# Search for Dark Matter Candidate with the ATLAS detector

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*On behalf of the ATLAS Collaboration*

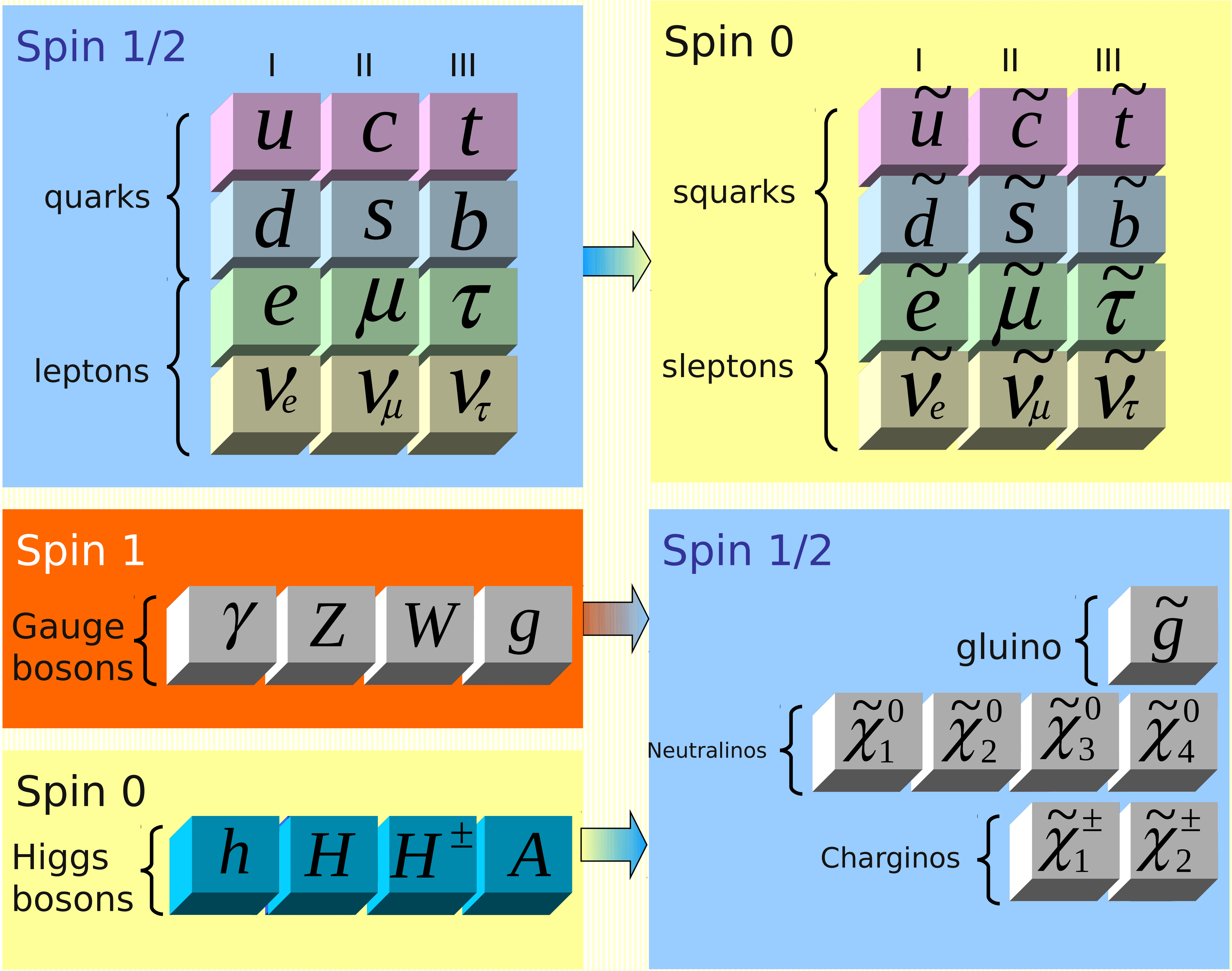
RICAP 2011

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Excellence Cluster Universe

# A brief reminder of SUSY

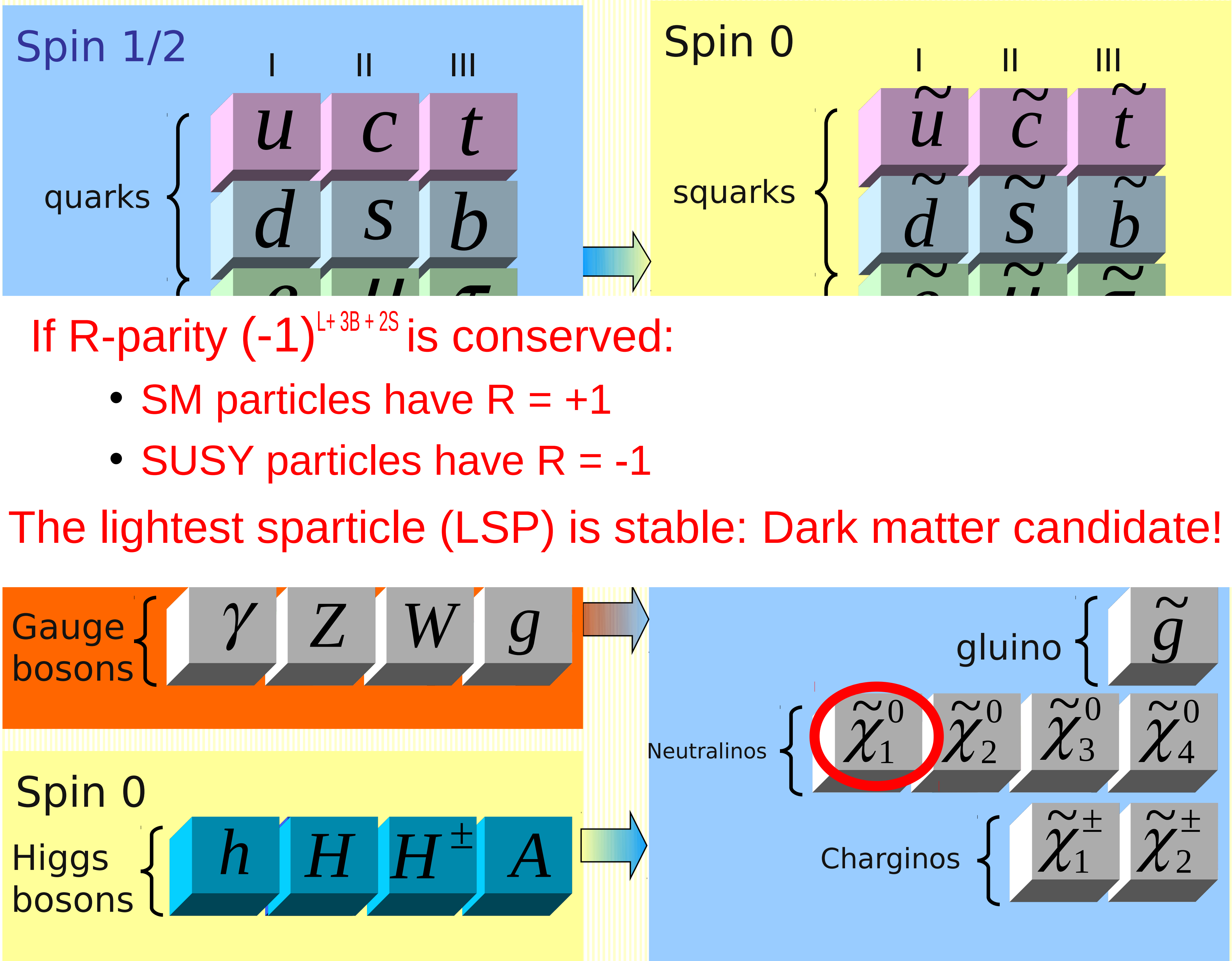


# A brief reminder of SUSY

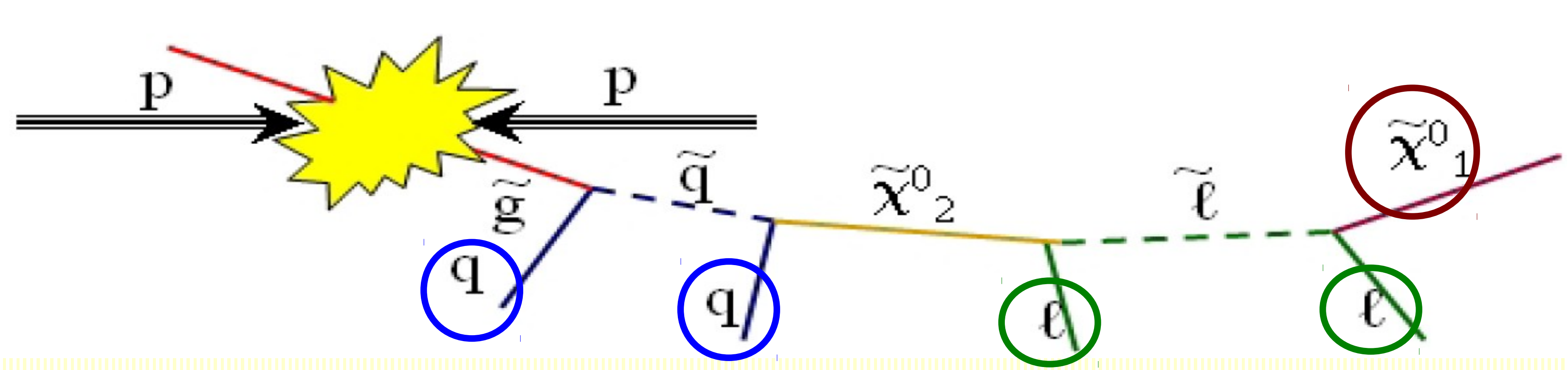
If R-parity $(-1)^{L+3B+2S}$ is conserved:

- SM particles have R = +1
- SUSY particles have R = -1

The lightest sparticle (LSP) is stable: Dark matter candidate!



