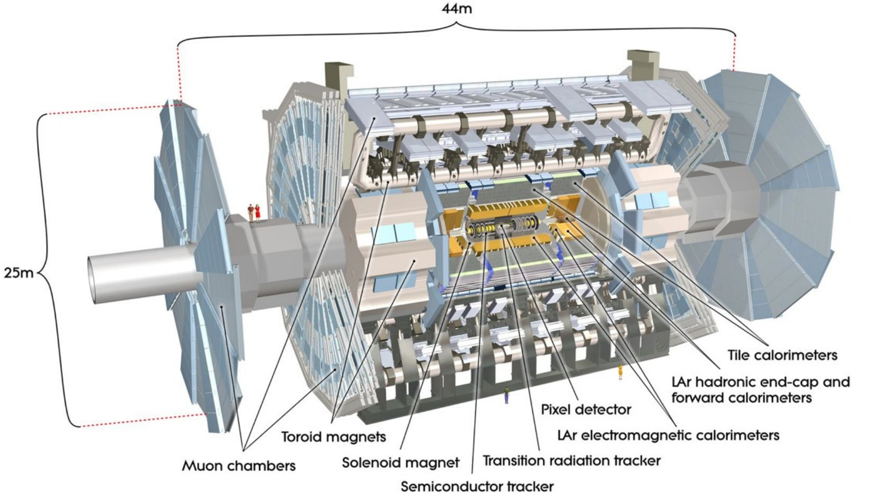
Physics Program
of the experiments at
Large Hadron Collider

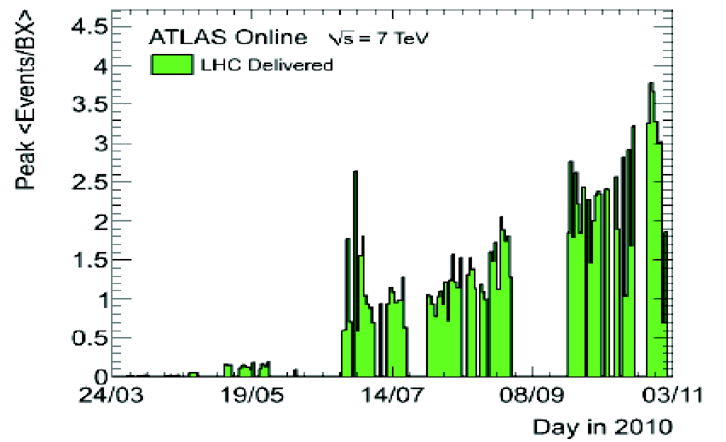
Lecture 14

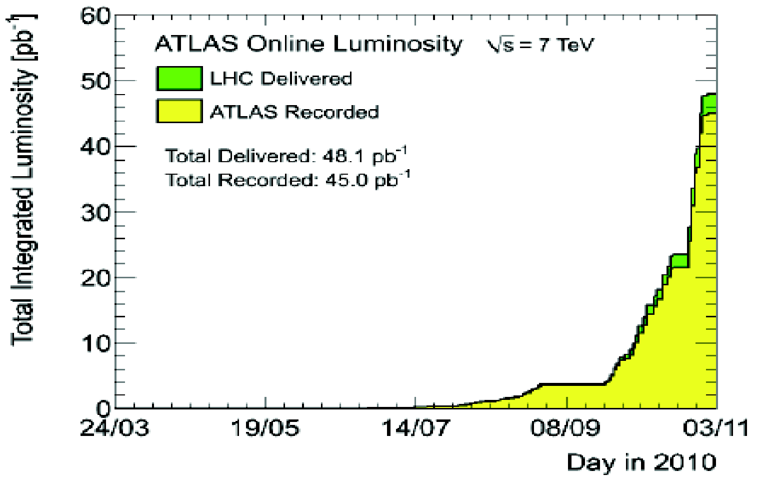
- **ATLAS with 2010 data**
  - **SM summary**
  - **BSM limits**
- **Perspectives for 2011**

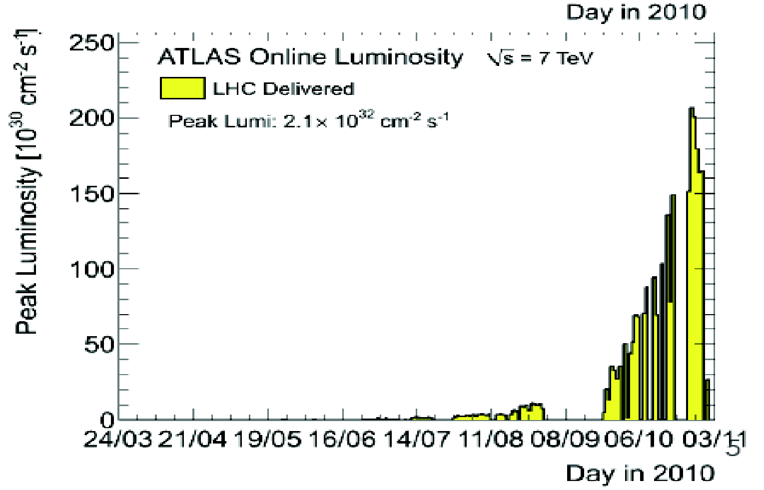


The LHC operation and luminosity

- Total: 48.1pb^{-1} delivered,
  45 pb^{-1} recorded.
- Instantaneous luminosity
  - Peak ~ 2X10^{32}/cm^{2}/s
  - Highest mean 3.8 int/crossing
- Luminosity calibrated by v. d. Meer scan
  11% uncertainty, dominated by knowledge of beam current, to be improved







ATLAS published physics papers

Published or submitted physics papers

- Charged-particle multiplicities in pp interactions at $\sqrt{s}$ = 900 GeV measured with the ATLAS detector at the LHC
- Search for New Particles in Two-Jet Final States in 7 TeV Proton-Proton Collisions with the ATLAS Detector at the LHC
- Search for Quark Contact Interactions in Dijet Angular Distributions in pp Collisions at $\sqrt{s}$ = 7 TeV Measured with the ATLAS Detector
- Measurement of inclusive jet and dijet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with the ATLAS detector
- Measurement of the W->lν and Z->ll production cross sections in proton-proton collisions at $\sqrt{s}$=7 TeV with the ATLAS detector
- Observation of a centrality-dependent dijet asymmetry in lead-lead collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the ATLAS detector at the LHC
- Measurement of underlying event characteristics using charged particles in pp collisions at $\sqrt{s}$ = 900 GeV and 7 TeV with the ATLAS detector
- Measurement of the top quark-pair production cross section with ATLAS in pp collisions at $\sqrt{s}$ =7 TeV

- There are ~ 100 CONF notes with preliminary physics results and detector performance
  - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/
- More new papers are in preparation
  - L ~ a few pb^{-1}
- More results on 2010 data in the upcoming winter conferences
  - Full 2010 luminosity

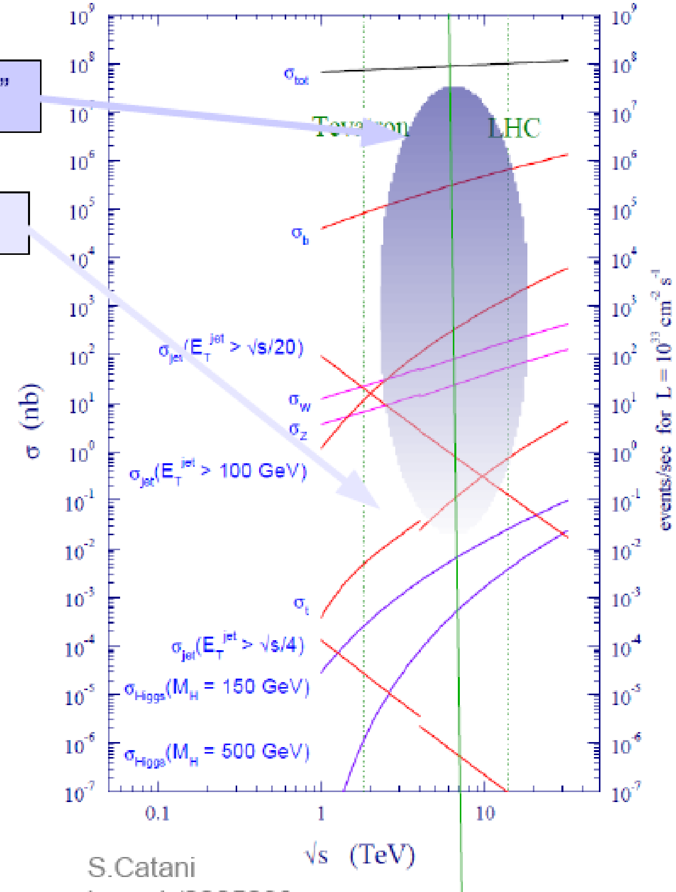
SM processes at the LHC

Current Luminosity
~30 pb^{-1}

"measurements"

"observations"

Process	σ (nb)	Events ($\int Ldt$ = 100 pb^{-1})*
Min bias	10^8	~10^{13}
bb	$5 \cdot 10^5$	~10^{12}
Jets p_T > 200 GeV	100	~ 10^7
W → lepton+ ν	10	~ 10^6
Z → l+ l-	1.0	~ 10^5
tt	~0.1	~ 10^4
Higgs (M=150 GeV)	~0.001	~100



S.Catani
hep-ph/0005233

current energy
7 TeV

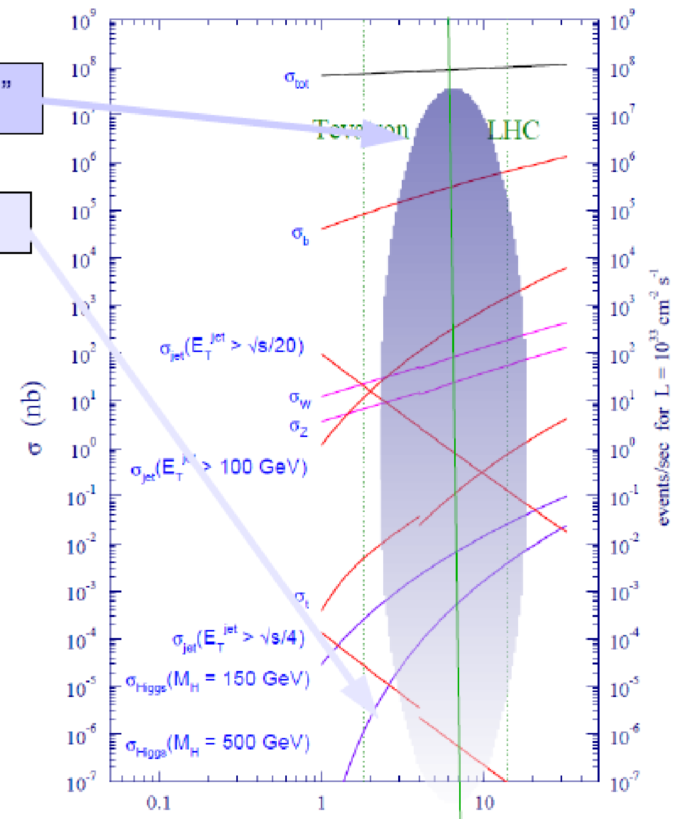
SM processes at the LHC

~ 1 year from now
~1 fb^{-1}

"measurements"

"observations"

Process	σ (nb)	Events ($\int L dt$ = 1 fb^{-1})
Min bias	10^8	~10^{14}
bb	$5 \cdot 10^5$	~10^{13}
Jets p_T > 200 GeV	100	~ 10^8
W → lepton+ ν	10	~ 10^7
Z → l+ l-	1.5	~ 10^6
tt	~0.1	~ 10^5
Higgs (M=150 GeV)	~0.001	~1000



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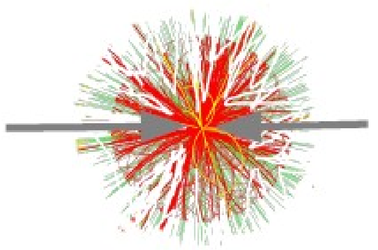
current energy
7 TeV

Measurements and observations

SM tests with early data

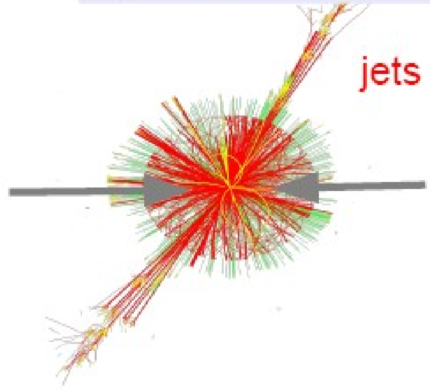
"softQCD"
p_T < few GeV



>99.999% collisions:

Tests:
- LO matrix elements
- LL parton showers (PS)
- models for softQCD
- consistency in tunings
- etc.

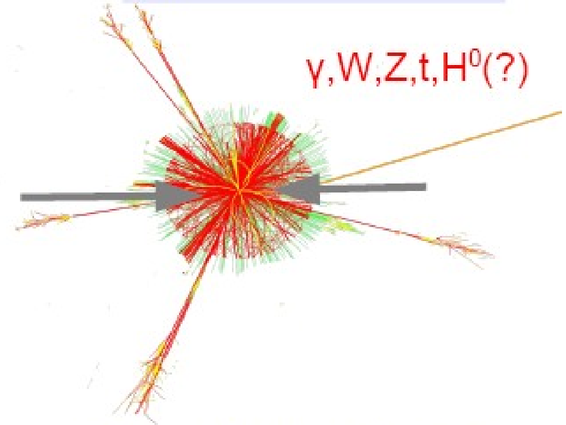
"Hard QCD"
p_T > tens of GeV



~10^{-5} % collisions

Tests:
- **NLO QCD ($O(\alpha_s^3)$)**
- running α_S
- PDF
- LO QCD $O(\alpha_S^2)$ +PS
- etc.

"Hard EWK"
p_T > tens of GeV

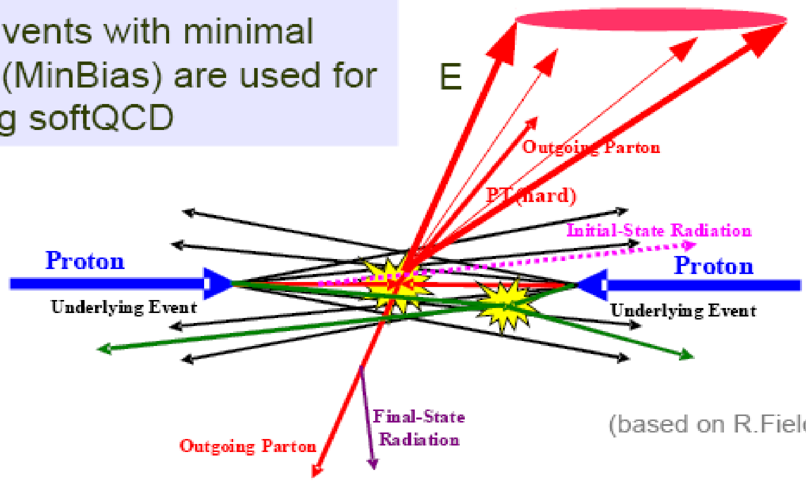


~10^{-6} - 10^{-8} % collisions

Tests:
- **NLO, NNLO QCD**
- mass measurements
- PDF
- LO QCD $O(\alpha_S^2)$ +PS
- etc.

