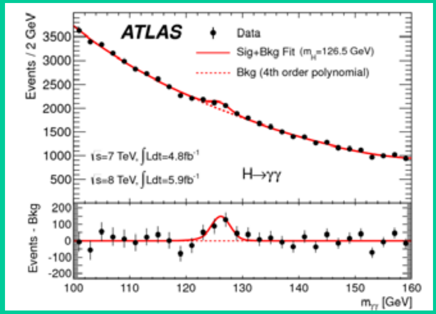
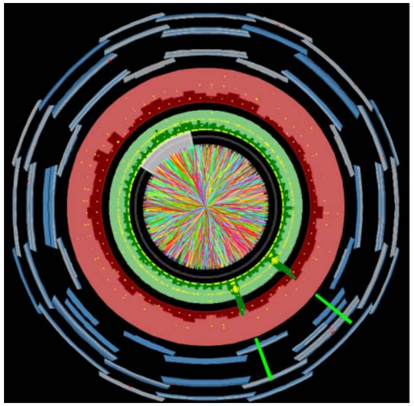
ATLAS Highlights



Recent results for Pb-Pb collisions with the ATLAS detector



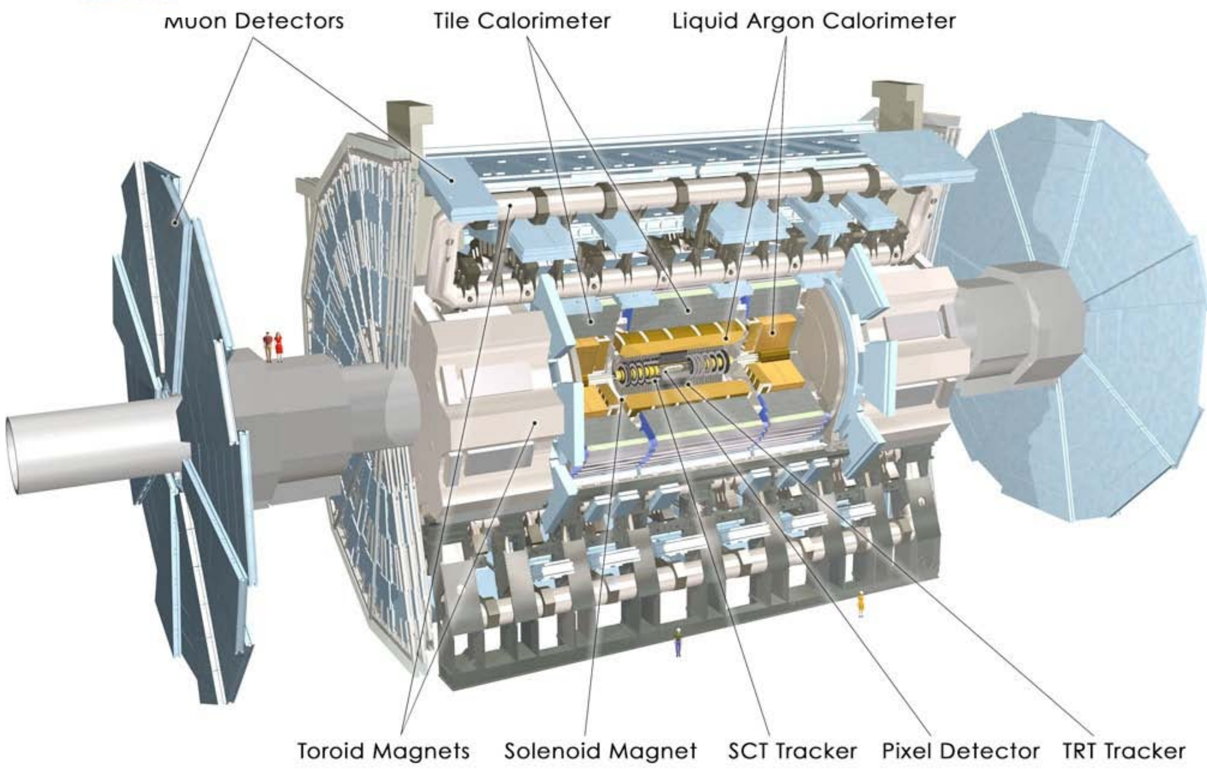
Barbara Wosiek, for the ATLAS Collaboration
Institute of Nuclear Physics PAS, Kraków, Poland

