V. Poszukiwania cząstek Higgsa

Spontaniczne Łamanie Symetrii (EWSB)

CZĄSTKI HIGGSA

Higgs w Modelu Standardowym

Bezmasowe W i B oraz bezmasowe fermiony wymagają dodania członów masowych.

Te człony nie są niezmiennicze względem lokalnej grupy cechowania

$$\mathcal{L}_{SM} = \mathcal{L}_0 + \mathcal{L}_{mass}$$

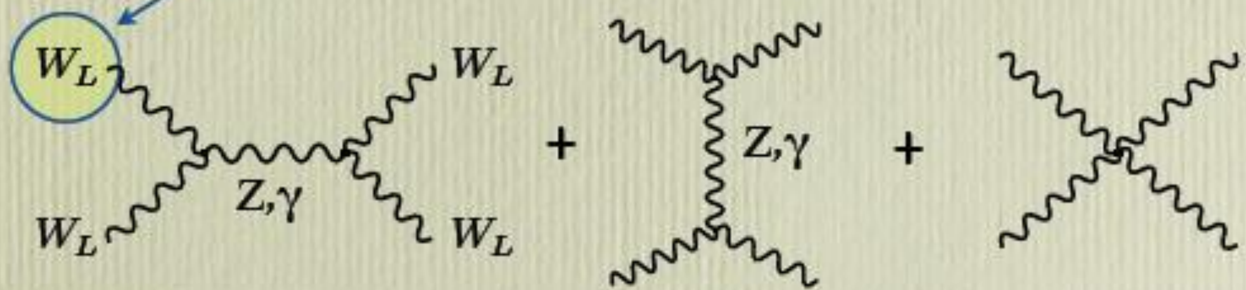
$$\mathcal{L}_0 = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \sum_{j=1}^{3}\left(\bar{\Psi}^{(j)}_L i\not{D}\Psi^{(j)}_L + \bar{\Psi}^{(j)}_R i\not{D}\Psi^{(j)}_R\right)$$

$$\mathcal{L}_{mass} = M^2_W\, W^+_\mu W^{-\,\mu} + \frac{1}{2}M^2_Z\, Z^\mu Z_\mu - \sum_{i,j}\left\{\bar{u}^{(i)}_L M^u_{ij} u^{(j)}_R + \bar{d}^{(i)}_L M^d_{ij} d^{(j)}_R + \bar{e}^{(i)}_L M^e_{ij} e^{(j)}_R + \bar{\nu}^{(i)}_L M^\nu_{ij} \nu^{(j)}_R + h.c.\right\}$$

The amplitude for scattering of longitudinal W's and Z's grows with the energy and eventually violates the unitarity bound:

Ex: $$A(W_L^+ W_L^- \to W_L^+ W_L^-) = \frac{g_2^2}{4M_W^2}(s+t)$$

each longitudinal polarization gives a factor E $$\epsilon_L^\mu = \frac{p^\mu}{M_W} + O\left(\frac{E}{M_W}\right)$$



Unitarity is violated at $\sqrt{s} \simeq \Lambda = 1.2\,\mathrm{TeV}$

EWSB within the Standard Model

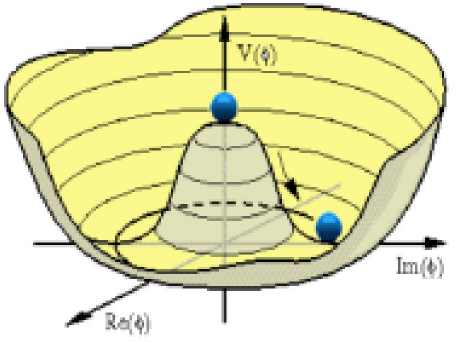
- The most economical way is to introduce a single scalar field:

  (T, T, Y)=(1, 1/2, 1/2) Higgs doublet

- Higgs self-interactions lead to:

$$V(\phi) = \mu^2 \phi^+ \phi + \lambda\, (\phi^+ \phi)^2;\ \mu^2 < 0,\ \lambda > 0$$

$$\langle \phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \qquad v = (\sqrt{2} G_F)^{-1/2} = 246\ \text{GeV}$$



- Fluctuations around <ϕ> are:

$$\phi(x) = e^{i\xi^a(x)\tau_a/2v} \begin{pmatrix} 0 \\ [v + H(x)]\,/\sqrt{2} \end{pmatrix}$$

- Particles generated by $\xi^a(x)$ will constitute the longitudinal degrees of freedom of the weak gauge bosons, whereas H(x) will become the neutral Higgs boson.
- Yukawa Interactions of ϕ(x) with fermions generate their masses and in general flavor physics: CKM matrix and thus, CP-violation.

  The Higgs mass is not predicted!

$$m_H^2 = 2\lambda v^2$$
$$m_W^2 = g^2 v^2 / 4$$
$$m_Z^2 = (g^2 + g'^2) v^2 / 4$$
$$m_l = \lambda_l v / \sqrt{2}$$
$$m_q = \text{eigenvalue}(\lambda_Q) v / \sqrt{2}$$

3

Problem hierarchii i naturalność

The physical Higgs mass is set by the quartic coupling, which is a running parameter $m_h^2 = 2\lambda_4 v^2$

$$16\pi^2 \frac{d}{d\log Q}\lambda_4 = 24\,\lambda_4^2 - \left(3g'^2 + 9g^2 - 12y_t^2\right)\lambda_4 + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 6\,y_t^4 + \cdots$$

- For a too heavy Higgs, the first term dominates and drives λ_4 to a Landau pole at large energy scales

$$m_h^2 \lesssim \frac{4\pi^2 v^2}{3\log(\Lambda/v)}$$

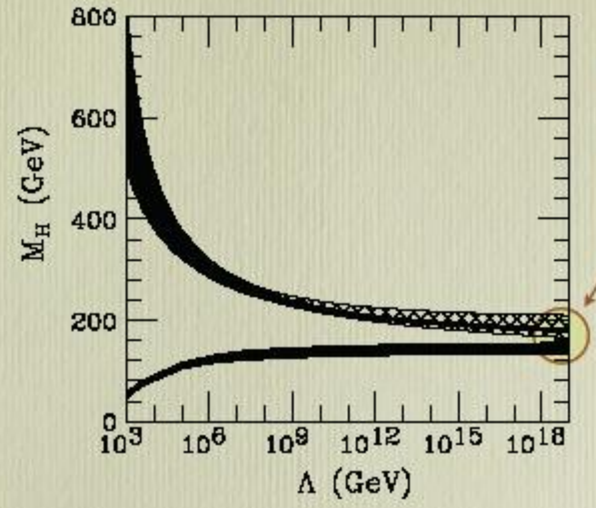
TRIVIALITY BOUND

largest scale of validity of the theory (cutoff scale)

- For a too small Higgs, the last term dominates and drives λ_4 negative at large energy scales

$$m_h^2 \gtrsim \frac{3y_t^4 v^2}{4\pi^2}\log(\Lambda/v)$$

VACUUM STABILITY BOUND



perturbativity up to the Planck scale requires

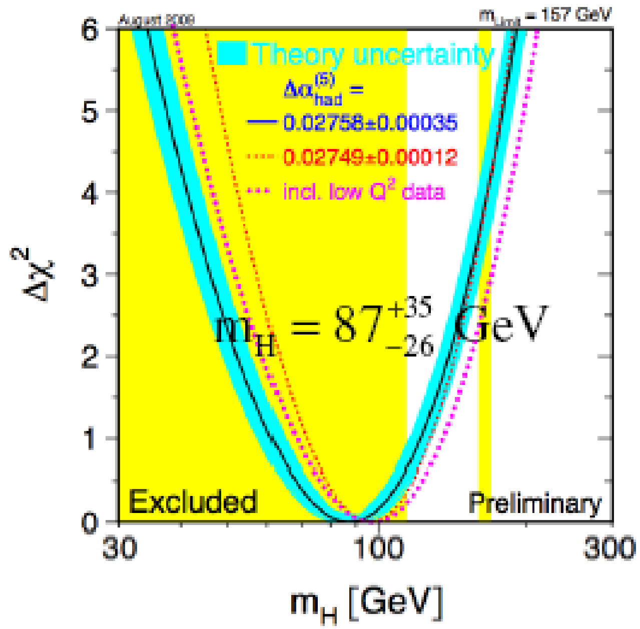
$m_h < 180\,\mathrm{GeV}$

$\Lambda = 10^{19}\,\mathrm{GeV}$

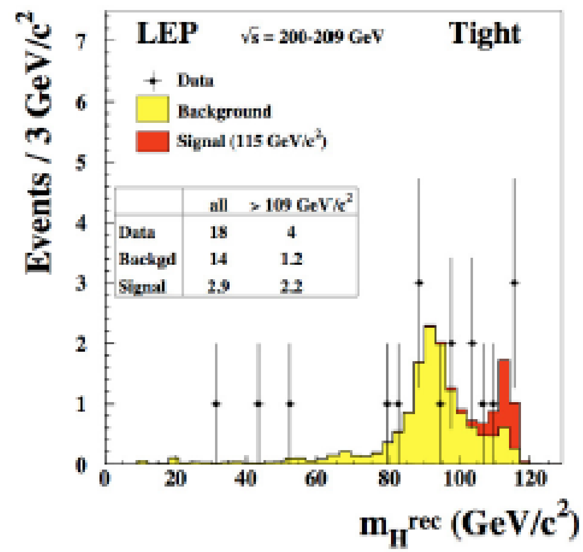
from: T. Hambye, K. Riesselmann Phys Rev, D55 (1997) 7255

Stalking the Higgs Boson

Indirect constraints
- Precision EW observables at the one-loop level.



Direct searches at LEP
- Tantalizing hints (~1.7σ) of a SM-like Higgs boson with m_H~115 GeV:



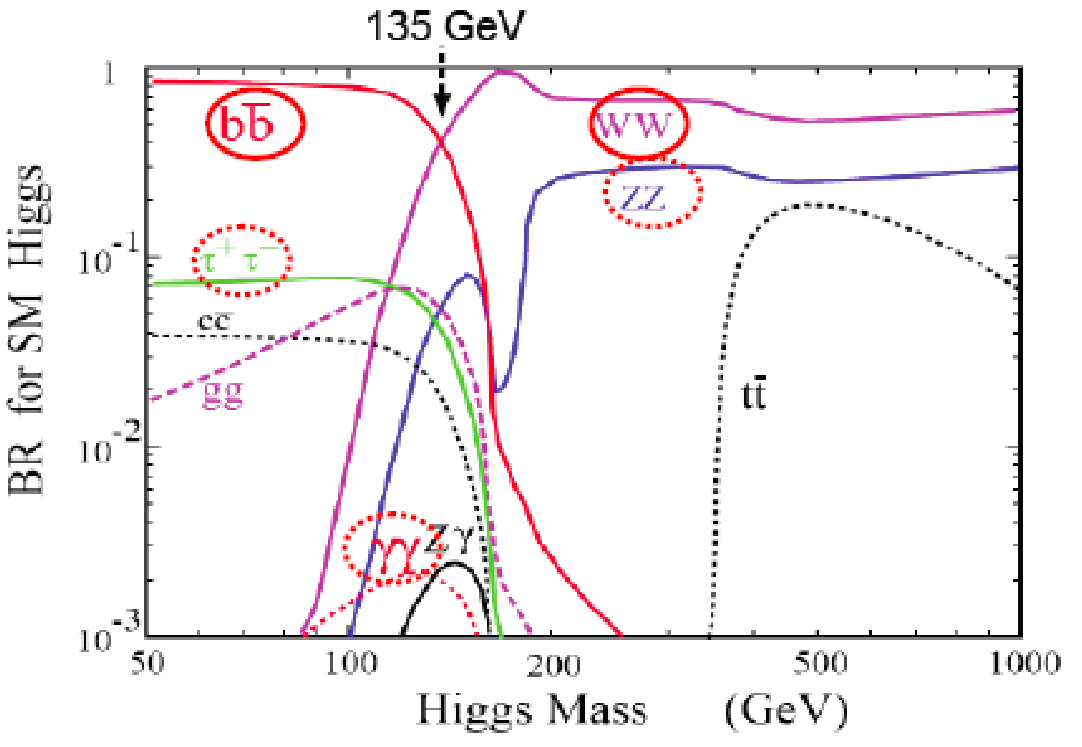
Kinematic limit: $\sqrt{s}-m_Z$~115.4 GeV

m_H< 157 GeV (95% CL)	m_H> 114.4 GeV (95% CL)

114.4 < m_H< 186 GeV (95% CL)

4

SM Higgs Decay Modes



➔ Many decay modes being explored to increase the sensitivity of the search to both a SM and non-SM Higgs boson!

