Higgs and BSM Phenomenology

Sven Heinemeyer, IFCA (Santander)

DESY Hamburg, 10/2011

1. SM Higgs
2. MSSM Higgs
3. SUSY
4. Other BSM physics

Higgs and BSM Phenomenology at the LHC

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The (un)official (optimistic?) LHC time line:

03/2010: first collisions at record breaking energy

2010: $\lesssim 0.05$ fb^{-1} (at $\sqrt{s} = 7$ TeV)

2011/12: $\lesssim 15$ fb^{-1} (at $\sqrt{s} = 7$ TeV) ⇒ first physics results!

2013: shutdown, further splice checks, repairs, . . .

2014 – 2016: $10+$ fb^{-1} per year at $\sqrt{s} = 14(?)$ TeV
⇒ physics results with "low" luminosity

2017: shutdown, preparation for "high luminosity"

2018 – 2020: 100 fb^{-1} per year ⇒ physics results with "high" luminosity

2021: upgrade to sLHC?

2022 + X (X > 0): sLHC?

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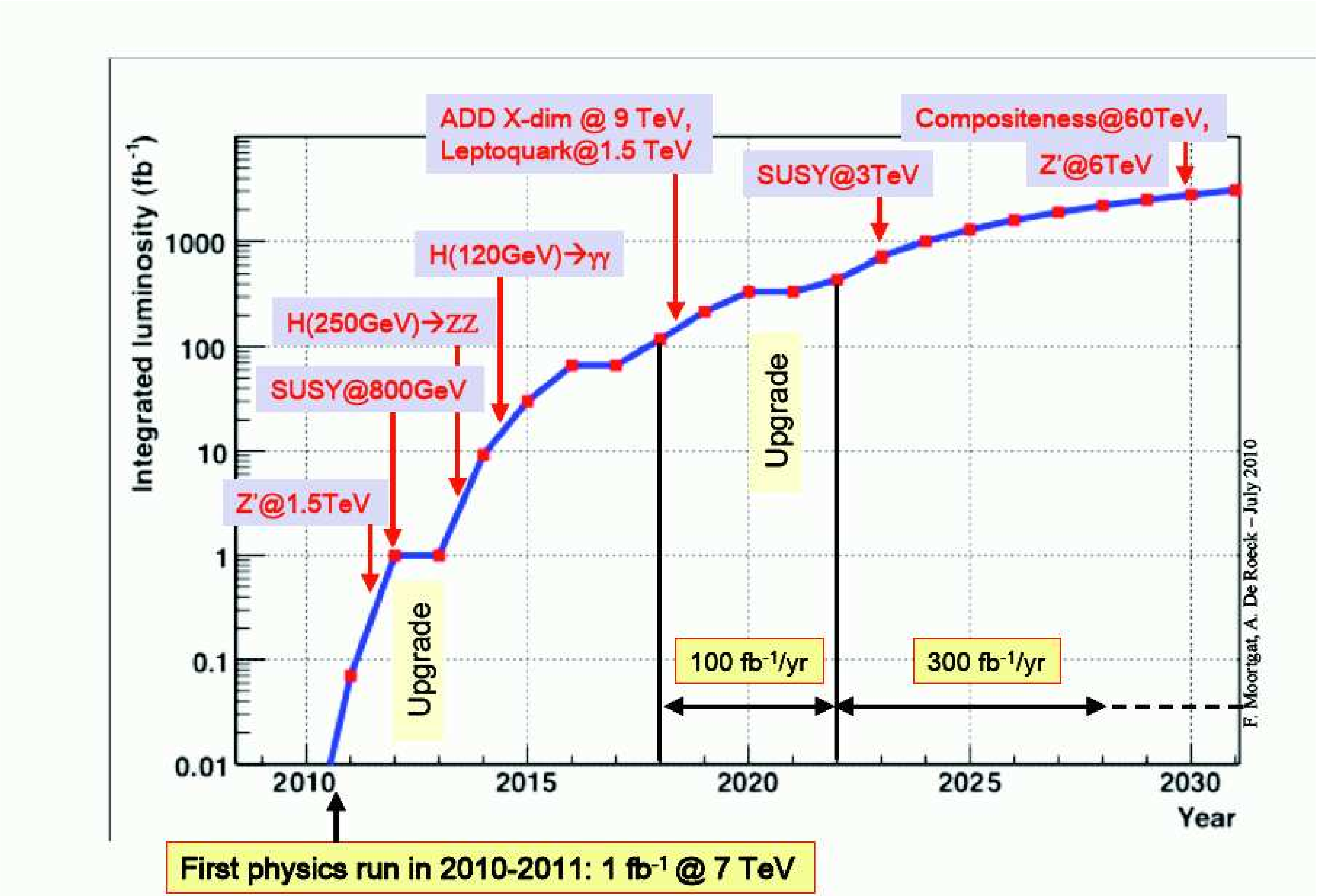
2022 + X (X > 0): sLHC?

YOU live in an exciting time!!!

Overview: [*A. De Roeck et al. '10*]



CERN TH institute 02/09: LHC2FC: From the LHC to Future Colliders

1. SM Higgs

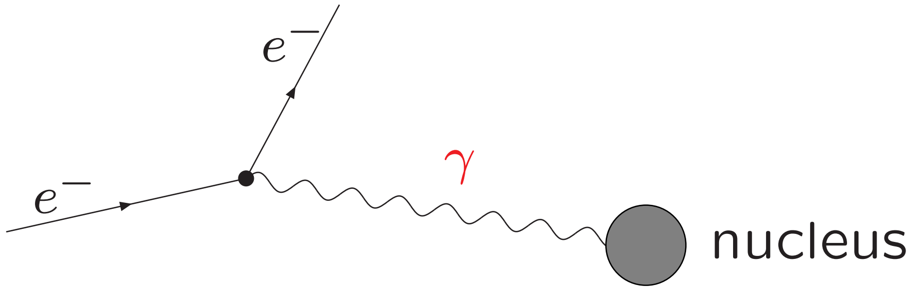
Standard Model (SM) of the electroweak and strong interaction

SM: Quantum field theory ⇒ interaction: exchange of field quanta

Construction principle of the SM: gauge invariance

Example: Quantum electro-dynamics (QED)

field quanta: photon A_μ



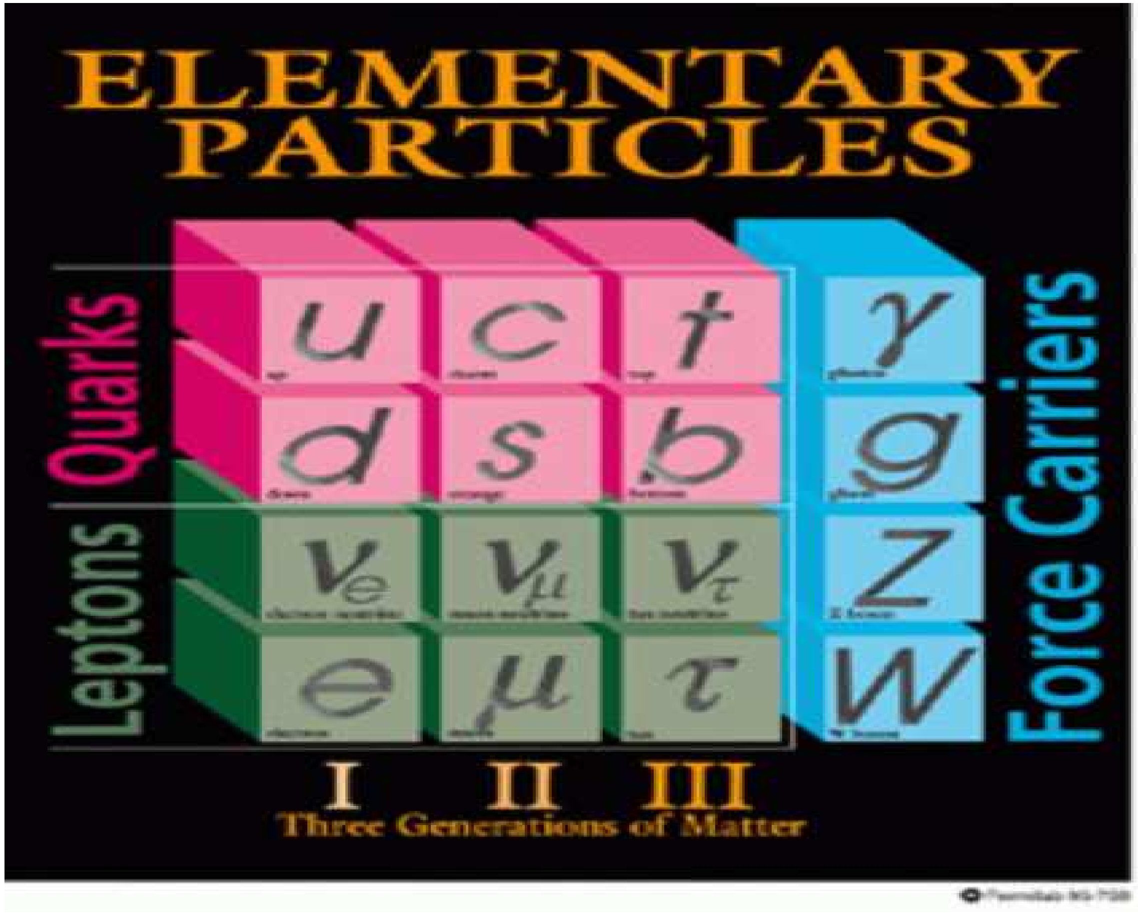
$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

$\Psi \to e^{i\,e\,\lambda(x)}\Psi$, $A_\mu \to A_\mu + \partial_\mu\lambda(x)$

mass term for photon: $m^2 A^\mu A_\mu$ not gauge invariant

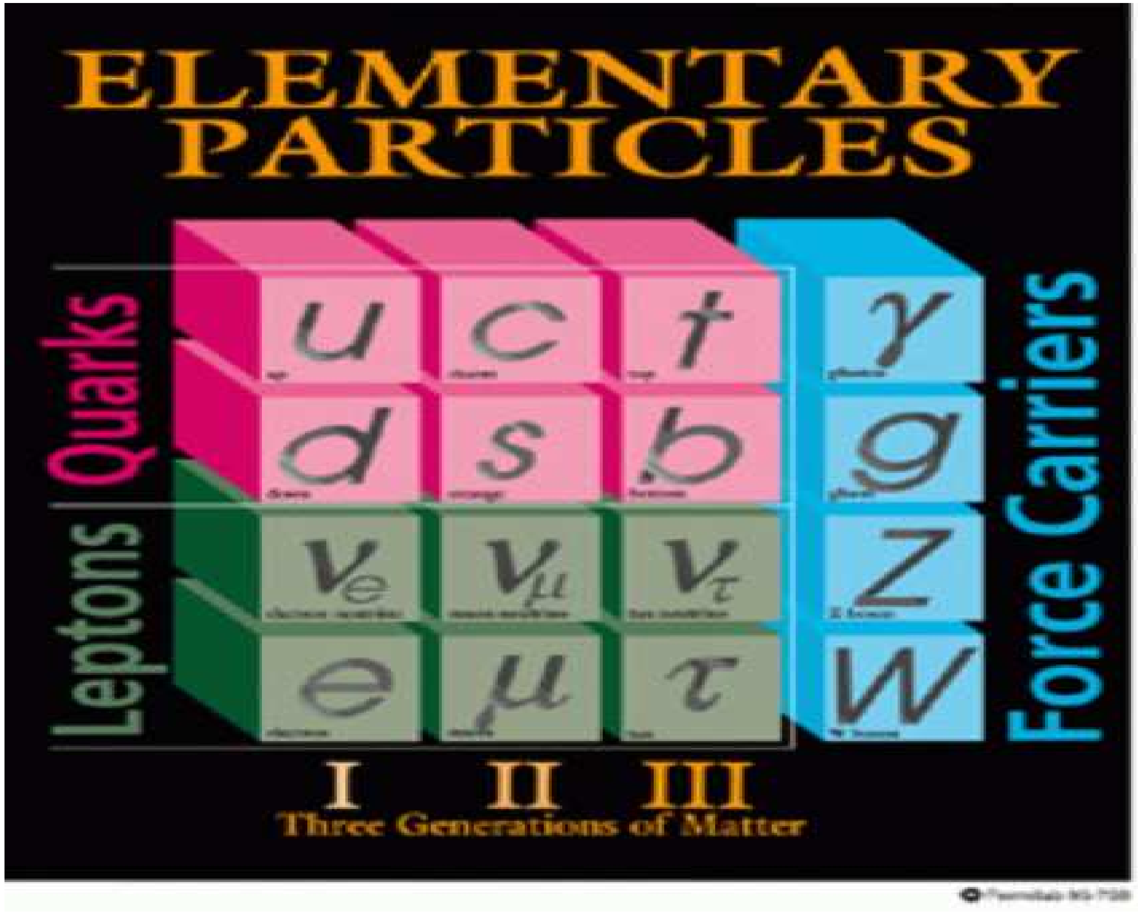
⇒ A_μ is massless gauge field

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

Current status of knowledge: the Standard Model (SM)



⇒ all particles experimentally seen

⇒ but theory predicts massless gauge bosons . . .

Problem:

Gauge fields Z, W^+, W^- are massive

explicite mass terms in the Lagrangian $\Leftrightarrow$ breaking of gauge invariance

Solution: Higgs mechanism

scalar field postulated, mass terms from coupling to Higgs field

Higgs sector in the Standard Model:

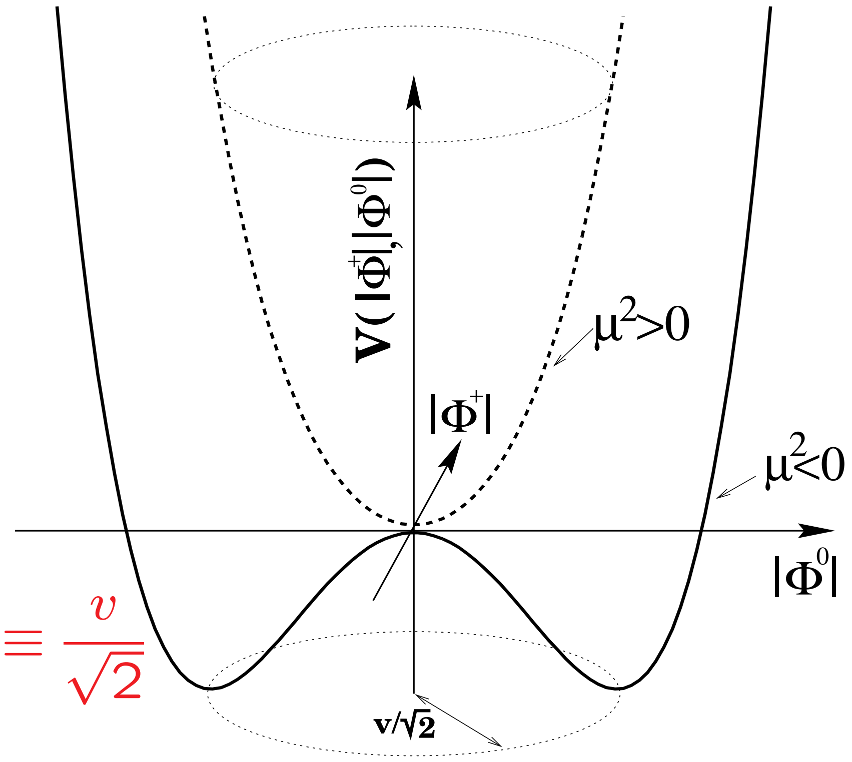
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

Higgs potential:

$$V(\phi) = \mu^2 \left|\Phi^\dagger \Phi\right| + \lambda \left|\Phi^\dagger \Phi\right|^2, \quad \lambda > 0$$

$\mu^2 < 0$: Spontaneous symmetry breaking

minimum of potential at $|\langle \Phi_0 \rangle| = \sqrt{\frac{-\mu^2}{2\,\lambda}} \equiv \frac{v}{\sqrt{2}}$



$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \qquad \text{(unitary gauge)}$$

H: elementary scalar field, Higgs boson

Lagrange density:

$$\begin{aligned} \mathcal{L}_{\text{Higgs}} = \quad & (D_\mu \Phi)^\dagger (D^\mu \Phi) \\ & - g_d \bar{Q}_L \Phi d_R \; - \; g_u \bar{Q}_L \Phi_c u_R \\ & - V(\Phi) \end{aligned}$$

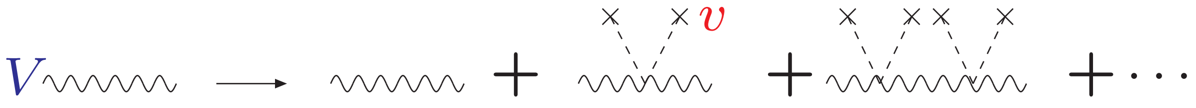
with

$$\begin{aligned} f iD_\mu &= i\partial_\mu - g_2 \vec{I}\vec{W}_\mu - g_1 Y B_\mu \\ \Phi_c &= i\sigma_2 \Phi^\dagger \qquad\qquad Q_L \sim \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \; \Phi \sim \begin{pmatrix} 0 \\ v \end{pmatrix}, \; \Phi_c \sim \begin{pmatrix} v \\ 0 \end{pmatrix} \end{aligned}$$

Gauge invariant coupling to gauge fields

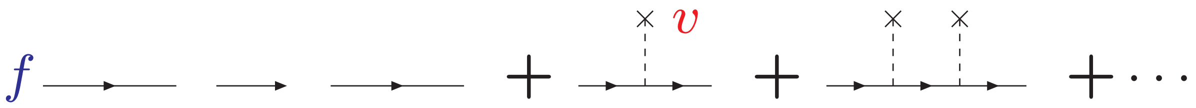
⇒ mass terms for gauge bosons and fermions

1.) $VV\Phi\Phi$ coupling:



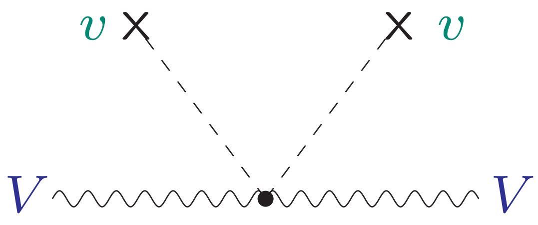
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \;:\; M^2 = g^2\frac{v^2}{2}$$

2.) fermion mass terms: Yukawa couplings:

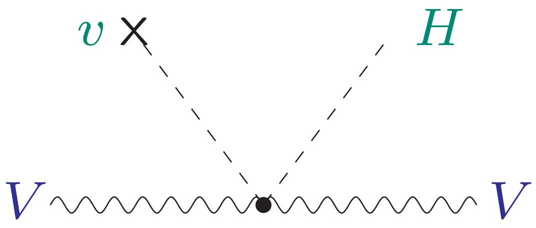


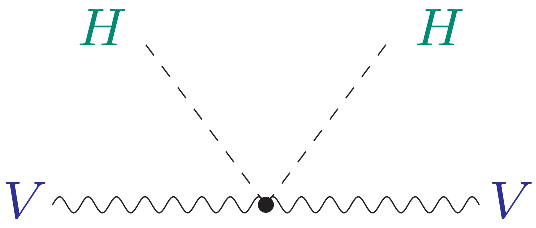
$$\frac{1}{\not{q}} \to \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}} \frac{1}{\not{q}}\right]^j = \frac{1}{\not{q} - m_f} \;:\; m_f = g_f\frac{v}{\sqrt{2}}$$

1.) $VV\Phi\Phi$ coupling:



⇒ VV mass terms: $g_2^2 v^2/2 \equiv M_W^2$, $(g_1^2 + g_2^2) v^2/2 \equiv M_Z^2$

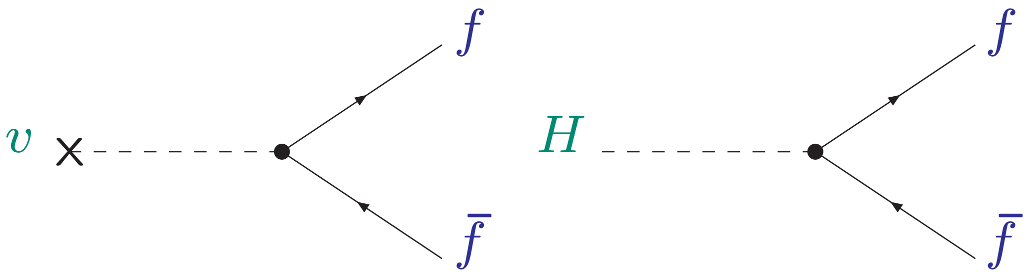




⇒ triple/quartic couplings to gauge bosons

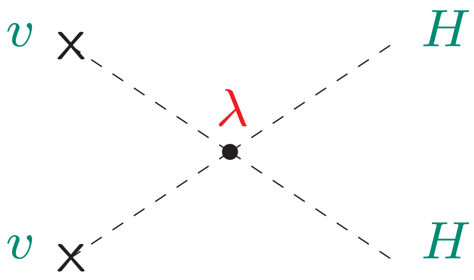
⇒ coupling $\propto$ masses

2.) fermion mass terms: Yukawa couplings



$m_f = v\, g_f \Rightarrow$ coupling $\propto$ masses

3.) mass of the Higgs boson: self coupling



. . .

$\lambda = M_H^2/v$

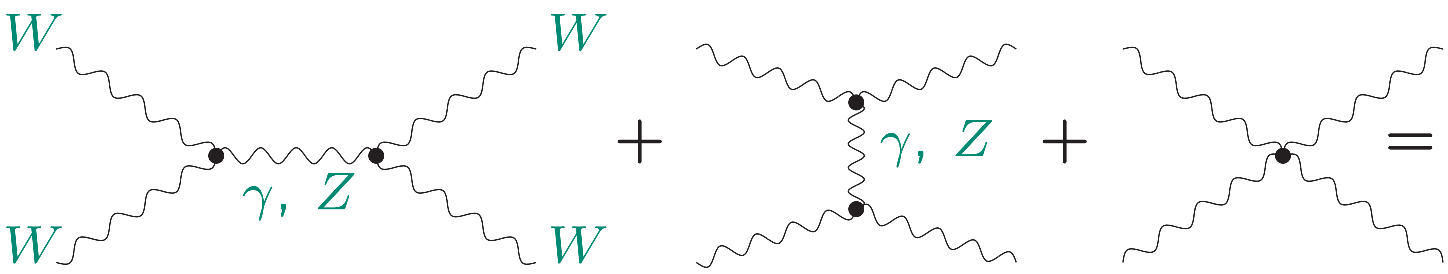
$M_H = v\sqrt{\lambda}$ free parameter

$\longrightarrow$ last unknown parameter of the SM

$\Rightarrow$ establish Higgs mechanism $\equiv$ find the Higgs $\oplus$ measure its couplings

Another effect of the Higgs field:

Scattering of longitudinal W bosons: $W_L W_L \to W_L W_L$

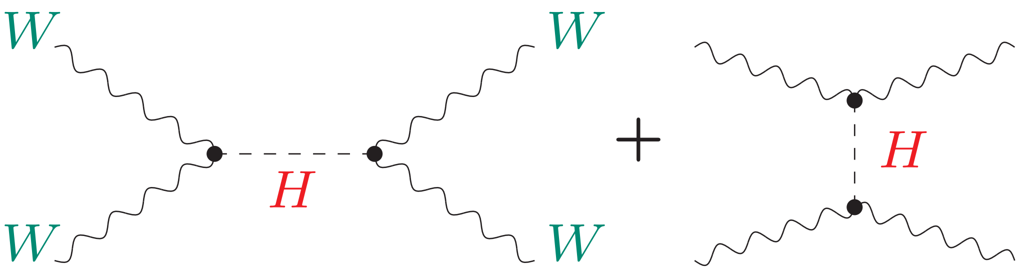


$$\mathcal{M}_V = \quad + \quad + \quad = -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$$

for $E \to \infty$

$\Rightarrow$ violation of unitarity

Contribution of a scalar particle with couplings prop. to the mass:



$$\mathcal{M}_S = \quad + \quad = g_{WWH}^2 \frac{E^2}{M_W^4} + \mathcal{O}(1)$$

for $E \to \infty$

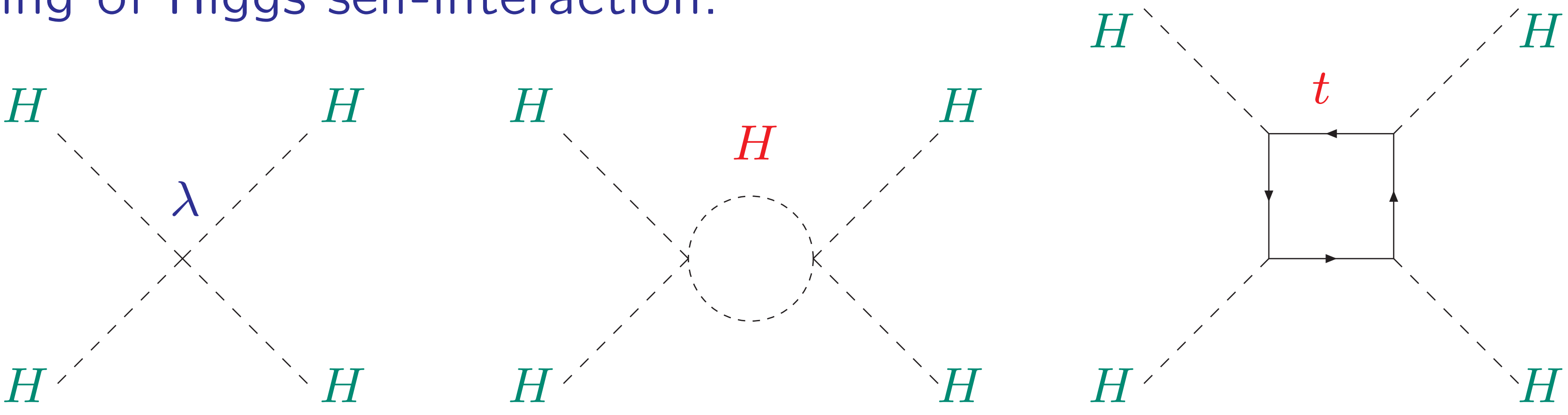
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4} \left(g_{WWH}^2 - g^2 \, M_W^2 \right) + \ldots$$

$\Rightarrow$ compensation of terms with bad high-energy behavior for

$$g_{WWH} = g \, M_W$$

What else do we know about the Higgs boson?

Running of Higgs self-interaction:



Renormalization group equation:

$$\frac{d\,\lambda}{d\,t} = \frac{3}{8\,\pi^2}\left[\lambda^2 + \lambda g_t^2 - g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right] \;, \qquad t = \log\left(\frac{Q^2}{v^2}\right)$$

Two conditions:

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

2.) avoid vacuum instability (for small/negative λ)

1.) avoid Landau pole (for large $\lambda \sim M_H^2$)

$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[\lambda^2\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\pi^2}\log\left(\frac{Q^2}{v^2}\right)}$$

$$\lambda(\Lambda) < \infty \;\Rightarrow\; M_H^2 \leq \frac{8\pi^2 v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)}$$: upper bound on M_H

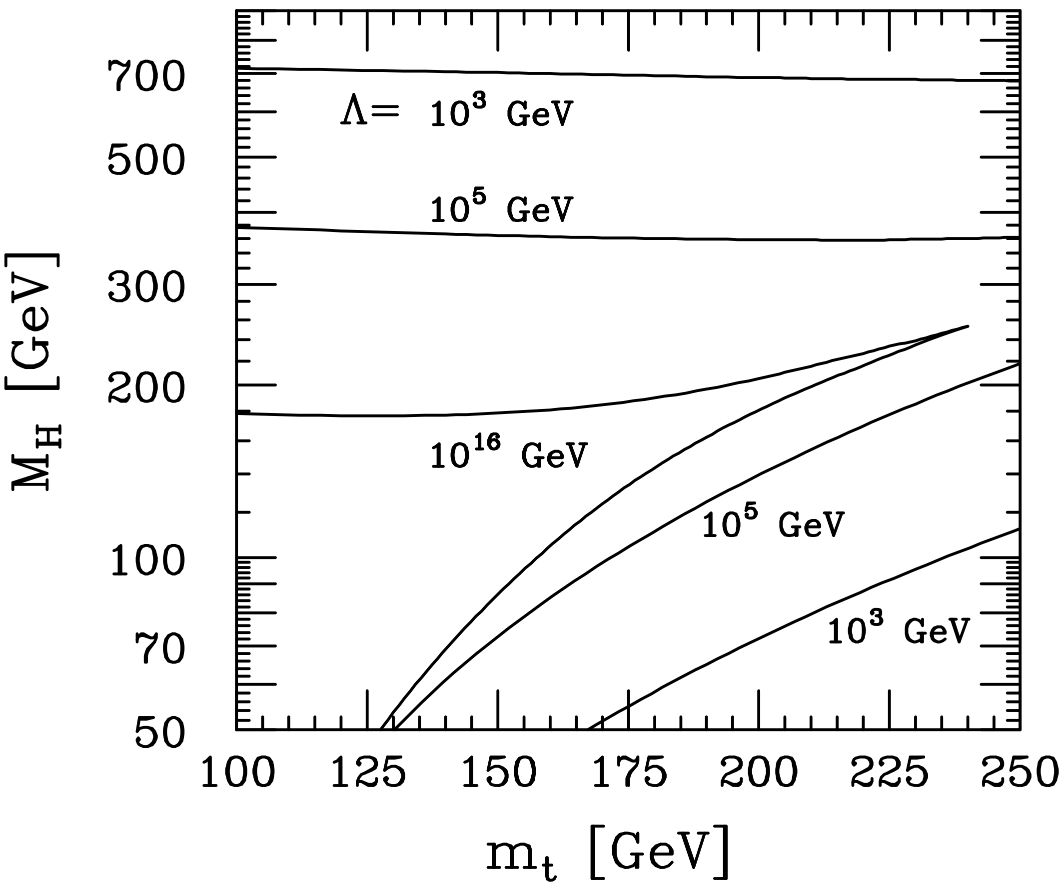
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

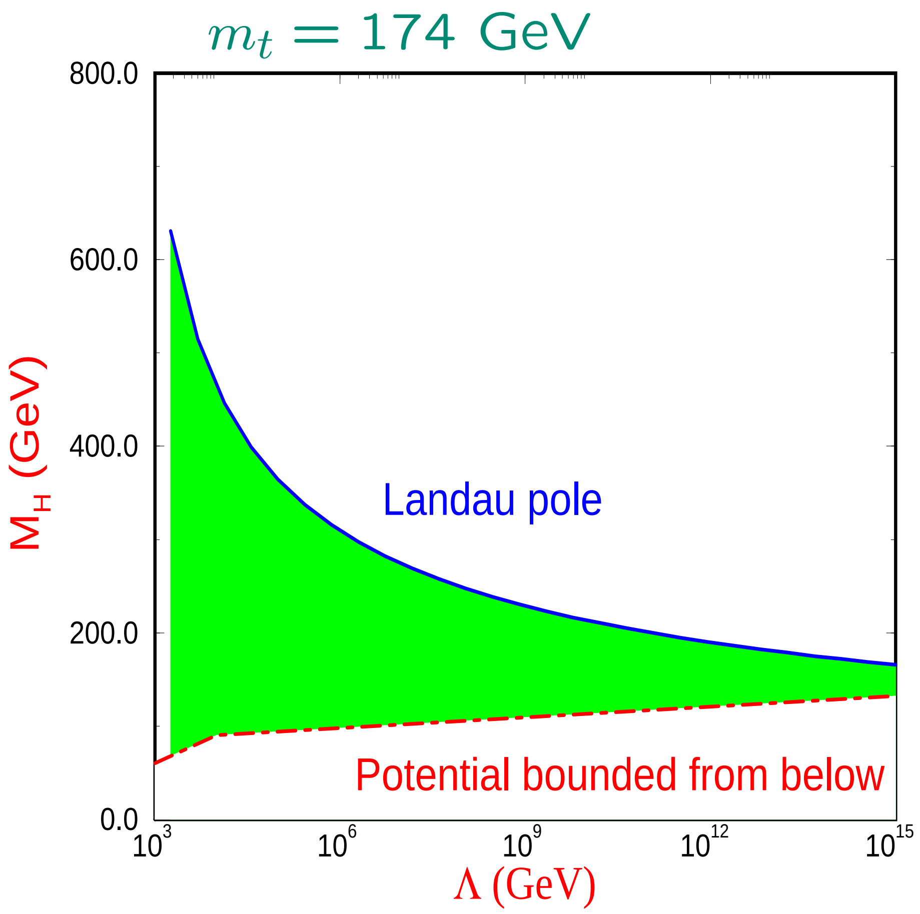
$$\frac{d\lambda}{dt} = \frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]$$

$$\Rightarrow \qquad \lambda(Q^2) = \lambda(v^2)\frac{3}{8\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{Q^2}{v^2}\right)$$

$$\lambda(\Lambda) > 0 \;\Rightarrow\; M_H^2 > \frac{v^2}{4\pi^2}\left[-g_t^4 + \frac{1}{16}\left(2g_2^4 + (g_2^2 + g_1^2)^2\right)\right]\log\left(\frac{\Lambda^2}{v^2}\right)$$: lower bound

Both limits combined:





Λ: scale up to which the SM is valid

$\Lambda = M_{\text{GUT}} \Rightarrow 130 \text{ GeV} \lesssim M_H \lesssim 180 \text{ GeV}$

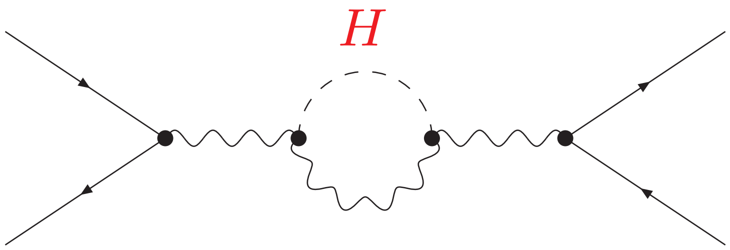
Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:

EW Precision data: $M_W, \sin^2\theta_{\text{eff}}, a_\mu$ ↔ Theory: SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. H



$\Downarrow$

SM: limits on M_H

Very high accuracy of measurements and theoretical predictions needed

Example: prediction of M_W, $\sin^2\theta_{\text{eff}}$

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2}\right) = \frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1 + \Delta r)$$

$$\Updownarrow$$

loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[*A. Sirlin '80*] , [*W. Marciano, A. Sirlin '80*]

$$\begin{array}{ccccccc} \Delta r_{1-\text{loop}} = & \Delta\alpha & - & \frac{c_W^2}{s_W^2}\Delta\rho & + & \Delta r_{\text{rem}}(M_H) \\ & \sim \log\frac{M_Z}{m_f} & & \sim m_t^2 & & \log(M_H/M_W) \\ & \sim 6\% & & \sim 3.3\% & & \sim 1\% \end{array}$$

Example: prediction of M_W, $\sin^2\theta_{\text{eff}}$

A) Theoretical prediction for M_W in terms

of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}(1+\Delta r)$$

$$\Updownarrow$$

loop corrections

B) Effective mixing angle:

$$\sin^2\theta_{\text{eff}}=\frac{1}{4\,|Q_f|}\left(1-\frac{\text{Re}\,g_V^f}{\text{Re}\,g_A^f}\right)$$

Higher order contributions:

$$g_V^f \to g_V^f+\Delta g_V^f, \quad g_A^f \to g_A^f+\Delta g_A^f$$

Comparison of SM prediction of M_W with direct measurements:

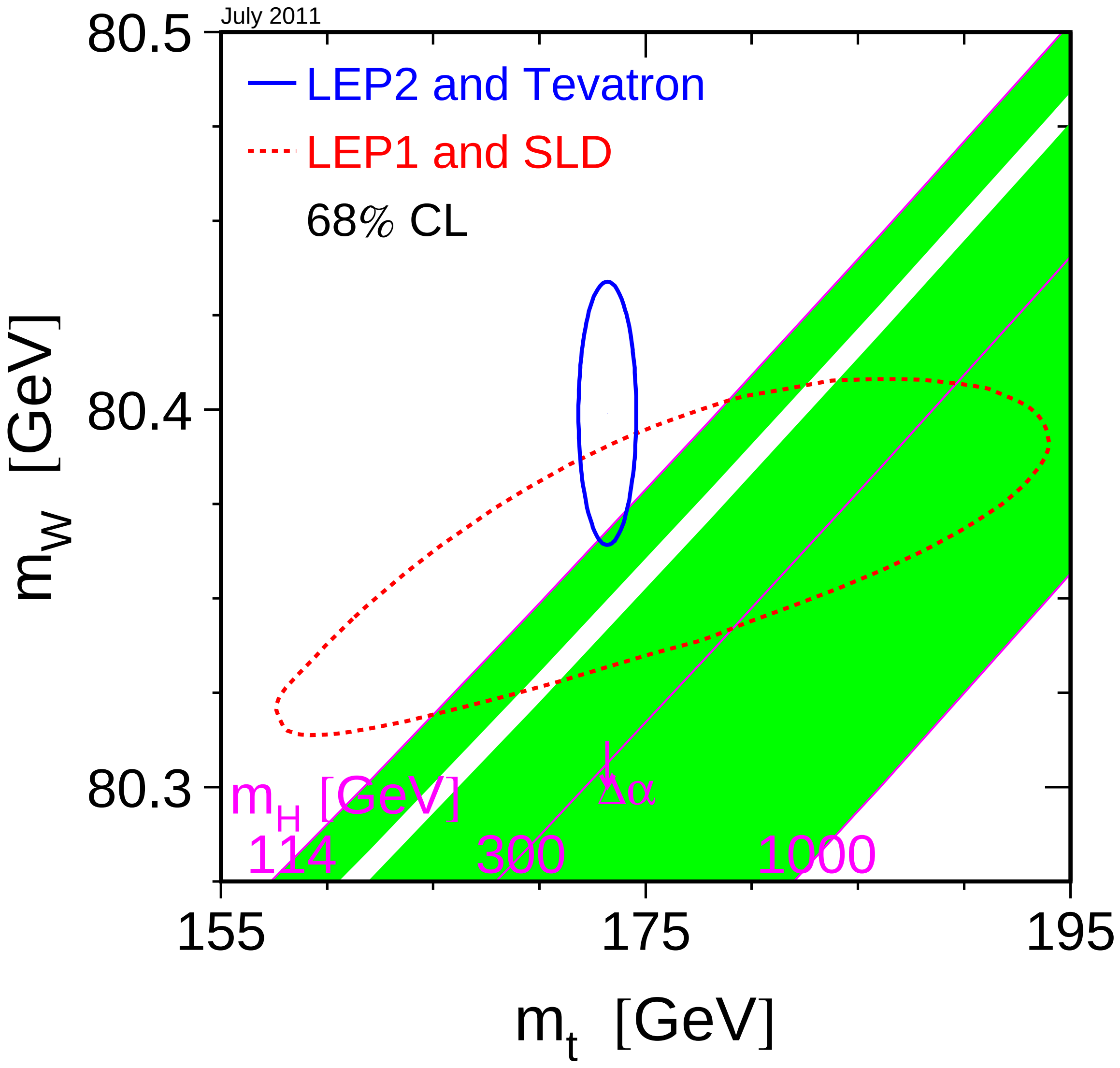
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2\left[\log\left(\frac{M_H}{M_W}\right) + g_2^2\frac{M_H^2}{M_W^2}\right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4



⇒ light Higgs boson preferred

[LEPEWWG '11]

Results for M_H from other EWPO:

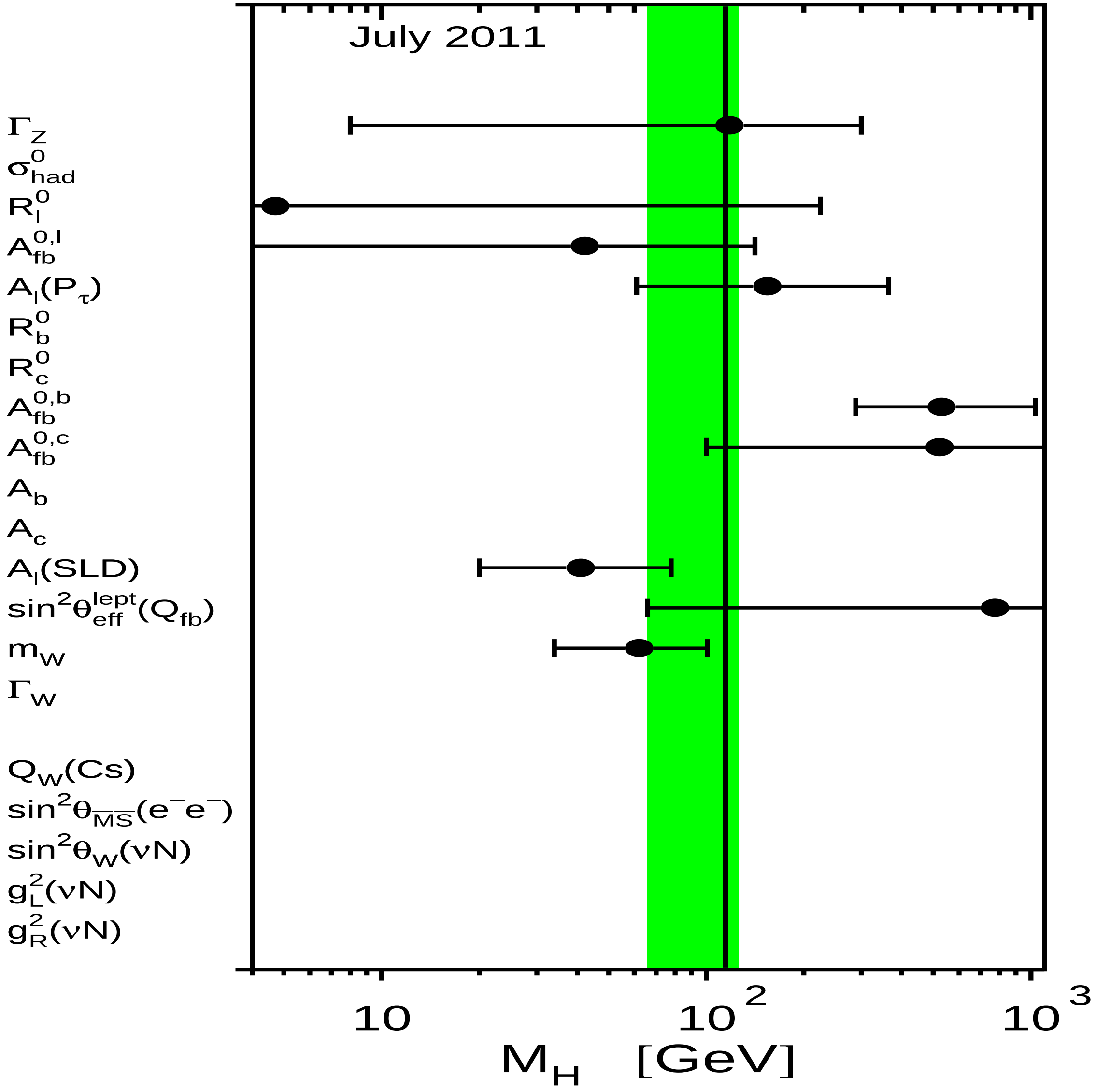
light Higgs preferred by:

M_W, A_l^{LR} (SLD)

heavier Higgs preferred by:

A_b^{FB} (LEP)

⇒ keeps SM alive



[LEPEWWG '11]

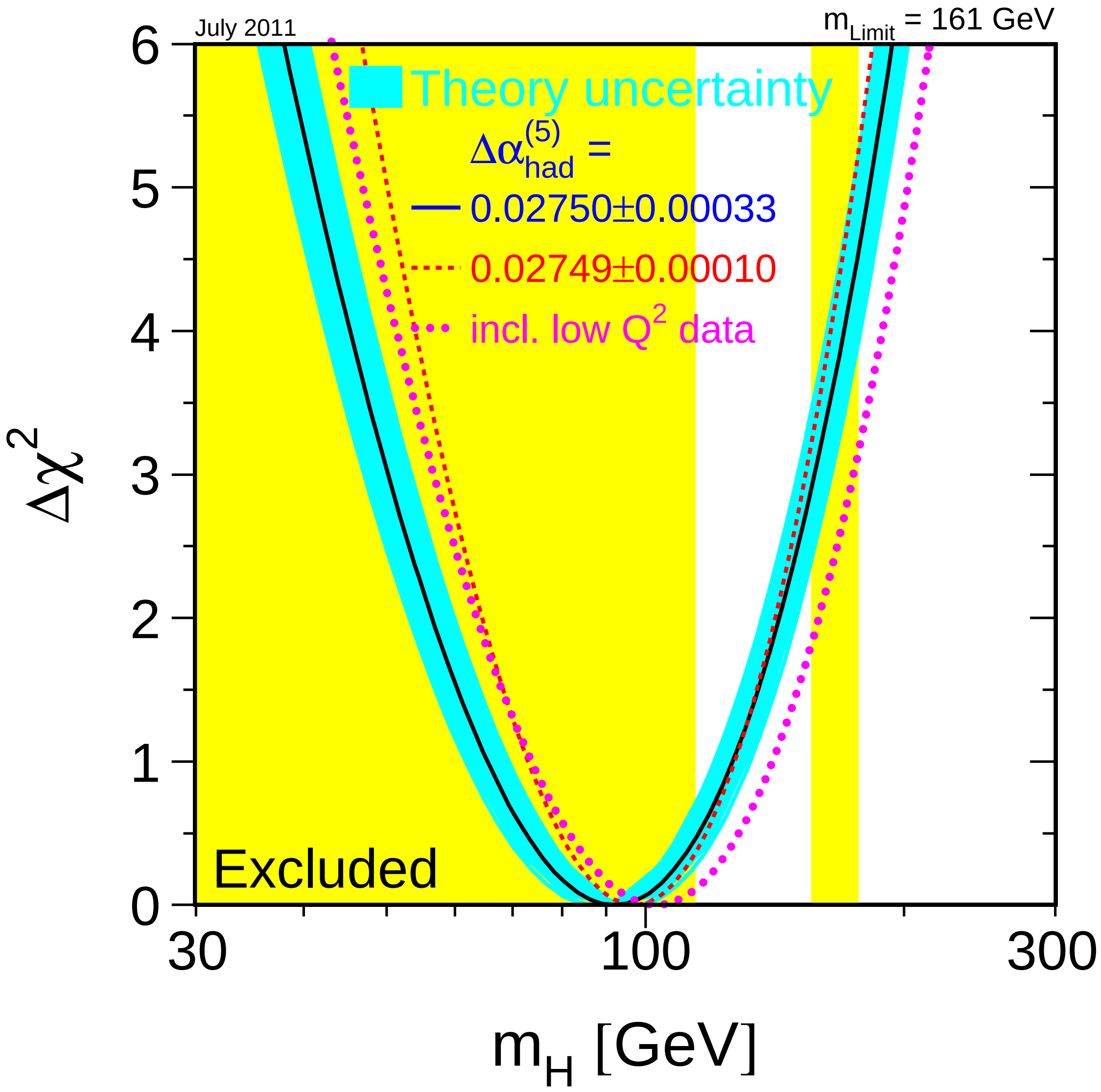
⇒ light Higgs boson preferred

Global fit to all SM data:

[*LEPEWWG '11*]

$\Rightarrow M_H = 92^{+34}_{-26}$ GeV

$M_H < 161$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

Properties of the SM Higgs boson

1.) Decay to fermions:

coupling:

$$g_{f\bar{f}H} = \left[\sqrt{2}\,G_\mu\right]^{1/2} m_f$$

decay width:

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_\mu\, M_H}{4\sqrt{2}\,\pi} m_f^2(M_H^2) \left(1 - 4\frac{m_f^2}{M_H^2}\right)^{3/2}$$

with N_c = number of colors

Bulk of QCD corrections for decays to quarks are mapped into

$$m_q^2(\text{pole}) \to m_q^2(M_H^2)$$

Dominant decay process: $H \to b\bar{b}$

2.) Decay to heavy gauge bosons ($V = W, Z$):

coupling:

$$g_{VVH} = 2 \left[\sqrt{2}\, G_\mu\right]^{1/2} M_V^2$$

on-shell decay width ($M_H > 2 M_V$):

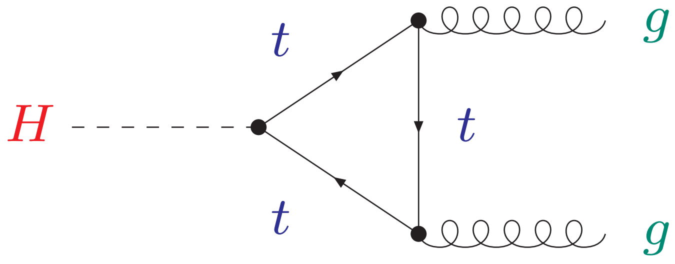
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi} \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

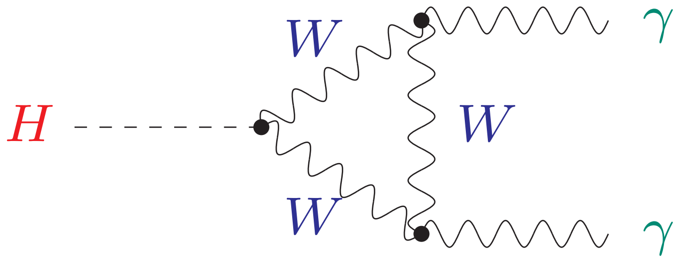
with $\delta_{W,Z} = 2, 1$

off-shell decay width ($M_H < 2 M_V$):

$$\Gamma(H \to VV^*) = \delta'_V \frac{3 G_\mu^2 M_H}{16\,\pi^3} M_V^4 \times \text{Integral}$$

3.) Decay to massless gauge bosons (gg, $\gamma\gamma$):





$$\Gamma(H \to gg) = \frac{G_\mu \, \alpha_s^2(M_H^2) \, M_H^3}{36\sqrt{2}\,\pi^3} \left[1 + C \frac{\alpha_s(\mu)}{\pi} \right]$$

via the top quark loop with

$$C = \frac{215}{12} - \frac{23}{6} \log\left(\frac{\mu^2}{M_H^2}\right) + \mathcal{O}(\alpha_s)$$

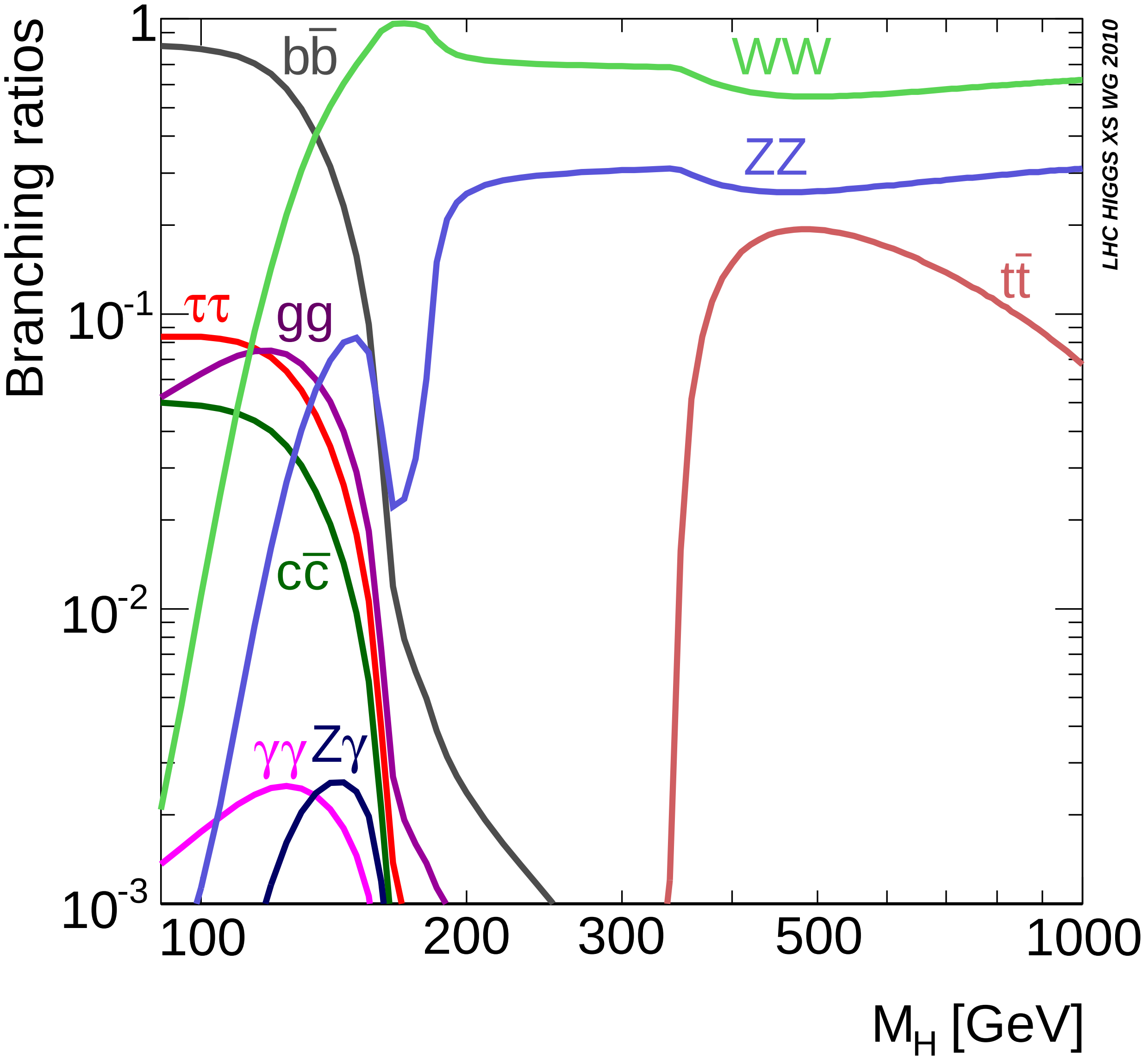
⇒ huge QCD corrections

$$\Gamma(H \to \gamma\gamma) = \frac{G_\mu \, \alpha^2 \, M_H^3}{128\sqrt{2}\,\pi^3} \left| \frac{4}{3} e_t^2 - 7 \right|^2$$

via the top quark and W boson loop

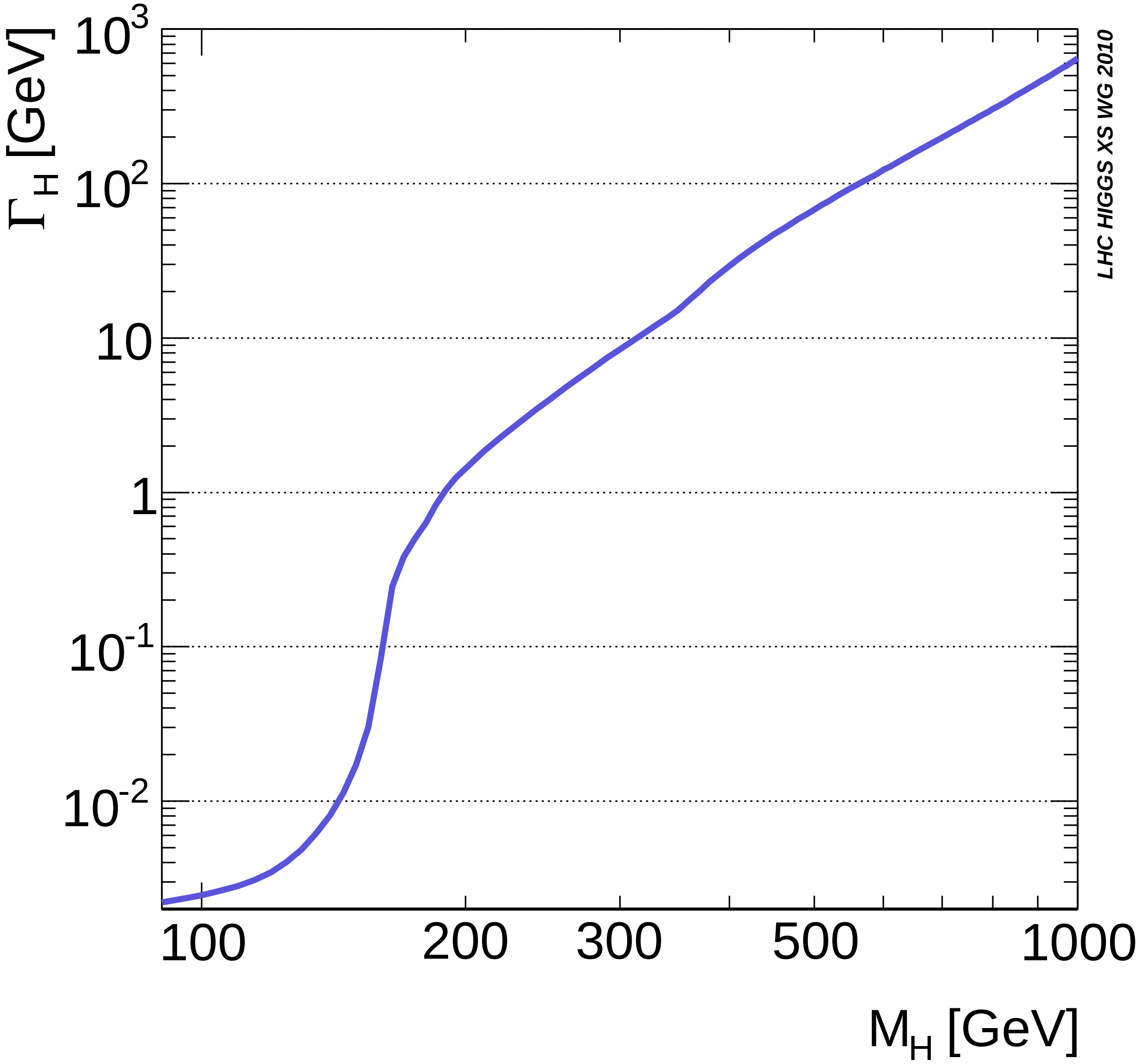
Latest theory predictions for the SM Higgs: branching ratios

[LHC Higgs XS WG '11]



Latest theory predictions for the SM Higgs: total width

[*LHC Higgs XS WG '11*]



SM Higgs at the LHC

Discovering the Higgs boson

What has to be done?

1. Find the new particle

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass ($\Rightarrow$ ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings

Discovering the Higgs boson

What has to be done?

1. Find the new particle
2. measure its mass (⇒ ok?)
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

Discovering the Higgs boson

What has to be done?

1. Find the new particle T
2. measure its mass ($\Rightarrow$ ok?) T
3. measure coupling to gauge bosons
4. measure couplings to fermions
5. measure self-couplings
6. measure spin, . . .

T = Tevatron,

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T	L
2. measure its mass ($\Rightarrow$ ok?)	T	L
3. measure coupling to gauge bosons		L
4. measure couplings to fermions		L
5. measure self-couplings		
6. measure spin, . . .		

T = Tevatron, L = LHC,

Discovering the Higgs boson

What has to be done?

1. Find the new particle	T	L	I
2. measure its mass ($\Rightarrow$ ok?)	T	L	I
3. measure coupling to gauge bosons		L	I
4. measure couplings to fermions		L	I
5. measure self-couplings			I
6. measure spin, . . .		L	I

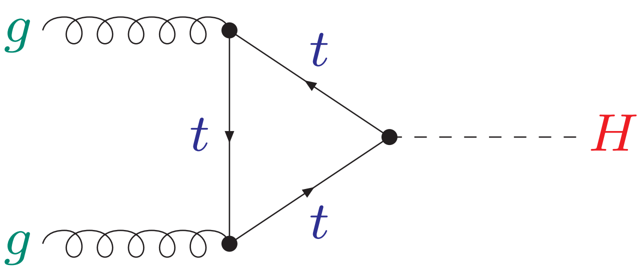
T = Tevatron, L = LHC, I = ILC

We need the ILC to find the Higgs
and to establish the Higgs mechanism!
But the LHC can do a crucial part already!

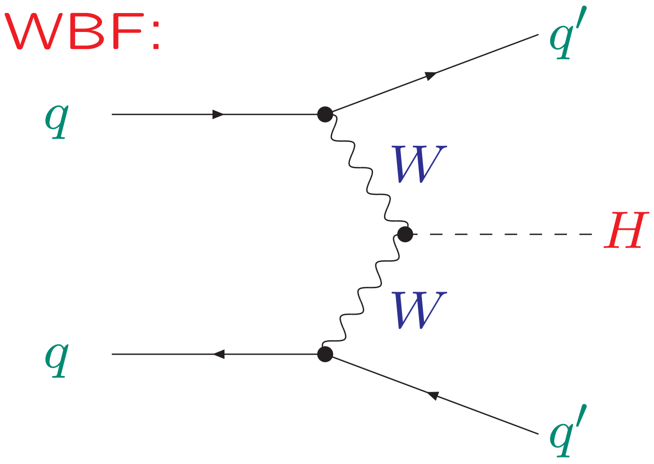
Higgs search at the LHC:

Important SM production channel at the LHC:

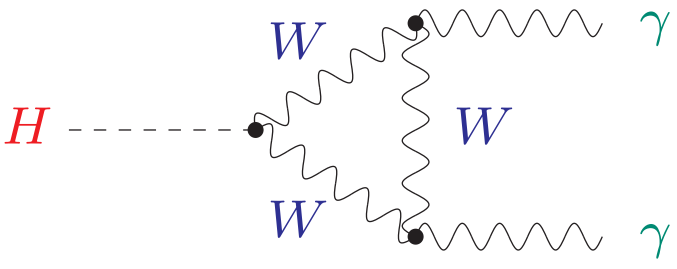
Gluon-Fusion:

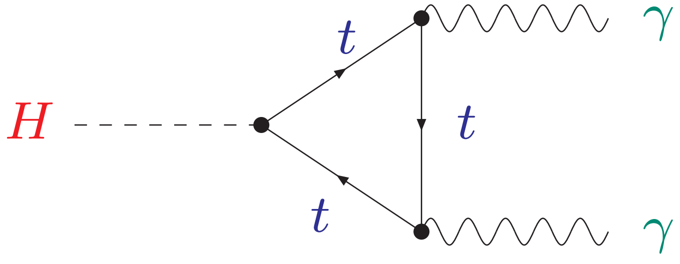


WBF:



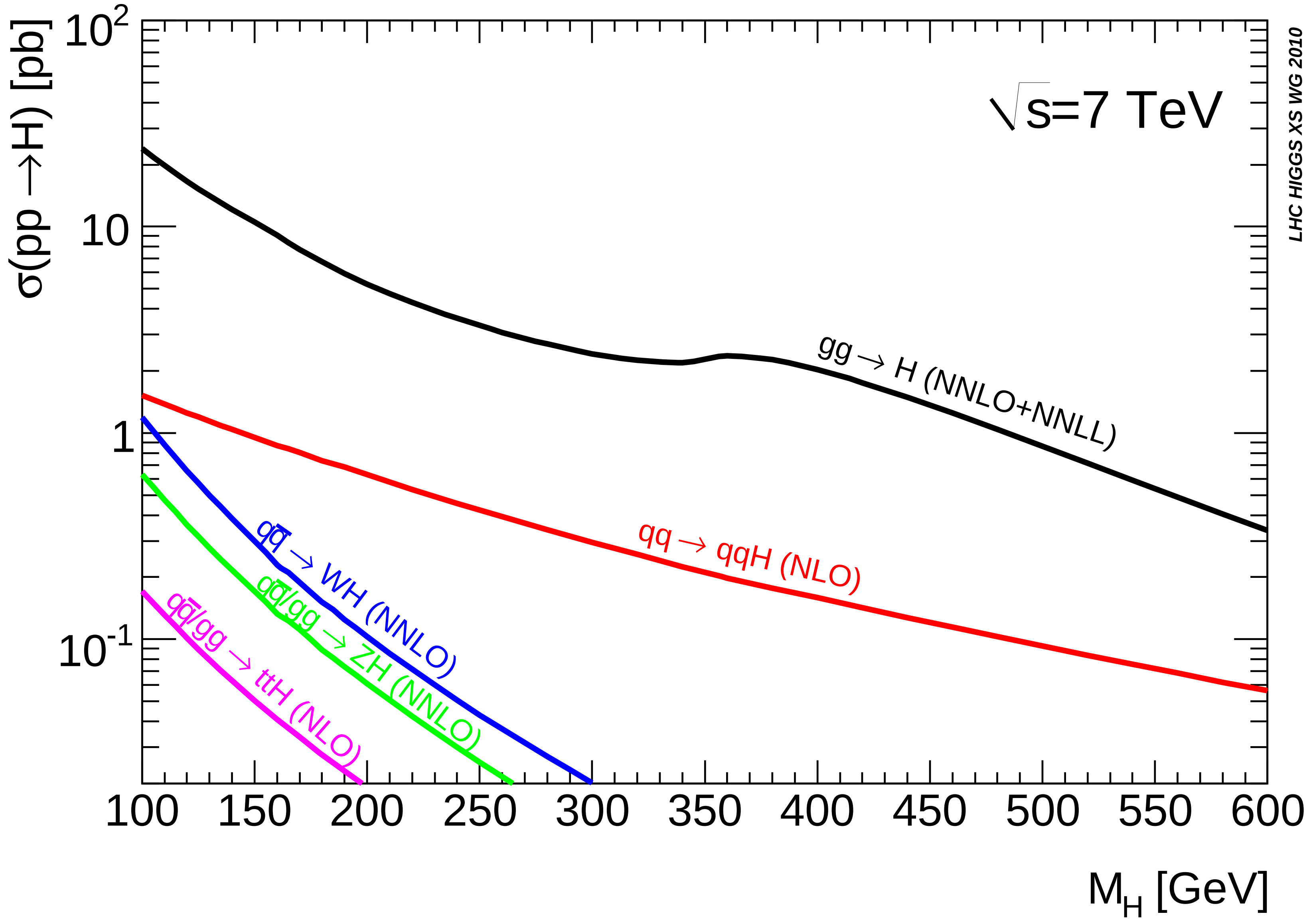
Important decay for Higgs mass measurement:





Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG ’11*]



LHC Higgs Cross Section Working Group

`https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections`

- Mixed group of ATLAS/CMS experimentalists and theorists (crucial!)

- Subgroups for each LHC Higgs production cross section or BRs

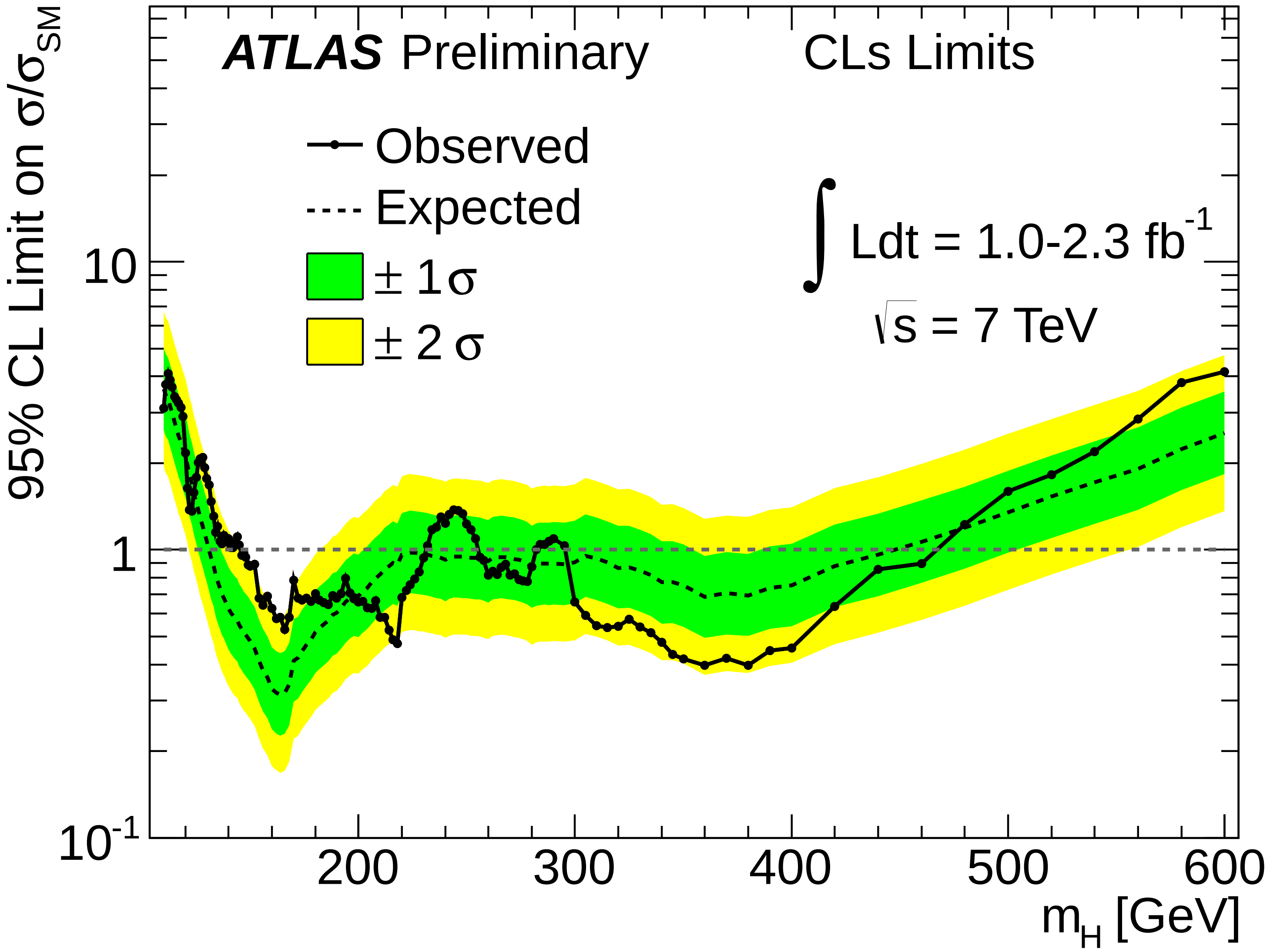
- Goal: obtain best theory predictions to facilitate
  - "best" Higgs boson search
  - "best" combination of ATLAS and CMS
  - "best" extraction of parameters

- Much to do for theorists:
  - improve cross section/BR calculation
  - calculation of distributions
  - extract/fit Higgs couplings
  - ...

- ⇒ more workforce always appreciated!

Latest ATLAS results in search for a SM Higgs:

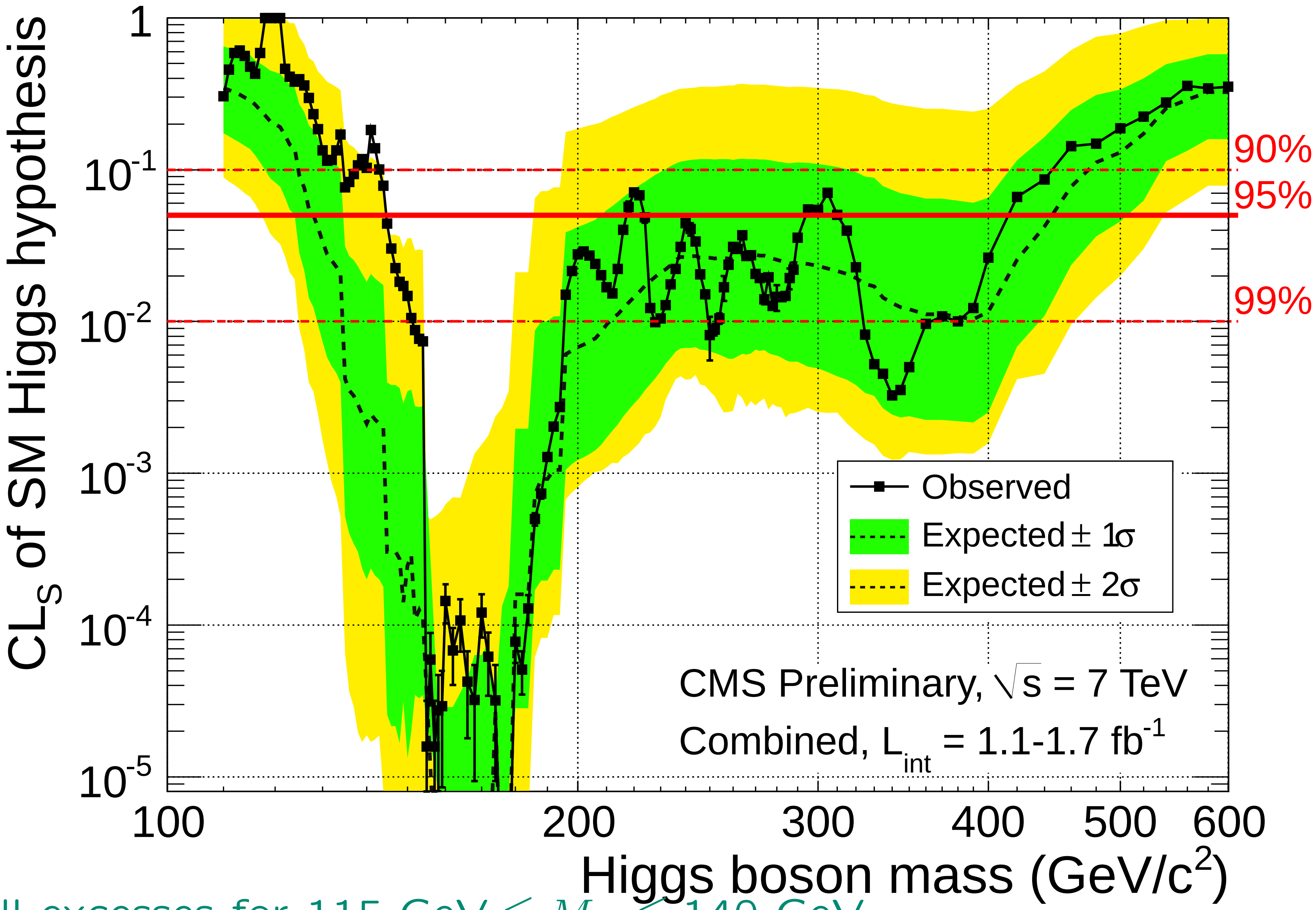
[ATLAS '11]



⇒ small excesses for 115 GeV $\lesssim M_H \lesssim$ 140 GeV

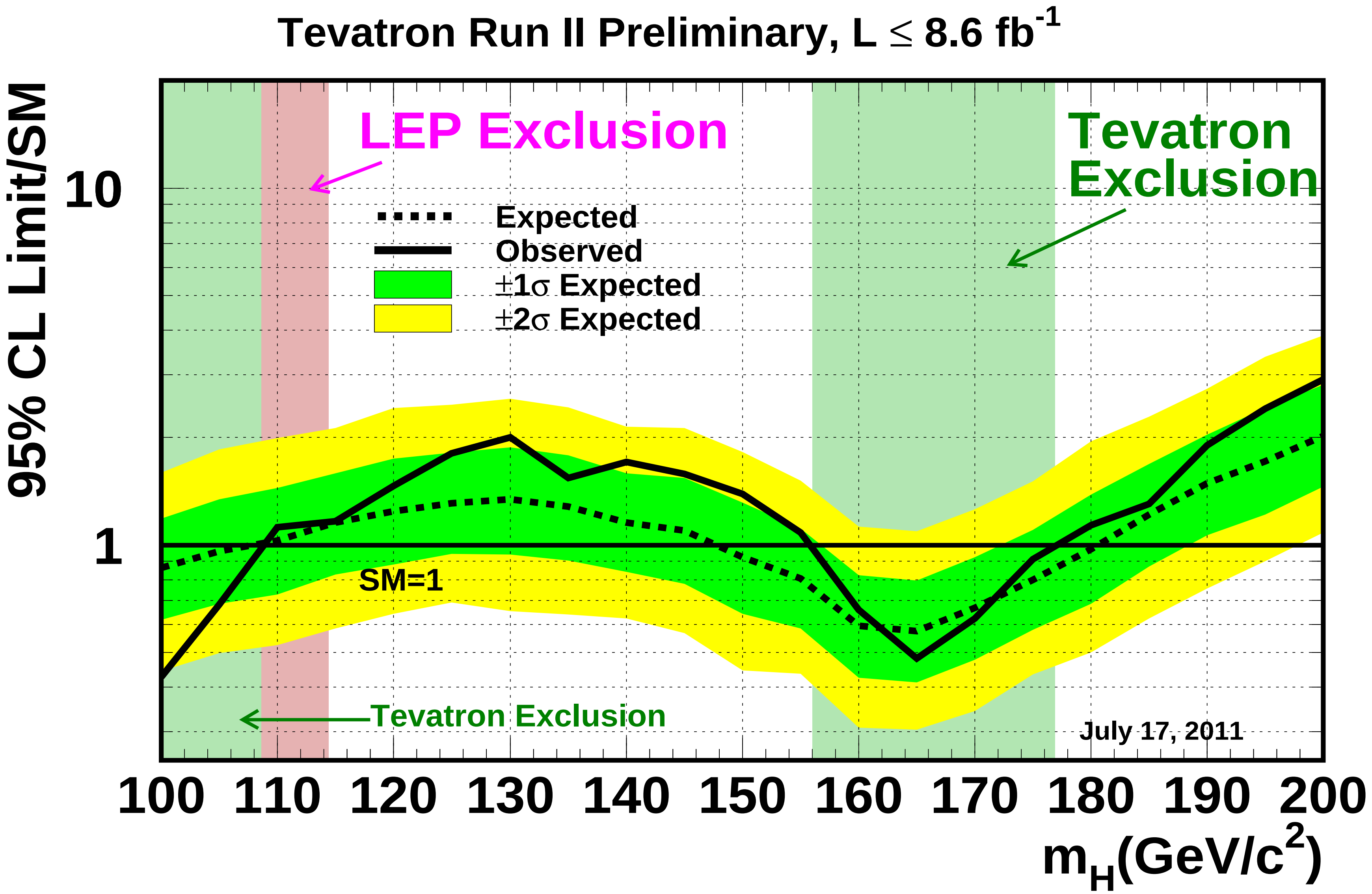
Latest CMS results in search for a SM Higgs:

[CMS '11]



⇒ small excesses for 115 GeV $\lesssim M_H \lesssim$ 140 GeV

Latest Tevatron results in search for a SM Higgs: [CDF/DØ'11]



⇒ small excesses for 115 GeV $\lesssim M_H \lesssim$ 150 GeV

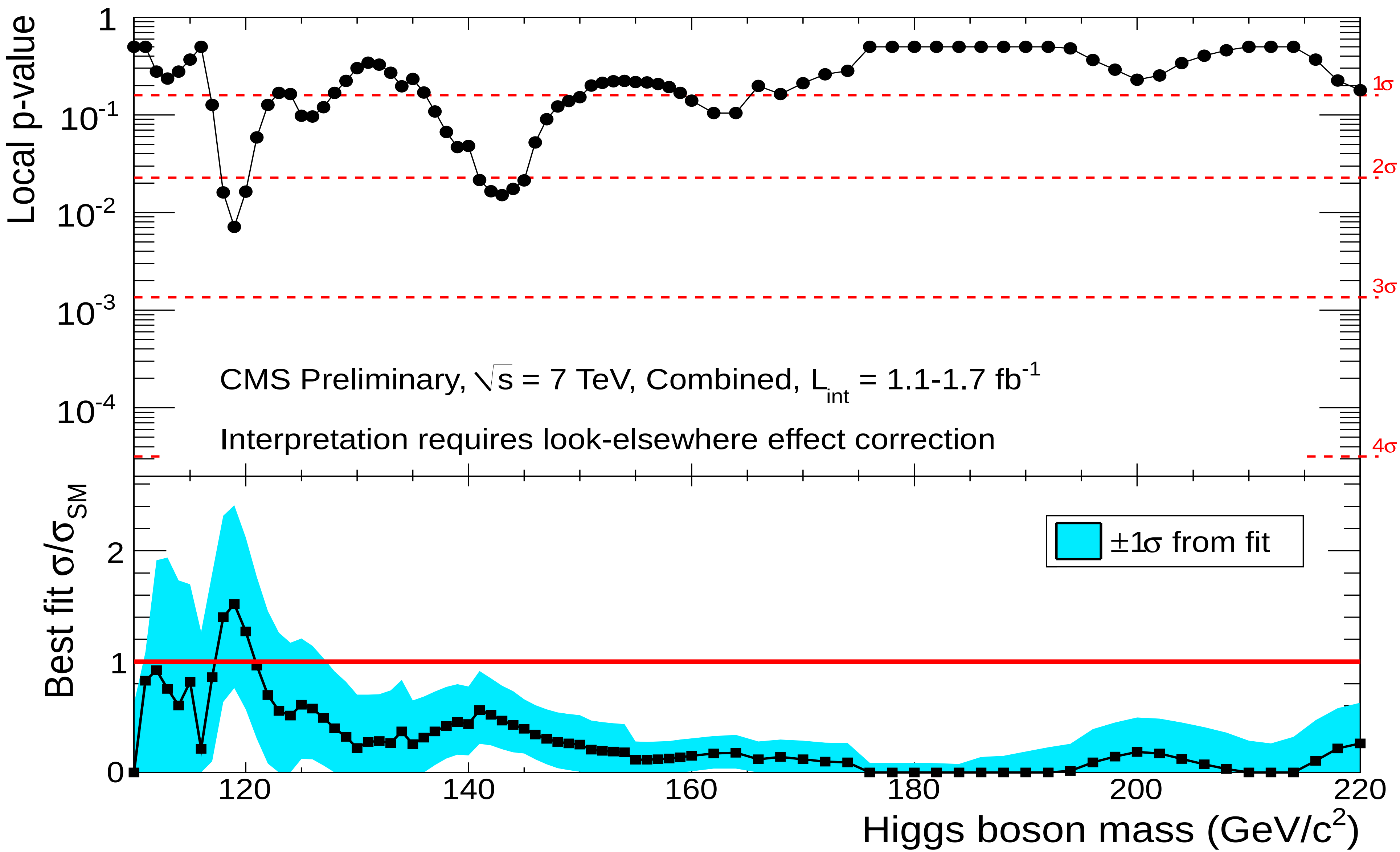
Results for the combination of all experiments:

Results for the combination of all experiments:

Combination does not exist :-(

What to look out for? p_0 and μ

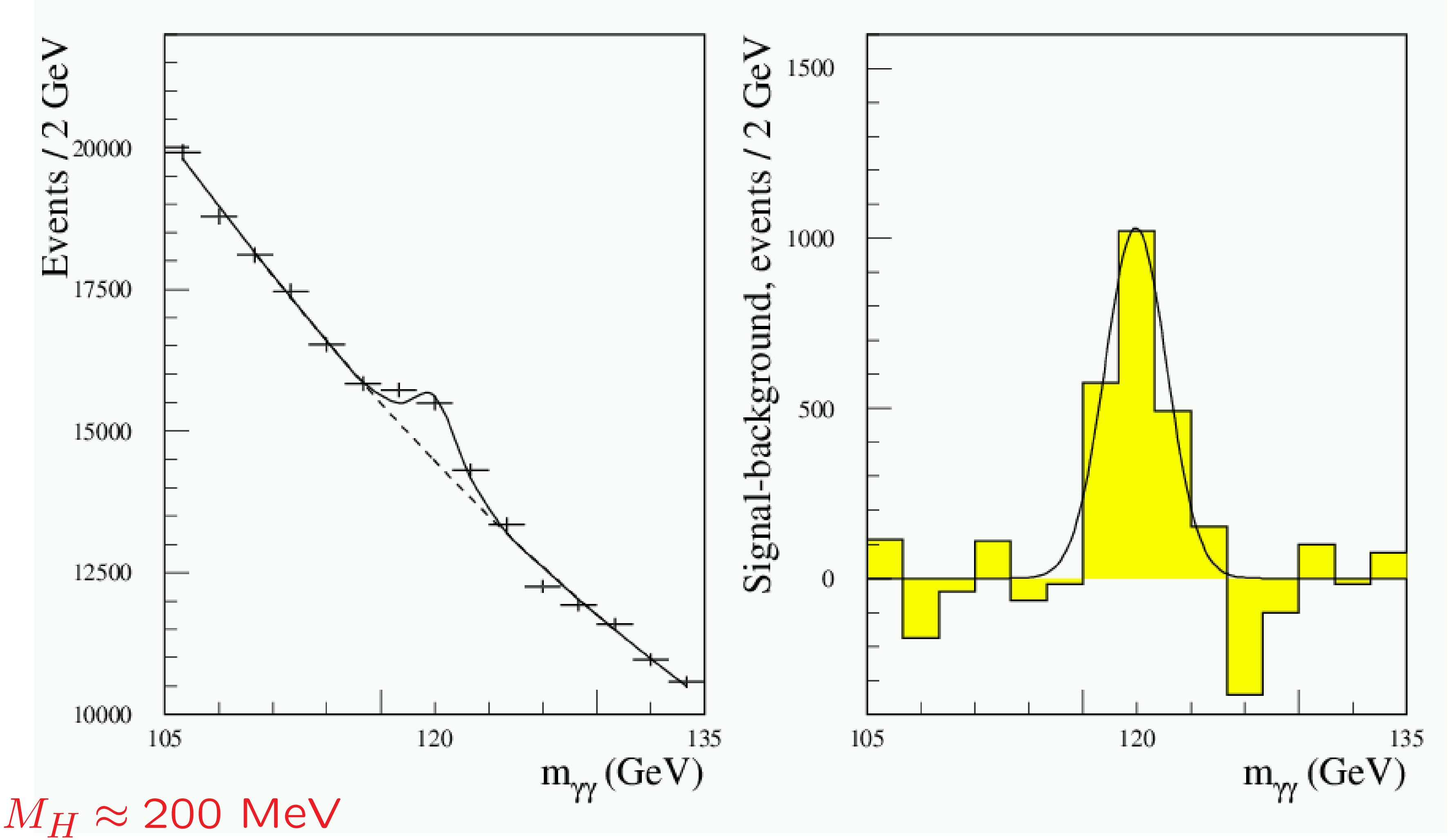
[*CMS '11*]



⇒ only the combined information tells us about the SM Higgs

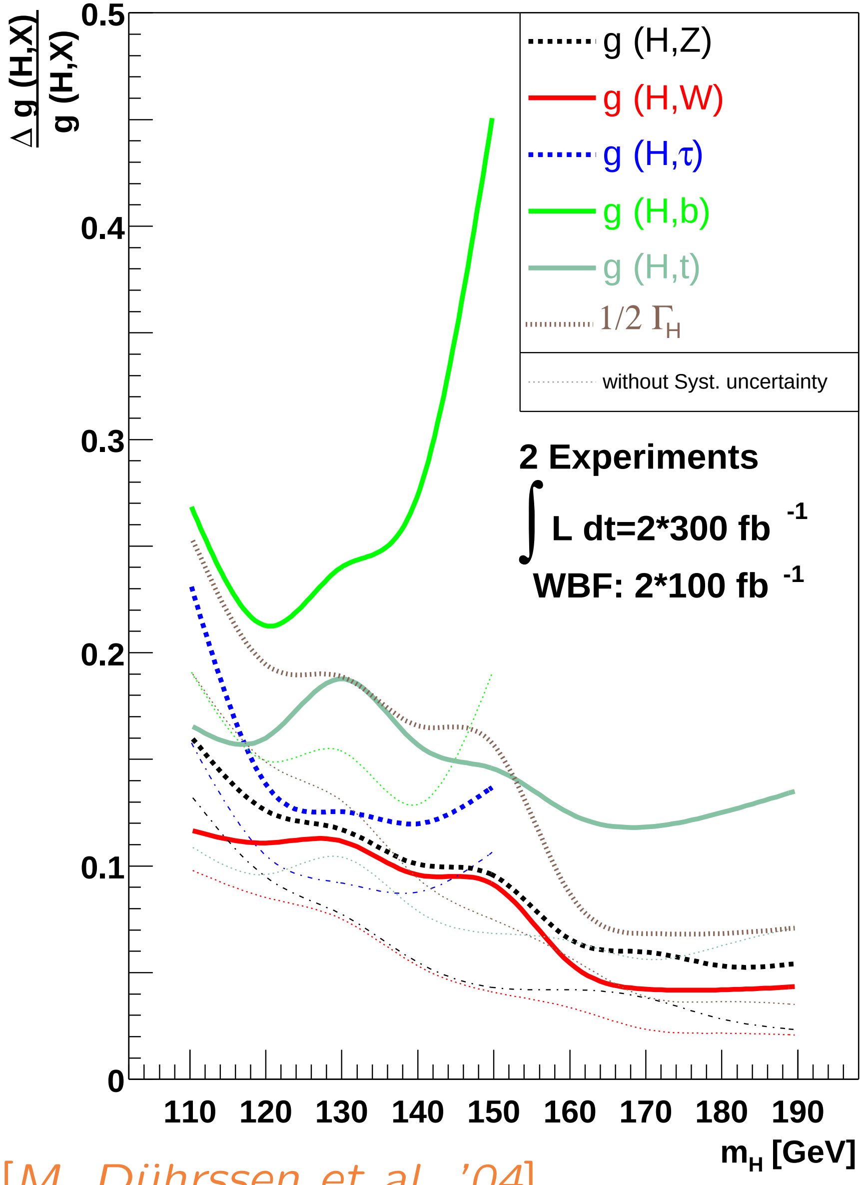
Step 2: Measurement of the mass

Best channel for mass measurement in the SM: $H \to \gamma\gamma$
[*ATLAS '99*]



$\Rightarrow \delta M_H \approx$ 200 MeV

Step 3,4: Higgs couplings at the LHC (older analysis):



[M. Dührssen et al. '04]

- mass: $\delta M_h \approx$ 200 MeV
- couplings: $(2*300+2*100)$ fb^{-1} :

  typical accuracies of 20-30%
  for $m_H \leq$ 150 GeV

  10% accuracies for HVV couplings
  above WW threshold

Assumption:

- $g^2_{HVV} \leq g^2_{HVV,\text{SM}} \times 1.05$
- SM rates for the Higgs

Problems:

- old $t\bar{t}H, H \to b\bar{b}$ studies used
- valid in weakly interacting models
- rates much lower than in SM ??
- physics can/will hide in 5% margin
- self-couplings out of reach

Higgs coupling measurement at the LHC

[*LHC2FC '09*]

Assuming that $(g_{HVV})^2 \le (g^{\rm SM}_{HVV})^2 \times 1.05$ yields for 10 fb^{-1} at 14 TeV:

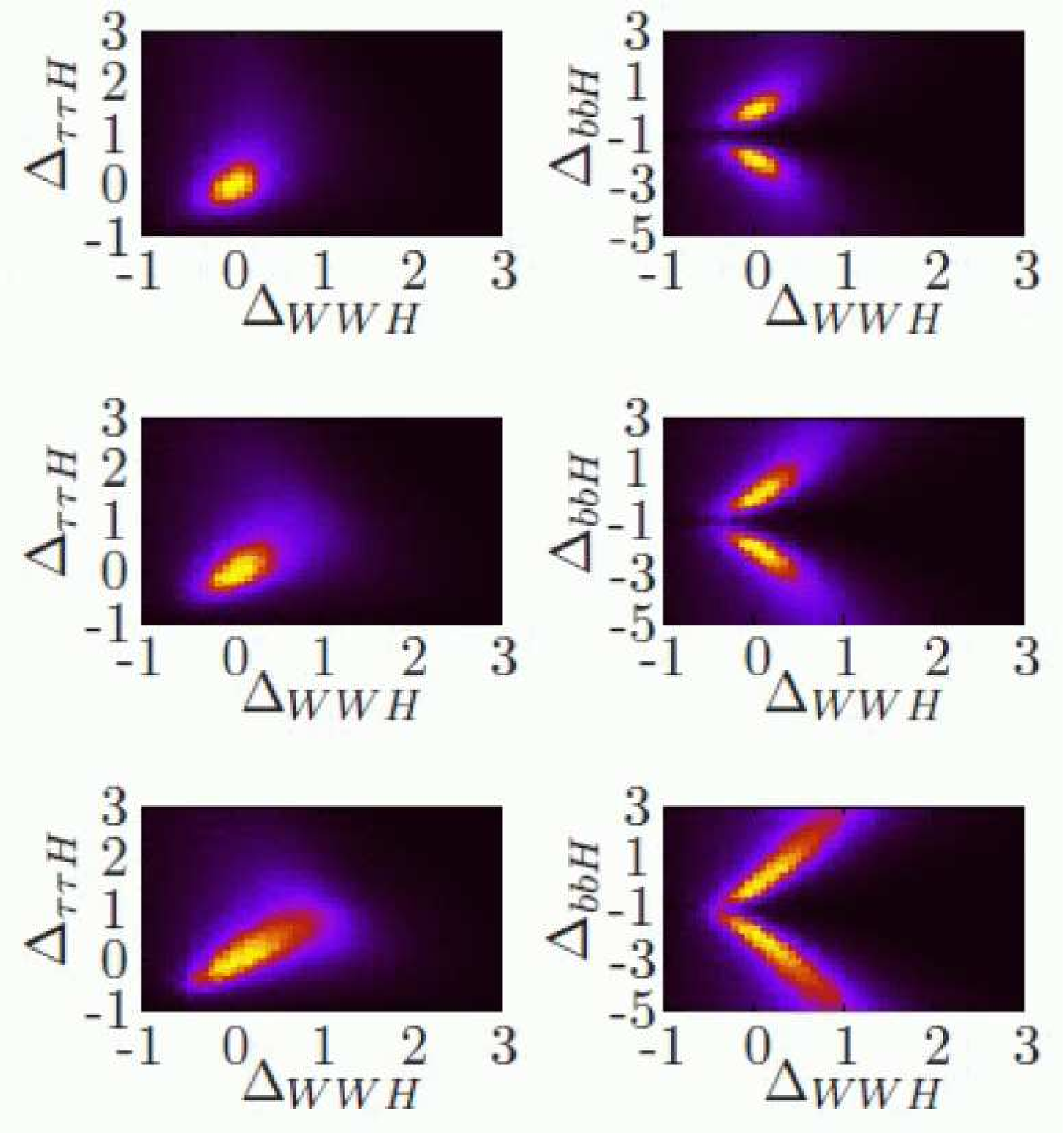
channel / M_H [GeV]	120	130	140	150	160	170	180	190
g_{HWW}	29%	25%	20%	14%	9%	8%	8%	9%
g_{HZZ}	30%	27%	21%	16%	15%	19%	14%	11%
$g_{H\tau\tau}$	63%	39%	38%	50%				
g_{Hbb}	72%	54%	56%	73%				
g_{Htt}	87%	62%	45%	36%	31%	32%	36%	45%
Γ_H		77%	60%	42%	27%	25%	26%	29%
$\Gamma_{\rm inv}/\Gamma_H$	81%	72%	56%	39%	23%	20%	22%	24%

⇒ interesting, but not too convincing . . .

