Searches for dark matter candidates at the LHC

CosPA2009 @ University of Melbourne, Australia

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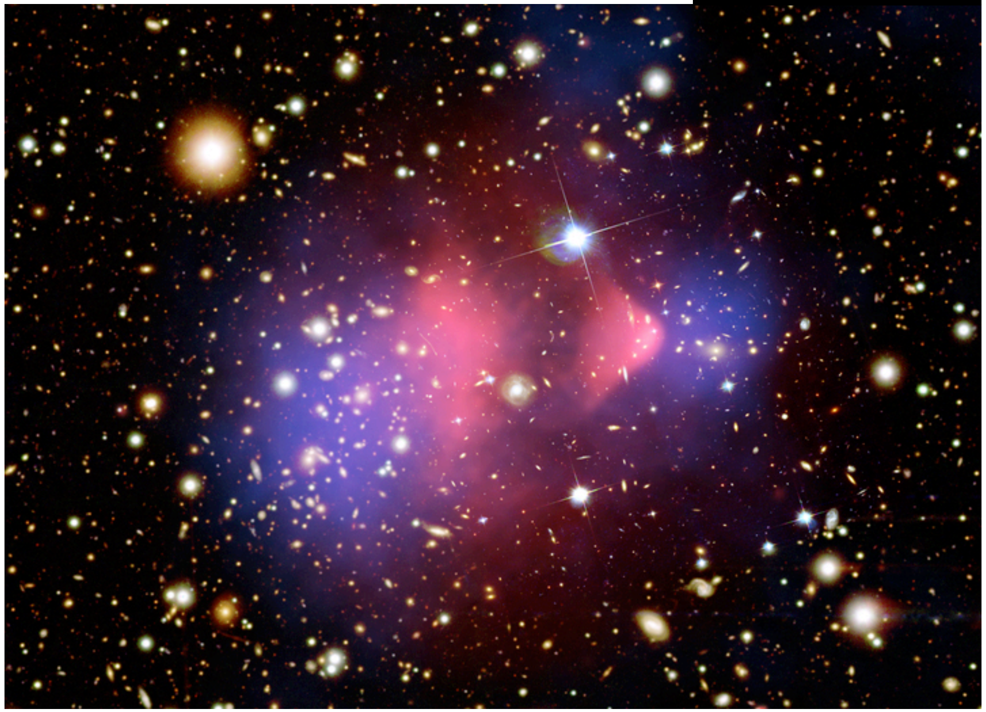
On behalf of the ATLAS and CMS collaborations

http://atlas.ch



Dark Matter···

A variety of evidence in favor of existence dark matter.
But only through its gravitational influence and the identity is unknown.

We may create dark matter particles at LHC and can determine its mass and interactions.

In this talk, I will focus on how to identify a dark matter particle at LHC with supersymmetry neutralino DM scenario because:

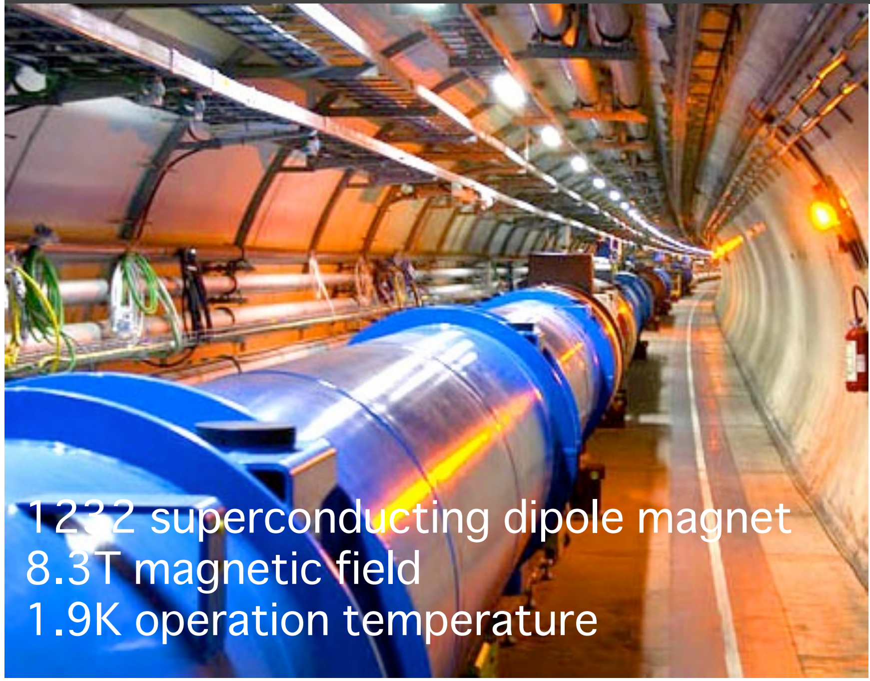
- SUSY is one of the attractive extension of the Standard Model to solve the hierarchy problem, enable grand unification···
- SUSY can provide good WIMP dark matter candidates.
- A lot of study has been done so far with SUSY scenarios.
- Basically, the strategy is applicable for other models with Z_2 parity conservation (UED, Little Higgs···)

Outline of this talk

- LHC experiments
- Inclusive SUSY discovery
- Mass spectrum measurement
- Connection to astro-particle experiments
- Conclusion

LHC experiments - ATLAS and CMS

The LHC machine

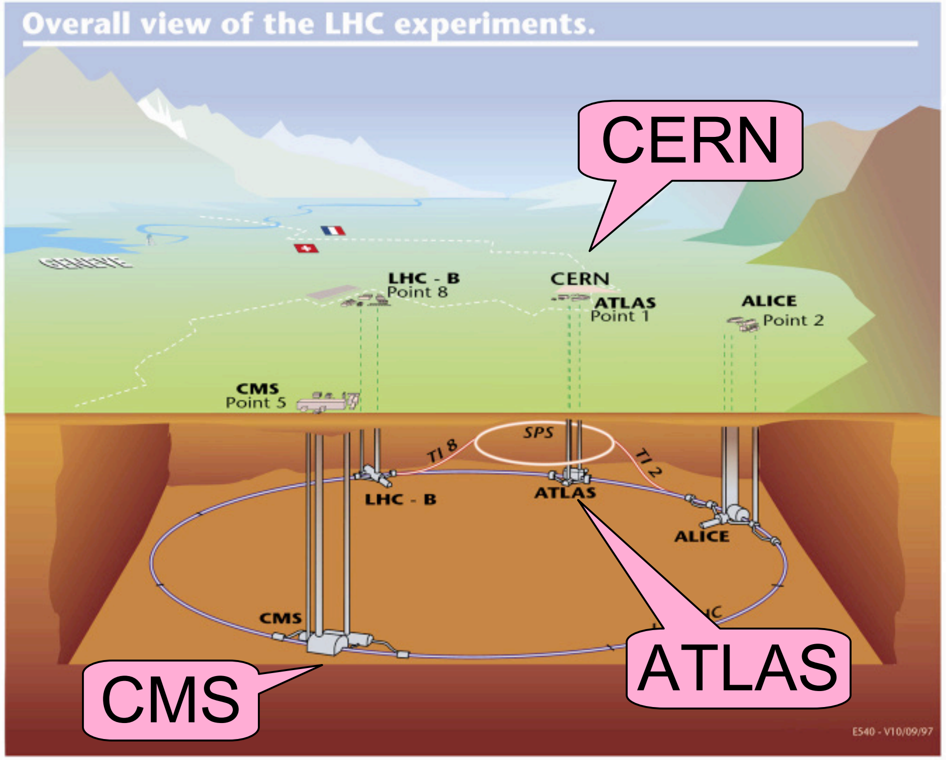


LHC is a proton-proton collider located in Geneve, CERN.

