Searches for New Physics with the ATLAS detector

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On behalf of the **ATLAS Collaboration**

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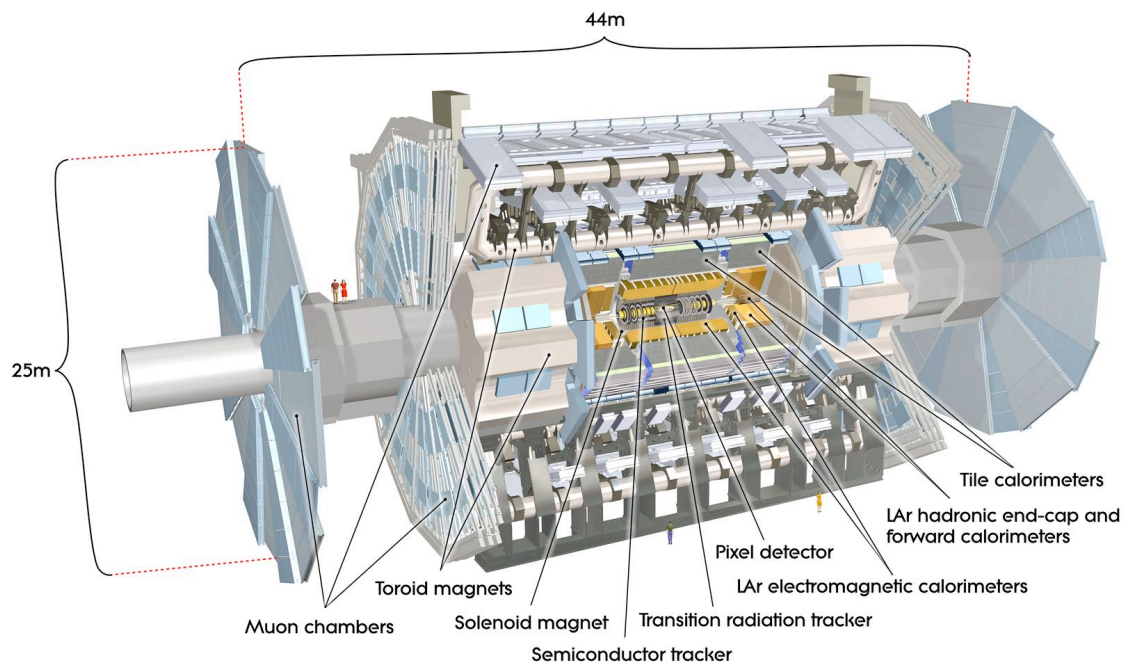
On the first year of the LHC

Overview

Covering early results on **New Physics Searches**, beyond the **Standard Model**, from the **ATLAS experiment** at the **LHC**

Outline

- Motivation
- SUSY Searches
- Other BSM Searches:
  - Dijet Final States
  - Multi-Object
  - γγ+EtMiss search
  - W' (Lepton+EtMiss)
- Summary

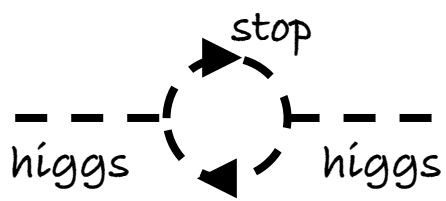


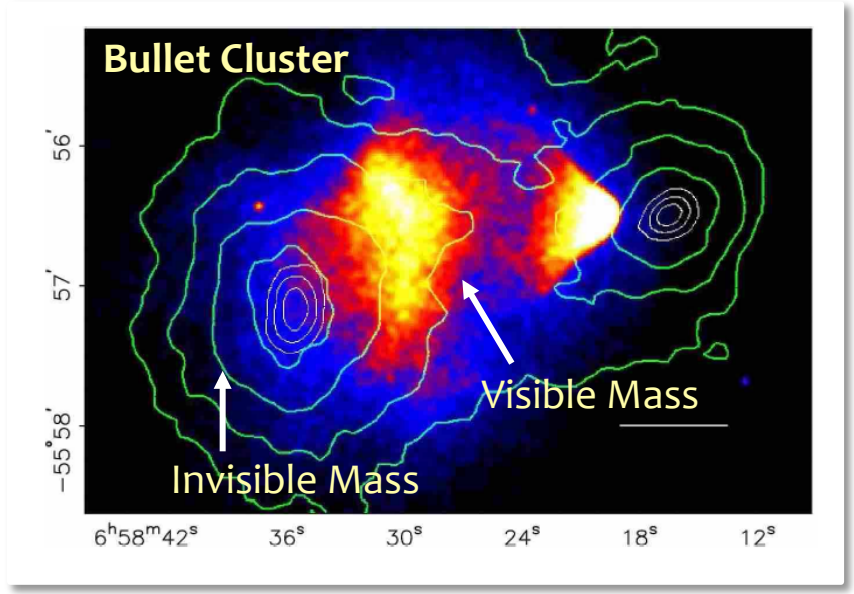
Shown in this Talk: early ATLAS results based on a few 10's nb^{-1} – a few pb^{-1} of pp collision data at $\sqrt{s}$ = 7TeV

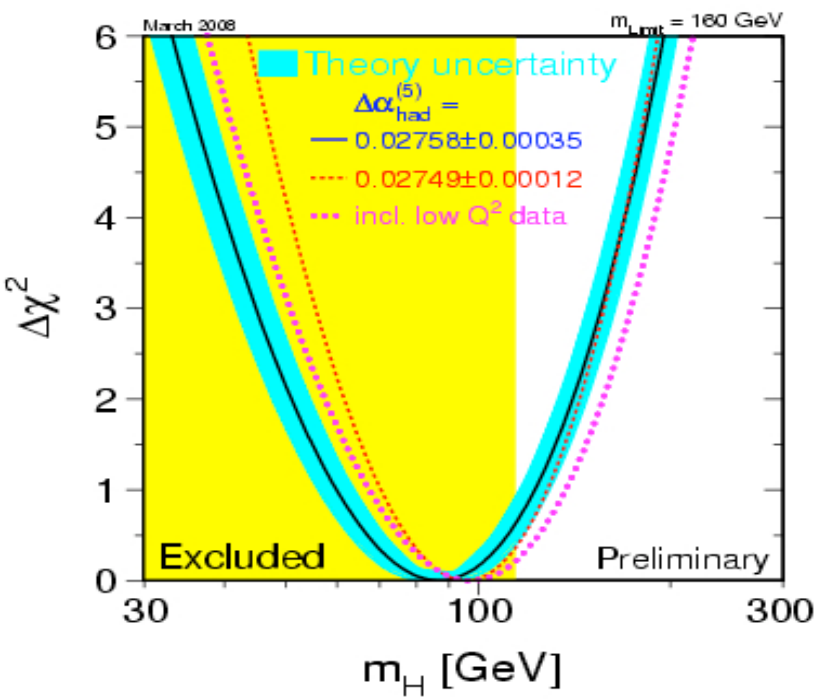
More results on 2010 data in upcoming winter conferences (full ATLAS 2010 luminosity ≅ 45 pb^{-1})

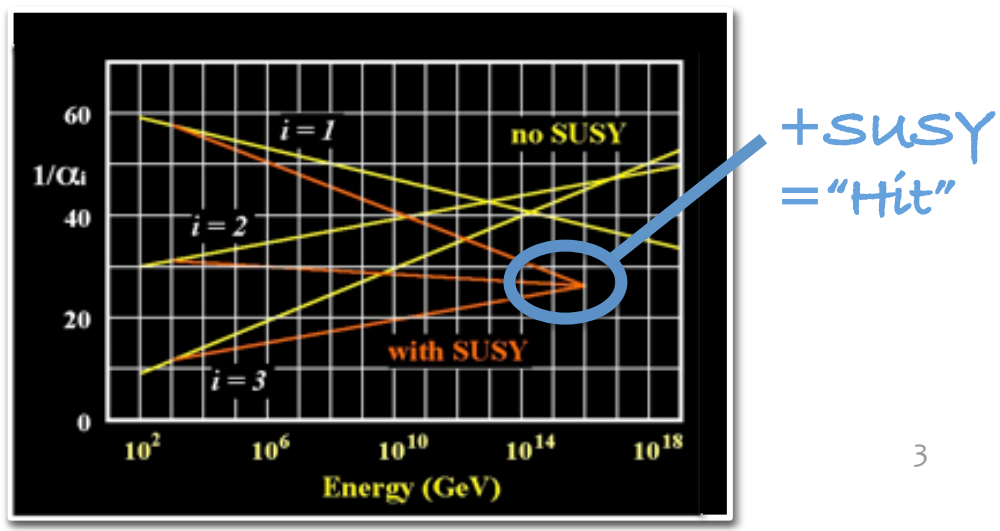
Motivation

- **Standard Model (SM)** of **Particle Physics** incomplete, e.g.
- Dark Matter?
- Hierarchy Problem?
- Gravity?
- Mass Generation?
- …

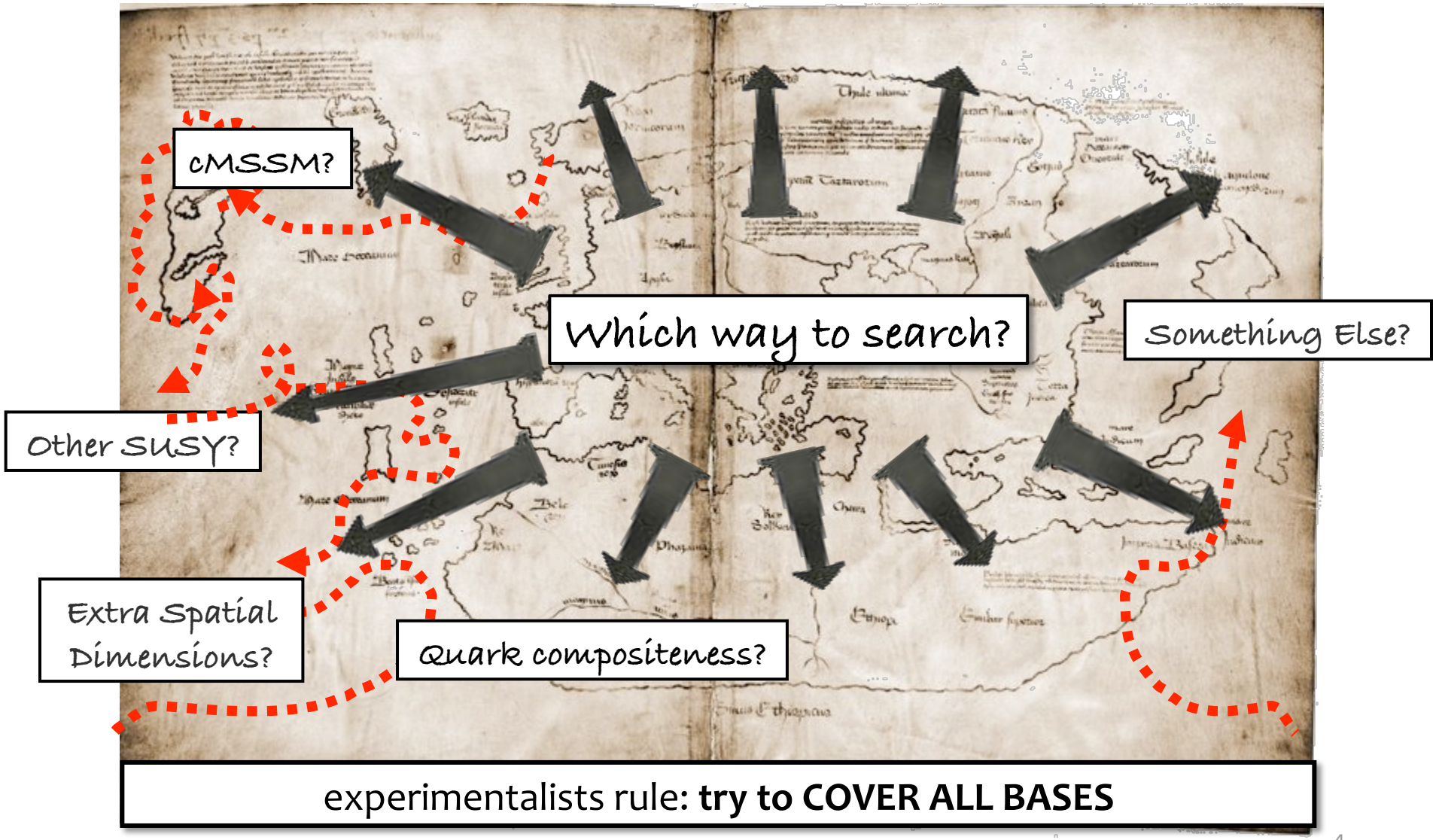








How to Make a Discovery?



experimentalists rule: **try to COVER ALL BASES**

Slide courtesy of A. Barr

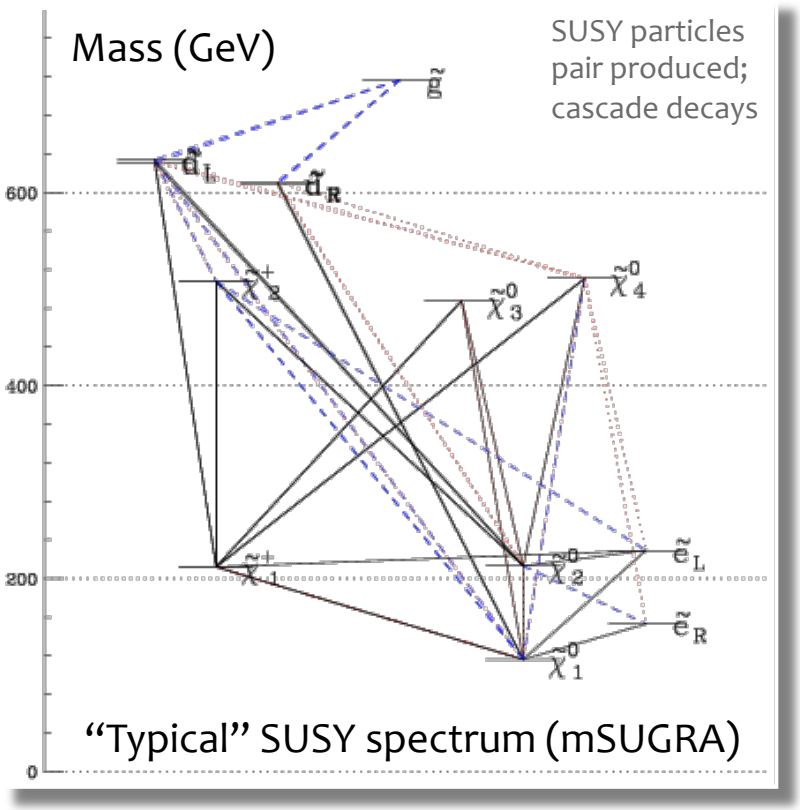
Supersymmetry Searches

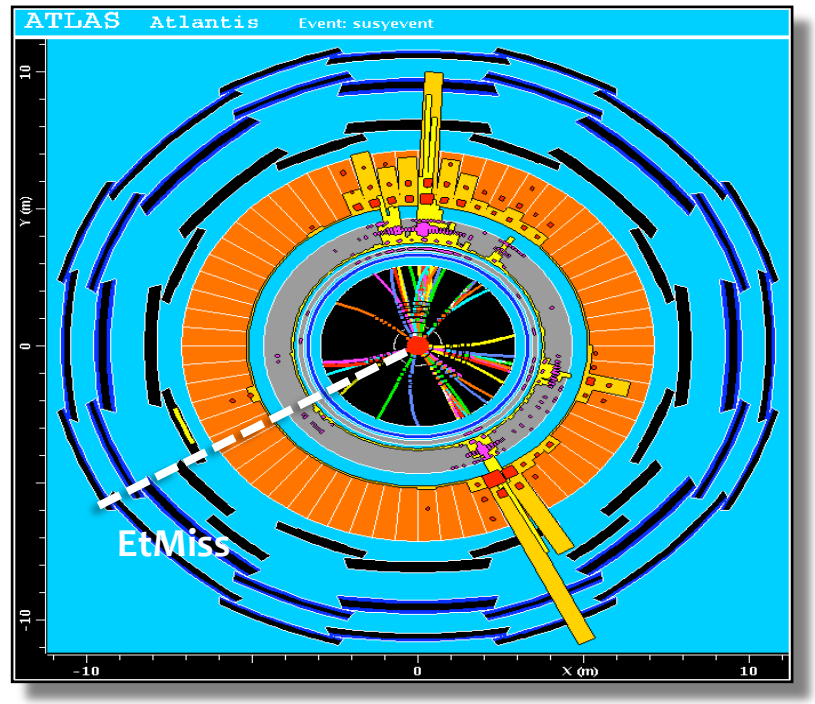
with early ATLAS data

SUSY:

- **SuperSymmetry** (SUSY): theoretically favoured candidate for **BSM physics**
- Strongly interacting sparticles should be abundantly produced at the **LHC** (provided not prohibitively heavy)

SUSY example search (assuming R-parity):

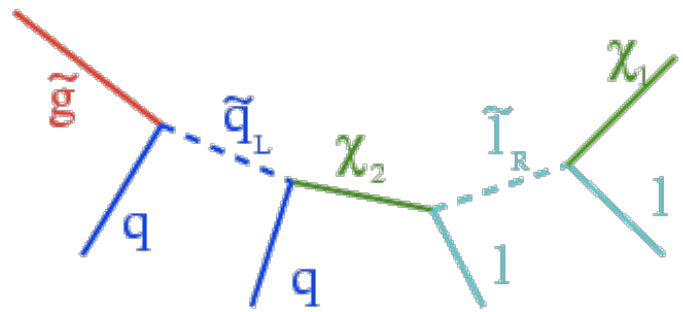




- Search for:
  - **Jets** from squark and gluino decays
  - **Leptons** from gaugino and slepton decays
  - **Missing Tranverse Momentum** (EtMiss) from (stable) LSPs [**Cold Dark Matter** candidate]

ATLAS SUSY search strategy

- Several complementary, generic SUSY search strategies on ATLAS
  - Search for **excess** of events with (b-)Jets, EtMiss, leptons



- Inclusive, "model independent" searches
- Compare with low mass mSUGRA benchmark (SU4)
- Sensitive to **any** model with strongly interacting particles decaying semi-invisibly

- Early studies; focus on understanding BGs, systematics, detector performance
- L ≅ few 10's – 100's nb^{-1}
- Check control regions
- First data-MC comparisons of **SUSY sensitive** observables

(Cuts loosened c.f. previous studies, for low luminosity)

Jets+EtMiss channels
- without/with Leptons
- with b-tagged Jets

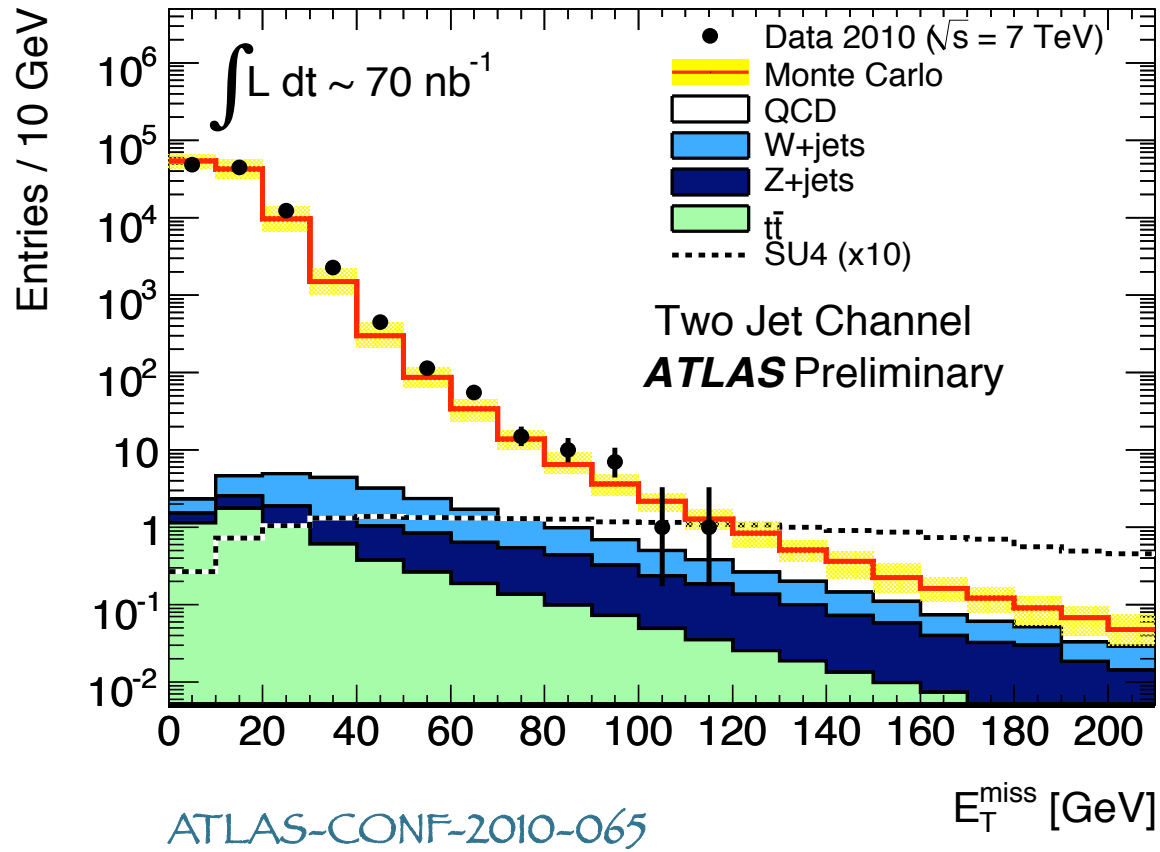
Many more, interesting results soon …

SUSY searches without leptons

- SUSY signal typically dominated by **squark** and **gluino** production (MultiJet+EtMiss)
- Generically most sensitive search mode
- Competitive limits achievable with very little data

Cuts: Jet-Pt > 70, 30 GeV

- Jets+EtMiss (0-lepton)
- = 1, ≥ 2, ≥ 3, ≥ 4-Jet channels
- QCD MC normalised to data (after dijet cuts)
- systematic uncertainties
  - Jet Energy Scale (25 – 40% on N_{evt})
  - Luminosity (11%)
  - Others smaller