Higgsy w Modelu Standardowym i SUSY

MS:

H^0 skalarny higgs o nieznanej masie

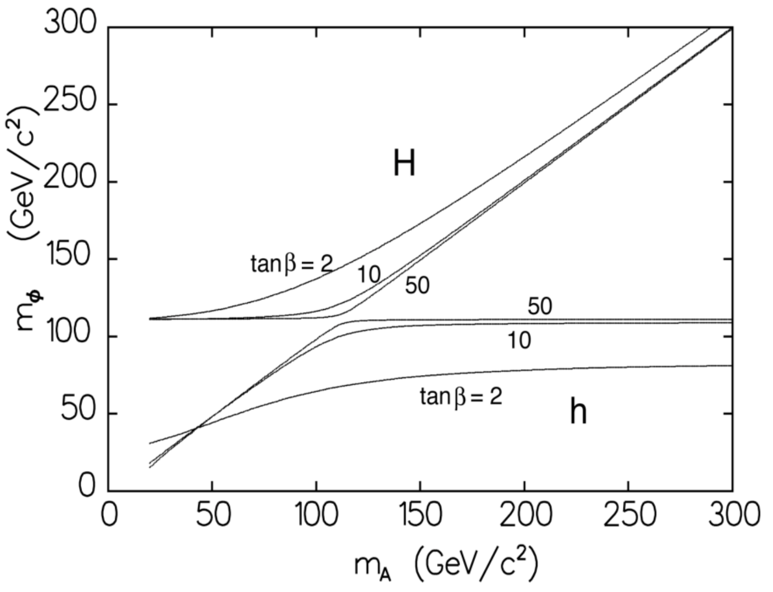
SUSY MSSM:

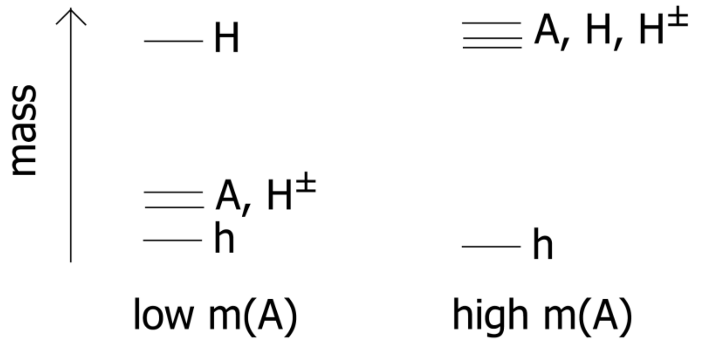
5 cząstek higgsa

h^0, H^0, $H^{\pm}$-- $J^P=0^+$

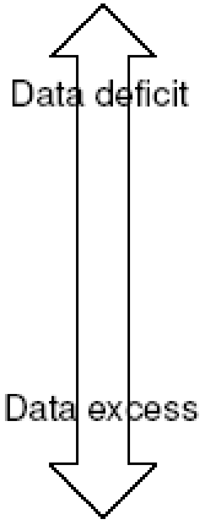
A^0-- $J^P=0^-$

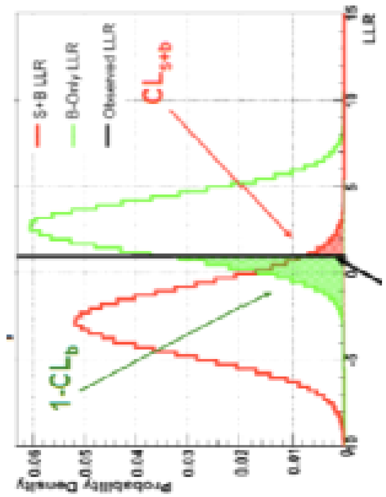
Własności h^0 podobne do higgsa MS, ale słabsze sprzężenia

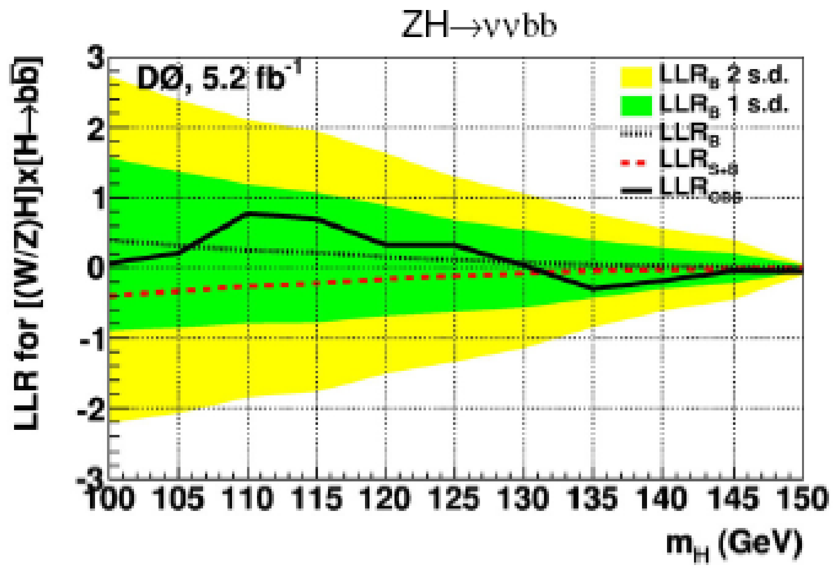

H
h
tanβ = 2
10
50
50
10
tanβ = 2
m_ϕ (GeV/c^2)
m_A (GeV/c^2)
0
50
100
150
200
250
300


mass
H
A, H$^\pm$
h
A, H, H$^\pm$
h
low m(A)
high m(A)

Interpreting the Data







- Dashed lines show S+B and B-only mean value.
- Shaded bands indicate 1 and 2σ variation of B-only distribution
- Solid black line indicates **data observation**

The breaking of gauge invariance is in fact a fake: the symmetry is just hidden

$\rho = 1$ follows from a larger global SU(2)$_L$xSU(2)$_R$ approximate invariance

$$\Sigma \to U_L \, \Sigma \, U_R^\dagger$$

broken only by g_1 and $\lambda^u \neq \lambda^d$

$$\Sigma = \exp\left(i\sigma^a \chi^a / v\right)$$

$$D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

$$\mathcal{L}_{mass} = \frac{v^2}{4} \mathrm{Tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right] - \frac{v}{\sqrt{2}} \sum_{i,j} (\bar{u}_L^{(i)} \, \bar{d}_L^{(i)}) \Sigma \begin{pmatrix} \lambda_{ij}^u u_R^{(j)} \\ \lambda_{ij}^d d_R^{(j)} \end{pmatrix} + h.c.$$

$$+ a \, v^2 \, \mathrm{Tr}\left[\Sigma^\dagger D_\mu \Sigma T^3\right]^2$$

In fact, an additional term that breaks the LR symmetry has been omitted as $\rho_{exp} \simeq 1$

- The SU(2)$_L$xU(1)$_Y$ symmetry is now manifest, although non-linearly realized

$$\Sigma \to U_L \, \Sigma \, U_Y^\dagger \qquad U_L(x) = \exp(i\,\alpha_L^a(x)\sigma^a/2) \quad U_Y(x) = \exp(i\,\alpha_Y(x)\sigma^3/2)$$

- In the unitary gauge $\langle\Sigma\rangle = 1$, $\mathcal{L}_{mass}$ is equal to the original mass Lagrangian with

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1$$

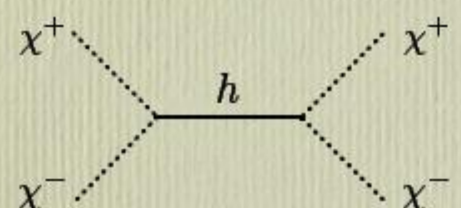
Sektor Higgsa unitaryzuje rozpraszanie $W_L W_L$

The most economical EWSB sector consists of 1 scalar field singlet under the $SU(2)_L xSU(2)_R$ (and the local $SU(2)_L xU(1)_Y$) symmetry :

$$\mathcal{L}_{EWSB} = \frac{v^2}{4}\mathrm{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right] + a\frac{v}{2}\, h\, \mathrm{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right] + b\frac{1}{4}\, h^2\, \mathrm{Tr}\left[D_\mu \Sigma^\dagger D^\mu \Sigma\right] + V(h)$$

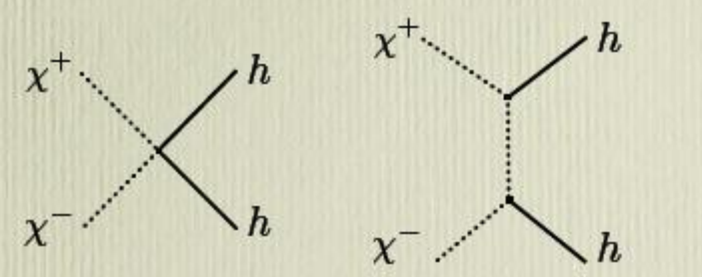
a and b are free parameters

- For a=1 the scalar exchange unitarizes the WW scattering



$$A(\chi^+\chi^- \to \chi^+\chi^-) = \frac{1}{v^2}\left[s - \frac{a\, s^2}{s - m_h^2} + (s \leftrightarrow t)\right]$$

- For b=1 also the inelastic channels respect unitarity



a=b=1 defines the Higgs Model, whose Lagrangian can be rewritten in the standard form in terms of the $SU(2)_L$ doublet

$$H = \frac{1}{\sqrt{2}} e^{i\sigma^a \chi^a / v} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

Unitarity of the Higgs Model can be traced back to its renormalizability

There is an unbroken custodial symmetry SO(3) preserved by the Higgs vev that leads to $\rho = 1$

$$H = \begin{pmatrix} w_1 + i\, w_2 \\ w_3 + i\, w_4 \end{pmatrix} \qquad H^\dagger H = \sum_i (w_i)^2$$

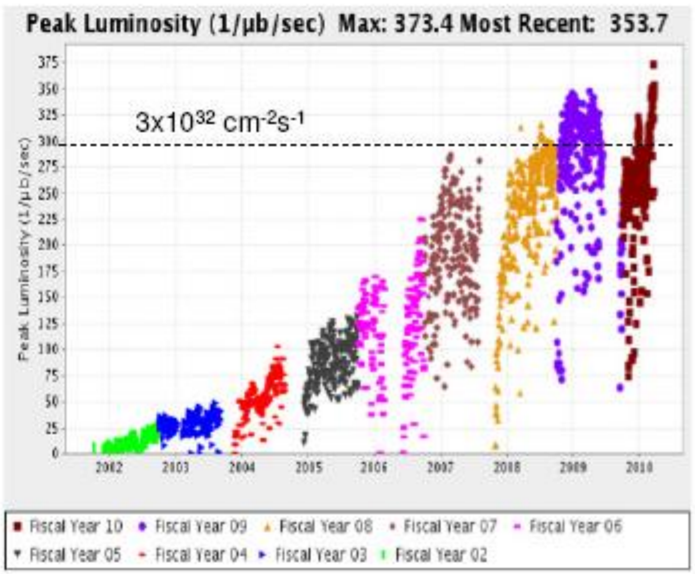
$V(H^\dagger H)$ is $SO(4) \sim SU(2)_L \times SU(2)_R$ invariant

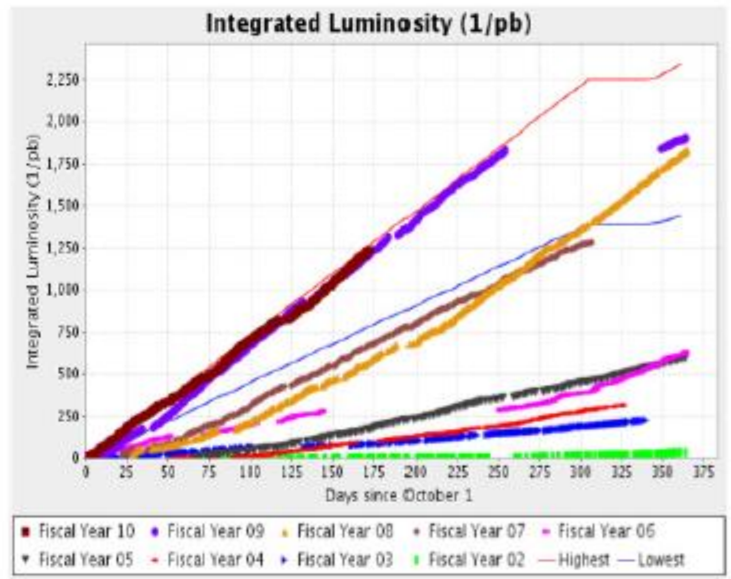
$\langle H^\dagger H \rangle = v^2$ breaks $SO(4) \rightarrow SO(3)$

Poszukiwanie higgsów w TeVatronie

Aurelio Juste
ICREA and IFAE (Barcelona)

Tevatron Accelerator



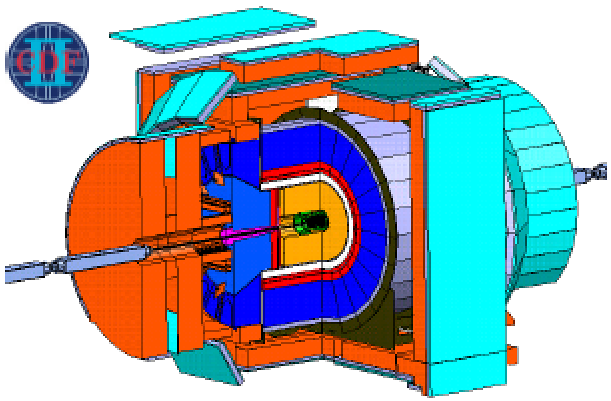


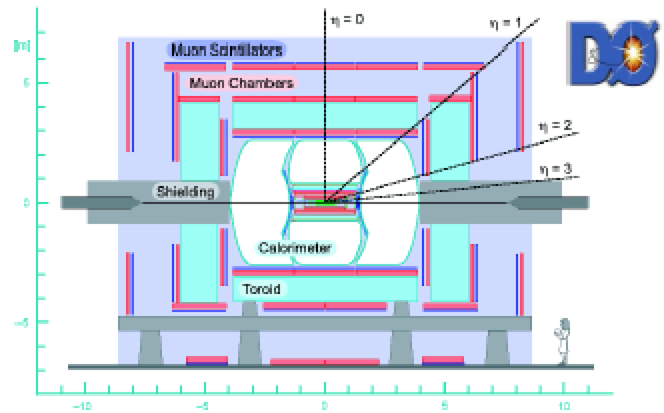
Excellent performance:

- Typical instantaneous luminosity: >$3x10^{32}$ $cm^{-2}s^{-1}$
- Integrated lum./week: ~60 pb^{-1} ➔ equiv. Run I dataset every 2 weeks!
- Can deliver ~2-2.5 fb^{-1}/year.