- $\sqrt{s}$=14 TeV at the highest
- design luminosity 10^{34} $cm^{-2}s^{-1}$
- 40MHz bunch crossing

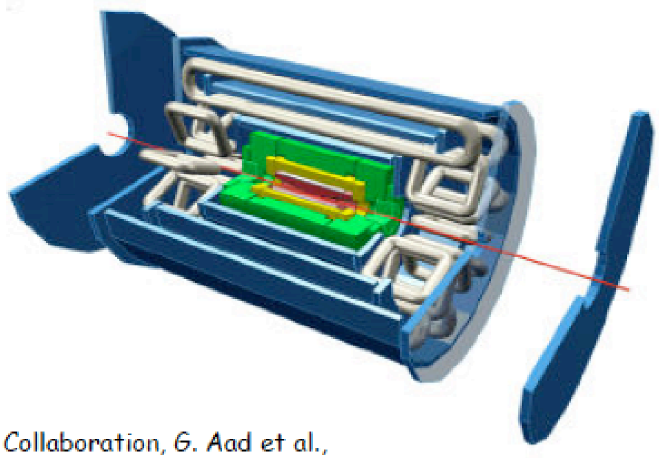
Two multi-purpose detectors located 100m underground, ATLAS and CMS

- LHCb : Bphysics, CP violation
- ALICE : Heavy ion experiment
- TOTEM, LHCf : Very forward physics

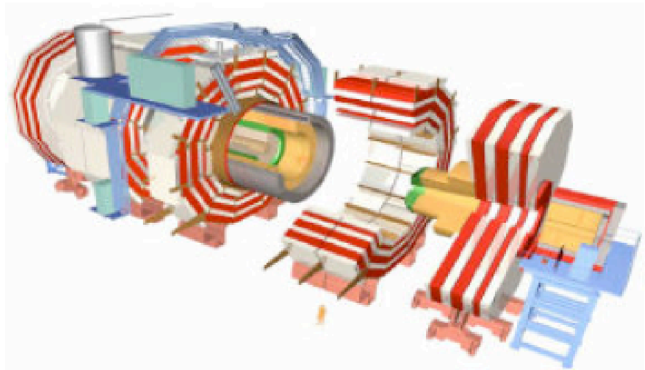


ATLAS and CMS

	ATLAS	CMS
Magnetic field	2 T solenoid + toroid (0.5 T barrel 1 T endcap)	4 T solenoid + return yoke
Tracker	Si pixels, strips + TRT $\sigma/p_T \approx 5\times10^{-4} p_T + 0.01$	Si pixels, strips $\sigma/p_T \approx 1.5\times10^{-4} p_T + 0.005$
EM calorimeter	Pb+LAr $\sigma/E \approx 10\%/\sqrt{E} + 0.007$	PbWO4 crystals $\sigma/E \approx 3\%/\sqrt{E} + 0.003$
Hadronic calorimeter	Fe+scint. / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV	Brass+scintillator (7 λ + catcher) $\sigma/E \approx 100\%/\sqrt{E} + 0.05$ GeV
Muon	$\sigma/p_T \approx$ 2% @ 50GeV to 10% @ 1TeV (ID +MS)	$\sigma/p_T \approx$ 1% @ 50GeV to 10% @ 1TeV (DT/CSC+Tracker)
Trigger	L1 + RoI-based HLT (L2+EF)	L1+HLT (L2 + L3)



The ATLAS Collaboration, G. Aad et al.,
The ATLAS Experiment at the CERN Large Hadron Collider,
JINST 3 (2008) S08003.



The CMS Collaboration, S. Chatrchyan et al.,
The CMS Experiment at the CERN Large Hadron Collider,
JINST 3 (2008) S08004.

LHC Schedule

Particles are back in the LHC at the end of October!
First circulating beam is expected today!
http://op-webtools.web.cern.ch/op-webtools/vistar/vistars.php?usr=LHC1
http://lhc-commissioning.web.cern.ch/lhc-commissioning/news/LHC-latest-news.htm

2009

First Beam
Expected end of November in 2009

First Collisions
$\sqrt{s}$ = 900 GeV (no acceleration at LHC) for a few days?

First High Energy Collisions
$\sqrt{s}$ = 2 TeV ?

2010

High Energy Collisions
$\sqrt{s}$ = 7 TeV , three months
$\sqrt{s}$ = 8-10 TeV , five months
(One month for ion collision in November)

Expected integrated luminosity is 200-300 pb^{-1} in total by the end of 2010

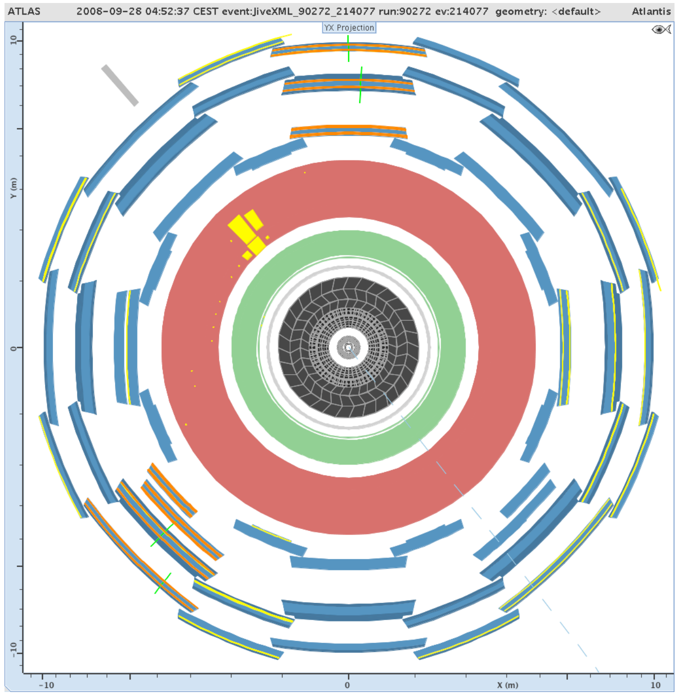
N.B. Numbers shown here have uncertainties.

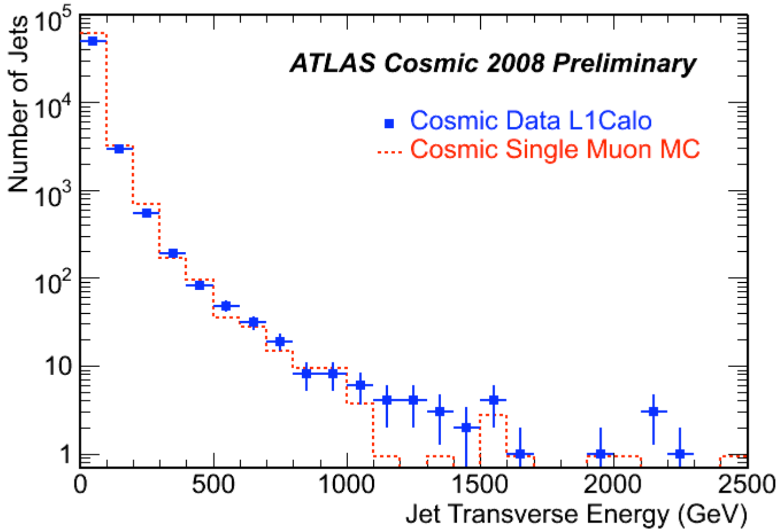
ATLAS/CMS Status & Plan

Need several steps towards new physics discovery: understand our detector, event reconstruction and background.

0) Understanding detector using cosmic-Ray

WE ARE HERE





Day-1

$1\text{-}50\,pb^{-1}$

$>0.1\text{-}1\,fb^{-1}$

1) Understanding detector/reconstruction
2) Re-discovery Standard Model processes
3) Discovery new physics signature..?

SUSY Discovery

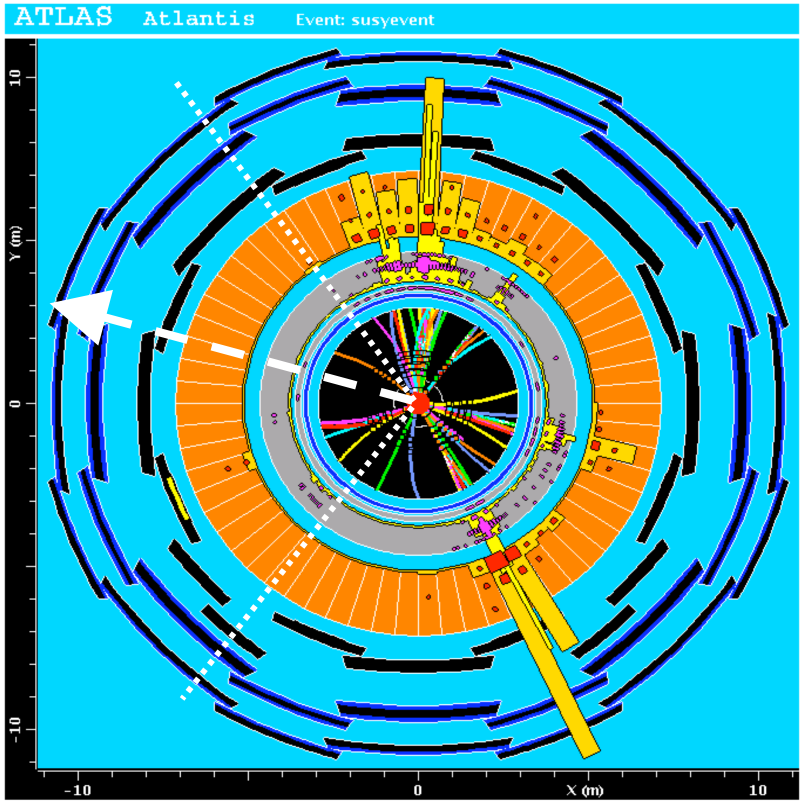
SUSY @ LHC … how it looks like?

