LHC Physics Day
New Physics: Exotica

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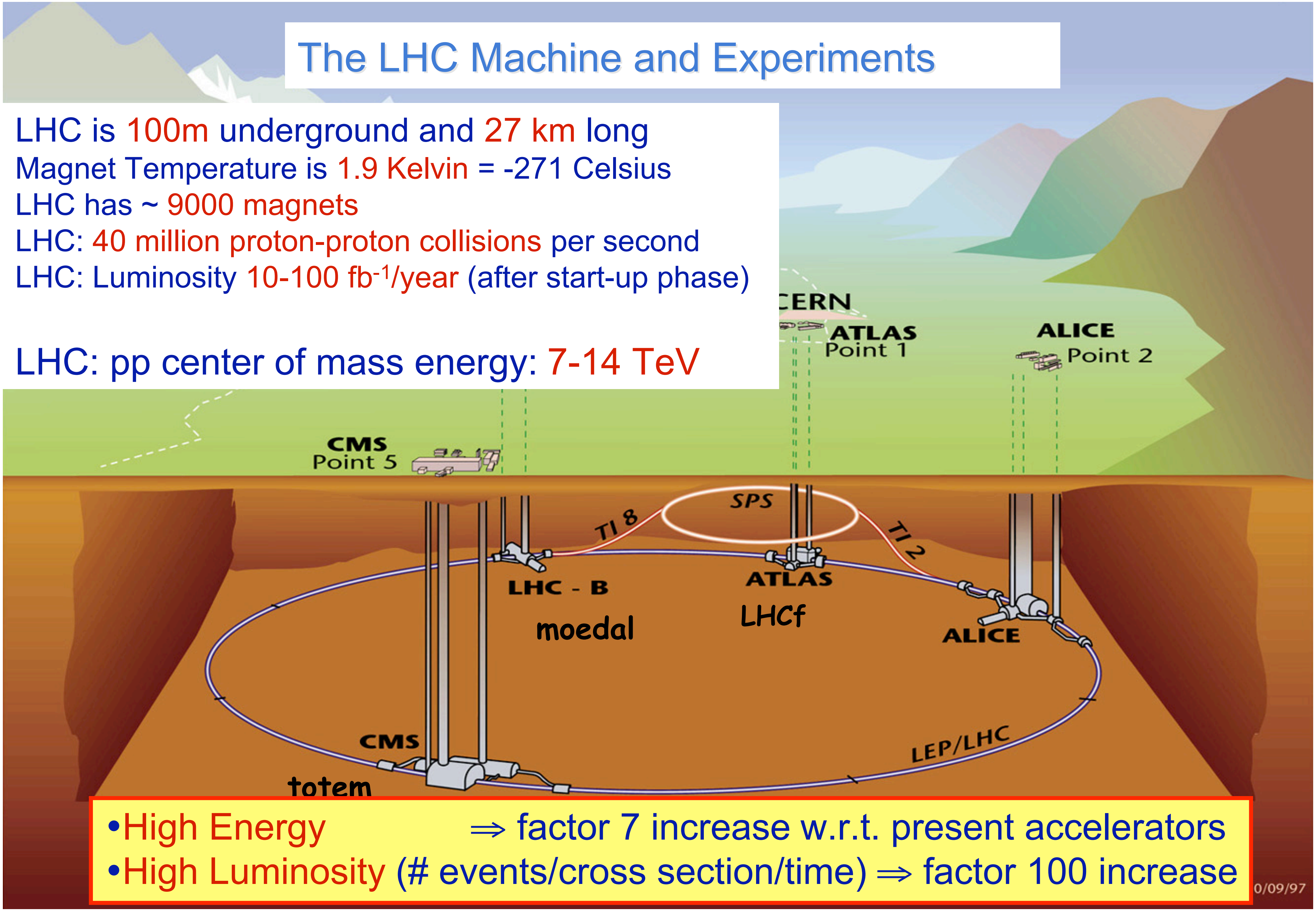
15 January 2010

Warszawa/Krakow - LHC Meeting

The LHC Machine and Experiments

LHC is 100m underground and 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)

LHC: pp center of mass energy: 7-14 TeV

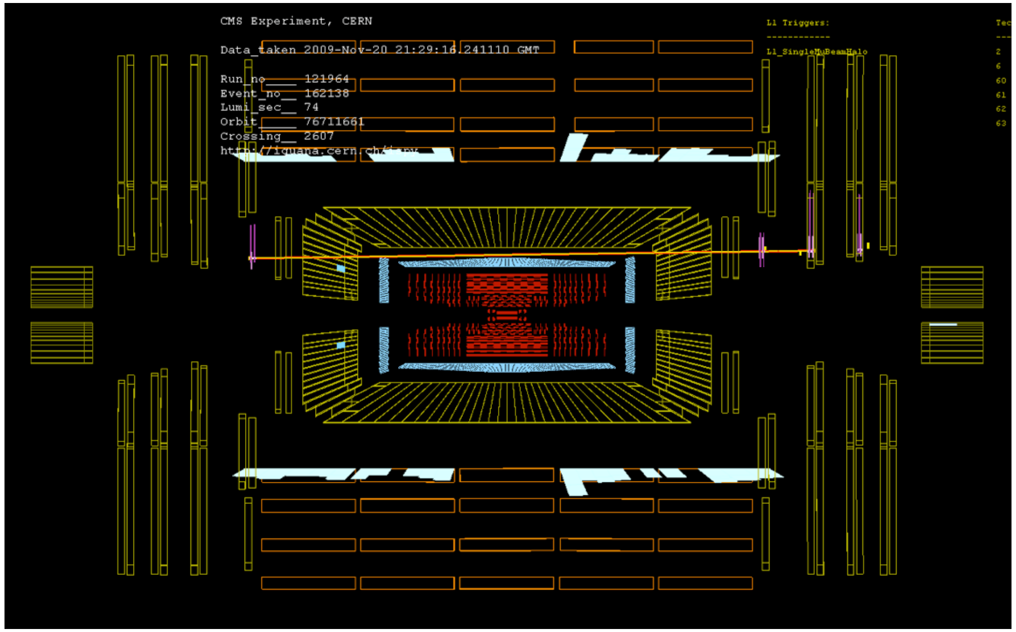


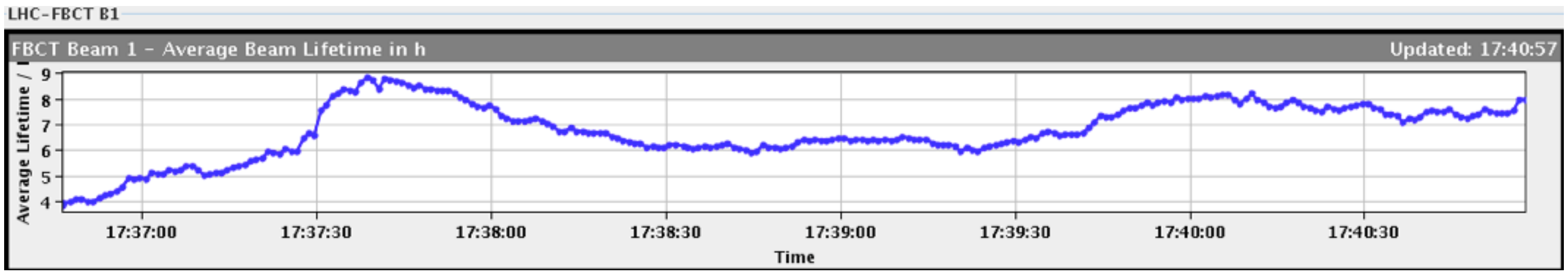
- High Energy ⇒ factor 7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase

Restart of the LHC November 2009

20/11/09: …A few hours after the startup of the machine

⇒ Keep beam 1 in the machine for over an hour…



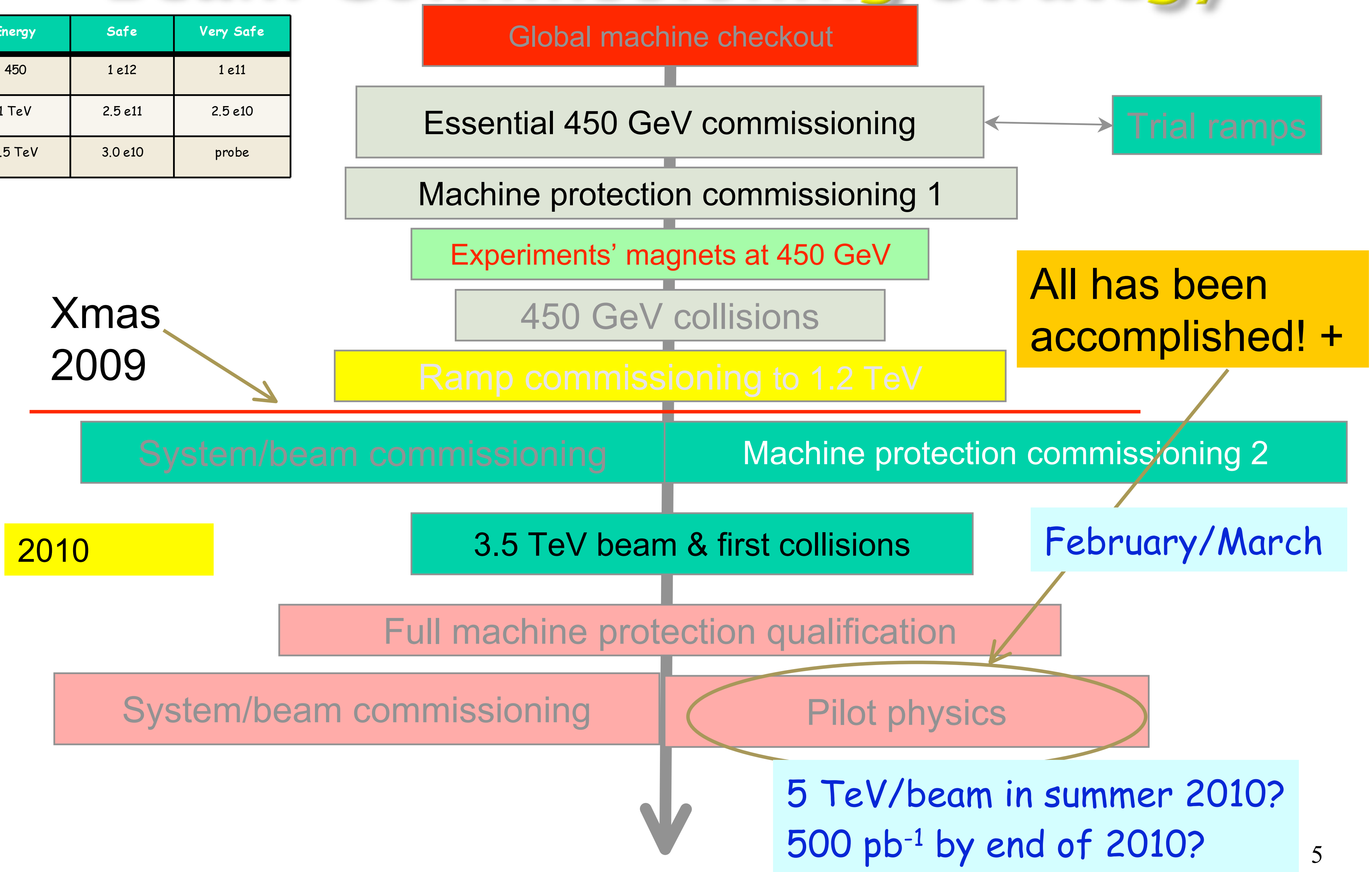


Exciting Times !! : Summary of the events

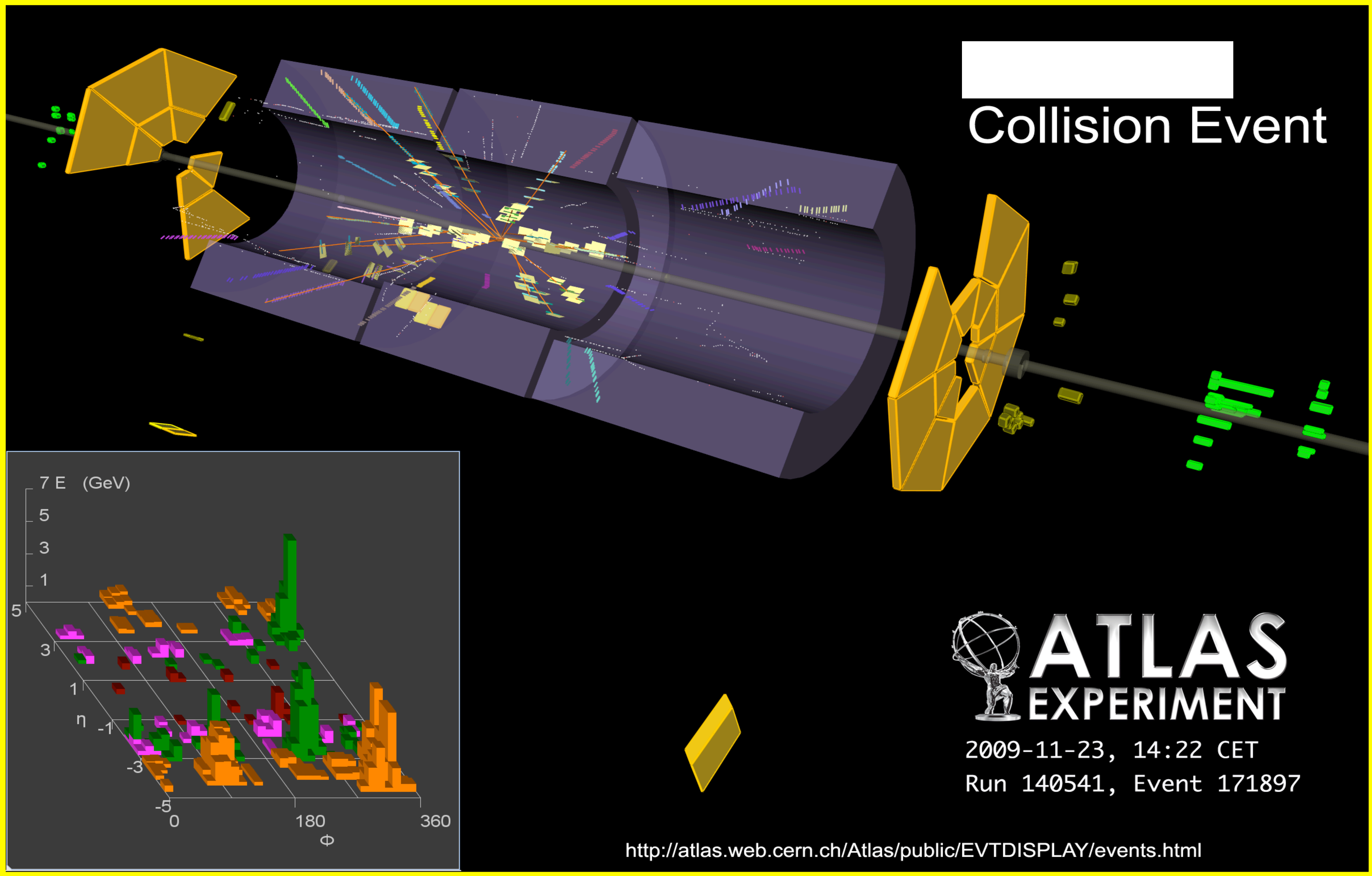
Date	Day	Achieved
Nov 20	1	Each beam circulating. Key beam instrumentation working.
Nov 23	4	First collisions at 450 GeV. First ramp (reached 560 GeV).
Nov 26	7	Magnetic cycling established (reproducibility).
Nov 27	8	Energy matching.
Nov 29	10	Ramp to 1.18 TeV.
Nov 30	11	Experiment solenoids on.
Dec 04	15	Aperture measurement campaign finished. LHCb and ALICE dipoles on.
Dec 05	16	Machine protection (Injection, Beam dump, Collimators) ready for safe operation with pilots.
Dec 06	17	First collisions with STABLE BEAMS, 4 on 4 pilots at 450 GeV, rates around 1Hz
Dec 08	19	Ramp colliding bunches to 1.18 TeV.
Dec 11	22	Collisions with STABLE BEAMS, 4 on 4 at 450 GeV, > 10^{10} per bunch, rates around 10Hz.
Dec 13	24	Ramp 2 bunches per beam to 1.18 TeV. Collisions for 90mins.
Dec 14	25	Collisions with STABLE BEAMS, 16 on 16 at 450 GeV, > 10^{10} per bunch, rates around 50Hz.
Dec 16	27	Ramp 4 on 4 to 1.18 TeV. Squeeze to 7 m.

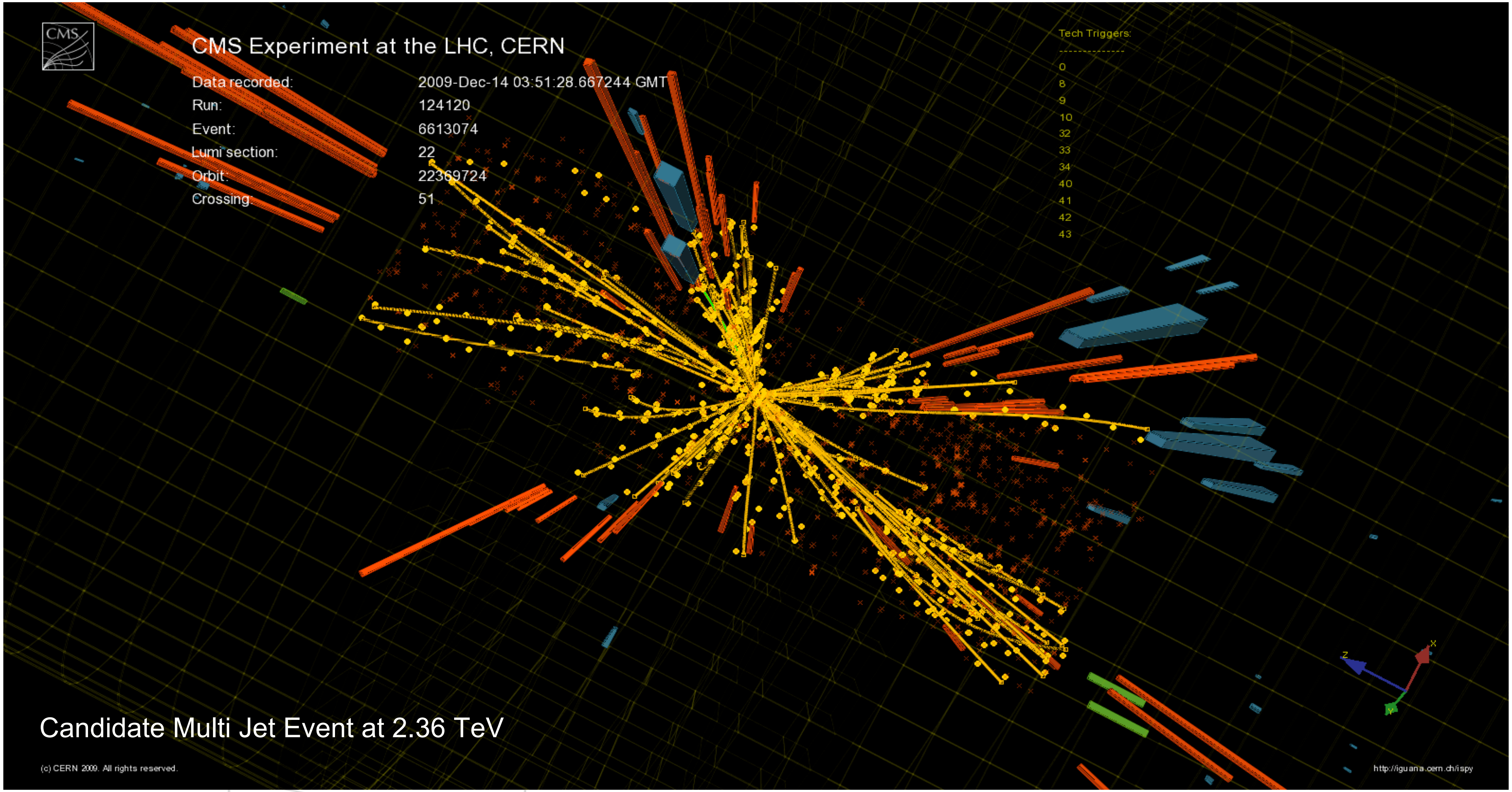
Beam Commissioning Strategy

Energy	Safe	Very Safe
450	1 e12	1 e11
1 TeV	2.5 e11	2.5 e10
3.5 TeV	3.0 e10	probe



Monday 23 November: first collisions at $\sqrt{s}$ = 900 GeV !
→ ATLAS records ~ 200 events (first one observed at 14:22)

