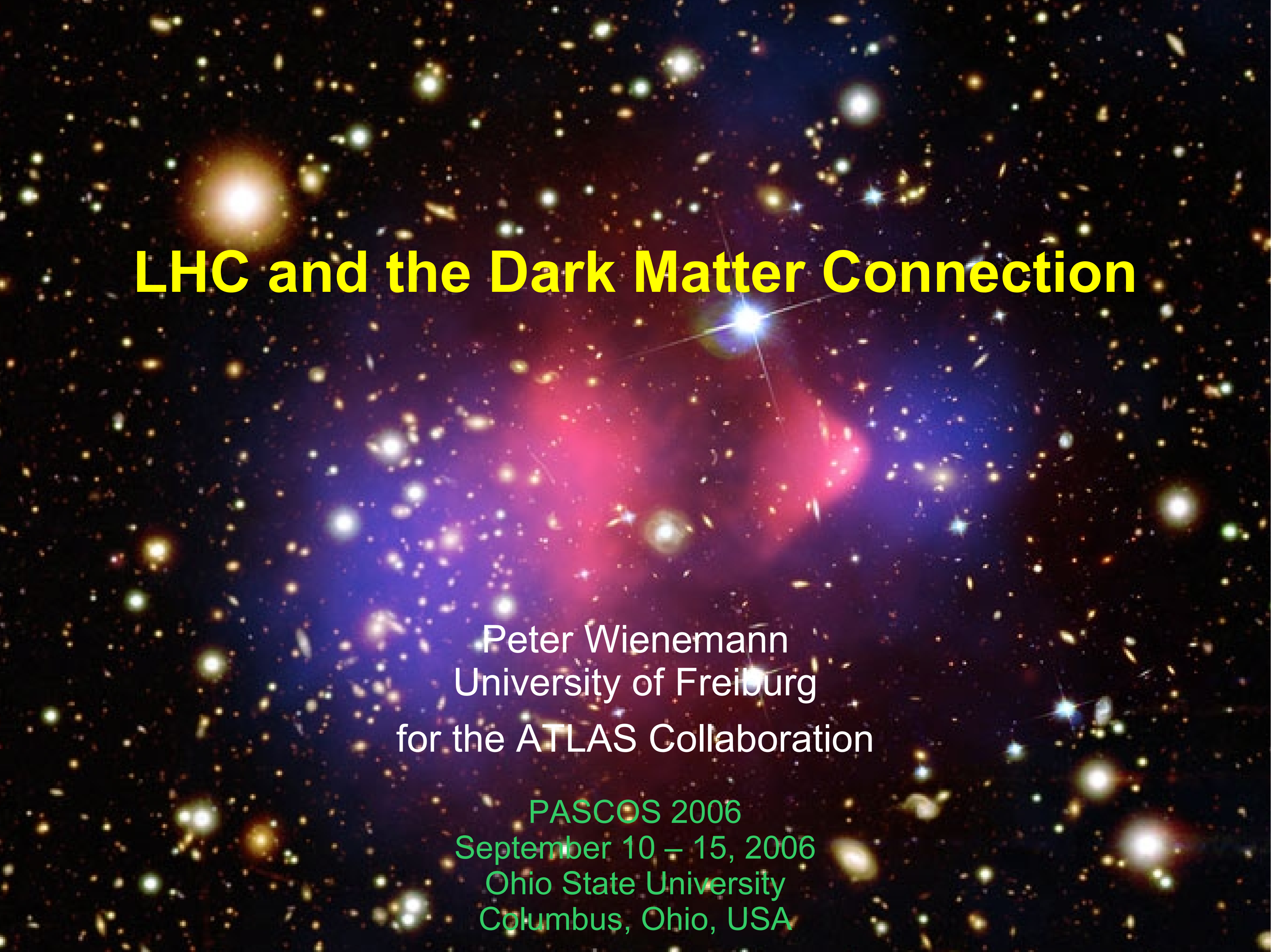


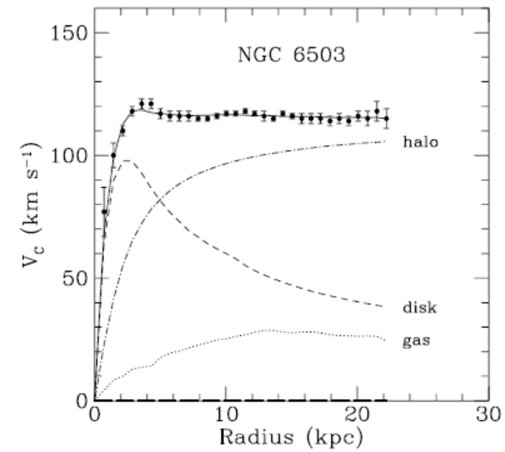
LHC and the Dark Matter Connection

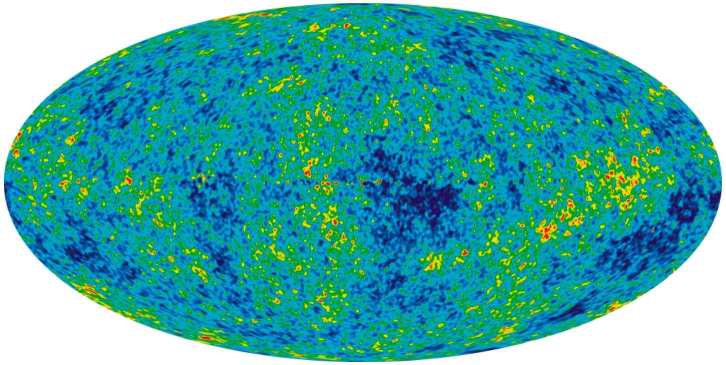
Peter Wienemann
University of Freiburg
for the ATLAS Collaboration

PASCOS 2006
September 10 – 15, 2006
Ohio State University
Columbus, Ohio, USA

Brief History of Dark Matter

- Jan Oort introduced idea of dark matter (DM) to explain galactic rotation curves (1932)
- Further evidence from gravitational lensing, structure formation ("cold" DM) and primordial nucleosynthesis
- From anisotropy of cosmic microwave background (COBE (1992), WMAP (2003)): (22 ± 4) % of energy density of the universe from DM
- First observation of DM spatially segregated from visible baryonic matter (2006)
- Direct detection still pending





DM during Evolution of Universe

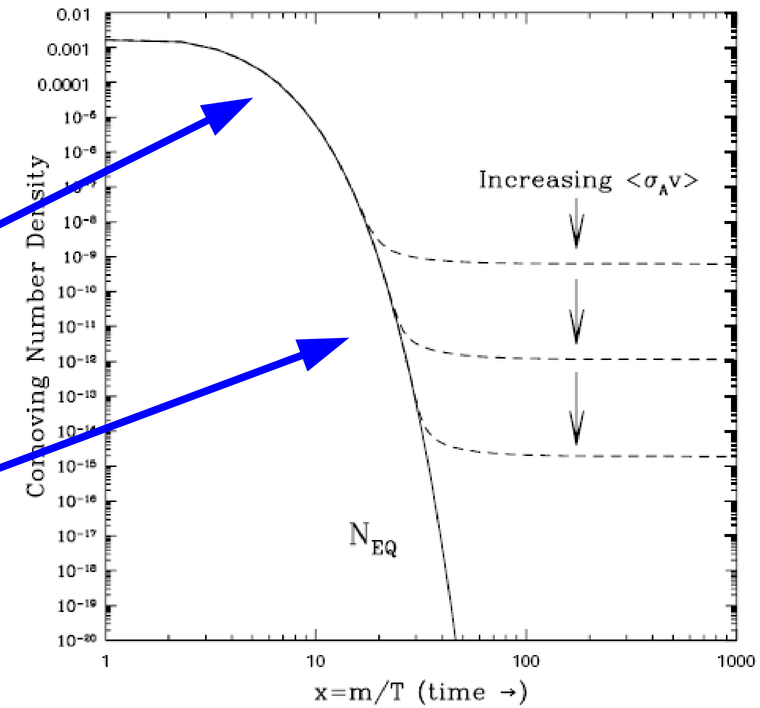
Early universe hot ($T \gg m_\chi$, χ = DM particle) and dense:

$\chi\bar{\chi} \rightleftharpoons f\bar{f}$ in thermal equilibrium

Universe expands and cools down:

When $T < m_\chi$: annihilation prevails,
χ number density $n_\chi \propto \exp(-m_\chi/T)$

When density becomes too low:
annihilations stops due to too small collision rate, freeze out $\longrightarrow$ relic density



Dark matter relic density: $\Omega_\chi = m_\chi n_\chi / \rho_{\rm crit} \propto 1/\langle\sigma_A v\rangle$

depends on annihilation cross-section

WMAP+SDSS result: $\Omega_\chi h^2 = 0.111^{+0.006}_{-0.011}$

(astro-ph/0603449)

DM and Particle Physics

- Standard Model (SM) of particle physics provides no candidate for (the majority of) DM
- DM is hint for physics beyond the SM
- Plethora of DM candidates in extensions of the SM:
  Neutralino, Gravitino, Axion, Axino, lightest Kaluza-Klein excitation, T-odd little Higgs, Branons, Q-balls, sterile neutrinos, etc. etc. ...
- Clarifying nature of DM requires interplay between astrophysics and particle physics

What the LHC can contribute:

1. Find electrically neutral, weakly interacting massive particle (WIMP), stable on cosmological time scales
   (large $\not{E}_T$ events in inclusive studies)

   Note: LHC experiments are only sensitive to lifetimes < 1 ms
   $\Rightarrow$ Confirmation from direct detection experiments needed

