# Dark Matter and ATLAS

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# Dark Matter

What we know from astrophysical observations:

• From CMB anisotropies (WMAP): $\Omega_{DM} \sim 0.23$ ($\Omega_X = \rho_X/\rho_{crit}$)

• From nucleosynthesis, only 4% of total matter density baryonic

• From structure formation: most DM "cold" and weakly interacting

• DM candidates must be stable on cosmological time scales, interact very weakly with EM radiation

We would like to learn whether DM is a fundamental particle and its properties

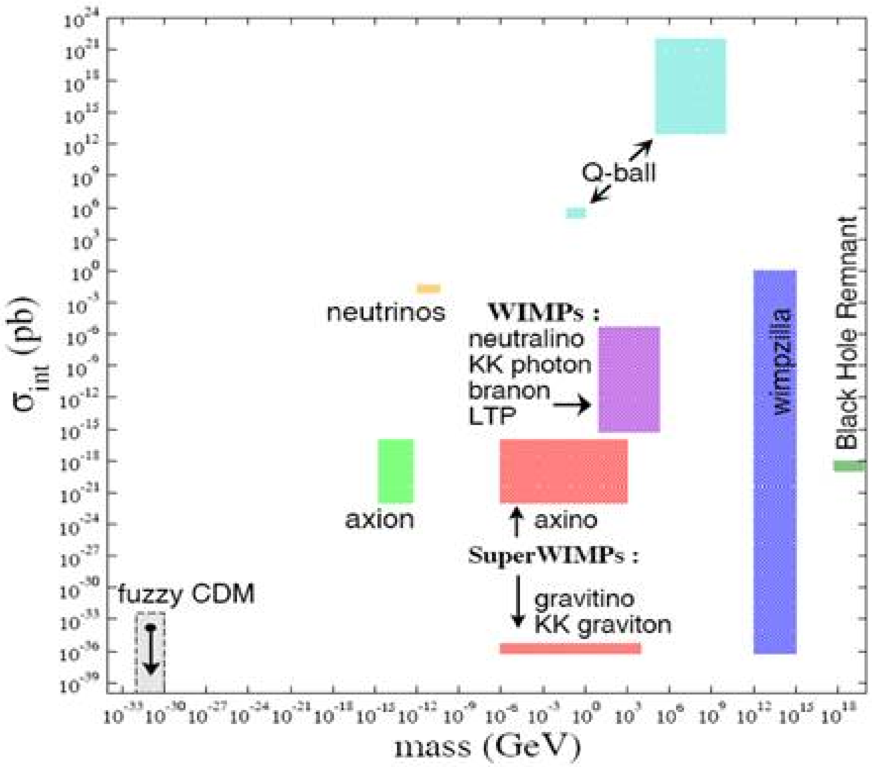
• Can try to detect it directly or indirectly

• Can try to produce it at a collider

Next big chance is the LHC. Try to figure out what are the perspective for producing and studying the DM properties at the LHC

Main goal would be to measure particle properties well enough to be able to predict results of astrophysical and direct detection measurements

# What kind of Dark Matter at Colliders




Enormous Zoo of Dark Matter candidates

LHC experiments designed for the discovery of particles on the GeV-TeV range

Need production cross-sections at least of the order of electroweak interaction

This approximately restricts the field to WIMPS Weakly Interacting Massive Particles

The WIMP, being neutral and weakly interacting is invisible in our “small” Collider experiments $\Rightarrow$ Difficult to discover in direct production (use ISR??)

Best chance of WIMP detection is when it is produced in the decay of other particles

# WIMPS Dark Matter and new physics

Consider WIMP with mass O(100) GeV and EWK interaction strength

Simplest way of ensuring stability of WIMPs is attributing them a conserved quantum number $X$ not shared by SM particles

Models proposed to complete SM typically contain new conserved quantum numbers, from new symmetries, or introduced to avoid large corrections to EWK observables

If one has a spectrum of $X$-odd particles, $X$-parity conservation implies:

- $X$-odd particles are produced in pairs
- They cascade into the lightest $X$-odd particle
- lightest $X$-odd particle is neutral, stable weakly interacting

Examples are SUSY (R-parity), Little Higgs (T-parity), UED (KK-parity)

Study of DM candidate implies understanding the complete structure of the model

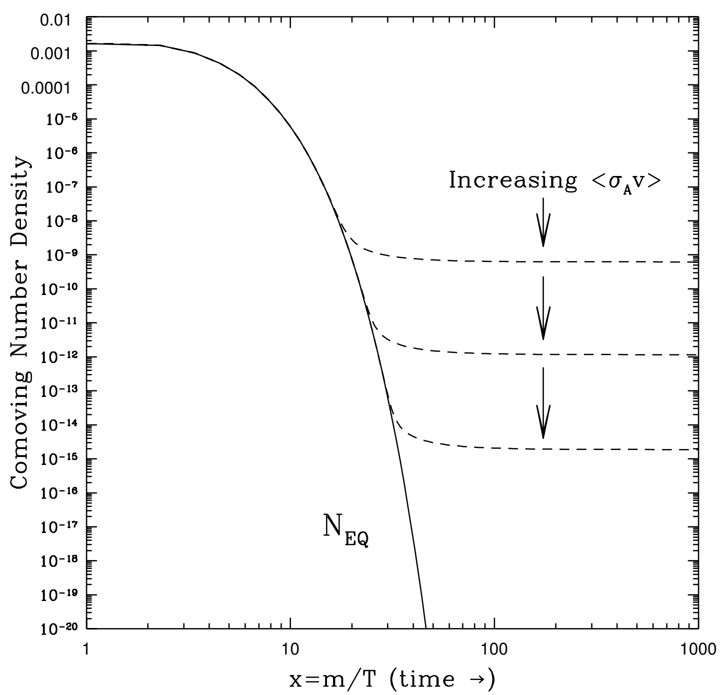
Concentrate in the following on Minimal Supersymmetric Standard Model

# Relic Density and annihilation Cross-Section

At first, when $T \gg m_\chi$ all particles in thermal equilibrium. Universe cools down and expands:

When $T < m_\chi$ is reached only annihilation: density becomes exponentially suppressed

As expansion goes on, particles can not find each other: freeze out and leave a relic density




After freezeout relic density is:

$$\Omega_\chi \equiv \frac{m_\chi n_\chi}{\rho_c} \propto \frac{1}{< \sigma_A v >} \quad (1)$$

where $< \sigma_A v >$ is DM pair annihilation X-section

times relative velocity

Assuming $\Omega_\chi = 0.2$ gives: $< \sigma_A v >= 1$ pb

Using $< \sigma_A v >= \pi \alpha^2 / 8 m_\chi^2$ we find:

$m_\chi \sim 100$ GeV, scale of EW symmetry breaking

From LHC measurements can evaluate LSP annihilation X-section and thence

predict relic density and verify agreement with cosmological measurements

# The LHC machine

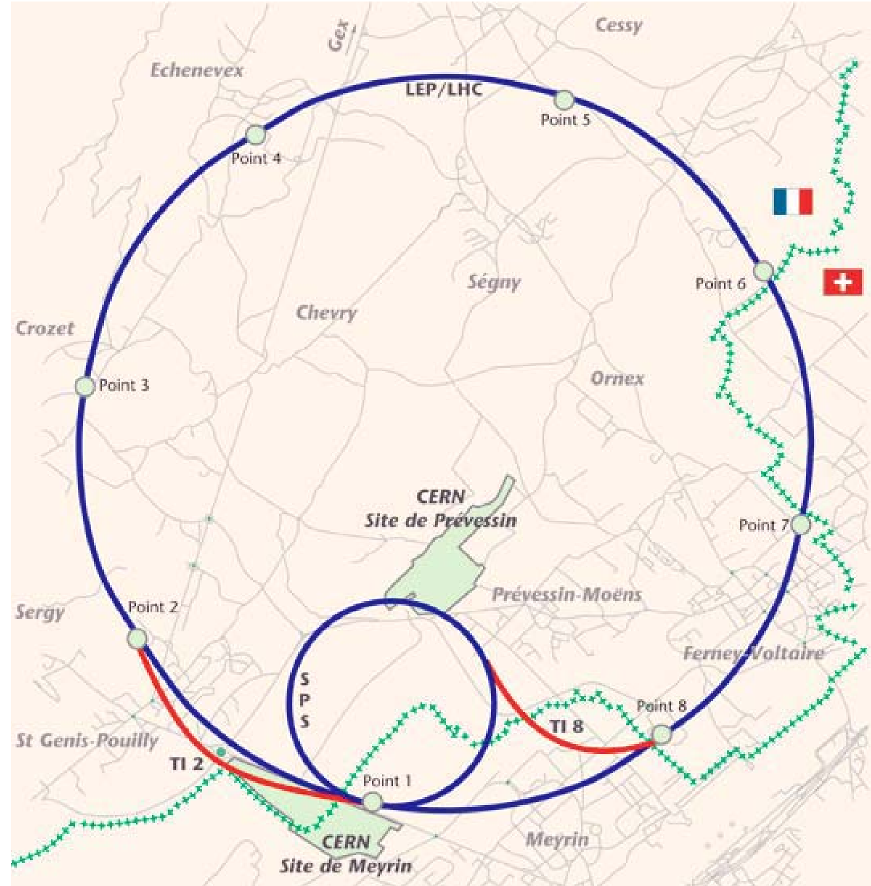
Energy: $\sqrt{s}$=14 TeV

LEP tunnel: 27 Km circumference

1232 Superconducting dipoles, field 8.33 T

Luminosity scenarios:

- peak$\sim 10^{33}$ cm$^{-2}$s$^{-1}$ $\int \mathcal{L}\mathrm{d}t = 10\ \mathrm{f}b^{-1}$ /year
- peak$\sim 10^{34}$ cm$^{-2}$s$^{-1}$ $\int \mathcal{L}\mathrm{d}t = 100\ \mathrm{f}b^{-1}$ /year




Eight sectors

Point 1: ATLAS General purpose

Point 2: ALICE Heavy ions

Point 5: CMS General purpose

Point 8: LHCb B-physics

# The 2010-2011 Run

Run at $\sqrt{s}$=7 TeV

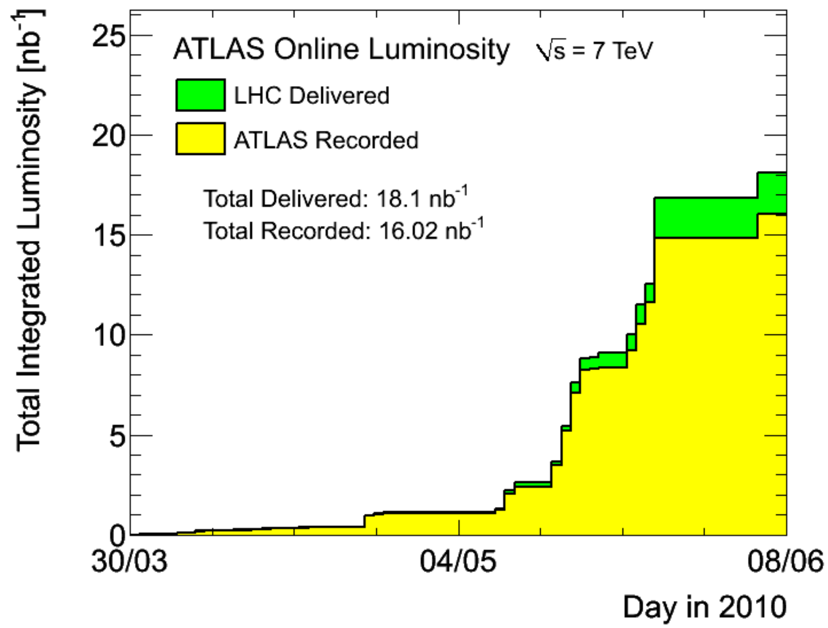
Target peak luminosity: $\sim 10^{32}$ cm$^{-2}$s$^{-1}$

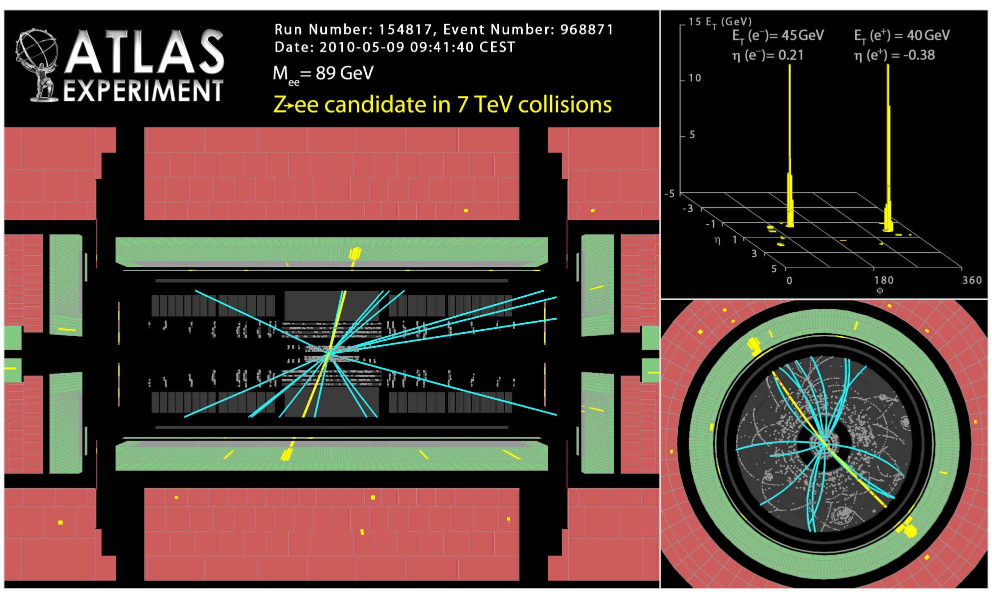
Target $\int \mathcal{L}dt$ by end 2011: 1 fb$^{-1}$

Thereafter long shutdown to implement protection system for ramping energy up to nominal value

Status: delivered $\sim 18.1$ nb$^{-1}$

Peak lumi: $\sim 2 \times 10^{29}$ cm$^{-2}$s$^{-1}$




Both ATLAS and CMS detectors work really well!

First Z's being observed

Accelerator progressing really fast, but many orders of magnitude still to cover

# SUSY Dark Matter Strategy at the LHC

- Discovery of deviation from SM in $\not{E}_T$+X channel: 2012 if m(susy)<7-800 GeV
- First inclusive studies: 2012 if m(susy)<7-800 GeV

  Relevance to DM: verify if discovered signal provides dark matter candidate, possibly first rough evaluation of LSP mass

- First mass measurements based on kinematics of high-BR decays

  Unless SUSY mass very low (4-500 GeV), need 14 TeV data taking, moderate luminosity

  Relevance to DM: Model-independent calculation of LSP mass, comparison with direct detection experiments

- Focus onto the physics of the model: Precision measurements involving branching ratios, angular distributions, rare decays : Need 14 TeV and high luminosity

  Relevance to DM: model-independent calculation of relic density, interaction cross-section, etc.

# SUSY production at the LHC

Production dominated by strongly interacting sparticles: $\tilde{q}$, $\tilde{g}$

$\tilde{q}$ and $\tilde{g}$ production cross-section $\sim$only function of their masses, $\sim$independent of model details

LO Cross-sections for two ATLAS benchmark points and NLO for top

| $\sqrt{s}$ (TeV) | $\sigma_{SUSY}$ (pb) SU3 | $\sigma_{SUSY}$ (pb) SU4 | $\sigma_{tt}$ (pb) |
|---|---|---|---|
| 7 | 1.9 | 36 | 148 |
| 10 | 6.5 | 103 | 374 |
| 14 | 18.9 | 264 | 827 |
| $m_{\tilde{g}}$ (GeV) | 717 | 413 | 172.5 |
| $m_{\tilde{q}}$ (GeV) | 620 | 410 | |

SU3: $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan\beta = 6$, $\mu > 0$.

SU4: $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan\beta = 10$, $\mu > 0$.

Squarks and gluinos are typically the heaviest sparticles

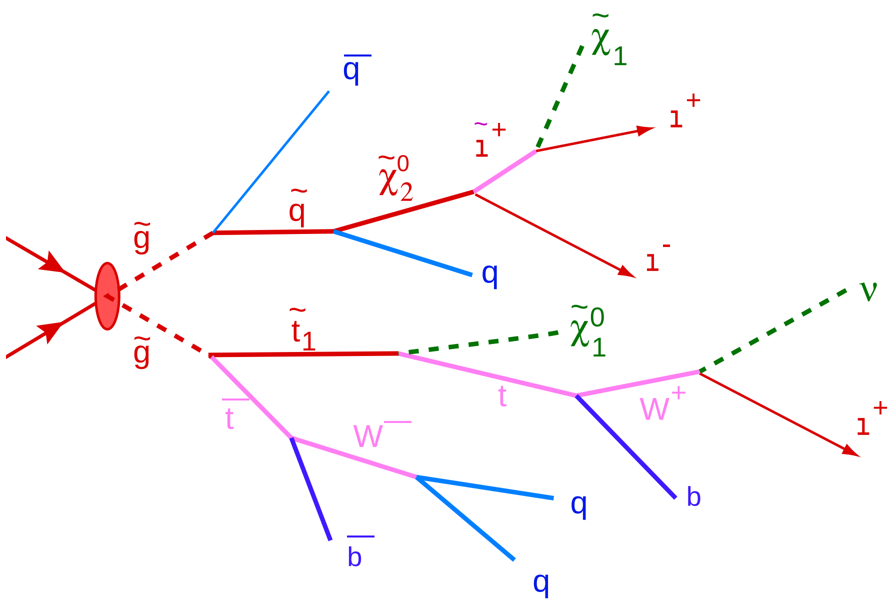
$\Rightarrow$ If $R_p$ conserved, complex cascades to undetected LSP

