# Measurement of SUSY parameters using events with dileptons with ATLAS.

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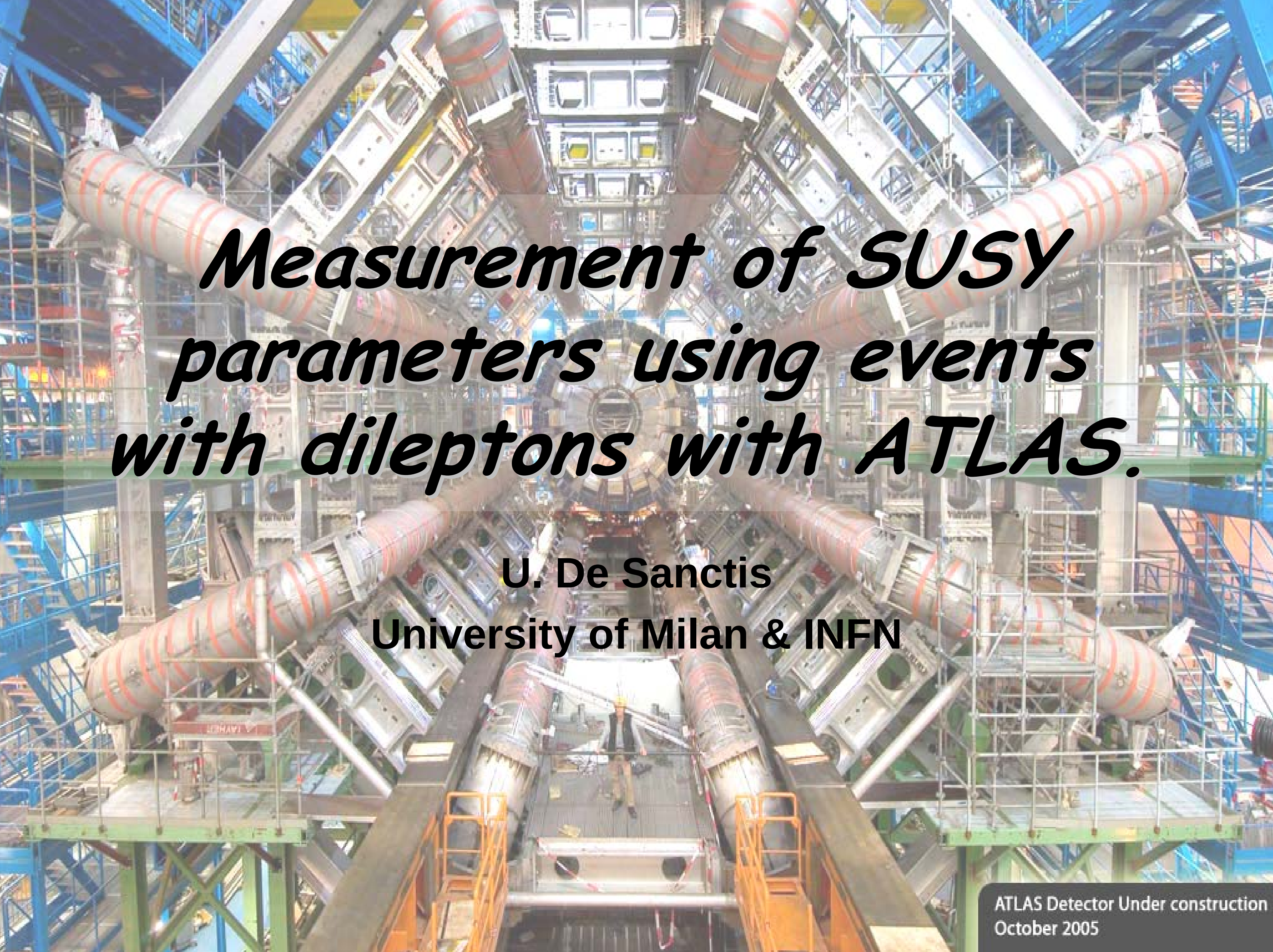


ATLAS Detector Under construction
October 2005

# Outline

- Reminder of SUSY and mSUGRA framework;
- Topology of the SUSY events;
- Leptons identification;
- Measurement of masses and other properties of SUSY particles in the 2-lepton channel.
- Extracting masses and parameters from measurements

# SUPERSYMMETRY REMINDER

Adds to each SM **fermion** (**boson**) a **bosonic** (**fermionic**) partner.

| 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: $\gamma$ | $\gamma$ | photino: $\tilde{\gamma}$ | | |

- **R-parity** $R = (-1)^{3(B-L)+2S}$ can be conserved (**RPC**) or violated (**RPV**)
- **RPC** implies:
  - SUSY particles produced in pairs
  - stable and neutral lightest SUSY particle (**LSP**)
  - no proton decay
- **LSP** is a good candidate for cold **Dark Matter**

**MSSM** Lagrangian depends on 105 parameters

**mSUGRA** requires only 5 parameters

- Also other SUSY models exist: **GMSB**, **AMSB**, …

| 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($\mu$) | $\mu$ from Higgs sector |

# mSUGRA benchmark points

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

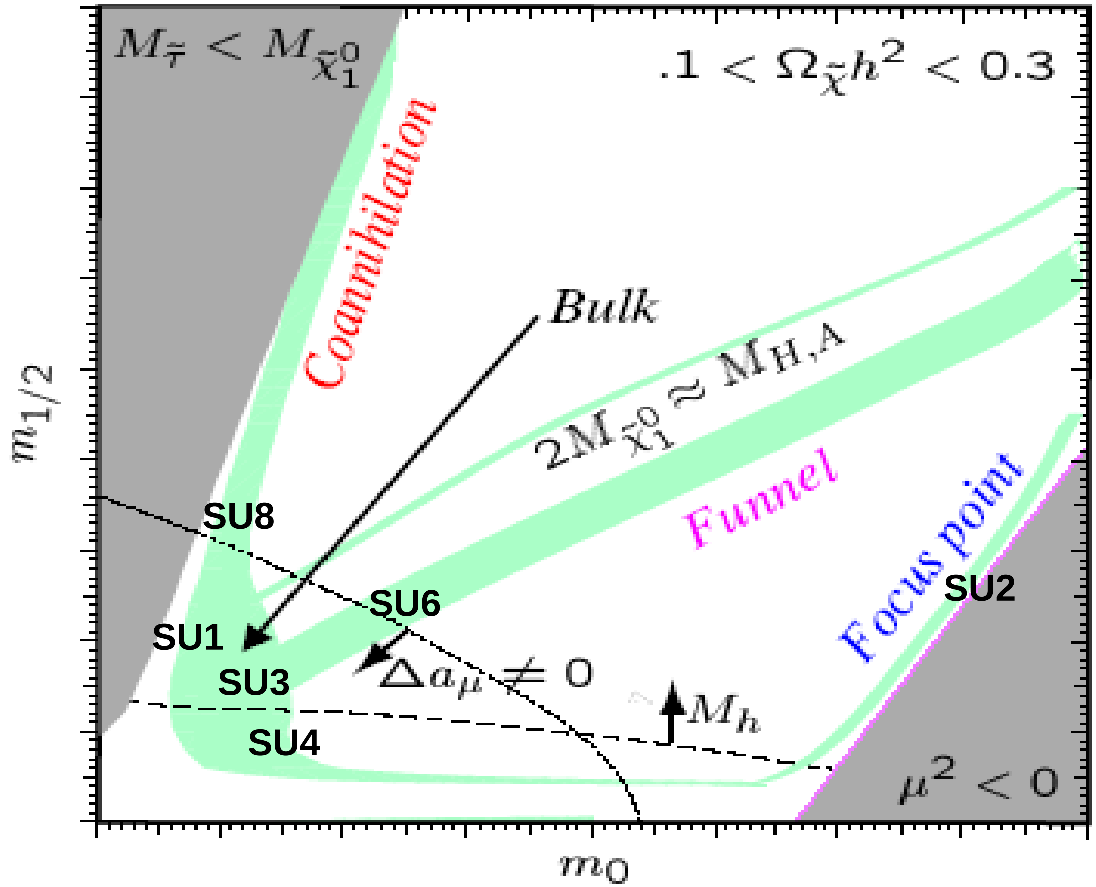
- ✓ Systematically exploring phenomenological signatures
- ✓ Scanning the parameter phase space constrained by latest experimental data and Cold Dark Matter abundance.

