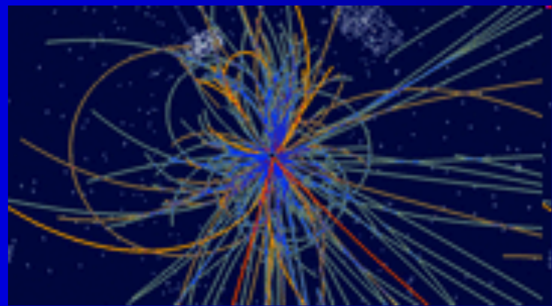
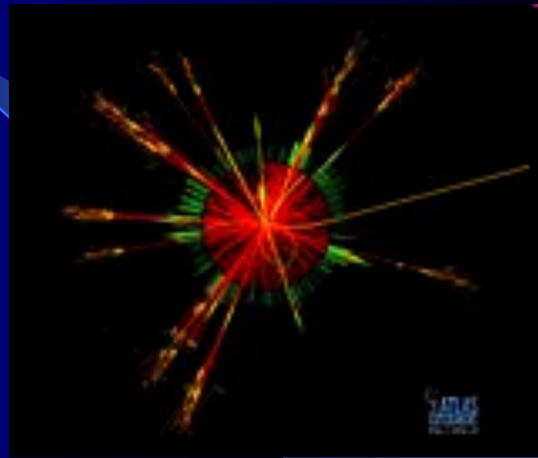
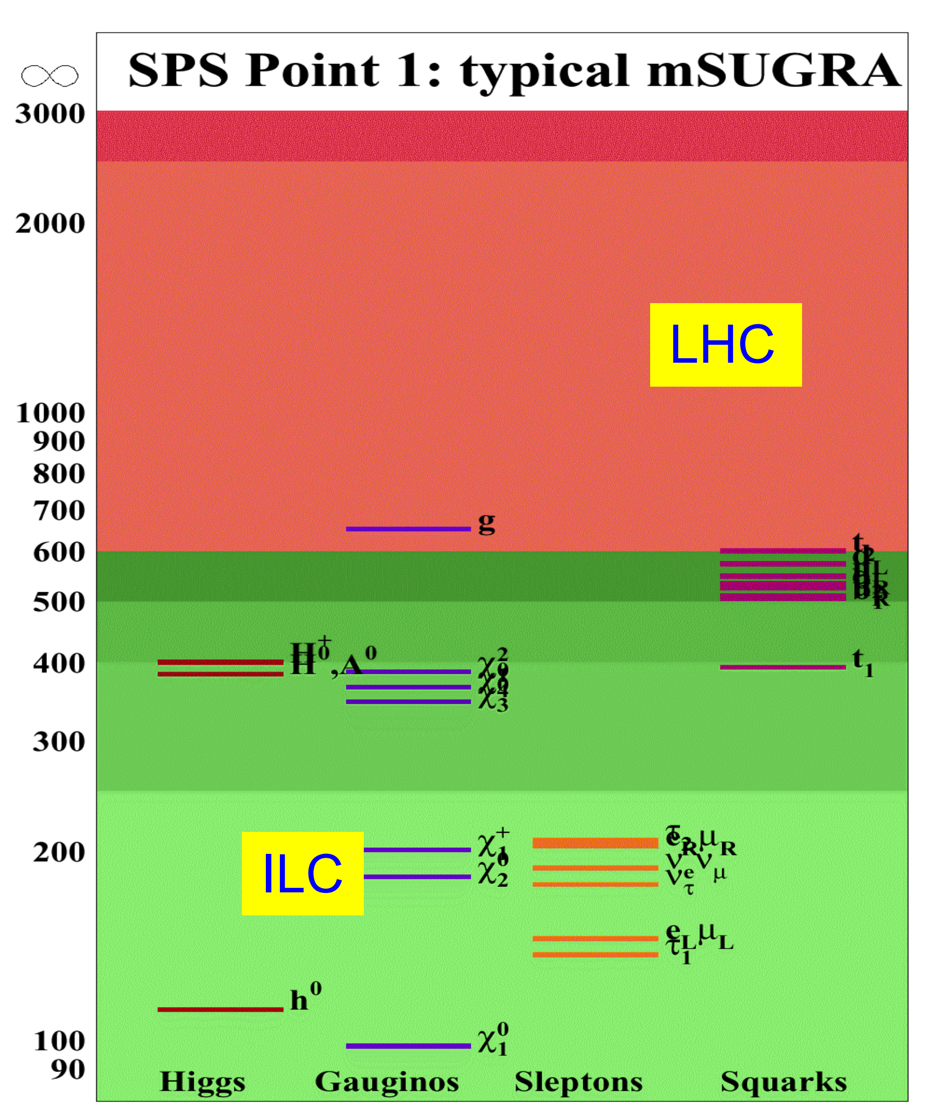
Search for Superpartners @ Colliders

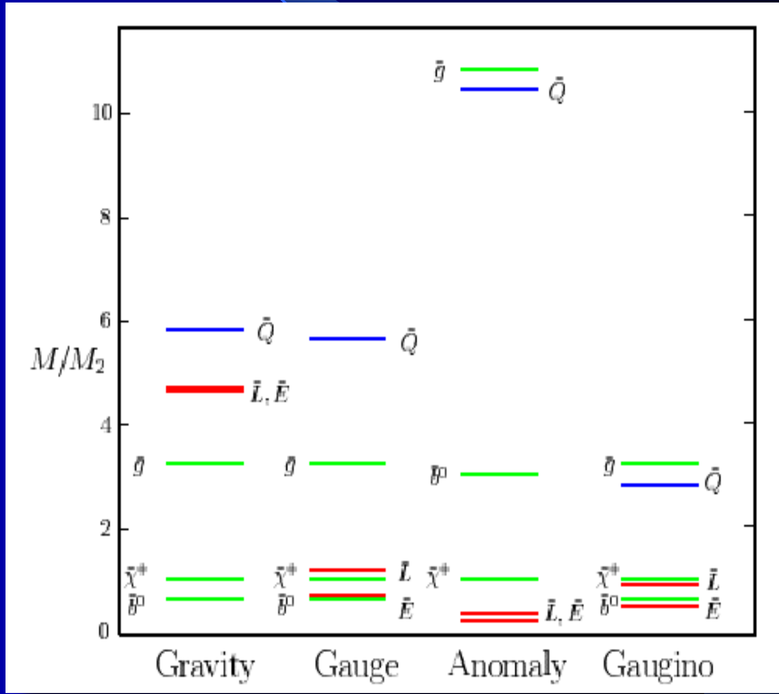




The Mass Spectrum



Model Dependent

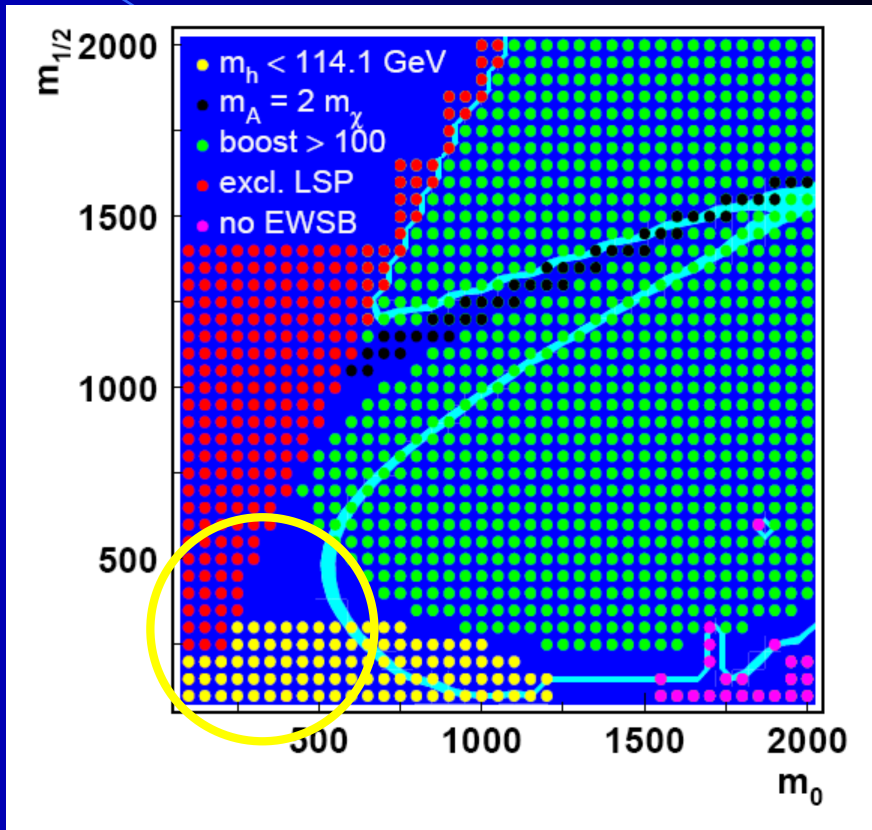


Favoured regions of parameter space

Bulk region

The region is characterized by low m_0 and low $m_{1/2}$ thus leading to light superpartners (< 500 GeV)

The region is restricted by the Higgs searches and LEP II non-observation limits



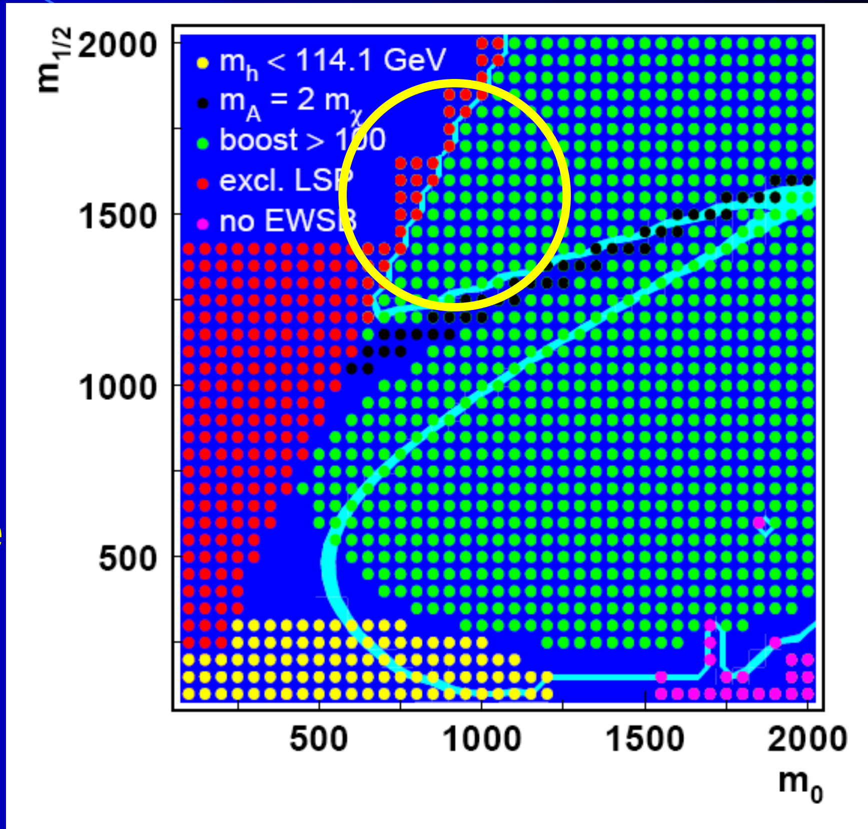
Strong SM background

The bulk region is practically excluded by LEP II

Favoured regions of parameter space

$\tilde{\chi}^0\tilde{\tau}$ -coannihilation region

The region is characterized by low m_0 but large $m_{1/2}$, *hence, heavy charginos*



Masses of tau-slepton and neutralino are almost degenerate

Typical processes: neutralino-stau co-annililation:

$$\chi\tilde{\tau} \rightarrow \tau^* \rightarrow \tau\gamma$$

Possibility of long-lived heavy charged staus flying through the detector or decaying at a distance !

Favoured regions of parameter space

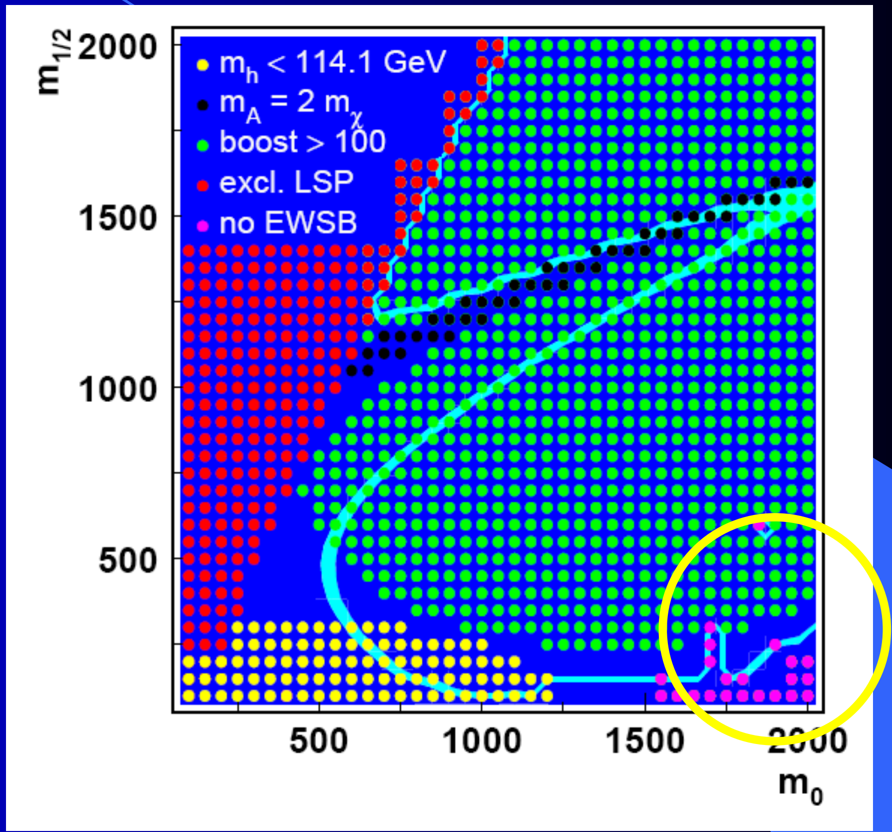
Focus point region

The region is characterized by large m_0 and low $m_{1/2}$

At the boundary of REWSB excluded region neutralino is almost higgsino
Possible long-lived chraginos

Splitting of heavy squarks and sleptons from light gauginos

Neutralino LSP ~ 100 GeV



Favoured regions of parameter space

<u>*A*-annihilation funnel region</u>

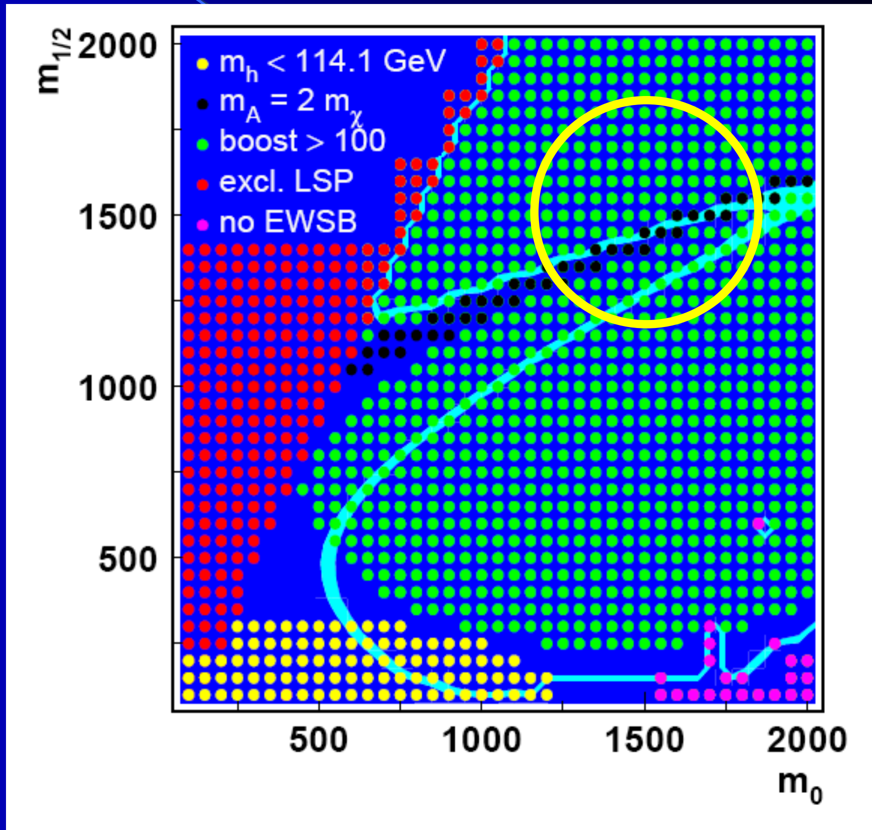
The region where

$$m_A \simeq 2m_\chi$$

Typical processes: resonance annihilation of neutralinos to fermion pairs through exchange of heavy Higgses *A* (and/or *H*):

$$\chi\chi \rightarrow A(H) \rightarrow f\bar{f}$$

The region requires large tan β and leads to heavy sparticles



Favoured regions of parameter space

EGRET region

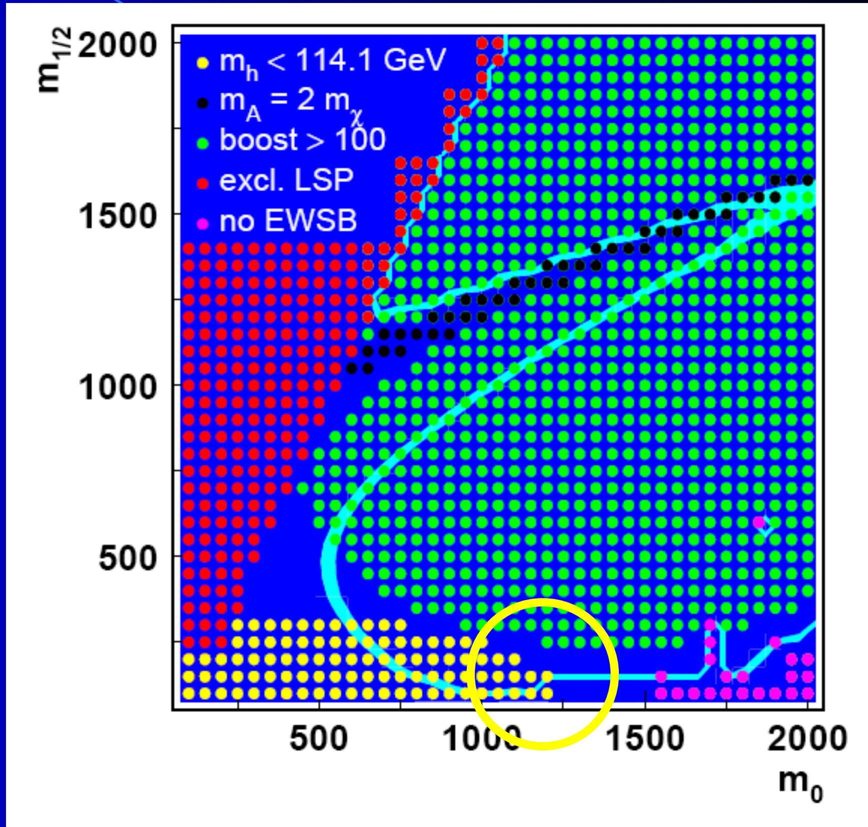
The region is compatible with diffuse gamma ray flux from the DM annihilation

