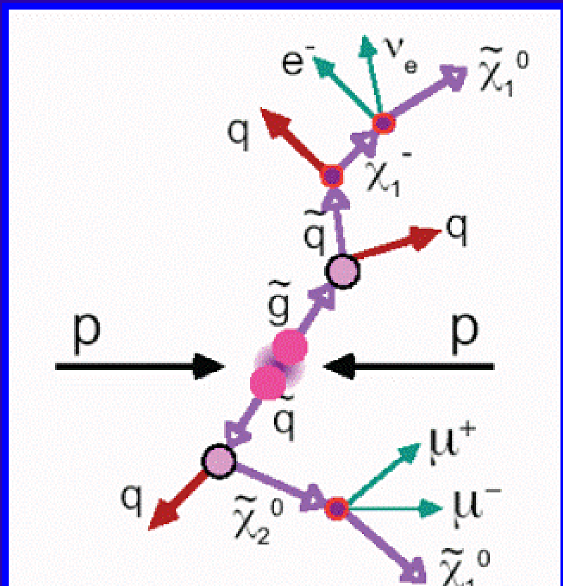
The ATLAS Search for Supersymmetry and its Connection to Dark Matter

PPC 2008

2ND INTERNATIONAL WORKSHOP ON THE INTERCONNECTION BETWEEN PARTICLE PHYSICS AND COSMOLOGY

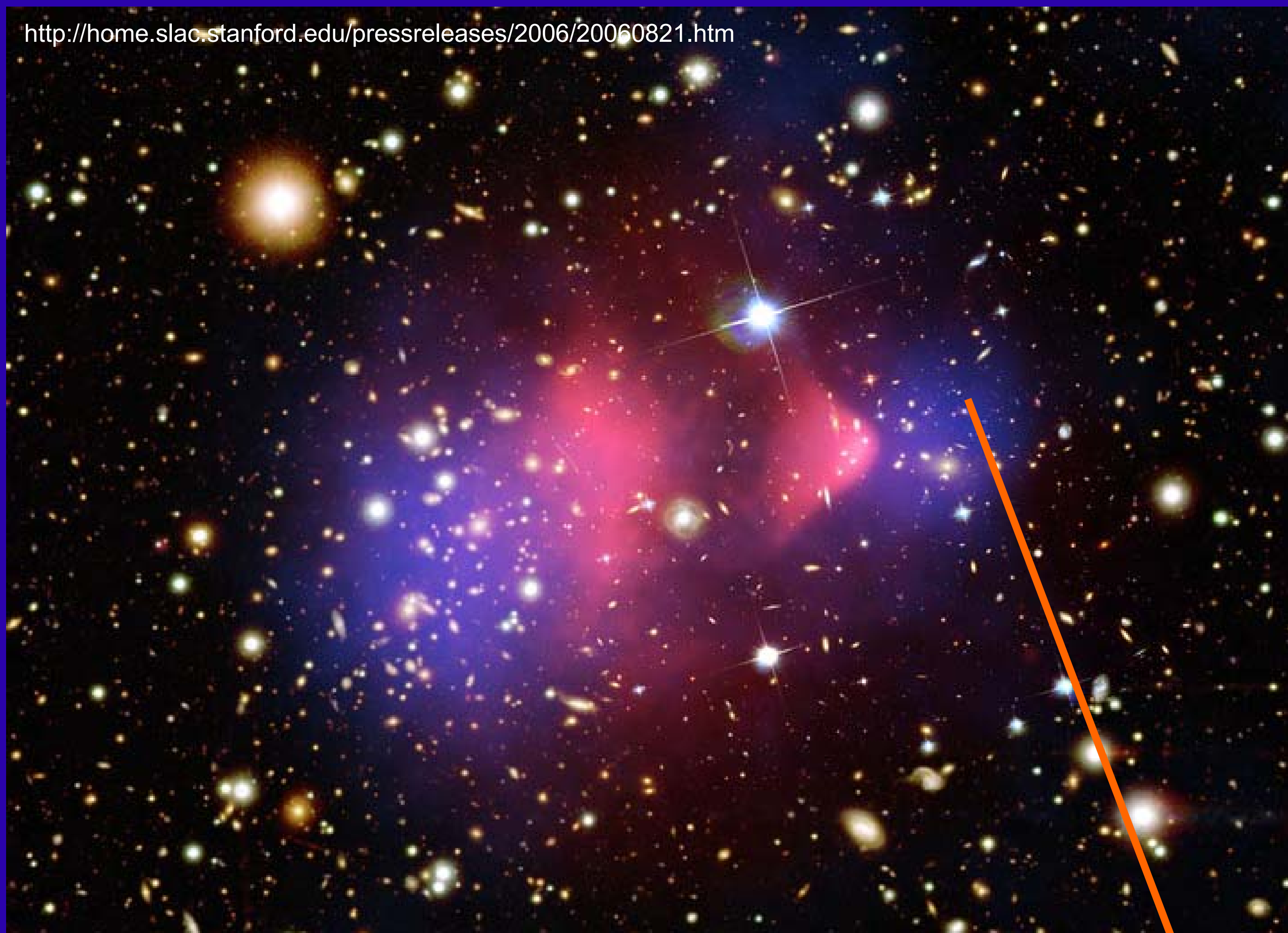


http://www.icepp.s.u-tokyo.ac.jp/~kenta/analysis.html


http://home.slac.stanford.edu/pressreleases/2006/20060821.htm

Sven Vahsen (Lawrence Berkeley Lab) for the ATLAS Collaboration

Is the Dark Matter Supersymmetric?

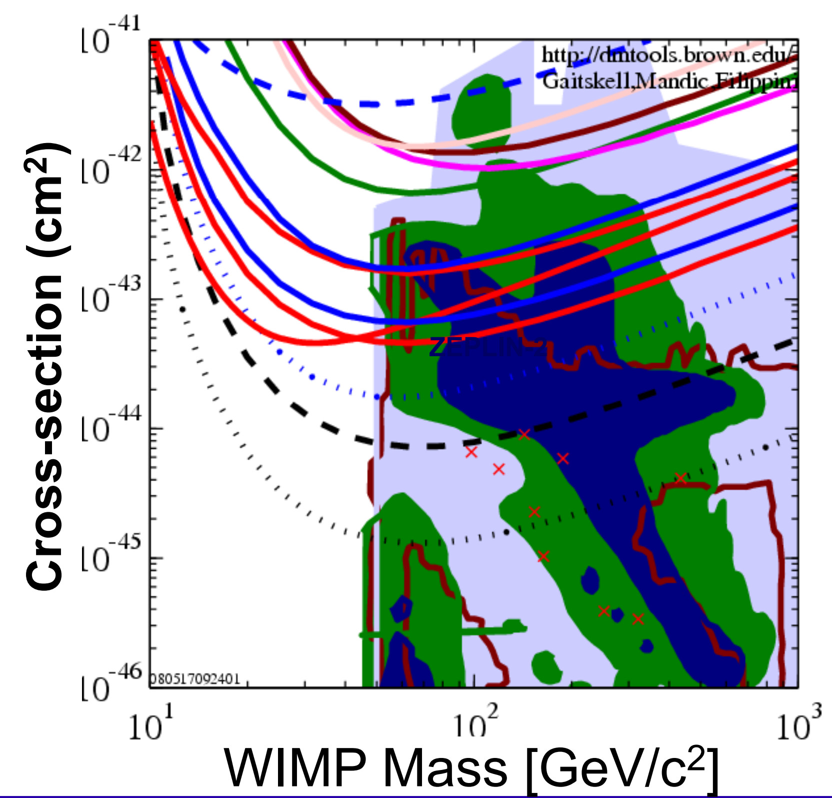


- What can we learn from the LHC?

$\tilde{\chi}^0_1$?

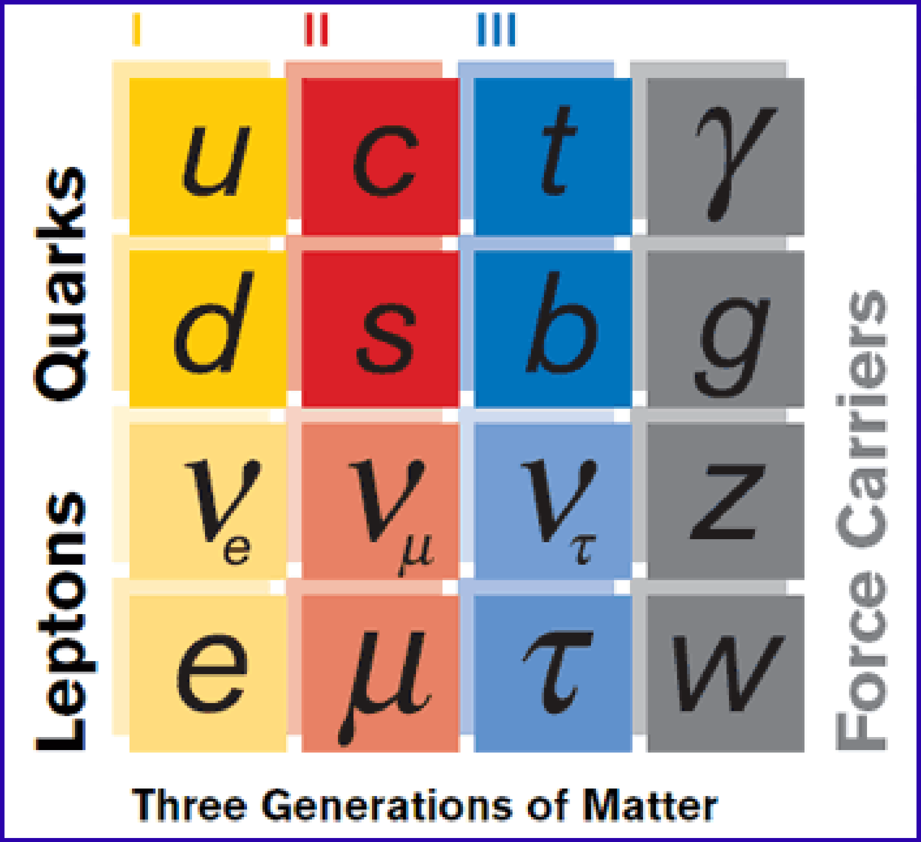
How the LHC can help

- If new physics discovered at LHC
  - WIMP DM candidate?
  - What fraction of DM?
- Try to measure enough to compute
  - Mass m_{WIMP}
  - Cross-section $\sigma_{WIMP\text{-}nucleon}$
  - Relic density Ω_{WIMP}
- Compare with
  - Astro Particle Physics (m, σ)
  - Experimental Cosmology $\Omega_{WIMP} = \Omega_{DM}$?



