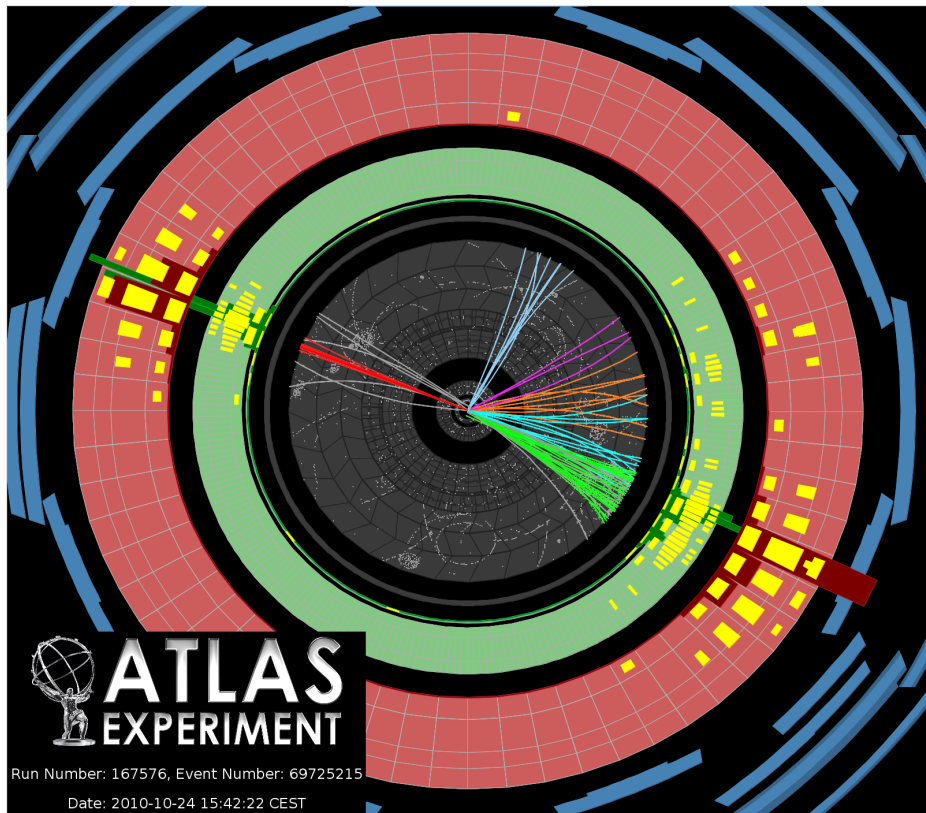


# QCD at ATLAS: The Story so Far



Paul Newman (Birmingham)

Excited QCD'11, Les Houches  
22 February 2011

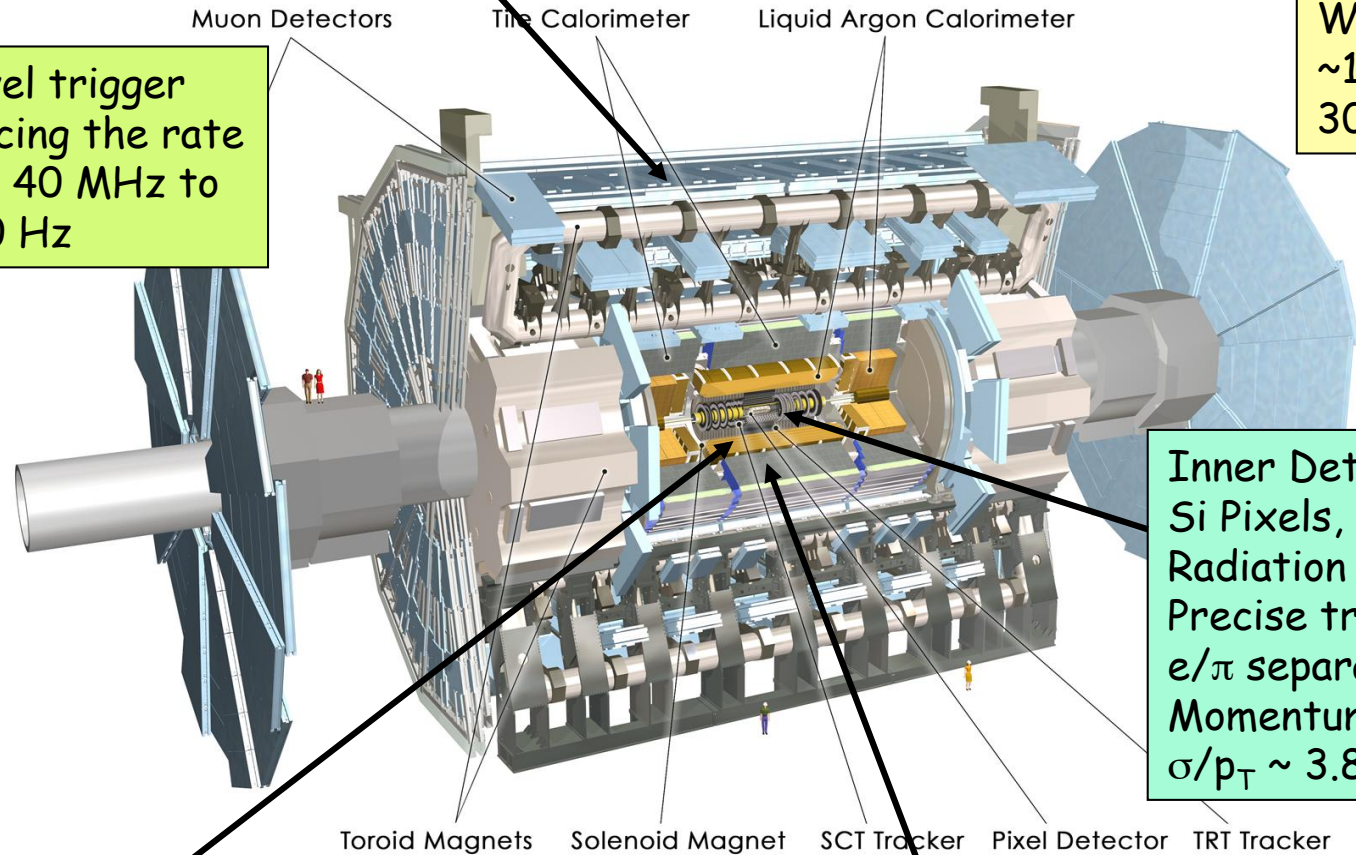


- ATLAS 2010 Data
- Minimum bias events
- W and Z production
- Direct photons
- Multi-jets
- Heavy ion collisions

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

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

3-level trigger  
reducing the rate  
from 40 MHz to  
 $\sim 200$  Hz



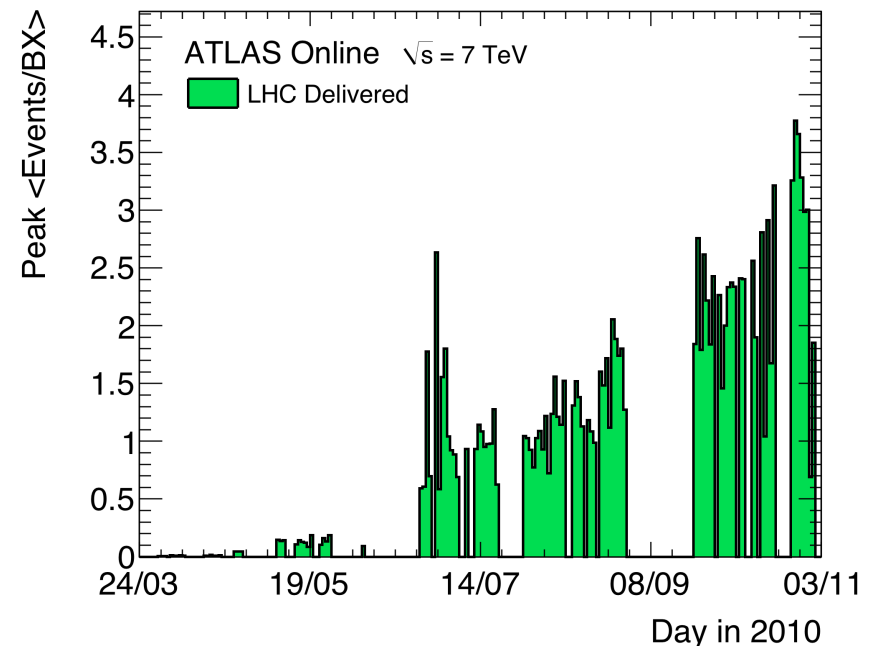
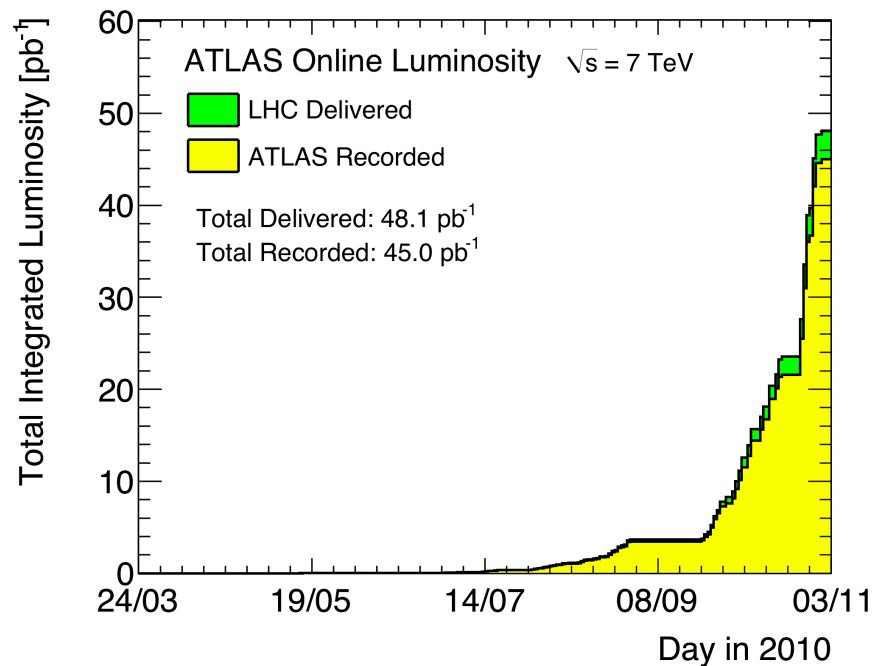
Inner Detector ( $|\eta| < 2.5$ ,  $B=2$ T):  
Si Pixels, Si strips, Transition  
Radiation detector (straws)  
Precise tracking and vertexing,  
 $e/\pi$  separation  
Momentum resolution:  
 $\sigma/p_T \sim 3.8 \times 10^{-4} p_T (\text{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion  
 $e/\gamma$  trigger, identification and measurement  
E-resolution:  $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ( $|\eta| < 5$ ): segmentation, hermeticity  
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)  
Trigger and measurement of jets and missing  $E_T$   
E-resolution:  $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

