Search for Dark Matter at Colliders

Recontres de Blois 2008
May 18-23, 2008

Naoko Kanaya
Universtiy of Tokyo / ICEPP
(on behalf of ATLAS/CMS)

Contents

- LHC experiment
- How to search/study DM candidate @ LHC

  SUSY is one of examples which has dark matter candidate.
  The strategy will be applicable to other models.
- How to connect to astrophysics
- Summary

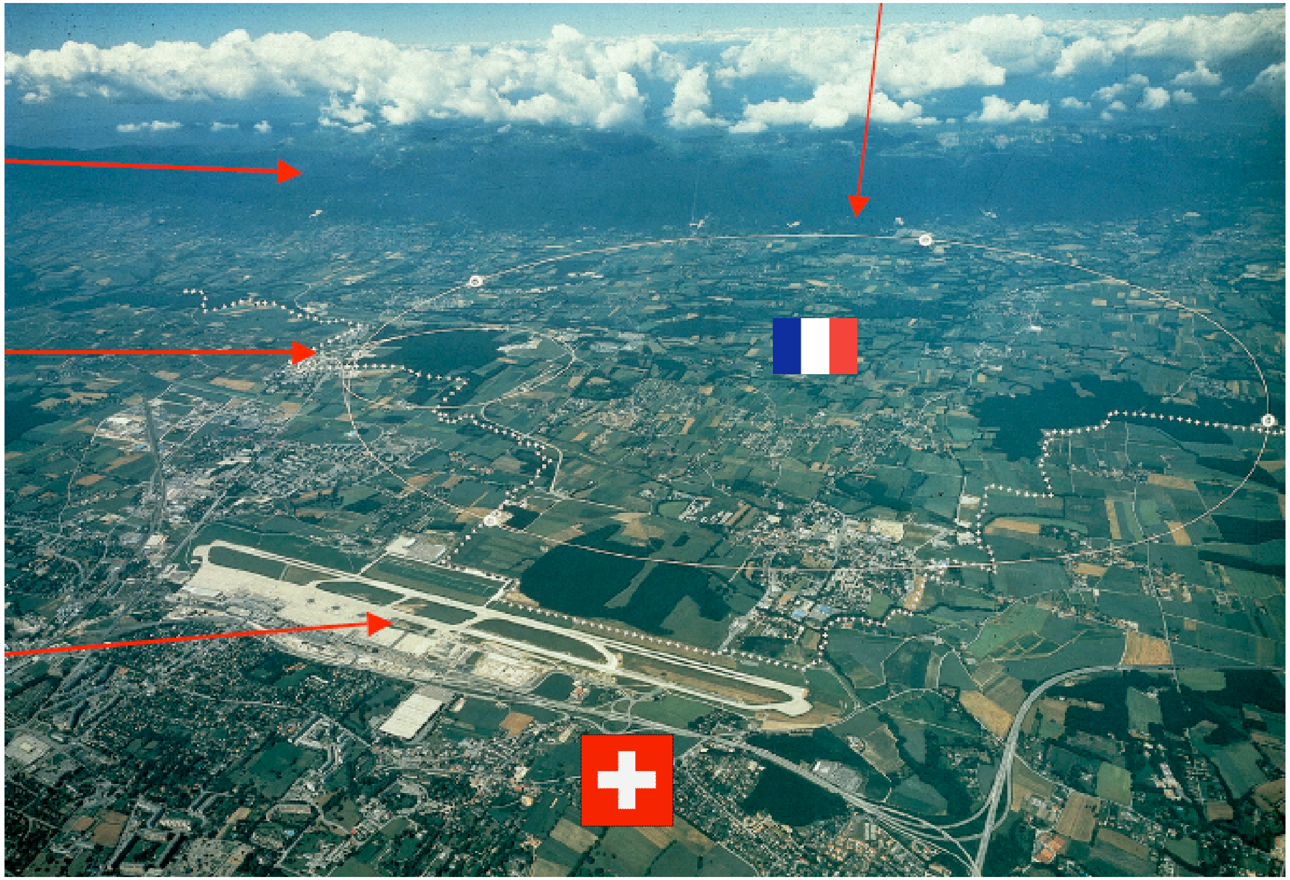
Large Hadron Collider (LHC)

LHC ring:27km in circumference
@~100m underground

Mt.Jura

CERN

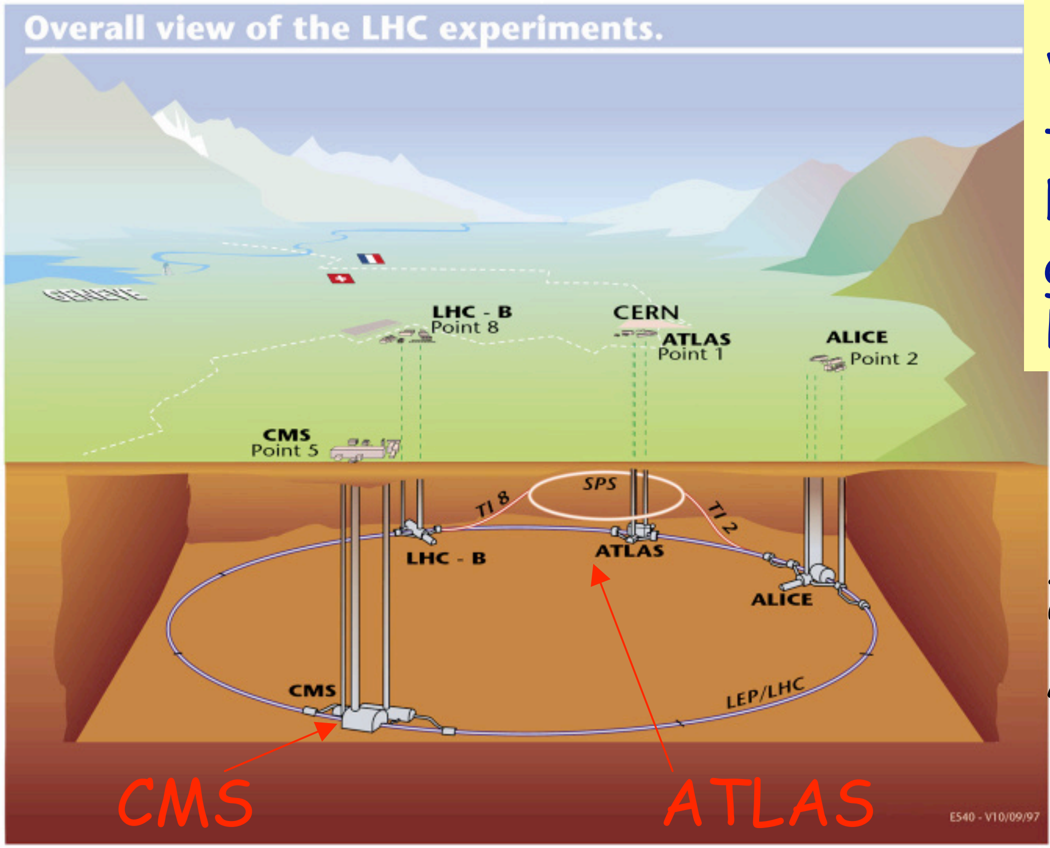
Geneve
airport



Large Hadron Collider (LHC)

- proton-proton collider with $\sqrt{s}$=14TeV
- 40MHz, design luminosity is $10^{34}cm^{-2}s^{-1}$
- high energy & huge event statistics

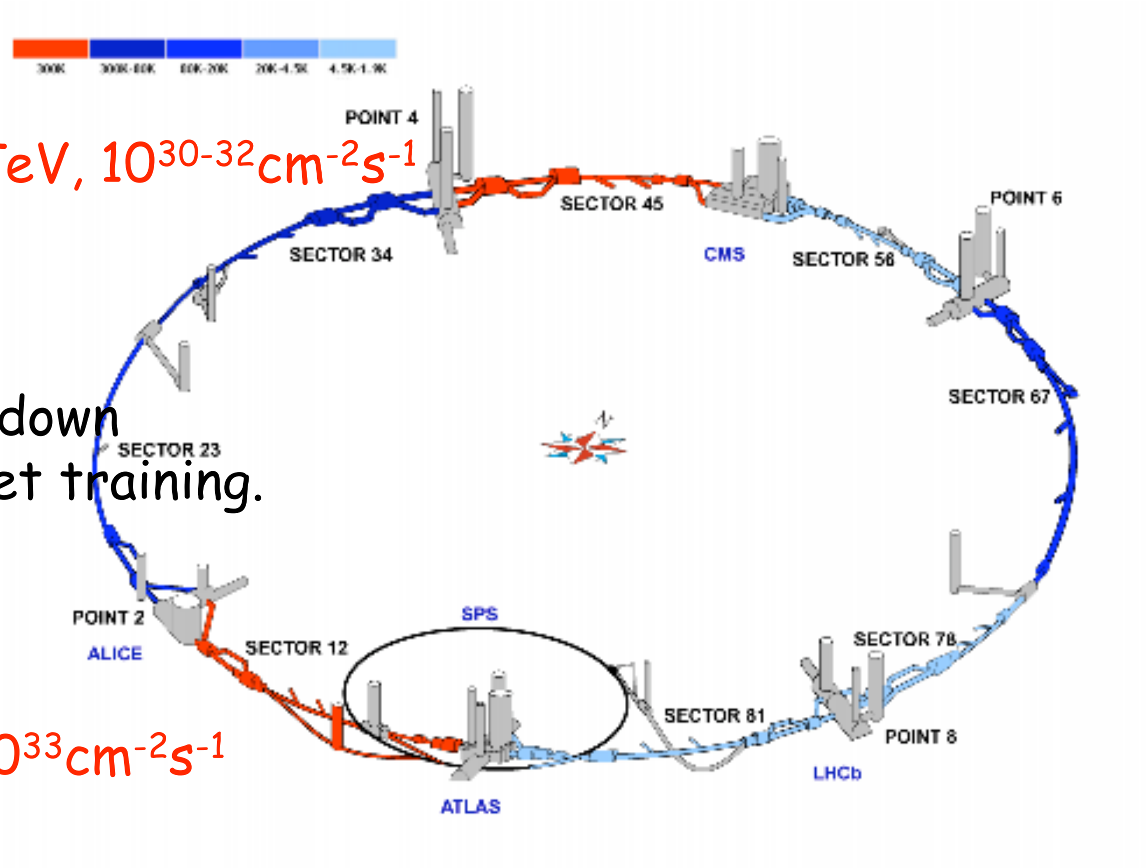
Process	Rate (10^{33})	evt/year (10^{33})
W(eν)	15	10^8
tt	1	10^7
h(130GeV)	0.02	10^5
gg(1TeV)	0.001	10^4
BH(3TeV)	0.0001	10^3



2 multi-purpose detectors
ATLAS and CMS

LHC status

- 2008 End of June : The LHC will be expected cool down.
- 2008 Mid of July : The experimental caverns will be closed.
- 2008 End of July : First particles will be injected.
  The commissioning with the beams and collision will start.

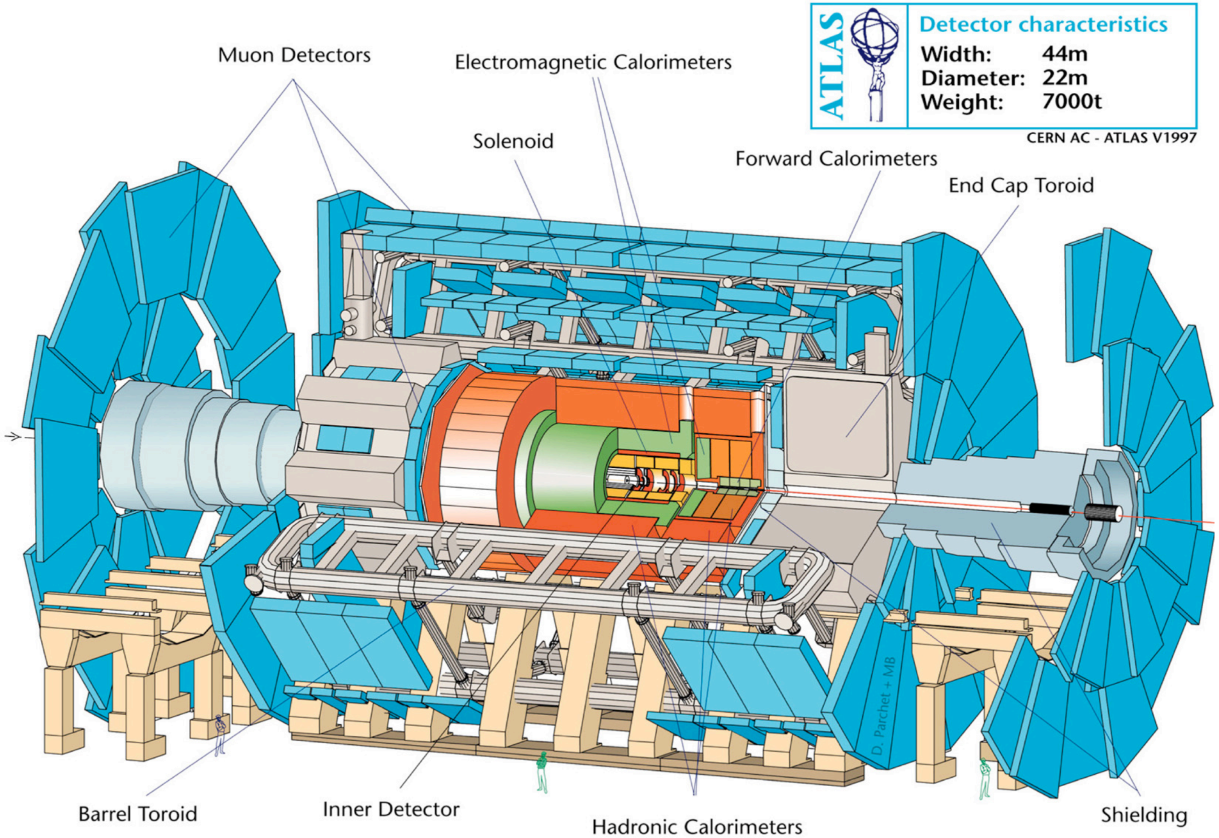


- 2008 Aug-Sep? :
  First collisions @ $\sqrt{s}$~10TeV, $10^{30\text{-}32}cm^{-2}s^{-1}$

- End of Nov : winter shutdown
  commissioning and magnet training.