Detektory

CDF and DØ Detectors



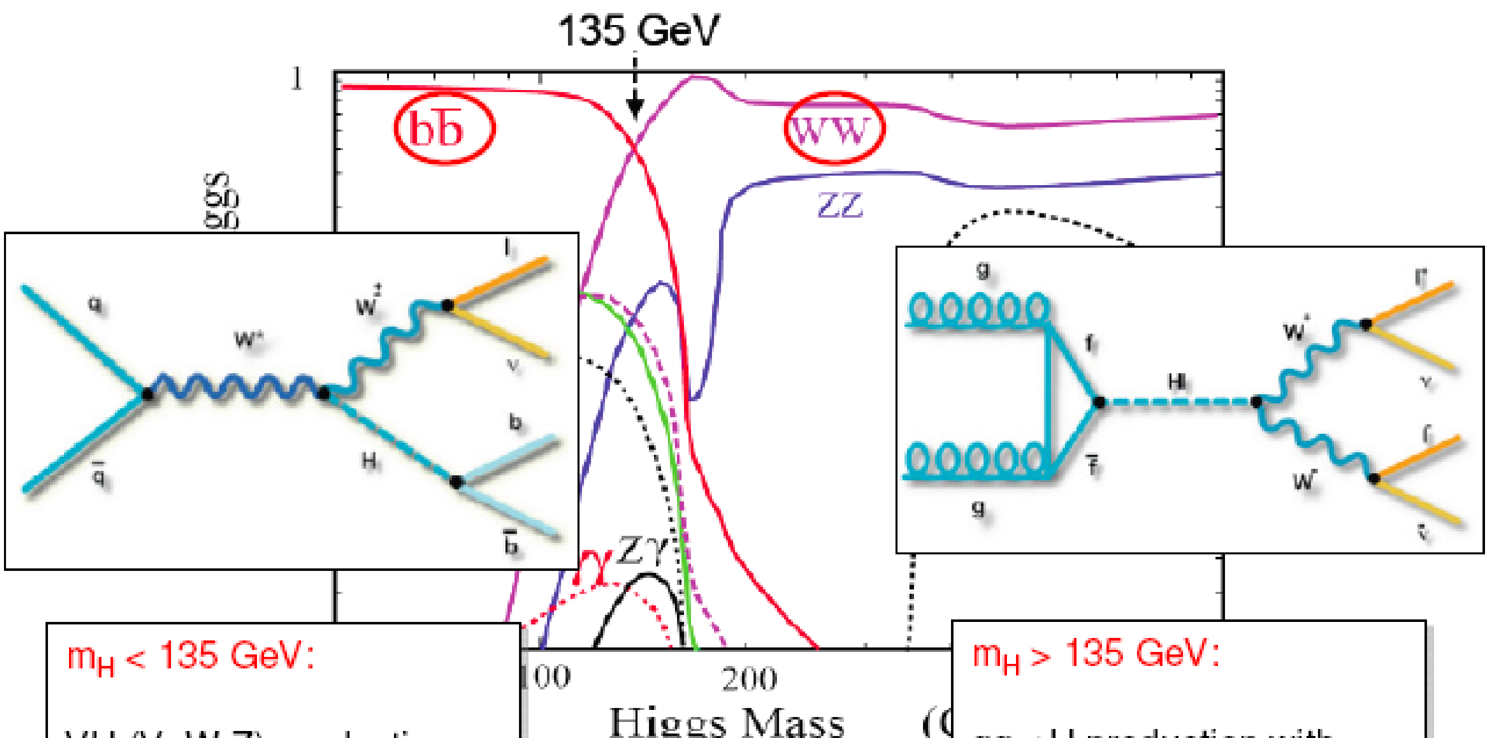


Multipurpose detectors:

- Central tracking system embedded in a solenoidal magnetic field:
  - Silicon vertex detector
  - Tracking chamber (CDF)
    Fiber tracker (DØ)
- Preshowers
- Electromagnetic and hadronic calorimeters
- Muon system

- All detector subsystems expected to survive till the end of the run.
  No further upgrades, stable triggers.
- Data taking efficiency: ~85-90%

Search Strategy at the Tevatron



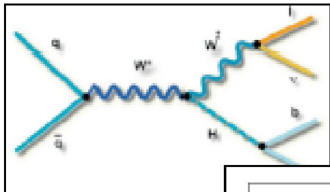
m_H < 135 GeV:

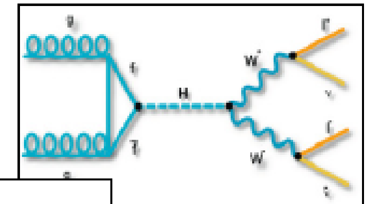
VH (V=W,Z) production with H→bb decay

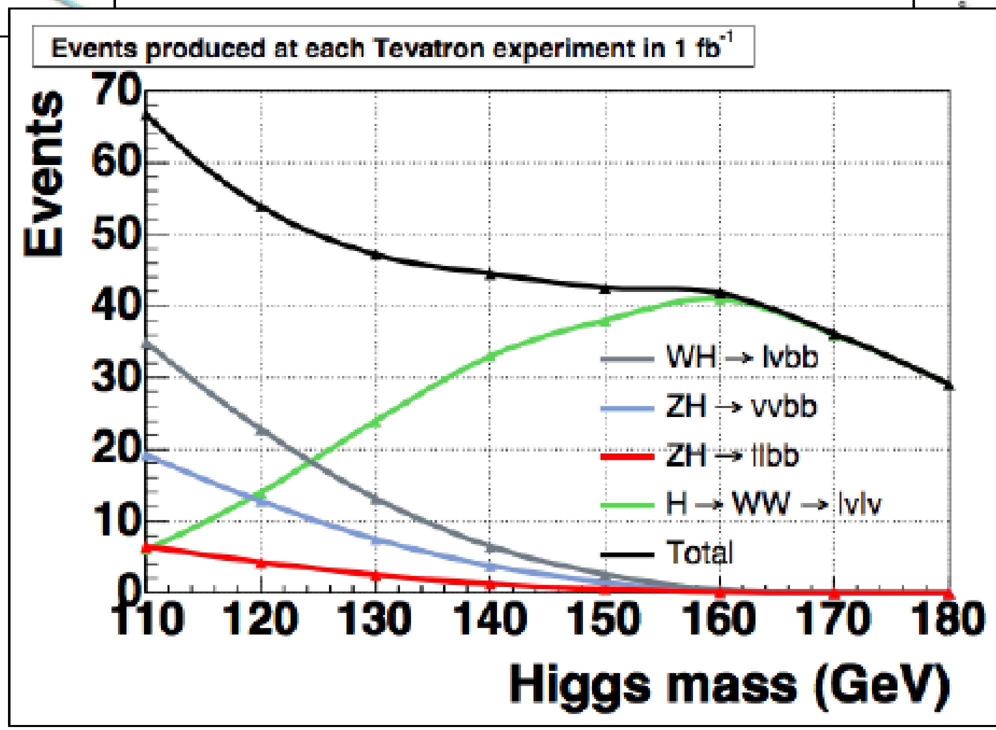
m_H > 135 GeV:

gg→H production with H→WW→lνlν decay

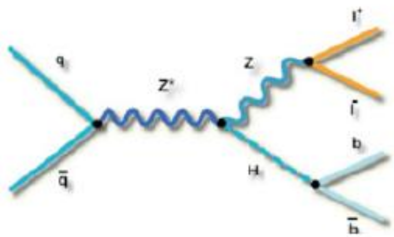
Search Strategy at the Tevatron



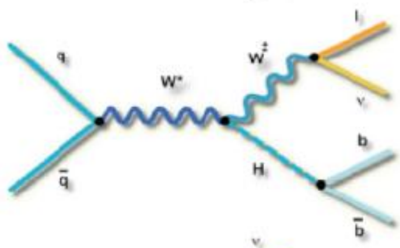




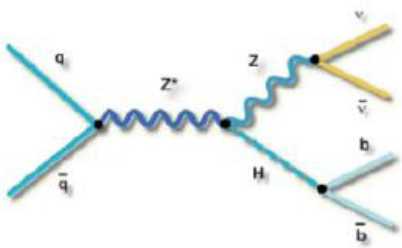
Low Mass SM Higgs Searches



ZH→llbb: dilepton+2 b-jets
Smallest signal rate
Smallest background
Kinematically constrained

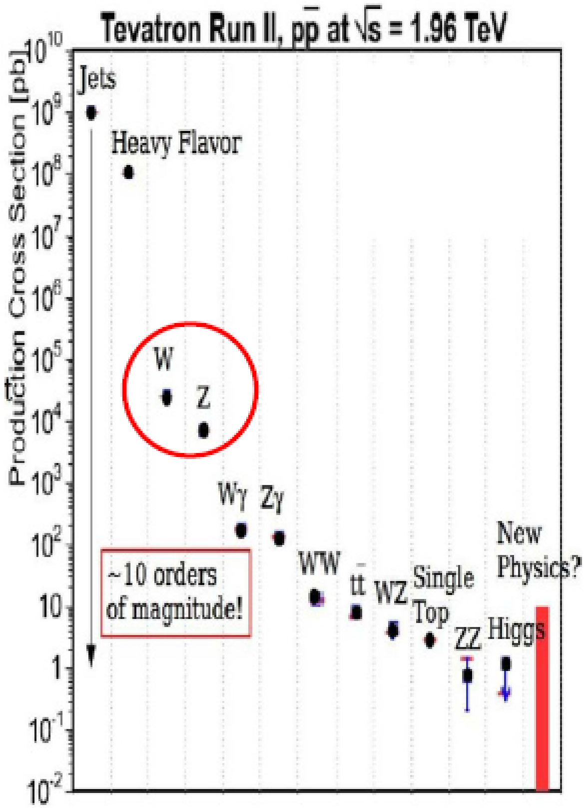


WH→lνbb: lepton+MET+2 b-jets
Largest signal rate
Larger V+jets background

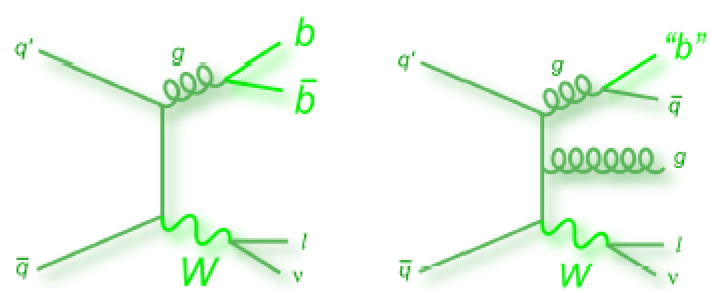


ZH→lνbb: MET+2 b-jets
Comparable signal rate to WH
(significant contribution from
WH→lνbb with missing lepton)
Challenging instrumental background

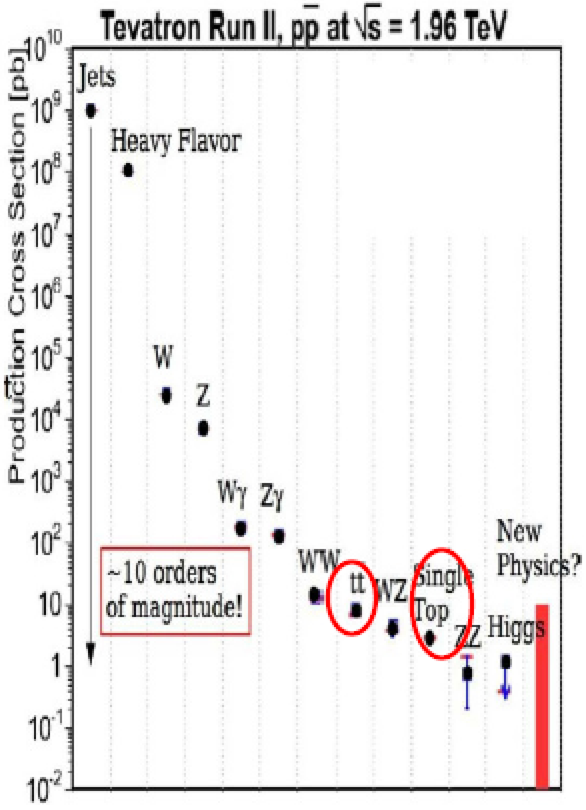
Backgrounds are Ferocious



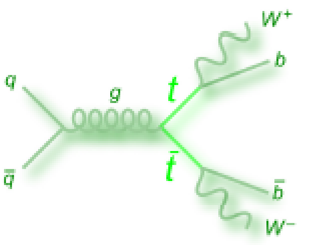
- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)