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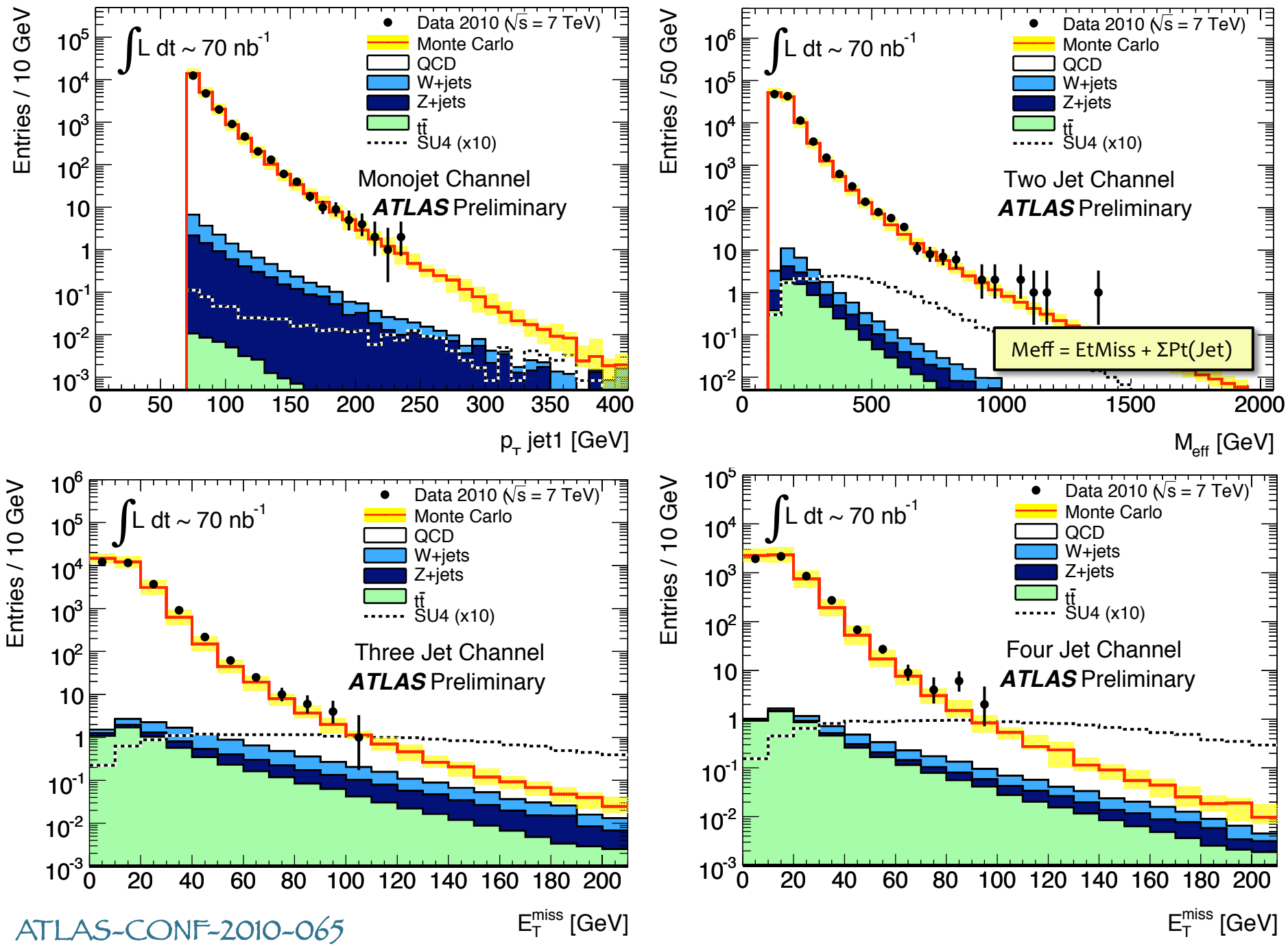
- Good description by MC of key observables (EtMiss, Meff … and many more)



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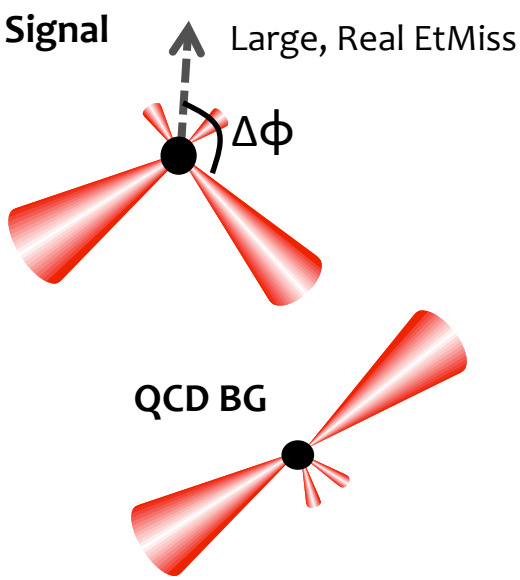
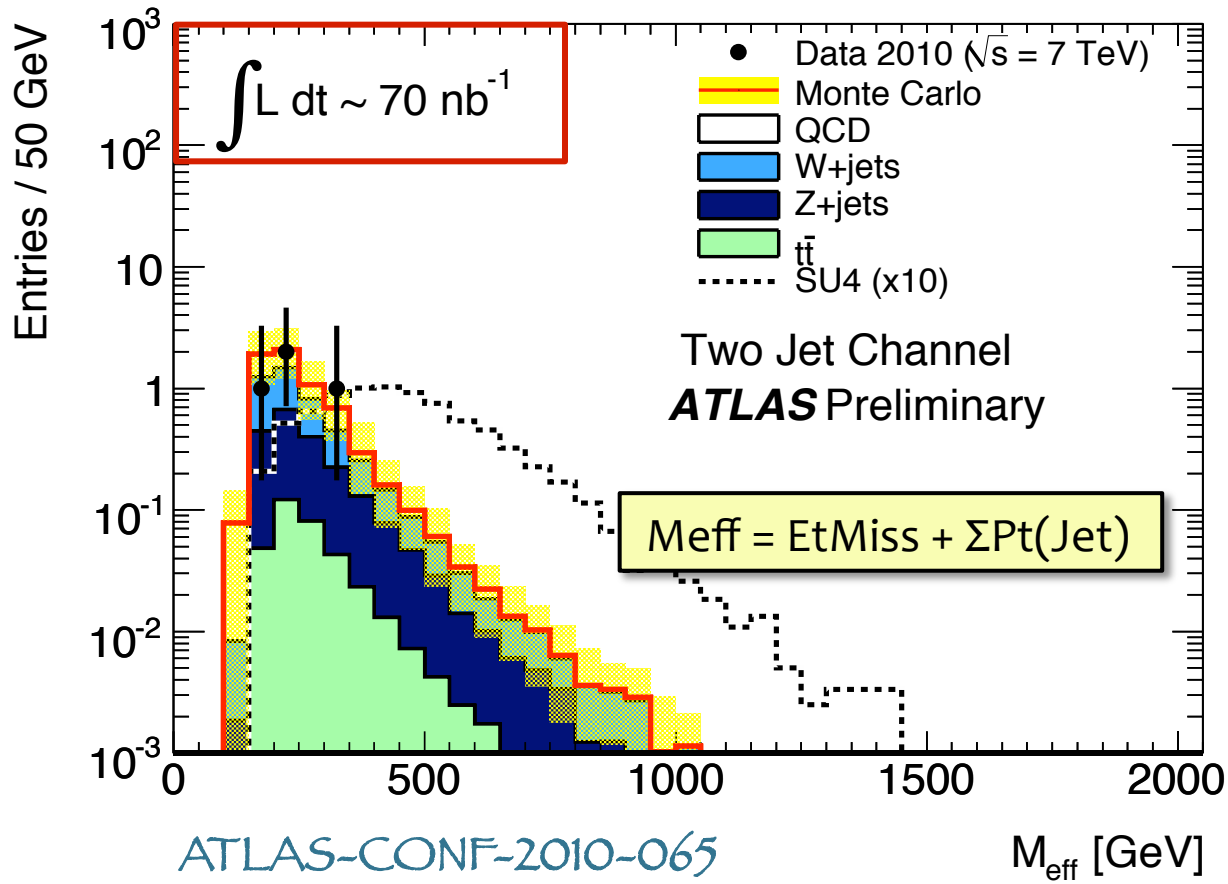
SUSY searches without leptons

EG.

2-Jets+EtMiss (0-lepton)

- SUSY cuts:
  - Jet-Pt > 70, 30 GeV
  - EtMiss > 40 GeV
  - $\Delta\phi$(Jet, EtMiss) > 0.2
  - EtMiss > 0.3×Meff





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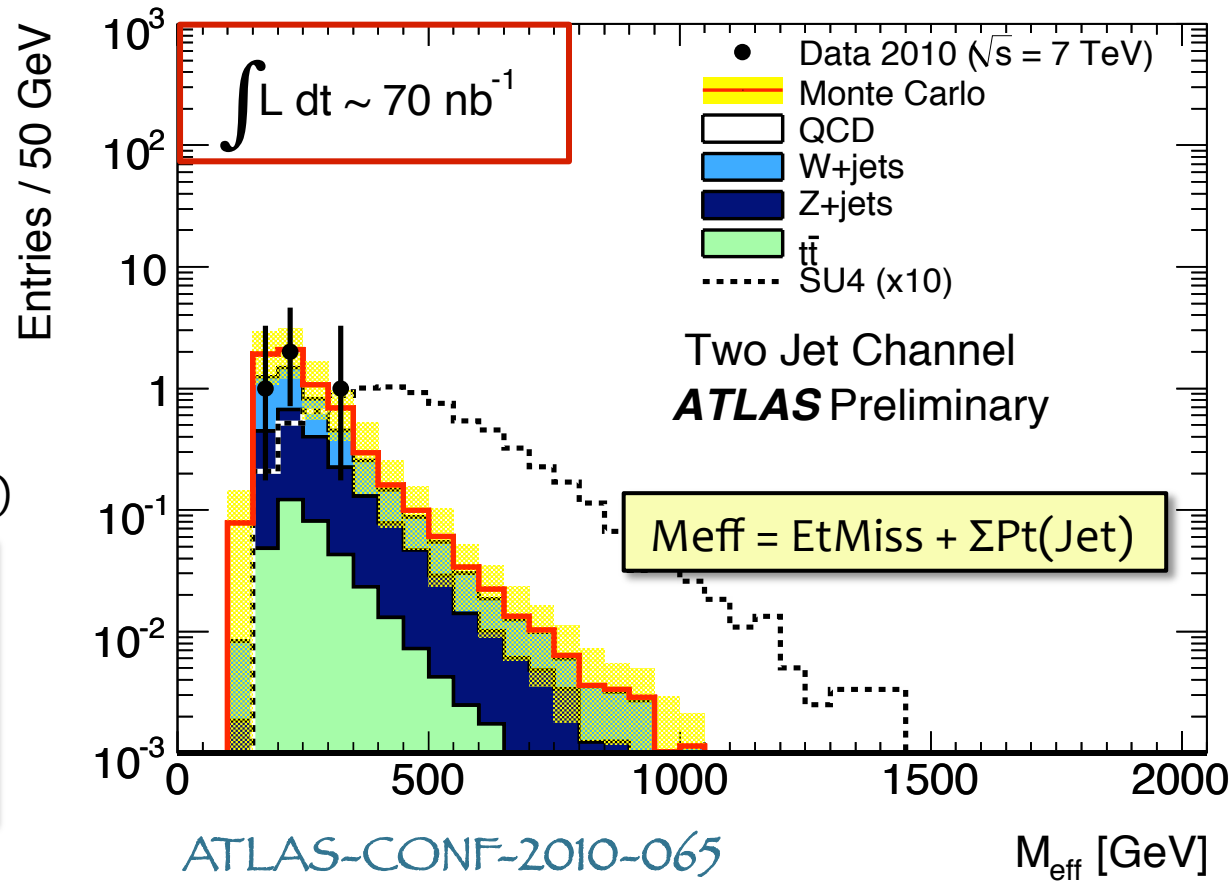
After SUSY cuts (inclusive channels)

	Data	SM expectation
2-Jet	4	6.6 ± 3.0
3-Jet	0	1.9 ± 0.9
4-Jet	1	1.0 ± 0.6

No significant deviations from expected SM BG



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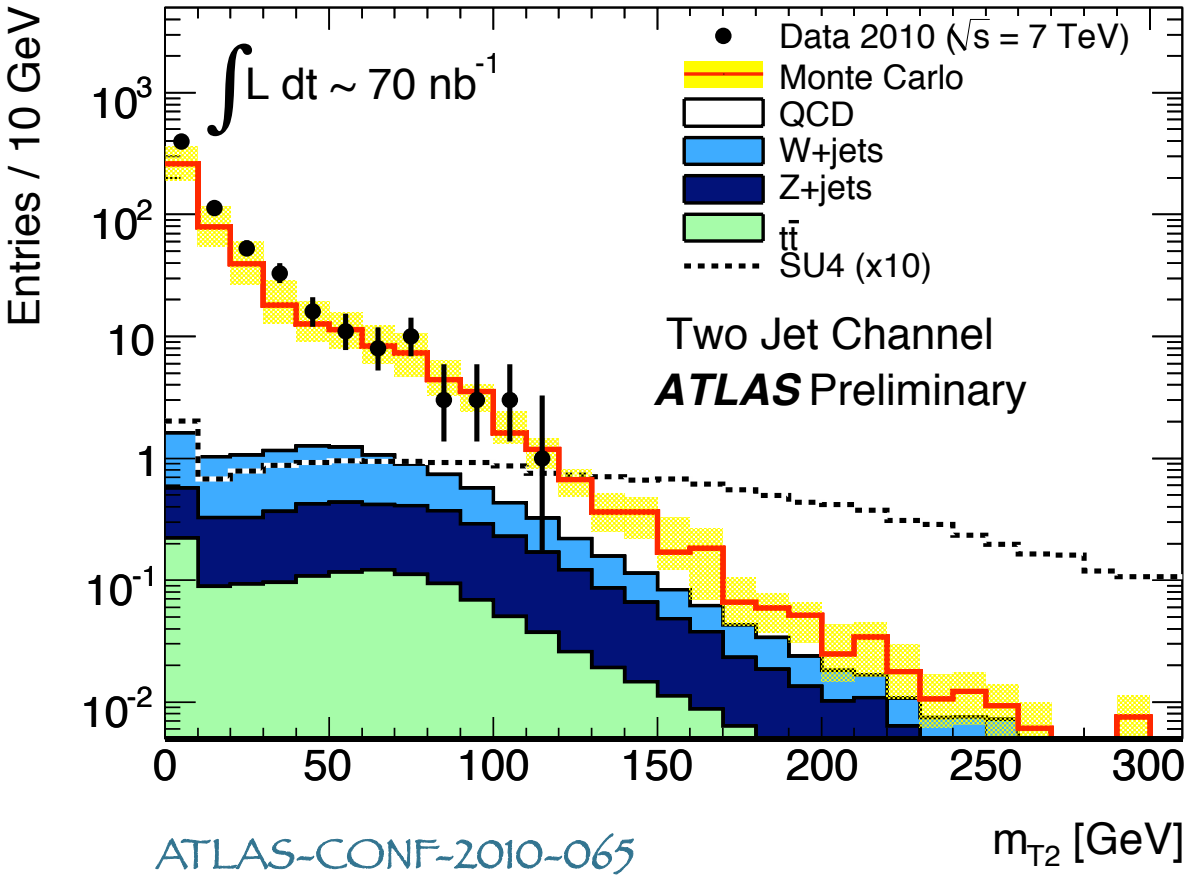
Mass variables for discovery?

- **stransverse mass** (M_{T2}): generalisation of transverse mass to pair decays
- Gives event-by-event lower bound on mass of any pair-produced semi-invisibly decaying particle



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General Properties:

- Small M_{T2} values if:
  - Jet-Pt small
  - EtMiss small
  - $\Delta\phi$(Jet,EtMiss) small
  - FS particles are from decay of "low mass" parents (e.g. W)

arXiv:0907.2713 [hep-ph]

SUSY searches with leptons

- In addition to Jets and EtMiss, SUSY events can copiously produce **leptons** (from gaugino, slepton, heavy flavour decays)

- Jets+EtMiss+1-Lepton

- 1 lepton requirement reduces QCD
- BG dominated by W+Jets (and QCD)
- normalised to data in control regions

- Good agreement with MC (1-e and 1-μ channels)

After all SUSY cuts:

	Data	SM expectation
1-e	2	3.6 ± 1.6
1-μ	1	2.8 ± 1.2

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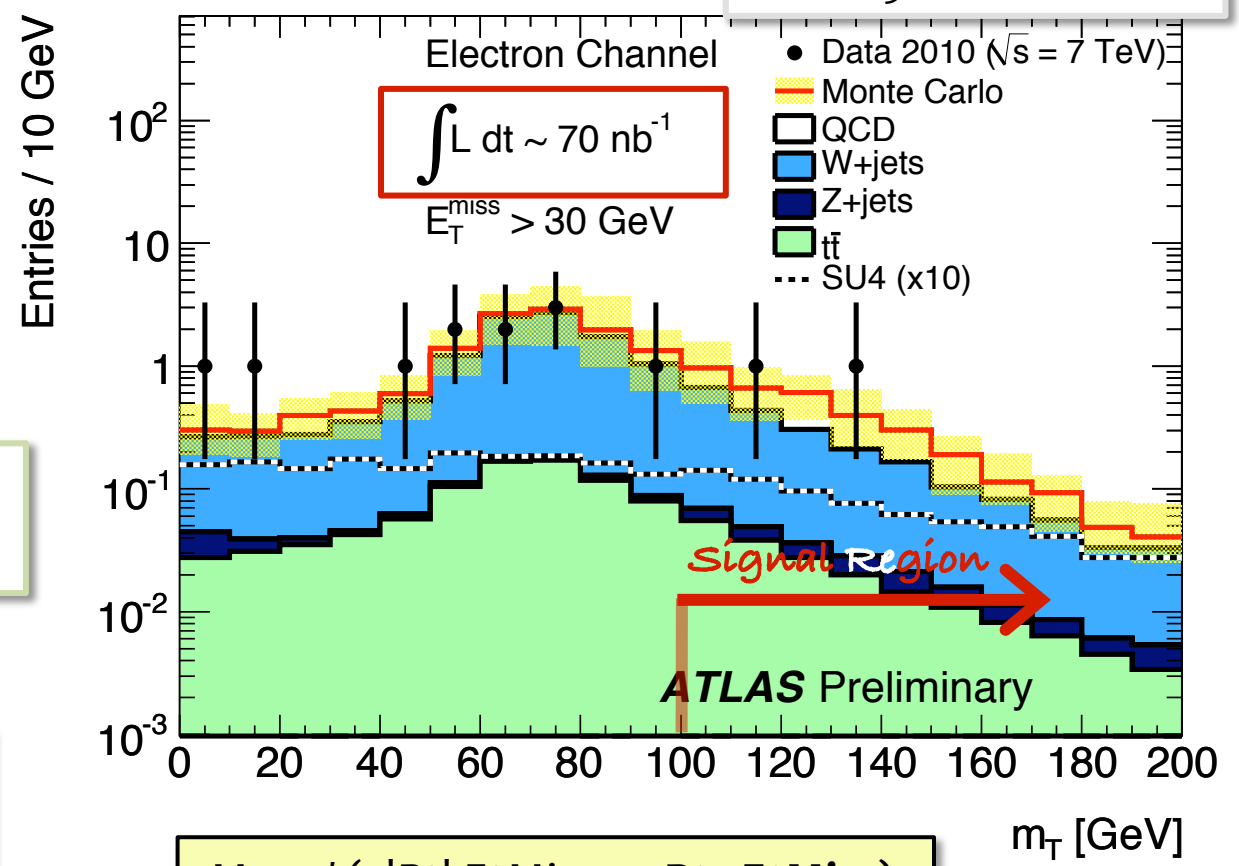
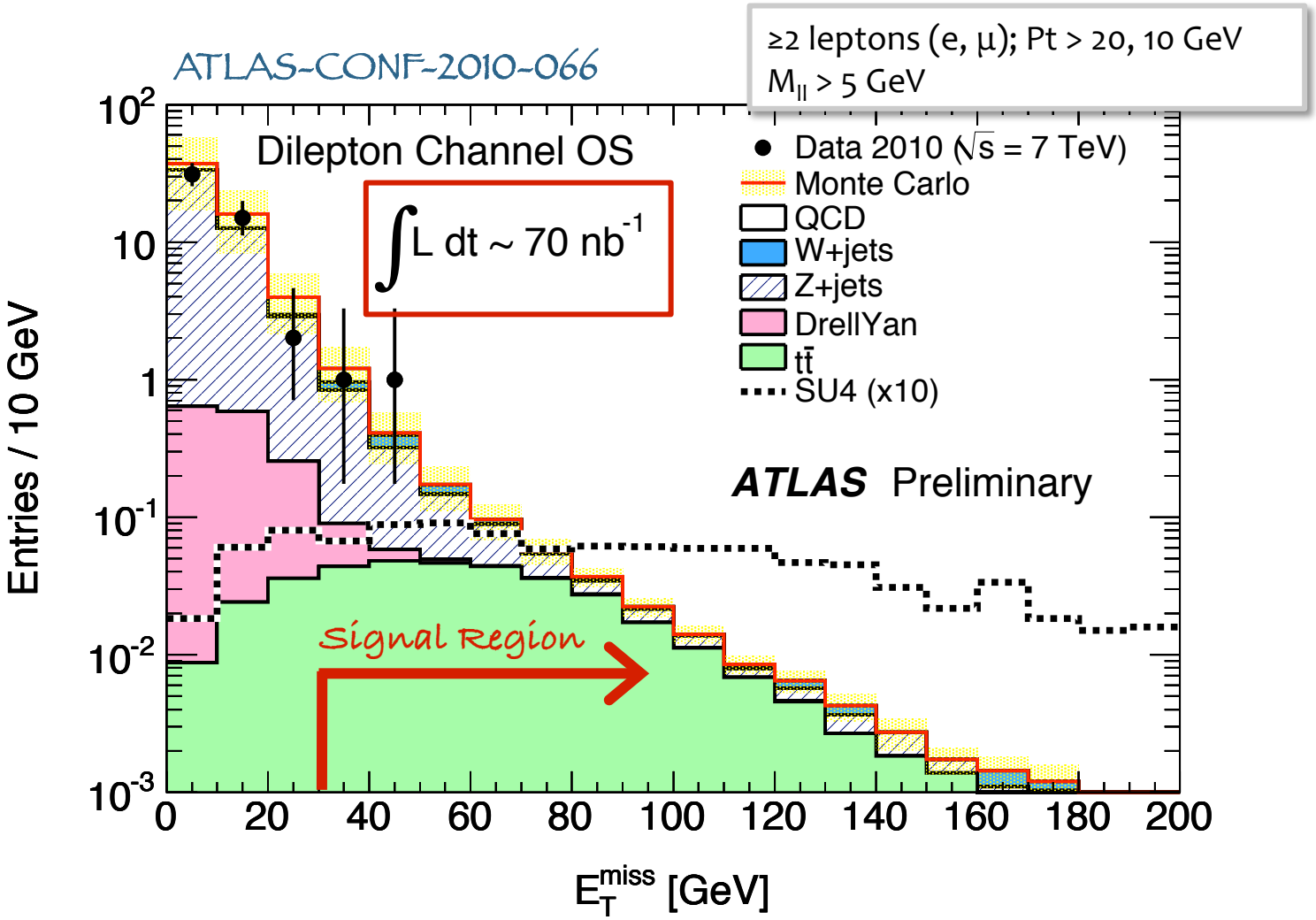
= 1 lepton (e, μ); Pt > 20 GeV
≥2 Jets; Pt > 30 GeV
EtMiss > 30 GeV