- 2009 :
  Start with $\sqrt{s}$=14TeV, ~$10^{33}cm^{-2}s^{-1}$

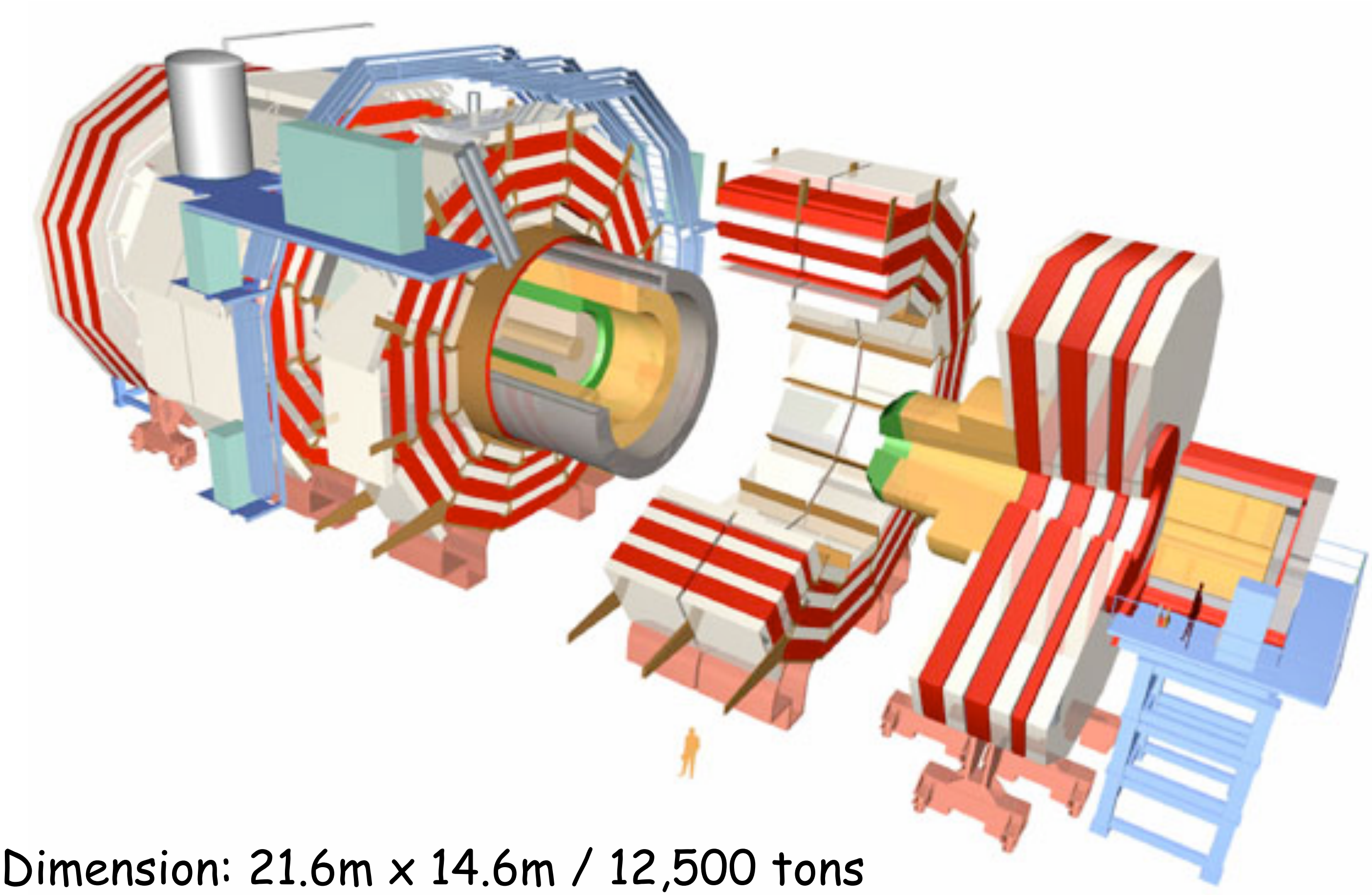
ATLAS (A Troidal Lhc ApparatuS)



- 44m x 22m / 7000tons
- 2T solenoid + Aircore Toroid Magnet
- Hadron calorimeter with good resolution
- Calorimeter with fine granularity and lateral segmentation

$\sigma(E) \sim 50\%\sqrt{E}$ for jet
$\sigma(E) \sim 1\%$ for electron (100GeV)
$\sigma(PT) \sim 3\%$ for muon (100GeV)

CMS (Compact Muon Solenoid)



- Dimension: 21.6m x 14.6m / 12,500 tons
- 4T superconducting solenoid, Fe yoke
- All silicon inner-tracker
- $PbWO_4$ EM calorimeter
- Calorimeter inside magnet

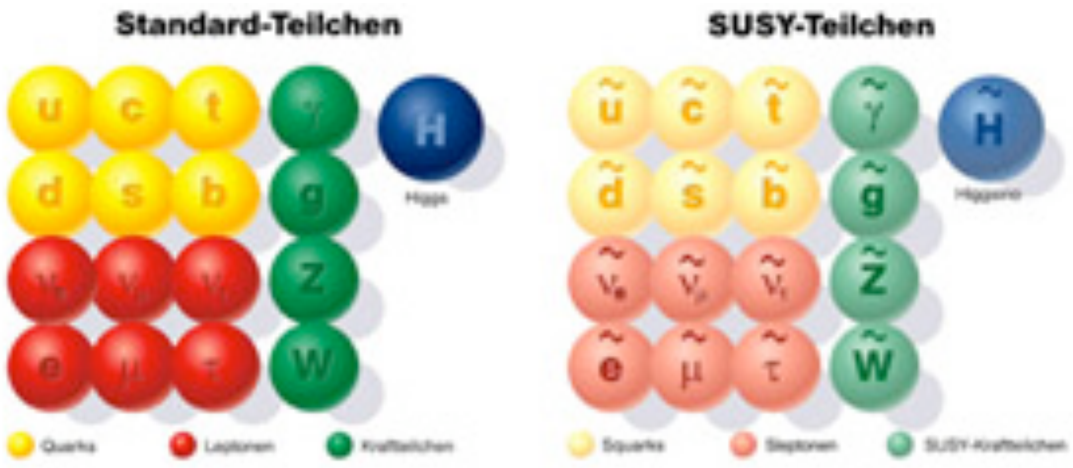
$\sigma(E) \sim 100\%/\sqrt{E}$ for jet
$\sigma(E) \sim 0.4\%$ for electron (100GeV)
$\sigma(PT) \sim 1\%$ for muon (100GeV)

Dark Matter @ Colliders

Supersymmetry (SUSY)

Supersymmetry is one of promising candidates of beyond the SM.

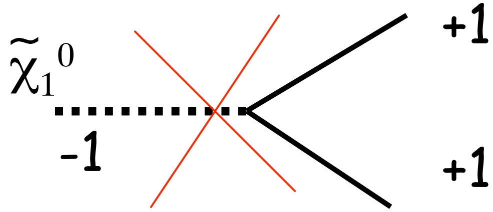
- Grand coupling unification
- Hierarchy problem
- DM candidate



Each ordinal SM particle has a supersymmetric partner with spin=1/2 different.

If R-parity is conserved,
the lightest SUSY particle can be dark matter.

$$R=(-1)^{3B+L+2S} \begin{cases} 1 : \text{SM} \\ -1 : \text{SUSY} \end{cases}$$



Supersymmetry (2)

In most of cases, neutralino is the lightest SUSY particle(LSP).

$$\begin{bmatrix} M_1 & 0 & -M_Z sin\theta_W \cos\beta & M_Z sin\theta_W sin\beta \\ 0 & M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W sin\beta \\ -M_Z sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z sin\theta_W sin\beta & -M_Z \cos\theta_W sin\beta & -\mu & 0 \end{bmatrix} \begin{pmatrix} \tilde{B}^0 \\ \tilde{W}^0 \\ \tilde{H}_1^0 \\ \tilde{H}_2^0 \end{pmatrix} \xrightarrow[\text{eigenstate}]{\text{mass}} \begin{pmatrix} \tilde{\chi}_1^0 \\ \tilde{\chi}_2^0 \\ \tilde{\chi}_3^0 \\ \tilde{\chi}_4^0 \end{pmatrix}$$

The components defines the neutralino coupling.

Mass spectrum and couplings depend on how SUSY breaking is mediated to EW sector and universality.

minimal Super-gravity (mSUGRA)

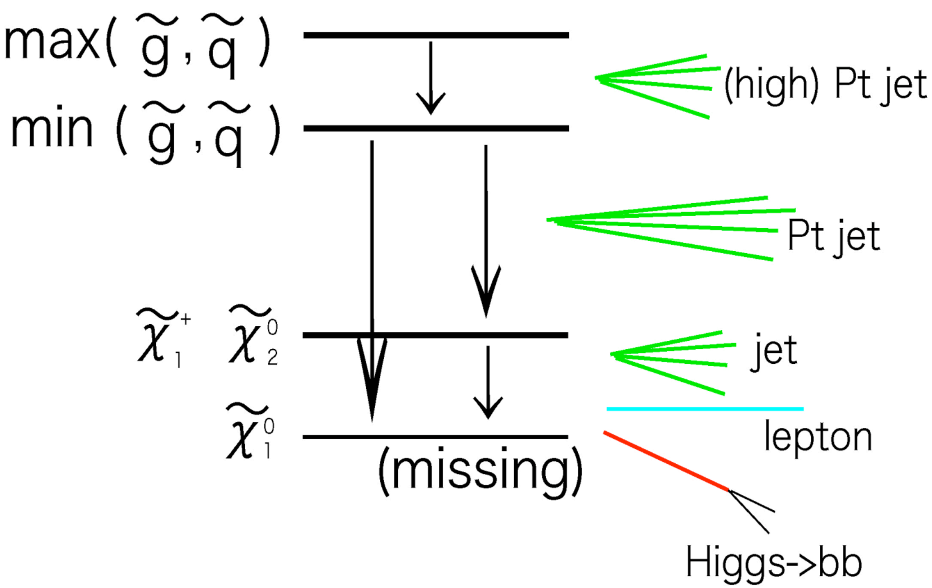
It is described by 4 parameters plus 1 sign.

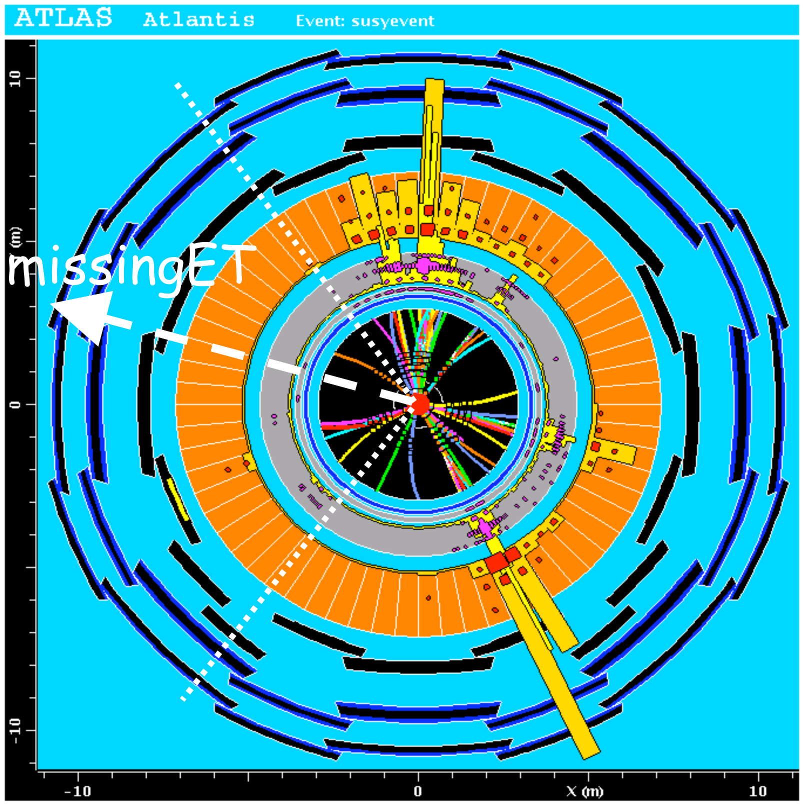
$$\boxed{m_o, \quad m_{1/2}, \quad \tan\beta, \quad A_0, \quad \text{sign}(\mu)}$$

- m_0 : universal scalar mass @ GUT
- $m_{1/2}$: universal gaugino mass @ GUT
- $\tan\beta$: the ratio of higgs vev (v_u/v_d)
- A_0 : universal trilinear coupling
- sign(μ) : sign of higgsino mass term

SUSY DM at LHC

- DM(LSP) is stable(comparing to t_u) and weakly interacting particle. Escape from detection => missing energy
- LHC is pp collider. => Large production cross-section with colored (s)particles.





DM candidate appears in cascade decay : Multijet + missingET

Dark Matters Strategy at LHC

Experimental issue

(1) Discovery and inclusive study

- Firstly, need detector commissioning, especially missingET and understand SM background
- Mass scale of initially produced particles can be roughly known.

Possibility of existence of a DM candidate

(2) Exclusive study

- model independent mass measurements

Mass measurement of a DM candidate

(3) Interpretation

- calculate $\Omega_{LSP}h^2$, σ_{SI} within specific model assumption. The degree of model dependency depends on the situation.

Test compatibility with astro physics observation

Show the result of SUSY case as an example.
The strategy will be applicable for other models.

MissingEt + Multijet

SUSY signature(R-parity conserved) is characterized by multijet + missingET @LHC

Basic selection

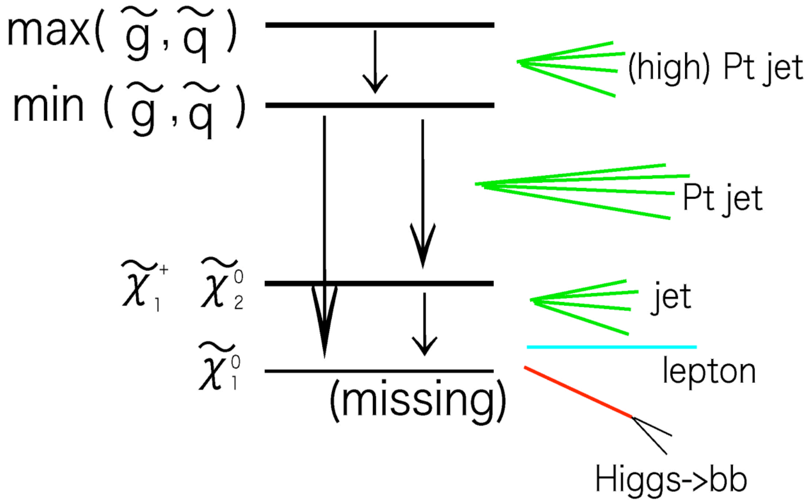
- N_{Jet}>=3-4 (p_T depends on N_{Jet})
- missingEt>100GeV or more
- S_T>0.2 (event shape variable)
- N^{iso}_{Lep}=0,1,2…
- $\Delta\phi$(missingET, Jet_i)>0.2

At the beginning, selection should be not so tight and complicated to understand SM background.