# 2010 Data Taking

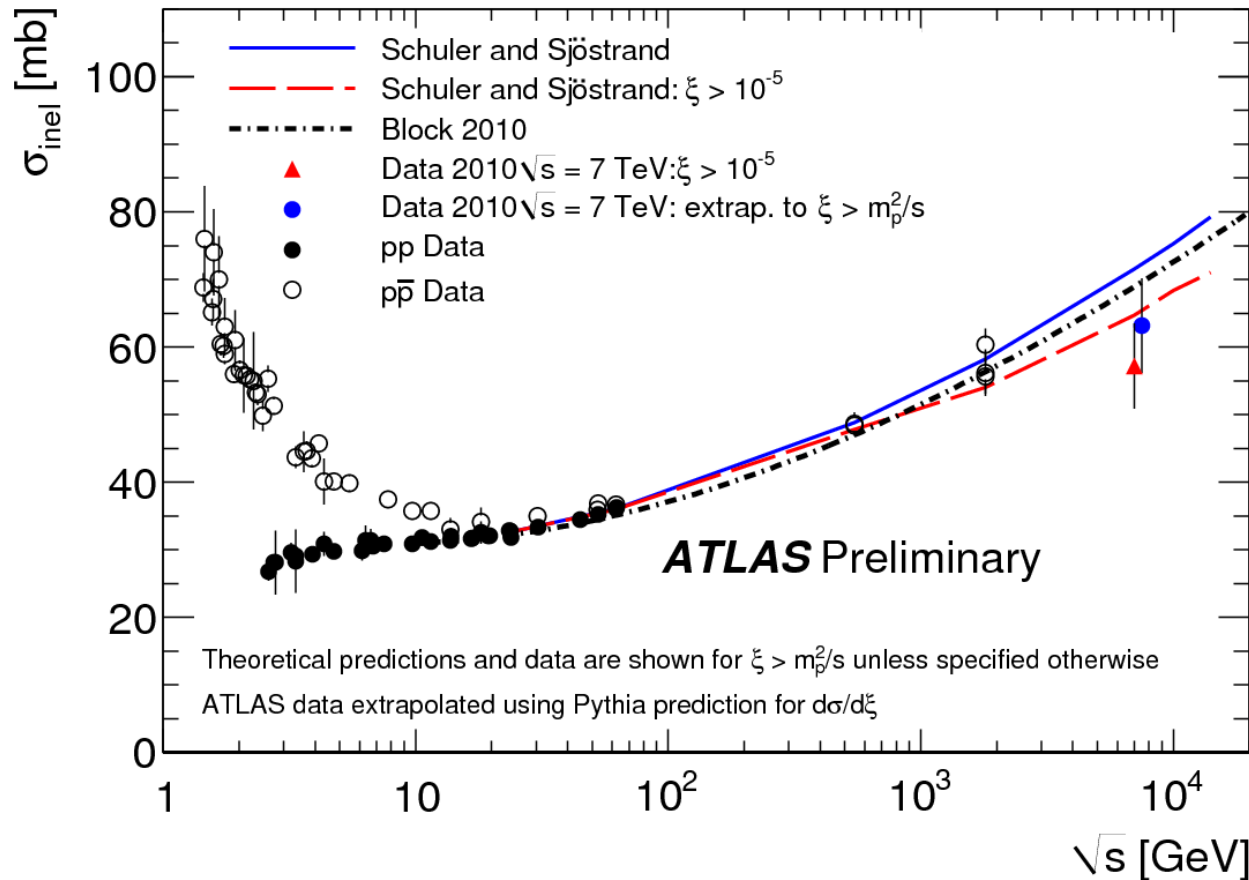
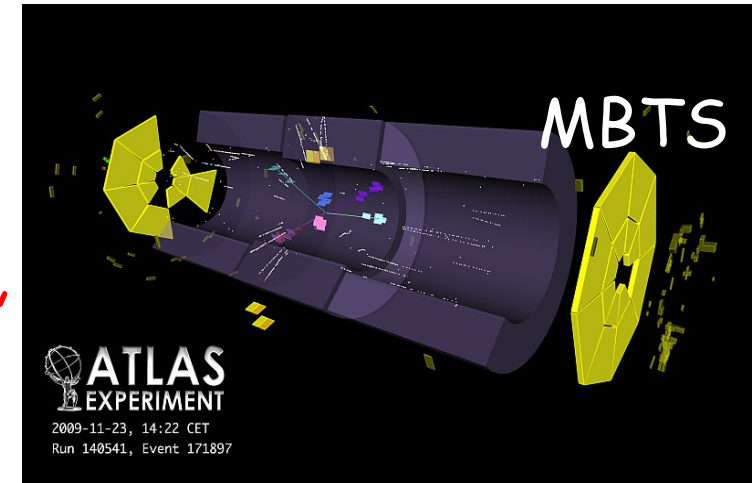
- LHC luminosity production beyond expectations
- ATLAS detector operated efficiently and response quickly well understood (e.g. jet energy scale to  $\sim 6\%$  with  $17 \text{ nb}^{-1}$ )



- Data taking mostly in pp mode at  $\sqrt{s} = 7 \text{ TeV}$ 
  - Integrated lumi  $\sim 45 \text{ pb}^{-1}$  in pp
  - Peak luminosity  $\sim 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
  - pile-up  $\sim 3$  events per bunch crossing

# Total Inelastic pp Cross Section

- Using MBTS trigger ( $2.1 < |\eta| < 3.8$ ), miss only elastic ( $pp \rightarrow pp$ ) and low mass diffraction ( $pp \rightarrow pX$  etc)

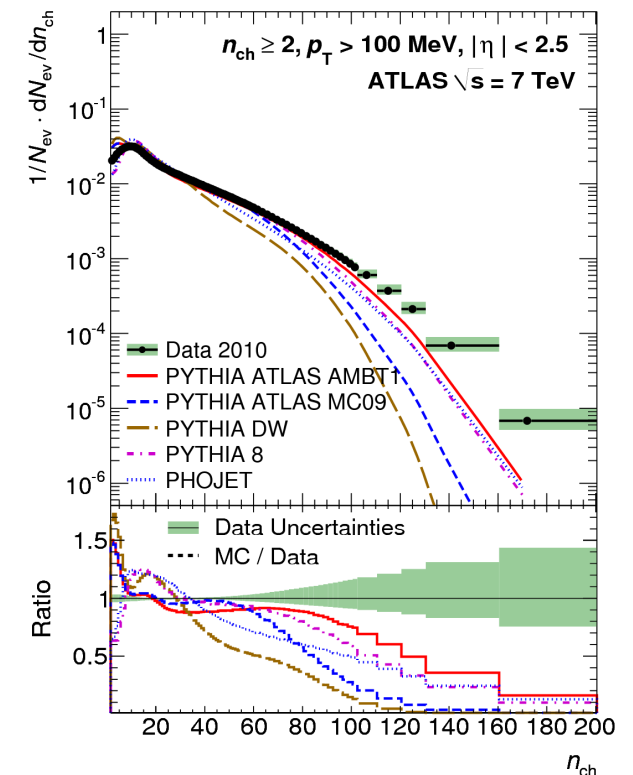
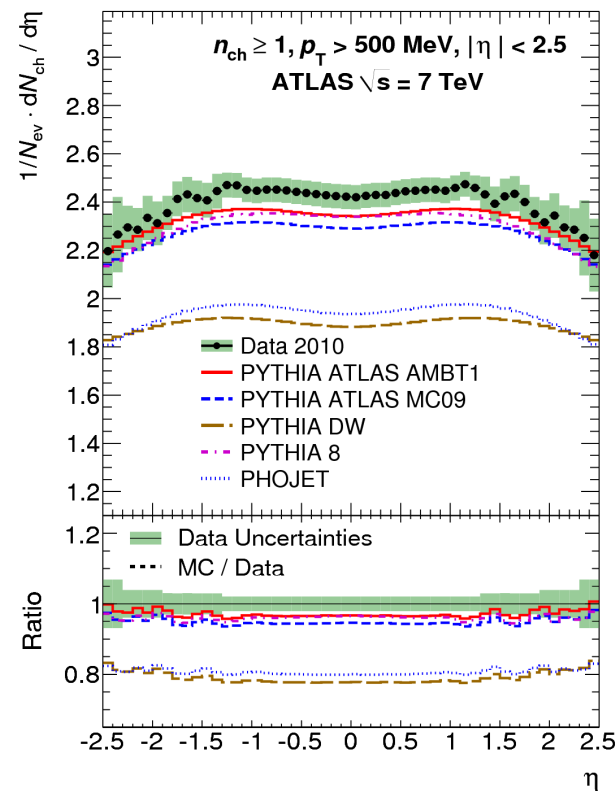
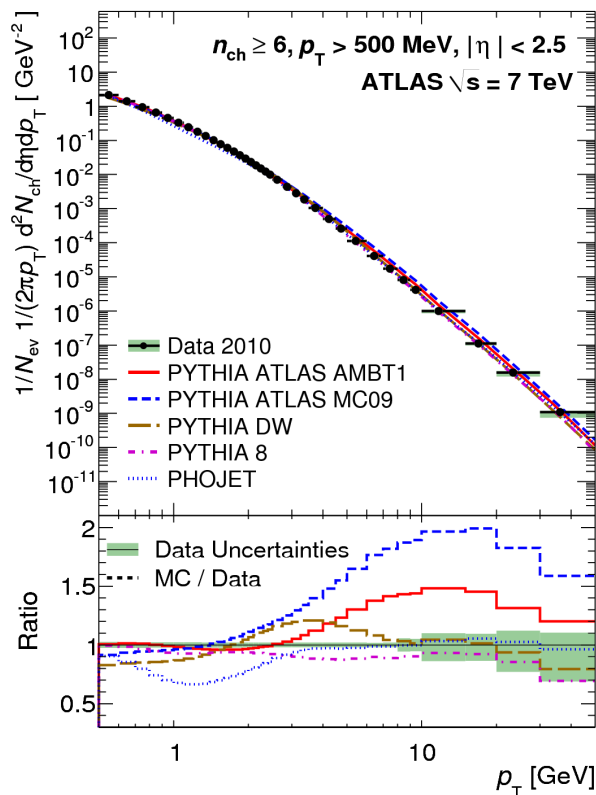


- After 5-10% extrapolation, obtain total inelastic cross section at  $\sqrt{s} = 7$  TeV
- ... dominated by 11% luminosity error (will improve soon)
- Most models agree ... for now ...

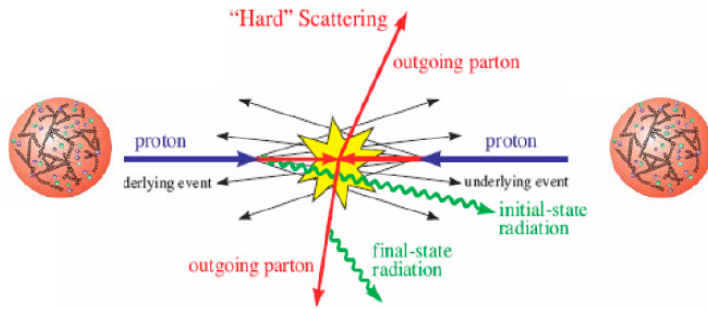


# Charged Particle Multiplicities

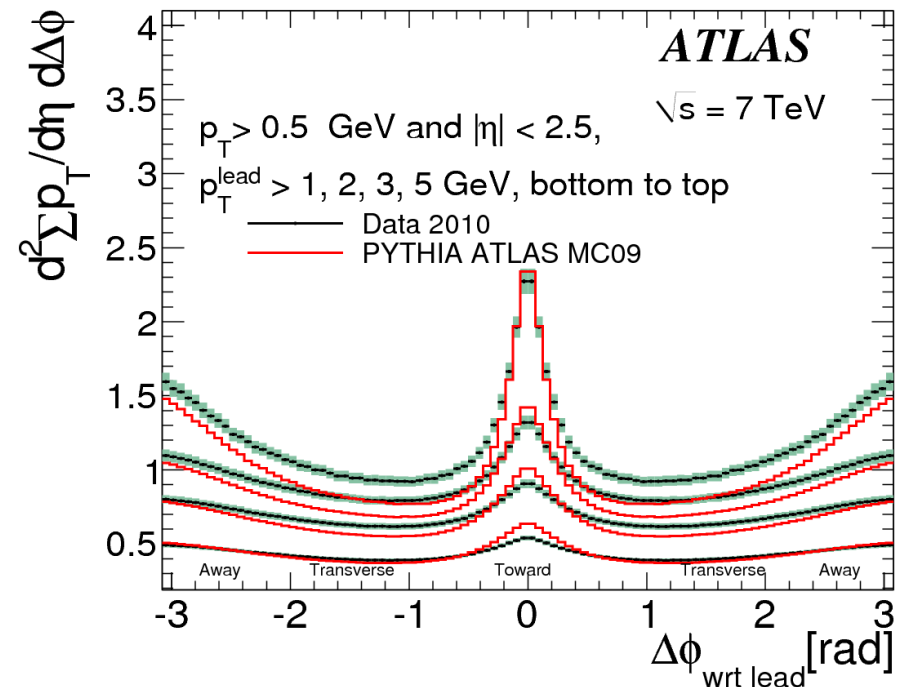
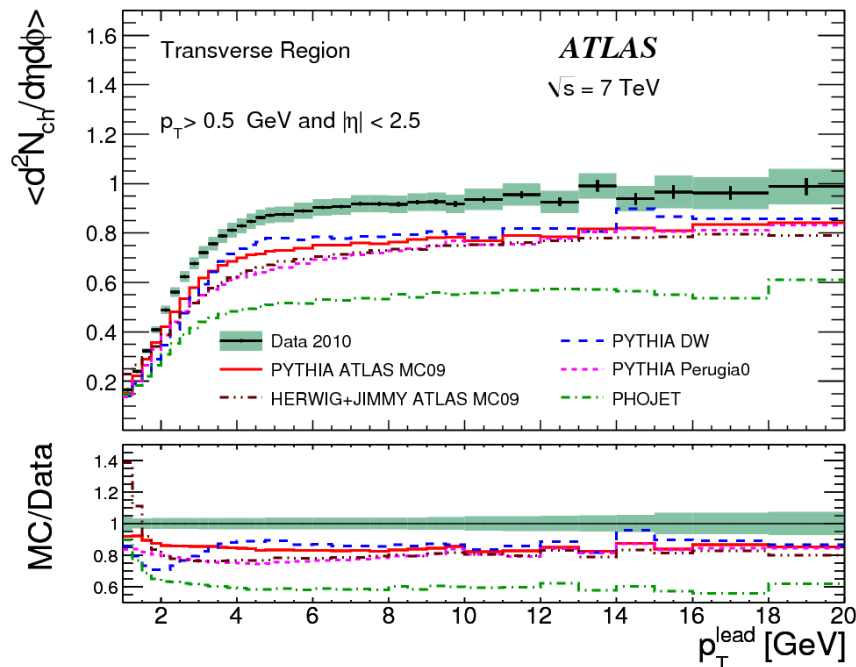
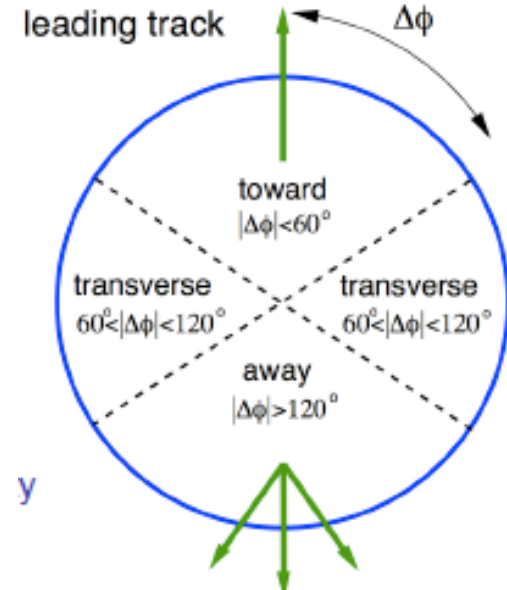
- Extremely precise data (2<sup>nd</sup> publication out already)
- Also measured for diffraction enhanced / suppressed samples
- Up to 200 tracks per event
- No MC fully describes data (e.g. consistently low at central  $\eta$ )
- MC Tunes in progress ... description from 1<sup>st</sup> principles? ...