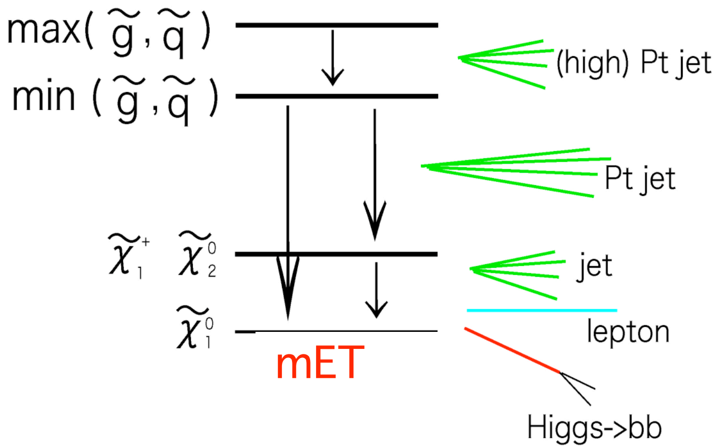
- LHC is a p-p collider:

→Large production cross-section for colored sparticles

- WIMPs/neutralinos (RPC) escape detection:

→Large missingET(mET = $-\Sigma \vec{p}_{T,\mathrm{visisble}}$) in the final state.

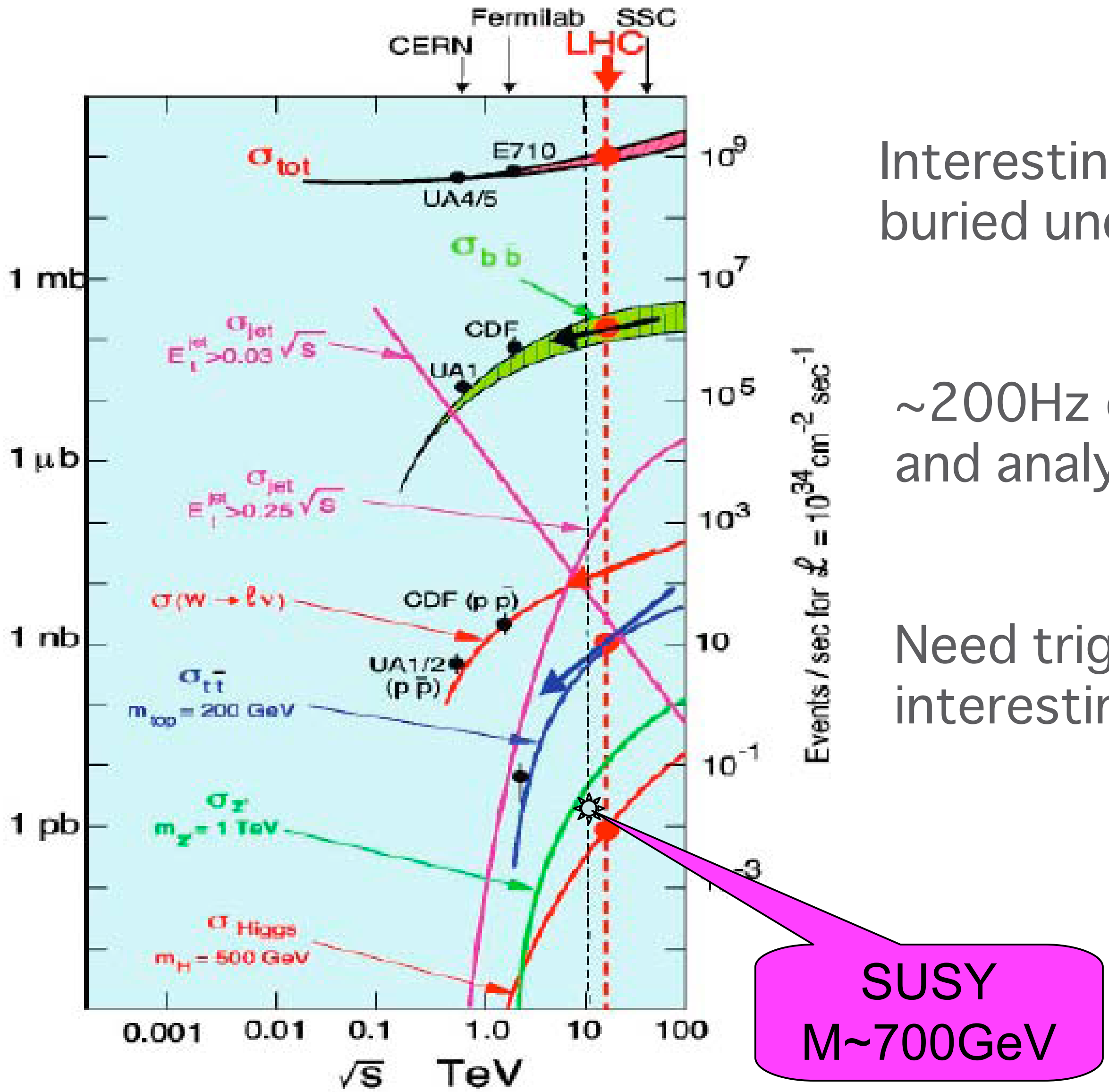




mET is a key parameter(WIMP signature!) and also powerful to distinguish signal and SM background.

Searches for mET + multijets + X

Inclusive Analysis for Discovery mEt + jets + X



Interesting physics processes are buried under huge background.

~200Hz of data can be recorded and analyzed.

Need trigger strategies to take interesting events effectively.

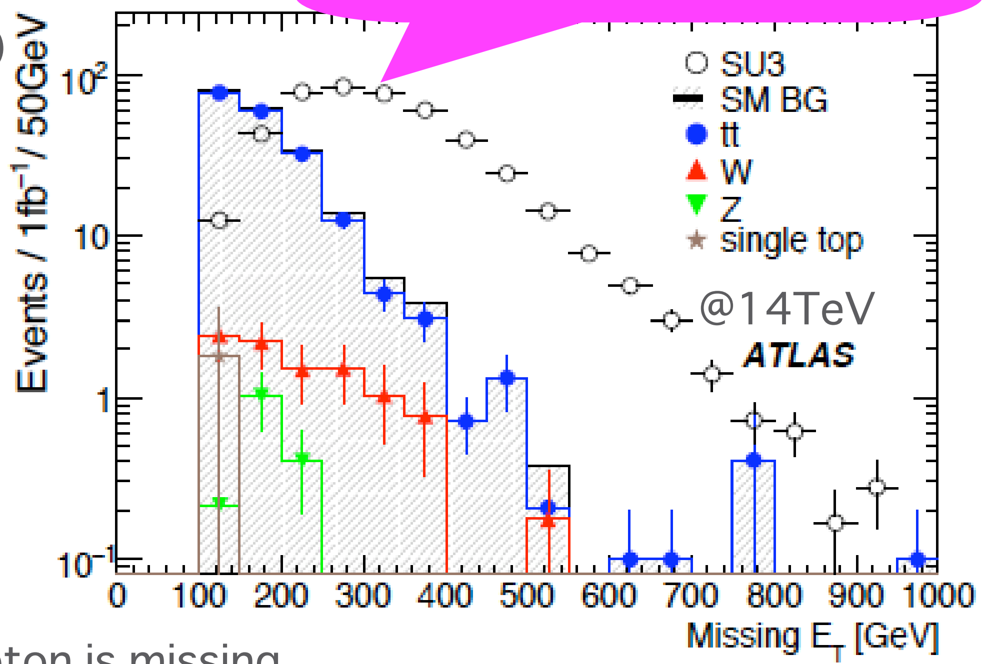
Inclusive Analysis for Discovery mET + jets + X

Example inclusive selection
mET + jets + 1lepton

(Result shown here is for $\sqrt{s}$=14TeV, 1fb^{-1})

- # of jets ≥4 (p_T>50GeV,|η|<2.5)
- p_T^{1st} > 100GeV
- mET>max(100GeV, 0.2Meff)
- s_T(sphericity)>0.2
- m_T(mET,l)>100GeV
- # of leptons=1 (p_T>20GeV)