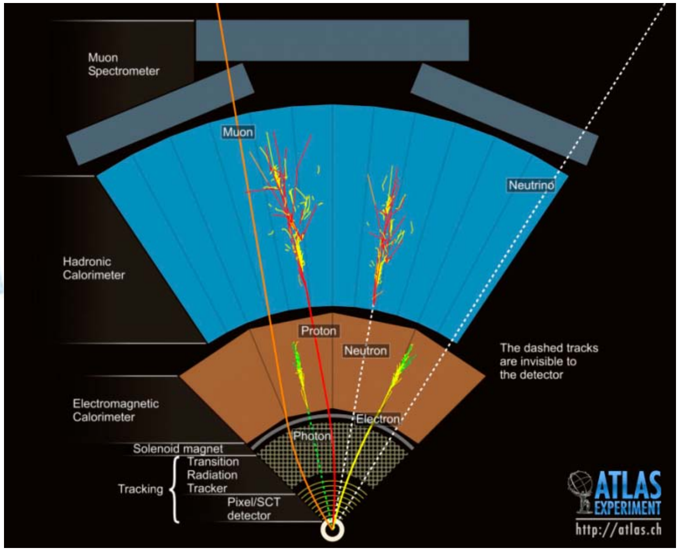
Talk given at Quark Matter 2012, Washington D.C., August 2012

Outline

- **ATLAS detector**
- **Lead-lead data taking**
- **Collective flow**
- **Electroweak probes**
- **Medium-sensitive probes**
  - Charged hadron suppression
  - Heavy quark production
  - Jet suppression
  - Jet fragmentation
  - Path length dependence of jet suppression
  - Jet v_2
  - γ,Z – jet correlations
- **Summary**

The ATLAS detector



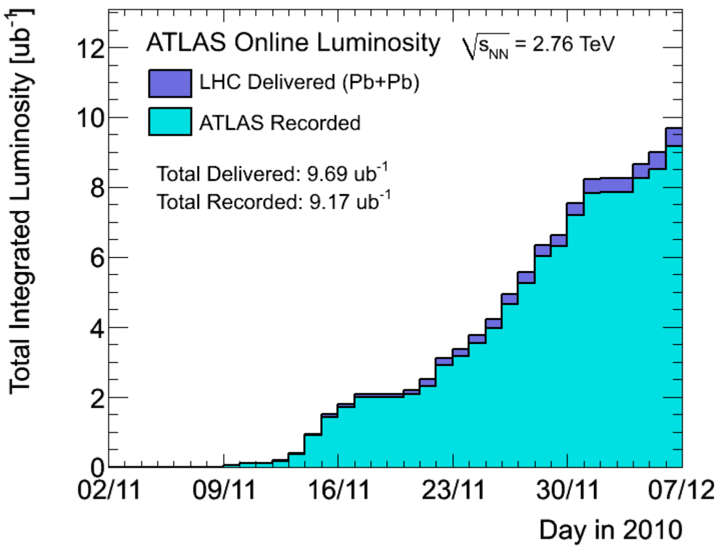


Three main subsystems with a full coverage in azimuth:

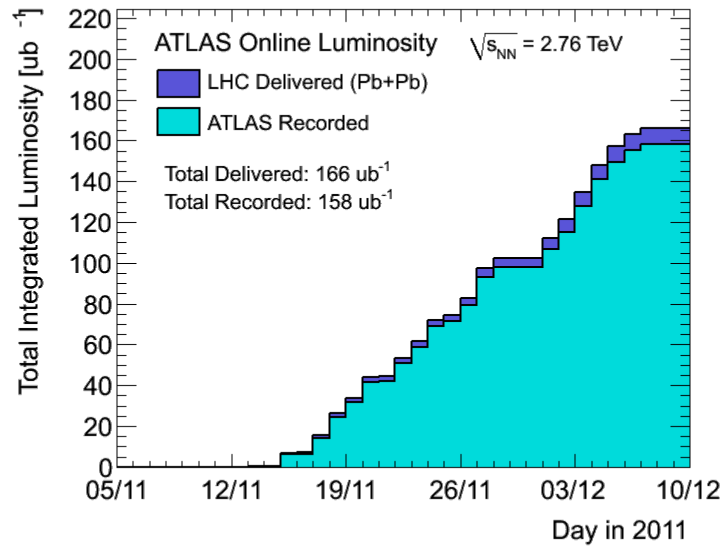
- **Inner Detector – tracking $|\eta|<2.5$**
- **Calorimetry – $|\eta|<4.9$**
- **Muon Spectrometer - $|\eta|<2.7$**

Lead-lead data taking

2010



2011

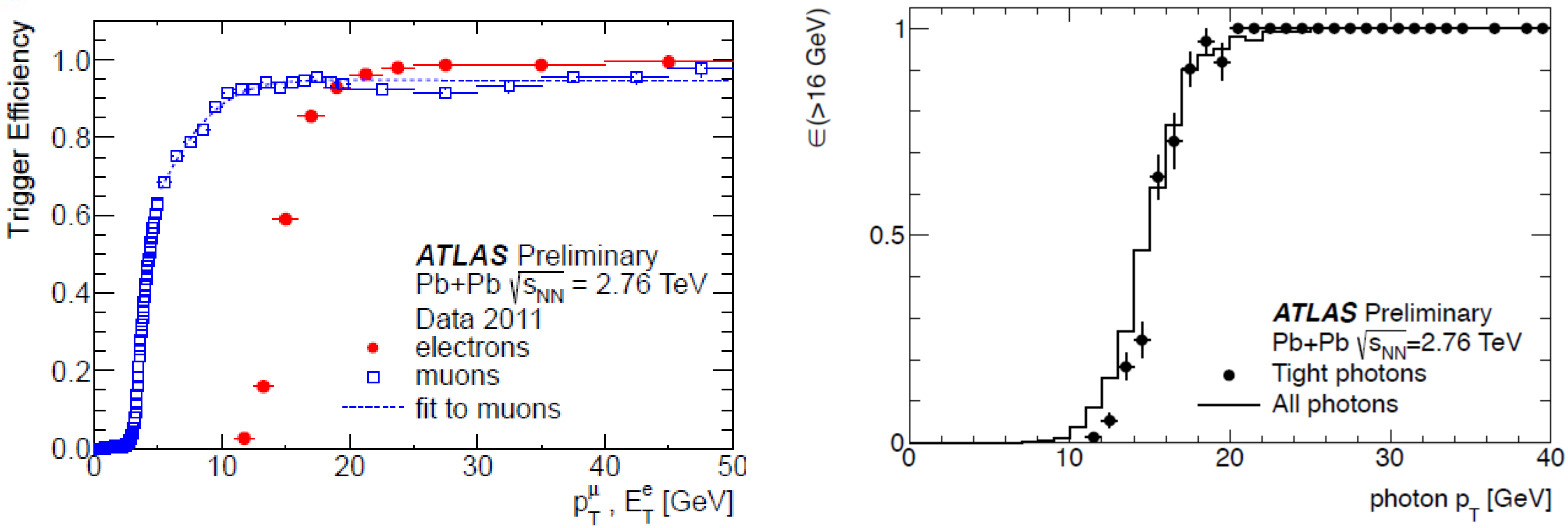


L_{int}	**8 μb^{-1}**	**0.15 nb^{-1}**
Detector eff.	**> 97%**	**> 97%**
Triggers	**MB**	**MB, e, μ, γ, jets, UPC**
Events[$\times 10^6$]	**~50**	**~1000**

MB – Minimum Bias

Thanks LHC!

