Physics Program

of the experiments at

Large Hadron Collider

Lecture 12

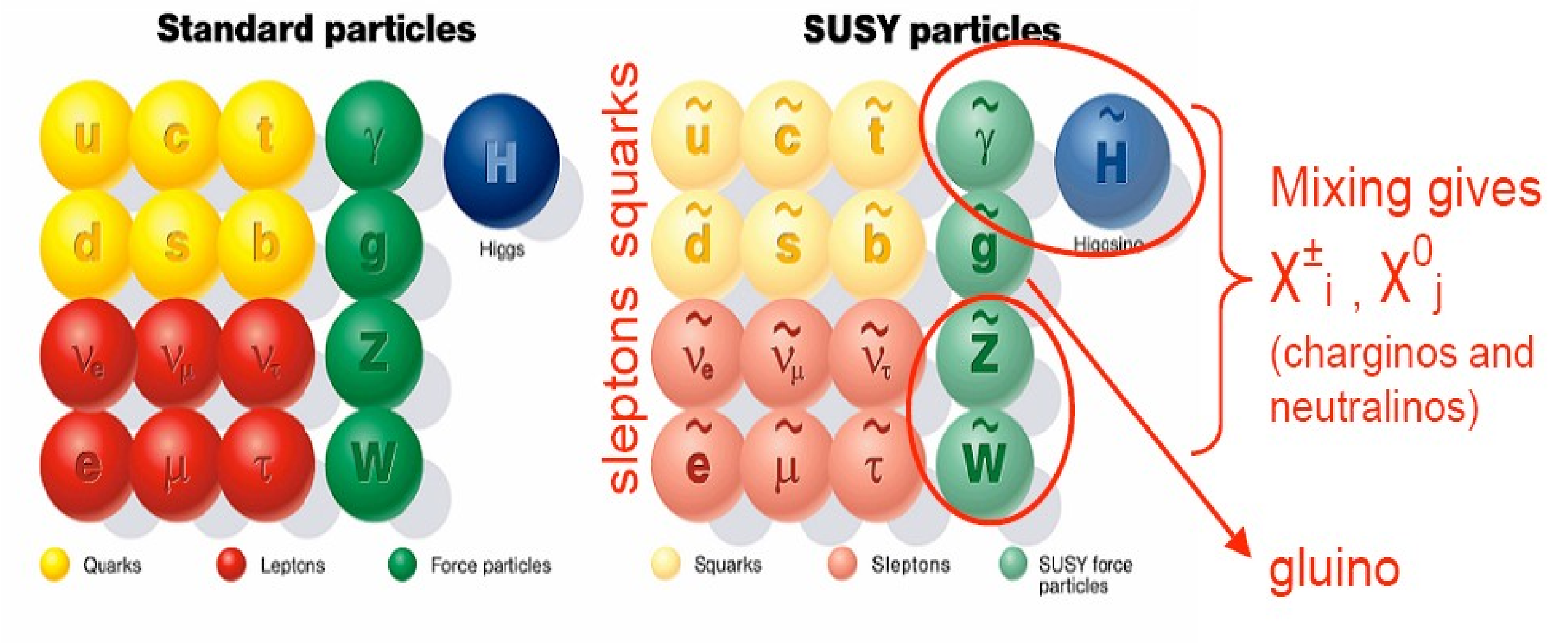
- **Supersymmetry:**
  - **Analyses status of 2008 and earlier results**
  - **14 TeV energy assumed**

Just few words about model

- One of the the theoretically favored candidate for physics beyond SM;
  - Protects Higgs mass from quadratically diverging radiative corrections
- Proposed solution postulates the invariace of the theory under a symmetry which transforms fermions into bosons and vice-versa
- The SUSY generator commute with SU(2)xU(1)xSU(3) symmetries of the SM
- In unbroken SUSY, partners have same quantum numbers and masses. But SUSY must be broken, non-observation of such to date! Common approach for breaking part in Lagragian is the one which would not reintroduce quadratic divergences
- To warrant conservation of leptonic and barionic quantum numbers, a new multiplicative quantum number R-parity introduced(+1 for SM particles, -1 for SUSY); most models assume R-parity conservation .
  - SUSY particles produced in pairs, the lightest one (LSP) stable
  - Cosmological arguments suggest LSP must be weakly interacting

Supersymmetry

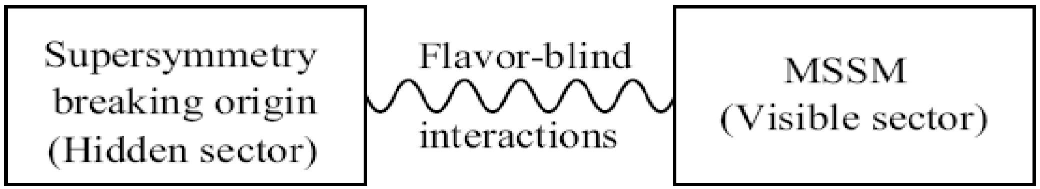
Create an extension of the SM, where for each boson we have a fermion and vice versa (superpartners differ only in their spin)



To learn more see eg. attached
S.P. Martin, "A Supersymmetry Primer", preprint 9709356 (updated 2008)

Models of SUSY breaking

Spontaneous breaking not possible in MSSM, need to postulate hidden sector



Phenomenological predictions determined by messenger field:

Three examples, sparticle masses and couplings function of few parameters:

- Gravity: mSUGRA. Parameters: m_0, $m_{1/2}$, A_0, $\tan\beta$, sgn μ

  Variations:

  – Decouple Higgs bosons from sfermions (NUHM). Add 2 parameters: $m(A), \mu$

  – Give up gaugino mass unification. $m_{1/2} \Rightarrow m_1, m_2, m_3$

- Gauge interactions: GMSB. Parameters: $\Lambda = F_m/M_m$, M_m, N_5 (number of messenger fields) $\tan\beta$, $sgn(\mu)$, C_{grav}

- Anomalies: AMSB. Parameters: m_0, $m_{3/2}$, $\tan\beta$, $sign(\mu)$

Models of SUSY breaking

SUSY breaking communicated to visible sector at some high scale

$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \text{sgn}\,\mu$ (mSUGRA)

Evolve down to EW scale through Renormalization Group Equations (RGE)

$M_1,\ M_2,\ M_3,\ m(\tilde{f}_R),\ m(\tilde{f}_L),\ A_t,\ A_b,\ A_\tau,\ m(A),\ \tan\beta, \mu$

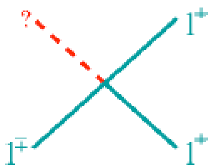
From 'soft' terms derive mass eigenstates and sparticle couplings.

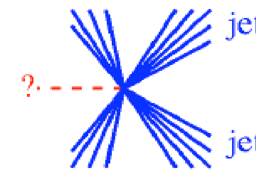
$m(\tilde{\chi}^0_j),\ m(\tilde{\chi}^\pm_j),\ m(\tilde{q}_R),\ m(\tilde{q}_L),\ m(\tilde{b}_1),\ m(\tilde{b}_2),\ m(\tilde{t}_1),\ m(\tilde{t}_2)$......

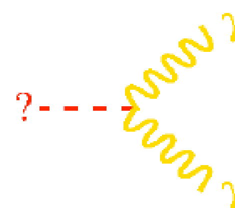
Task of the experimental SUSY searches is to go up the chain, i.e. measure enough masses and branching ratio to infer information on the SUSY breaking mechanism.

SUSY comes in many flavors

- Breaking mechanism determines phenomenology and search strategy at colliders
  - mSUGRA/CMSSM
    - Neutralino is the LSP
    - Many different final states
    - Common scalar and gaugino masses
  - GMSB:
    - Gravitino is the LSP
    - Photon or tau final states expected
  - Other:
    - AMSB,Split-SUSY,…







- R-parity
  - Conserved: Sparticles produced in pairs
    - natural dark matter candidate
  - Not conserved: Sparticles can be produced singly
    - constrained by proton decay if violation in quark sector

mSUGRA model

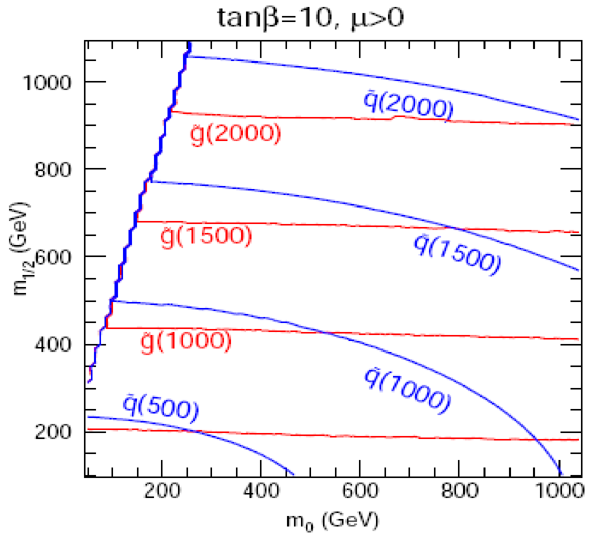
SM Particles	SUSY Particles		
quarks: q	q	squarks: $\tilde{q}$	
leptons: l	l	sleptons: $\tilde{l}$	
gluons: g	g	gluino: $\tilde{g}$	
charged weak boson: $W^{\pm}$	$W^{\pm}$	Wino: $\tilde{W}^{\pm}$	$\tilde{\chi}^{\pm}_{1,2}$ chargino
Higgs: H^{0}	$H^{\pm}$	charged higgsino: $\tilde{H}^{\pm}$	
	h^{0}, A^{0}, H^{0}	neutral higgsino: $\tilde{h}^{0}, \tilde{A}^{0}$,	$\tilde{\chi}^{0}_{1,2,3,4}$ neutralino
neutral weak boson: Z^{0}	Z^{0}	Zino: $\tilde{Z}^{0}$	
photon: γ	γ	photino: $\tilde{\gamma}$	

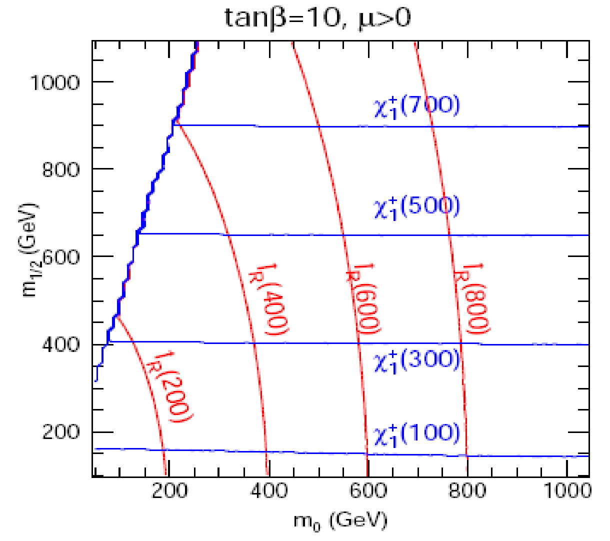
MSSM Lagrangian depends on 105 parameters

mSUGRA requires only 5 parameters

Par.	Description
m_0	Common scalar mass
$m_{1/2}$	Common gaugino mass
A_0	Common trilinear term
$\tan\beta$	Ratio of Higgs vev
sign(μ)	μ from Higgs sector

mSUGRA model





RGE for $m_{1/2}$ give for soft gaugino terms $M_3 : M_2 : M_1 : m_{1/2} \approx= 7 : 2 : 1 : 2.5$

$m(\tilde{g}) \approx M_3$. In mSUGRA $m(\tilde{\chi}_1^0) \approx M_1$, $m(\tilde{\chi}_2^0) \approx m(\tilde{\chi}_1^\pm) \approx M_2$

Sfermion mass determined by RGE running of m_0 and coupling to gauginos:

$m(\tilde{\ell}_L) \approx \sqrt{m_0^2 + 0.5 m_{1/2}^2}$; $m(\tilde{\ell}_R) \approx \sqrt{m_0^2 + 0.15 m_{1/2}^2}$; $m(\tilde{q}) \approx \sqrt{m_0^2 + 6 m_{1/2}^2}$

A and $\tan\beta$: significant contribution only to 3^{rd} generation RGE and mixing

Benchmark in SUSY parameter space

SUSY benchmark points chosen in the **(m_0, $m_{1/2}$)** plane for different **tanβ** values:

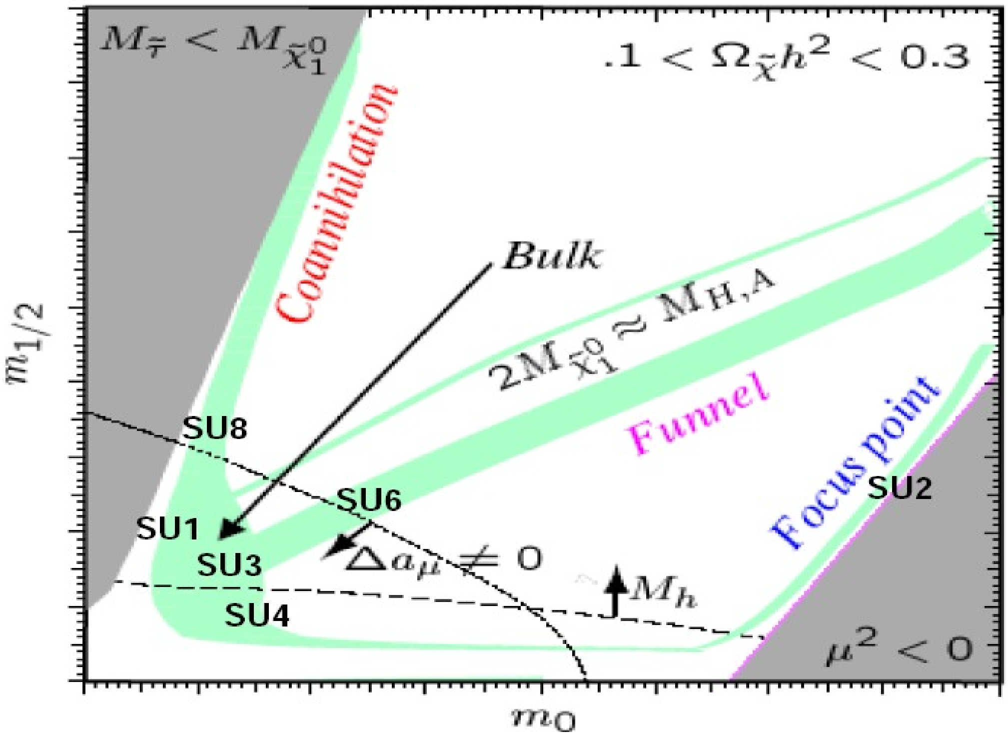
- ✓ Systematically exploring phenomenological signatures
- ✓ Scanning the parameter phase space constrained by latest experimental data and Cold Dark Matter abundance.

Coannihilation: Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}^0_1$, so annihilate via $\tilde{\chi}^0_1 \tilde{\tau}_1 \to \gamma\tau$.

