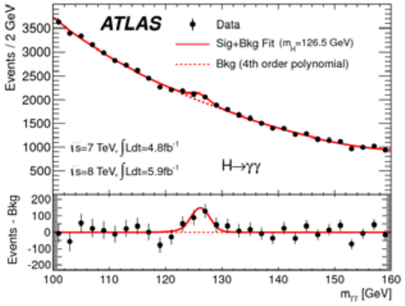
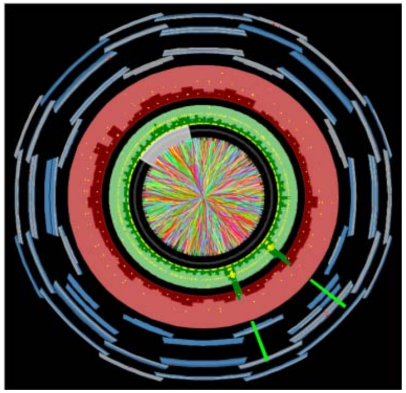


Recent results for Pb-Pb collisions with the ATLAS detector

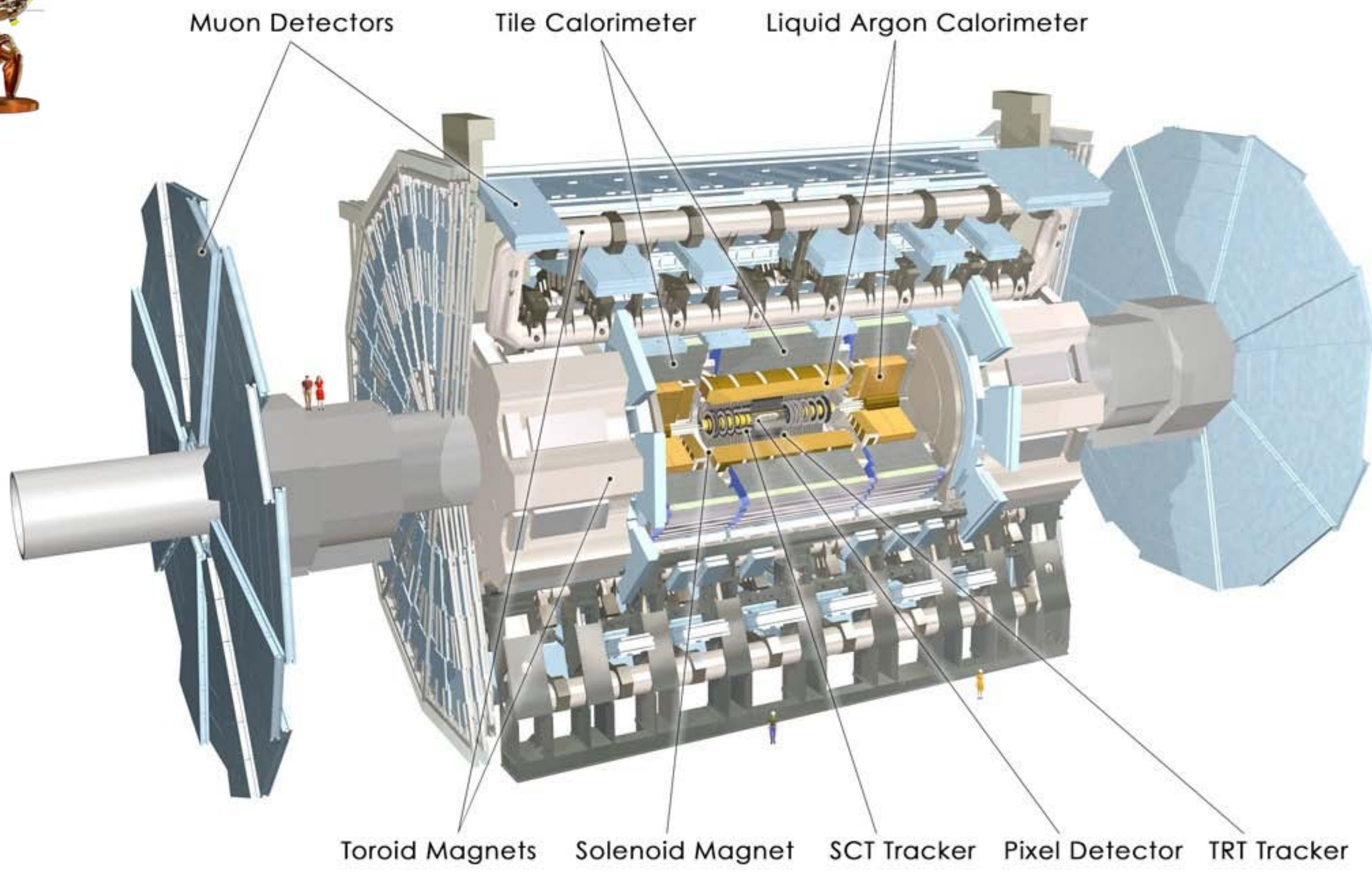


Barbara Wosiek, for the ATLAS Collaboration
Institute of Nuclear Physics PAS, Kraków, Poland

Outline

- ATLAS detector
- Lead-lead data taking
- Collective flow
- Electroweak probes
- Medium-sensitive probes
  - Heavy quark production
  - Jet suppression
  - Jet fragmentation
  - Path length dependence of jet suppression
  - Jet v2
  - γ,Z – jet correlations
- Summary

The ATLAS detector

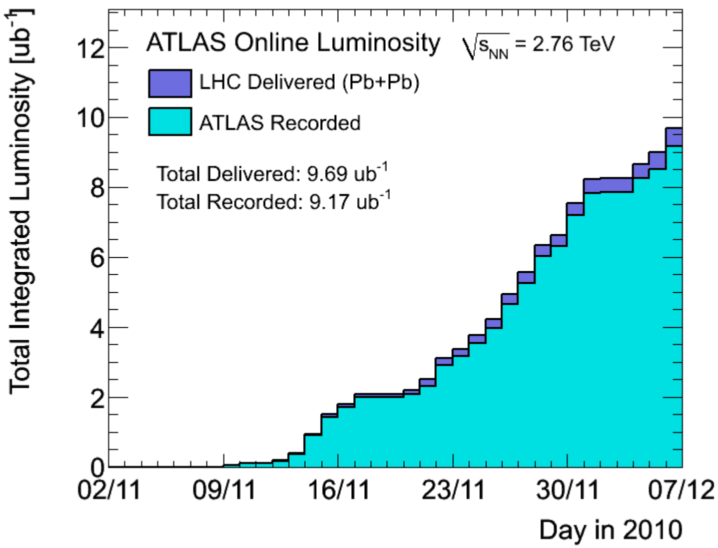


Three main subsystems with a full coverage in azimuth:

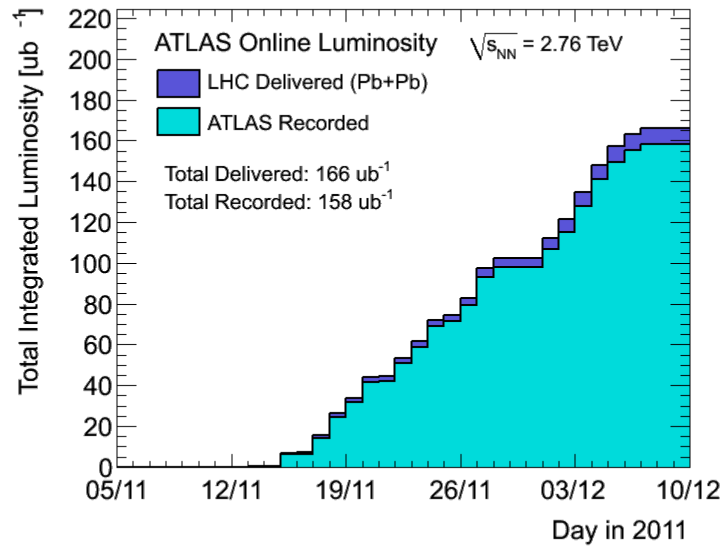
- **Inner Detector – tracking $|\eta|<2.5$**
- **Calorimetry – $|\eta|<4.9$**
- **Muon Spectrometer - $|\eta|<2.7$**

Lead-lead data taking

2010



2011

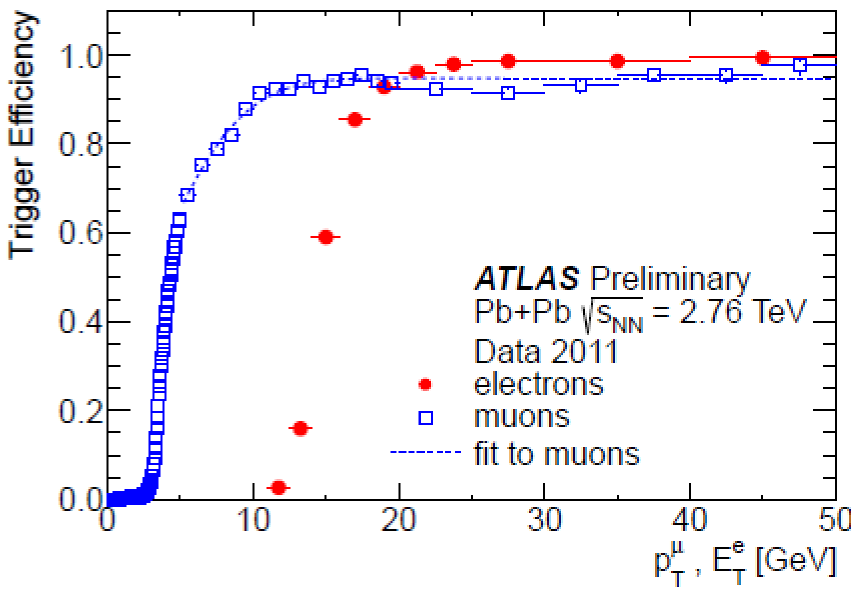


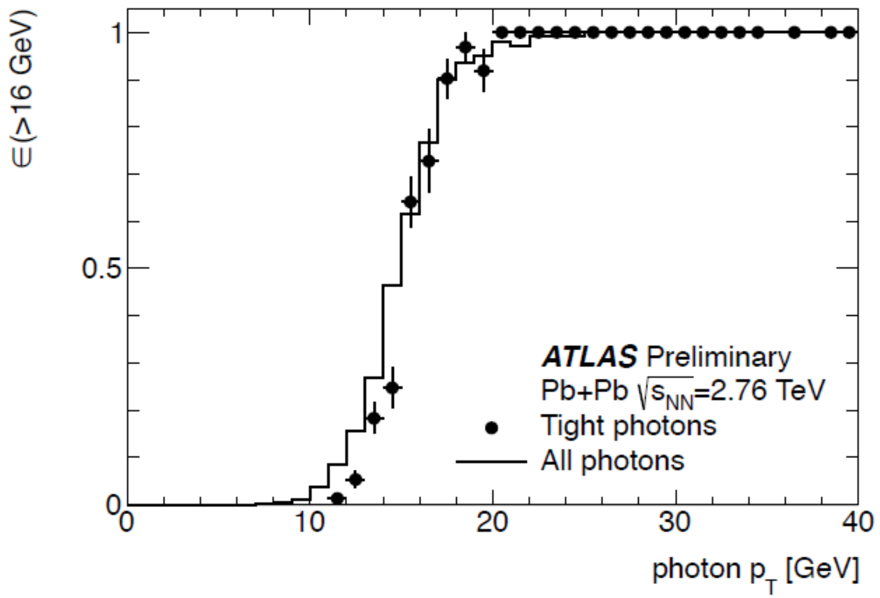
L_{int}	**8 μb^{-1}**	**0.15 nb^{-1}**
Detector eff.	**> 97%**	**> 97%**
Triggers	**MB**	**MB, e, μ, γ, jets, UPC**
Events[$\times 10^6$]	**~50**	**~1000**

MB – Minimum Bias

Thanks LHC!

