First QCD results from the ATLAS Collaboration

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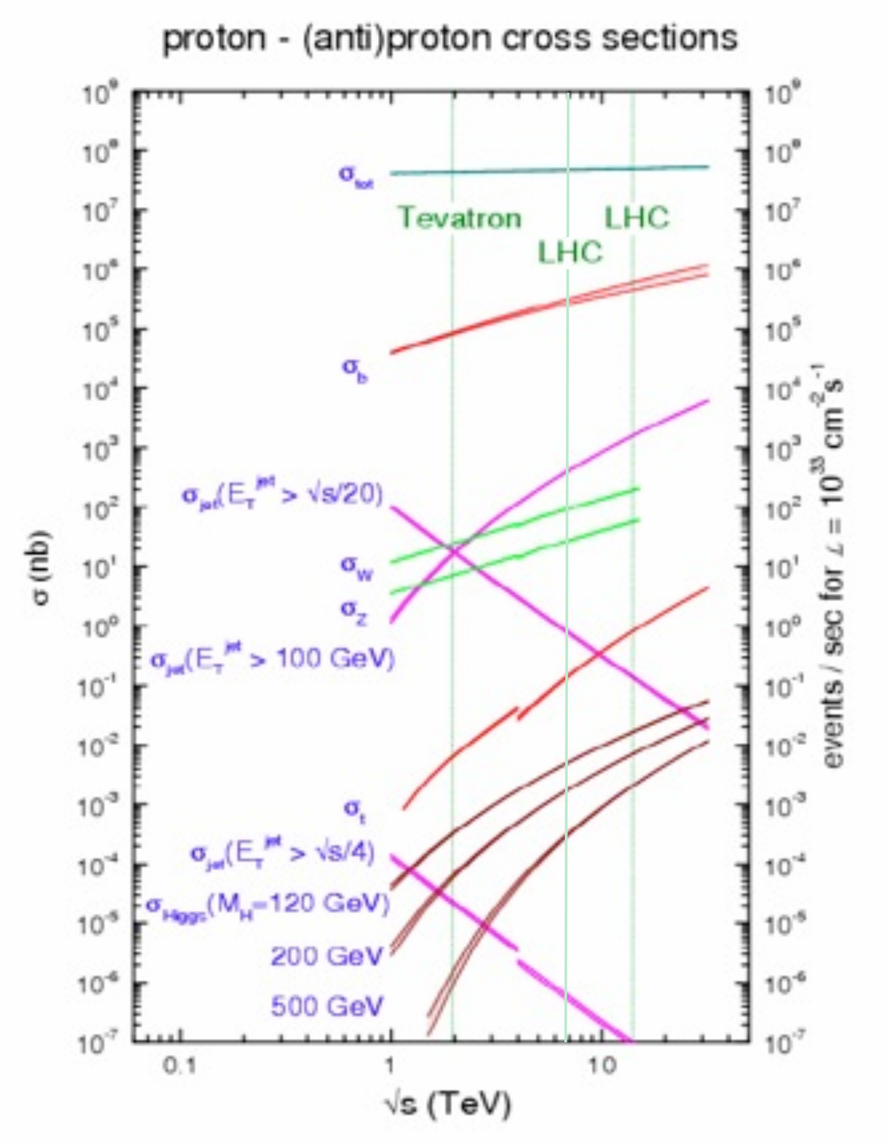
on behalf of the
ATLAS Collaboration

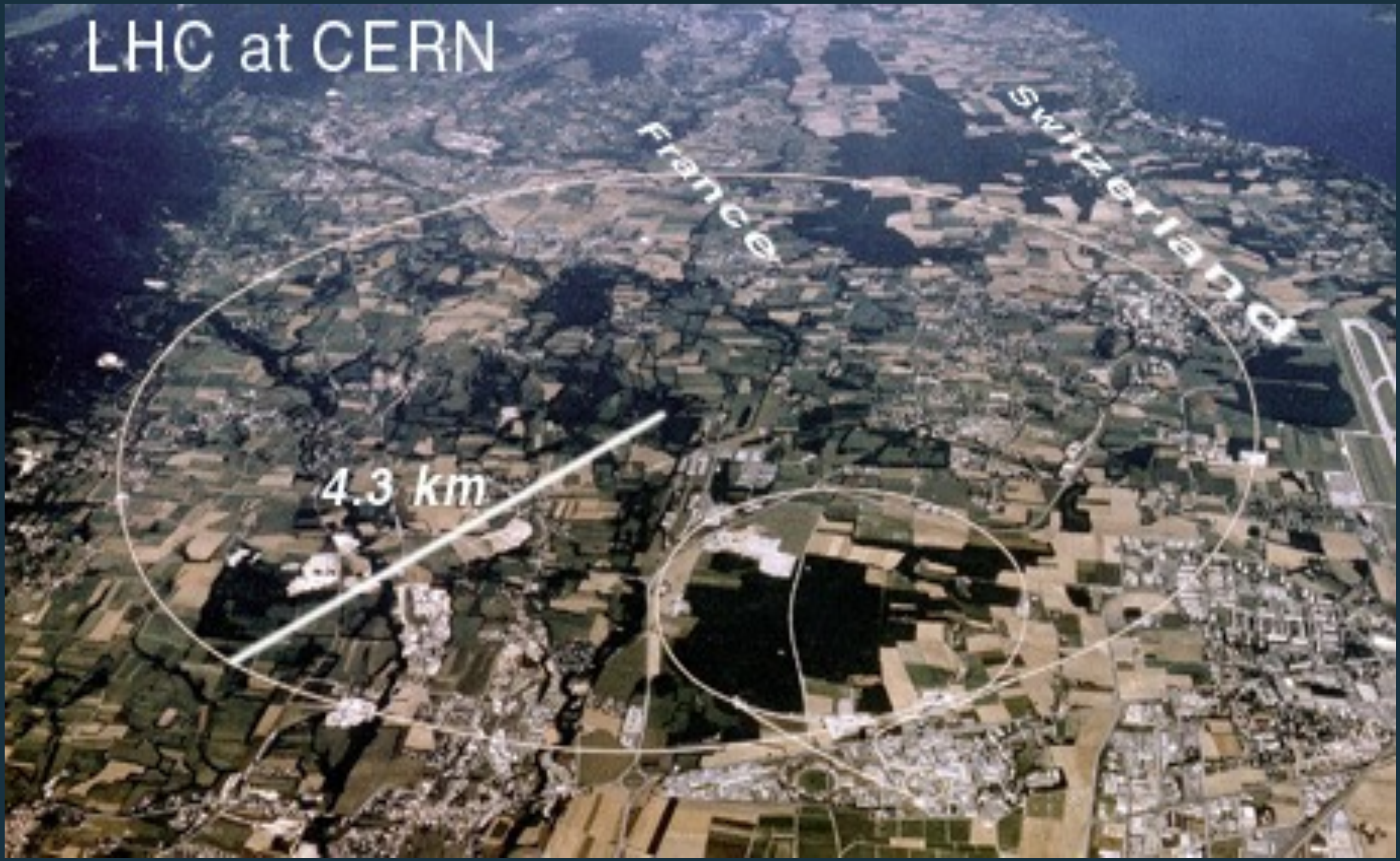
29th November 2010

Introduction

- The LHC is a exceptional QCD machine.
  - O(100) jets with E_T>100 GeV every second.
- Effectively all physics at the LHC is QCD, determined by interactions between quarks and gluons within the proton.
- The study of QCD at the LHC enables us to achieve significant goals:
  - The high precision study of the QCD hard subprocess over an unprecedented large range of scale.
  - Understand the parton distribution functions within the proton in great detail.
- Interesting in it's own right, also *essential* stages in understanding the backgrounds for all other processes, Higgs production, Supersymmetry and other new physics etc.



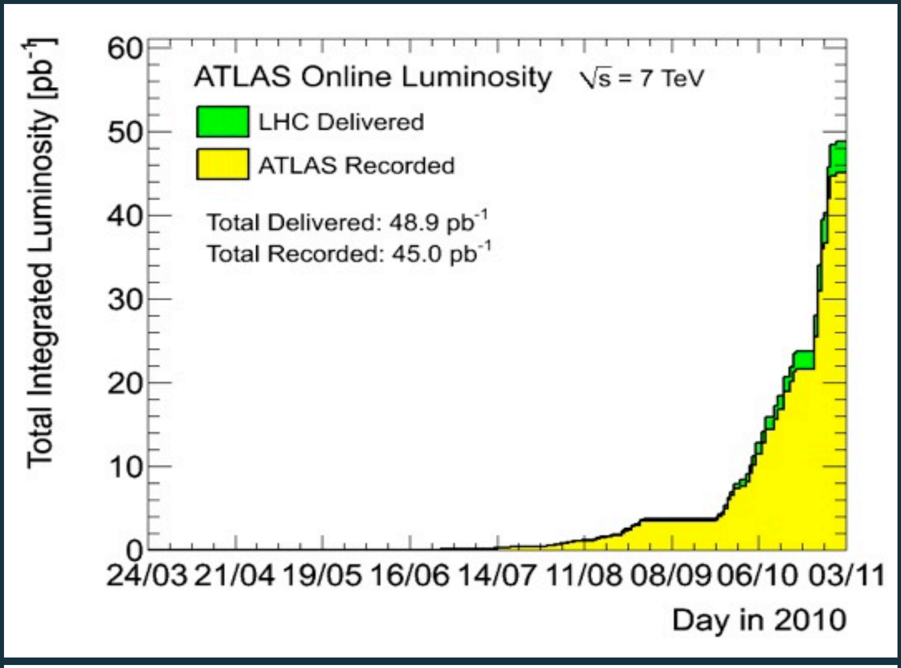
The Large Hadron Collider

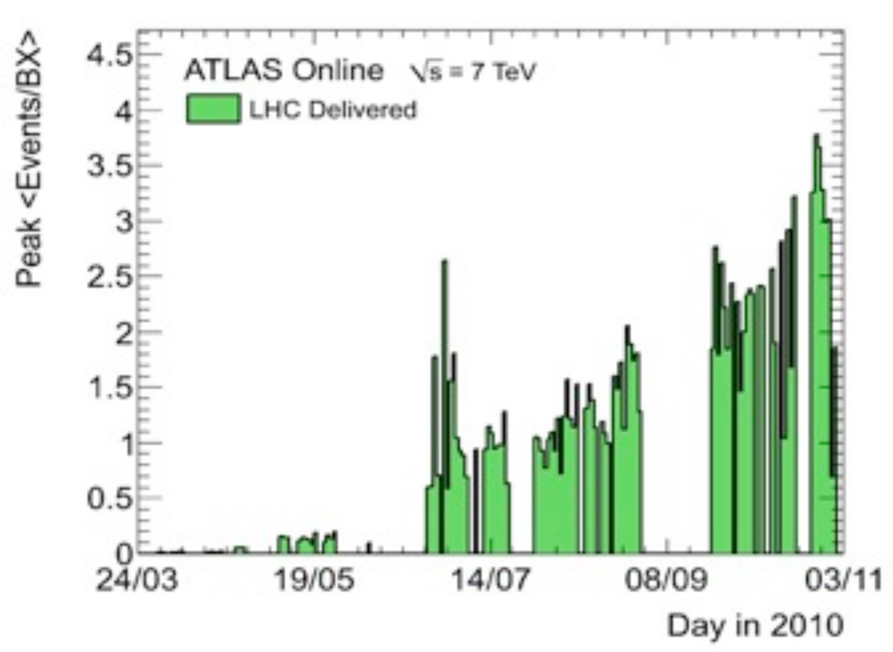


- LHC took it first 900 GeV collisions in November 2009
  - L=~9 μb^{-1} at ~5×10^{26} $cm^{-2}s^{-1}$
- Since March 2010 running with 7 TeV collisions.
- Since Early November, running Heavy Ion collisions.

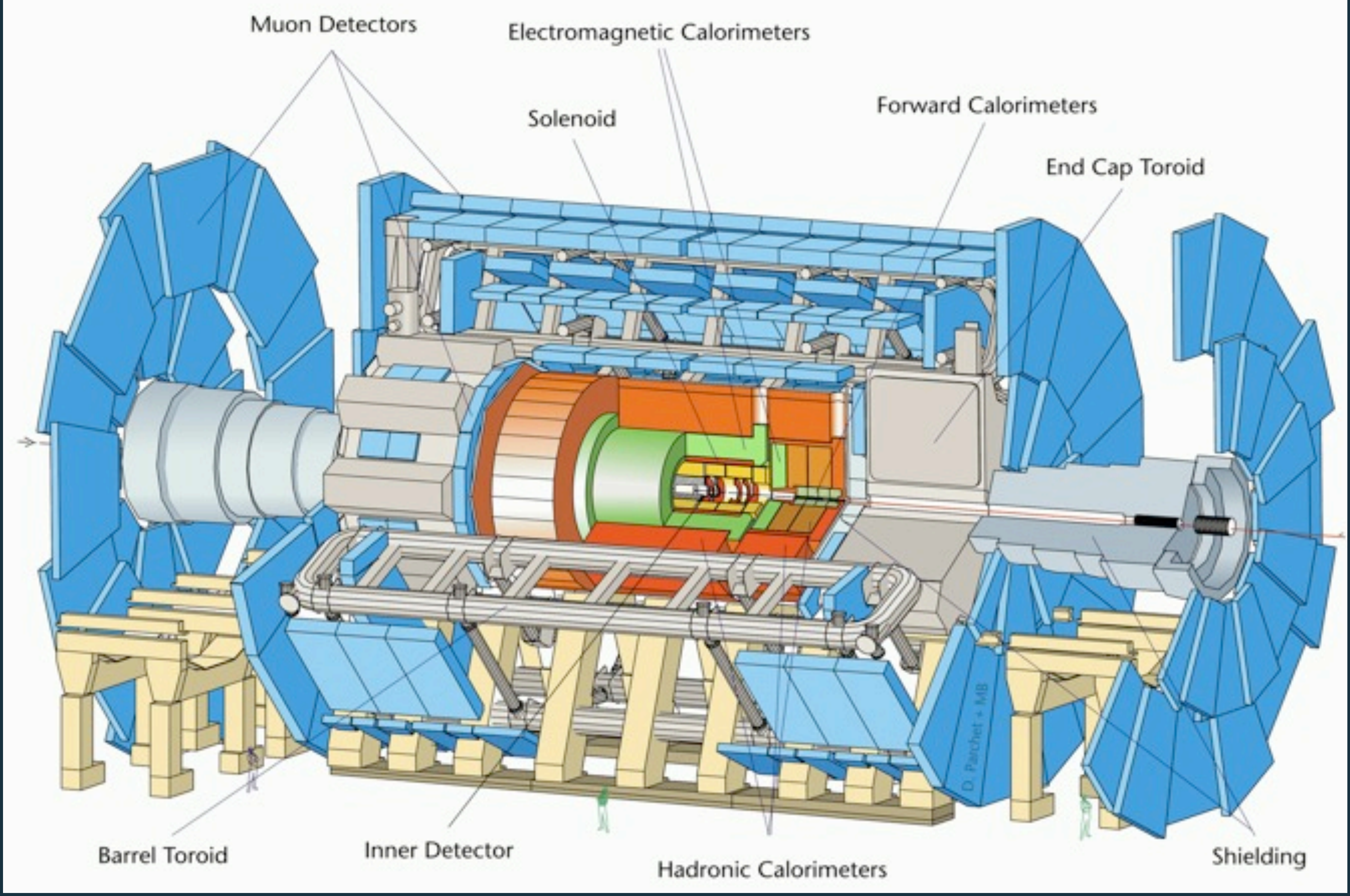
Collected data at 7 TeV

- First collisions at 7 TeV at the end of March 2010
  - ATLAS collected integrated luminosity L = 45 pb^{-1}
  - So far, over 3.2×10^{9} events written to tape with stable beams
  - Luminosity systematic uncertainty ~ 11%
- Last configuration
  - 368 colliding bunches in ATLAS
  - ~ 10^{11} protons per bunch
  - Peak instantaneous luminosity of $2.1\times10^{32}cm^{-2}s^{-1}$
  - Around 3 pp interactions per bunch crossing
- Near future plans - 2011
  - Around 800 bunches per beams
  - Aim to collect ~ 1-8 fb^{-1}
  - May run in 2012