Bulk: bino $\tilde{\chi}^0_1$; light $\tilde{\ell}_R$ enhances annihilation.

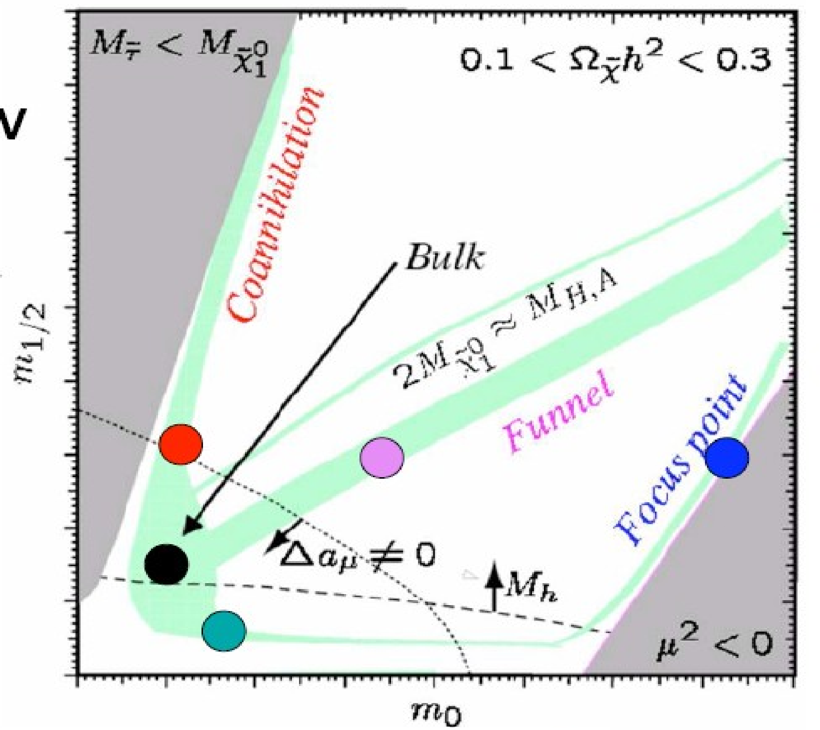
Funnel: H,A poles enhance annihilation for $\tan\beta \gg 1$.

Focus point: Small μ^2, so Higgsino $\tilde{\chi}^0_1$ annihilate. Heavy s-fermions, so small FCNC.



Benchmark in SUSY parameter space

- **SU1:** **m(g̃)≈830 GeV,m(q̃)≈750 GeV**
  - Coannihilation region
- **SU2:** **m(g̃)≈860 GeV,m(q̃)≈3500 GeV**
  - Focus point
- **SU3:** **m(g̃)≈720 GeV,m(q̃)≈620 GeV**
  - Bulk point
- **SU4:** **m(g̃)≈420 GeV,m(q̃)≈420 GeV**
  - Just beyond Tevatron reach
- **SU6:** **m(g̃)≈900 GeV,m(q̃)≈870 GeV**
  - Funnel regions



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Models studies extensively by ATLAS: mSUGRA case

SU1 $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Coannihilation region where $\tilde{\chi}_1^0$ annihilate with near-degenerate $\tilde{\ell}$.

SU2 $m_0 = 3550$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$. Focus point region near the boundary where $\mu^2 < 0$. This is the only region in mSUGRA where the $\tilde{\chi}_1^0$ has a high higgsino component, thereby enhancing the annihilation cross-section for processes such as $\tilde{\chi}_1^0\tilde{\chi}_1^0 \to WW$.

SU3 $m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $A_0 = -300$ GeV, $\tan\beta = 6$, $\mu > 0$. Bulk region: LSP annihilation happens through the exchange of light sleptons.

SU4 $m_0 = 200$ GeV, $m_{1/2} = 160$ GeV, $A_0 = -400$ GeV, $\tan\beta = 10$, $\mu > 0$. Low mass point close to Tevatron bound.

SU6 $m_0 = 320$ GeV, $m_{1/2} = 375$ GeV, $A_0 = 0$, $\tan\beta = 50$, $\mu > 0$. The funnel region where $2m_{\tilde{\chi}_1^0} \approx m_A$. Since $\tan\beta \gg 1$, the width of the pseudoscalar Higgs boson A is large and τ decays dominate.

SU8.1 $m_0 = 210$ GeV, $m_{1/2} = 360$ GeV, $A_0 = 0$, $\tan\beta = 40$, $\mu > 0$. Variant of coannihilation region with $\tan\beta \gg 1$, so that only $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ is small.

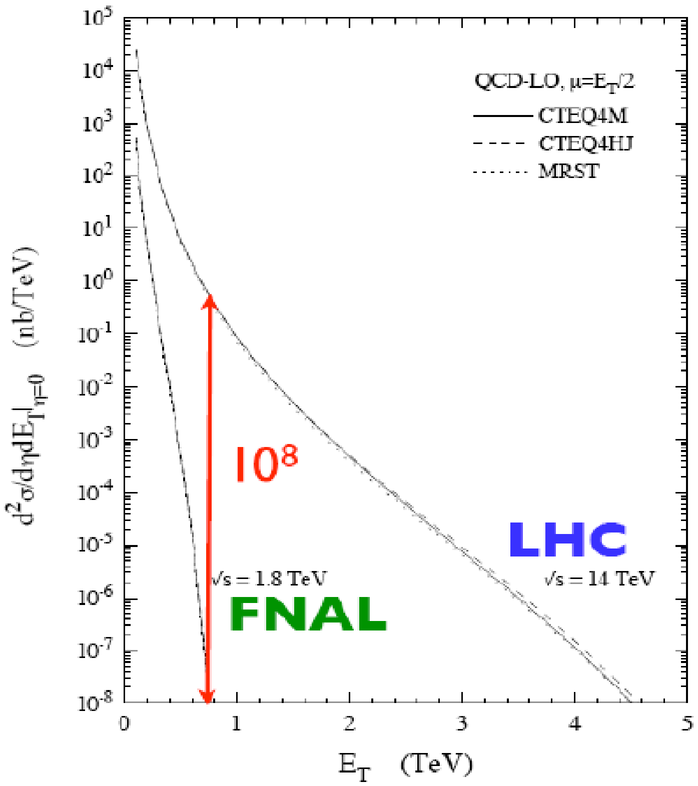
SU9 $m_0 = 300$ GeV, $m_{1/2} = 425$ GeV, $A_0 = 20$, $\tan\beta = 20$, $\mu > 0$. Point in the bulk region with enhanced Higgs production

Physics opportunities at LHC

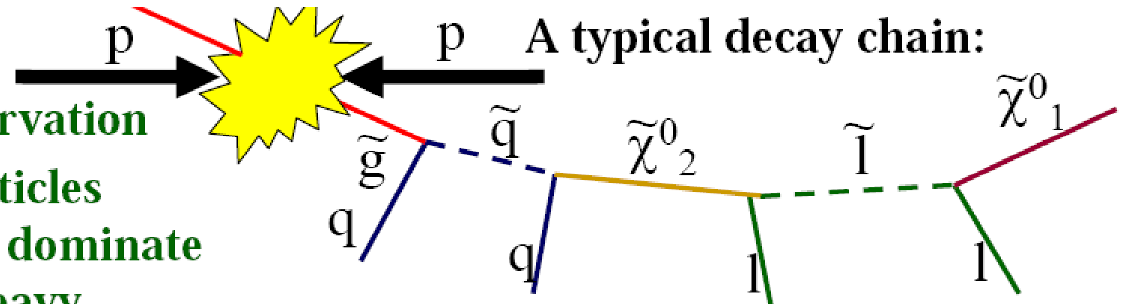
Cross Sections of Physics Processes (pb)

	Tevatron	LHC √s=14TeV	Ratio
$W^{\pm}$ (80 GeV)	2600	20000	~10
tt (2x172 GeV)	7	900	~100
gg->H (120 GeV)	1	40	~40
$\tilde{\chi}^{+}_{1}\tilde{\chi}^{2}_{0}$ (2x150 GeV)	0.1	1	~10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	~1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	~20000
Z' (1 TeV)	0.1	30	~300

Jet Cross Section

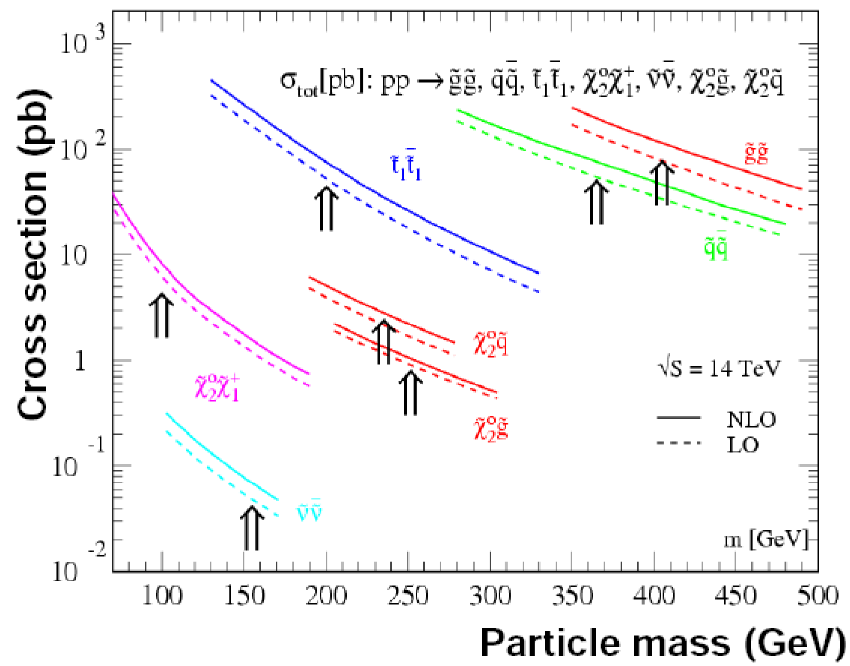


SUSY signatures at a hadronic colliders



- **Assuming R-parity conservation**
- **Strongly interacting sparticles (squarks, gluinos) should dominate production unless very heavy.**
- **Cascade decays to the stable, weakly interacting lightest neutralino follows.**
- **Event topology:**
  - **high p_T jets (from squark/gluino decay)**
  - **Large E_T^{miss} signature (from LSP)**
  - **High p_T leptons, b-jets, τ-jets (depending on model parameters).**

Several other possibilities exist, but our effort has to be as more "model independent" as possible.



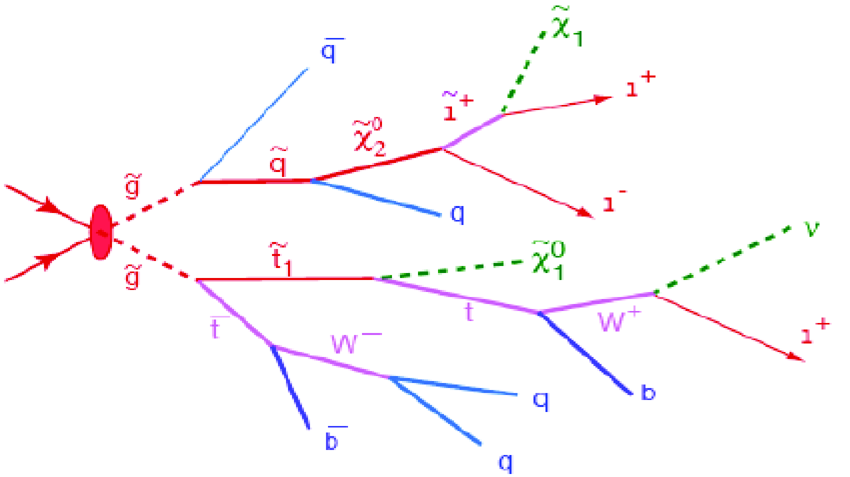
SUSY discovery: basic strategy

- Details of cascade decays are a function of model parameters
- The search should rely on robust signatures
  - covers large classes of models
  - clearly distinctive from SM background

typically,

$$\not{E}_T + \text{High } P_T \text{ (multi) jets} + \begin{cases}\text{leptons} \\ \text{b-jets} \\ \tau\text{-jets}\end{cases}$$

In some other models, photons, or special signatures based on long-lived sparticles co-exist



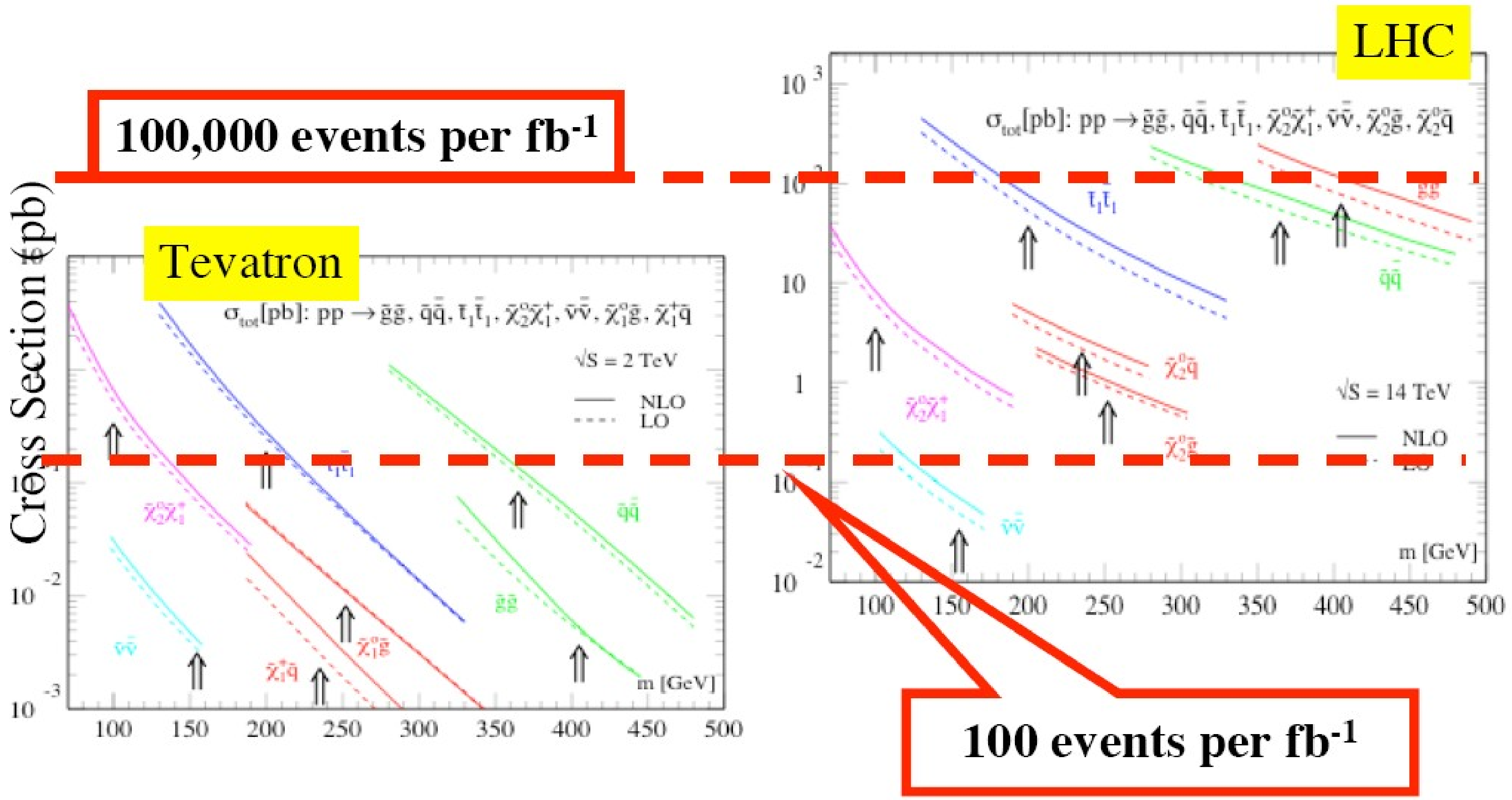
Missing E_T: LSP escaping detection

High p_T jets: squark/gluinos production

leptons: decays of gauginos, stops

(tau-jets or *b*-jets: from third generation sparticle production)