Triggers in 2011





Electrons and photons

- **based on EM calorimeter**
- **efficiency > 98% for E_T > 20 GeV**

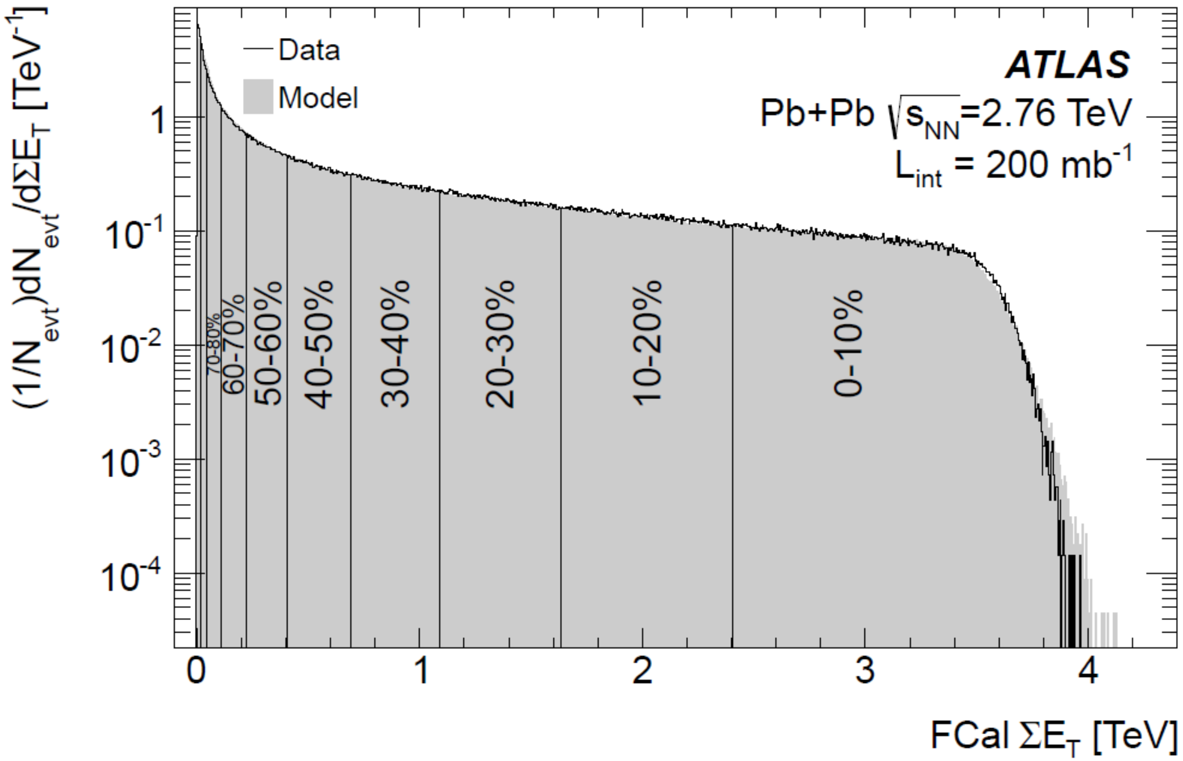
Muons

Based on combination: L1 and HLT with p_T>4 GeV based on RoI

OR full scan with p_T>10 GeV

- **Efficiency > 90% above 10 GeV**

Lead-lead collision centrality



- **Energy sum in forward calorimeter (FCal) ΣE_T (3.2 $|\eta|$<4.9) compared with Glauber MC $\otimes$ 2.76 TeV pp data**
- **Sampling fraction f = 98 $\pm$ 2% of total inelastic cross-section**
- **Centrality parameters $\langle N_{part} \rangle$, $\langle N_{coll} \rangle$ calculated from Glauber MC (binning in the simulated FCal ΣE_T)**

Collective flow measurements

- **Spatial deformations in the initial overlap region are transformed into the final state momentum anisotropy**
  - studied via Fourier decomposition of the azimuthal angle distribution measured relative to the initial symmetry plane Φ_n

    A.M. Poskanzer, S. A. Voloshin, Phys. Rev. C58, 1671 (1998) :

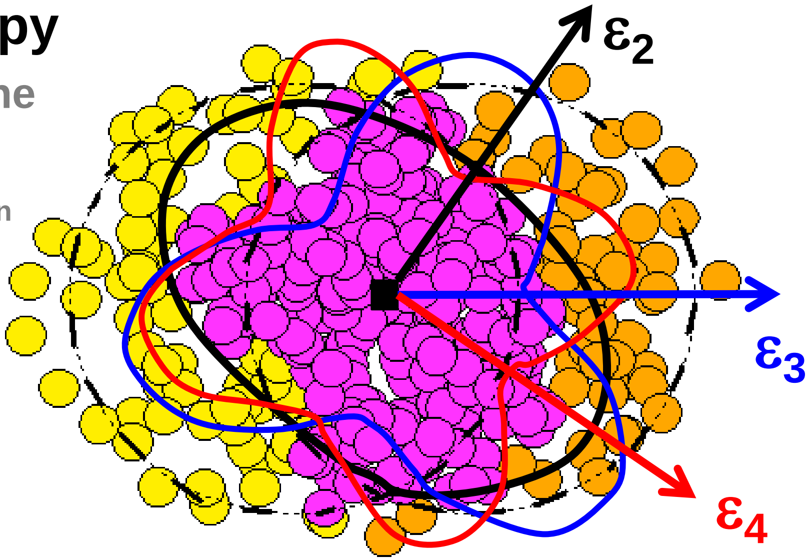
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N}{dp_T d\eta}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos[n(\phi - \Phi_n)]\right)$$

  - with two-particle correlations (2PC)

$$\frac{dN_{pairs}}{d(\phi_a - \phi_b)} \propto 1 + 2\sum_{n=1}^{\infty} v_{n,n}(p_T^a, p_T^b)\cos[n(\phi_a - \phi_b)]$$

  - with 2- and 4-particle cumulants

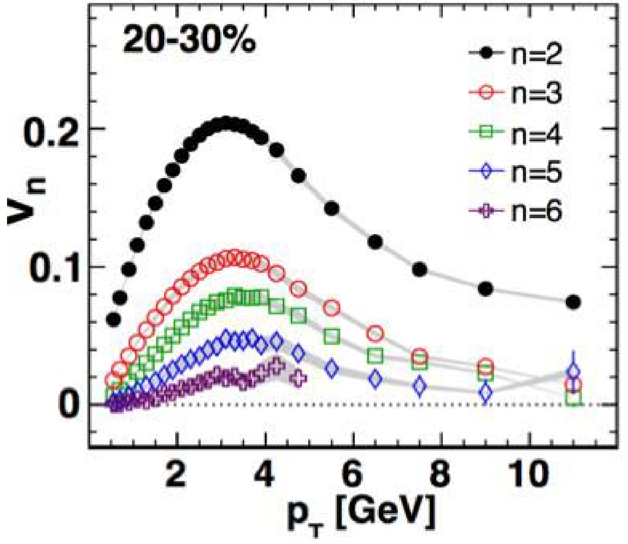
    N. Borghini, P.M. Dinh, J.Y. Ollitrault, Phys. Rev. C64, 054901(2001)

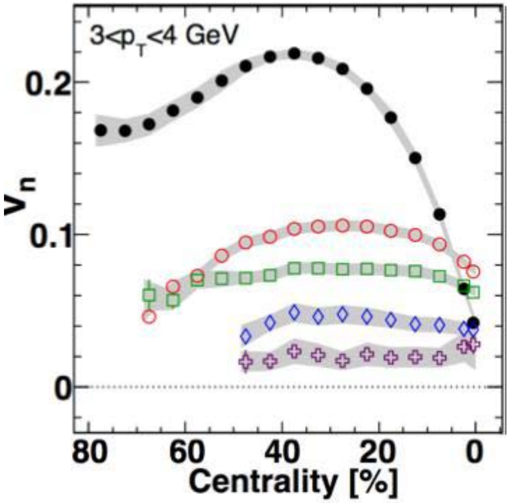


Measurement of Fourier coefficients

Phys. Rev. C86 (2012)014907

$v_2 - v_6$





- Similar p_T dependence for n=2-6 flow harmonics
- Weak centrality dependence observed for v_3-v_6
- For the 5% most central events $v_3 > v_2$

Significant v_n (n>2)

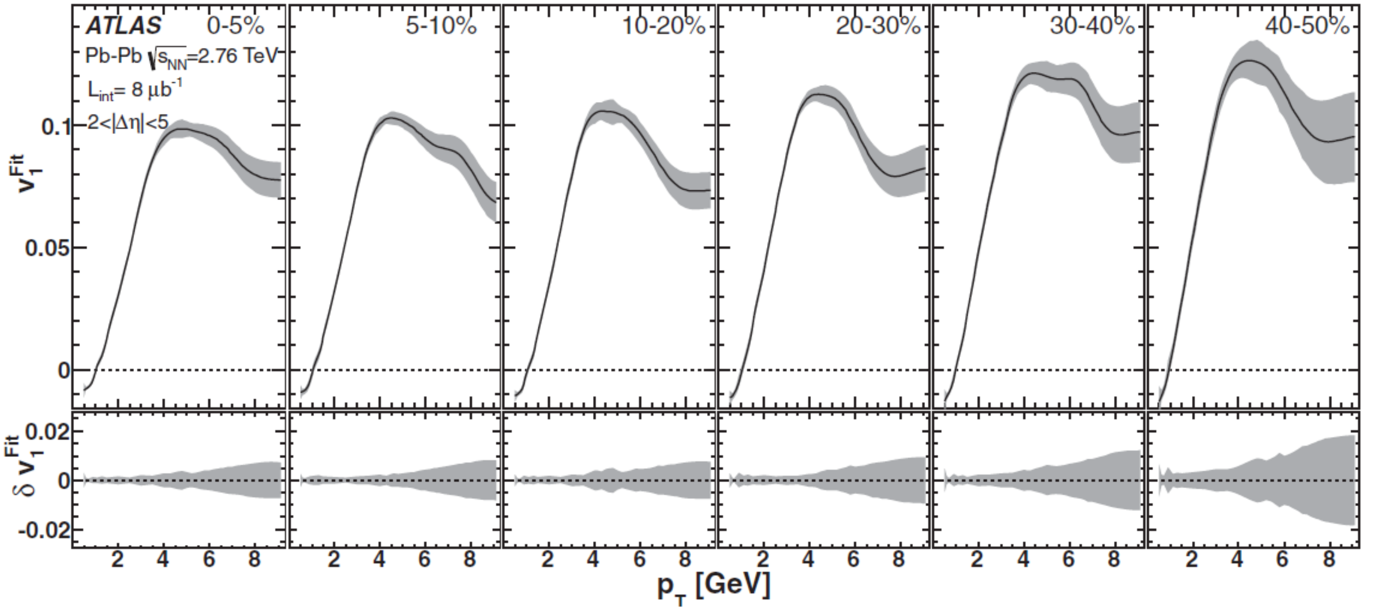
➢**Fluctuations of the nucleon positions in the overlap region**

First order flow harmonic

Phys. Rev. C86 (2012)014907

$v_{1,1}$ from the 2PC

v_1 from the two-component fit: $v_{1,1}(p_T^a, p_T^b) \approx v_1(p_T^a) v_1(p_T^b) - \frac{p_T^a p_T^b}{M\langle p_T^2 \rangle}$

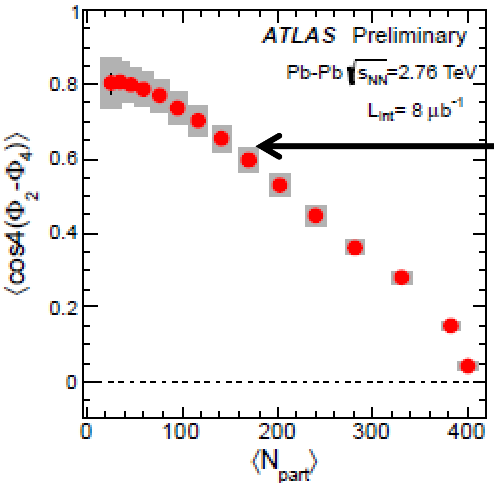


- v_1 signal is negative at p_T<~ 1 GeV, reaches a maximum at around 4–5 GeV and decreases at higher p_T
- The magnitude of v_1 at peak is comparable to that of v_3
- v_1 signal arises from the dipole asymmetry of the nuclear overlap due to fluctuations in the initial geometry

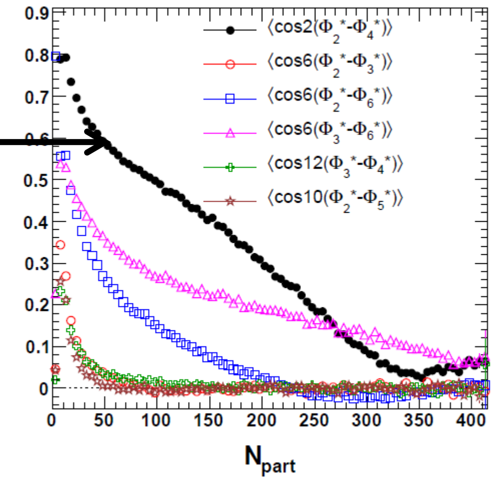
Fluctuations in the initial geometry

- The resolution corrected correlations between EP of different orders: (Φ_n,Φ_m), (Φ_n,Φ_m,Φ_k) ATLAS-CONF-2012-049