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

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

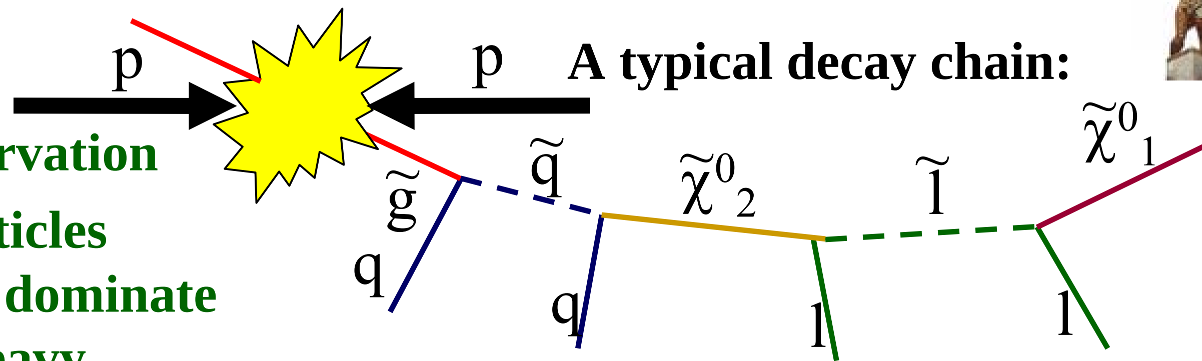
*Funnel: H,A* poles enhance annihilation for $\tan\beta \gg 1$.

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

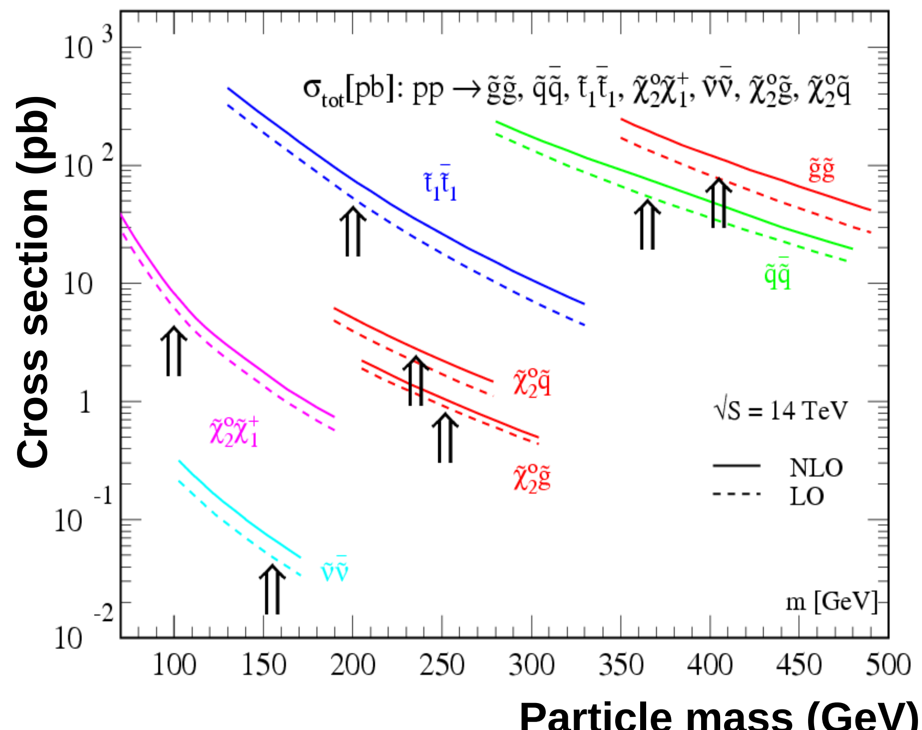


# SUSY signatures at an hadronic collider

**A typical decay chain:**




- **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.**

# 2-lepton channel: strengths and weaknesses

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

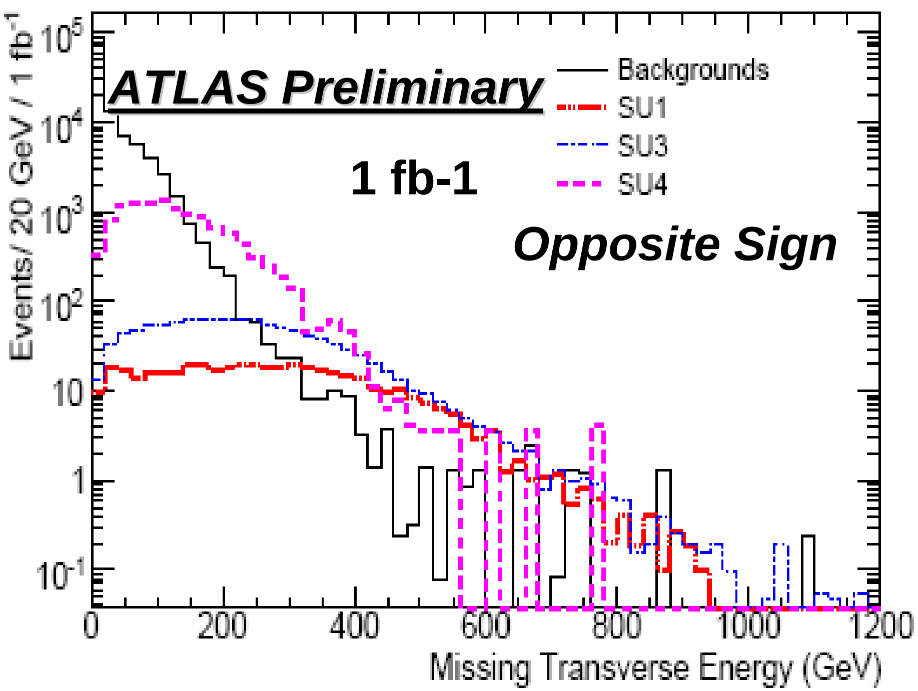
– Heavily suppresses the background: top is the dominant one;

