Electroweak Boson Production in Pb+Pb

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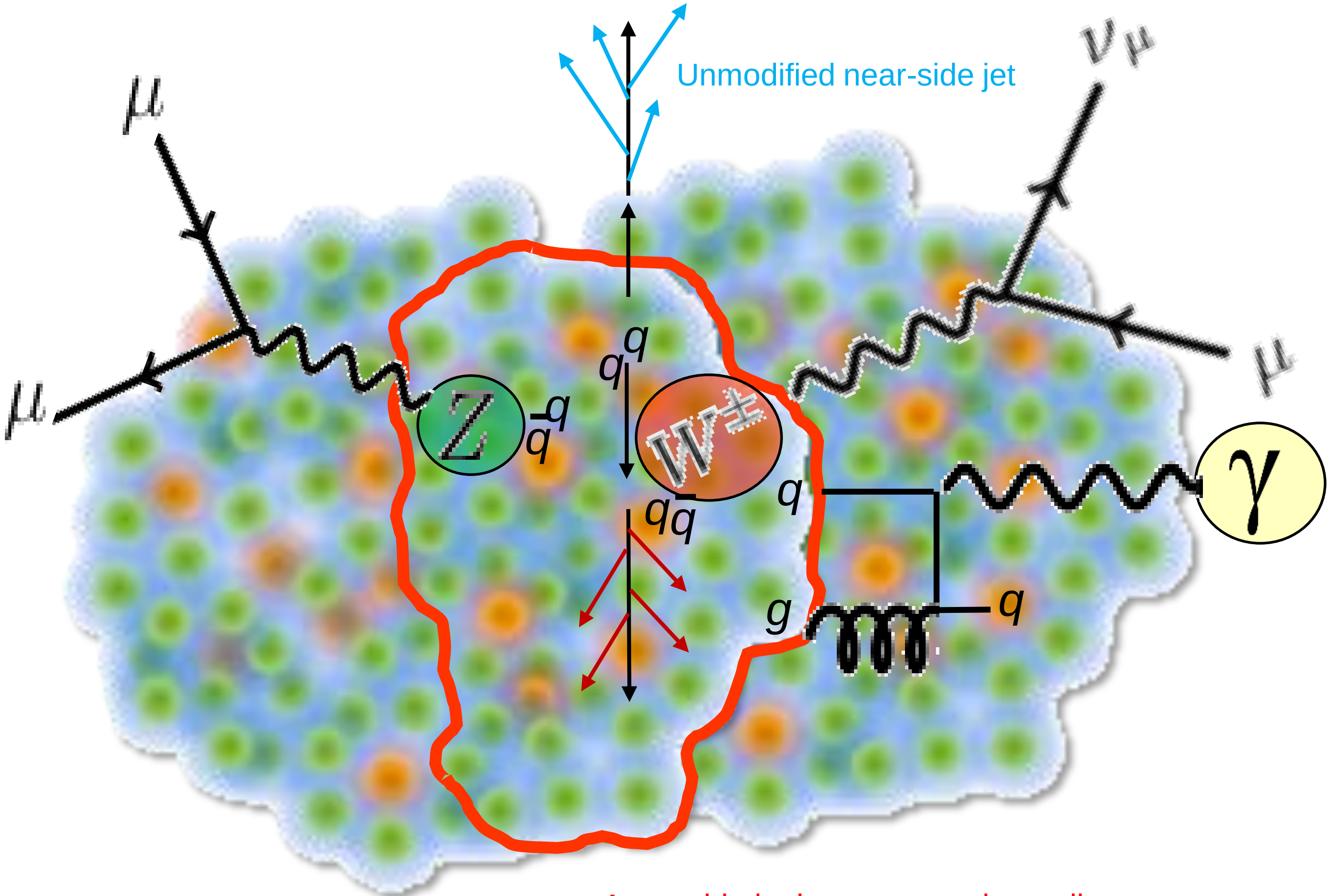
Electroweak Bosons in HI: Standard Candles

Electroweak bosons (photons, W/Z) may be used as benchmarks for in-medium effects ("jet-quenching")

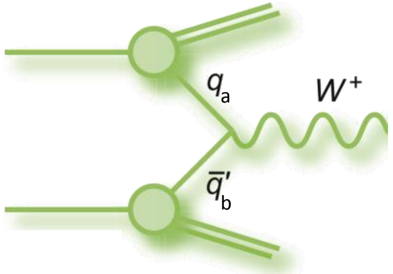
Can also be used to check understanding of collision geometry (i.e. Glauber)

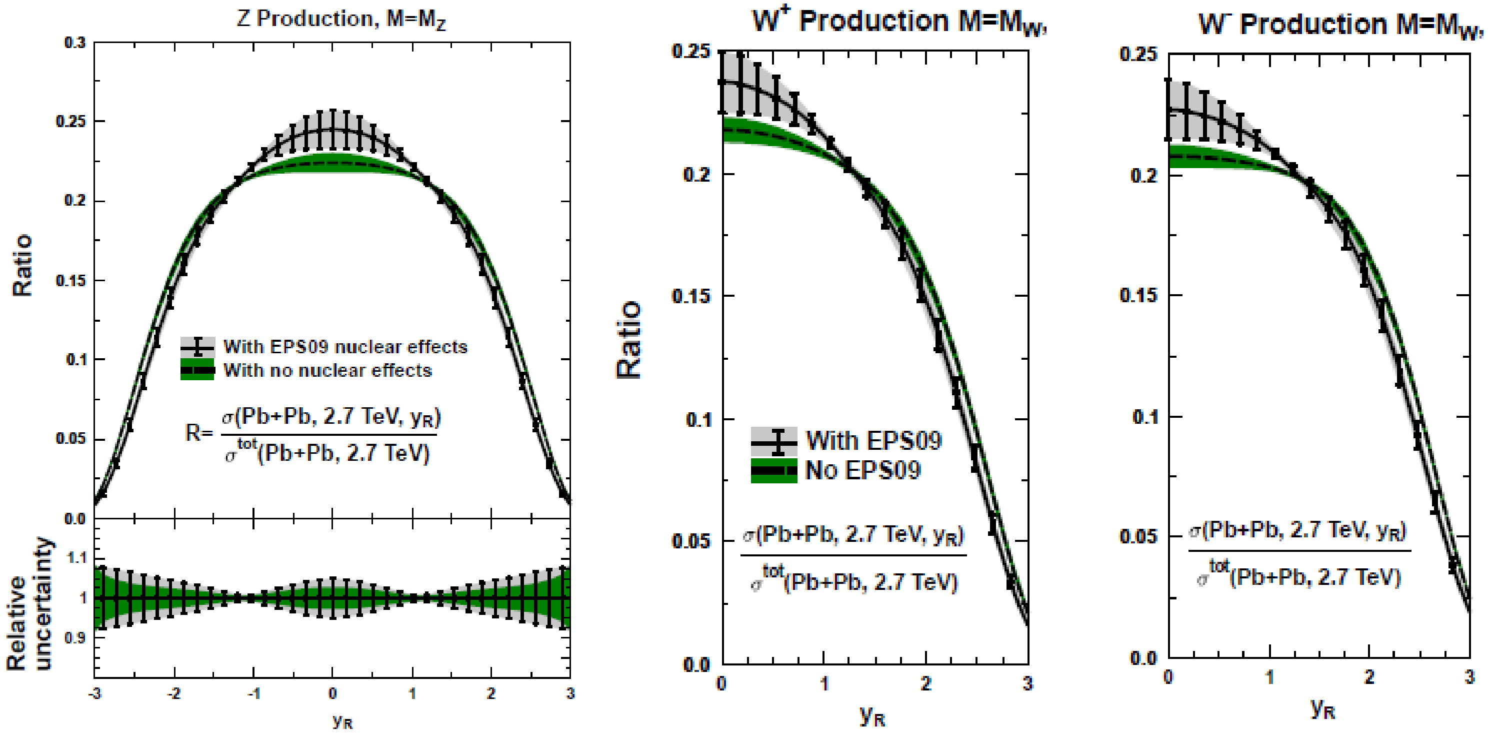


Electroweak Bosons in HI: Nuclear PDFs

Nuclear effects: difference between cross-sections in collisions involving heavy ion and those involving free nucleons (EPS09)

$$x_a = \frac{m_W}{\sqrt{s}} \exp(y_W), \quad x_b = \frac{m_W}{\sqrt{s}} \exp(-y_W).$$

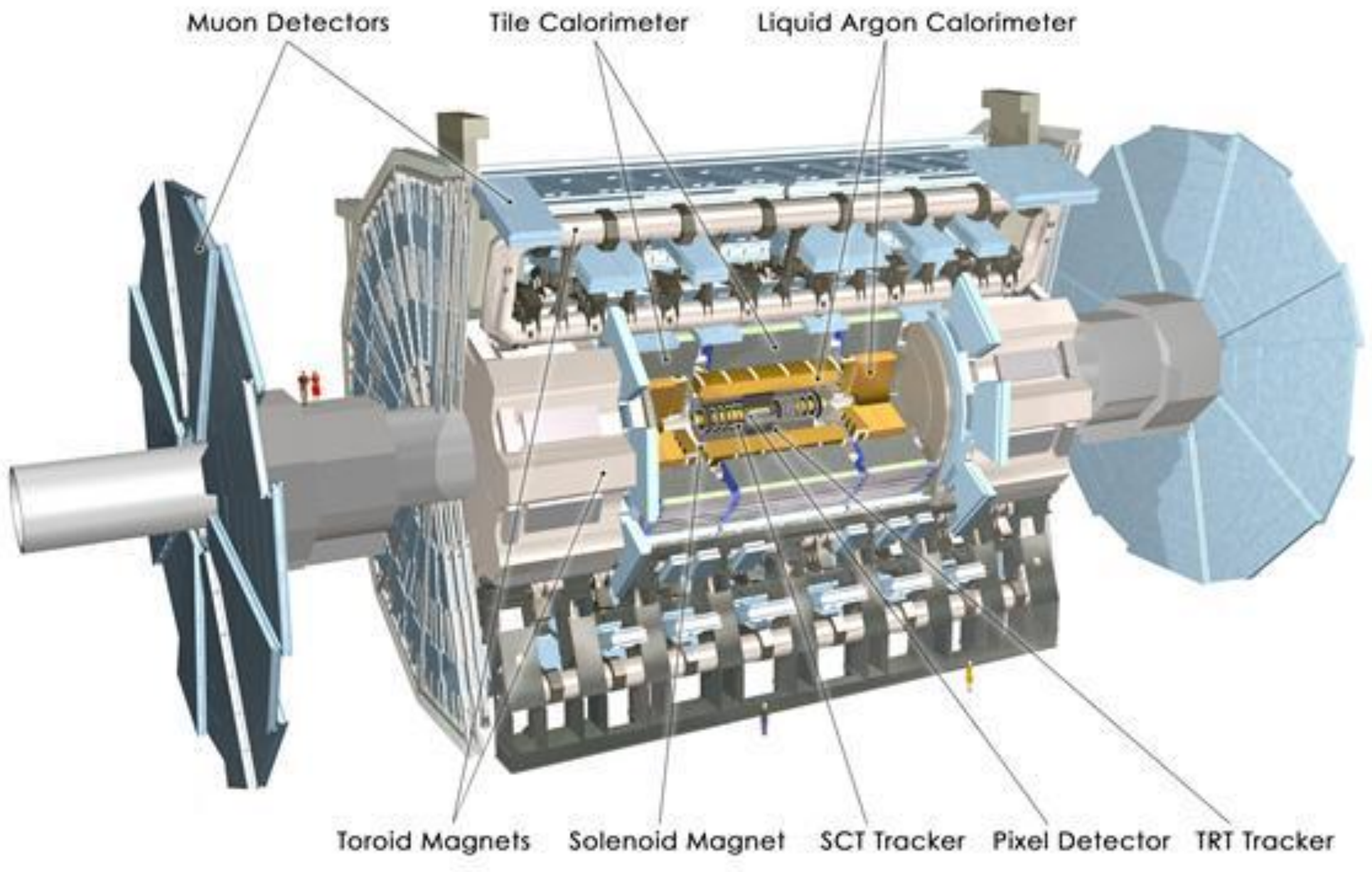




- EW probes are sensitive to nuclear effects:
  - Fermi motion
  - EMC-effect
  - Anti-shadowing
  - Shadowing

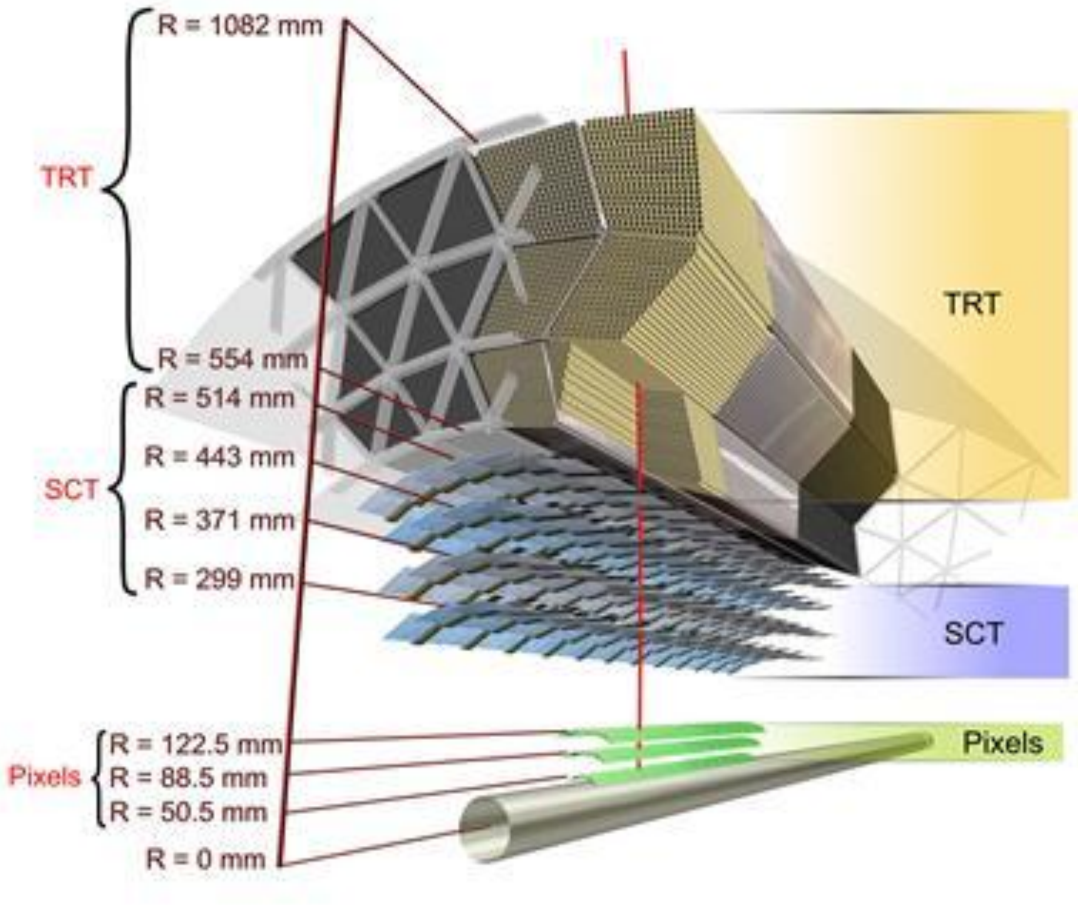
arXiv:1010.5392v2

The ATLAS Detector



- Comprised of 3 sub-systems
  - Inner Detector
  - Calorimeter
  - Muon Spectrometer