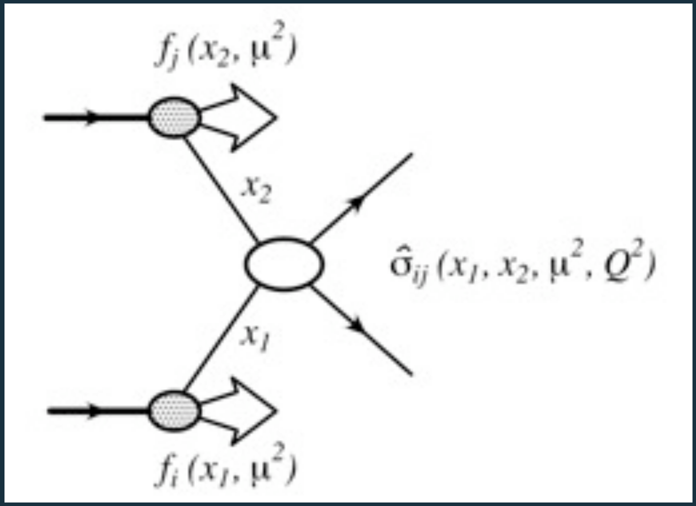




The ATLAS Detector



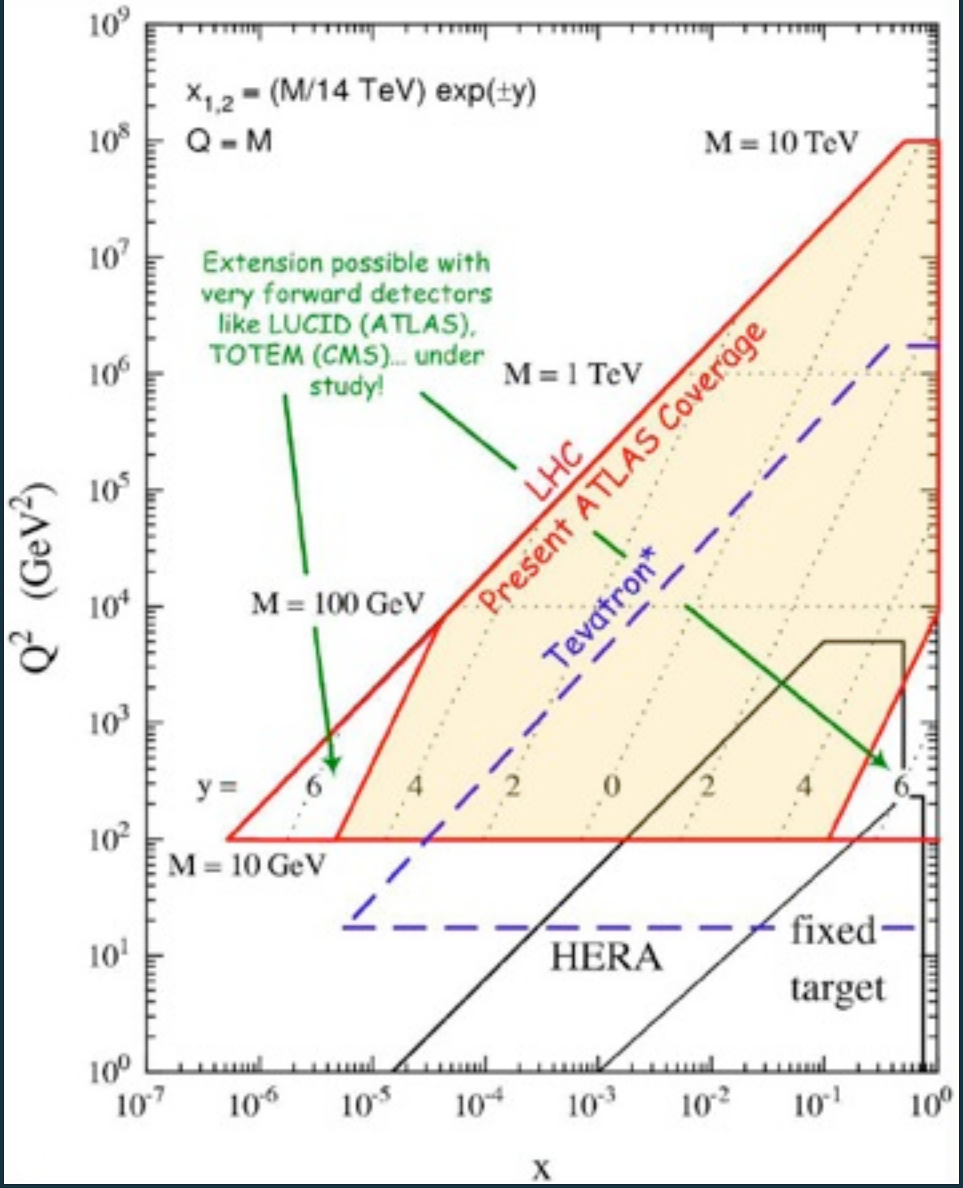
The LHC kinematic plane



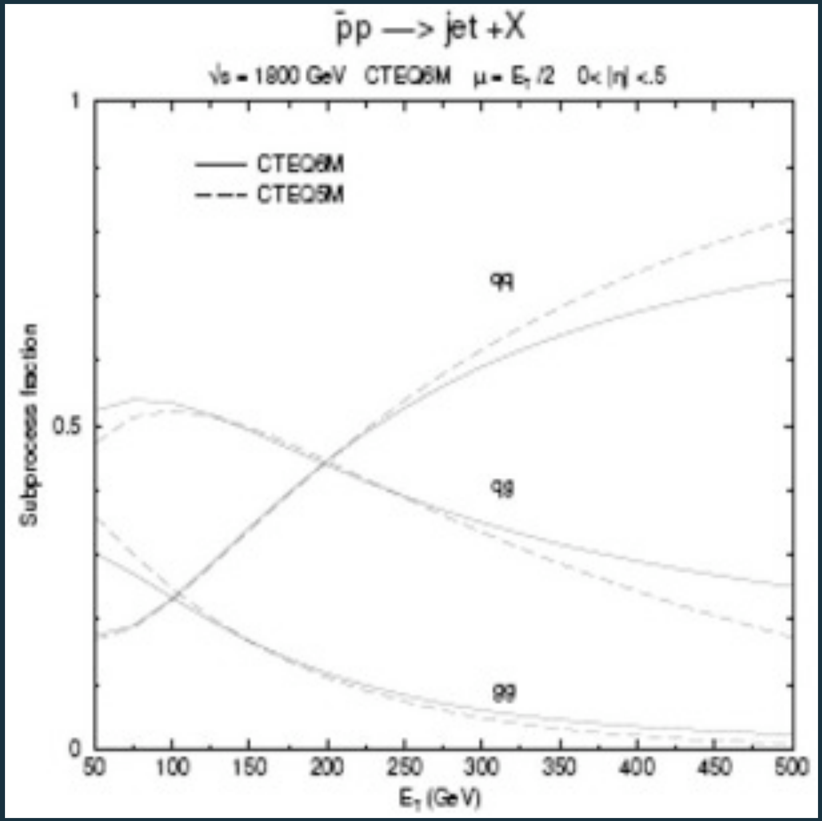
- Greatly extend kinematic coverage, mass reach to around 5 TeV.

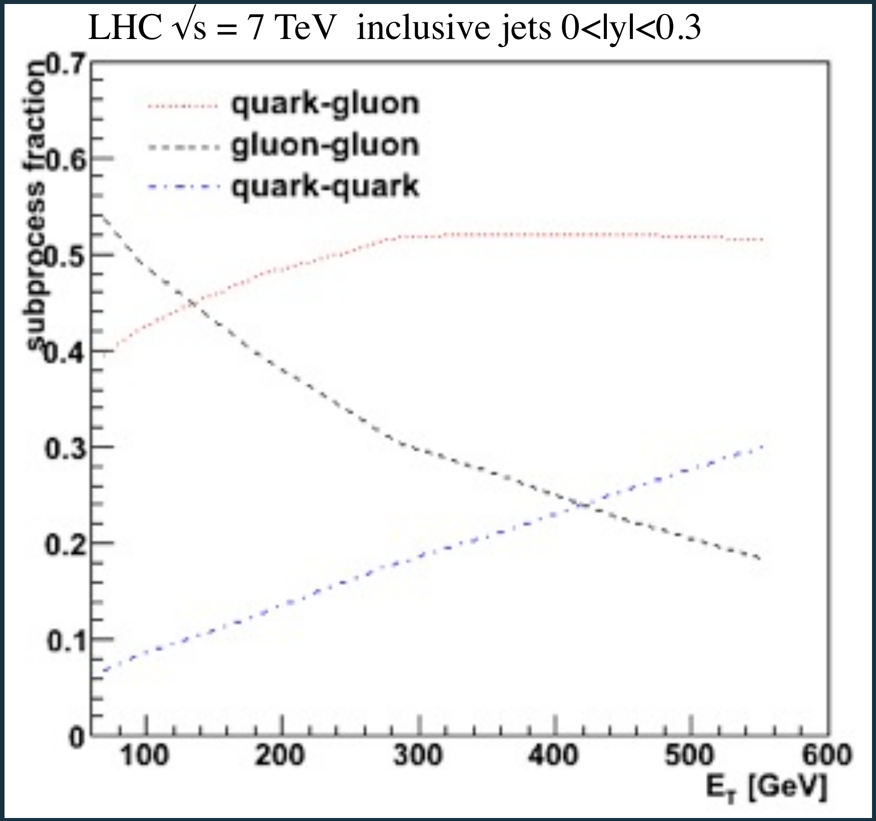
- Many cross sections dominated by parton interactions at small *x*,
  - Dominance of gluon and sea quark scattering,
  - Large phase space for gluon emission.

- Greater precision at high *x*.



Incoming partons

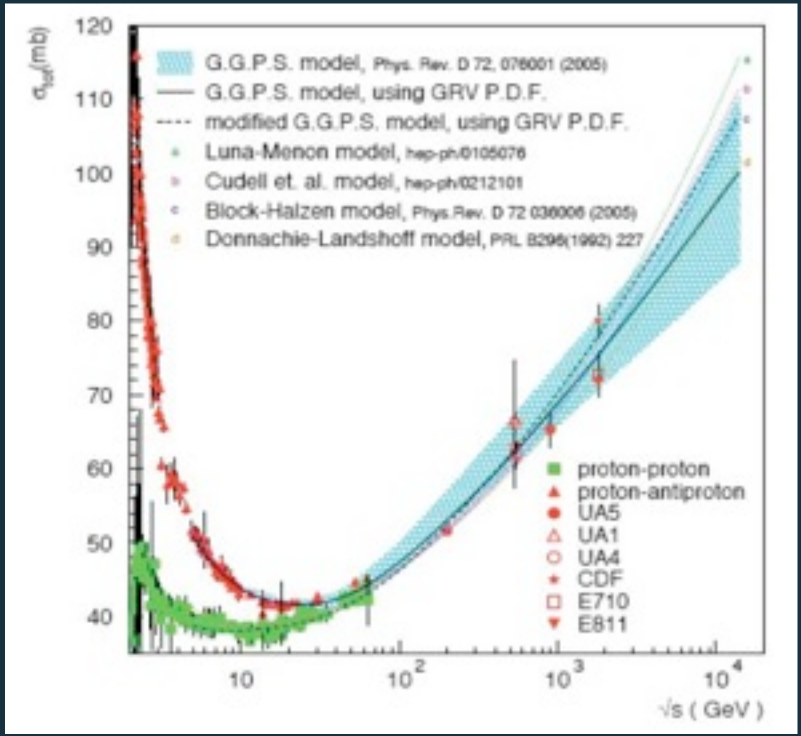




- High E_T jets (~500 GeV) at the Tevatron produced predominantly due to *qq* scattering.
- At the LHC, 500 GeV jets will be produced from partons at much lower x
- More significant contribution from the gluon and at high Q^2 so more phase space for initial state radiation.

Pileup, Soft QCD and Underlying event

- Most of the hadronic interaction cross section is "Soft" ie, does not contain high E_T interaction,
  $\sigma_{total} = \sigma_{elastic} + \sigma_{single\text{-}diff} + \sigma_{double\text{-}diff} + \sigma_{non\text{-}diff}$
  - Large uncertainty on the total cross section - ln(s) or $\ln^2$ (s) behaviour?



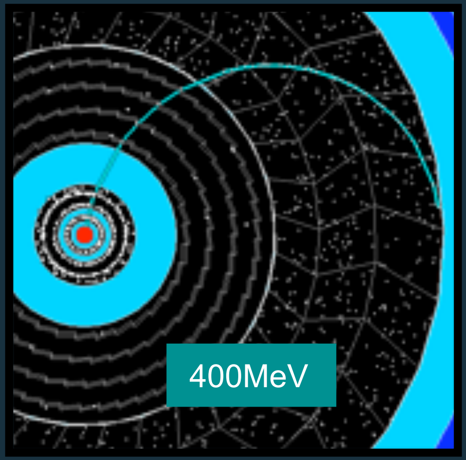
- Hard interactions also have "secondary" interactions between partons in the proton
  - multi-parton interactions, underlying event.

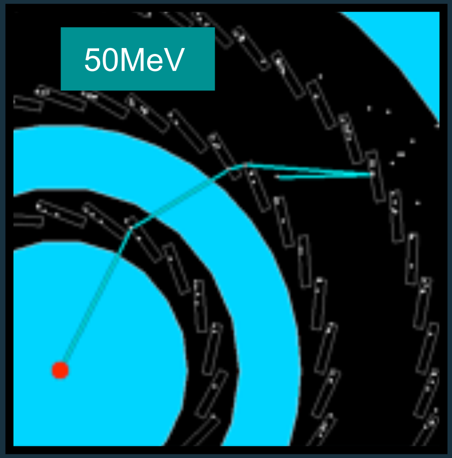
- In addition, multiple, independent soft pp interactions in the same bunch crossing - "pileup".

- Both lead to additional energy flow in the event, both are dominated by soft, or semi-hard processes.
  - Minimum bias collisions not associated with the hard interaction
  - Underlying event closely related to the hard interaction.

- Need to be able to model, these processes to enable precision measurements of hard QCD interactions

Soft QCD interactions



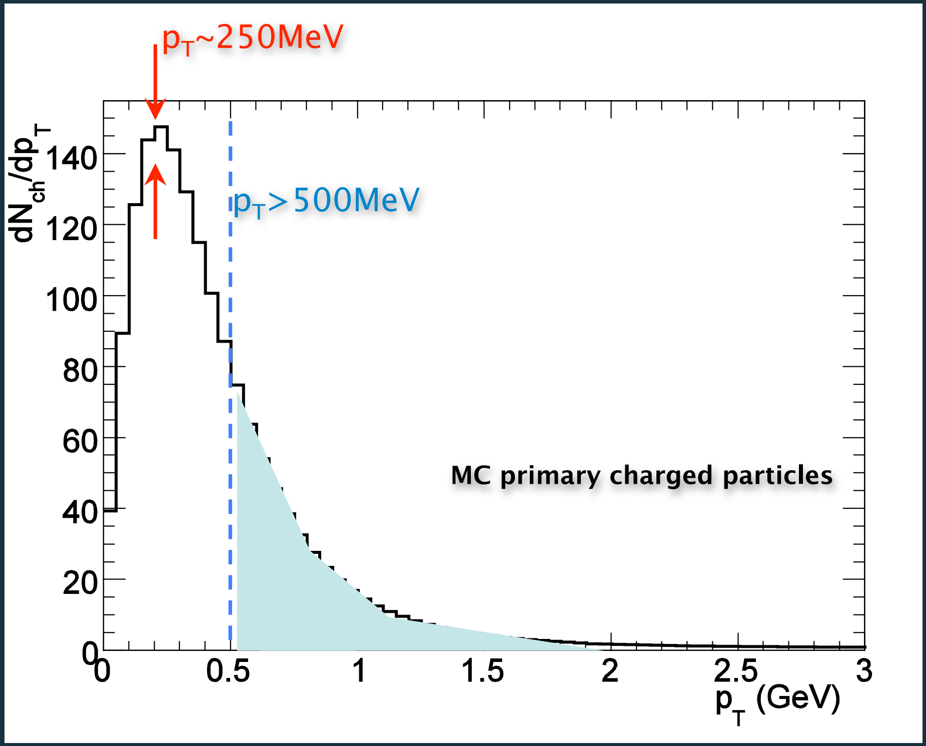


- Minimum Bias at ATLAS is triggered by 1 side of low angle trigger scintillator
  - Sensitive to everything but the elastic cross section.