# The Underlying Event



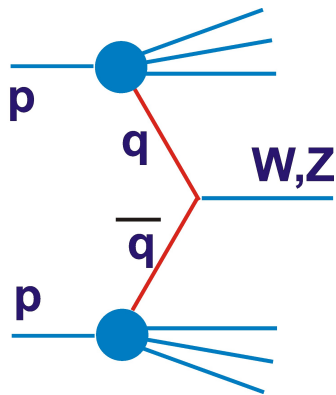
- Transverse region particularly sensitive to multiple (parton) int's.
- All commonly used MC models predict too little transverse activity and jettiness at  $\Delta\phi \sim 180^\circ \rightarrow$  tunes



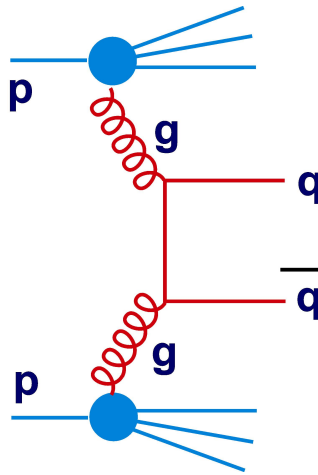
# QCD Hard Scattering Processes

... The main focus for recent ATLAS publications  
(also with mixed signatures such as  $W$ +jets)

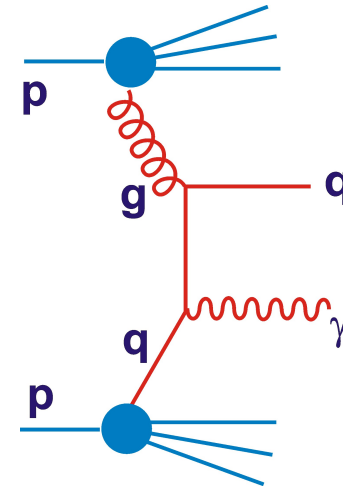
**EW gauge bosons**



**Dijets**



**Direct photons**



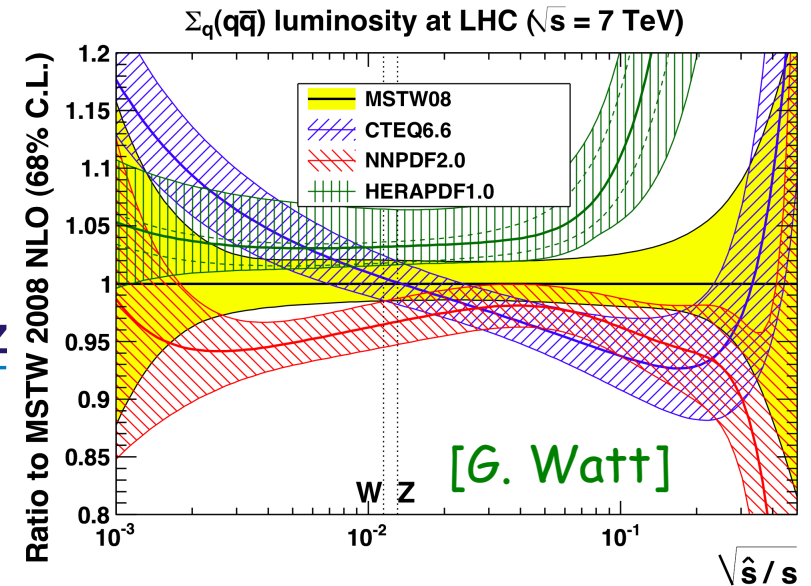
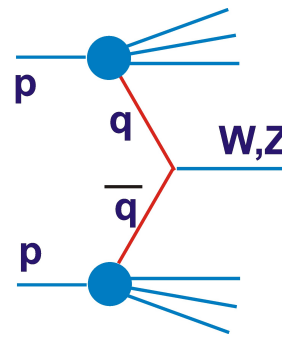
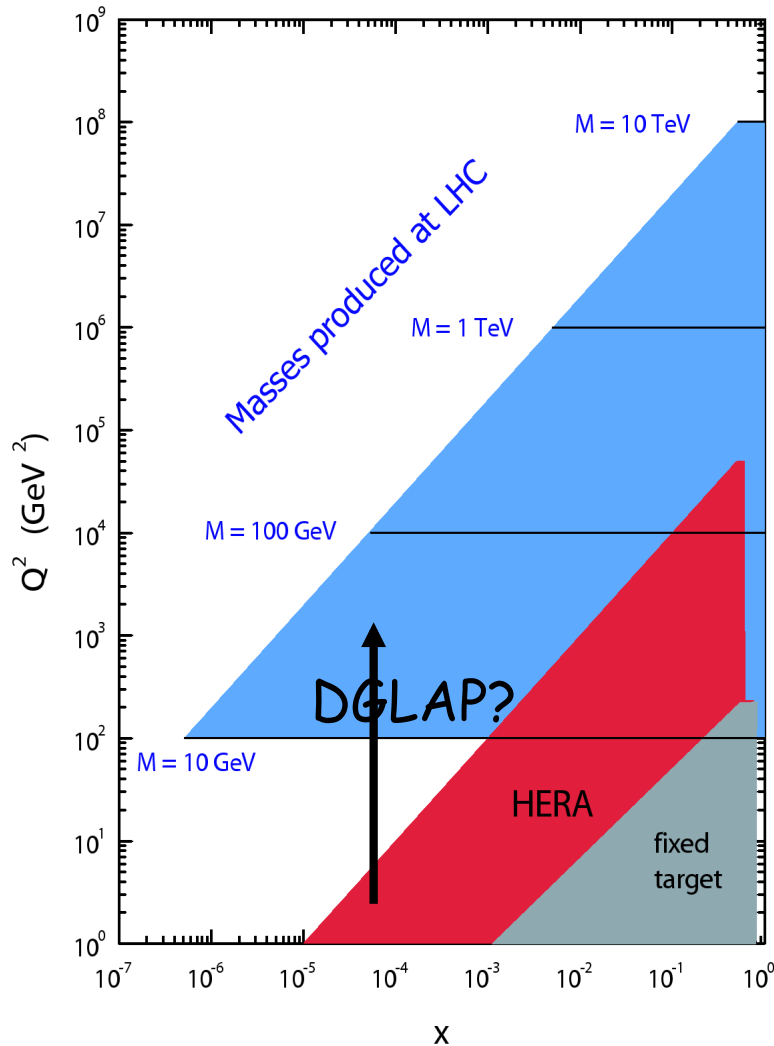
Measuring these processes tests our understanding of:

- Partonic structure of proton
- QCD scattering via calculations to (N)NLO
- Hadronisation / underlying event
- What makes a good jet algorithm
- Data-driven background estimates for rare processes

- ~5% uncertainty on  $\sigma(W)$ ,  $\sigma(Z)$  just from PDF set choice in standard NLO DGLAP fits

- Larger in gluon initiated processes

# Parton Density & LHC Uncertainties

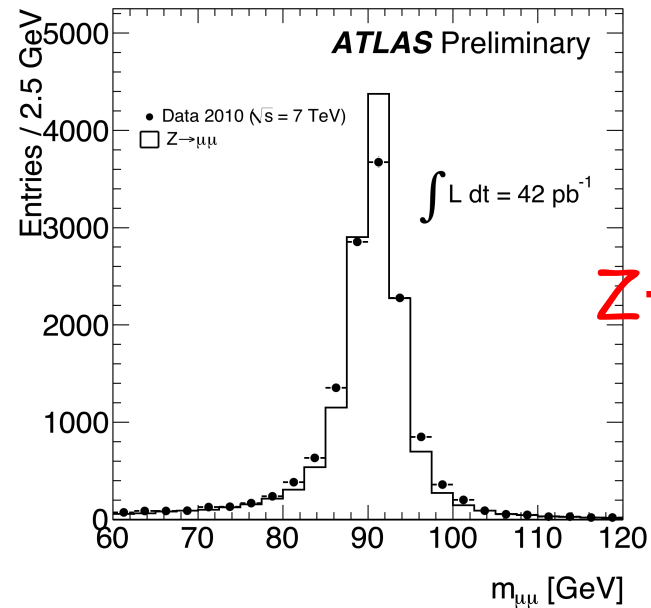
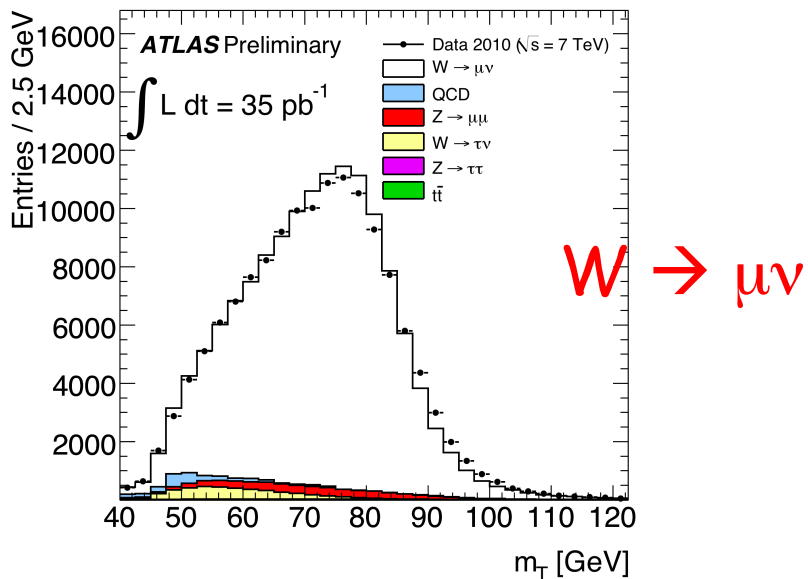
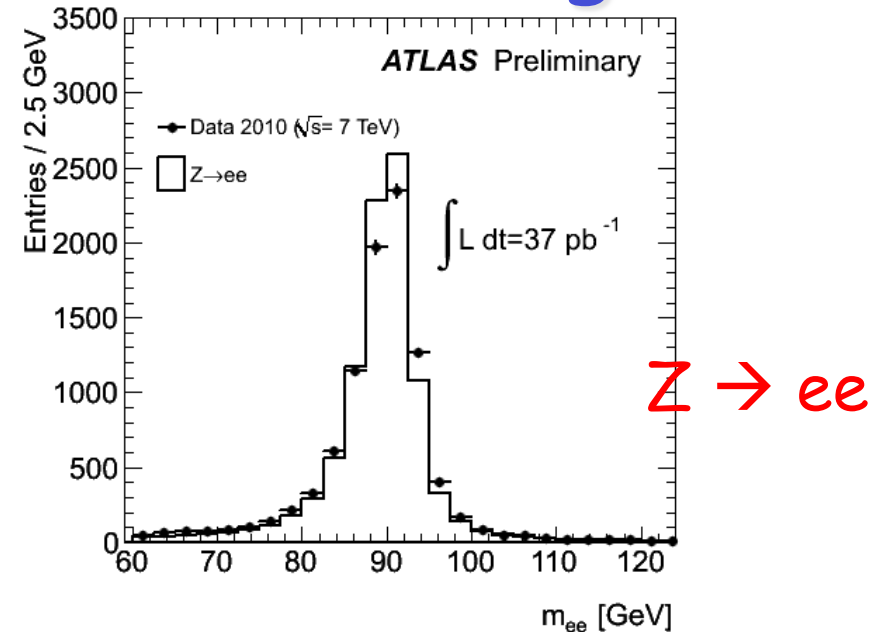
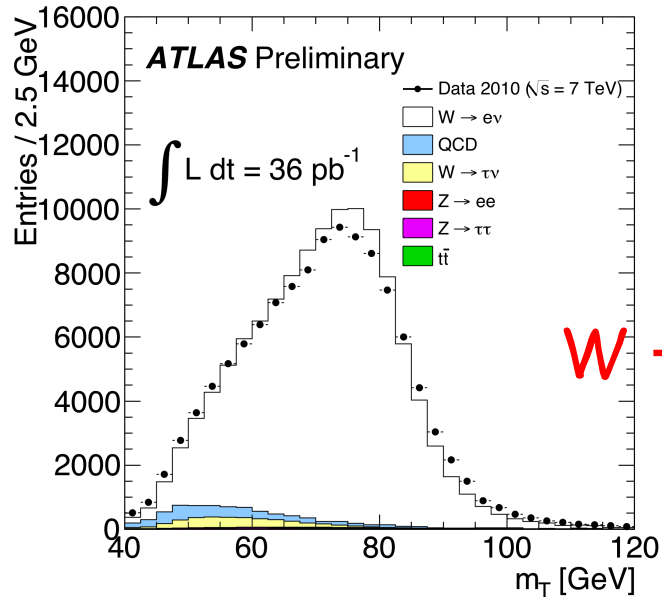