⇒ a lot of physics can hide in these uncertainties

higher luminosity?

Impact of $H \to b\bar{b}$ analyses:



old: $t\bar{t}H, H \to b\bar{b}$
no longer viable :-(

new(er) idea:
$WH, H \to b\bar{b}$ in boosted system
[*Butterworth et al. '08*]

partially confirmed
by ATLAS

Impact: [*SFitter '09*]
$Hb\bar{b}$ crucial!

2. MSSM Higgs

Supersymmetry (SUSY) : Symmetry between

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q \;|\text{Fermion}\rangle \rightarrow |\text{Boson}\rangle$$
$$Q \;|\text{Boson}\rangle \rightarrow |\text{Fermion}\rangle$$

Simplified examples:

$$Q \;|\text{top}, \; t\rangle \rightarrow |\text{scalar top}, \; \tilde{t}\rangle$$
$$Q \;|\text{gluon}, \; g\rangle \rightarrow |\text{gluino}, \; \tilde{g}\rangle$$

⇒ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}}$ ⇒ SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})}$

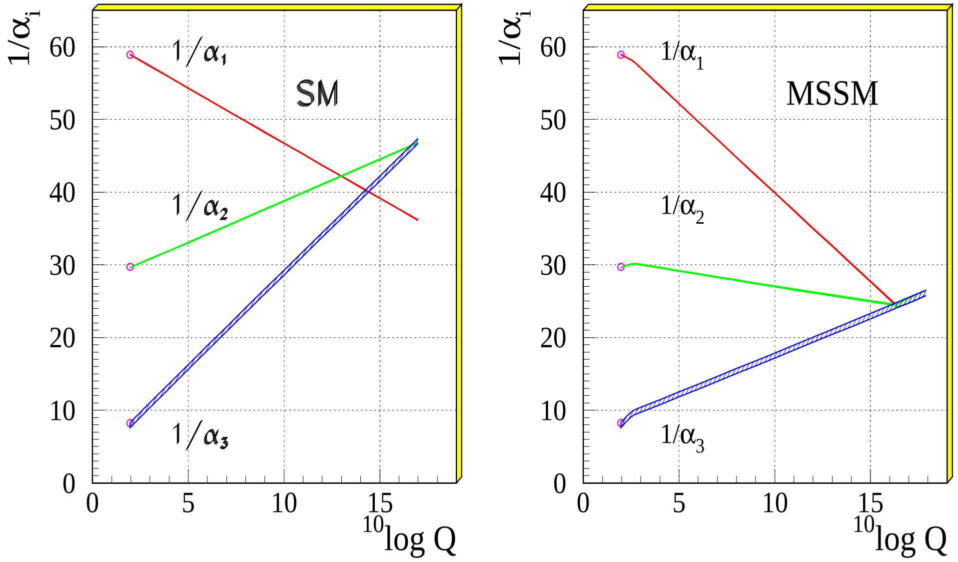
Supersymmetry: Motivation

The SM is in a pretty good shape.

Why MSSM? (Is it worth to double the particle spectrum?)

1.) Stability of the Higgs mass against higher-order corr.
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)
3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs
4.) SUSY provides CDM candidate
5.) . . .

Unification of the Coupling Constants
in the SM and the minimal MSSM



[*Amaldi, de Boer, Fürstenau ’92*]

Particle content of the MSSM:

Superpartners for Standard Model particles:

$$\Big[u, d, c, s, t, b\Big]_{L,R} \quad \Big[e, \mu, \tau\Big]_{L,R} \quad \Big[\nu_{e,\mu,\tau}\Big]_L \qquad \text{Spin } \tfrac{1}{2}$$

$$\Big[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\Big]_{L,R} \quad \Big[\tilde{e}, \tilde{\mu}, \tilde{\tau}\Big]_{L,R} \quad \Big[\tilde{\nu}_{e,\mu,\tau}\Big]_L \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector:
Two Higgs doublets, physical states: $h^0, H^0, A^0, H^{\pm}$

as usual: Breaking of SU(2) × U(1)$_Y$ (electroweak symmetry breaking)

⇒ fields with different SU(2) × U(1)$_Y$ quantum numbers can mix if they have the same SU(3)$_c$, U(1)$_{\text{em}}$ quantum numbers

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets

$$
\begin{aligned}
H_1 &= \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix} \\
H_2 &= \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}
\end{aligned}
$$

$$
\begin{aligned}
V &= m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\
&\quad + \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}\, |H_1 \bar{H}_2|^2
\end{aligned}
$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

Squark mixing:

Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

off-diagonal element prop. to mass of partner quark ($\tan\beta \equiv v_u/v_d$)

⇒ mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

gauge invariance ⇒ $M_{\tilde{t}_L} = M_{\tilde{b}_L}$

⇒ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

⇒ prediction for collider phenomenology!

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix} \qquad \tan(2\alpha) = \tan(2\beta)\frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}$$

$$\begin{pmatrix} G^0 \\ A^0 \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \chi_1^0 \\ \chi_2^0 \end{pmatrix}, \quad \begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

Three Goldstone bosons (as in SM): G^0, $G^\pm$

$\longrightarrow$ longitudinal components of $W^\pm$, Z

$\Rightarrow$ Five physical states: $h^0, H^0, A^0, H^\pm$

h, H: neutral, $\mathcal{CP}$-even, A^0: neutral, $\mathcal{CP}$-odd, $H^\pm$: charged

Gauge-boson masses:

$$M_W^2 = \frac{1}{2}g'^2(v_1^2 + v_2^2), \quad M_Z^2 = \frac{1}{2}(g^2 + g'^2)(v_1^2 + v_2^2), \quad M_\gamma = 0$$

Parameters in MSSM Higgs potential V (besides g, g'):

$$v_1,\ v_2,\ m_1,\ m_2,\ m_{12}$$

relation for M_W^2, M_Z^2 $\Rightarrow$ 1 condition

minimization of V w.r.t. neutral Higgs fields H_1^1, H_2^2 $\Rightarrow$ 2 conditions

$\Rightarrow$ only two free parameters remain in V, conventionally chosen as

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2(\tan\beta + \cot\beta)$$

$\Rightarrow$ m_h, m_H, mixing angle α, $m_{\mathrm{H}^\pm}$: no free parameters, can be predicted

In lowest order:

$$m_{\mathrm{H}^\pm}^2 = M_A^2 + M_W^2$$

Predictions for m_h, m_H from diagonalization of tree-level mass matrix:

$\phi_1 - \phi_2$ basis:

$$M^{2,\text{tree}}_{\text{Higgs}} = \begin{pmatrix} m^2_{\phi_1} & m^2_{\phi_1\phi_2} \\ m^2_{\phi_1\phi_2} & m^2_{\phi_2} \end{pmatrix} =$$

$$\begin{pmatrix} M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta & -(M_A^2 + M_Z^2)\sin\beta\cos\beta \\ -(M_A^2 + M_Z^2)\sin\beta\cos\beta & M_A^2 \cos^2\beta + M_Z^2 \sin^2\beta \end{pmatrix}$$

$$\Big\Downarrow \quad \longleftarrow \ \text{Diagonalization}, \alpha$$

$$\begin{pmatrix} m_H^{2,\text{tree}} & 0 \\ 0 & m_h^{2,\text{tree}} \end{pmatrix}$$

Tree-level result for m_h, m_H:

$$m^2_{H,h} = \frac{1}{2}\left[M_A^2 + M_Z^2 \pm \sqrt{(M_A^2 + M_Z^2)^2 - 4 M_Z^2 M_A^2 \cos^2 2\beta}\right]$$

$\Rightarrow$ $m_h \le M_Z$ at tree level

$\Rightarrow$ Light Higgs boson h required in SUSY

Measurement of m_h, Higgs couplings

$\Rightarrow$ test of the theory (more directly than in SM)

The lightest MSSM Higgs boson

MSSM predicts upper bound on M_h:

tree-level bound: $m_h < M_Z$, excluded by LEP Higgs searches!

Large radiative corrections:

Yukawa couplings: $\frac{\mathrm{e}\, m_t}{2 M_W s_\mathrm{W}}, \frac{\mathrm{e}\, m_t^2}{M_W s_\mathrm{W}}, \ldots$

$\Rightarrow$ Dominant one-loop corrections: $\Delta M_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

> The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector)

Present status of M_h prediction in the MSSM:

Complete one-loop and ‘almost complete’ two-loop result available

Upper bound on M_h in the MSSM:

"Unconstrained MSSM":

M_A, $\tan\beta$, 5 parameters in $\tilde{t}$–$\tilde{b}$ sector, μ, $m_{\tilde{g}}$, M_2

$$\boxed{M_h \lesssim 135 \text{ GeV}}$$

for $m_t = 173.2 \pm 0.9\,\text{GeV}$

(including theoretical uncertainties from unknown higher orders)
⇒ observable at the LHC

Obtained with:

FeynHiggs

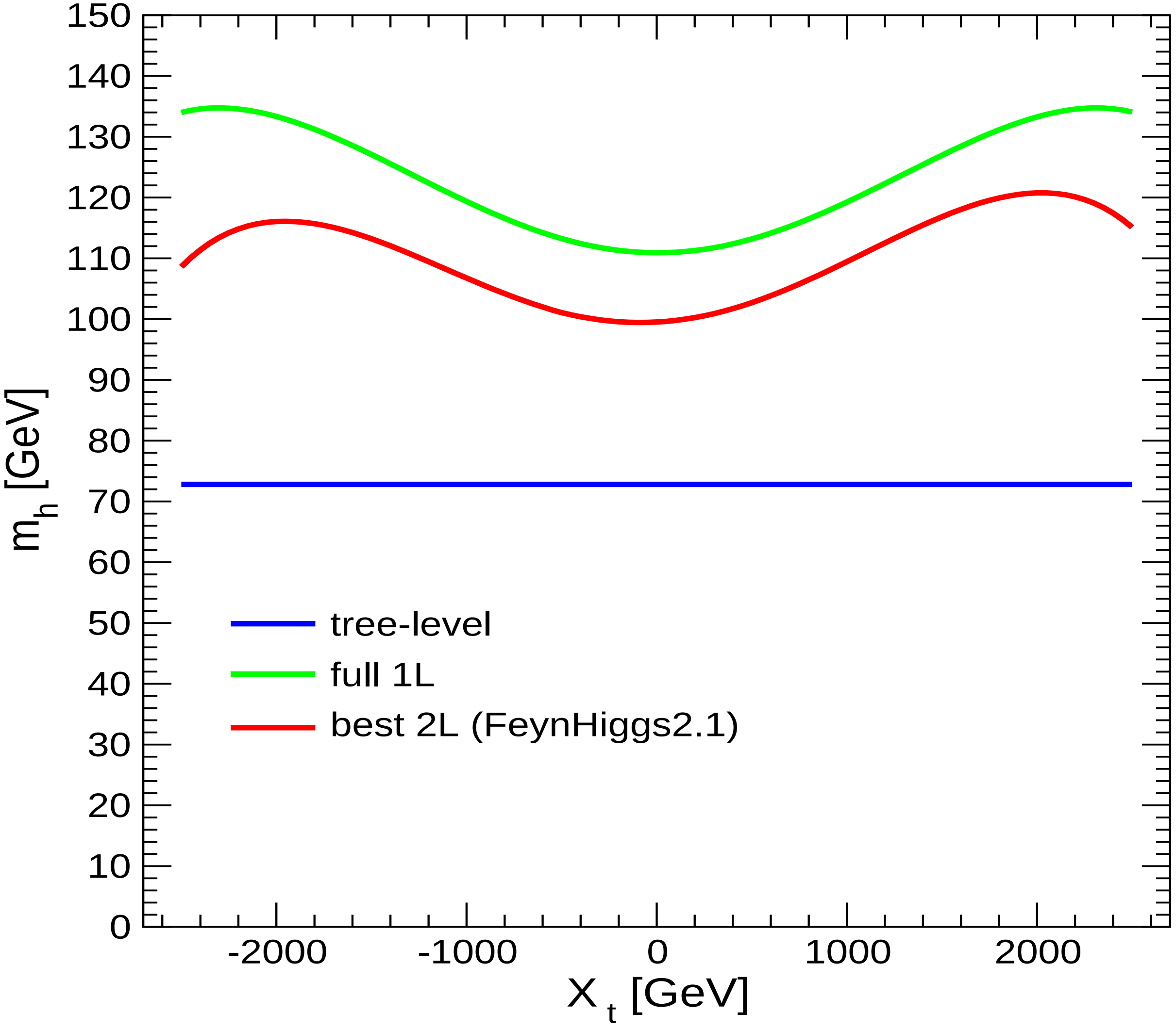
`www.feynhiggs.de`

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein K. Williams '98 – '11*]

→ all Higgs masses, couplings, BRs, XSs (easy to link, easy to use :-)

Effects of the two-loop corrections to the lightest Higgs mass:

Example for one set of MSSM parameters



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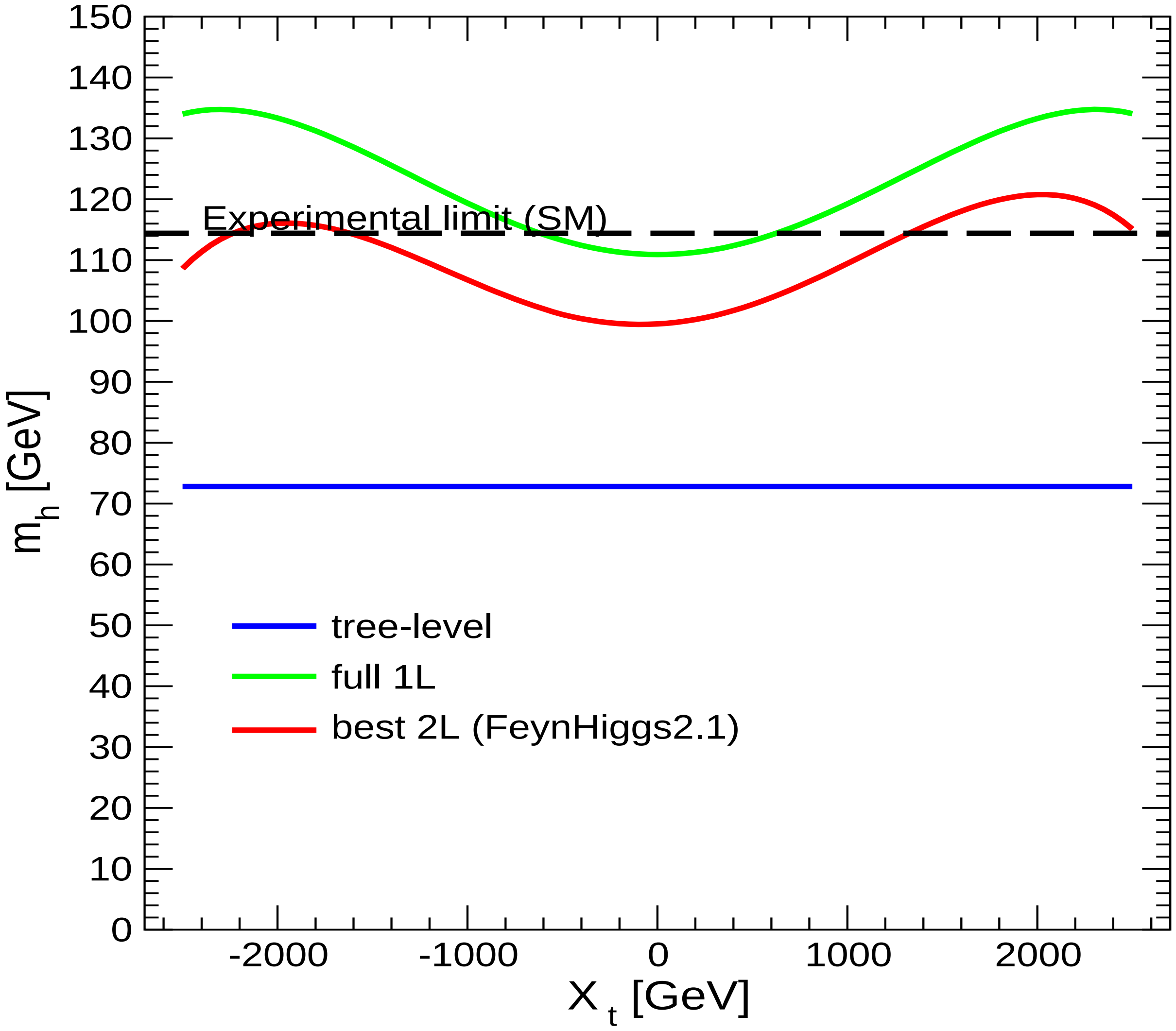


Comparison with experimental limits

⇒ strong impact on bound on SUSY parameters

Higgs couplings, tree level:

$$
\begin{aligned}
g_{hVV} &= \sin(\beta-\alpha)\, g_{HVV}^{\text{SM}}, \qquad V = W^{\pm}, Z \\
g_{HVV} &= \cos(\beta-\alpha)\, g_{HVV}^{\text{SM}} \\
g_{hAZ} &= \cos(\beta-\alpha)\, \frac{g'}{2\cos\theta_W} \\
g_{hb\bar{b}}, g_{h\tau^+\tau^-} &= -\frac{\sin\alpha}{\cos\beta}\, g_{Hb\bar{b},H\tau^+\tau^-}^{\text{SM}} \\
g_{ht\bar{t}} &= \frac{\cos\alpha}{\sin\beta}\, g_{Ht\bar{t}}^{\text{SM}} \\
g_{Ab\bar{b}}, g_{A\tau^+\tau^-} &= \gamma_5 \tan\beta\, g_{Hb\bar{b}}^{\text{SM}}
\end{aligned}
$$

⇒ $g_{hVV} \le g_{HVV}^{\text{SM}}$, g_{hVV}, g_{HVV}, g_{hAZ} cannot all be small

$g_{hb\bar{b}}, g_{h\tau^+\tau^-}$: significant suppression or enhancement w.r.t. SM coupling possible

The decoupling limit:

For $M_A \gtrsim 150$ GeV:

The lightest MSSM Higgs
is SM-like

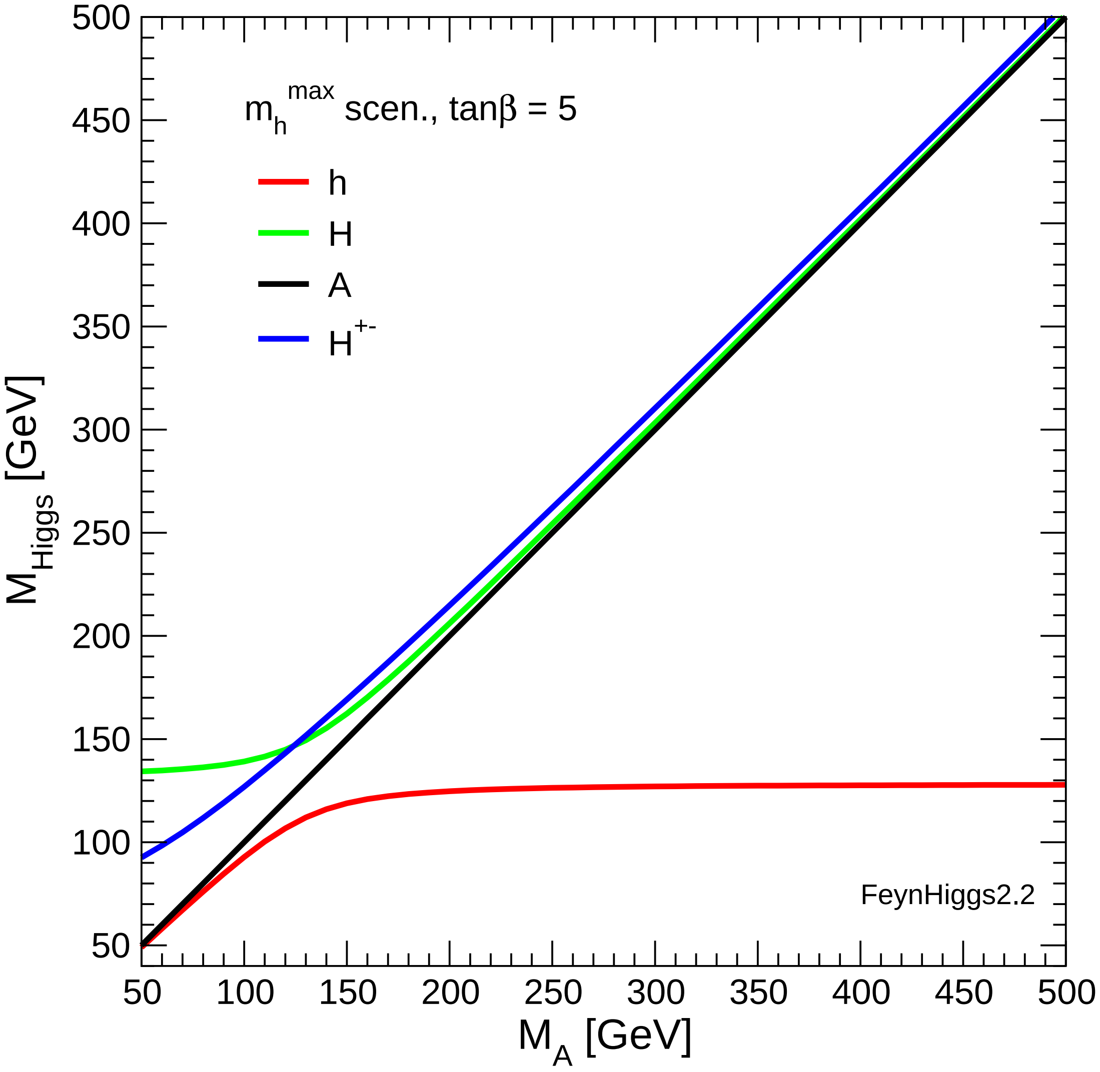
⇒ SM analysis applies!

The heavy MSSM Higgses:

$M_A \approx M_H \approx M_{H^\pm}$

→ coupling to gauge bosons ∼ 0

⇒ no production via WH, . . .



Remaining theoretical uncertainties in prediction for M_h in the MSSM:

[G. Degrassi, S.H., W. Hollik, P. Slavich, G. Weiglein '02]

- From unknown higher-order corrections:
  $\Rightarrow \Delta M_h \approx 3$ GeV

- From uncertainties in input parameters

  $m_t, \ldots, M_A, \tan\beta, m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{g}}, \ldots$

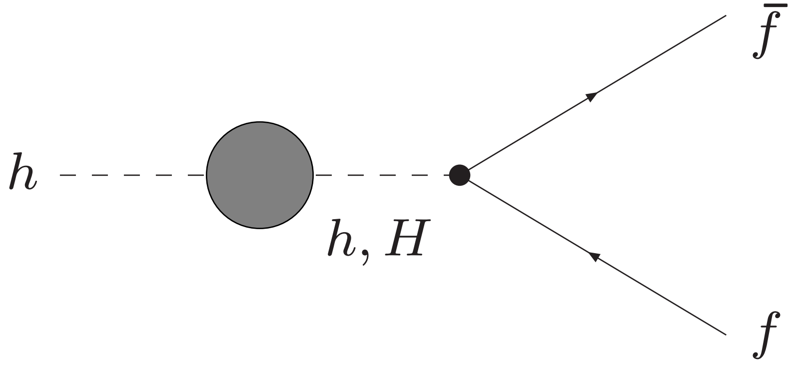
  $\Delta m_t \approx 1$ GeV $\Rightarrow \Delta M_h \approx 1$ GeV

Higgs couplings, production cross sections

$\Rightarrow$ also affected by large SUSY loop corrections

Extreme example: $\Gamma(h \to b\bar{b}) \to 0$ via loop corrections possible

$hf\bar{f}$ coupling:



$$A(h \to f\bar{f}) = \sqrt{Z_h}\left(\Gamma_h - \frac{\hat{\Sigma}_{\mathrm{hH}}(M_h^2)}{M_h^2 - m_H^2 + \hat{\Sigma}_{\mathrm{HH}}(M_h^2)}\Gamma_H\right)$$

⇒ Effective $hf\bar{f}$ coupling can vanish for large $\hat{\Sigma}_{\mathrm{hH}}$

Gluino vertex corrections to $h \to q\bar{q}$:

⇒ ratio $\Gamma(h \to \tau^+\tau^-)/\Gamma(h \to b\bar{b})$ can significantly differ from SM value for large $\tan\beta$

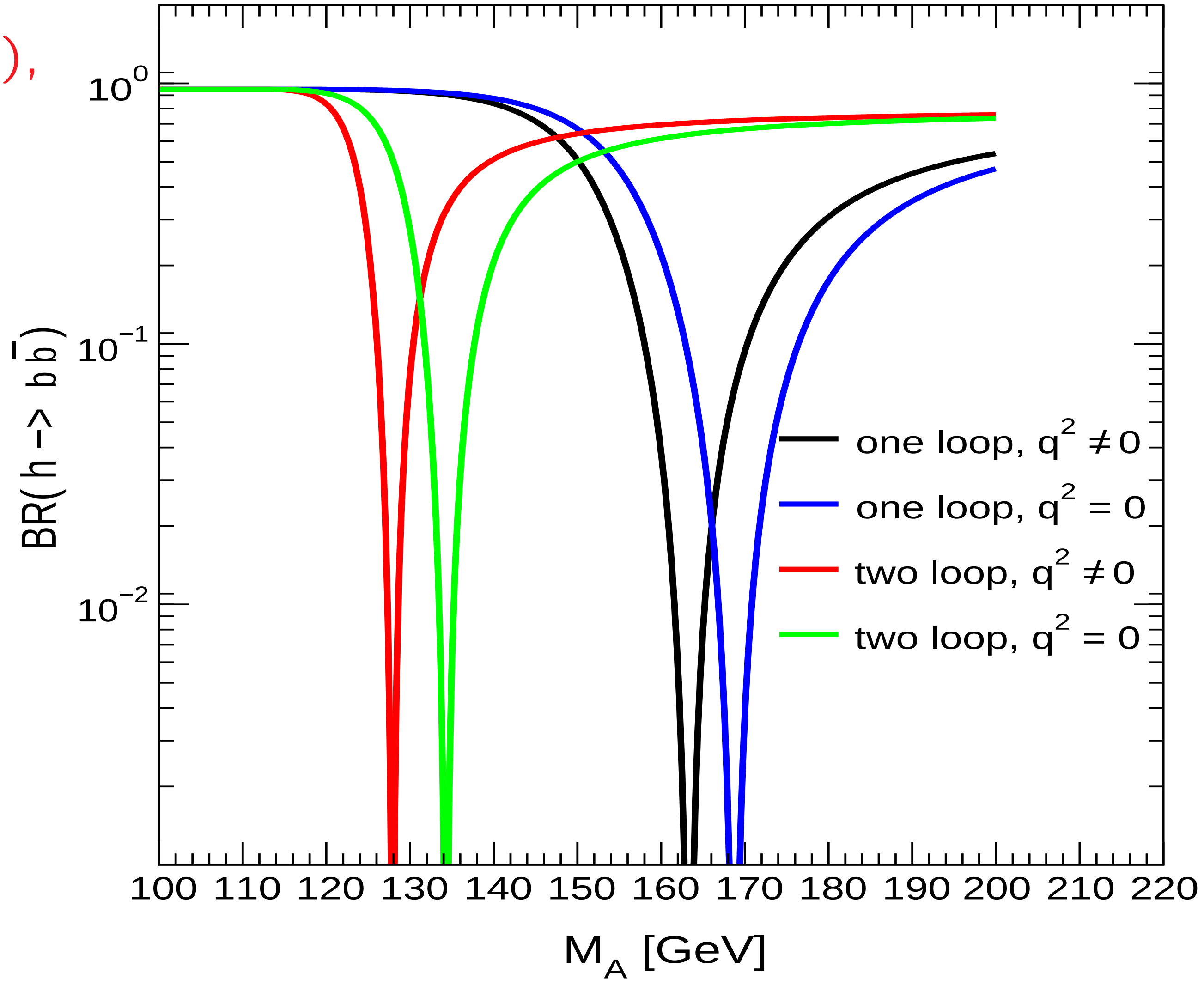
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{\rm hH}$

$\Rightarrow$ "Pathological regions"

[*W. Loinaz, J. Wells '98*] [*M. Carena, S. Mrenna, C. Wagner '99*]

$\Rightarrow$ Suppression of BR($h \to b\bar{b}$),
BR($h \to \tau\tau$), . . .

[*S.H., W. Hollik, G. Weiglein '00*]



MSSM Higgs boson searches at the LHC

Overview about MSSM Higgs boson searches at the LHC:

1. Light MSSM Higgs boson in the decoupling limit:
   → SM Higgs searches apply
   → keep in mind the upper limit of 135 GeV
   ⇒ no limits beyond LEP so far!

2. Light MSSM Higgs boson "before" the decoupling limit:
   → dedicated search necessary
   → SM-like search with reduced couplings
   → $p_0 \oplus \mu$ with reduced $\sigma \times$ BR

3. Hevay MSSM Higgs boson:
   → dedicated search
   ⇒ model independent results on $\sigma \times$ BR
   ⇒ specific MSSM results for H/A

Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

→ investigate benchmark scenarios:

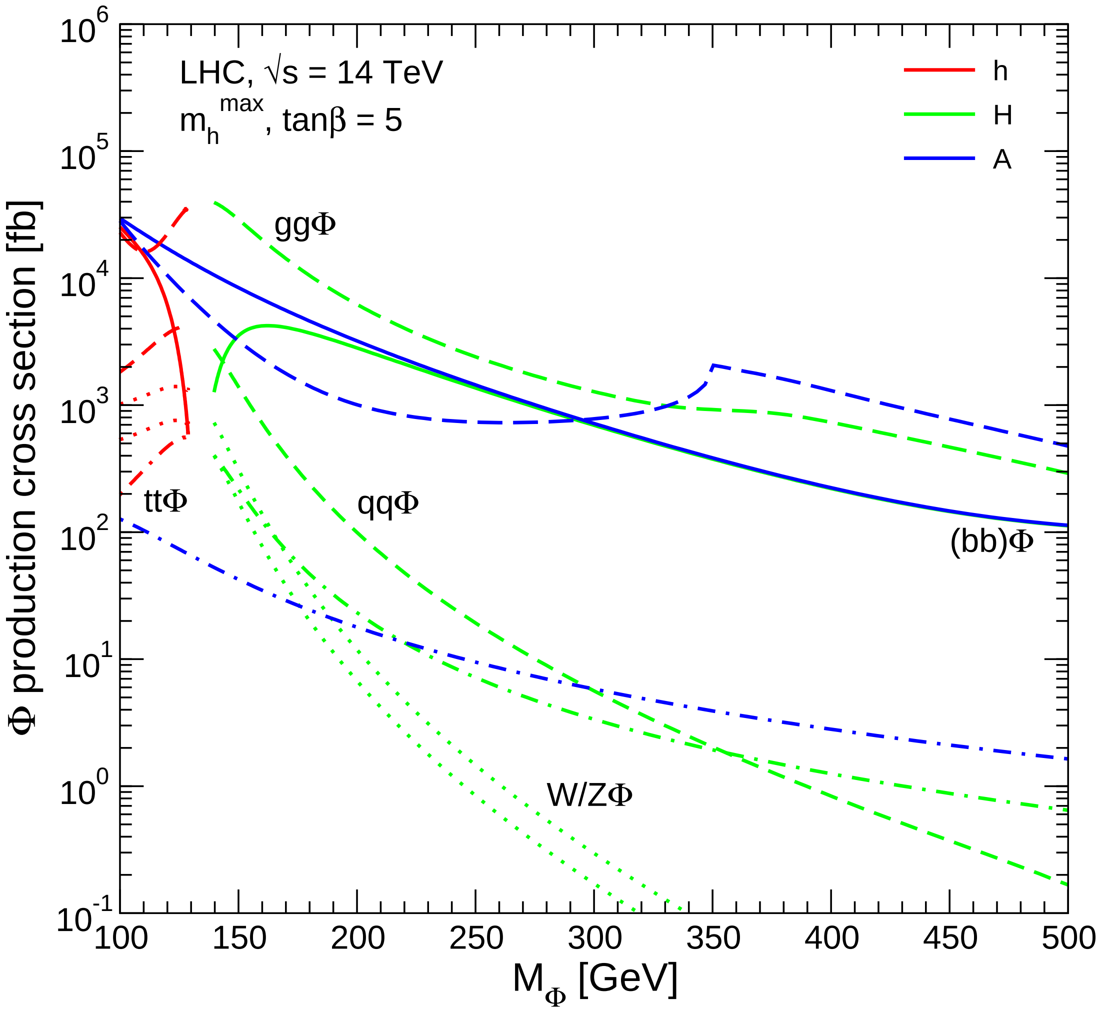
→ Vary only M_A and $\tan\beta$
→ Keep all other SUSY parameters fixed

1. m_h^{max} scenario:
   → obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\text{SUSY}}$)
2. no-mixing scenario
   → no mixing in the scalar top sector ($X_t = 0$)
3. small α_{eff} scenario
   → $hb\bar{b}$ coupling $\sim \sin\alpha_{\text{eff}}/\cos\beta$ can be zero: $\alpha_{\text{eff}} \to 0$:
   main decay mode vanishes, important search channel vanishes
4. gluophobic Higgs scenario
   → hgg coupling is small: main LHC production mode vanishes

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

Overview about SUSY Higgs production cross sections ($\phi = h, H, A$)

[*Tev4LHC Higgs working group report '06*]



gluon fusion: $gg \to \phi$

weak boson fusion (WBF): $q\bar{q} \to q'\bar{q}'\phi$

top quark associated production: $gg, q\bar{q} \to t\bar{t}\phi$

weak boson associated production: $q\bar{q}' \to W\phi, Z\phi$

NEW: $b\bar{b}\phi$

Search for the lightest MSSM Higgs at the LHC:

⇒ full parameter accessible But there might be problems . . .

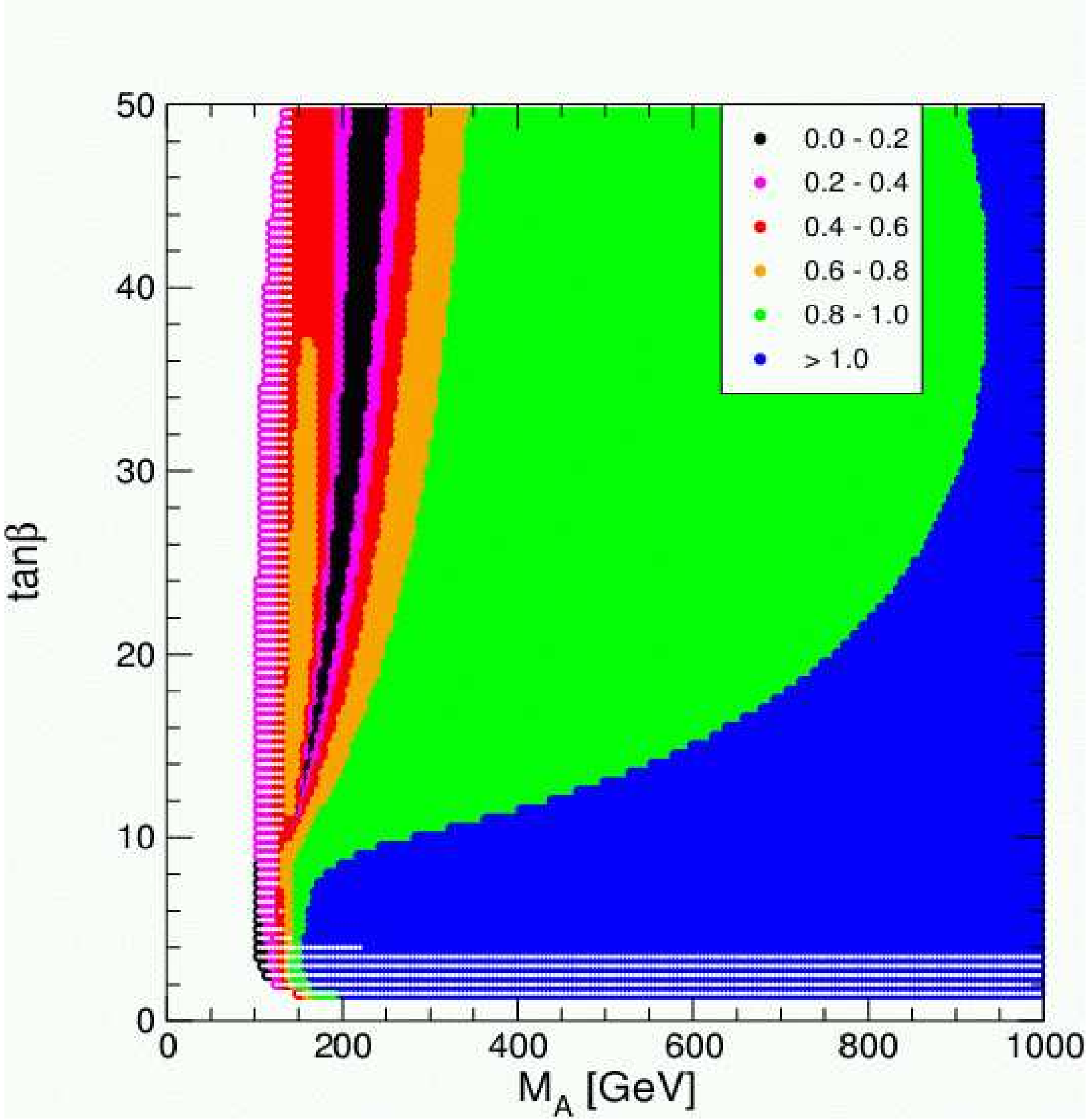
Possible problem in SUSY:

$$h \to b\bar{b}$$

can be strongly suppressed

→ "Small $\alpha_{\rm eff}$ scenario"

[*M. Carena, S.H., C. Wagner,*
G. Weiglein '02]



⇒ Strong suppression of
$h \to b\bar{b}$ possible,
up to $M_A \lesssim 350$ GeV

(not realized in
CMSSM, GMSB, AMSB, . . .)

Possible problem in SUSY:

$$gg \to h \to \gamma\gamma$$

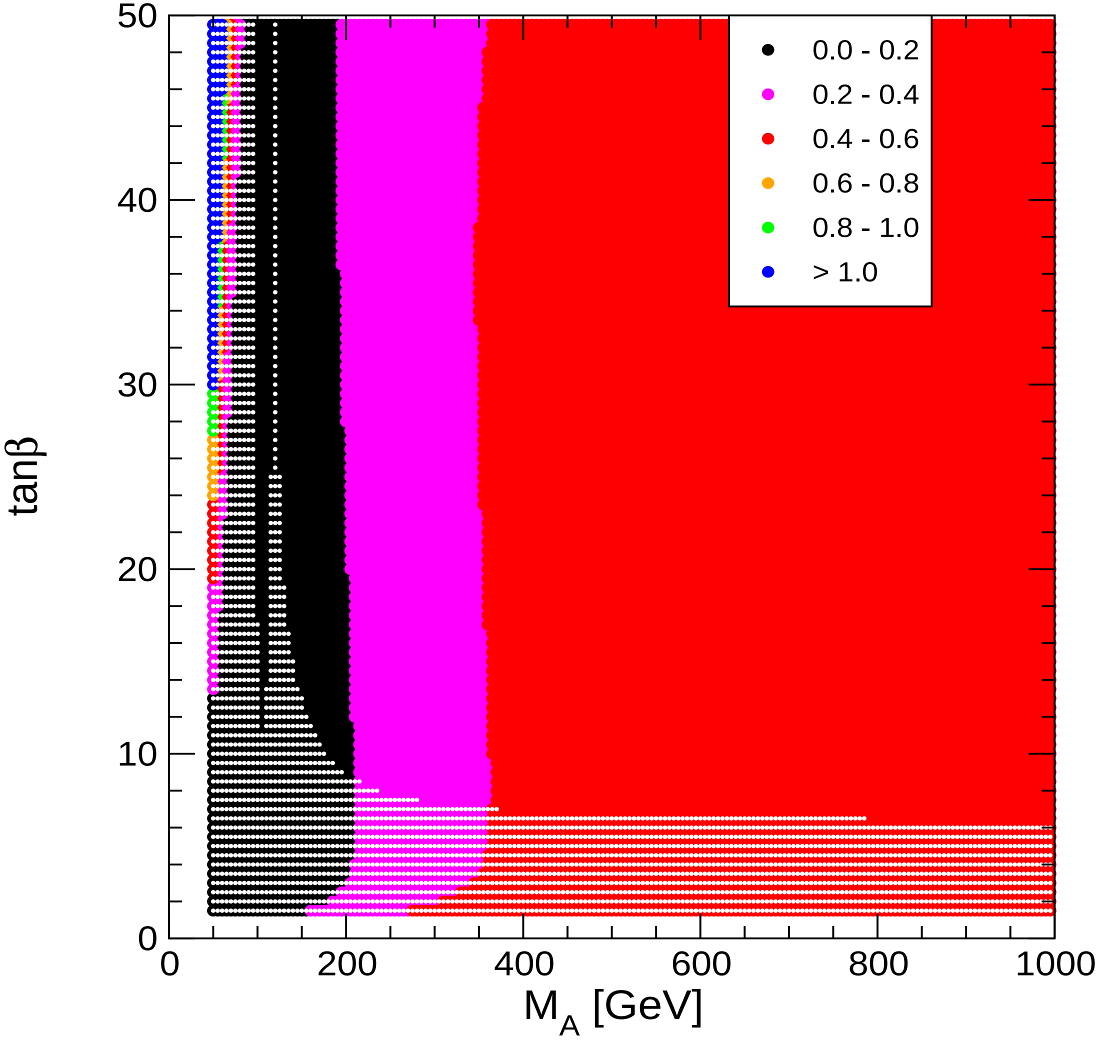
can be strongly suppressed

→ "gluophobic Higgs scenario"

[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

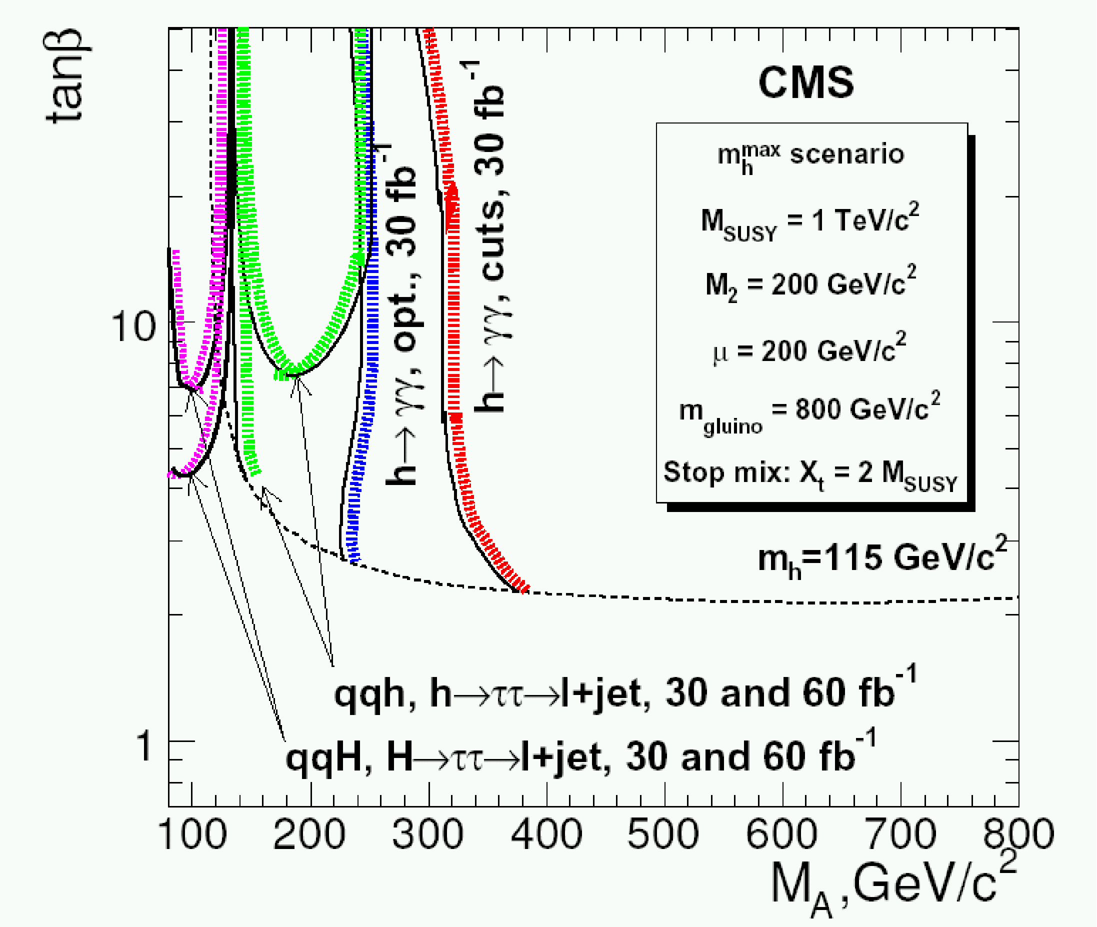
⇒ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

(not realized in CMSSM, GMSB, AMSB, . . .)



