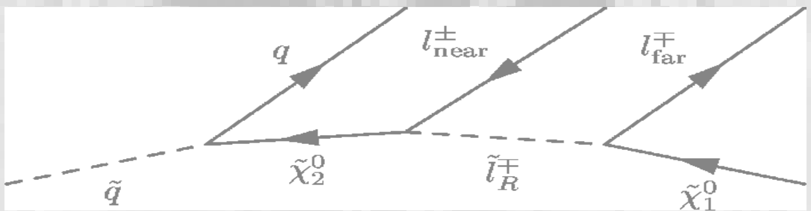
Mass Reconstruction Methods *in ATLAS*

S. Laplace

On behalf of the ATLAS collaboration



Physics at LHC – Cracow, Poland
SUSY Session, July 4th 2006

Outline

- Introduction: ATLAS Activities in SUSY
- SUSY Phenomenology and Meas. Strategies
- Discovering SUSY
- Mass Measurements:
  - $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{q}_L, \tilde{q}_R$ Masses: Endpoint Method
  - $\tilde{g}, \tilde{b}_1, \tilde{b}_2$ Masses near Dilepton Endpoint and Mass Relation Method
  - From Measurements to Model Parameters
- Conclusion

(note: no time to talk about stop mass measurement and other methods than endpoints like Mass Relation Method…)

Introduction

ATLAS activities in SUSY:

- **TDR (1998): fast simulation studies → discovery potential**
- **Currently:**
  - **Full simulation studies (preliminary results)**
  - **Commissioning, systematics**
  - **Background estimation (from latest MC and plans to measure it from data)**
  - **New measurement techniques**

Note: in this talk,

- ***MET = Missing Transverse Energy***
- ***Sleptons = selectrons and smuons (will explicitly call a stau a stau)***

SUSY Phenomenology and Mass Measurement Strategies

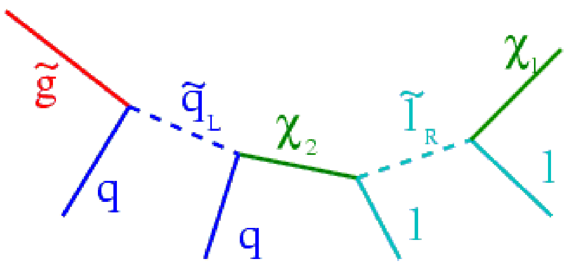
- If R-parity ($R = (-1)^{3(B-L)+2s}$) is conserved, then:

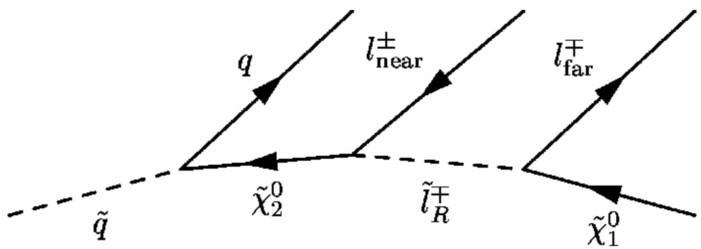
• Lightest Supersymetric Particle (LSP) is stable
• LSP not detected thus large MET (few x 100 GeV)
• Event is not fully reconstructed: no mass peak
• Sparticles produced in pairs: both sides of event are not reconstructed !

$\rightarrow$ Mass measurement strategy: exploit kinematics of long decay chains

- Production of SUSY at LHC: strong interactions dominates:

$\rightarrow$ decay chain starts from a gluino or a squark:





(RPC) SUSY Models

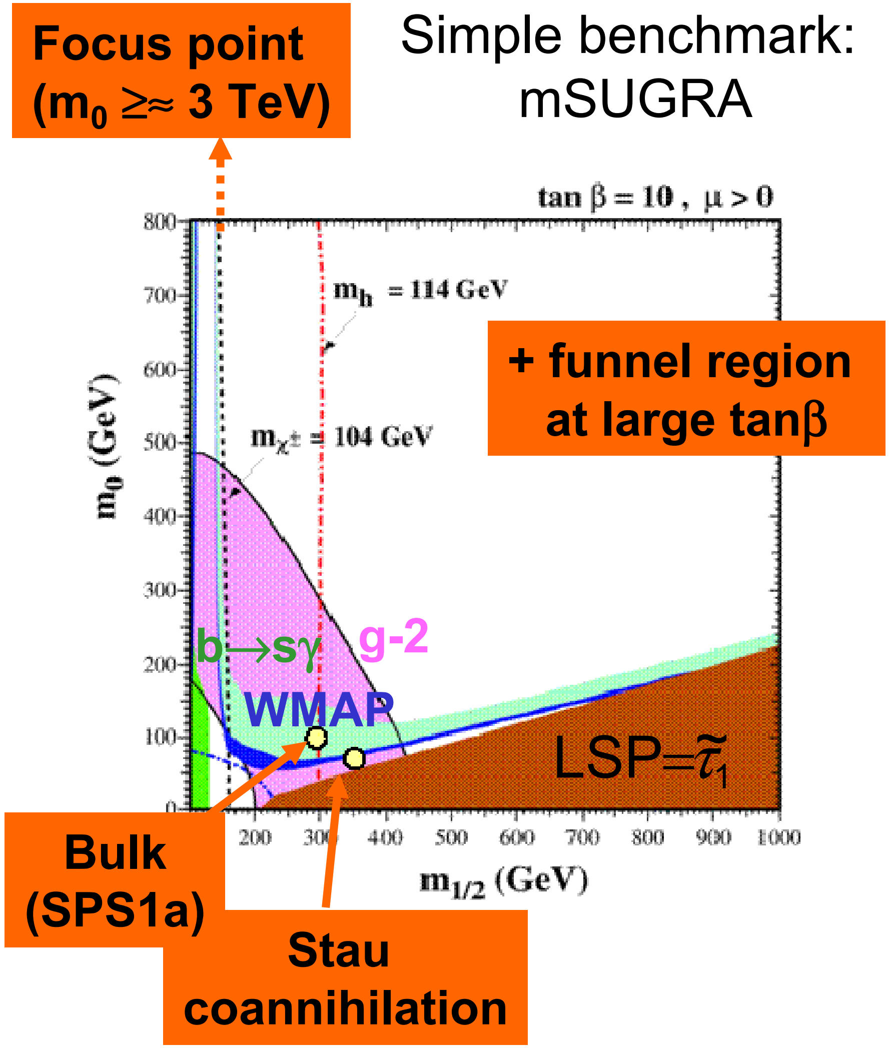
SUSY Parameters (SM = 19):

- **M.S.S.M.** 105
  - (note: if RPV + 48)

Constrained models:

- **mSUGRA**
  - m_0, $m_{1/2}$, A_0, tan β, sgn μ 5
- **G.M.S.B.**
  - λ, M_{mes}, N_5, tan β, sgn μ, C_{grav} 6
- **A.M.S.B.**
  - m_0, $m_{3/2}$, tan β, sgn μ 4