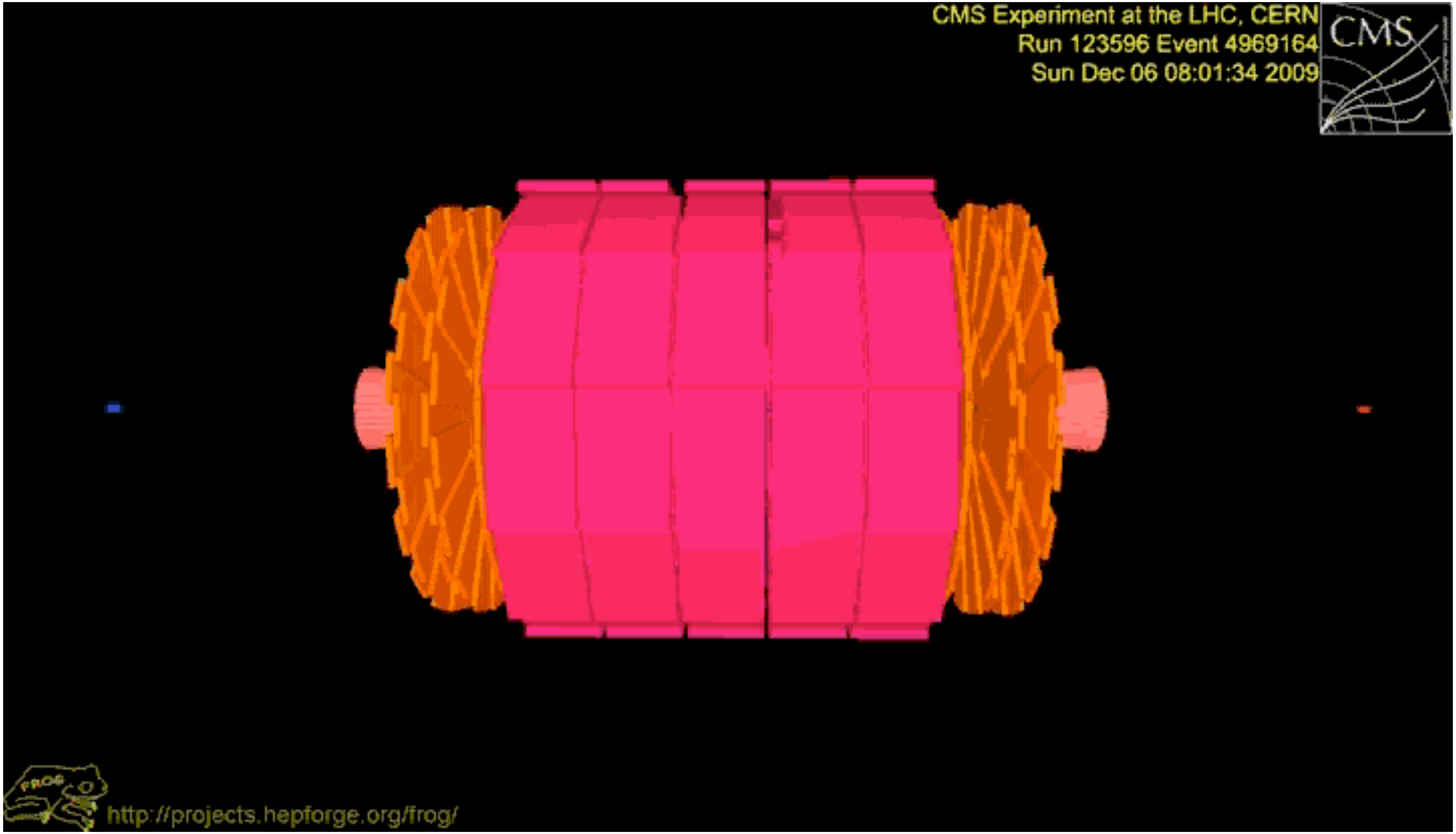




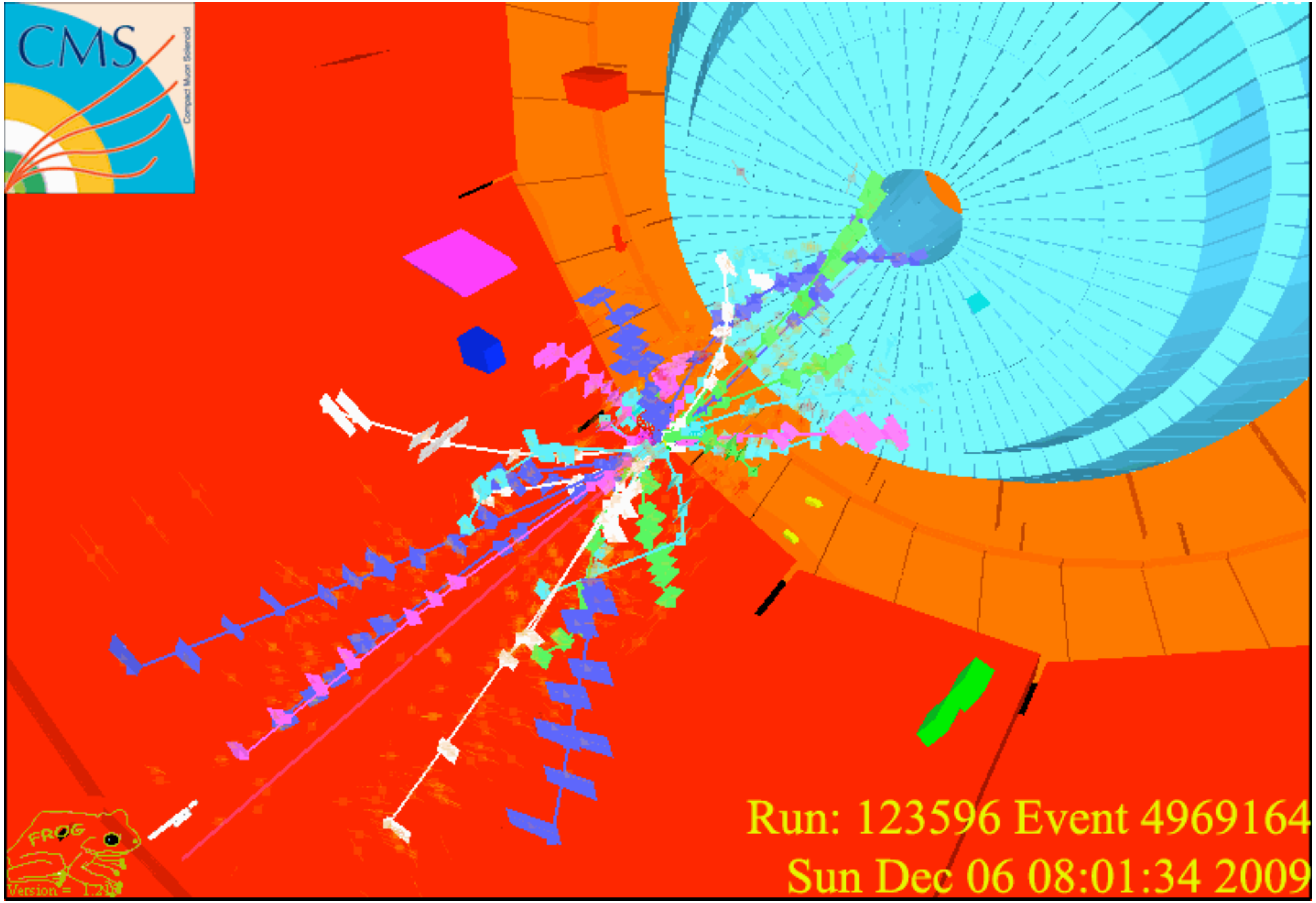
CMS

2nd LHC Status Report

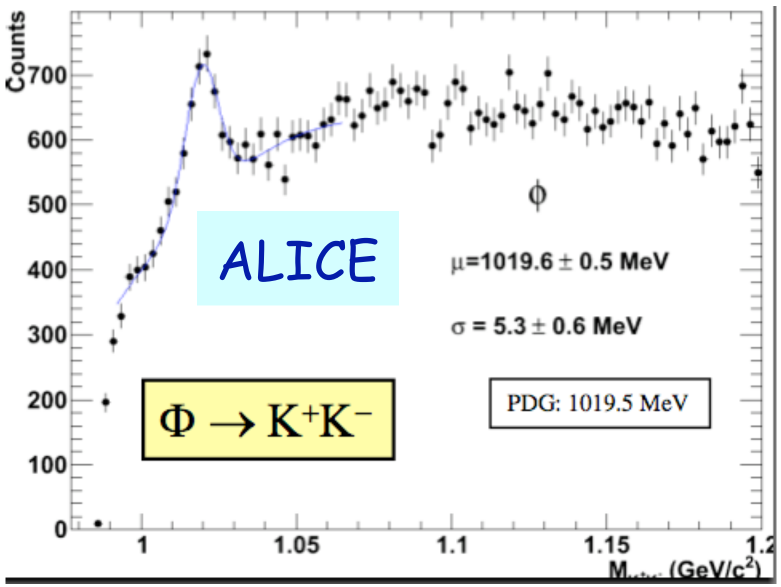
CERN 18 Dec'09

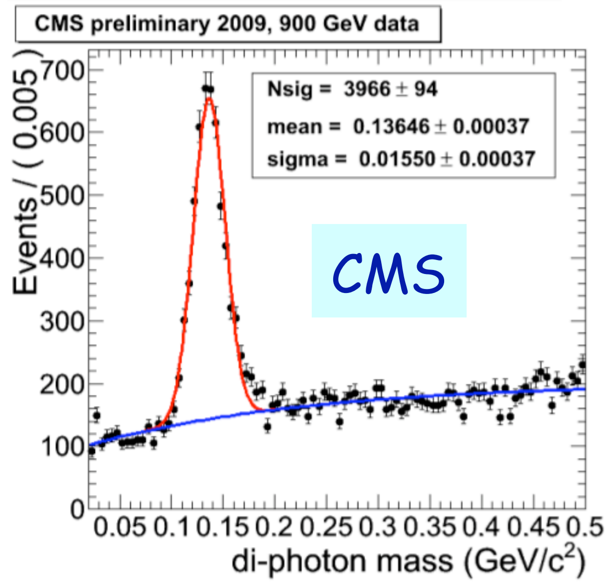

CMS Experiment at the LHC, CERN
Run 123596 Event 4969164
Sun Dec 06 08:01:34 2009
CMS
http://projects.hepforge.org/frog/

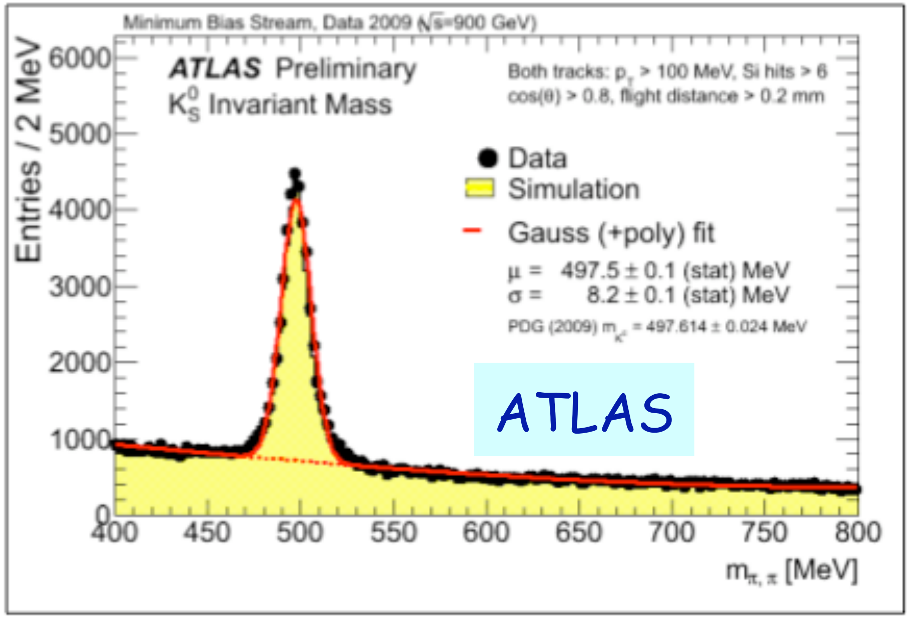
Looking at events

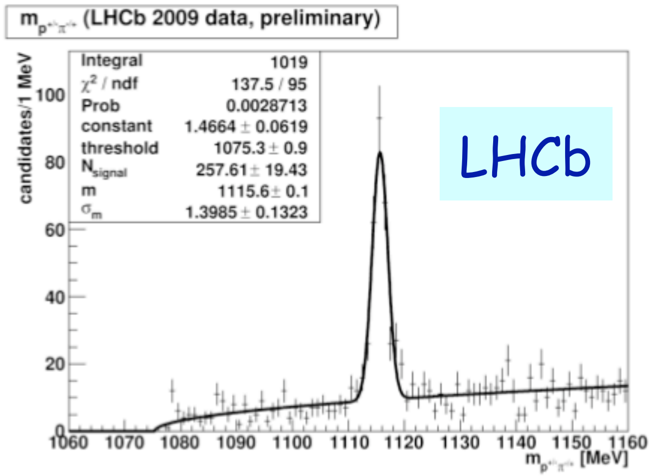


Rediscovering "Standard Model" Particles









$M(\Lambda)$ = 1115.6 ± 0.1 MeV/c^2
σ = 1.4 ± 0.1 MeV/c^2

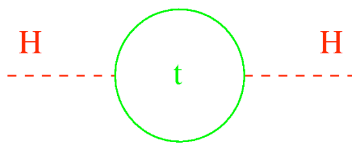
$M(\Lambda^{PDG})$ = 1115.7 MeV/c^2

Why we believe the Standard Model is NOT the Ultimate Theory?

SM predictions confirmed by experiments (at LEP, Tevatron, SLAC, etc.) with precision $\approx 10^{-3}$ or better

So, what is wrong with it ?

- About 20 free parameters (masses of fermions and bosons, couplings
- Higgs: mass $m_H \approx 115$ GeV? Then New Physics for $\Lambda < 10^6$ GeV
- "Naturalness" problem :

  radiative corrections 

 $\delta m_H^2 \sim \Lambda^2$ $\Rightarrow$ diverge for large Λ

  $\Rightarrow$ fine tuning!!
- "Hierarchy" problem: why $M_{EW}/M_{Planck} \sim 10^{-17}$?

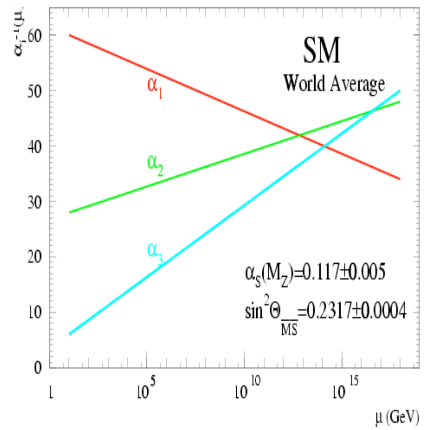
+ contribution of EW vacuum to cosmological constant ($\sim v^4$) is ~ 55 orders of magnitudes too large !
+ flavour/family problem, coupling unification, gravity incorporation, ν masses/oscillations, … Dark Matter. Dark Energy?

Physics case for new High Energy Machines

- Understand the mechanism Electroweak Symmetry Breaking
- Discover physics beyond the Standard Model

Reminder: The Standard Model

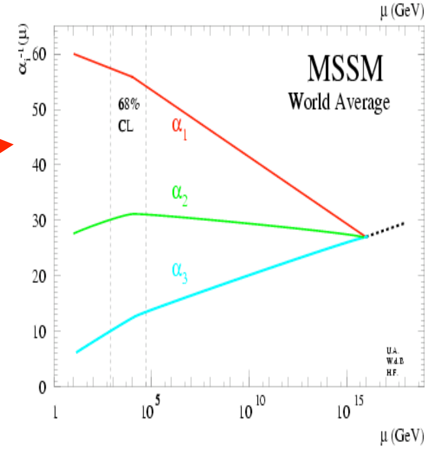
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity. Dark Matter/Energy?
- no unification of the forces at high energy



Most popular extensions these days

If a Higgs field exists:

- Supersymmetry
- Extra space dimensions



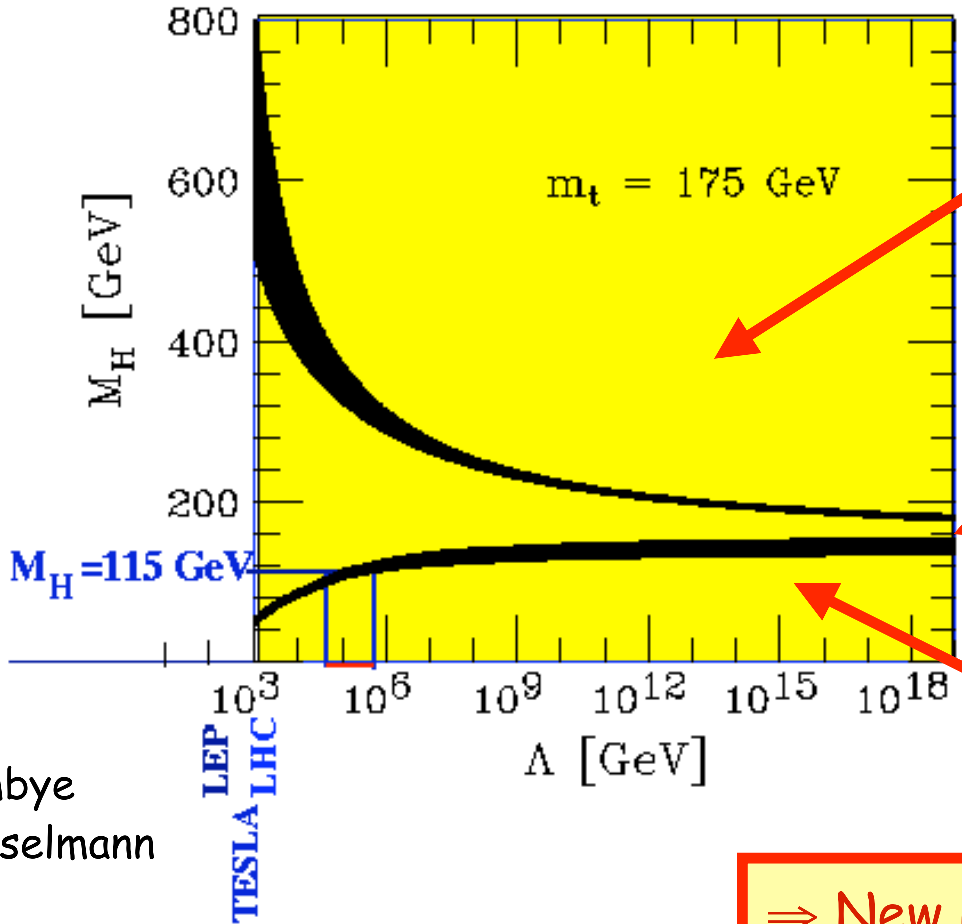
If there is no Higgs below ~ 700 GeV

- Strong electroweak symmetry breaking around 1 TeV

Other ideas: more gauge bosons/quark & lepton substructure, Little Higgs models, Technicolor…

Higgs Mass?

A light Higgs implies that the Standard Model cannot be stable up to the GUT (= Grand Unified Theory) or Planck scale (10^{19} GeV)



Hambye
Riesselmann

The effective potential blows up, due to heavy top quark mass

Allowed corridor but needs strong fine-tuning…

The electroweak vacuum is unstable to corrections from scales $\Lambda \gg v$= 246 GeV

⇒ New Physics expected in O(TeV) range

A Cellar of New Ideas

J. Hewett/Lishep09

'67	The Standard Model	a classic! aged to perfection
'77	Vin de Technicolor	better drink now
'70's	Supersymmetry: MSSM	mature, balanced, well developed – the Wino's choice
'90's	SUSY Beyond MSSM	svinters blend
'90's	CP Violating Higgs	all upfront, no finish lacks symmetry
'98	Extra Dimensions	bold, peppery, spicy uncertain terrior
'02	Little Higgs	complex structure
'03	Fat Higgs	young, still tannic needs to develop
'03	Higgsless	sleeper of the vintage what a surprise!
'04	Split Supersymmetry	finely-tuned
'05	Twin Higgs	double the taste

J. Hewett

We have a lot of signatures to look for…

Last Minute Model Building

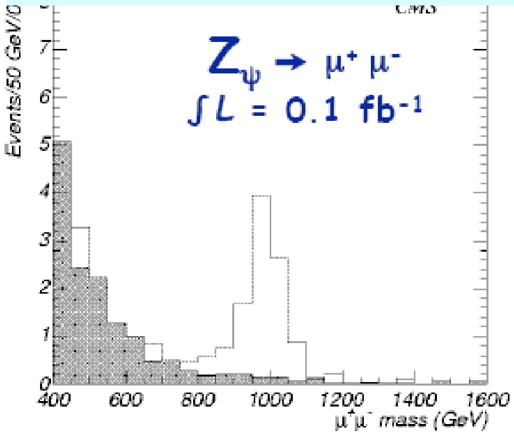
Anything Goes!

- Non-Communtative Geometries
- Return of the 4th Generation
- Hidden Valleys
- Quirks - Macroscopic Strings
- Lee-Wick Field Theories
- Unparticle Physics
- .....

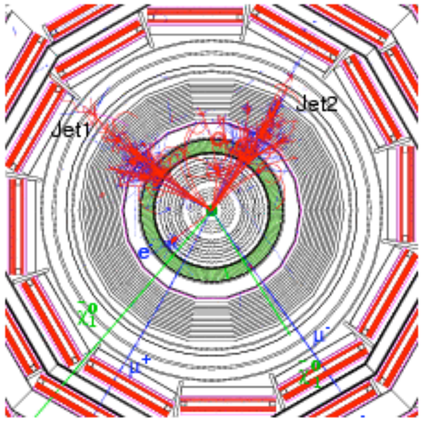
It is really high time we get the LHC data!

BSM Physics at the LHC: pp @ 7/10/14 TeV

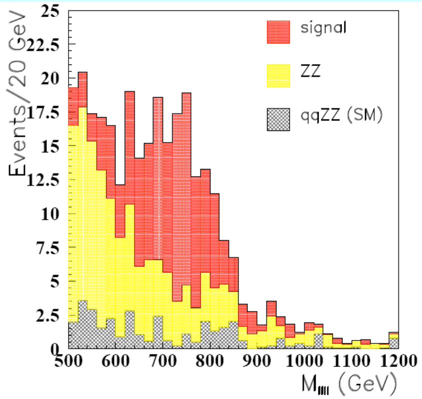
New Gauge Bosons?



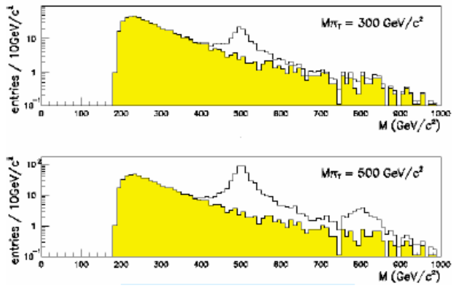
Supersymmetry



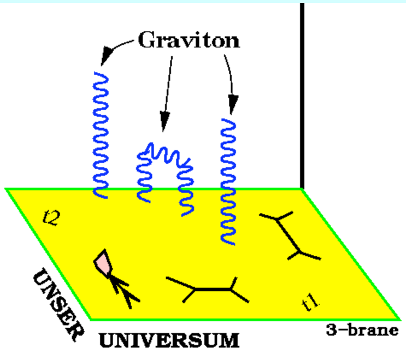
ZZ/WW resonances?



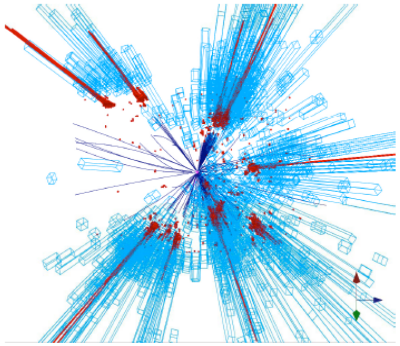
Technicolor?



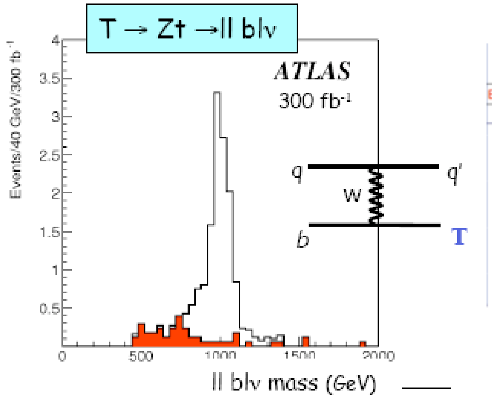
Extra Dimensions?



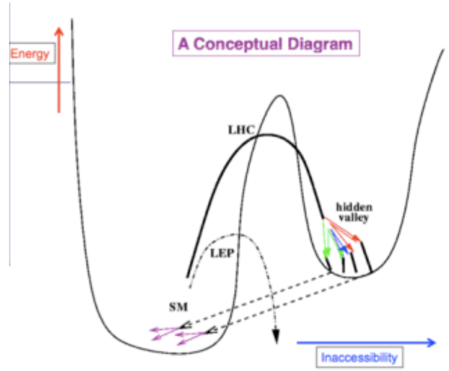
Black Holes???



Little Higgs?



Hidden Valleys?