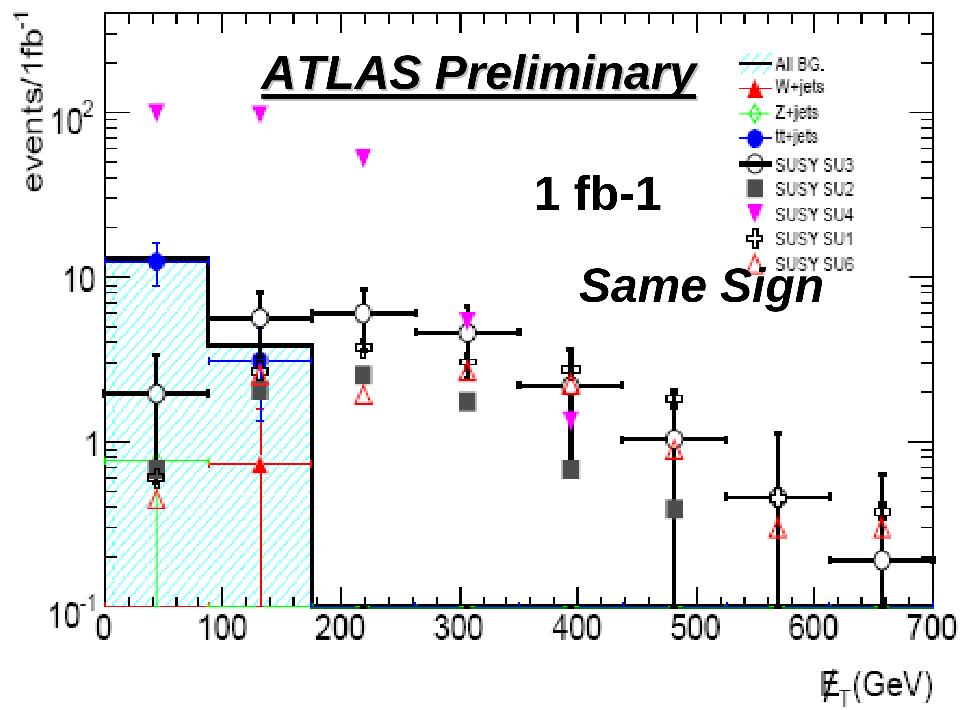
– Statistical significance is smaller but S/B ratio larger.

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

<u>Baseline selection :</u>

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



# Electron & Muon selections for 2-leptons channel

- Pt > 10 GeV, $|\eta|<2.5$;
- Calorimetric isolation < 10 GeV in a 0.2 radius cone;
- Combined muons (e.g. using information from both the muon spectrometer and the Inner Detector)
- Overlap removal procedure.

  Say $\Delta R$ (muon, jet) the distance muon-jet in $(\eta,\phi)$ plane:

  - if $\Delta R < 0.4 \rightarrow$ muon discarded

- Pt > 10 GeV, $|\eta|<2.5$;
- Calorimetric isolation < 10 GeV in a 0.2 radius cone;
- If an electron is found in the $1.37 < |\eta| < 1.52$ region, the event is rejected (ID services and ECAL barrel-extended barrel transition worsen the performances);
- Overlap removal procedure.

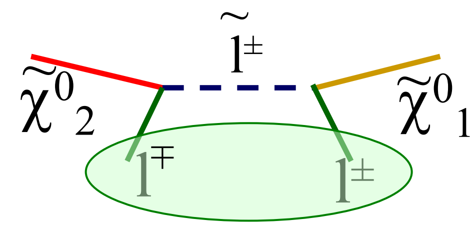
  Say $\Delta R$ (e, jet) the distance electron-jet in $(\eta,\phi)$ plane:

  - if $\Delta R < 0.2 \rightarrow$ jet discarded

  - if $0.2 < \Delta R < 0.4 \rightarrow$ electron discarded.

# Di-Lepton Edge mass measurement (1)

- 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.

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

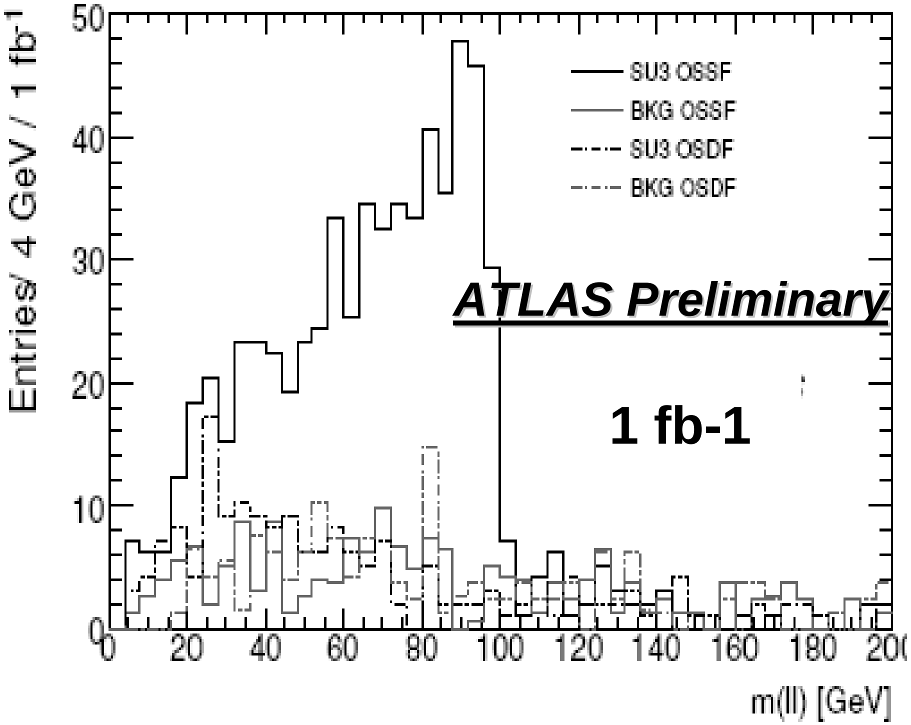
✓ Uncorrelated (SUSY+SM) background (two leptons from independent chains) **removed** by **flavour subtraction**:

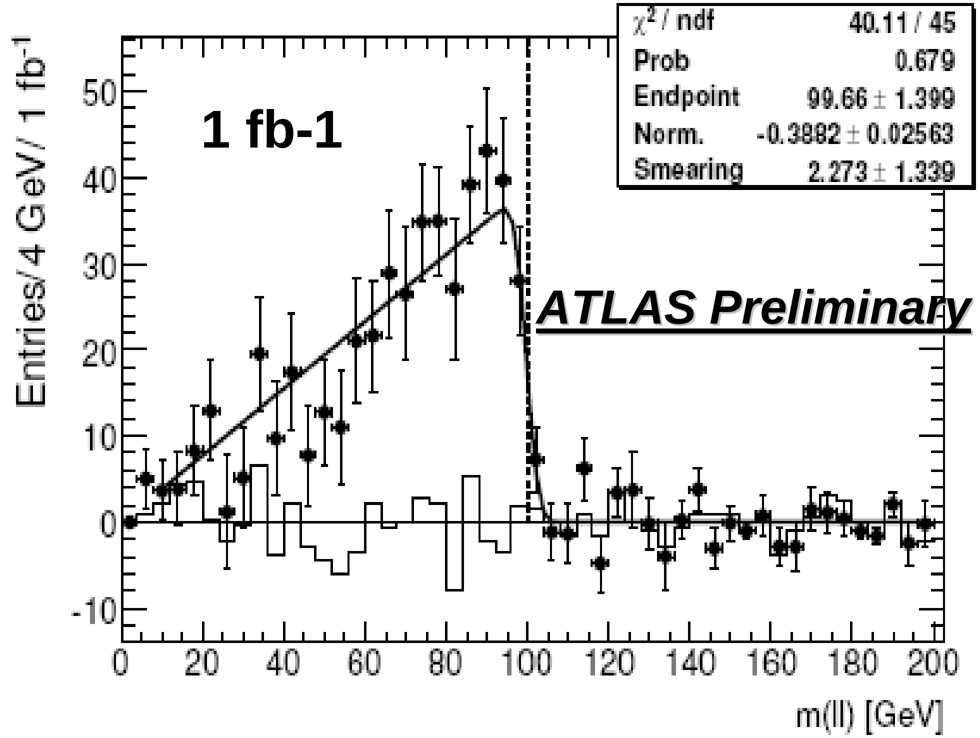
$$e^+e^- + \beta^2\,\mu^+\mu^- - \beta\,(e^+\mu^- - e^-\mu^+)\ ,\ \beta=\varepsilon_e/\varepsilon_\mu$$

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

# *Di-Lepton Edge mass measurement (2)*

## Flavour subtraction at work….




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

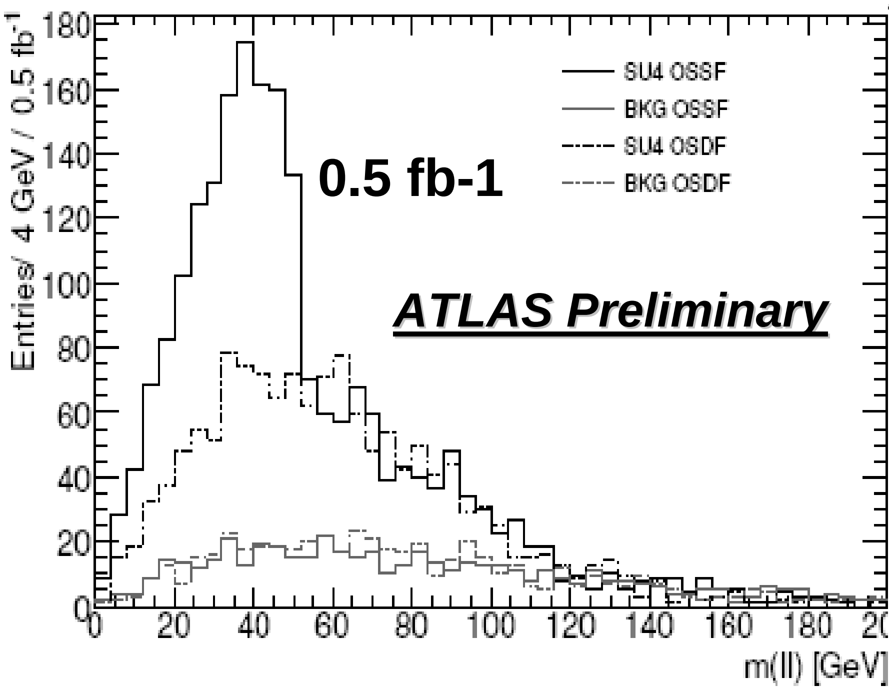
***Flavour Subtraction***

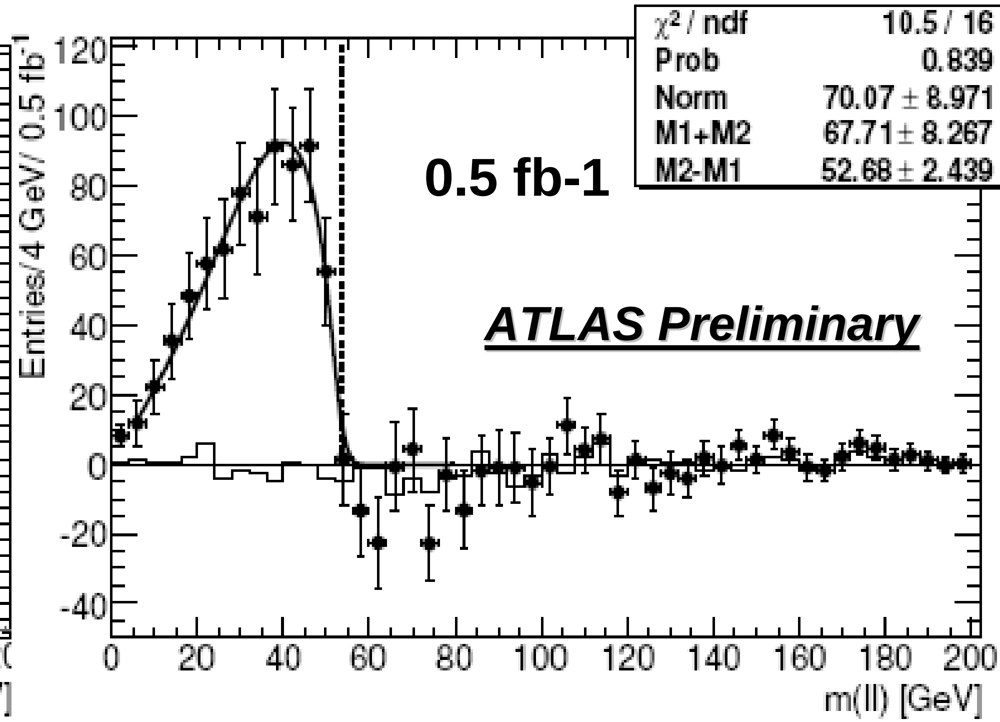
**Fitting function:**
Triangle smeared with a Gaussian with $\sigma = 2$ GeV (to take into account experimental resolution)