Simple benchmark: mSUGRA



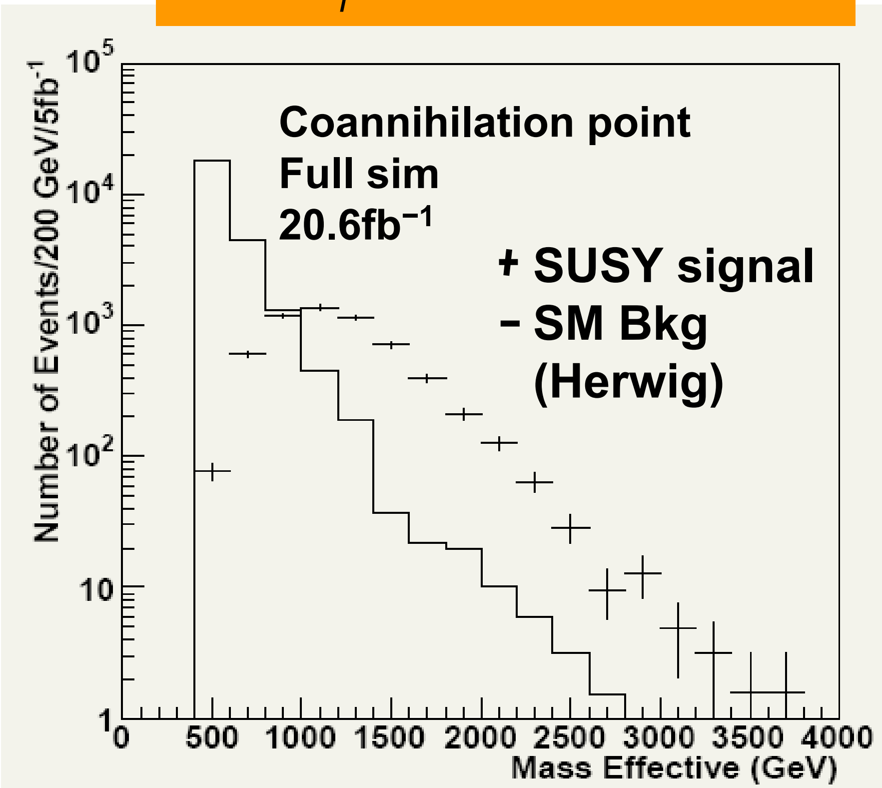
Ellis et al., Phys. B565 (2003) 176

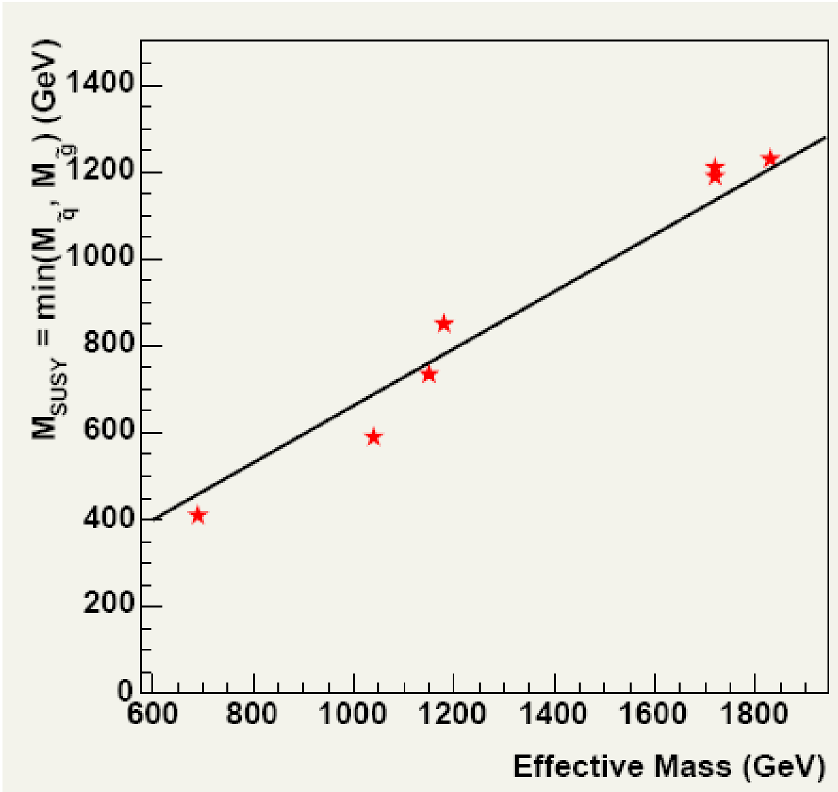
Discovering SUSY and Evaluating M_{SUSY}

RPC models signature: MET + several high-pT jets

→ Build discriminating variable M_{eff}:

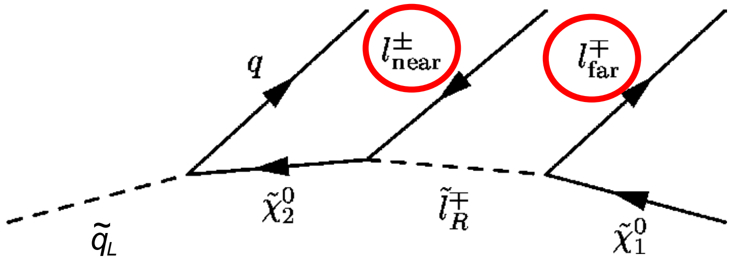
$$M_{eff} = \sum_{i}^{4} |p_T^i| + E_T^{miss} \propto M_{SUSY}$$ where $$M_{SUSY} = \min(m_{\tilde{g}}, m_{\tilde{q}})$$



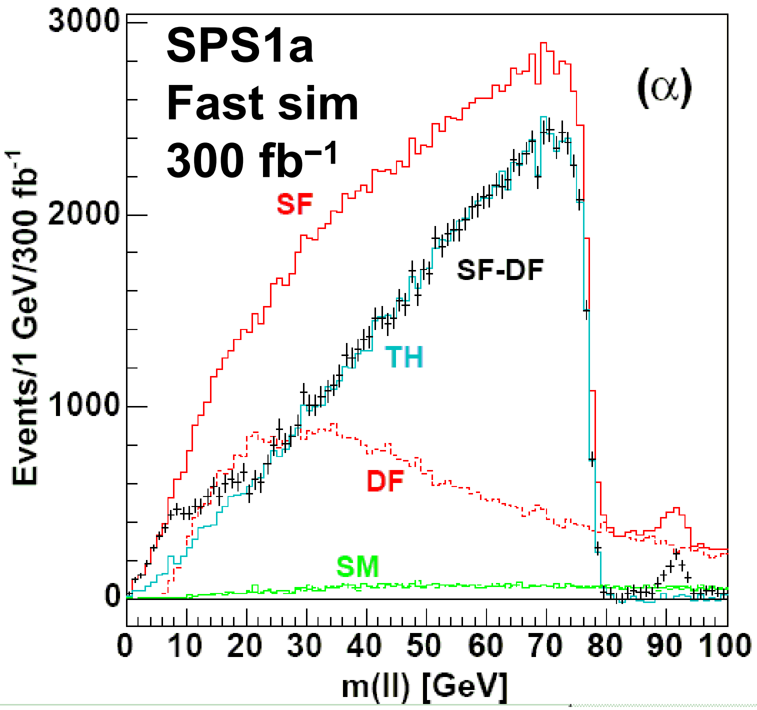


$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{q}_L$ Mass Measurement: Endpoint Method

- **Example:** dilepton endpoint
  m_{ll} has a kinematic endpoint that depends on the masses of the sparticles in the chain



$$m_{ll}^{max} = m_{\tilde{\chi}_2^0} \cdot \sqrt{1 - \frac{m_{\tilde{l}_R}^2}{m_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\tilde{l}_R}^2}}$$

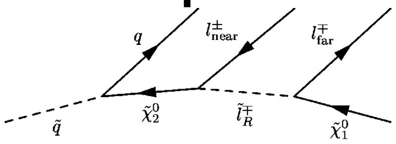


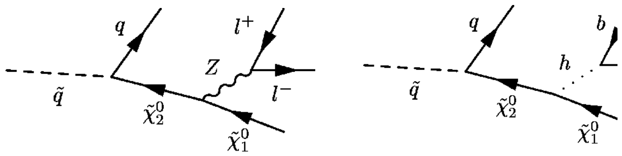
- **Does not need a-priori knowledge of any sparticle mass**
- **Backgrounds:**
  - SM & uncorrelated (not Z) SUSY: use Same Flavour (SF) – Different Flavour (DF)
    $m(e^{\pm}e^{\mp}) + m(\mu^{\pm}\mu^{\mp}) - m(e^{\pm}\mu^{\mp})$
- **Edge fit:** stat. error = 0.05%, syst. error dominated by lepton energy scale (0.1%)