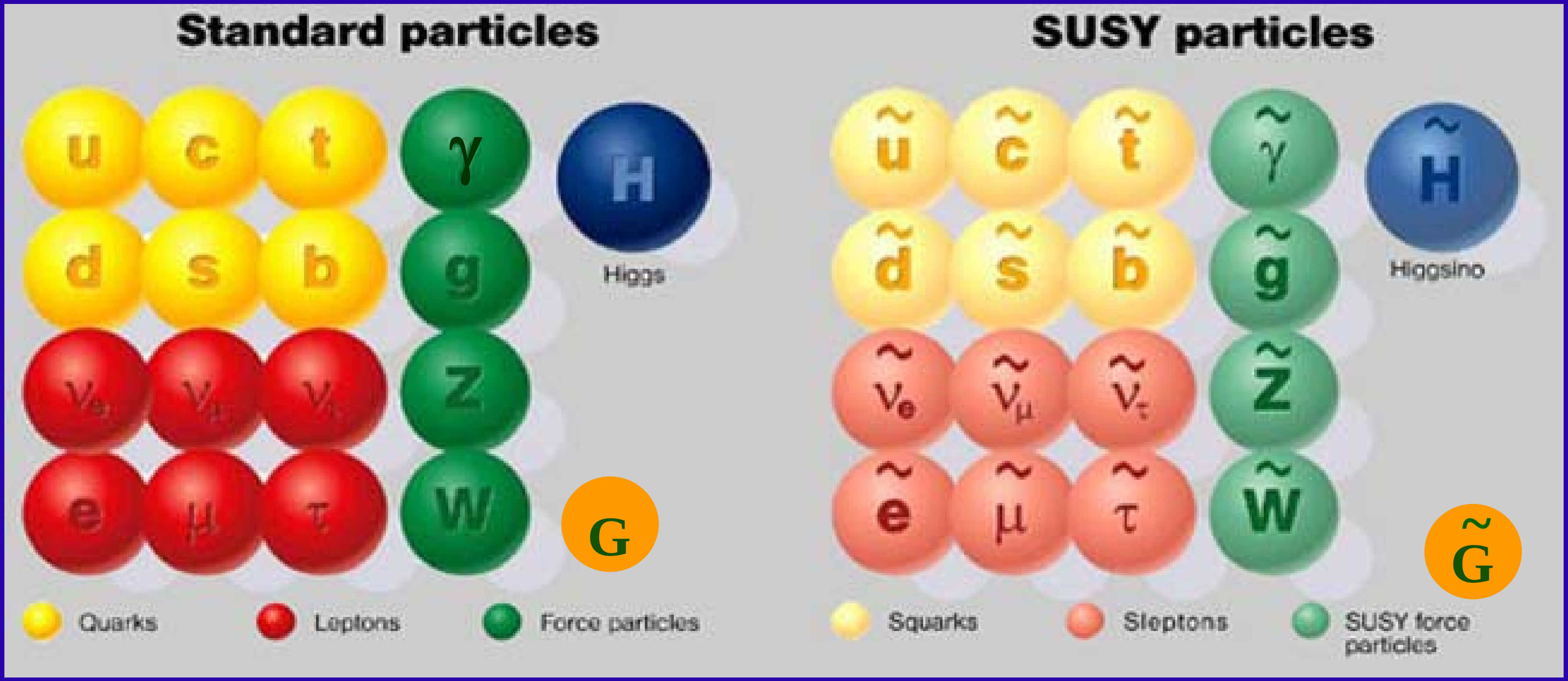
Potential for major impact on our understanding of Dark Matter!
Will discuss ATLAS prospects if new physics is SUSY

The Standard Model of Particle Physics



- Successful theory of fundamental interactions since early 1970s
- Survived numerous experimental tests
- Only Higgs missing
- LHC built to look for Higgs and Physics beyond the Standard Model…

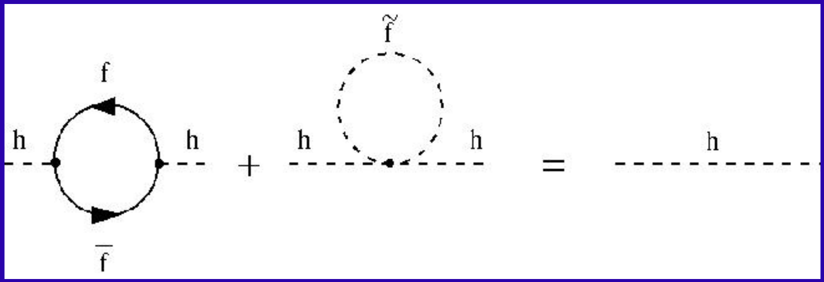
Supersymmetry (SUSY)

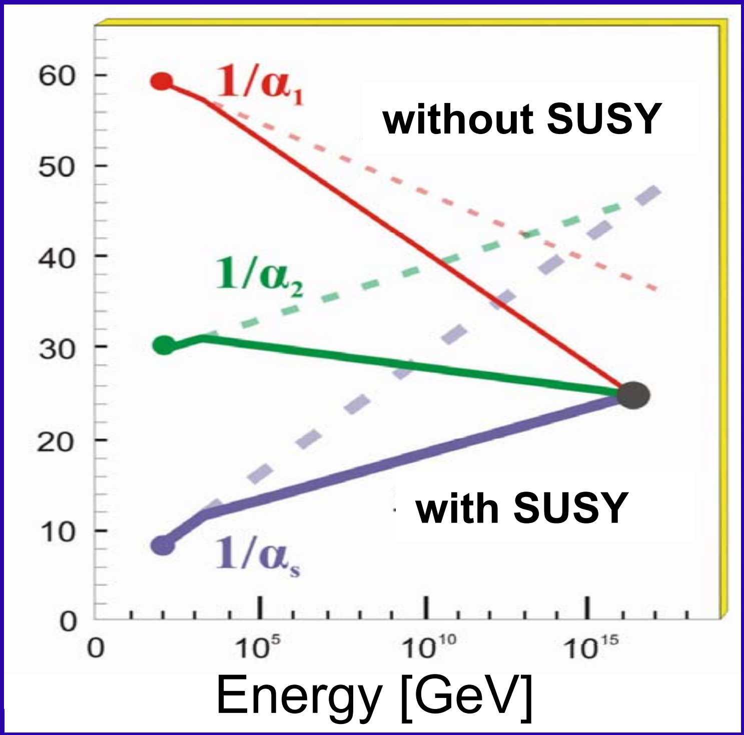


- Well motivated extension of the Standard Model
- Standard Model particles have supersymmetric partners
  - Differ by 1/2 unit in spin
- EW-gaugino+higgsino mixing → 2 charginos $\tilde{\chi}^{+/-}_{1,2}$ 4 neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$

Why We Like SUSY

- Keeps corrections to Higgs mass small. Requires wino and stop masses ~ few hundred GeV
- Unifies gauge couplings at large Q^2. Requires sparticle masses ~ few hundred GeV
- Can provide plausible WIMP Dark matter candidates. Cosmological arguments prefer WIMP mass ~ hundred GeV
- Highest mass limits from Tevatron ~ 300 & 400 GeV (gluinos, squarks)

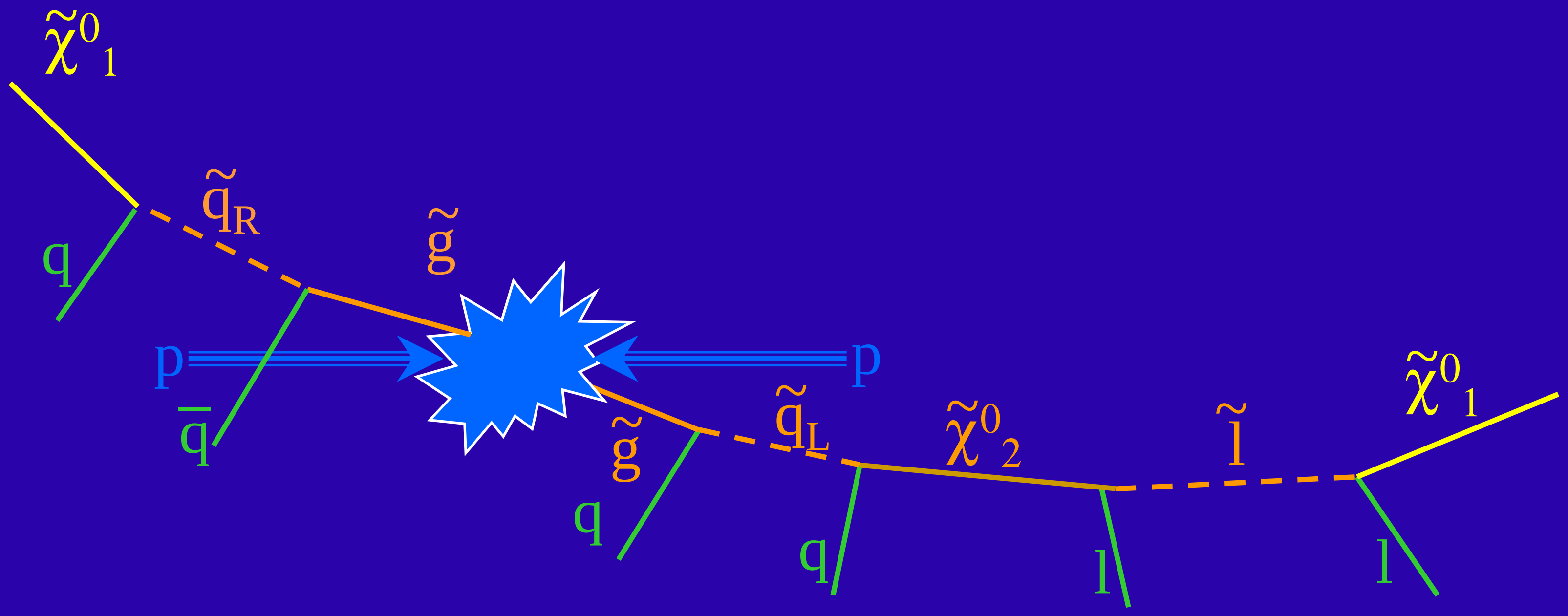




W. de Boer, C. Sander
Phys.Lett.B (2004)

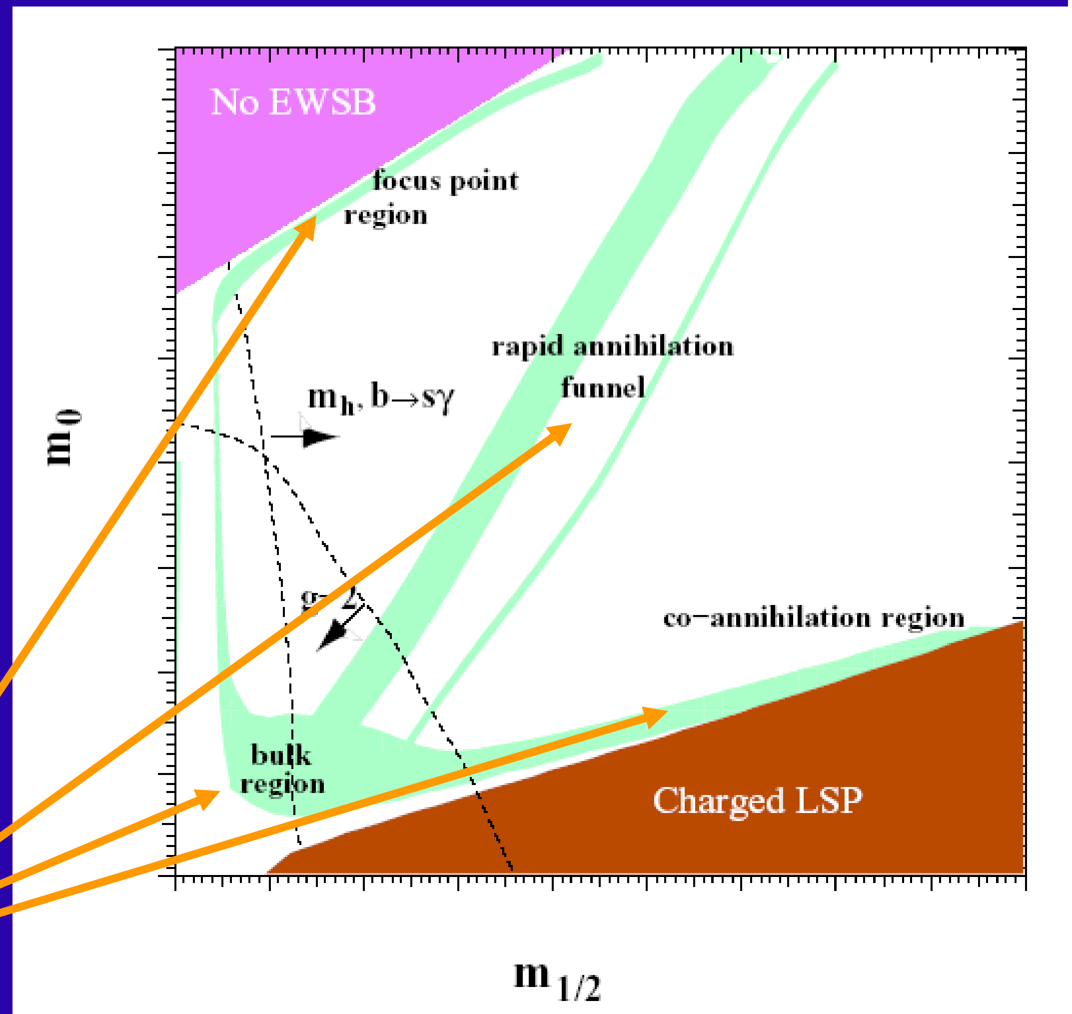
R-Parity, Stable LSP

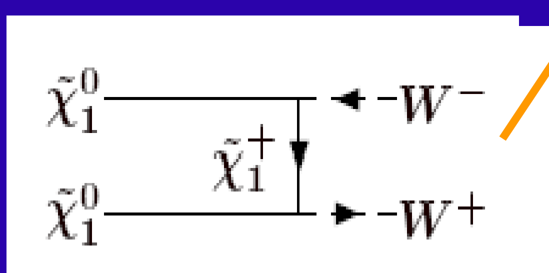
- Consider only R-parity conserving SUSY models
- Even number of SUSY particles for every vertex
  - SUSY particles always produced in pairs
  - Get decay chains as below
  - Lightest SUSY particle (LSP) cannot decay, hence potential WIMP Dark Matter candidate