The ATLAS Detector: Inner Detector



Tracking

- Precision tracking and vertexing
- Coverage: $|\eta| < 2.5$
- B(solenoid) = 2T
- Pixel Detector
  - Three layers of silicon pixel detectors
- Semi-Conductor Tracker (SCT)
  - Silicon strip detectors in back-to-back wafers
  - Four layers in barrel, nine layers in end-caps
- Transition Radiation Tracker (TRT)
  - 4mm diameter straw drift tubes

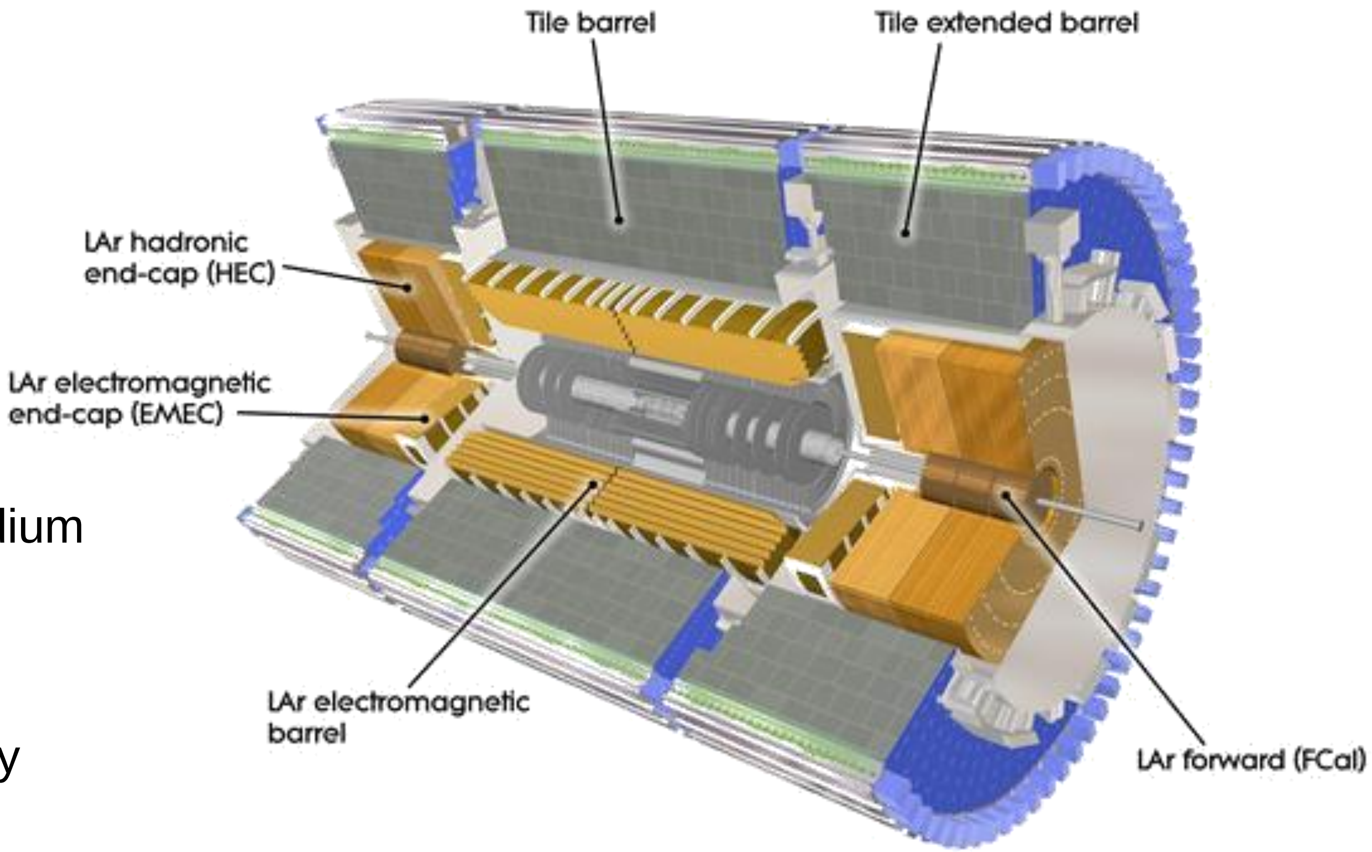
The ATLAS Detector: Calorimeters

EM Calorimeter

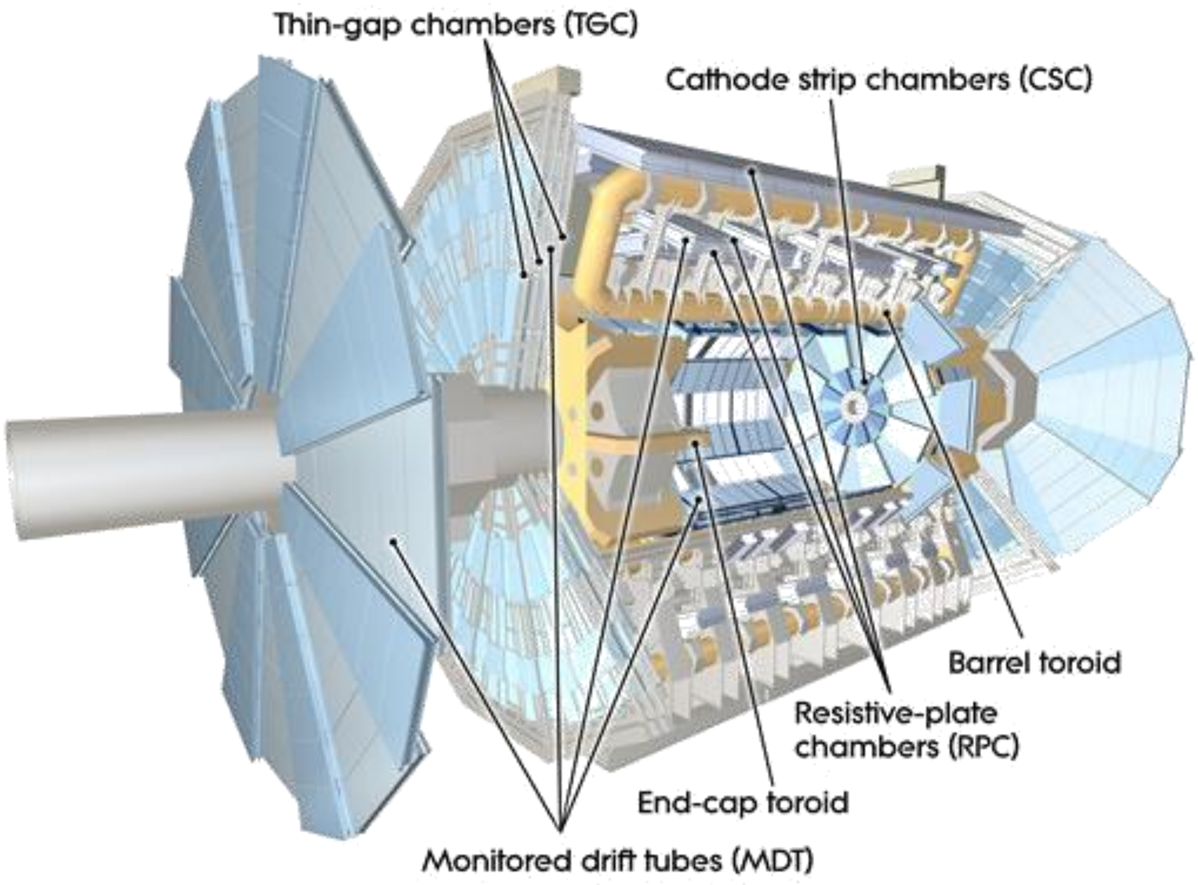
- Pb/LAr detectors
- Three active layers |η|< 2.5
- Two active layers 2.5 < |η|< 4.9
- Pre-samplers at 0 < |η|< 1.8
- e/γ identification and triggering

Hadronic Calorimeter

- Scintillator tiles and steel as absorber medium
- Tile calorimeter 0 < |η|< 1.7
- Cu/LAr HEC 1.5 < |η|< 3.2
- Cu/W-LAr FCal 3.2 < |η|< 4.9
- Hadron, jet, and missing transverse energy identification



The ATLAS Detector: Muon Spectrometer

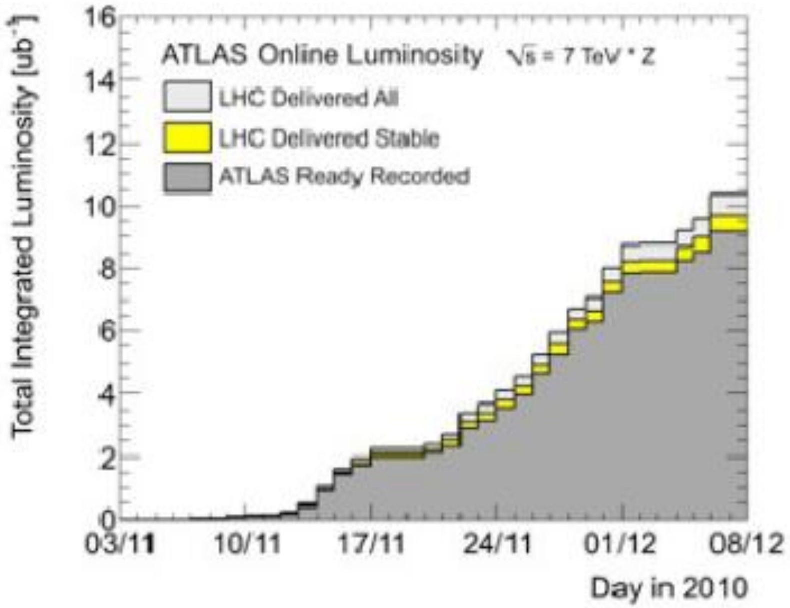


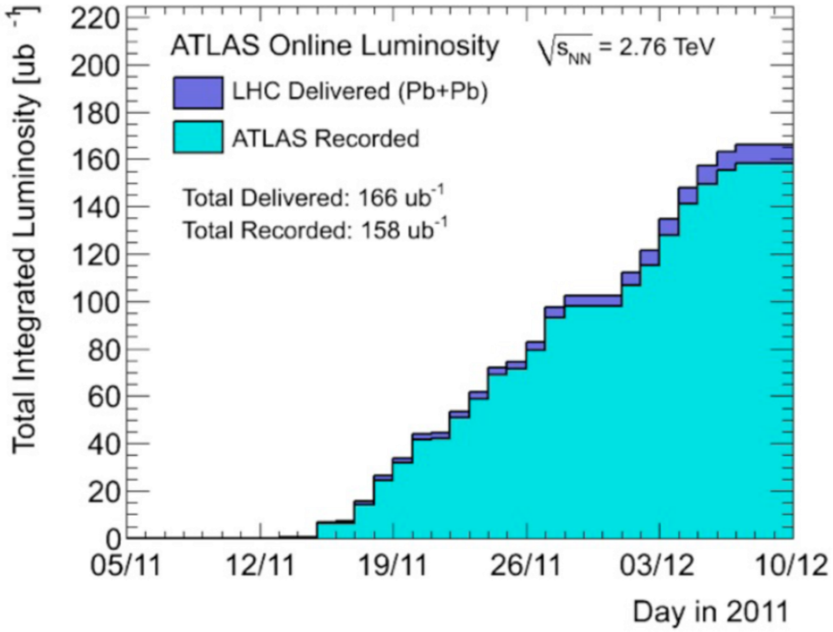
Muon Spectrometer

- Muon coverage up to $|\eta|< 2.7$
- Air-core toroid B-field on average 0.5 T
- Monitored Drift Tubes (MDT) and Cathode Strip Chambers (CSC) measure position in bending plane
- Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) provide muon triggering up to $|\eta|< 2.4$ and position in the non-bending plane

Heavy Ions in ATLAS

Pb+Pb runs at $\sqrt{s_{NN}}$ = 2.76 TeV in Nov-Dec 2010 (8 μb^{-1}) and Nov-Dec 2011 (0.158 nb^{-1})