Triggers in 2011



Electrons and photons

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

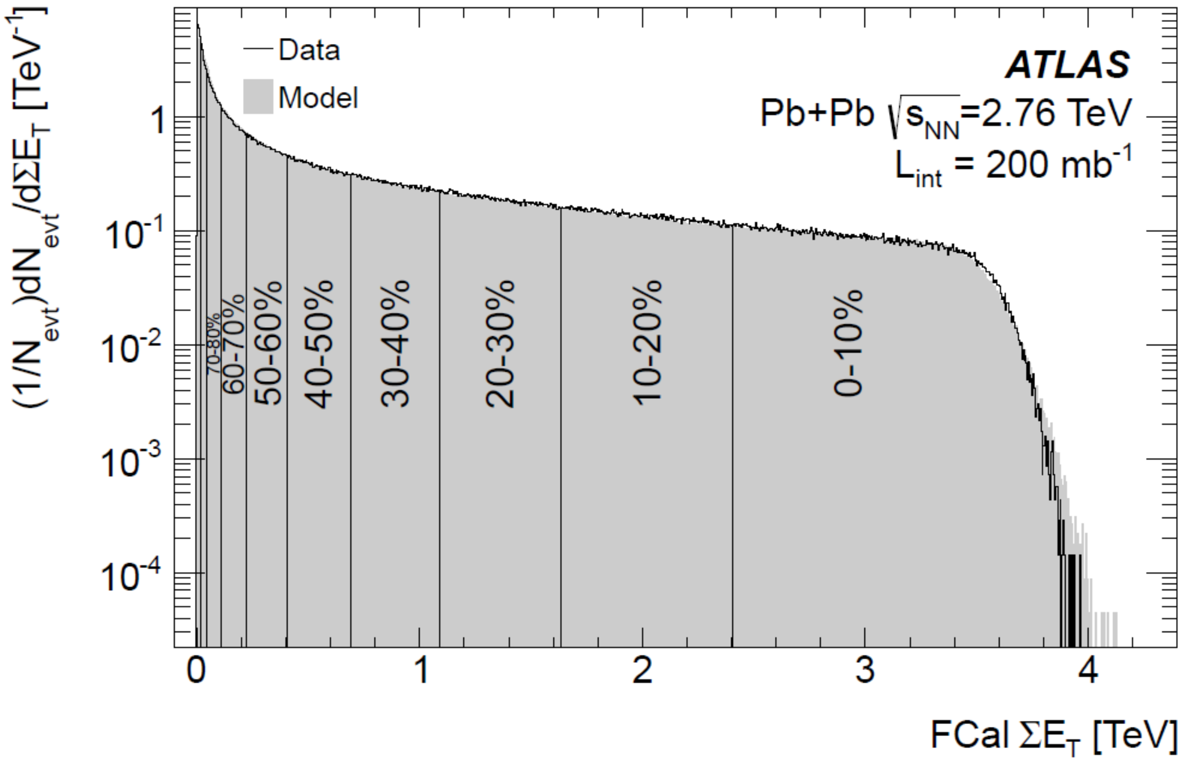
Muons

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) :