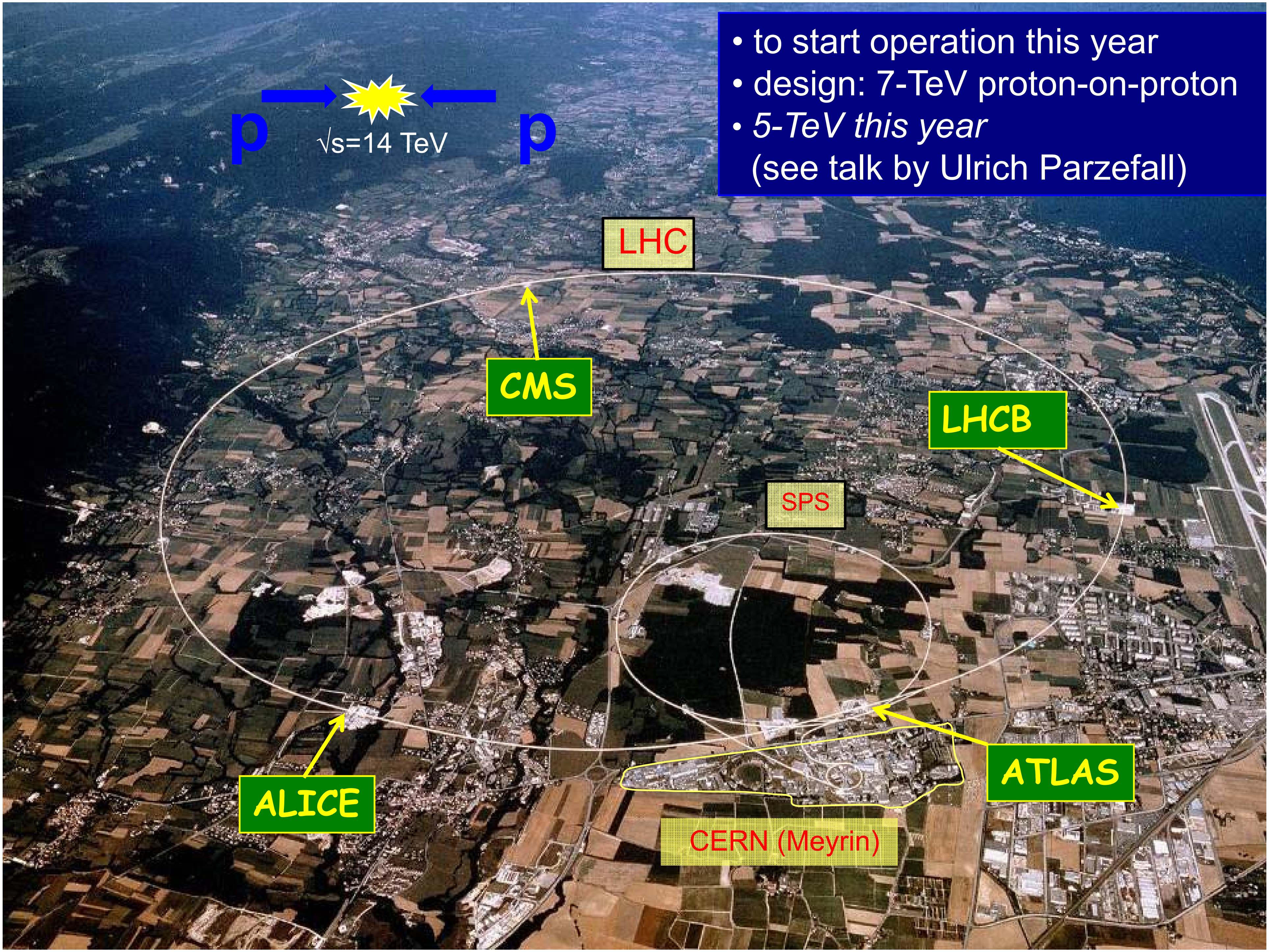
mSUGRA and dark matter

- mSUGRA
  - — SUSY masses unify at GUT-scale m_0, $m_{1/2}$
  - — $\tan\beta$, A_0, sign(μ)
  - — Neutralino LSP
- Four regions with $\Omega_{NEUTRALINO} \approx \Omega_{DM}$ due to enhanced annihilation in early universe





Pseudo-projection – no units!

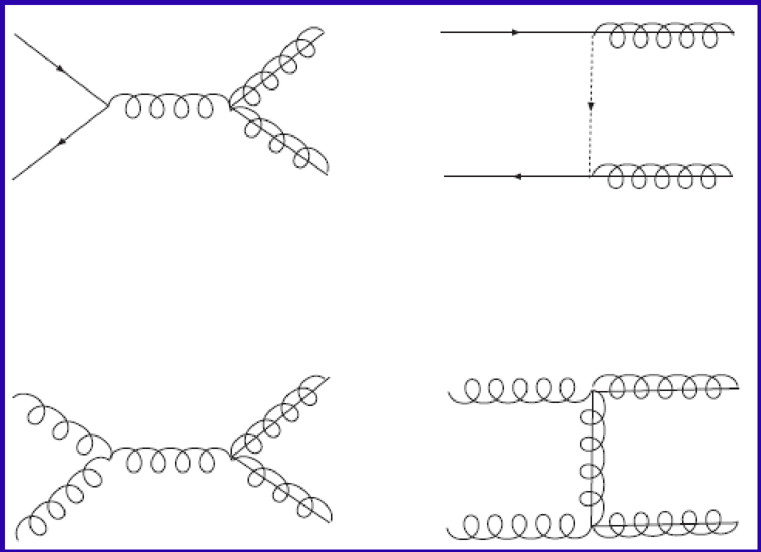


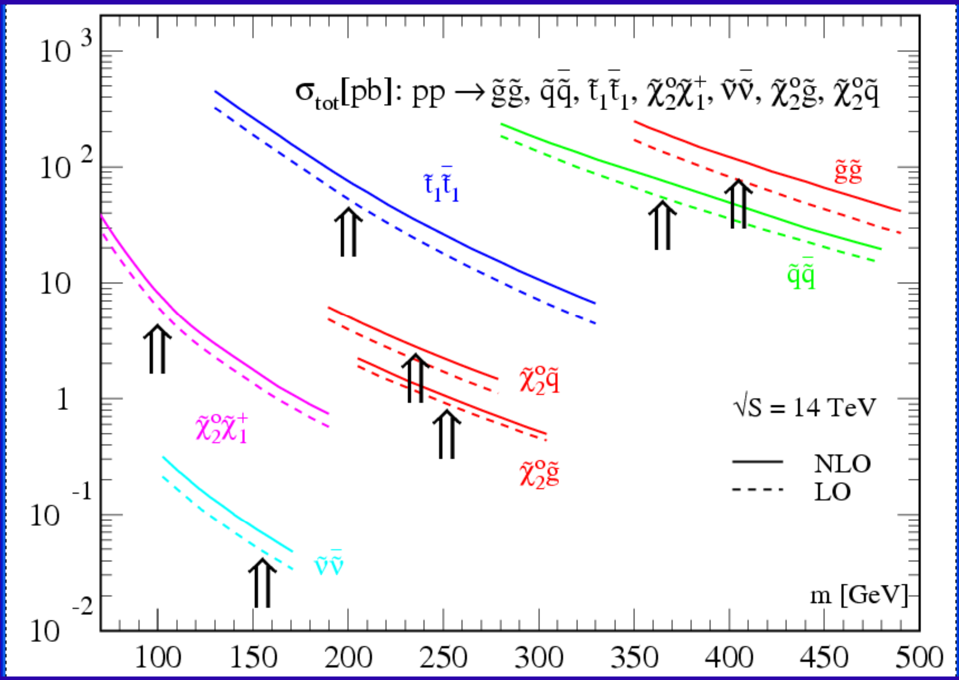
• to start operation this year
• design: 7-TeV proton-on-proton
• *5-TeV this year*
(see talk by Ulrich Parzefall)
p
√s=14 TeV
p
LHC
CMS
LHCB
SPS
ALICE
ATLAS
CERN (Meyrin)

Will the LHC be a SUSY Factory?

- If SUSY exists at the TeV scale, expect copious production of squarks and gluinos
- Just QCD, nearly independent of SUSY model

- σ (pp→SUSY) calculated at NLO
- √s=14TeV, m_{SUSY} ~ 0.5-1.0 TeV → $\sigma_{pp\rightarrow SUSY}$ ~ 1-100 pb

