# Doing LHC analyses without knowing everything

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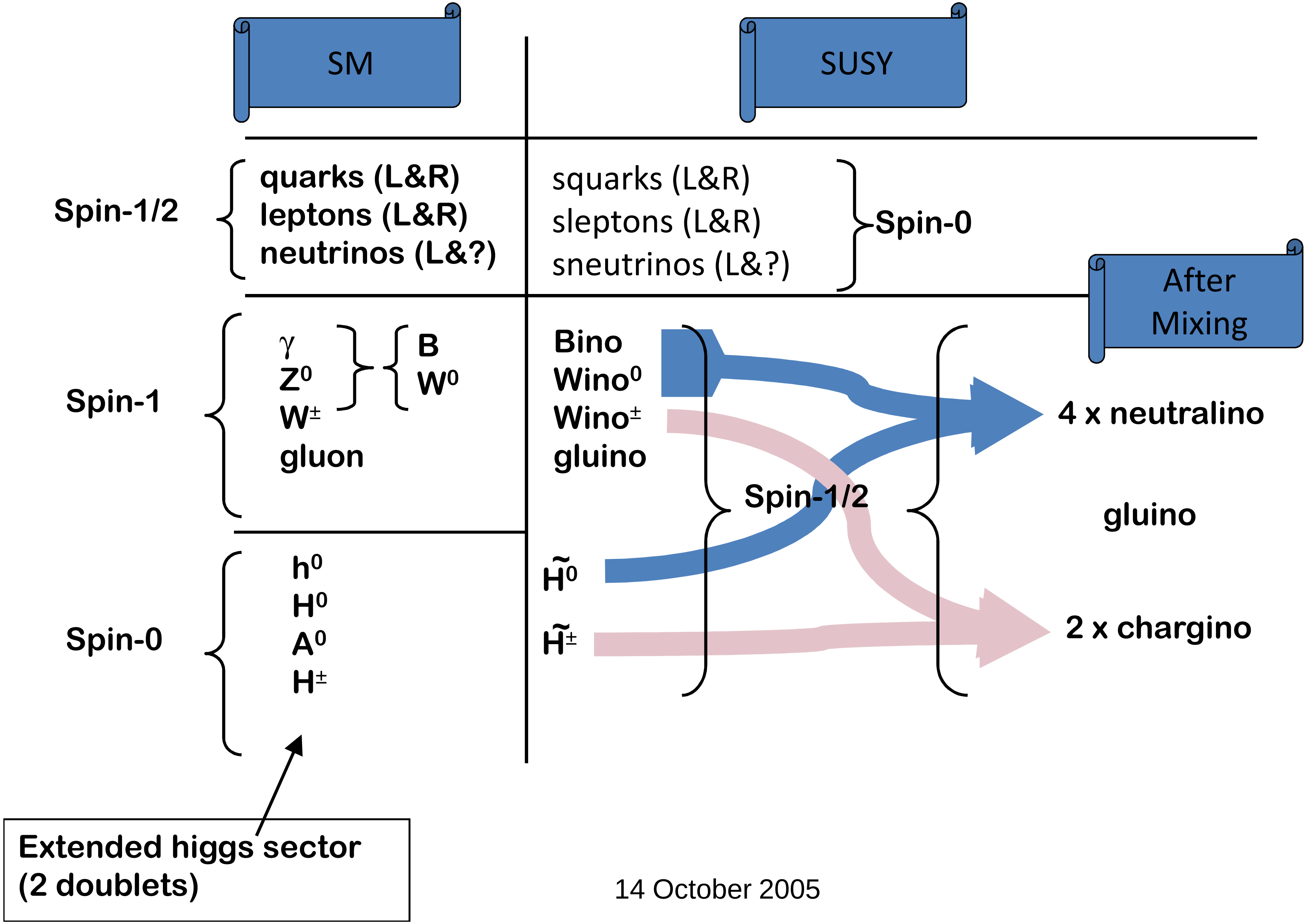
University of Oxford

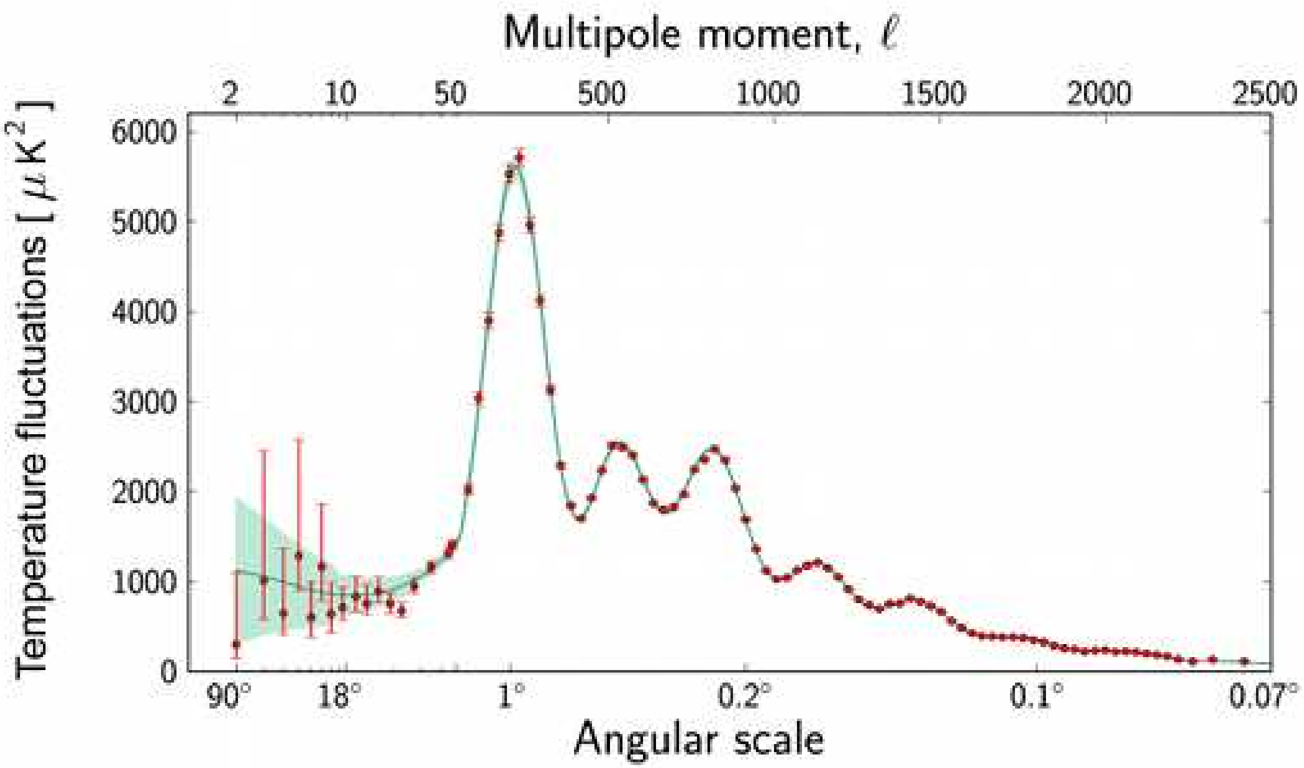
# Not knowing everything

- **Absolute** ignorance
  - Limits & bounds
- **Relative** ignorance
  - Significance-like variables
- Working out what you do know
  - Analysis design matters

# (S)particles


SM
SUSY
Spin-1/2
quarks (L&R)
leptons (L&R)
neutrinos (L&?)
squarks (L&R)
sleptons (L&R)
sneutrinos (L&?)
Spin-0
After Mixing
Spin-1
γ
Z0
W±
gluon
B
W0
Bino
Wino0
Wino±
gluino
Spin-1/2
4 x neutralino
gluino
2 x chargino
Spin-0
h0
H0
A0
H±
H̃0
H̃±
Extended higgs sector
(2 doublets)

# Motivational arguments…

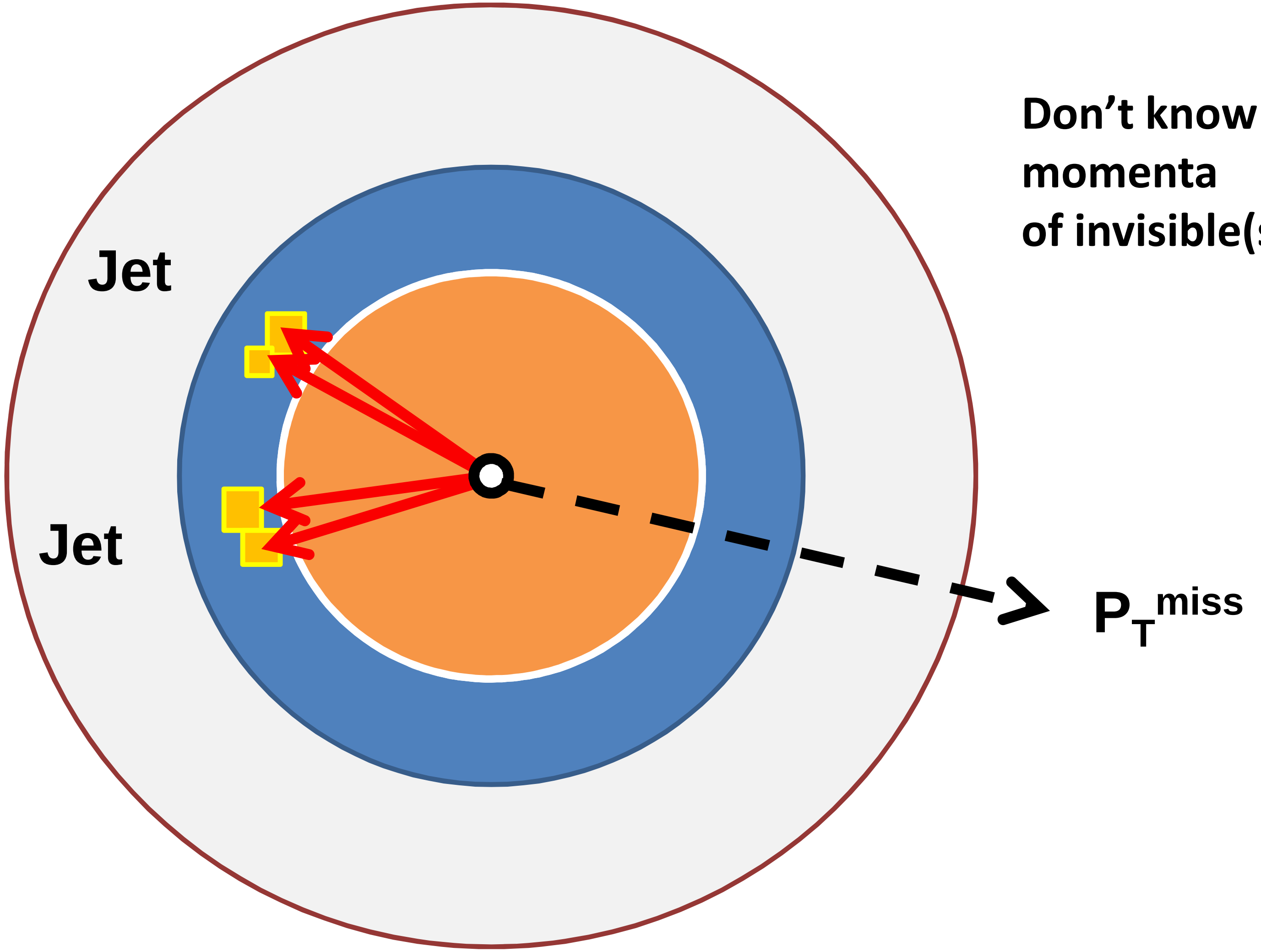



**We should look for WIMPs at the LHC**



http://www.sciops.esa.int/index.php?project=PLANCK&page=Planck_Published_Papers

# The basic example




**Don’t know momenta of invisible(s)**

# *Missing transverse momentum*

- Know that momentum ⊥ beam was zero in initial state
- Can measure momentum ⊥ beam in final state for visible particles

$$\not{\vec{p}}_T$$

- Construct Sum of $P_T$ of invisibles
  - Construct from negative sum $P_T$ of visibles

$$\sum_{i=1}^{N_{\mathcal{I}}} \vec{q}_{iT} = \not{\vec{p}}_T \qquad\qquad \not{\vec{p}}_T \equiv - \sum \vec{p}_{iT}$$

**\begin{digression}**

# Missing $E_T$ / MET – ARRGH!

- These are **not well defined quantities**
- What is a "transverse energy?"
- Under transverse projection:
  - $P_x$ and $P_y$ components should stay the same
  - $P_z$ component should be set to zero
  - **What happens to energy component?**
  - Three different procedures (at least…)

| Quantity | Transverse projection method | | |
|---|---|---|---|
| | Mass-preserving '$\top$' | Speed-preserving '$\vee$' | Massless '$\circ$' |
| Original (4)-momentum | $P^\mu = (E, \vec{p}_T, p_z)$ | | |
| (1+3)-mass invariant | $M = \sqrt{E^2 - \vec{p}_T^2 - p_z^2}$ | | |
| Transverse momentum | $\vec{p}_T \equiv (p_x, p_y)$ | | |
| (1+2)-vectors | $p_\top^\alpha \equiv (e_\top, \vec{p}_\top)$ | $p_\vee^\alpha \equiv (e_\vee, \vec{p}_\vee)$ | $p_\circ^\alpha \equiv (e_\circ, \vec{p}_\circ)$ |
| Transverse momentum under the projection | $\vec{p}_\top \equiv \vec{p}_T$ | $\vec{p}_\vee \equiv \vec{p}_T$ | $\vec{p}_\circ \equiv \vec{p}_T$ |
| Transverse energy under the projection | $e_\top \equiv \sqrt{M^2 + \vec{p}_T^2}$ | $e_\vee \equiv E\,\lvert\sin\theta\rvert = \lvert\vec{p}_T\rvert / V$ | $e_\circ \equiv \lvert\vec{p}_T\rvert$ |
| Transverse mass under the projection | $m_\top^2 = e_\top^2 - \vec{p}_\top^2$ | $m_\vee^2 \equiv e_\vee^2 - \vec{p}_\vee^2$ | $m_\circ^2 \equiv e_\circ^2 - \vec{p}_\circ^2 = 0$ |
| Relationship between transverse quantity and its (1+3) analogue | $m_\top = M$ | $m_\vee = M\,\lvert\sin\theta\rvert$ | $m_\circ = 0$ |
| | $\frac{1}{v_\top} = \frac{1}{V}\sqrt{1 + (1 - V^2)\frac{p_z^2}{p_T^2}}$ | $v_\vee = V$ | $v_\circ = 1$ |
| Equivalence classes under $(1+3) \xrightarrow{\text{proj}} (1+2)$ | All $P^\mu$ with the same $p_x$, $p_y$ and $M$ | All $P^\mu$ with the same $p_x$, $p_y$ and $V$ | All $P^\mu$ with the same $p_x$ and $p_y$ |

# \end{digression}

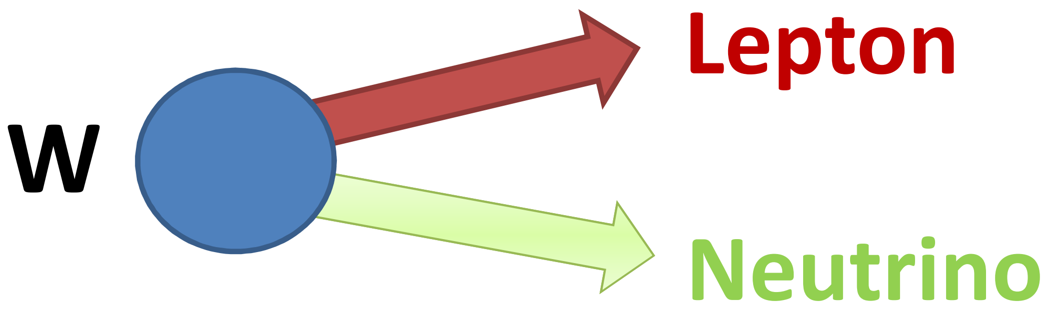
Answer 1

# DESIGNING AN ANALYSIS TO BE INSENSITIVE TO THE UNKNOWNS

A useful guiding principle:

In the absence of complete information we should place the best possible **bound** on any Lorentz invariants of interest

# A familiar example




**Transverse mass:**

$$m_T^2 \equiv m_v^2 + m_i^2 + 2(e_v e_i - \mathbf{p}_v \cdot \mathbf{p}_i)$$

$$e = \sqrt{\mathbf{p} \cdot \mathbf{p} + m^2}$$

# Mathematical meaning?

$m_T$ is the **greatest lower bound** on the mass of the parent (W) given the unknowns and the constraints