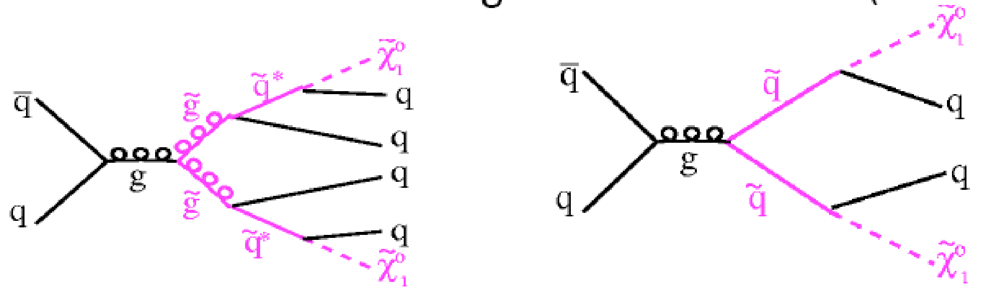
Sparticle cross-section: LHC vs Tevatron



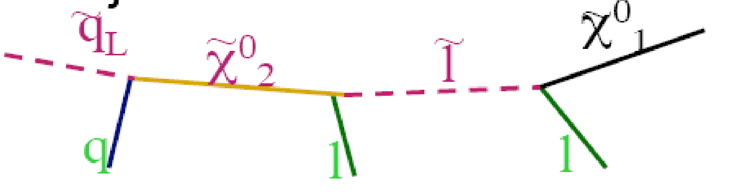
T. Plehn, PROSPINO

Squarks and gluinos at LHC

- Cross section nearly model-independent
  - for m($\tilde{g}$)=400 GeV: $\sigma_{LHC}(\tilde{g}\tilde{g}) / \sigma_{Tevatron}(\tilde{g}\tilde{g}) \approx 20{,}000$
  - for m($\tilde{q}$)=400 GeV: $\sigma_{LHC}(\tilde{q}\tilde{q}) / \sigma_{Tevatron}(\tilde{q}\tilde{q}) \approx 1{,}000$
    - Since there are a lot more gluons at the LHC (lower x)



- At higher masses more phase space => decay in cascades
  - Results in additional leptons or jets
  - Very model-dependent



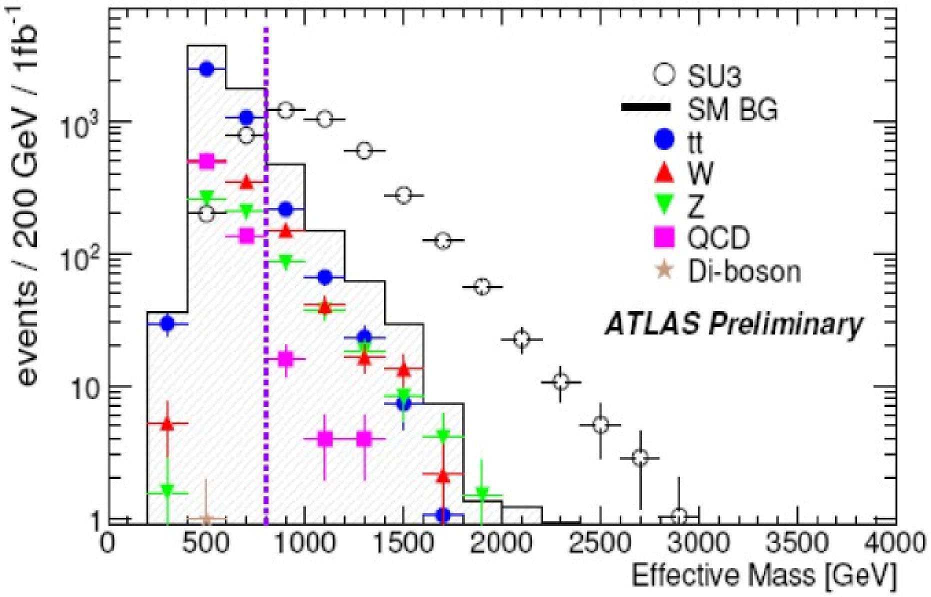
Inclusive signatures for zero leptons

SUSY selection:

- 4 jets ($P_T < 100, 50, 50, 50$) GeV)
- $\not{E}_T > 100$ GeV and $\not{E}_T > 0.2 M_{\text{eff}}$
- $\Delta\phi(j, \not{E}_T) > 0.2$
- Transverse sphericity > 0.2

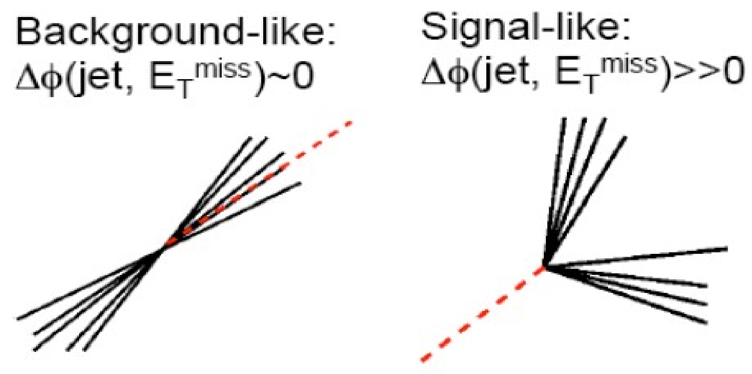
Plot $M_{\text{eff}} = \Sigma_{i=1}^{4} |p_{T(jet_i)}| + E_T^{\text{miss}}$

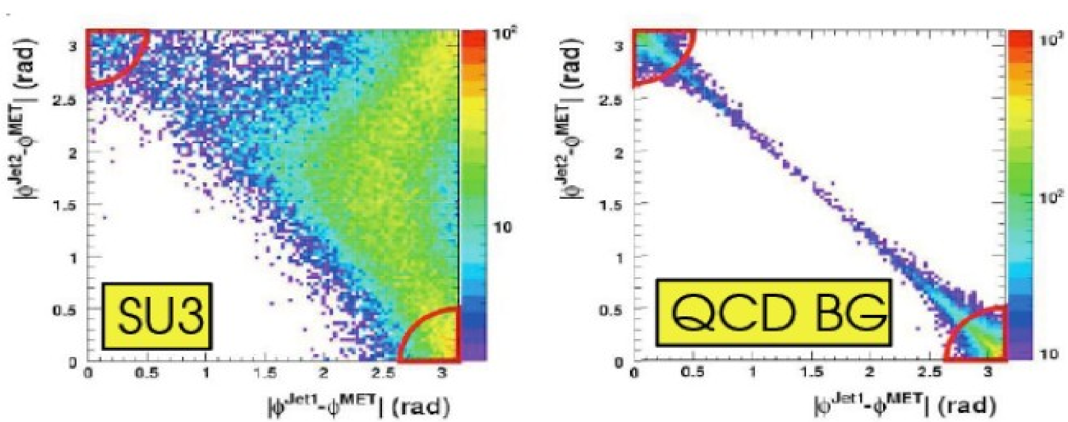
Typical cut: $M_{\text{eff}} > 800$ GeV



QCD multi-jet

- Require large $\Delta\phi$
  - Between missing E_T and jets and between jets
  - Suppresses QCD dijet background due to jet mismeasurements

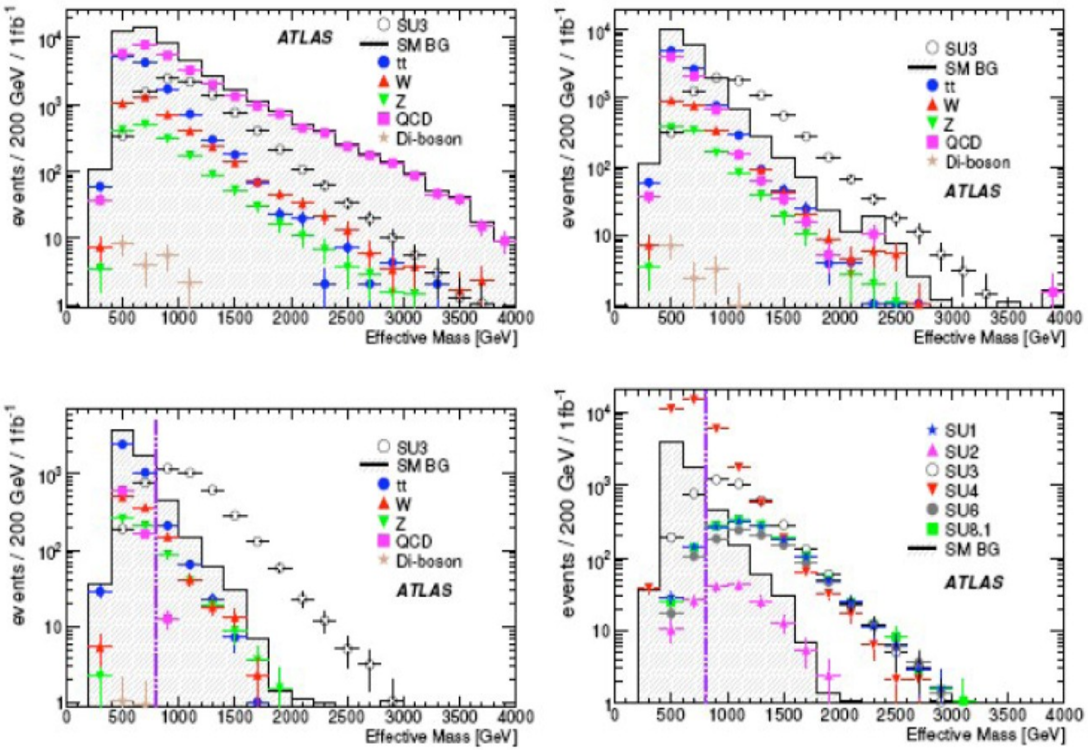




- Many studies on how to determine this background with data

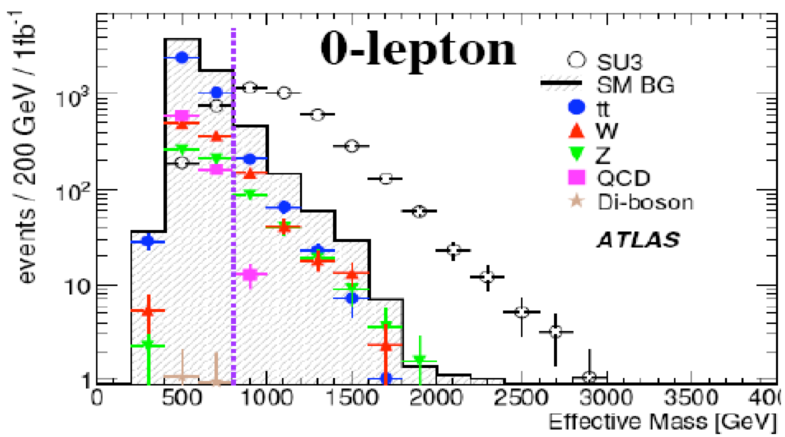
Hermetic and well understood calorimeter critical for tl

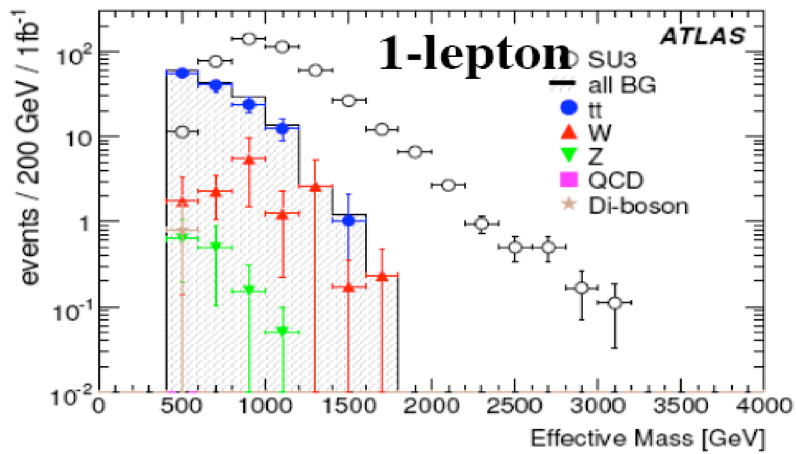
0 lepton analysis: details



- 4 energetic jets and E_T^{miss}>100 GeV
- E_T^{miss}>0.2 M_{eff} where $M_{eff}=\sum_i E_{T,i}+E_t^{miss}$
- Sphericity>0.2, phi-correlation cuts, lepton veto