M_h measurement in the “nice” $m_h^{\rm max}$ scenario:

[*CMS '06*]



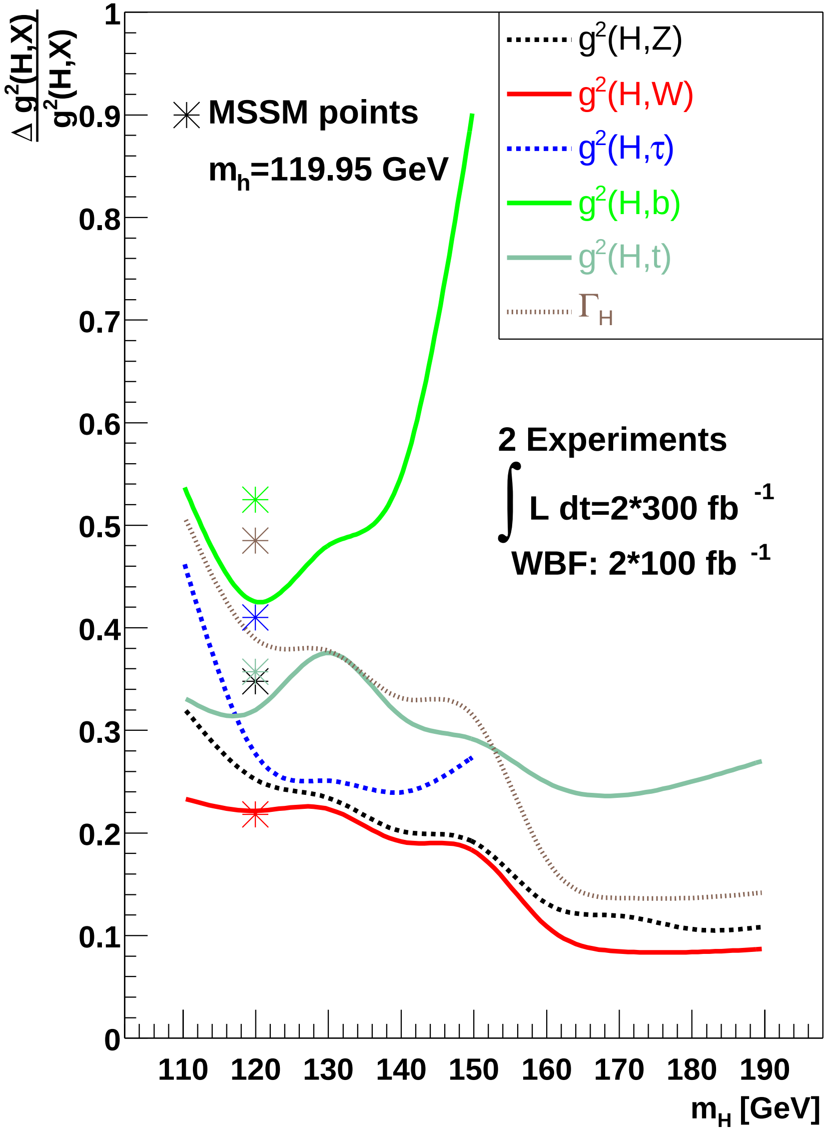
Measurement possible only for
$M_A \gtrsim 250$ GeV
$\Rightarrow \delta M_h \approx 200$ MeV

other channels:
$h \to ZZ^* \to 4\mu$ $(M_h \gtrsim 130$ GeV$)$

otherwise: $\delta M_h \gtrsim 1 - 2$ GeV

MSSM Higgs couplings at the LHC:

One BSM example: one light MSSM Higgs [M. Dührssen et al. '04]



scenario with low M_A, large $\tan\beta$:

$h \to b\bar{b}$ enhanced (but old analyses)

$h \to \tau^+\tau^-$ enhanced

BR$(h \to VV^*) \approx 1/2$ SM

BR$(h \to \gamma\gamma) \approx 1/2$ SM

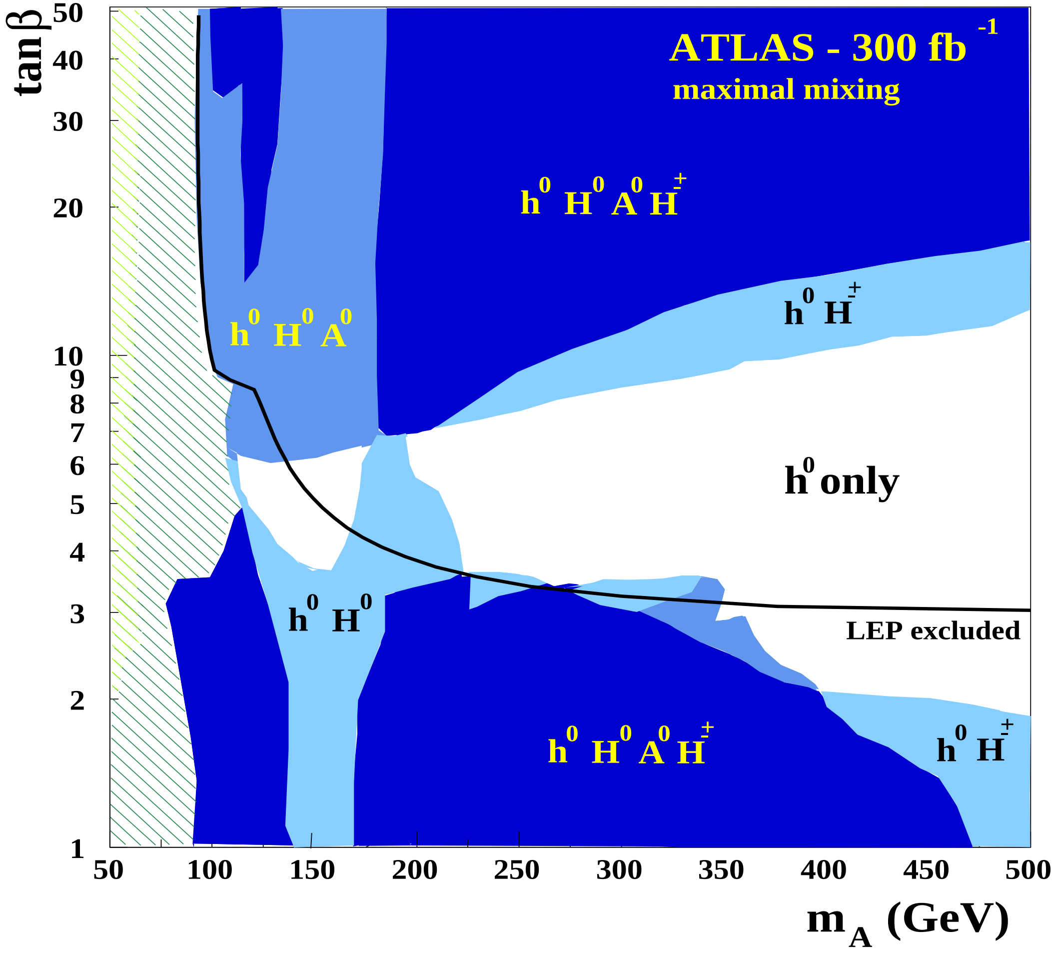
BR$(h \to gg) \approx 1/5$ SM

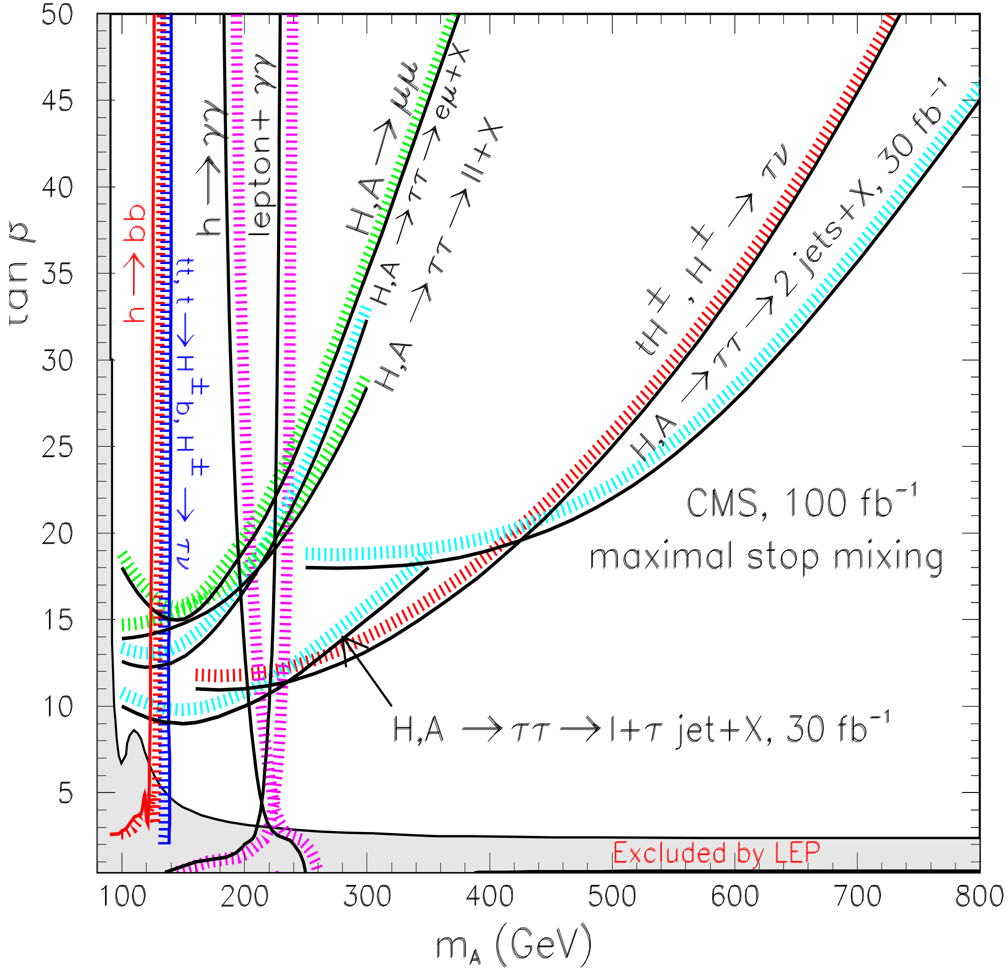
⇒ not too bad . . .

⇒ more analyses needed!

The heavy MSSM Higgs bosons

MSSM Higgs discovery contours in M_A–$\tan\beta$ plane (m_h^{max} benchmark scenario): [*ATLAS '99*] [*CMS '03*]

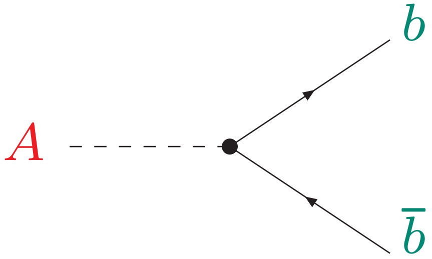




areas where only h is observable ⇒ "LHC wedge"

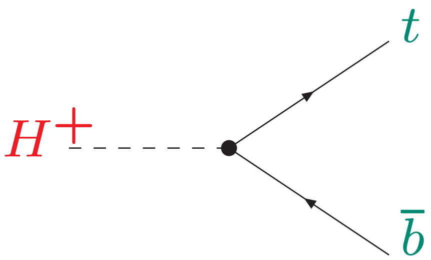
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



$$y_b \quad \longrightarrow \quad y_b \, \frac{\tan\beta}{1+\Delta_b}$$

At large $\tan\beta$: either $H \approx A$ or $h \approx A$



$$y_b \, \frac{\tan\beta}{1+\Delta_b}$$

$$\begin{aligned} \Delta_b &= \frac{2\alpha_s}{3\,\pi} m_{\tilde{g}}\, \mu \, \tan\beta \, \times \, I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) \\ &+ \frac{\alpha_t}{4\,\pi} A_t\, \mu \, \tan\beta \, \times \, I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) \end{aligned}$$

$\Rightarrow$ other parameters enter $\Rightarrow$ strong μ dependence

Most powerful search modes for heavy MSSM Higgs bosons:

$$\boxed{\begin{array}{l} b\bar{b} \to H/A \to \tau^+\tau^- + X \\ gb \to tH^\pm + X,\ \ H^\pm \to \tau\nu_\tau \\ pp \to t\bar{t} \to H^\pm + X,\ \ H^\pm \to \tau\nu_\tau \end{array}}$$

Enhancement factors compared to the SM case:

$$H/A \ : \ \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \frac{\mathrm{BR}(H \to \tau^+\tau^-) + \mathrm{BR}(A \to \tau^+\tau^-)}{\mathrm{BR}(H \to \tau^+\tau^-)_{\mathrm{SM}}}$$

$$H^\pm \ : \ \frac{\tan^2\beta}{(1+\Delta_b)^2} \times \mathrm{BR}(H^\pm \to \tau\nu_\tau)$$

$\Rightarrow$ Δ_b dependence often neglected in ATLAS/CMS analyses

also relevant for $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

also relevant: correct evaluation of $\Gamma(H/A/H^\pm \to \mathrm{SUSY})$

$\Rightarrow$ additional effects on $\mathrm{BR}(H/A \to \tau^+\tau^-)$, $\mathrm{BR}(H^\pm \to \tau\nu_\tau)$

Suggestion for new benchmark scenarios:

[*M. Carena, S.H., C. Wagner, G. Weiglein '05*]

→ investigate benchmark scenarios:

→ Vary only M_A and $\tan\beta$ (large!)
→ Keep all other SUSY parameters fixed

→ Vary in addition μ: $\mu = \pm 1000, \pm 500, \pm 200$ GeV
(if perturbativity allows)

1. m_h^{max} scenario:
   → obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\, M_{\mathrm{SUSY}}$)

   A_t large ⇒ large $\mathcal{O}(\alpha_t)$ contribution to Δ_b

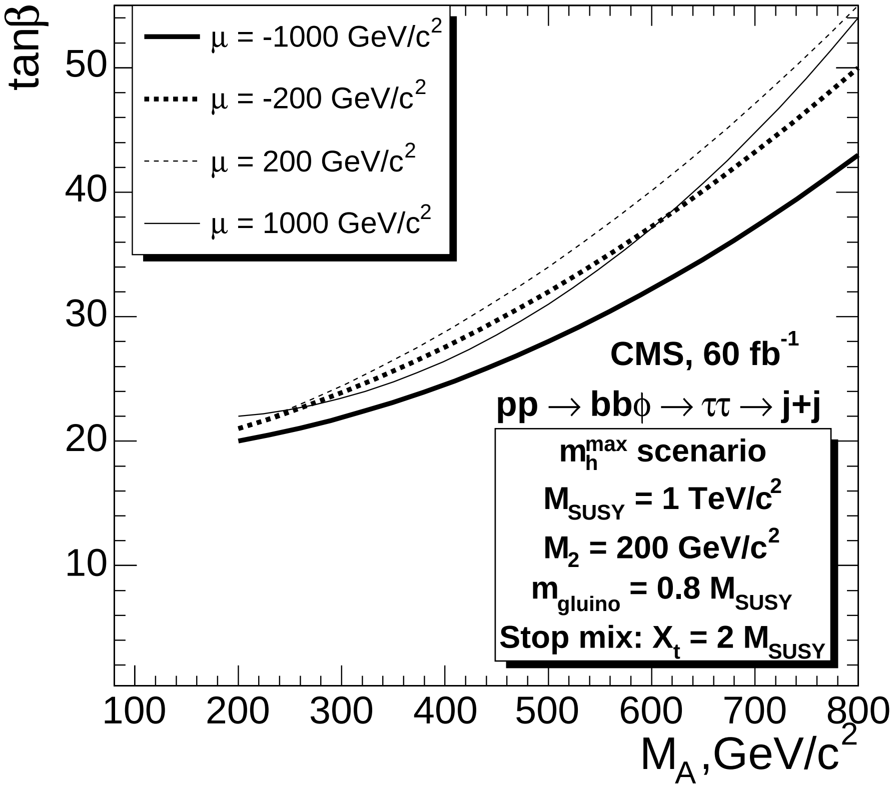
2. no-mixing scenario
   → no mixing in the scalar top sector ($X_t = 0$)

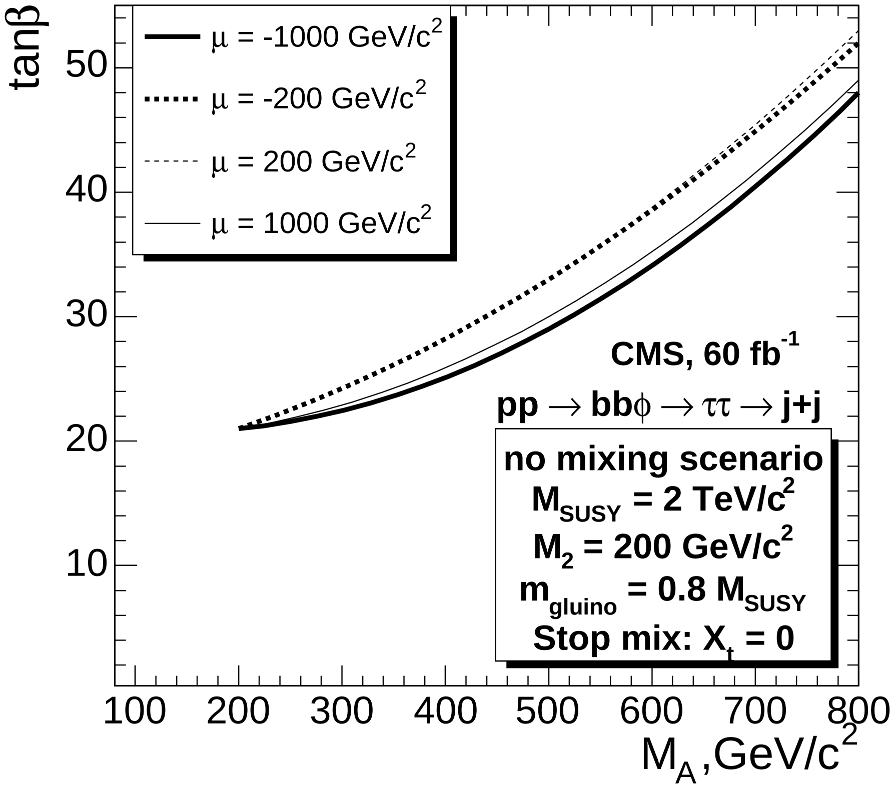
   A_t small ⇒ small $\mathcal{O}(\alpha_t)$ contribution to Δ_b

   ⇒ large difference to m_h^{max} scenario

Dependence of LHC wedge from $b\bar{b} \to H/A \to \tau^+\tau^- \to 2\,$jets on μ:

[S.H., A. Nikitenko, G. Weiglein et al. '06]



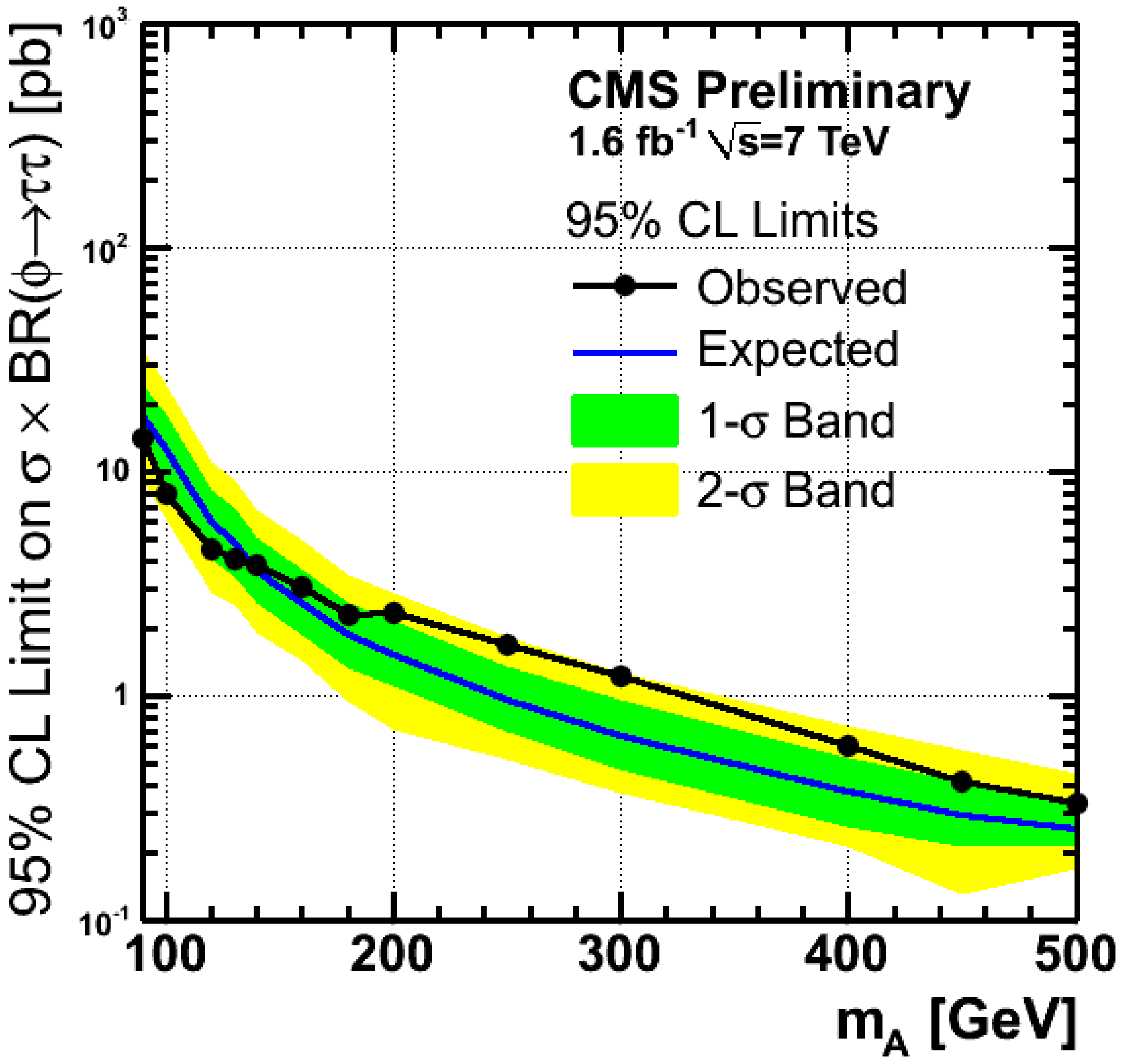


⇒ now based on full CMS simulation

⇒ non-negligible variation with the sign and absolute value of μ
(→ numerical compensations in production and decay)

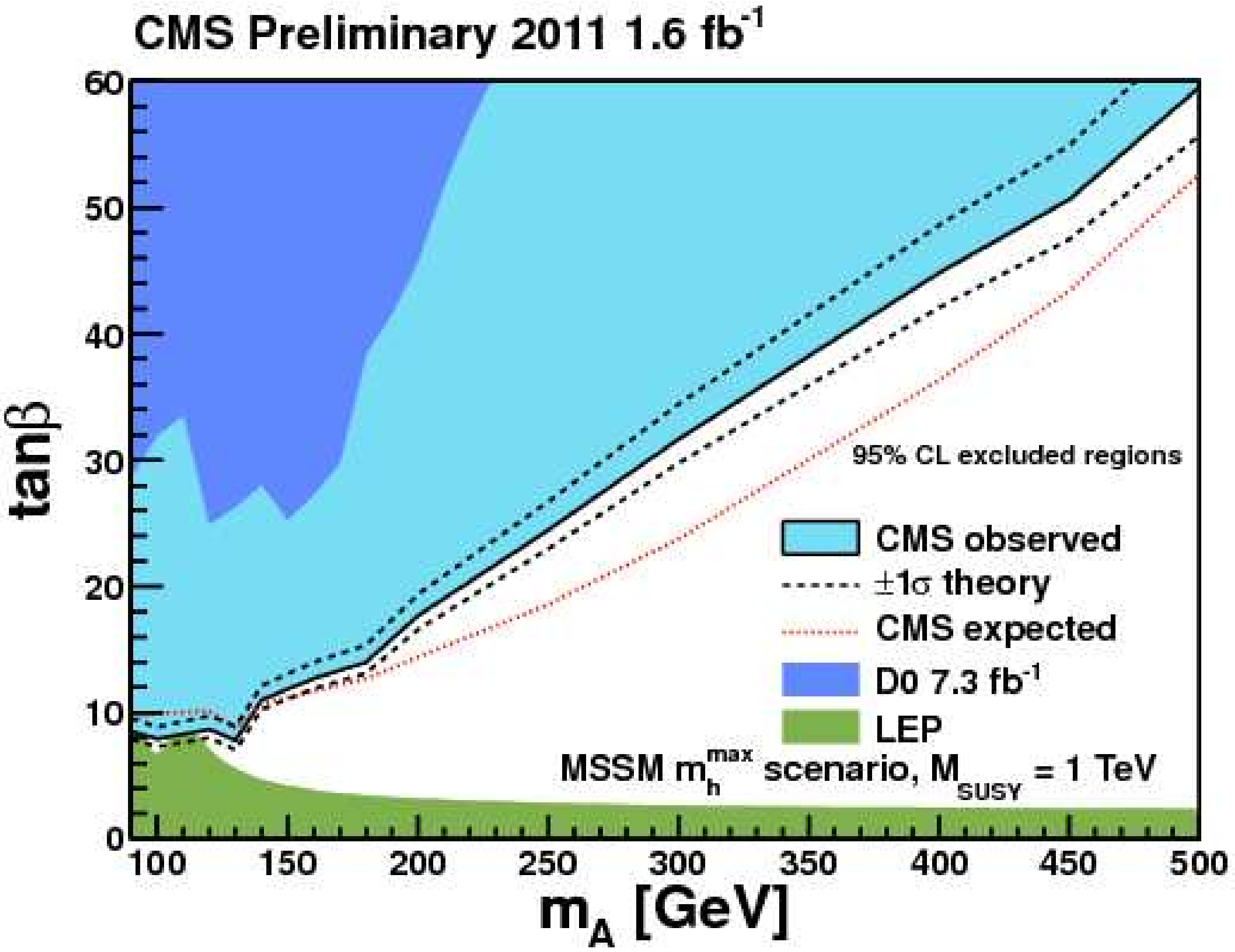
Latest CMS resuls for model independent limits:

[*CMS '11*]



⇒ small "excess" around $M_A \gtrsim 200$ GeV

Latest CMS results in search for the heavy MSSM Higgses: [*CMS '11*]



⇒ LHC ⊕ LEP start to excluded low M_A values!

⇒ small "excess" around $M_A \approx 300$ GeV

3. Supersymmetry

Supersymmetry (SUSY) : Symmetry between

$$\text{Bosons} \leftrightarrow \text{Fermions}$$

$$Q\ |\text{Fermion}\rangle \to |\text{Boson}\rangle$$

$$Q\ |\text{Boson}\rangle \to |\text{Fermion}\rangle$$

Simplified examples:

$$Q\ |\text{top},\ t\rangle \to |\text{scalar top},\ \tilde{t}\rangle$$

$$Q\ |\text{gluon},\ g\rangle \to |\text{gluino},\ \tilde{g}\rangle$$

⇒ each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}}$ ⇒ SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})}$

Soft SUSY-breaking

Exact SUSY: $m_f = m_{\tilde{f}}$, . . .

⇒ in a realistic model: SUSY must be broken

Only satisfactory way for model of SUSY breaking:

$$\boxed{\text{spontaneous SUSY breaking}}$$

Specific SUSY-breaking schemes (see below) in general yield effective Lagrangian at low energies, which is supersymmetric except for explicit soft SUSY-breaking terms

Soft SUSY-breaking terms: do not alter dimensionless couplings

(i.e. dimension of coupling constants of soft SUSY-breaking terms > 0)
otherwise: re-introduction of the hierarchy problem

⇒ no quadratic divergences (in all orders of perturbation theory)

scale of SUSY-breaking terms: $M_{\text{SUSY}} \lesssim 1$ TeV

Classification of possible soft breaking terms:

[*L. Girardello, M. Grisaru '82*]

- scalar mass terms: $m^2_{\phi_i} |\phi_i|^2$
- trilinear scalar interactions: $A_{ijk}\phi_i\phi_j\phi_k + \text{h.c.}$
- gaugino mass terms: $\frac{1}{2}m\bar{\lambda}\lambda$
- bilinear terms: $B_{ij}\phi_i\phi_j + \text{h.c.}$
- linear terms: $C_i\phi_i$

⇒ relations between dimensionless couplings unchanged

no additional mass terms for chiral fermions

A. Unconstrained models (MSSM):

agnostic about how SUSY breaking is achieved
no particular SUSY breaking mechanism assumed, parameterization of possible soft SUSY-breaking terms

⇒ relations between dimensionless couplings unchanged
no quadratic divergences

most general case:

⇒ 105 new parameters: masses, mixing angles, phases

Good phenomenological description for universal breaking terms

B. Constrained models (CMSSM, . . .):

assumption on the scenario that achieves spontaneous SUSY breaking
⇒ prediction for soft SUSY-breaking terms
in terms of small set of parameters

Experimental determination of SUSY parameters

⇒ Patterns of SUSY breaking

"Hidden sector": ⟶ Visible sector:

SUSY breaking MSSM

"Gravity-mediated": CMSSM/mSUGRA
"Gauge-mediated": GMSB
"Anomaly-mediated": AMSB
"Gaugino-mediated"
. . .

CMSSM/mSUGRA: mediating interactions are gravitational

GMSB: mediating interactions are ordinary electroweak and QCD gauge interactions

AMSB, Gaugino-mediation: SUSY breaking happens on a different brane in a higher-dimensional theory

Particle content of the MSSM:

Superpartners for Standard Model particles:

$$\left[u,d,c,s,t,b\right]_{L,R} \quad \left[e,\mu,\tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u},\tilde{d},\tilde{c},\tilde{s},\tilde{t},\tilde{b}\right]_{L,R} \quad \left[\tilde{e},\tilde{\mu},\tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: $h^0, H^0, A^0, H^{\pm}$

as usual: Breaking of SU(2) × U(1)$_Y$ (electroweak symmetry breaking)

⇒ fields with different SU(2) × U(1)$_Y$ quantum numbers can mix if they have the same SU(3)$_c$, U(1)$_{\text{em}}$ quantum numbers

Squark mixing:

Stop, sbottom mass matrices ($X_t = A_t - \mu/\tan\beta$, $X_b = A_b - \mu\tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

off-diagonal element prop. to mass of partner quark ($\tan\beta \equiv v_u/v_d$)

$\Rightarrow$ mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

gauge invariance $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

$\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

$\Rightarrow$ prediction for collider phenomenology!

Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

⇒ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

⇒ neutralinos: mass eigenstates

mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

⇒ only one new parameter

⇒ MSSM predicts mass relations between neutralinos and charginos
⇒ prediction for collider phenomenology!

R parity

Most general gauge-invariant and renormalizable superpotential with chiral superfields of the MSSM:

$$\mathcal{V} = \mathcal{V}_{\text{MSSM}} + \underbrace{\frac{1}{2}\lambda^{ijk} L_i L_j E_k + \lambda'^{ijk} L_i Q_j D_k + \mu'^i L_i H_u}_{\text{violate lepton number}} + \underbrace{\frac{1}{2}\lambda''^{ijk} U_i D_j D_k}_{\text{violates baryon number}}$$

If both lepton and baryon number are violated

⇒ rapid proton decay

Minimal choice (MSSM) contains only terms in the Lagrangian with even number of SUSY particles

⇒ additional symmetry: "R parity"

⇒ all SM particles have even R parity, all SUSY particles have odd R parity

R-parity $\Rightarrow$ the LSP

MSSM has further symmetry: “R-parity”

all SM-particles and Higgs bosons: even R-parity, $P_R = +1$

all superpartners: odd R-parity, $P_R = -1$

$\Rightarrow$ SUSY particles appear only in pairs, e.g. $e^+e^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$

$\Rightarrow$ lightest SUSY particle (LSP) is stable

(usually the lightest neutralino)

good candidate for Cold Dark Matter

$\boxed{\Rightarrow M_{\text{SUSY}} \lesssim 1 \text{ TeV}}$

LSP neutral, uncolored $\Rightarrow$ leaves no traces in collider detectors

$\Rightarrow$ Typical SUSY signatures: “missing energy”

$\Rightarrow$ prediction for collider phenomenology!

Relations between SUSY parameters

Symmetry properties of MSSM Lagrangian (SUSY, gauge invariance) give rise to coupling and mass relations

Soft SUSY breaking does not affect SUSY relations between dimensionless couplings

E.g.:

gauge boson–fermion coupling

=

gaugino–fermion–sfermion coupling

for U(1), SU(2), SU(3) gauge groups

⇒ prediction for collider phenomenology!

In SM: all masses are free input parameters
(except M_W–M_Z interdependence)

MSSM:

- Upper bound on mass of lightest $\mathcal{CP}$-even Higgs boson
- Relations between neutralino and chargino masses
- Sfermion mass relations, e.g.

$$m^2_{\tilde{e}_L} = m^2_{\tilde{\nu}_L} - M_W^2 \cos(2\beta)$$

All relations receive corrections from loop effects

⇔ effects of soft SUSY breaking, electroweak symmetry breaking

⇒ Experimental verification of parameter relations is a crucial test of SUSY!

⇒ prediction for collider phenomenology!

Simplified models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sign}\,\mu$$

$$\left.\begin{array}{l} m_0 : \text{universal scalar mass parameter} \\ m_{1/2} : \text{universal gaugino mass parameter} \\ A_0 : \text{universal trilinear coupling} \end{array}\right\}\ \text{at the GUT scale}$$

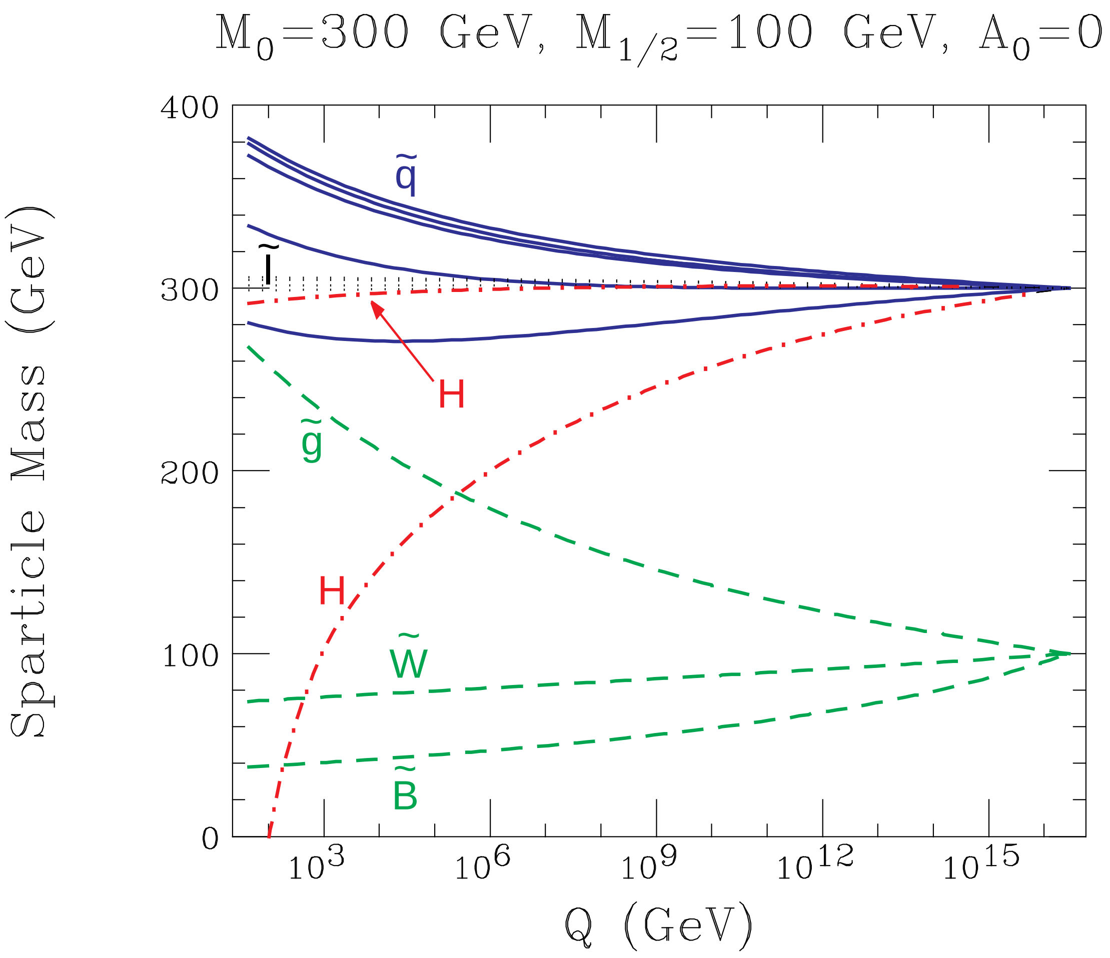
$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino

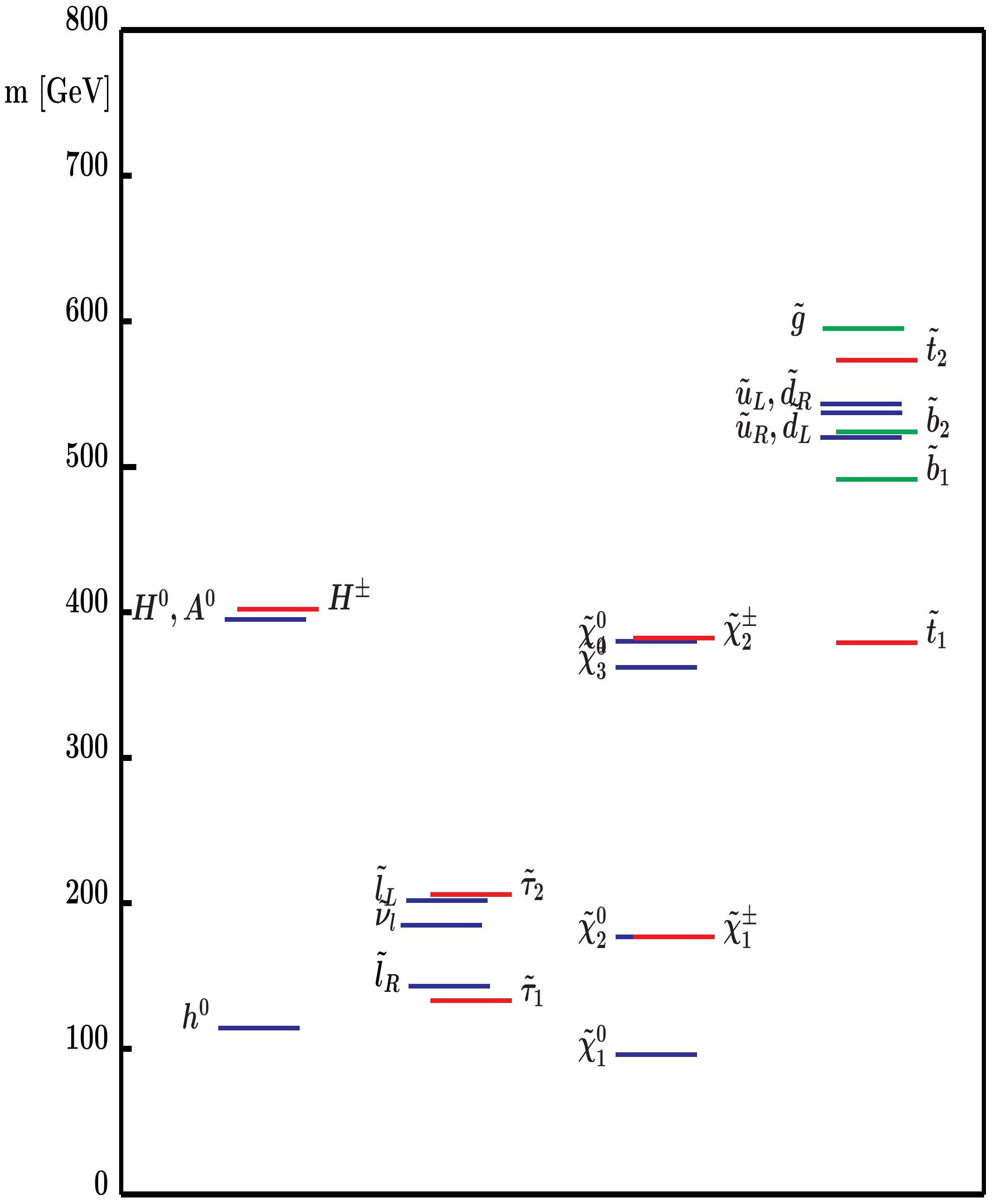
$\Rightarrow$ particle spectra from renormalization group running to weak scale



$\Rightarrow$ one parameter turns negative $\Rightarrow$ Higgs mechanism for free

“Typical” CMSSM scenario (SPS 1a benchmark scenario):

Strong connection between all the sectors



Simplified models: 2.) NUHM1: (Non-universal Higgs mass model)

Assumption: no unification of scalar fermion and scalar Higgs parameter at the GUT scale

$\Rightarrow$ effectively M_A or μ as free parameters at the EW scale

$\Rightarrow$ besides the CMSSM parameters

$$M_A \text{ or } \mu$$

And there is more: 3.) VCMSSM
4.) mSUGRA
5.) NUHM2

. . . no time here . . .

Searches for signs of SUSY (at the LHC)

Two possible ways:

1.) Search for SUSY particles

2.) Search for indirect effects of SUSY particles

⇒ both are important

⇒ both will be explored

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⇒ both will have to be combined

Searches for signs of SUSY (at the LHC)

Two possible ways:

1.) Search for SUSY particles

2.) Search for indirect effects of SUSY particles

⇒ both are important

⇒ both will be explored

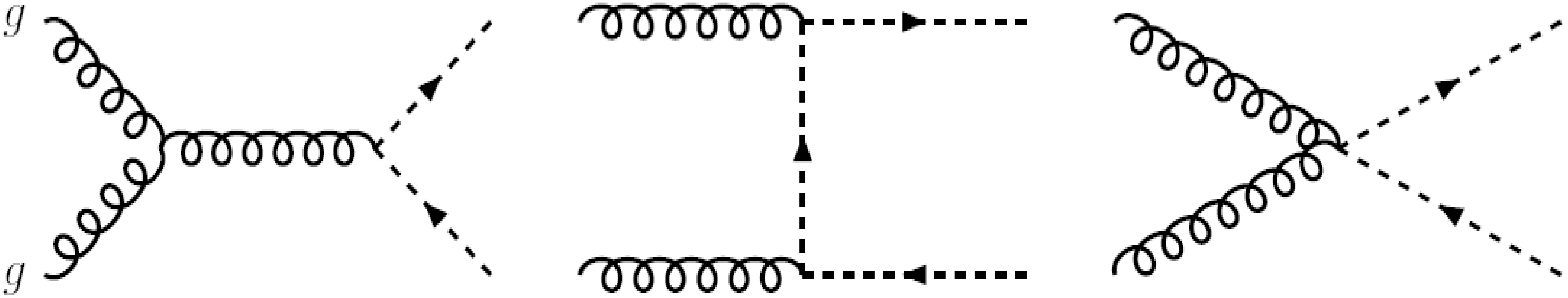
⇒ both will have to be combined

⇒ both will have to give (eventually) the same answer
⇒ crucial test of the model!