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

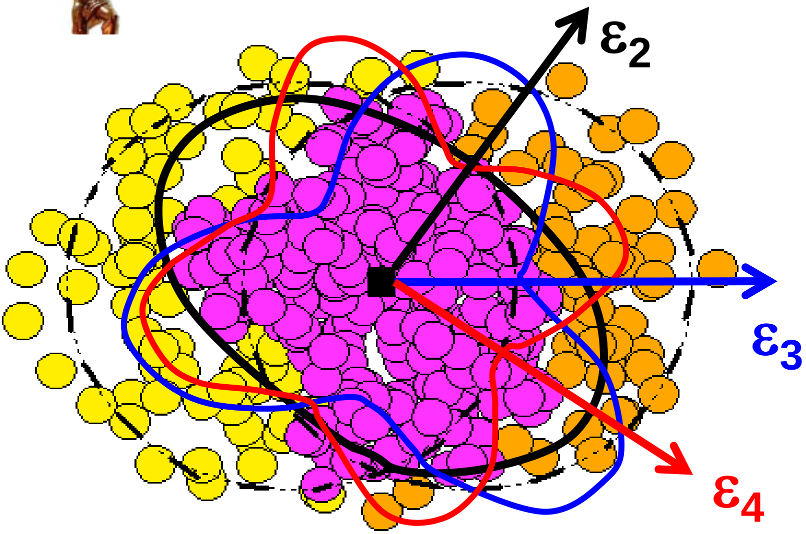
  - **with two-particle correlations (2PC)**

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

  - **with 2- and 4-particle cumulants**

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

Collective flow measurements



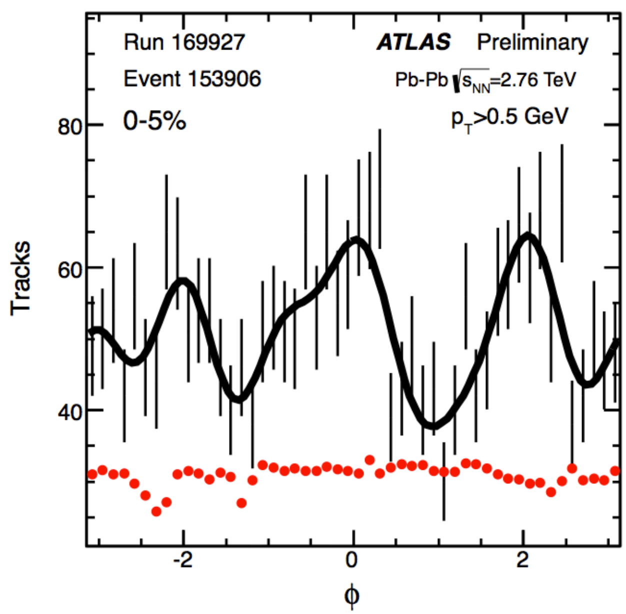
Initial configuration plane

- Transverse positions of nucleons (r, ϕ)
- From Glauber or KLN models amplitude and direction
  arXiv:nucl-ex/0701025, Phys. Rev. C 74, 044905 (2006)

$$\varepsilon_n = \frac{\sqrt{<r^n \cos n\phi>^2 + <r^n \sin n\phi>^2}}{<r^n>}$$

$$\tan(n\Phi_n^*) = \frac{<r^n \sin n\phi>}{<r^n \cos n\phi>}$$

HYDRODYNAMICS



Final state symmetry plane

Charged particle azimuthal angle $\phi = p_y/p_x$

$$n\Phi_n = \tan^{-1}\left(\frac{\Sigma w_i \sin(n\phi_i)}{\Sigma w_i \cos(n\phi_i)}\right)$$

