The Physics Case for a TeV Linear Collider

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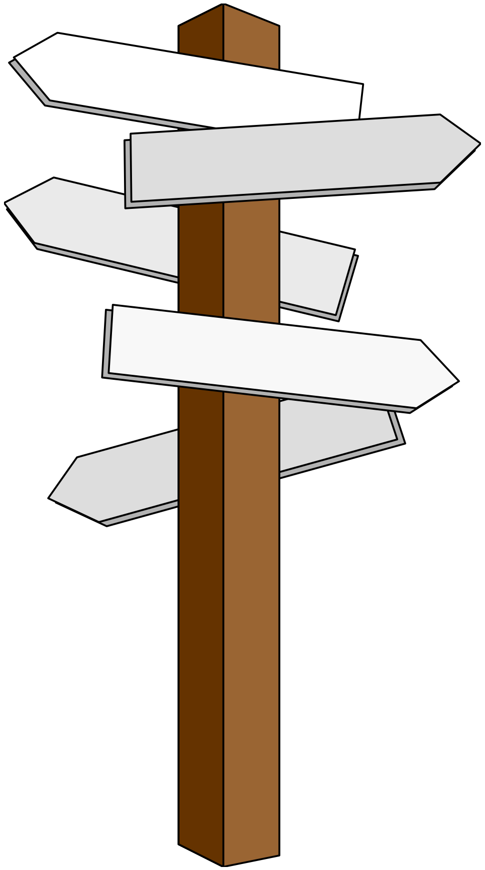
How to decide?

- How will the LHC help us to decide whether 500 GeV or a (multi) TeV scale lepton collider is optimal?
- What can we expect to learn from the LHC?
  - The time is now
- Electroweak symmetry breaking, the search for supersymmetry, and precision measurements form the backbone of the lepton collider physics case
  - The LHC gives information on all three areas

LHC will point the way

Direct observation of new particles & precision measurements at the LHC

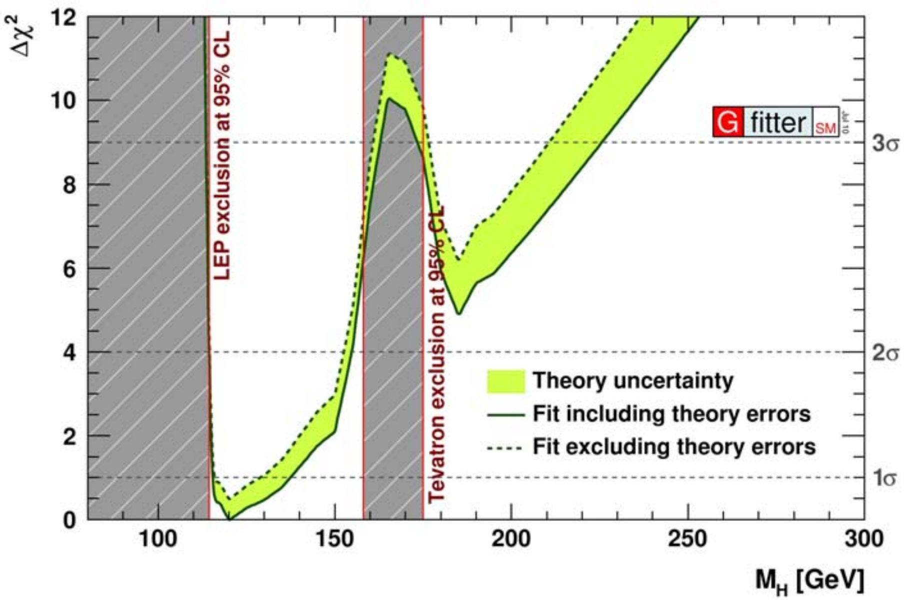
In a year or two, we will know much (much!) more about the TeV energy scale



But we already have learned a lot

Higgs Boson(s)

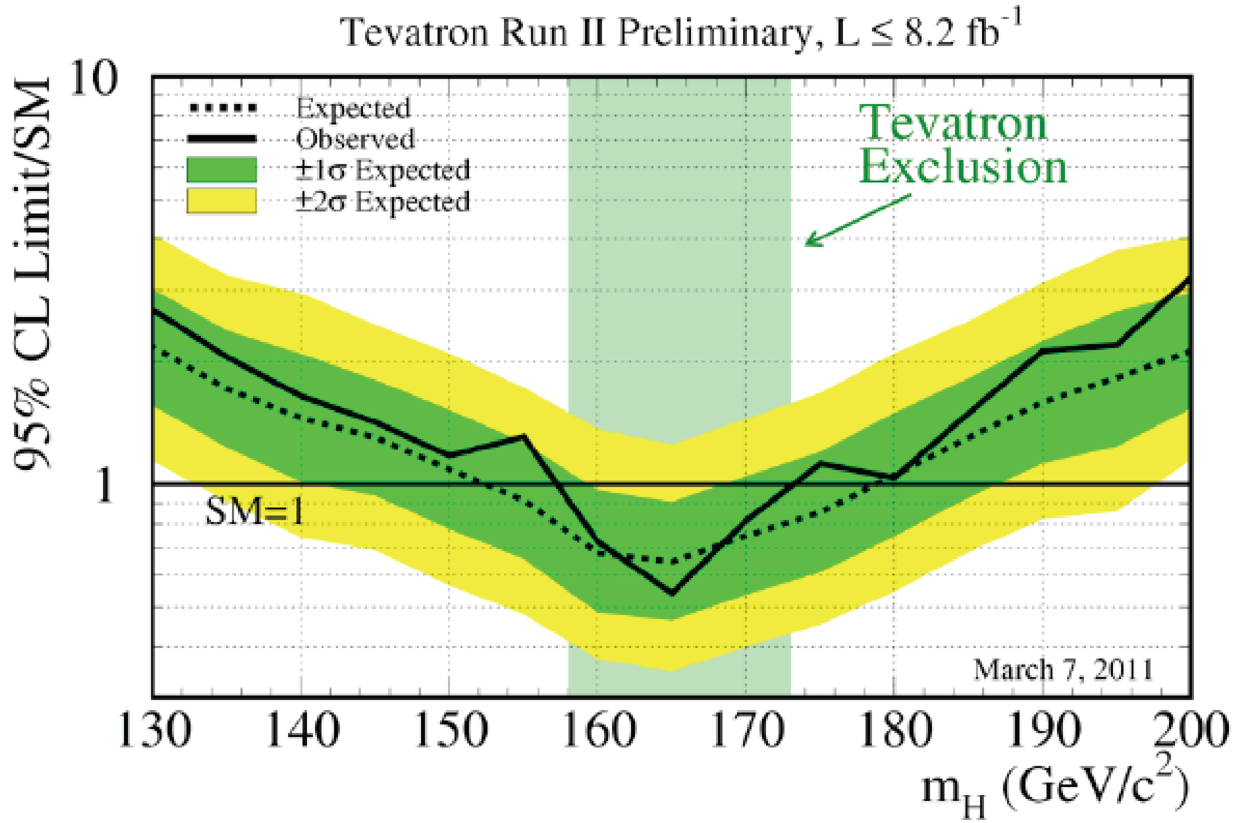
- SM Higgs expected to be light



- This assumes the SM!