SU3 bench mark point
M_{SUSY}~700GeV, bulk region



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Background composition

- 90% for tt (bblvlv) ← One lepton is missing
- 10% for W

One of most promising discovery channels

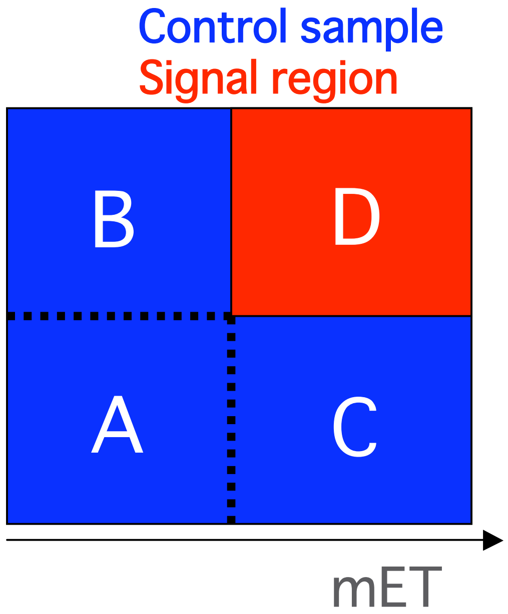
Requiring one lepton will suppress dangerous QCD background
(huge cross-section, large uncertainties)

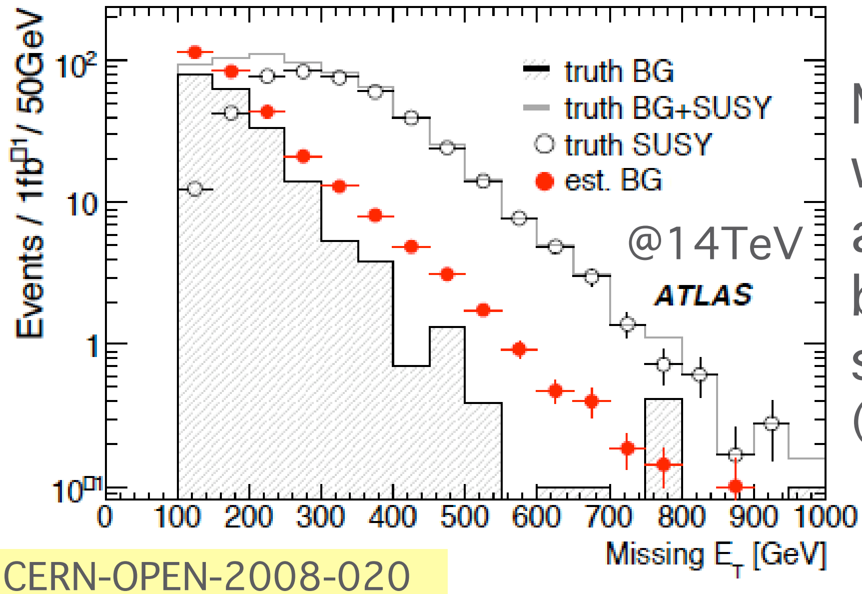
Background Estimation

We cannot rely on Monte Carlo at the beginning.
→Estimate SM background by data-driven way
(side band technique, D=CxB/A)

Not always possible to take clean control samples.
(SUSY contamination in control sample->overestimate)

However, discovery is promising!





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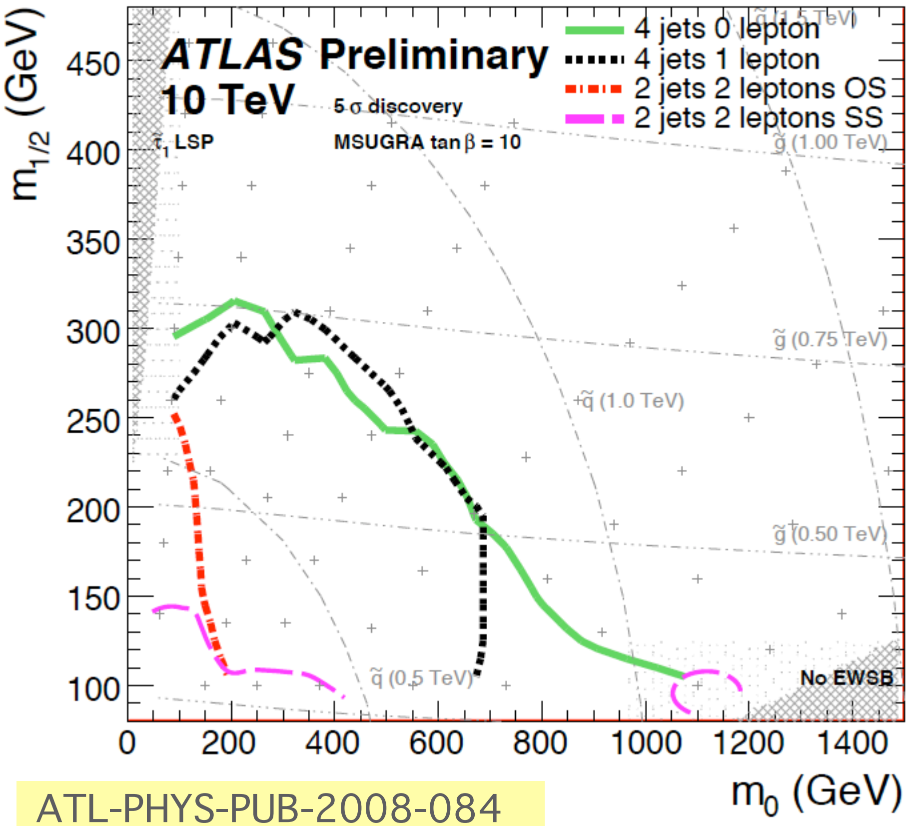
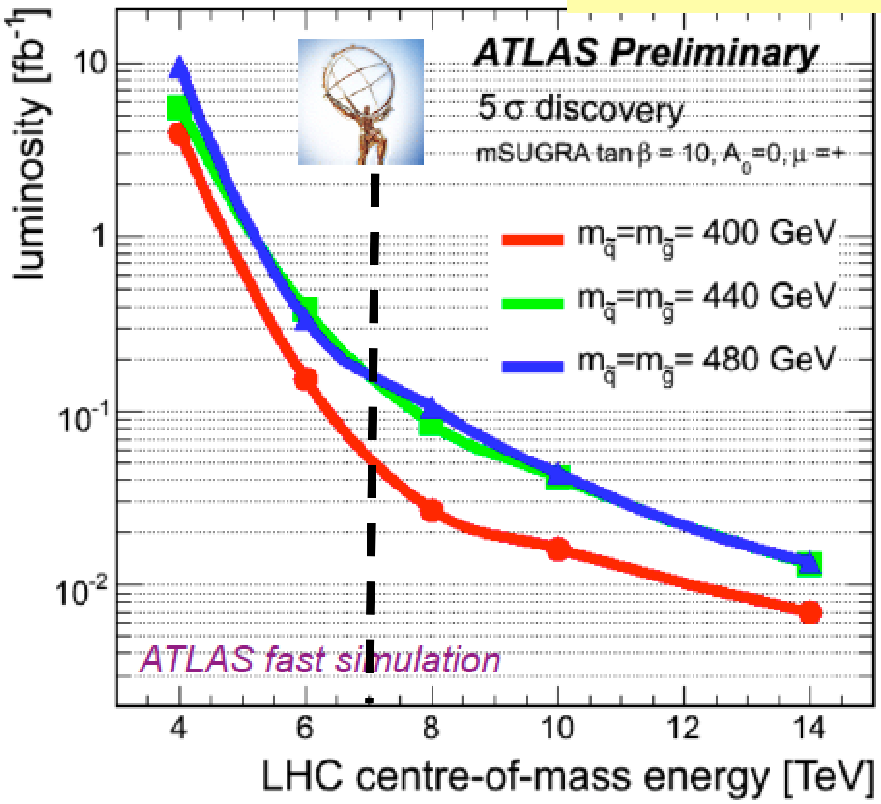
More precise background estimation will be done by using Monte Carlo as an extra source of information on background predictions for cross-section measurement etc.
(Need sufficient data to validate Monte Carlo)

Discovery Reaches (@10TeV)

The discovery reach strongly depends on SUSY mass scales (strong coupling).
Current Tevatron exclusion limit ~390GeV for $m(\tilde{q}) \sim m(\tilde{g})$ case.