$M_T = \sqrt{(2|Pt|\ EtMiss - 2\mathbf{Pt}\ .\ \mathbf{EtMiss})}$

SUSY searches with leptons

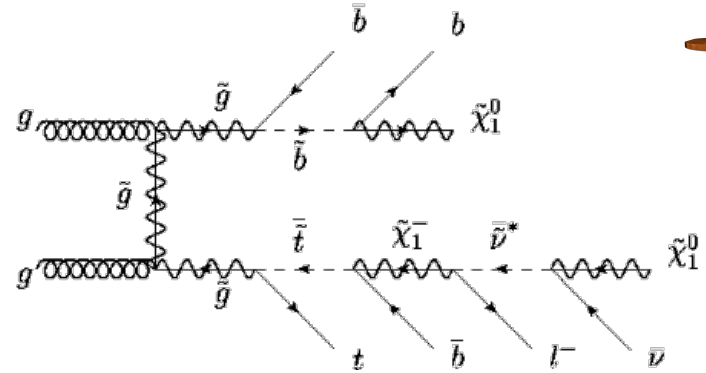


- 2-Lepton+EtMiss (OS and SS measured); Good agreement with MC

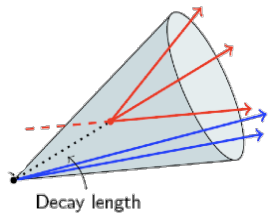
SUSY searches with b-Jets

- SUSY signals typically rich in **b-Jets**

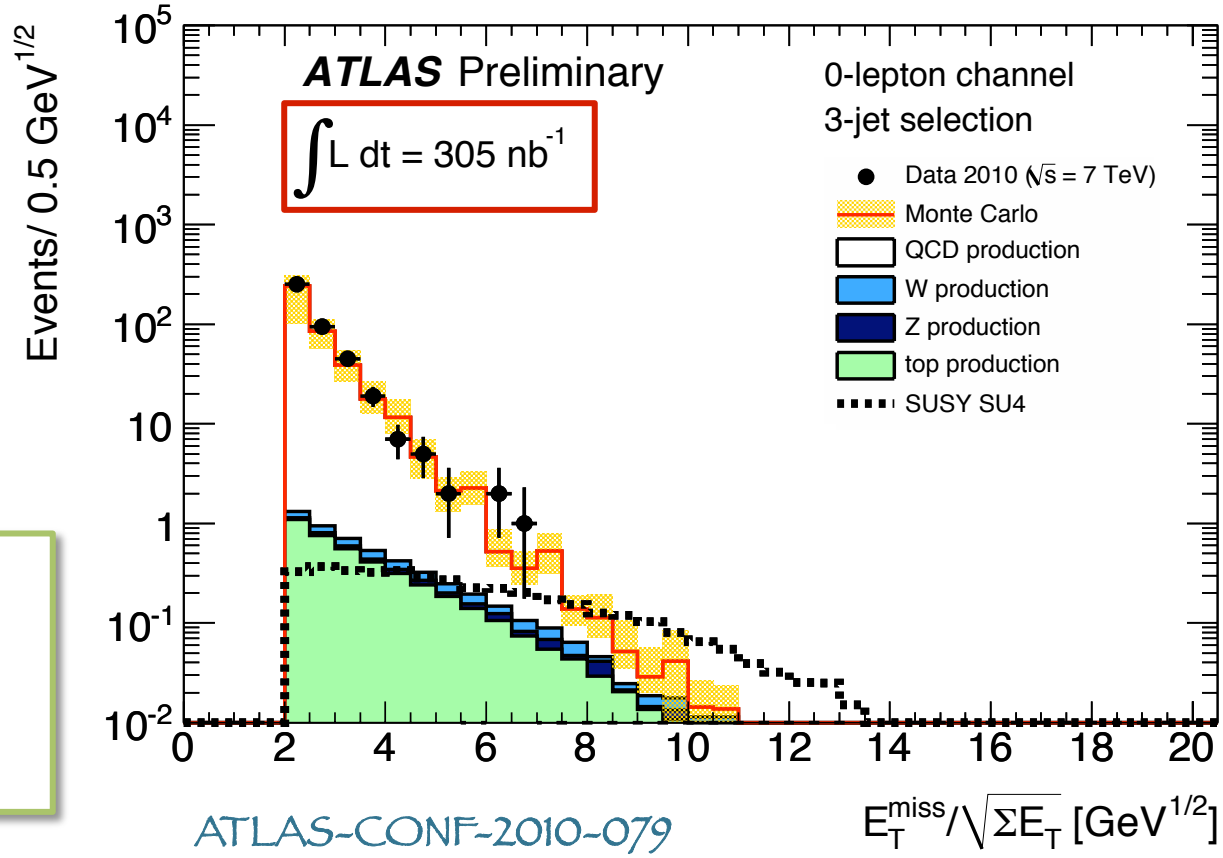
EG.



- B-tagging algorithm: reconstructed secondary vertices



- Decay length significance: $L/\sigma(L) > 6$
- $\varepsilon \cong O(50\%)$
- 2, 3-Jet; 0, 1-lepton channels studied (at least 1 b-Jet)
- Cut on EtMiss **significance**: $EtMiss/\sqrt{\Sigma E_T} > 2\ \sqrt{GeV}$



- Good agreement between data and MC for range of observables (before and after b-tagging)

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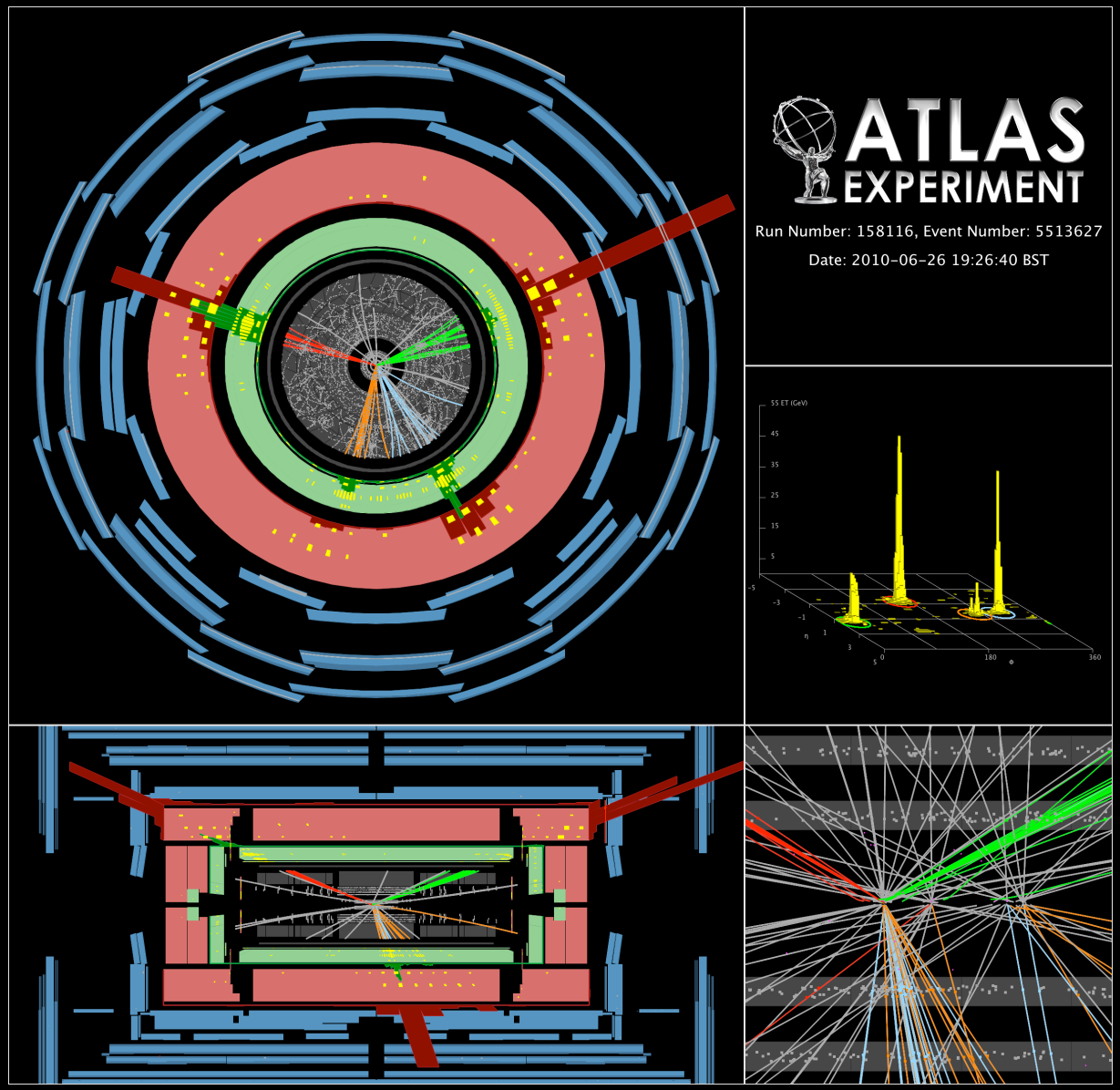
MultiJet+EtMiss

ATLAS-CONF-2010-065



Meff = 1.5 TeV (3 jets)
= 1.65 TeV (4 jets)

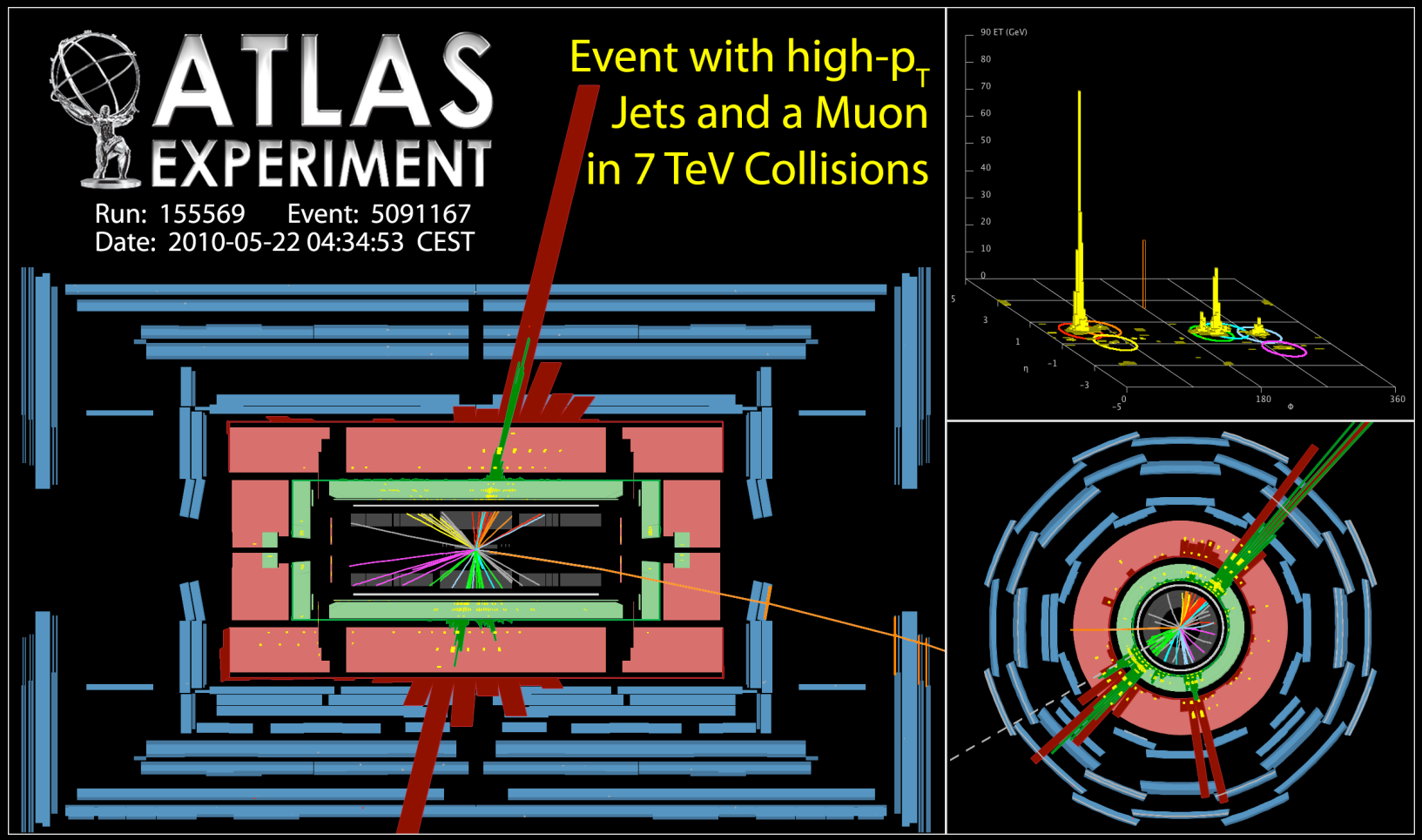
All high energy jets associated with same vertex

EtMiss = 100 GeV

Fails final selection ($\Delta\phi$(Jet, EtMiss))

MultiJet+EtMiss+1-Lepton

ATLAS-CONF-2010-066



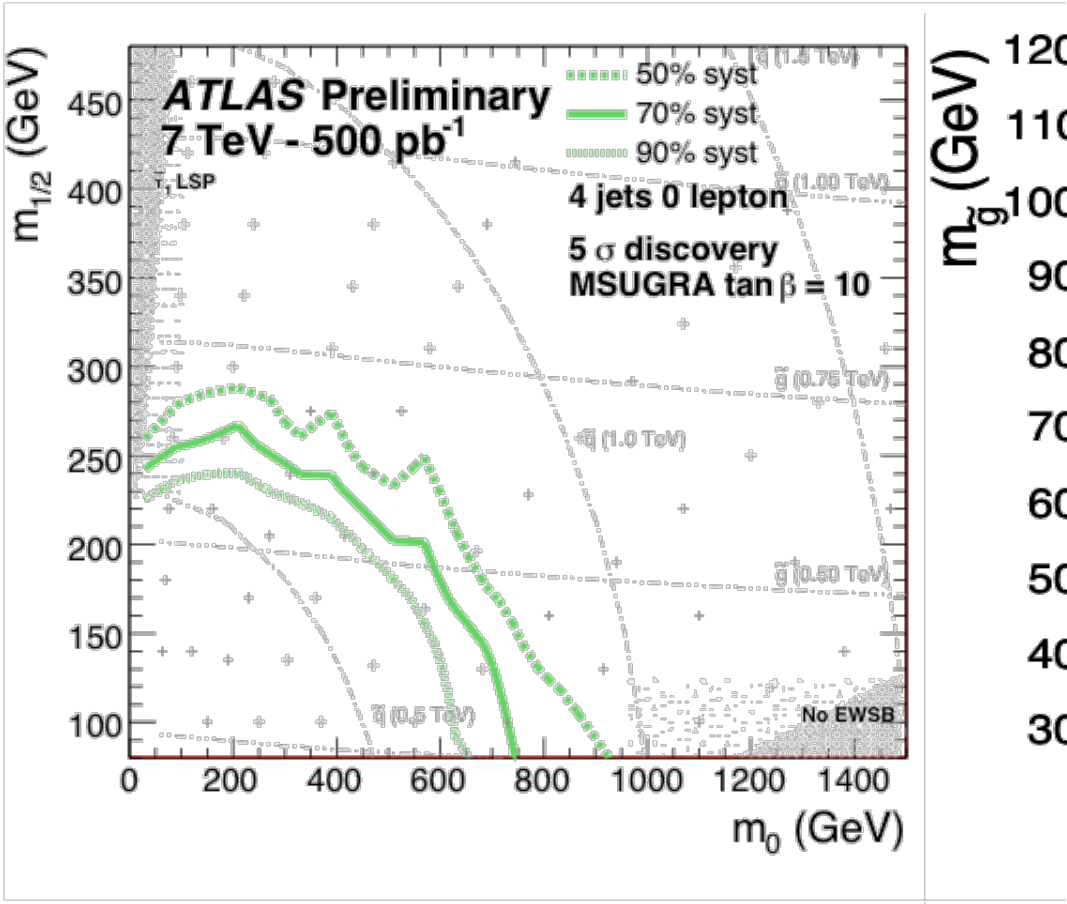
Meff = 915 GeV (2 jets)
= 1.12 TeV (all jets)

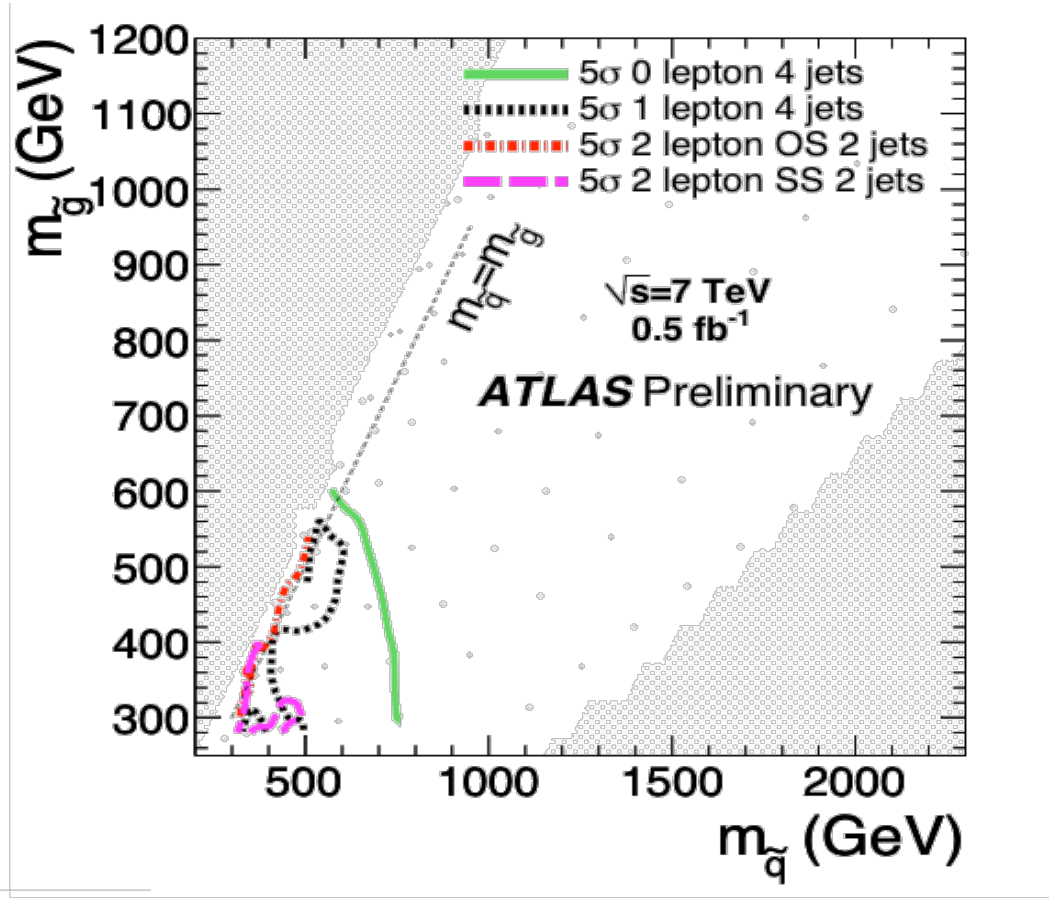
EtMiss = 118 GeV

No secondary vertex

1 well isolated, positive muon, Pt = 25 GeV, η = 2.33

SUSY prospects at √s = 7TeV





- Significant increase in sensitivity with full 2010 integrated luminosity

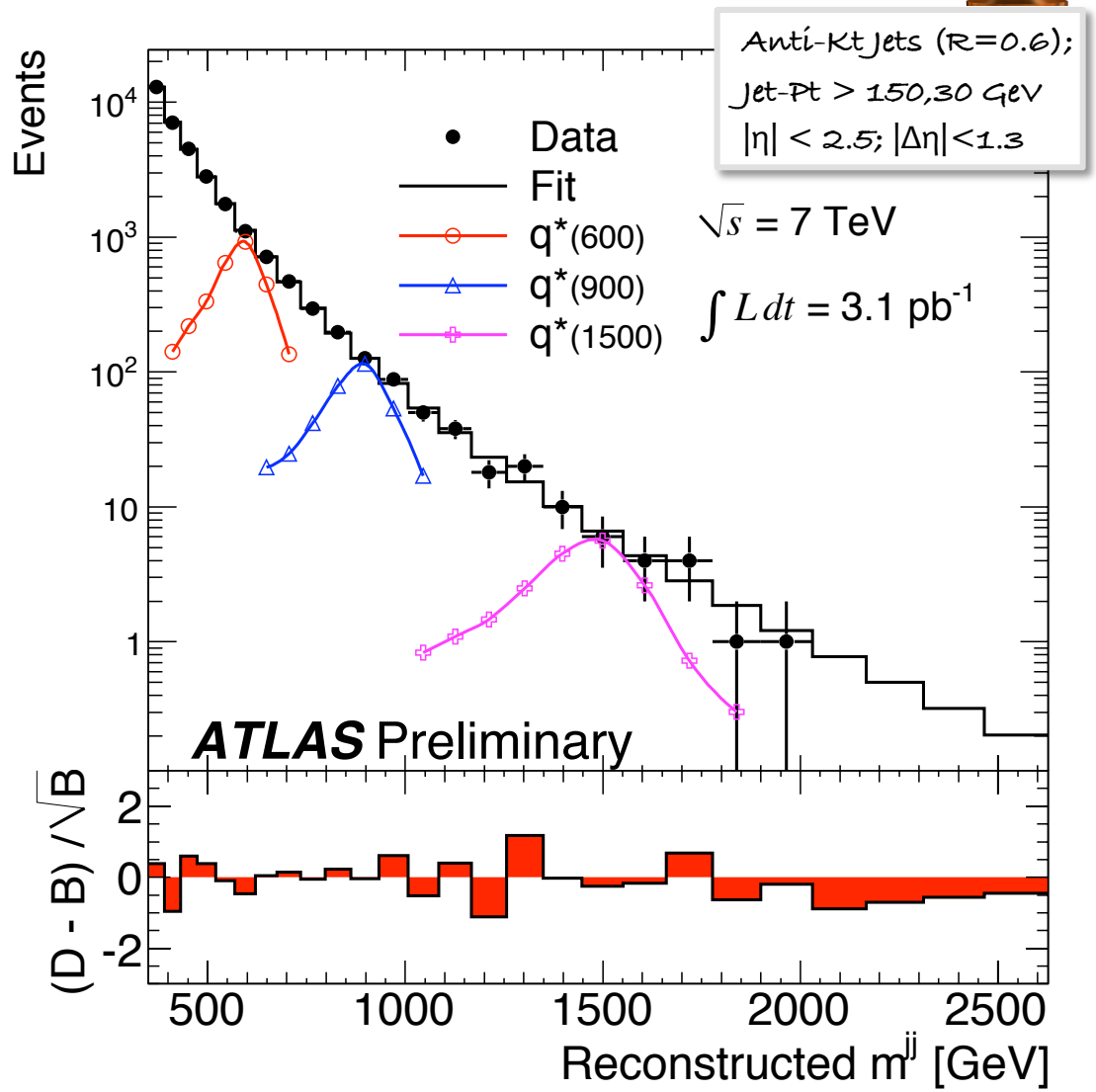
Other BSM searches

ATLAS search for Heavy Dijet Resonances

- Several BSM models predict new heavy particles, decaying to energetic dijets
- BenchMark: excited quarks (q*) e.g. in compositeness models
- Dijet Invariant Mass (very sensitive to New Physics)

$$M_{jj} = \sqrt{(E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2}$$

- Data well described by **smooth fit** function
- Multiple statistical tests reveal no significant features
- ➔ set limits on q* mass