2. Test and narrow down theoretical frameworks providing WIMP candidate(s)

3. Measure parameters of corresponding theory (from exclusive measurements)

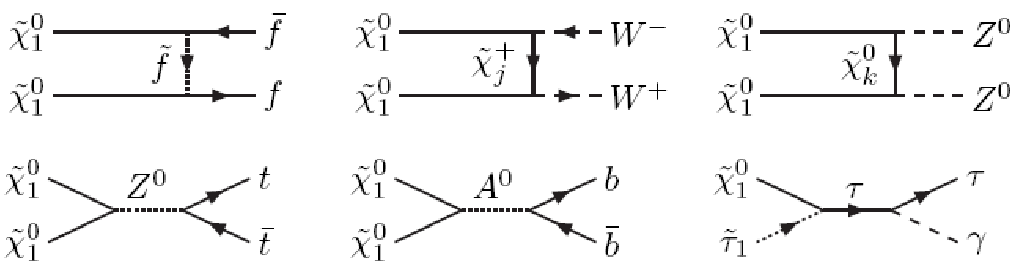
4. If possible, constrain relic density within that model and compare with astrophysical measurements,
   compare WIMP properties (mass, $\sigma_{\chi\mathrm{N}}$) with measurements from direct detection experiments (assuming positive outcome)

From LHC Data to Relic Density

Simplification: Only consider SUSY scenarios with lightest neutralino as DM candidate in this talk

Need cross-sections for all relevant neutralino (co-)annihilation processes

Examples:



relative importance depends on model point

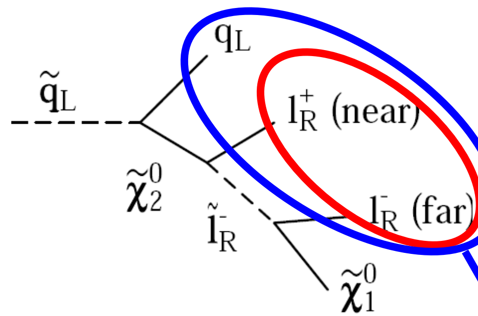
Depend on masses and couplings of involved sparticles

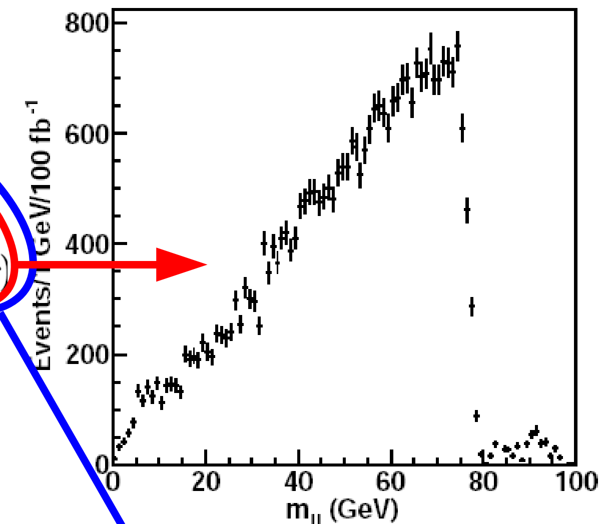
Is it possible to infer these quantities from measurements at the LHC?

LHC Measurements

First investigation done in well constrained mSUGRA model:

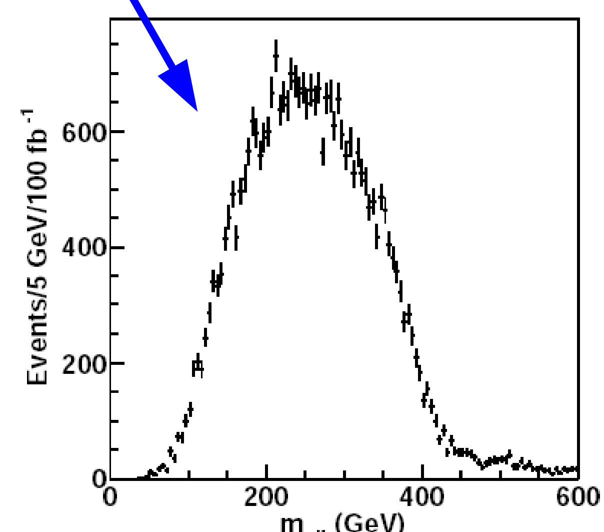
(Polesello, Tovey, hep-ph/0403047)





ATLAS study for LHC friendly SPS1a scenario (300 fb^{-1}):