From soft to hard QCD

Inelastic pp events with minimal selection criteria (MinBias) are used for testing softQCD



~ $\log^2 E$ pQCD

~ $\log(s)$? Models.. Models..

(based on R.Field's figure)

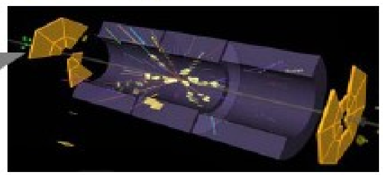
- **MinBias events:**
  - measurements can be done with small luminosity
  - Examples:
    - basic properties of particle production, multiplicity measurements, energy flows etc
- **High-precision measurements for high-pT physics require substantial statistics**

Soft QCD: charged particles multiplicities

ATLAS arXiv:1012.5104

Minimum Bias Trigger Scintillators (MBTS)

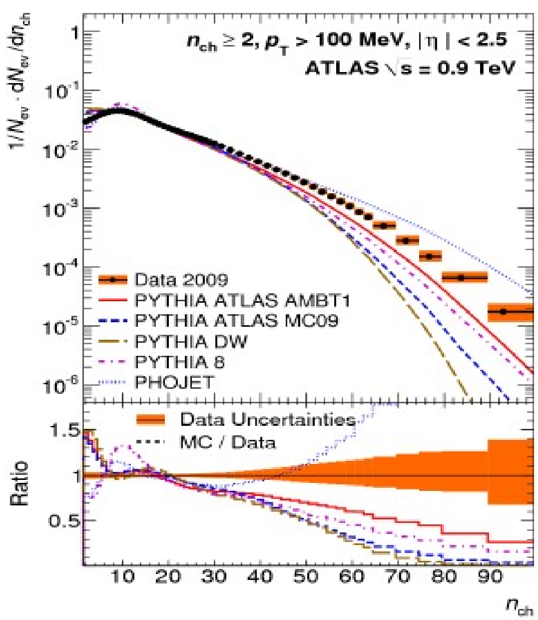
MBTS



32 plastic scintillators with coverage: 2.09< η < 3.84

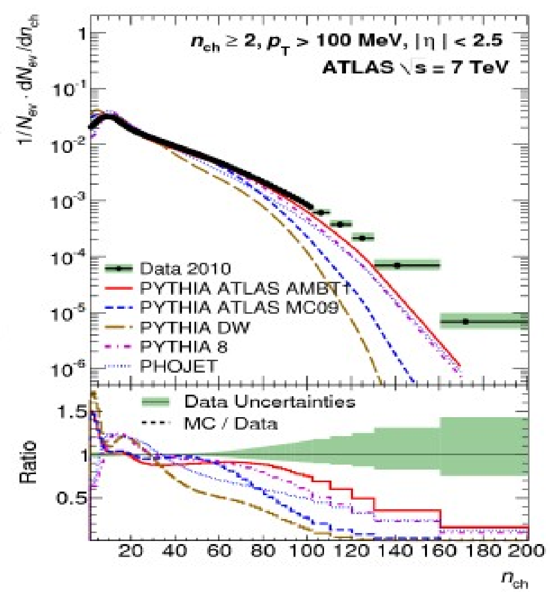
Trigger and event selection in MinBias events
- Data: 900 GeV and 7 TeV (~10M events)
- Selection:
  ≥ 1 MBTS counter to fire on either side

Primary track selection:
- pT > 100 MeV, | η| < 2.5 + other track quality cuts



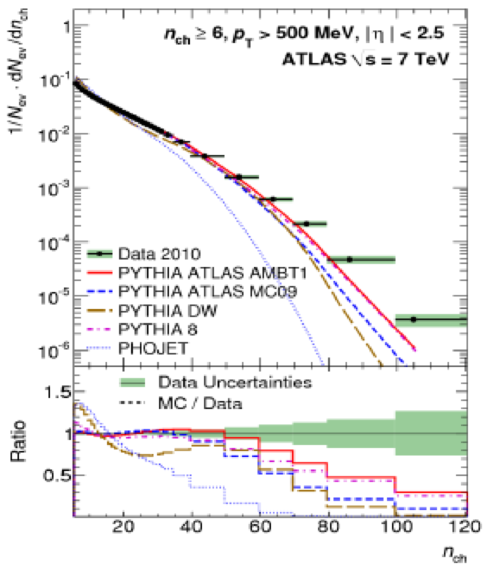
900 GeV

7 TeV

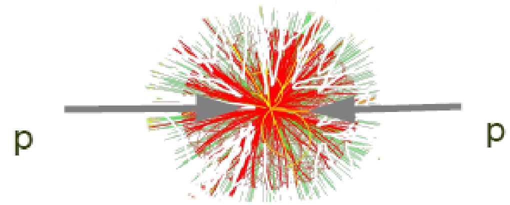


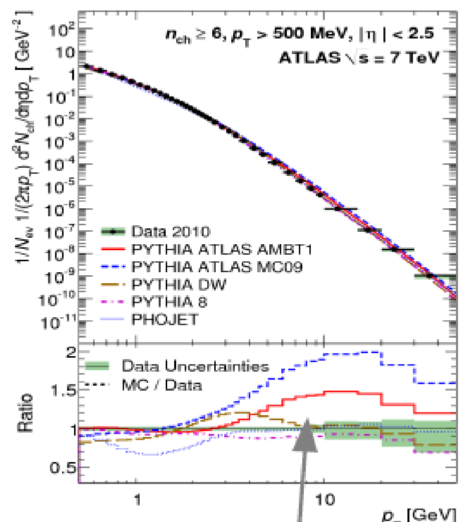
- 7 TeV: up to ~200 charged particles per event!
- All pre-LHC MC fail
- PYTHIA AMBT1 is closest to data
- PHOJET overestimates 900 GeV and underestimates 7 TeV
- Low n(ch) region affected by diffraction

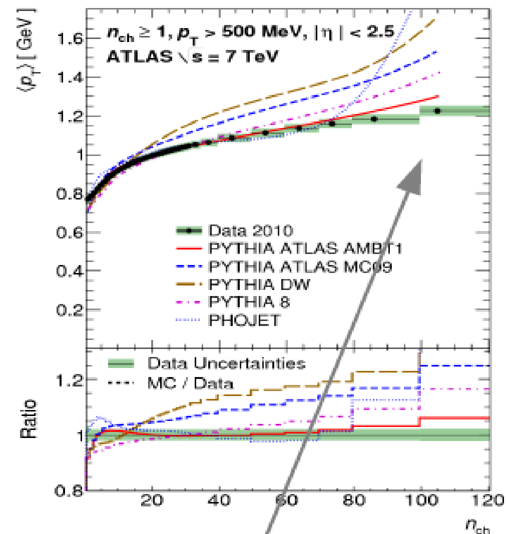
Particles spectra with reduced contribution from diffraction



All pre-LHC tunes of MC models fail







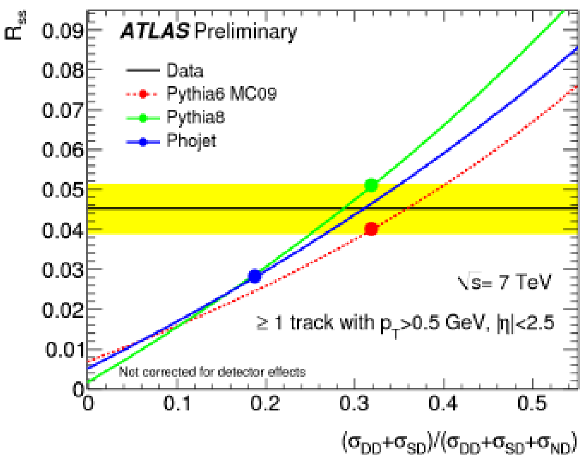
Entering hard QCD

PHOJET completely fails
AMBT1 tune improves agreement (but still has problems!):
- increasing probability for head-on collisions (more events with large N(ch), PARP84)
- reducing color reconnection for high-momentum hadrons (reduces <pT>, PARP(77))

Observation of diffraction

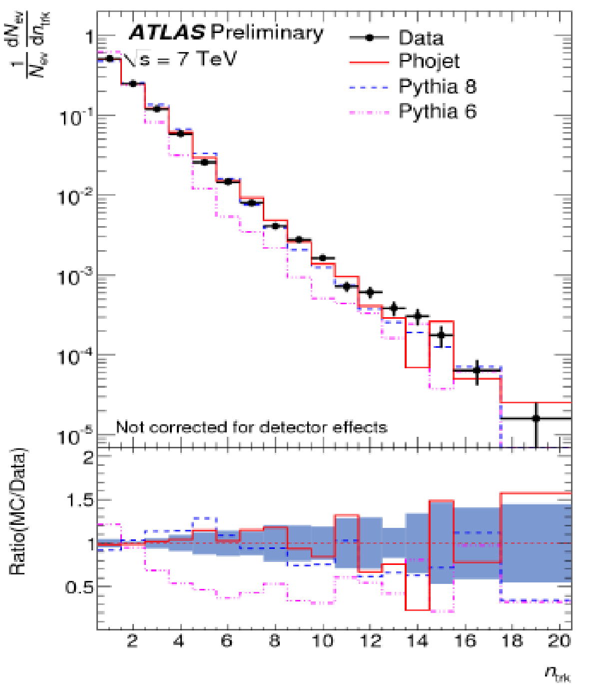
$$\sigma(pp) = \sigma(el) + \sigma(ND) + \underbrace{\sigma(SD) + \sigma(DD)}_{30\%}$$

- Uncertainty for luminosity measurements
- Introduce uncertainty for MC tuning
- Hard component is not well known



The ratio of events with hits only on one side of the MBTS scintillators to events with any hits in the MBTS scintillators

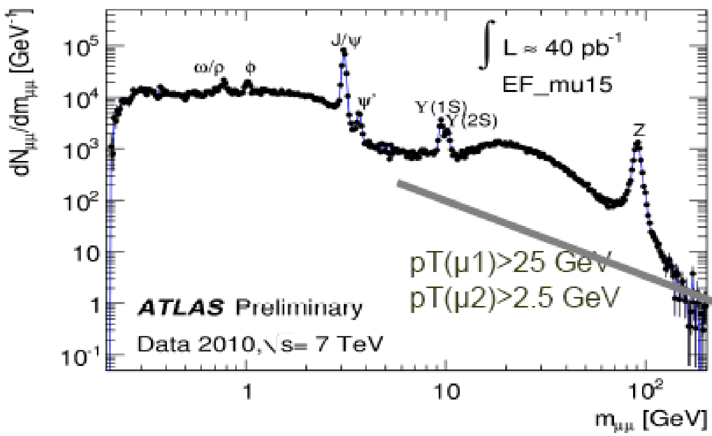
(single-sided MBTS requirement)



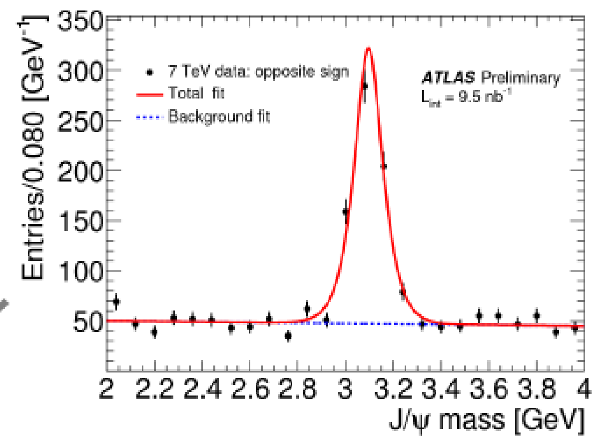
PYTHIA8 & PHOJET (with 30% diffraction) describes well the rate & multiplicities for diffractive events

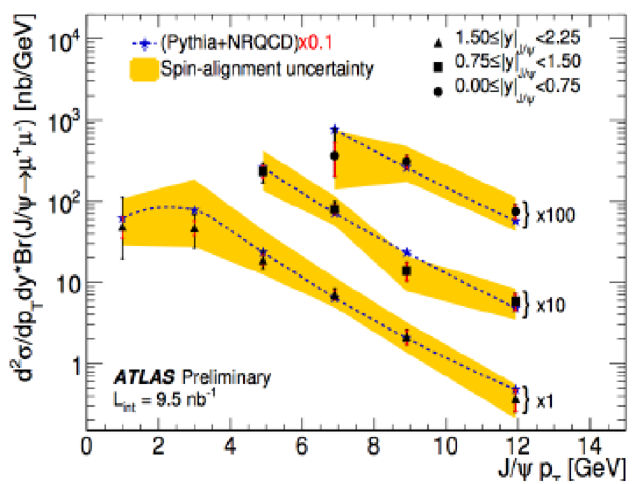
Charmonium production

- In many areas, ATLAS is still in the phase of “rediscovery” of heavy-flavor states
- High-precision measurements at the new energy frontier have started to emerge



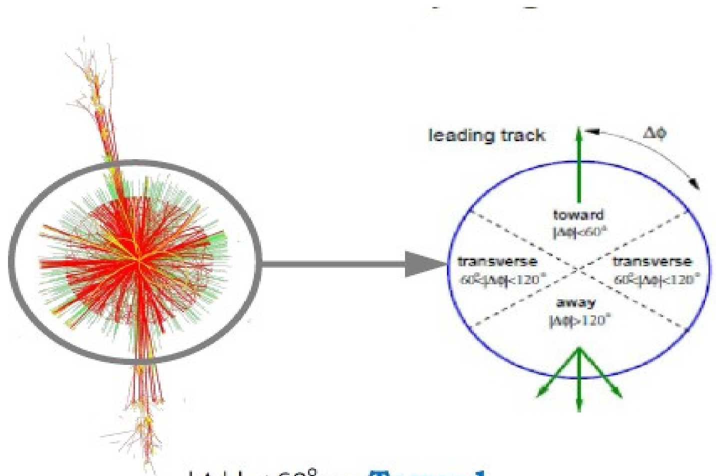
First measurement of the differential cross section for the J/ψ→μμ resonance





PYTHIA (+Colour-Octet Mechanism) with MC09 tune is in good agreement with the data
(note spin-alignment uncertainty)