It corresponds to the best fit values of parameters

tan β= 51

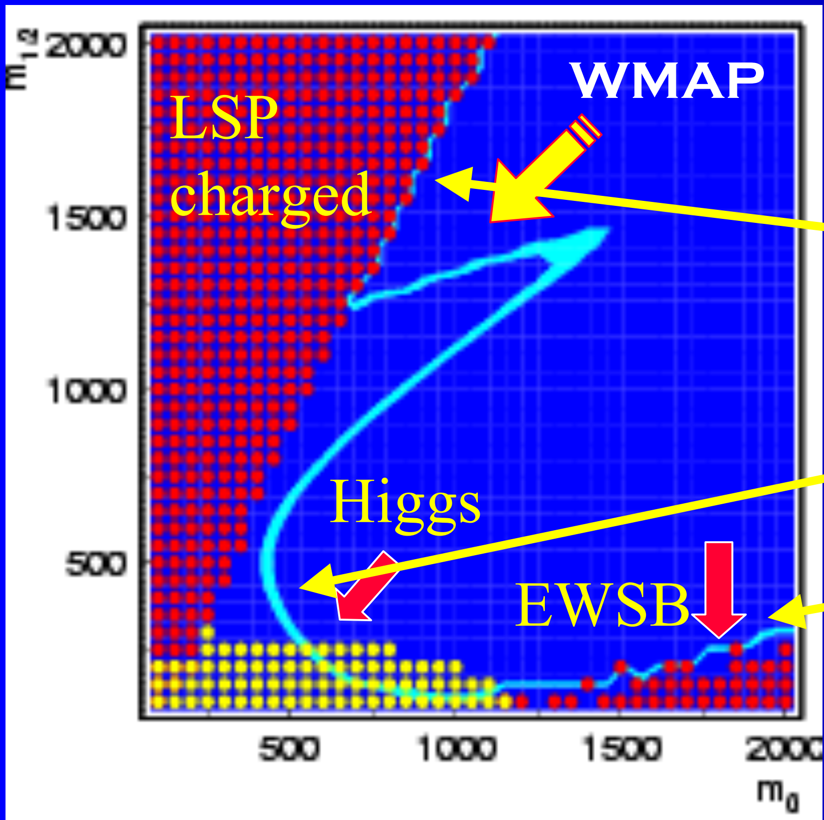
m0 = 1400 GeV

m1/2 = 180 GeV



SUSY DM: $m_{\chi^0} \sim 65$ GeV → $m_{\chi^\pm} \sim 115$ GeV

Long-Lived Superparticles



The MSSM parameter space

The reason for long-lived particles – mass degeneracy with the LSP

Long-lived $\tilde{\tau}^{\pm}$

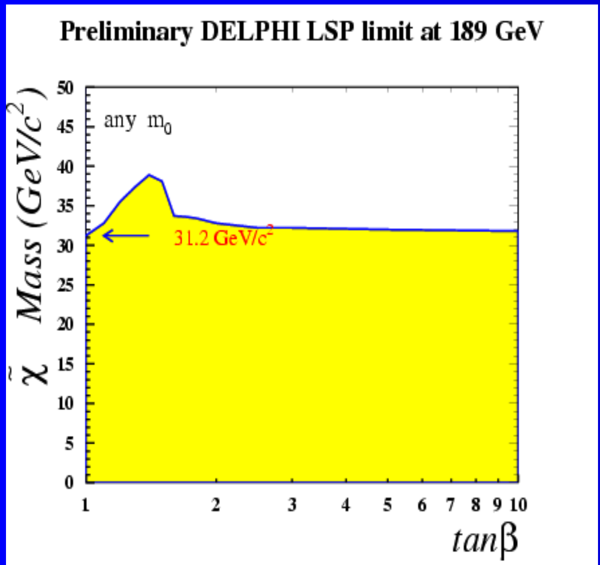
Long-lived $\tilde{t}^{\pm}$

Long-lived $\tilde{\chi}_2^0, \tilde{\chi}_1^{\pm}$

Time of life > 10^{-10} сек, M ~ 100 ГэВ
Decay with creation of the secondary vertex or running through the detector

Needs the fine-tuning of parameters

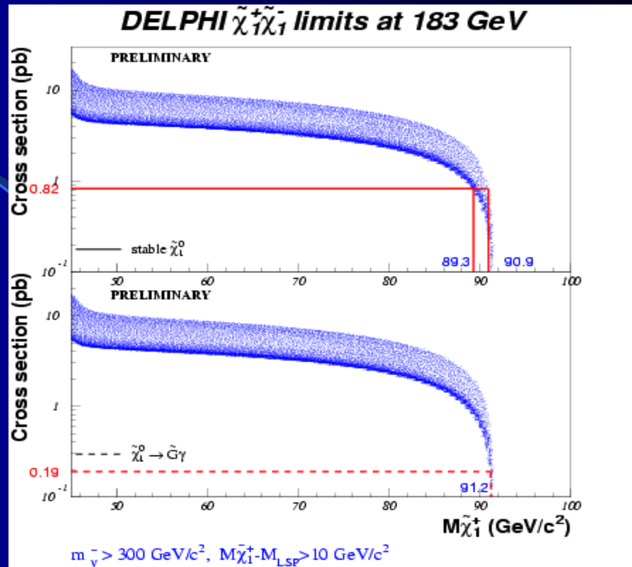
SUSY Searches at LEP



neutralinos

←

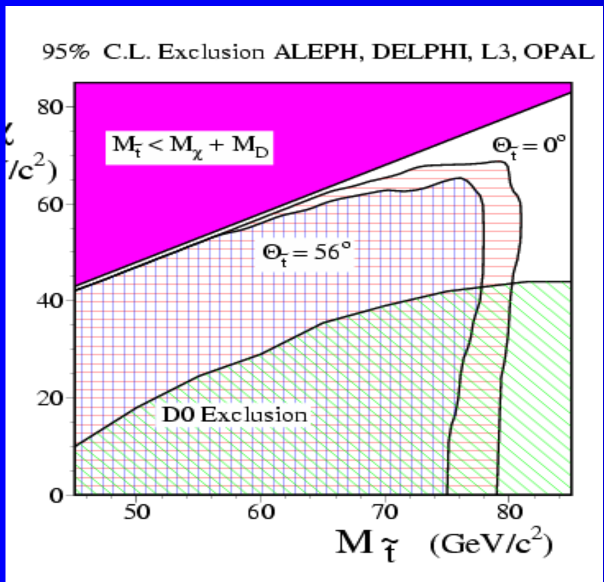
$\tilde{m}\chi^0 \geq$ 40 GeV



charginos

→

$\tilde{m}\chi^+ \geq$ 100 GeV



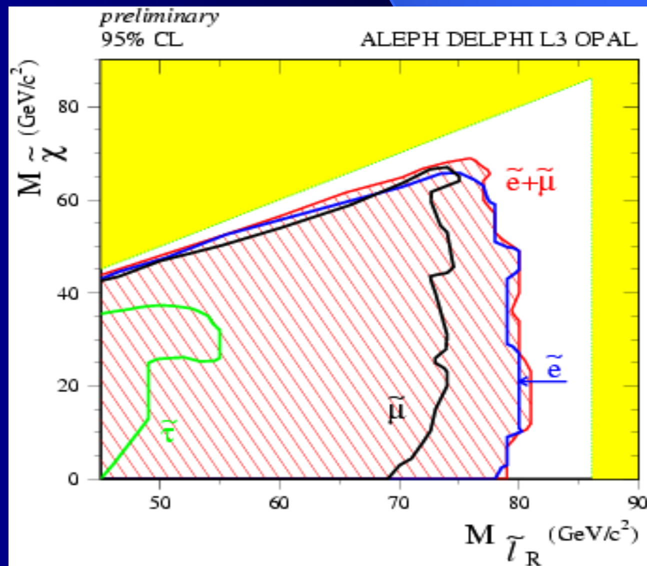
squarks

←

sleptons

→

$\tilde{m}_l \geq$ 100 GeV

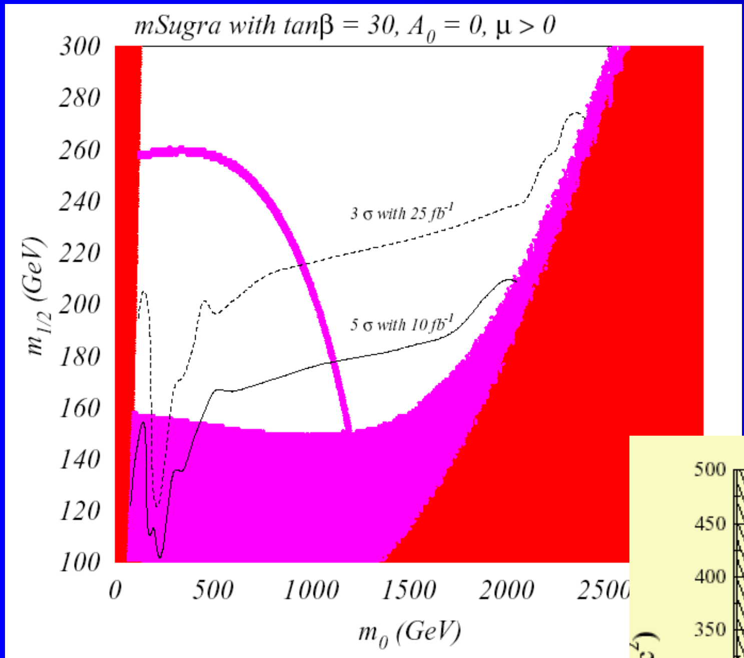


SUSY Production at Hadron Colliders

Production	Key Decay Modes	Signatures
• $\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\tilde{g} \to q\bar{q}\tilde{\chi}_1^0$, $q\bar{q}'\tilde{\chi}_1^{\pm}$, $g\tilde{\chi}_1^0$ } $m_{\tilde{q}} > m_{\tilde{g}}$	$\not{E}_T$ + multijets (+leptons)
	$\tilde{q} \to q\tilde{\chi}_i^0$, $\tilde{q} \to q'\tilde{\chi}_i^{\pm}$ } $m_{\tilde{g}} > m_{\tilde{q}}$	
• $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$	$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l^{\pm}\nu$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll$	Trilepton + $\not{E}_T$
	$\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 q\bar{q}'$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll$,	Dilepton + jet + $\not{E}_T$
• $\tilde{\chi}_1^{+}\tilde{\chi}_1^{-}$	$\tilde{\chi}_1^{+} \to l\tilde{\chi}_1^0 l^{\pm}\nu$	Dilepton + $\not{E}_T$
• $\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X$, $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	$\not{E}_T$ + Dilept+(jets)+lept
• $\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$	2 acollinear jets + $\not{E}_T$
	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 q\bar{q}'$	single lepton + $\not{E}_T$ + $b's$
	$\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l^{\pm}\nu$,	Dilepton + $\not{E}_T$ + $b's$
• $\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \tilde{\nu}\tilde{\nu}$	$\tilde{l}^{\pm} \to l \pm \tilde{\chi}_i^0$, $\tilde{l}^{\pm} \to \nu_l\tilde{\chi}_i^{\pm}$	Dilepton + $\not{E}_T$
	$\tilde{\nu} \to \nu\tilde{\chi}_1^0$	Single lept + $\not{E}_T$ + jets
		$\not{E}_T$

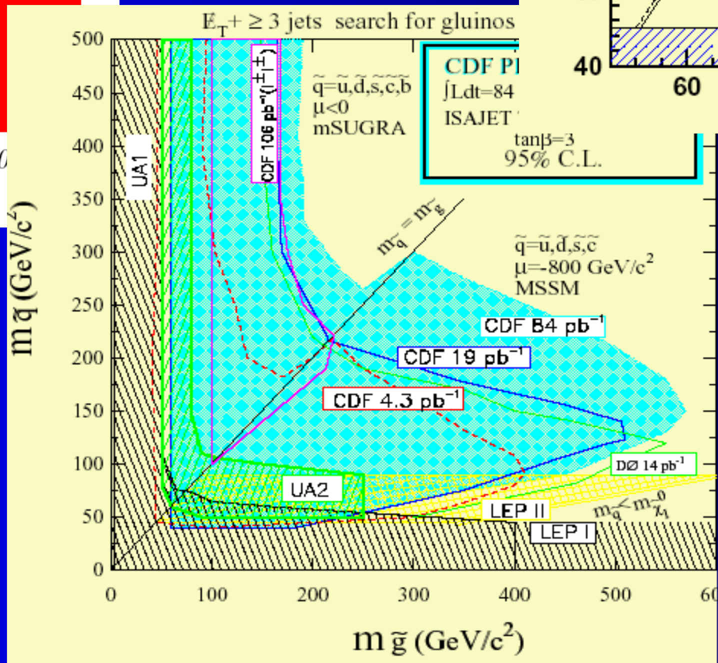
SUSY Searches at Tevatron

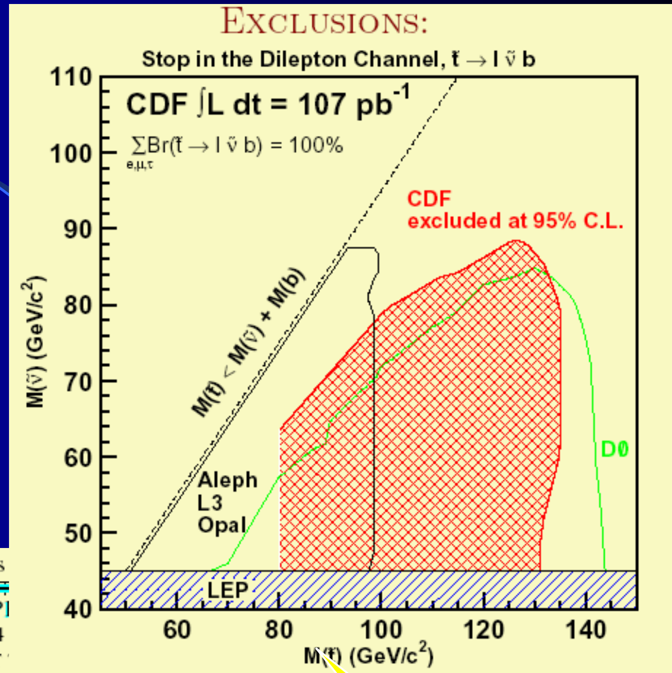
The reach of Tevatron in $m_0 / m_{1/2}$ plane