For each signal event $m_W > m_T$

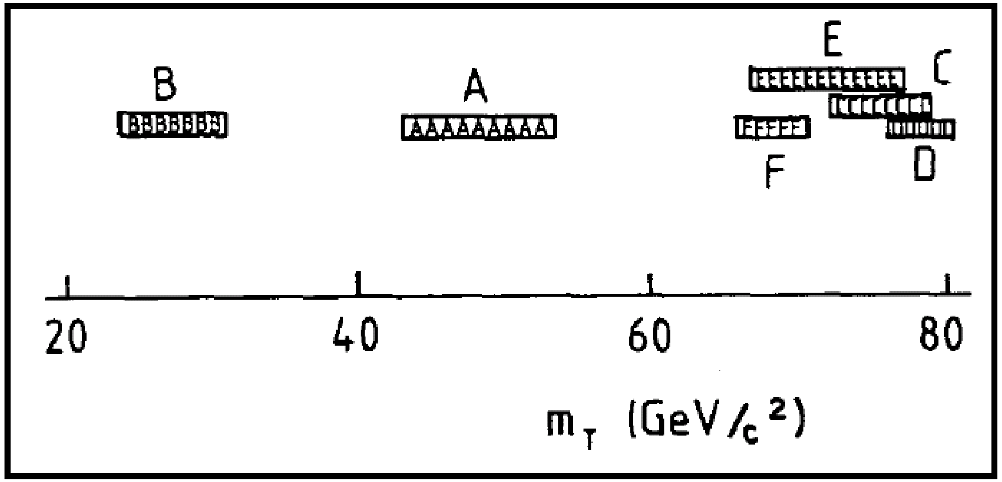
# The use of $m_T$ in discovery physics

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/83-25
February 15th 1983

OBSERVATION OF SINGLE ISOLATED ELECTRONS
OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH
MISSING TRANSVERSE ENERGY AT THE CERN
$\bar{p}p$ COLLIDER

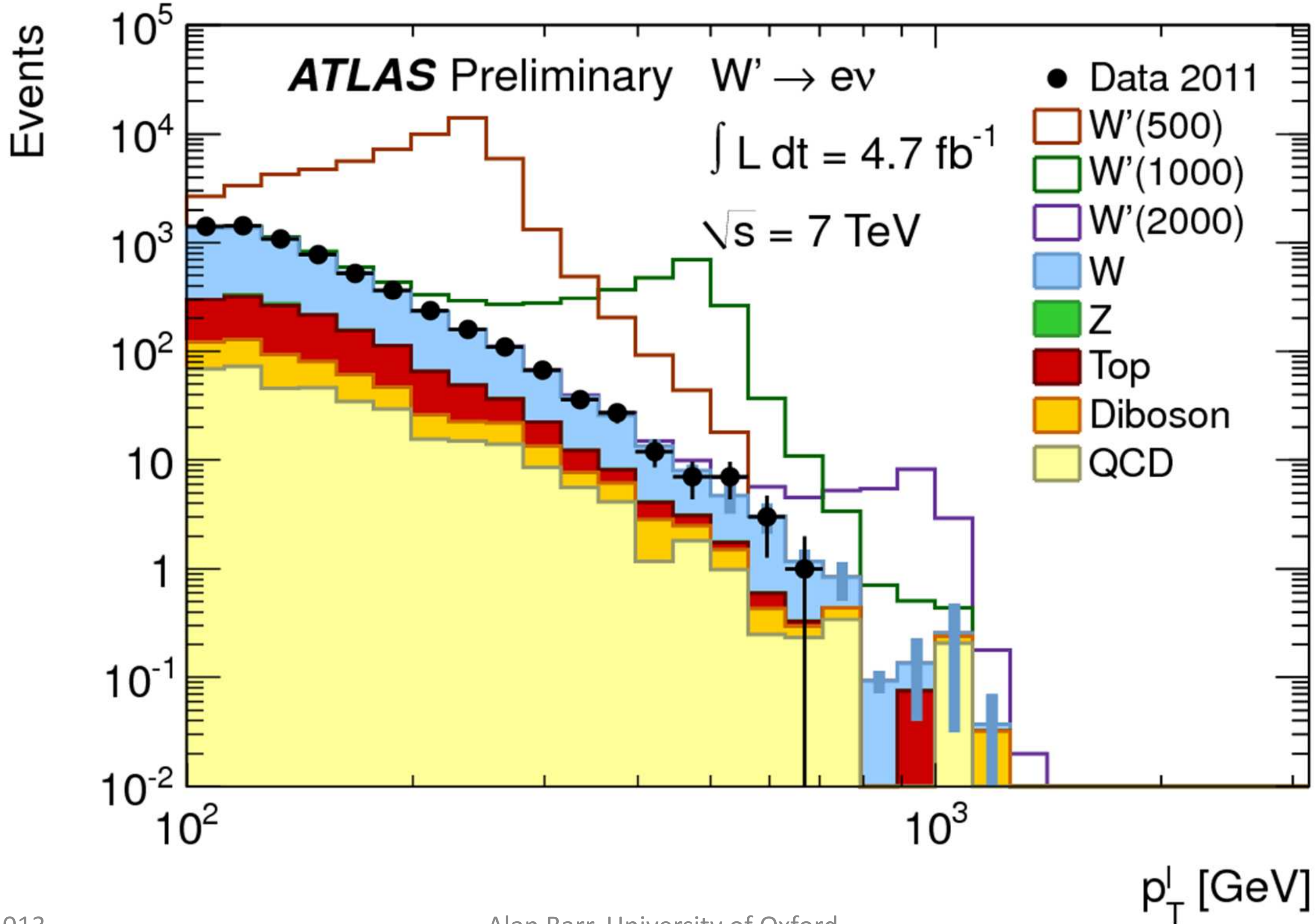
The UA2 Collaboration.



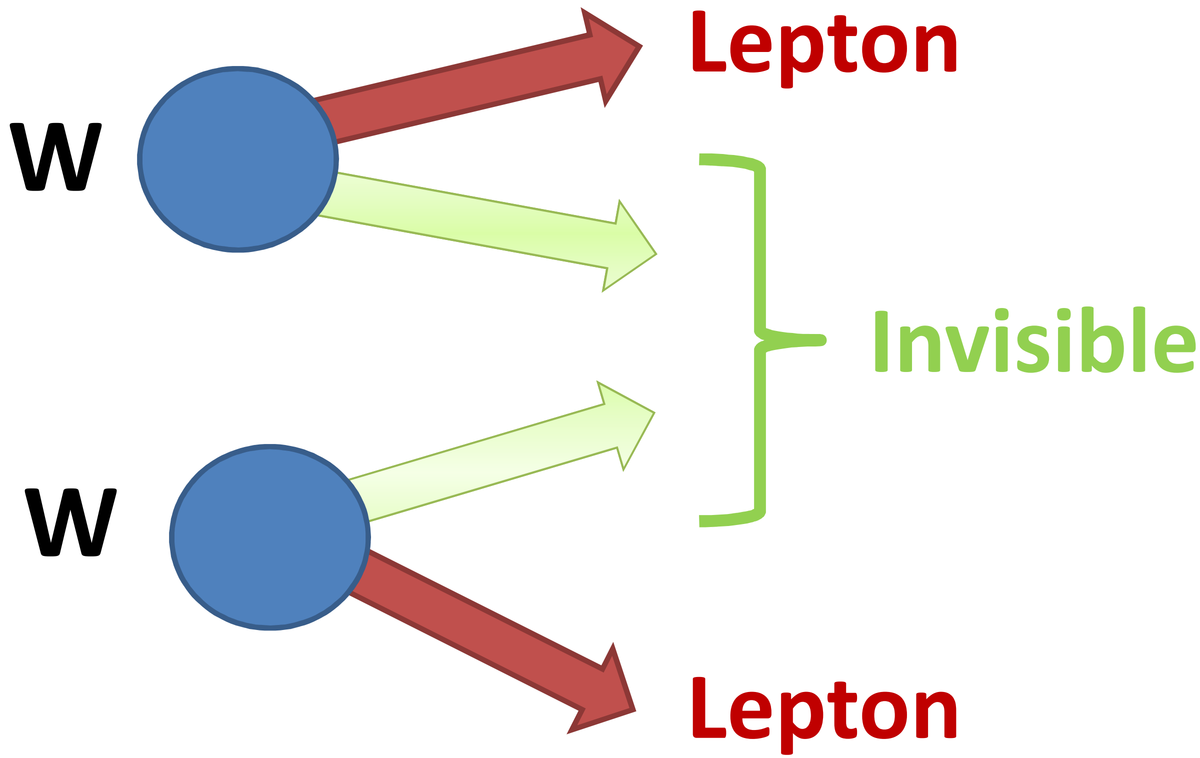

For B → lυ : $m_T < m_B$
For W → lυ : $m_T < m_W$

Range $m_B < m_T < m_W$
is signal dominated

# Similar search for new W’ at ATLAS



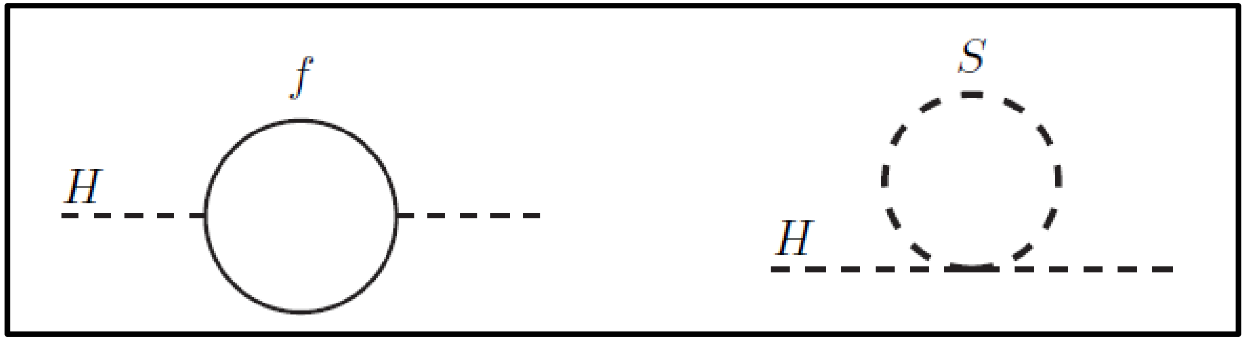
# Identical pair decays:




$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_T + \mathbf{r}_T = \mathbf{p}_T^{miss}} \left\{ \max[\, m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T) \,] \right\}$$

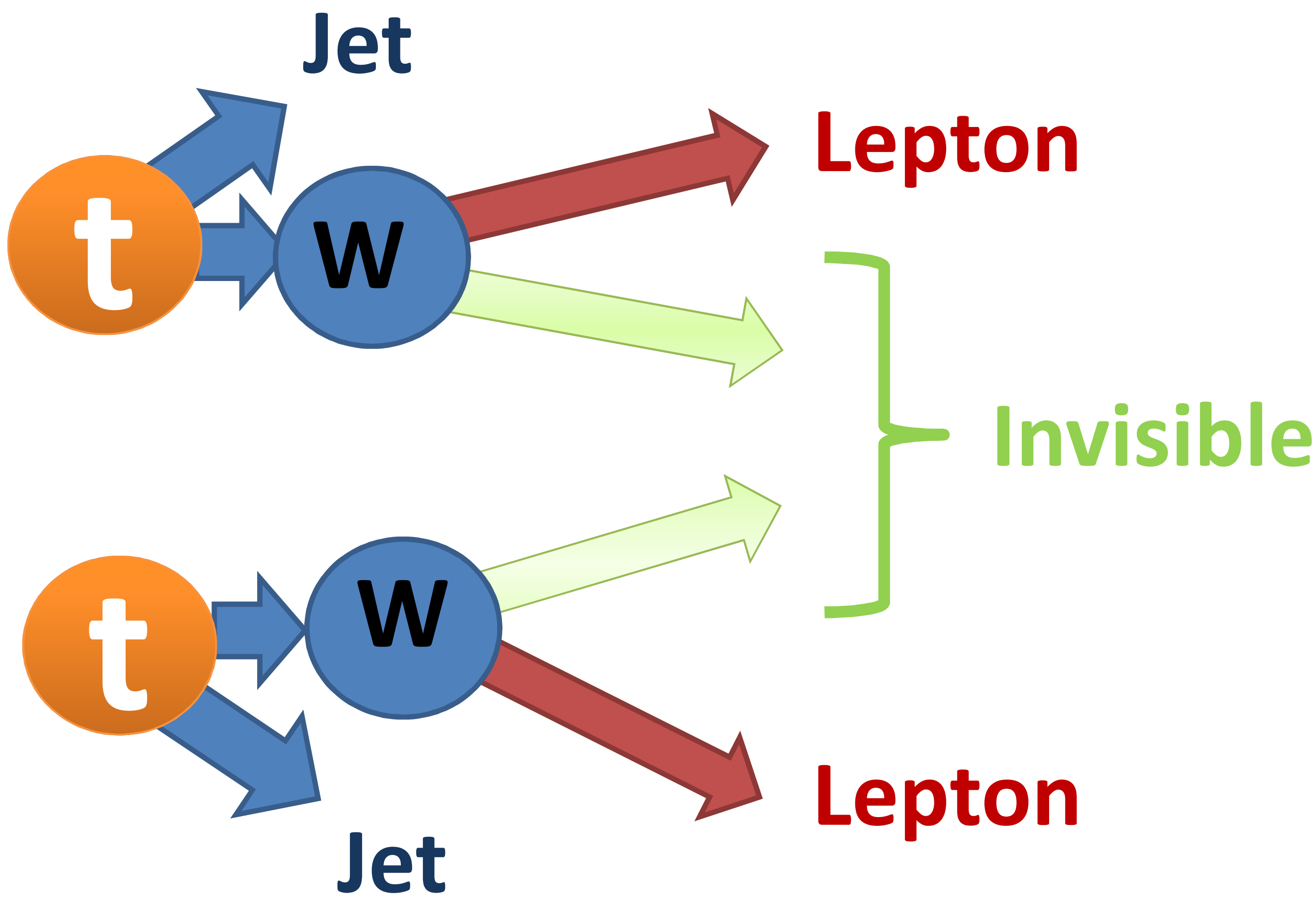
# Example: the **stop squark** search

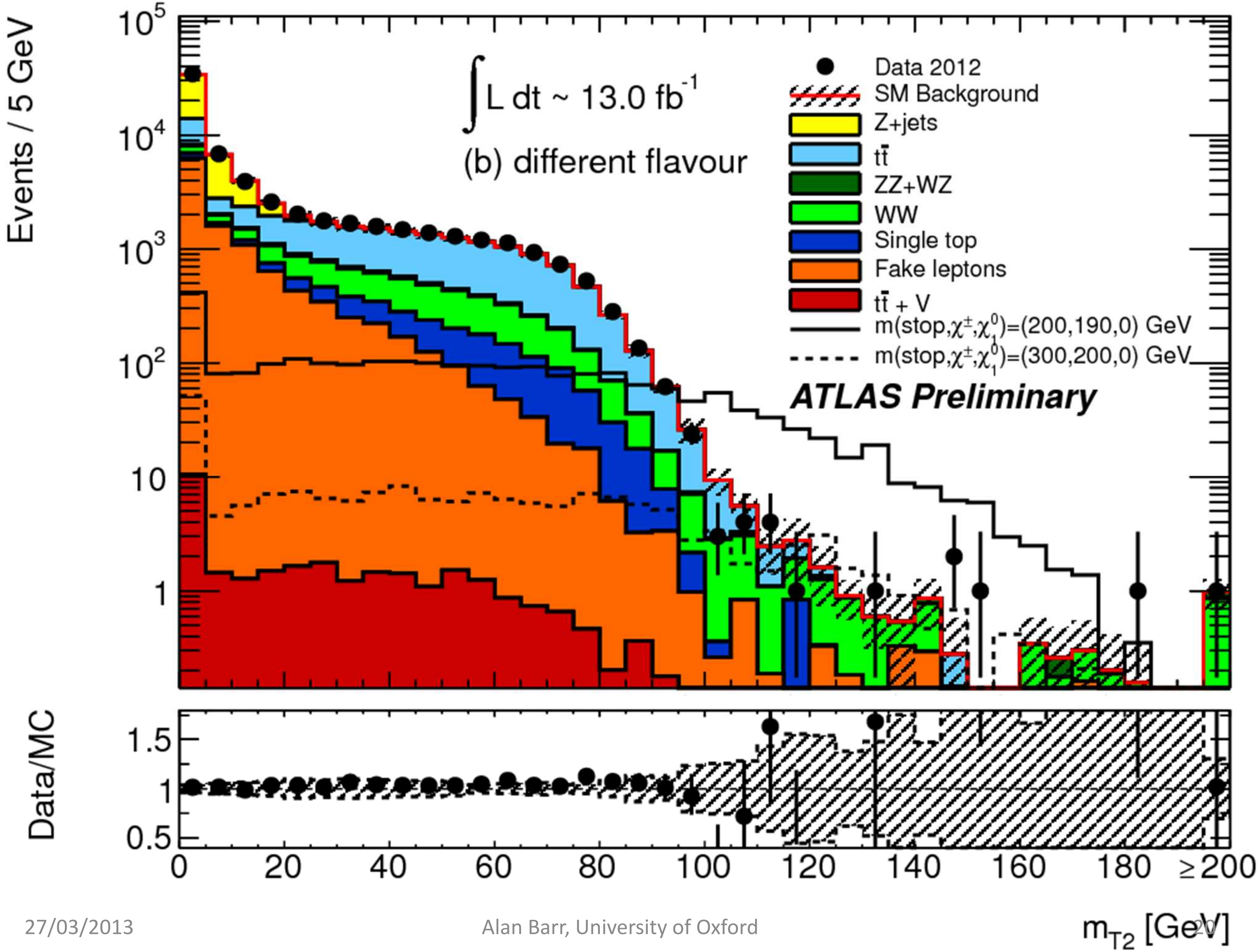
- Stop should be light if SUPERSYMMETRY is NATURAL