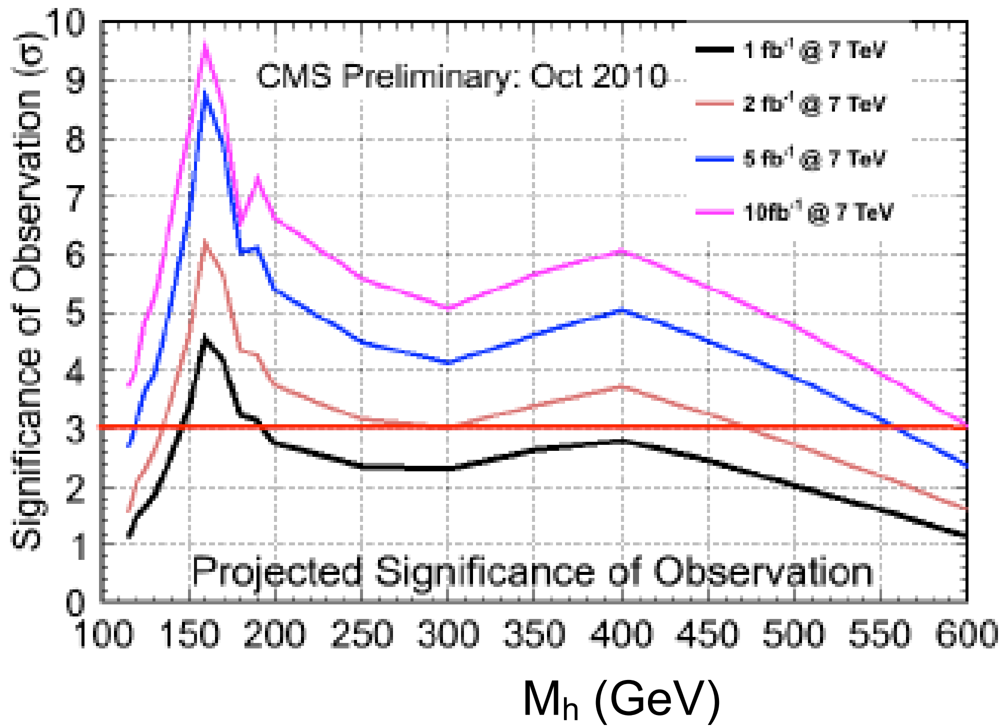
SM prefers light (M_h < 158 GeV) Higgs boson

Tevatron Higgs Exclusion



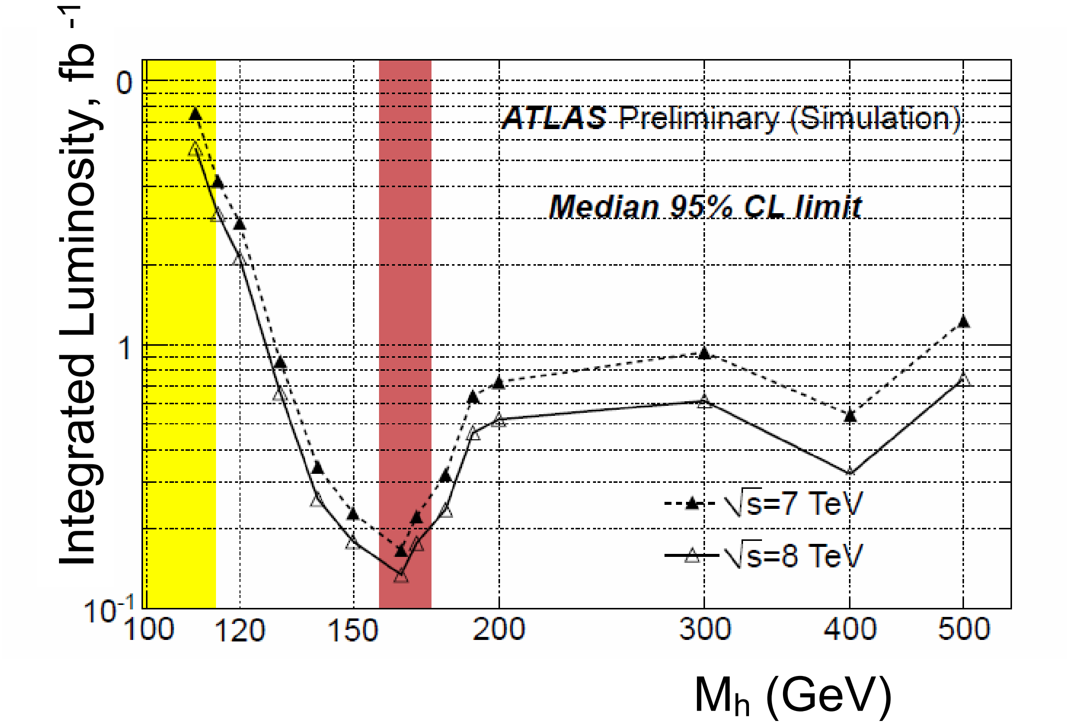
Tevatron Exclusion: [158 GeV < M_h < 173 GeV]

Higgs Discovery Soon



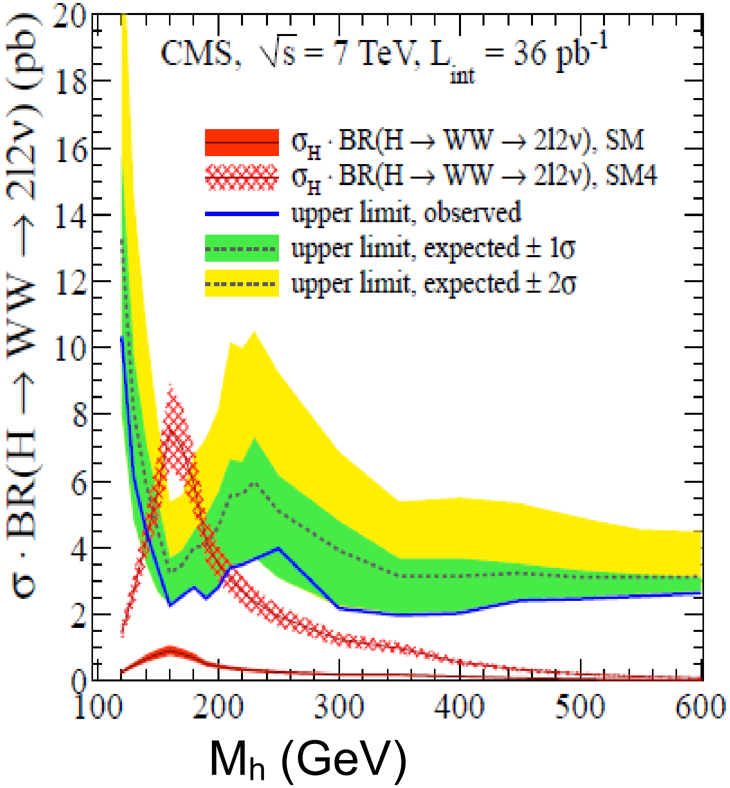
CMS: 10 fb^{-1} gives 3σ discovery for M_h=115-600 GeV