Colored sparticles at the LHC

SUSY particle production at the LHC:

⇒ colored (s)particles are copiously produced

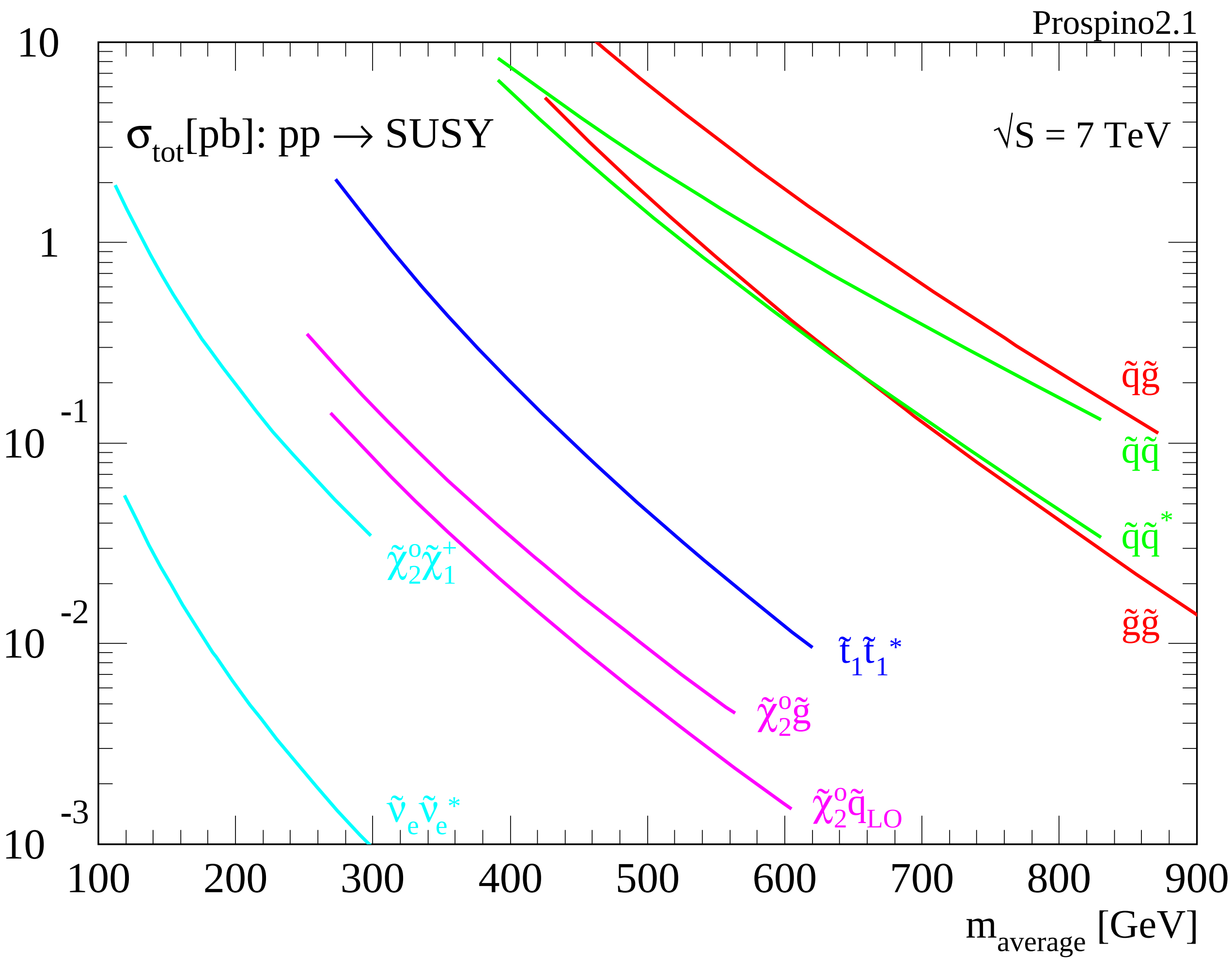


⇒ production of gluinos, squarks, . . .

As in QCD: NLO corrections are crucial!

Example for SUSY production:

[*Prospino collaboration*]



As in QCD: NLO corrections are crucial!

Production of SUSY particles at the LHC

will in general result in complicated final states

⇒ cascade decays

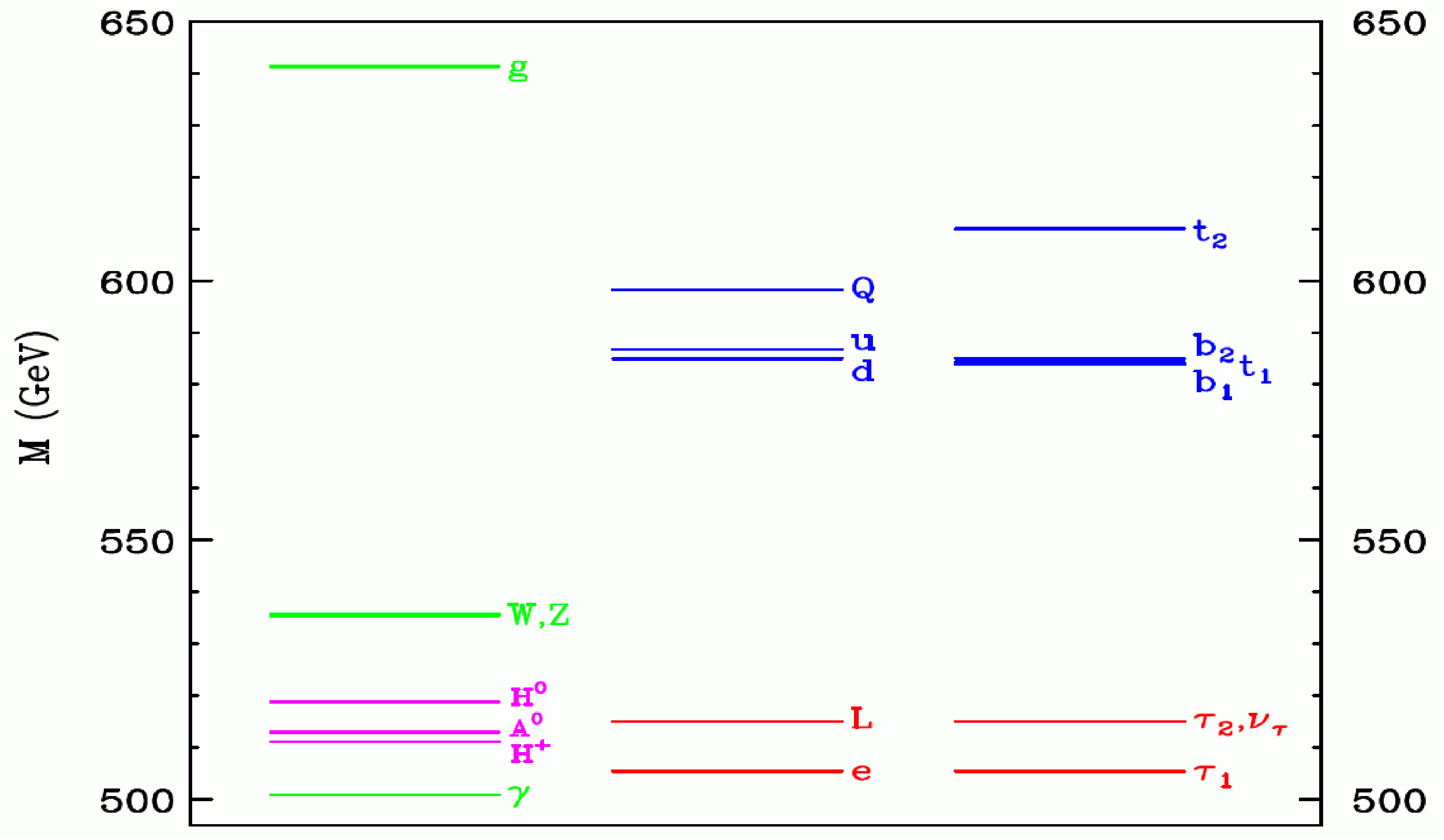
$$\tilde{g} \longrightarrow \bar{q}\tilde{q} \longrightarrow \bar{q}q\tilde{\chi}_2^0 \longrightarrow \bar{q}q\tilde{\tau}\tau \longrightarrow \bar{q}q\tau\tau\tilde{\chi}_1^0$$

Production of uncolored particles via cascade decays often dominates over direct production

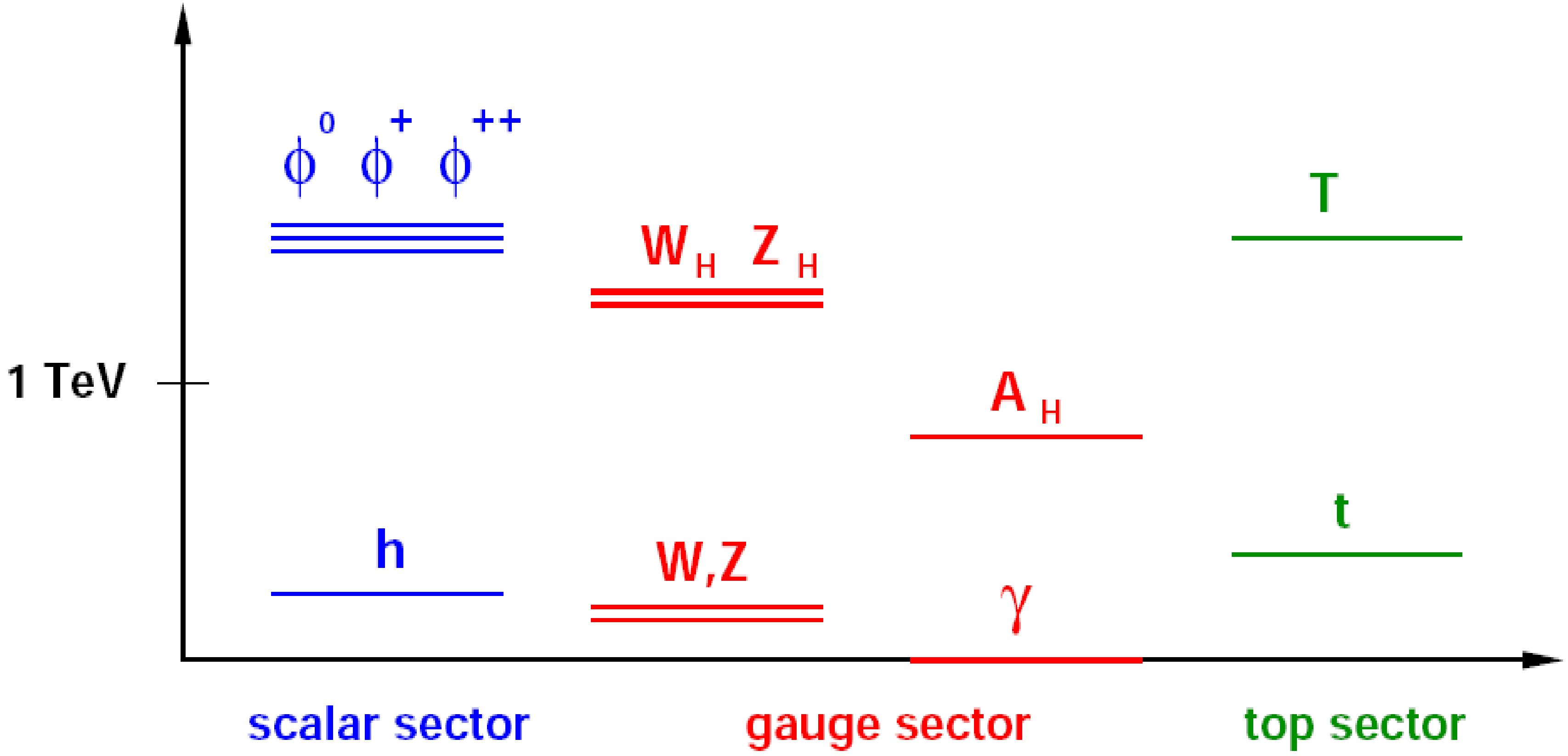
Many states are produced at once

⇒ **Main background for SUSY is SUSY itself!**

Another model beyond the SM: Extra dimensions

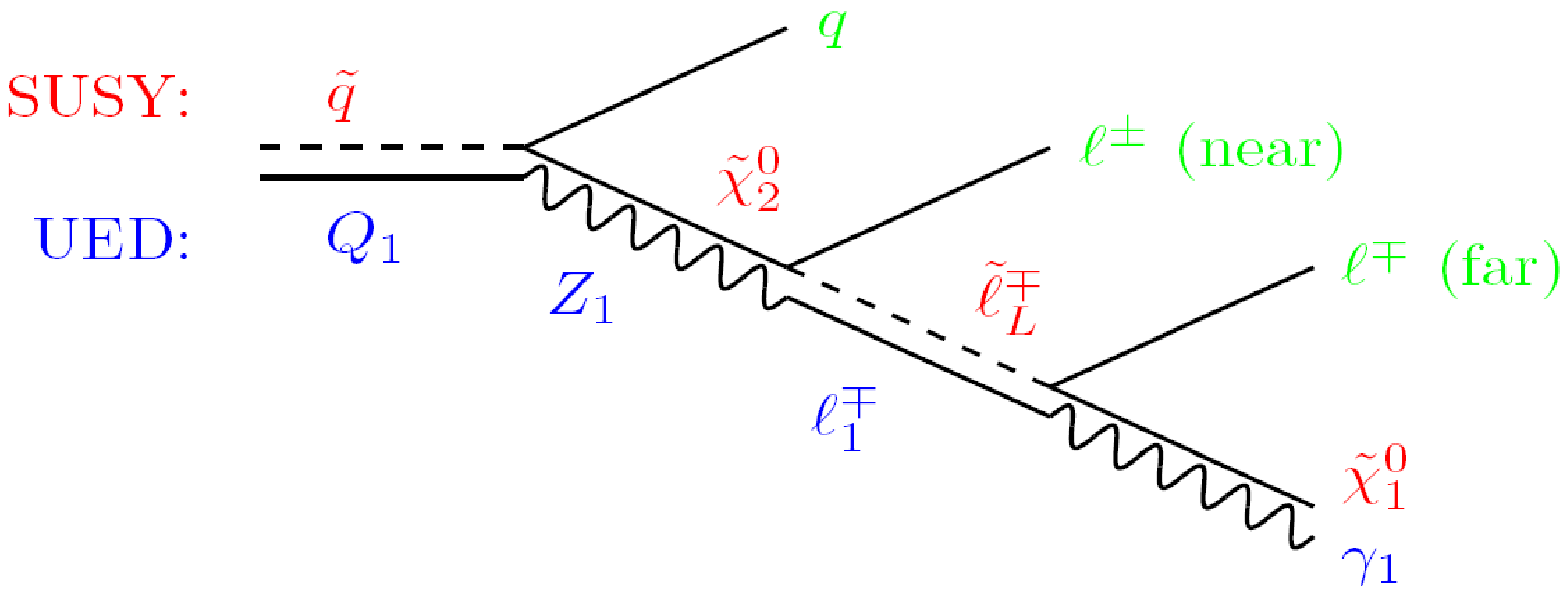


Another model beyond the SM: Little Higgs



Comparison of SUSY with e.g. Extra Dimensions:

⇒ cascades may look very similar:



⇒ In order to establish SUSY experimentally:

Need to demonstrate that:

– every particle has superpartner

– their spins differ by 1/2

– their gauge quantum numbers are the same

– their couplings are identical

– mass relations hold

...

⇒ Precise measurements of masses, branching ratios, cross sections, angular distributions, ... mandatory for

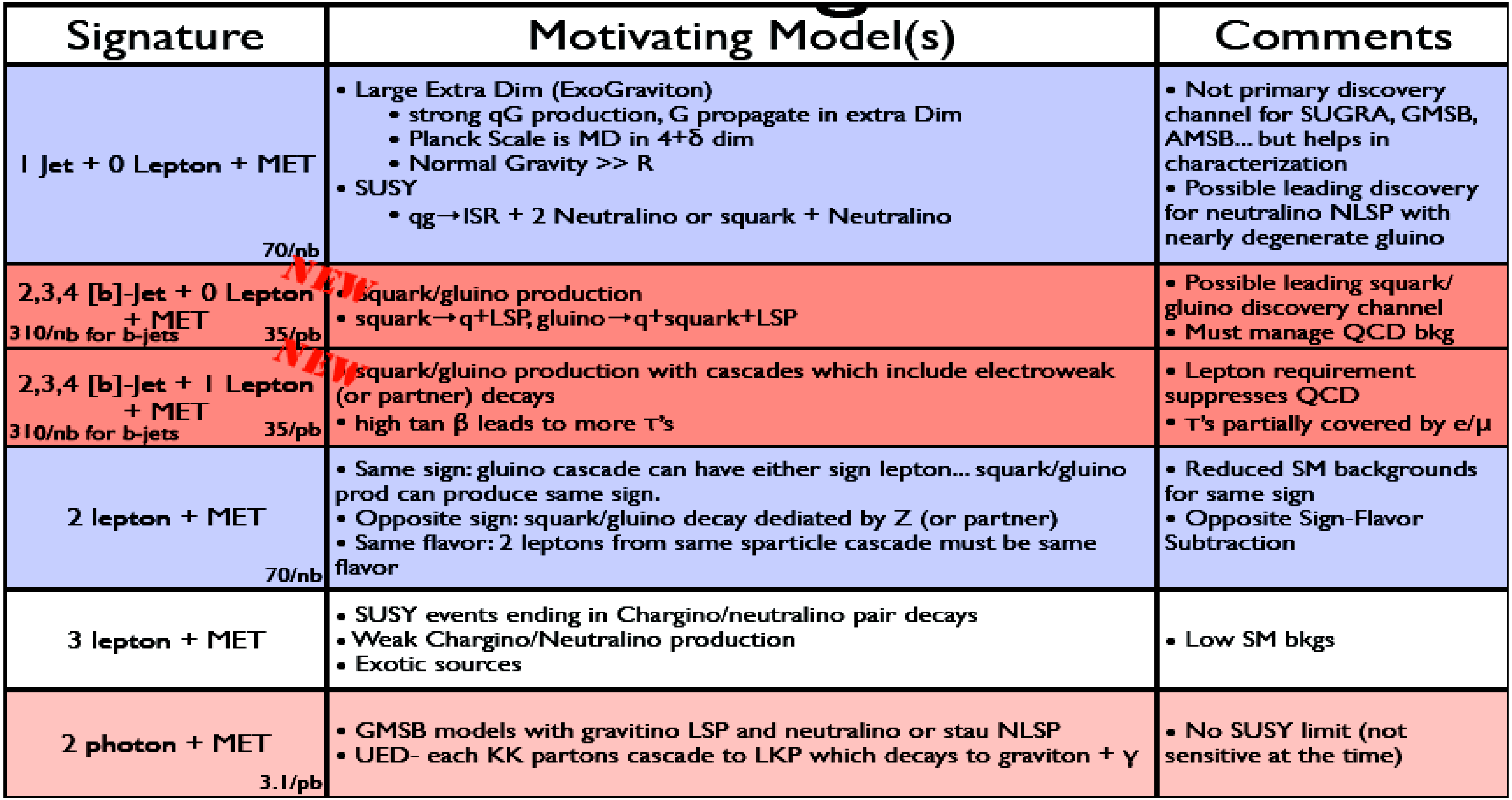
- – establishing SUSY experimentally
- – disentangling patterns of SUSY breaking

⇒ We need both: hadron colliders (Tev./LHC) and high luminosity ILC

Cascade decays:

taken from talk by [A. Farbin '11]

different patterns due to different SM particles "coming out":



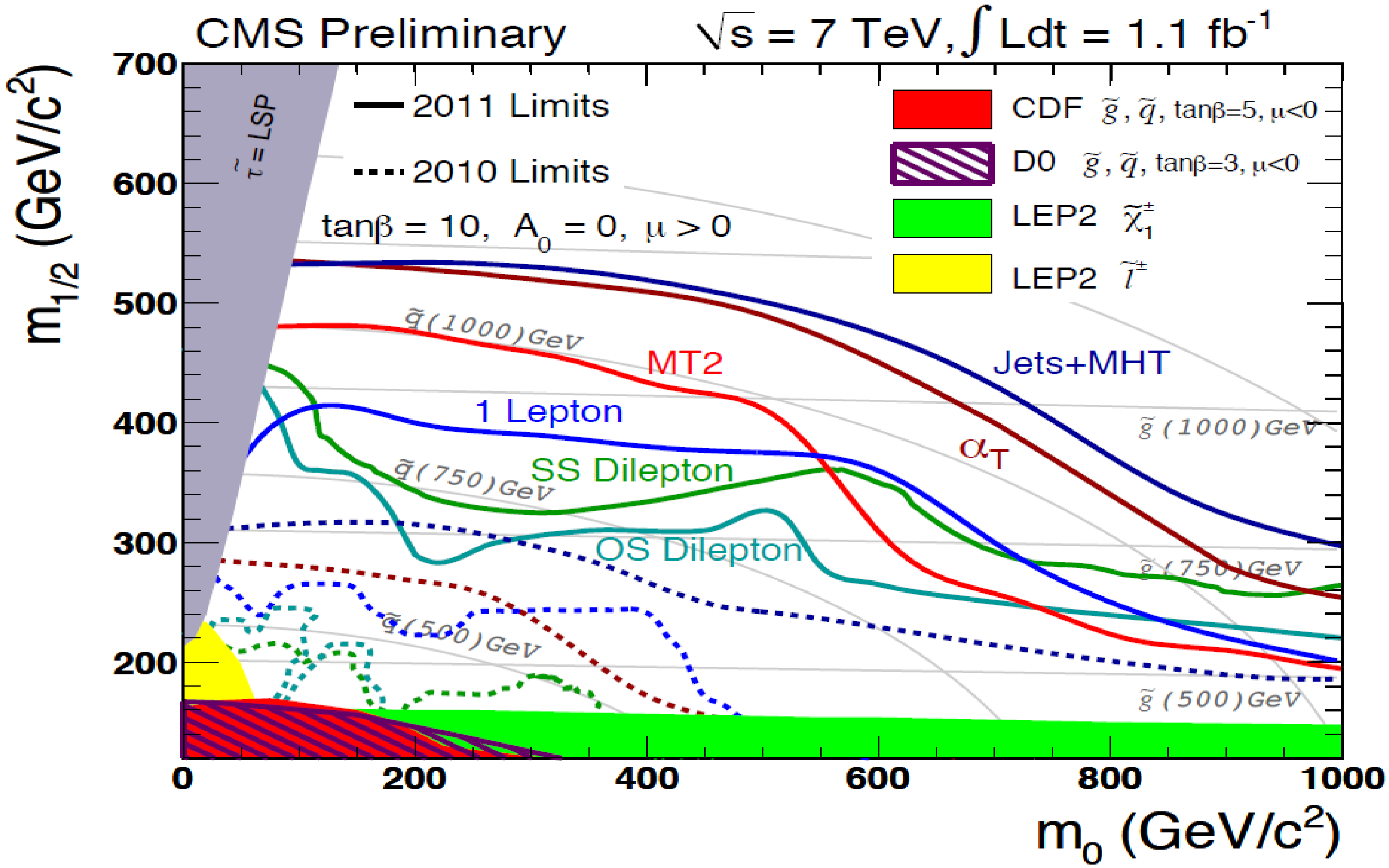
Signature	Motivating Model(s)	Comments

1 Jet + 0 Lepton + MET
70/nb
	• Large Extra Dim (ExoGraviton)
	  • strong qG production, G propagate in extra Dim
	  • Planck Scale is MD in 4+δ dim
	  • Normal Gravity >> R
	• SUSY
	  • qg→ISR + 2 Neutralino or squark + Neutralino
		• Not primary discovery channel for SUGRA, GMSB, AMSB... but helps in characterization
		• Possible leading discovery for neutralino NLSP with nearly degenerate gluino

NEW 2,3,4 [b]-Jet + 0 Lepton + MET 310/nb for b-jets 35/pb	• squark/gluino production • squark→q+LSP, gluino→q+squark+LSP	• Possible leading squark/gluino discovery channel • Must manage QCD bkg
NEW 2,3,4 [b]-Jet + 1 Lepton + MET 310/nb for b-jets 35/pb	• squark/gluino production with cascades which include electroweak (or partner) decays • high tan β leads to more τ's	• Lepton requirement suppresses QCD • τ's partially covered by e/μ
2 lepton + MET 70/nb	• Same sign: gluino cascade can have either sign lepton... squark/gluino prod can produce same sign. • Opposite sign: squark/gluino decay dediated by Z (or partner) • Same flavor: 2 leptons from same sparticle cascade must be same flavor	• Reduced SM backgrounds for same sign • Opposite Sign-Flavor Subtraction
3 lepton + MET	• SUSY events ending in Chargino/neutralino pair decays • Weak Chargino/Neutralino production • Exotic sources	• Low SM bkgs
2 photon + MET 3.1/pb	• GMSB models with gravitino LSP and neutralino or stau NLSP • UED- each KK partons cascade to LKP which decays to graviton + γ	• No SUSY limit (not sensitive at the time)

Search for SUSY: CMS results: 0 lepton + MET (and others)

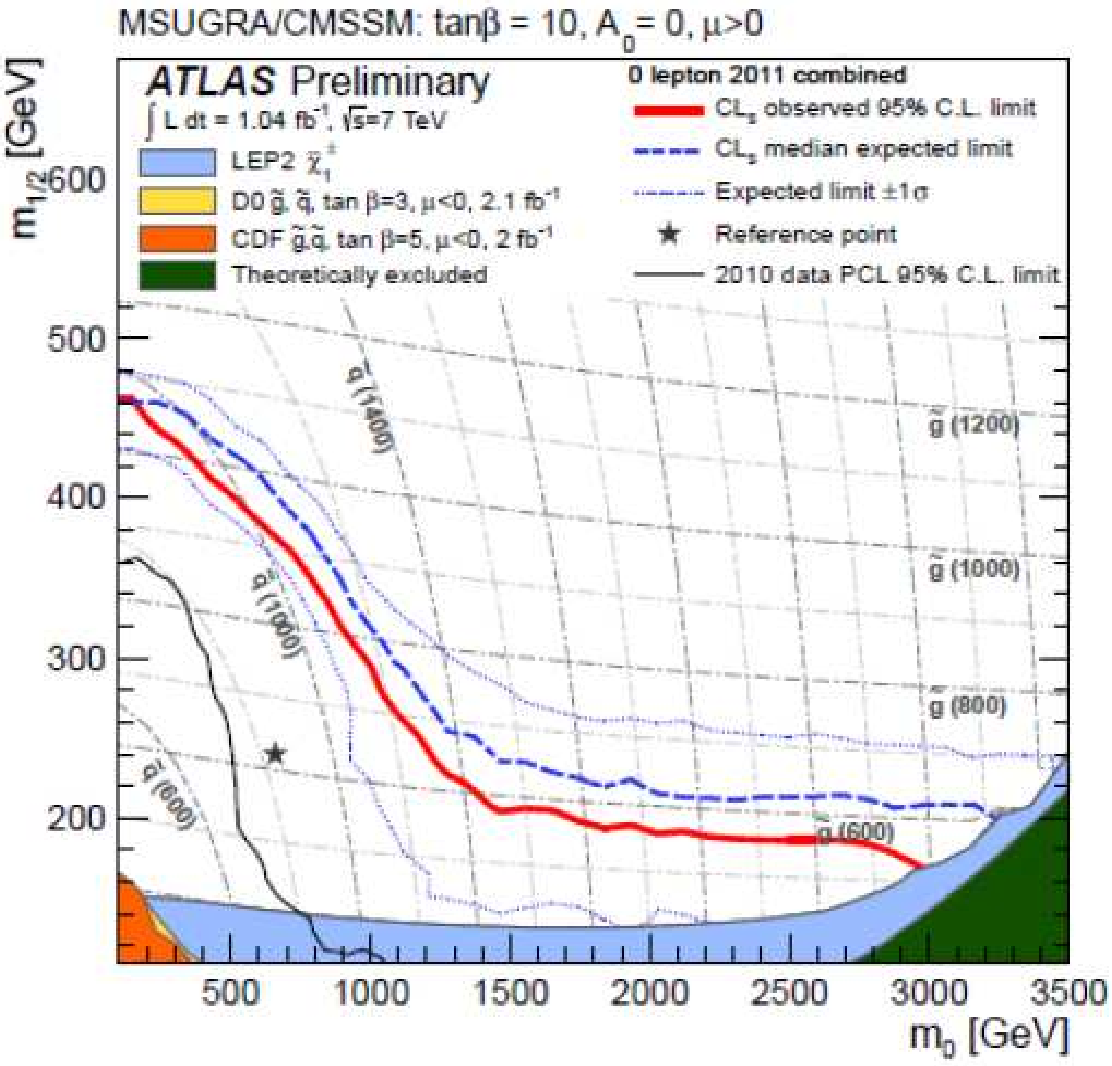
[*CMS '11*]



⇒ valid also for other $\tan\beta$ and A_0 values ??

Search for SUSY particles: ATLAS results: 0 lepton

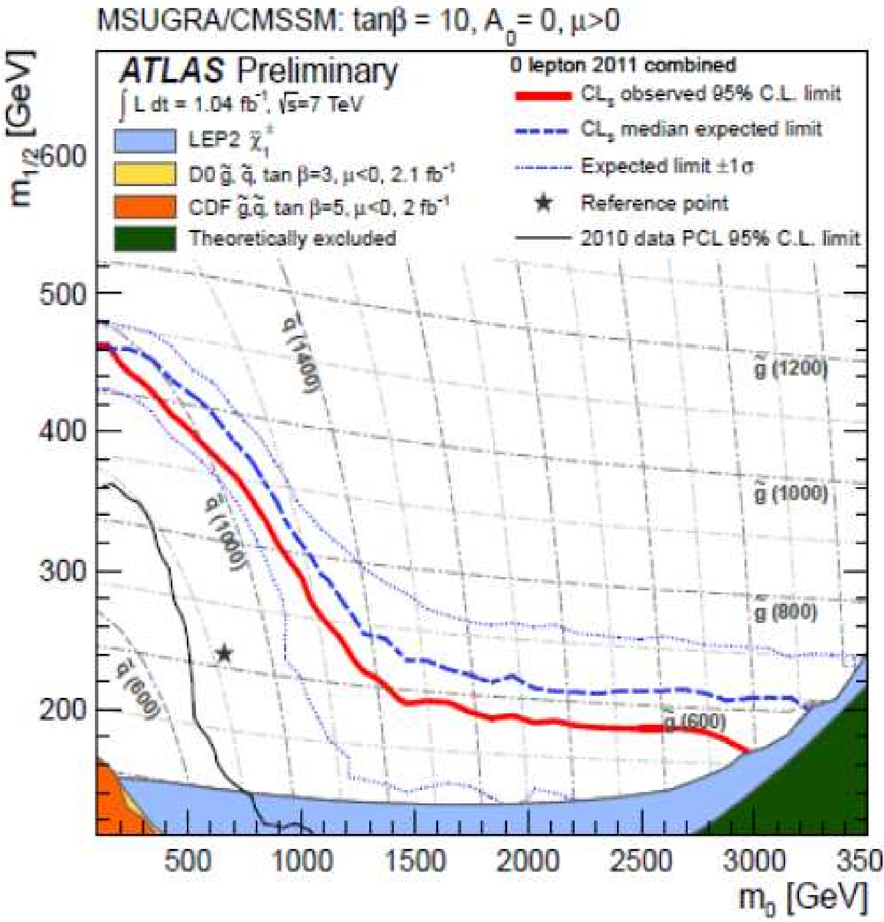
[ATLAS '11]



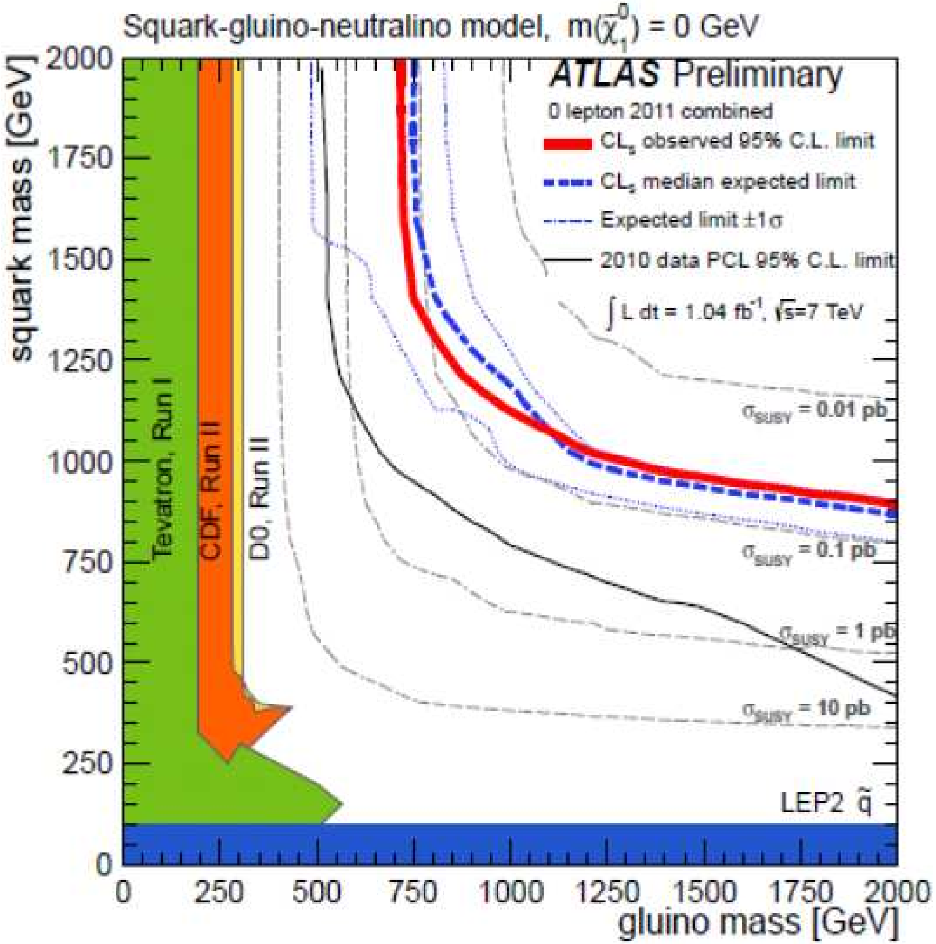
⇒ valid also for other $\tan\beta$ and A_0 values ??

The results are presented in two ways:

CMSSM



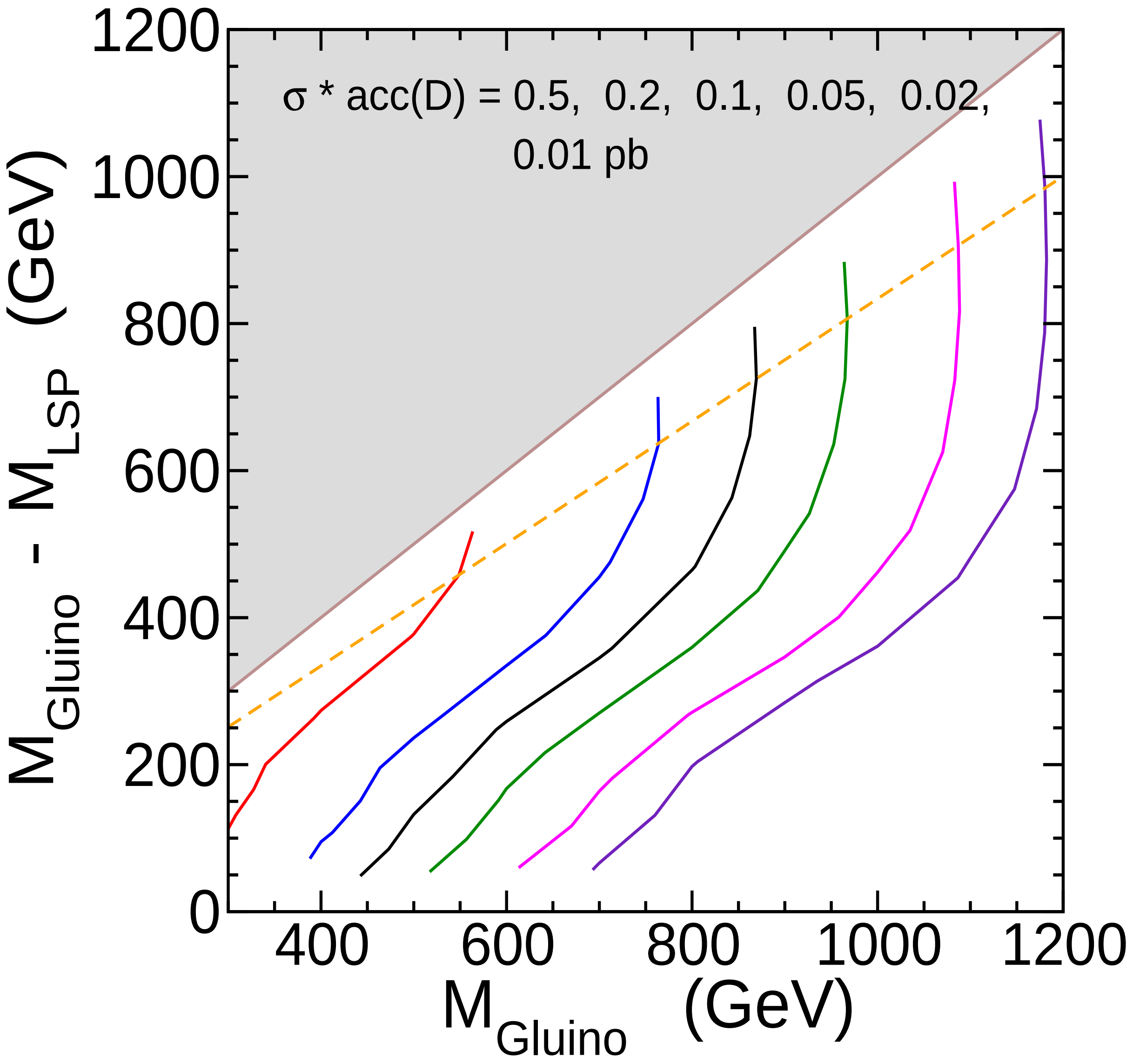
"simplified model"



⇒ How general is this? How useful is this?

Three “easy” ways to “avoid” these constraints

1. not valid for stops and sbottoms (→ excess? :-)
2. compressed spectrum
3. “extended” spectrum



[*T. LeCompte, S. Martin '11*]

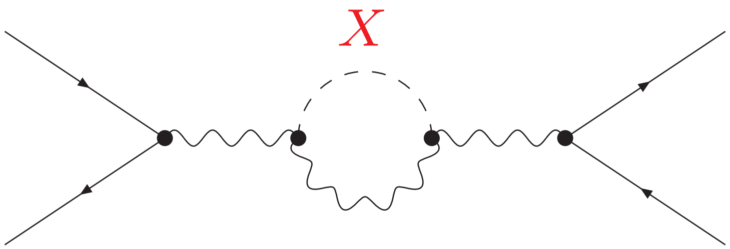
SUSY prediction for and from the LHC

Comparison of precision observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu, \ldots$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections



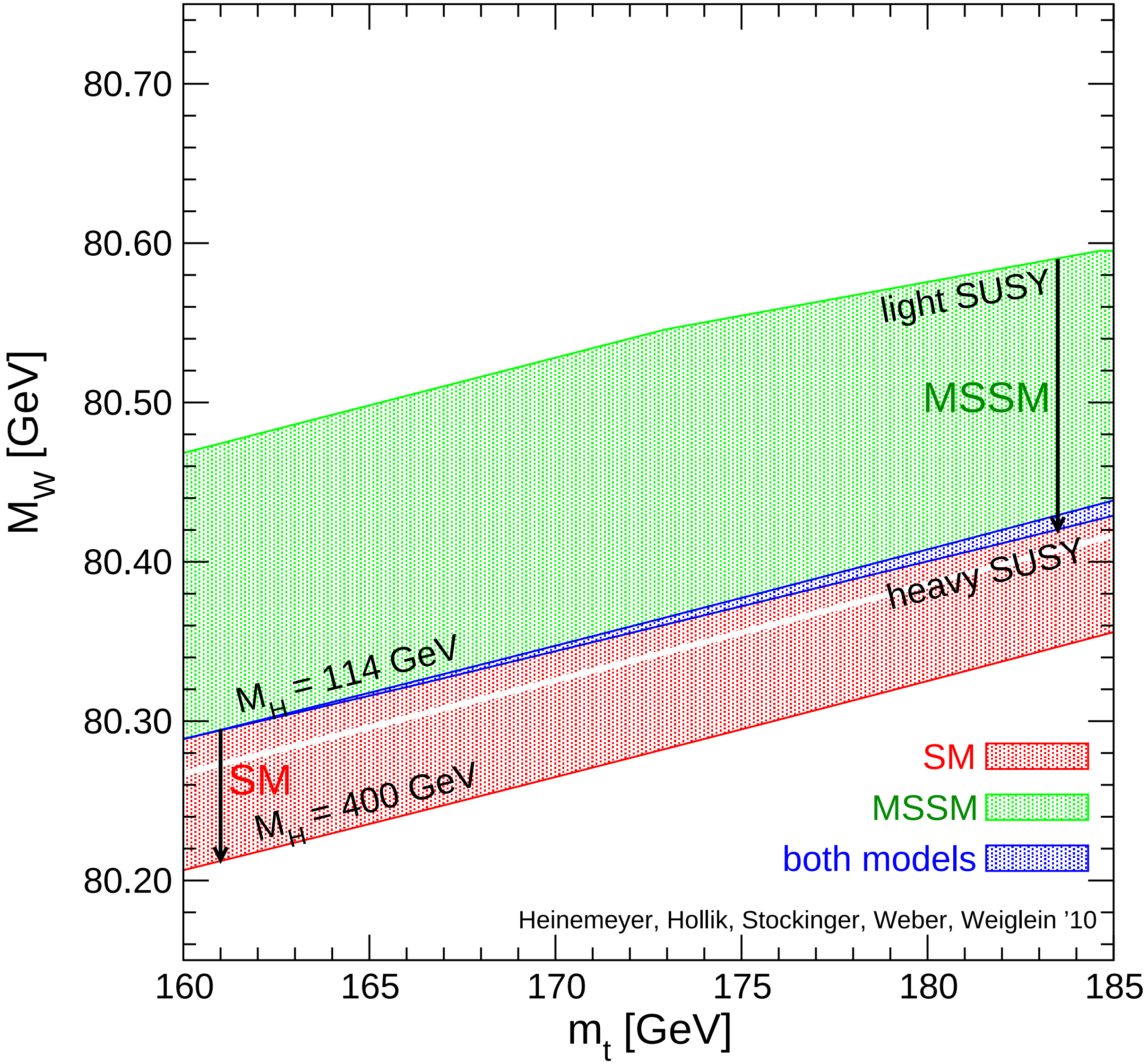
$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed

The most beautiful example: Prediction for M_W in the SM and MSSM :

[S.H., W. Hollik, D. Stockinger, A. Weber, G. Weiglein '07]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

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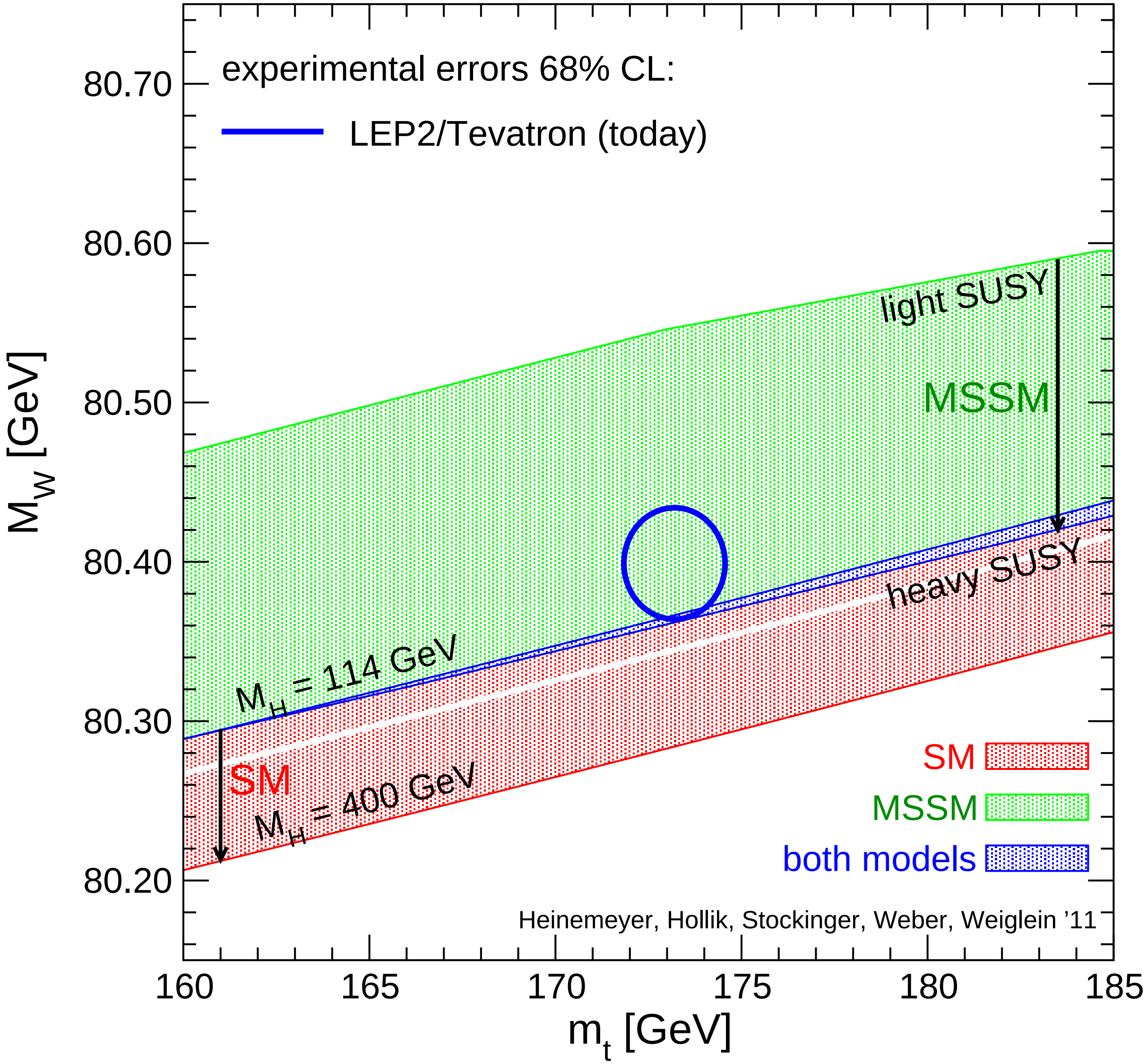

MSSM band:
scan over
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overlap:
SM is MSSM-like
MSSM is SM-like

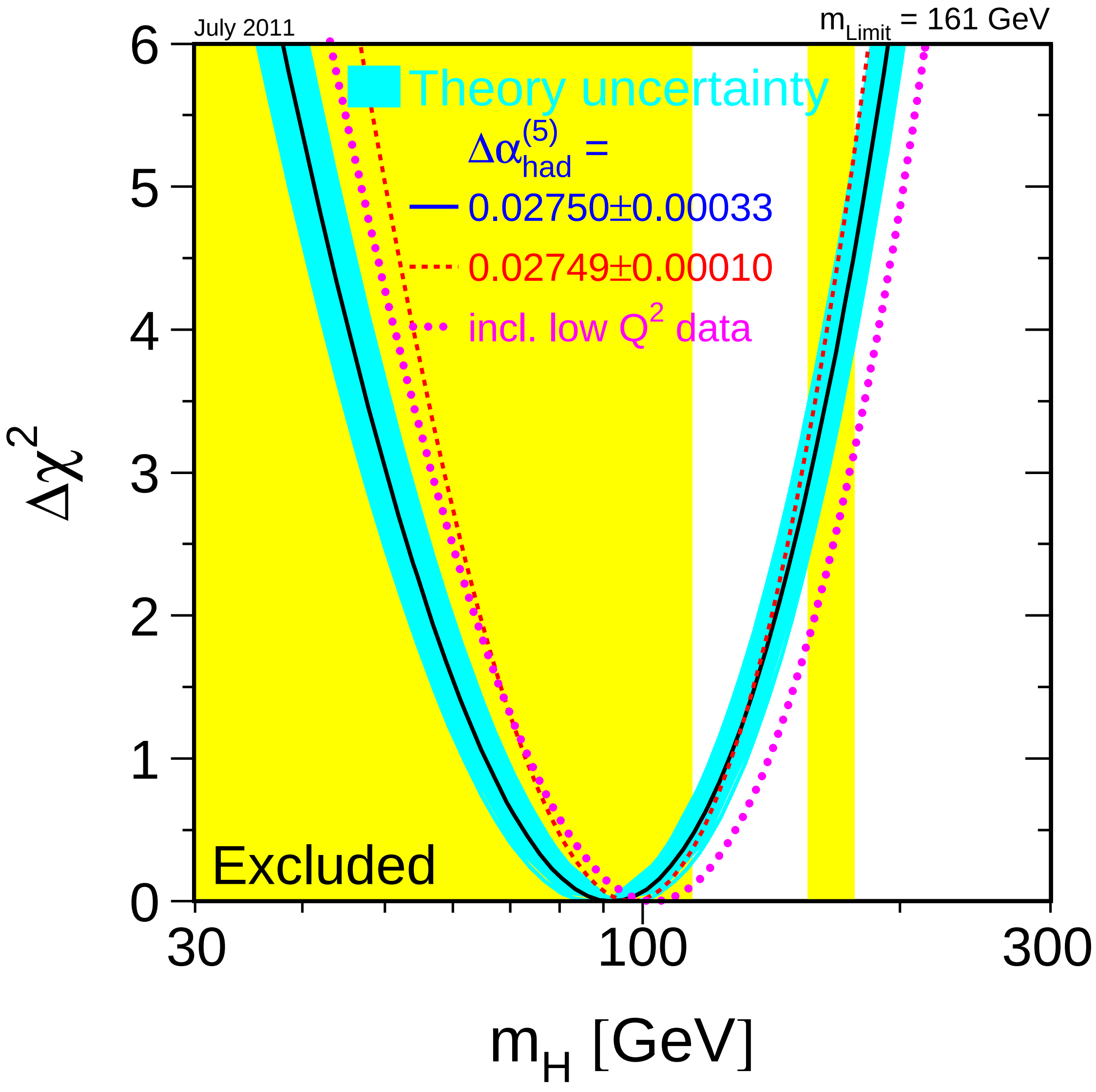
SM band:
variation of M_H^{SM}

Global fit to all SM data:

[LEPEWWG '11]

$\Rightarrow M_H = 92^{+34}_{-26}$ GeV

$M_H < 161$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of Higgs mechanism

$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

Main idea of SUSY fits:

Combine all existing precision data:

- Electroweak precision observables (EWPO)
- B physics observables (BPO)
- Cold dark matter (CDM)
- . . .