Search analyses: 0,1 ,2 leptons+jets



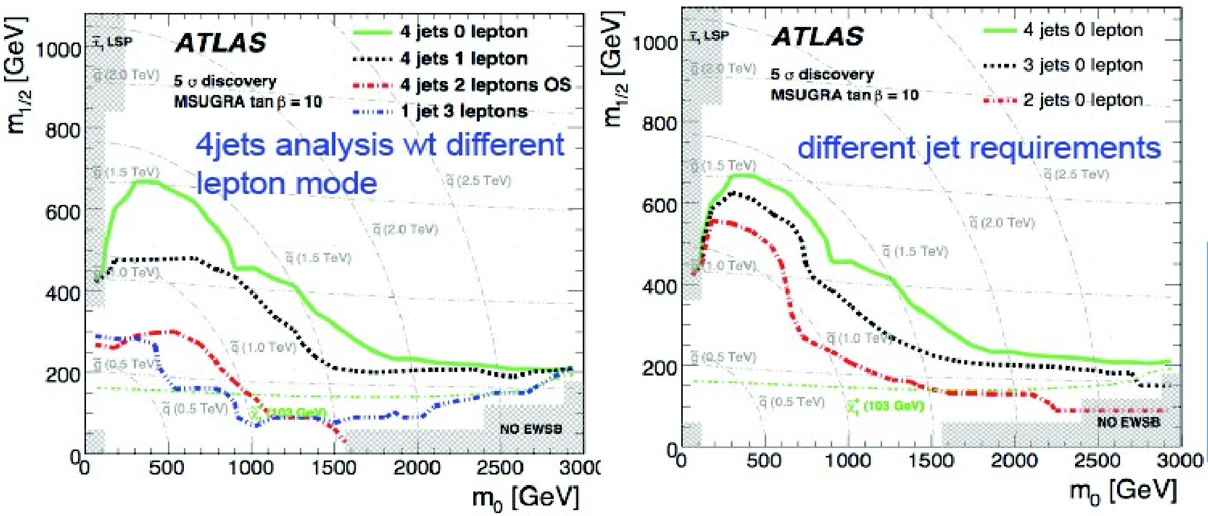


- Signal can appear in many search analyses simultaneously
  - Depends on model details
  - Important to do all of them
- Top is most severe background

2-lepton

Sample	Nevent/fb^{-1}
SU1 $m(\tilde{g})\approx 860$ GeV	72.6
SU2 $m(\tilde{g})\approx 830$ GeV	18.8
SU3 $m(\tilde{g})\approx 720$ GeV	159.8
SU4 $m(\tilde{g})\approx 420$ GeV)	809.5
Top	81.5
Other backgrounds	3.2

Inclusive reach in mSUGRA parameter space (14 TeV)

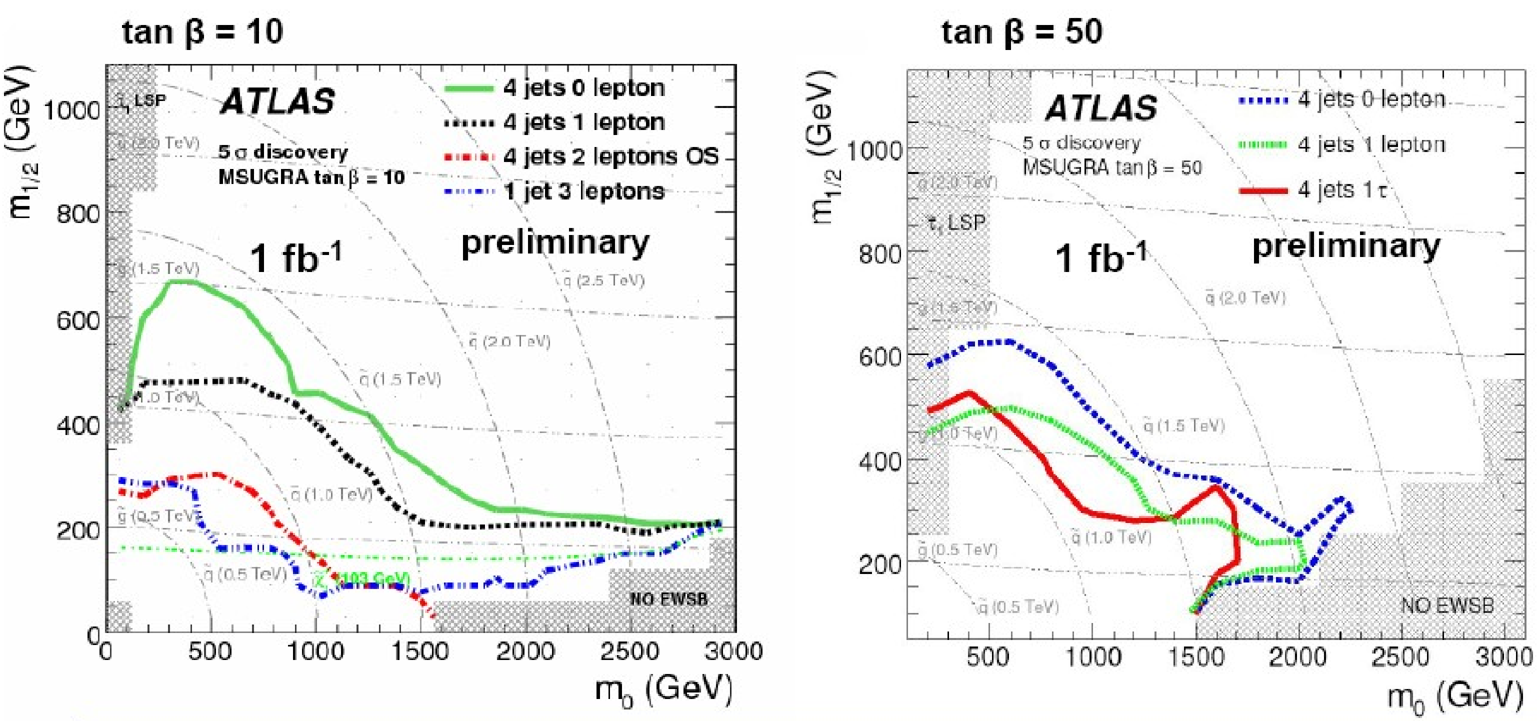


reach for $\tilde{q}, \tilde{g}$ (14TeV)

0.1 fb^{-1}	750GeV
1.0 fb^{-1}	1350GeV
10. fb^{-1}	1800GeV

- ATLAS Reach for 14TeV, 1fb^{-1}
- included expected uncertainties on SM background at 1fb^{-1} of data
  - 50% on QCD backgrounds
  - 20% on tt, W, Z+jets
- multiple signatures over most of the spaces

Inclusive reach in mSUGRA parameter space (14 TeV)



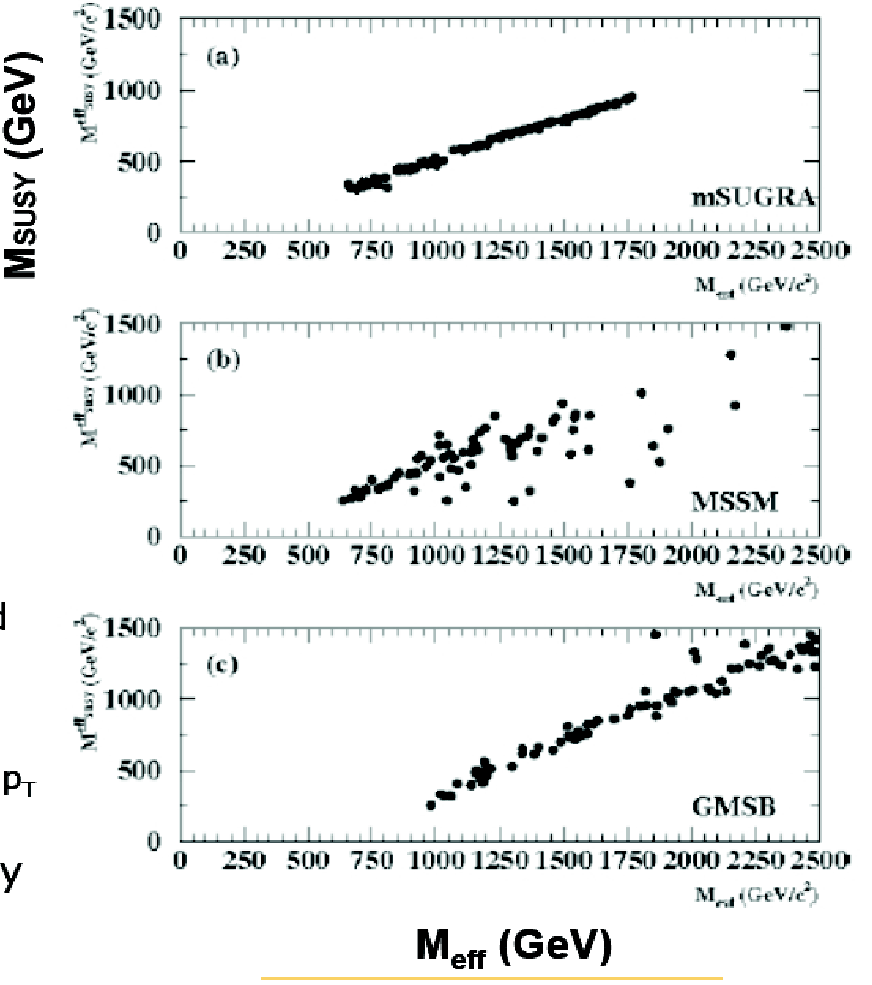
- for 1 fb^{-1} : cover a large part of mSUGRA phase space favored by electroweak, heavy-flavour physics and low energy precision data!
- tau channel can help for large tanβ

SUSY mass scale vs M_{eff}

- SUSY mass scale, M_{SUSY} := average of squark and gluino masses

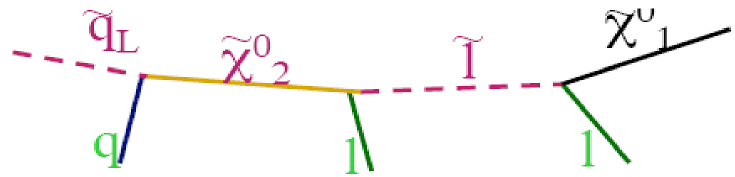
$$M_{\rm eff} \equiv \sum_{i=1}^{4} p_T^{{\rm jet},i} + \sum_{i=1} p_T^{{\rm lep},i} + E_{\rm T}^{\rm miss}$$

- M_{eff} peak strongly correlated to the SUSY mass scale
- Measurement of M_{SUSY} feasible with 10 fb^{-1}
  - 15% precision for mSUGRA
  - 40% precision for MSSM
  - also possible for GMSB with rapid decays to gravitino LSP
    - significantly increased statistics needed
    - *or* variables using photon or lepton p_T
- Total SUSY cross section, σ_{SUSY}, can be estimated in a similar way with 10 fb^{-1} with a precision of 15% (50%) in mSUGRA (MSSM)

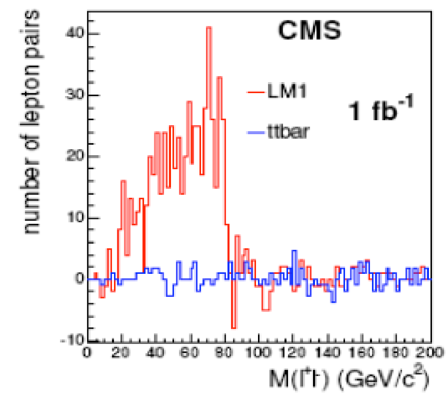


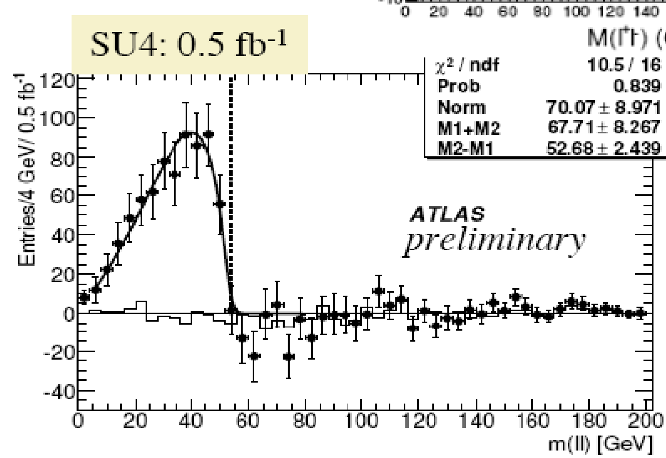
What kind of SUSY is it?

- We will need to do SUSY spectroscopy!
  - Rate of 0 vs 1 vs 2 vs n leptons
    - Sensitive to neutralino masses
  - Rate of tau-leptons:
    - Sensitive to tanβ
  - Kinematic edges
    - obtain mass values
  - Trileptons
    - Examine chargino/ neutralino couplings
  - Detailed examination of inclusive spectra



$$m_{\ell\ell}^{\mathrm{edge}} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$





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General strategy

- Select signatures identifying well defined decay chains
- Extract constraints on masses, couplings, spin from decay/kinematic rates
- Try to match emerging pattern to template models, SUSY or anything else
- Having adjusted template models to measurements try to find additional signatures to discriminate different options
- Most of the work done on sparticle mass measurement.

Dilepton channel

– Reduces the signal because of (model dependent) leptonic BRs;

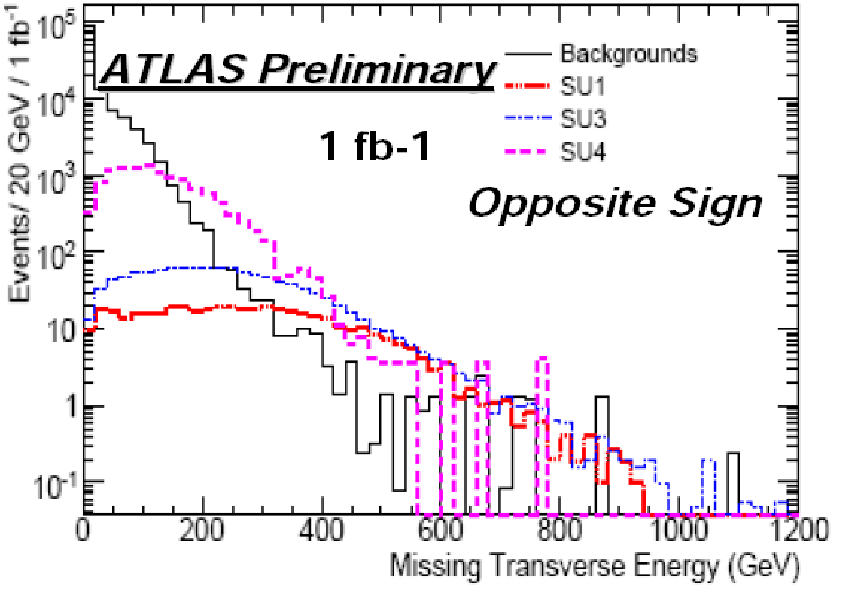
– Heavily suppresses the background: top is the dominant one;

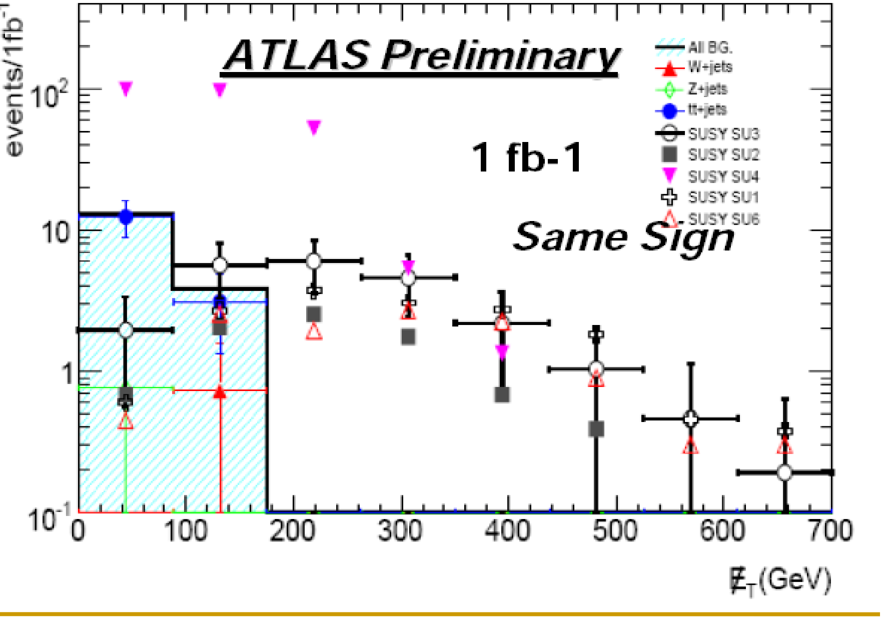
– Statistical significance is smaller but S/B ratio larger.