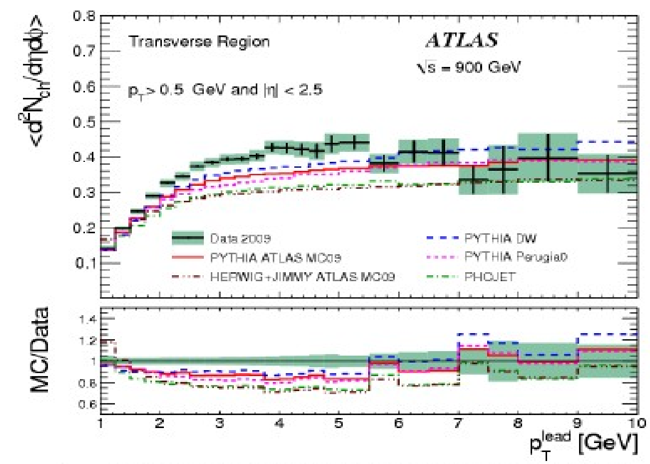
Studies of underlying event in minimum bias data



$|\Delta\phi| < 60^\circ$ as **Toward**

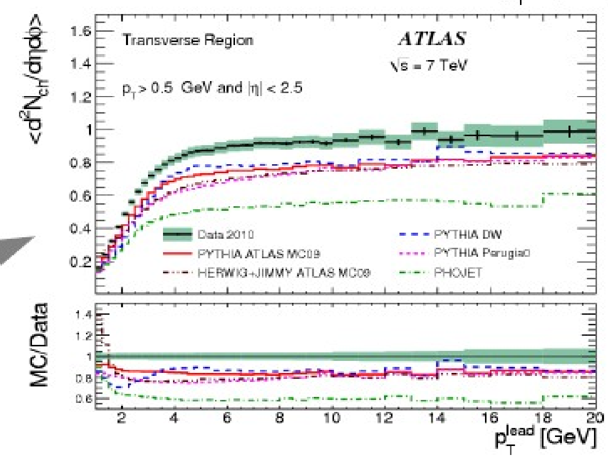
$60^\circ < |\Delta\phi| < 120^\circ$ as **Transverse**

$|\Delta\phi| > 120^\circ$ as **Away**



All MC models have lower activity in the transverse region

Discrepancies increase with CM energy

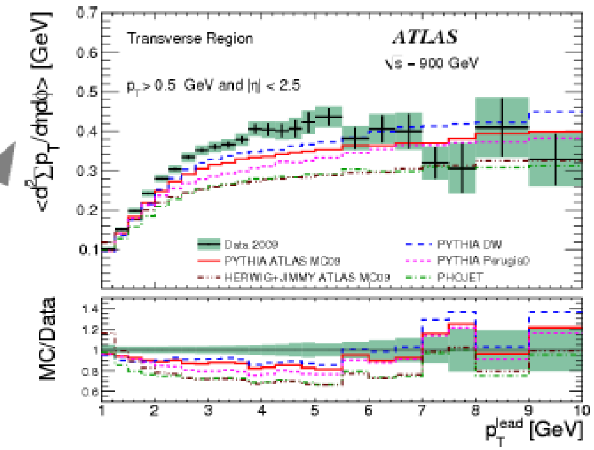


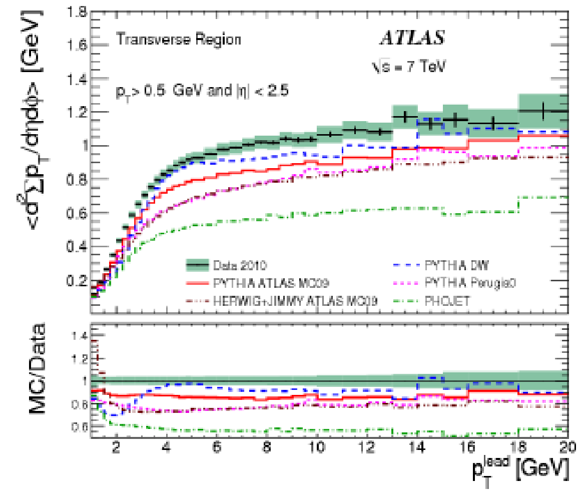
ATLAS arXiv:1012.0791

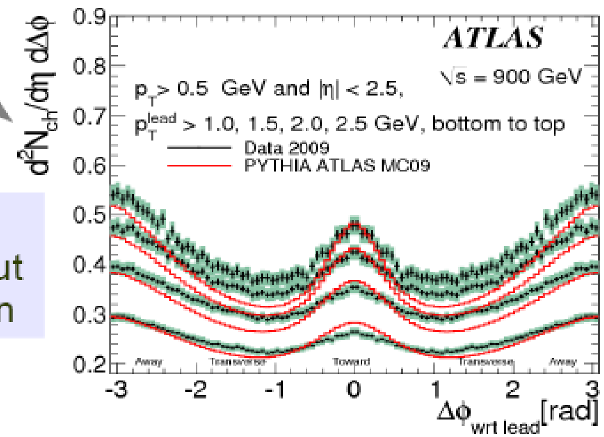
Studies of underlying event in minimum bias data

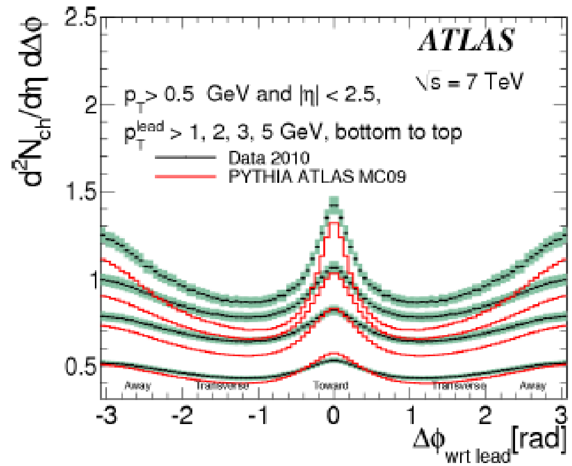
- Scalar sum-PT shows similar discrepancies
- PHOJET fails for 7 TeV
  - not enough particle activity at large pT
- development of ‘jet-like’ structure

Pre-LHC MC models describe general features, but fail in quantitative description



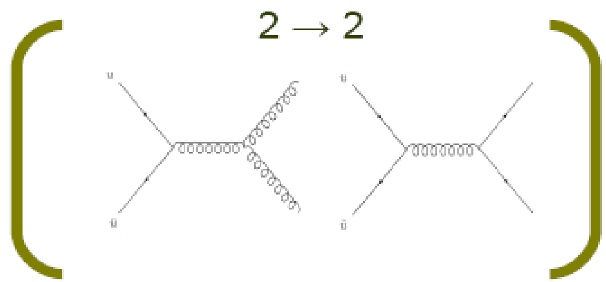






Jets

- Jets are sensitive probe of many aspects of pQCD:
  - matrix elements at LO(+PS) and NLO QCD
  - PDF's
  - running α_S
  - refine our understanding of soft QCD
  - important for searches beyond SM
- For 30 pb^{-1}, the reach in jet transverse momentum at the LHC is twice that attained by previous experiments

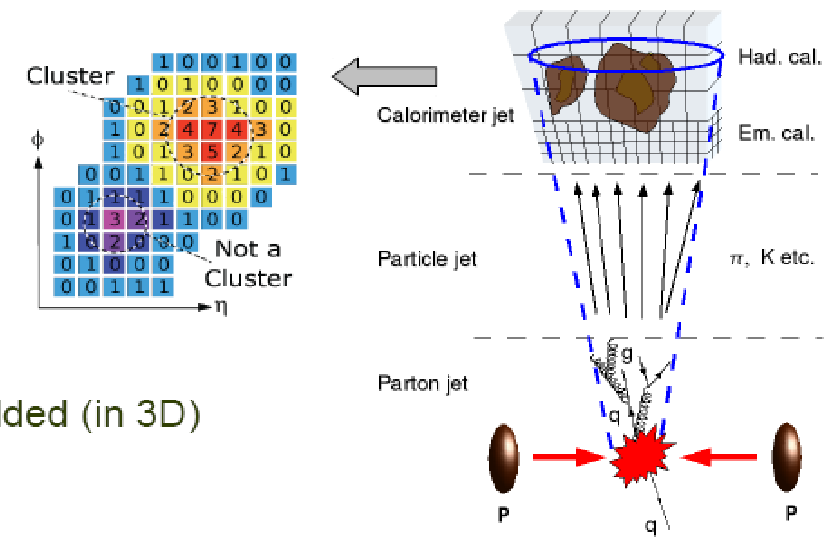


LO processes $O(\alpha_S^2)$

Input for jet algorithms:

Topological clusters built from calorimeter cells
- follow shower development
- reduce noise

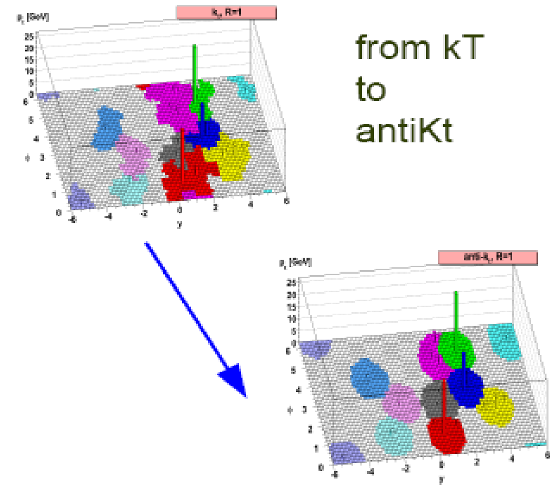
Seeded by cells with |E| > 4 x (noise level)
Neighboring cells with |E| > 2 x noise iteratively added (in 3D)
All neighbors around cluster (|E| > 0) added



Jets

Building jets

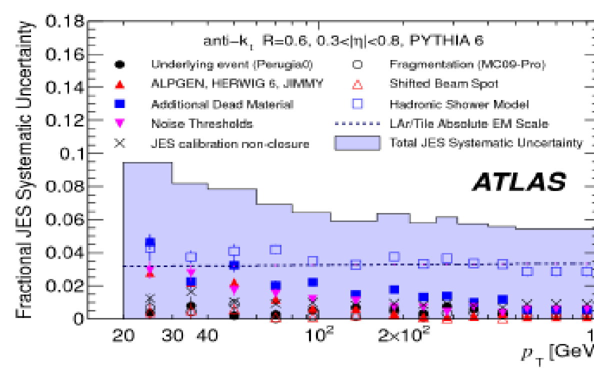
- Jets reconstructed using the anti-kT algorithm
  - M. Cacciari and G. P. Salam, Phys. Lett. B 641, 57 (2006)
- Infrared and collinear safe
- Produces geometrically well-defined cone-like jets
- Size parameters R=0.4 or 0.6



from kT
to
antiKt

Jet-energy scale

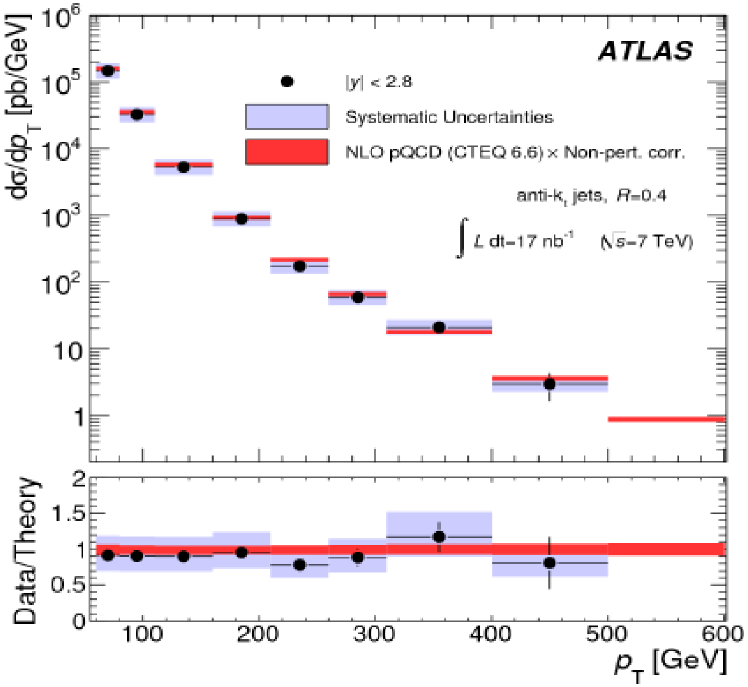
- Dominant uncertainty for all jet-related measurements
- Currently: pT and η dependent correction applied to uncalibrated objects (“EM” scale)
- Other corrections are coming:
  - “Global Cell Weighting” cell weights based on cell energy density
  - Local Cluster Weighting: use properties of topological clusters to classify (EM, hadronic) and calibrate clusters; weights depend on shower topology



- Overall uncertainty 6-10% for |η| <2.8
- Depends on pT and η

Inclusive jet production

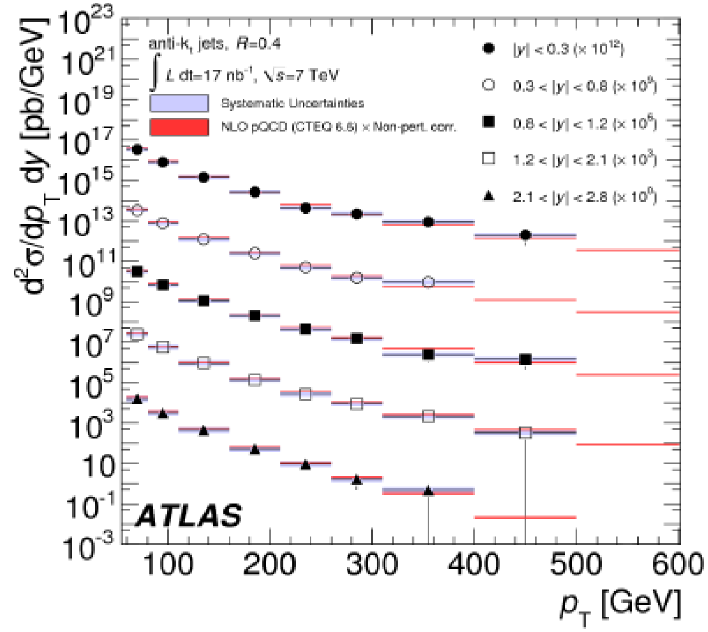
ATLAS arXiv:1009.5908



Very good agreement with NLO QCD &CTEQ6.6

- measurement is dominated by systematical uncertainties (pT<400 GeV)
- dominant uncertainty– jet-energy scale

cross section differential in **rapidity**

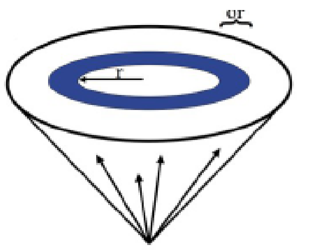


Theory:
NLO QCD (NLOJET++/JETRAD) together with softQCD corrections (~5%) from PYTHIA model