Predict:

- best-fit points
- ranges for Higgs masses
- ranges for SM parameters
- ranges for SUSY masses
  ⇒ Implications for current and future experiments

Indirect constraints on M_{SUSY} from existing data?

- Electroweak precision observables (EWPO) ?
- B physics observables (BPO) ?
- Cold dark matter (CDM) ?

  $\Rightarrow$ combination of EWPO, BPO, CDM ?

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  $\Rightarrow$ combination of EWPO, BPO, CDM ?

EWPO M_W : information on $m_{\tilde{t}}$, $m_{\tilde{b}}$ or M_A, $\tan\beta$ or . . .

EWPO $(g-2)_\mu$: information on $\tan\beta$ and/or $m_{\tilde{\chi}^0}$, $m_{\tilde{\chi}^\pm}$ and/or $m_{\tilde{\mu}}$, $m_{\tilde{\nu}_\mu}$

BPO $\text{BR}(b \to s\gamma)$: information on $\tan\beta$ and/or $M_{H^\pm}$ and/or $m_{\tilde{t}}$, $m_{\tilde{\chi}^\pm}$

CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or . . .

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CDM (LSP gives CDM) : information on $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{\tau}}$ or M_A or . . .

⇒ combination makes only sense if all parameters are connected!

⇒ this brings us back to GUT based models: CMSSM, NUHM1, . . .

The results presented here are based on:

The "MasterCode"

⇒ collaborative effort of theorists and experimentalists

[Buchmüller, Cavanaugh, De Roeck, Dolan, Ellis, Flächer, SH, Isidori, Olive, Rogerson, Ronga, Weiglein]

Über-code for the combination of different tools:

- tools are included as subroutines
- compatibility ensured by collaboration of authors of "MasterCode" and authors of "sub tools" /SLHA(2)
- one "MasterCode" for one model . . .

⇒ evaluate observables of one parameter point consistently with various tools

cern.ch/mastercode

χ^2 calculation:

→ global χ^2 likelihood function
combines all theoretical predictions with experimental constraints:

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}})^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

N: number of observables studied
M: SM parameters: $\Delta\alpha_{\mathrm{had}}, m_t, M_Z$
C_i: experimentally measured value (constraint)
P_i: MSSM parameter-dependent prediction for the corresponding constraint

Assumption: measurements are uncorrelated - fulfilled to a high degree

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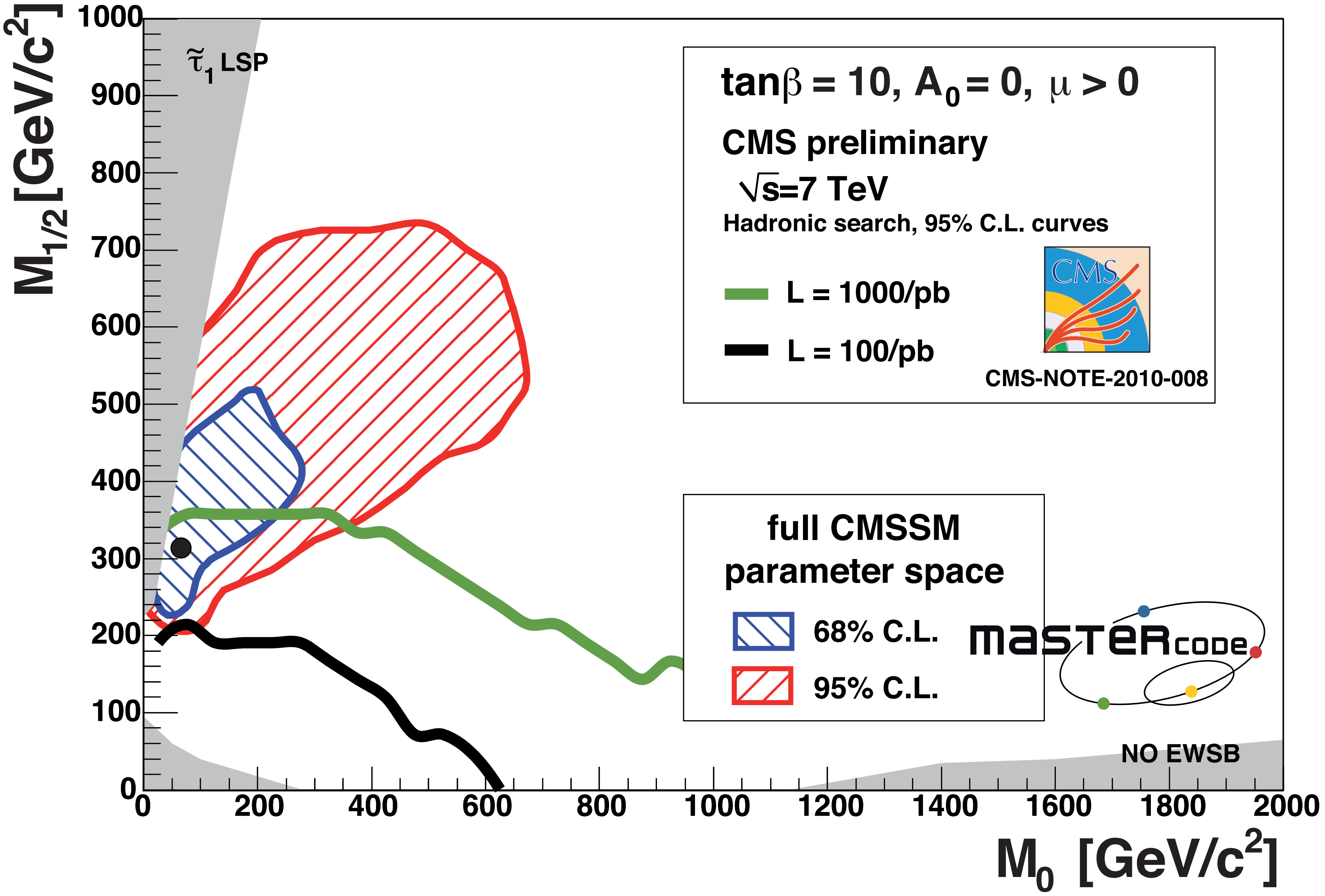
What to do if only a lower/upper bound exists?

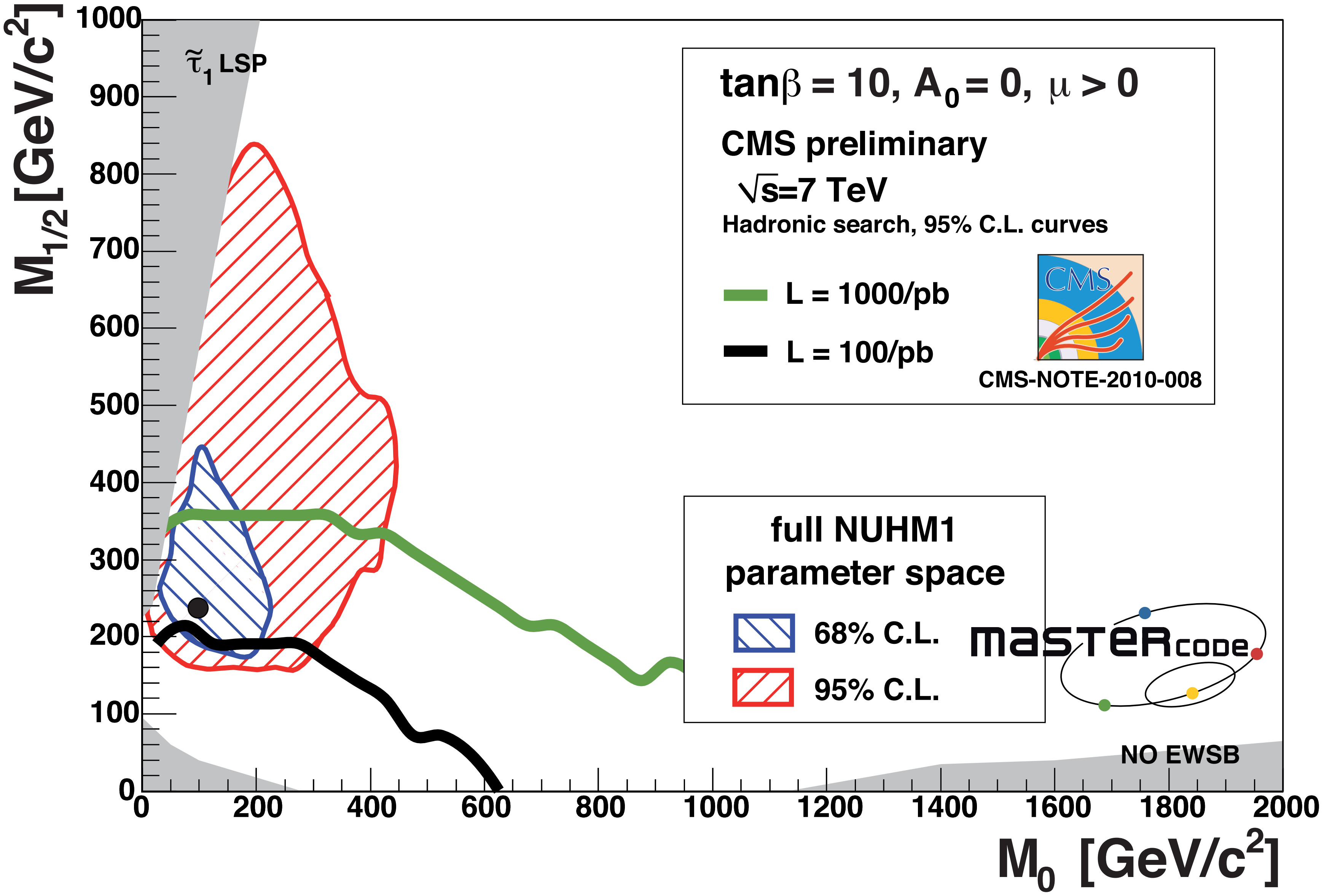
→ especially important: M_h → no time - ask me over coffee

pre-LHC predictions: CMSSM:



⇒ "best-fit point and part of 68% C.L. are can be tested in 2011"

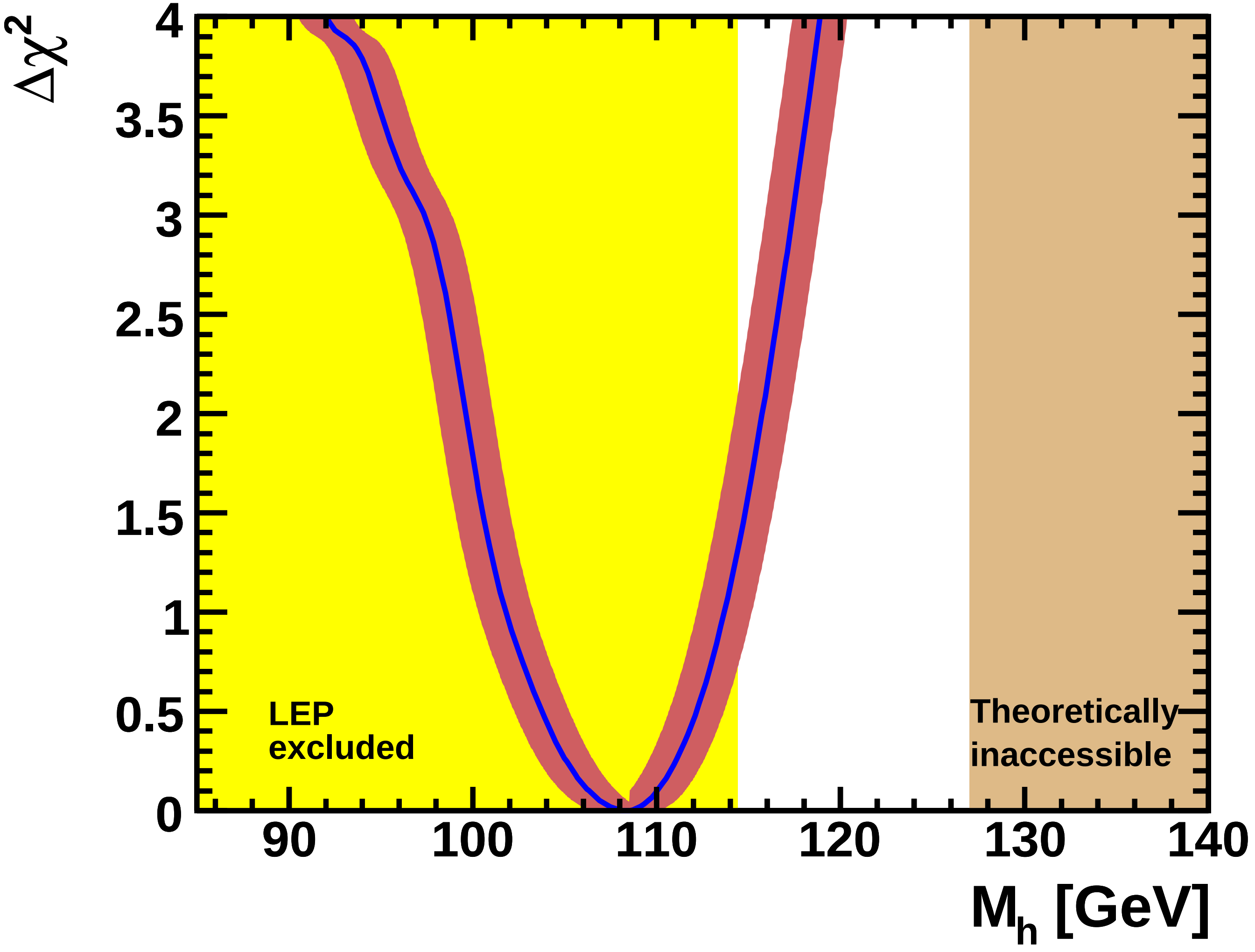
pre-LHC predictions: NUHM1:



⇒ "best-fit point and part of 68% C.L. are can be tested in 2011"

pre-LHC-CMSSM: red band plot:

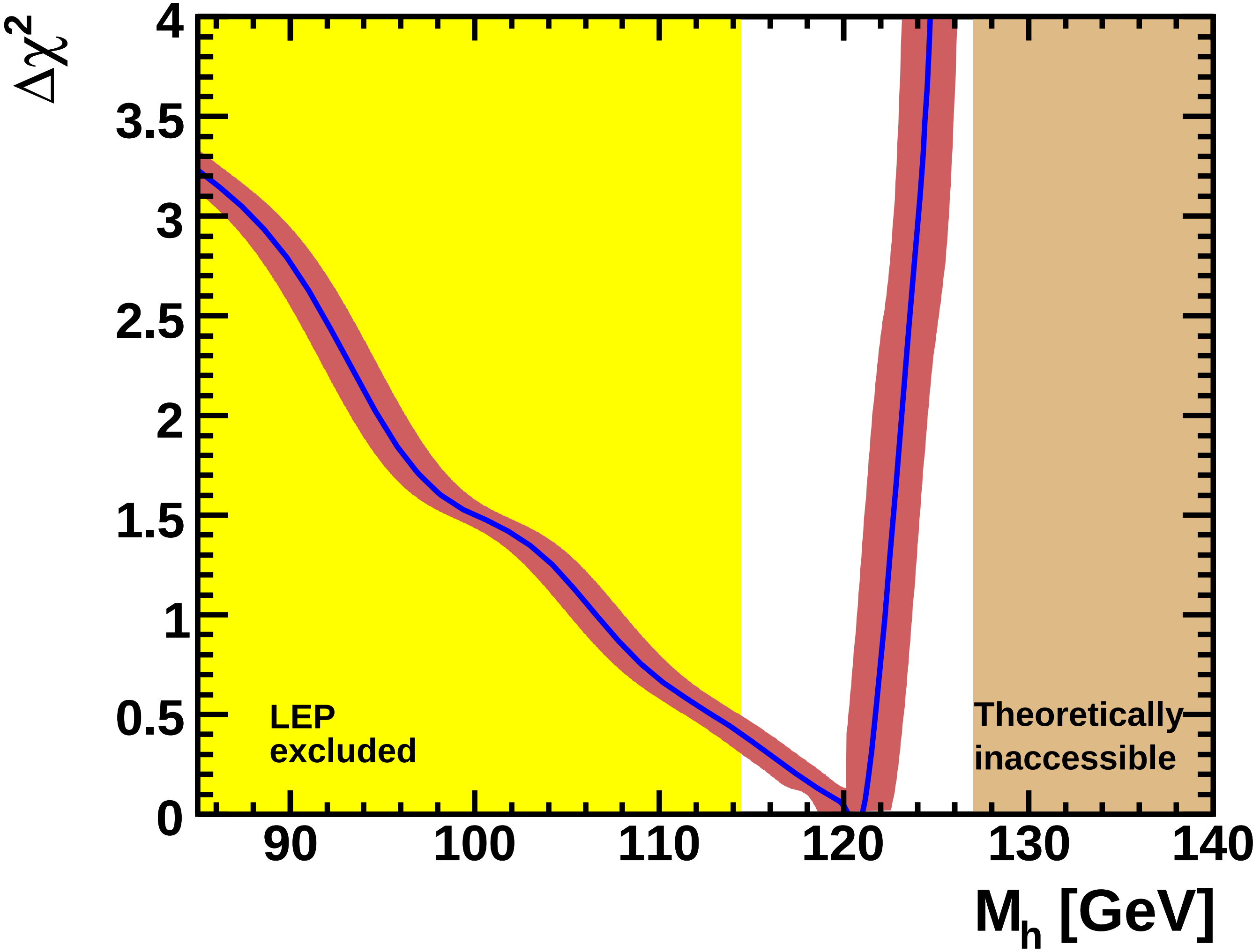
[2009]



$M_h = 108 \pm 6\,(\text{exp}) \pm 1.5(\text{theo})$ GeV

pre-LHC-NUHM1: red band plot:

[2009]



$M_h = 121^{+1}_{-14}$ (exp) ± 1.5(theo) GeV ⇒ naturally above LEP limit

Inclusion of LHC searches

Obvious idea:

(so far) negative search results for SUSY particles/effects yield

$$\boxed{\text{new } \chi^2\text{(LHC-SUSY, LHC-Higgs, \dots) contribution}}$$

Expected effect: disfavor low m_0-$m_{1/2}$ values

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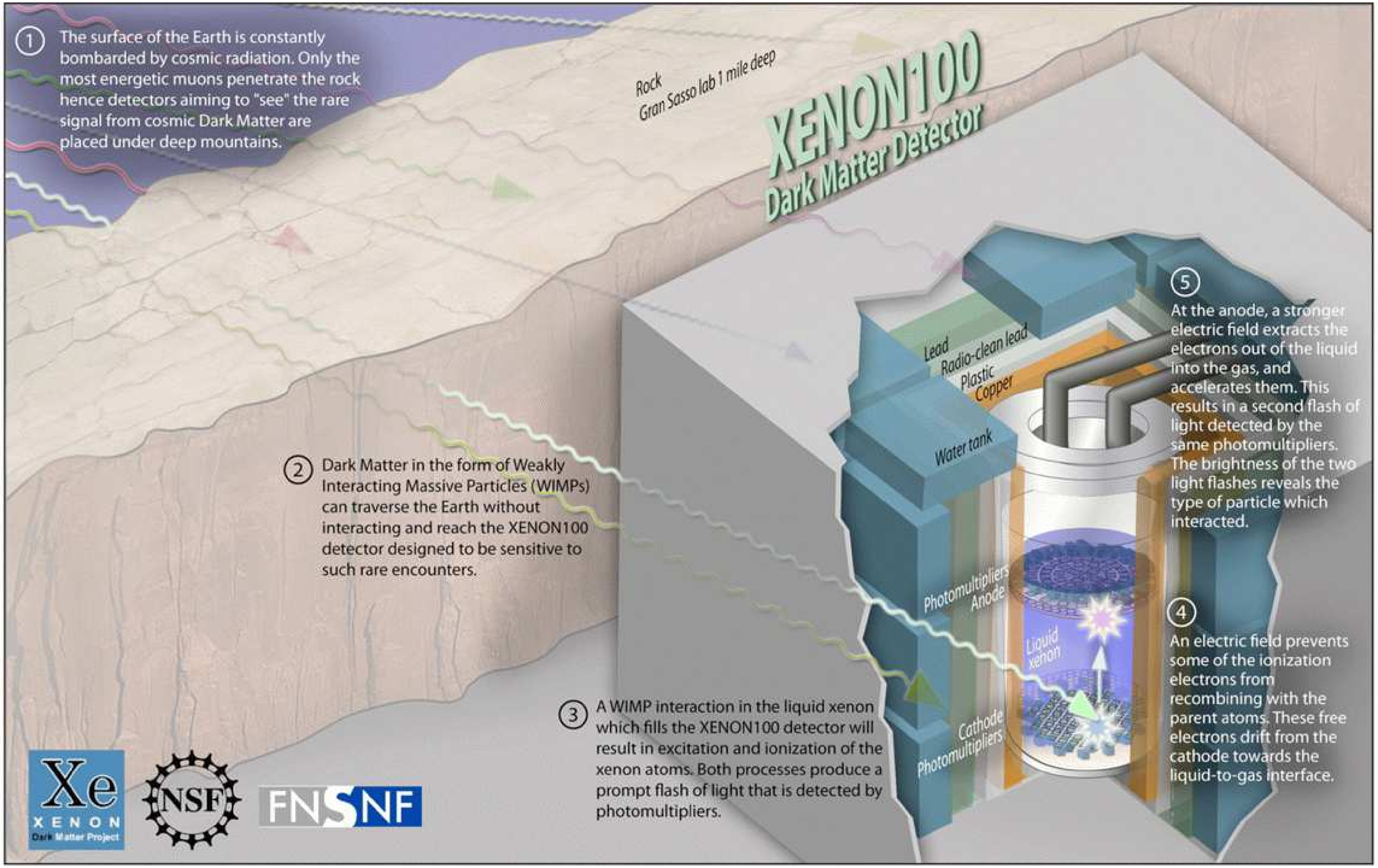
⇒ Implications for SUSY fits?

⇒ Implications for future colliders?

Additional new constraint:

Direct Dark Matter detection: Xenon100



① The surface of the Earth is constantly bombarded by cosmic radiation. Only the most energetic muons penetrate the rock hence detectors aiming to "see" the rare signal from cosmic Dark Matter are placed under deep mountains.

② Dark Matter in the form of Weakly Interacting Massive Particles (WIMPs) can traverse the Earth without interacting and reach the XENON100 detector designed to be sensitive to such rare encounters.

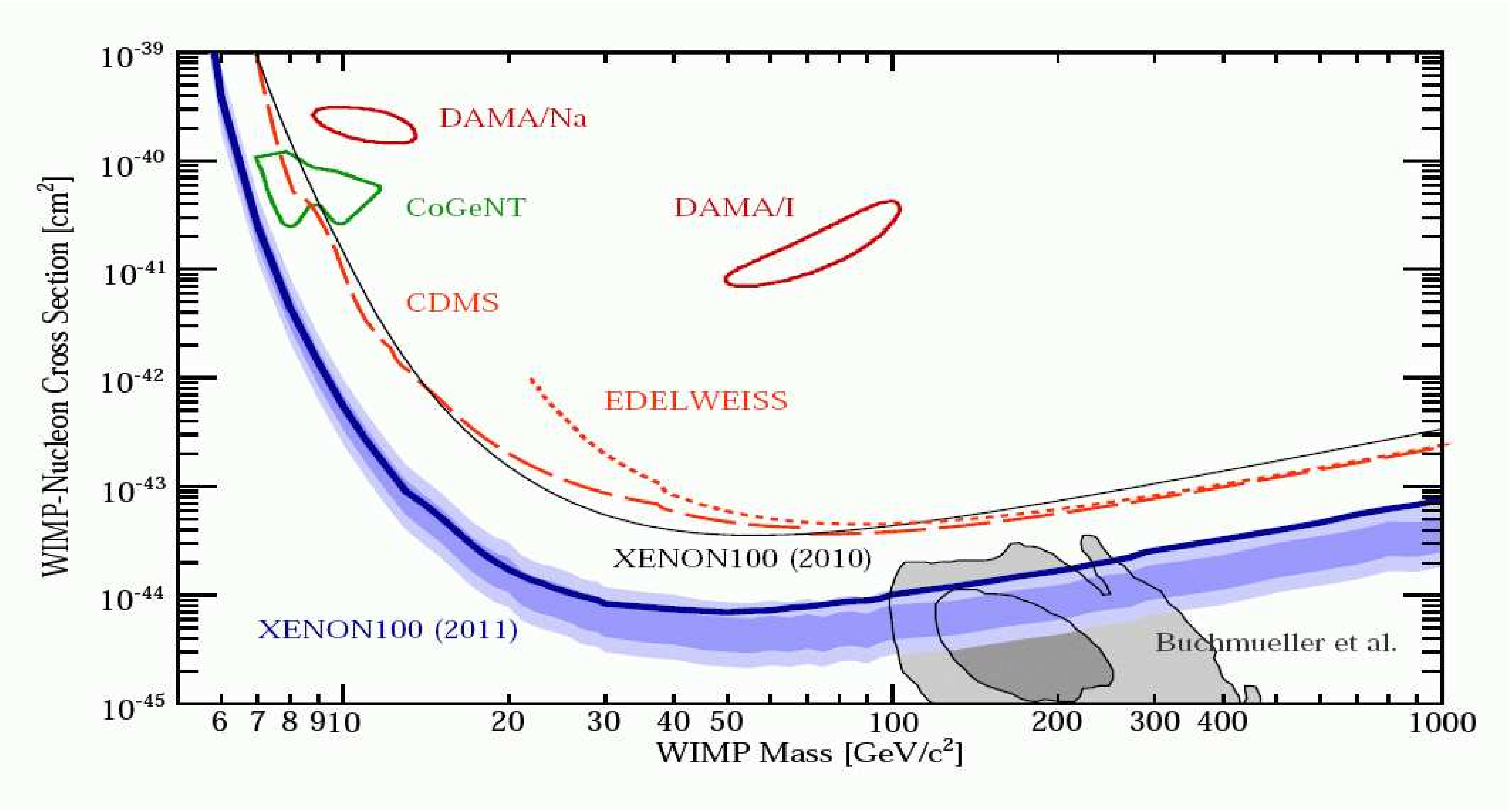
③ A WIMP interaction in the liquid xenon which fills the XENON100 detector will result in excitation and ionization of the xenon atoms. Both processes produce a prompt flash of light that is detected by photomultipliers.

④ An electric field prevents some of the ionization electrons from recombining with the parent atoms. These free electrons drift from the cathode towards the liquid-to-gas interface.

⑤ At the anode, a stronger electric field extracts the electrons out of the liquid into the gas, and accelerates them. This results in a second flash of light detected by the same photomultipliers. The brightness of the two light flashes reveals the type of particle which interacted.

Xenon100 results:

[*Xenon100 collaboration '11*]



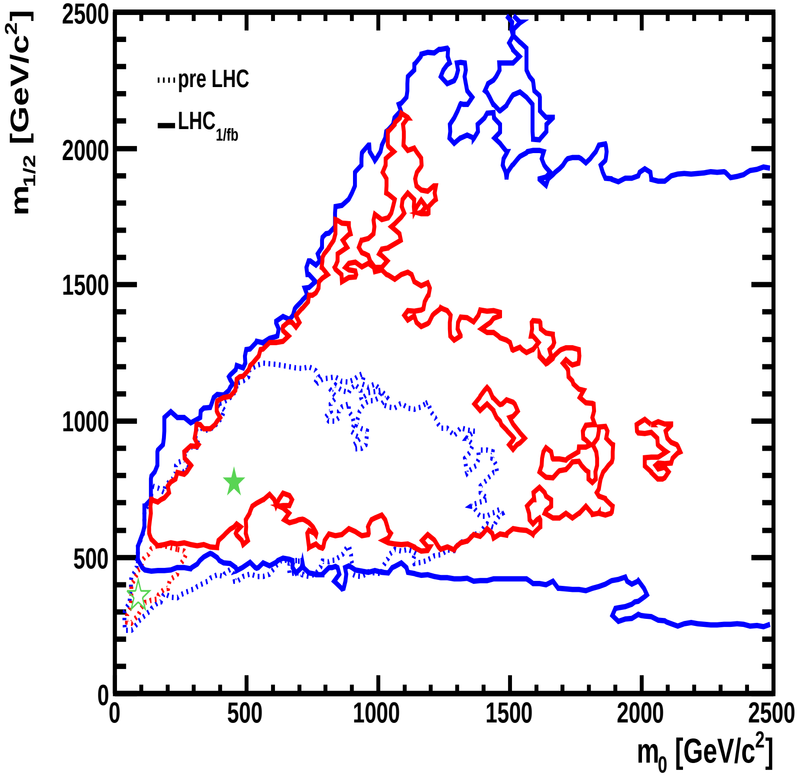
expected: 1.8 ± 0.6 events

observed: 3 events

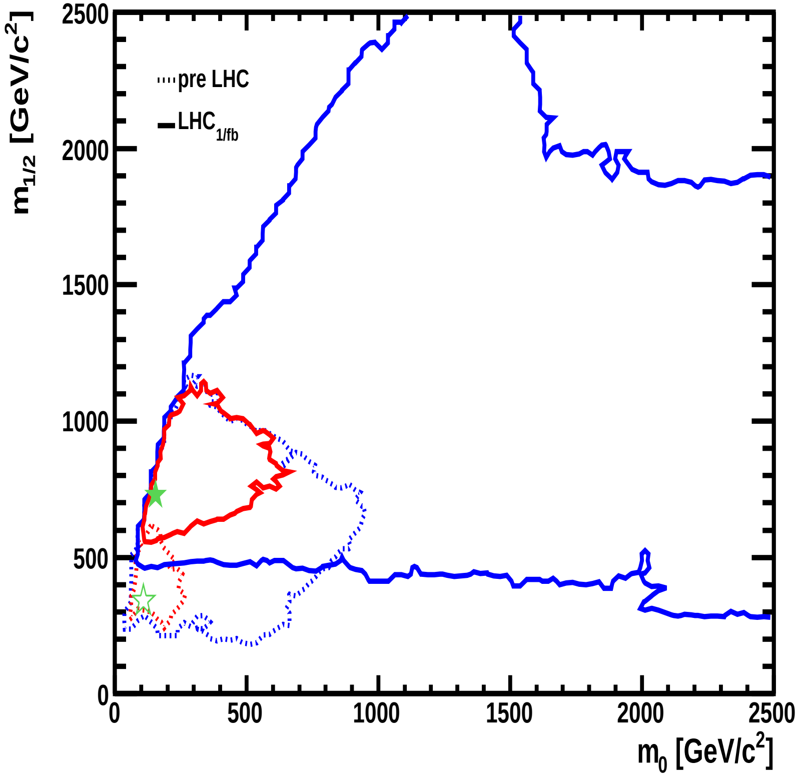
m_0-$m_{1/2}$ plane:

[2011]

CMSSM



NUHM1



dotted: pre-LHC/Xenon, solid: post-LHC (1 fb^{-1})/Xenon

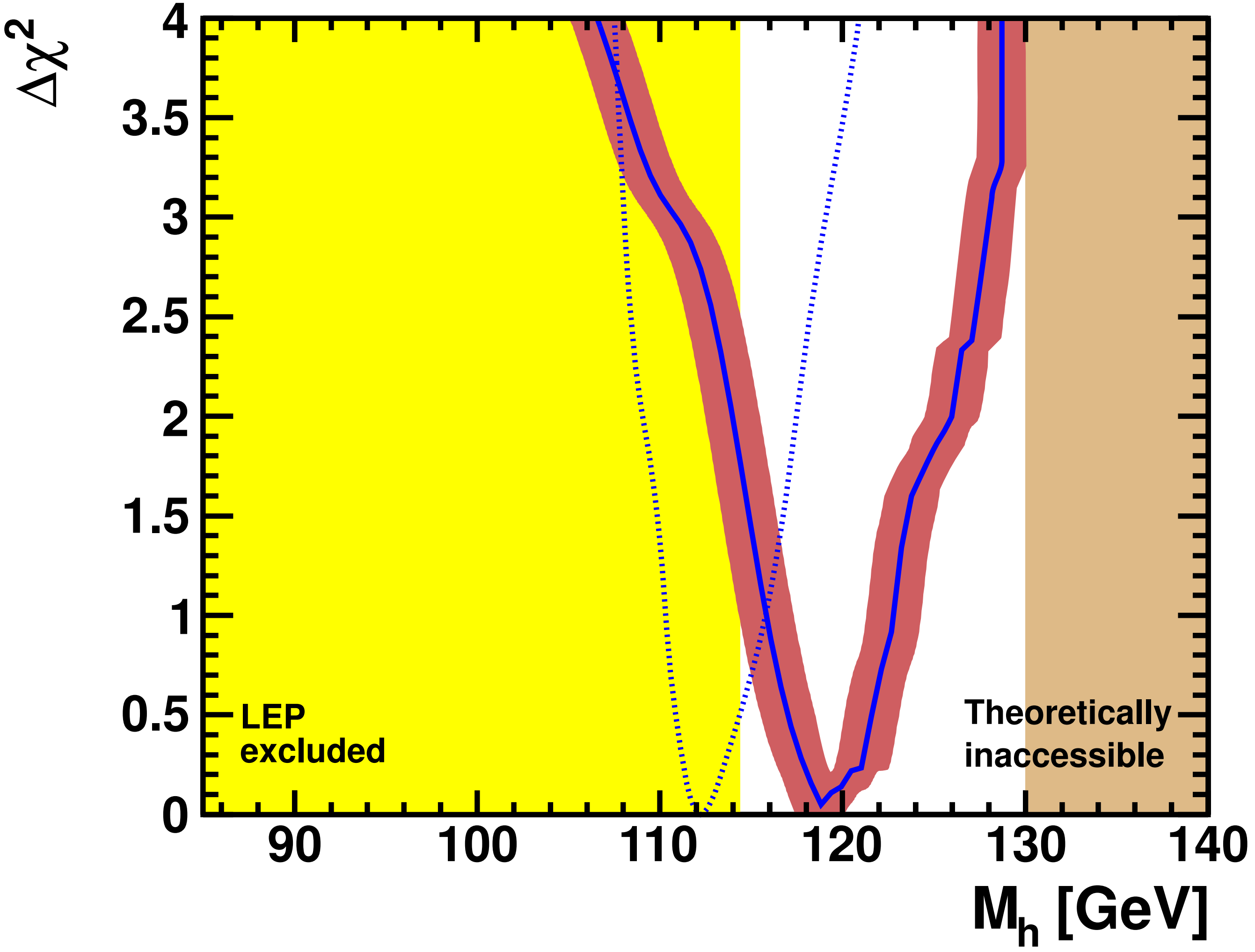
⇒ new best-fit point within old 95% CL area

⇒ hardly any overlap between old and new 68% CL areas

⇒ shift to higher masses

CMSSM: post-LHC red band plot:

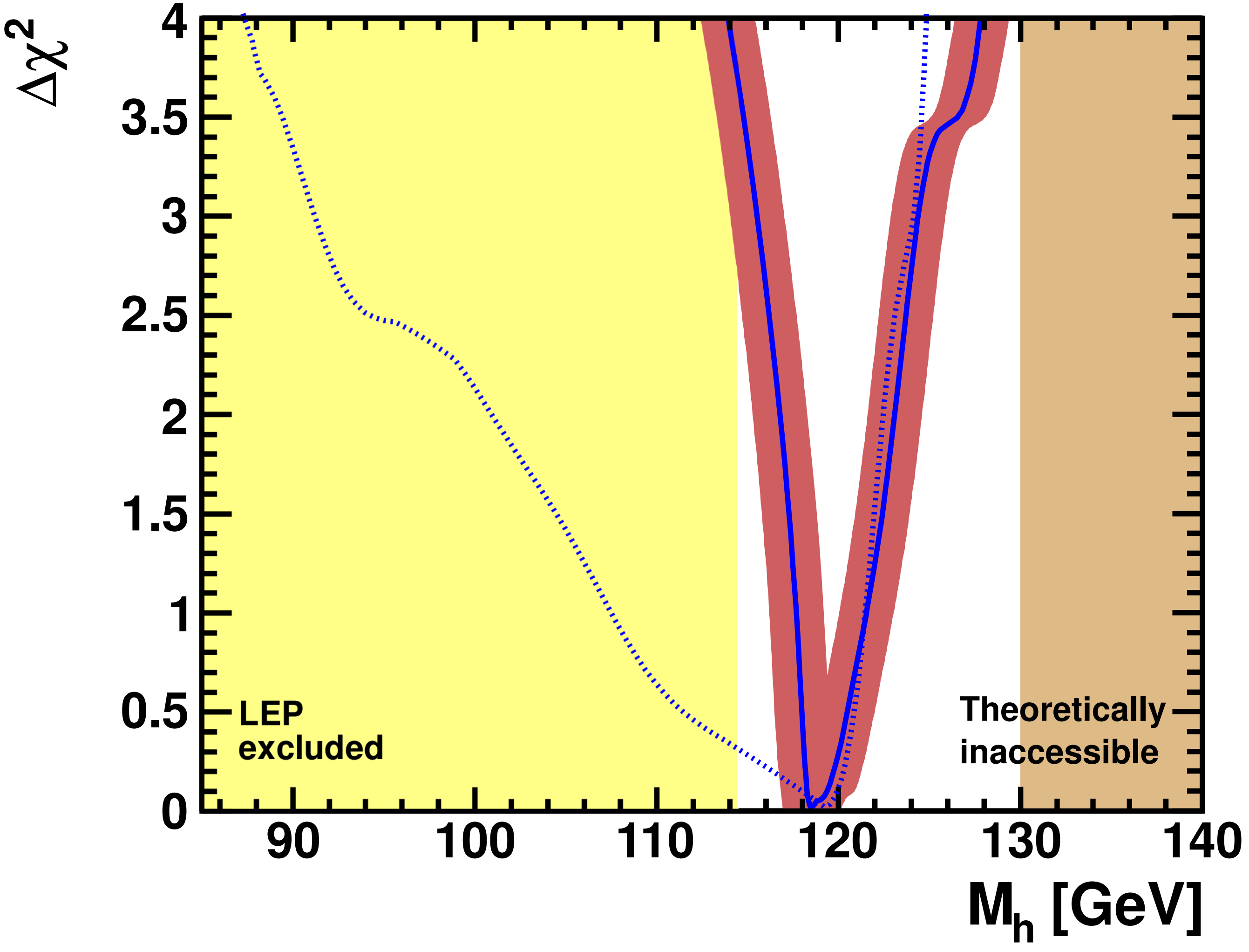
[2011]



$M_h = 119.1^{+3.4}_{-2.9}$(exp) $\pm\,1.5$(theo) GeV $\Rightarrow$ fits "better" than pre-LHC

NUHM1: post-LHC red band plot:

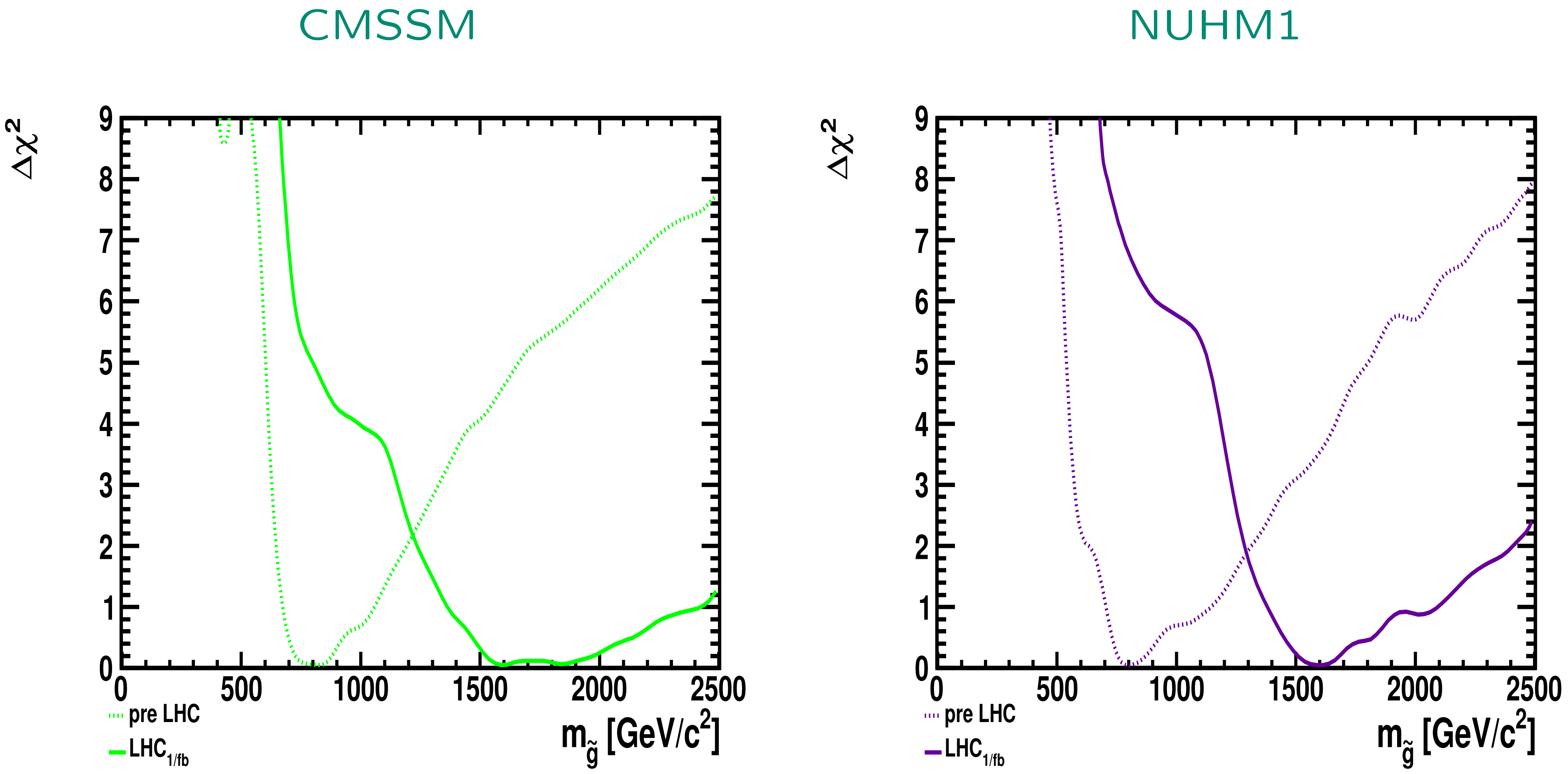
[2011]



$$M_h = 118.8^{+2.7}_{-1.1}(\text{exp}) \pm 1.5(\text{theo})\ \text{GeV}$$

Starting point of the cascade: gluino (35 pb^{-1})

[2011]



dotted: pre-LHC/Xenon, solid: post-LHC/Xenon

⇒ substantial upward shift

What is happening to the χ^2?