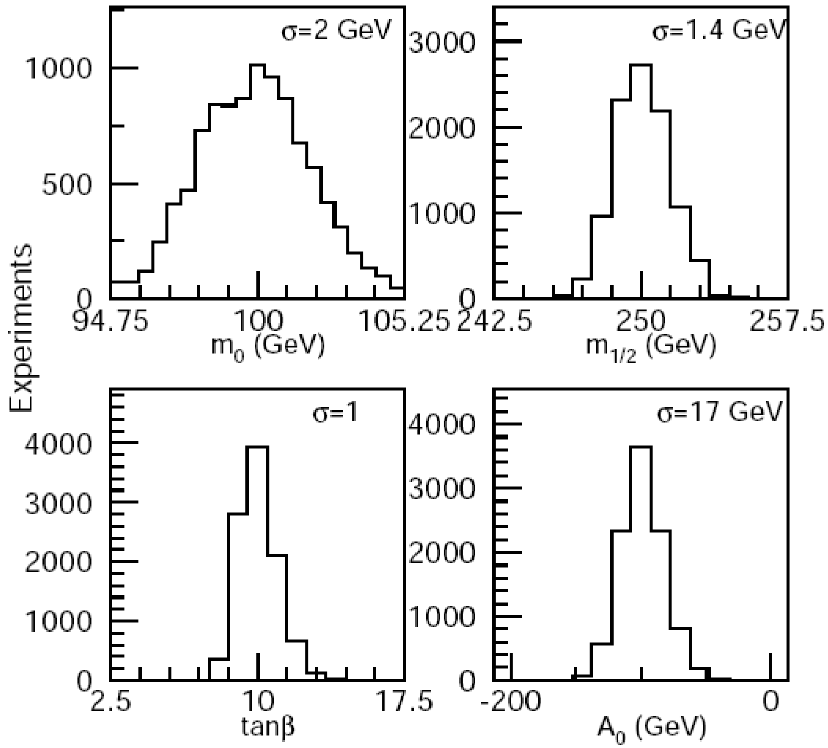
Variable	Value (GeV)	Errors: Stat+Sys (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	83.37	0.03	0.08	0.09
$m_{\ell\ell q}^{max}$	457.55	1.4	4.6	4.8
$m_{\ell q}^{low}$	321.28	0.9	3.2	3.3
$m_{\ell q}^{high}$	400.63	1.0	4.0	4.1
$m_{\ell\ell q}^{min}$	220.81	1.6	2.2	2.7
$m_{\ell\ell b}^{min}$	199.48	3.6	2.0	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



etc. etc.

Relic Density in mSUGRA

Step 1: Reconstruction of mSUGRA parameters

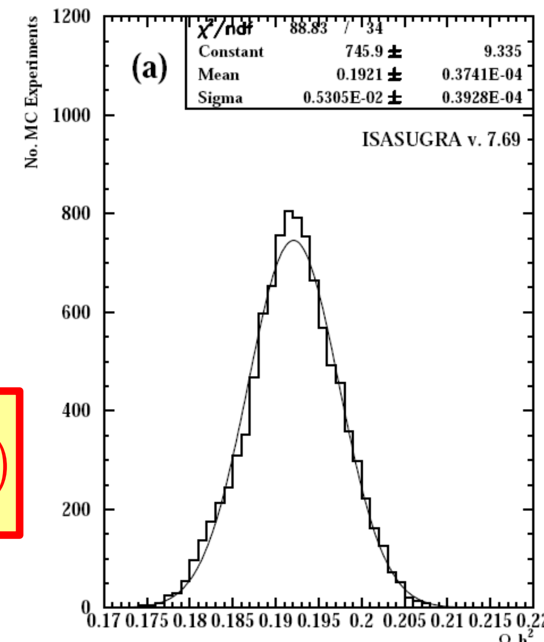


- m_0 dominated by sleptons ($\Delta m_0 \approx$ 2 %)
- $m_{1/2}$ dominated by gauginos ($\Delta m_{1/2} \approx$ 0.6 %)
- A_0 determined by $\tilde{\chi}^0_4$
- $\tilde{b}_1$ and $\tilde{b}_2$ needed for $\tan\beta$, otherwise long tails
- Wrong μ sign ruled out by bad fit