11% uncertainty on luminosity measurement is not shown

Jets shapes

Hard interaction is always associated with extra QCD radiation

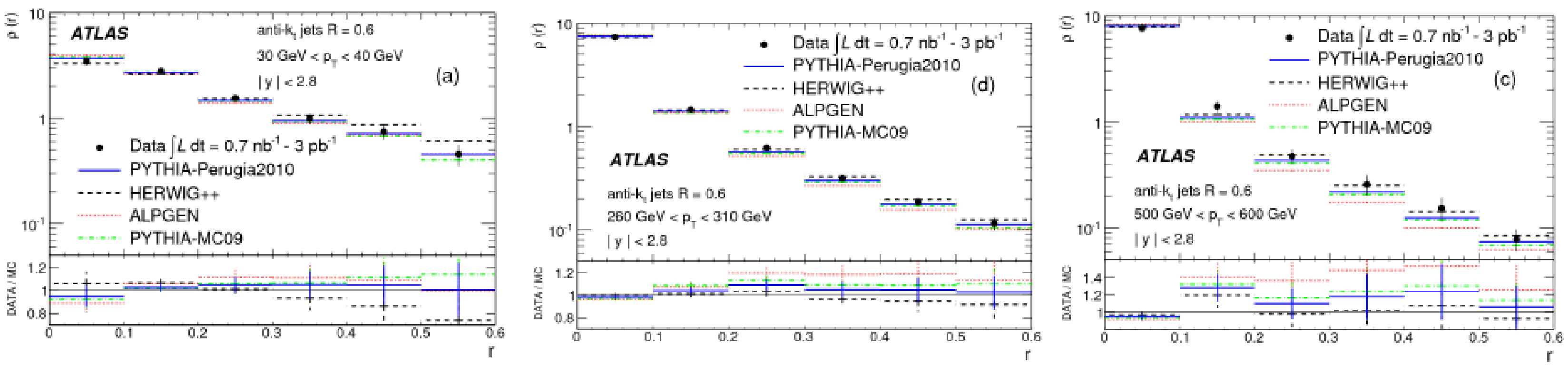


Essential for understanding:

- Soft QCD effects inside jets. Testing PS models
- Sensitive to quark/gluon jet mixture
- For searches of boosted particles (Higgs) and new physics beyond the Standard Model

$$\left\langle \frac{1}{r}\frac{dp_T}{dr} \right\rangle_{jets} = \frac{1}{A}\frac{1}{N_{\text{jet}}}\sum_{jets} p_{\text{T}}(r-\Delta r/2, r+\Delta r/2)$$

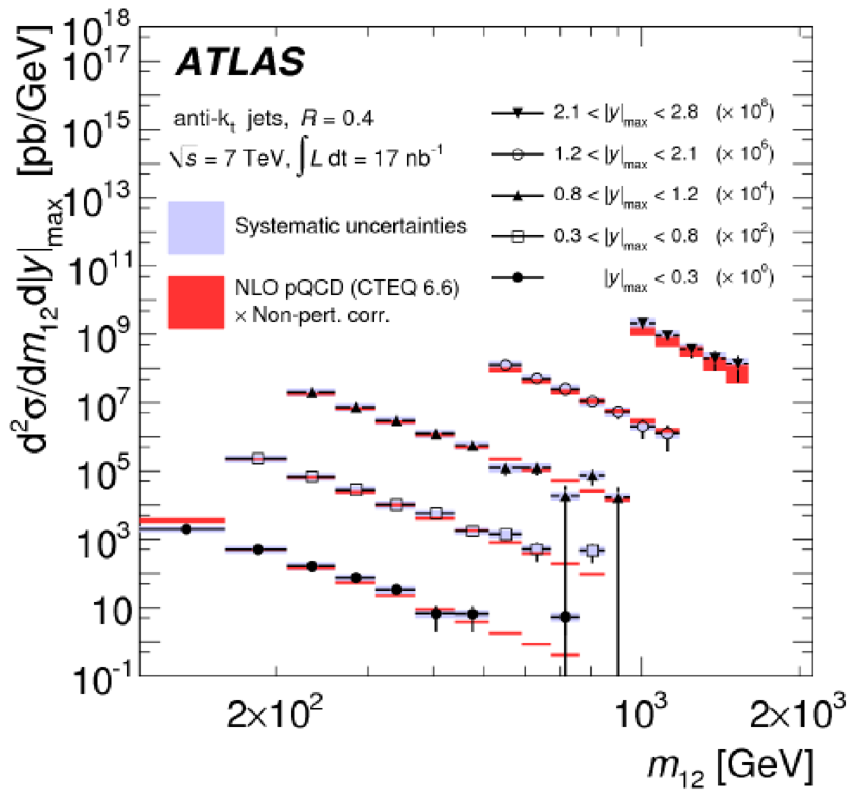
Jets are reconstructed with antiKT=0.6 using topological clusters & corrected



- Jets become narrower as jet pT increases
- Good agreement with LO+PS Monte Carlo models
- ALPGEN (with HERWIG 6.5+JIMMY) generates too narrow jets at large pT

15

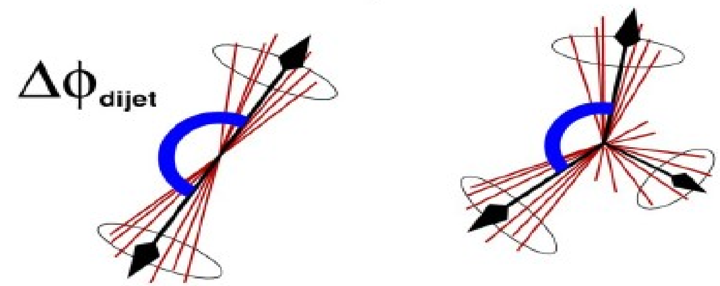
Dijet measurements

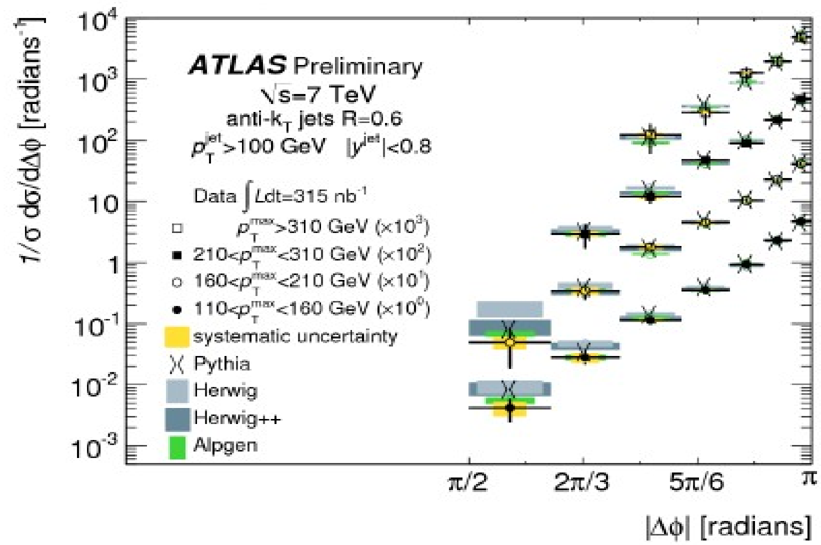


Perfect agreement with NLO QCD & CTEQ6.6.

Azimuthal decorrelation:

Looking at softer QCD without reconstructing soft jets!

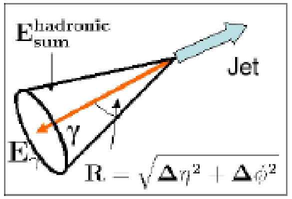




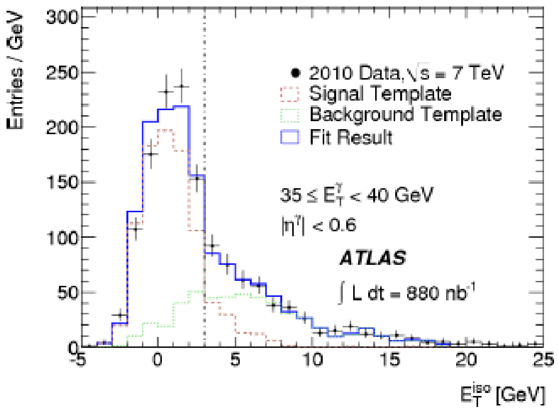
Direct photon production

ATLAS
arXiv:1012.4389

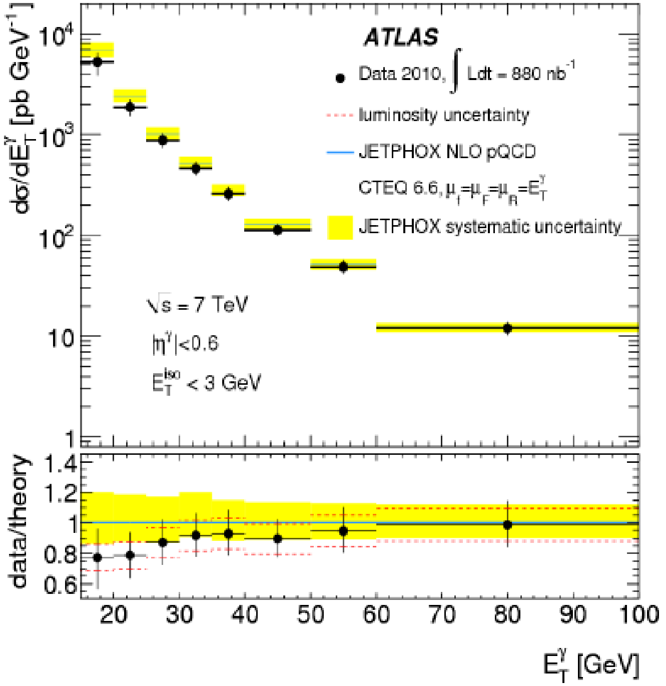
- On theoretical level, considered to be a clean environment to study QCD (no jet reconstruction)
- But difficult in practice as one should deal with large background from hadrons



~90% ~10%



E_T^{ISO} - isolation energy in the cone excluding 5x7 cells around barycenter

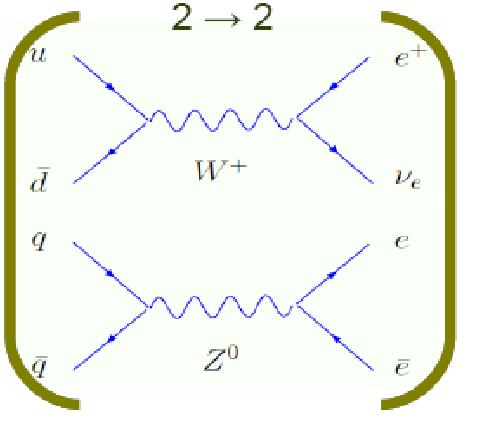


Good agreement with NLO QCD & CTEQ6.6

Probing high-PT EWK sector

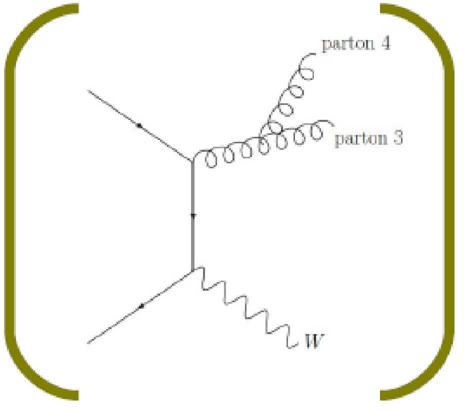
Inclusive W/Z measurements:

- Precise test of NNLO QCD
- Probing PDF
- Tune MC model parameters
- Decay into easily identifiable leptonic states
- Experimental view:
  - Establishing experimental procedure for calibration, trigger, alignment, luminosity and finally a gateway to probe SM at highest CM energies



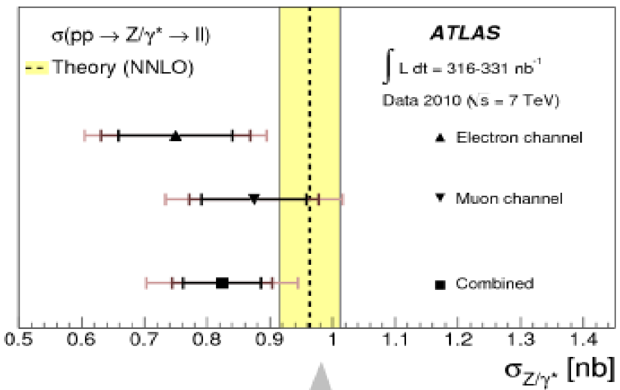
W+jet measurements

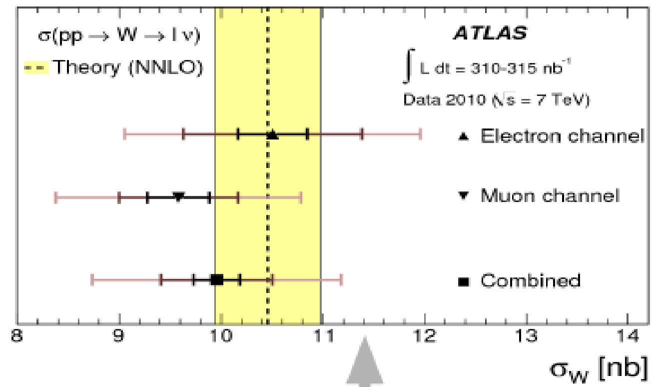
- Constrain measurements to well-known physics
- Precise test of QCD matrix elements, PDF
- Important background for tt, single-top, Higgs searches