- Novel QCD / unitarisation effects in low  $x$  /  $Q^2$  gluon at HERA could show up at large rapidity at LHC

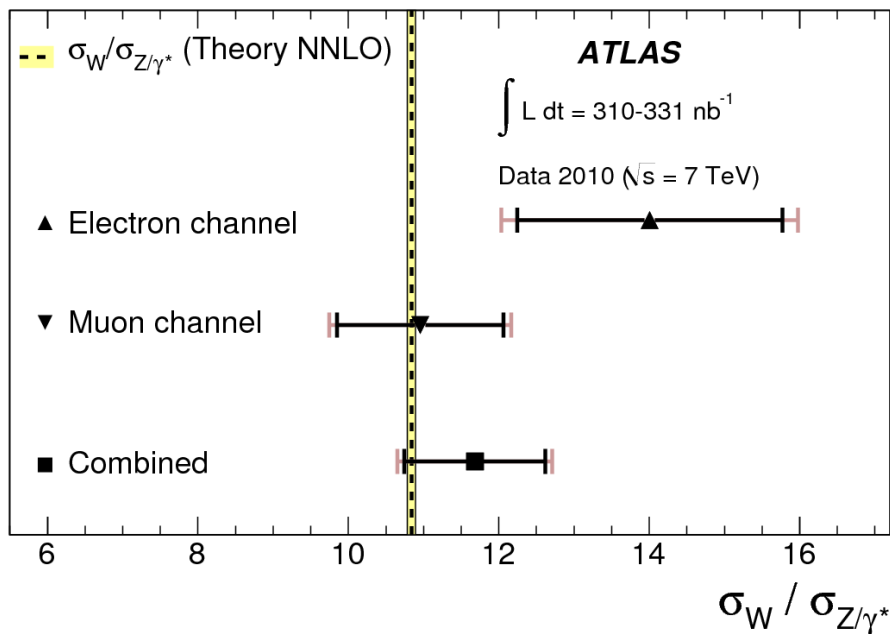
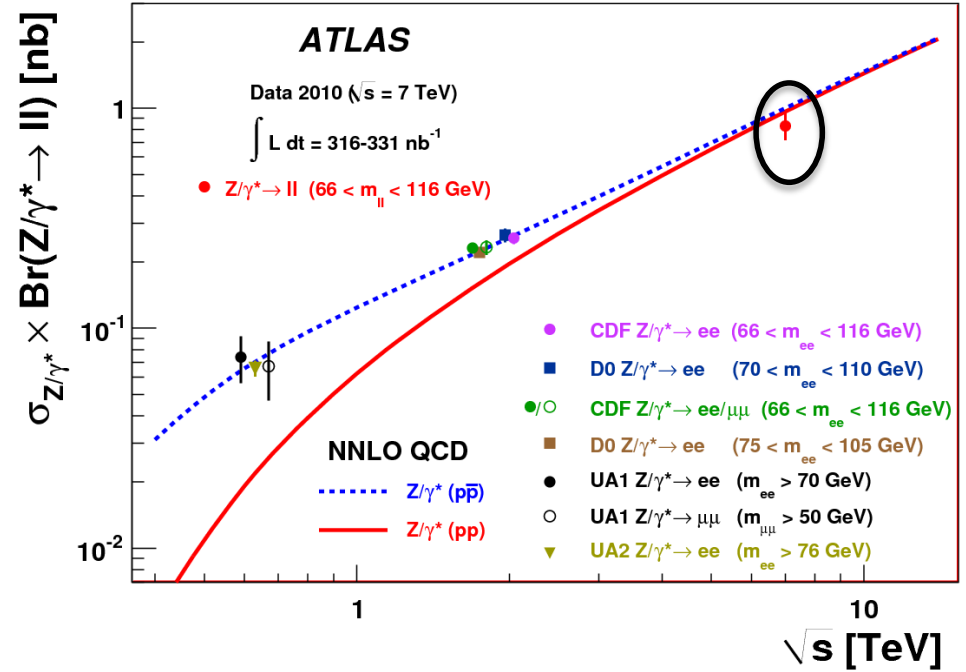
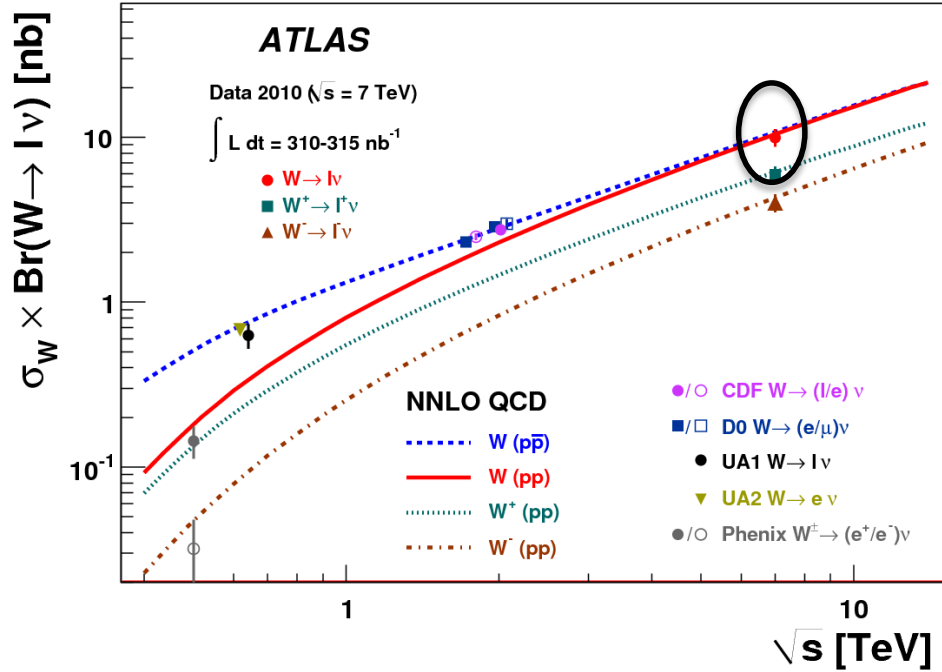
- Not (yet) main focus. First test pQCD at relatively large  $x$  in best understood regions of detector



# Sizeable Electroweak Gauge Boson Signals, well understood small backgrounds



# Electroweak Gauge Boson Cross Sections

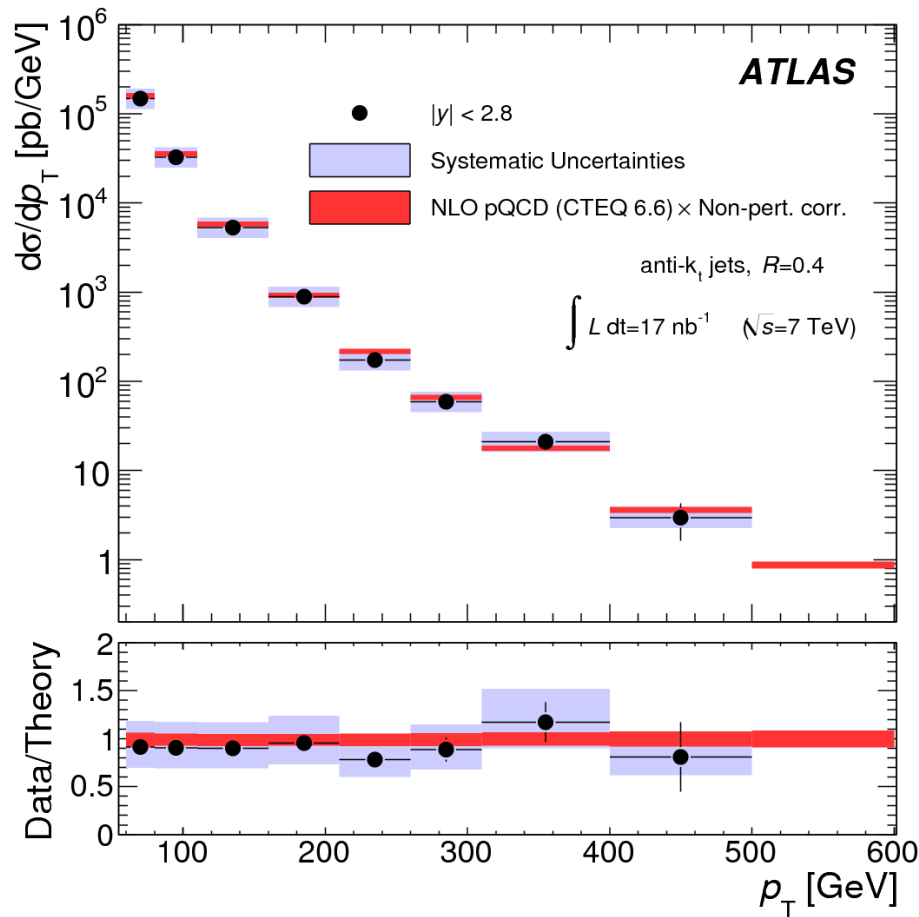


• First cross sections & ratios in good agreement with NNLO theory

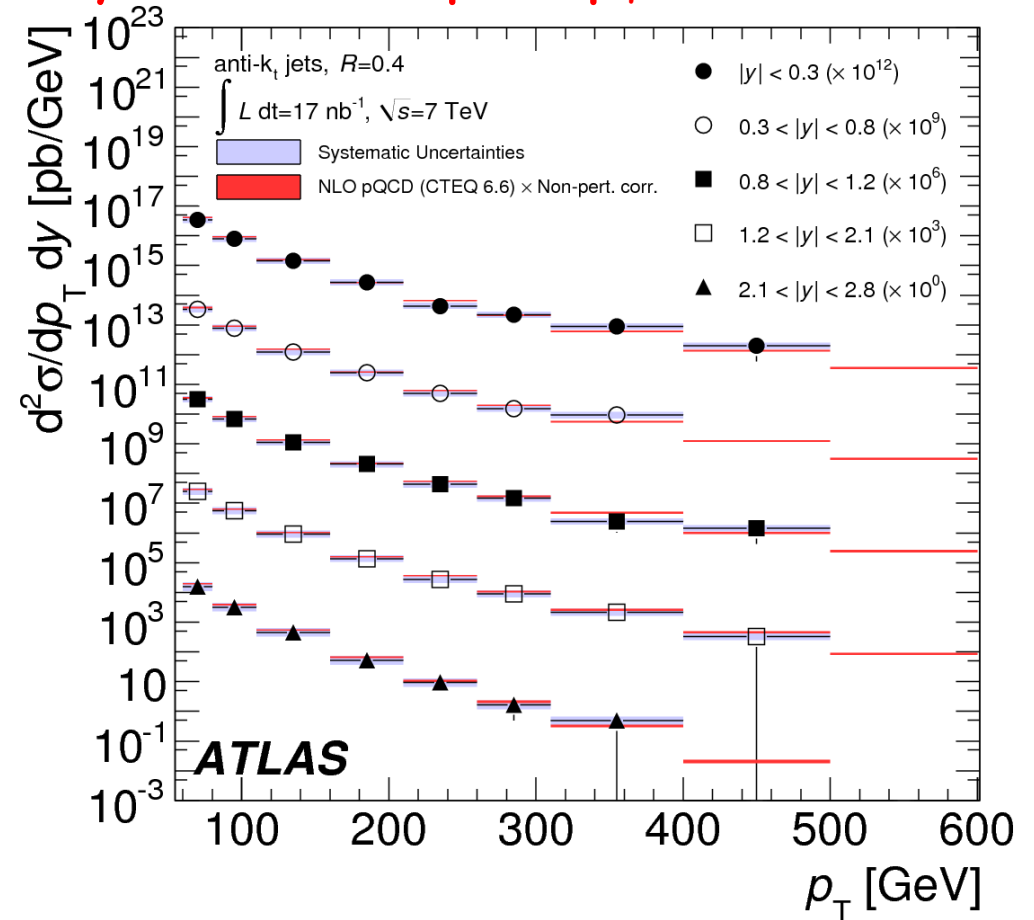
• Largest uncertainties:  
 ~10% (Z statistics)  
 ~11% (lumi)

... plenty of scope to improve!

