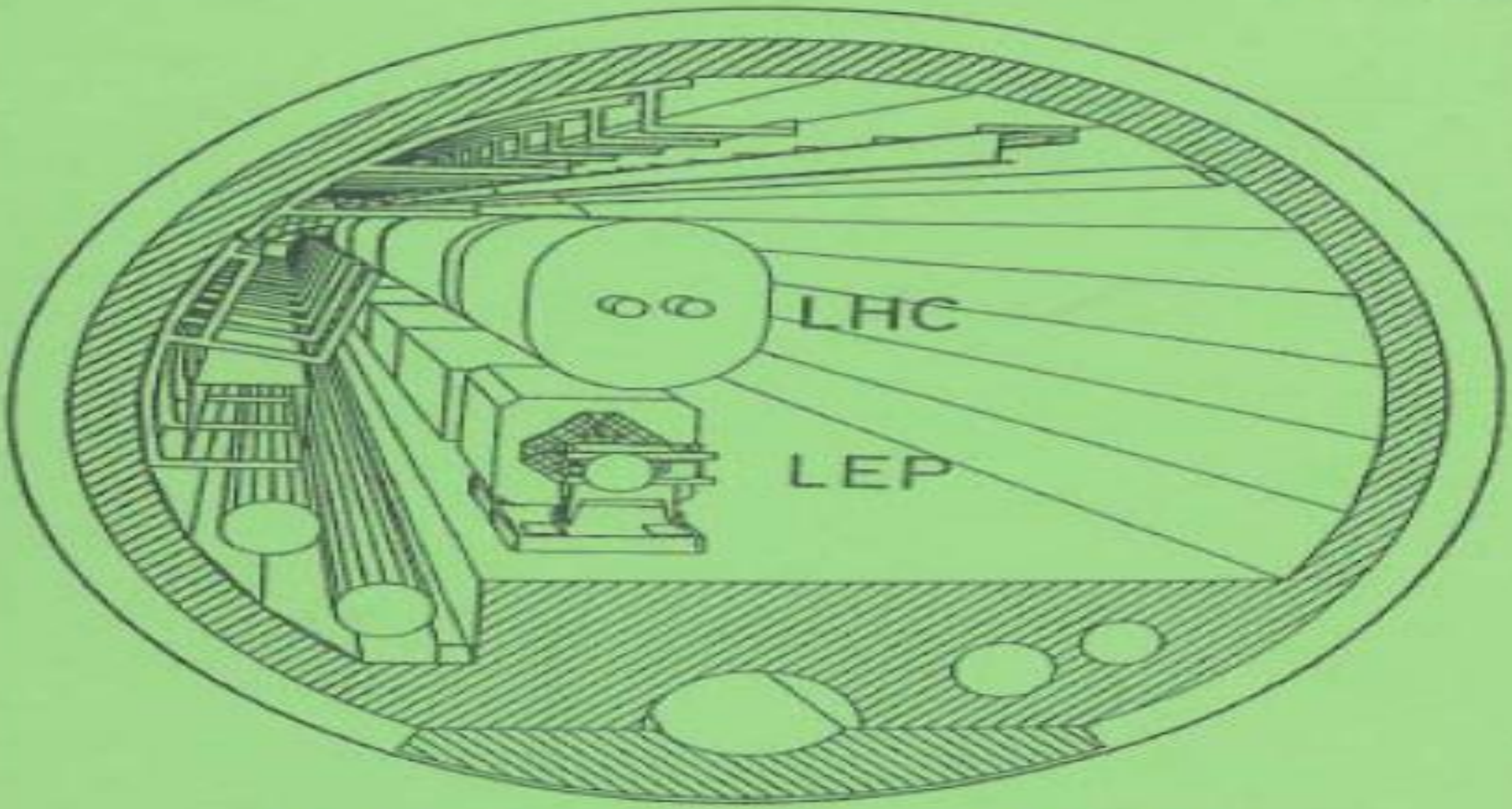
Physics at the LHC

ECFA 84/85
CERN 84–10
5 September 1984



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. II

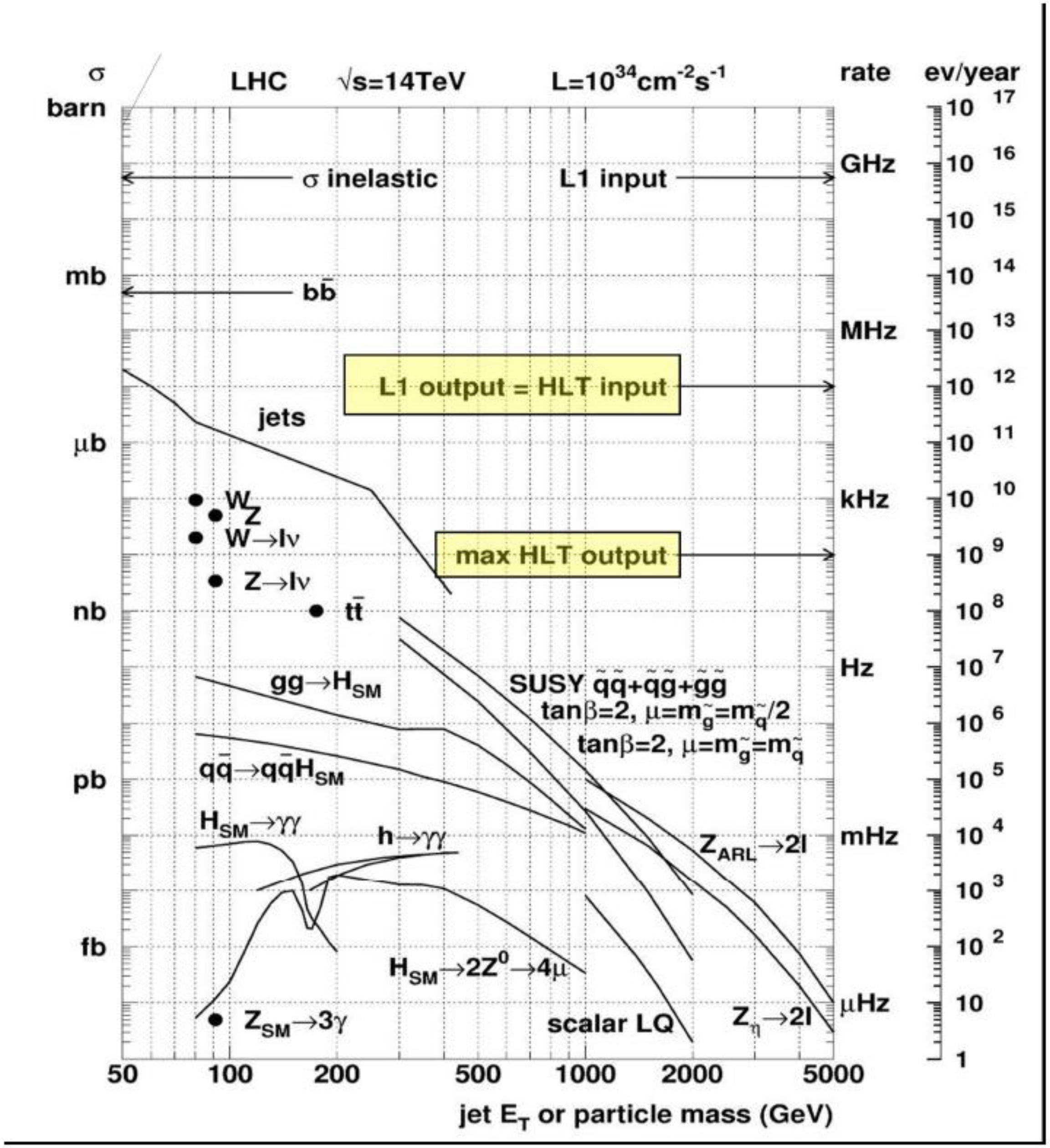
PROCEEDINGS OF THE ECFA–CERN WORKSHOP

held at Lausanne and Geneva,
21–27 March 1984

Introduction

Large Hadron Collider (LHC)
pp collider
$2\pi R \sim 27$ km
$\sqrt{s} = 14$ TeV
$L=10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
ALICE, CMS, LHCb, ATLAS,…
Many physics processes
High event rates
High energies
New physics

Start-up
November 2009
Single beams
Followed by collisions
@$\sqrt{s} = 10$ TeV
$L=10^{30,31,32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Introduction

LHC looking for something beyond SM
SM tried and tested experimentally in all possible ways →

Fortunately/unfortunately SM rather robust
Few deviations observed
→ still compatible with statistical fluctuations

Looking for direct/indirect deviations from SM
Measure SM observables with highest precision ever
Direct searches for new physics

Many many 10^{105} more models
than final states →

Strongly encouraged to look at
various final state topologies
Also certainly wiser with first data

	e	μ	τ	$\not p_T$	γ	jj	bb	e e	e μ	e τ	e $\not p_T$	e γ	e jj	e bb	$\mu\mu$	$\mu\tau$	$\mu \not p_T$	$\mu\gamma$	μ jj	μ bb	$\tau\tau$	$\tau \not p_T$	$\tau\gamma$	τ jj	τ bb	$\not p_T \gamma$	$\not p_T$ jj	$\not p_T$ bb	$\gamma\gamma$	γ jj	γ bb
bb bb																															
jj bb																															
jj jj																															
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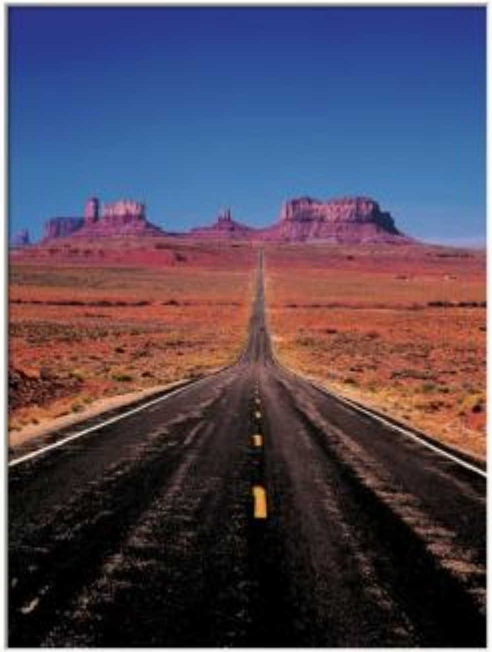
τ	A																														
μ																															
e	Z'			W'																											

Outline



LHC

ATLAS (and a tiny bit of CMS)

Early Physics

Phenomenological tools

Higgs hunt

Beyond the SM

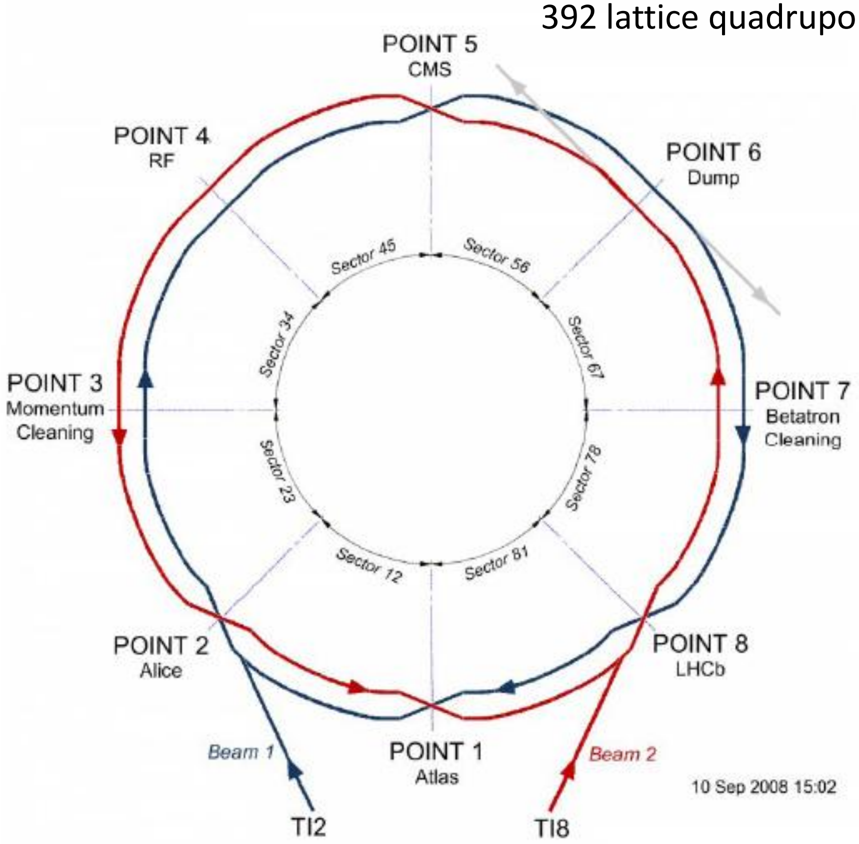
SUSY

N.B. All analyses performed for E_{cm}=14TeV unless otherwise mentioned

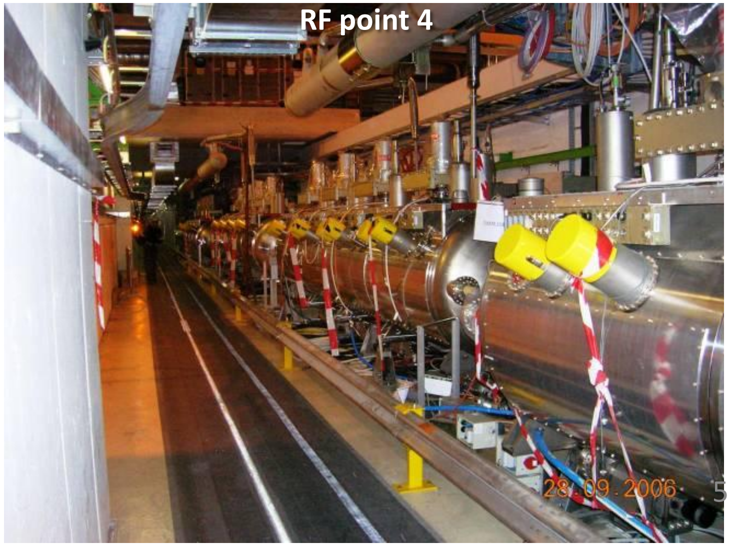
LHC

LHC beam 2808 bunches
→ 1.15 x 10^{11} protons/bunch
→ Xing rate 40 MHz (every 25ns)
→ 10^9 interactions/s
→ on average 23 minimum bias evts/Xing

Beam circulates in pipe → vacuum 10^{-13} atm
Radiofrequency (RF) electric field cavities → accelerate particles
1232 two-beams-in-one SC dipole magnets 8.33 T - 11.85 kA - cryogenic 1.9 K → bend beam trajectory
392 lattice quadrupoles → focalize beam



8 distinct sectors for cryogenics and powering
RF systems (Point 4)
Collimators (Points 3, 7) for beam cleanup
Injection (Points 2, 8)
Beam extraction/dump (Point 6)



LHC

19.09.2008

Making last step of dipole circuit in sector 34, to 9.3kA

At 8.7kA, development of resistive zone in dipole bus bar splice

Electrical arc developed which punctured helium enclosure, allowing helium release into insulating vacuum

Large pressure wave travelled along accelerator in both directions

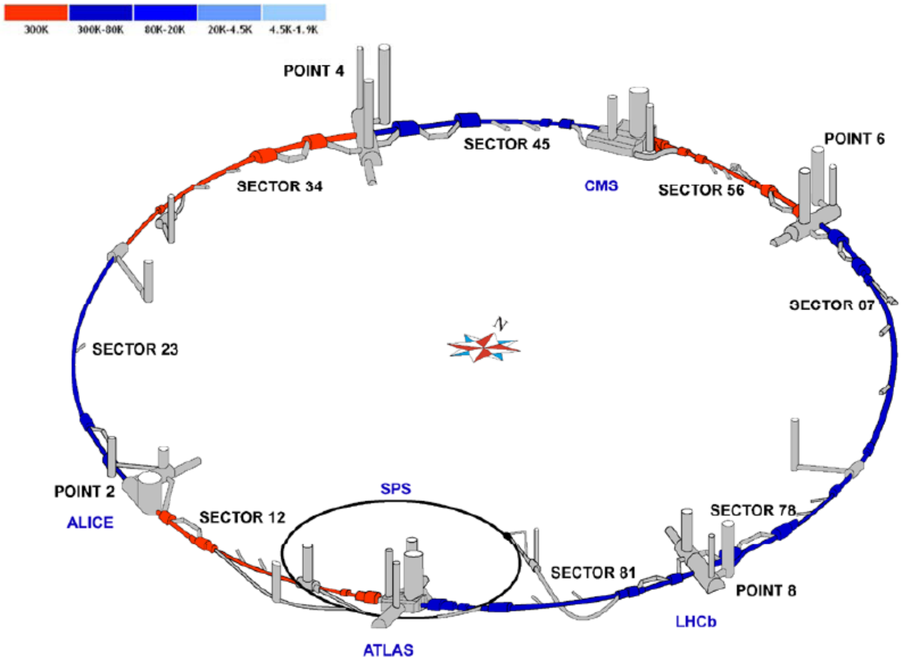
Today

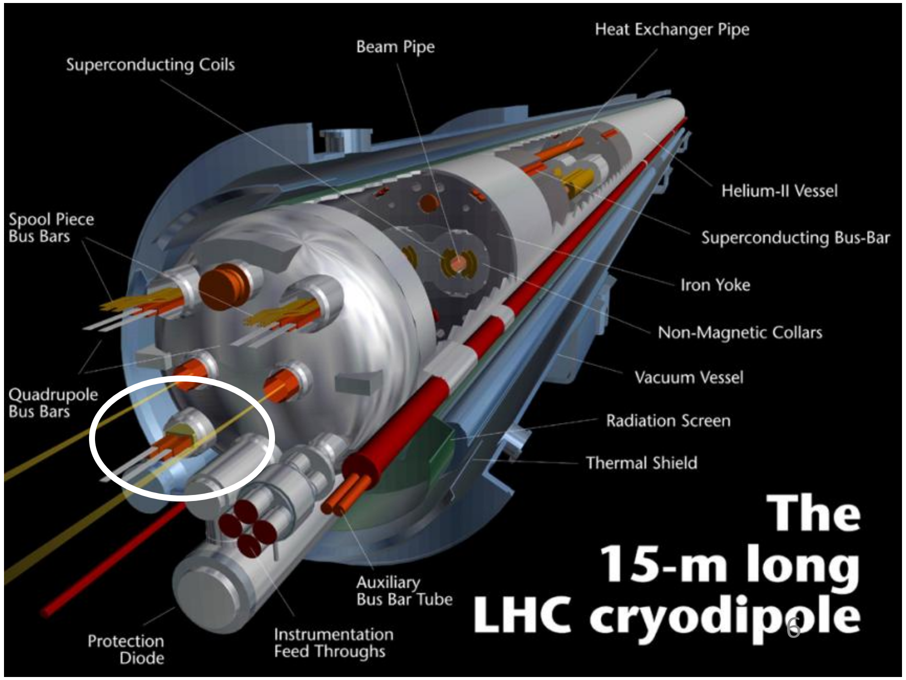
All dipole resistance measurements were investigated

High resistance in bus bars had been monitored and is now understood

Problematic dipoles fixed

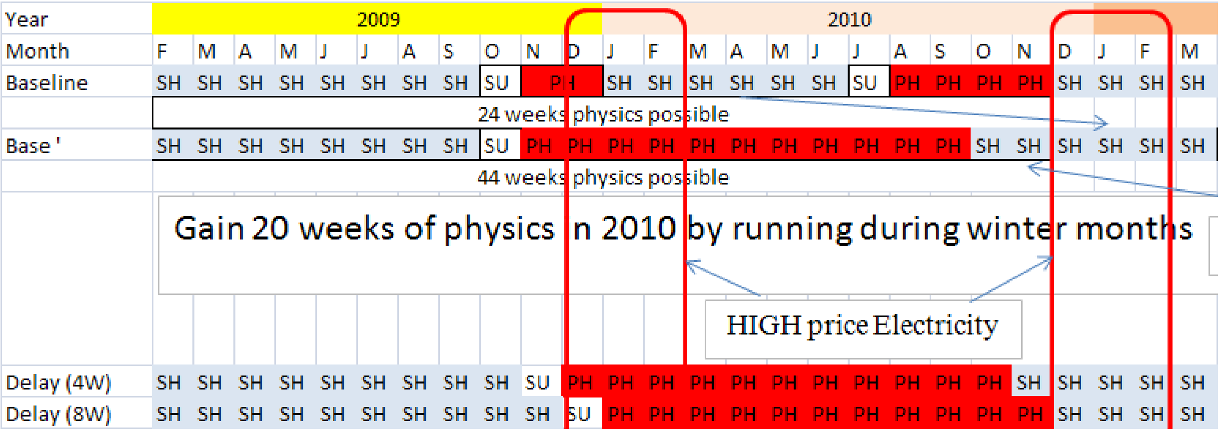
Additional security measures: quench protection system upgrade





LHC

Latest schedule →
running through winter 2009-2010
E_{beam} = 5TeV



Year	2009											2010														
Month	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
Baseline	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH		SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	SH	SH	SH	SH
	24 weeks physics possible																									
Base '	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH	SH	SH
	44 weeks physics possible																									
Delay (4W)	SH	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH	SH
Delay (8W)	SH	SH	SH	SH	SH	SH	SH	SH	SH	SH	SU	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	PH	SH	SH	SH	SH

Gain 20 weeks of physics in 2010 by running during winter months

HIGH price Electricity

Expected luminosity

Month	No. Bunches	Protons per bunch	β* [m]	% Nom	Peak luminosity cm-2s-1	Integrated luminosity
1	Beam Commissioning					
2	43	3×10^{10}	4	0.4	1.2×10^{30}	100 – 200 nb^{-1}
3	43	5×10^{10}	4	0.7	3.4×10^{30}	~2 pb^{-1}
4	156	5×10^{10}	2	2.5	2.5×10^{31}	~13 pb^{-1}
5	156	7×10^{10}	2	3.3	4.9×10^{31}	~25 pb^{-1}
6	720	3×10^{10}	2	6.7	4.0×10^{31}	~21 pb^{-1}
7	720	5×10^{10}	2	11.2	1.1×10^{32}	~60 pb^{-1}
8	720	5×10^{10}	2	11.2	1.1×10^{32}	~60 pb^{-1}
9	720	5×10^{10}	2	11.2	1.1×10^{32}	~60 pb^{-1}
10	Ions					
Total						**200 – 300 pb^{-1}**

ATLAS

A Toroidal LHC Apparatus

Calorimetry $|\eta| < 4.9$

- **EMBC, EMEC** accordion LAr + Pb $|\eta|<3.2$
- **Tile** Hadronic Fe + scintillator $|\eta|<1.7$
- **HEC** Hadr end cap Cu+Lar $1.5<|\eta|<3.2$
- **FCAL** Forward calo Cu+W+Lar $3.1<|\eta|<4.9$

Muon spectrometer $|\eta| < 2.7$

High precision tracking

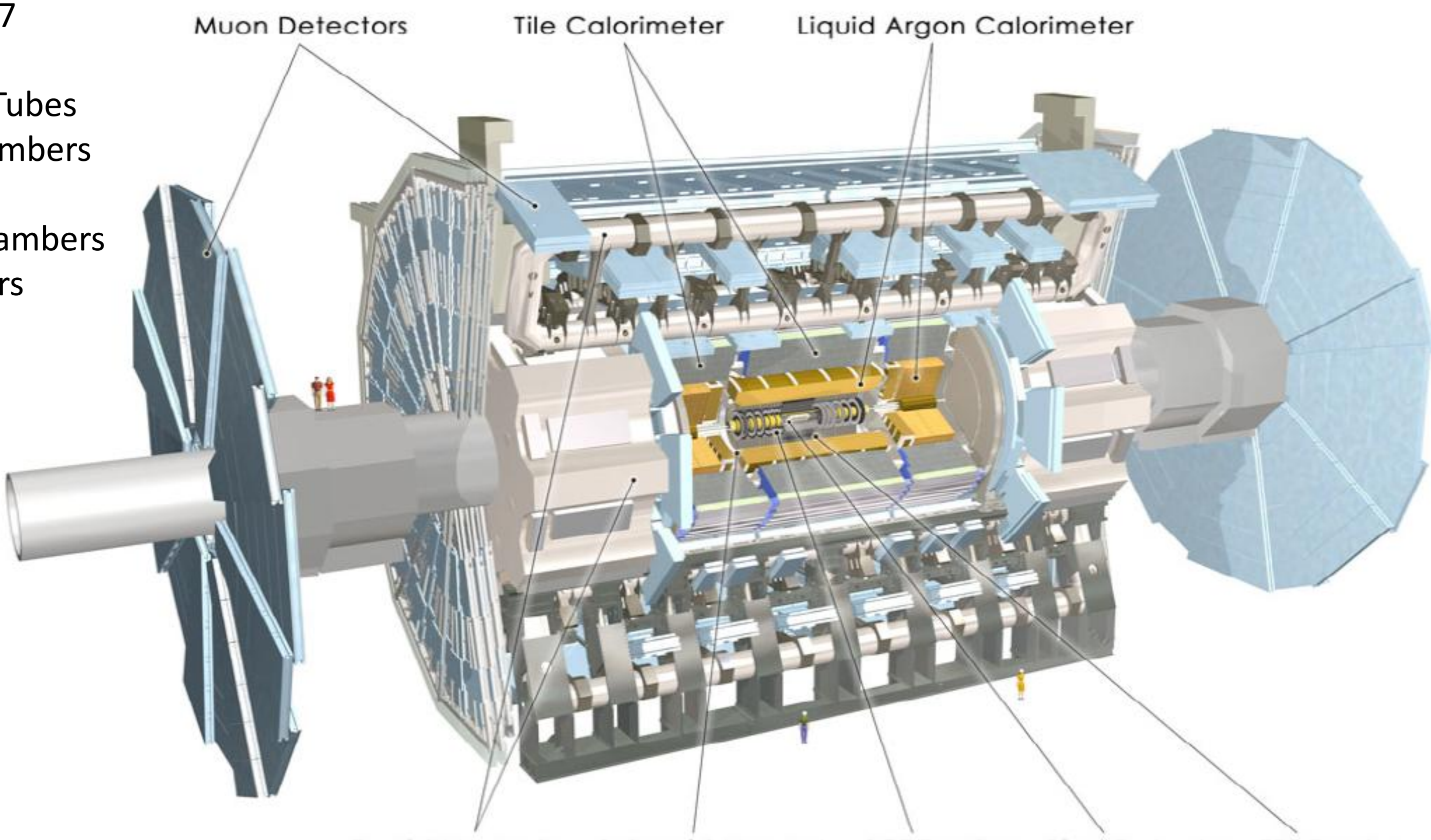
- **MDT** Monitored Drift Tubes
- **CSC** Cathode Strip Chambers

Trigger chambers

- **RPC** Resistive Plate Chambers
- **TGC** Thin Gap Chambers

Air core toroid system

→ strong bending power
in large volume

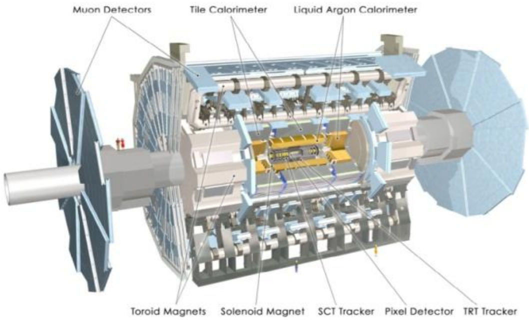


Inner Detector

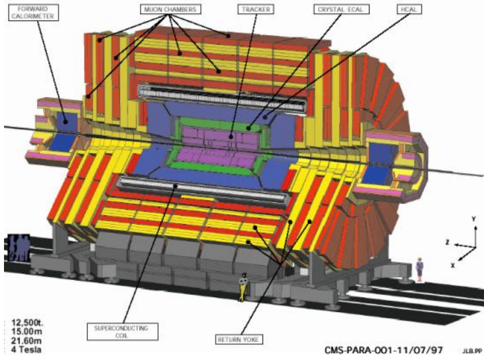
~6m long 1.1m radius inside 2T **Solenoid**

- **Pixels**
- **SCT** Silicon Strips
- **TRT** Transition Radiation Tracker e/π separation

3 trigger levels : L1, L2, Event Filter (L2+EF=HLT)
40 MHz → 200 Hz



CMS vs ATLAS



Parameter	***ATLAS***	***CMS***
Weight (tons)	7k	12.5k
Diameter (m)	22	15
Length (m)	46	20
Magnetic field for tracking (T)	2	4
Toroid peak fields (T)	3.9 (B) 4.1 (EC)	– –
Solid angle lepton id for tracking ($\Delta\phi$ X $\Delta\eta$)	2π X 5.0	2π X 5.0
Solid angle : E measurement ($\Delta\phi$ X $\Delta\eta$)	2π X 9.6	2π X 9.6
Cost (MCHF)	550	550

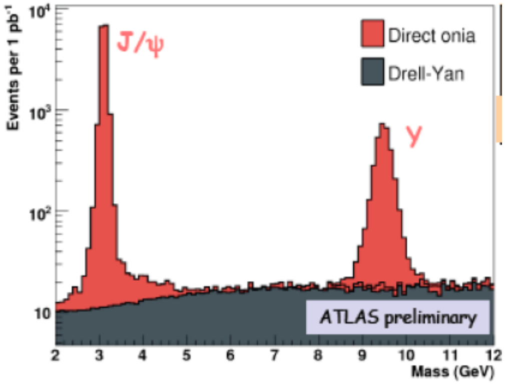
Resolution performances

	ATLAS	CMS
Tracker	Si pixels, strips + TRT (pid) $\sigma/p_T \approx 5\text{x}10^{-4} p_T \oplus 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\text{x}10^{-4} p_T \oplus 0.005$
EM calorimeter	Pb + LAr $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.007$	$PbWO_4$ crystals $\sigma/E \approx 2\text{-}5\%/\sqrt{E} \oplus 0.005$
Hadronic calorimeter	Fe+scintillator / Cu + Lar $\sigma/E \approx 50\%/\sqrt{E} \oplus 0.03$	Cu+scintillator $\sigma/E \approx 100\%/\sqrt{E} \oplus 0.05$
Combined Muons (ID+MS)	2%@50GeV to 10%@1TeV	1%@50GeV to 5%@1TeV

Identification performances

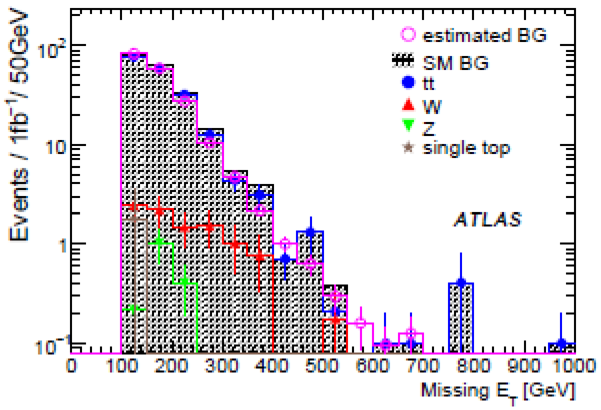
Photons	Jet rejection ~ few 10^3 for $\varepsilon_\gamma \sim 80\%$
Electrons	Jet rejection ~ 10^5 for $\varepsilon_e \sim 80\%$
B-jets	Light flavor jet rejection ~ 100 for $\varepsilon_{B\text{-jets}} \sim 60\%$
$\tau \rightarrow$hadrons	Jet rejection ~ few hundreds for $\varepsilon_{\tau had} \sim 50\%$

Early physics



1pb-1 = 3.85 days @ $L=10^{31}$ cm^{-2}s^{-1}

($\varepsilon_{machine}$ x $\varepsilon_{detector}$ = 30%)



e.g.