- Three data samples
  - 900 GeV interactions
  - 2.36 TeV interactions
  - 7 TeV interactions

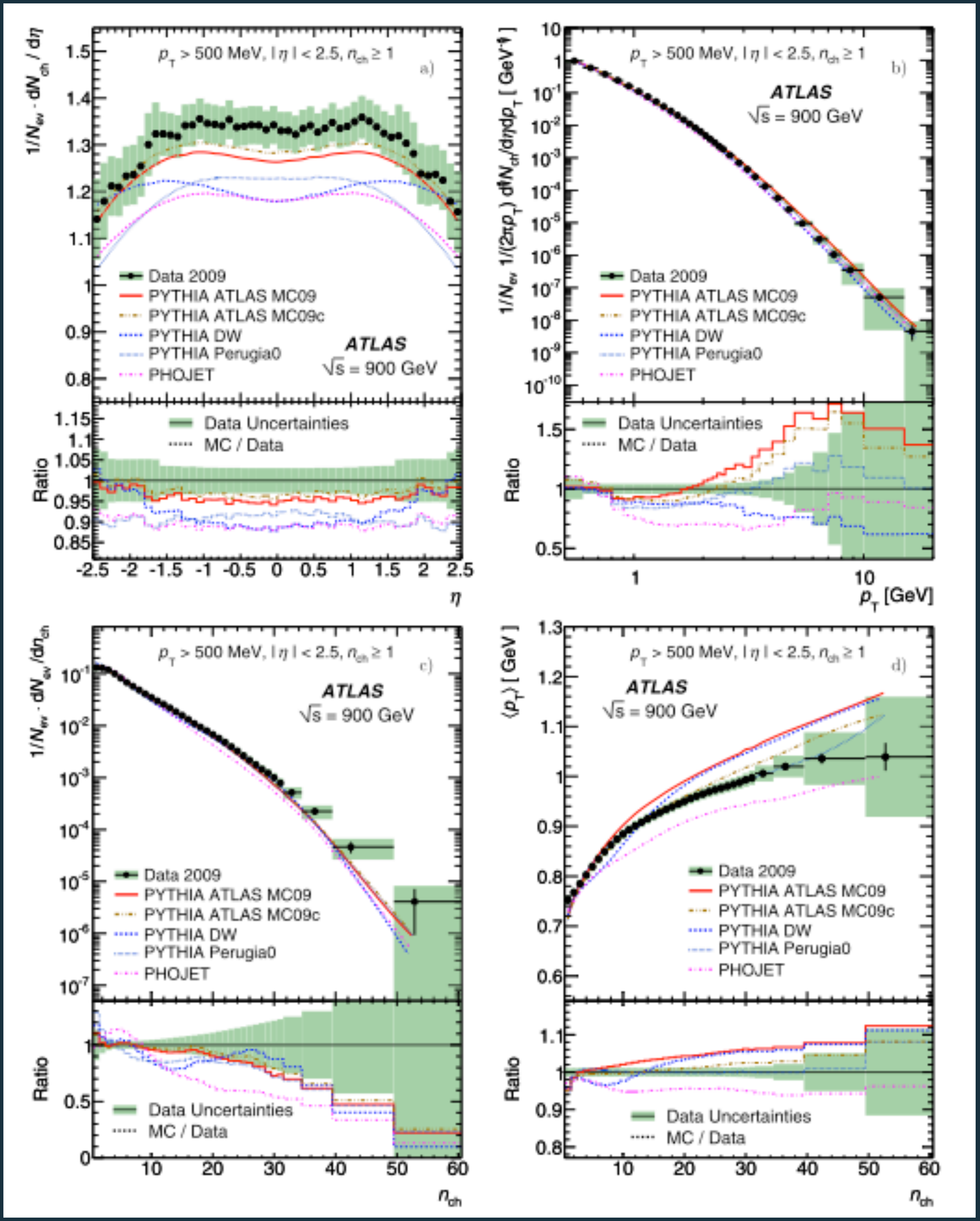
- Due to track bending in the 2 T Solenoid field, difficult to reconstruct tracks at very low p_T

- Two event selection, both require at least 1 primary vertex, all tracks $|\eta|<2.5$
  - At least 1 track with $p_T > 500$ MeV
  - At least 2 tracks p_T>100 MeV



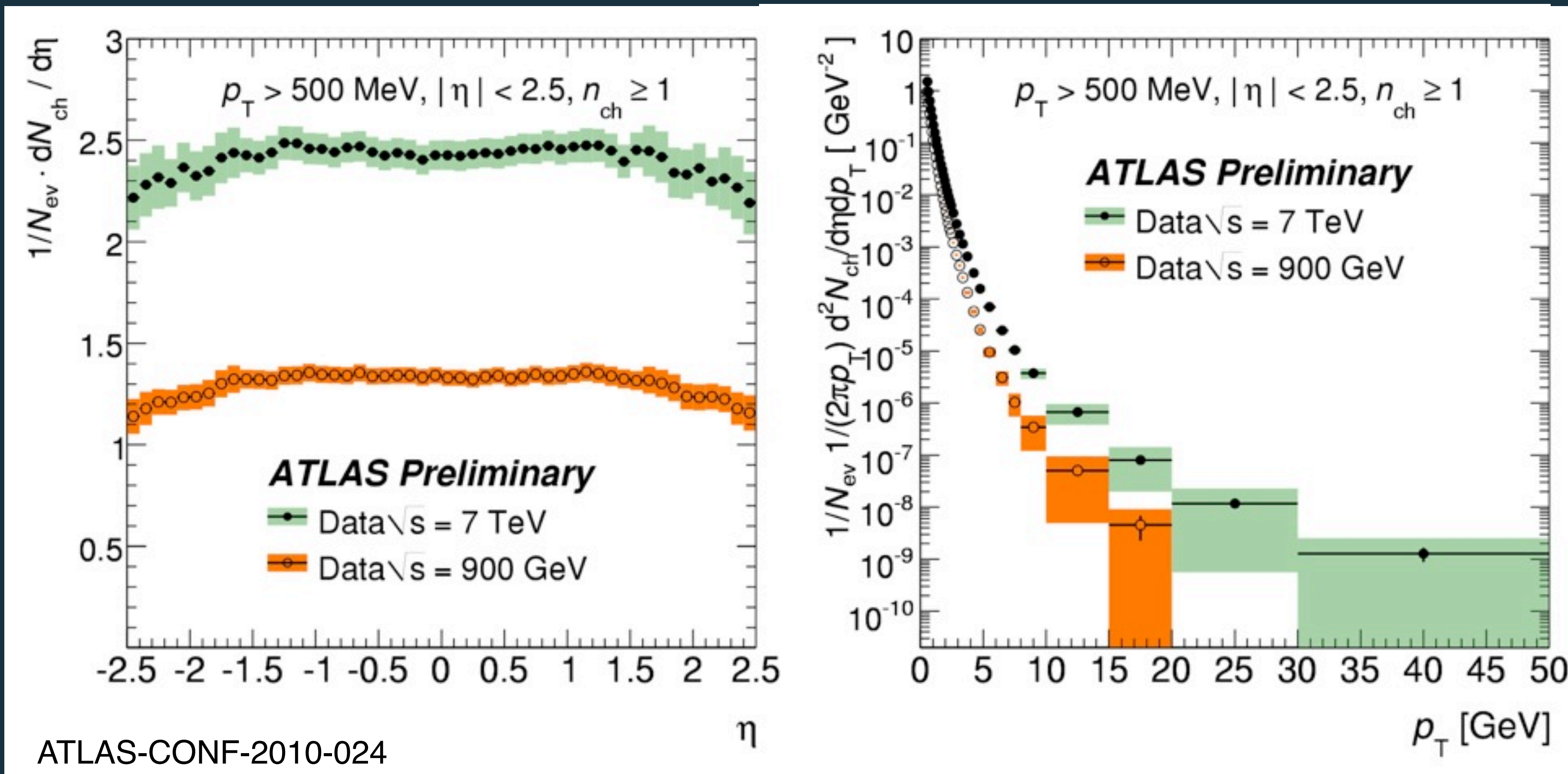
Soft QCD at 900 GeV

Phys Lett B 688, 1, 21



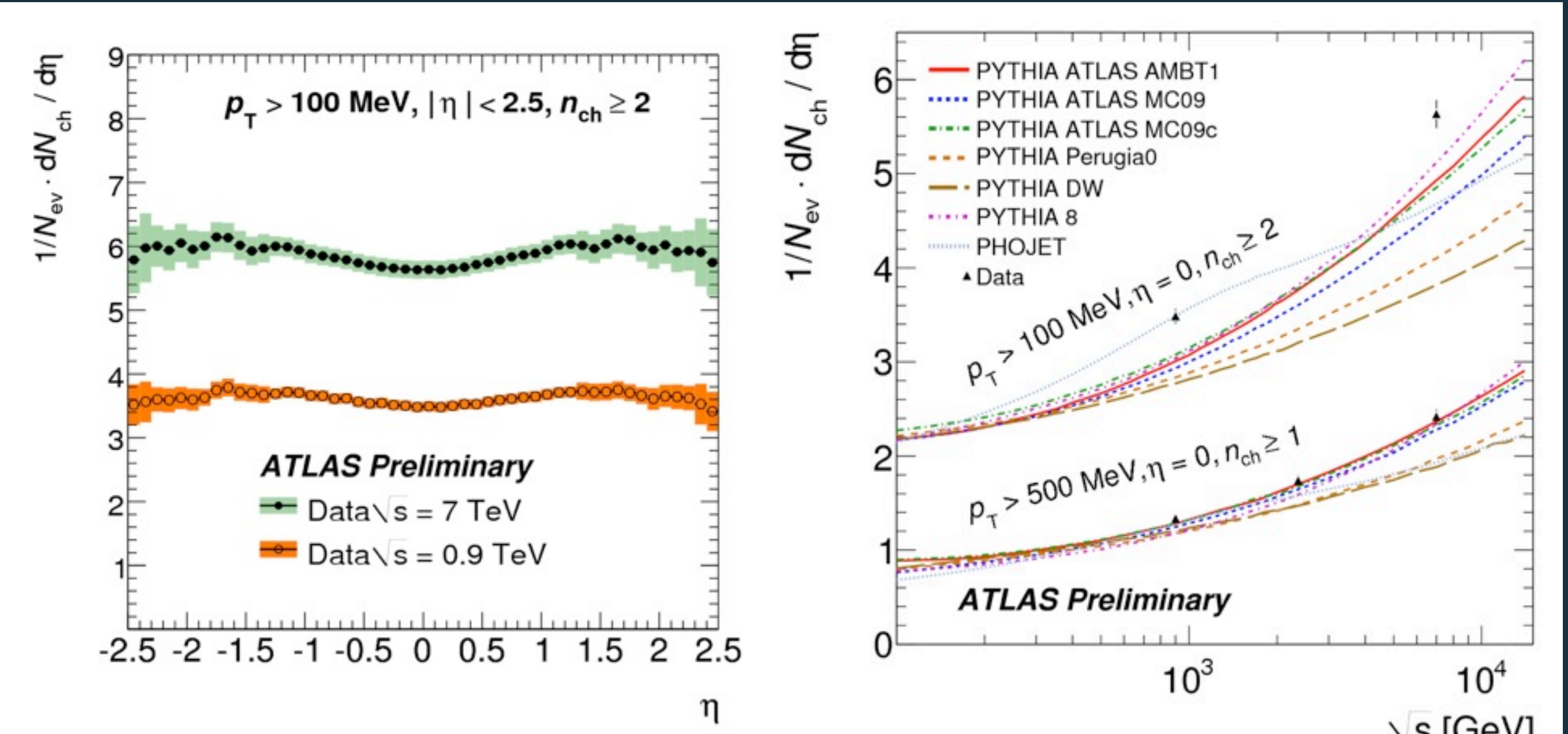
- Fully model independent measurement, ie corrected back to hadron level rather than non-single diffractive.
- Models underestimate frequency of high multiplicity events, and overestimate the p_T in such events

Charged track muliplicities at 900 GeV and 7 TeV



- At 7 TeV track momentum distribution is significantly harder.

Track multiplicities lower momentum

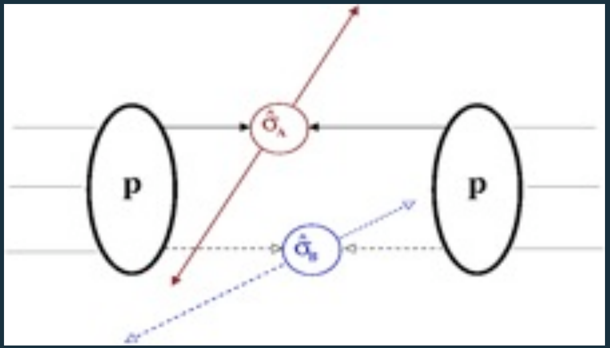


ATLAS-CONF-2010-046

- Probing softer hadron production with p_T>100 MeV is underestimated by Monte Carlo tunes.
- Tuned PYTHIA prefers $\ln^2(s)$ behaviour and in agreement with p_T>500 MeV data.
- No tune able to describe dependence for lower p_T particles.

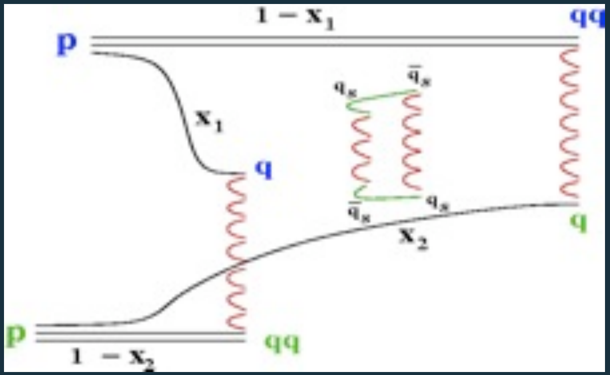
The Underlying Event

- The underlying event consists of all particles from a single pp interaction that are not from the hard interaction
  - Colour connected with the rest of the event, ISR/FSR, beam remnants, hard subprocess
  - Not experimentally separable from the hard interaction- Don't correct data for underlying event, correct Predictions!



- Several models exist…
- Pythia, Herwig (Jimmy), multi-parton interactions,
  - Multiple independent "hard" 2-to-2 scattering processes.

- Phojet
  - Dual Parton Model to generate the low p_T processes. multiple Pomeron exchange to generate the event activity, Hard processes added with conditions to satisfy unitarity.



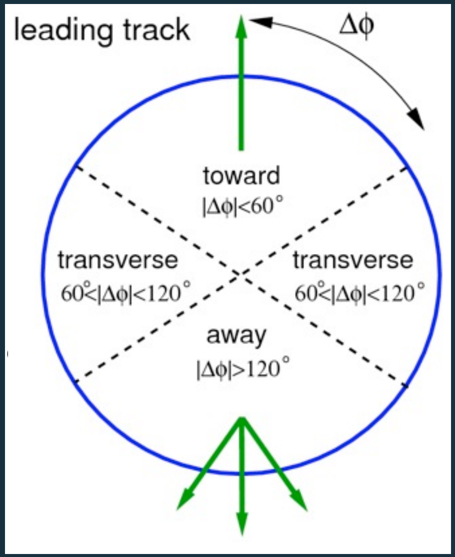
- Need to study the dependence of the underlying event on the hard interaction to make accurate predictions

Measuring the Underlying Event

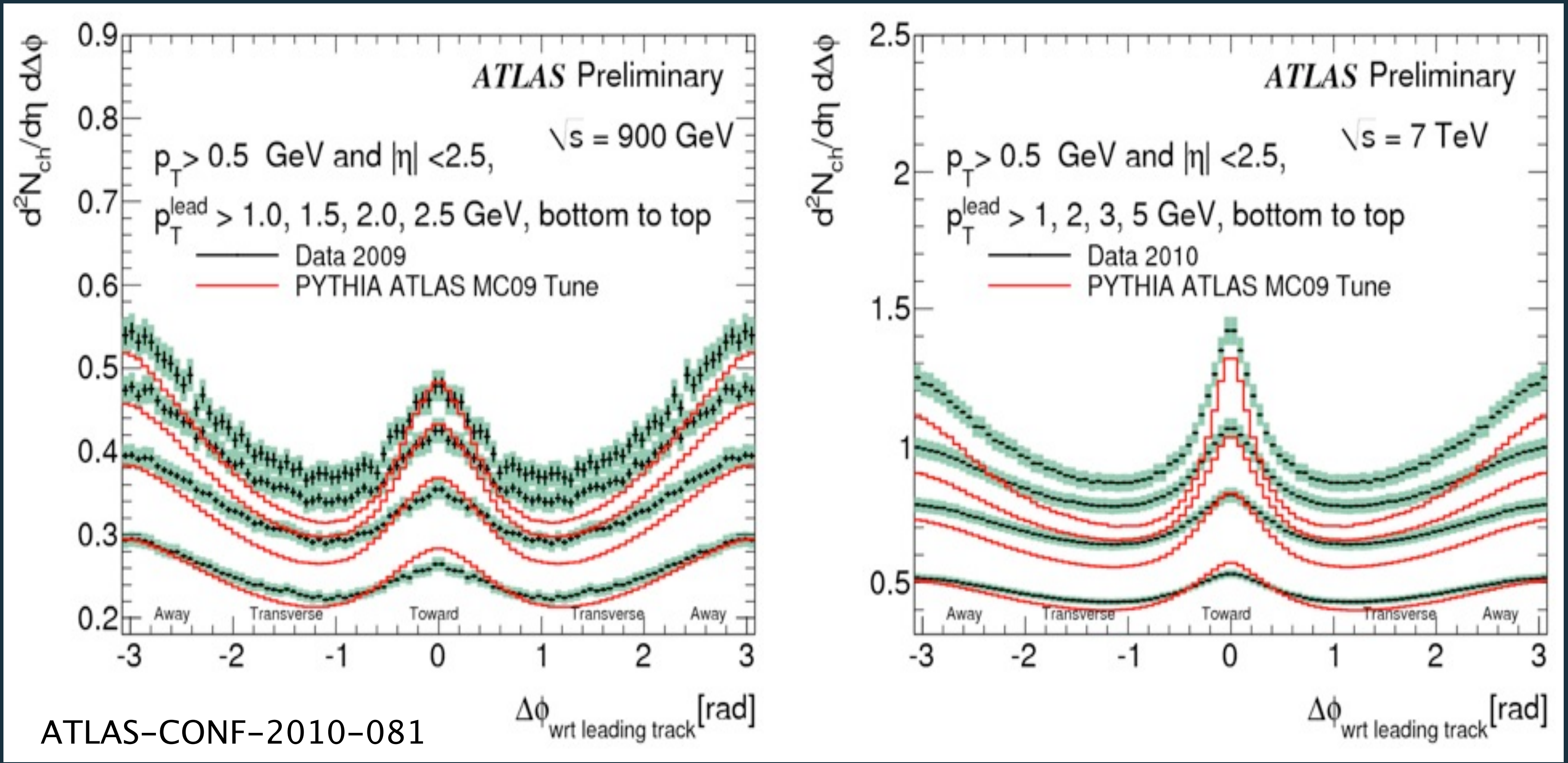
- In dijet configuration, charged multiplicity transverse to the jets is sensitive to the underlying event.