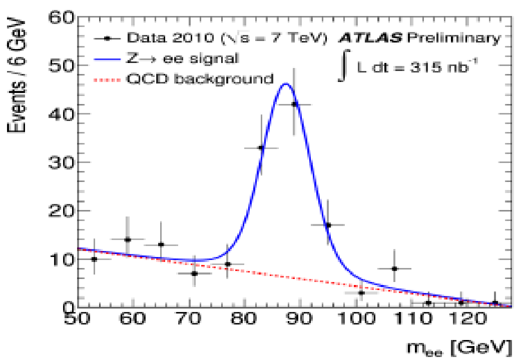


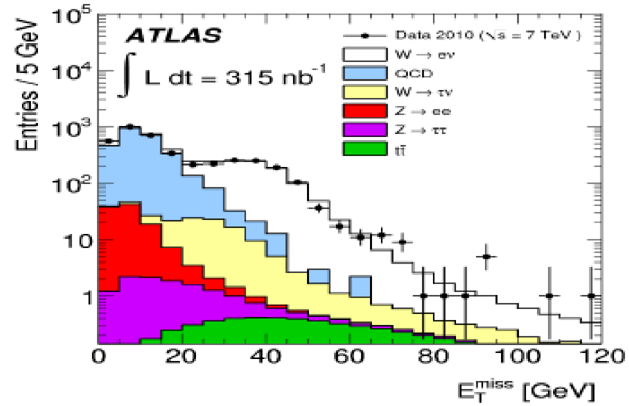
Probing high-PT EWK sector

ATLAS arXiv:1010.2130







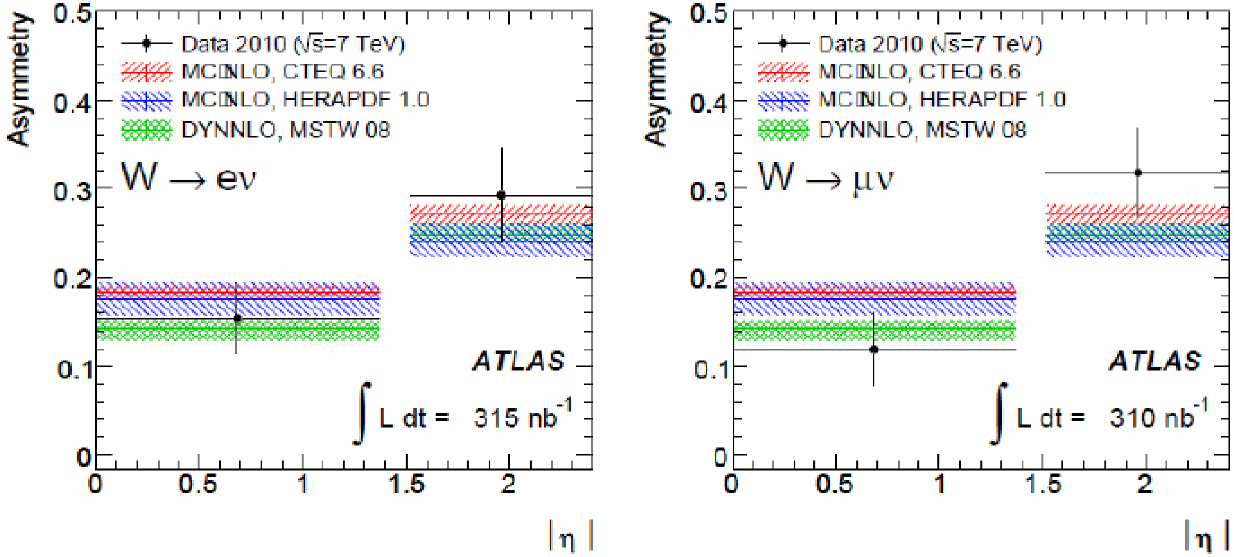


"Golden" channels

- $Z \rightarrow e+ e-$ ($\mu+\mu-$)
- W: isolated lepton + missing E_T

- EWK cross sections at highest CM energies!
- Perfect agreement with the SM

Lepton charge asymmetry



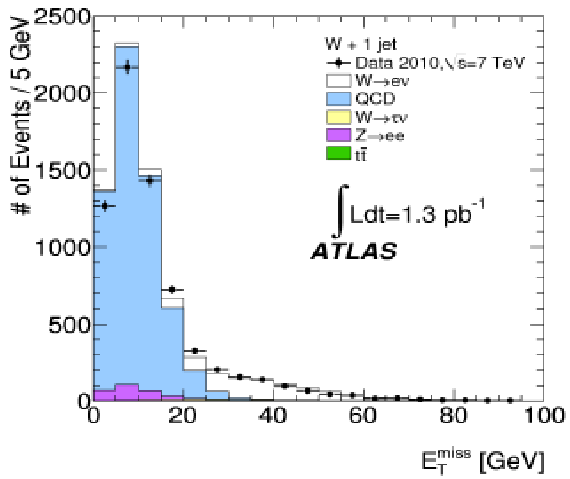
$$A_\ell = \frac{\sigma^{\mathrm{fid}}_{W^+} - \sigma^{\mathrm{fid}}_{W^-}}{\sigma^{\mathrm{fid}}_{W^+} + \sigma^{\mathrm{fid}}_{W^-}}$$

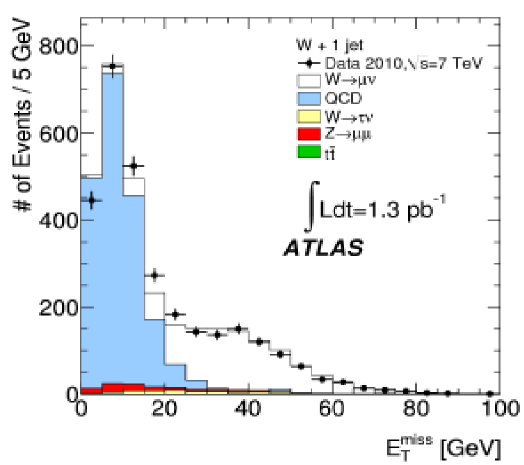
- charge asymmetry is related to the dominance of **u** quarks to **d** quarks in the proton
  - for proton-anitprotons, W+ and W- are produced in equal quantities
- provides important information about parton distribution functions
- with the current statistics, data agree with all models & all PDF

W+jets measurements

ATLAS arXiv:1012.5382

- Events are selected by requiring:
  - E_T (e) >20 GeV or E_T (μ)>20 GeV & |η|<2.4
  - E_T(miss)>25 GeV & M_T>40 GeV
  - antiKT(jet) with R=0.4 & pT>20 & |η|<2.8. Pileup is removed using jet-vertex association
- W+jet signal yield was obtained as difference between data and sum of all background contributions
- Background calculations:
  - Leptonic channels: ALPGEN/PYTHIA with NNLO or NNLL normalizations
  - QCD background: fitting E_T^{miss} using data using template shapes

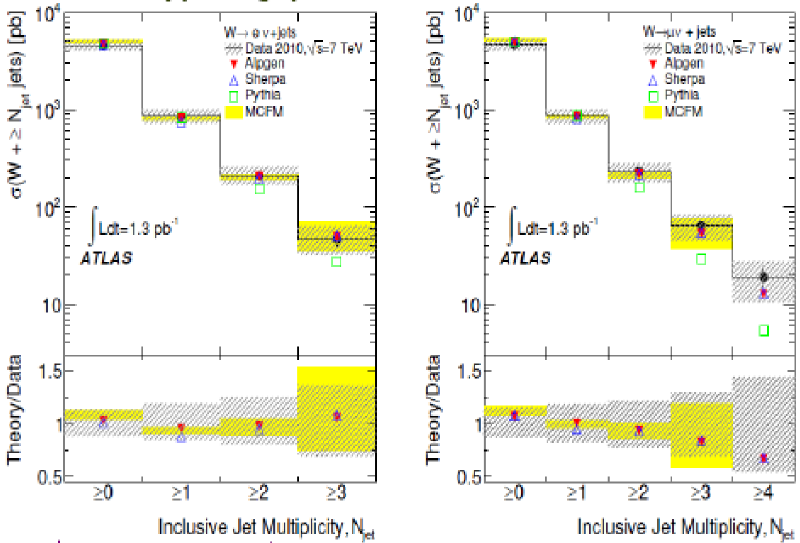


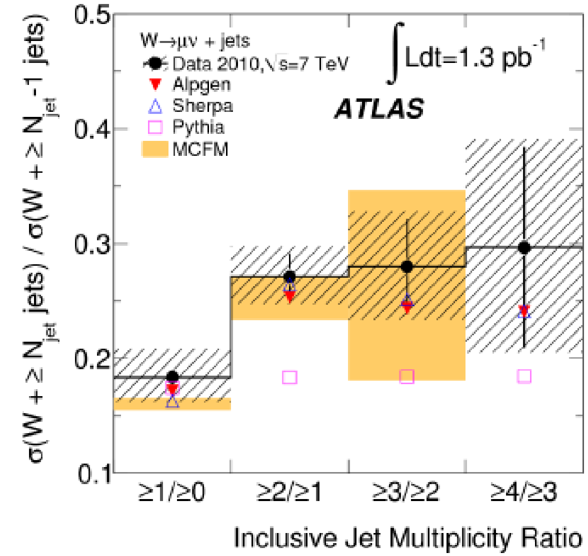


W+ jets measurements

ATLAS arXiv:1012.5382

W → e ν　　　　W → μ ν





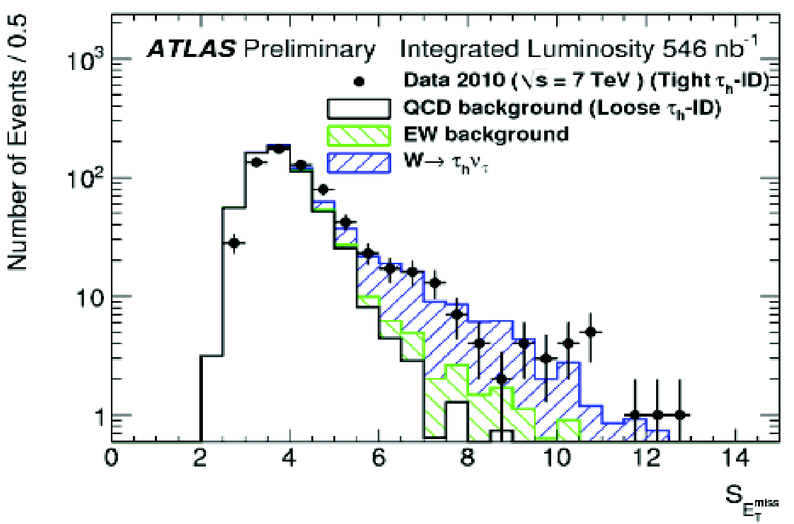
MCFM: NLO　　LO　　NLO　　LO

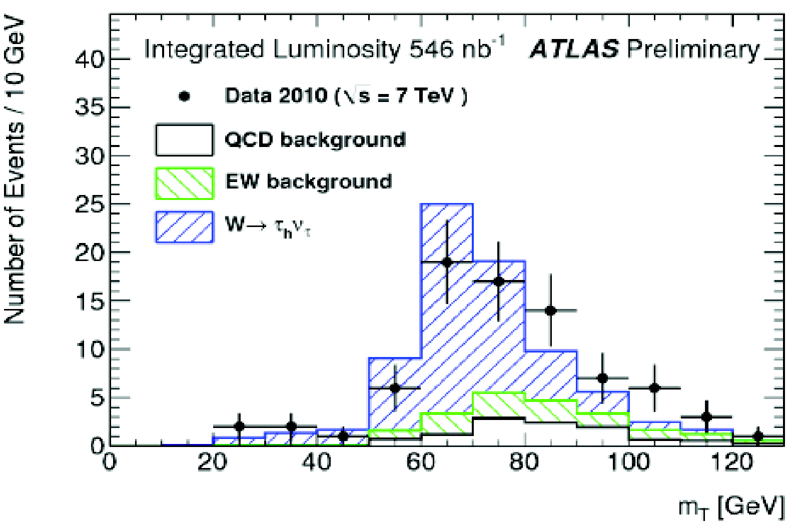
- Good agreement with ALPGEN & SHERPA
- Good agreement with MCFM (NLO QCD) & CTEQ6.6 for <3 jets & LO for >2 jets
  - includes corrections (~10%) for hadronisation & underlying events using AMBT1 tune
- Only MC+PS available for W+4 jets (muon channel)

W →τν observation

- Signature: tau candidate + missing Et
- QCD background determined by data driven method
- Requiring high Missing Et significance

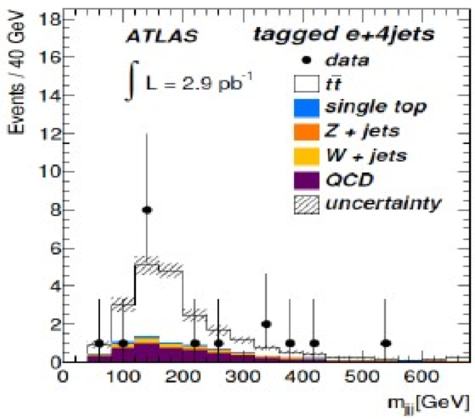
- Observation based on 550nb^{-1}
- 78 hadronic tau candidates
- 22 background events
- Event properties consistent with W→τν





Top cross-section measurements

ATLAS arXiv:1012.1792



2 topologies:
- single-lepton channel (+ >3 jets)
- double lepton channel (+ miss ET)

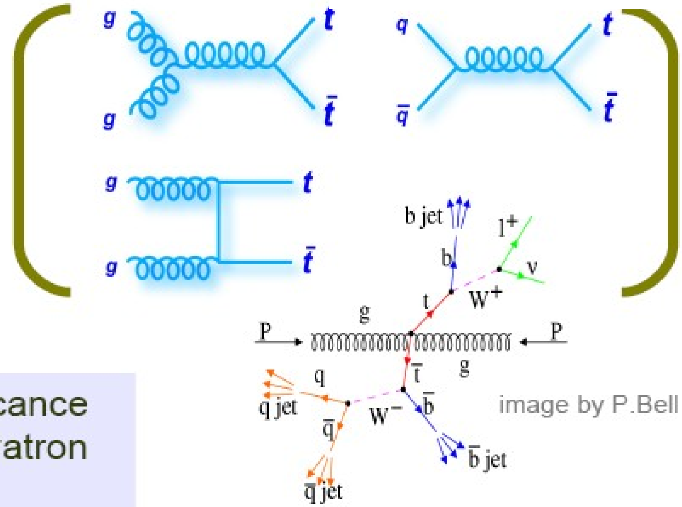
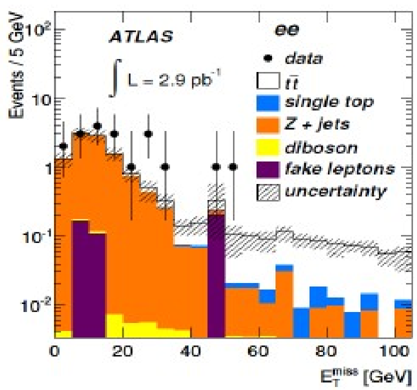
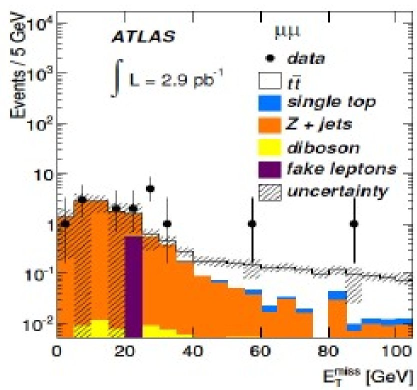
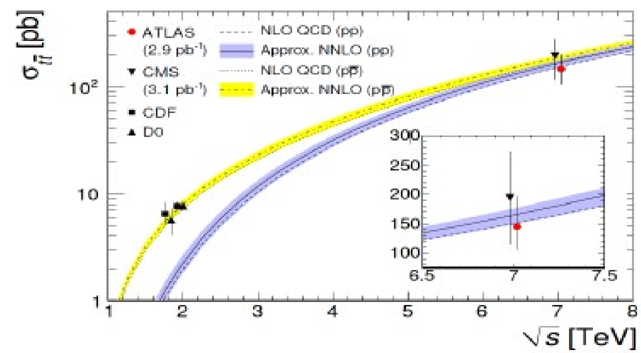


image by P.Bell

- 4.8 σ statistical significance
- confirmation of the Tevatron observation







Good agreement with NLO & NNLO (app) QCD

Searches and limits

(SUSY discussed last Wednesday)