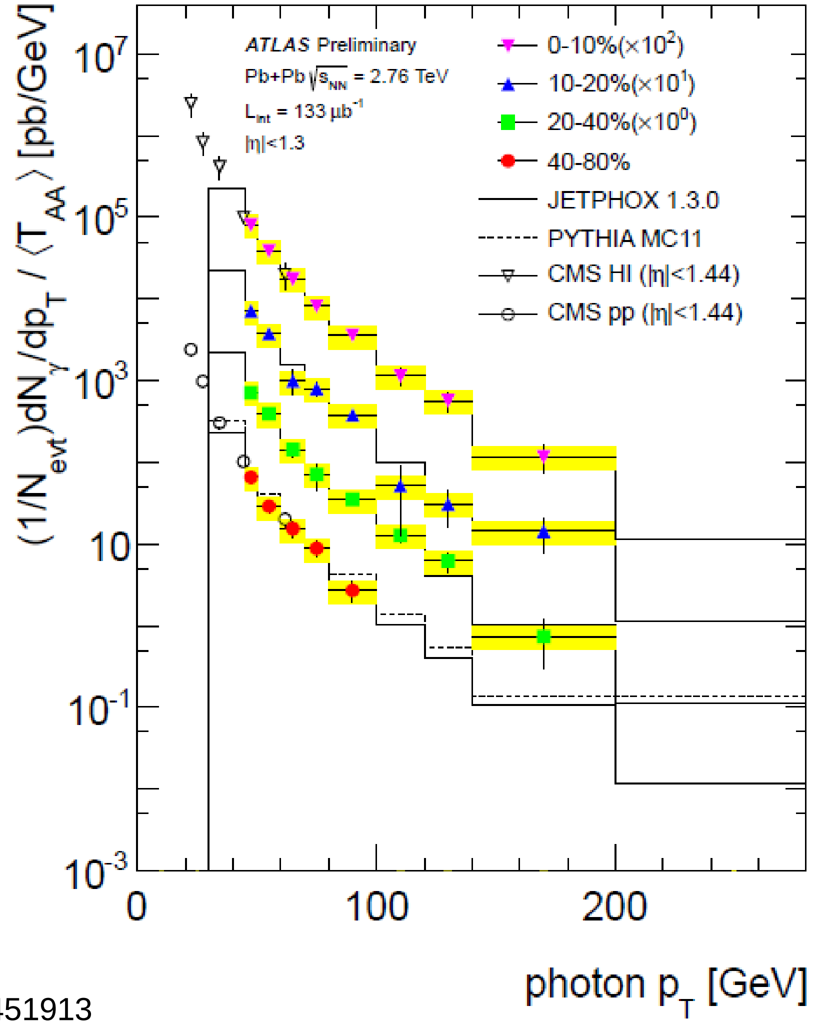
Data-taking efficiency > 95%

Run	2010	2011
L_{int} Recorded	8 μb^{-1}	158 μb^{-1}
Triggers	Min Bias	γ,e,μ,jets,UPC, Min Bias
N_{events} Sampled	43.6 million	1.03 billion

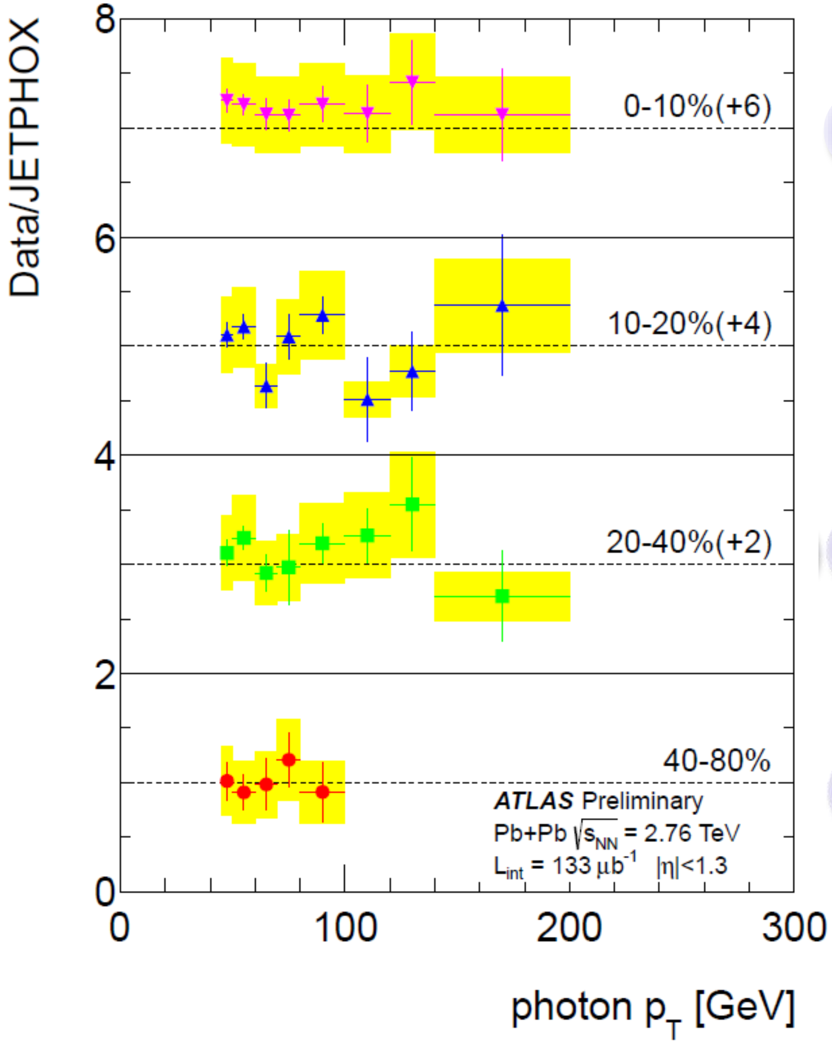
Direct Photon Spectra

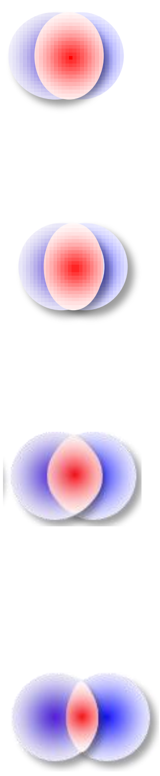
Direct Pb+Pb photon cross-section as function of p_T

Good agreement with model (JETPHOX) and CMS result in HI and pp



Agreement in Pb+Pb and pp cross-section from JETPHOX (R_{AA} equivalent)

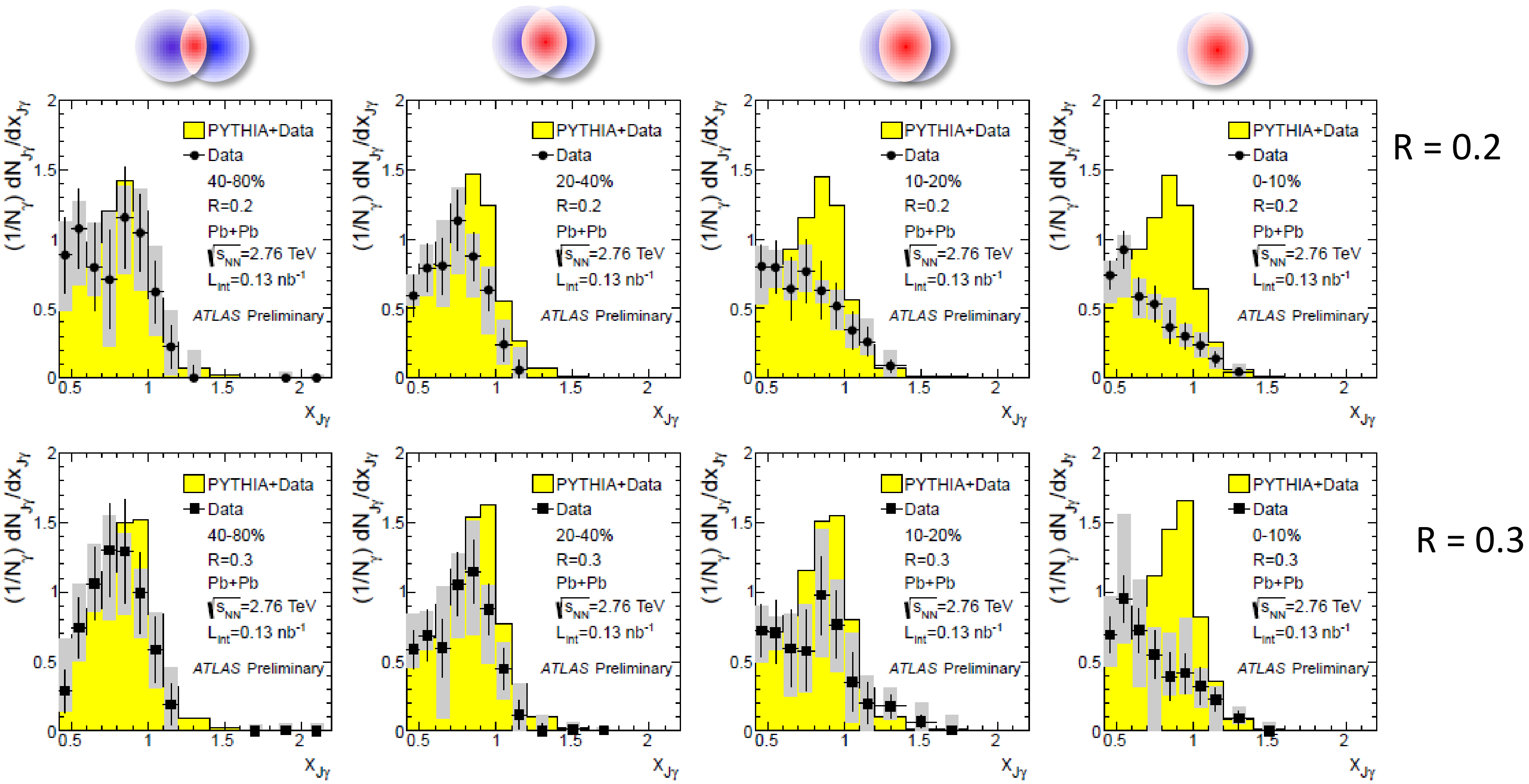




https://cds.cern.ch/record/1451913

Photon+jet

$$x_{j\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$



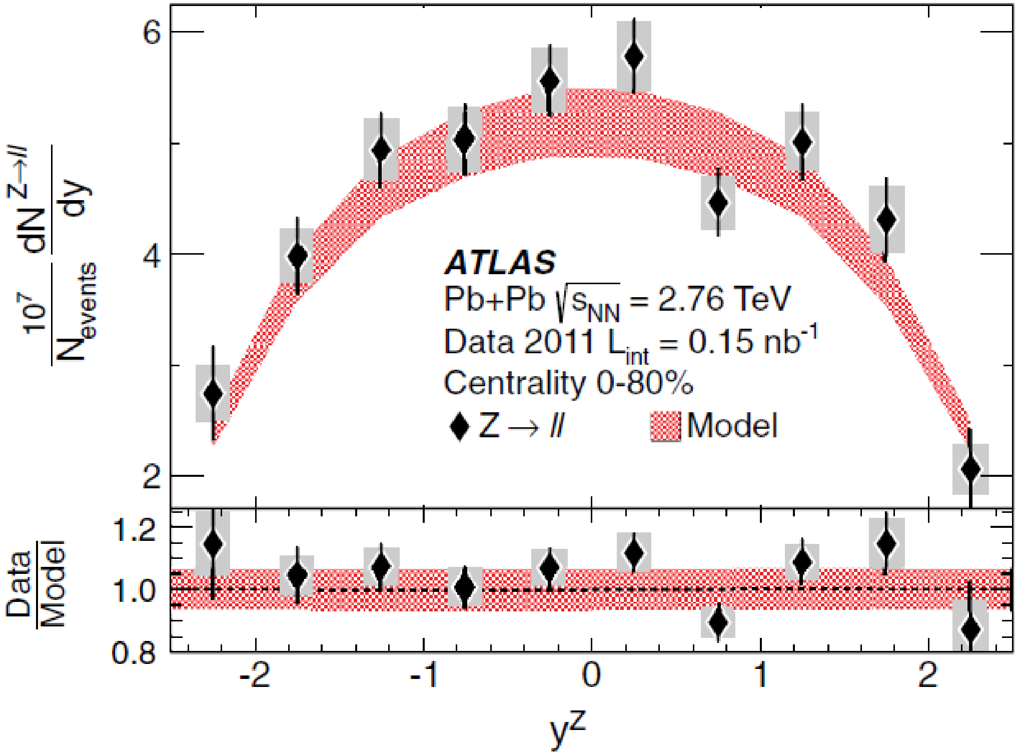
Photon-jet yield (normalized per photon) as a function of momentum fraction

Agreement with PYTHIA prediction decreases when moving to more central collisions, indicative of large jet energy-loss relative to photons

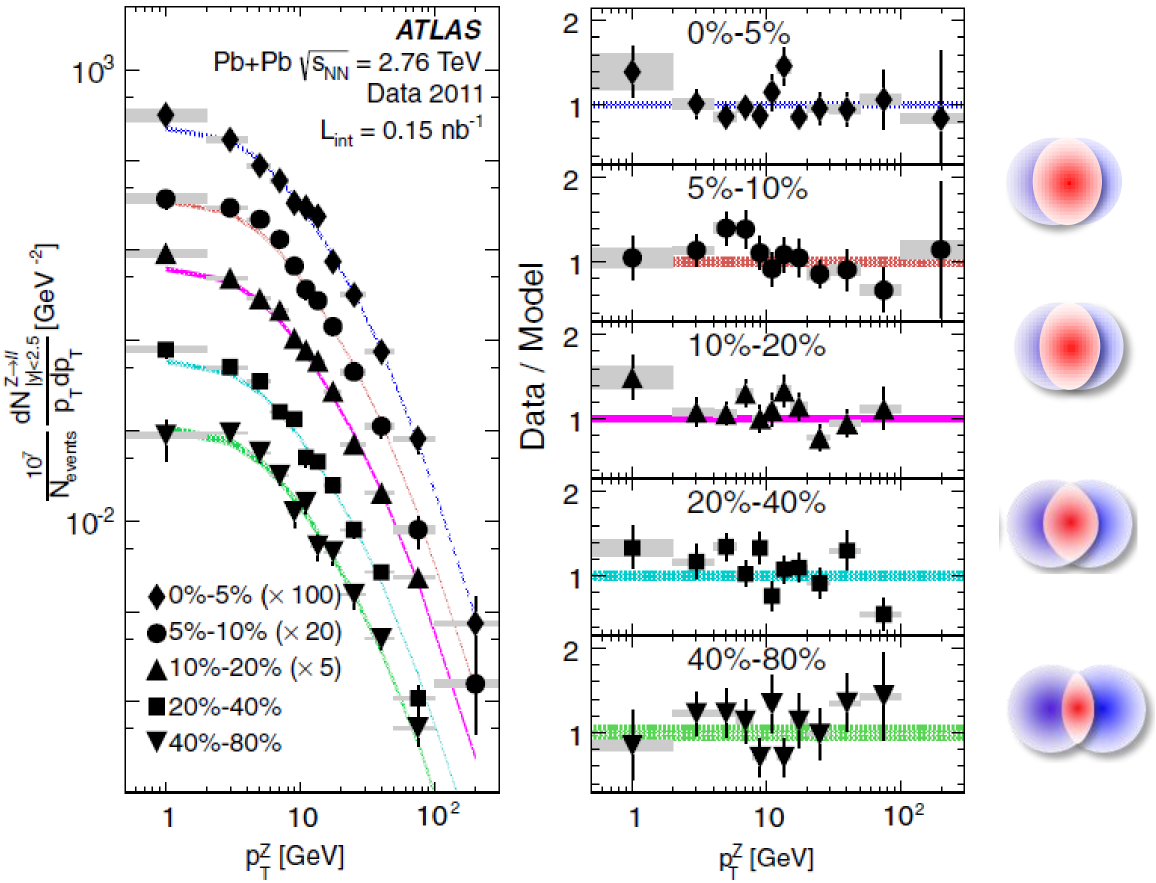
https://cds.cern.ch/record/1451913

Z→ll Corrected Yields

Phys. Rev. Lett 110, 022301 (2013)