Chamonix2008





ATL-PHYS-PUB-2008-084

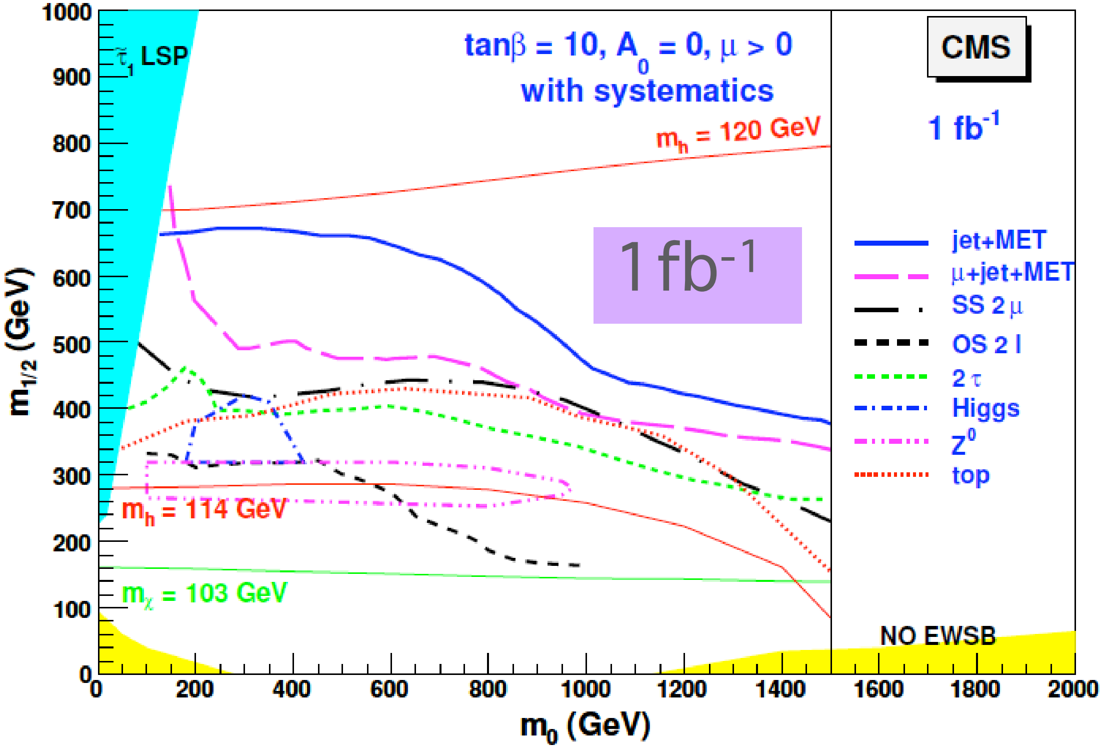
The discovery reach is ~700GeV in $m(\tilde{q}) \sim m(\tilde{g})$ case
with $200pb^{-1}$@10TeV.

Discovery Reaches (@14TeV)

Discovering SUSY in the various final states:

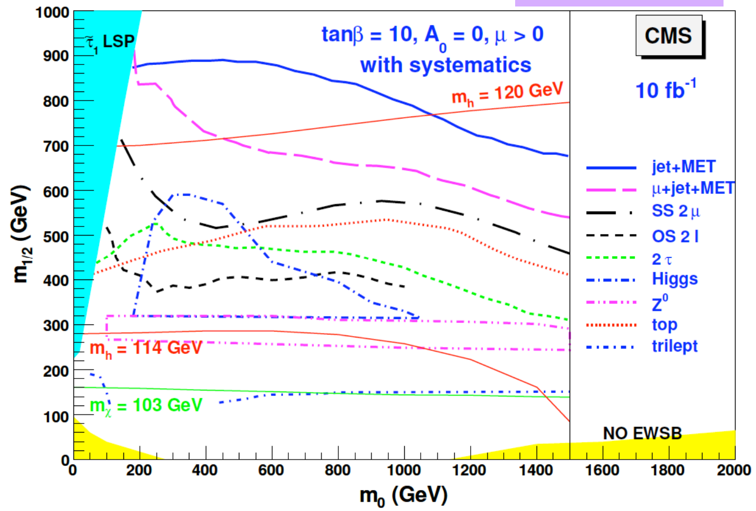
mET + jets + X(=di-lepton, higgs, tau, top…)

→ Multiple observation gives strong hints to know what type of SUSY(mass spectrum, coupling) is favored.



CERN-LHC-2006-021

$10fb^{-1}$



The discovery reach is ~1.5TeV in $m(\tilde{q})\sim m(\tilde{g})$ case with $1fb^{-1}$@14TeV (~2TeV with $10fb^{-1}$@14TeV)

Exclusive analysis (measurement)

After Discovery···

Inclusive analysis

Establish the discovery of large mET signatures after understanding detector and background

Possible to identify preferable scenarios, e.g. heavy squark case, light 3rd generation···

- Refine background estimation
- mET + jets + X(taus, b-jets, tops···)

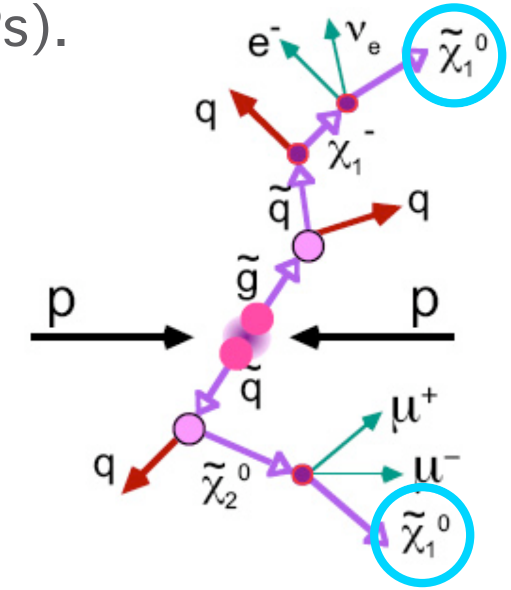
Exclusive analysis

SUSY mass spectrum measurement

Ultimate mass, coupling (and spin) measurements

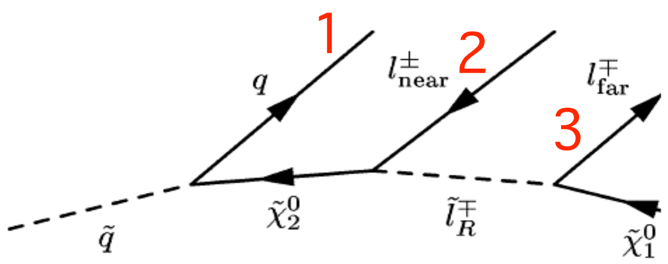
Mass measurement

Several techniques have been developed for measuring SUSY masses in the events with mET (dominantly from two WIMPs).



A mass peak is not reconstructed and WIMPs are not detected … how to know mass spectrum?

Measure multiple endpoints in invariant masses



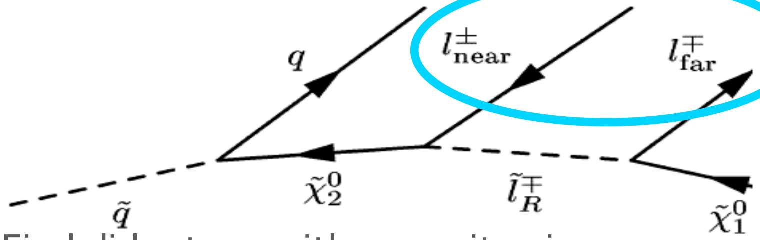
In three successive two-body decays, we can reconstruct invariant masses of (12)(13)(23)(123) and measure their maxima (minima) → Obtain more than three constraints wrt four unknown masses.

Measure endpoints in invariant masses reconstructed by identified decay products in the same decay chain

→ Obtain an individual mass appear in the decay.