Exclusion:
World's Best Limits

$m\tilde{q} \geq$ 300 GeV
$m\tilde{g} \geq$ 195 GeV



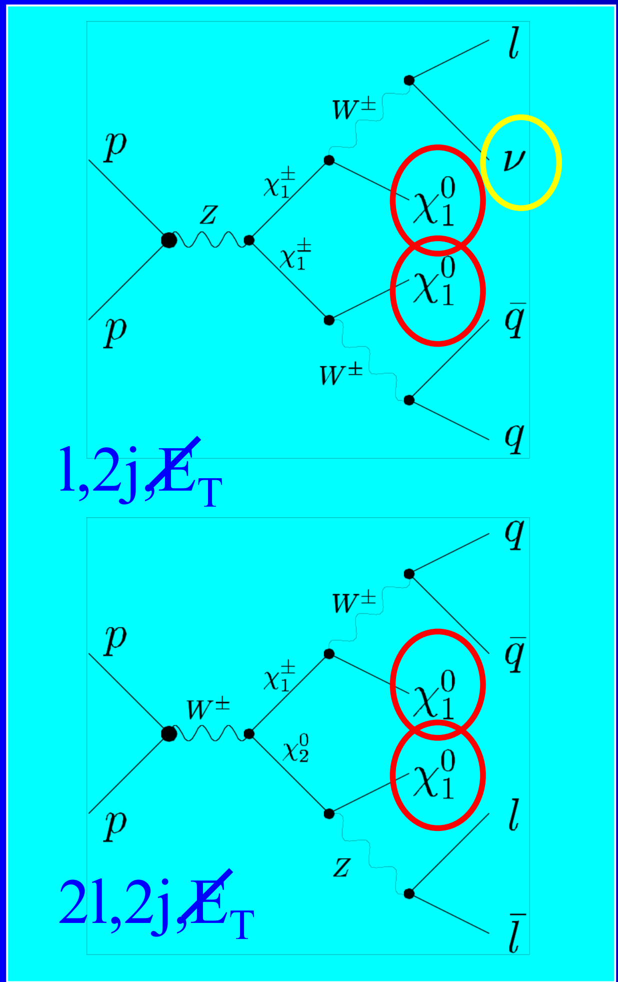


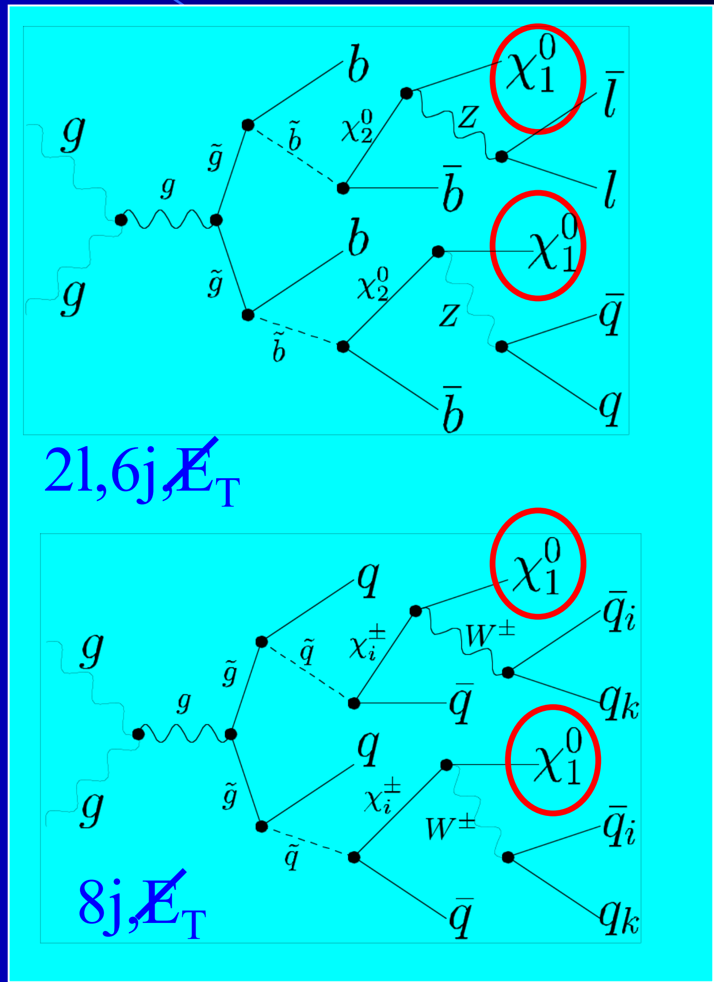
Dilepton Channel

3 jet channel

Creation and Decay of Superpartners in Cascade Processes @ LHC

weak int's

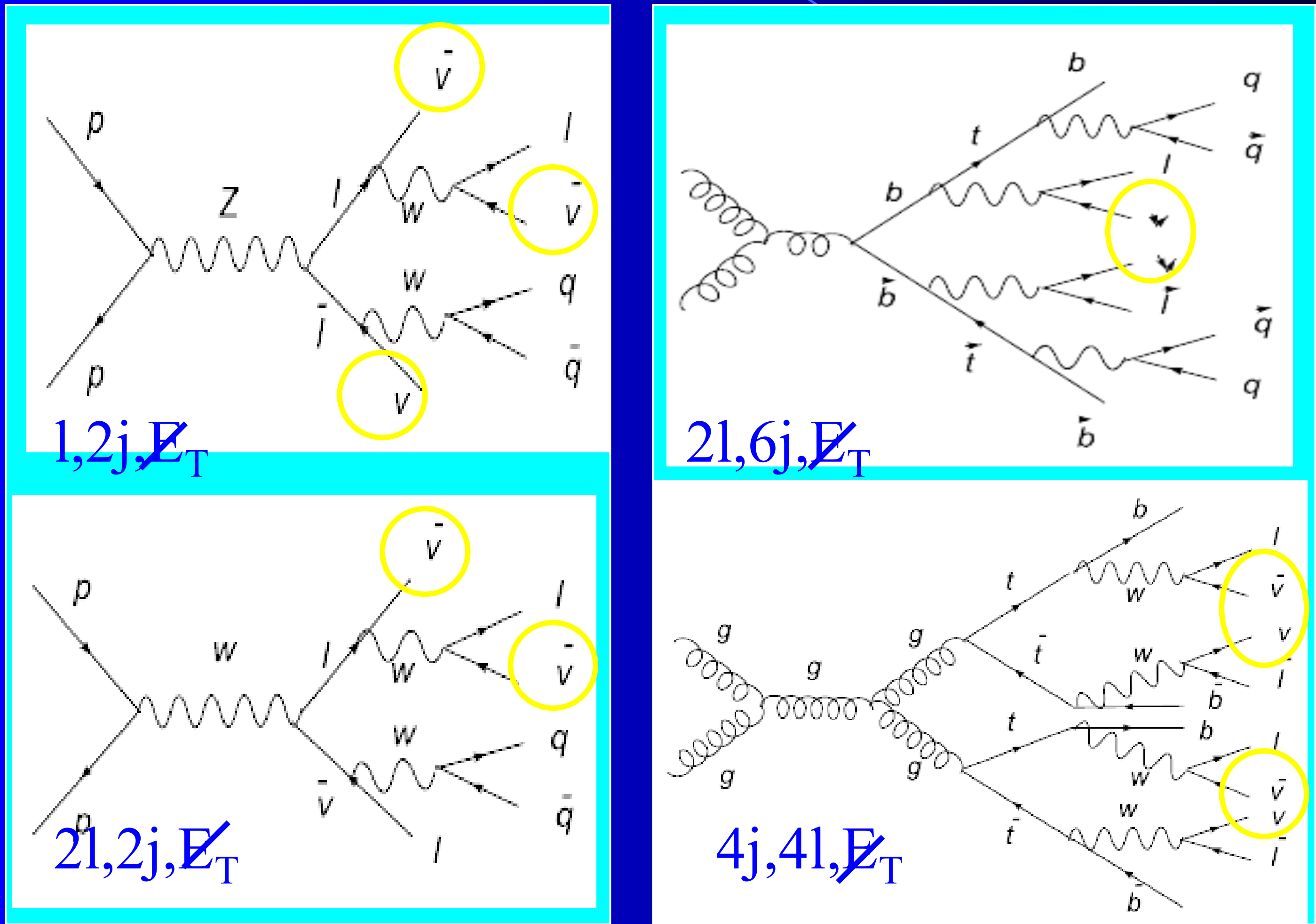




strong int's

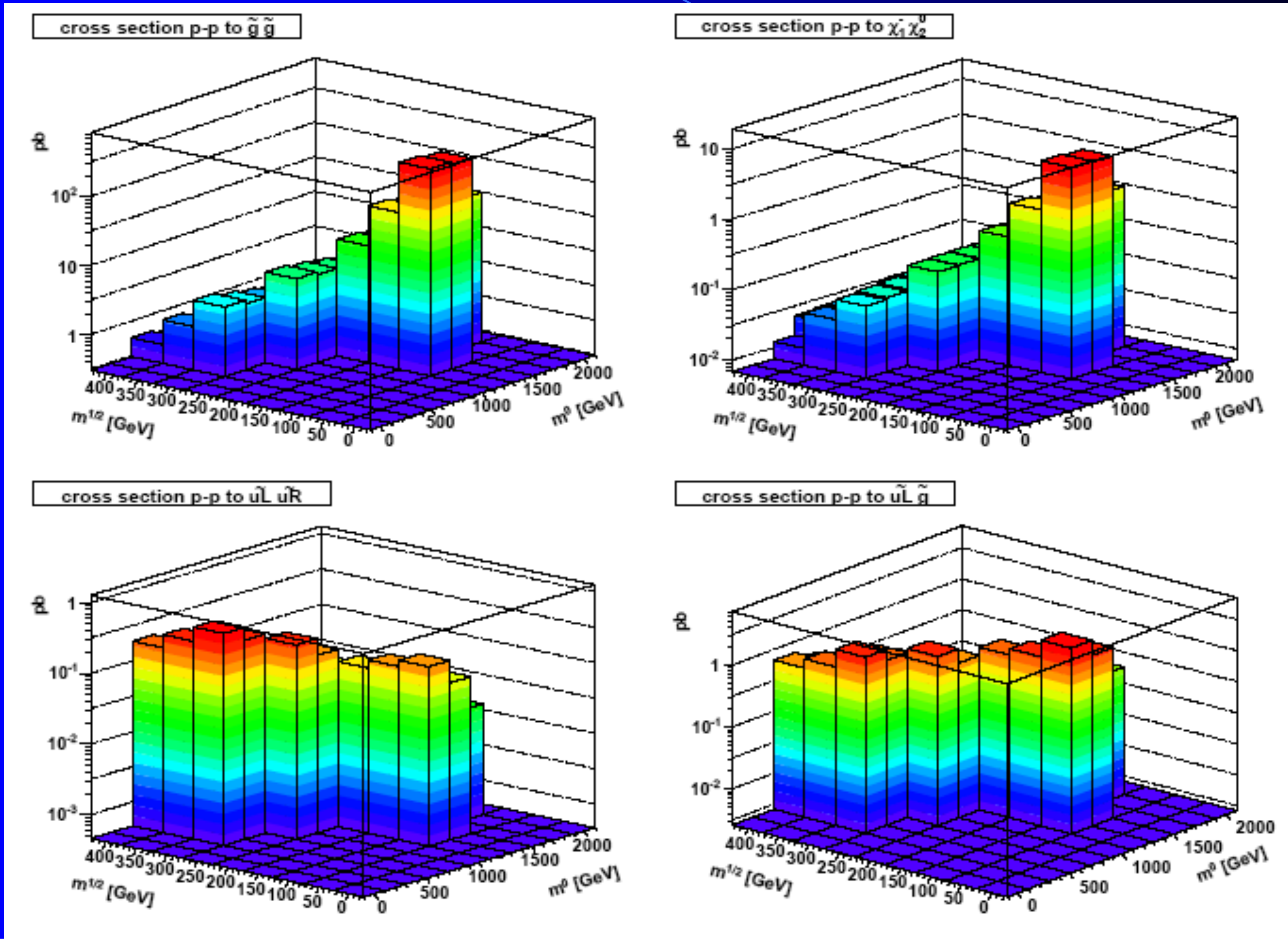
Typical SUSY signature: Missing Energy and Transverse Momentum

Background Processes of the SM for creation of Superpartners

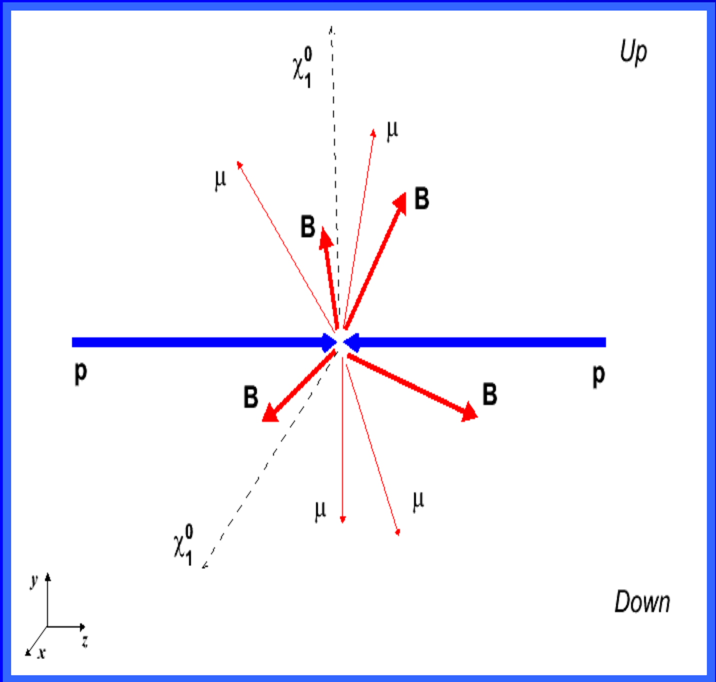


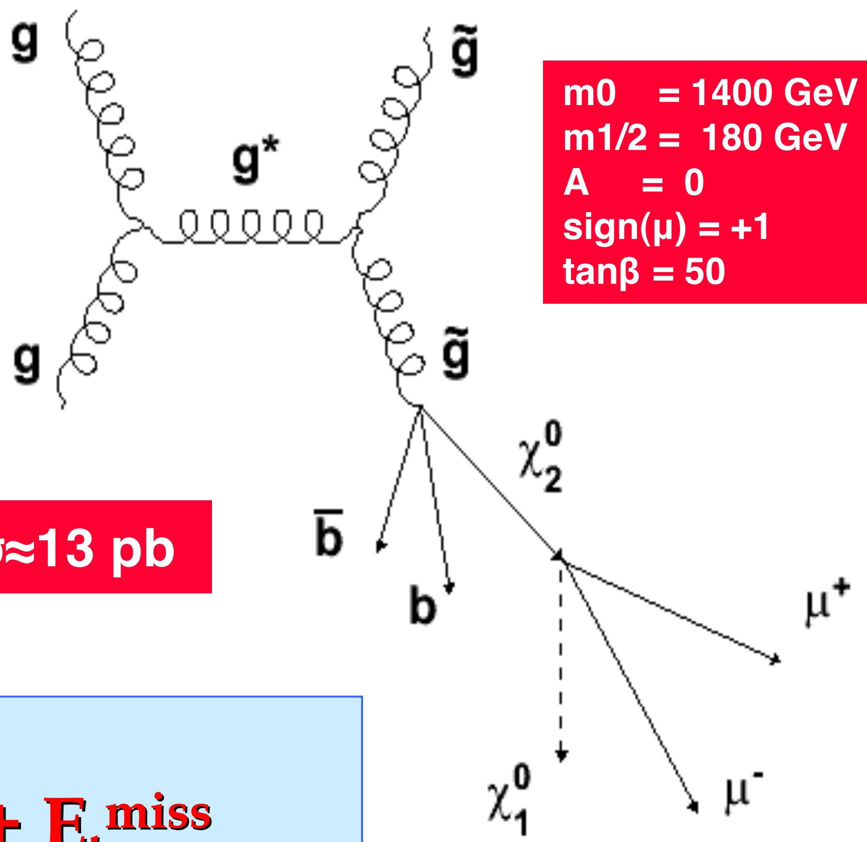
The x-sections are usually much smaller than for creation of SUSY

Cross-sections for SUSY creation @ LHC



Creation of Gluino @ LHC





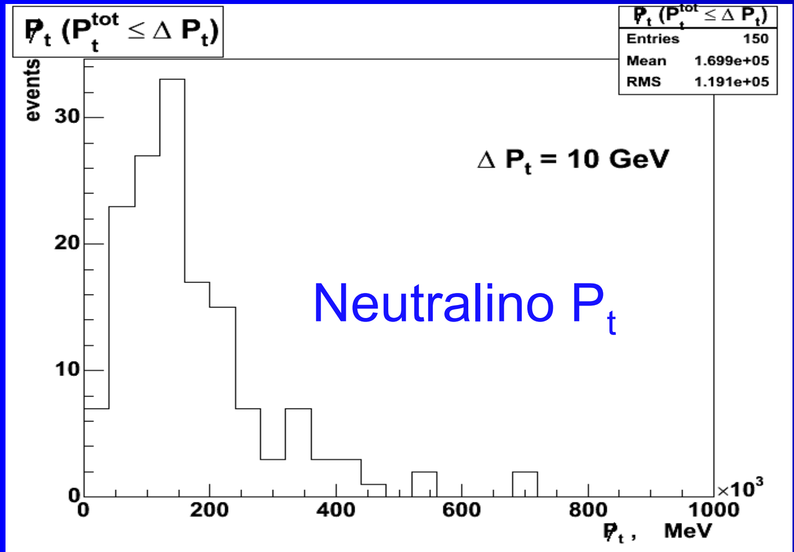
m0 = 1400 GeV
m1/2 = 180 GeV
A = 0
sign(μ) = +1
tanβ = 50

σ≈13 pb

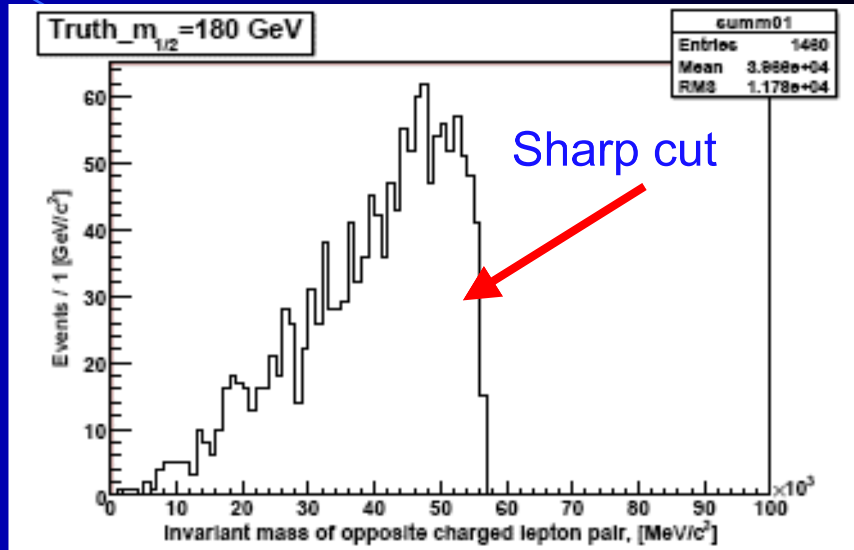
Signature:
4 b-jets + 4 muons + E_t^{miss}

Large!

SUSY Signal @ LHC



Missing Momentum



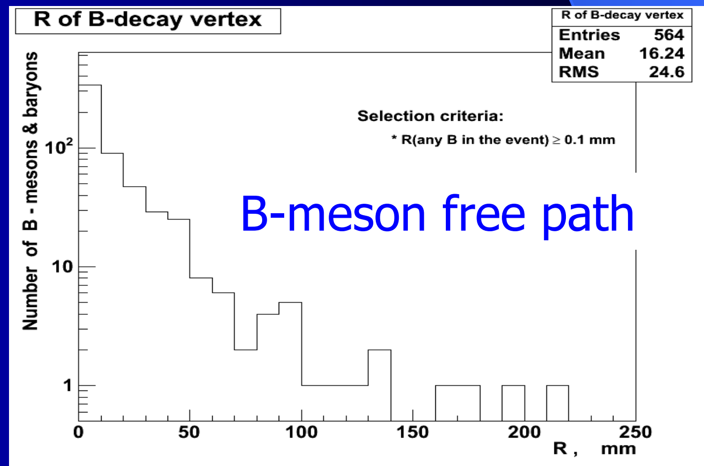
Invariant Mass of lepton pair

$$\Sigma P_t^{B,B,\mu,\mu} \text{(down)} - \Sigma P_t^{B,B,\mu,\mu} \text{(up)} = \not{P}_t \equiv \not{E}_t$$