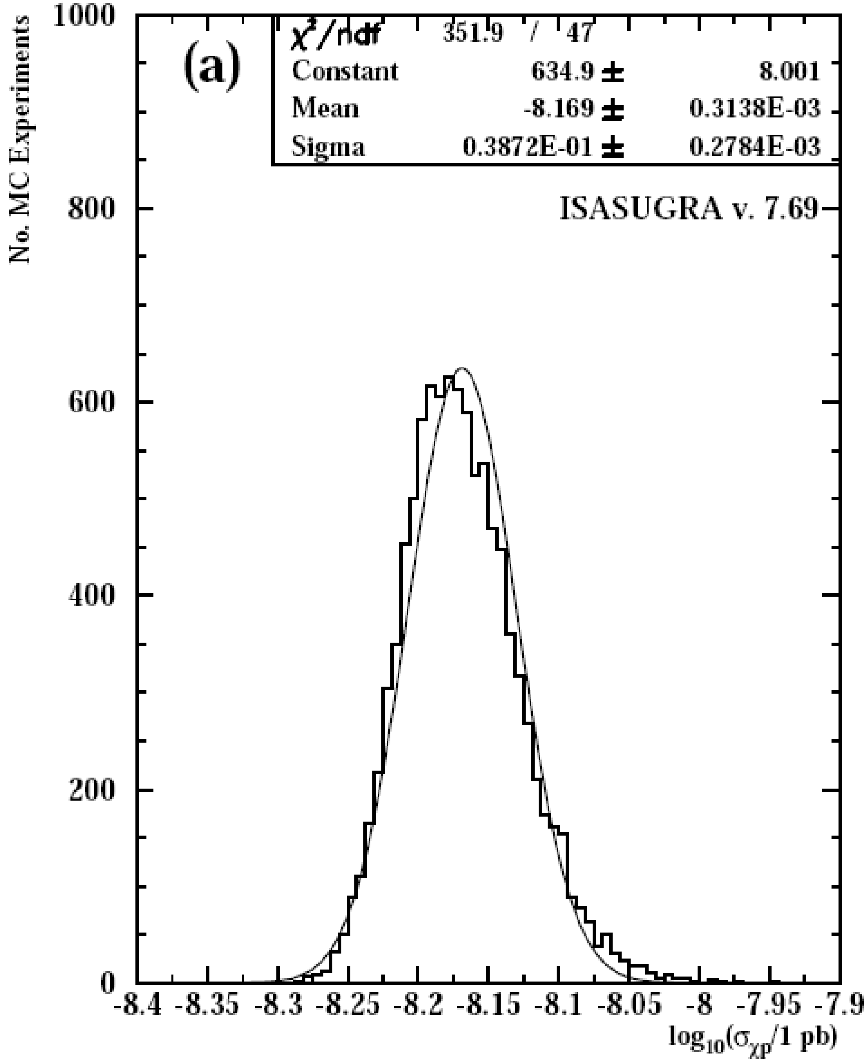
Step 2: Translation to relic density

Result: $\Omega_\chi h^2 = 0.192 \pm 0.005(\text{stat}) \pm 0.006(\text{sys})$

($\approx$ precision of astrophys. meas.)



Implications for Direct Detection



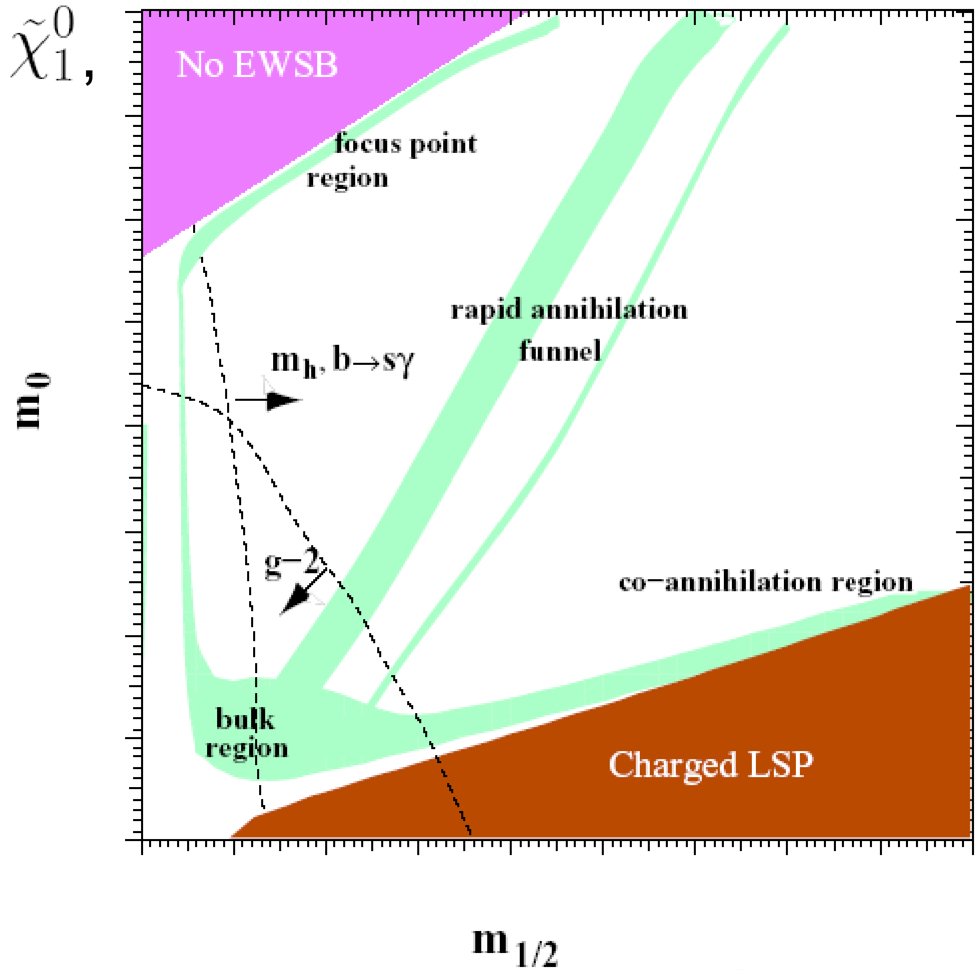
Constraints inferable from LHC data (300 fb^{-1}) for considered scenario:

$$m_{\tilde{\chi}_1^0} = 96.05 \pm 4.7 \text{ GeV}$$

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

WMAP Constraints for mSUGRA

Assuming DM consists solely of $\tilde{\chi}_1^0$, mSUGRA parameter space already much constrained by WMAP measurement