ATLAS-CONF-2010-093; Phys Rev Lett 105, 161801 (2010)

Dijet resonances: q* mass limit

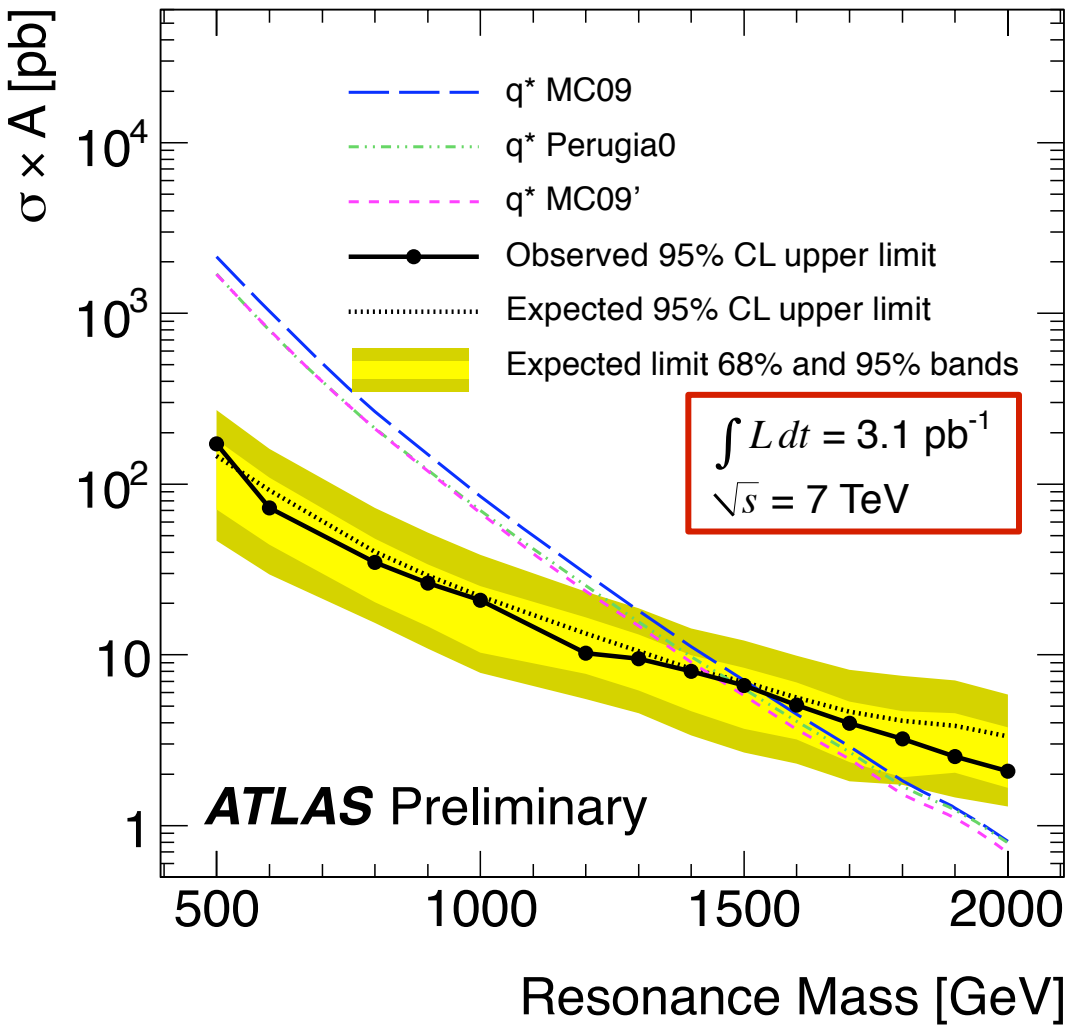
- Systematic uncertainties
  - Jet Energy Scale
  - BG fit parameters
  - Luminosity
  - Jet Energy Resolution

- ATLAS result excludes (95% CL)

$0.5 < m_{q*} < 1.53$ TeV

- 1st ATLAS result surpassed previous best limit
  - $m_{q*} > 1.26$ TeV (with 0.3 pb^{-1})

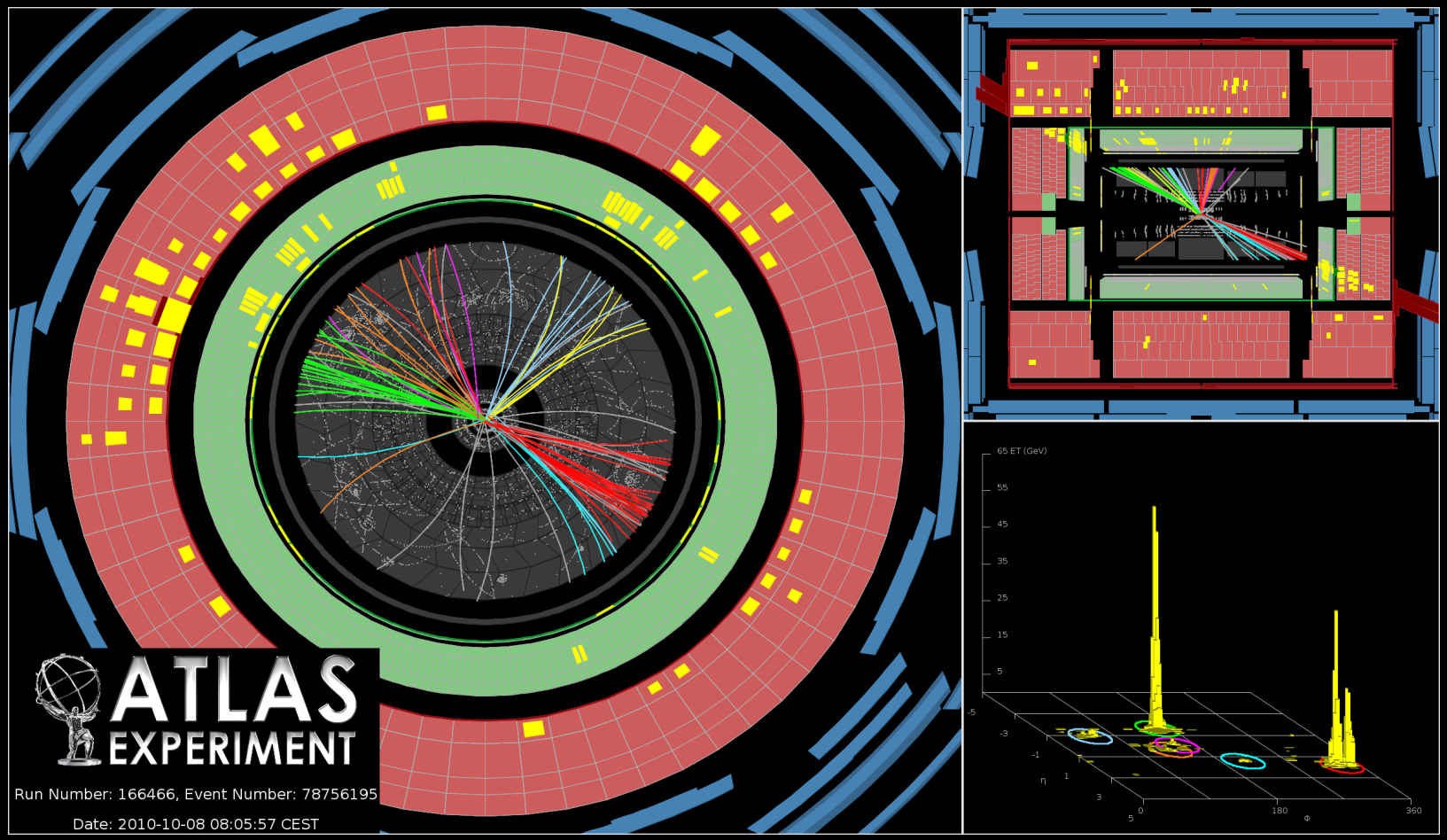
c.f. Tevatron $m_{q*} > 0.87$ TeV (1.13 fb^{-1})
CDF Coll., Phys Rev D79 (2009) 112002



ATLAS-CONF-2010-093; Phys Rev Lett 105, 161801 (2010)

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

ATLAS Dijet event



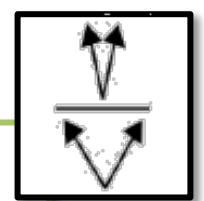
M_{jj} = 3.7 TeV

Pt(Jet1) = 670 GeV
Pt(Jet2) = 610 GeV

ATLAS search for Contact Interactions

- **Goal:** Search for **New Physics** in non-resonant dijet production (at high M_{jj})
- Benchmark Signal: **quark contact interaction** with compositeness scale Λ
- e.g. quark compositeness; if √s << Λ compositeness manifested as effective 4-fermion contact interaction

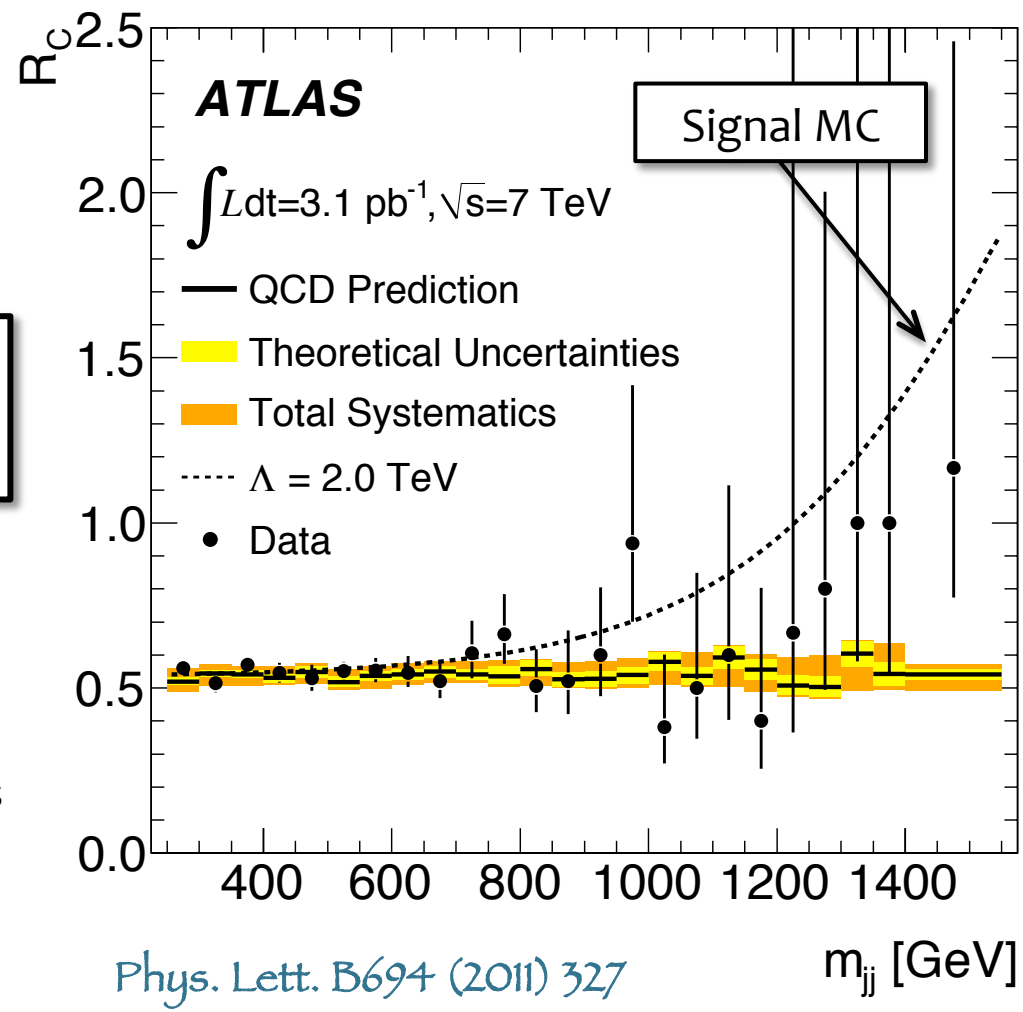
- Search for deviations in dijet angular distributions
- Observables:



$$R_c = \frac{N(|\eta_{1,2}| < 0.7)}{N(0.7 < |\eta_{1,2}| < 1.3)}$$

$$X = \exp(|y_1 - y_2|)$$

- (LO) QCD: approximately flat distributions
- New Physics (more "central"): rise in R_c and at low X at high M_{jj}



Phys. Lett. B694 (2011) 327

Angles → Contact Interaction Limit

$$\mathcal{L}_{qqqq}(\Lambda) = \frac{\xi g^2}{2\Lambda_q^2}\bar{\Psi}_q^L\gamma^\mu\Psi_q^L\bar{\Psi}_q^L\gamma_\mu\Psi_q^L$$

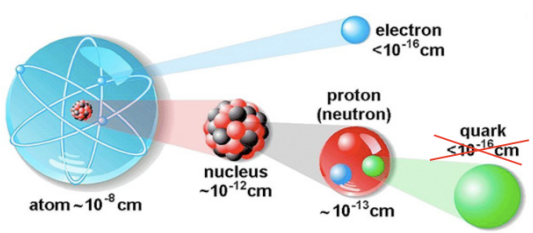
$g^2/4\pi = 1$ and the quark fields Ψ_q^L are left-handed.

- Good agreement between data and NLO QCD
- systematic uncertainties
  - JES, QCD scale uncerts., PDFs
- ATLAS excludes (95% CL):

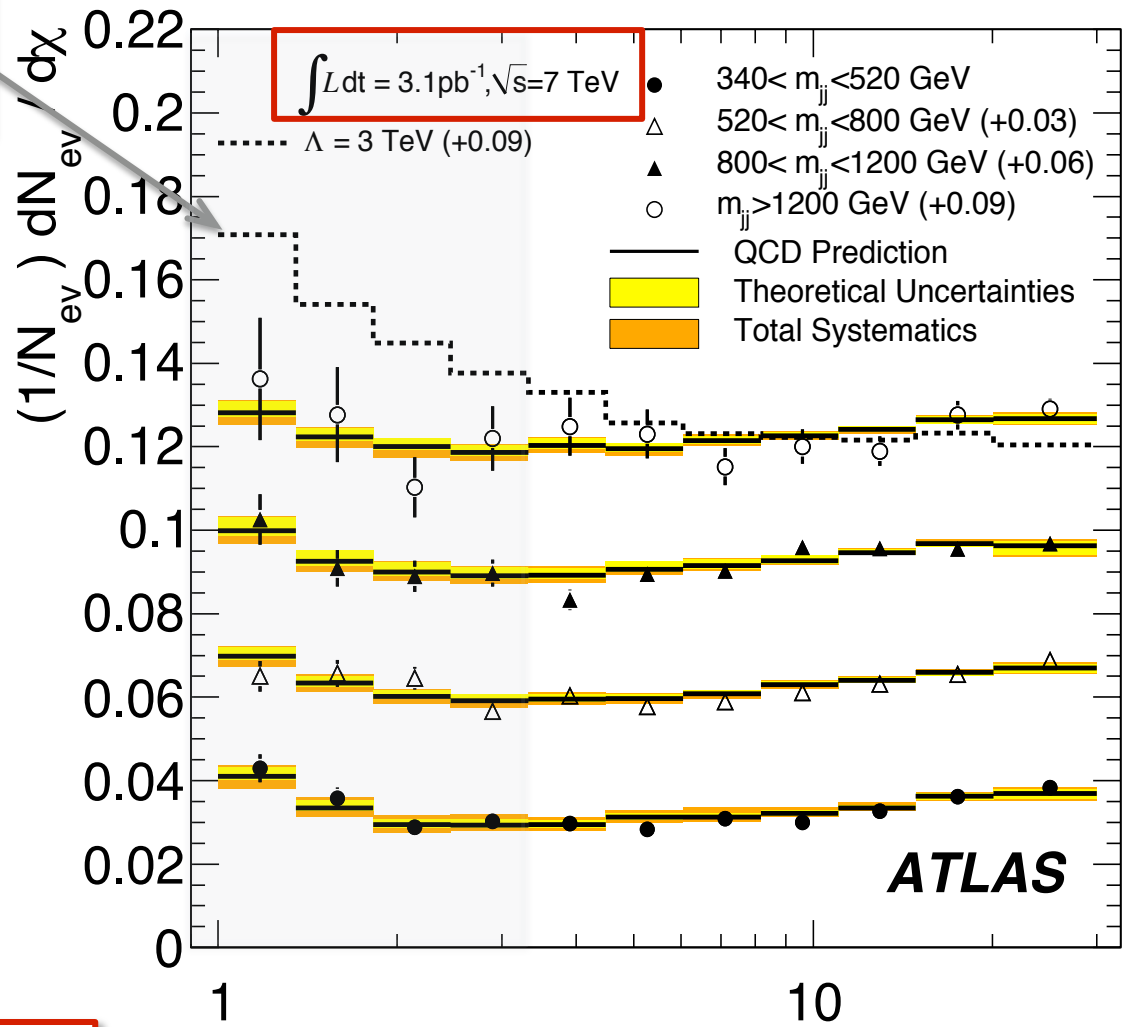
$\Lambda < 3.4$ TeV

Previous Tevatron exclusion:
$\Lambda < 2.8 - 3.1$ TeV

Do Coll., Phys Rev Lett 103:191803 (2009)



$< 6\times10^{-18}$ cm



Phys Lett B694 (2011) 327

$\chi = e^{|y_1 - y_2|}$

Multi-body final states at High Mass

- **Goal:** Search for evidence of Quantum Gravity States with large cross section
  - "General search" in context of TeV-scale Gravity Models with scale M_D (e.g. Black Holes, String Balls) (expect deviation from SM at High Mass)

- Assumptions:
  - Decays of heavy gravitational objects democratic to SM particles
  - Signature of several high-Pt objects (Jet, e, μ, γ)

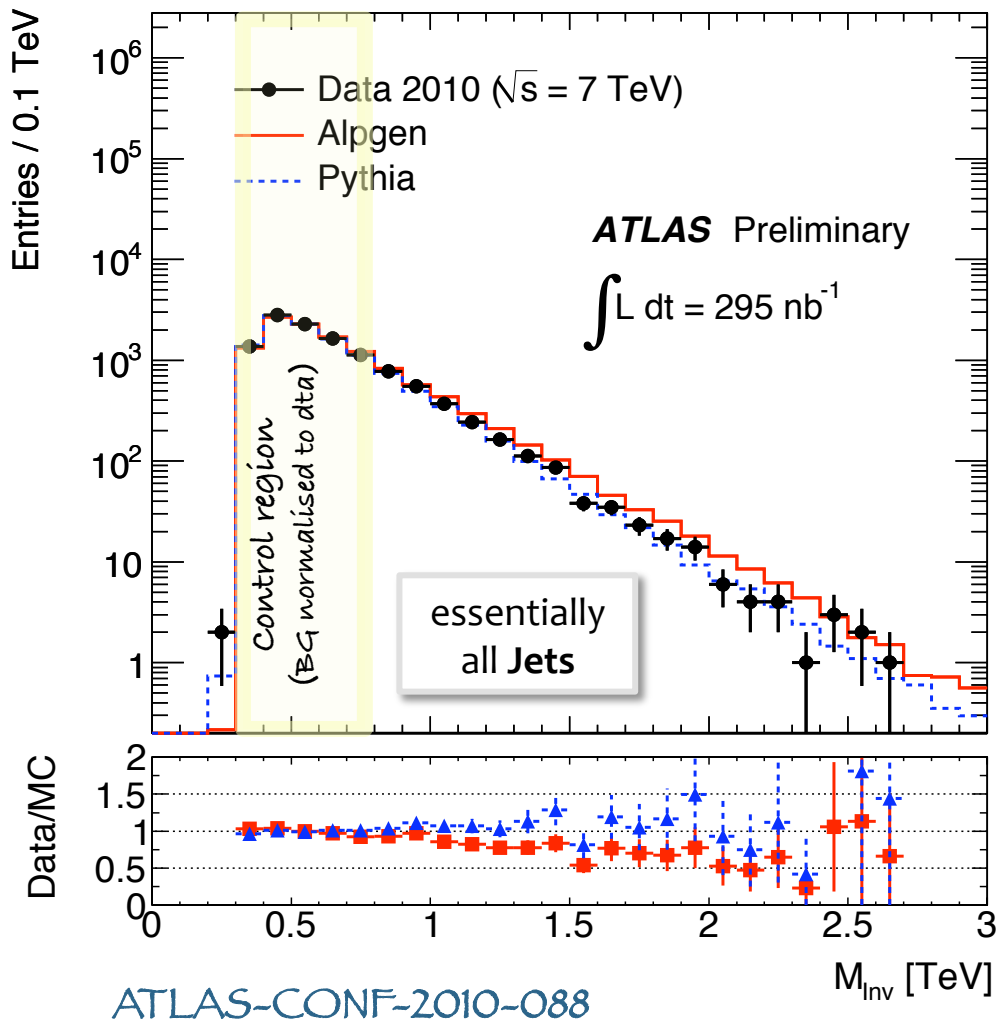
- Observable:
  - M_{inv} with ≥3 objects in F.S.