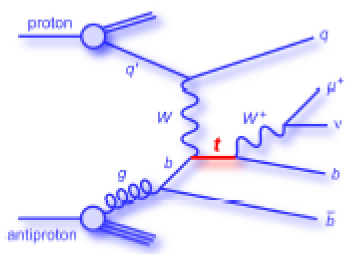


Backgrounds are Ferocious



- Instrumental backgrounds: measured directly from data
  - QCD multijet production with mismeasured jets leadings to missing transverse energy or jets misidentified as leptons.
- Physics backgrounds: estimated using simulation and state-of-art theoretical predictions
  - W/Z+jets production (w/ real or misidentified heavy flavor jets)
  - Diboson production
  - Double and single top quark production



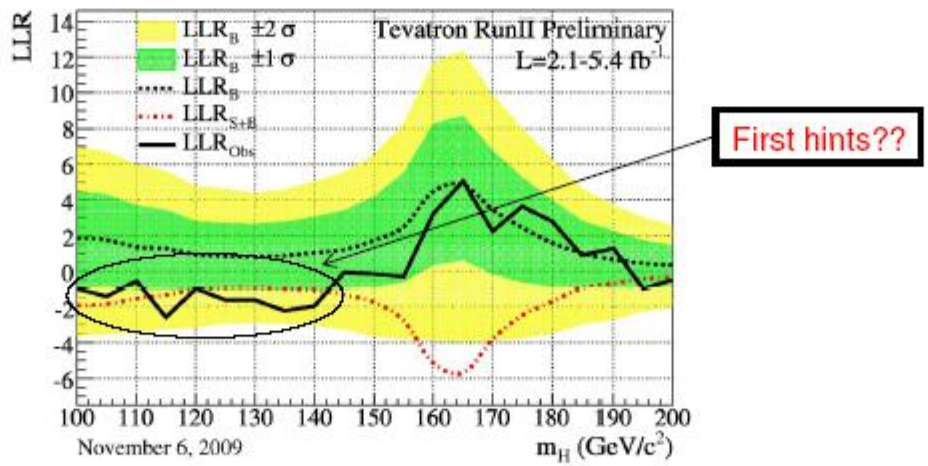


21

➔ Further constrain data modeling in "sideband regions"

Conclusions

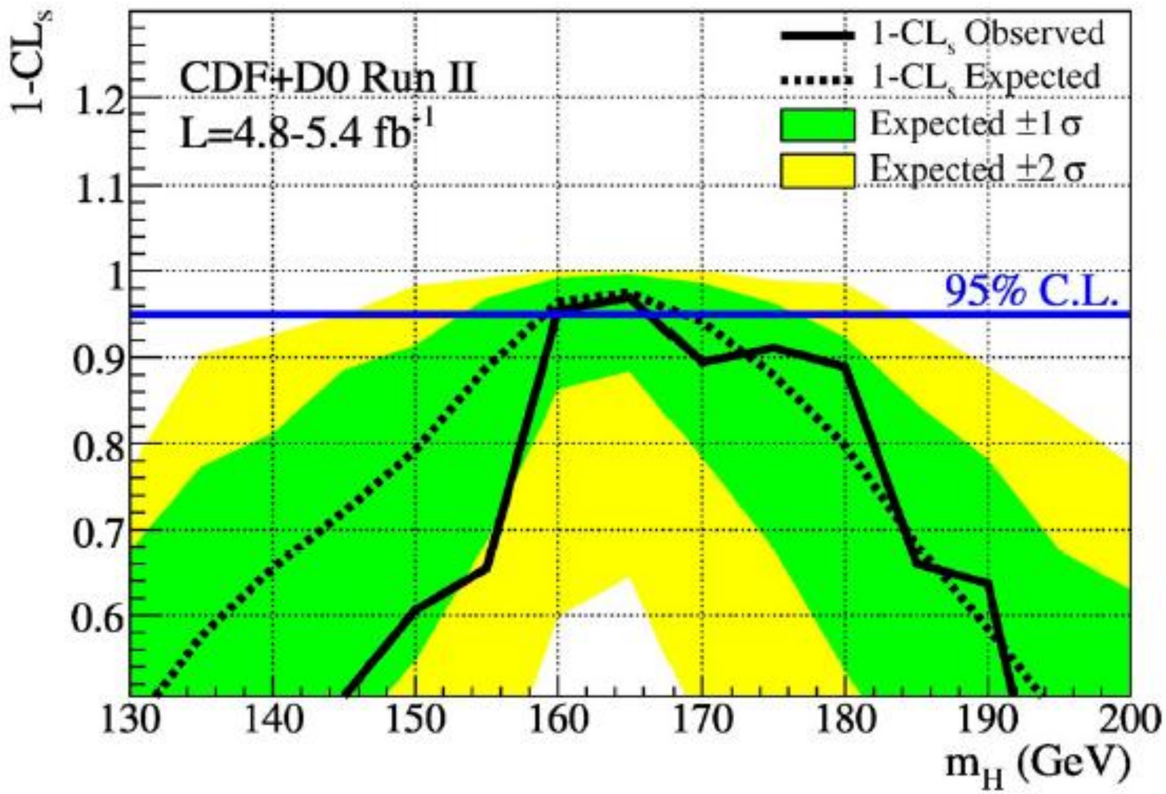
- The Tevatron Higgs program continues to make steady progress in sensitivity thanks to the excellent performance of the accelerator and detectors and continued improvements in algorithms and analysis techniques.



- With 10 fb^{-1}/exp + additional improvements underway expect to be able to exclude at 95% C.L. up to m_H~185 GeV (if the Higgs doesn't exist)….
… or we may have first evidence!

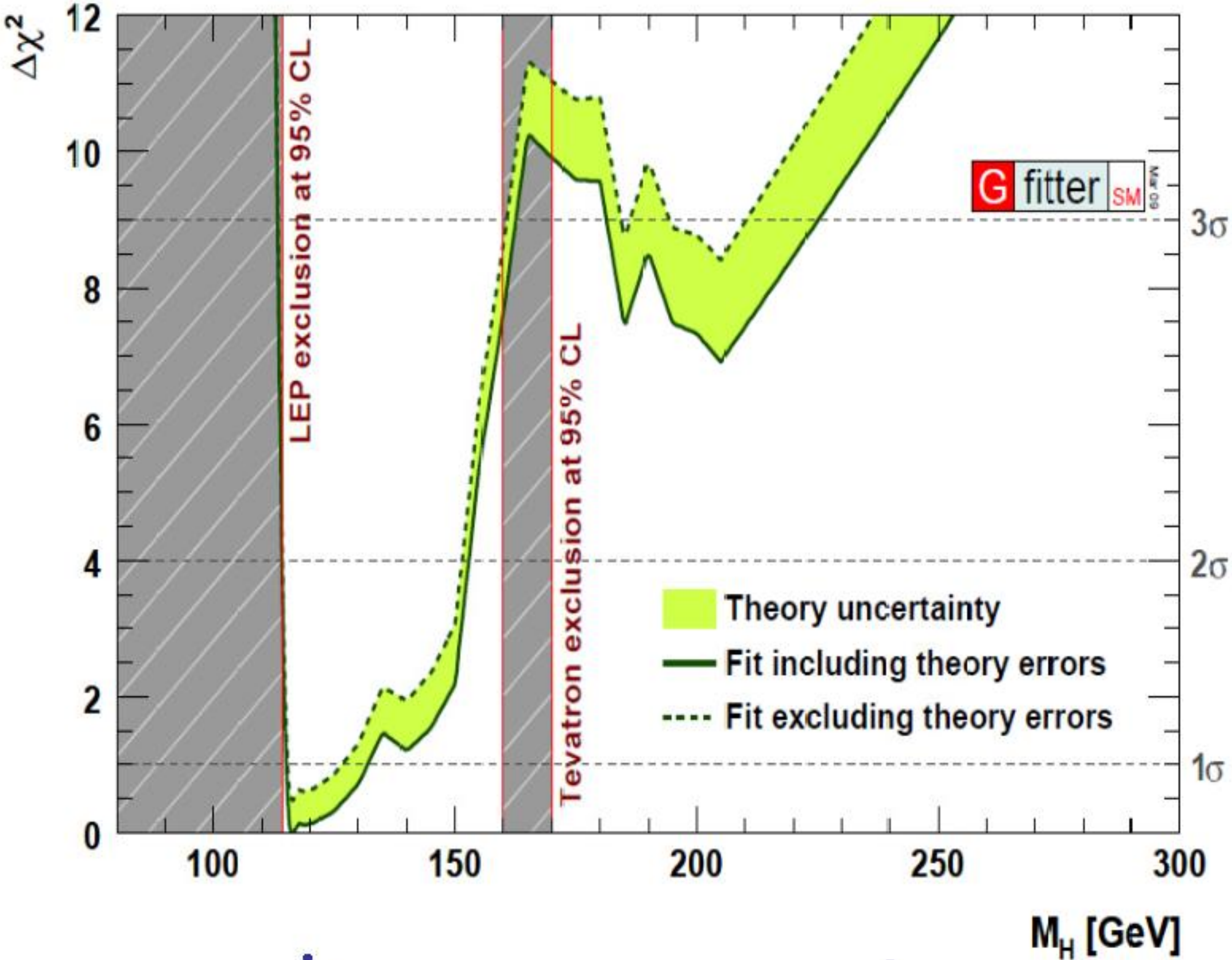
Exciting prospects for concurrent analysis of Tevatron and LHC data!

Exclusion Probability vs m_H

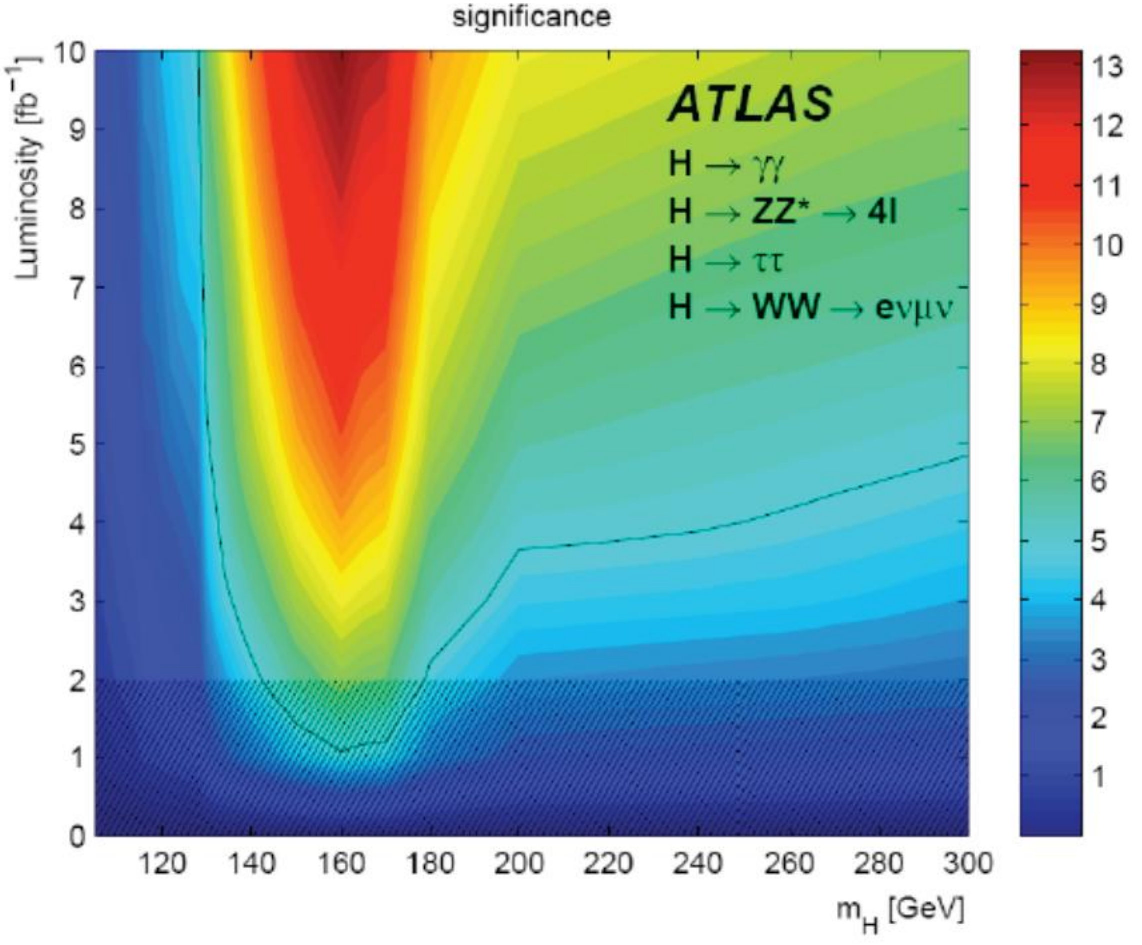


Still, 160-170 GeV excluded ≥90% C.L.