Four regions reveal right $\Omega_\chi h^2$:

- bulk region:
  Bino-like LSP, case presented here
- co-annihilation region:
  small mass difference $m(\tilde{\tau}_1) - m(\tilde{\chi}^0{}_1)$,
  soft leptons, rest similar to bulk,
  most important processes for relic density:
  $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$, $\tilde{\chi}_1^0\tilde{\tau} \to \tau\gamma$
- funnel region:
  annihilation through resonant heavy Higgses in s-channel, resonance condition $m(\tilde{\chi}_1^0) \simeq m(H/A)/2$
- focus point region:
  Higgsino-like LSP, heavy sfermions outside LHC reach, study gluino decays

What about more general models?

More General Model

What happens if high scale unification assumptions are dropped?

An ATLAS study assuming 300 fb^{-1} has been performed checking how much the MSSM parameters most relevant to the determination of the relic density can be constrained for the SPA point
(Nojiri, Polesello, Tovey, hep-ph/0512204)

Contributions of processes to $\Omega_\chi h^2$:

Process	Fraction
$\tilde\chi_1^0\tilde\chi_1^0 \to \ell^+\ell^-$	40%
$\tilde\chi_1^0\tilde\chi_1^0 \to \tau^+\tau^-$	28%
$\tilde\chi_1^0\tilde\chi_1^0 \to \nu\bar\nu$	3%
$\tilde\chi_1^0\tilde\tau_1 \to Z\tau$	4%
$\tilde\chi_1^0\tilde\tau_1 \to A\tau$	18%
$\tilde\tau_1\tilde\tau_1 \to \tau\tau$	2%

Stepwise analysis based on following ingredients:

Neutralino sector

- Masses of $\tilde\chi^0_1$, $\tilde\chi^0_2$ and $\tilde\chi^0_4$ from edges to constrain all parameters of neutralino mixing matrix (M_1, M_2, μ and $\tan\beta$) except

Slepton sector

- Measurement of $\tilde\chi^0_2 \to \tilde\ell_R\ell$, $\tilde\tau_1\tau$: $\tau\tau$ endpoint sensitive to $\tilde\tau_1$ mass, uncertainty varied between 0.5 GeV and 5 GeV
- Measurement of $\mathrm{BR}(\tilde\chi^0_2 \to \tilde\ell_R\ell)$ / $\mathrm{BR}(\tilde\chi^0_2 \to \tilde\tau_1\tau)$, to constrain θ_τ, 10 % uncertainty assumed (no detailed study available)

Higgs sector

- (Non-)observation of $\mathrm{H/A} \to \tau^+\tau^-$, $\tilde\chi^0_2\tilde\chi^0_2$ to constrain $\tan\beta$, m_A

Neutralino Mixing Matrix

First, constraints on neutralino mixing matrix (needed to understand neutralino couplings) are derived:

Neutralino mixing matrix:

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 & -m_Z \cos\beta s_W & m_Z \sin\beta s_W \\ 0 & M_2 & m_Z \cos\beta c_W & -m_Z \sin\beta c_W \\ -m_Z \cos\beta s_W & m_Z \cos\beta c_W & 0 & -\mu \\ m_Z \sin\beta s_W & -m_Z \sin\beta c_W & -\mu & 0 \end{pmatrix}$$

4 SUSY parameters

Measurements:

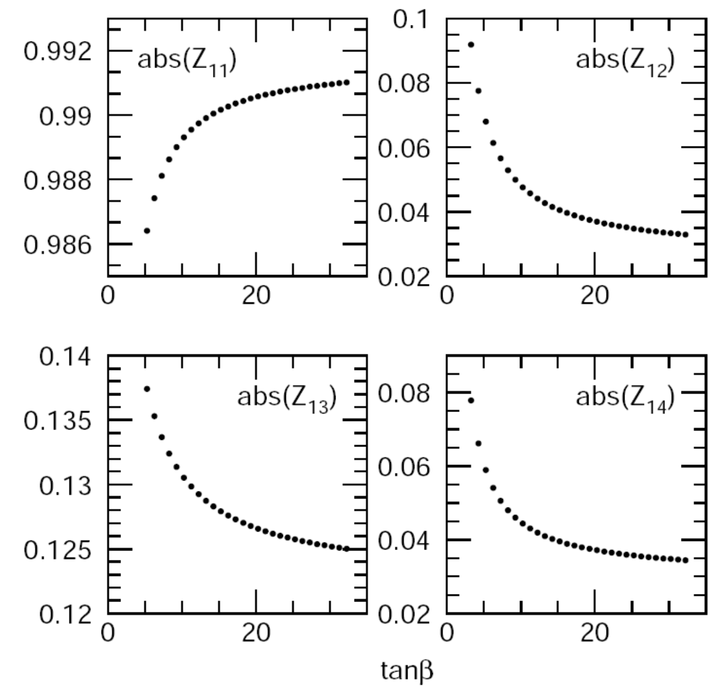
masses of $\widetilde{\chi}^0_1$, $\widetilde{\chi}^0_2$ and $\widetilde{\chi}^0_4$