Basic discovery route: observe squark/gluinos cascading to undetectable LSP

# SUSY discovery: basic strategy

Cascade of squark gluinos may be very complex and model-dependent

Focus on robust signatures covering large classes of models and large rejection of SM backgrounds



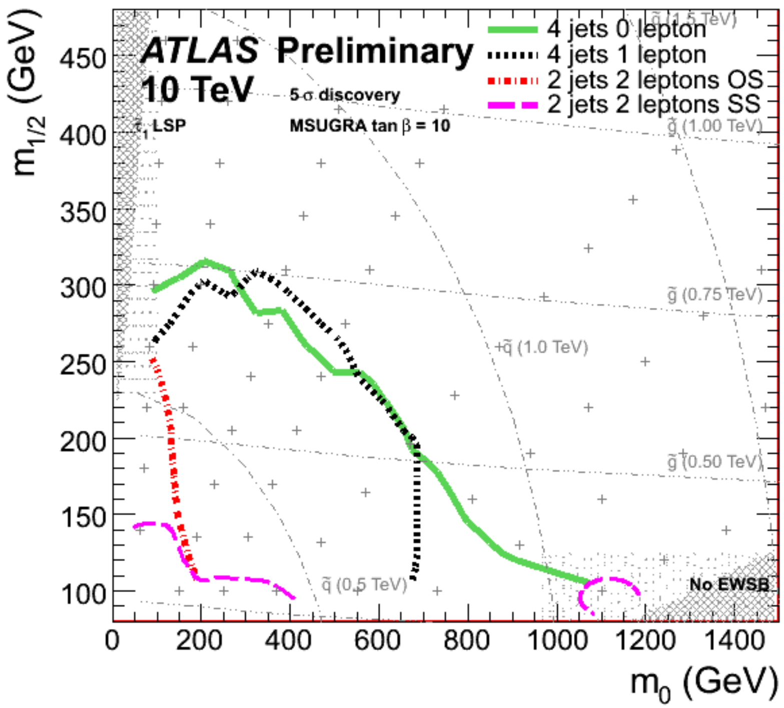

- $\not{E}_T$: from LSP escaping detection
- High $E_T$ jets: guaranteed if squarks/gluinos if unification of gaugino masses assumed.
- Multiple leptons $(Z)$: from decays of Charginos/neutralinos in cascade
- Multiple $\tau$-jets or $b$-jets $(h)$: Often abundant production of third generation sparticles

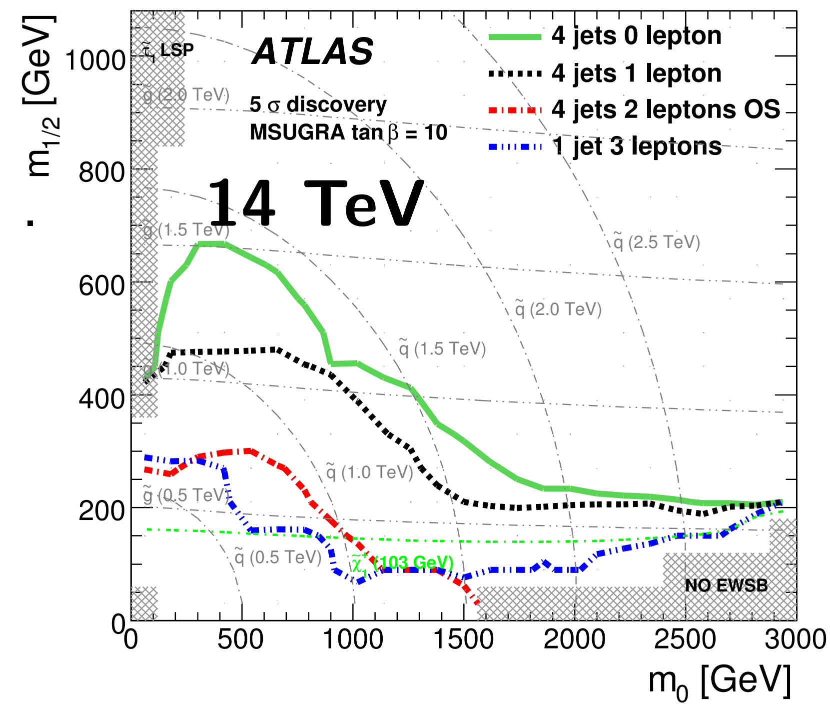
Select events including $\not{E}_T + \geq 2$ Jets $+ \geq 0$ leptons or photons or taus or $b$'s.

For each signature define appropriate cuts to reject SM

Scan low-dimensional parameter space (mSUGRA) to assess experimental reach

# Reach in MSUGRA space: 10 TeV, 200 $pb^{-1}$, 14 TeV 1 $fb^{-1}$




Rule of the thumb: to get reach at 7 TeV, require approx two times more luminosity than for 10 TeV

Reach essentially determined by:

- Production cross-section (mass) for squark/gluino
- Level of systematic control on backgrounds. Very difficult experimental challenge.

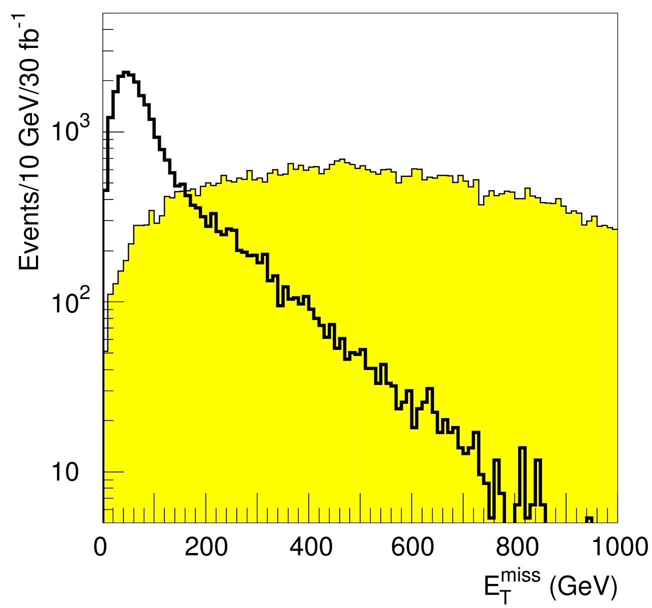
Main focus of work is development of techniques for background control

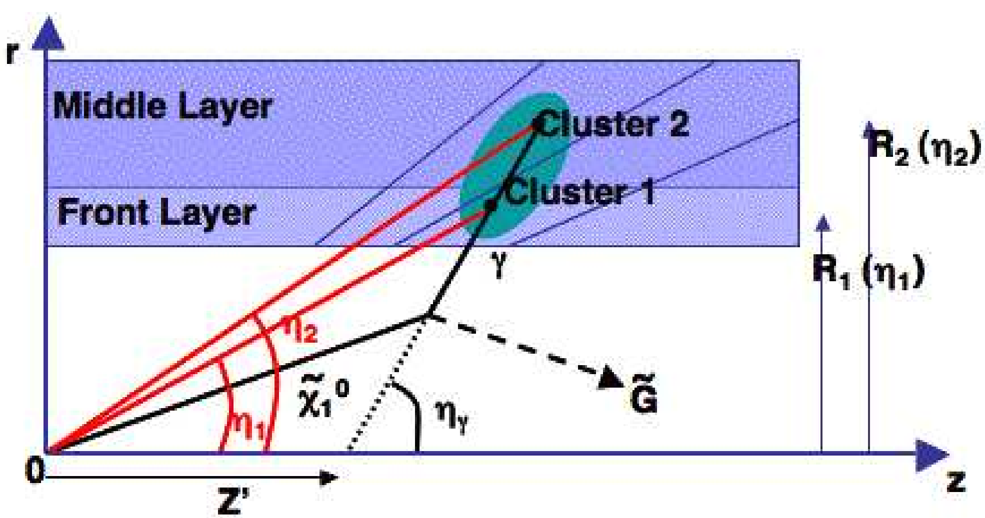
# Inclusive Studies

Following any discovery next task will be to test broad features of potential Dark Matter candidate

Question 1: Do we get a significant $\not{E}_T$ signal (stable WIMP frm some kind of parity conservation (R,KK,T)?