B.K. Gjelsten *et al*, *J. High Energy Phys.* JHEP12(2004)003

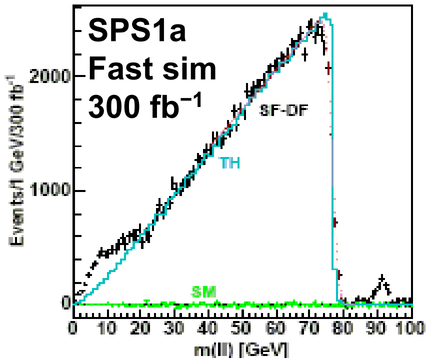
A Variety of Endpoint Measurements

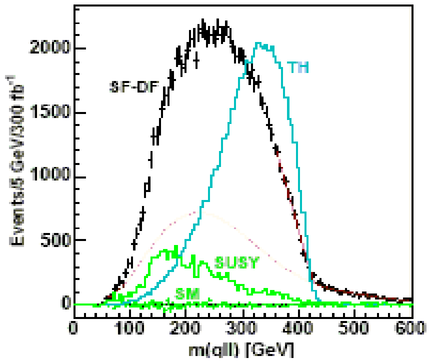
Sequential: **Branched:**

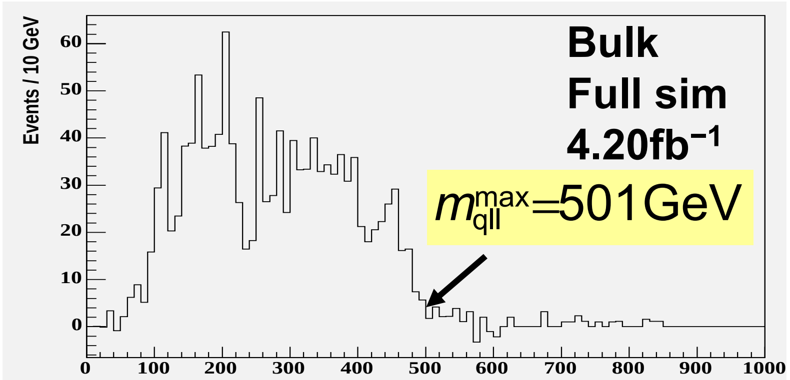


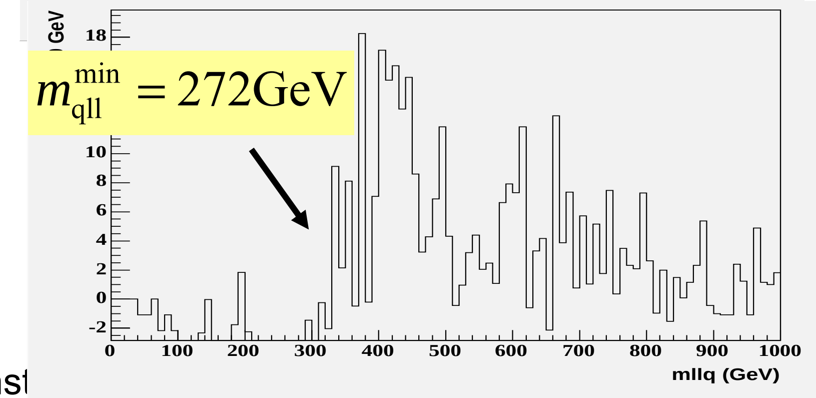


Related edge	Kinematic endpoint
l^+l^- edge	$(m_{ll}^{max})^2 = (\tilde\xi - \tilde l)(\tilde l - \tilde\chi)/\tilde l$
l^+l^-q edge	$(m_{llq}^{max})^2 = \begin{cases} \max\left[\frac{(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi)}{\tilde\xi}, \frac{(\tilde q-\tilde l)(\tilde l-\tilde\chi)}{\tilde l}, \frac{(\tilde q\tilde l-\tilde\xi\tilde\chi)(\tilde\xi-\tilde l)}{\tilde\xi\tilde l}\right] \\ \text{except for the special case in which } \tilde l^2<\tilde q\tilde\chi<\tilde\xi^2 \text{ and} \\ \tilde\xi^2\tilde\chi<\tilde q\tilde l^2 \text{ where one must use } (m_{\tilde q}-m_{\tilde\chi_1^0})^2. \end{cases}$
Xq edge	$(m_{Xq}^{max})^2 = X + (\tilde q-\tilde\xi)\left[\tilde\xi + X - \tilde\chi + \sqrt{(\tilde\xi - X-\tilde\chi)^2 - 4X\tilde\chi}\right]/(2\tilde\xi)$
l^+l^-q threshold	$(m_{llq}^{min})^2 = \begin{cases} [\ 2\tilde l(\tilde q-\tilde\xi)(\tilde\xi-\tilde\chi)+(\tilde q+\tilde\xi)(\tilde\xi-\tilde l)(\tilde l-\tilde\chi) \\ -(\tilde q-\tilde\xi)\sqrt{(\tilde\xi+\tilde l)^2(\tilde l+\tilde\chi)^2-16\tilde\xi\tilde l^2\tilde\chi}\ ]/(4\tilde l\tilde\xi) \end{cases}$
$l^{\pm}_{near}q$ edge	$(m_{l_{near}q}^{max})^2 = (\tilde q-\tilde\xi)(\tilde\xi-\tilde l)/\tilde\xi$
$l^{\pm}_{far}q$ edge	$(m_{l_{far}q}^{max})^2 = (\tilde q-\tilde\xi)(\tilde l-\tilde\chi)/\tilde l$
$l^{\pm}q$ high-edge	$(m_{lq(high)}^{max})^2 = \max\left[(m_{l_{near}q}^{max})^2, (m_{l_{far}q}^{max})^2\right]$
$l^{\pm}q$ low-edge	$(m_{lq(low)}^{max})^2 = \min\left[(m_{l_{near}q}^{max})^2, (\tilde q-\tilde\xi)(\tilde l-\tilde\chi)/(2\tilde l-\tilde\chi)\right]$
M_{T2} edge	$\Delta M = m_{\tilde l} - m_{\tilde\chi_1^0}$