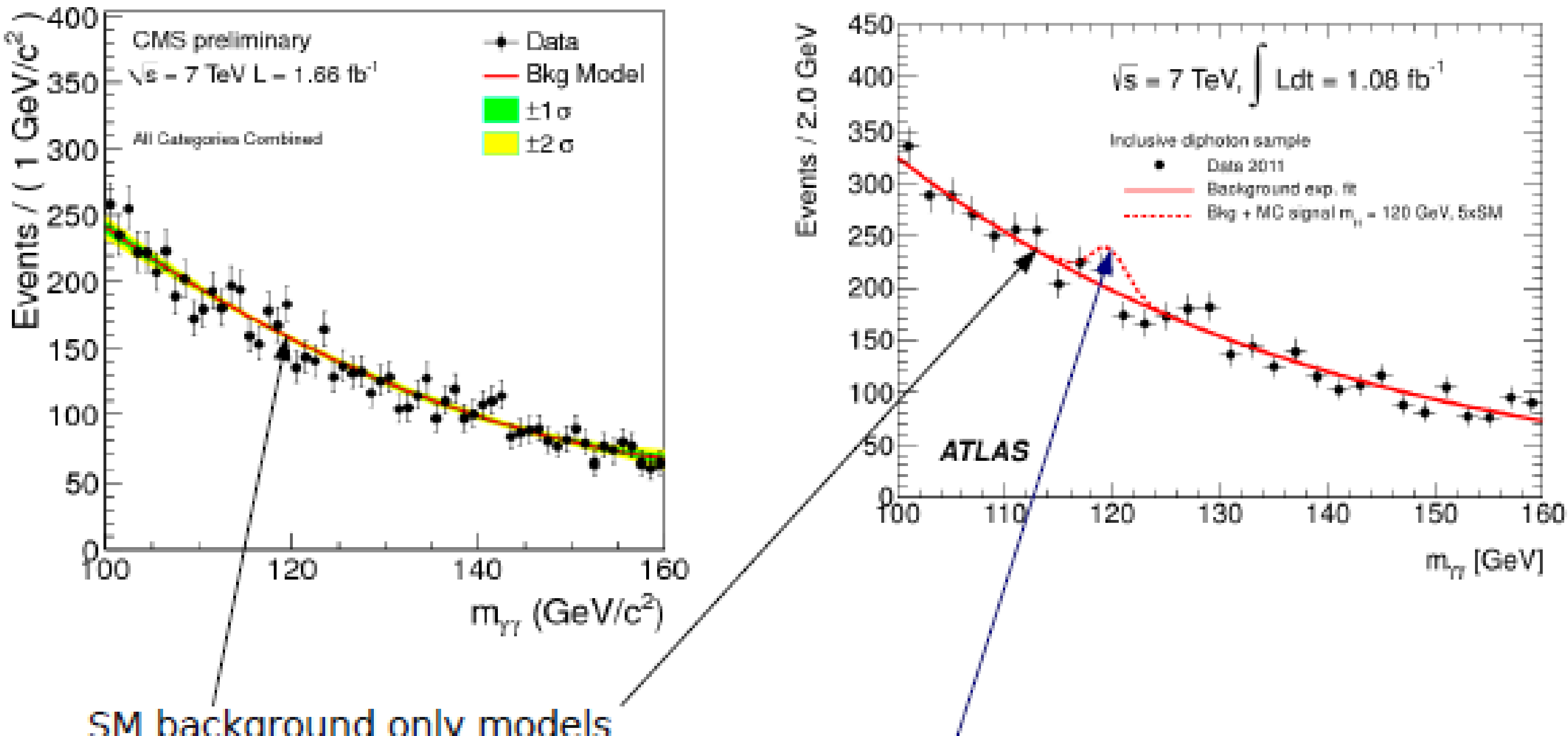
As the a-priori sensitivity continues to improve, it will become more stable. 77



$\Delta\chi^2$
12
10
8
6
4
2
0
100
150
200
250
300
M_H [GeV]
LEP exclusion at 95% CL
Tevatron exclusion at 95% CL
G fitter SM
3σ
2σ
1σ
Theory uncertainty
Fit including theory errors
Fit excluding theory errors


significance
Luminosity [fb^{-1}]
10
9
8
7
6
5
4
3
2
1
0
120
140
160
180
200
220
240
260
280
300
m_H [GeV]
ATLAS
$H \to \gamma\gamma$
$H \to ZZ^* \to 4l$
$H \to \tau\tau$
$H \to WW \to e\nu\mu\nu$
13
12
11
10
9
8
7
6
5
4
3
2
1

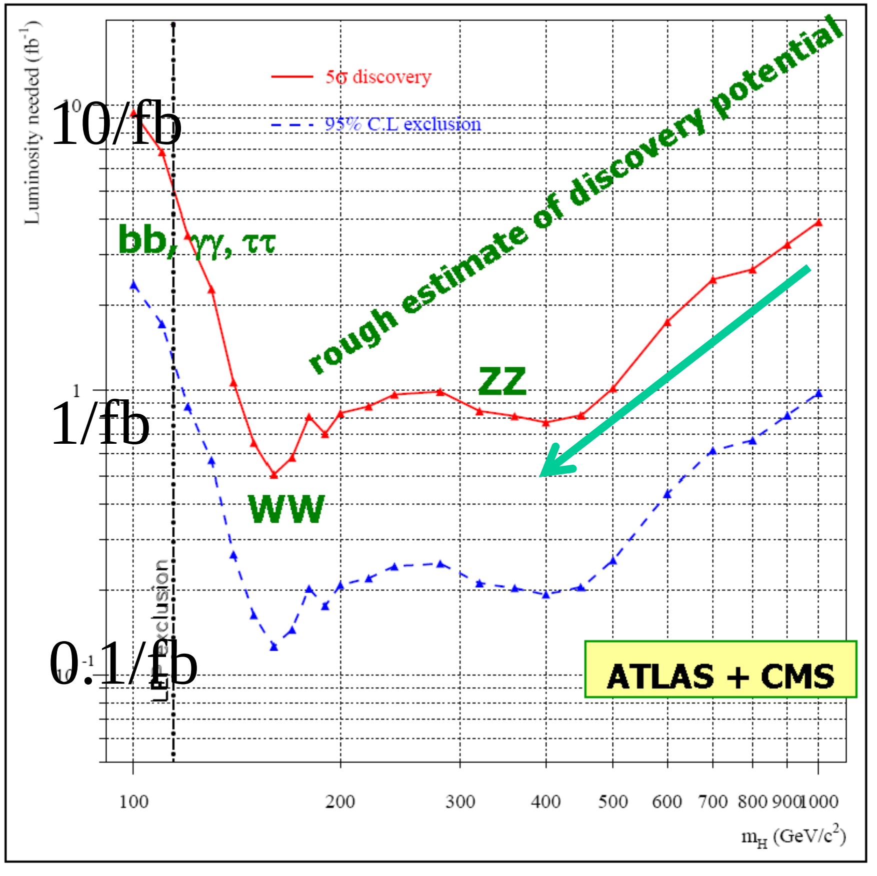
Searches in γγ final state



SM background only models

SM background Higgs boson with m_H=120 GeV/c²,
assuming **5x larger cross section than SM expectation**

ODKRYCIE HIGGSA z>5



$$z = \frac{S}{\sqrt{B}} \propto \sqrt{\int L dt}$$

Znaczoność sygnału wzrasta ze scałkowaną świetlnością *L*.

***L* (2009-2010) ~200-250 /pb=**

= 0.20-0.25 /fb

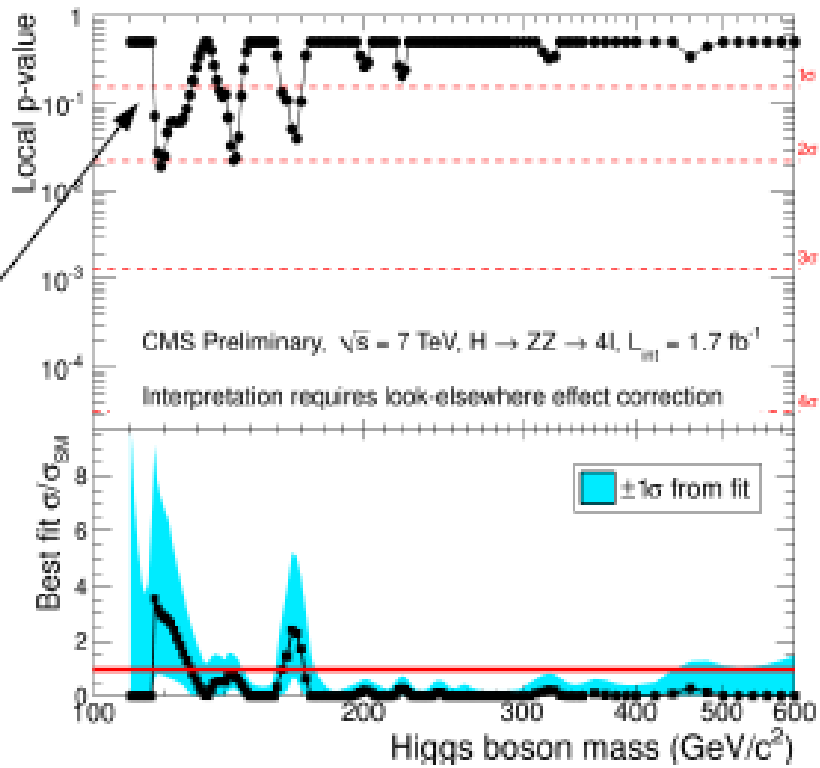
Search statistics

- q – test statistics
- $P(q_\mu > q_\mu^{obs} | \mu s(\theta_\mu^{obs}) + b(\theta_\mu^{obs}))$ – "p-value", probability, that value of q could be greater than the value observed, assuming some model, **parametrised with signal strength μ,** and set of nuisance parameters θ
- **μ = 0** - background only hypothesis
- **μ = 1** - SM signal+background hypothesis

$$CL_S = \frac{P(q_\mu \geqslant q_\mu^{obs} | \mu * s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs}))}{P(q_\mu \geqslant q_\mu^{obs} | b(\hat{\theta}_0^{obs}))}$$

Word of caution: LEE

- we are looking at wide mass range divided in many bins
- probability of upward fluctuation in each bin can be small
- **but given many bins, global probability of observing upward fluctuation can be significant**
- the effect is called "look elsewhere effect", or "trial factor"



- for H→ZZ→4l CMS estimates the trial factor of order of 100
- **local probability for background-only should be multiplied by a factor of order 100**
- For local p~0.01, Z_{max}~2.3 with LEE we get globally p~0.4, Z_{global}~0.25

Test statistics q

- **For $CL_s < \alpha$ we claim than signal existence is excluded at 1-α confidence level**
- The CL_s method is conservative, i.e the real confidence level is larger than 1-α

- As LHC a **profile likelihood ratio** is used as a test statistics for hypothesis verification
- The **profile likelihood ratio** is a bit different method than ratio of profiled likelihoods used at Tevatron, or simple likelihood ratio used at LEP

Likelihood

$$L = Poisson(data | \underbrace{\mu * s(\theta) + b(\theta)) * p(\theta | \tilde{\theta})}$$

Model assuming:
- signal cross section wrt SM: **μ**
- number of background events: **b**
- uncertainty on measurements i.e reconstruction efficiency uncertainty, parametrised by **θ**,
- distribution of true values of θ, given some measured/estimated values

$$P(n, \mu) = \frac{\mu^n}{n!} e^{-\mu}$$

Nuisance parameters

- Expected number of signal and background events depend on many parameters that are estimated using data*
- Uncertainty of such estimates enters likelihood through nuisance parameters distribution

group	nuisance	comments
cross section (pdf)	gg	$gg \to H$, $t\bar{t}H$, VQQ, $t\bar{t}$, tW, tb (s-channel), $gg \to VV$
	qqbar	VBF H, VH, V, VV, $\gamma\gamma$
cross section (QCD scales)	ggH	total inclusive $gg \to H$
	ggH1in	inclusive $gg/qg \to H + \geq 1$ jets
	ggH2in	inclusive $gg/qg \to H + \geq 2$ jets
	qqH	VBF H
	VH	associate VH
	ttH	$t\bar{t}H$
	VV	WW, WZ, and ZZ up to NLO
	ggVV	$gg \to WW$ and $gg \to ZZ$
Higgs BR	ZZ	Branching ratio BR($H \to ZZ$)
phenomenology	UE & PS	modeling of underlying event (UE) and parton showering (PS)
luminosity	lumi	uncertainties in integrated luminosity
efficiencies	muon	prompt muon efficiency (includes reconstruction, isolation)
	electron	prompt electron efficiency (includes reconstruction, isolation)
	tau	reconstruction efficiency of prompt hadronicly decaying tau
	b-tag	b-tag efficiency for b-jets (anti-correlated with b-jet veto)
p_T scales	muon	prompt muon p_T-scale
	electron	prompt electron p_T-scale
	tau	p_T scale for prompt hadronicly decaying tau
	jets	jet energy scale
p_T resolutions	electron	prompt electron p_T-resolution
fake rates	lepton	determination of fake lepton rates in data
trigger efficiencies	muon	prompt muon efficiency (includes trigger, reconstruction, isolation)
	electron	prompt electron efficiency (includes trigger, reconstruction, isolation)