$$v_n = \langle \cos(n[\phi - \Phi_n]) \rangle$$

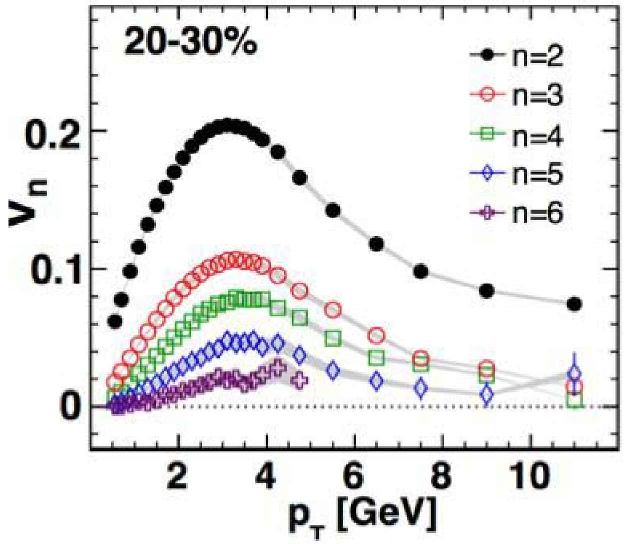
Corrected for resolution

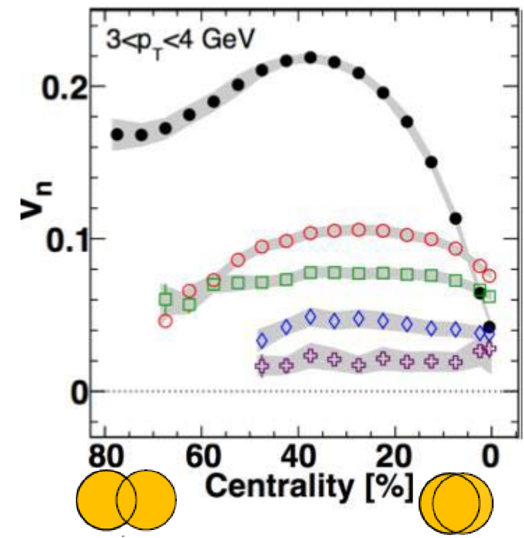
$$\frac{dN_{ch}}{d\phi} \propto 1 + \sum_n v_n \cos(n[\phi - \Phi_n])$$

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 $v_3 > v_2$

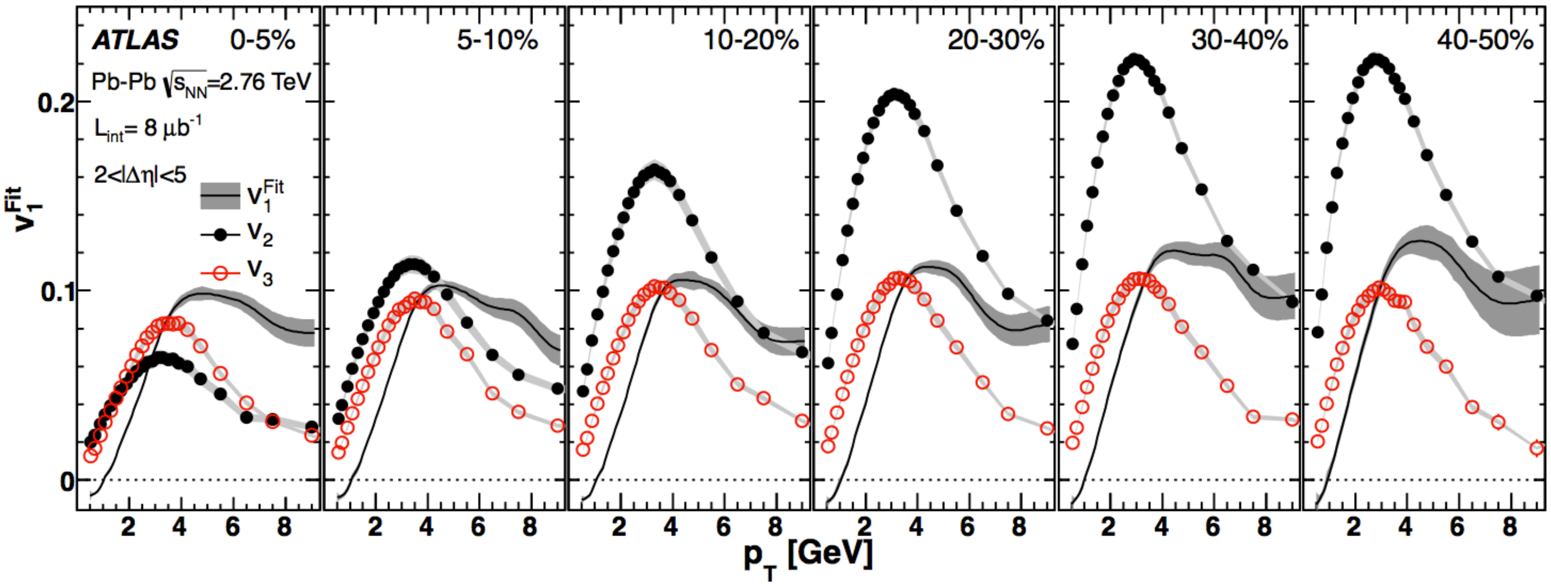
Significant v_n (n>2)

