Recent LHC Results from a Theory Perspective

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1. Introduction
2. Recent Higgs searches at the LHC
3. Recent SUSY searches at the LHC
4. Implications for SUSY fits
5. Implications for future e^+e^- colliders
6. Conclusions

1. Introduction

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"?

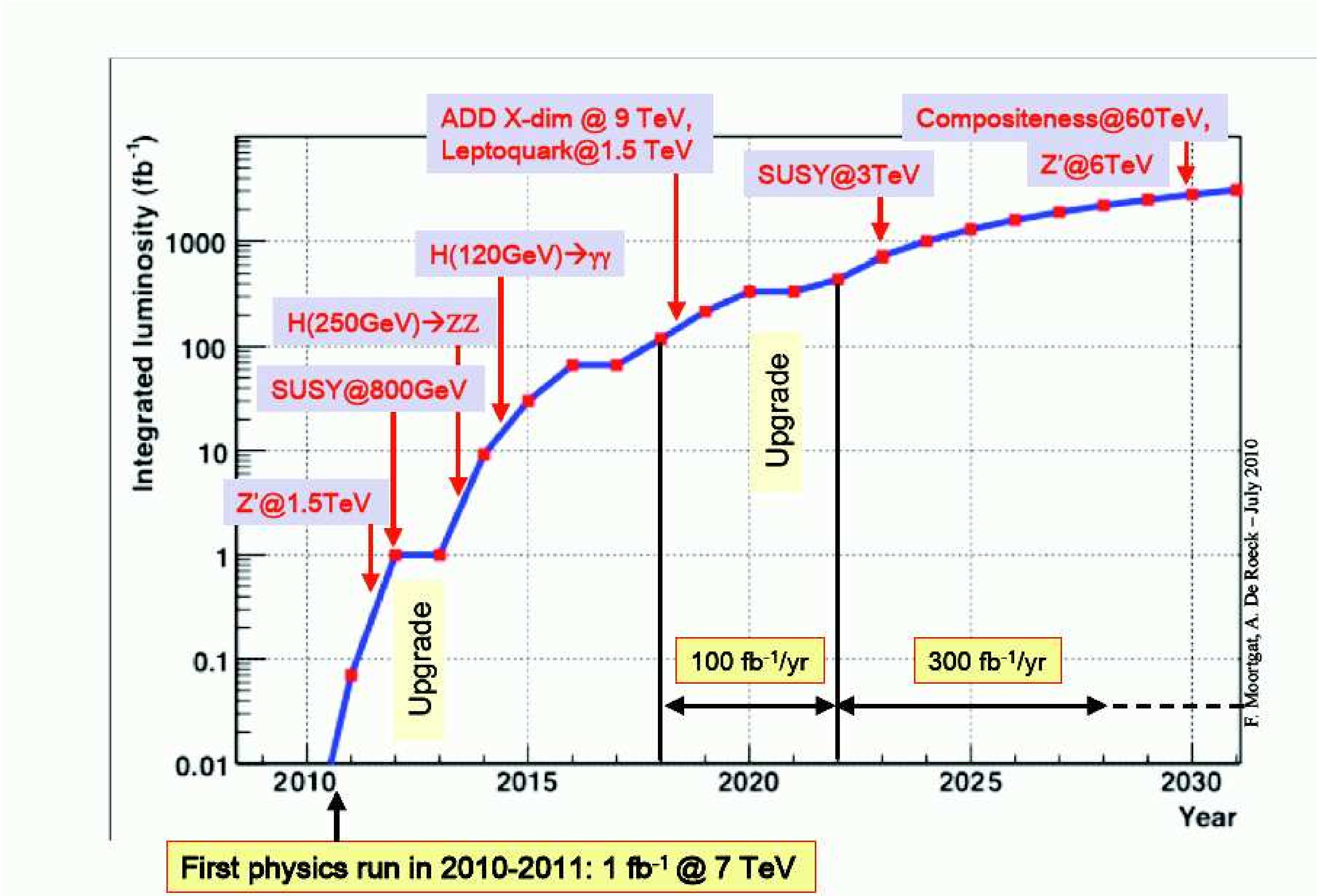
- Can dark matter be produced in the laboratory?

- . . .

$\Rightarrow$ so we set out and built the LHC!

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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$\boxed{\text{Standard Model has been rediscovered!}}$

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$\boxed{\text{Standard Model has been rediscovered!}}$

$\boxed{\text{No evidence for new physics - yet!}}$

The big problem in the SM:

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:

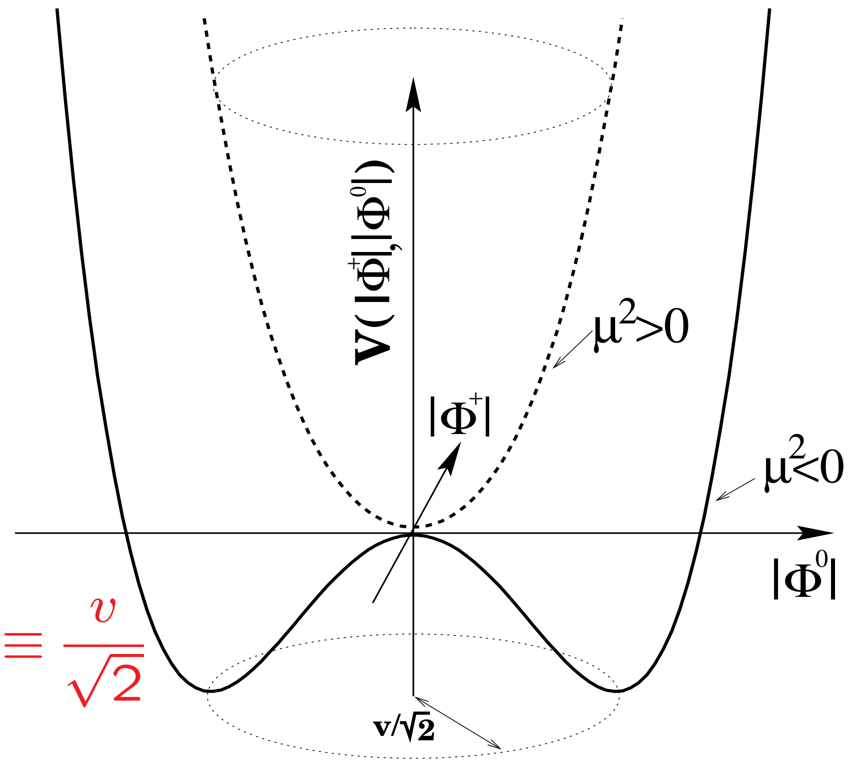
Scalar SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

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

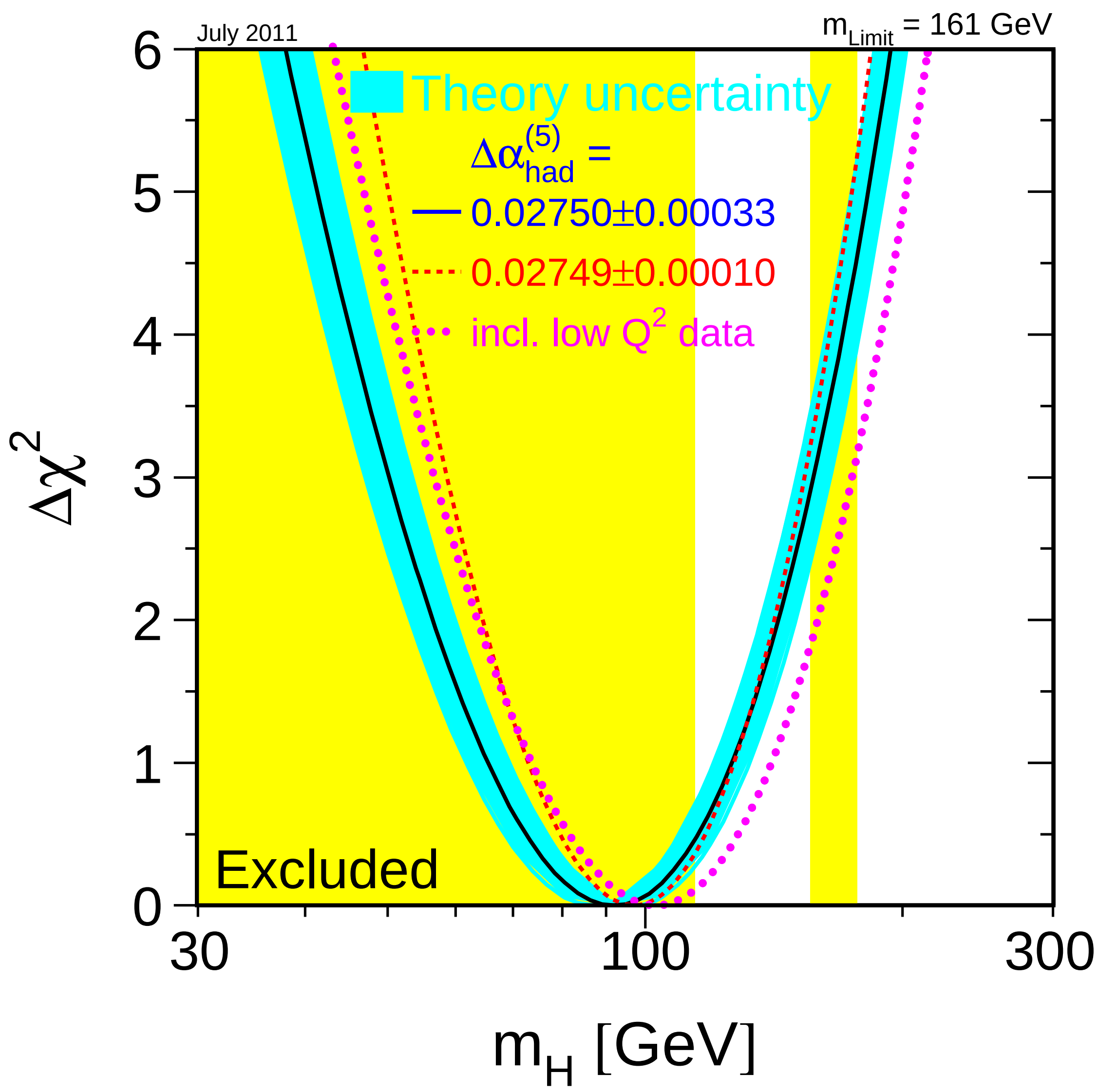
$\Rightarrow$ mass terms for gauge bosons and fermions

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

Supersymmetry:

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:

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

$\Rightarrow$ each SM multiplet is enlarged to its double size

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

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

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

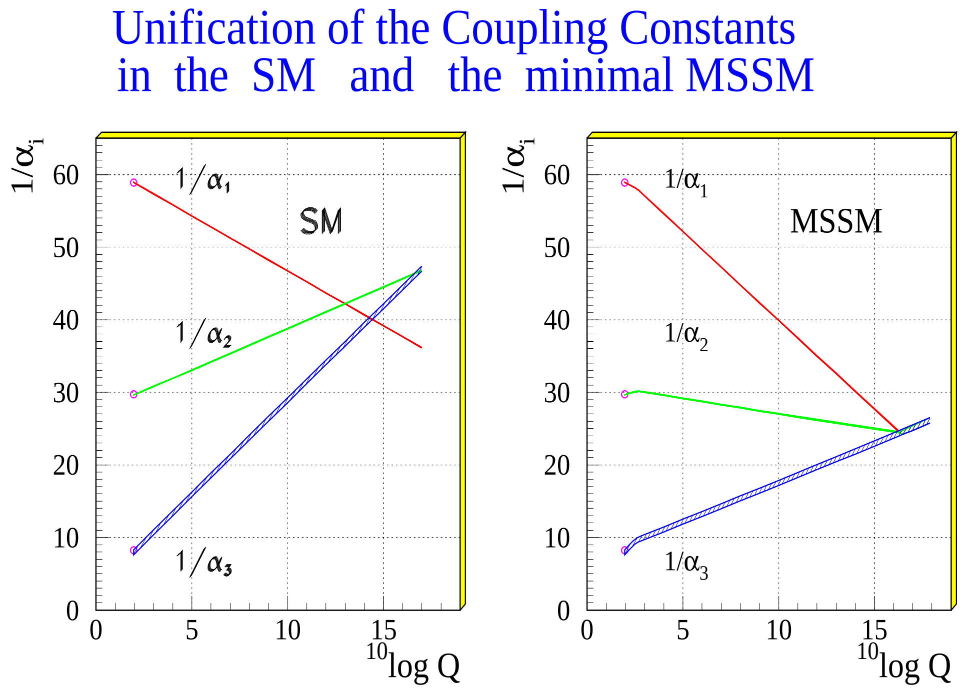
SUSY particles are made heavy: $\boxed{M_{\text{SUSY}} = \mathcal{O}(1\ \text{TeV})}$

Supersymmetry: Motivation

The SM is in a pretty good shape.

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

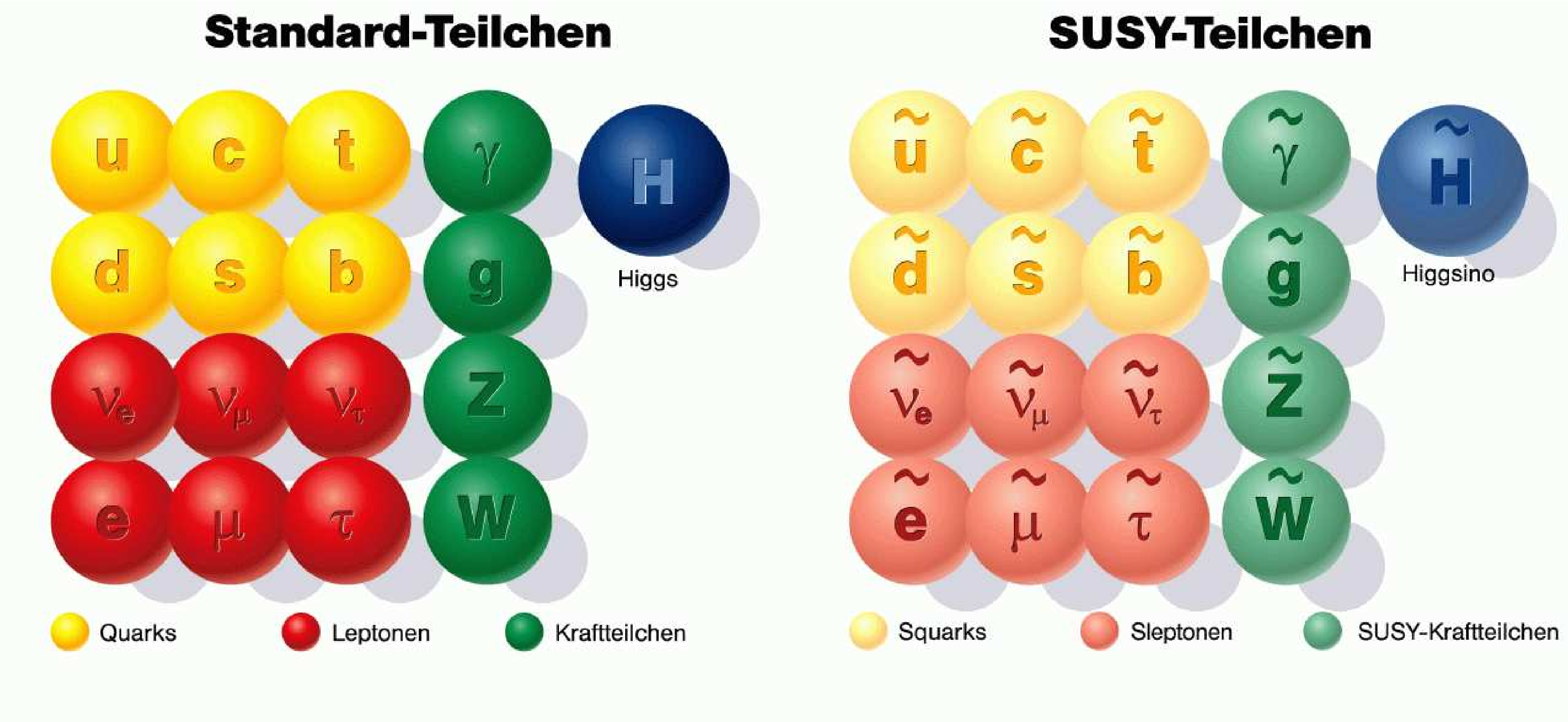
1.) Stability of the Higgs mass against higher-order corr.
2.) Unification of gauge couplings: Not possible in the SM, but in the MSSM (although it was not designed for it.)
3.) Spontaneous symmetry breaking via Higgs mechanism is automatic in SUSY GUTs
4.) SUSY provides CDM candidate
5.) . . .



[*Amaldi, de Boer, Fürstenau '92*]

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles



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”: $\longrightarrow$ 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

$\Rightarrow$ all new low-energy parameters expressed through a few GUT scale parameters!

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

⇒ Scenario characterized by

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

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

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

sign(μ) : sign of supersymmetric Higgs parameter

⇒ particle spectra from renormalization group running to weak scale

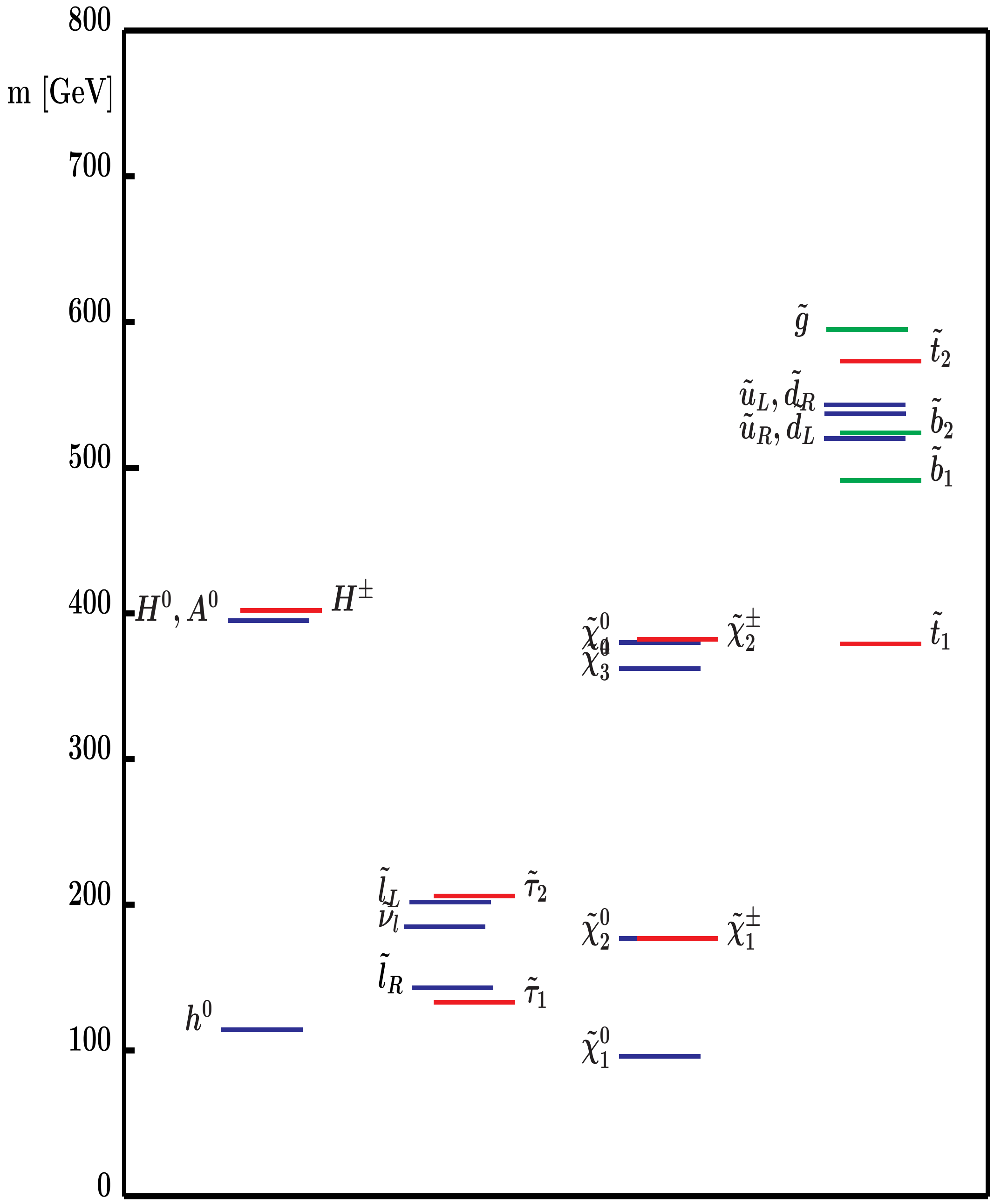
⇒ Lightest SUSY particle (LSP) is the lightest neutralino

"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

$\Rightarrow$ 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 . . .

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)

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

The decoupling limit:

For $M_A \gtrsim 150$ GeV:

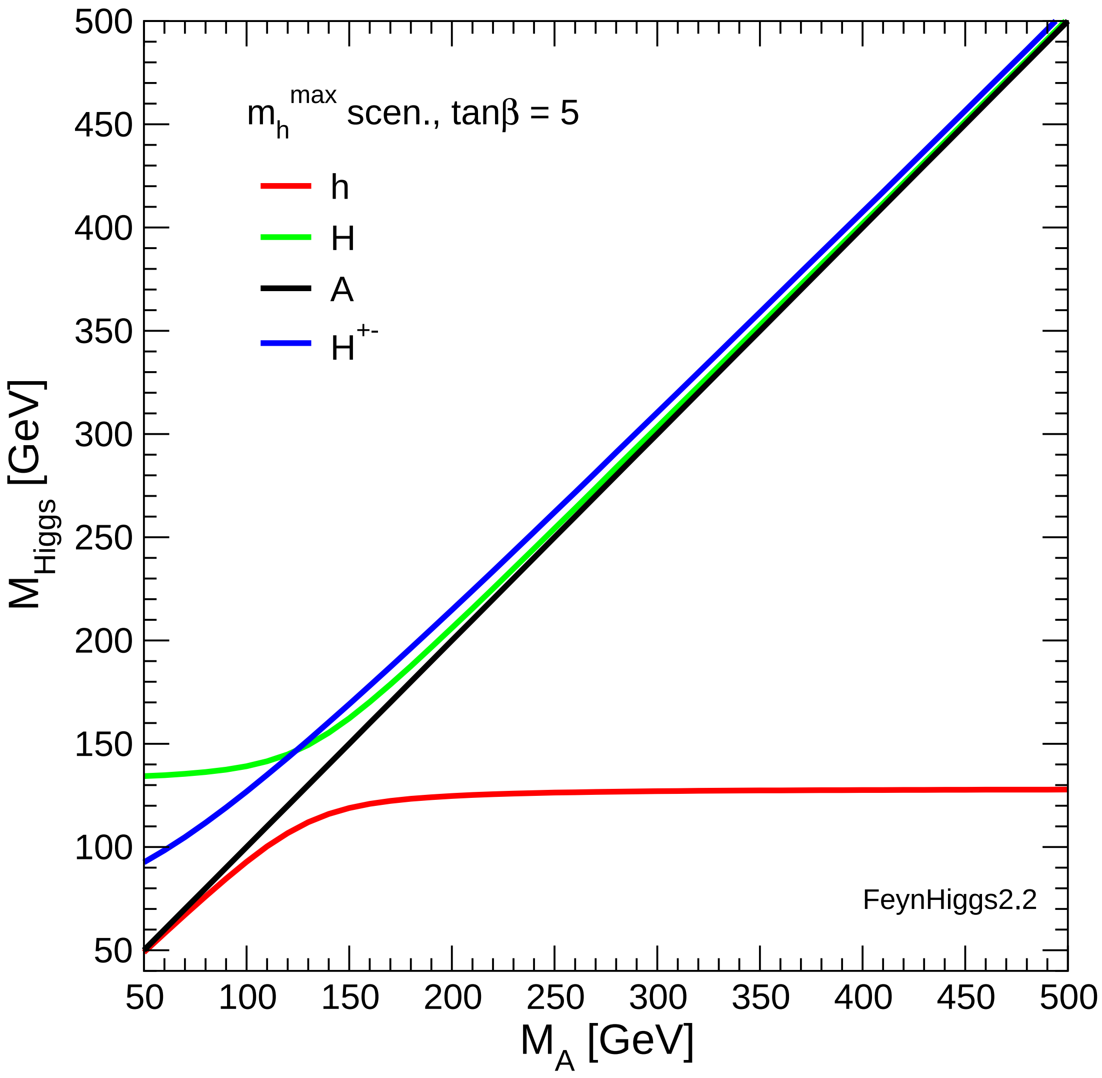
The lightest MSSM Higgs
is SM-like

$\Rightarrow$ SM analysis applies!