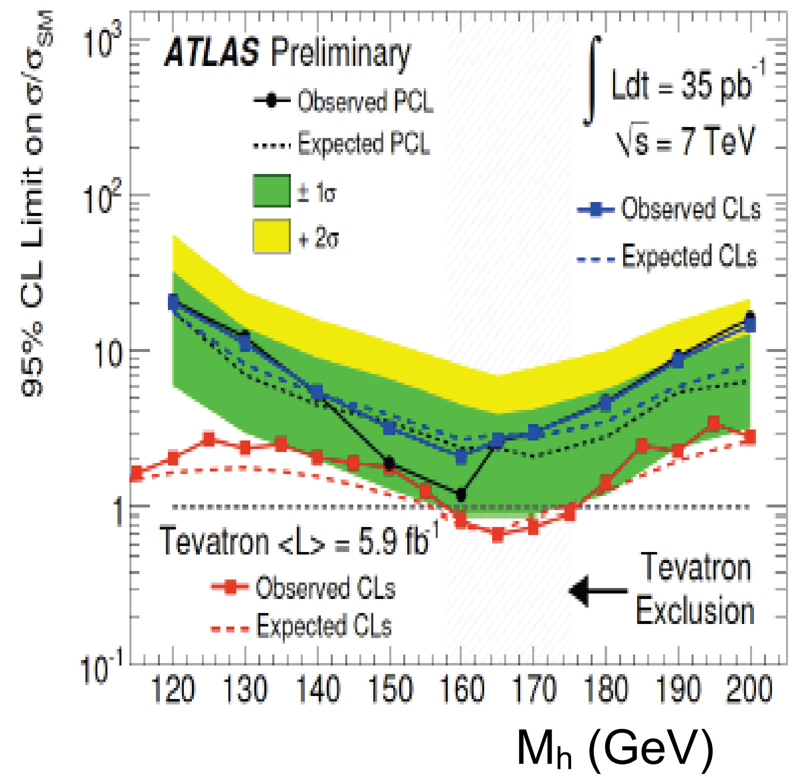
Higgs Exclusion



4 fb^{-1} will exclude to 500 GeV @ 7 TeV

LHC Higgs Limits with 35 pb^{-1}





Closing in on the Standard Model

Higgs Discovery

$\sqrt{s}$=7 TeV

ATLAS + CMS ≈ 2 x CMS	95% CL exclusion	3σ sensitivity	5σ sensitivity
1 fb^{-1}	120 - 530	135 - 475	152 - 175
2 fb^{-1}	114 - 585	120 - 545	140 - 200
5 fb^{-1}	114 - 600	114 - 600	128 - 482
10 fb^{-1}	114 - 600	114 - 600	117 - 535

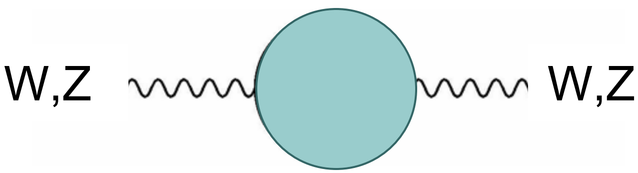
2011

2012

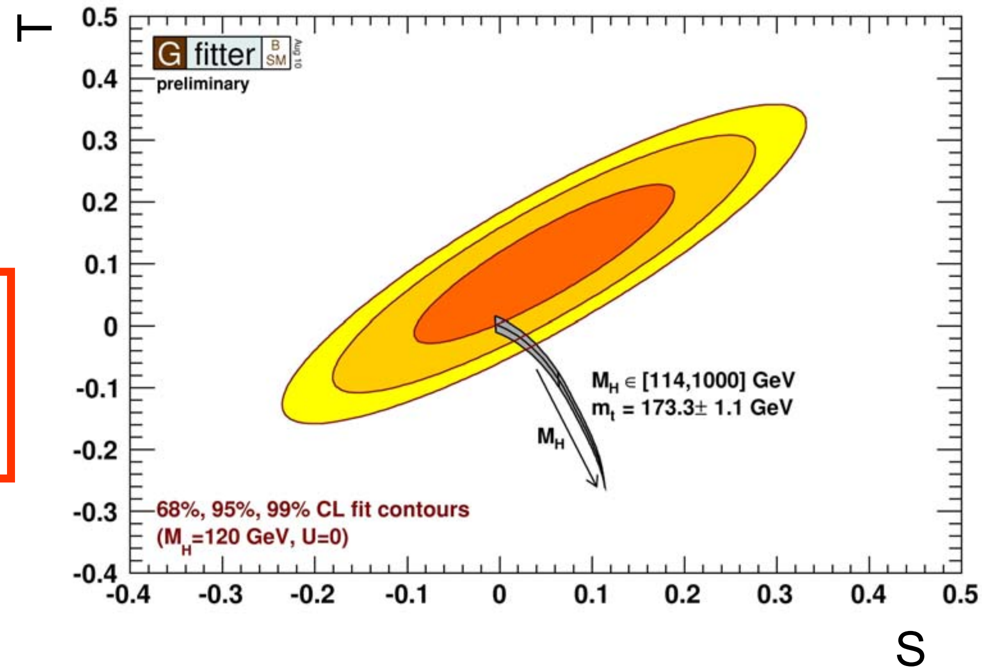
If the SM Higgs exists, we'll know its mass soon

Easy to Evade SM Higgs Limit

- If new physics is at scale Λ>> M_Z, then STU describe precision electroweak measurements



Large M_h requires positive ΔT

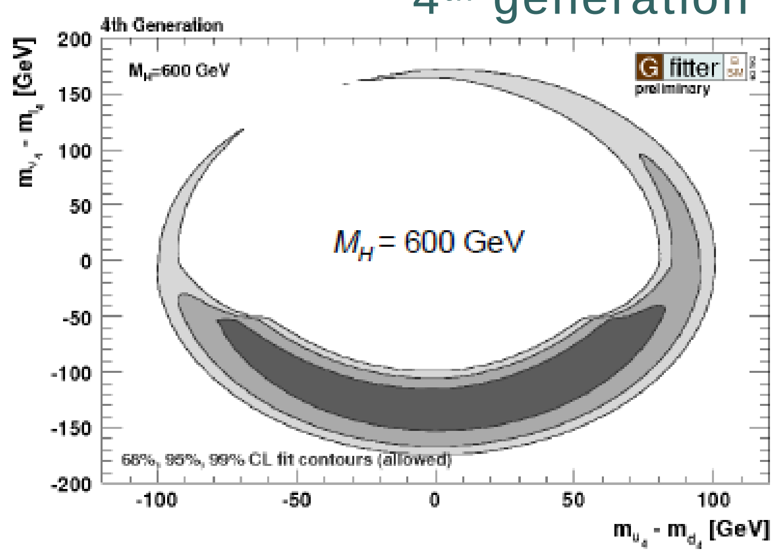


Precision data restrict BSM scenarios

- General 2 Higgs doublet
- Kaluza Klein particles
- Little Higgs with T parity
- NMSSM
- 4 generations

Can accommodate heavy Higgs with some types of new physics

4th generation



Is it ***the*** Higgs?

- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

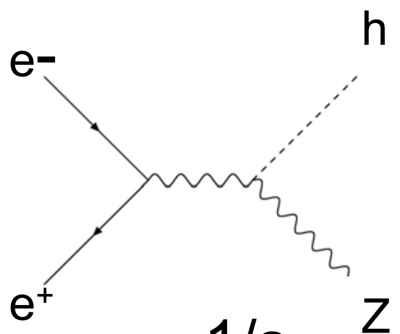
$$J^{PC} = 0^{++}$$

Golden Arguments for LC

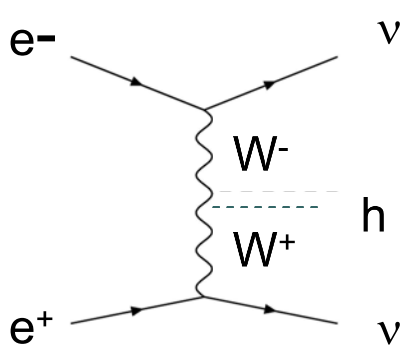
- Measure self interactions

$$V = \frac{M_h{}^2}{2}h^2 + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$

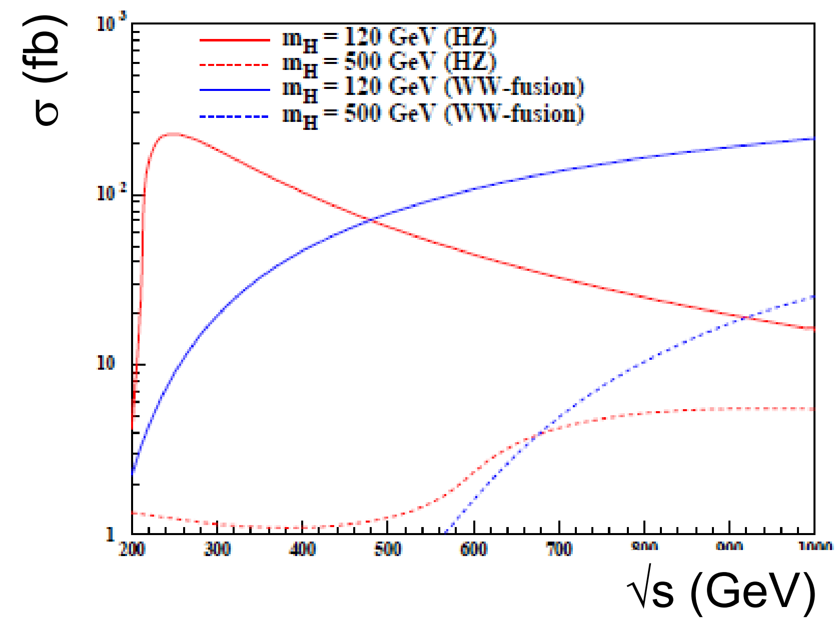
Higgs Production at LC



σ~1/s



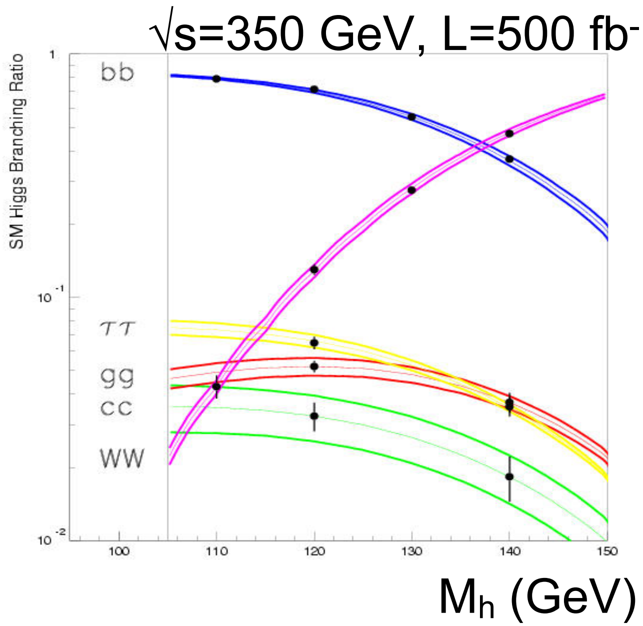
σ~log(s)

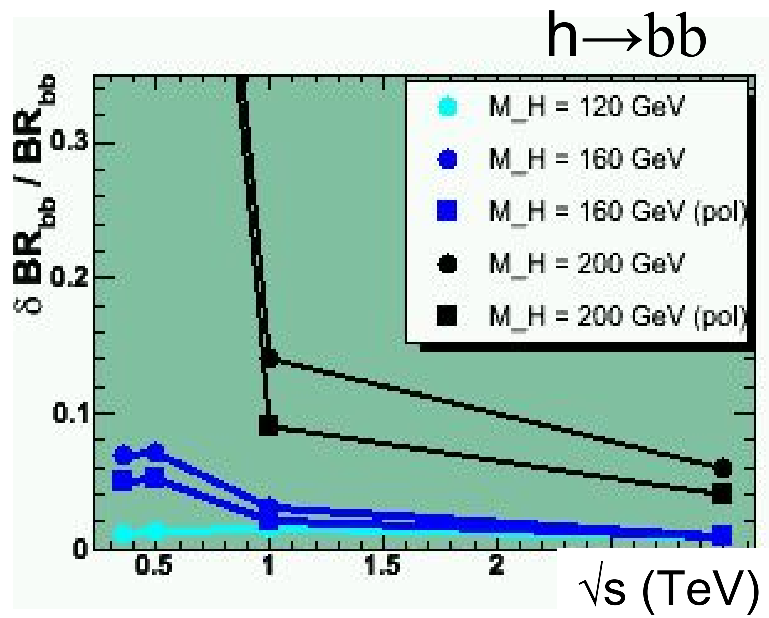


Need $e^+e^- \rightarrow h\nu\nu$ for heavy Higgs

Light Higgs Couplings well explored at LC

- $e^+e^- \to Zh$: Optimal energy is $\sqrt{s} \sim M_h + M_Z +$ 40 GeV



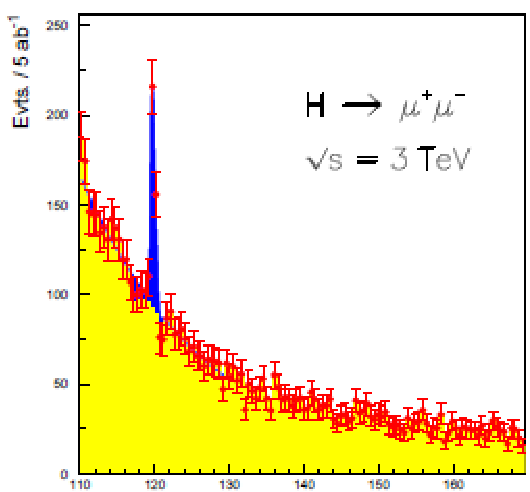


Theory uncertainty (mostly from m_b) larger than experimental accuracy

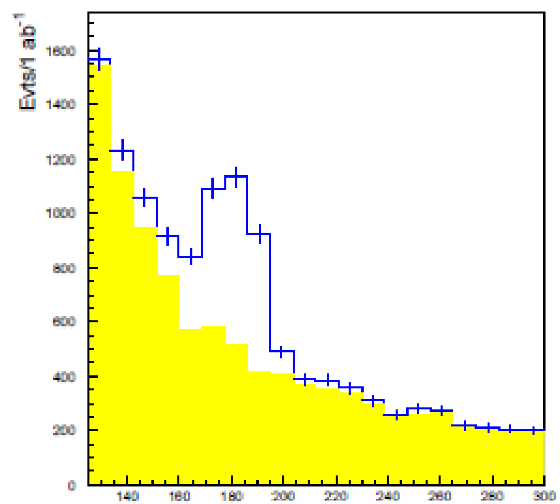
[Battaglia]

Vector Boson Fusion useful at Higher Energy

- $e^+e^- \rightarrow h\nu\bar{\nu}$ grows with energy: Allows measurements of
  - $BR(h\rightarrow\mu^+\mu^-)$
  - Increased precision on $BR(h\rightarrow bb)$



$M_{\mu\mu}$(GeV)



M_{bb}(GeV)