# Typical signature




- Pair of gluinos/squarks produced by strong interactions
- Their decays give high-$p_T$ jets and charginos/neutralinos
- Charginos/neutralinos decays can give leptons and the decay chain stops when the LSP is produced (R-parity conserving scenarios)
- The pair of stable LSP produced escapes the detector undetected leading to high transverse missing energy

multi-Jets + n leptons + $E_T^{miss}$

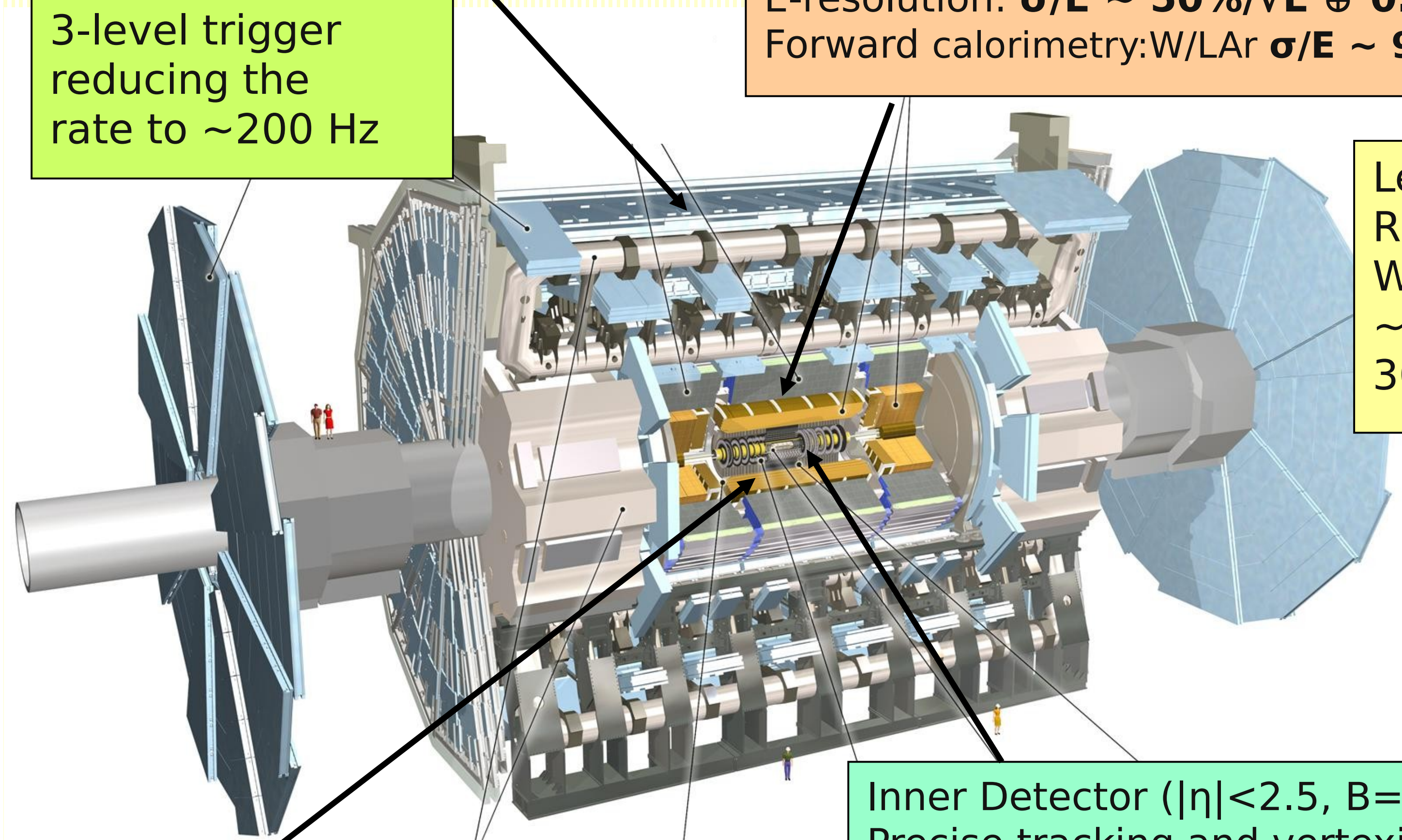
Standard Model backgrounds (tt, W+jets, Z+jets, QCD jets and dibosons)

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution **$< 10\%$ up to $E_\mu \sim 1$ TeV**

Hadronic calorimetry ($|\eta|<3$): segmentation **0.1 x 0.1**
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
E-resolution: **$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$**
Forward calorimetry:W/LAr **$\sigma/E \sim 90\%/\sqrt{E} \oplus 0.07$**

3-level trigger reducing the rate to ~200 Hz

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~$10^8$ electronic channels
3000 km of cables



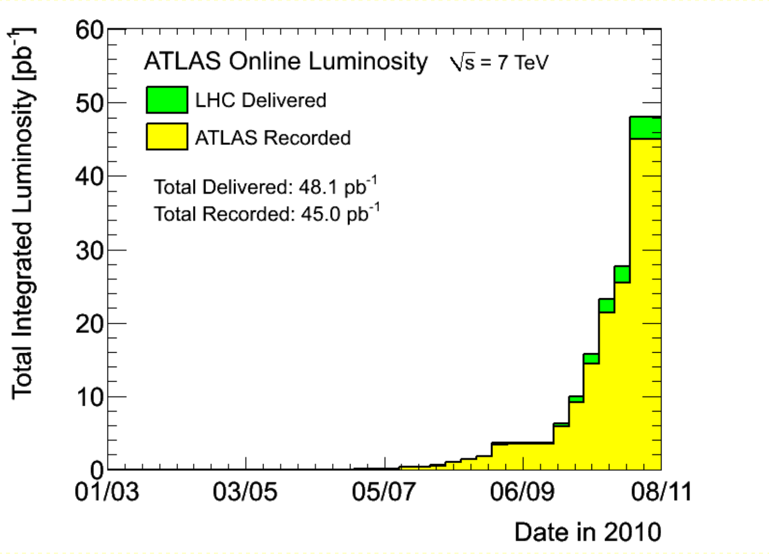
Inner Detector ($|\eta|<2.5$, B=2T):
Precise tracking and vertexing,
**$\sigma/p_T \sim 3.8\times10^{-4}\, p_T(\text{GeV}) \oplus 0.015$**

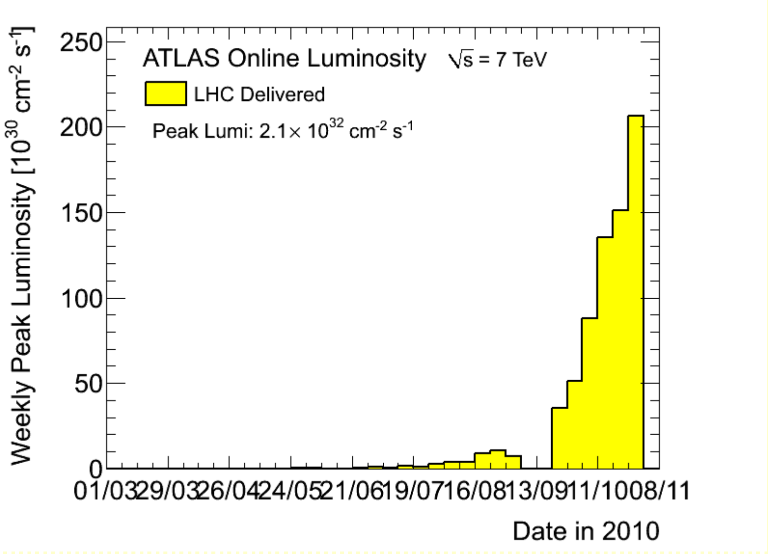
Electromagnetic calorimeter: Pb-Liquid Argon Accordion
e/γ trigger, identification and measurement
E-resolution: **$\sigma/E \sim 10\%/\sqrt{E} \oplus 0.007$**
**granularity :.025 x .025** $\oplus$ strips


5

# Data accumulated in 2010

- Excellent LHC performance



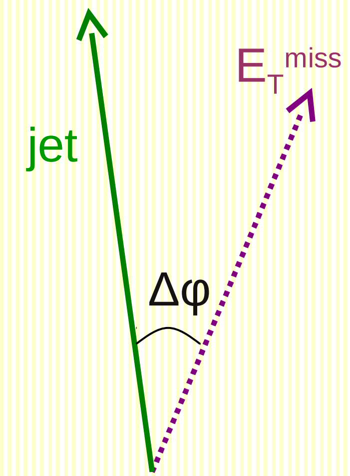

- Very good detector efficiency:
  - Inner tracking detectors: 99.1% to 100%
  - Calorimeters: 90.7% to 100%
  - Muon detectors: 96.2% to 99.8%

# ATLAS public results of R-parity conserving SUSY searches

Covered today

| | |
|---|---|
| one lepton, jets, and missing transverse momentum | ArXiV:1102.2357<br>Phys. Rev. Lett. 106, 131802 (2011) |
| jets and missing transverse momentum | ArXiV:1102.5290, submitted to PLB |
| Multilepton final state with jets and missing transverse momentum | ATLAS-CONF-2011-039 |
| b-tagged jets and missing transverse momentum | ArXiV:1103.4344, submitted to PLB |
| Dilepton final states with missing transverse momentum | ArXiV:1103.6214, submitted EPJLC<br><br>Same-flavour:<br>ArXiV:1103.6208, accepted EPJLC |

# Some useful variables




- $\Delta\phi(\text{jets}, E_T^{miss})$

  - Cutting on $\Delta\phi$ eliminates events in which $E_t^{miss}$ is closely related to one of the leading jets (QCD)

- Effective mass $m_{eff}$ (scalar sum of sel. jets & leptons $p_T$ and $E_T^{miss}$)

  - peaks at a value which is correlated with the mass of the pair of SUSY particles produced in the *pp* interaction

- The transverse mass $m_T$ $m_T^2 \equiv 2|\mathbf{p}_T^{\ell}||E_T^{miss}| - 2\mathbf{p}_T^{\ell} \cdot \vec{E}_T^{miss}$

  - useful to remove BG in which a W decays leptonically

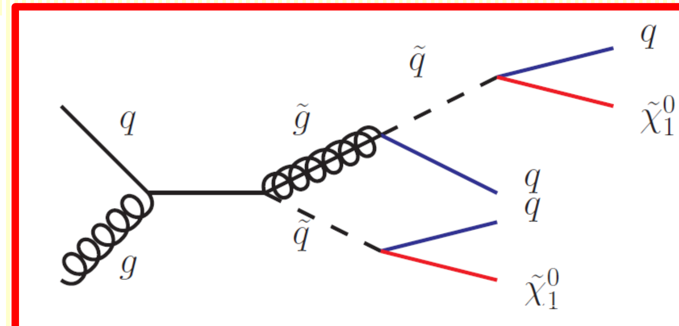
# The 0-lepton channel

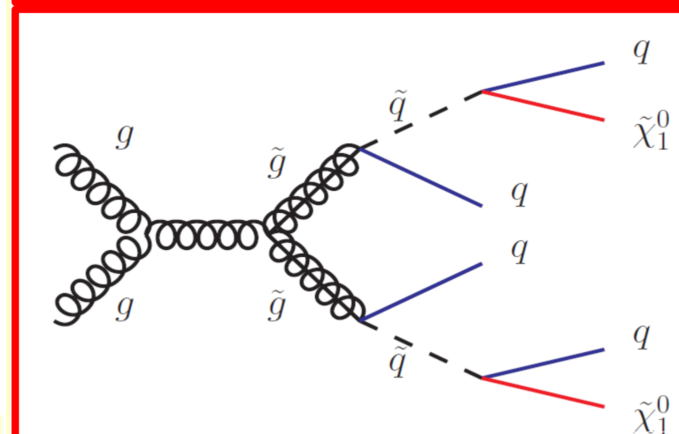
*Select events with jets, missing transverse momentum and no lepton (veto e/$\mu$)*