- Major background is **top quark** pair production

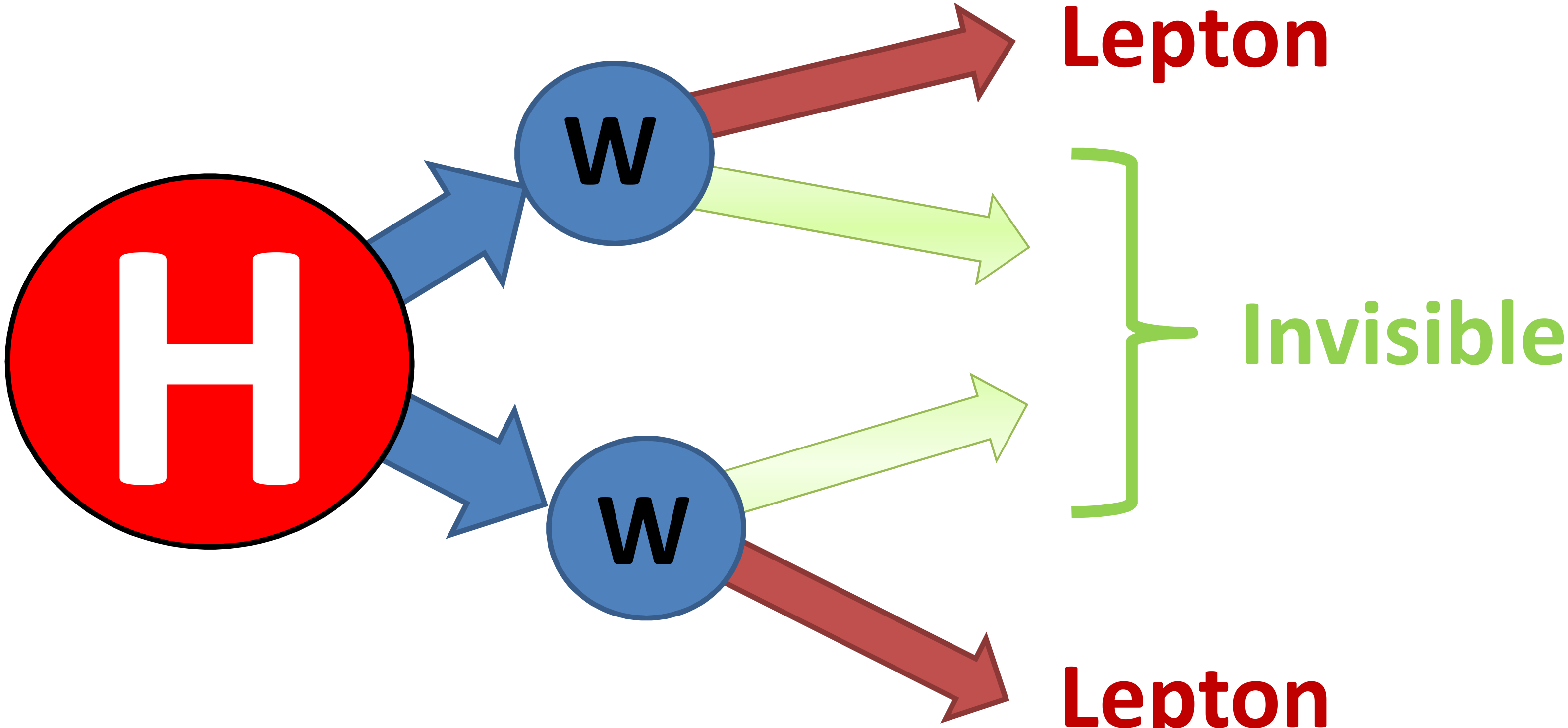
# The top quark background



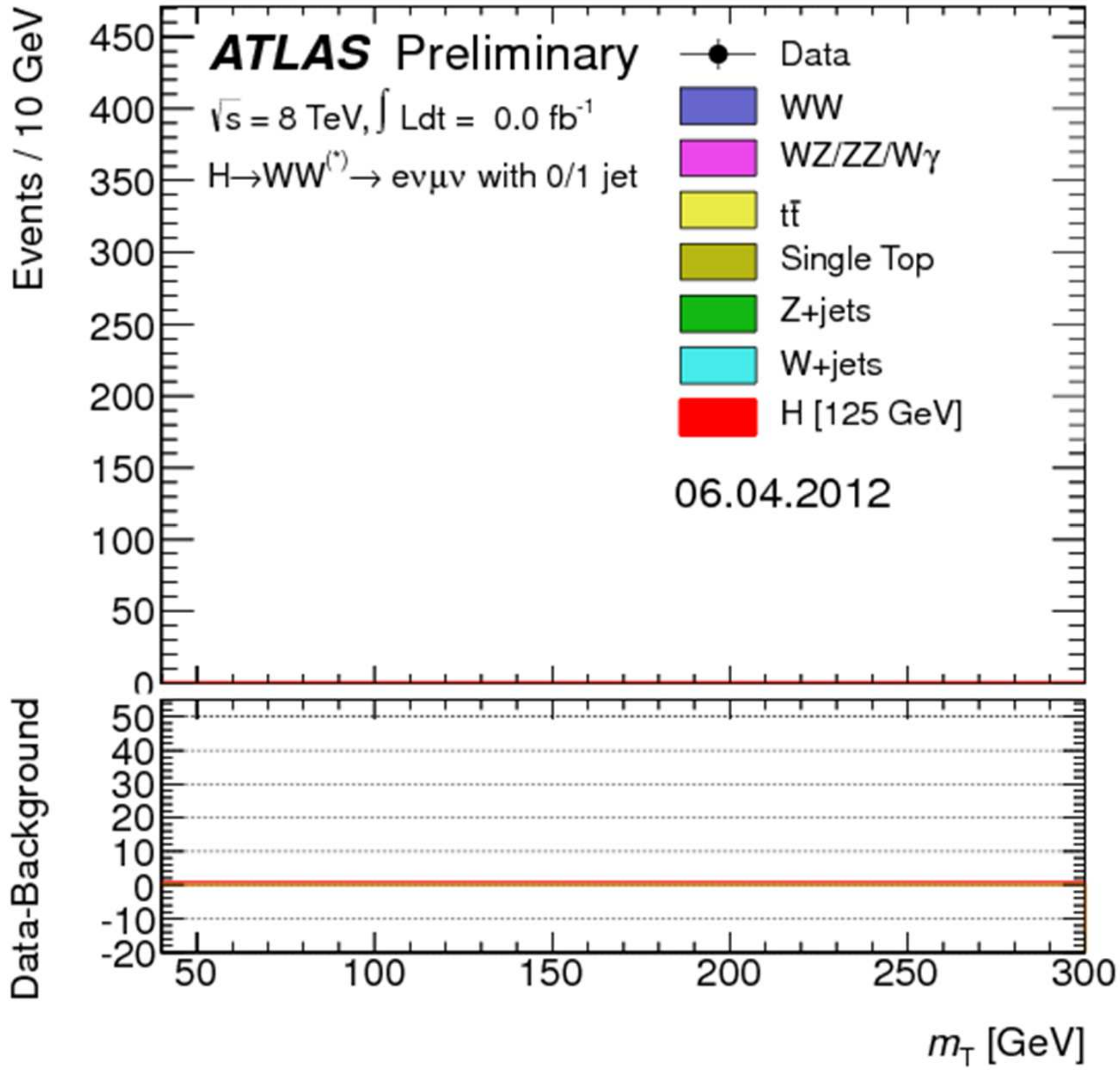


Events / 5 GeV
$\int L\,dt \sim 13.0\ fb^{-1}$
(b) different flavour
Data 2012
SM Background
Z+jets
$t\bar{t}$
ZZ+WZ
WW
Single top
Fake leptons
$t\bar{t}$ + V
m(stop,$\chi^\pm$,$\chi_1^0$)=(200,190,0) GeV
m(stop,$\chi^\pm$,$\chi_1^0$)=(300,200,0) GeV
ATLAS Preliminary
Data/MC
$m_{T2}$ [GeV]

# Higgs → WW* → (l υ) (l υ)

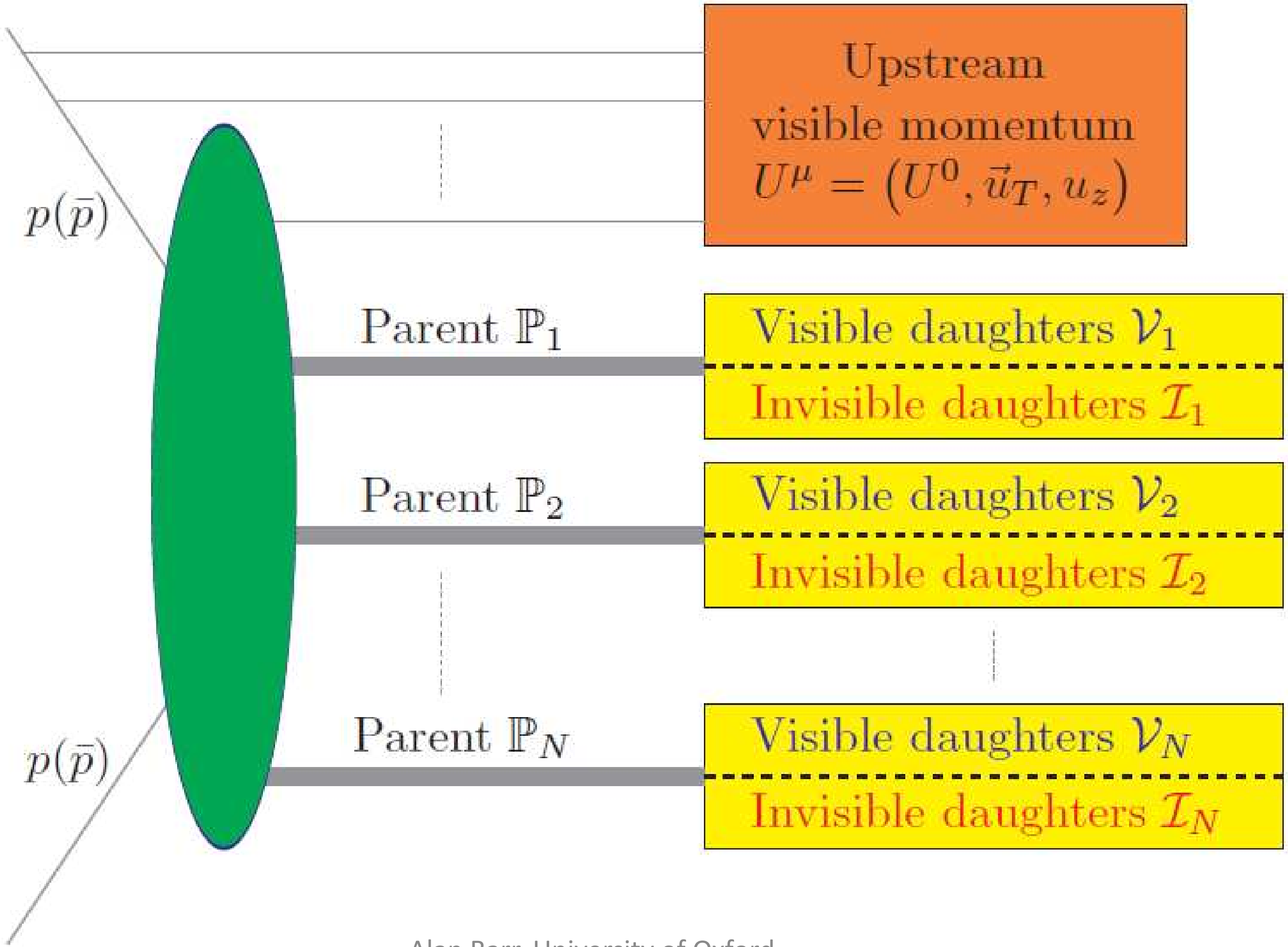



**An example from the Higgs world**




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

# A rather general situation



# Constructing a bound

Know the momenta **P** for visible particles
Choose some momenta **Q** for the invisible particles

$$\mathcal{M}_a \equiv \sqrt{g_{\mu\nu}\,(\mathbf{P}_a^\mu + \mathbf{Q}_a^\mu)(\mathbf{P}_a^\nu + \mathbf{Q}_a^\nu)}$$

Each $M_a$ can provide a lower bound for the selected **Q**

Constructing the bound achieved by minimising over our ignorance

$$M_N \equiv \min_{\sum \vec{q}_{iT} = \vec{p}\!\!/_T} \left[ \max_a \left[ \mathcal{M}_a \right] \right]$$

# A table of examples…

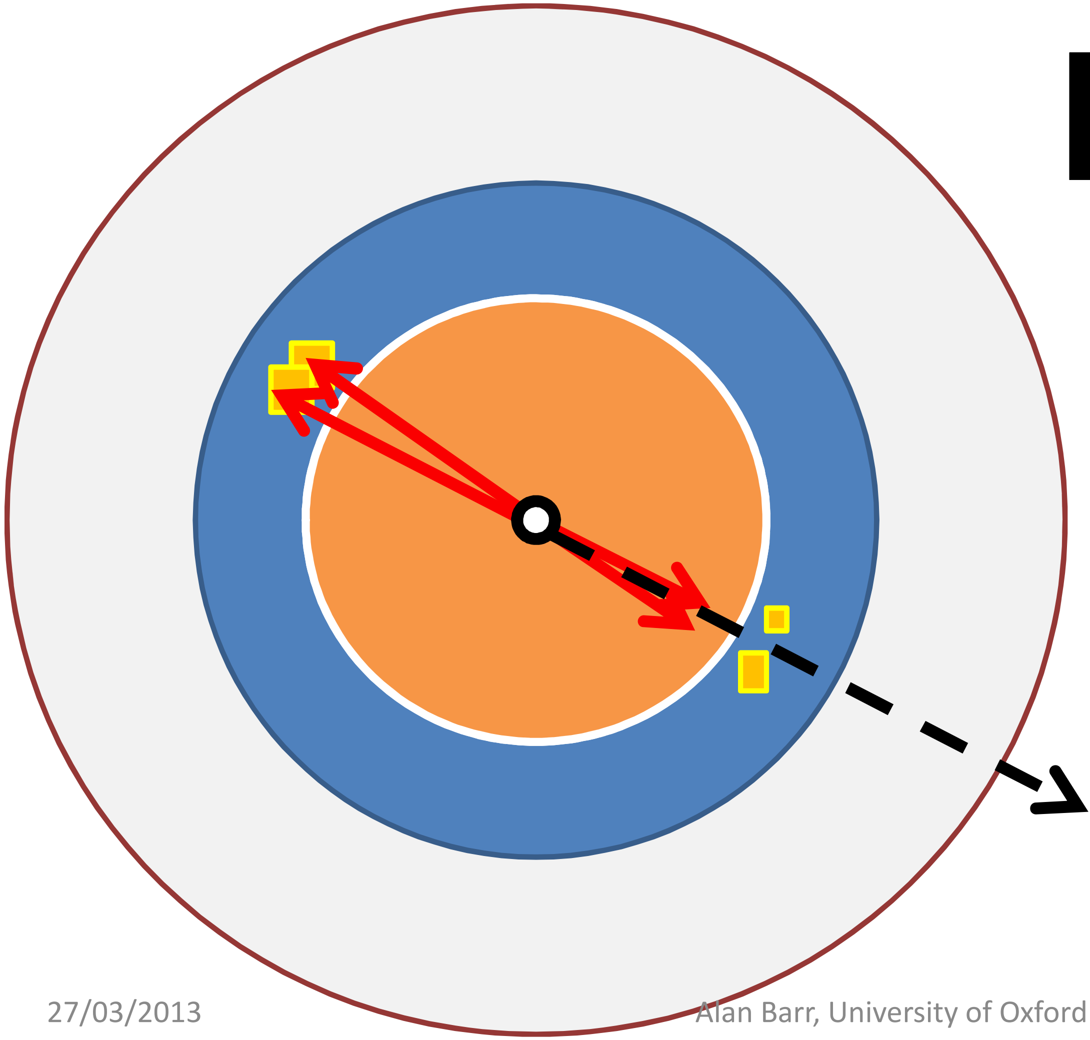
| Existing variable | Mass-bound variable | | | | | |
|---|---|---|---|---|---|---|
| | $N=1$ | | | | $N=2$ | |
| | $M_1(\not{M}_1) = M_{1\top}(\not{M}_1)$ | $M_{\top 1}(\not{M}_1)$ | $M_{\circ 1}$ | $M_{1\circ}$ | $M_2(\not{M}) = M_{2\top}(\not{M})$ | $M_{2\top\perp}(\not{M})$ |
| $2\not{p}_T = 2\not{E}_T$ | | | | $u_T \to 0$ | | |
| $m_{\text{eff}}$ | | $\not{M}_1 \to 0, u_T \to 0$ | $u_T \to 0$ | | | |
| $\sqrt{\hat{s}_{\min}^{(\text{sub})}}(\not{M}_1)$ | ✓ | | | | | |
| $\sqrt{\hat{s}}_{\min}(\not{M}_1)$ | $u_T \to 0$ | | | | | |
| $m_{Te\nu}(M_e, M_\nu)$ | ✓ | ✓ | $M_e, M_\nu \to 0$ | $M_e, M_\nu \to 0$ | | |
| $M_{T,ZZ}(M_Z)$ | ✓ | ✓ | | | | |
| $M_{C,WW}$ | $\not{M}_1 \to 0$ | | | | | |
| $m_T^{\text{true}}$ | $\not{M}_1 \to 0$ | | | | | |
| $m_{TZ'}^{reco}(M_Z)$ | $u_T \to 0$ | $u_T \to 0$ | | | | |
| $m_{T2}(\not{M})$ | | | | | ✓ | |
| $m_{T2\perp}(\not{M})$ | | | | | | ✓ |