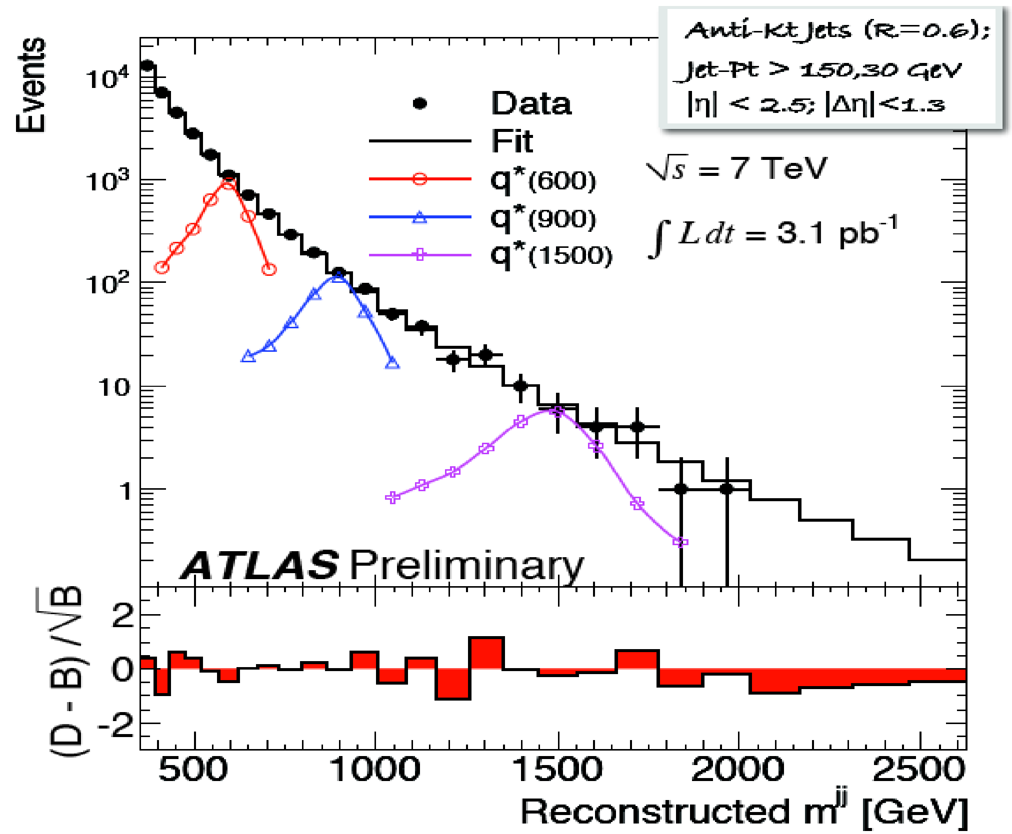
ATLAS search for heavy dijet resonances

- 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

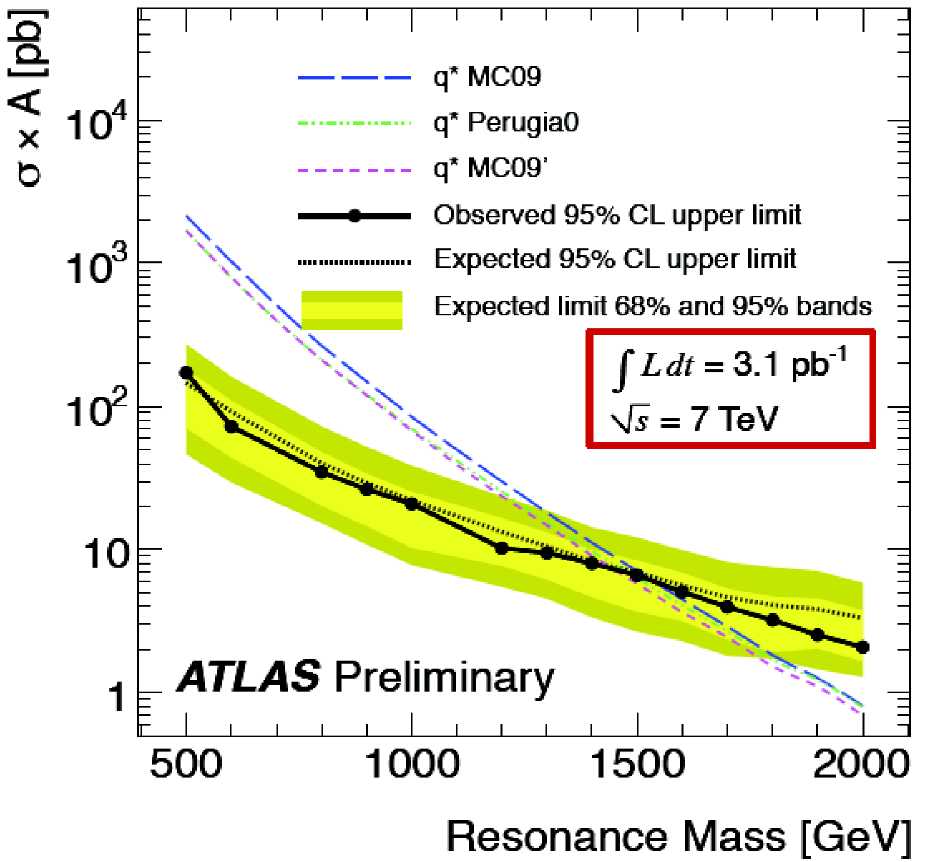
- Systematic uncertainties
  - Jet Energy Scale
  - BG fit parameters
  - Luminosity
  - Jet Energy Resolution

- 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

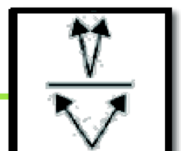


ATLAS-CONF-2010-093; Phys Rev Lett 105, 161801 (2010)

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 $\sqrt{s} << \Lambda$ compositeness manifested as effective 4-fermion contact interaction

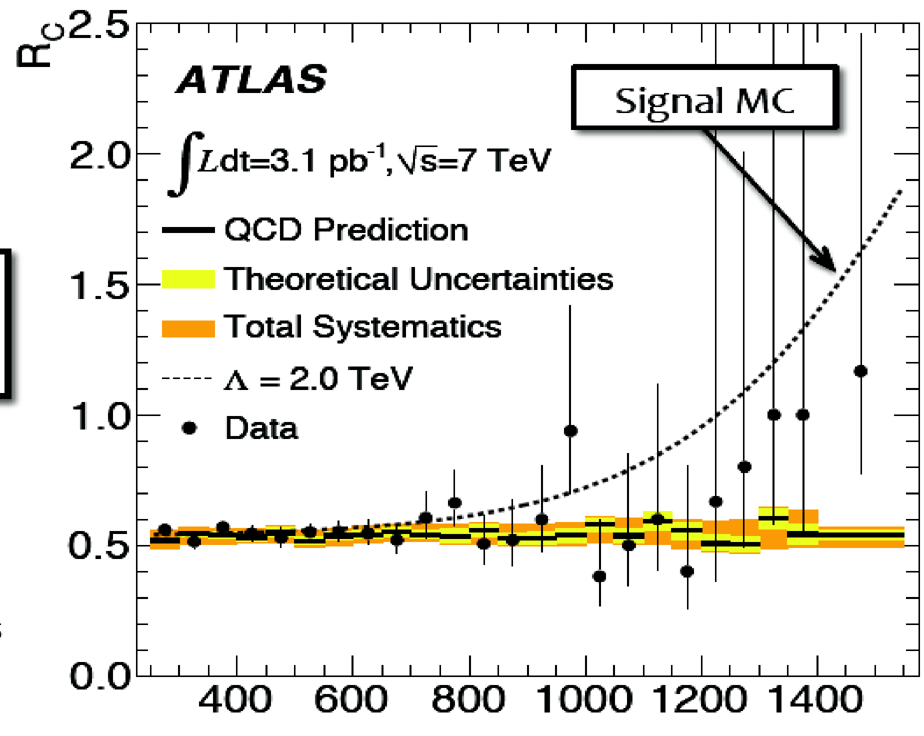
- Search for deviations in dijet angular distributions
- Observables:



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

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

- (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

Contact interactions limits

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

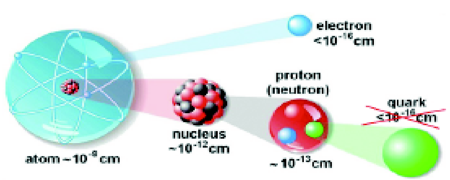
$g^2/4\pi = 1$ and the quark fields Ψ_q^L are left-handed.

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

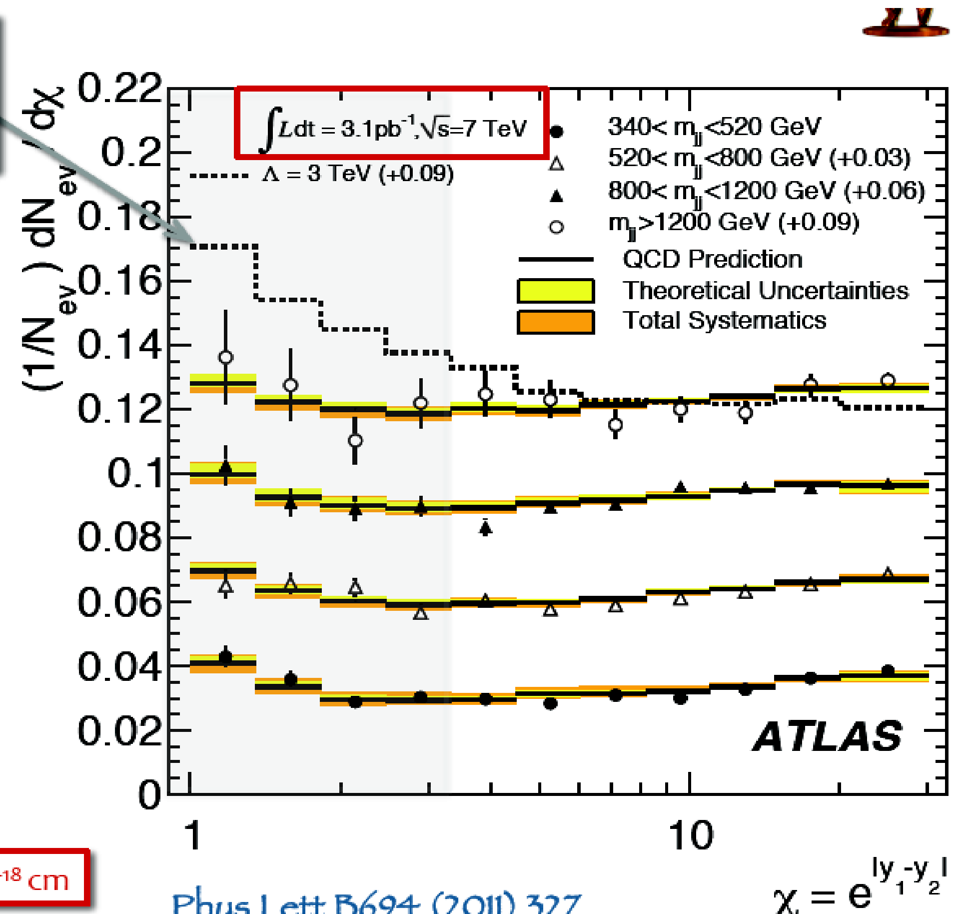
$\boxed{\Lambda < 3.4 \text{ TeV}}$

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

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



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



Phys Lett B694 (2011) 327

Multi-body final state at high mass

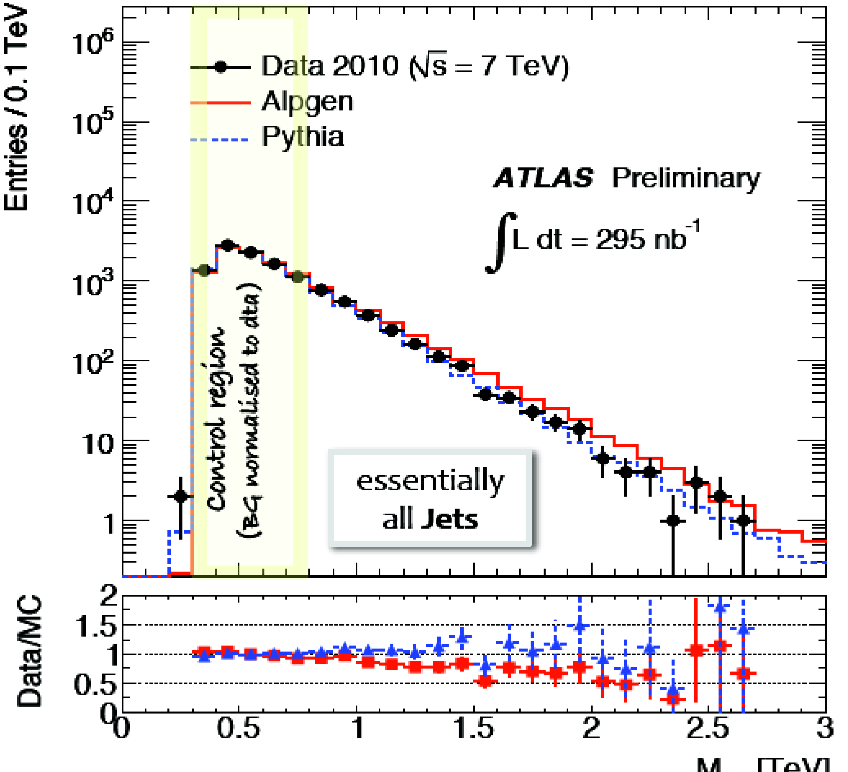
- **Goal:** Search for evidence of Quantum Gravity States with large cross section
  - "General search" in context of TeV-scale Gravity Models with scale M_D (e.g. Black Holes, String Balls) (expect deviation from SM at High Mass)
- Assumptions:
  - Decays of heavy gravitational objects democratic to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