Spin at LHC

- If $h \rightarrow Z^*Z \rightarrow 4$ leptons, then discrimination between spin hypothesis possible (need M_h >140 GeV for rate)*

Minimum number of events to get 5σ discrimination between hypothesis

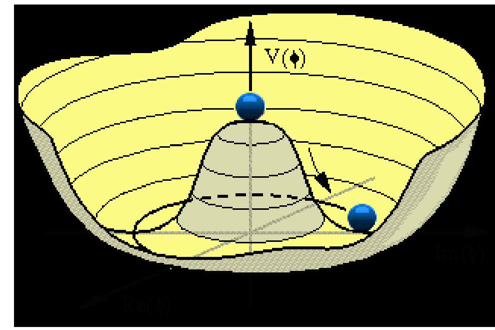
	0^+	0^-	1^-	1^+
0^+		52	37	50
0^-	44		34	54
1^-	33	32		112
1^+	54	55	109	

*M_h=145 GeV, BR($h \rightarrow Z^*Z \rightarrow 4$ leptons)~.00036 $\Rightarrow$ ~10^5 Z's needed

[DeRujula et al, arXiv:1001.5300]

Higgs Potential

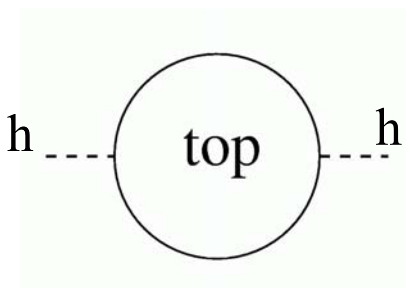
$$V = \frac{M_h^{\ 2}}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

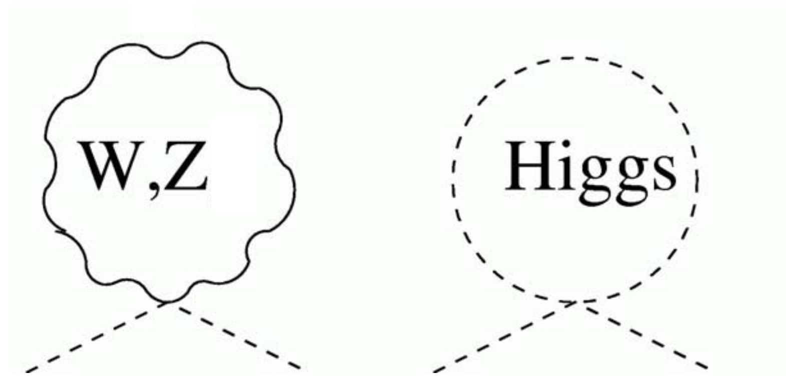


- Notoriously difficult
  - Requires 2 Higgs production
  - Many new physics examples enhanced at large energy
- SLHC (3000 fb^{-1}) $\delta\lambda_3/\lambda_3$ ~ 20-30%
- 500 GeV LC $\delta\lambda_3/\lambda_3$ ~ 20% with 1 ab^{-1}
  - Use also 1 ab^{-1} at 1 TeV $\delta\lambda_3/\lambda_3$ ~ 12%

Very, very (!) hard both at LHC and LC

Many Good Reasons to Expect More Physics than Higgs





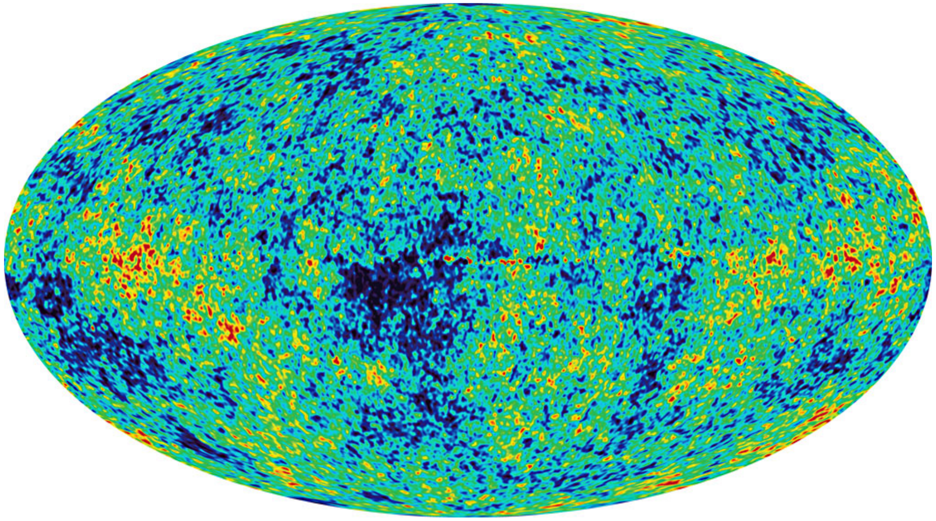
- Higgs mass grows with high scale, Λ (*a priori* $\Lambda = M_{pl}$)

$M_h \leq 200$ GeV suggests $\Lambda \sim$ TeV

Points to 1 TeV as scale of new physics

No Dark Matter Candidate in SM

- WIMP Miracle: Electroweak scale particles have right properties to provide dark matter



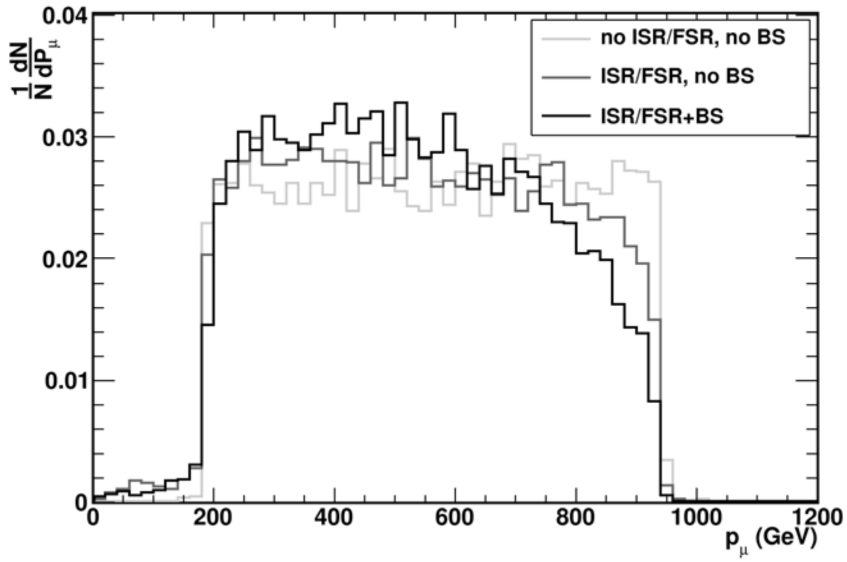
Supersymmetry: A favorite

- Solves hierarchy problem, $M_W << M_{GUT}$
- Radiative EWSB
- Light Higgs boson
- Dark Matter candidate
- Need to test SUSY
  - Observe superpartner for each particle
  - Spin measurements
  - SUSY coupling relations

Beautiful Tests of SUSY at LCs

- Question: What states are kinematically accessible?
- Masses from measuring endpoints (to ~1-2%)

$$e^+e^- \to \tilde{\mu}_R \tilde{\mu}_R^* \to \mu^+ \mu^- \tilde{\chi}^0 \tilde{\chi}^0$$