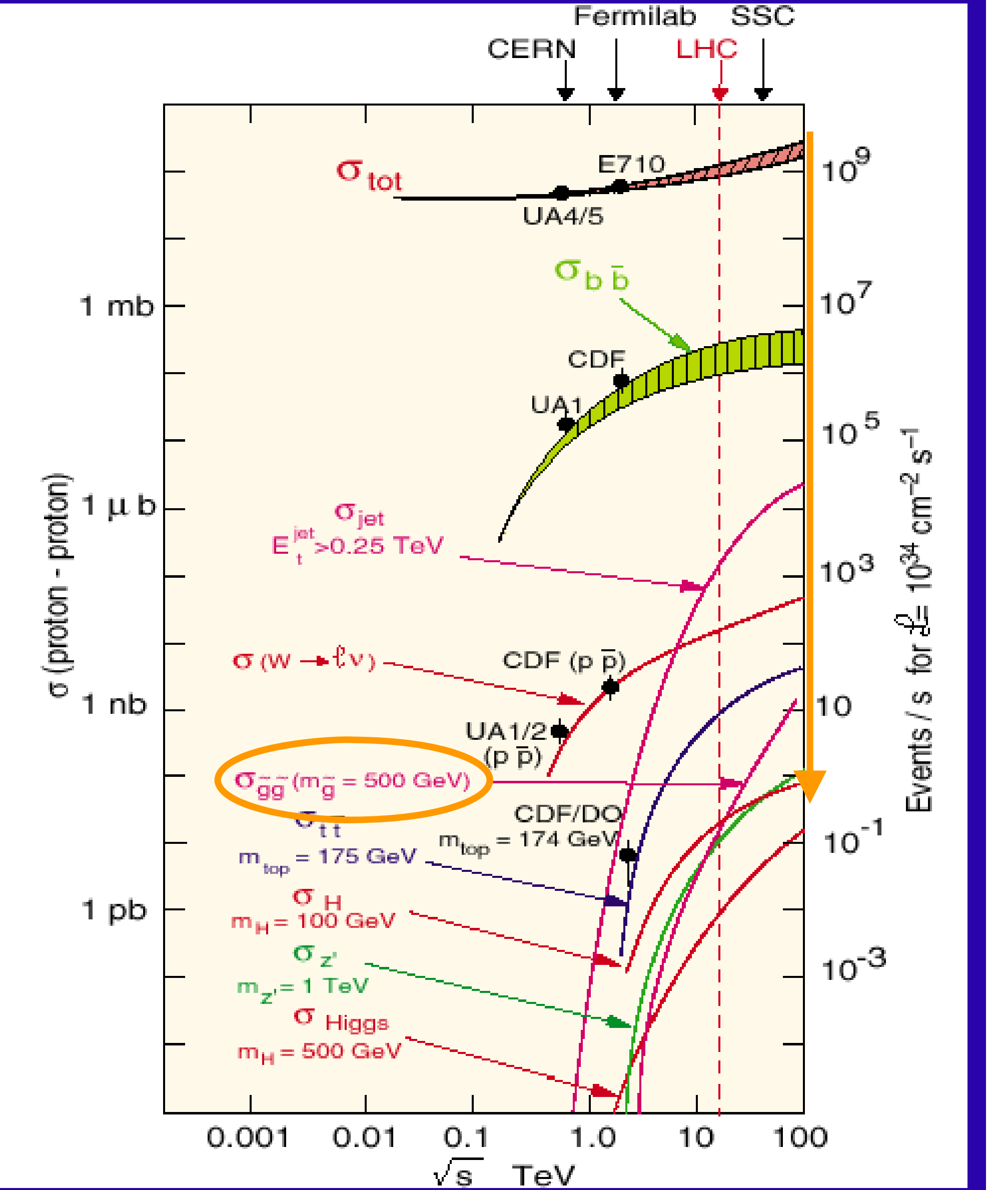




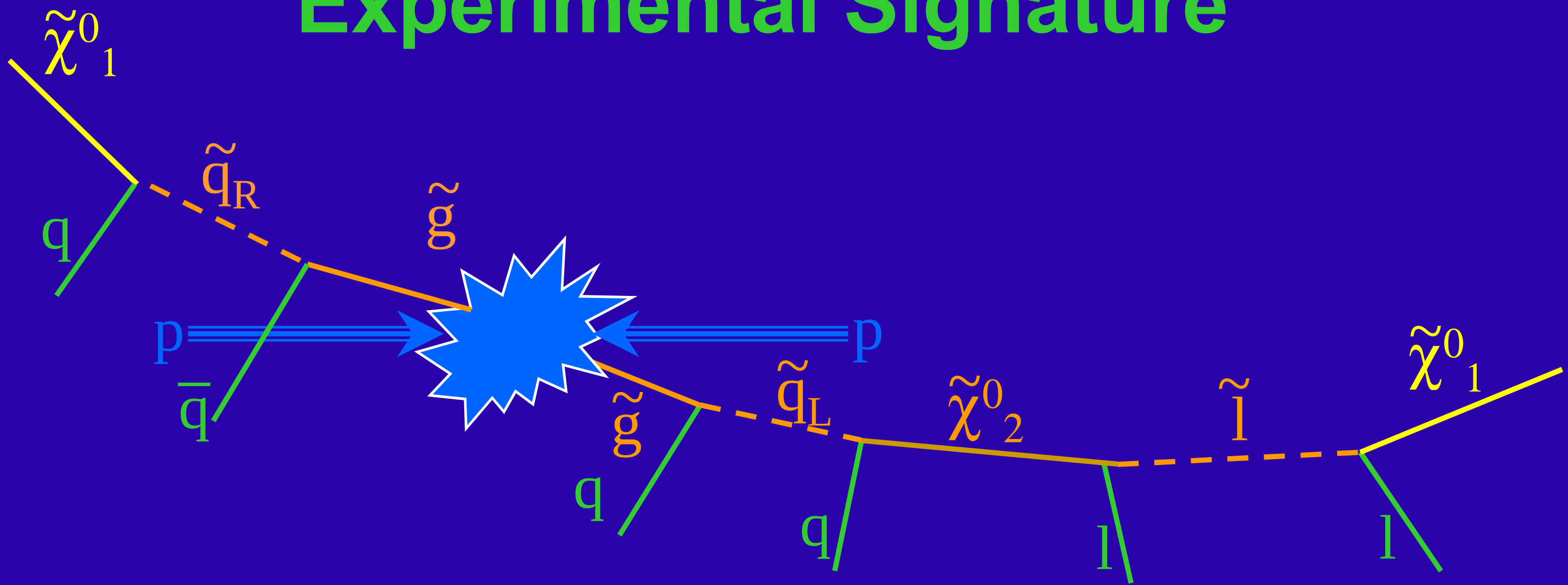
References: Beenakker, Höpker, Spira, Zerwas, 1995, 1997; Beenakker, MK, Plehn, Spira, Zerwas, 1998; Baer, Hall, Reno, 1998; Beenakker, Klasen, MK, Plehn, Spira, Zerwas, 1999; Beenakker, MK, Plehn, Spira, Zerwas, 2000; Berger, Klasen, Tait, 1999-2002; Beenakker, MK, Plehn, Spira, Zerwas, 2006

Tevatron → LHC

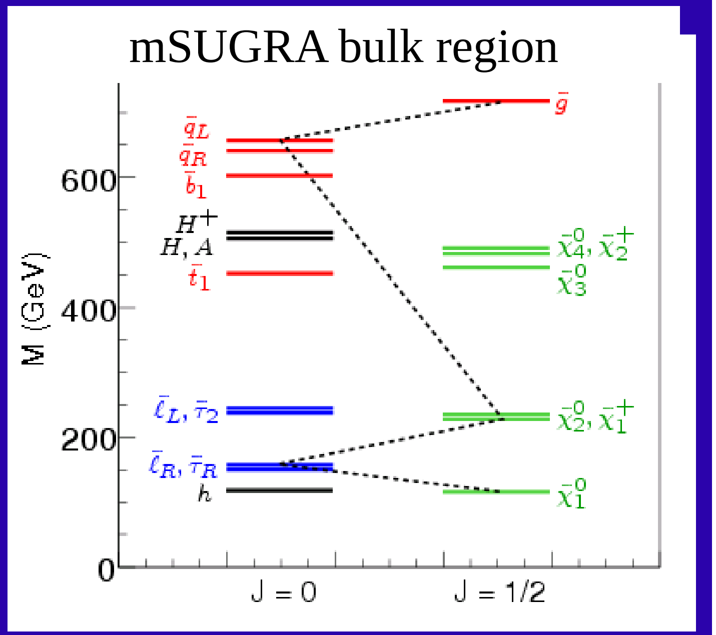
- Win twice when moving to LHC
  - σ_{SUSY} increases 20000(!) for m_{gluino}=400 GeV
  - S/B improves
- SUSY-discovery challenge
  - — reject SM by factor of ~10^{11}
  - — understand SM events that survive SUSY selection



Experimental Signature

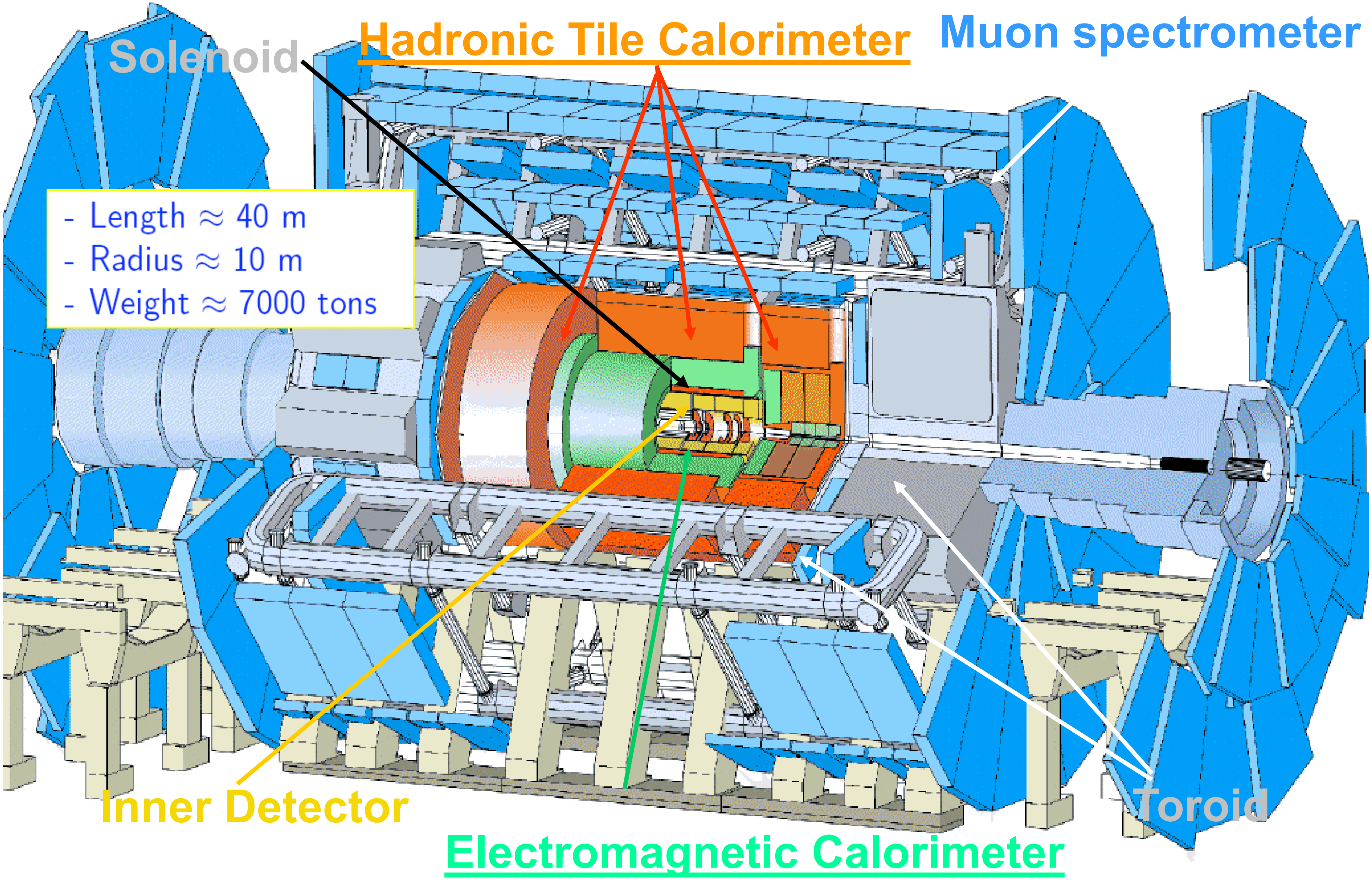


- Two sparticles initially
- Cascade decays down to LSP: *jets, leptons*
- LSP escapes undetected: *large E_T^{miss}*