# Inclusive Jets



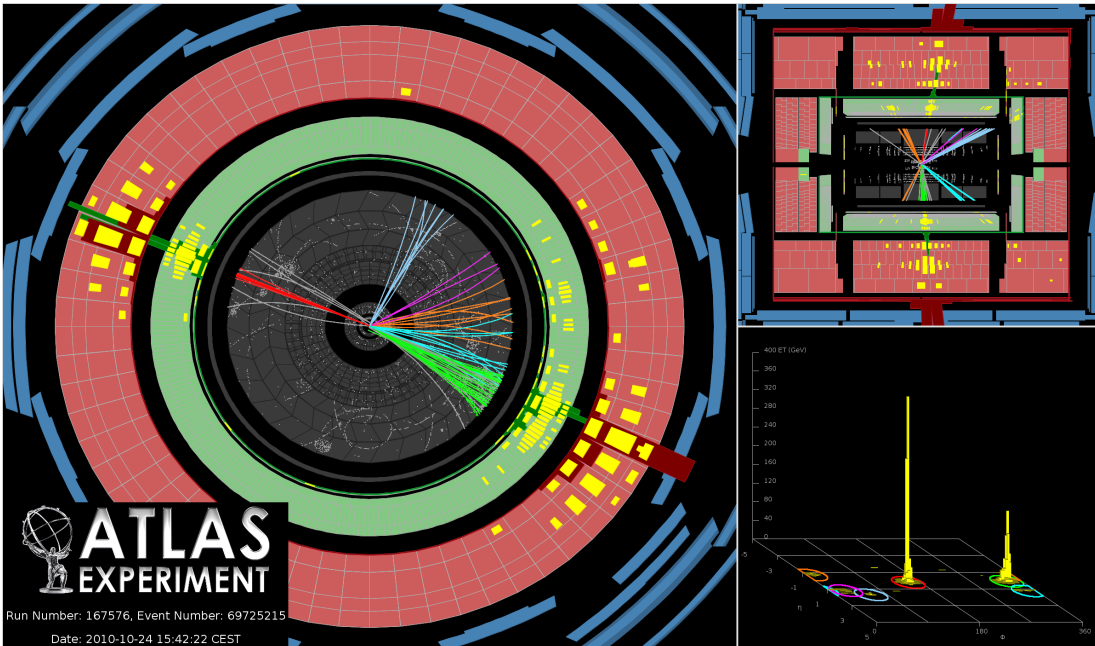
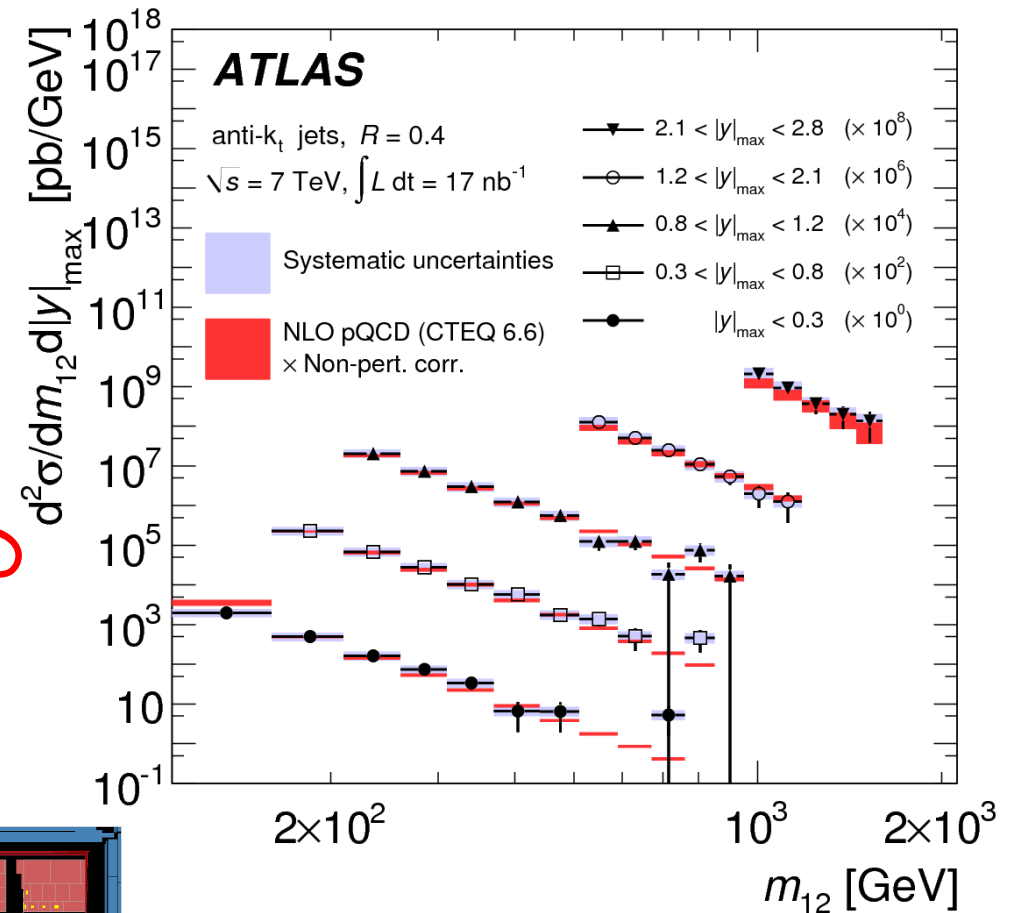
- 11% lumi uncertainty not shown
- Sys limited up to  $p_T = 400 \text{ GeV}$



- Inclusive jets with  $p_T$  up to  $> 500 \text{ GeV}$  & cross section varying over 5 orders of magnitude well described by NLO QCD
- ... also when measured double differentially in  $p_T$  and rapidity

# Dijets

- Dijets with highest invariant masses ever observed, extending to  $m_{12} > 2$  TeV
- ... well described by NLO QCD



An exceptional event:

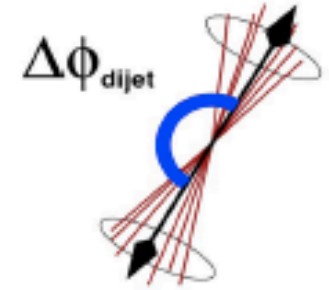
1st jet:  $p_T = 1.3$  TeV,  
 2nd jet:  $p_T = 1.2$  TeV  
 Total  $E_T = 2.2$  TeV  
 $m_{12} = 2.6$  TeV



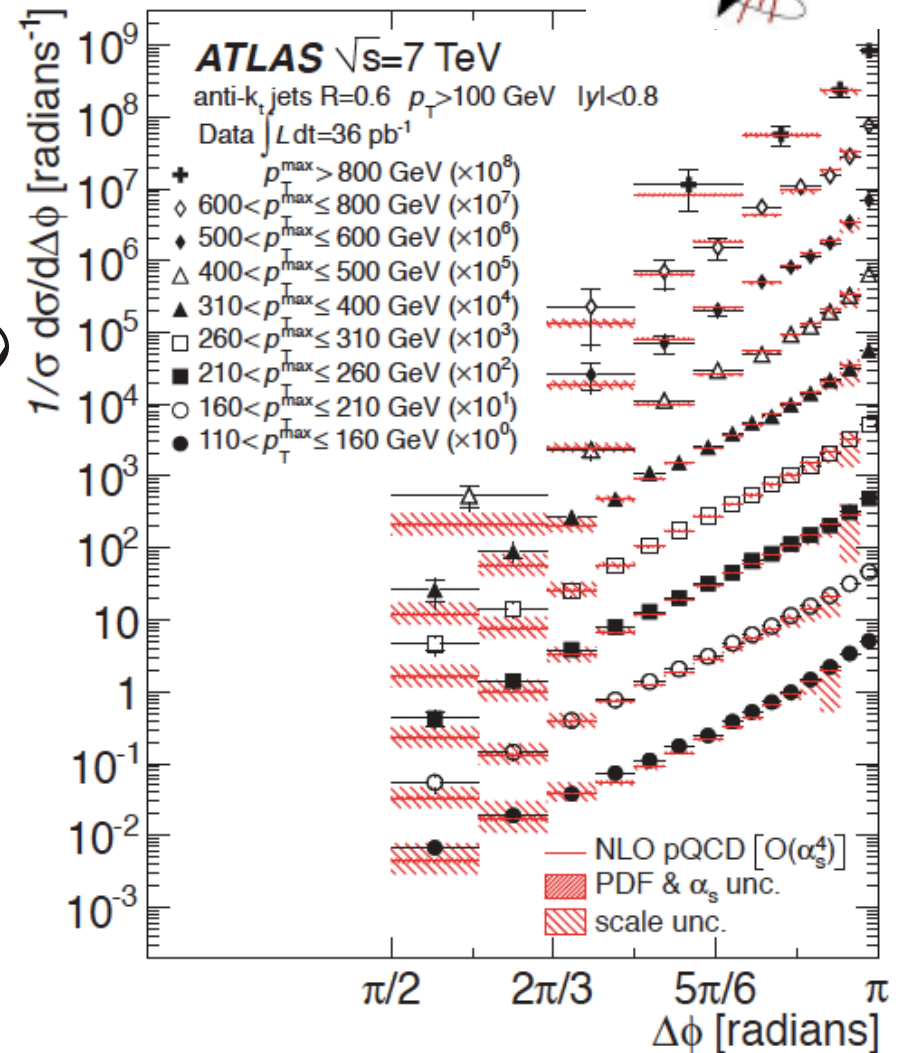
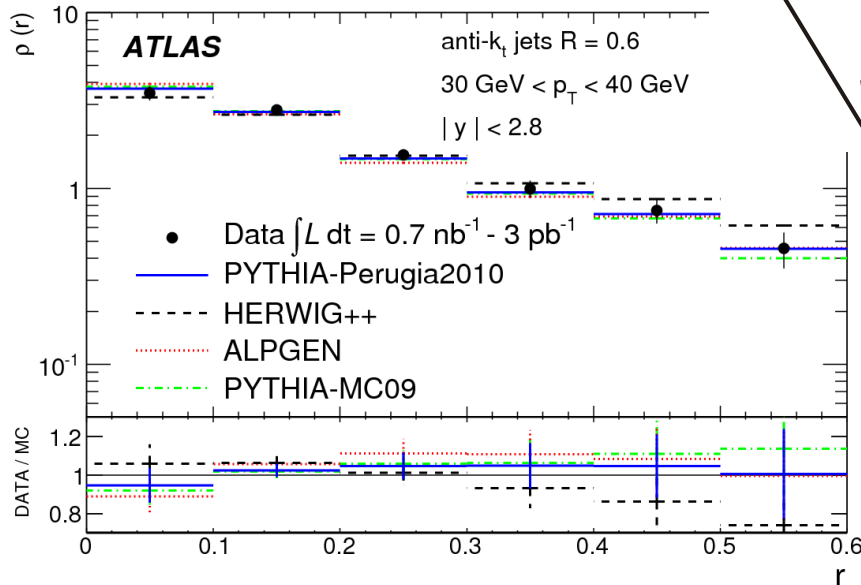
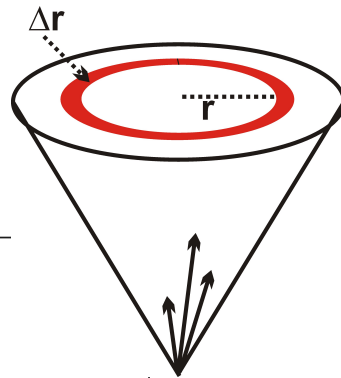
# Studies of Higher Order QCD Radiation

Azimuthal decorrelations in dijet events and distribution of energy within jets sensitive to QCD radiation structures.