$\langle\cos4(\Phi_2-\Phi_4)\rangle$



Glauber MC predictions

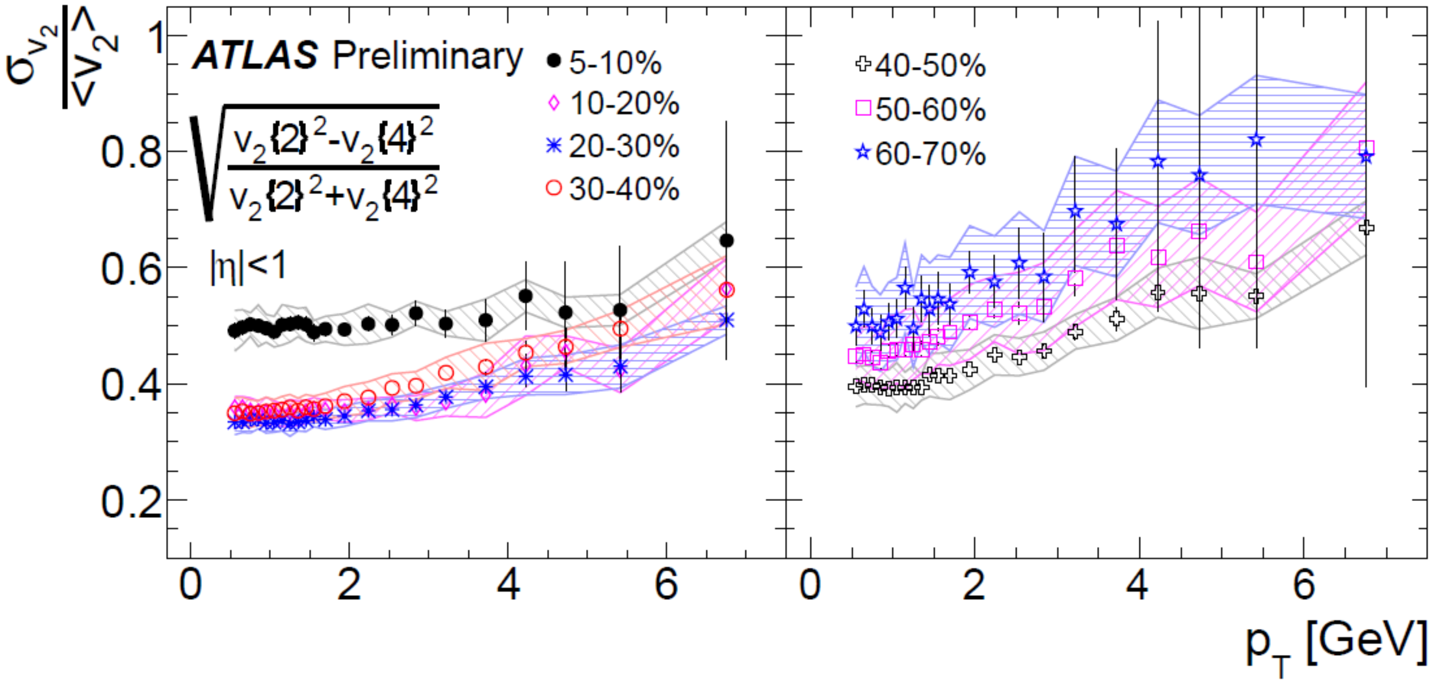


- **Some correlations show trends qualitatively, but not quantitatively, similar to Glauber model, others differ significanlty**
- **Observed correlations can be partially attributed to the fluctuations in the initial geometry, but may also arise during the dynamical evolution of the created system**

Elliptic flow fluctuations

- **Extracted from 2- and 4-particle cumulants**

$$\frac{\sigma_2}{<\mathbf{v}_2>} \approx \sqrt{\frac{\mathbf{v}_2\{2\}^2 - \mathbf{v}_2\{4\}^2}{\mathbf{v}_2\{2\}^2 + \mathbf{v}_2\{4\}^2}}$$

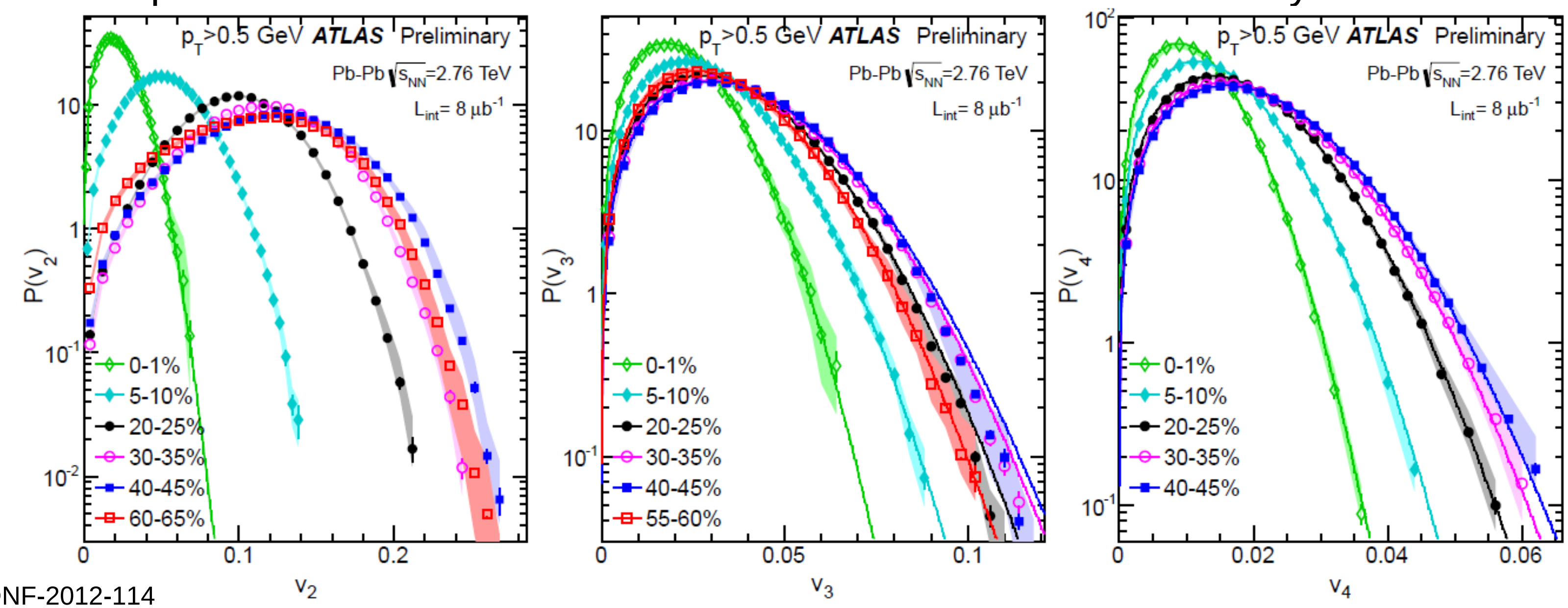


- **weak p_T dependence for p_T < 2 GeV across all centralities;**
- **in 5-10% central p_T-independence holds up to higher p_T**

ATLAS-CONF-2012-118

Flow harmonics fluctuations

- New technique – direct measurement of flow fluctuations!
- Event-by-event unfolded v_n distributions, for n=2 – 4
  - Raw v_n distributions are unfolded with response functions accounting for v_n smearing
  - Response functions are obtained from correlations between two symmetric subevents



ATLAS-CONF-2012-114

- **v_n distributions are 2D Gaussian (curves):**
  - for v_2 only in the 1% of most central collisions
  - for v_3 and v_4 over all centralities

resulting from random fluctuations in the initial state

More details on EbE v_n studies in talk by Jiangyong Jia, 4A Thursday

ATLAS results on collective flow studies at Quark Matter 2012:

✓ **Provide information on the initial geometry and its fluctuations**
✓ **Provide constraints on the hydrodynamic evolution of the system**

- **Adam Trzupek**, Flow & Correlations*, plenary Today*
- **Dominik Derendarz**, Measurement of elliptic and higher-order harmonics at sqrt(s_NN)=2.76TeV Pb-Pb collisions with the ATLAS detector, *parallel 2A Tuesday*
- **Jiangyong Jia**, Measurement of dipolar flow and event-by-event harmonic flow distributions in Pb-Pb collisions at sqrt(s_NN) =2.76 TeV, *parallel 4A Thursday*
- **Tomasz Bold**, Measurements of flow harmonics with the cumulant method and the integrated v_2 with low-p_T threshold from the ATLAS experiment , *parallel 6D Friday*
- **Soumya Mohapatra**, Measurement of event plane correlations in Pb-Pb collisions with the ATLAS detector, *parallel 7D Friday*

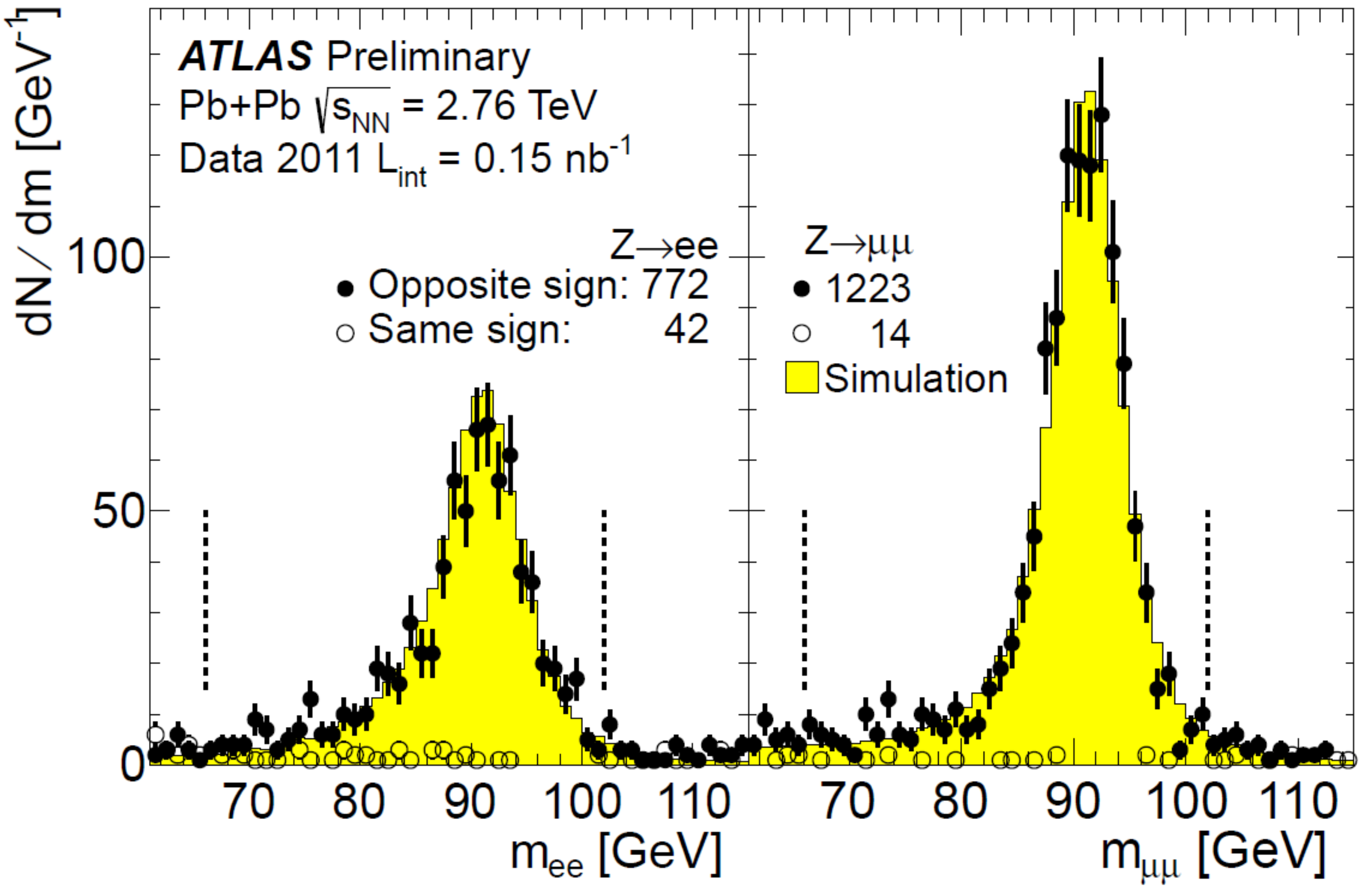
Electroweak probes

Z^0 and $W^{\pm}$ bosons and photons are not strongly interacting with the medium constituents:

should obey QCD factorization (scaling with N_{coll})