- $J/\psi \to \mu\mu$ 800/day
- $Z \to \mu\mu$ 160/day
- $Z \to ee$
- ***Top events***
- ***Inclusive jets***
- ***Minimum bias events***
- ***Underlying events***

→ Detector/Trigger commissioning and calibration
→ Tune simulation/reconstruction software
→ Some SM with W,Z,top,jets
→ PDFs
→ Some new physics (see BSM, SUSY)
etc.

Uncertainties for 100pb-1 (10 fb-1)

• e/γ	**fake rates** =50 (10) %	σ_p=20 (5) %	ε_{id} = 1 (0.2) %	**Escale**=1 (0.1) %
• μ	p_T < 100 GeV	σ_p=12 (1) %	ε_{id} = 1 (0.1) %	
	p_T = 1TeV	σ_p=100 %	ε_{id} = 5 (0.1) %	**Escale**= 1 (0.1) %
• ***Jets***		σ_E =10 %		**Escale**=±5 % |η|<3.2
				Escale=±10 % 3.2<|η|<4.9

- ***MET***=-($\Sigma pT_{\ell s}$+ Σ ET_{jets} + $\Sigma ET_{unclustered}$) sum of all uncertainties! + "fake" MET
- ***Luminosity*** 20 (3) %
- ***Theoretical e.g. EW and QCD Xsections*** 15-50 %
- ***PDFs*** 5-20 %

etc.

Phenomenological tools - Generators

HO QCD corrections → K-factors
If K-factors known for signal and dominant bgd → included in analyses
If K-factors unknown → Born-level predictions for signal and bgd
Both LO and NLO MC generators used
For several processes, tree-level Matrix Element calculations + Parton Shower matching
All tree level MC Xsec normalized to NLO Xsec
CTEQ6L (LO) and CTEQ6M ((N)NLO) structure function parametrizations used

General-purpose MC generators

PYTHIA, HERWIG
Sherpa : EW bosons + jets
AcerMC : Zbbar, Zttbar
ALPGEN : W/Z + jets with MLM PS + ME matching
MadGraph/MadEvent : W/Z + partons
MC@NLO : inclusive W and Z, Higgs, ttbar

Specific processes

Charybdis : Black Holes
CompHEP/CalcHEP : New Physics
TopReX : top
WINHAC : hadro production of Ws decaying into leptons
DIPHOX, RESBOS : NLO for $\gamma\gamma$

Hadronisation and underlying event (UE) modelling

PYTHIA, HERWIG (hadronisation) / JIMMY (UE)
UE parameters tuned to published data from Tevatron and other experiments

Specific decays

TAUOLA → Decay of τ leptons
PHOTOS QED → Radiation of photons from charged leptons
EvtGen → b-hadron decays

Higgs hunt

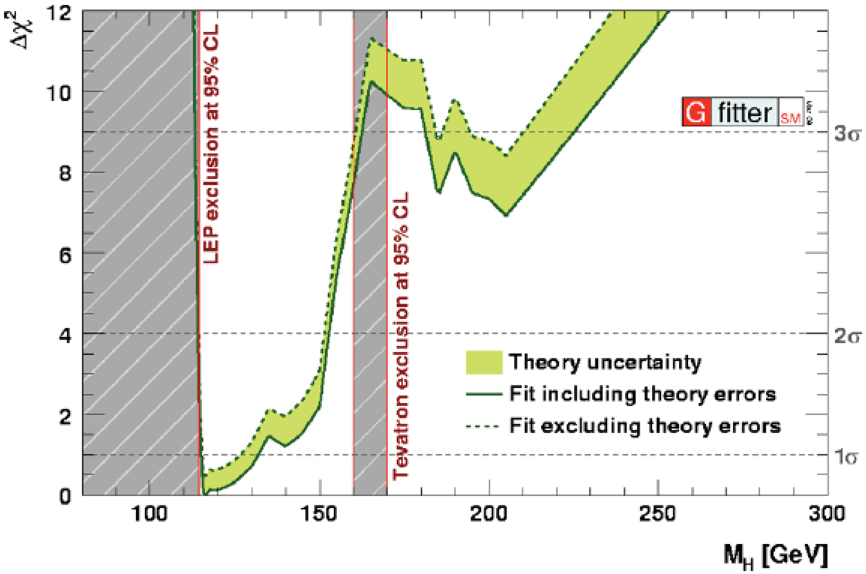
Velazquez

Higgs hunt

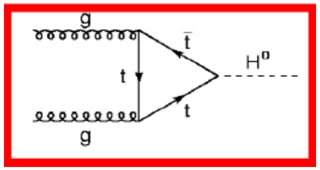
Today's experimental limits

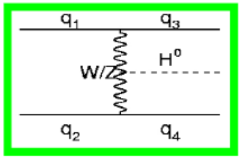
χ^2 vs m_{Higgs}
for fit to data
Tevatron limit and m_{top}/m_W
from Moriond EW 2009

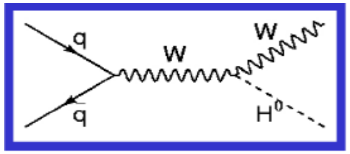
$m_{Higgs} = 116\ ^{+15.6}_{-1.3}$ GeV

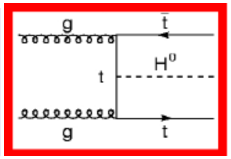


SM Higgs Production@LHC
gluon fusion (GF)
vector boson fusion (VBF)
ZH, WH
ttH

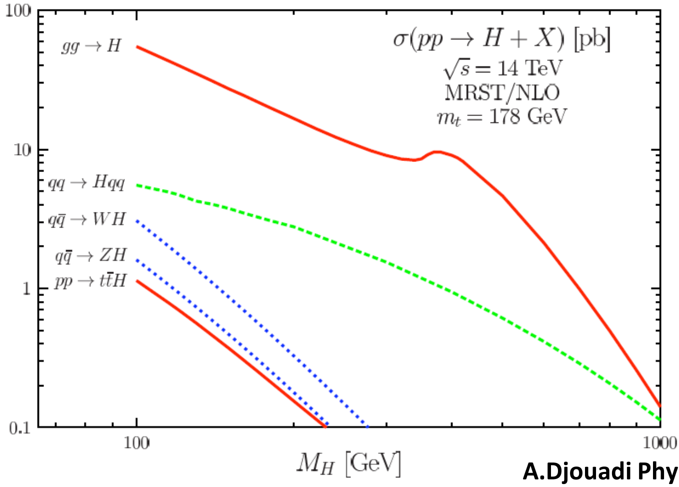


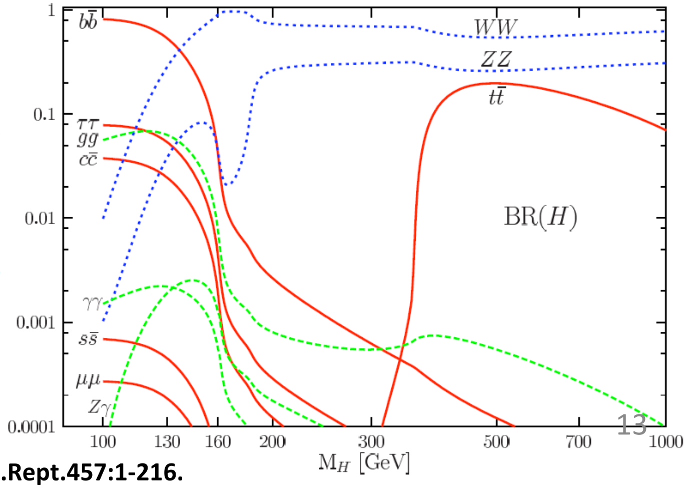






SM Higgs Decay@LHC
low mass: bbbar, ττ, γγ,
high mass: WW, ZZ

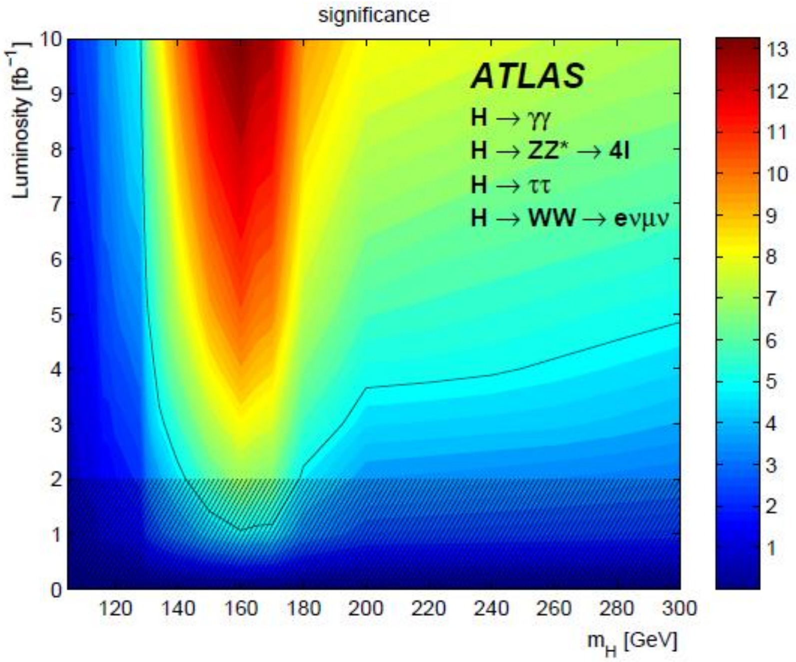


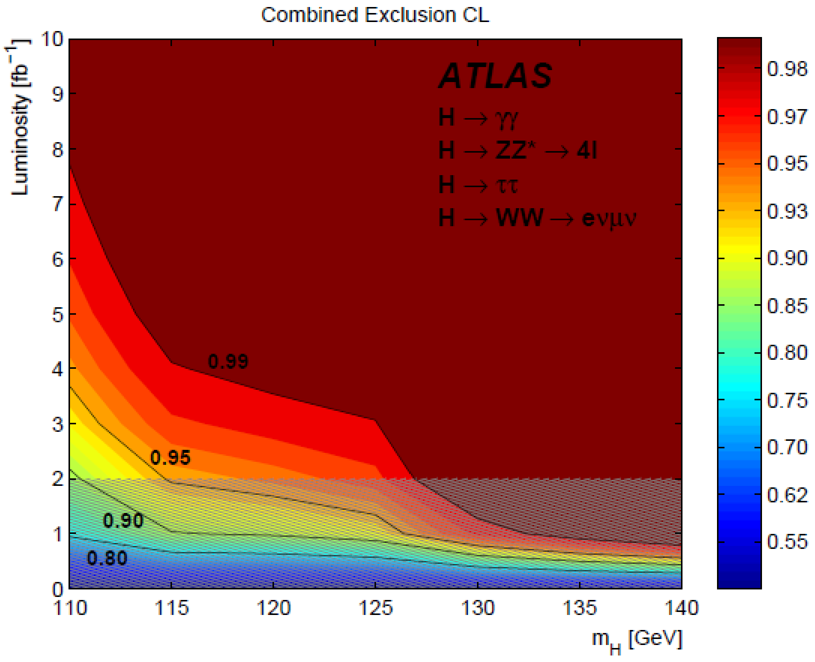


A.Djouadi Phys.Rept.457:1-216.

SM Higgs Hunt – discovery/exclusion

Left: Significance contours for ∫Ldt vs m_H
Thick curve → 5σ discovery
Approximations used in combination → conservative but not valid <2fb-1 (hatched area)
Right: Expected ∫Ldt to exclude Higgs vs m_H





Not all search channels exploited in combination → conservative estimates of sensitivity
With 2fb−1 expected sensitivity ≥ 5σ for 143 GeV < m_{Higgs} < 179 GeV
and expected upper limit @95% CL on Higgs mass is 115 GeV

SM Higgs Hunt - Determining Higgs properties

Older analyses→ need updating

Mass

300 fb^{-1} $\sigma_m \sim$ 0.1% for m_H=100-400 GeV/c^2 $\sigma_m \sim$ 1% for $m_H \sim$ 700 GeV/c^2

Width

Direct measurement from fit to mass peak

300 fb^{-1} $\sigma_\Gamma \sim$ 6% for m_H>200 GeV/c^2

Spin and CP eigenvalues

Is it the $J^{CP}=0^{++}$ SM Higgs ?

Study angular distributions and correlations in H→ZZ→4ℓ (μ or e) and VBF H→WW/ττ

30 fb^{-1} exclusion of non-SM CP with 2 [5]σ for m_H=120 [160] GeV/c^2

≤ 300 fb^{-1} (J,CP)=(1,-1), (1,+1), (0,-1) ruled out for m_H>200 GeV/c^2

Coupling parameters

By measuring rates of a large number of Higgs production and decay channels

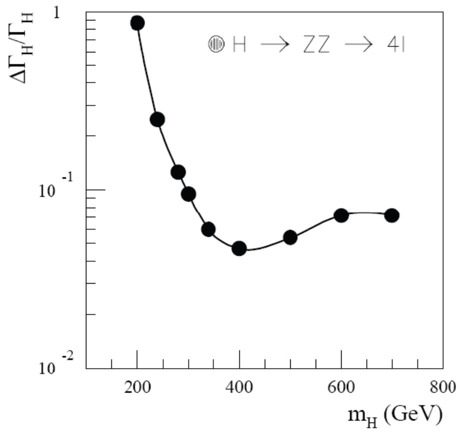
Various combinations of couplings can be determined

300 fb^{-1} 110<m_H<190 GeV/c^2 $\Delta g^2/g^2 \sim$ 10%-60% (≠ b) $\Delta\Gamma_H/\Gamma_H \sim$ 10%-75%

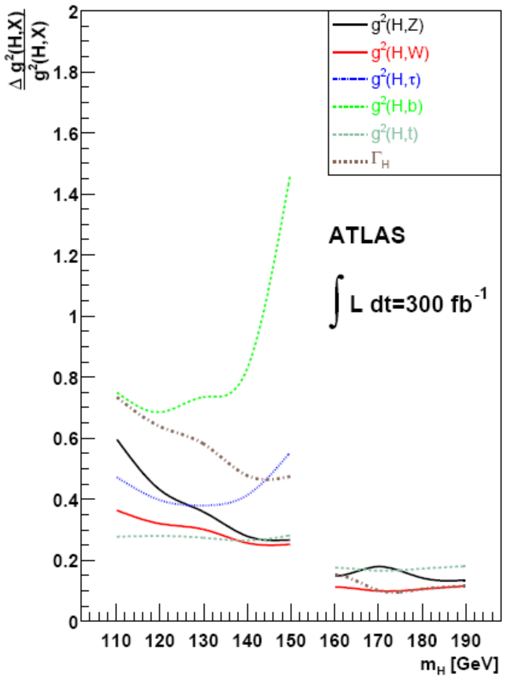
Self coupling

Difficult

Will need at the very least 300 fb-1



ATLAS-PHYS-2003-030



MSSM Higgs Hunt

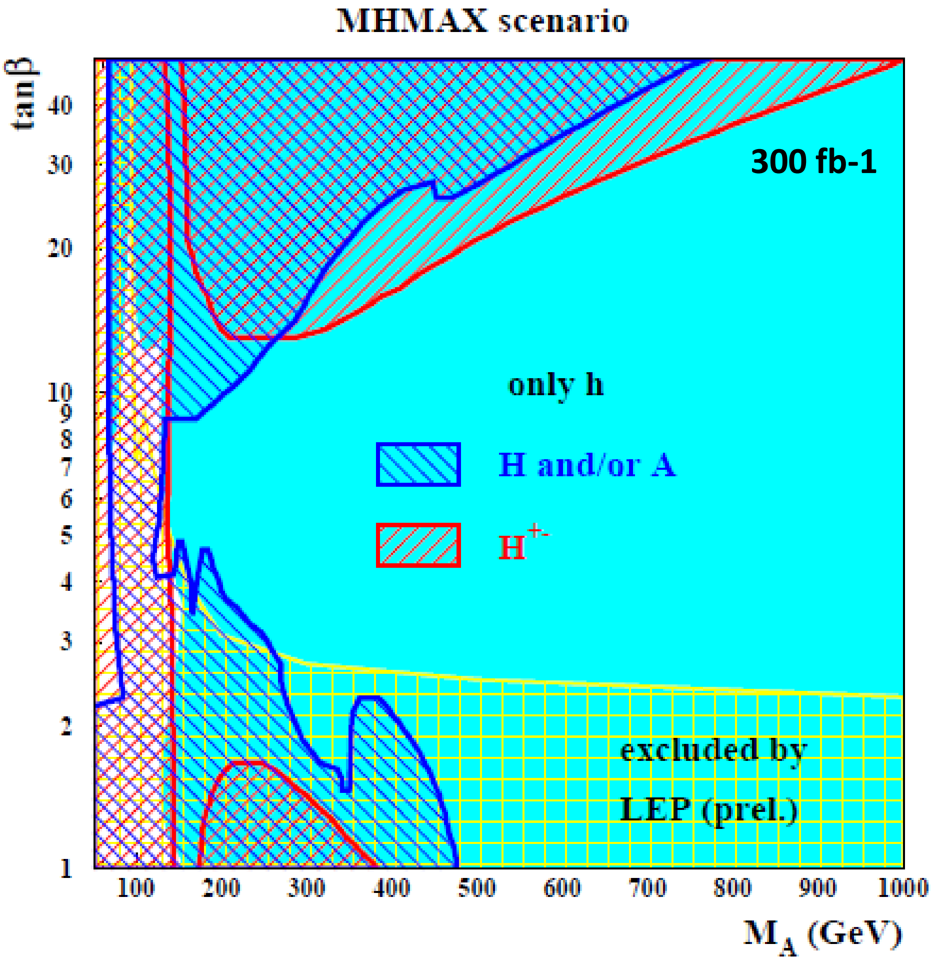
h, H, A and H±

Benchmark scenario m_h^{max} maximal theoretically allowed region for m_h

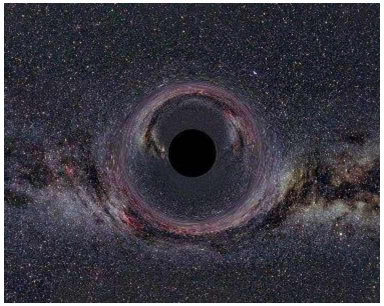
300 fb-1
tanβ vs m_A
MSSM Higgses discovery potential

- **≥ 1 Higgs observable for all parameter points**
- **In some parts >1 Higgs observable**
  → SM vs MSSM
- **Significant area where only h observable**

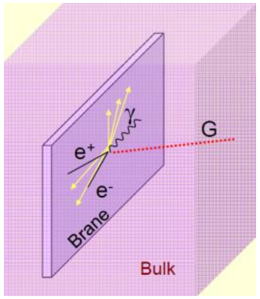
N.B.
Plots not recently updated
No systematic uncertainties included

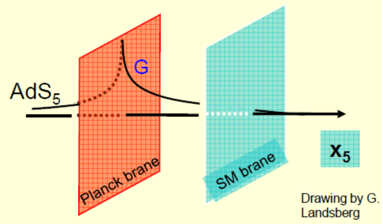


Beyond the SM



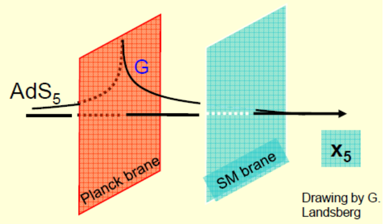
Topological searches
and
Model dependent searches





Drawing by G. Landsberg

BSM



Dilepton resonances at high mass

Simplicity of final state → important channel with early data

Tevatron excludes resonance m ~< 1 TeV

Z'

In context of Sequential SM (SSM), E_6, and Left-Right symmetric models

Randall Sundrum Graviton

Warped extra-dimension linking SM brane and Planck brane

Only graviton propagates into XtraD → tower of KK excitations G* → ℓ+ℓ-

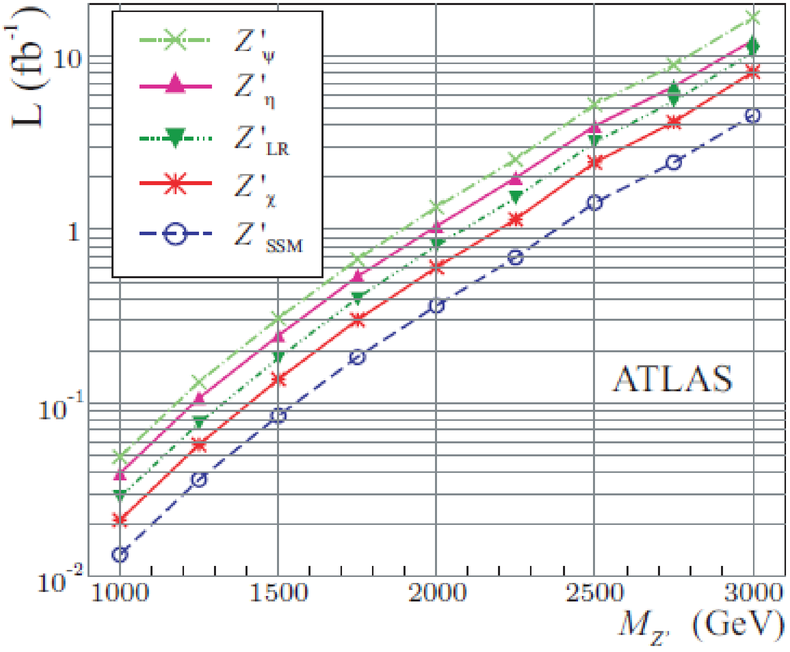
Technicolor Strawman model

New techni-fermions bound together by QCD-like force : ρ_{TC} and ω_{TC} dilepton decay

Z'→e+e-

5σ significance with stats errors only

Systematic errors change result by ~ few %



$m_{Z'}$ = 1 TeV

e+e- < 100 pb−1

μ+μ- 20 to 40 pb−1

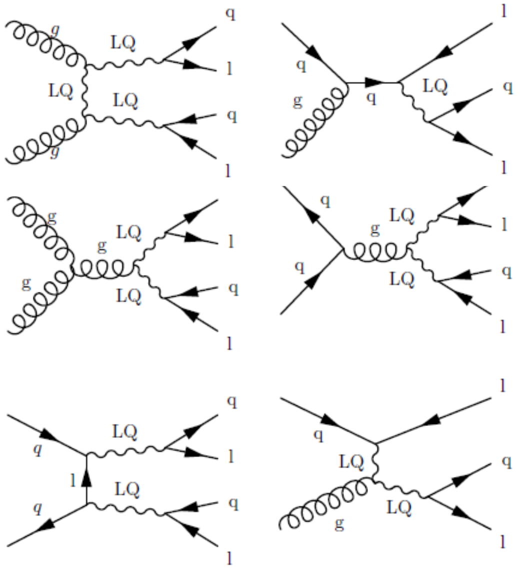
τ+τ- ~ 1fb-1

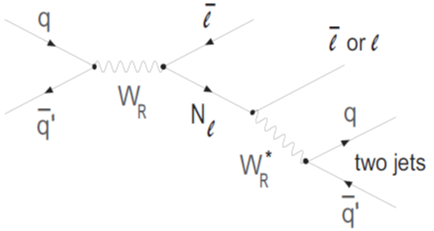
RS and technicolor

~ 1fb-1 for ~0.5-1.5 TeV dilepton resonance

BSM

Dilepton + dijets





Leptoquarks

LQ → leptons+quarks

Tevatron exclusion limits for $\beta=BR(LQ\to\ell^{\pm}q)=1$ ~< 300-350 GeV

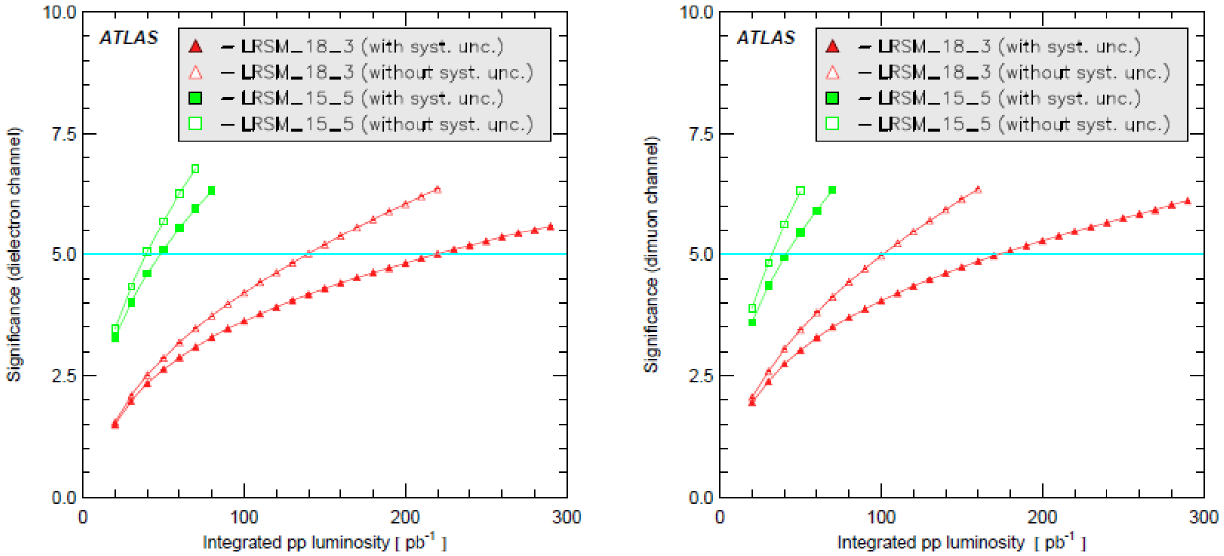
Left Right Symmetric Model

3 heavy right-handed Majorana ν's N_e, N_μ and N_τ

W_R and Z' produced via DY

$m(K_L)-m(K_S)\to m_{WR}>1.6$ TeV

SN1987A + LEP invisible Z → $m_N\sim$ few 100 GeV



LRSM
Dielectron+dimuon channels
150 pb-1 for m_{WR}=1800 GeV , $m_{Ne,\mu}$= 300 GeV
40 pb-1 for m_{WR}=1500 GeV , $m_{Ne,\mu}$= 500 GeV

LQ
100 pb-1 for $\beta=BR(LQ\to\ell q)=1$
$m_{LQ}\leq$ 565 GeV (1st gen)
$m_{LQ}\leq$ 575 GeV (2nd gen)

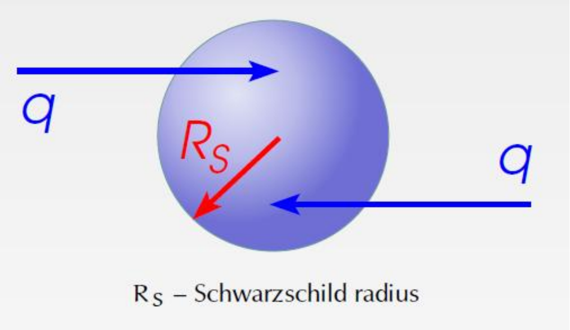
BSM

Black Holes

In XtraD models M_{Planck} → M_{EWSB}
→ gravity coupling strength increased to size ~ other interactions
→ unification of gravity and gauge interactions
→ Black Holes (BH) production @ LHC

BH formation, radiation and decay

BHs form if impact parameter of head-on collision between 2 partons < $R_{schwarzschild}$
R_s depends on n=umber of XtraDs and M_D=fundamental Planck scale
Parton level Xsec valid for $M_{BH} >> M_D$
BHs emit pairs of virtual particles and decay by balding (Graviton radiation),
followed by evaporation (Hawking radiation)
ending by Planck phase $M_{BH} \sim M_D$ (QG regime : predictions very difficult…)



Charybdis BH MC

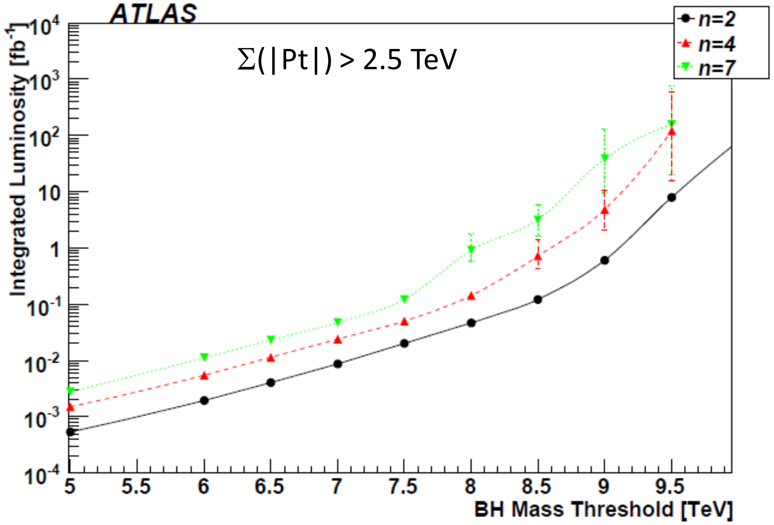
Only simulates SM particles emitted during evaporation and Planck phases
$M_{BH} \geq 5M_D$ with $M_D \sim$ 1TeV

Discovery reach N.B.