We do not know what is out there for us…

A large variety of possible signals. We have to be ready for that

Experimental New Physics Signatures

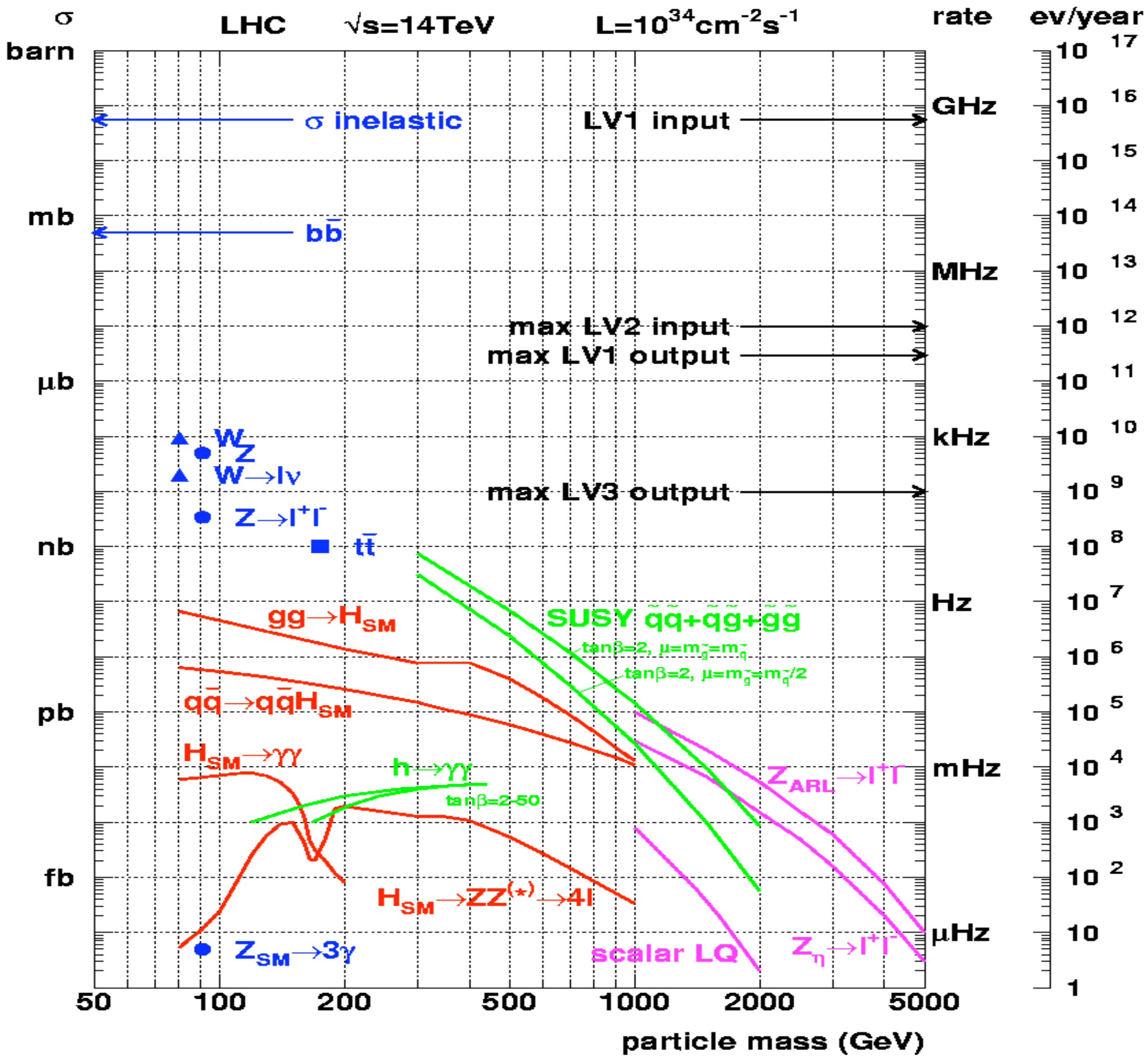
- Many channels in New Physics :Typical signals
  - Di-leptons resonance/non-resonance, like sign/oposite sign
  - Leptons + MET (=Missing transverse momentum/energy)
  - Photons + MET
  - Multi-jets (2 → ~10)
  - Mono/Multi-jets +MET (few 10 → few 100 GeV)
  - Multi jets + leptons + MET…
  - B/τ final states…
- Also: new unusual signatures
  - Large displaced vertices
  - Heavy ionizing particles (heavy stable charged particles)
  - Non-pointing photons
  - Special showers in the calorimeters
  - Unexpected jet structures
  - Very short tracks (stubs)…

Progress over the last years

- Full simulation/Closer to the real experimental set-up
- Improved signal & backgrounds (More complex MCs, NLO (QCD/EW) corrections)
- Studies for first luminosities (10-100 pb^{-1})
- Studies for detectors with start-up conditions (energy calibration, misalignment of the detectors)
- Special attention to the trigger
- Data driven methods to estimate backgrounds for discoveries.
- In a few cases, real in situ background estimates (cosmics, beam halo)

Sources: CMS Physics TDR Vol II, J. Phys. G34 (2007) 995 + updates
ATLAS CERN-OPEN-2008-20 (December 2008) + updates

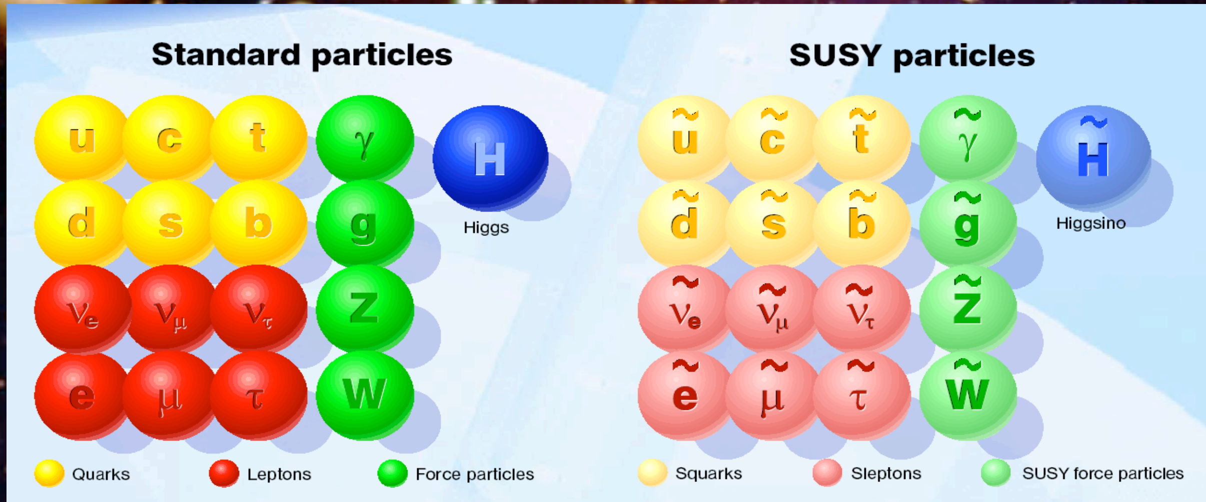
Cross Sections at the LHC

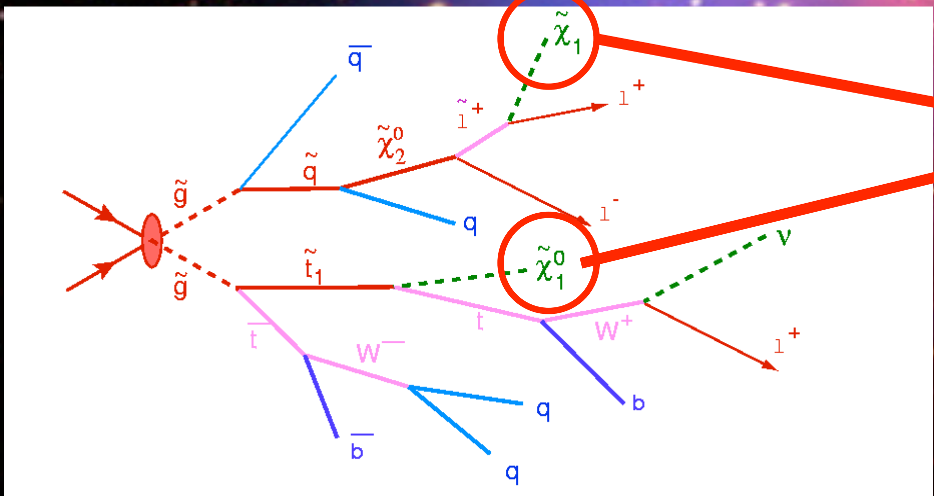


"Well known" processes, don't need to keep all of them …

New Physics!!
This we want to keep!!

Supersymmetry: a new symmetry in Nature

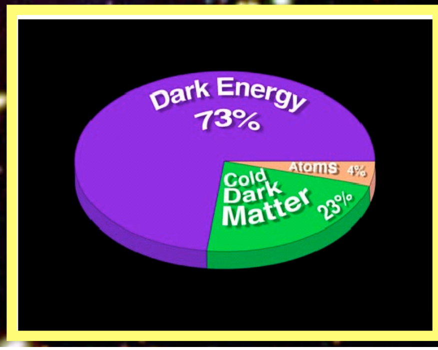




SUSY particle production at the LHC

Candidate particles for Dark Matter

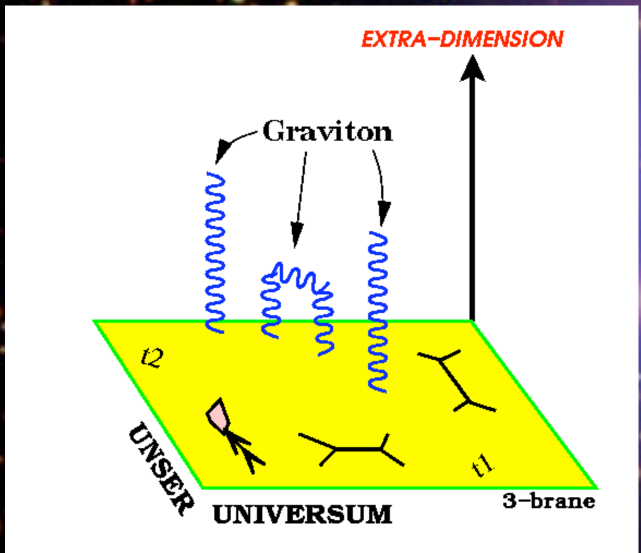
⇒ Produce Dark Matter in the lab

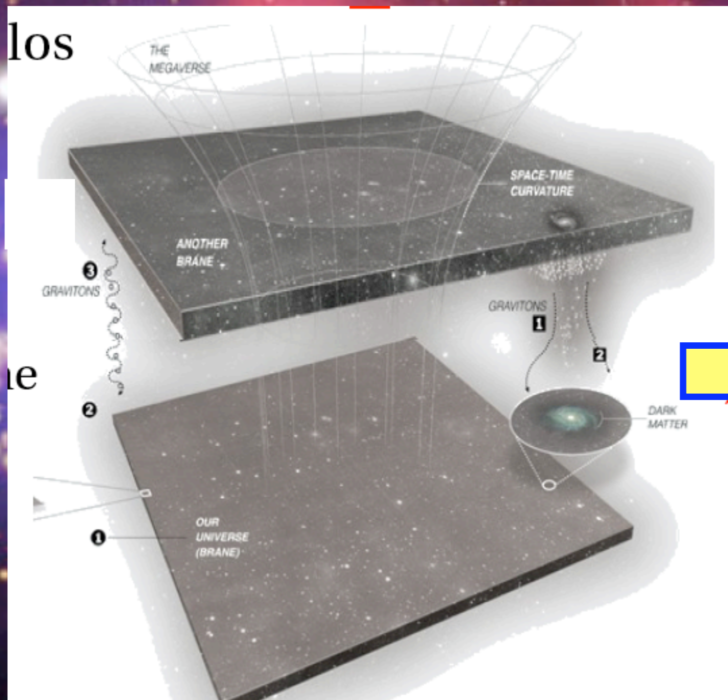


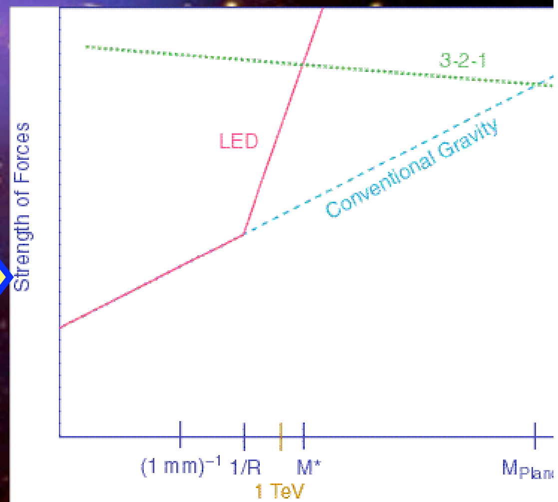
Extra Space Dimensions

Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV} \quad \longleftrightarrow \quad M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV}$$







The Gravity force becomes strong!

Models with Extra Dimensions

Large Extra Dimensions Planck scale (M_D) ~ TeV

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk
KK-towers (small spacing); KK-exchange; graviton prod.
Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

Warped Extra Dimensions

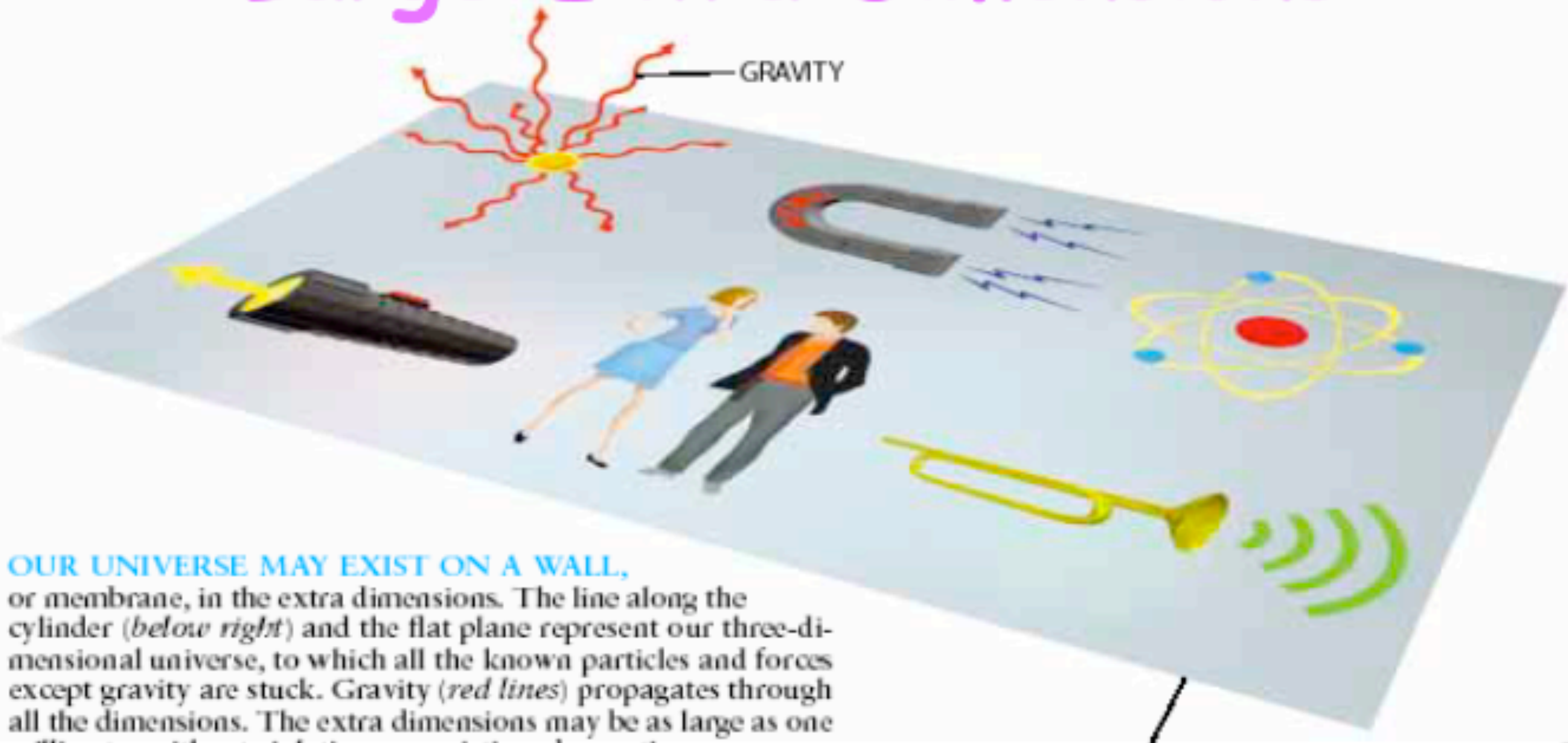
5-dimensional spacetime with warped geometry
Graviton KK-modes (large spacing); graviton resonances
Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions look-like SUSY

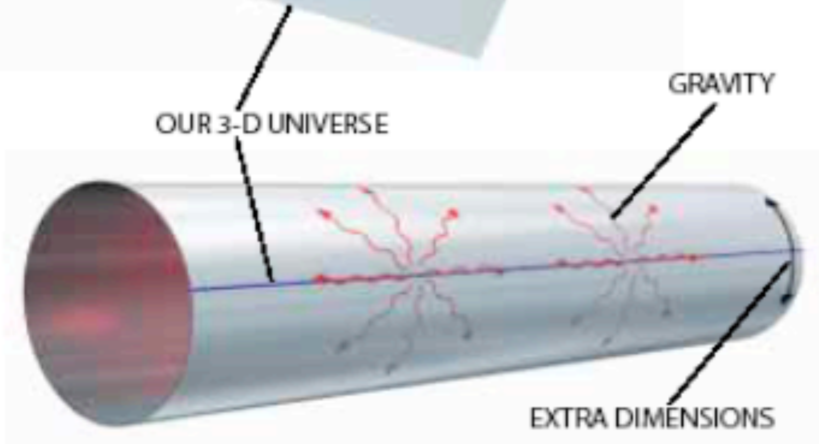
SM particles allowed to propagate in ED of size TeV^{-1}
[scenarios: gauge fields only (nUED) or all SM particles (UED)]

nUED : KK excitations of gauge bosons
UED : KK number conservation; KK states pair produced (at tree-level) ...
Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...

Large Extra Dimensions



OUR UNIVERSE MAY EXIST ON A WALL, or membrane, in the extra dimensions. The line along the cylinder (*below right*) and the flat plane represent our three-dimensional universe, to which all the known particles and forces except gravity are stuck. Gravity (*red lines*) propagates through all the dimensions. The extra dimensions may be as large as one millimeter without violating any existing observations.

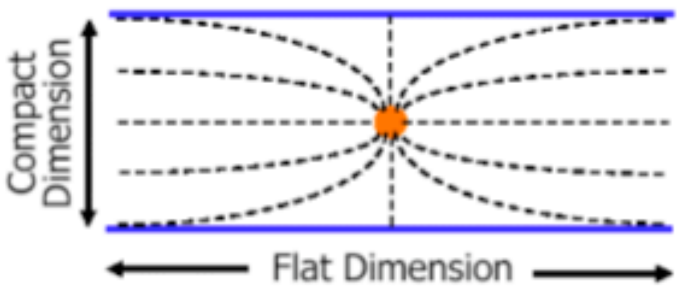


Model of Arkani-Hamed, Dvali, Dimopoulos: Standard Model particles are localized on a 3-D brane. Gravity propagates inside the bulk (a more dimensional space)

Large Extra Dimensions

- Model of Arkani-Hamed, Dvali, Dimopoulos:
  - World at 4 + n dimensions. Only the gravitons may propagate in extra dimensions. Gravity appears to be diluted.

$$V(r) = \frac{1}{M_{Pl}^2}\frac{m_1 m_2}{r} \to \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{r^{n+1}}$$



$$V(r) \propto \frac{1}{\left(M_{Pl}^{[3+n]}\right)^{n+2}}\frac{m_1 m_2}{R^n r} \quad \text{for } r >> R$$

The Newton's Law is verified up to distances ~0.2 mm. Extra dimensions must be smaller than 0.2 mm and compactified.

The real Planck mass $M_D = M_{PL}^{[n+4]}$:

$$(M_D)^{(2+n)} = (M_{PL}^{[4]})^2 R^n$$

If $M_D \sim 1$ TeV (= no more hierarchy problem):

$$R = \frac{1}{2\sqrt{\pi} M_D}\left(\frac{M_{Pl}}{M_D}\right)^{2/n} \propto \begin{cases} 8\times 10^{12} m, & n=1 \\ 0.7\ mm, & n=2 \\ 3\ nm, & n=3 \\ 6\times 10^{-12} m, & n=4 \end{cases}$$

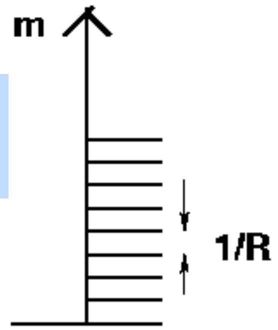
Large Extra Dimension Signatures at LHC

Particles in compact extra dimensions ($2\pi R$)

$\Rightarrow$ Towers of momentum eigenstates

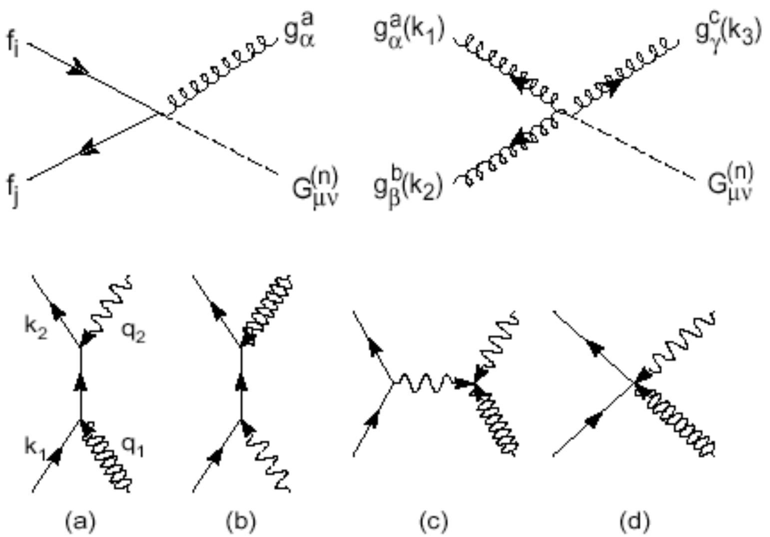
Eg. graviton excitations (Δm=400 eV for δ =3)

$$\Delta m_{G_{KK}} \sim \frac{1}{R}$$



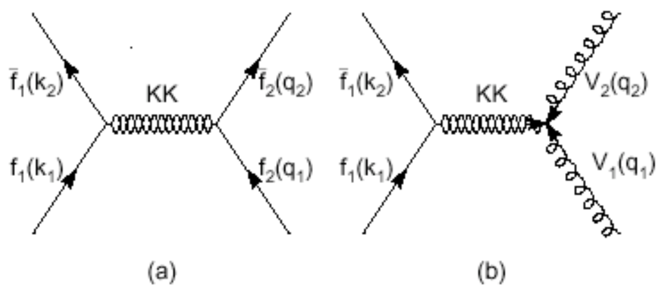
$\Rightarrow$ Strong increase of graviton exchange at high energies

Direct Graviton Emission



- Jets + Missing E_T
- Photon + Missing E_T

Virtual Graviton Exchange



- Dileptons
- Diphotons

Present Limits for Large Extra Dimensions

Experiment	$R_\perp(n=2)$	$R_\perp(n=4)$	$R_\perp(n=6)$
Collider bounds			
LEP 2	4.8×10^{-1}	1.9×10^{-8}	6.8×10^{-11}
Tevatron	5.5×10^{-1}	1.4×10^{-8}	4.1×10^{-11}
LHC	4.5×10^{-3}	5.6×10^{-10}	2.7×10^{-12}
NLC	1.2×10^{-2}	1.2×10^{-9}	6.5×10^{-12}
Astrophysics/cosmology bounds			
SN1987A	3×10^{-4}	1×10^{-8}	6×10^{-10}
COMPTEL	5×10^{-5}	-	-

Limits on the size of the extra dimensions (2001)

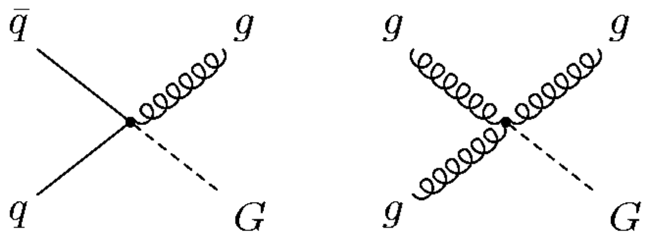
Limits on the Planck Scale M_D

	LEP	DØ		CDF		
δ	$\gamma + E_T^{miss}$	jet+E_T^{miss}	$\gamma + E_T^{miss}$	jet+E_T^{miss}	$\gamma + E_T^{miss}$	combined
2	1.600	0.99	0.921	1.310	1.080	1.400
3	1.200	0.80	0.877	1.080	1.000	1.150
4	0.940	0.73	0.848	0.980	0.970	1.040
5	0.770	0.66	0.821	0.910	0.930	0.980
6	0.660	0.65	0.810	0.880	0.900	0.940

D0: PPRL 90, 251802 (2003); PRL 101, 011601 (2008)
CDF: 0807.3132v1[hep-ex]