- In ATLAS, instead define the "toward" direction with respect to the most energetic, "leading" track
  - Study the onset of perturbative QCD

- Select events where ...
  - Leading track with p_T>1 GeV
  - No additional "good" vertices
  - Consider tracks in transverse and away directions,
    - pT>500 MeV, |η|<2.5



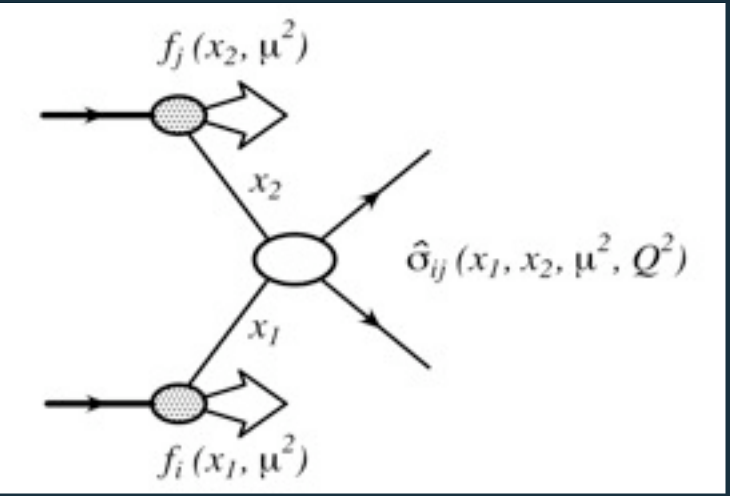
Angular distribution



ATLAS-CONF-2010-081

- For harder leading track, jet like distributions towards and away from leading particle appear
  - Transition towards hard QCD.
  - This is more pronounced in the Monte Carlo
- Will provide valuable information on modeling the underlying event for theoretical predictions

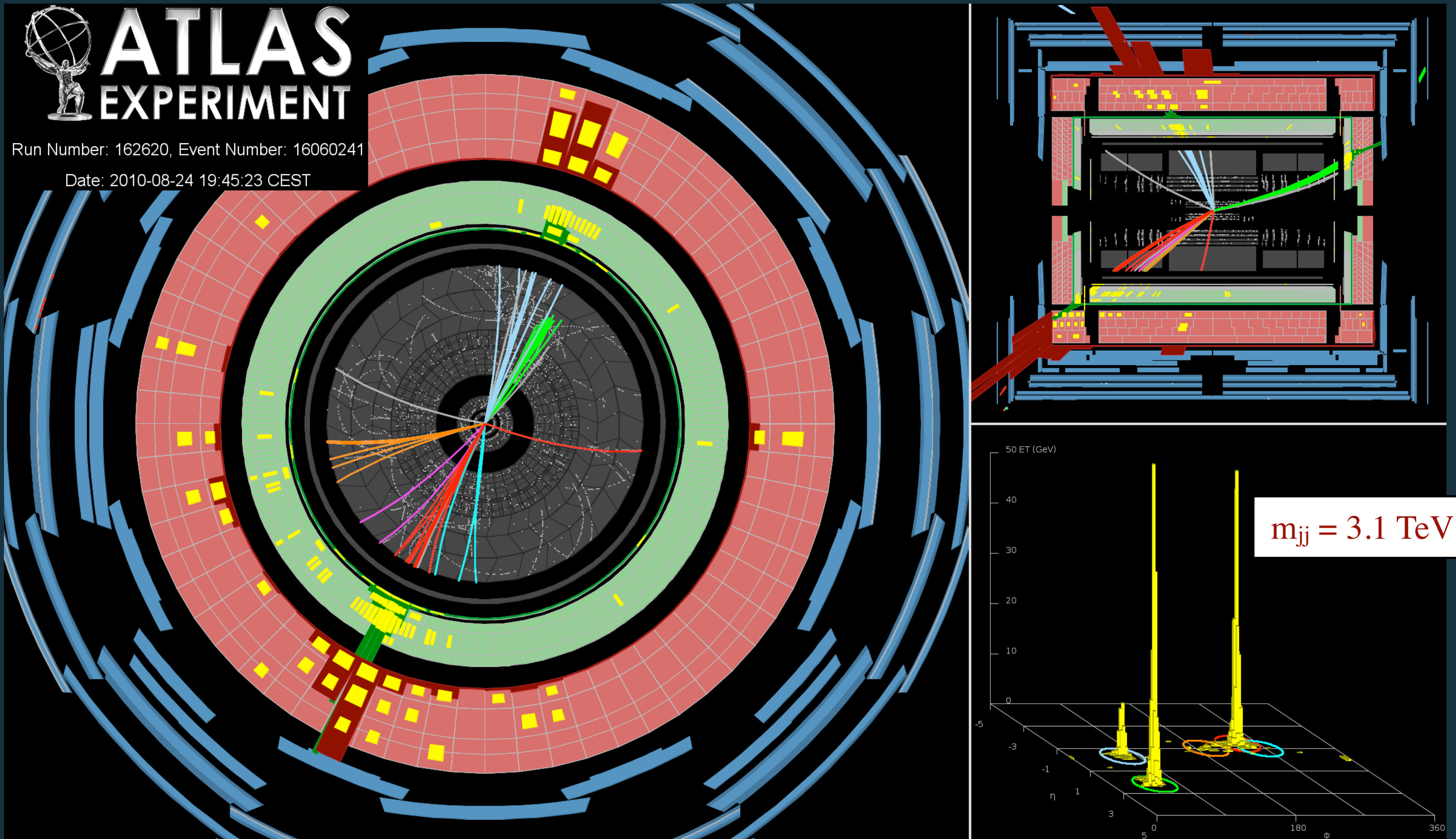
Jet Production



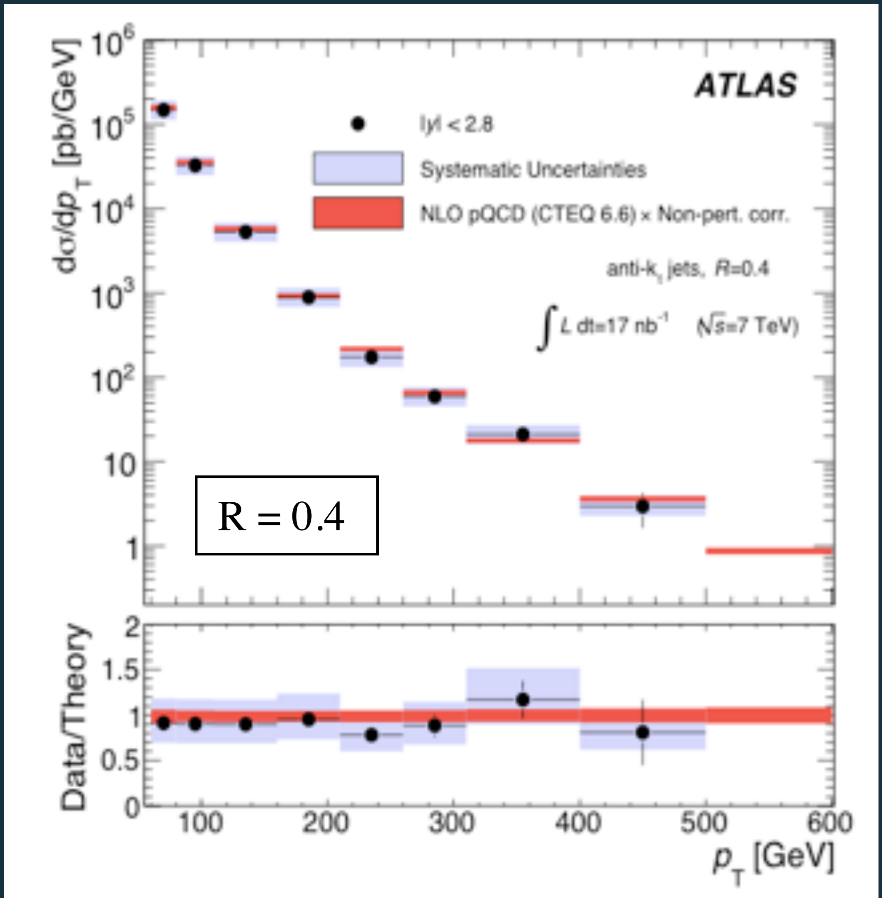
- Jet production O (α_s^2) at Leading order.
- All cross sections directly sensitive to quark and gluon densities within the proton.

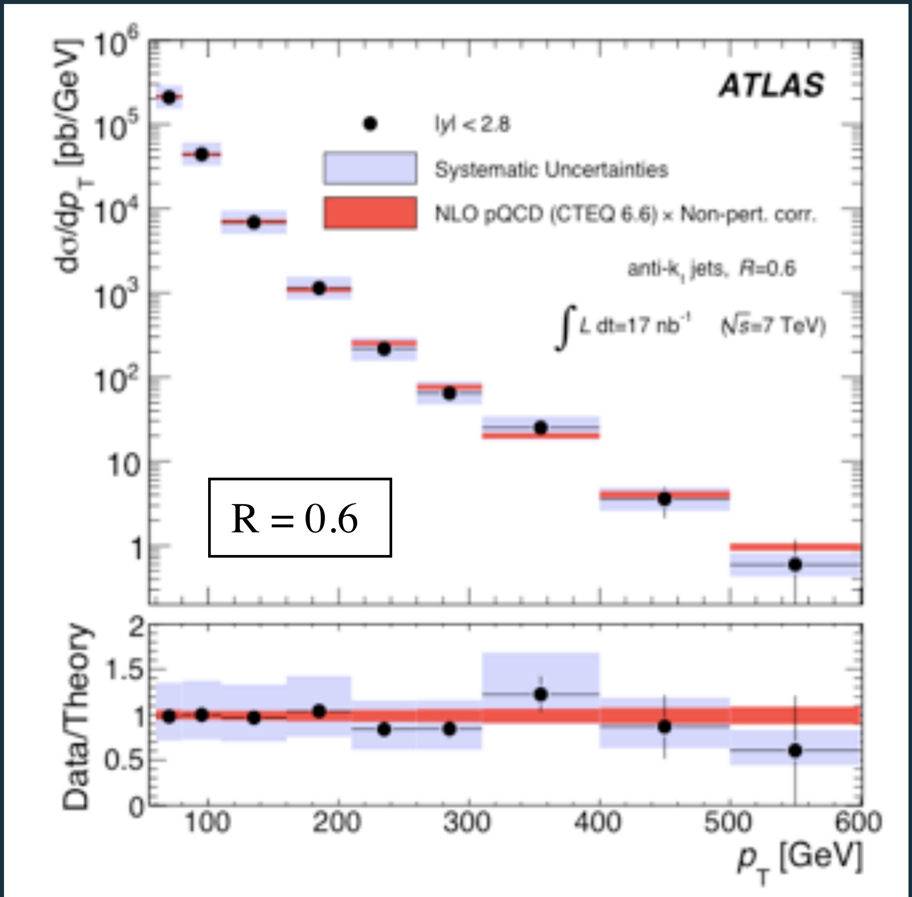
$$\sigma = \sum_{i,j} \int \mathrm{d}x_1 \int \mathrm{d}x_2\ f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \hat{\sigma}_{ij}(x_1, x_2, \mu_R^2)$$

- Uncertainty from the description of the hard subprocess - Scale uncertainties.
- Where the hard sub process is well described, can extract data on the PDF's.
- Inclusive jet production, one jet may be unobserved, integrate over the phase space of the sub-leading jet - smaller renormalisation scale uncertainties.
- Inclusive dijet production larger scale uncertainties, but better control over the kinematics.


ATLAS
EXPERIMENT
Run Number: 162620, Event Number: 16060241
Date: 2010-08-24 19:45:23 CEST
50 ET (GeV)
40
30
20
10
0
η
Φ
0
180
360
m_{jj} = 3.1 TeV

Inclusive jet cross section

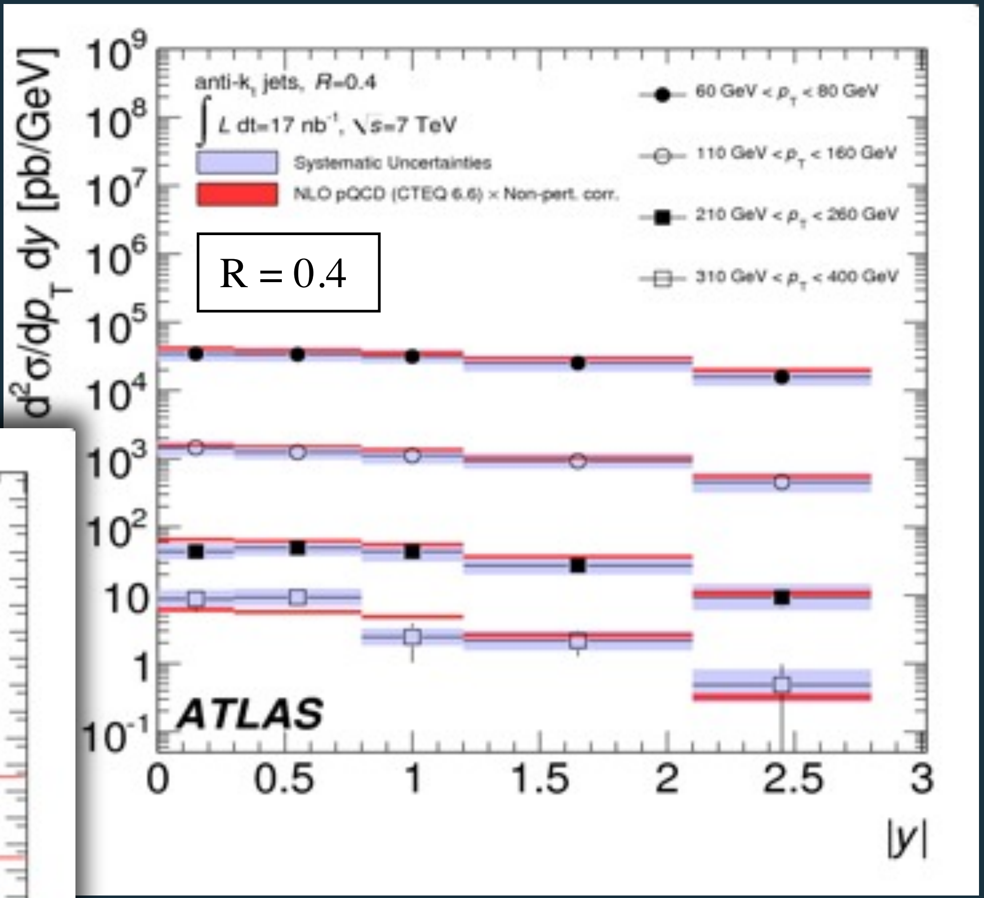


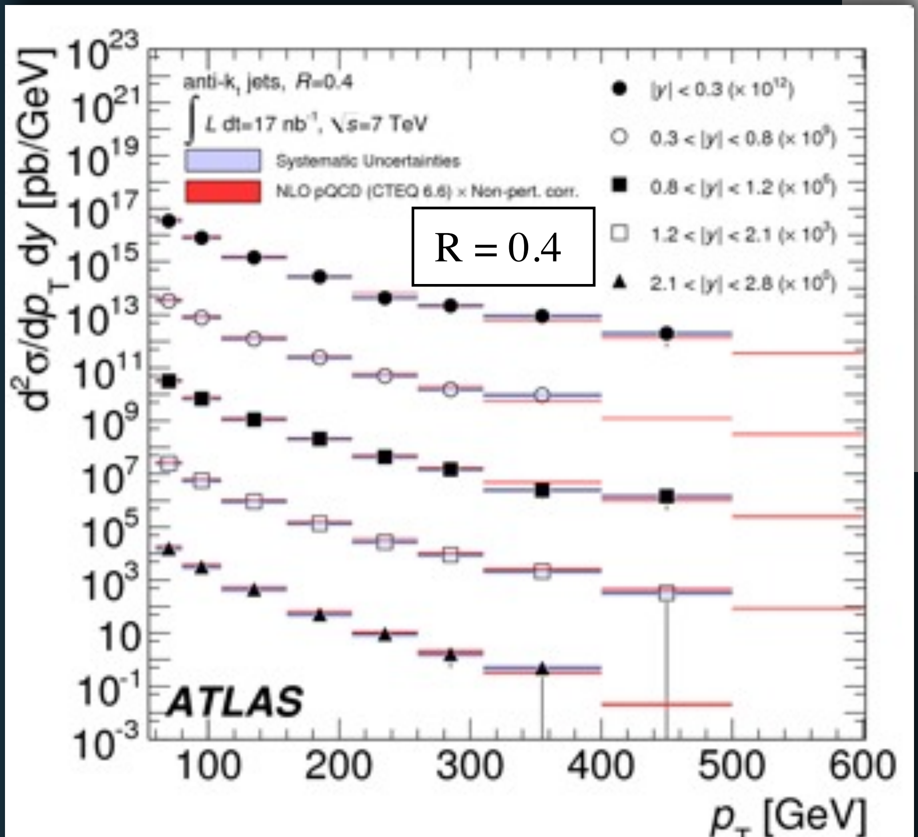


Accepted by EPJC, CERN-PH-EP-2010-034

- Largest systematic uncertainty, jet energy scale (6-10%), translates to 30-40% uncertainty on cross section.
- Good agreement with NLO prediction over 5 orders of magnitude for R=0.4 and R=0.6 jets