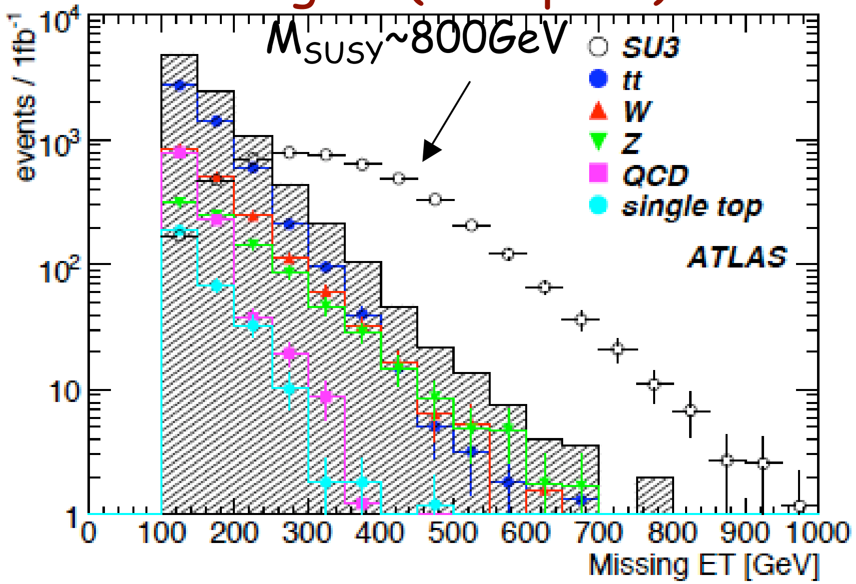
Also robust to any new signature with missingET+multijet

Expected background (4jet+missingET)
ttbar, W($\tau\nu$), Z($\nu\nu$) and QCD(bbar)

SUSY cascade decay



Jets+MissingET (no lepton)



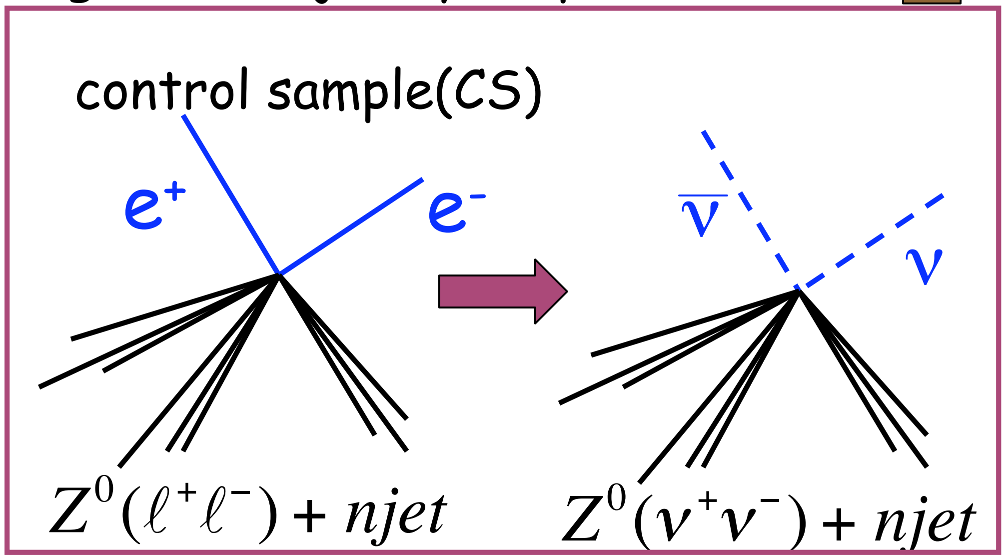
Background estimation

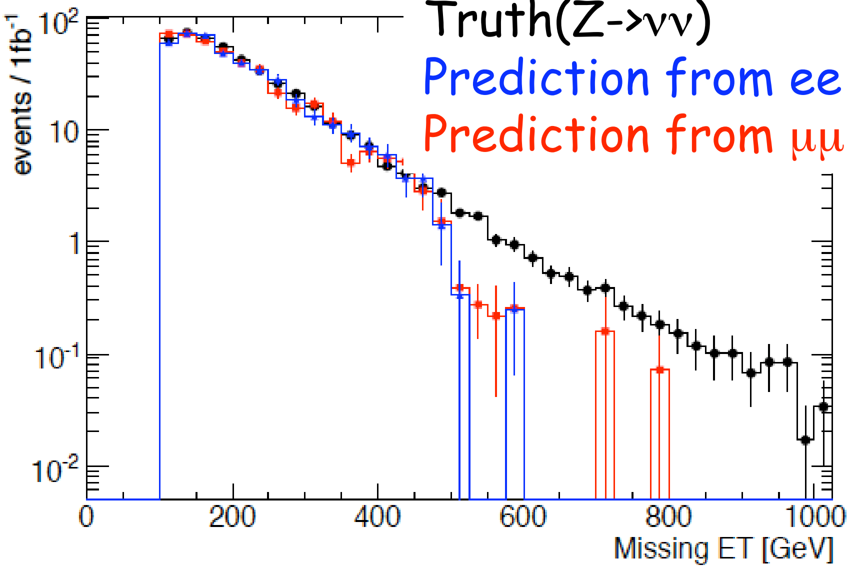
Need to evaluate background by real data as much as possible especially at the beginning of experiment.

(1) Shape estimation
(2) Normalization

$$\alpha^{corr} \times \frac{Br(Z \to \nu\nu)}{Br(Z \to \ell^+\ell^-)}$$

e.g. Z(νν)+njet by "replacement"





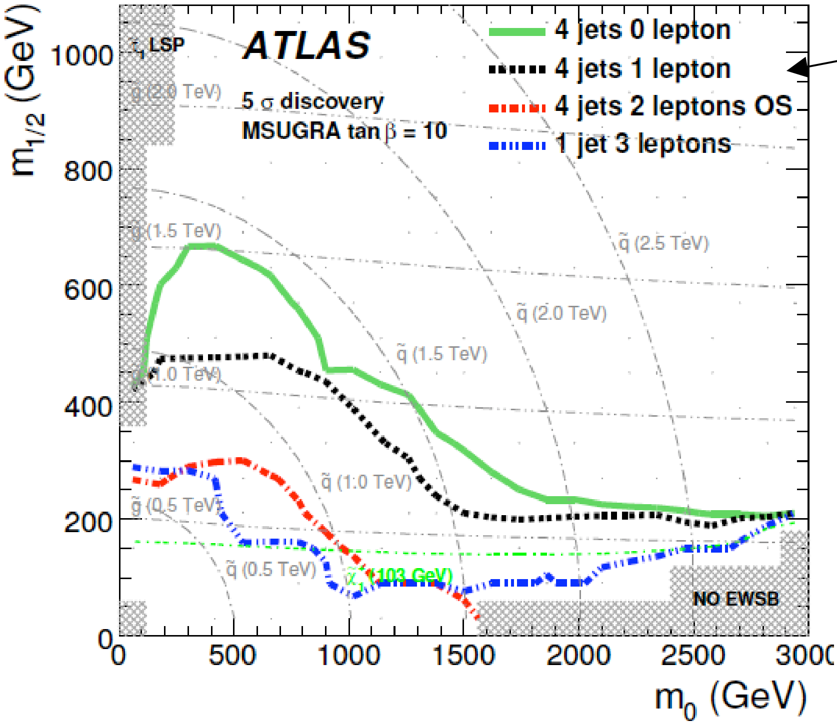
Similar technique can be used for

- $Z^0(\tau^+\tau^-) \Leftarrow Z^0(\ell^+\ell^-)$
- $tt(bb\ell\nu qq) \Leftarrow tt(bb\ell\nu\ell\nu)$

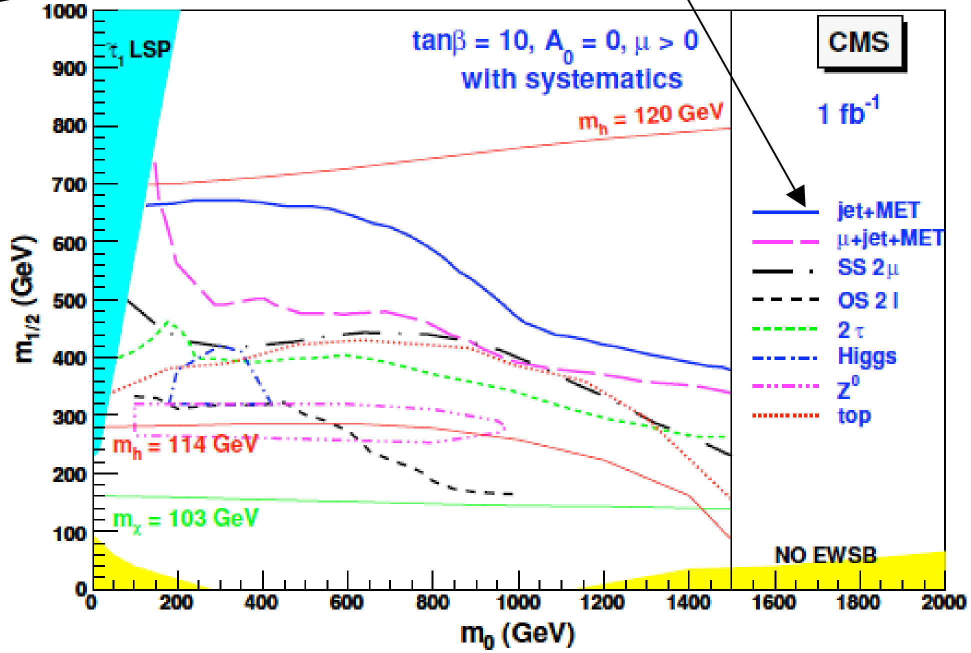
Expected performance @ 1fb^{-1}
13%(stat)+8%(sys) for Z->νν

Discovery Potential

Expected discovery reach within mSUGRA at 1fb^{-1} after successful commissioning in ATLAS and CMS.



Various analysis mode is adopted

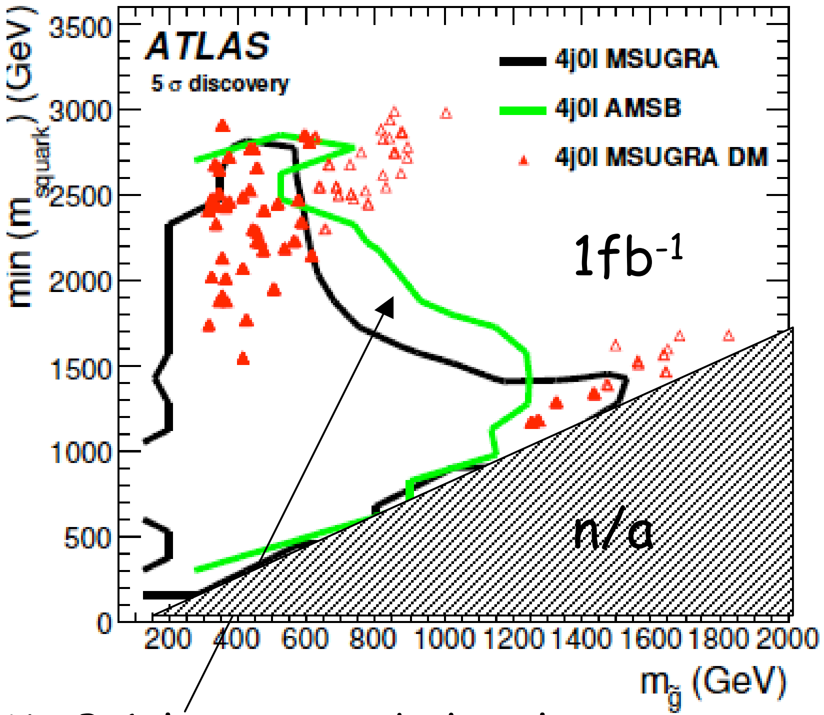


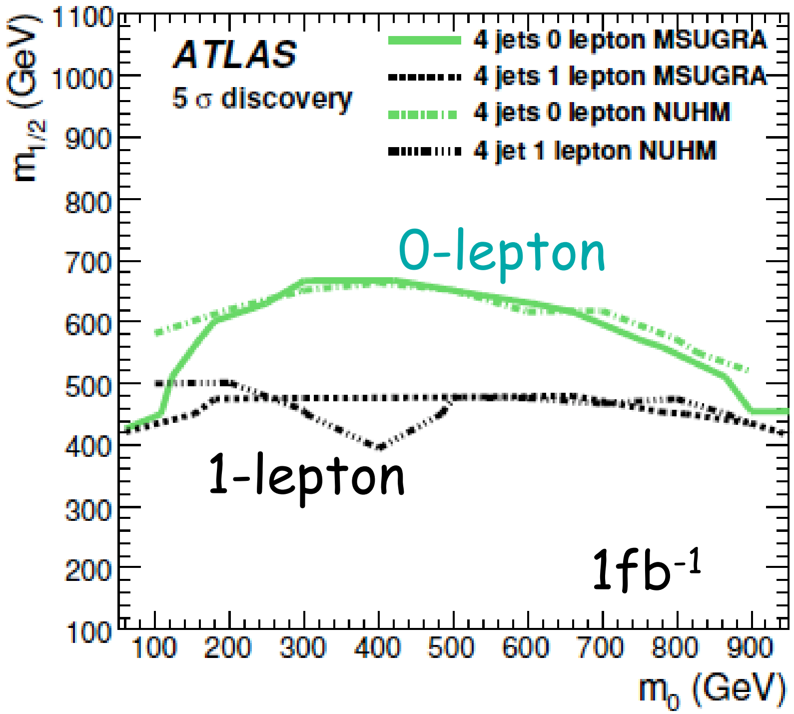
- MissingEt + jets gives the best discovery potential
- requiring a lepton will be the promising analysis mode at the point of "cleanness" (less QCD background)

Reach in Msusy=min($\tilde{g}$,$\tilde{q}$) : ~1.4TeV @ 1fb^{-1} (~0.7TeV for heavy squark)

Discovery Potential (2)

Discovery reach for other SUSY case (missing ET signature)





AMSB 1-lepton mode has less sensitive than mSUGRA because of $\tilde{g} \to qq\tilde{\chi}_1^+ \to qq\pi^+\tilde{\chi}_1^0$ at large m0.

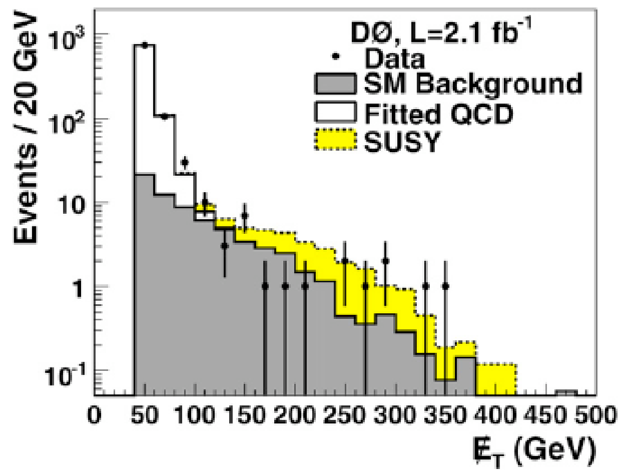
NUHM with tuned μ and m_A for Ωh^2 from WMAP.

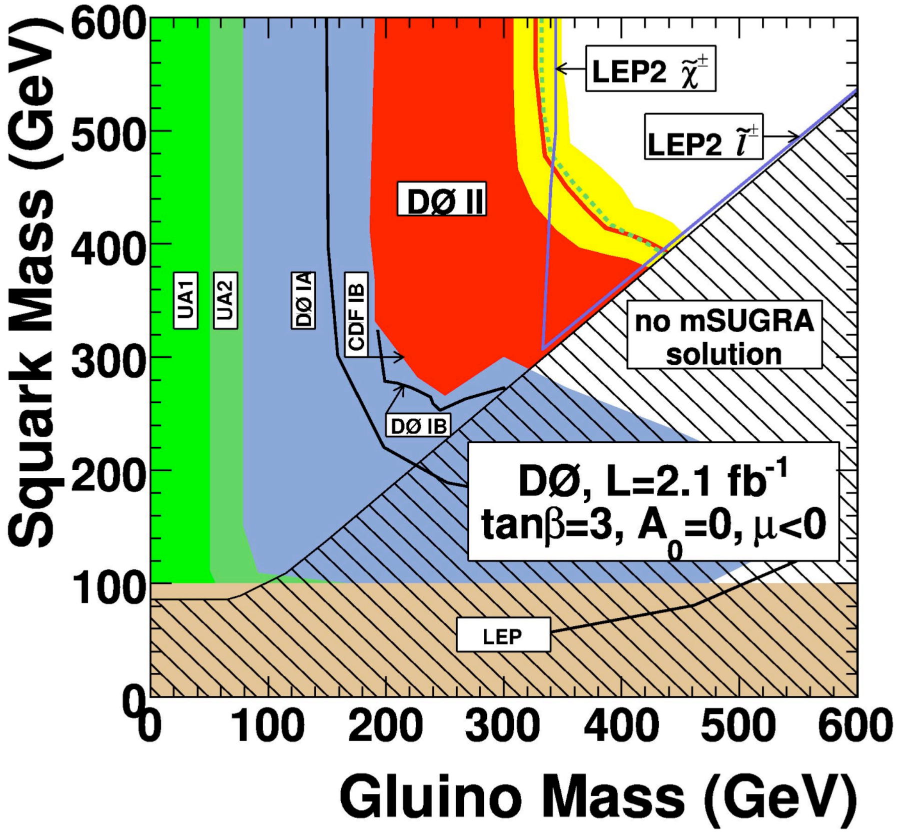
Discovery reach is predominantly defined by gluino and lightest squark mass, i.e. ~production cross-section and less model dependent.