– The Same Sign channel has the best S/B ratio – but limited by signal rate

<u>Baseline selection :</u>

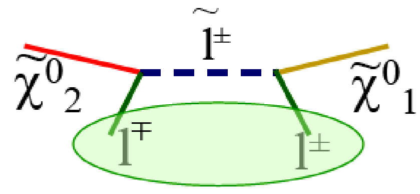
- Jet multiplicity ≥ 4, $p_T^{1st} > 100$GeV, $p_T^{others} > 50$GeV
- $E_T^{miss} > \max(100\text{GeV}, 0.2 \text{x} M_{eff})$; Transverse sphericity > 0.2 .





Dilepton edge mass measurement

- In case of a discovery of SUSY, **particle properties** can be measured to verify that they are indeed SUSY partners



- Edge(s) of **di-lepton invariant mass** correlated with slepton and neutralino masses

$$\tilde{\chi}^0{}_2 \rightarrow \tilde{l}\,l \rightarrow \tilde{\chi}^0{}_1 \; l^+ l^-$$

- Impossible to reconstruct peaks because $\chi^0{}_1$ (LSP) escapes detection, more complicated relations between masses of particles involved.

$$M_{ll}^{\max} = M(\tilde{\chi}_2^0)\sqrt{1-\frac{M^2(\tilde{l}_R)}{M^2(\tilde{\chi}_2^0)}}\sqrt{1-\frac{M^2(\tilde{\chi}_1^0)}{M^2(\tilde{l}_R)}}$$

✓ Uncorrelated (SUSY+SM) background (two leptons from independent chains) **removed** by **flavour subtraction**:

$e^+e^- + \beta^2 \mu^+\mu^- - \beta\,(e^+\mu^- - e^-\mu^+)$, $\beta=\varepsilon_e/\varepsilon_\mu$

✓ Leptons can also be combined with jets of the full decay chain to look for other **kinematical edges** (M_{llj} or M_{lj})

Lepton + jets combinations

decay chain

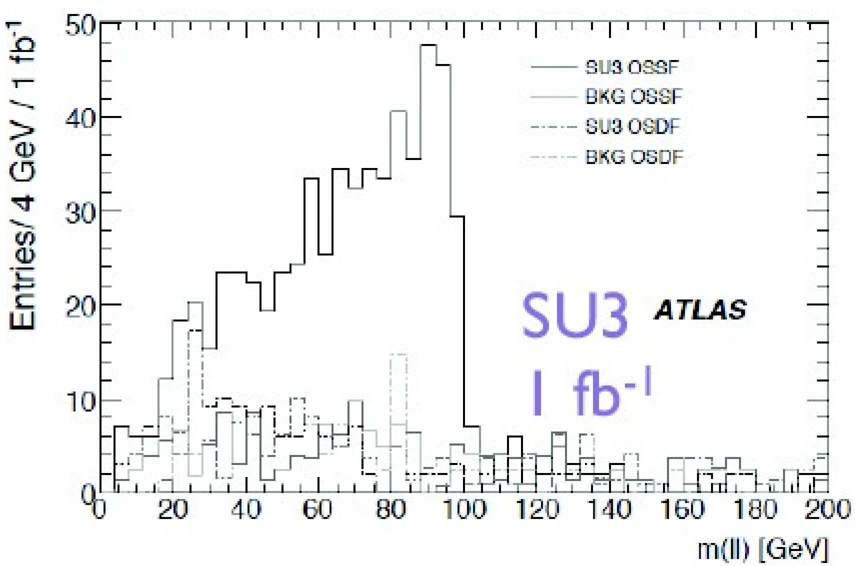
$$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q(\rightarrow \tilde{\ell}^\pm \ell^\mp q) \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^- q$$

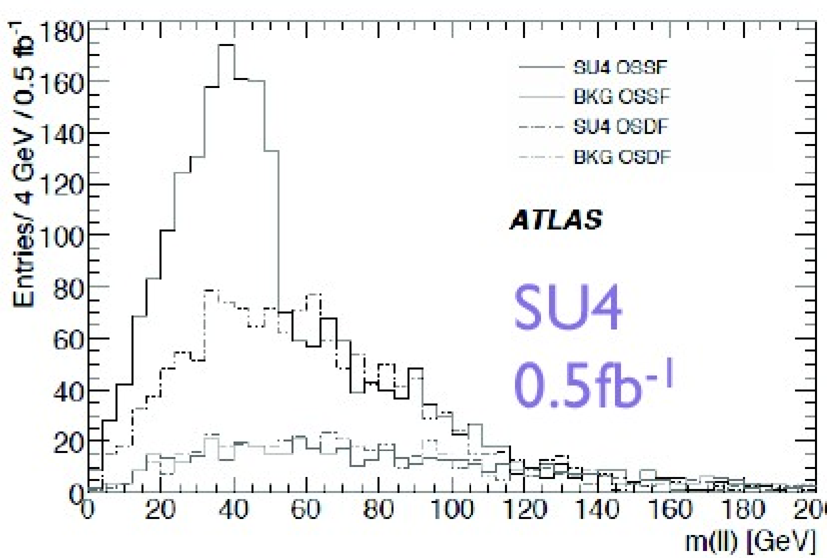
$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0} \sqrt{1 - \left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2} \sqrt{1 - \left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2} .$$

3-body decay

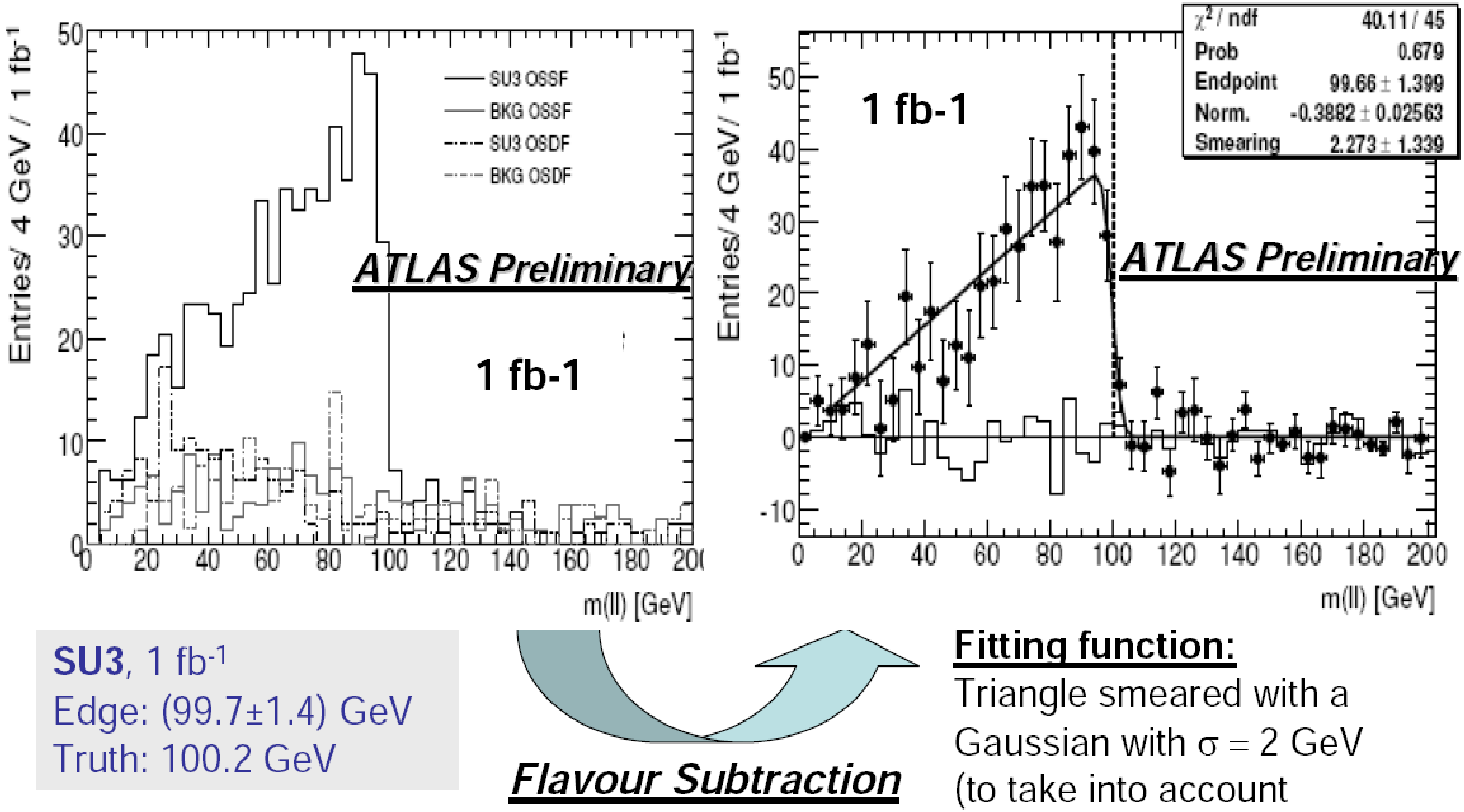
$$\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-$$

$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$$





Dilepton edge mass measurement

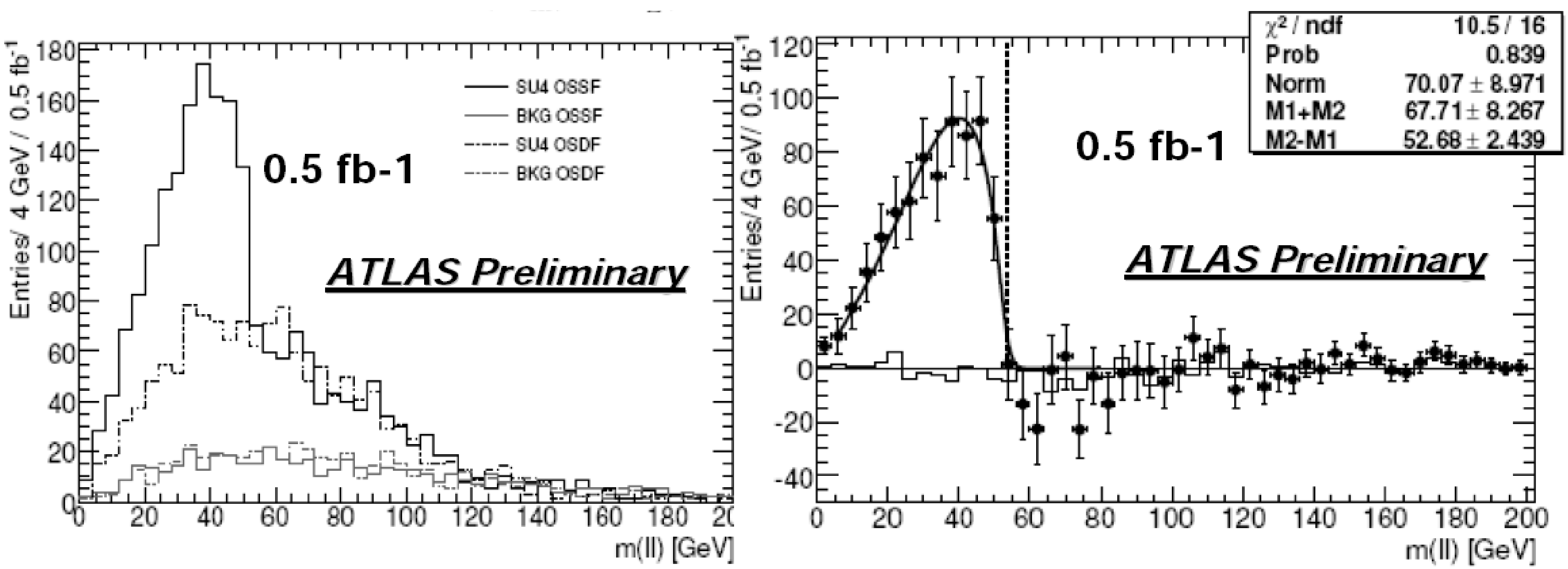


SU3, 1 fb^{-1}
Edge: (99.7±1.4) GeV
Truth: 100.2 GeV

Fitting function:
Triangle smeared with a Gaussian with $\sigma = 2$ GeV (to take into account experimental resolution)

Dilepton edge mass measurement

For **SU4**, the slepton is heavier than χ_2^0 → The decay is: $\chi_2^0 \rightarrow \chi_1^0 l^+ l^-$



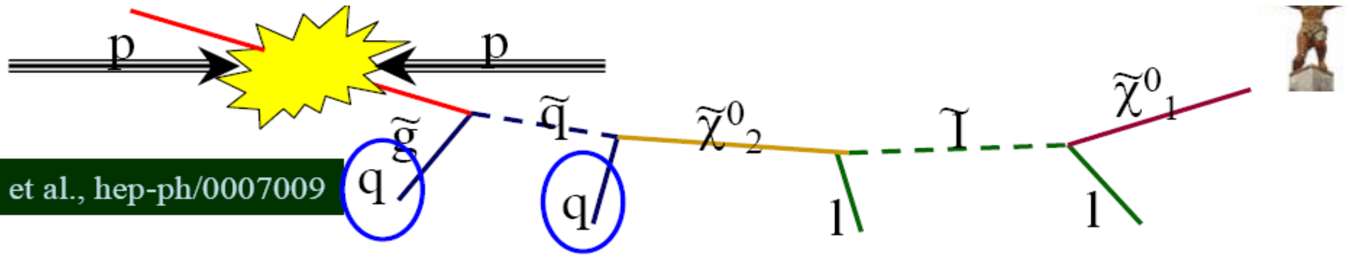
SU4, 0.5 fb^{-1}
Edge: (52.7±2.4) GeV
Truth: 53.6 GeV

Flavour Subtraction

Fitting function:
Theoretical three body decay function in the limit of large slepton mass, smeared by the experimental resolution with $\sigma = 2$ GeV. **10**