- **Measurements of Z/W/γ production in Pb+Pb provide constraints on the nuclear PDF**
- **Z/W/γ bosons can be used as a reference**
- **Production of Z/W/γ in association with jets provides a handle for understanding the parton energy loss in medium**

Measurement of $Z \to e^+e^-, \mu^+\mu^-$



Electron selection

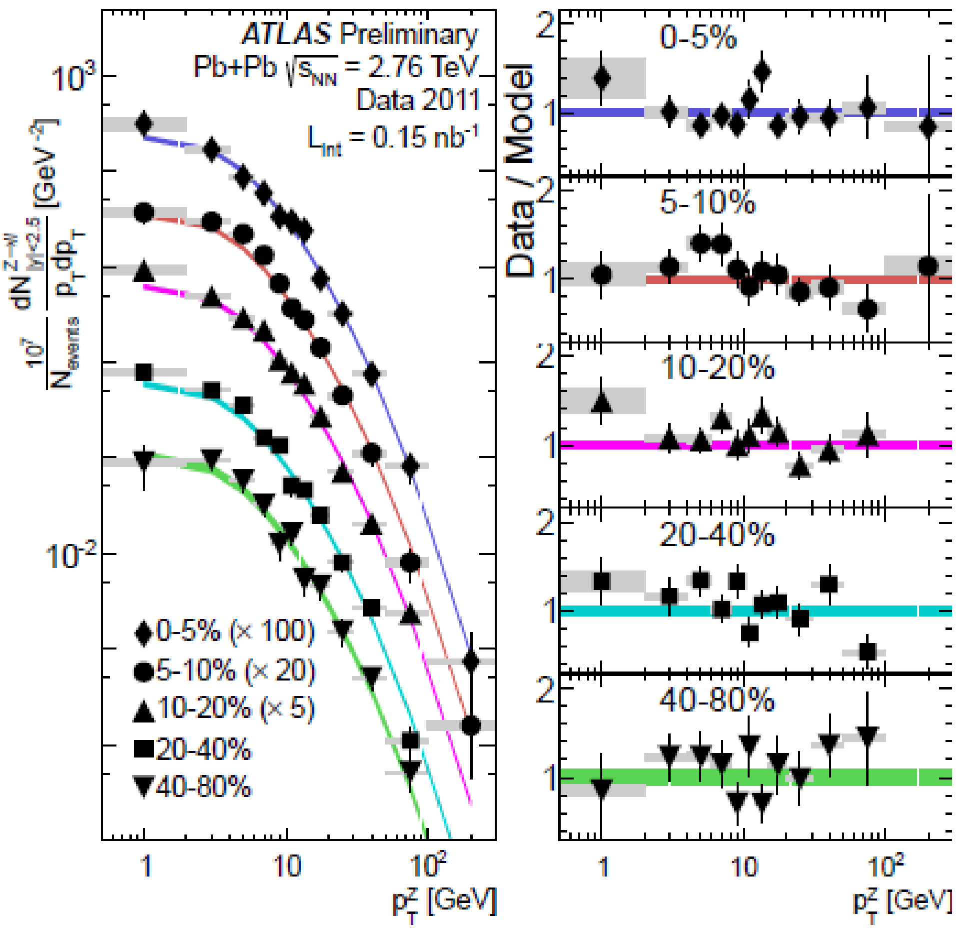
- E_T >20 GeV
- $|\eta|$<2.5
- Shower shape and energy cuts
- Subtraction of the UE energy

Muon selection:

- p_T > 10 GeV
- $|\eta|$<2.7
- track quality cuts

p_T distributions of Z bosons

$Z \to e^+e^-$ and $Z \to \mu^+\mu^-$

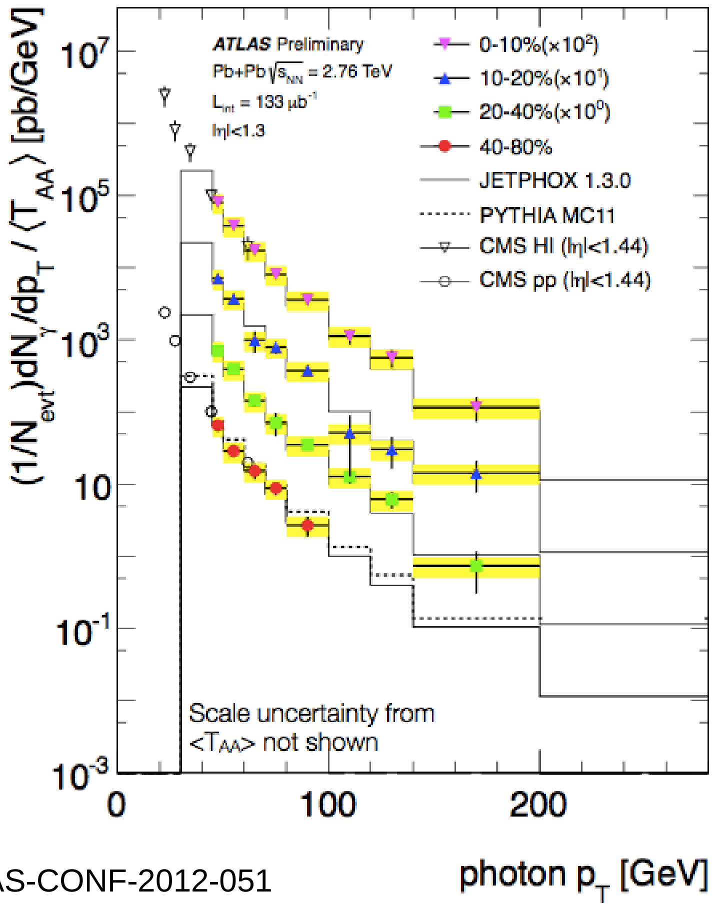


Centrality dependence

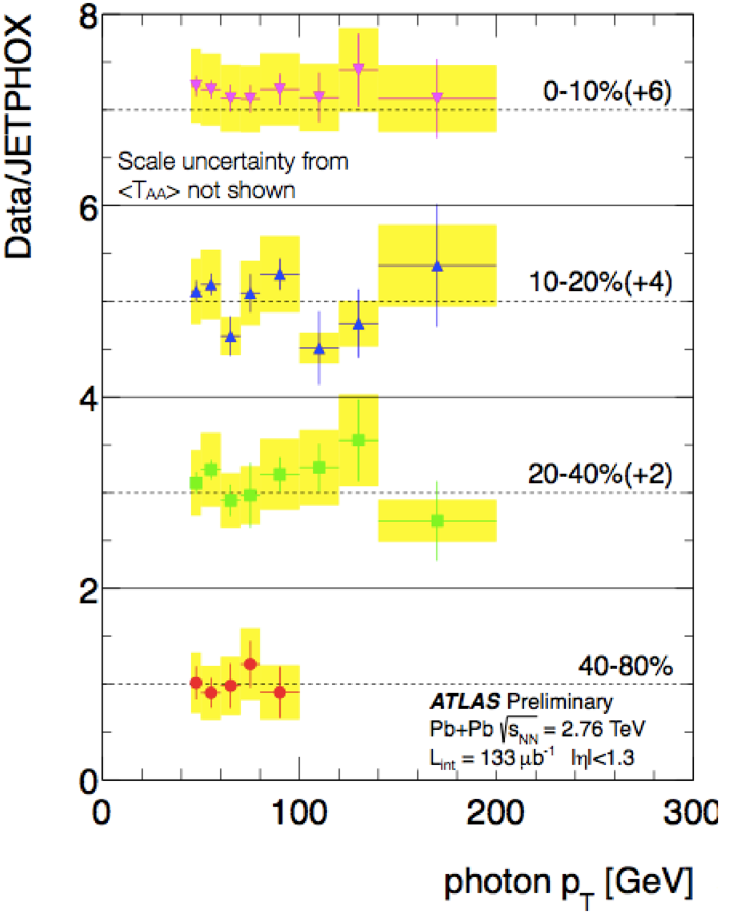
p_T (and y) distributions consistent with Pythia simulations for pp with NNLO cross section × $\langle T_{AA} \rangle$

Yields consistent with N_{coll} scaling

Prompt photon production



ATLAS-CONF-2012-051



Yields scaled by T_{AA} and compared to JETPHOX predictions

Ratio: Data/JETPHOX ≈ 1 (~R_{AA})

Electroweak probes: Summary

- Z, γ yields scale with N_{coll}
  - No significant violation of QCD factorization
- Using N_{coll} as a normalization of AA spectra is justified

Analysis details and more results in the electroweak sector in talks by :

- Peter Steinberg *plenary Thursday*
- Zvi Citron *parallel 1B Tuesday*
- Iwona Grabowska-Bold *parallel 4C Wednesday*
- Jiri Dolejsi *parallel 4C Wednesday*

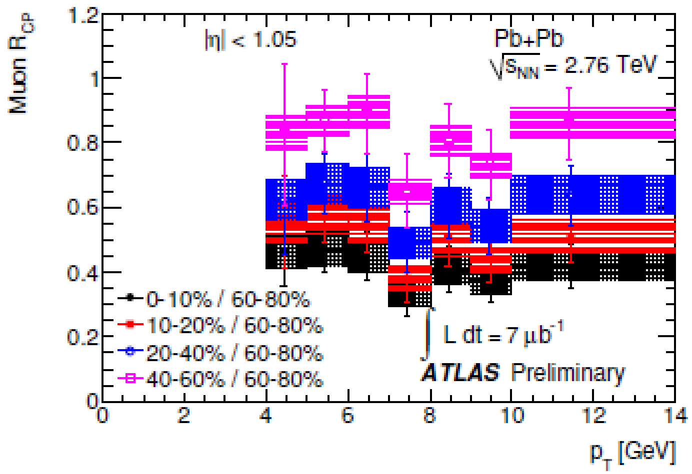
Medium-sensitive probes

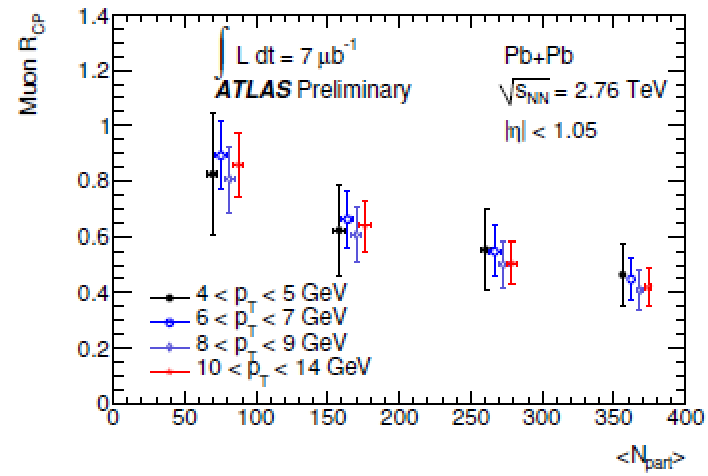
- **Heavy quark production**
- **Jet studies**

Open heavy flavour production

- Studied via semileptonic decays to muons
  - **4 < p_T < 14 GeV, |η|<1.05**

ATLAS-CONF-2012-081

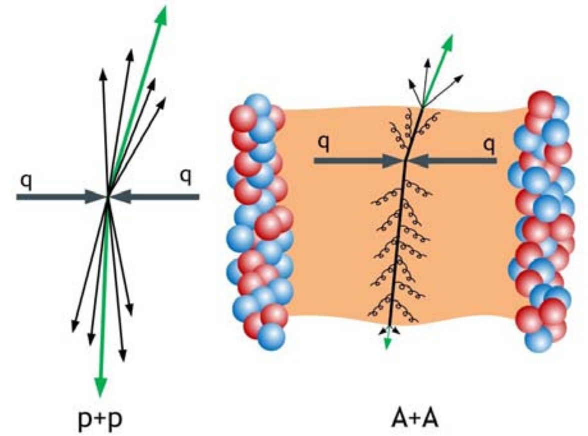




- A factor of 2 suppression 0-10%/60-80%, independent of p_T
- Weaker suppression than for charged hadrons
- Weaker suppression as compared to RHIC electron results