Profile likelihood ratio

$$q_\mu = -2\ln\frac{L(data|\mu,\hat{\hat{\theta}}_\mu)}{L(data|\hat{\mu},\hat{\theta})}$$

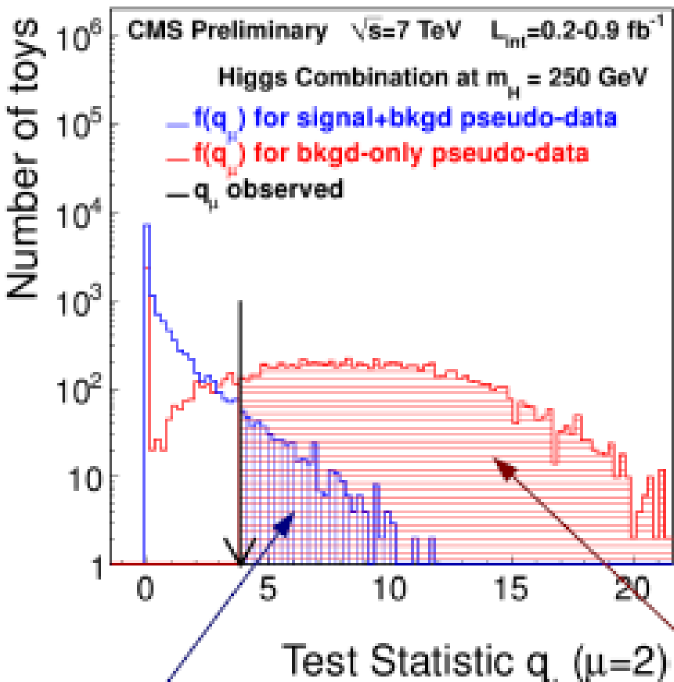
Numerator:

- calculated assuming some μ
- **maximised wrt nuisance parameters θ** (i.e measured μ selection eff. was 0.91, but best fit of 0.89 is used)

Denominator:

- **maximised for both μ and nuisance parameters θ,** (i.e at global maximum)
- **range of μ is restricted to be between 0 and μ assumed in numerator**

Quantifying an exclusion



- to compute pdf of q_μ we generate large number of toy Monte Carlo events assuming:
- **μ - signal+background**
- **$\mu=0$ - background only**
- **we calculate $P(q_\mu > q_\mu^{obs} | \mu s(\theta_\mu^{obs}) + b(\theta_\mu^{obs}))$ until for some μ until we get $CL_S < 0.05$**

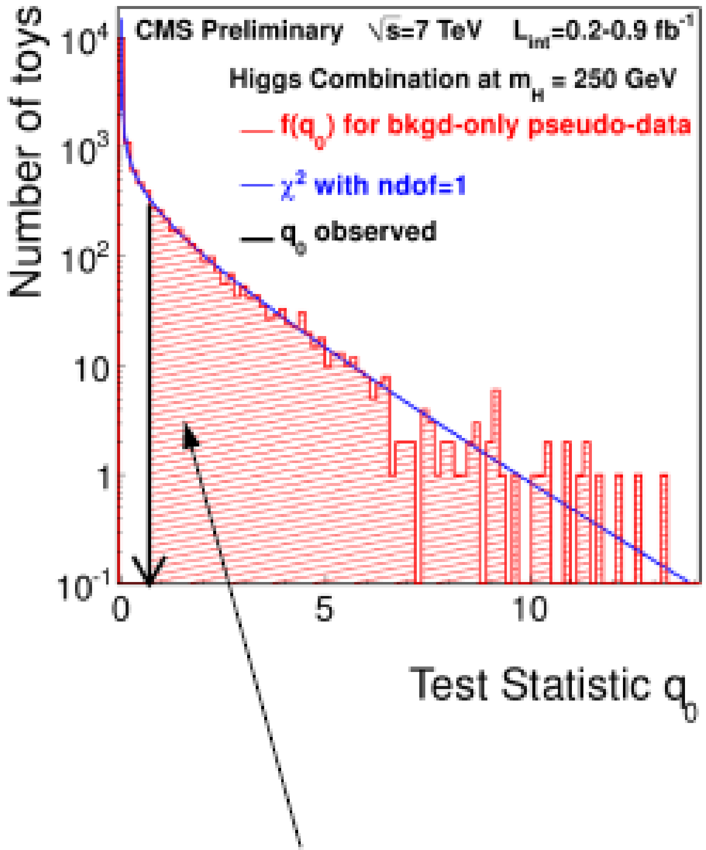
$$CL_S = \frac{P(q_\mu \geqslant q_\mu^{obs} | \mu * s(\hat{\theta}_\mu^{obs}) + b(\hat{\theta}_\mu^{obs}))}{P(q_\mu \geqslant q_\mu^{obs} | b(\hat{\theta}_0^{obs}))}$$

$P(q_\mu > q_\mu^{obs} | \mu * s(\theta_\mu^{obs}) + b(\theta_\mu^{obs})) = 0.868$

$P(q_\mu > q_\mu^{obs} | b(\theta_\mu^{obs})) = 0.04$

$$= \frac{0.04}{0.868} = 0.046$$

Quantifying an excess



- to estimate significance of excess we use following test statistics:

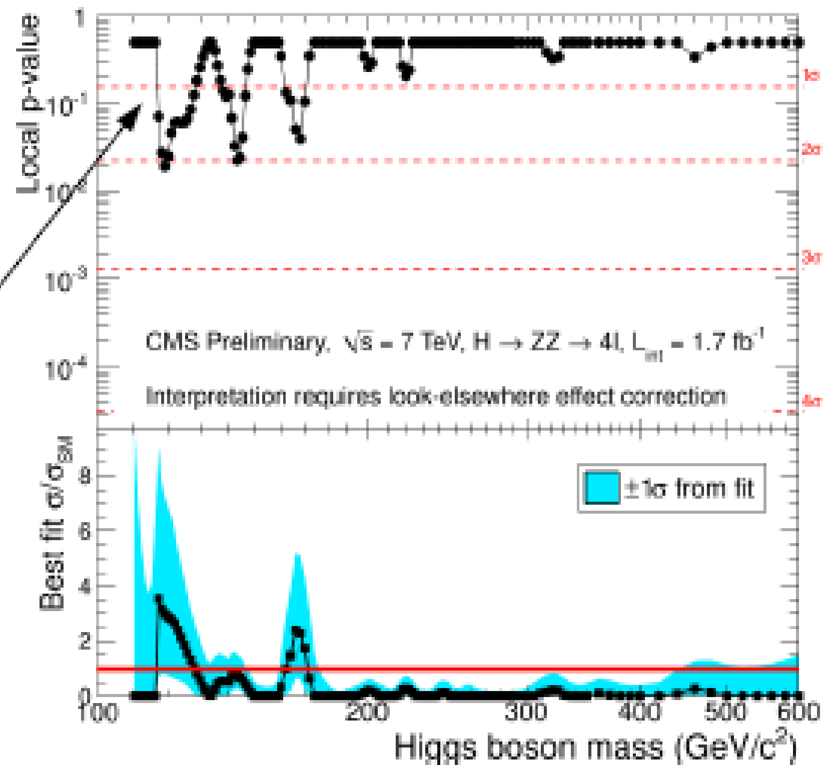
$$q_0 = -2\ln\frac{L(data|0,\hat{\theta}_0)}{L(data|\hat{\mu},\hat{\theta})}$$

- $p_0 = P(q_0 > q_0^{obs})$ is used to calculate single sided Gaussian significance Z
- **Z=5 corresponds to $p_0 = 2.8 * 10^{-7}$**
- At the same time wit get μ that best fits the data

$p_0 = P(q_0 > q_0^{obs}) = 0.18 \sim Z = 0.9$

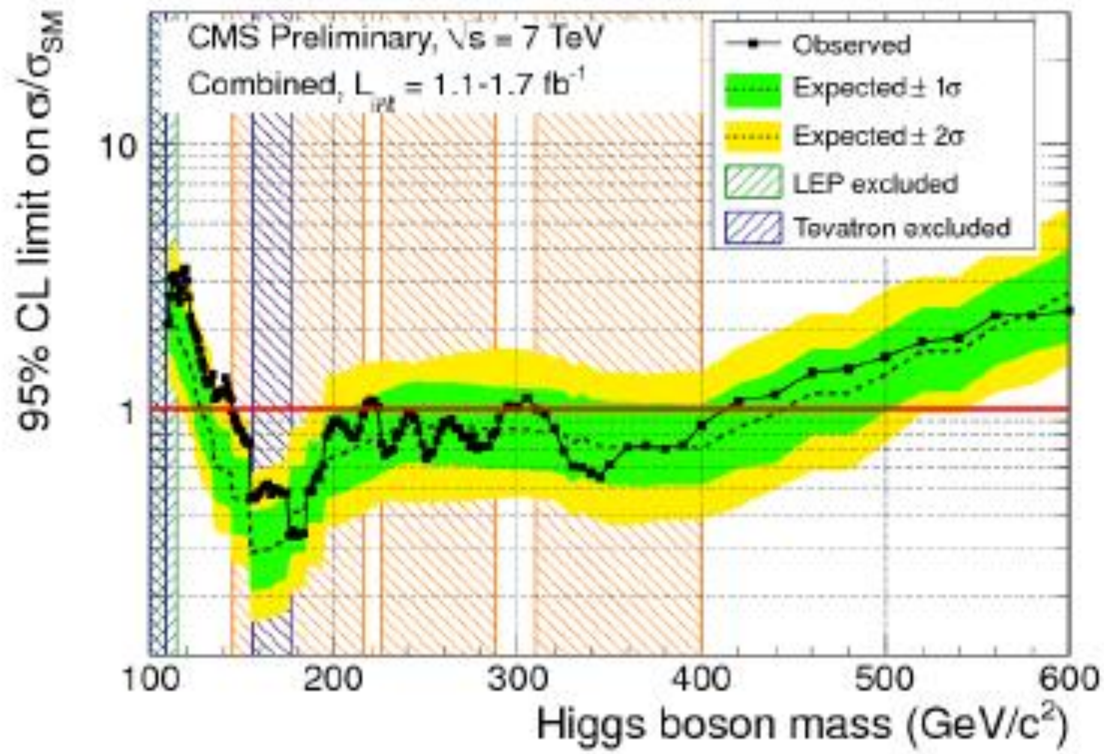
Word of caution: LEE

- we are looking at wide mass range divided in many bins
- probability of upward fluctuation in each bin can be small
- **but given many bins, global probability of observing upward fluctuation can be significant**
- the effect is called “look elsewhere effect”, or “trial factor”