Lepton + jets combinations

Formulas in Allanach et al., hep-ph/0007009



Assuming that the squarks decays originate the **two hardest jets** of the event, one can use the ***qll*** combinations. Each combination has a minimum or a maximum which provides one constraint on the masses of $\tilde{\chi}^0{}_1$ $\tilde{\chi}^0{}_2$ $\tilde{l}$ $\tilde{q}$.

$$m_{llq}^{EDGE} \to \{ llq_1, \; llq_2 \} \Rightarrow$$

Keep the minimum

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

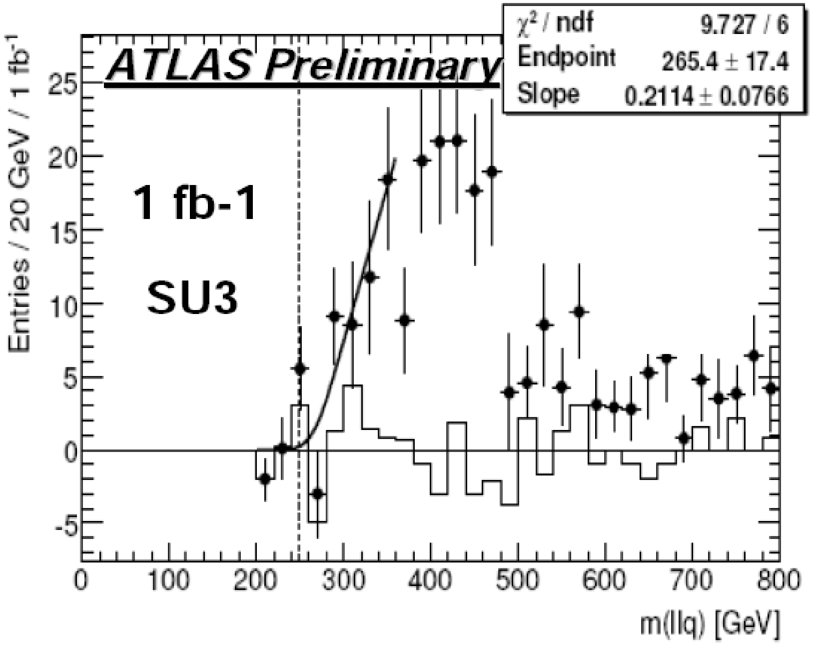
$$m_{llq}^{THRESH} \to \{ llq_1, \; llq_2 \} \Rightarrow$$

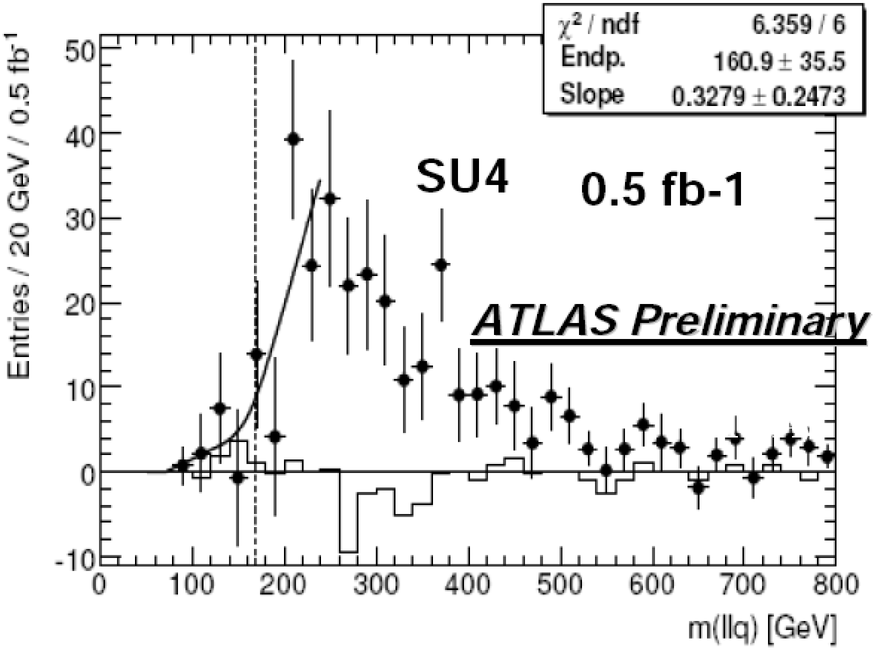
Keep the maximum

$$\left(m^2_{qll}\right)^{\text{thres}} = [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}) - (m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})\sqrt{(m^2_{\tilde{\chi}^0_2} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}^0_1})^2 - 16 m^2_{\tilde{\chi}^0_2} m^4_{\tilde{l}_R} m^2_{\tilde{\chi}^0_1}} + 2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})]/(4m^2_{\tilde{l}_R} m^2_{\tilde{\chi}^0_2})$$

Lepton + jets combinations

llq thresholds





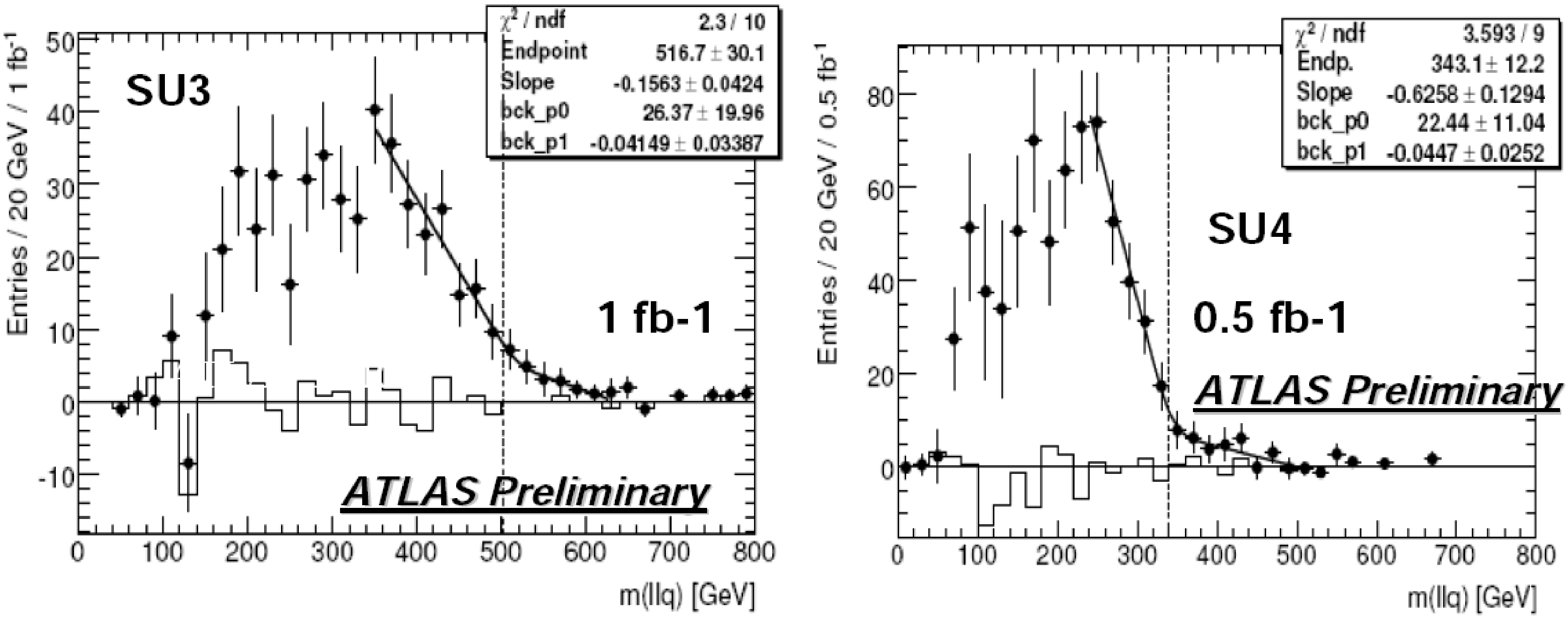
Fit formula: 2 straight lines (for signal and background) smeared by a Gaussian distribution to take into account the experimental resolution.

Edge: 265±17±15±7 GeV
Truth: 249 GeV

Edge: 161±36±20±4 GeV
Truth: 168 GeV

Lepton + jets combinations

llq edges



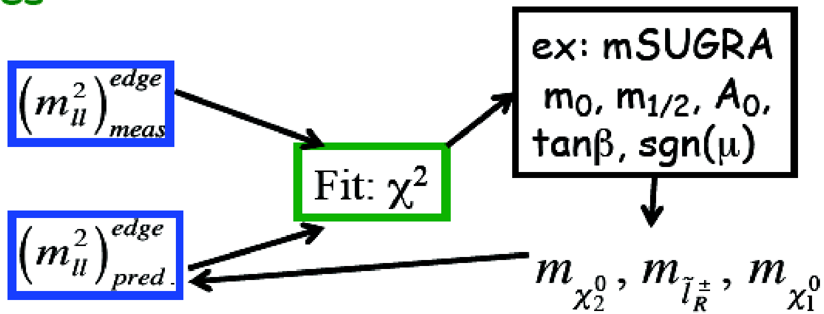
Fit formula: 2 straight lines (for signal and background) smeared by a Gaussian distribution to take into account the experimental resolution.

Edge: 517±30±10±13 GeV
Truth: 501 GeV

Edge: 343±12±3±9 GeV
Truth: 340 GeV

Measuring model parameters

e.g. mSUGRA/CMSSM model and perform global fit of model parameters to observables



Point	m_0	$m_{1/2}$	A_0	tan(β)	sign(μ)
Bulk	100 Gev	300 GeV	-300	6	+1

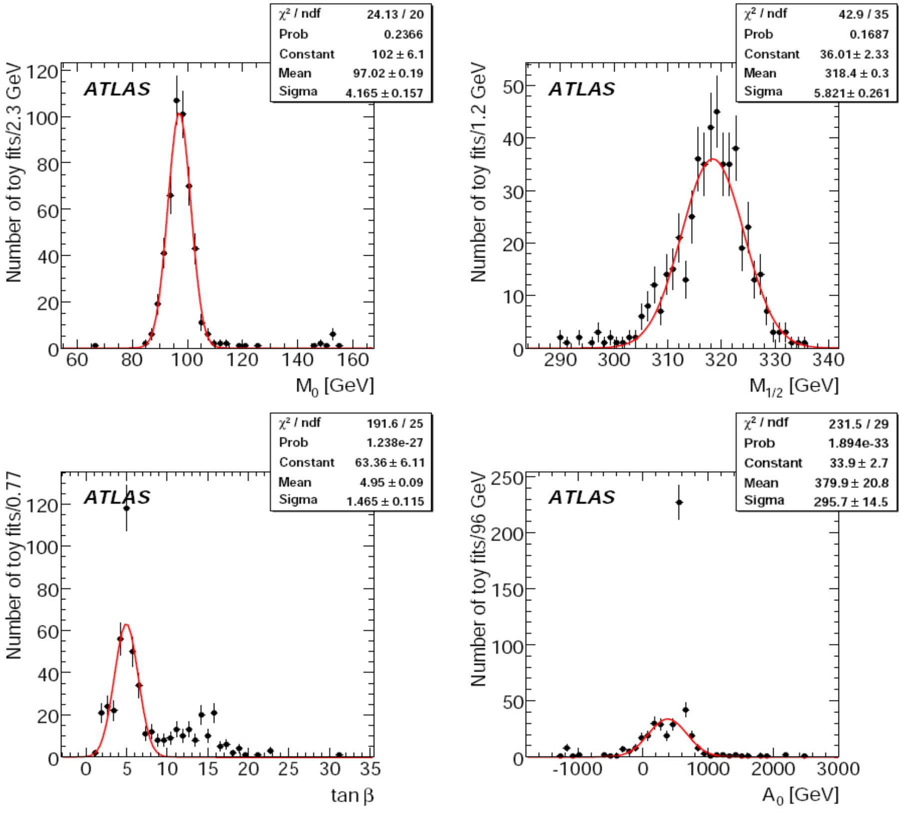
Variable	Value (GeV)	Errors Stat. (GeV)	Scale (GeV)	Total
$m_{\ell\ell}^{max}$	77.07	0.03	0.08	0.08
$m_{\ell\ell q}^{max}$	428.5	1.4	4.3	4.5
$m_{\ell q}^{low}$	300.3	0.9	3.0	3.1
$m_{\ell q}^{high}$	378.0	1.0	3.8	3.9
$m_{\ell\ell q}^{min}$	201.9	1.6	2.0	2.6
$m_{\ell\ell b}^{min}$	183.1	3.6	1.8	4.1
$m(\ell_L) - m(\tilde{\chi}_1^0)$	106.1	1.6	0.1	1.6
$m_{\ell\ell}^{max}(\tilde{\chi}_4^0)$	280.9	2.3	0.3	2.3
$m_{\tau\tau}^{max}$	80.6	5.0	0.8	5.1
$m(\tilde{g}) - 0.99 \times m(\tilde{\chi}_1^0)$	500.0	2.3	6.0	6.4
$m(\tilde{q}_R) - m(\tilde{\chi}_1^0)$	424.2	10.0	4.2	10.9
$m(\tilde{g}) - m(\tilde{b}_1)$	103.3	1.5	1.0	1.8
$m(\tilde{g}) - m(\tilde{b}_2)$	70.6	2.5	0.7	2.6

sign(μ)=+1		expected unc. 1 fb^{-1}
m_0	98.5 GeV	± 9.3 GeV
$m_{1/2}$	317.7 GeV	± 6.9 GeV
tan(β)	7.4	4.6
A_0	445.0 GeV	± 408 GeV

Results for SU3 (1fb^{-1}) and SU4(0.5fb^{-1})

Observable	SU3 $m_{\rm meas}$ [GeV]	SU3 $m_{\rm MC}$ [GeV]	SU4 $m_{\rm meas}$ [GeV]	SU4 $m_{\rm MC}$ [GeV]
$m_{\tilde\chi_1^0}$	$88 \pm 60 \mp 2$	118	$62 \pm 126 \mp 0.4$	60
$m_{\tilde\chi_2^0}$	$189 \pm 60 \mp 2$	219	$115 \pm 126 \mp 0.4$	114
$m_{\tilde q}$	$614 \pm 91 \pm 11$	634	$406 \pm 180 \pm 9$	416
$m_{\tilde\ell}$	$122 \pm 61 \mp 2$	155		
Observable	SU3 $\Delta m_{\rm meas}$ [GeV]	SU3 $\Delta m_{\rm MC}$ [GeV]	SU4 $\Delta m_{\rm meas}$ [GeV]	SU4 $\Delta m_{\rm MC}$ [GeV]
$m_{\tilde\chi_2^0} - m_{\tilde\chi_1^0}$	$100.6 \pm 1.9 \mp 0.0$	100.7	$52.7 \pm 2.4 \mp 0.0$	53.6
$m_{\tilde q} - m_{\tilde\chi_1^0}$	$526 \pm 34 \pm 13$	516.0	$344 \pm 53 \pm 9$	356
$m_{\tilde\ell} - m_{\tilde\chi_1^0}$	$34.2 \pm 3.8 \mp 0.1$	37.6		