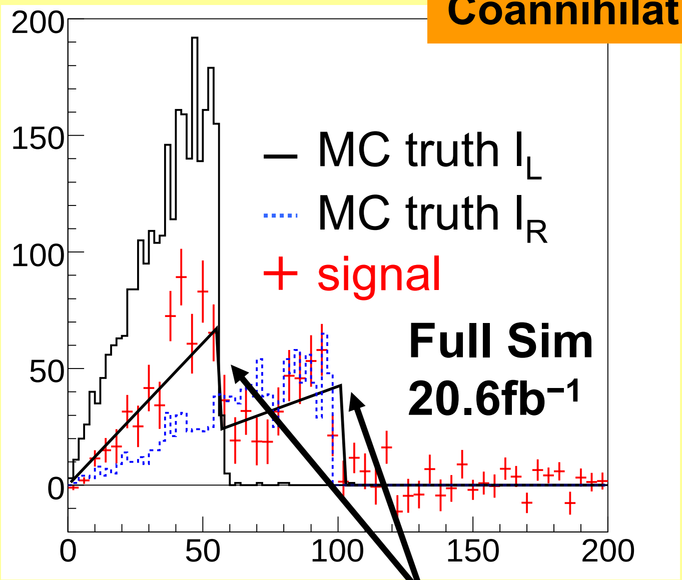




Di-lepton Endpoint in Various mSUGRA Scenarii

Depending on point: different shape, number of edges, 2-body vs 3-body decay, …

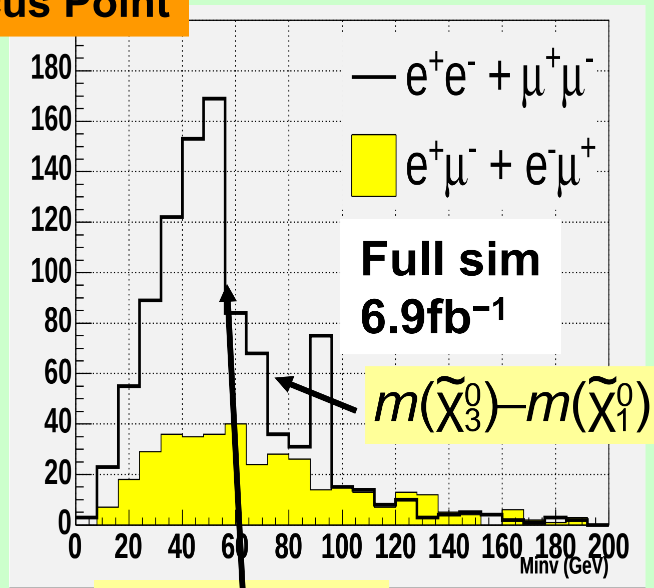
Coannihilation



$m(\tilde{\chi}_2^0) > m(\tilde{l}_{L,R})$ → **2 edges for left and right slepton**

- **small BR**
- **at least 1 lepton with small p_T**

Focus Point



$m(\tilde{\chi}_2^0)-m(\tilde{\chi}_1^0)$

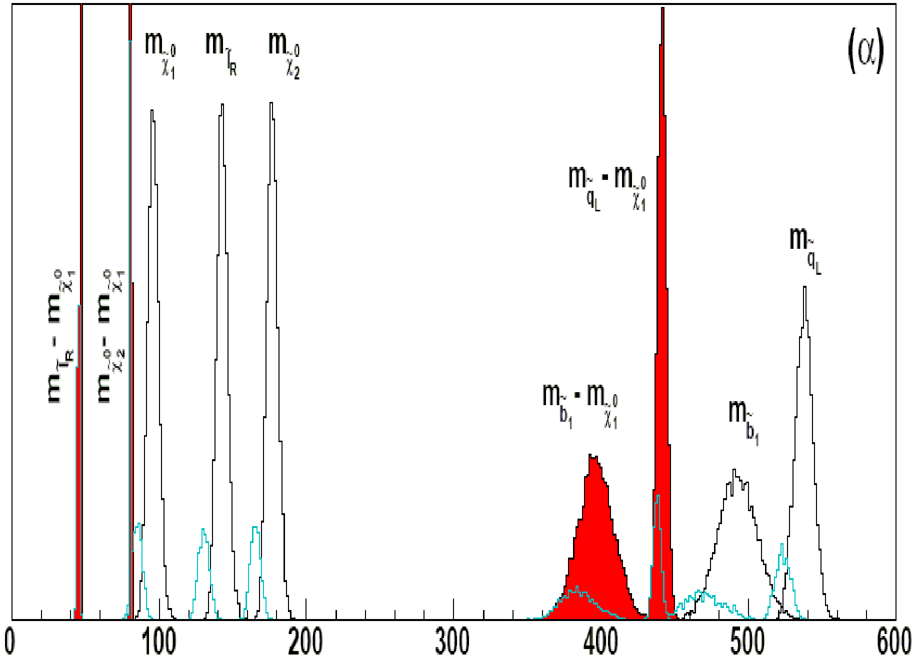
- **m_0 large, heavy scalars → no sleptons in χ decays**
- **direct 3-body decay:**

$$\tilde{\chi}_{2,3}^0 \rightarrow l^{\pm} l^{\mp} \tilde{\chi}_1^0$$

Extraction of Sparticle Masses from Endpoints

100 fb^{-1}

MC toy of 10000 ATLAS experiments, use inversion formulae to get masses from edges:



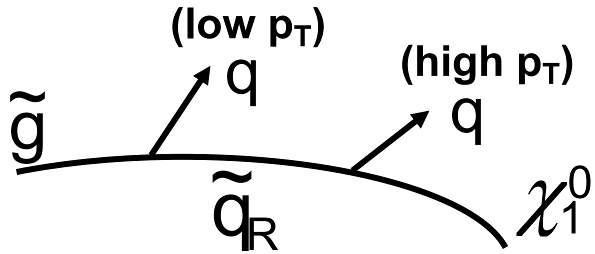
SPS1a	Nom	$\langle m \rangle$	σ
$m_{\tilde{\chi}_1^0}$	96.1	96.3	3.8
$m_{\tilde{l}_R}$	143.0	143.2	3.8
$m_{\tilde{\chi}_2^0}$	176.8	177.0	3.7
$m_{\tilde{q}_L}$	537.2	537.5	6.1
$m_{\tilde{b}_1}$	491.9	492.4	13.4
$m_{\tilde{l}_R} - m_{\tilde{\chi}_1^0}$	46.92	46.93	0.28
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	80.77	80.77	0.18
$m_{\tilde{q}_L} - m_{\tilde{\chi}_1^0}$	441.2	441.3	3.1
$m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0}$	395.9	396.2	12.0

All masses are strongly correlated with $m(\tilde{\chi}_1^0)$

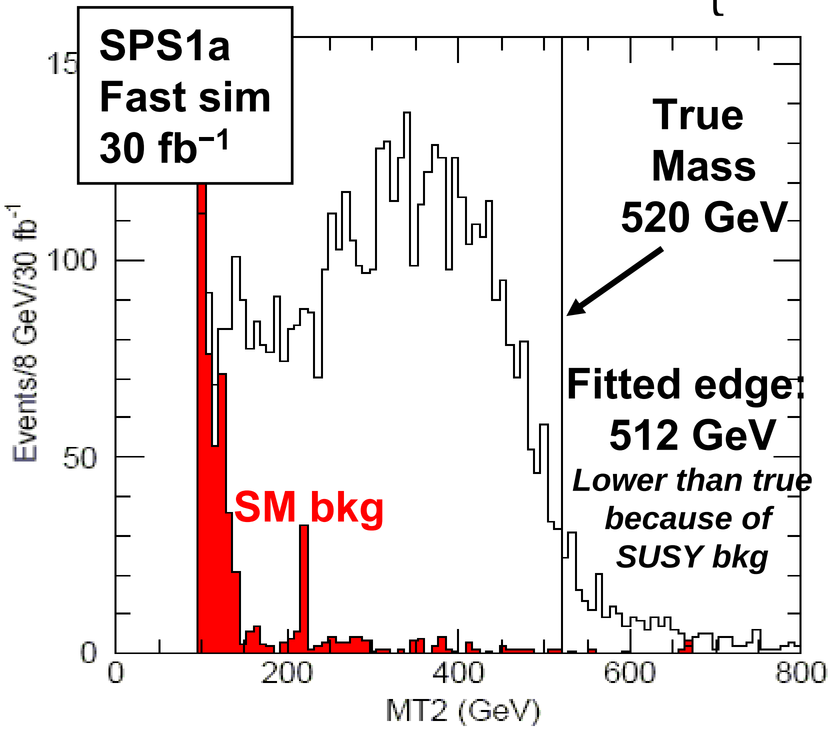
B.K. Gjelsten *et al*, *J. High Energy Phys.* JHEP12(2004)003