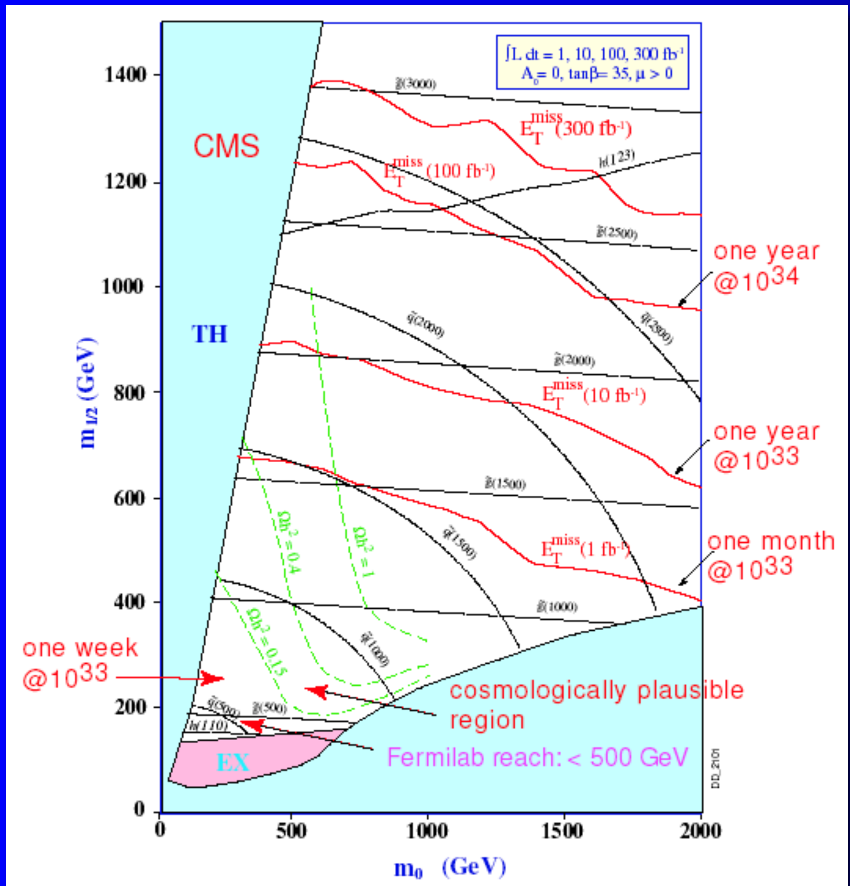
Pythia within ATHENA,

B-vertex tagging

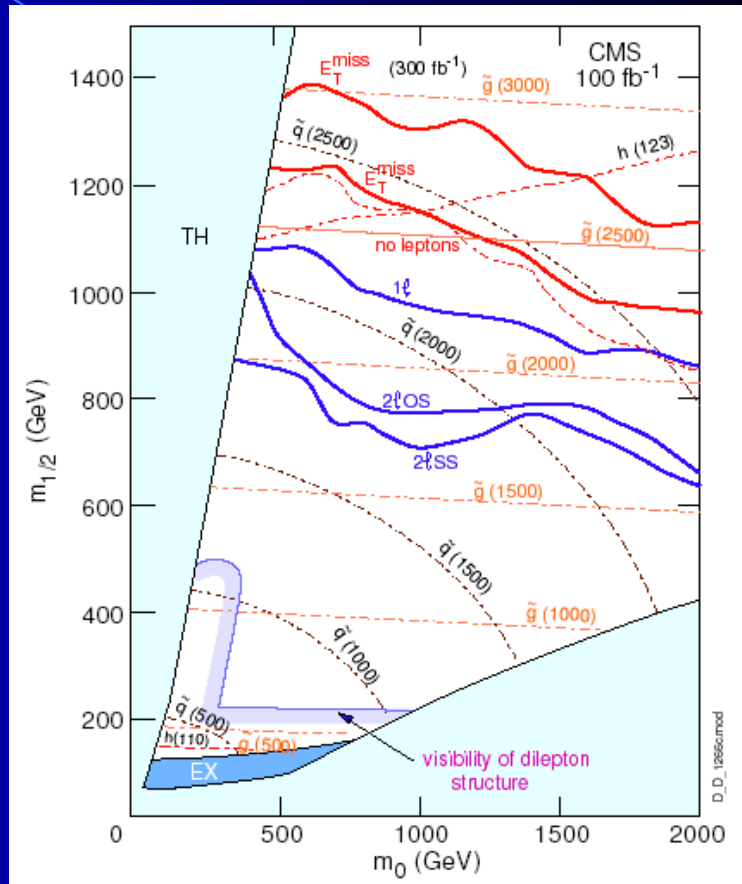
JINR ATLAS Group



Search for Supersymmetry @ LHC

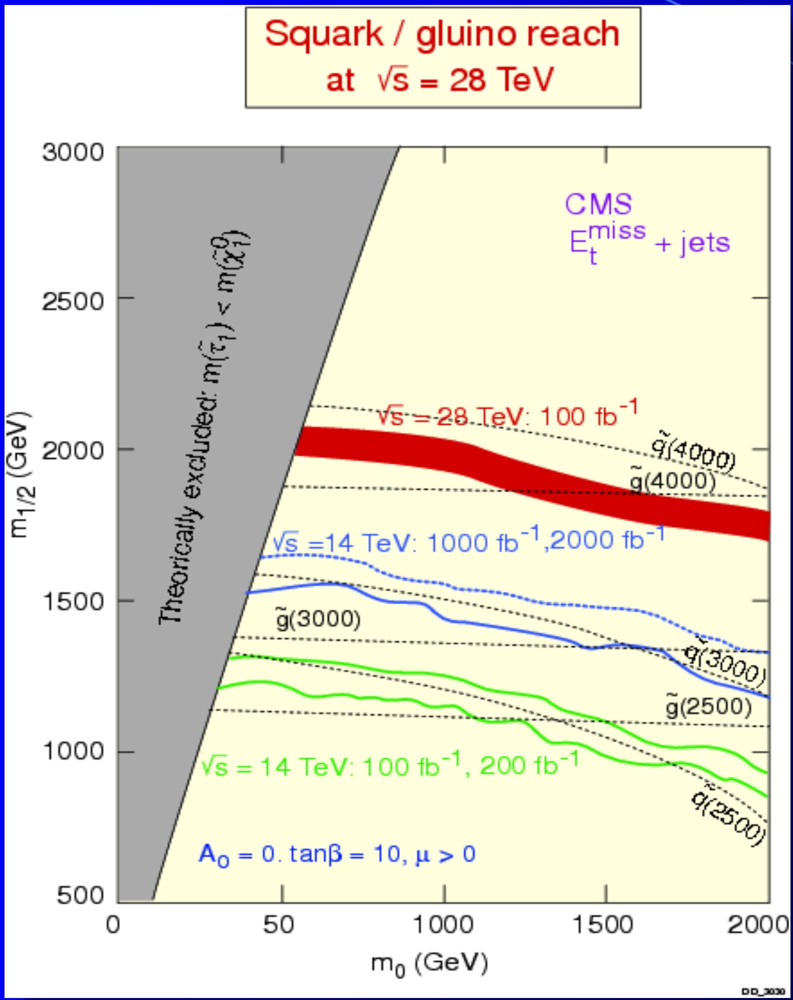


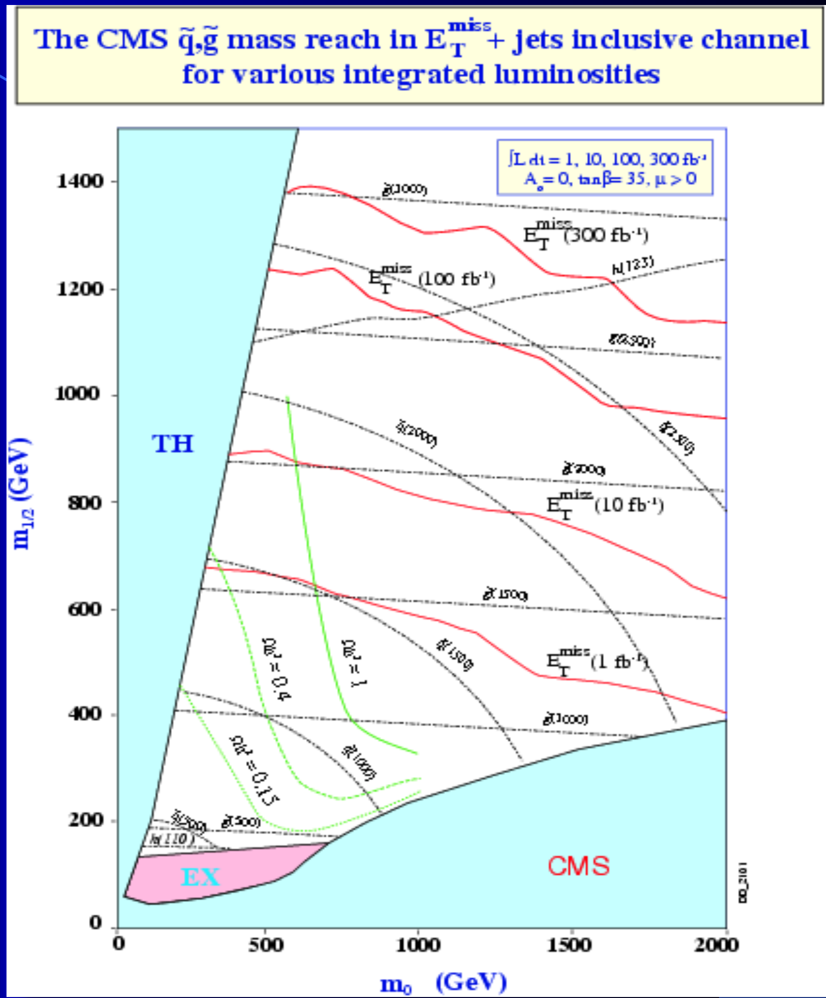
5 σ reach in jets $+\not{E}_T$ channel



Reach limits for various channels at 100 fb^{-1}

SUSY Searches @ LHC



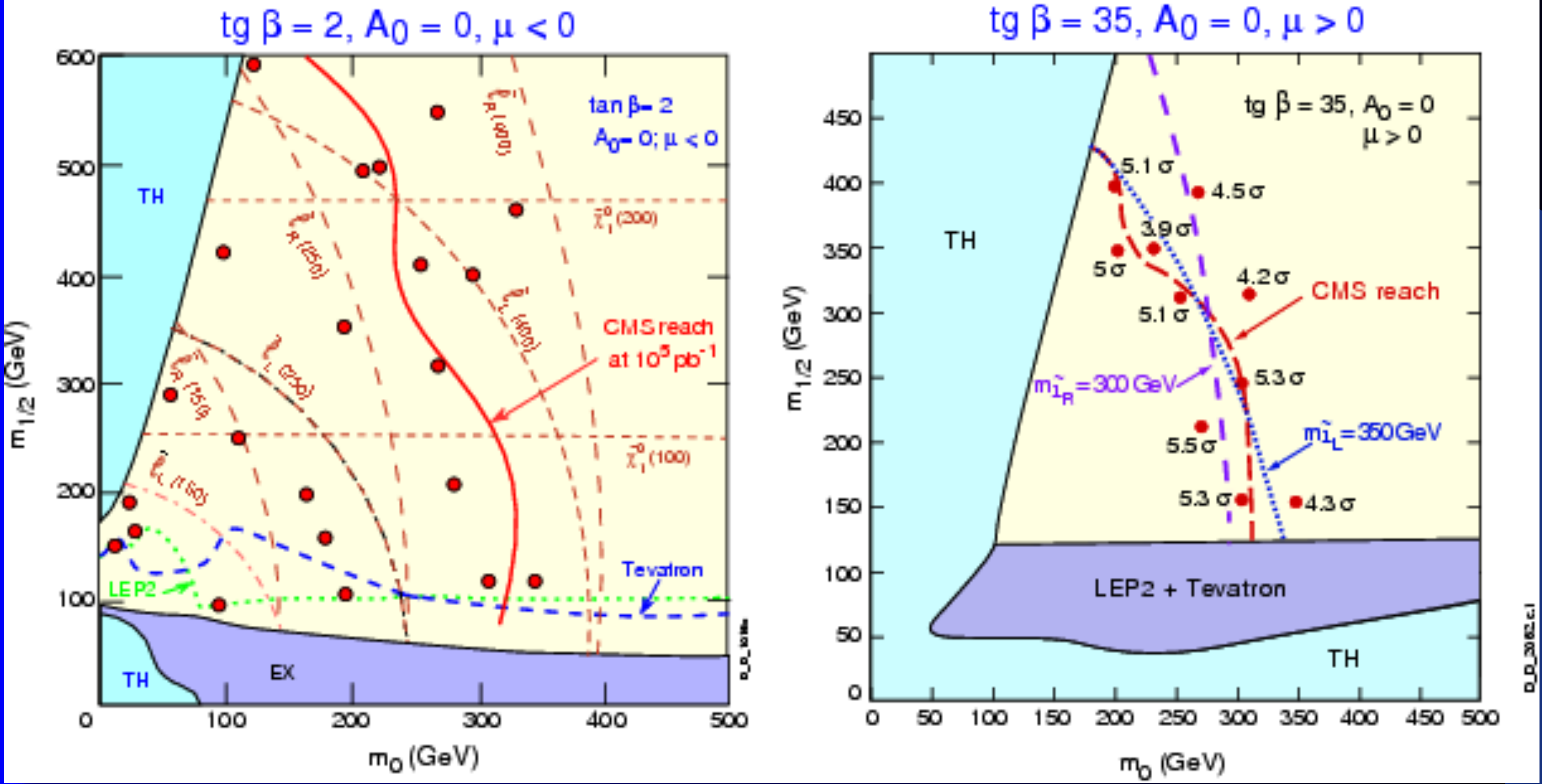


Squark and gluino reaches at various luminosities

SUSY Searches @ LHC

Slepton mapping of parameter space

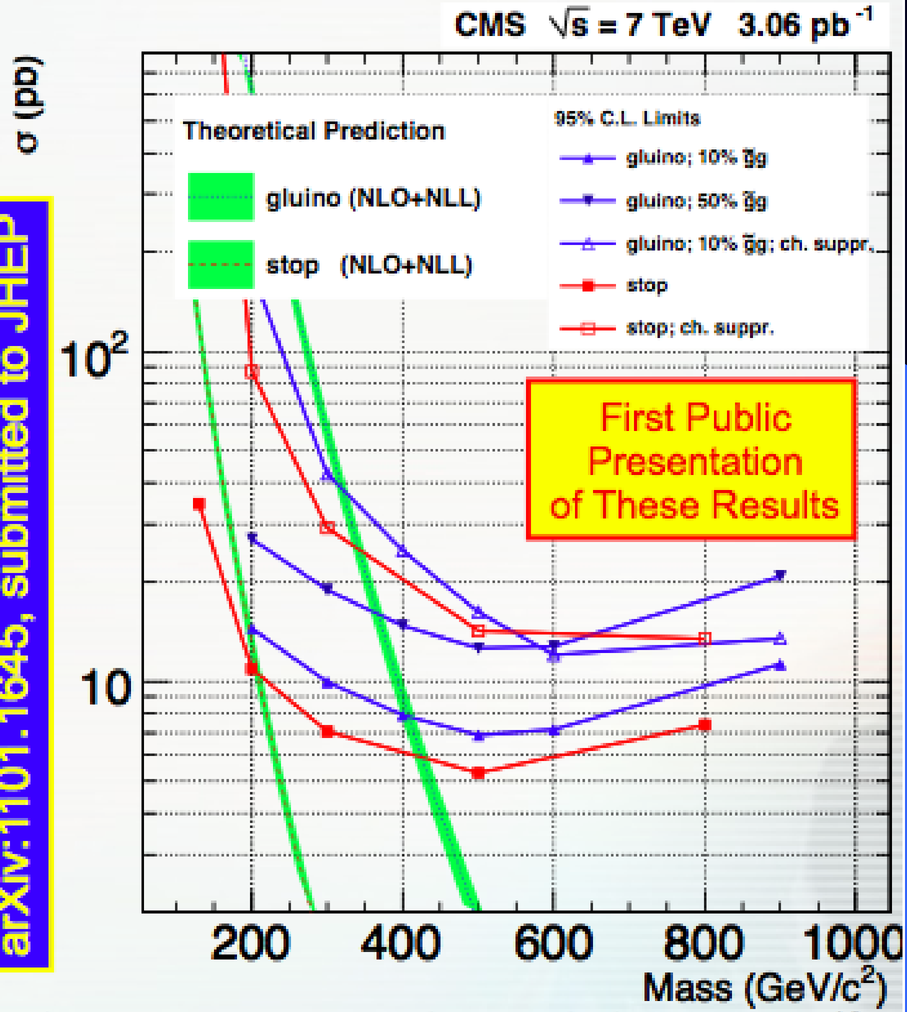
mSUGRA-MSSM
Significance of expected excess of events in 2 lepton final state over SM + SUSY bkgd with 10^5 pb^{-1}
5σ contour, $\sigma = S / \sqrt{S+B}$



Search for Gluinos and Stops

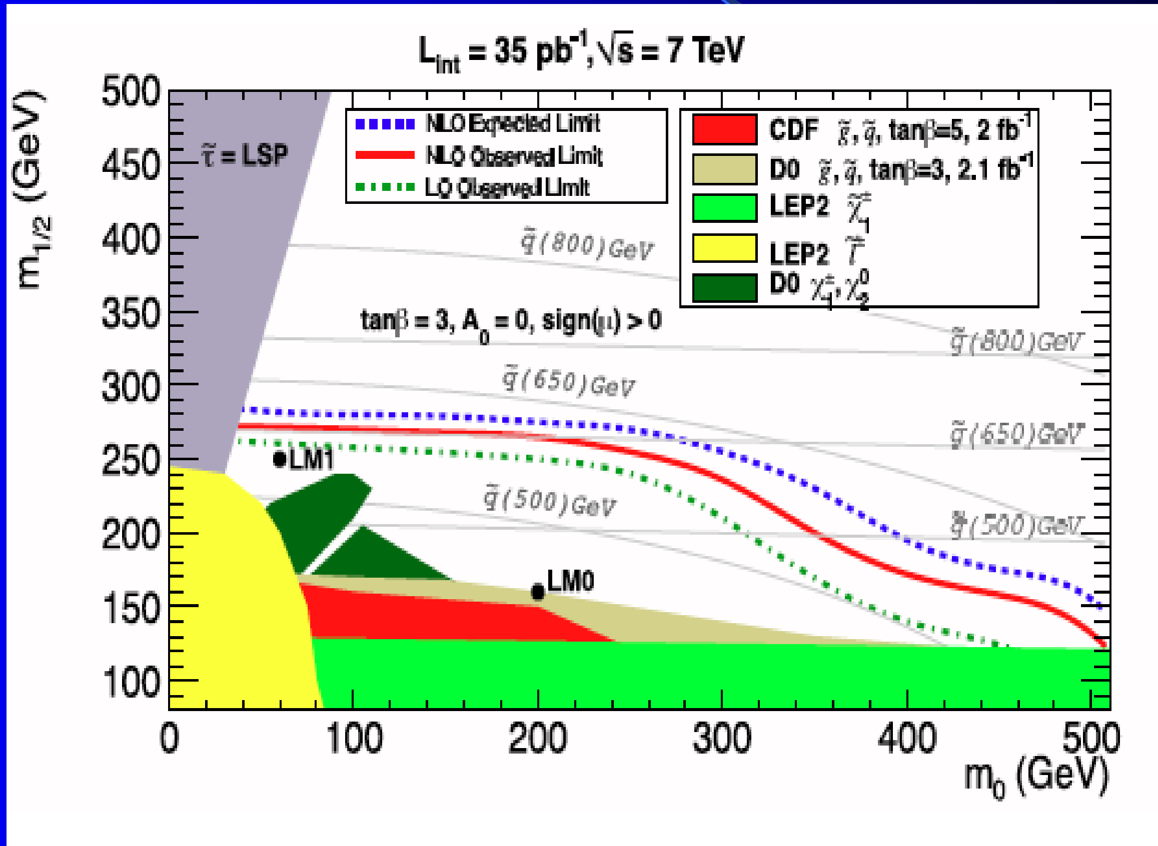
- Tight sample is picked to have very low background (discovery optimization), optimal for low-statistics dataset
  - B = 0.025 ± 0.004 (0.074 ± 0.011) events for μ+Tr (Tr-only)
- Use tracker-only analysis for the charge suppression scenario (R-hadron emerges as a neutral object); μ+Tr for the other ones
- Set limits on the gluino mass of 357-398 GeV for the fraction f of gg hadronization between 0.5 and 0.1 (μ+Tr)
  - In the charge suppression scenario, the limit is 311 GeV (for f = 0.1)
  - These are the most restrictive limits to date
- The analogous stop limit is 202 GeV - still a bit below the Tevatron's 249 GeV limit

arXiv:1101.1645, submitted to JHEP



First SUSY results @ LHC

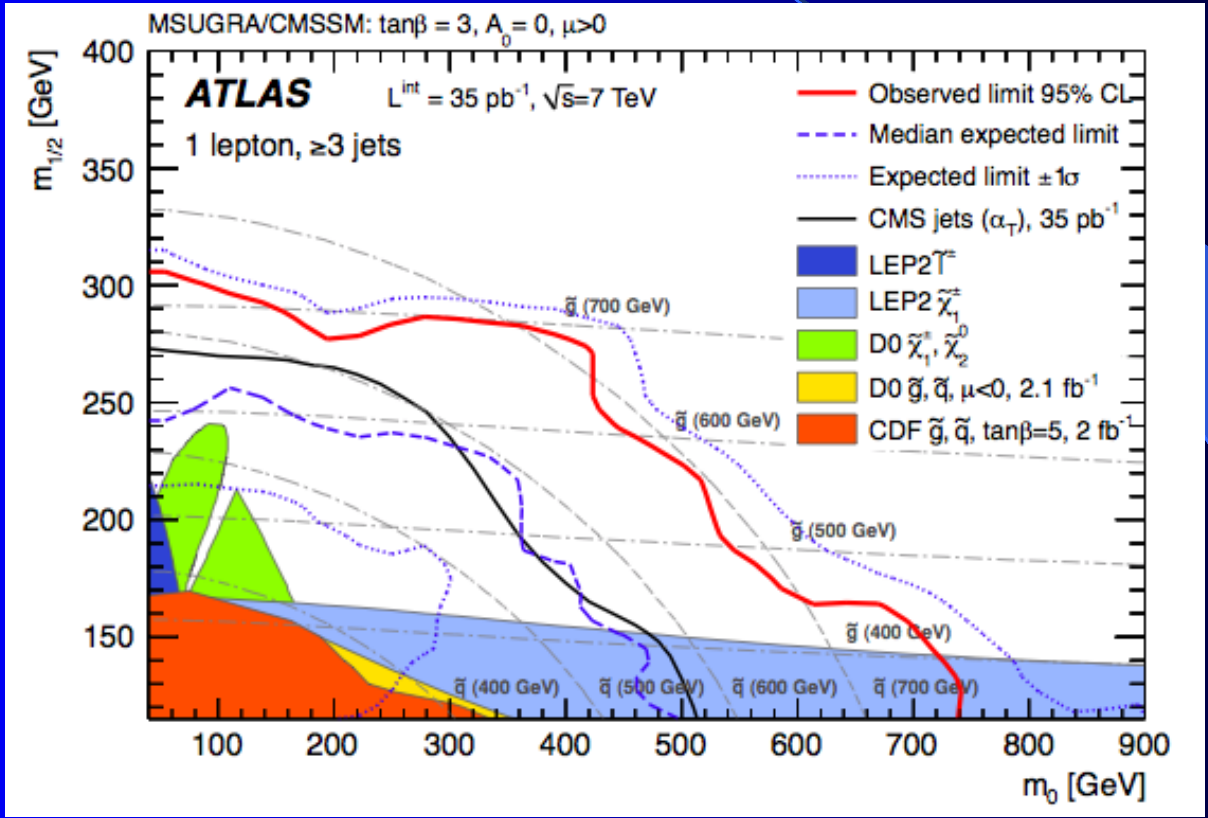
Search for high-mass squark and gluino production in events with large missing transverse energy and two or more jets