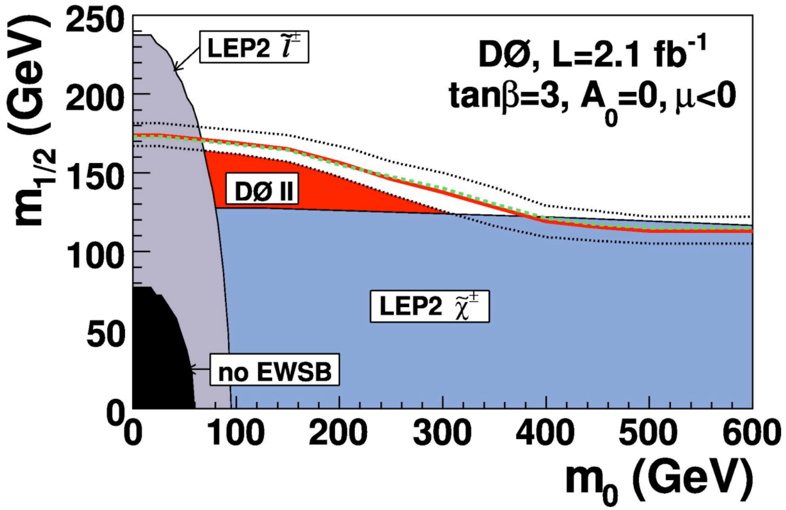
Current Collider Constraints

Current mass limits on gluino and squark from Tevatron within mSUGRA assumption
(A0=0, tanβ=5, μ<0)

Phys.Lett.B 660(2008)449





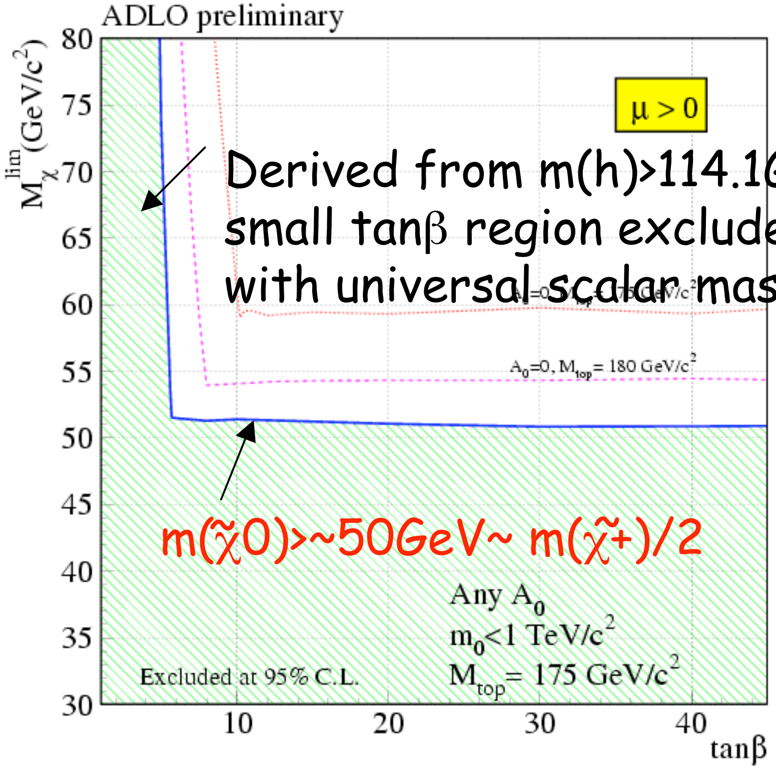


Lower Limit (95%CL)
$m(\tilde{q})$ > 379GeV , $m(\tilde{g})$ > 308 GeV

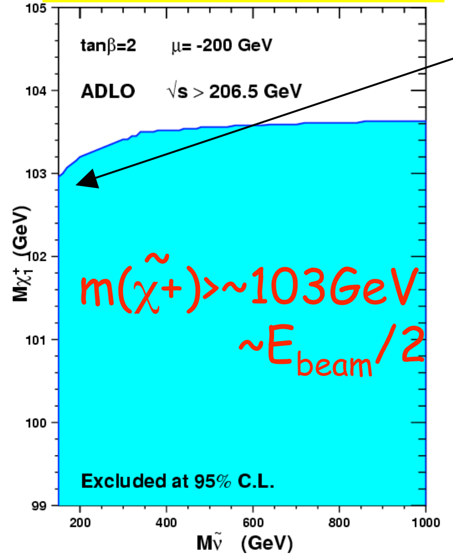
Current Collider Constraints(2)

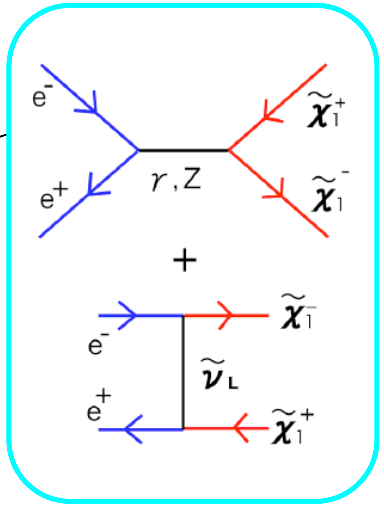
Current mass limits on chargino/neutralino from LEP.
within mSUGRA assumption(and large m0)

Lightest Neutralino(LSP)



Lightest Chargino





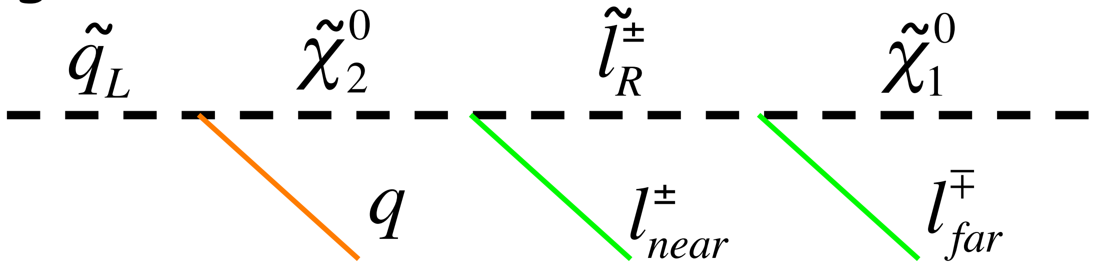
At collider experiment,
basically search $\tilde{\chi}_2^0$, $\tilde{\chi}_1^+$ and not $\tilde{\chi}_1^0$

Constraint is less sensitive on LSP mass if no universality is assumed.

(2) Mass Measurement

Mass reconstruction

R-parity conservation -> two LPSs in the final state.
Not possible to measure each initially produced sparticle mass using one channel.



- No mass peak -> measure endpoint of various invariant masses.

$$m(\ell\ell), m(q\ell), m(q\ell\ell)\ldots$$

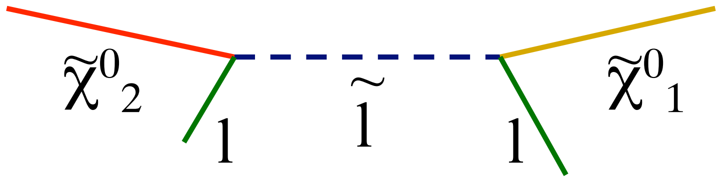
- We could know the mass differences from endpoint(edge).

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

- With successive (at least) three two-body decay, i.e. four unknown masses and four equations => solve equations and get $\tilde{\chi}_1^0$ mass!

No model assumed
=> Applicable to other models providing similar topologies

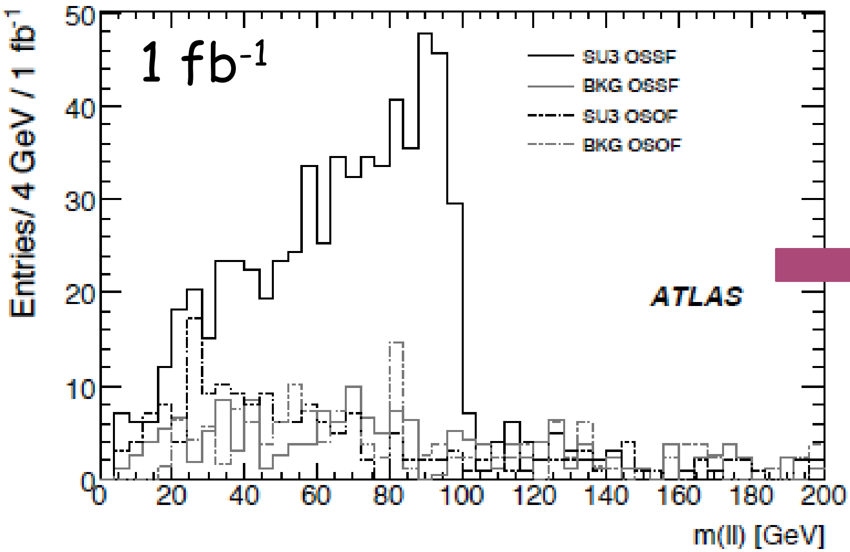
Di-lepton Edge

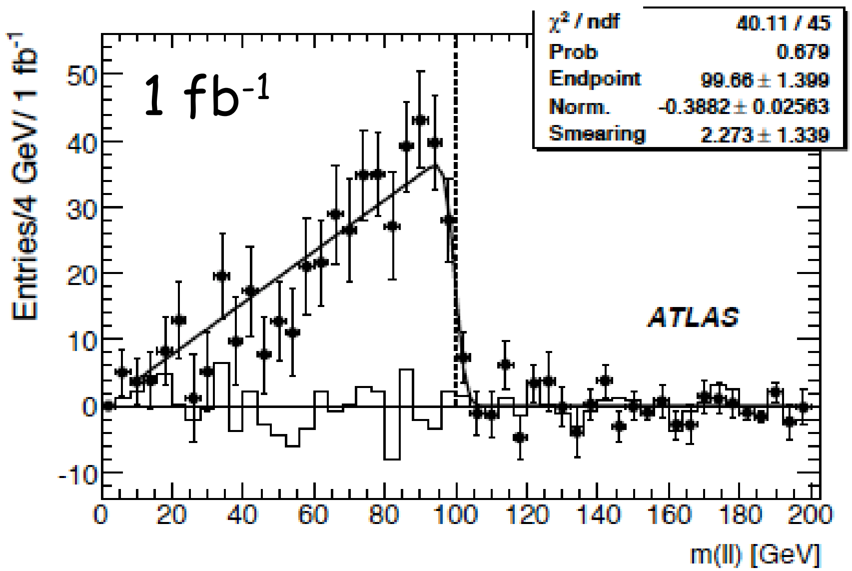


$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

(In case of two body decay)

Combinatorial background (take lepton from another decay chain) can be subtracted by $N(e^+e^-)/\beta + \beta N(\mu^+\mu^-) - N(e^\pm\mu^\mp)$





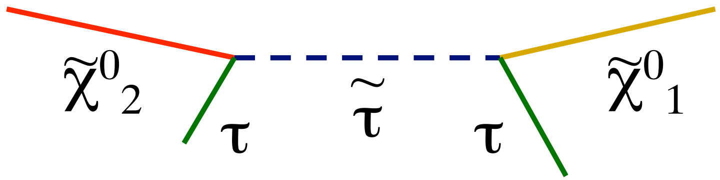
$$m_{\ell\ell}^{edge} = 99.7 \pm 1.4(stat) \pm 0.3(sys)$$

(true value : 100.2GeV)

Fitting by triangle shape with Gaussian smearing.

SU3:m_0=100GeV,$m_{1/2}$=300GeV,tanβ=7,A_0=300GeV,μ>0
σ=18.6pb(LO)

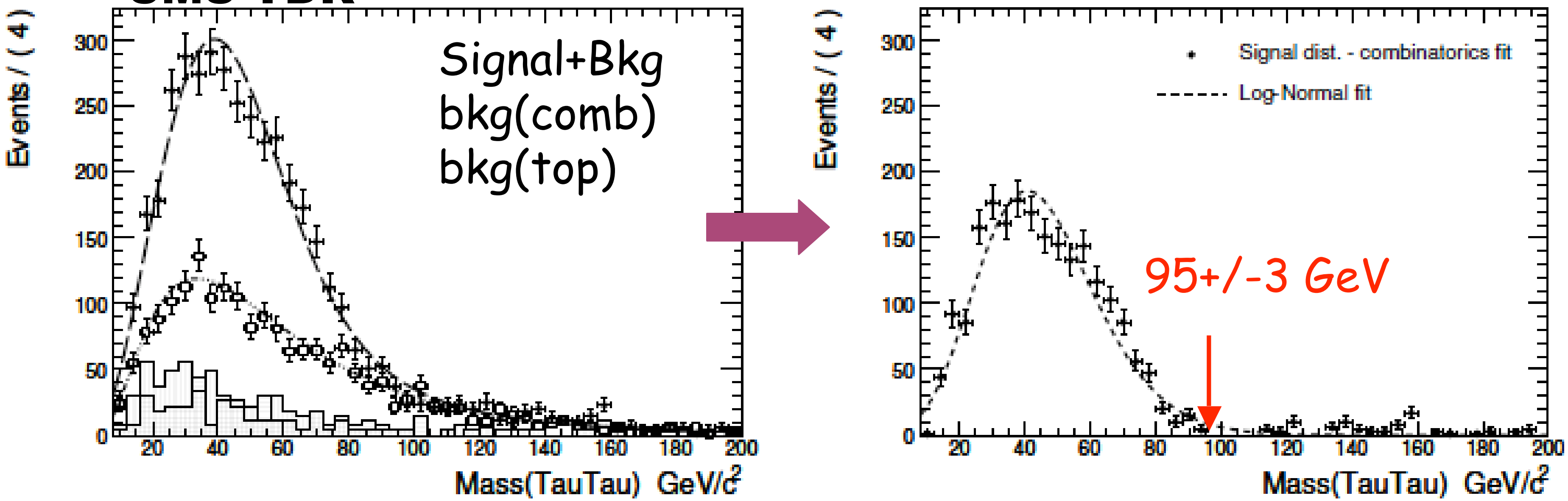
Di-lepton tau



Triangle shape is smeared by neutrino(s) coming from tau decays.
Lower τ efficiency and higher fake rate <u>-> more combinatorial bkg.</u>

- top background is estimated by Monte Carlo
- Combinatorial background is estimated by $N(\tau^{\pm}\tau^{\pm})$

CMS TDR

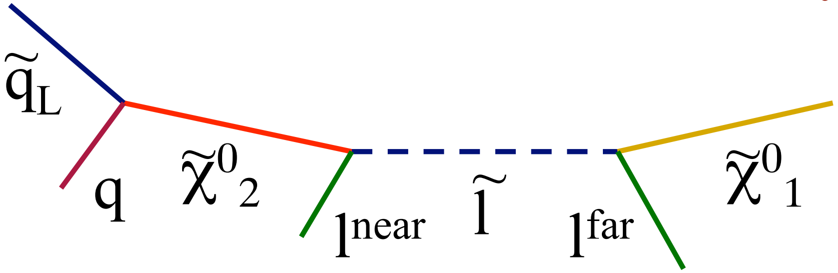


Expected performance @CMS(40fb^{-1})

$$M(\tau)^{meas} = 165 \pm 10(stat) \pm 20(sys)GeV$$

(true value : 153.9GeV)

lq Kinematics Endpoints



$$\left(m^2_{ql}\right)^{\rm edge}_{\rm min} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)}{m^2_{\tilde{\chi}^0_2}}$$

$$\left(m^2_{ql}\right)^{\rm edge}_{\rm max} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}_R}}$$

In experiment, don't know which lepton is 'far' or 'near'.