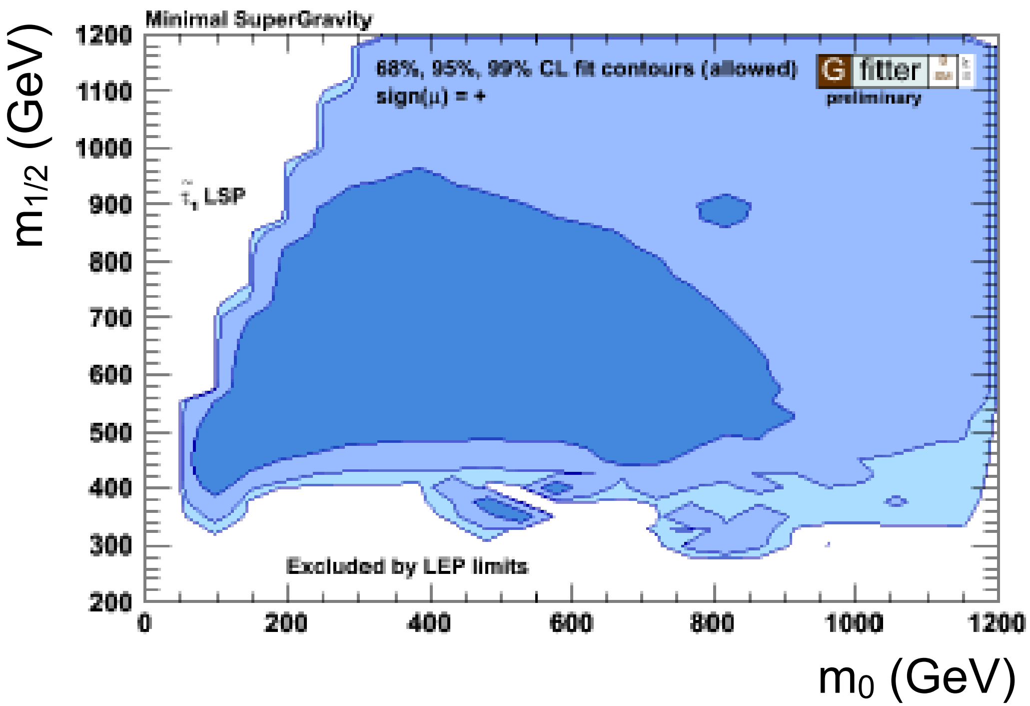


[Battaglia and Blaising, 1006.2547]

3 TeV CLIC, m_μ=1108 GeV, m_χ=554 GeV, L=2 ab^{-1}

Global fits suggest light SUSY

- Gfitter fit includes:
  - LEP limits, $(g\text{-}2)_\mu$, dark matter, heavy flavor constraints

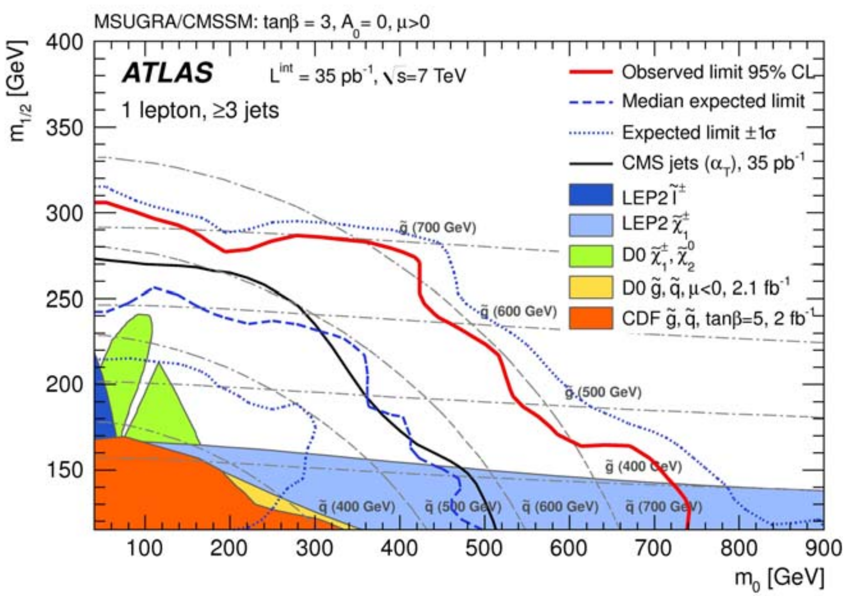


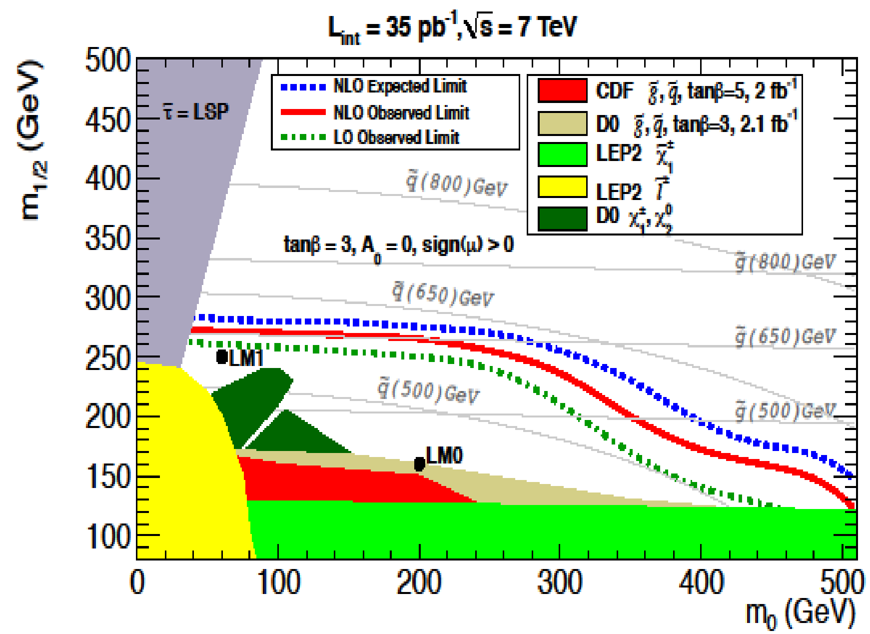
Similar fit from sFittino

[tan β, A_0 float in this fit]

Finding Supersymmetry

- CMS and ATLAS SUSY limits

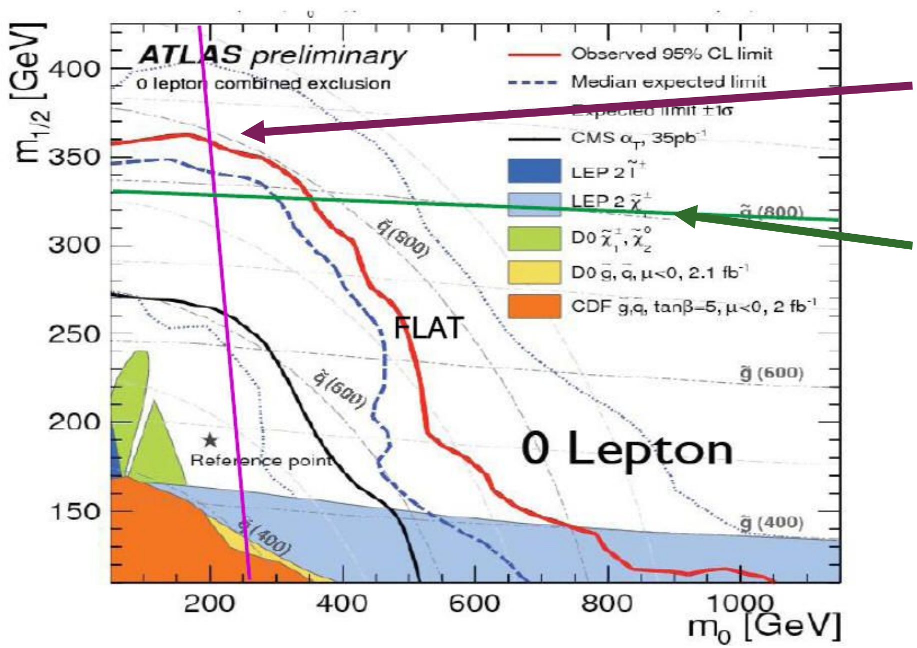




mSUGRA fit: M(gluino) ~ M(squark) > 775 GeV

mSUGRA Models

- In CMSSM/mSUGRA all masses related
- Limits on m_0 and $m_{1/2} \Rightarrow$ limits on charginos and sleptons