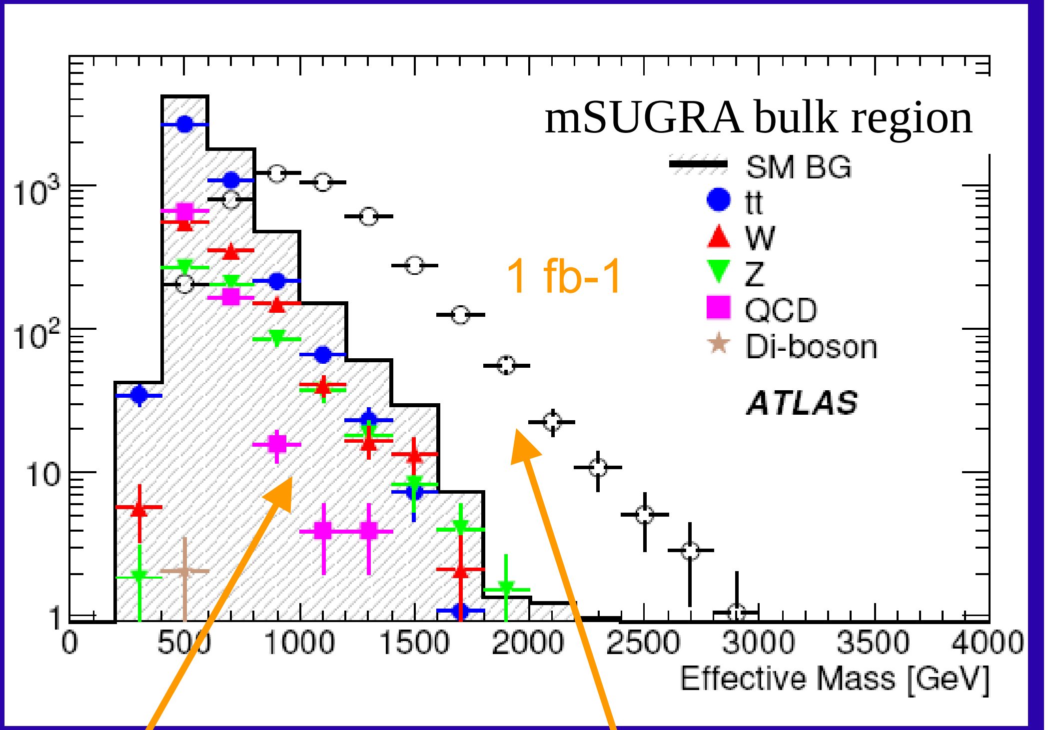
→ Canonical SUSY signature:
E_T^{miss}, high-p_T jets, often leptons

A Toroidal LHC Apparatus (ATLAS)



Generic SUSY signature: Missing E_T + jets

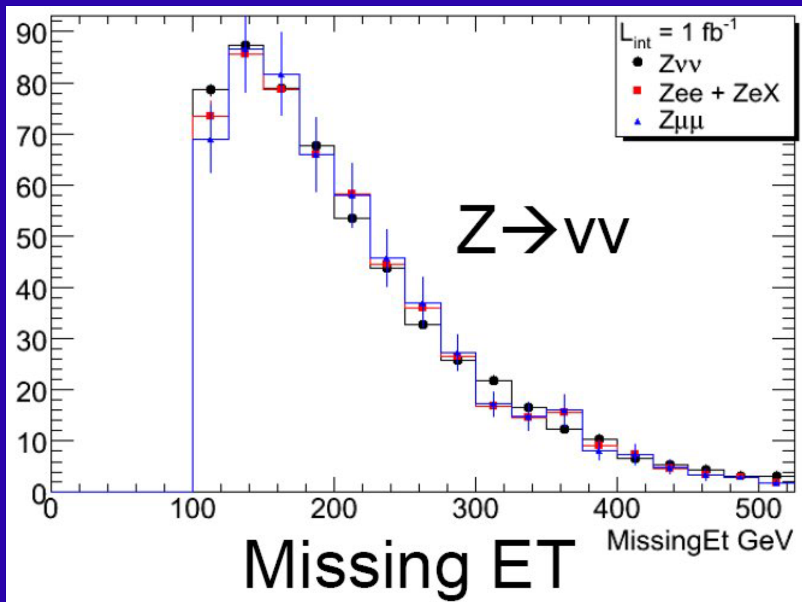
- Event selection
  - — Jets 1,2 with p_T>100 GeV
  - — Jets 3,4 with p_T> 50 GeV
  - — E_T^{MISS} > 100 GeV
  - — E_T^{MISS} > 0.2 Meff
  - — Transverse Sphericity > 0.2
  - — veto isolated leptons
- Plot Effective Mass variable
  - — $M_{eff} = \Sigma|p_T^i| + E_T^{miss}$



Events with several hard, (often miss-measured) QCD jets: Monte Carlo predictions have large systematic uncertainties

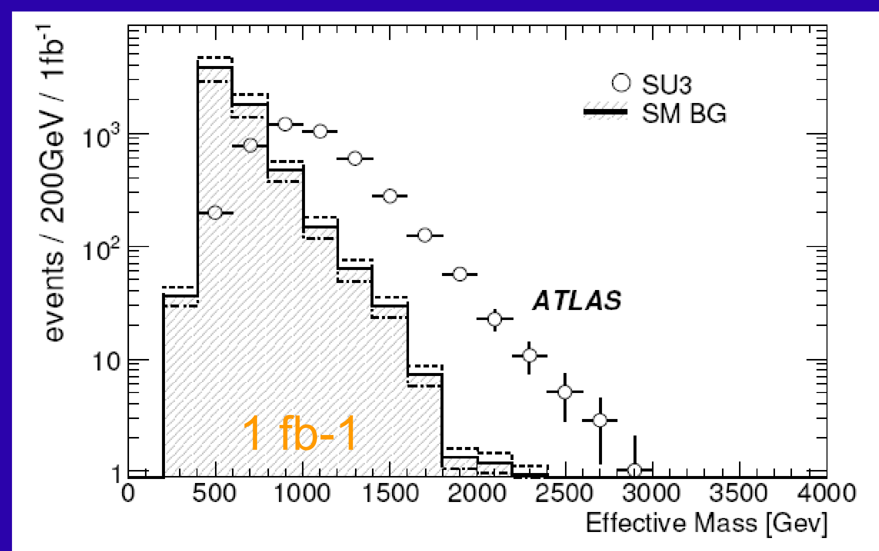
Excess at large $M_{effective}$ potential discovery of SUSY

Measuring SUSY Backgrounds



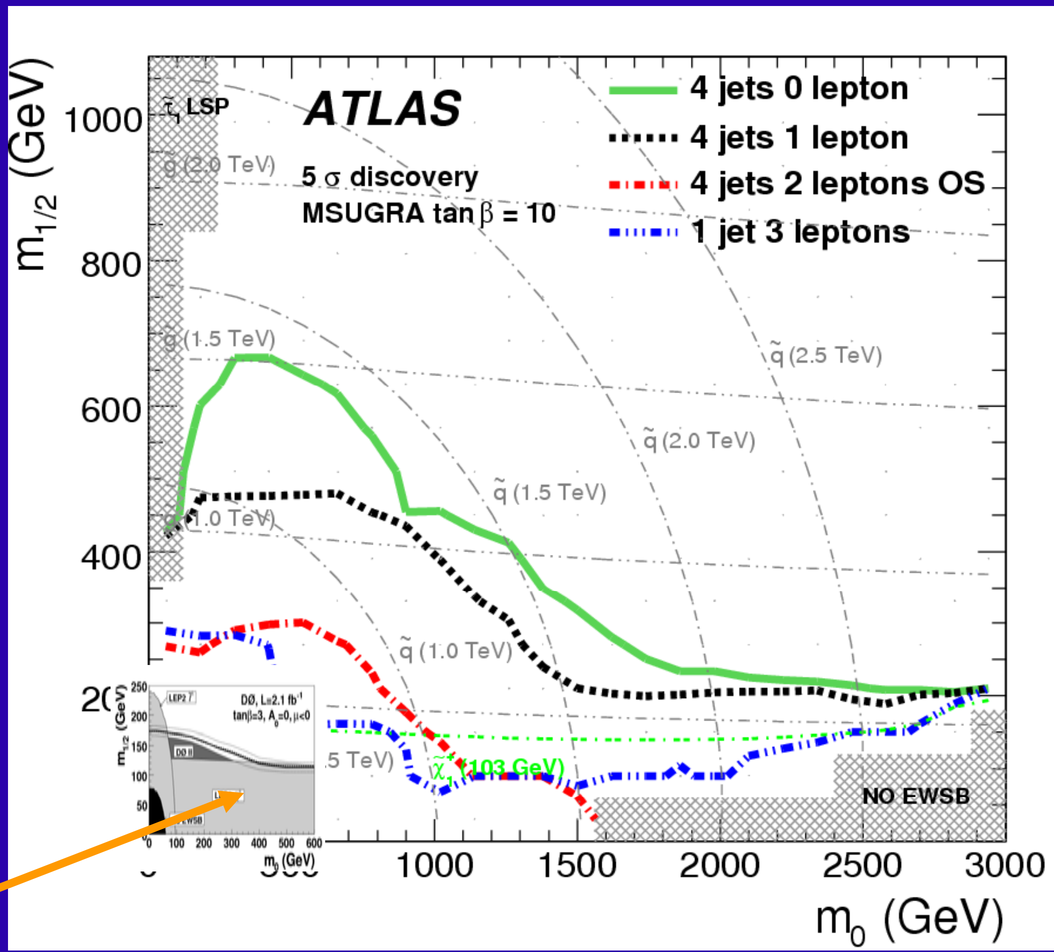
13%(stat.) @1fb^{-1}
8%(sys.)
15%(total)

- Estimate Standard Model background passing SUSY selection using data-driven techniques
- Example: Select Z→ll and replace charged leptons by neutrinos
- Obtain shape of E_T^{MISS}, $M_{effective}$



L ~ 1 fb^{-1}: SUSY Discovery Potential

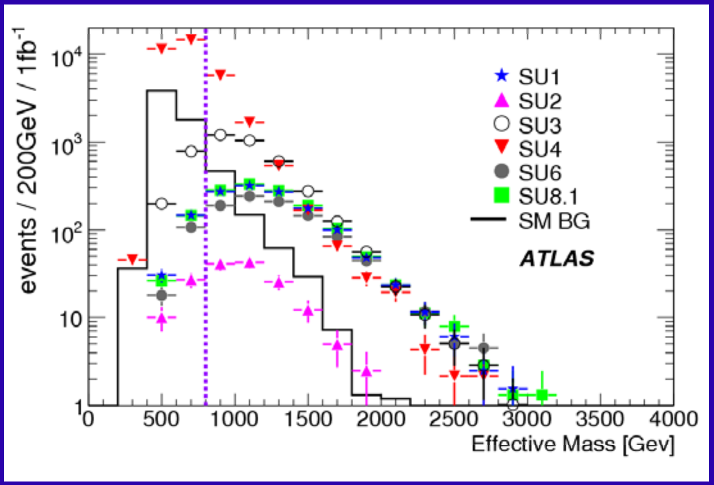
- Full simulation of backgrounds
- Includes expected systematic (JES, background estimation)
- Good chance of finding TeV scale SUSY with $1fb^{-1}$ of data
  - — Dream scenario!
- SUSY at higher mass scales could still show up later, but would make detailed studies difficult

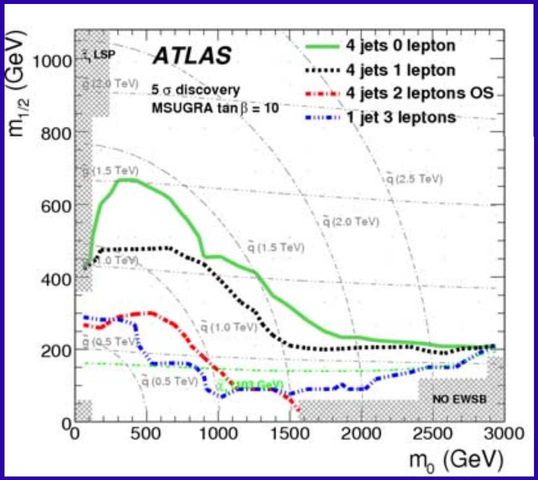


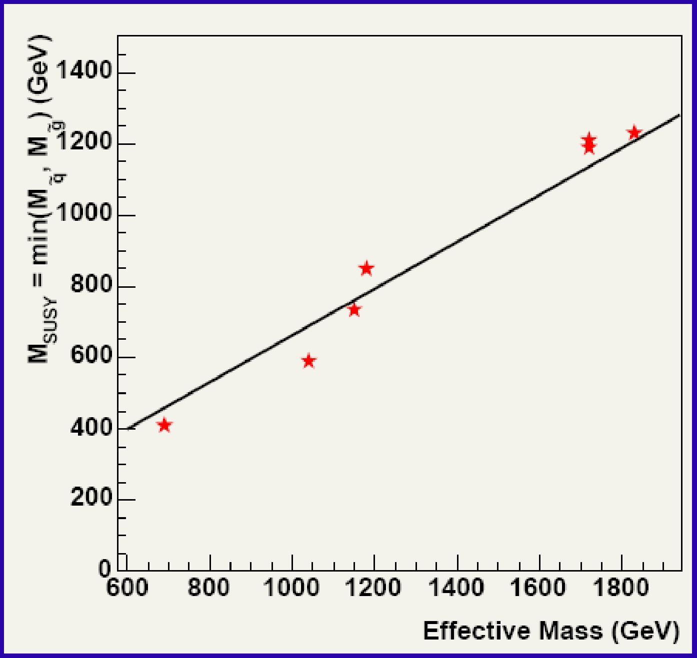
Tevatron Exclusion!