- Well described, except near  $\Delta\phi = \pi$  where radiation is softest.
- Jets narrower as  $p_T$  increases

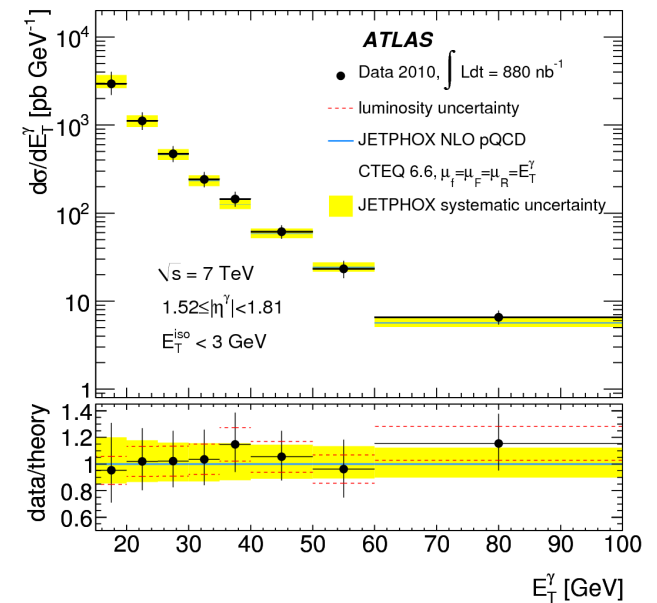
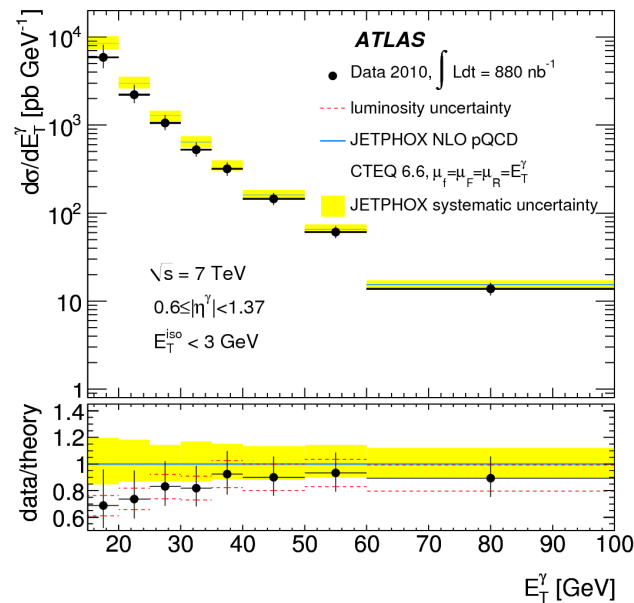
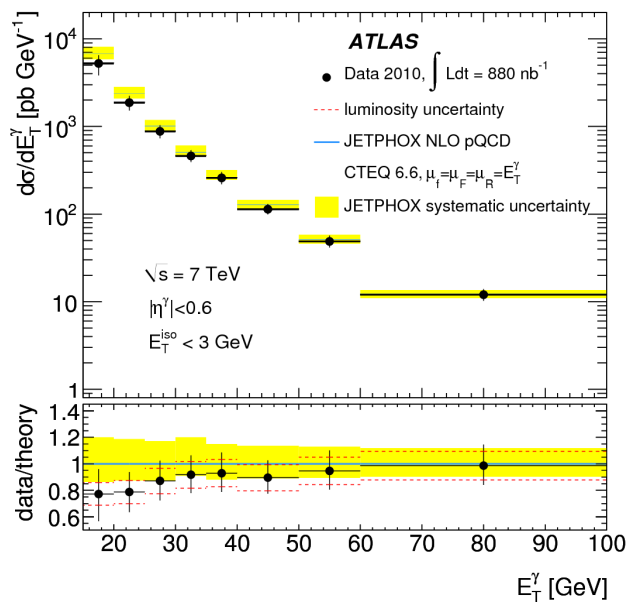
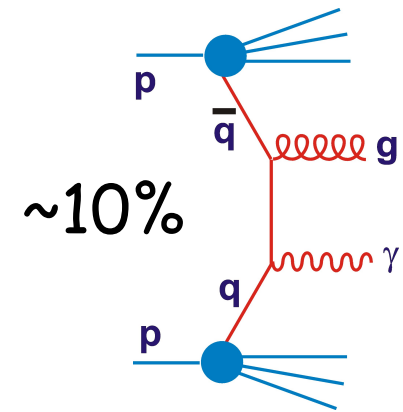
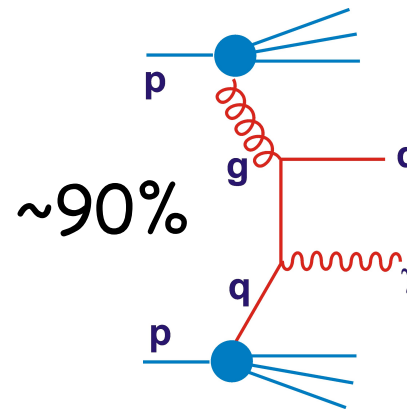


$$\rho(r) = \frac{p_T(r \rightarrow r + \Delta r)}{\Delta r p_T^{tot}}$$

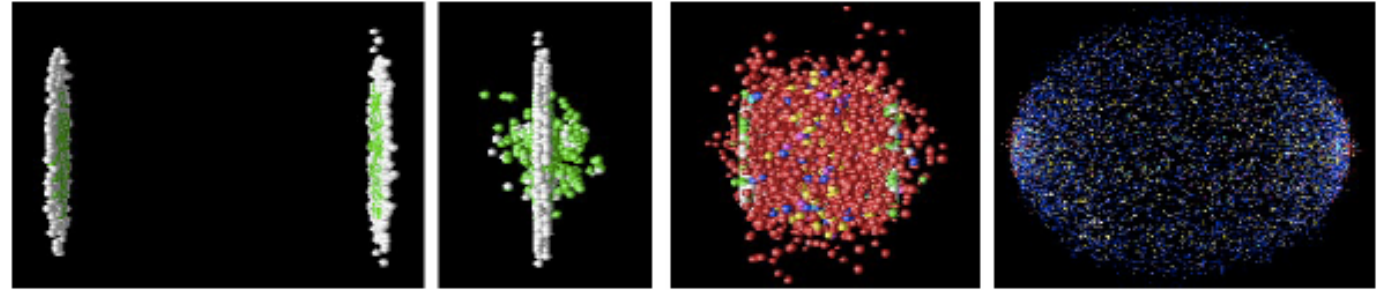


# Direct Photons

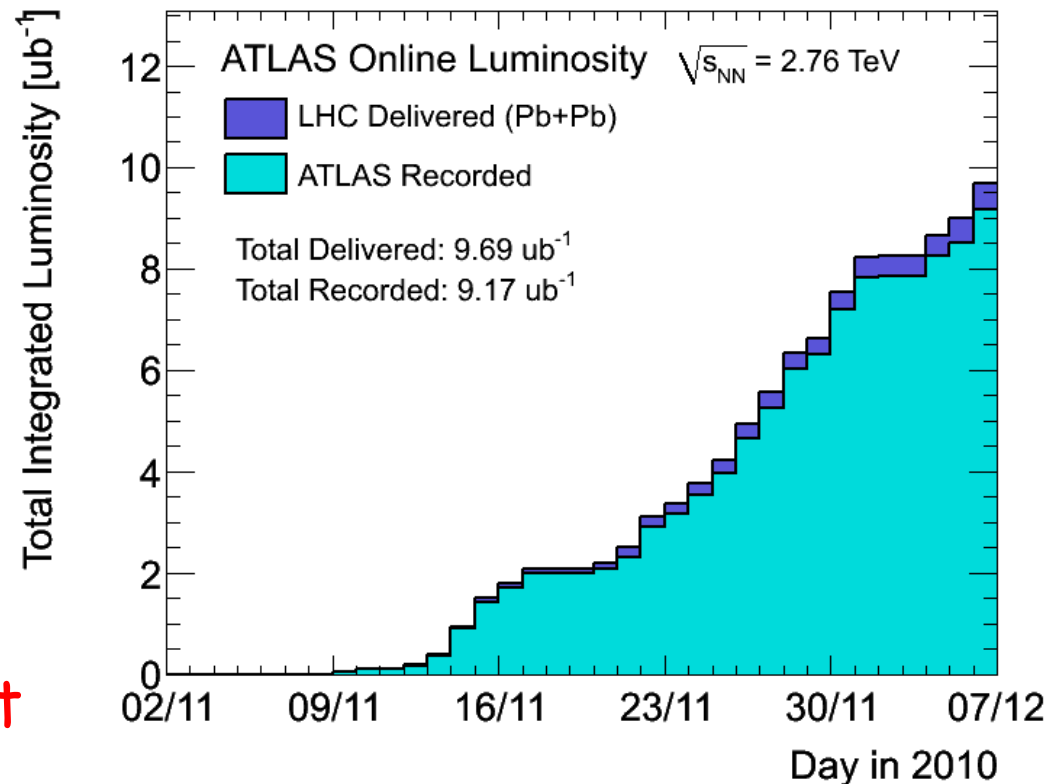
- Sensitivity to LO gluon initiated processes without need for jet reconstruction
- Complicated interface to radiative jet processes beyond LO
- Background from hadrons ( $\pi^0 \rightarrow \gamma\gamma$ ) well suppressed by isolation and shower shape requirements
- Results (so far for relatively large  $E_T$  and central rapidity) in fairly good agreement with NLO QCD calculations

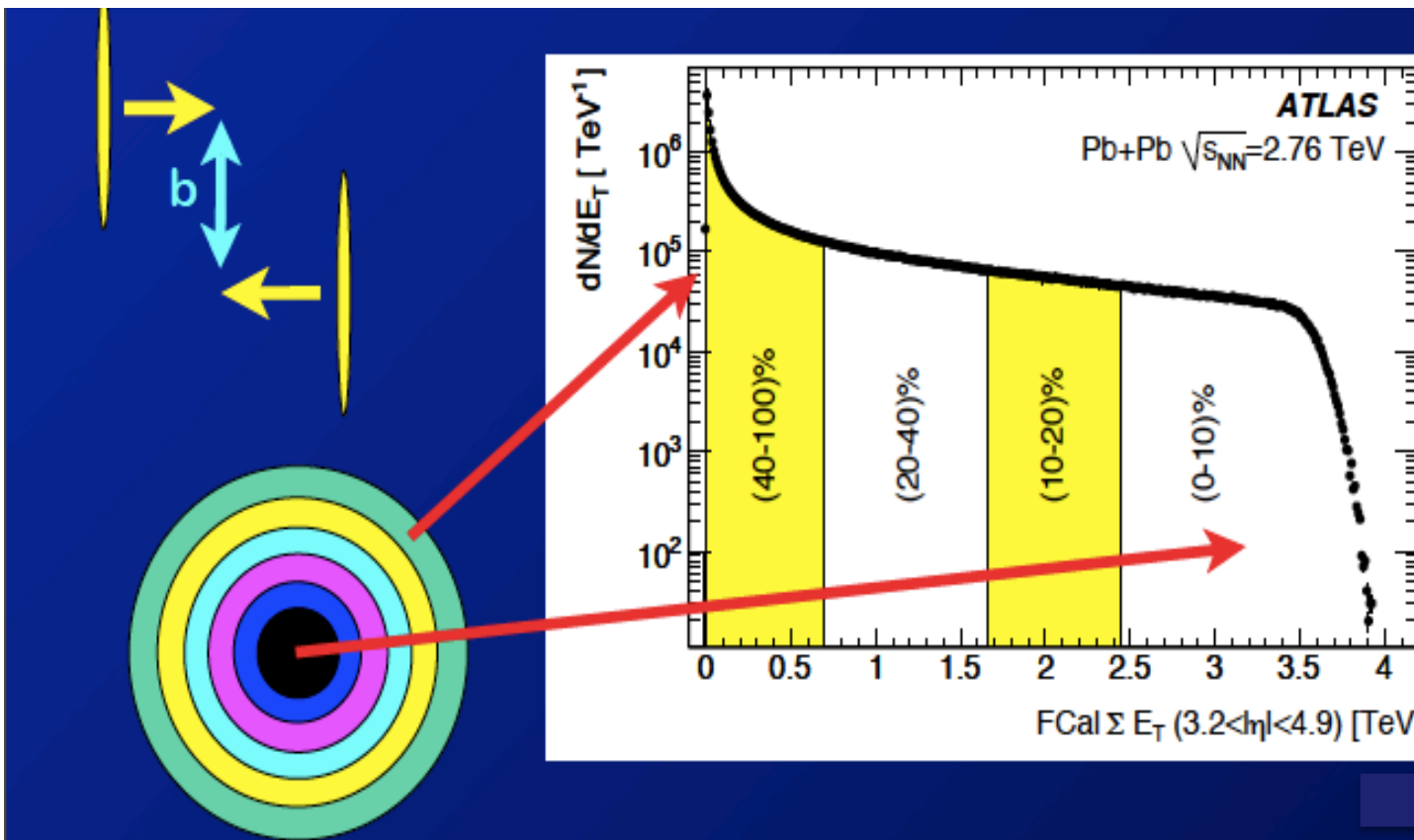


# The First LHC Heavy Ion Run



- $9 \mu\text{b}^{-1}$  of PbPb data collected at end of 2010.
- $\sqrt{s_{\text{NN}}} = 2.76 \text{ TeV}$   
[Factor  $>10$  increase over RHIC]
- Huge energy densities
- Hermetic ATLAS detector able to reconstruct full event