$M_{inv} = \sqrt{|p^{\mu}p_{\mu}|}$ with:

$p^{\mu} = \Sigma p^{\mu}(i) + (EtMiss, EtMissx, EtMissy, 0)$

- Control Region:
  - SumPt = ΣPt > 300 GeV
  - 300 < M_{inv} < 800 GeV

Previous limits (ADD model): $M_D \geq 800$ GeV



ATLAS-CONF-2010-088

Multi-body final states at High Mass

- Signal Region:
  - SumPt = ΣPt > 700 GeV
  - M_{inv} > 800 GeV

- Agreement with SM
- systematic uncertainties
  - JES, choice of BG MC, PDFs

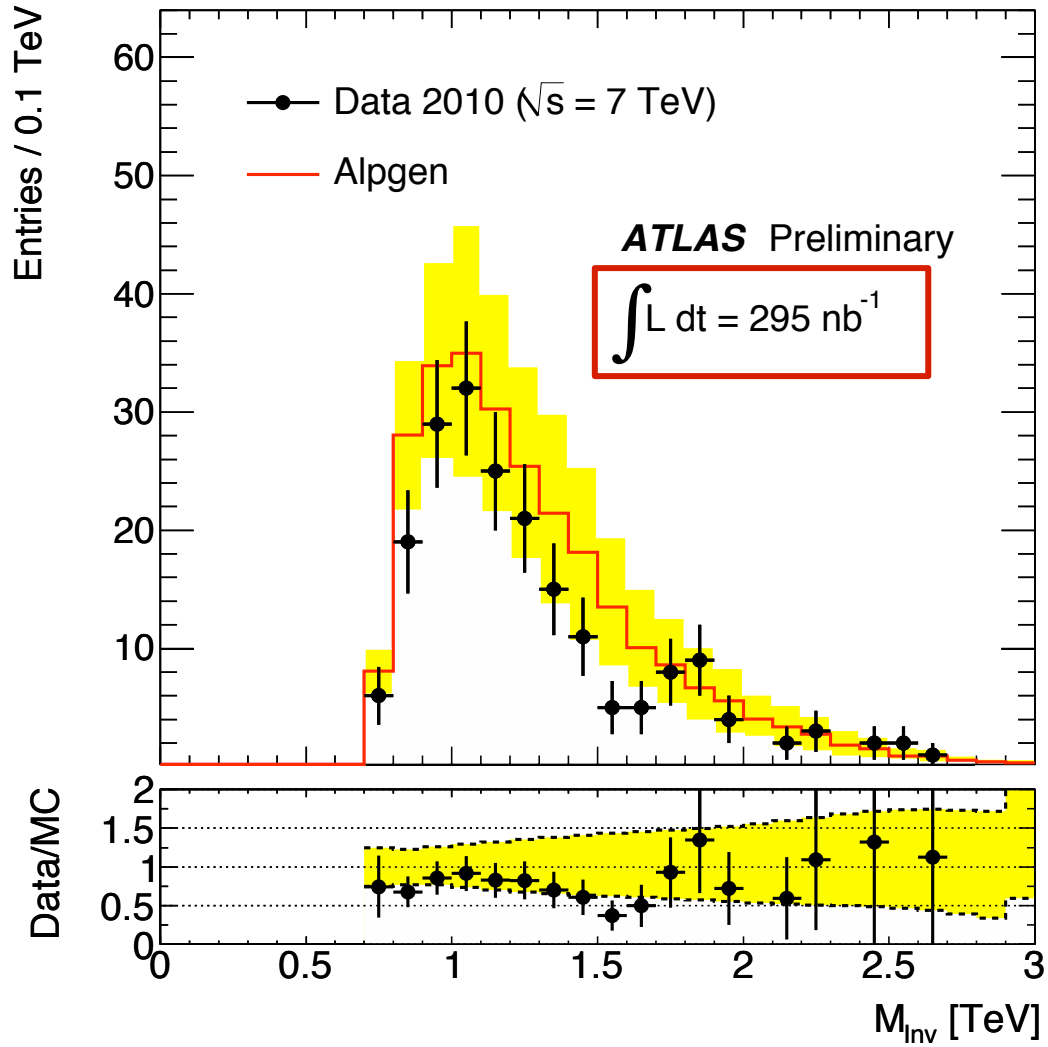
Data	SM expectation
193	295 ± 18 ± 84

- 95% CL upper limit on **σ×A:**

  0.34 nb

- Corresponding σ < 0.6 nb (using BenchMark models to estimate acceptance A)

  c.f. some models with σ ≅ O(100nb)

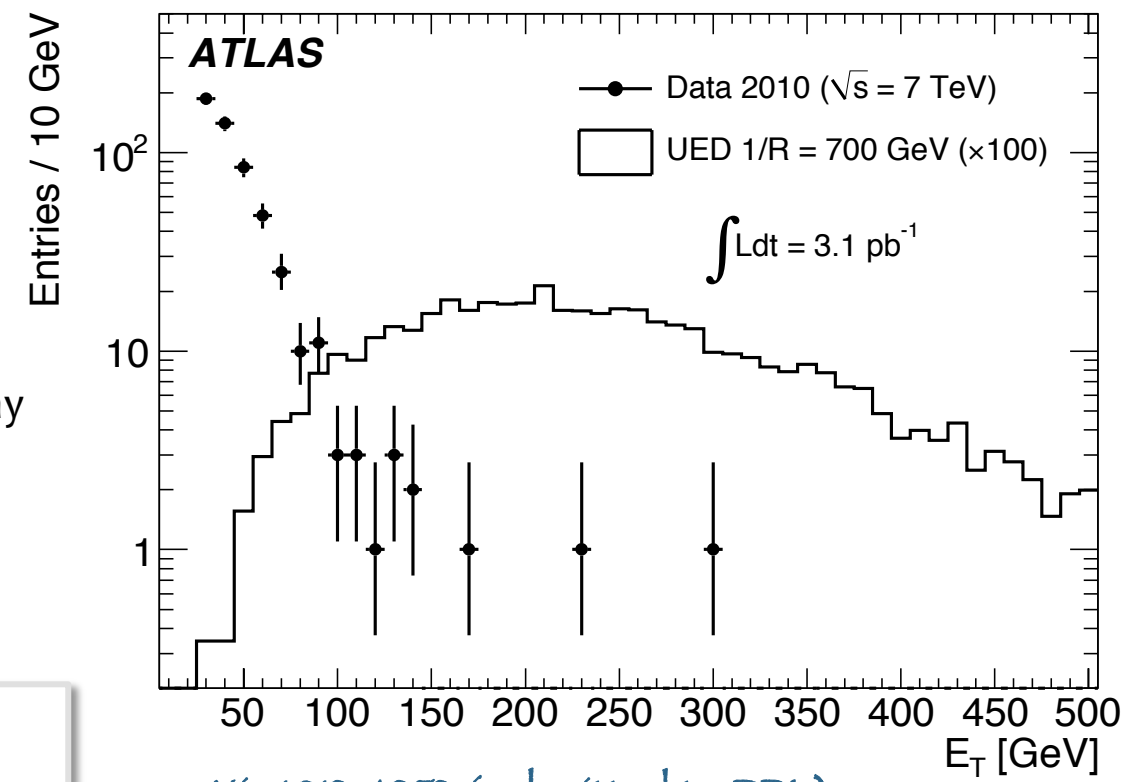


ATLAS-CONF-2010-088

Search for final states with γγ and EtMiss

- **Goal**: Search for final states with two photons and non-interacting particles
- Sensitive to certain **New Physics** e.g. Universal Extra Dimensions (UED), GMSB SUSY
- SM rate small; main source = W/Z+γγ; cross sections of a few fb

- Interpreted in context of UED
  (Postulates existence of extra spatial dimensions in which SM fields can propagate; KK excitations)
- Benchmark Model: one TeV^{-1} sized UED, with compactification radius **R**
- KK particles (pair-produced) decay to pair of γ*'s (LKPs), which decay 100% to γγ+GG
- Final State: γγ+EtMiss+X

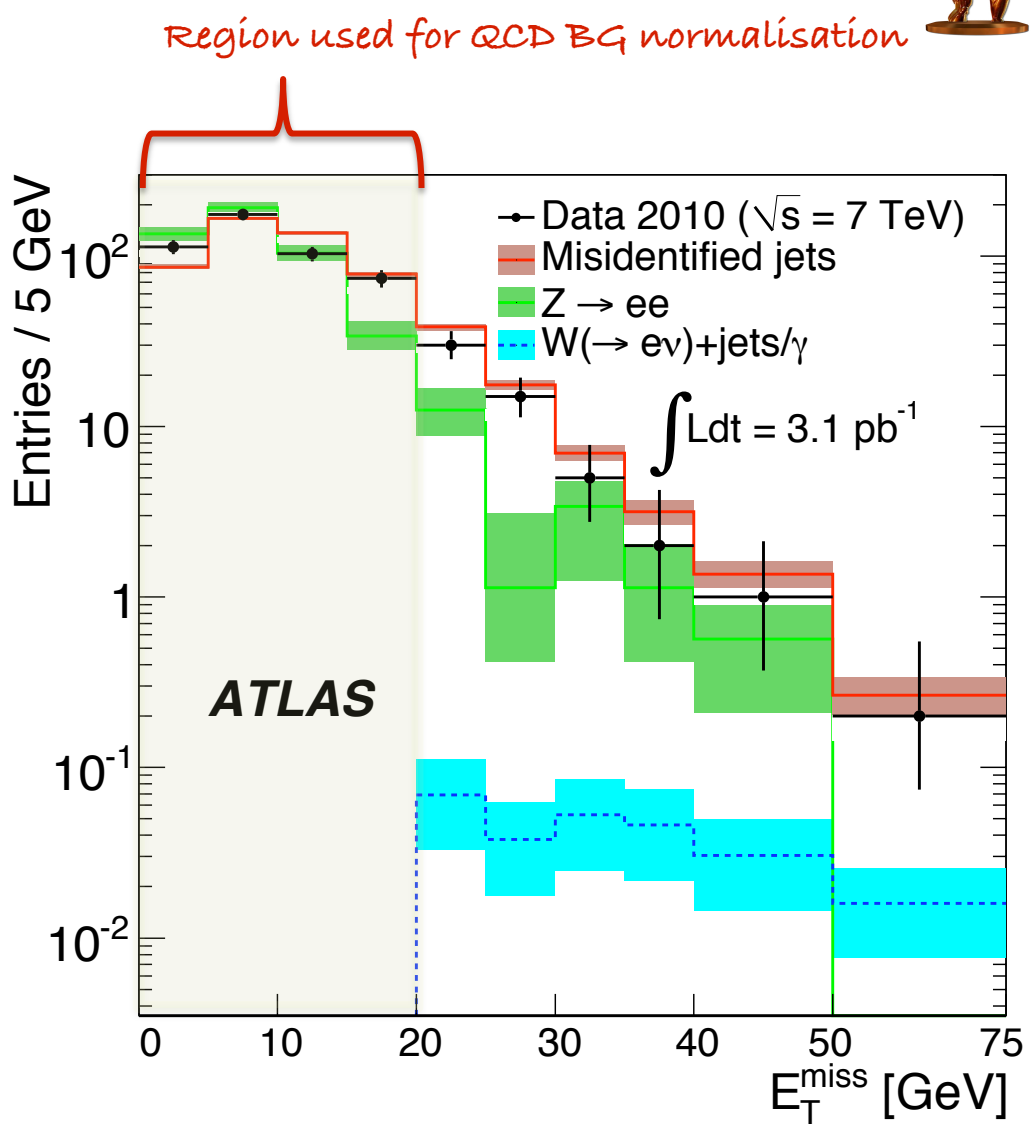


arXiv:1012.4272 (submitted to PRL)

- Cuts:
- ≥2 isolated photons, Et > 25 GeV
- |η| < 1.81 (except 1.37 < |η| < 1.52)

Search for final states with γγ and EtMiss

- BGs (from data-driven methods):
- "QCD":
  - γγ; γ+Jet, MultiJet (mis-ID) (MET due to instrumental resolution)
  - Zee; mis-identified Jets samples used to model EtMiss spectrum; normalised in fit region
- Weν (with genuine EtMiss)
  - Normalisation from W+γ
  - EtMiss shape from W+Jets
  - Flatter as function of EtMiss c.f. QCD (significant contribution at high EtMiss)



arXiv:1012.4272 (submitted to PRL)

Search for final states with γγ and EtMiss

- Signal Region:

  (Keep expected BG below 1 event)

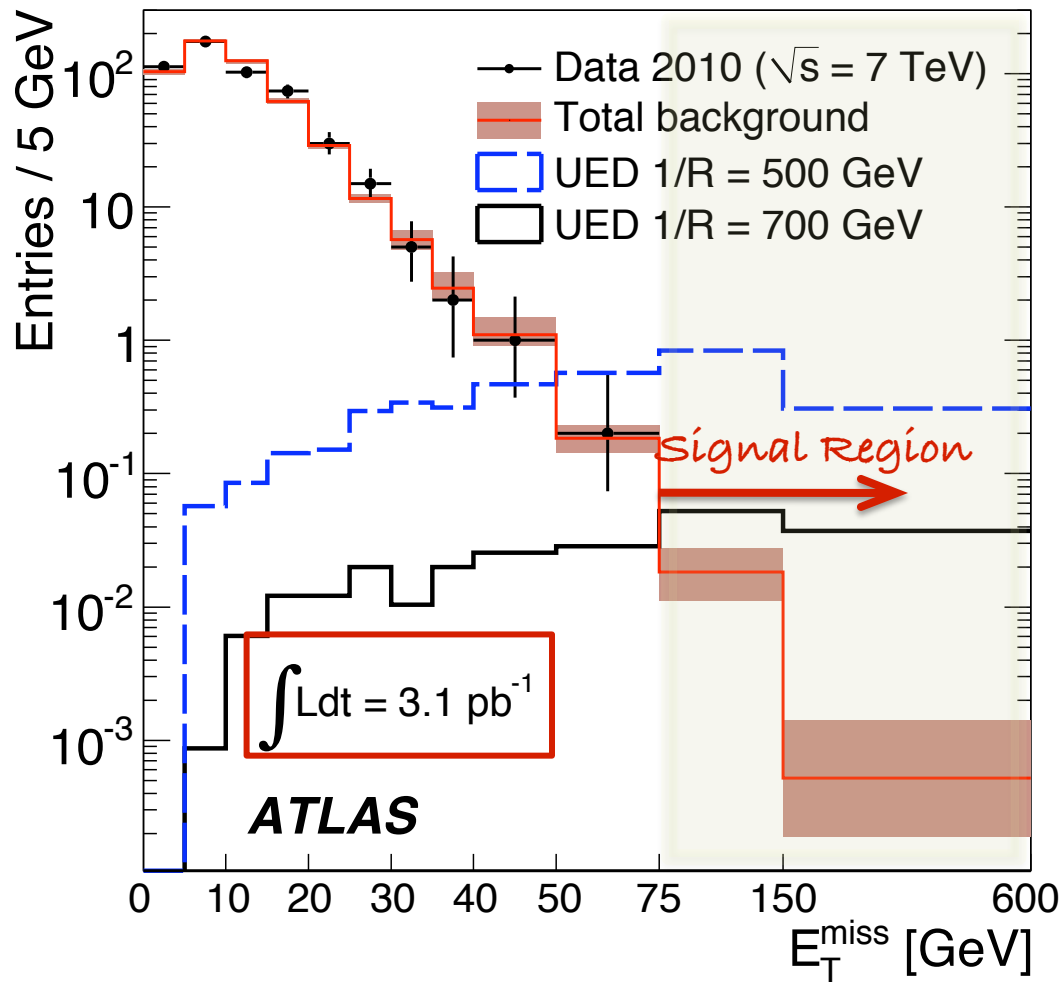
Data	SM expectation
0	0.32 ± 1.6

- Good agreement with total BG prediction
- Set limit on UED production cross section
- ATLAS excludes (95% CL)

  1/R < 728 GeV

c.f. Tevatron exclusion: 1/R < 477 GeV

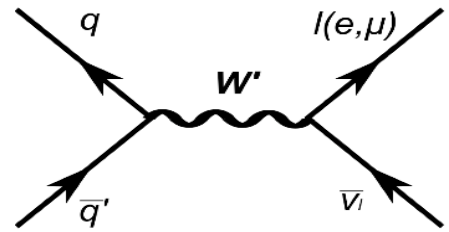
Do Coll., Phys Rev Lett, 105 (2010) 221802



arXiv:1012.4272 (submitted to PRL)

Search for W' with early ATLAS data

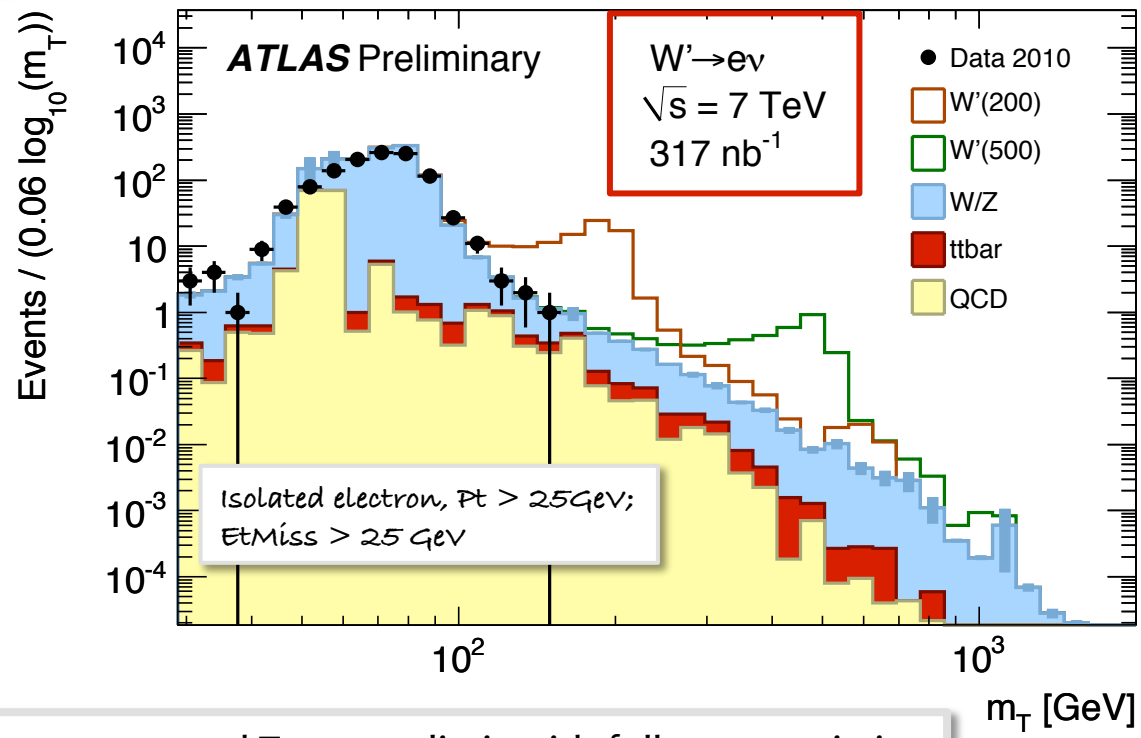
- Search for high mass states decaying to lν e.g. heavy, charged gauge bosons (common to many BSM models)
- BenchMark Signal: Sequential SM W'



- Search for evidence of resonance in **transverse mass** spectrum

$$M_T = \sqrt{2.Pt.EtMiss\,(1-\cos\phi)}$$

ATLAS-CONF-2010-089



- Good agreement with MC
  - No evidence for existence of W'
  - ➔ set limit on SSM W' mass
- Systematic uncertainties
  - Luminosity, electron ID, BG estimation
- Using W' (σ×BR), ATLAS excludes:

$M_{W'} > 465$ GeV (95% CL)

Current Tevatron limit: $M_{W'} > 1.0$ TeV

Do Coll. Phys Rev Lett 100 (2008) 031804

expect to exceed Tevatron limit with full 2010 statistics

Summary & Outlook

- ATLAS is now exploring uncharted territory at the **TeV scale**
  - In 2010, 45 pb^{-1} of pp collision data have been collected at $\sqrt{s}$ = 7 TeV
  - Detector working well, performance under control; things progressing quickly
- Already extended limits for New Physics, beyond previous experiments
- Important benchmark searches: W' (Z'), quark compositeness, …
- SUSY searches underway
  - Higher sensitivity searches and limits exceeding Tevatron with full 2010 dataset
- Sensitivity to New Physics supported by good understanding of BGs

Much more on the way…

BackUps

More information

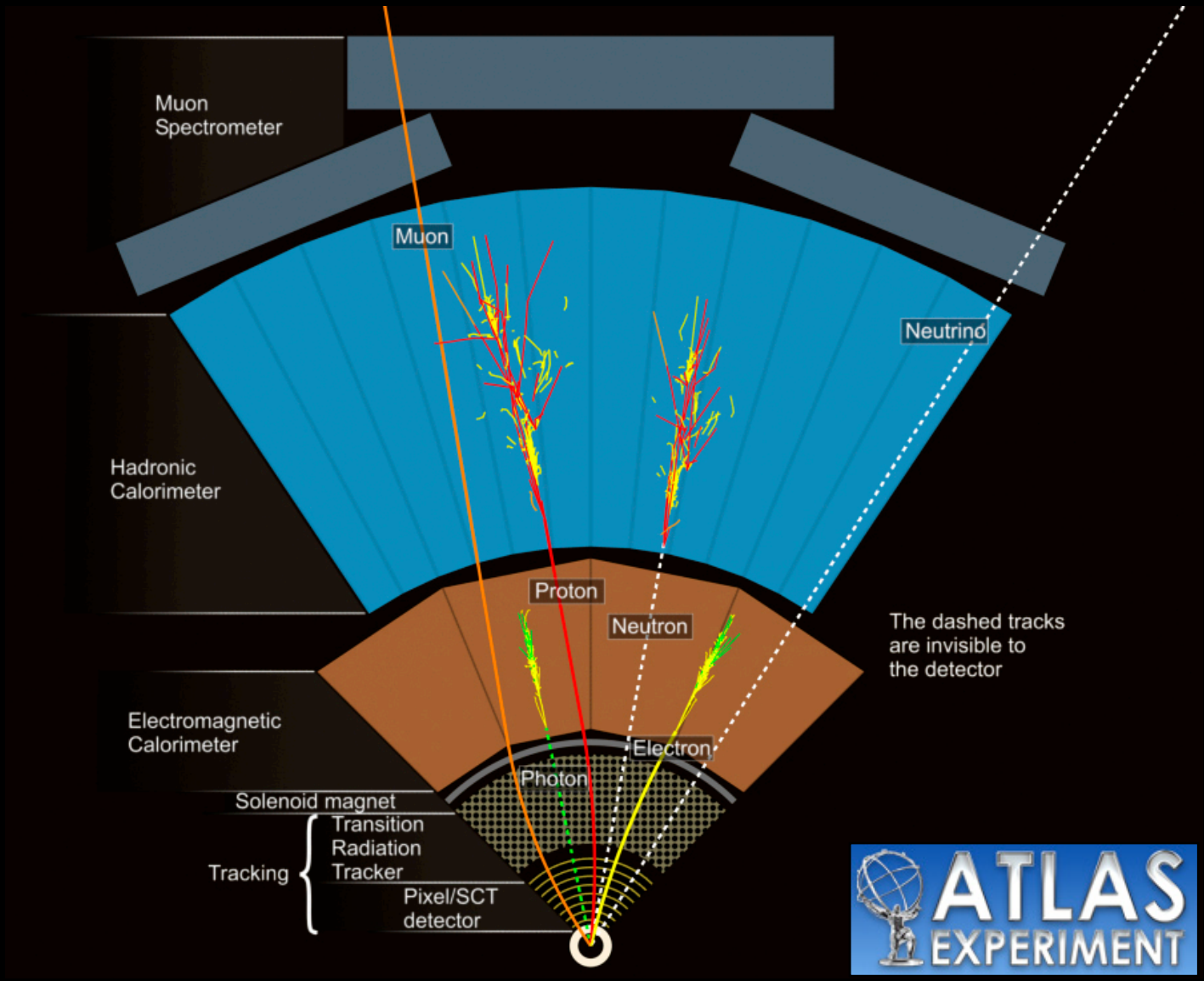
Published or submitted (BSM) physics papers

