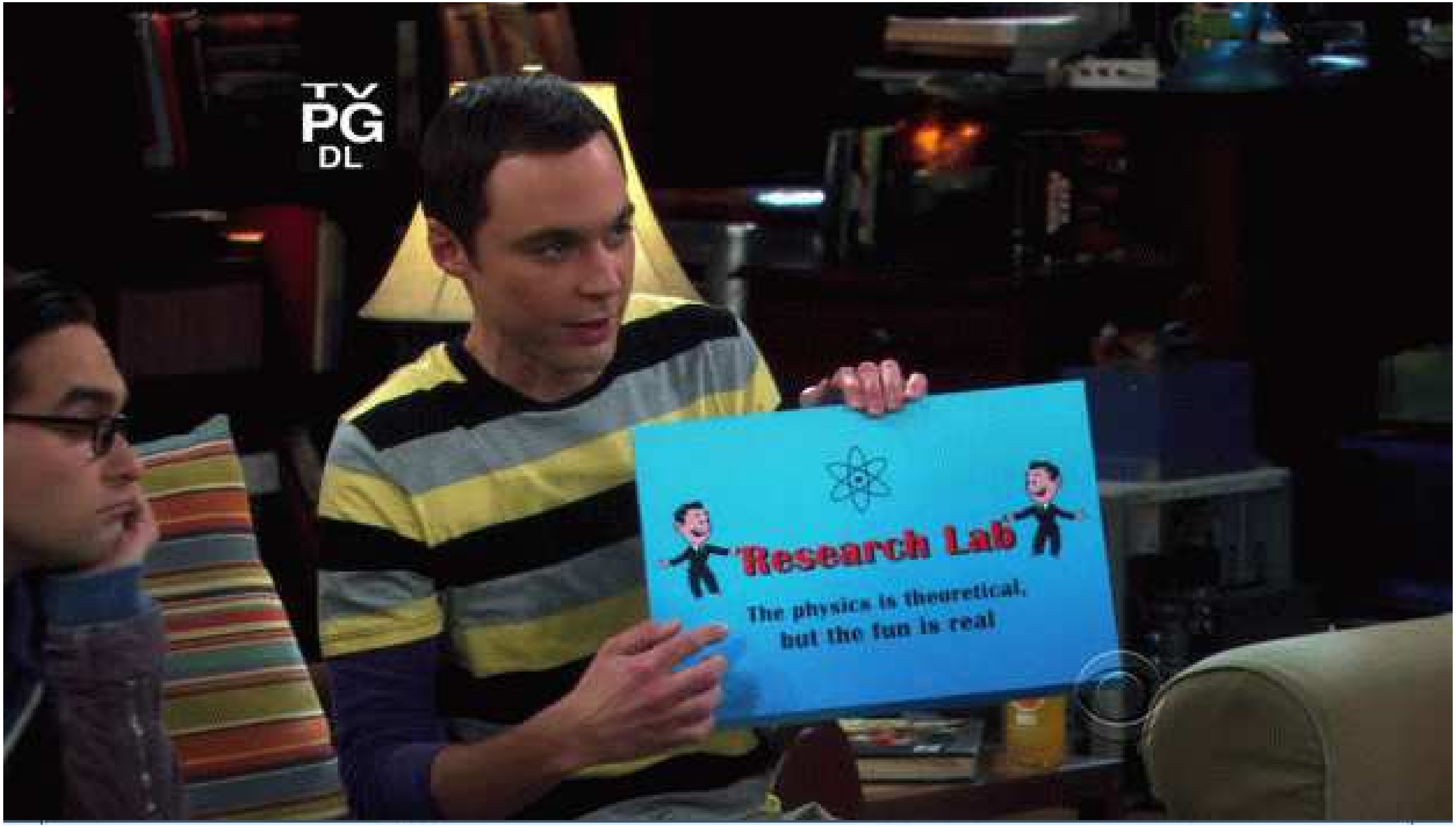
> “Tell me that you have found no sign of New Physics again, I dare you. I double dare you. Tell me one more goddamn time!”



Sheldon: "Research Lab" is more than a game:
The physics is theoretical, but the fun is real!

The Standard Model of Particle Physics
(and an Important Alternative)

Sven Heinemeyer, IFCA (CSIC, Santander)

St. Cruz de La Palma, 07/2012

1. The Standard Model and the Higgs boson
2. The Standard Model and the LHC
3. Supersymmetry and the cosmic connection
4. SUSY Higgs bosons and the LHC

1. The Standard Model and the Higgs boson

Current status of knowledge: the Standard Model (SM)

1. family: quarks: d, u leptons: e^-, ν_e (neutrino)

2. family: quarks: s, c leptons: μ^-, ν_μ (neutrino)

3. family: quarks: b, t leptons: τ^-, ν_τ (neutrino)

In total:

6 quarks and 6 leptons

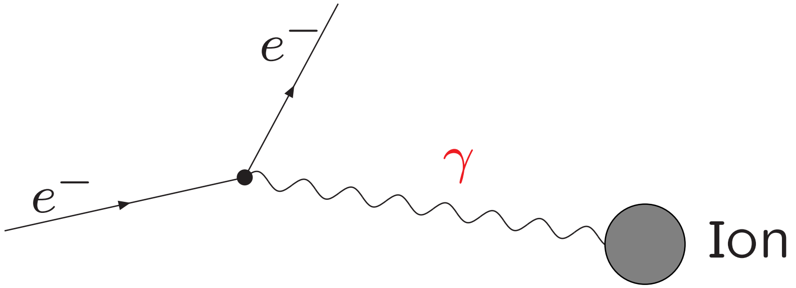
The heavier particles (2. and 3. family) decay in very short time into the lighter particles (1. family)

Example:

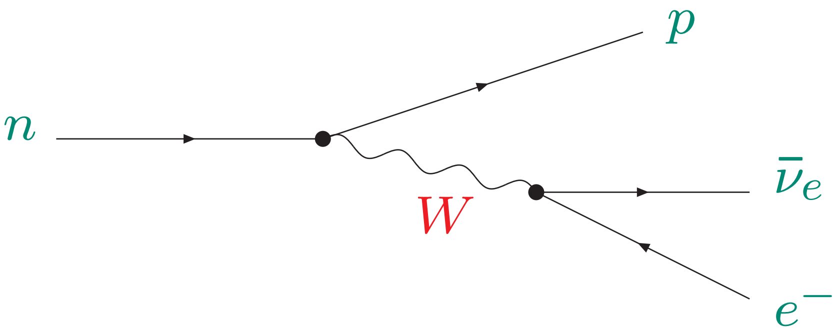
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$

Forces and force particles (I):

1. electromagnetic force: photon: γ

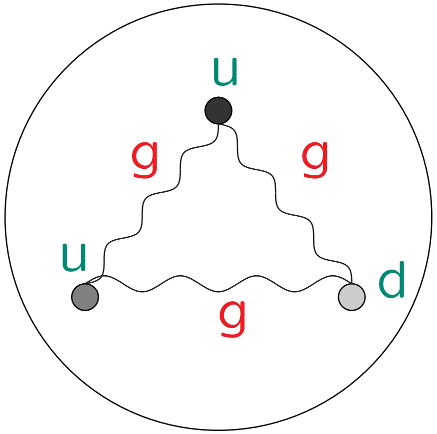


2. weak force: W^+, W^-, Z^0

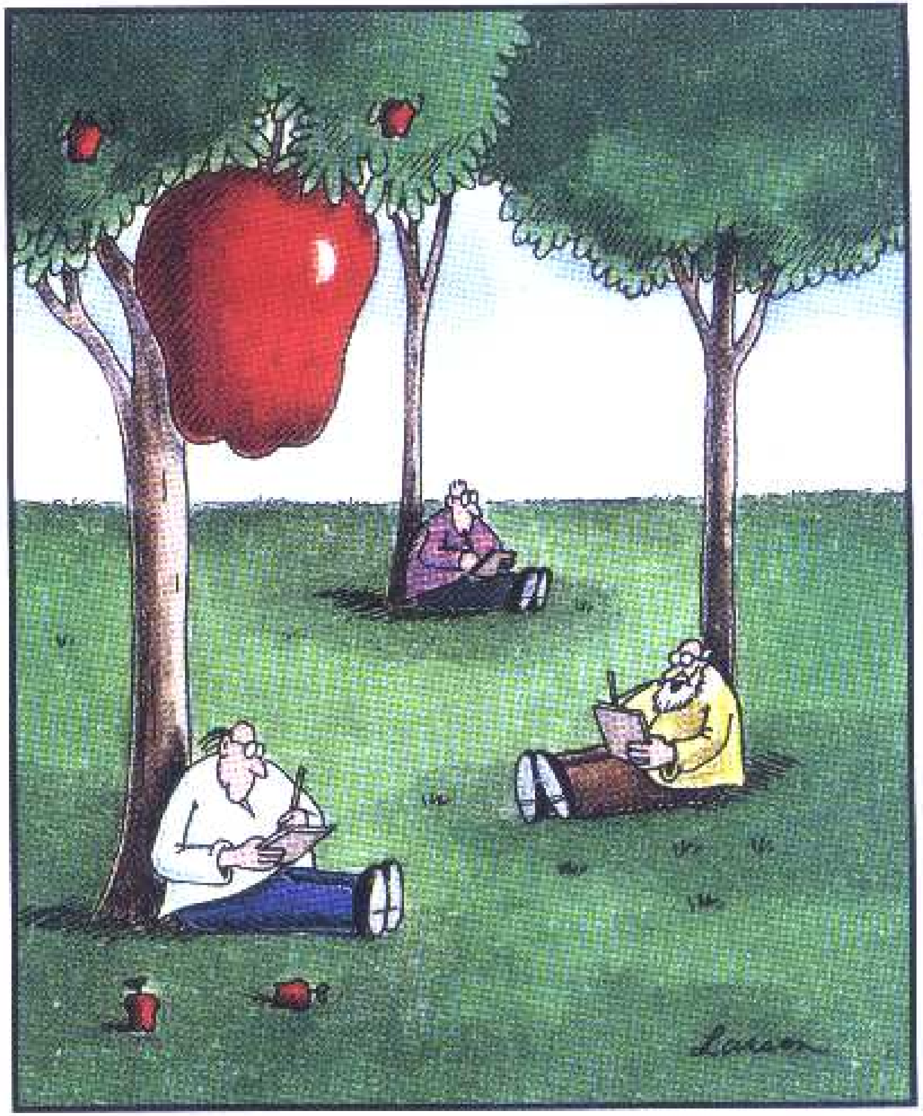


Forces and force particles (II):

3. strong force: gluon: g



4. gravitational force: graviton(?)



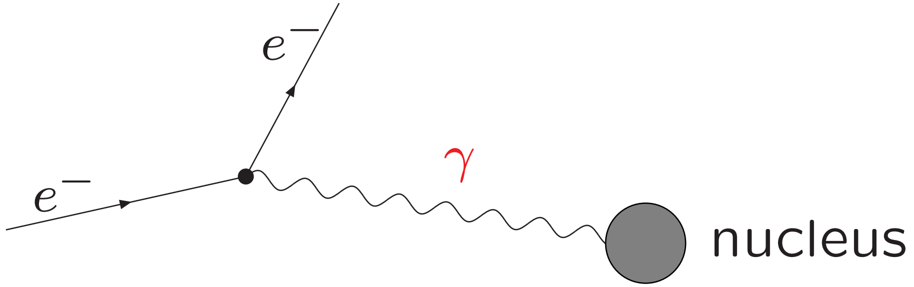
"Nothing yet. ... How about you, Newton?"

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



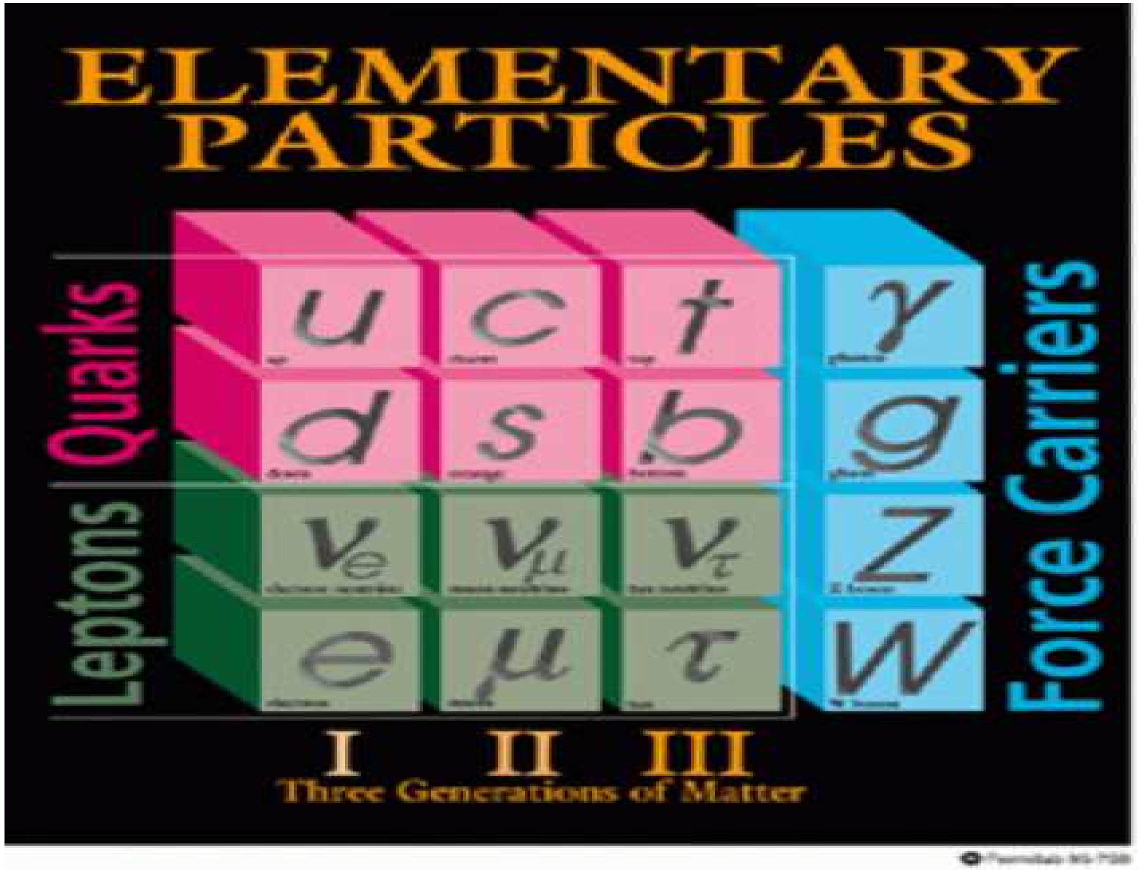
$\mathcal{L}_{\text{QED}}$ invariant under gauge transformation:

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

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

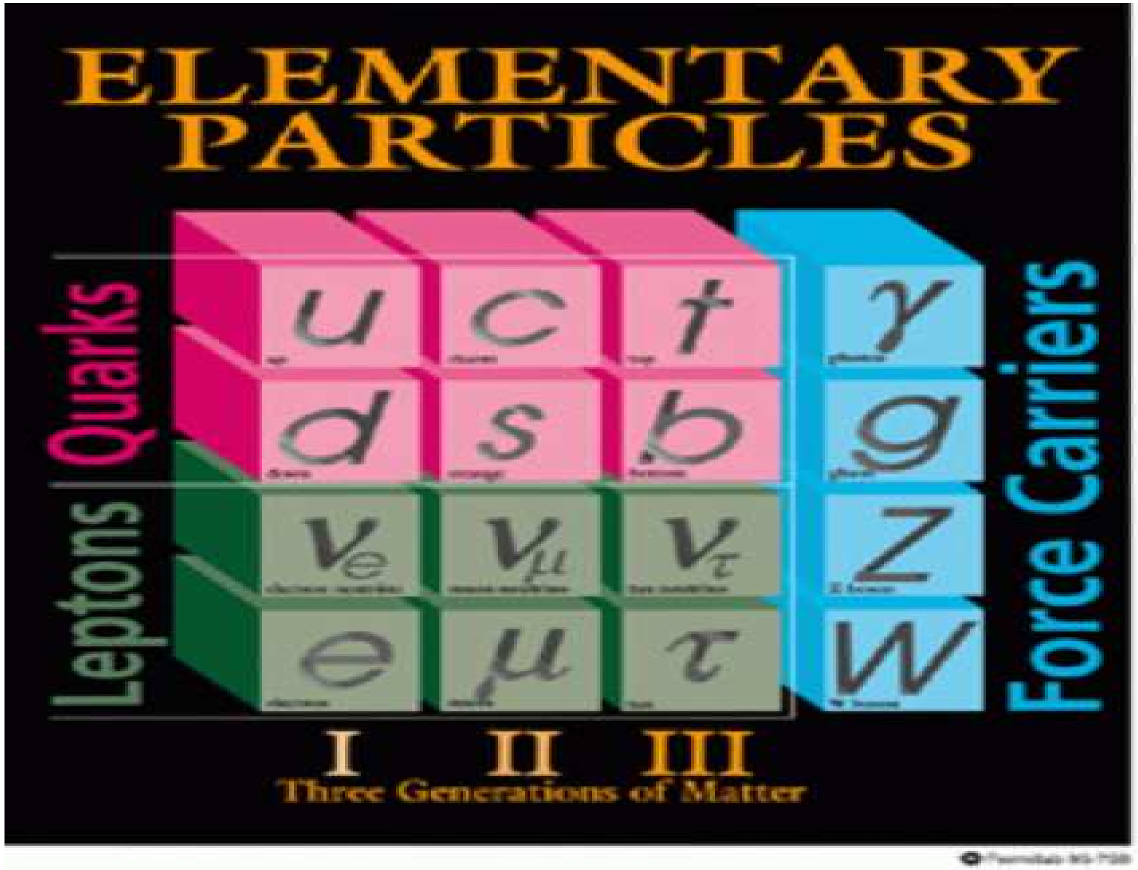
⇒ A_μ is massless gauge field

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 it predicts massless gauge bosons . . .

Problem:

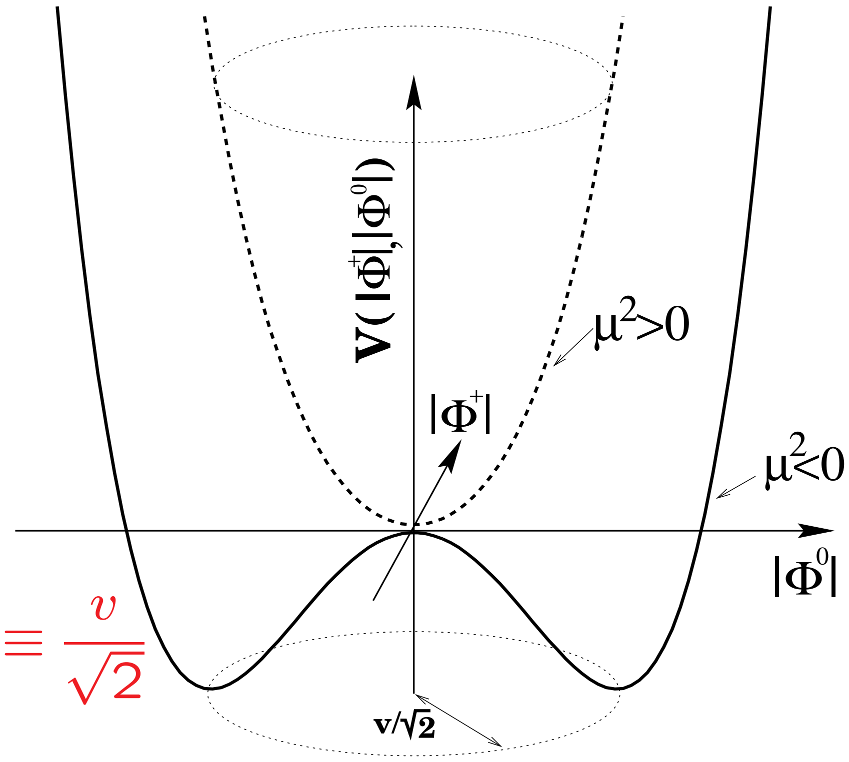
Gauge fields Z, W^+, W^- are massive

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

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

H: elementary scalar field, Higgs boson

Lagrange density:

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

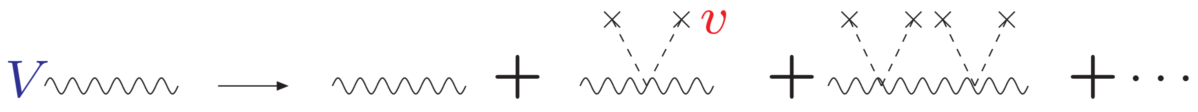
with

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

Gauge invariant coupling to gauge fields

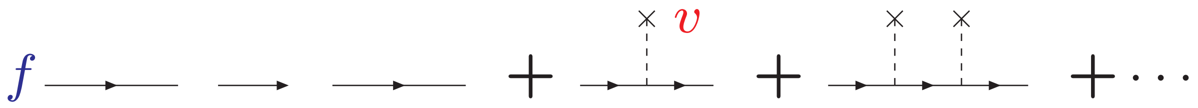
⇒ mass terms for gauge bosons and fermions

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



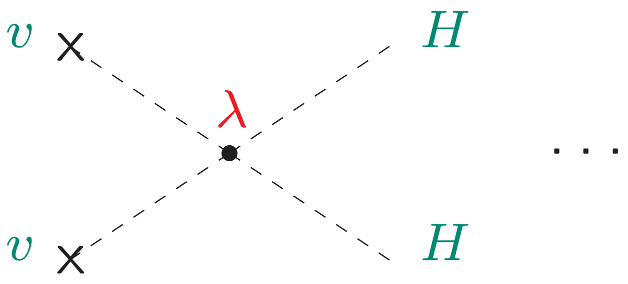
$$\frac{1}{q^2} \to \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{\sqrt{2}}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \; : \; M^2 = g^2\frac{v^2}{2} \qquad \Rightarrow M \propto g$$

2.) fermion mass terms: Yukawa couplings:



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

3.) mass of the Higgs boson: self coupling

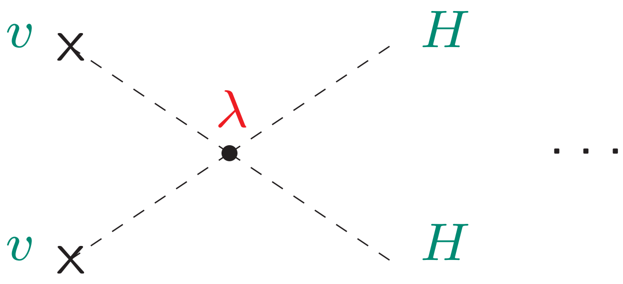


$$\lambda = M_H^2/v$$

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

→ last unknown(??) parameter of the SM

3.) mass of the Higgs boson: self coupling



$$\lambda = M_H^2/v$$

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

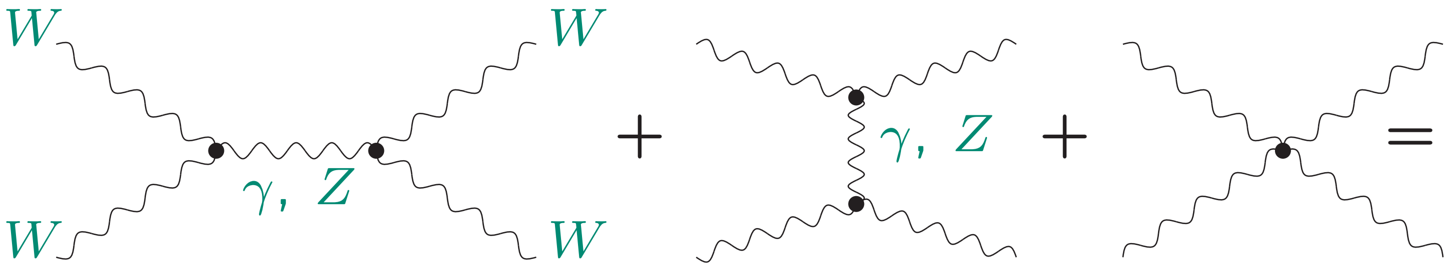
→ last unknown(??) parameter of the SM

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

Another effect of the Higgs field:

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

$\mathcal{M}_V =$



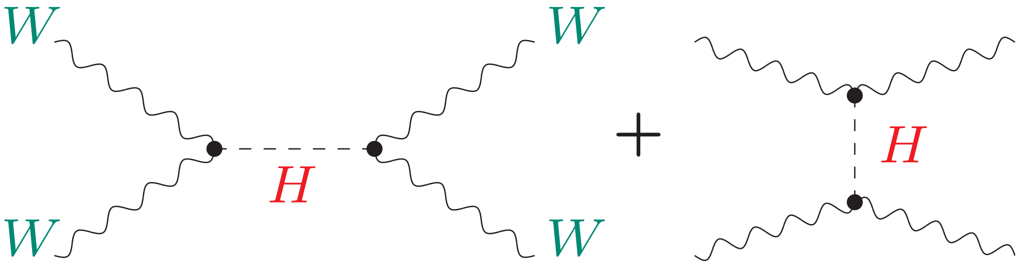
$= -g^2 \frac{E^2}{M_W^2} + \mathcal{O}(1)$

for $E \to \infty$

⇒ violation of unitarity

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

$\mathcal{M}_S =$



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

for $E \to \infty$

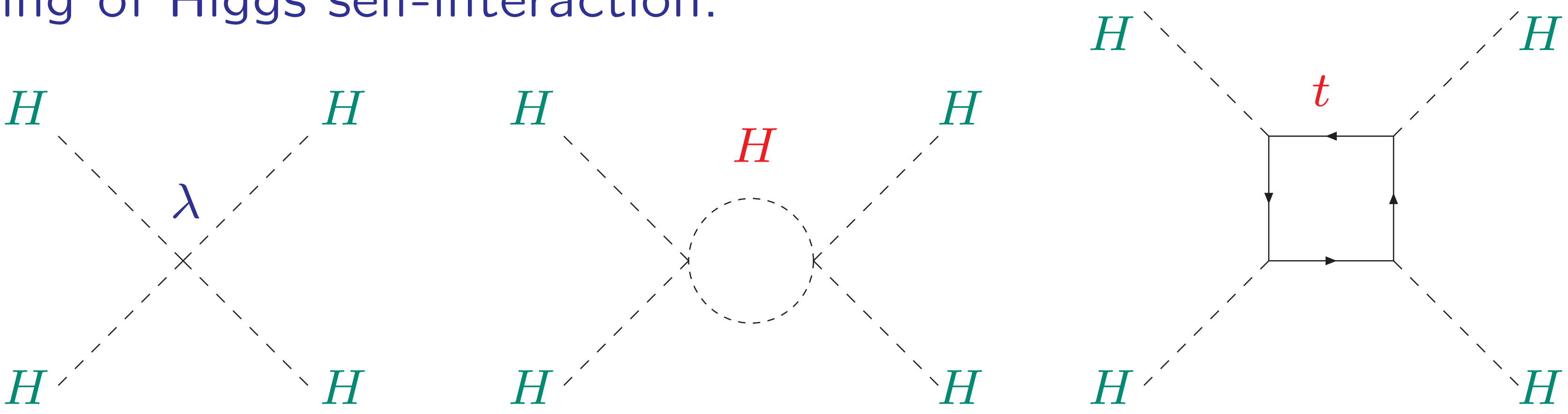
$$\mathcal{M}_{\text{tot}} = \mathcal{M}_V + \mathcal{M}_S = \frac{E^2}{M_W^4} \left(g_{WWH}^2 - g^2 \, M_W^2 \right) + \ldots$$

⇒ 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 $\lambda \sim M_H^2$)

$$\begin{aligned} \frac{d\,\lambda}{d\,t} &= \frac{3}{8\,\pi^2}\left[\lambda^2\right] \\ \Rightarrow \qquad \lambda(Q^2) &= \frac{\lambda(v^2)}{1 - \frac{3\lambda(v^2)}{8\,\pi^2}\log\left(\frac{Q^2}{v^2}\right)} \end{aligned}$$

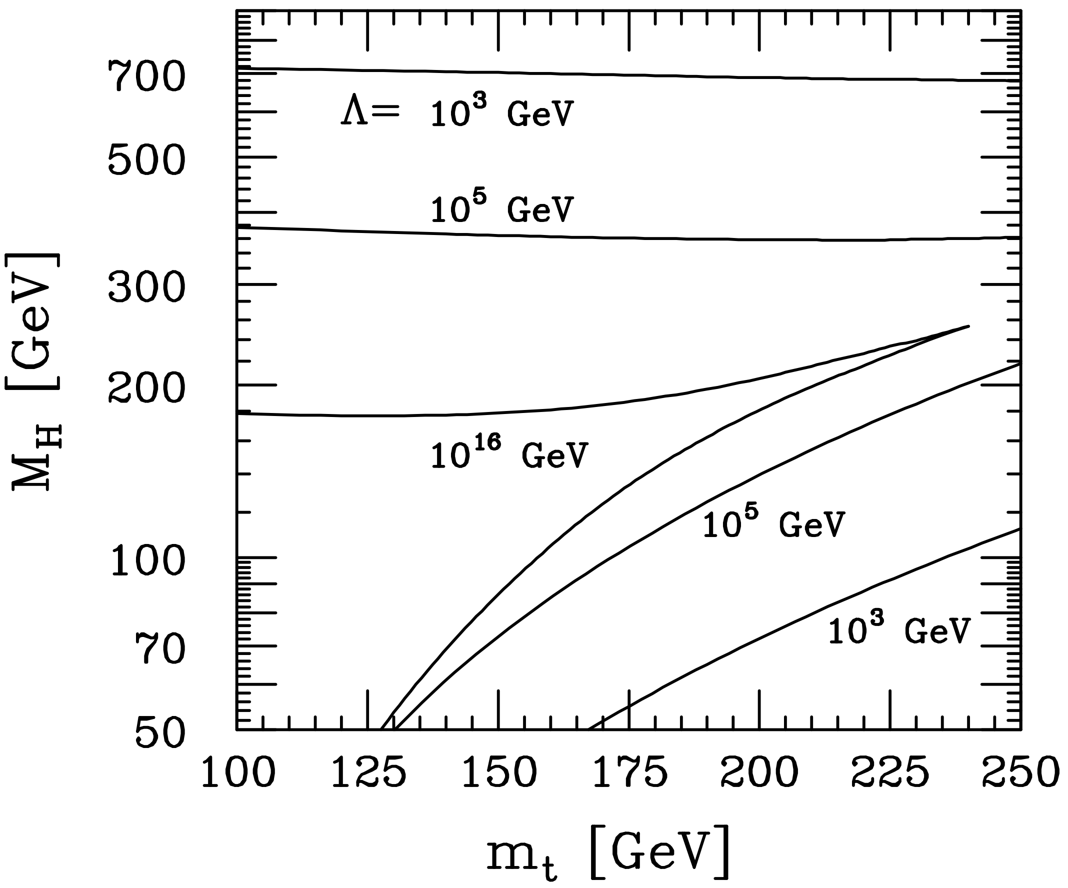
$$\lambda(\Lambda) < \infty \;\Rightarrow\; M_H^2 \le \frac{8\,\pi^2\,v^2}{3\log\left(\frac{\Lambda^2}{v^2}\right)} \qquad : \text{ upper bound on } M_H$$

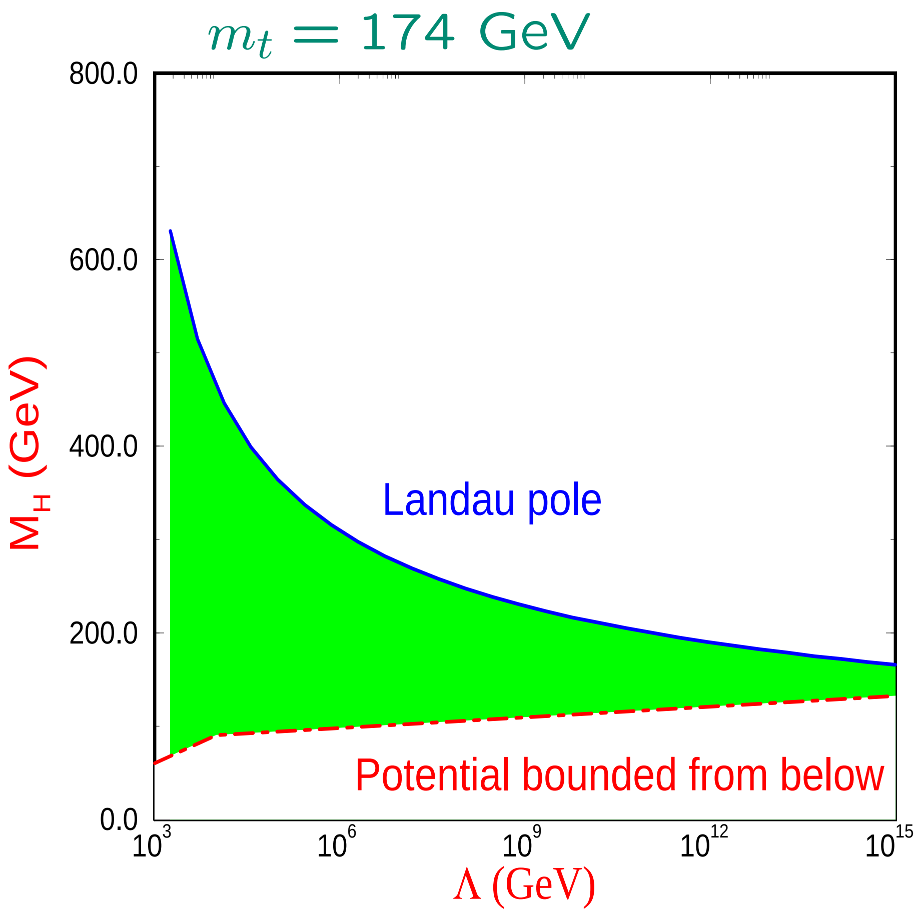
2.) avoid vacuum instability (for small/negative λ): $V(v) < V(0) \Rightarrow \lambda(\Lambda) > 0$

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

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

Both limits combined:





Λ: scale up to which the SM is valid

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

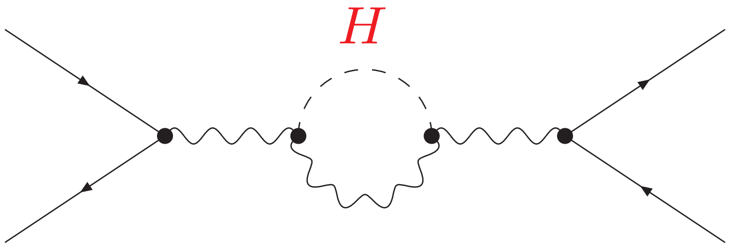
Electroweak Precision Observables (EWPO):

Comparison of electro-weak precision observables with theory:

EW Precision data:		Theory:
$M_W, \sin^2\theta_{\mathrm{eff}}, a_\mu$	$\leftrightarrow$	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*]

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

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

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:

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

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:

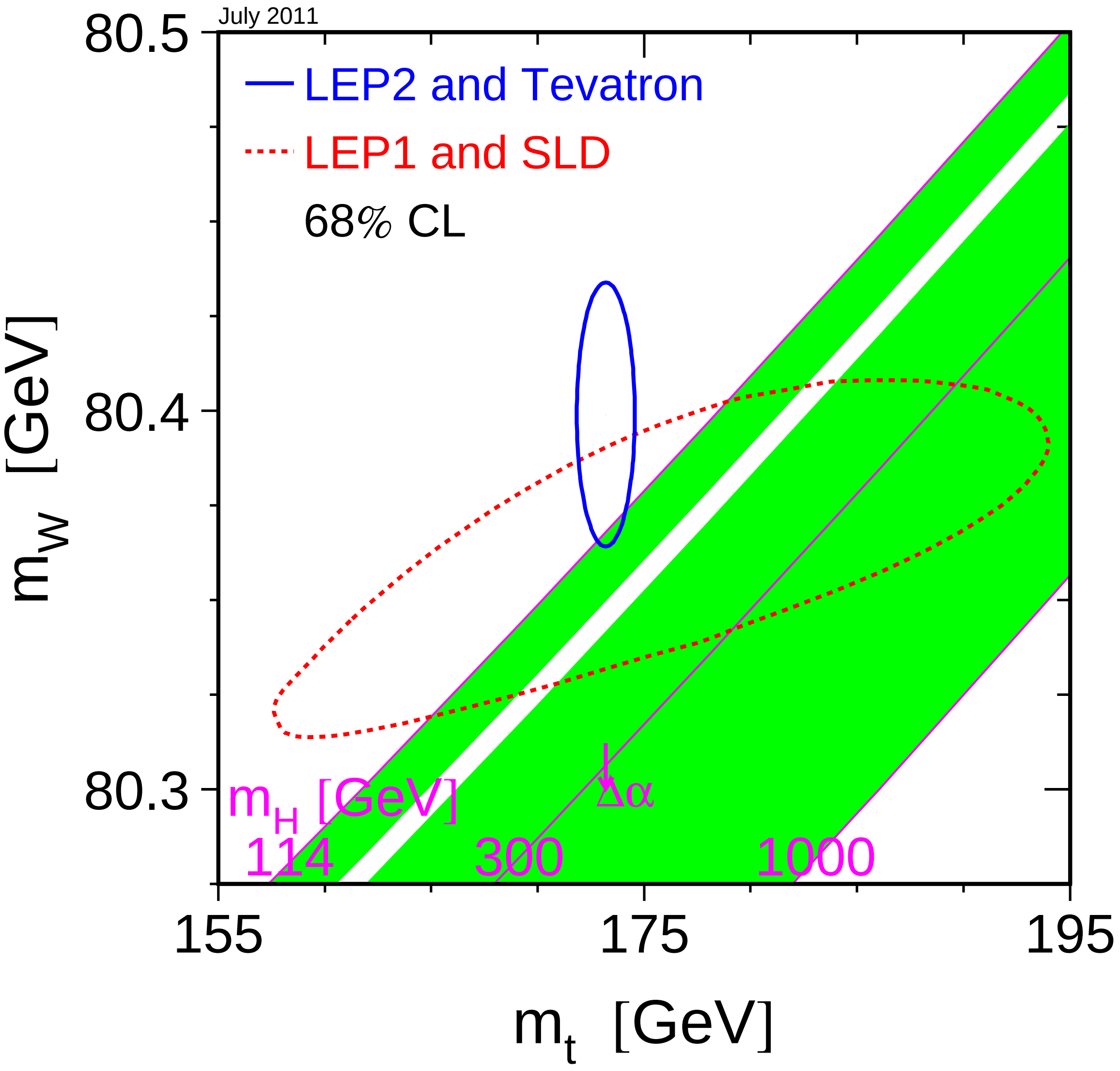
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

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:

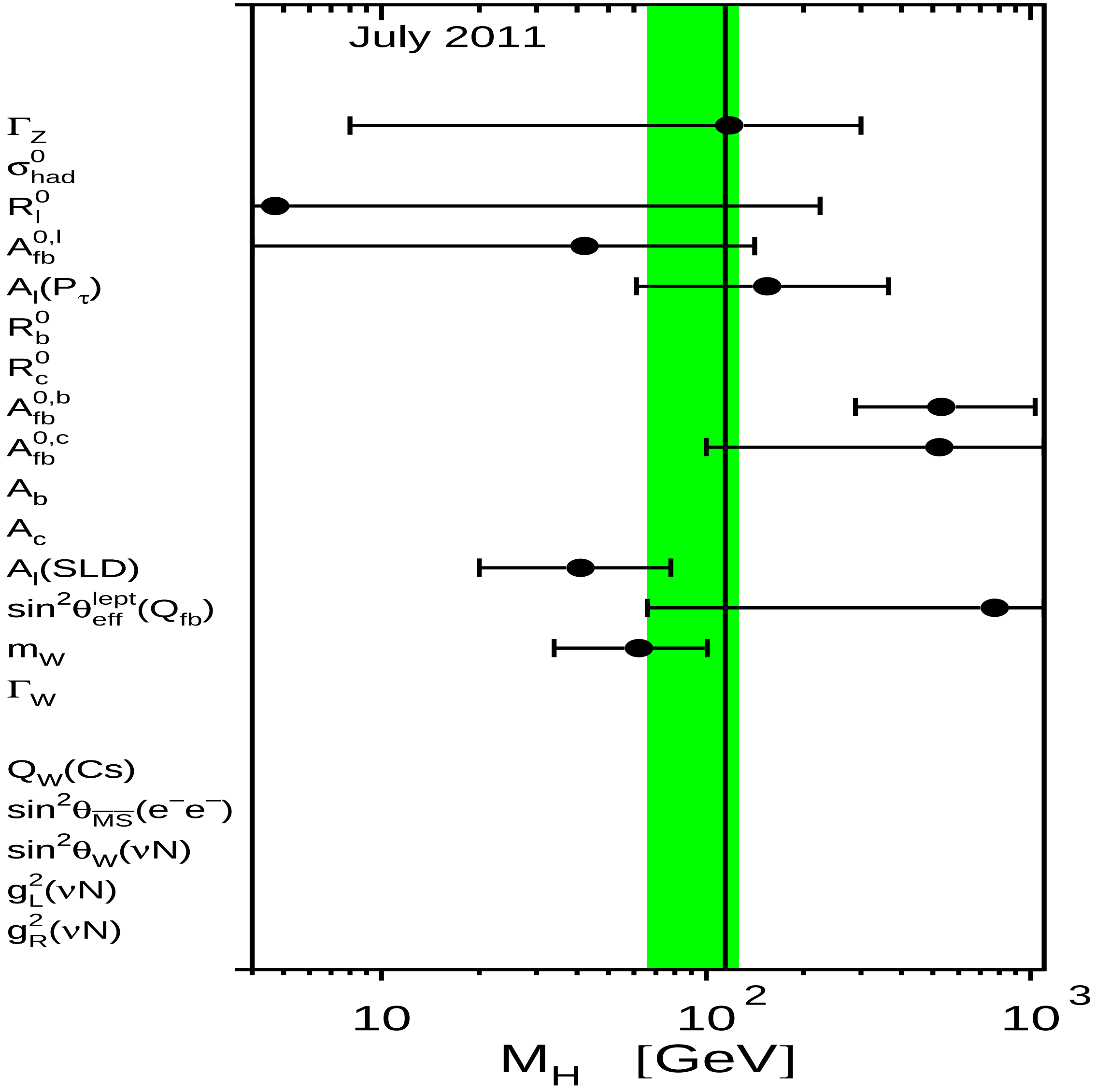
light Higgs preferred by:

M_W, A_l^{LR} (SLD)

heavier Higgs preferred by:

A_b^{FB} (LEP)

$\Rightarrow$ keeps SM alive



[*LEPEWWG '11*]

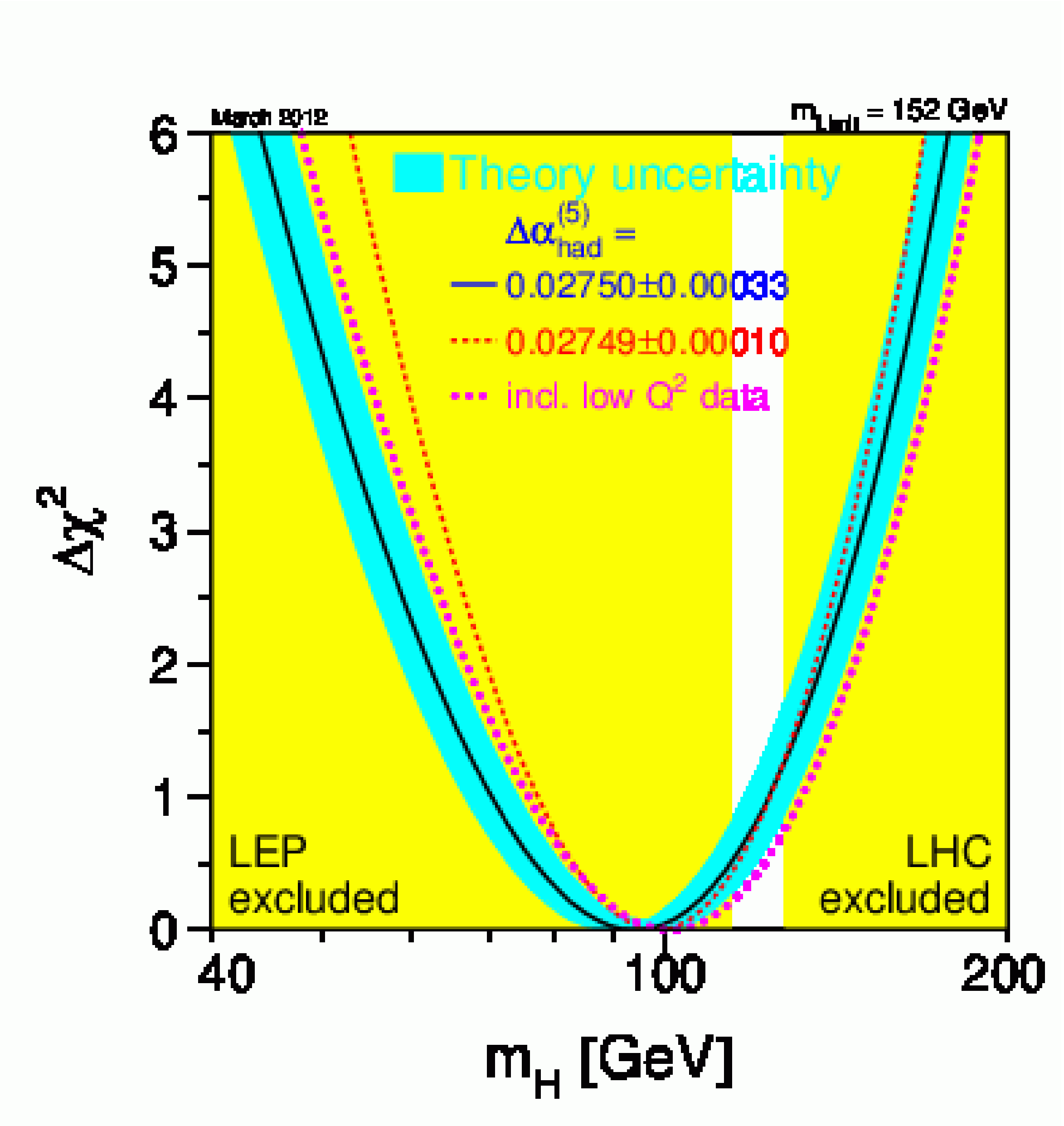
$\Rightarrow$ light Higgs boson preferred

Global fit to all SM data:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.



Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

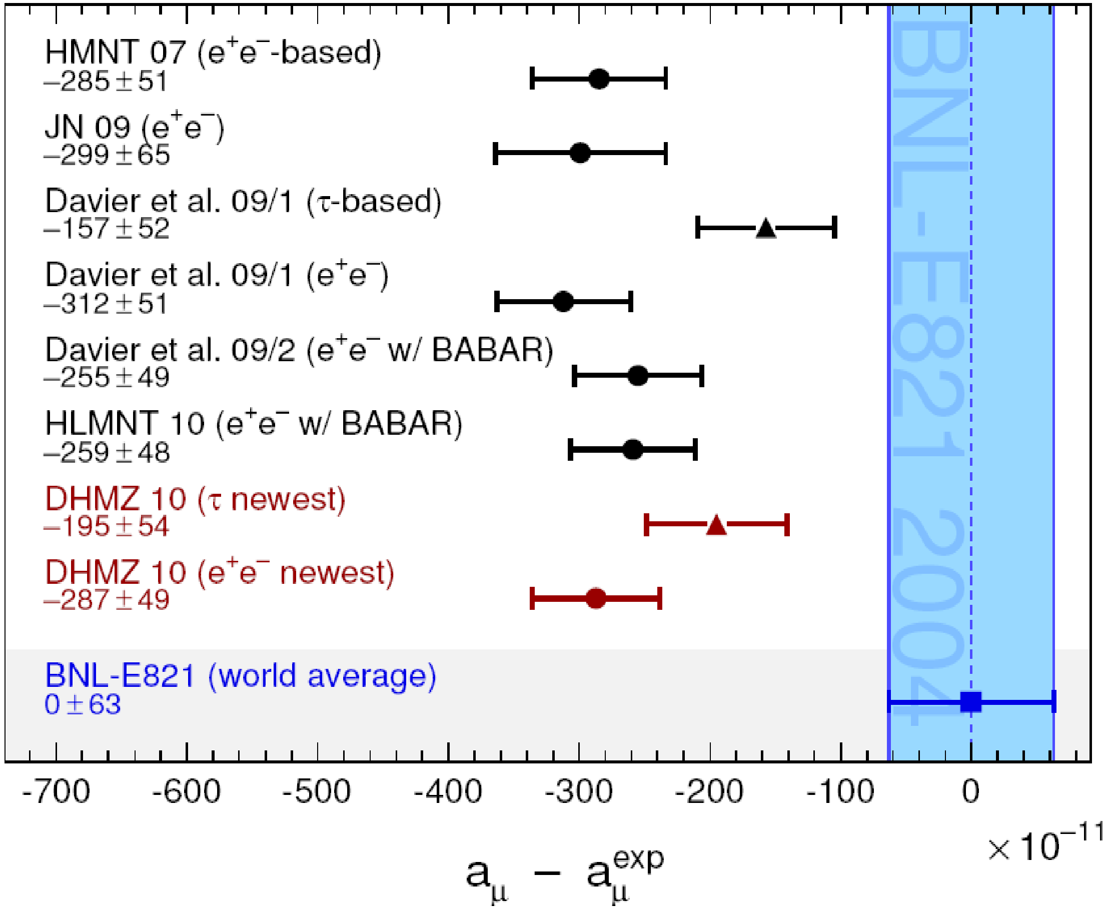
$\Rightarrow$ Higgs boson seems to be light, $M_H \lesssim 160$ GeV

Another EWPO: the anomalous magnetic moment of the muon

$$a_\mu \equiv (g-2)_\mu/2$$

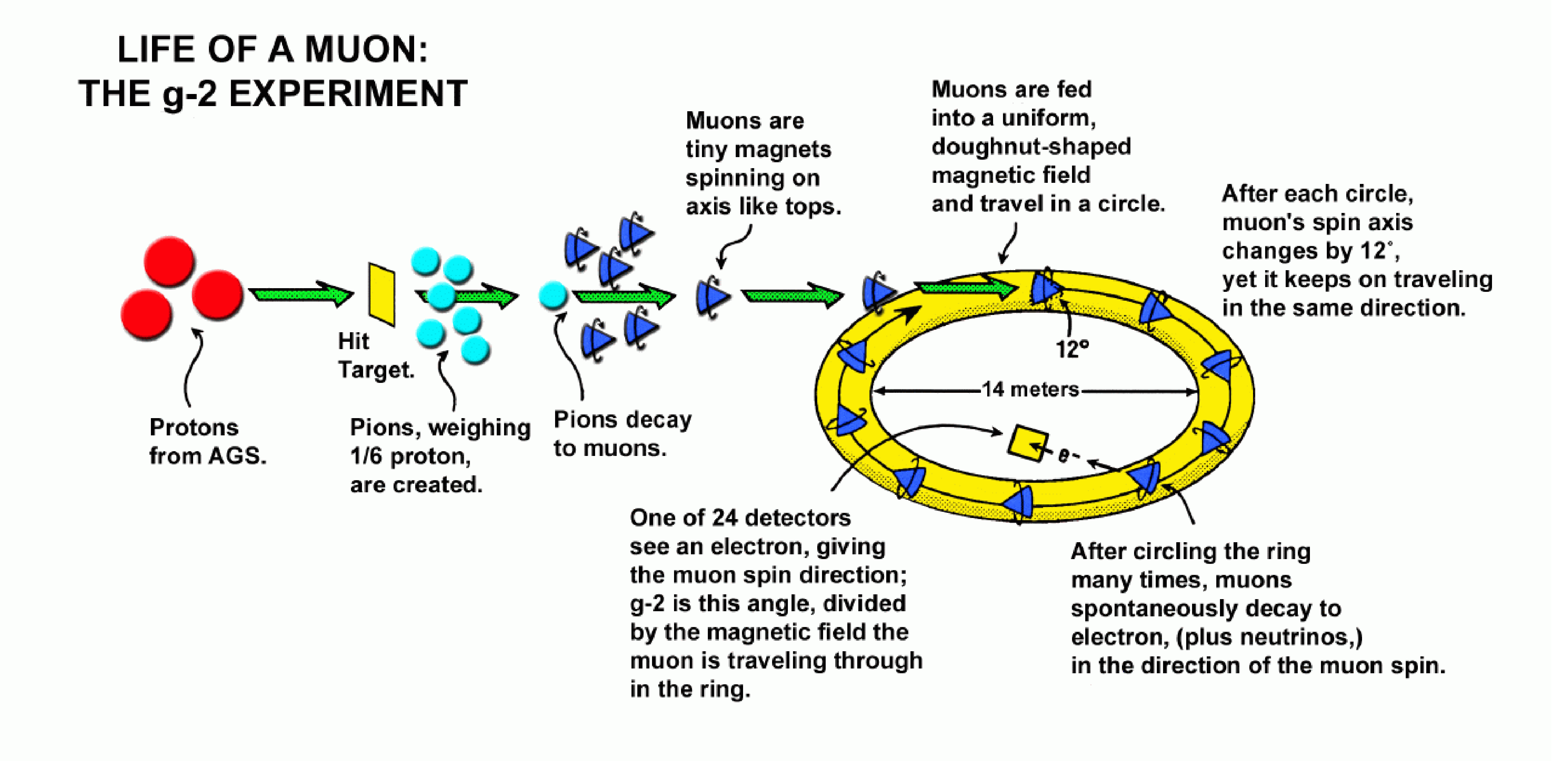
Overview about the current experimental and SM (theory) result:

[*M. Davier, A. Hoecker, B. Malaescu, Z. Zhang '10*] → T



$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (28.7 \pm 8) \times 10^{-10} \quad : \; 3.6\,\sigma$$

The $(g-2)_\mu$ experiment:



Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p') \left[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu} \sigma^{\mu\nu} q_\nu F_2(q^2) \right] u(p) A_\mu \qquad F_2(0) = a_\mu$$

Current status of $(g-2)_\mu$:

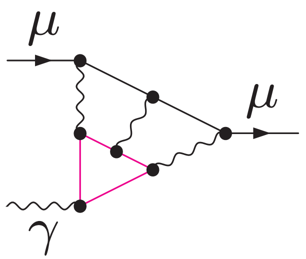
Experiment:

– 2001 - 2006: very stable development

– final error: 6×10^{-10} , still statistically dominated

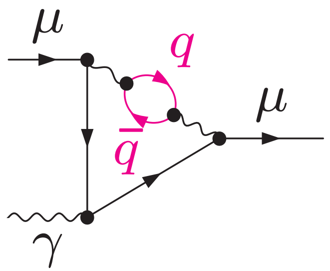
Theory:

– the light-by-light contribution:



2002: sign error discovered; since then stabilized

– the hadronic vacuum contribution:



problems with the τ data ⇒ hardly used anymore

'direct' e^+e^- data:
from CMD-II, SND, KLOE (radiative return)
⇒ agree quite well (also with old e^+e^- data)

new SM evaluations, based on new exp e^+e^- data for a_μ^{had} :

$$a_\mu(\text{Exp-SM}) = \left\{ \begin{array}{ll} \text{[HMNT '06]} & 28(8) \\ \text{[DEHZ '06]} & 28(8) \\ \text{[FJ '07]} & 29(9) \\ \text{[MRR '07]} & 29(9) \\ \text{[DH '10]} & 28.7(8.0) \end{array} \right\} \times 10^{-10}$$

better agreement between evaluations, more precise,
larger deviation from exp than ever before

$\Downarrow$

3σ deviation has now been definitely established

(based on e^+e^- data)

New development for τ data:

[*F. Jegerlehner, R. Szafron '11*]

Re-evaluation of τ data: improved evaluation of ρ–γ mixing
$\Rightarrow$ shift in τ data:

Now: agreement with e^+e^- data! $\Rightarrow$ still tbc!

If correct: $\Rightarrow$ new average of all data possible . . .

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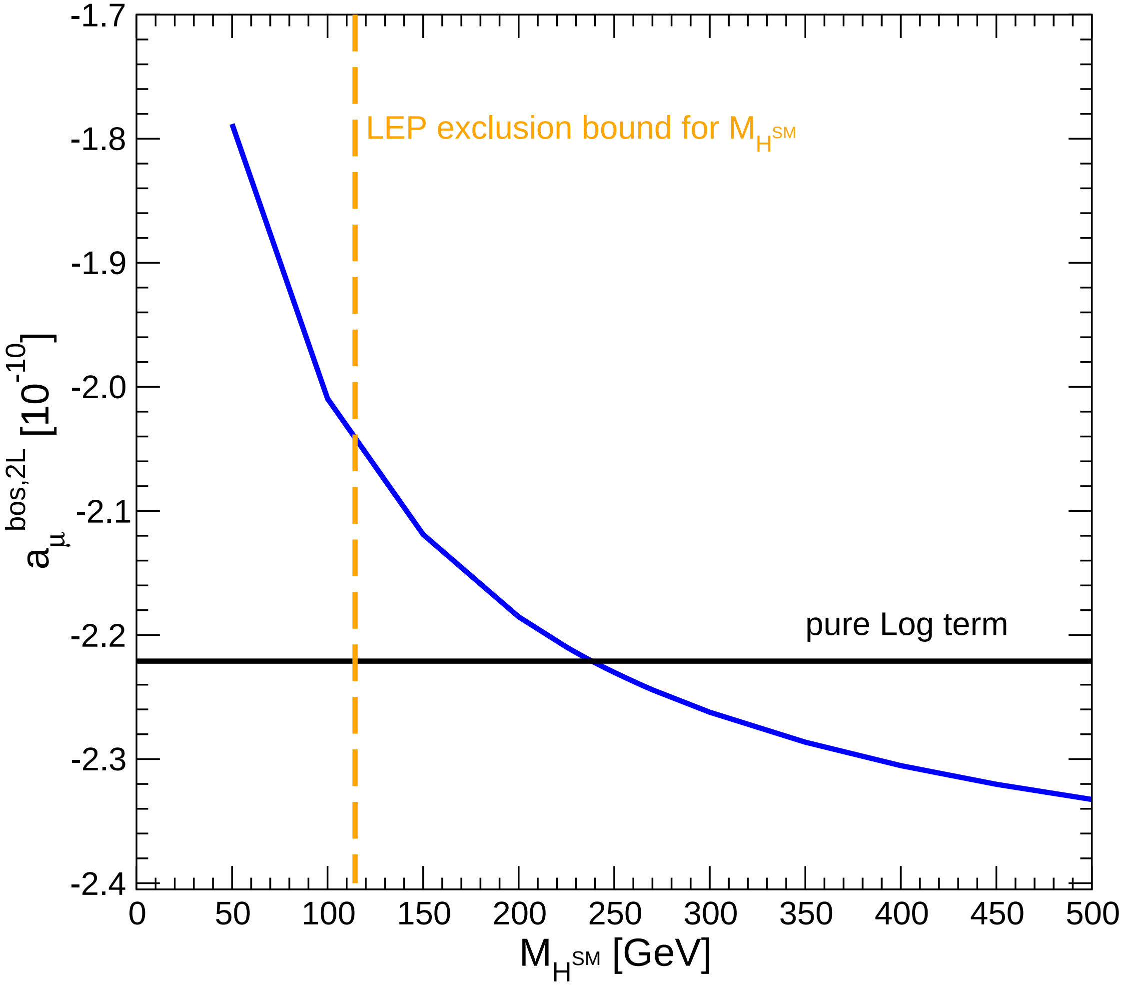
If correct: $\Rightarrow$ new average of all data possible . . .

New physics needed to explain this discrepancy?

Restrictions on M_H from a_μ?

⇒ Higgs enters only at the two-loop level

Example for M_H dependence: [S.H., D. Stöckinger, G. Weiglein '04]



⇒ no restrictions on M_H (but just wait a bit . . . :-)

Back to the Higgs:

Back to the Higgs: 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 ($M_H > 2M_V$):

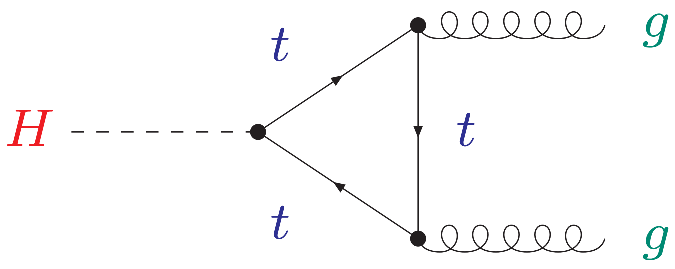
$$\Gamma(H \to VV) = \delta_V \frac{G_\mu M_H^3}{16\sqrt{2}\,\pi} \left(1 - 4\frac{M_V^2}{M_H^2} + 12\frac{M_V^4}{M_H^4}\right) \left(1 - 4\frac{M_V^2}{M_H^2}\right)^{1/2}$$

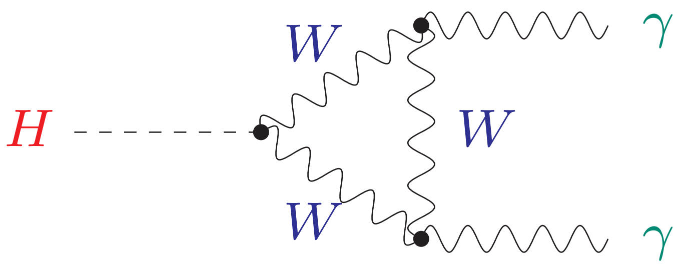
with $\delta_{W,Z} = 2, 1$

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

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

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

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

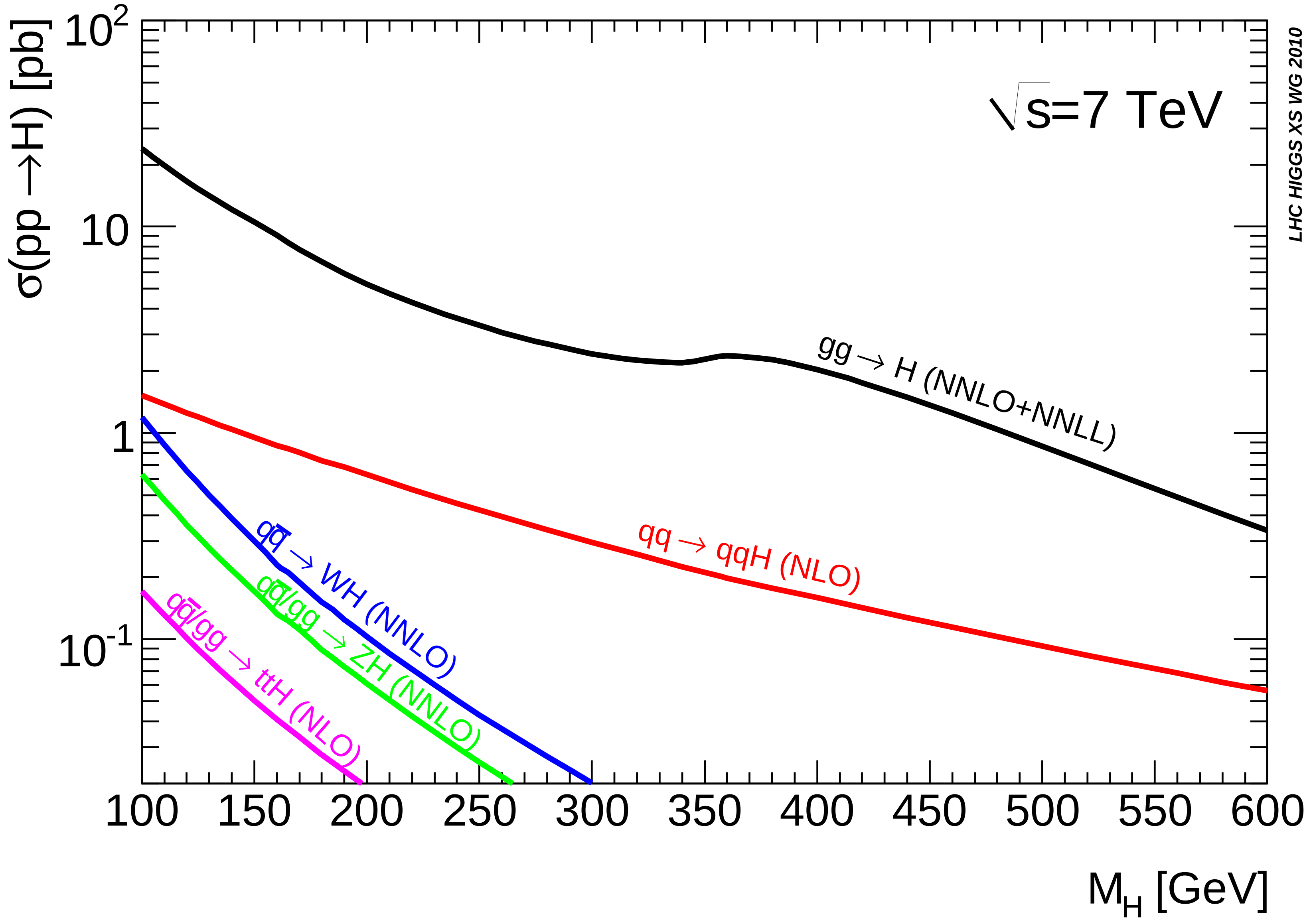
⇒ huge QCD corrections

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

via the top quark and W boson loop

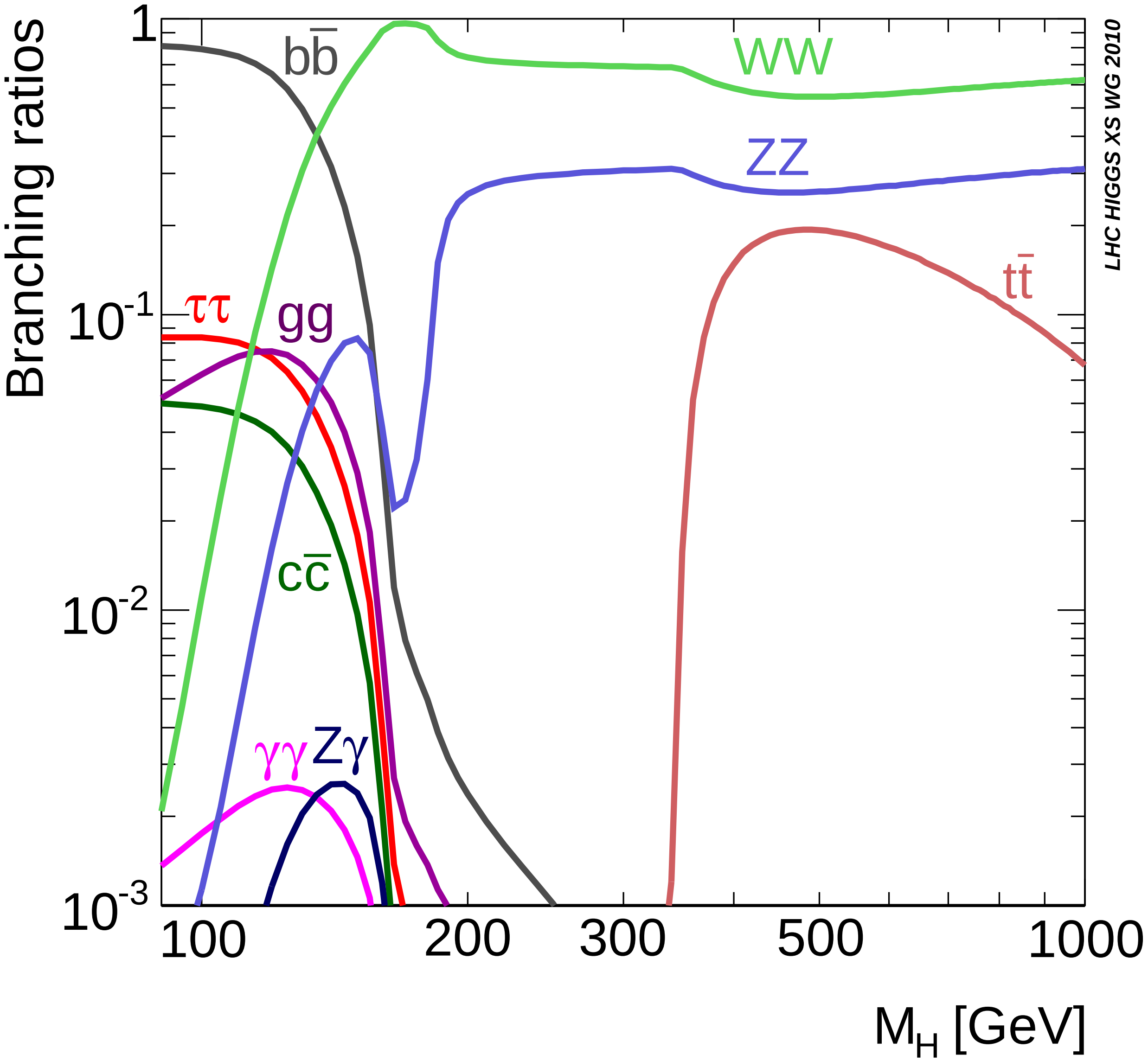
Latest theory predictions for the SM Higgs: LHC production XS

[*LHC Higgs XS WG '10*]



Latest theory predictions for the SM Higgs: branching ratios

[LHC Higgs XS WG '10]



Discovering the Higgs boson

What has to be done?

1. Find the new particle

Discovering the Higgs boson

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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,

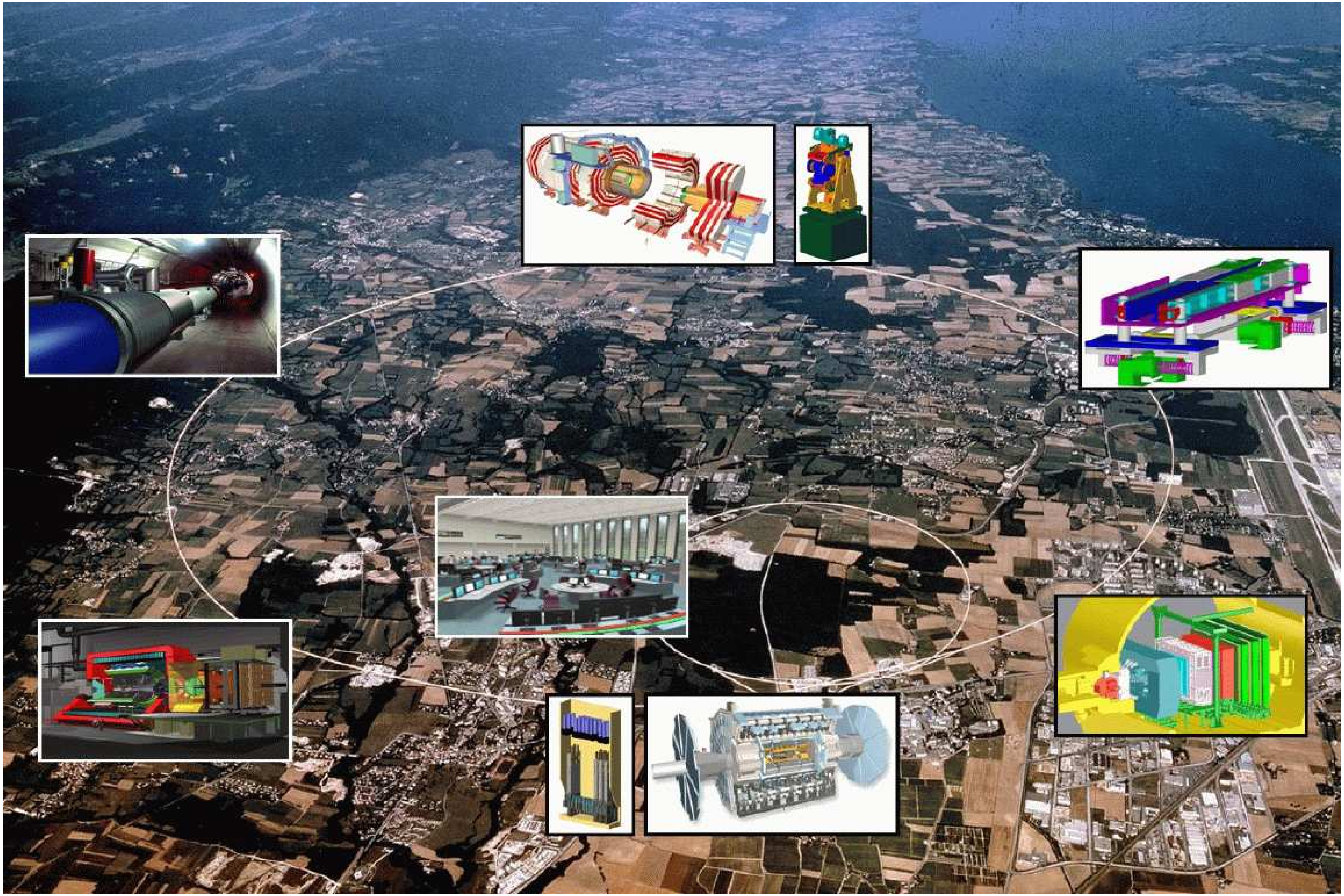
Discovering the Higgs boson

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

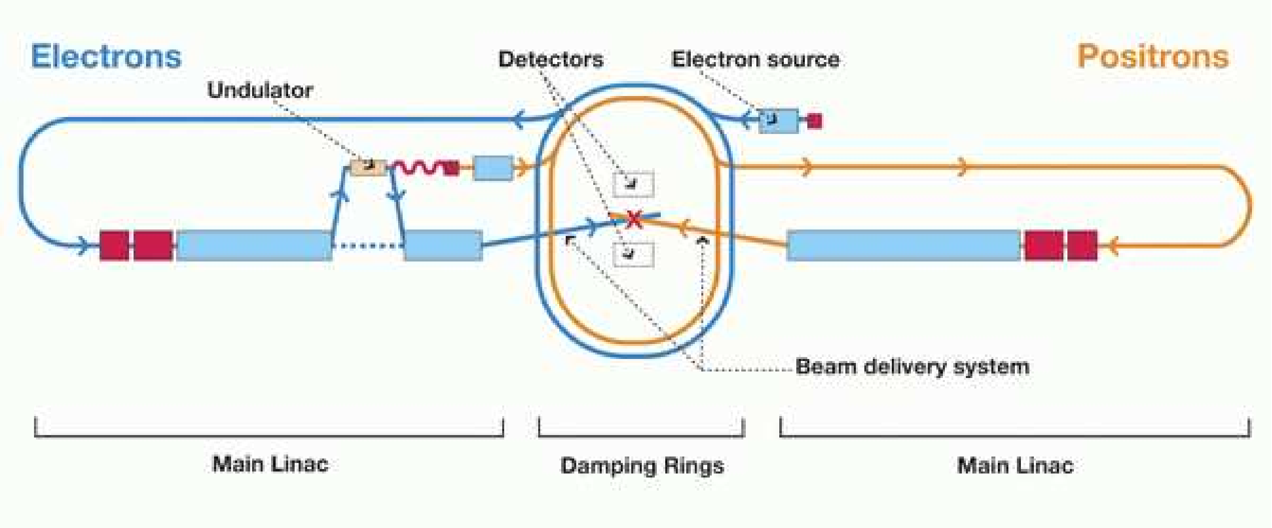
We need the ILC to find the Higgs
and to establish the Higgs mechanism!
But the LHC can do a crucial part already!



Linear e^+e^- collider, $\sqrt{s} = 500 - 1000$ GeV

based on superconducting cavities (cold technology) (ITRP decision 2004)

Schematic:



- two detectors in one interaction region (push-pull)
- undulator based e^+ source
- polarized beams for e^- and e^+ ($P_{e^-} = 80\%$, $P_{e^+} = 60\%$)

⇒ clearly defined and tunable innitial state

⇒ extremely "clean" physics

2. The Standard Model and the LHC

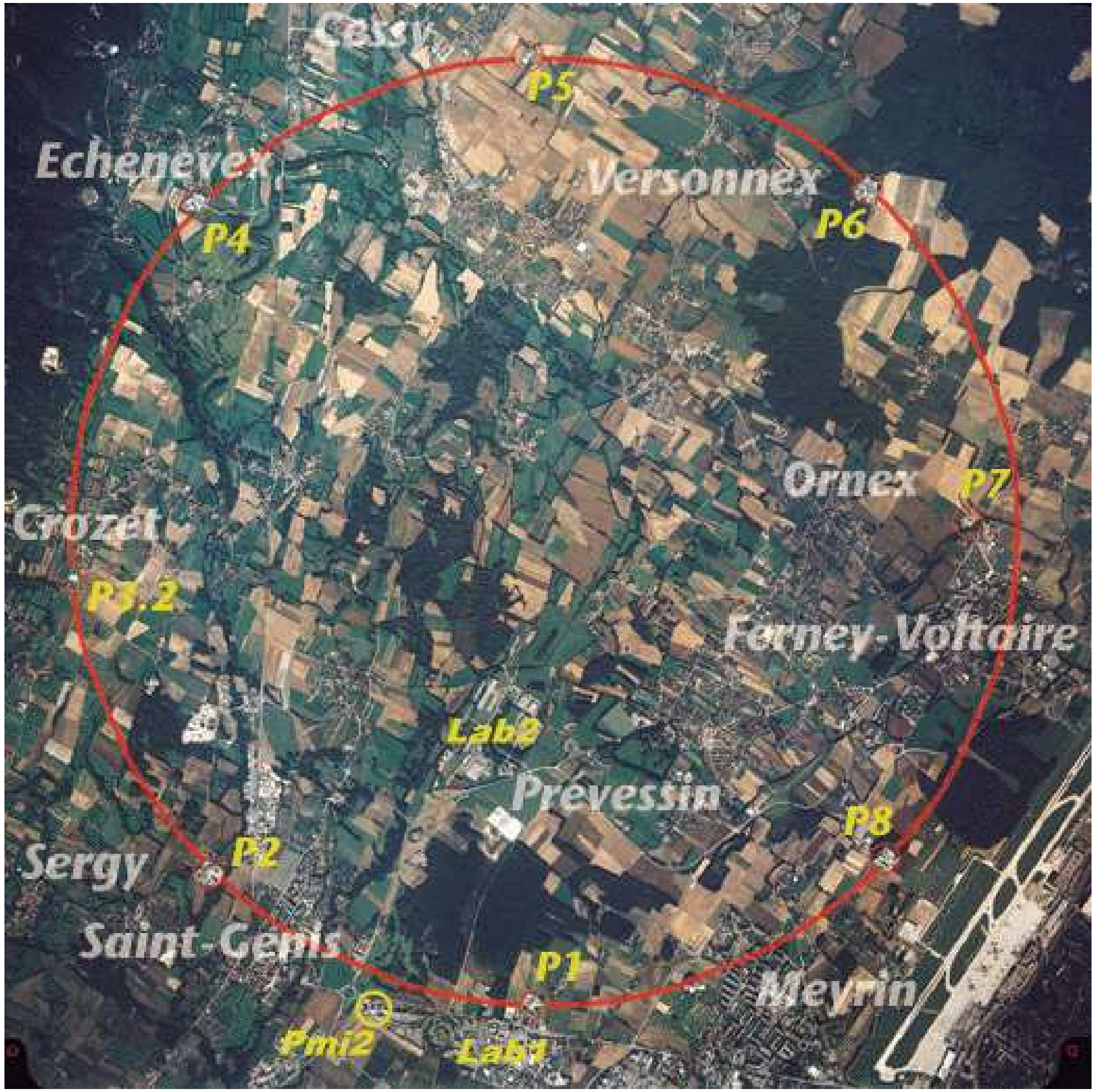
What can we learn from exploring the new territory of TeV-scale physics?

- How do elementary particles obtain the property of mass:
  what is the mechanism of electroweak symmetry breaking?
- Do all the forces of nature arise from a single fundamental interaction?
- Are there more than three dimensions of space?
- Are space and time embedded into a "superspace"?
- Can dark matter be produced in the laboratory?
- . . .

⇒ so we set out and built the LHC!

LHC:

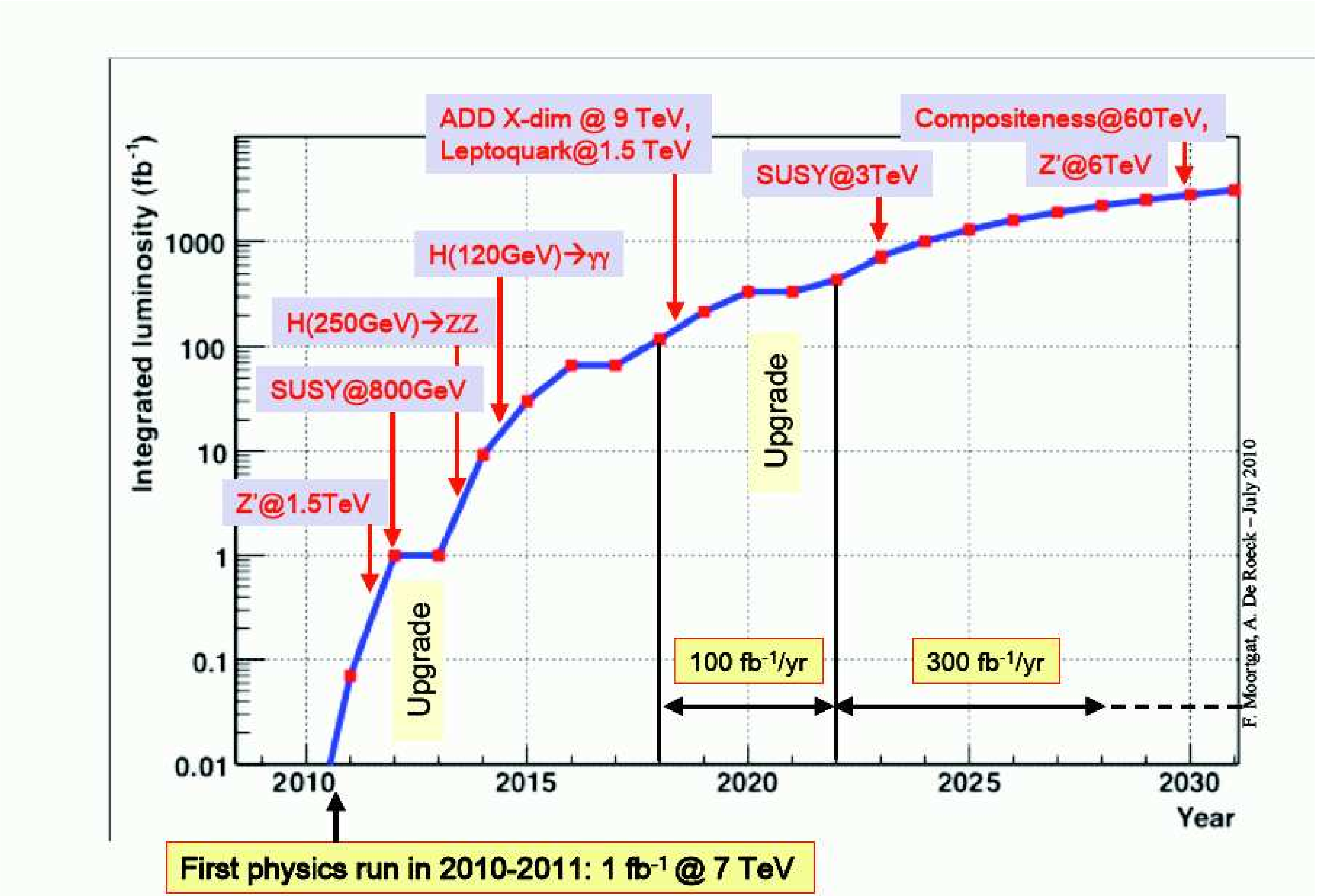
$p\,p$ collisions at $\sqrt{s} = 7, 8, 14$ TeV



- 27 km circumfence
- two general purpose detectors: ATLAS and CMS
- one B physics detector: LHCb
- one heavy ion detector: Alice

LHC overview:

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



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

LHC Results: Executive Summary

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Standard Model has been rediscovered!

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No evidence for new physics - yet!

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. . . most probably with one exception in the Higgs searches!

Physics at the LHC: basics

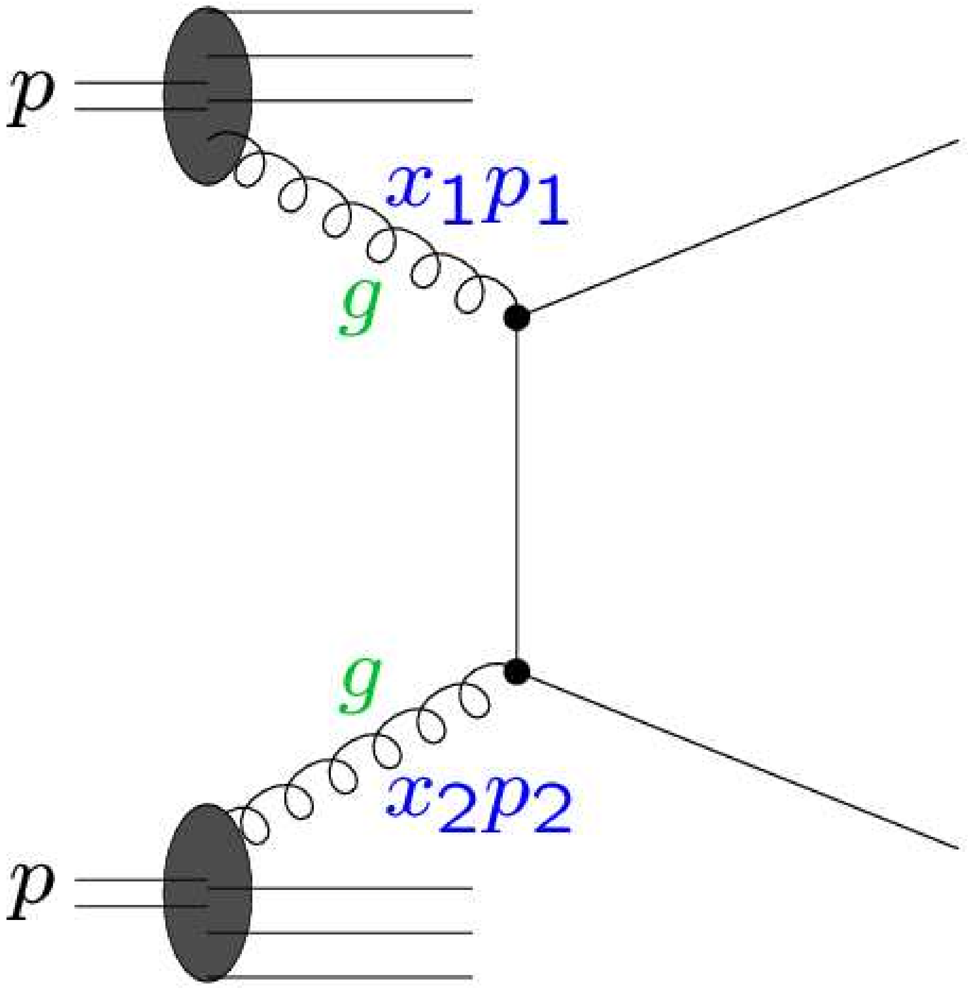
pp scattering at $\sqrt{s} = 14$ TeV

Scattering process of proton constituents (q, $\bar{q}$, g) with energy up to several TeV,
strongly interacting

⇒ huge QCD backgrounds,
low signal–to–background ratios

interaction rate of 10^9 events$/s$

⇒ can trigger on only
1 event in 10^7



How to calculate cross sections at the LHC?

First step:

Calculate cross section for incoming partons and outgoing X:

$$\hat{\sigma}(ij \to X), \; i,j = q, \bar{q}, g$$

Perturbative calculation is possible:

– α_s is sufficiently small at LHC energies

– α is sufficiently small anyway

Still to be done:

1. connect incoming quarks and gluons with the (incoming) colliding protons

2. connect the outgoing particles with the observed (outgoing) jets

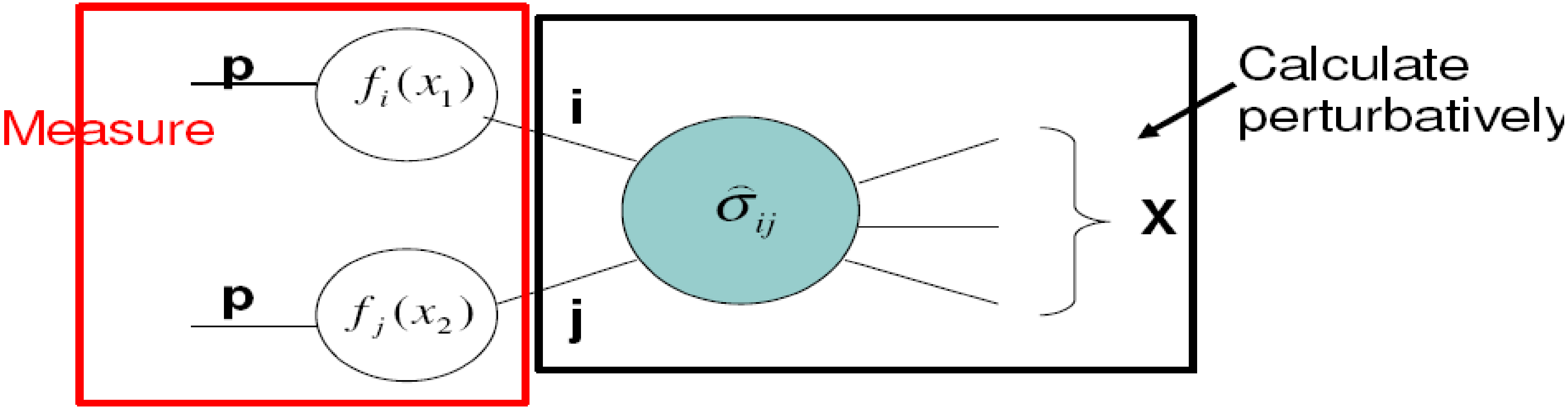
Making the connections:

1. To connect protons with quarks an gluons we need to know the probability that a quark or gluon is carrying a certain fraction x of the proton momentum,
   provided by parton distribution functions (PDFs):
   $$f_i(x, \mu_f)$$
   μ_f: factorization scale

2. at lowest order: each outgoing quark or gluon is identified with a hadronic jet – provided they are well separated in pseudo-rapidity – azimuth space:
   $$\Delta R := \left(\Delta\eta^2 + \Delta\Phi^2\right)^{-1/2} > R_{\text{min}}$$
   Φ: angle in plane perpendicular to beam axis
   η : pseudo rapidity: $\eta = -\log(\tan\theta/2)$

The Master formula for all LHC cross section calculations:

$$\sigma(pp \to X) = \sum_{ij} \int dx_1 dx_2\, f_i(x_1, \mu_f)\, f_j(x_2, \mu_f)\, \hat{\sigma}(ij \to X)$$



$x_{1,2}$: momentum fraction carried by the incoming quarks, gluons

$\hat{\sigma}$: partonic cross section, calculated perturbatively

Parton Density Functions (PDFs):

- PDFs cannot be calculated perturbatively
  ⇒ they have to be measured experimentally (at a certain scale)

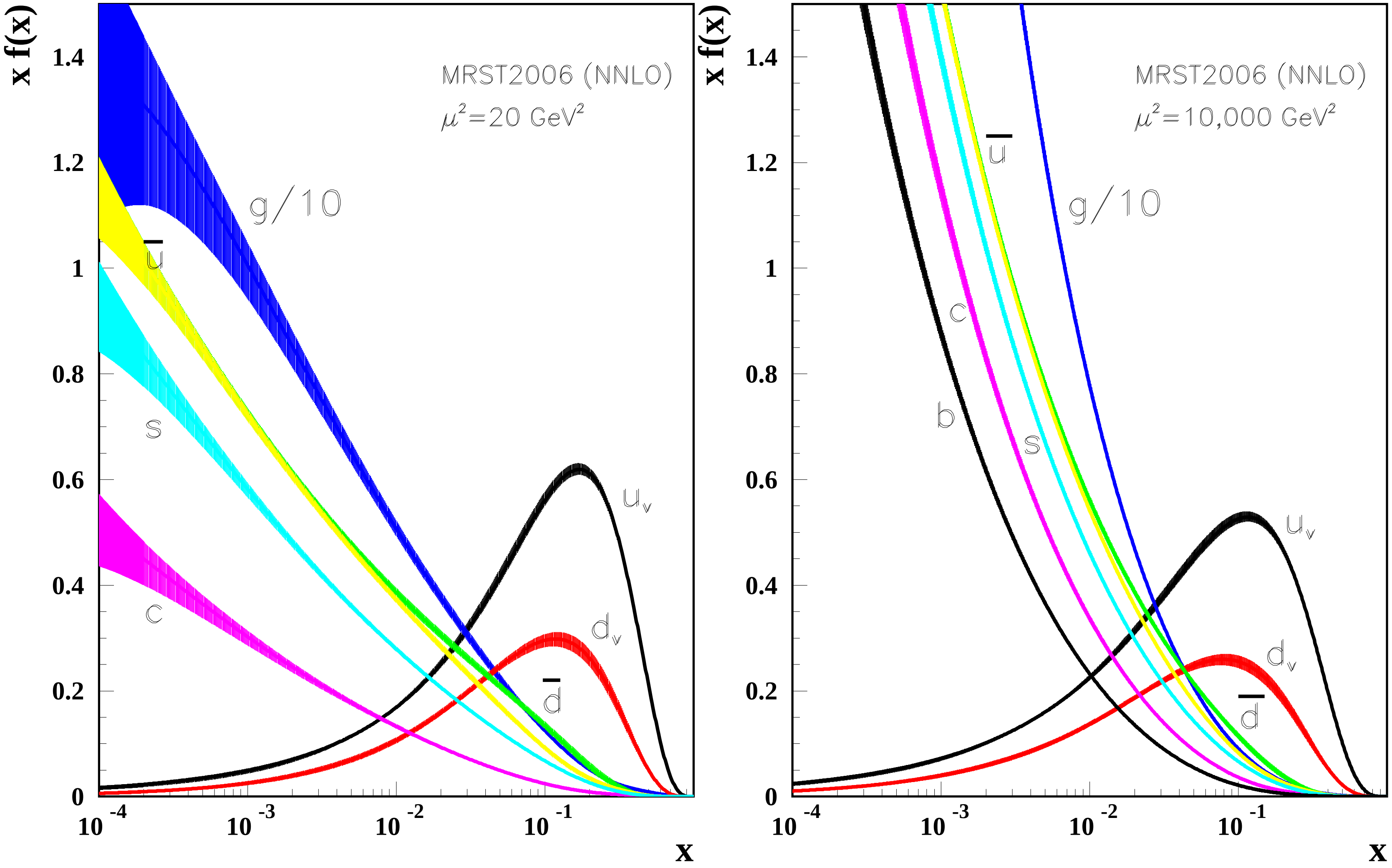
- QCD predicts the evolution of the PDFs via the
  Altarelli-Parisi equations,
  i.e. once we know the PDFs for a certain scale, QCD predicts them for all other scales

- PDFs are universal, e.g. PDFs determined at HERA can directly be used for LHC calculations

- PDFs are different for valence and sea quarks

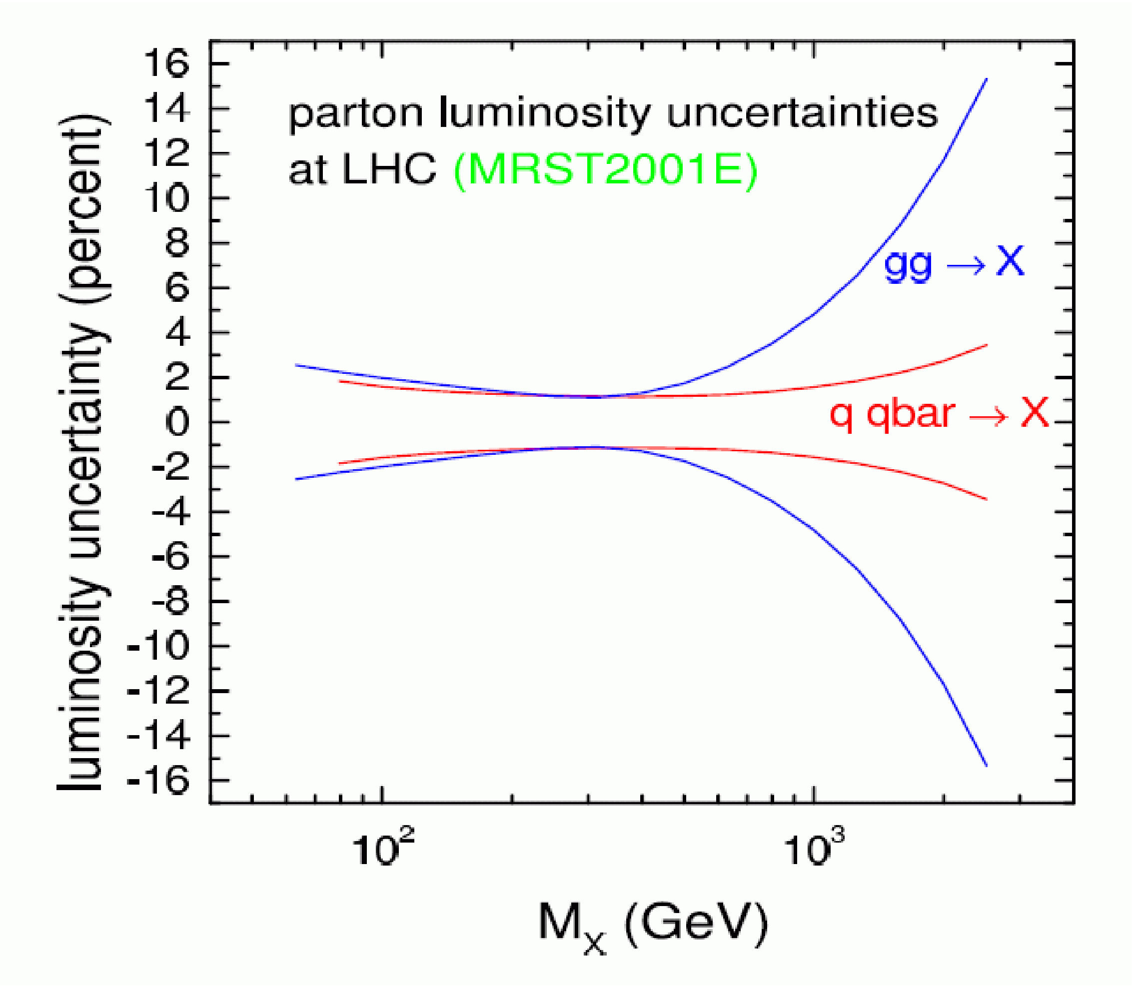
- PDFs come in the form of Fortran codes, mainly by two groups:
  MRST and CTEQ collaborations

Example for PDFs of the proton:



⇒ The LHC is (mainly) a gluon gluon collider

Uncertainties in cross section calculations induced by uncertainties in PDFs:



Final state X
with mass M_X:

PDF induced uncertainties
mostly below 5%

[MRST, CTEQ, Alekhin, . . .]

Generic QCD cross sections (I):

- focus on pure QCD cross section for the moment, but electroweak or mixed QCD/electroweak cross sections go analogous

- calculate $\hat{\sigma}$ as a power series in α_s :

$$\hat{\sigma}(ij \to X) = \alpha_s^k(\mu_r) \sum_{n=0}^{N} \alpha_s^n(\mu_r) \hat{\sigma}_n(ij \to X)$$

  μ_r : renormalization scale
  k : depends on the (number of legs of the) final state

- if one could do an all order calculation $(N \to \infty)$ the cross section σ would be independent of μ_f and μ_r

- $n = 0$: leading order (LO)
  $n = 1$: next-to-leading order (NLO)
  ...

Generic QCD cross sections (II):

- Understanding physics discoveries at the LHC requires
  accurate SM predictions . . .
  . . . this can be difficult

- We need precise (QCD) calculations ,
  together with Monte Carlo techniques to connect to the real world (jets etc.)