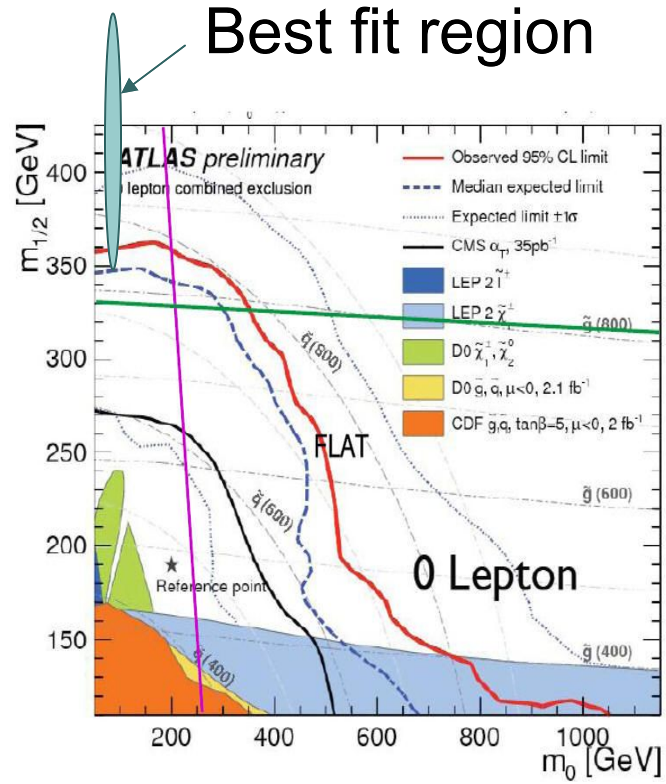
All sleptons heavier than 250 GeV

χ_1^+ heavier than 250 GeV

[Rizzo]

Global fits to SUSY

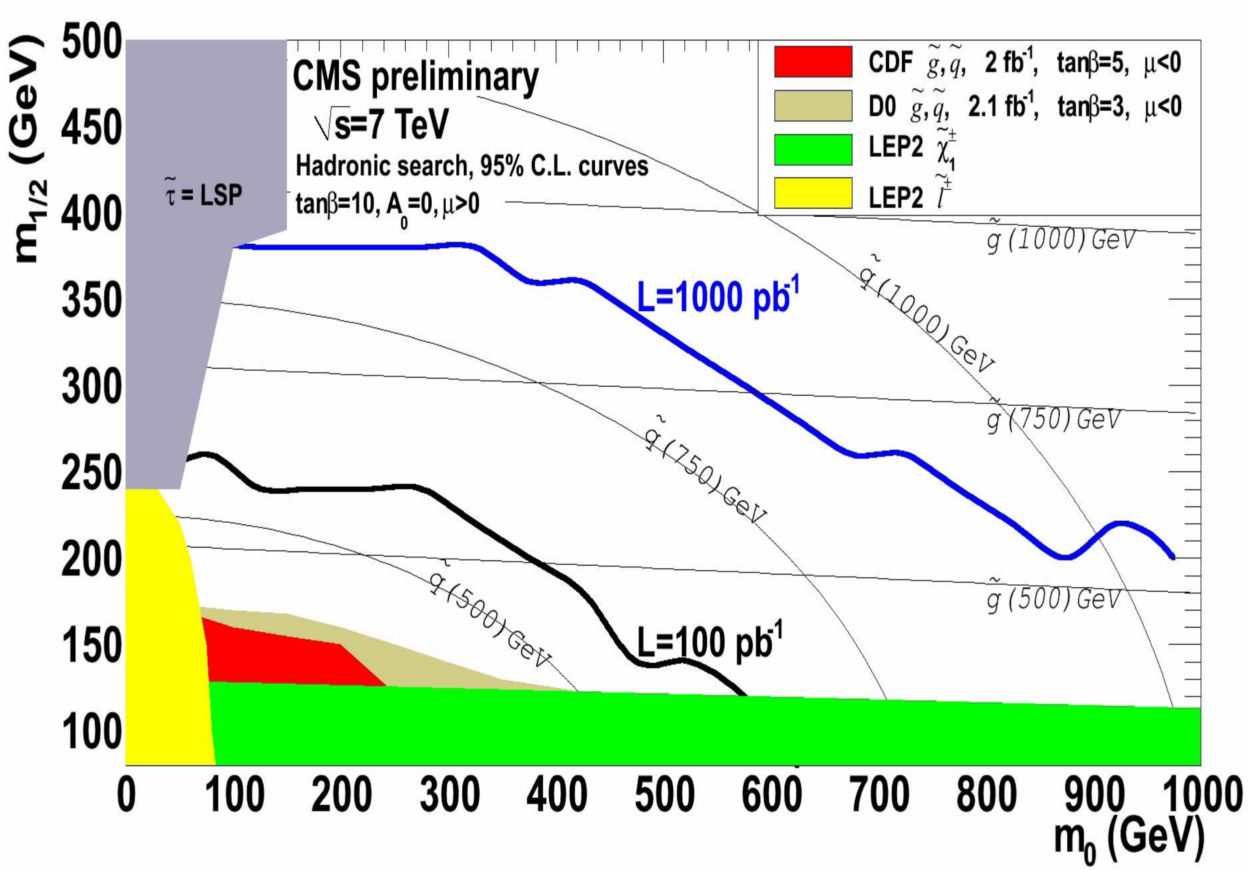
- Constraints: $(g-2)_{\mu}$, dark matter relic density, direct searches, EW observables
- Best fits suggest “light” SUSY particles
  - $m_{1/2}$ ~ 340-490 GeV
    m_0 ~100 GeV