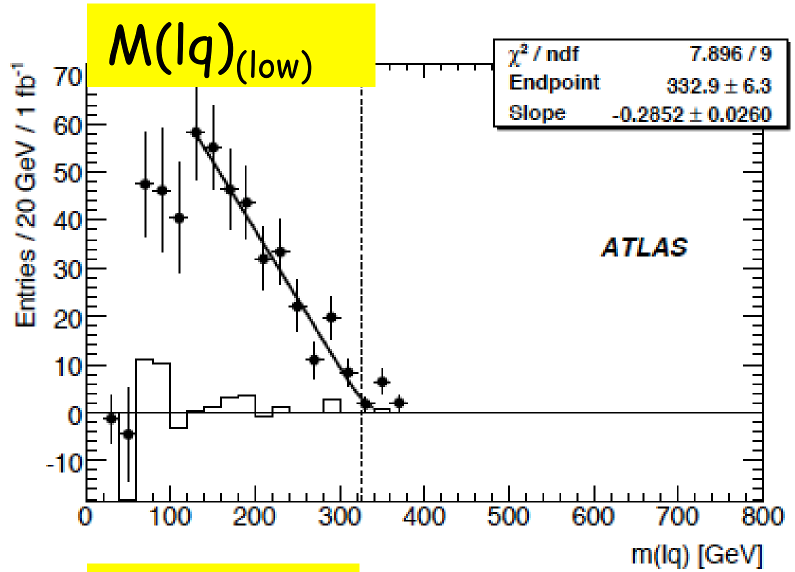
(stat) (fit) (JES)

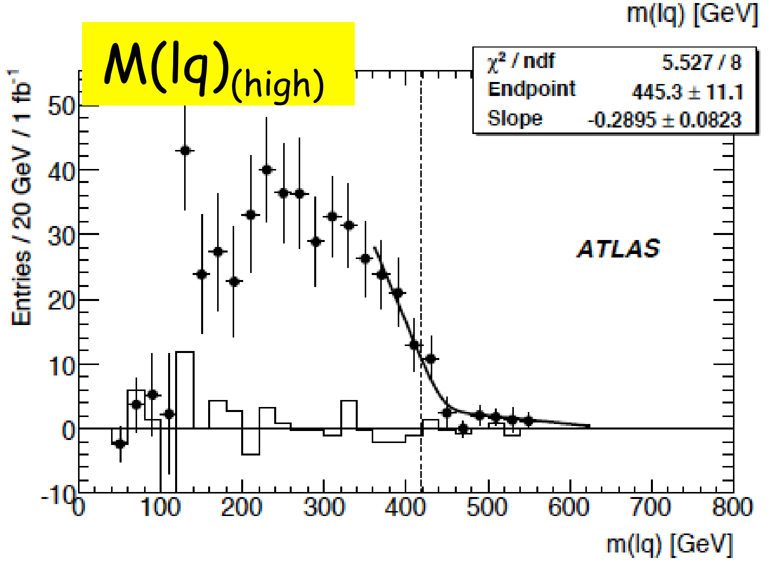
$$m(\ell q)^{\max}_{(low)} = 333 \pm 6 \pm 6 \pm 8\,GeV$$

(true value : 325GeV)

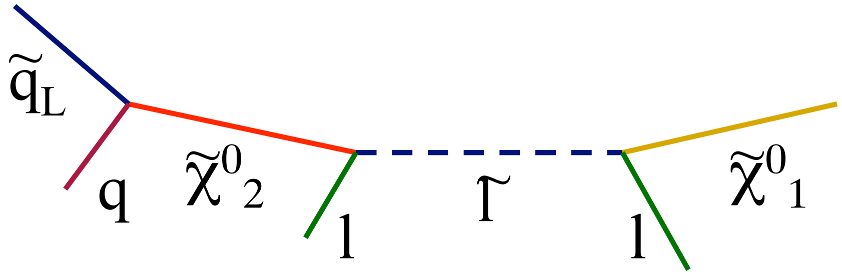
$$m(\ell q)^{\max}_{(high)} = 445 \pm 11 \pm 11 \pm 11\,GeV$$

(true value : 445GeV)



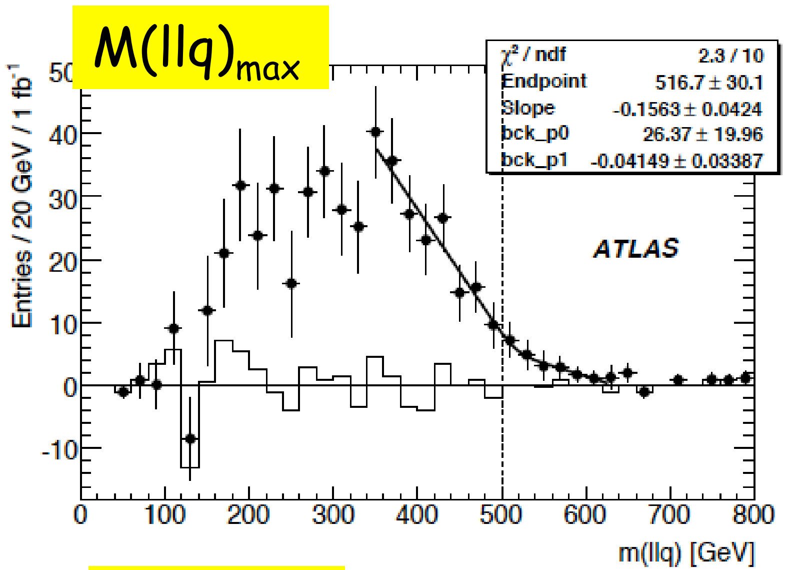


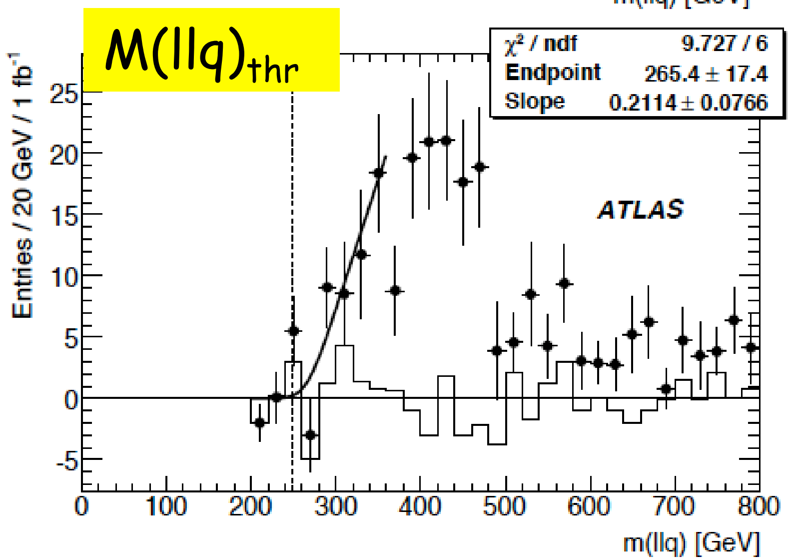
llq Kinematics Endpoints



$$M_{llq}^{\max} = \left[\frac{(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2})(M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\chi}^0_1})}{M^2_{\tilde{\chi}^0_2}}\right]^{1/2}$$

$$M_{llq}^{thr} = M_{llq}^{\max} \quad (M_{\ell\ell}^{\max}/\sqrt{2} < M_{\ell\ell} < M_{\ell\ell}^{\max})$$





(stat) (fit) (JES)

$$m(\ell\ell q)^{\max} = 517 \pm 30 \pm 10 \pm 13 GeV$$

(true value : 501GeV)

$$m(\ell\ell q)^{thr} = 265 \pm 17 \pm 15 \pm 7 GeV$$

(true value : 249GeV)

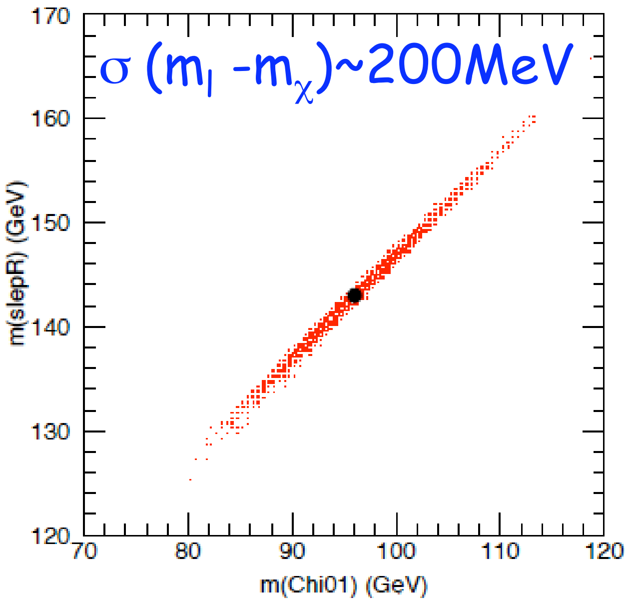
LSP mass Determination

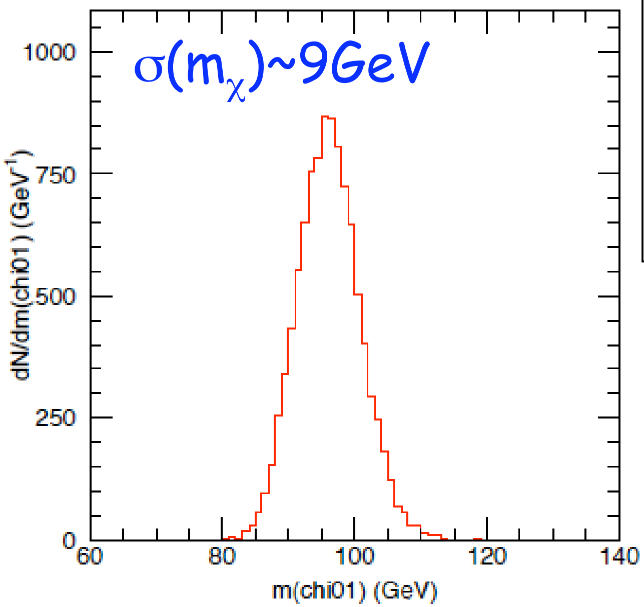
Eur.Phys.J. C25(2002)113

Solve numerically equations for sparticle masses for each set of MC experiments(endpoint measurements).

Example : sps1a SUSY bench mark point @ 300fb^{-1}

m_0=100GeV, $m_{1/2}$=250GeV, A_0=-100GeV, $\tan\beta$=10, μ>0



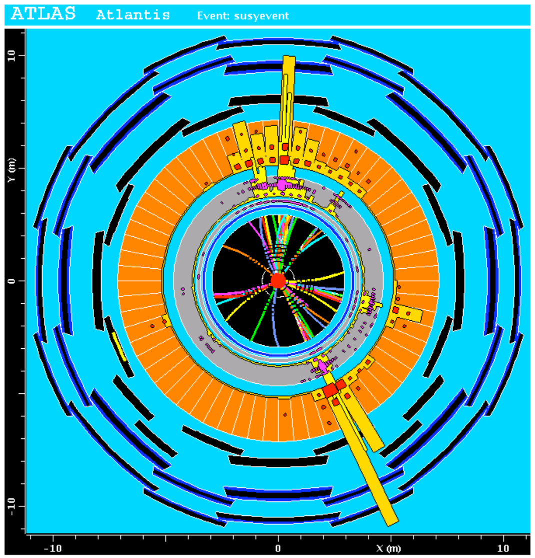


		error
$m_{\ell\ell}^{max}$	83.37	0.09
$m_{\ell\ell q}^{max}$	457.55	4.8
$m_{\ell q}^{low}$	321.28	3.3
$m_{\ell q}^{high}$	400.63	4.1

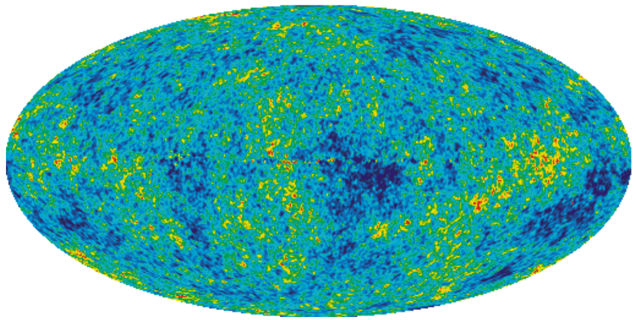
Kinematics endpoint measurement is sensitive to mass difference, e.g. strong correlation among calculation.

Even mass difference can be obtained by an accuracy of a few hundred MeV, the precision of LSP mass is O(GeV).

Complementarity
(translation)



?



From Particle- to Astro- experiment

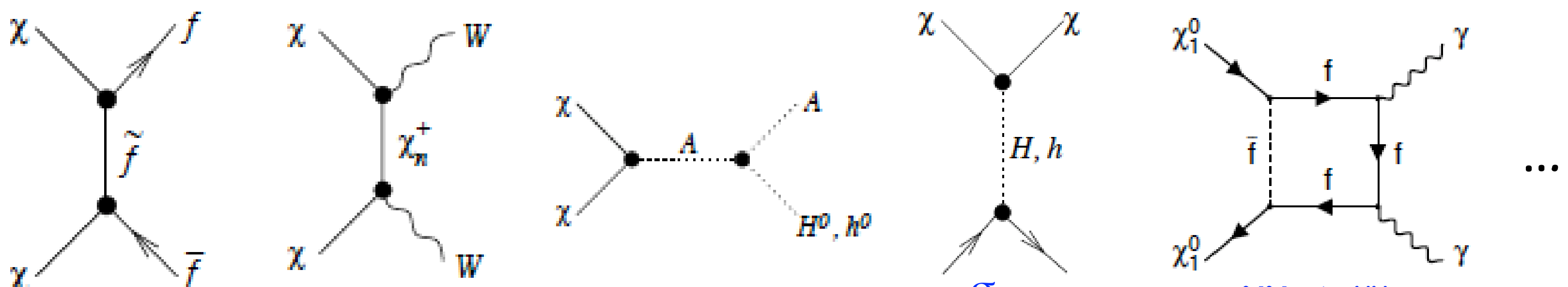
Observable:

Particle) masses, couplings, production rate@pp…
Astro) $\Omega_\chi h^2$, $\sigma_{SI,SD}$, m_χ…

For compatibility test, need to translate from particle- to astro-physics observable quantities.

- Uncorrelated systematic uncertainties
- Measure different parameters
- usually difficult to access all necessary parameters.
  i.e. need to assume model/universality in the most of cases.

Important ingredient : neutralino mass and components.
Also related parameters in diagrams contribute to $\Omega_\chi h^2$, $\sigma_{SI,SD}$
(or verify the contribution is negligible..)



χ annhilation σ_{SI} $\chi\chi$ -> $\gamma\gamma$

Baltz, Battaglia,Peskin,Wizansky (hep-ph/0602187)

MSSM scan (example)

- Perform scan over the full 24 parameters of MSSM.
- Calculate the p.d.f. $p(x_k)$ for the relevant observables m_i and O_j is given by the expectation value of the funtion(x_k).