1st LHC BSM paper

- Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS detector; **ATLAS Coll., Phys. Rev. Lett. 105, 161801 (2010)**
- Search for Quark Contact Interactions in Dijet Angular Distributions in pp Collisions at √s = 7 TeV Measured with the ATLAS Detector; **ATLAS Coll., Phys. Lett. B694 (2011) 327**
- Search for DiPhoton Events with Large Missing Transverse Energy in 7 TeV Proton-Proton Collisions with the ATLAS Detector, **submitted to PRL**

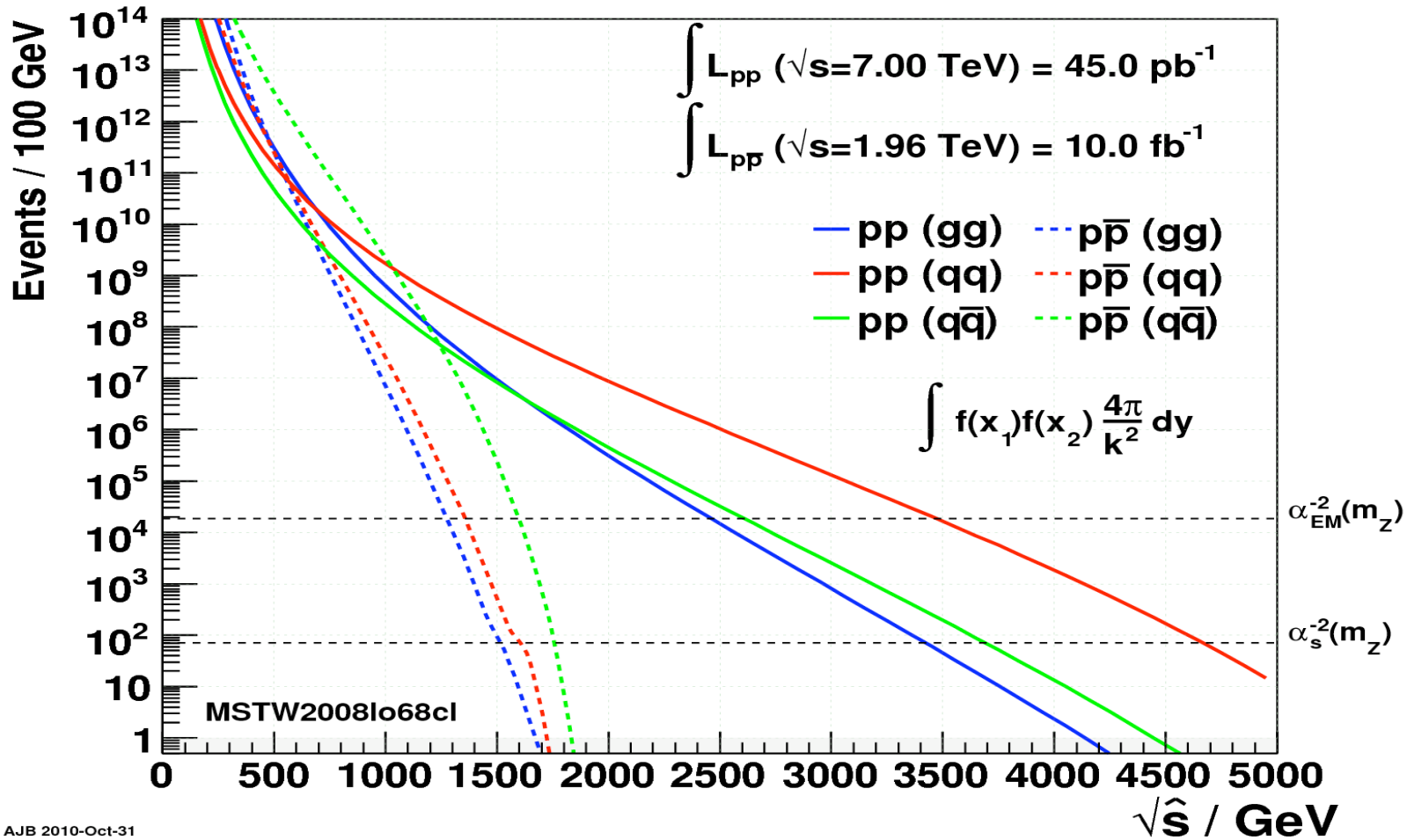
- CONF notes with preliminary physics results:
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/
- More new papers in preparation (L ≅ a few pb^{-1})
- More results on 2010 data in upcoming winter conferences
  – 2010 full integrated luminosity

ATLAS: segment of 4π detector

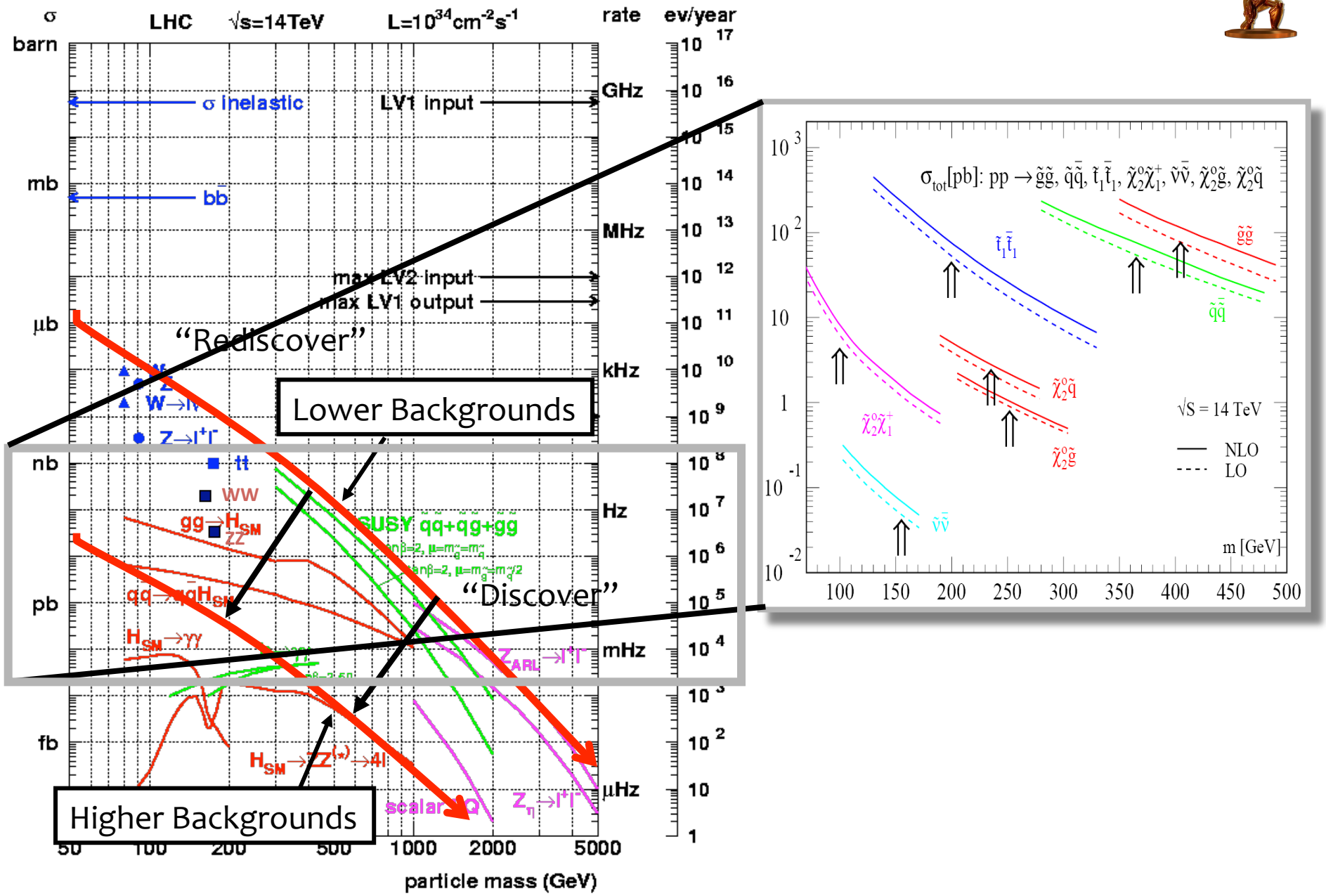


LHC vs Tevatron

- **LHC:** already higher **parton-parton luminosity** for High Mass States



Cross Sections etc.



Anti-Kt Jet algorithm

- For each input object (Topological Clusters), d_{ij} and d_{iB} are defined as

$$d_{ij} = \min\left(p_{Ti}^{-2}, p_{Tj}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

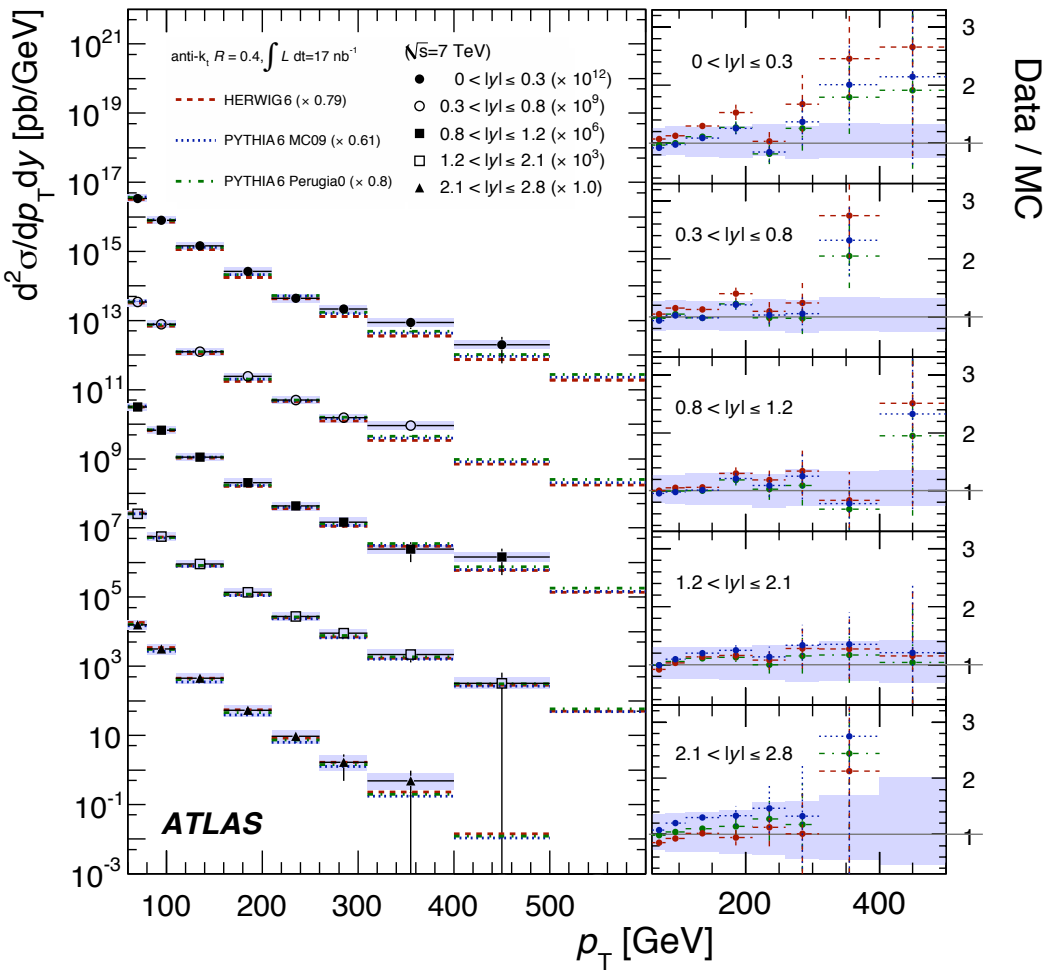
$$d_{iB} = p_{Ti}^{-2}$$

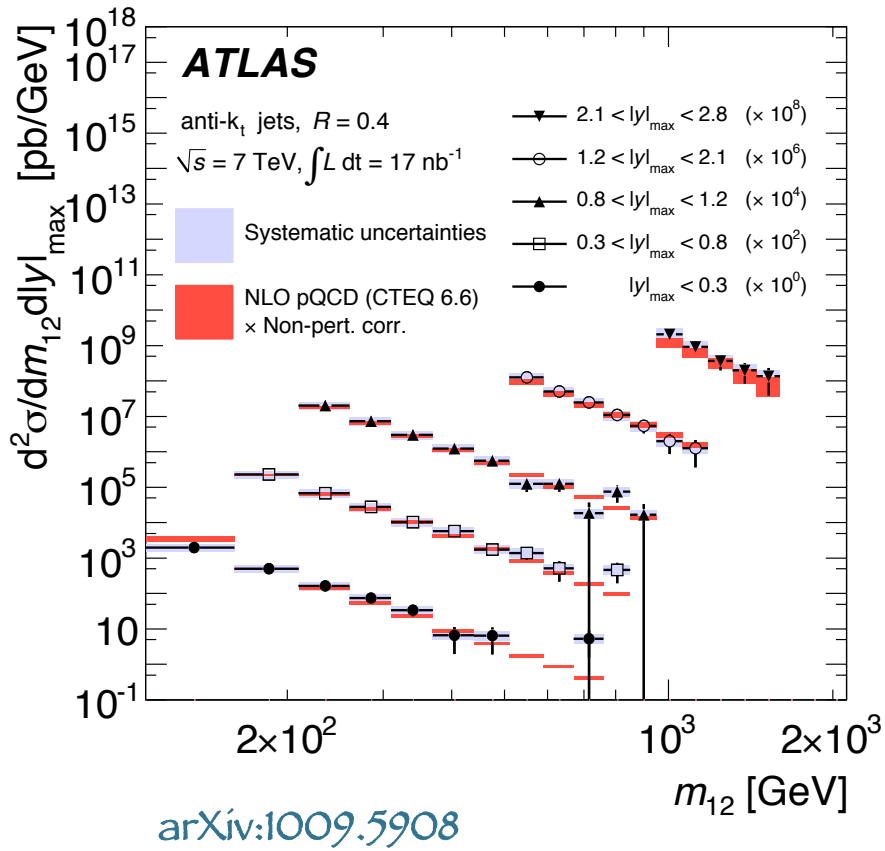
$$\Delta R_{ij}^2 = \left(y_i - y_j\right)^2 + \left(\varphi_i - \varphi_j\right)^2$$

- A list of d_{ij} and d_{iB} are formed;
  - If d_{ij} is the smallest entry; objects i and j are combined and the list remade
  - If d_{iB} is smallest, it is a jet by itself

- Anti-Kt algorithm:
- is infra-red and collinear safe
- produces geometrically well-defined (cone-like) jets

Jet performance



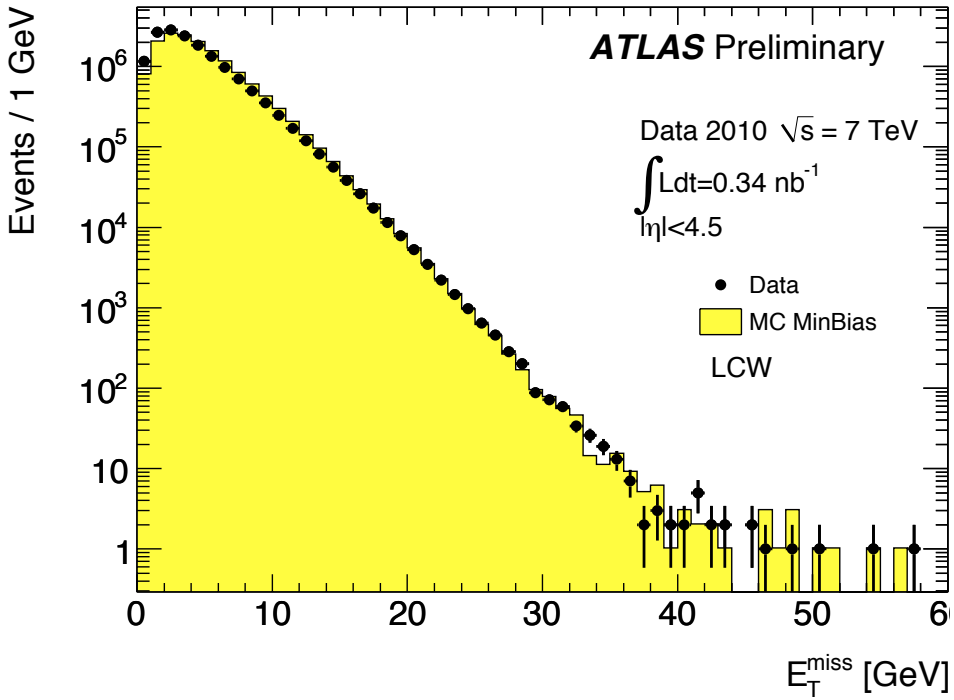


arXiv:1009.5908

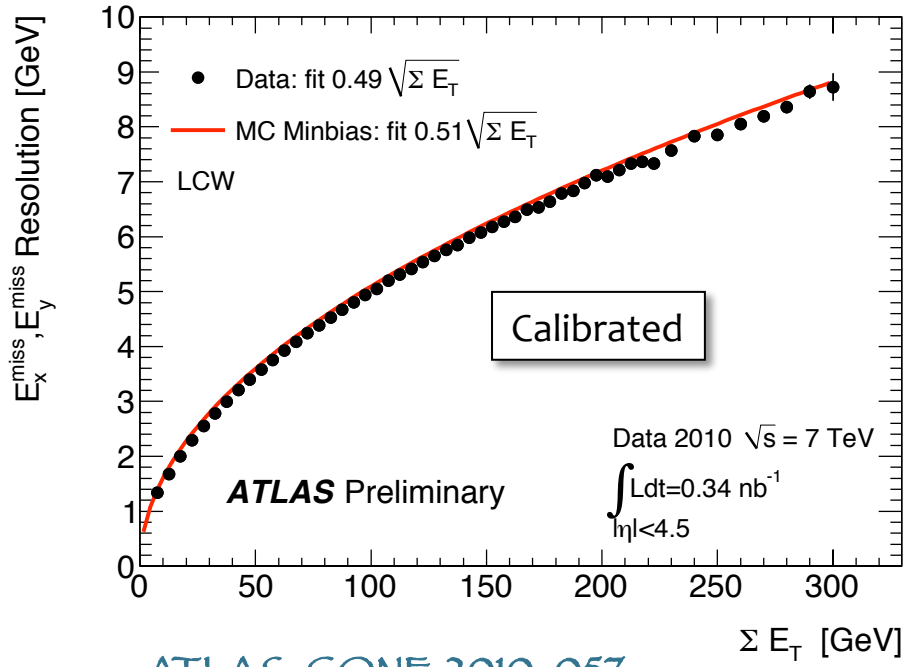
- Data and theoretical predictions consistent in all rapidity regions over wide Pt and Mjj range

EtMiss performance

Calibrated EtMiss from minimum-bias events



Measured over ~ full calorimeter coverage (360° in φ, |η| < 4.5, ~ 200k cells)

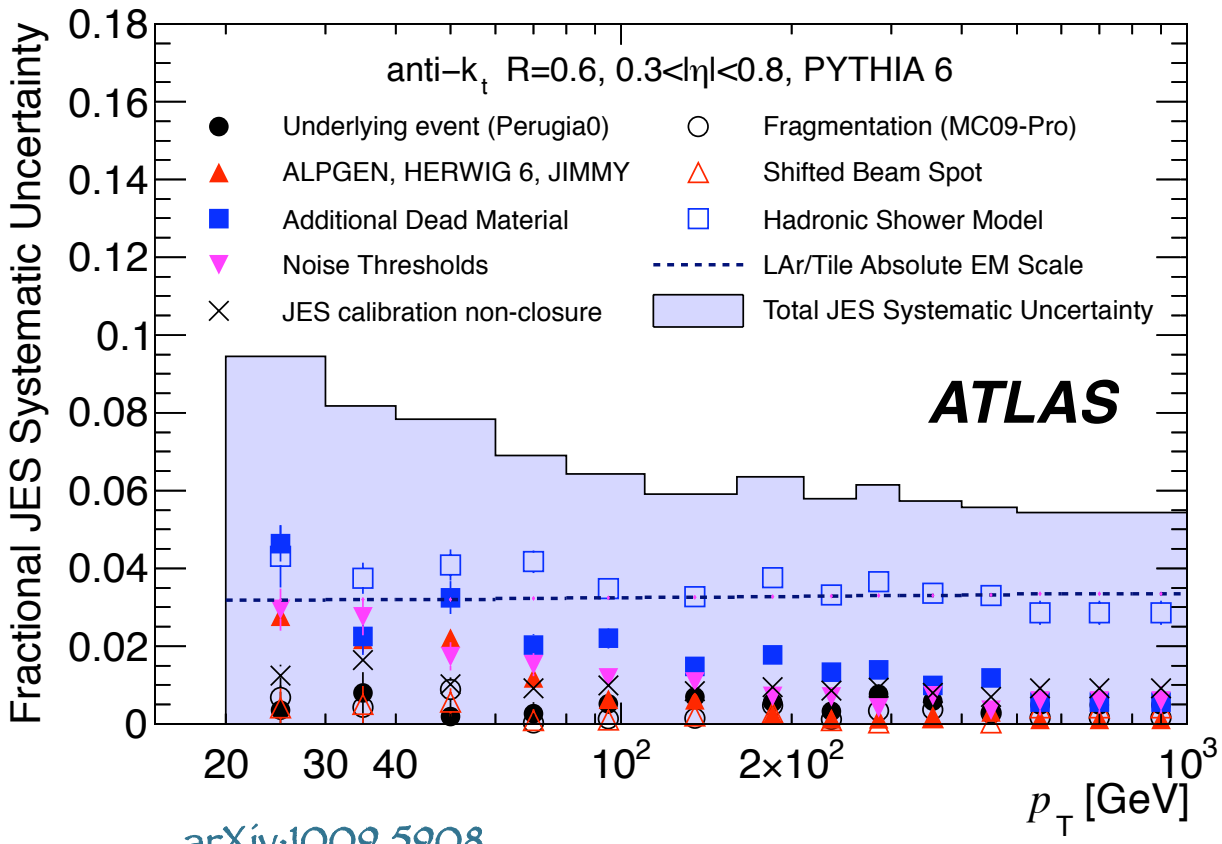


ATLAS-CONF-2010-057

- Sensitive to calorimeter performance (noise, coherent noise, dead cells, mis-calibrations, cracks etc.), cosmics and beam-related BGs
- Good agreement between data and MC