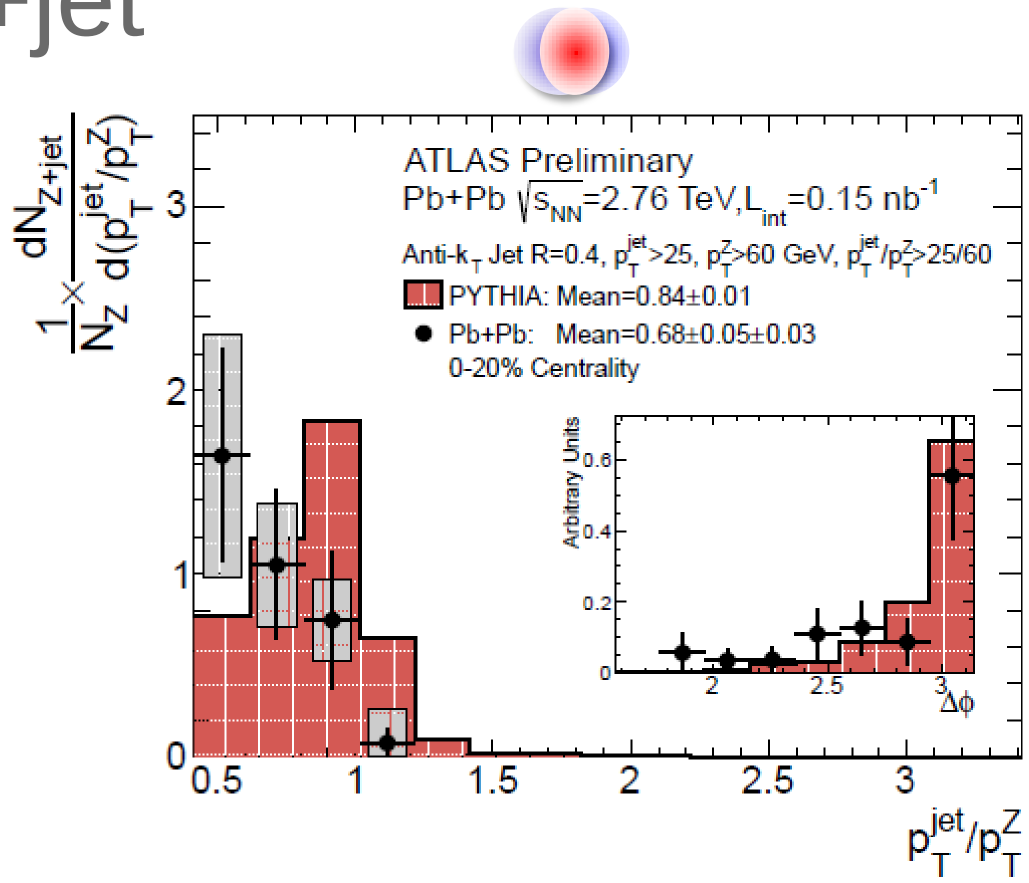
Corrected Z boson rapidity distribution

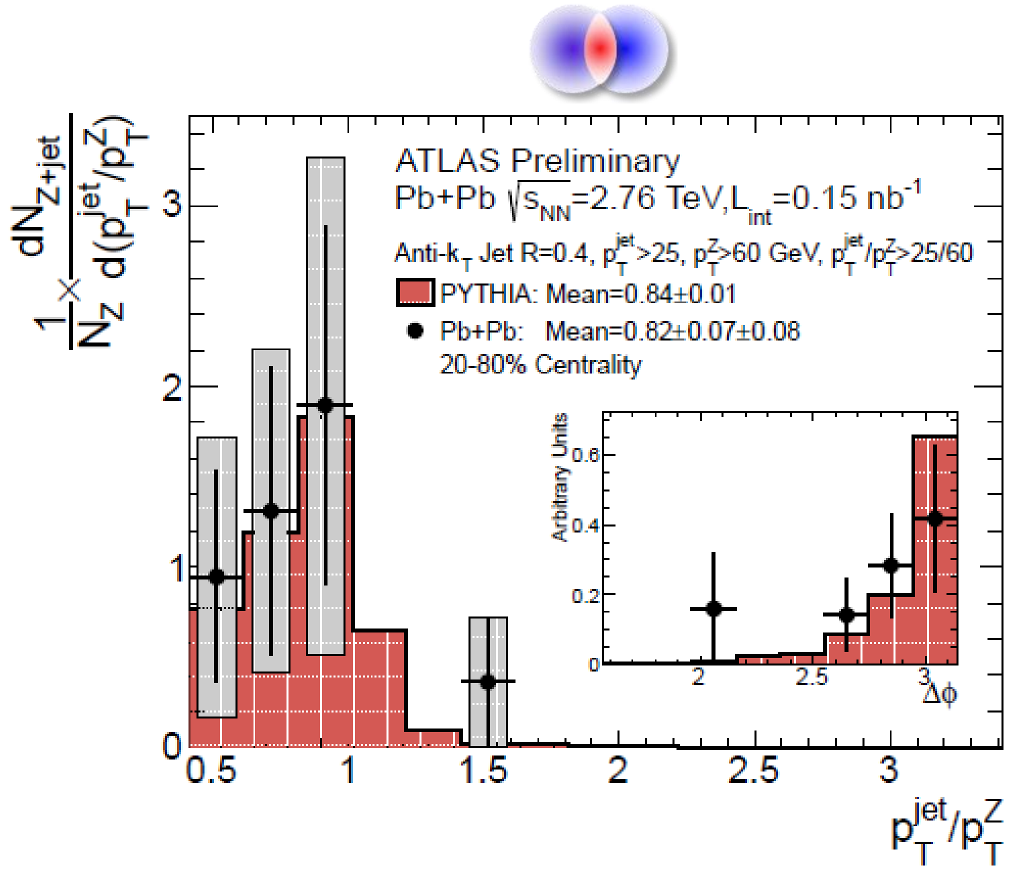


Corrected Z boson p_T distribution in five centrality classes

Agreement with NNLO PYTHIA prediction scaled to the Z→ll cross-section and

Z+jet





Number of Z+jet events (fully unfolded and normalized per Z boson) as function of momentum fraction

Jets and Z bosons produced back-to-back in azimuth

Agreement with the PYTHIA prediction decreases when moving to more central events, however low statistical precision

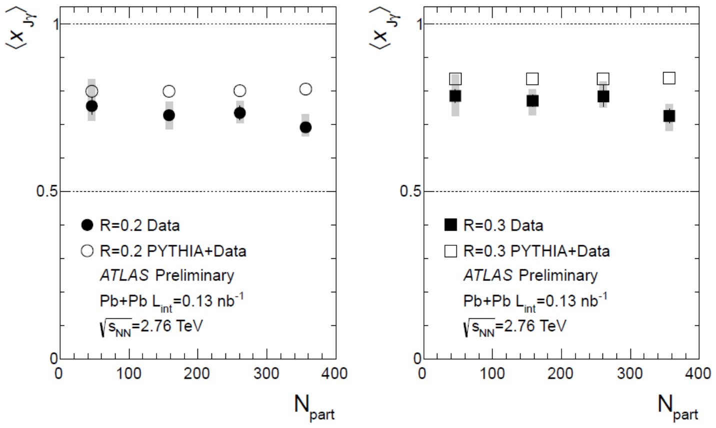
https://cdsweb.cern.ch/record/1472941

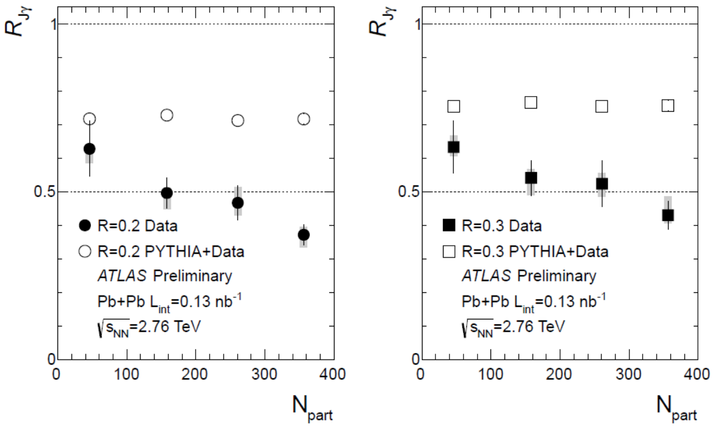
Boson+jet

Momentum fraction

Production ratios

photons

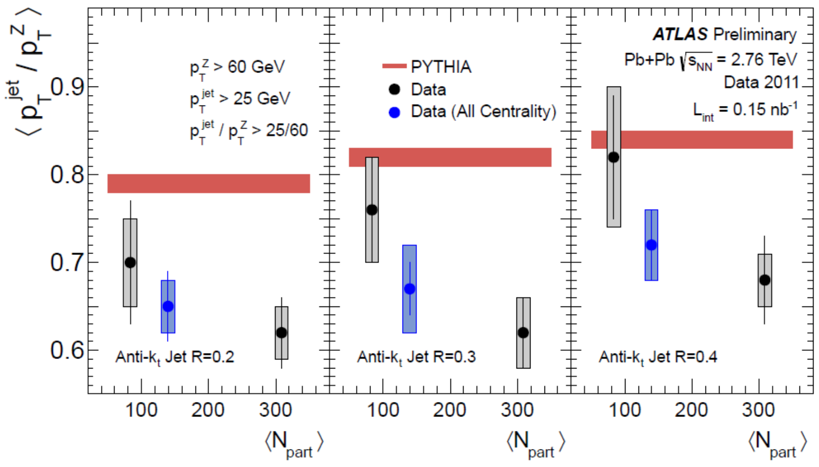


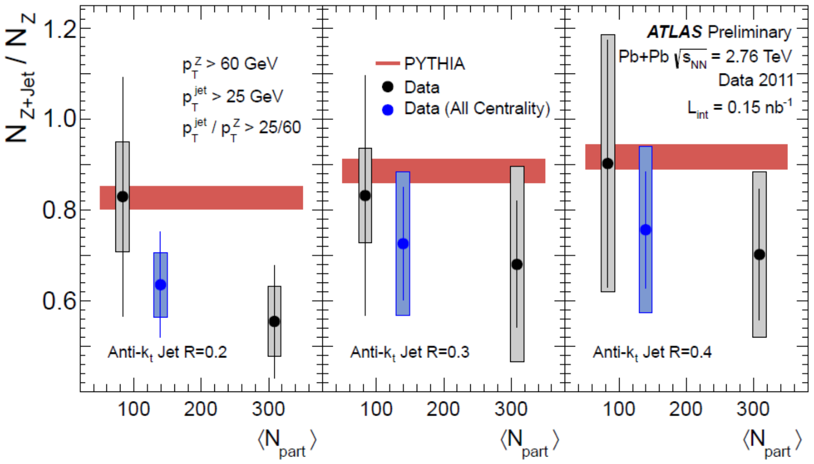


Jet-quenching increases with respect to EW bosons in more central events

Boson-jet production decreases relative to EW bosons in more central events

Z bosons





https://cdsweb.cern.ch/record/1472941 https://cds.cern.ch/record/1451913

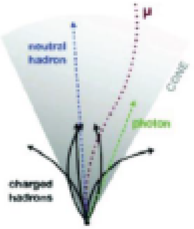
$W^{\pm}$ Bosons in Pb+Pb

ATLAS-CONF-2013-106

- Measured via W→μν channel
  - ID-MS combined muons
- Fiducial region:

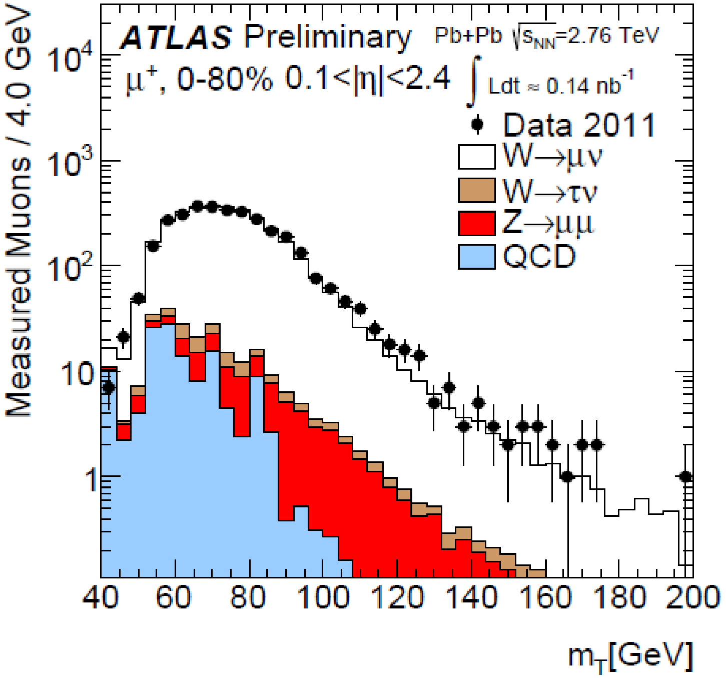
$$p_T^{\mu} > 25 \text{ GeV}, \quad 0.1 < |\eta_\mu| < 2.4,$$
$$p_T^{\nu} > 25 \text{ GeV}, \quad m_T > 40 \text{ GeV}.$$