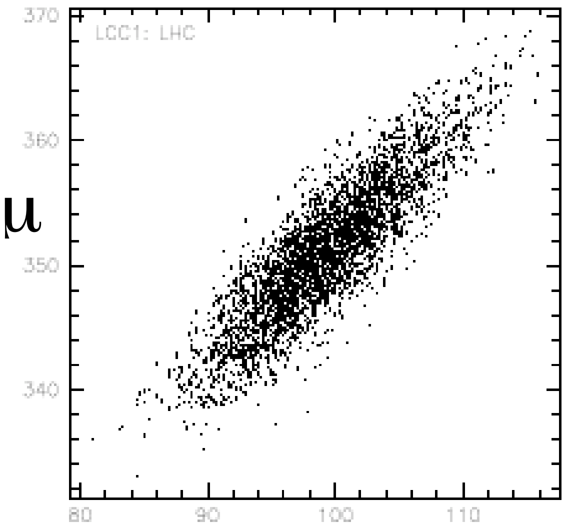
$$\underbrace{m_i \pm \sigma_i}_{\text{Collider}} \Rightarrow \underbrace{x_k (k = 1 \ldots 24)}_{\text{MSSM}} \Rightarrow \underbrace{\mathrm{O}_j (x_k)}_{\text{Astro-exp}}$$

$$d^n x \; \mathrm{L}(x) = d^n x \; \prod_i \exp\left[-\frac{(M_i(x) - m_i)^2}{2\sigma_i^2} \right]$$

- Scan over 24-parameters space using a Markov chain technique

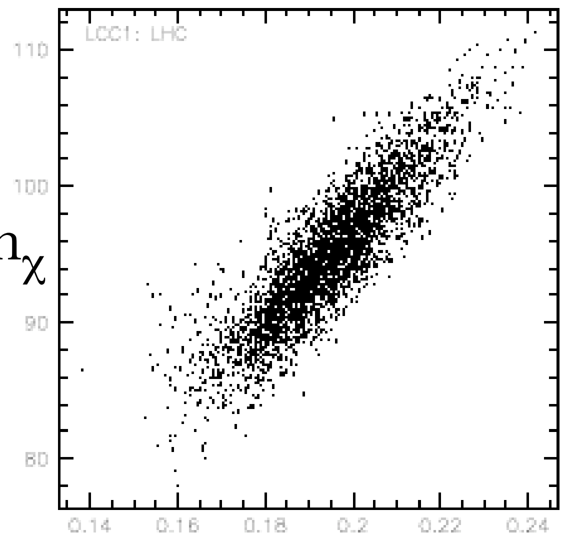
A set of measurements

μ



M_1

m_χ

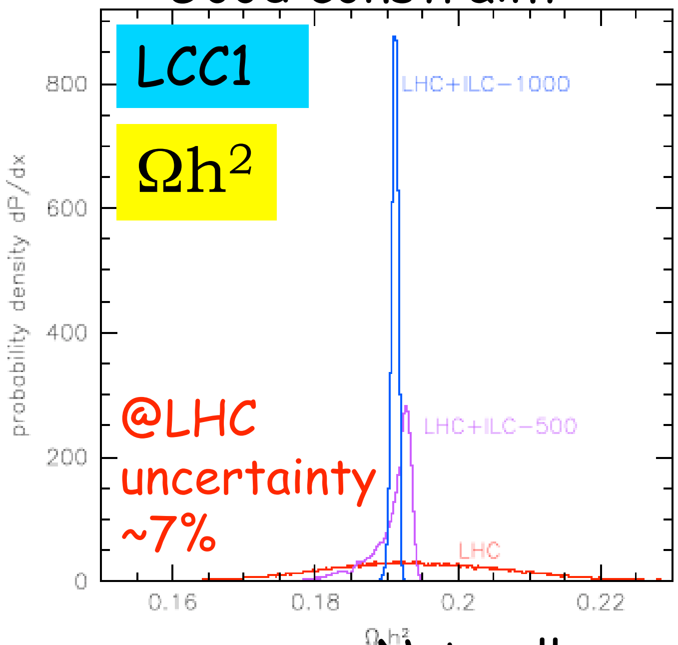


Ωh^2

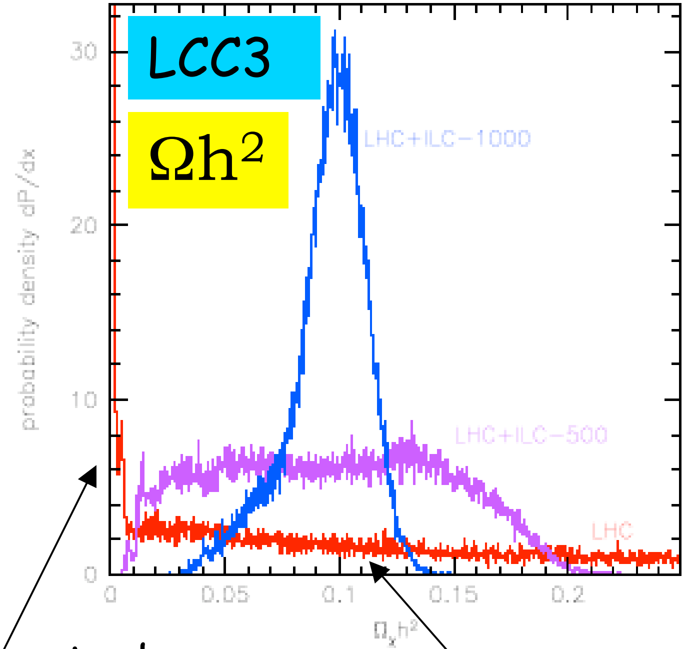
Baltz, Battaglia,Peskin,Wizansky (hep-ph/0602187)

How well constrained?

Good constraint



Poor constraint



Not well constraint on tanb

Ambiguity of neutralino component

[LCC1] : Well-constrainted (7%) :

⇨ major limitation is measurement-intrinsic(sensitive to ΔM).

[LCC3] : No constraints or multiple solutions

⇨ limited information accessible, especially in neutralino sector

Usually difficult to give constraint on $\tan\beta$, m(A) and m($\tilde{\tau}_2$)

Case study in general MSSM Nojiri, Polesello, Tovey JHEP03(2006)063

Other topology searches

(i.e. not missingET)

Heavy Stable Charged Particle

Next LSP (decaying to LSP) may decay outside of detector, or LSP can be a charged/colored stable particle.

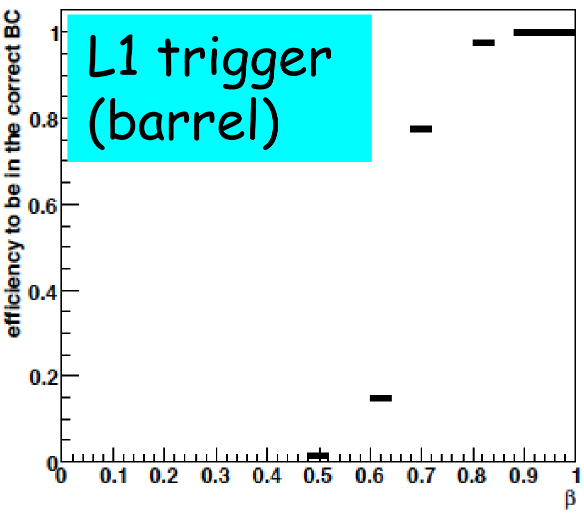
It can be discovered by slow (β<1) muon-like particle.

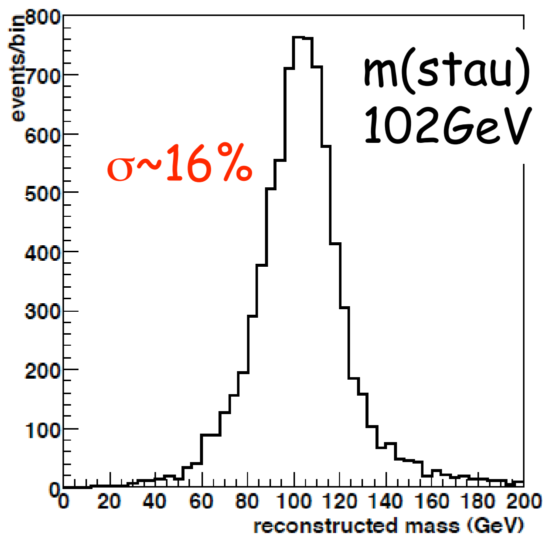
Beta-measurement
- dE/dx in Si tracker (CMS)
- Time of flight by drift tube (ATLAS,CMS)

L1 trigger efficiency is lost, but recovered by other trigger.

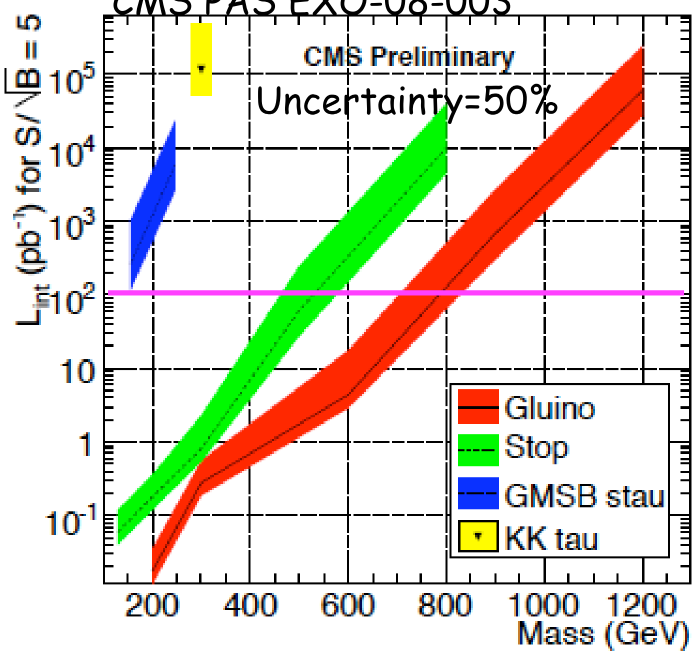
Background is need to be evaluated by real data.

ATL-PHYS-PUB-2008-01



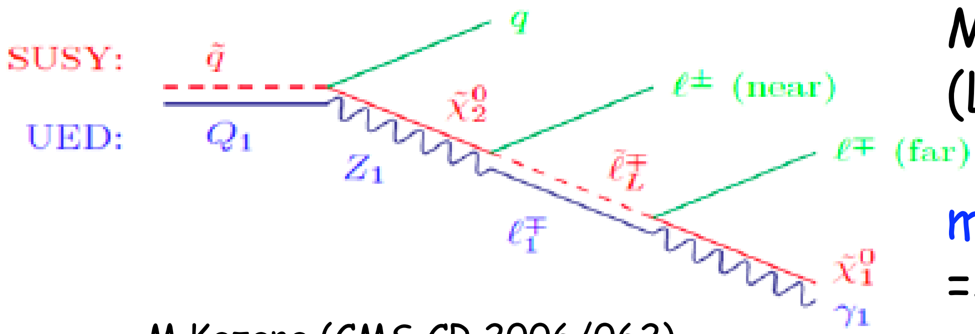


CMS PAS EXO-08-003



Degenerate mass spectrum

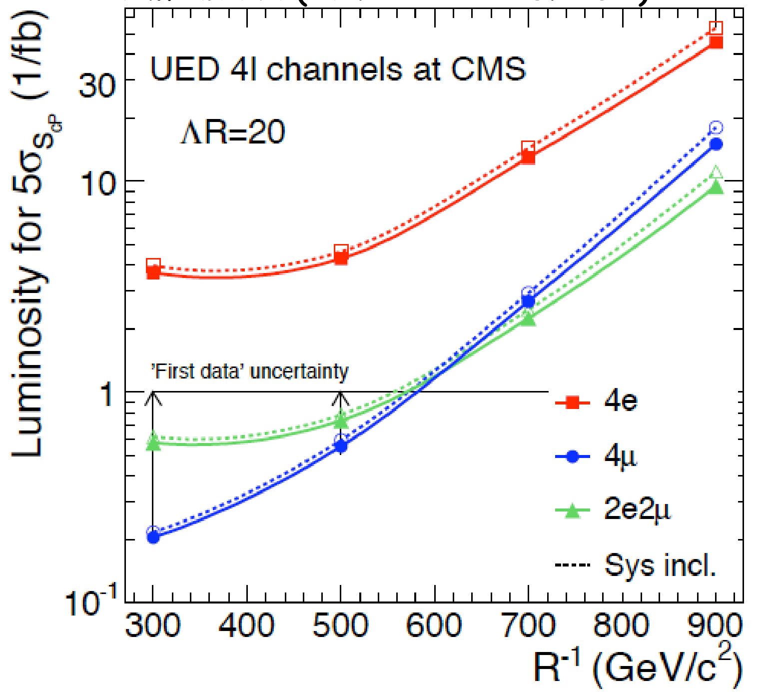
Degenerate mass spectrum is predicted in minimal UED.
In most of mUED, LKP is a KK partner of γ, $\gamma 1$.



Mass spectrum is degenerate.
(LKP is heavier than LSP in SUSY).

missingET and jet are softer
=> difficult to distinguish from SM.

M.Kazana (CMS CR 2006/062)



~ m_{LKP}

4-lepton analysis

- minimal UED (one ED)
- Main background : ttbar, Z
- expected Nbkg<5 @ 30fb^{-1}
- Expected uncertainties ~ 6%

Discovery : 1/R~900GeV @ 30fb^{-1}

Summary

Discovery of BSM signatures are highly expected at LHC.
Successful detector commissioning and understanding SM background are mandatory.

Discovery and kinematic endpoints measurements are done model-independently.

The first goal is model dependent translation from collider- to astro- observable quantities.
Try to reduce dependency as much as possible.

Proof of existence and identity of DM will be possible combining LHC and astroparticle data.

LHC will start this summer with $\sqrt{s}$~10TeV and run at the full energy(14TeV) in 2009!

Backup Slides

ATLAS and CMS (2)

	CMS	ATLAS
track	$\sigma(p_T)/p_T$~1.5%@100GeV, η~0	$\sigma(p_T)/p_T$~3.8%@100GeV, η~0
muon	$\sigma(E)/E$~1%@100GeV ~4%@1TeV ($\|\eta\|<0.2$)	$\sigma(p_T)/p_T$~3%@100GeV ~8%@1TeV ($\eta<1.05$)
electron	$\sigma(E)/E$~3%/$\sqrt{E}\oplus$0.5% ~0.4%@100GeV	$\sigma(E)/E$=~10%/$\sqrt{E}\oplus$1% 1.2%@100GeV (η~0.3)
jet	$\sigma(E_T^{JET})/E$=14%@100GeV =5% @1TeV	$\sigma(E_T^{JET})/E$=8%@100GeV,$\|\eta\|<0.5$ =3.5% @1TeV
ETmiss	$\sigma(E_T^{miss})$~100%$\sqrt{E}$ (QCD)	$\sigma(E_T^{miss})$~55%$\sqrt{E}$ (QCD)
tau	$\sigma(E_T^{tau})/E$~10%@100GeV ε=50% wrt R_{jet}=250, R_c=30	$\sigma(E_T^{tau})/E$~8%@100GeV ε=50% wrt R_{jet}~250@~50GeV
b-jet	ε=50% wrt R_{uds}=250, R_c=30	ε=65% wrt R_{uds}=150 @100GeV

CSM-TDR(VolI),2006 ATLAS detector paper(will come)

MissingEt

MissingET is very powerful to distinguish from SM background.