The heavy MSSM Higgses:
$M_A \approx M_H \approx M_{H^\pm}$

$\to$ coupling to gauge bosons ~ 0

$\Rightarrow$ no decay $H \to WW^{(*)}$, . . .



2. Recent Higgs searches at the LHC

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?

	T	L	I
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

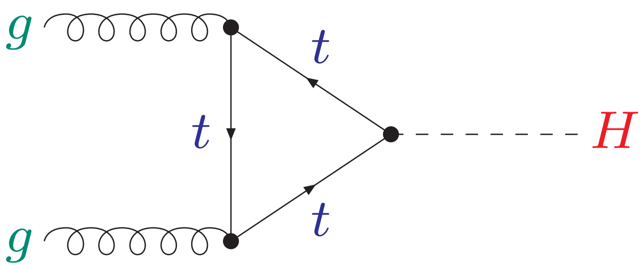
T = Tevatron, L = LHC, I = ILC

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

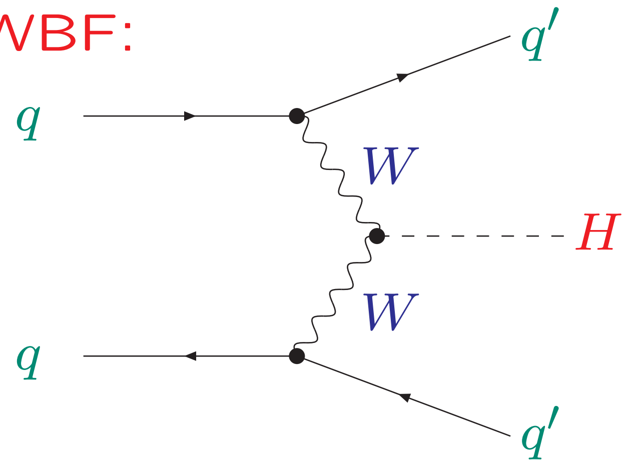
SM Higgs search at the LHC:

Important SM production channel at the LHC:

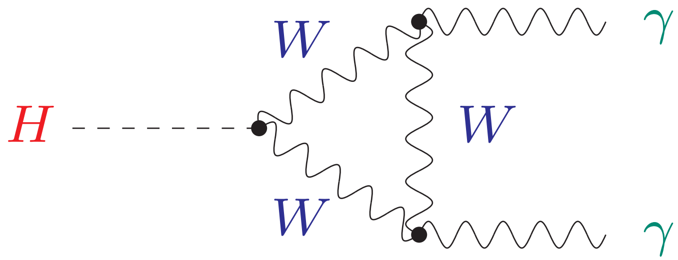
Gluon-Fusion:

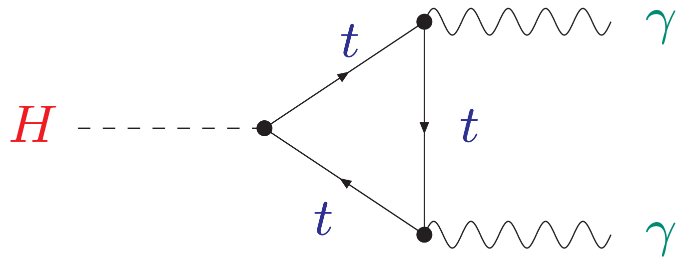


WBF:



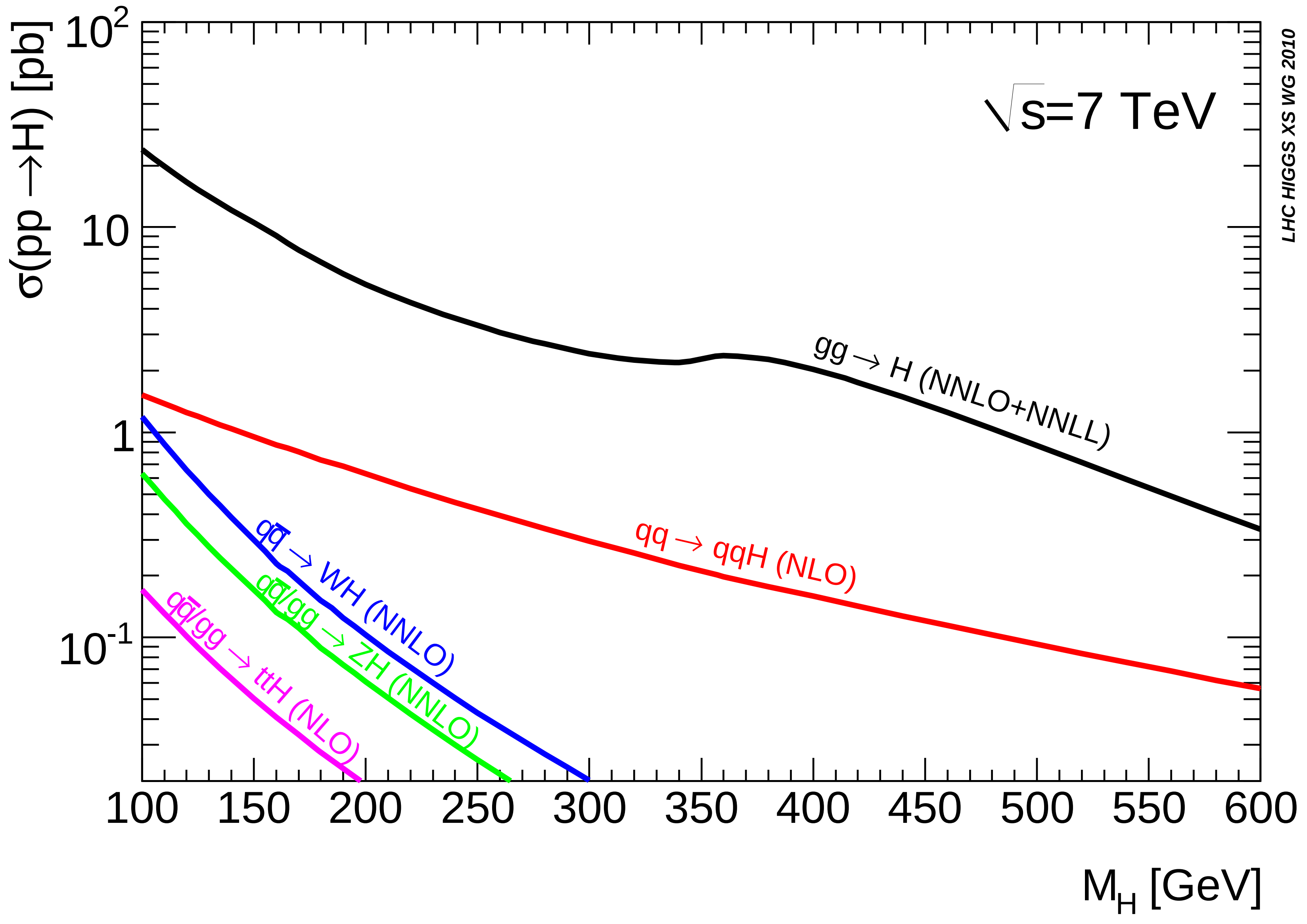
Important decay for Higgs mass measurement:





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

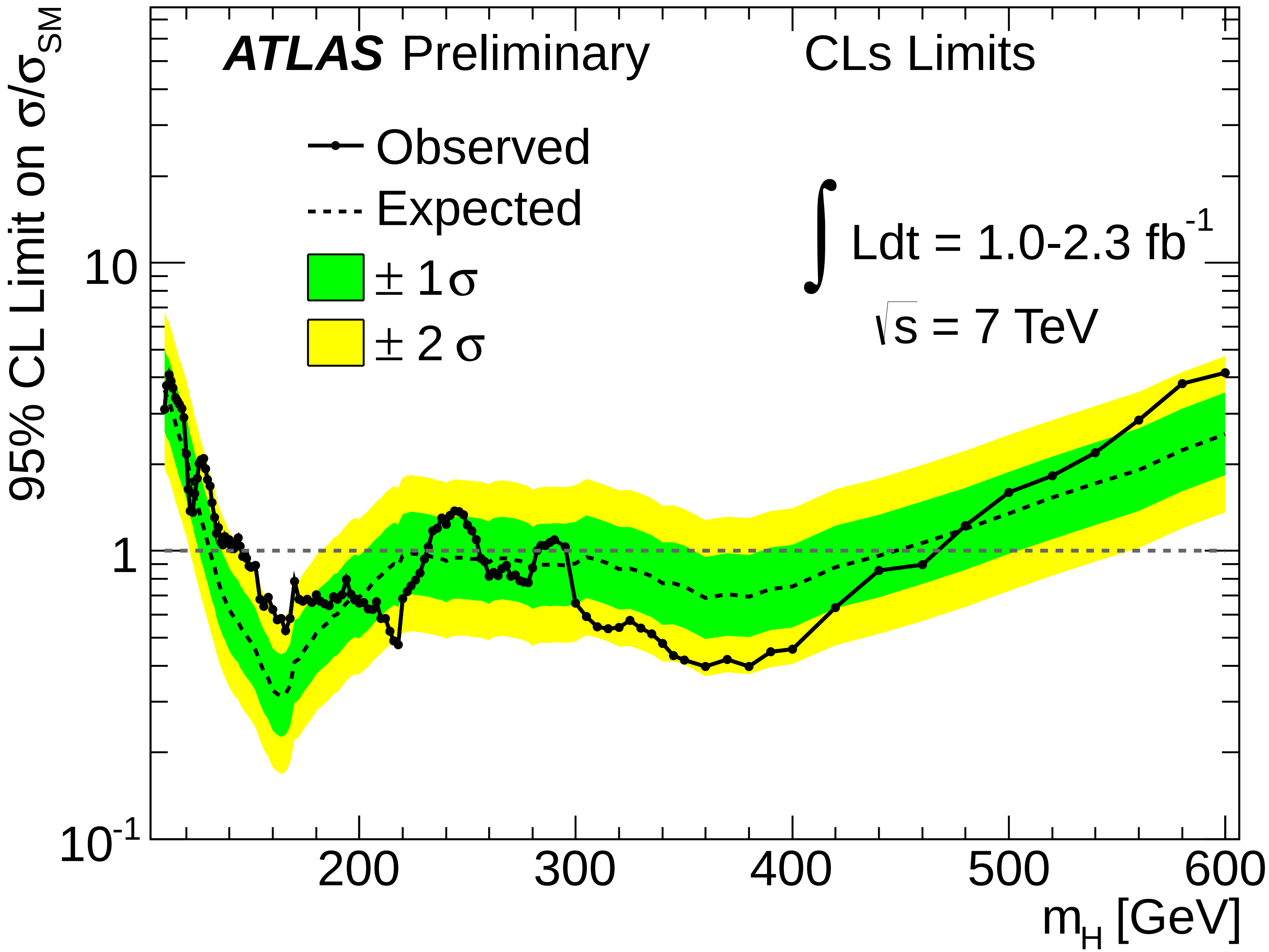
- Mixed group of ATLAS/CMS experimentalists and theorists (crucial!)

- Subgroups for each LHC Higgs production cross section or BRs

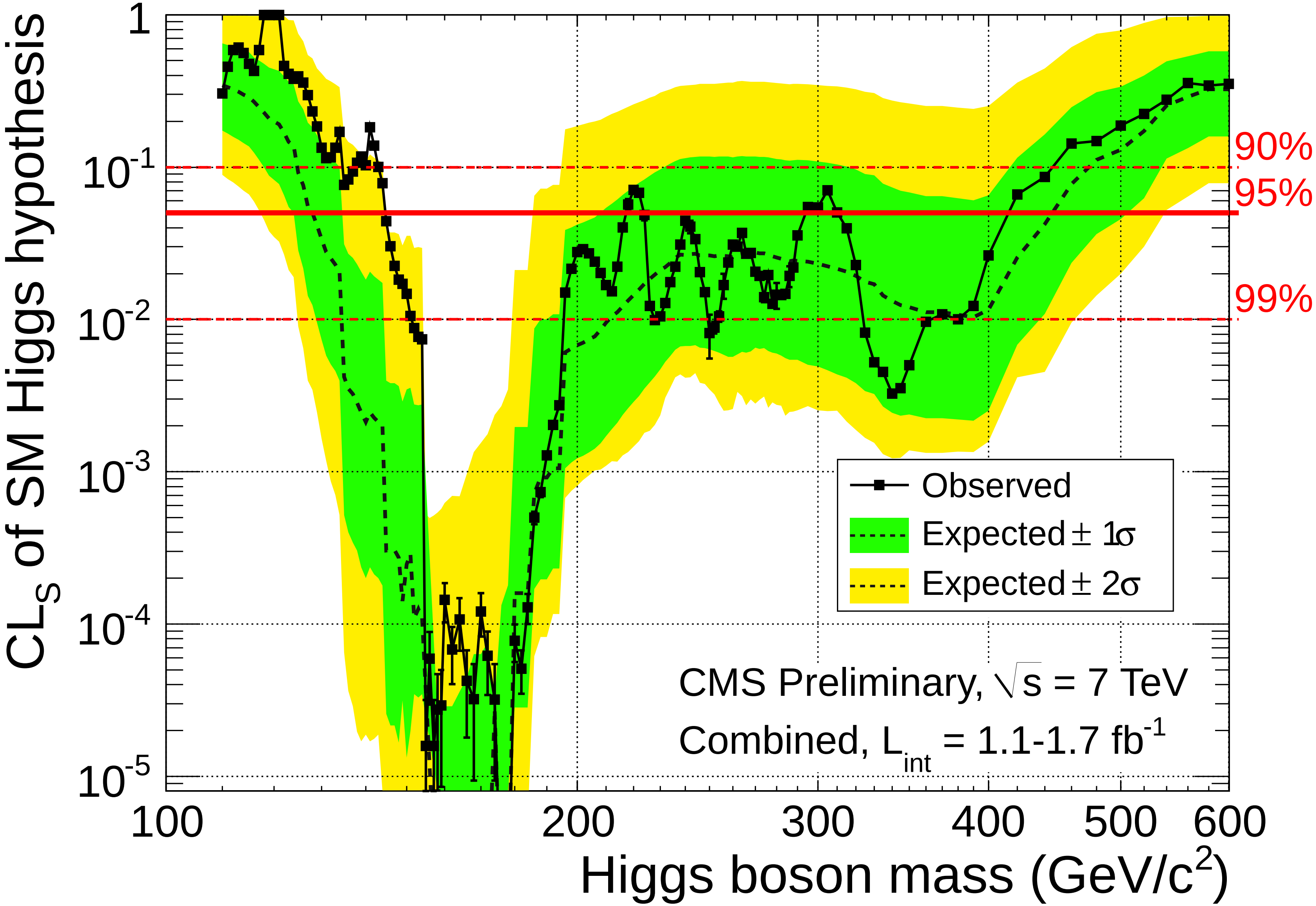
- Goal: obtain best theory predictions to facilitate
  - "best" Higgs boson search
  - "best" combination of ATLAS and CMS
  - "best" extraction of parameters

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

- $\Rightarrow$ more workforce always appreciated!

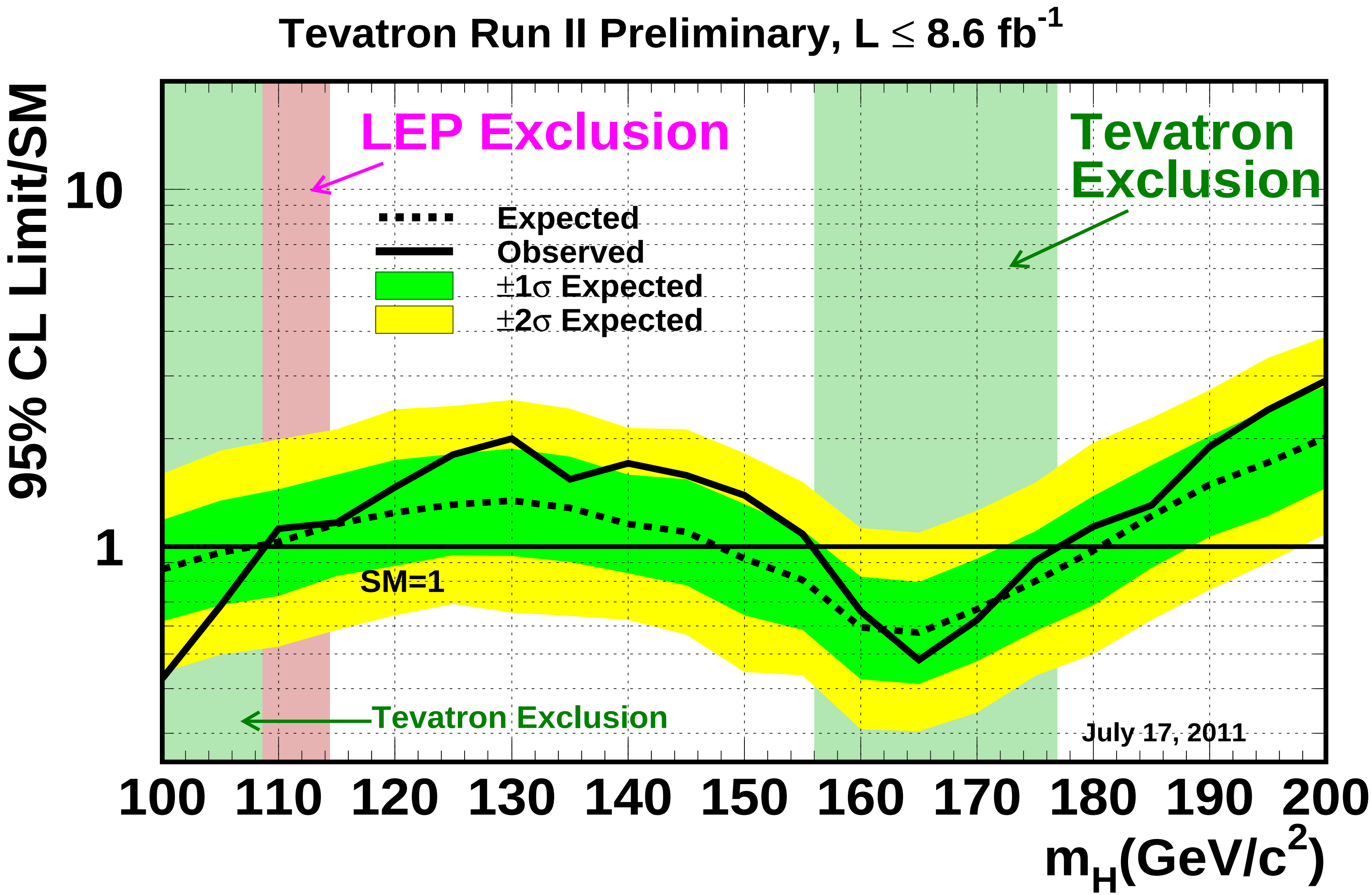


$\Rightarrow$ small excesses for 115 GeV $\lesssim M_H \lesssim$ 140 GeV



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

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



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

Results for the combination of all experiments:

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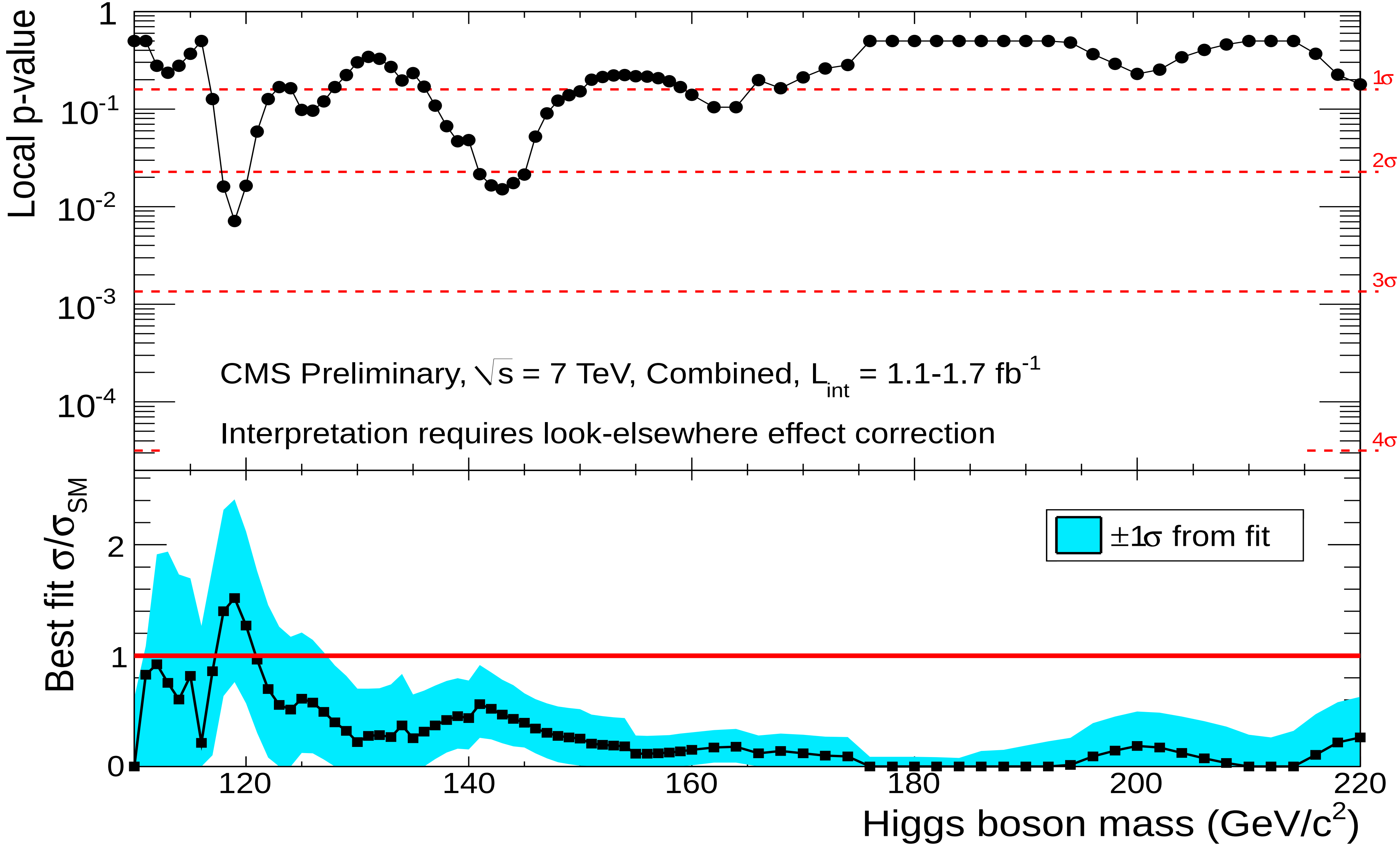
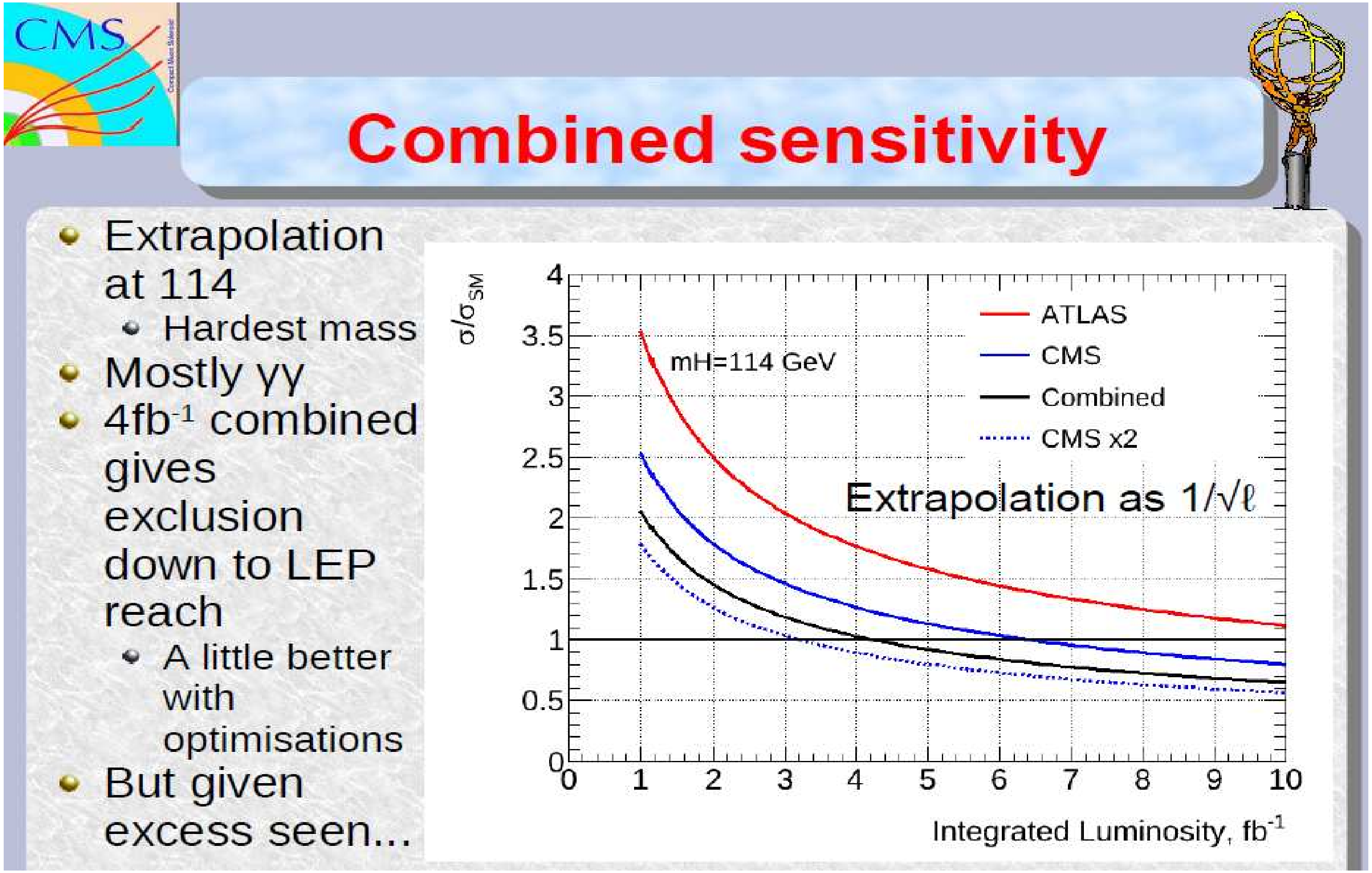
Combination does not exist :-(