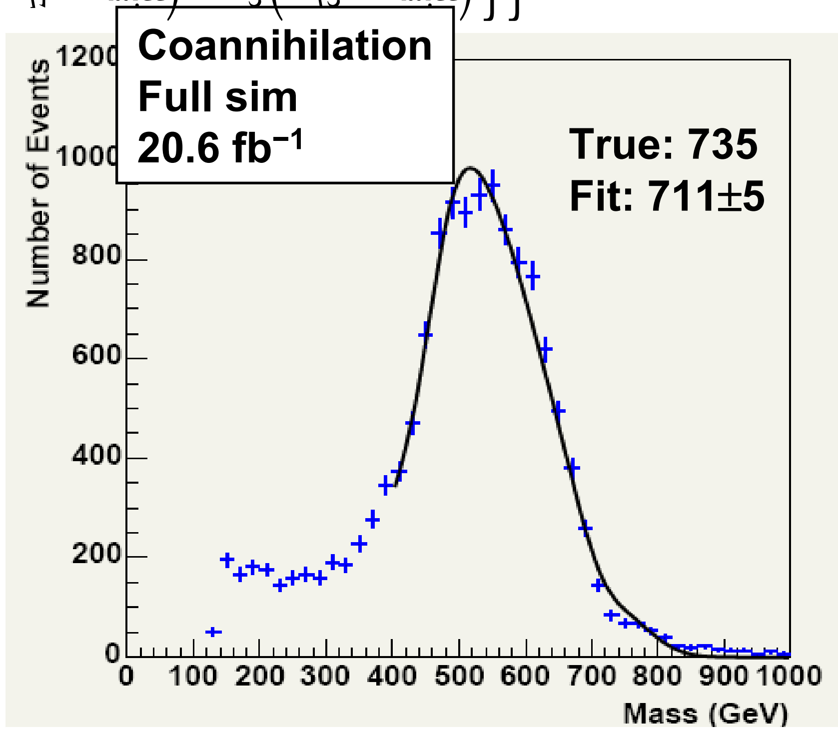
Right-Handed Squark Mass

- **mSUGRA: χ_1 essentially a bino: Br($\tilde{q}_R \rightarrow q\chi_1^0$) ≈ 100%**
  If both gluino decay to right-handed squarks:
  → require 2 high-p_T jets, MET
- **Discriminant: Cambridge variable M_{T2} endpoint gives the right squark mass:**



$$M_{T2} = \min_{p_T^{miss}=p_T^{miss1}+p_T^{miss2}} \left\{ \max\left\{ m_T^2\left(p_{T1}, p_T^{miss1}\right), m_T^2\left(p_{T2}, p_T^{miss2}\right) \right\} \right\}$$

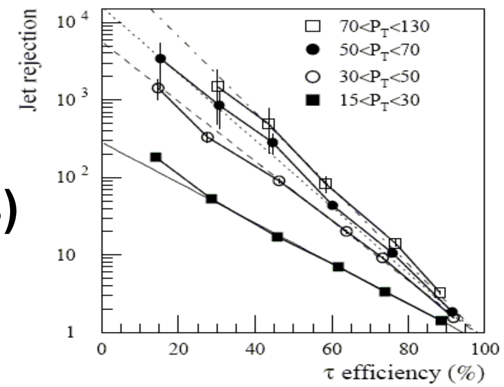


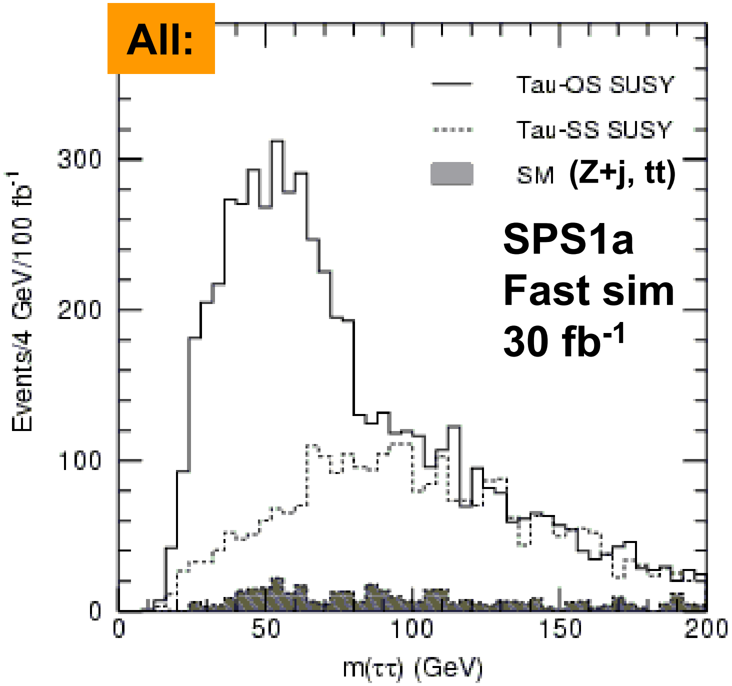


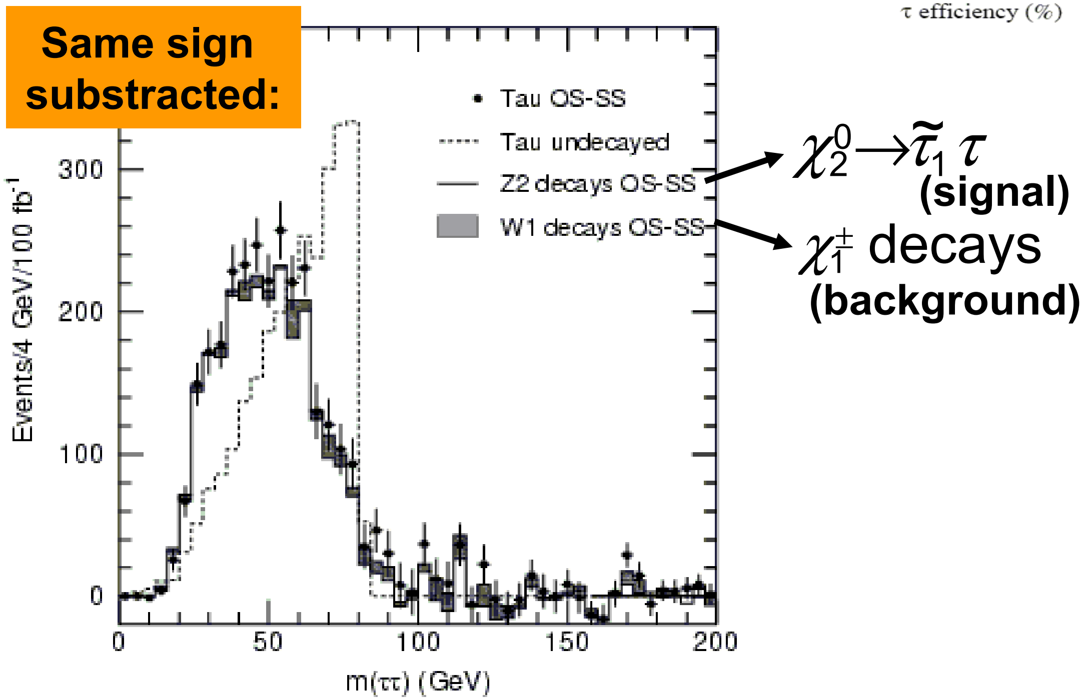
Staus Signatures

- SPS1a: dominant $\tilde{\chi}_2^0$ decay is $\tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \rightarrow \tau^+\tau^- \tilde{\chi}_1^0$ (because of relatively high tanβ value)

- Look at hadronic τ decays (dedicated algorithms for τ-jets) Background (QCD jets misidentified as τ) evaluated from same signs events:



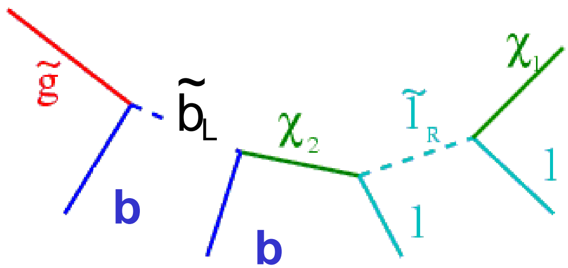




B.K. Gjelsten *et al*, *ATL-PHYS-2004-007*

Sbottom and Gluino Masses: Near The l^+l^- Endpoint

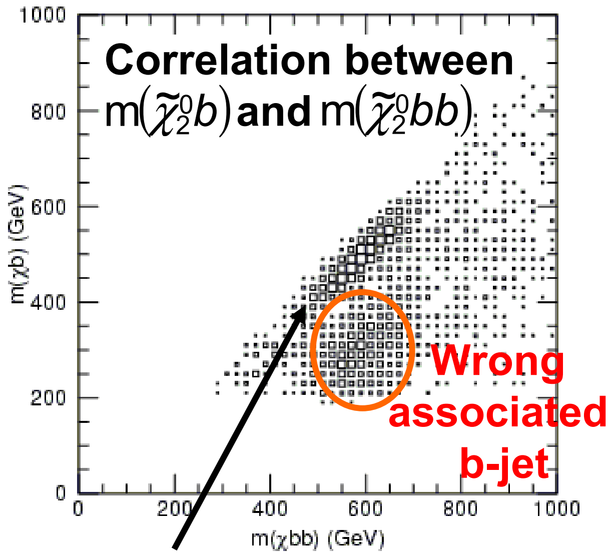
- **Near l^+l^- endpoint**: **LSP and l^+l^- are at rest in $\tilde\chi^0_2$ frame, thus can evaluate $\tilde\chi^0_2$ momentum (approximation):**



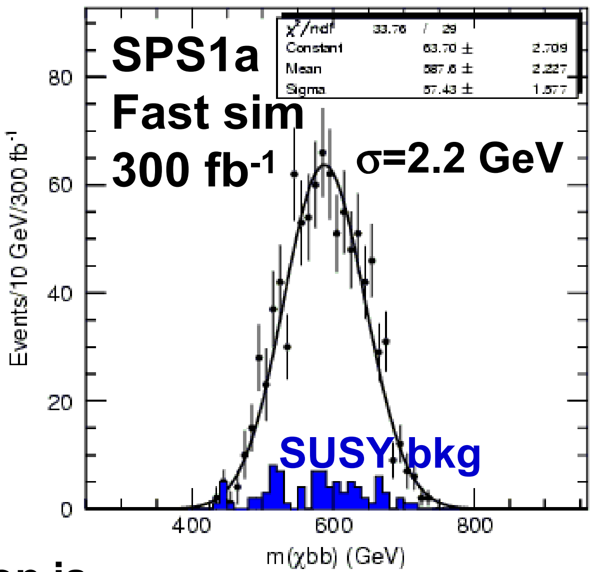
$$\vec{p}(\tilde\chi^0_2) \approx \left(1+\frac{m_{\tilde\chi^0_1}}{m_{l^+l^-}}\right)\vec{p}(l^+l^-)$$

where $m(\tilde\chi^0_1)$ **and** $m(\tilde\chi^0_2)$ **are known from endpoints**

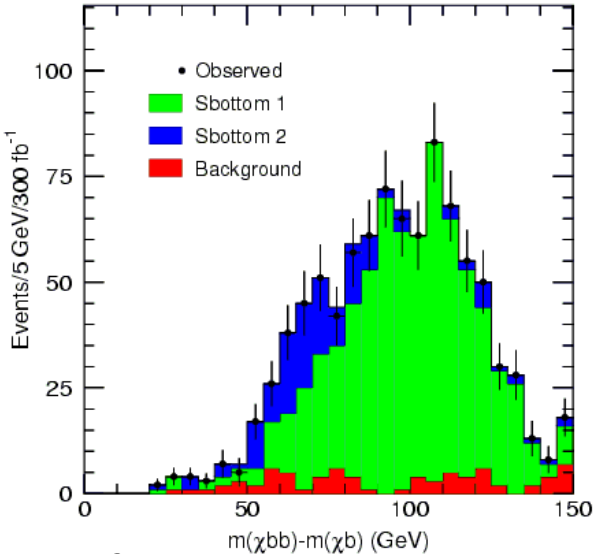
- **Add 1 or 2 b-jet to get sbottom and gluino masses:** $m(\tilde\chi^0_2 b)$ **and** $m(\tilde\chi^0_2 bb)$



Spread from p(χ2) approximation is common to both masses



Gluino mass



Gluino – sbottom masses

B.K. Gjelsten *et al*, *ATL-PHYS-2004-007*

Sbottom and Gluino Masses: Mass Relation Method

Alternative method to previous one using ALL data set (not only near endpoint)

$$
\begin{aligned}
m^2_{\tilde\chi^0_1} &= p^2_{\tilde\chi^0_1}, \\
m^2_{\tilde\ell} &= (p_{\tilde\chi^0_1} + p_{\ell_1})^2, \\
m^2_{\tilde\chi^0_2} &= (p_{\tilde\chi^0_1} + p_{\ell_1} + p_{\ell_2})^2, \\
m^2_{\tilde b} &= (p_{\tilde\chi^0_1} + p_{\ell_1} + p_{\ell_2} + p_{b_1})^2, \\
m^2_{\tilde g} &= (p_{\tilde\chi^0_1} + p_{\ell_1} + p_{\ell_2} + p_{b_1} + p_{b_2})^2.
\end{aligned}
$$

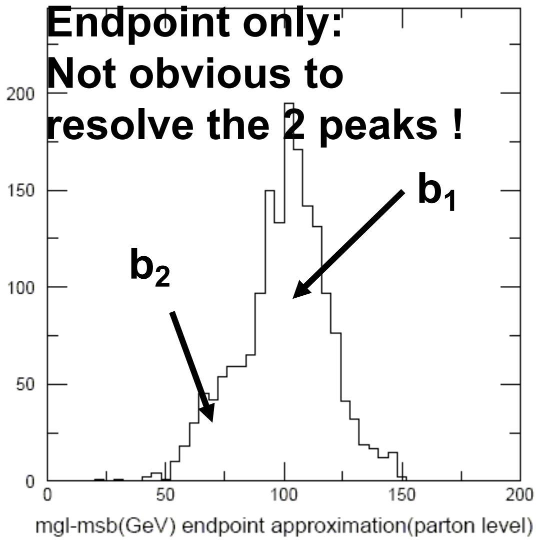
5 parameters **4 unknowns (4-momentum)**

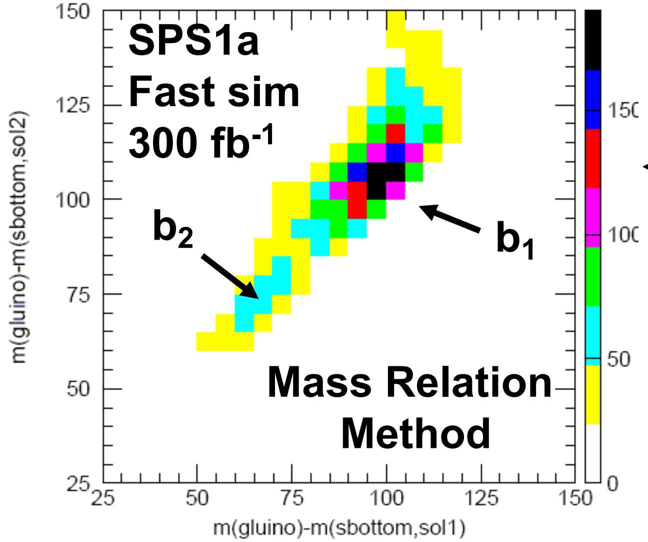
- **Each event = 4D surface in 5D space**
- **In principle: 5 events to determine the 4 unknowns !**
- **In practice: know $(m_{\chi_1}, m_{\tilde\ell_R}, m_{\chi_2})$ so have following constraint:**

$$am^4_{\tilde g} + bm^2_{\tilde g}m^2_{\tilde b} + cm^4_{\tilde b} + dm^2_{\tilde g} + em^2_{\tilde b} + f = 0$$