- Loophole: LHC experiments sensitive only to lifetimes $\lesssim 1$ ms ($\ll t_U \sim 13.7$ Gyr) $\Rightarrow$ need confirmation from direct DM detection




Question 2: Can we have a glimpse of which decays produces DM candidate: Examples in SUSY:

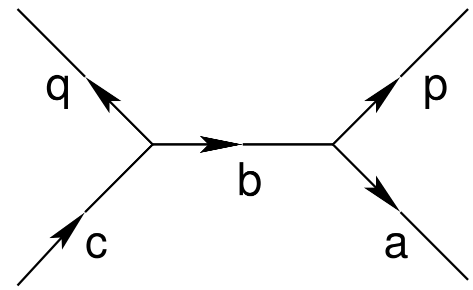
- Always two photons together with $\not{E}_T$, and some of the photons non-pointing (GMSB with light gravitino LSP and $\tilde{\chi}_1^0$ NLSP)
- Always two leptons together with $\not{E}_T$ (GMSB with light gravitino LSP and $\tilde{\chi}_1^0$ NLSP)

# Mass measurements:start from sequence of two-body decays

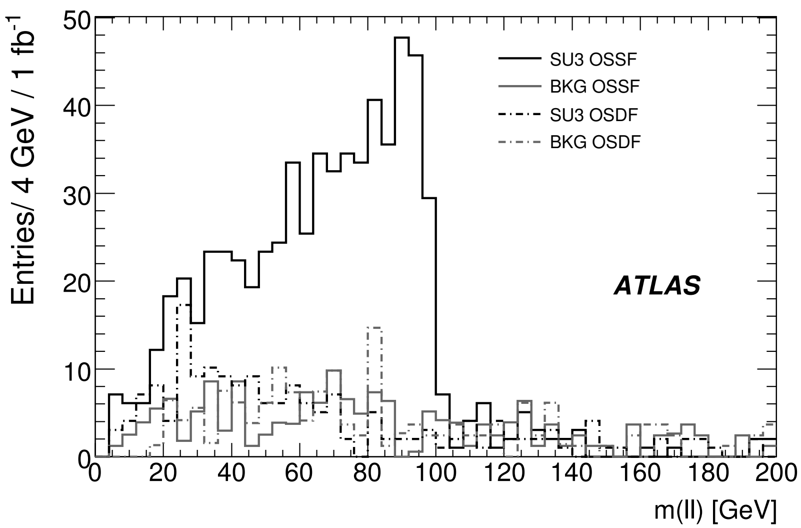
Decay chain: $c \to qb \to qpa$

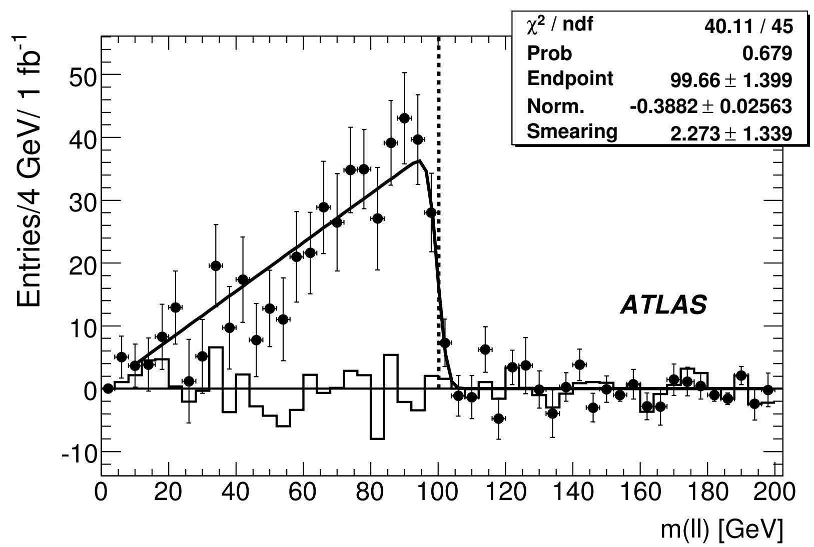
$p$, $q$ massless visible particles:

$a$ invisible LSP:




$$(m_{pq}^{max})^2 = 4|\vec{p_p}||\vec{p_q}| = \frac{(m_c^2 - m_b^2)(m_b^2 - m_a^2)}{m_b^2}$$




Apply to: $\tilde{\chi}_2^0 \to \ell^\pm \tilde{\ell}_R^\mp \to \ell^\pm \ell^\mp \tilde{\chi}_1^0$ for ATLAS SU3 Point

Plot $\ell^+\ell^-$ invariant mass; Perform flavour subtraction $ee + \mu\mu - e\mu$

Fit smeared triangular function: fitted edge: $99.7 \pm 1.4 \pm 0.3$ GeV (14 TeV, 1 fb$^{-1}$)

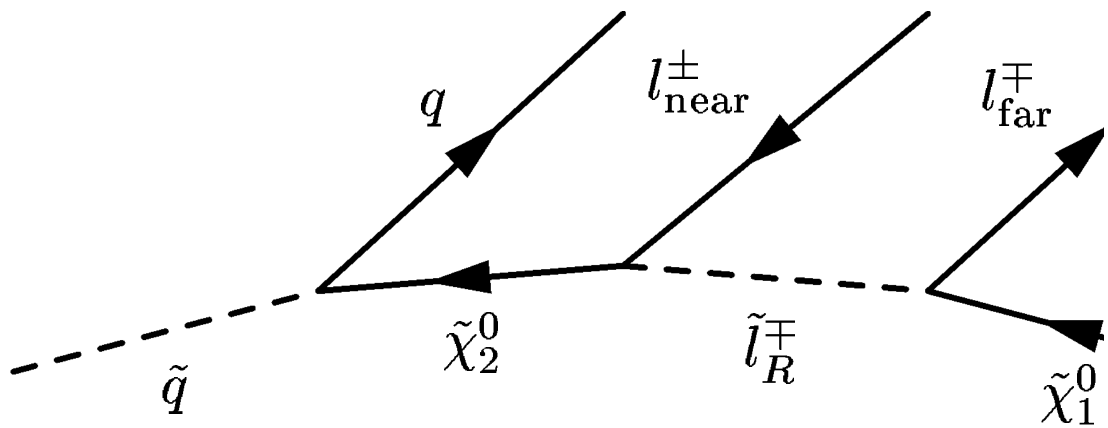
Systematics: lepton energy scale (0.1%), lepton efficiencies (10%, very pessimistic)

# Mass determination through kinematic edges

With two decays only single mass combination $\Rightarrow$ only one edge constraint

If a chain of at least three two-body decays can be isolated, enough constraints to measure all involved masses

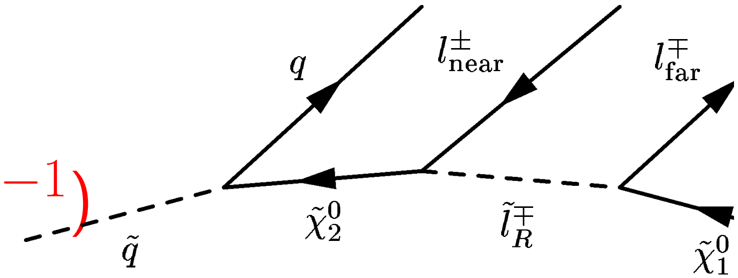
Example: full reconstruction of squark decays in models with light $\tilde{\ell}_R$ ($m_{\tilde{\ell}_R} < m_{\tilde{\chi}_2^0}$):



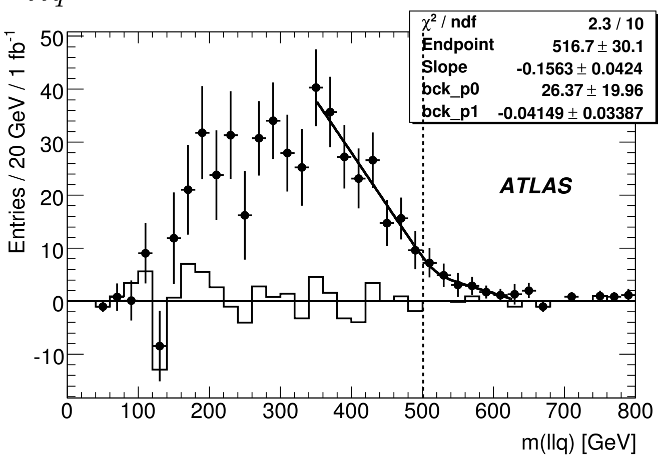

Three visible particles: 4 invariant mass combinations: $(\ell_1\ell_2)$, $(q\ell_1)$, $(q\ell_2)$ , $(q\ell_1\ell 2)$

For first three minimum value is zero: only $M_{max}$ constraint. For $(q\ell_1\ell 2)$ combination, if lower limit is set on $(\ell_1\ell_2)$, both $M_{max}$ and $M_{min}$ constraint: total 5 constraints

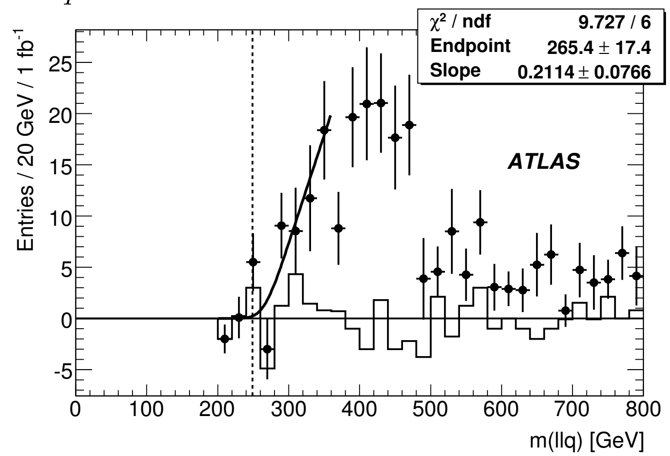
# Application to SU3 (14 TeV, 1 fb$^{-1}$)