L > 1 fb^{-1}: What exactly did we discover?

- Inclusive studies provide first hints of where in SUSY parameters
  - — $M_{effective} \rightarrow$ Mass scale
  - — Relative Significance in 0,1,2 lepton channels $\rightarrow m_0, m_{1/2}$
  - — 3^{rd} generation $\rightarrow \tan\beta$
- Is it really SUSY? → want spin, hard at LHC. See talk by Martin White this afternoon.

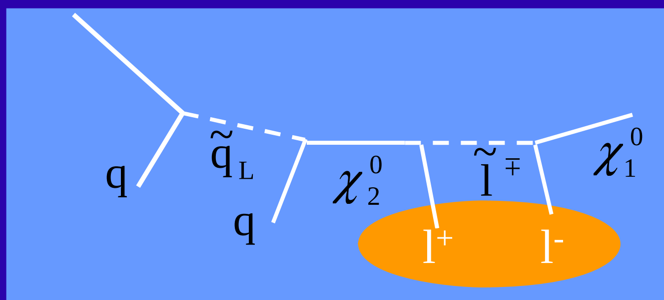


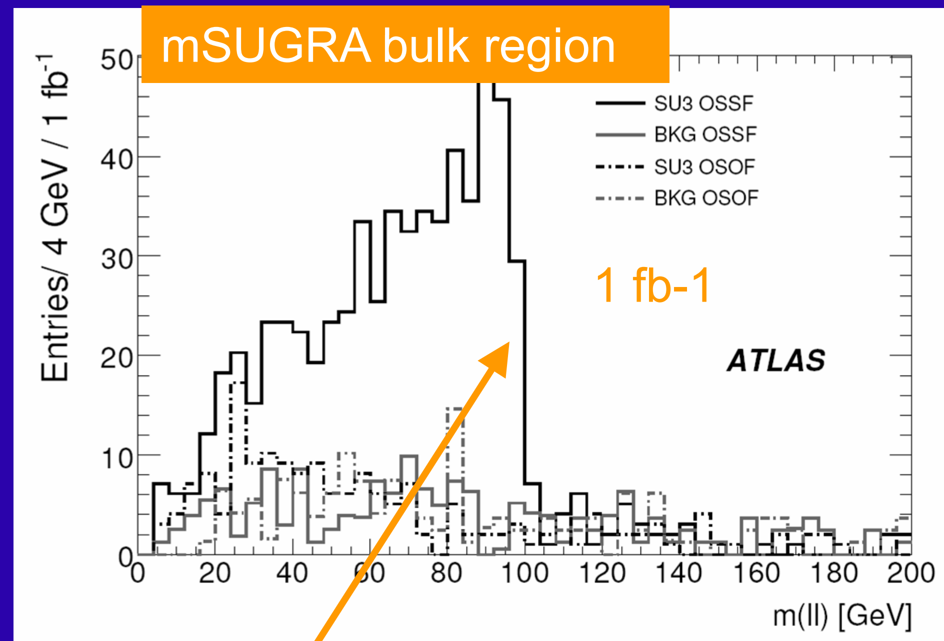




Mass reconstruction

- Most promising: *Opposite sign, same flavor* di-leptons from single neutralino decay





- Subtract background (from Standard Model *and SUSY itself*) using flavor information
  - $e^+e^- + \mu^+\mu^- - e^+\mu^- - e^-\mu^+$ (after efficiency correction)
- Low background, relatively high statistics

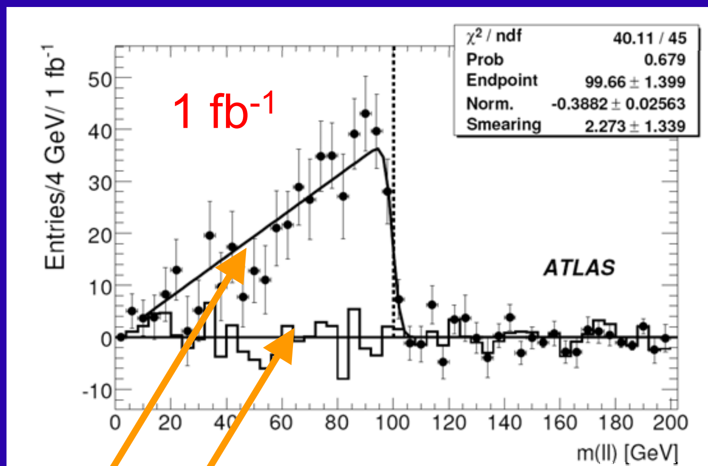
- Position of mass-edge sensitive to combination of sparticle masses

$$m_{\ell\ell}^{\mathrm{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

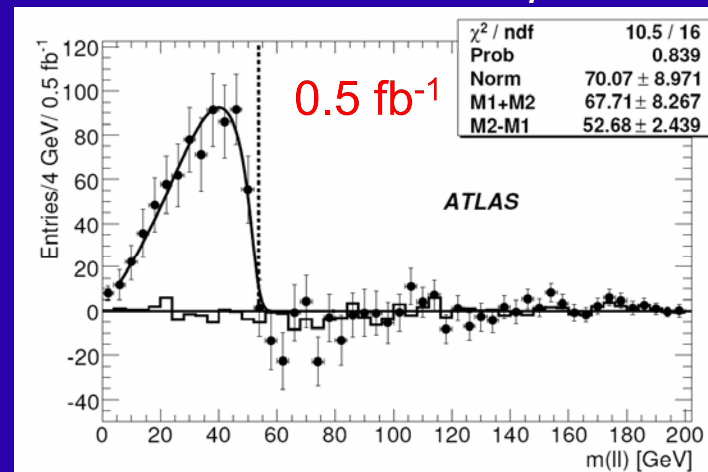
Fitting for edges after flavor subtraction

- Method sensitive to any sleptons lighter than 2nd neutralino

$m_{\tilde{\chi}_2^0} > m_{\tilde{l}^{+/-}}$ *Bulk region*



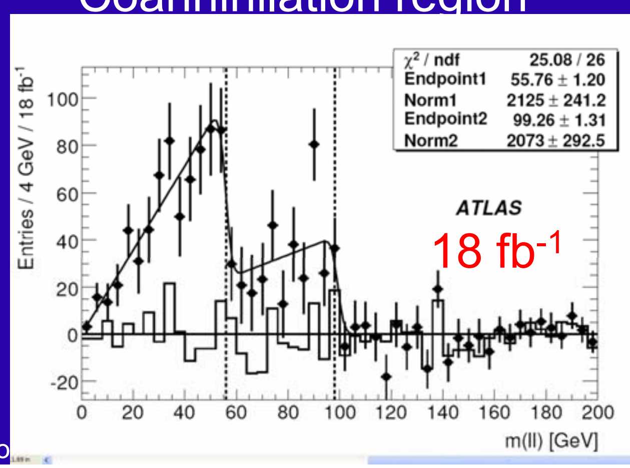
$m_{\tilde{l}^{+/-}} > m_{\tilde{\chi}_2^0}$ *Low mass point*

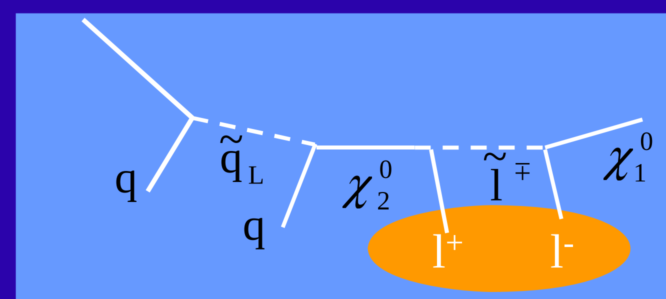


SUSY

Standard Model

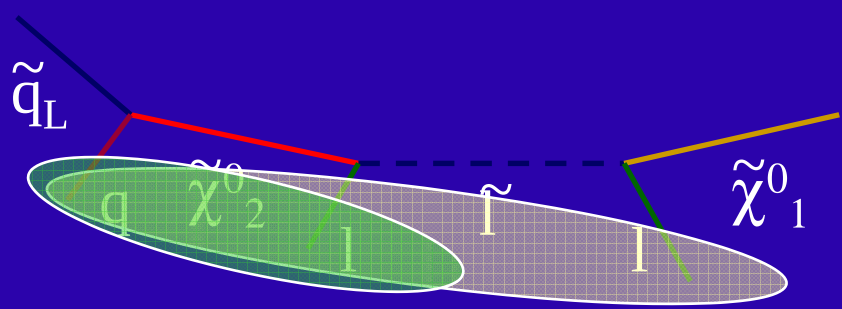
Two light sleptons, Coannihilation region





Just add quarks

- Use same dilepton events, similar mass-edge extraction w/ m_{lq} and m_{llq}
- Use position of all edges to fit for sparticle masses