- LO cross sections suffer from large uncertainties
  caused by the dependencies on μ_r and μ_f ,
  especially for processes with many particles in the final state

- Including higher-order (NLO, NNLO, . . .) QCD corrections reduces the scale dependencies of the cross sections

General recipe for NLO calculations:

$$\hat{\sigma}_{\text{NLO}} \;\propto\; \text{phasespace} \times |\text{amplitude}_{\text{NLO}}|^2$$

Calculation of σ_{NLO} involves:

- virtual (loop) diagrams
- real (tree-level) contributions
- cancellation of ultraviolet and infrared divergencies

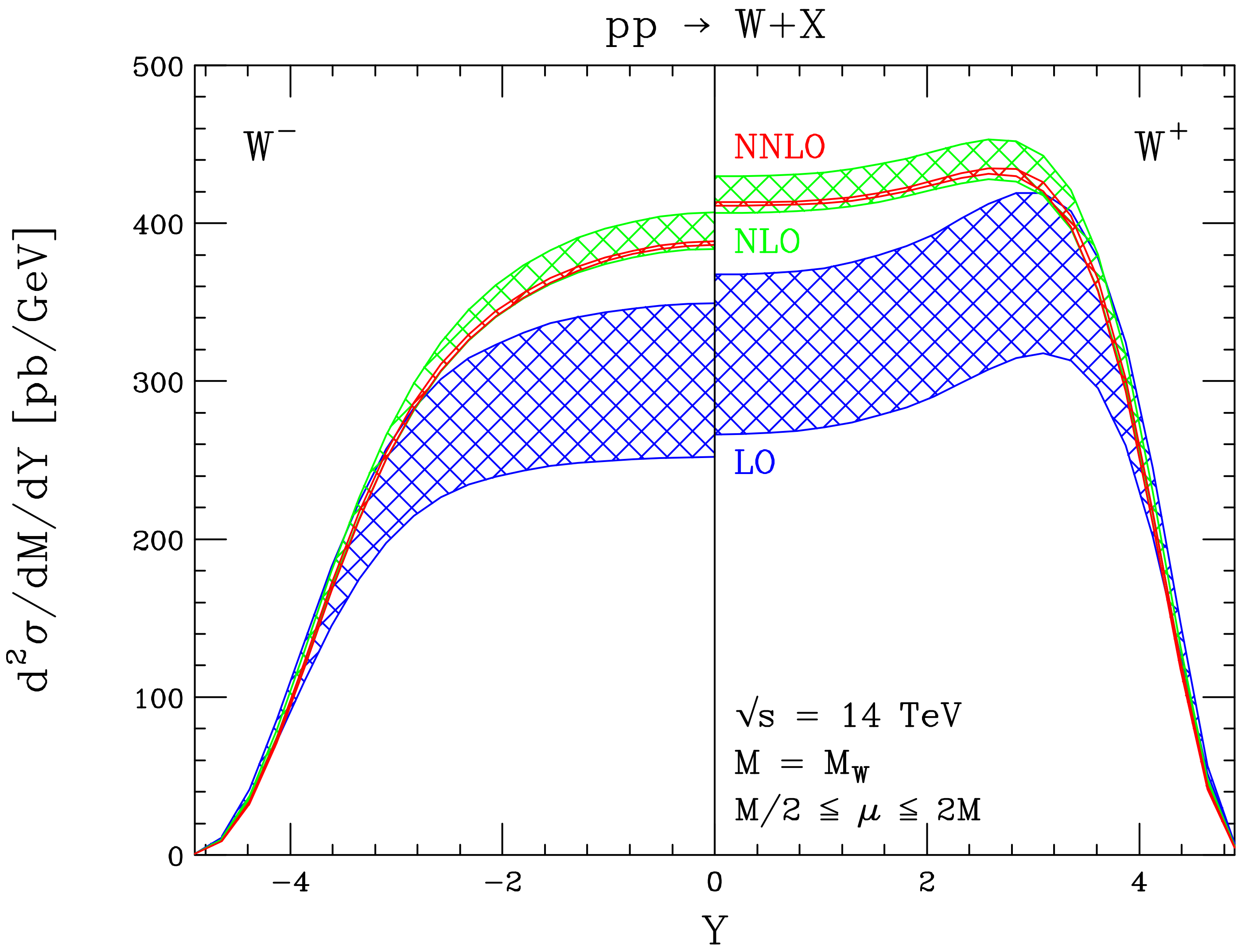
$$\hat{\sigma}_{\text{NLO}} = \hat{\sigma}_{\text{LO}} + \frac{\alpha_s(\mu_r)}{4\,\pi}\,\delta\hat{\sigma}_{\text{NLO}}$$

Contributions to $\delta\hat{\sigma}_{\text{NLO}}$:

- 1-loop virtual corrections
- real gluon and quark emissions
  (new parton subprocesses may contribute!)
- PDFs including NLO corrections

Example: $W + X$ production at the LHC:

[*C. Anastasiou, L. Dixon, K. Melnikov, F. Petriello '03*]



Nature is more complicated than NLO

Nature is more complicated than NLO

- NLO amplitudes are not sufficient:
  - only one additional parton with respect to LO, we need more
  - large logarithms (soft, Sudakov, . . .) appear
    $\Rightarrow$ have to be resummed
  - fixed order calculations do not include hadronization

- Needed: NLO calculations merged into MC codes
  - examples for MC: PYTHIA, HERWIG, SHERPA
  - examples for merger: MC@NLO

- complication: additional parton in NLO is also part of normal showering
  $\Rightarrow$ need to avoid double counting

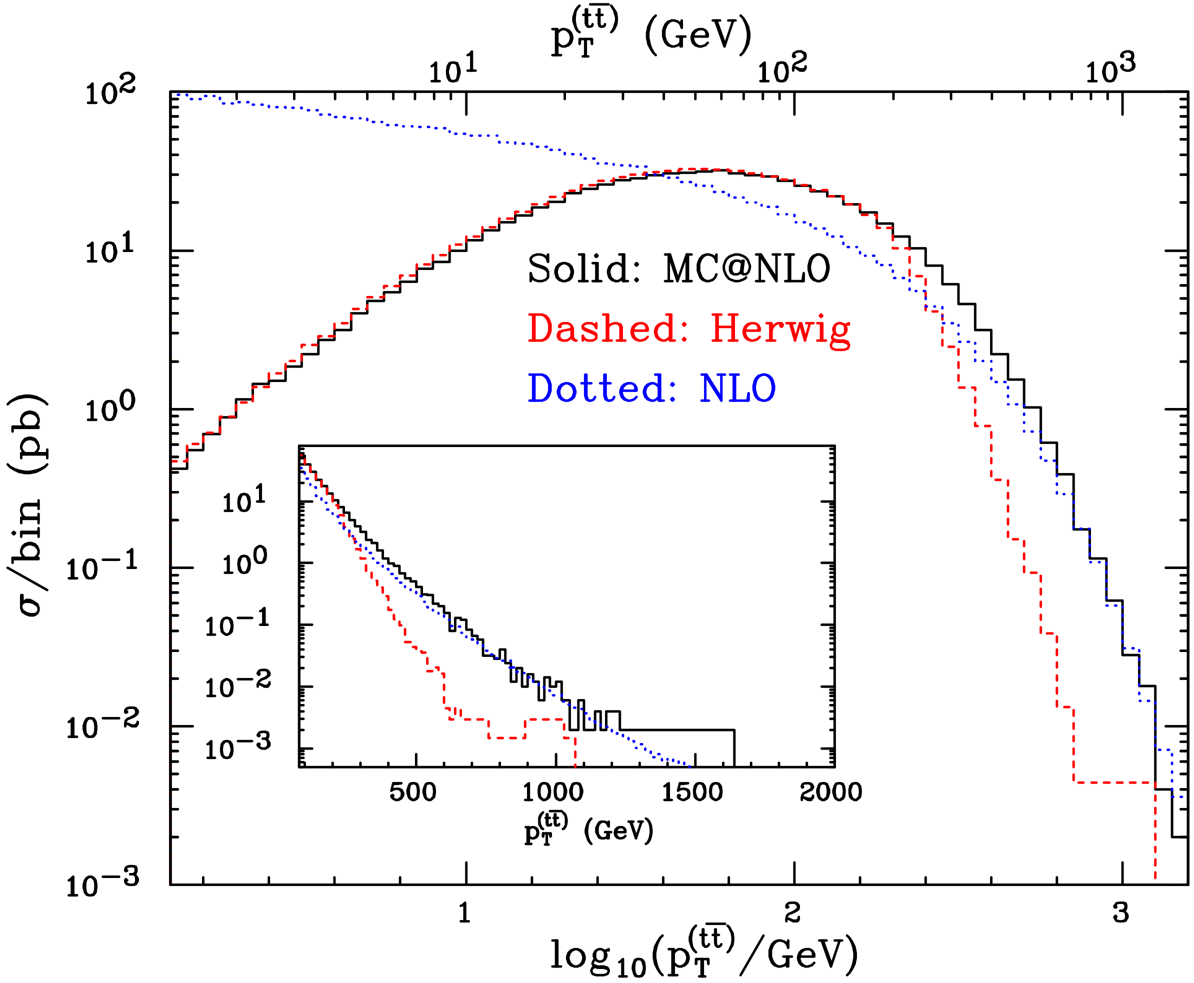
MC@NLO: $pp \to t\bar{t}$ at the LHC

Combination of HERWIG
and NLO calculation

double counting subtracted

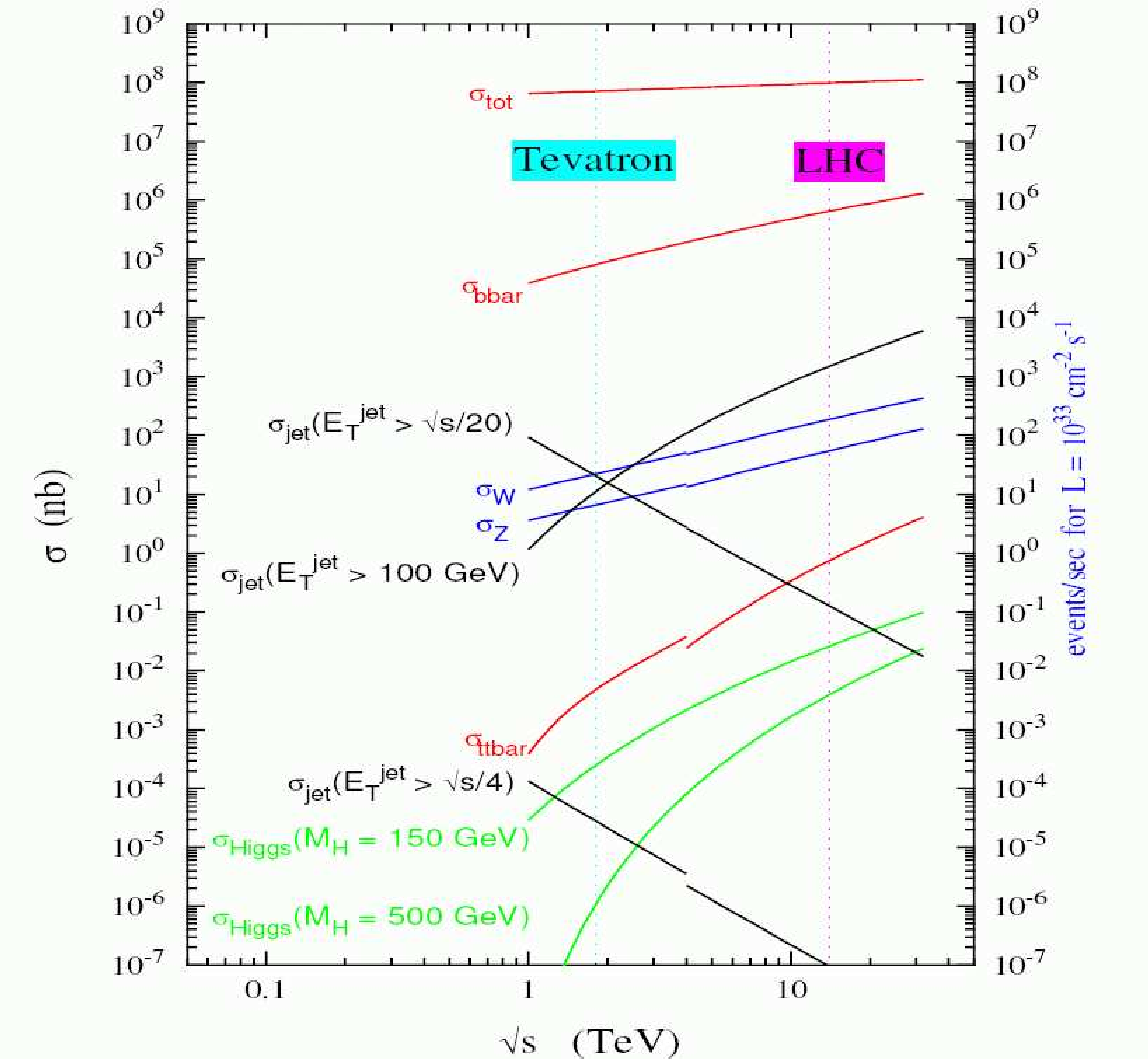
at low p_T: NLO
at high p_T: MC

$\Rightarrow$ MC@NLO



[*Frixione, Nason, Webber '03*]

LHC cross section overview:



SM physics at the LHC

A) W boson physics

B) top quark physics

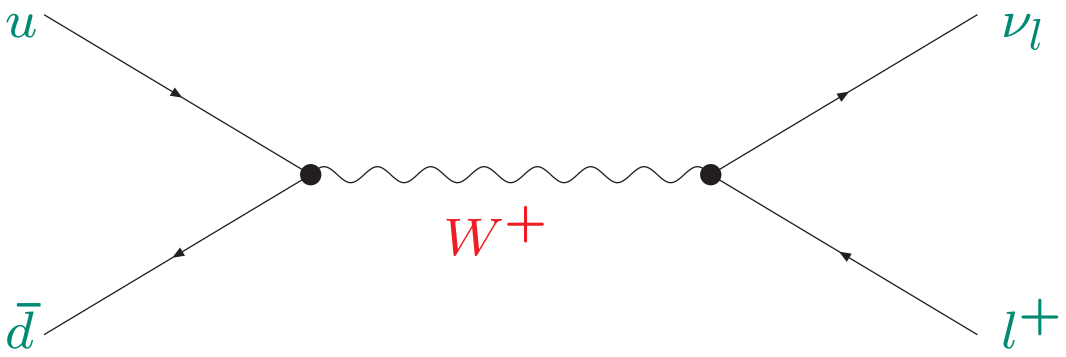
C) jet production

D) B physics

E) Higgs searches at the LHC

A) W boson physics

W production and decay at the LHC:



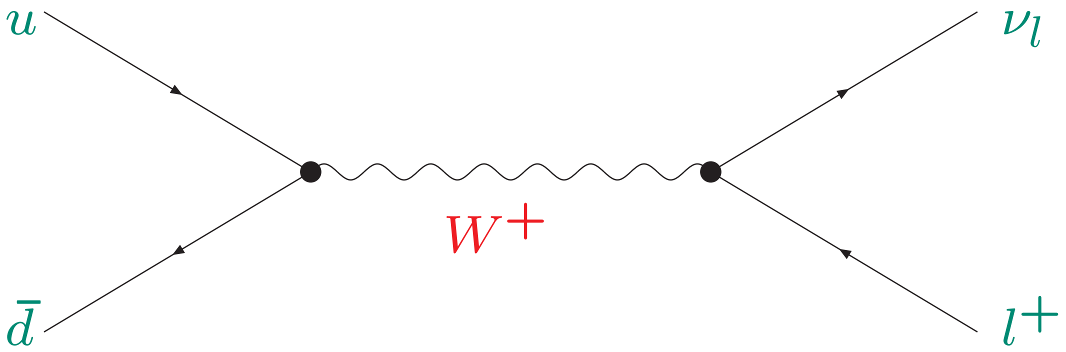
$\Rightarrow$ measurement of M_W and Γ_W

$\Rightarrow$ precision test of the SM

	now	Tevatron	LHC
δM_W [MeV]	15	15	≥ 5
$\delta\sin^2\theta_{\text{eff}}(\times 10^5)$	16	—	14–20
δm_t [GeV]	0.9	0.9	$\lesssim 1.0$

$\Rightarrow$ improvement in indirect M_H determination

W boson mass measurement:



$$u(p_u)\,\bar{d}(p_d) \;\to\; l^+(p_l)\,\nu_l(p_\nu)$$

A little calculation (LO):

$$\overline{\sum}|\mathcal{M}(u\bar{d} \to l^+\nu_l)|^2 = 16(\sqrt{2}G_\mu M_W^2)|V_{ud}|^2 \frac{(p_u \cdot p_l)^2}{((p_u + p_d)^2 - M_W^2)^2 + M_W^2\Gamma_W^2}$$

M_W method I: the p_{Tl} distribution

Θ^*: polar angle of l^+ in the W^+ rest frame

⇒
$$(p_u \cdot p_l)^2 = \frac{M_W^2}{16}(1 + \cos^2\Theta^*)$$

⇒
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\Theta^*} = \frac{3}{8}(1 + \cos^2\Theta^*)$$

If the W has zero transverse momentum the polar angle is given in terms of the lepton transverse momentum: p_{Tl}:

$$\cos\Theta^* = \sqrt{1 - 4p_{Tl}^2/M_W^2}$$

⇒
$$\frac{1}{\sigma}\frac{d\sigma}{dp_{Tl}^2} = \frac{3}{M_W^2}\frac{1 - 2p_{Tl}^2/M_W^2}{\sqrt{1 - 4p_{Tl}^2/M_W^2}}$$

⇒ the p_{Tl} distribution is strongly peaked at $M_W/2$ (Jacobian peak)

However:
The peak is smeared out by the finite W width
and non-zero W transverse momentum.

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M_W method II: the M_T distribution

Therefore one often uses the transverse mass

$$M_T^2 = 2|p_{Tl}|\,|p_{T\nu}|(1 - \cos\Delta\phi_{l\nu})$$

which is less sensitive to the W transverse momentum.

At LO one has $|p_{Tl}| = |p_{T\nu}|,\ \Delta\phi_{l\nu} = \pi \quad \Rightarrow\ M_T = 2|p_{Tl}|$

⇒ the M_T distribution has a Jacobian peak at $M_T = M_W$

However:
The peak is smeared out by the finite W width
and non-zero W transverse momentum.

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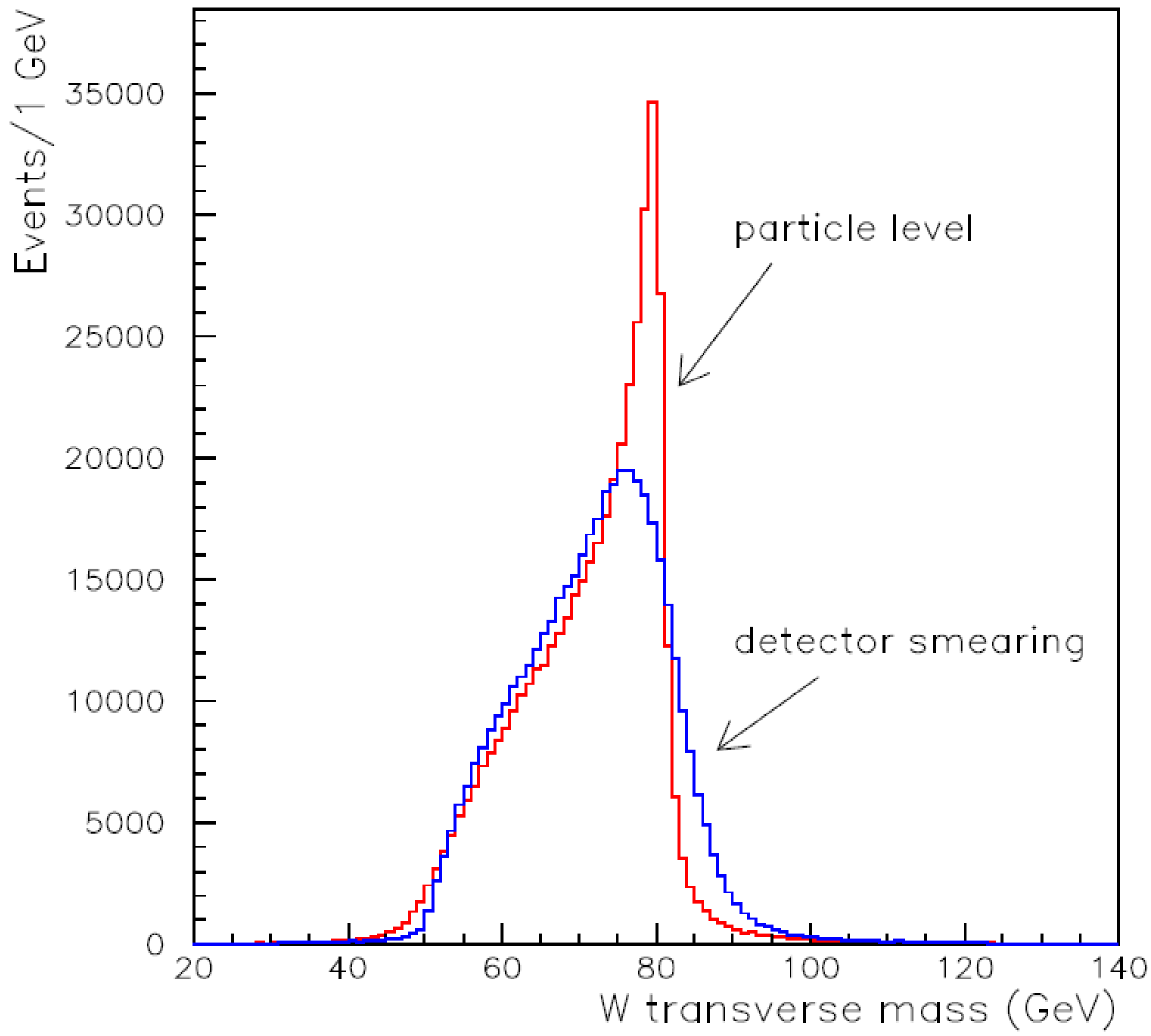
$\Rightarrow$ the M_T distribution has a Jacobian peak at $M_T = M_W$

Not taken into account yet:

- non-zero W transverse momentum from gluon/quark radiation
- detector smearing
- . . .

Expectations at the LHC:

effects of detector smearing:



statistical uncertainty:

$\delta M_W \lesssim 2$ MeV

for $\int \mathcal{L} = 10\,\text{fb}^{-1}$

overall uncertainty:

$\delta M_W \lesssim 20$ MeV

possible if lepton energy and momentum scale are know to 0.02%

B) top quark physics

Top-quark mass is a fundamental parameter of the electroweak theory

By far the largest quark mass,
largest mass of all known fundamental particles

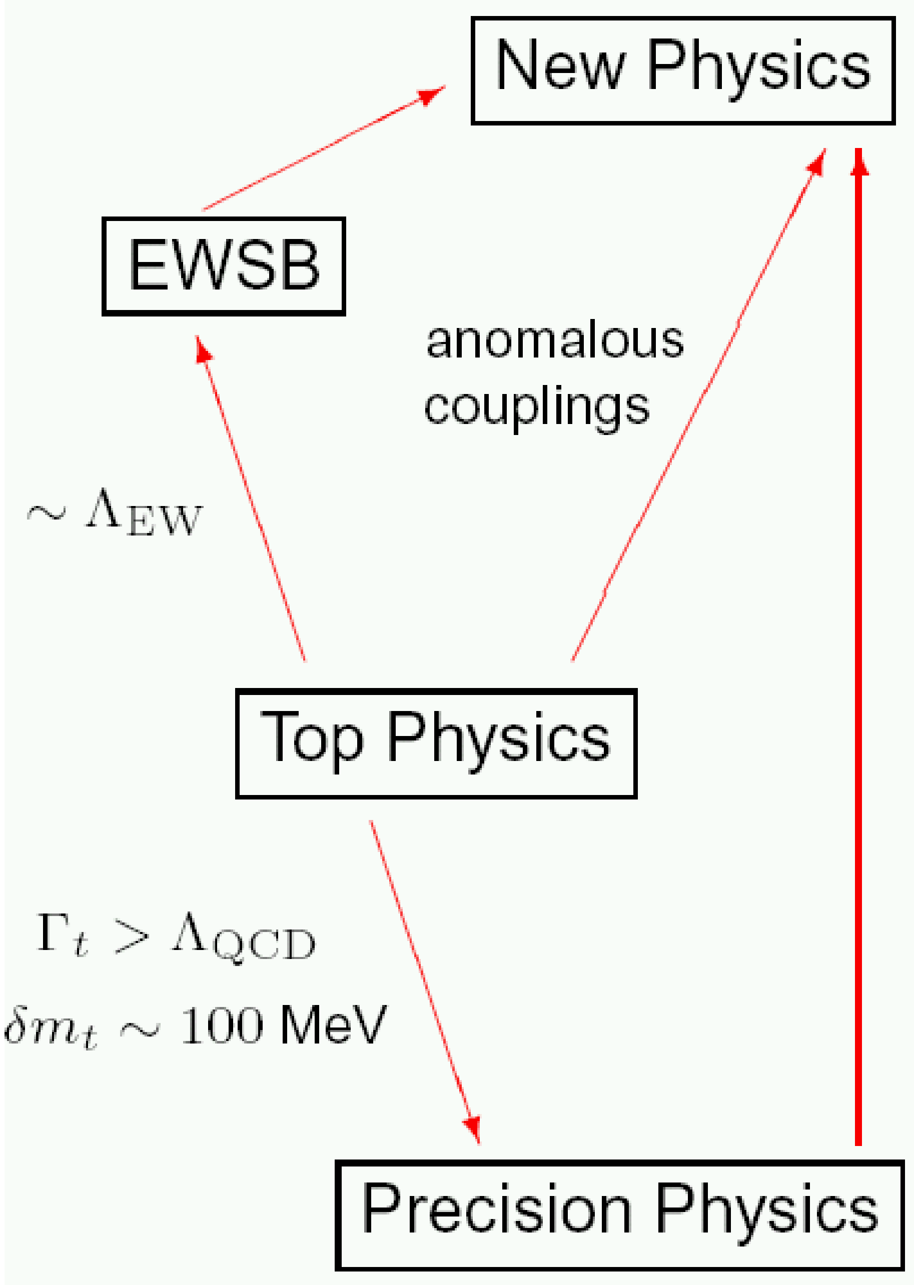
Window to new physics?

Large coupling to the Higgs boson; physics of flavor;
prediction of m_t from underlying theory?

Radiative corrections

$\Rightarrow$ non-decoupling effects proportional to powers of m_t

$\Rightarrow$ Need to know m_t very precisely in order to have sensitivity to effects of new physics



New Physics

EWSB

anomalous couplings

$\sim \Lambda_{\mathrm{EW}}$

Top Physics

$\Gamma_t > \Lambda_{\mathrm{QCD}}$

$\delta m_t \sim$ 100 MeV

Precision Physics

EWSB: just a heavy quark?
special role for t in EWSB?
strong constraint on any model

Precision physics:
$\delta m_t^{\mathrm{exp}}$ leading parametric uncertainty
→ could obscure new physics

SUSY: m_t crucial input parameter
drives SSB/unification

Little Higgs: heavier top

What can be done at the LHC?

What is the top mass?

Particle masses are not observables
one can only measure cross sections, decay rates, . . .

Additional problem for the top mass:

what is the mass of a colored object?

Top pole mass is not IR safe (affected by large long-distance contributions), cannot be determined to better than $\mathcal{O}(\Lambda_{\rm QCD})$

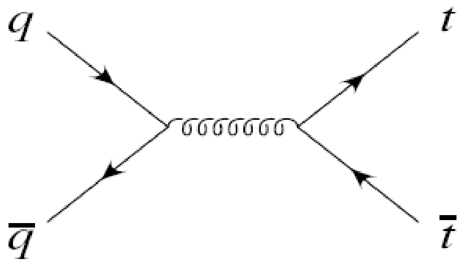
Measurement of m_t:

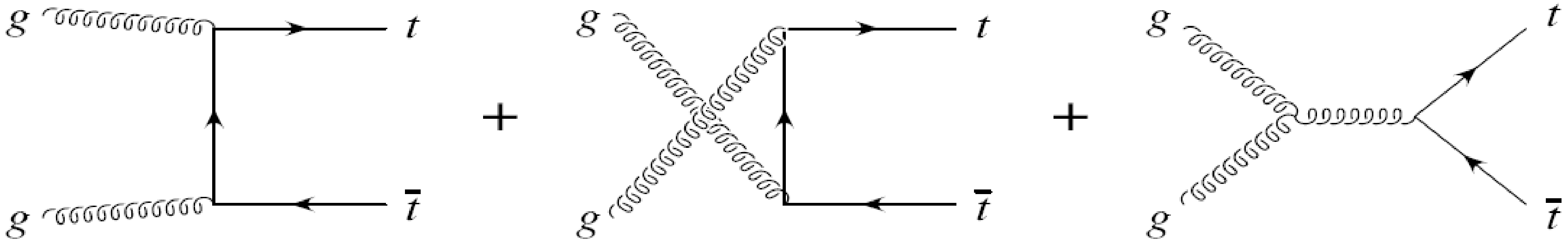
- At Tevatron, LHC:
  kinematic reconstruction, fit to invariant mass distribution
  ⇒ “pole” mass

- At the ILC:
  mainly from threshold behavior ⇒ threshold mass

Top quark production at the LHC:

Top production through quark antiquark annihilation and gluon gluon fusion



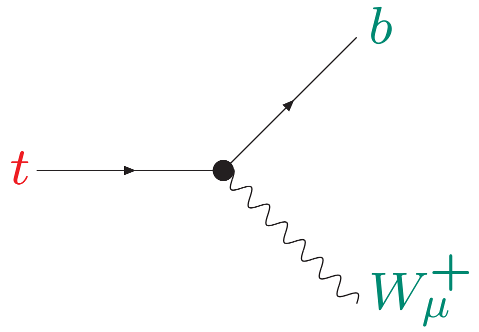


$q\bar{q} \to t\bar{t}$: 10% $gg \to t\bar{t}$: 90%

$$\sigma_{\text{NLO}}^{\text{LHC}} = 830 \text{ pb } \pm 15\%$$

Top quark decays (I):

The dominant decay is $t \to W^+ b$:



$$= -i\frac{g}{2\sqrt{2}}\,|V_{tq}|^2\,\gamma_\mu\,(1-\gamma_5)$$

$$\Gamma(t \to W^+ b) = \frac{G_\mu m_t^2}{8\,\pi\,\sqrt{2}}|V_{tb}|^2\left(1-\frac{M_W^2}{m_t^2}\right)\left(1-\frac{2M_W^2}{m_t^2}\right) \approx |V_{tb}|^2 \times 1.42\ \mathrm{GeV}$$

Unitarity of CKM matrix: $|V_{tb}|^2 + |V_{cb}|^2 + |V_{ub}|^2 = 1 \Rightarrow |V_{tb}|^2 \approx 1$

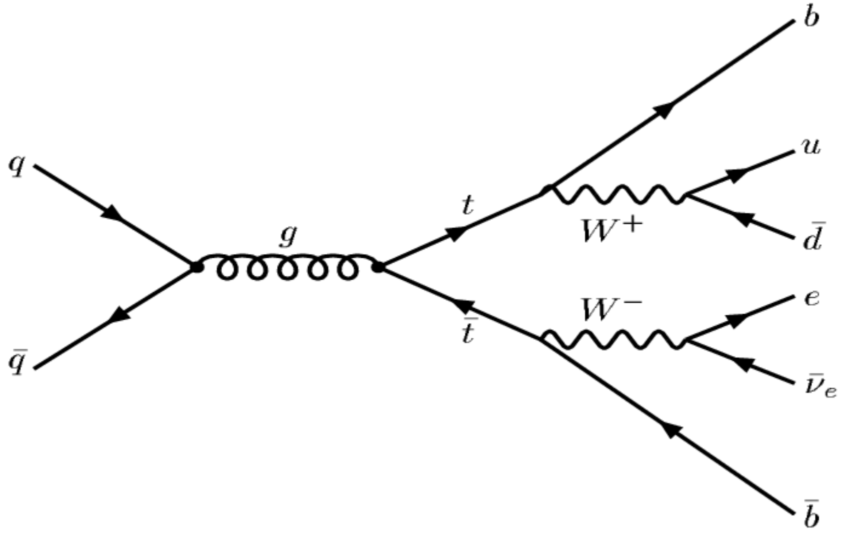
⇒ top quark life time $\tau_t \approx 5 \times 10^{-25}$ sec

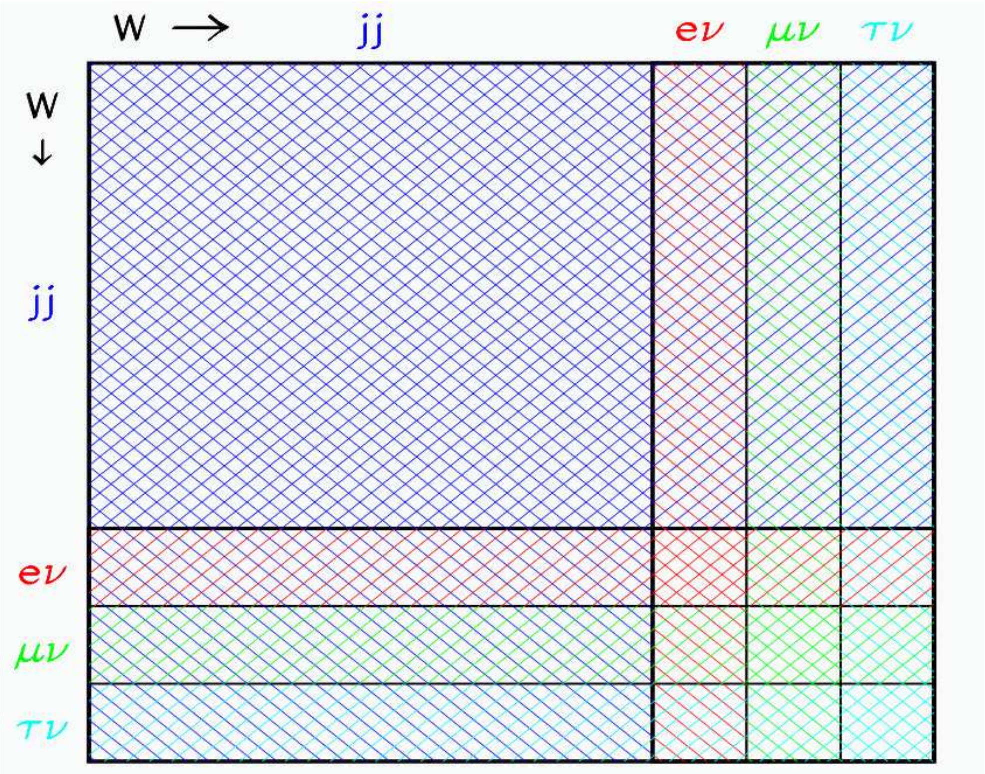
Typical QCD time scale for hadron formation: $\tau_{\mathrm{QCD}} \approx 3 \times 10^{-24}$ sec

⇒ the top quark decays before it can form bound states

Top quark decays (II):

Signature depends on the WW decay modes





⇒ often semi-leptonic channels easiest

Measurement of V_{tb} (I):

Measure the ratio

$$\frac{\text{BR}(t \to W^+ b)}{\text{BR}(t \to W^+ q)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{cb}|^2 + |V_{ub}|^2}$$

If one assumes 3 generations then $|V_{tb}|^2 + |V_{cb}|^2 + |V_{ub}|^2 = 1$

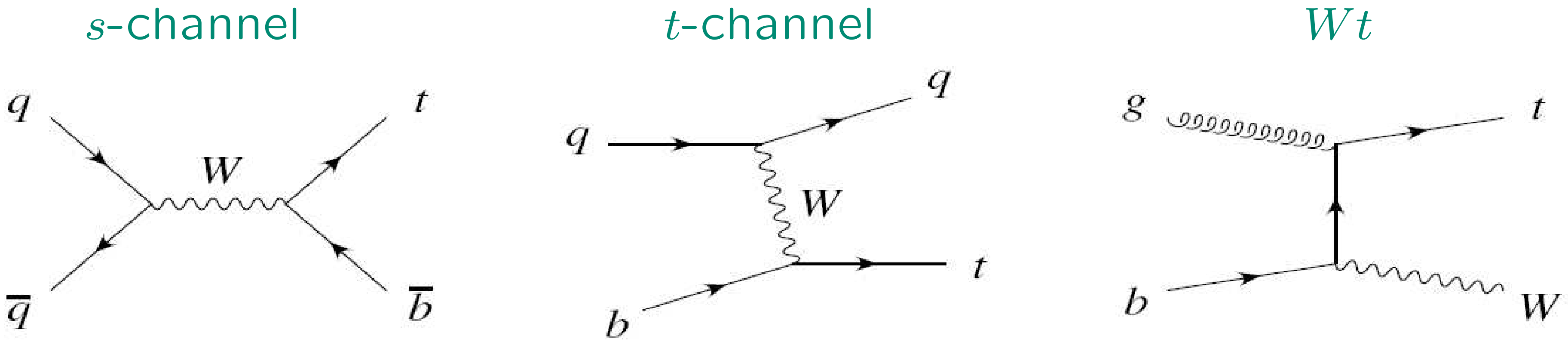
Current Tevatron measurements:

$$|V_{tb}| = \begin{cases} 1.05^{+0.10}_{-0.09} & \text{(CDF)} \\ 1.01^{+0.09}_{-0.09} & \text{(D0)} \end{cases}$$

However:
assuming three generations we know $0.9990 < |V_{tb}| < 0.9993$ anyway from unitarity of the CKM matrix

Measurement of V_{tb} (II):

Cleaner: single top production



	s-channel	t-channel	Wt
σ_t^{NLO} [pb]	~ 7	~ 153	~ 31
$\sigma_{\bar{t}}^{\mathrm{NLO}}$ [pb]	~ 4	~ 90	~ 31

⇒ better prospects, no assumption on unitarity needed

Top quark physics at the LHC:

The top cross section is $\sigma_{tt} \approx 830$ pb

One year LHC running at low luminosity, $\sim 10\,\text{fb}^{-1} \Rightarrow \mathcal{O}\left(10^7\right)$ top events

Physics goals:

- $\delta m_t = 1$ GeV with $\int \mathcal{L} = 100\,\text{fb}^{-1}$
- Observation of single top production, measurement of V_{tb} with $\int \mathcal{L} = 30\,\text{fb}^{-1}$
- test of quantum numbers
- measurement of rare (BSM) decay modes

M_W and m_t as a test of the SM and SUSY:

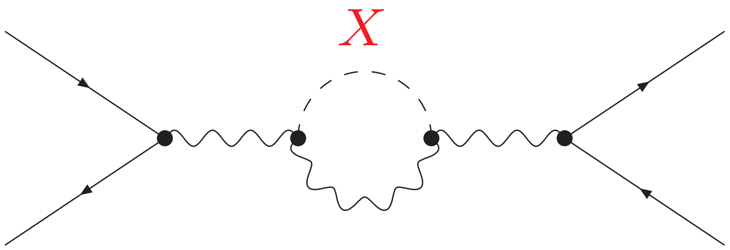
Idea: predict M_W as a function of m_t (and other well measured parameters)

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



X: the whole model enters ⇒ test of the theory at the quantum level

⇒ SM and SUSY give different predictions

Final step: compare with experimental data

Comparison of SM prediction of M_W with direct measurements:

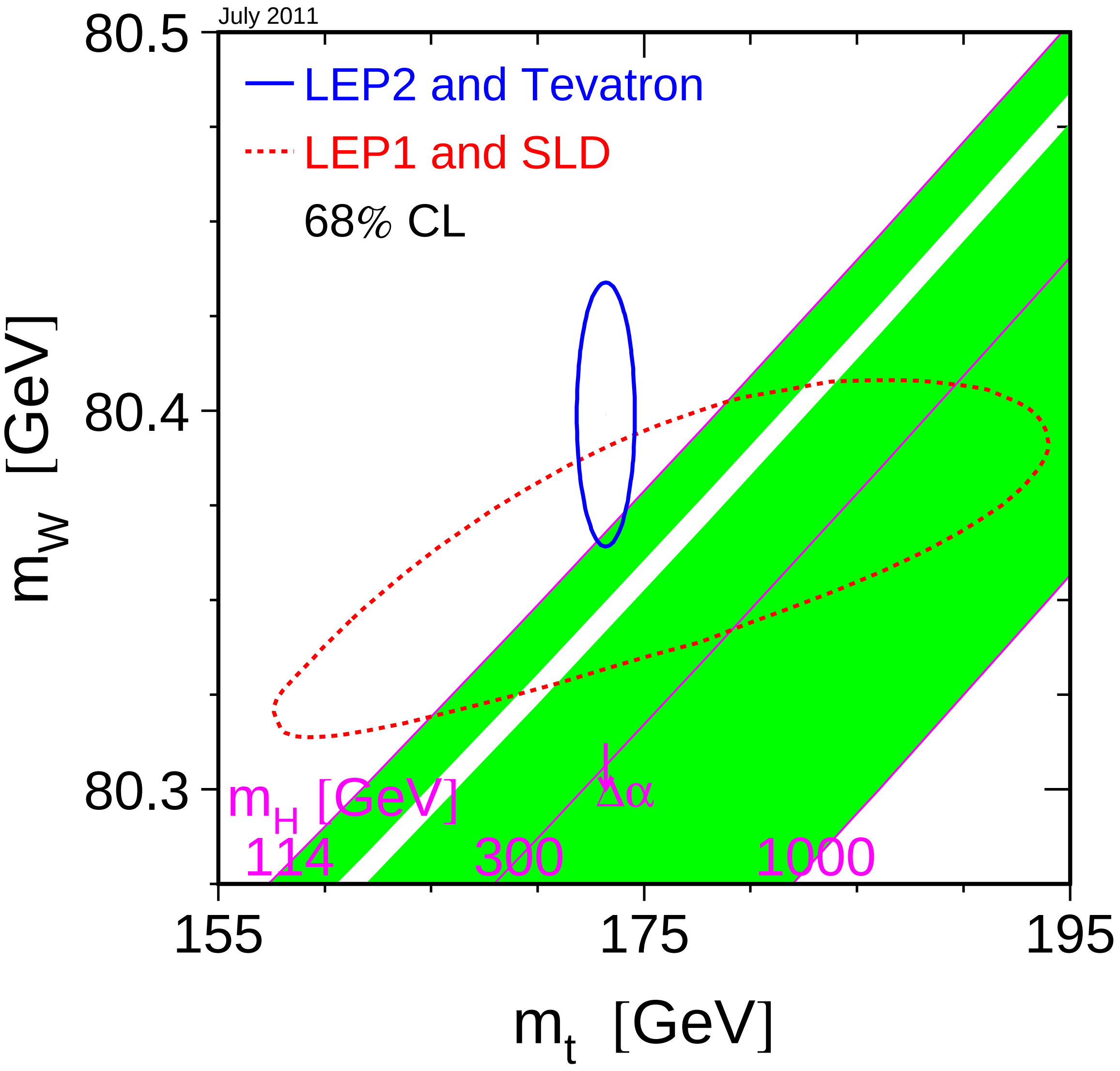
$$\Delta r = -\frac{11 g_2^2}{96\,\pi^2}\frac{s_W^2}{c_W^2}\log\left(\frac{M_H}{M_W}\right)$$

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

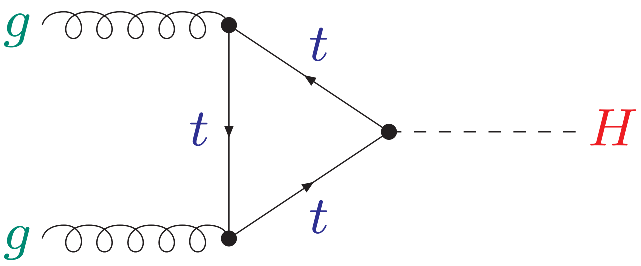
[*LEPEWWG '11*]

E) Most recent Higgs searches at the LHC

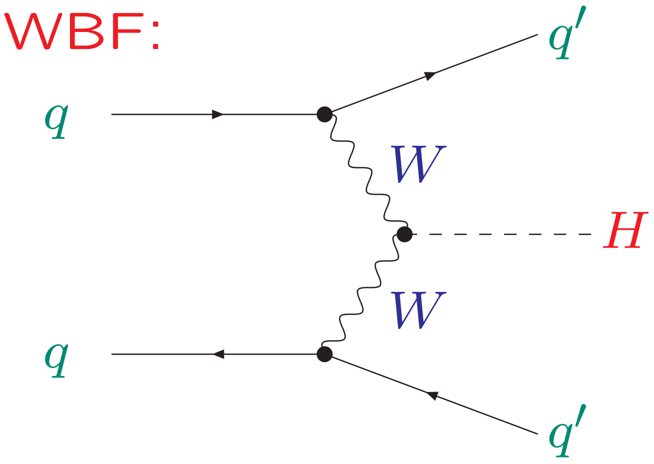
SM Higgs search at the LHC:

Important SM production channel at the LHC:

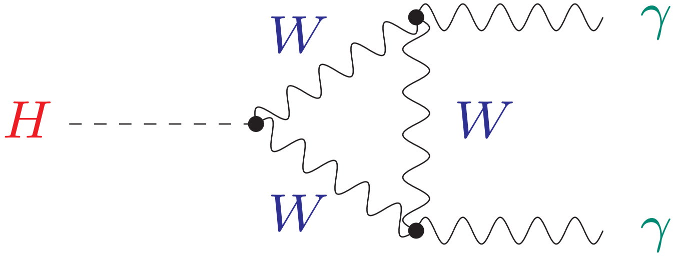
Gluon-Fusion:

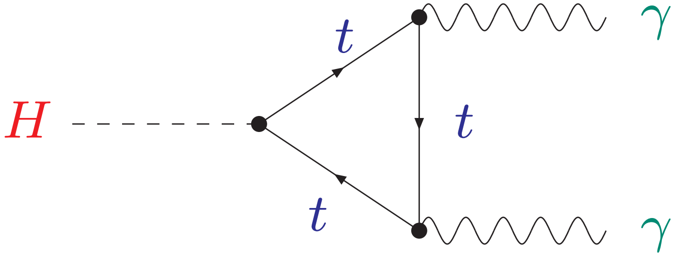


WBF:



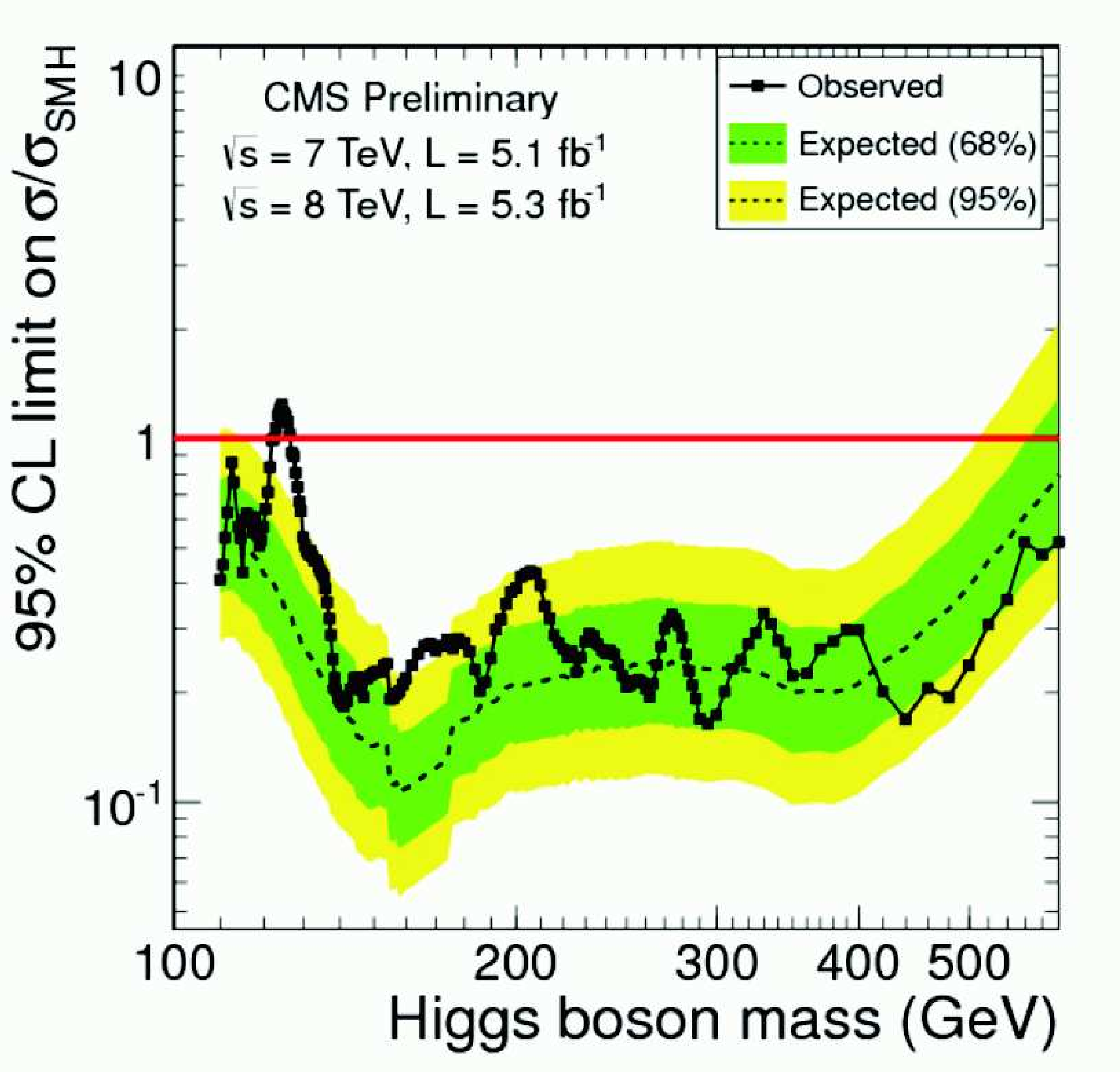
Important decay for Higgs mass measurement:





Latest CMS results in search for a SM Higgs:

[*CMS '12*]



⇒ clear excesses for around $M_H \simeq 125$ GeV

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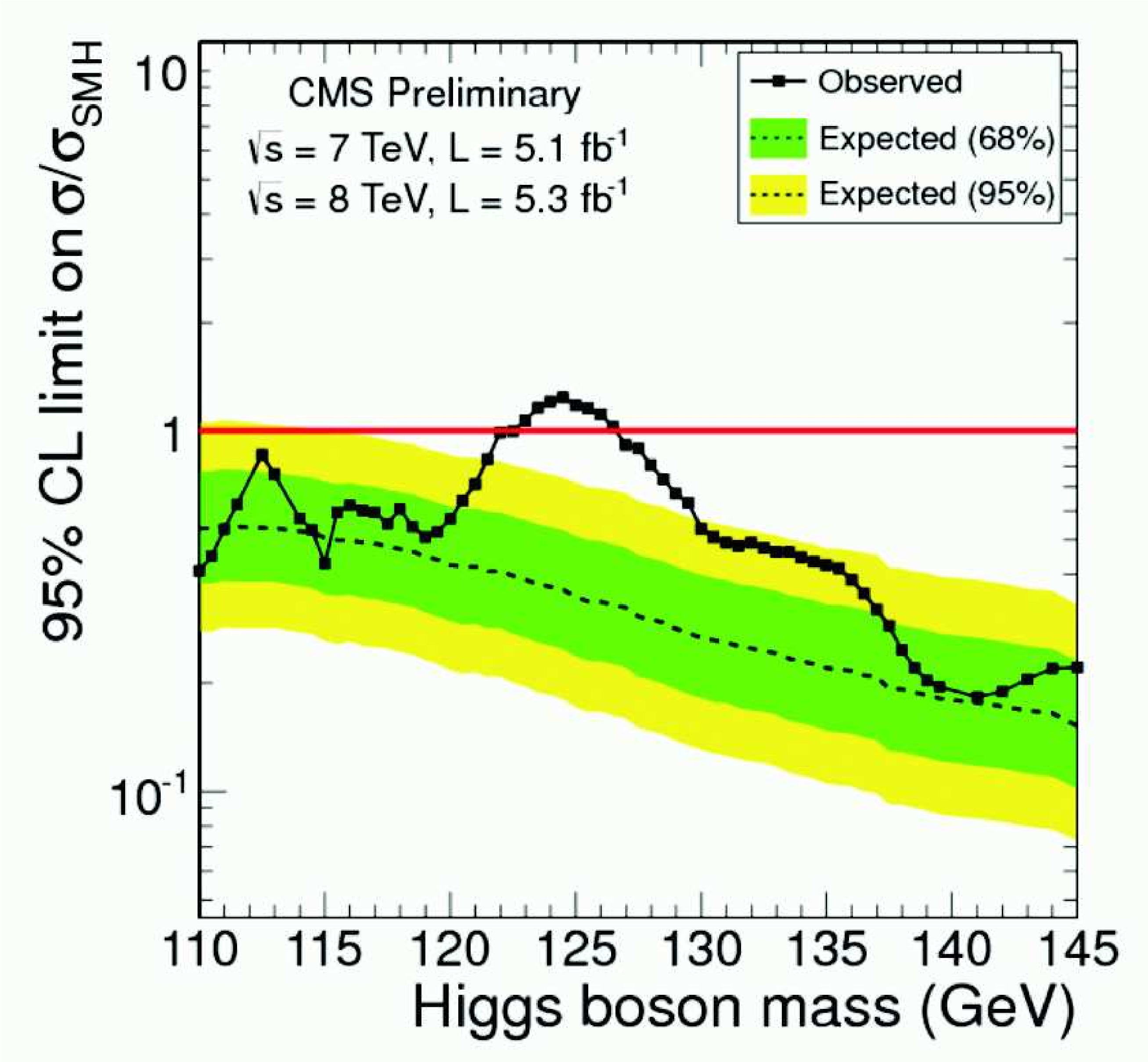

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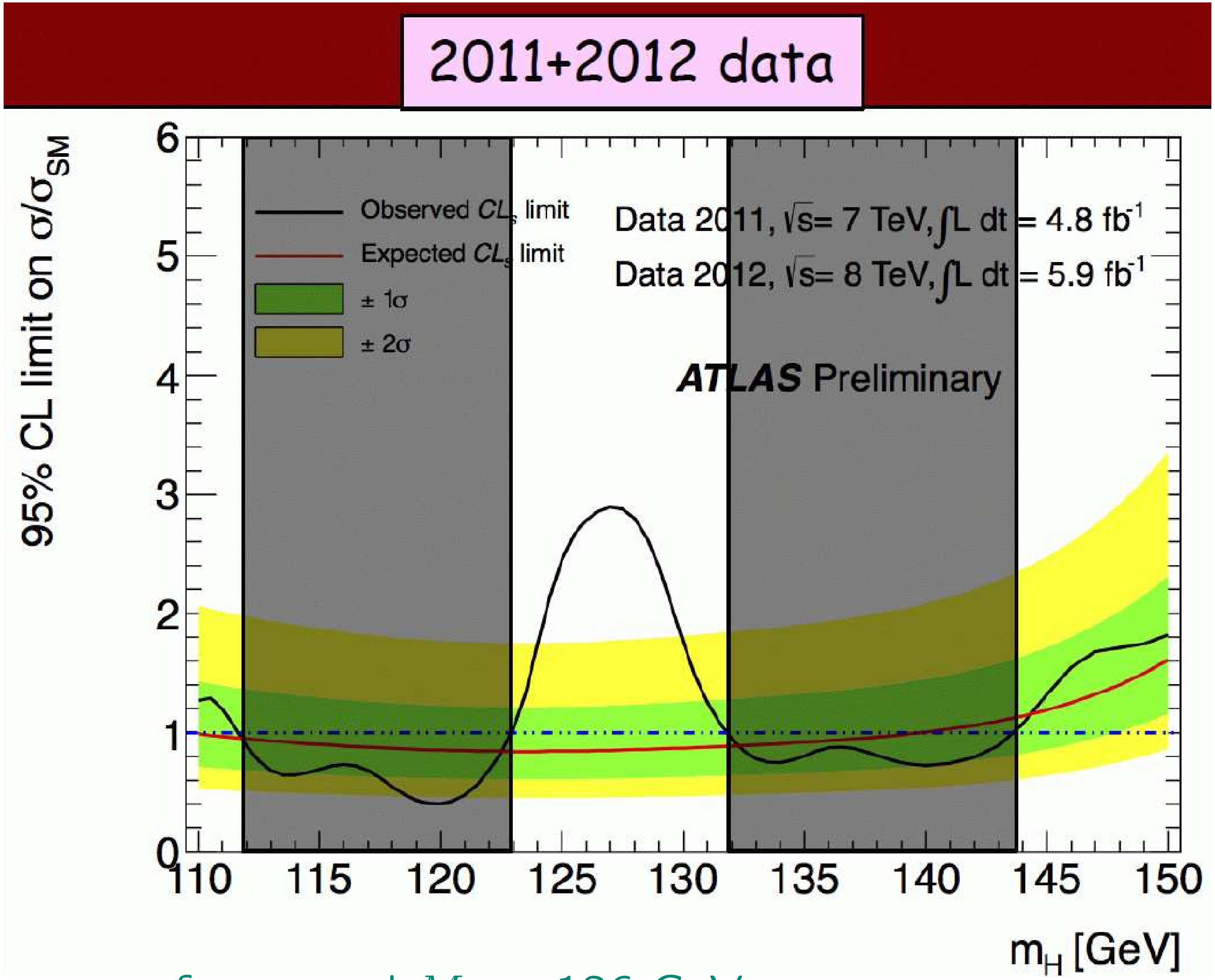
Latest ATLAS results in search for a SM Higgs in $\gamma\gamma$: [*ATLAS '12*]



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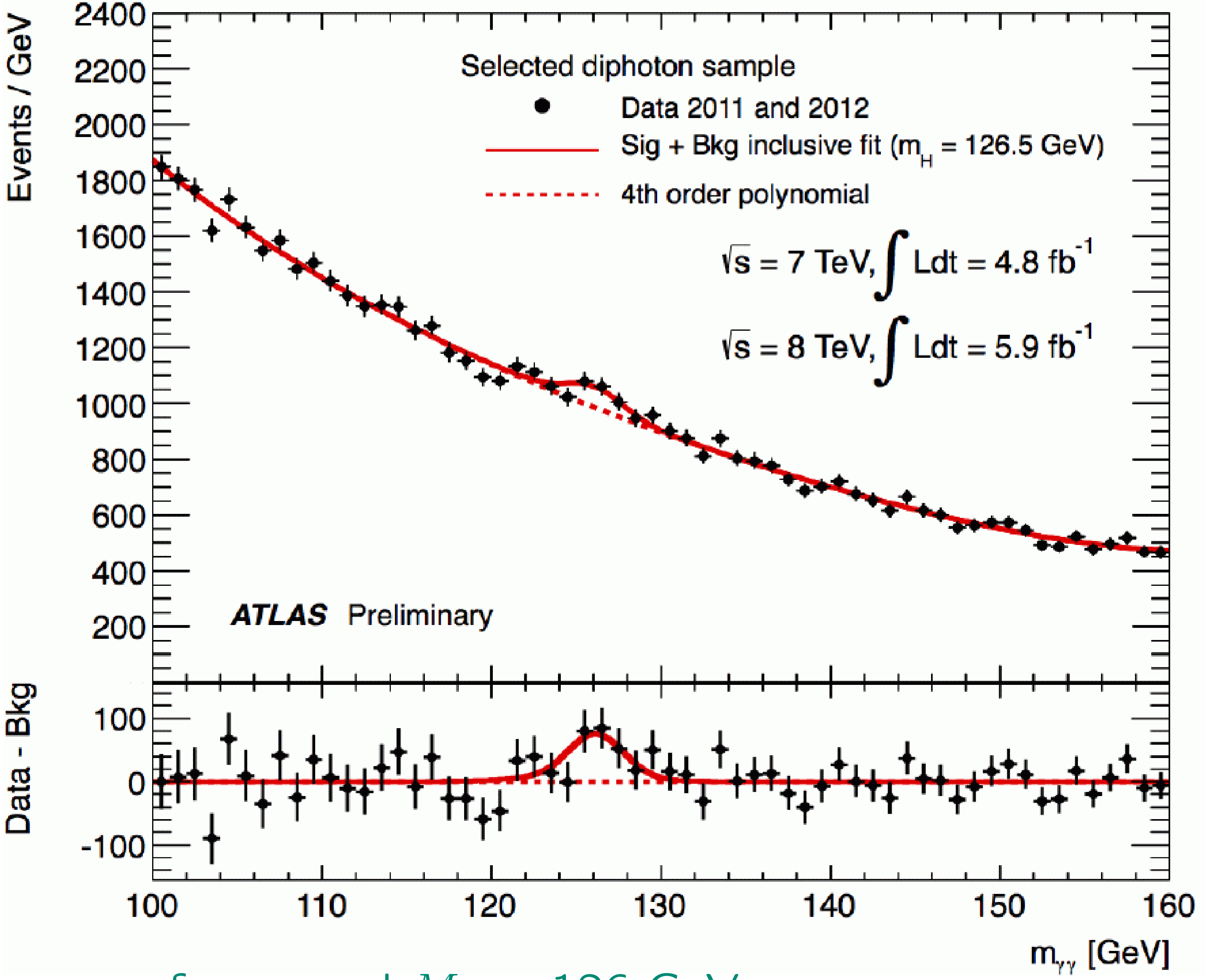
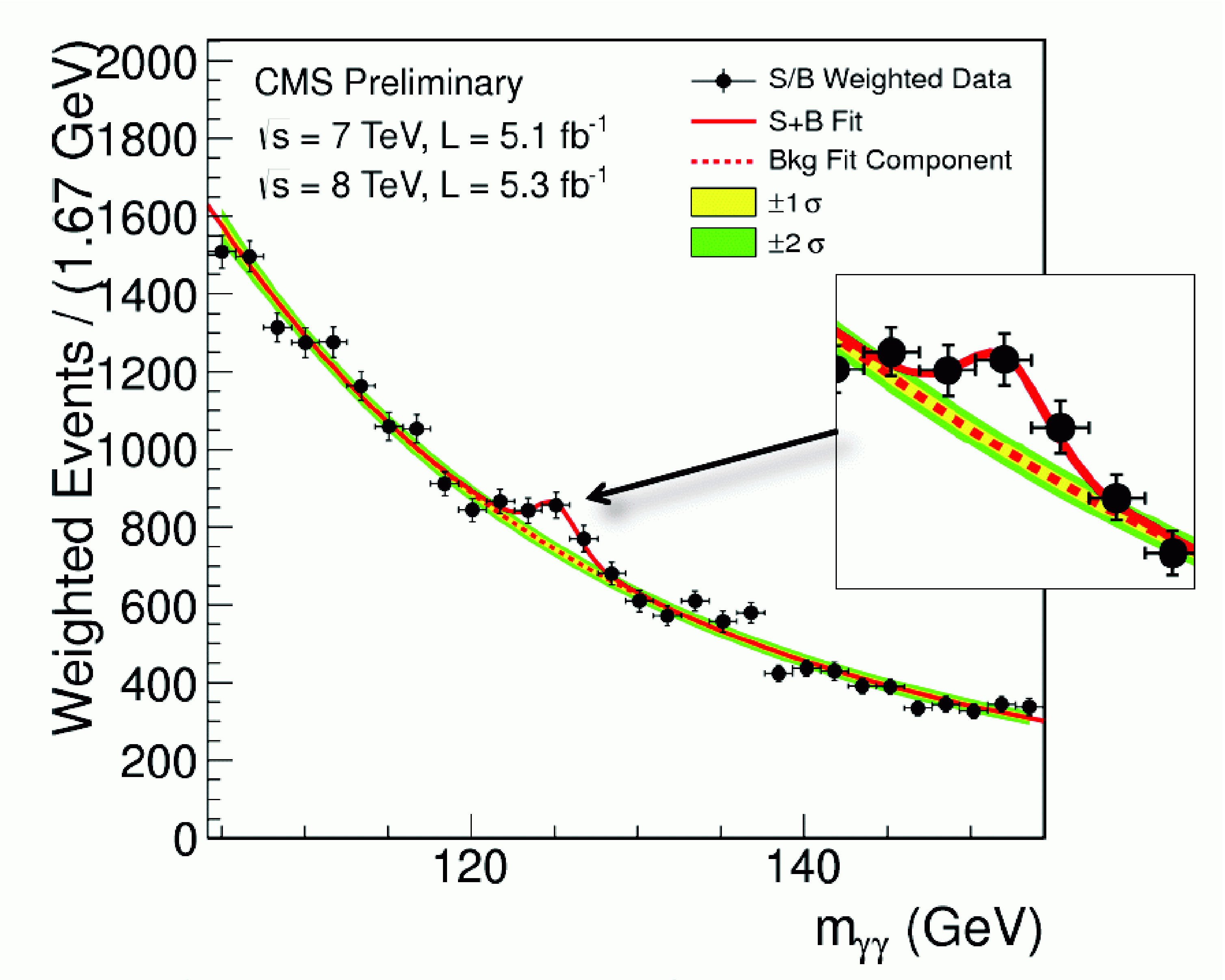


$\Rightarrow$ clear excesses for around $M_H \simeq 126$ GeV

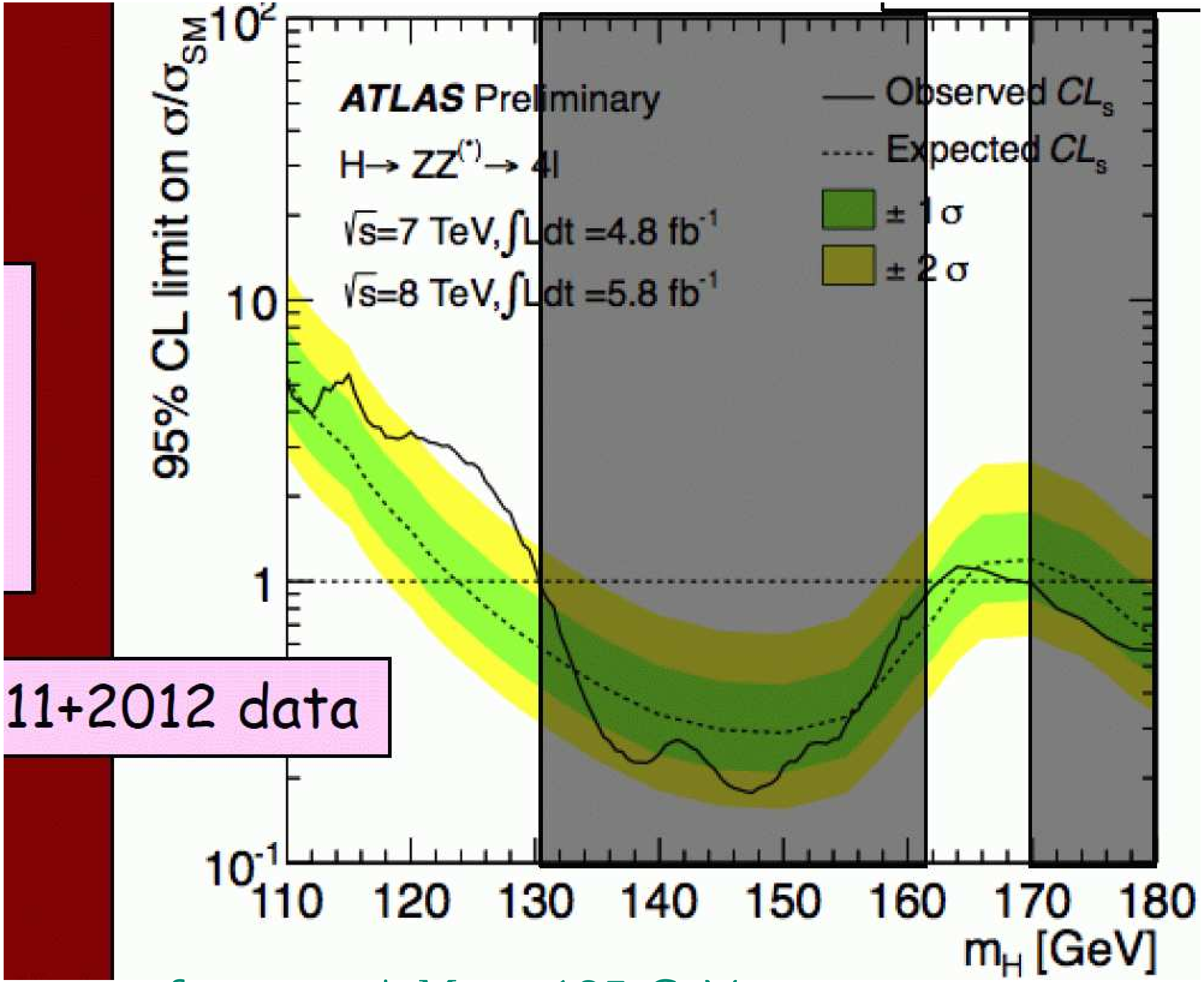
Latest CMS results in search for a SM Higgs in $\gamma\gamma$:

[*CMS '12*]



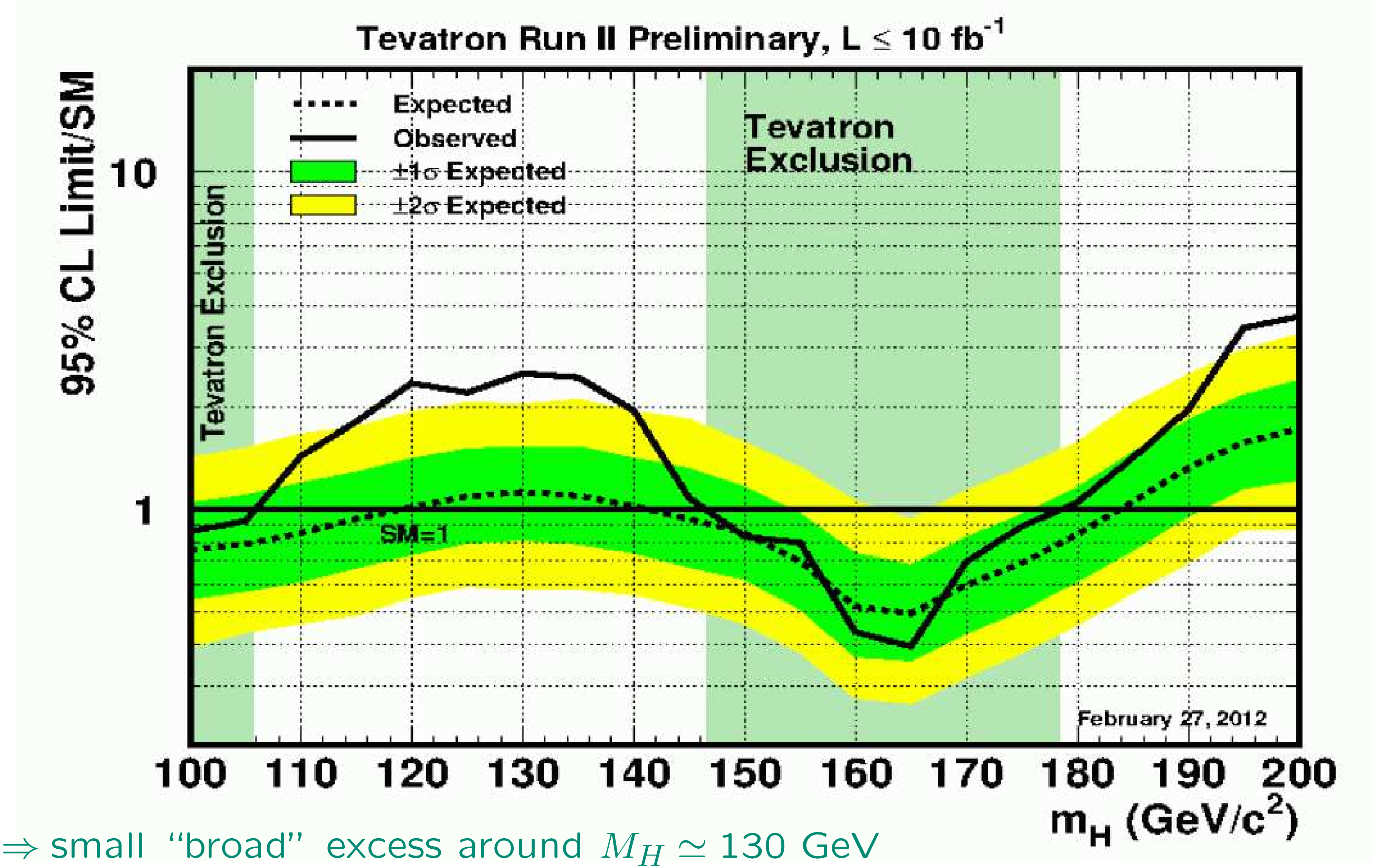
⇒ clear excesses for around $M_H \simeq 125$ GeV

Latest ATLAS results in search for a SM Higgs in ZZ^*: [ATLAS '12]



⇒ clear excesses for around $M_H \simeq 125$ GeV

Do not forget the final result of SM Higgs searches at the Tevatron:



⇒ small "broad" excess around $M_H \simeq 130$ GeV

Results for the combination of all experiments:

Results for the combination of all experiments:

Official combination does not exist :-(

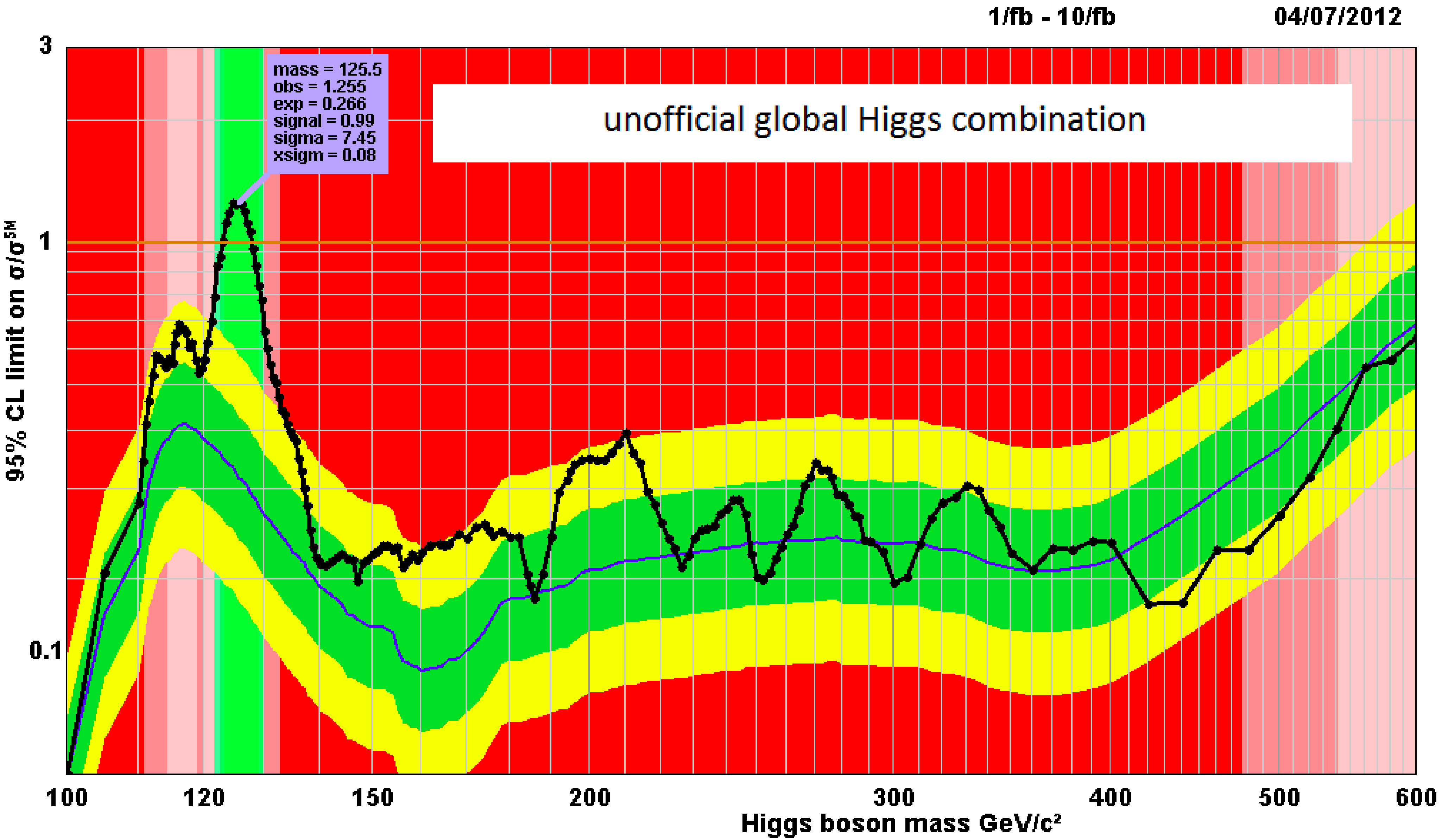
Results for the combination of all experiments:

Official combination does not exist :-(

However: unofficial combination exists . . .

Unofficial(!) LHC combination:

[*vixra.org*]

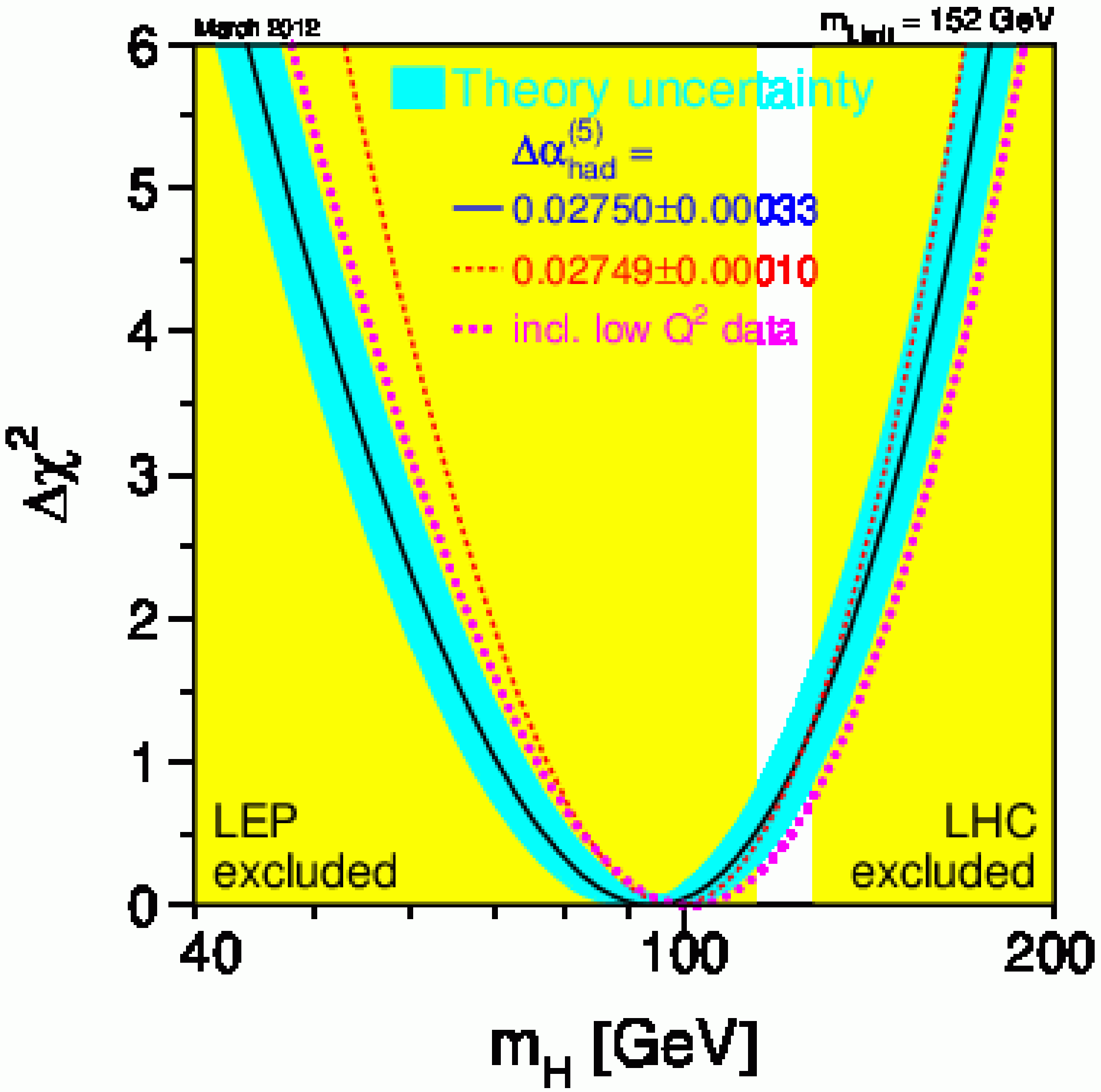


Comparison to SM prediction:

[*LEPEWWG '12*]

$\Rightarrow M_H = 94^{+29}_{-24}$ GeV

$M_H < 152$ GeV, 95% C.L.

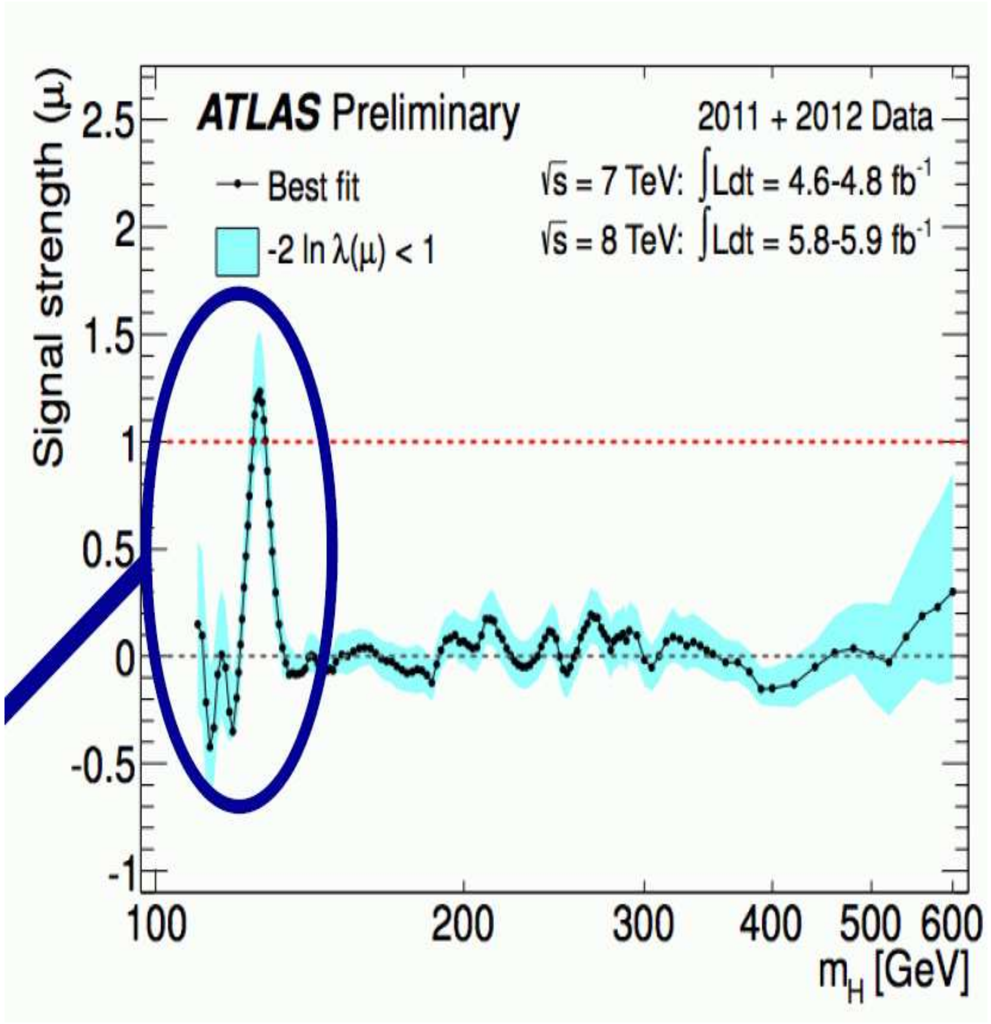


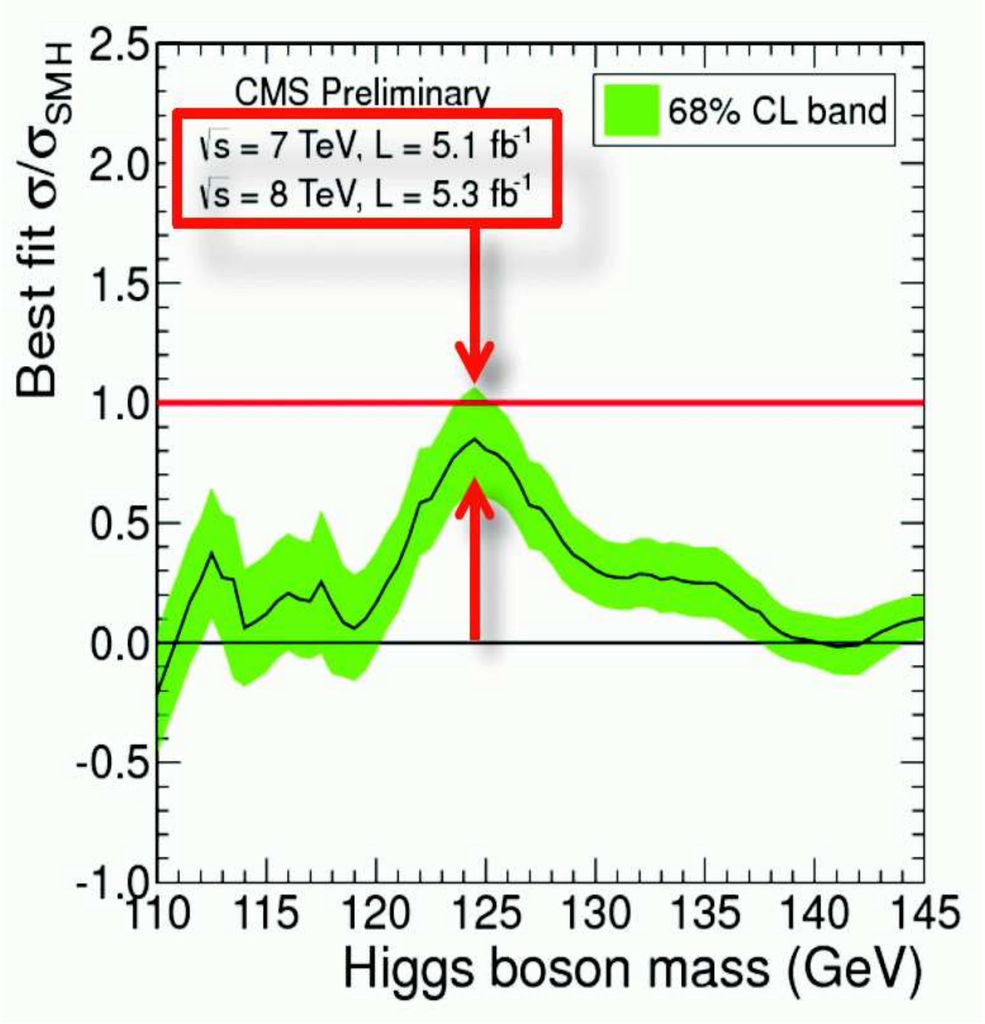
Assumption for the fit:
SM incl. Higgs boson

$\Rightarrow$ no confirmation of
Higgs mechanism

$\Rightarrow$ Observed excess well compatible with SM prediction

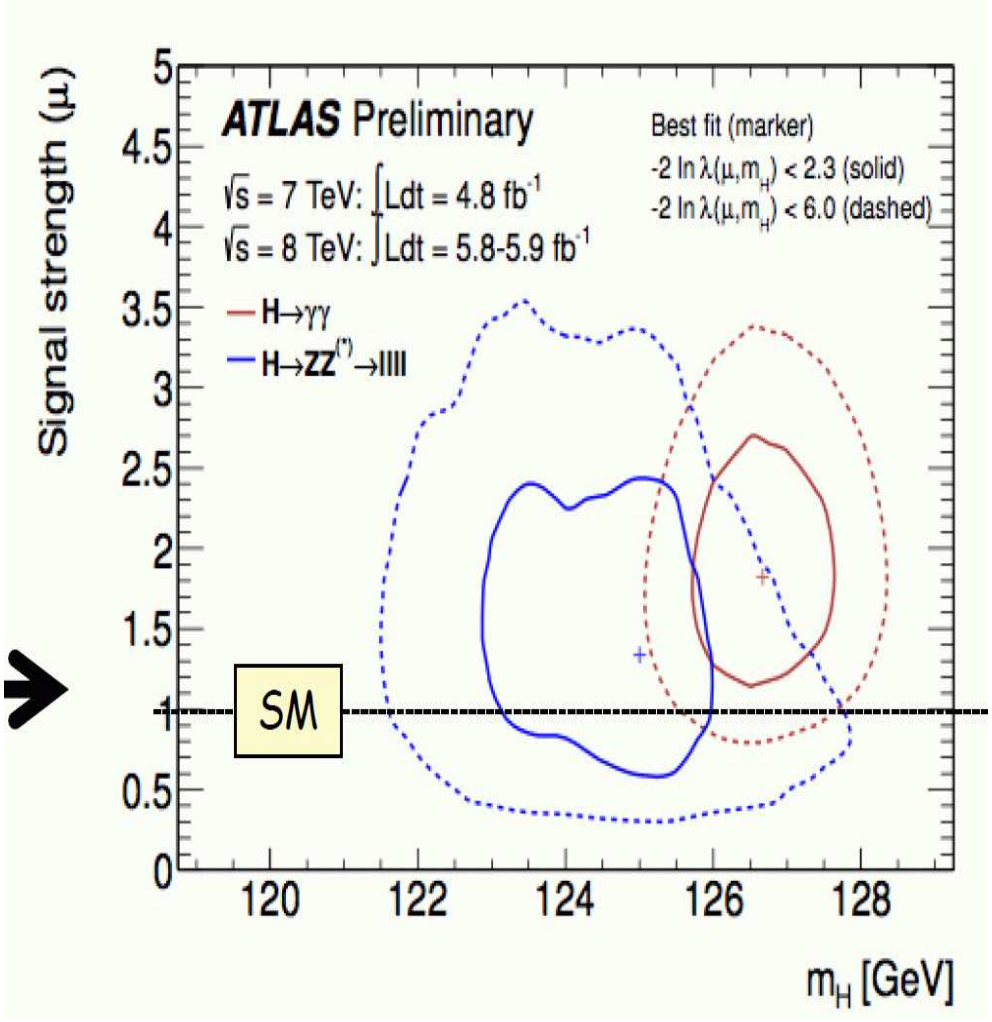
Towards a coupling measurement: signal strength:

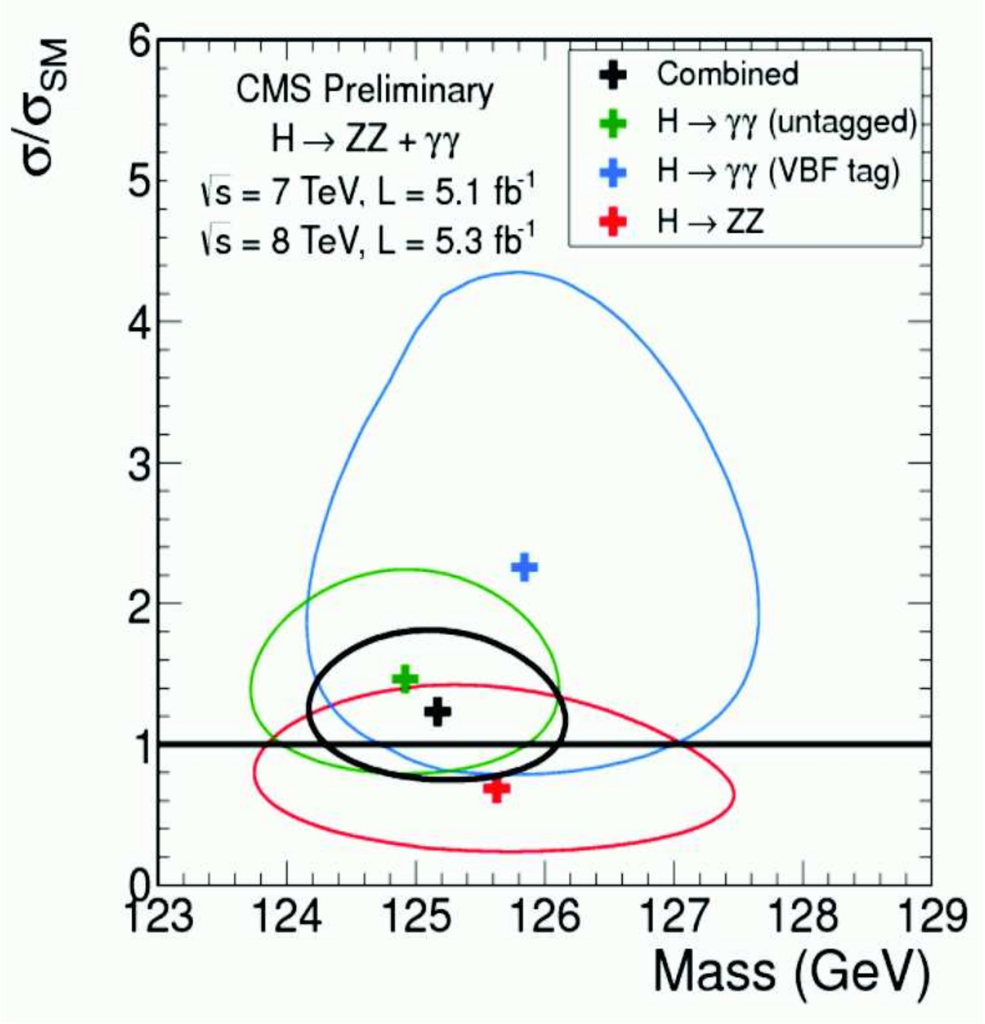




⇒ looks well compatible with the SM Higgs!

Towards a coupling measurement: signal strength vs. M_H:





⇒ looks well compatible with the SM Higgs!

Has the Higgs particle been discovered?

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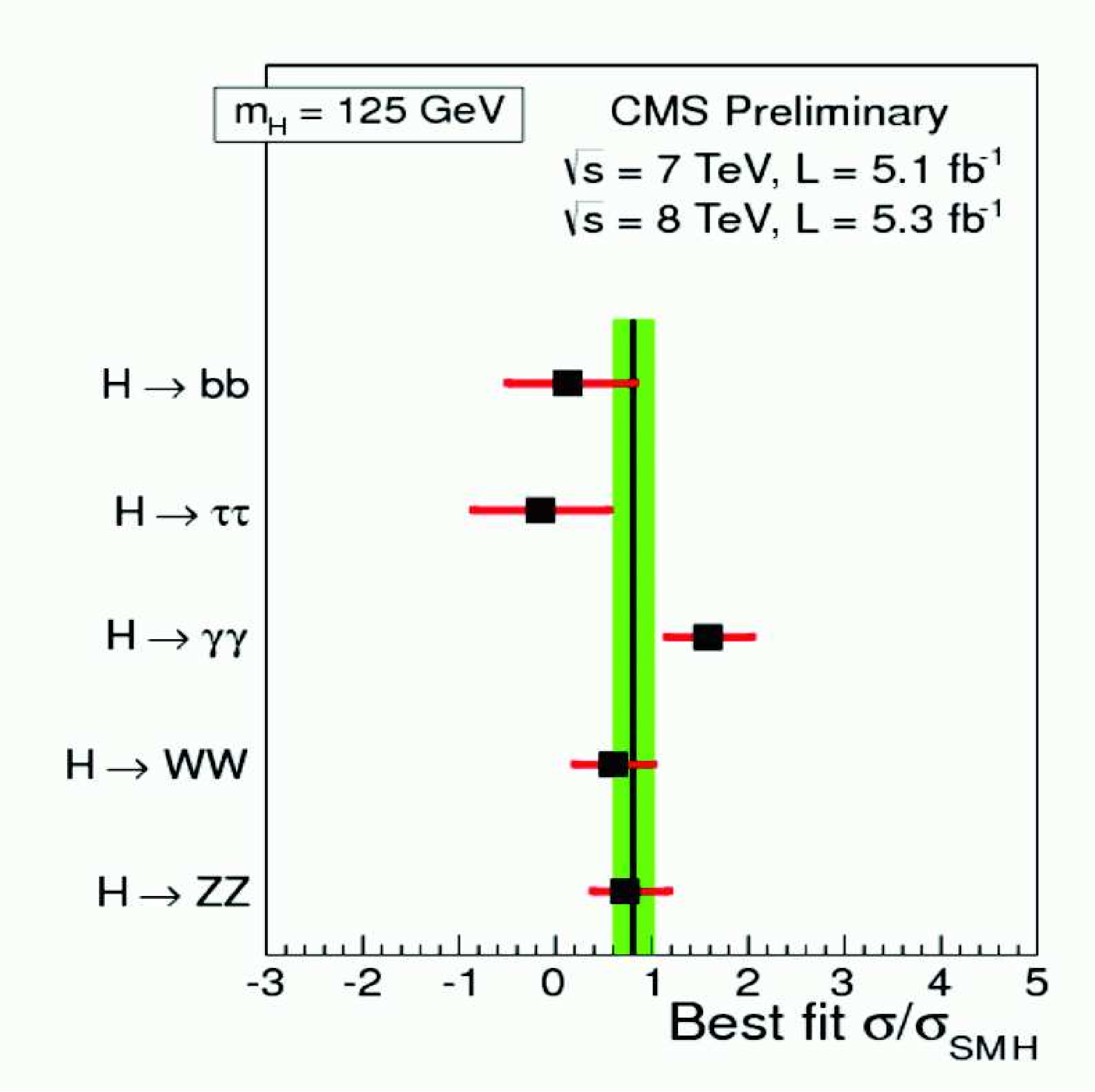
We have
discovered a new particle ,
which is compatible with the
predictions of the SM Higgs boson

How can we be sure about SM?
⇒ we have to measure
all its characteristics
– mass
– couplings to SM particles
– CP, quantum numbers, . . .

⇒ exploit the LHC!

⇒ move on to the ILC!