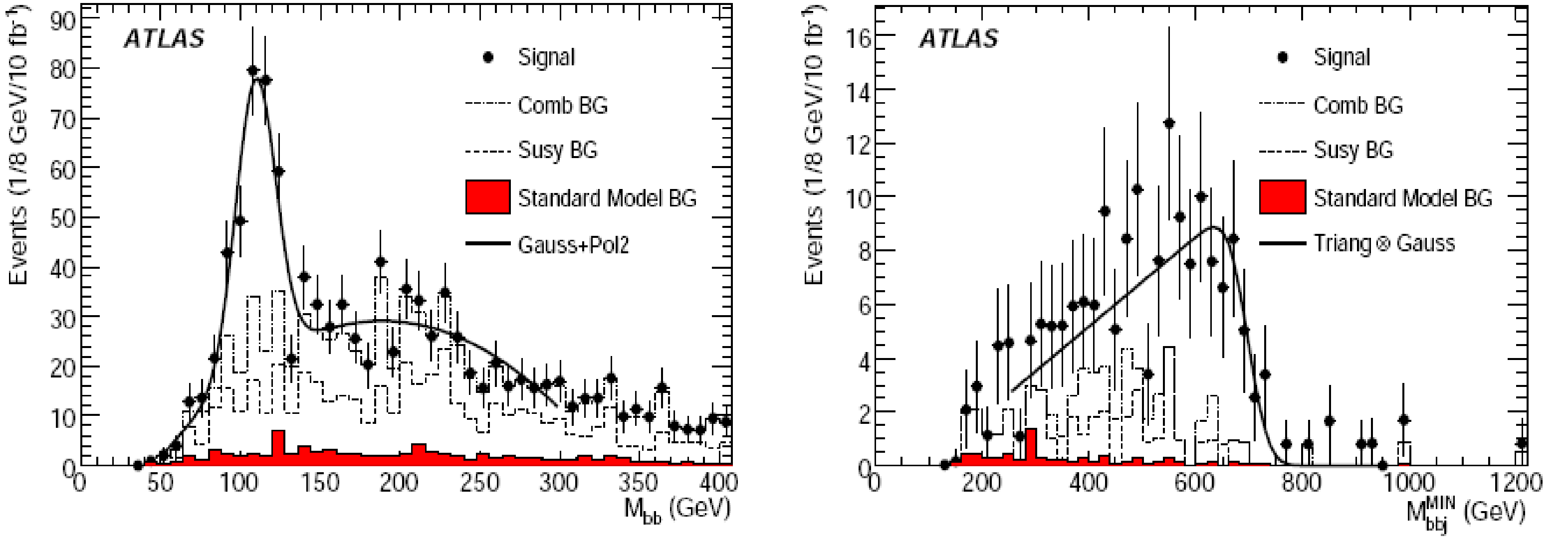
Fit results for SU3 ($1fb^{-1}$)



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

Light Higgs in decays of neutralino ($10fb^{-1}$)

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\chi}_1^0 h q.$$



Light Higgs in decay of neutralino, enhanced in some corners of parameter space SU9

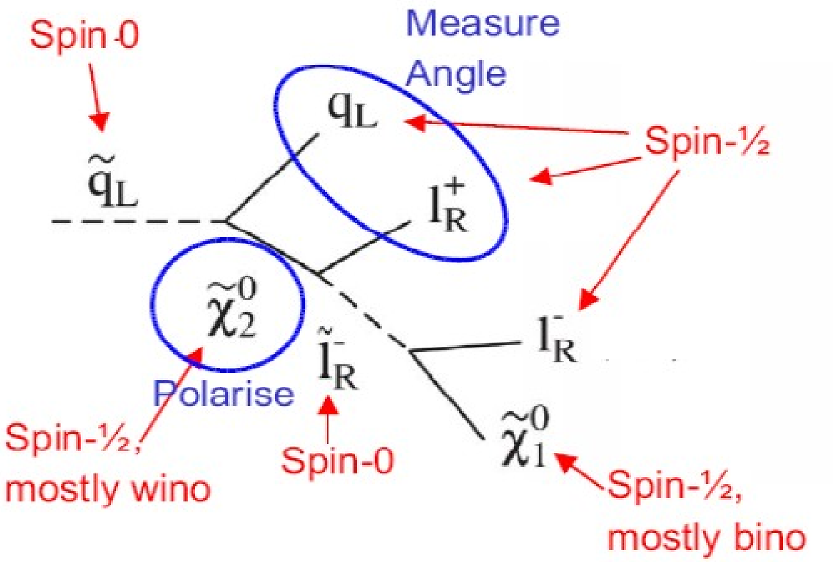
Spin measurement in squark decay

Consider 'golden' squark decay chain in SPA point

Three visible particles in final state: 1 jet, two leptons

Spin analyser is the angle between the quark and the lepton from $\tilde{\chi}_2^0$ decay

No dynamic information from angle between two leptons, as $\tilde{\ell}_R$ is spin zero



Reminder: can cast invariant mass of two adjacent particles, e.g. ℓq in chain as dimensionless variable measuring θ:

$$\hat{m}^2 = \frac{m_{\ell q}^2}{(m_{\ell q}^{max})^2} = \frac{1}{2}(1 - \cos\theta) = \sin^2\frac{\theta}{2}$$

E

Spin measurement in squark decay

We have seen that for intermediate particle with spin zero:

$$\frac{dP}{d\cos\theta} = \frac{1}{2} \quad \Rightarrow \frac{dP}{d\hat{m}} = 2\hat{m}$$

Spin 1/2: two cases:

- Lepton same helicity as quark:

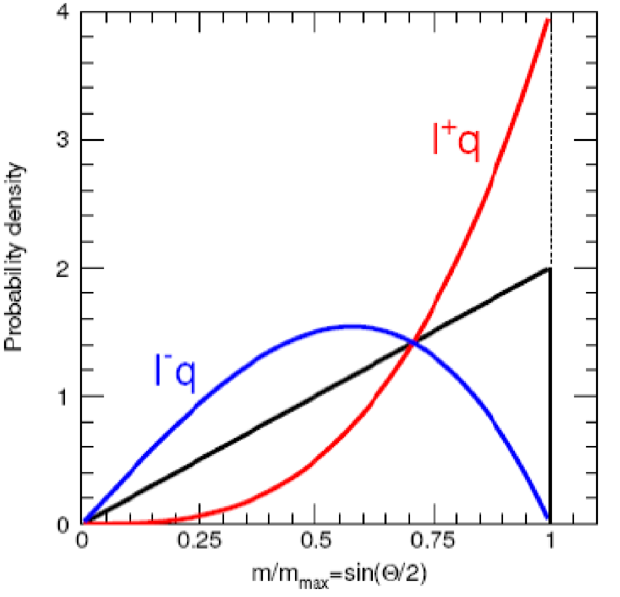
  l^+q, $l^-\bar{q}$ for $\tilde{q}_L$, $\tilde{\ell}_L$

  $$\frac{dP}{d\cos\theta} = \frac{1}{2}(1-\cos\theta) \quad \Rightarrow \frac{dP}{d\hat{m}} = 4\hat{m}^3$$

- Lepton opposite helicity to quark:

  l^-q, $l^+\bar{q}$ for $\tilde{q}_L$, $\tilde{\ell}_R$

  $$\frac{dP}{d\cos\theta} = \frac{1}{2}(1+\cos\theta) \quad \Rightarrow \frac{dP}{d\hat{m}} = 4\hat{m}(1-\hat{m}^2)$$



Difference in shape of m_{ℓ^+q} and m_{ℓ^-q}: indication for $\tilde{\chi}^0_2$ spin $1/2$

Gauge mediated supersymmetry breaking (GMSB)

SUSY broken in hidden sector at a scale $F_m \ll$ mSUGRA breaking scale

Breaking communicated to visible sector by messenger fields with mass scale

$M_m \ll M_{pl}$ coupled to MSSM particles through $SU(3) \times SU(2) \times U(1)$ interactions

EW symmetry breaking radiatively generated through large top Yukawa coupling

The gravitino $\tilde{G}$ gets mass through gravitational coupling at M_{pl}

$\rightarrow \quad M_{\tilde{G}} \ll 1$ GeV $\quad \rightarrow \quad \tilde{G}$ is the LSP

Model parameters:

$\Lambda = F_m/M_m$, $\quad M_m$, $\quad N_5$ (number of messenger fields)

$\tan\beta$, $\quad sgn(\mu)$, $\quad C_{grav}$ $(\tau(NLSP \rightarrow \tilde{G}) \propto C^2_{grav})$

- $m(\tilde{\chi}) \sim \Lambda N_5$
- $m(\tilde{f}) \sim \Lambda\sqrt{N_5}$

NLSP can be either the $\tilde{\chi}^0_1$ or l_R ($\tilde{\tau}_1$ or all l_R co-nlsp)

Gauge mediated supersymmetry breaking (GMSB)

The phenomenology is determined by the nature of the NLSP

- NLSP is $\tilde{\chi}_1^0$, decaying $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$
  - $c\tau_{\tilde{\chi}_1^0}$ <<detector size: two γ and $\not{E}_T$
  - $c\tau_{\tilde{\chi}_1^0}$ $\gtrsim$detector size: similar to mSUGRA
- NLSP is l_R ($\tilde{\tau}_1$ or all l_R co-nlsp), decaying $\tilde{l}_R \rightarrow l\tilde{G}$
  - $c\tau_{\tilde{l}_R}$ <<detector size: two leptons and $\not{E}_T$
  - $c\tau_{\tilde{l}_R}$ $\gtrsim$detector size: heavy long-lived particles

Measurement of NLSP mass and lifetime only way to measure the actual scale of supersymmetry breaking $\sqrt{F}$

(not necessarily equal to $\sqrt{F_m}$, breaking seen by messenger sector)

$$c\tau_{NLSP} \sim 16\pi \frac{\sqrt{F}^4}{m_{NLSP}^5}$$

From comparison of F_m and F scales information on messenger mechanism

Lifetime studies need detailed simulation of detectors

Gauge mediated supersymmetry breaking (GMSB)

ATLAS studies focused on four points:

Point	Λ (TeV)	M_m (TeV)	N_5	$\tan\beta$	sgn μ	$C_{grav} \geq 1$	NLSP	$c\tau$(NLSP)
G1a	90	500	1	5.0	$+$	1.0	$\tilde{\chi}_1^0$	1.2 mm
G1b	90	500	1	5.0	$+$	10^3	$\tilde{\chi}_1^0$	$\sim$1 km
G2a	30	250	3	5.0	$+$	1.0	$\tilde{l}_R$	52μm
G2b	30	250	3	5.0	$+$	5×10^3	$\tilde{l}_R$	$\sim$1 km

σ(SUSY)=7.6 pb for G1 and 22 pb for G2

For both G1 and G2: $m(\tilde{g}) \simeq 750$ GeV, $m(\tilde{\chi}_1^0) \simeq 115$ GeV

G1: $m(\tilde{q}) \simeq 950$ GeV, $m(\tilde{\ell}_R) = 164$ GeV; G2: $m(\tilde{q}) \simeq 650$ GeV, $m(\tilde{\ell}_R) = 103$ GeV

Gauge mediated supersymmetry breaking (GMSB)

Point	Λ (TeV)	M_m (TeV)	N_5	$\tan\beta$	sgn μ
G1a	90±1.7	500±170	1±0.014	5.0±1.3	YES
G1b	90±11.5	$< 7 \times 10^8$	$\Lambda N_5 = 90 \pm 0.88$	$5.0^{+2.7}_{-1.8}$	NO
G2a	30±0.54	250±60	3±0.05	5.0±1.0	YES
G2b	30±0.25	250±32	3±0.02	5.0±0.3	YES

Sparticle masses basically determined by Λ

Spectra sensitive only logarithmically to M_m

Error on $\tan\beta$ determined by theoretical error assigned to higgs mass

Relation among sparticle masses in GMSB very different from mSUGRA case: For Point G1b no good solution for mSUGRA fit!

AMSB phenomenology

- Three parameters: m_0, $m_{3/2}$ $\tan\beta$ $sign(\mu)$
- $\tilde{\chi}_1^0$ is Wino ; $\Rightarrow m(\tilde{\chi}_1^\pm) \approx m(\tilde{\chi}_1^0)$ (in mSUGRA: $m(\tilde{\chi}_1^\pm) \approx 2m(\tilde{\chi}_1^0)$)
  $\Rightarrow$ only open decays: $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 \pi^\pm$, $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 e^\pm \nu$
- $m_{3/2} \gg 1$ TeV
- Left and right sleptons almost degenerate

Study example point

m_0=200 GeV, $m_{3/2} = 35$ TeV, $\tan\beta = 3$, $\mu > 0$

Mass spectrum:

$m_{\tilde{g}} \sim 815$ GeV $\quad m_{\tilde{\chi}_1^0, \tilde{\chi}_1^\pm} = 101$ GeV

$m_{\tilde{q}} = 754$ GeV $\quad m_{\tilde{\chi}_2^0} = 322$ GeV

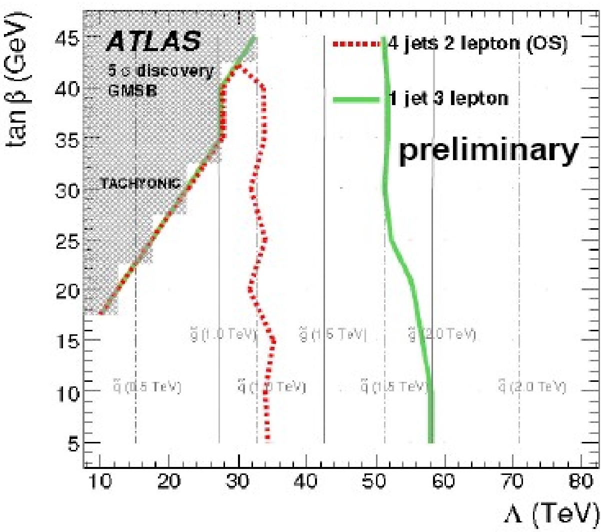
$m_{\tilde{\ell}_R} = 153$ GeV $\quad m_{\tilde{\ell}_L} = 155$ GeV