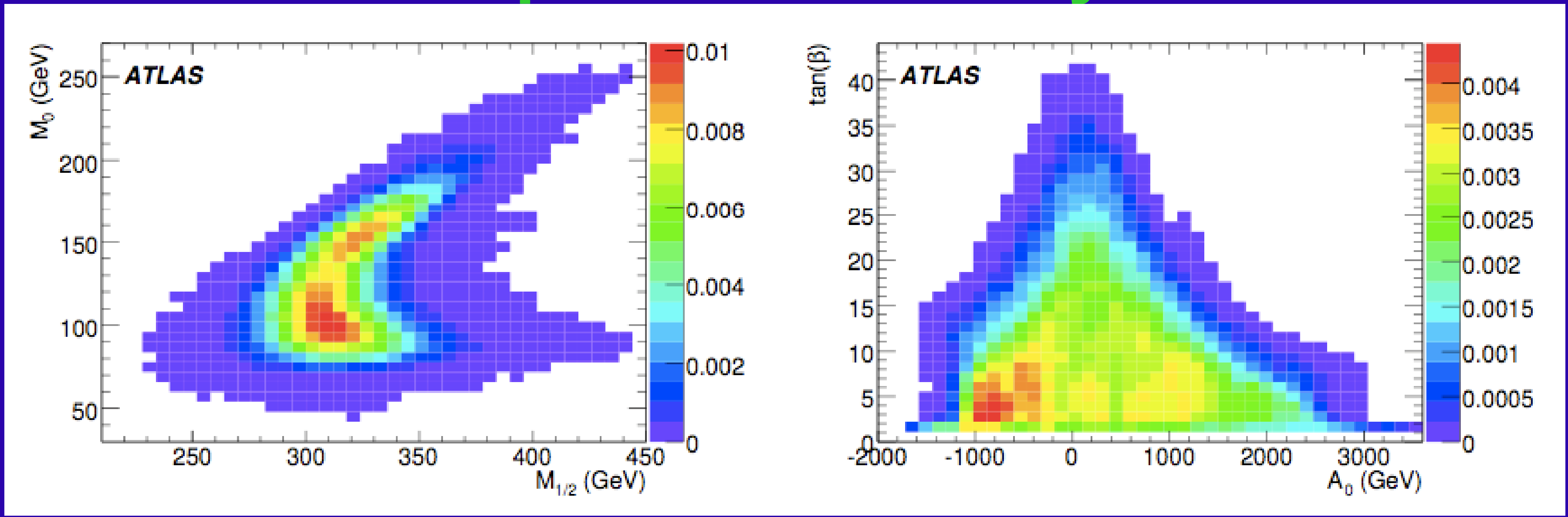


	Measured [GeV/c^2]	Monte Carlo [GeV/c^2]
$m_{\tilde{\chi}_1^0}$	$88 \pm 60 \mp 2$	118
$m_{\tilde{\chi}_2^0}$	$189 \pm 60 \mp 2$	219
$m_{\tilde{q}}$	$614 \pm 91 \pm 11$	634
$m_{\tilde{\ell}}$	$122 \pm 61 \mp 2$	155
Observable	[GeV/c^2]	[GeV/c^2]
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	$100.6 \pm 1.9 \mp 0.0$	100.7
$m_{\tilde{q}} - m_{\tilde{\chi}_1^0}$	$526 \pm 34 \pm 13$	516.0
$m_{\tilde{\ell}} - m_{\tilde{\chi}_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6

mSUGRA bulk region, 1 fb^{-1}

- Fit assumes we know mass hierarchy, e.g. from di-lepton edge shape
- Otherwise model-independent
- Need more data for precise masses
- Quite sensitive to mass differences

Assuming model known - can we extract model parameters early on?



- Input data: kinematic edges
  - Dilepton, (Di)lepton+jet, $\tilde{q}_R \to \tilde{\chi}^0_1 q$
- Scan of mSUGRA parameter space
- Pseudo Experiments + Fit
- *A_0 not well constrained, μ ambiguity*
- *Even in highly constrained model, ambiguous parameter determination with $1fb^{-1}$*

mSUGRA bulk region, 1 fb^{-1}

Parameter	SU3 value	fitted value	exp. unc.	theo. + exp. unc.
		$\text{sign}(\mu) = +1$		
$\tan\beta$	6	7.4	4.6	–
M_0	100 GeV	98.5 GeV	±9.3 GeV	±9.5 GeV
$M_{1/2}$	300 GeV	317.7 GeV	±6.9 GeV	±7.8 GeV
A_0	−300 GeV	445 GeV	±408 GeV	–
		$\text{sign}(\mu) = -1$		
$\tan\beta$		13.9	±2.8	–
M_0		104 GeV	±18 GeV	–
$M_{1/2}$		309.6 GeV	±5.9 GeV	–
A_0		489 GeV	±189 GeV	–

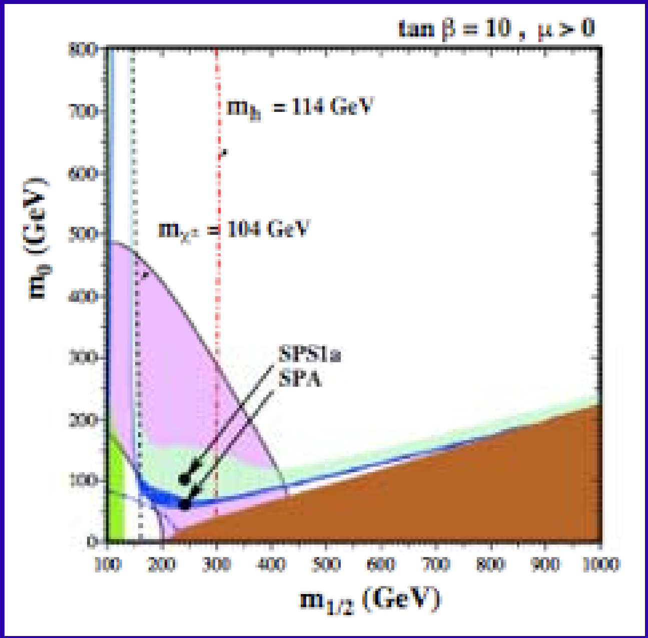
Ultimate LHC precision (300 fb^{-1})

- *SPS1a Snowmass Point (mSUGRA bulk)*
- older work using fast simulation
- *kinematic endpoints using leptons, Taus, jets, b-jets*

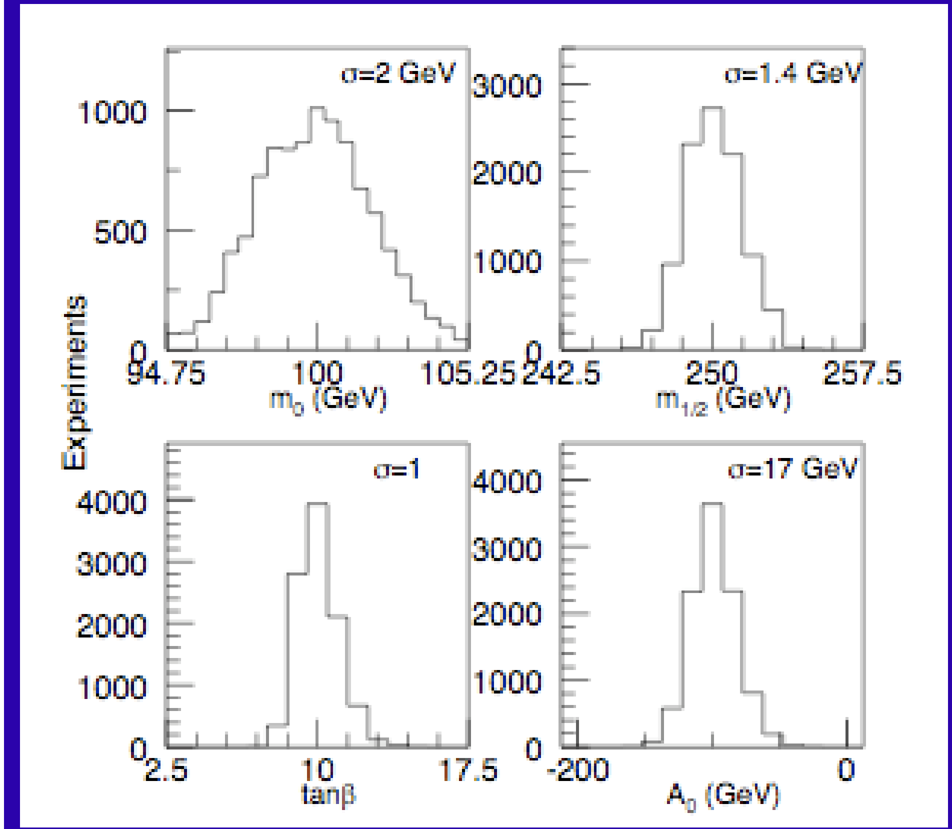
Polesello, Tovey *JHEP* 0405 (2004) 071

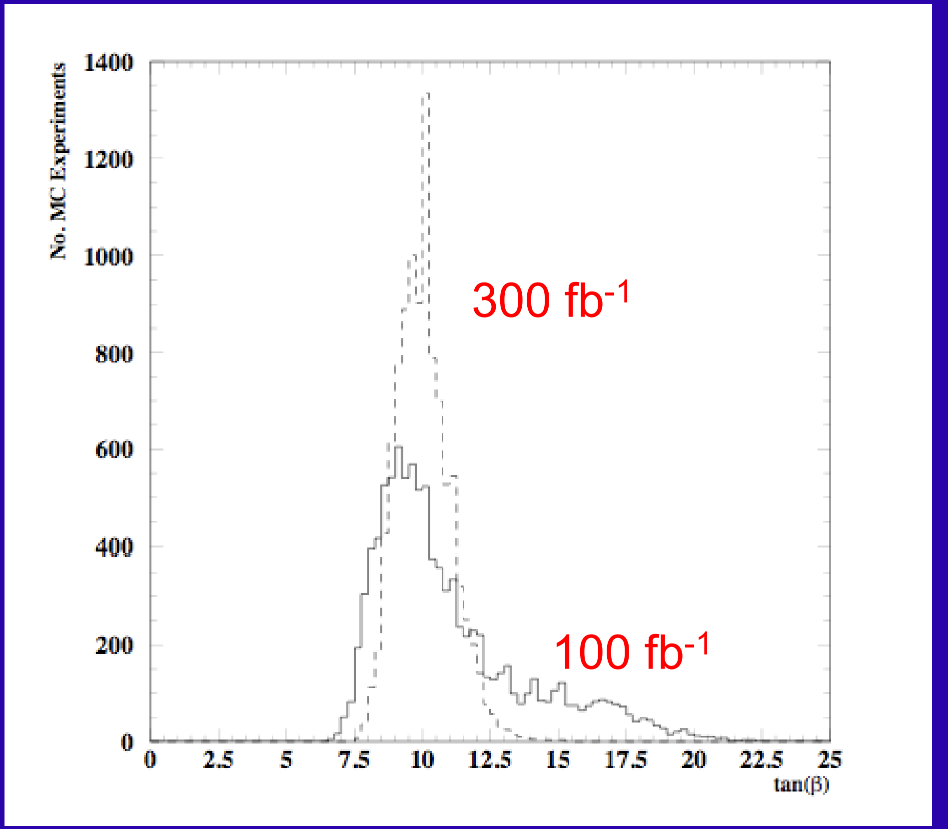
Variable	Value (GeV)	Errors Stat+Sys (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	83.37	0.03	0.08	0.09
$m_{\ell\ell q}^{max}$	457.55	1.4	4.6	4.8
$m_{\ell q}^{low}$	321.28	0.9	3.2	3.3
$m_{\ell q}^{high}$	400.63	1.0	4.0	4.1
$m_{\ell\ell q}^{min}$	220.81	1.6	2.2	2.7
$m_{\ell\ell b}^{min}$	199.48	3.6	2.0	4.2
$m(\ell_L) - m(\tilde{\chi}_1^0)$	109.18	1.5	0.1	1.5
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	279.07	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	86.03	5.0	0.9	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	517.22	2.3	5.2	5.7
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	452.62	10.0	4.5	11.0
$m(\tilde{g}) - m(\tilde{b}_1)$	96.98	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	72.75	2.5	0.7	2.6

300 fb^{-1}



Ultimate LHC precision (300 fb^{-1})