Inclusive double-differential jet cross section

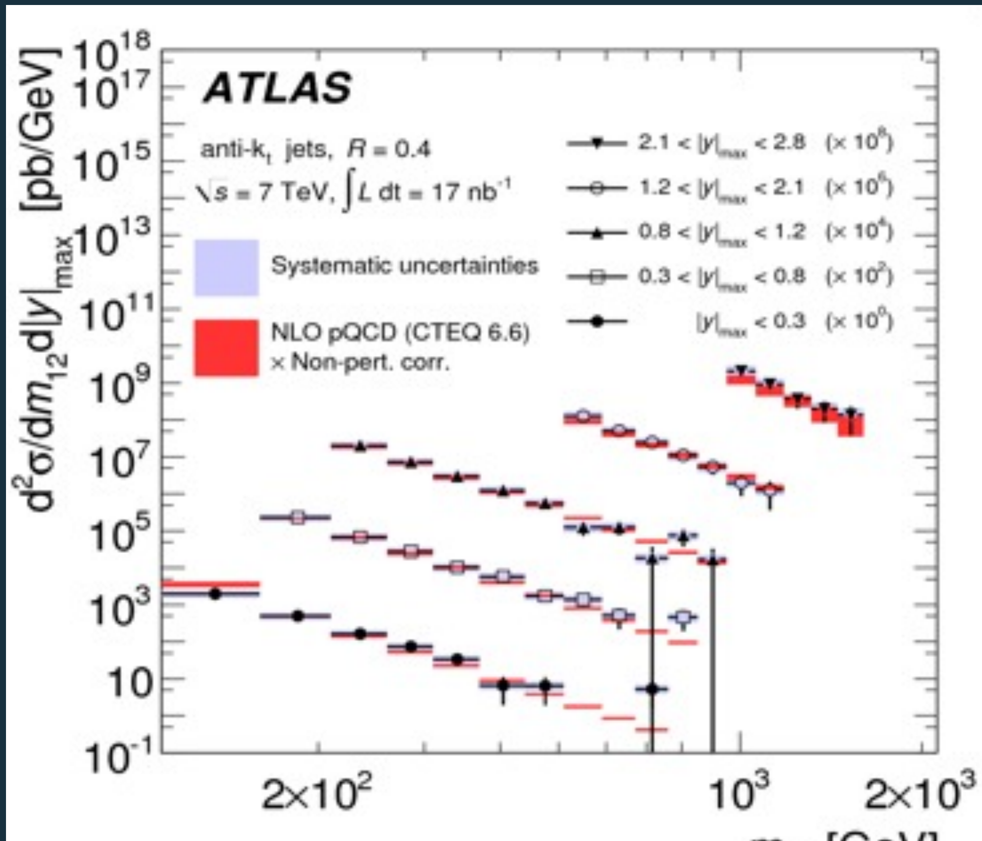




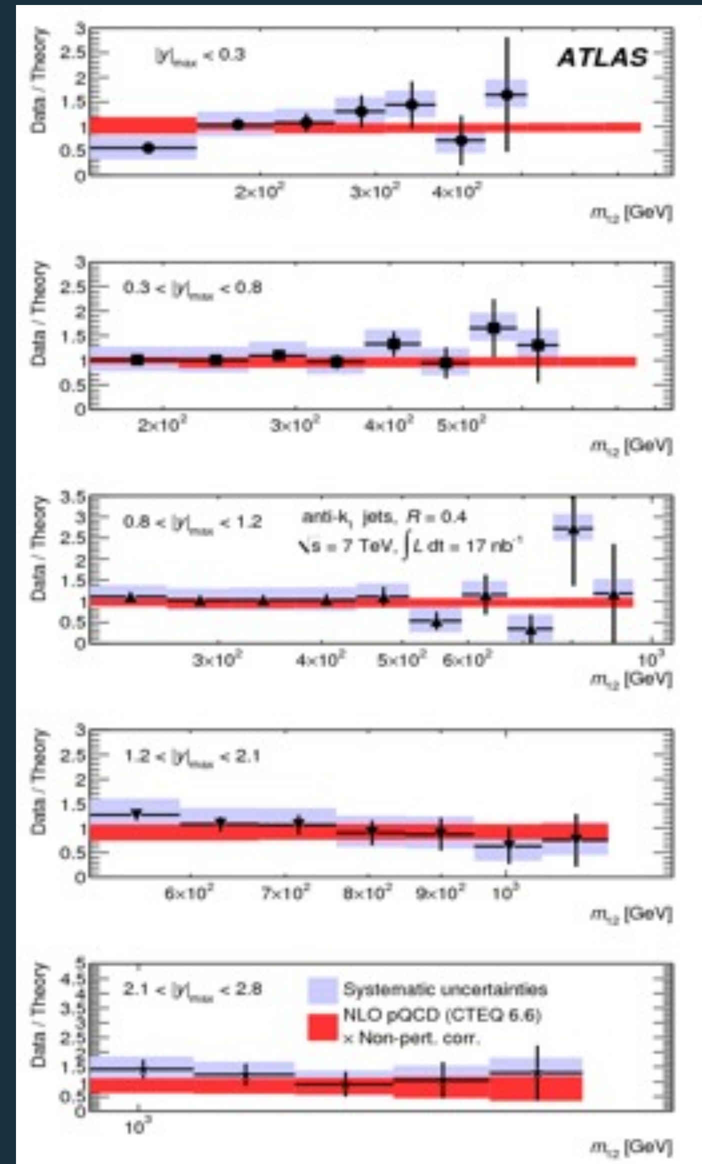
Accepted by EPJC, CERN-PH-EP-2010-034

- Reasonable agreement with the NLO calculation.

Double-differential dijet cross section

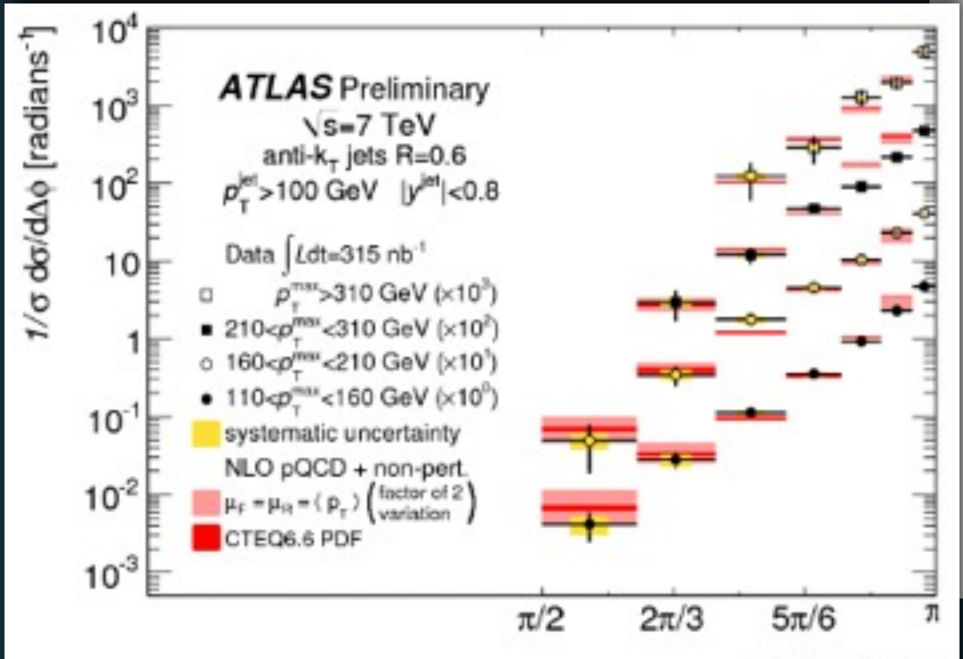


Accepted by EPJC, CERN-PH-EP-2010-034

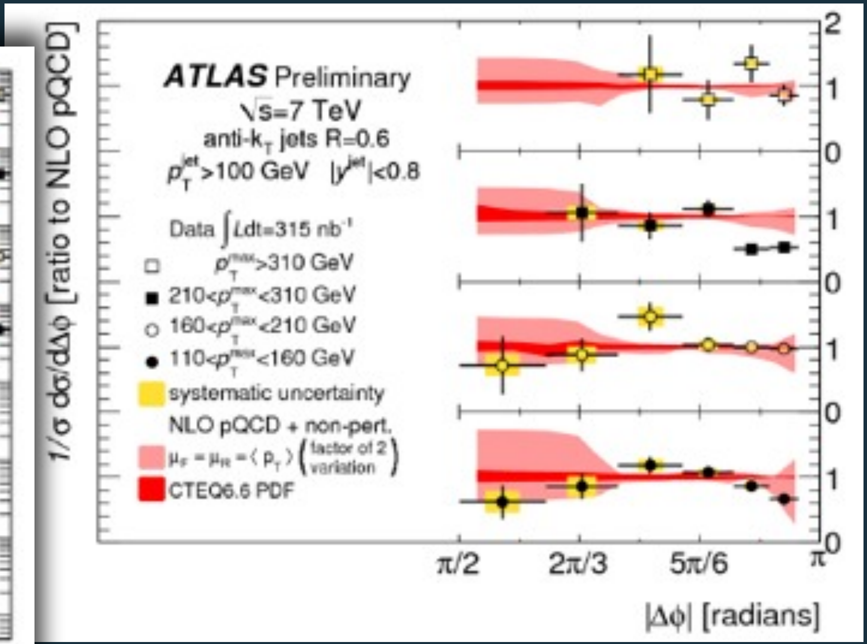


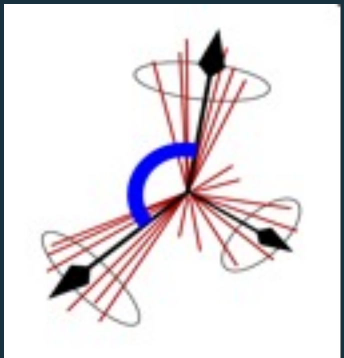
- Inclusive dijet cross section as a function of the dijet invariant mass.
- Good agreement within the uncertainties over the entire kinematic plane.
- Large theoretical uncertainties in the forward direction.

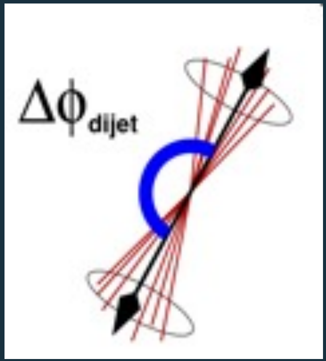
Dijet azimuthal decorrelation



ATLAS-CONF-2010-083

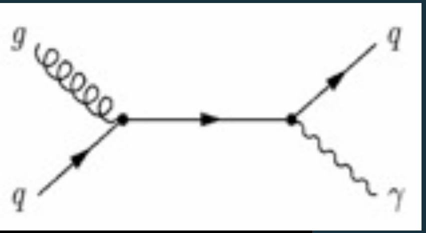


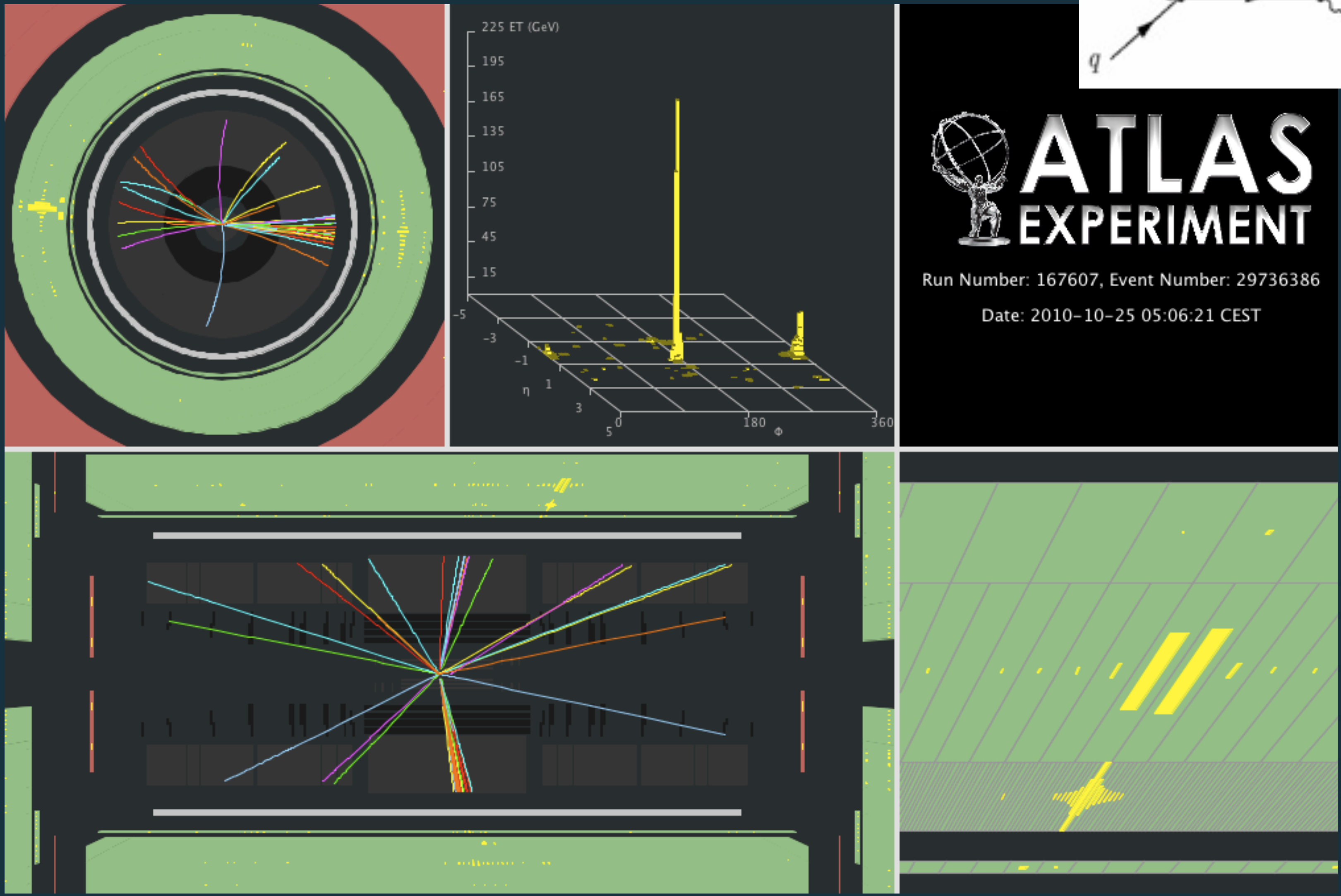




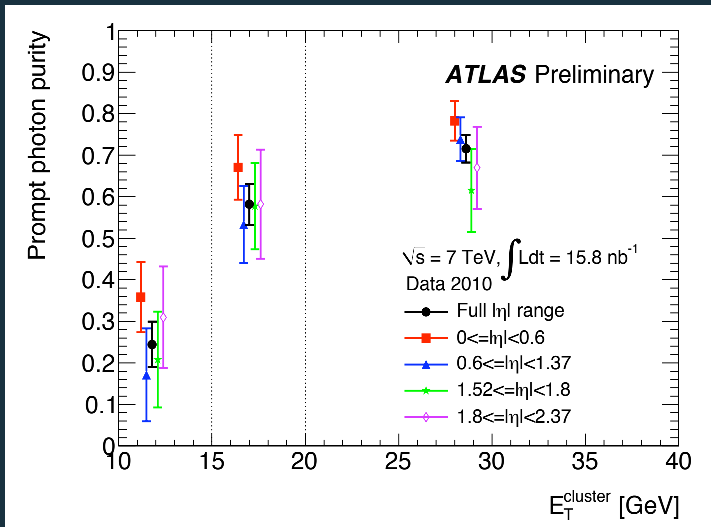
- Deviation of dijet topology with respect to back-to-back configuration sensitive to higher order QCD radiation
  - Study the hard sub process in more detail
  - Cross section away from $\Delta\phi \sim \pi$ is intrinsically an O (α_s^3) process.
- NLO prediction including hadronization and underlying event corrections describes the data well.