Low energy data (mostly $(g-2)_\mu$) favors low SUSY mass scales

LHC data favors higher SUSY scales

$\Rightarrow$ tension, reflected in rising χ^2:

Model	Min. χ^2	Prob.	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	$M_h^{\text{no LEP}}$ (GeV)
CMSSM	22.3/20	32%	360	90	-400	15	111
LHC 2011	29.3/22	14%	780	450	-1100	41	119
NUHM1	20.8/18	29%	340	110	520	13	119
LHC 2011	27.4/21	16%	730	150	-910	41	119

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The LHC searches (mainly) for colored particles,
Uncolored particles practically unconstrained (so far)!

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Uncolored particles practically unconstrained (so far)!

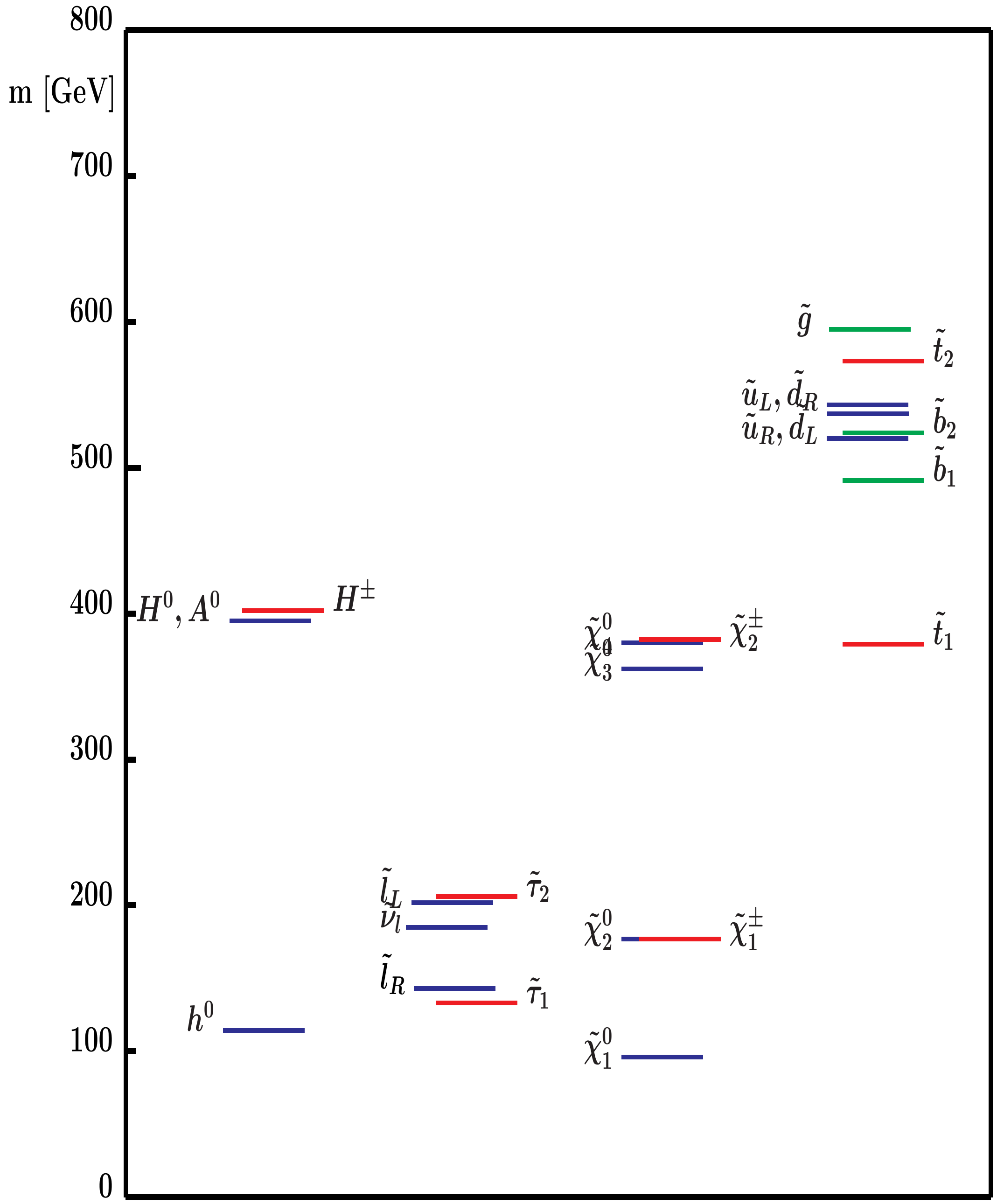
Any inference from one sector to the other is strongly model dependent!

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



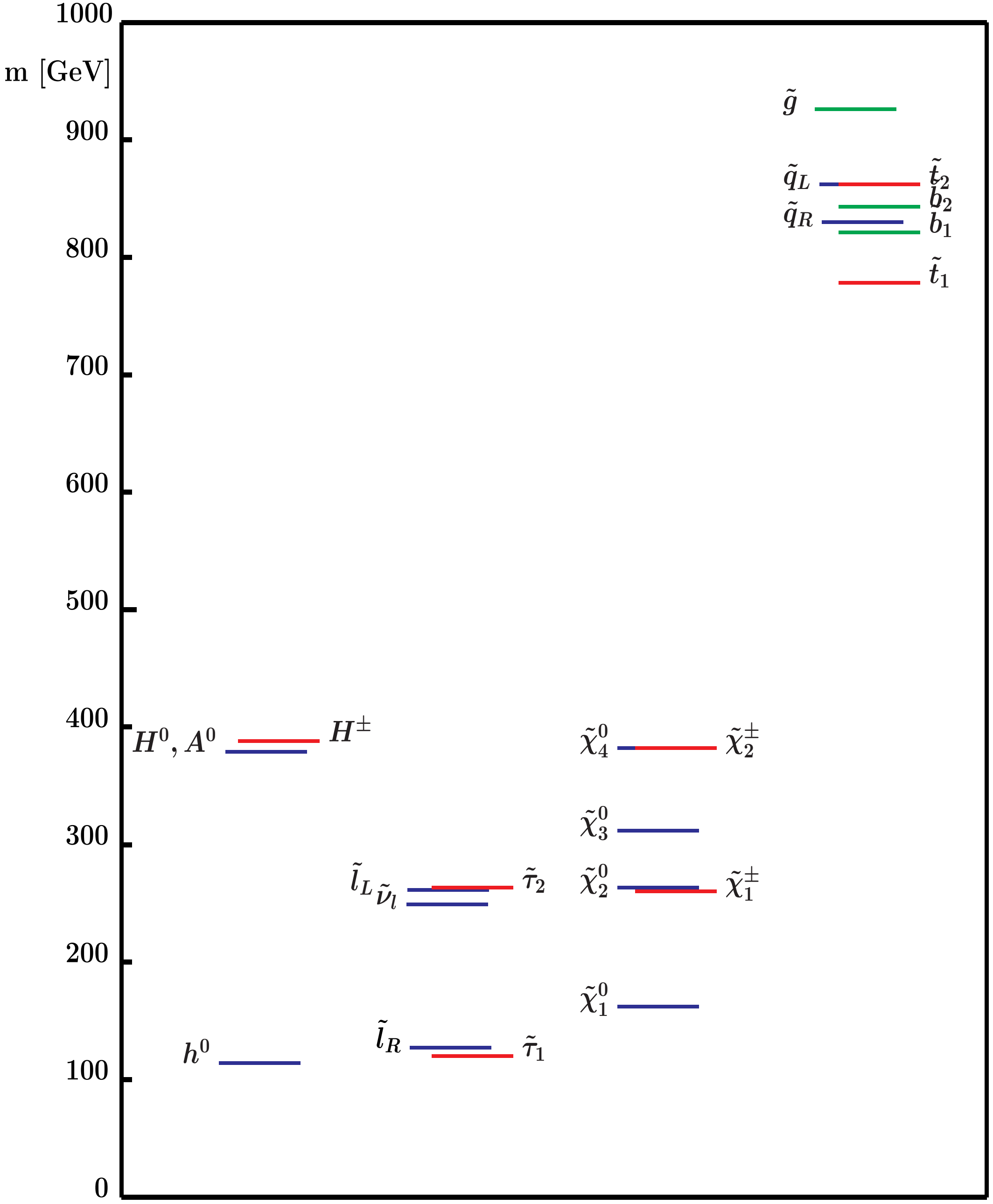
“Typical” GMSB scenario

(SPS 7 benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/~georg/sps`

One possible example
for natural larger splitting
between colored and
uncolored sector



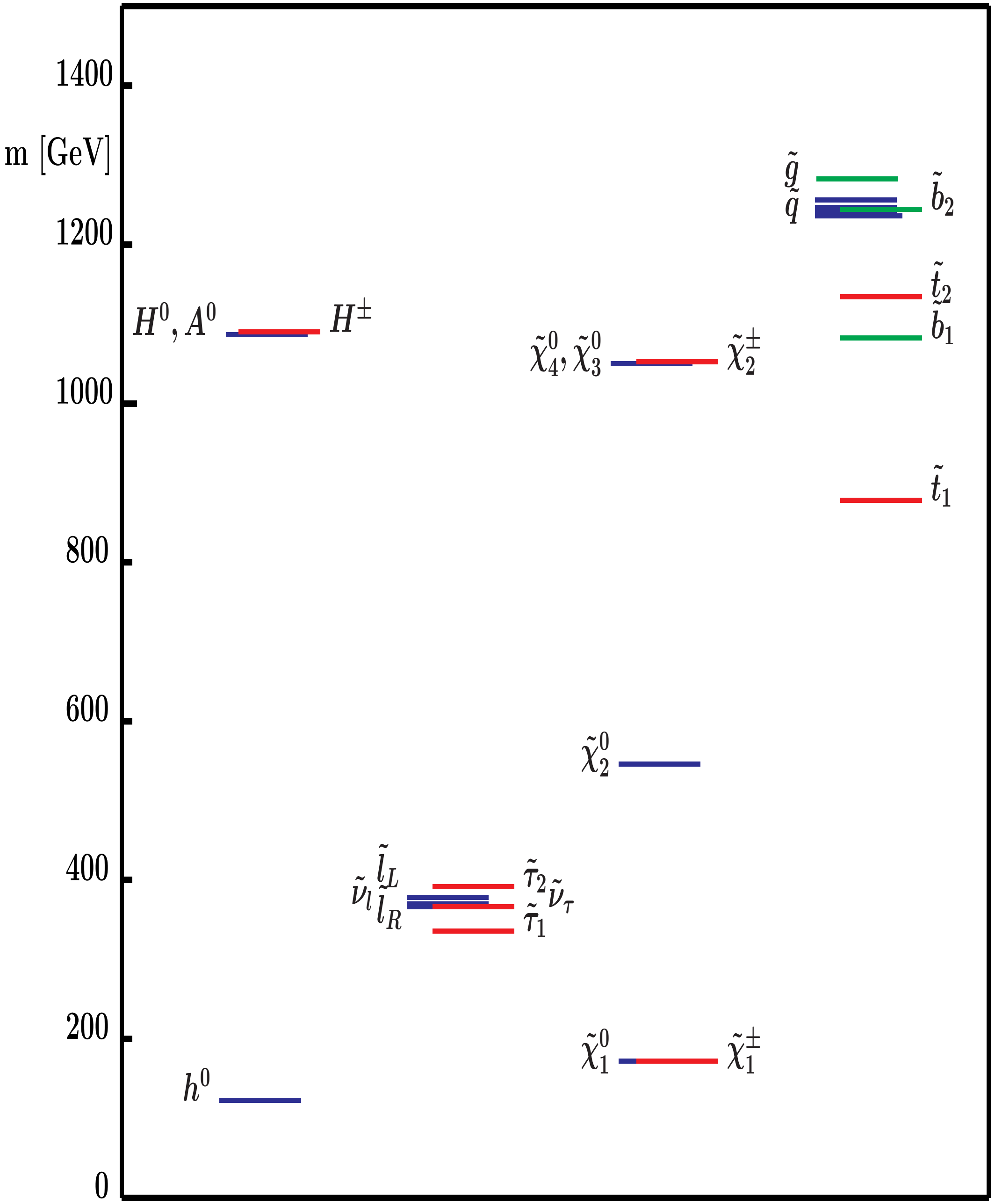
"Typical" AMSB scenario

(SPS 9 benchmark scenario):

SPS home page:

`www.ippp.dur.ac.uk/∼georg/sps`

One possible example
for natural larger splitting
between colored and
uncolored sector



4. Other BSM physics - if time permits

1. Z' models

2. 4th generation models

3. Extra dimensions

4. Little Higgs models

Z' models

Z' is the gauge boson of an additional $U(1)$

→ remnant of a larger gauge symmetry

$$\begin{aligned} SO(10) &\to SU(5) \otimes U(1) \\ &\to SU(3) \otimes SU(2) \otimes U(1) \otimes U(1) \\ E_6 &\to SO(10) \\ &\to SU(5) \otimes U(1) \\ \ldots &\to \ldots \end{aligned}$$

⇒ many^2 possibilities!

…all with slightly different couplings of the Z'

Z' mass:

$$M^2_{ZZ'} = \begin{pmatrix} M^2_Z & \Delta^2 \\ \Delta^2 & M^2_{Z'} \end{pmatrix}$$

$$\begin{aligned} M^2_1 &= M^2_Z - \frac{\Delta^4}{M^2_{Z'}} \ll M^2_2 \\ M^2_2 &\approx M^2_{Z'} \\ \theta_{ZZ'} &\approx -\frac{\Delta^2}{M^2_{Z'}} \end{aligned}$$

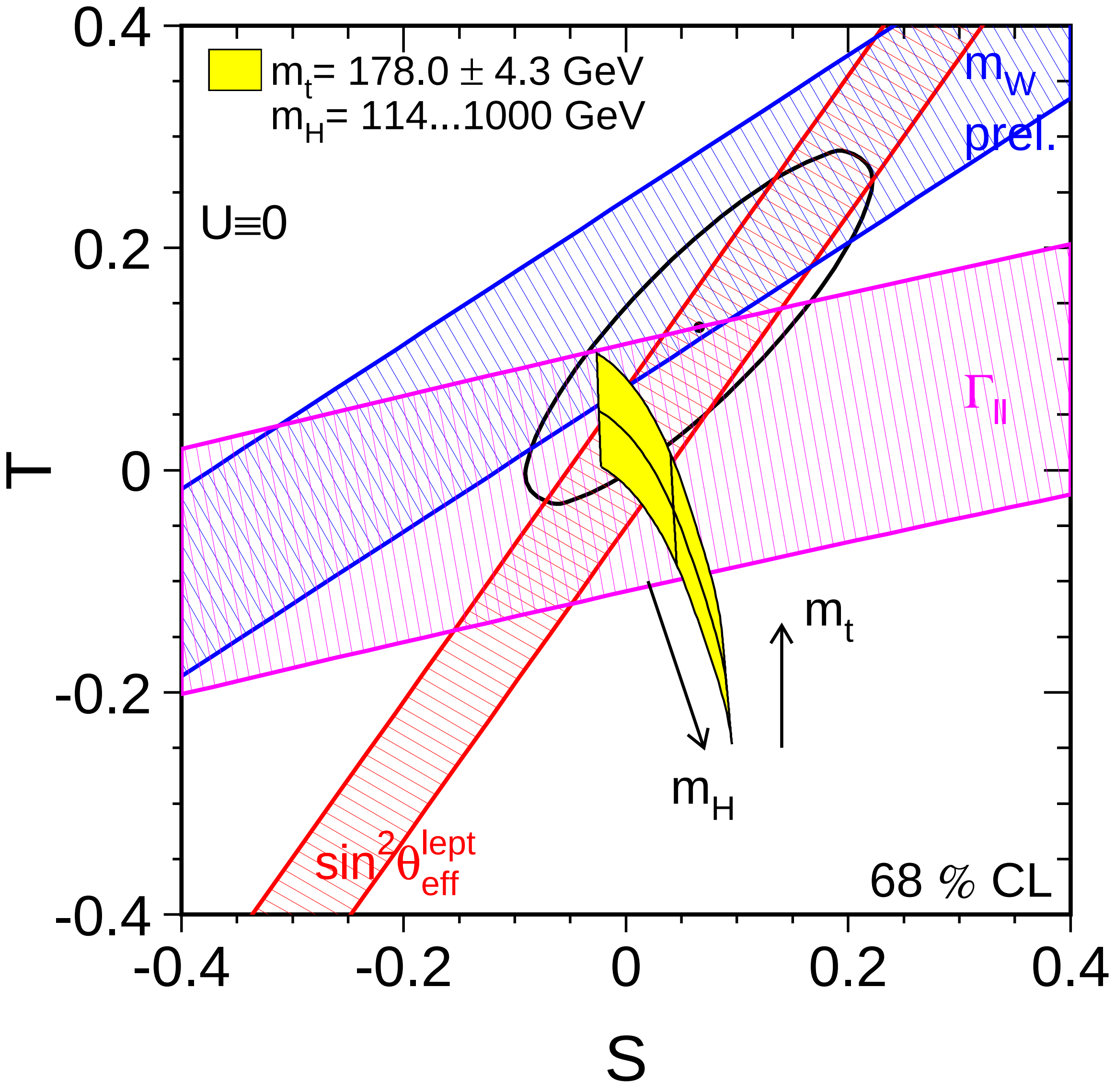
ρ parameter:

$$\rho \equiv \frac{M^2_W}{M^2_1 c^2_\mathrm{W}} \sim T$$

⇒ strong constraints from electroweak precision data

(Z pole experiments have little sensitivity to Z_2 exchange)

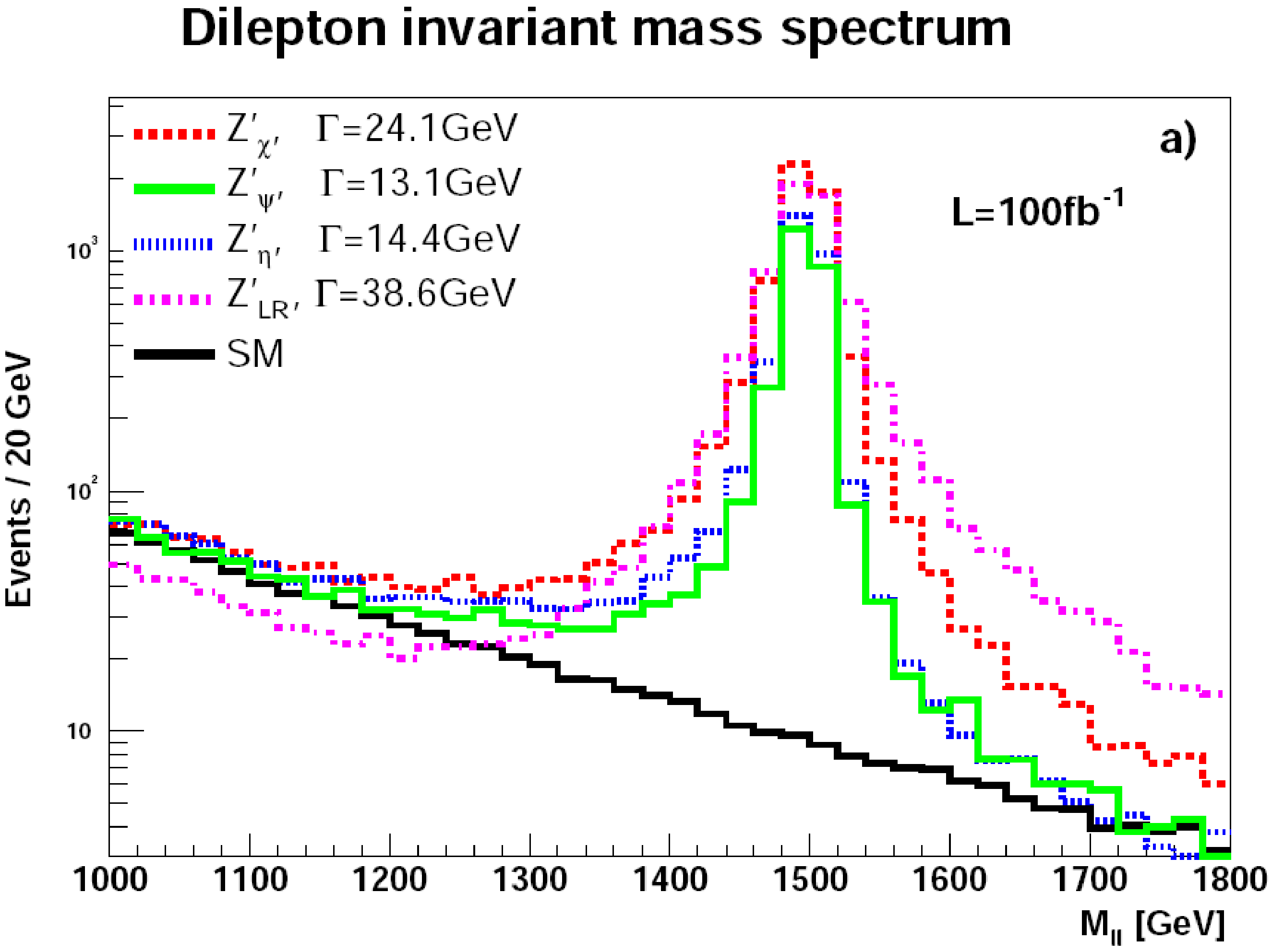
Electroweak precision constraints:



Z' compatible with heavier Higgs boson!

Golden channel: $Z' \to \ell\ell$ $(\ell = e, \mu)$

[M. Dittmar, A. Nicollerat, A. Djouadi '03]

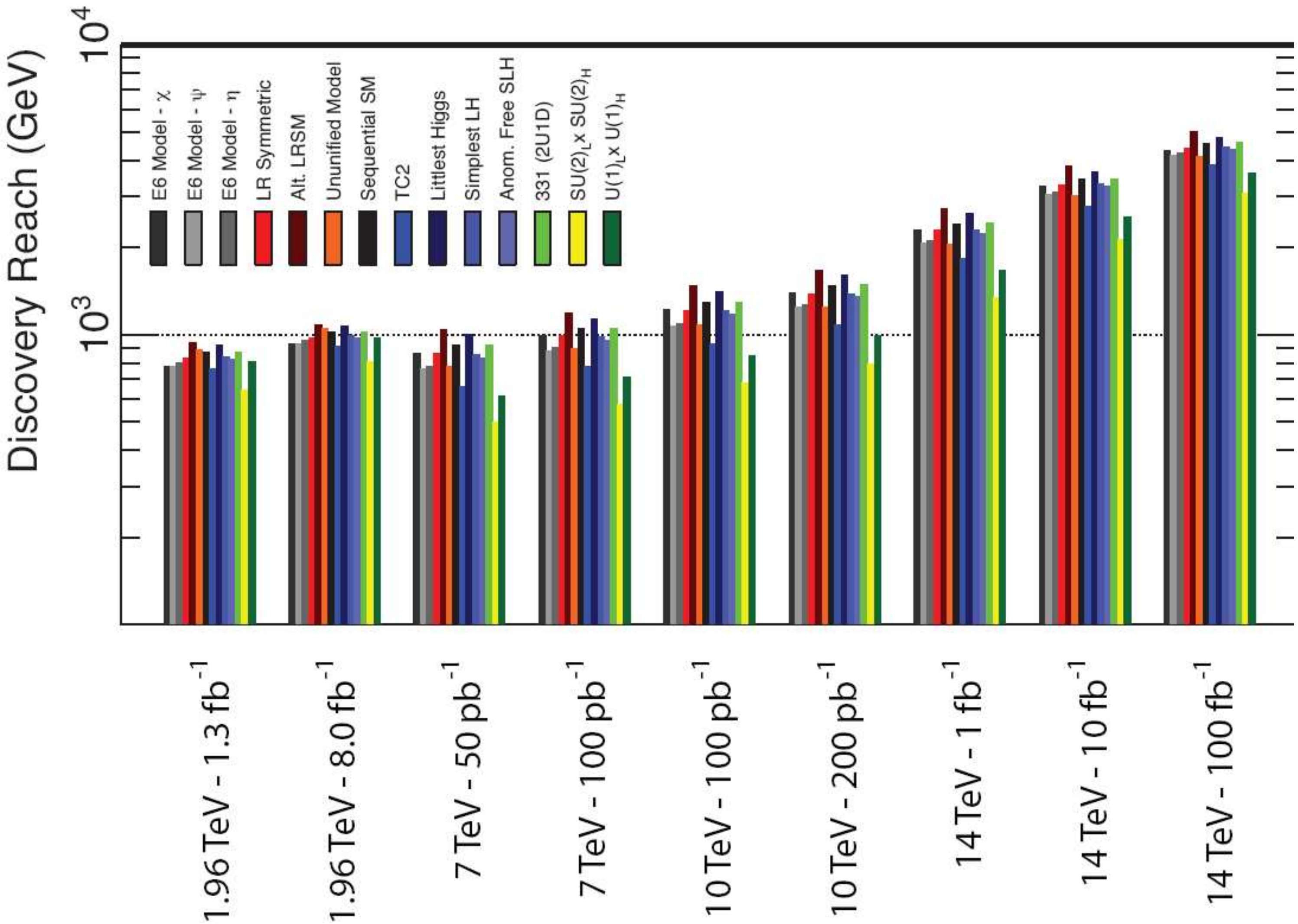


$M_{Z'} = 1.5$ TeV, $\sqrt{s} = 14$ TeV, $\mathcal{L}_{\text{int}} = 100$ fb^{-1}

⇒ "easy" signal

Reach for various Z' models:

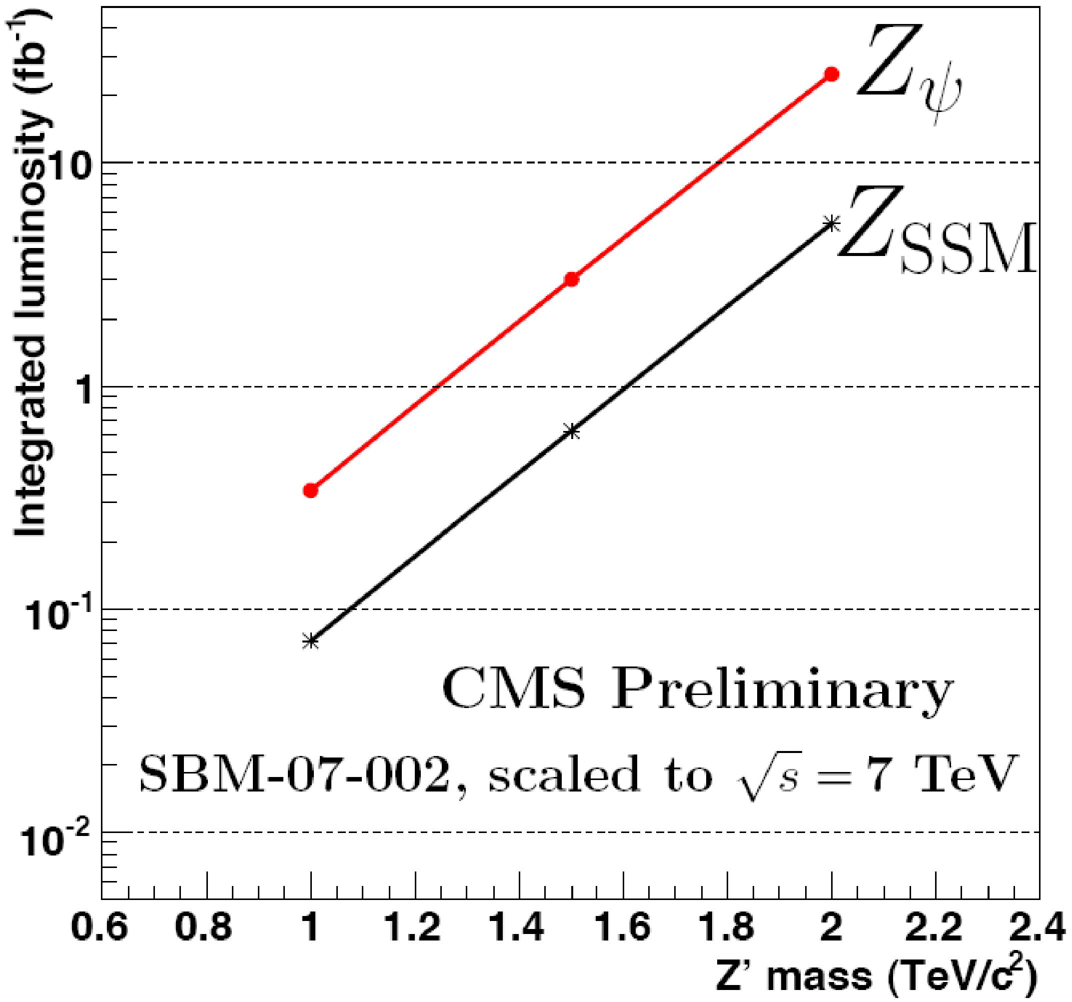
[*R. Diener, S. Godfrey, T. Martin '09*]



⇒ large reach with low luminosity

Reach for two Z' models:

[*CMS '10*]



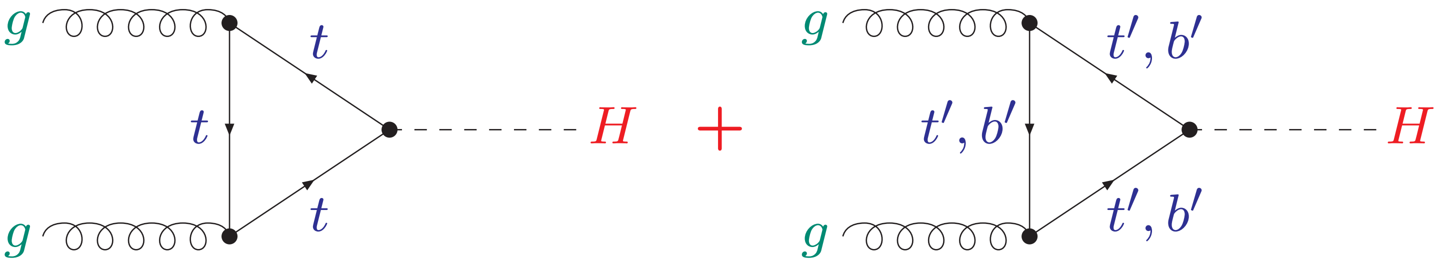
$\Rightarrow$ large reach with low luminosity, already at $\sqrt{s} = 7$ TeV

4th generation models

Assume the SM with a 4th generation of heavy fermions
(SM4 = SM + 4th generation of quarks and leptons)

Relevant changes:

1. additional contribution to $gg \to H$:



   $\Rightarrow$ factor of ~ 9 in Higgs production cross section

2. $\Rightarrow$ factor of ~ 9 in $\Gamma(H \to gg)$

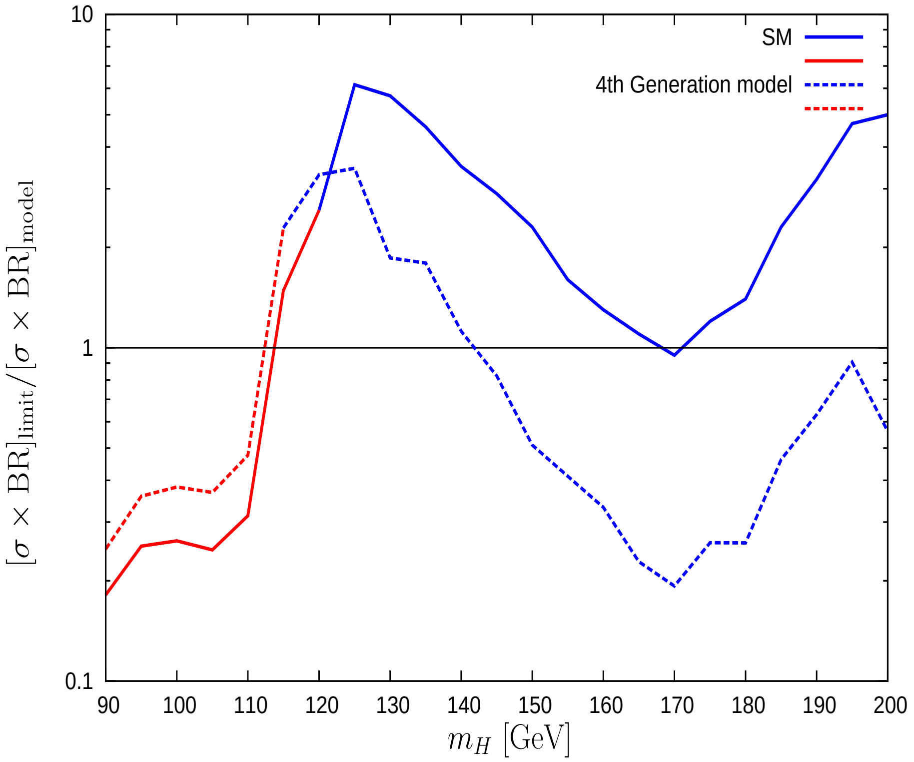
   $\Rightarrow$ reduced $\mathrm{BR}(H \to b\bar{b})$, $\mathrm{BR}(H \to \tau^+\tau^-)$

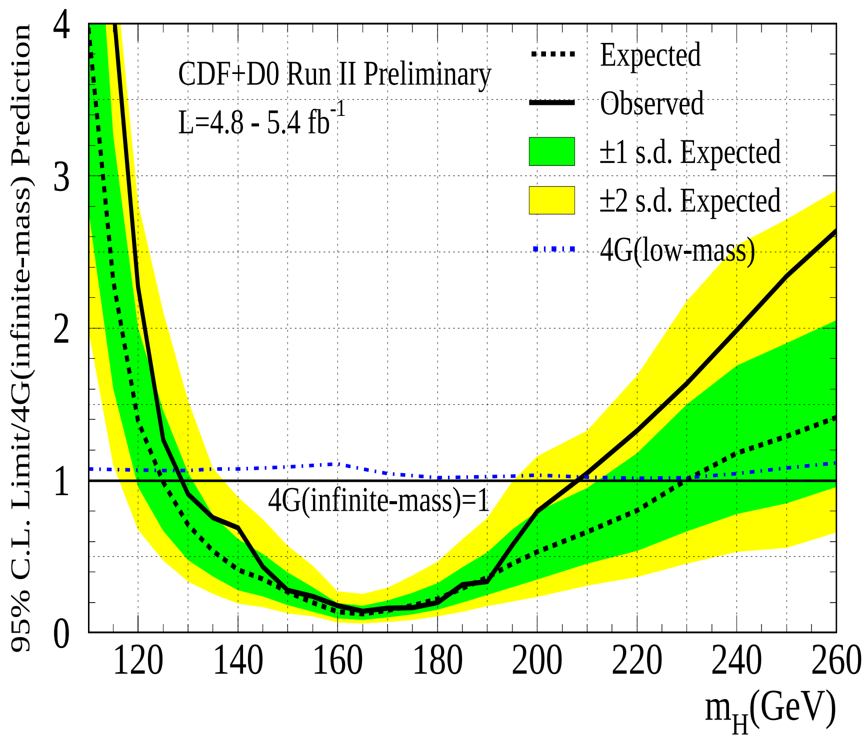
Simple approximation recently confirmed by explicit calculation
[*C. Anastasiou, R. Boughezal, E. Furlan '10*]

Limits on M_H from LEP and Tevatron searches

[P. Bechtle, O. Brein, S.H., G. Weiglein, K. Williams '08] [CDF, DØ '10]

code: HiggsBounds



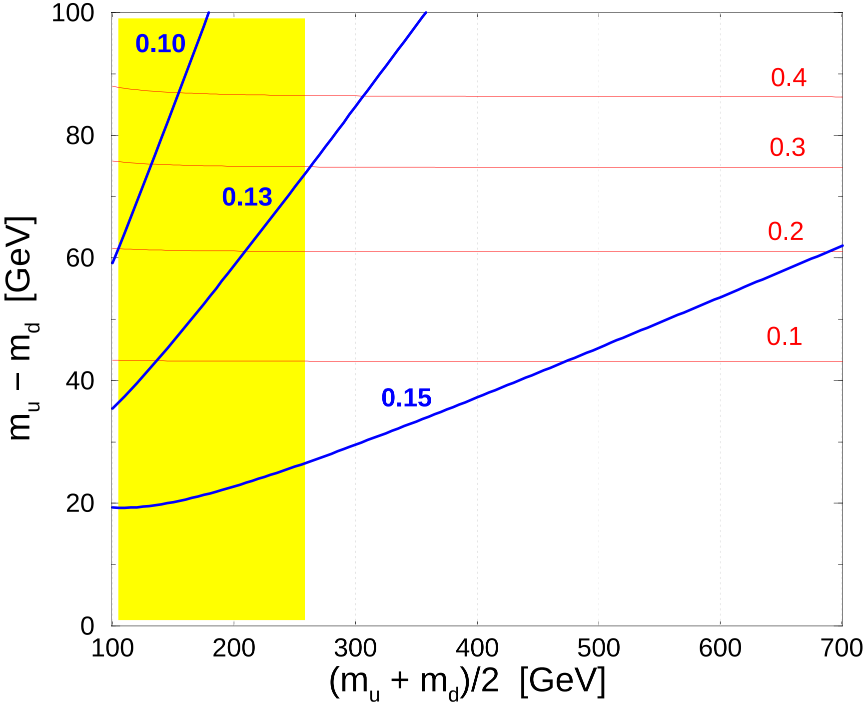


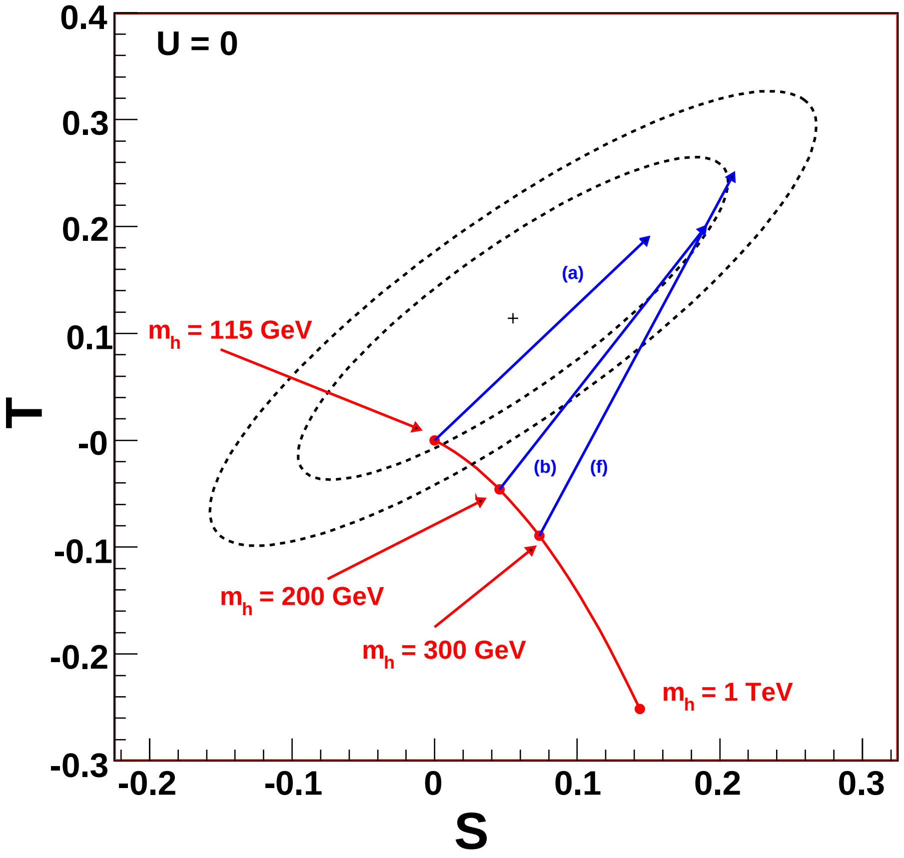
⇒ only 112 GeV $\lesssim M_H \lesssim$ 130 GeV, $M_H \gtrsim$ 210 GeV still allowed

⇒ tested soon by the Tevatron ??