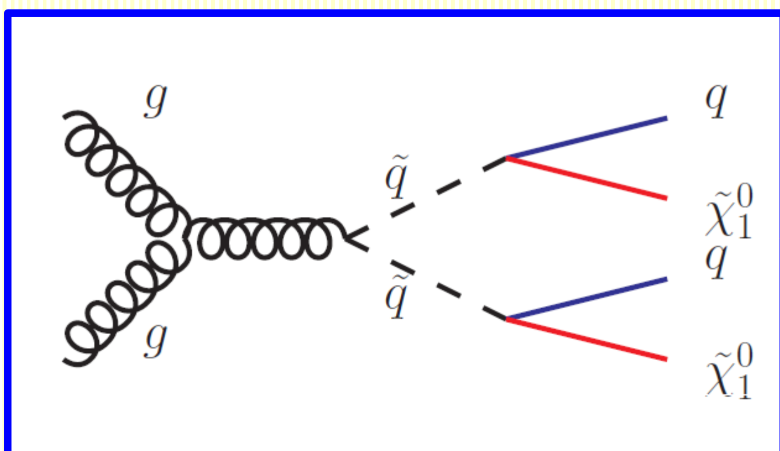
*arXiV:1102.5290*
*submitted to PLB*

# Defining the signal regions

| | | A | B | C | D |
|---|---|---|---|---|---|
| Pre-selection | Number of required jets | $\geq 2$ | $\geq 2$ | $\geq 3$ | $\geq 3$ |
| | Leading jet $p_{\mathrm{T}}$ [GeV] | $> 120$ | $> 120$ | $> 120$ | $> 120$ |
| | Other jet(s) $p_{\mathrm{T}}$ [GeV] | $> 40$ | $> 40$ | $> 40$ | $> 40$ |
| | $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] | $> 100$ | $> 100$ | $> 100$ | $> 100$ |
| Final selection | $\Delta\phi(\mathrm{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ | $> 0.4$ | $> 0.4$ | $> 0.4$ | $> 0.4$ |
| | $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ | $> 0.3$ | – | $> 0.25$ | $> 0.25$ |
| | $m_{\mathrm{eff}}$ [GeV] | $> 500$ | – | $> 500$ | $> 1000$ |
| | $m_{\mathrm{T2}}$ [GeV] | – | $> 300$ | – | – |




Low- and high-mass squark pair production

gluino/gluino and squark/gluino production

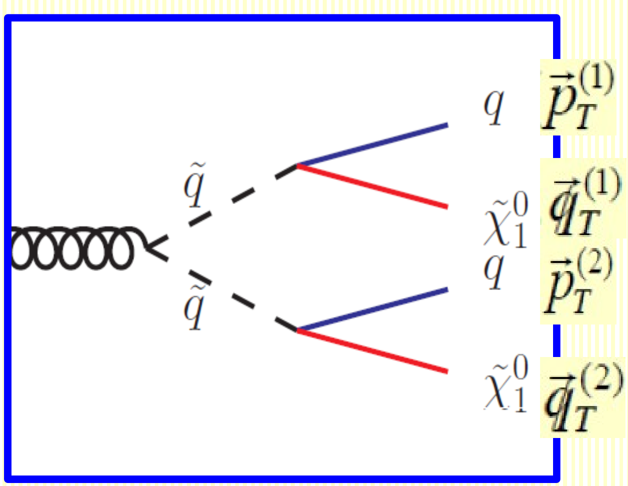
# Defining the signal regions

| | | A | B | C | D |
|---|---|---|---|---|---|
| Pre-selection | Number of required jets | $\geq 2$ | $\geq 2$ | $\geq 3$ | $\geq 3$ |
| | Leading jet $p_{\mathrm{T}}$ [GeV] | $> 120$ | $> 120$ | $> 120$ | $> 120$ |
| | Other jet(s) $p_{\mathrm{T}}$ [GeV] | $> 40$ | $> 40$ | $> 40$ | $> 40$ |
| | $E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] | $> 100$ | $> 100$ | $> 100$ | $> 100$ |
| Final selection | $\Delta\phi(\mathrm{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\mathrm{min}}$ | $> 0.4$ | $> 0.4$ | $> 0.4$ | $> 0.4$ |
| | $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ | $> 0.3$ | – | $> 0.25$ | $> 0.25$ |
| | $m_{\mathrm{eff}}$ [GeV] | $> 500$ | – | $> 500$ | $> 1000$ |
| | $m_{\mathrm{T2}}$ [GeV] | – | $> 300$ | – | – |

Trigger requirements

Reject the QCD BG

Optimize for SUSY




Stranverse mass $m_{T2}$:

- The sum of the transverse missing momentum of the two neutralinos is know: $\vec{q}_T^{(1)} + \vec{q}_T^{(2)} = E_T^{miss}$

- Using this constraint, calculate the stransverse mass as:

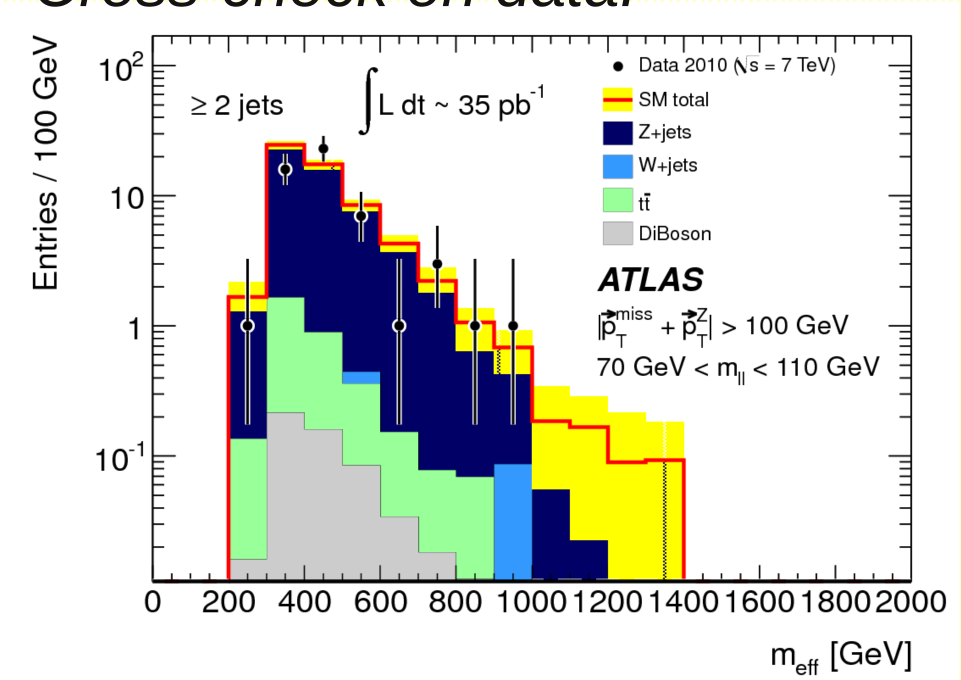
$$m_{T2}(\vec{p}_T^{(1)}, \vec{p}_T^{(2)}, \vec{p}_T) \equiv \min_{\vec{q}_T^{(1)} + \vec{q}_T^{(2)} = E_T^{miss}} \{\max(m_T(\vec{p}_T^{(1)}, \vec{q}_T^{(1)}), m_T(\vec{p}_T^{(2)}, \vec{q}_T^{(2)}))\}$$

# Main backgrounds

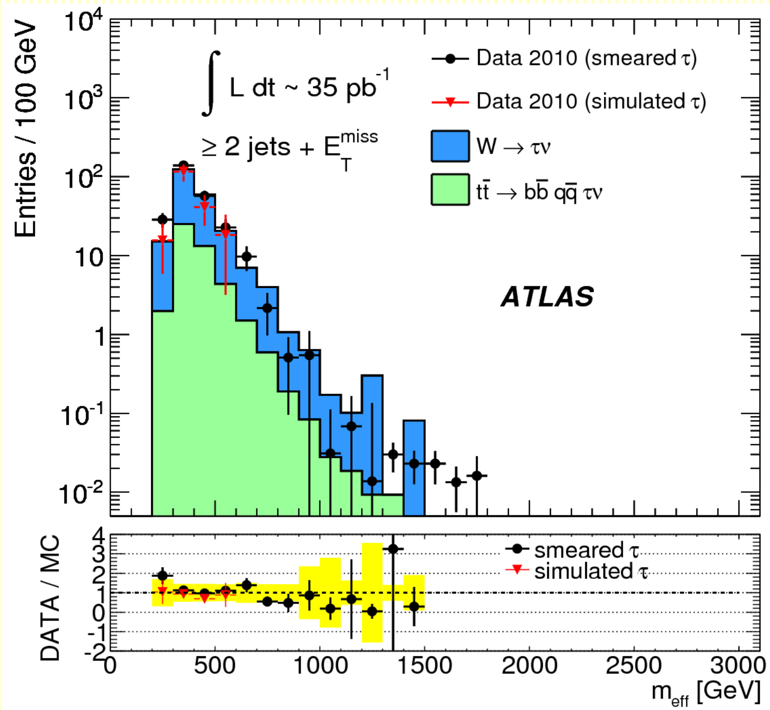
W+jets: $\tau\nu$ decay or missed e/$\mu$
Z+jets: $\nu\nu$ decay
} Alpgen with NNLO normalization

Top pair production: $\tau$ decay of a W } MC@NLO

*Cross-check on data:*

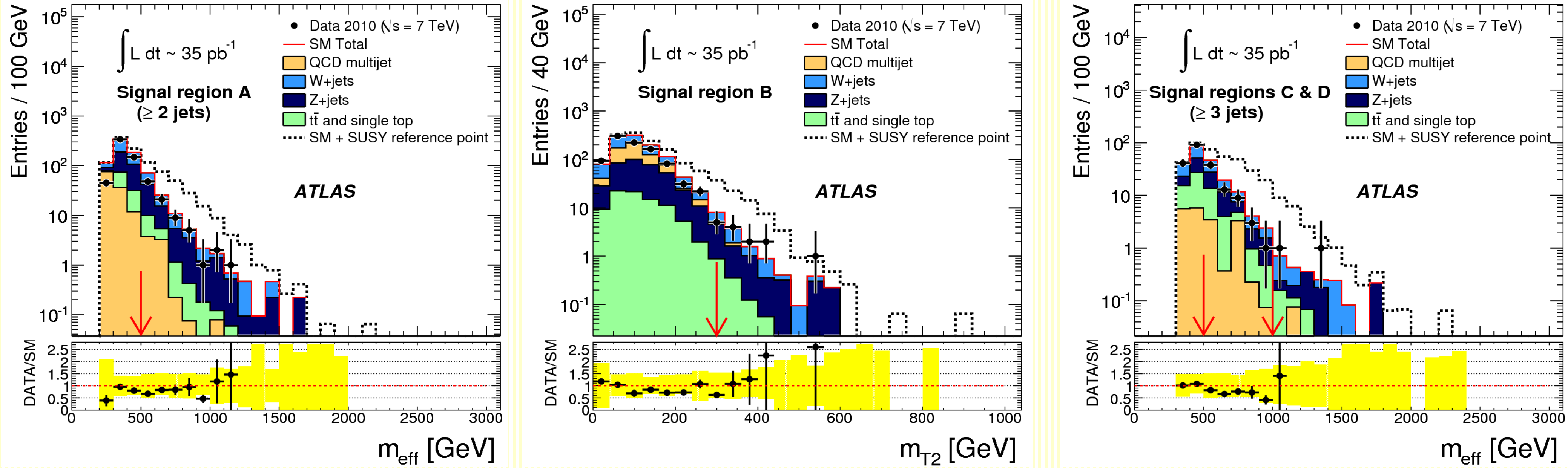



Z(ll)+jets control sample with leptons removed to recalculate the missing transverse momentum