Talk by **Dennis Perepelitsa** parallel 7A friday

Jet studies



Jet quenching:
jet energy loss in hot/dense medium
(J.D. Bjorken – 1982)

- **Suppression of the jet yields**
- **Modification of the fragmentation function**

} Preliminary results shown at QM'2011

- Much more advanced analyses
- Fully unfolded jet p_T spectra
- Dependence on the jet size
- Full control of systematic uncertainties

- **Dependence on the path length**
- **Jet v_2**
- **γ,Z - jet correlations**

} New results

Jet suppression

arXiv:1208.1967 [hep-ex] Submitted to Phys. Lett.B

First LHC result on jet suppression

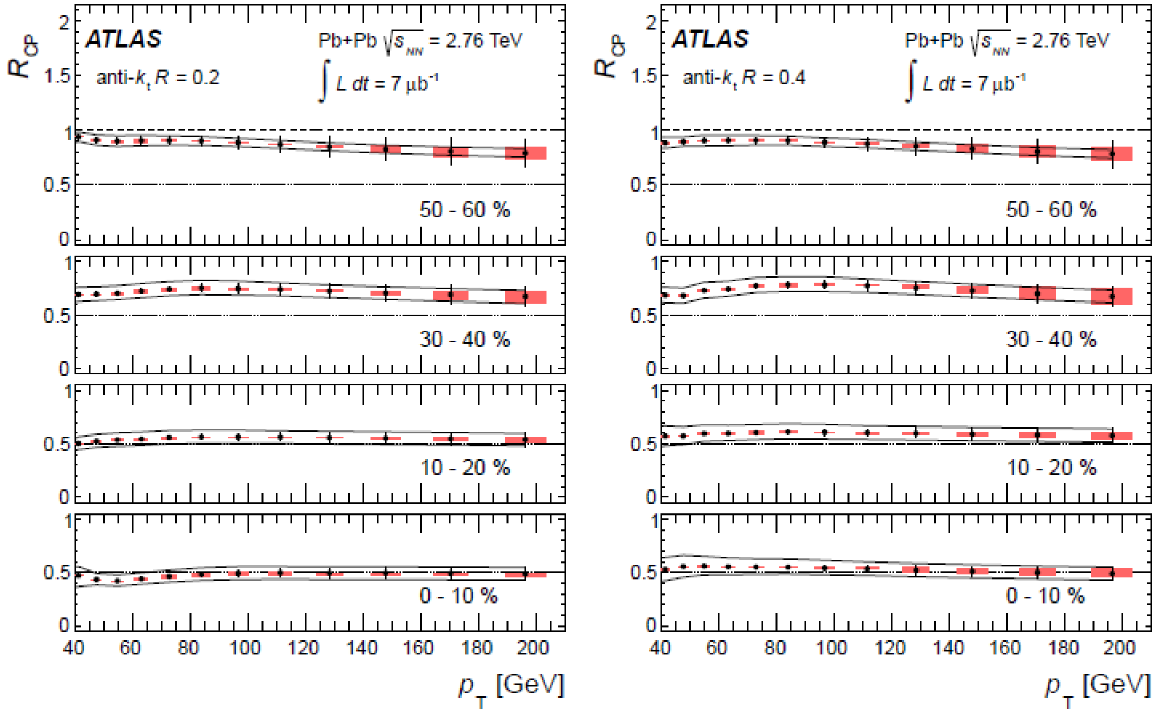
Unfolded p_T spectra

For jet sizes R=0.2, 0.3, 0.4 and 0.5

$$R_{cp} = \frac{\frac{1}{N_{coll}^{cent}} E \frac{d^3N^{cent}}{dp^3}}{\frac{1}{N_{coll}^{periph}} E \frac{d^3N^{periph}}{dp^3}}$$

peripheral reference: 60-80%

R=0.2



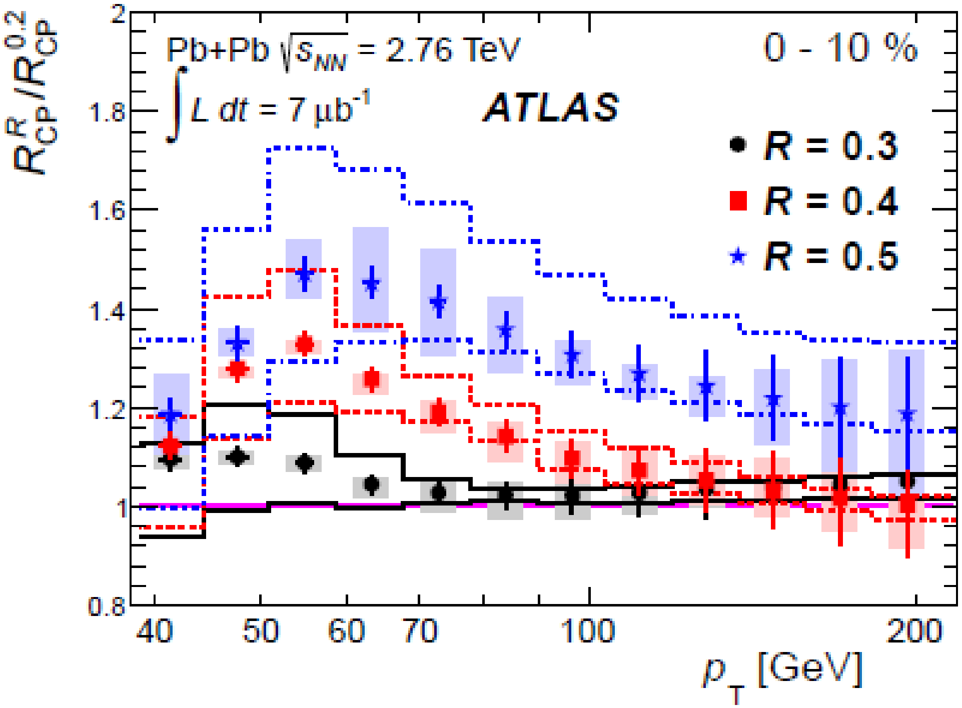
R=0.4

- **A factor of ~2 suppression in 0-10% most central collisions**
- **Suppression independent of jet p_T**

R-dependence of jet suppression

arXiv:1208.1967 [hep-ex] Submitted to Phys. Lett.B

Ratio of R_{CP} values between R=0.3, 0.4 and 0.5 jets and R=0.2 jets

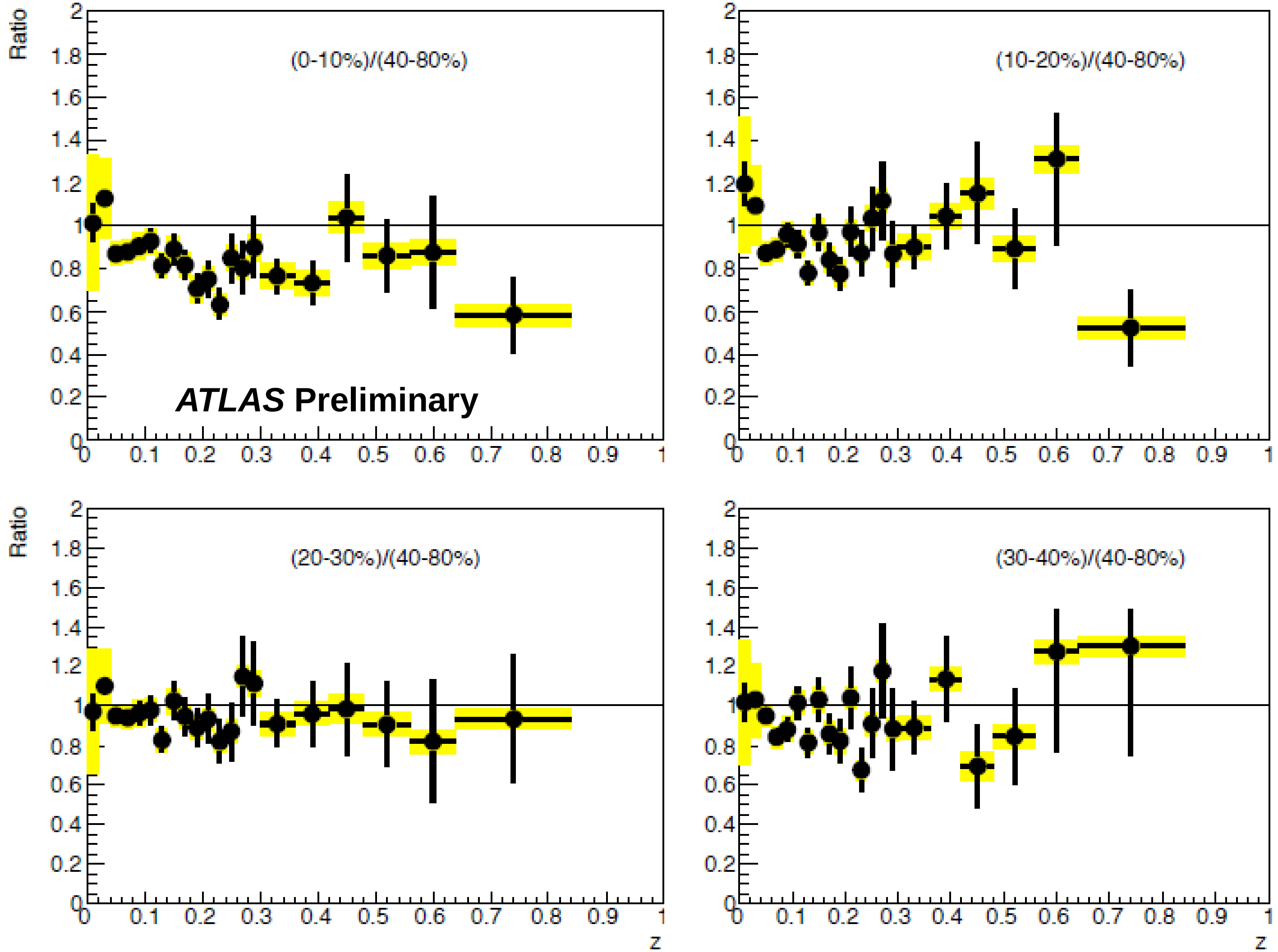


Dependence on jet radius for p_T<100 GeV in 0-10% central
Weaker dependence is observed in 10-20% centrality bin
No dependence on the jet radius is seen for more peripheral collisions