Di-lepton edge

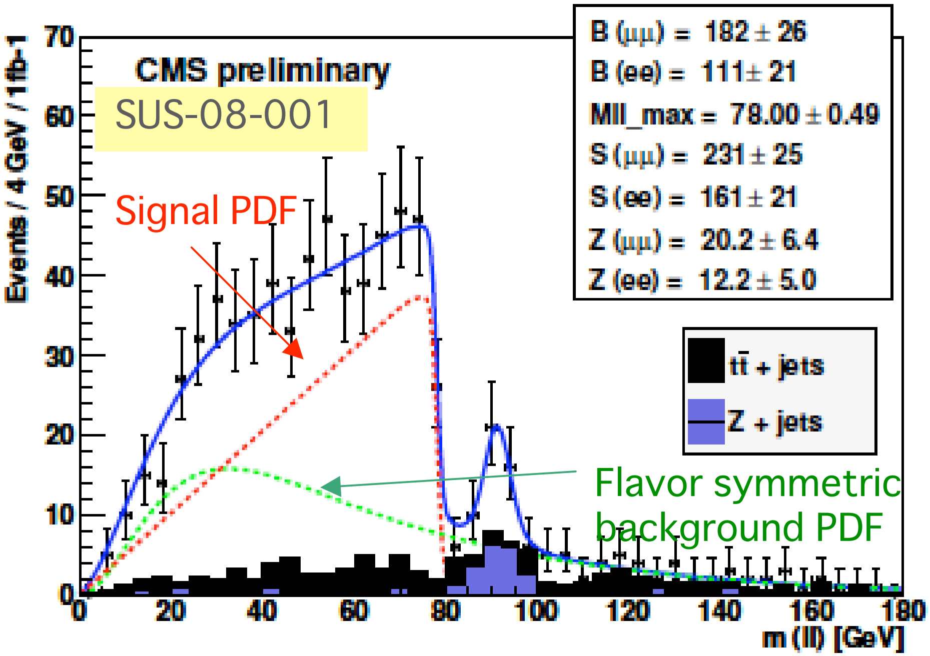
Assume a decay chain with two leptons(e,μ). A lepton is reconstructed good resolution(0.1% ultimately) and high efficiency (80-90%)



Find di-leptons with opposite sign
And same flavour(e or μ)

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

M(ll) endpoint gives the mass relation among three sparticles.



Background PDF to flavor-symmetric signal can be estimated by different flavor events (eμ).

$$N(\mu\mu) = \frac{1}{2} \times \frac{\epsilon^{\mu}}{\epsilon^{e}} \times N(e\mu)$$

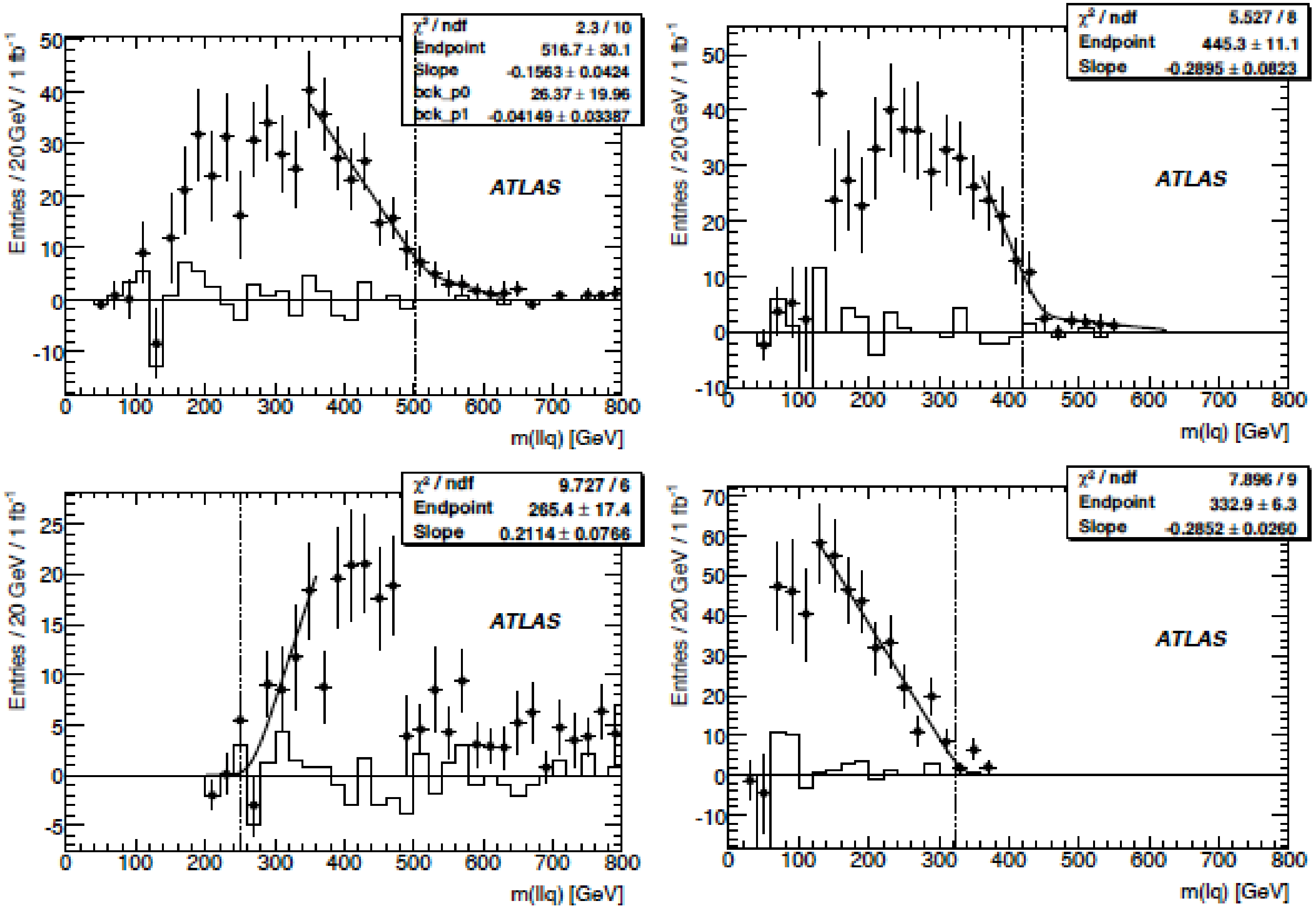
LM1(M_{SUSY}~550GeV), 1fb^{-1}
$M_{\mu\mu}$=78.03 ± 0.75 ± 0.18 GeV
(truth=78.15GeV)

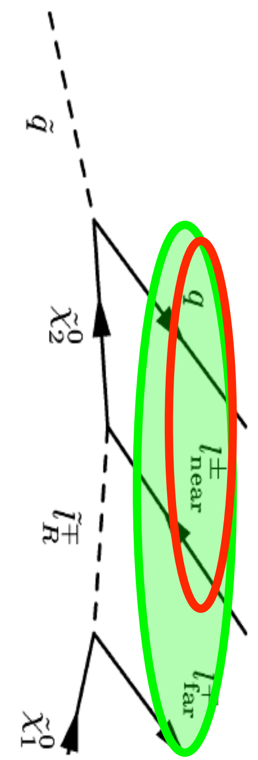
Leptons + Jets edges

There is an ambiguity in selecting leptons and jets combination.

→ Combinatorial SUSY background is the main source of the tail.

Although the edge and the threshold are successfully reconstructed with accuracy of 5-10% with 1fb^{-1} for SU3(M_{SUSY}~700GeV).





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Mass and parameters fit

Mass differences are more reliably measured than individual masses since kinematic endpoints are directly related to mass differences.

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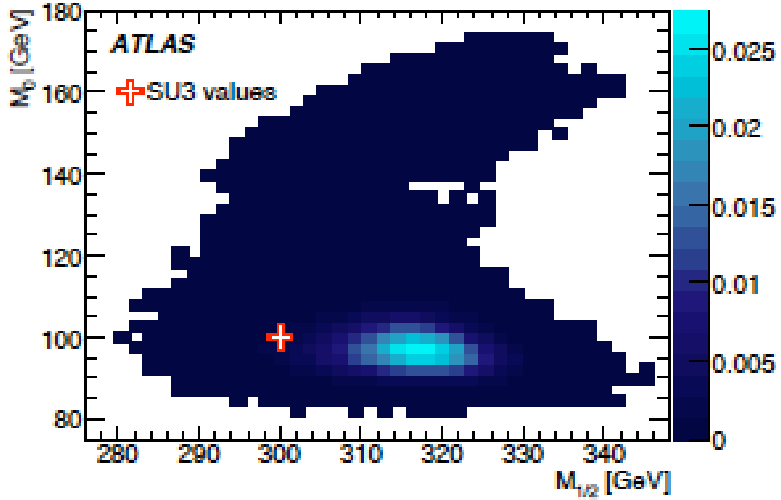
1 fb^{-1}

Observable	SU3 m_{meas} [GeV]	SU3 m_{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
$m_{\tilde{l}}$	$122 \pm 61 \mp 2$	155
Observable	**SU3 Δm_{meas} [GeV]**	**SU3 Δm_{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
$m_{\tilde{l}} - m_{\tilde{\chi}_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6

Interpret experimental measurements
In mSUGRA parameter spaces



B.K.Gjelsten et al (ATLAS-PHYS-2004-007)