Large Extra Dimension signals at the LHC

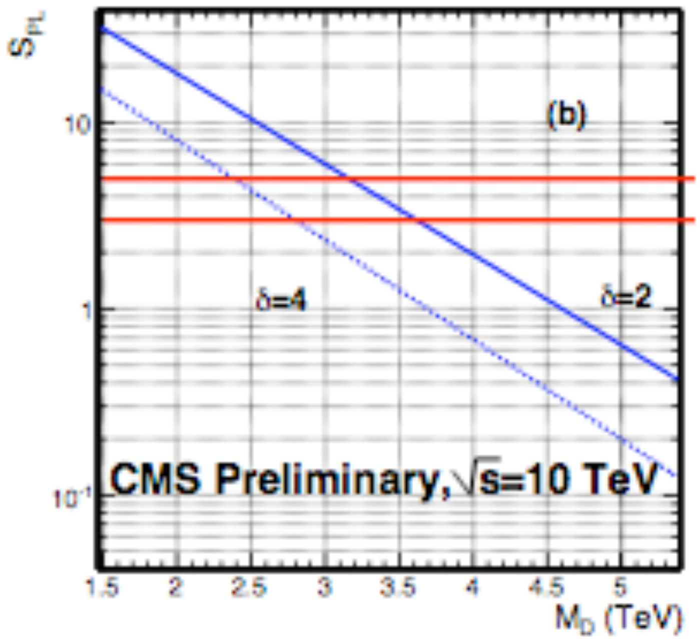
ADD: Arkani –Hamed, Dimopolous,Dvali

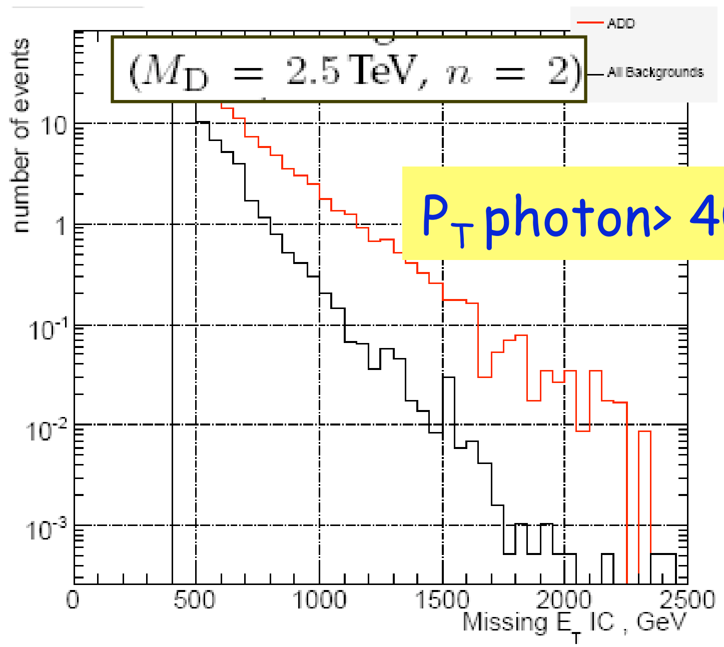


Graviton production!
Graviton escapes detection

Signal: single jet + large missing ET

Signal: single photon + large missing ET





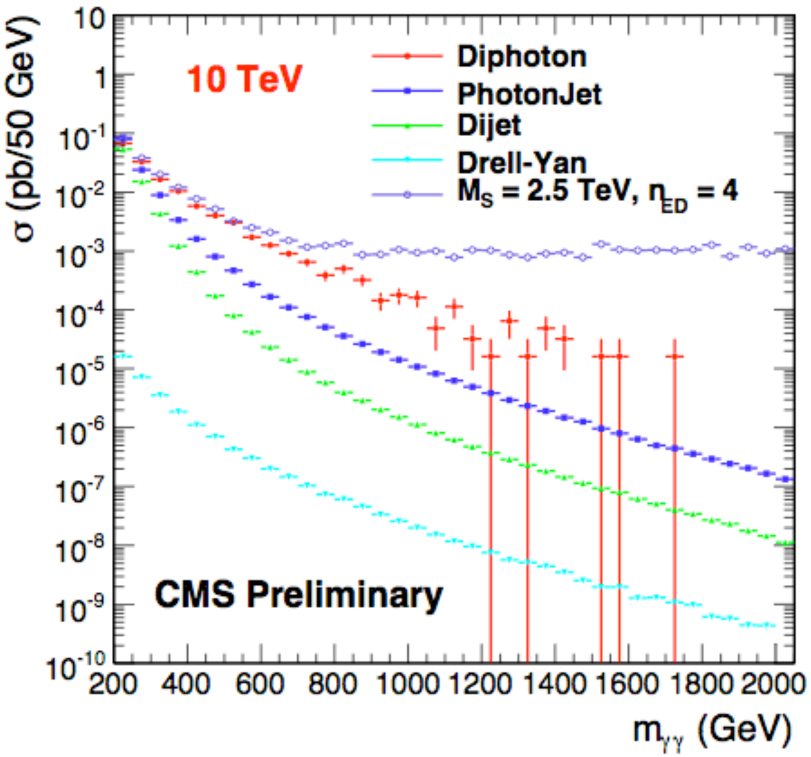
$30 fb^{-1}$

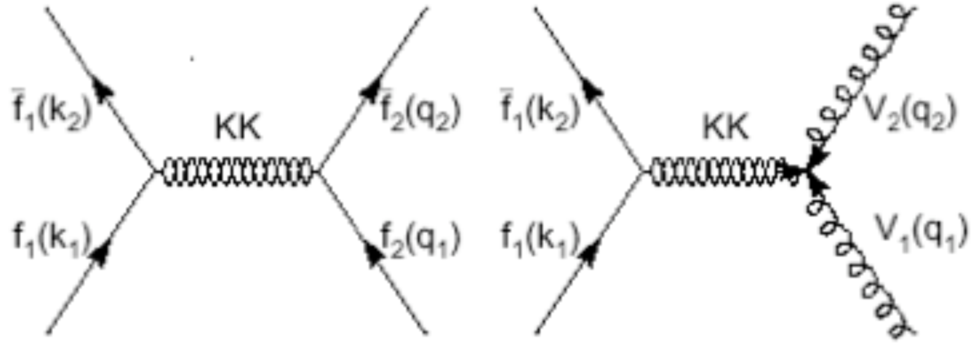
P_T photon> 400 GeV

Test M_D to 2.5-3 TeV for 100 pb^{-1}
Test M_D to 7-9 TeV for 100 fb^{-1}

Test M_D to ~ 2 TeV for O(300) pb^{-1}
Test M_D to ~ 4 TeV for 100 fb^{-1}

Large Extra Dimensions: Diphotons





n_{ED}	95% CL Limit on M_S		
	$50\ pb^{-1}$	$100\ pb^{-1}$	$200\ pb^{-1}$
2	2.5 TeV	2.7 TeV	2.9 TeV
3	3.0 TeV	3.3 TeV	3.5 TeV
4	2.6 TeV	2.8 TeV	3.0 TeV
5	2.3 TeV	2.5 TeV	2.7 TeV
6	2.1 TeV	2.3 TeV	2.5 TeV
7	2.0 TeV	2.2 TeV	2.4 TeV

$100\ pb^{-1} \Rightarrow$ exclude M_S in range of 2.2-3.3 TeV

Probe M_S = 2-2.5 TeV with O(100) pb^{-1}

Quantum Back Holes

- Schwarzschild radius

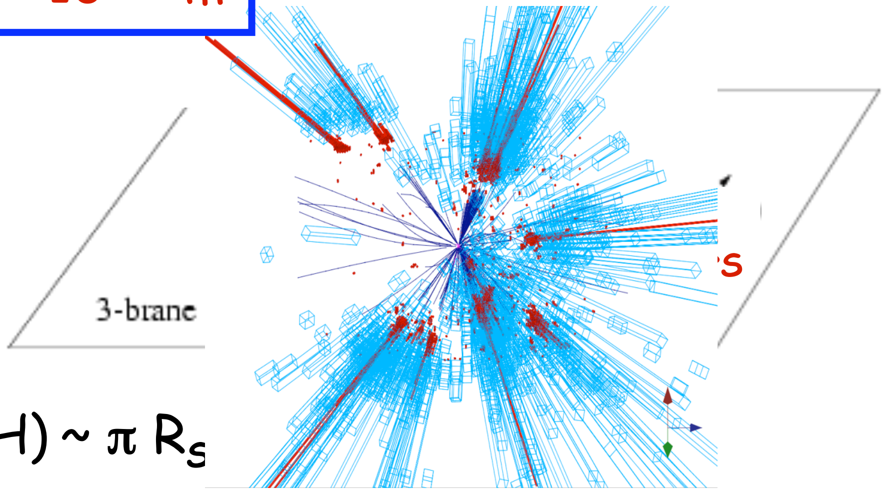
Landsberg, Dimopoulos
Giddings, Thomas, Rizzo...

4-dim., $M_{gravity} = M_{Planck}$ (~10^{19}GeV) $R_s \rightarrow \ll 10^{-35}$ m

4 + n-dim., $M_{gravity} = M_D \sim$ TeV $R_s \rightarrow \sim 10^{-19}$ m

⬇

Since M_D is low, tiny black holes of $M_{BH} \sim$ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_s



- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_s^2$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb – 1 fb

e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

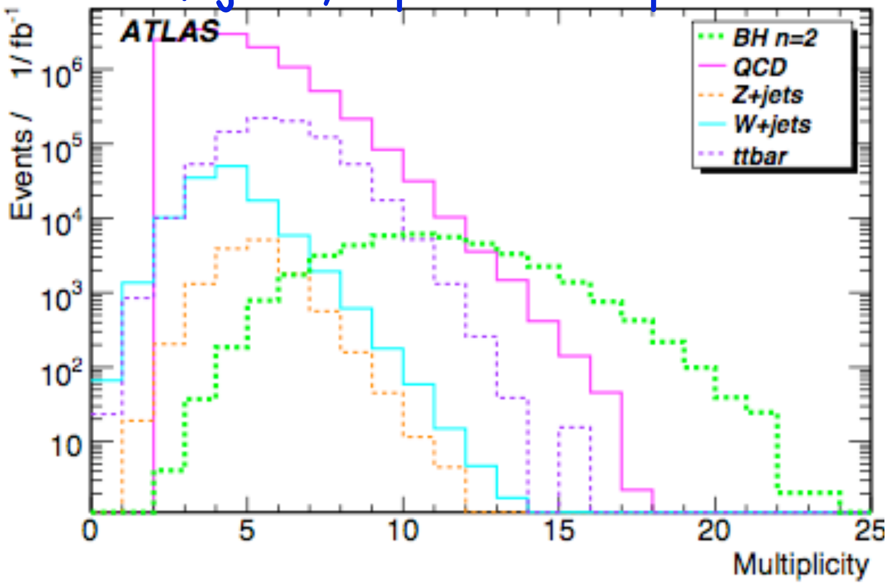
- Black holes decay immediately by Hawking radiation (democratic evaporation) :

-- large multiplicity
-- small missing E
-- jets/leptons ~ 5

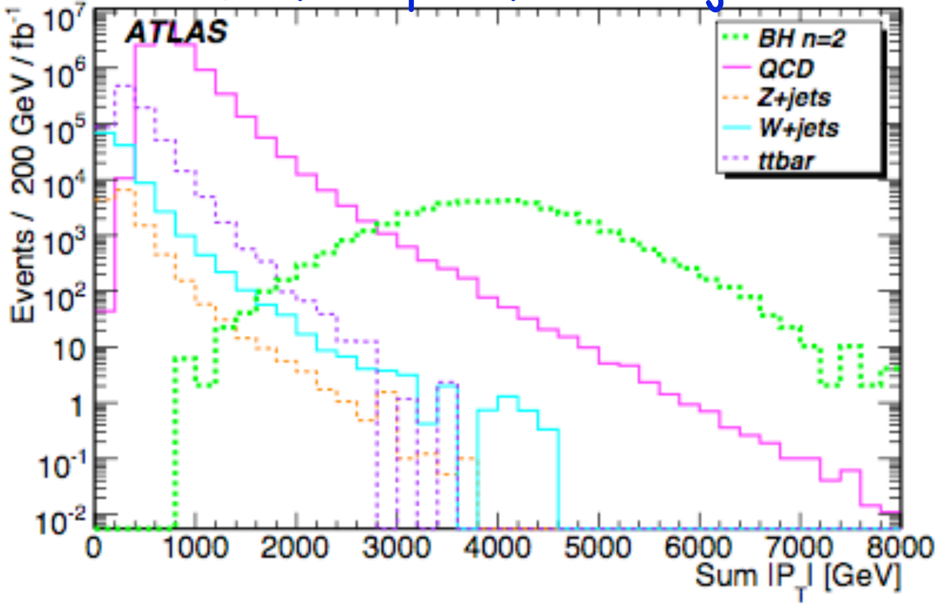
expected signature (quite spectacular ...)

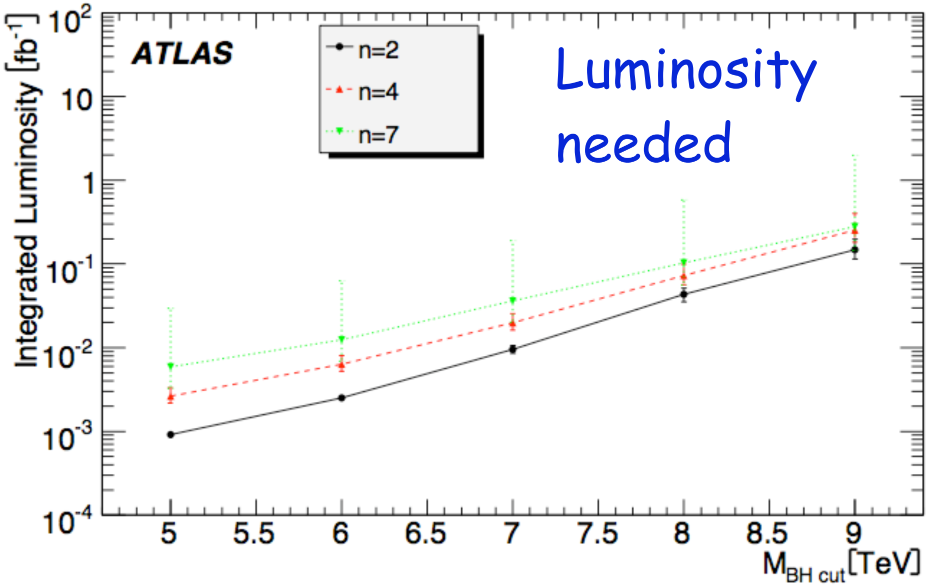
Black Hole Studies

of jets, leptons and photons



Sum of all pt of the objects





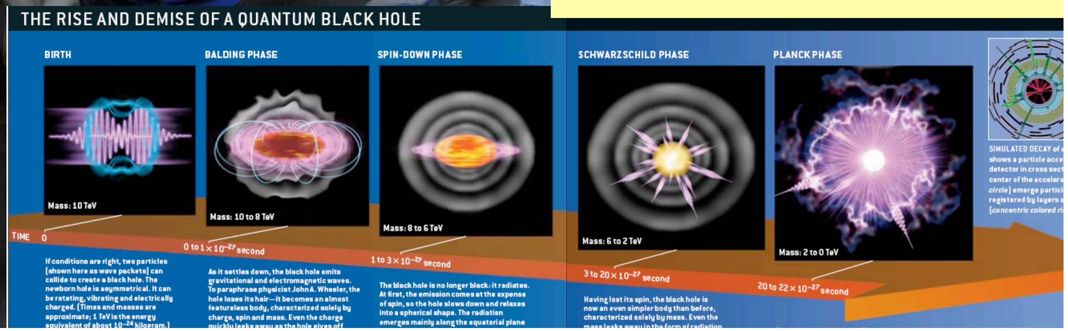
Luminosity needed

Already possible to discover with 1 pb^{-1}!!!

However cross sections largely unknown (and challenged)

Black Holes Hunters at the LHC…

Scientific American



Quantum Black Holes

ProfessorLandsberg was fast regretting becoming the first man to successfully create a mini black hole in the laboratory.

- Can LHC destroy the planet?

  ⇒ No!

- See the report of the LHC Safety assesment group (LSAG) *http://arXiv.org/pdf/0806.3414*
- More information on
  - S.B. Giddings and M. Mangano, *http://arXiv.org/pdf/0806.3381* LSAG,*http://arXiv.org/pdf/0806.3414*
  - Scientific Policy Committee Review, *http://indico.cern.ch/getFile.py/access?contribId=20&resId=0&materialId=0&confId=35065*
  - CERN public web page, *http://public.web.cern.ch/public/en/LHC/Safety-en.html*

Black holes evaporate in 10^{-27} sec

Extra Dimensions: String Balls?

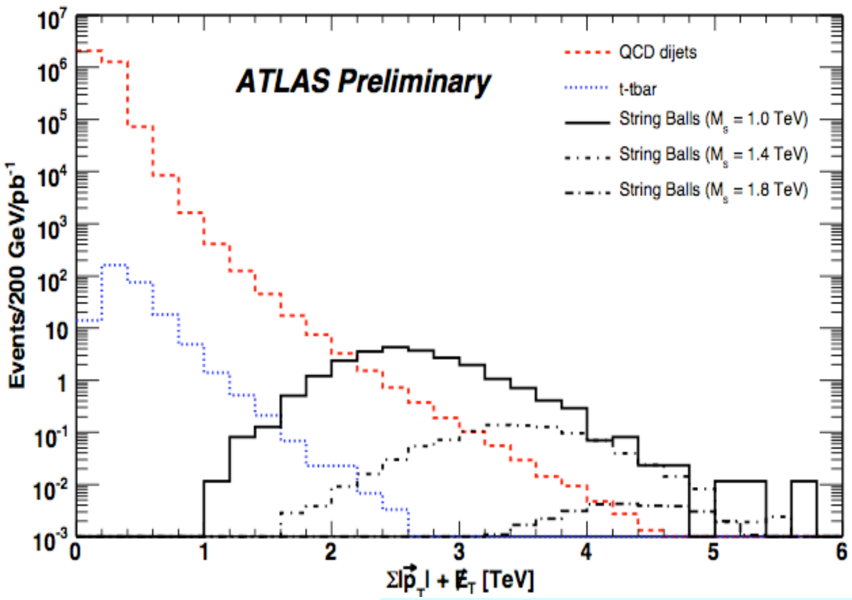
Black Holes: general relativity description only for $M_{BH} >> M_D$, eg $5 \cdot M_D$
Weakly-coupled coupled string theory→excited string states?

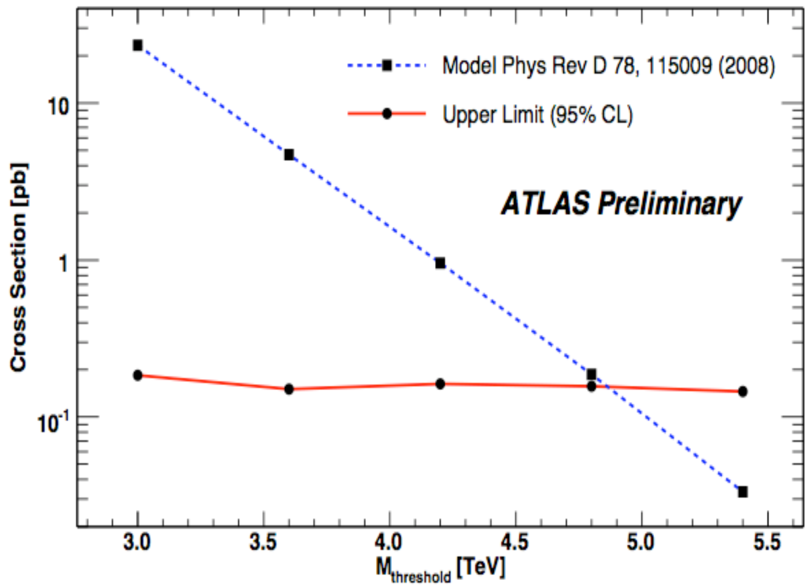
Dimopoulos et al, Ginrich et al.

$$M_s < M_D < \frac{M_s}{g_s^2}$$

M_s (TeV)	M_D (TeV)	M_{thresh} (TeV)	σ (pb)
1.0	1.5	3.0	$2.3 \times 10^{+1}$
1.2	1.8	3.6	$4.7 \times 10^{+0}$
1.4	2.1	4.2	9.6×10^{-1}
1.6	2.4	4.8	1.9×10^{-1}
1.8	2.7	5.4	3.3×10^{-2}

Thermal radiation of jets + leptons



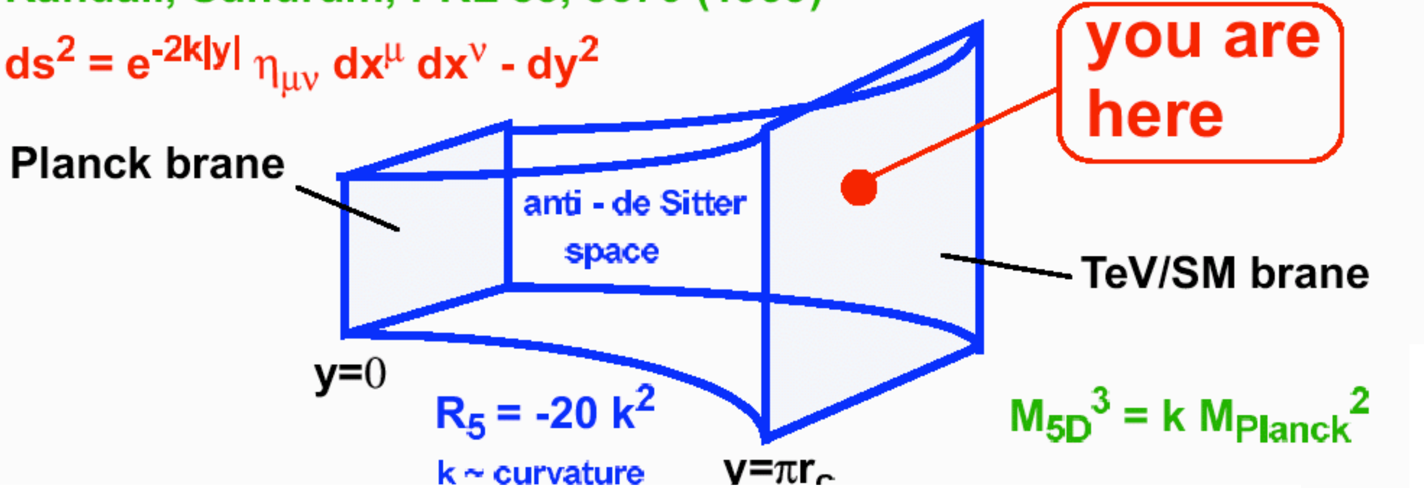


Exclusion of masses of up to ~ 4.8 TeV with 100 pb^{-1}

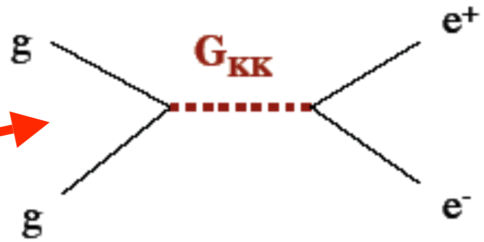
Curved Space: RS Extra Dimensions

Randall, Sundrum, PRL 83, 3370 (1999)

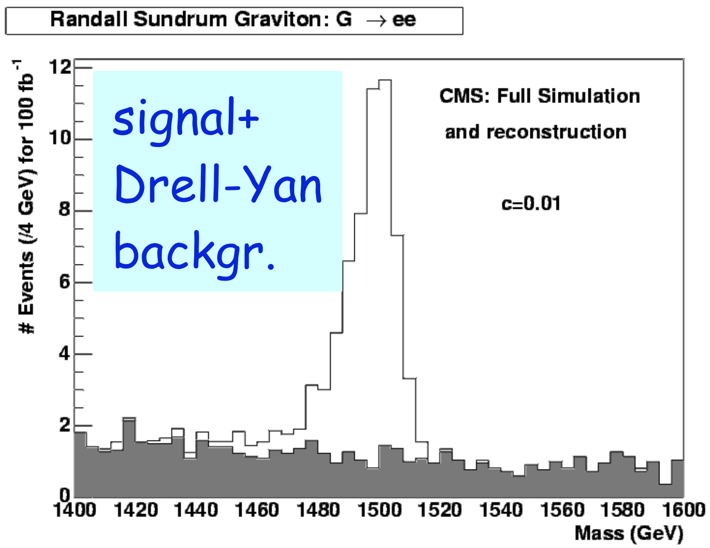
$$ds^2 = e^{-2k|y|}\,\eta_{\mu\nu}\,dx^\mu\,dx^\nu - dy^2$$



phenomenology



Study the channel pp→Graviton→ e+e-



Signature: a resonance in the di-electron or di-muon final state

a priori easy for the experiments

Caveat: new developments suggest that G_{KK} would couple dominantly to top anti-top…

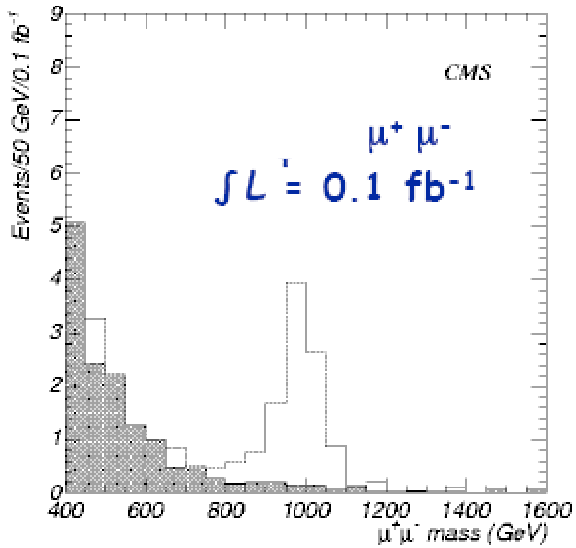
Early Discoveries? E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

A peak!!

A new particle!!

A discovery!!