arXiv:1105.2977

Intermezzo

# KNOW WHAT CAN GO WRONG

# JETS + MISSING MOMENTUM



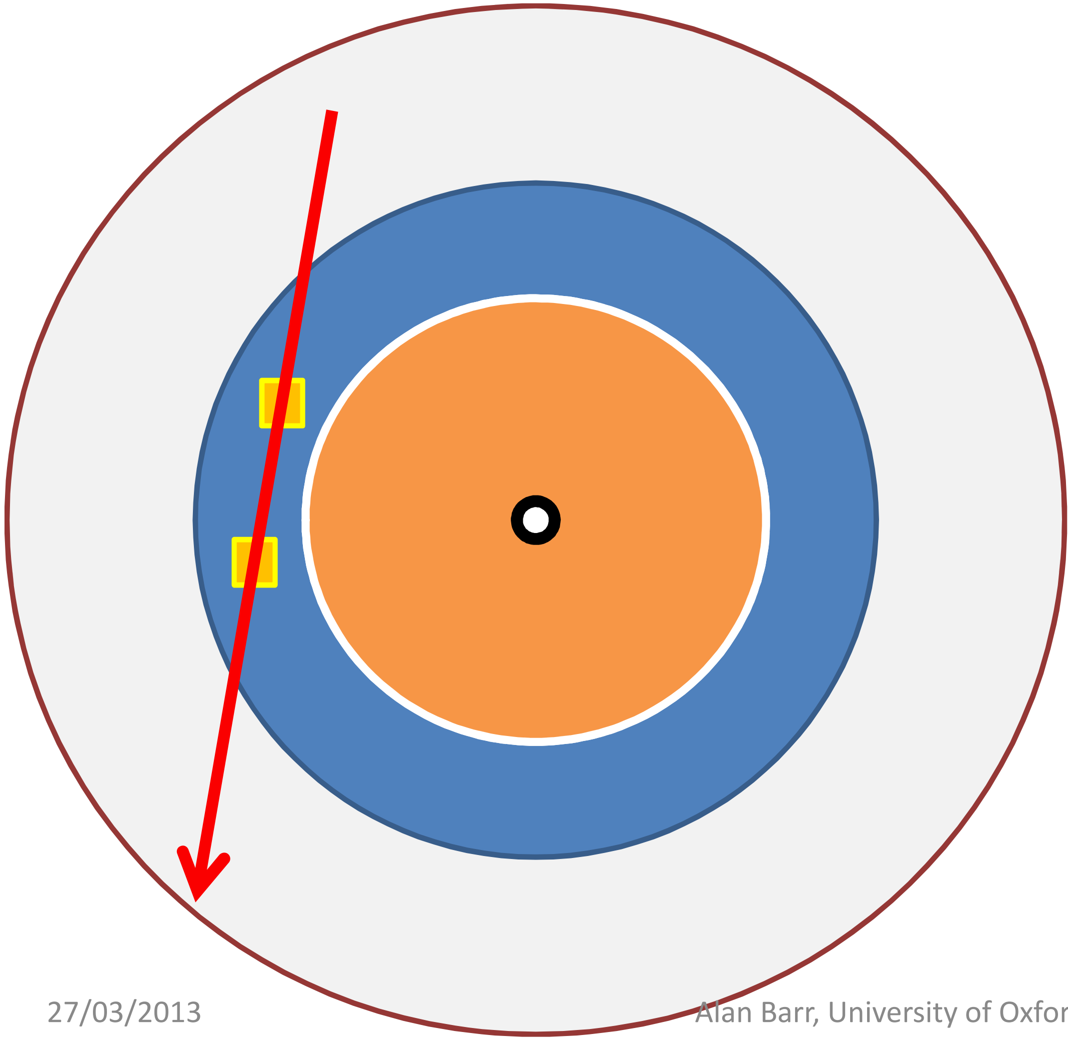
## Measurements

**Jets:**
$\Delta\phi$ cut

Reduce:
Had. Calorimeter
E.M. Calorimeter
Tracks from vertex

**Measure** remainder at small $\Delta\phi$

# JETS + MISSING MOMENTUM



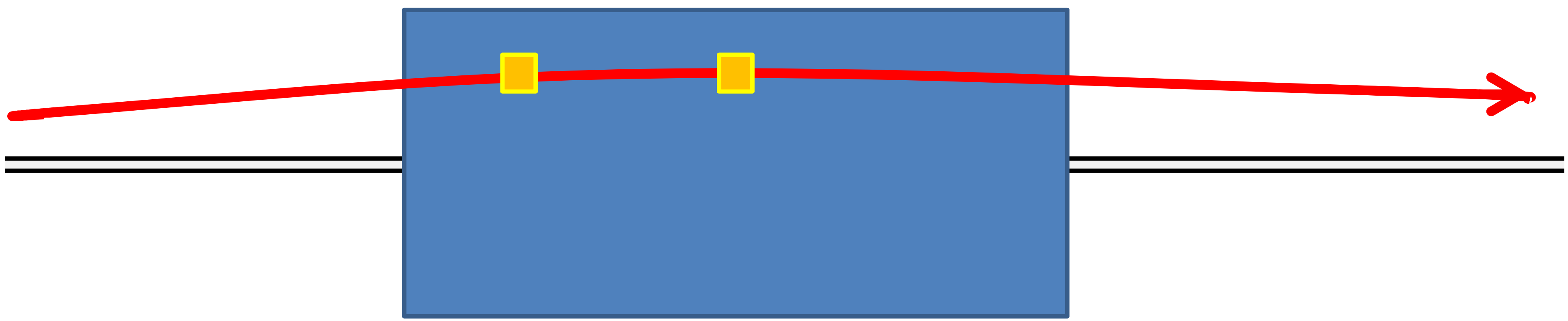
From cosmics

Reduce by:
(a) requiring tracks with jets
(b) look for muon hits

**Measure** remainder:
(a) no beam
(b) timing

# JETS + MISSING MOMENTUM

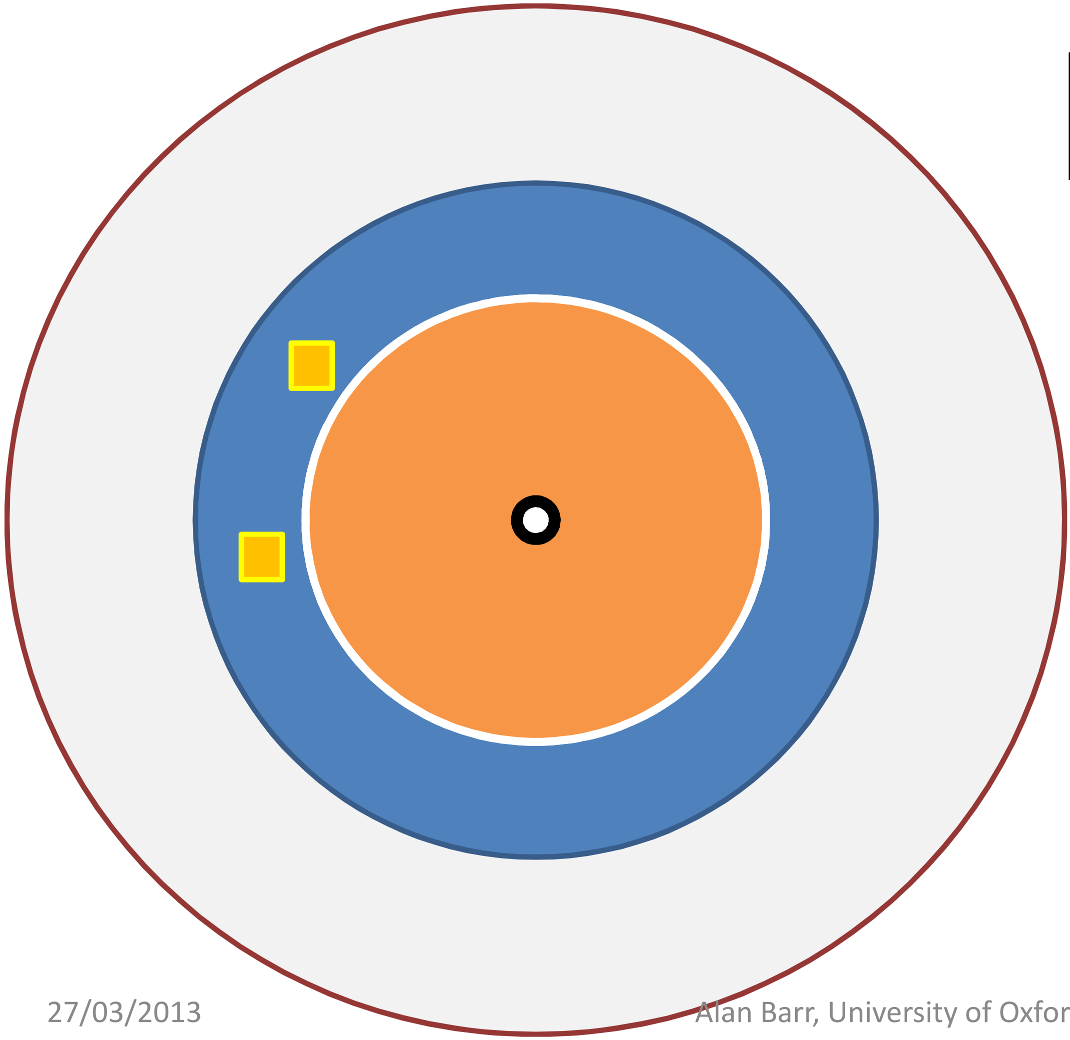
From beam halo



Reduce by requiring tracks with jets

**Measure** remainder with single beam /  timing

# JETS + MISSING MOMENTUM

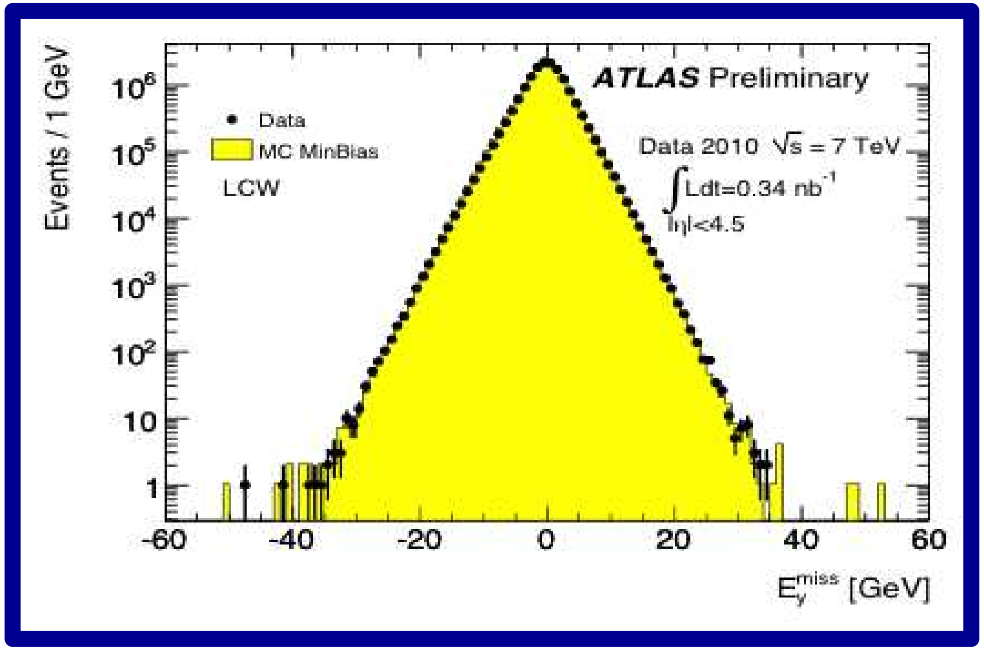


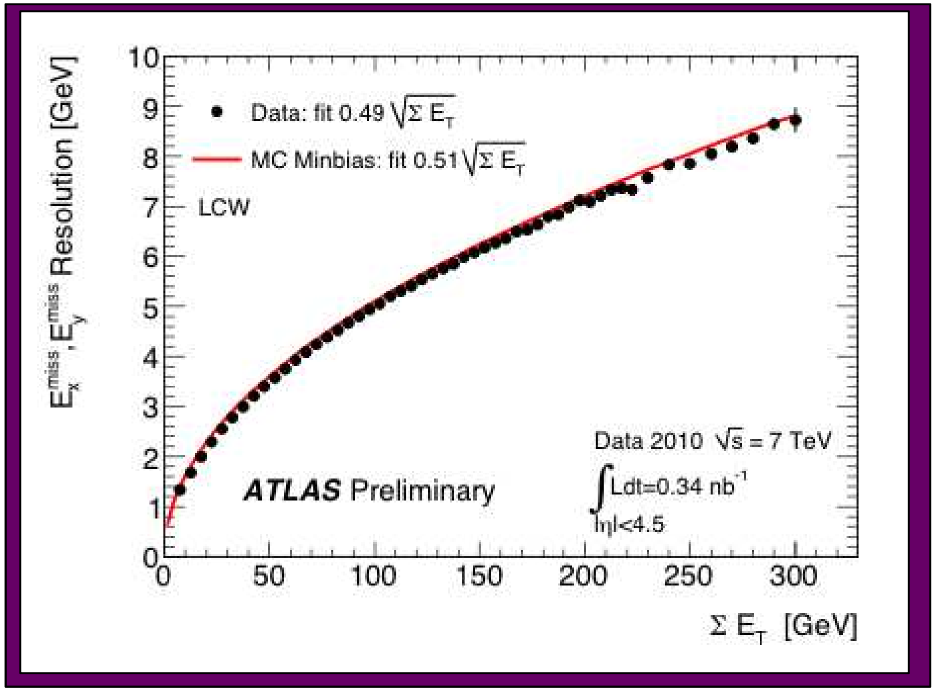
Calorimeter noise

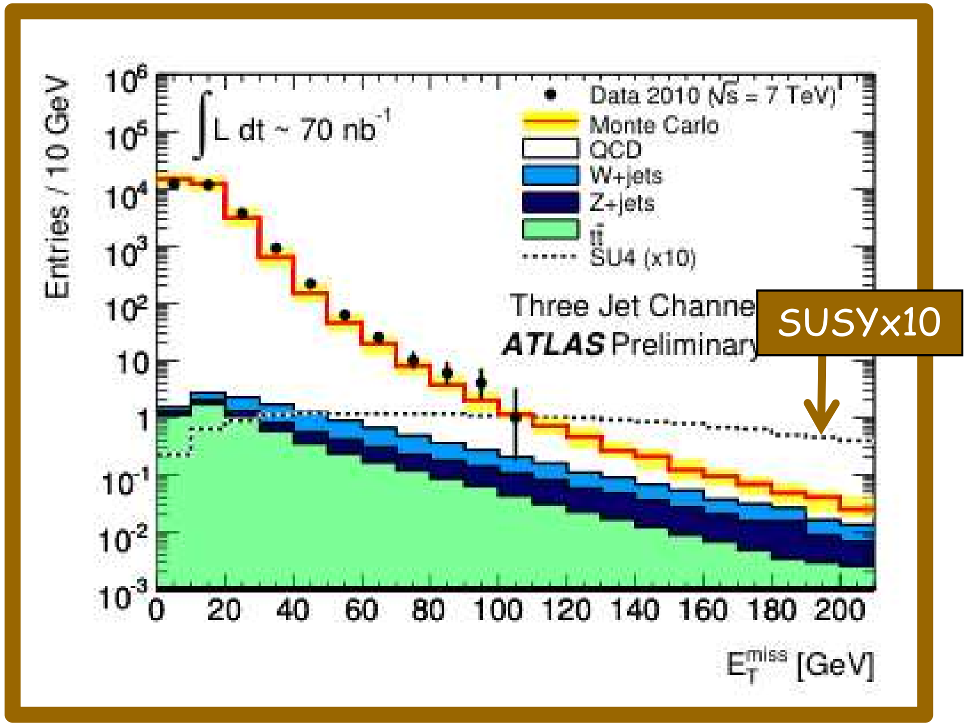
Reduce by requiring tracks with jets

**Measure** remainder
(a) no beam
(b) timing

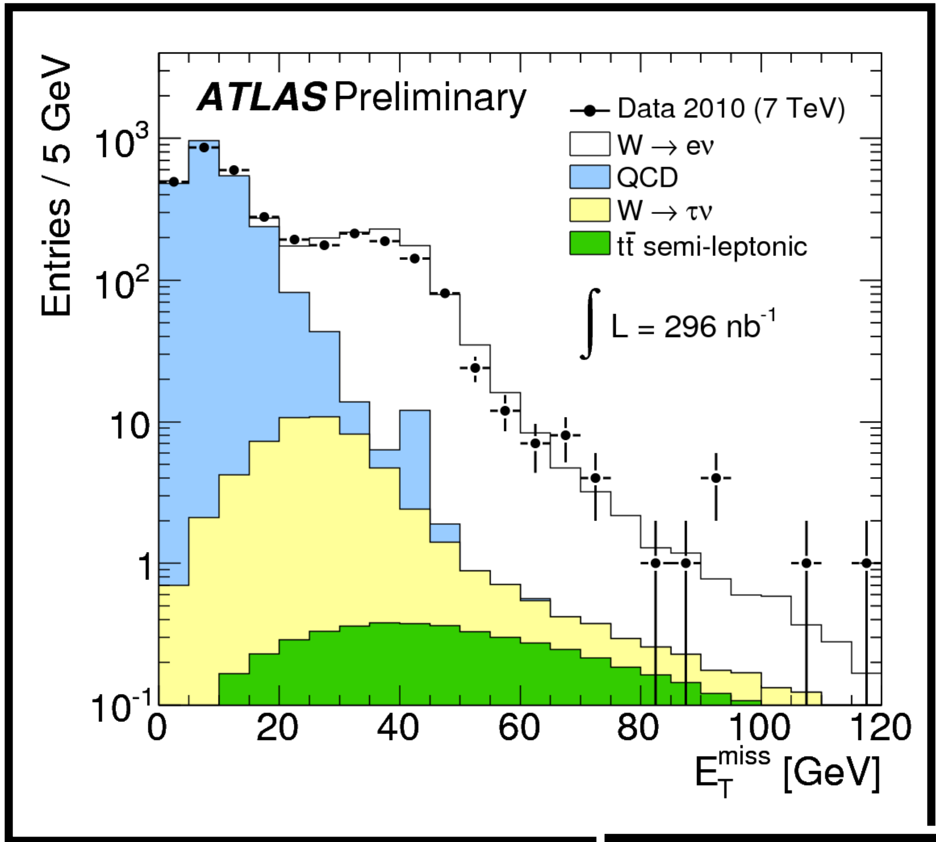