Expanded the excluded range established during
The last 20 years (!) by factor of two with only 35 pb^-1

First SUSY results @ LHC

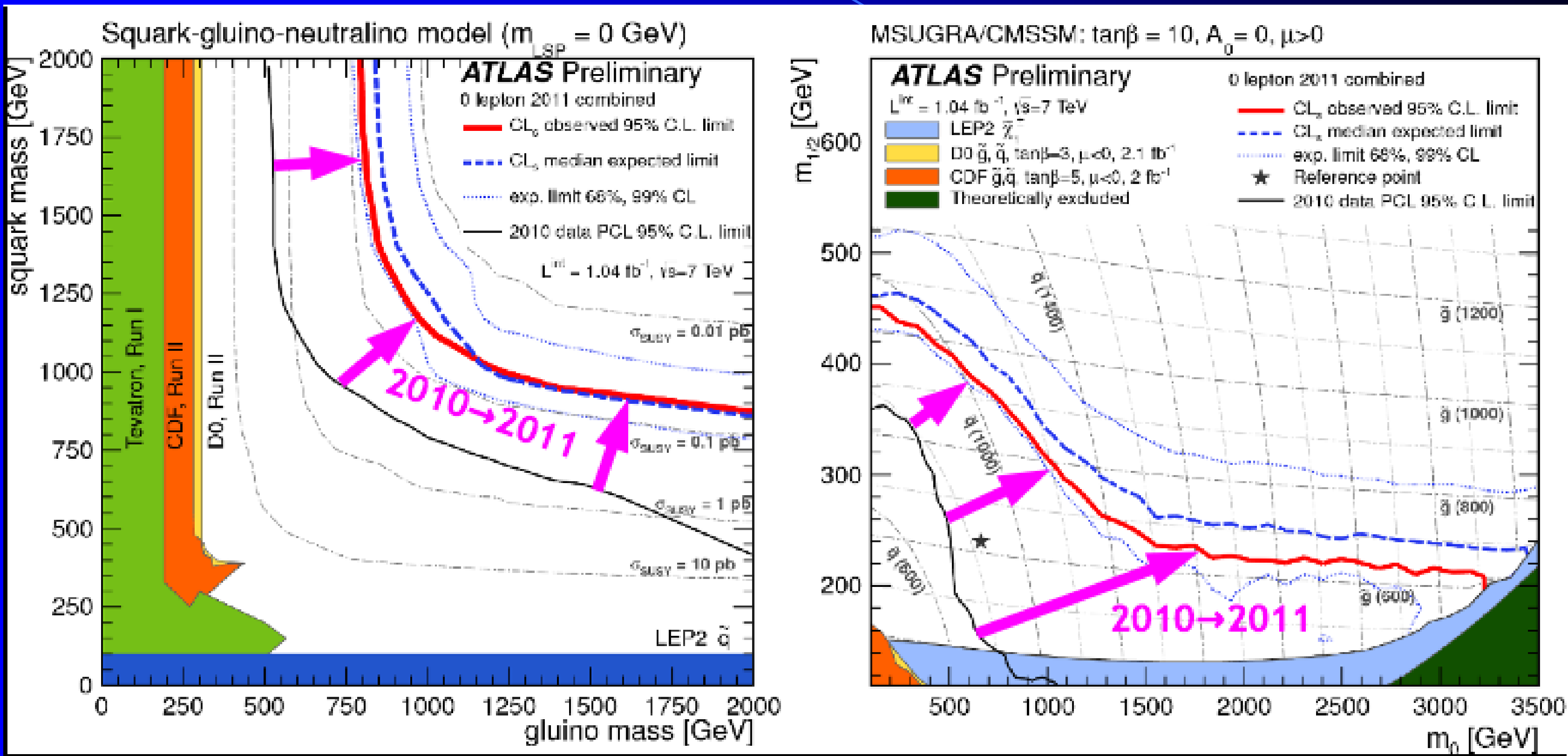
ATLAS



Search for lepton + jets + missing transverse energy with 35 pb^-1

First SUSY results @ LHC

SUSY in 0-lepton channel



Simplified model with two q generations, m(χ 0)~01mg>800 GeV mq>850 GeV
Equal mass case: mg=mq>1.075 TeV

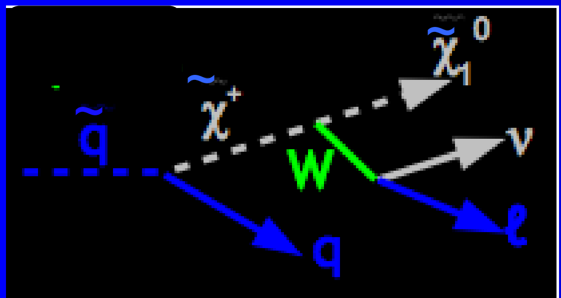
MSUGRA/CMSSM: tanβ=10, A0=0, μ>0 Equal mass case: mq=mg > 980 GeV

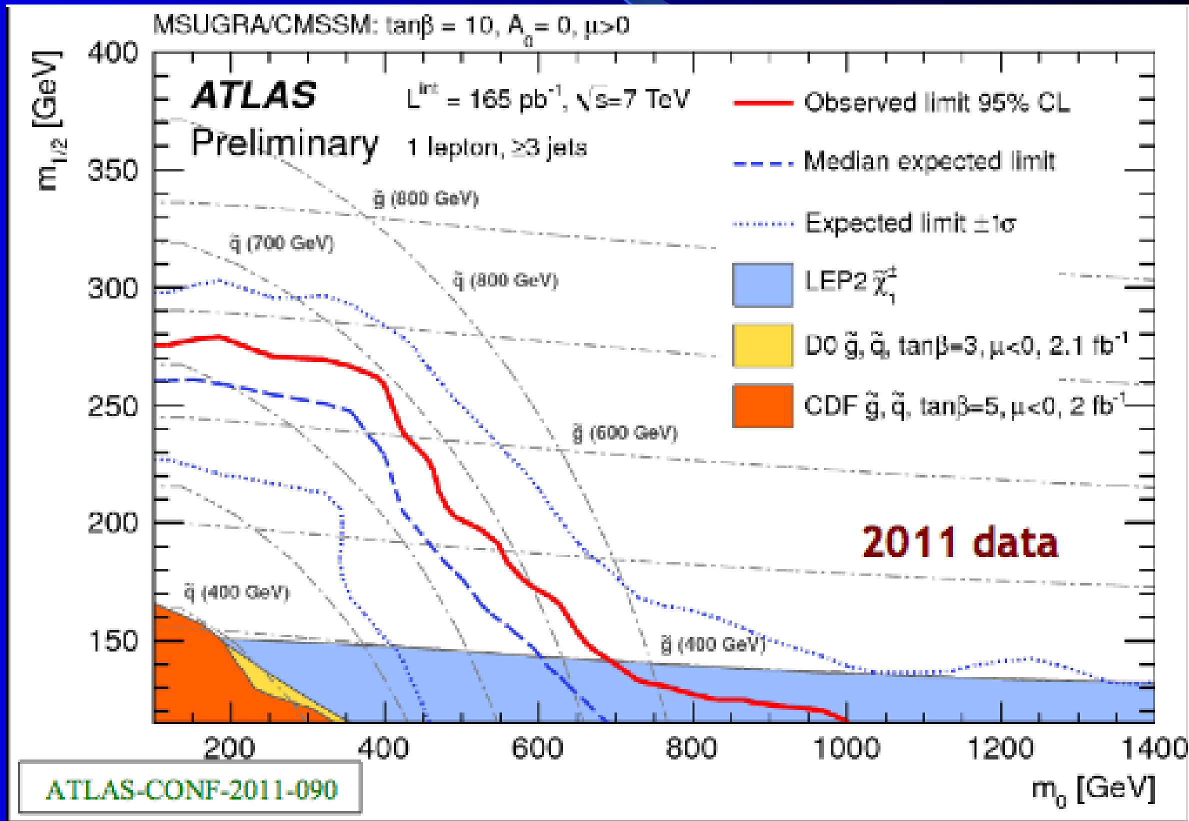
First SUSY results @ LHC

SUSY in 1-lepton channel

$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ may give isolated leptons

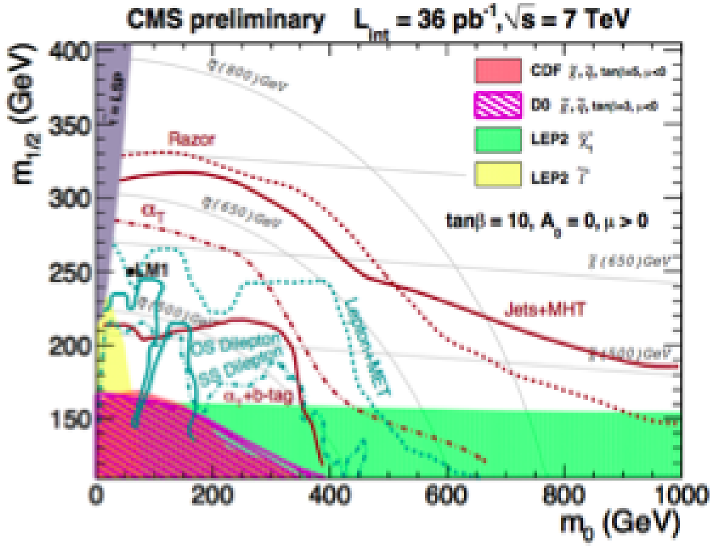
Single e/μ, jets, E miss

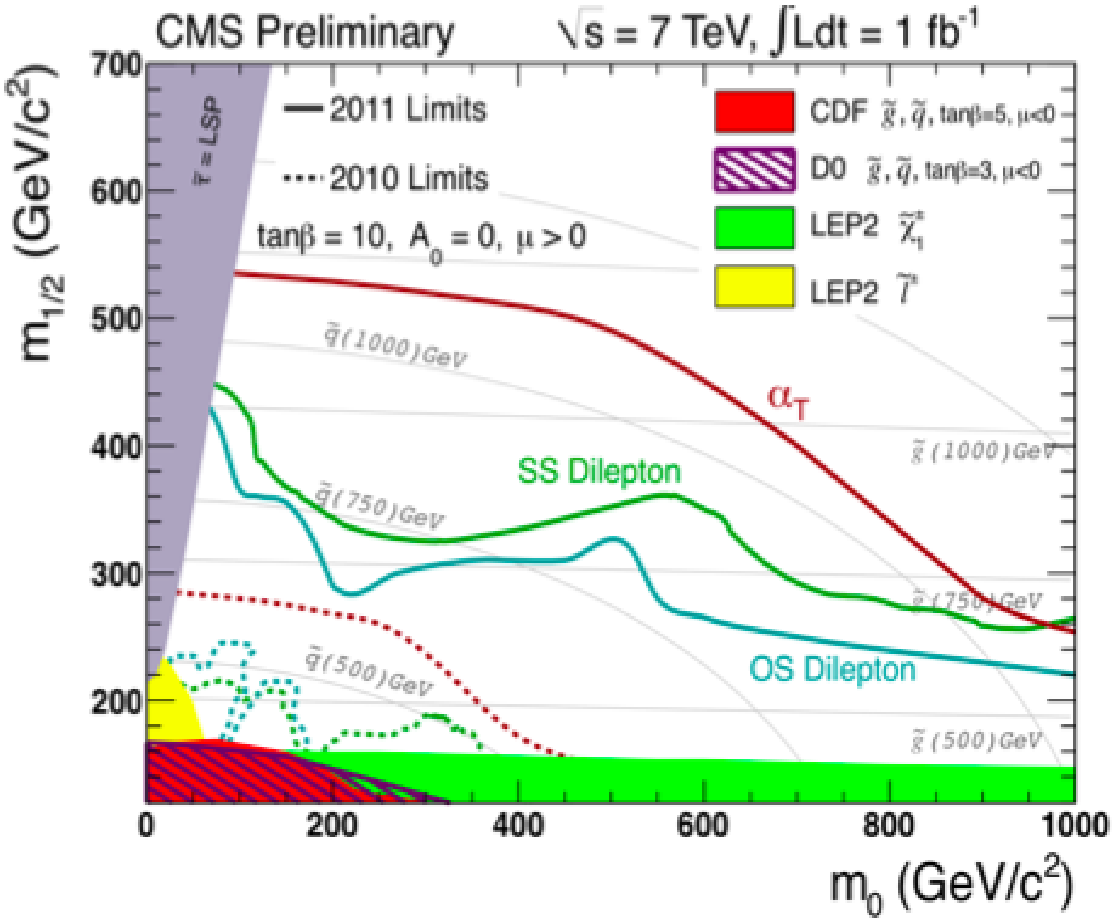




Progress on SUSY Search

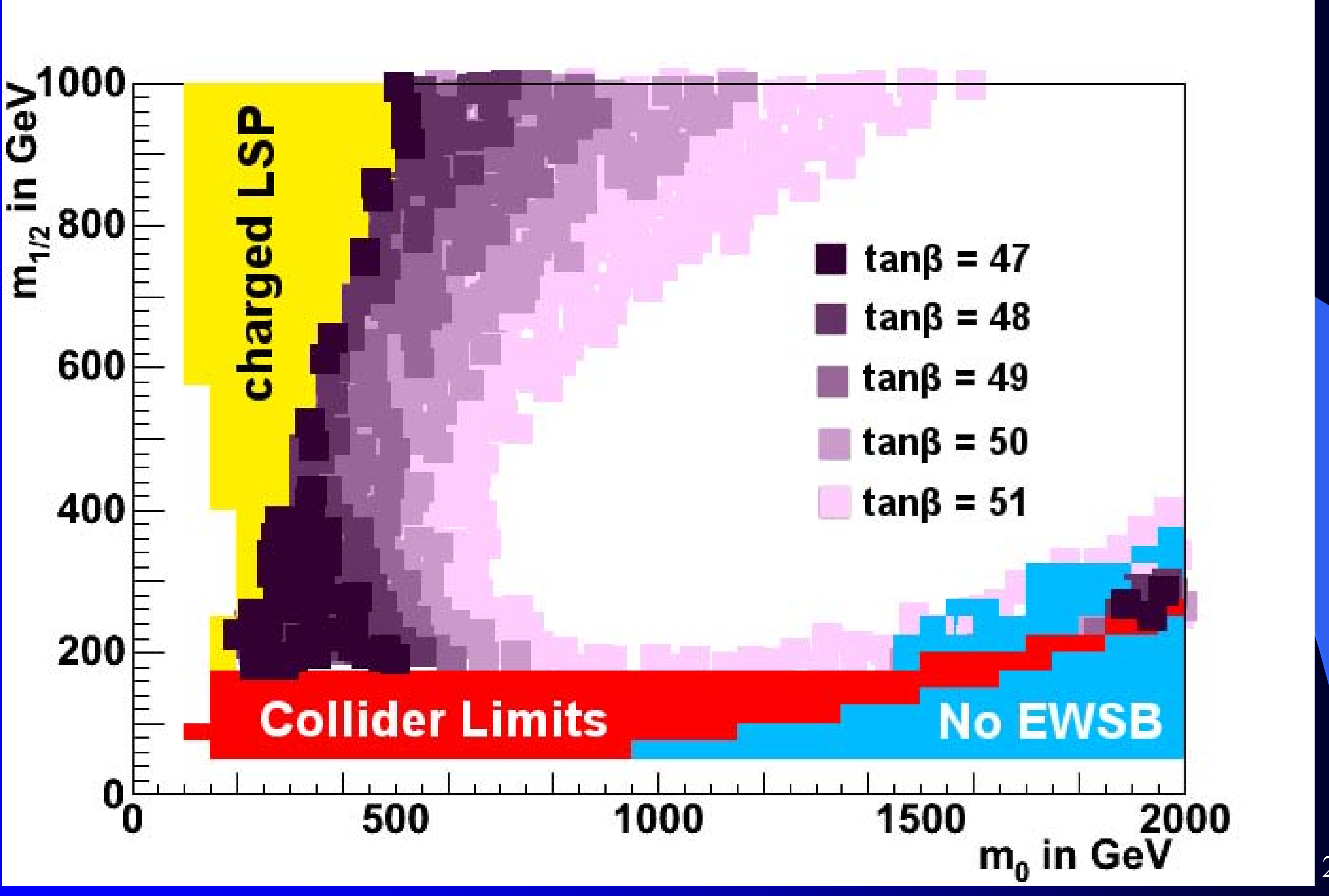
Results of the first three SUSY analyses completed on 2011 data (α_T , Same Sign and Opposite Sign dileptons).

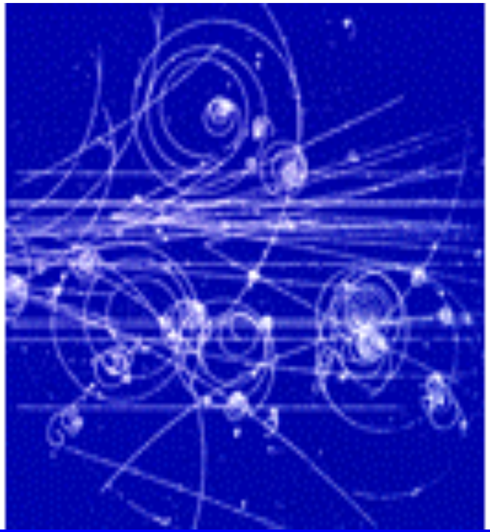




Within the constrained SSM models we are crossing the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. More conclusive results after summer.