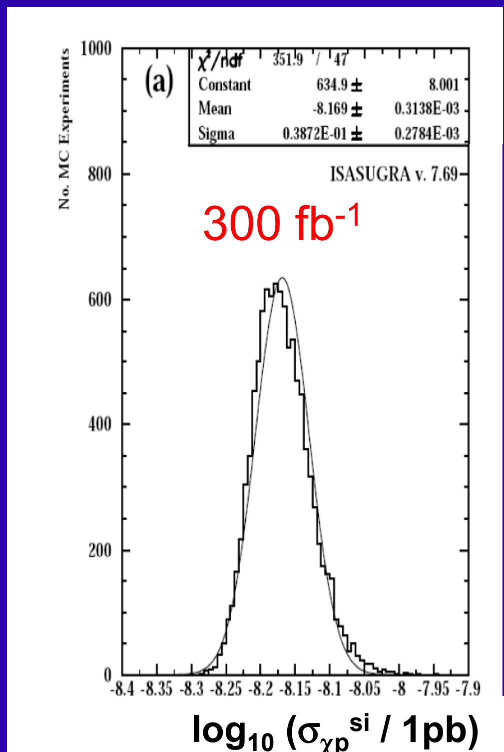




- *mSUGRA parameters well constrained at 300 fb^{-1} → calculate m_χ, σ_χ, Ω_χ*

Comparing with Direct Detection

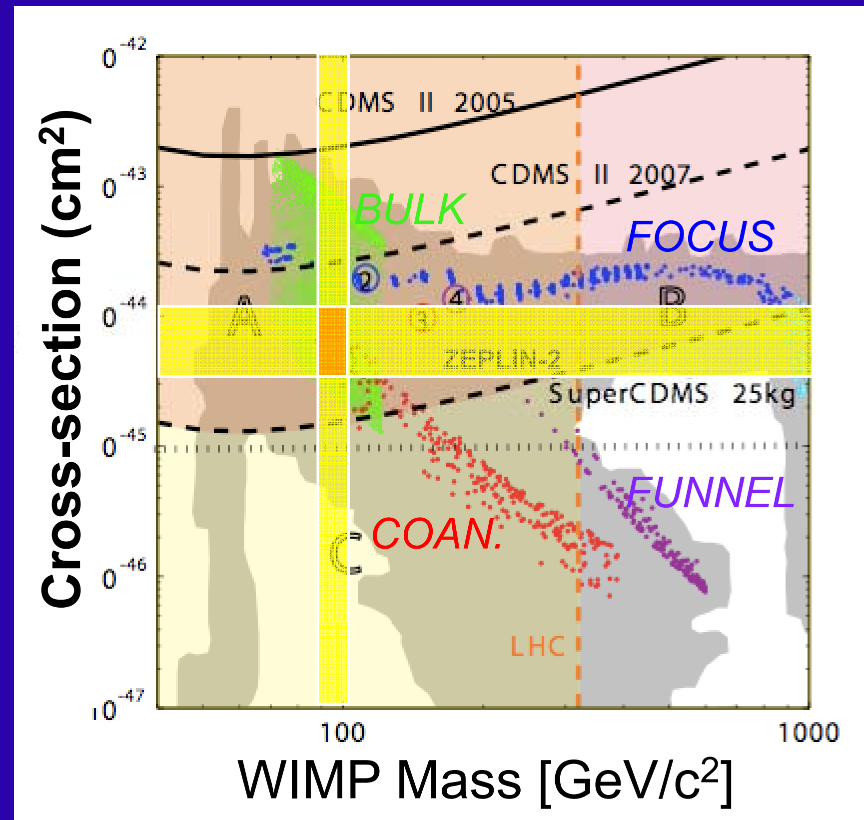
- Calculate neutralino mass m_χ and cross section $\sigma_{\chi\text{-nucleon}}$
- Compare with direct detection



NOW

2009?

2012?



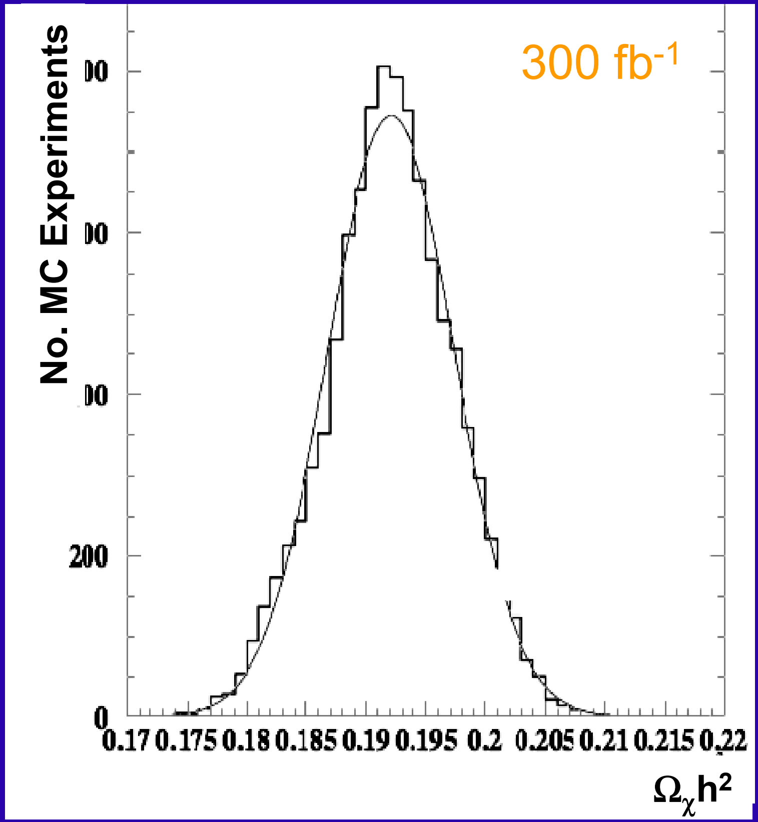
$$m_{\tilde{\chi}_1^0} = 96.05 \pm 4.7 \text{ GeV} \quad \textcolor{red}{300 \text{ fb}^{-1}}$$

$$\log_{10}(\sigma_{\chi p}/1\text{pb}) = -8.17 \pm 0.039$$

Same WIMP in lab and space?

Comparing with Observational Cosmology

- Calculate neutralino relic density
- Precision comparable to that from cosmology: $\Omega_\chi = \Omega_{DM}$?



- $\Omega_\chi h^2 = 0.192 \pm 0.005$ (stat) ± 0.006 (sys)
- What fraction of the dark matter is neutralinos?

(simulated point is *pre-WMAP)*

Caveat: this precision depends on assuming very constrained SUSY breaking scenario. In more general scenario: much looser constraints.

Model Independent Approach I

- In calculations of m_χ, σ_χ , Ω_χ
  — mSUGRA unification assumption constrains
- MSSM analysis not assuming specific SUSY breaking scenario needs more measurements
- e.g. to calculate Ω_χ need
  — LSP mass
  — LSP mixing matrix
  — to establish which processes are relevant to LSP annihilation…
  — …and measure them

Nojiri, Polesello,Tovey *JHEP* 0603:063 (2006)

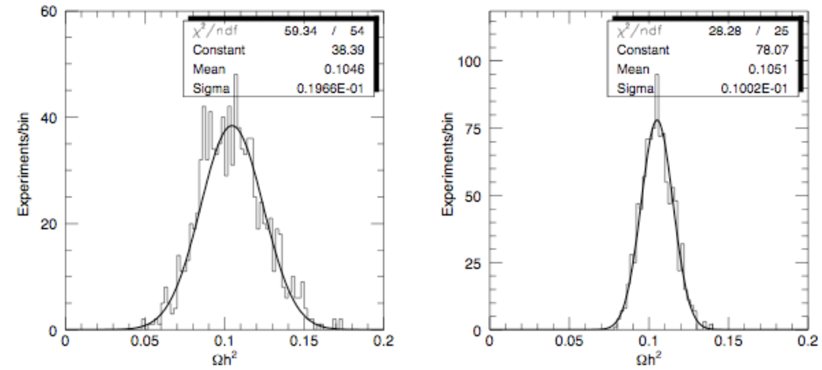


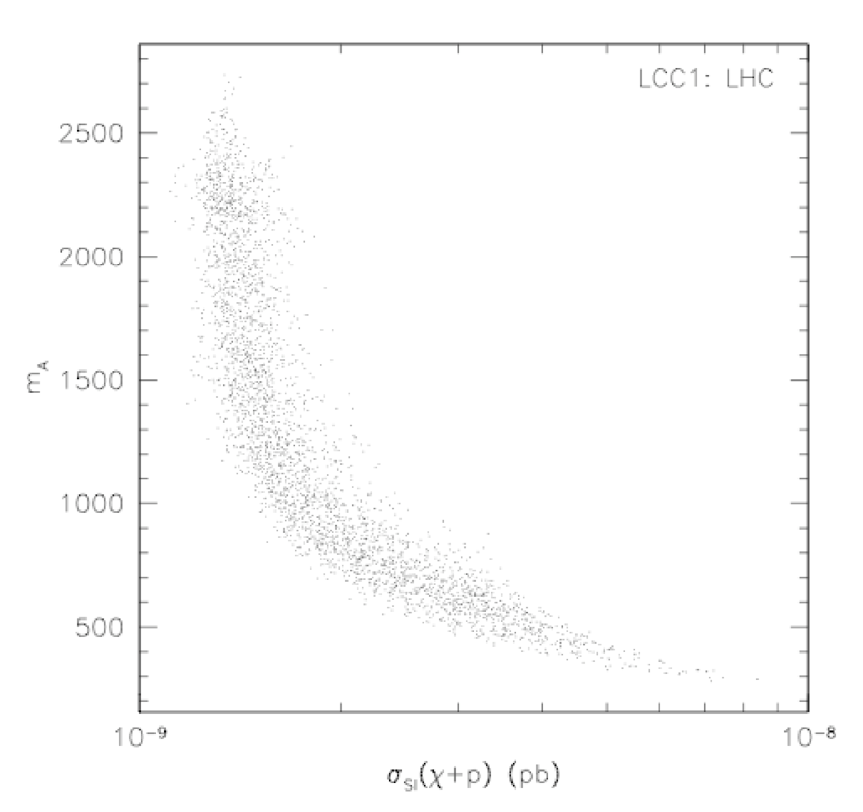
Figure 7: *Distributions of the predicted relic density $\Omega_\chi h^2$ incorporating the experimental errors. The distributions are shown for an assumed error on the $\tau\tau$ edge respectively of 5 GeV (left) and 0.5 GeV (right).*

300 fb^{-1}

- *SPA mSUGRA bulk region point, analyzed as MSSM*
- Less restrictive on Ω_χ: precision ~ 10-20% at 300 fb^{-1}

Model Independent Approach II

- Several mSUGRA points also analyzed as MSSM to evaluate LHC + ILC prospects by Baltz et al.
- Bulk region, 300 fb^{-1}:
  - Ω_χ precision in agreement with Polesello et al.
  - $\sigma_{\chi\text{-nucleon}}$ not well constrained, as it depends on heavy Higgs mass (not observable at LHC in this model)



Baltz, Battaglia, Peskin, Wizansky
PRD 74:103521 (2006)

Less favorable scenarios

- mSUGRA bulk region points discussed are LHC friendly scenarios
- Caveat1: Situation may be less ideal, even with low SUSY mass scale
  - High tanβ →Tau's dominate
  - Small mass-gaps → very soft leptons
  - If slepton too heavy, depend on other $\tilde{\chi}^0_2$ decays

$$
\begin{aligned}
\tilde{\chi}^0_2 &\rightarrow \tilde{l}l, \\
\tilde{\chi}^0_2 &\rightarrow \tilde{\nu}\nu, \\
\tilde{\chi}^0_2 &\rightarrow h^0\tilde{\chi}^0_1, \\
\tilde{\chi}^0_2 &\rightarrow Z^0\tilde{\chi}^0_1, \\
\tilde{\chi}^0_2 &\rightarrow l^+l^-\tilde{\chi}^0_1
\end{aligned}
$$

- Caveat2: Part of SUSY particle spectrum could be heavy
- Several scenarios considered in Baltz, Battaglia, Peskin, Wizansky PRD74:103521 (2006)
- Progress will depend on SUSY scenario Nature has chosen

Conclusion

- If SUSY at TeV-scale, LHC discovery possible with ~1fb-1
  - In this case, rates at LHC would be high, allowing detailed studies in large number of final states
- To calculate m_χ, σ_χ , Ω_χ, need to understand much of SUSY phenomenology
  - Model assumptions can reduce needed measurements
- Degree of progress at LHC will depend on Nature's benevolence in breaking SUSY
- Favorable scenarios suggest precise calculations of m_χ, σ_χ, Ω_χ possible with ~300fb^{-1} of data
- When combined with Astroparticle & Cosmology measurements, this would reveal the relation of the SUSY LSP to the dark matter