# Early 2010 data

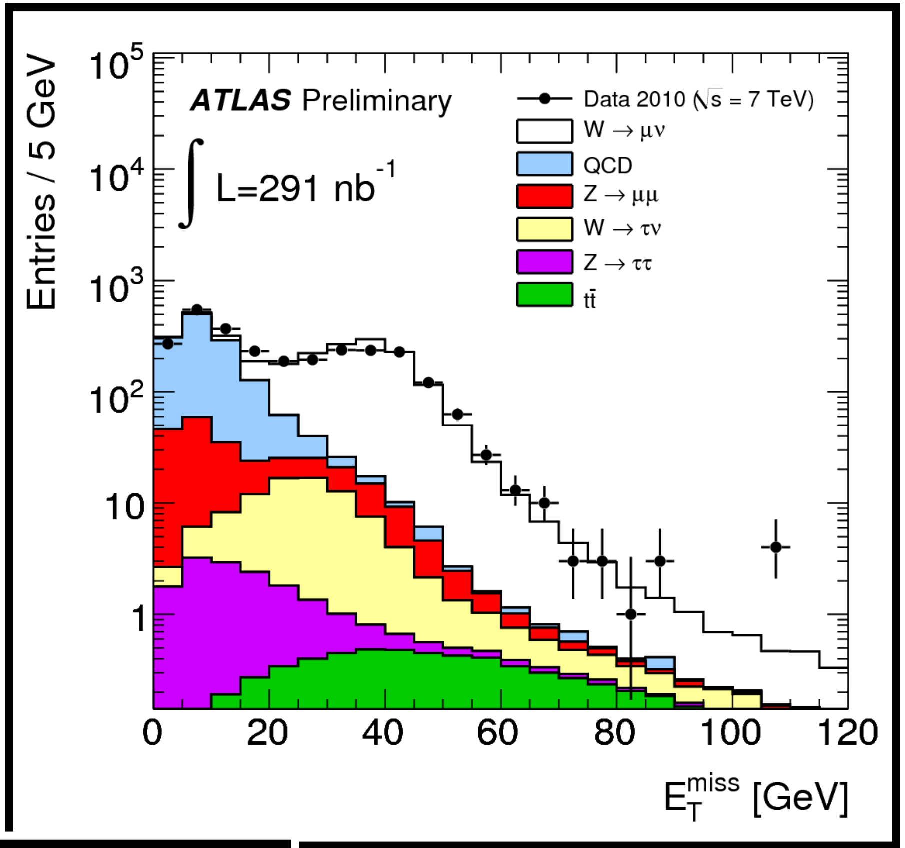


# Real missing momentum:
# W → υℓ

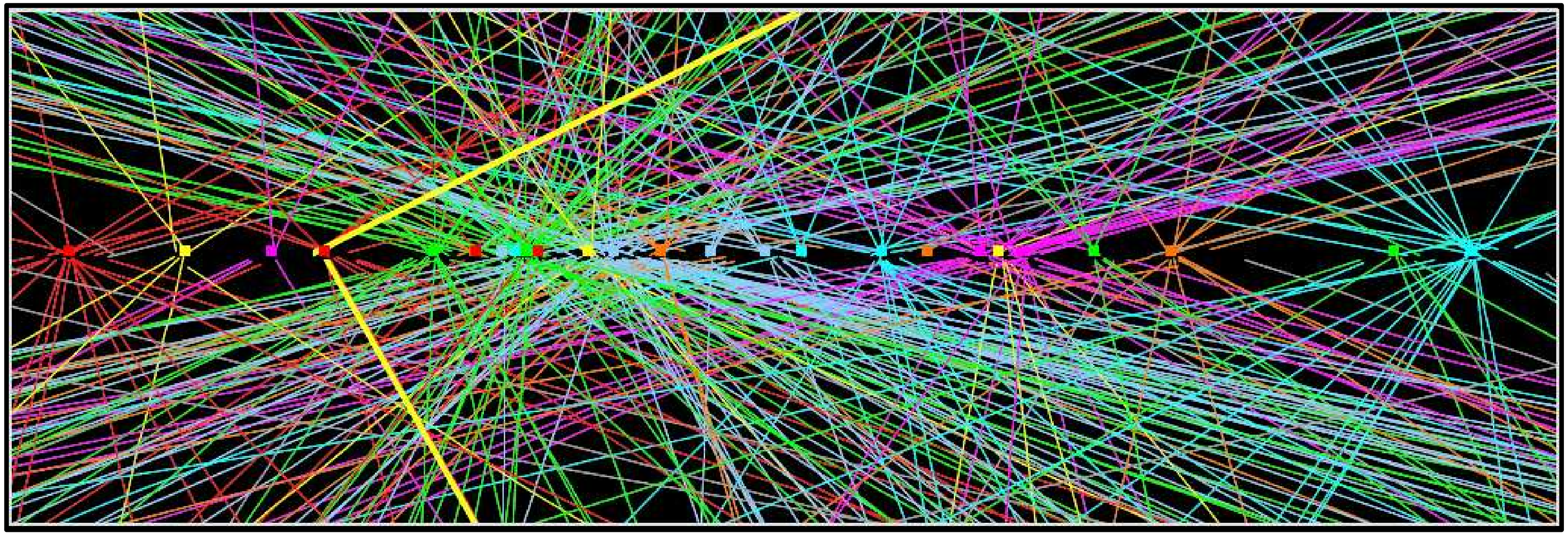



**Early 2010 data**

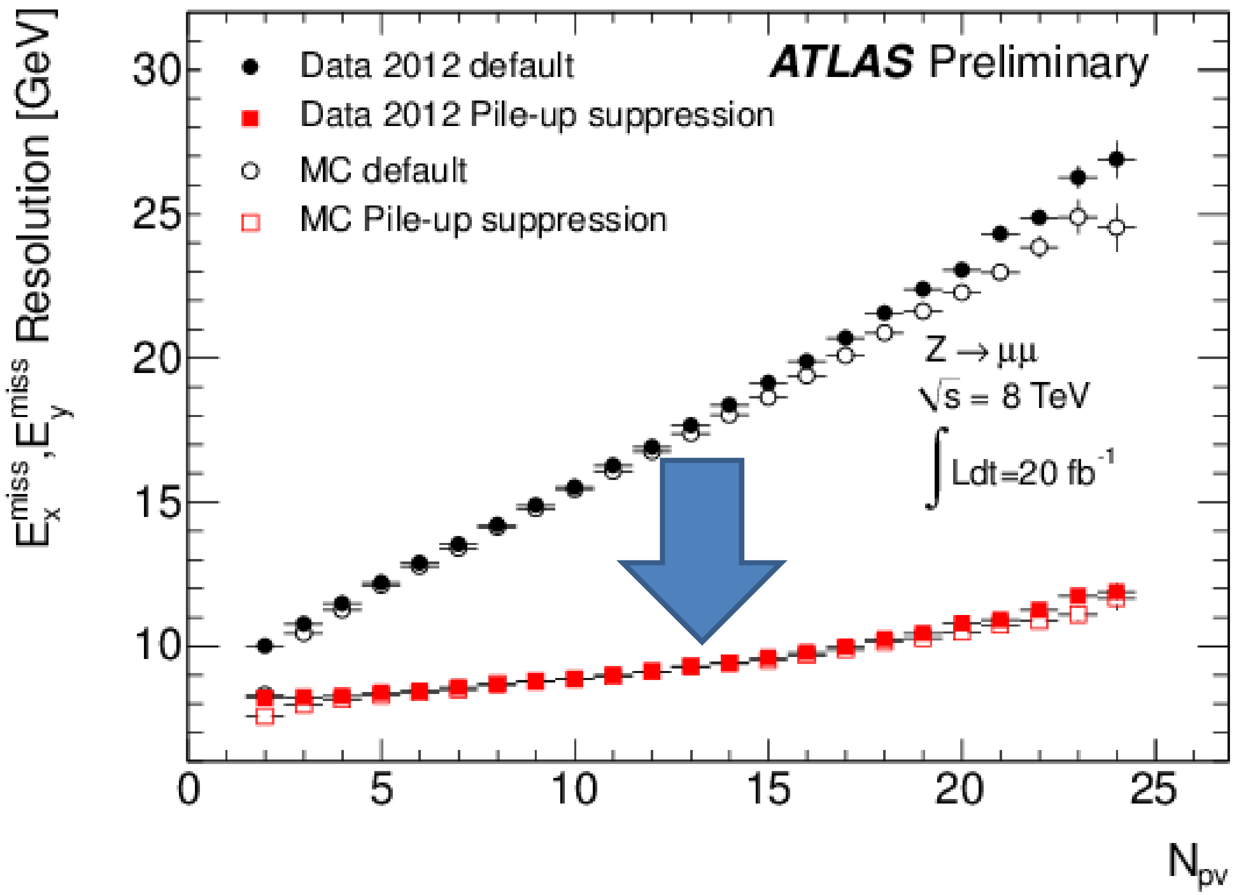
Simulation normalized to data

# Pile-up



# Dealing with pile-up …

Pile up suppression by e.g. associating jets with primary vertex






See ATLAS-CONF-2012-101

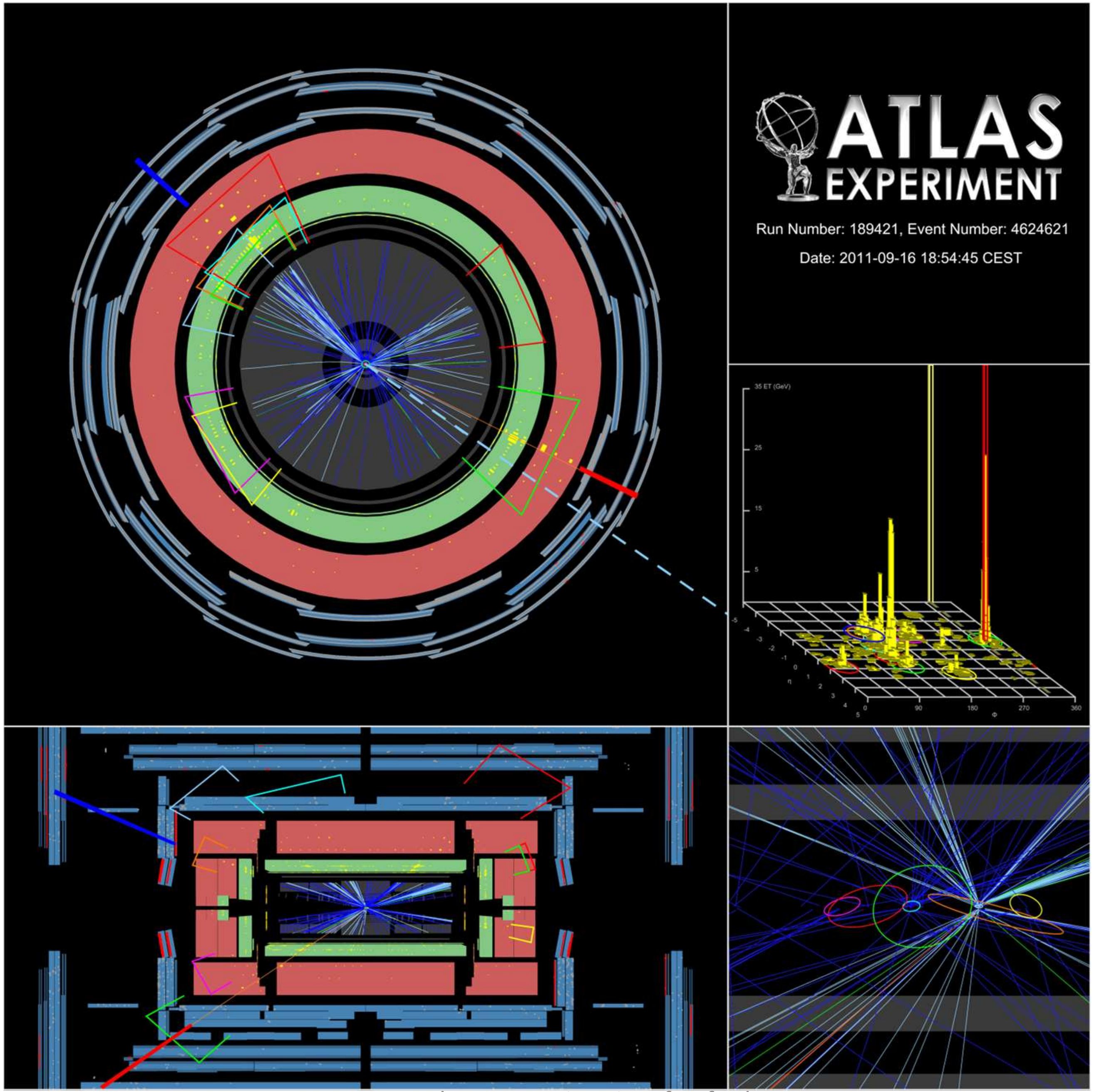
Answer 2

# KNOW HOW WELL YOU GET THINGS WRONG (RESOLUTION)

# An unexpected channel…

$$\tilde{g} + \tilde{g} \rightarrow \left(t + \bar{t} + \tilde{\chi}_1^0\right) + \left(t + \bar{t} + \tilde{\chi}_1^0\right)$$

- Each top quark can decay to 3 jets
- Want to be sensitive to e.g. **9 (!) jets + $P_T^{miss}$**
- **No way** to make this prediction with current MC
- Absolutely **not** something done in the pre-data preparation (there we went up to 4 jets…)


ATLAS
EXPERIMENT
Run Number: 189421, Event Number: 4624621
Date: 2011-09-16 18:54:45 CEST