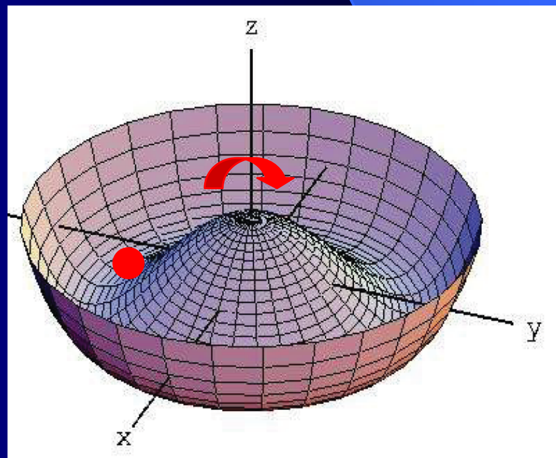
Global Fit to data in full Parameter Space





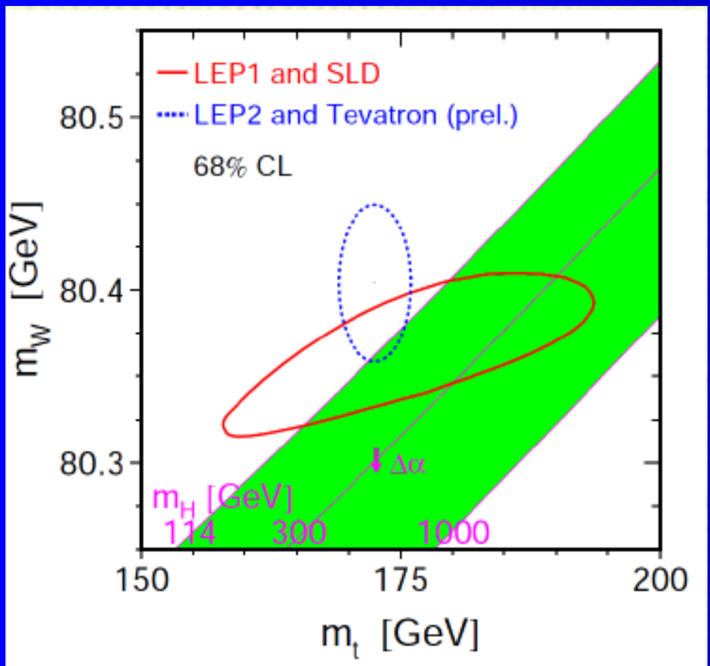
The Run for the Higgs Boson

- Is it there?
- Where is it?
- When and where we find it?

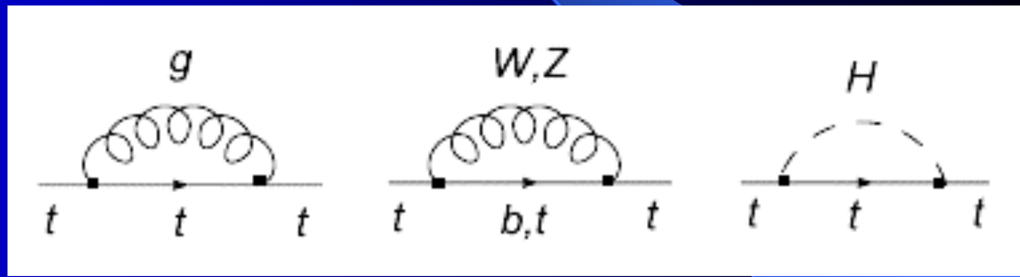


The SM Higgs Boson

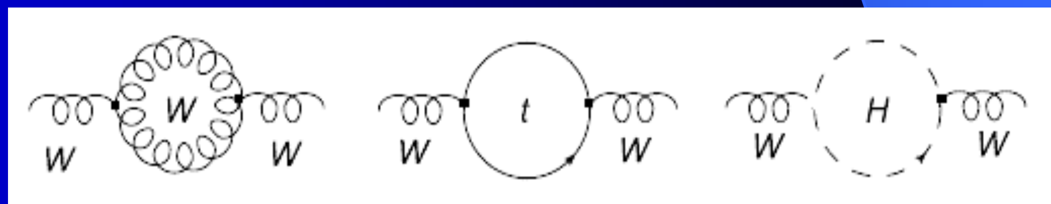
- Indirect limit from radiative corrections
- Direct limit from Higgs non observation at LEP II (CERN)
- Precision measurement of M_W and m_t



Radiative corrections to M_W and m_t

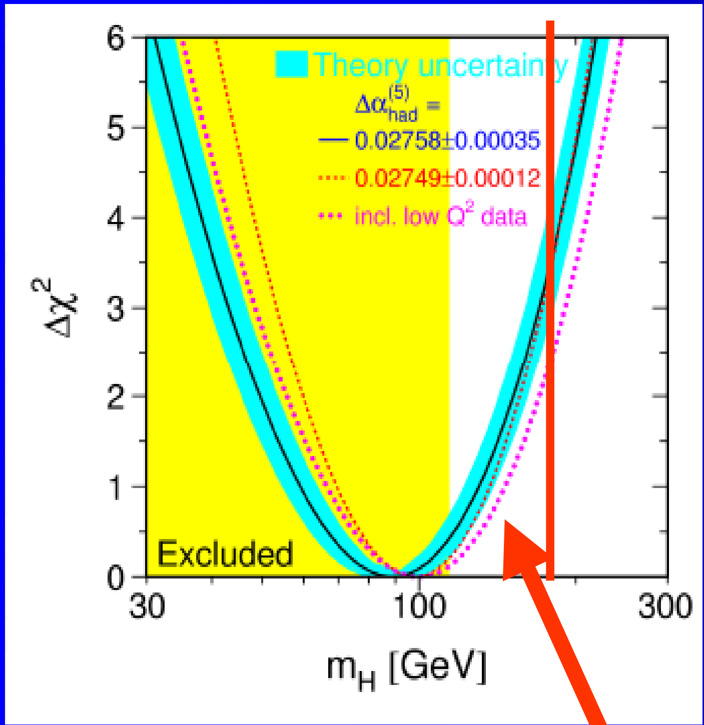


$\sim \alpha_s m_t$ $\quad \sim \alpha_2 m_t \log \frac{m_Z^2}{m_t^2}$ $\quad \sim y_t^2 m_t \log \frac{m_H^2}{m_t^2}$



$\sim \alpha_2 \mathrm{M}_\mathrm{W}^2$ $\quad \sim \alpha_2 \mathrm{M}_\mathrm{W}^2 \log \frac{m_t^2}{m_W^2}$ $\quad \sim \alpha_2 \mathrm{M}_\mathrm{W}^2 \log \frac{m_H^2}{m_W^2}$

SM Fit to Precision EW Data



χ^2 versus M_H for SM Fit

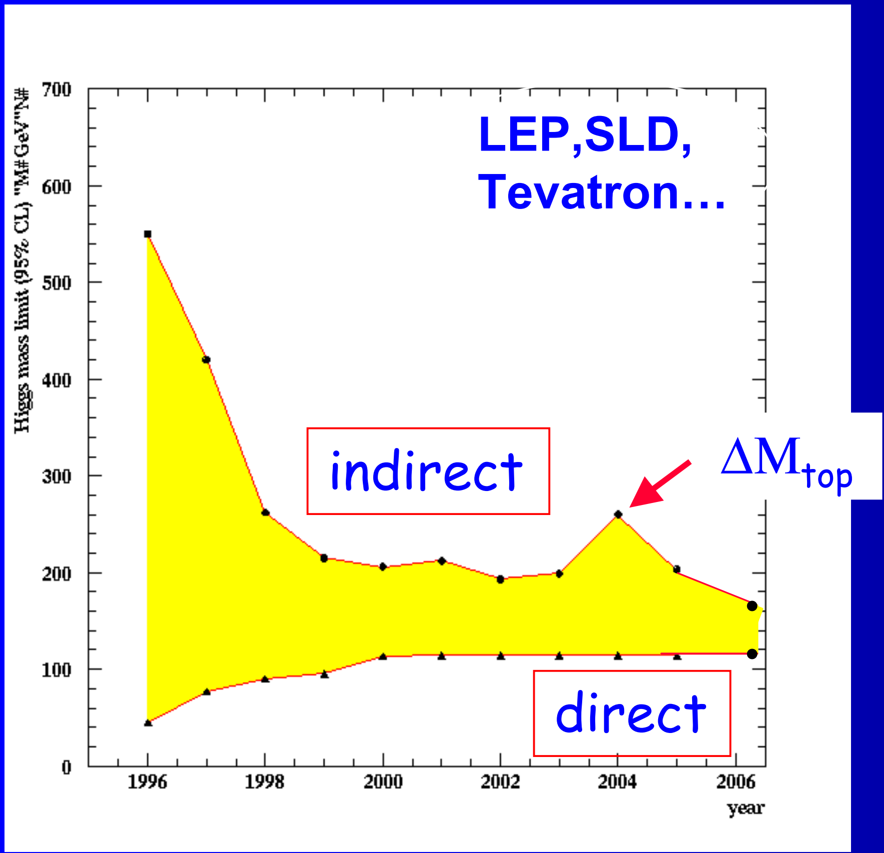
- M_H=89 +42-30 @68%CL
- M_H < 165 GeV @95%CL

for m_{top} =172.5 GeV

If it is there we may see it soon

SM:Testing Quantum Fluctuations

Time evolution of experimental limits on the Higgs boson mass



M_H *between 114 and ~160 GeV*

$$\propto \left(\frac{M_t}{M_W}\right)^2, \ln\left(\frac{M_h}{M_W}\right)$$

knowledge obtained
only through combination of
results from different
accelerator types

in particular:
Lepton and Hadron Collider

The Higgs Mass Limits (Theory)

The Higgs Mass

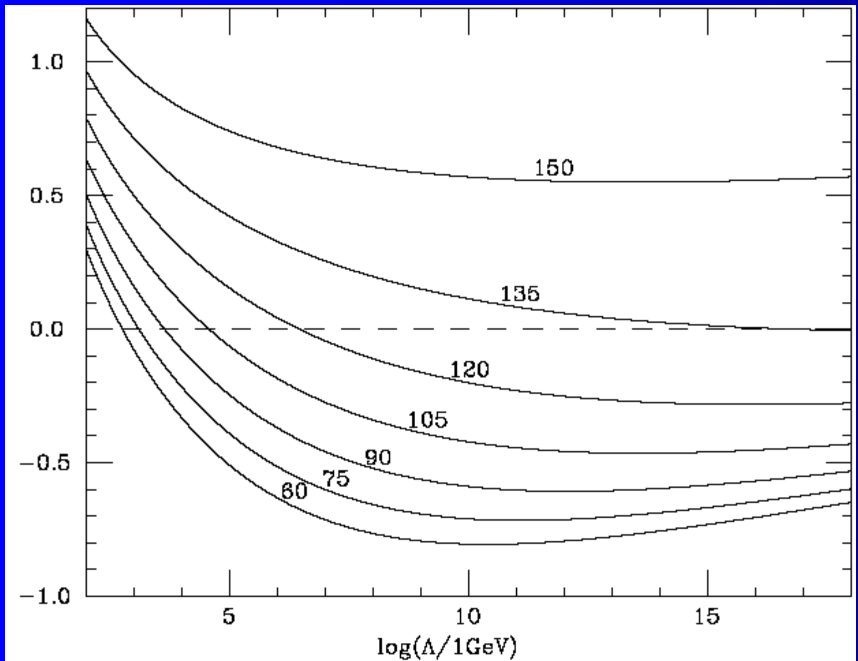
$$m_h^2 = \lambda v^2$$

RG Eq.

$$\frac{d\lambda}{dt} = \frac{1}{16\pi^2}\left(6\lambda^2 + 6\lambda y_t^2 - 6y_t^4 + \text{ gauge terms}\right)$$

To run together with RG eqs. for the gauge and Yukawa couplings

m_h

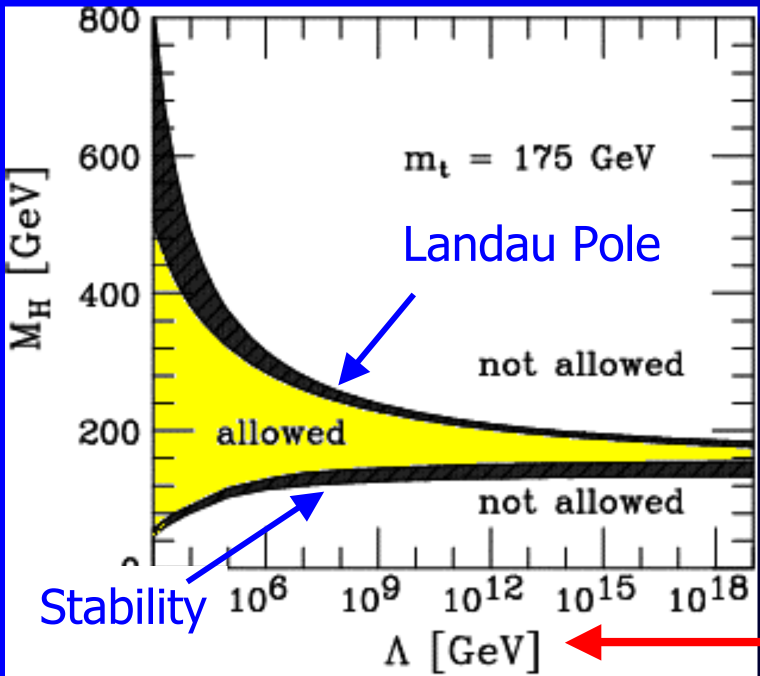


- Initial value too big -> Landau pole
- Initial value too small -> negative coupling (stability bound)

The Higgs Mass Bounds

Stability bound

$$m_h > 135 + 2.1[m_t - 174] - 4.5\left[\frac{\alpha_s(M_Z) - 0.118}{0.006}\right], \quad \Lambda = 10^{19}\ \text{GeV},$$
$$m_h > 72 + 0.9[m_t - 174] - 1.0\left[\frac{\alpha_s(M_Z) - 0.118}{0.006}\right], \quad \Lambda = 1\ \text{TeV},$$



- The SM Higgs

mH ≥ 134 GeV

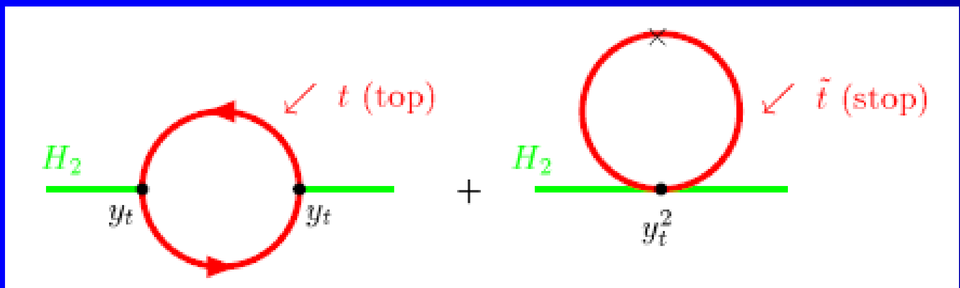
Assuming the SM is valid up to the Plank scale

The scale up to which the SM is valid

The Higgs Mass Limit (MSSM)

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{16\pi^2 M_W^2} \log \frac{\tilde{m}_{t_1}^2 \tilde{m}_{t_2}^2}{m_t^4} + 2\ loops$$

Radiative corrections to Higgs boson mass



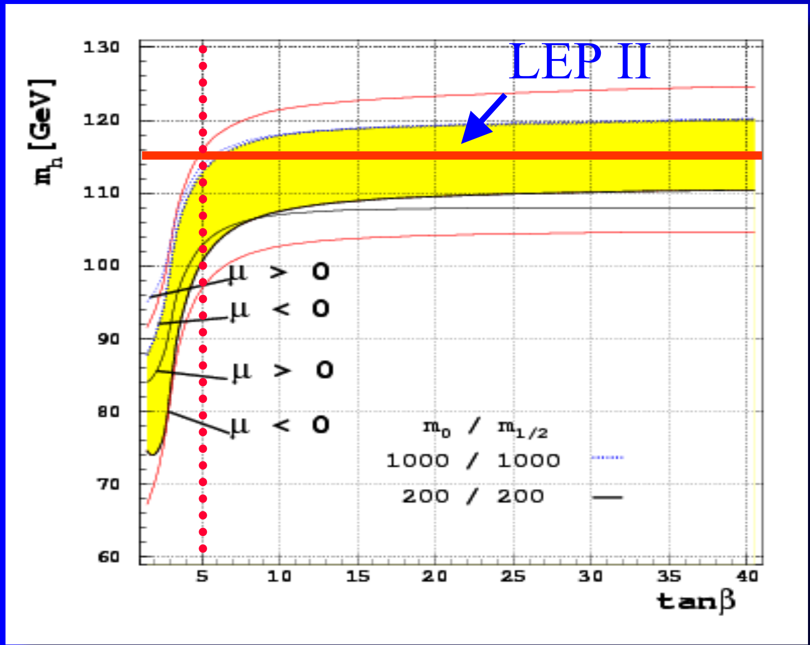
$$\sim -\frac{y_t^2}{16\pi^2} m_t^2 \log \frac{m_t^2}{\mu^2} \qquad \sim \frac{y_t^2}{16\pi^2} \tilde{m}_t^2 \log \frac{\tilde{m}_t^2}{\mu^2}$$

$\tilde{m}_t \sim 1$ TeV

$\Delta m_h(1loop) \sim +40$ GeV

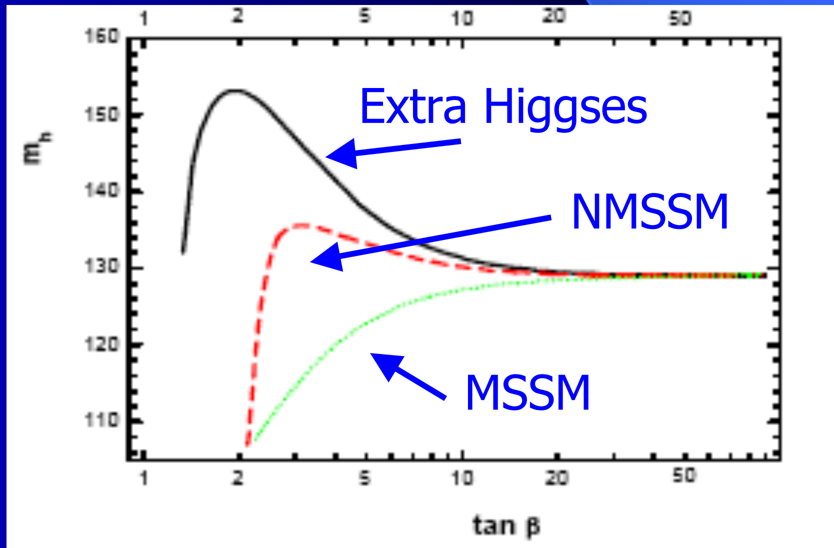
$\Delta m_h(2loop) \sim -5$ GeV

The Higgs Mass Limit (MSSM)