Using semi-classical assumptions valid only above Planck scale
(minimum m_{BH} imposed in simulations)
Assuming correct transition parton level → hadron level Xsec
in Transplanckian region

Minimum m_{BH} varied to obtain conservative discovery reach

Few pb-1 → discovery of BH with m_{BH} > 5 TeV
1 fb−1 → m_{BH} > 8 TeV



BSM

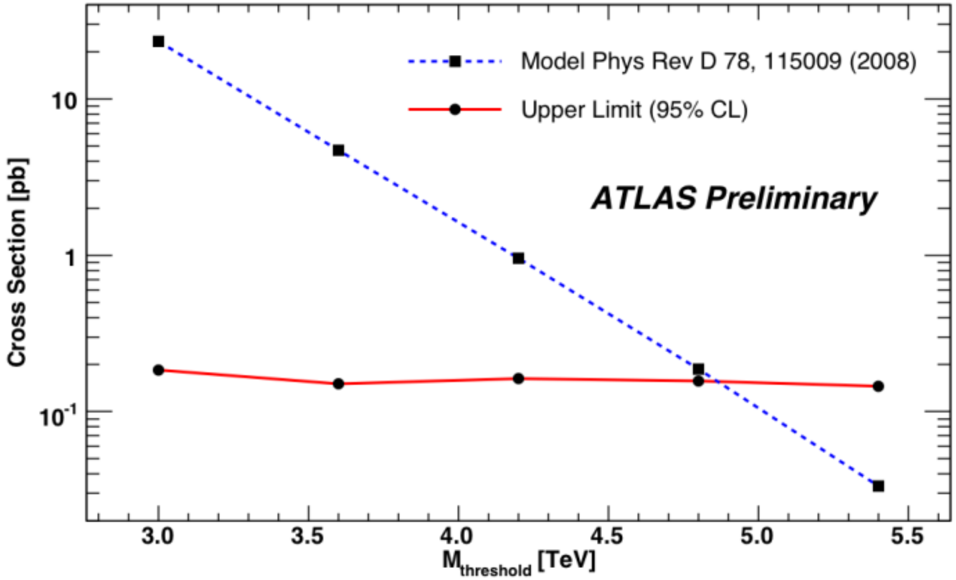
String balls

If $M_{BH} < 5M_D$ == the General Relativity threshold not satisfied → Quantum Gravity
In context of weakly-coupled string theory, highly-excited string states produced with Xsec $\sim$ $Xsec_{BH}$
Even if BHs produced → evolve into string states
String balls → new form of matter involving gravity and string theory

4 parameters : string scale M_S and coupling g_S , n=umber of extraDs, M_D=fundamental Planck scale
$M_S < M_D < M_S/g_S^2 \sim 5\ M_D$ (BH prod threshold)
Highly-excited long strings emit particles in bulk or on brane
SB decay mainly on brane

Limits on Xsec vs $m_{threshold}$
for string ball production
100 pb^{-1} at E_{cm}=10 TeV
Exclude@95%CL
Xsec > 185 fb for 3.0 TeV < $m_{threshold}$ <5.4 TeV

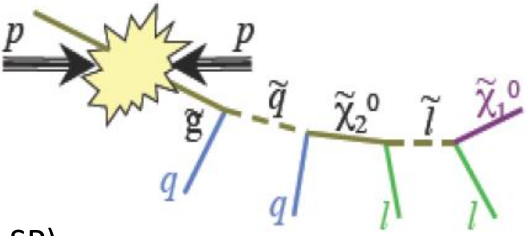
Based on a simple model
for string ball production
M_S < 1.6 TeV and M_D < 2.4 TeV excluded



SUSY

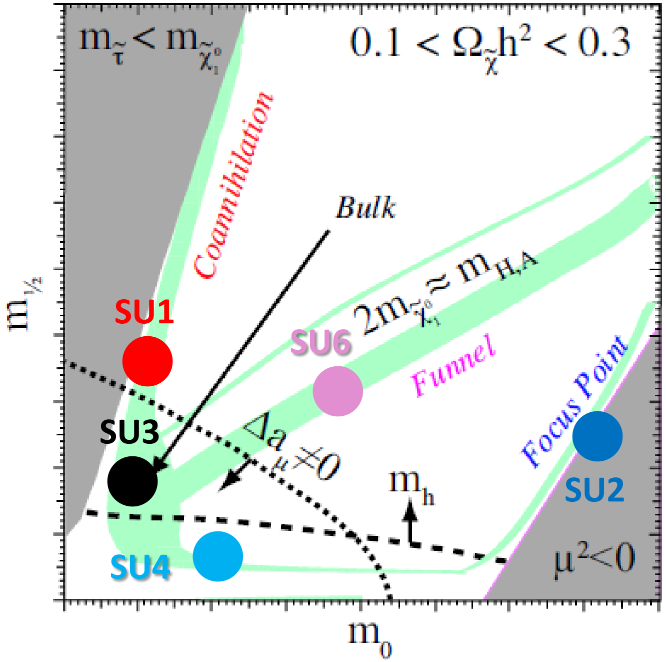
↔

SUSY



If R-parity is conserved
→ sparticles produced in pairs (squarks, gluinos)
→ cascade decay down to stable lightest SUSY particle (LSP)

Some investigated scenarios :
mSUGRA (LSP=neutralino)
SUSY breaking mediated by gravitational interaction
GMSB (LSP=gravitino)
SUSY breaking mediated by gauge interactions
through messenger gauge fields
Split SUSY
Gluinos can be meta-stable forming a bound state
so-called $R_{\sim g}$-hadron
Gravitino LSP and stop NLSP scenario
Generic possible candidate for NLSP is lightest ~t_1
which would form stable bound states
denoted $R_{\sim t}$



Current experimental limits $m_{squarks,gluinos}$<~600 GeV, tan β = 3-5, A_0=0, μ<0 @ e.g. Tevatron 2fb-1

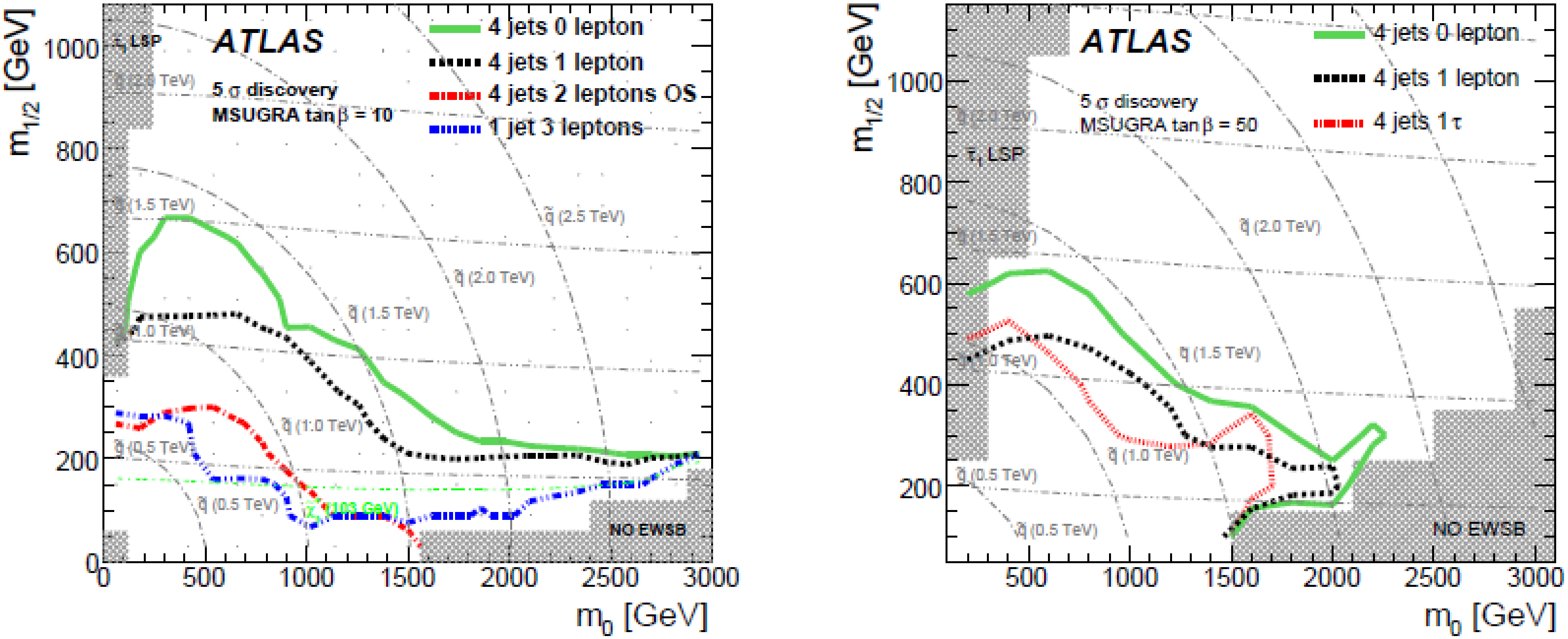
SUSY discovery based on inclusive searches
Least model-dependent SUSY signature → multiple jets (e.g. ≥4) + MET
Final state → jets + possible leptons + MET
Variables e.g. MET, Effective mass (Meff) = $\Sigma_{i=1,4}$ pT_{jeti} $\Sigma_{i=1,4}$ pT_{lepti} + MET
Data driven determination of bgds : W,Z,top 20% QCD 50% with 1fb-1

2 different approaches
→ Detailed studies for various signatures (jets + MET + 0,1,2,3… leptons) → full simulation
→ Scans over subsets of SUSY parameter space → fast simulation

SUSY scans

Over parameters of several R-parity conserving SUSY models
Look for excess above cut on Meff (best performance) or MET

Scans 1fb-1
Plots based on analyses that require a certain number of jets and leptons (e or μ)
Find an optimal M_{eff} cut in steps of 400 GeV to maximize significance (20% bgd uncertainty included)



5σ discovery for mSUGRA $\tan\beta = 10$ and 50 4 jets + N lepts = 0,1,2,3

Scans and detailed analyses with SM bgds estimated from data →
R-parity conserving SUSY observable for $m_{gluino, squark} \leq 1$ TeV with 1fb−1 of understood data

SUSY or something else?

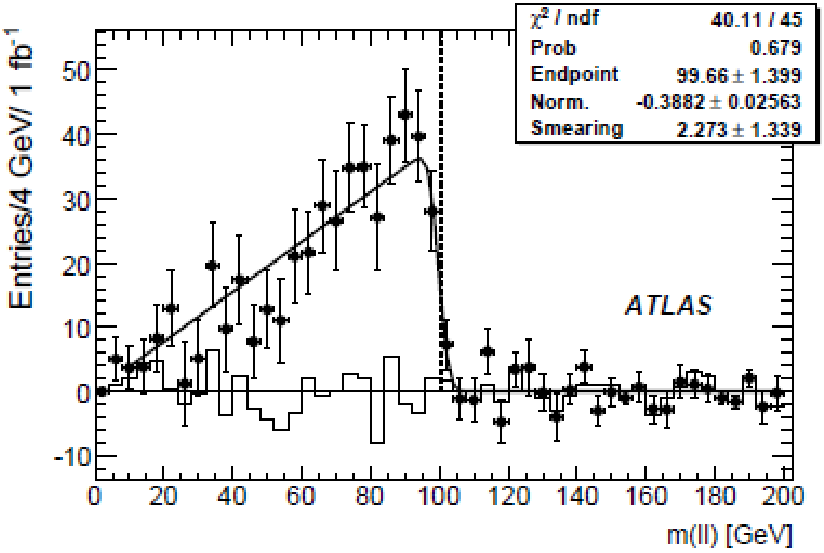
Is it SUSY ?

e.g. Universal Extra Dimensions vs SUSY → 2nd level KK particle discovery (if light enough)

or spin measurements (100 fb-1 at the very least)

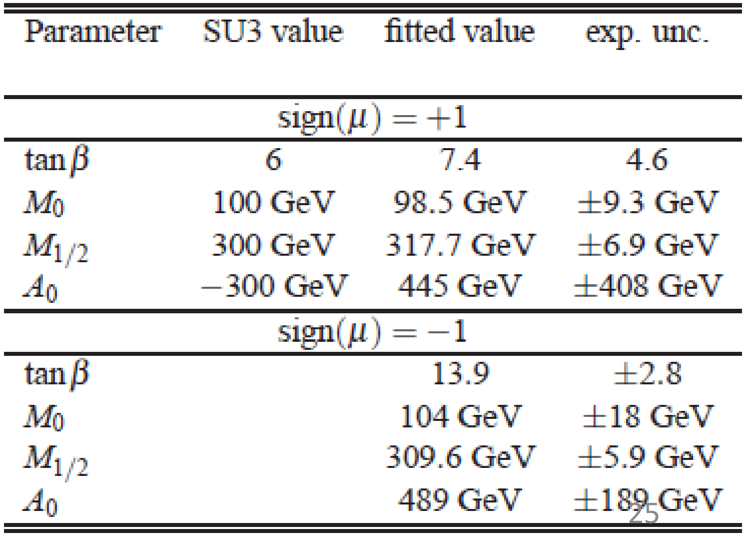
If SUSY, what kind ?

- Edges and thresholds in dilepton, lepton-jet, dijet invariant mass distributions → Mass values
- All observables in a fit to SUSY parameters → $m_{1/2}$, m_0, tanβ , A_0



1 fb−1 SU3 χ^0_2→ ~ℓ+ℓ− → χ^0_1 ℓ+ℓ−
SM=line histo, points=SM+SUSY

Results of fit of
SU3 mSUGRA parameters
to observables
Effect from theoretical
uncertainties shown



Parameter	SU3 value	fitted value	exp. unc.
	sign(μ) = +1		
tan β	6	7.4	4.6
M_0	100 GeV	98.5 GeV	±9.3 GeV
$M_{1/2}$	300 GeV	317.7 GeV	±6.9 GeV
A_0	−300 GeV	445 GeV	±408 GeV
	sign(μ) = −1		
tan β		13.9	±2.8
M_0		104 GeV	±18 GeV
$M_{1/2}$		309.6 GeV	±5.9 GeV
A_0		489 GeV	±189 GeV

Summary, conclusion and outlook

100m sprint "random BIG grid" scan over LHC physics and phenomenological models

$m_{NP} < 1$TeV discovery with 1fb-1 in many final states
In some cases even 100pb-1 will do

In all cases one needs a mastered detector

Simple final states are most reliable e.g. dilepton resonances (Z, Z', G). Contribute to
→Understanding detector
→ Discovery

SM, detector, EW and QCD backgrounds, PDFs, MET, etc.
understanding will definitely need at least 1 fb-1

Lots of work awaiting

References

Most of the results shown in this talks are published in:

The ATLAS Experiment at the CERN Large Hadron Collider, JINST 3 S08003, 2008

Expected Performance of the ATLAS Experiment Detector, Trigger and Physics, CERN-OPEN-2008-020; http://arxiv.org/abs/0901.0512

Physics Performance Technical Design Report CMS Collaboration, CERN/LHCC 2006-021, J. Phys. G: Nucl. Part. Phys. 34 (2007)

For string balls

S. Dimopoulos and R. Emparan, String balls at the LHC and beyond, Phys. Lett. B 526 (2002) 393–398, [arXiv:hep-ph/0108060v1].

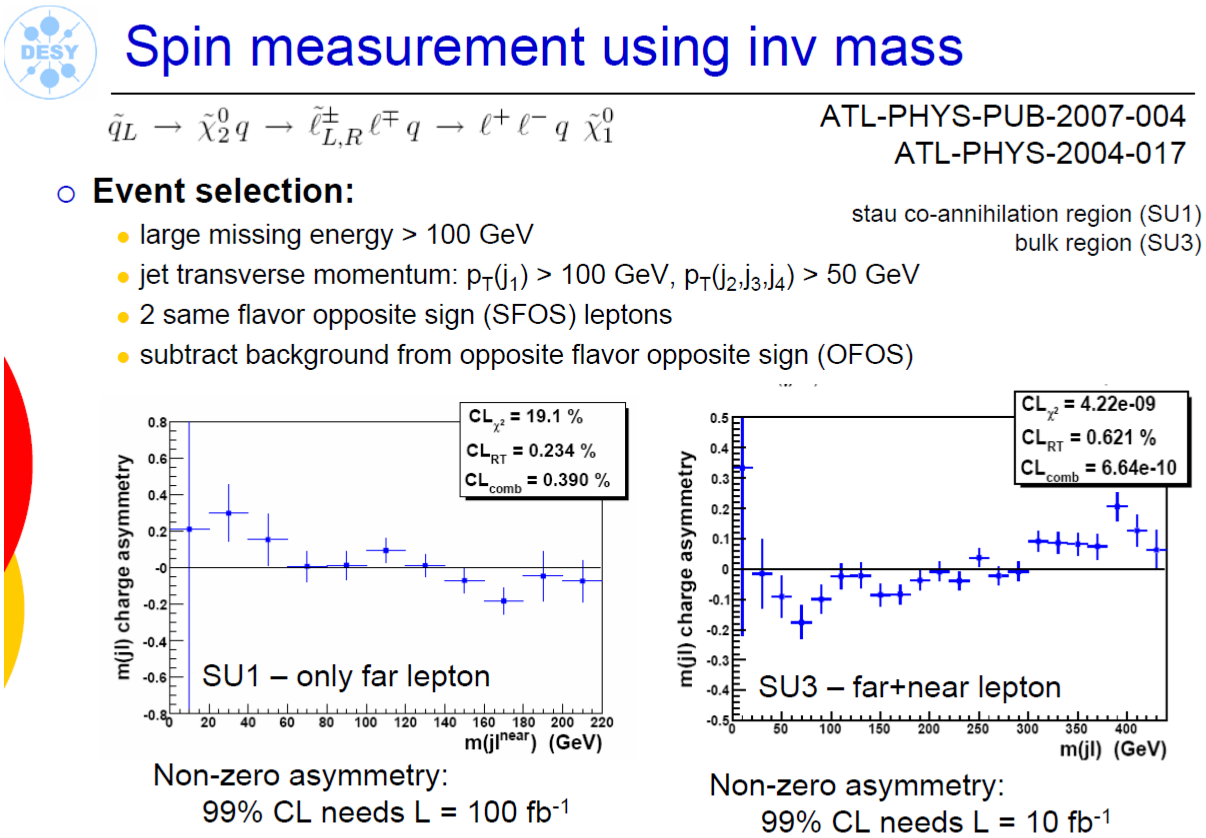
K. Cheung, Black hole, string ball, and p-brane production at hadronic supercolliders, Phys. Rev. D 66 (2002) 036007, [arXiv:hep-ph/0205033v4].

A. Chamblin and G. C. Nayak, Black hole production at the CERN LHC: String balls and black holes from pp and lead-lead collisions, Phys. Rev. D 66 (2002) 091901(R), [arXiv:hep-ph/0206060v3].

Backup slides

Spin measurements

Older results, not recently updated



Spin measurement using inv mass

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}^{\pm}_{L,R}\,\ell^{\mp} q \to \ell^+ \ell^- q\; \tilde{\chi}_1^0$$

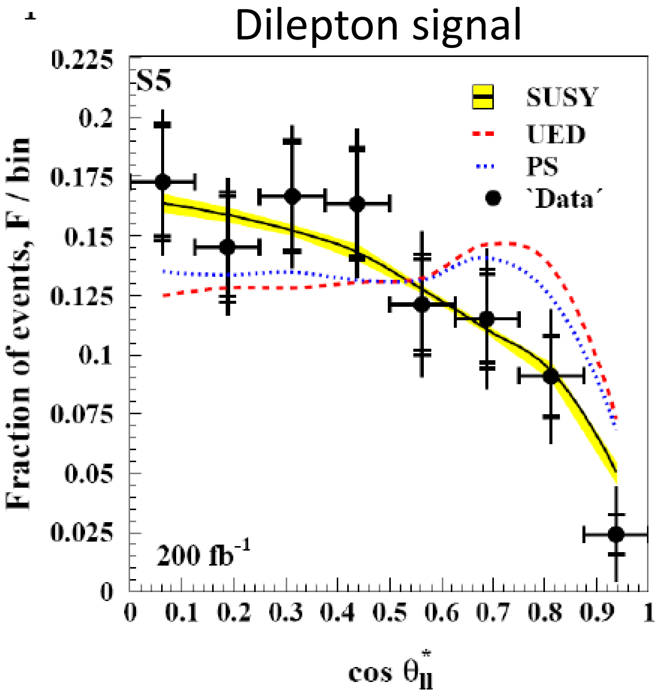
ATL-PHYS-PUB-2007-004
ATL-PHYS-2004-017

- **Event selection:**
  - large missing energy > 100 GeV
  - jet transverse momentum: $p_T(j_1) > 100$ GeV, $p_T(j_2,j_3,j_4) > 50$ GeV
  - 2 same flavor opposite sign (SFOS) leptons
  - subtract background from opposite flavor opposite sign (OFOS)

stau co-annihilation region (SU1)
bulk region (SU3)

Non-zero asymmetry:
99% CL needs L = 100 fb^{-1}

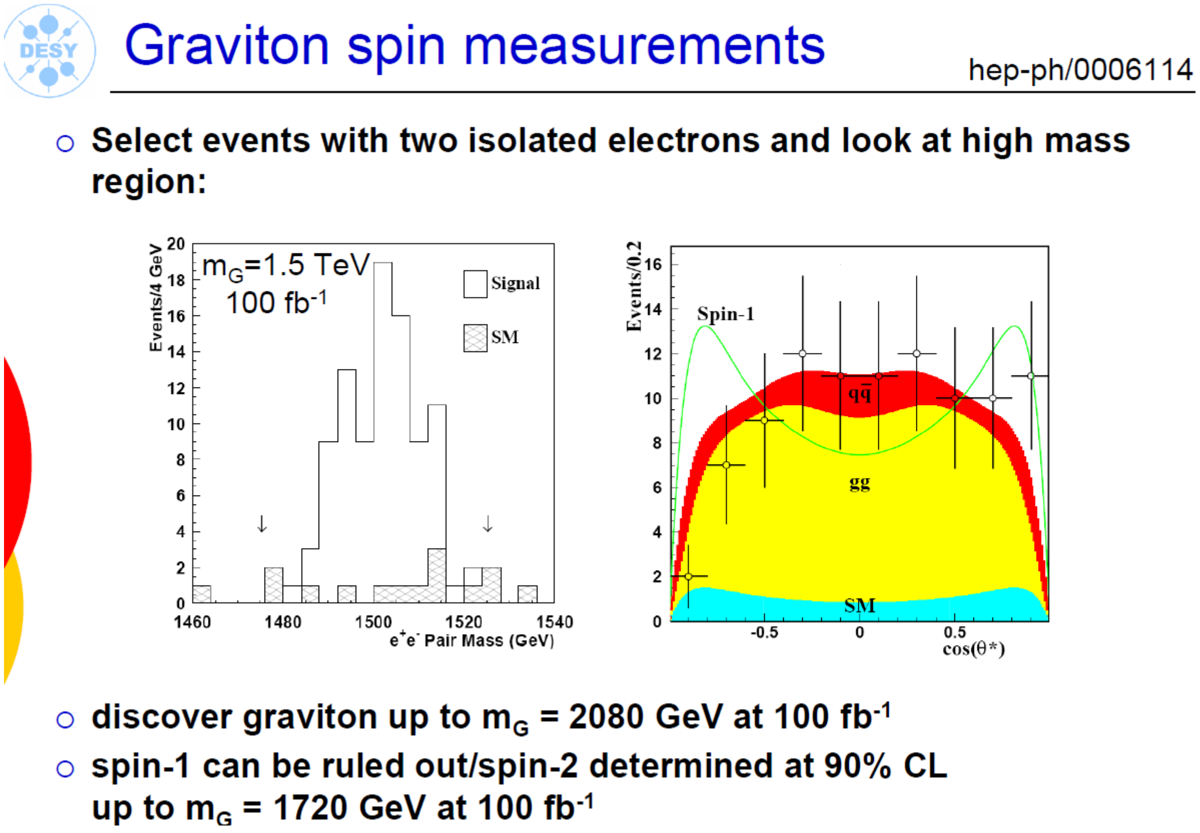
Non-zero asymmetry:
99% CL needs L = 10 fb^{-1}



Dilepton signal

Spin measurements

Older results, not recently updated



Graviton spin measurements

hep-ph/0006114

- Select events with two isolated electrons and look at high mass region:

- discover graviton up to m_G = 2080 GeV at 100 fb^{-1}
- spin-1 can be ruled out/spin-2 determined at 90% CL up to m_G = 1720 GeV at 100 fb^{-1}

LHC

19.09.2008

- While recovering from transformer failure
- Making last step of dipole circuit in sector 34, to 9.3kA
- At 8.7kA, development of resistive zone in dipole bus bar splice
  - Later estimated from cryogenic data on heat deposition to be 220nΩ
- Electrical arc developed which punctured helium enclosure, allowing helium release into insulating vacuum
- Large pressure wave travelled along accelerator in both directions

Today

- All dipole resistance measurements were investigated
- High resistance in bus bars had been monitored and is now understood
- Problematic dipoles fixed
- Additional security measures: quench protection system upgrade

LHC

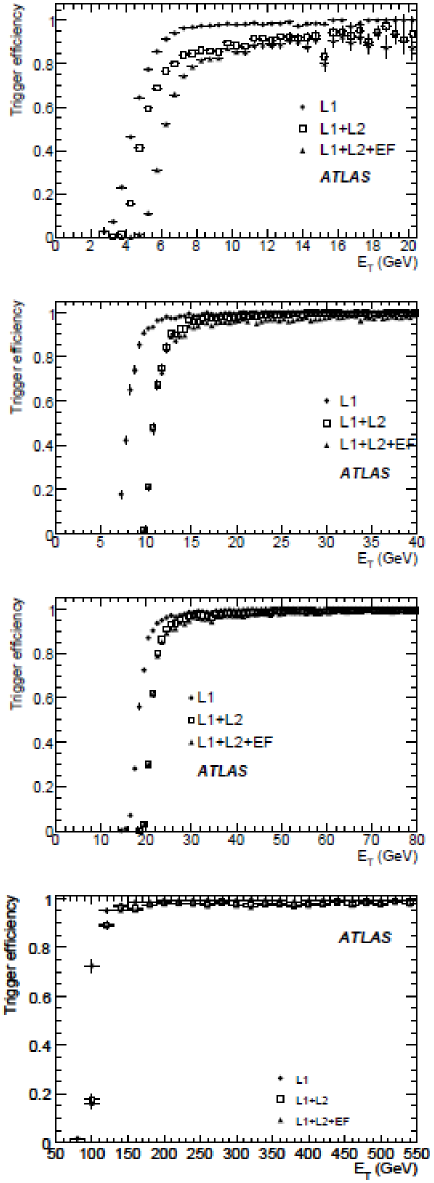
Incident: The magnet circuits in the seven other sectors of the LHC had been fully commissioned to their nominal currents (corresponding to beam energy of 5.5 TeV) before the first beam injection on 10 September 2008. For the main dipole circuit, this meant a powering in stages up to a current of 9.3 kA. The dipole circuit of sector 3-4, the last one to be commissioned, had only been powered to 7 kA prior to 10 September 2008. After the successful injection and circulation of the first beams at 0.45 TeV, commissioning of this sector up to the 5.5 TeV beam energy level was resumed as planned and according to established procedures.

On 19 September 2008 morning, the current was being ramped up to 9.3 kA in the main dipole circuit at the nominal rate of 10 A/s, when at a value of 8.7 kA, a resistive zone developed in the electrical bus in the region between dipole and quadrupole Q24. The first evidence was the appearance of a voltage of 300 mV detected in the circuit above the noise level: the time was 11:18:36 CEST. No resistive voltage appeared on the dipoles of the circuit, individually equipped with quench detectors with a detection sensitivity of 100 mV each, so that the quench of any magnet can be excluded as initial event. After 0.39 s, the resistive voltage had grown to and the power converter, unable to maintain the current ramp, tripped off at 0.46 s (slow discharge mode). The current started to decrease in the circuit and at 0.86 s, the energy discharge switch opened, inserting dump resistors in the circuit to produce a fast power abort. In this sequence of events, the quench detection, power converter and energy discharge systems behaved as expected.

Within the first second, an electrical arc developed and punctured the helium enclosure, leading to release of helium into the insulation vacuum of the cryostat.

The spring-loaded relief discs on the vacuum enclosure opened when the pressure exceeded atmospheric, thus relieving the helium to the tunnel. They were however unable to contain the pressure rise below the nominal 0.15 MPa absolute in the vacuum enclosures of subsector 23-25, thus resulting in large pressure forces acting on the vacuum barriers separating neighboring subsectors, which most probably damaged them. These forces displaced dipoles in the subsectors affected from their cold internal supports, and knocked the Short Straight Section cryostats housing the quadrupoles and vacuum barriers from their external support jacks at positions Q23, Q27 and Q31, in some locations breaking their anchors in the concrete floor of the tunnel. The displacement of the Short Straight Section cryostats also damaged the “jumper” connections to the cryogenic distribution line, but without rupture of the transverse vacuum barriers equipping these jumper connections, so that the insulation vacuum in the cryogenic line did not degrade.

ATLAS


e5, e10, e20, e105 trigger effi

L1   40 MHz → 75 kHz (40 kHz @startup)

Decision within 2.5 µs

Data from calorimeters (Lar and Tile) and muon detectors

Calorimeter → multiplicities and E thresholds of EM clusters, taus, jets, MET, sum ET, Etjets

Muon → trajectories in Resistive Plate Chambers (RPC) + Thin Gap Chambers (TGC) in endcap

→ multiplicity for various muon pT thresholds

L2   75 kHz → 2kHz (1 kHz @startup)

Sw running on PC farm

Uses regions-of-interest (RoI) identified at L1

Seed → pT threshold and η-ϕ position from L1, specialized timing optimized algorithms

RoI constructed around seed

Size of RoI determined by L2 (smaller for e than for jets)

Data is then unpacked, analyzed and a decision is made

Event is built/reconstructed

EF   2kHz → 200 Hz

4s/evt

Sw running on farm of CPUs

Seed → access to built event and offline reconstruction algorithms

Trigger menus

e (electron), g (photon), EM (electromagnetic), J (jets), FJ (forward jets), XE (MET)

TE (Total scalar sum ET), JE (Scalar sum of jet ET), MU (muons), and tau (tau leptons)

e.g.   2e15i == 2 isolated electrons, pT > 15 GeV

tau20i XE30 == isolated hadr tau, pTvis > 20 GeV, MET > 30 GeV

Early physics

e.g.

- ***$J/\psi\rightarrow\mu\mu$*** 800/day → tracker p scale, trigger
- ***$Z\rightarrow\mu\mu$*** 160/day → μ spectrometer alignement, E/p scale, trigger, ε_μ , EM calo uniformity
- ***$Z\rightarrow ee$*** → EM calo uniformity (10^5 evts /~0.7%), module/module variations, T effects
- ***Top events*** → light jet calibration/E scale, $\varepsilon_{b\text{-jet}}$, m_{Top}, ttbar Xsec
- ***Inclusive jets*** → sensitive to NP
- ***Minimum bias events*** (inel had-had int) → pp int, multiparton int, proton struct, UE
- ***Underlying events*** everything except 2 outgoing hard scattered jets

First 100 pb-1

1pb-1 = 3.85 days L=10^{31} cm^{-2}s^{-1} with machine X detector ε = 30%

Channel	*Evts to tape (1 expt)*	*Total stats : LEP,Tevatron*
W→$\mu\nu$	10^6	10^4, 10^{6-7}
Z→$\mu\mu$	10^5	10^6, 10^{5-6}
ttbar→WbWb → $\mu\nu$+X	10^4	–, 10^{3-4}
QCD jets pT>1TeV	> 10^3	–
Gluino gluino m=1TeV	50	–

Early physics

- ***Inclusive jets*** → sensitive to NP
- ***W→$\ell\nu$*** → angular distribution to constrain PDFs
- ***Top events*** → light jet calibration/Escale, $\varepsilon_{b\text{-jet}}$, m_{Top}, ttbar Xsec
- ***Narrow resonances at ~ 1 TeV e.g. Z', Graviton*** → 5σ with 100 pb-1 in e+e-
- ***Di jet narrow resonances e.g. Z', W'*** → 2 TeV excited quark with 100 pb-1

First 100 pb-1

Minimum bias events

- Inelastic hadron-hadron events selected with the minimum bias trigger
-Usually associated with inelastic non-single-diffractive events
- σ_{total} (102-118mb) = $\sigma_{\text{elastic}} + \sigma_{\text{single diffractive}} + \sigma_{\text{double diffractive}} + \sigma_{\text{non diffractive}}$

Need these evts to study proton-proton interactions, investigate multiparton int. and struct. of proton, understand UE

Underlying events

Soft part associated with hard scatters.
In parton-parton scatt., UE defined as everything except two outgoing hard scattered jets
(beam-beam remnants, addition parton-parton int., ISR+FSR)
Can we use MB to model UE? Beam-beam remnant and multiple int.

Inclusive jets

Jet spectrum at high pT sensitive to new physics. Can fake/mask signal if not well understood.

W→ℓν

Angular distribution to constrain PDFs. Experimental uncertainty <5% making it possible to discriminate between PDFs.