What to look out for? p_0 and μ [CMS '11]

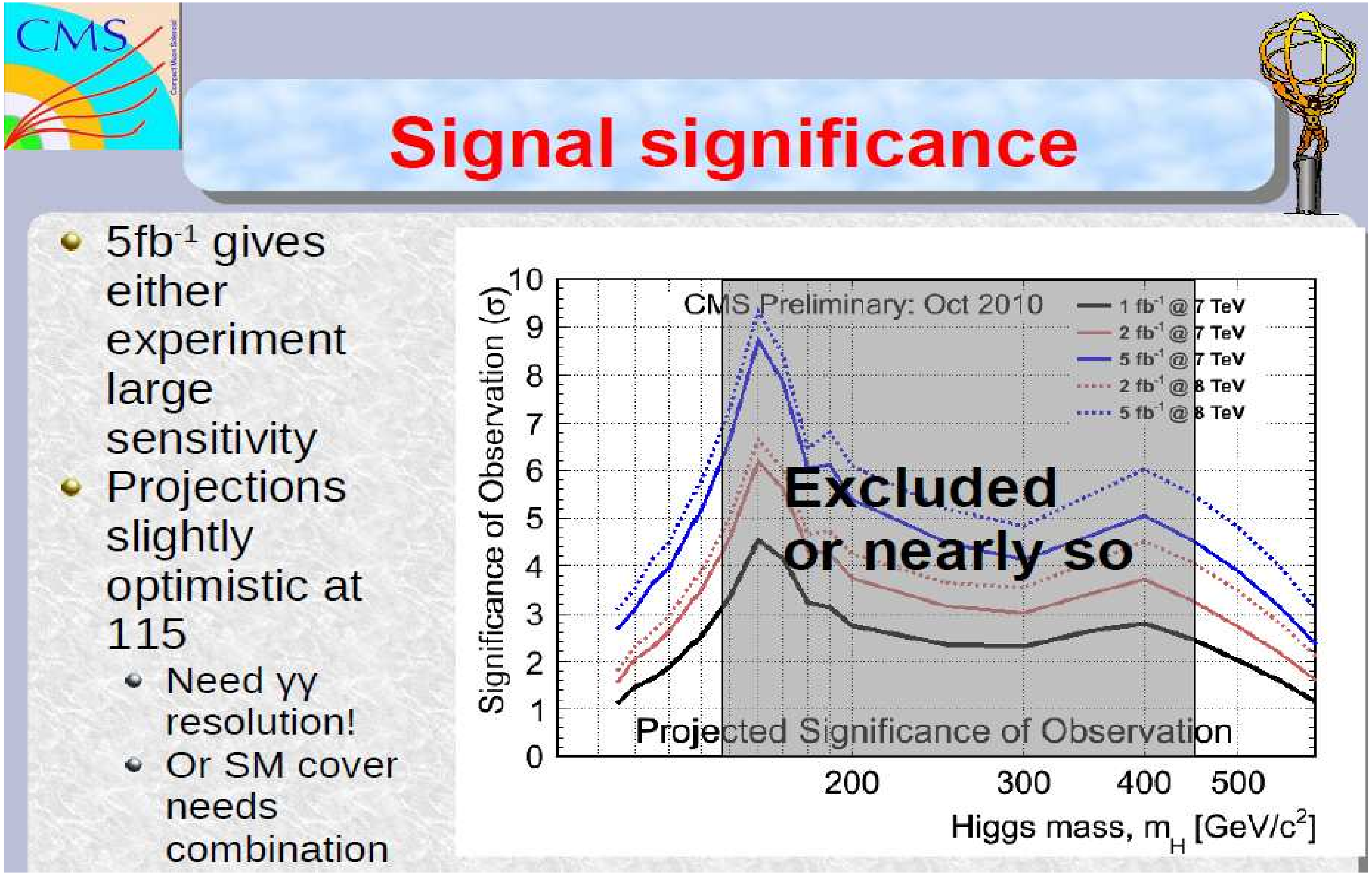


⇒ only the combined information tells us about the SM Higgs



$\Rightarrow$ 2011 data, when combined between ATLAS + CMS, should provide 2σ sensitivity down to $M_H = 114$ GeV

Further prospects: 2012



⇒ 2012 data, when combined between ATLAS + CMS,
expected sensitivity at least 3.5σ

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:
   $\longrightarrow$ SM Higgs searches apply
   $\longrightarrow$ keep in mind the upper limit of 135 GeV
   $\Rightarrow$ no limits beyond LEP so far!

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

3. Heavy MSSM Higgs boson:
   $\longrightarrow$ dedicated search
   $\Rightarrow$ model independent results on $\sigma \times$ BR
   $\Rightarrow$ specific MSSM results for H/A

Search for the MSSM Higgs bosons:

Situation is more involved due to many SUSY parameters

$\longrightarrow$ investigate benchmark scenarios:

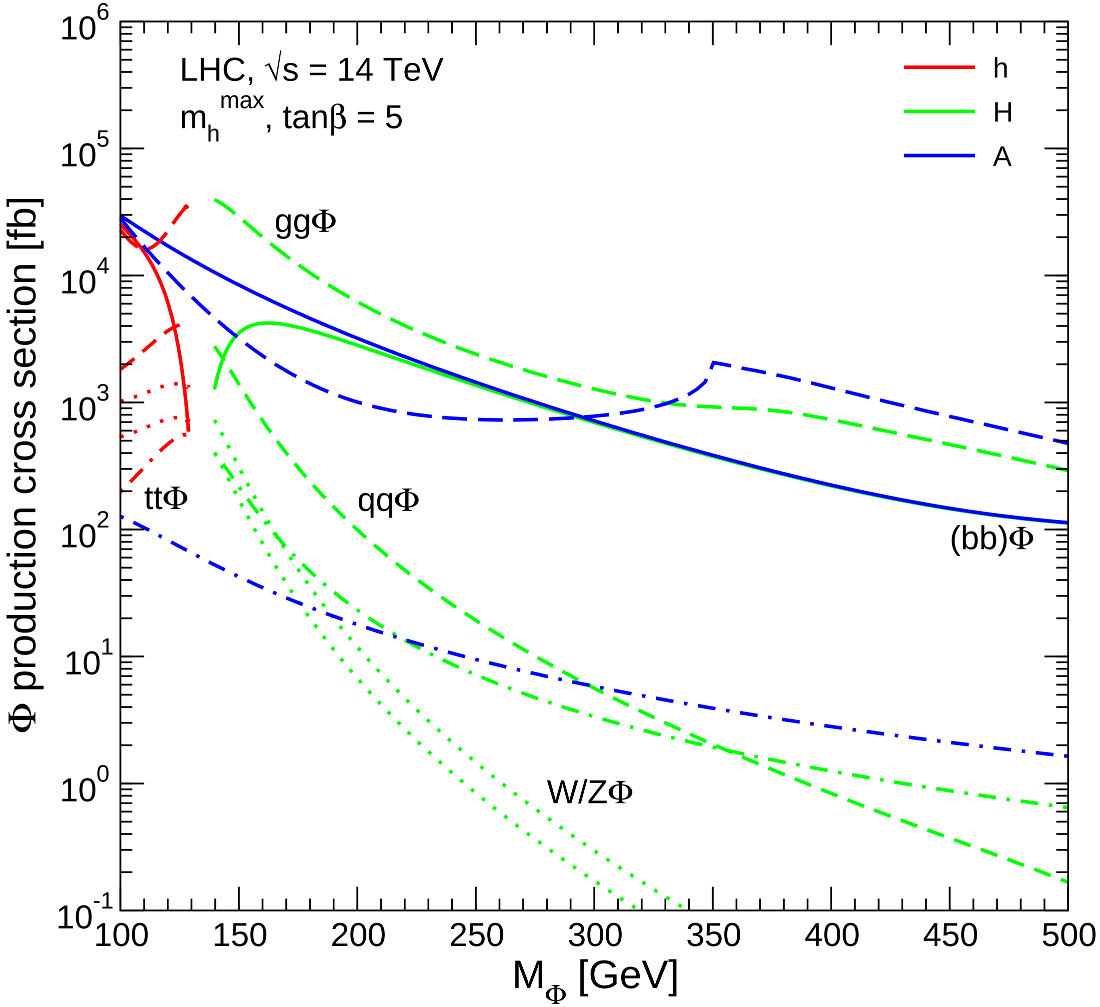
$\longrightarrow$ Vary only M_A and $\tan\beta$
$\longrightarrow$ Keep all other SUSY parameters fixed

1. $m_h^{\rm max}$ scenario:
   $\longrightarrow$ obtain conservative $\tan\beta$ exclusion bounds ($X_t = 2\,M_{\rm SUSY}$)
2. no-mixing scenario
   $\longrightarrow$ no mixing in the scalar top sector ($X_t = 0$)
3. small $\alpha_{\rm eff}$ scenario
   $\longrightarrow$ $hb\bar{b}$ 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
   $\longrightarrow$ 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:

$\Rightarrow$ full parameter accessible   But there might be problems . . .

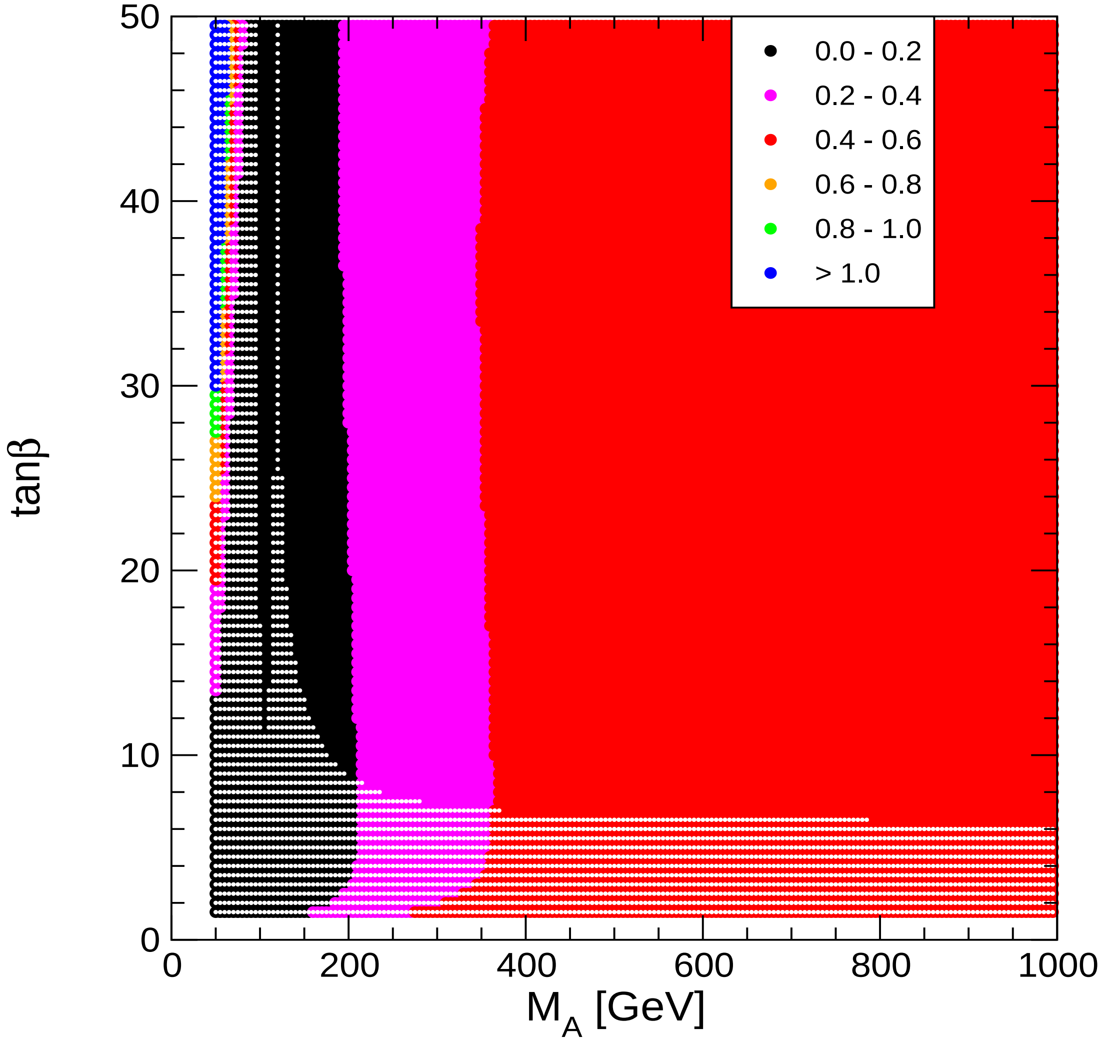
Possible problem in SUSY:

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

can be strongly suppressed

$\to$ "gluophobic Higgs scenario"

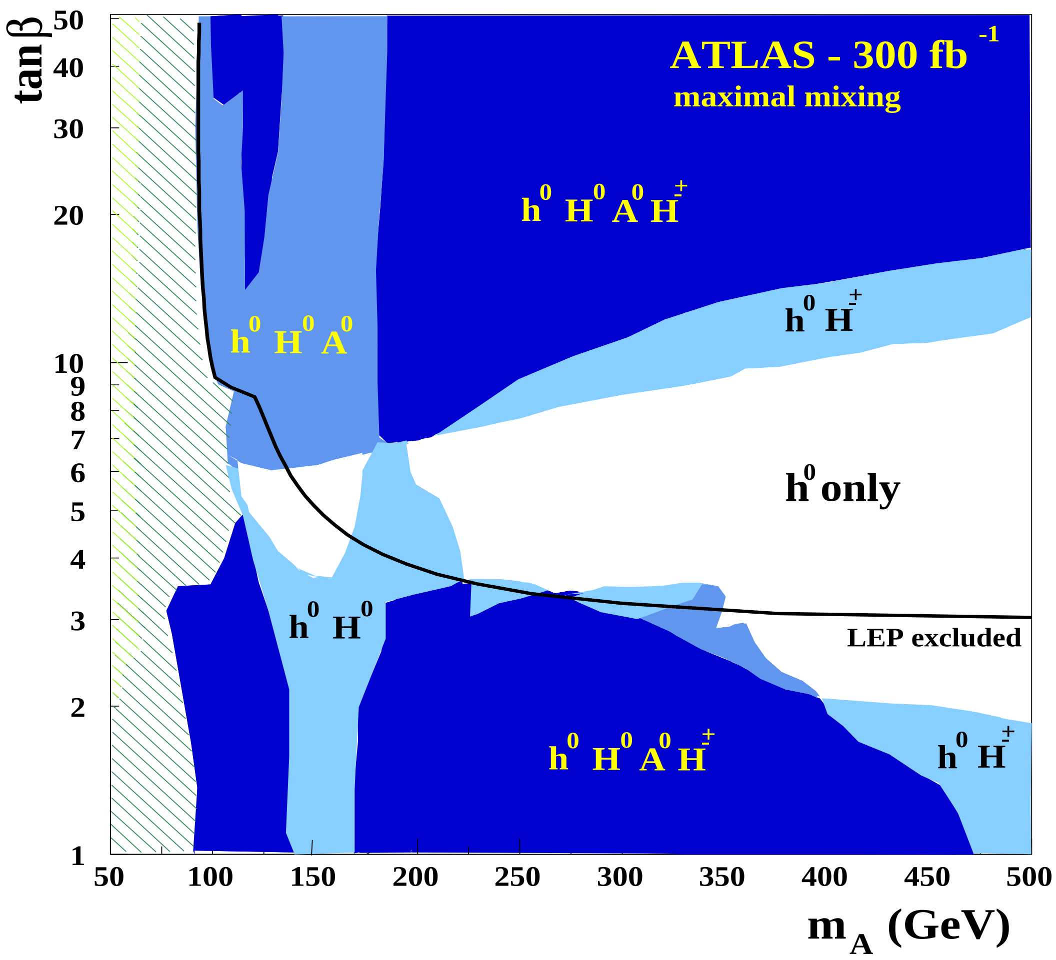
[*M. Carena, S.H., C. Wagner, G. Weiglein '02*]

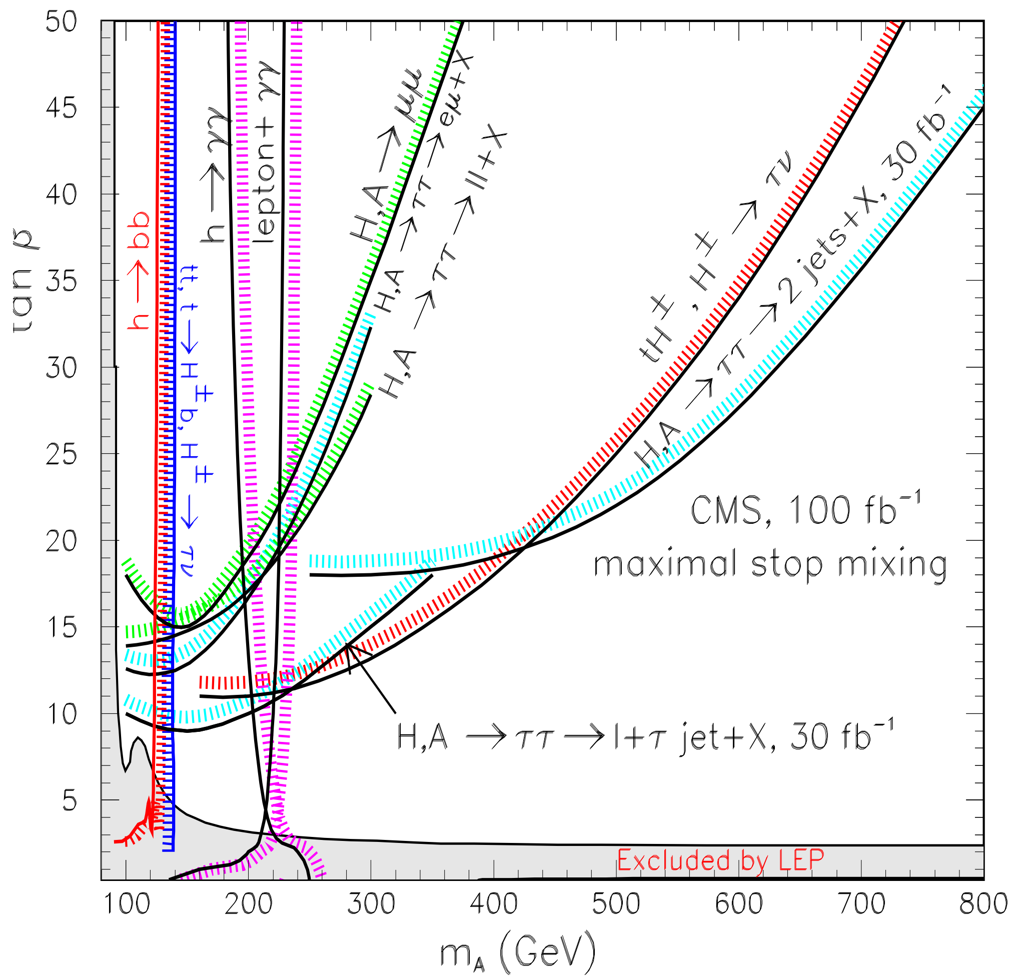


$\Rightarrow$ Strong suppression of $gg \to h \to \gamma\gamma$ possible over the whole parameter space

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

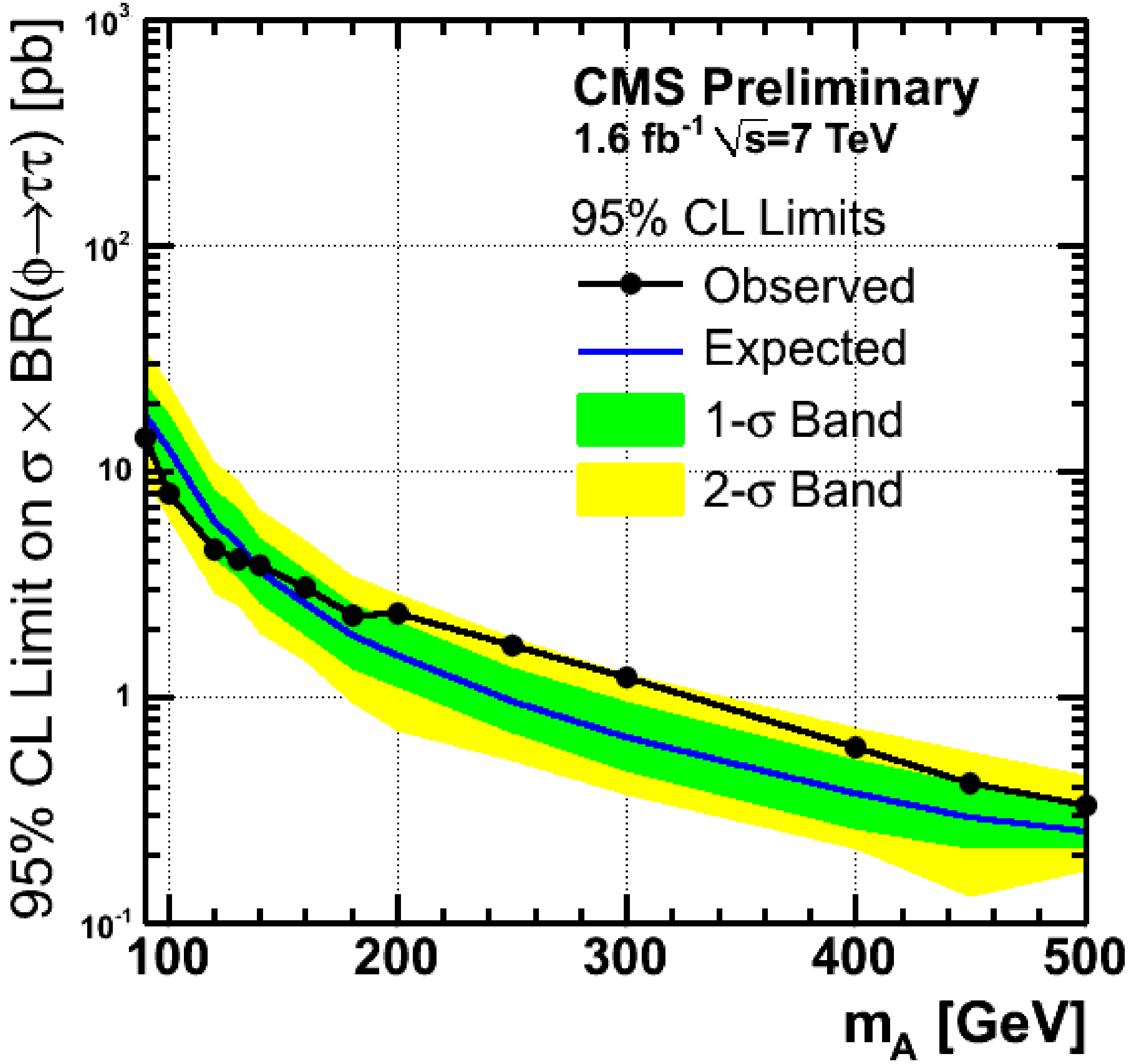
MSSM Higgs discovery contours in M_A–$\tan\beta$ plane
($m_h^{\rm max}$ benchmark scenario): [*ATLAS '99*] [*CMS '03*]