## Multijets + missing transverse momentum: QCD background

**Nature knows the multi-jet cross section**

**We know the detector behaviour**

**→ Can determine QCD BG!**

# A quick reminder on jet resolution

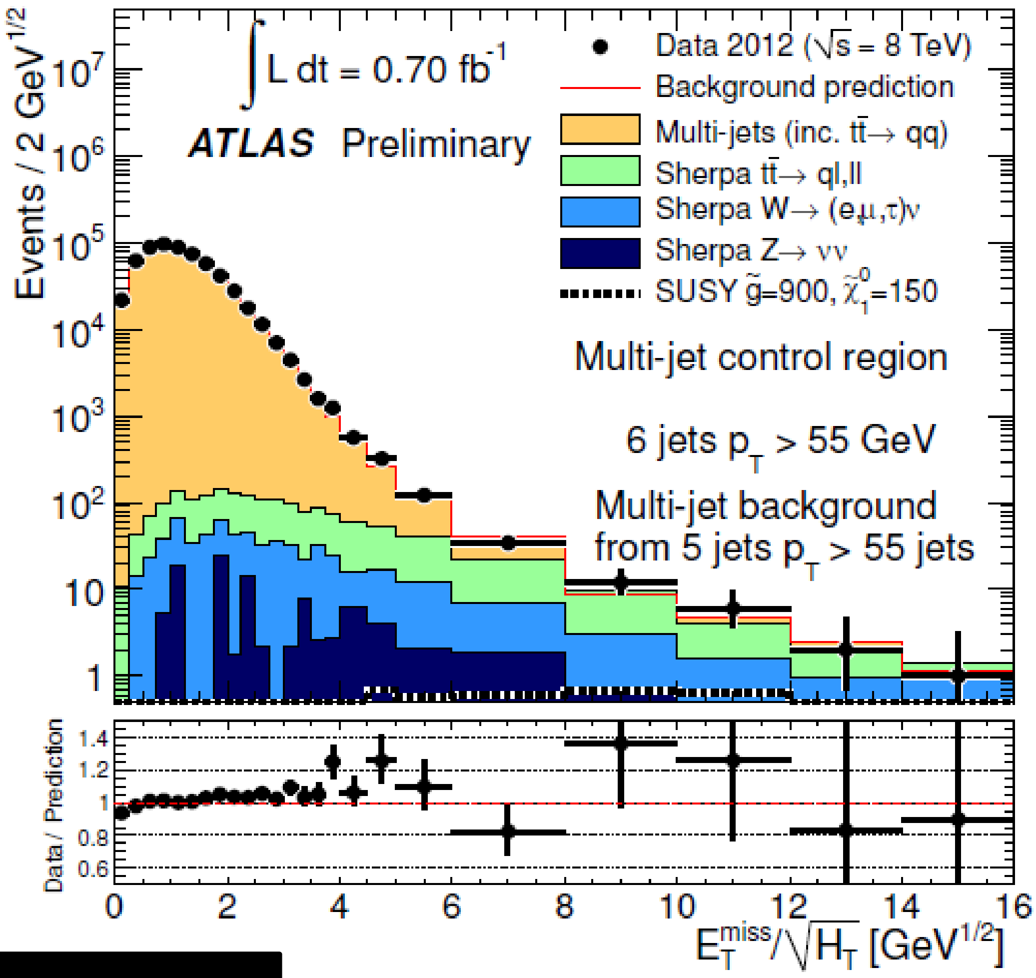
- QCD backgrounds dominated by FAKE $P_T^{miss}$
- Resolution (largely) determined by Poisson sampling statistics*
- Expect $\sigma_E \propto \sqrt{E}$

$$E_T^{miss} / \sqrt{H_T}$$

**Has almost universal distribution for QCD events**

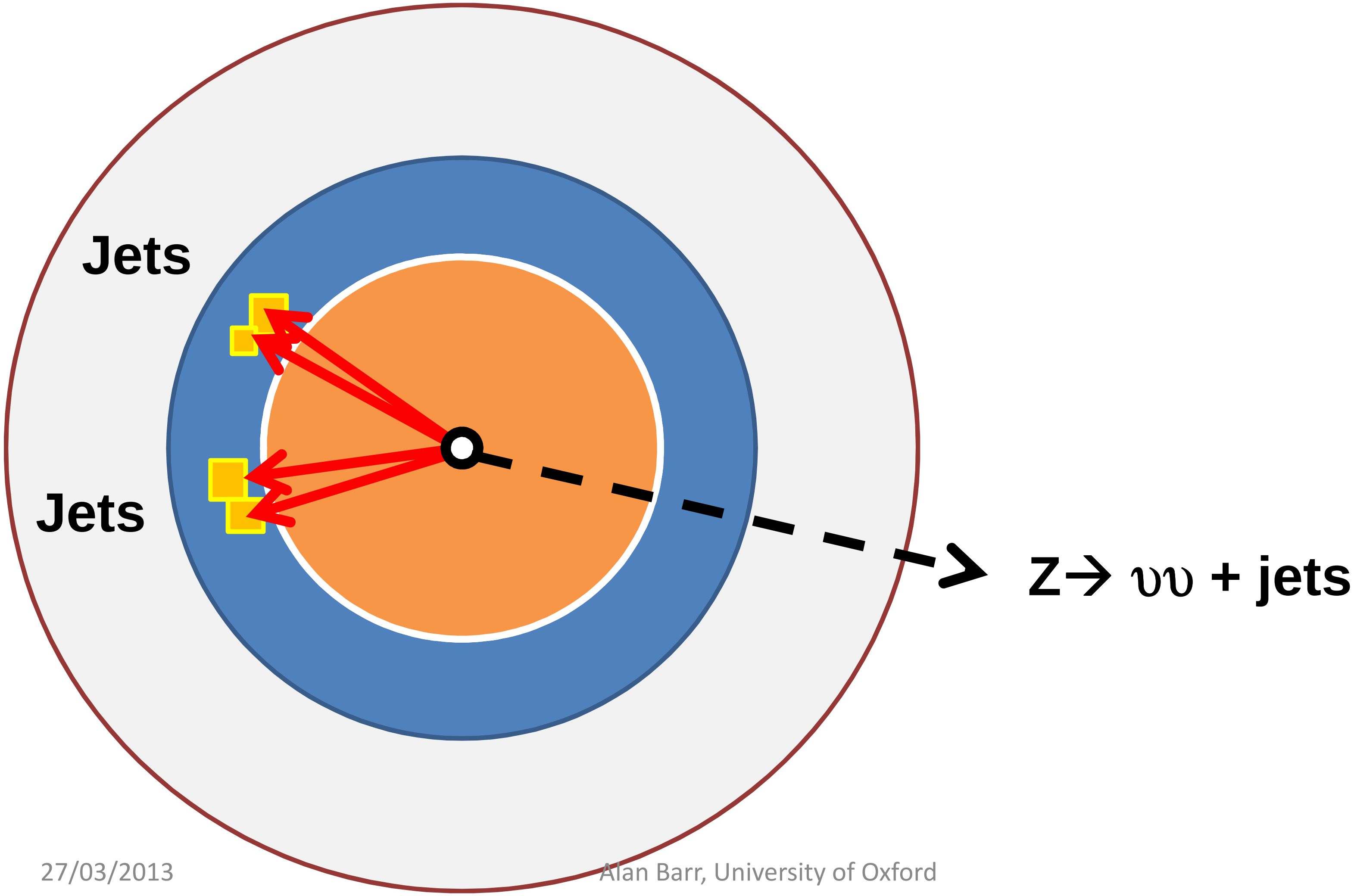
* There are also noise and constant terms which the experts will be well aware of

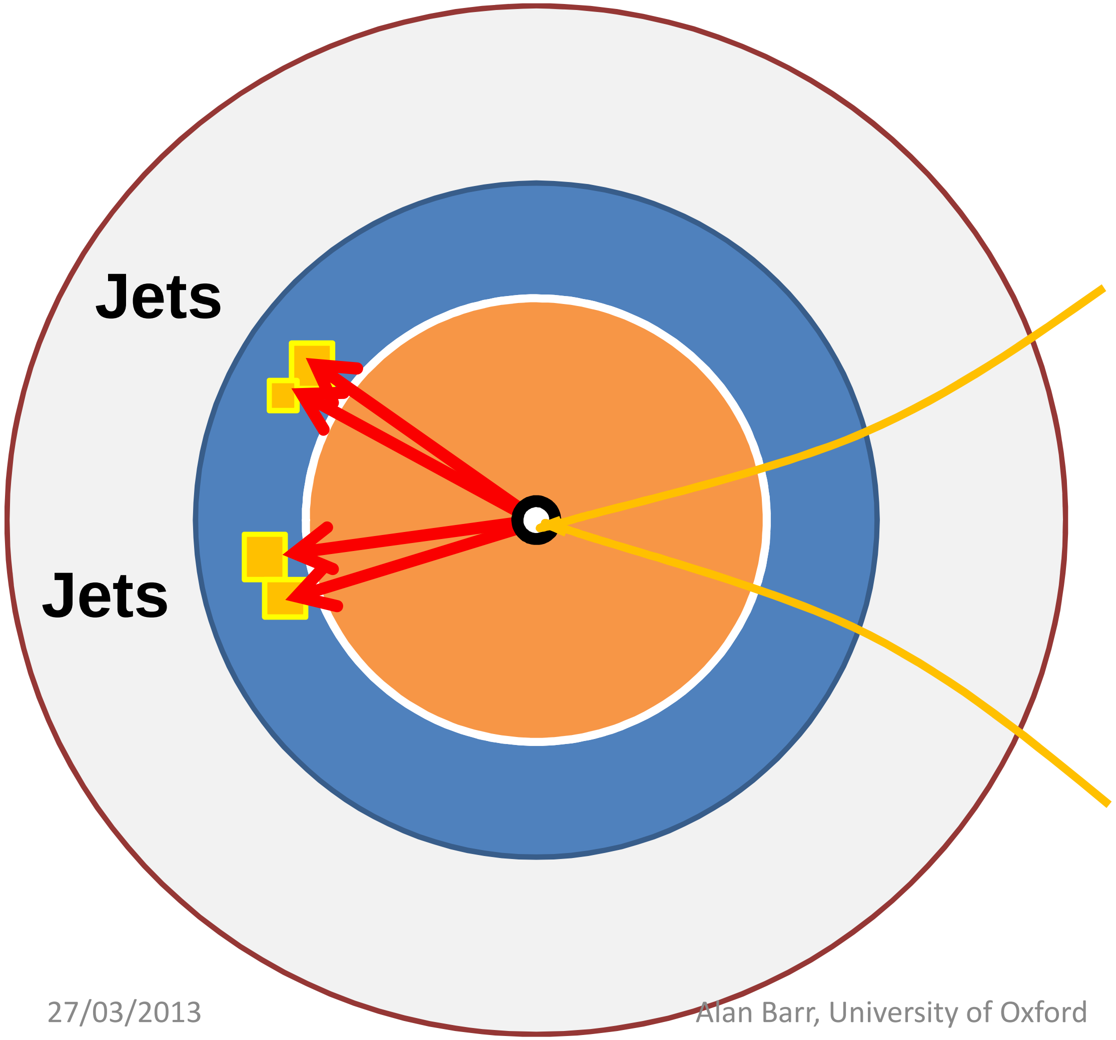
# Proof of principal… universal shape




6-jet distribution
from 5-jet template

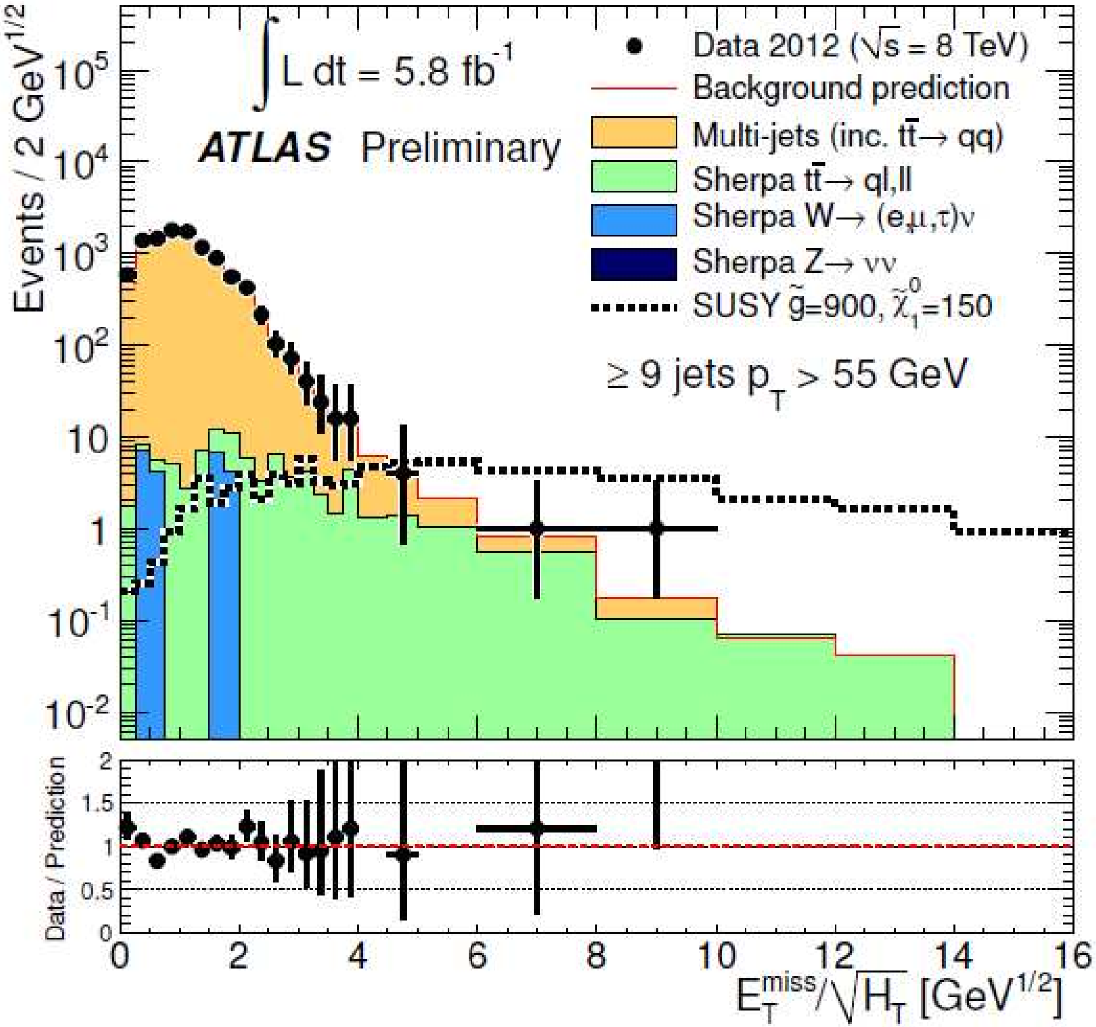
# Other backgrounds also depend largely on **measurements** from control regions