3 measurements

$\Rightarrow$ use fixed value for $\tan\beta$

Composition of $\tilde{\chi}^0_1$:

$$\tilde{\chi}^0_1 = Z_{11}\tilde{B} + Z_{12}\tilde{W}^3 + Z_{13}\tilde{H}^0_1 + Z_{14}\tilde{H}^0_2$$



Experimental uncertainties:

Z_{11}: 0.02 %   others: 1.5 %

Systematics due to $\tan\beta$ ignorance:

Z_{11}: 0.8 % Z_{13}: 15 %   others: > 100 %

Slepton Sector

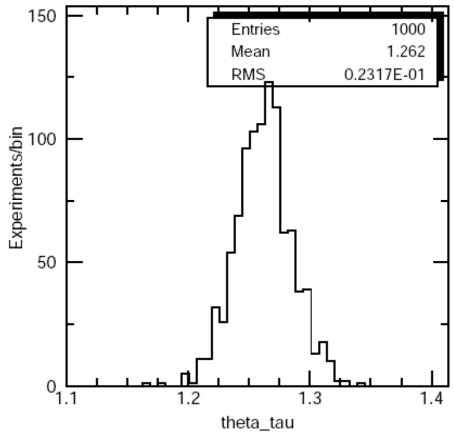
Slepton masses from edge positions

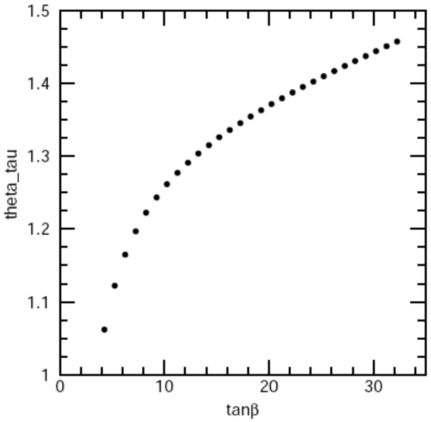
Extract θ_τ from neutralino mixing matrix, $m(\widetilde{\tau}_1)$, $m(\widetilde{\chi}^0{}_2)$ and $\mathrm{BR}(\widetilde{\chi}^0{}_2 \to \widetilde{\ell}_R \ell)$ / $\mathrm{BR}(\widetilde{\chi}^0{}_2 \to \widetilde{\tau}_1 \tau)$ (assuming no slepton mixing in first two generations)

$\tan\beta$ is kept fixed again

Experimental θ_τ uncertainty: 2 %

θ_τ uncertainty from $\tan\beta$ variation: 35 %





Only missing parameter to fully determine stau sector is $m(\widetilde{\tau}_2)$

Natural bounds can be imposed:

- $m(\widetilde{\tau}_2) > m(\widetilde{\chi}^0{}_2) - m(\tau)$, otherwise visible in $\widetilde{\chi}^0{}_2$ decay
- Requirement $|A_\tau| < 5\ \mathrm{TeV}$ to avoid charge breaking minima leads to $m(\widetilde{\tau}_2) < 250\ \mathrm{GeV}$ for $\tan\beta$=10

Constraints from Higgs Sector

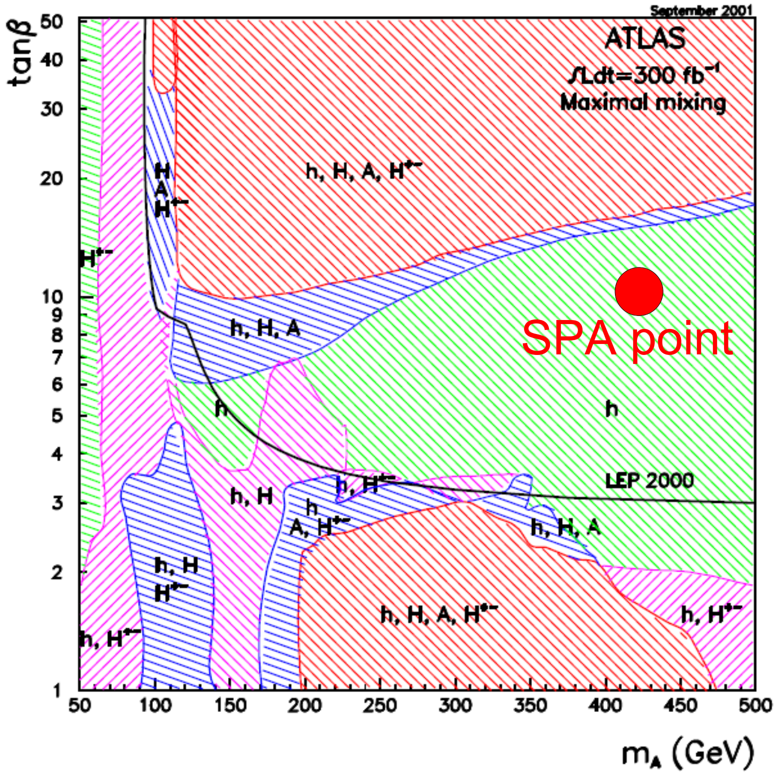
Try to obtain information on $\tan\beta$ from Higgs sector