Jet Energy Scale

- Constraints from:
- Test beam
- MC simulation
- In situ calibration
- Momentum balance
- …



arXiv:1009.5908

MC samples

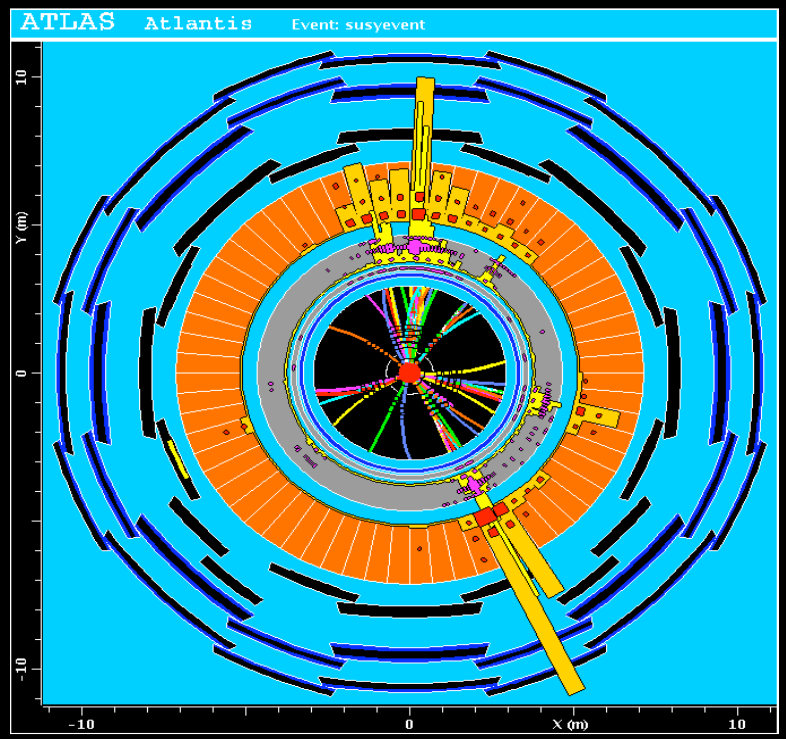
MC samples used in SUSY studies:

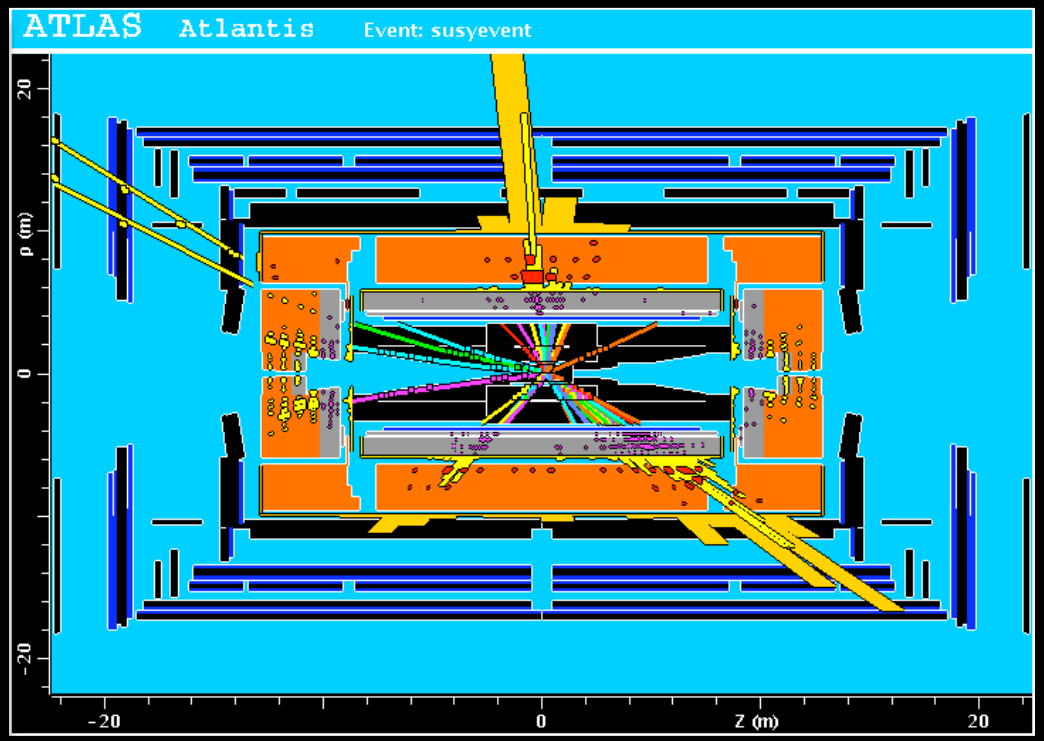
- QCD Jet: Pythia 6.4.21
- QCD normalised to data after dijet cuts
  - c.f. Alpgen+Herwig (2 ➔ 5 ME + PS)
- W/Z+Jets: Alpgen+Herwig+Jimmy
- Normalised to integrated luminosity
- Overall W inclusive cross section from NNLO
- top: MC@NLO +Herwig+Jimmy
- Normalised to integrated luminosity
- Overall cross section from NLO+NLL
- SUSY (SU4): Herwig++ 2.4.2
- Normalised to integrated luminosity
- NLO cross section (Prospino)
- Spectrum and decay from IsaJet 7.75

MC samples used in exotics searches:

- QCD Jet:
  - Pythia 6.421
  - Alpgen+Herwig+Jimmy (multi-body)
- Other BGS (as opposite)
- Signal samples: Pythia 6.421

ATLAS simulated SUSY event





Missing Transverse Momentum

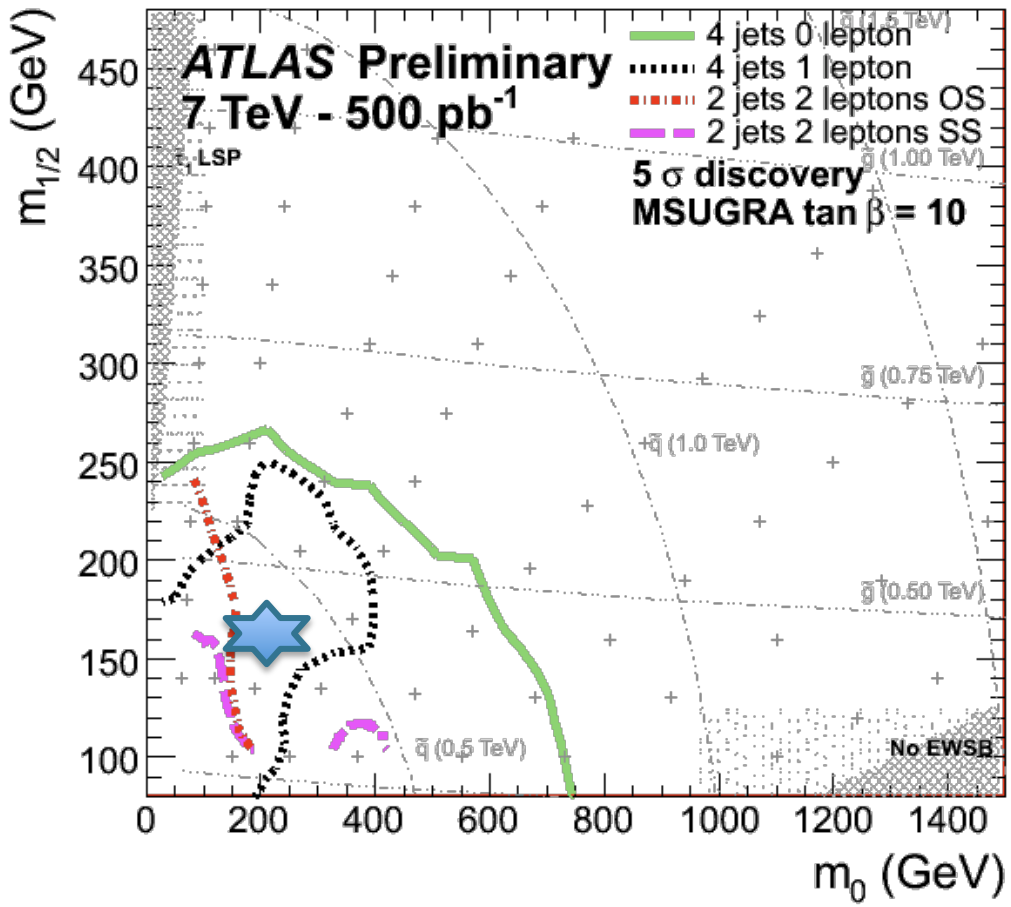
Jets

Leptons

Heavy Quarks

SUSY benchmark point: SU4

- mSUGRA low mass point, close to Tevatron bounds
- m_0 = 200 GeV
- $m_{1/2}$ = 160 GeV
- A_0 = -400 GeV
- tanβ = 10
- μ > 0



SUSY searches: event selection

- Cuts loosened c.f. previous feasibility studies, for low luminosity

Anti-Kt jet algorithm (R=0.4)

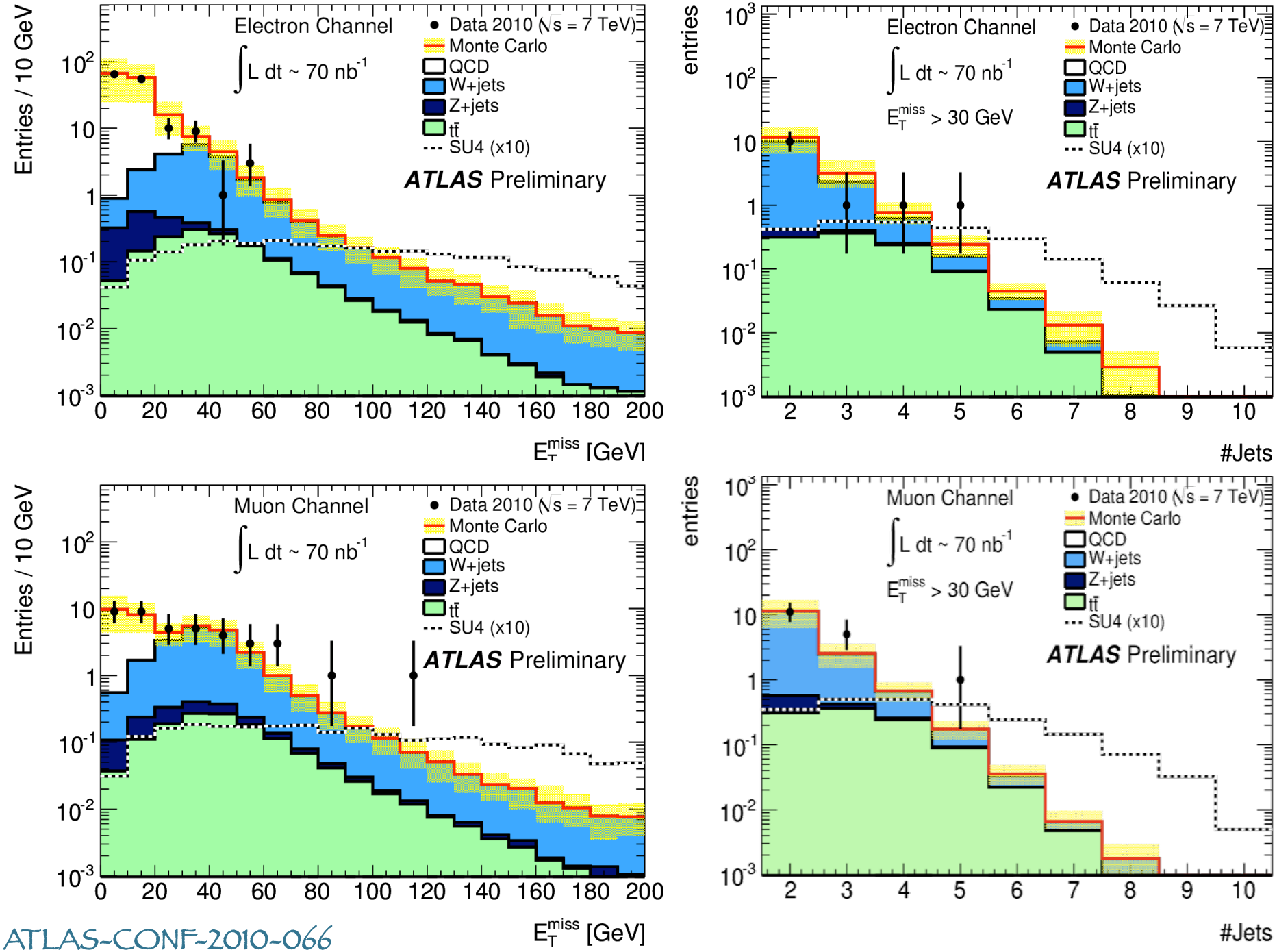
0-lepton channel

Number of jets	Monojets	≥ 2 jets	≥ 3 jets	≥ 4 jets
Leading jet p_T (GeV)	> 70	> 70	> 70	> 70
Subsequent jets p_T (GeV)	veto if > 30	> 30	> 30 (Jets 2 and 3)	> 30 (Jets 2 to 4)
E_T^{miss}	> 40 GeV	> 40 GeV	> 40 GeV	> 40 GeV
$\Delta\phi(\text{jet}_i, \vec{E}_T^{miss})$	no cut	$[> 0.2, > 0.2]$	$[> 0.2, > 0.2, > 0.2]$	$[> 0.2, > 0.2, > 0.2, > 0]$
$E_T^{miss} > f \times M_{eff}$	no cut	$f = 0.3$	$f = 0.25$	$f = 0.2$

1-lepton channel

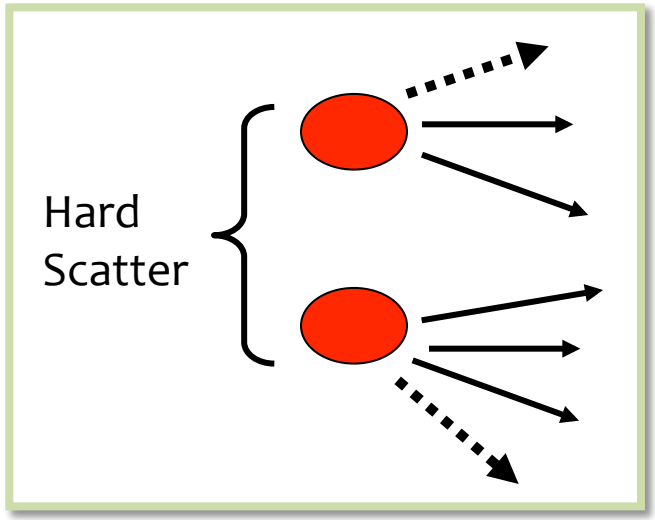
Selection	Electron channel		Muon channel	
	Data	Monte Carlo	Data	Monte Carlo
$p_T(\ell) > 20$ GeV $\cap$ ≥ 2 jets with $p_T > 30$ GeV	143	157 ± 85	40	37 ± 14
$\cap\, E_T^{miss} > 30$ GeV	13	16 ± 7	17	15 ± 7
$\cap\, m_T > 100$ GeV	2	3.6 ± 1.6	1	2.8 ± 1.2

- Good agreement found between data and MC



ATLAS-CONF-2010-066

stransverse mass: M_{T2}



M_{T2} useful in events where 2 identical particles decay semi-invisibly

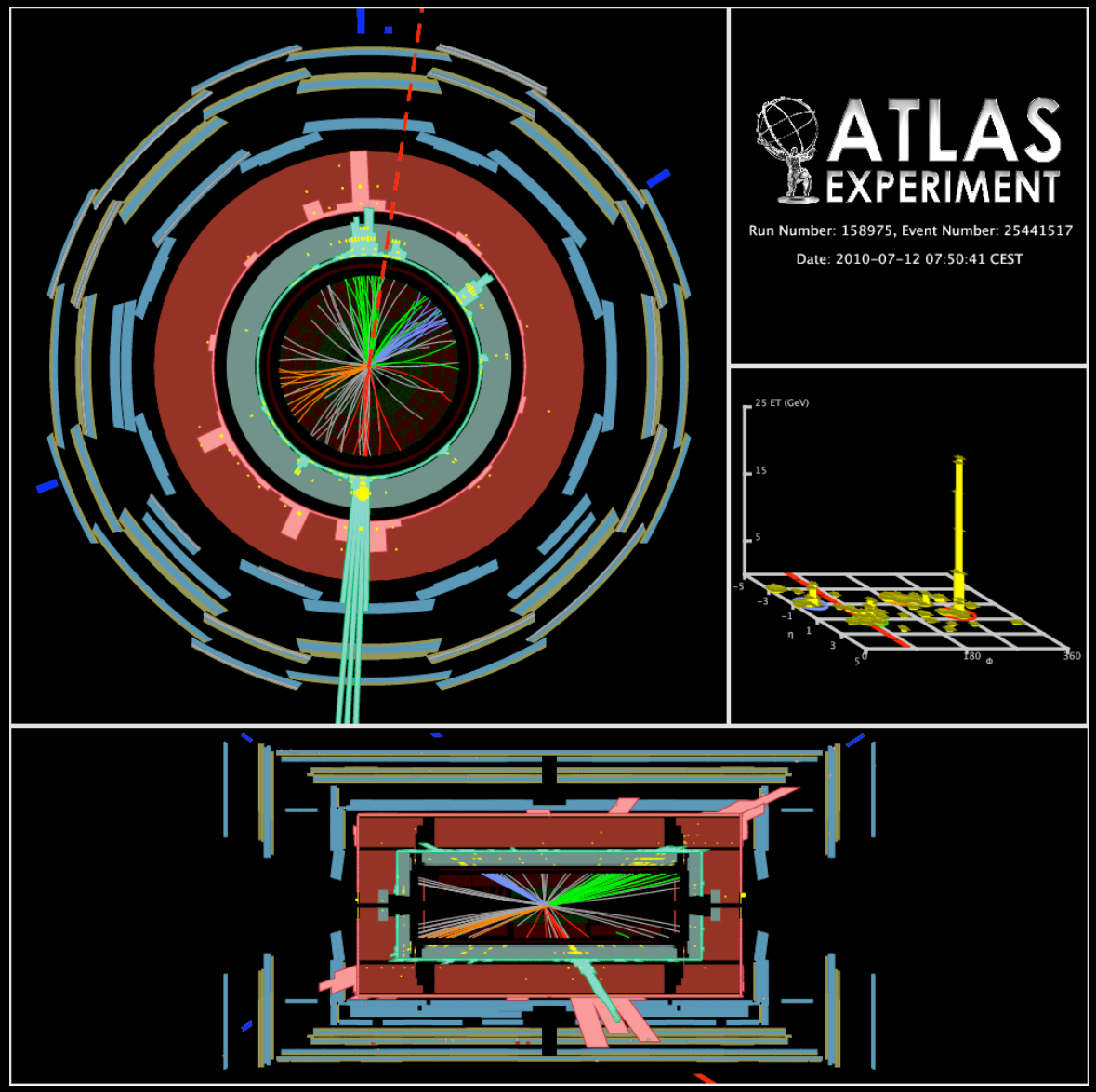
"Try all possible directions for the neutralinos and find the minimum heavy sparticle mass"

$$M_{T2} \equiv \min_{\not{\mathbf{p}}^{(1)}+\not{\mathbf{p}}^{(2)}=\not{\mathbf{p}}_T} \left[\max\left\{m_T\left(\mathbf{p}_T^{j(1)},\not{\mathbf{p}}^{(1)}\right), m_T\left(\mathbf{p}_T^{j(2)},\not{\mathbf{p}}^{(2)}\right)\right\}\right]$$

J.Phys.G29:2343-2363,2003 Phys.Lett.B463:99-103,1999

b-Jet+EtMiss

ATLAS-CONF-2010-079

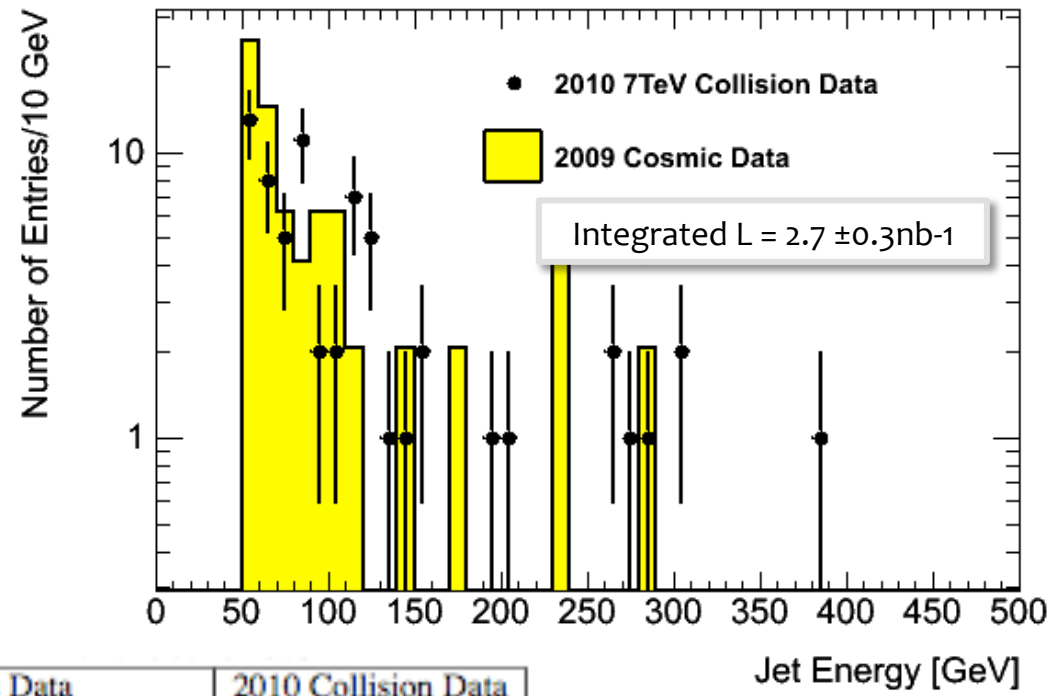


3 b-tagged jets

Stopped Gluinos

- Meta-Stable heavy particles predicted in many BSM models:
  - Split-SUSY, GMSB
- Could be created in collisions, then come to rest in ATLAS
- Search for signatures of hard jet events in empty bunch crossing