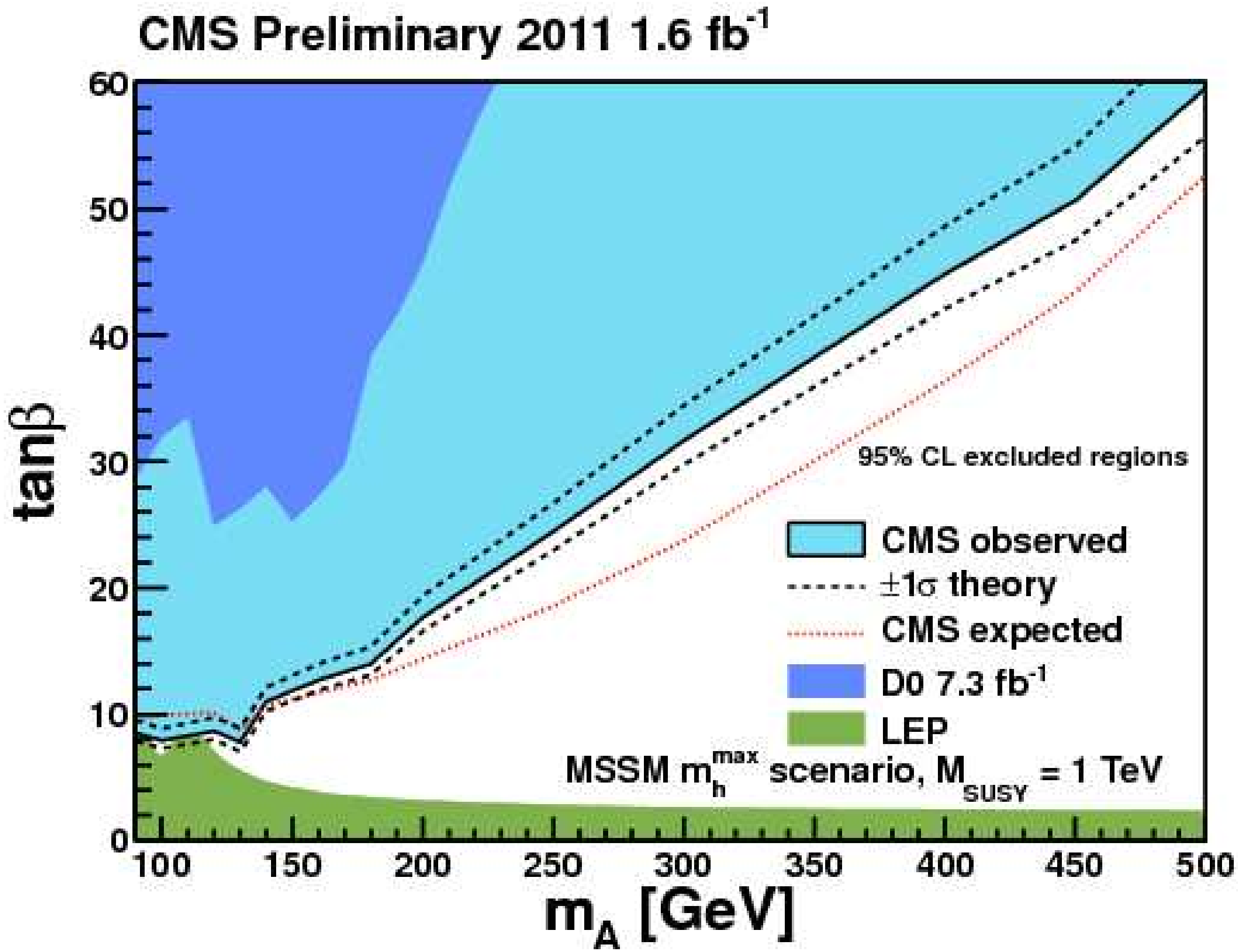
areas where only h is observable $\Rightarrow$ "LHC wedge"

Latest CMS results for model independent limits: [CMS '11]



$\Rightarrow$ 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. Recent SUSY searches at the LHC

Two possible ways:

1.) Search for SUSY particles

2.) Search for indirect effects of SUSY particles

$\Rightarrow$ both are important

$\Rightarrow$ both will be explored

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3. Recent SUSY searches at the LHC

Two possible ways:

1.) Search for SUSY particles

2.) Search for indirect effects of SUSY particles

$\Rightarrow$ both are important

$\Rightarrow$ both will be explored

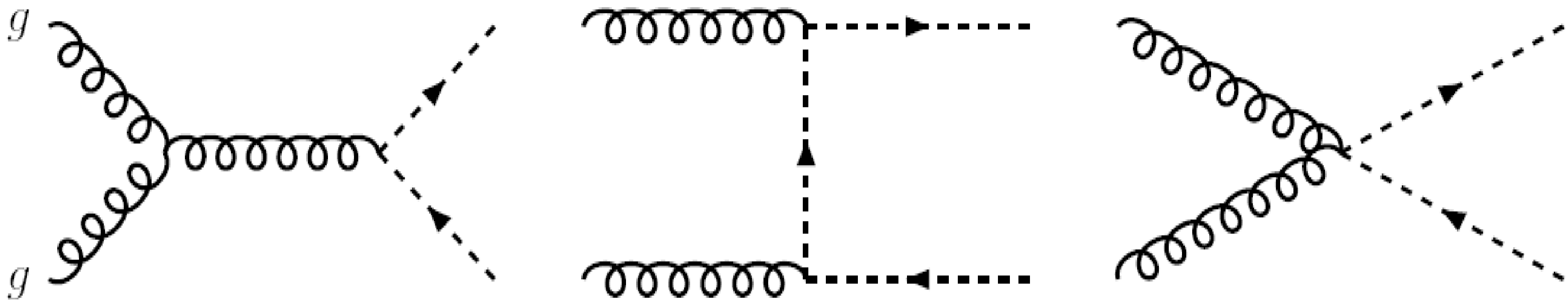
$\Rightarrow$ both will have to be combined

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

Colored sparticles at the LHC

SUSY particle production at the LHC:

$\Rightarrow$ colored (s)particles are copiously produced

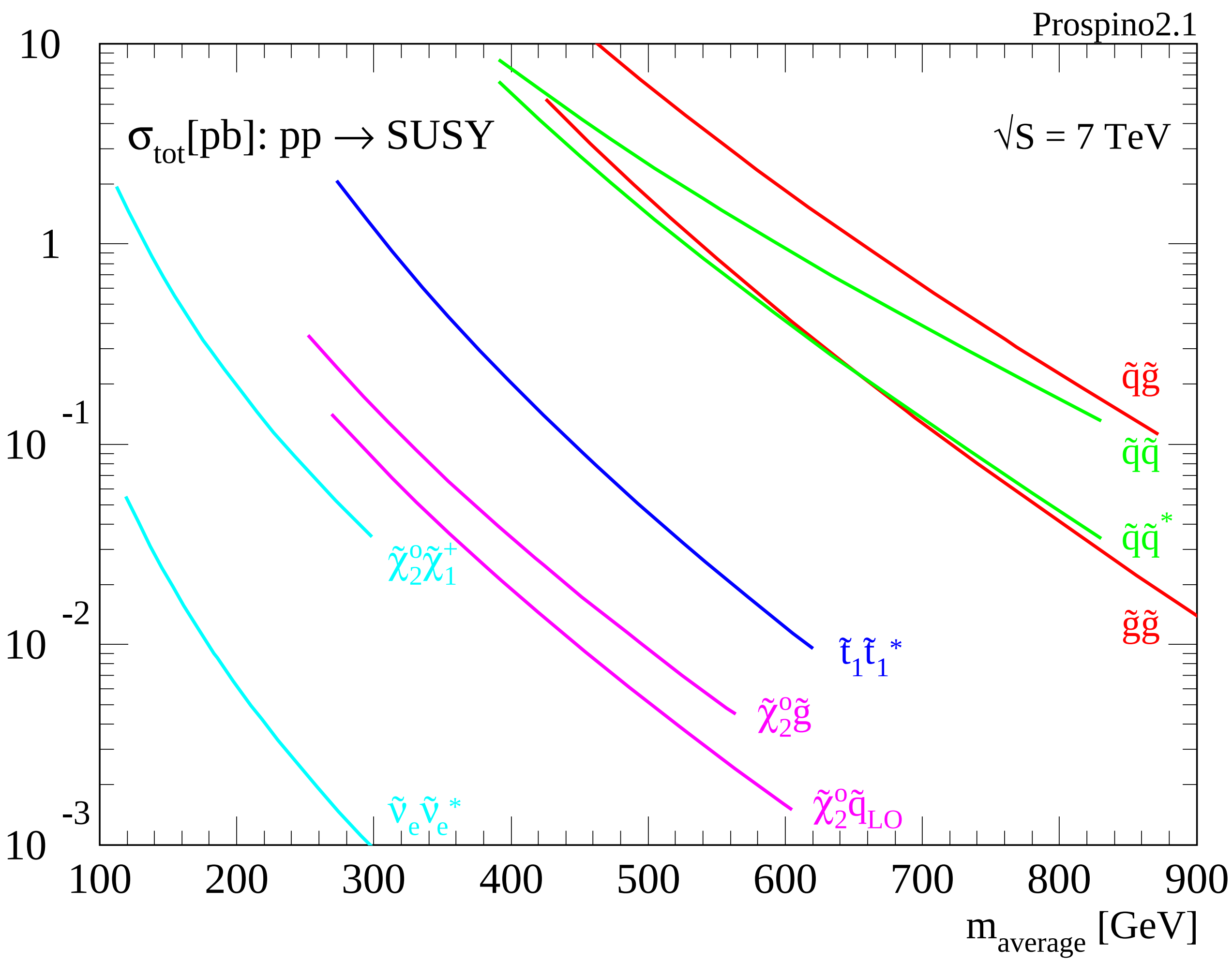


$\Rightarrow$ production of gluinos, squarks, ...

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 uncolored particles via cascade decays often dominates over direct production

Many states are produced at once

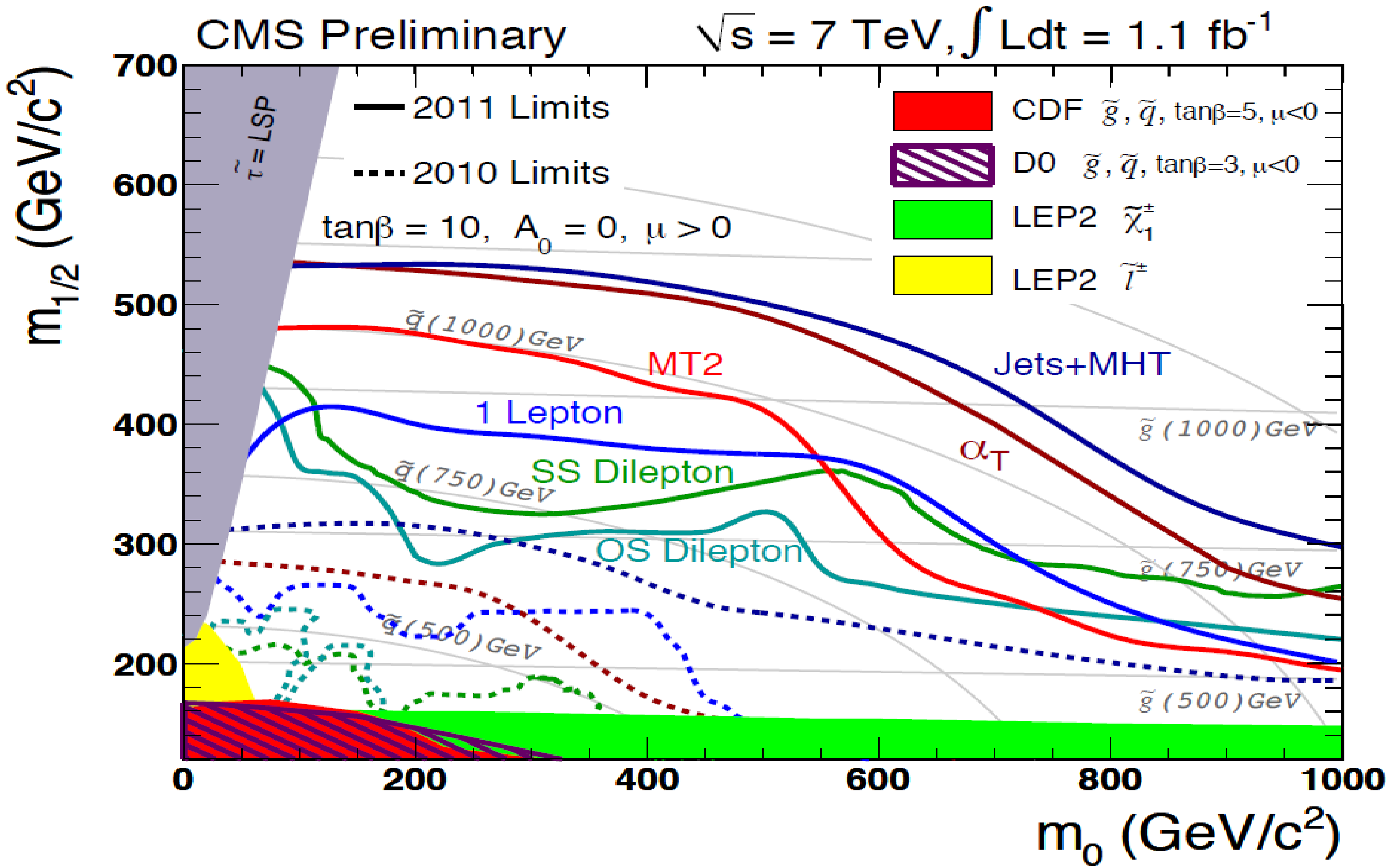
⇒ **Main background for SUSY is SUSY itself!**

Cascade decays:

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

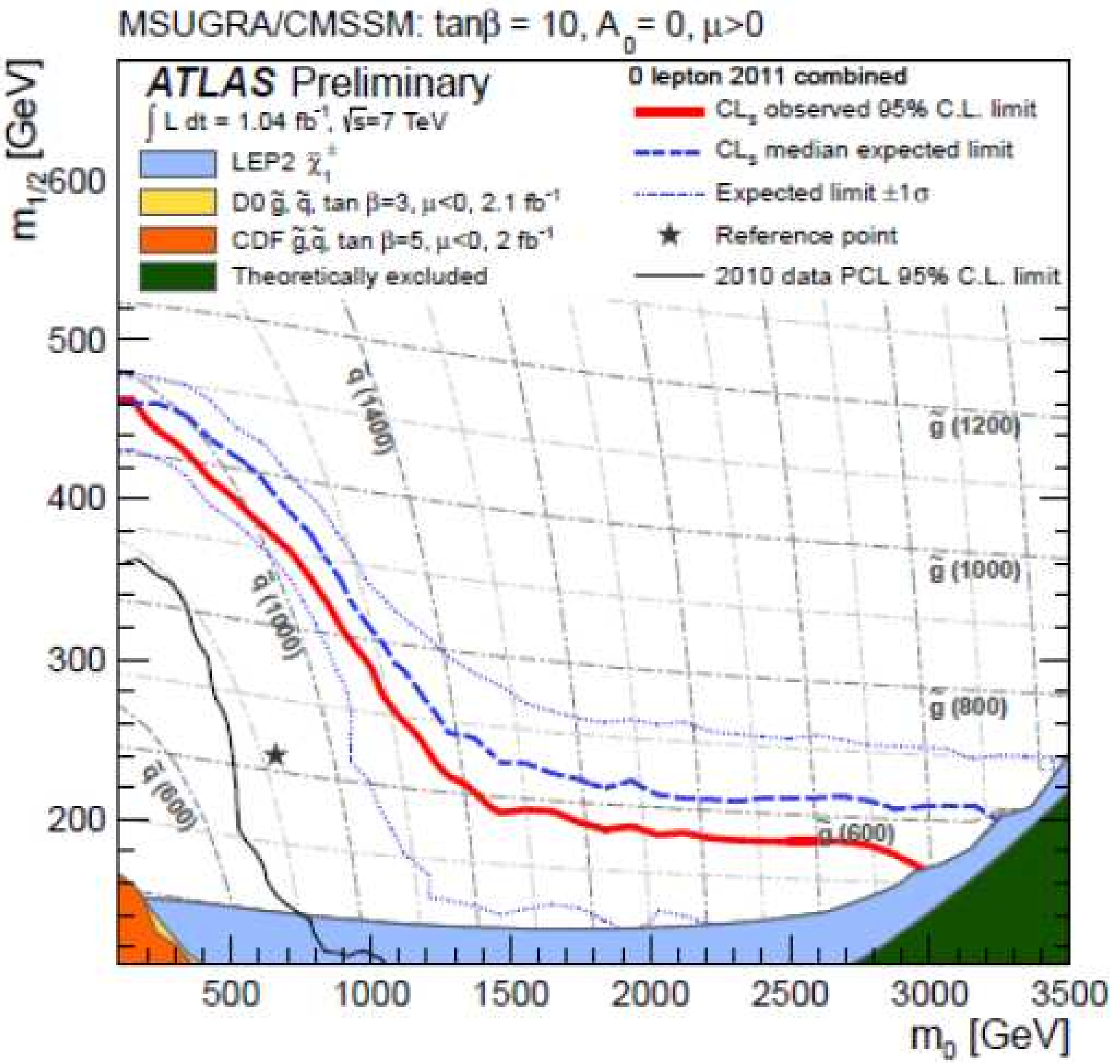
different patterns due to different SM particles "coming out":

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+δ dim • Normal Gravity >> R • SUSY • qg$\rightarrow$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$\rightarrow$q+LSP, gluino$\rightarrow$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)



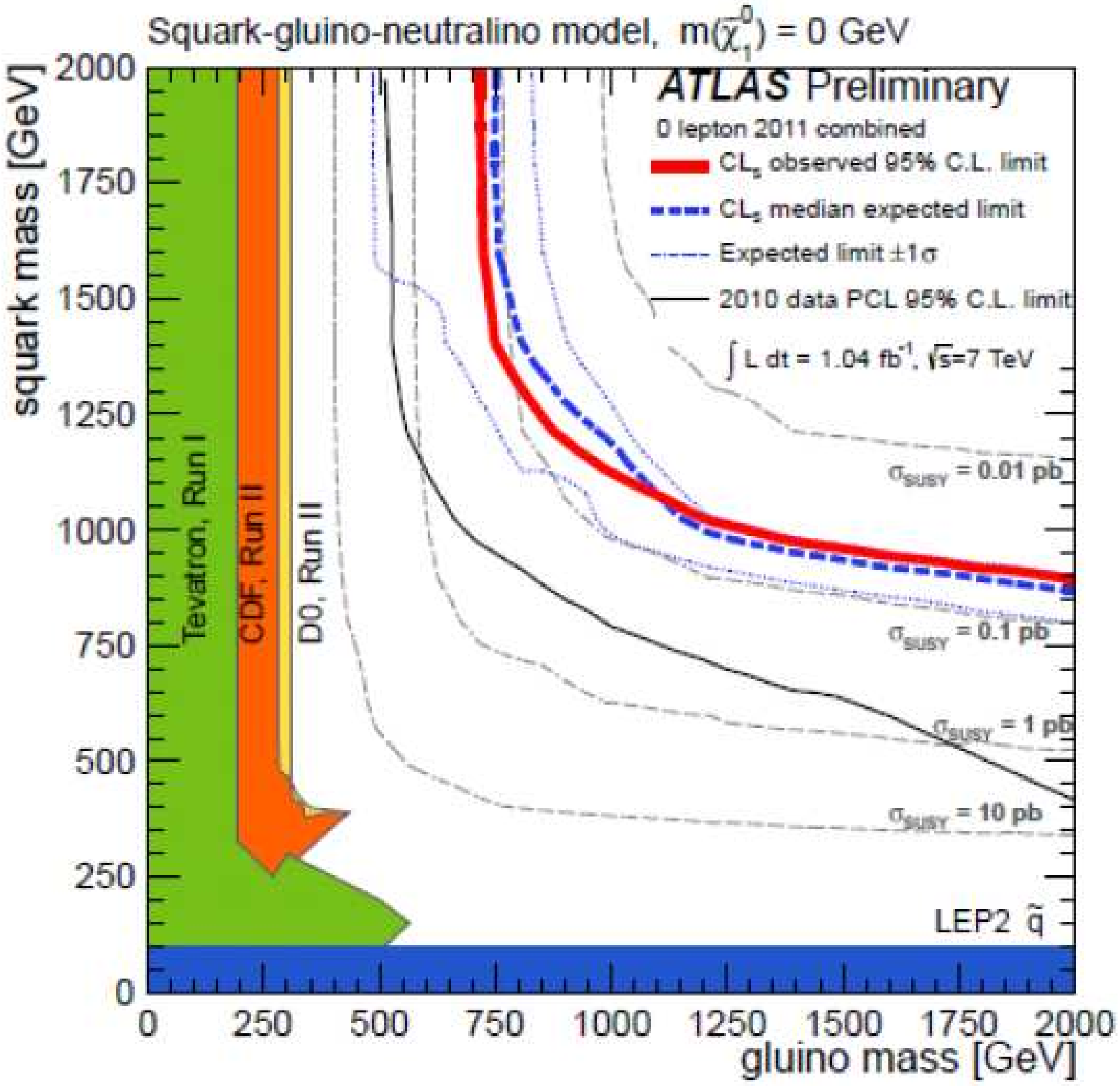
$\Rightarrow$ valid also for other $\tan\beta$ and A_0 values ??