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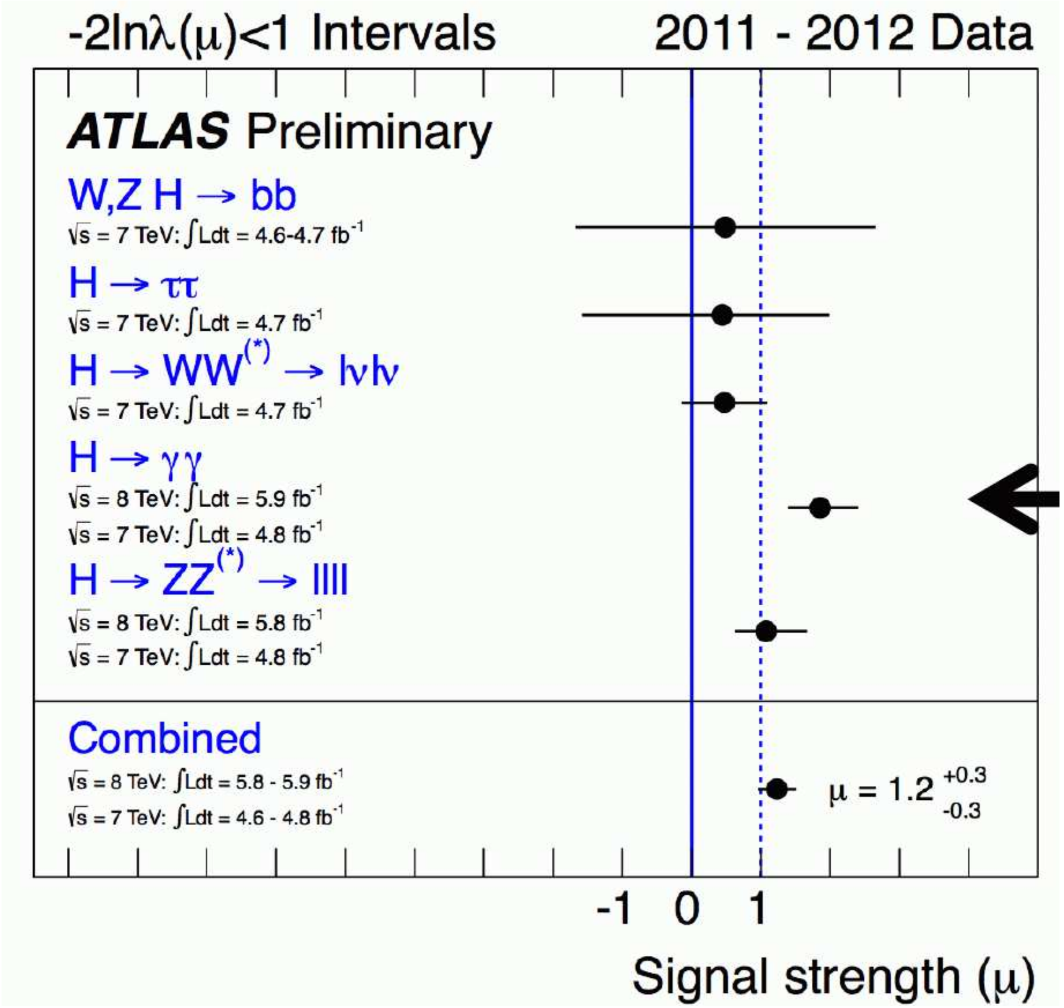


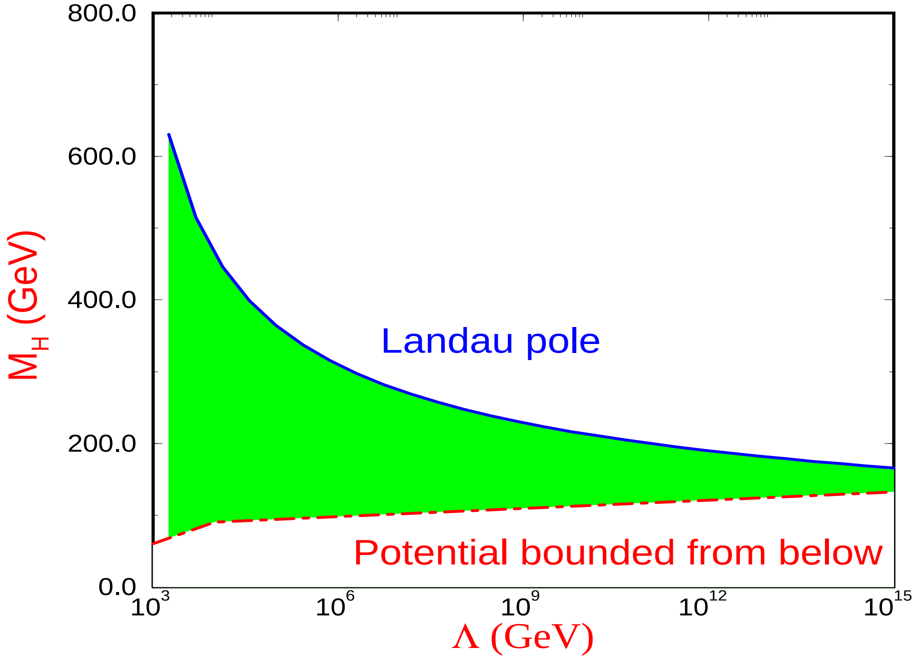
3. Supersymmetry and the cosmic connection:

The Standard Model (SM) cannot be the ultimate theory

- The SM does not contain gravity
- Further problems: Hierarchy problem
- And another one: SM does not provide Cold Dark Matter candidate

Up to which energy scale Λ can the SM be valid?

- $\Lambda < M_{\text{Pl}}$: inclusion of gravity effects necessary
- stability of Higgs potential: $\Rightarrow$
- Hierarchy problem : Higgs mass unstable w.r.t. quantum corrections $\delta M_H^2 \sim \Lambda^2$

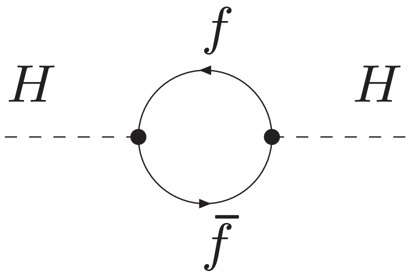


Mass is what determines the properties of the free propagation of a particle

Free propagation:

inverse propagator: $i(p^2 - M_H^2)$

Loop corrections:



inverse propagator: $i(p^2 - M_H^2 + \Sigma_H^f)$

QM: integration over all possible loop momenta k

dimensional analysis:

$$\Sigma_H^f \sim N_f \, \lambda_f^2 \int d^4k \left(\frac{1}{k^2 - m_f^2} + \frac{2m_f^2}{(k^2 - m_f^2)^2} \right)$$

for $\Lambda \to \infty$:

$$\Sigma_H^f \sim N_f \, \lambda_f^2 \left(\underbrace{\int \frac{d^4k}{k^2}}_{\sim \Lambda^2} + 2m_\mathrm{f}^2 \underbrace{\int \frac{dk}{k}}_{\sim \ln \Lambda} \right)$$

⇒ quadratically divergent!

For $\Lambda = M_{\mathrm{Pl}}$:

$$\Sigma_H^f \approx \delta M_H^2 \sim M_{\mathrm{Pl}}^2 \quad \Rightarrow \quad \delta M_H^2 \approx 10^{30}\, M_H^2$$

(for $M_H \lesssim 1$ TeV)

– no additional symmetry for $M_H = 0$

– no protection against large corrections

⇒ Hierarchy problem is instability of small Higgs mass to large corrections in a theory with a large mass scale in addition to the weak scale

E.g.: Grand Unified Theory (GUT): $\delta M_H^2 \approx M_{\mathrm{GUT}}^2$

Note however: there is another fine-tuning problem in nature, for which we have no clue so far – cosmological constant

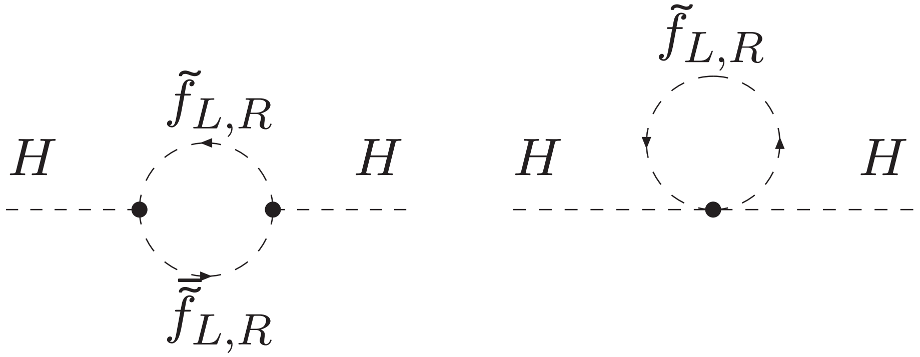
Supersymmetry:

Symmetry between fermions and bosons

$$\begin{aligned} Q|\text{boson}\rangle &= |\text{fermion}\rangle \\ Q|\text{fermion}\rangle &= |\text{boson}\rangle \end{aligned}$$

Effectively: SM particles have SUSY partners (e.g. $f_{L,R} \to \tilde f_{L,R}$)

SUSY: additional contributions from scalar fields:



$$\Sigma_H^{\tilde f} \sim \; N_{\tilde f}\, \lambda_{\tilde f}^2 \int d^4k \left(\frac{1}{k^2 - m_{\tilde f_L}^2} + \frac{1}{k^2 - m_{\tilde f_R}^2} \right) + \text{ terms without quadratic div.}$$

for $\Lambda \to \infty$: $\quad \Sigma_H^{\tilde f} \sim N_{\tilde f}\, \lambda_{\tilde f}^2\, \Lambda^2$

⇒ quadratic divergences cancel for

$$\begin{aligned} N_{\tilde f_L} = N_{\tilde f_R} &= N_f \\ \lambda^2_{\tilde f} &= \lambda^2_f \end{aligned}$$

complete correction vanishes if furthermore

$$m_{\tilde f} = m_f$$

Soft SUSY breaking: $m^2_{\tilde f} = m^2_f + \Delta^2, \quad \lambda^2_{\tilde f} = \lambda^2_f$

$$\Rightarrow \; \Sigma_H^{f+\tilde f} \sim N_f \, \lambda^2_f \, \Delta^2 + \ldots$$

⇒ correction stays acceptably small if mass splitting is of weak scale

⇒ realized if mass scale of SUSY partners

$$M_{\text{SUSY}} \lesssim 1\,\text{TeV}$$

⇒ SUSY at TeV scale provides attractive solution of hierarchy problem

Physics beyond the SM:

Interesting (new) physics models :

- 2HDM:
  - two Higgs doublets more natural than one
- MSSM:
  - solves hierarchy problem
  - automatic electroweak symmetry breaking
  - gauge coupling unification
  - cold dark matter candidate
- Little Higgs:
  - (partially) solves the hierarchy problem
  - cold dark matter candidate
- Extra dimensions:
  - solves the hierarchy problem
  - cold dark matter candidate
- . . .

⇒ pick your favorite model now (I pick the MSSM)

Supersymmetry:

Symmetry between

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

$$\begin{aligned} Q\ |\text{Fermion}\rangle &\rightarrow |\text{Boson}\rangle \\ Q\ |\text{Boson}\rangle &\rightarrow |\text{Fermion}\rangle \end{aligned}$$

Simplified examples:

$$\begin{aligned} Q\ |\text{top},\ t\rangle &\rightarrow |\text{scalar top},\ \tilde{t}\rangle \\ Q\ |\text{gluon},\ g\rangle &\rightarrow |\text{gluino},\ \tilde{g}\rangle \end{aligned}$$

⇒ 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.

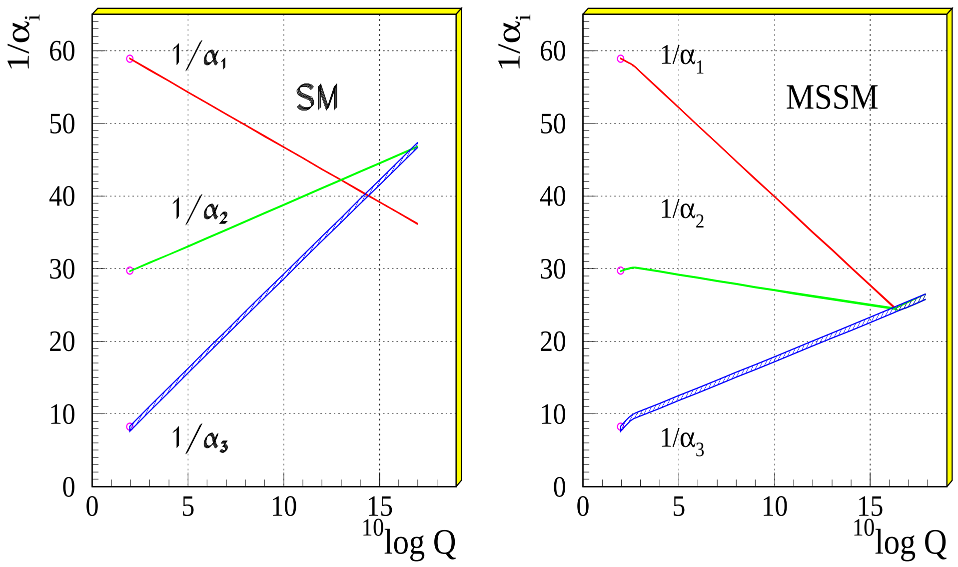
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)

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]

The Minimal Supersymmetric Standard Model (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: Two Higgs doublets

Problem in the MSSM: more than 100 free parameters

Nobody(?) believes that a model describing nature
has so many free parameters!

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

⇒ all new low-energy parameters expressed through a few GUT scale parameters!

GUT based models: 1.) CMSSM (sometimes wrongly called mSUGRA):

⇒ Scenario characterized by

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

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

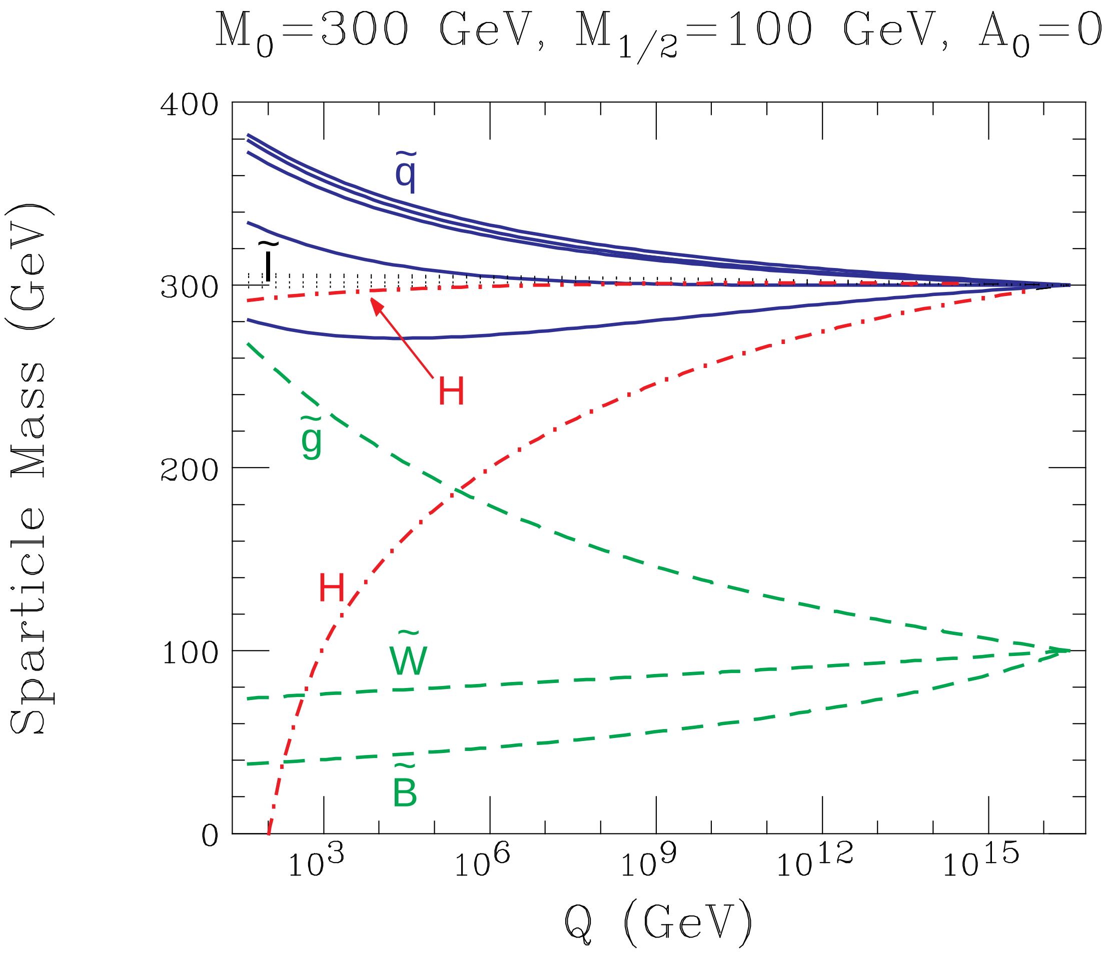
$\tan\beta$: ratio of Higgs vacuum expectation values

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

⇒ Lightest SUSY particle (LSP) is the lightest neutralino

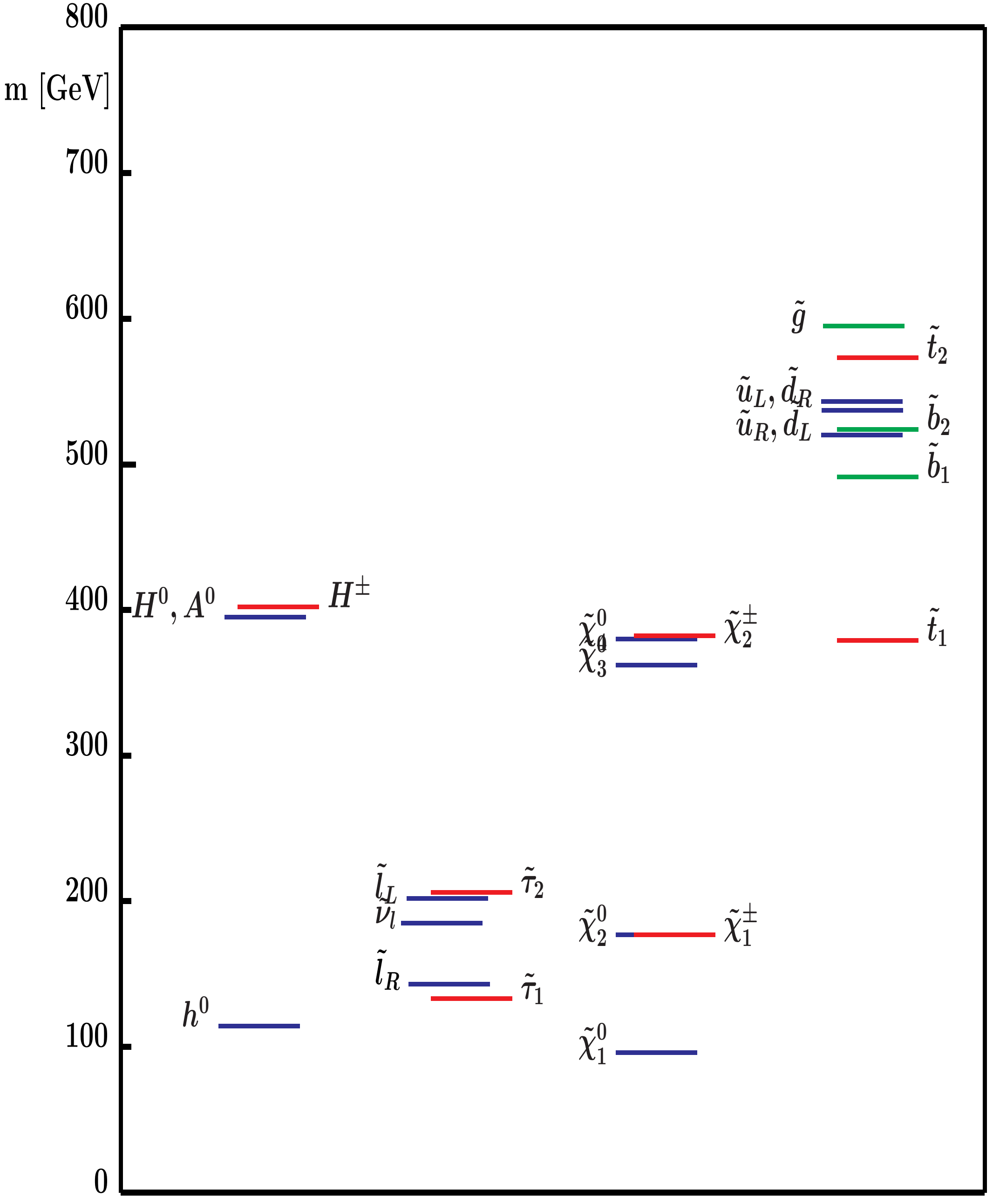
⇒ particle spectra from renormalization group running to weak scale



⇒ one parameter turns negative ⇒ Higgs mechanism for free

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

Strong connection between all the sectors



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

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

⇒ effectively M_A or μ as free parameters at the EW scale

⇒ besides the CMSSM parameters

M_A or μ

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

. . . no time here . . .

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

$\Rightarrow$ rapid proton decay

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

$\Rightarrow$ additional symmetry: “R parity”

$\Rightarrow$ all SM particles have even R parity, all SUSY particles have odd R parity

R-parity ⇒ 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, $P_R = -1$

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

⇒ 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 ⇒ leaves no traces in collider detectors

⇒ Typical SUSY signatures: “missing energy”

⇒ prediction for collider phenomenology!

Cold Dark Matter

Cold Dark Matter exists:

⇒ It all fits together

$$\Omega_{\rm tot} \approx 1$$

$$\Omega_M h^2 = 0.135^{+0.008}_{-0.009}$$

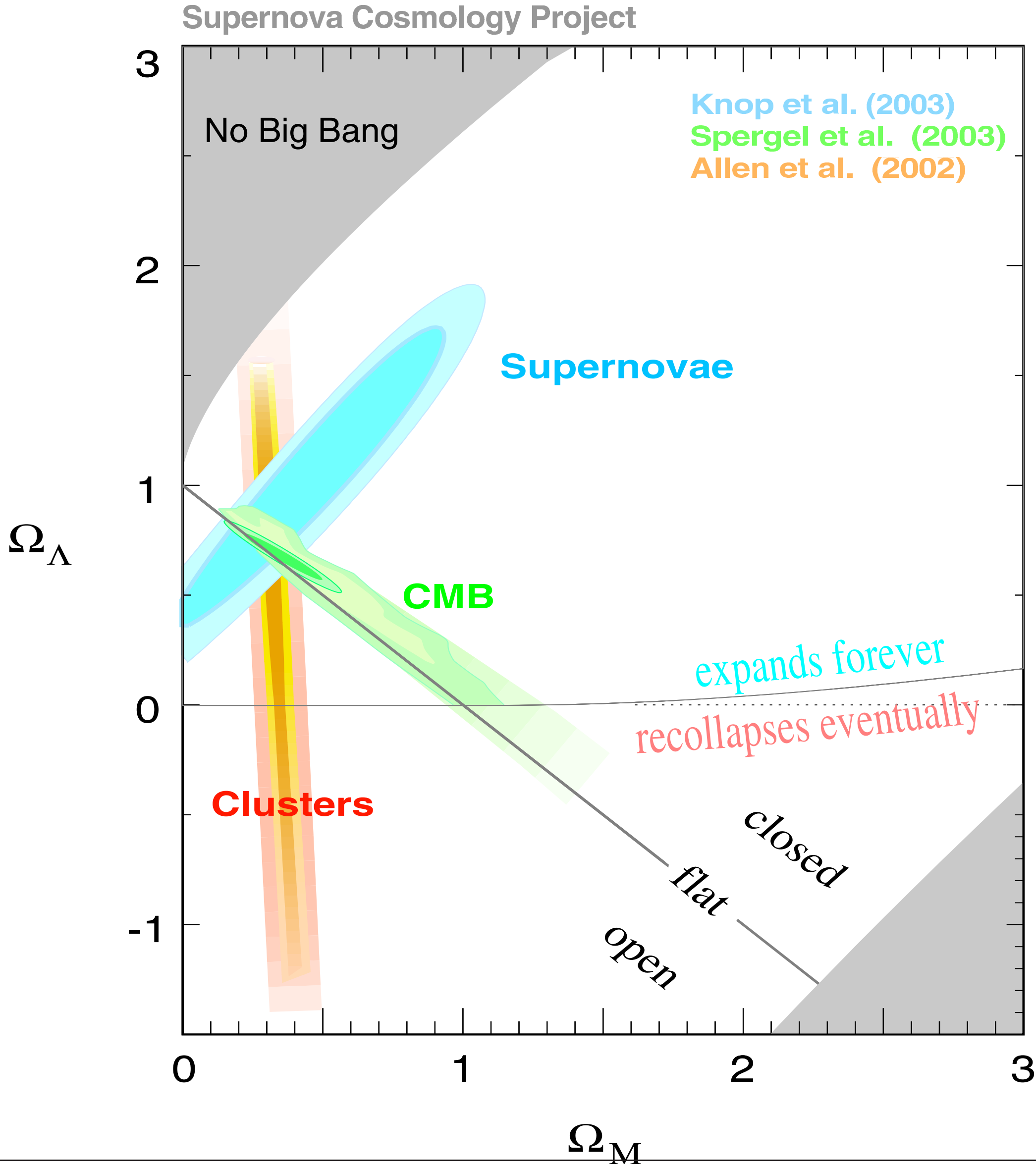
$$\Omega_B h^2 = 0.0224 \pm 0.0009$$

$$\Omega_\chi h^2 = 0.112 \pm 0.018$$

$$\Omega_\Lambda \approx 0.73$$

Ω_χ ⇒ dark matter

Ω_Λ ⇒ dark energy . . .



Dark Matter in the CMSSM parameter space:

schematic picture

$(0.1 \leq \Omega_\chi h^2 \leq 0.3)$

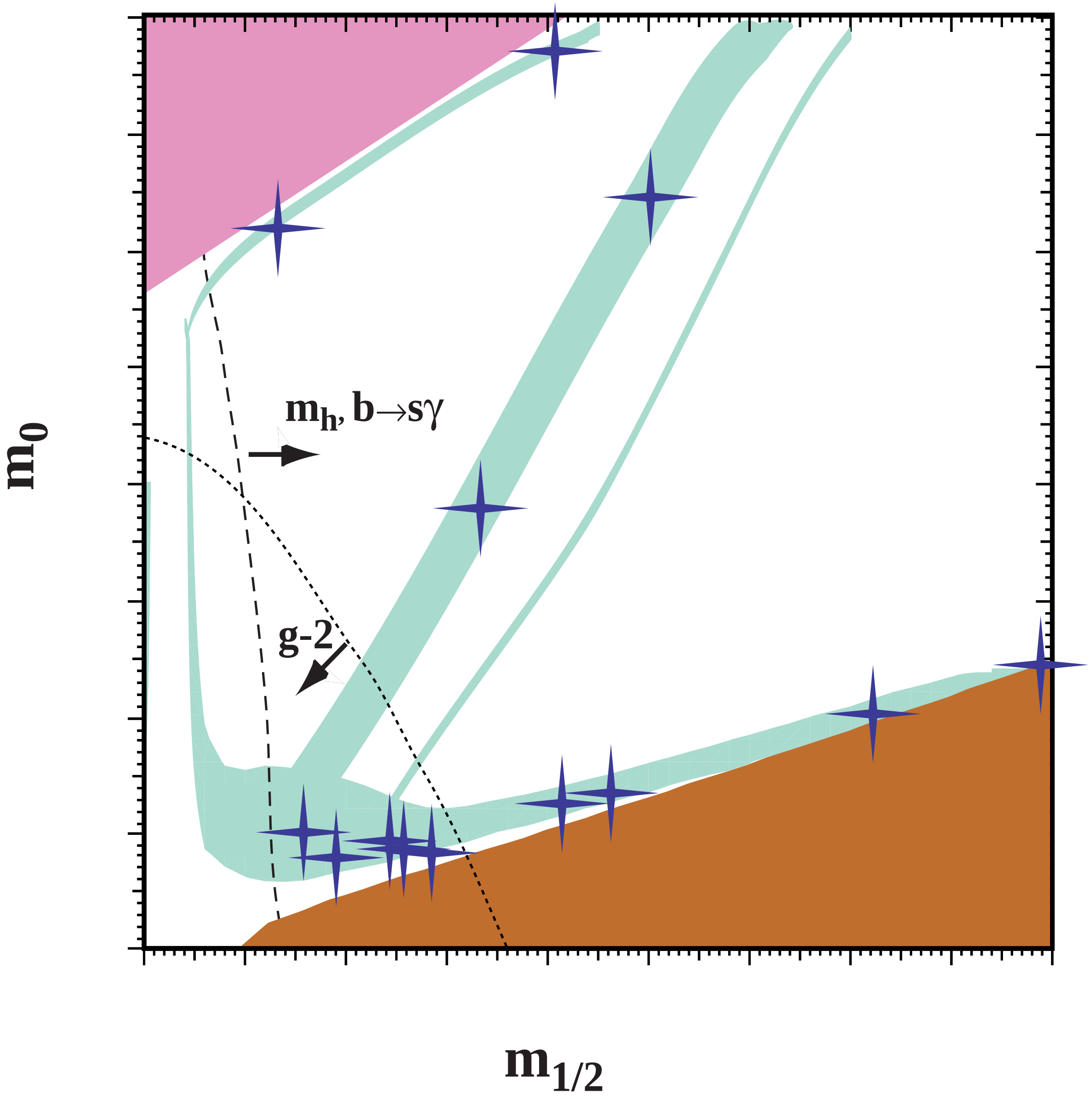
[*K. Olive et al. '02*]

Despite its simplicity CMSSM fulfils all experimental bounds

Four mechanisms for "good" $\langle \sigma\, v \rangle$:

- Bulk
- Stau coannihilation
- Higgs-pole annihilation
- Focus-Point

crosses: benchmark points



4. SUSY Higgs bosons and the LHC

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 $\Rightarrow m_h \leq M_Z$

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

Input parameters: (to be determined experimentally)

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

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

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

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:

$$M_{\text{Higgs}}^{2,\text{tree}} = \begin{pmatrix} m_{\phi_1}^2 & m_{\phi_1\phi_2}^2 \\ m_{\phi_1\phi_2}^2 & m_{\phi_2}^2 \end{pmatrix} =$$

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

$$\Big\Downarrow \leftarrow \text{Diagonalization}, \alpha$$

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

Tree-level result for m_h, m_H:

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

⇒ $m_h \leq M_Z$ at tree level

⇒ Light Higgs boson h required in SUSY

Measurement of m_h, Higgs couplings

⇒ test of the theory (more directly than in SM)

Higgs couplings, tree level:

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

$\Rightarrow$ $g_{hVV} \le g_{HVV}^{\text{SM}}$, 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

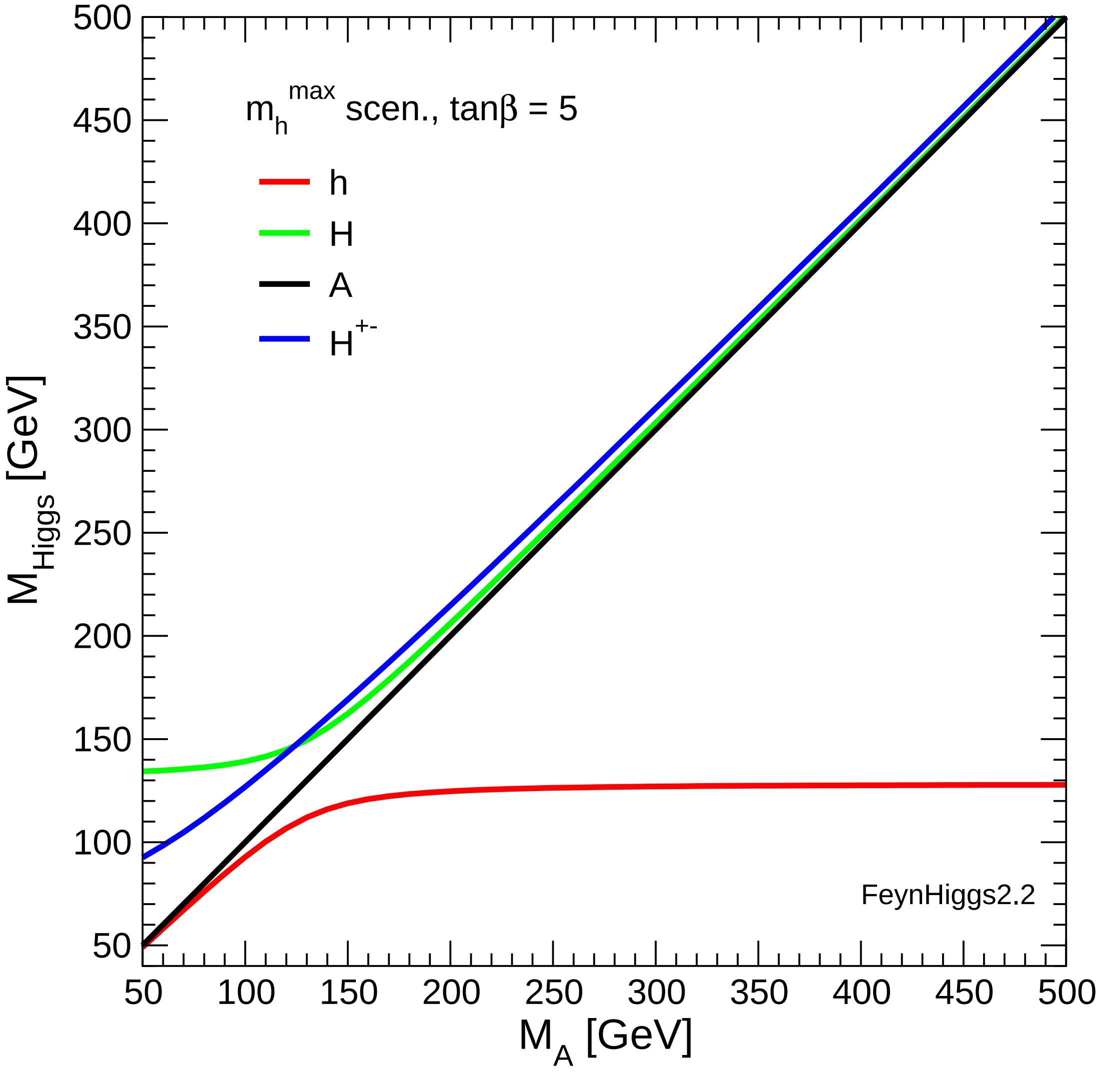
⇒ SM analysis applies!

The heavy MSSM Higgses:

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

→ coupling to gauge bosons ∼ 0

⇒ no decay $H \to WW^{(*)}$, . . .



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: → excursion

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

⇒ 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

What is a mass

Definition: The mass of a particle is the pole of the propagator

Example: scalar particle

Propagator:

$$\frac{i}{q^2 - m^2}$$

q^2 : four-momentum squared
m^2: constant in the Lagrangian

If one chooses $q^2 = m^2$ then the propagator has a pole.
This q^2 is then the mass of the particle.

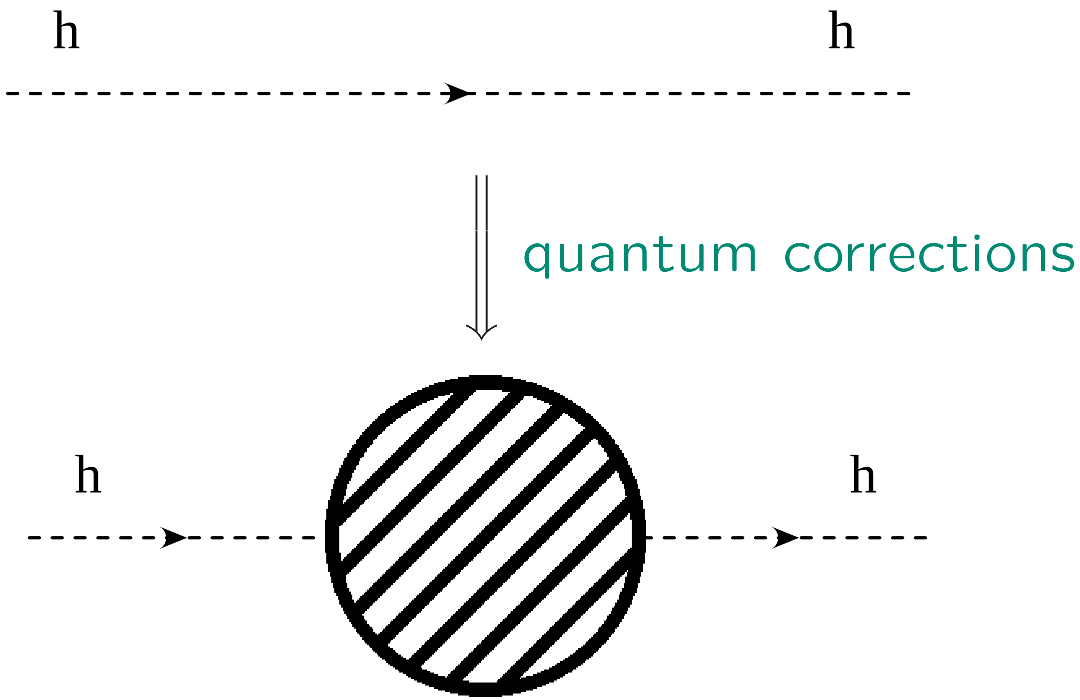
⇒ Pole of the propagator corresponds to zeroth of the inverse propagator.

Inverse propagator:

$$-i(q^2 - m^2)$$

Problem: quantum corrections

Higgs propagator:



quantum corrections

Inverse propagator:

$$-i(q^2 - m^2) \quad \longrightarrow \quad -i\left(q^2 - m^2 + \hat{\Sigma}_h(q^2)\right)$$

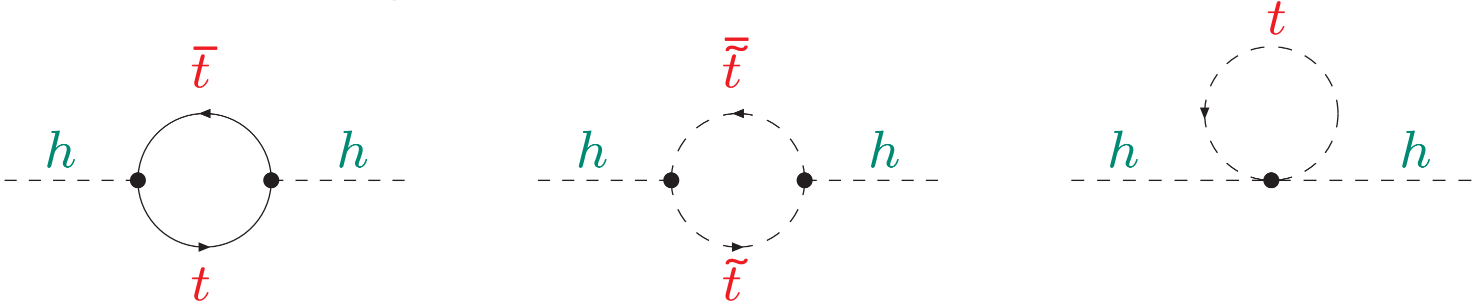
$\hat{\Sigma}_h(q^2)$: renormalized Higgs self-energy

Calculation of the blob:

▨ $= \hat{\Sigma}(q^2) = \hat{\Sigma}^{(1)}(q^2) + \hat{\Sigma}^{(2)}(q^2) + \dots$

▨ : all MSSM particles contribute
main contribution: $t/\tilde{t}$ sector ($\tilde{t}$: scalar top, SUSY partner of the t)

1-Loop: Feynman diagrams:



Dominant 1-loop corrections: $\Delta m_h^2 \sim G_\mu m_t^4 \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$

size of the corrections: $\mathcal{O}$(50 GeV)

⇒ 2-Loop calculation necessary!

2-loop: $\hat{\Sigma}^{(2)}(0)$

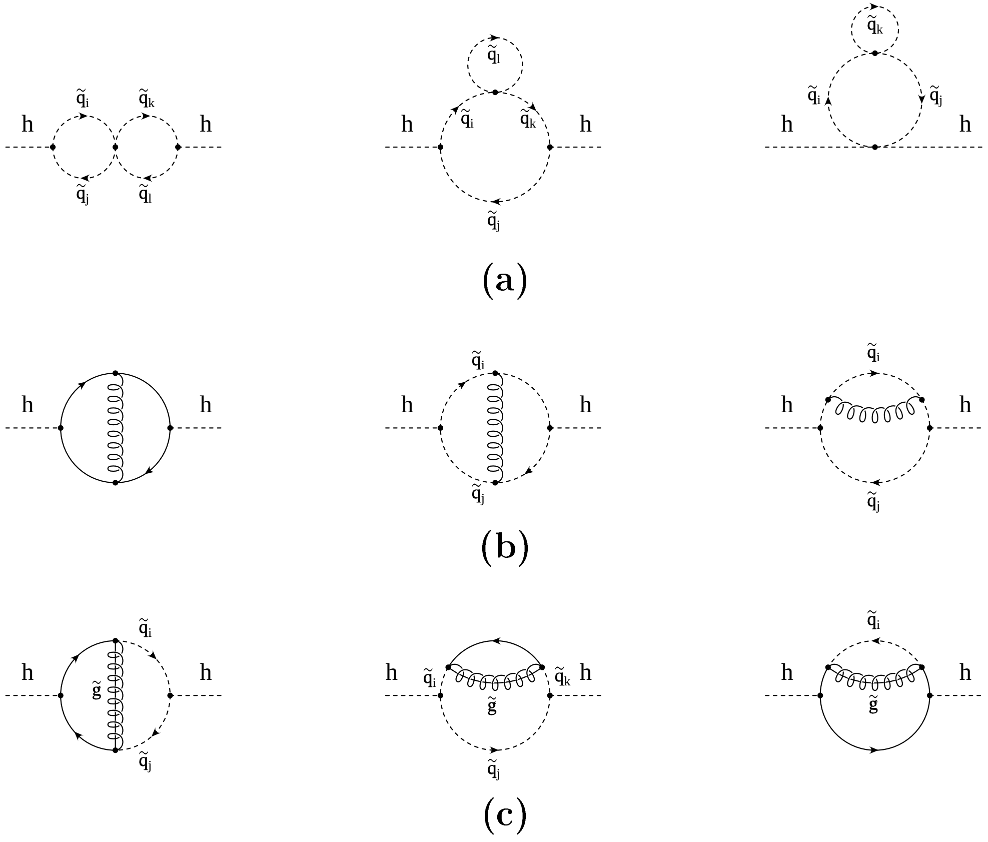
[S. H., W. Hollik, G. Weiglein '98]

dominant contributions of $\mathcal{O}(\alpha_t \alpha_s)$:

(a) pure scalar diagrams
(b) diagrams with gluonexchange
(c) diagrams with gluinoexchange

Quite complicated calculation . . .
⇒ Need for computer algebra programms

['98 - '12:] ⇒ many more corrections calculated!



End of excursion: Higgs mass calculations

Mixing of the $\mathcal{CP}$-even Higgs bosons:

Propagator/Mass matrix at tree-level:

$$\begin{pmatrix} q^2 - m_H^2 & 0 \\ 0 & q^2 - m_h^2 \end{pmatrix}$$

Propagator / mass matrix with higher-order corrections
(→ Feynman-diagrammatic approach):

$$M_{hH}^2(q^2) = \begin{pmatrix} q^2 - m_H^2 + \hat{\Sigma}_{HH}(q^2) & \hat{\Sigma}_{Hh}(q^2) \\ & \\ \hat{\Sigma}_{hH}(q^2) & q^2 - m_h^2 + \hat{\Sigma}_{hh}(q^2) \end{pmatrix}$$

$\hat{\Sigma}_{ij}(q^2)$ $(i, j = h, H)$: renormalized Higgs self-energies

$\mathcal{CP}$-even fields can mix

$\Rightarrow$ complex roots of $\det(M_{hH}^2(q^2))$: $\mathcal{M}_{h_i}^2 (i = 1, 2)$: $\mathcal{M}^2 = M^2 - iM\Gamma$

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 $m_t = 173.2 \pm 0.9$ GeV

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

Obtained with:

FeynHiggs

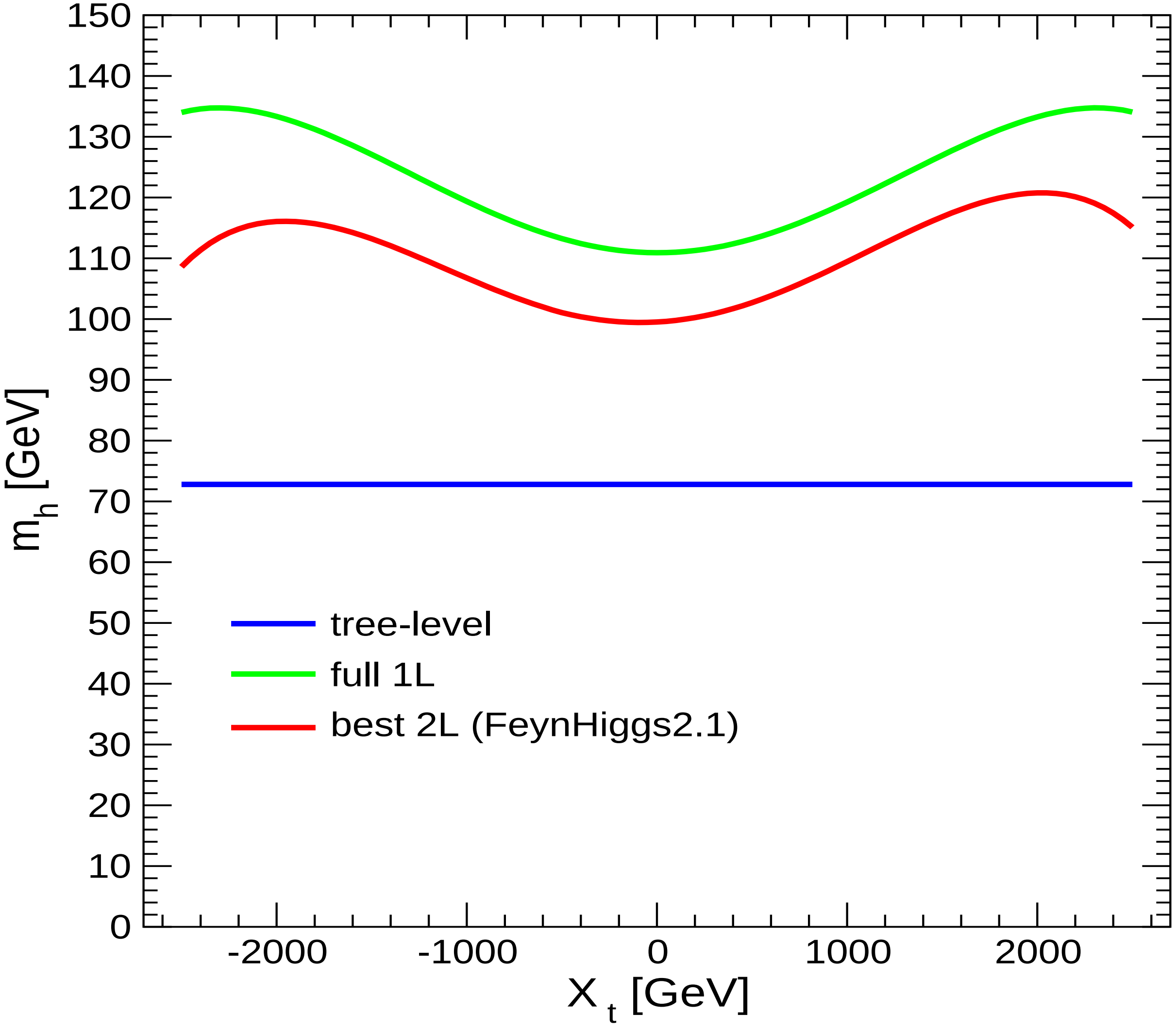
`www.feynhiggs.de`

[*T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein, K. Williams '98 – '12*]

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

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

Example for one set of MSSM parameters



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

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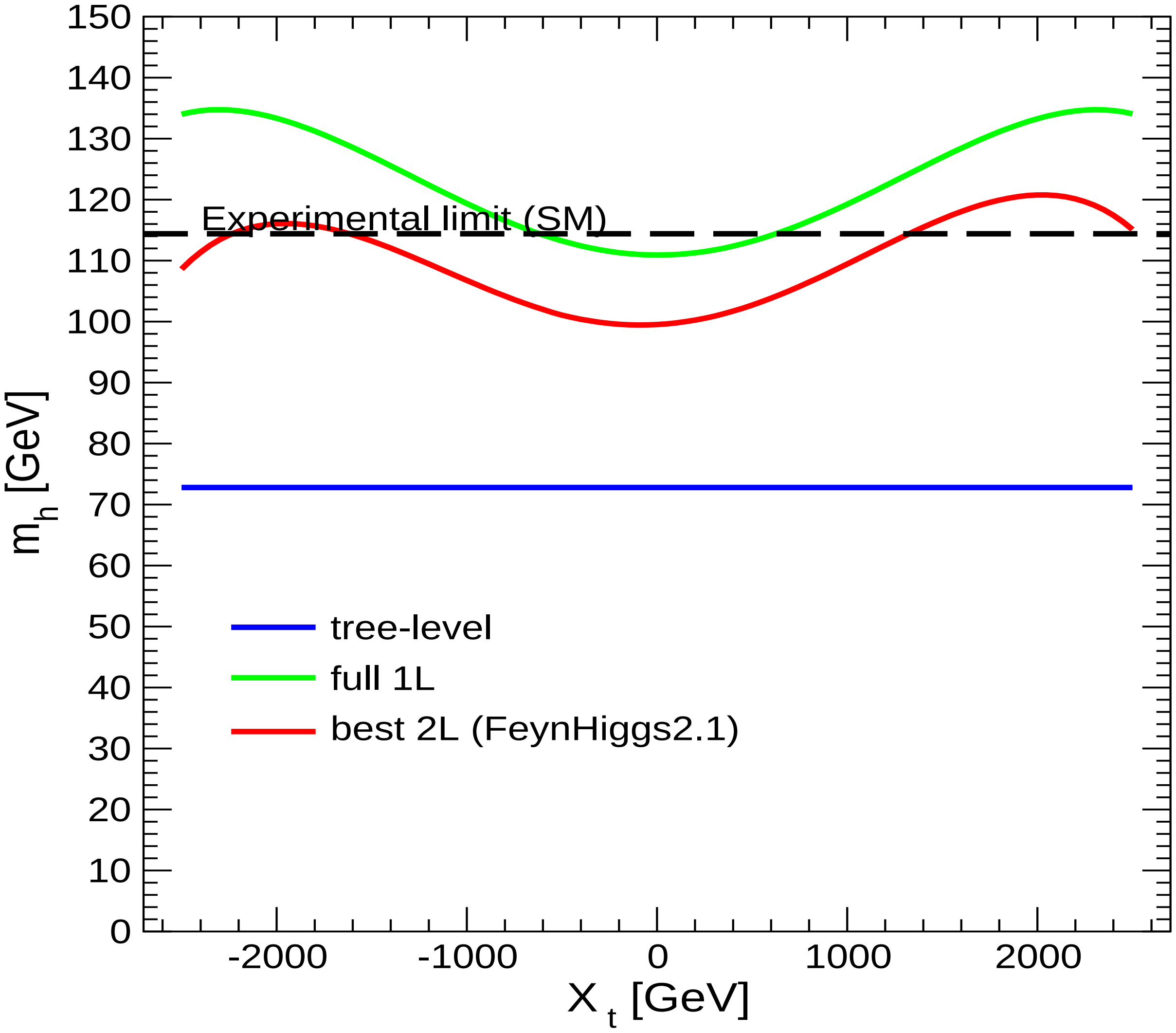