↓

Two possible solutions (2 lepton assignments)





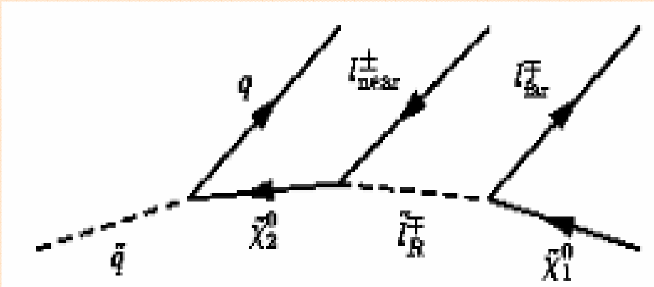
→ The two b-peaks are well resolved

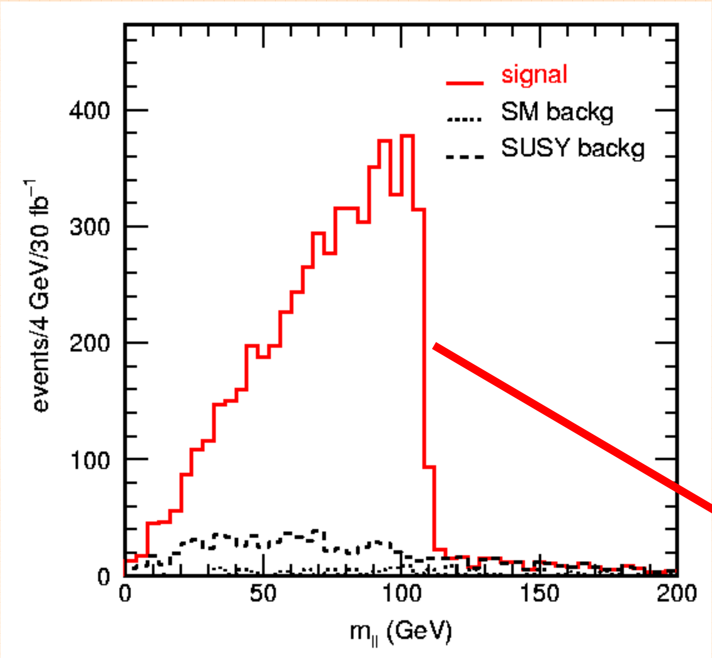
Kawagoe et al, hep-ph/0410160

Obtaining the Fundamental Model Parameters

LHC Measurements

Ex: endpoints





SUSY Model

Ex: mSUGRA

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

Spectrum Generator (Ex: SUSPECT, SoftSUSY, …)

$m_{\chi_2^0}$, $m_{\tilde{l}_R^{\pm}}$, $m_{\chi_1^0}$

$(m_{ll}^2)^{edge}_{Pred.}$

Fit: χ^2

$$(m_{ll}^2)^{edge}_{Mes.} = \frac{\left(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{l}_R}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}_1^0}\right)}{m^2_{\tilde{l}_R}}$$

Note: better to exploit edges than masses (correlations)

An Example

List of measurements (300 fb^{-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

SFITTER program:

mSUGRA Parameter determination

	SPS1a	ΔLHC edges
m_0	100	**1.2**
$m_{1/2}$	250	**1.0**
tanβ	10	**0.9**
A0	-100	**20**
Sign(μ) fixed		

Note: m(ll) most powerful input (m_0 driven by 1st and 2nd generation slepton sector)

R. Lafaye, T. Plehn, D. Zerwas, hep-ph/0512028

Conclusion

- New era for SUSY studies in ATLAS is currently starting:

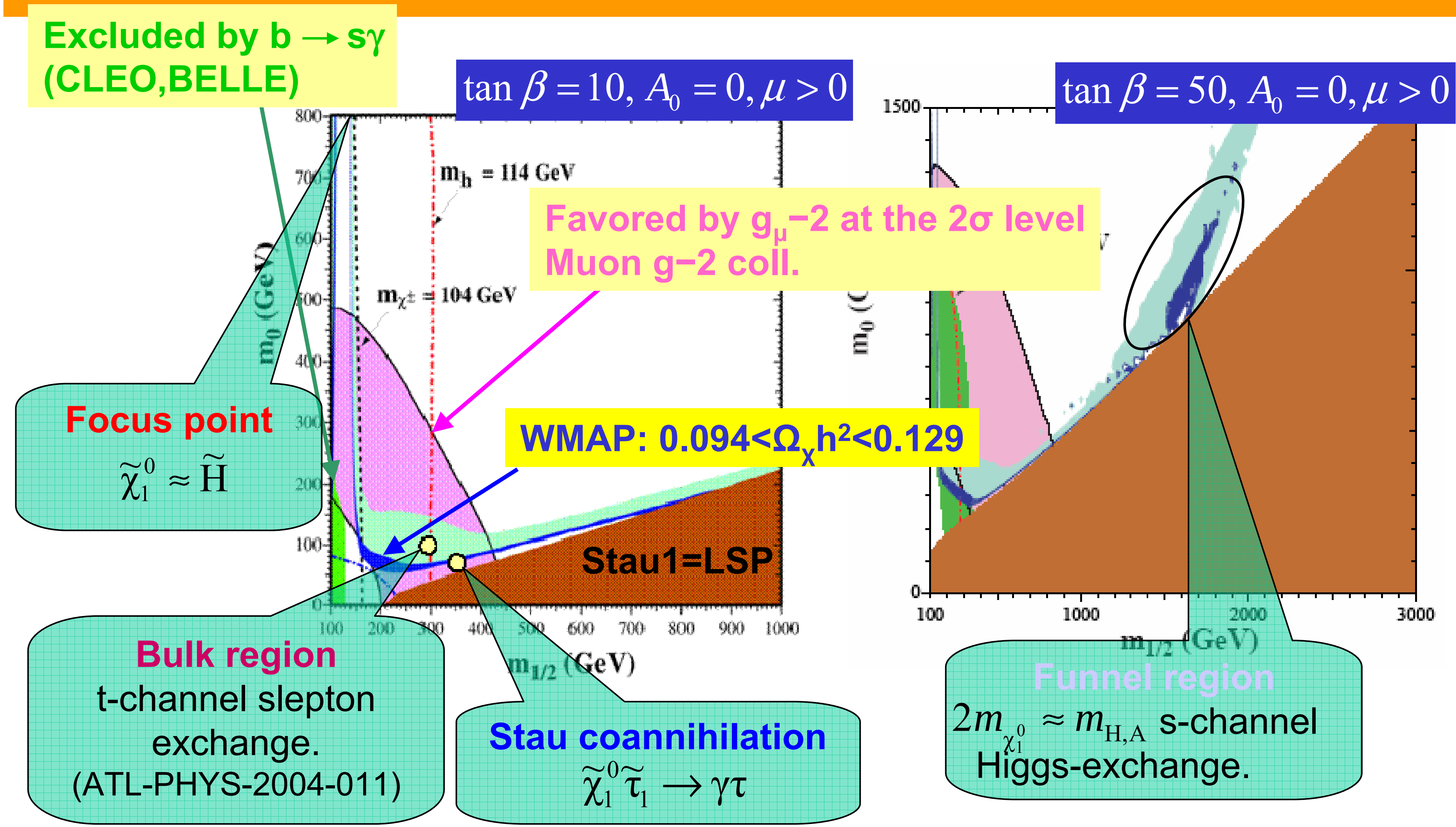
• large scale productions to prepare for real data analysis
• study detector systematics
• SM background: latest MC and plans to measure it from data
• new models studied
• new techniques developed