Search for SUSY particles: ATLAS results: 0 lepton [ATLAS '11]



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

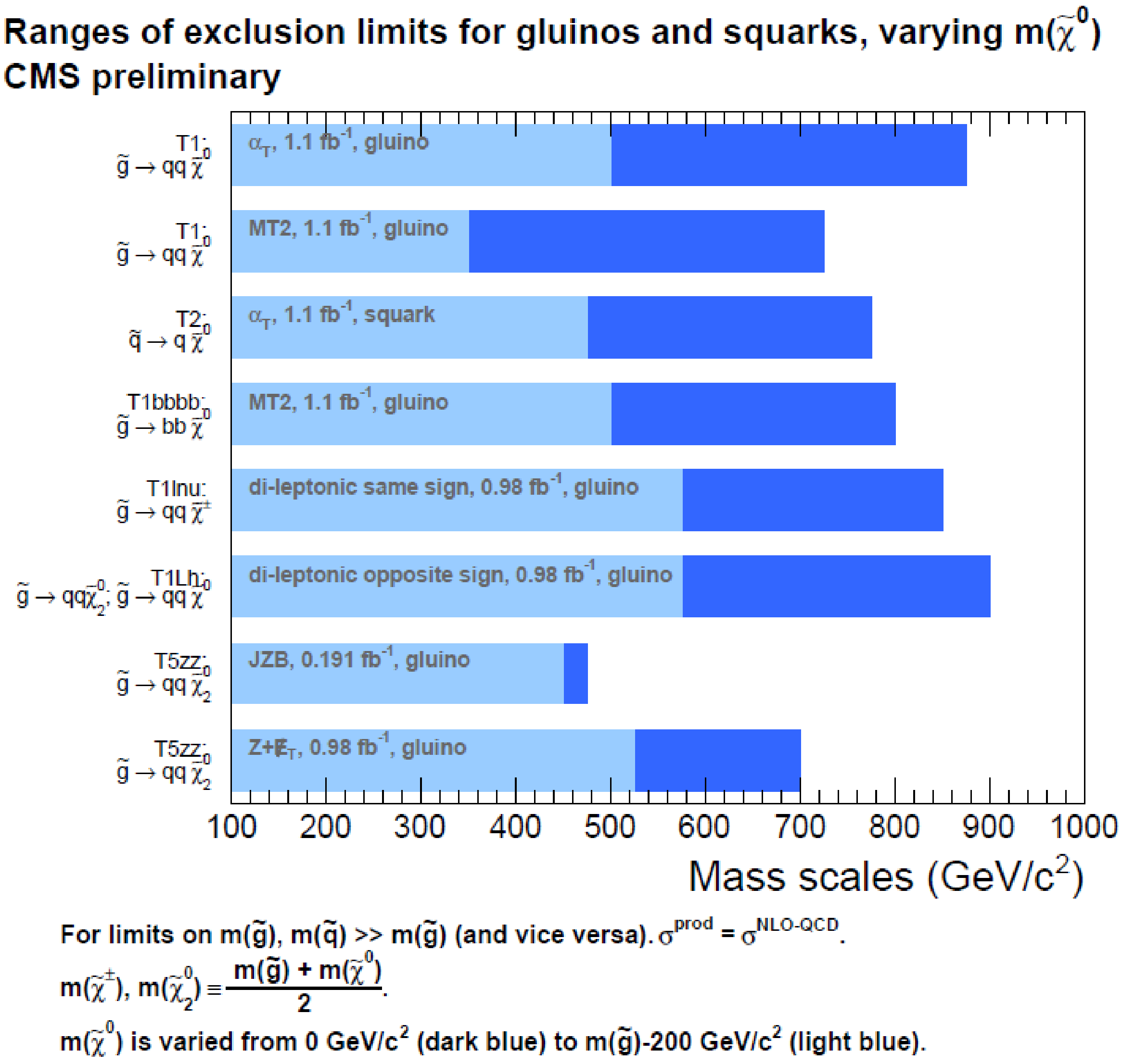
Interpretation of SUSY search results in "simplified models": [ATLAS '11]



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

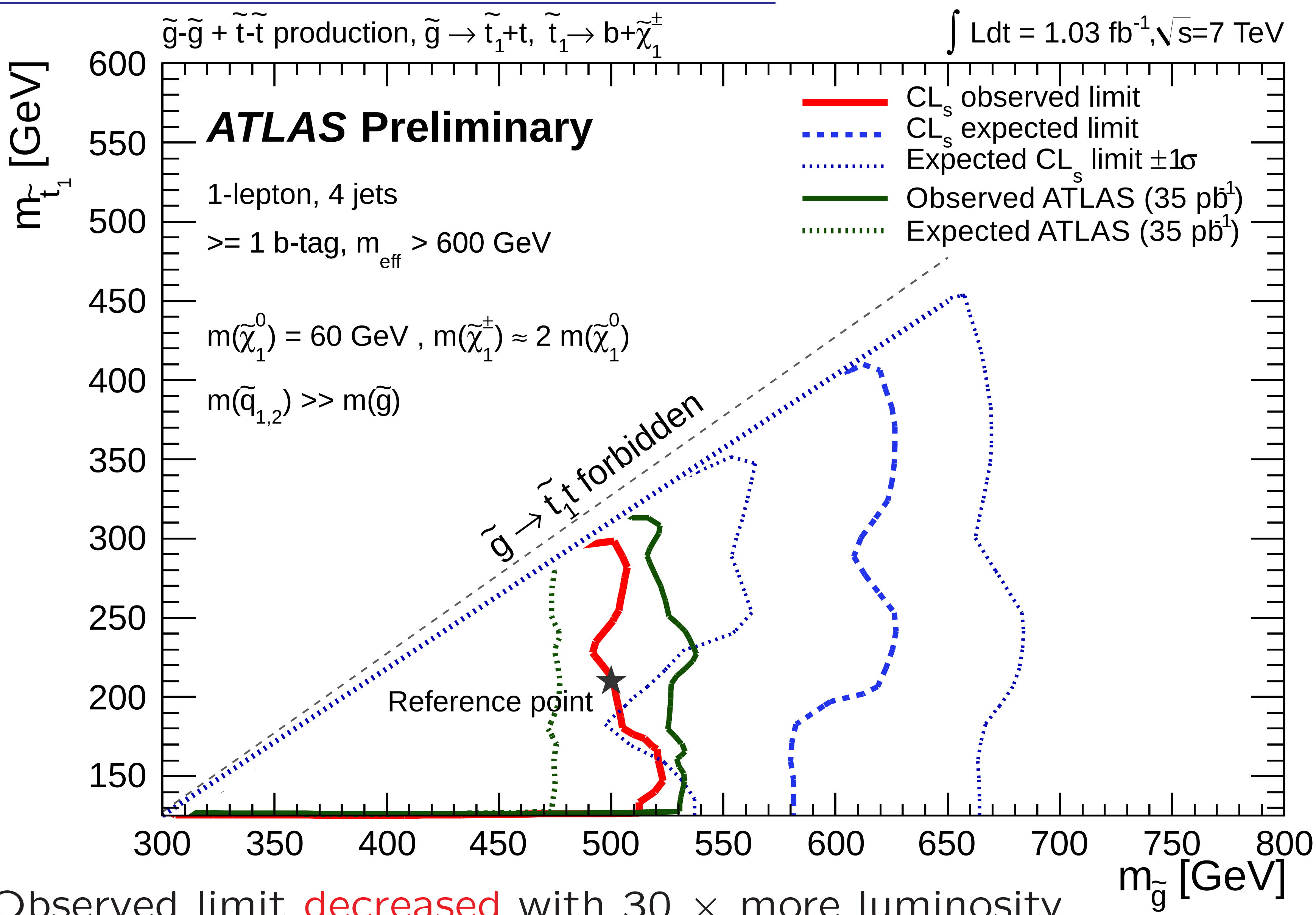
SUSY limits in "simplified models" with LSP mass varied from 0 to $m_{\tilde{g}} - 200$ GeV:

[CMS '11]



$\Rightarrow$ strong dependence on LSP mass!

Limits on third generation squark masses: [ATLAS '11]



⇒ Observed limit decreased with 30 × more luminosity

1.2 σ excess in both electron and muon channels

LHC limits on . . .

- charginos
- neutralinos
- sleptons

“EW SUSY particles”

LHC limits on . . .

- charginos
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“EW SUSY particles”

⇒ smaller production cross section

⇒ more difficult analyses . . .

LHC limits on . . .

- charginos
- neutralinos
- sleptons

"EW SUSY particles"

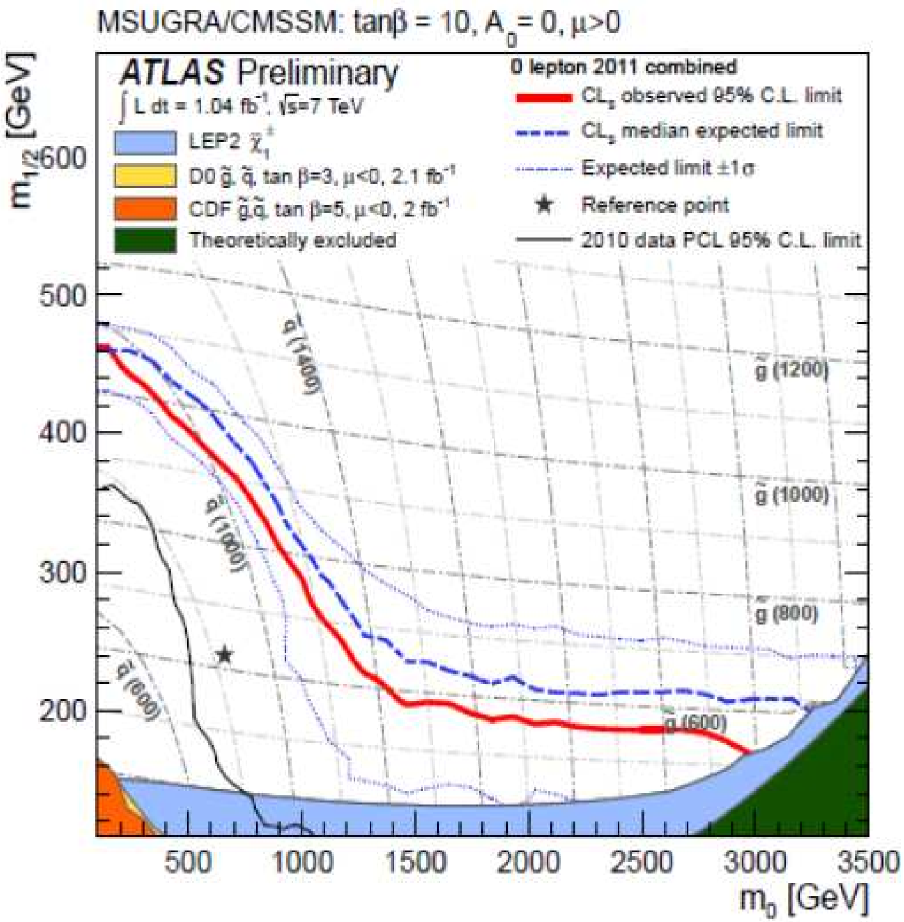
$\Rightarrow$ smaller production cross section
$\Rightarrow$ more difficult analyses . . .

$\Rightarrow$ no LHC limits - yet

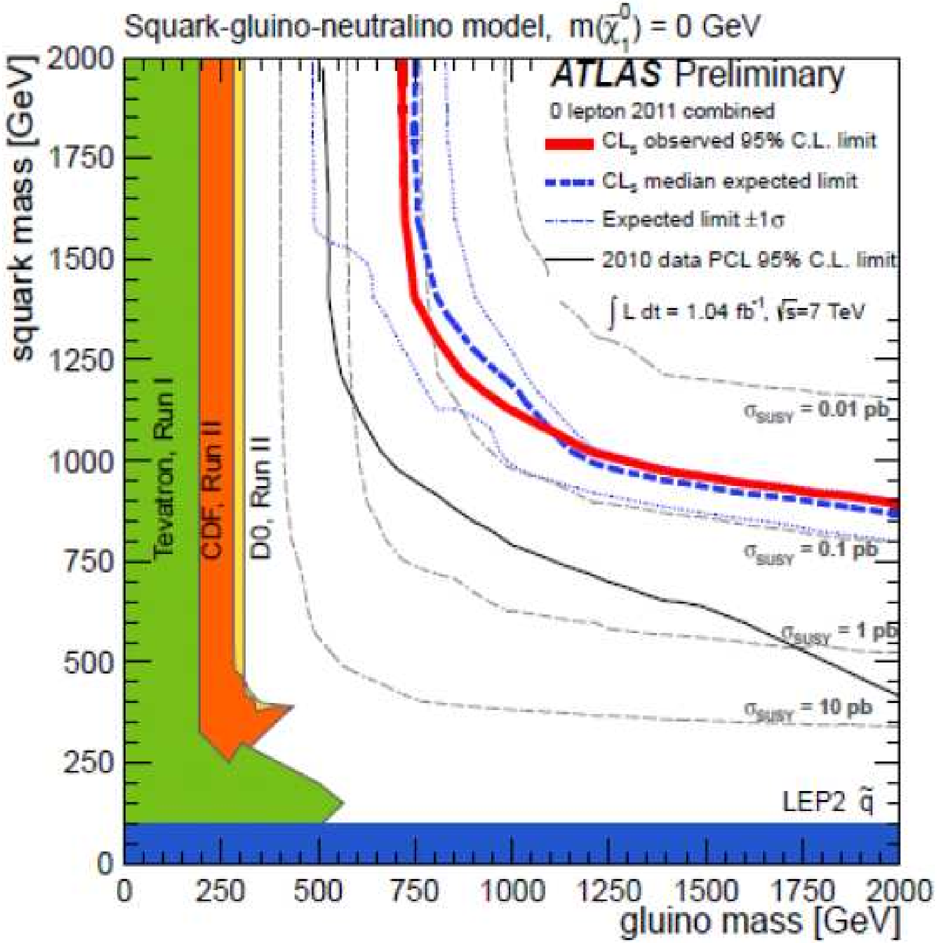
We are eagerly waiting for these results!

The results are presented in two ways:

CMSSM



"simplified model"



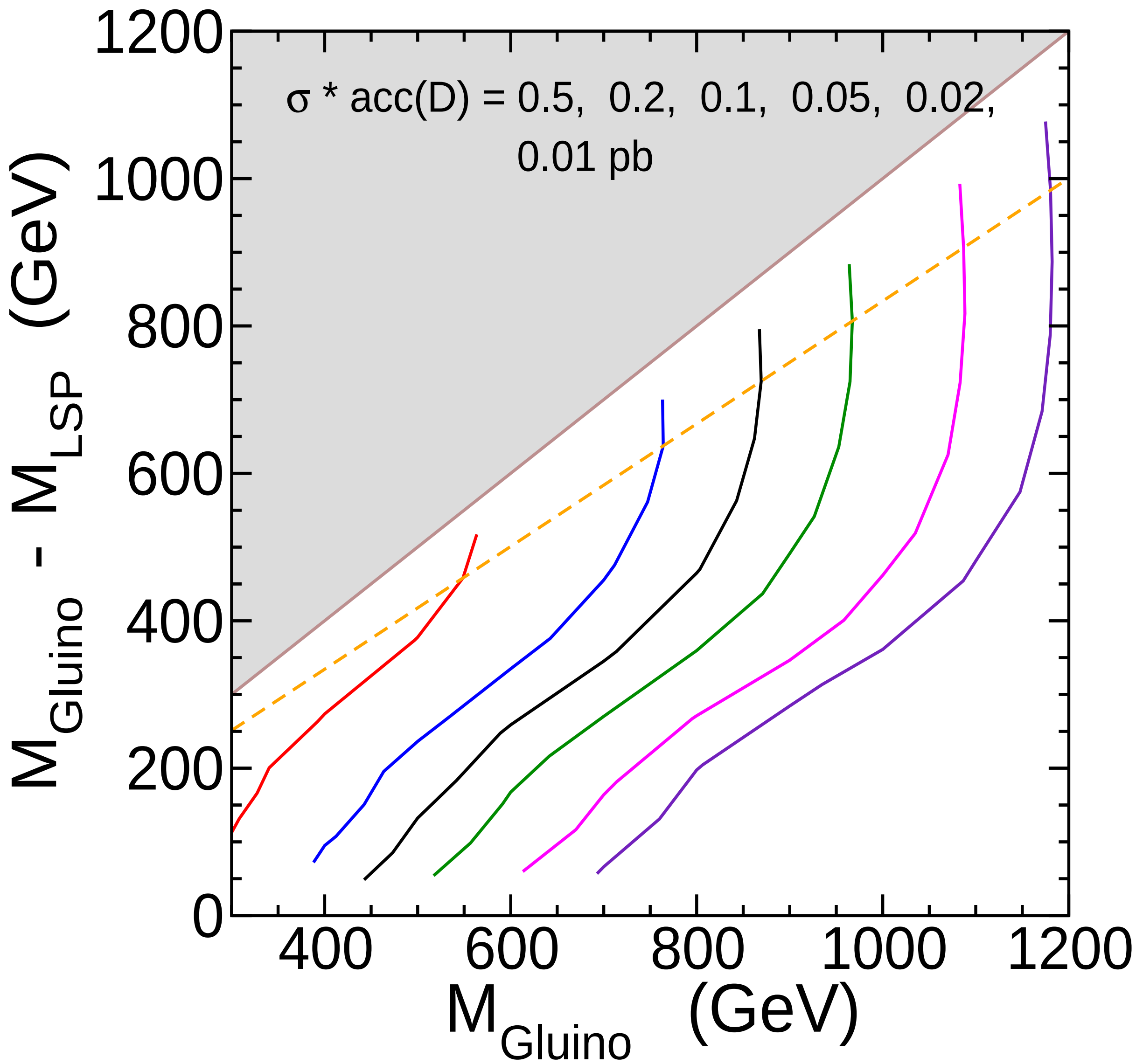
⇒ How general is this? How useful is this?

Three "easy" ways to "avoid" these constraints

1. not valid for stops and sbottoms ($\rightarrow$ excess? :-)

2. compressed spectrum

3. "extended" spectrum



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

SUSY/Higgs bounds from a theory perspective

SUSY limits

What is the best way to present the results?

Cross section $\times$ BR limits possible?

Limits incl. cuts, but with detector effects folded out?

$\Rightarrow$ theorists need limits that can be applied to any model!
. . . or at least limits in more benchmark models

$\Rightarrow$ theorists also need "as much likelihood information as possible"
not only 95% CL, not for fixed A_0, $\tan\beta$, . . .

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Higgs limits

The situation is partially better :-)
(nearly) model independent limits on $\sigma \times$ BR available

. . . but we need more than just the 95% CL exclusion bound!
$\Rightarrow$ HiggsBounds!

More benchmark scenarios?

Request by ATLAS/CMS in early 2011:
"Please provide us models in which you want us to present the results!"

⇒ Initiative for a new benchmark proposal

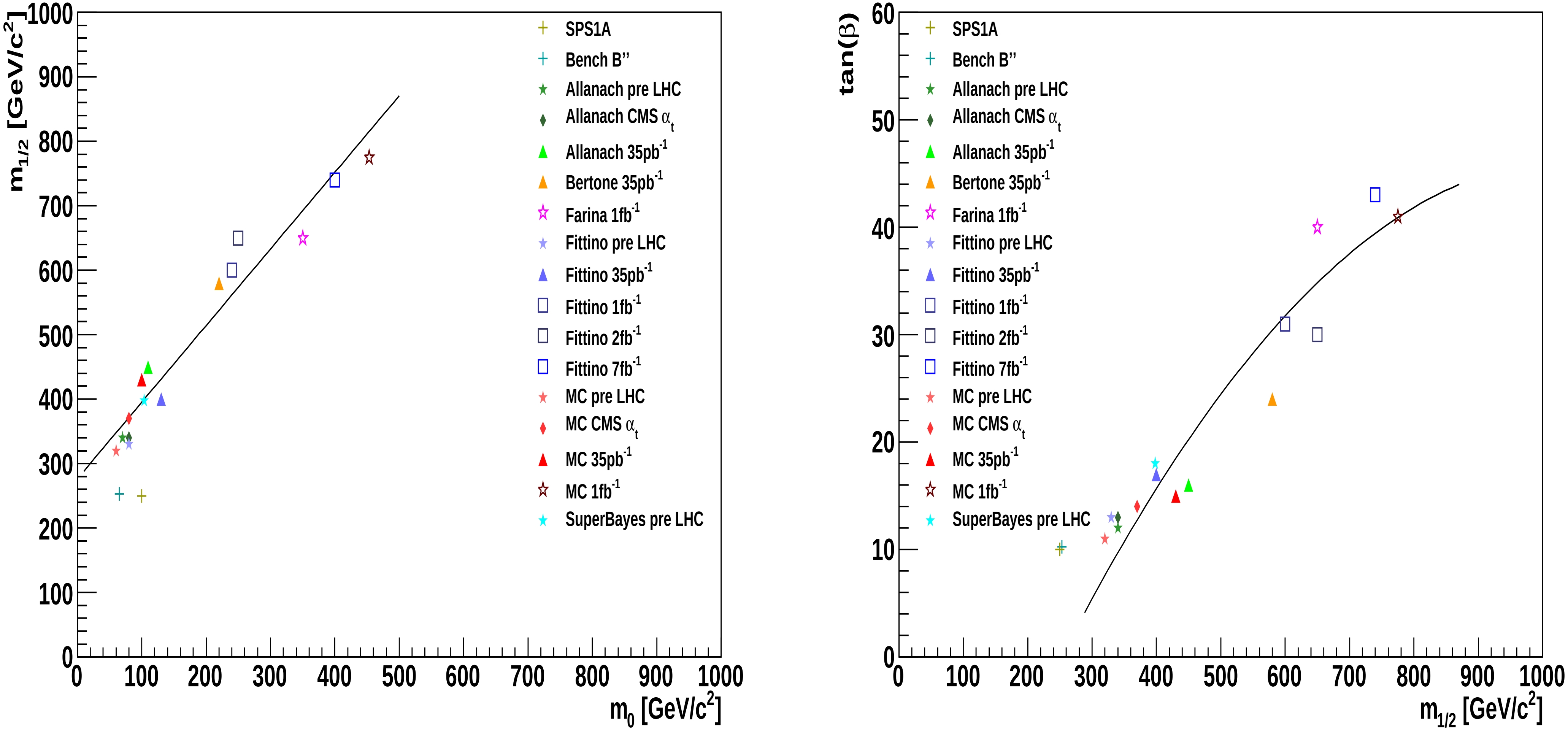
[S.S. AbdusSalam, B.C. Allanach, H. Dreiner, J. Ellis, U. Ellwanger, J. Gunion, S.H., M. Krämer, M. Mangano, K.A. Olive, S. Rogerson, L. Roszkowski, M. Schlaffer, G. Weiglein]

1. Clear definition of models:
   (why is it called CMSSM and not mSUGRA?)
2. Benchmark models:
   – CMSSM
   – NUHM1, NUHM2
   – RPV-CMSSM
   – mGMSB
   – mAMSB
   – p19MSSM
3. Model planes: either based on the old SPS points or . . .
4. Model lines: within the planes
   ⇒ (infinitely) new points are defined along the (infinite) lines

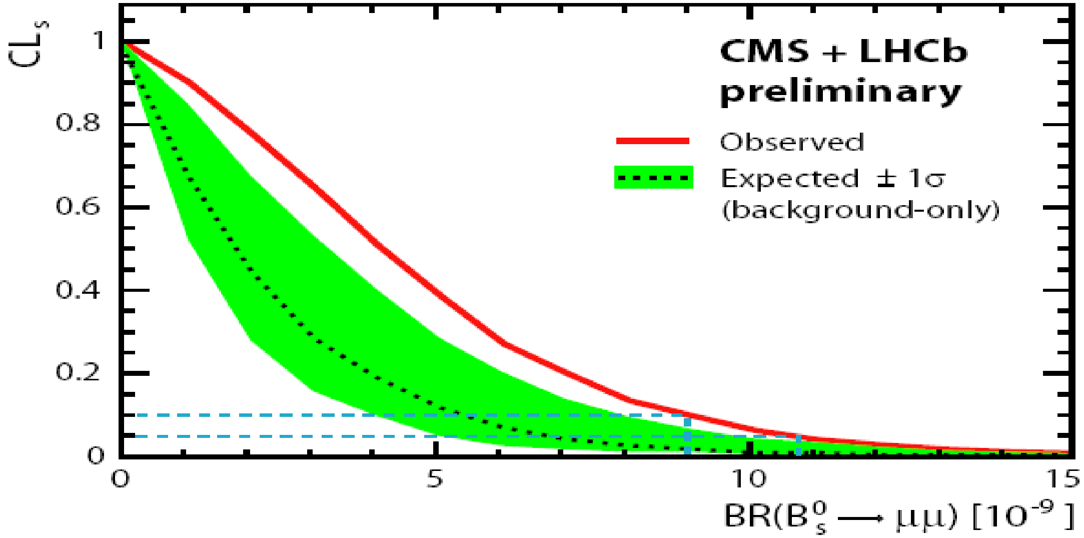
or . . .