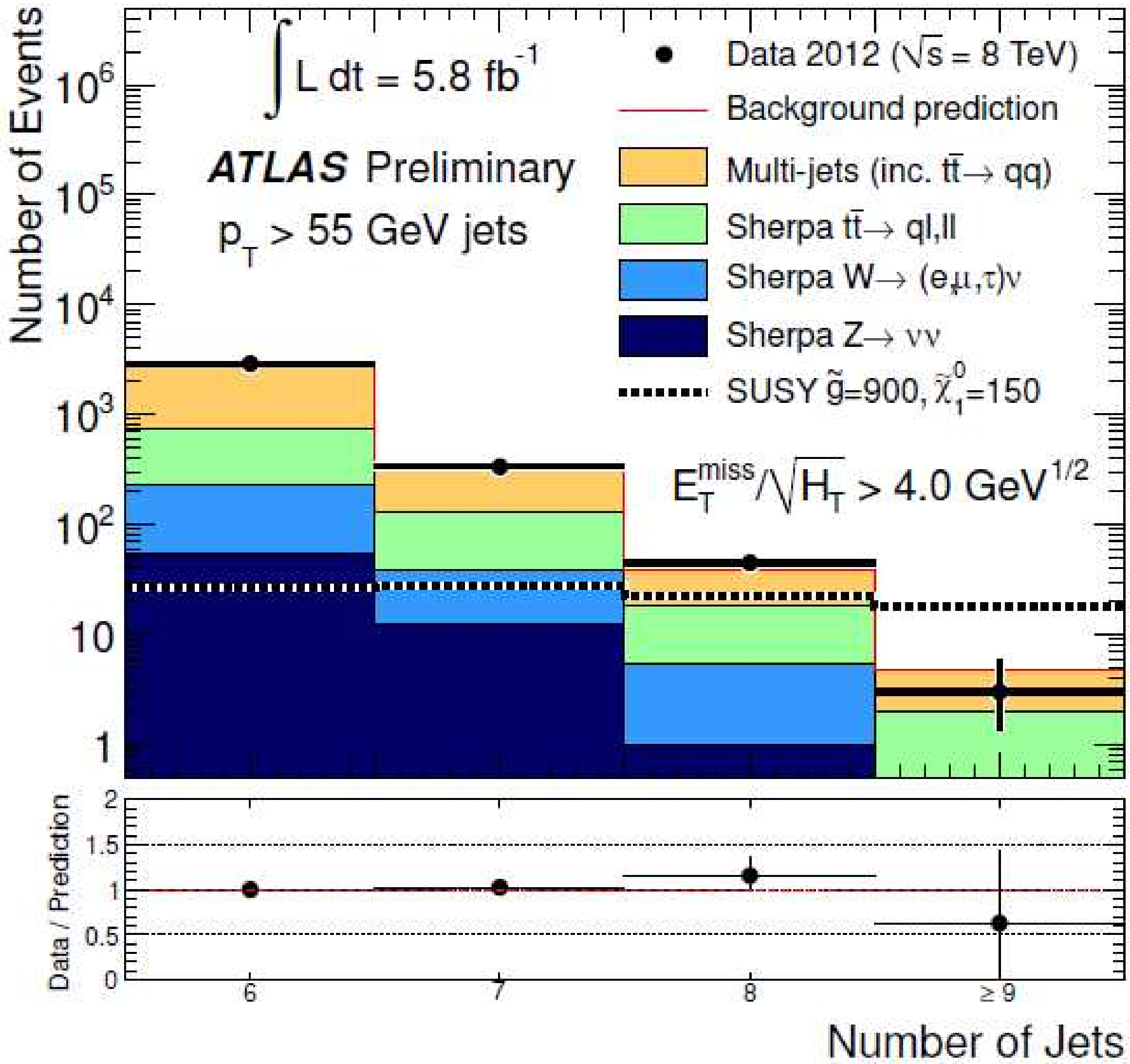




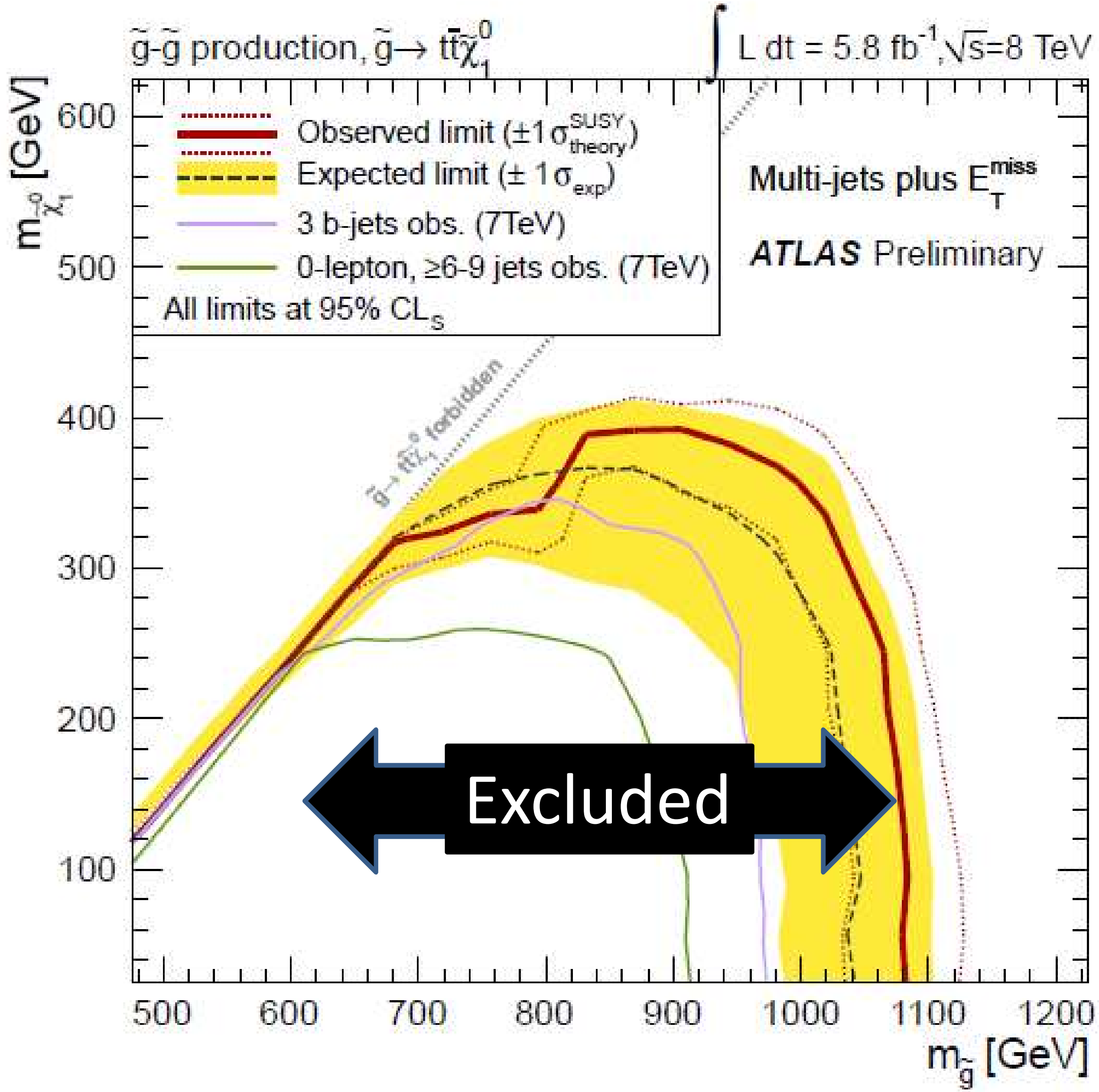

Z→μμ + jets

# A nine–jet prediction





∫L dt = 5.8 fb⁻¹
ATLAS Preliminary
$p_T$ > 55 GeV jets
Data 2012 (√s = 8 TeV)
Background prediction
Multi-jets (inc. $t\bar{t} \to qq$)
Sherpa $t\bar{t} \to ql,ll$
Sherpa $W \to (e,\mu,\tau)\nu$
Sherpa $Z \to \nu\nu$
SUSY $\tilde{g}$=900, $\tilde{\chi}_1^0$=150
$E_T^{miss}/\sqrt{H_T}$ > 4.0 GeV$^{1/2}$
Number of Events
Data / Prediction
Number of Jets



g̃-g̃ production, g̃→ tt̄χ̃₁⁰
∫ L dt = 5.8 fb⁻¹, √s=8 TeV
Observed limit (±1σ theory SUSY)
Expected limit (± 1σ exp)
3 b-jets obs. (7TeV)
0-lepton, ≥6-9 jets obs. (7TeV)
All limits at 95% CLs
Multi-jets plus E_T^miss
ATLAS Preliminary
g̃→ tt̄χ̃₁⁰ forbidden
Excluded
m χ̃₁⁰ [GeV]
600
500
400
300
200
100
500
600
700
800
900
1000
1100
1200
m g̃ [GeV]

# LHC Seminar

SPEAKER: Iacopo Vivarelli (Albert-Ludwigs-Universitaet Freiburg (DE))

TITLE: **Searches for natural supersymmetry with the ATLAS detector**

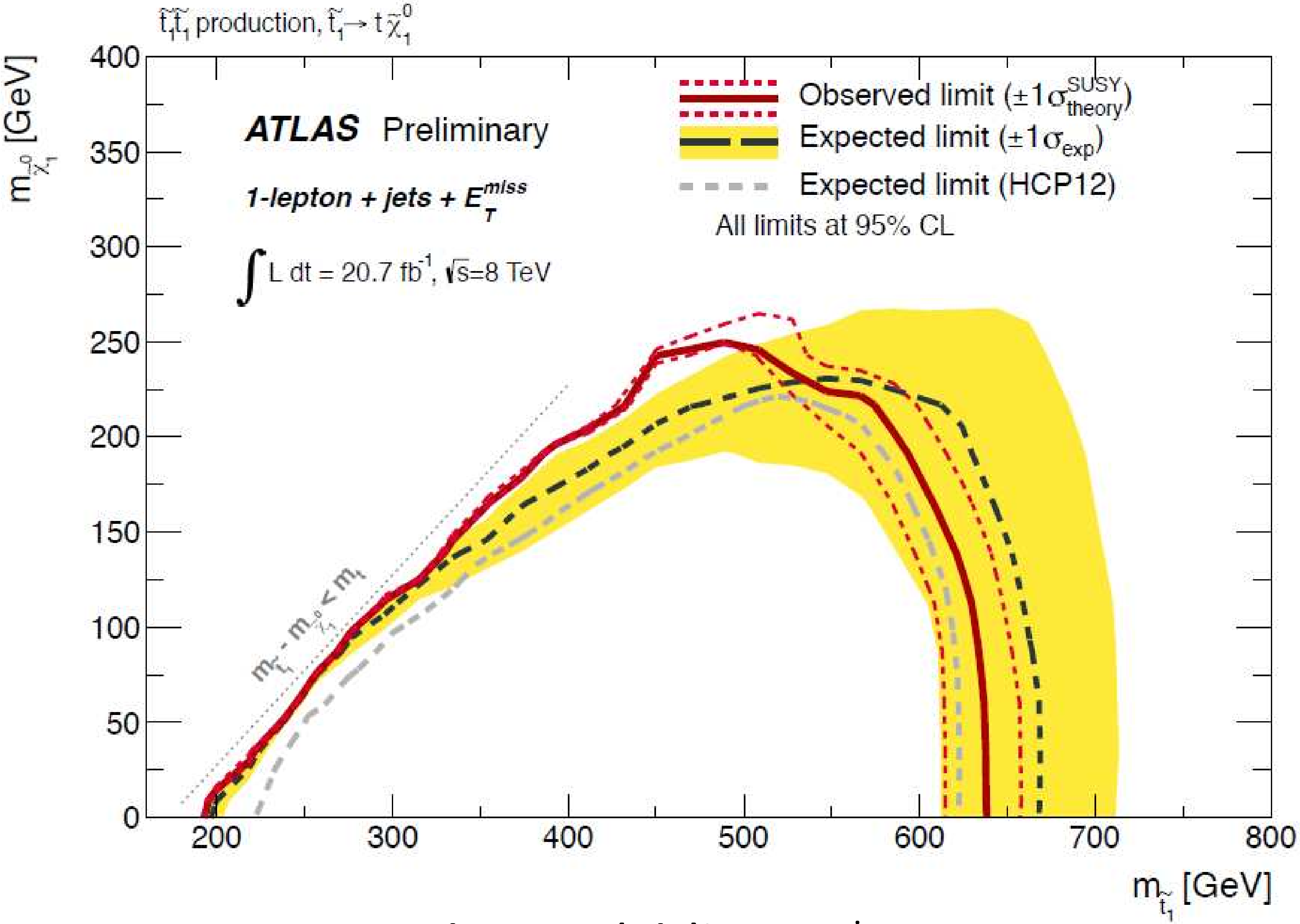
DATE: Tue 26/03/2013 11:00

PLACE: Council Chamber

http://indico.cern.ch/conferenceDisplay.py?confId=240895

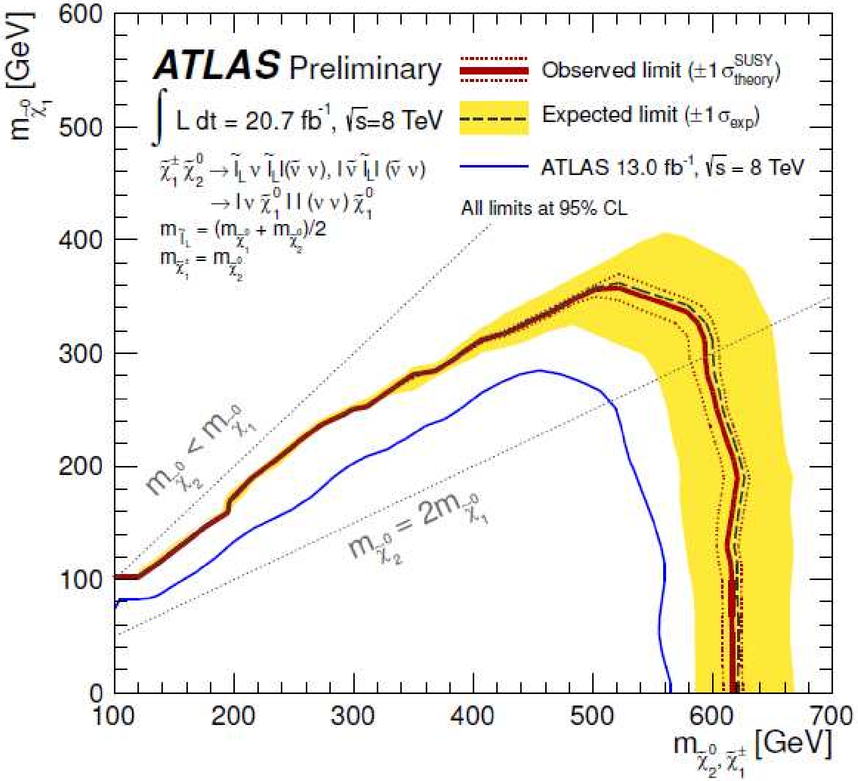
| Short Title of the CONF note | Date | √s (TeV) | L ($fb^{-1}$) | Document | Plots |
|---|---|---|---|---|---|
| 1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-037 | Link |
| 3 leptons + Etmiss [EW production] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-035 | Link |
| 4 leptons + Etmiss [EW production, RPV] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-036 | Link |
| 0 lepton + 6 (2 b-)jets + Etmiss [Heavy stop] NEW | 03/2013 | 8 | 20.5 | ATLAS-CONF-2013-024 | Link |
| Z + b-jet + jets + Etmiss [Direct stop in GMSB, direct stop2] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-025 | Link |
| 1-2 taus + jets + Etmiss [GMSB] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-026 | Link |
| 2 taus + Etmiss [EW production] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-028 | Link |
| 2 same-sign leptons + 0-3 b-jets + Etmiss NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-007 | Link |
| 0 lepton + 2 b-jets + Etmiss [Medium / heavy stop] | 12/2012 | 8 | 12.8 | ATLAS-CONF-2013-001 | Link |
| 2 leptons + Etmiss [Medium stop] | 12/2012 | 8 | 13.0 | ATLAS-CONF-2012-167 | Link |
| 1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop] | 12/2012 | 8 | 13.0 | ATLAS-CONF-2012-166 | Link |
| 2 bjets + Etmiss [Direct sbottom] | 12/2012 | 8 | 12.8 | ATLAS-CONF-2012-165 | Link |
| 3 leptons + Etmiss [EW production] | 11/2012 | 8 | 13.0 | ATLAS-CONF-2012-154 | Link |
| 4 leptons + Etmiss [RPV] | 11/2012 | 8 | 13.0 | ATLAS-CONF-2012-153 | Link |
| 0 lepton + >=3 b-jets + Etmiss [3rd gen. squarks] | 11/2012 | 8 | 12.8 | ATLAS-CONF-2012-145 | Link |
| 3 leptons + jets + Etmiss [3rd gen. squarks] | 11/2012 | 8 | 13.0 | ATLAS-CONF-2012-151 | Link |
| Monojet + Etmiss [WIMP, gravitino prod.] | 11/2012 | 8 | 10.5 | ATLAS-CONF-2012-147 | Link |
| Z + jets + Etmiss [GGM, higgsino NLSP] | 11/2012 | 8 | 5.8 | ATLAS-CONF-2012-152 | Link |
| 0 leptons + >=2-6 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-109 | Link |
| 0 leptons + >=6-9 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-103 | Link |
| 1 lepton + >=4 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-104 | Link |
| 2 same-sign leptons + >=4 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-105 | Link |