- MSSM Higgs $m_H \leq 130$ GeV

NMSSM

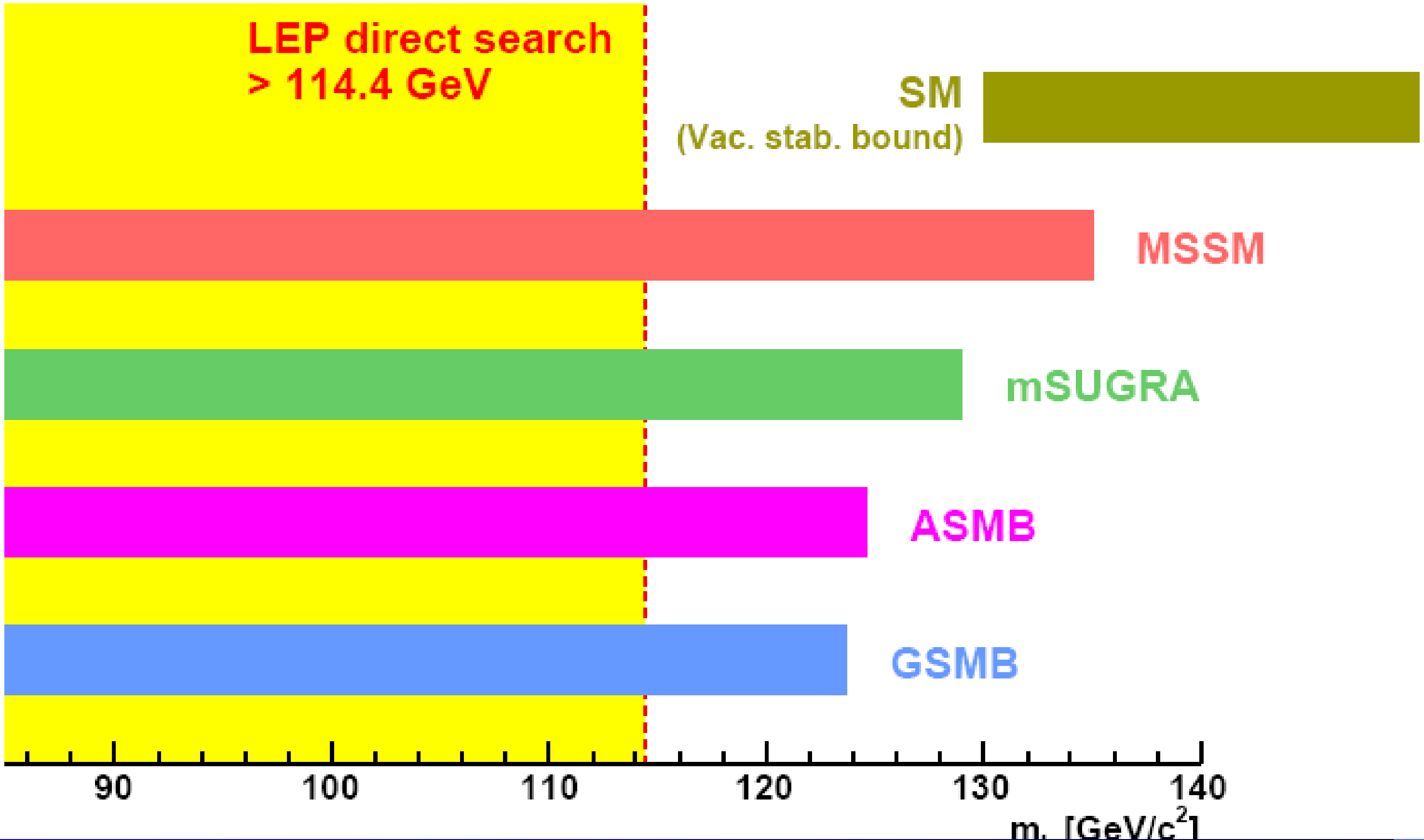


$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \ldots$$

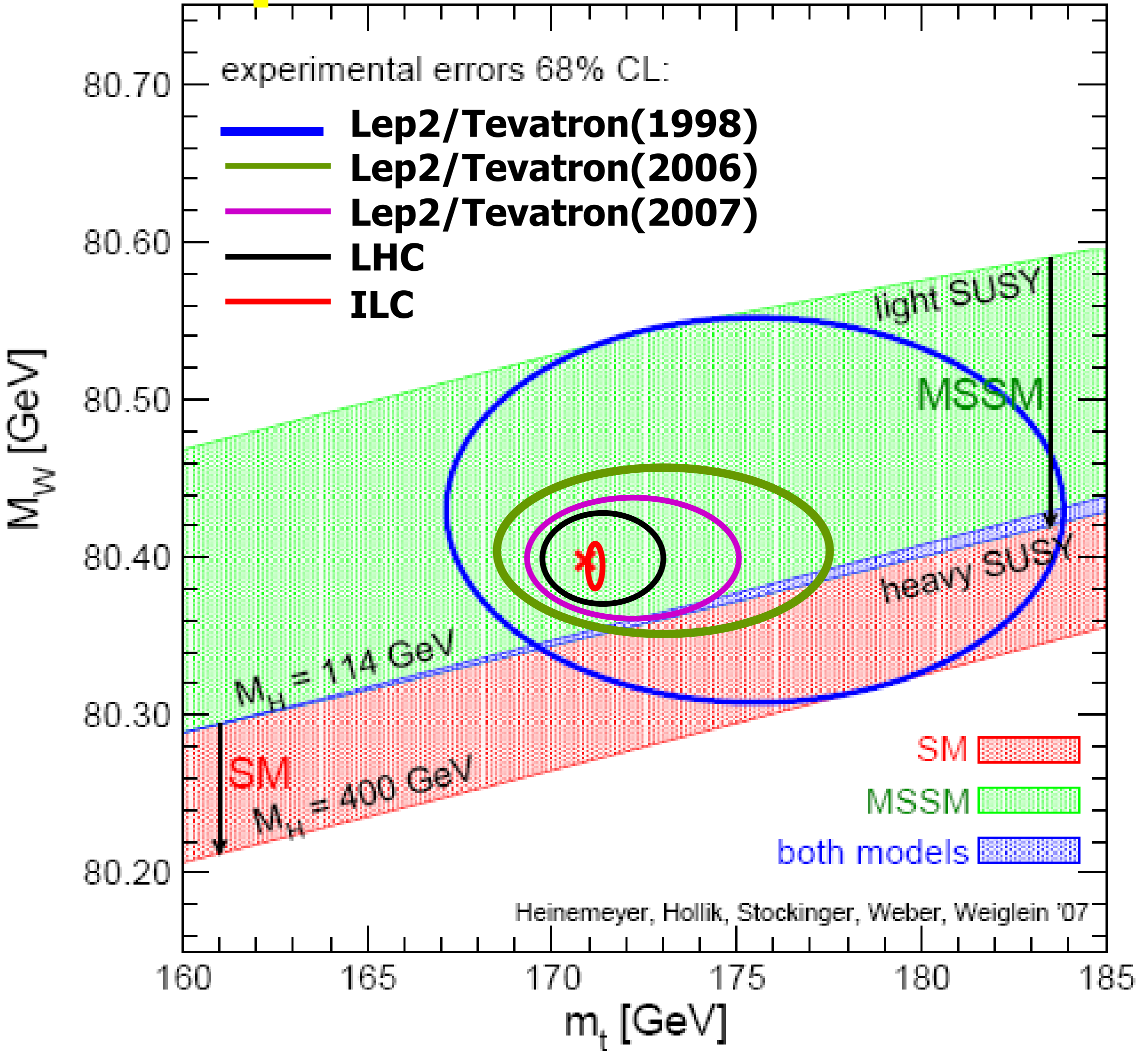
Higgs Mass Predictions in Various Models

Comparison of allowed ranges for M_h:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]



Measurement of M_W and m_t and Comparison with SM and MSSM



MSSM band:
scan over
SUSY masses

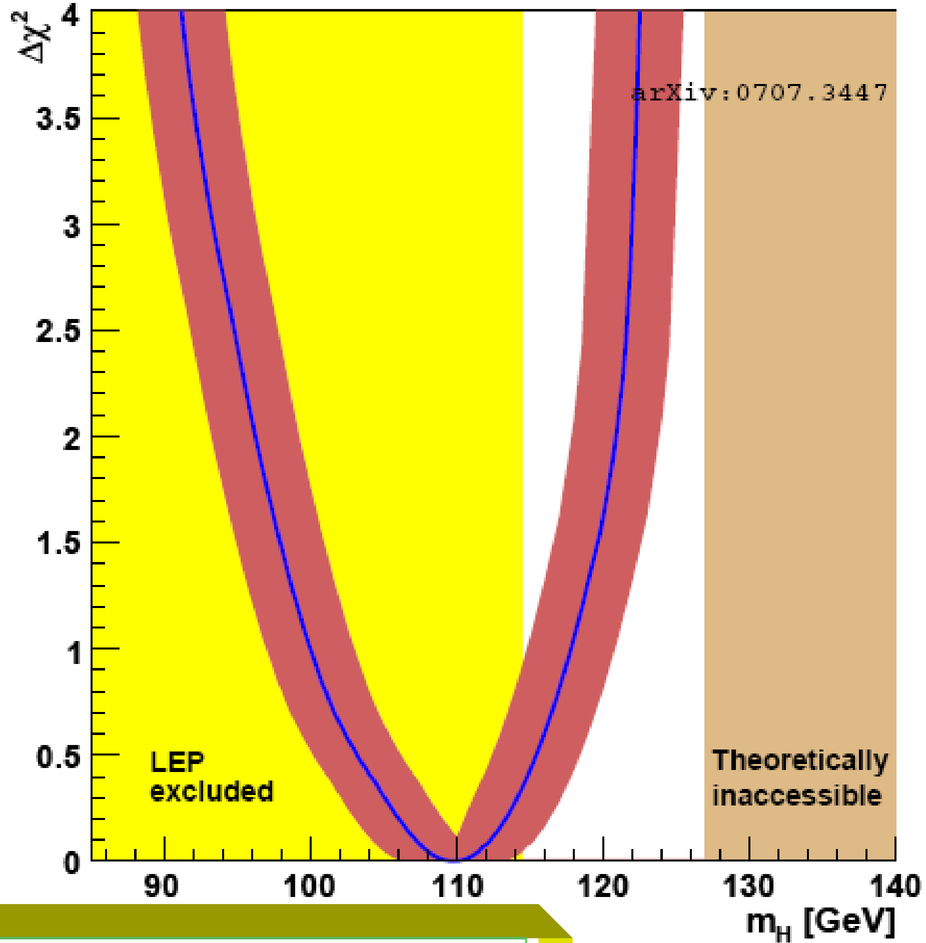
overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

Fit to EW Data in the MSSM

Red band plot:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]

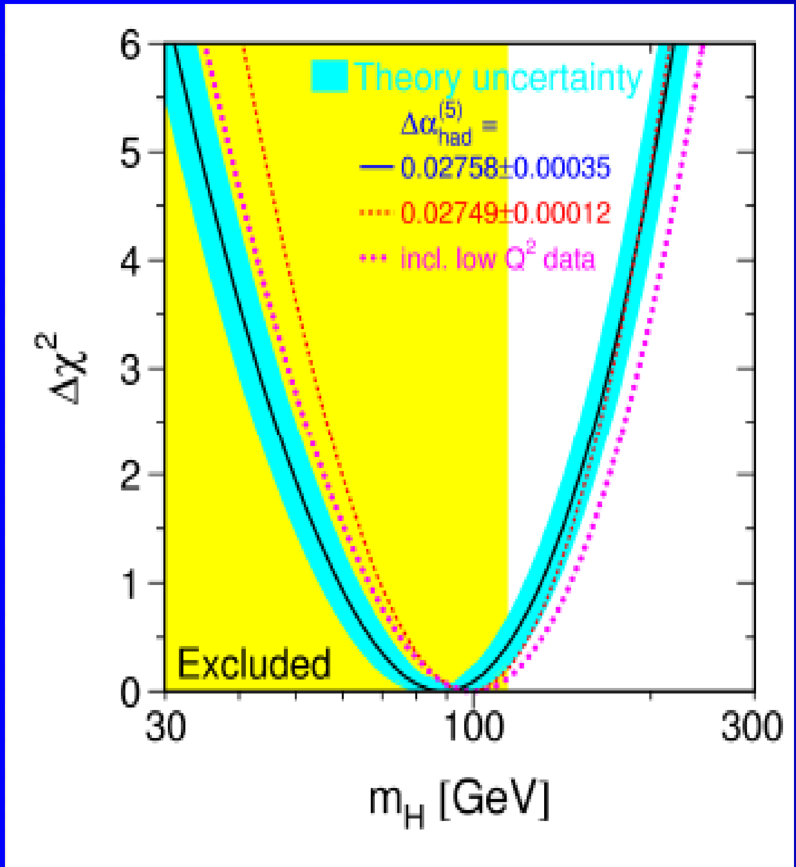


$M_h = 110^{+8}_{-10}\,(\text{exp}) \pm 3(\text{theo})$ GeV

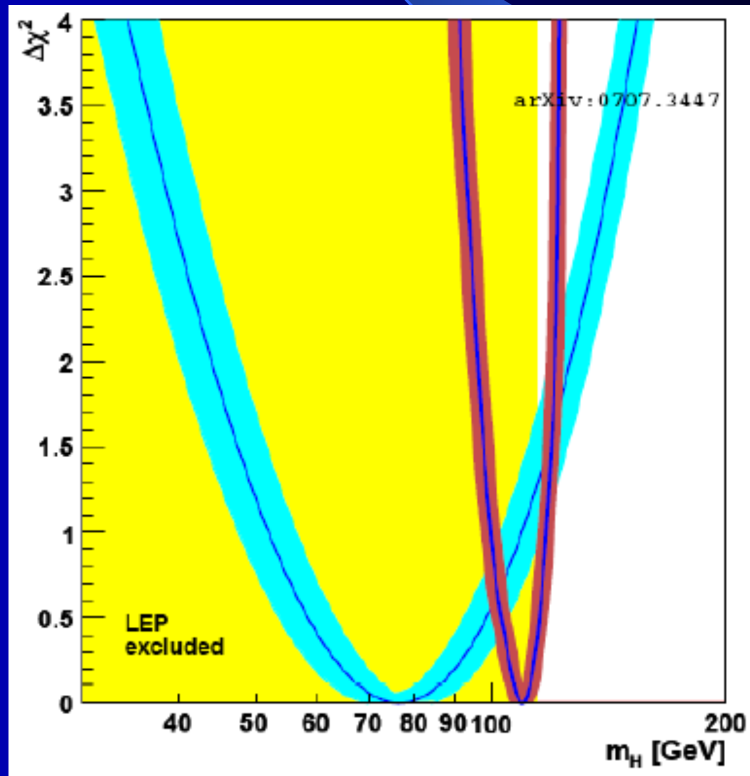
The SM versus MSSM

Fit for the Higgs Boson Mass

SM

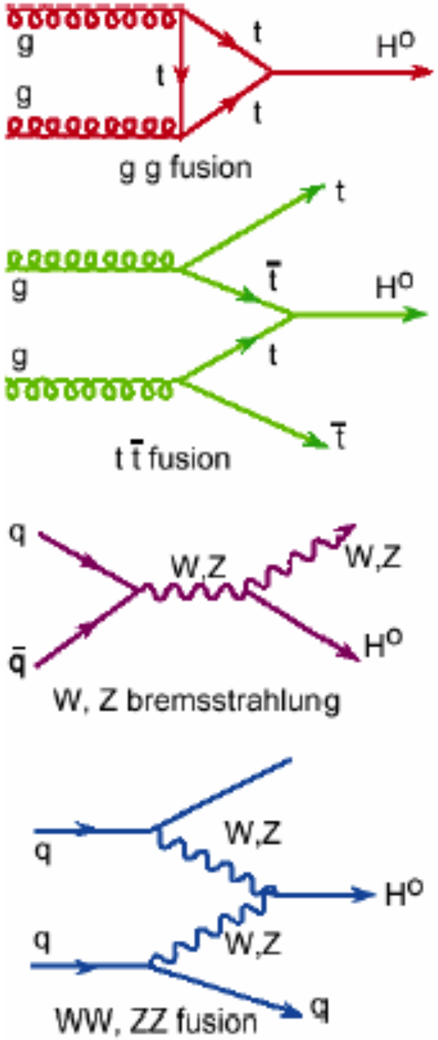


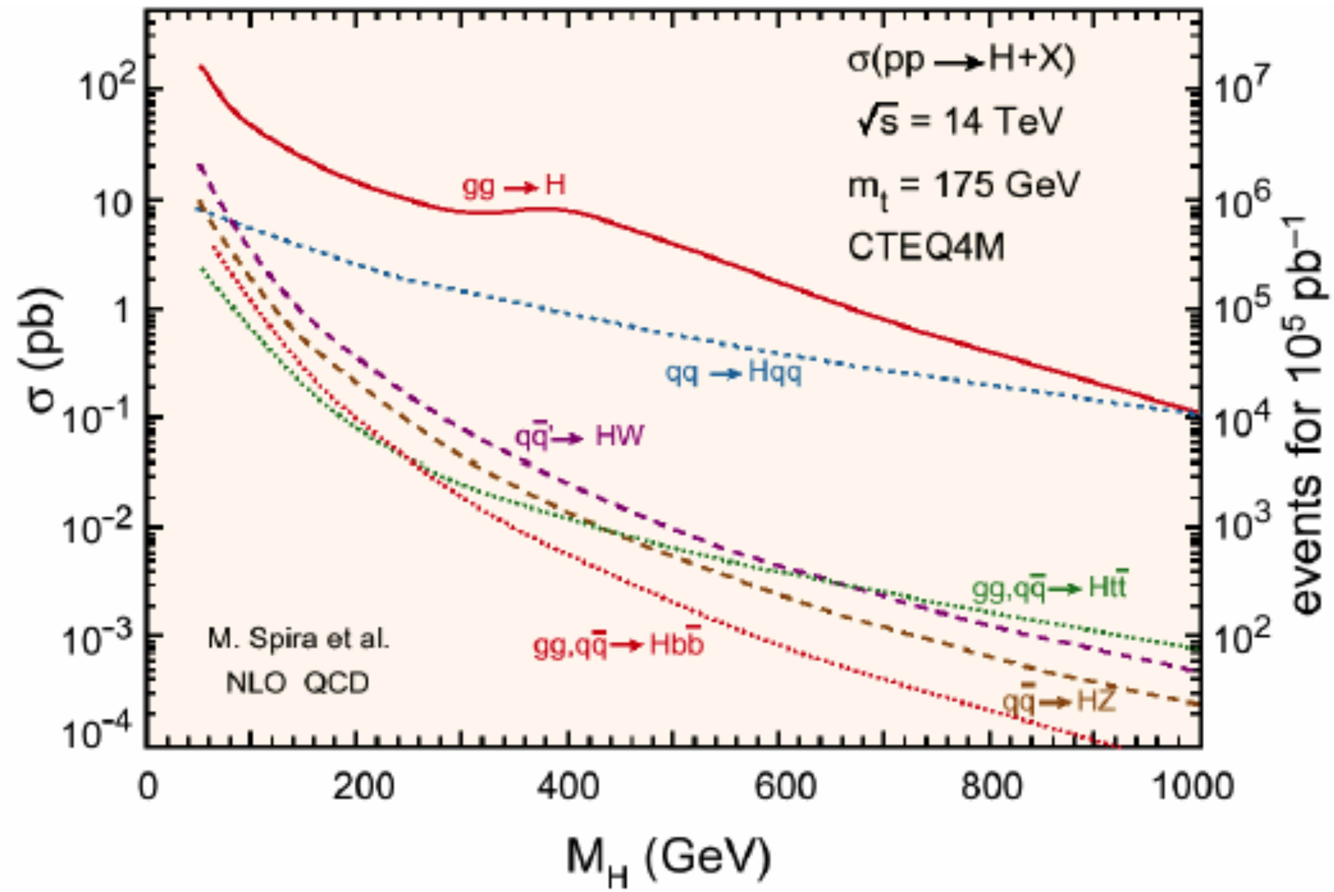
MSSM



Search for Higgs Boson at LHC

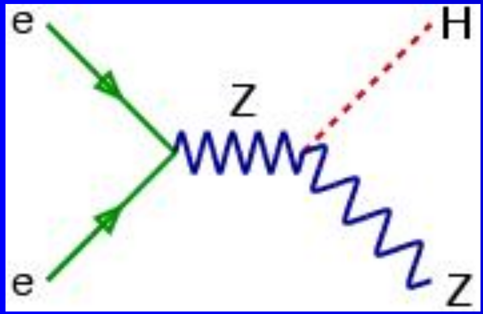
- **Production mechanisms & cross section**