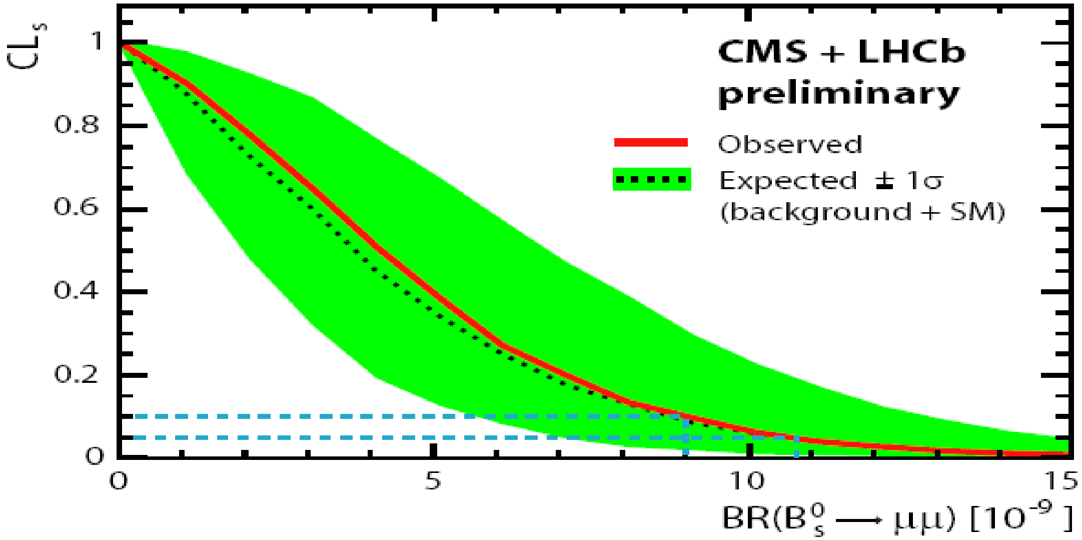
planes based on best-fit points (details in a minute!)

Results for the CMSSM only:



Searches for $B_s \to \mu^+\mu^-$ at ATLAS/CMS/LHCb:





. . . again the SM?

$\Rightarrow$ combination of BPO and SUSY searches?

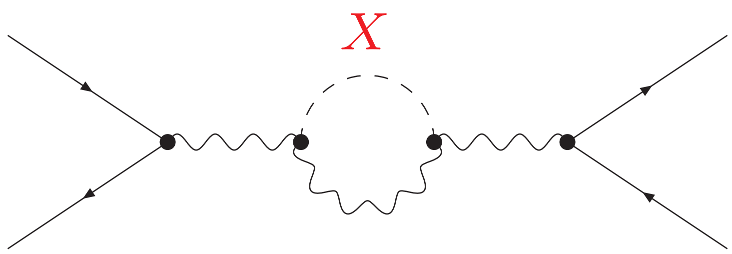
4. Implications for SUSY fits

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

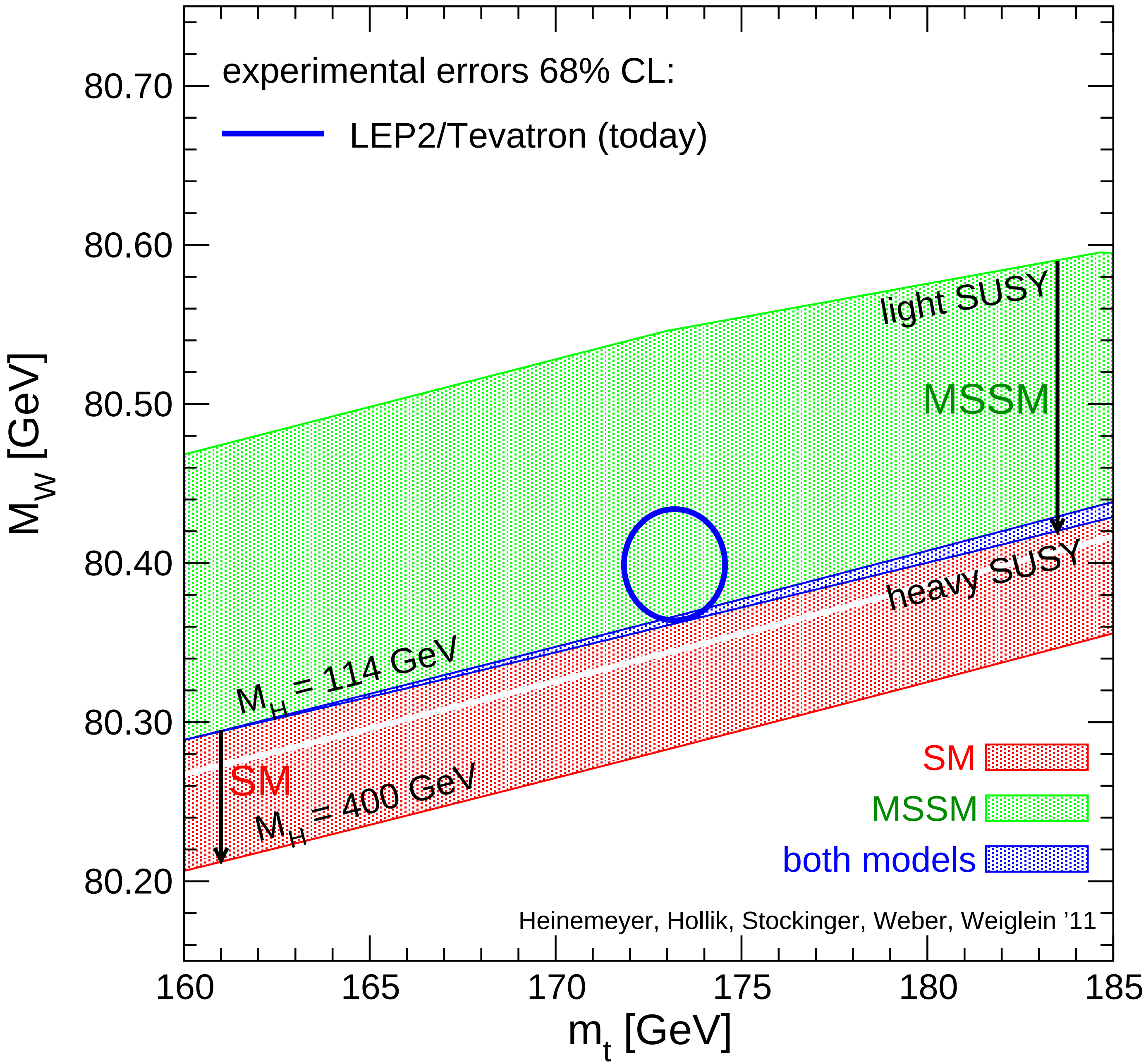


$\Downarrow$

$\Rightarrow$ Information about unknown parameters

Very high accuracy of measurements and theoretical predictions needed

The most beautiful example:

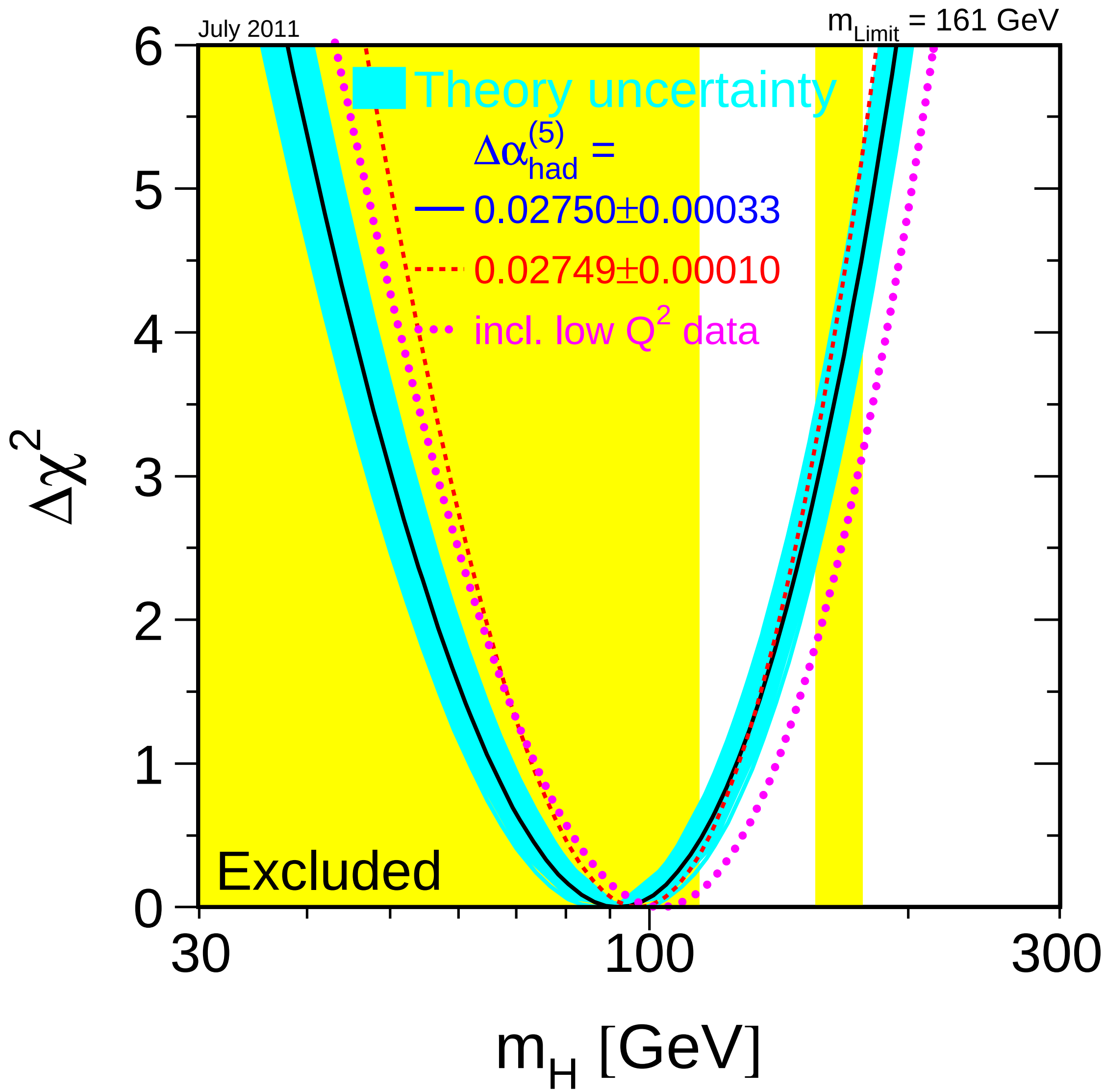


Global fit to all SM data:

[*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
  $\Rightarrow$ 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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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 ...

$\Rightarrow$ combination makes only sense if all parameters are connected!

$\Rightarrow$ 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:

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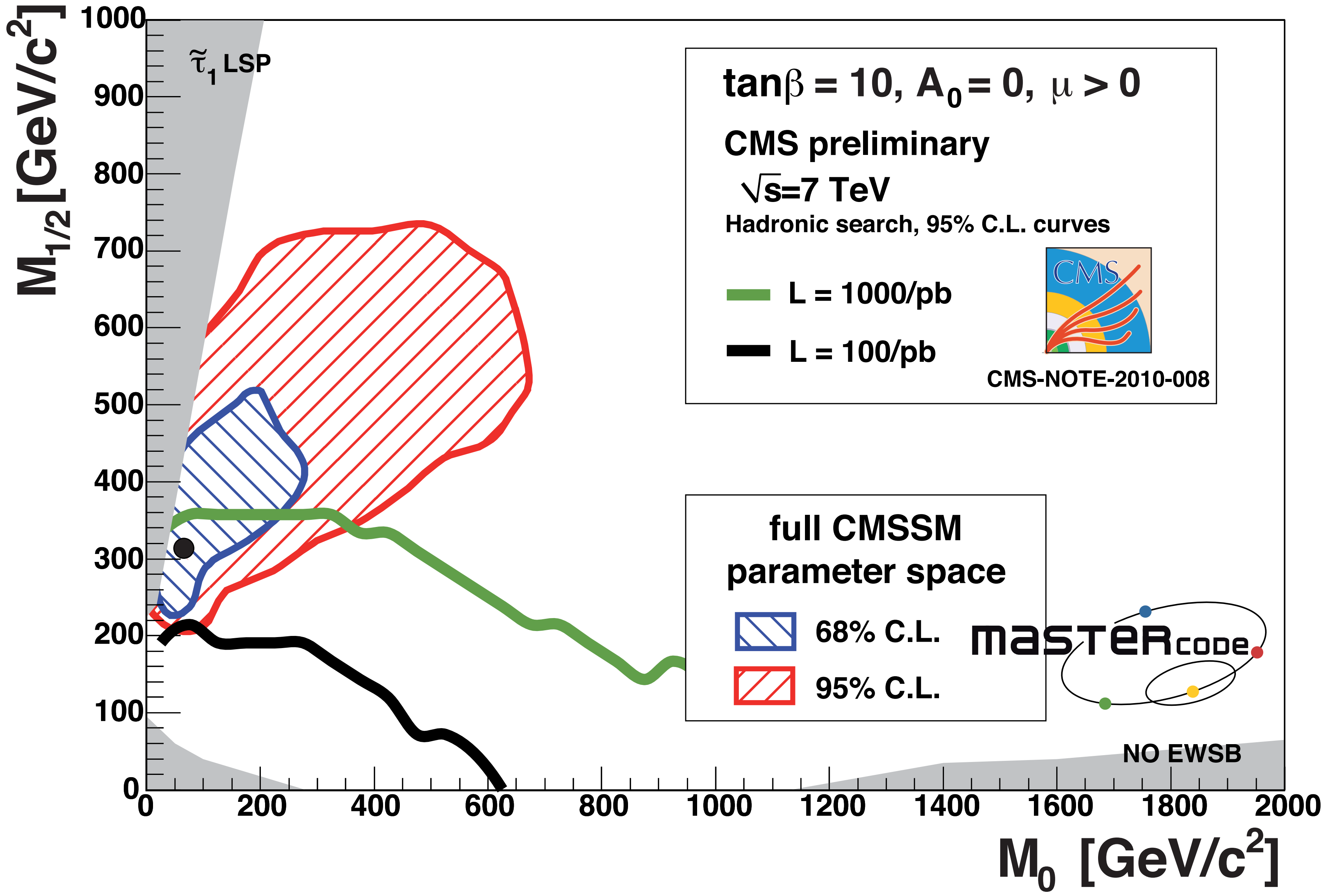
What to do if only a lower/upper bound exists?

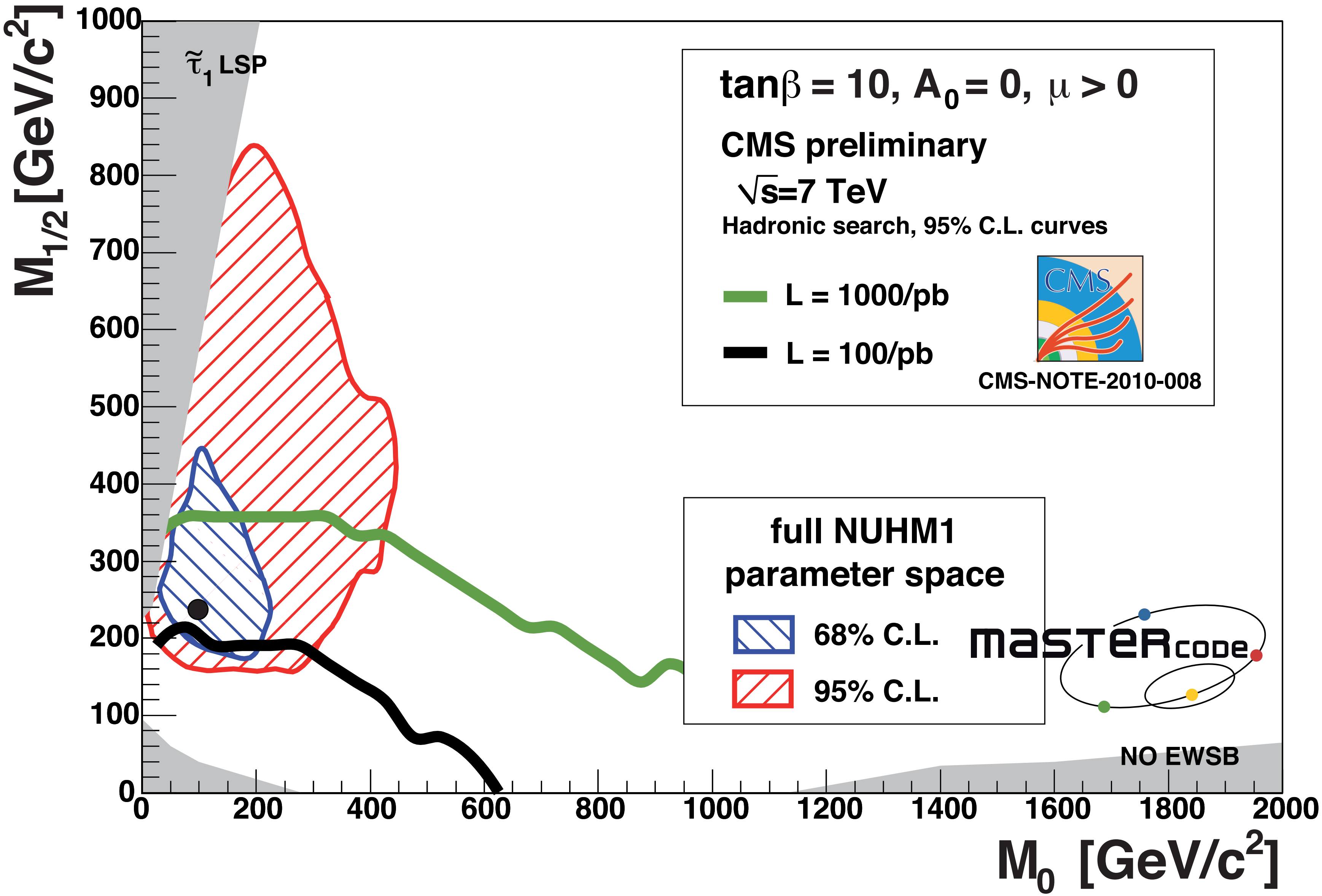
$\rightarrow$ especially important: M_h $\rightarrow$ no time - ask me over soft-drinks

pre-LHC predictions: CMSSM:



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

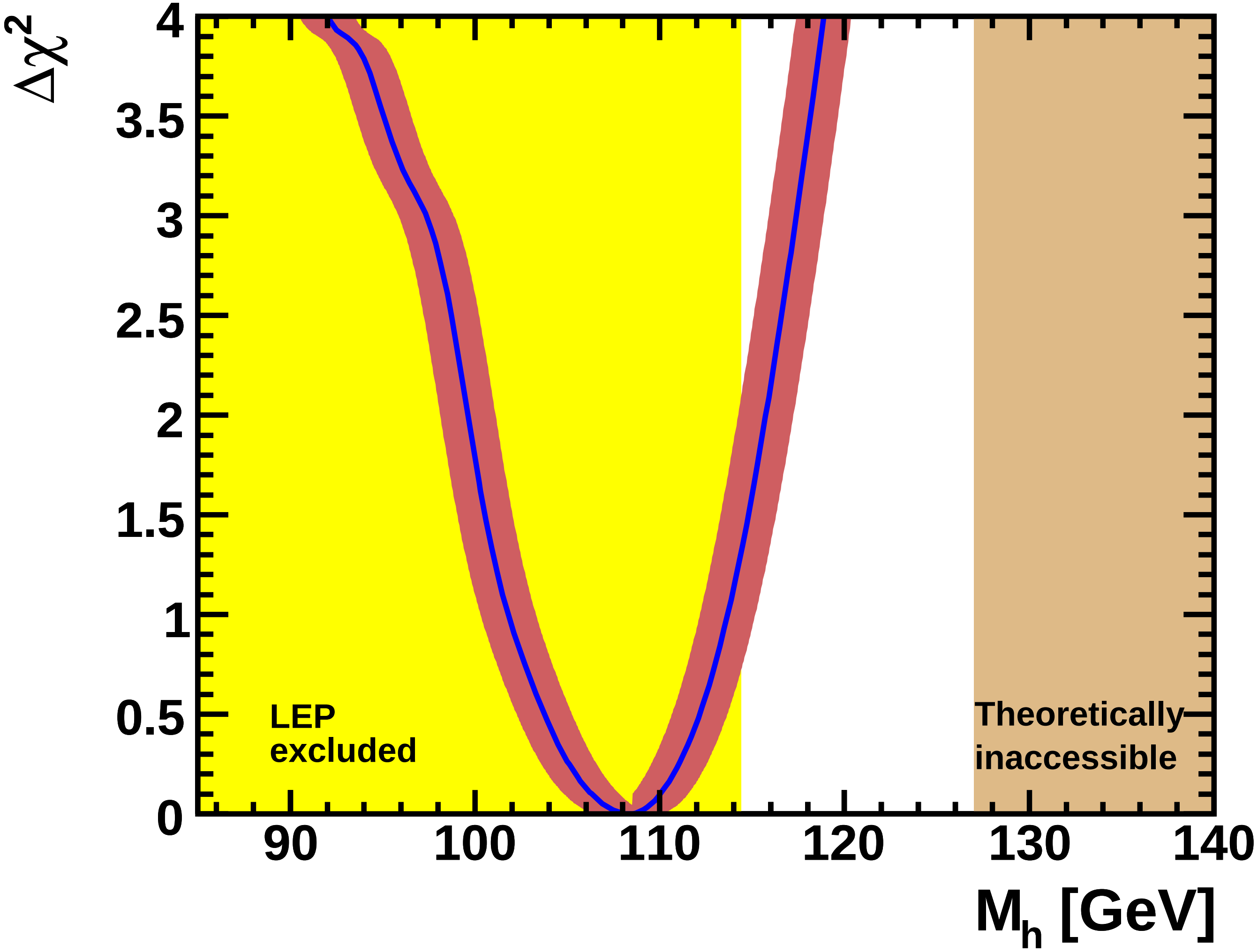
pre-LHC predictions: NUHM1:



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

pre-LHC-CMSSM: red band plot:

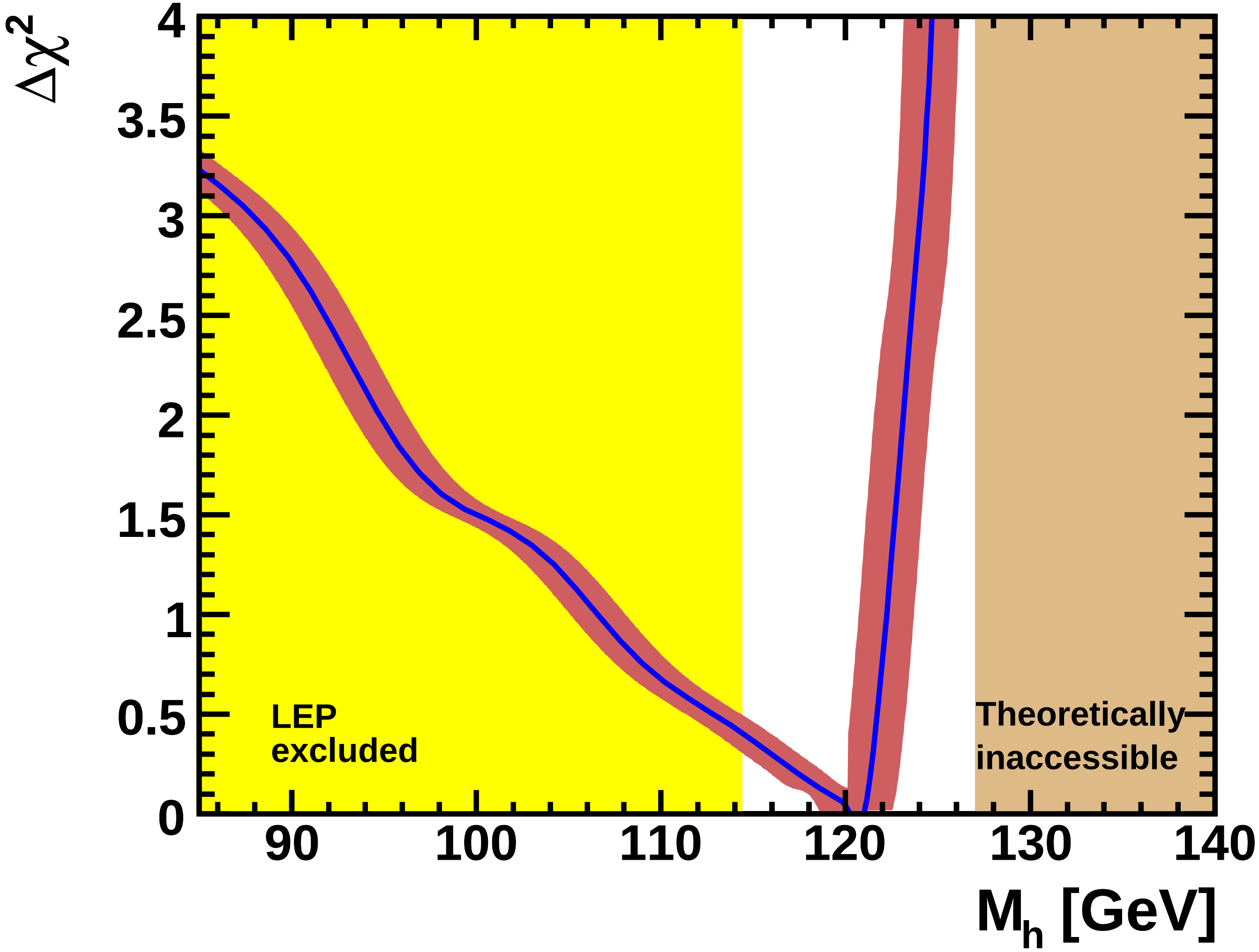
[2009]