ATLAS-CONF-2013-037

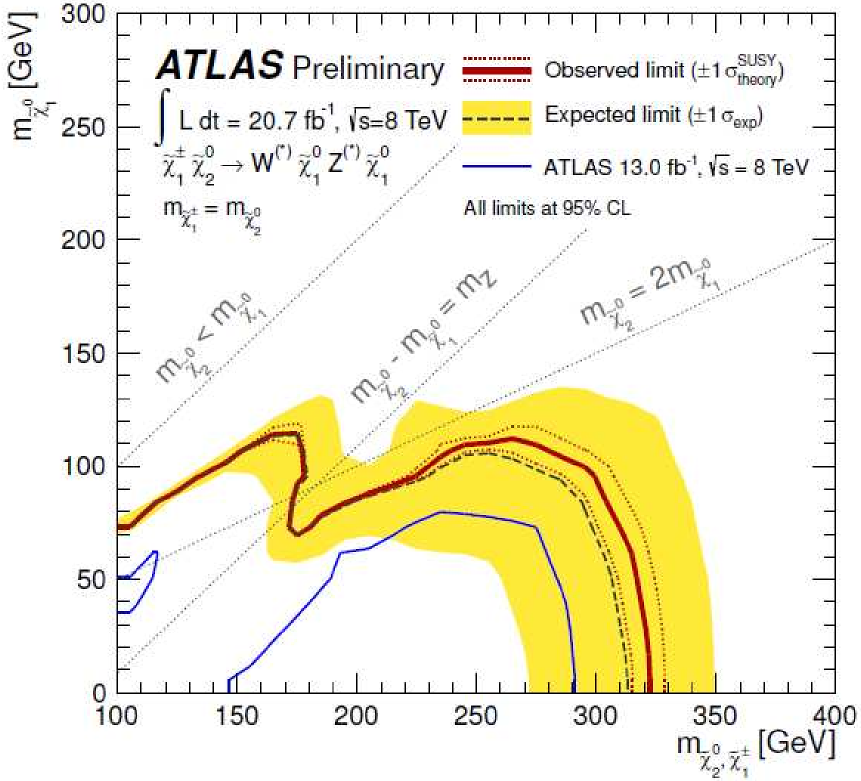



**1 lepton + 4(1 b-)jets + $P_T^{miss}$**

**ATLAS-CONF-2013-035**

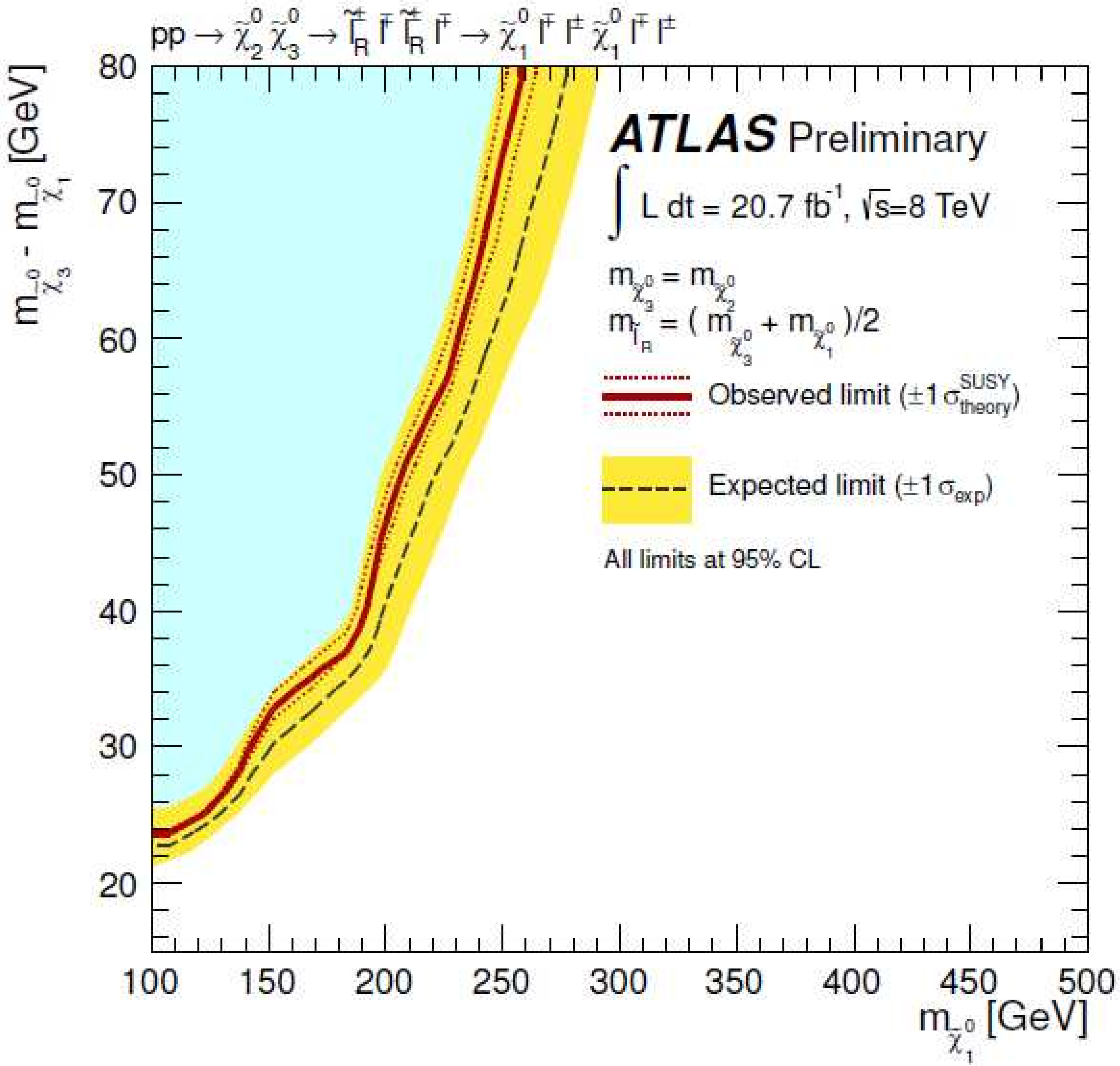



(a) Decay via sleptons




(b) Decay via gauge bosons

**3 leptons + $P_T^{miss}$**

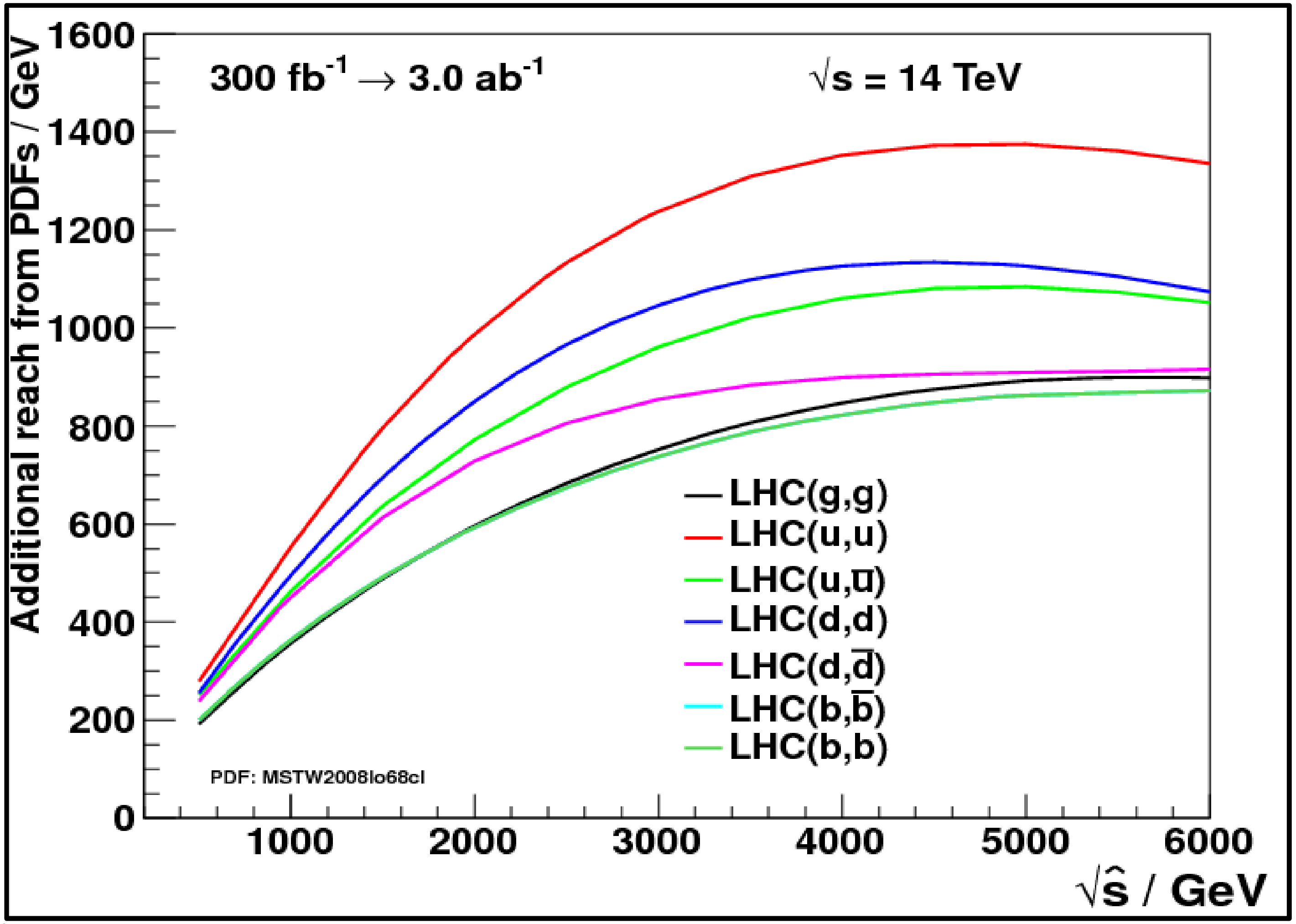



**4 leptons + $P_T^{miss}$**

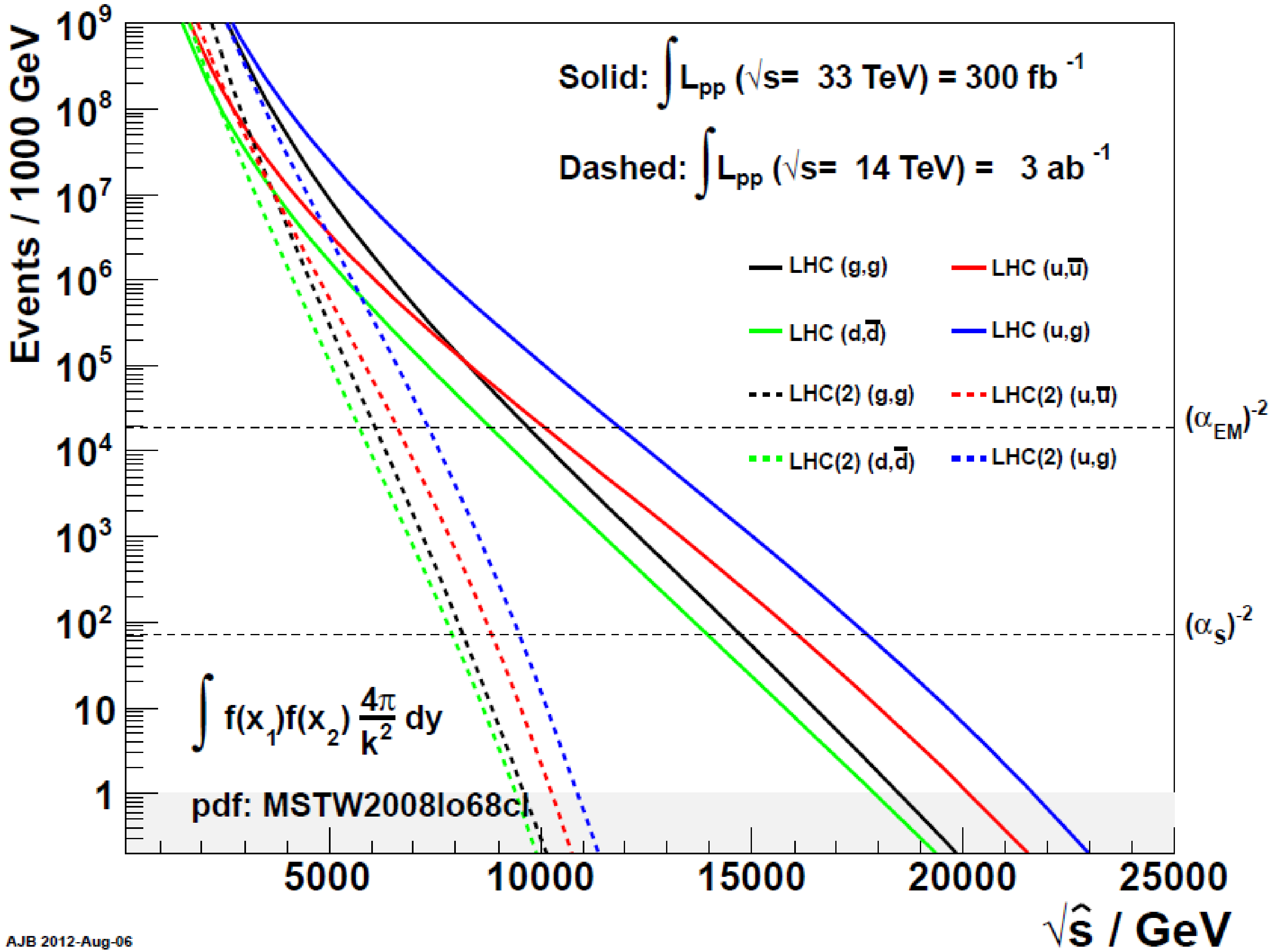
Beyond Run 1

# INTO THE FUTURE… ULTIMATE GOALS?

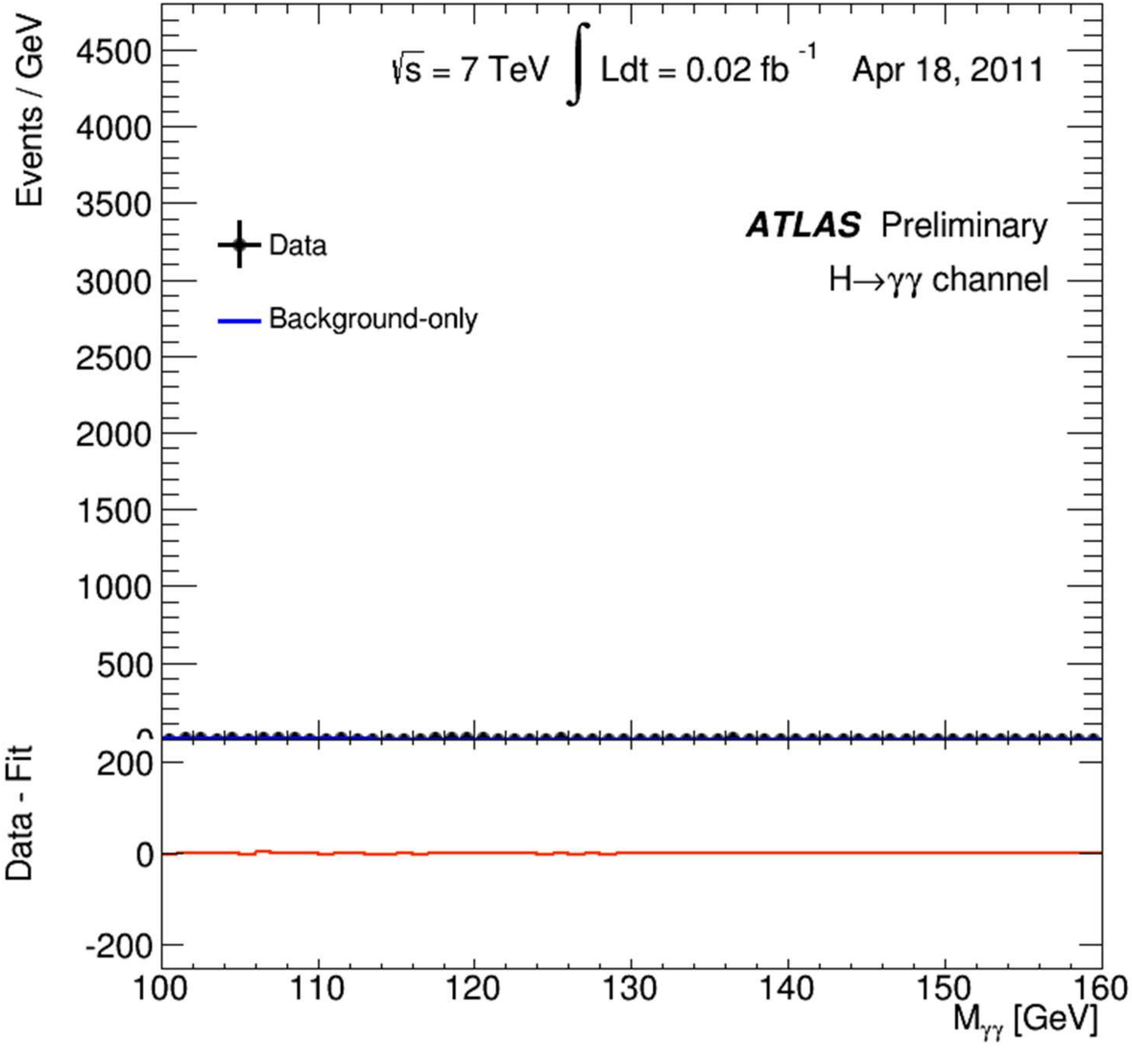
# A luminosity upgrade: additional reach…



# Reach of a 33 TeV machine?



# THE END




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

## 2012 data (8 TeV)

| Short Title of the CONF note | Date | √s (TeV) | L ($fb^{-1}$) | Document | Plots |
|---|---|---|---|---|---|
| 0 lepton + 6 (2 b-)jets + Etmiss [Heavy stop] NEW | 03/2013 | 8 | 20.5 | ATLAS-CONF-2013-024 | Link |
| Z + b-jet + jets + Etmiss [Direct stop in GMSB, direct stop2] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-025 | Link |
| 1-2 taus + jets + Etmiss [GMSB] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-026 | Link |
| 2 taus + Etmiss [EW production] NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-028 | Link |
| 2 same-sign leptons + 0-3 b-jets + Etmiss NEW | 03/2013 | 8 | 20.7 | ATLAS-CONF-2013-007 | Link |
| 0 lepton + 2 b-jets + Etmiss [Medium / heavy stop] | 12/2012 | 8 | 12.8 | ATLAS-CONF-2013-001 | Link |
| 2 leptons + Etmiss [Medium stop] | 12/2012 | 8 | 13.0 | ATLAS-CONF-2012-167 | Link |
| 1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop] | 12/2012 | 8 | 13.0 | ATLAS-CONF-2012-166 | Link |
| 2 bjets + Etmiss [Direct sbottom] | 12/2012 | 8 | 12.8 | ATLAS-CONF-2012-165 | Link |
| 3 leptons + Etmiss [EW production] | 11/2012 | 8 | 13.0 | ATLAS-CONF-2012-154 | Link |
| 4 leptons + Etmiss [RPV] | 11/2012 | 8 | 13.0 | ATLAS-CONF-2012-153 | Link |
| 0 lepton + >=3 b-jets + Etmiss [3rd gen. squarks] | 11/2012 | 8 | 12.8 | ATLAS-CONF-2012-145 | Link |
| 3 leptons + jets + Etmiss [3rd gen. squarks] | 11/2012 | 8 | 13.0 | ATLAS-CONF-2012-151 | Link |
| Monojet + Etmiss [WIMP, gravitino prod.] | 11/2012 | 8 | 10.5 | ATLAS-CONF-2012-147 | Link |
| Z + jets + Etmiss [GGM, higgsino NLSP] | 11/2012 | 8 | 5.8 | ATLAS-CONF-2012-152 | Link |
| 0 leptons + >=2-6 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-109 | Link |
| 0 leptons + >=6-9 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-103 | Link |
| 1 lepton + >=4 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-104 | Link |
| 2 same-sign leptons + >=4 jets + Etmiss | 08/2012 | 8 | 5.8 | ATLAS-CONF-2012-105 | Link |

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