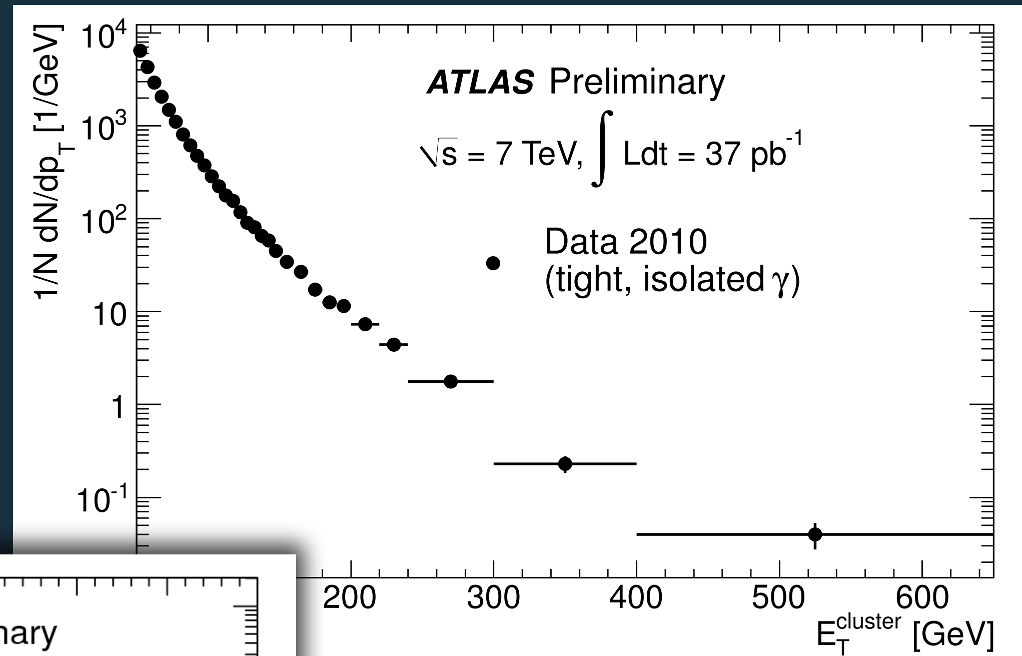
Prompt (Direct) photon production

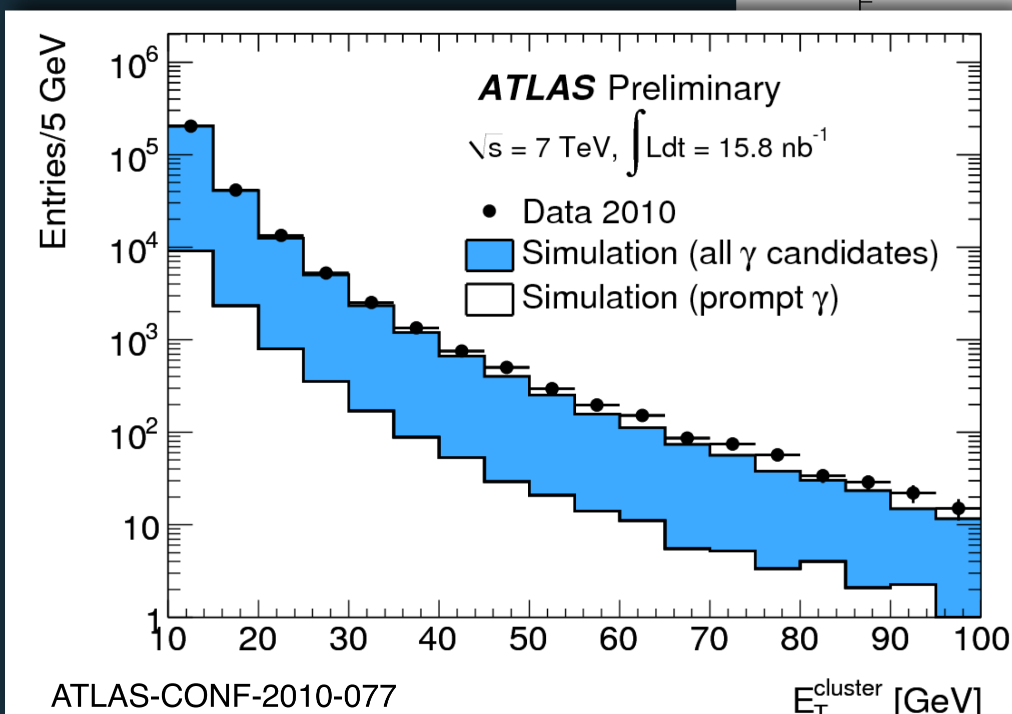




- High E_T photons in the final state, directly sensitive to the gluon distribution in the proton.



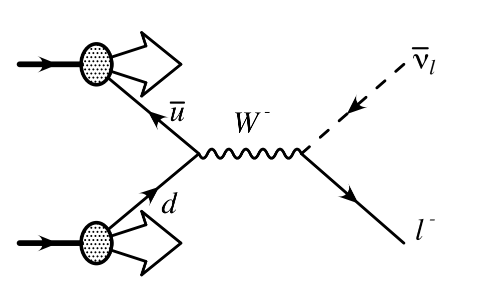


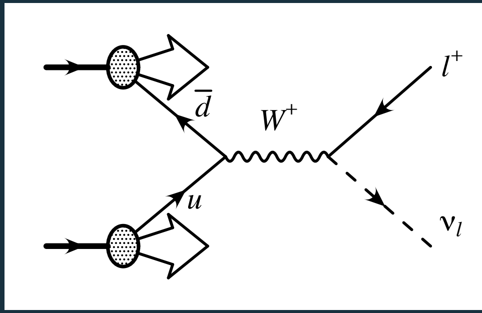


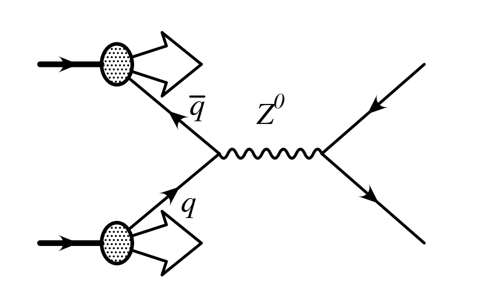
Prompt (Direct) Photon production

- Significant prompt photon signal observed with purity greater than 70%
- Inclusive paper on the horizon

Electroweak Boson production





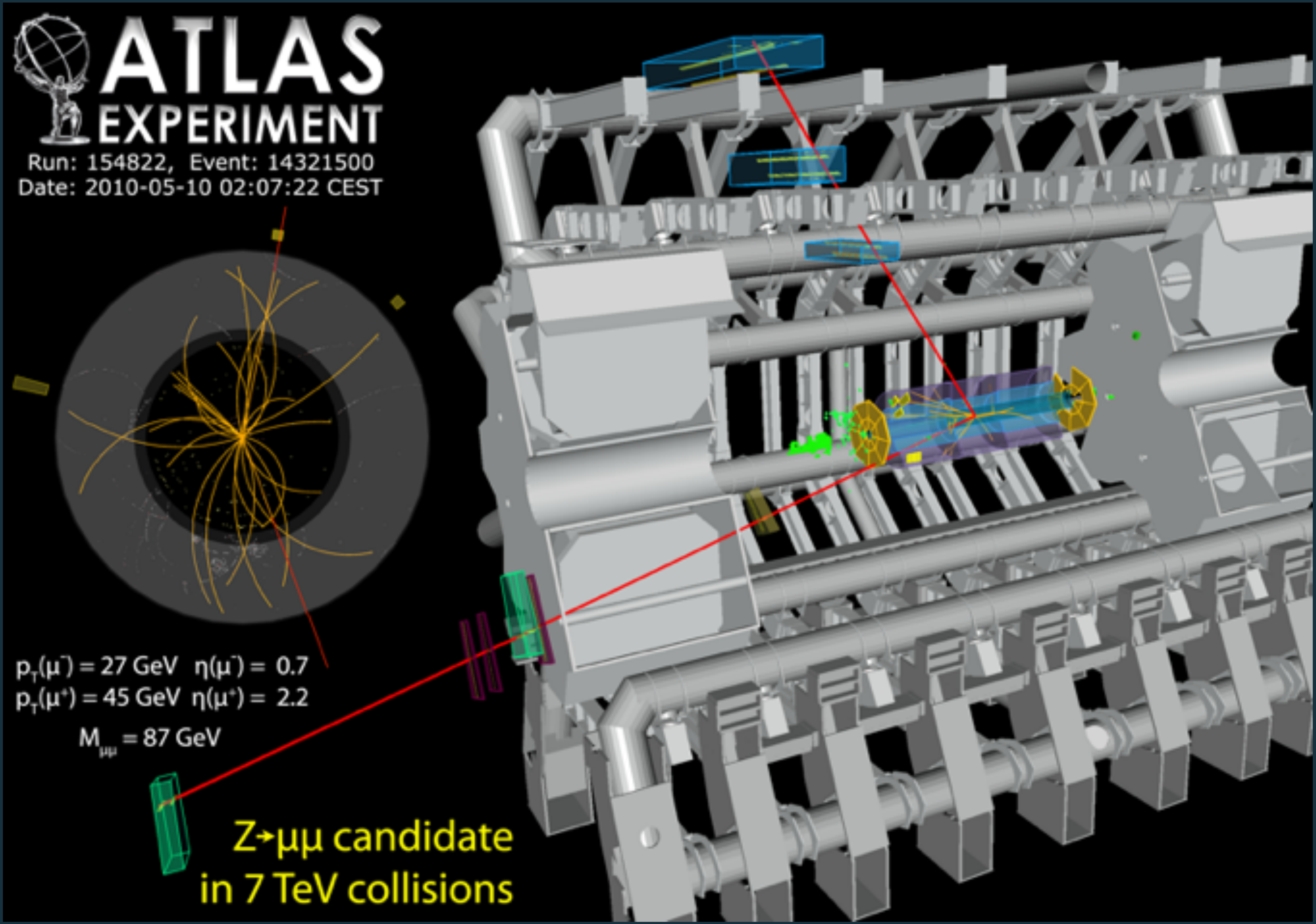


- W and Z bosons should be produced copiously
  - For L = 1 fb^{-1} expect around $O(10^4)$ W and (10^3) Z bosons with $p_T > 400$ GeV

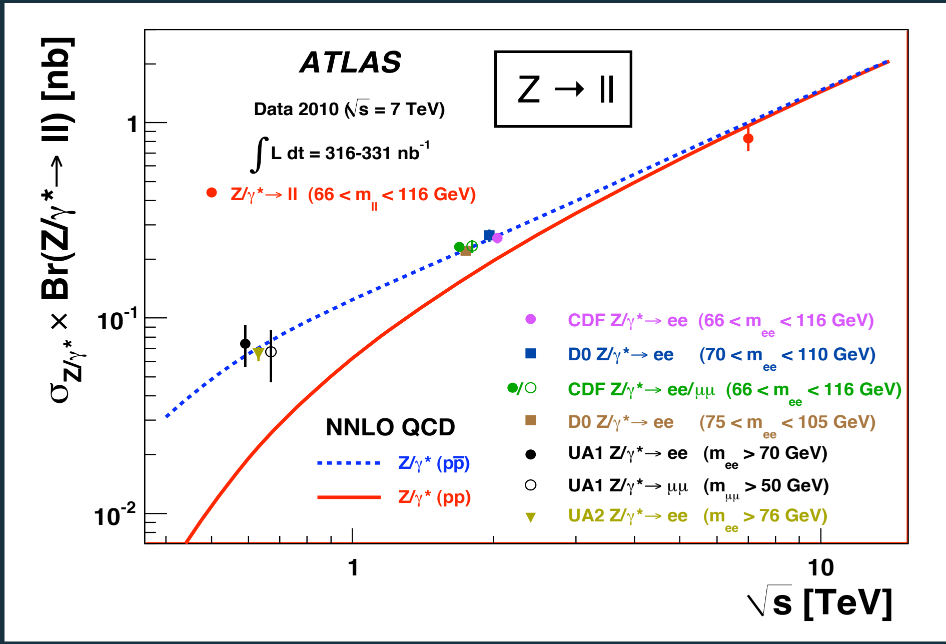
- Measure the lepton decay channels.
- Drell-Yan cross section known to NNLO
  - Boson distributions should be well described at high p_T.
- For inclusive measurements at low p_T should resum logs in $M(Z,W)/Q^2$.

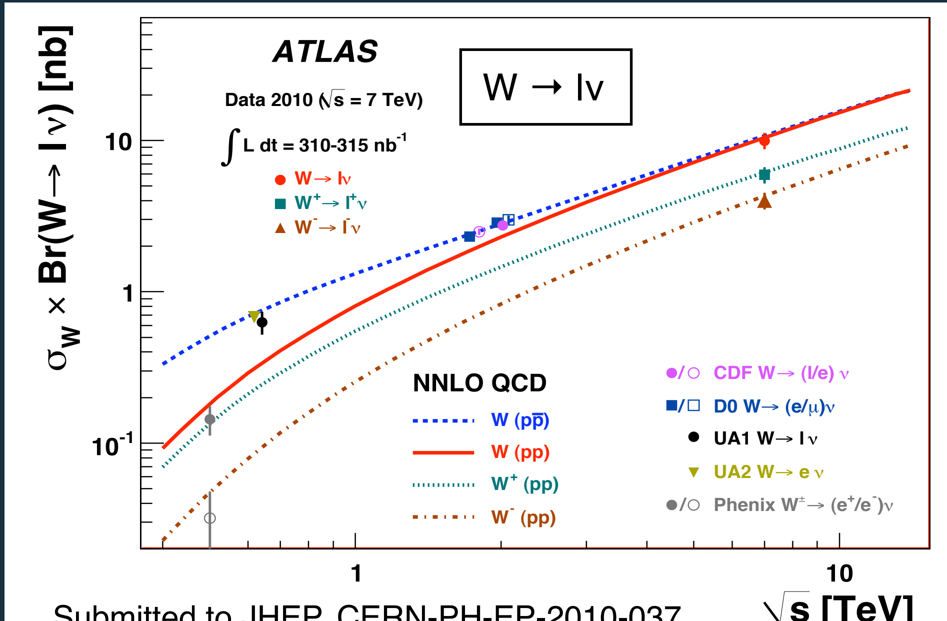
- Good benchmark for understanding ISR effects.

- Independent of jet energy scale.
- Can be used to calibrate accompanying jets.