# *Di-Lepton Edge mass measurement (3)*

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

$$\frac{d\Gamma}{dM_{\rm inv}} = 2CM_{\rm inv}\frac{\sqrt{M_{\rm inv}^4 - M_{\rm inv}^2(\mu^2+M^2)+(\mu M)^2}}{(M_{\rm inv}^2 - m_Z^2)^2}\cdot\left[-2M_{\rm inv}^4 + M_{\rm inv}^2(2M^2+\mu^2)+(\mu M)^2\right]$$



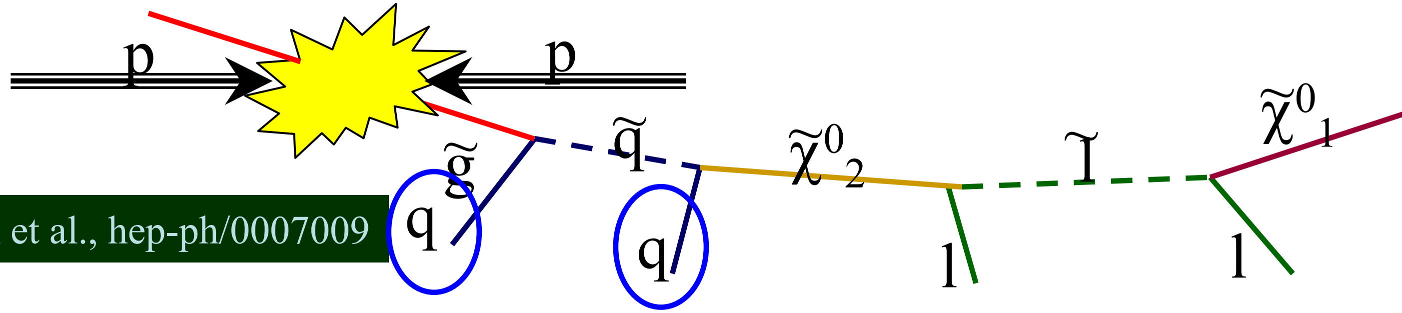

**SU4**, 0.5 fb$^{-1}$
Edge: (52.7±2.4) GeV
Truth: 53.6 GeV

***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.

# Lepton+jets combination

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 $\tilde{\chi}^0{}_1$ $\tilde{\chi}^0{}_2$ $\tilde{l}$ $\tilde{q}$ .

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

**Keep the minimum**

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

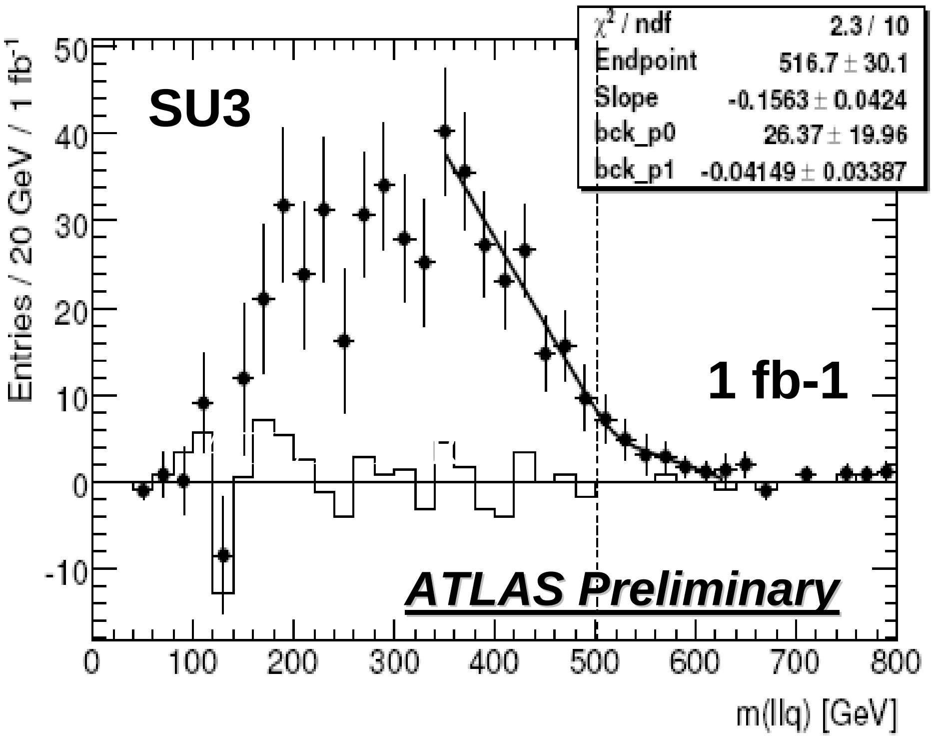
$m_{llq}^{THRESH}$ → $llq_1$, $llq_2$ $\Rightarrow$

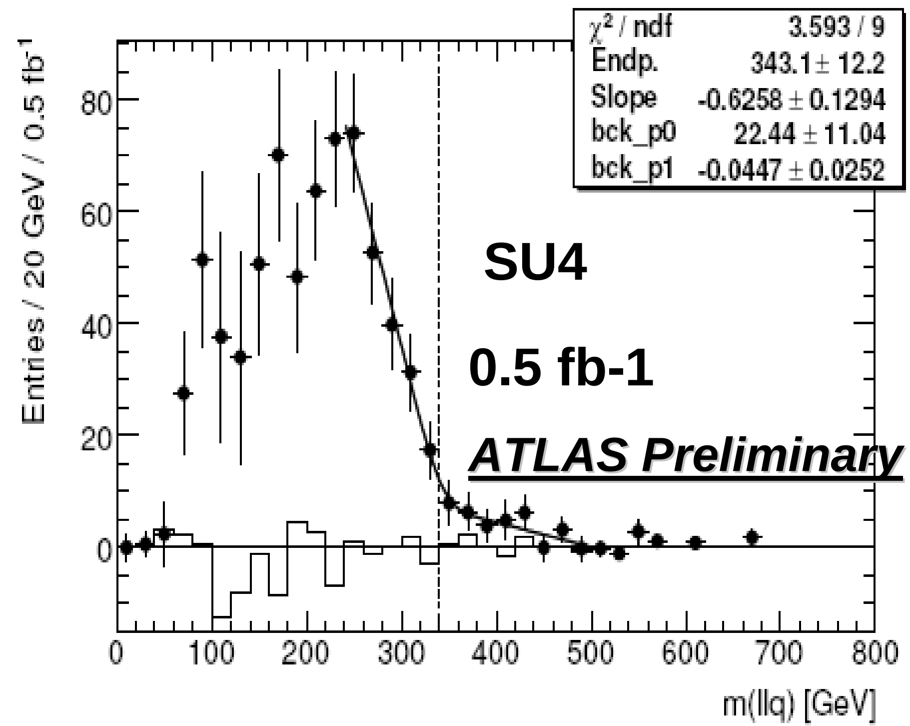
**Keep the maximum**

$$\begin{aligned}(m^2_{qll})^{\rm thres} = \ & [(m^2_{\tilde{q}_L} + m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R})(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}) \\ & -(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})\sqrt{(m^2_{\tilde{\chi}^0_2} + m^2_{\tilde{l}_R})^2(m^2_{\tilde{l}_R} + m^2_{\tilde{\chi}^0_1})^2 - 16 m^2_{\tilde{\chi}^0_2} m^4_{\tilde{l}_R} m^2_{\tilde{\chi}^0_1}} \\ & +2m^2_{\tilde{l}_R}(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2})(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1})]/(4m^2_{\tilde{l}_R} m^2_{\tilde{\chi}^0_2})\end{aligned}$$