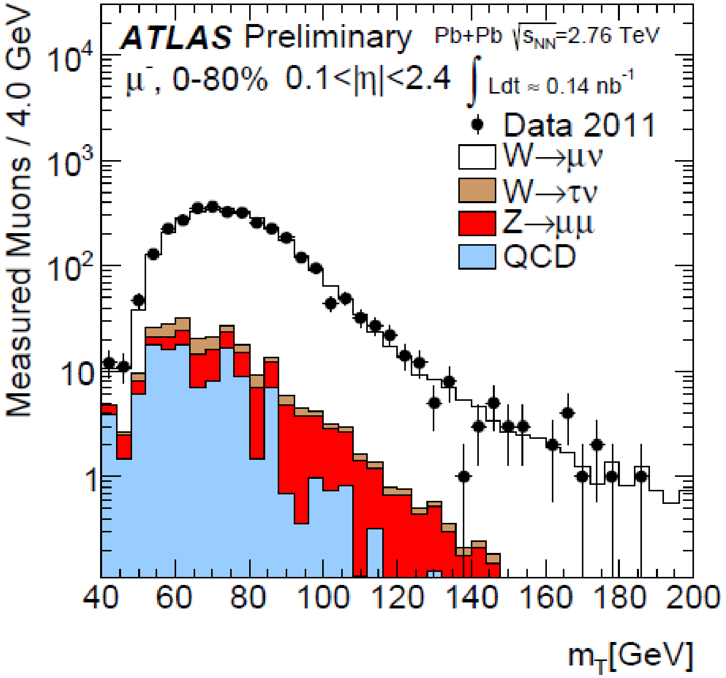
- Muon isolation
  - $\Sigma p_T^{ID}/p_T^{\mu} < 0.1$ in $\Delta R < 0.2$
  - Reduces jet contamination



- Reject muon from Z bosons
  - Reject opposite-sign muons pairs with invariant mass combinations > 66 GeV
- Cannot directly detect neutrino
  - Use track-based p_T^{miss} variable as a proxy

$$\mathbf{p}^{\text{miss}} = \sum_{i=1}^{ntrks} \mathbf{p}_i^{\text{miss}} = -(\mathbf{p}_1 + \mathbf{p}_2 + \ldots \mathbf{p}_{ntrks})$$

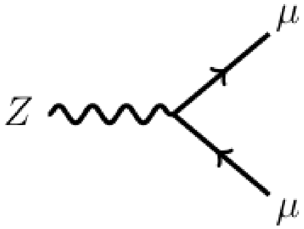


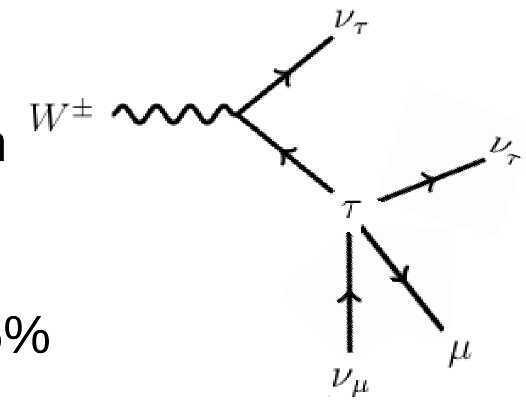


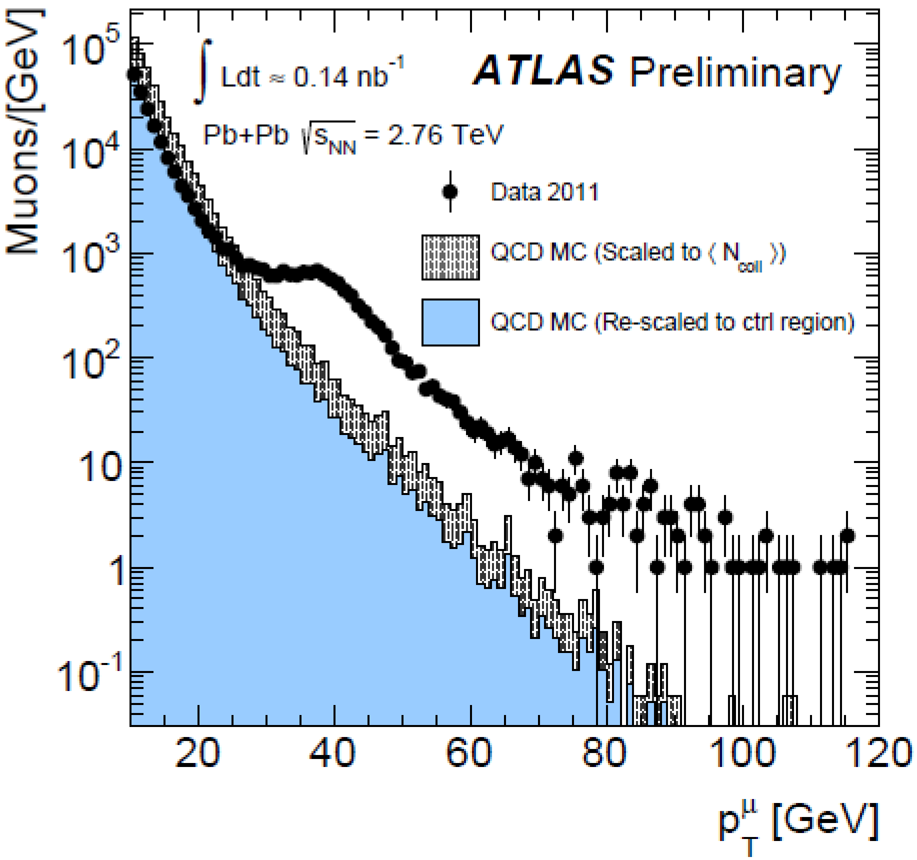
$$m_T = \sqrt{2 p_T^{\mu} p_T^{\text{miss}} (1 - \cos \Delta\phi_{\mu, p_T^{\text{miss}}})}$$

W: Background Sources

- QCD (e.g. $B \rightarrow \mu \nu X$)
  - Scale MC to $\langle N_{coll} \rangle$
  - Jet quenching: Re-scale to data in control region
  - Extrapolate to signal region
  - ≈ 3.7% contribution
- Z ⟶ $\mu^+\mu^-$
  - One muon of decay is outside acceptance
  - Uses data and MC
  - ≈ 2.4% contribution
- W ⟶ $\tau\nu_\tau$ ⟶ $\mu\nu_\mu\nu_\tau$
  - 17.4% of taus decay to a muon
  - Estimated with MC
  - ≈ 1.5% contribution
- Total background at the level of 7.6%