ATLAS
EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

Electroweak Boson production

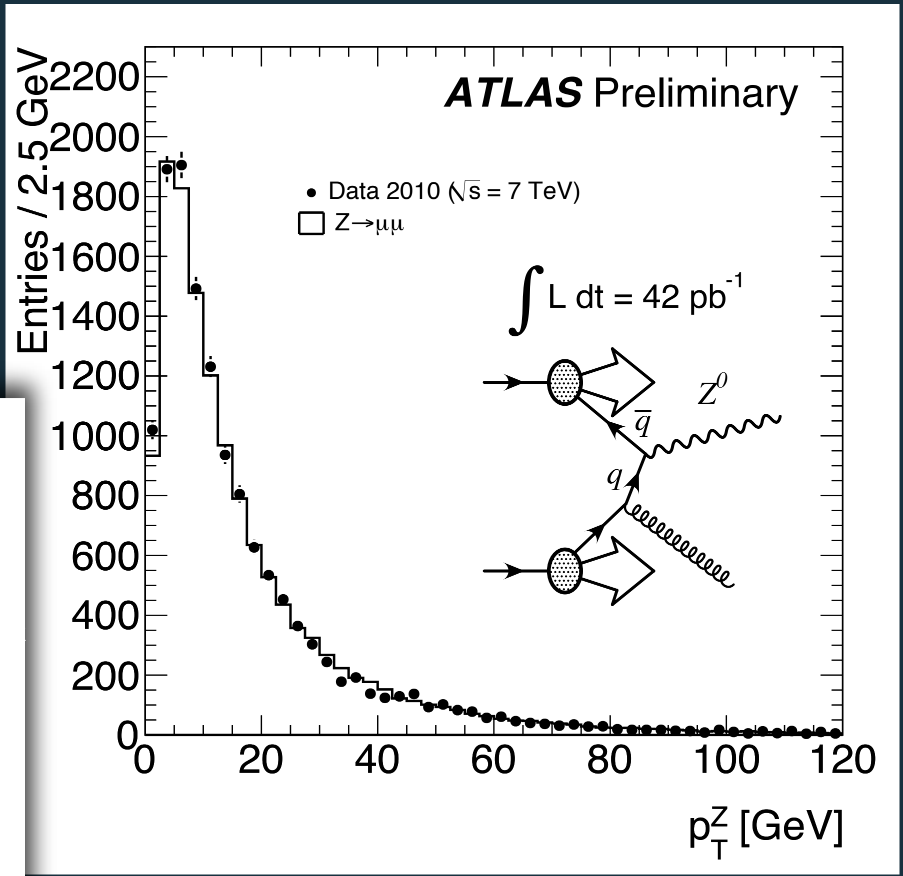


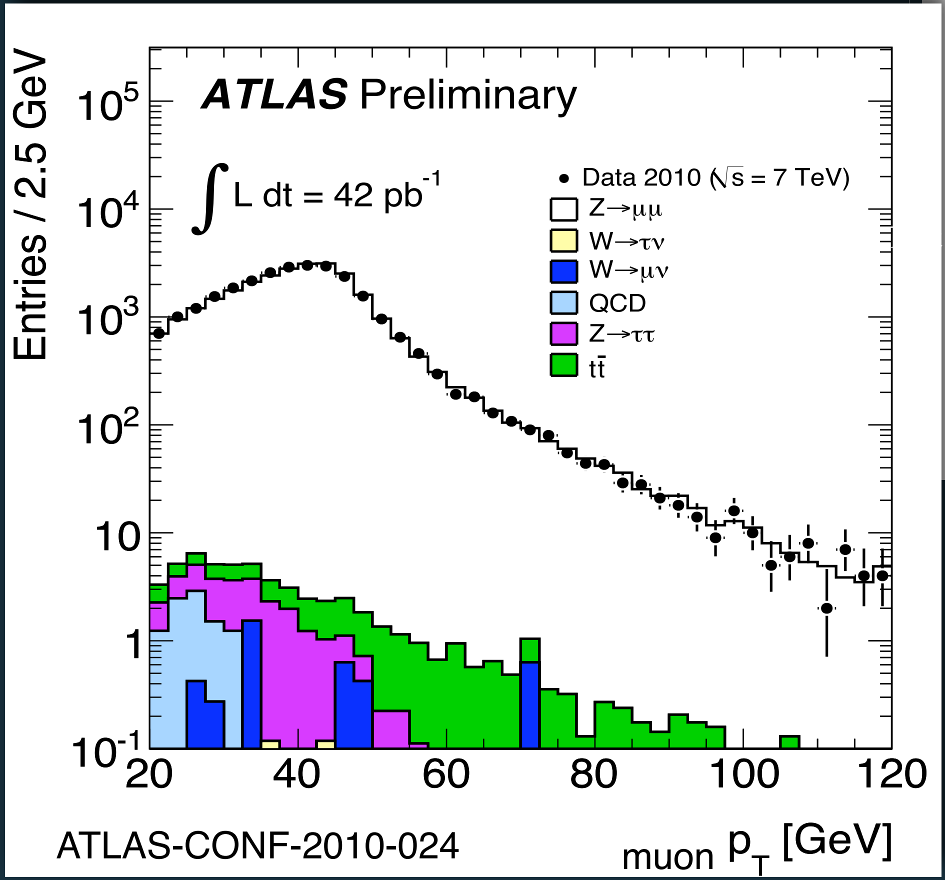


Submitted to JHEP, CERN-PH-EP-2010-037

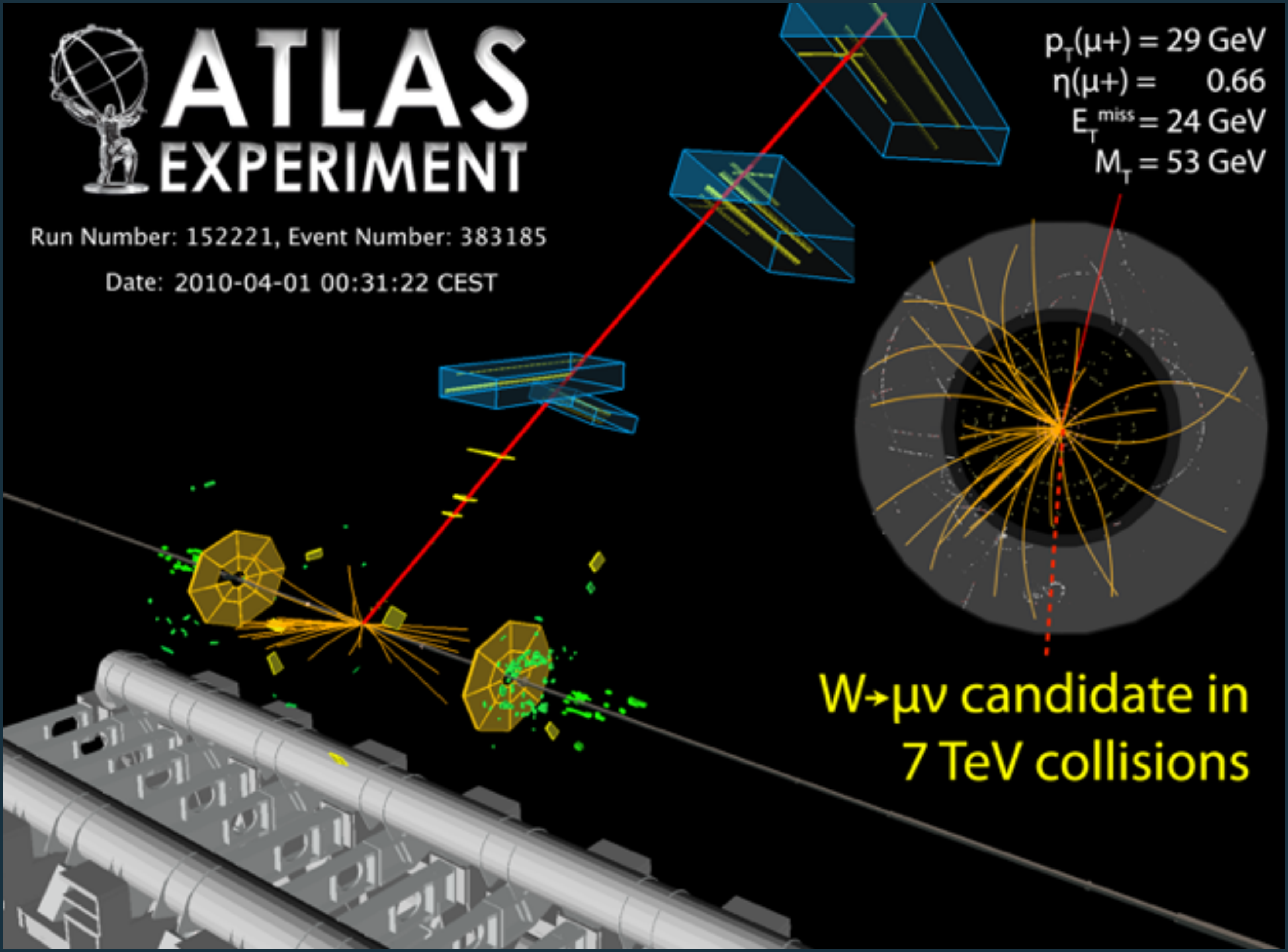
- NNLO uncertainty around 5% (not shown)
- Data well described by the NNLO calculation.
- Energy dependence well described

Inclusive Z production





- Excellent agreement with Monte Carlo over 3 orders of magnitude.
- Z boson transverse momentum from QCD radiation.
- Largest uncertainty from lepton reconstruction.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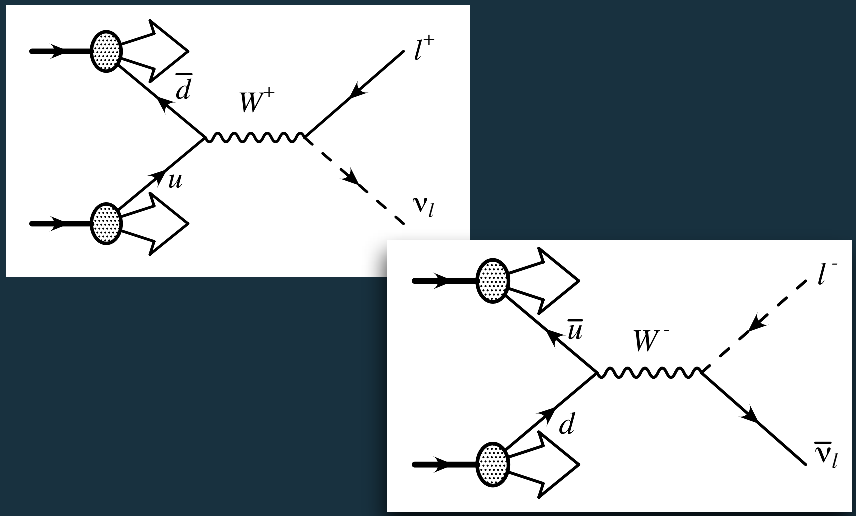
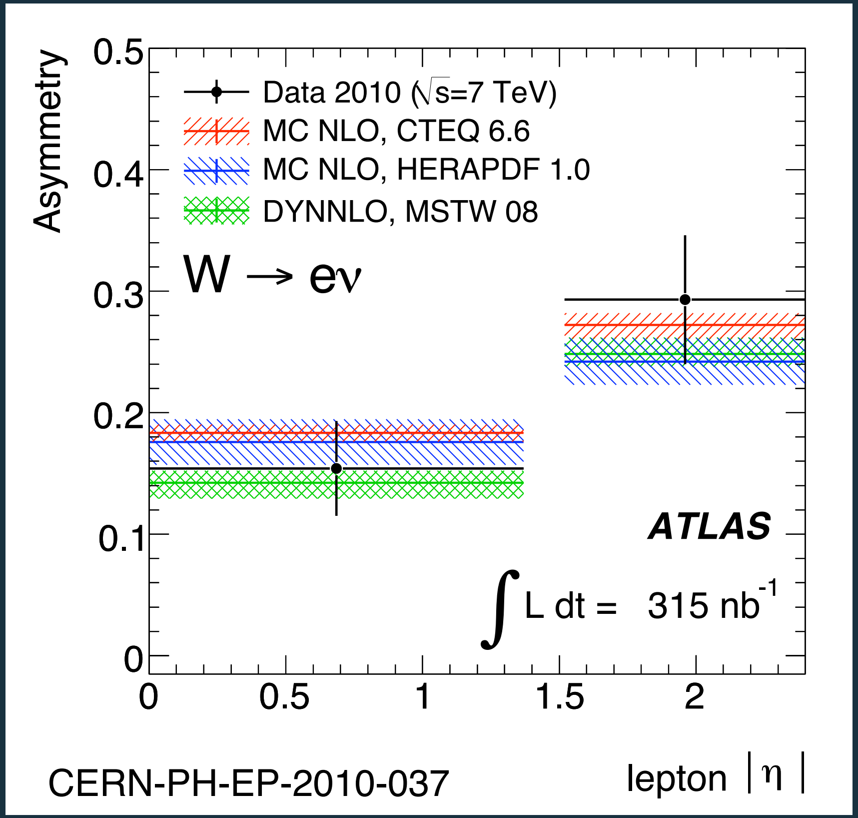
EXPERIMENT
Run Number: 152221, Event Number: 383185
Date: 2010-04-01 00:31:22 CEST
$p_T(\mu+)$ = 29 GeV
$\eta(\mu+)$ = 0.66
E_T^{miss} = 24 GeV
M_T = 53 GeV
$W \to \mu\nu$ candidate in
7 TeV collisions



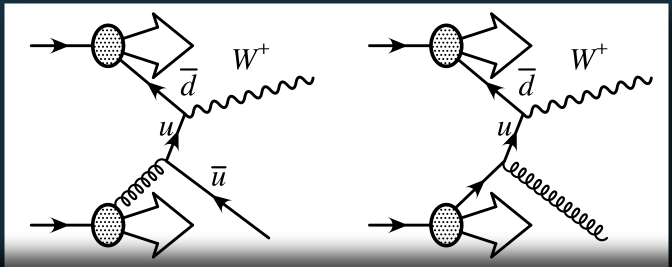


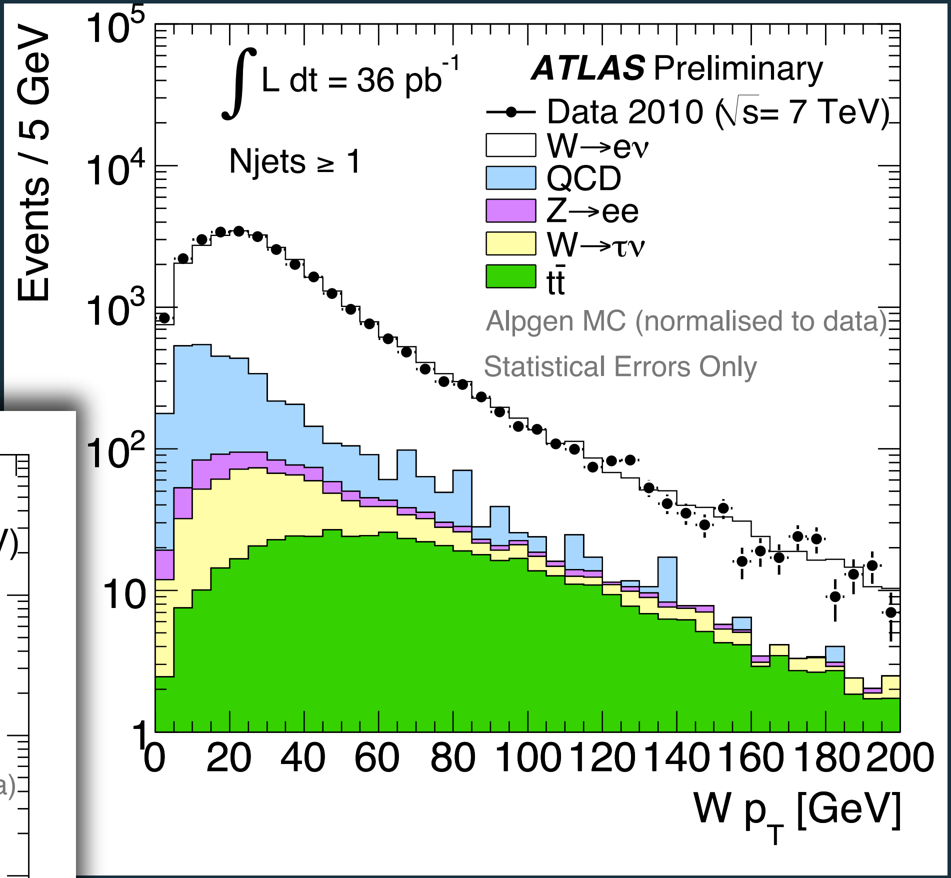
The W charge asymmetry

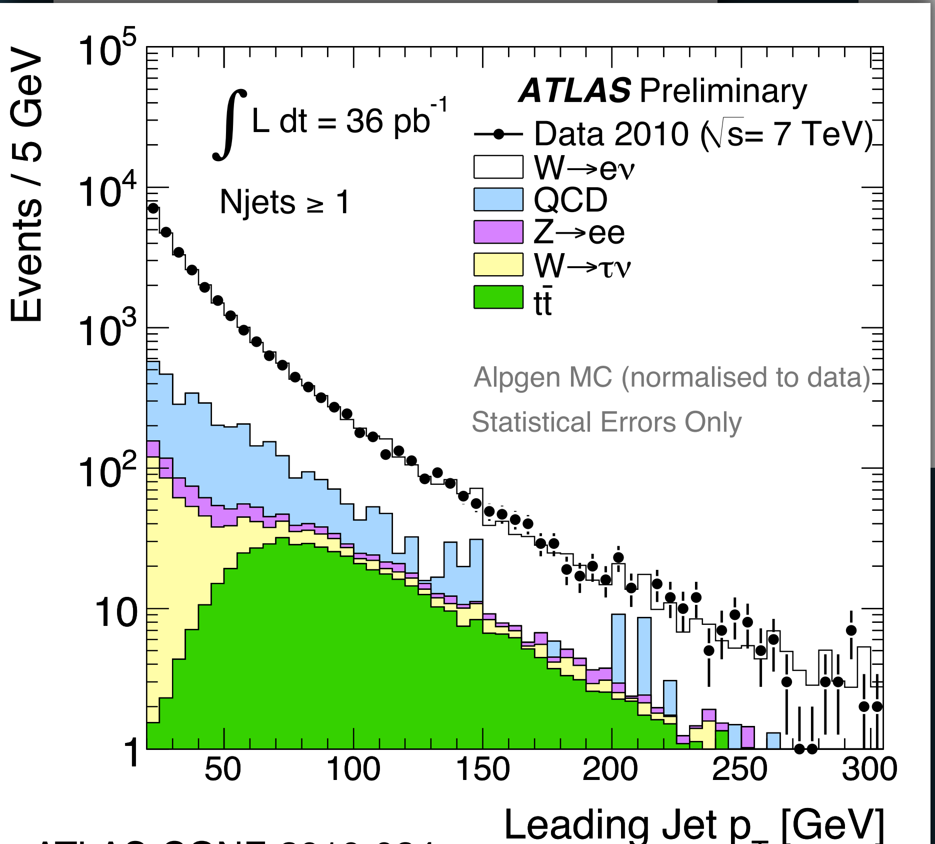
$$A_W = \frac{W^+ - W^-}{W^+ + W^-}$$

- Charge asymmetry for W boson sensitive to u and d valence quark distributions at large *x*.
- Cross section uncertainty dominated by gluon distribution, cancels in the asymmetry, as do many systematic uncertainties.
- Due to the ν, cannot reconstruct the W kinematics completely, but the charged lepton asymmetry also sensitive to the valence quark distribution.