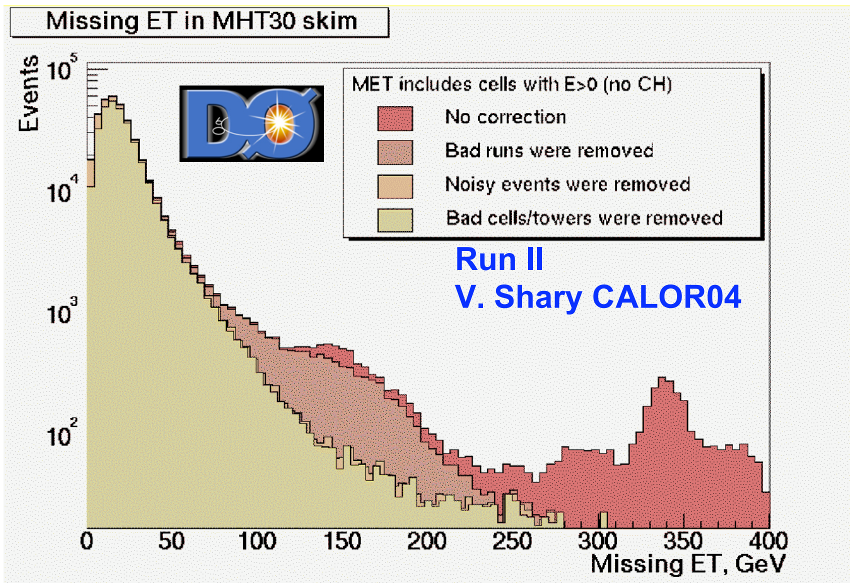
$$\text{MissingET} = -\left[\sum E_T^{CALO} + \sum E_T^{MUON}\right] \quad \text{(as simple case)}$$

"Fake" missingET makes SM events look like SUSY!
QCD background is dangerous since it is not predicted well and huge statistics.

Source of fake missingET

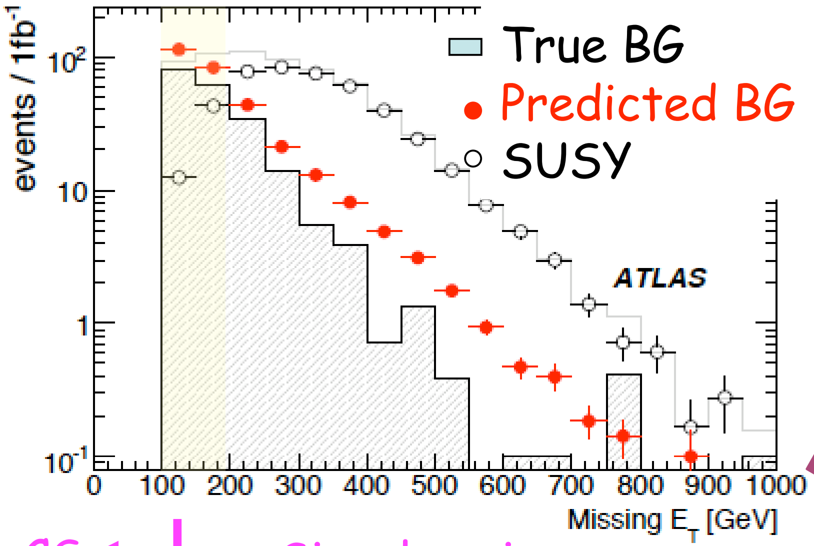
- Hot/dead channels
- Jet mismeasurement
- Muon lost/ghost
- beam halo

Need data quality check and suppress beam gas/beam halo events.
Especially understanding missingET tail is important.



Background (SUSY contamination)

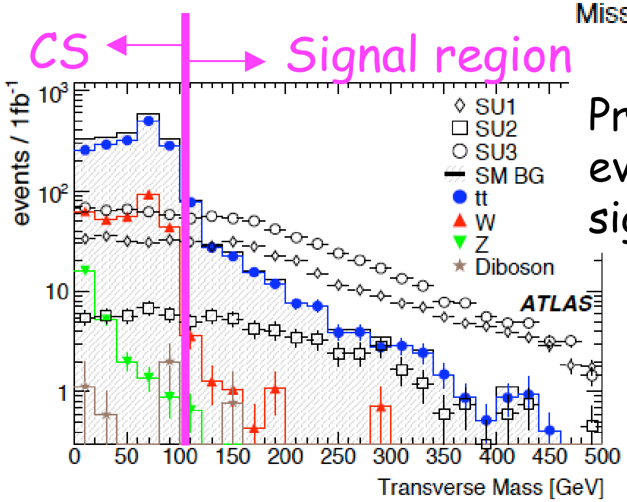
In case of low mass SUSY (~<500GeV), SUSY contamination deteriorates the background estimation.



SUSY contamination

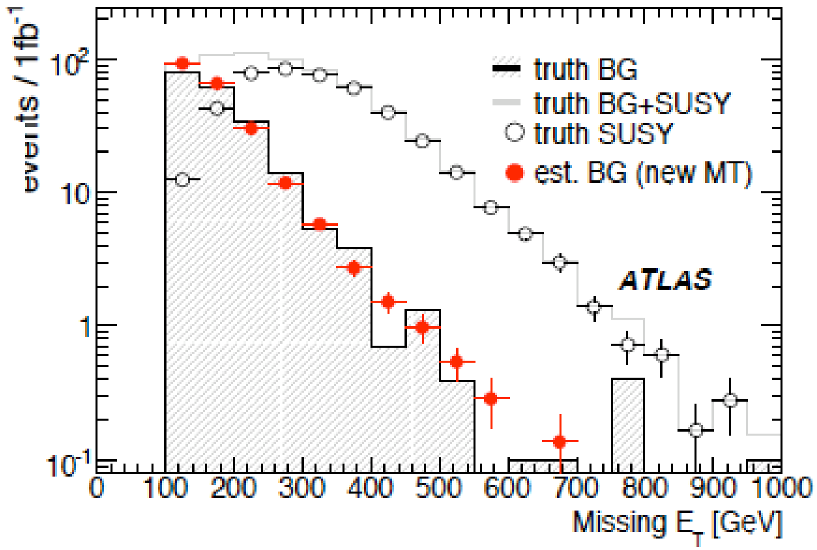
- Control sample -> shape distortion
- Normalization region -> wrong scale

(e.g. Use small MET region)



Predict # of SUSY events in CS from signal region

Subtract SUSY contamination in control sample



LCC1 and LCC3

Baltz, Battaglia,Peskin,Wizansky
(hep-ph/0602187)

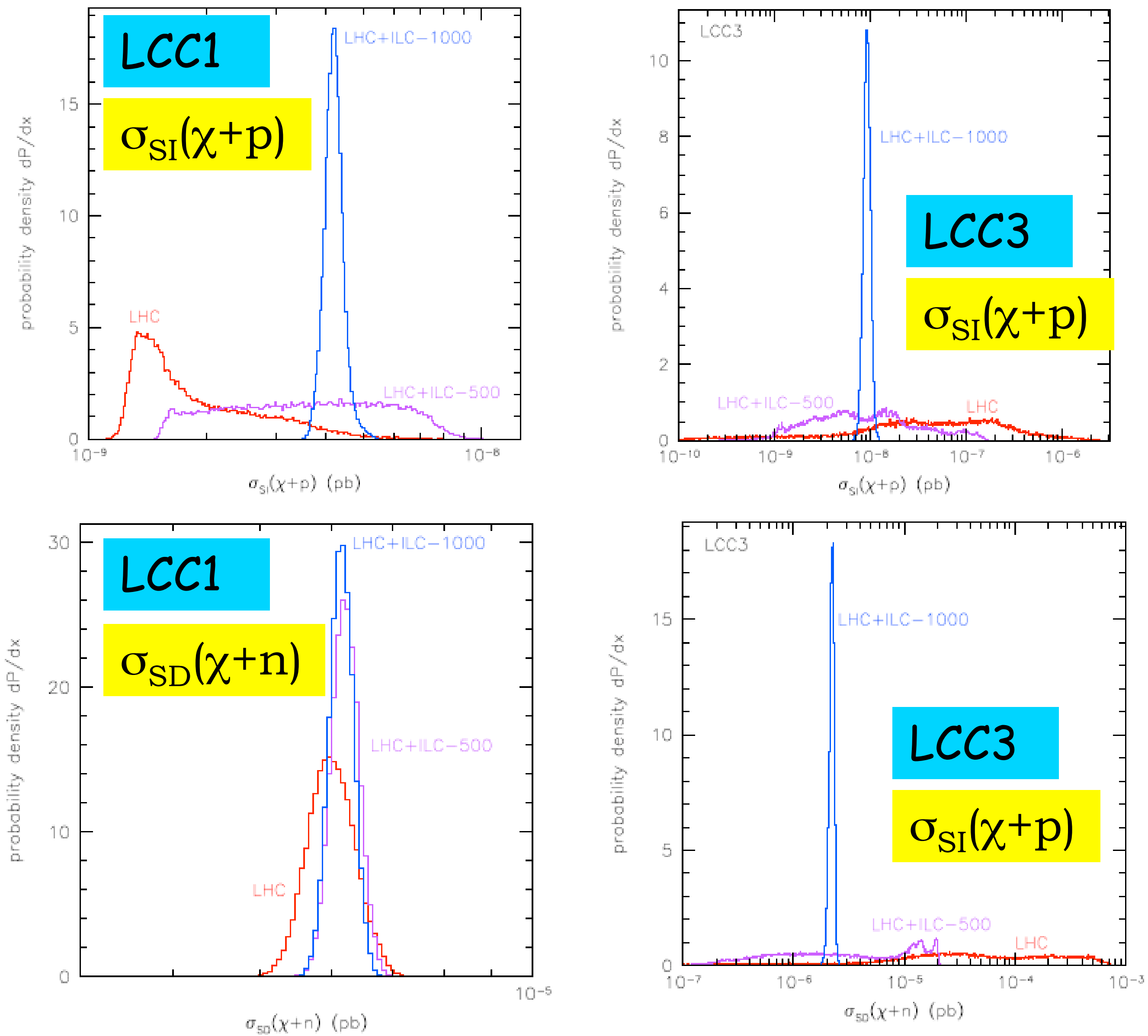
Point	m_0	$m_{\frac{1}{2}}$	$\tan\beta$	A_0	sign mu	m_t	reference	$\Omega_\chi h^2$
LCC1	100	250	10	−100	+	175	[86]	0.192
LCC3	213	360	40	0	+	175	[88]	0.101

mass/mass splitting	LCC1 Value		LHC
$m(\tilde{\chi}^0_1)$	95.5	±	4.8
$m(\tilde{\chi}^0_2) - m(\tilde{\chi}^0_1)$	86.1	±	1.2
$m(\tilde{\chi}^0_3) - m(\tilde{\chi}^0_1)$	261.2	±	@[a]
$m(\tilde{\chi}^0_4) - m(\tilde{\chi}^0_1)$	280.1	±	2.2[a]
$m(\tilde{\chi}^+_1)$	181.7	±	-
$m(\tilde{\chi}^+_2)$	374.7	±	-
$m(\tilde{e}_R)$	143.1	±	-
$m(\tilde{e}_R) - m(\tilde{\chi}^0_1)$	47.6	±	1.0
$m(\tilde{\mu}_R) - m(\tilde{\chi}^0_1)$	47.5	±	1.0
$m(\tilde{\tau}_1) - m(\tilde{\chi}^0_1)$	38.6	±	5.0
$BR(\tilde{\chi}^0_2 \to \tilde{e}e)/BR(\tilde{\chi}^0_2 \to \tilde{\tau}\tau)$	0.077	±	0.008
$m(\tilde{e}_L) - m(\tilde{\chi}^0_1)$	109.1	±	1.2
$m(\tilde{\mu}_L) - m(\tilde{\chi}^0_1)$	109.1	±	1.2
$m(\tilde{\tau}_2) - m(\tilde{\chi}^0_1)$	112.3	±	-
$m(\tilde{\nu}_e)$	186.2	±	-
$m(h)$	113.68	±	0.25
$m(A)$	394.4	±	*
$m(\tilde{u}_R)$, $m(\tilde{d}_R)$	548.	±	19.0
$m(\tilde{s}_R)$, $m(\tilde{c}_R)$	548.	±	19.0
$m(\tilde{u}_L)$, $m(\tilde{d}_L)$	564., 570.	±	17.4
$m(\tilde{s}_L)$, $m(\tilde{c}_L)$	570., 564.	±	17.4
$m(\tilde{b}_1)$	514.	±	7.5
$m(\tilde{b}_2)$	539.	±	7.9
$m(\tilde{t}_1)$	401.	±	(> 270)
$m(\tilde{g})$	611.	±	8.0

mass/mass splitting	LCC3 value		LHC
$m(\tilde{\chi}^0_1)$	142.6	±	14.
$m(\tilde{\chi}^0_2)$	274.2	±	41.
$m(\tilde{\chi}^0_2) - m(\tilde{\chi}^0_1)$	131.5	±	-
$m(\tilde{\chi}^0_3) - m(\tilde{\chi}^0_1)$	320.2	±	-
$m(\tilde{\chi}^0_4) - m(\tilde{\chi}^0_1)$	335.4	±	-
$m(\tilde{\chi}^+_1)$	274.5	±	-
$m(\tilde{\chi}^+_2)$	478.2	±	-
$m(\tilde{e}_R)$	254.9	±	50.[a]
$m(\tilde{\mu}_R)$	254.7	±	50.[b]
$m(\tilde{e}_R) - m(\tilde{\chi}^0_1)$	112.3	±	-
$m(\tilde{\mu}_R) - m(\tilde{\chi}^0_1)$	112.1	±	-
$m(\tilde{\tau}_1)$	153.4	±	-
$m(\tilde{\tau}_1) - m(\tilde{\chi}^0_1)$	10.8	±	-
$m(\tilde{e}_L)$	328.9	±	@[a]
$m(\tilde{\mu}_L)$	329.1	±	@[b]
$m(\tilde{e}_L) - m(\tilde{\chi}^1_0)$	186.3	±	-
$m(\tilde{\mu}_L) - m(\tilde{\chi}^1_0)$	186.5	±	-
$m(\tilde{\tau}_2) - m(\tilde{\chi}^1_0)$	191.3	±	-
$m(h)$	116.58	±	0.25
$m(A)$	429.5	±	1.5 *
$\Gamma(A)$	9.1	±	
$m(\tilde{u}_R)$, $m(\tilde{d}_R)$	780., 778.	±	78.
$m(\tilde{s}_R)$, $m(\tilde{c}_R)$	778., 780.	±	78.
$m(\tilde{u}_L)$, $m(\tilde{d}_L)$	805., 809.	±	121.
$m(\tilde{s}_L)$, $m(\tilde{c}_L)$	809., 805.	±	121.
$m(\tilde{b}_1)$	690.	±	35.
$m(\tilde{b}_2)$	743.	±	74.
$m(\tilde{t}_1)$	603.	±	(> 315)
$m(\tilde{g})$	856.	±	171.