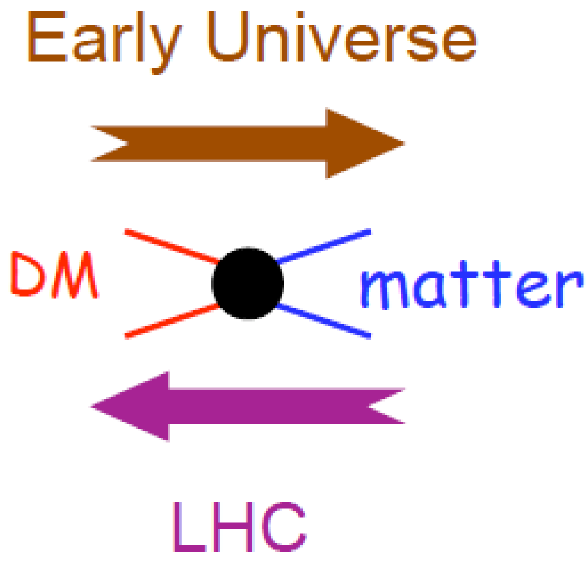
100 fb^{-1}

Edge	Nominal Value	Fit Value	Syst. Error Energy Scale	Statistical Error
$m(ll)^{edge}$	77.077	77.024	0.08	0.05
$m(qll)^{edge}$	431.1	431.3	4.3	2.4
$m(ql)^{edge}_{min}$	302.1	300.8	3.0	1.5
$m(ql)^{edge}_{max}$	380.3	379.4	3.8	1.8
$m(qll)^{thres}$	203.0	204.6	2.0	2.8
$m(bll)^{thres}$	183.1	181.1	1.8	6.3

Expected performance for SPS1

Sparticle	Expected precision (100 fb^{-1})
$\tilde{q}_L$	± 3%
$\tilde{\chi}^0_2$	± 6%
$\tilde{l}_R$	± 9%
$\tilde{\chi}^0_1$	± 12%

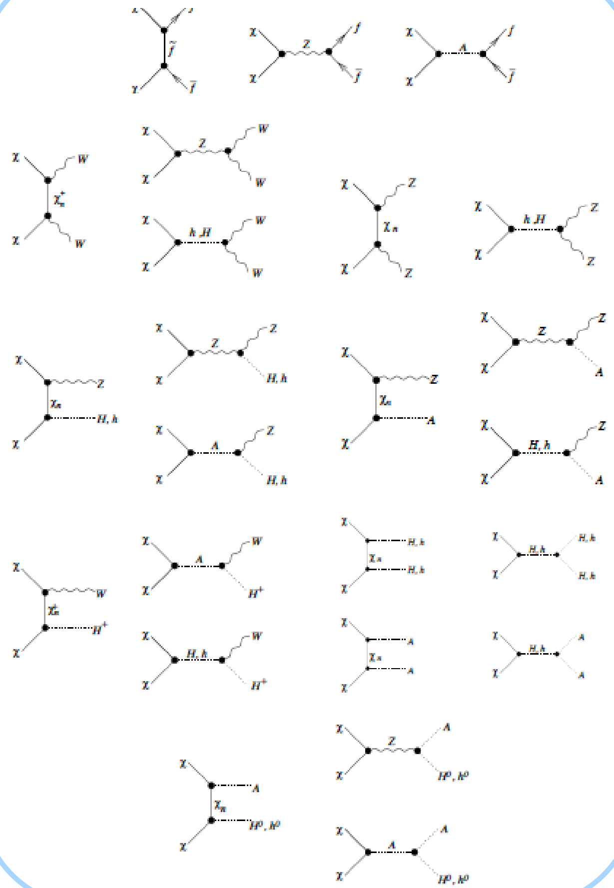
Interpretation:
Connection to astro-particle physics



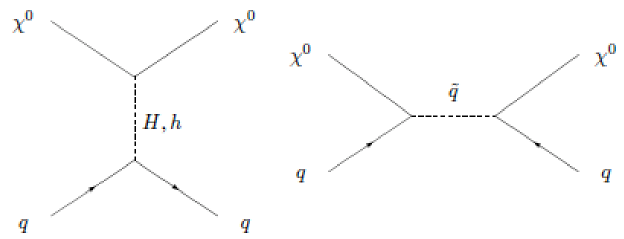
Connection to astro-particle experiments (1)

For direct comparison with result obtained by direct/indirect detection, need to calculate χ-nucleon elastic scattering cross-section and relic density.

Neutrino annihilation



Neutrino annihilation



Not possible to access all SUSY parameters (mass, coupling,property) needed for the calculation. But possible to identify which processes are relevant or not.
Also compare hep/astro experimental results by interpreting within the certain SUSY model

References

Polesello, Tovey JHEP0405(071)
Nojiri, Polesello,Tovey JHEP0603(063)
Baltz,Battaglia, Peskin,Wizansky PRD74:103521(206)

Connection to astro-particle experiments (2)

Ultimate precise measurement with 300 fb^{-1} for sps1a

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

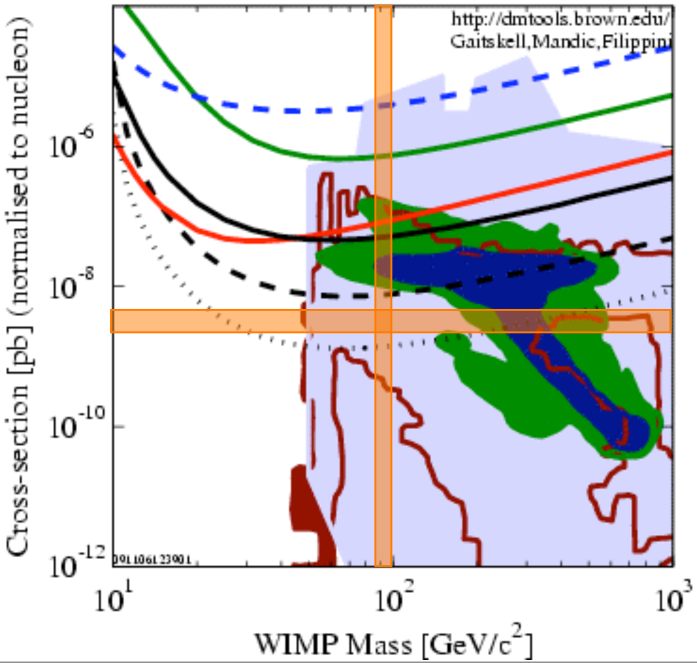
G.Polesello, D.Tovey JHEP0405(071)

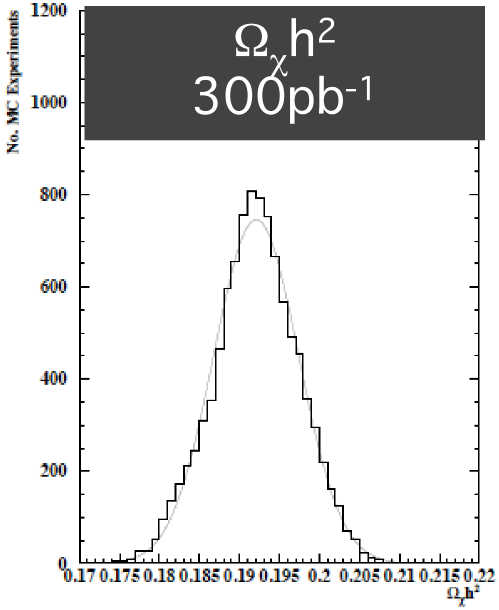
Interpret experimental results under mSUGRA model assumption.