W plus Jet production







- Excellent agreement with Monte Carlo over 3 orders of magnitude.
- Largest uncertainty from jet energy scale, followed by lepton acceptance and QCD background estimation.

Summary and outlook

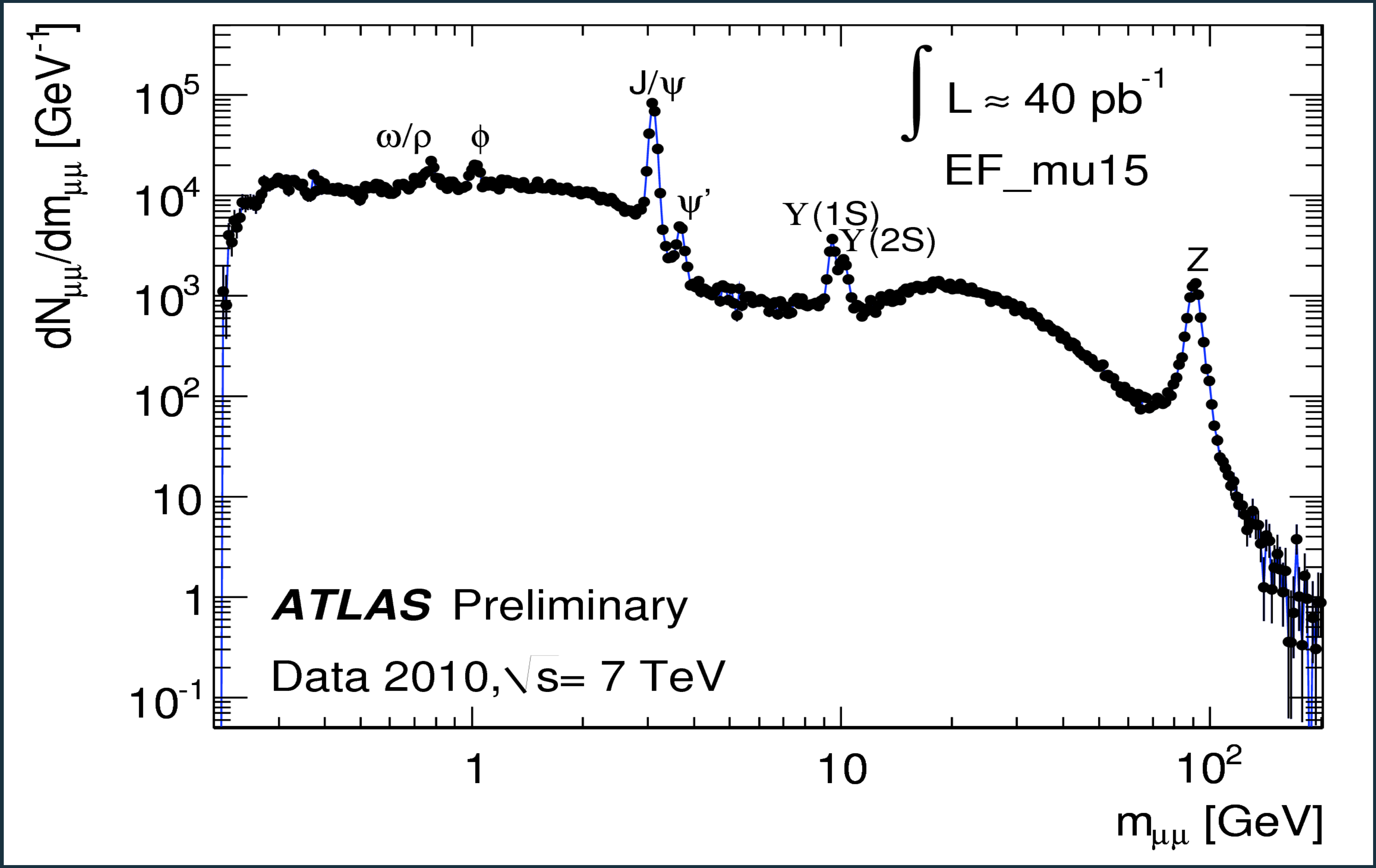
- ATLAS analyses are developing well and we are rapidly increasing our understanding of the detector with real data.

- After less than a year of collisions at 7 TeV the LHC has been working well and is already providing a large range of high quality physics results, and we are only beginning to explore the available phase space of important QCD results.
  - Analyses are still statistically limited in the most interesting regions of phase space
  - Working hard to reduce the systematic uncertainties.

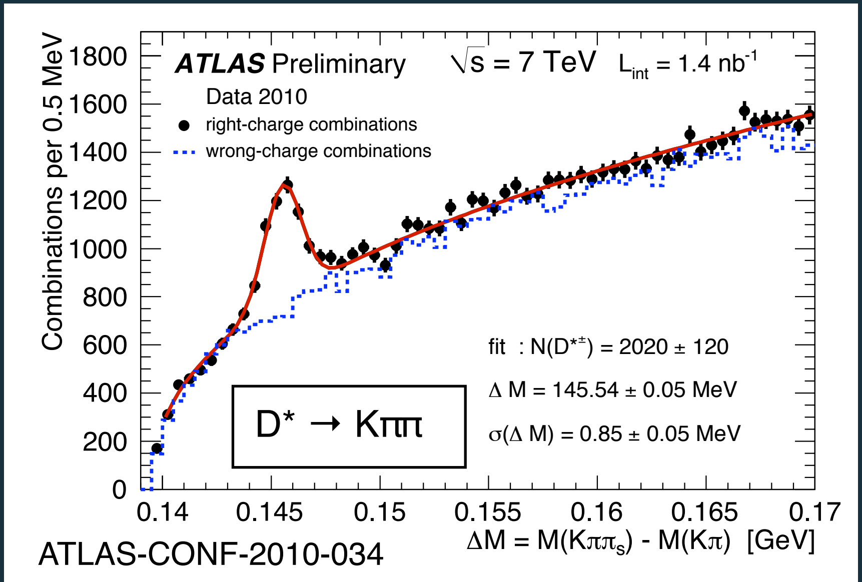
- Given the status of the statistical and systematic uncertainties, perturbative QCD appears to be in good shape (so far).

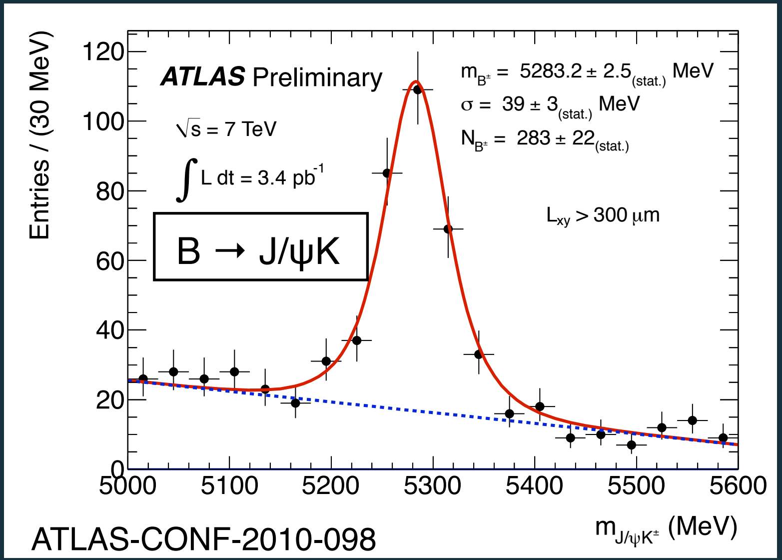
- We are on the verge of a new era in our understanding of QCD at the hardest momentum transfers.

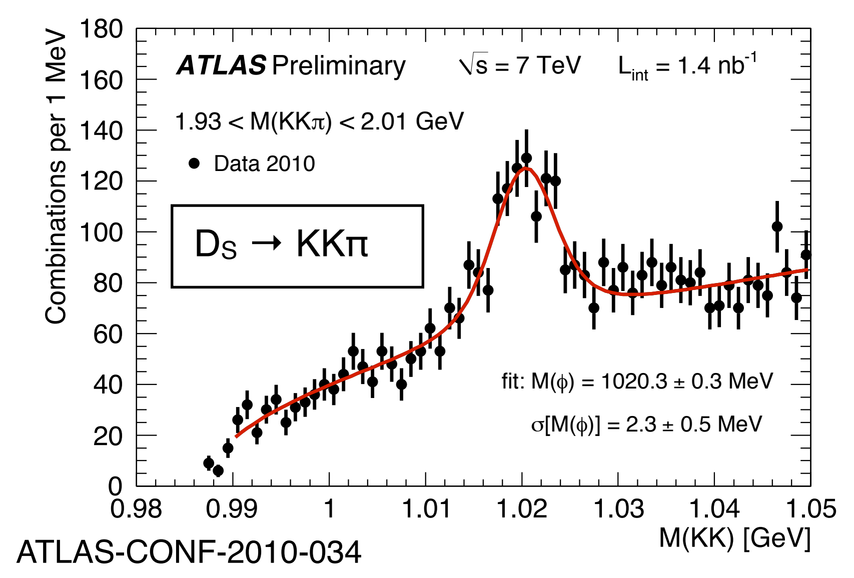
Appendix A: The dimuon mass spectrum

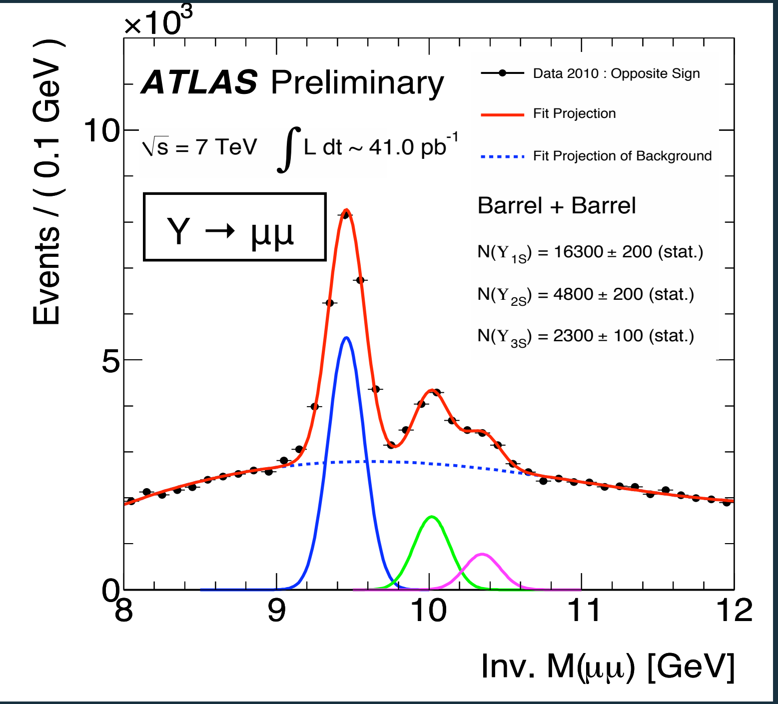


Appendix B: Heavy Flavour

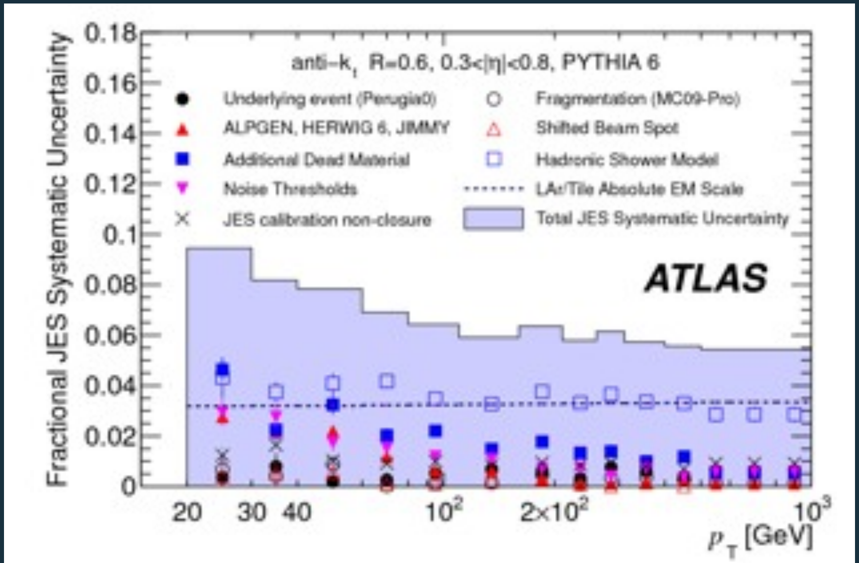


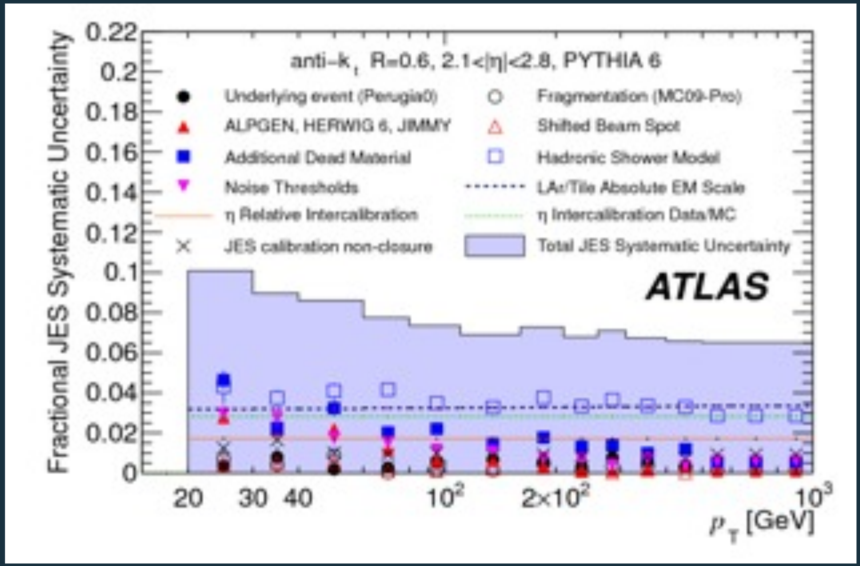






Appendix C: Jet Energy scale uncertainty





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- ATLAS uses the Anti-kT algorithm with cone radii R=0.4 or R=0.6, unfolded to hadron level.
- The dominant systematic uncertainty is that due to the jet energy scale.
  - Evaluated by comparing the unfolded varying detector configurations, hadronic shower models, physics models etc in the Monte Carlo
  - Largest single contributions from GEANT hadronic shower model (GEANT), detector material simulation, soft QCD modeling, and the Calorimeter energy scale, 3%
- Overall uncertainty 6-10% for $|\eta| < 2.8$
  - Dependent on p_T, η
- Overall uncertainty on the steeply falling jet cross section of around 40%.