$pp \to \mu\mu + X$

First year of operation

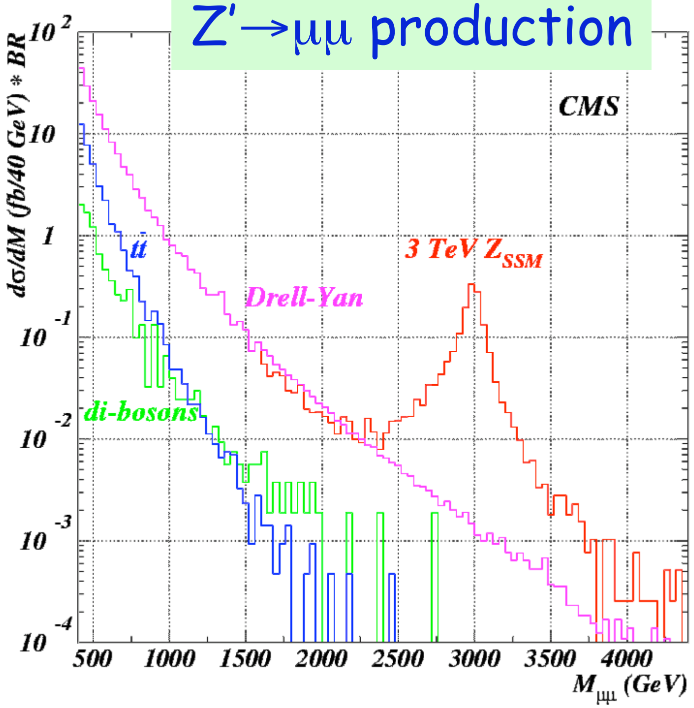
Example : The Di-lepton channel

- Z' (New gauge bosons)
- A_H, Z_H (Little Higgs)
- $G^{(1)}$ (Randall-Sundrum)
- $\gamma^{(1)}/Z^{(1)}$ (TeV^{-1} Extra Dimensions)
- $G^{(KK)}$ (ADD)
- ...

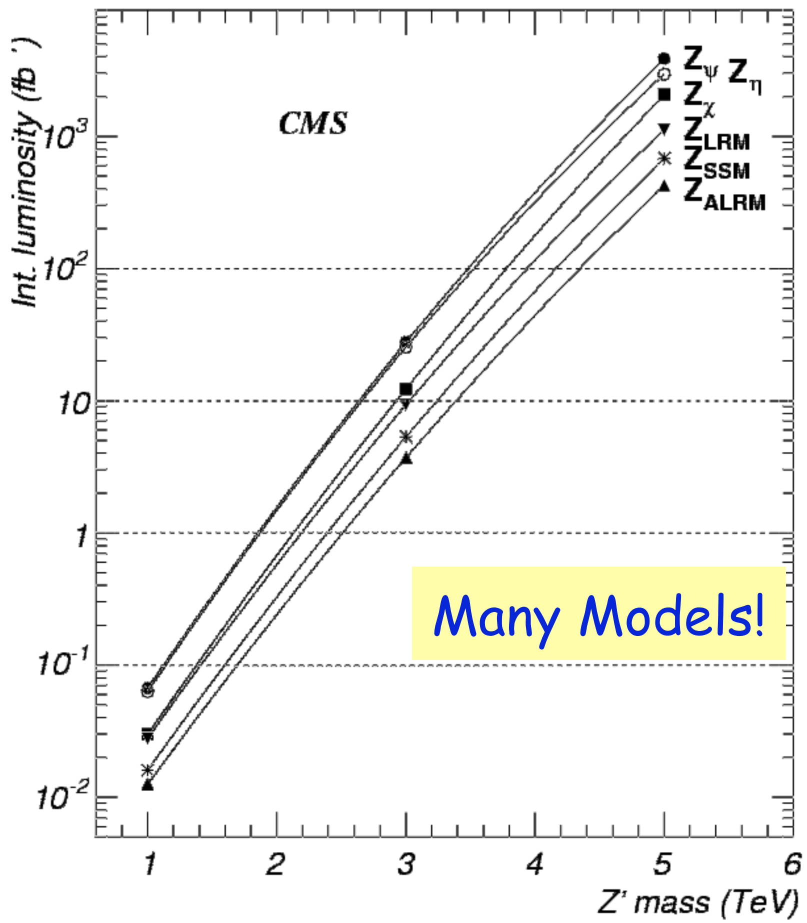
New Heavy Gauge Bosons: Z'

EG due a new symmetry group…

Z'→μμ production



Z' → μ⁺μ⁻: 5σ significance curves



Many Models!

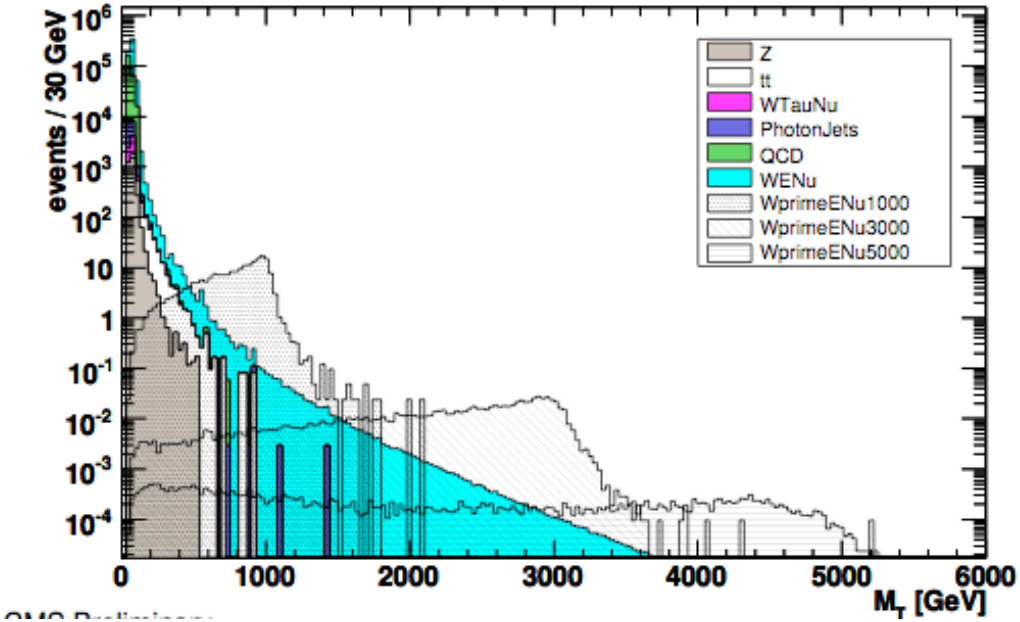
Note: Best possible theory knowledge on DY spectrum will be needed (tails!)

- Low lumi 100 pb^{-1} : discovery of 1-1.6 TeV possible, beyond Tevatron run-II
- High lumi 100 fb^{-1}: extend range to 3.4-4.3 TeV

New Heavy Gauge Bosons: W'

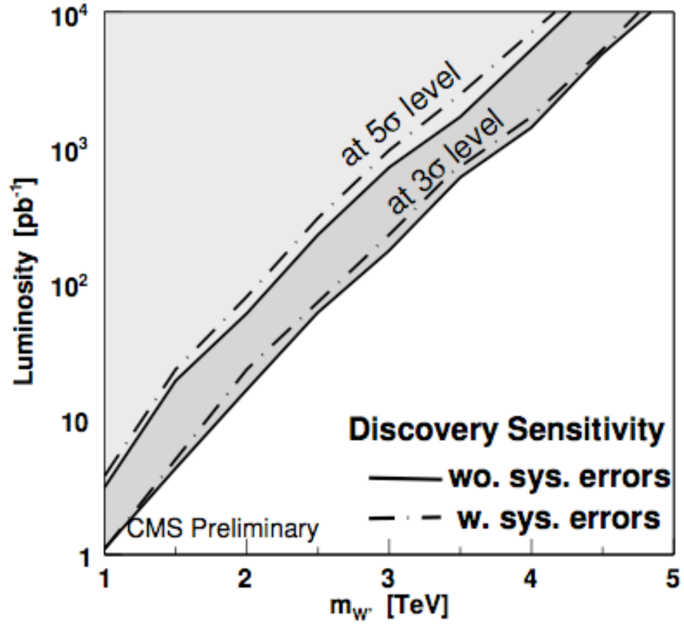
If a Z' exists: what about a W'?

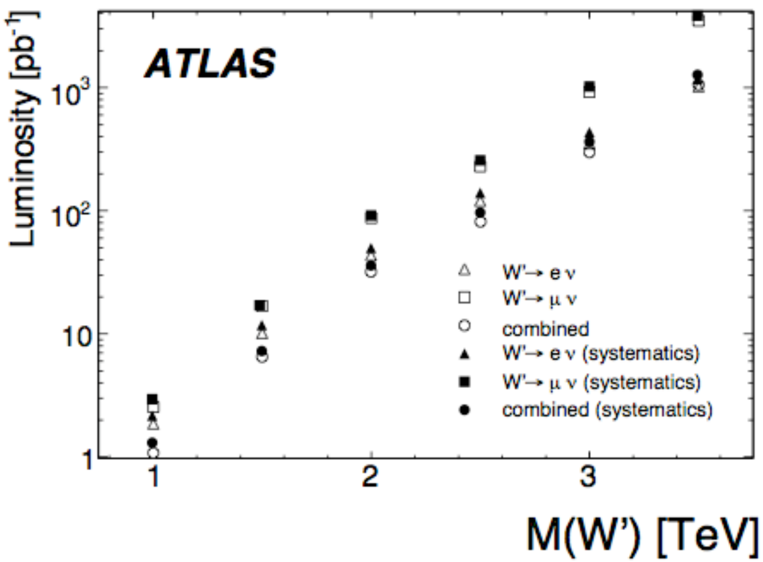
$W \to \mu\nu$, $e\nu$ channels



Tevatron > ~ 1 TeV

Sensitivity already for 10 pb^{-1}

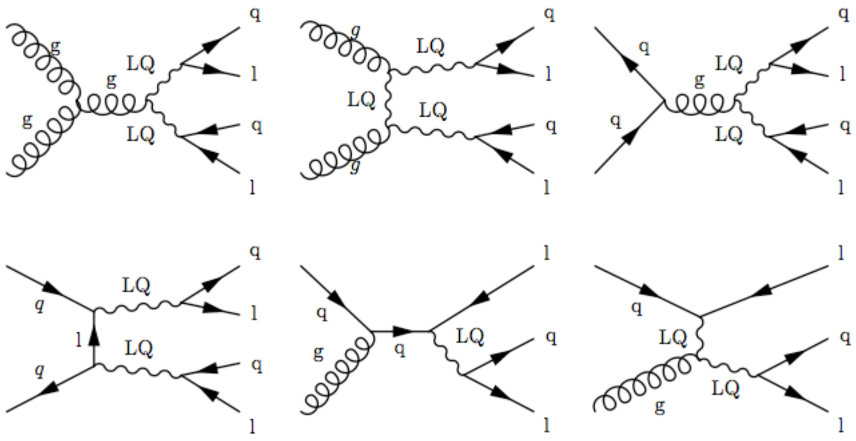




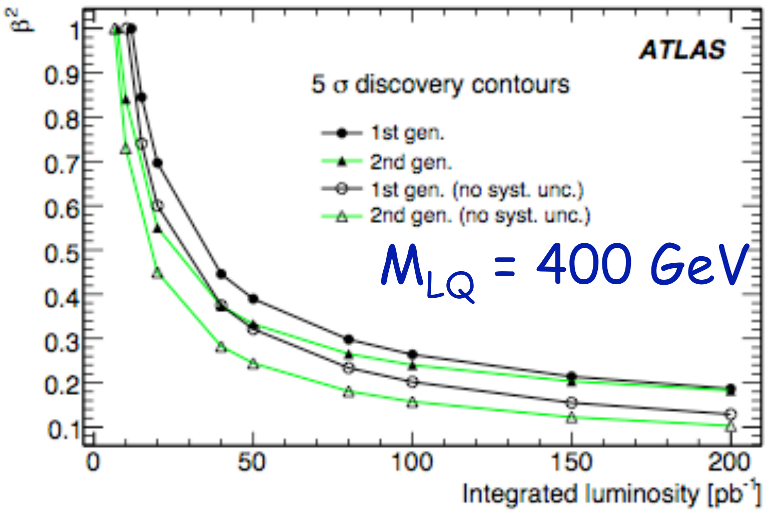
Leptoquark Production

GUT inspired models predict new particles with lepton and quark properties

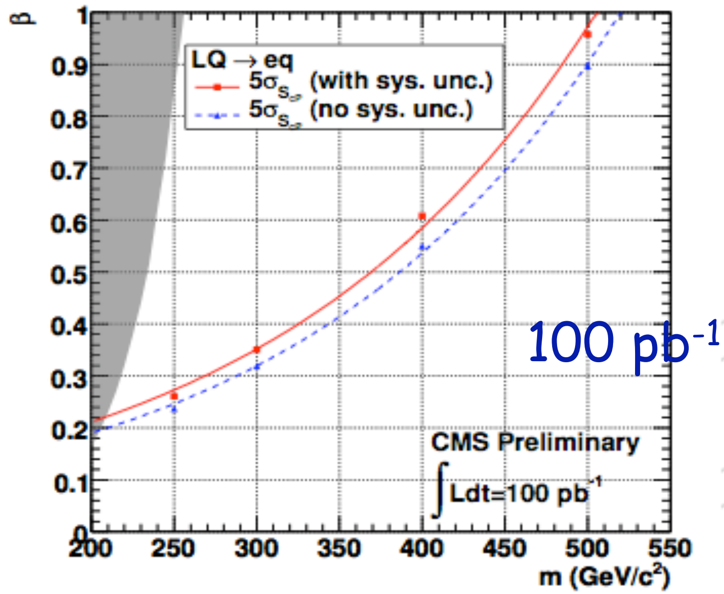
Tevatron limits ~ 300 GeV



Leptoquark mass	Expected luminosity needed for a 5σ discovery	
	1st gen.	2nd gen.
300 GeV	2.8 pb^{-1}	1.6 pb^{-1}
400 GeV	11.8 pb^{-1}	7.7 pb^{-1}
600 GeV	123 pb^{-1}	103 pb^{-1}
800 GeV	1094 pb^{-1}	664 pb^{-1}



M_{LQ} = 400 GeV

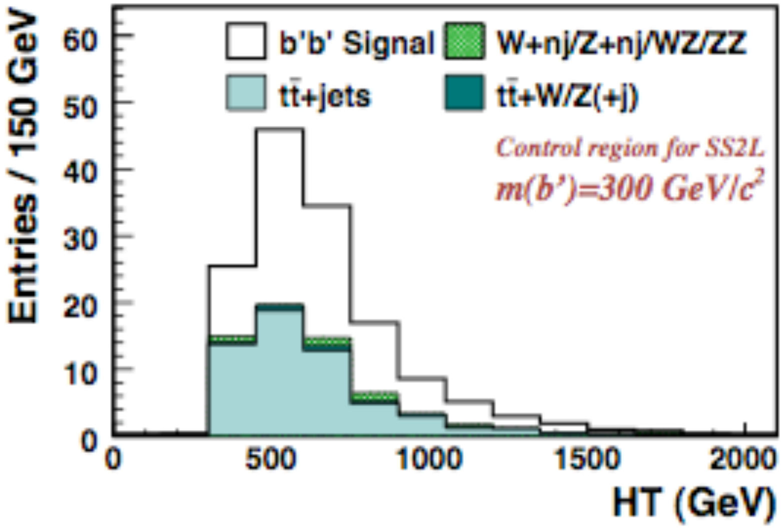


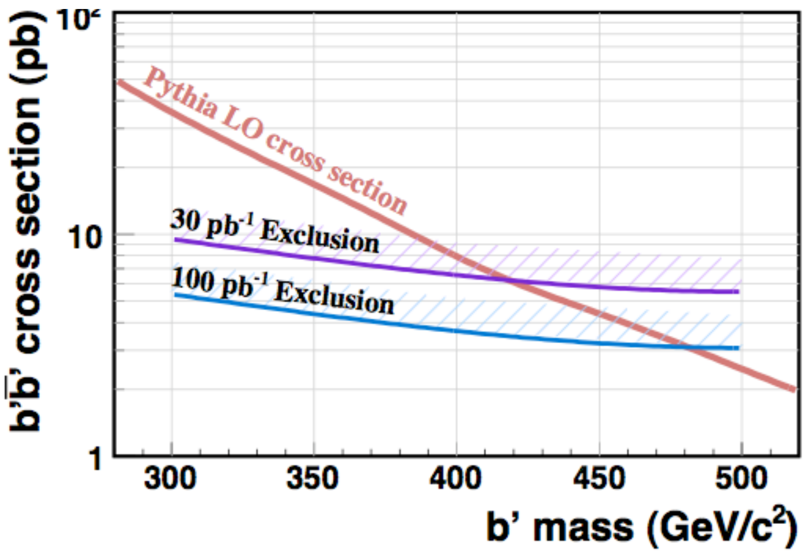
100 pb^{-1}

β: fraction decaying into eq (vs νq)

> 10 pb^{-1} to enter a new mass domain

A Fourth Quark Flavor Generation?





We can't be sure that there are only 3 generations (u,d) (s,c) (b,t)
A possible new generation should be heavy!

Look for b′ and t′ quarks
This channel: b′→ tW decays

Present limits ~ 200 GeV

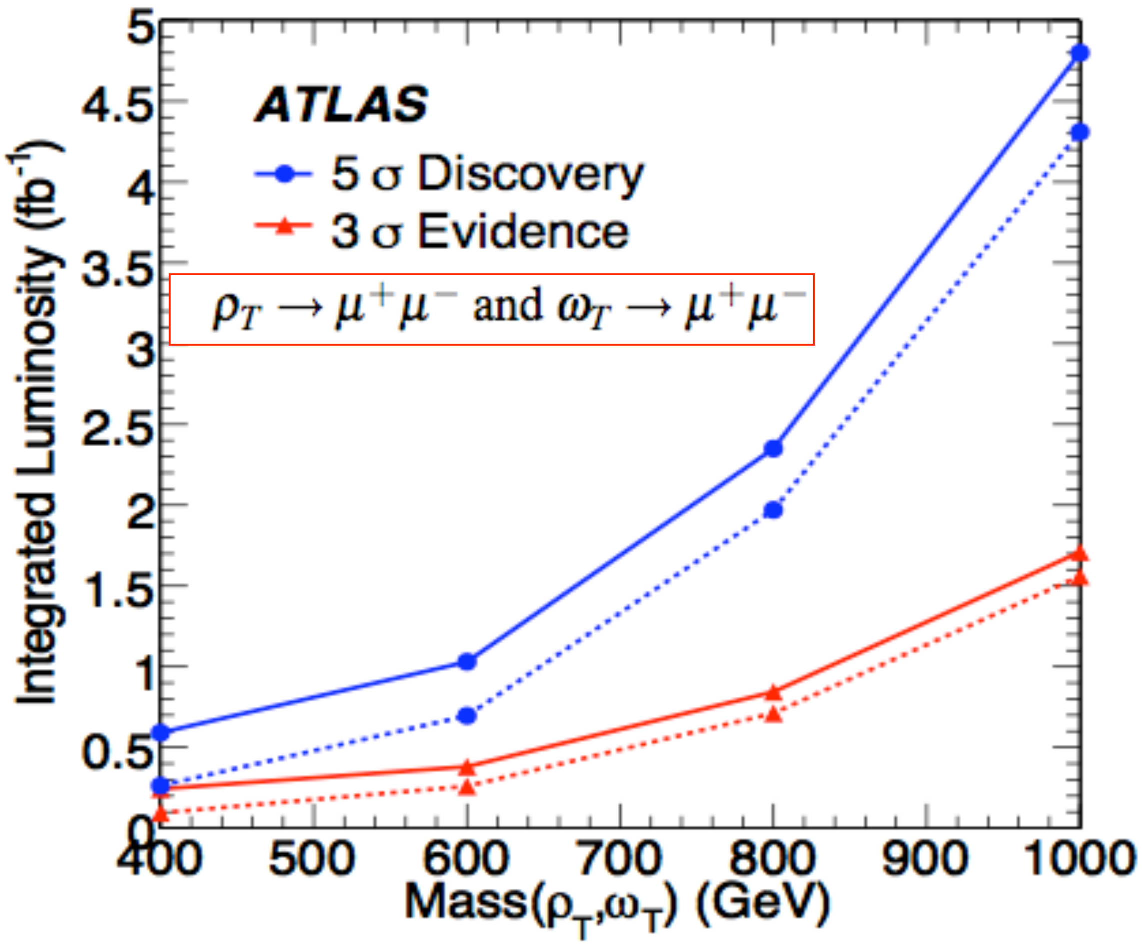
Tevatron Limits

$m_{t'}$ >311 GeV ($t'\rightarrow bW$) $m_{b'}$ >199 GeV ($b'\rightarrow bZ$)

Senstivity ~400 GeV with 100 pb^{-1}

A new strong force: Technicolor?

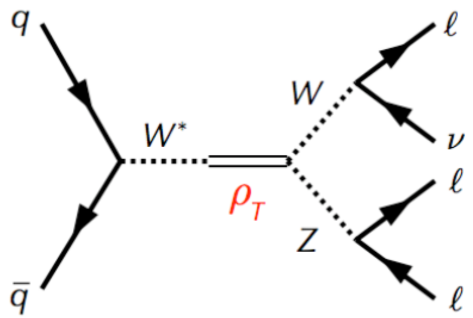
No elementary Higgs but a new type of color-like force, predicting particles called techni-pions, techni-rhos, techni-omegas…with masses ~ few 100 GeV



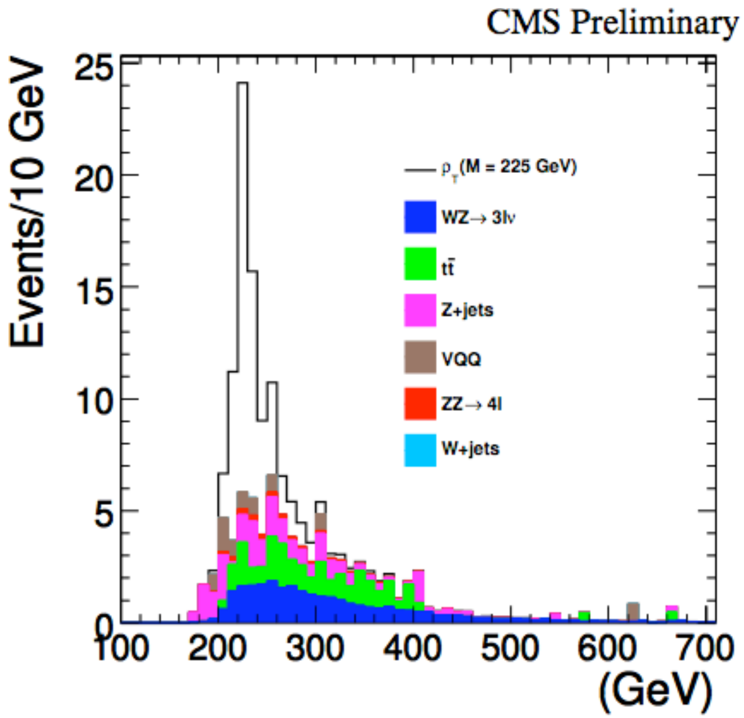
Luminosities of ~ 0.5-1 fb^{-1} or more needed

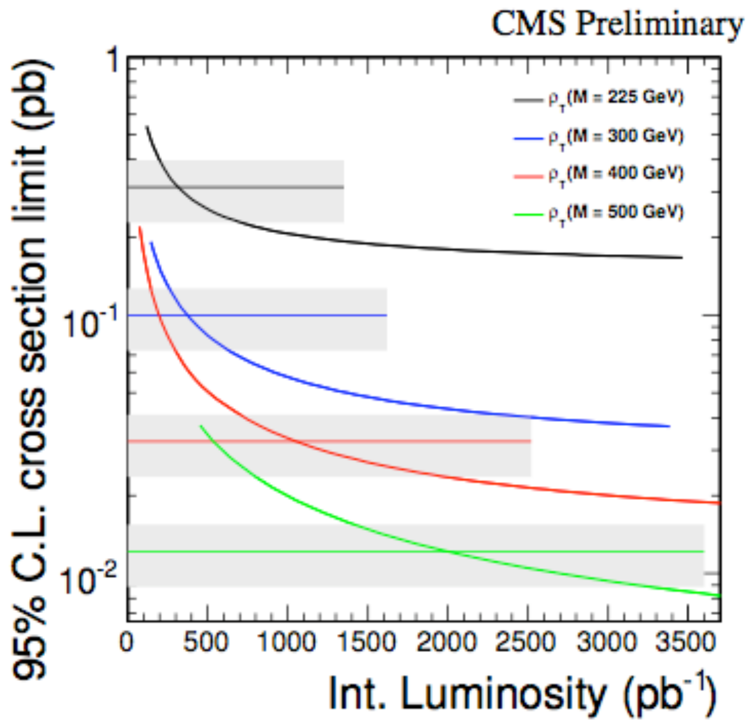
A New Force: Technicolor

No elementary Higgs but a new type of color-like force, predicting particles called tehni-pions, techni-rhos, techni-omegas…with masses ~ few 100 GeV