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

pre-LHC-NUHM1: red band plot:

[2009]



$M_h = 121^{+1}_{-14}\,(\mathrm{exp}) \pm 1.5(\mathrm{theo})$ GeV $\Rightarrow$ naturally above LEP limit

Inclusion of LHC searches

Obvious idea:

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

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

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

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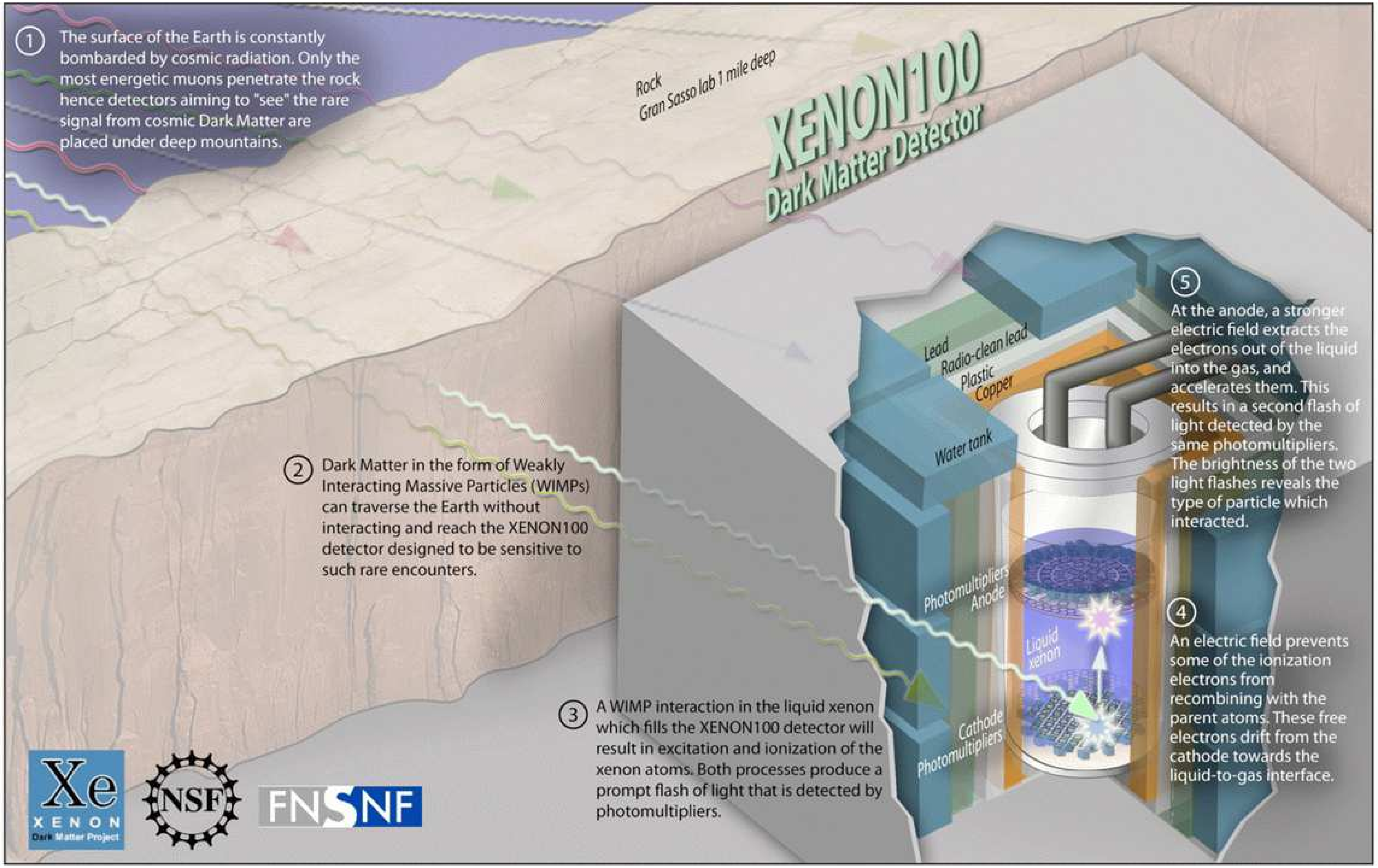
Expected effect: disfavor low m_0-$m_{1/2}$ values

$\Rightarrow$ Implications for SUSY fits?

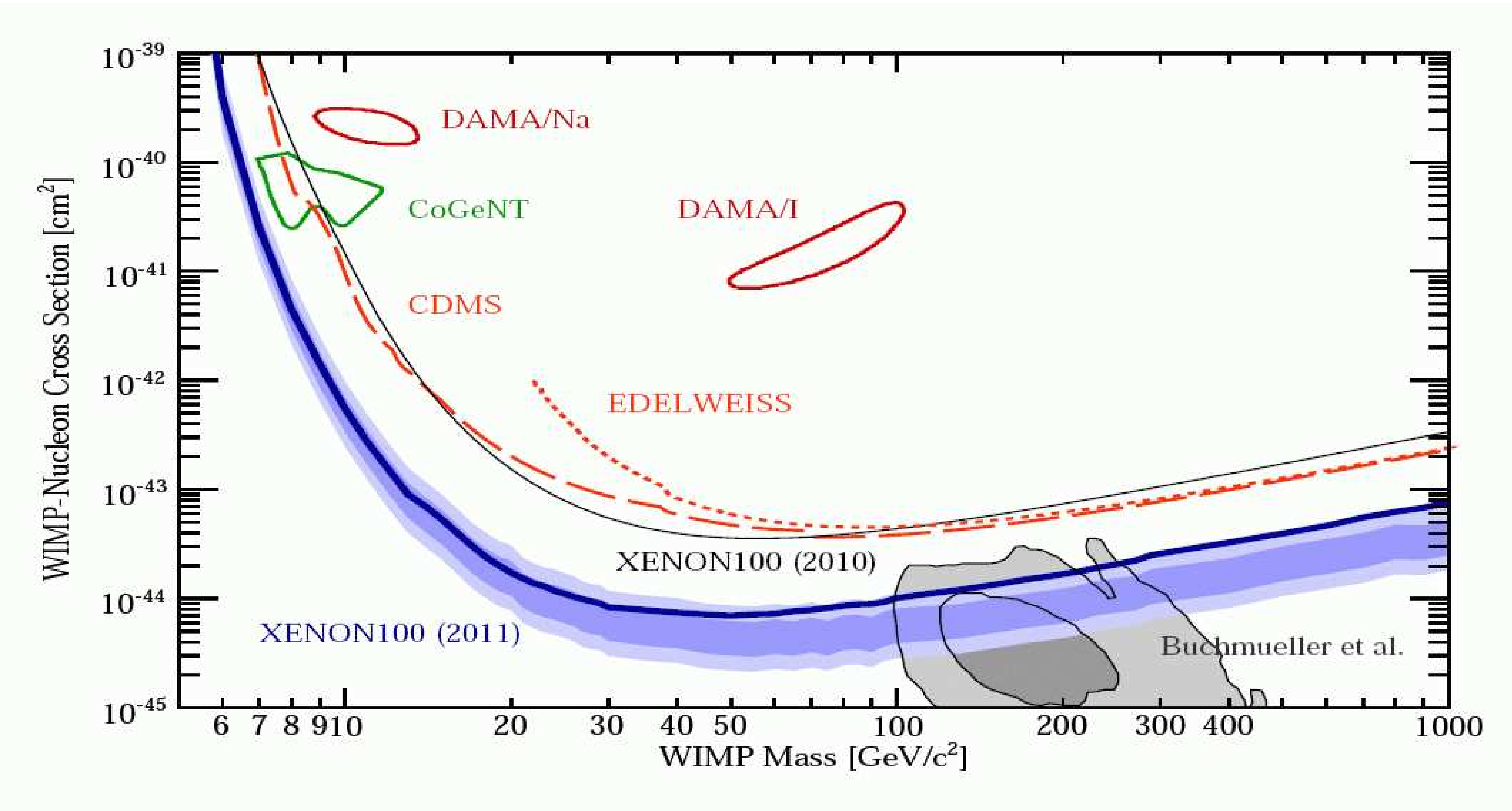
$\Rightarrow$ Implications for future colliders?

Additional new constraint:

Direct Dark Matter detection: Xenon100



Xenon100 results: [Xenon100 collaboration '11]



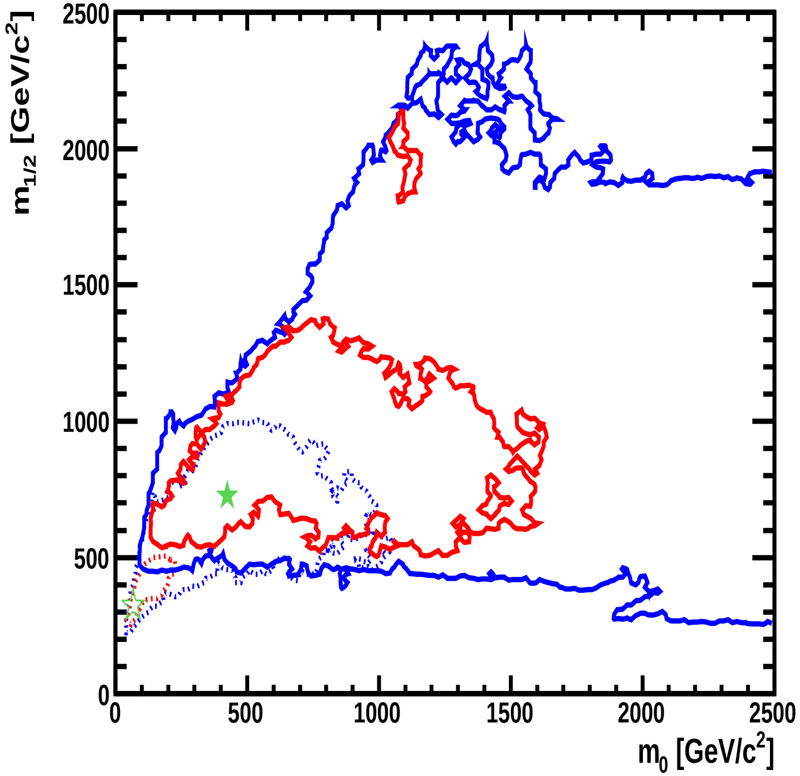
expected: 1.8 ± 0.6 events

observed: 3 events

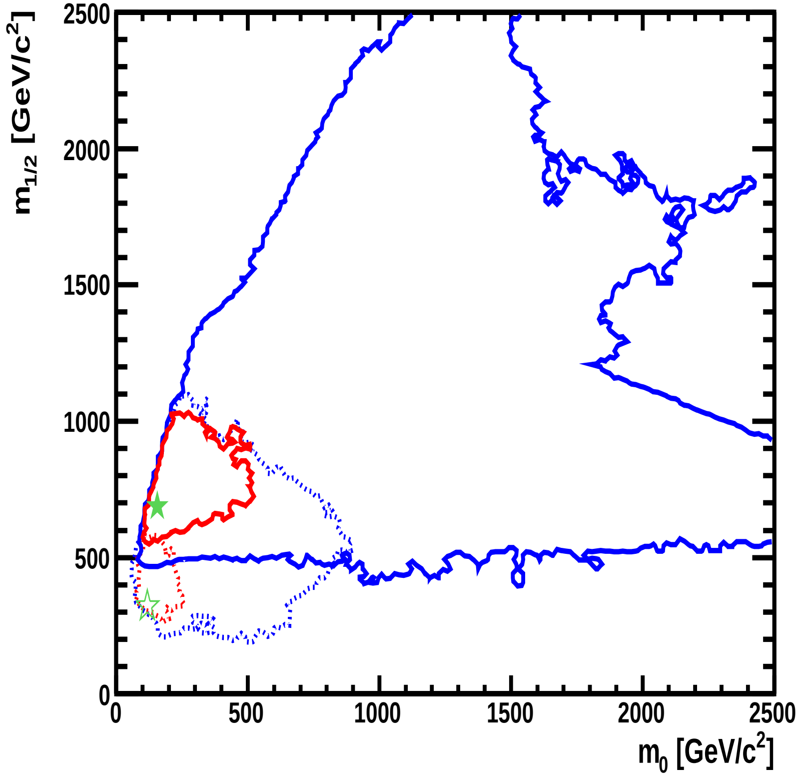
m_0-$m_{1/2}$ plane:

[2011]

CMSSM



NUHM1



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

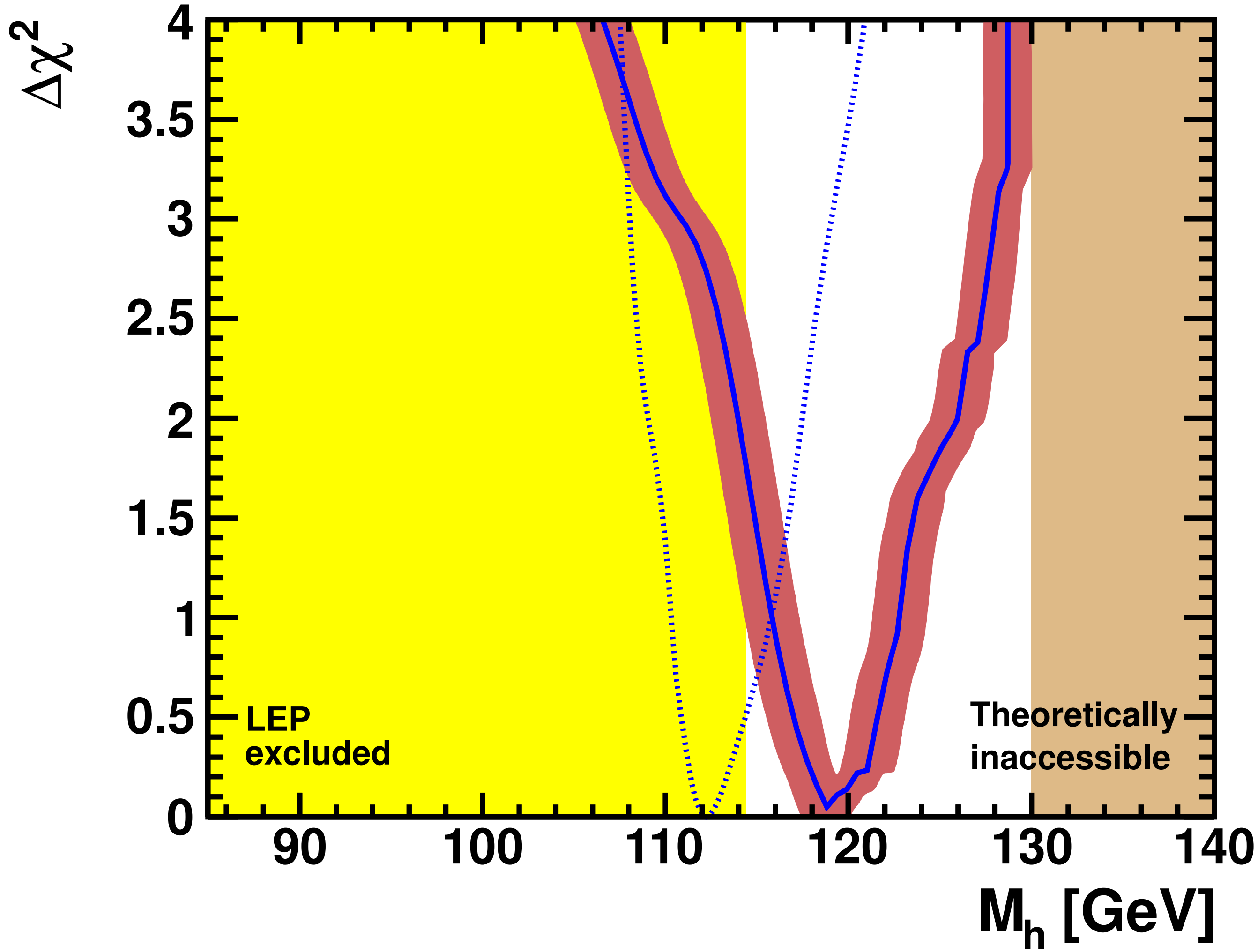
$\Rightarrow$ new best-fit point within old 95% CL area

$\Rightarrow$ hardly any overlap between old and new 68% CL areas

$\Rightarrow$ shift to higher masses

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

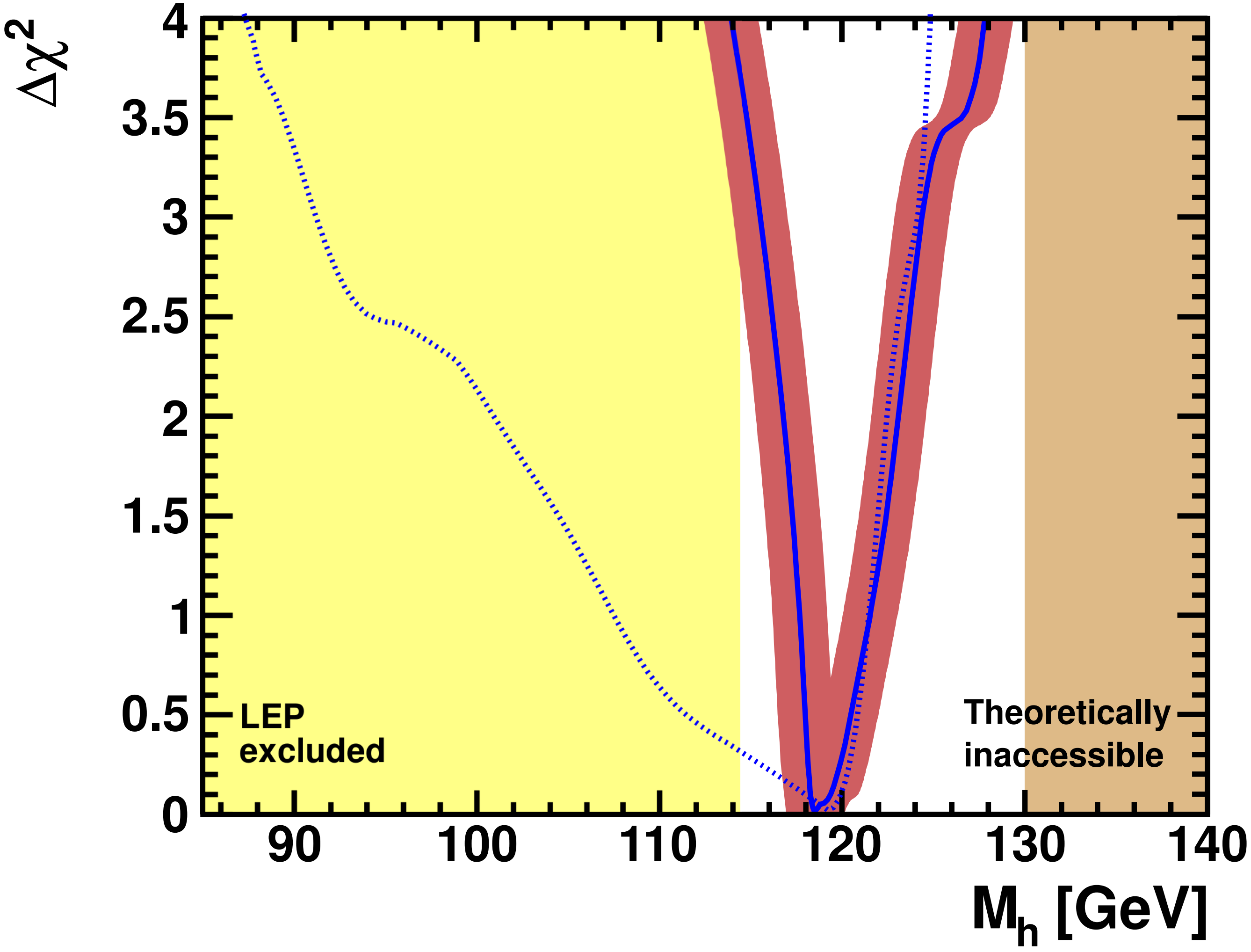
[2011]



$M_h = 119 \pm 3\,(\text{exp}) \pm 1.5(\text{theo})$ GeV $\Rightarrow$ fits "better" than pre-LHC

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

[2011]



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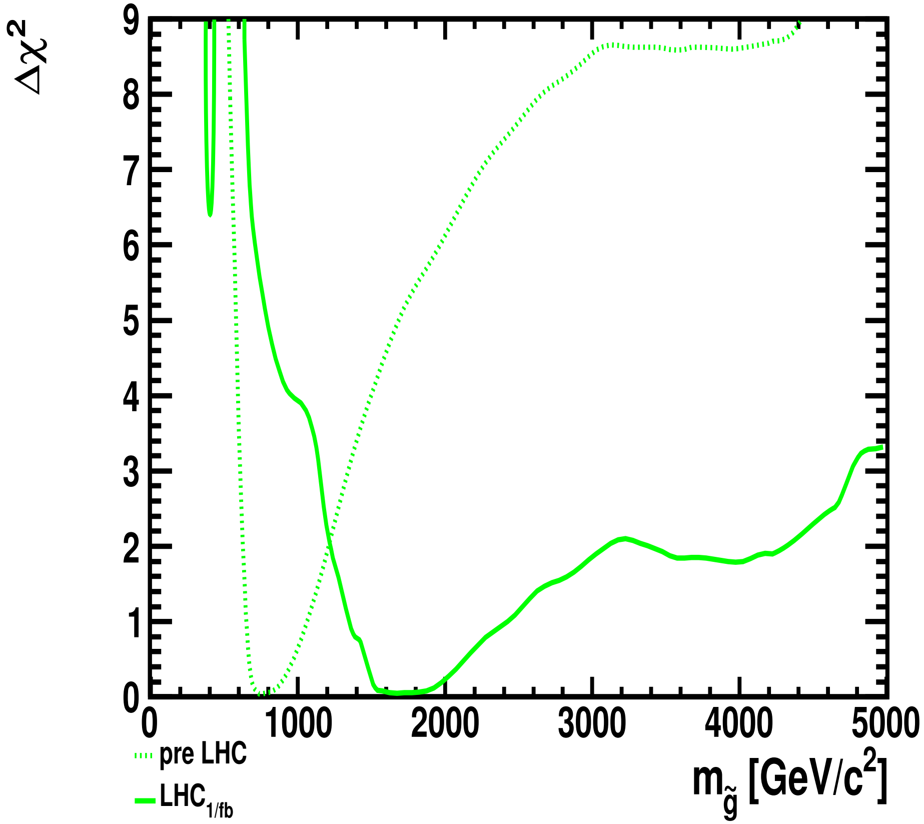
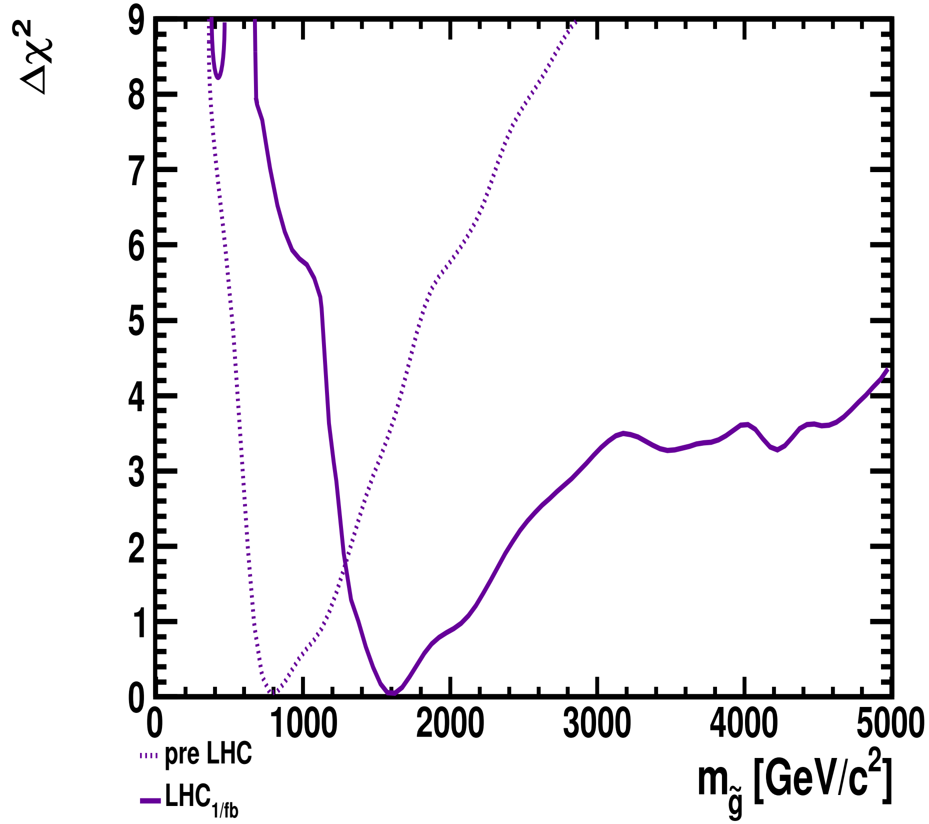
Starting point of the cascade: gluino

[2011]

CMSSM



NUHM1



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

$\Rightarrow$ 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	21.5/20	37%	360	90	-50	15	111
LHC 1 fb^{-1}	28.8/22	15%	780	450	-1100	41	119
NUHM1	20.8/18	29%	340	110	520	13	119
LHC 1 fb^{-1}	27.3/21	16%	730	150	-910	41	119

5. Implications for future e^+e^- colliders

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Do we need an e^+e^- collider at all?