Comparison with experimental limits

⇒ strong impact on bound on SUSY parameters

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

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

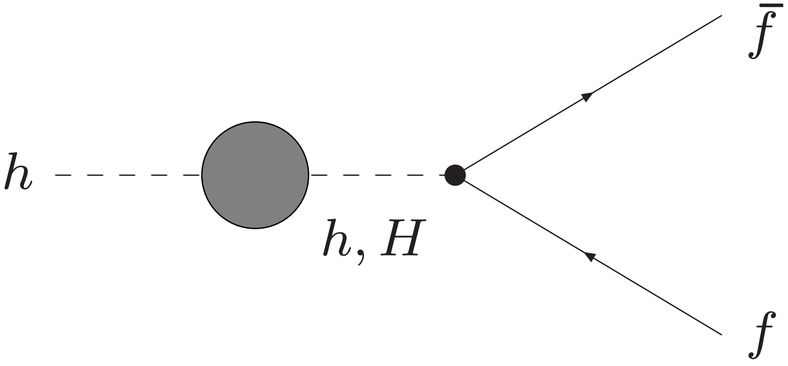
  $\Delta m_t \approx 1$ GeV $\Rightarrow \Delta M_h \approx 1$ GeV

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 $\tan\beta$

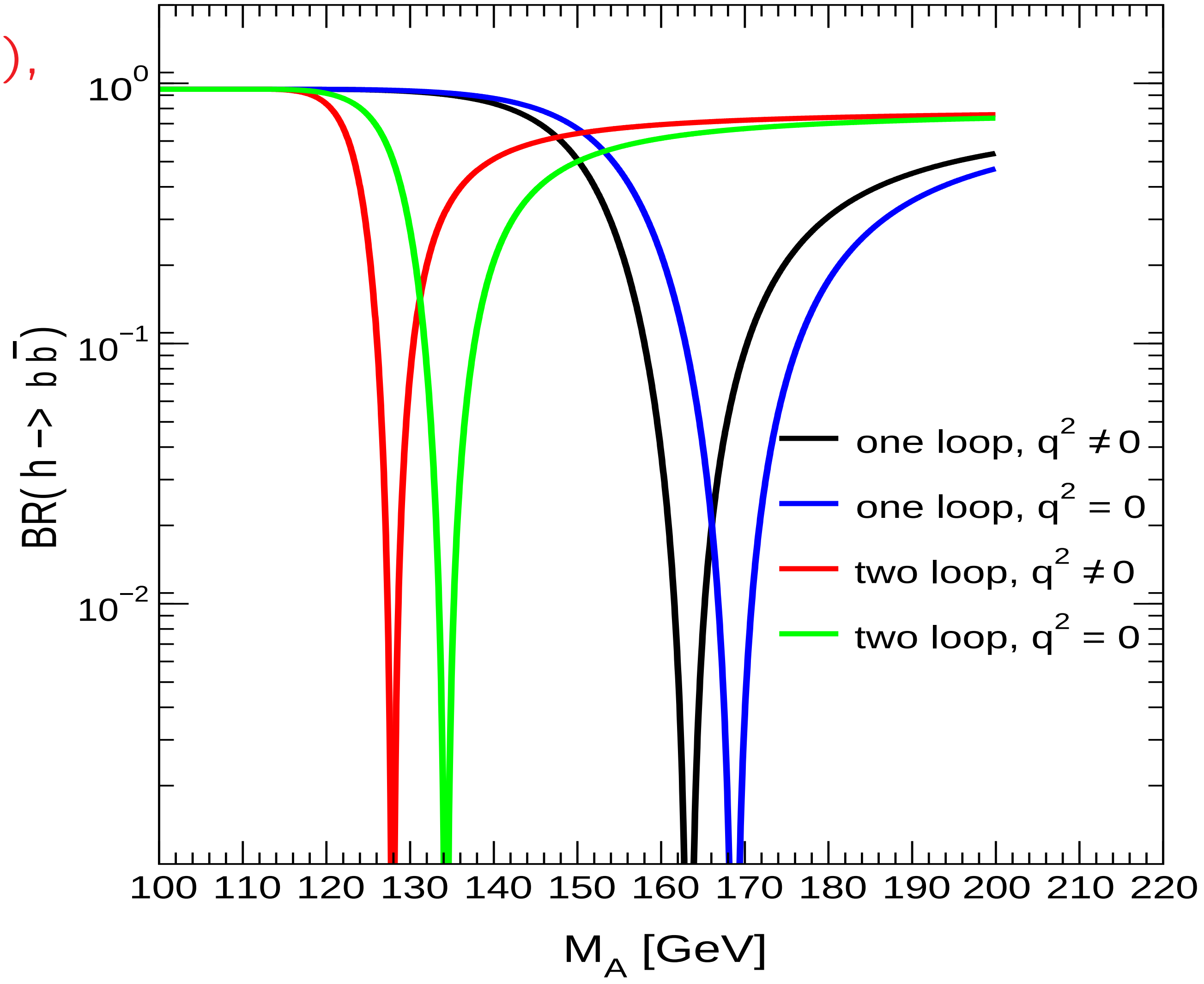
Effective $hf\bar{f}$ coupling can go to zero for large $\hat{\Sigma}_{\mathrm{hH}}$

⇒ “Pathological regions”

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

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

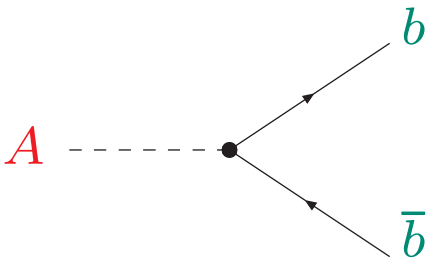
[*S.H., W. Hollik, G. Weiglein ’00*]



The heavy MSSM Higgs bosons

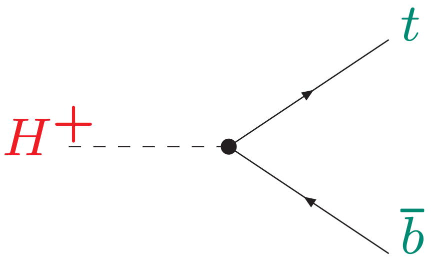
Differences compared to the SM Higgs:

Additional enhancement factors compared to the SM case:



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

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



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

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

⇒ other parameters enter ⇒ strong μ dependence

Most powerful LHC search modes for heavy MSSM Higgs bosons:

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

Enhancement factors compared to the SM case:

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

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

⇒ Δ_b effects (often neglected by 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 $\Gamma(H/A/H^\pm \to \mathrm{SUSY})$

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

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:

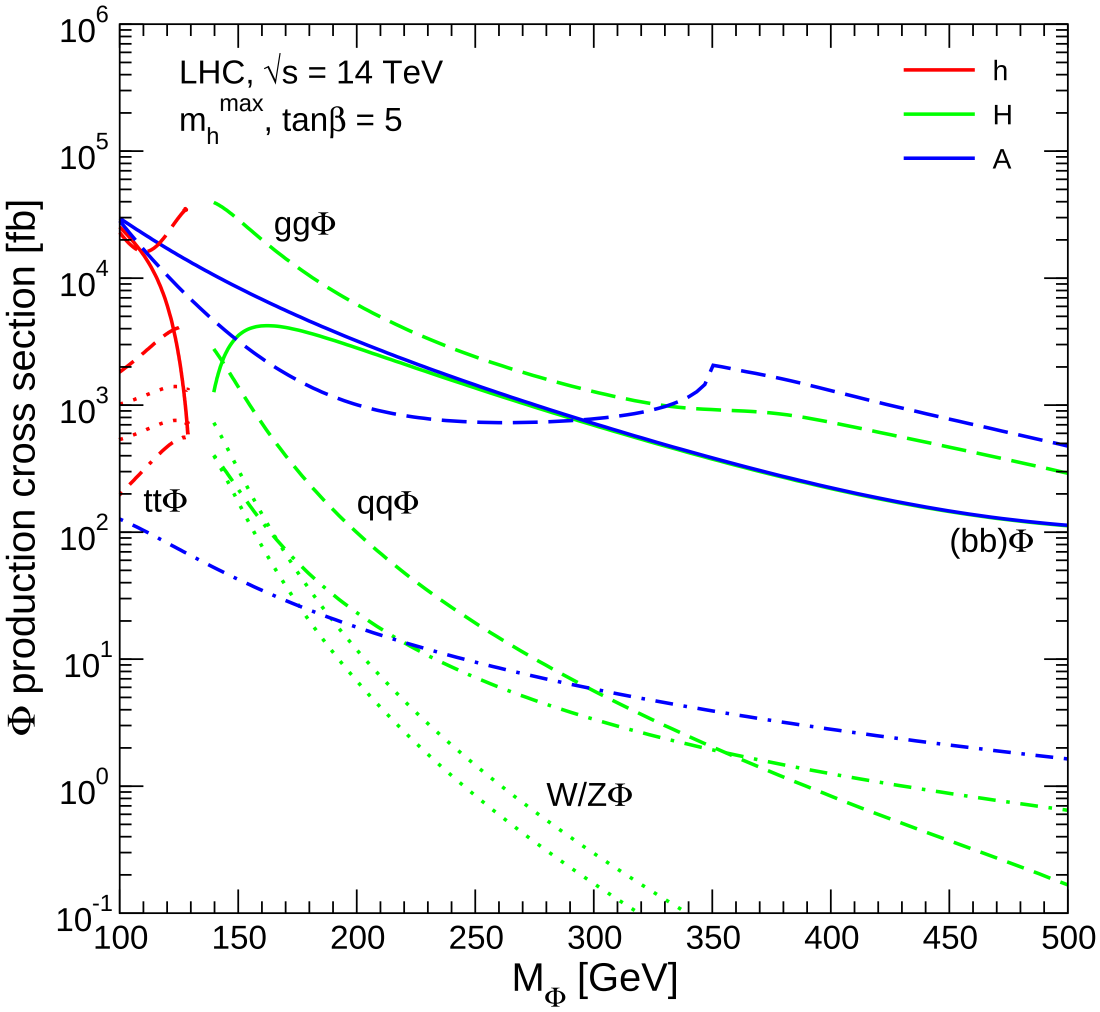
→ Vary only M_A and $\tan\beta$
→ Keep all other SUSY parameters fixed

1. $m_h^{\rm max}$ scenario:
   → obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\rm SUSY}$)
2. no-mixing scenario
   → no mixing in the scalar top sector ($X_t = 0$)
3. small $\alpha_{\rm eff}$ scenario
   → $hb\bar{b}$ coupling $\sim \sin\alpha_{\rm eff}/\cos\beta$ can be zero: $\alpha_{\rm eff} \to 0$:
   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:

$h \to b\bar{b}$

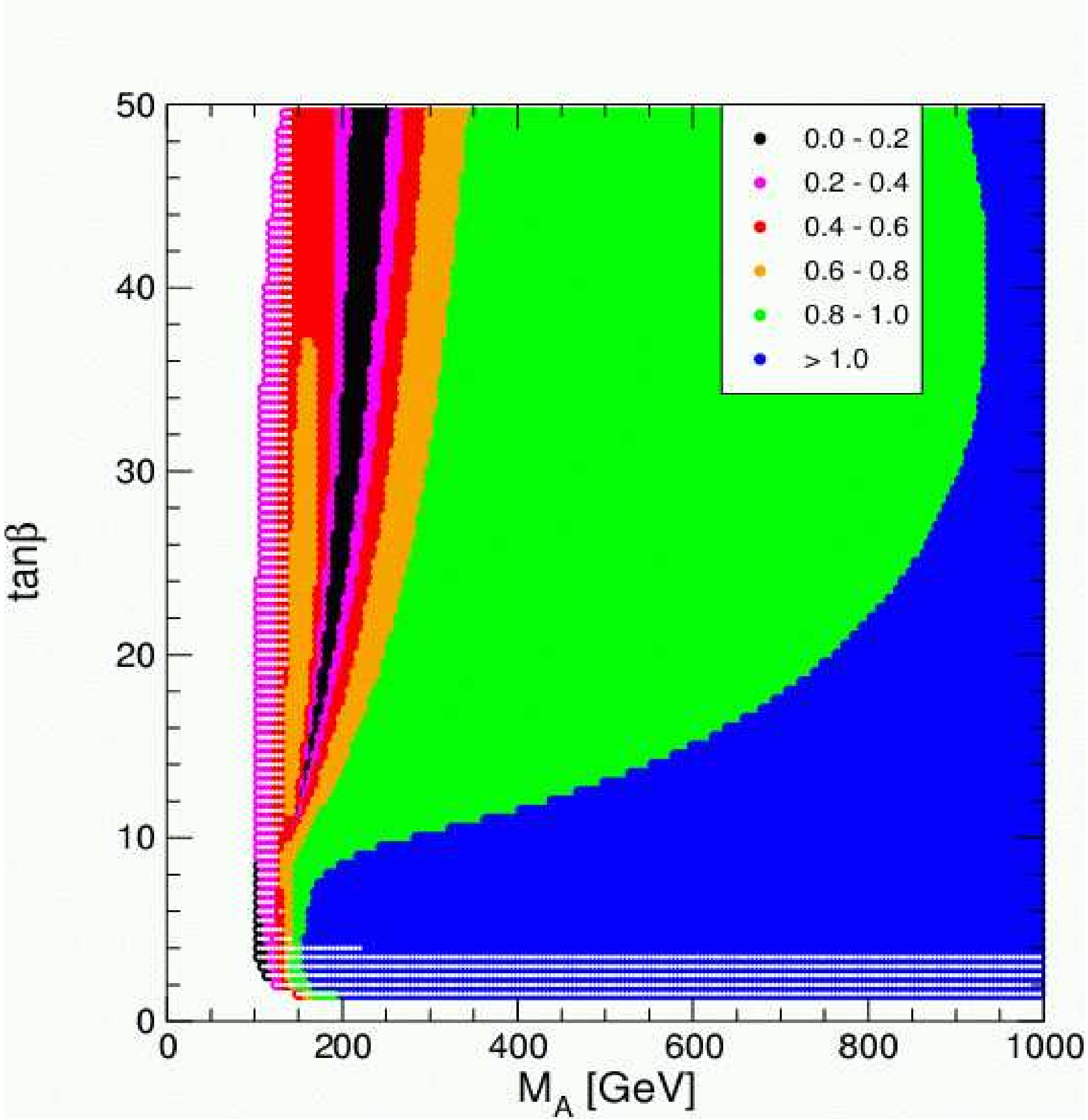
can be strongly suppressed

→ "Small α_{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:

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

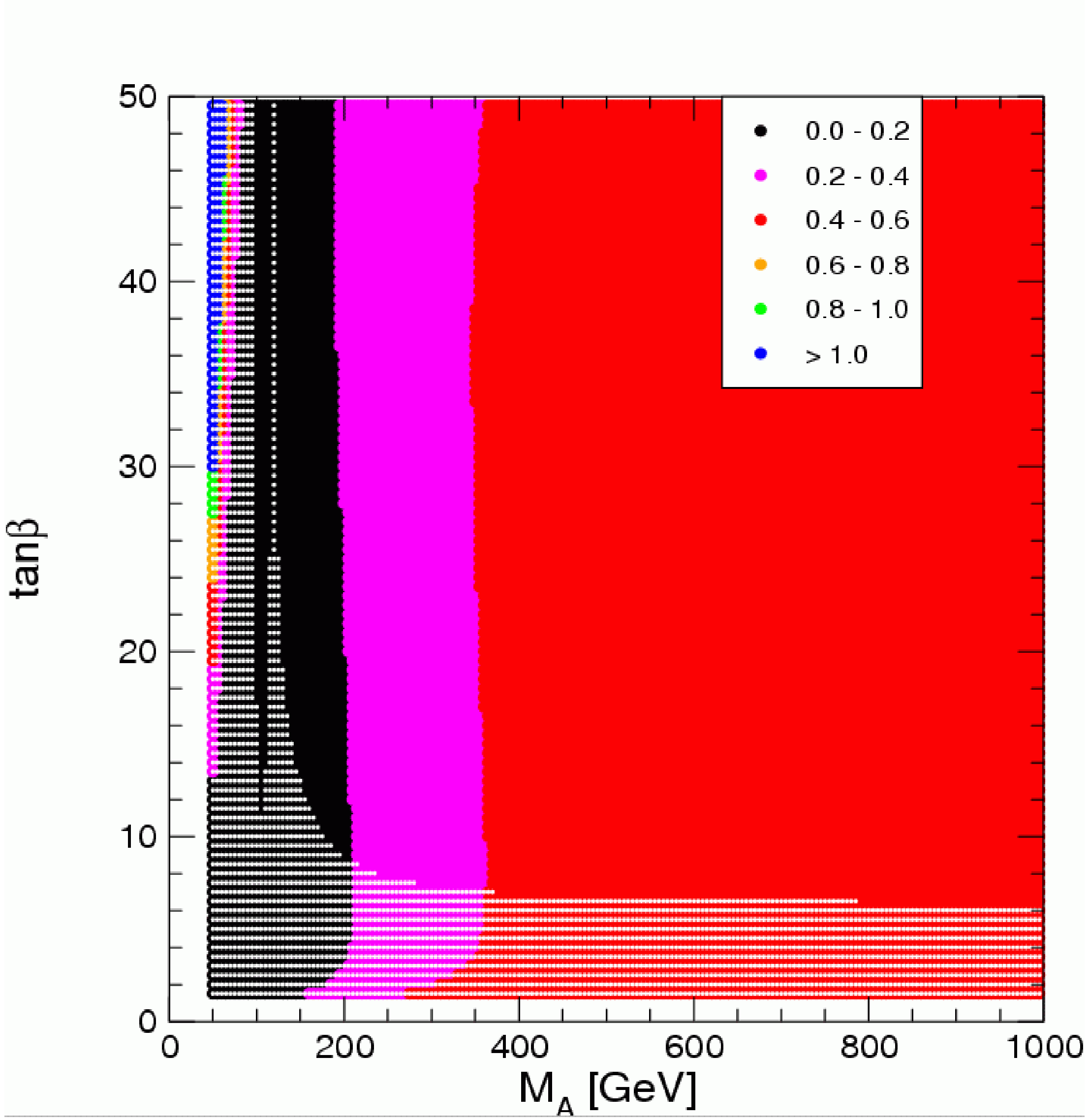
can be strongly suppressed

→ "gluophobic Higgs scenario"

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

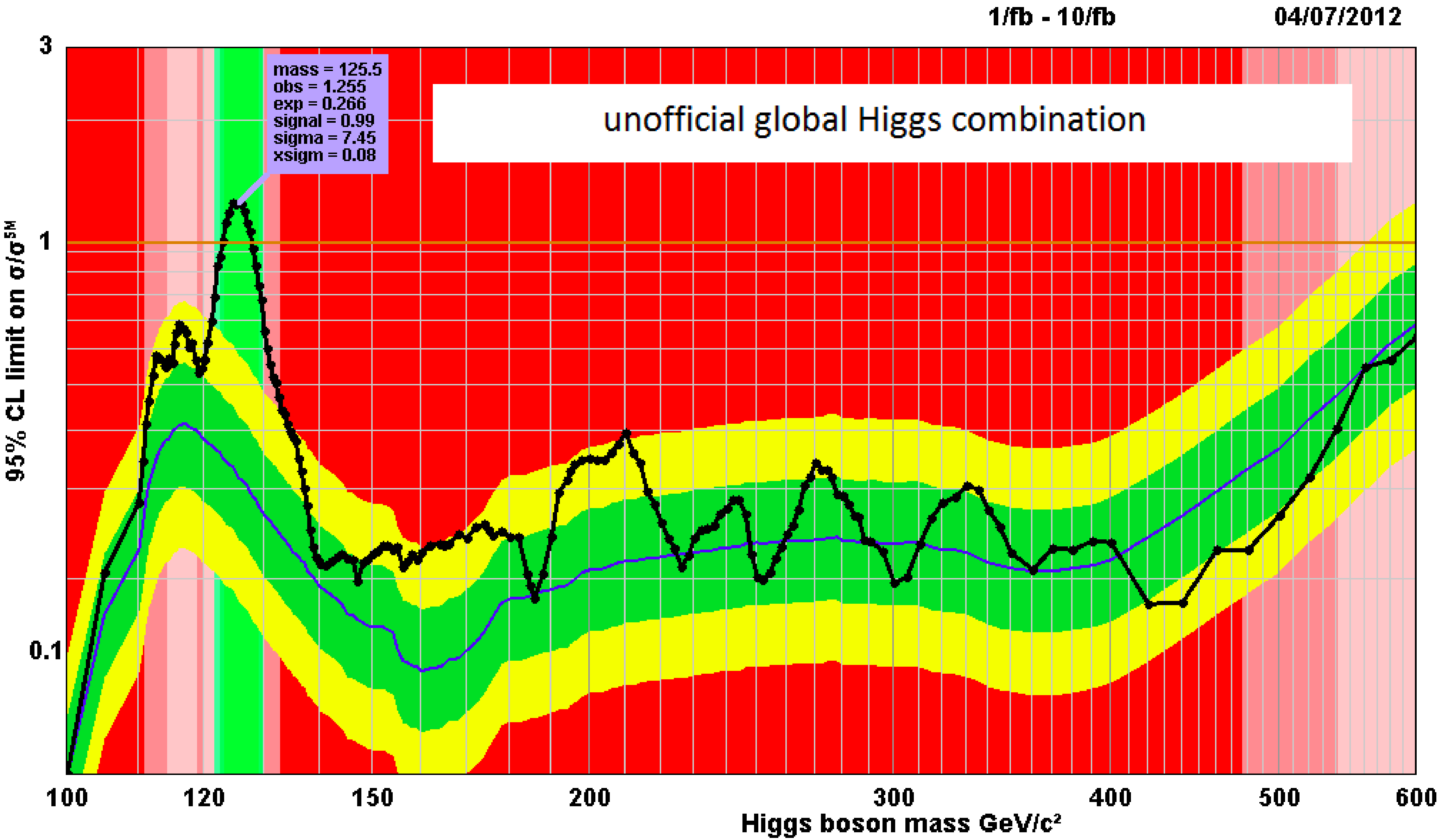
⇒ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

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



Unofficial(!) LHC combination:

[*vixra.org*]



Implications of Higgs searches for SUSY

The latest results on ATLAS/CMS Higgs searches were presented on 04.07.2012 before 11am

On 05.07.2011 about 3 articles appeared on the arXiv, analyzing the implications

Most of them analyzed them in the framework of SUSY

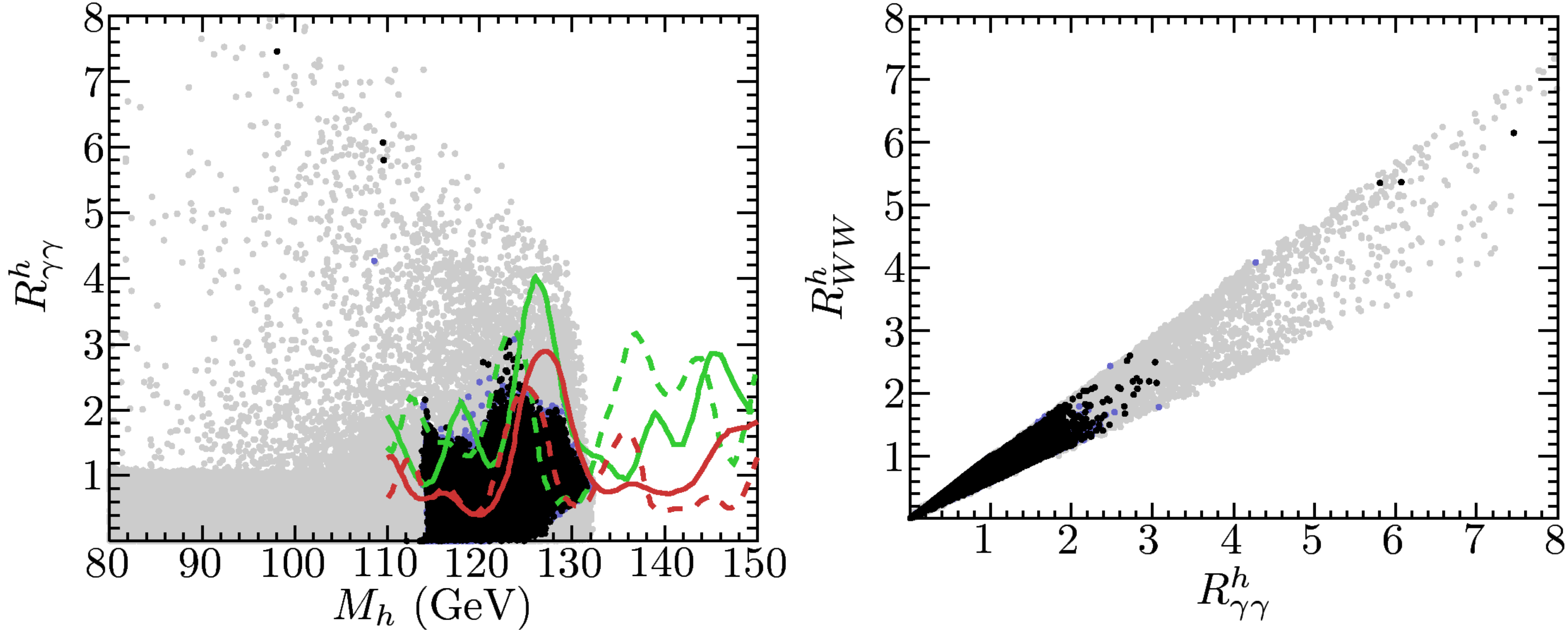
Here a few results from one randomly picked article:
[arXiv:1207.1096 [hep-ph]
(R. Benbrik, M. Gomez Bock, S.H., O. Stal, G. Weiglein, L. Zeune)]

$$M_h = 125 \pm 1(\text{exp.}) \pm 2(\text{theo.})\ \text{GeV}$$

Possible MSSM interpretation:

[*R. Benbrik, M. Gomez Bock, S.H., O. Stal, G. Weiglein, L. Zeune '12*]

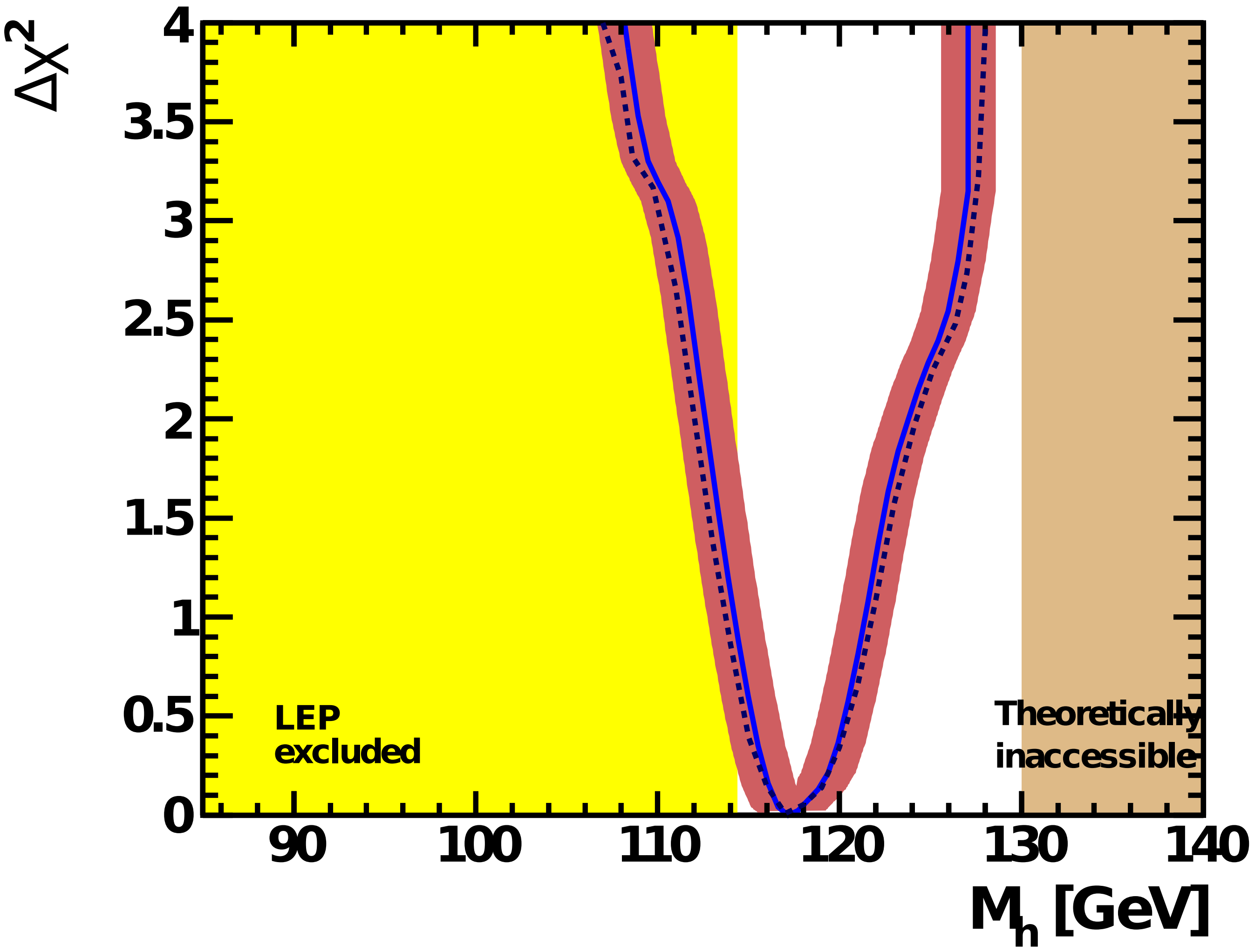
Scan over the MSSM parameter space:



⇒ enhanced $\gamma\gamma$ rate, suppressed WW, $b\bar{b}$ rate possible!

CMSSM: post-LHC ($1\ \mathrm{fb}^{-1}$) red band plot:

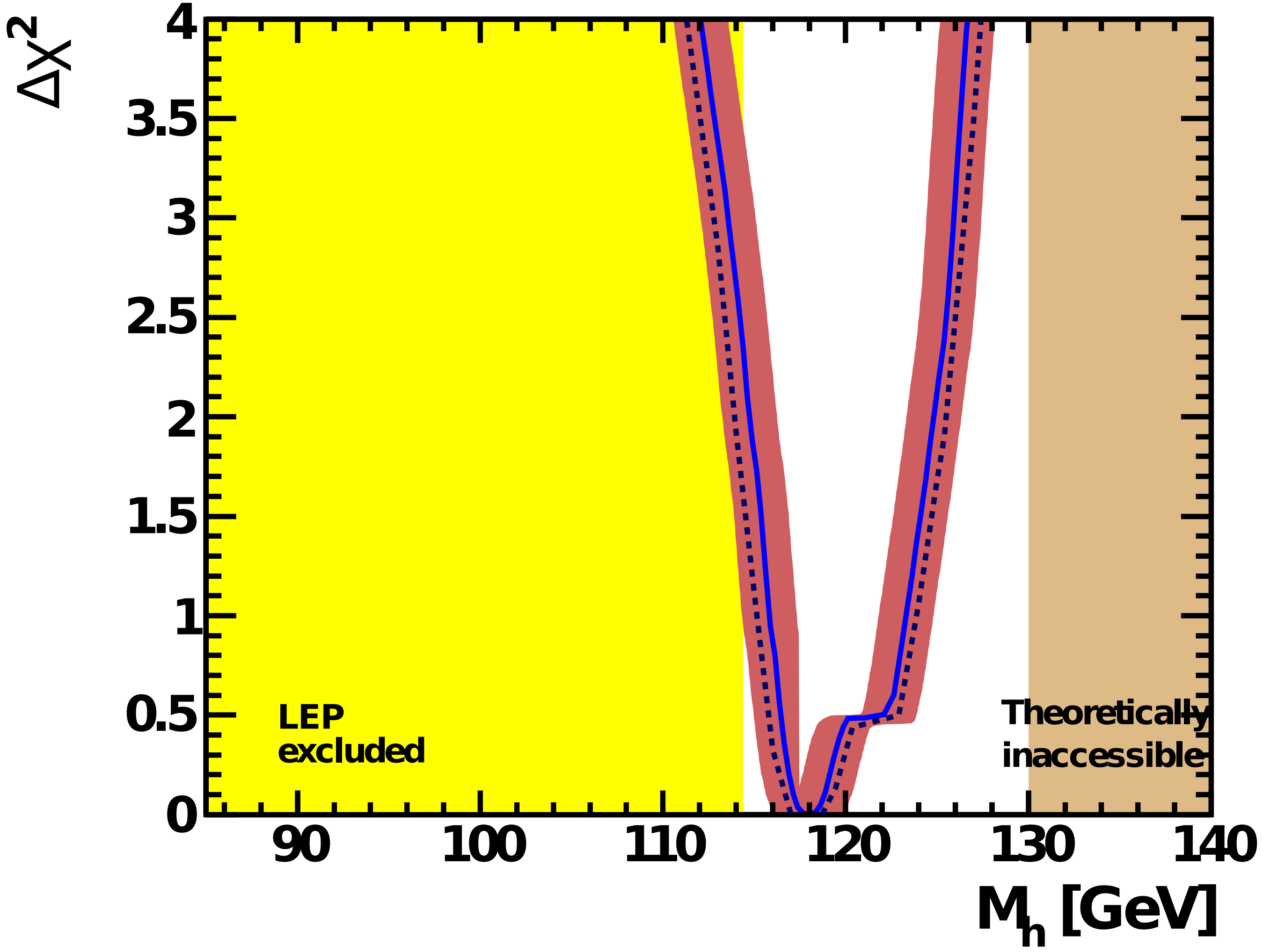
[2011]



$M_h = 118 \pm 3\,(\text{exp}) \pm 1.5(\text{theo})$ GeV $\quad \Delta\chi^2(M_h = 125\ \text{GeV}) \approx 2.2$

NUHM1: post-LHC (1 fb^{-1}) red band plot:

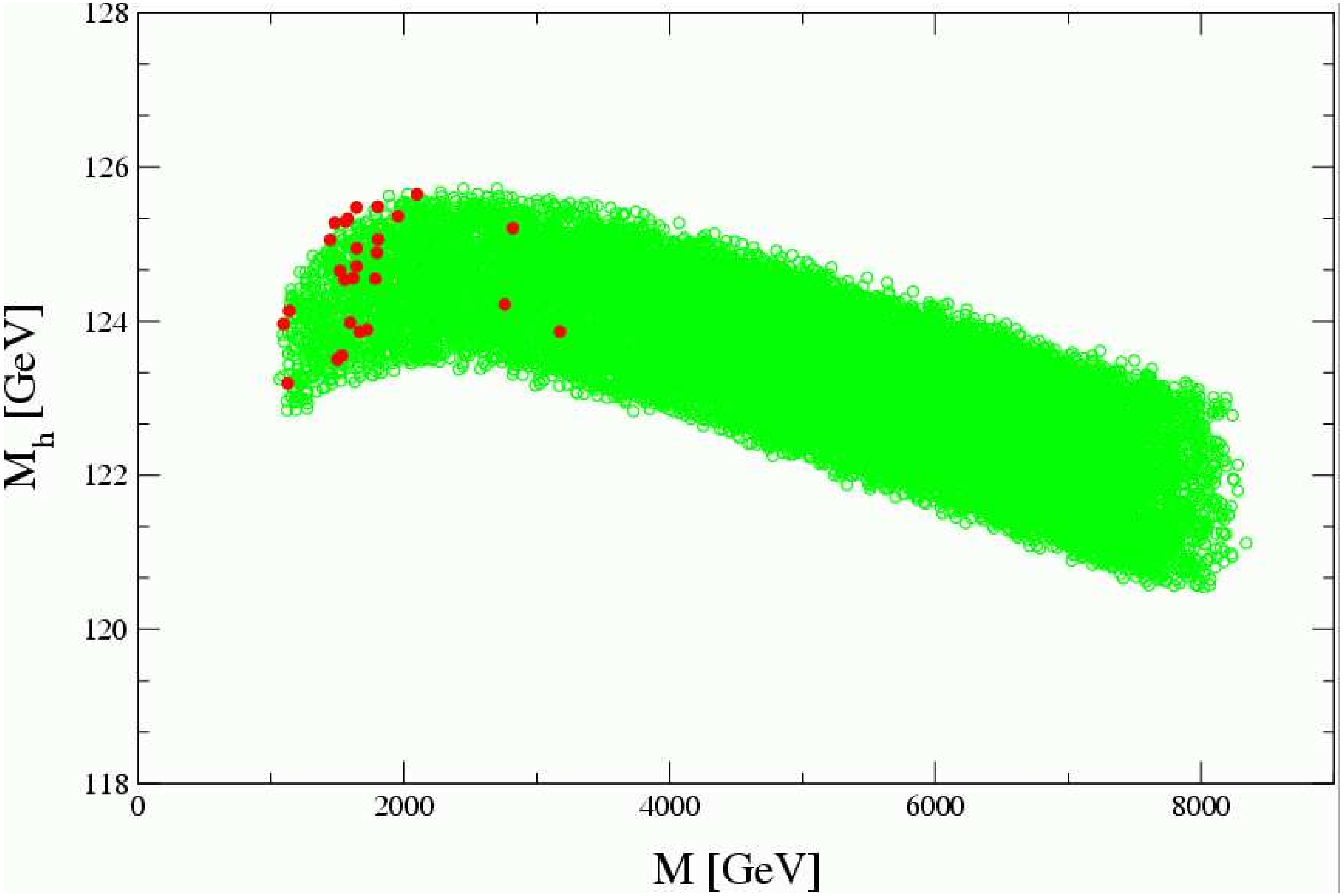
[2011]



$M_h = 118^{+3}_{-1}$ (exp) ± 1.5(theo) GeV $\Delta\chi^2(M_h = 125 \text{ GeV}) \approx 1.6$

Randomly picked analysis: Finite Unified MSSM prediction (2008)

[*S.H., M. Mondragon, G. Zoupanos '08*]



green: consistent with B physics constraints

red: agreement with (loose) CDM bound

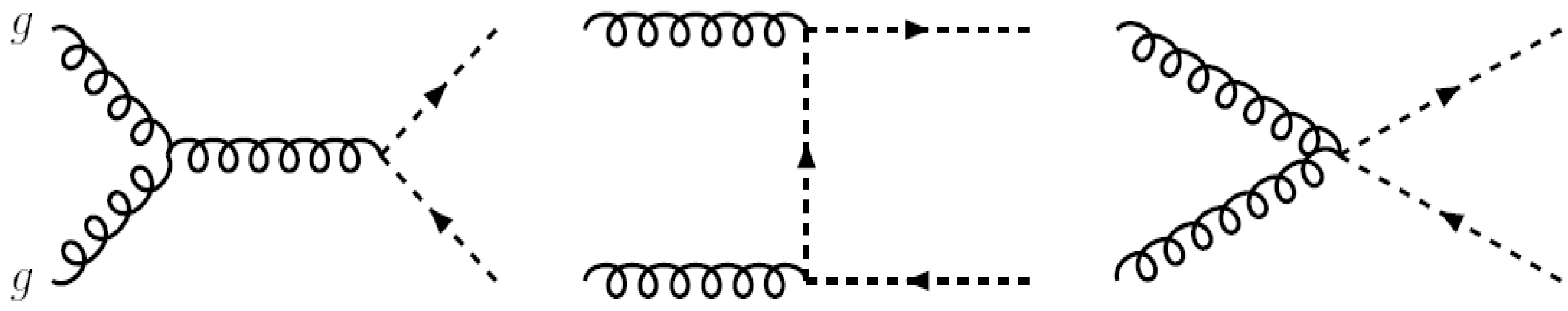
$\Rightarrow$ 120 GeV $\leq M_h \leq$ 126 GeV (no theory error incl. yet)

Recent SUSY searches at the LHC

Colored sparticles at the LHC

SUSY particle production at the LHC:

⇒ colored (s)particles are copiously produced

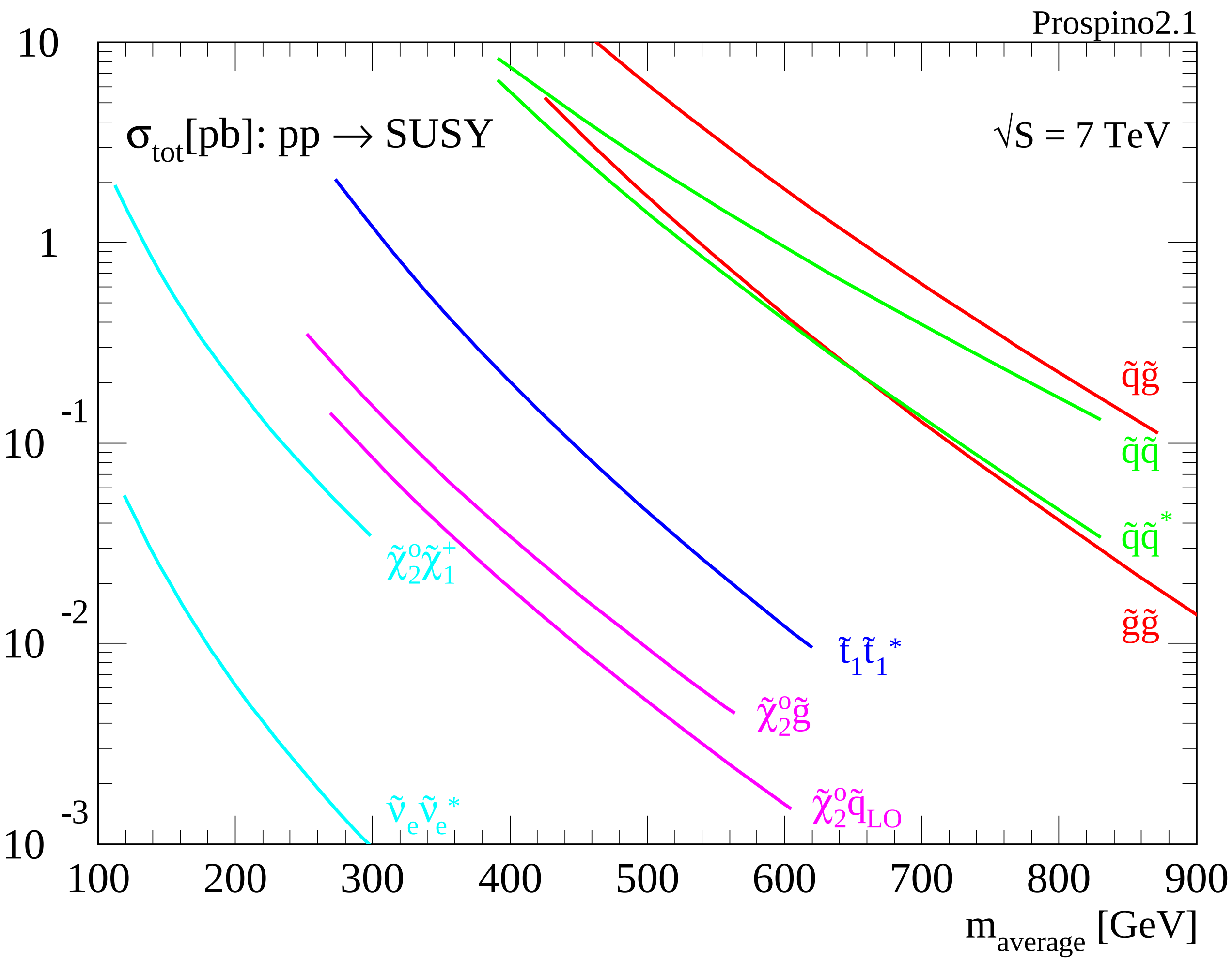


⇒ production of gluinos, squarks, . . .