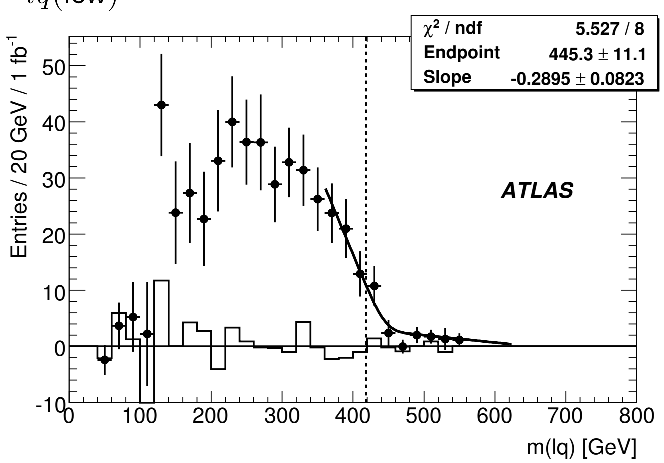

$m_{\ell\ell q}^{\max} = 517 \pm 30 \pm 10 \pm 13$ GeV



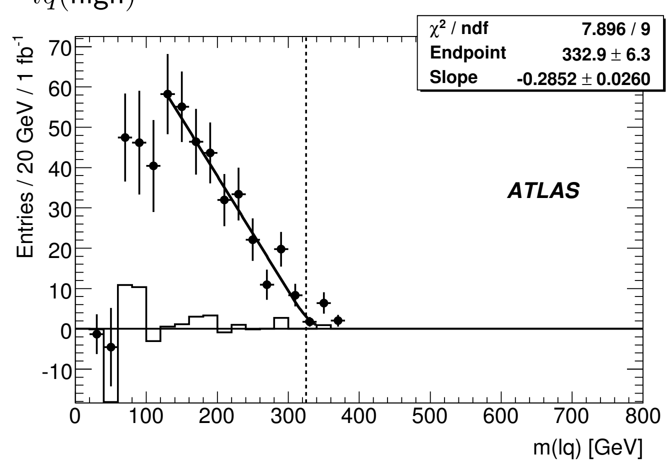

$m_{\ell\ell q}^{\min} = 265 \pm 17 \pm 15 \pm 7$ GeV




$m_{lq(\text{low})}^{\max} 333 \pm 6 \pm 6 \pm 8$ GeV




$m_{lq(\text{high})}^{\max} = 445 \pm 11 \pm 11 \pm 11$ GeV




$\sim 5\%$ Statistical error, $2\%$ from fit technique, $5\%$ from Jet energy scale

# Mass measurement (14 TeV 1 fb$^{-1}$)

Invert algebraical relations defining edges in terms masses through a minuit fit

First error from MIGRAD, second one from lepton energy scale

Much better measurement for mass differences, as the edges are essentially sensitive to the differences

| Observable | SU3 $m_{\rm meas}$ (GeV) | $m_{\rm MC}$ (GeV) |
|---|---|---|
| $m_{\tilde\chi_1^0}$ | $88 \pm 60 \mp 2$ | 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 | SU3 $\Delta m_{\rm meas}$ (GeV) | $\Delta m_{\rm MC}$ (GeV) |
| $m_{\tilde\chi_2^0} - m_{\tilde\chi_1^0}$ | $100.6 \pm 1.9 \mp 0.0$ | 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 |

Despite low statistics considered, can define absolute mass scale

$\Rightarrow$ Comparison with constraints from direct WIMP detection

Based on this kind of measurements the soft SUSY breaking parameters can be constrained (Sfitter, Fittino)

# Neutralino relic density prediction from SUSY parameter measurement

In MSSM the $\tilde{\chi}_1^0$ is a mix of gauginos ($\tilde{B}$,$\tilde{W_3}$) and higgsinos ($\tilde{h_u}$,$\tilde{h_d}$)

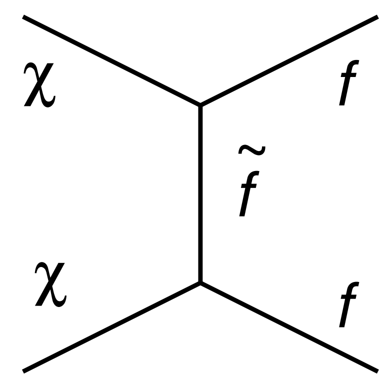
Cross section for $\tilde{\chi}_1^0$ annihilation depends on its composition (gaugino or higgsino) and on the masses of lighter sfermions and higgses. Main mechanisms:

Names correspond to the regions the mSUGRA parameter space where each of the mechanisms appear

(1) Annihilation through sfermion exchange

One sfermion light and $\tilde{\chi}_1^0$ mostly gaugino

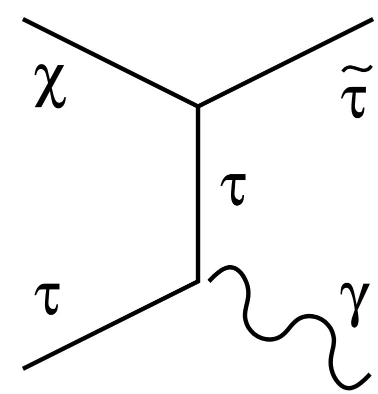
"bulk" region



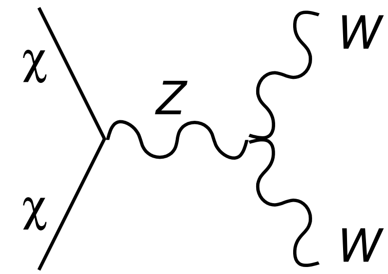

(2) Co-annihilation: $\tilde{\chi}_1^0$ mostly gaugino,

a sfermion almost degenerate with $\tilde{\chi}_1^0$

Example: $\tilde{\chi}_1^0\tau \to \tilde{\tau}\gamma$, $\tilde{\tau}\tilde{\chi}_1^+ \to \tau W^+$ "coannihilation" region



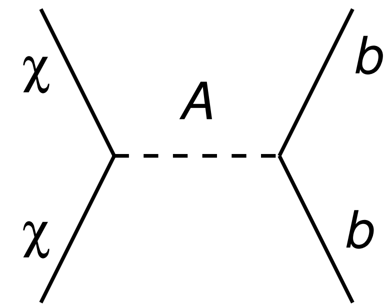
(3) Annihilation into $W(Z)$ through $Z$ or $h$ exchange




$\tilde{\chi}_1^0$ mostly higgsino

"focus point" region

(4) Resonant annihilation into higgs boson




$m(H/A) \sim 2 \times m(\tilde{\chi}_1^0)$ "funnel" region

Benchmark points are typically chosen in one of this regions

Discuss today full analysis of LHC constraints for two configurations for which detailed studies available in literature:

Bulk Region: SPS1a, SPA, ATLAS SU3 (shown above), CMS LM1, Peskin LCC1

$m(\tilde{g}) \gtrsim m(\tilde{q}) \sim$ 700 GeV. Significant BR for $\tilde{\chi}_2^0 \to \ell\tilde{\ell}_R$

Focus point region: ATLAS SU2, CMS LM7, Peskin LCC2

Very heavy sfermions (Multi-TeV), light gluinos (6-800 GeV)

Can study gaugino spectrum from gluino decays

# From LHC measurements to relic density

Discuss two detailed studies addressing LHC (ultimate luminosity, O(100) $\mathrm{fb}^{-1}$).

Assume unconstrained MSSM as template model.

Nojiri, G.P., Tovey: JHEP 0603:063,2006 (hep-ph/0512204)

Only SPA point (bulk), only relic density, only LHC. Use micrOMEGAs

- Build MonteCarlo experiments from constraints from detailed studies
- For each experiment constrain soft MSSM parameters, and from them calculate relic density

Requires careful "a posteriori" consideration of unconstrained parameters

Baltz, Battaglia, Peskin, Wizansky: PRD 74:10351, 2006 (hep-ph/0602187)

All four main annihilation processes. Studies LHC, ILC-500, ILC-1000

Use DarkSUSY program, several different DM variables

Scan on MSSM 24-parameter space using a Markov chain technique

Final distribution may depend on priors for scan

Two independent methods, good agreement of results

# Bulk region: inputs

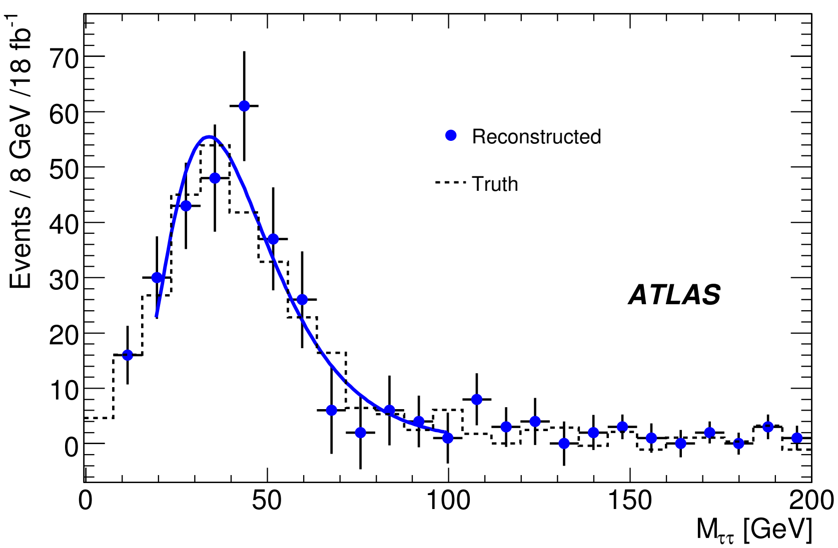
From the chain $\tilde{q}_L \to q\tilde{\chi}_2^0 \to \ell\tilde{\ell}_R \to \ell\tilde{\chi}_1^0$ measure $m(\tilde{q}_L)$, $m(\tilde{\chi}_2^0)$, $m(\tilde{\ell}_R)$, $m(\tilde{\chi}_1^0)$