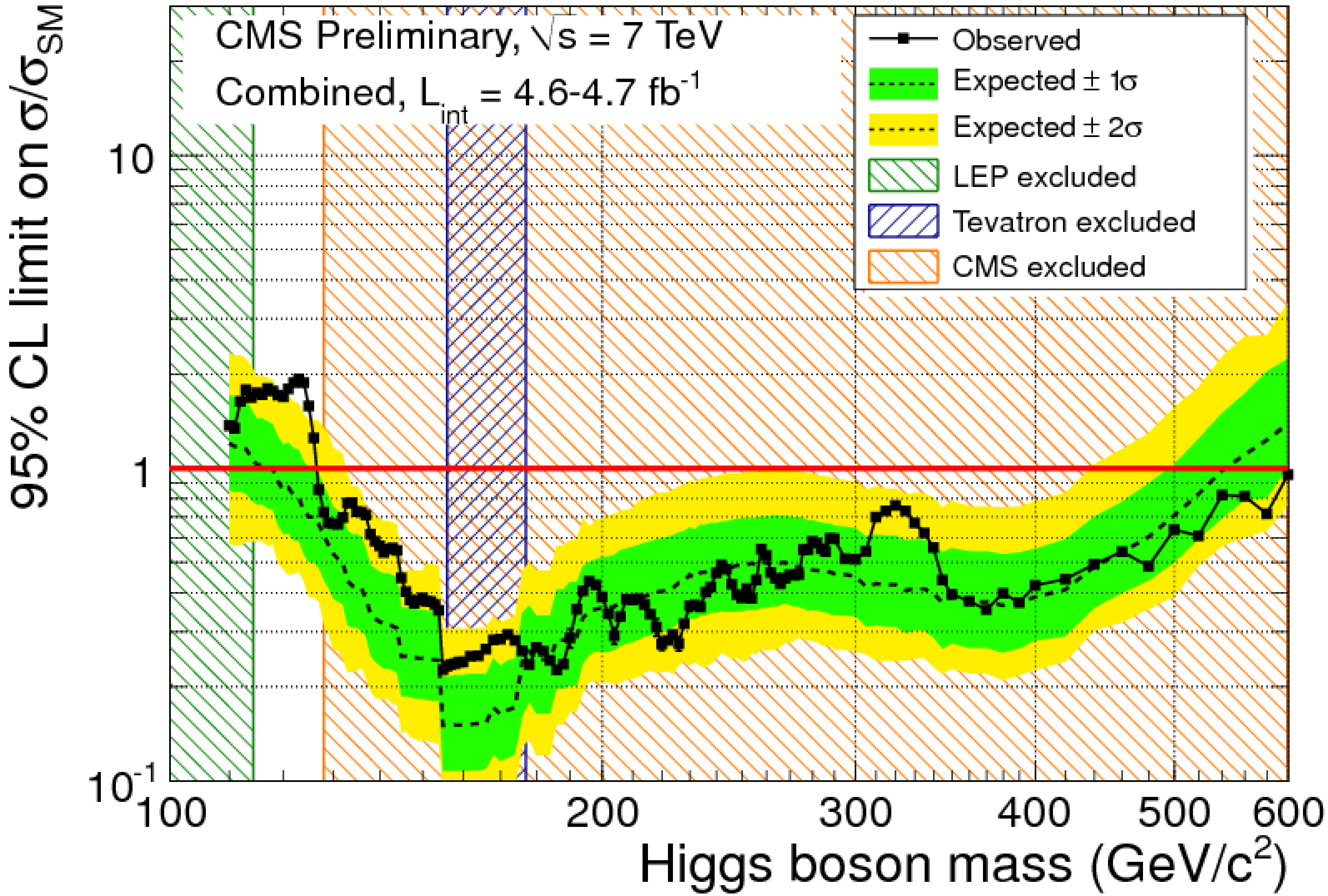


- for $H \to ZZ \to 4l$ CMS estimates the trial factor of order of 100
- **local probability for background-only should be multiplied by a factor of order 100**
- For local p~0.01, Z_{max}~2.3 with LEE we get globally p~0.4, Z_{global}~0.25

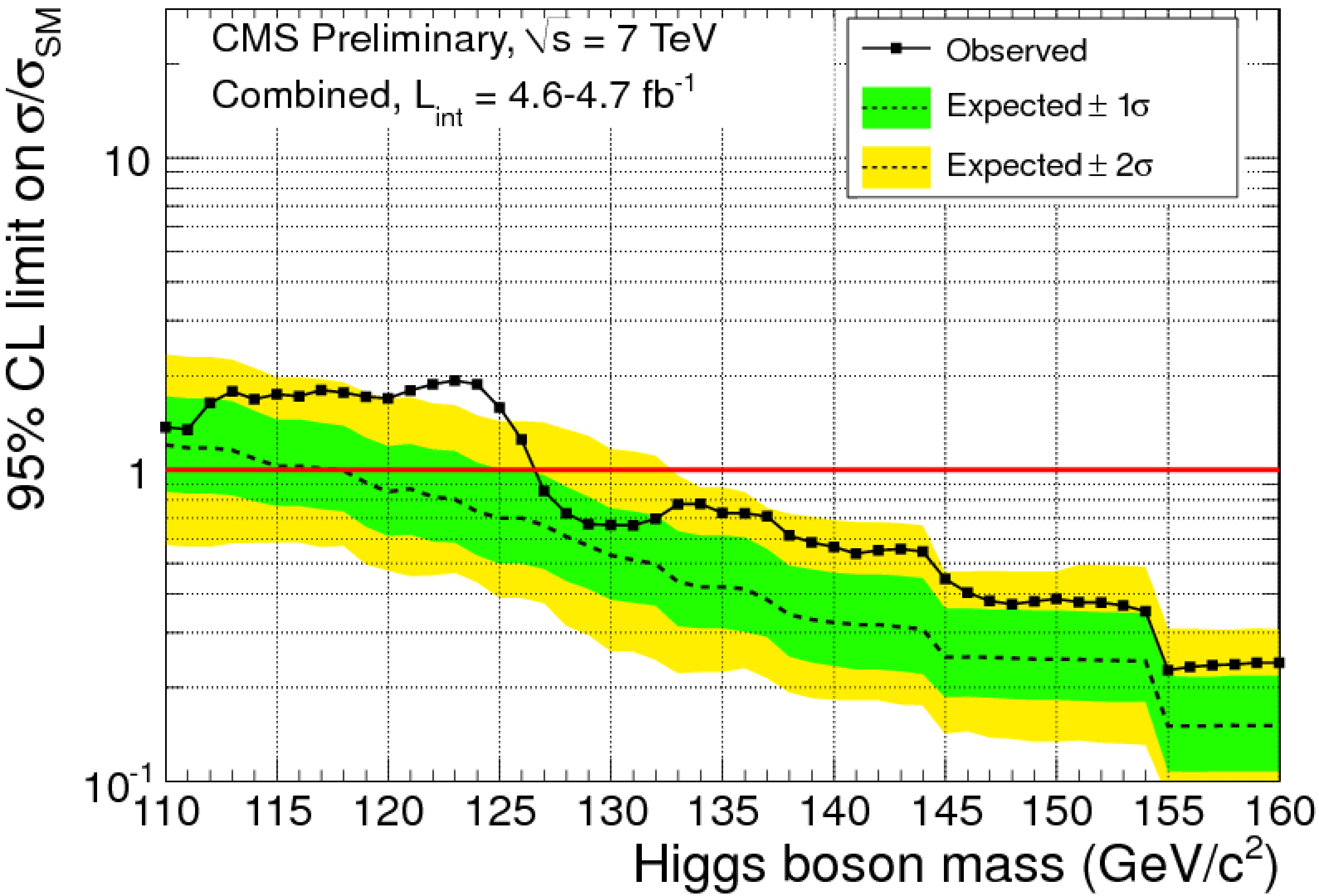
SM Higgs exclusion limits



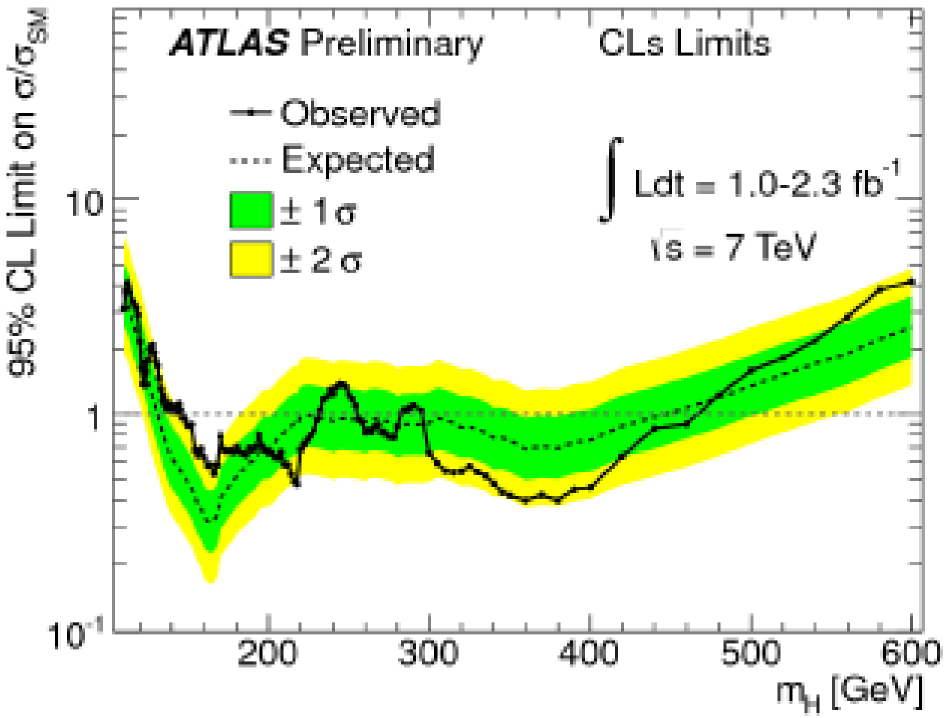
- 95% CL exclusion range: **145 - 216, 226 - 288 and 310 - 400 GeV/c^2**


CMS Preliminary, √s = 7 TeV
Combined, L_{int} = 4.6-4.7 fb^{-1}
Observed
Expected ± 1σ
Expected ± 2σ
LEP excluded
Tevatron excluded
CMS excluded
95% CL limit on σ/σ_{SM}
Higgs boson mass (GeV/c^2)
10
1
10^{-1}
100
200
300
400
500
600