At analyzed SPA point, only h can be discovered

For high $\tan\beta$ little information on $\tan\beta$ from $m(\mathrm{h})$

Heavy Higgses cannot be discovered in SM decay modes

$\rightarrow$ try SUSY decays:



- $\mathrm{H/A} \rightarrow \mathrm{bb}$ in chargino/neutralino decays

  If kinematically closed, set limit $m(A/H) < m(\tilde{\chi}^0_4) - m(\tilde{\chi}^0_1) \sim 300$ GeV

- $\mathrm{H/A} \rightarrow \tilde{\chi}^0_2 \tilde{\chi}^0_2 \rightarrow 4\ell$

  Very small rate, observability unclear

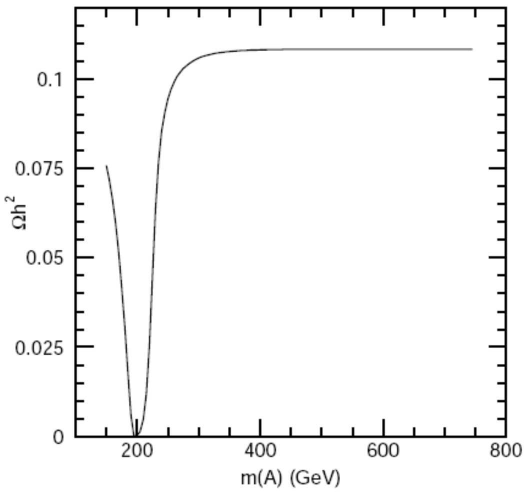
Relic Density in MSSM

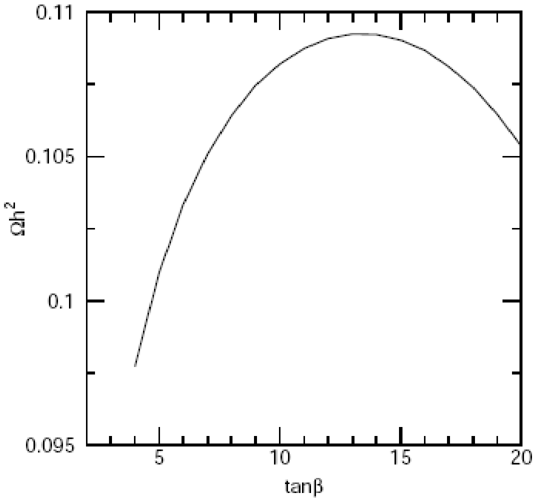
Achievable precision crucially depends on available information from the Higgs sector:

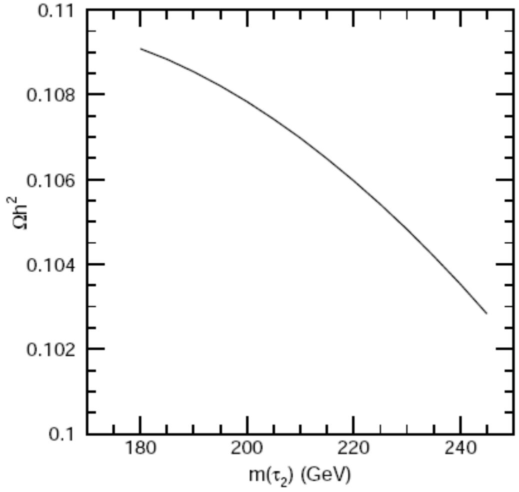
- No information on heavy Higgses available:
  Only upper limit on relic density possible
- Lower limit of 300 GeV on heavy Higgses possible:

$$\Omega_\chi h^2 = 0.108 \pm 0.01(stat + sys)^{+0.00}_{-0.002}(M(A))^{+0.001}_{-0.011}(\tan\beta)^{+0.002}_{-0.005}(m(\tilde{\tau}_2))$$

- Heavy Higgses directly observable:
  Dominant contributions to uncertainty from poorly constrained $\tan\beta$ and $m(\widetilde{\tau}_2)$.







Summary

- Nature of dark matter is one of today's great scientific puzzles
- LHC can lead the way how to extend the SM, many extensions (including SUSY) provide good DM candidates
- At least in a subset of SUSY parameter space relic density can be inferred from LHC data with reasonable precision, statements about general case are difficult (too different phenomenology)
- Agreement of inferred relic density with astrophysical measurements would be major discovery for astronomy and particle physics