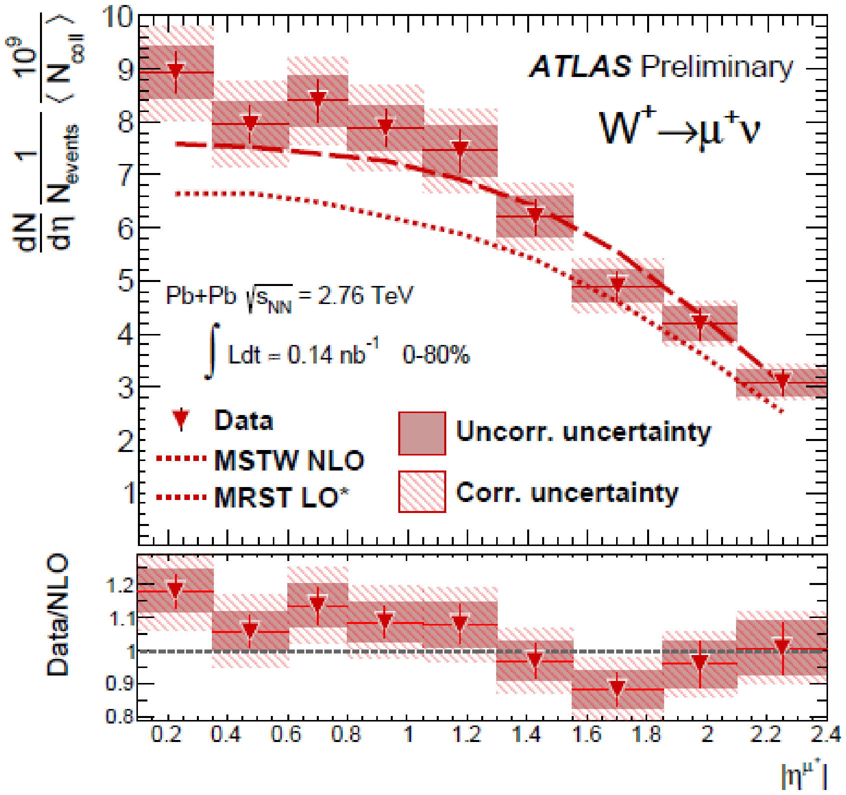




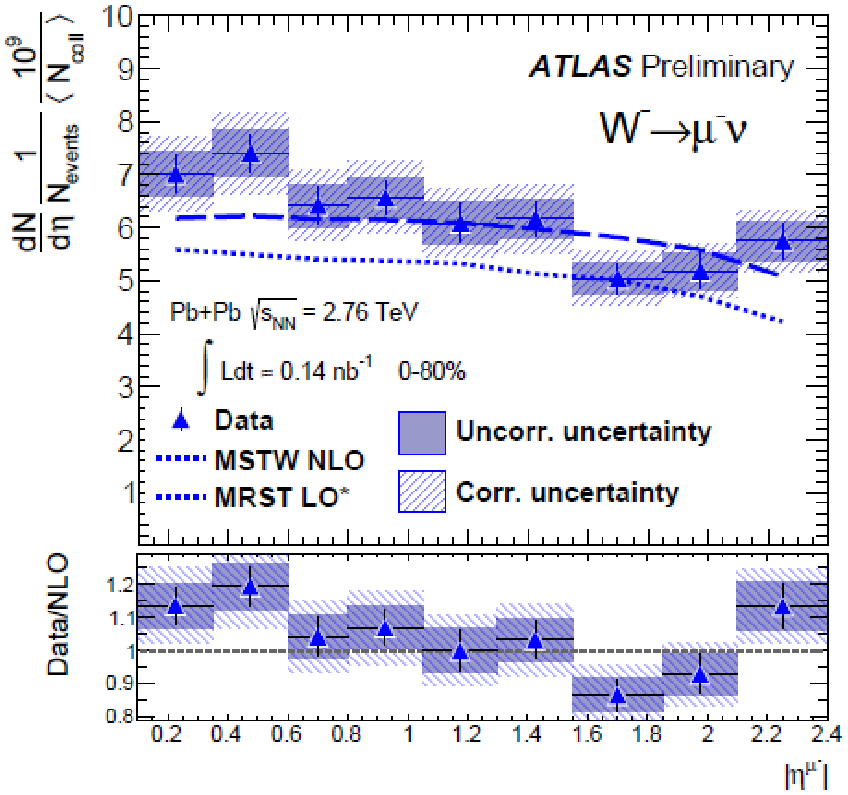


W: Corrected Yields

5487 ±96(stat.) ±86(syst) W^+ candidates



5262 ±95(stat.) ±83(syst) W^- candidates

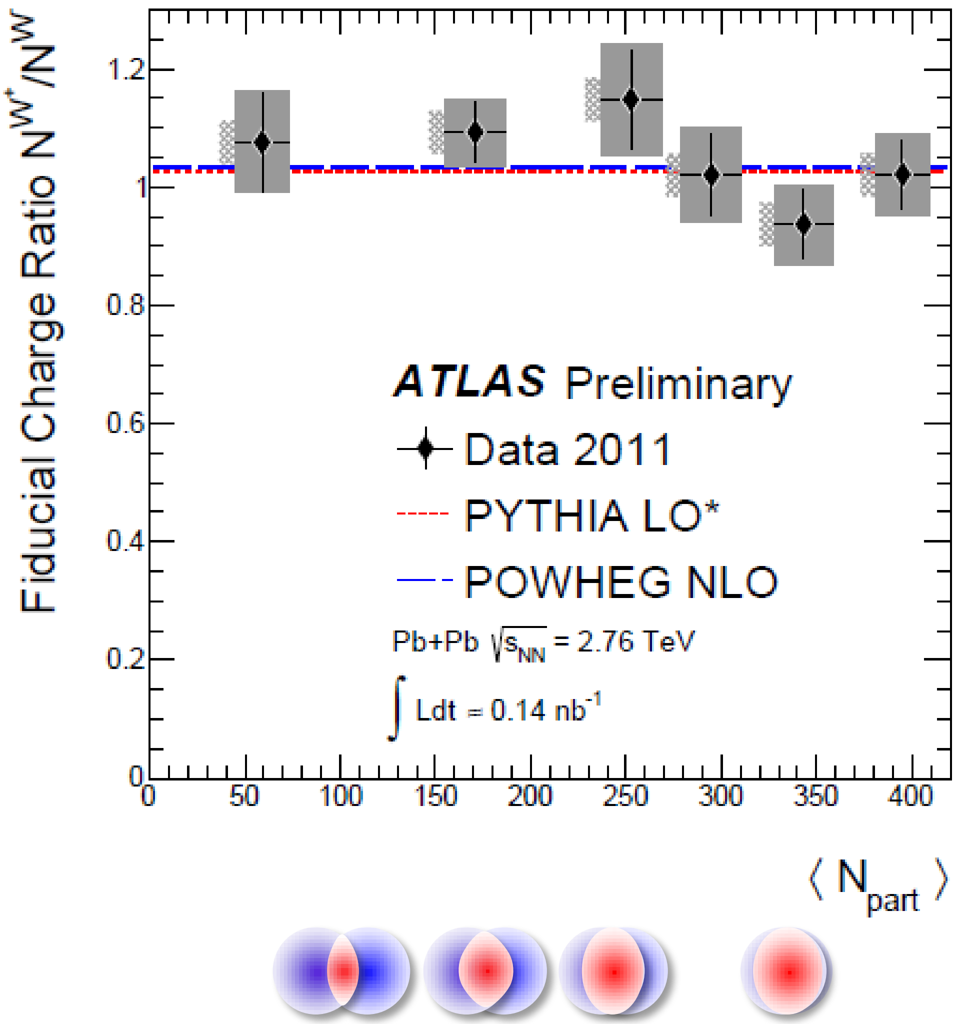


W bosons per binary collision in each $|\eta_\mu|$ interval

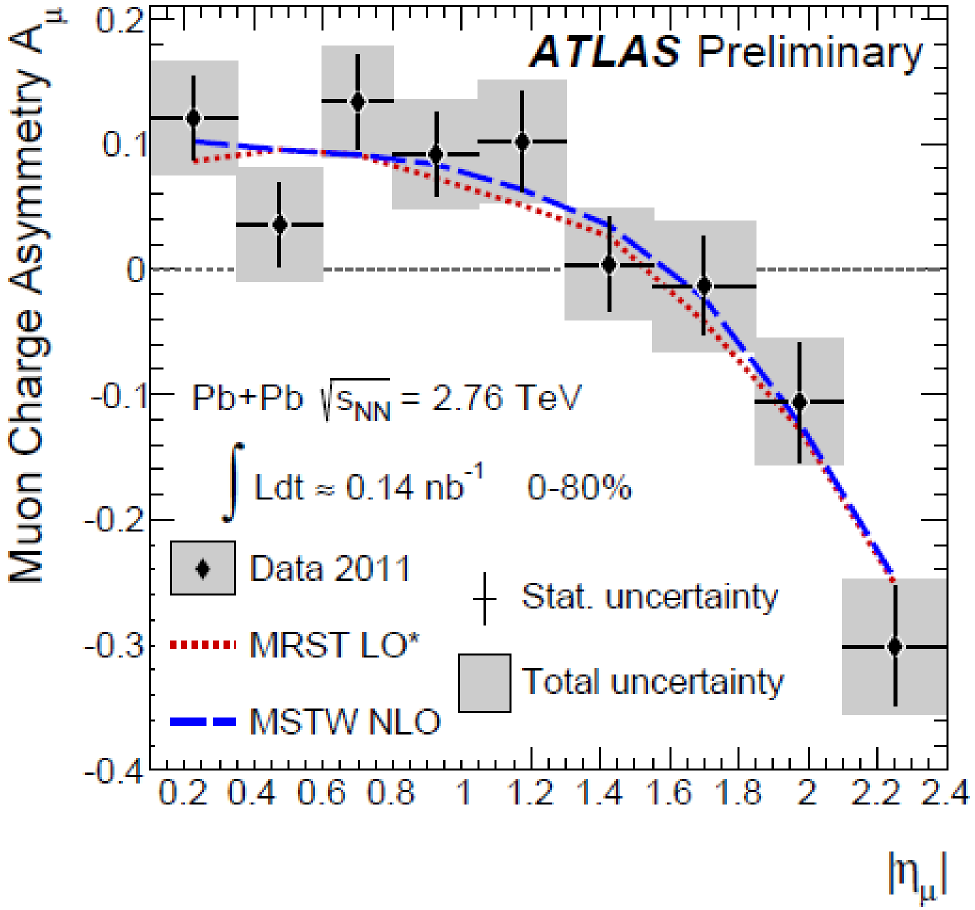
LO prediction tends to undershoot data, whereas NLO is in much better agreement

W^+ / W^- Charge Ratio

- Integrated ratio: 1.04 ±0.03(stat.) ±0.2(syst)
  - Consistent with unity in each centrality class
- LO* and NLO predictions both accurately represent the data
- Conclusion: NLO K-factor is independent of charge and cancels in ratio



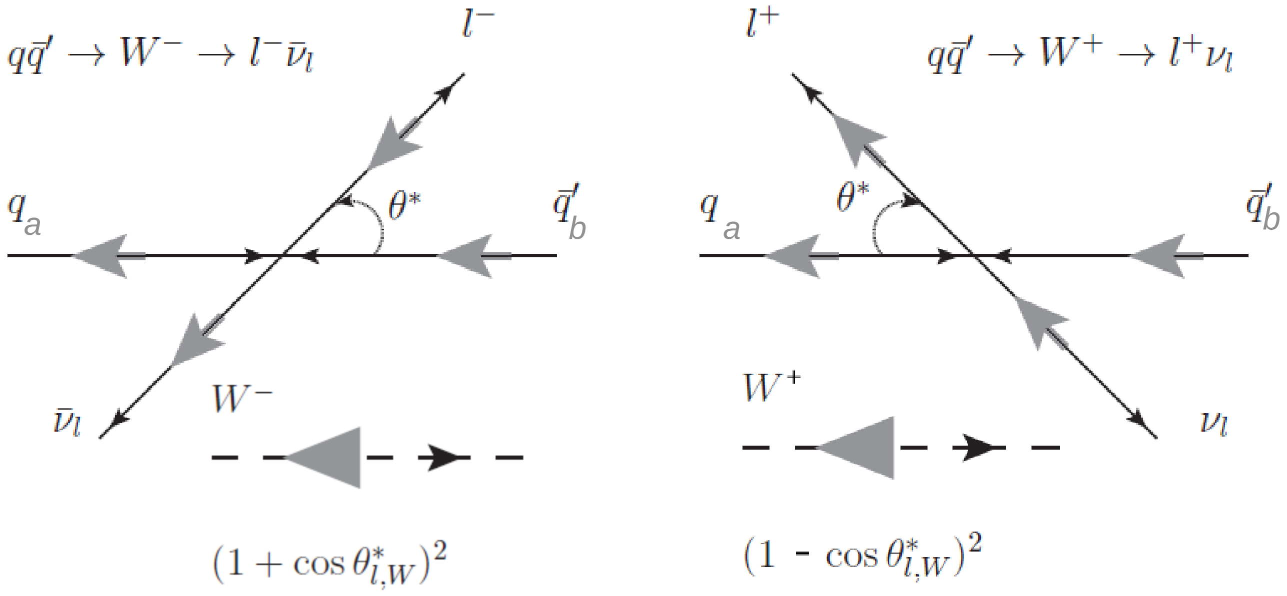
W: Muon Charge Asymmetry



Data agrees with both LO* and NLO model

No visible nuclear modifications

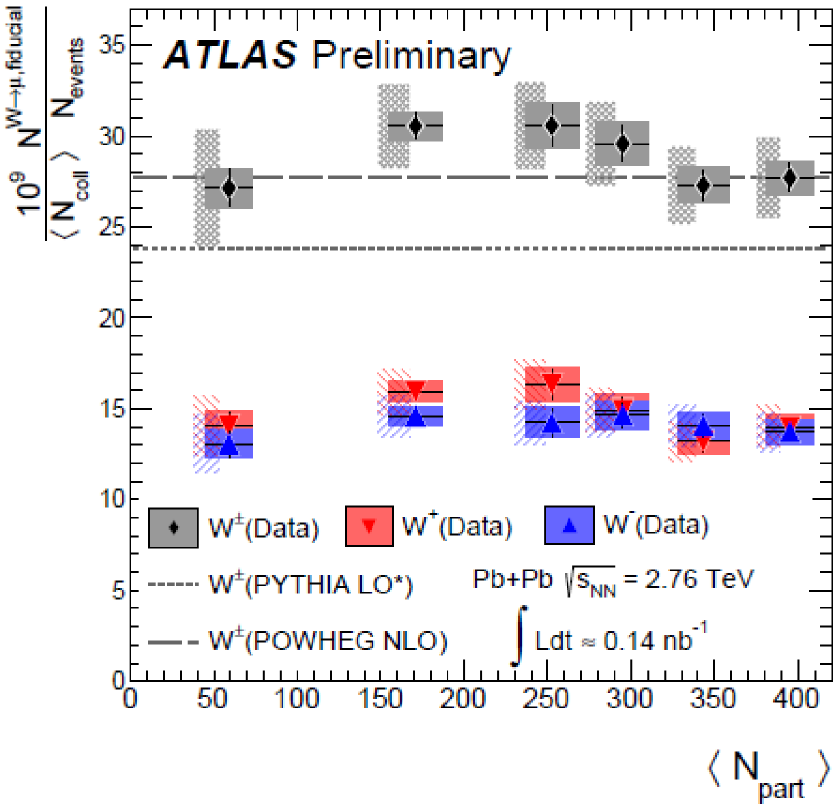
$$A_\mu = \frac{d\sigma_{W^+\to\mu^+}/d\eta_\mu - d\sigma_{W^-\to\mu^-}/d\eta_\mu}{d\sigma_{W^+\to\mu^+}/d\eta_\mu + d\sigma_{W^-\to\mu^-}/d\eta_\mu}$$



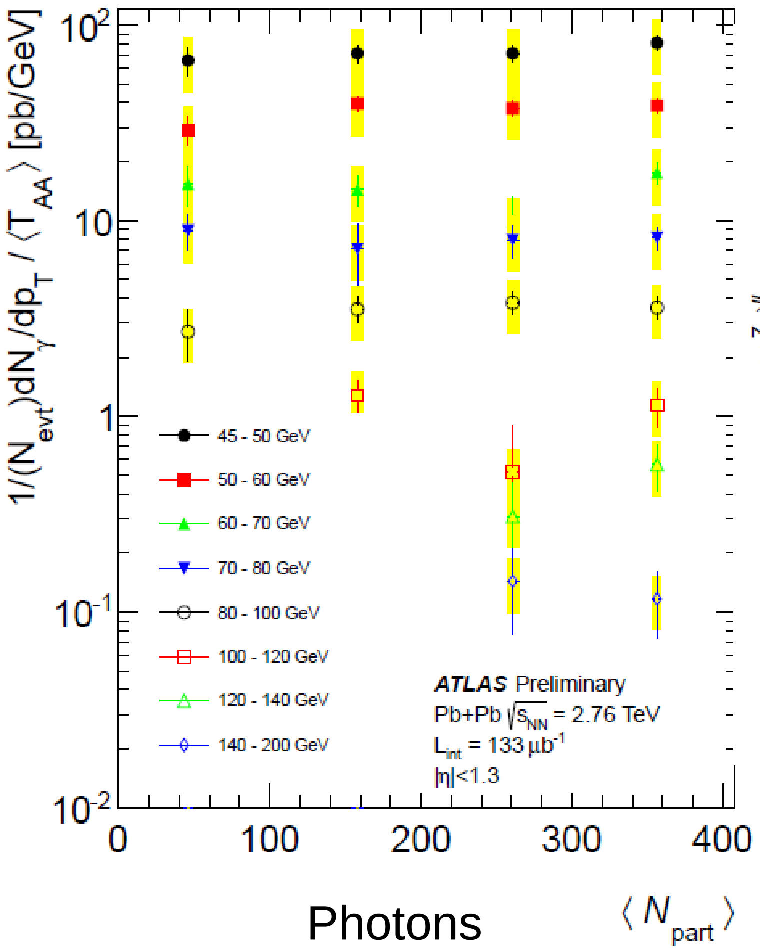
- W bosons at large y_W produced from high-x (valence) quarks
  - left-handed q + right-handed $\bar{q}$ = left-handed $W^\pm$
  - Decay angle determined by product of $\mu^\pm$ and $W^\pm$ helicities
  - μ^- boosted in direction of W^- → more μ^- at large η_μ

Electroweak Boson Binary Scaling

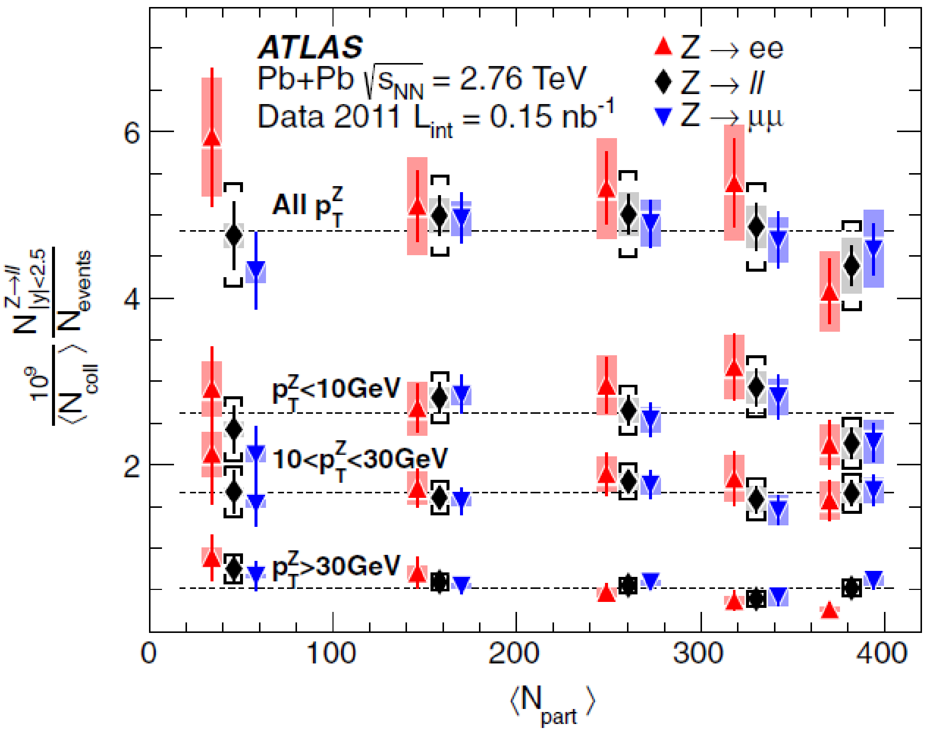
Boson yields show clear scaling with the number of binary collisions



W± bosons



Photons



Z bosons

Summary

- Presented boson ($W^{\pm}$, Z, γ) measurements in HI collected with ATLAS in 2011
- Presented W production rates as a function of $\langle N_{part} \rangle$ and $|\eta_{\mu}|$
  - NLO predictions with represent the data well, whereas LO* tends to underestimate yields
- Presented the fiducial W+/W- as a function of $\langle N_{part} \rangle$
  - Consistent with unity in each centrality class considered
- Presented the $W \rightarrow \mu\nu$ charge asymmetry as a function of $|\eta_{\mu}|$
  - Both NLO and LO* prediction (without any nuclear modifications) describes the data well
- All bosons scale with the number of binary collisions
  - Confirms an understanding of collision geometry (Glauber)
  - Provides standard candle for colour-charge interactions in a QCD medium
  - Exemplified by photon-jet and Z-jet measurements
- Sets the stage for exciting new results in future Pb+Pb and p+Pb EW boson measurements

Thank you for your attention!