Top events

Top signal quickly observed even with limited detector performance (leptons+jets) but MET problem
→ light jet-calibration (jet E scale), b-jet efficiency, general detector performance
Top mass, ttbar cross section

Phenomenological tools - Generators

Total Xsec at LHC

$\sigma_{\text{pp tot}}$ at 14 TeV = 102 mb (PYTHIA) = 23 mb (elastic) + 79 mb (inelastic)

$\sigma_{\text{inelastic}}$ = 14mb (single diffractive scatt) + 10 mb (double diffractive scatt) + X

$\sigma_{\text{non single difractive}} == \sigma_{\text{minimum bias}} = \sigma_{\text{inelastic}} - \sigma_{\text{single diffractive}}$ = 65 mb

Multijet prod

Even if NLO corrections partially known, uncertainties from missing HO corrections large

Mostly use LO estimates with large errors to cover HO uncertainty

W/Z (+jets)

Inclusive production Xsecs of W and Z bosons known at NNLO and used

Residual uncertainties at few % level

Exclusive W/Z + jet Xsecs LO MC → PYTHIA or PS matched MCs ALPGEN or Sherpa → normalized to inclusive NNLO Xsecs

Diboson

NLO Xsec

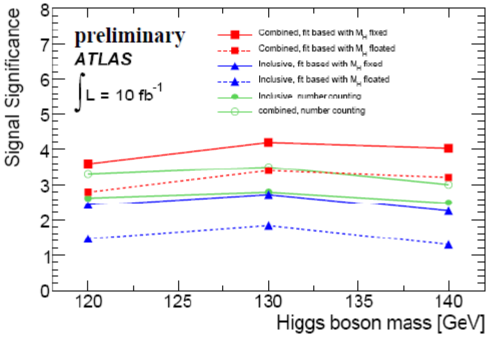
qqbar and gg box-diagram (30% for ZZ using RESBOS) taken into account

SM Higgs Hunt

$H \to \gamma\gamma$ in GF, ttH, VBF

good γ/jet separation to remove reducible bgd

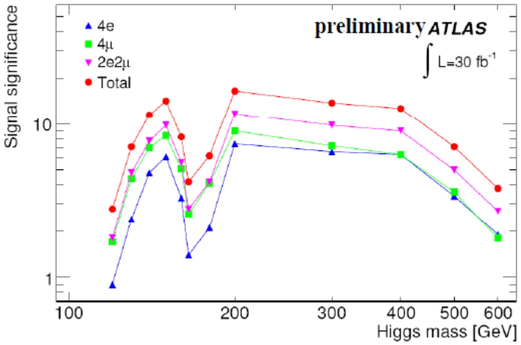
vertex reconstruction for good mass resolution



$H \to ZZ \to 4\ell$ ($4e$, 4μ, $2e2\mu$) in GF

main bgd ZZ irreducible, ttbar and Zbb reducible

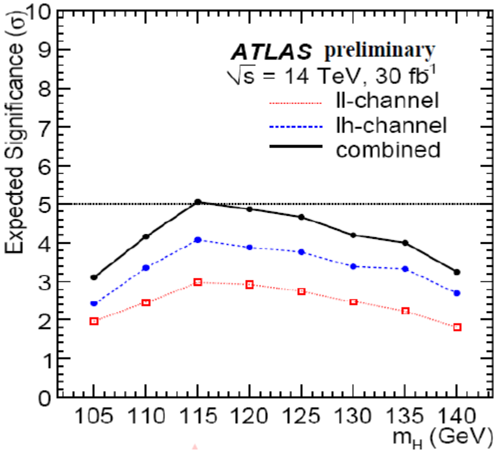
lepton isolation and impact parameter



VBF $H \to \tau\tau$

2 high pT jets at large rapidity;

no color flow between tagged jets → rapidity gap



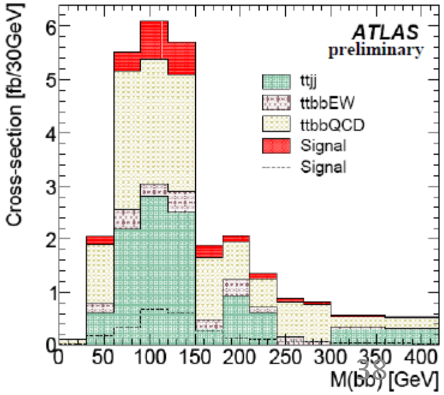
$H \to WW$ in GF, WH, ttH, VBF

no mass peak in this channel

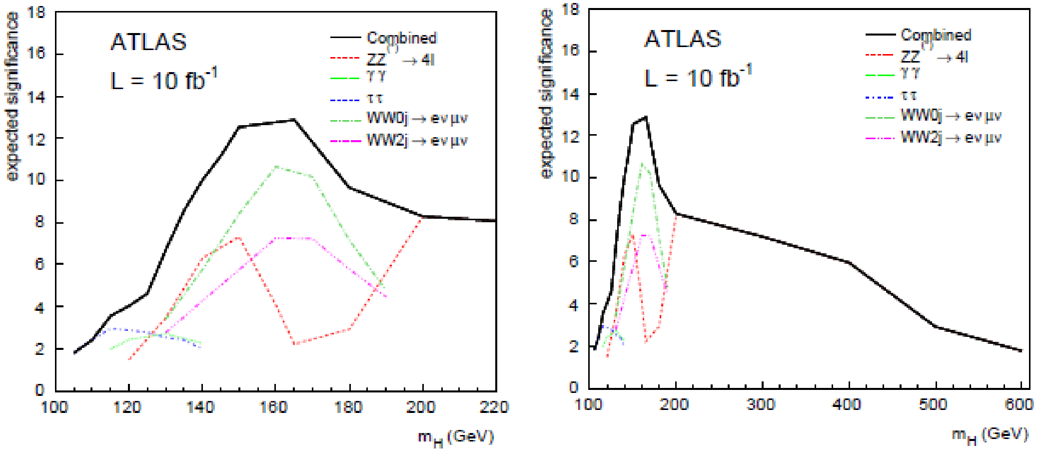
need good understanding of bgd

$H \to$ bbbar in ttH

large background which looks very much like signal



SM Higgs Hunt – discovery/exclusion



10 fb-1
Expected significance
for various channels
and for combination
for low mass range (left)
and masses up to 600 GeV (right)

SM Higgs Hunt

Combination approximations

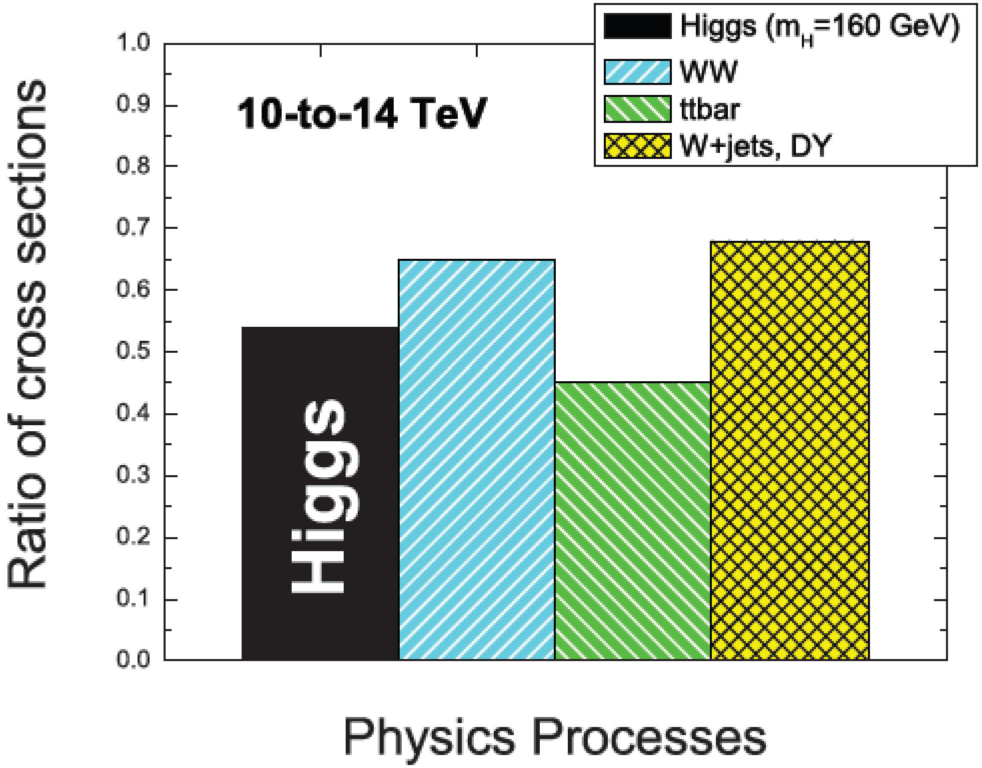
The statistical treatment requires knowledge of the distribution of a test statistic based on the profile likelihood ratio. To determine these distributions by Monte Carlo so as to establish discovery at a high level of significance would require an enormous amount of simulated data, which is not practical at present. Therefore the distributions have been estimated using the functional form expected to hold in the large sample limit. Investigations shown in Section 3 indicate that this approximation should be reliable for an integrated luminosity above 2 fb−1.

To determine the discovery significance or to set limits using a given data set, one must carry out a global fit. For this one needs first to combine the likelihood functions for the individual channels into the full likelihood function containing a single strength parameter m, and use this to find the profile likelihood ratio. It is possible, however, to find approximate values for the median discovery significance and limits in a way that only requires as input the separate profile likelihood ratio values from each of the channels. This is very useful especially in the planning phase of a search that combines multiple channels.

The procedure relies on two separate approximations. First, we estimate the median value of the profile likelihood ratio by evaluating the likelihood function with a single, artificial data set in which all statistical fluctuations are suppressed. Second, to determine the significance values from the likelihood ratios, we use the asymptotic form of the distribution of $-2\ln\lambda(\mu)$ valid for sufficiently large data samples.

The limitations of the approximation are investigated and for one case where it is found to be insufficiently accurate (the discovery significance for the channel $H \rightarrow W+W-$ plus no jets), an alternate procedure is followed.

SM Higgs Hunt – E_{cm} = 10 vs 14 TeV



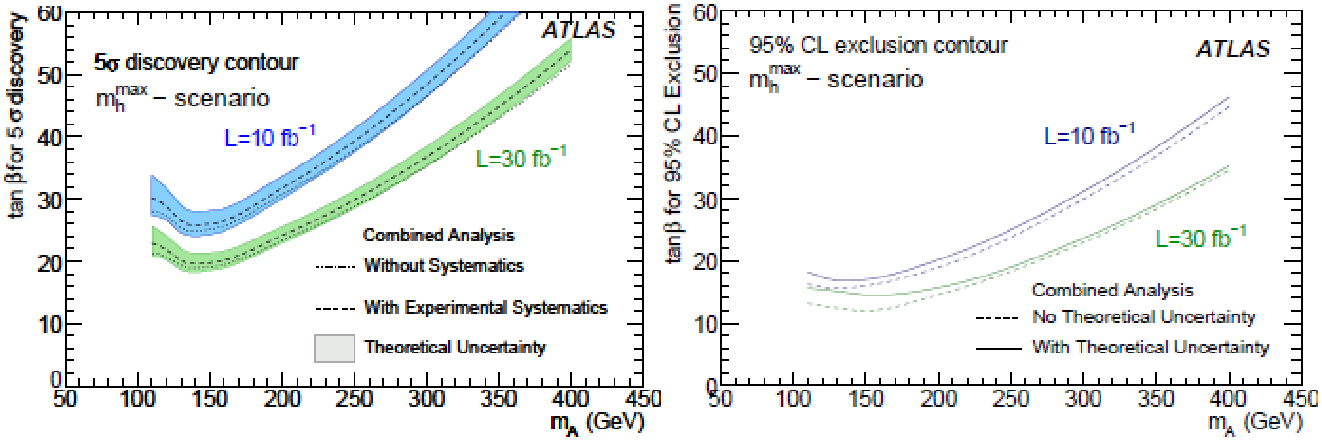
Higgs Xsec decreases by factor ~ 2
Signficance reduction by factor ~ 1.5

MSSM Higgs Hunt

h, H, A and H±

Benchmark scenario m_h^{max} maximal theoretically allowed region for m_h

10 fb-1 [30 fb-1]
Discovery of
neutral Higgs
up to m_A=350 GeV
for 30<tanβ<60 [20<tanβ<60]
Theoretical and detector
systematic uncertainties
degrade signal significance
by up to 20%

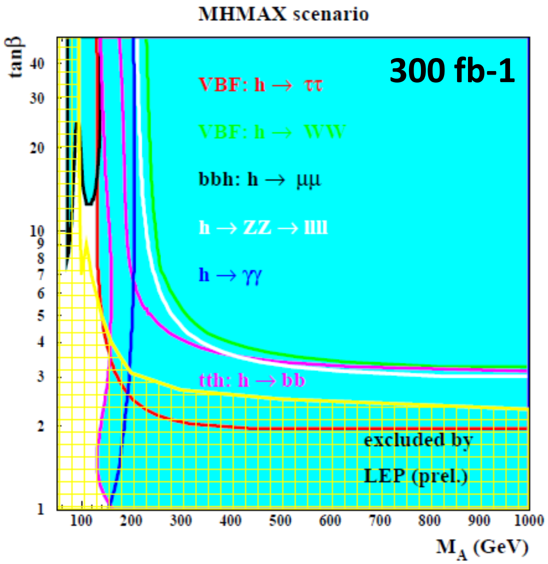


tanβ vs M_A for 5 σ discovery and for 95% CL exclusion vs m_A

300 fb-1
tanβ vs m_A
MSSM Higgses discovery potential

- **Small area uncovered (M_h = 90 to 100 GeV)**

N.B.
Plots not recently updated
No systematic uncertainties included



Discovery potential for h

300 fb-1

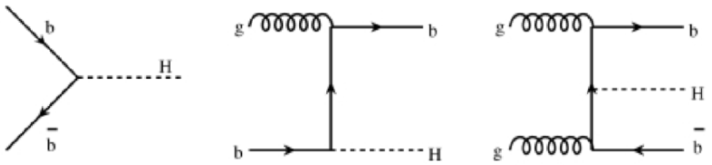
MSSM Higgs Hunt

h, H, and A and H±

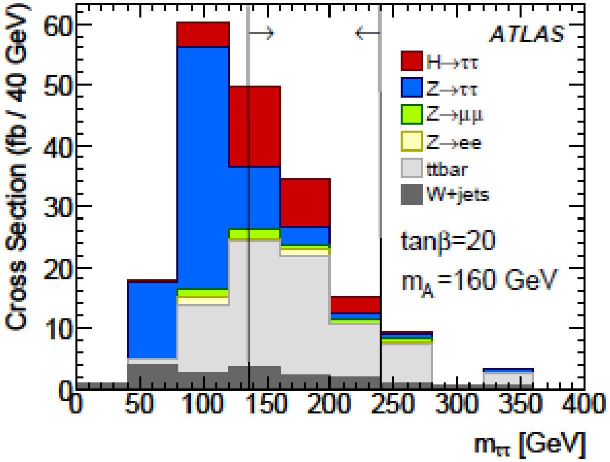
WW and ZZ decay modes
→ suppressed like cos($\beta - \alpha$) for H (α=mixing angle of 2 CP-even Higgs), absent for A
Coupling of Higgses to 3rd generation fermions strongly enhanced for large regions of parameter space
Benchmark scenario m_h^{max} maximal theoretically allowed region for m_h

Neutral Higgs searches

h, A,H → $\tau^+ \tau^-$ → $\ell^+ \ell^-$ 4ν [associated with a b]

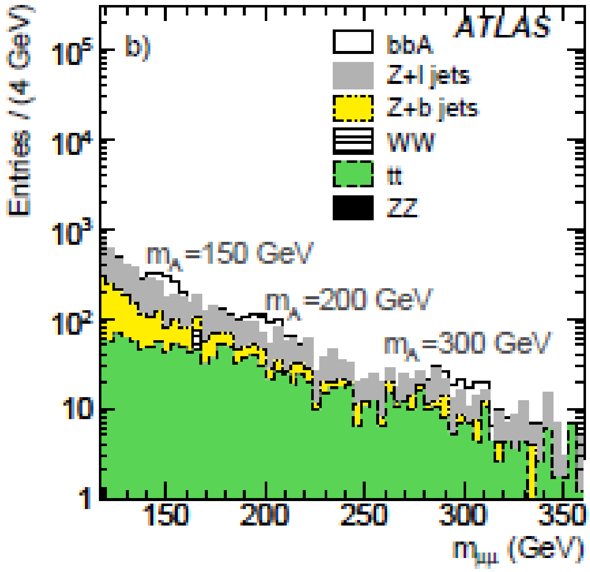


1fb-1
$m_{\tau\tau}$ for signal and bgd
after all selection cuts
Vertical lines :
mass window
for calculating
significance.



h, A,H → $\mu^+\mu^-$ [GF and bbbarH]

→ clear signature in detector
→ fully reconstructed Higgs
and most accurate m_{Higgs}



30 fb-1
Signal and bgd $m_{\mu\mu}$
tanβ = 30
H and A prod rates
have been added
as they are degenerate
for m_A>130GeV

MSSM Higgs Hunt

Charged Higgs searches

The search strategies for charged Higgs bosons depend on their hypothesized mass, which dictates both the production rate and the available decay modes.

Below the top quark mass, the main production mode is through top quark decays,
$t \rightarrow H^+ b$, and in this range the $H+ \rightarrow \tau\nu$ decay mode is dominant.

Above the top quark threshold, production mainly takes place through gb fusion ($gb \rightarrow tH+$), and for such high charged Higgs boson masses the decay into a top quark and a b quark dominates, $H+ \rightarrow tb$

MSSM Higgs Hunt

2 Higgs doublets resulting in five 5 Higges

3 neutral h, H, and A and 2 charged H±

At tree level their properties (mass, width and BR) can be predicted in terms of only two parameters typically

m_A mass of the CP-odd Higgs boson

tan β tangent of the ratio of the vacuum expectation values of the two Higgs doublets

MSSM couplings of Higgses to fermions and bosons different from SM :

- WW and ZZ decay modes

→ suppressed like cos($\beta - \alpha$) for H where α=mixing angle of 2 CP-even Higgs h,H

→ absent for A

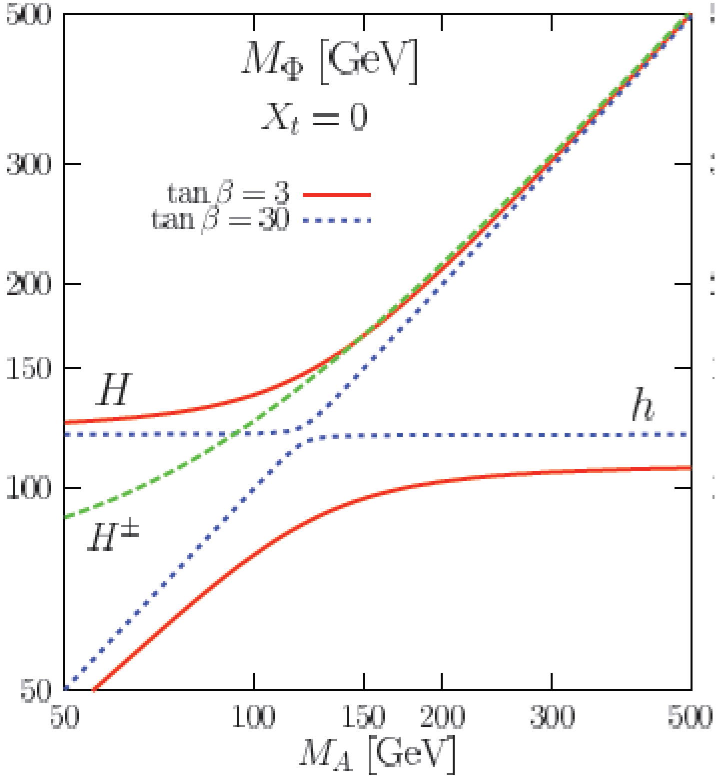
- coupling of Higgses to 3rd generation fermions strongly enhanced for large regions of parameter space

h,H,A → $\tau\tau$ → important discovery channel. GF prod or associated prod with b quarks

h,H,A → $\mu\mu$ → strongly enhanced large values of tan β

Discovery channel or for exclusion of a large region of m_A - tanβ

MSSM Higgs



D.Rainwater hep-ph/0702124

MSSM Higgs Hunt

2 Higgs doublets resulting in five 5 Higges

3 neutral h, H, and A and 2 charged H±

At tree level, mass, width and BR can be predicted in terms of

m_A mass of the CP-odd Higgs boson

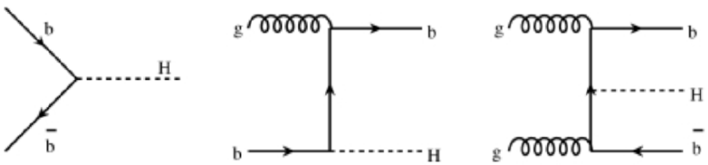
tan β tangent of ratio of vacuum expectation values of 2 Higgs doublets

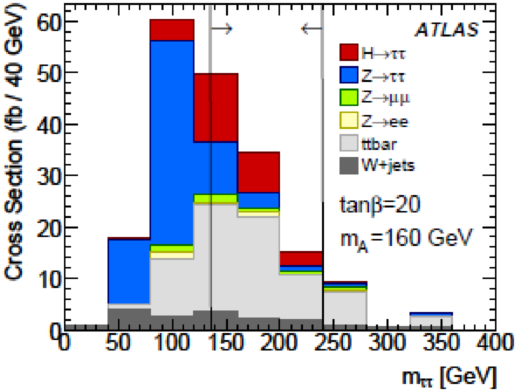
WW and ZZ decay modes → suppressed like $\cos(\beta - \alpha)$ for H (α=mixing angle of 2 CP-even Higgs) , absent for A

coupling of Higgses to 3rd generation fermions strongly enhanced for large regions of parameter space

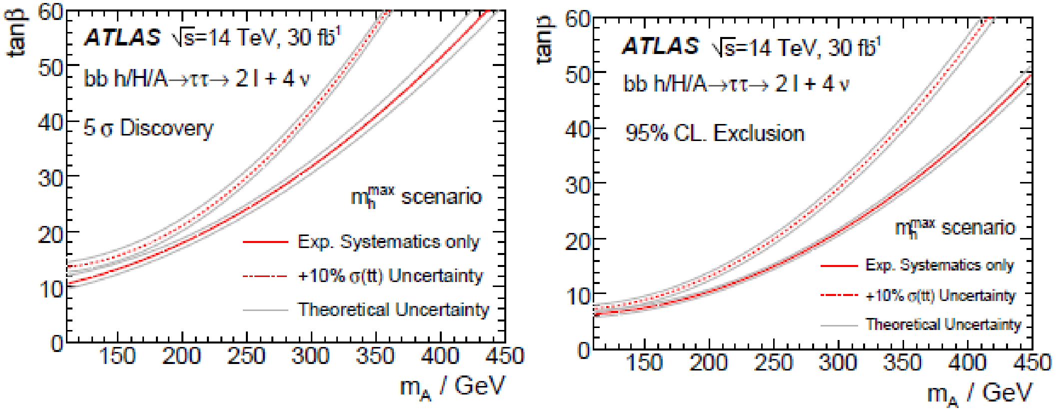
Benchmark scenario m_h^{max} maximal theoretically allowed region for m_h

h, A,H → τ+ τ- → ℓ+ ℓ- 4 ν [associated with a b]





$m_{\tau\tau}$ for signal and bgd after all selection cuts
Vertical lines indicate mass window
used for calculating significance.



5σ discovery potential and 95% exclusion limit as a function of m_A and tanβ
Solid line → main result of the analysis
Dashed lines → includes an additional 10% uncertainty on the ttbar Xsec
Bands → influence of the syst uncert on the signal Xsec conclusion

MSSM Higgs Hunt

The A and H bosons are degenerate for M_A>130 GeV therefore they are added together.
A and h are degenerate for M_A<130 GeV therefore they are added together.
Finally at 130 GeV A,H,h are almost degenerate and they have been added together.

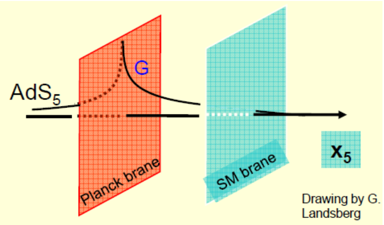
Eps plots in
https://twiki.cern.ch/twiki/bin/view/Atlas/HiggsMaterialForPublicTalks#Global_Analysis_of_MSSM_Higgs_MS

BSM

Dilepton resonances at high mass

Simplicity of final state → important channel with early data

Strictest direct limits on heavy neutral particles → Tevatron m ~< 1 TeV



Z’

In context of Sequential SM (SSM), E_6, and Left-Right symmetric models

Randall Sundrum Graviton

Warped extra-dimension linking SM brane and Planck brane

Only graviton propagates into XtraD → tower of KK excitations G* → ℓ+ℓ-

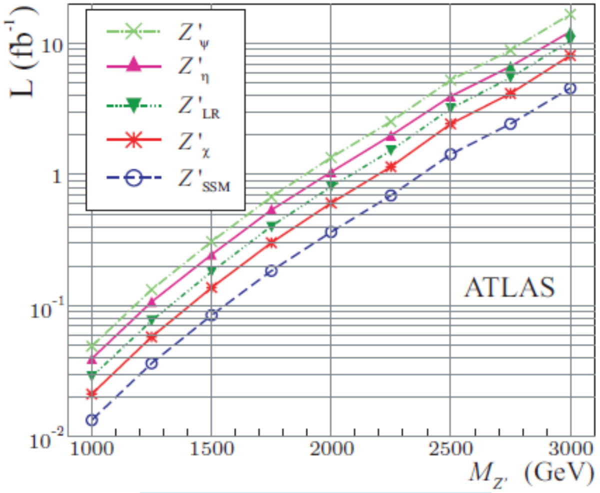
Technicolor Strawman model

New techni-fermions bound together by QCD-like force : ρ_{TC} and ω_{TC} dilepton decay

Z’→e+e-

5σ significance with stats errors only.

Syst change result by ~ few %



$m_{Z'}$ = 1 TeV

e+e- < 100 pb−1

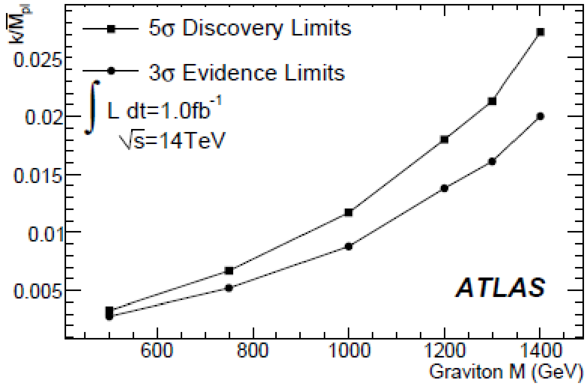
μ+μ- 20 to 40 pb−1

τ+τ- ~1fb-1

G → e+e-

M_{Pl} = fundamental Planck scale mass

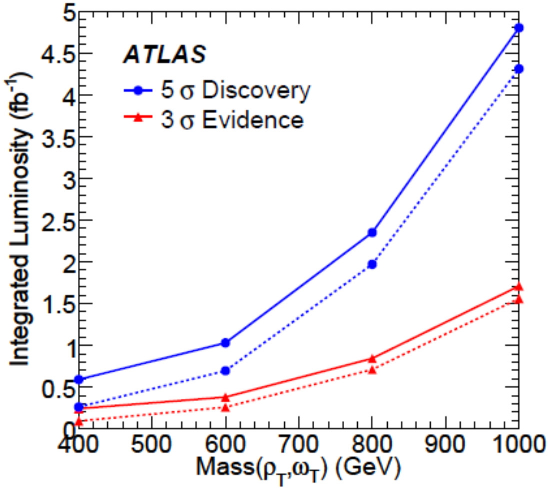
Syst change result by + 10 to 15 %



$\rho_T \to \mu\mu$ and $\omega_T \to \mu\mu$

Dashed = stats errors only

Solid = stats+syst



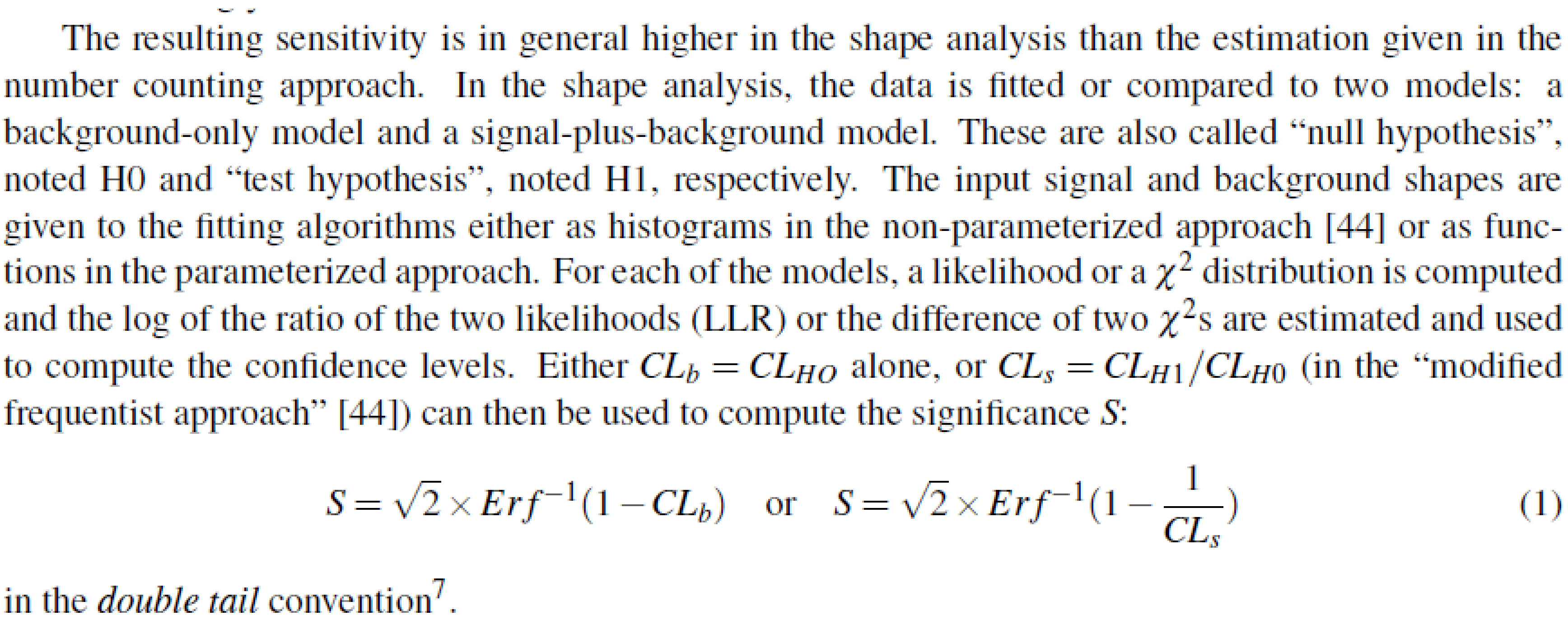
RS and technicolor

~ 1fb-1 for ~0.5-1 TeV dilepton resonance

BSM

Dilepton resonances at high mass

Z’ shape analysis significance dertermination



The resulting sensitivity is in general higher in the shape analysis than the estimation given in the number counting approach. In the shape analysis, the data is fitted or compared to two models: a background-only model and a signal-plus-background model. These are also called “null hypothesis”, noted H0 and “test hypothesis”, noted H1, respectively. The input signal and background shapes are given to the fitting algorithms either as histograms in the non-parameterized approach [44] or as functions in the parameterized approach. For each of the models, a likelihood or a χ^2 distribution is computed and the log of the ratio of the two likelihoods (LLR) or the difference of two χ^2s are estimated and used to compute the confidence levels. Either $CL_b = CL_{HO}$ alone, or $CL_s = CL_{H1}/CL_{H0}$ (in the “modified frequentist approach” [44]) can then be used to compute the significance S:

$$S = \sqrt{2} \times Erf^{-1}(1 - CL_b) \quad \text{or} \quad S = \sqrt{2} \times Erf^{-1}(1 - \frac{1}{CL_s}) \qquad (1)$$

in the *double tail* convention[7].