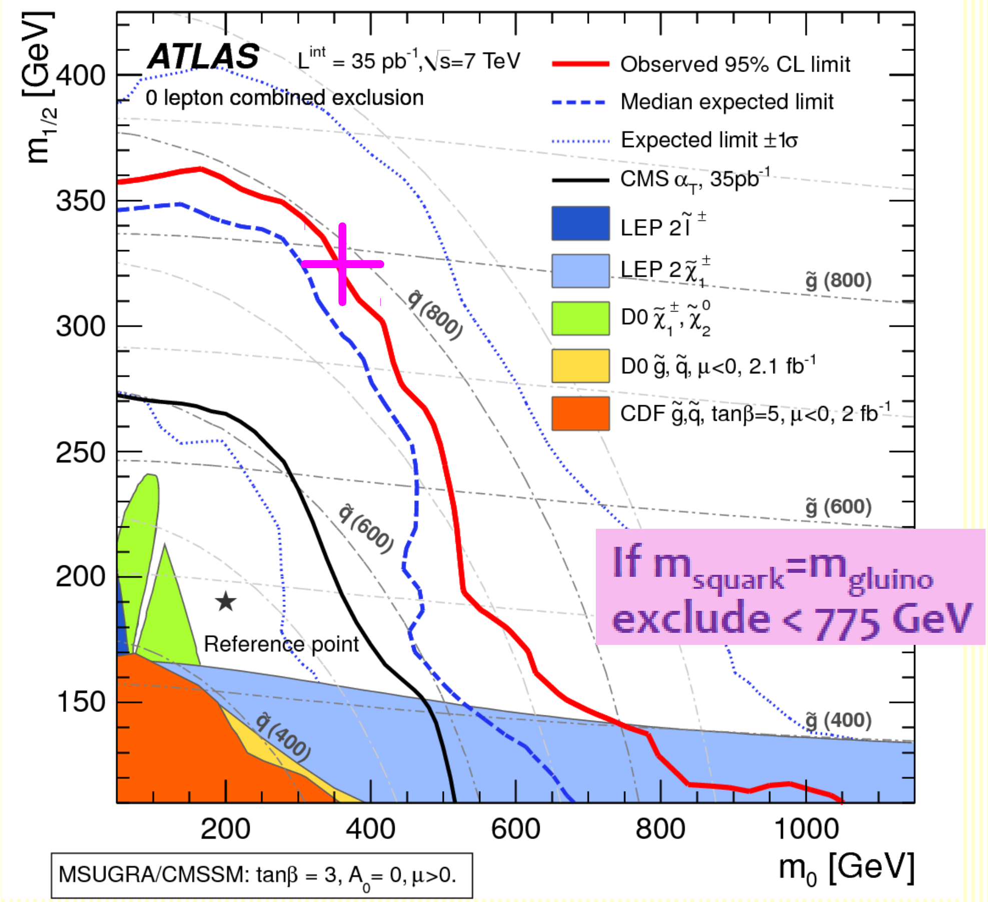

W $\rightarrow$ $\mu\nu$ control sample with the muon replaced by a MC $\tau$ decay

# Results




95% CL limits on cross section · acceptance · efficiency:
1.3 pb (A), 0.35 pb (B), 1.1 pb (C) and 0.11 pb (D)

# Exclusion plot




The limit does not depend strongly on tanβ, A0 or sign(μ)

# The 1-lepton channel

*Select events with jets, missing transverse momentum and exactly one lepton (e/$\mu$)*

*ArXiV:1102.2357*
*Phys. Rev. Lett. 106, 131802 (2011)*

# Defining the signal region

*The isolated one-lepton requirement suppresses QCD multijet and allows a lepton-based trigger*

- Exactly one lepton ($e/\mu$) with pT>20 GeV
- At least 3 jets with pT>60,30,30 GeV

gluino/squark cascade decay with intermediate steps

- $\Delta\phi(\text{jets}, E_T^{miss}) > 0.2$
- $E_T^{miss}/m_{eff} > 0.25$

Reduce the QCD BG further

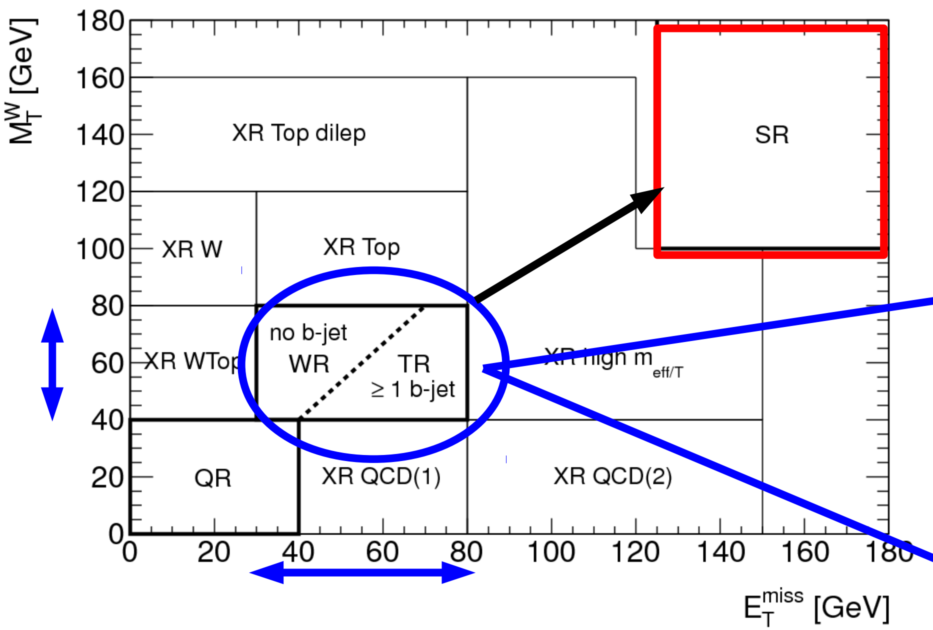
- $m_T > 100$ GeV

Suppresses W+jets and tt

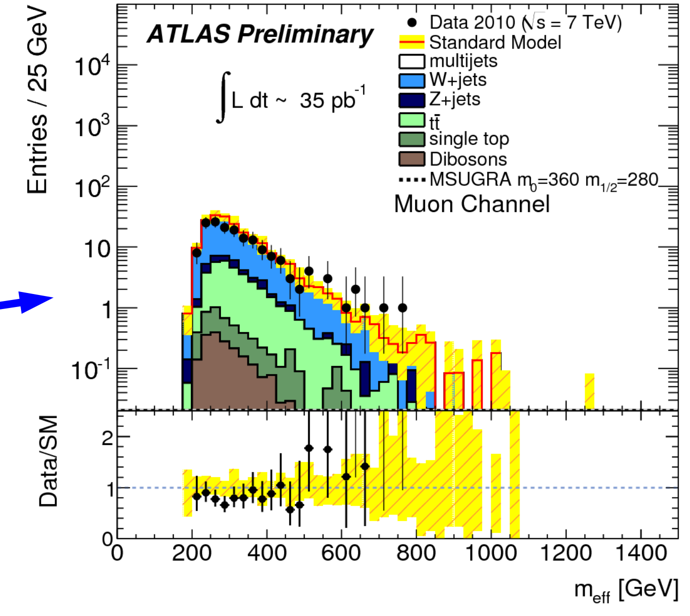
- $m_{eff} > 500$ GeV

Optimize for SUSY

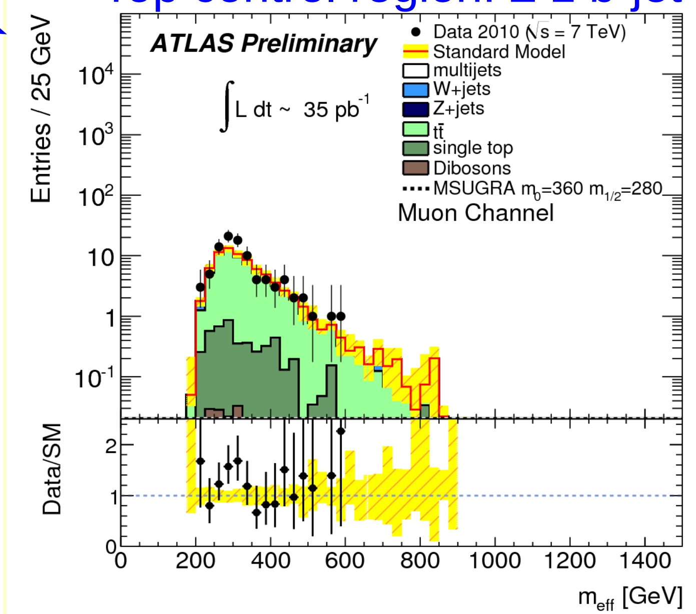
# Main backgrounds: W+jets and tt




W control region: no b-jet




Top control region: ≥ 1 b-jet




$$\underbrace{N(t\bar{t}\ pred.,\ SR)}_{\text{predicted events in signal region}} = \underbrace{(N(fitted\ t\bar{t}(data),\ CR))}_{\text{measured events in control region - other BG}} \times \underbrace{\frac{N(t\bar{t}(MC),\ SR)}{N(t\bar{t}(MC),\ CR)}}_{\text{extrapolation factor CR to SR}}$$