From the decay $\tilde{\chi}_4^0 \to \ell\tilde{\ell}_L$ measure $m(\tilde{\chi}_4^0)$

In this region dominant $\tilde{\chi}_1^0$ annihilation process trough $\tilde{\tau}_1$ exchange

Need precise measurement of $\tilde{\tau}_1$ mass and mixing paramters

Measure $\tilde{\tau}_1$ mass from edge in di-tau invariant mass from $\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau \to \tilde{\chi}_1^0\tau^{\pm}\tau^{\mp}$




Invariant mass of visible decay products of two $\tau$

No sharp end-point because of escaping neutrinos

Measured end-point:

$m_{EP} = (70 \pm 6.5^{\text{stat}} \pm 5^{\text{syst}})$ GeV

Stat is for 1 fb$^{-1}$, systematic is from fitting procedure

Use measurement of ratio $BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau)/BR(\tilde{\chi}_2^0 \to \tilde{\ell}_R\ell)$ to constrain $\tilde{\tau}_1$ mixing

# Bulk region: relic density prediction

Use the soft parameters as extracted from the mass and BR measurements.

$\tan\beta$, $m(A)$, $m(\tilde{\tau}_2)$ badly constrained

Assume limits on $m(A) - \tan\beta$ from direct higgs searches: $\tan\beta < 7.0(m(A)/200)$

Assume $m(A) > 300$ GeV from its non-appearance in SUSY cascade decays

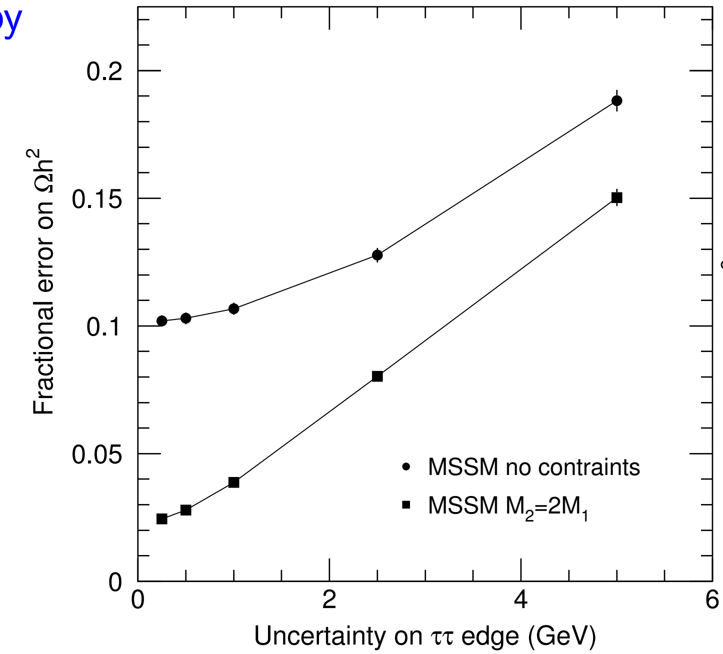
Uncertainty dominated by error on on $\tau\tau$ edge position

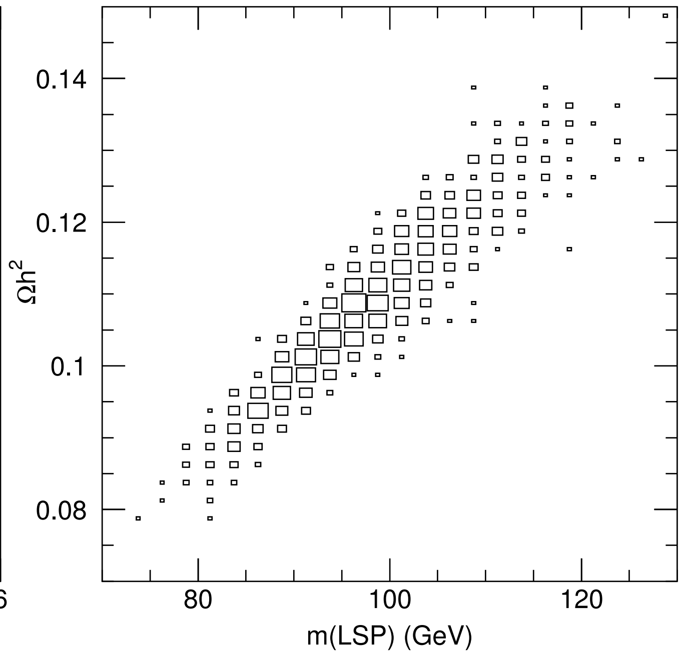
For $\Delta(m_{\tau\tau}) = 5$ GeV:

$\Delta\Omega_\chi h^2 \sim 20\%$

For $\Delta(m_{\tau\tau}) = 1$ GeV:

$\Delta\Omega_\chi h^2 \sim 11\%$



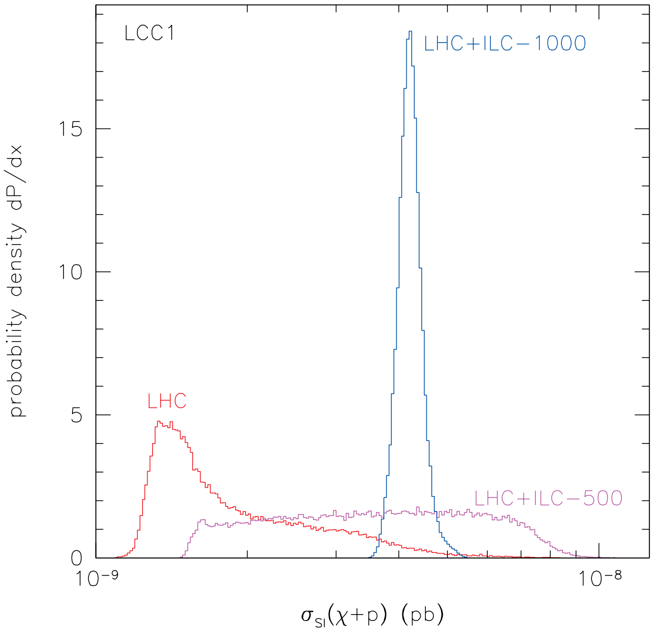




Next most important uncertainty: $\tilde{\chi}_1^0$ mass, known only to a few GeV at the LHC

Errors on $\tan\beta$, $m(A)$, $m(\tilde{\tau}_2)$ subdominant

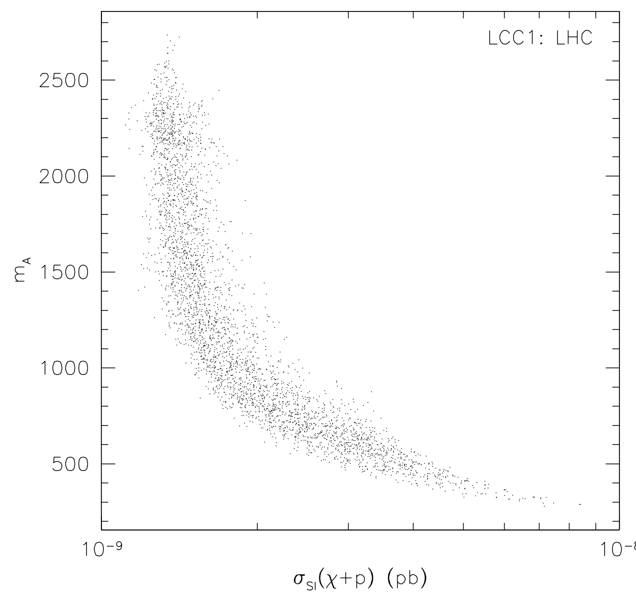
# Bulk Region: Direct detection cross section

## Evaluate spin-averaged neutralino-proton cross-section $\sigma_{\chi p}$ at threshold




Basically no constraint from LHC measurements

Spurious shape in probability distribution due to scanning technique and initial assumption on distribution of scan variables.