Obszar niskiej masy

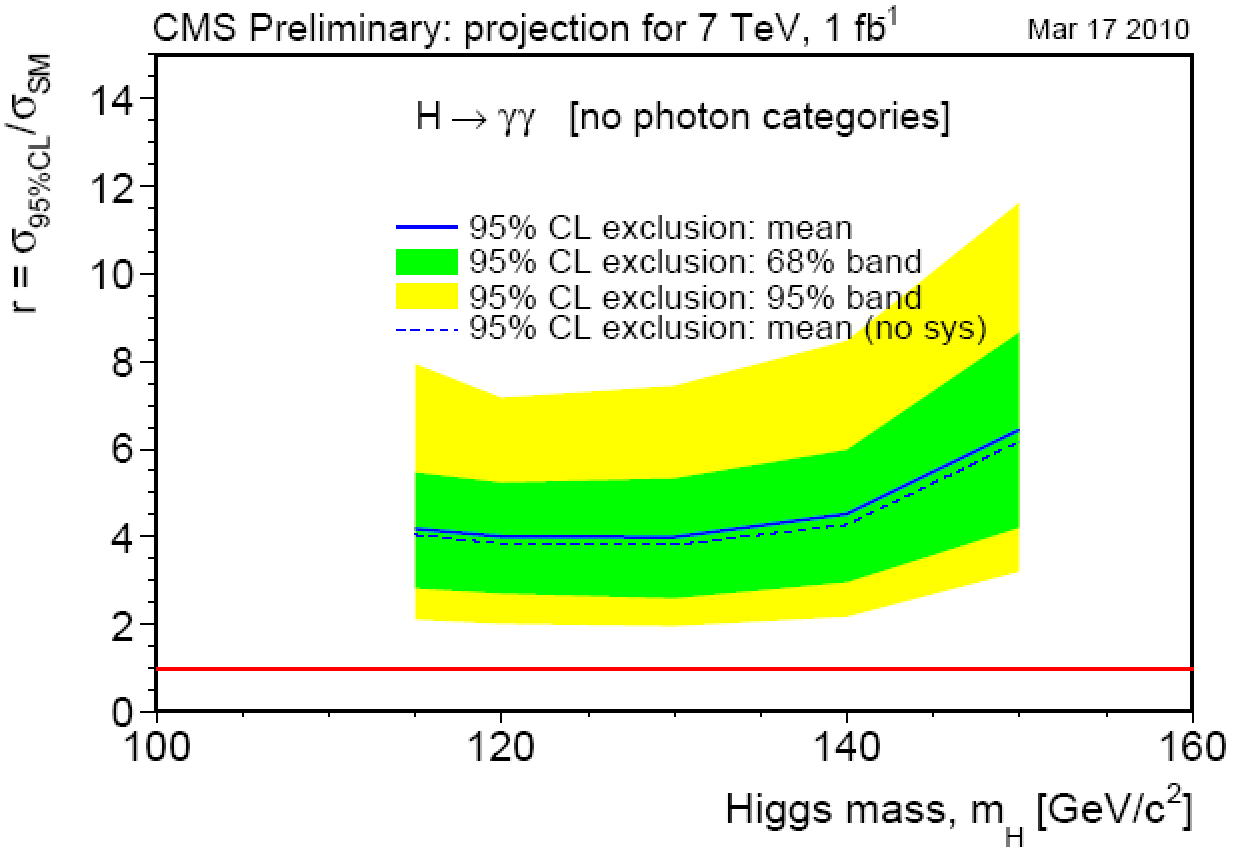


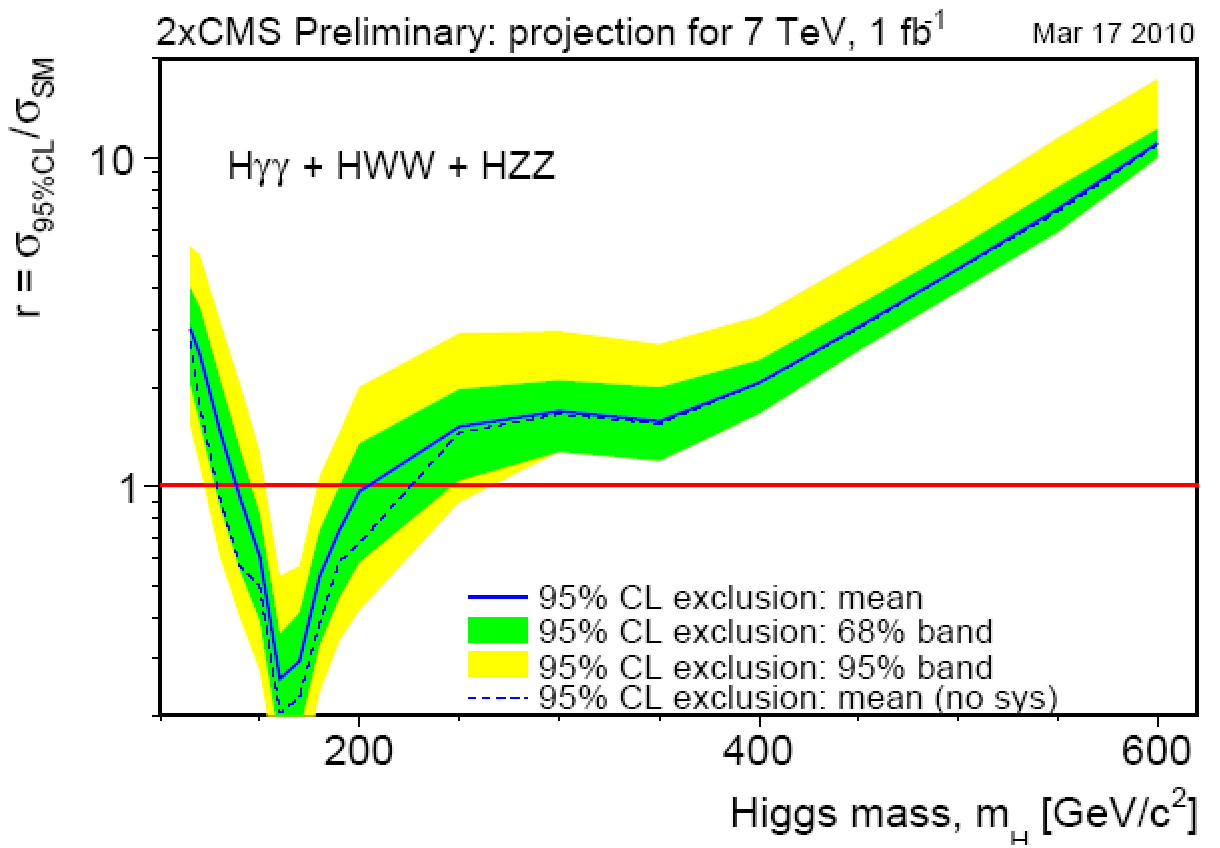
SM Higgs exclusion limits



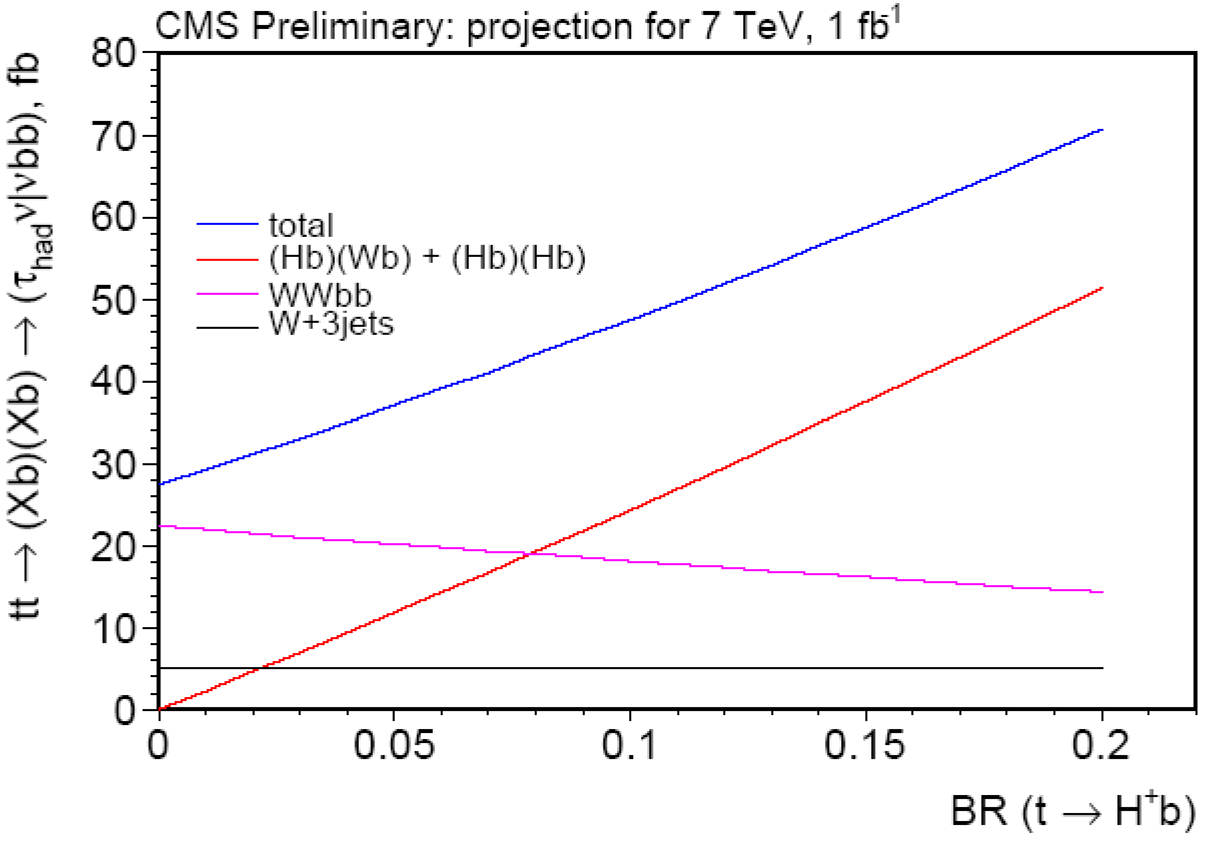
• 95% CL exclusion range: **146 - 230, 256 - 282 and 296 - 459 GeV/c²**

SM: CMS lekki H na dwie gammy

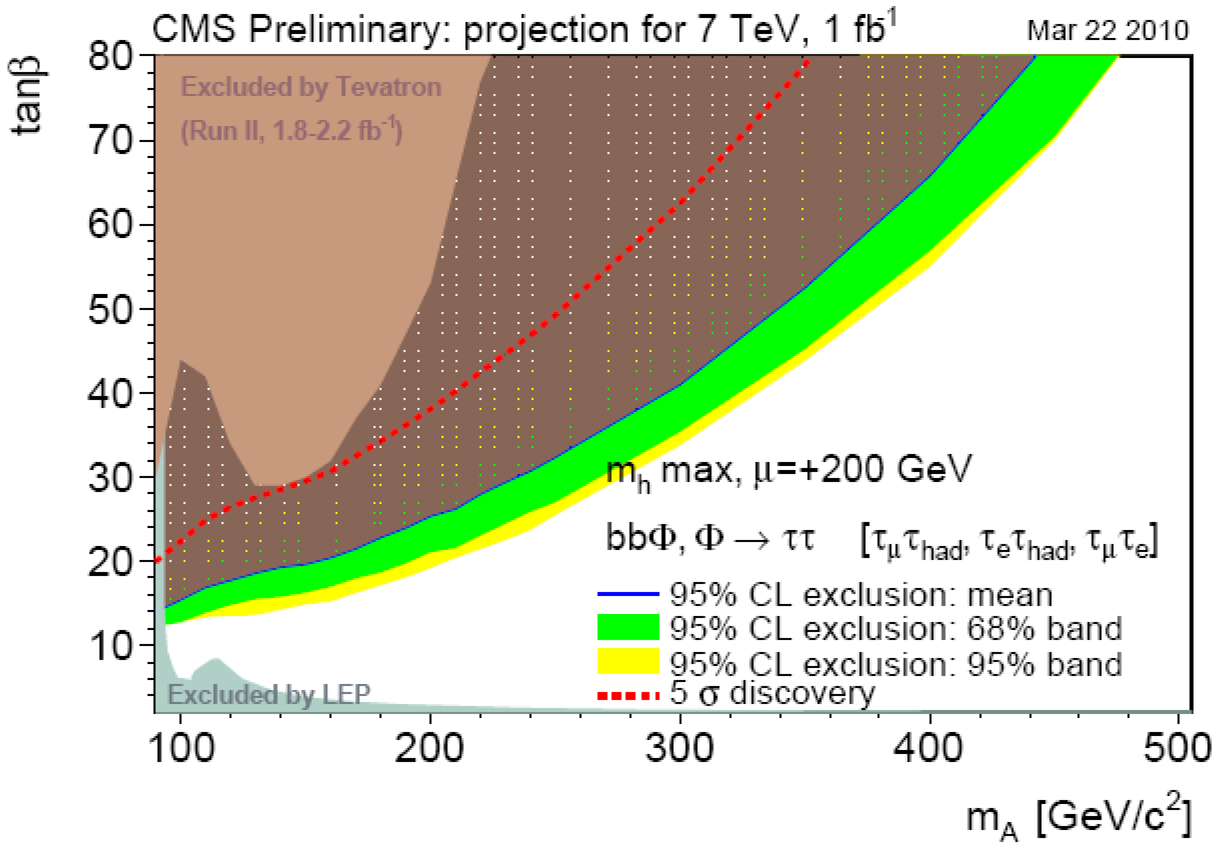



2xCMS Preliminary: projection for 7 TeV, 1 fb-1
Mar 17 2010
Hγγ + HWW + HZZ
r = σ95%CL/σSM
10
1
200
400
600
Higgs mass, mH [GeV/c2]
95% CL exclusion: mean
95% CL exclusion: 68% band
95% CL exclusion: 95% band
95% CL exclusion: mean (no sys)

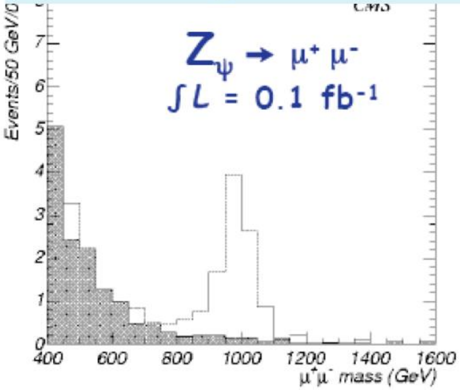
MSSM: CMS poszukiwanie H^+



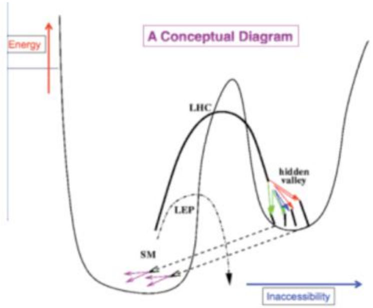
MSSM: CMS-poszukiwanie h przy 7 TeV



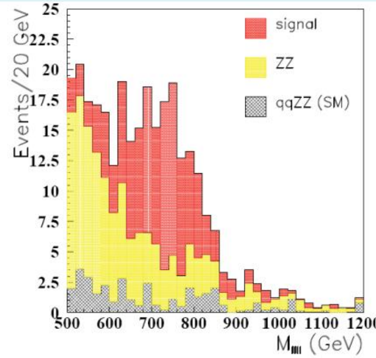
New Gauge Bosons?



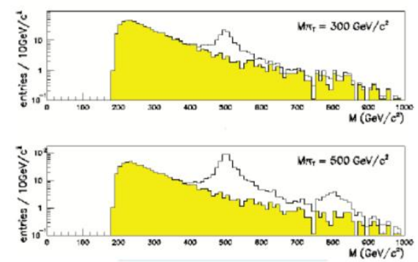
Hidden Valleys?



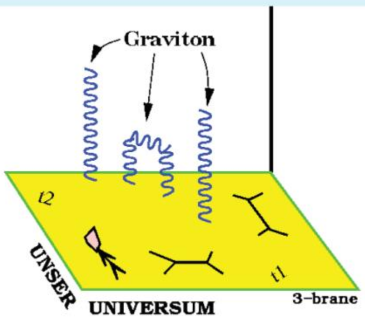
ZZ/WW resonances?



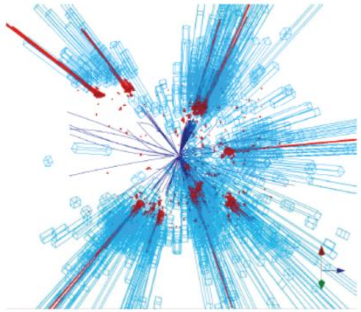
Technicolor?



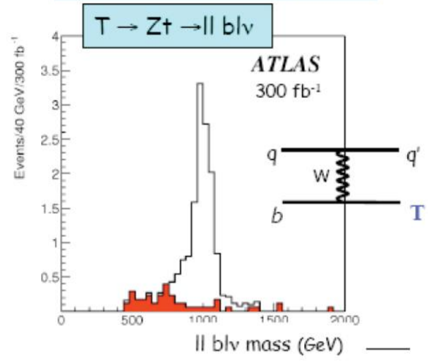
Extra Dimensions?



Black Holes???



Little Higgs?



Split Susy?

PYTHIA R-hadron event from ATLSIM