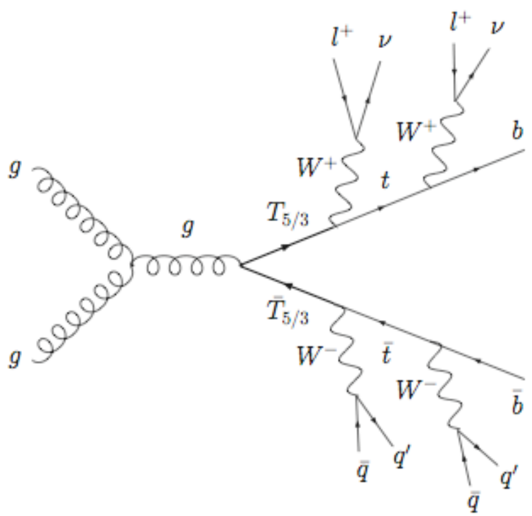
Luminosities of ~ O(0.5) fb^{-1} or more needed





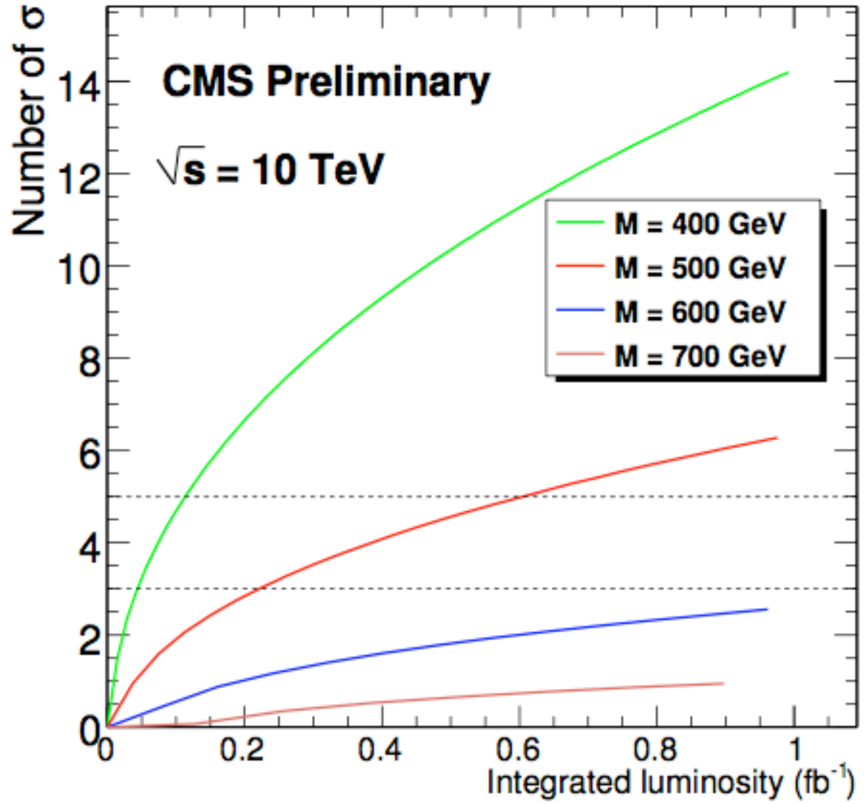
Particles with Unusual Properties

Top partners with exotic quantum numbers, eg Q = 5/3



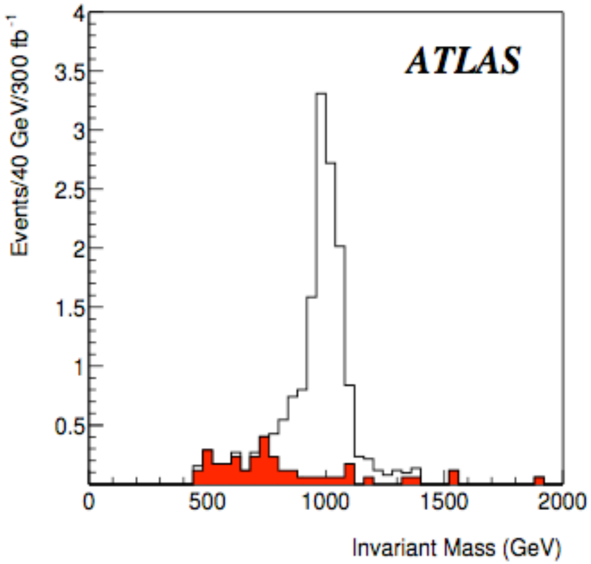
Produced in models with warped space dimensions
Characteristic: like sign leptons in decay

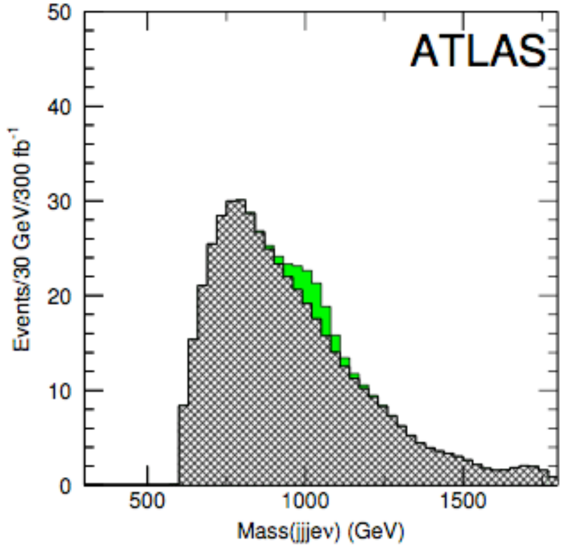
Reach up to 400 GeV with 100 pb^{-1}



Little Higgs Models

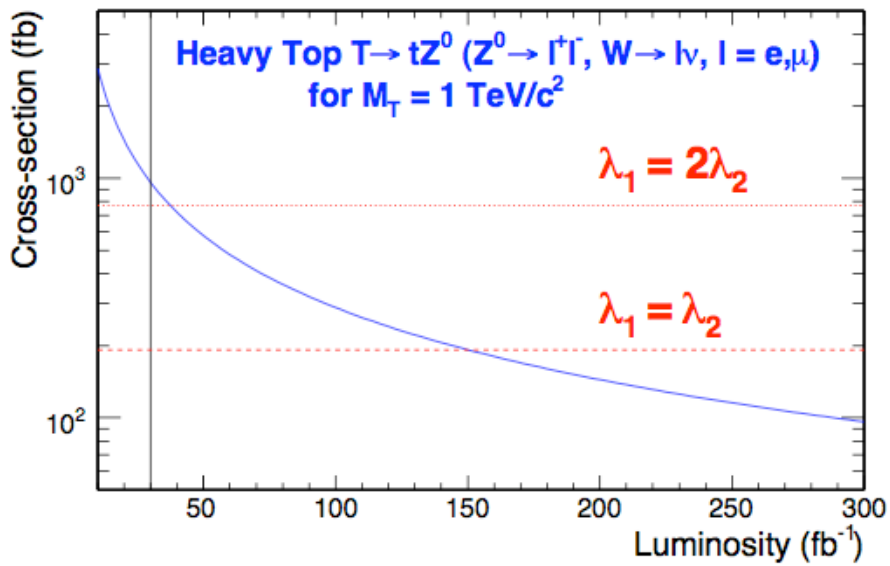
Heavy top partner around 1 TeV ⇒ Decay eg into $T \to tZ$, $T \to tH$



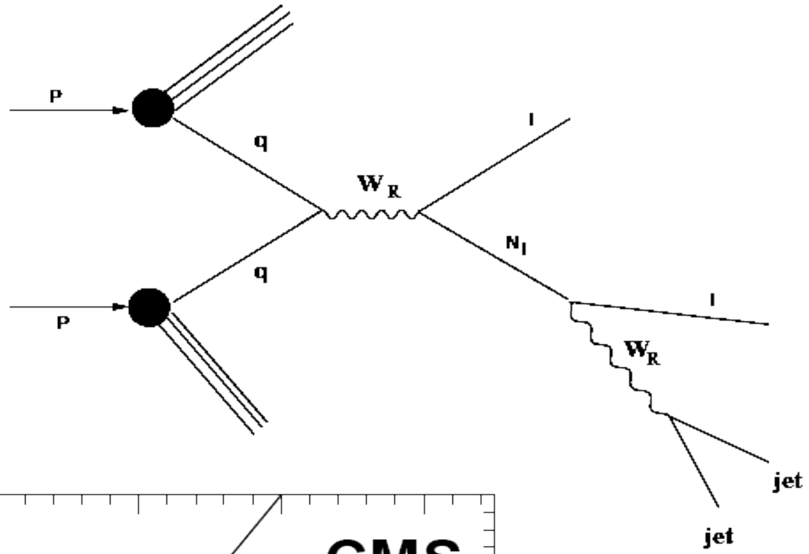


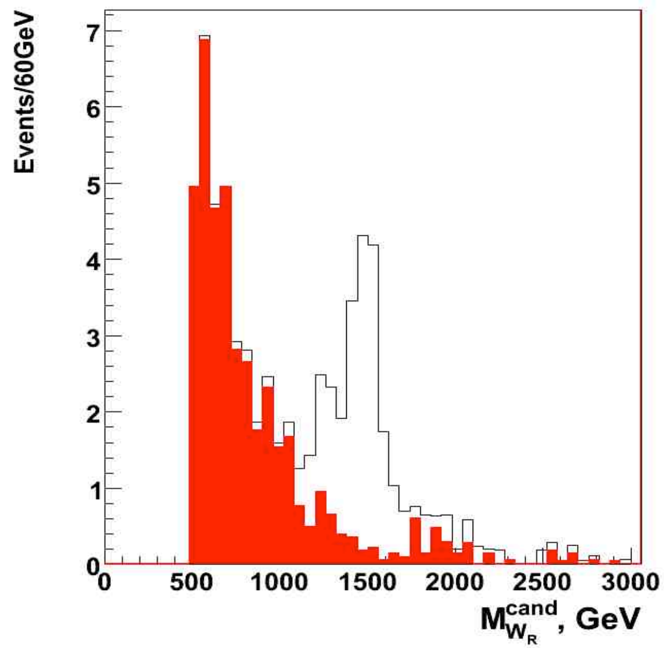
Signals+BG
Needs a lot of luminosity!!

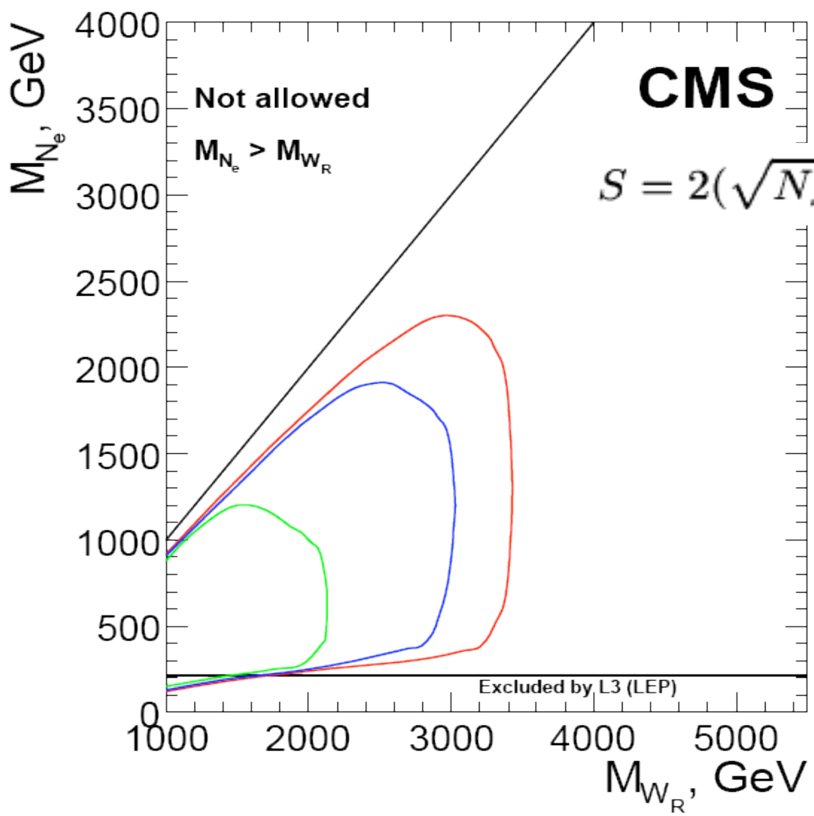
CMS PTDR:
Sensitivity to heavy top cross section



Heavy Neutrinos







$$S = 2(\sqrt{N_S + N_B} - \sqrt{N_B}) \geq 5$$

CMS discovery potential of the W_R boson and right-handed Majorana neutrino for luminosity 30 fb^{-1}, 10 fb^{-1}, 1 fb^{-1}.

Tevatron limits
WR>0.7 TeV

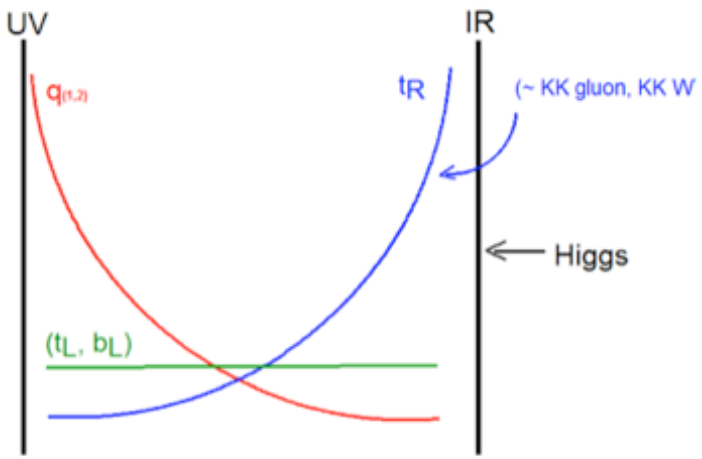
N>0.3 TeV

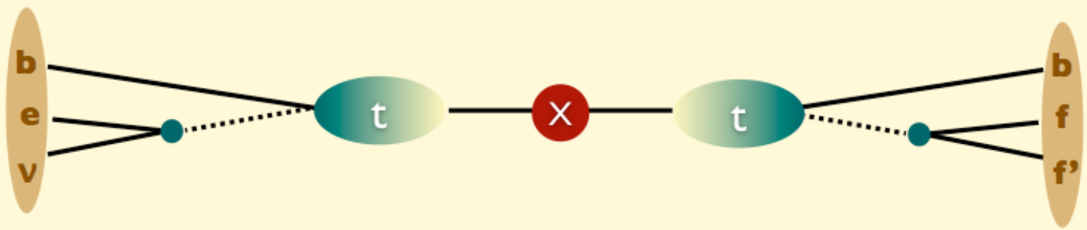
M(WR) = 1.2 TeV, M(Nl) = 500 GeV can be discovered with 40 pb^{-1} @ 10 TeV

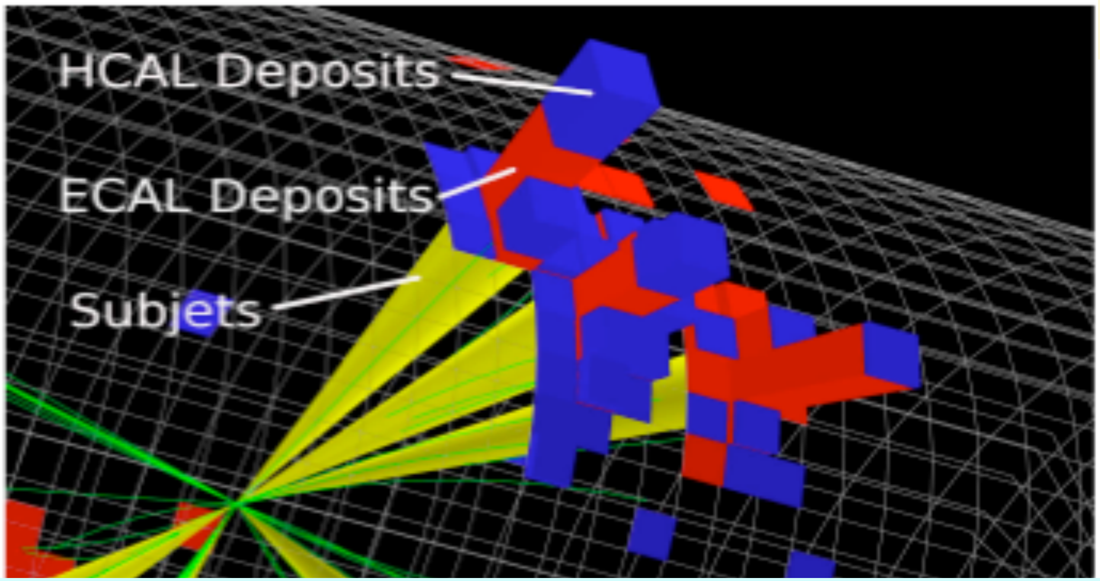
TeV Resonances into Top Quark Pairs

Recent developments in models: a prominent role of top production
-light SM fermions live near Planck brane, heavy (top) near TeV brane
-decay of Randall Sundrum gravitons into top pairs!!

- Eg RS → t tbar





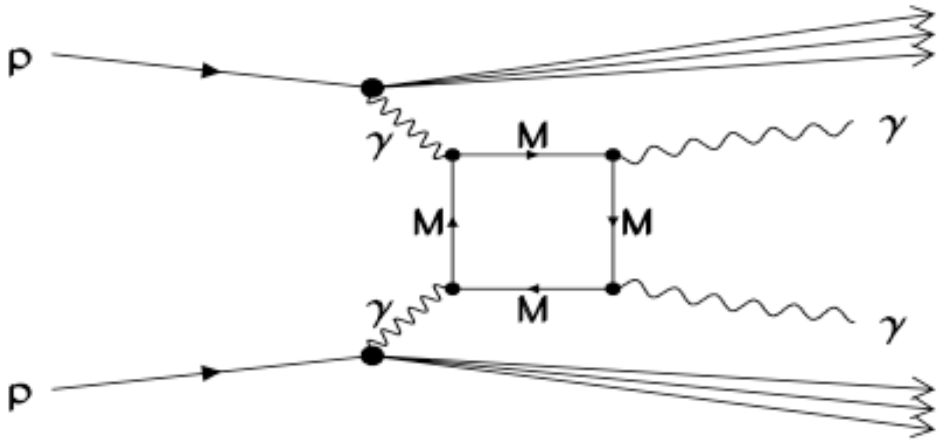


⇒High P_T tops

Methods are prepared to tackle the early data

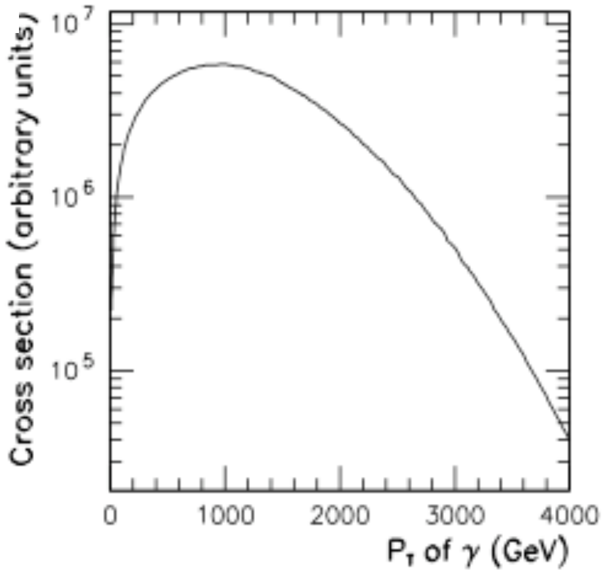
Magnetic Monopoles

Heavy particles which carry "magnetic charge"
Could eg explain why particles have "integer electric charge"



Virtual production:
Look eg into di-photon final state

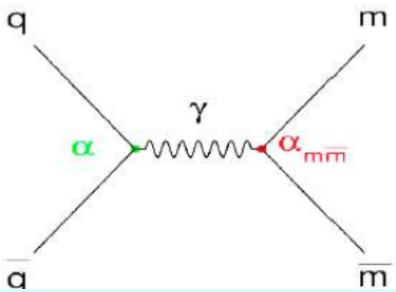
$$\sigma_{pp \to \gamma\gamma X}(E, M, P, n) = 108P\left(\frac{nE}{M}\right)^8\left(\frac{N(E))}{N(1\mathrm{TeV})}\right)^2\left(\frac{1TeV}{E}\right)^2 \mathrm{fb}$$



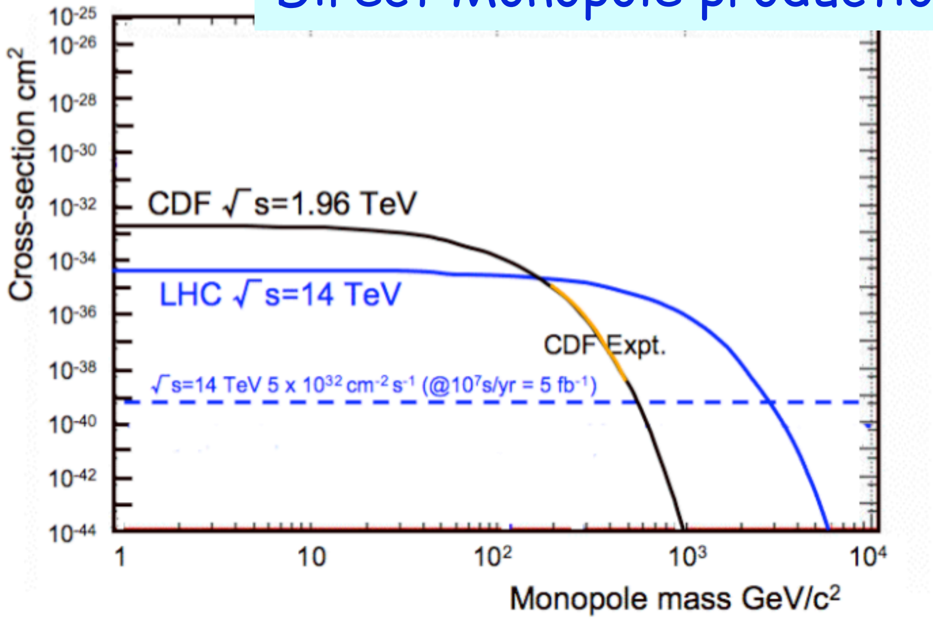
Cross section O(fb)
High luminosity required

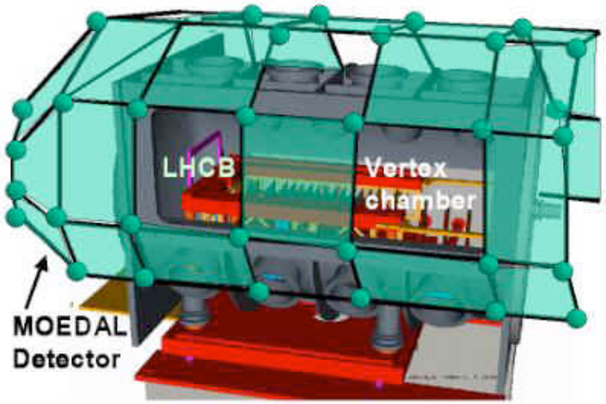
Moedal: MOnopole and Exotics Detector at LHC

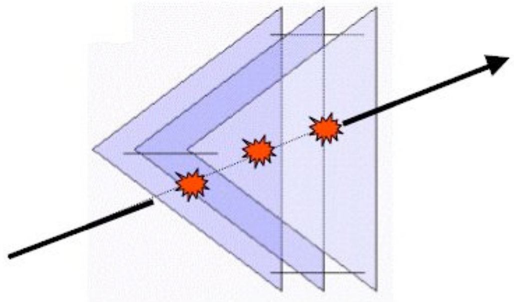
Heavy particles which carry "magnetic charge"
Could eg explain why particles have "integer electric charge"



Direct Monopole production







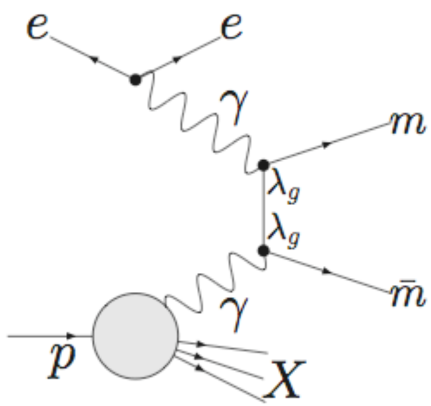
Remove the sheets after some running time and inspect for 'holes'
Can also be studied at ATLAS/CMS

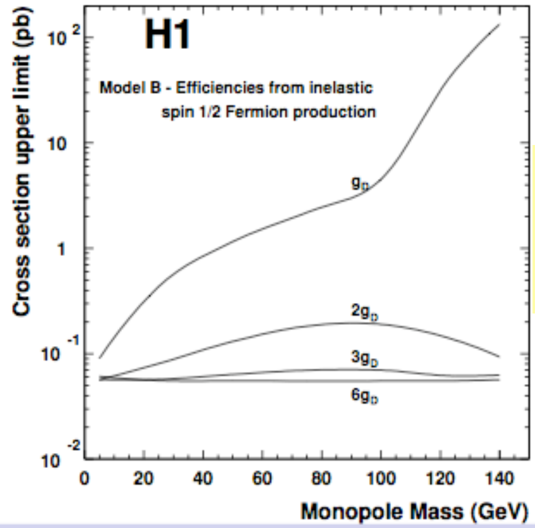
Monopole Search

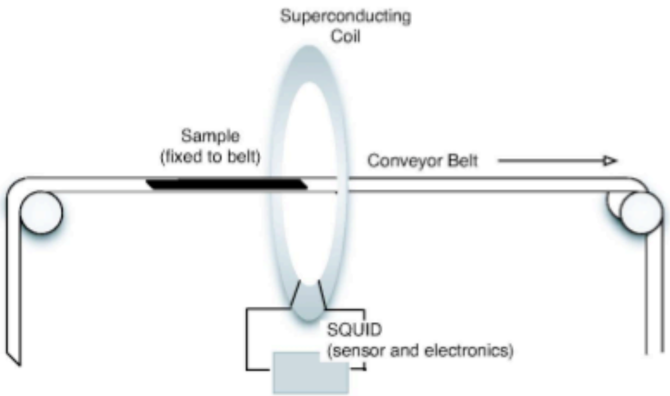
H1 experiment at the ep collider HERA, Hamburg

Magnetic Monopoles stuck in the beampipe?