BSM

Dilepton resonances at high mass

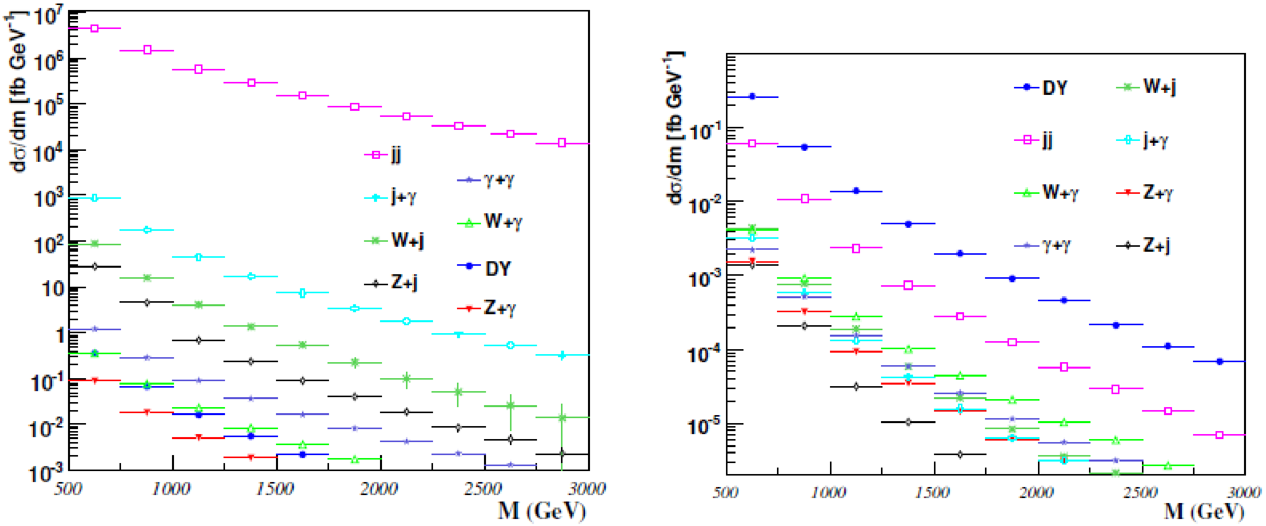
Systematics :

- DY dominant bgd
- Tree-level dilepton Xsec have large NLO EW and QCD corrections for SM DY and NP

  EW NLO → −4 to −16 % for e+e- , −12 to −38 % for $\mu+\mu-$ for 300 GeV < m_{inv} < 2 TeV

  QCD th uncert → ±8.5% at 1 TeV, ±14% at 3 TeV
- Muon spectrometer alignement → resonance peak resolution degradation
- Particle id efficiency 5% for muons, 1% for electrons, and 5% for τ
- Energy scale 1% for muons, 1% for electrons, and 5% for τ
- pT resolution
- Luminosity

Pythia e+e- tree level bgds before cuts and after $|\eta|<2.5$ and Nlepton ≥1 with pT>65GeV



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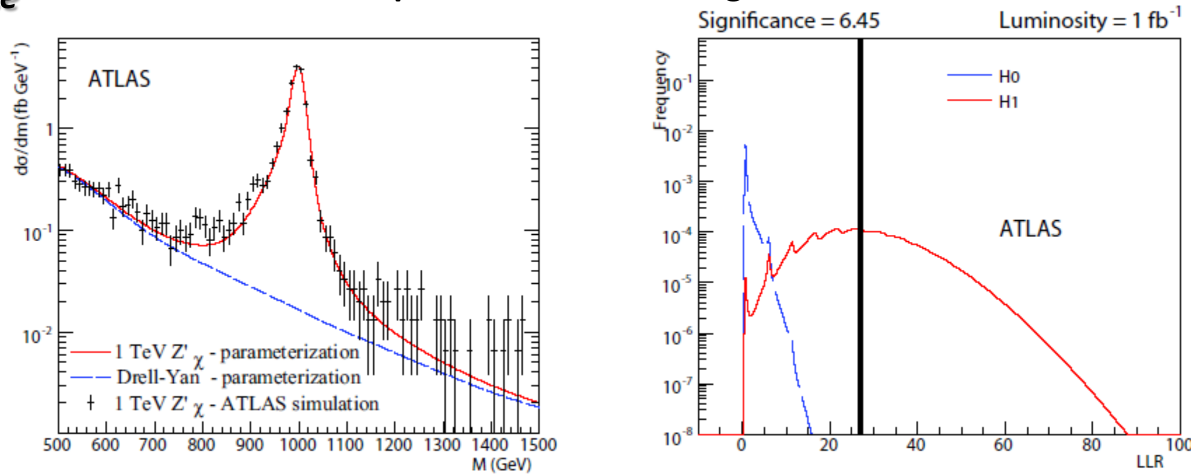
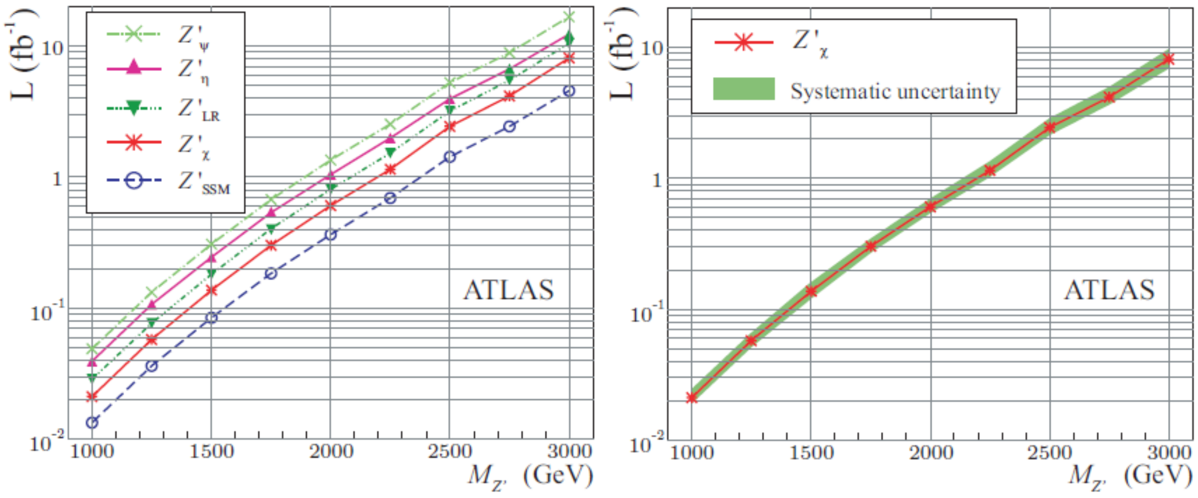
Dilepton resonances at high mass

Z’ →e+e- resonance



(left) Diff Xsec of 1 TeV Z’ → e+e−full simulation with parametrization of peak and of DY
(right) 1fb-1 Log-likelihood ratio densities 2 TeV Z’ for signal and bgd hypotheses
Vertical line = median experiment in H1 hypothesis.



(left) Luminosity for 5σ significance stat errors only
(right) stat+syst (DY bgd, HO EQ and QCD Xsecs)

Z’→e+e-
< 100 pb−1 for 1 TeV Z’
~ 1 fb−1 for 2 TeV Z’
~ 10 fb−1 for 3 TeV Z’

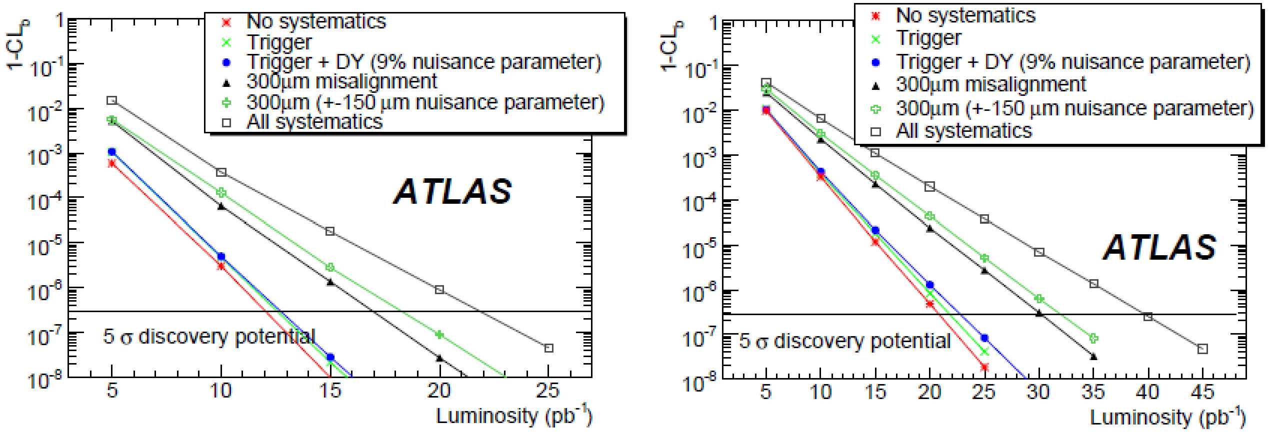
But also
Z’→μ+μ- 20 to 40 pb−1
Z’ → τ+τ- resonance ~1fb-1
For 1 TeV Z’

BSM

Dilepton resonances at high mass

Z' → $\mu^+\mu^-$ resonance

Luminosity for 5σ : from 20 to 40 pb−1



1 TeV (left) Z'_{SSM} (right) Z'_{χ}

Z' → $\tau^+\tau^-$ resonance ~1fb-1 for significance of > 5

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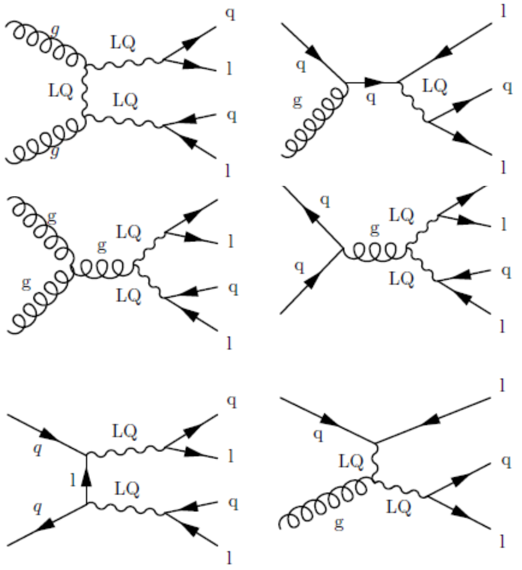
Dilepton + dijets



Leptoquarks LQ → leptons+quarks

DØ and CDF 95%CL limits, respectively for β=BR(LQ→$\ell^{\pm}$q)=1

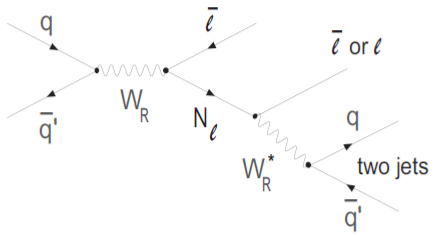
- 1st gen m_{LQ1} > 256 GeV (250 pb-1) m_{LQ1} > 236 GeV (200 pb-1)
- 2nd gen m_{LQ2} > 251 GeV (300 pb-1) mL_{Q2} > 226 GeV (200 pb-1)
- Full lumi Tevatron exclusion limits ~> 300-350 GeV

Left Right Symmetric Model

3 heavy right-handed Majorana ν's N_e, N_μ and N_τ

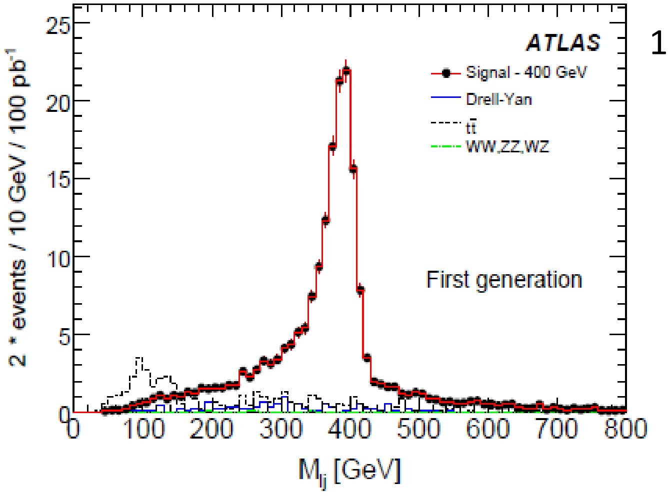
W_R and Z' produced via DY

W_R→ eN_e /μN_μ with N_e/N_μ→ e/μ q' qbar



Current experimental limits (no direct searches for heavy Majorana ν's)

- $m(K_L)$ −$m(K_S)$ → m_{WR} > 1.6 TeV
- SN1987A + LEP invisible Z → m_N ~ few 100 GeV → m_{WR} ~Tev
- NCs → m(Z') > 400 GeV
- D0 direct searches m_{WR} ~> 750



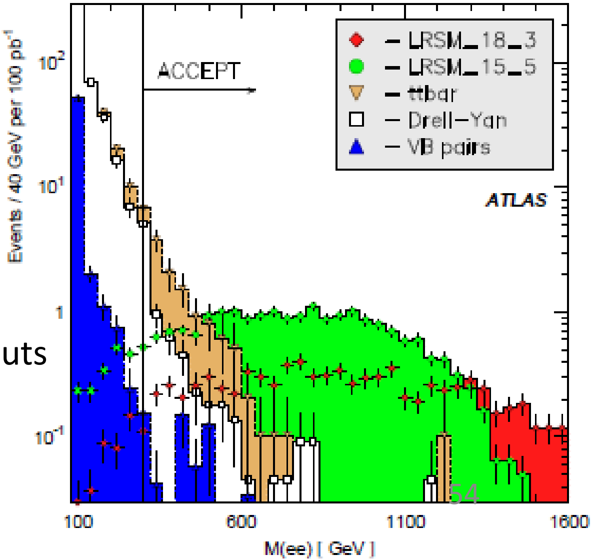
100 pb-1 1st gen m_{LQ}=400 GeV

Electron channel after cuts

100 pb-1 LRSM electron channel after cuts

m_{WR}=1800 GeV $m_{Ne,\mu}$= 300 GeV

and m_{WR}=1500 GeV $m_{Ne,\mu}$= 500 GeV



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Dilepton + dijets

Leptoquarks

Symmetry between leptons and quarks → search for leptoquarks LQ
LQ = bosons with quark and lepton quantum numbers and fractional el charge
LQ → leptons+quarks
Exp limits on lepton number violation, FCNC and proton decay → 3 gen of LQ
Each LQ couples to a lepton and a quark from same SM gen
LQs can be produced in pairs by strong interaction
or in association with a lepton via LQ-quark-lepton coupling

DØ and CDF 95%CL limits, respectively for β=BR(LQ→$\ell^{\pm}$q)=1

1st gen	m_{LQ1} > 256 GeV (250 pb-1)	m_{LQ1} > 236 GeV (200 pb-1)
2nd gen	m_{LQ2} > 251 GeV (300 pb-1)	mL_{Q2} > 226 GeV (200 pb-1)

Full lumi Tevatron exclusion limits ~> 300-350 GeV

Left Right Symmetric Model : non zero L-handed ν masses and baryogenesis

LRSMs of the weak interaction conserve parity at high E → 3 new heavy right-handed Majorana ν's N_e, N_μ and N_τ
Smallest gauge group for LRSM $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. At low E, LR symmetry broken and parity is violated
Majorana nature of heavy ν's explains masses of 3 L-handed ν's through See-Saw mechanism
Lepton number L viol in processes with Majorana ν's → baryogenesis via leptogenesis → B, L violated but B−L conserved
Most LRSMs also introduce new VB W_R and Z', Higgs bosons, and L-R mixing parameter
W_R and Z' produced via DY ; W_R→ eN_e followed by N_e → e q' qbar; W_R → μN_μ followed by N_μ → μ q' qbar

- $m(K_L) - m(K_S)$ → m_{WR} > 1.6 TeV
- Supernova SN1987A and LEP invisible Z → heavy R-handed Majorana ν's with m ~ few 100 GeV → W_R at TEV scale
- Exp data on NCs → m(Z') > 400 GeV
- D0 direct searches m_{WR} > 739 GeV (decay to dileptons and to diquarks) and 768 GeV (decays to diquarks)
- No direct searches for heavy Majorana ν's

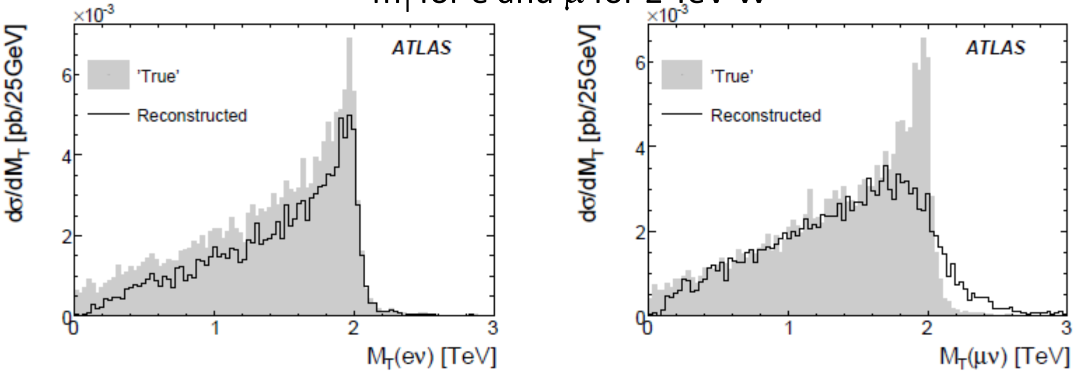
BSM

Lepton + MET at high mass

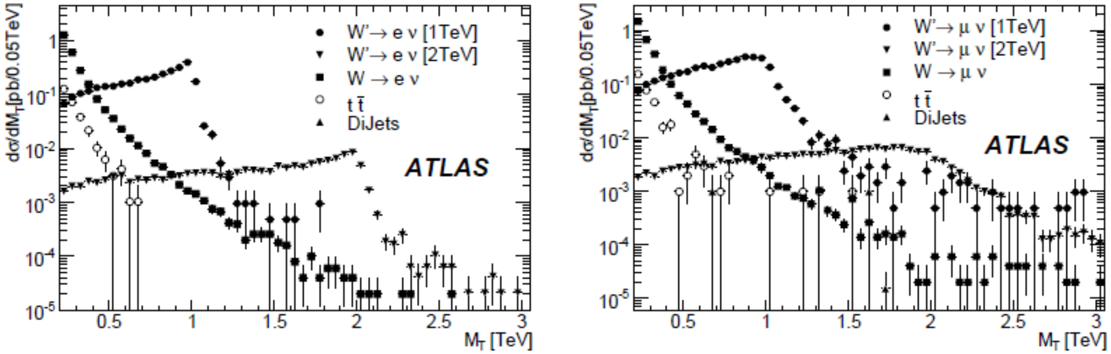
Muon - MET resolution for W' → $\mu\nu$ σ~18 (25) GeV mW' = 1 (2) TeV
Degraded performance of muon reconstruction at high pT
Electron - MET resolution for W' → eν σ~10 (14) GeV mW' = 1 (2) TeV
Electron trigger ε~98% at L=10^{32}
Muon trigger ε~74 at L=10^{32}

Transverse mass
$m_T = \sqrt{[2 p_T \text{ MET } (1-\cos \Delta\phi_{\ell,\text{MET}})]}$

m_T for e and μ for 2 TeV W'



- N_{lepton} =1 , pT > 50 GeV |η| < 2.5
- MET > 50 GeV
- lepton isolation
- leptonic fraction in ET
- jet veto and jet multiplicity



Systematics
- generators: NLO, PDFs
- detector: lept, jet, MET
- luminosity

BSM

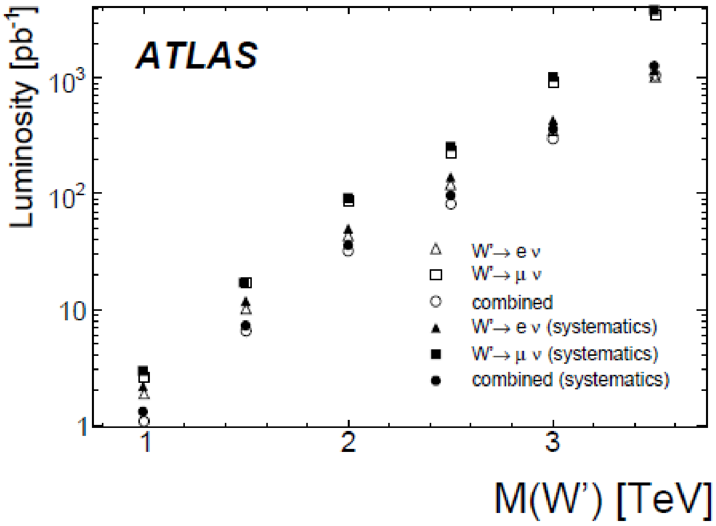
Lepton + MET at high mass

Lepton + MET at high mass

Discovery limits

Significance = √[2((s+b)ln(1+s/b)-s]

Int lumi for 5σ discovery with and wo syst.



~ 10 pb-1 to discover W' with m> $m_{\text{exp limit}}$
1 fb−1 to discover W' of 3TeV mass.

BSM

Vector Boson Scattering

If no light Higgs boson → alternative to SM, SUSY, Little Higgs

EWSB could result from strong coupling interaction

- Technicolor with Goldstone boson resulting from chiral symmetry breaking
- Higgsless extra dimensions, where KK gauge bosons exchanged in s-channel
- Extra vector bosons mixing with SM vector bosons

Chiral Lagrangian model effective theory valid up to 4πv ~ 3 TeV, where v = 246 GeV vev of SM Higgs

Not an early discovery!

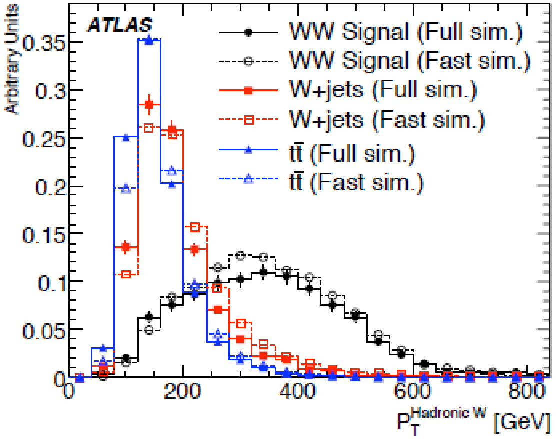
- 2 highly boosted VBs in central rapidity region
- For p_T >~ 250 GeV, hadr decaying VB seen as one single wide and heavy jet
- 2 high rapidity/high energy “tag” jets
- No colour exchange between protons → suppression of QCD rad between jets → central jet veto

Systematics : bgd and signal Xsec, limited MC stats, lumi, pile-up and UE, etc.

1.1 TeV W+W− → ℓν + jj

Full-sim (solid line) norm to unit area

Fast-sim (dashed) norm to full-sim Xsec



Process	Cross section (fb)		Luminosity (fb^{-1})		Significance
	signal	background	for 3σ	for 5σ	for 100 fb^{-1}
$WW/WZ \to \ell\nu\ jj$, $m = 500$ GeV	0.31 ± 0.05	0.79 ± 0.26	85	235	3.3 ± 0.7
$WW/WZ \to \ell\nu\ jj$, $m = 800$ GeV	0.65 ± 0.04	0.87 ± 0.28	20	60	6.3 ± 0.9
$WW/WZ \to \ell\nu\ jj$, $m = 1.1$ TeV	0.24 ± 0.03	0.46 ± 0.25	85	230	3.3 ± 0.8
$W_{jj}Z_{\ell\ell}$, $m = 500$ GeV	0.28 ± 0.04	0.20 ± 0.18	30	90	5.3 ± 1.9
$W_{\ell\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.40 ± 0.03	0.25 ± 0.03	20	55	6.6 ± 0.5
$W_{jj}Z_{\ell\ell}$, $m = 800$ GeV	0.24 ± 0.02	0.30 ± 0.22	60	160	3.9 ± 1.2
$W_jZ_{\ell\ell}$, $m = 800$ GeV	$0.27 \pm 0.02 \pm 0.05$	$0.23 \pm 0.07 \pm 0.05$	38	105	4.9 ± 1.1
$W_jZ_{\ell\ell}$, $m = 1.1$ TeV	$0.19 \pm 0.01 \pm 0.04$	$0.22 \pm 0.07 \pm 0.05$	68	191	3.6 ± 1.0
$W_{\ell\nu}Z_{\ell\ell}$, $m = 1.1$ TeV	0.070 ± 0.004	0.020 ± 0.009	70	200	3.6 ± 0.5
$Z_{\nu\nu}Z_{\ell\ell}$, $m = 500$ GeV	0.32 ± 0.02	0.15 ± 0.03	20	60	6.6 ± 0.6

For m=500 GeV and 800 GeV, chiral Lagrangian vector resonance discovered with < 100 fb−1

BSM

Vector Boson Scattering

Not an early data analysis !

If no light Higgs boson → alternative to SM, SUSY, Little Higgs
EWSB could result from strong coupling interaction
No assumptions about underlying dynamics of EWSB
SM low energy effective theory

In SM, perturbative unitarity violated in VBS at high energy
for m_H >870 GeV or if no Higgs for $E_{cm} \sim 1.7$ TeV
→ NP at high energy, possibly vector boson pair resonances

- Technicolor with Goldstone boson resulting from chiral symmetry breaking
- Higgsless extra dimensions, where KK gauge bosons exchanged in s-channel
- Extra vector bosons mixing with SM vector bosons

→ Perform generic search

Chiral Lagrangian model

Effective theory valid up to $4\pi v \sim 3$ TeV, where v = 246 GeV vev of SM Higgs
If no light scalar Higgs, description of longitudinal gauge boson scattering at TeV scale
With non linear EWSB

Set of dimension-4 effective operators describe low energy interactions
At LHC, VBS at TeV where interaction becomes strong → necessary to unitarise scattering amplitudes
Unitarisation prescriptions : Pade or Inverse Amplitude Method based on meson scattering in QCD

In Lagrangian which describes VBS only 2 parameters namely a4 and a5 are important
Depending on their values : Higgs-like scalar resonances and/or technicolour-like vector resonances
Properly-unitarised amplitudes for VBS suited in higher energy range
Poles for certain values of α_4 and α_5 → resonances
Other unitarisation procedures possible → resonances not necessarily produced

BSM

Black Holes

In ED models $M_{Planck} \sim M_{EWSB}$
→ coupling strength of gravity increased to size ~ other interactions → unification of gravity and gauge interactions
→ quantum gravity effects observable at LHC → Black Holes (BH) production @ LHC
BHs would decay semi-classically by Hawking radiation emitting high energy particles
N.B. Semi-classical assumptions, valid only above Planck scale, necessary to enable quantitative description and predictions
→ minimum m_{BH} imposed in simulations

1. BH Formation

Semi classical arguments → BH formed if impact parameter of head-on collision between 2 partons < $R_{schwarzschild}$
Schwarzschild 1916 + generalization by Myers and Perry 1986

for D=4+n dimensions $R_S \propto (1/M_D)\,(M_{BH}/M_D)^{1/(n+1)}$

R_s depends on n=number of xtra-dims and on M_D=effective Planck scale
Exact Xsec needs QG theory → use quasi classical black disc approximation

$\sigma = f\, \pi\, R_S^2$ (f=formation factor~1)

Parton level Xsec grows with energy, non perturbative

valid for $M_{BH} >> M_D$

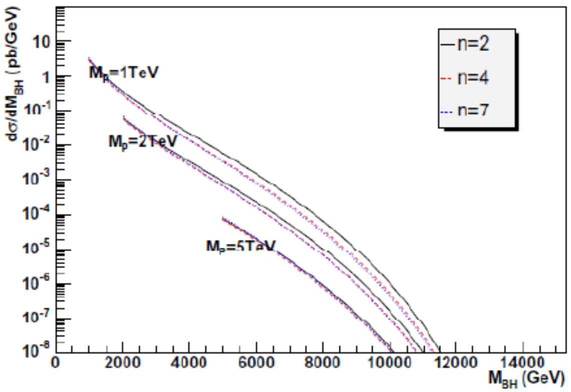
Possible for any combination of q/g . All gauge/spin quantum numbers allowed. BH charged and colored

2. Hawking radiation (1975)

Pairs of virtual particles appear at event horizon with one particle escaping
Black body spectrum in D=4+n with
$T_{Hawking}=(n+1)/(4\pi R_S) \propto M_D \times (M_{BH}/M_D)^{1/(n+1)} \times (n+1)$

3. BH decay

1. Balding phase : Graviton radiation
2. Evaporation phase : $M_{BH}>>M_D$ Hawking radiation
   where most of initial energy is emitted mostly in SM particles
3. Planck phase : $M_{BH} \rightarrow M_D$ QG regime : predictions "very difficult"…



Cross section of Black Hole in 14TeV pp collision

BSM

Black Holes

Semi-classical assumptions, valid only above Planck scale,
necessary to enable quantitative description and predictions
→ minimum m_{BH} imposed in simulations

Parton level Xsec grows with energy, non perturbative valid for $M_{BH} >> M_D$

MCs reasonable for $M_{BH}>>M_D$

Total Xsec = convoluting parton-level Xsec with PDFs integrating over phase space, summing over parton types
Transition from parton-level to hadron-level Xsec based on a factorization ansatz
Validity of this formula for energy region above the Planck scale is unclear
Even if factorisation is valid, extrapolation of the PDFs into this transplanckian region is questionable

BSM

Black Holes

Charybdis BH MC

1. Balding phase : not simulated
2. Evaporation phase : only SM particles are generated, no gravitons. Democratic decay into SM particles.
3. Planck phase : only SM particles generated. Two body decays.

→ MCs reasonable for $M_{BH} >> M_D$

→ Total Xsec = convoluting parton-level Xsec with PDFs integrating over phase space, summing over parton types

Transition from parton-level to hadron-level Xsec based on a factorization ansatz

Validity of this formula for energy region above the Planck scale is unclear

Even if factorisation is valid, extrapolation of the PDFs into this transplanckian region is questionable

BH event simulation with Charybdis

→ Semi classical model : $M_{BH} \geq 5M_D$

→ Due to high $T_{Hawking}$ and mass scale, semi-classical BHs tend to emit particles with very high E and pT

→ High multiplicity and high sphericity events

→ Democratic BH decay into SM particles only loosely achieved because of charged and coloured input state

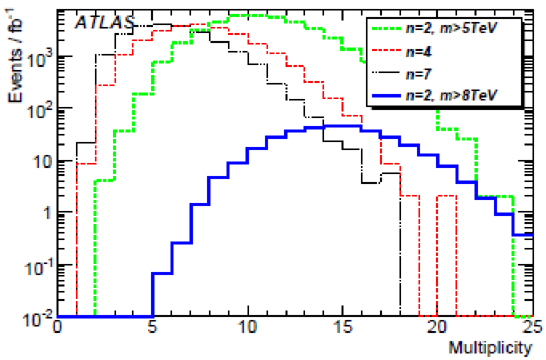


FIGURE 1. Particle Multiplicities in BH datasets, with n extra dimensions and minimum BH mass m.