ATLAS-CONF-2010-071

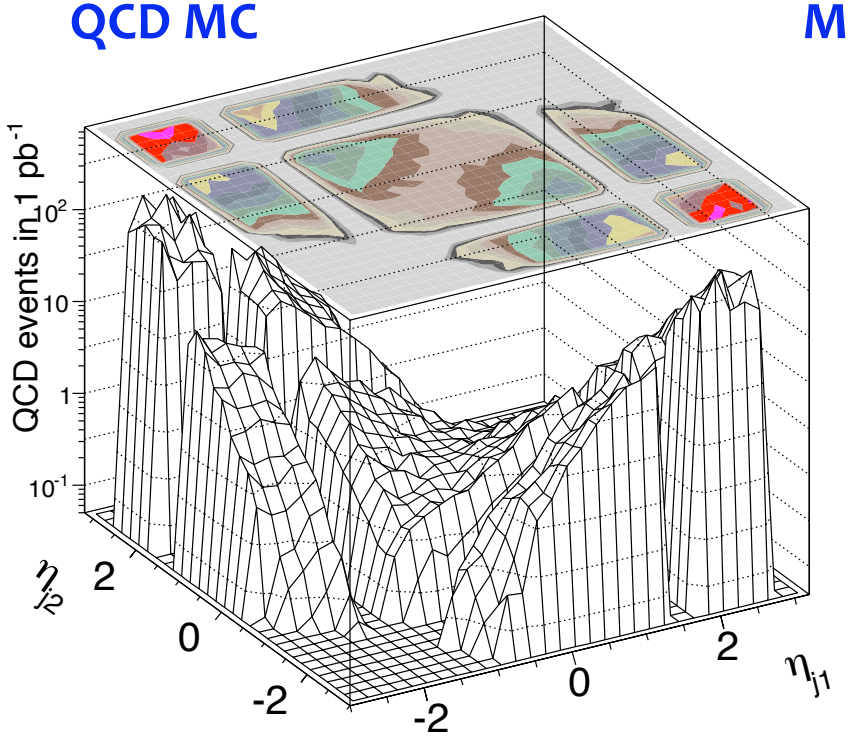


	2009 Cosmic Data		2010 Collision Data
Selection Criteria	Yield of cosmics	Cosmics (scaled)	Yield of data
Good runs and data quality cuts	9.43×10^5	–	1.58×10^6
Leading Jet $\|\eta\|<1.2$	6.26×10^5	1.29×10^6	1.29×10^6
Jet n90>3	3.83×10^5	7.89×10^5	7.90×10^5
number of Jets<4	3.82×10^5	7.87×10^5	7.83×10^5
Muon Segment Veto	530±23.0	1092±47.4	1170
Leading Jet Energy > 50 GeV	39±6.2	80±12.8	75
Leading Jet Width > 0.05	6±2.4	12±4.9	8
Jet n50<6	3±1.7	6±3.5	4
Leading Jet EMF<0.95	2±1.4	4±2.9	4

Dijet resonance: event topology

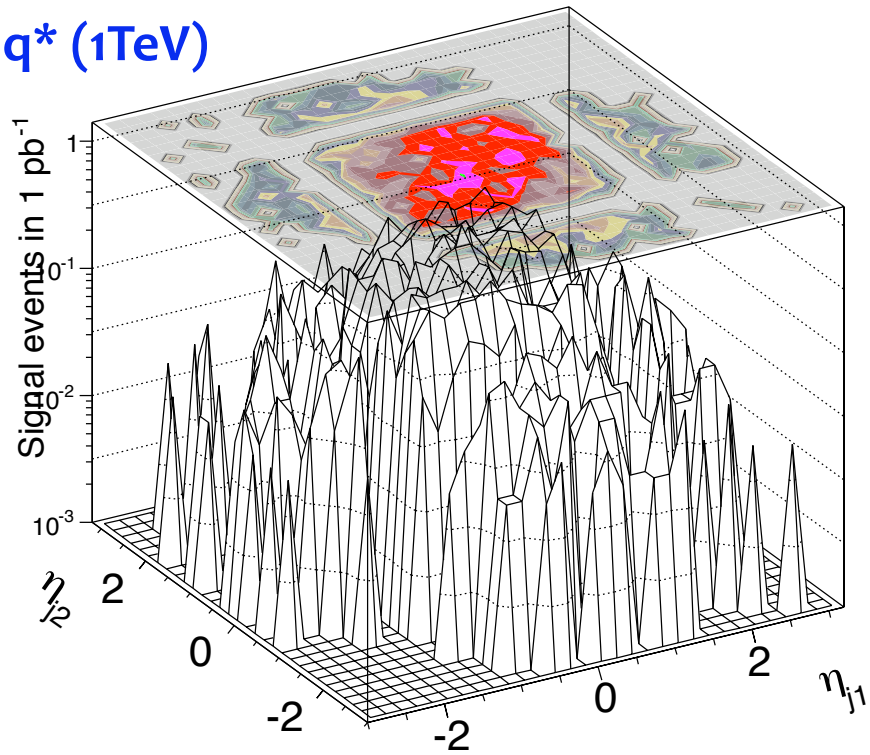
$875 < M_{jj} < 1020$ GeV

QCD MC



ATLAS Preliminary

MC q* (1TeV)



ATLAS Preliminary

- QCD jets more forward (large |η|)
- Signal events central

ATLAS-CONF-2010-080

Dijet searches: event selection & systematics

Dijet resonance event selection & systs.:

- Anti-Kt jet algorithm (R=0.6)
- Jet-Pt > 150, 30 GeV
- veto events with poorly reconstructed 3rd jet with Pt > 15 GeV
- $|\eta| < 2.5$; except $1.3 < |\eta| < 1.8$
- $|\Delta\eta| < 1.3$ ← reduce QCD BG
- $M_{jj} > 350$ ← prevent kinematic bias
- Systematic uncertainties
  - JES (6 – 9%)
  - JER (14%)
  - BG fit parameters (3 – 30%) (also see next slide)
  - Integrated luminosity (11%)

Dijet angular distributions:

- Anti-Kt jet algorithm (R=0.6)
- Jet-Pt > 60, 30 GeV
- veto events with poorly reconstructed 3rd jet with Pt > 15 GeV
- $|\eta| < 2.8$; except $1.3 < |\eta| < 1.8$
- $|y_1+y_2| < 1.5$
- Systematic uncertainties
  - JES (< 9%; X), (< 7%; R_c)
  - JER (negligible)
  - QCD scale uncerts (1 – 3%)
  - PDFs (1%)

Dijet resonance search: BG fit

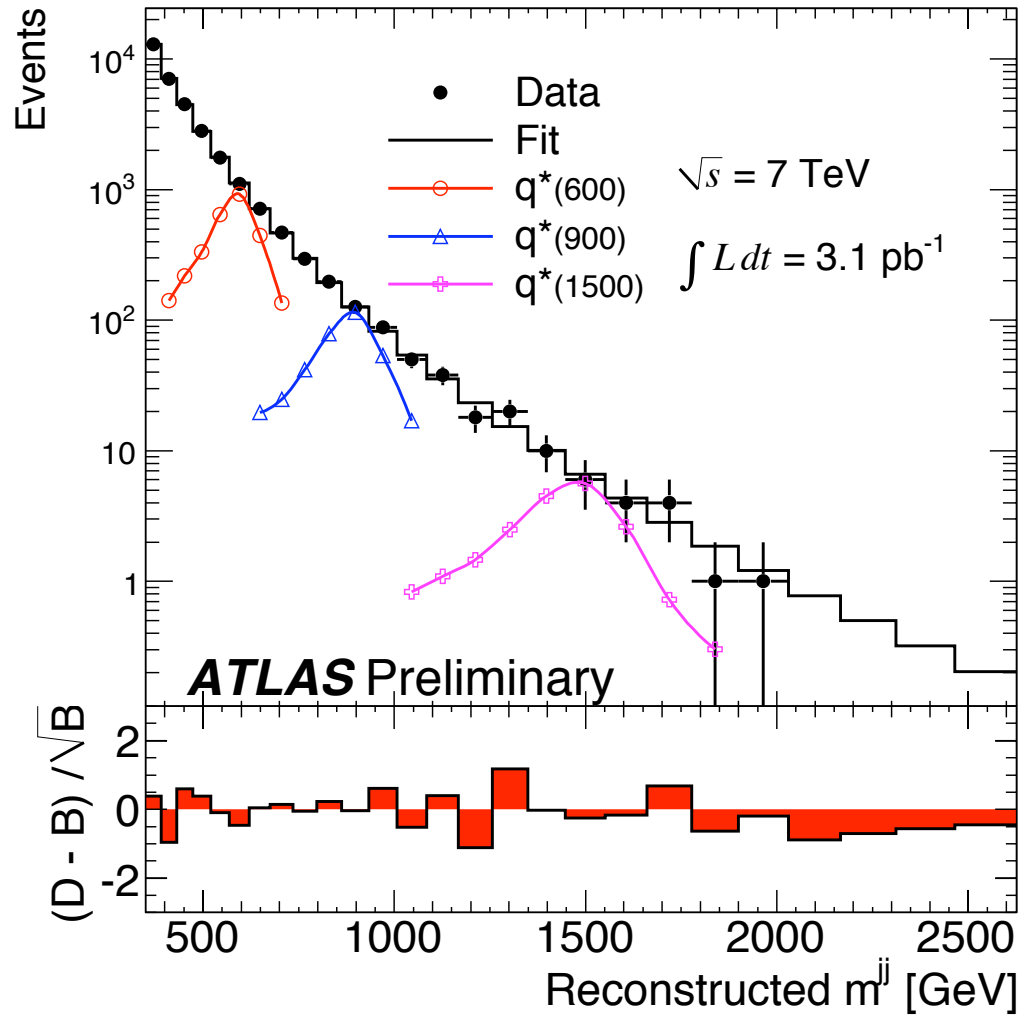
- M_{jj} spectrum fitted with:

$$f(x) = p1\,(1-x)^{p2}\,x^{p3+p4\ln x}$$

where $x=mjj/\sqrt{s}$; $f(1)=0$, $f(0)=+\infty$

[Also used in CDF Coll., Phys Rev D79 (2009) 112002]

Multiple statistical tests indicate data consistent with smooth, monotonically decreasing function



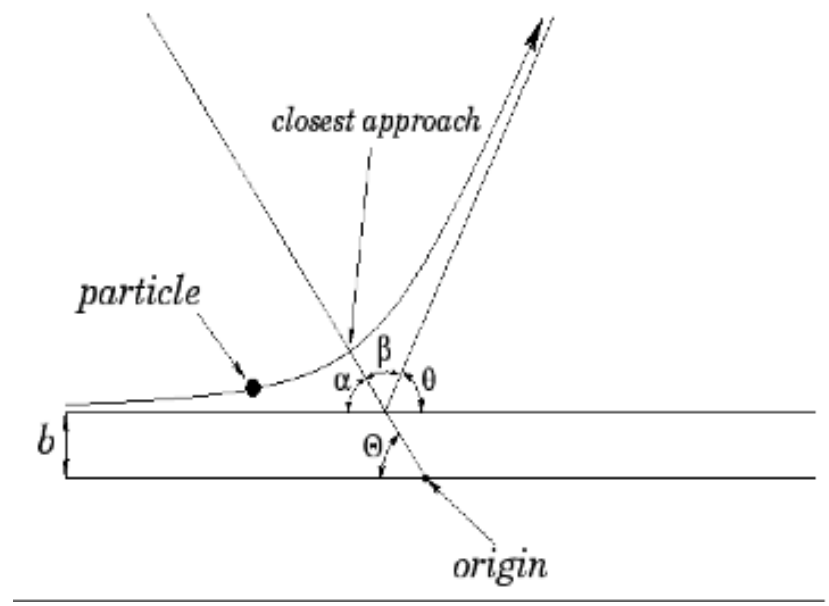
Dijet angular distributions: X

- For LO QCD, get Rutherford scattering in the centre-of-mass frame

$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim \frac{1}{\sin^4(\theta^*/2)}$$

- New Physics: expected to be more isotropic
- **X variable**: removes Rutherford singularity, uses variables in the laboratory frame and is invariant under a Lorentz boost

$$\chi = \exp(2|y^*|) = \exp(|y_1 - y_2|) = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



- For Rutherford scattering:

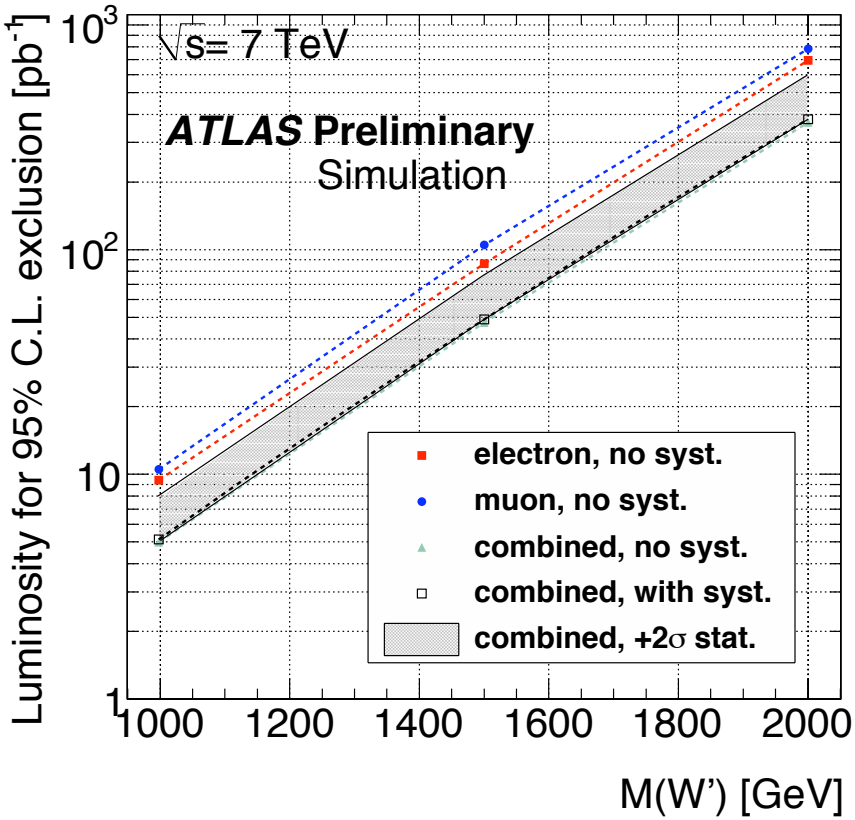
$$\frac{d\hat{\sigma}}{d\chi} \sim const.$$ ➔ flat distribution for LO QCD

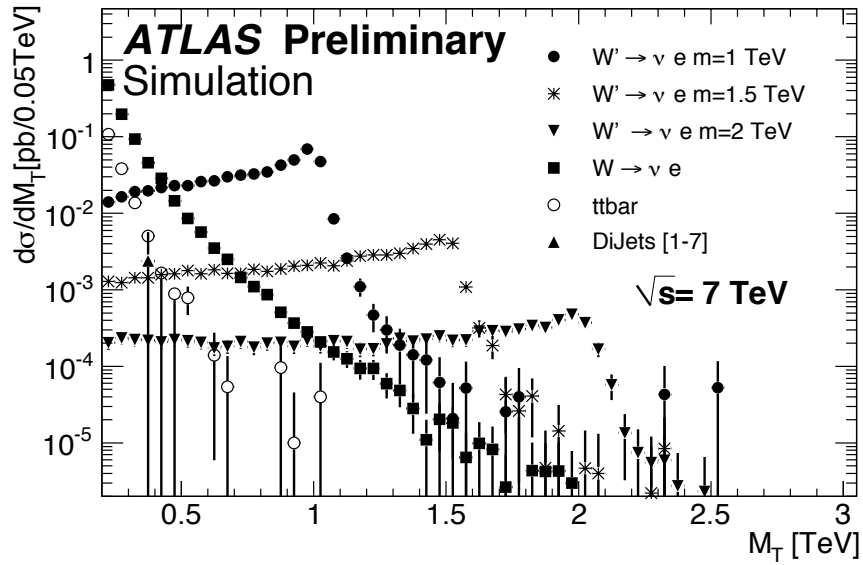
- For isotropic distribution

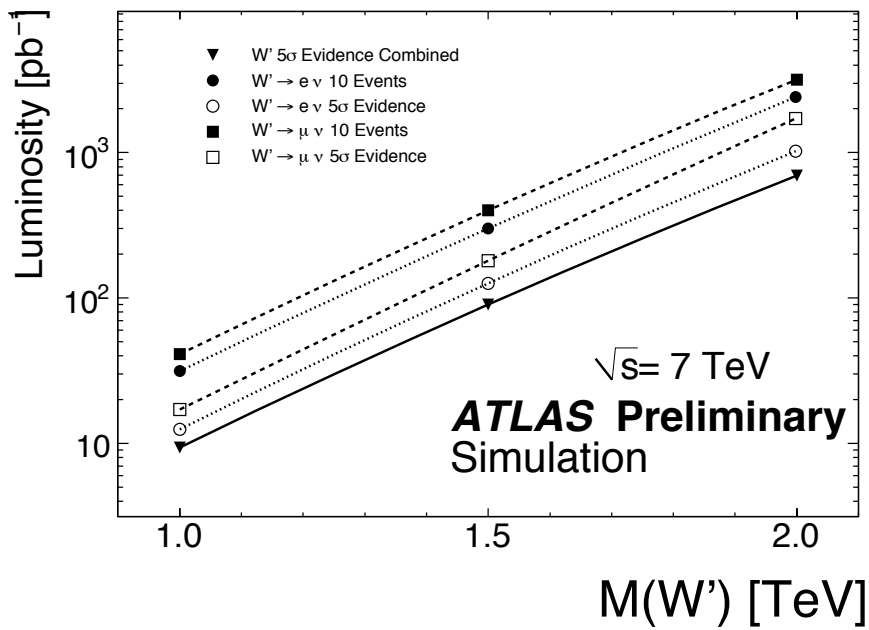
$$\frac{d\hat{\sigma}}{d\cos\theta^*} \sim const. \Rightarrow \frac{d\hat{\sigma}}{d\chi} \sim \frac{1}{(1+\chi)^2}$$ ➔ expect rise at low X for New Physics

W' prospects at √s = 7TeV

ATLAS-PHYS-PUB-2010-007



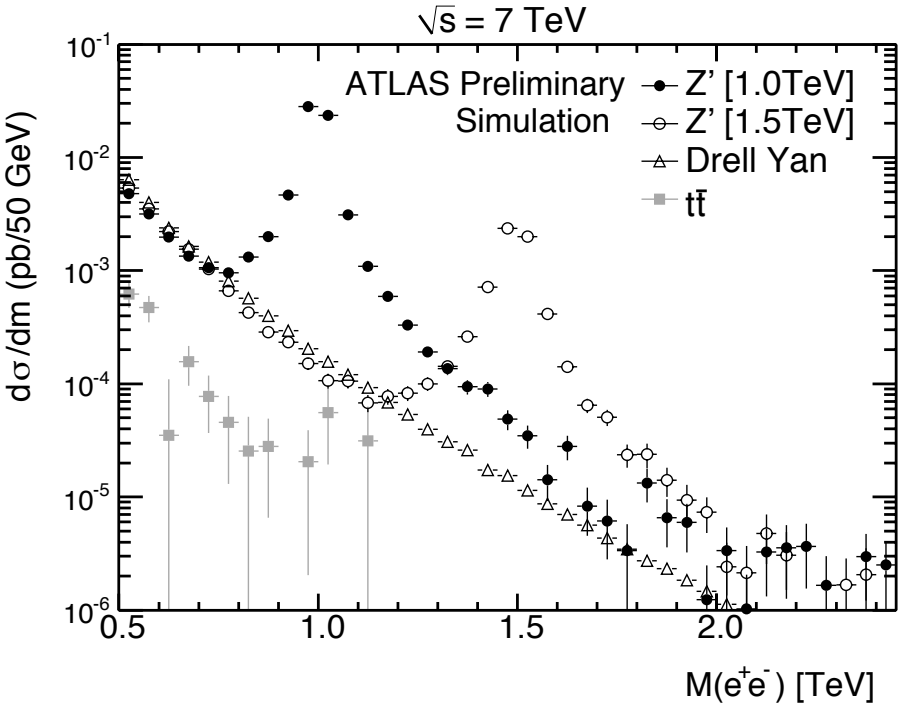


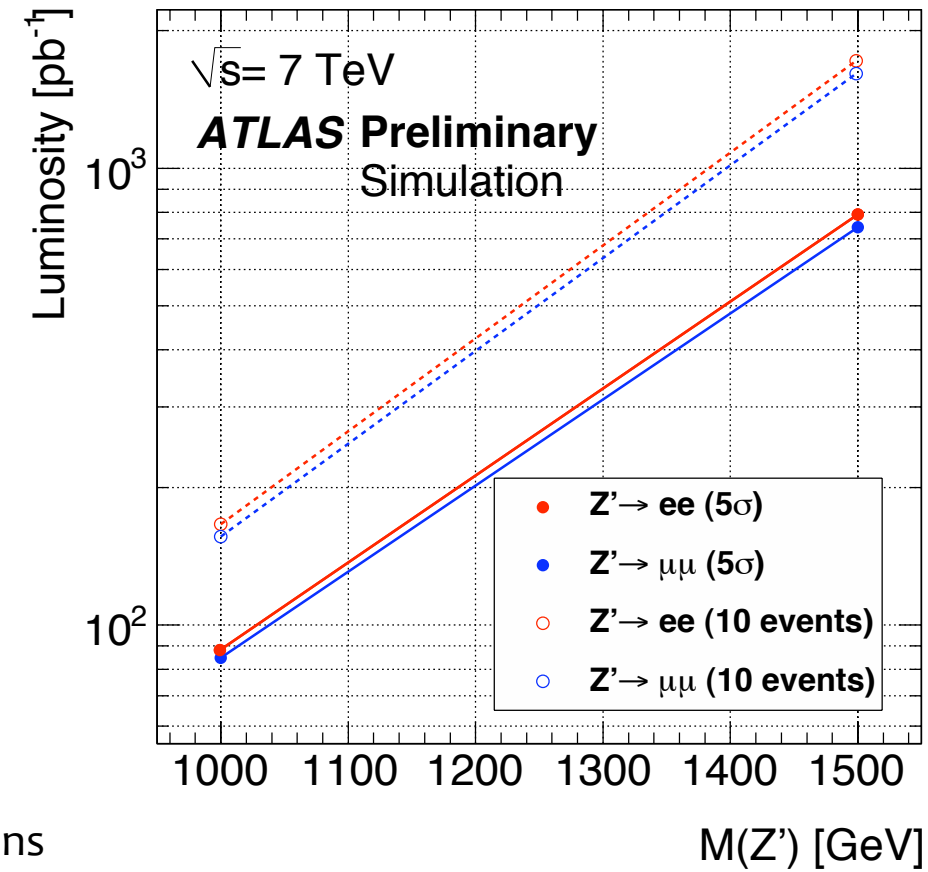


- ATLAS expected sensitivity to heavy gauge bosons decaying to lν

Di-lepton resonances: Z'

ATLAS-PHYS-PUB-2010-007





- Z' ➔ 2l; simple, clean signature
- 2 oppositely charged, same flavour leptons
- Need ≅100pb^{-1} for first sensitive studies