# Lepton+jets combination (2)

## llq edges



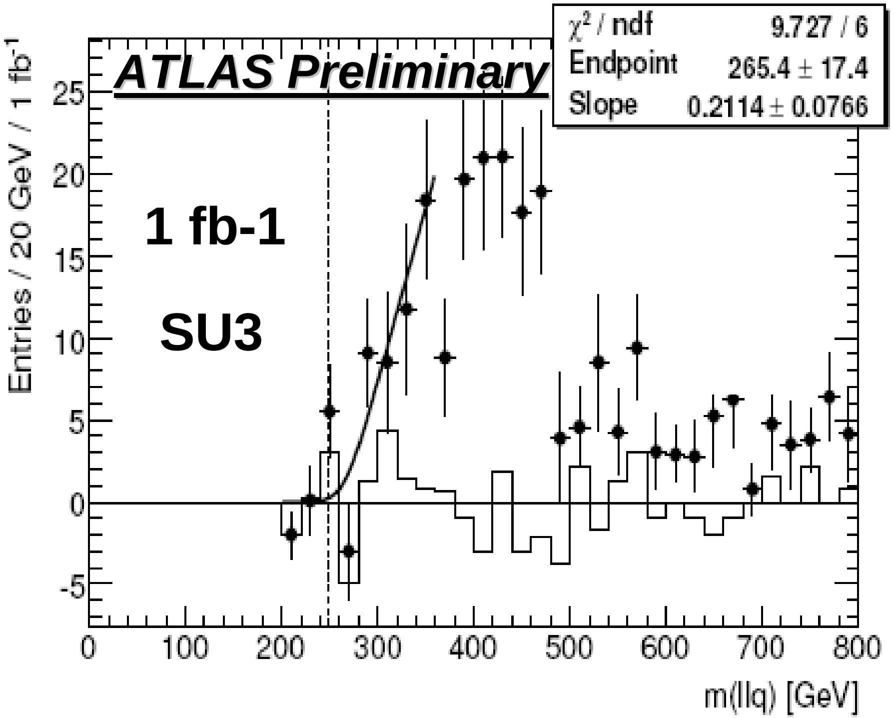

Fit formula: 2 straight lines (for signal and background) smeared by a Gaussian distribution to take into account the experimental resolution.

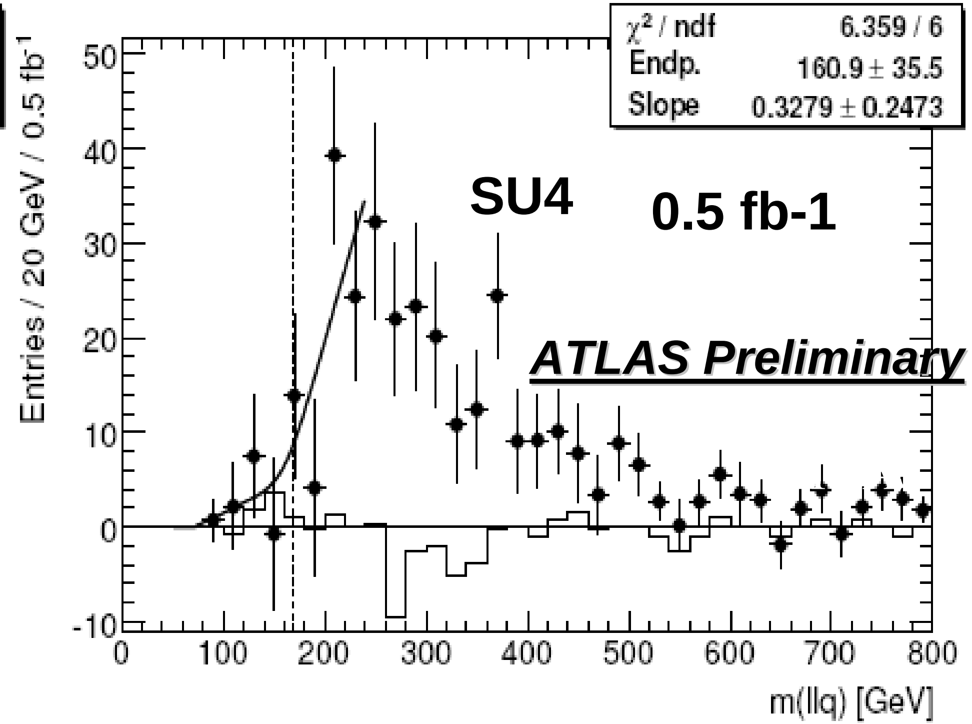
**Edge: 517±30±10±13 GeV**
**Truth: 501 GeV**

**Edge: 343±12±3±9 GeV**
**Truth: 340 GeV**

# Lepton+jets combination (3)

## 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**

# Extracting masses and parameters

Using the previous measurements (with also $q\ell$ edges and thresholds) , a global fit is performed in order to extract the value of the masses of the particles involved:

Masses of SUSY particles

| Observable | SU3 $m_{\text{meas}}$ [GeV/$c^2$] | SU3 $m_{\text{MC}}$ [GeV/$c^2$] | SU4 $m_{\text{meas}}$ [GeV/$c^2$] | SU4 $m_{\text{MC}}$ [GeV/$c^2$] |
|---|---|---|---|---|
| $m_{\tilde{\chi}_1^0}$ | $88 \pm 60 \mp 2$ | 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 | | |