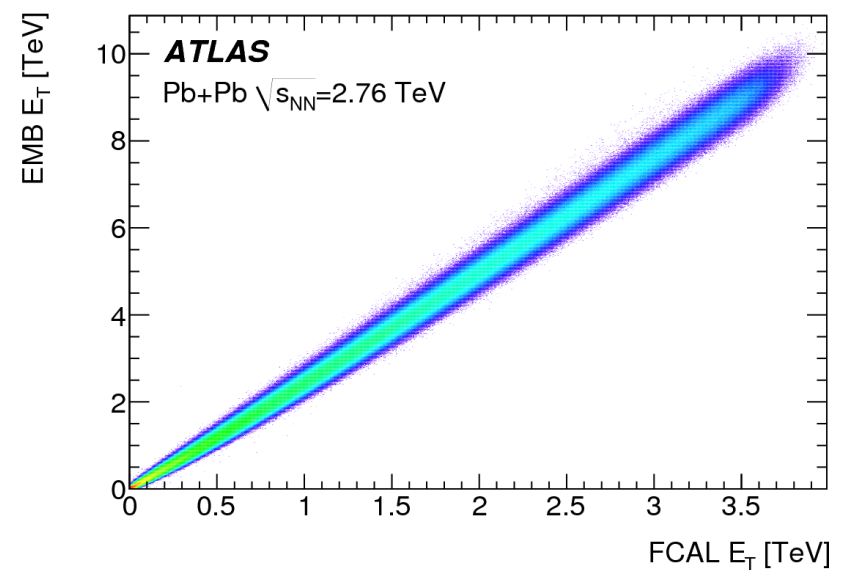




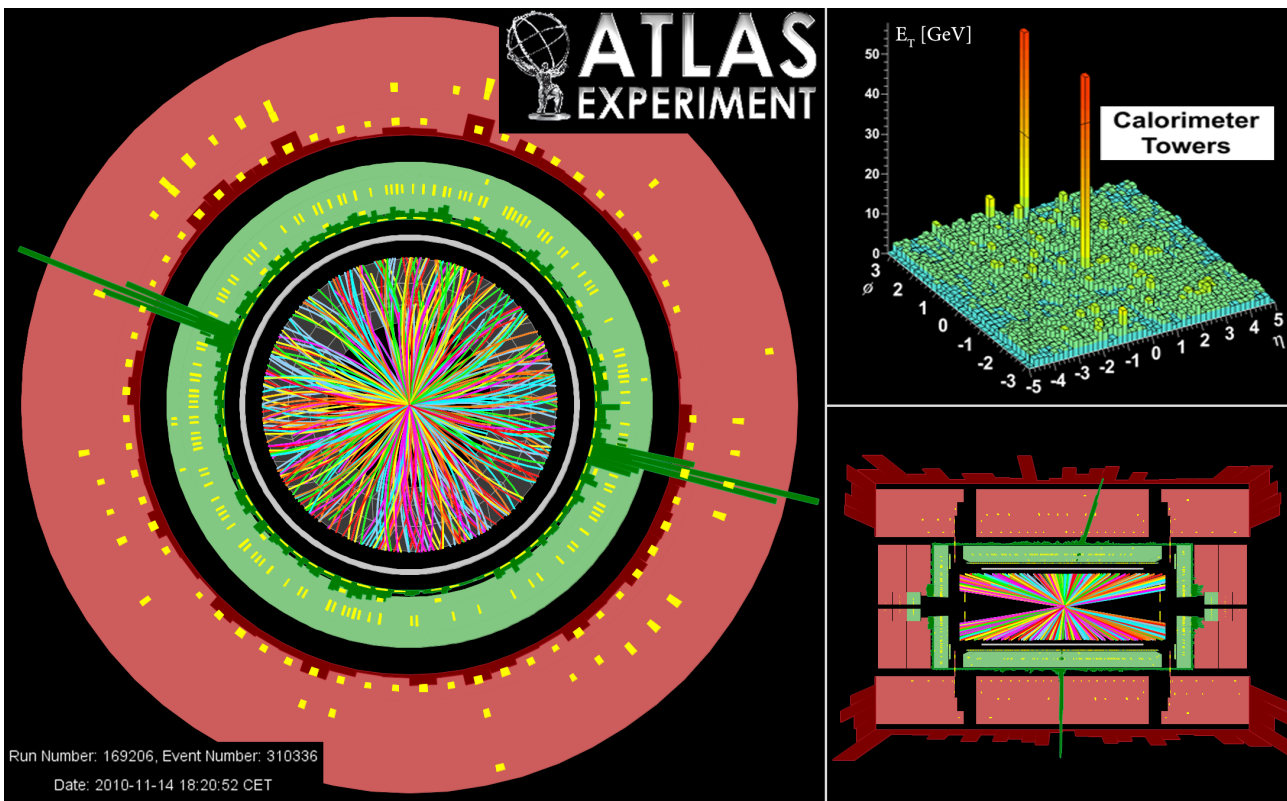
## Determining Centrality

[Min bias events triggered by MBTS, ZDC]

- Impact parameter  $b$  / centrality estimated through correlation between number of binary collisions and forward  $E_T$  (4 bins defined)
- ... also strongly correlated with  $E_T$  flow in barrel calorimeter

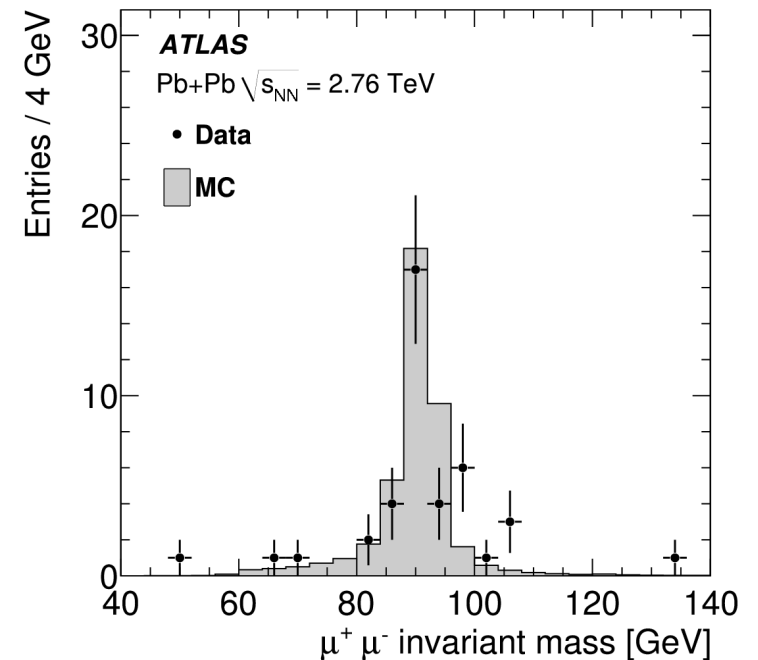






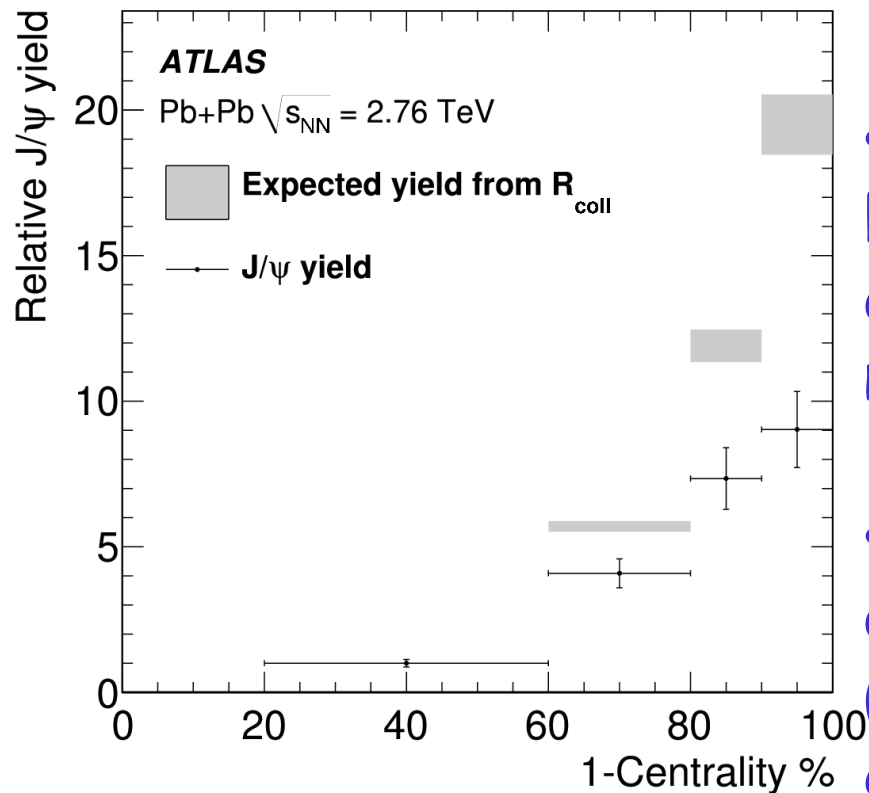
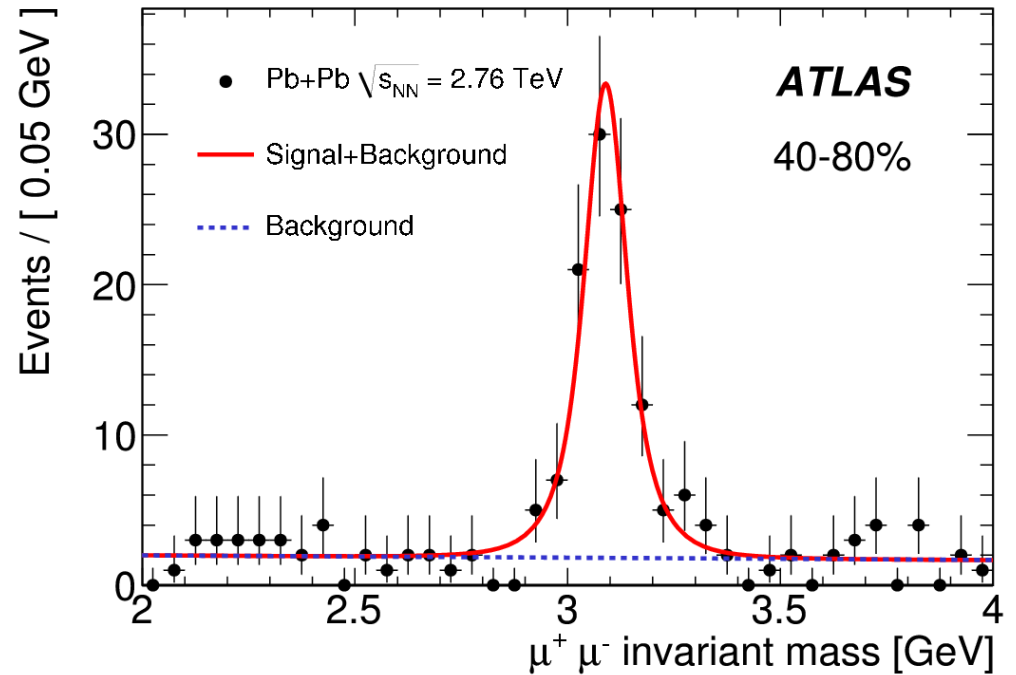
# Z Boson Dimuon and Dielectron Signals in Pb Pb

- Clear Z boson signals observed (38 events in muon channel)
- Yield compatible with linear scaling with number of binary collisions
- Current low statistics preclude strong conclusions  $\rightarrow$  2011 data 😊



# J/ψ Dimuon Signal

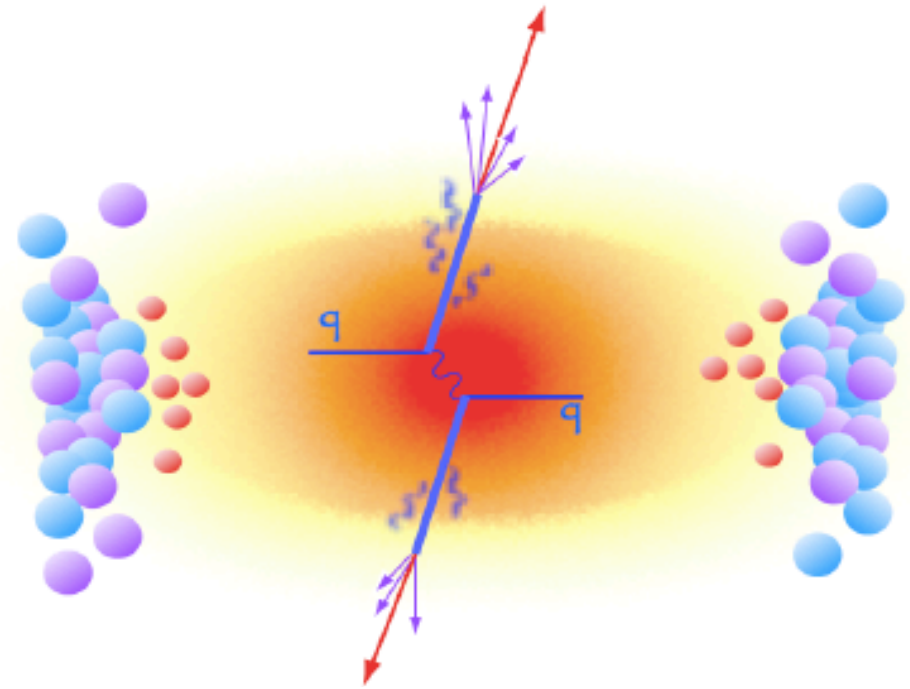
- Clear signal with sufficient statistics to investigate centrality dependence