Cross-section dominated by $t$-channel exchange of heavy Higgs $H^0$

For high $m(A)$, $\sigma$ dominated by light higgs $h$

Constraint if $H/A \to \tilde{\chi}_2^0 \tilde{\chi}_2^0$ detectable (SuperLHC)

# Focus point: inputs

Scalars 2-3 TeV, put a limit from non-observation of $\tilde{q}\tilde{q}$ and $\tilde{\ell}\tilde{\ell}$ production

Main observable process at the LHC: gluino production

Three-body gluino decay: $\tilde{g} \longrightarrow qq\tilde{\chi}$, with $\tilde{\chi}$ chargino or neutralino

ATLAS study for SU2 Point: De Sanctis et al. ATLAS-PHYS-PUB-2006-023

Produce both $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$ in $\tilde{g} \longrightarrow qq\tilde{\chi}_i^0$ decays

Study lepton-lepton invariant mass for decays

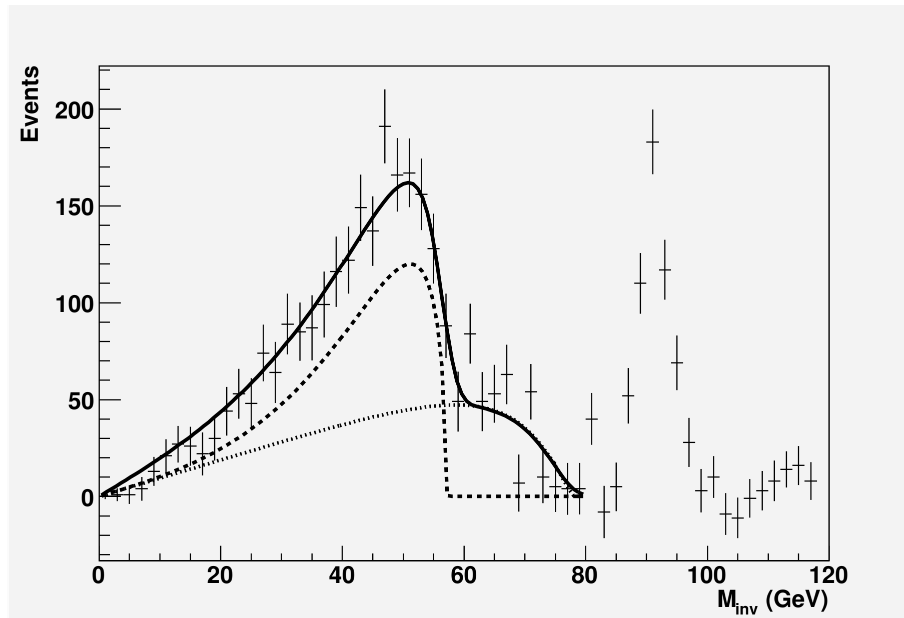
$\tilde{\chi}_2^0 \longrightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$

$\tilde{\chi}_3^0 \longrightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$

From fit of three-body shape: (300 fb$^{-1}$)

$\Delta(m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)) = 0.4$ GeV

$\Delta(m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)) = 1.4$ GeV




Constraint from direct production cross-section $pp \longrightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^{\pm} \longrightarrow 3\ell$

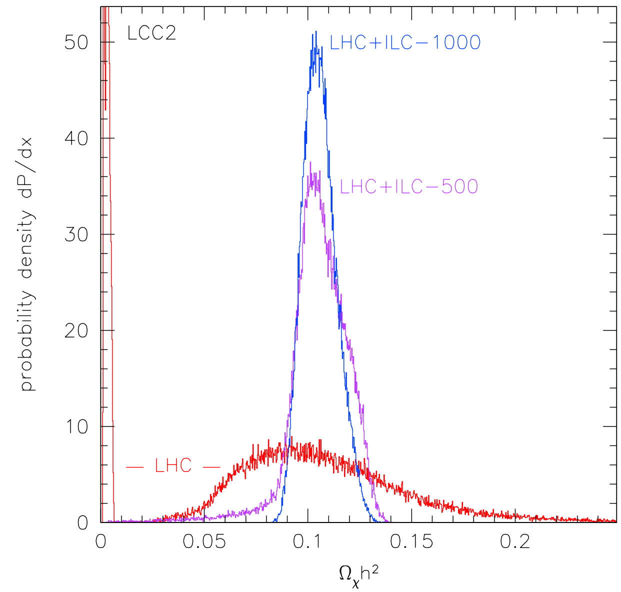
($\sigma \times BR = \sim 40$ fb) may constrain $\tilde{\chi}_2^0$ mass scale to $\sim 10$ GeV

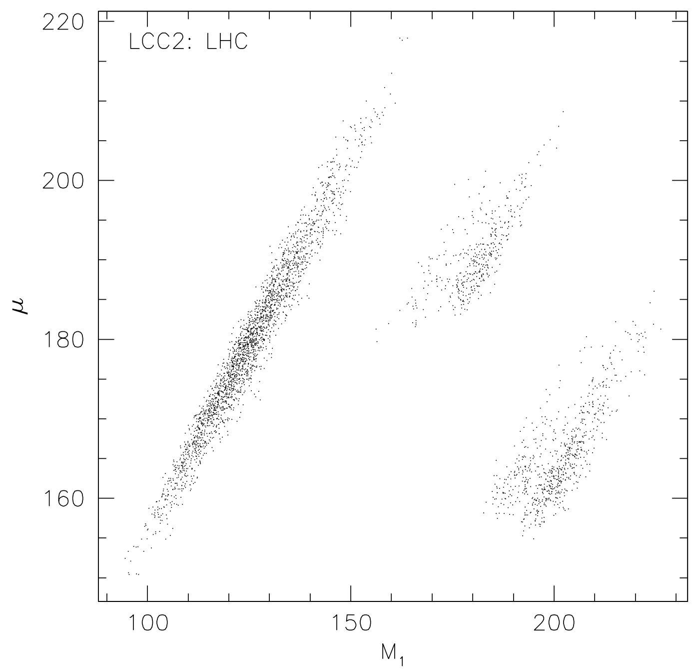
# Focus point: MSSM scan results for relic density

Assume (extrap. from ILC analyses):

- $\Delta(m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)) = 1$ GeV
- $\Delta(m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)) = 1$ GeV
- $\Delta(m(\tilde{\chi}_1^0)) = 10$ GeV

$m(\tilde{\chi}_1^0)$ constraint is based on no explicit analysis




For LHC data three different solution islands in $(M_1, \mu)$ plane, corresponding to bino-, wino-, and higgsino-like neutralino.

Wrong solutions responsible for peak at zero in relic density estimate

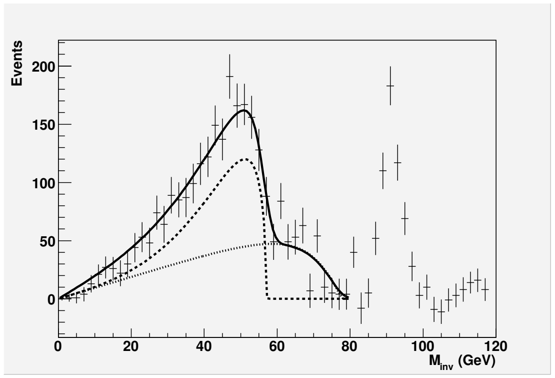
LHC contraints on three neutralino masses not enough to define unique solution

# Focus point: solving the ambiguities

Mearurement of three neutralino masses not enough to fix gaugino mixing

Try to use ratios of BR's, also sensitive to mixing

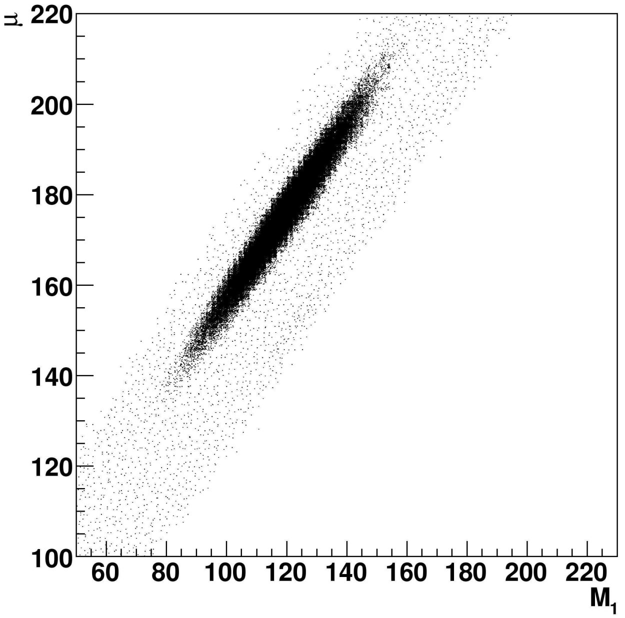
Recent work by White and Feroz (hep-ph/1002.1922).