Electroweak precision data for SM4:

[*G. Kribs, T. Plehn, M. Spannowsky, T. Tait '07*]



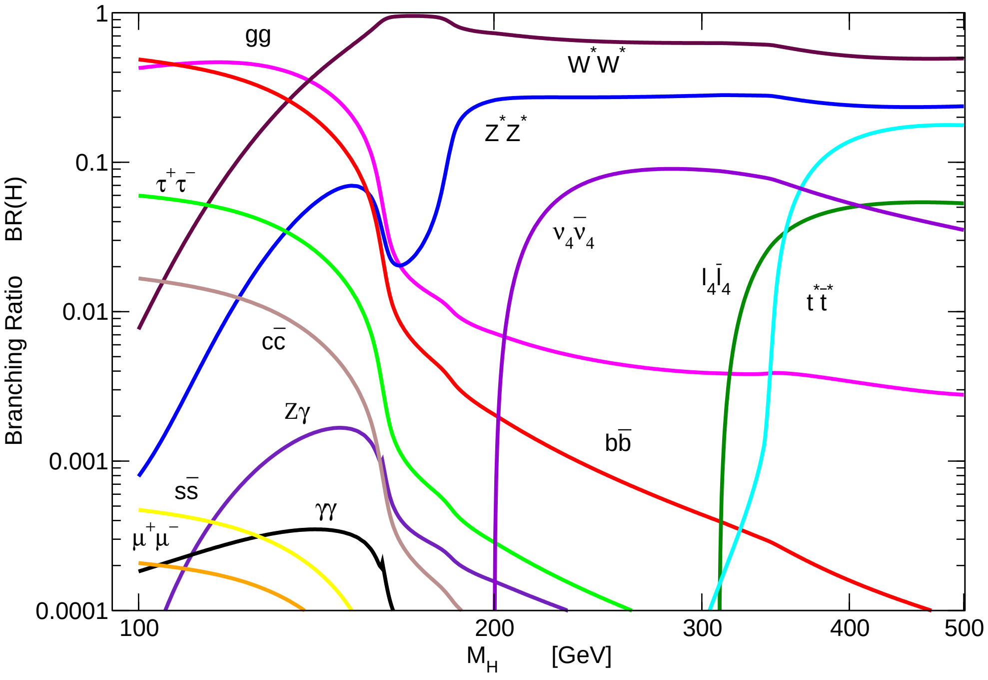


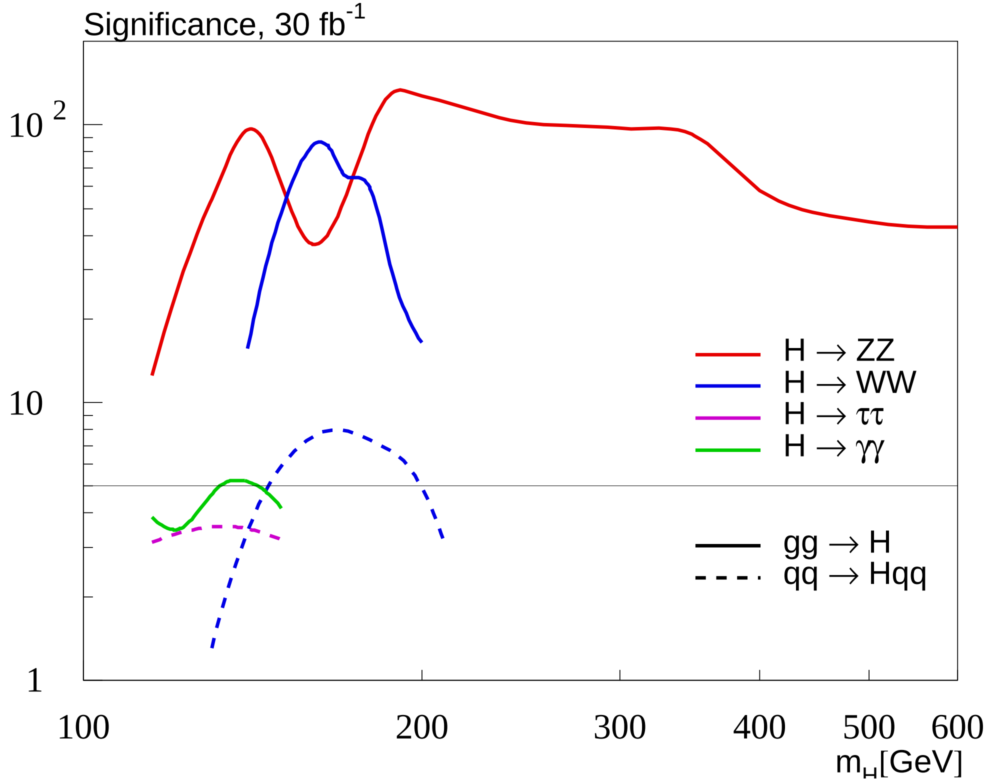
⇒ heavy Higgs can be accommodated

. . . by some fine-tuning of 4th generation masses

SM4 Higgs physics at the LHC:

[G. Kribs, T. Plehn, M. Spannowsky, T. Tait ’07]





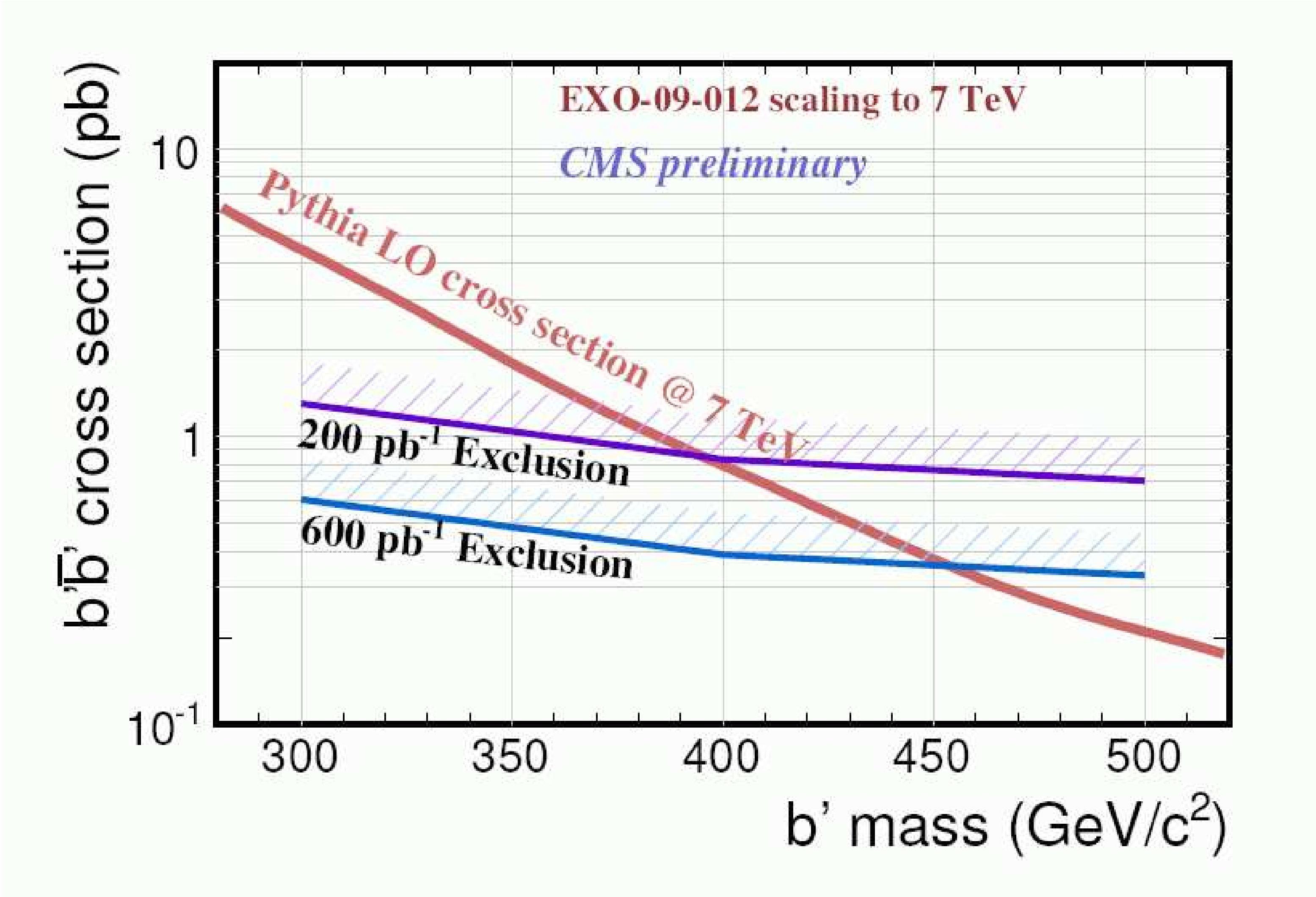
⇒ modified branching ratios

but BR($H \to WW^{(*)}$) and BR($H \to ZZ^{(*)}$) still strong

⇒ discovery possible with 30 fb^{-1}

Reach for b' quarks:

[*CMS '10*]



⇒ large reach with low luminosity, already at $\sqrt{s} = 7$ TeV

Extra dimensions

Two general types:

1. flat (or factorizable) geometry

   → any number of (additional) dimensions:
   3+1 space-time + (D-4) extra dimensions

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \quad (\mu, \nu = 0, 1, 2, 3, \dots D)$$

2. warped (or non-factorizable) geometry

   → “warp factor” (for one extra dimension:) $a(y)$

$$ds^2 = a(y)(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2 \quad (\mu, \nu = 0, 1, 2, 3)$$

Size of the extra dimensions:

For flat geometries the extra dimensions must be small, i.e. compact

Compactifying extra dimensions leads to periodicity conditions

One extra dimension:

$$\phi(x_\mu, y) = \sum_{k=-\infty}^{k=+\infty} \phi^{(k)}(x_\mu) e^{iky/R}$$

R: inverse compactification size / radius

→ Kaluza-Klein (KK) modes $\phi^{(k)}(x_\mu)$

→ infinite number of KK modes!

Masses of KK modes:

$$m_k^2 = m_0^2 + \frac{k^2}{R^2}$$

Many options: which field sits where?

- ADD:
  n compactified extra dimensions with flat geometry → bulk
  only gravity propagates in the full D dimensional space-time
  SM fields live in the 4-dim subspace → brane
- TeV^{-1}:
  one or more compactified extra dimensions with flat geometry and sizes of $\mathcal{O}\left(10^{-19}\right)$ m, i.e. of TeV scale
  SM fields live in the 4-dim subspace → brane
- UED:
  → Universal Extra Dimensions
  also SM gauge bosons and fermions can propagate in the bulk
- RS:
  only gravity propagates in a 5-dim warped bulk
  one compactified extra dim + two 4-dim branes:
  – SM fields live in the "TeV brane"
  – other: "Planck brane"

  → adding a scalar field to the warped bulk to stabilize the brane distance

ADD at the LHC (I):

solution to the hierarchy problem:

$$M_{\mathrm{Pl}(4)}^2 = M_{\mathrm{Pl}(4+n)}^{n+2}\, R^n \quad \Rightarrow \quad M_{\mathrm{Pl}(4)} = \mathcal{O}(1\ \mathrm{TeV})$$

mass difference of KK gravitons:

$$\Delta m \approx \left(\frac{M_{\mathrm{Pl}(4)}}{1\ \mathrm{TeV}}\right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}}$$

⇒ very close to each other

⇒ very characteristic for ADD

Possible detection modes:

– direct KK graviton production

– indirect KK graviton effects as quantum corrections

ADD at the LHC (II):

direct KK graviton production

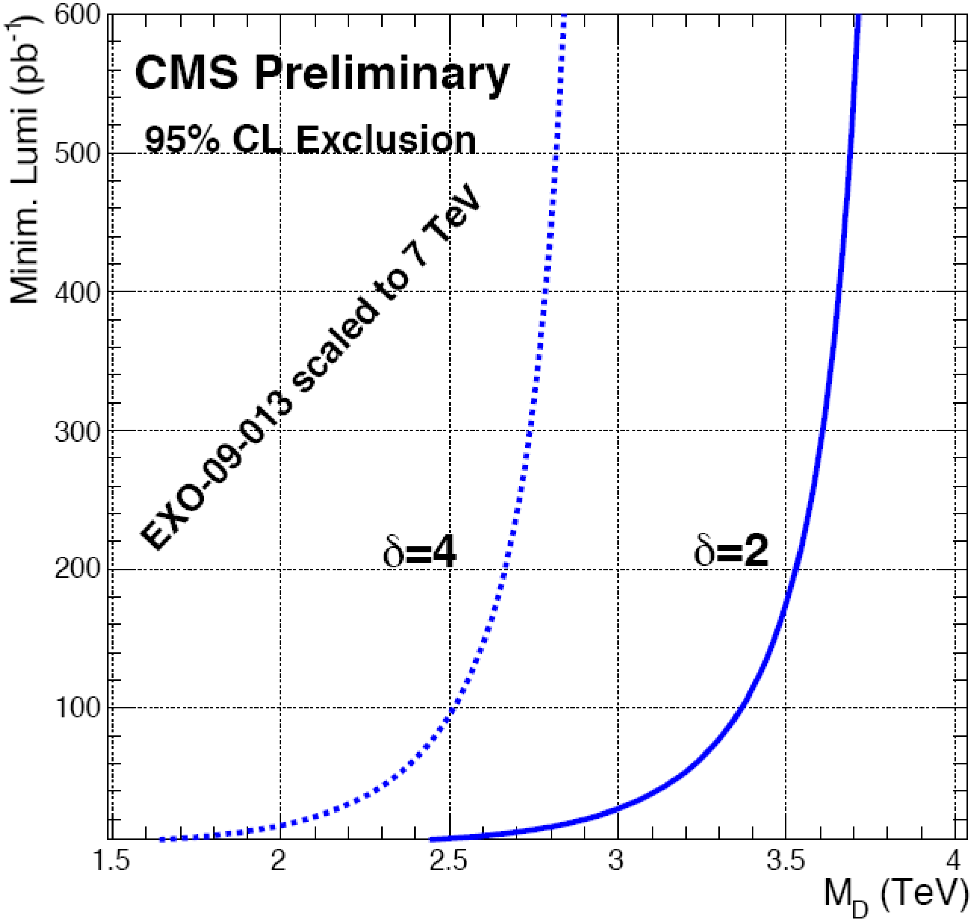
$$pp \to G_n G_n + \{g, \gamma, Z\}$$

G_n escape undetected

$\Rightarrow$ signature: $\{g, \gamma, Z\}$
+ missing energy

$(n \leftrightarrow \delta,\ M_D \leftrightarrow M_{\mathrm{Pl}(4)})$

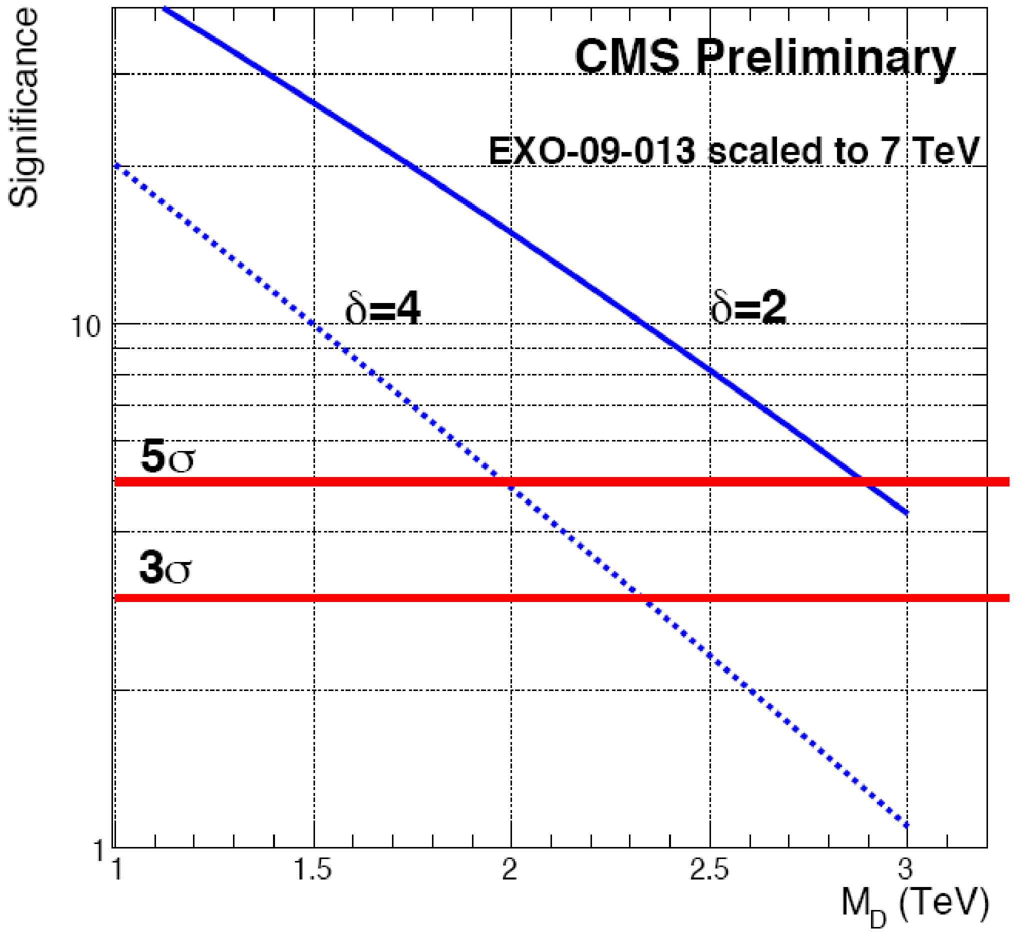
$\Rightarrow$ exclusion potential



ADD at the LHC (III):

direct KK graviton production

$$pp \to G_n G_n + \{g, \gamma, Z\}$$



G_n escape undetected

$\Rightarrow$ signature: $\{g, \gamma, Z\}$
$+$ missing energy

$(n \leftrightarrow \delta,\ M_D \leftrightarrow M_{\text{Pl}(4)})$

$\Rightarrow$ discovery potential

UED at the LHC (I):

KK 0th modes are identified with 4-dim SM particles

each SM particles has its 1st KK mode

⇒ part of the spectrum is similar to the MSSM → T

"KK parity" conserved:

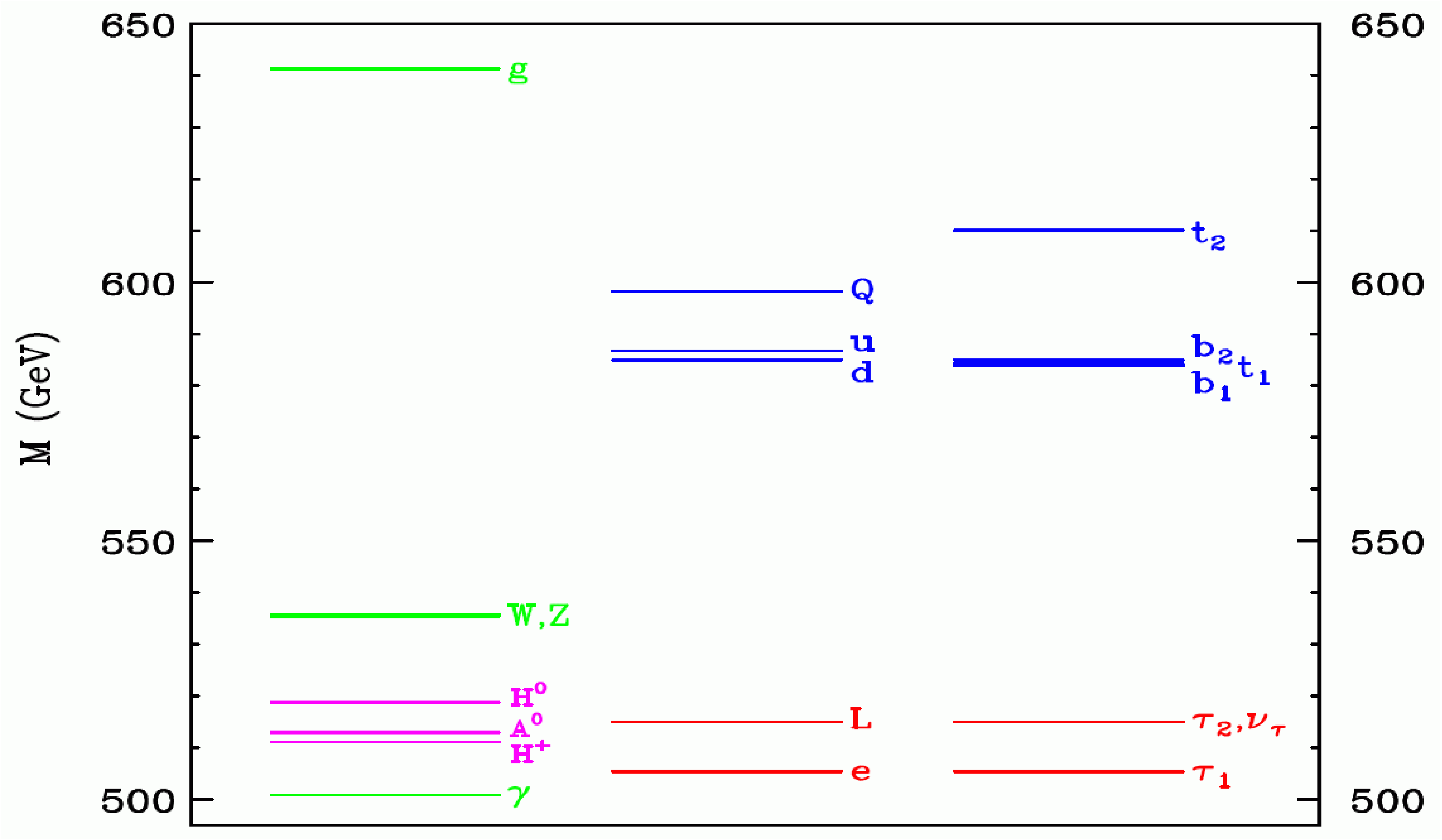
⇒ light UED KK modes are pair produced
light UED KK modes decay to SM particle
and other light UED KK mode

⇒ LKP (lightest Kaluza-Klein particle) is stable, DM candidates: γ_1, ν_1

⇒ phenomenology very similar to MSSM

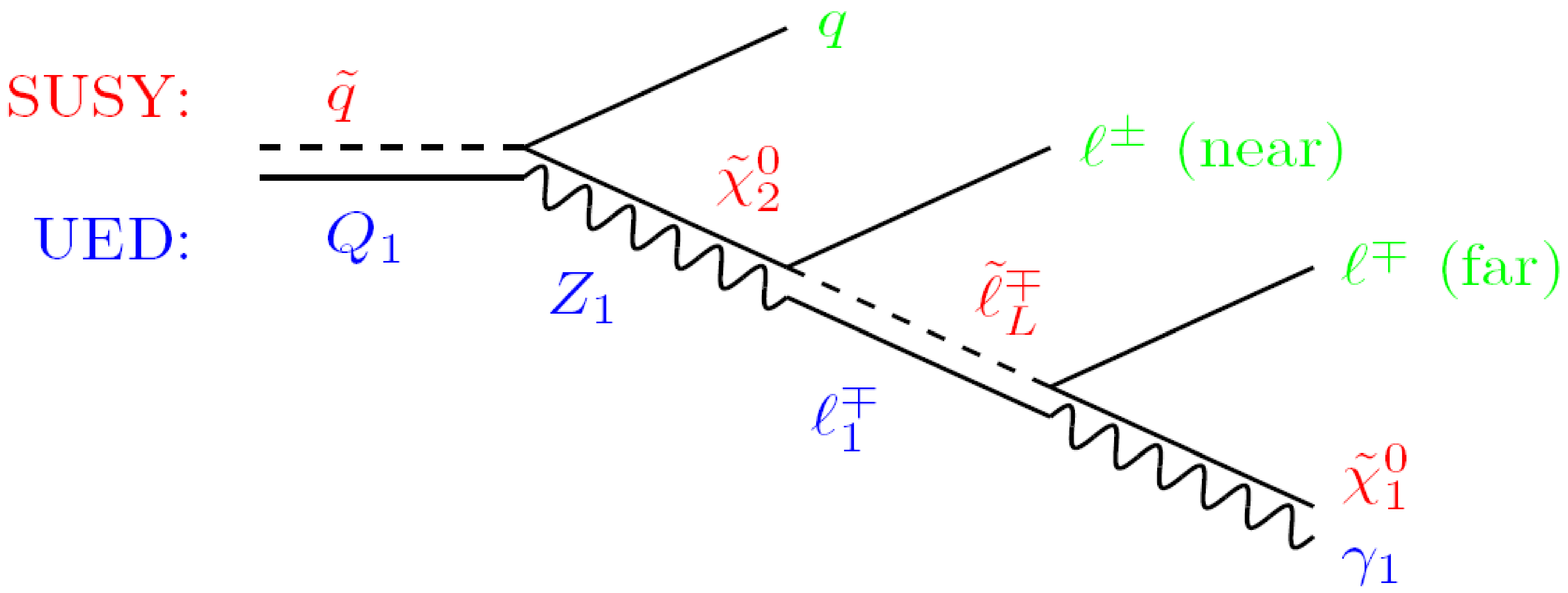
⇒ very similar decay chains

UED particle spectrum:



Comparison of SUSY with e.g. Extra Dimensions:

⇒ cascades may look very similar:



UED at the LHC (II):

Possibilities for distinction of UED and SUSY:

1. size of cross section:

   colored SM particles: quarks
   SUSY partners: scalar quarks
   UED partners: fermionic KK states

$$\begin{aligned} \text{scalar}: &\quad \sigma \propto (1 - \cos^2\theta) \\ \text{fermion}: &\quad \sigma \propto (1 + \cos^2\theta) \end{aligned}$$

   ⇒ UED has larger cross sections for same masses than MSSM

2. search for 2nd KK mode:

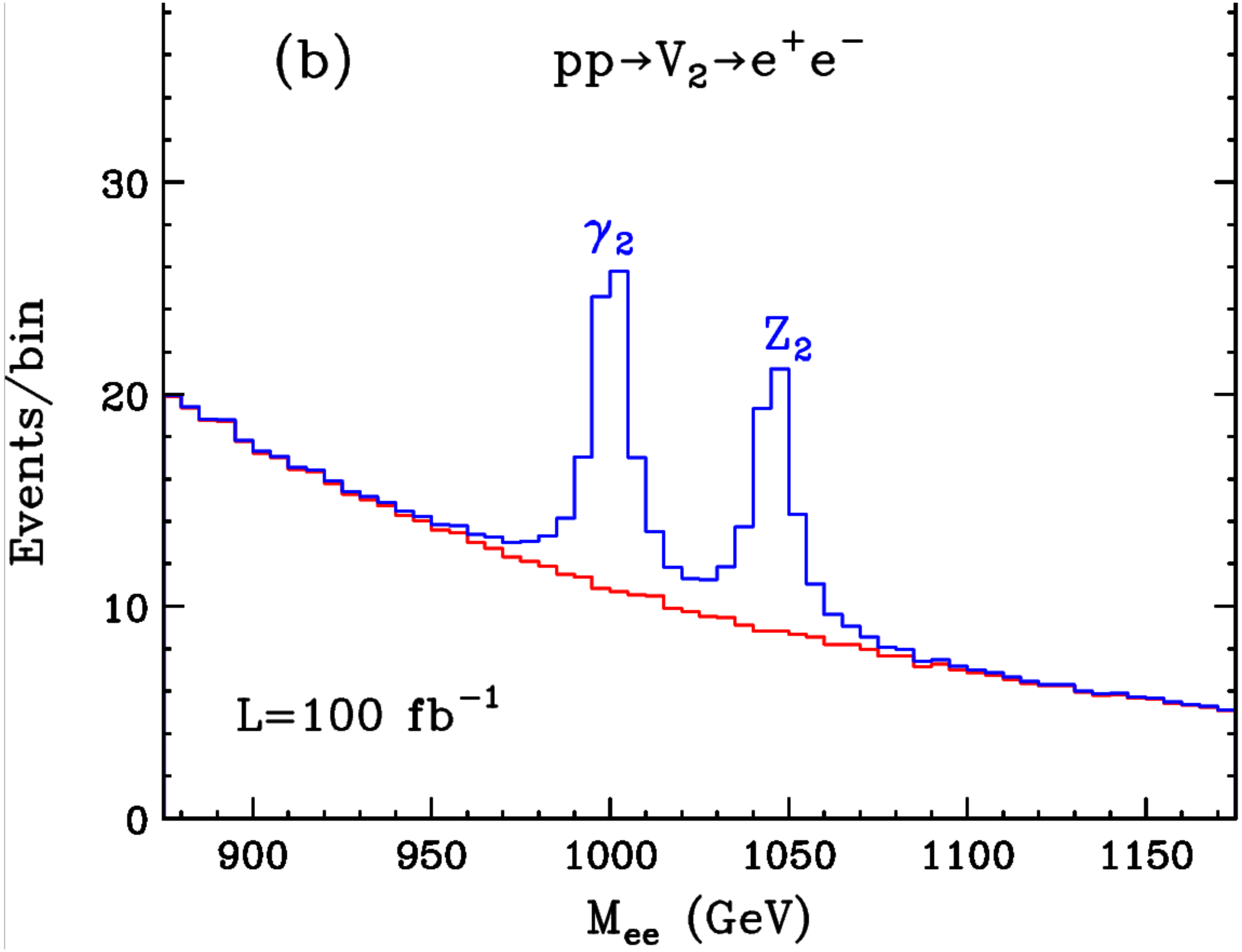
   possible:

$$pp \to V_2 \to \ell\ell \quad (V_2 = \gamma_2, Z_2,\ \ell = e, \mu)$$

3. measurement of mass differences, spin, . . .

UED at the LHC (III):

[A. Datta, K. Kong, T. Matchev '05]



$R^{-1} = 500$ GeV, $\sqrt{s} = 14$ TeV, $\mathcal{L}_{\rm int} = 100$ fb^{-1} $\Rightarrow$ clear signal

RS at the LHC (I):

search mode: $pp \to G_{\mathsf{KK}} \to \gamma\gamma$

Parameter dependence:

- graviton mass: G_{KK}
- coupling strength: $\tilde{k} = k/\overline{M}_{\mathsf{Pl}}$

RS at the LHC (II):

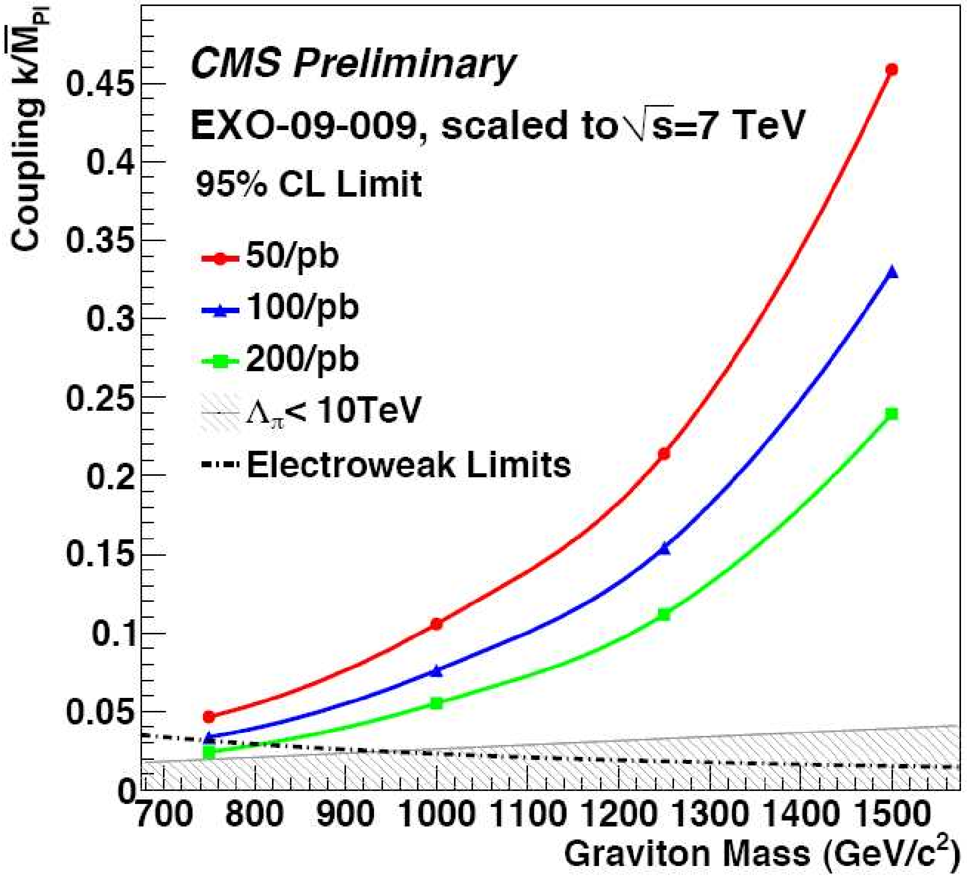
di-photon channel:

$$pp \to G_{\mathsf{KK}} \to \gamma\gamma$$

⇒ peak in the invariant

di-photon mass spectrum

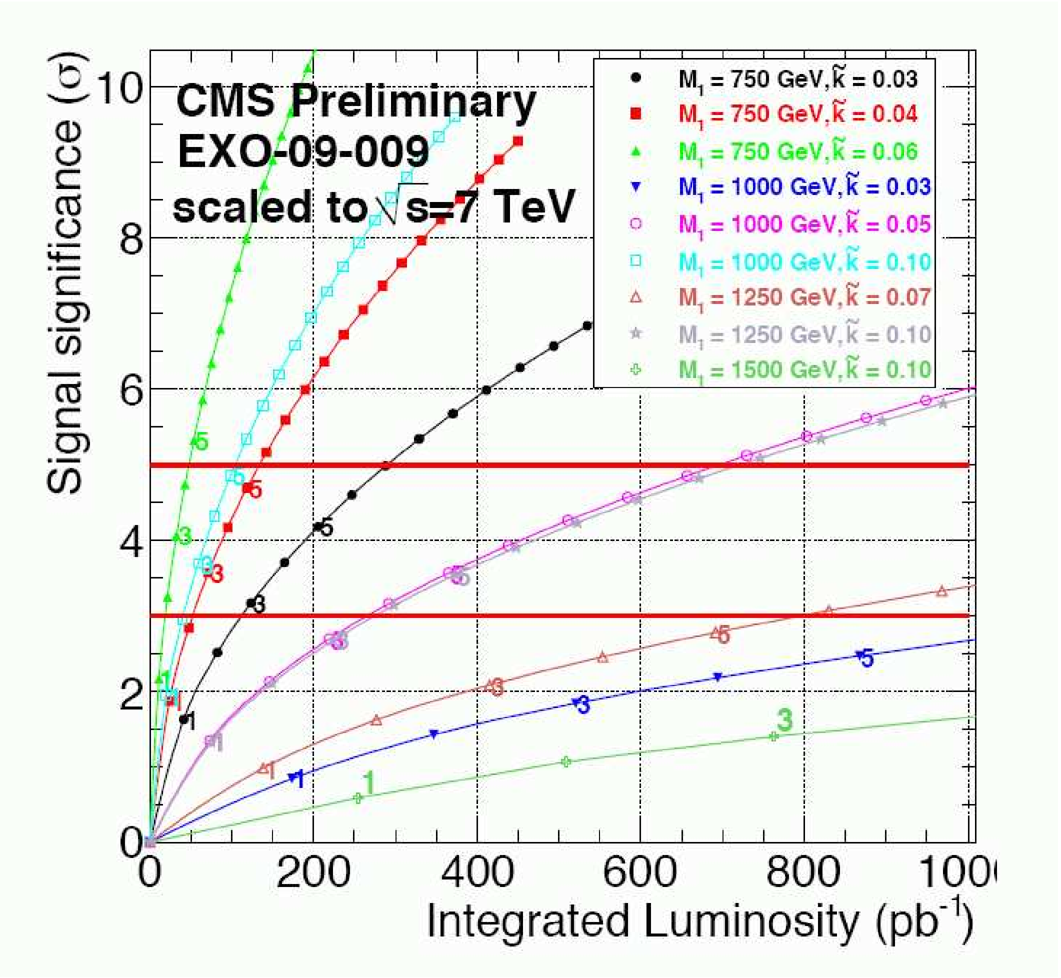
⇒ exclusion potential



RS at the LHC (III):

di-photon channel:

$$pp \to G_{\mathsf{KK}} \to \gamma\gamma$$



⇒ peak in the invariant

di-photon mass spectrum

⇒ discovery potential

Little Higgs models

Main idea of Little Higgs (LH):

light Higgs boson as a Nambu-Goldstone boson
of an approximate symmetry

Breaking of a gauge group:

$$G \to H \quad \text{at the scale } f$$

(with H being e.g. the SM gauge group)

Problem:

this set-up induces via gauge boson loops (quadratic divergences)

$$v \approx f$$

EWPO: $f = \mathcal{O}(1\text{ TeV})$

$+$ quadratic divergences from top loops

⇒ simple idea does not work

Solution in LH models: “collective symmetry breaking”

consider a gauge group G such that

$$G \supset G_1 \times G_2$$

and each G_i contains the SM gauge group

Now after

$$G \to H \quad \text{at the scale } f$$

the gauge bosons of the extended gauge group (with $M \approx g\,f$) cancel the quadratic divergences and

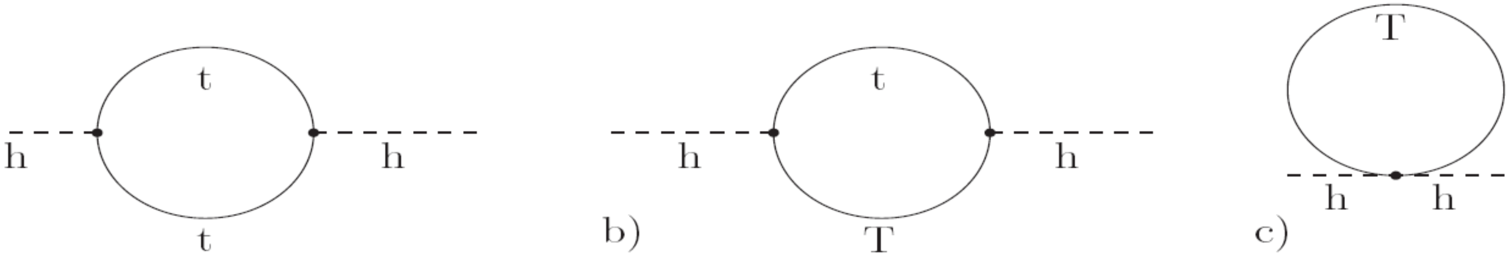
$$v \ll f$$

is possible

Still a problem: quadratic divergences from top loops

Still a problem: quadratic divergences from top loops

⇒ introduction of vectorial top-partner T fermions



Quadratic divergences:

- removed at one-loop
- not removed at two-loop
- log-divergences already at one-loop

⇒ theory valid up to $\Lambda = 4\pi f$

Little Higgs models:

Model depends on the gauge group G:

$[SU(3)_L \times SU(3)_R]^4$: minimal moose model

$SU(5), SO(5)$: littlest Higgs

$[SU(3) \times U(1)]^2$: simplest LH

Common features:

– new gauge bosons
– new top partners (and possibly other partners)
– often additional scalar states . . .

General problem of LH models: EWPO!

New gauge bosons mix with SM gauge bosons
$\Rightarrow$ large tree-level contributions to EWPO

Solution 1:
$\Rightarrow$ make f large, $f =$ several TeV
($\rightarrow$ little hierarchy problem)

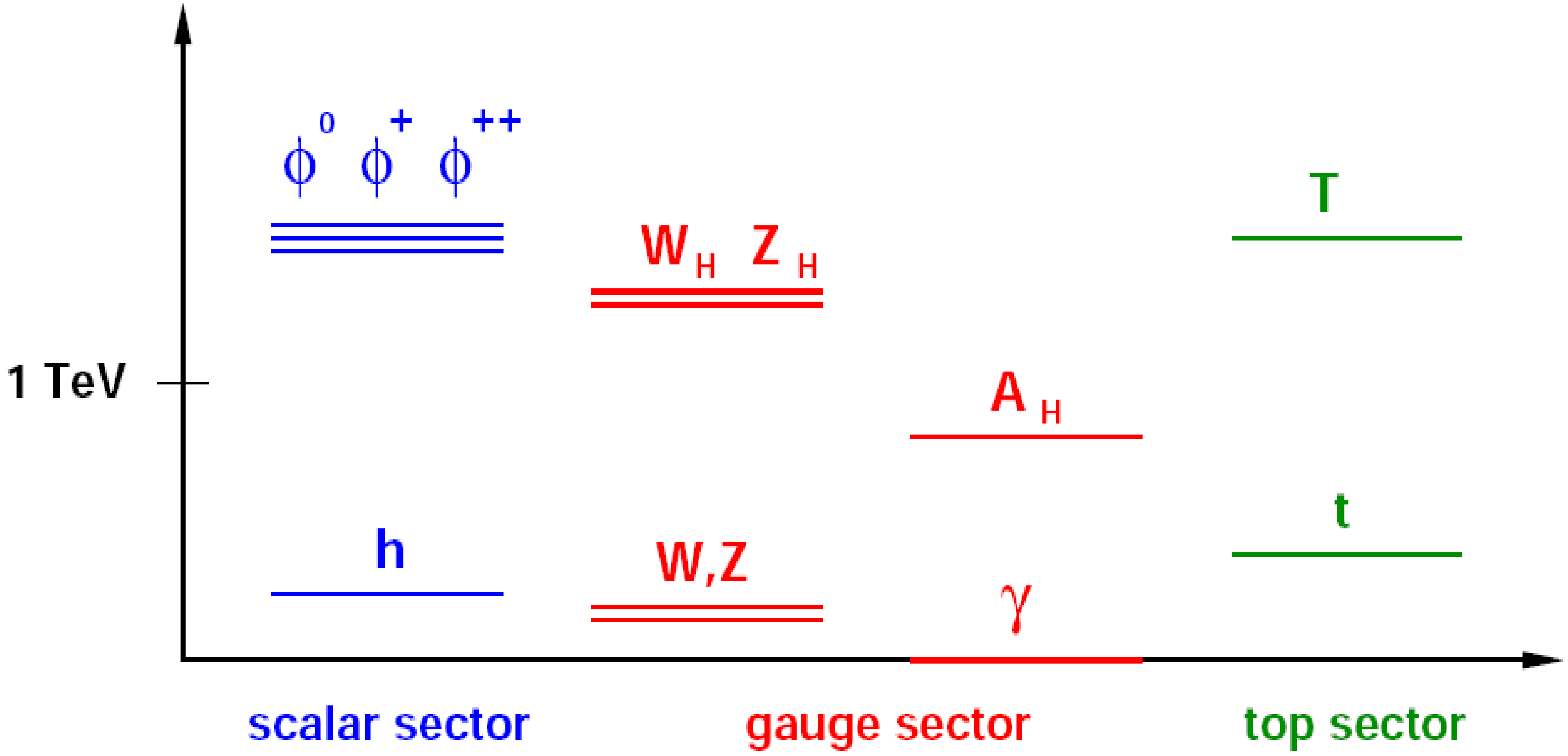
Solution 2:
new discrete symmetry: T parity (Z_2 symmetry)

SM: $T = +1$
LH: $T = -1$ $\Rightarrow$ no mixing between SM and new gauge bosons

additional heavy top states: allow for “heavy” Higgs boson

LTP is stable $\Rightarrow$ B_H is DM candidate

Generic Little Higgs particle spectrum:



LHC phenomenology of LH models:

very different for LH with or without T parity

LH with T parity:

QCD pair production: $pp \to TT$

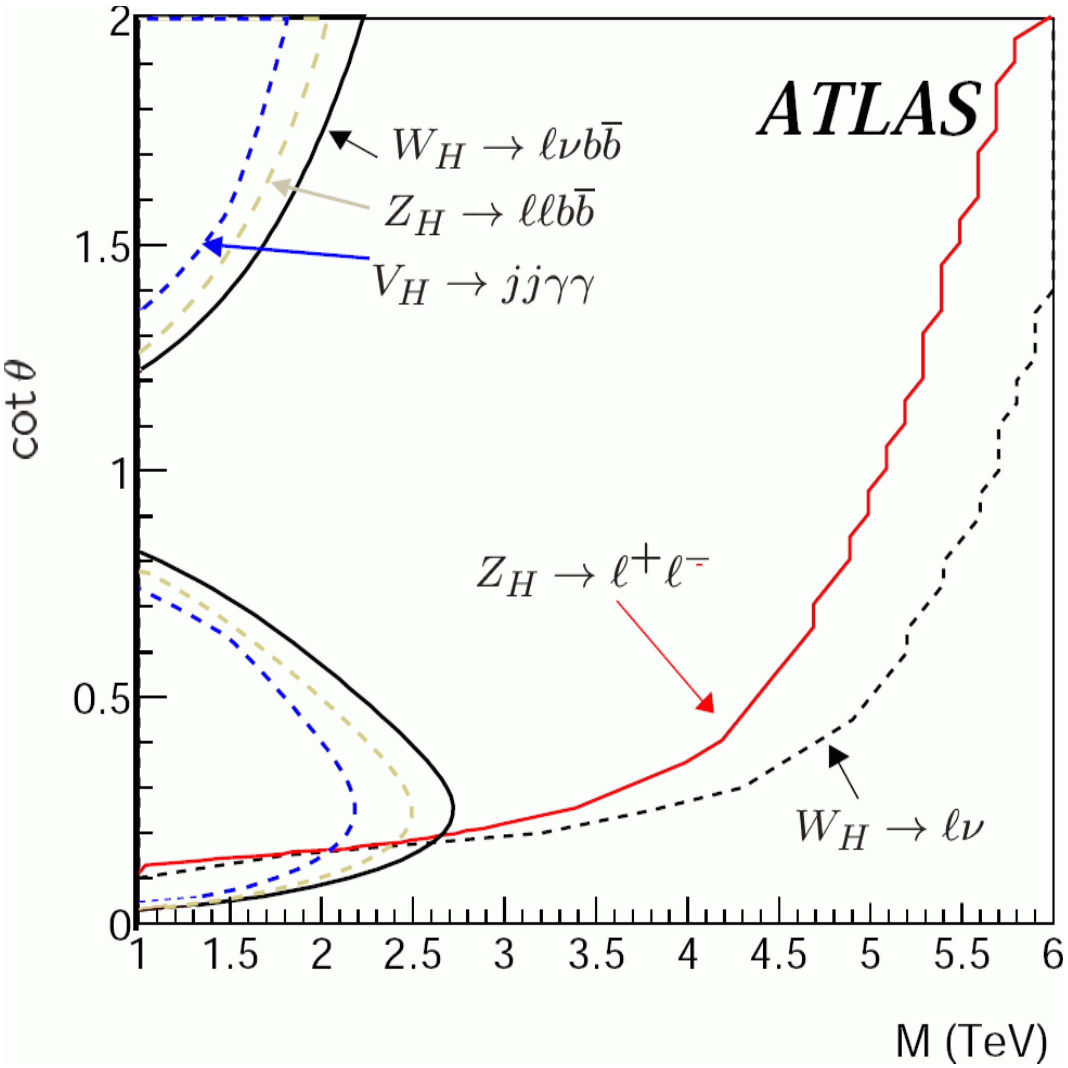
with (cascade) decays of T: $T \to tB_H$
$\Rightarrow$ signal: missing energy

LH without T parity:

single production of T, B_H, Z_H, W_H, $\ldots$
with subsequent decay to SM particles
$\Rightarrow$ no missing energy

LHC phenomenology of LH models:

very different for LH with or without T parity



LH without T parity:

single production and decay of new LH particles possible

Outlook

- The LHC has re-discovered the SM
  Important improvements expected for the W, top, B physics . . .
  ⇒ sensitive test of the SM
- The Higgs mechanism continues to be our best bet for EWSB
- Low-energy Supersymmetry continues to be our best bet for physics beyond the Standard Model
- Within the next years the LHC will bring a decisive test of our ideas about SM extensions and the Higgs
- Before the end of 2012 we will (most likely) know about the SM Higgs
- Data rules:

  We need experimental information from Tevatron, LHC, ILC,
  ν experiments, dark matter searches, low-energy experiments, . . .
  to verify / falsify our ideas about electroweak symmetry breaking,
  the Higgs, extensions of the SM, . . .

⇒ Very exciting prospects for the coming years

Expect the unexpected!

Interested in Theory Predictions?

Interested in

- theory analyses for Tevatron data?
- theory predictions for the LHC?
- theory predictions for the ILC?
- phenomenology analyses in Higgs/SUSY?

⇒ You can do your PhD at IFCA (Santander, Spain)

contact: Sven.Heinemeyer @ cern.ch

Santander, Spain: (15 minutes by foot from the institute :-)

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