- Dirac monopoles with large magnetic charge → highly ionizing
- $\lambda_D = \frac{g_D}{\sqrt{4\pi}}$
- Predicted to be light by some models
- Could be trapped in beampipe (Al)
- 1994-97 beampipe was cut into strips and passed through superconducting coil







Also accessible at the LHC

But maybe the “New World” is far more weird than what we thought so far…

Recent developments in many models lead to the possible existence of heavy particles that have unusual long lifetimes

These can decay in the middle of the detector (nanoseconds) or live even much longer eg seconds, hours, days…

This leads to very special detector signatures!

Long Lived Particles in Supersymmetry

Split Supersymmetry

- Assumes nature is fine tuned and SUSY is broken at some high scale
- The only light particles are the Higgs and the gauginos

- Gluino can live long: sec, min, years!

- R-hadron formation (eg: gluino+ gluon): slow, heavy particles containing a heavy gluino.

Unusual interactions with material

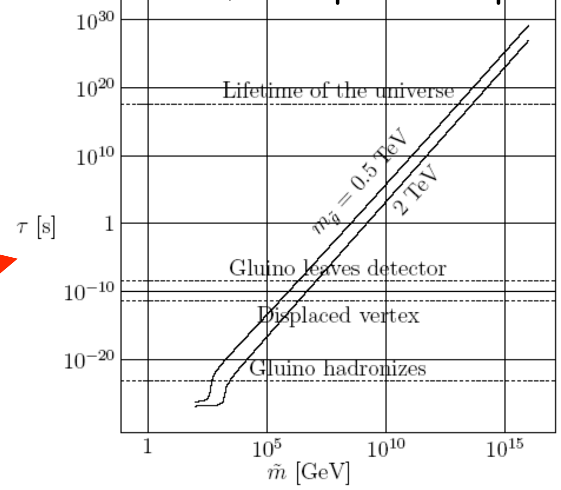
eg. with the calorimeters of the experiments!

Gravitino Dark Matter and GMSB

- In some models/phase space the gravitino is the LSP
- ⇒ NLSP (neutralino, stau lepton) can live 'long'
- ⇒ non-pointing photons

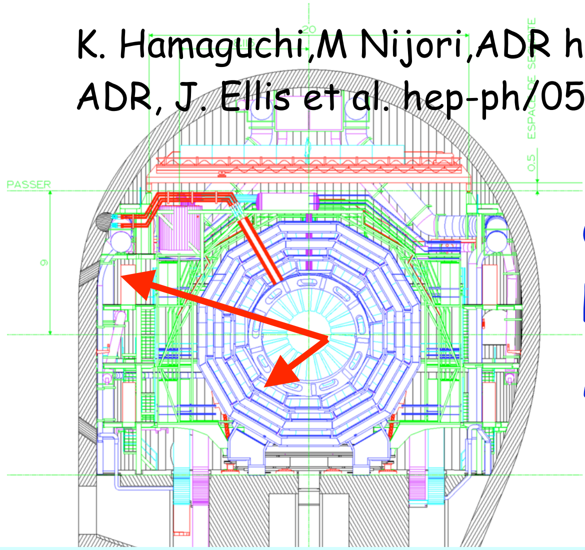
⇒Challenge to the experiments!

Arkani-Hamed, Dimopoulos hep-th/0405159



K. Hamaguchi,M Nijori,ADR hep-ph/0612060

ADR, J. Ellis et al. hep-ph/0508198



CMS e.g

P. Zalewski

M. Kazana

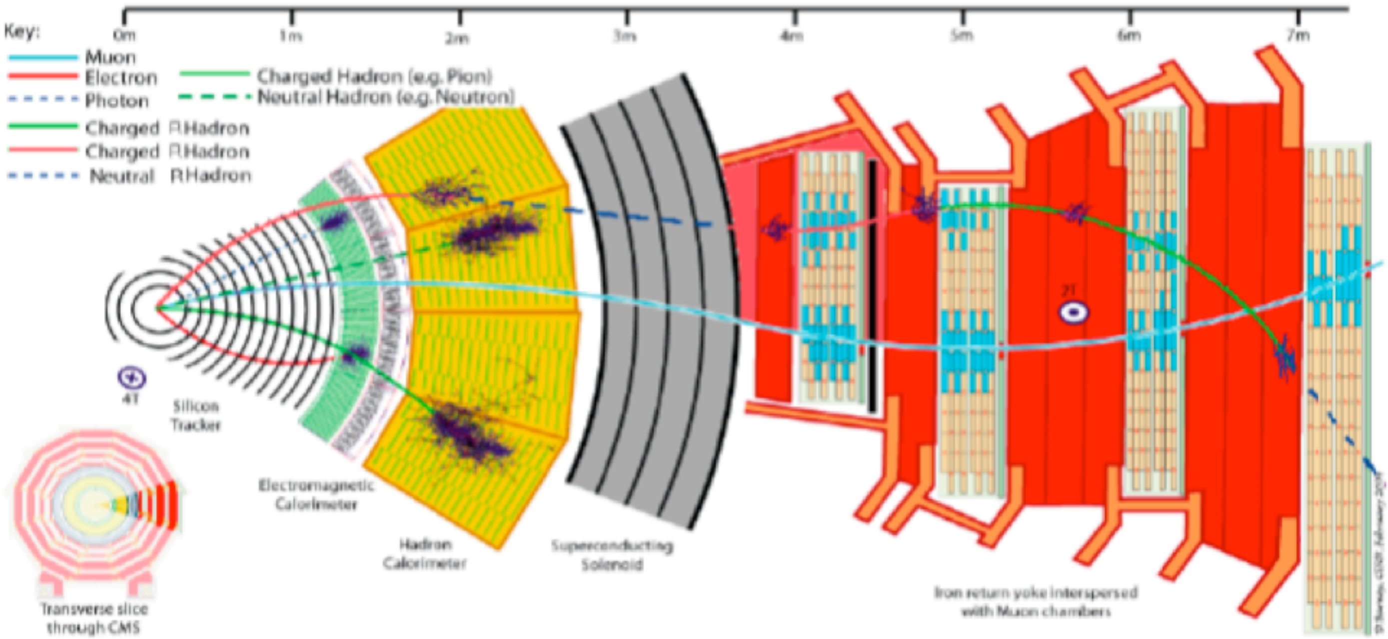
....

Sparticles stopped in the detector,walls of the cavern, or dense 'stopper' detector. They decay after hours---months...

R-Hadrons Passing Through the Detector

R-hadrons would have a mass of at least a few 100 GeV

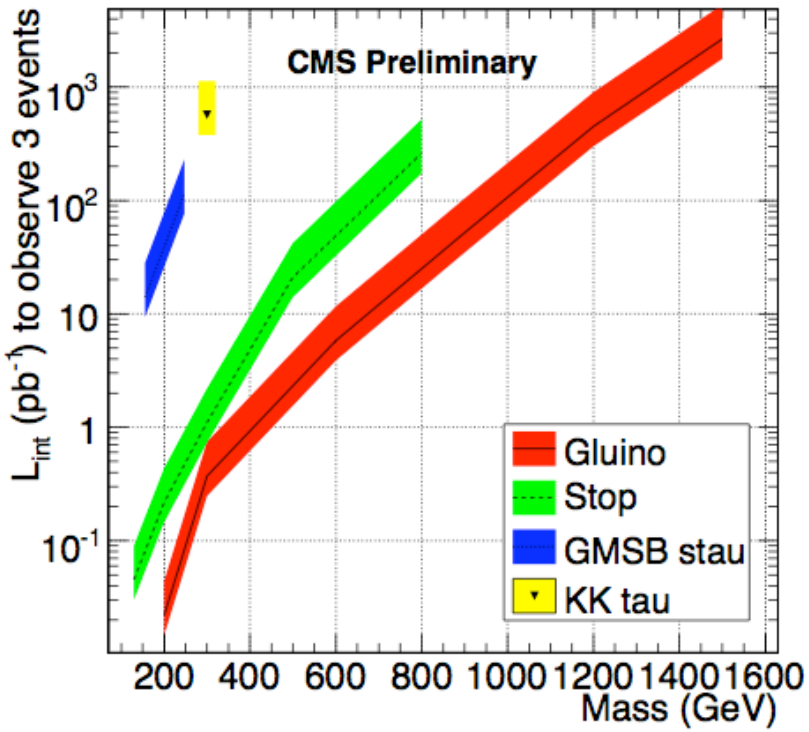
- They 'sail' through the detector like a 'heavy muon'
- In certain (hadronization) models they may change charge on the way
- They also loose a lot of energy when passing the detector (dE/dx)



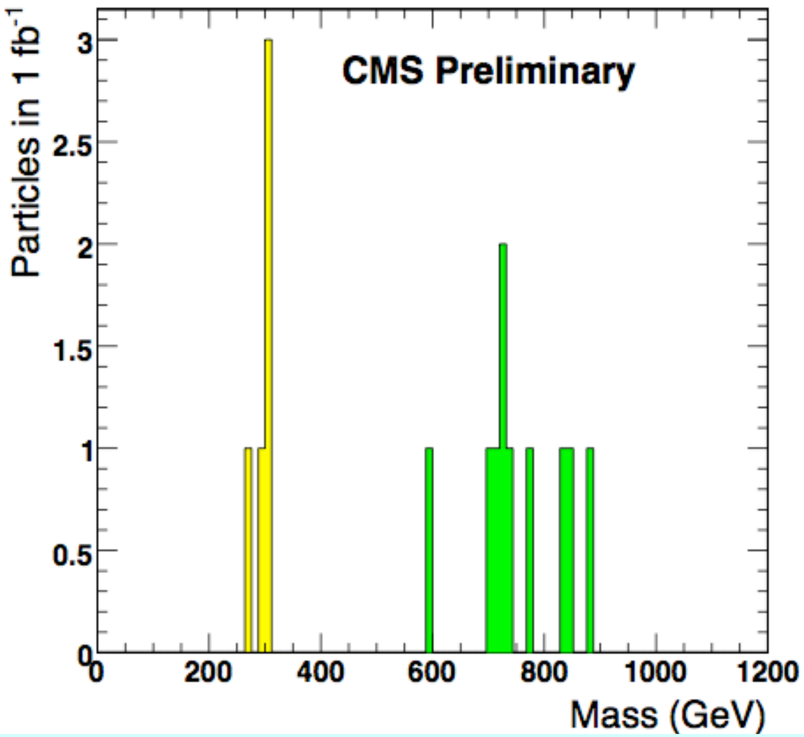
Weird signature!!

Heavy Stable Charged Particles

Sensitivity for different models:
⇒ Gluinos, stop, stau and KKtau production



Luminosity needed for a discovery



Mass reconstruction for a 200 GeV KKtau and a 800 GeV stop particle

Stopped R-hadrons or Gluinos!

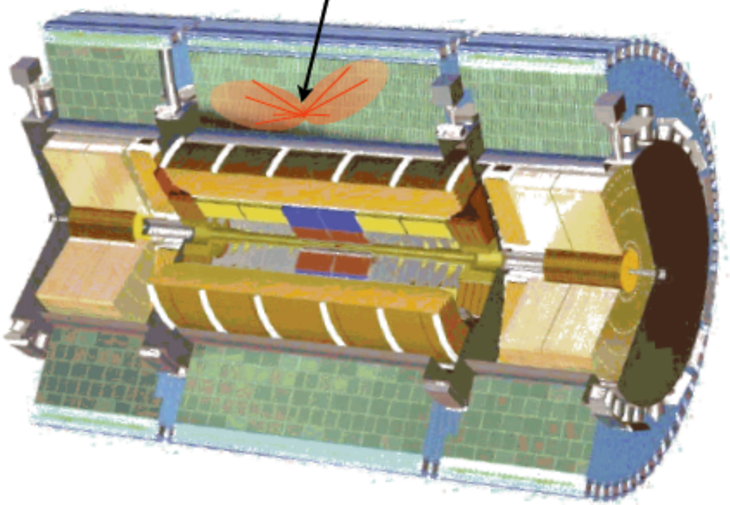
The R-hadrons may loose so much energy that they simply stop in the detector

Long Lived Gluinos

$\tau_{\tilde{g}} > 100$ ns

looking for stopped gluinos that later decay

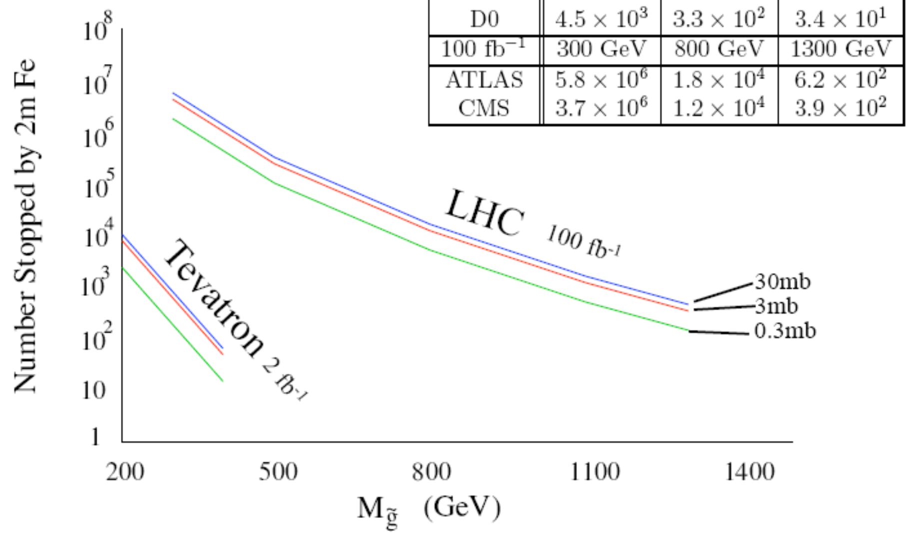
100s GeV Unbalanced $= \not{E}_T$



Uncorrelated with any beam crossing
No tracks going to or from activity

Total Number of Stopped Gluinos

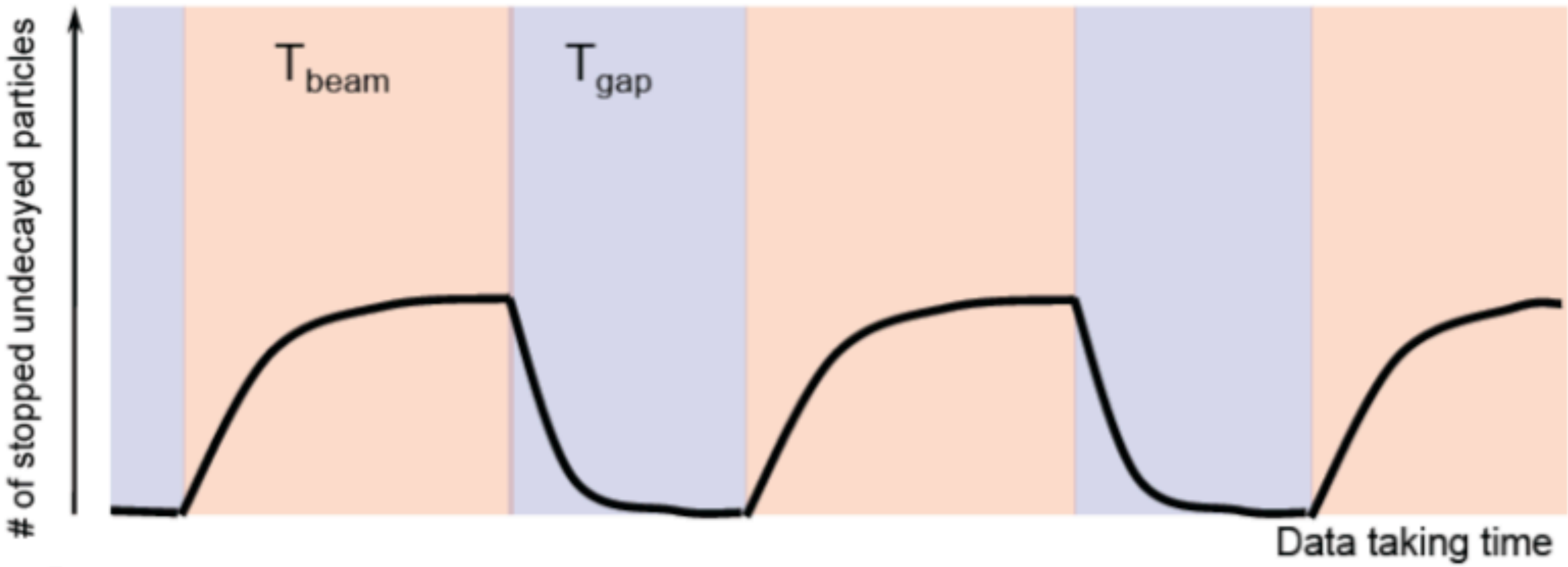
Arvanitaki, Dimopoulos, Pierce, Rajendran, JW hep-ph/0506242



2 fb^{-1}	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
100 fb^{-1}	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2

$\Rightarrow$ Special triggers needed, asynchronous with the bunch crossing

Stopped gluinos



- Basic idea: R-hadrons can loose enough energy in the detector to stop somewhere inside (usually calorimeters)
- Sooner or later they must decay

Eg when there is no beam!

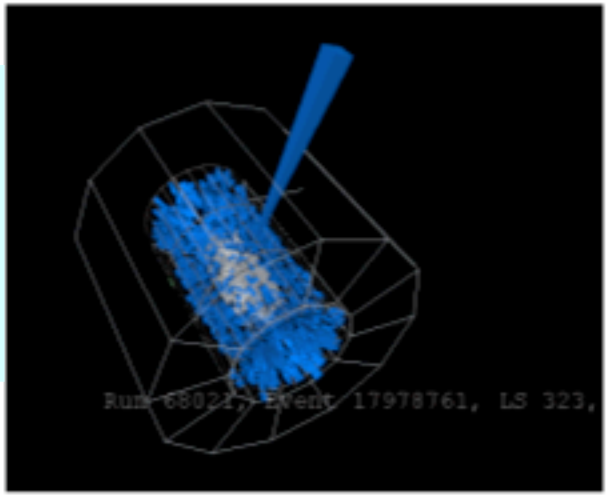
- Trigger: (jet) && !(beam)
- Only possible backgrounds: cosmics and noise

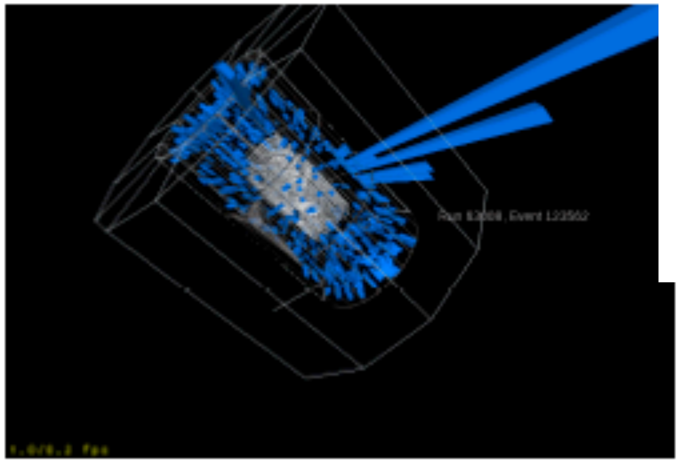
Can be studied in the experiments NOW with cosmic data

Stopped Gluinos

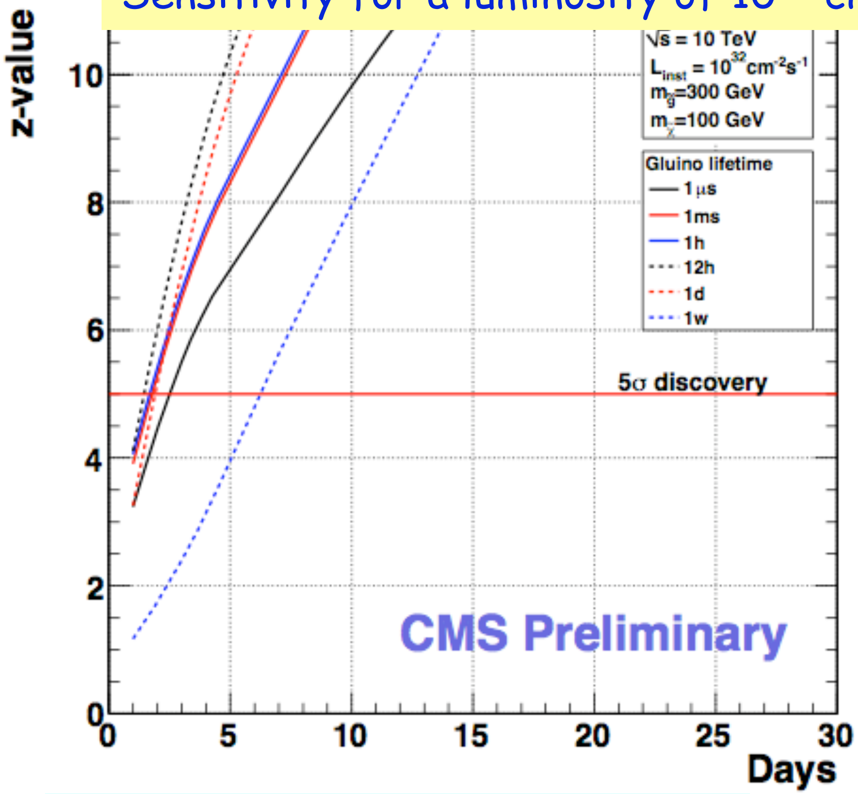
Studies in CMS with the 2008/2009 cosmic data:
All events we find now are background and we can learn how to cut on them!