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

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

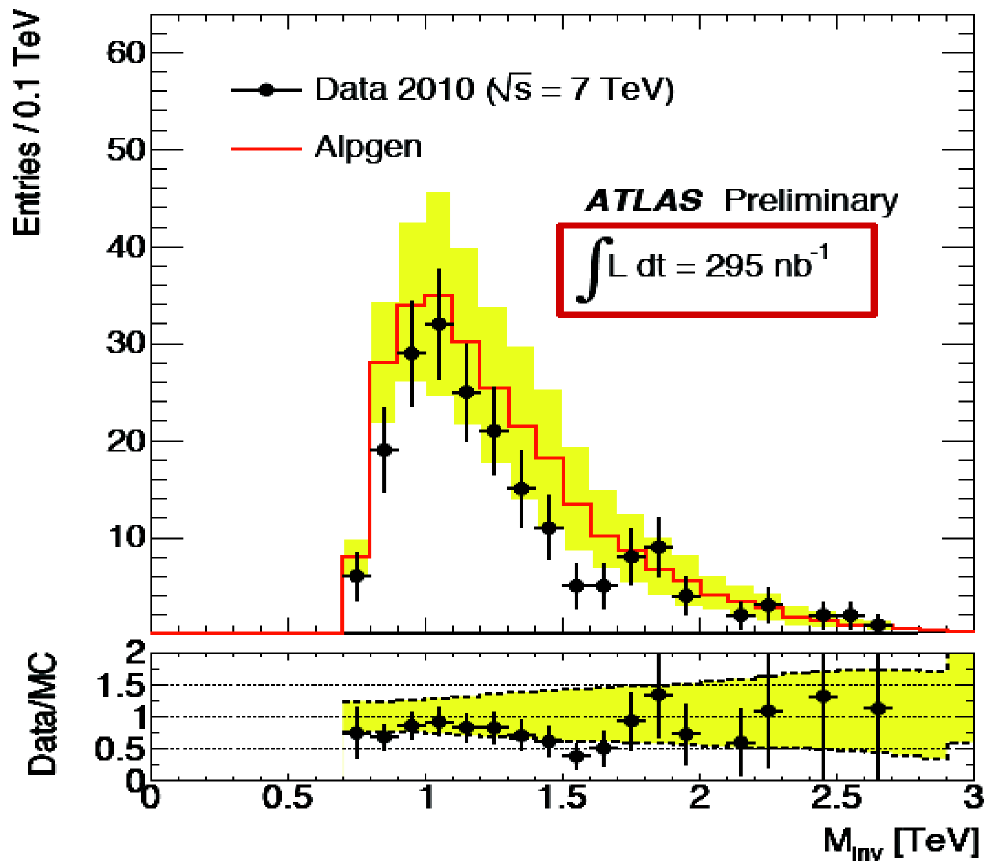
Data	SM expectation
193	295 ± 18 ± 84

- 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)



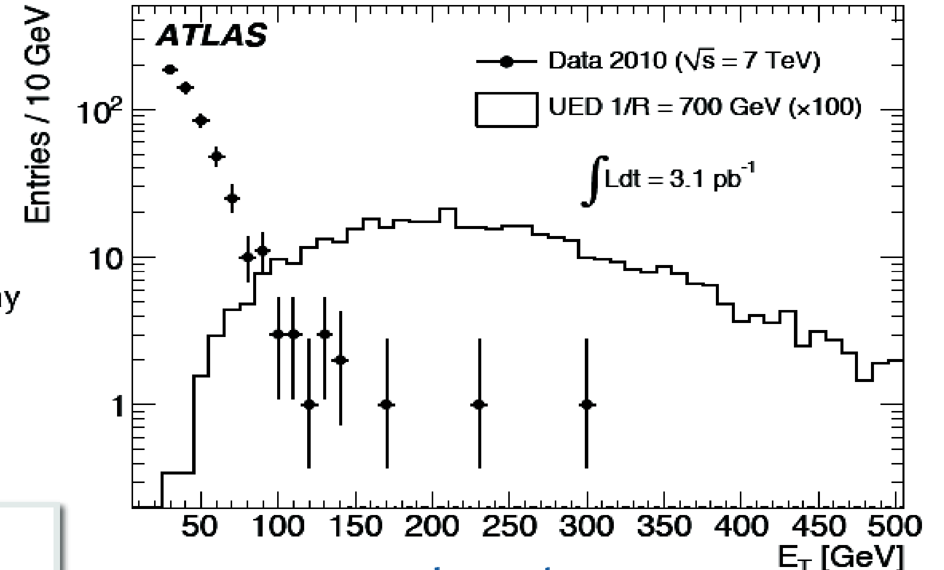
ATLAS-CONF-2010-088

Search for final states with $\gamma\gamma$ 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

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

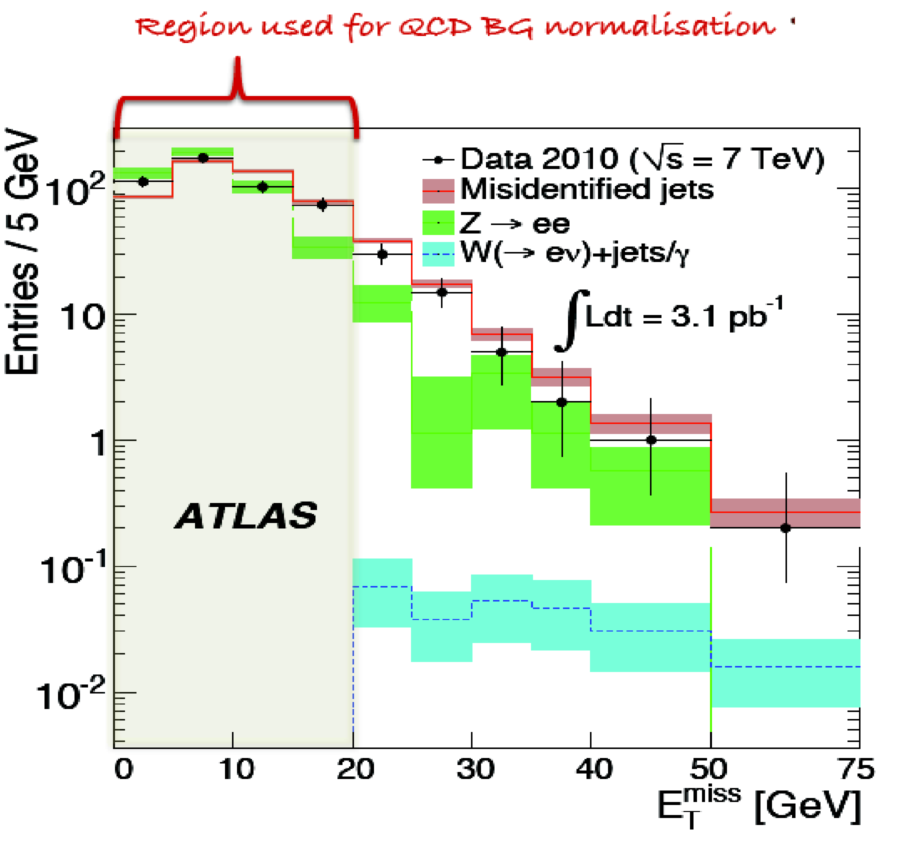


arXiv:1012.4272 (submitted to PRL)

27

Search for final states with $\gamma\gamma$ 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)

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Search for final states with $\gamma\gamma$ and EtMiss

- Signal Region:

  (Keep expected BG below 1 event)

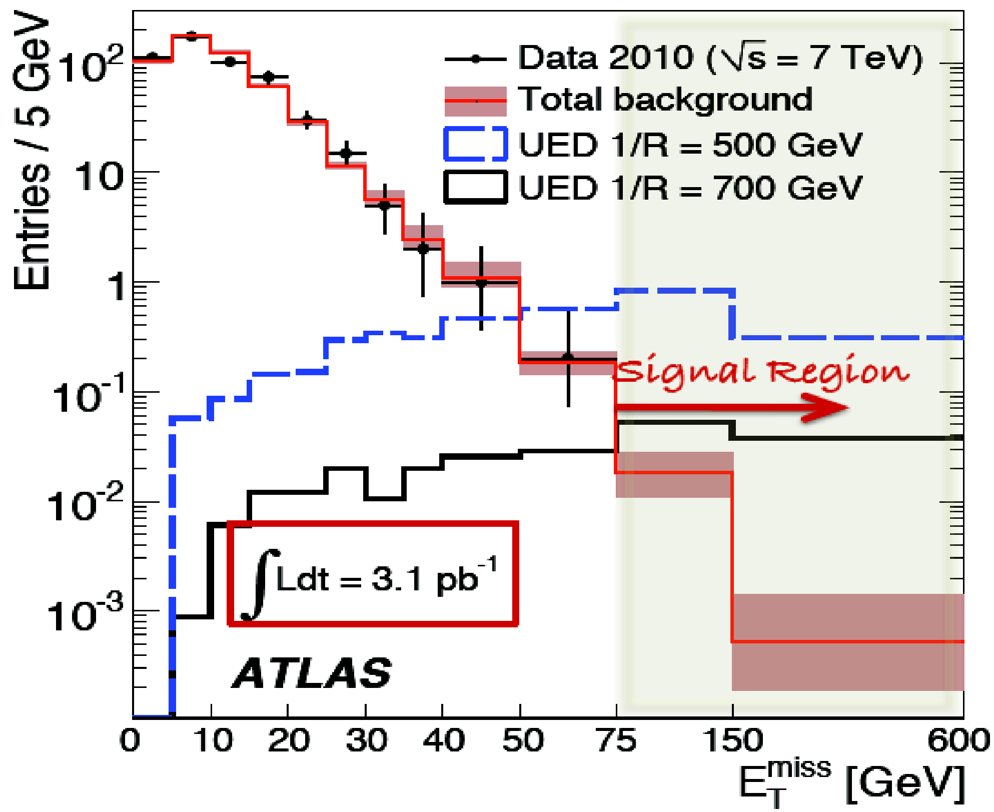
Data	SM expectation
0	0.32 ± 1.6

- 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

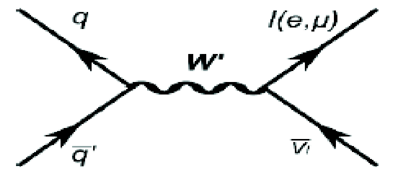
  Do Coll., Phys Rev Lett, 105 (2010) 221802



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

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

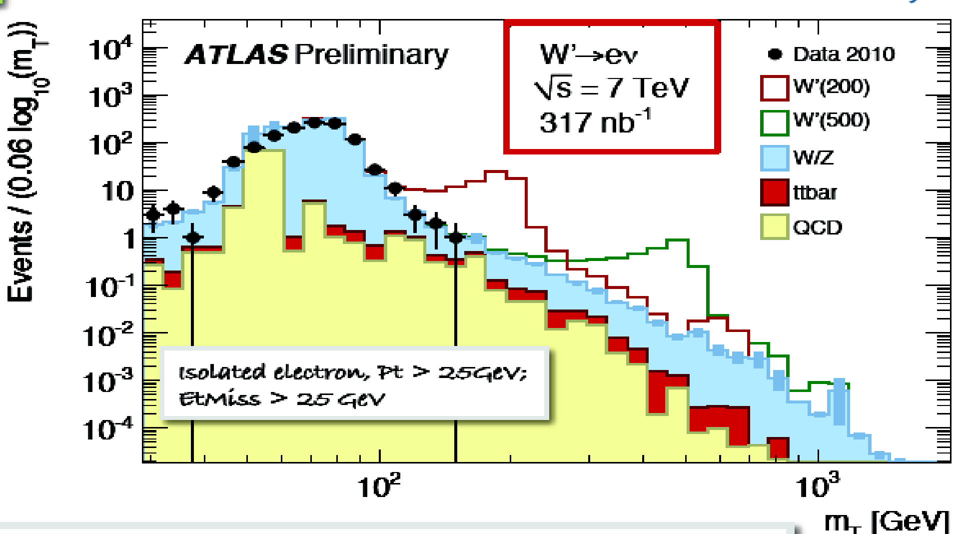
ATLAS-CONF-2010-089

- 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)

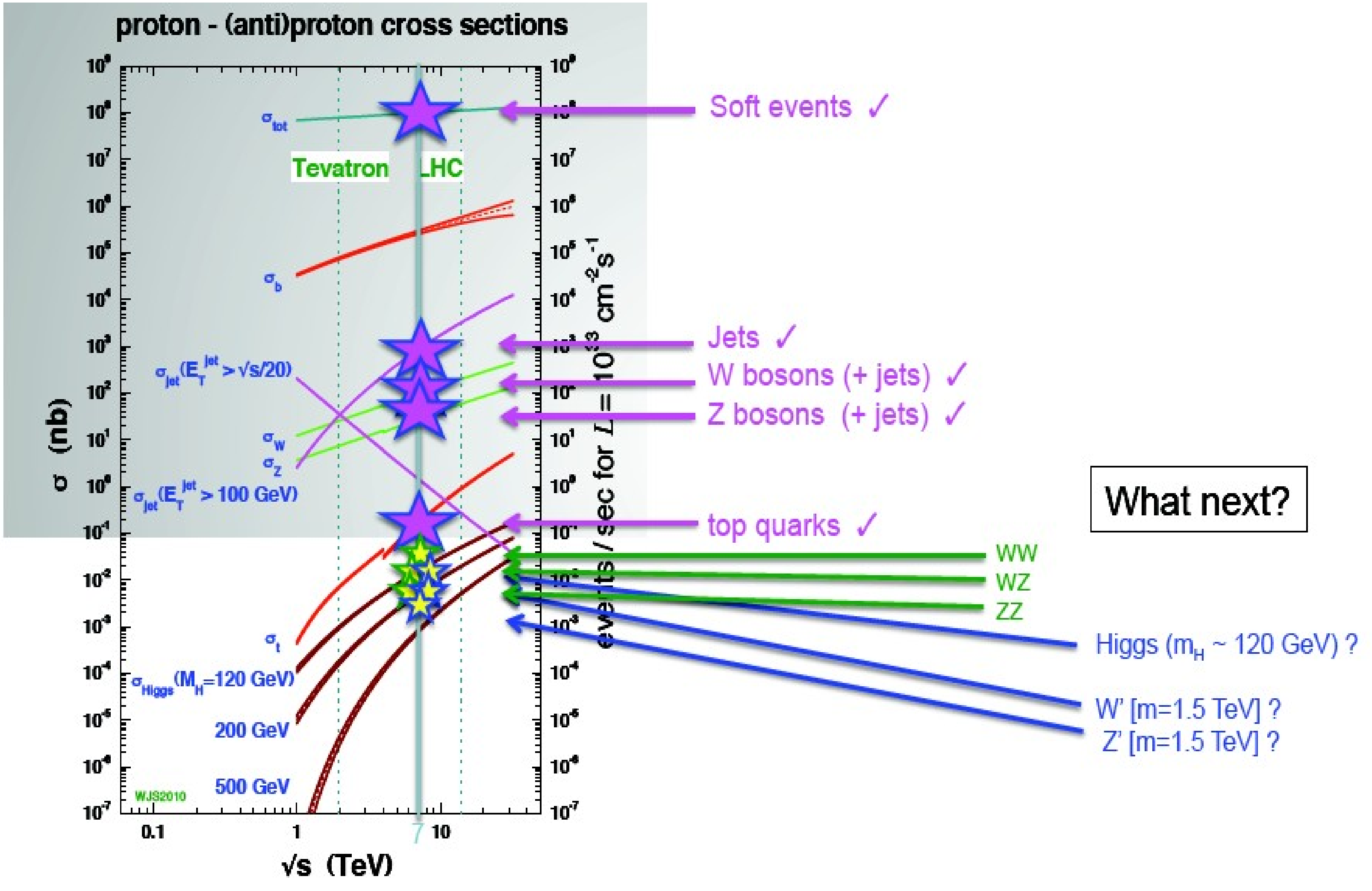
Current Tevatron limit: $M_{W'} > 1.0$ TeV

Do Coll. Phys Rev Lett 100 (2008) 031804



expect to exceed Tevatron limit with full 2010 statistics

Summary on pp physics



What next?