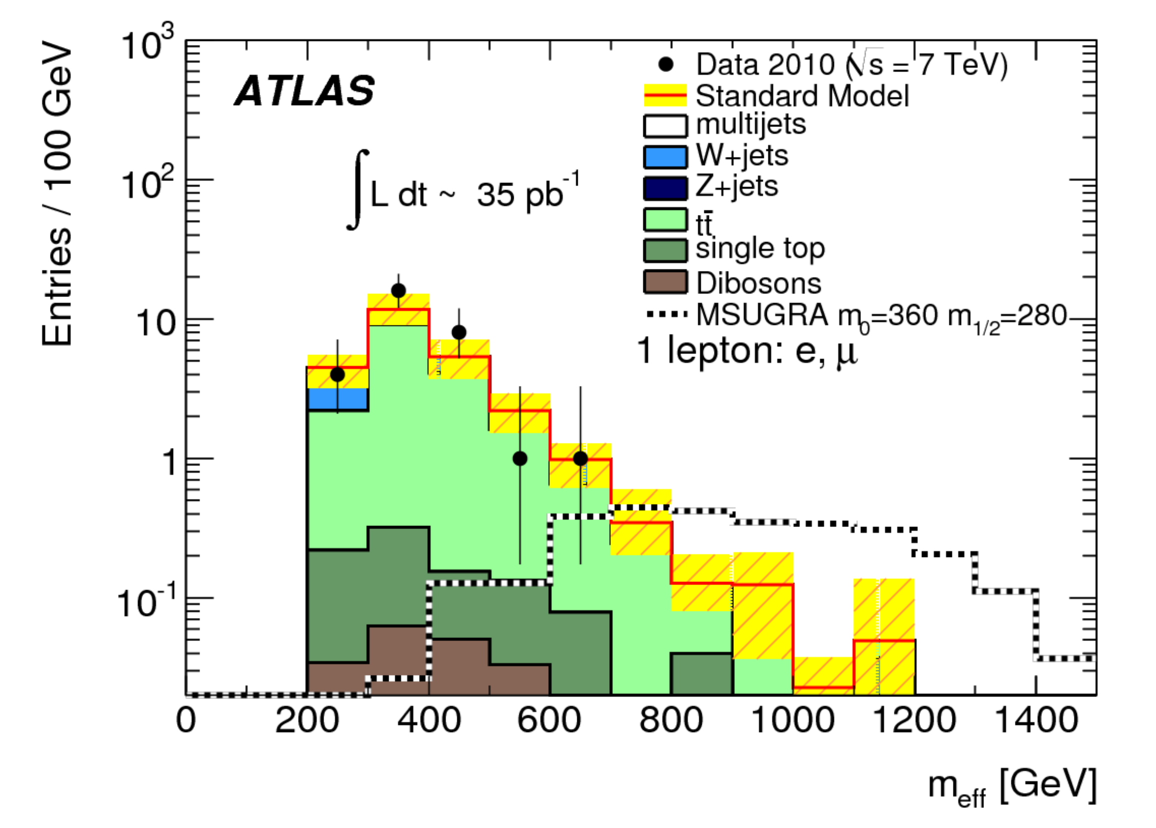
③

① From data

② From MC

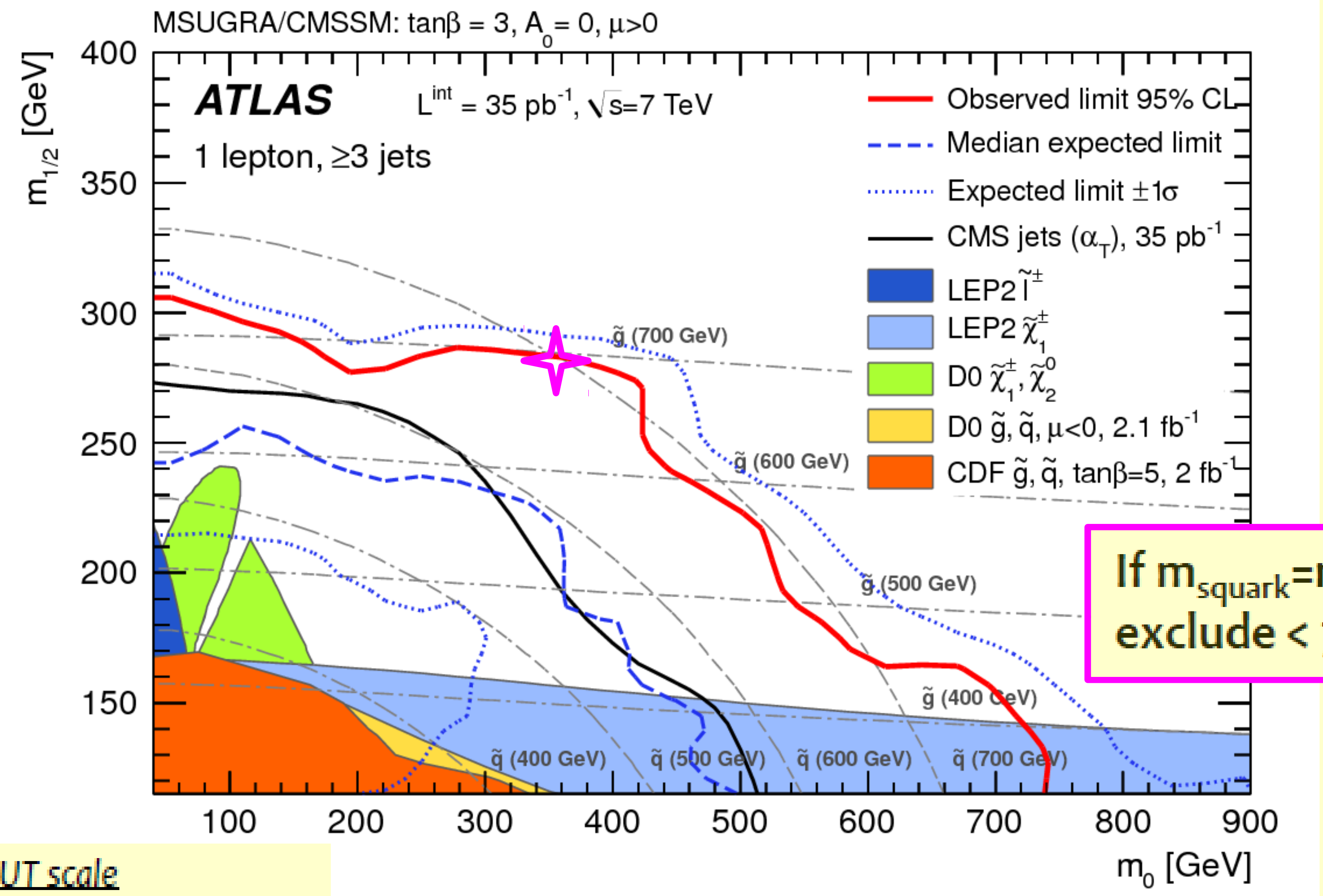
*Method cross-checked with additional control regions*

# Results




95% CL limits on cross section · acceptance · efficiency:
0.065 pb (electron), 0.073 pb (muon)

# Exclusion plot

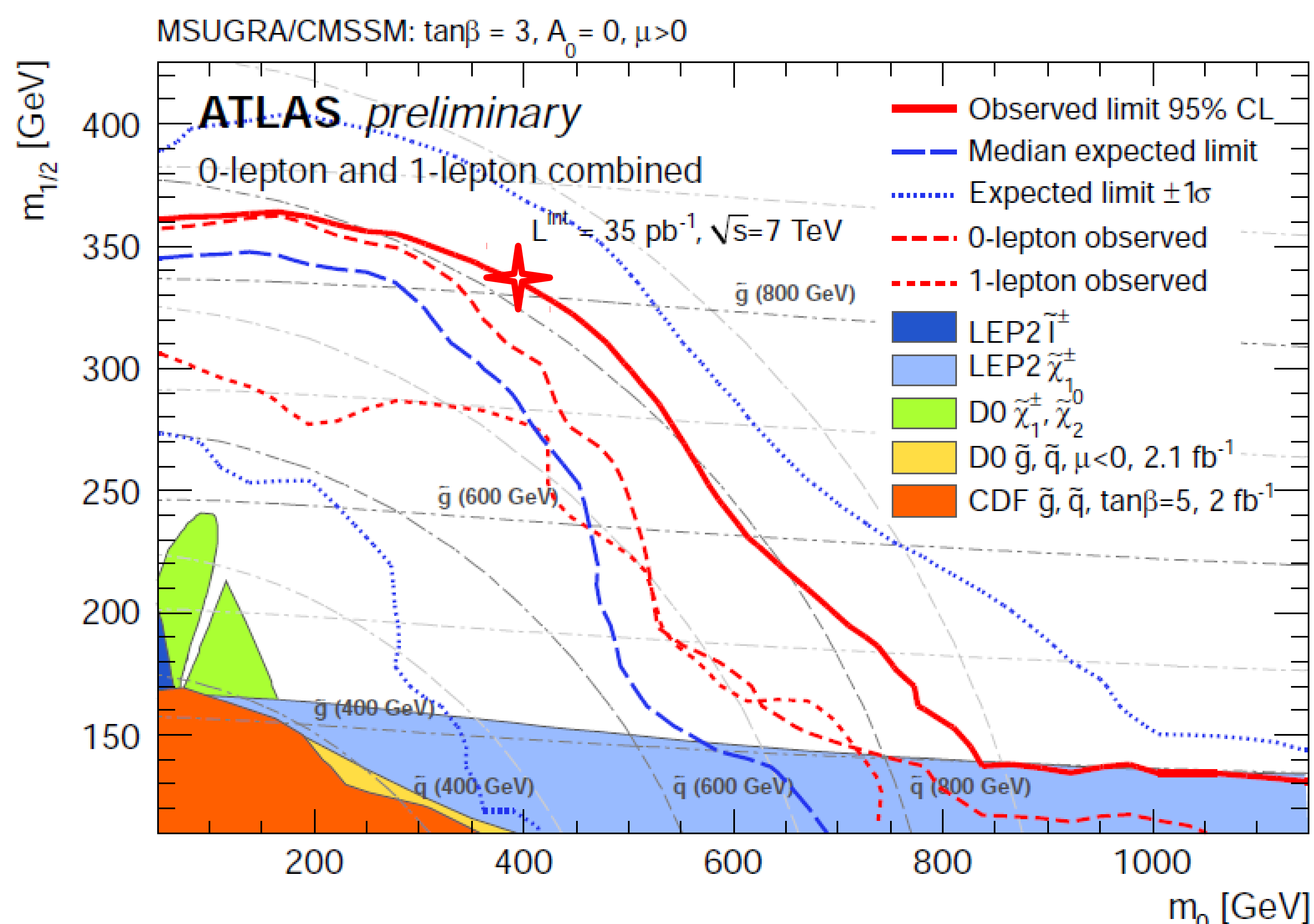



If $m_{squark}=m_{gluino}$ exclude < 700 GeV

parameters at GUT scale

1. Unified gaugino(scalar) mass $m_{1/2}(m_0)$
3. Ratio of $H_1$, $H_2$ vevs $\tan\beta$
4. Trilinear coupling $A_0$
5. Higgs mass term $\mathrm{sgn}(\mu)$