- Normalise yield in most peripheral bin  $\rightarrow$  compare with centrality dependence assuming scaling with number of binary collisions...
- Strong evidence for centrality dependent suppression of yield (as seen at NA50, PHENIX ... & consistent with colour screening)

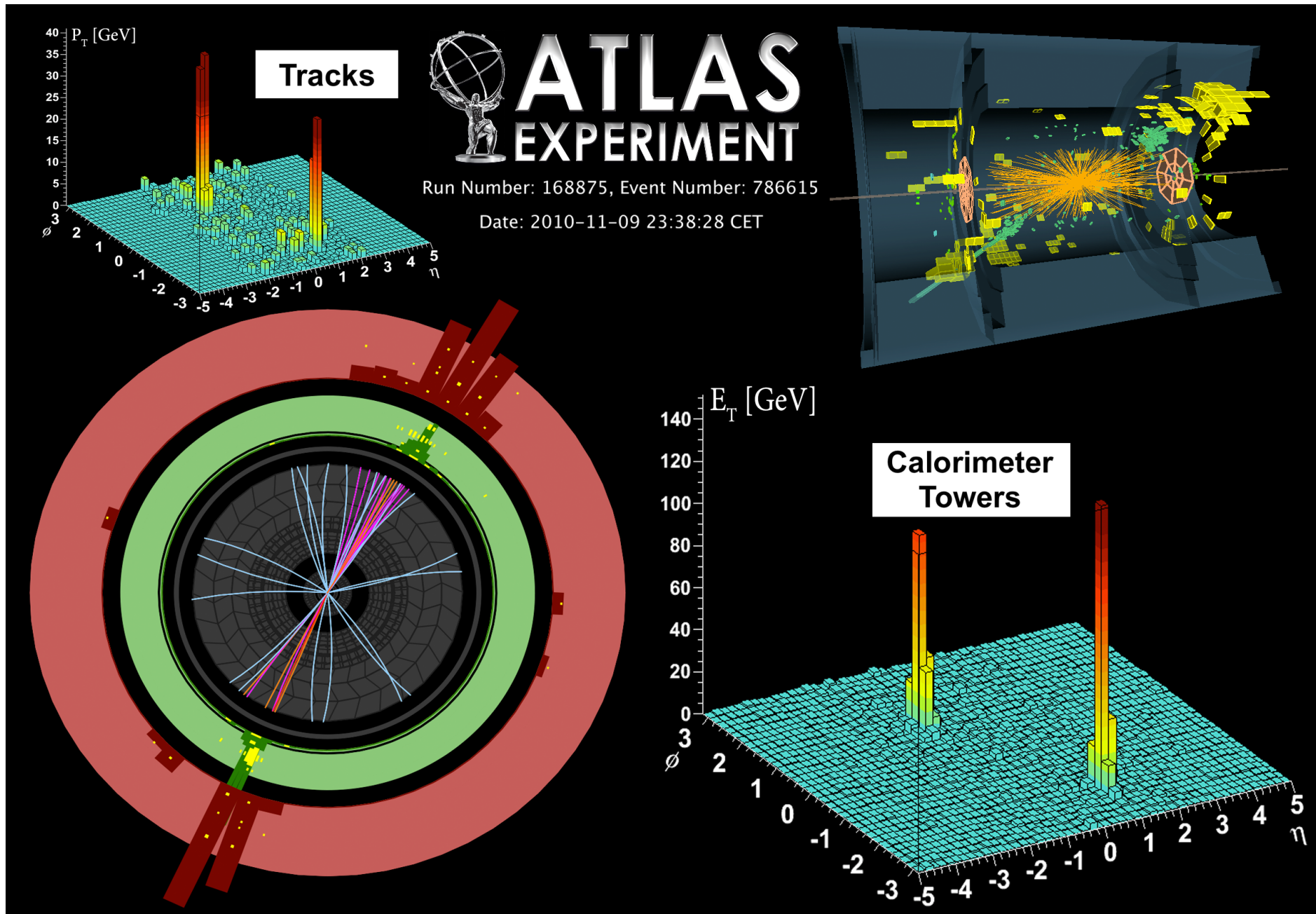
# First Look at High $E_T$ Jets from Heavy Ions

- How is behaviour of partons emerging from hard scattering influenced by presence of (hot, dense) nuclear medium?
- Previous jet quenching signal (STAR) ... search for confirmation at higher LHC energies with more complete rapidity coverage.
- Dijet imbalance quantified as  $E_T$  asymmetry between 2 leading jets with  $E_{T1} > 100 \text{ GeV}$ ,  $E_{T2} > 25 \text{ GeV}$  after <underlying event> subtractions
- Proper normalisation to pp at same  $\sqrt{s_{NN}}$  is in 2011 programme



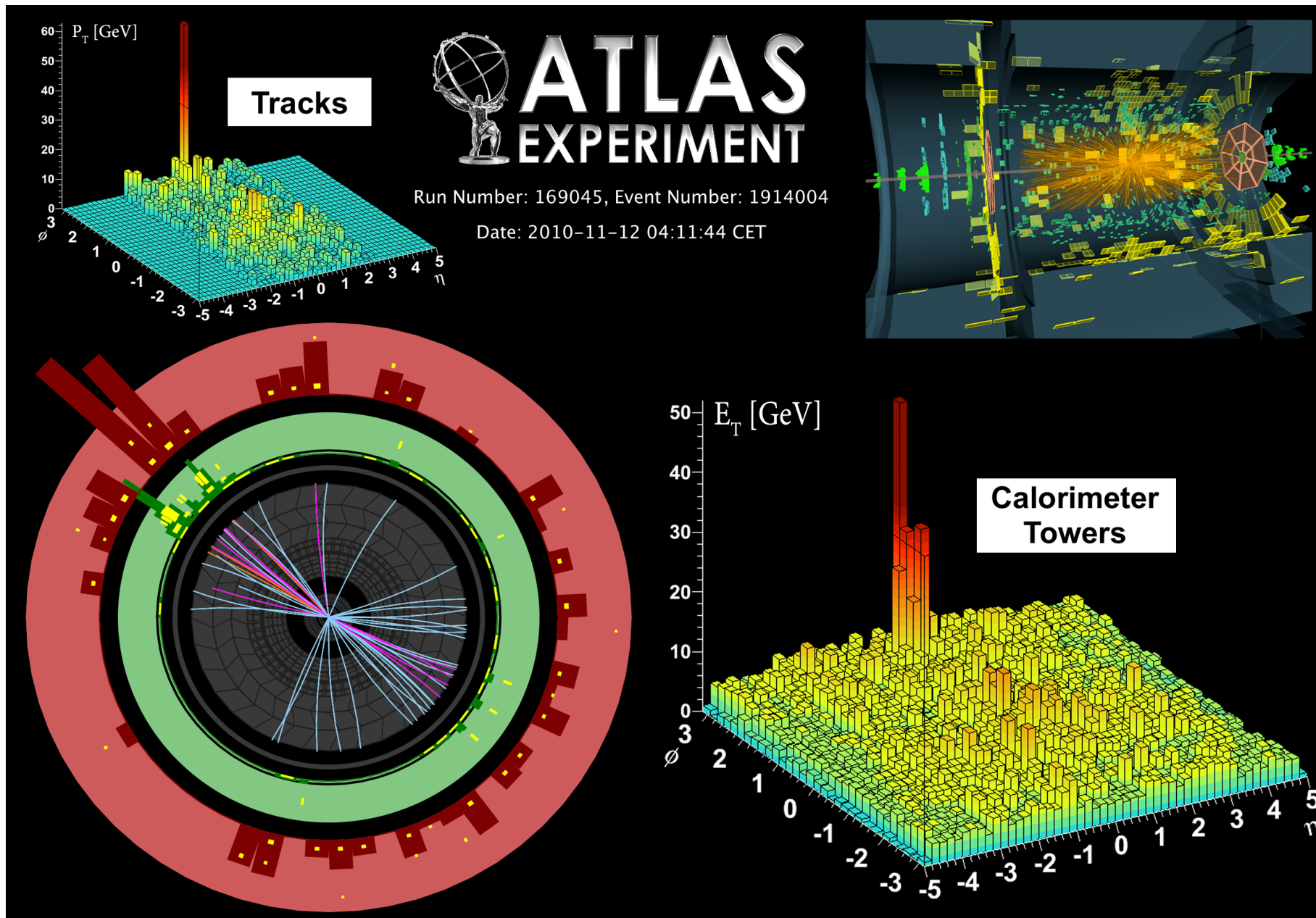
$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

# A peripheral Pb-Pb event with jets



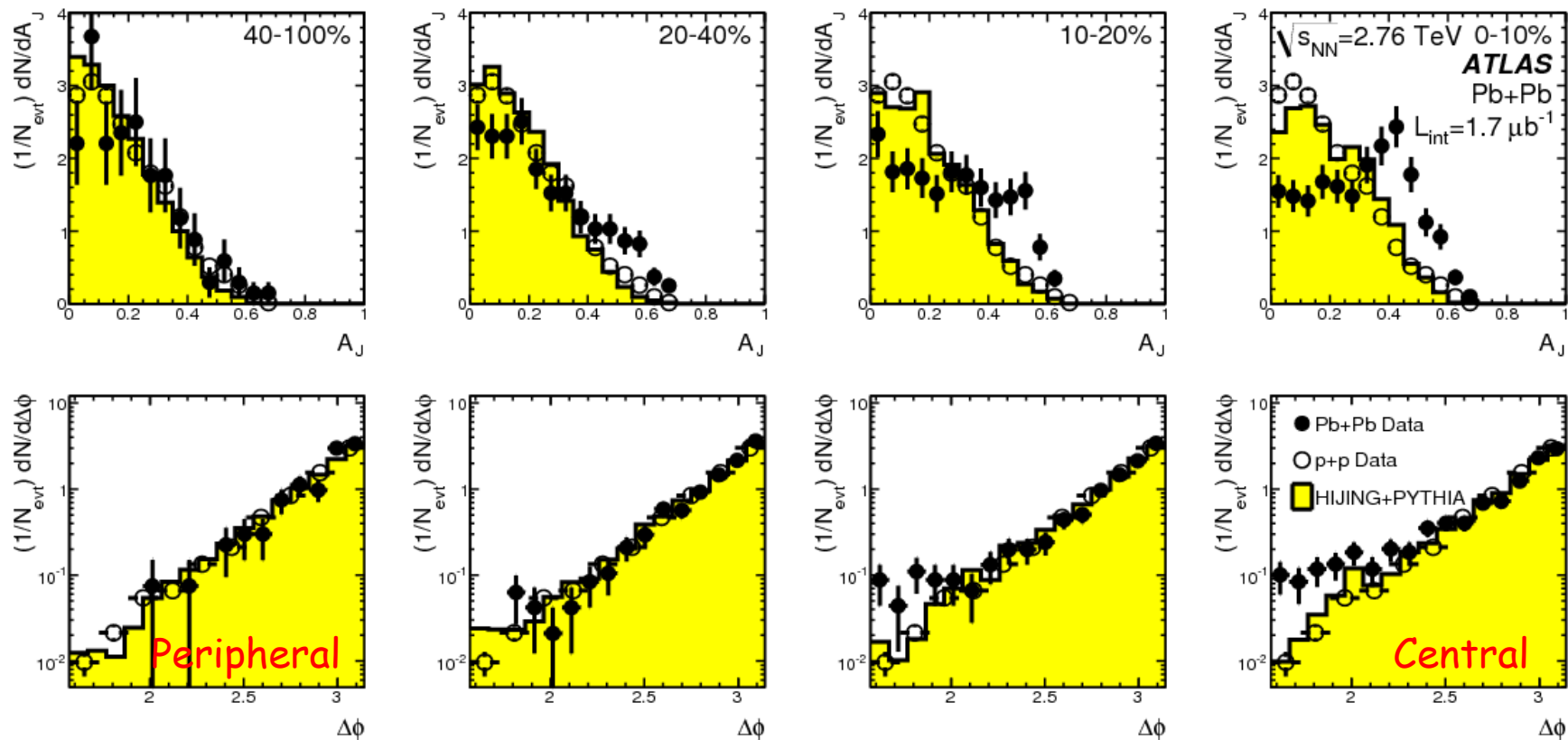


# A central Pb-Pb event with jet(s)



# Centrality Dependence of Asymmetries

- Pb Pb ( $1.7 \mu\text{b}^{-1}$ ) v 7 TeV pp data & MC (with no quenching)
- With increasing centrality:
  - More PbPb events with large asymmetry
  - Poorly described by MC and differs from pp
  - $\Delta\phi$  still peaked at  $180^\circ$
- Good evidence for jet energy loss in nuclear medium



# Summary

- Highly successful 2010 LHC run for ATLAS is yielding lots of results on strong interaction physics in pp and PbPb  
[lots more at <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>]
- 2011 run due to start in Spring ... ~ 100 times more lumi!