Jet fragmentation at QM'2011

$p_T^{had} > 2\text{GeV}$ $z \equiv \frac{p_T^{had}}{p_T^{jet}} \cos\Delta R$

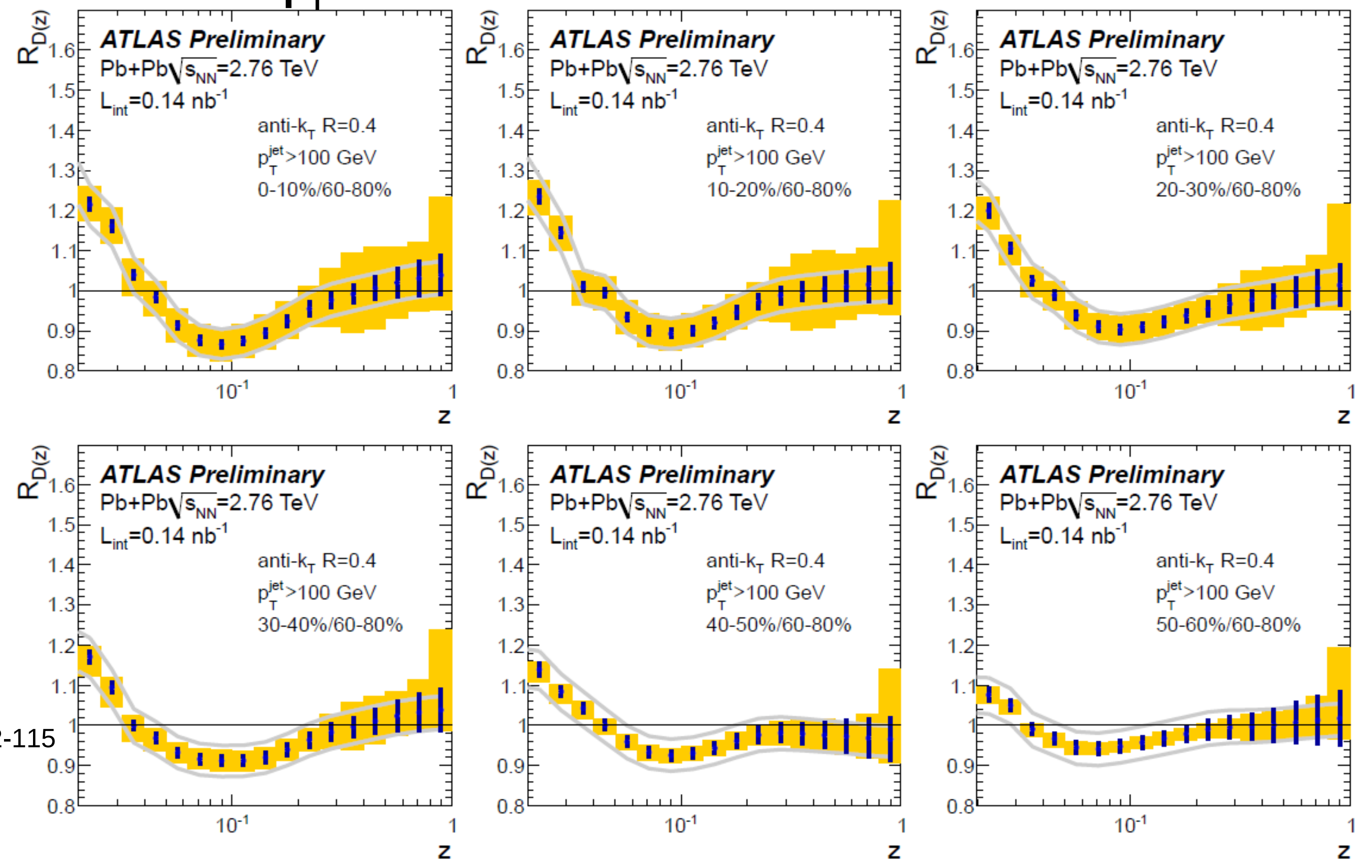
$R_{D(z)} \equiv D(z)_{cent} / D(z)_{40-80\%}$



Data 2010

Jet fragmentation

$p_T^{had} > 2\text{GeV}$ $\quad z \equiv \frac{p_T^{had}}{p_T^{jet}} \cos \Delta R$ $\quad R_{D(z)} \equiv D(z)_{cent} / D(z)_{60-80\%}$



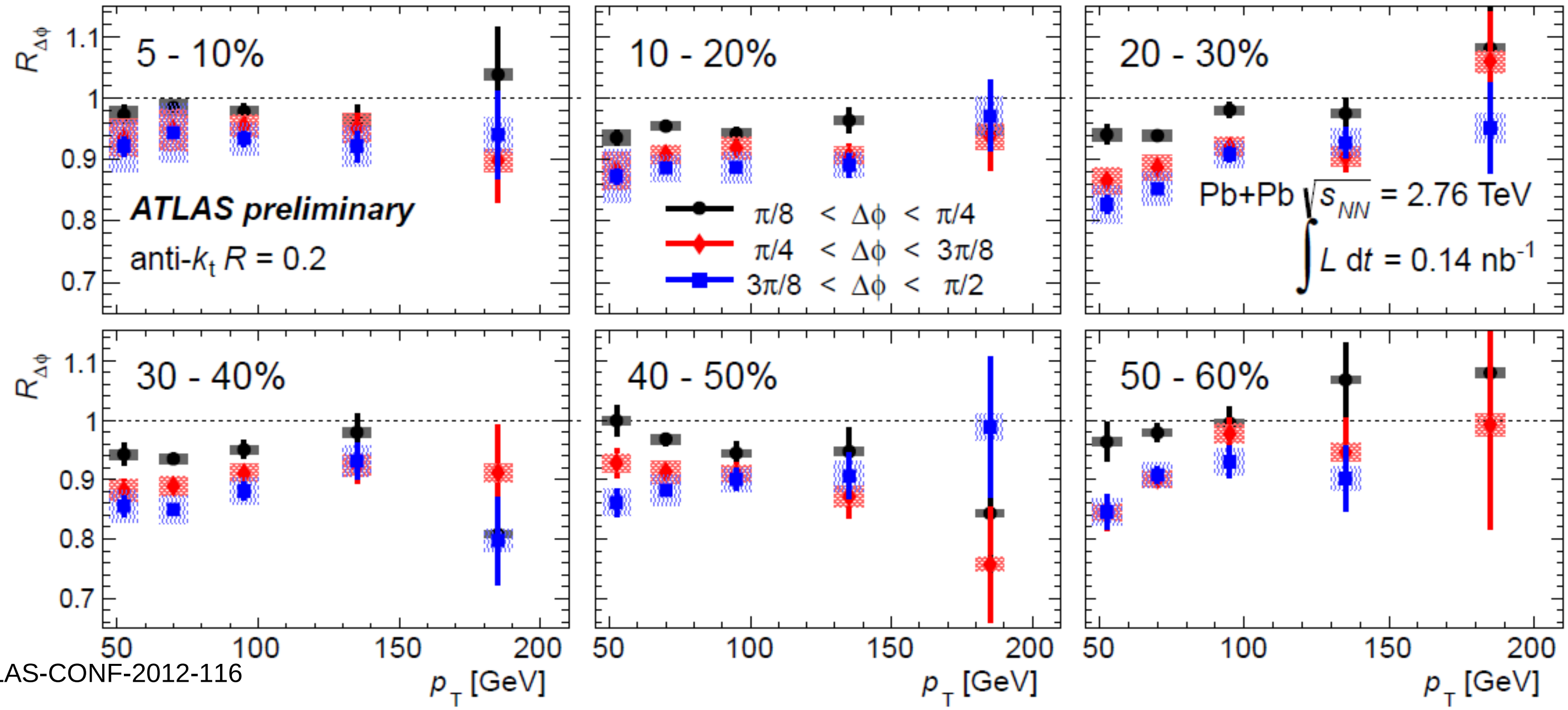
ATLAS-CONF-2012-115

- Enhancement at low z, suppression at z≈0.1
- No modification at high z
- Similar results found for R=0.2 and 0.3 jets

Azimuthal dependence of jet yields

- Path length dependence of jet suppression
- Ratios of yields in different slices of $\Delta\phi = \phi^{jet} - \Psi_2$

$$R_{\Delta\phi} = \frac{\left.\frac{d^2N_{jet}}{dp_T d\Delta\phi}\right|_{\Delta\phi=\Delta\phi_i}}{\left.\frac{d^2N_{jet}}{dp_T d\Delta\phi}\right|_{\Delta\phi=0-\pi/8}}$$

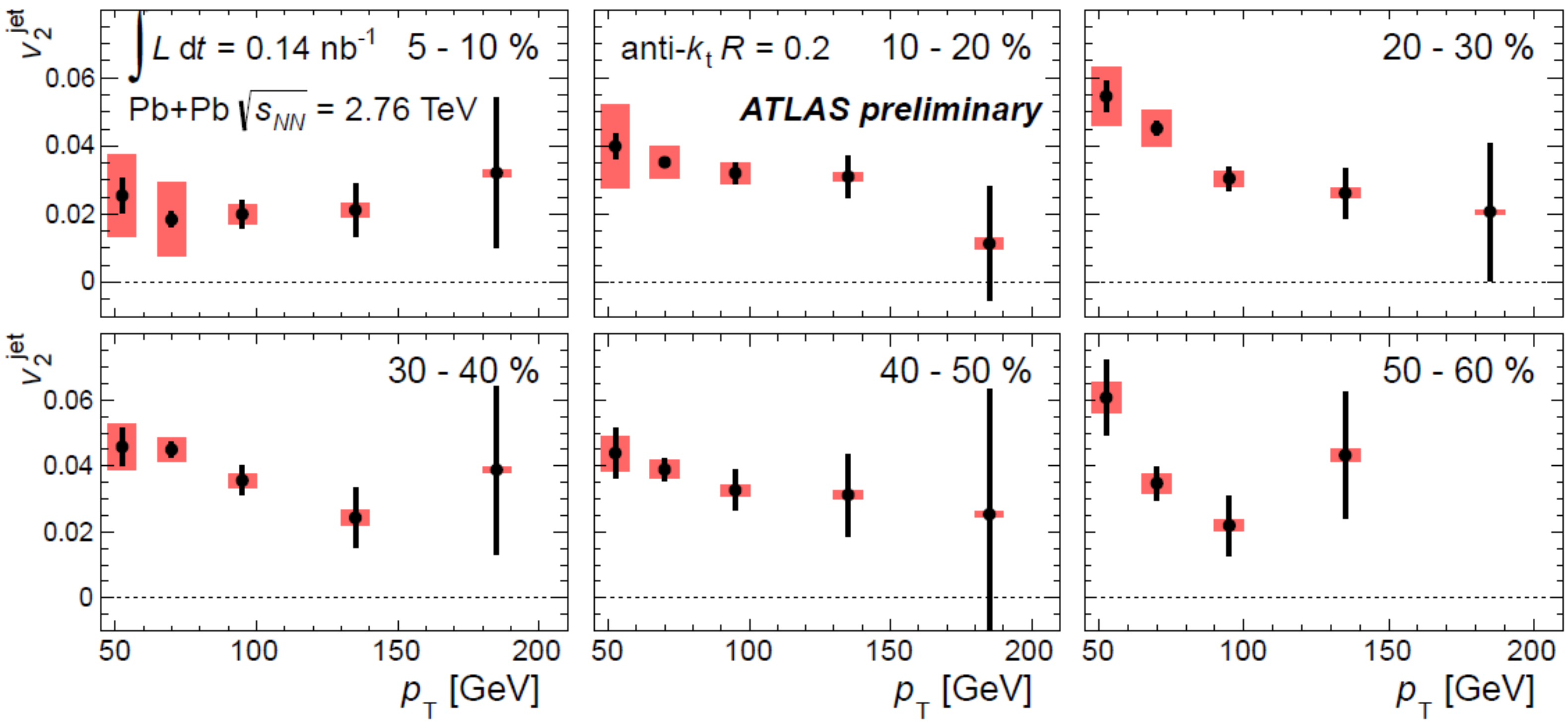


ATLAS-CONF-2012-116

  – Yields are reduced by about 15% for $3\pi/8<\Delta\phi<\pi/2$ relative to $0<\Delta\phi<\pi/8$

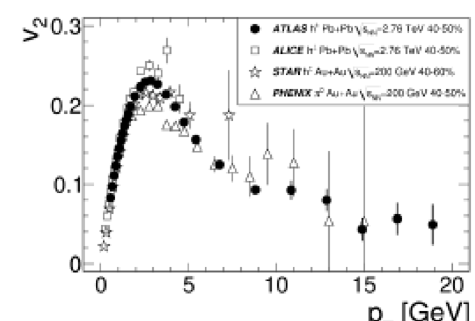
Jet v_2

- **Jet v_2 measured for $45 < p_T < 210$ GeV R=0.2 jets**



Charged hadrons

Phys. Lett. B707 (2012) 330-348



- **Weak dependence on p_T above 100 GeV**
- **Some evidence for increase at lower p_T**