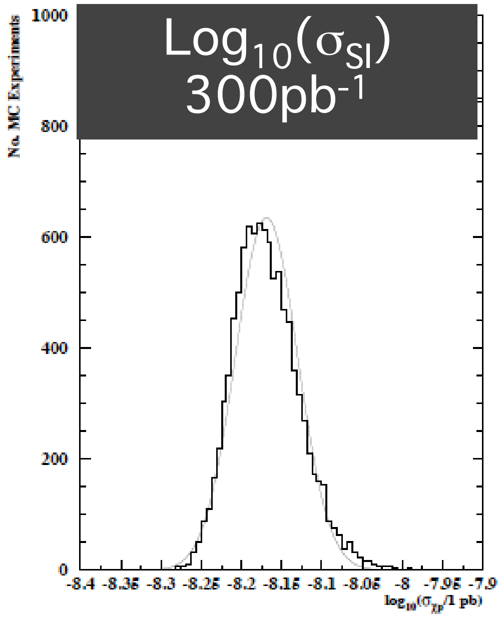
$$m(\chi) = 96.05 \pm 4.7 GeV$$

$$\log_{10}(\sigma_{\chi p}/1pb) = -8.17 \pm 0.04$$

$$\Omega_\chi h^2 = 0.192 \pm 0.0053$$



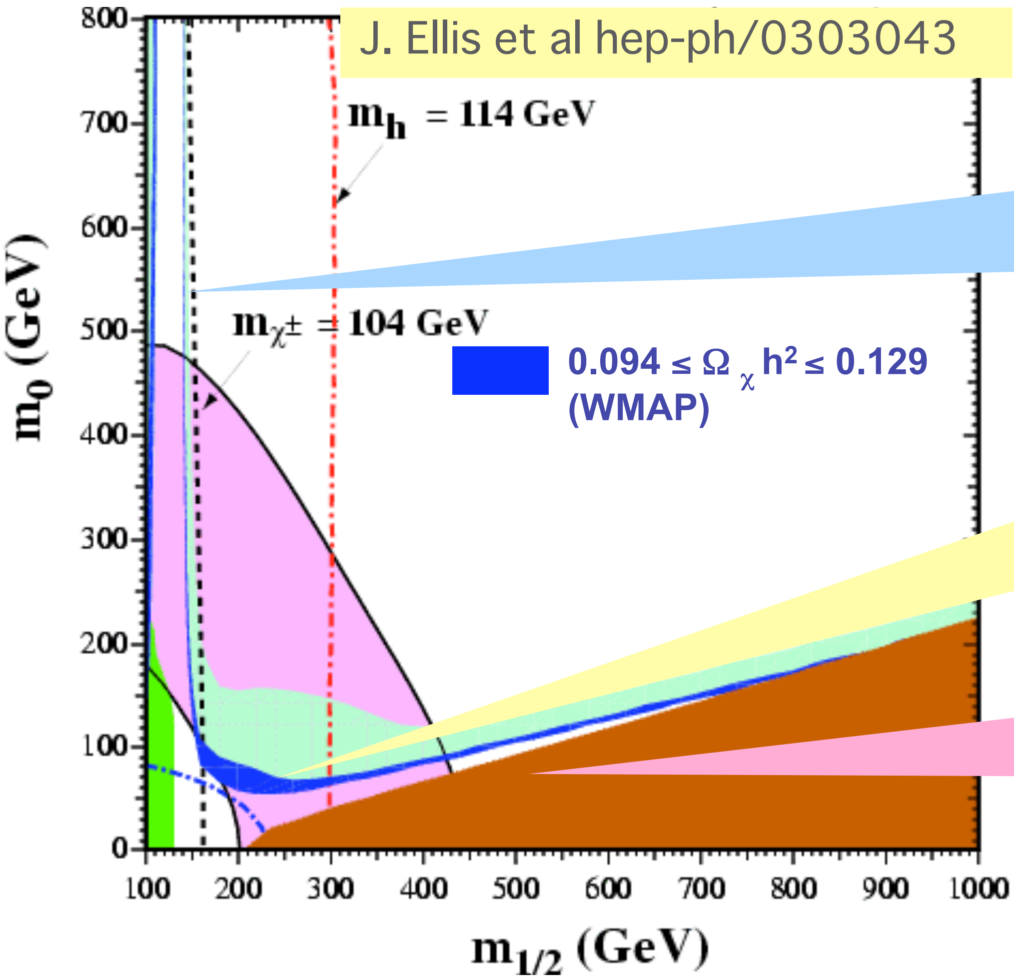




Connection to astro-particle experiments (3)

The accuracy and model dependency strongly depends on which SUSY breaking model/parameter regions the nature has chosen

→which BR and masses can be measured in p-p collision events.



Focus point ($\tilde{\chi}\tilde{\chi}$→VV)

Sufficient higgsino component to boost annihilation rates to W/Z. Heavy squarks(small σ) and stop/sbottom appear in decay

Bulk region ($\tilde{\chi}\tilde{\chi}$→ll)

Preferable region for LHC. Since many decay patterns are observed.

co-annihilation($\tilde{\tau}\tilde{\chi}$→τZ/γ)

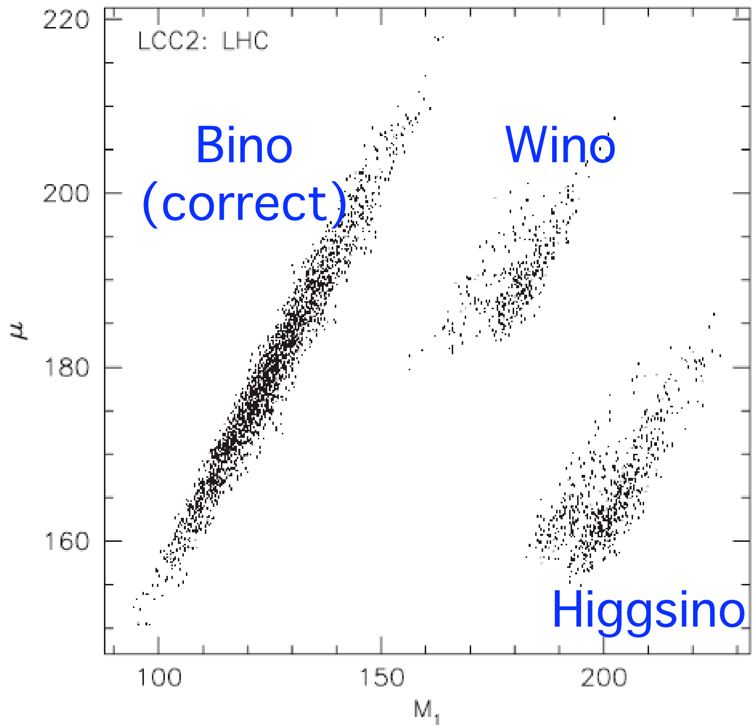
Difficult to identify tau due to the small mass difference ΔM($\tilde{\chi}\tilde{\tau}$), ie. low p_T tau)

Connection to astro-particle experiments (4)

One of less favored examples : Focus point

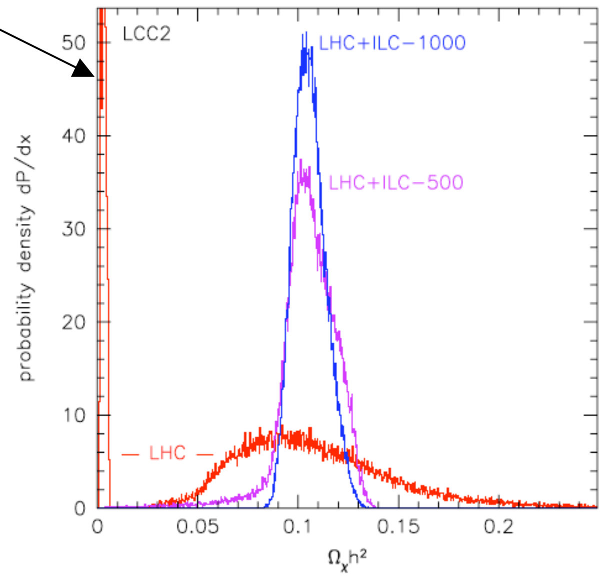
- heavy sfermions
- gaugino-Higgsino mixing χ

Mass/mass splitting	LCC2 value		LHC	ILC 500	ILC 1000
$m(\tilde{\chi}_1^0)$	107.9	±	10	1.0	
$m(\tilde{\chi}_2^0) - m(\tilde{\chi}_1^0)$	58.5	±	1.0	0.3	
$m(\tilde{\chi}_3^0) - m(\tilde{\chi}_1^0)$	82.3	±	1.0	0.2	



Large ambiguity in the neutralino components due to only two precise mass-difference measurements

Can reject incorrect solution with additional constraints $m(\chi^+)>125$GeV



Baltz,Battaglia, Peskin,Wizansky PRD74:103521(206)

Conclusion

The LHC machine is under commissioning and will be ready for high energy collision in the near future.

SUSY discovery(R-parity conserved) is rather promising if SUSY mass scale is within kinematically accessible region.

The LHC cannot distinguish between stable and long-lived dark matter particles, but provide its mass and property.
The accuracy/impact depends on which SUSY is selected by the nature.

The LHC cannot provide information on cosmological abundance, halo density etc, but provide underlying theory behind dark matter particles.

ATLAS & CMS results

- ATLAS Recent result https://twiki.cern.ch/twiki/bin/view/Atlas/AtlasResults
- ATLAS TDR http://cdsweb.cern.ch/record/1125884?ln=en
- CMS Recent result https://twiki.cern.ch/twiki/bin/view/CMS/PhysicsResults
- CMS TDR http://cmsdoc.cern.ch/cms/cpt/tdr/