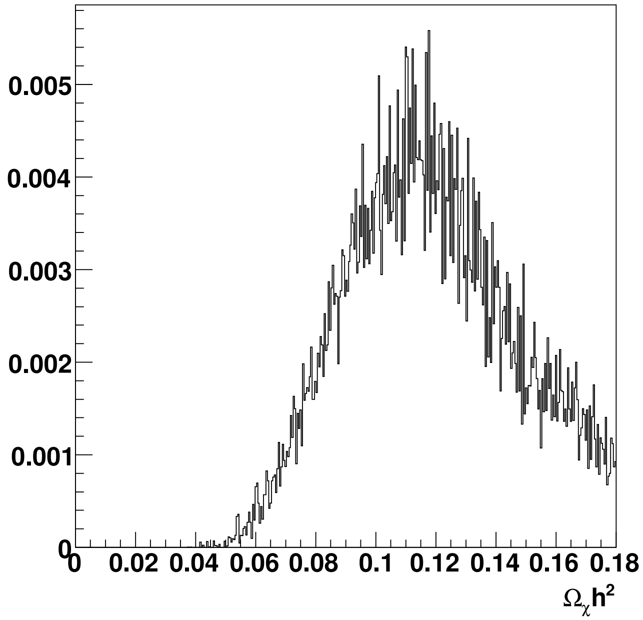



Propose to use the measurement of:

$$\frac{BR(\tilde{g} \to \tilde{\chi}_2^0) \times BR(\tilde{\chi}_2^0 \to \ell^+\ell^-\tilde{\chi}_1^0)}{BR(\tilde{g} \to \tilde{\chi}_3^0) \times BR(\tilde{\chi}_3^0 \to \ell^+\ell^-\tilde{\chi}_1^0)}$$

Ratio measured as $1.4 \pm 0.3$ in ATLAS-PHYS-PUB-2006-023




24-parameter MSSM scan with new constraint: discrimination among possble solutions and prediction of $\Omega_h$

# Conclusions

Already in first 7 TeV run LHC might discover SUSY up to a scale of 7-800 GeV, and give first hints about particle DM

With the 14 TeV run the LHC will be able to measure through kinematic analysis part of the mass spectra and some ratios of couplings for models of new physics

In two test regions with favourable kinematics, it has been shown through detailed studies that LHC information might be able to constrain $\tilde{\chi}_1^0$ relic density

Main LHC weakness is in region of intermediate $\tan\beta$ with heavy Higgs bosons of mass$\gtrsim$300 GeV, where $\tan\beta$ and heavy Higgs masses undetermined

Situation greatly improved with high energy lepton Collider

Combination of results of Collider and DM experiments necessary to achieve global understanding of DM issue

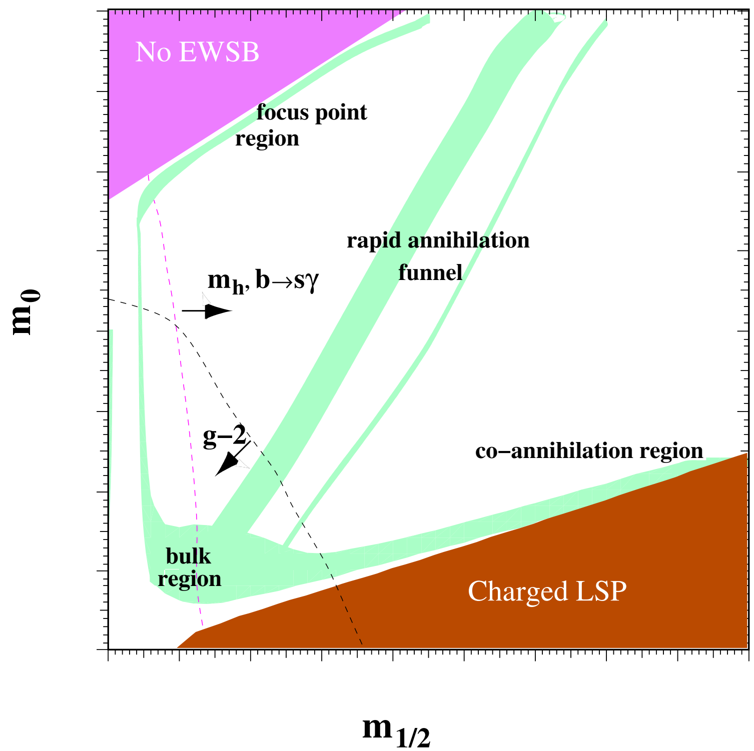
Backup

# ATLAS Benchmarks

Large annihilation sross-section required by WMAP data

Boost annihilation via quasi-degeneracy of a sparticle with $\tilde{\chi}_1^0$, or large higgsino content of $\tilde{\chi}_1^0$

Regions in mSUGRA $(m_{1/2}, m_0)$ plane with acceptable $\tilde{\chi}_1^0$ relic density (e.g. Ellis et al.):




- SU3: Bulk region. Annihilation dominated by slepton exchange, easy LHC signatures fom $\tilde{\chi}_2^0 \to \tilde{\ell}\ell$
- SU1: Coannihilation region. Small $m(\tilde{\chi}_1^0) - m(\tilde{\tau})$ (1-10 Gev). Dominant processes $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to \tau\tau$, $\tilde{\chi}_1^0\tilde{\tau} \to \tau\gamma$
  Similar to bulk, but softer leptons!
- SU6: Funnel region. $m(\tilde{\chi}_1^0) \simeq m(H/A)/2$ at high $\tan\beta$
  Annihilation through resonant heavy Higgs exchange.
  Heavy higgs at the LHC observable up to ∼800 GeV
- SU2: Focus Point high $m_0$, large higgsino content, annihilation through coupling to W/Z
  Sfermions outside LHC reach, study gluino decays.
- SU4: Light point. Not inspired by cosmology. Mass scale $\sim 400$ GeV, at limit of Tevatron reach

# Parameters and cross-sections of benchmark Points

SU1: $m_0 = 70\,\mathrm{GeV}$, $m_{1/2} = 350\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

SU2: $m_0 = 3550\,\mathrm{GeV}$, $m_{1/2} = 300\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$.

SU3: $m_0 = 100\,\mathrm{GeV}$, $m_{1/2} = 300\,\mathrm{GeV}$, $A_0 = -300\,\mathrm{GeV}$, $\tan\beta = 6$, $\mu > 0$.

SU4: $m_0 = 200\,\mathrm{GeV}$, $m_{1/2} = 160\,\mathrm{GeV}$, $A_0 = -400\,\mathrm{GeV}$, $\tan\beta = 10$, $\mu > 0$.

SU6: $m_0 = 320\,\mathrm{GeV}$, $m_{1/2} = 375\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$.

| Signal | $\sigma^{LO}$ (pb) | $\sigma^{NLO}$ (pb) | N |
|---|---|---|---|
| SU1 | 8.15 | 10.86 | 200 K |
| SU2 | 5.17 | 7.18 | 50 K |
| SU3 | 20.85 | 27.68 | 500 K |
| SU4 | 294.46 | 402.19 | 200 K |
| SU6 | 4.47 | 6.07 | 30 K |

| Particle | SU1 | SU2 | SU3 | SU4 | SU6 |
|---|---|---|---|---|---|
| $\tilde{u}_L$ | 760.42 | 3563.24 | 631.51 | 412.25 | 866.84 |
| $\tilde{b}_1$ | 697.90 | 2924.80 | 575.23 | 358.49 | 716.83 |
| $\tilde{t}_1$ | 572.96 | 2131.11 | 424.12 | 206.04 | 641.61 |
| $\tilde{u}_R$ | 735.41 | 3574.18 | 611.81 | 404.92 | 842.16 |
| $\tilde{b}_2$ | 722.87 | 3500.55 | 610.73 | 399.18 | 779.42 |
| $\tilde{t}_2$ | 749.46 | 2935.36 | 650.50 | 445.00 | 797.99 |
| $\tilde{e}_L$ | 255.13 | 3547.50 | 230.45 | 231.94 | 411.89 |
| $\tilde{\nu}_e$ | 238.31 | 3546.32 | 216.96 | 217.92 | 401.89 |
| $\tilde{\tau}_1$ | 146.50 | 3519.62 | 149.99 | 200.50 | 181.31 |
| $\tilde{\nu}_\tau$ | 237.56 | 3532.27 | 216.29 | 215.53 | 358.26 |
| $\tilde{e}_R$ | 154.06 | 3547.46 | 155.45 | 212.88 | 351.10 |
| $\tilde{\tau}_2$ | 256.98 | 3533.69 | 232.17 | 236.04 | 392.58 |
| $\tilde{g}$ | 832.33 | 856.59 | 717.46 | 413.37 | 894.70 |
| $\tilde{\chi}_1^0$ | 136.98 | 103.35 | 117.91 | 59.84 | 149.57 |
| $\tilde{\chi}_2^0$ | 263.64 | 160.37 | 218.60 | 113.48 | 287.97 |
| $\tilde{\chi}_3^0$ | 466.44 | 179.76 | 463.99 | 308.94 | 477.23 |
| $\tilde{\chi}_4^0$ | 483.30 | 294.90 | 480.59 | 327.76 | 492.23 |
| $\tilde{\chi}_1^+$ | 262.06 | 149.42 | 218.33 | 113.22 | 288.29 |
| $\tilde{\chi}_2^+$ | 483.62 | 286.81 | 480.16 | 326.59 | 492.42 |