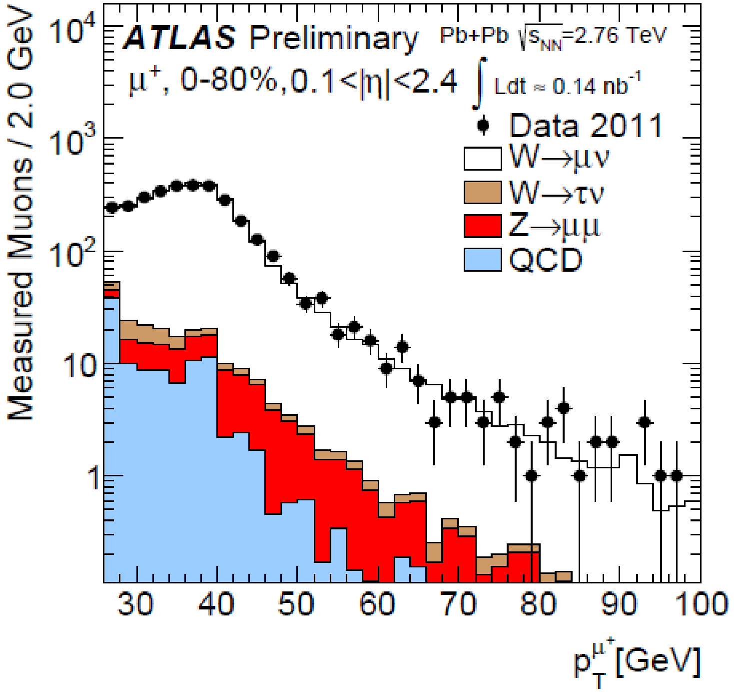
Backup

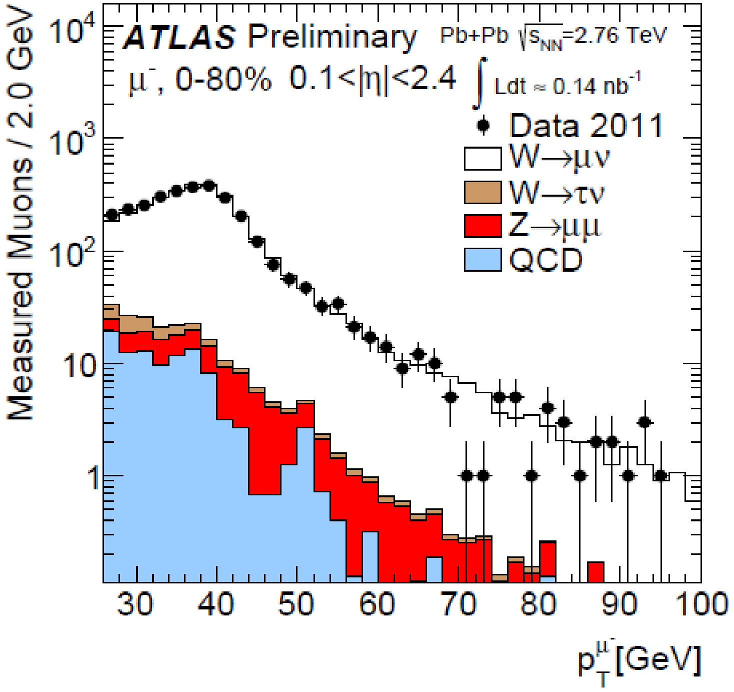
W: Reconstruction-Level Kinematics (p_T)

Show for both μ^+ and μ^- signal candidates

Background normalized to expected fraction

Signal MC normalized to background-subtracted counts in data



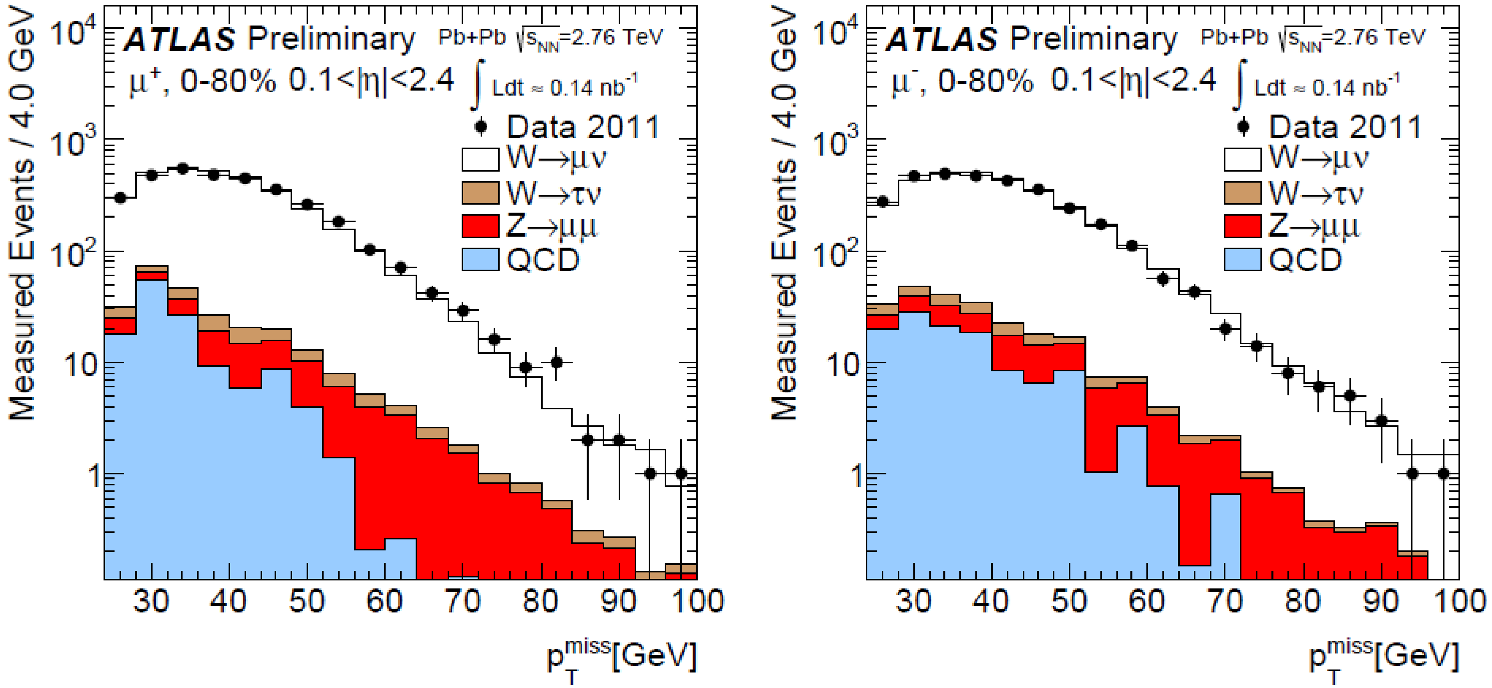


W: Reconstruction-Level Kinematics (p_T^{miss})

Show for both μ^+ and μ^- signal candidates

Background normalized to expected fraction

Signal MC normalized to background-subtracted counts in data

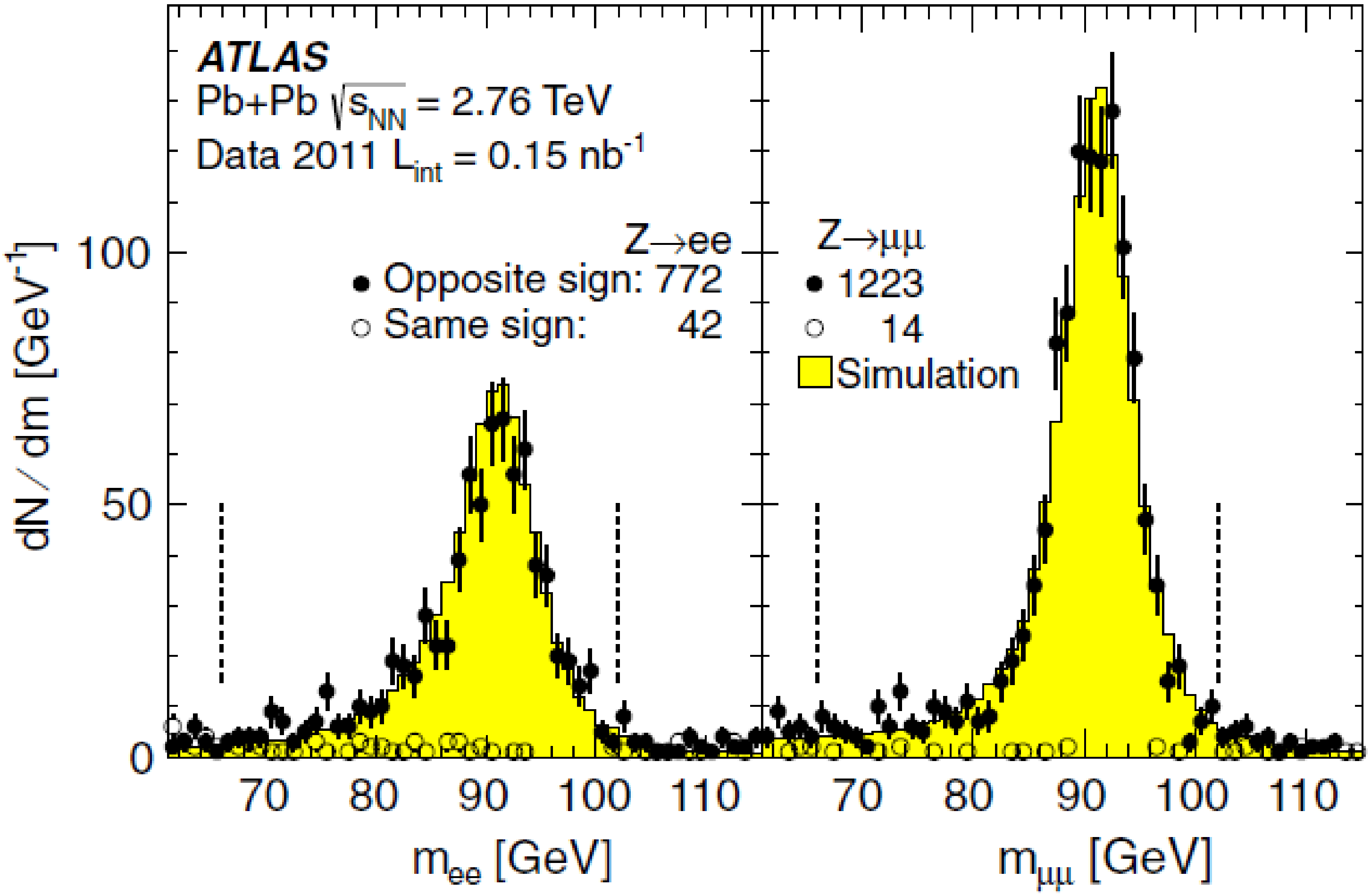


Z Bosons in Pb+Pb

Phys. Rev. Lett 110, 022301 (2013)

Invariant mass distributions integrated over momentum, rapidity, and centrality

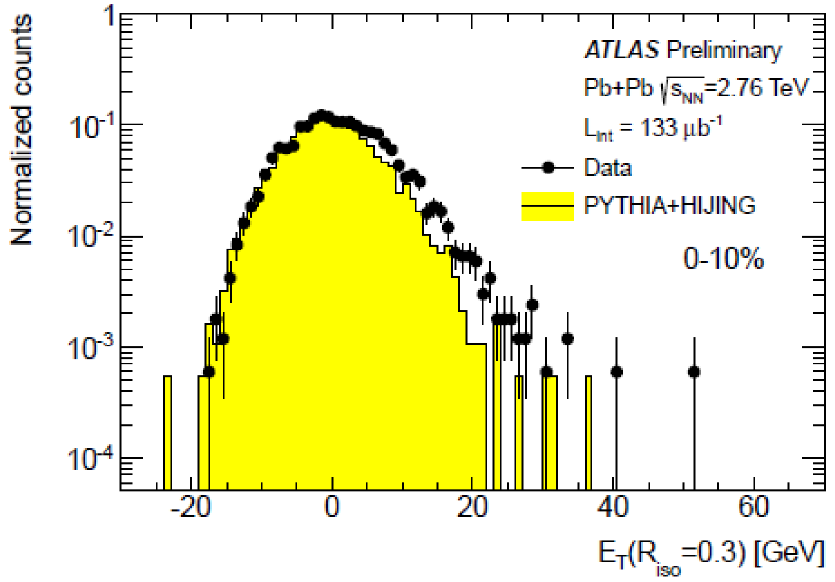
- Z → ee
  - $E_T > 20$ GeV, $|\eta_e| < 2.5$
  - UE subtracted from each electron
  - Background ≈ 5%
- Z → μμ
  - $p_T > 10$ GeV, $|\eta_\mu| < 2.7$
  - Background ≈ 1%
- Signal region
  - $66 < m_{\mu\mu} < 116$ GeV