Fit from Buchmueller et al, ArXiv: 1102.4585

See also, Akula et al, arXiv:1103.1197

LHC Limits in “Rapid Improvement” Phase

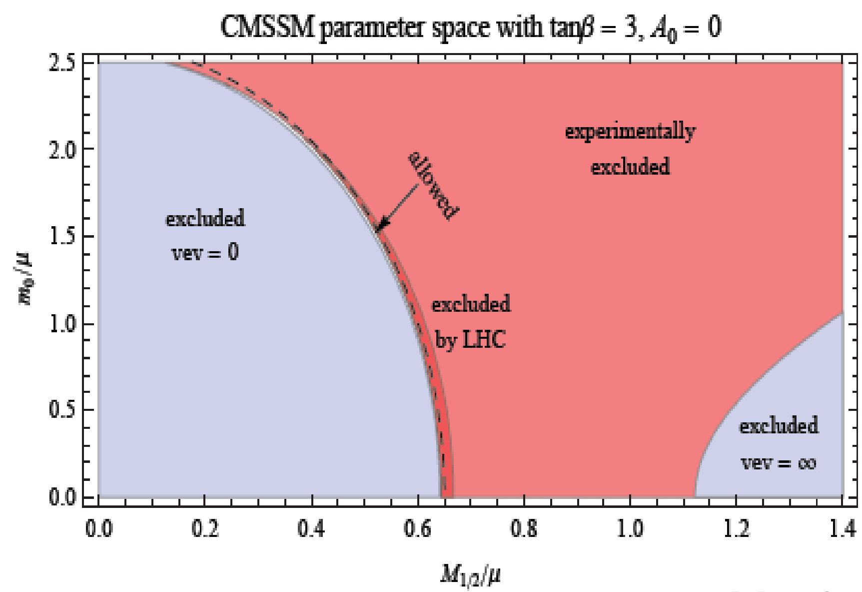


[CMS Note 2010/008]

MSSM Space Highly Constrained

- Question: If parameters are allowed by LHC searches, do they have light sparticles which can be seen at 500 GeV (1 TeV) LC?
- Fine tuning: $M_Z^2 \sim .2m_0^2+.7M_3^2-2\mu^2$

Little sliver of white space is allowed region



[Strumia: arXiv:1101.2195]

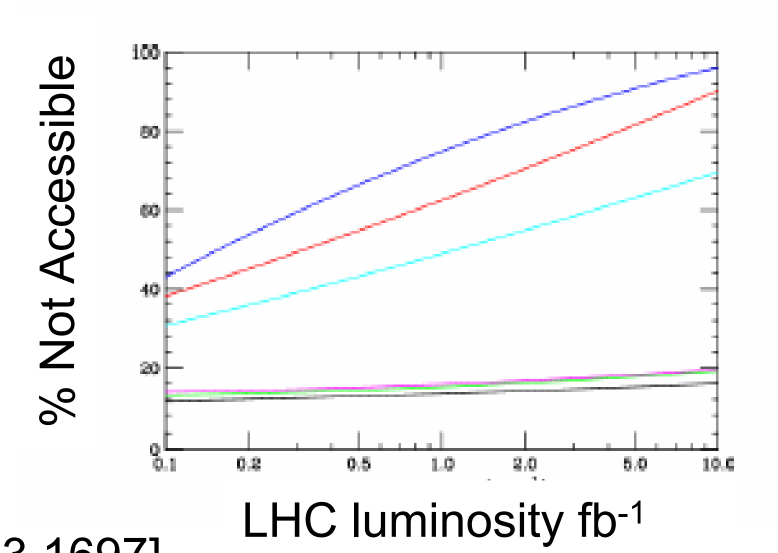
$M_3 \sim 2.6\ m_{1/2}$

Not just mSUGRA (CMSSM)

- MSSM is broad class of theories
- mSUGRA mass relationships **not needed/not always true**
- In general, a broad parameter space
- (phenomenological) MSSM has 19 parameters (mostly masses)
  - Require parameter space to satisfy flavor, EW constraints, Tevatron limits, have dark matter candidate
  - Generate acceptable MSSM models

LHC SUSY Limits ⇒ LC Conclusions

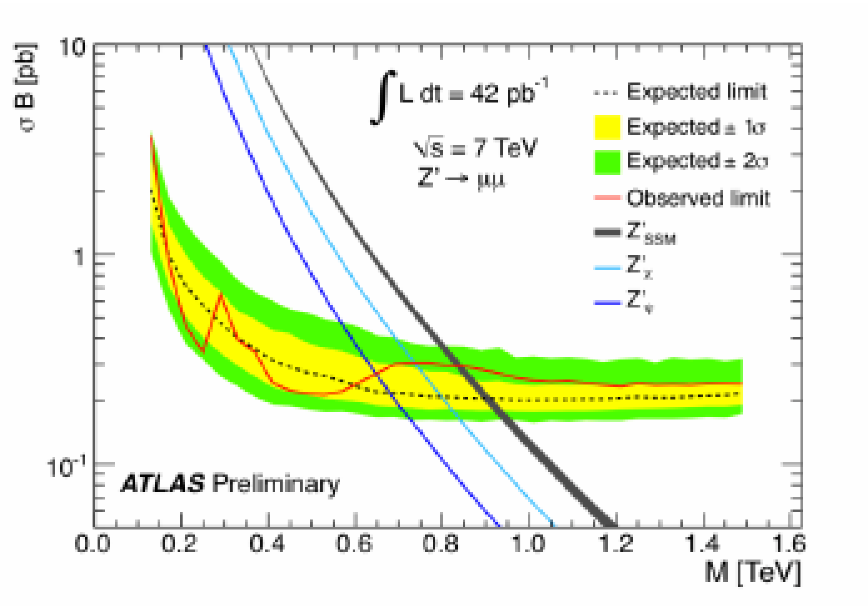
- Intuitively, the better the LHC SUSY exclusion limits, the less likely there will be SUSY particles kinematically accessible at a 500 GeV linear collider
- Try to quantify this: y-axis: % of generated models which escape LHC observation which have no SUSY particles accessible at 500 GeV LC



[Conley et al, arXiv:1103.1697]

Searches for New Z's

- LHC limits already at the TeV scale

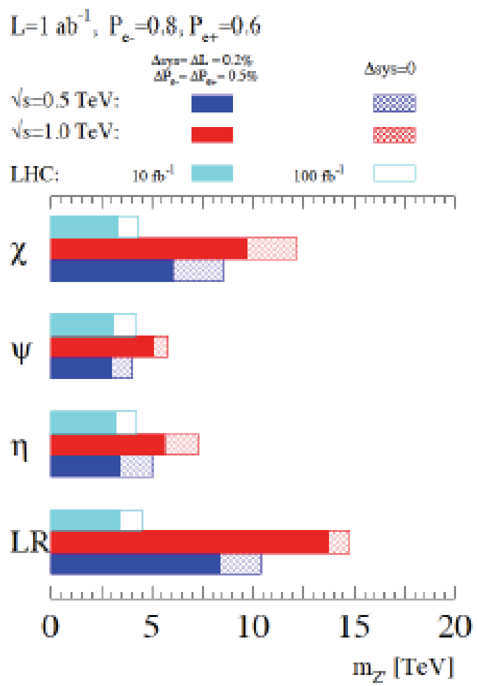


CMS limits (35 – 40 pb^{-1})

Channel	μμ	ee	Combined
Z_{SSM}	1027 GeV	958 GeV	1140 GeV
Z_{ψ}	792 GeV	731 GeV	887 GeV
G_{KK}, k/M_{Pl} = 0.05	778 GeV	729 GeV	855 GeV
G_{KK}, k/M_{Pl} = 0.10	987 GeV	931 GeV	1079 GeV

Precision Measurements

- ILC measures indirect effects of Z’: $e^+e^- \rightarrow f\bar{f}$
- LHC is already squeezing 500 GeV ILC parameter space



S. Riemann

Conclusions

- The LHC is honing in on the 1 TeV scale
- We will soon know
  - Is there a light Higgs?
  - Is there SUSY at the TeV scale?
  - Are there Z’ resonances at the TeV scale?
  - Something totally unexpected