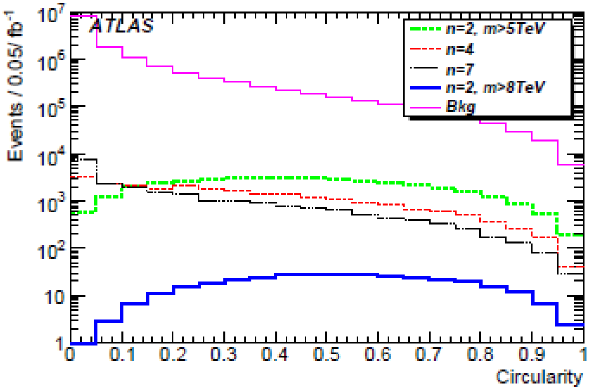
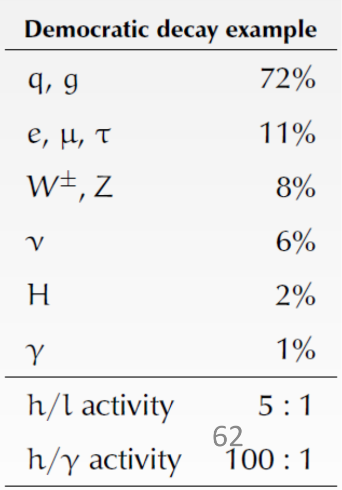


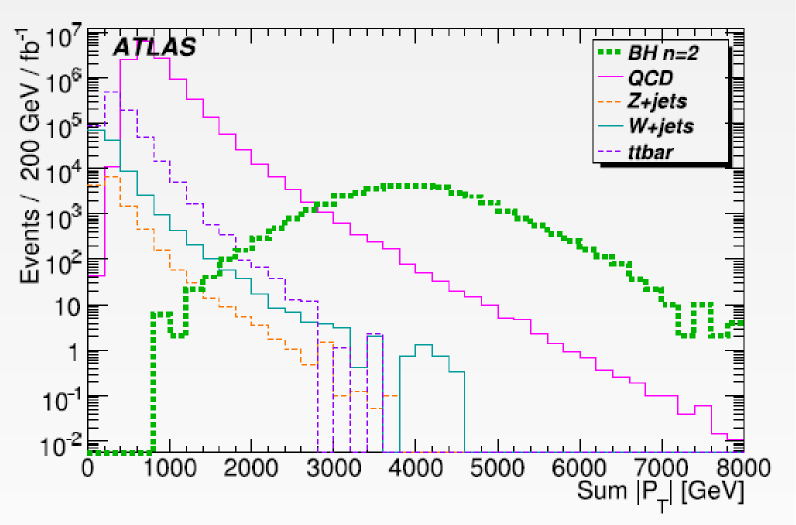
FIGURE 2. Circularity in BH and SM background events



Democratic decay example	
q, g	72%
e, μ, τ	11%
$W^{\pm}$, Z	8%
ν	6%
H	2%
γ	1%
h/l activity	5 : 1
h/γ activity	100 : 1

BSM

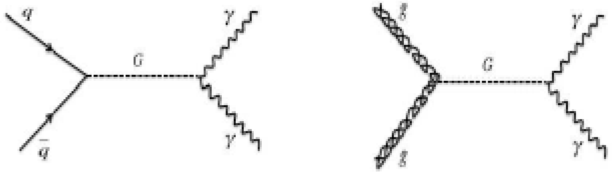
Black Holes



BSM

Diphoton resonance in Randall Sundrum XtraD

Tevatron excludes $M_G < 240$ GeV/c^2 with coupling k/ $M_{Planck} = 0.01$

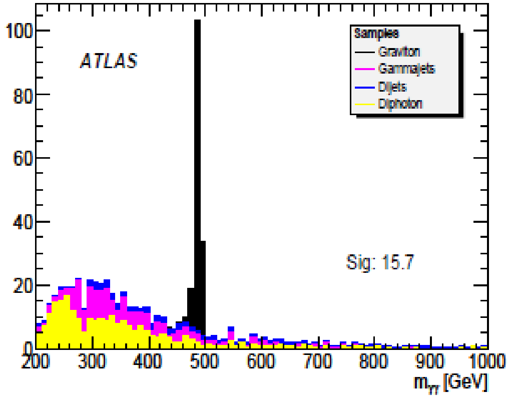


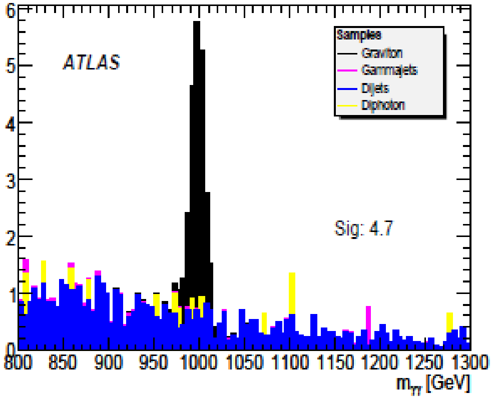
Signal and background

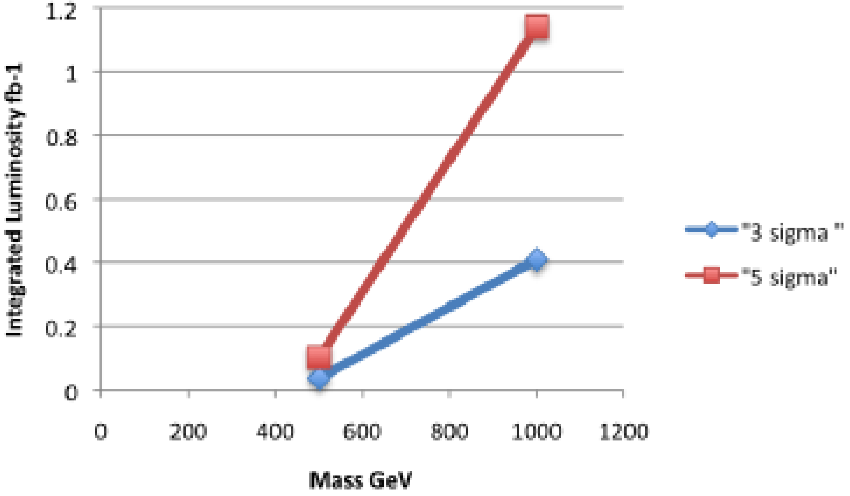
G→γγ with $M_G = 500$ GeV/c^2 , 1 TeV/c^2
with k/ $M_{Planck} = 0.01$

Significance

Taking into account systematic uncertainties (PDFs, Luminosity)







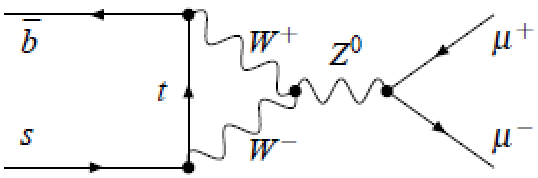
102 pb-1 [1.14 fb-1]
5σ discovery
for
$M_G = 500$ [1000] GeV/c^2
k/ $M_{Planck} = 0.01$

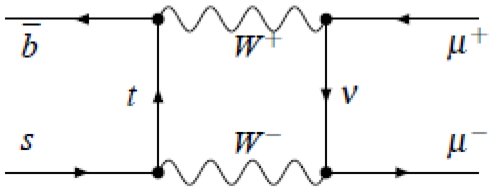
BSM

Devations from SM in rare b decays

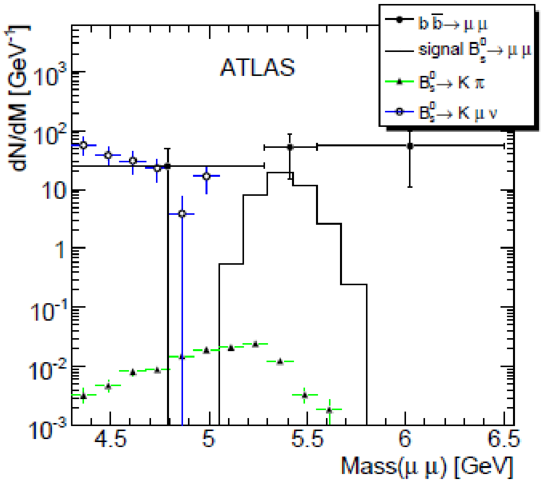
$B^0_s \rightarrow \mu+\mu-$

$B^0_s \rightarrow \ell+\ell-$ with ℓ± = e±,μ±, or τ±, decays mediated by FCNC forbidden in the SM at tree level.
Lowest-order contributions in SM involve weak penguin loops and weak box diagrams that are CKM suppressed.
Below lowest order SM contributions diagrams.
Since the B0s meson is a pseudoscalar that has positive C parity and the transition proceeds in an ℓ = 0 state, electromagnetic penguin loop forbidden. Two leptons are either both right-handed or both left-handed leading to additional helicity suppression. Thus, branching fractions expected in the Standard Model are tiny.





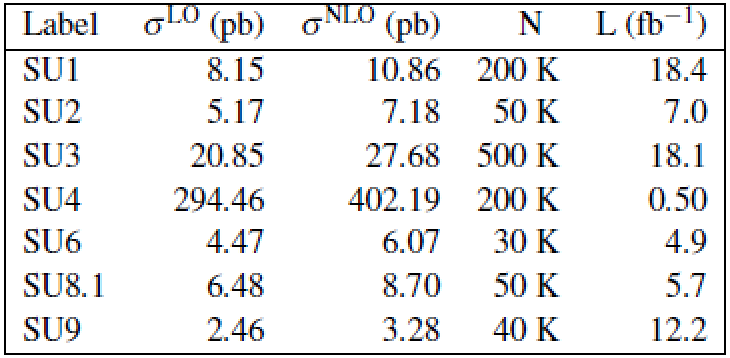
In extensions of the SM, the $B^0_s \rightarrow \mu+\mu-$ branching fraction may be enhanced by several orders of magnitude.
CDF and D0 have not yet observed a signal (2fb-1).
CDF limit $B(B^0_s \rightarrow \mu+\mu-) < 5.8\times10^{-8}$ @ 95% CL ~ 1 order of magnitude higher than SM prediction
New physics could be SUSY, Higgs doublet models, models with extra gauge bosons



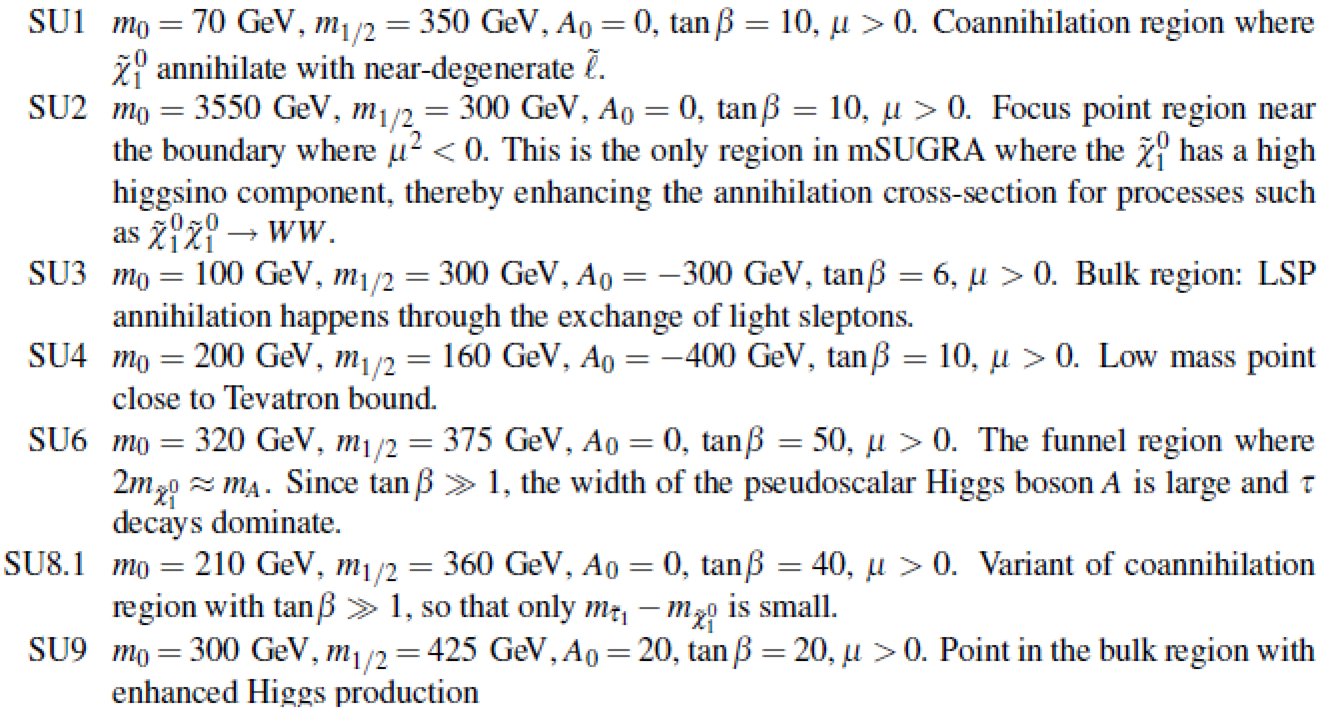
$m_{\mu\mu}$ distribution after selection cuts for 10 fb-1
Signal → histogram,
combinatorial bgd → closed circles
non-combinatorial bgd → opened circles and triangles

SUSY

LO and NLO Xsec : PROSPINO + CTEQ6M



Label	$\sigma^{\rm LO}$ (pb)	$\sigma^{\rm NLO}$ (pb)	N	L ($\rm fb^{-1}$)
SU1	8.15	10.86	200 K	18.4
SU2	5.17	7.18	50 K	7.0
SU3	20.85	27.68	500 K	18.1
SU4	294.46	402.19	200 K	0.50
SU6	4.47	6.07	30 K	4.9
SU8.1	6.48	8.70	50 K	5.7
SU9	2.46	3.28	40 K	12.2



SU1 $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.

SU2 $m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$.

SU3 $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan\beta = 6$, $\mu > 0$. Bulk region: LSP annihilation happens through the exchange of light sleptons.

SU4 $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan\beta = 10$, $\mu > 0$. Low mass point close to Tevatron bound.

SU6 $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$. The funnel region where $2m_{\tilde{\chi}_1^0} \approx m_A$. Since $\tan\beta \gg 1$, the width of the pseudoscalar Higgs boson A is large and τ decays dominate.

SU8.1 $m_0 = 210$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 40$, $\mu > 0$. Variant of coannihilation region with $\tan\beta \gg 1$, so that only $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ is small.

SU9 $m_0 = 300$ GeV, $m_{1/2} = 425$ GeV, $A_0 = 20$, $\tan\beta = 20$, $\mu > 0$. Point in the bulk region with enhanced Higgs production

SUSY

Theoretical framework
SUSY theoretically favoured candidate for BSM
Protect Higgs boson mass from quadratically diverging radiative corrections,
in a theory where SM is only valid up to a scale Λ.
Invariance of the theory under a symmetry which transforms fermions into bosons and vice-versa.

SUSY predictions :
for each SM particle degree of freedom → corresponding sparticle with Δspin = ½
SUSY generators commute with SU(2)×U(1)×SU(3) symmetries of the SM, and with Poincare group.

In unbroken SUSY, partner particles would have the same quantum numbers and masses as SM particles.
Since no superpartner has been observed to date, SUSY must be broken.

Assume minimal possible particle content i.e. common simplification approach,
and parametrize SUSY-breaking Lagrangian as Σ of all terms which do not reintroduce quadratic divergences
→ MSSM characterised by a large number of parameters (100)
Conservation of baryonic and leptonic quantum numbers
→ new multiplicative quantum number R-parity = 1 (-1) for (s)particles

If R-parity is conserved → sparticles produced in pairs.
Subsequent decay down to stable lightest SUSY particle (LSP).
Cosmological arguments → LSPs weakly interacting and escape direct detection → MET

Impossible to explore 100-dim param space of MSSM → adopt some specific assumptions for SUSY breaking :

- mSUGRA : SUSY breaking mediated by gravitational interaction
- GMSB : SUSY breaking mediated by gauge interaction through messenger gauge fields

LSP=neutralino in mSUGRA, gravitino in GMSB → different topologies

SUSY

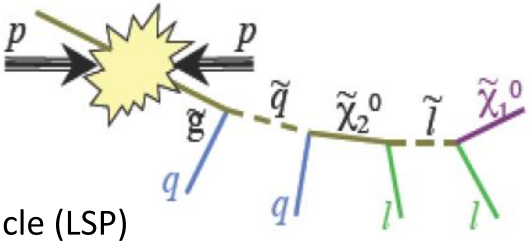
mSUGRA points

Predicted cosmological relic density of neutralinos should be consistent with observed density of CDM.
To reproduce observed relic density, mSUGRA must ensure efficient annihilation of neutralinos in early U.
Possible only in restricted regions of mSUGRA parameter space, where annihilation enhanced :
either by a significant higgsino component in lightest neutralino or through mass relationships.
Points defined in terms of mSUGRA parameters at GUT :

SU1	m_0=70 GeV, $m_{1/2}$=350 GeV, A_0= 0, tan β = 10, $\mu > 0$ Coannihilation region where χ^0_1 annihilate with slepton
SU2	m_0=3550 GeV, $m_{1/2}$=300 GeV, A_0= 0, tan β = 10, $\mu > 0$ Focus point region near boundary where $\mu^2 < 0$. Only region in mSUGRA where ~χ^0_1 has high higgsino component→ annih Xsec enhanced
SU3	m_0=100 GeV, $m_{1/2}$=300 GeV, A_0= -300 GeV, tan β = 6, $\mu > 0$ Bulk region: LSP annih through exchange of light sleptons
SU4	m_0=200 GeV, $m_{1/2}$=160 GeV, A_0= -400 GeV, tan β = 10, $\mu > 0$ Low mass point close to Tevatron bound
SU6	m_0=320 GeV, $m_{1/2}$=375 GeV, A_0= 0, tan β = 50, $\mu > 0$ Funnel region where 2m(χ^0_1) ~ m(A). Since tan β>>1, Γ(A)>> and τ decays dominate
SU8.1	m_0=210 GeV, $m_{1/2}$=360 GeV, A_0= 0, tan β = 40, $\mu > 0$ Variant of coannih region with tan β>>1 such that only m(~τ_1)-m(~χ^0_1) is small
SU9	m_0=300 GeV, $m_{1/2}$=425 GeV, A_0= 20, tan β = 20, $\mu > 0$ Point in bulk region with enhanced Higgs prod

Wide range of possible decay topologies. Common features e.g. gluino mass < 1 TeV, m(~g)/m(~χ^0_1)= 6–8
For all except SU2, m(~q) $\cong$ m(~g). Gluinos and squarks copiously produced.
Decays give relatively high pT jets, possibly leptons, and MET.

SUSY



If R-parity is conserved
→ sparticles produced in pairs (squarks, gluinos)
→ sparticle cascade decay down to stable lightest SUSY particle (LSP)

Some possible scenarios :

mSUGRA (LSP=neutralino) SUSY breaking mediated by gravitational interaction

SU1	m_0=70 GeV	$m_{1/2}$=350 GeV	A_0= 0	tan β = 10	$\mu > 0$	10.9pb	Coannih where $\chi^0{}_1$ annih with slept
SU2	m_0=3550 GeV	$m_{1/2}$=300 GeV	A_0= 0	tan β = 10	$\mu > 0$	7.18pb	Focus point near boundary where $\mu^2 < 0$
SU3	m_0=100 GeV	$m_{1/2}$=300 GeV	A_0=-300GeV	tanβ=6	μ>0	27.7pb	Bulk: LSP annih through exch of light slepts
SU4	m_0=200 GeV	$m_{1/2}$=160 GeV	A_0=-400GeV	tanβ=10	μ>0	402pb	Low mass point close to Tevatron bound
SU6	m_0=320 GeV	$m_{1/2}$=375 GeV	A_0= 0	tan β = 50	$\mu > 0$	6.1pb	Funnel : 2m($\chi^0{}_1$) ~ m(A). τ decays dominate
SU8.1	m_0=210 GeV	$m_{1/2}$=360 GeV	A_0= 0	tan β = 40	$\mu > 0$	8.7pb	Variant of coannih: tan β>>1
SU9	m_0=300 GeV	$m_{1/2}$=425 GeV	A_0= 20	tan β = 20	$\mu > 0$	3.3pb	Point in bulk with enhanced Higgs prod

GMSB (LSP=gravitino)
SUSY breaking mediated by gauge interactions
through messenger gauge fields

Split SUSY
Gluinos can be meta-stable forming a bound state
so-called $R_{\sim g}$-hadron

Gravitino LSP and stop NLSP scenario
Generic possible candidate for NLSP is lightest $\sim t_1$
which would form stable bound states
denoted $R_{\sim t}$

SUSY

GMSB

SUSY breaking which takes place in hidden sector is transmitted to visible MSSM fields through a messenger sector whose mass scale is much below Planck scale ($M_{mess} \ll M_{Planck}$) via the ordinary SM gauge interactions

Gravitino is very light (in general $\ll$ 1 GeV) and is always the LSP

In minimal GMSB, all SUSY breaking interactions are determined by a few parameters

Squarks, sleptons, and gauginos obtain their masses radiatively from the gauge interactions with massive messengers

their masses depend on number of messenger generations, N_5

(messenger fields form complete SU(5) representations)

Gaugino masses scale like N_5 while scalar masses scale like $\sqrt{N_5}$

For $N_5 = 1$, NLSP = $\sim\chi^0_1$ wich decays as $\rightarrow \gamma + \sim G$

For $N_5 \geq 2$, NLSP = $\sim \tau_1$

When $\tan\beta$ not too large, mass splitting between $\sim\tau_1$ and $\sim e_R$,$\tilde{\ }\mu_R$ is small, rendering them co-NLSP's which decay into leptons and ~G

When $\tan\beta$ large $\sim\tau_1$ is sole NLSP

Effective visible sector SUSY breaking parameter Λ sets overall mass scale for all MSSM superpartners, which scales linearly with Λ

These masses only depend logarithmically on messenger scale M_{mess}

→ MSSM masses predominantly determined by Λ

$N_5 = 1$, $\tan\beta = 5$, $\mathrm{sgn}(\mu) = +$

$N_5 = 3$, $\tan\beta = 5$, $\mathrm{sgn}(\mu) = +$

name	NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	$M_{\tilde{\tau}_1}$ [GeV]
GMSB5	21.0 (15.5)	30	250	102.3

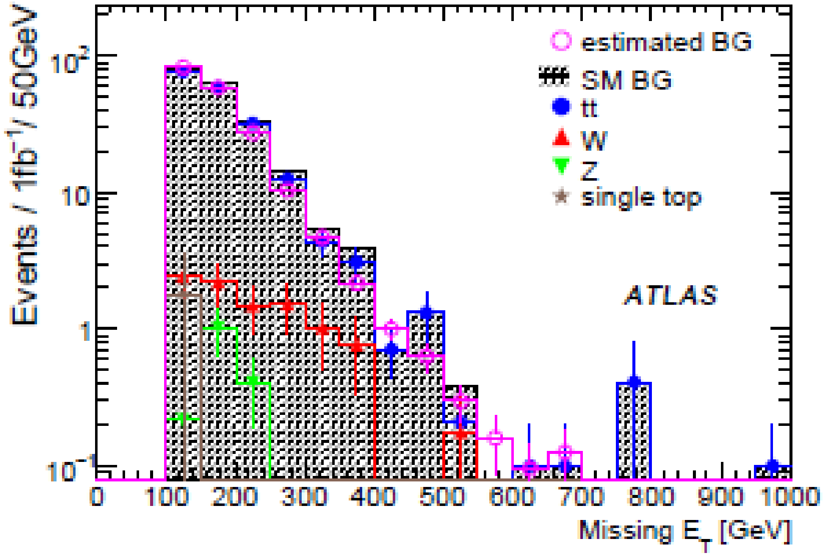
SUSY

→ Data-driven determinations of W, Z, and top backgrounds to Supersymmetry :

Claim for discovery of NP possible only if SM bgds understood and under control
MC alone not sufficient
Bgds will have to be derived from data, possibly helped by MC
Careful combination of multiple, independent methods needed : complementary bgd sources and systematics

SUSY signal will affect bgd estimates, at a level that depends on SUSY signal properties, as well as on method
Methods with very tight control samples see almost no effect
For looser methods, bgd is overestimated (contaminated by SUSY) by ~20–30% for SU1, SU2, SU3 and SU6.
If SUSY excess observed (possible with 1 fb−1), correct for bgd overestimation.
More work is needed in this area.
SU4 is special case because of its light spectrum : kinematics similar to SM bgds and high Xsec
Difficult to provide bgd predictions but SU4 would not be missed.

1fb-1
MET for bgd of one-lepton mode
Open circles = estimated bgd
Hatched histo= true Σ of all SM bgds



SUSY

→ *Estimation of QCD backgrounds to Searches for Supersymmetry*

Difficult to undertand/distinguish QCD jet events amongst SUSY evts with jets and MET
Sub-dominant bgds at high MET and large jet multiplicity, but not so clear with real data
Dead material, jet punch-through, pile-up of machine bgds and other effects → non-Gaussian tails to detector jet response
→ “fake” MET QCD bgd

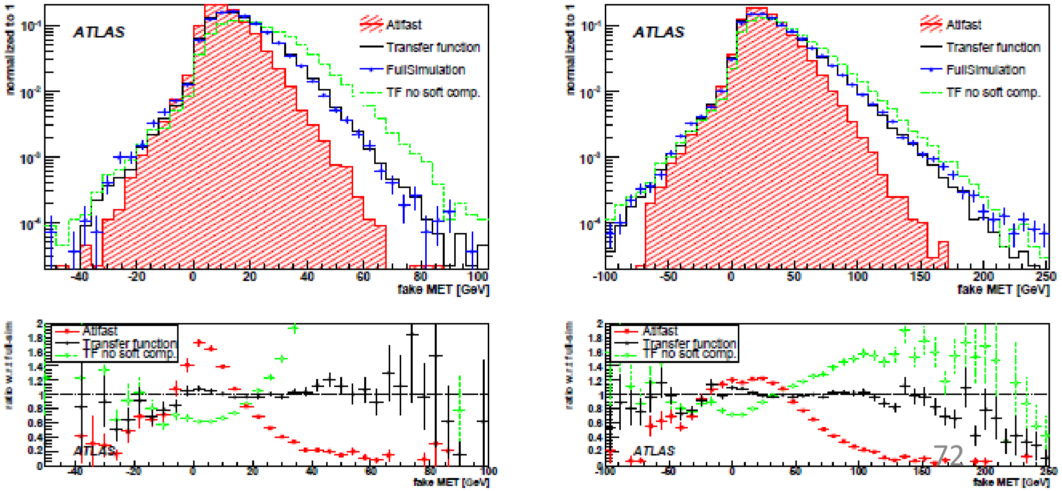
Accurate estimation of QCD jet bgds difficult:
- fake MET poorly modeled in GEANT4
- theoretical and experimental uncertainties
- large QCD Xsect → difficult to produce statistically significant MC samples

Variables sensitive to SUSY : MET and Meff=$\Sigma_{i=1,4}|pT(j_i)|$+MET

MC based bgd estimates systematic uncertainties
- PDFs and underlying event ~ 20% each
- jet energy scale ~ 5% → ~ 30%
- MC modelling of QCD jet physics at 14 TeV :
  Δ(dijet PS.vs.ME+PS) ~ 50%
- luminosity ~20–30% at start-up (machine params)
  < 3–5% (from total Xsec; W/Z counting)

Detector simulation uncertainties due to imperfect description of ATLAS response to QCD jets
Uncertainty in response of ATLAS calorimetry to jets ~ 100% → similar uncertainties in bgd estimate.

Fake MET from fast sim, transfer function technique, and full sim,
for 140<pT<280 GeV (left) and for 560<pT<1120 GeV (right).
Ratio w.r.t. full sim.



SUSY

→ *Prospects for Supersymmetry Discovery Based on Inclusive Searches*

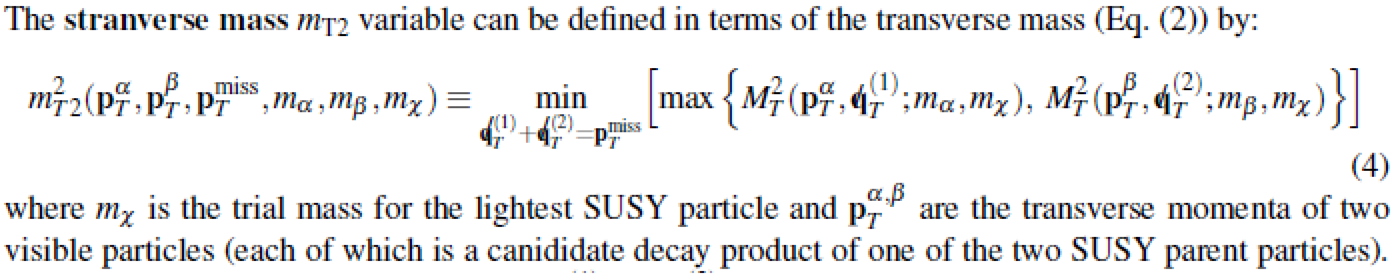
Search for generic SUSY with R parity conserved : SUSY particles produced in pairs and decay to LSP χ^0_1
→ jets, possible leptons and MET

Common variables used:

Effective mass (Meff)

$$M_{\text{eff}} \equiv \sum_{i=1}^{4} p_T^{\text{jet},i} + \sum_{i=1} p_T^{\text{lep},i} + E_{\text{T}}^{\text{miss}}$$

Stransverse mass (m_{T2})

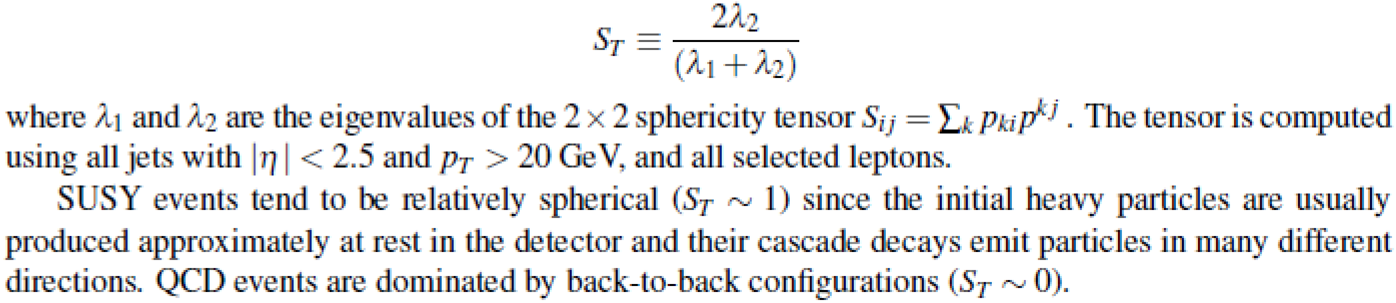


The **stranverse mass** m_{T2} variable can be defined in terms of the transverse mass (Eq. (2)) by:

$$m_{T2}^2(\mathbf{p}_T^{\alpha}, \mathbf{p}_T^{\beta}, \mathbf{p}_T^{\text{miss}}, m_\alpha, m_\beta, m_\chi) \equiv \min_{\mathbf{q}_T^{(1)} + \mathbf{q}_T^{(2)} = \mathbf{p}_T^{\text{miss}}} \left[\max \left\{ M_T^2(\mathbf{p}_T^{\alpha}, \mathbf{q}_T^{(1)}; m_\alpha, m_\chi),\ M_T^2(\mathbf{p}_T^{\beta}, \mathbf{q}_T^{(2)}; m_\beta, m_\chi) \right\} \right] \quad (4)$$

where m_χ is the trial mass for the lightest SUSY particle and $\mathbf{p}_T^{\alpha,\beta}$ are the transverse momenta of two visible particles (each of which is a canididate decay product of one of the two SUSY parent particles).