ATLAS-CONF-2012-116

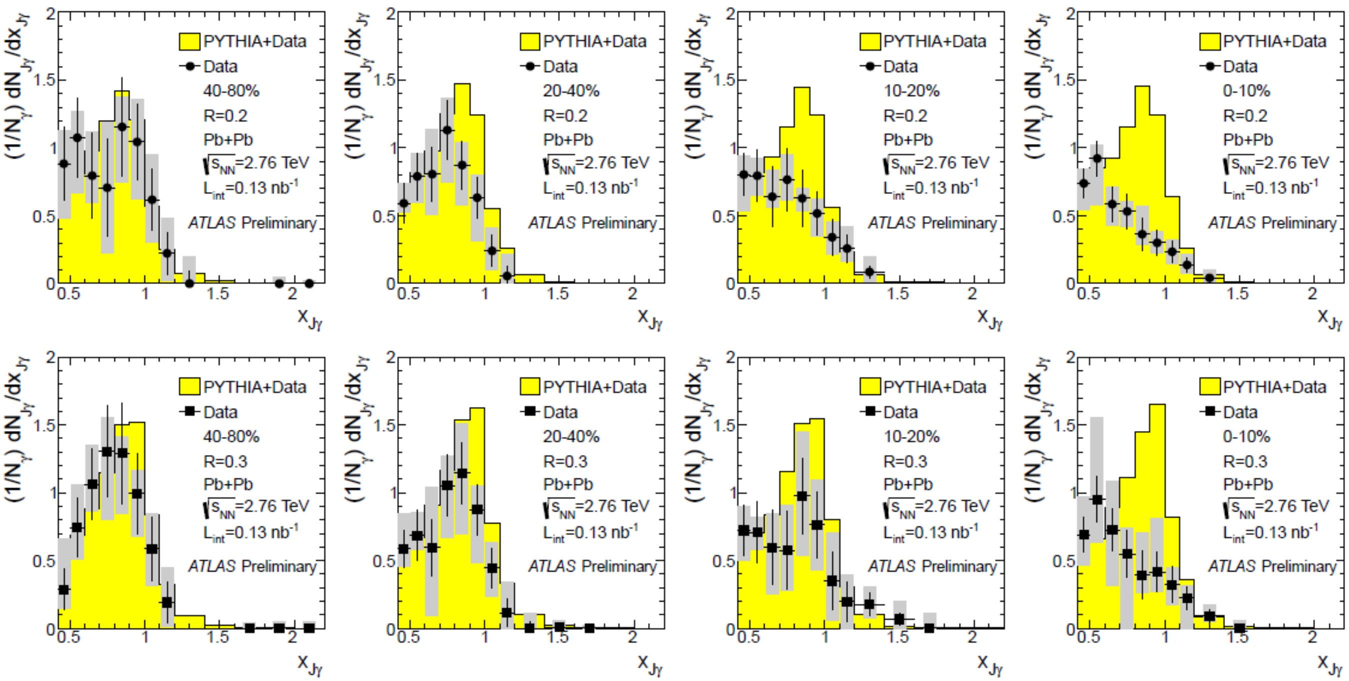
γ, Z – jet correlations

Modification of the jet energy relative to the probe not affected by the medium

γ - jet correlations

- **Large cross-section, purity 75-85%**
- **Eγ > 60 GeV: 60-90 GeV, |η|<1.3**
- **Jet: anti-kT, R=0.2, 0.3, p_T>25 GeV, |η|<2.1**
- **γ-jet separation Δϕ > 7π/8 (back-to-back)**

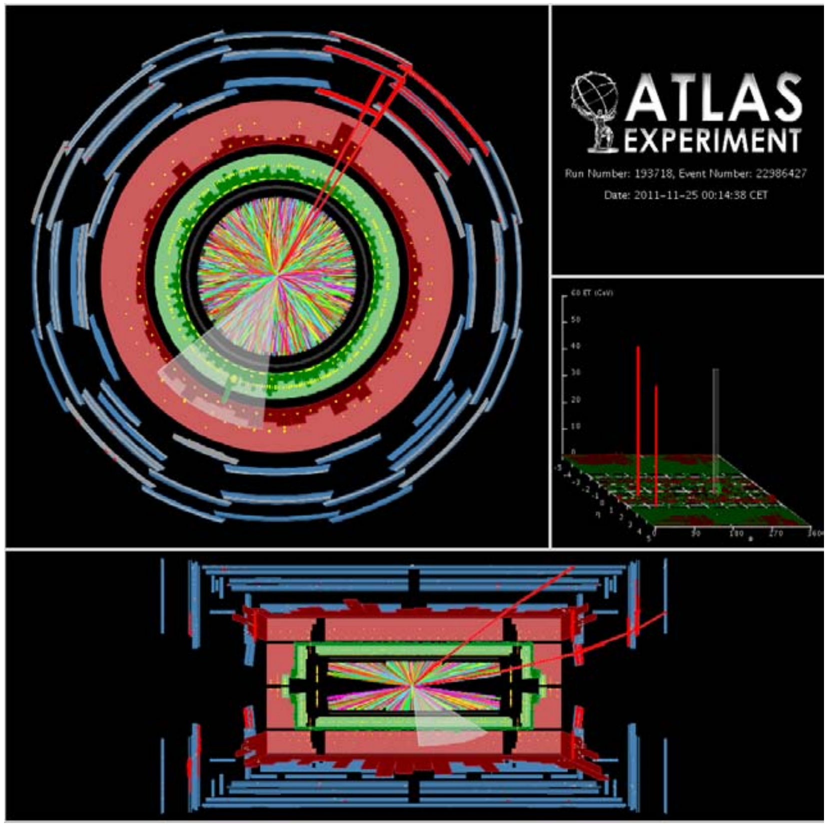
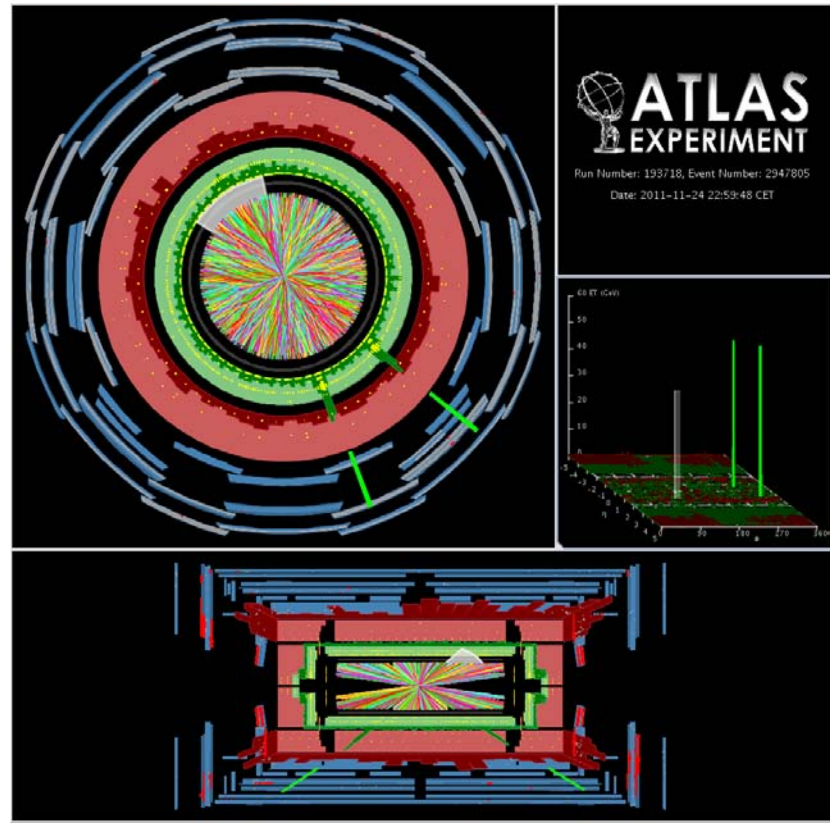
$$x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$$



- **Shape and integral compatible with PYTHIA for peripheral collisions**
- **With increasing centrality shift towards smaller $x_{J\gamma}$ and reduction of the integral**

ATLAS-CONF-2012-121

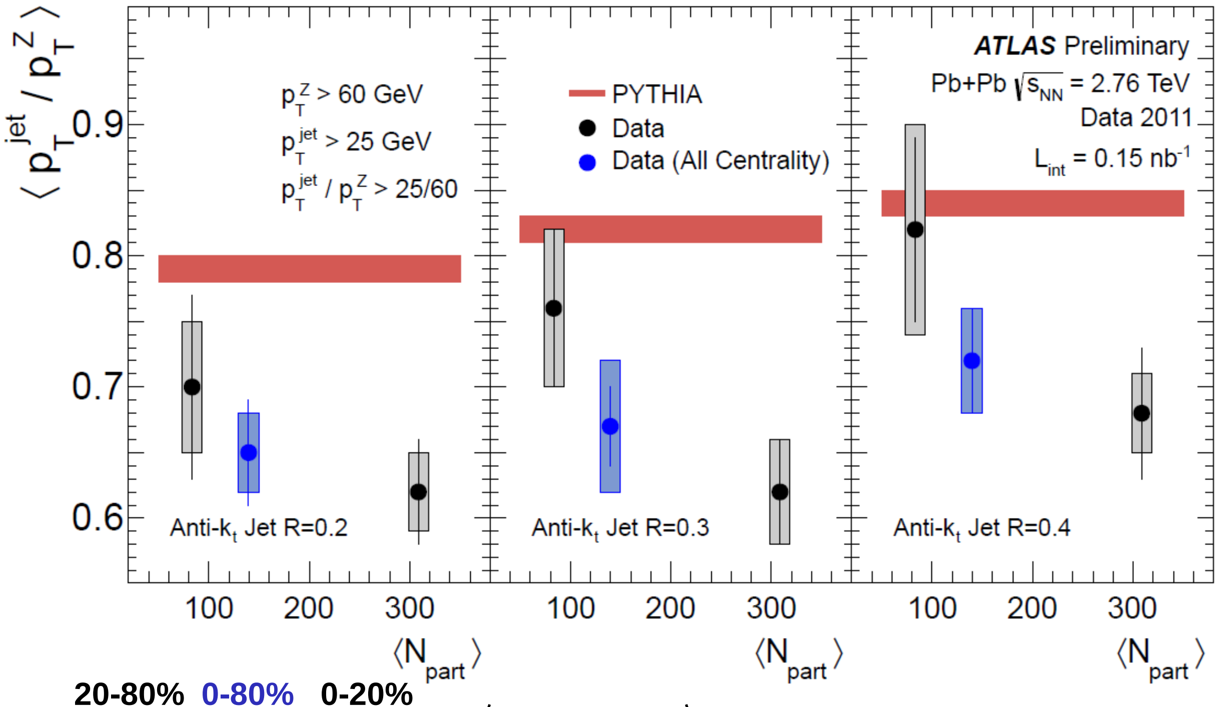
Z - jet correlations

$Z(\rightarrow \mu^+\mu^-)$ - jet	$Z(\rightarrow e^+e^-)$ - jet
	

ATLAS-CONF-2012-119

Z - jet correlations

- $Z \rightarrow e^+e^-, \mu^+\mu^-$ $p_T > 60$ GeV
- Jet: anti-kT, R=0.2, 0.3, 0.4, p_T>25 GeV, $|\eta|$<2.1
- Z-jet separation > $\pi/2$ $\rightarrow$ 37 events for L_{int}=0.15 nb^{-1}



$\langle p_T^{jet} / p_T^Z \rangle$

- Suppression of the $\langle p_T^{jet} / p_T^Z \rangle$ relative to MC simulations with no energy loss (PYTHIA: Z+jet events)
- Stronger suppression for more central collisions

ATLAS-CONF-2012-119

ATLAS results on jet studies at Quark Matter 2012:

Details in talks by:

- **Martin Spousta**, *plenary Tuesday*
- **Peter Steinberg**, Z,γ-jets, *plenary Thursday*
- **Zvi Citron**, Z-jet, *parallel 1B Tuesday*
- **Aaron R. Angerami**, *parallel 2B Tuesday*
- **Martin Rybar**, *parallel 3B Wednesday*