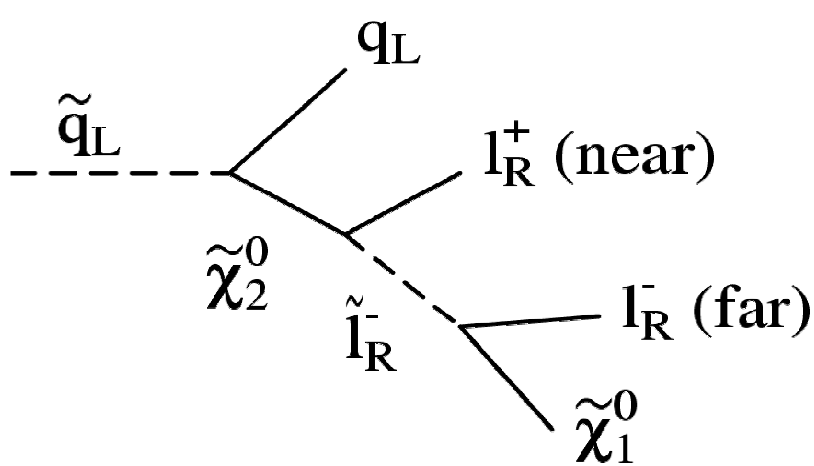
**mSUGRA** parameters determination

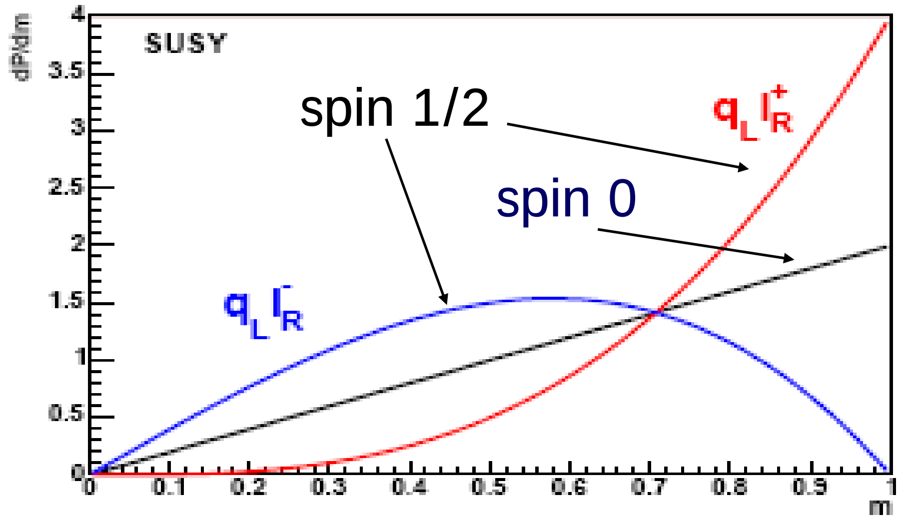
| Parameter | SU3 value | fitted value | exp. unc. |
|---|---|---|---|
| | $\text{sign}(\mu) = +1$ | | |
| $\tan\beta$ | 6 | 7.4 | 4.6 |
| $M_0$ | 100 GeV | 98.5 GeV | $\pm 9.3$ GeV |
| $M_{1/2}$ | 300 GeV | 317.7 GeV | $\pm 6.9$ GeV |
| $A_0$ | $-300$ GeV | 445 GeV | $\pm 408$ GeV |
| | $\text{sign}(\mu)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

With **1 fb-1** the uncertainties on the masses and on the mSUGRA space parameters are very big → more statistics is needed.

# Measurement of neutralino spin (1)

**Important to measure the spin of new particles: it's the fundamental check to ensure that what we have discovered is SUSY!!**




The charge asymmetry is **diluted** because:

1. Usually it is not possible to discriminate the *near* and *far* leptons: we sum $m(ql^{far})$ and $m(ql^{near})$ invariant masses
2. The charge conjugated cascade decay (from the anti-squark) gives the opposite asymmetry. However, cancelation is not exact because at LHC a larger number of squarks than anti-squarks is produced (pp collider)

# Measurement of neutralino spin (2)

SU1 point: 7.8 pb x 1.6%

Ratio squarks/anti-squarks ~3.5

$$\tilde{q}_L \rightarrow q\,\tilde{\chi}_2^0 \rightarrow q\,\tilde{l}_L\,l \rightarrow q l^{\pm} l^{\mp} + \tilde{\chi}_1^0$$

264   255 soft   hard 137

$$\tilde{q}_L \rightarrow q\,\tilde{\chi}_2^0 \rightarrow q\,\tilde{l}_R\,l \rightarrow q l^{\pm} l^{\mp} + \tilde{\chi}_1^0$$

264   154 hard   soft 137

SU3 point: 19.3 pb x 3.8%

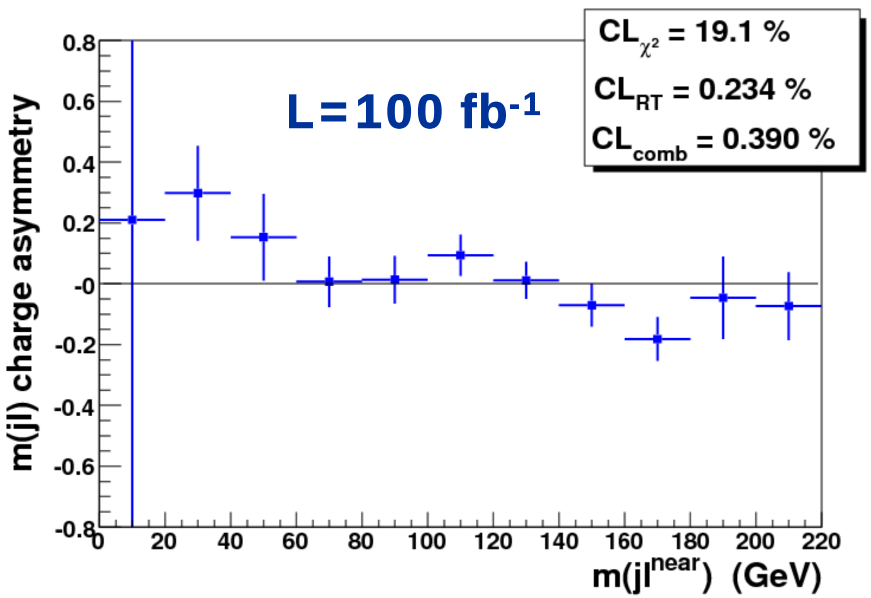
Ratio squarks/anti-squarks ~3

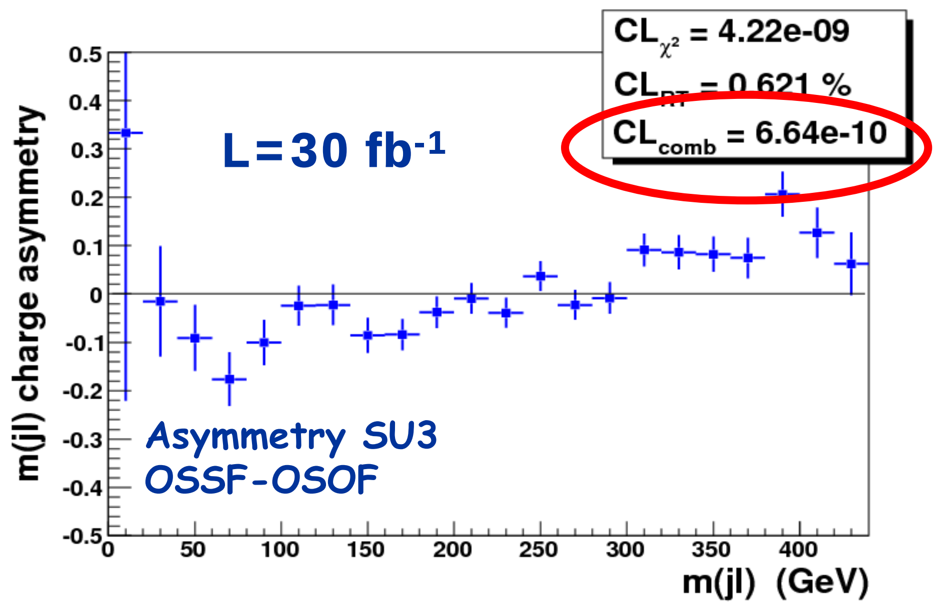
$$\tilde{q}_L \rightarrow q\,\tilde{\chi}_2^0 \rightarrow q\,\tilde{l}_R\,l^{\pm} \rightarrow q l^{\pm} l^{\mp} + \tilde{\chi}_1^0$$