Transverse Sphericity (ST)



$$S_T \equiv \frac{2\lambda_2}{(\lambda_1 + \lambda_2)}$$

where λ_1 and λ_2 are the eigenvalues of the 2×2 sphericity tensor $S_{ij} = \sum_k p_{ki} p^{kj}$. The tensor is computed using all jets with $|\eta| < 2.5$ and $p_T > 20$ GeV, and all selected leptons.

SUSY events tend to be relatively spherical ($S_T \sim 1$) since the initial heavy particles are usually produced approximately at rest in the detector and their cascade decays emit particles in many different directions. QCD events are dominated by back-to-back configurations ($S_T \sim 0$).

SUSY

SUSY discovery based on inclusive searches

Least model-dependent SUSY signature → multiple jets (e.g. ≥ 4) + MET

High jet multiplicity → bgd reduction : QCD and W/Z+jets

Final state → jets + possible leptons + MET

Variables commonly used

- MET
- Effective mass (Meff) = $\Sigma_{i=1,4}$ pT_{jeti} $\Sigma_{i=1,4}$ pT_{lepti} + MET
- Stransverse mass (m_{T2})
- Transverse Sphericity (ST)

Data driven determination of bgds

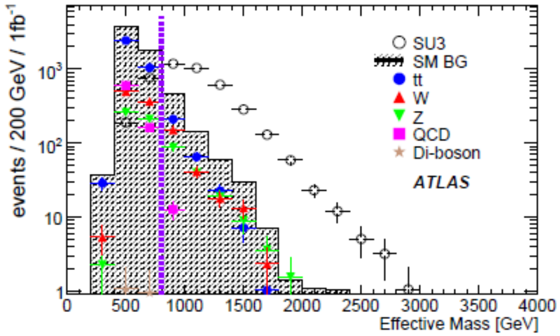
W,Z,top 20% QCD 50% with 1fb-1

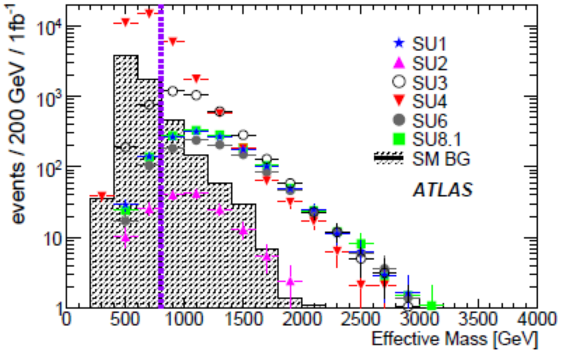
2 different approaches

→ Detailed studies for various signatures (jets + MET + 0,1,2,3… leptons) → full simulation

→ Scans over subsets of SUSY parameter space using → fast simulation

SUSY





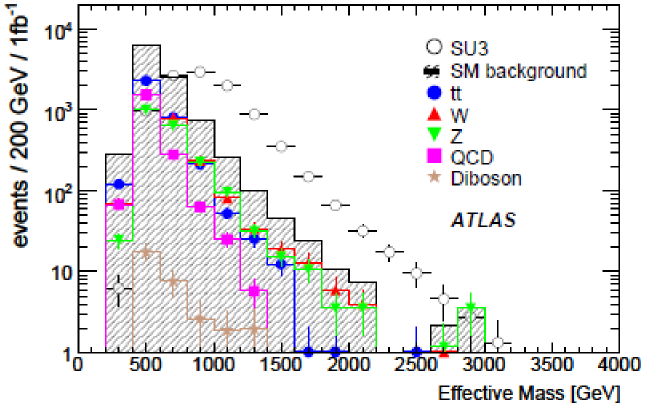
Zero lepton mode (1 fb-1)

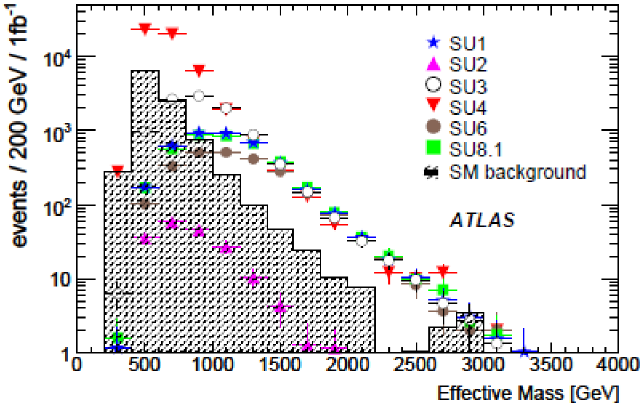
For this topology and for leptonic topologies, very simple sets of cuts:
Evts with Njet ≥4 and with
1<Njet<4 : high bgd but easier to reconstruct, favoured in some SUSY models

Njet ≥4

1. pTjets > 50 GeV + ≥ 1 jet with pT > 100 GeV; MET >100 GeV
2. MET > 0.2 x Meff
3. Transverse sphericity ST > 0.2
4. $\Delta\phi$(jet1−MET) > 0.2, $\Delta\phi$(jet2−MET) > 0.2, $\Delta\phi$(jet3−MET) > 0.2
5. Reject events with e or μ
6. Meff > 800 GeV

Njet=2





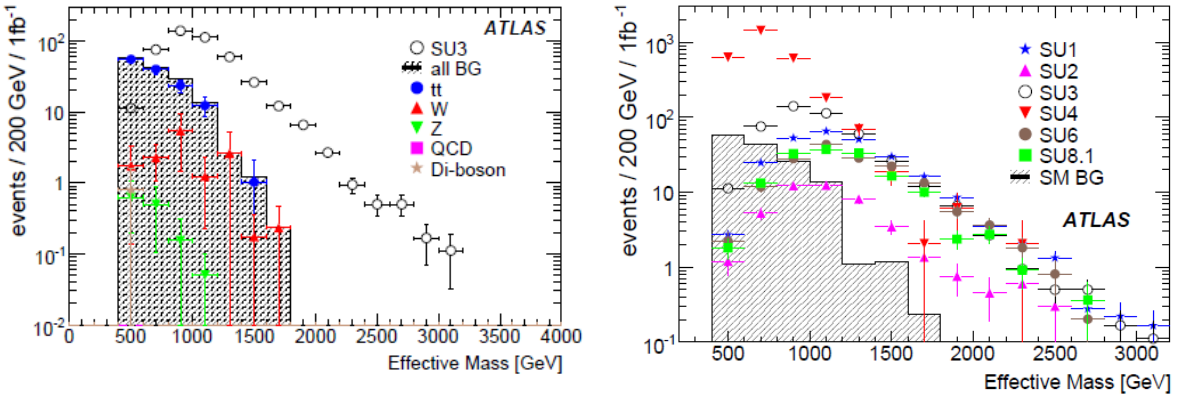
SUSY

One lepton mode (1fb-1)

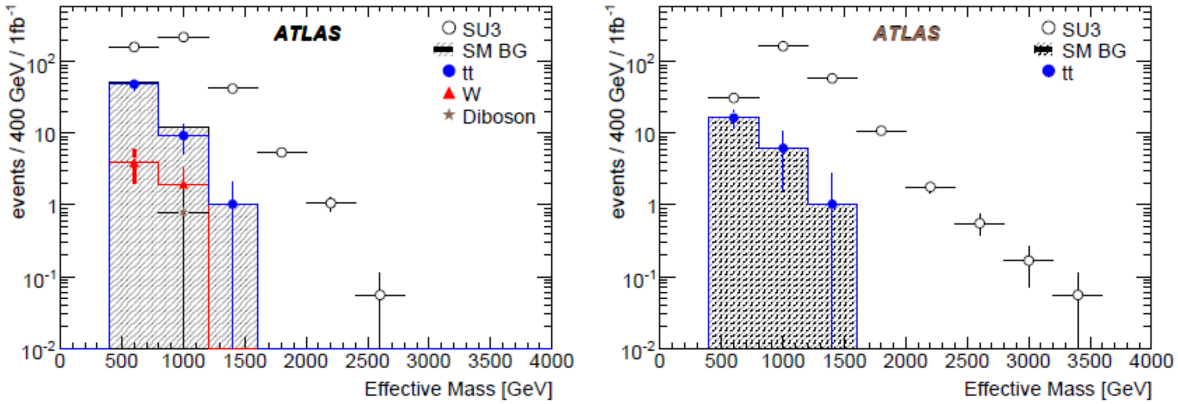
≥4 jets

For Nlepton=1 → multijet QCD bgd greatly reduced

τ decays of gauginos are dominant but leptonic τ decays → significant 1-lepton rate for high masses.



2 (left) or 3 (right) jets



SUSY mSUGRA

Detailed studies of signatures e.g. Two lepton mode (1fb-1)

Opposite-sign di-leptons from neutralino decays, especially $\chi^0_2 \rightarrow \ell^+\ell^- + \chi^0_1$ directly or through an intermediate slepton
Leptons produced from independent decays → same-flavour (OSSF) or different-flavour (OSDF) dilepton pairs $\ell = e,\mu$

Opposite sign + ≥ 4 jets

1. $N_{lepton} = 2$ isolated opposite-sign pT > 10 GeV $|\eta| < 2.5$ if $N_{lepton} > 2$ → evts vetoed
2. $N_{jets} \geq 4$ pT > 50 GeV, $N_{jets} \geq 1$ with pT > 100, 200, 300, 320 GeV
3. MET> 100, 110, 140 GeV MET > $0.2M_{eff}$
4. Transverse sphericity ST > 0.2

Sample	E_T^{miss} cut	Leading jet cut	signal	background	Significance
SU1	100 GeV	320 GeV	37.97	6.30	6.94
SU2	140 GeV	200 GeV	13.74	22.68	1.07
SU3	140 GeV	200 GeV	125.34	22.68	11.45
SU4	110 GeV	100 GeV	772.53	66.80	24.70

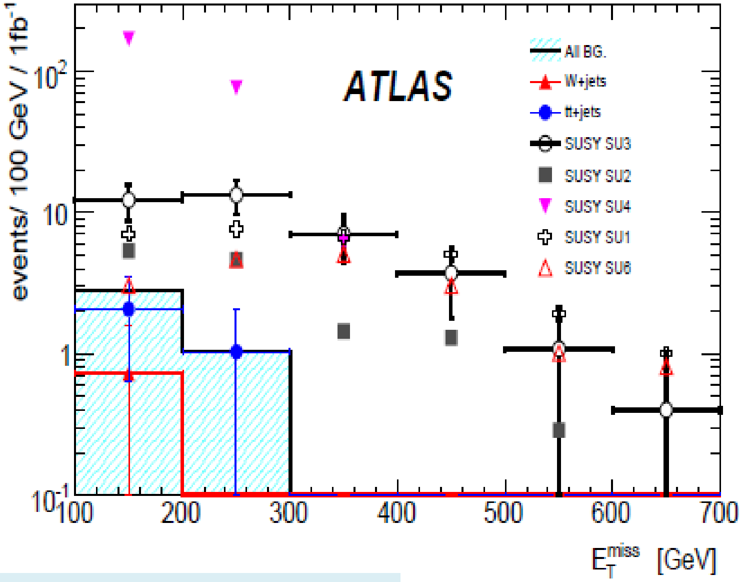
Same sign + ≥ 4 jets

SM, small rate for prompt, isolated, same-sign dilepts
→ some ℓ from hadronized heavy/light quarks

SUSY gluino is self-conjugate Majorana fermion
→ like-sign dileptons common.

1. $N_{lepton}=2$ same-sign pT > 20 GeV
2. $N_{jets} \geq 4$ pT > 50 GeV
   $N_{jets} \geq 1$ pT > 100 GeV
3. MET > 100 GeV
4. MET > 0.2 X Meff

Process	Cuts 1–3	Cut 4	Z_n
SU1	30.1	21.9	7.2
SU2	13.0	6.6	1.9
SU3	37.9	24.9	7.7
SU4	251.8	138.8	19.9
SU6	18.0	13.9	4.5
$t\bar{t}$	2.1	< 2.3	
$W+$jets	0.7	0.0	
$Z+$jets	0.0	0.0	



2leptons + ≥ 4 jets : SU1, SU3, SU4 (SU6) ≤1fb-1 for ≥ 5σ

SUSY mSUGRA

Three lepton mode (1fb-1)

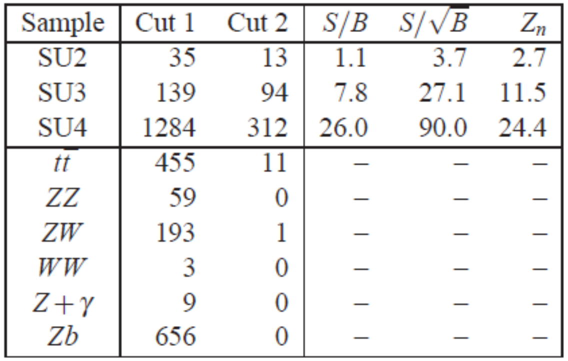
Trileptons from all sources, not just from direct gaugino production

Two approaches

3-leptons + jet with high-pT jet

1. $N_{lepton} \geq 3$, pT > 10 GeV
2. $N_{jet} \geq 1$, pT > 200 GeV

Zn significance + 20% bgd uncert.



Sample	Cut 1	Cut 2	S/B	$S/\sqrt{B}$	Z_n
SU2	35	13	1.1	3.7	2.7
SU3	139	94	7.8	27.1	11.5
SU4	1284	312	26.0	90.0	24.4
$t\bar{t}$	455	11	–	–	–
ZZ	59	0	–	–	–
ZW	193	1	–	–	–
WW	3	0	–	–	–
$Z+\gamma$	9	0	–	–	–
Zb	656	0	–	–	–

3-leptons + MET :

No veto on jets

→ sensitive to direct gaugino prod and to tri-ℓ from squark and gluino decays

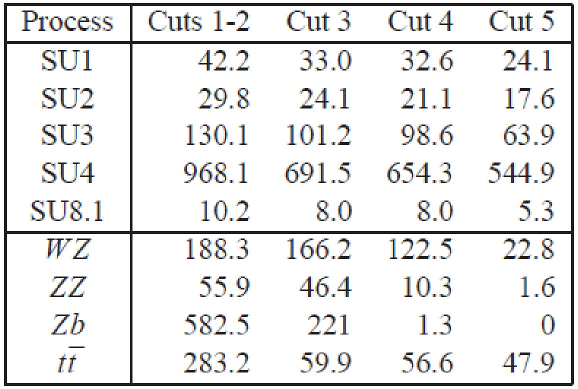
Analysis cuts optimized for SU2

→ gaugino pair prod dominates

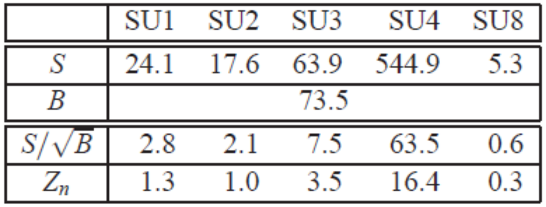
SUSY dominant source of tri-ℓ includes χ^0_2 → ℓ+ℓ- + χ^0_1

→ require at least 1 OSSF lepton pair

1. Nℓ ≥ 3, pT > 10 GeV
2. ≥ 1 OSSF dilepton pair, M > 20 GeV
3. Isol cut $p^{0.2}_{T,trk} < 1$ GeV for μ and < 2 GeV for el
   i.e. pTmax of any extra track within cone R = 0.2 around lepton
4. MET > 30 GeV
5. $M < M_Z - 10$ GeV for any OSSF dilepton pair



Process	Cuts 1-2	Cut 3	Cut 4	Cut 5
SU1	42.2	33.0	32.6	24.1
SU2	29.8	24.1	21.1	17.6
SU3	130.1	101.2	98.6	63.9
SU4	968.1	691.5	654.3	544.9
SU8.1	10.2	8.0	8.0	5.3
WZ	188.3	166.2	122.5	22.8
ZZ	55.9	46.4	10.3	1.6
Zb	582.5	221	1.3	0
$t\bar{t}$	283.2	59.9	56.6	47.9



	SU1	SU2	SU3	SU4	SU8
S	24.1	17.6	63.9	544.9	5.3
B	73.5				
$S/\sqrt{B}$	2.8	2.1	7.5	63.5	0.6
Z_n	1.3	1.0	3.5	16.4	0.3

3 leptons : SU3, SU4 ≤1fb-1 for ≥5σ

SUSY mSUGRA

Tau mode (1fb-1)

SUSY models generically violate e/μ/τ universality

τ Decays dominant for tanβ ≫ 1

Look for signatures involving hadronic τ decays

1. $N_{jets} \geq 4$, pT > 50 GeV and $N_{jets} \geq 1$, pT > 100 GeV
2. MET> 100 GeV
3. $\Delta\phi(j_i, MET) > 0.2$ for 3 leading jets
4. No isolated leptons
5. $N_\tau \geq 1$, pT >40 GeV and $|\eta| < 2.5$ (lik method)
6. MET > 0.2 X Meff
7. M_T > 100 GeV, calculated using p_{vis} of hardest τ and MET

Sample	S	B	S/B	$S/\sqrt{B}$	Z_n
SU3	259	51	5.1	36.3	12
SU6	119	51	2.3	16.7	6.8

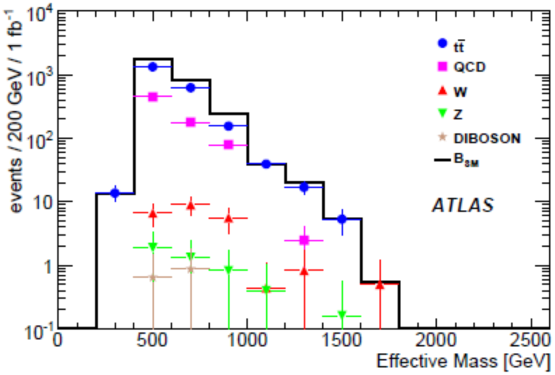
	S/B	Z_n for 0.1 fb^{-1}	Z_n for 1 fb^{-1}
SU1	3.8	6.0	9.3
SU2	1.3	2.3	5.0
SU3	6.2	7.5	13.0
SU4	13.4	12.6	21.7
SU6	4.9	7.1	11.2

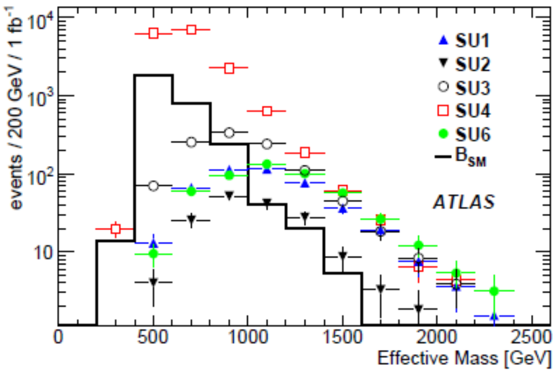
b-jet mode (1fb-1)

SUSY rich in b quarks : sbottom/stop lighter than 1st and 2nd gen. squarks and Higgsino couplings enhance heavy flavour production

% evts containing b jets : from 14.4% for SU2 to 72.8% for SU4, whereas QCD ~ 1%

1. $N_{jets} \geq 4$, pT > 50 GeV
2. Leading jet pT > 100 GeV
3. MET > 100 GeV
4. MET > 0.2 X Meff
5. Transverse sphericity ST > 0.2
6. $N_{jets} \geq 2$ tagged as b jets
7. M_{eff} > 600, 800, or 1000 GeV





Tau mode : SU3, SU6 ≤1fb-1 for ≥5σ

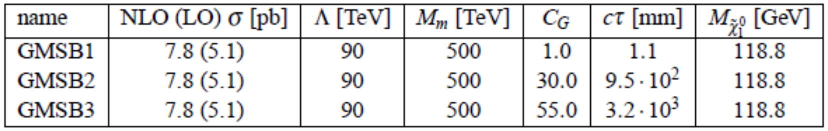
b-jet mode : SU1, SU2, SU3, SU4, SU6 ≤1fb-1 for ≥5σ

SUSY GMSB

High-pT photons in GMSB models

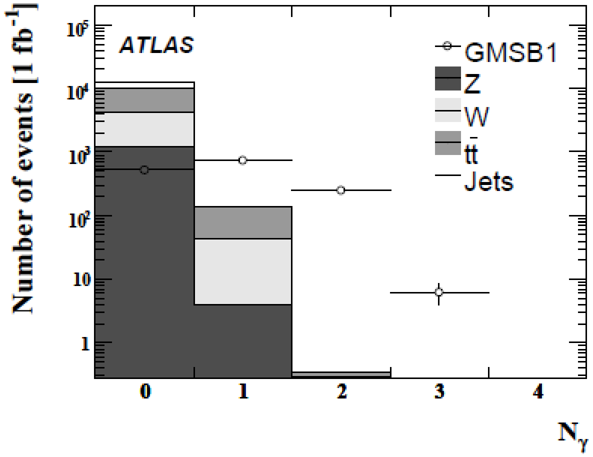
$\chi^0_1 \rightarrow$ ~G + γ gives 2 high pT photons + MET
long lived ~χ^0_1 give non pointing photons

- Njets≥ 4 with pT > 50 GeV and pT > 100 GeV for leading jet
- MET > 100 GeV and MET > 20% X Meff
- ≥ 1 photon with pT>20 GeV and |η|<2.5



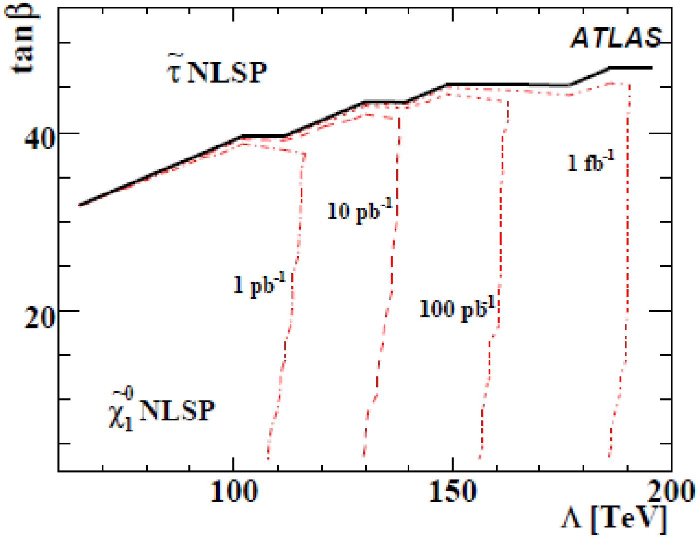
name	NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	C_G	$c\tau$ [mm]	$M_{\tilde{\chi}^0_1}$ [GeV]
GMSB1	7.8 (5.1)	90	500	1.0	1.1	118.8
GMSB2	7.8 (5.1)	90	500	30.0	$9.5 \cdot 10^2$	118.8
GMSB3	7.8 (5.1)	90	500	55.0	$3.2 \cdot 10^3$	118.8

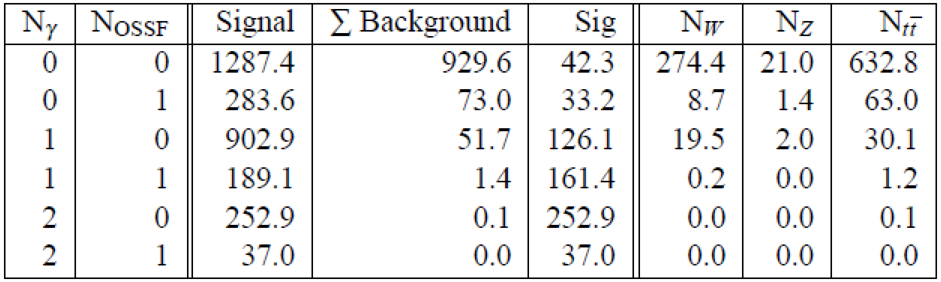
N_5 = 1 (# mess gen), tanβ = 5, sgn(μ) = +



1fb−1
Number of reco photons
pT >20 GeV and |η| < 2.5

5σ contour lines for GMSB SUSY





N_γ	N_{OSSF}	Signal	$\sum$ Background	Sig	N_W	N_Z	$N_{t\bar{t}}$
0	0	1287.4	929.6	42.3	274.4	21.0	632.8
0	1	283.6	73.0	33.2	8.7	1.4	63.0
1	0	902.9	51.7	126.1	19.5	2.0	30.1
1	1	189.1	1.4	161.4	0.2	0.0	1.2
2	0	252.9	0.1	252.9	0.0	0.0	0.1
2	1	37.0	0.0	37.0	0.0	0.0	0.0

100pb-1 for Λ<150 TeV and tanβ<30-40
for 5 σ discovery

SUSY R-hadrons

Long Lived Heavy particles in Split-SUSY and gravitino LSP

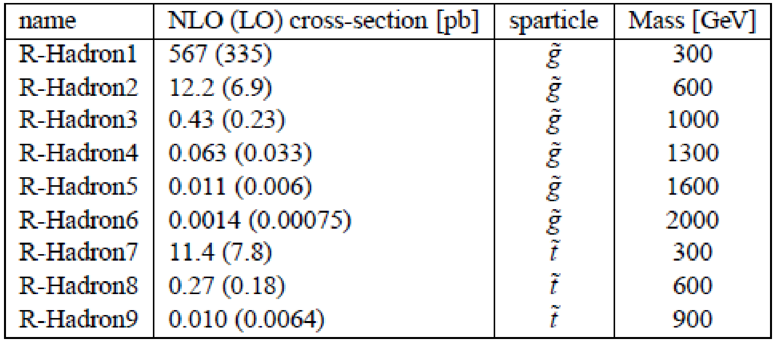
Penetrating hard charged track with high E deposition and long time of flight
May undergo charge exchange in calorimeter
Multiple nuclear interactions before reaching muon system
→ appearance of high pT tracks in muon system with no matching track in ID
→ electric charge flipping between ID and muon system
$m_{\text{R-hadrons}}$ ~< 200 GeV already excluded

Selection

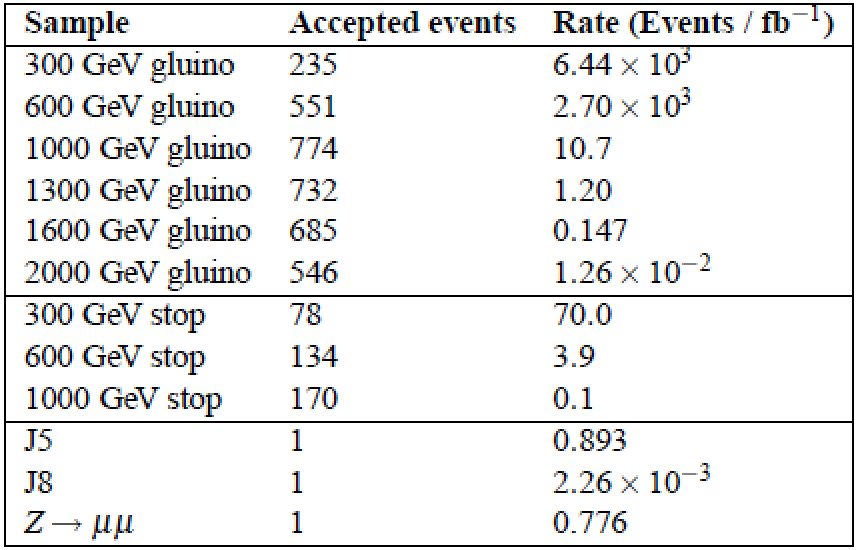
low trigger efficiency 20 (30) % for m=2 TeV (few 100GeV)
no hard muon-like track (pT > 250 GeV) near (R < 0.36) a hard jet (pT > 100 GeV)

- at least one hard muon track with no linked ID track
- 2 hard back-to-back ID tracks
- 2 hard back-to-back like-sign muon tracks
- at least one hard muon track with hard matching ID track of opposite charge

R1 to R6 are $R_{\sim g}$-hadron while R7 to R0 are $R_{\sim t}$



name	NLO (LO) cross-section [pb]	sparticle	Mass [GeV]
R-Hadron1	567 (335)	$\tilde{g}$	300
R-Hadron2	12.2 (6.9)	$\tilde{g}$	600
R-Hadron3	0.43 (0.23)	$\tilde{g}$	1000
R-Hadron4	0.063 (0.033)	$\tilde{g}$	1300
R-Hadron5	0.011 (0.006)	$\tilde{g}$	1600
R-Hadron6	0.0014 (0.00075)	$\tilde{g}$	2000
R-Hadron7	11.4 (7.8)	$\tilde{t}$	300
R-Hadron8	0.27 (0.18)	$\tilde{t}$	600
R-Hadron9	0.010 (0.0064)	$\tilde{t}$	900



Sample	Accepted events	Rate (Events / fb^{-1})
300 GeV gluino	235	6.44×10^3
600 GeV gluino	551	2.70×10^3
1000 GeV gluino	774	10.7
1300 GeV gluino	732	1.20
1600 GeV gluino	685	0.147
2000 GeV gluino	546	1.26×10^{-2}
300 GeV stop	78	70.0
600 GeV stop	134	3.9
1000 GeV stop	170	0.1
J5	1	0.893
J8	1	2.26×10^{-3}
$Z \rightarrow \mu\mu$	1	0.776

1fb-1 discovery
$m(R_{\sim g}) < 1$ TeV
$m(R_{\sim t1})$ ~< 550 GeV

SUSY

Scans

Over parameters of several R-parity conserving SUSY models
Data-driven methods for SM bgds → 1fb−1 estimated errors ~50% for QCD jets and ~20% for W, Z, and t bgds
Look for excess above cut on Meff (best performance) or MET
Signal Xsec norm to LO HERWIG. Bgd Xsec norm to NLO (NLO usually increases Xsec = conservative)
Impossible to scan 105-dim parameter space of MSSM
or even 19-dim subspace with flavour and CP conservation and degeneracy of 1st two gens
→ use SUSY models with many fewer parameters

mSUGRA fixed 25X25 grid, tanβ = 10, A_0 = 0, μ > 0
(60 GeV < m_0 < 2940 GeV in steps of 120 GeV) X (30 GeV < $m_{1/2}$ < 1470 GeV in steps of 60 GeV)
SUSY spectra using ISAJET 7.75 with m_{top} = 175 GeV, 20k events/point. Only constraints from direct searches
mSUGRA fixed 14X14 grid: tanβ = 50, A_0 = 0, μ < 0
Large tanβ increases the mixing of $\tilde{}b_{L,R}$ and $\sim\tau_{L,R}$ → enhanced b and t production.
(200 GeV < m_0 < 3000 GeV in steps of 200 GeV) X (100 GeV < $m_{1/2}$ < 1500 GeV in steps of 100 GeV) m_{top} = 175 GeV
Only constraints from direct searches
mSUGRA random grid with constraints
All mSUGRA params varied in 2 regions compatible with DM and other constraints with μ > 0 and m_{top} = 175 GeV
ISAJET 7.75 used. All points satisfy : LEP m_h > 114.4 GeV, WMAP total DM limit $\Omega h^2 < 0.14$,
within 3σ BR limits $B(b \to s\gamma) = (3.55 \pm 0.26)\times10^{-4}$ and $B(Bs \to \mu+\mu-) < 1.5\cdot10^{-7}$,
with $\delta a_\mu < 3\sigma$ upper limit from muon anomalous magnetic moment measurement $a_\mu = (11659208\pm6)\times10^{-10}$
GMSB fixed grid
M_{mess} = 500 TeV, N_{mess} = 5, C_{grav} = 1: with N_{mess} = 5, NLSP = slepton which decays promptly to leptons or τ's
10 TeV < Λ < 80 TeV in 10 TeV steps and 5 < tanβ < 40 in steps of 5
Non Universal Higgs Model (NUHM) grid:
Similar to mSUGRA but does not assume that Higgs masses unify with squark and slepton ones at GUT scale
→ more gaugino/Higgsino mixing at weak scale → relaxes mSUGRA DM constraints
Step size of 100 GeV for m_0 and $m_{1/2}$. Values of μ and M_A at weak scale are adjusted to give acceptable CDM

SUSY

Measurements from R-parity-conserving mSUGRA evts

- Edges and thresholds in dilepton, lepton-jet, dijet invariant mass distributions → Mass values
- Rate of tau leptons → tanβ
- Trileptons → chargino/neutralino couplings

In R-parity-conserving models, decay chain of sparticles cannot be completely reconstructed (LSP undetected)
Edge positions are measured in m_{inv} distribution of sparticle decay products

- If m(sleptons) > $m(\chi^0_2)$
  - → $\chi^0_2 \rightarrow \chi^0_1 \ell^+\ell^-$ (as in SU4)
  - → Non triangular m_{inv} with $m_{\ell^+\ell^-}^{edge} = m(\chi^0_2) - m(\chi^0_1)$

- If at least one of sleptons m(slepton) < $m(\chi^0_2)$)
  - → $\chi^0_2 \rightarrow {\sim}\ell^+\ell^- \rightarrow \chi^0_1 \ell^+\ell^-$ (as in SU1 and SU3)
  - → Triangular m_{inv} with an endpoint at:

$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}\,.$$

To determine masses of all particles involved in decay chain, one can use $m_{\ell\ell q}$, $m^{thr}_{\ell\ell q}$, $m_{\ell q}$(low) and $m_{\ell q}$(high) where only 2 leading jets are considered

$m_{\ell\ell q}$ using jet giving lowest $m_{\ell\ell q}$ value
$m^{thr}_{\ell\ell q}$ jet giving highest $m_{\ell\ell q}$ value used
$m_{\ell q}$(low) and $m_{\ell q}$(high) lower and higher $m_{\ell q}$ value of each event using same jet as for $m_{\ell\ell q}$

Also studies of ~q_R pairs (~$q_R \rightarrow \chi^0_1$ q; SU3, SU4) and light stop signatures (SU4) ~$t_1 \rightarrow \chi^{\pm}_1$ b.