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$\Rightarrow$ 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

...

$\Rightarrow$ Precise measurements of masses, branching ratios, cross sections, angular distributions, ... mandatory for

- establishing SUSY experimentally
- disentangling patterns of SUSY breaking

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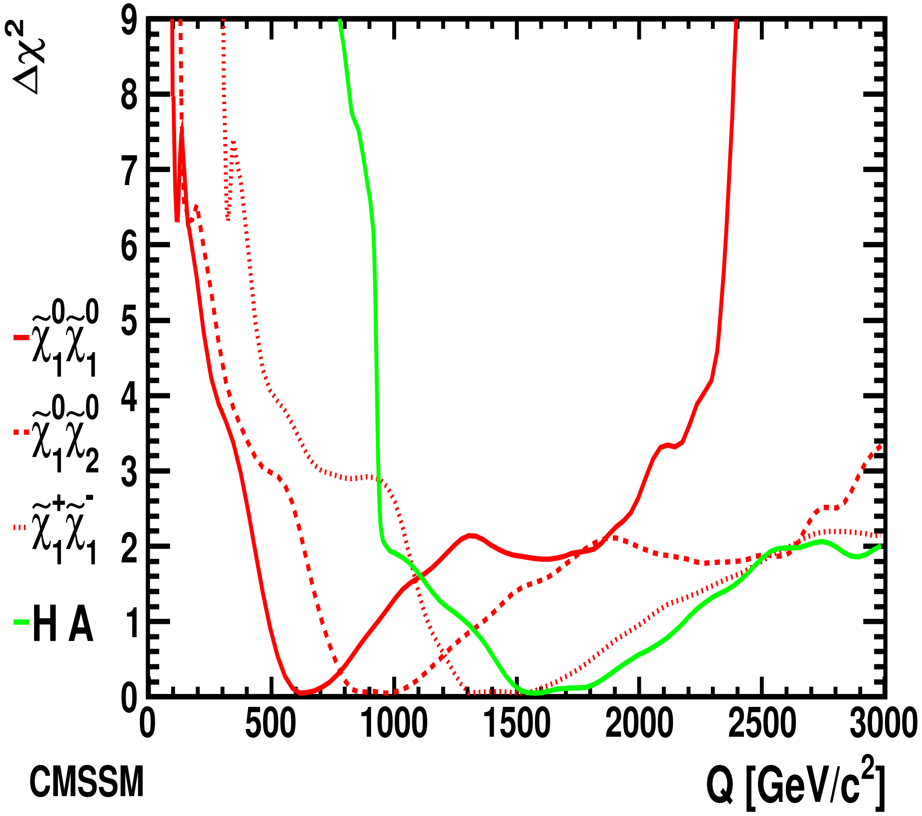
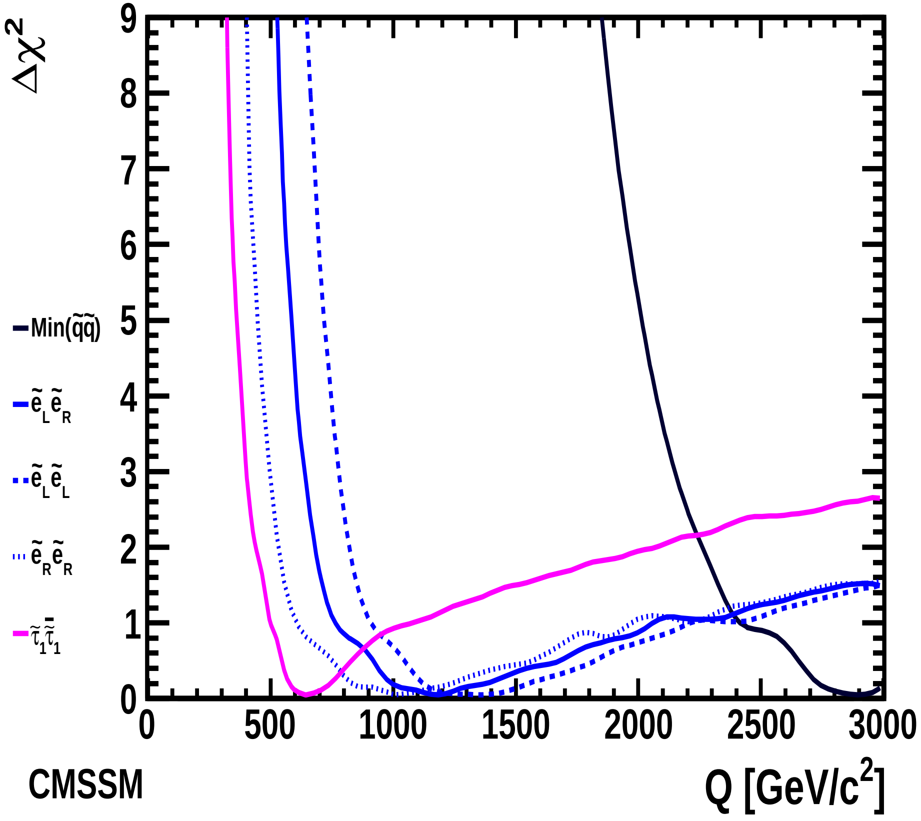
$\Rightarrow$ We need both: hadron colliders (LHC) and high luminosity LC

e^+e^- production thresholds in the CMSSM:

[2011]





What you will hear very often now:

this looks bad for an LC with $\sqrt{s} = 0.5 - 1$ TeV

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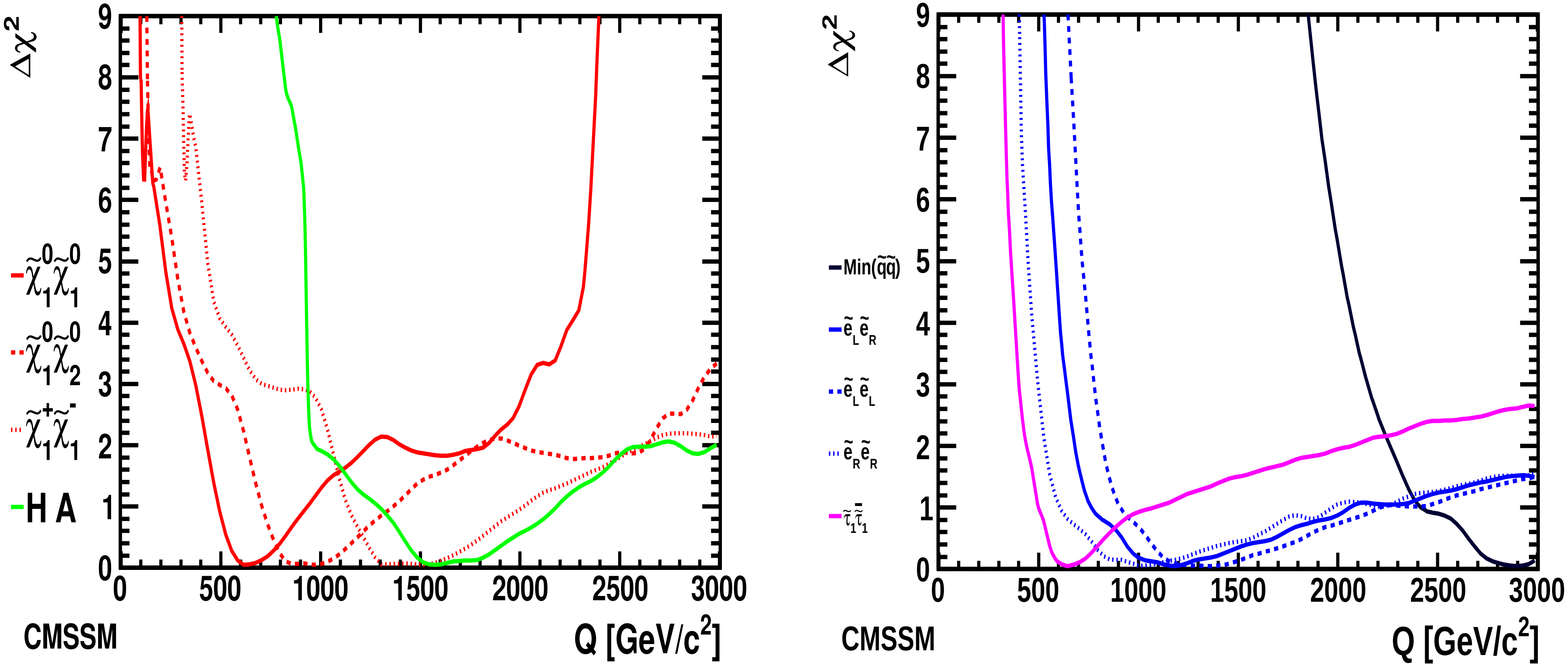

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And this is WRONG!

Change in best-fit points:

[2011]

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Not finding SUSY early does not make the LC looks bad,

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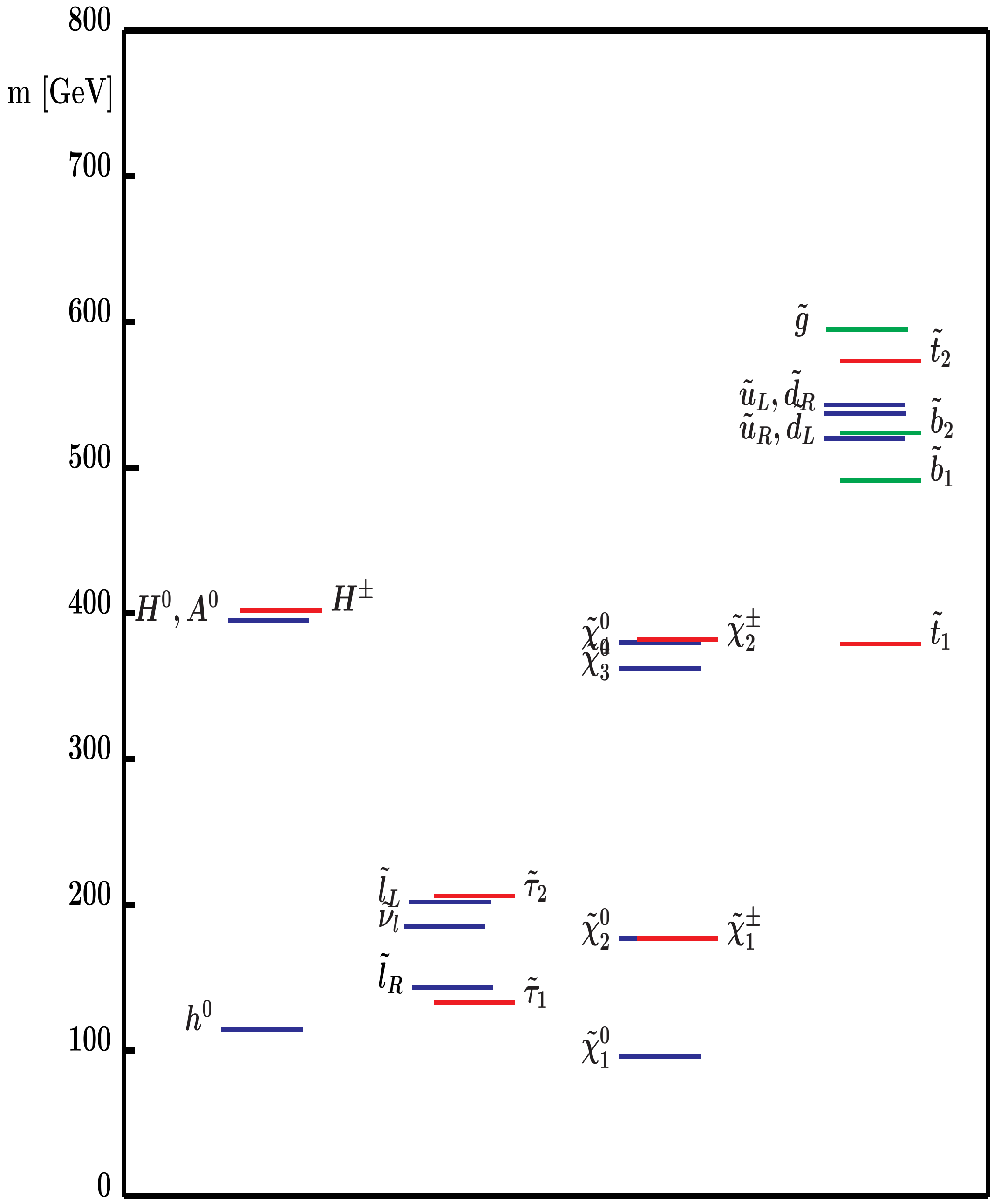
Any inference from one sector to the other is strongly model dependent!

"Typical" CMSSM scenario

(SPS 1a benchmark scenario):

Strong connection between

all the sectors



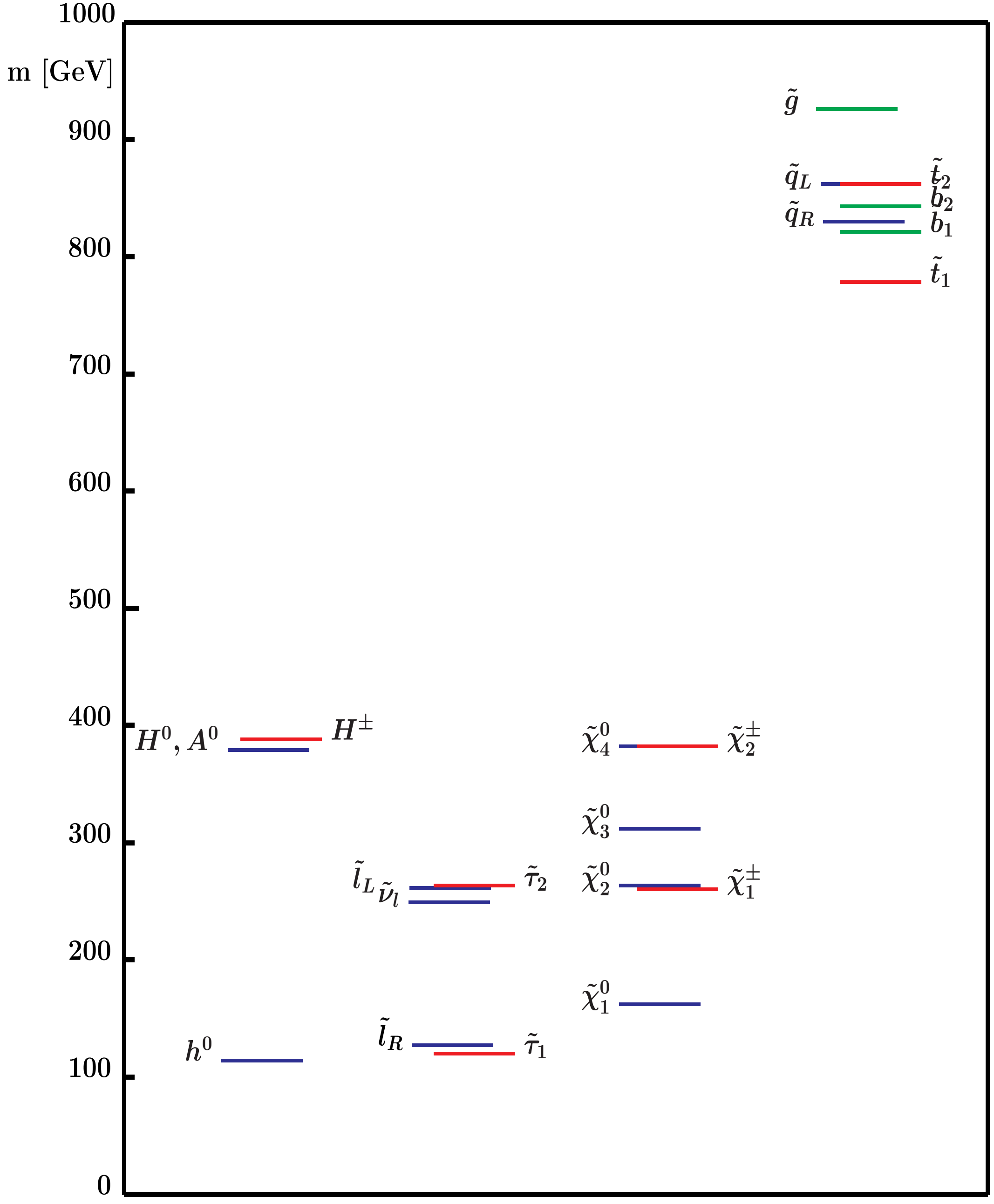
"Typical" GMSB scenario

(SPS 7 benchmark scenario):

SPS home page:

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

<u>One</u> 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`

<u>One</u> possible example
for natural larger splitting
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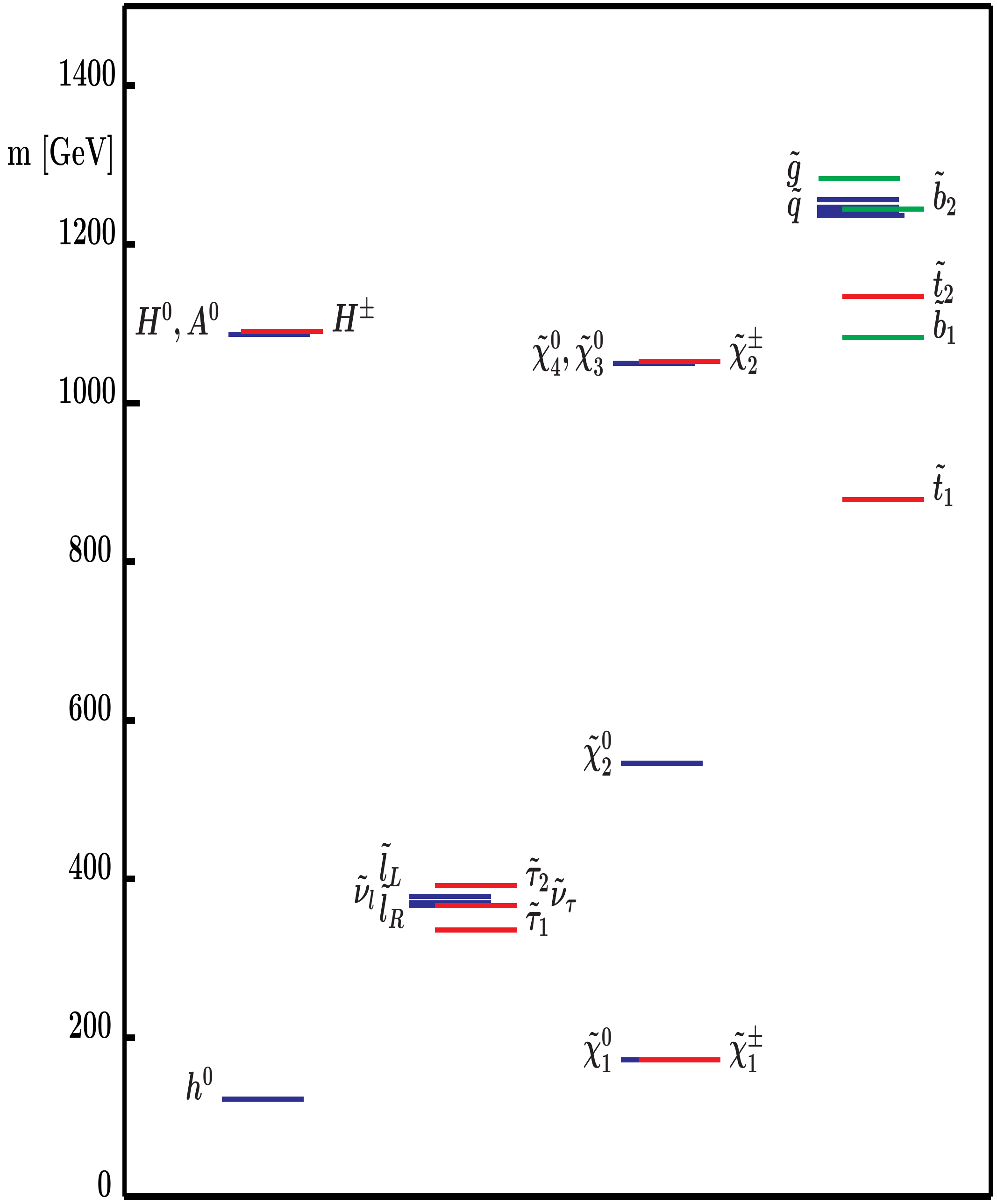

6. Conclusinos

- Finally we have the LHC running and searching for Higgs and SUSY :-)

- Higgs searches: 145 GeV $\lesssim M_H \lesssim$ 500 GeV excluded
  $\Rightarrow$ "excesses" in the low mass window . . .

- SUSY searches:
  Results are presented in the CMSSM or in "simplified models"
  $\Rightarrow$ limits of $\sim$ 500 – 1000 GeV
  $\Rightarrow$ no limits for 3rd generation squarks, "EW SUSY particles"

- SUSY fits with the MasterCode:
  post-LHC-2011 predictions: higher mass scales
  CMSSM, NUHM1, . . . still fit "so so"
  with somewhat lower probability

- Implications for future e^+e^- colliders:
  If in the next round of searches no SUSY is found:
  $\Rightarrow$ bad for CMSSM, NUHM1, . . .
  $\Rightarrow$ inference for LC ($\sqrt{s} = 0.5 - 1$ TeV) very moderate!