Baltz, Battaglia,Peskin,Wizansky (hep-ph/0602187)

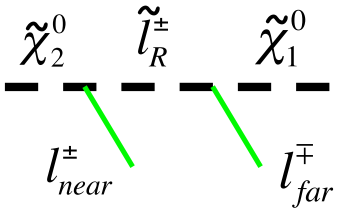
How well constrained? (2)

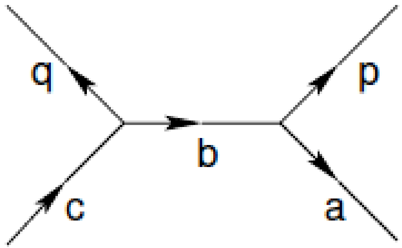


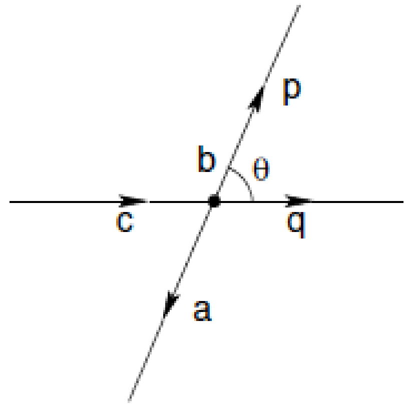
Kinematic endpoint

For single 2-body decay $a \longrightarrow b + c$, in a rest frame

$$|\vec{p}|^2 = [m_b^2, m_a^2, m_c^2] \quad \text{where} \quad [x, y, z] \equiv \frac{x^2+y^2+z^2-2(xy+xz+yz)}{4y}$$







In rest frame of b: $\quad m_{pq}^2 = m_p^2 + m_q^2 + 2(E_p E_q - |\vec{p_p}||\vec{p_q}|\cos\theta)$

Take the maximum ($\cos\theta = -1$) and p and q massless (quarks or leptons)

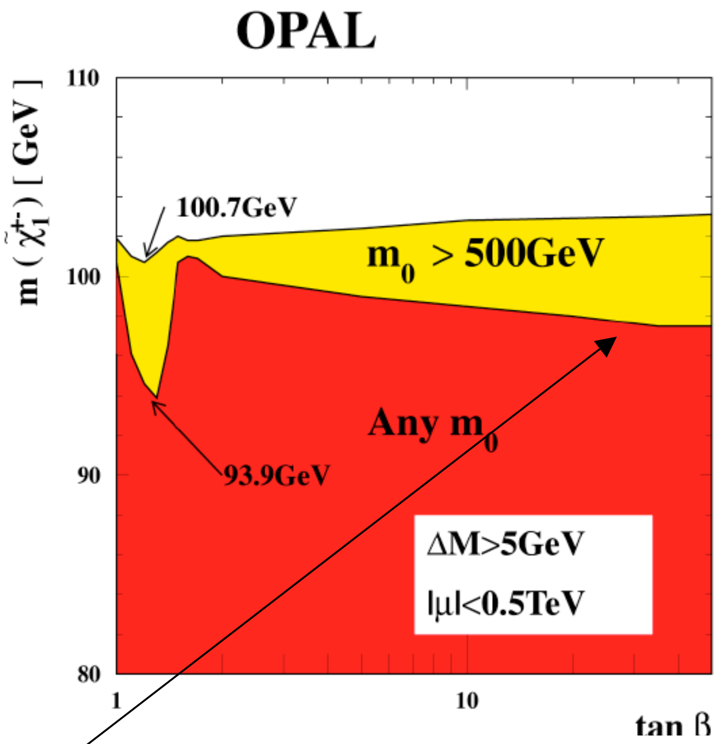
$$(m_{p,q}^{max})^2 = 4|\vec{p}||\vec{q}| = 4\sqrt{[0, m_b^2, m_a^2]}\sqrt{[0, m_b^2, m_c^2]}$$

Substitute formula for $[x, y, z]$: $\quad (m_{pq}^{max})^2 = \frac{(m_c^2-m_b^2)(m_b^2-m_a^2)}{m_a^2}$

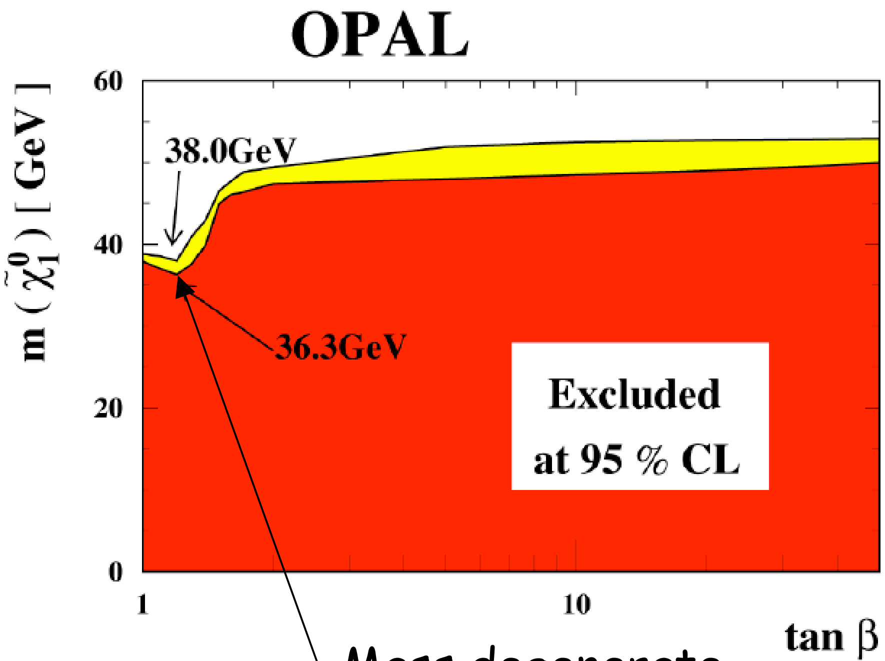
Current Limit (OPAL)

Relax m0 and do not consider higgs mass lower limit(114.1GeV)

Lightest Chargino

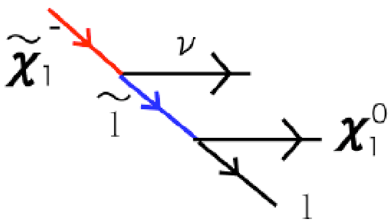


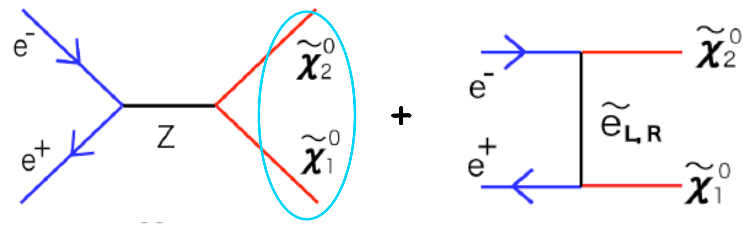
Lightest Neutralino



Mass degenerate

Chargino ~ higgsino
Larger coupling to stau

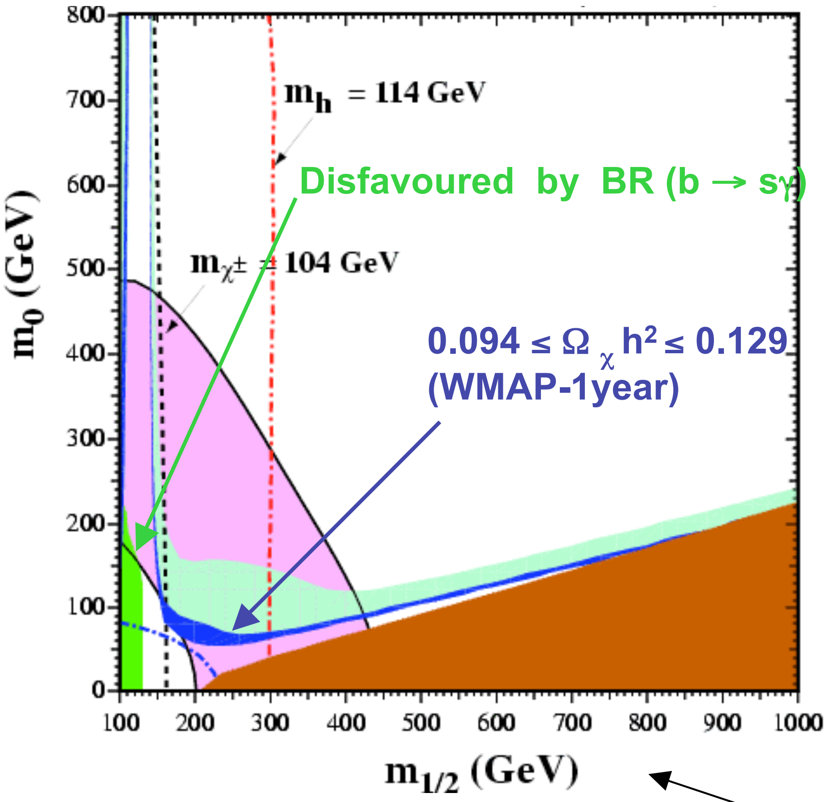




WMAP constraints

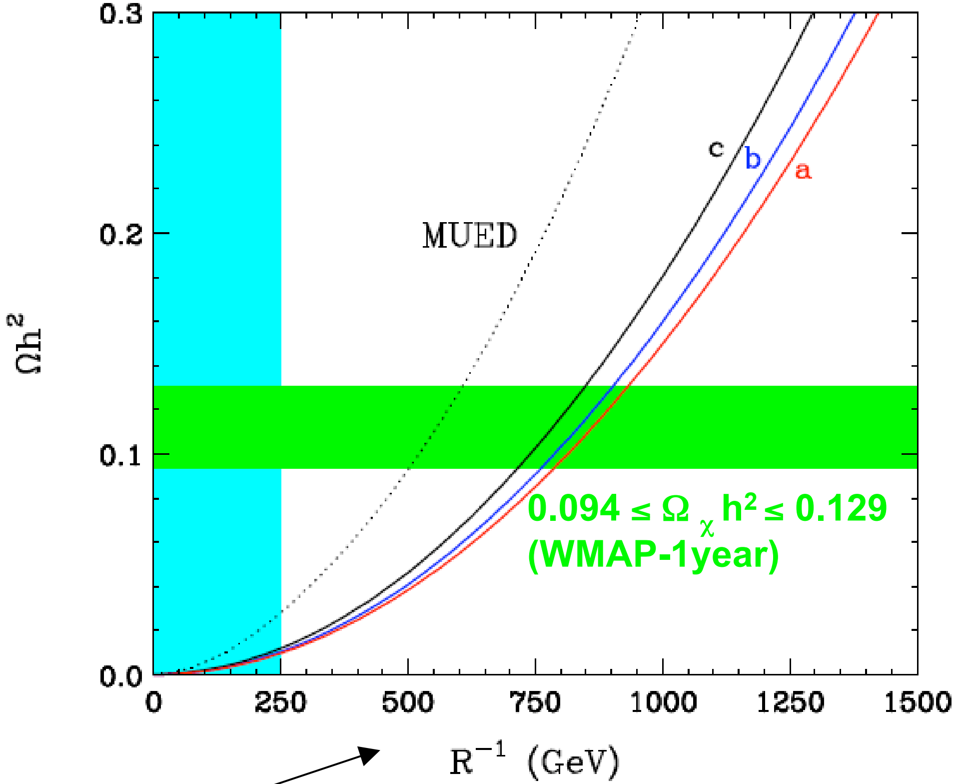
mSUGRA
A_0=0, tan(β) = 10, μ>0

Ellis et al. hep-ph/0303043



mUED
A_0=0, tan(β) = 10, μ>0

Kong, Matchev, JEP01(2006)038

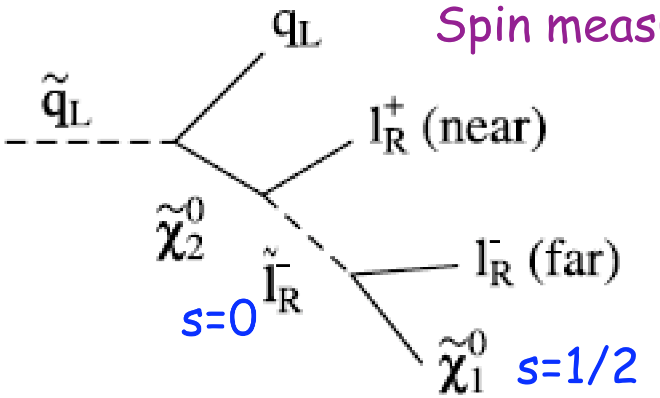


$\propto m_{LSP}$

Spin measurement

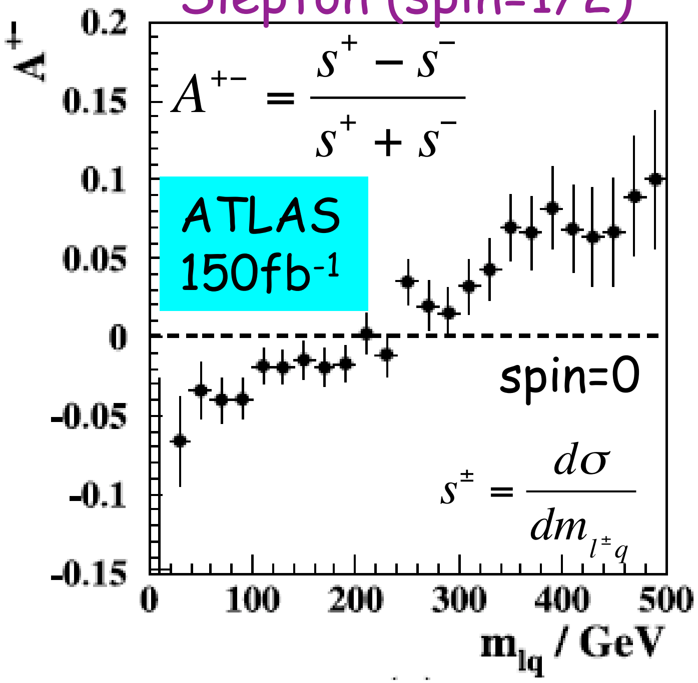
Barr, Phys.Lett.B596(2004)205

Resemble signatures are predicted in SUSY, UED, LHT…
Spin measurement can tell one model from others.

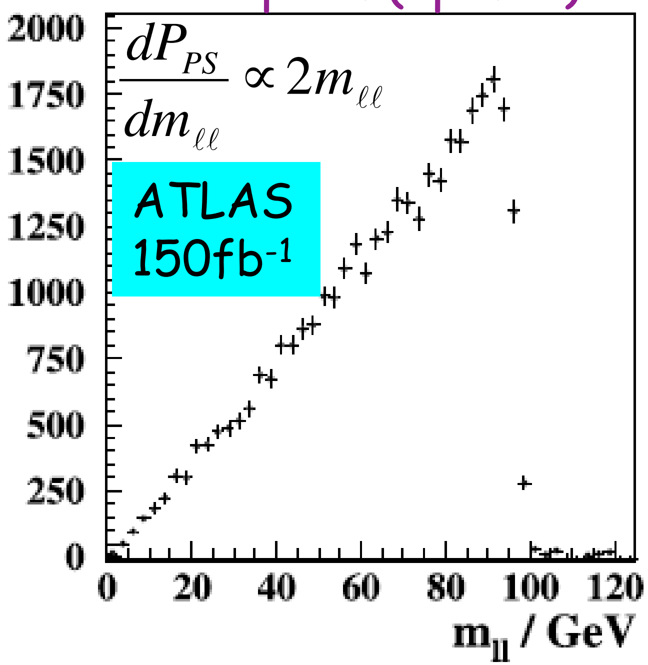


$\tilde{q}$-$\tilde{\bar{q}}$ asymmetry production (valence quark distribution) should be well-measured.

Slepton (spin=1/2)



Slepton (spin=0)



Nojiri, Polesello, Tovey JHEP03(2006)063

Stepwise Procedure

It might be possible to interpret measurements within general MSSM. But it is really depends on the situation, what can measure at LHC.

Not possible to measure all of parameters! So you must know which parameters are essential/negligible parameters to Ωh^2.

- Neutralino components (major ingredient)
- Slepton sector : especially light stau?
- Higgs sector : $M(H/A) \sim 2M(\tilde{\chi})$?

Usually difficult to get information of $\tan\beta$, $m(\tilde{\tau}_2)$ and $m(A)$.

Example : m(A/H)
- only h discovered -> only upper limit
- m(H/A)>300GeV -> $\Delta\Omega h^2 \sim O(1)\%$
- Negligible if observe $H/A \to \chi_2^0 \chi_2^0$