- Discovery potential: in most models, a few fb^{-1} are sufficient to:

• observe squarks and gluons below 1-2 TeV and sleptons below 300 GeV
• accurately measure squark, slepton and neutralino masses using cascades

Backup

mSUGRA



(Ellis et al., Phys. B565 (2003) 176)

SPS1a Point

- **mSUGRA fundamental parameters :**

$$m_0 = 100 \text{ GeV}, m_{1/2} = 250 \text{ GeV},$$

$$\tan\beta = 10,\ A = -100 \text{ GeV},\ \mu > 0$$

- **Main branching ratios :**

$BR(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau)$=87%

$BR(\tilde{\chi}_2^0 \to \tilde{\ell}_R\ell)$=12.6%

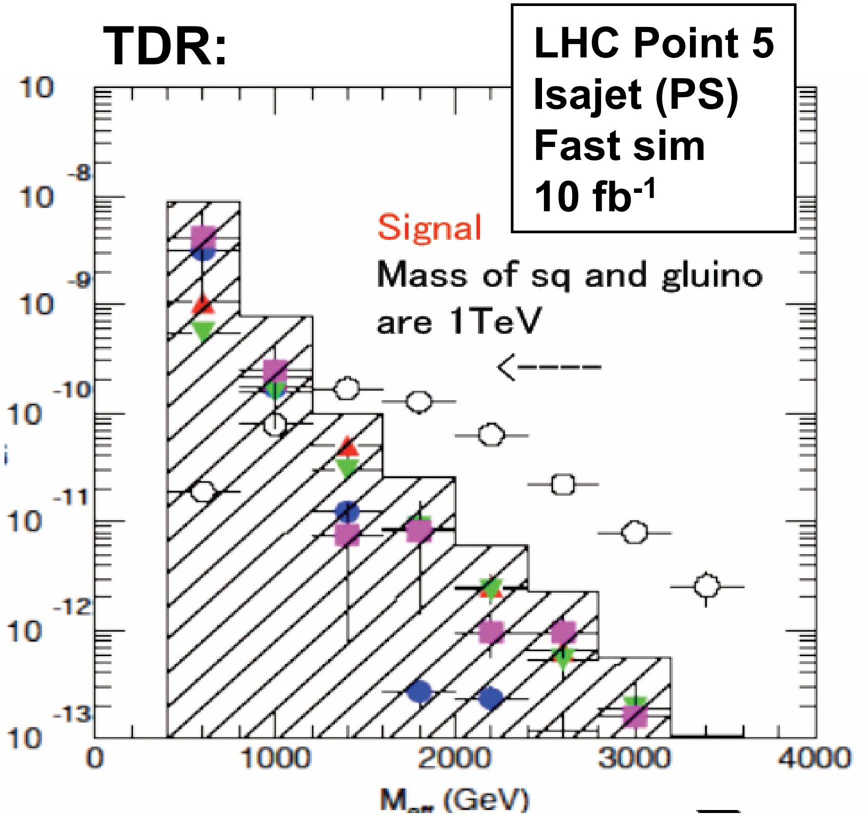
$BR(\tilde{\chi}_1^\pm \to \tilde{\tau}_1\nu_\tau)\sim$ 100%

(note: $m(\tilde{\chi}_2) < m(\tilde{l}_L)$ thus $\tilde{\chi}_2 \not\to \tilde{l}_L\, l$ **)**

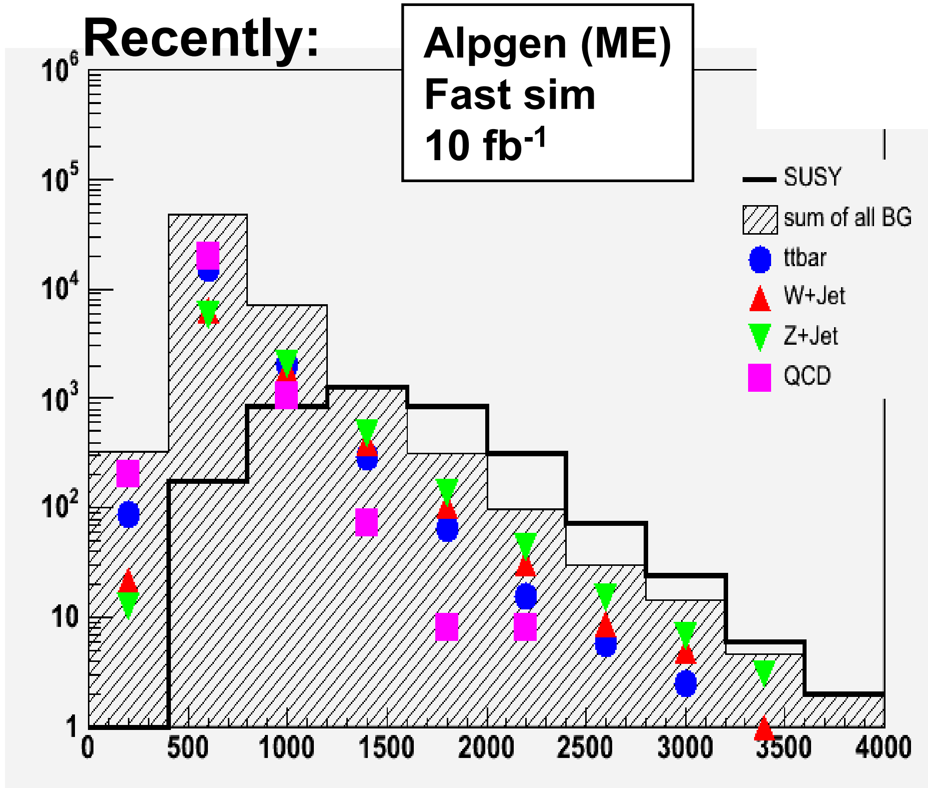
- **Mass spectrum :**

Particle	Mass (GeV)	Particle	Mass (GeV)
$\tilde{g}$	595.5	$\tilde{u}_R$	520.5
$\tilde{u}_L$	537.25	$\tilde{d}_L$	543.04
$\tilde{b}_1$	491.92	$\tilde{t}_1$	379.14
$\tilde{e}_L$	202.12	$\tilde{e}_R$	143.00
$\tilde{\tau}_1$	133.39	$\tilde{\tau}_2$	206.02
$\tilde{\chi}_1^0$	96.05	$\tilde{\chi}_1^\pm$	176.37
$\tilde{\chi}_2^0$	176.80	$\tilde{\chi}_4^0$	377.83
h	113.98	A	394.37

M_{eff}: Parton Shower vs Matrix Element for Bkg Simulation



Parton Shower (only good in collinear region)



Matrix Element (more correct)

→ Background increases by factor 2 to 5 !

Stop Mass Measurement

$$m_0 = 150 GeV, m_{1/2} = 300 GeV$$
$$A_0 = -1000 GeV, \tan\beta = 5, \mu > 0$$

- SPS5: light stop $m(\tilde{t}_1) = 236$ GeV
  Reconstruct stop mass via $\tilde{g} \to \tilde{t}_1 t \to tb\tilde{\chi}_1^{\pm}$

- Signature: 2 b-jets, MET, 3 light-quark jets

- Fit m(tb) distribution endpoint:

M(tb)fit= 258.7 ± 0.3(stat.) ± 2.6(syst.)