LHC Projections for 2011 *R Bailey LHCC Nov10*

2011: "reasonable" numbers

- **4 TeV (to be discussed at Chamonix)**
- 936 bunches (75 ns)
- 3 micron emittance
- 1.2 x 10^{11} protons/bunch
- beta* = 2.5 m, nominal crossing angle

Peak luminosity	6.4 x 10^{32}
Integrated per day	11 pb^{-1}
200 days	**2.2 fb^{-1}**
Stored energy	72 MJ

2011: Ultimate Reach

- **4 TeV**
- 1400 bunches (50 ns)
- 2.5 micron emittance
- 1.5 x 10^{11} protons/bunch
- beta* = 2.0 m, nominal crossing angle

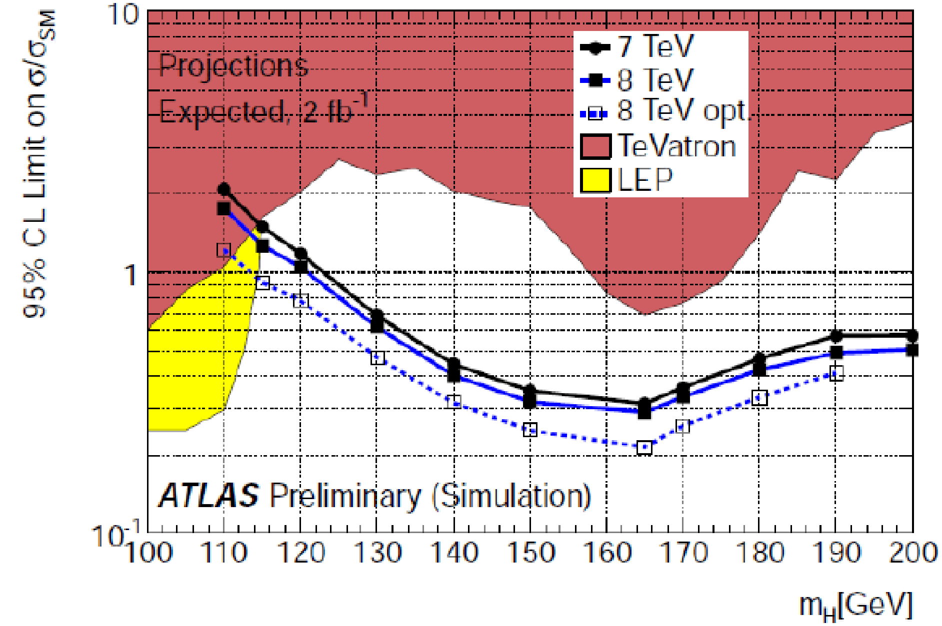
Peak luminosity	2.2 x 10^{33}
Integrated per day	38 pb^{-1}
200 days	**7.6 fb^{-1}**
Stored energy	134 MJ

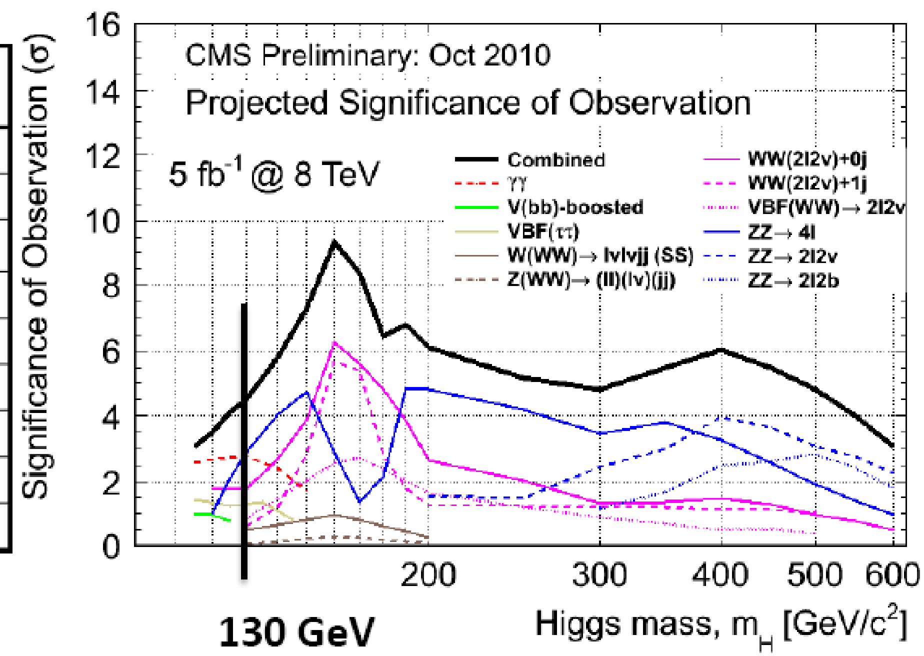
Usual warnings particularly apply – see problems, problems above

E

ATLAS /CMS projections for SM Higgs boson exclusion and discovery

Channels included	Higgs mass range used in analyses (GeV)
H→γγ	115-150
VBF H→ττ	115-145
VH, H→bb (highly boosted)	115-125
VH, H→WW→lvjj	130-200
H→WW→2l2v + 0/1 jets	120-600
VBF H→WW→2l2v	130-500
H→ZZ→4l	120-600
H→ZZ→2l2v	200-600
H→ZZ→2l2b	300-600





To complete those lectures I have borrowed slides from conference talks of many people.

THANKS to all of them!!!

I had great time following progress of the experimental measurements and observing like dreams are becoming a reality. I hope that, after those 14 lectures, you will continue following "physics at LHC" happening in the years 2011 and maybe also 2012.

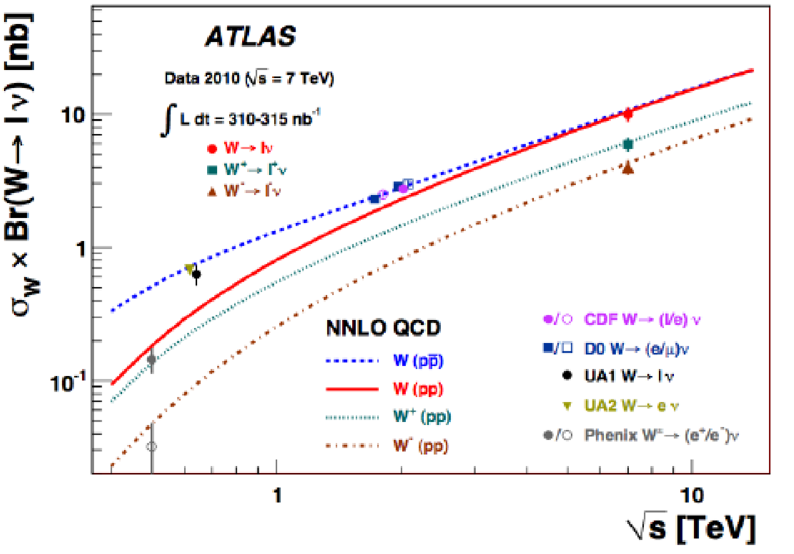
We will restart very soon .... But first.... watch out for decisions which will be taken at Chamonix in January 2011.

Theoretical predictions

- ATLAS Central values from QCD NNLO calculations by FEWZ with ~5% systematic uncertainty (based on 90% CL, including PDF and α_S uncertainties)

$$
\begin{aligned}
\sigma(W^+ \to \ell^+\nu) &= 6.16 \pm 0.31 \text{ nb} \\
\sigma(W^- \to \ell^-\nu) &= 4.30 \pm 0.21 \text{ nb} \\
\sigma(W^\pm \to \ell^\pm\nu) &= 10.46 \pm 0.52 \text{ nb} \\
\sigma(Z(\gamma^*) \to \ell\ell) &= 0.964 \pm 0.048 \text{ nb} \quad (66 < M_{\ell\ell} < 116\,\text{GeV})
\end{aligned}
$$

http://arxiv.org/pdf/1011.6259v1



- PDF uncertainties: uncertainties of NLO and NNLO calculations from 68% CL error sets vary between ±(1.6 − 2.0)%
  - Found to be about a factor of two larger using 90%CL error sets,
  - suggesting non-Gaussian distributions of the cross section variations.

- α_s value and its uncertainties
  - using MSTW2008 fits which include PDF sets with α_s values corresponding to ±1σ
  - 68% CL leads to 1.1%, 90% leads to 2.6% relative uncertainty
- Electroweak Radiative Corrections assumed to be negligible

Metodology

- The production cross sections for the W and Z bosons times the branching ratios for decays into leptons can be expressed as

$$\sigma^{\mathrm{tot}}_{W(Z)} \cdot BR(W(Z) \to \ell\nu\ (\ell\ell)) = \frac{N^{\mathrm{sig}}_{W(Z)}}{A_{W(Z)} \cdot C_{W(Z)} \cdot L_{W(Z)}}$$

- N^{sig} denote the numbers of background-subtracted signal events passing the selection criteria of the analyses in the W and Z channels

- A_W and A_Z denote the acceptances for the W and Z-boson decays

$$A = \frac{N^{\mathrm{Generated}}_{\mathrm{in\ Fiducial\ Region}}}{N^{All}_{Generated}}$$

- C_W and C_Z denote the ratios between the total number of generated events which pass the final selection on reco. level and the number of generated events within the fiducial acceptance

$$C_W = \varepsilon^W_{\mathrm{event}} \cdot \alpha^W_{\mathrm{reco}} \cdot \varepsilon^W_{\mathrm{lep}} \cdot \varepsilon^W_{\mathrm{trig}}$$

$$C_Z = \varepsilon^Z_{\mathrm{event}} \cdot \alpha^Z_{\mathrm{reco}} \cdot (\varepsilon^Z_{\mathrm{lep}})^2 \cdot [1 - (1 - \varepsilon^Z_{\mathrm{trig}})^2]$$

- Remarks
  - Acceptance Factor A and detector effect correction factors C can be treated as independent factors
  - Theoretical uncertainties affect dominantly the factor A

Theoretical uncertainties

- Acceptance correction factors extrapolate fiducial cross-sections to full cross-sections
  - Predicted by Monte Carlo event generators
  - Negligible impact on experimental factors C_W and C_Z

MC	A_{W^+} $W^+ \to e^+\nu$	A_{W^-} $W^- \to e^-\nu$	A_W $W \to e\nu$	A_Z $Z/\gamma^* \to e^+e^-$	A_W/A_Z
PYTHIA MRST LO*	0.466	0.457	0.462	0.446	1.036
PYTHIA CTEQ6.6	0.479	0.458	0.471	0.455	1.035
PYTHIA HERAPDF1.0	0.477	0.461	0.470	0.451	1.042
MC@NLO HERAPDF1.0	0.475	0.454	0.465	0.440	1.057
MC@NLO CTEQ6.6	0.478	0.452	0.465	0.445	1.045
	A_{W^+} $W^+ \to \mu^+\nu$	A_{W^-} $W^- \to \mu^-\nu$	A_W $W \to \mu\nu$	A_Z $Z/\gamma^* \to \mu^+\mu^-$	A_W/A_Z
PYTHIA MRSTLO*	0.484	0.475	0.480	0.486	0.988
PYTHIA CTEQ6.6	0.499	0.477	0.490	0.496	0.987
PYTHIA HERAPDF1.0	0.496	0.479	0.489	0.492	0.994
MC@NLO HERAPDF1.0	0.494	0.472	0.483	0.479	1.008
MC@NLO CTEQ6.6	0.496	0.470	0.483	0.485	0.996

- Theoretical uncertainty within on PDF-Set (here CTEQ 6.6) in combination with the MC@NLO acceptance calculation
  - $\pm$1.0% for W^+
  - $\pm$1.8% for W^-
  - $\pm$1.6% for $Z/\gamma*$
- Differences between different PDF-Sets (MRST LO*, CTEQ 6.6 and HERAPDF)
  - $\pm$2.7% for W+
  - $\pm$0.9% for W−
  - $\pm$2.0% for $Z/\gamma*$
- Uncertainties due to the modelling of W and Z production by comparing PYTHIA and MC@NLO with same PDF-Set
  - $\pm$0.4% for W+
  - $\pm$1.4% for W−
  - $\pm$2.3% for $Z/\gamma*$

Experimental uncertainties

- Current experimental uncertainties dominated by lepton identification
- Given the small statistics which was used for this measurement the current numbers are already impressively small
  - Expect large improvements for reprocessed data and full statistics

Parameter	$\delta C_W/C_W(\%)$	$\delta C_Z/C_Z(\%)$
Trigger efficiency	<0.2	<0.2
Material effects, reconstruction and identification	5.6	8.8
Energy scale and resolution	3.3	1.9
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	2.0	-
Problematic regions in the calorimeter	1.4	2.7
Pile-up	0.5	0.2
Charge misidentification	0.5	0.5
FSR modelling	0.3	0.3
Theoretical uncertainty (PDFs)	0.3	0.3
Total uncertainty	7.0	9.4

Parameter	$\delta C_W/C_W(\%)$	$\delta C_Z/C_Z(\%)$
Trigger efficiency	1.9	0.7
Reconstruction efficiency	2.5	5.0
Momentum scale	1.2	0.5
Momentum resolution	0.2	0.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution	2.0	-
Isolation efficiency	1.0	2.0
Theoretical uncertainty (PDFs)	0.3	0.3
Total uncertainty	4.0	5.5

Target precision for 2011

- Combining the experimental uncertainties on C_Z and the improved theoretical uncertainties on A lead to an estimated precision of **~2%** on the measured Z/γ^* cross-section

- Using measured cross-section to predict integrated luminosity requires the theoretical predicted cross-section
  - Using 68% confidence limit leads to a theoretical uncertainty of 2%
    - We know that this is too optimistic
  - Larger improvements expected when using LHC data to constrain PDFs
  - Lower bound on cross-section prediction given by renormalisation and factorisation scale uncertainties: 0.6-0.8%