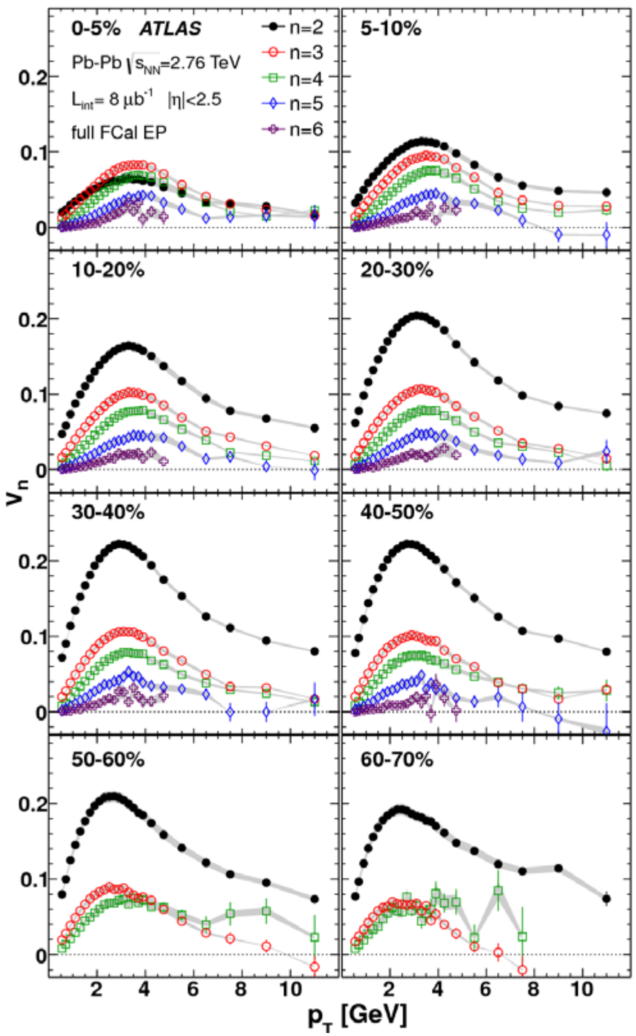
Summary

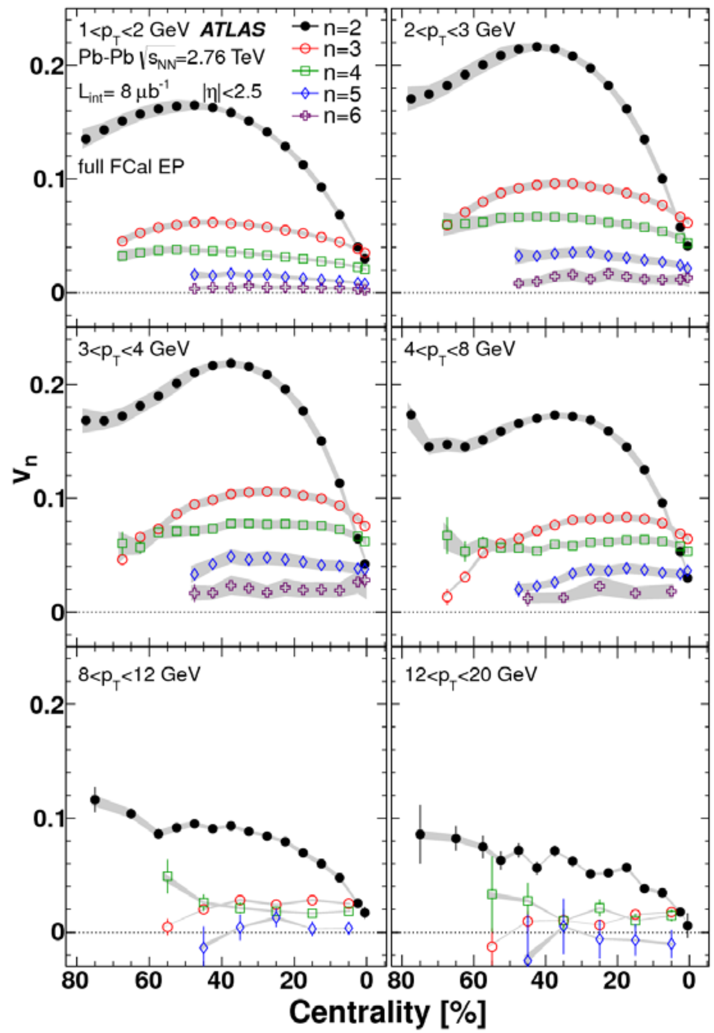
- **Collective flow**
  - New results on flow harmonics fluctuations
  - Constraints on hydrodynamic models
- **Electroweak probes**
  - Z and γ production consistent with N_{coll} scaling
- **Medium sensitive probes**
  - Heavy quarks are less suppressed than charged hadrons
  - Jet yields suppressed by a factor of 2 in central collisions
  - Jet suppression depends on the jet size in central collisions
  - Jet fragmentation function shows no modification at high z, but significant suppression with centrality at $z \approx 0.1$ and enhancement at very low z is observed
  - Azimuthal dependence of jet yields shows expected path length dependence
  - Jet v_2 weakly depends on jet p_T out to 200 GeV
  - Jet quenching also studied with Z,γ - jet correlations

Backups

Measurement of Fourier coefficients

Phys. Rev. C86 (2012)014907





Similar p_T dependence for n=2-6 flow harmonics

Weak centrality dependence observed for v_3-v_6

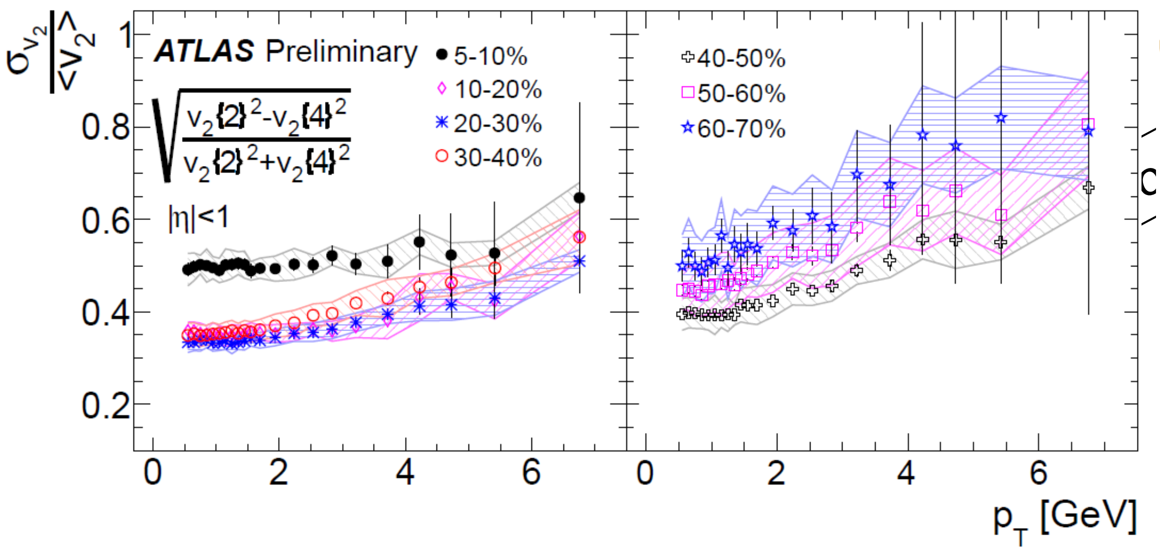
For the 5% most central events $v_3 > v_2$

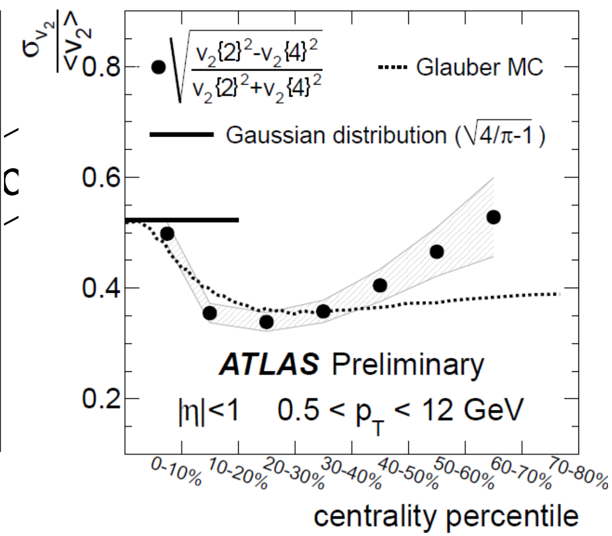
Elliptic flow fluctuations

- Extracted from 2- and 4-particle cumulants

$$\frac{\sigma_2}{< v_2 >} \approx \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$

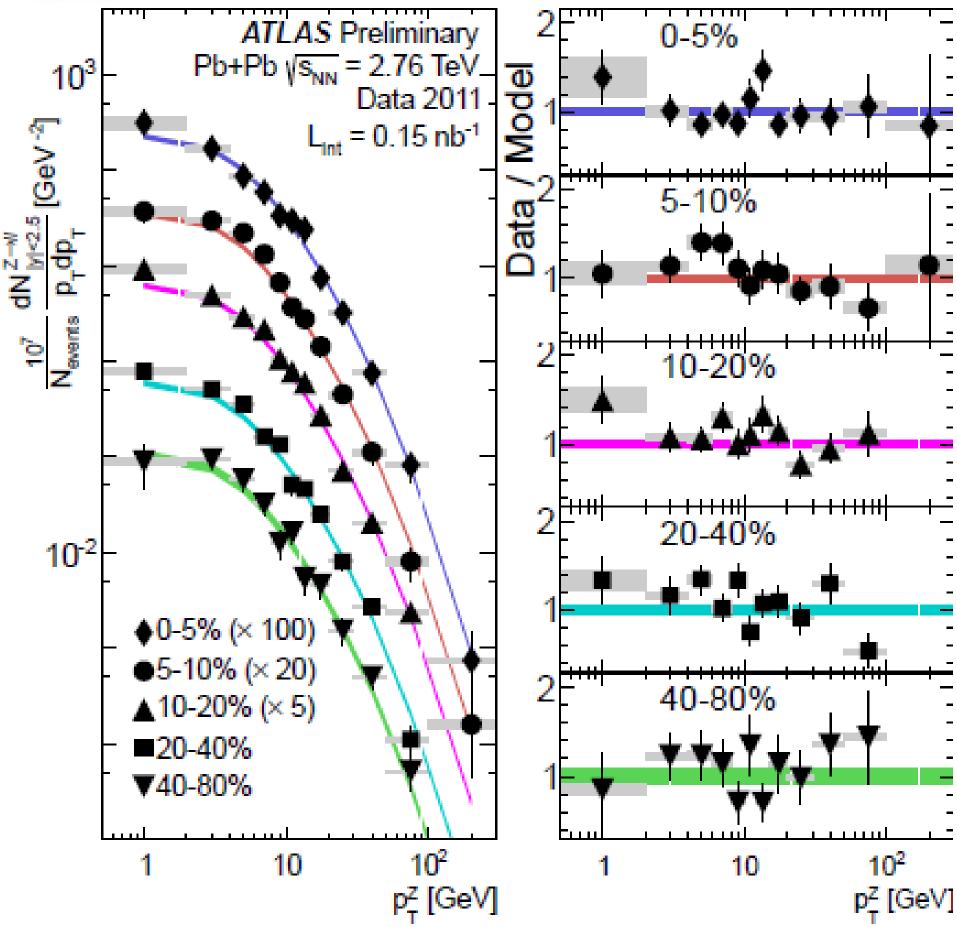
ATLAS-CONF-2012-137

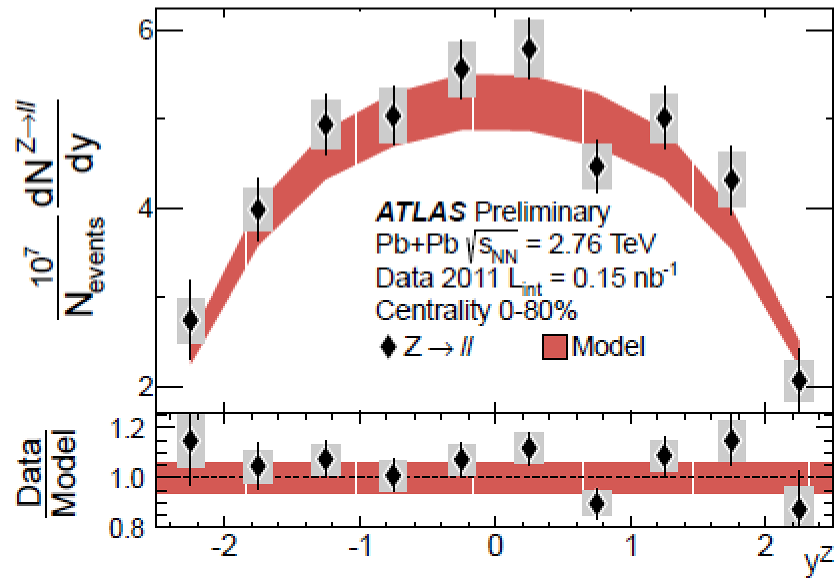




- weak p_T dependence for p_T < 2 GeV across all centralities; in 5-10% central p_T-independence holds up to higher p_T
- for p_T-integrated v_2, $\sigma_2/<v_2>$ comparable to Glauber model except for peripheral collisions
  (Glissando, W. Broniowki, M. Rybczynski, and P. Bozek, GLISSANDO: arXiv:0710.5731 [nucl-th])
- consistent with ALICE results arXiv:1205.5761 [nucl-ex].

Centrality dependence of Z yields





p_T and y distributions consistent with Pythia simulations for pp with NNLO cross section × $\langle T_{AA} \rangle$

Yields consistent with N_{coll} scaling

$v_2 = -0.011 \pm 0.018(\text{stat.}) \pm 0.014(\text{syst.})$