219   155   118

- Cuts on missing energy and jet pt to reject SM background
- 2 Opposite Sign, Same Flavour (OSSF) electrons or muons.
- Subtract background from independent decay chains with the combination $\mu^+\mu^- + e^+e^- - \mu^{\pm}e^{\mp}$

In **SU3** point, **5÷10 fb$^{-1}$** are **already enough** to exclude charge symmetry



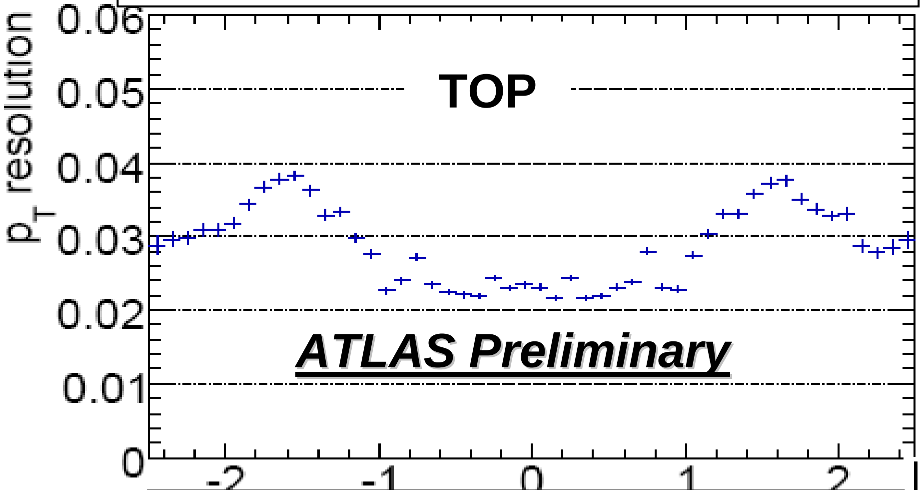
# Conclusions

- A brief review of the search strategies for SUSY in the 2-leptons channels with ATLAS has been presented;
  - New discoveries possible with early LHC data (O(100)$pb^{-1}$)
- Accurate knowledge of SM physics and of detector performance needed for any new discovery
  - **First data** taking period devoted to understanding of detector
  - After that, di-lepton channel could be competitive in the early LHC phase because its clear signature.
- Relations among masses can be determined with a 2-5% precision already with 1 fb-1 of “well understood” data.
- Larger statistics needed to measure the neutralino spin and to use the relations above to constraint the parameter space of mSUGRA and eventually to discriminate among the various SUSY models.

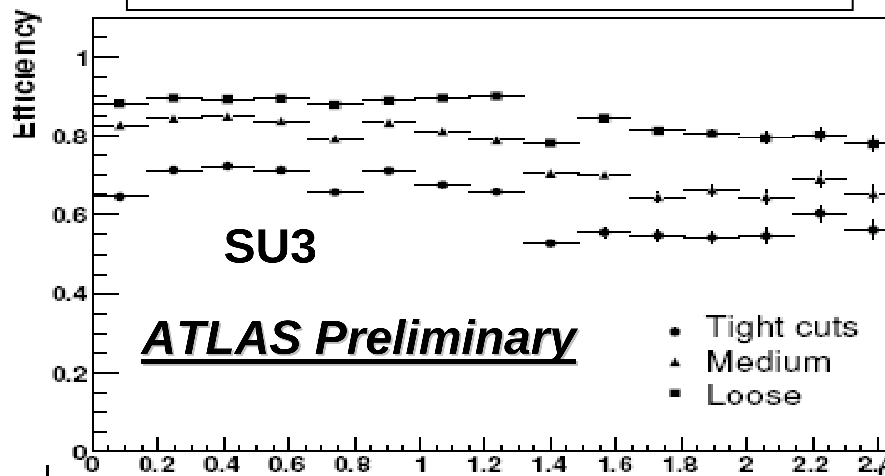
# BACKUP SLIDES

# Electron & Muon Performances

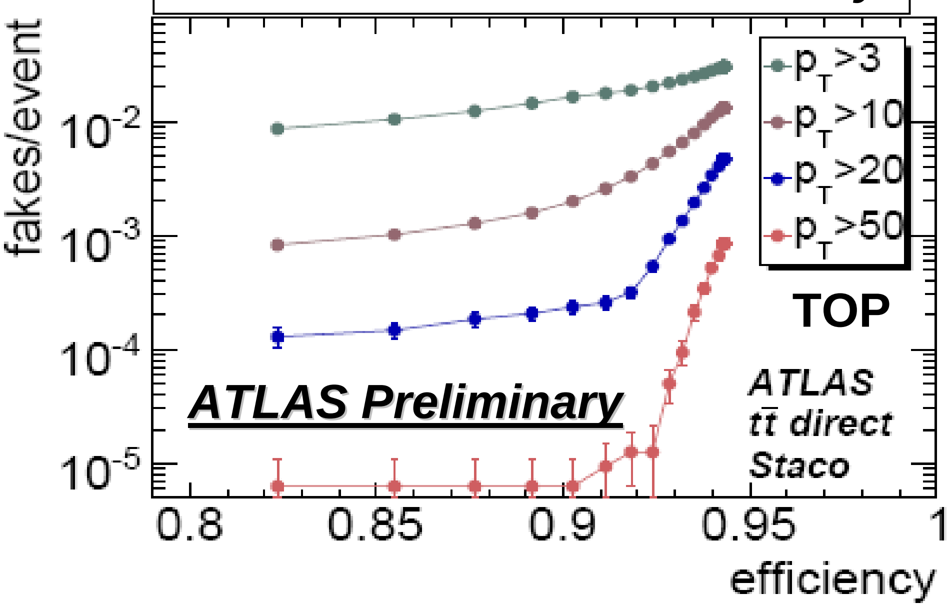
**Muons $(P_T^{RECO} - P_T^{TRUTH}) / P_T^{RECO}$**




**Electrons Efficiency vs |η|**




***Muons Fake rate vs. efficiency***




***Electrons Efficiency vs. rejection***