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

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

Production of SUSY particles at the LHC

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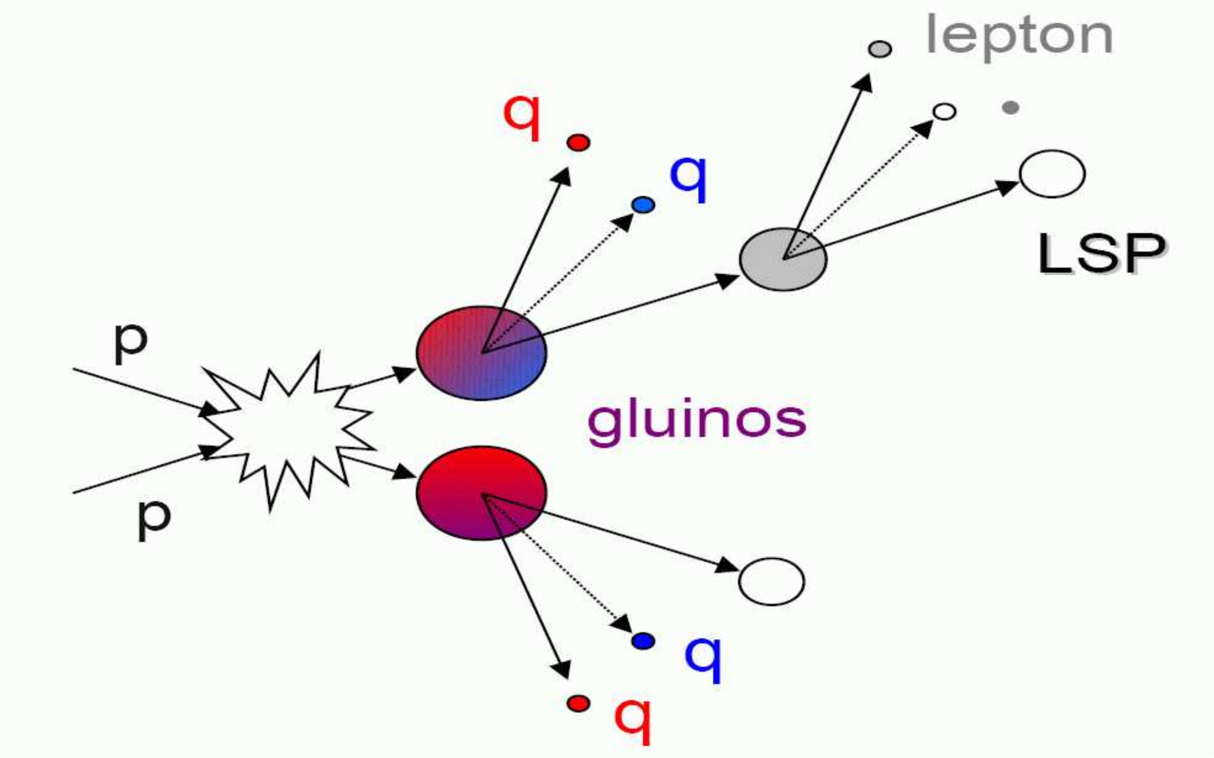
⇒ cascade decays

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



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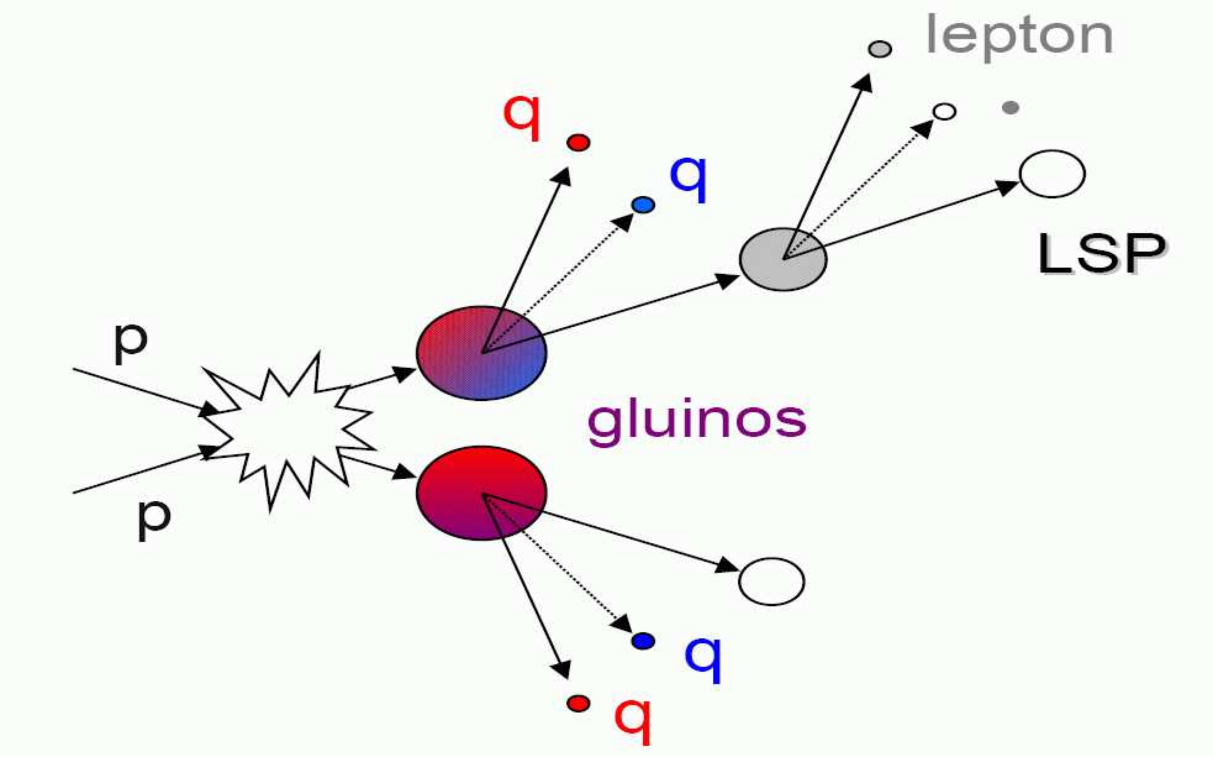
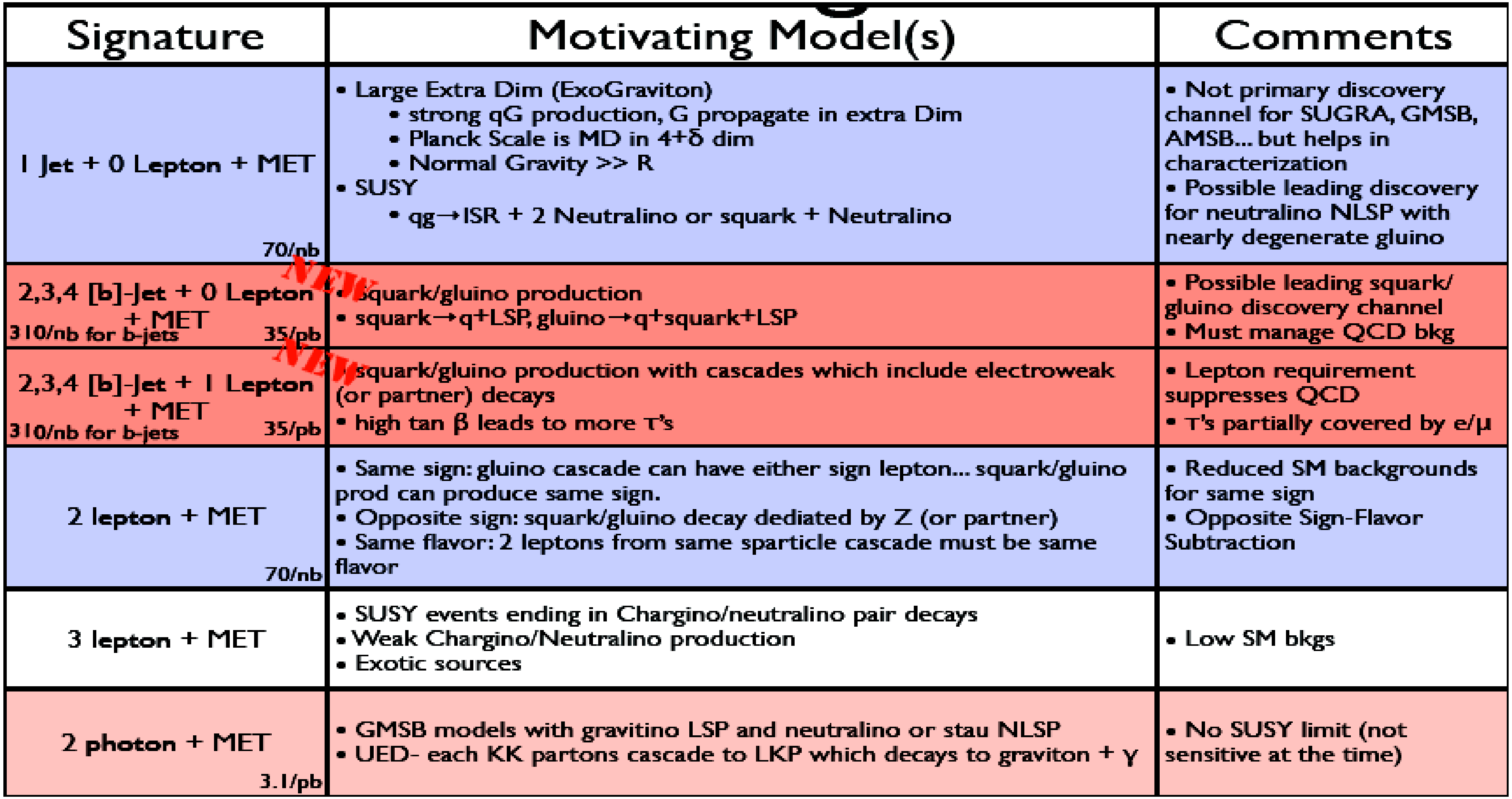


Production of uncolored particles via cascade decays often dominates over direct production – Many states are produced at once

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

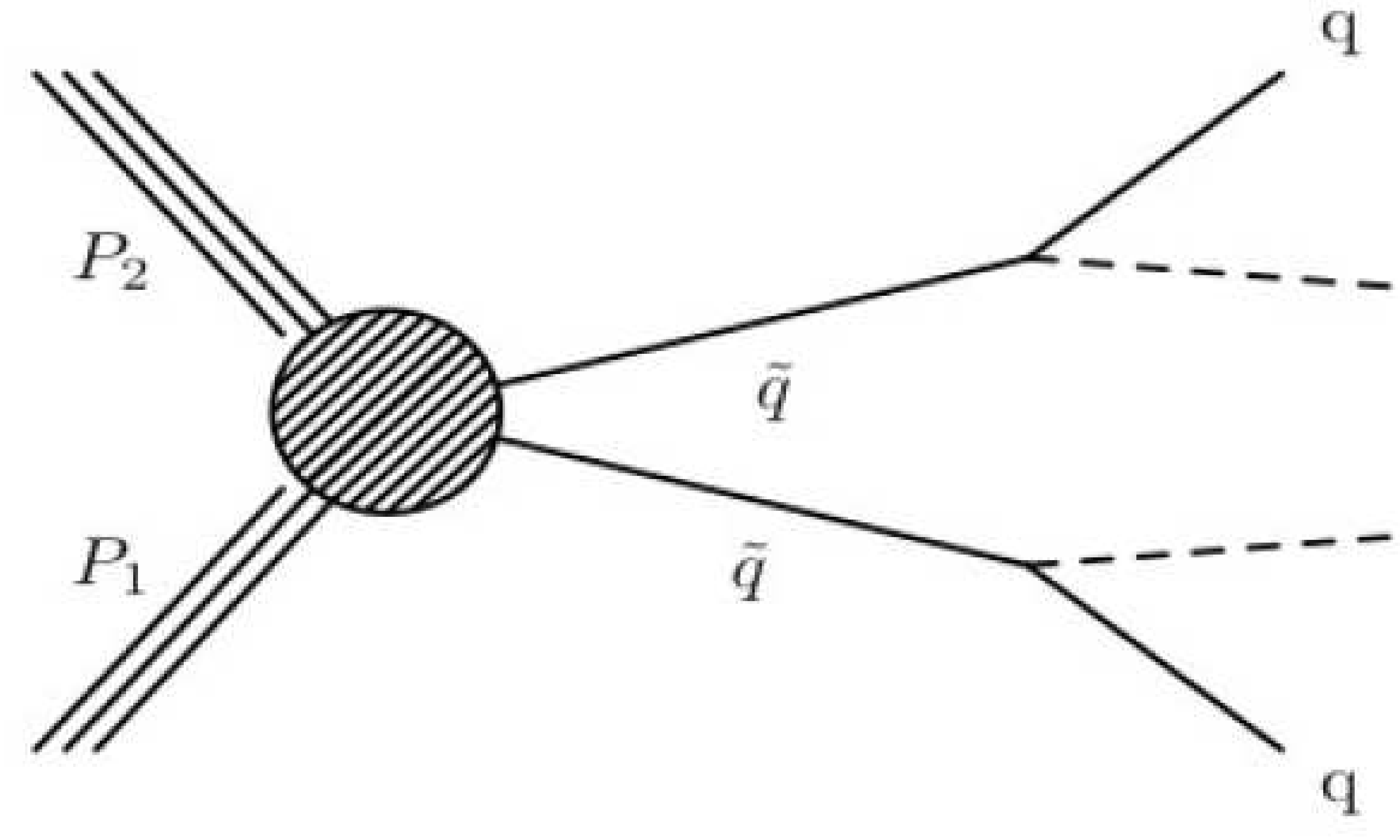
Cascade decays: taken from talk by [*A. Farbin '11*]

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



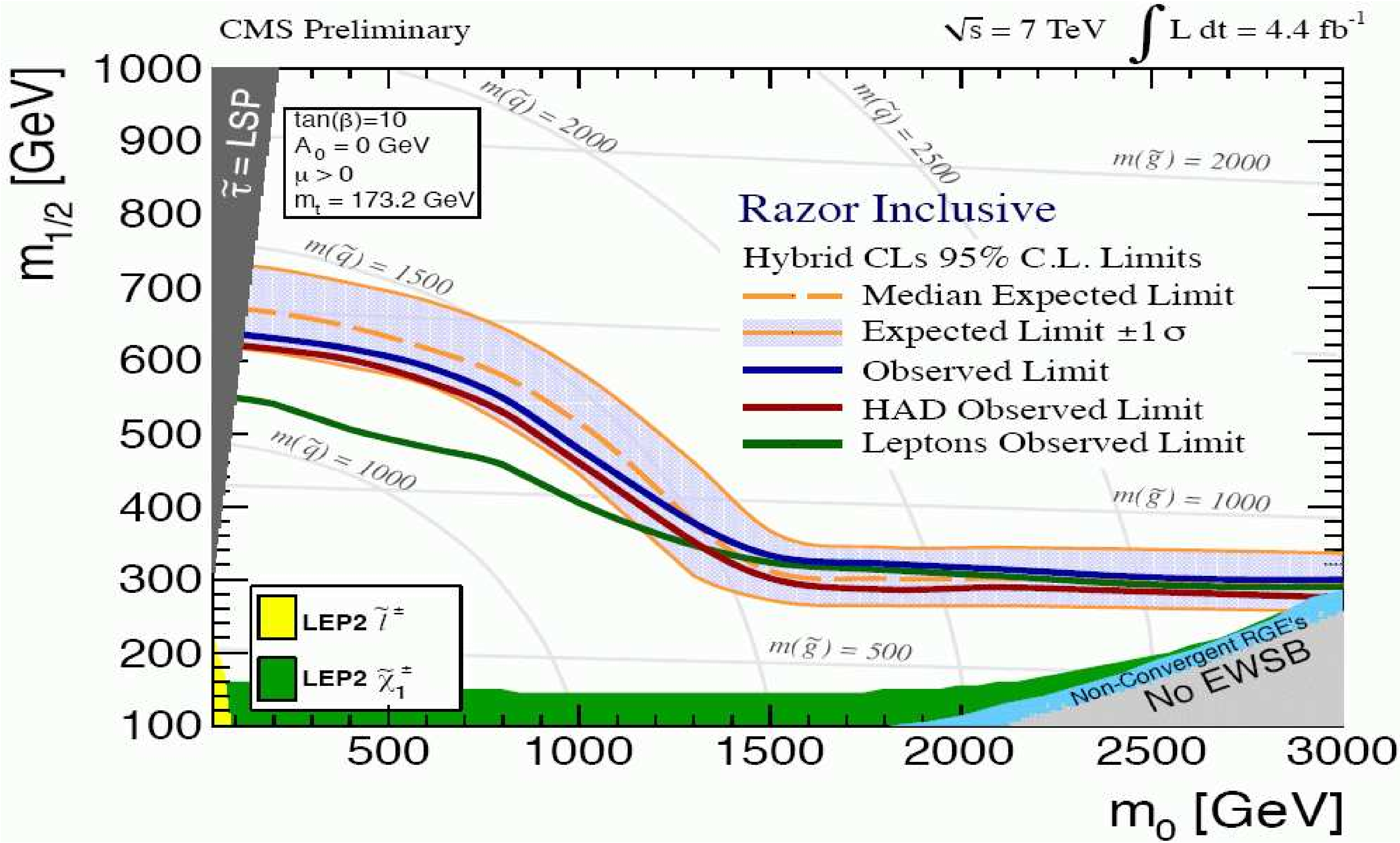
Signature	Motivating Model(s)	Comments
1 Jet + 0 Lepton + MET 70/nb	• Large Extra Dim (ExoGraviton) • strong qG production, G propagate in extra Dim • Planck Scale is MD in $4+\delta$ dim • Normal Gravity >> R • SUSY • qg→ISR + 2 Neutralino or squark + Neutralino	• Not primary discovery channel for SUGRA, 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 $\tan\beta$ 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 '12*]



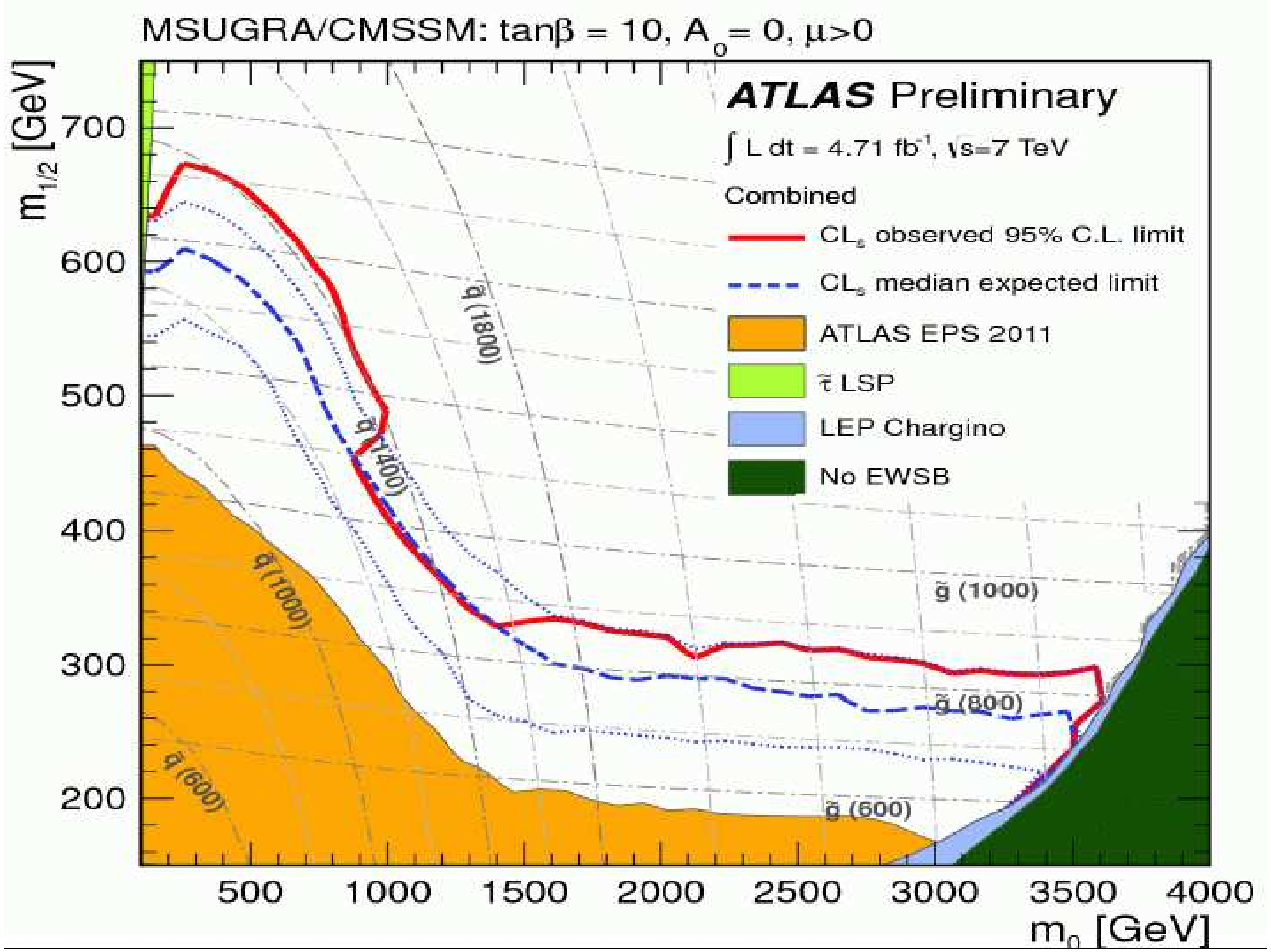
Search for SUSY: CMS results: 0 lepton + MET

[CMS '12]



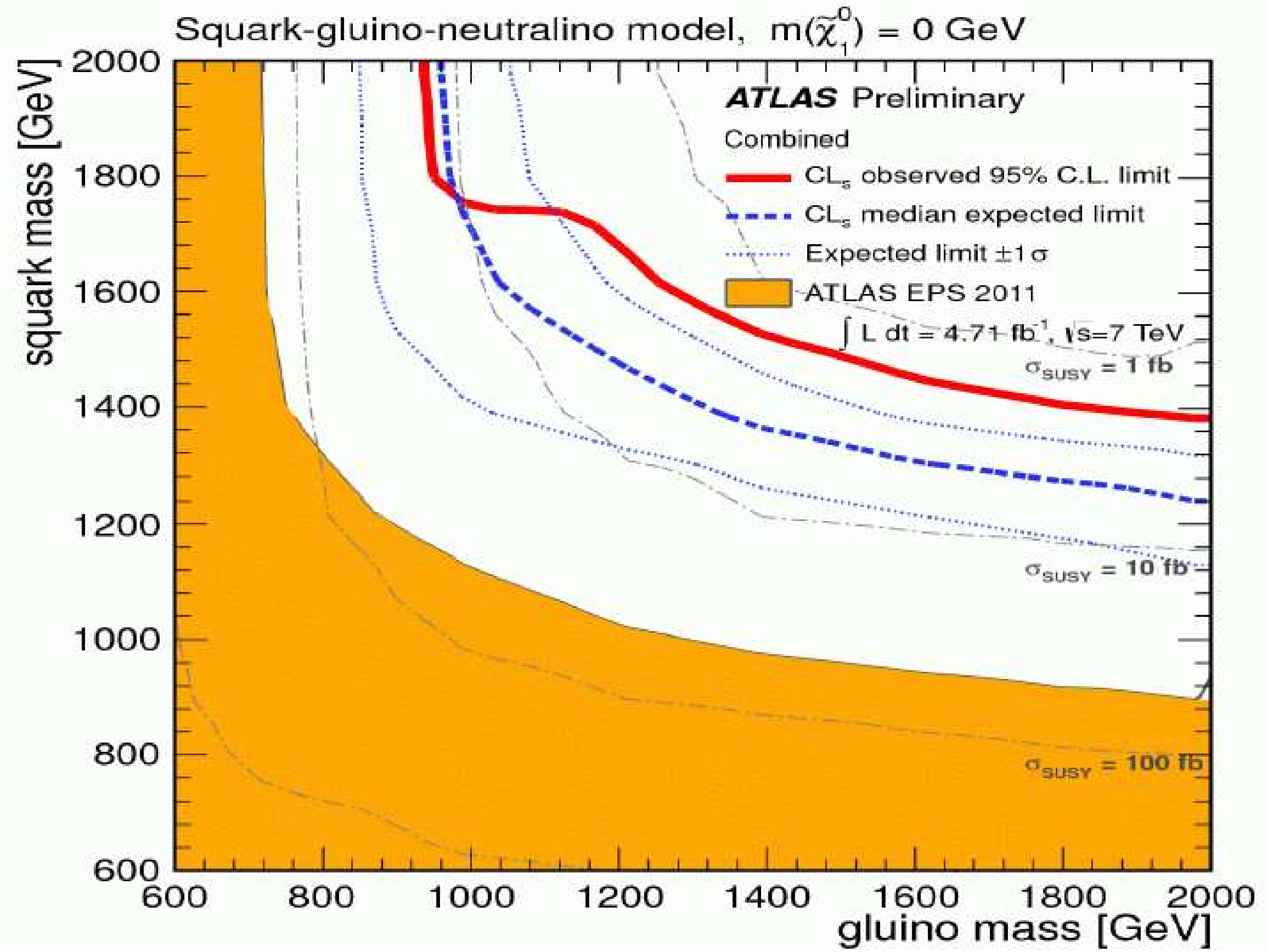
⇒ valid also for other tan β and A_0 values ??

Search for SUSY particles: ATLAS results: 0 lepton [ATLAS '12]



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

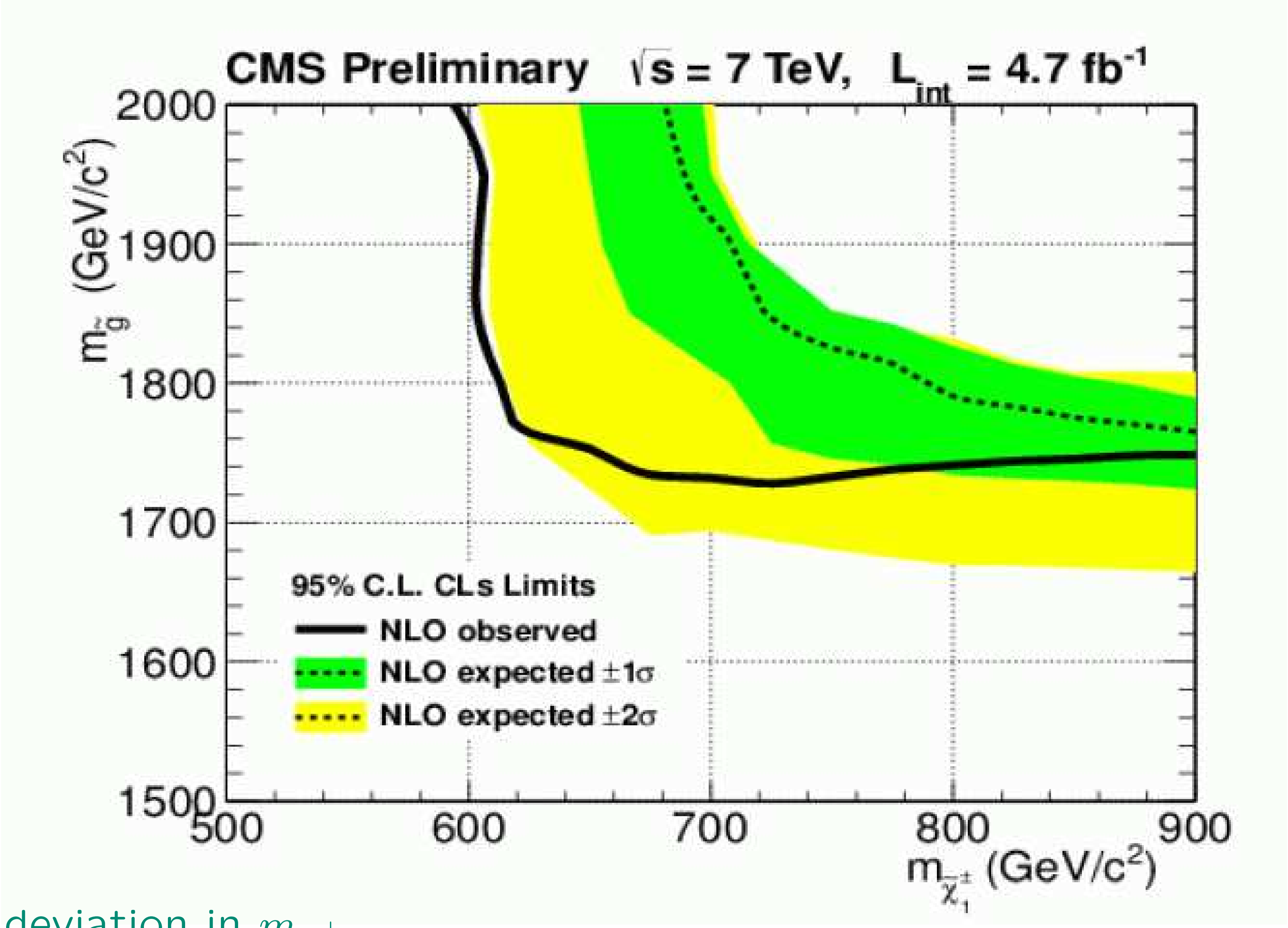
Interpretation of SUSY search results in "simplified models": [*ATLAS '12*]



"Simplified model": squarks of first two generations, gluino, massless neutralino (LSP), all other SUSY particles heavy

Limits on EW particles from cascade decays

[*CMS '12*]

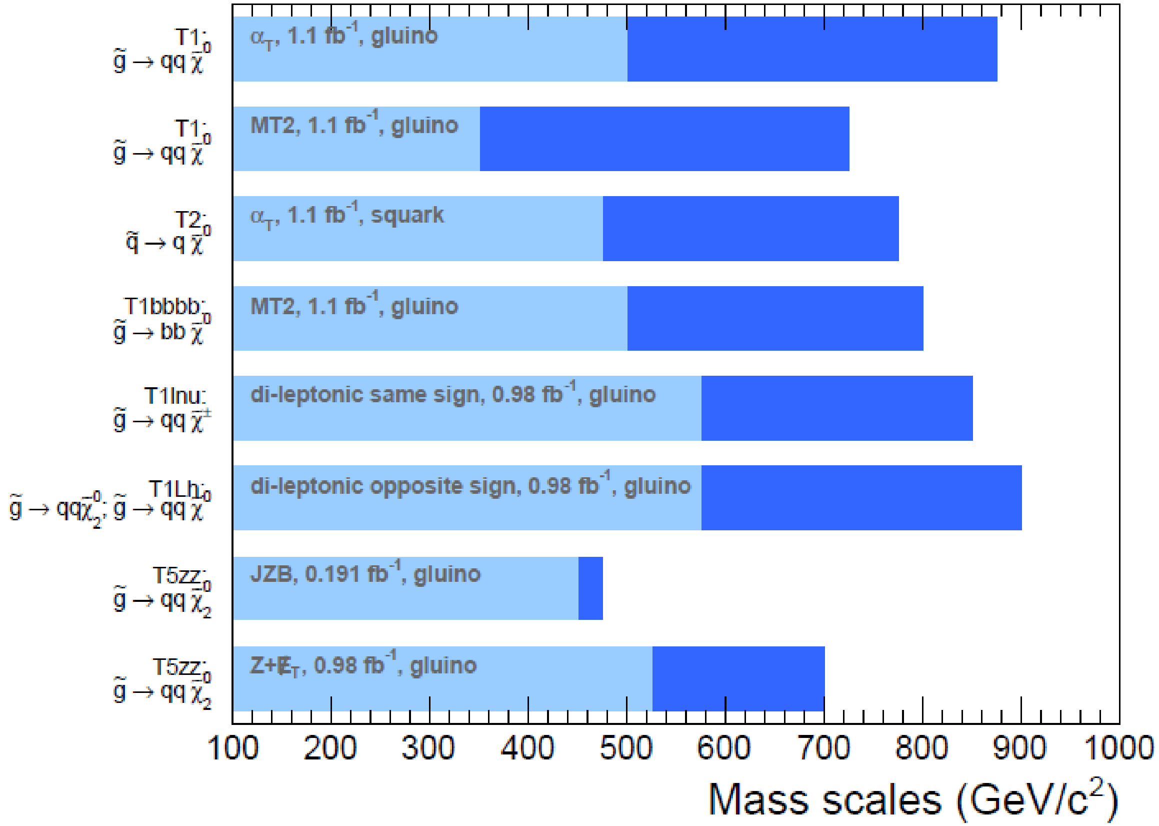


$\gtrsim 2\sigma$ deviation in $m_{\tilde{\chi}^{\pm}_1}$ . . .

SUSY limits in “simplified models” with LSP mass varied from 0 to $m_{\tilde{g}} - 200$ GeV:

[CMS ’11]

Ranges of exclusion limits for gluinos and squarks, varying $m(\tilde{\chi}^0)$
CMS preliminary



For limits on $m(\tilde{g})$, $m(\tilde{q}) >> m(\tilde{g})$ (and vice versa). $\sigma^{prod} = \sigma^{NLO\text{-}QCD}$.

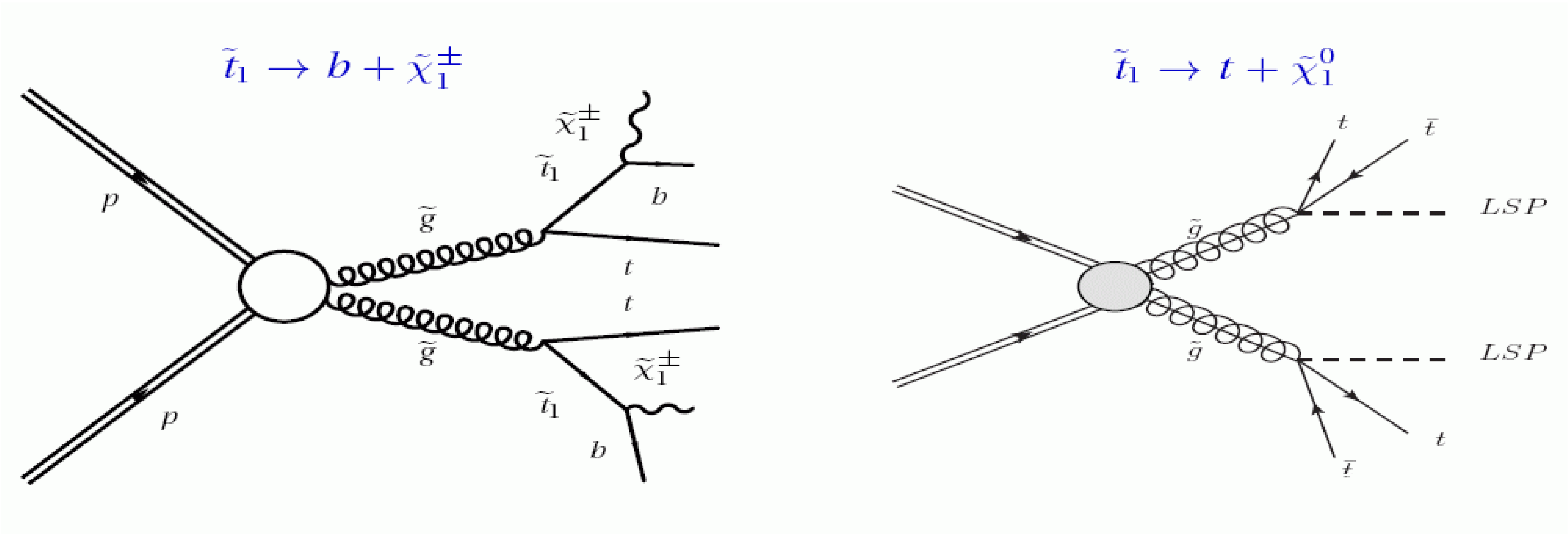
$$m(\tilde{\chi}^{\pm}),\ m(\tilde{\chi}_2^0) \equiv \frac{m(\tilde{g}) + m(\tilde{\chi}^0)}{2}.$$

$m(\tilde{\chi}^0)$ is varied from 0 GeV/c^2 (dark blue) to $m(\tilde{g})$-200 GeV/c^2 (light blue).

⇒ strong dependence on LSP mass!

Limits on third generation squark masses:

[ATLAS '12]



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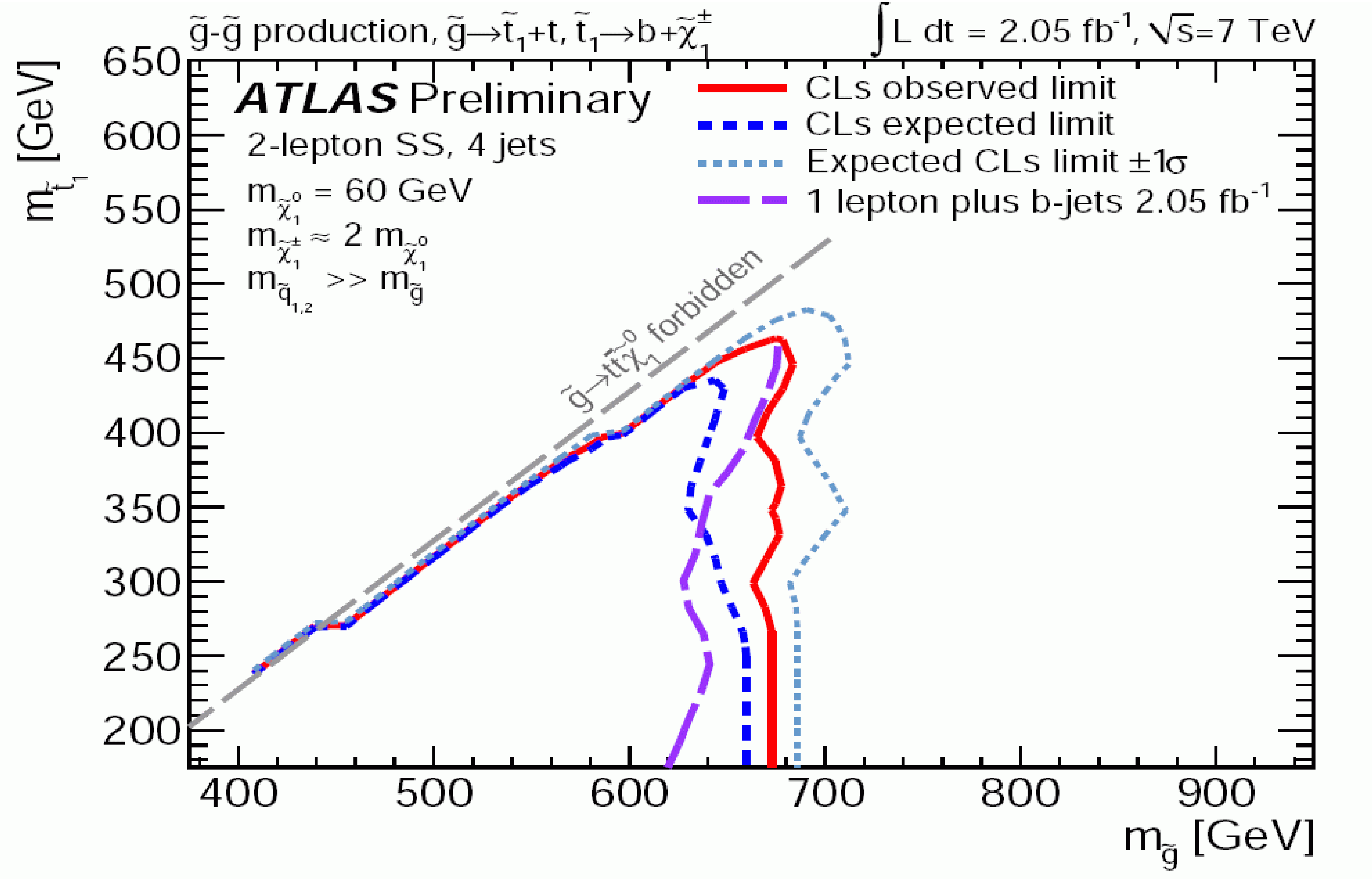
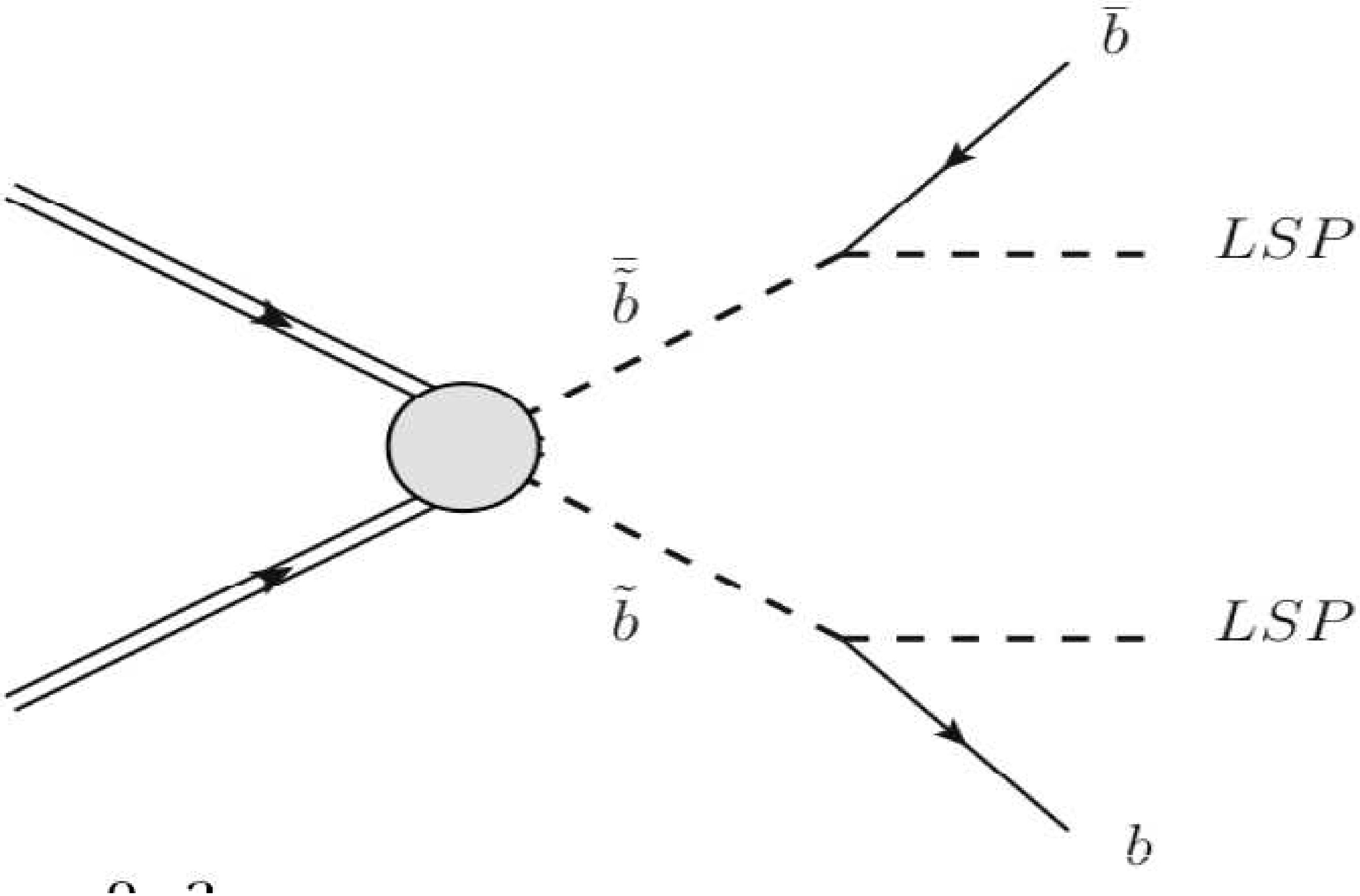


⇒ very light stop allowed for heavier gluinos

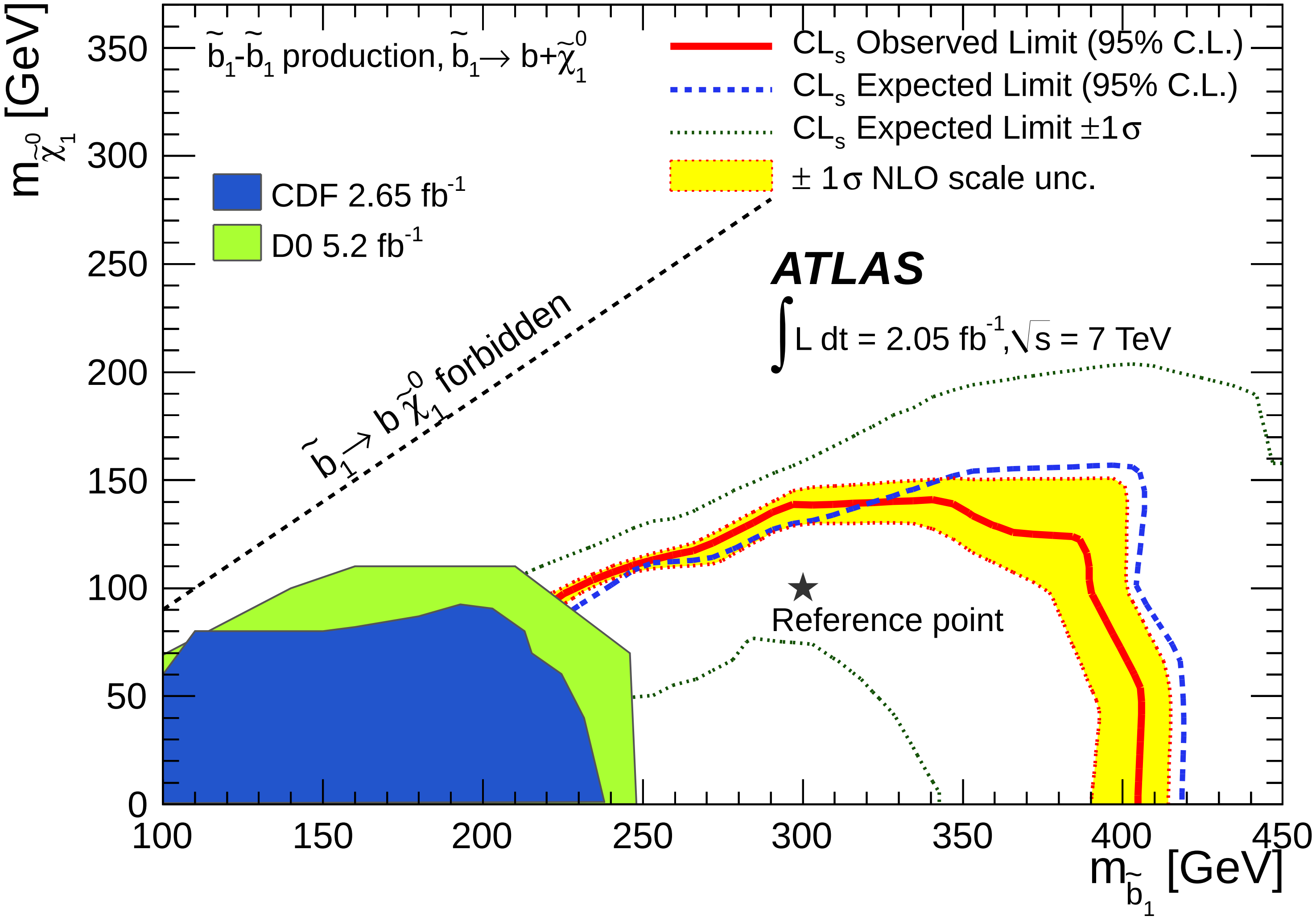
Limit on direct sbottom production:

[ATLAS '12]



Limit on direct sbottom production:

[ATLAS '12]



⇒ weak limits for $m_{\tilde{\chi}_1^0} \lesssim 125$ GeV

Direct LHC limits on . . .

(direct = not via cascade decay)

- charginos
- neutralinos
- sleptons

“EW SUSY particles”

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(direct = not via cascade decay)

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"EW SUSY particles"

⇒ smaller production cross section

⇒ more difficult analyses . . .

Direct LHC limits on . . .

(direct = not via cascade decay)

– charginos
– neutralinos
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“EW SUSY particles”

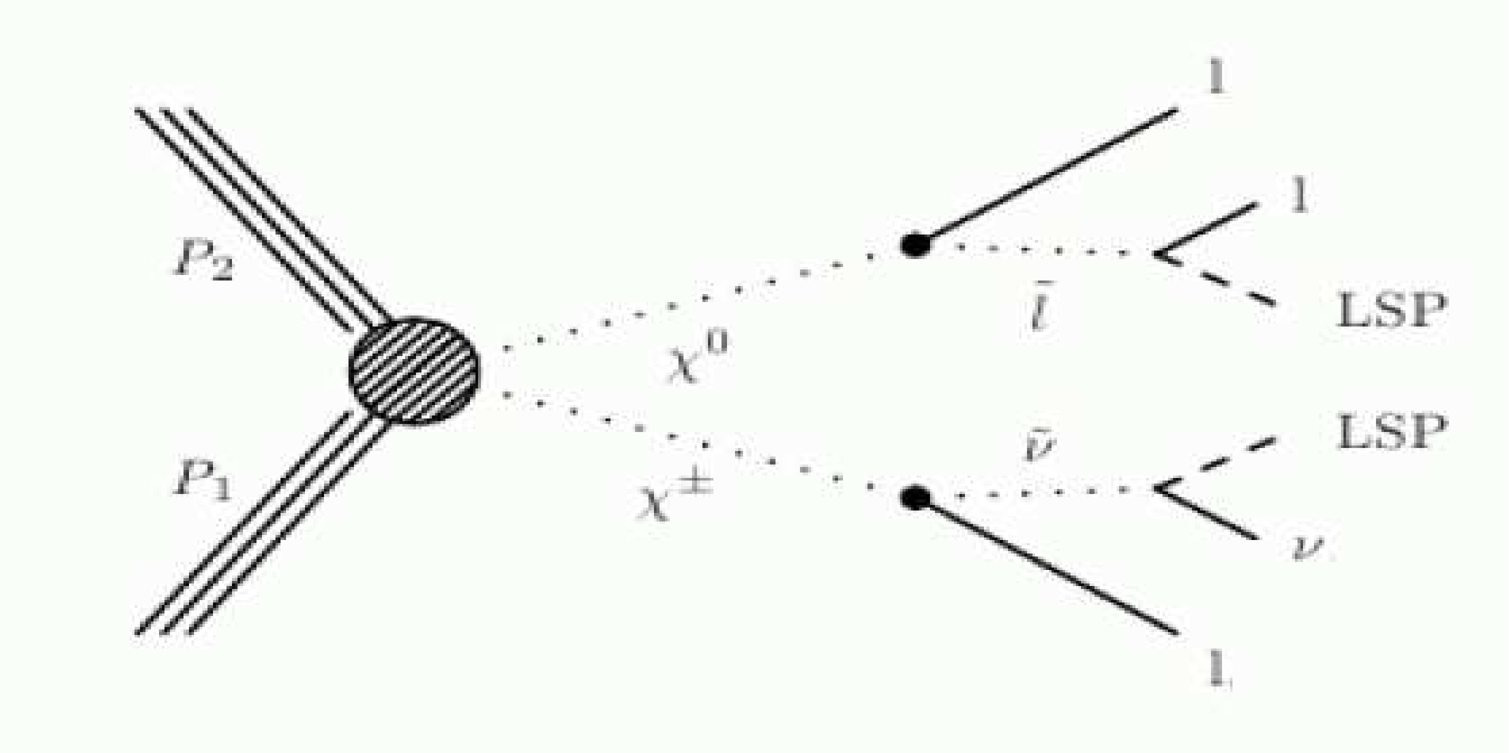
⇒ smaller production cross section
⇒ more difficult analyses . . .

⇒ no LHC limits - yet

We are eagerly waiting for these results!

Very recent exception: $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \dots$

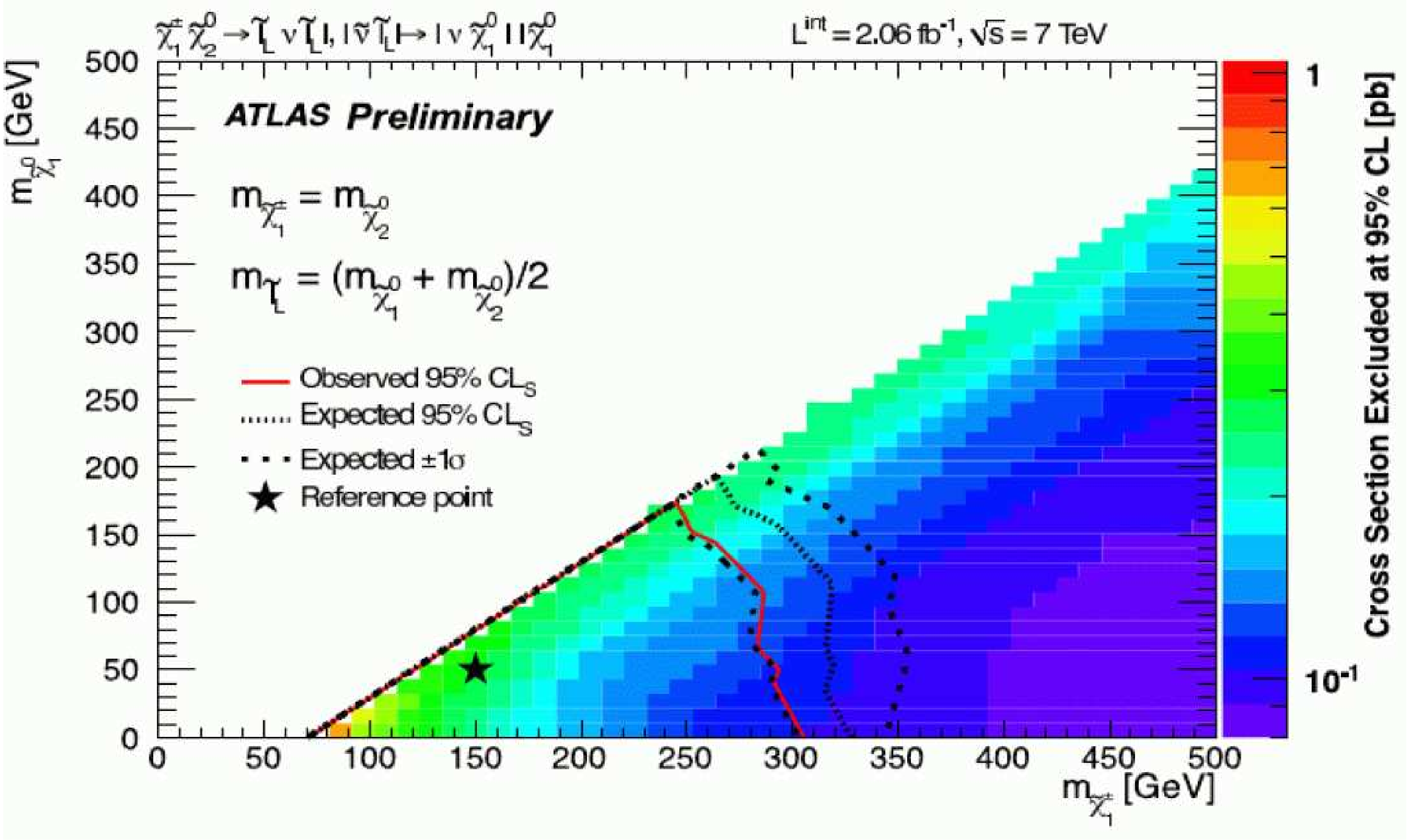
[*ATLAS '12*]



⇒ trilepton + MET

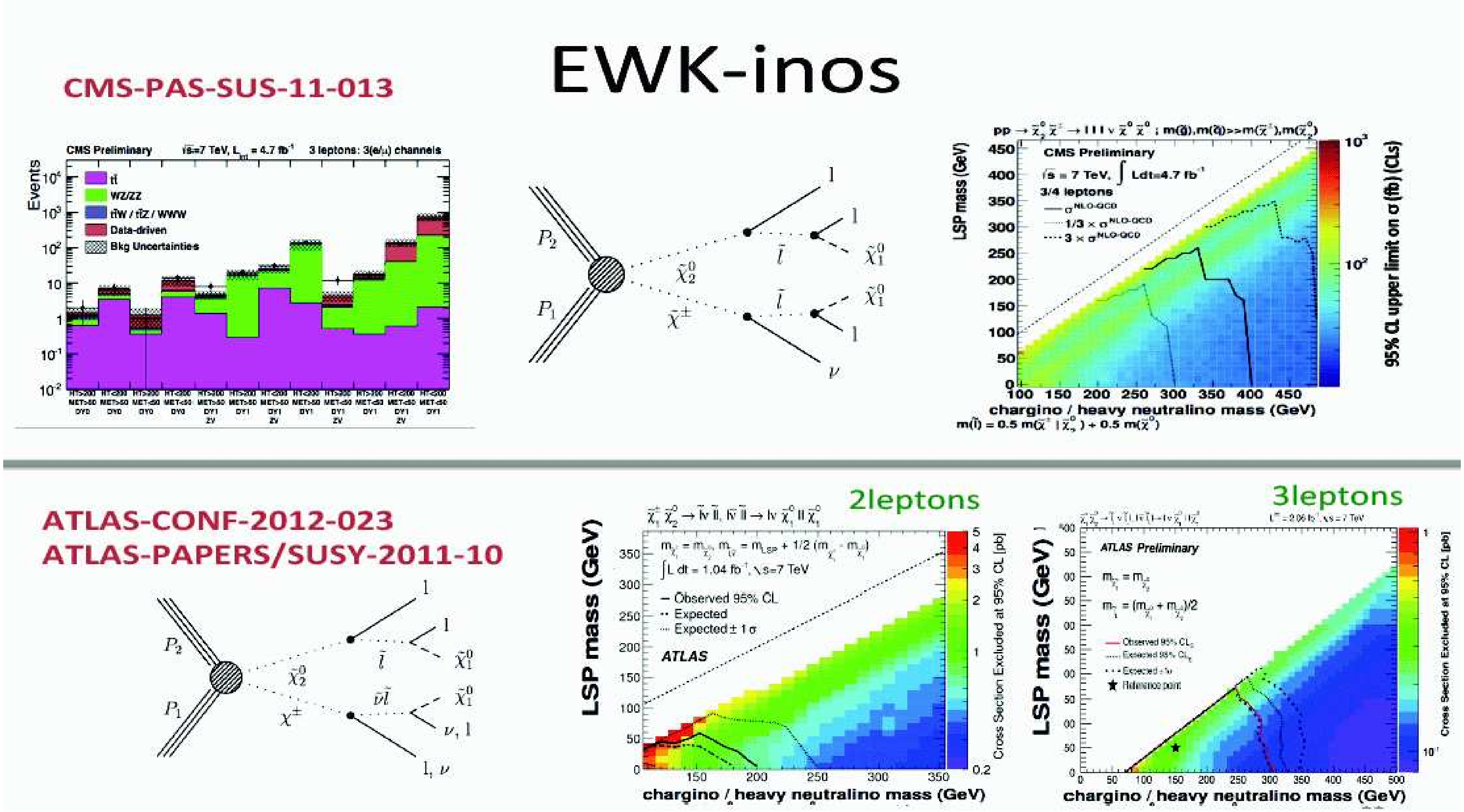
Very recent exception: $pp \to \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \dots$

[*ATLAS '12*]



⇒ no strong limits yet . . .