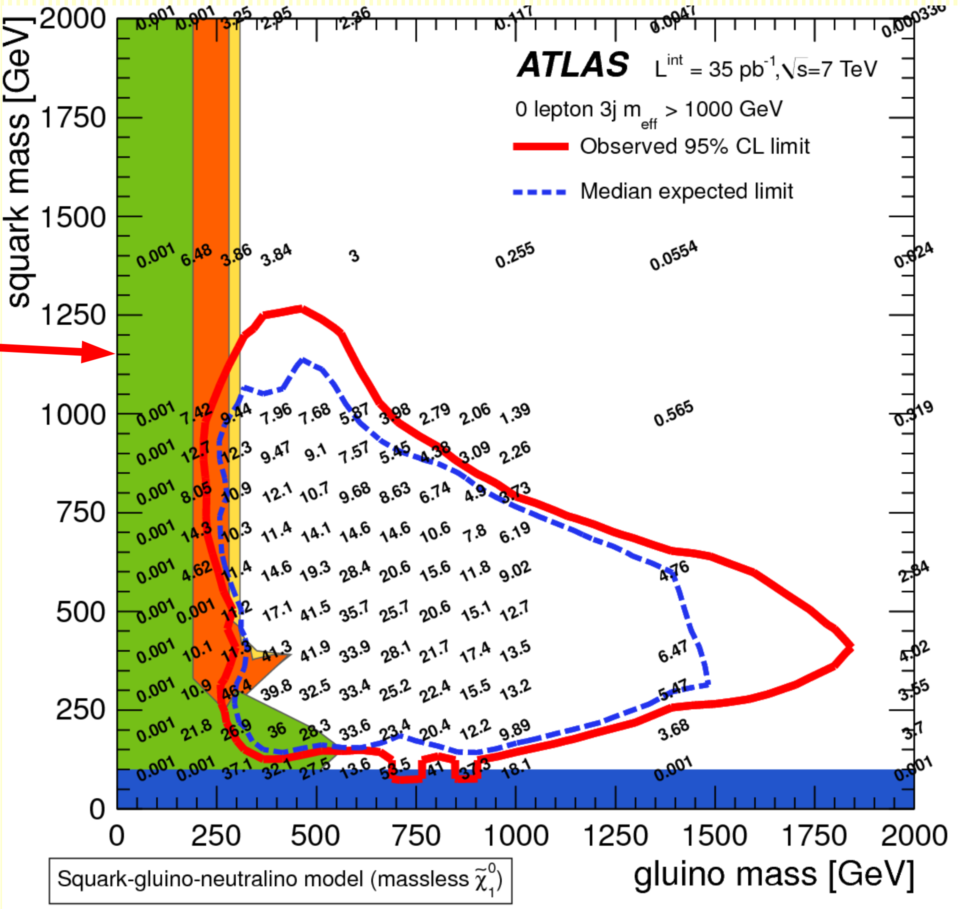
# 0- and 1-lepton combination




Exclude a mass of 815 GeV for $m_{gluino} = m_{squark}$

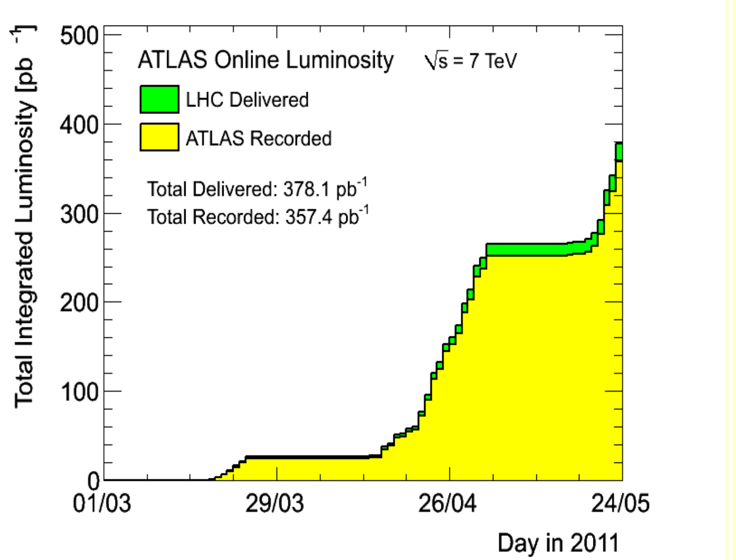
# How to use the data

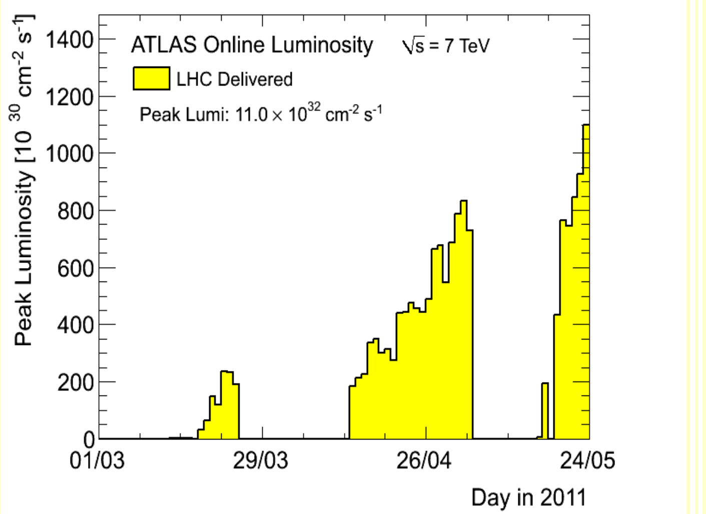
- For each signal region and analysis channel, the efficiency x acceptance is provided
- The LHA SUSY files are provided
  - → validate your setup
  - → interpret the data in your model



# Summary and outlook

- The search is on!
- ATLAS has already produced many results (in some scenarios the most stringent limits to date) in various channels and more are in the pipeline
- Already more than 350 $pb^{-1}$ recorded in 2011 with a new record luminosity of $1.1 \times 10^{33}$ $cm^{-2}s^{-1}$ !
- In 2011: more than 1 $fb^{-1}$ of data with luminosities on the order of $10^{33}$ $cm^{-2}s^{-1}$
- Sensitivity beyond 1 TeV already for 2011



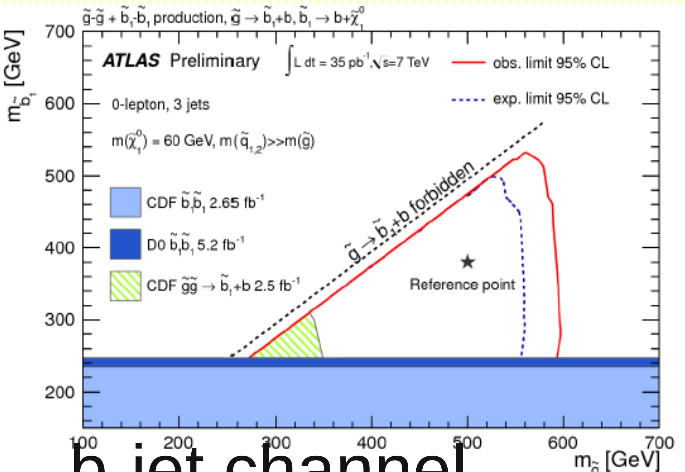




***This year is the SUSY year!***

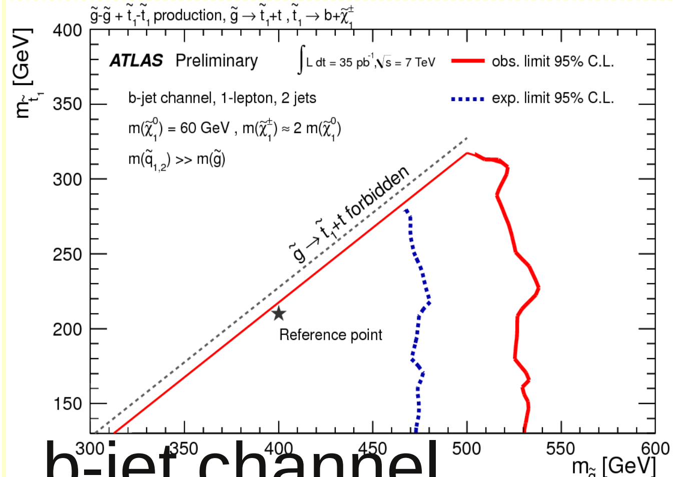
# Many more results...

*Have a look here:*

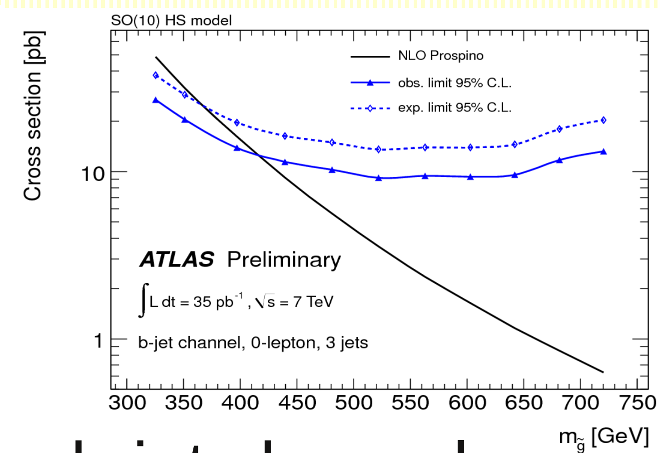
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults



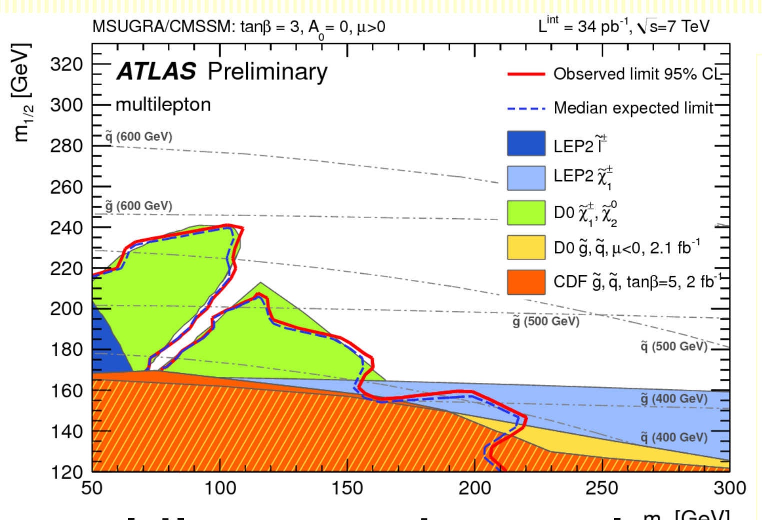

b-jet channel



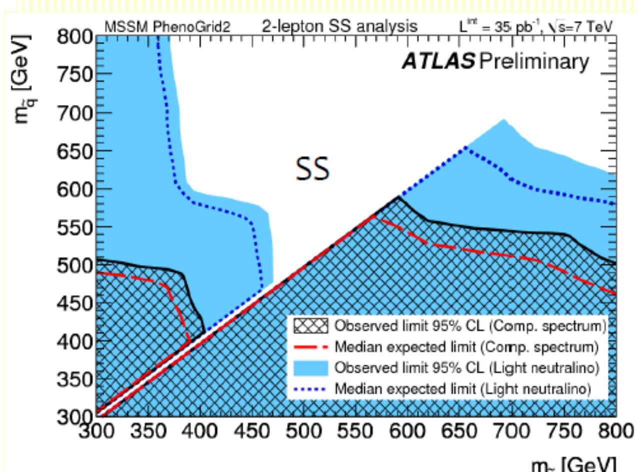

b-jet channel



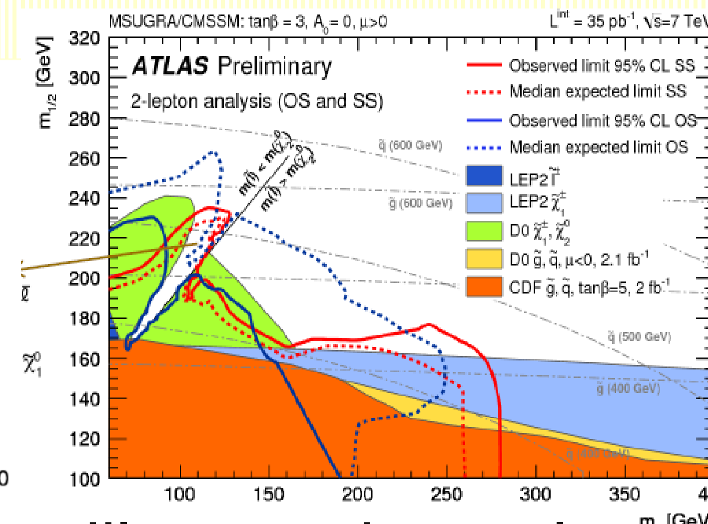

b-jet channel




multilepton channel




dilepton channel




dilepton channel

# Backup slides

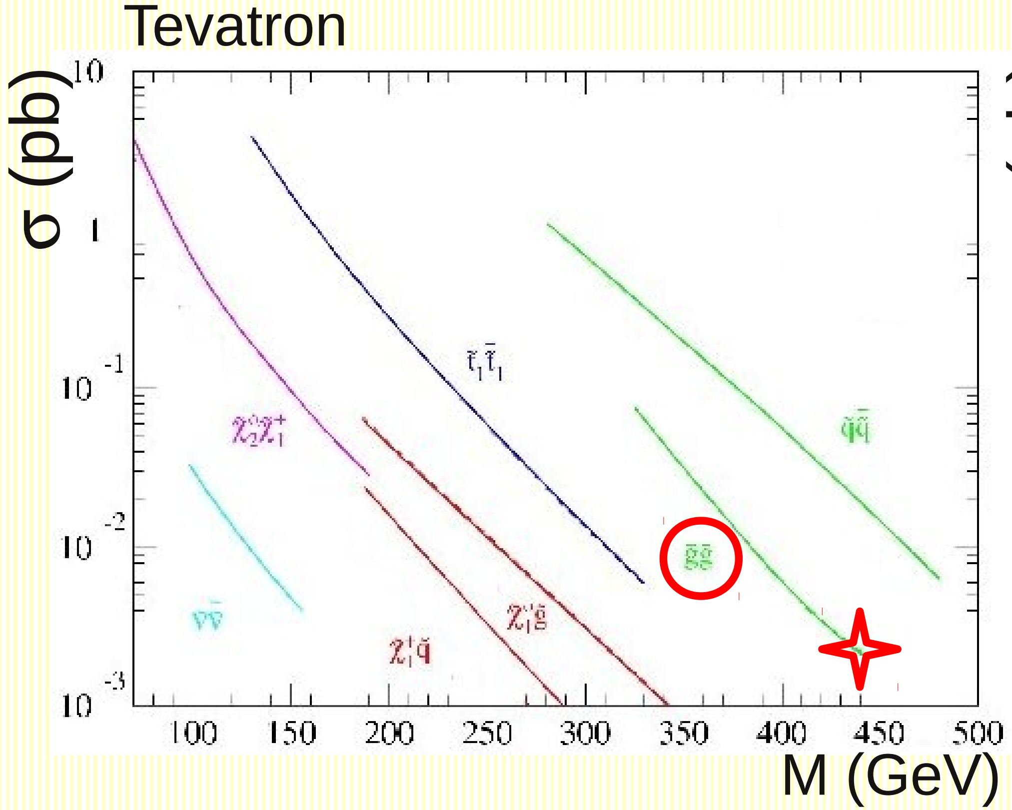
# Details of the results

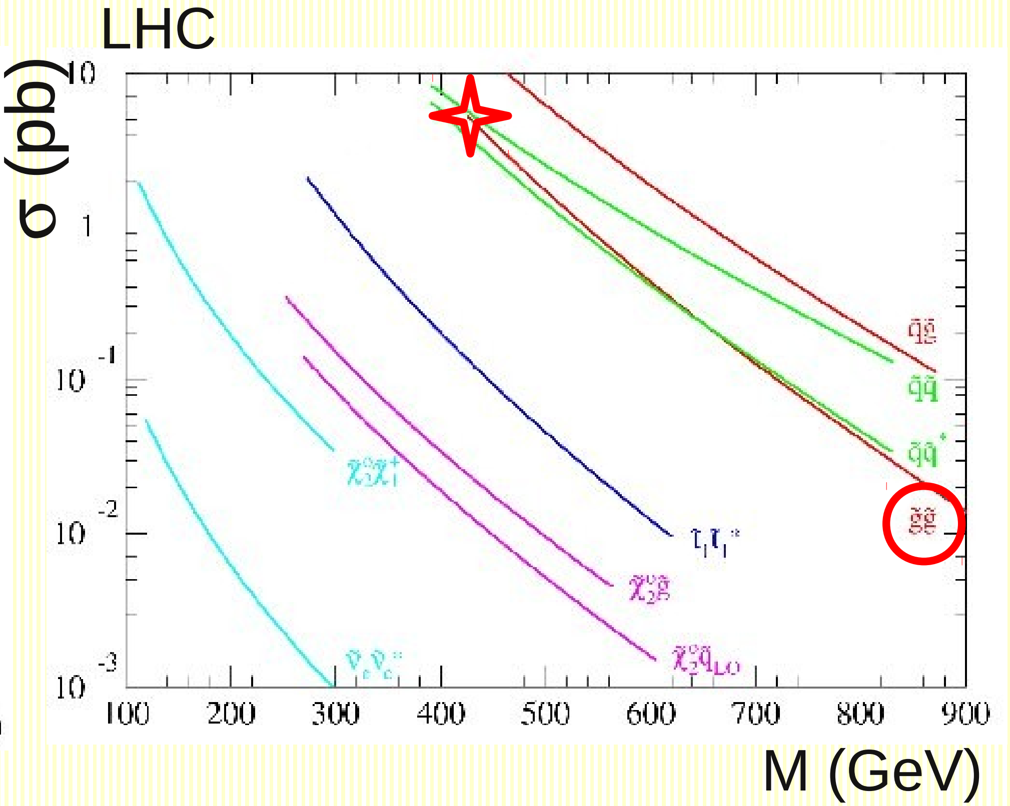
| | Signal region A | Signal region B | Signal region C | Signal region D |
|---|---|---|---|---|
| Total SM | $118 \pm 25[u]\ ^{+32}_{-23}[j] \pm 12[\mathcal{L}]$ | $10.0 \pm 4.3[u]\ ^{+4.0}_{-1.9}[j] \pm 1.0[\mathcal{L}]$ | $88 \pm 18[u]\ ^{+26}_{-18}[j] \pm 9[\mathcal{L}]$ | $2.5 \pm 1.0[u]\ ^{+1.0}_{-0.4}[j] \pm 0.2[\mathcal{L}]$ |
| Data | 87 | 11 | 66 | 2 |

| **Electron channel** | Signal region |
|---|---|
| Observed events | 1 |
| Fitted top events | $1.34 \pm 0.52$ (1.29) |
| Fitted $W/Z$ events | $0.47 \pm 0.40$ (0.46) |
| Fitted QCD events | $0.0^{+0.3}_{-0.0}$ |
| Fitted sum of background events | $1.81 \pm 0.75$ |

| **Muon channel** | Signal region |
|---|---|
| Observed events | 1 |
| Fitted top events | $1.76 \pm 0.67$ (1.39) |
| Fitted $W/Z$ events | $0.49 \pm 0.36$ (0.71) |
| Fitted QCD events | $0.0^{+0.5}_{-0.0}$ |
| Fitted sum of background events | $2.25 \pm 0.94$ |

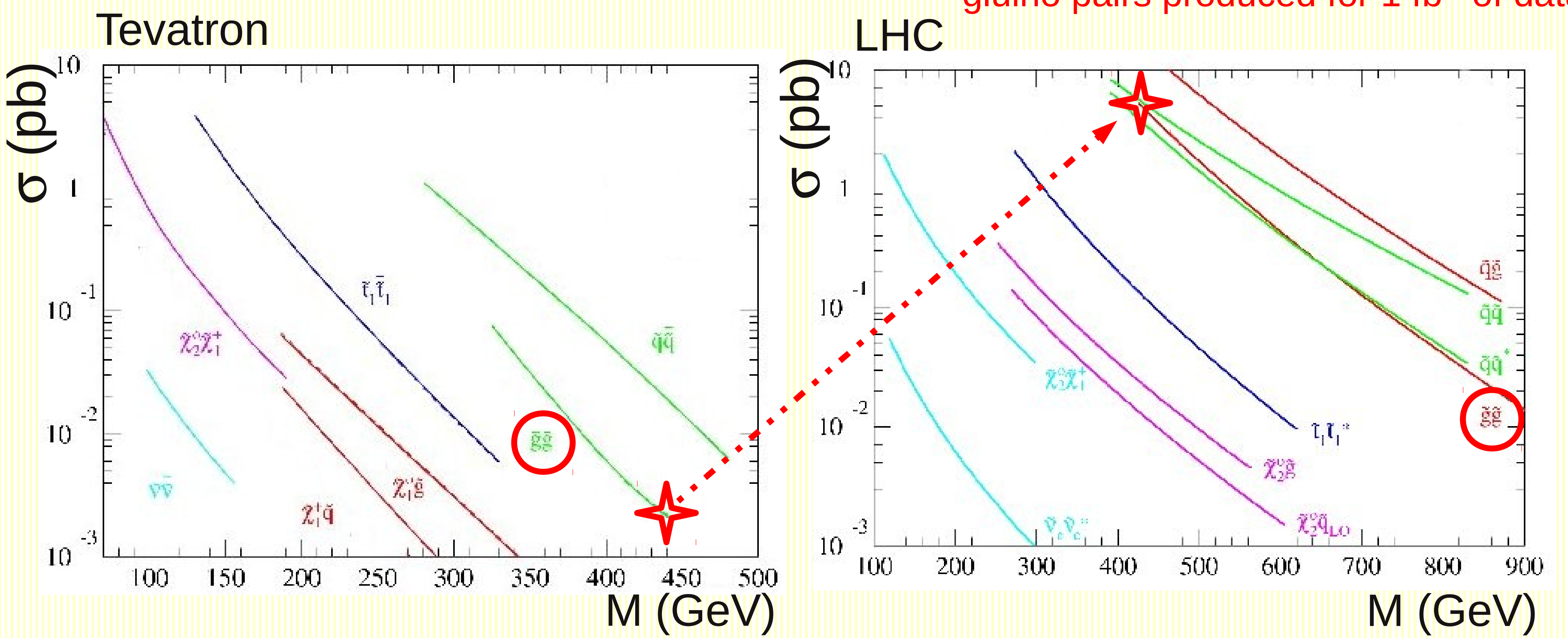
# SUSY production at LHC



# SUSY production at LHC

If m(gluino)~500 GeV, expect ~2000 gluino pairs produced for 1 $fb^{-1}$ of data




**The cross sections for SUSY processes are way higher at LHC**
**High-impact results possible with first data!**

# Object identification

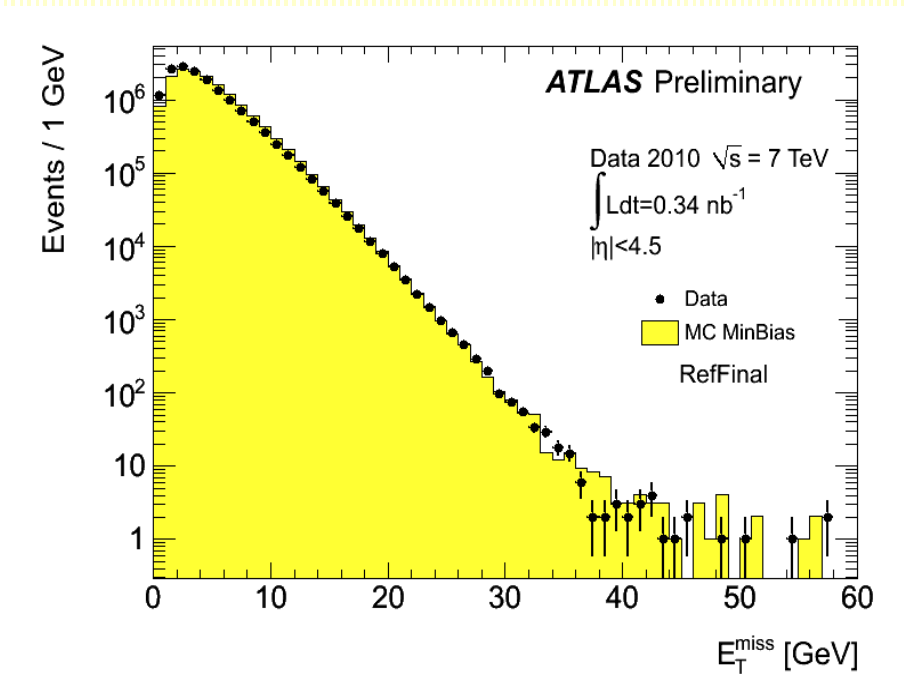
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