SUSY

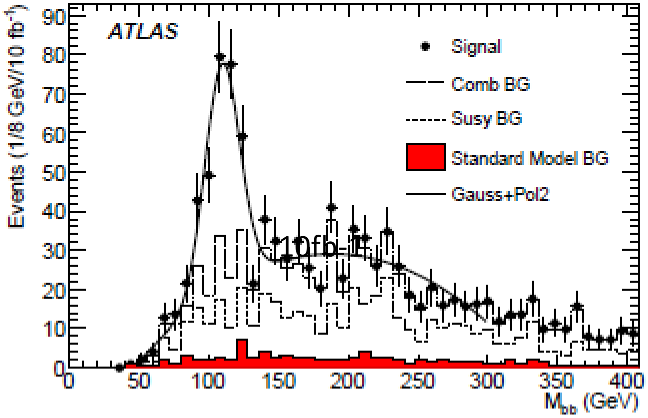
→ Measurements from R-parity-conserving mSUGRA evts
Higgs from the decay of a SUSY particle

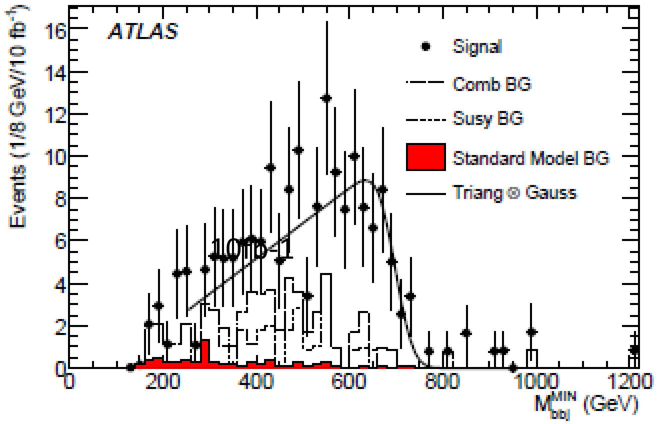
$\chi^0_2 \rightarrow \chi^0_1 h$ dominates unless slepton is lighter than χ^0_2 in which case the ~ℓ+ℓ− and ~$\nu\nu$bar decays open up

In SU9, BR($\chi^0_2 \rightarrow \chi^0_1 h$) ~ 87%

$\sim q_L \rightarrow \sim\chi^0_2\, q \rightarrow \sim\chi^0_1 hq \rightarrow$ MET + bbbar + jet

1. MET > 300 GeV
2. 2 light-flavoured pT > 100 GeV
3. 2 b jets pT > 50 GeV
4. no leptons with pT > 10 GeV

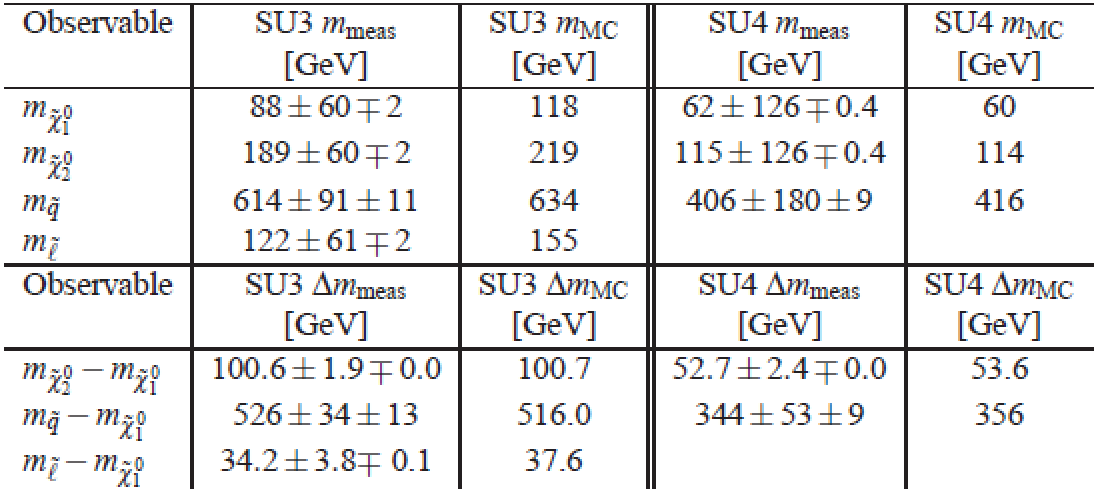




SUSY

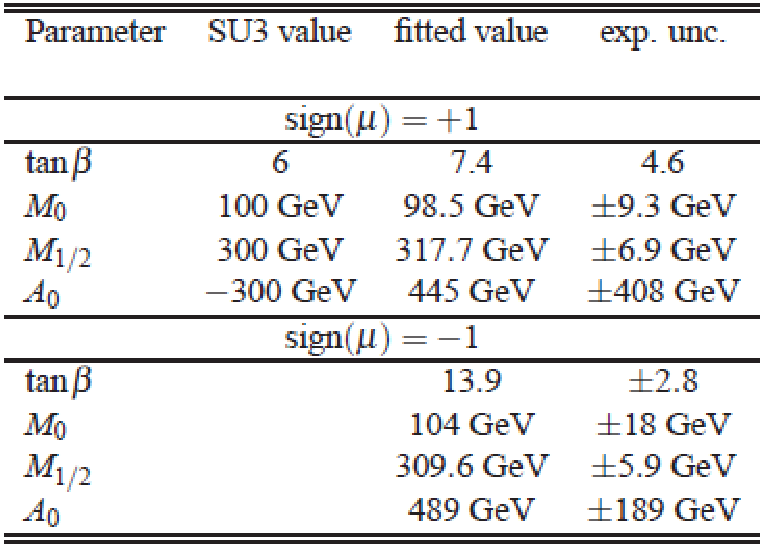
→ Measurements from R-parity-conserving mSUGRA evts
Masses and SUSY parameters

SUSY particle masses and mass differences in SU3 and SU4
From χ2 fit using dilepton and lepton+jets edges.
Parabolic MIGRAD errors and jet energy scale errors.
Error correlations (+-).
1 fb−1 for SU3 and 0.5 fb−1 for SU4.



Observable	SU3 m_{meas} [GeV]	SU3 m_{MC} [GeV]	SU4 m_{meas} [GeV]	SU4 m_{MC} [GeV]
$m_{\tilde{\chi}_1^0}$	$88 \pm 60 \mp 2$	118	$62 \pm 126 \mp 0.4$	60
$m_{\tilde{\chi}_2^0}$	$189 \pm 60 \mp 2$	219	$115 \pm 126 \mp 0.4$	114
$m_{\tilde{q}}$	$614 \pm 91 \pm 11$	634	$406 \pm 180 \pm 9$	416
$m_{\tilde{\ell}}$	$122 \pm 61 \mp 2$	155		
Observable	SU3 Δm_{meas} [GeV]	SU3 Δm_{MC} [GeV]	SU4 Δm_{meas} [GeV]	SU4 Δm_{MC} [GeV]
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	$100.6 \pm 1.9 \mp 0.0$	100.7	$52.7 \pm 2.4 \mp 0.0$	53.6
$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$	$526 \pm 34 \pm 13$	516.0	$344 \pm 53 \pm 9$	356
$m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6		

Fits to presudo experiment results in SU3.
Mean and RMS of fit.
2 possible assumptions for sign(μ) = ±1
Effect of different assumptions
on theoretical uncertainties is also shown.



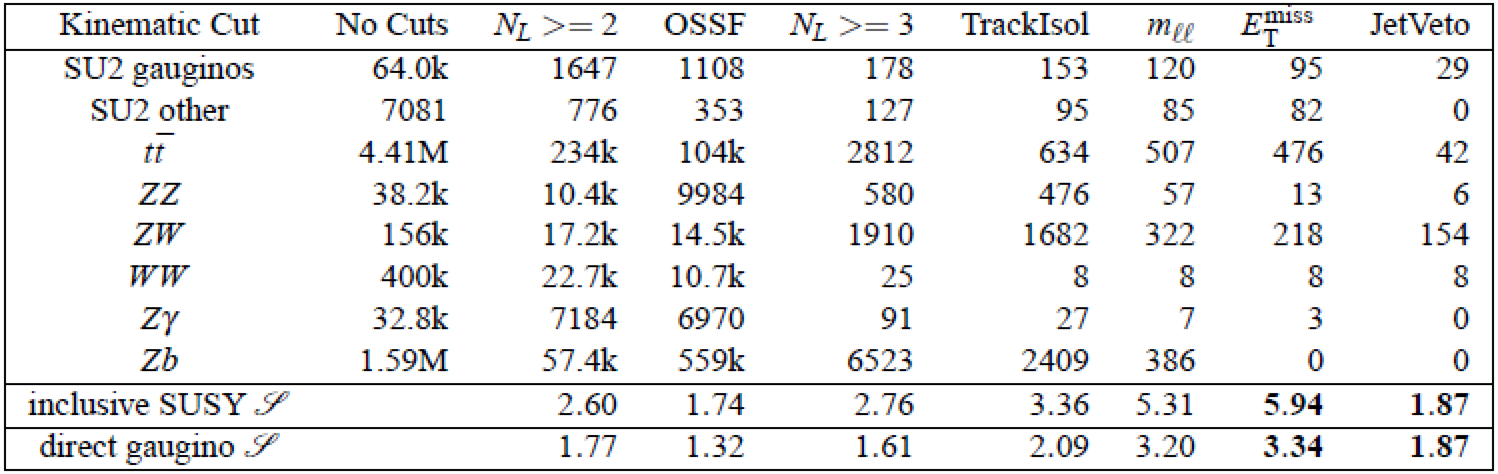
Parameter	SU3 value	fitted value	exp. unc.
	$\mathrm{sign}(\mu) = +1$		
$\tan\beta$	6	7.4	4.6
M_0	100 GeV	98.5 GeV	±9.3 GeV
$M_{1/2}$	300 GeV	317.7 GeV	±6.9 GeV
A_0	−300 GeV	445 GeV	±408 GeV
	$\mathrm{sign}(\mu) = -1$		
$\tan\beta$		13.9	±2.8
M_0		104 GeV	±18 GeV
$M_{1/2}$		309.6 GeV	±5.9 GeV
A_0		489 GeV	±189 GeV

SUSY

→ *Multi-lepton + MET searches in SU2*

Leptonic decay of pairs of heavy gauginos, such as χ^0_2 and χ^+_1 ,
through real or virtual $W^{\pm}$, Z^0 or sleptons to leptons and a pair of LSPs
Heavy gauginos produced directly or in decay of heavier partner particles
Most important bgds → ttbar, Zb and ZW
SU2 trileptons

Numbers of evts and significance SU2 10 fb-1



Kinematic Cut	No Cuts	$N_L >= 2$	OSSF	$N_L >= 3$	TrackIsol	$m_{\ell\ell}$	E_T^{miss}	JetVeto
SU2 gauginos	64.0k	1647	1108	178	153	120	95	29
SU2 other	7081	776	353	127	95	85	82	0
$t\bar{t}$	4.41M	234k	104k	2812	634	507	476	42
ZZ	38.2k	10.4k	9984	580	476	57	13	6
ZW	156k	17.2k	14.5k	1910	1682	322	218	154
WW	400k	22.7k	10.7k	25	8	8	8	8
$Z\gamma$	32.8k	7184	6970	91	27	7	3	0
Zb	1.59M	57.4k	559k	6523	2409	386	0	0
inclusive SUSY $\mathscr{S}$		2.60	1.74	2.76	3.36	5.31	**5.94**	**1.87**
direct gaugino $\mathscr{S}$		1.77	1.32	1.61	2.09	3.20	**3.34**	**1.87**

SUSY scans

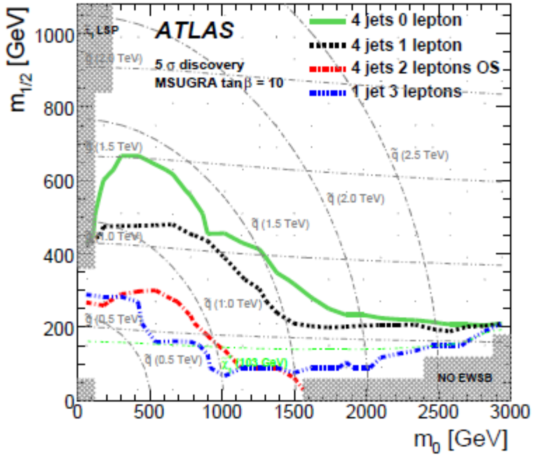
Over parameters of several R-parity conserving SUSY models
Look for excess above cut on Meff (best performance) or MET

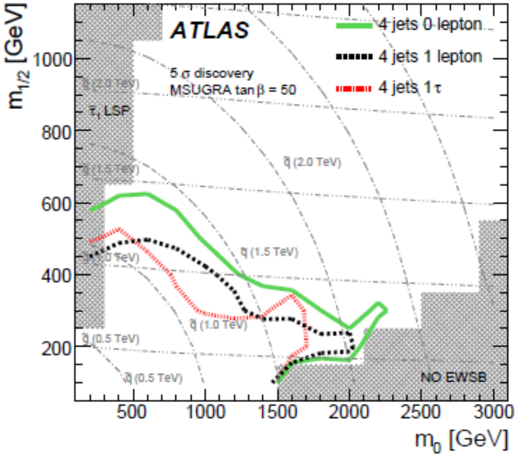
Scans 1fb-1

Plots based on analyses that require a certain number of jets and leptons (e or μ)
Find an optimal M_{eff} cut in steps of 400 GeV to maximize significance Zn with 20% bgd uncertainty

MSUGRA
fixed grid
tanβ = 10 and 50

4 jets +
N lepts = 0,1,2,3





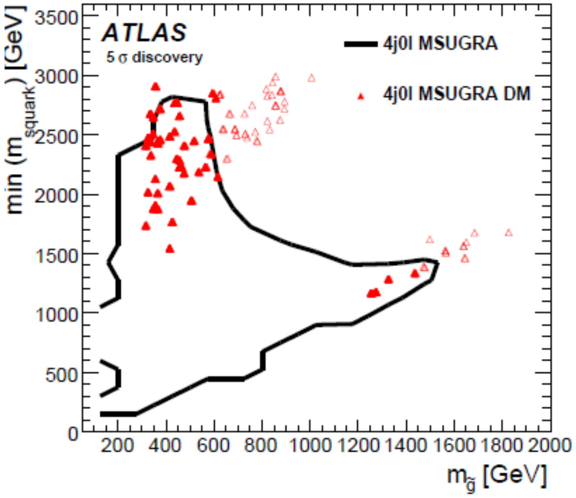
Scans and detailed analyses with SM bgds estimated from data →
R-parity conserving SUSY observable for $m_{gluino, squark} \lesssim$ 1 TeV with 1fb−1 of understood data

If SUSY is not found with 1fb−1, might still eventually be discovered @ LHC but difficult to study in detail

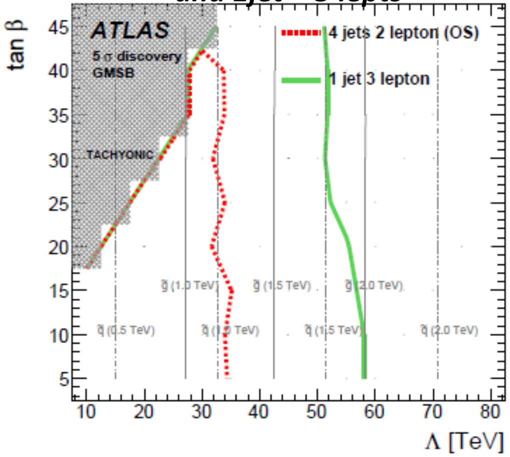
MSUGRA
random grid
wo and with
DM constraints
4 jets + 0 lept

Solid triangles :
observable

Open triangles:
not observ.



GMSB 4 jets + 2 lepts
and 1jet + 3 lepts



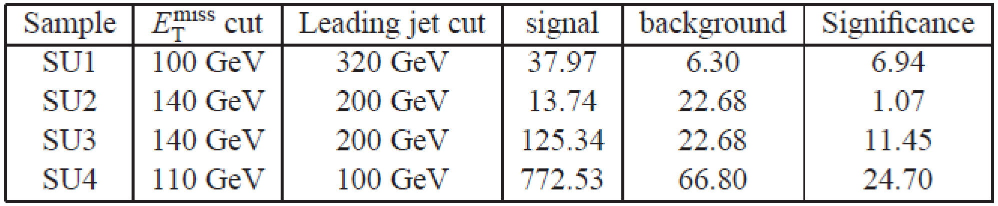
SUSY mSUGRA

Detailed studies of signatures e.g. Two lepton mode (1fb-1)

Opposite-sign di-leptons from neutralino decays, especially $\chi^0_2 \rightarrow \ell^+\ell^- + \chi^0_1$ directly or through an intermediate slepton

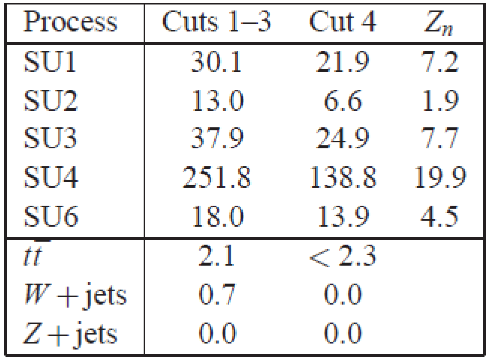
Leptons produced from independent decays → same-flavour (OSSF) or different-flavour (OSDF) dilepton pairs $\ell = e,\mu$

Opposite sign + ≥4 jets

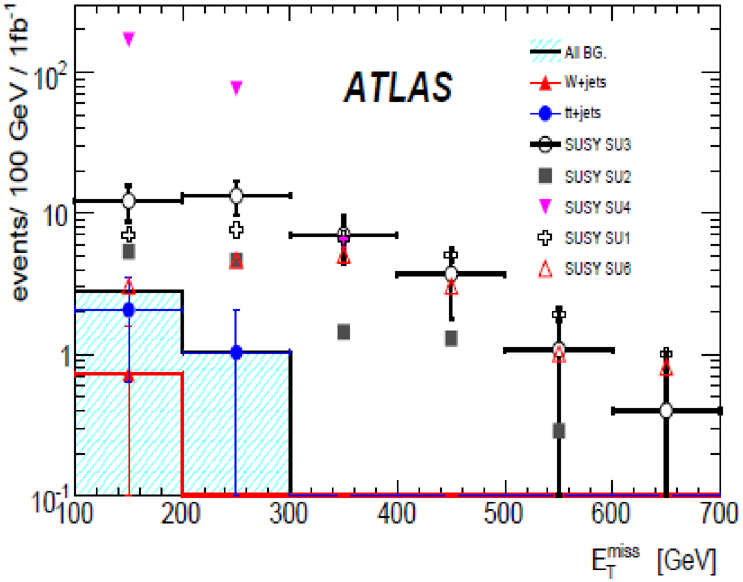


Sample	E_T^{miss} cut	Leading jet cut	signal	background	Significance
SU1	100 GeV	320 GeV	37.97	6.30	6.94
SU2	140 GeV	200 GeV	13.74	22.68	1.07
SU3	140 GeV	200 GeV	125.34	22.68	11.45
SU4	110 GeV	100 GeV	772.53	66.80	24.70

Same sign + ≥4 jets



Process	Cuts 1–3	Cut 4	Z_n
SU1	30.1	21.9	7.2
SU2	13.0	6.6	1.9
SU3	37.9	24.9	7.7
SU4	251.8	138.8	19.9
SU6	18.0	13.9	4.5
$t\bar{t}$	2.1	< 2.3	
$W+$jets	0.7	0.0	
$Z+$jets	0.0	0.0	



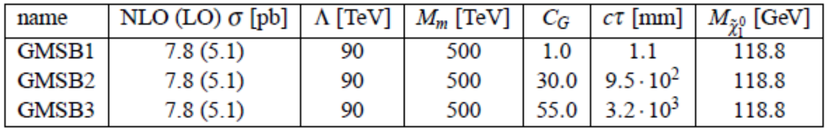
2leptons + ≥ 4 jets : SU1, SU3, SU4 ≤1fb-1 for ≥ 5σ

SUSY GMSB

High-pT photons in GMSB models

$\chi^0_1 \rightarrow \tilde{}G + \gamma$ gives 2 high pT photons + MET
long lived $\tilde{}\chi^0_1$ give non pointing photons

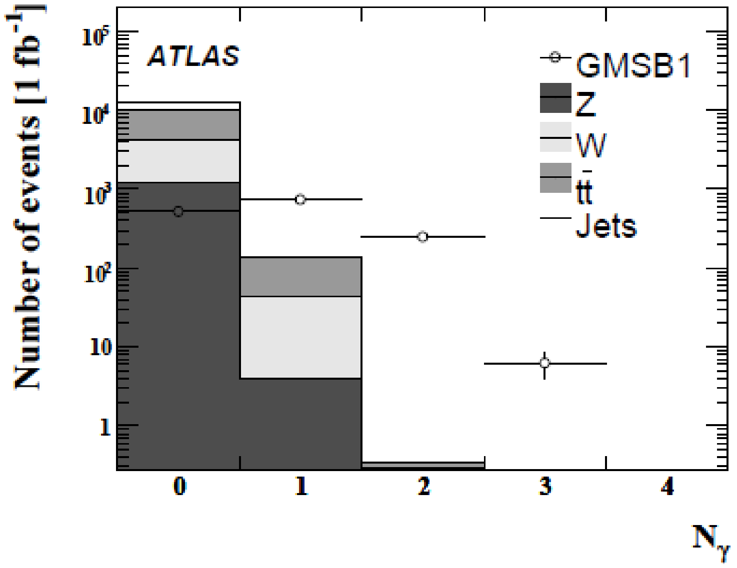
At least 4 high pT jets, MET, and photons



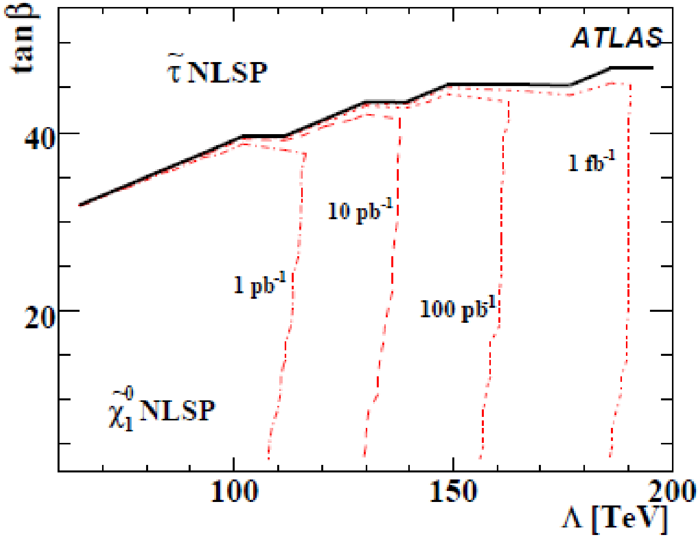
name	NLO (LO) σ [pb]	Λ [TeV]	M_m [TeV]	C_G	$c\tau$ [mm]	$M_{\tilde{\chi}^0_1}$ [GeV]
GMSB1	7.8 (5.1)	90	500	1.0	1.1	118.8
GMSB2	7.8 (5.1)	90	500	30.0	$9.5 \cdot 10^2$	118.8
GMSB3	7.8 (5.1)	90	500	55.0	$3.2 \cdot 10^3$	118.8

$N_5 = 1$ (# mess gen), $\tan\beta = 5$, $\mathrm{sgn}(\mu) = +$

1fb−1
Number of reco photons
pT >20 GeV and |η| < 2.5



5σ contour lines for GMSB SUSY



100pb-1 for Λ<150 TeV and $\tan\beta$<30-40
for 5 σ discovery

SUSY R-hadrons

Long Lived Heavy particles in Split-SUSY and gravitino LSP

Penetrating hard charged track with high E deposition and long time of flight

May undergo charge exchange in calorimeter

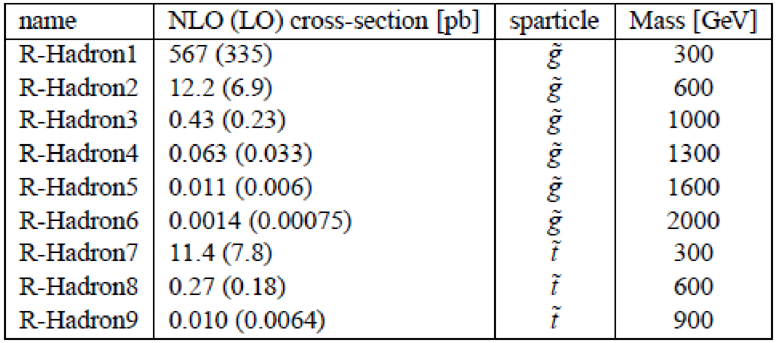
Multiple nuclear interactions before reaching muon system

→ appearance of high pT tracks in muon system with no matching track in ID

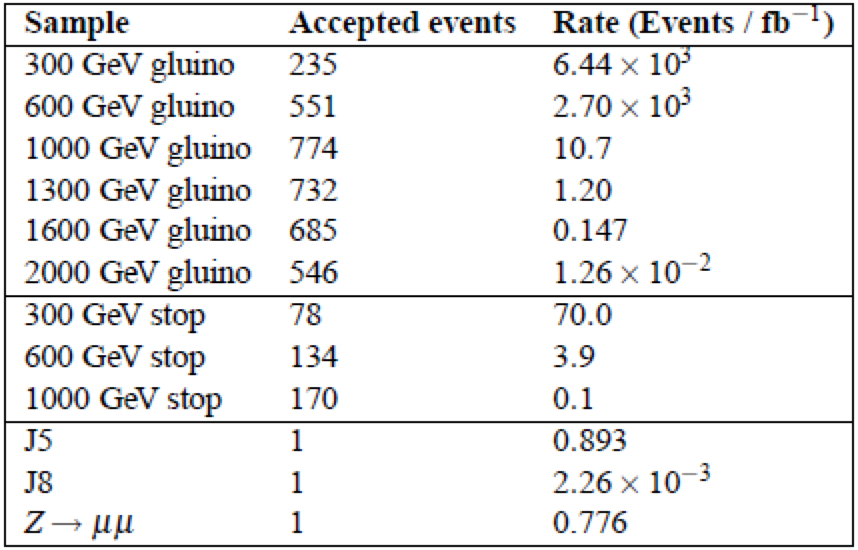
→ electric charge flipping between ID and muon system

$m_{\text{R-hadrons}}$ ~< 200 GeV already excluded

R1 to R6 are $R_{\tilde{g}}$-hadron
while R7 to R0 are $R_{\tilde{t}}$



name	NLO (LO) cross-section [pb]	sparticle	Mass [GeV]
R-Hadron1	567 (335)	$\tilde{g}$	300
R-Hadron2	12.2 (6.9)	$\tilde{g}$	600
R-Hadron3	0.43 (0.23)	$\tilde{g}$	1000
R-Hadron4	0.063 (0.033)	$\tilde{g}$	1300
R-Hadron5	0.011 (0.006)	$\tilde{g}$	1600
R-Hadron6	0.0014 (0.00075)	$\tilde{g}$	2000
R-Hadron7	11.4 (7.8)	$\tilde{t}$	300
R-Hadron8	0.27 (0.18)	$\tilde{t}$	600
R-Hadron9	0.010 (0.0064)	$\tilde{t}$	900



Sample	Accepted events	Rate (Events / fb^{-1})
300 GeV gluino	235	6.44×10^3
600 GeV gluino	551	2.70×10^3
1000 GeV gluino	774	10.7
1300 GeV gluino	732	1.20
1600 GeV gluino	685	0.147
2000 GeV gluino	546	1.26×10^{-2}
300 GeV stop	78	70.0
600 GeV stop	134	3.9
1000 GeV stop	170	0.1
J5	1	0.893
J8	1	2.26×10^{-3}
$Z \to \mu\mu$	1	0.776

1fb-1 discovery
$m(R_{\sim g}) < 1$ TeV
$m(R_{\sim t1})$ ~< 550 GeV