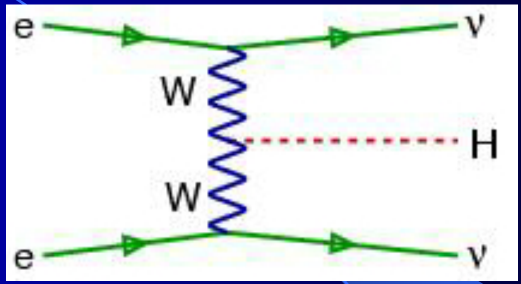


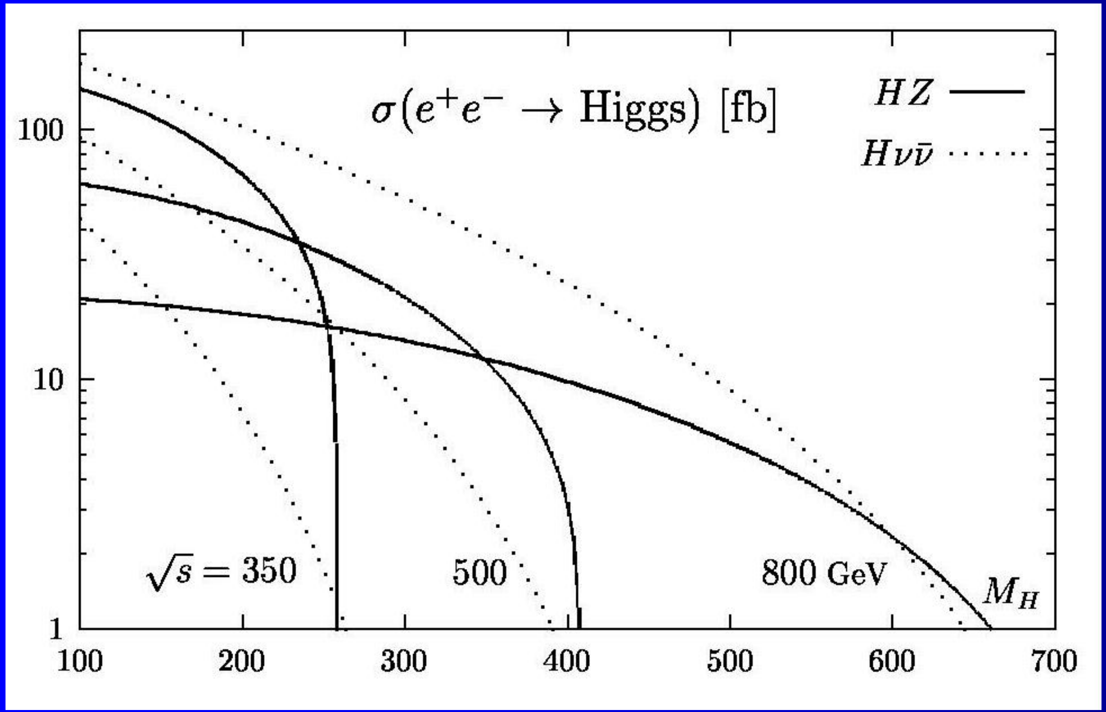


The Higgs Boson at ILC

The dominant creation process at ILC







The task for ILC:

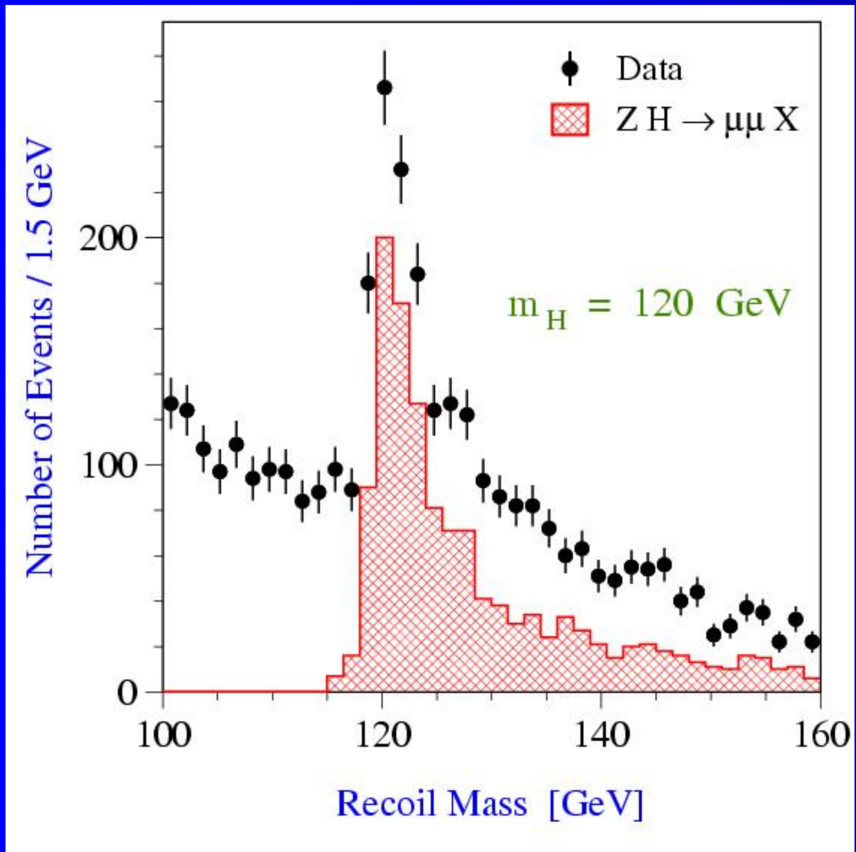
- Determine the properties of the Higgs boson

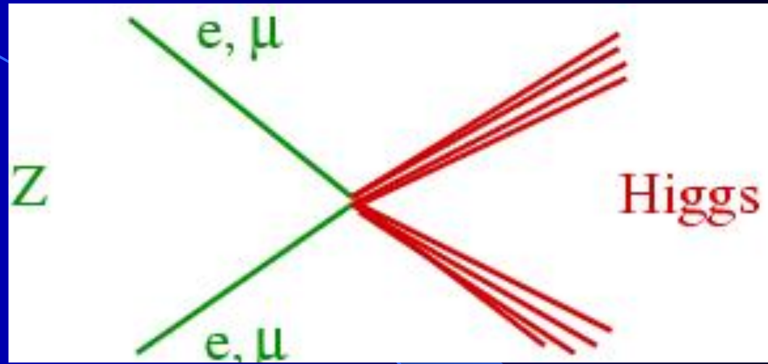
- To confirm the mechanism of EW symmetry breaking – the source of all particle masses

. . . Together with the LHC

The Higgs Boson Mass

Recoil mass spectrum
$ee \to HZ$ with $Z \to l^+l^-$





$\Delta\sigma \sim 3\%$

Model independent measurements

$\Delta m \sim 50$ MeV

accuracy ~0.001

Precision Measurement of the Higgs Boson Mass

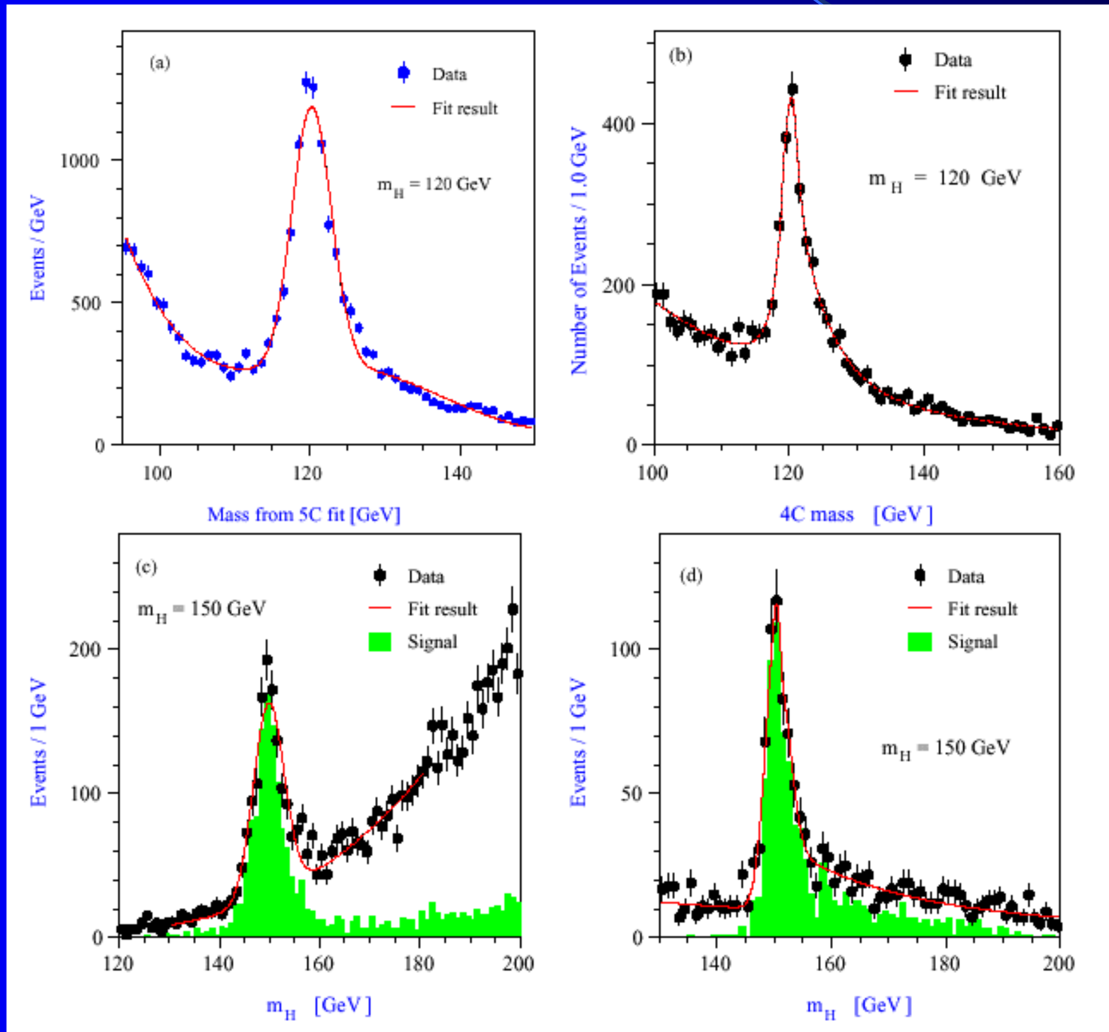
ee -> HZ different decay channels

m_H = 120 GeV

$\rightarrow b\bar{b}q\bar{q}$

$\rightarrow q\bar{q}\ell^+\ell^-$

Δm_H = 40 MeV



m_H = 150 GeV

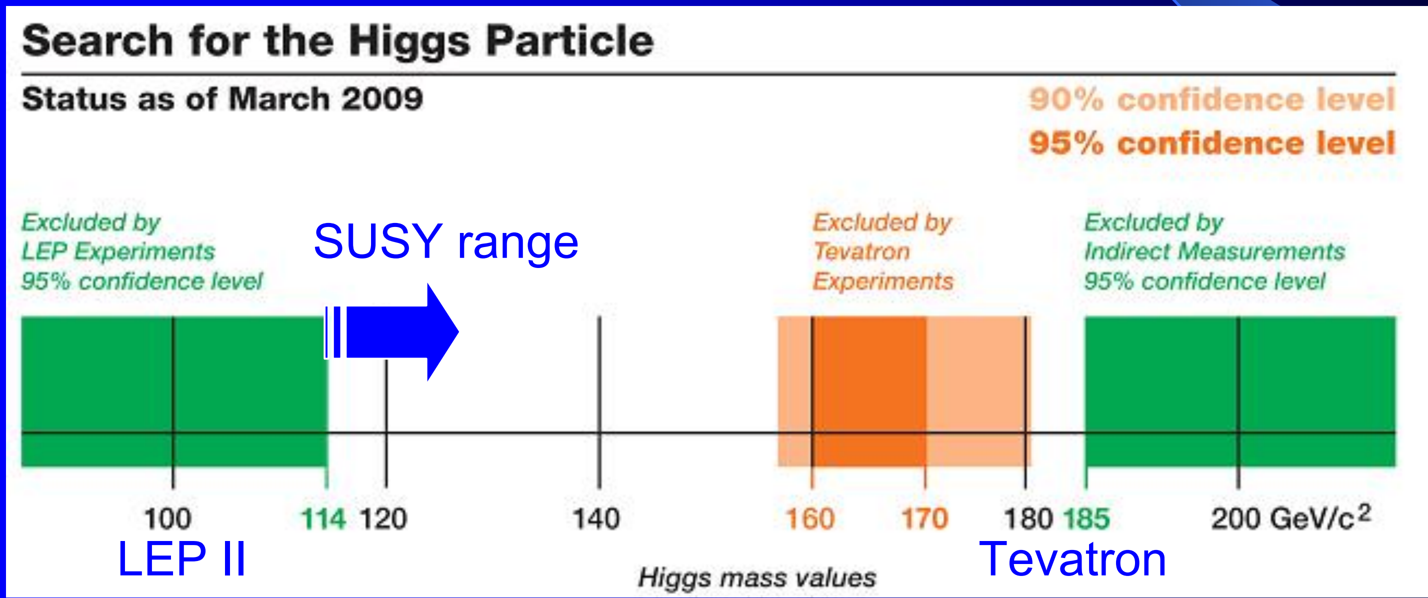
$\rightarrow W^+W^-q\bar{q}$

$\rightarrow W^+W^-\ell^+\ell^-$

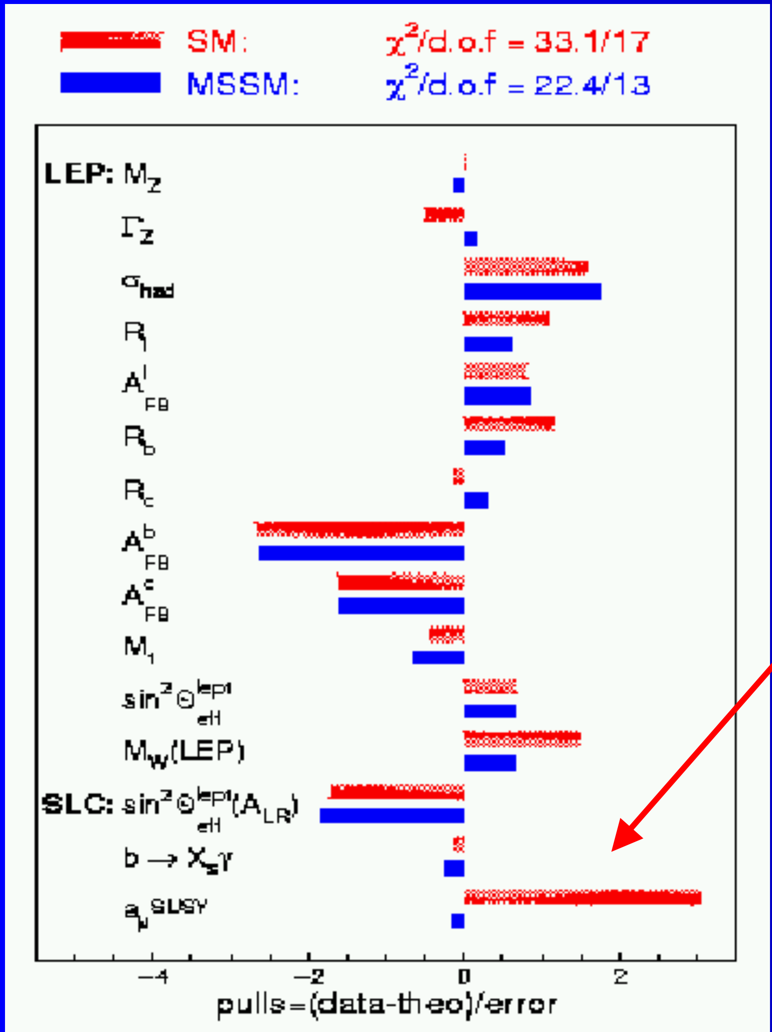
Δm_H = 70 MeV

Modern Higgs Window

(Direct Search)



MSSM versus SM



Global fit to precision EW data

- MSSM is as good as SM
- B->sγ
- a_μ

MSSM is better than SM

- Ω_{DM}

Is NOT described by SM, but is naturally described by MSSM

SUSY: Pros and Cons

Pro :

- Provides natural framework for unification with gravity
- Leads to gauge coupling unification (GUT)
- Solves the hierarchy problem
- Is a solid quantum field theory
- Provides natural candidate for the WIMP cold DM
- Predicts new particles and thus generates new job positions

Contra :

Does not shed new light on the problem of

- Quark and lepton mass spectrum
- Quark and lepton mixing angles
- the origin of CP violation
- Number of flavours
- Baryon assymetry of the Universe

Doubles the number of particles

Superparticles

SParticle Data Group

The SPDG is an international collaboration that reviews Sparticle Physics and related areas of Astrophysics, and compiles/analyzes data on particle properties. SPDG products are distributed to 130,000 physicists, teachers, and other interested people. The Review of Sparticle Physics is the most cited publication in particle physics during the last twenty years. Plots of SPDG statistics are available.

Mirror sites: USA (LBNL) Brazil CERN Italy (Genova) Japan (KEK) Russia (Novosibirsk) Russia (Protvino) UK (Durham)

Review of Sparticle Physics Charts, Educational materials, Sparticle Adventure Information and Databases
US-HEPFOLK Sparticle Physics: Twenty Years of Discoveries Home Pages of major HEP labs

The Review of Sparticle Physics

C. Caso *et al.* The European Physical Journal **C103** (2018) 1 (2018 Authors)

2019	2019 Web update of Reviews, Tables, Plots	New November 2, 2019
2019	2019 Web update of Sparticle Listings	New July 6, 2019
2018	2018 Summary Tables and Conservation Laws	
	2018 Reviews, Tables, Plots (incl. Intro. Text)	Superseded by 2019 Web Version
	2018 Sparticle Listings (published version)	Superseded by 2019 Web Version

- Errata (last changed January 18, 2020)
- Archived WWW editions: 2017 2016 2015
- Descriptions of the Summary Tables, Reviews, Listings, etc.
- Ordering Information and list of products
- 2018 Authors and Directory of Sparticle Data Group Authors, Associates, and Advisors
- Computer-readable files – masses, widths, cross-sections, etc., including Palm Pilot XXII files.
- Encoder tools (for SPDG collaborators)

Discovery of the new world of SUSY

Back to 60's

New discoveries every year