Overview about all "exceptions":



EWK-inos

CMS-PAS-SUS-11-013

ATLAS-CONF-2012-023
ATLAS-PAPERS/SUSY-2011-10

2leptons

3leptons

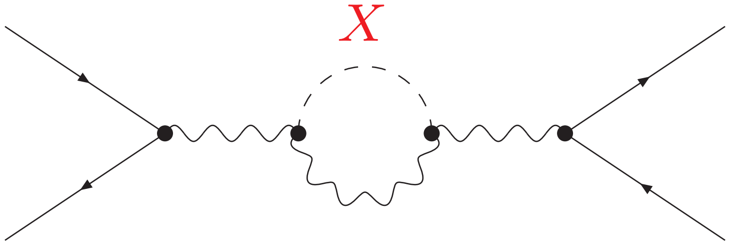
Implications for SUSY fits and Dark Matter

Comparison of precision observables with theory:

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

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections

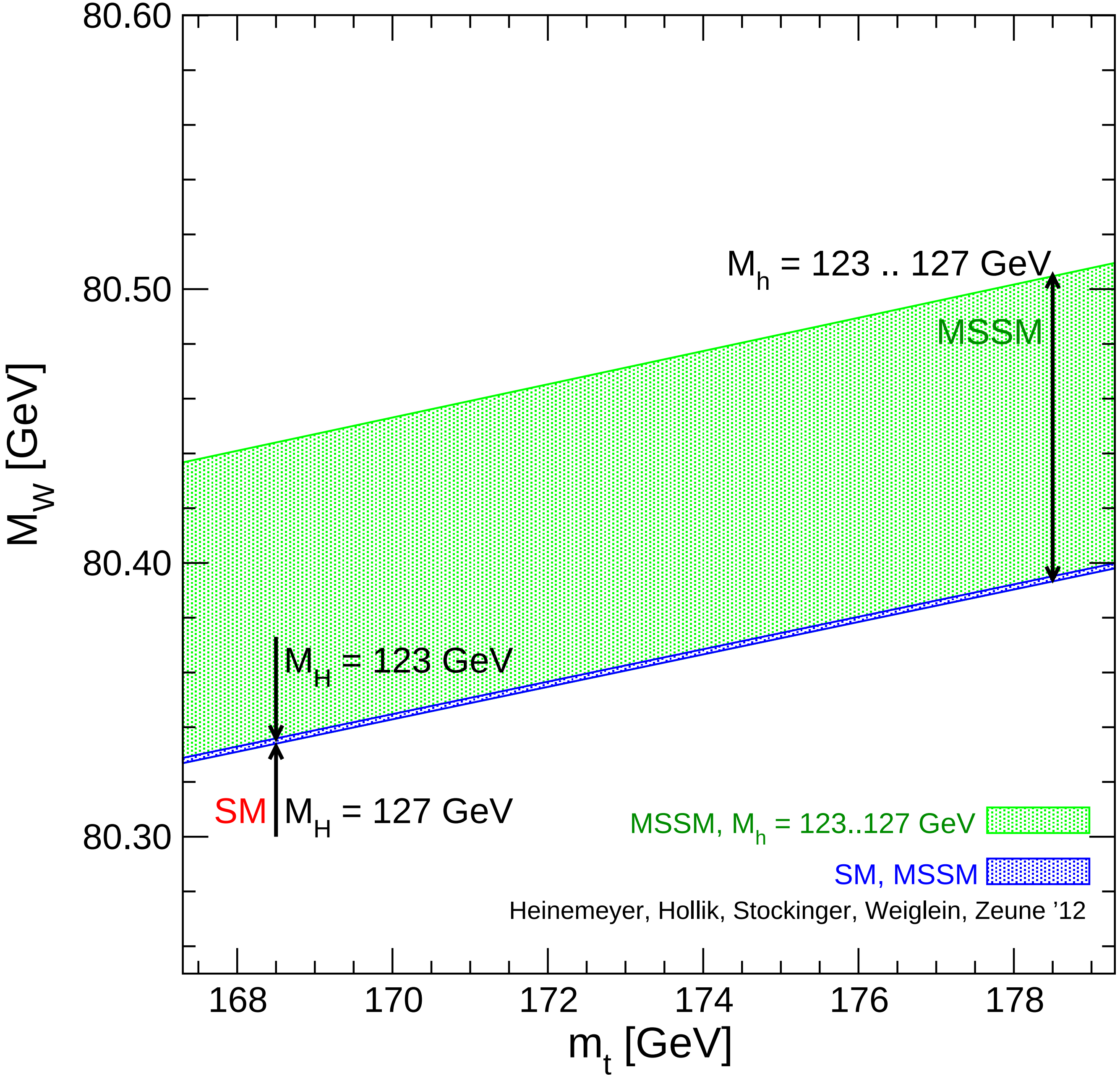


$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed

The most beautiful example:



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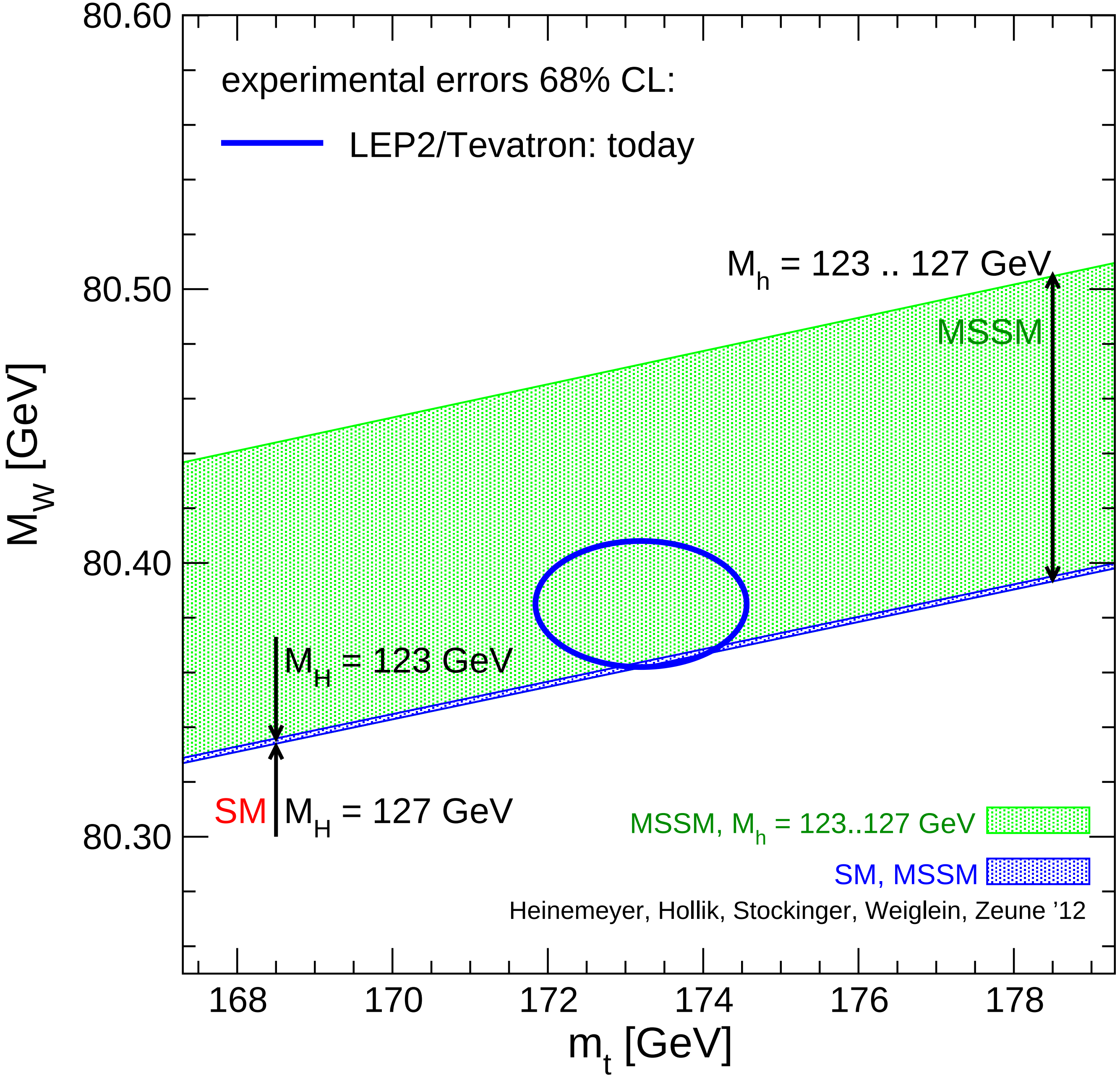


Main idea of SUSY fits:

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

⇒ Combination only possible in very const. 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, Marrouche, Martinez Santos, Olive, Rogerson, Ronga, de Vries, 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)

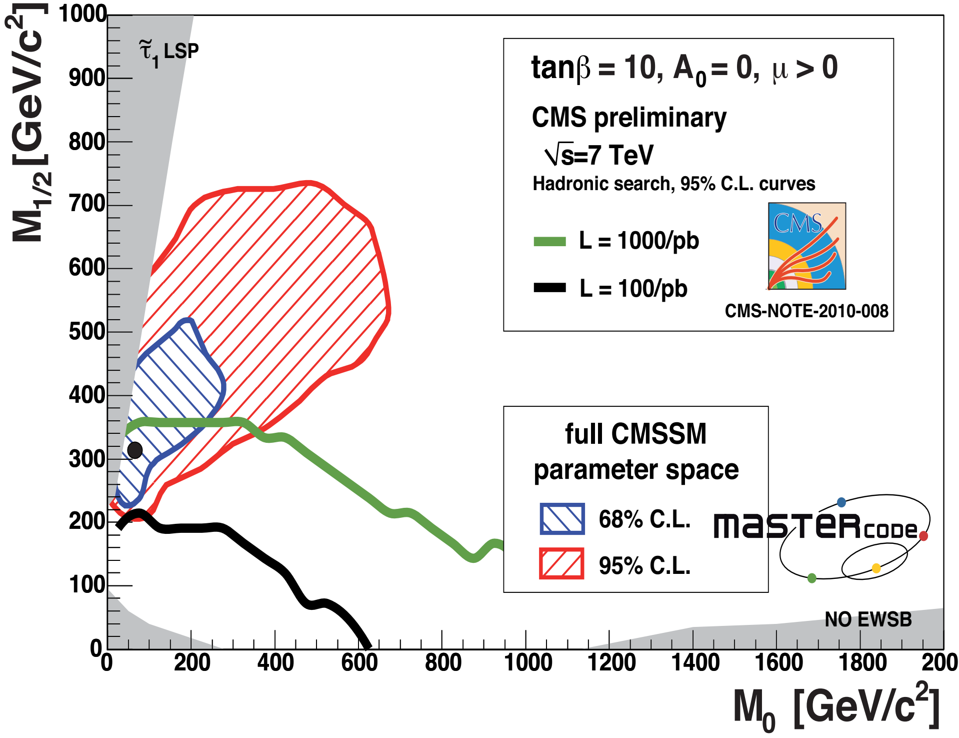
P_i: MSSM parameter-dependent prediction for the corresponding constraint

Assumption: measurements are uncorrelated - fulfilled to a high degree

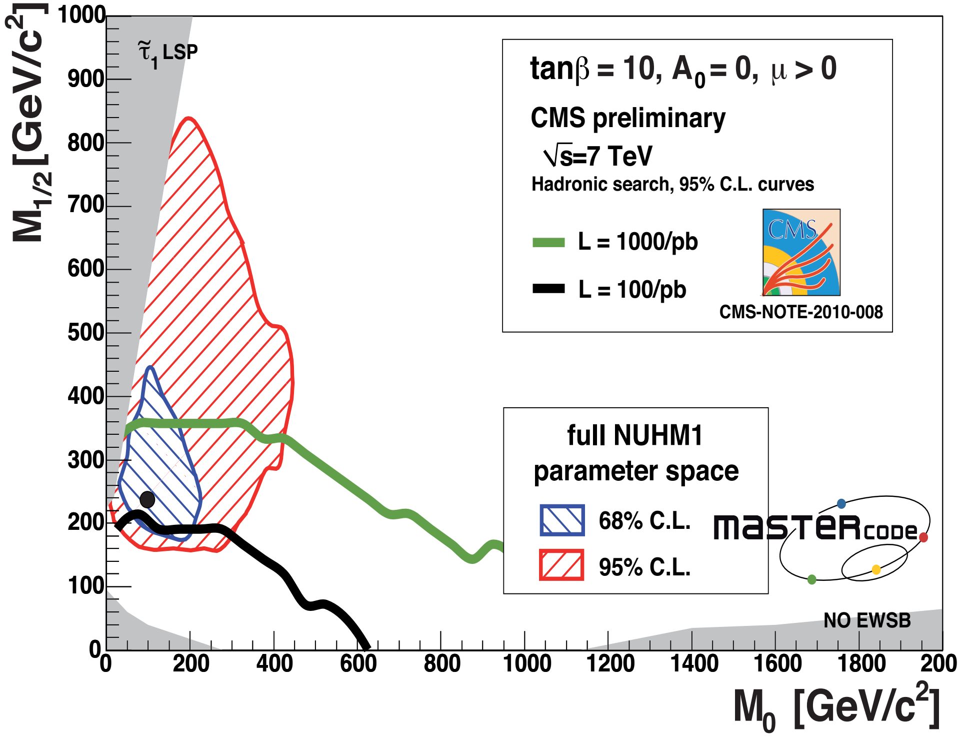
pre-LHC predictions:

[2010]

CMSSM



NUHM1



⇒ “best-fit points and part of 68% C.L. are can be tested in 2011”

Inclusion of LHC searches

Obvious idea:

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

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

Assumption for Higgs:

$$M_h = 125 \pm 1(\text{exp.}) \pm 1.5(\text{theo.})\ \text{GeV}$$

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

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⇒ Implications for SUSY fits?

⇒ Implications for Dark Matter?

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⇒ Implications for SUSY fits?

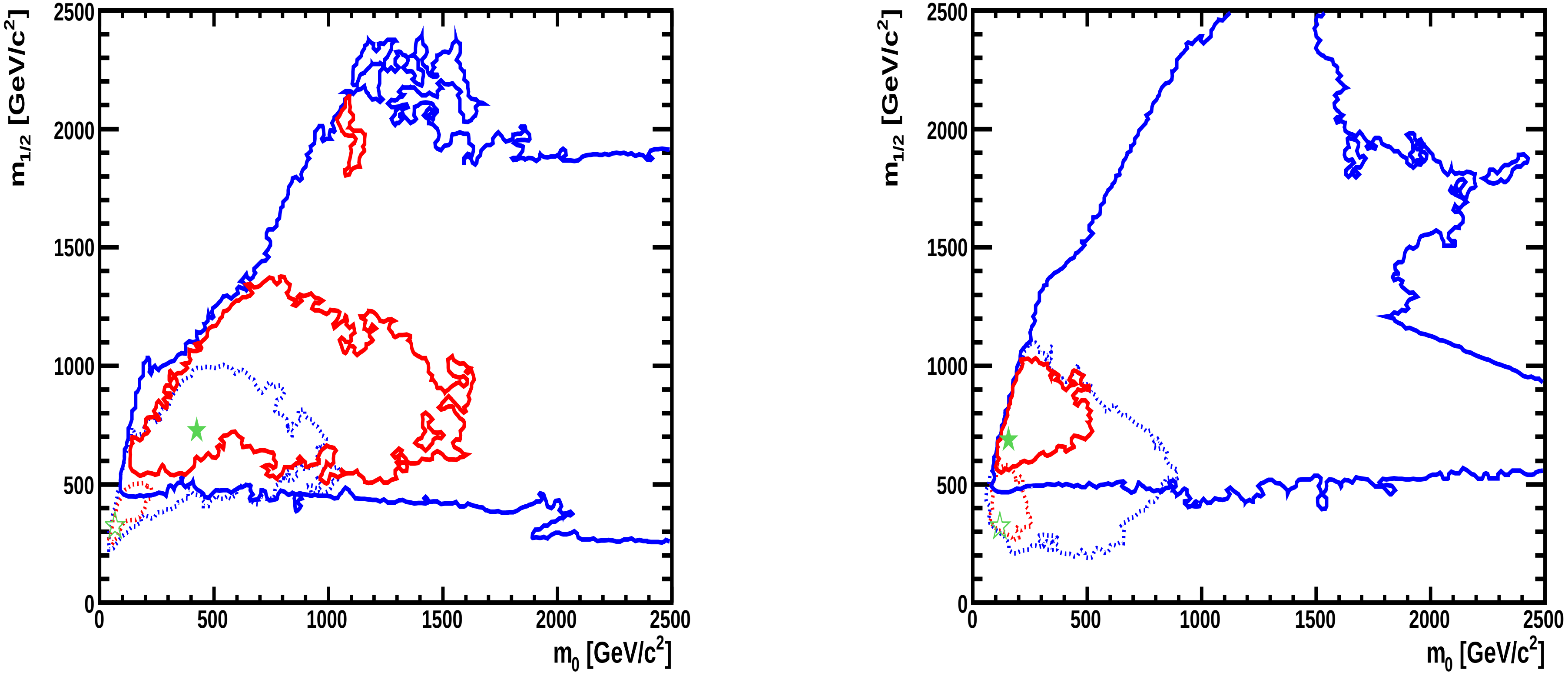
⇒ Implications for Dark Matter?

⇒ not as trivial as you might think!

m_0-$m_{1/2}$ plane including 1/fb of LHC data:

[2011]

CMSSM NUHM1



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

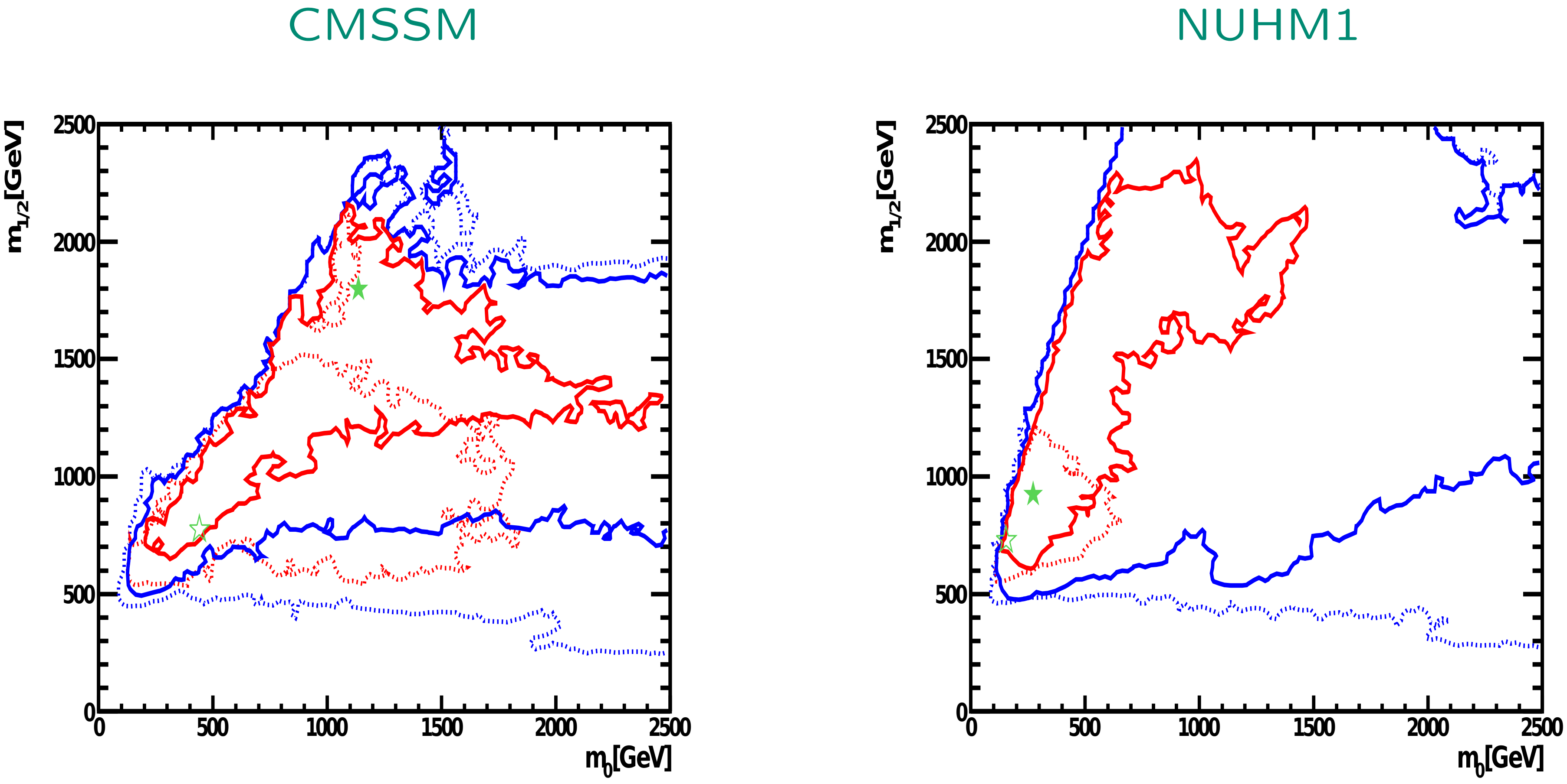
⇒ new best-fit point within old 95% CL area

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

⇒ shift to higher masses

m_0-$m_{1/2}$ plane including “Higgs measurement”:

[2011]



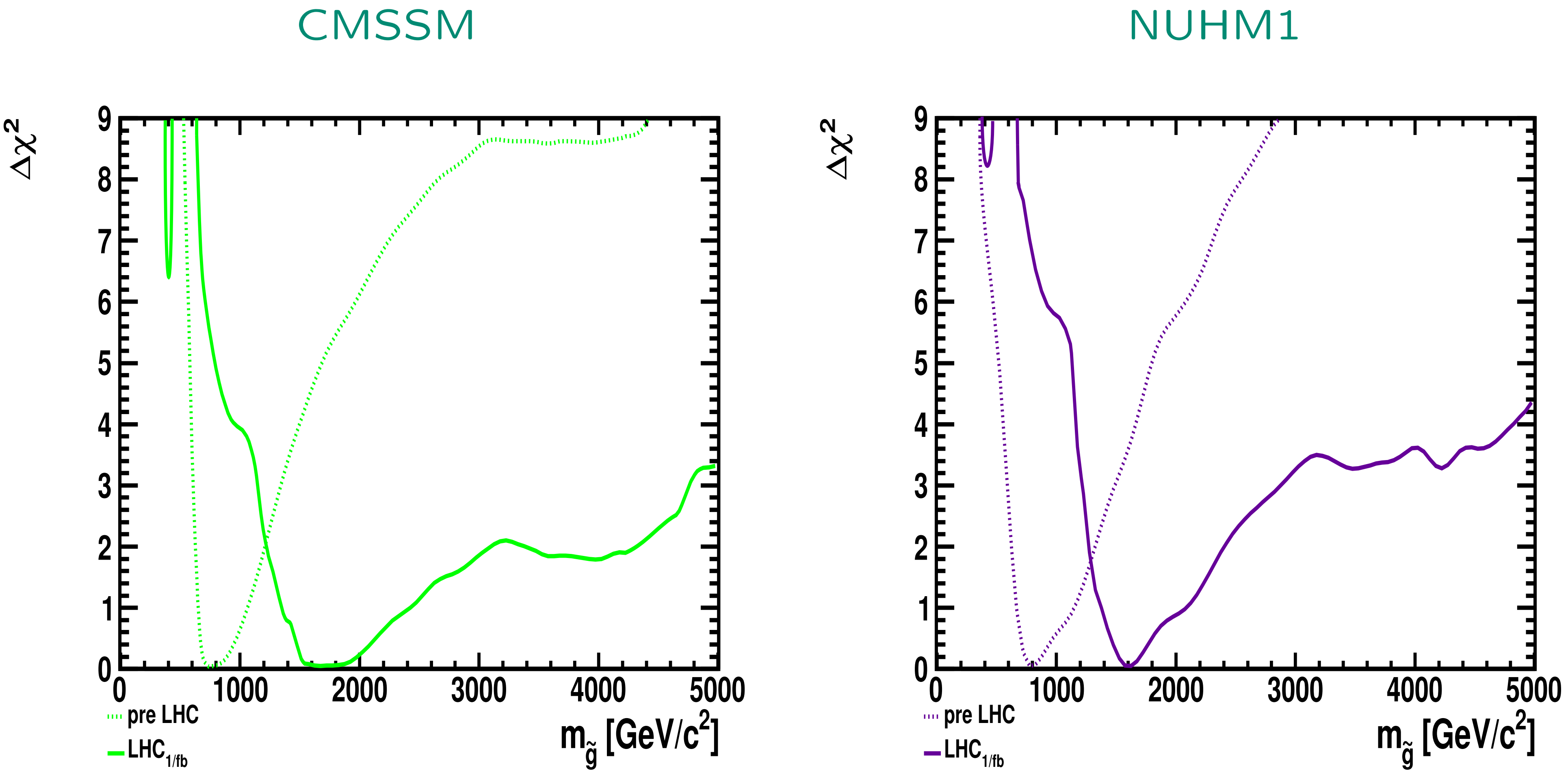
dotted: pre-Higgs, solid: post-Higgs

⇒ shift to even higher masses

even larger allowed ranges . . . ⇒ bad prospects for DM searches?

Starting point of the cascade: gluino (incl. 1/fb of LHC data)

[2011]



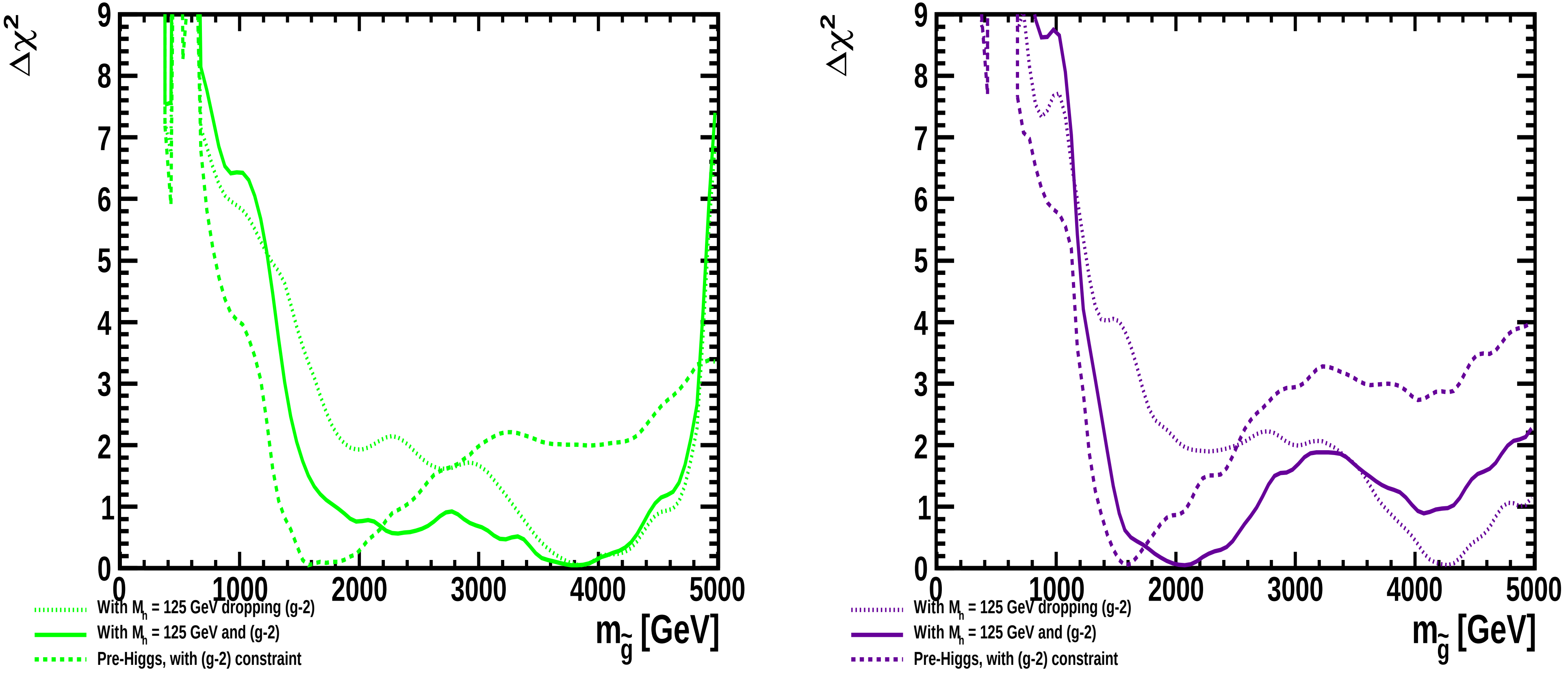
dotted: pre-LHC/Xenon, solid: post-LHC (1 fb^{-1})/Xenon

⇒ substantial upward shift

Starting point of the cascade: gluino (incl. “Higgs meas.”)

[2011]

CMSSM NUHM1



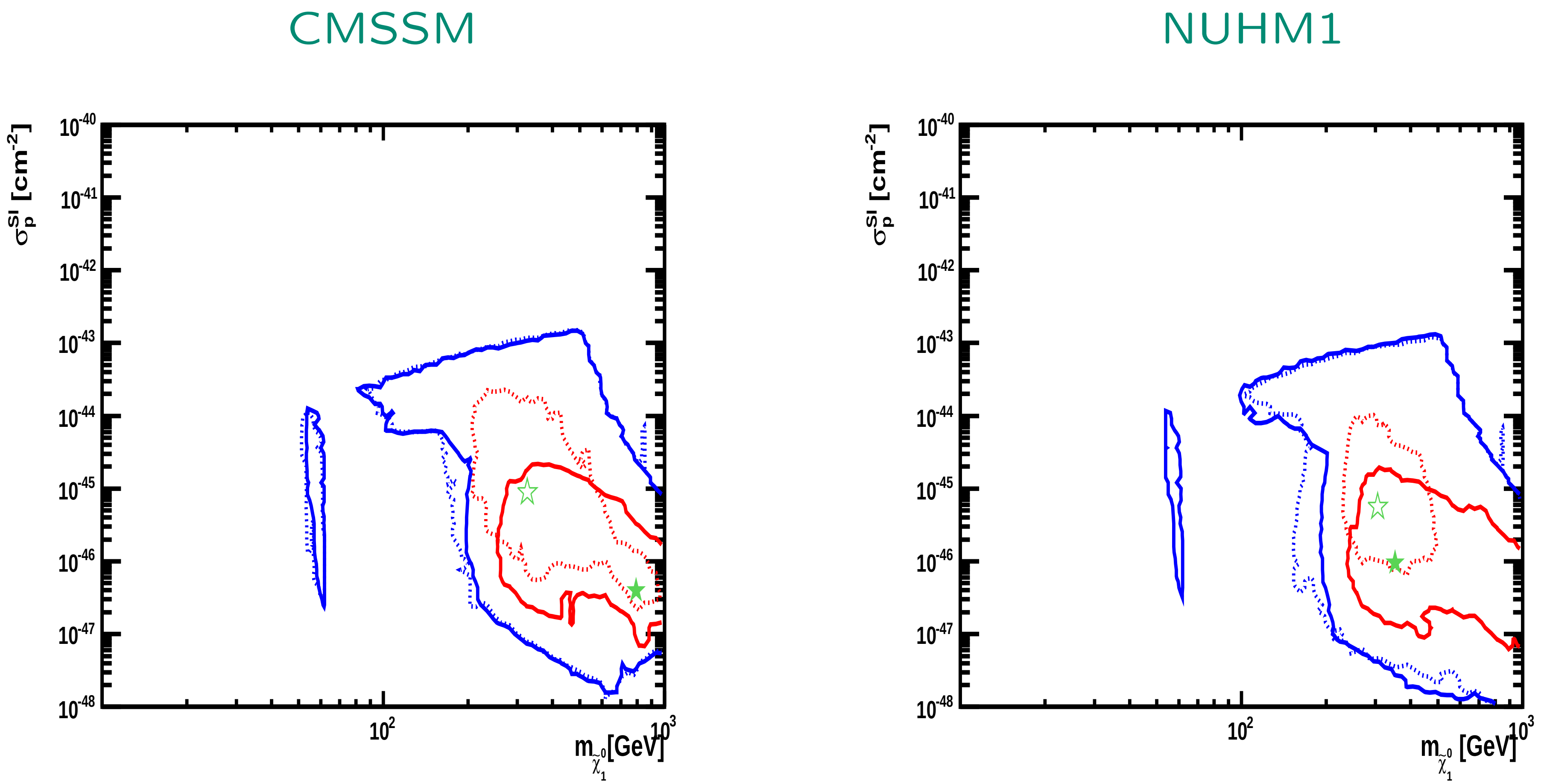
dashed: pre-Higgs, solid: post-Higgs

⇒ another upward shift - very shallow now

$m_{\tilde{\chi}_1^0}$-σ_p^{SI} plane including "Higgs measurement":

mastercode

[2011]



dotted: pre-Higgs, solid: post-Higgs

⇒ shift higher masses and lower cross sections

⇒ bad expectations?

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

M_h "measurement" moves the fit to even higher 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	21.5/20	37%	360	90	-50	15	111
LHC 1 fb^{-1}	28.8/22	15%	780	450	-1100	41	119
$M_h = 125$	31.0/23	12%	1800	1140	1370	46	–
NUHM1	20.8/18	29%	340	110	520	13	119
LHC 1 fb^{-1}	27.3/21	16%	730	150	-910	41	119
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Probabilities still ok, but this might change with more data.

Not finding SUSY early does not make DM looks bad,

makes some very constrained models look bad!

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An MSSM Higgs at 125 GeV makes CMSSM/NUHM1 unlikely

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And requires SUSY realizations that are in agreement with
- higher colored mass scales (LHC limits)
- lower uncolored mass scales (EWPO; $(g-2)_\mu$) ⇒ DM

An MSSM Higgs at 125 GeV makes CMSSM/NUHM1 unlikely

And requires SUSY realizations that are in agreement with
- higher colored mass scales (LHC limits)
- lower uncolored mass scales (EWPO; $(g-2)_\mu$) $\Rightarrow$ DM

The LHC searches (mainly) for colored particles,
DM requires (mainly) uncolored particles!

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

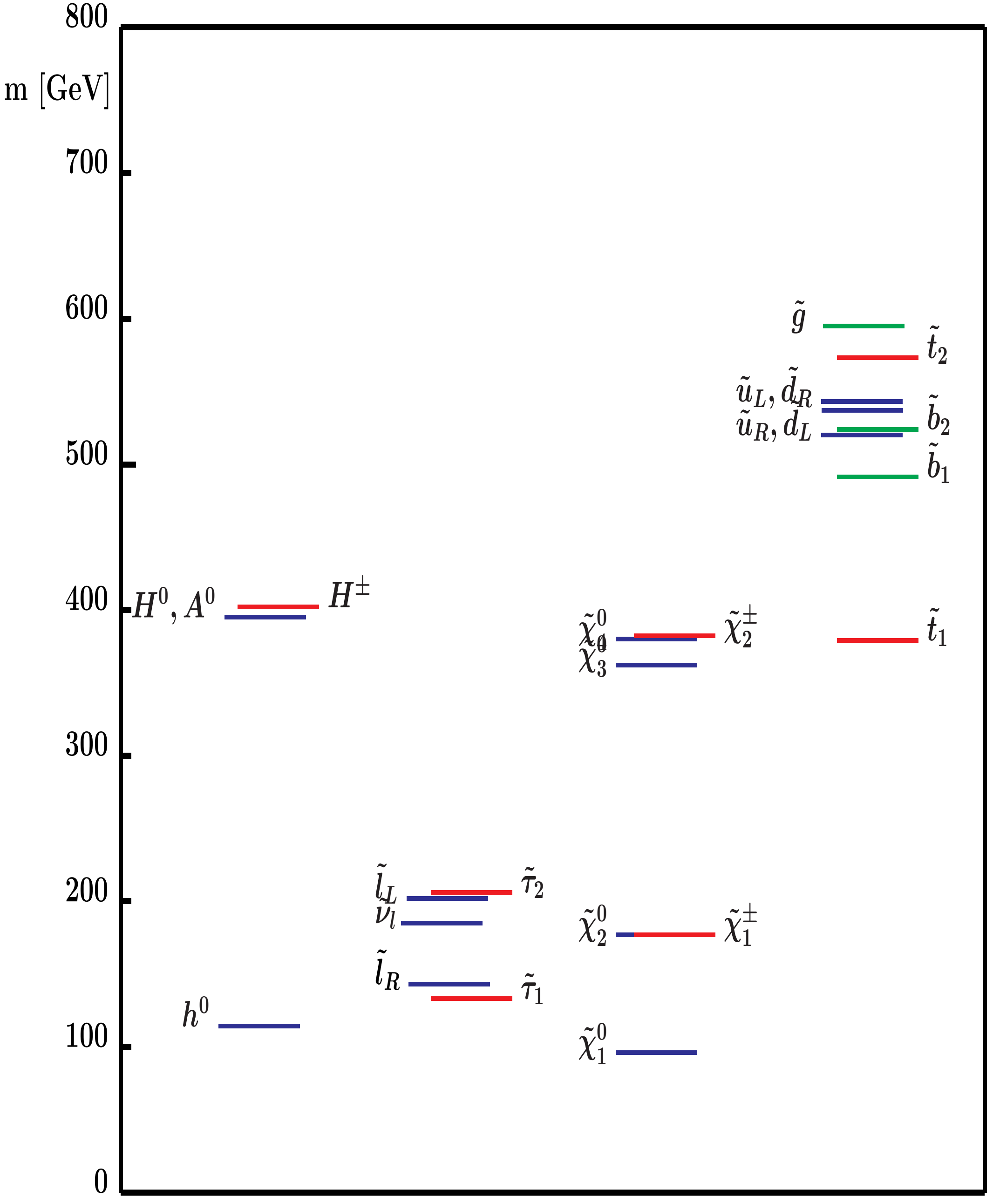
$\Rightarrow$ look for other models...?

“Typical” CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

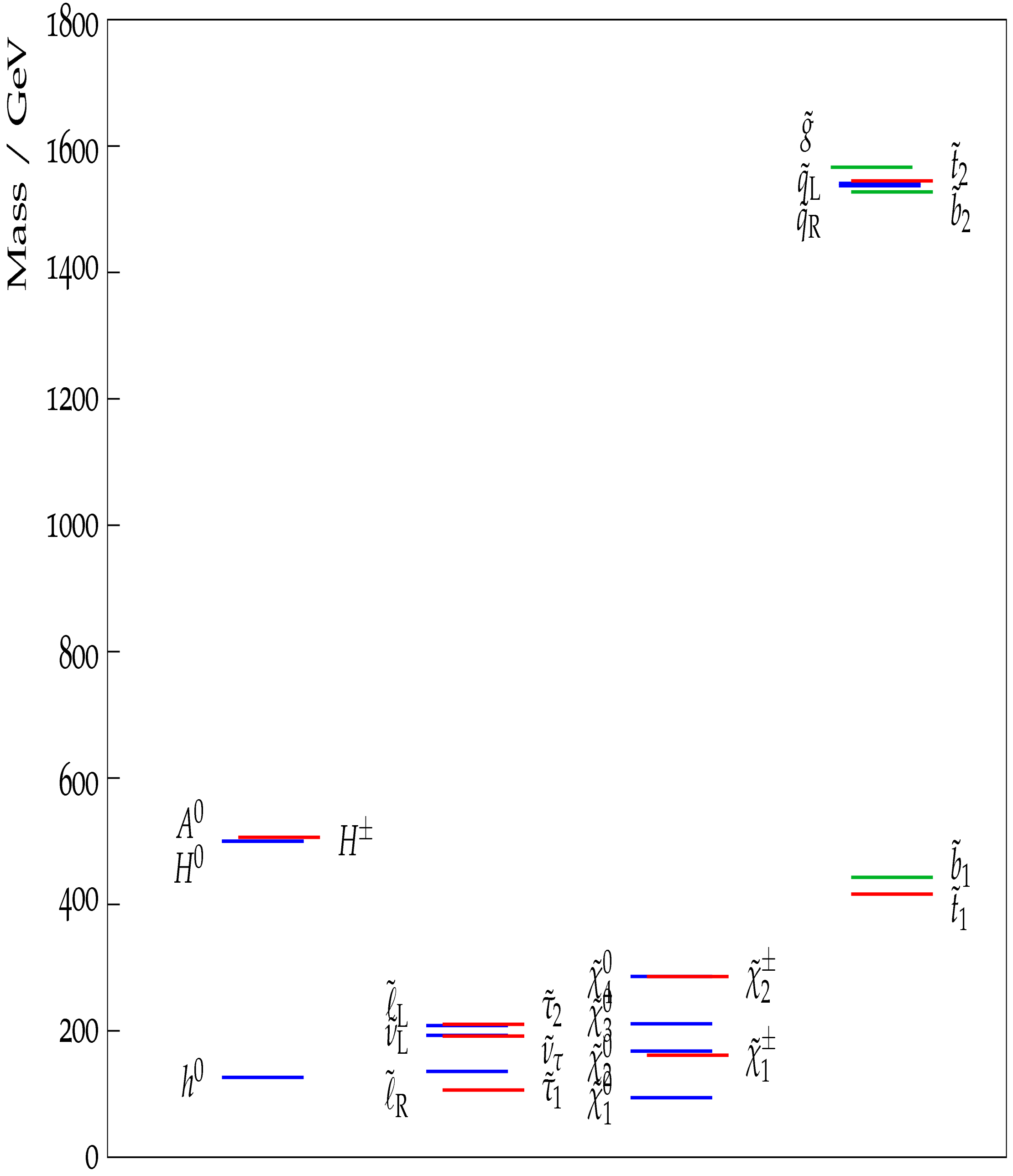
all the sectors



SPS1a variant (I)

colored and uncolored sector decoupled:

[J. List et al. ’12]



SPS1a variant (II)

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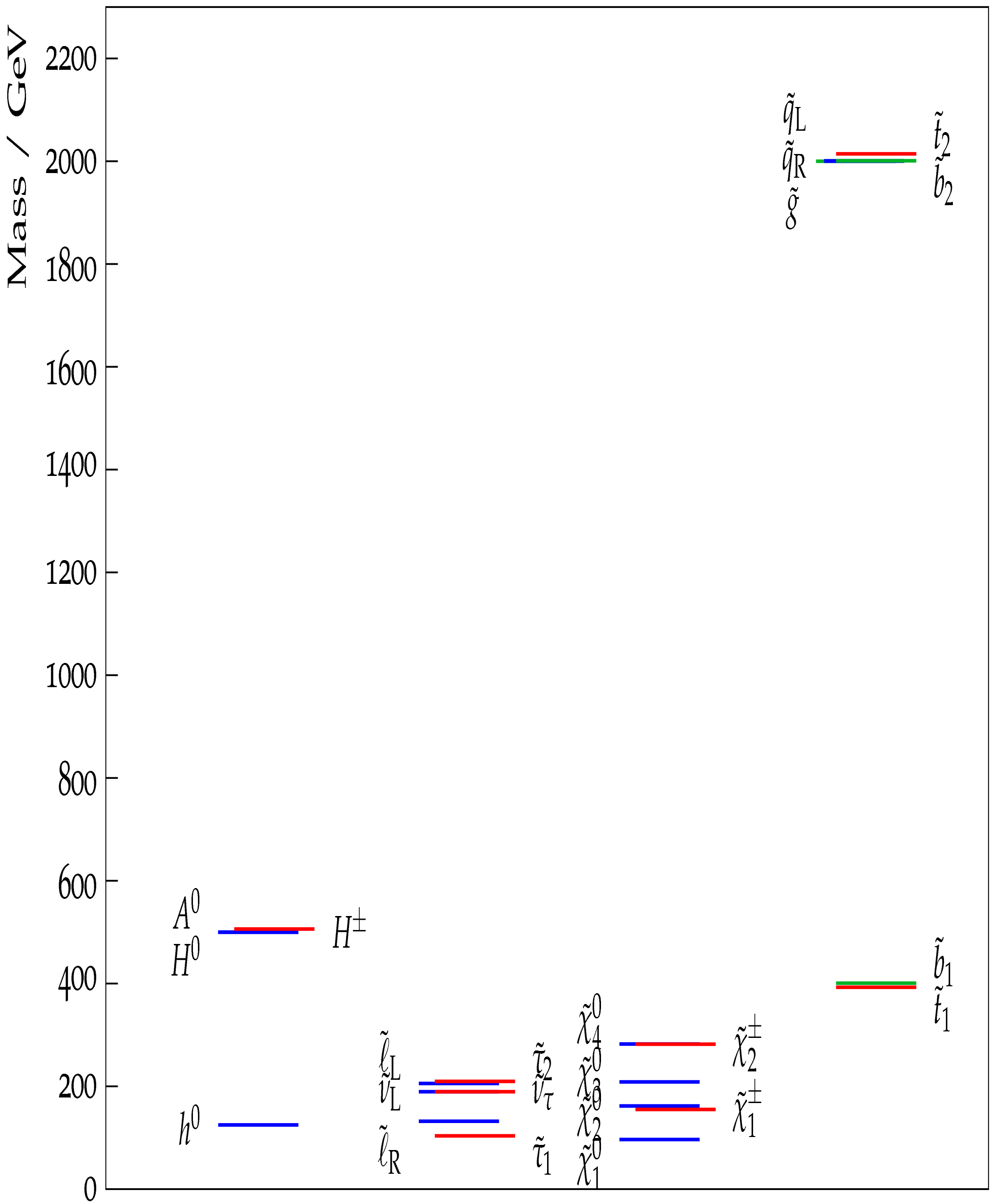
[J. List et al. '12]



5. Conclusinos

- The Standard Model (SM) of particle physics: rock-solid foundation

  problem: no Dark Matter candidate

- Interesting alternative: Supersymmetry

  → Minimal Supersymmetric Standard Model (MSSM)
  ⇒ Dark Matter candidate: $\tilde{\chi}_1^0$, coupling constrant unification, . . .

- Higgs searches at the LHC: we have a **DISCOVERY !!! :-)**

  ⇒ compatible with $M_H \simeq 125$ GeV

- SM interpretation: fits well
  MSSM interpretation: fits equally well – or even better?

  ⇒ slowly approaching coupling determination

- SUSY searches:
  Results are presented in the CMSSM or in "simplified models"
  ⇒ limits of $\sim 500 - 1200$ GeV
  ⇒ weak limits for 3rd generation squarks, "EW SUSY particles"

  ⇒ all limits strongly dependent on assumptions!

Higgs Days at Santander 2012

Theory meets Experiment

17.-21. September

contact: Sven.Heinemeyer@cern.ch

http://www.ifca.es/HDays12