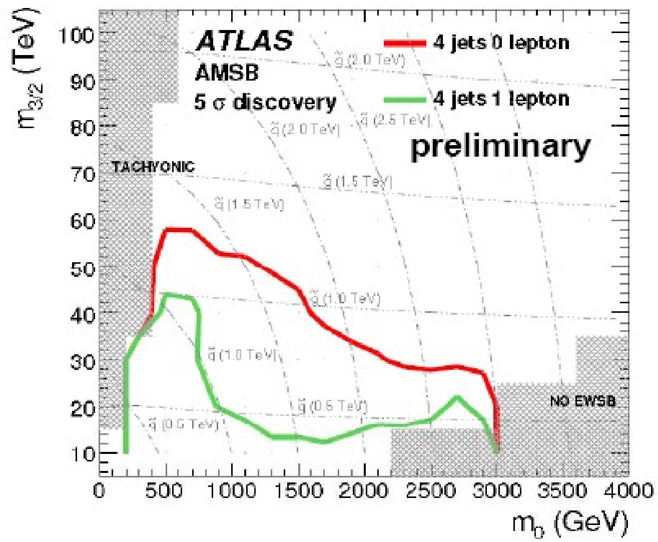
Qualitatively similar to SUGRA Point 5

Select events with requirements on M_{eff} and $\not{E}_T$ and study OS-SF lepton-lepton edge

Discovery reach for other models

discovery reach for other models (1 fb^{-1}):





GMSB :

- production: 2 leptons or τ on generator level
- 1 jet 3 lepton analysis shows highest discovery reach : less Standard Model background

AMSB:

- similar phenomenology as NUHM, but different masses and decay modes
- reach for 0 lepton channel similar to the reach for mSUGRA
- difference for 1 lepton channel: chargino decays in invisible leptons

R-parity violation

R-parity defined as: $R = (-1)^{3(B-L)+2S}$

R-parity conservation imposed to guarantee B and L conservation

Phenomenologically viable theories adding an R-violating term to the Lagrangian:

$$\mathcal{W}_{\not R} = \lambda_{ijk} L_i L_j E_k^c + \lambda'_{ijk} L_i Q_j D_k^c + \lambda''_{ijk} U_i^c D_j^c D_k^c$$

$9\ (\lambda)\ +\ 27\ (\lambda')\ +\ 9\ (\lambda'')$ new parameters in the theory

λ'' couplings B-violating, λ', λ L-violating

Proton decay puts strong constraint on the product of L-violating and B-violating couplings for first generation

If either L-violation or B-violation alone, no bound from proton decay

Experimental constraints on the λ parameters from bounds on LFV decays and SM precision measurements the range $10^{-2} - 1$

Weakest bounds on λ''

Phenomenology of LSP decays

If λ values at the lower end of $10^{-2} - 10^{-6}$ range $\rightarrow$ displaced decay vertexes in the detector, measurement of λ possible (still to be done)

Assume only one of the three terms in the superpotential non-zero. Decay patterns:

- $\tilde{\chi}_1^0 \rightarrow qqq$ for $\lambda''_{ijk} \neq 0$ (B violating) six jets, no $\not{E}_T$
- $\tilde{\chi}_1^0 \rightarrow l^+ l^- \nu$ for $\lambda_{ijk} \neq 0$ (L violating) four leptons, $\not{E}_T$
- $\tilde{\chi}_1^0 \rightarrow q\bar{q}l, q\bar{q}\nu$ for $\lambda'_{ijk} \neq 0$ (L violating) two leptons or $\not{E}_T$, four jets

Analysis strategy:

- Assume mSUGRA with only one R-violating coupling $\neq 0$, for each of the three terms in the superpotential
- Verify that inclusive SUSY signal can be separated from background
- Try to perform direct reconstruction of $\tilde{\chi}_1^0$ from its decay products
- Starting from $\tilde{\chi}_1^0$ reconstruct sparticles higher up in cascade decay

Phenomenology of LSP decays

$$\lambda''_{ijk} \neq 0$$

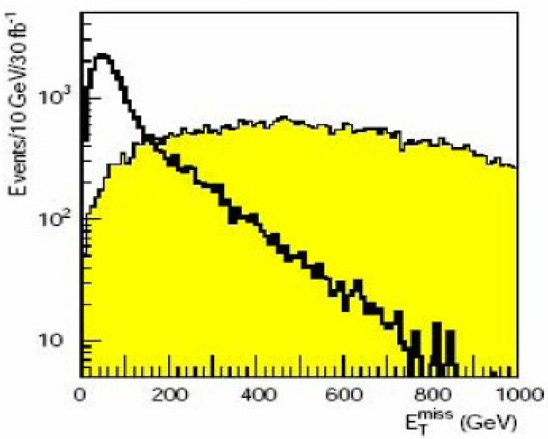
Most difficult case, more difficult than R_P conserving case

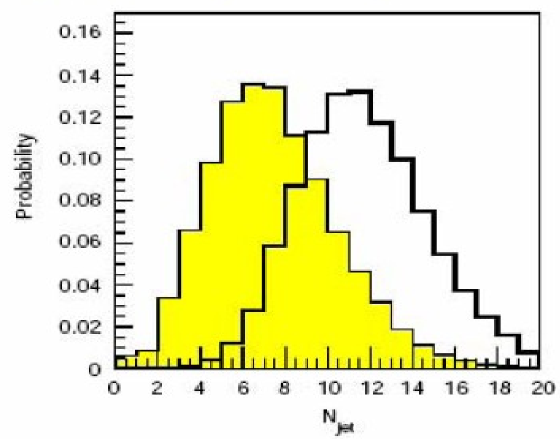
Concentrate on $\lambda''_{212} \neq 0$ yielding the decay $\tilde{\chi}_1^0 \to cds$

Essentially no constraints on coupling, use $\lambda''_{212} = 0.005$

Consider modified version of ATLAS Point 5 with $\tan\beta = 10$

Compare R_P conserving (yellow) and R_P violating $\not{E}_T$ and jet multiplicities





$\not{E}_T$ signature lost; huge additional jet multiplicity (+6).

Use leptons from cascade decay for separating SUSY from Standard Model

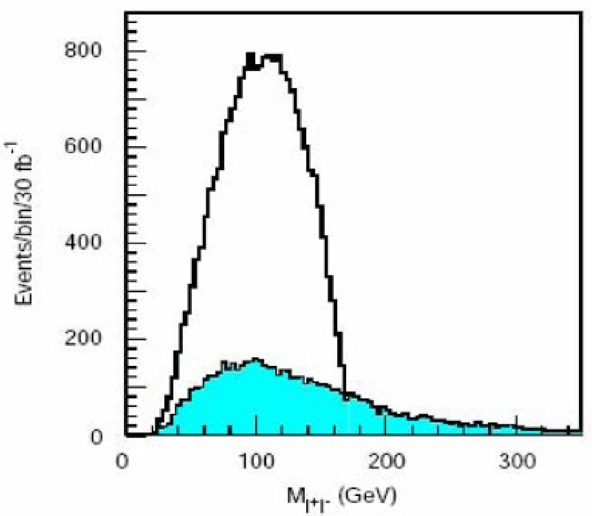
Phenomenology of LSP decays

$\lambda_{ijk} \neq 0$

Assume $\lambda_{122} \neq 0$, $\tilde{\chi}_1^0 \rightarrow \nu_{e(\mu)}\mu^{\pm}(e^{\pm})\mu^{\mp}$

In final state: two lepton pairs and two neutrinos

Study opposite-sign same-flavour pairs for mSUGRA Point 1: $m_{\tilde{\chi}_1^0} = 168$ GeV



Always two ν in final state:

$\Rightarrow$ no peak reconstruction

Measure $m_{\tilde{\chi}_1^0}$ from edge in $m_{\ell\ell}$

Systematic errors:

Lepton energy scale: 0.1%

Modeling of combinatorial background

Reconstruction of heavier sparticles taking lepton pairs near the edge as the $\tilde{\chi}_1^0$

If one of the i,j,k indices is a 3 $\rightarrow$ $\tilde{\chi}_1^0$ reconstruction difficult because τ in final state

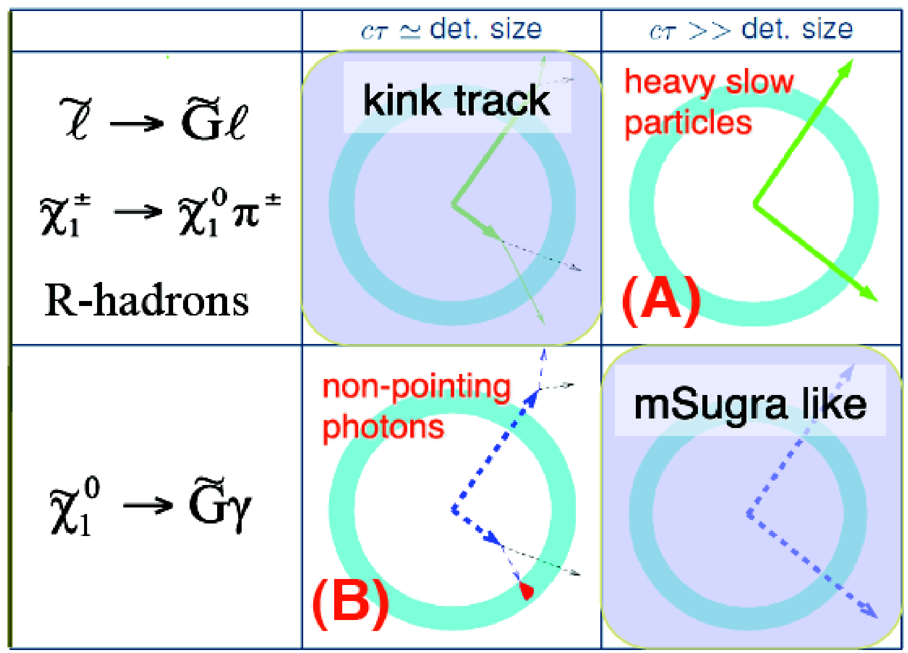
Long live the sparticle

- Long-lived particles ≡ they live long enough to pass through detector or decay in it
- Predicted in many SUSY scenarios (GMSB, RPV, …) and not only!...
- Regardless of the model, categorised by event signature
  - Charge: electric? magnetic? colour?
  - Decay length?

Two general cases:

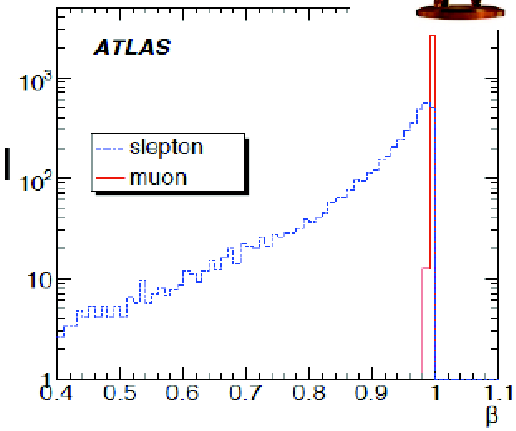
A. Sleptons, R-hadrons
   (heavy slow particles)
   - large ionisation energy loss
   - nuclear int. (R-hadron case)
   - delay (TOF) reconstructed in muon chambers

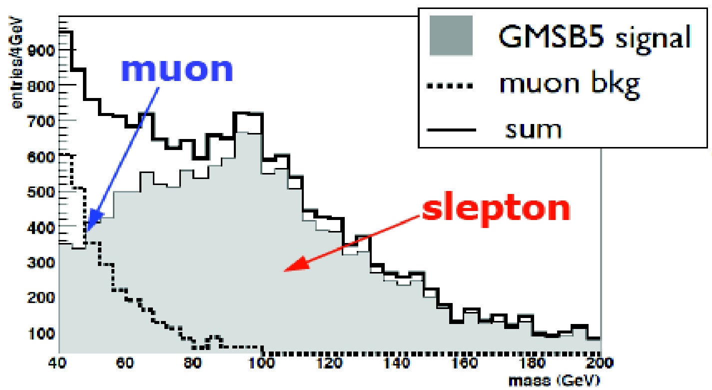
B. Long-lived neutralino
   (non-pointing photon)
   - decay vertex is somewhere in the inner tracker volume



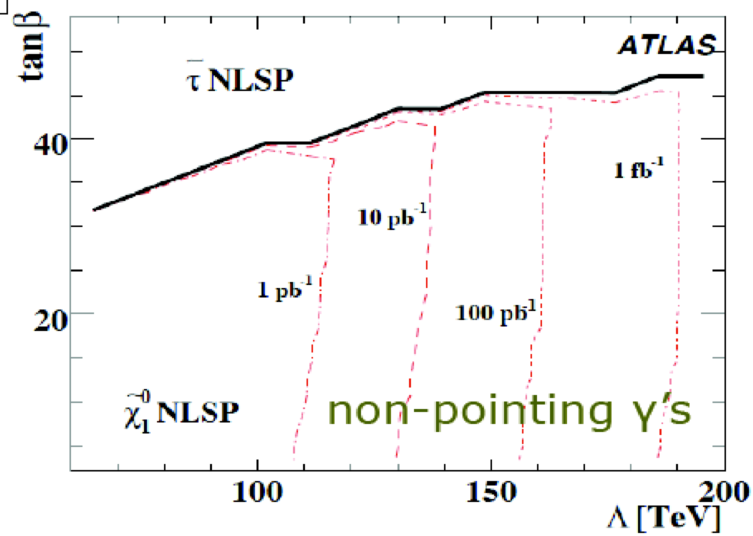
GMSB: sleptons and neutralinos

- **Slepton NLSP** couples weakly to gravitino
  -> long lifetime
- Detected as heavy, slow-moving muons
- Preselection of slepton-like events at trigger level
- β measurement: fast calculation with good resolution in the muon system





- **Neutralino NLSP** $\tilde{\chi}_1^0 \to \tilde{G}\gamma$
- Selection:
  - one or two non-pointing photons
  - two OS leptons (slepton decay)
  - high E_T^{miss} (gravitinos)



ATLAS Coll, arXiv: 0901.0512 (2008)

What LHC can(not) tell us about SUSY?

- SUSY discovery potential
  - SUSY @ 1 TeV with 0.1 fb^{-1} – could be first discovery
  - SUSY @ 2 TeV with 1-10 fb^{-1} – within 1 year of data taking
  - SUSY @ 5 TeV – may need SLHC
- Measurement of effective mass → mass scale, total SUSY cross section
- Endpoint measurements
  - sparticle masses at 10% level
  - model parameters at 1 – 10% level (assuming specific model!)
- How can we distinguish various SUSY models?
  - E_T^{miss} spectrum → *R*-parity
  - hard photons, NLSPs, long-lived gluinos → GMSB, split SUSY
  - τ leptons → large tanβ
- Higgs sector
  - discovery of SM Higgs: observable for the whole allowed mass range
  - additional Higgs bosons from the MSSM can be discovered on a large fraction of the parameter space
  - measurement of Higgs bosons properties is possible with 300 fb^{-1}
    - masses, total width, ratios of couplings, spin / CP properties
- *And what it cannot tell us ...*
  - *observe and measure the full gaugino spectrum (in particular charginos)*
  - *constrain model parameters to < 1%*
  - *define directly the nature of neutralino & chargino (higgsino / bino / wino -like?)*

Next topics

- 12.01 - SUSY:
  - Status of searches at Tevatron
  - Data-driven background estimates (LHC)
  - First analyses with data (LHC)
- 19.01 - Wrapping up on Data2010:
  - SM physics: selected public results
  - Searches: new exclusion limits