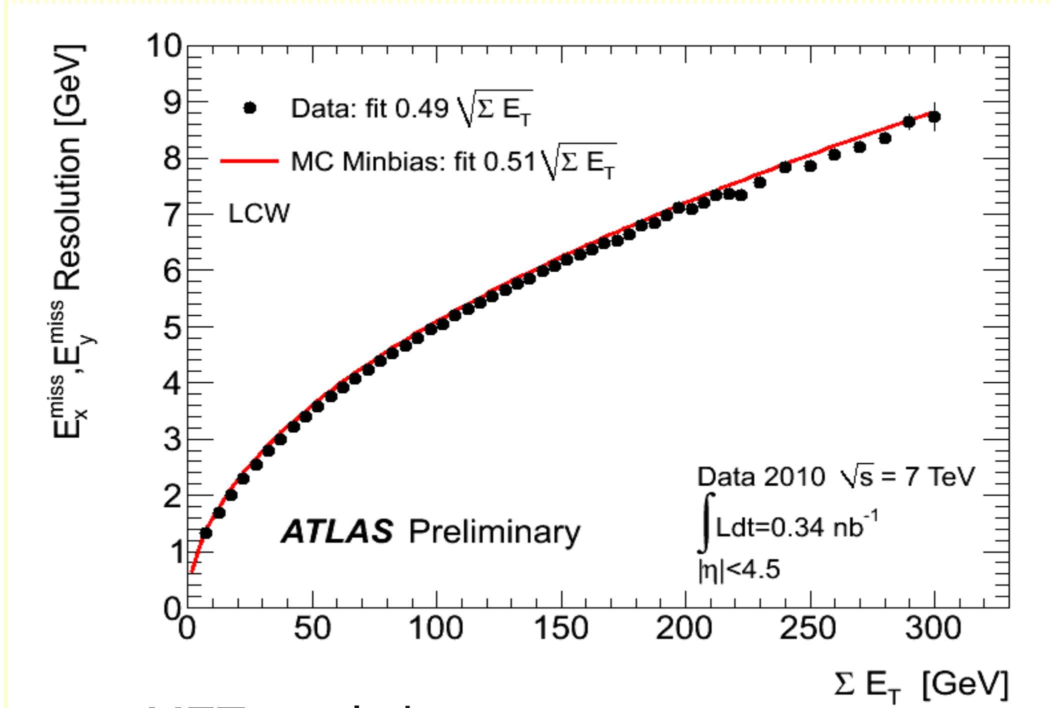
$\phi$: azimuthal angle around the beam pipe

$\eta$= -ln tan($\theta$/2) where $\theta$ is the polar angle

- Jets (anti-Kt, R=0.4): $p_T$>20 GeV, $|\eta|$<2.5
  - Reject events compatible with noise or cosmics
  - Remove if $\Delta R$(jet,electron)<0.2
- Electrons: $p_T$>20 GeV, $|\eta|$<2.47
  - Outside problematic regions of the calorimeter
  - Remove if $\Delta R$(jet,electron)<0.4
- Muons: $p_T$>20 GeV, $|\eta|$<2.4, Sum $p_T$ of tracks ($\Delta R$<0.2) < 1.8 GeV
  - Remove if $\Delta R$(jet,muon)<0.4
- Missing transverse momentum ($E_T^{miss}$):
  - sum over the transverse momentum of all jets (up to $|\eta|$<4.9), electrons, muons and all calorimeter clusters not associated to such objects

# $E_T^{miss}$ performance




MET resolution

# QCD background: 1-lepton channel

*Evaluated using the 'matrix method' which plays on the difference in isolation between the leptons in QCD events with respect to signal leptons*

- ***Loose*** control sample with isolation criteria relaxed with respect to the ***tight*** SUSY selections
- Define two categories: QCD leptons (***Q***) and non-QCD leptons (***$\not{Q}$***)
– ε is the probability that a loose lepton is also tight

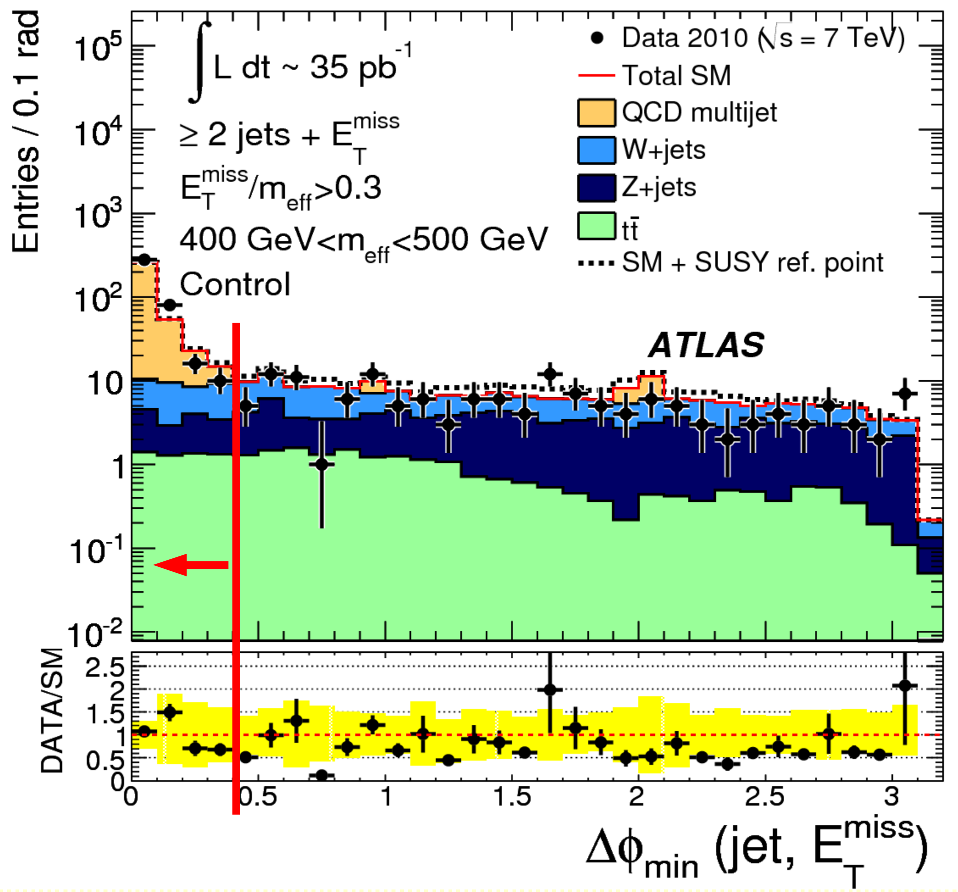
$$N^{obs}_{tight} = N^{\not{Q}}_{tight} + N^{Q}_{tight}$$

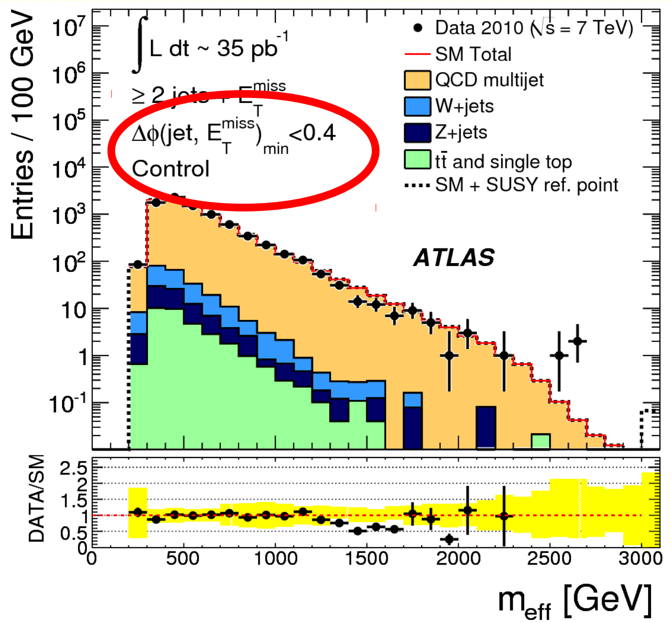
$$N^{obs}_{loose\ not\ tight} = (1/\epsilon_{\not{Q}} - 1)\, N^{\not{Q}}_{tight} + (1/\epsilon_{Q} - 1)\, N^{Q}_{tight}$$

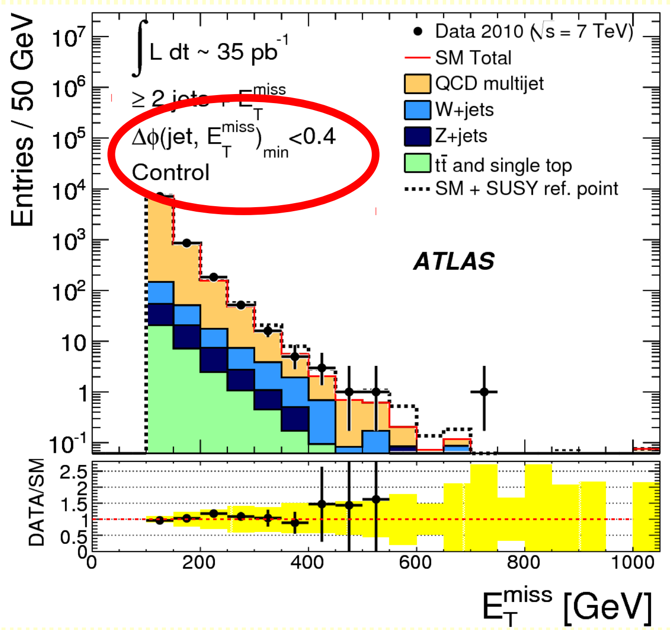
The quantities in red are measured: solve the equations and extract the number of QCD events

| electron channel | muon channel |
|---|---|
| $N^{Q}_{tight} < 0.3$ | $N^{Q}_{tight} < 0.5$ |

# QCD background: 0-lepton channel




Partially data-driven estimate:

rescale the MC in the control region defined by reversing the $\Delta\phi$ cut

<10% of the total BG

(cross checked with two other methods)

# Systematic uncertainties in the 1-lepton channel

- Background:
  - MC modeling of the $E_t^{miss}$ and $m_T$ distributions (variation of MC generator and internal generator parameters)
  - Finite statistics in the control regions
  - Experimental uncertainties dominated by the jet energy scale, b-tagging and luminosity uncertainties
- Signal:
  - Variation of the factorization and renormalization scales in Prospino
  - PDF uncertainties (eigenvector sets provided by CTEQ6)
  - Calculated separately for each production process

# Limit setting

$$\begin{aligned} L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu, \boldsymbol{b}, \boldsymbol{\theta}) &= P_{\mathrm{SR}} \times P_{\mathrm{CR}} \times P_{\mathrm{Syst}} \\ &= P(n_S | \lambda_S(\mu, \boldsymbol{b}, \boldsymbol{\theta})) \times \prod_{i \in \mathrm{CS}} P(n_i | \lambda_i(\mu, \boldsymbol{b}, \boldsymbol{\theta})) \times P_{\mathrm{Syst}}(\boldsymbol{\theta}^0, \boldsymbol{\theta}) \end{aligned}$$

The statistical treatment is based on the profile LLR, defined in the usual way as

$$\Lambda(\mu) \equiv \Lambda(\mu, \boldsymbol{n}, \boldsymbol{\theta}^0) \equiv -2\left(\ln L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \mu, \hat{\hat{\boldsymbol{b}}}, \hat{\hat{\boldsymbol{\theta}}}) - \ln L(\boldsymbol{n}, \boldsymbol{\theta}^0 | \hat{\mu}, \hat{\boldsymbol{b}}, \hat{\boldsymbol{\theta}})\right)$$

where $\hat{\boldsymbol{\mu}}, \hat{\boldsymbol{b}}, \hat{\boldsymbol{\theta}}$ maximize the likelihood function, and $\hat{\hat{\boldsymbol{b}}}, \hat{\hat{\boldsymbol{\theta}}}$ maximize the likelihood for the specific, fixed value of the signal strength $\mu$, and the data $\boldsymbol{n}, \boldsymbol{\theta}^0$.

- The 1-sigma exclusion band has the same meaning as in a typical Higgs analysis, which show the upper limit on the x-section (but here the x-section is mapped on the m0,m12 plane): any observation of number of events in the signal region that agrees with the bkg only prediction within 68% CL, gives an observed exclusion limit that lies within the 1-sigma uncertainty band.

- It can also be seen to correspond roughly to the 68% and 99% CL exclusion lines. The limit and bands have been obtained directly with toy MC. The coverage is therefore guaranteed to be exact.