Find energy splashes with certain topology



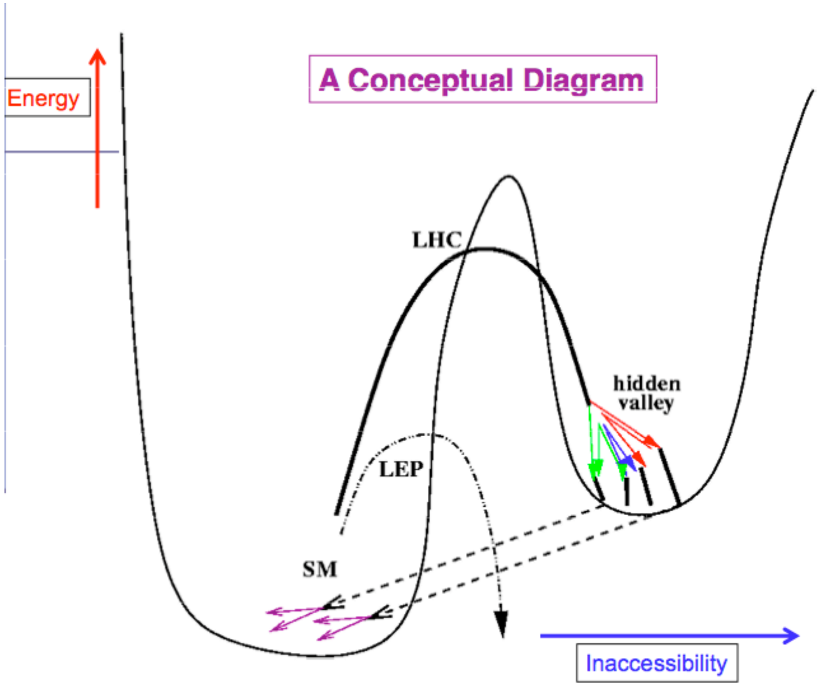


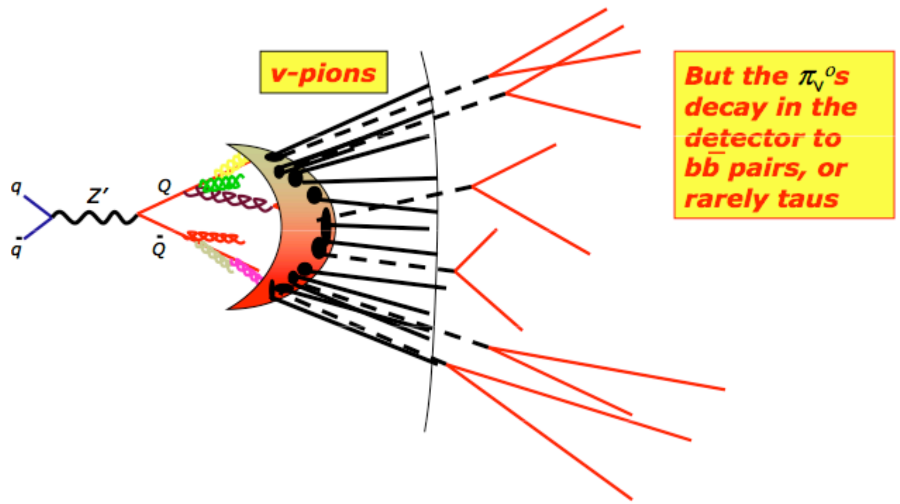
Sensitivity for a luminosity of 10^{32} $cm^{-2}s^{-1}$



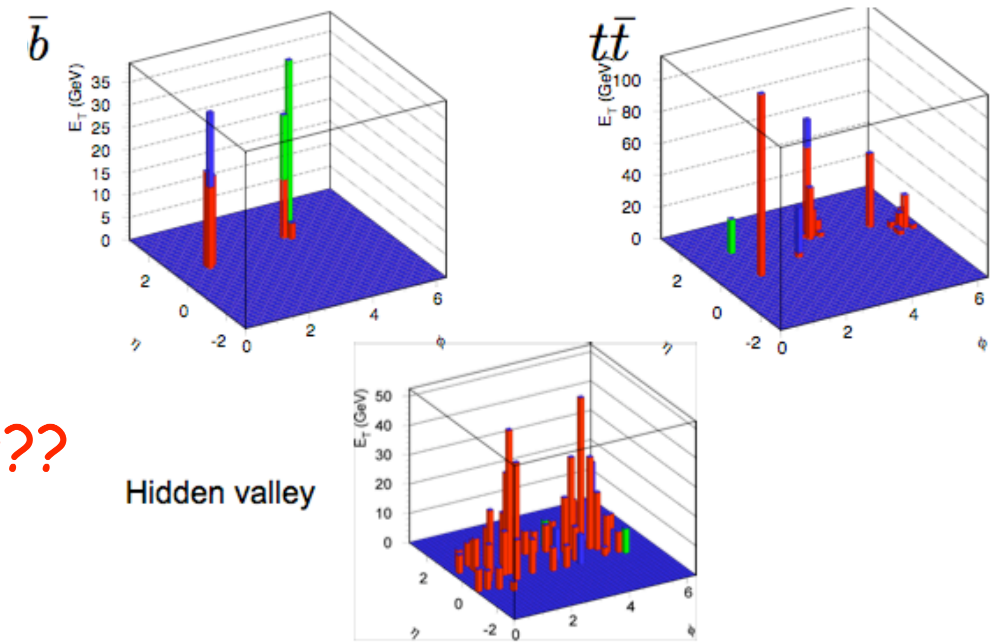
Discovery with only a few weeks running!

Hidden Valley Physics: New Signatures





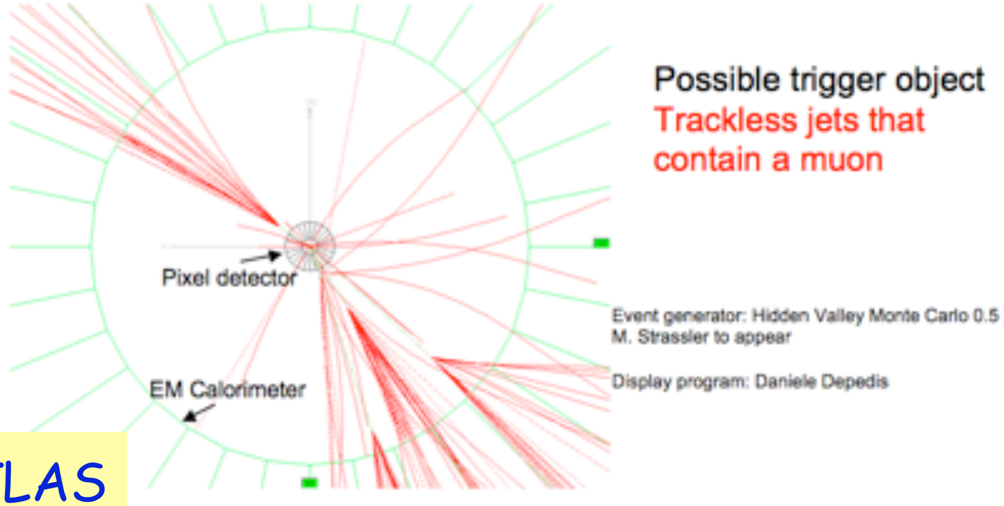
Will produce"Weird Jets" and a lot of secondary vertices



⇒ Difference with QCD jets??

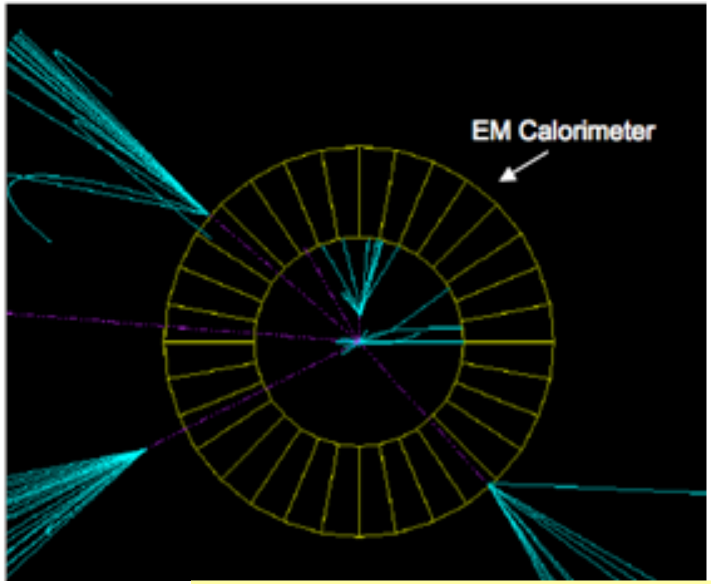
⇒ Study SM jet structure

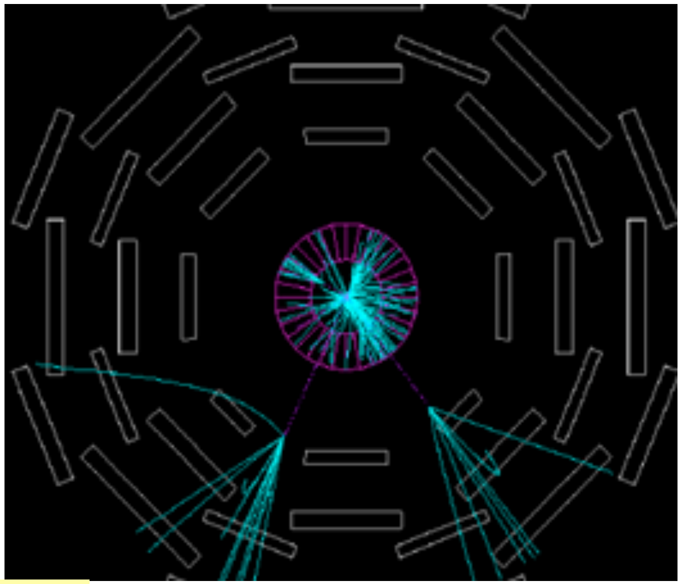
Hidden Valley Events



The experiments are not really prepared for this(*)
For example: Trigger problems for events with large displayed vertices

ATLAS





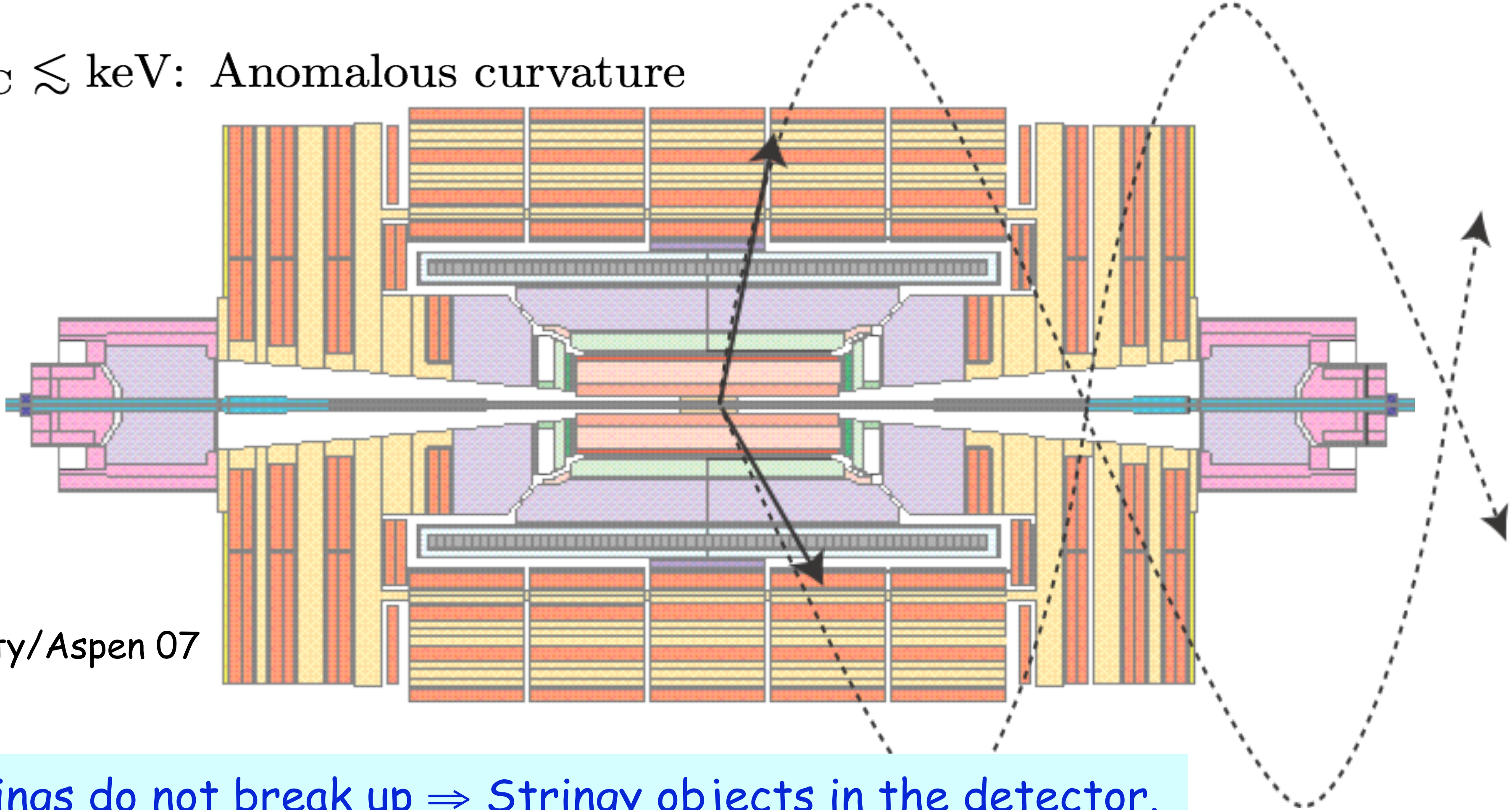
⇒Need special triggers

(*) except possibly LHCb

Macro-Strings at the LHC?

New strong interactions with small Λ & new quarks m_Q> several hundered GeV

$\Lambda_{IC} \lesssim$ keV: Anomalous curvature

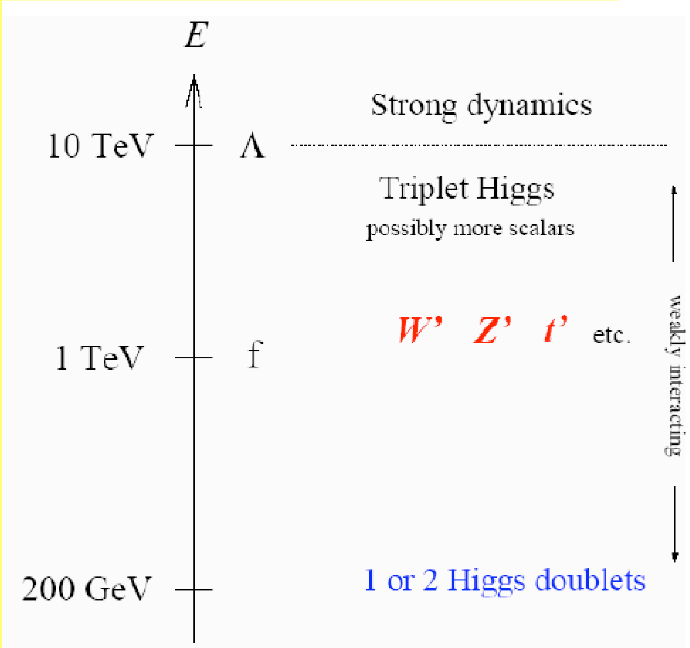


Markus Luty/Aspen 07

- Strings do not break up ⇒ Stringy objects in the detector.
- End points are massive quarks (quirks)
- The strings can oscillate⇒ strange signature in detectors

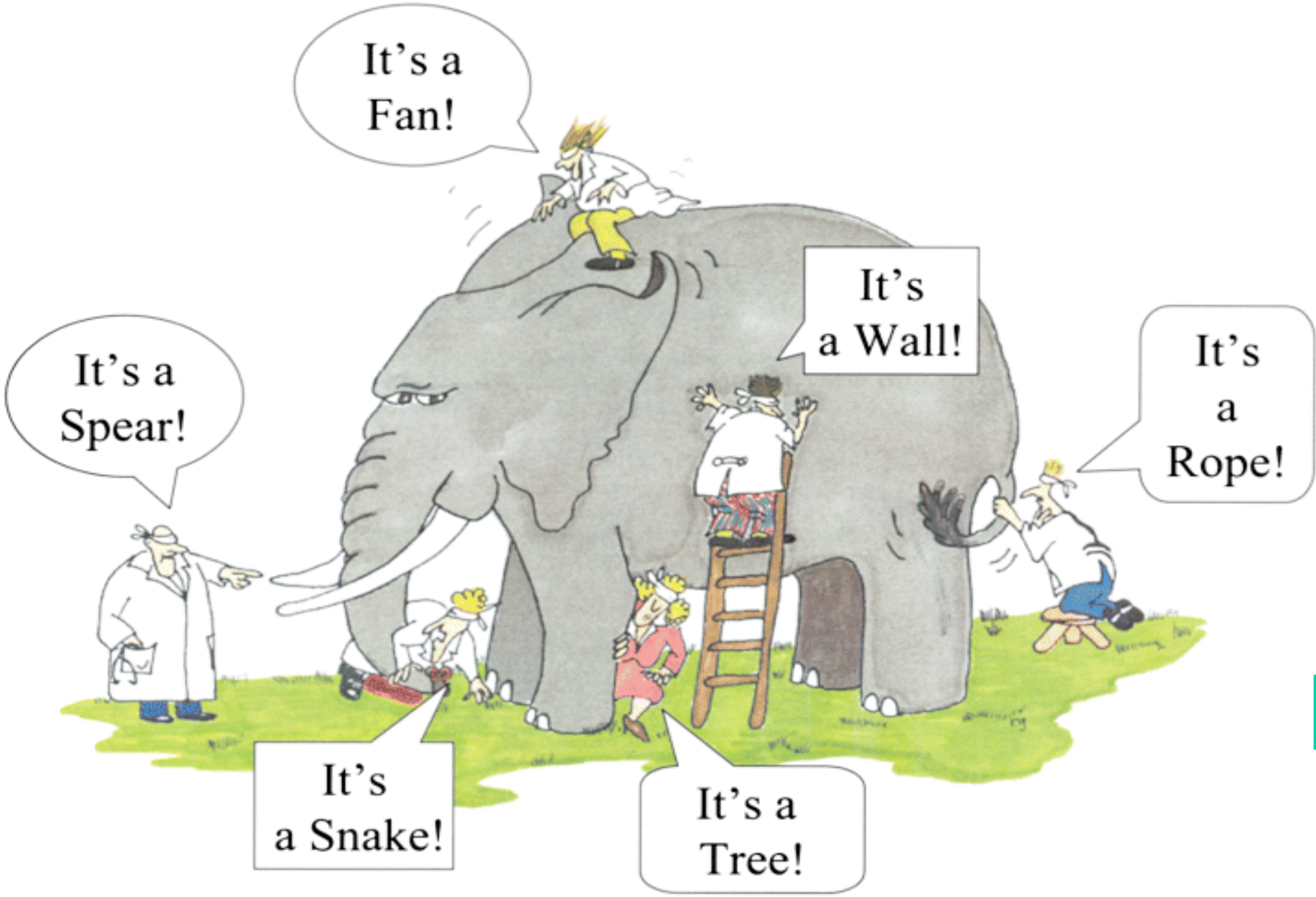
Other New Physics Ideas…

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Heavy Majorana Neutrinos
  - WW,WZ resonances
  - Unparticles
  - …



Have to keep our eyes open for all possibilities:
Food for many PhD theses!!

Since we do not know what we will find…



Nature.com

…we will look at it from all angles….

Close interaction between Experiment and Theory will be important

Tools & Theoretical Estimates

The LHC will be a precision and hopefully discovery machine
But it needs strong collaboration with theorists

Examples

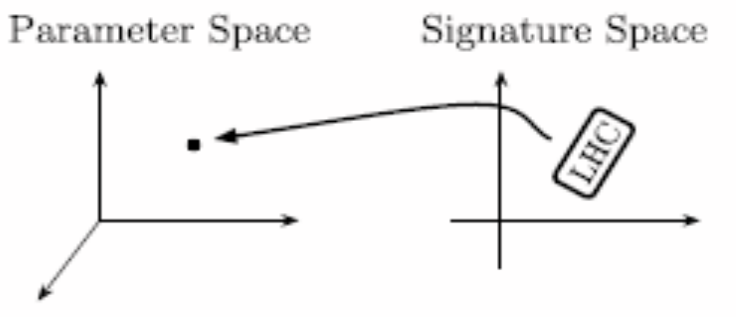
- Precision predictions of cross sections
- Estimates for backgrounds to new physics
- Monte Carlo programs (tuned) for SM processes: W,Z,t.. + njets and more..
- Monte Carlo programs for signals (ED's,…)
- Evaluation of systematics due to theory uncertainties
- Higher order calculations
- New phenomenology/signatures to look for
- Discriminating variables among different theories
- Getting spin information from particles
- Tools to interpret the new signals in an as model independent way as possible (MARMOSET, footprints?)
- …

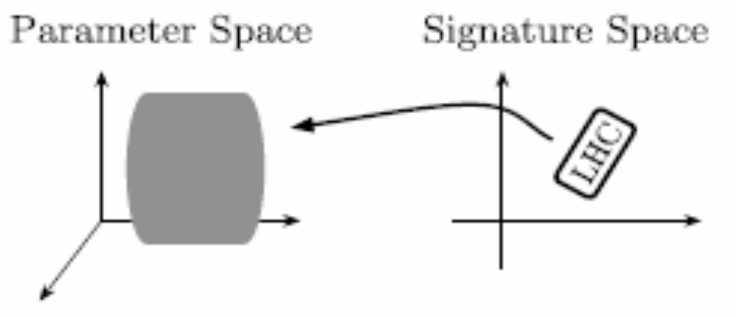
After the Champagne…

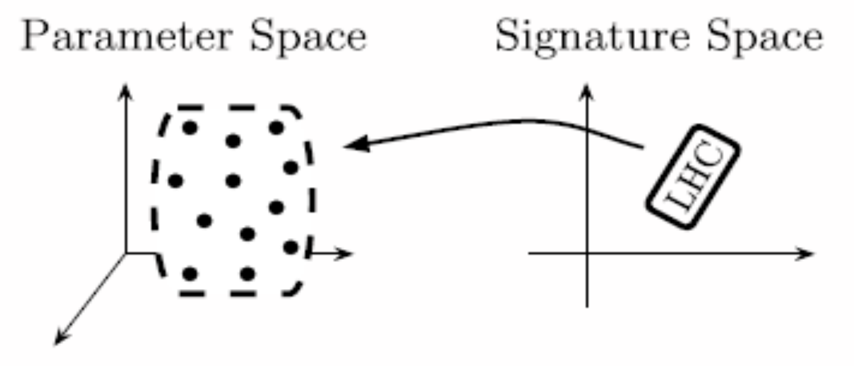
- WHEN new physics is discovered at the LHC, how well can we determine what it is? Does a specific experimental signature map back into a unique theory with a fixed set of parameters?

- Even within a very specific context, e.g., the MSSM, can one uniquely determine the values of, e.g., the weak scale Lagrangian parameters from LHC data alone?

The Inverse Mapping of Data: there are many possible outcomes….







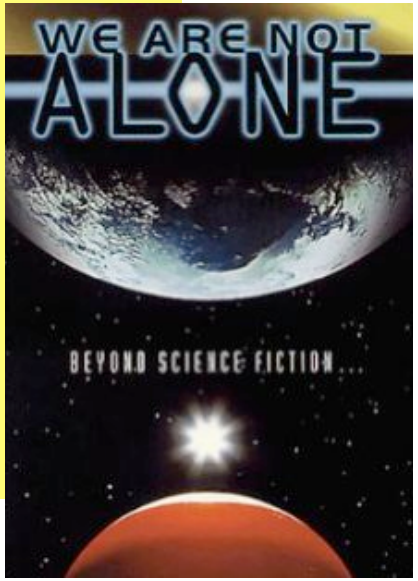
Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space… → model degeneracy

Arkani-Hamed, Kane, Thaler, Wang, hep-ph/0512190 + follow up papers

The efforts to understand the problems and design strategies - even before data- are very important!

We are not alone!

- LHC: LHCb has a complementary sensitivity to CMS/ATLAS for new physics.
  - Not yet explored in a systematic way
- Heavy flavor precision measurements (B-factories)
- g-2 new measurements (factor 5-10 improvement in O(5) years?)
- Dark matter hints from outer space (PAMELA/ATIC GLAST-Fermi..). The two CDMS events?
  - Wait until the dust settles…!
- New Collider?… not any time soon



Summary

- There is a plethora of new models for physics Beyond the Standard Model
  - Not all are equally well motivated
  - Main ones still Supersymmetry and Extra Dimensions
- Recent developments lead to expect signatures for which the "general purpose detectors" were not designed for (eg trigger, measurements of timing…)
  - Fear factor! Can we miss the signal??
  - So far:ATLAS and CMS are flexible enough
- Hence: the experiments are ready to go!!

And maybe not long from now ⇒

END