Direct Photon Measurement in Pb+Pb

https://cds.cern.ch/record/1451913

- UE subtraction from each event
- Isolated photons
  - Reject clusters arising from hadronic jet-fragments
- Shower shape cuts in multiple layers of EM and hadronic calo
  - Reject jets and hadrons
- Signal extraction with “double side-band” method
  - **Region A:** Primary signal region
  - **Region B:** Photons near a jet or UE fluctuation
  - **Region C:** Isolated jet-fragments + non-tight photons
  - **Region D:** Primary background region

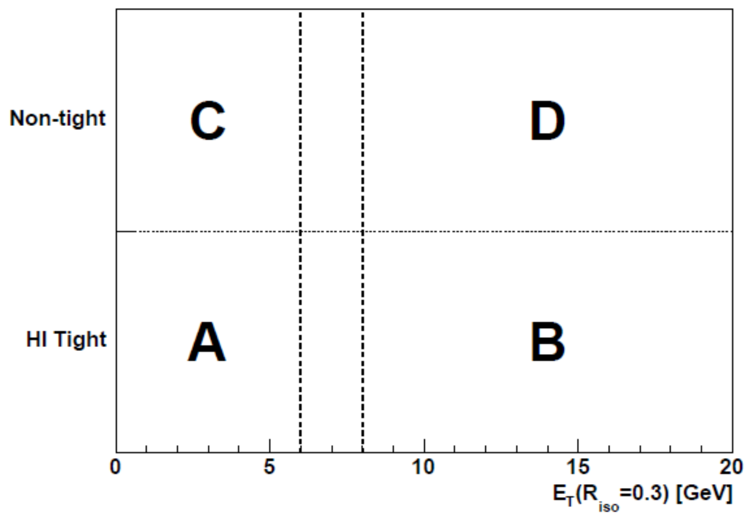


$$N^{sig} = N_A^{obs} - N_B^{obs} \frac{N_C^{obs}}{N_D^{obs}}$$

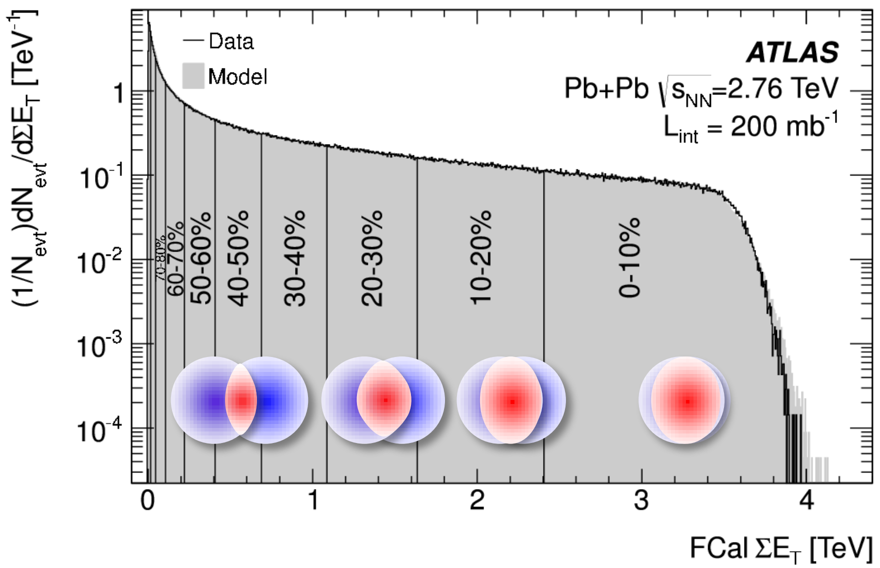
Correct for signal “leakage”

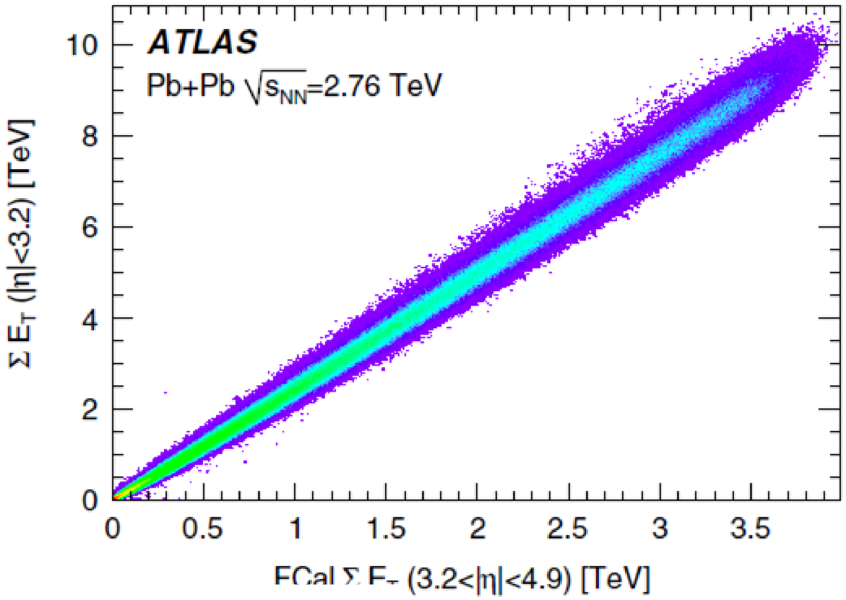
$c_i = N_i^{sig} / N_A^{sig}$

$$N_A^{sig} = N_A^{obs} - \left(N_B^{obs} - c_B N_A^{sig}\right) \frac{\left(N_C^{obs} - c_C N_A^{sig}\right)}{\left(N_D^{obs} - c_D N_A^{sig}\right)}$$



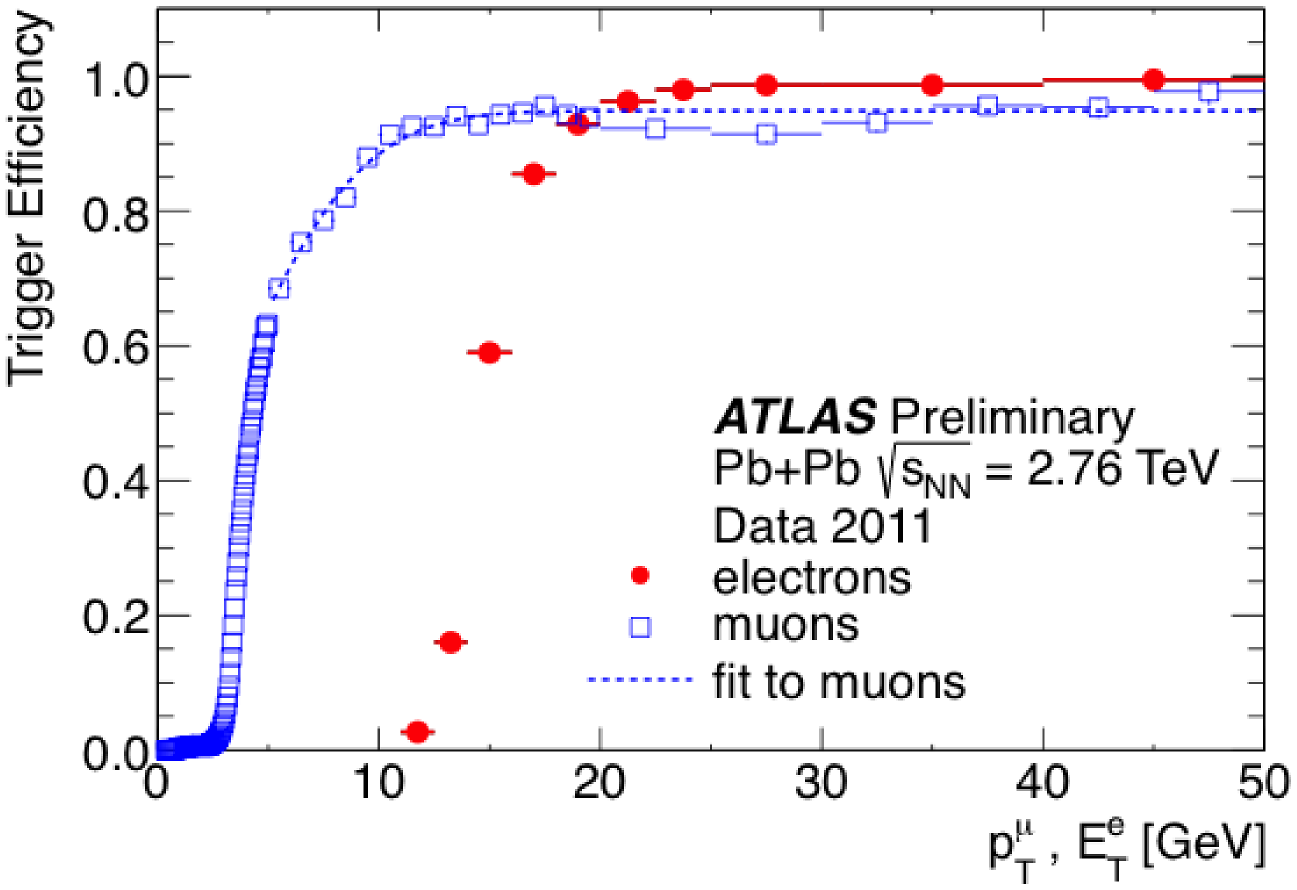
Centrality Definition



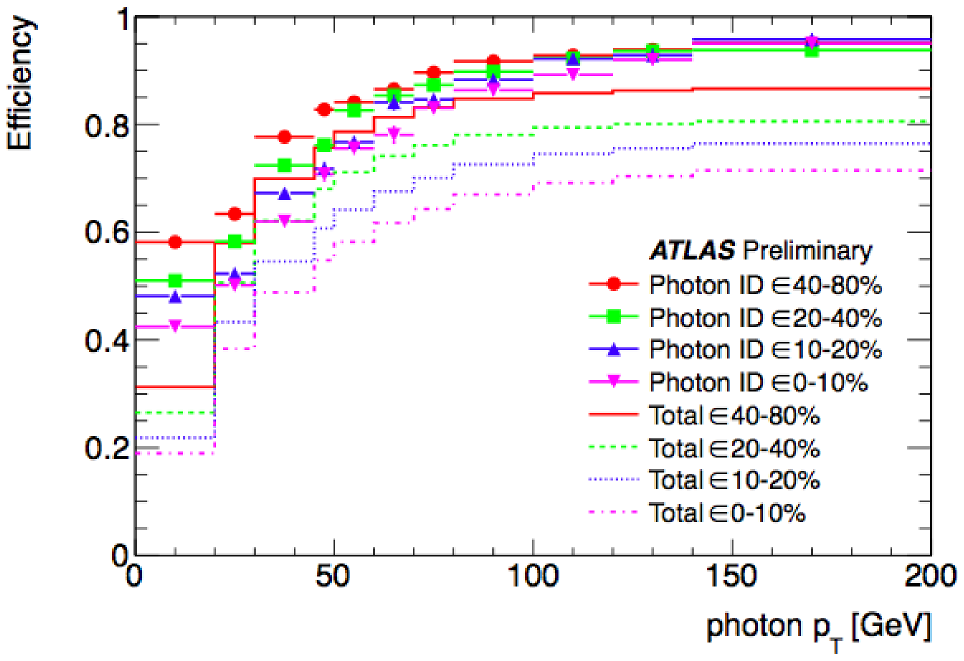


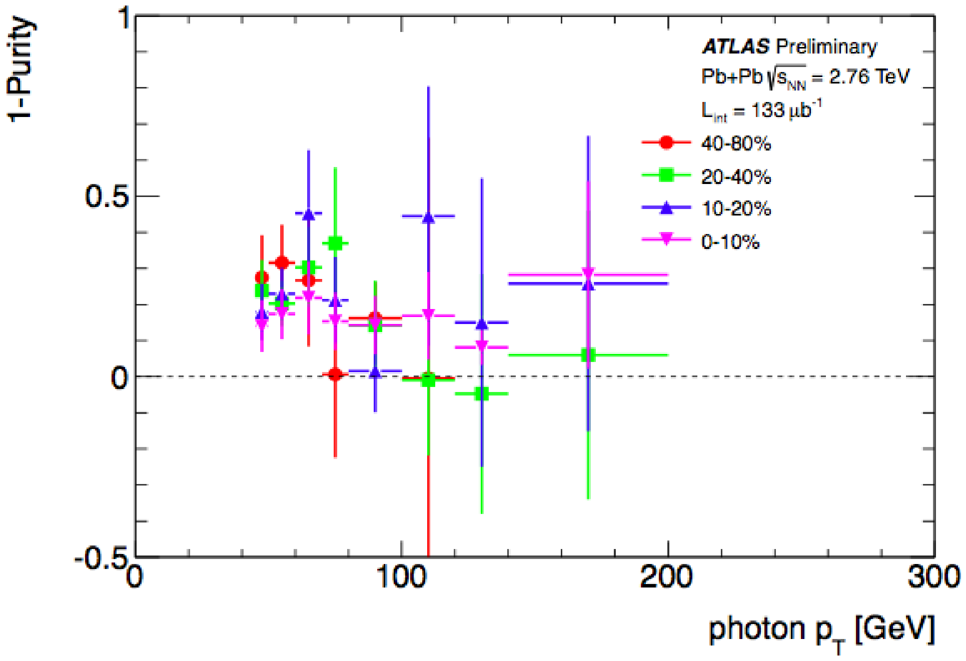
Centrality	$\langle N_{part} \rangle$		$\langle N_{coll} \rangle$	
0-5%	382.2	0.5%	1683.3	7.7 %
5-10%	330.3	0.9%	1318.0	7.5%
10-15%	281.9	1.3%	1035.4	7.4%
15-20%	239.5	1.6%	811.2	7.4%
20-40%	157.8	2.6%	440.6	7.3%
40-80%	45.9	7.6 %	77.8	14.2%
0-80%	139.5	4.7%	452.0	9.5%

Muon and Electron Triggers



Photon Efficiency and Purity





Photon identification efficiency as well as total efficiency (reconstruction, identification, and isolation) in 4 centrality classes

$1 - \text{Purity} = 1 - N_A^{sig}/N_A^{obs}$