➢**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: $v_{1,1}(p_T^a, p_T^b) \approx v_1(p_T^a) v_1(p_T^b) - \frac{p_T^a p_T^b}{M\langle p_T^2 \rangle}$



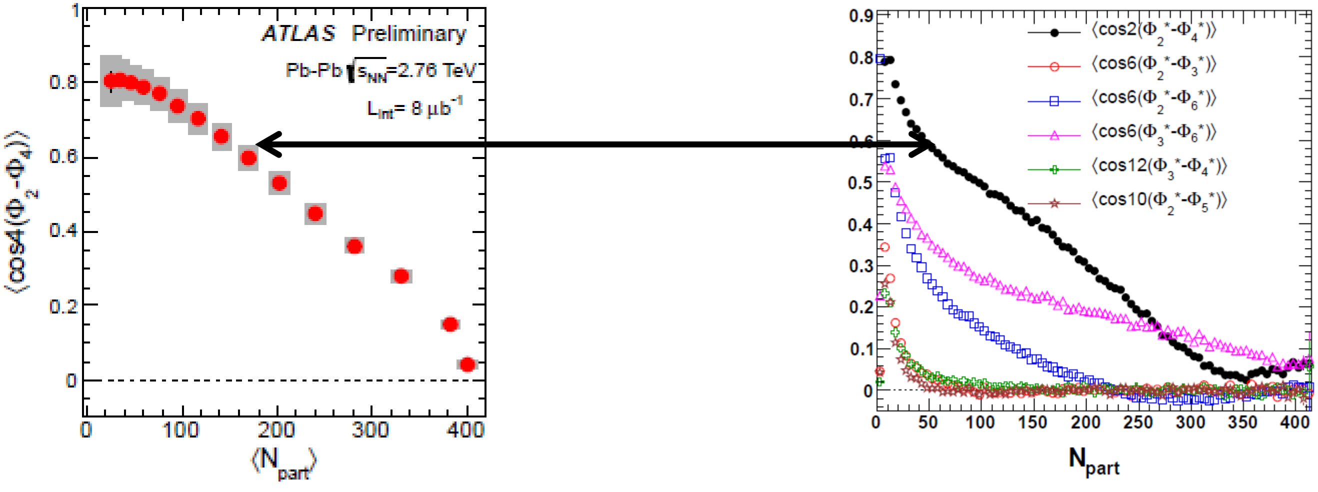
- v_1 signal is negative at p_T<~ 1 GeV, reaches a maximum at around 4–5 GeV and decreases at higher p_T
- The magnitude of v_1 at peak is comparable to that of v_3
- v_1 signal arises from the dipole asymmetry of the nuclear overlap due to fluctuations in the initial geometry

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

<cos4(Φ_2-Φ_4)>

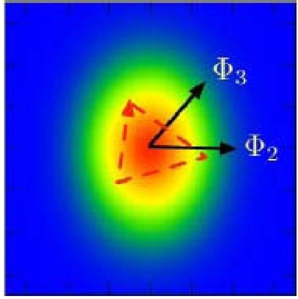
Glauber MC predictions



– Some correlations show trends qualitatively, but not quantitatively, similar to Glauber model, others differ significanlty

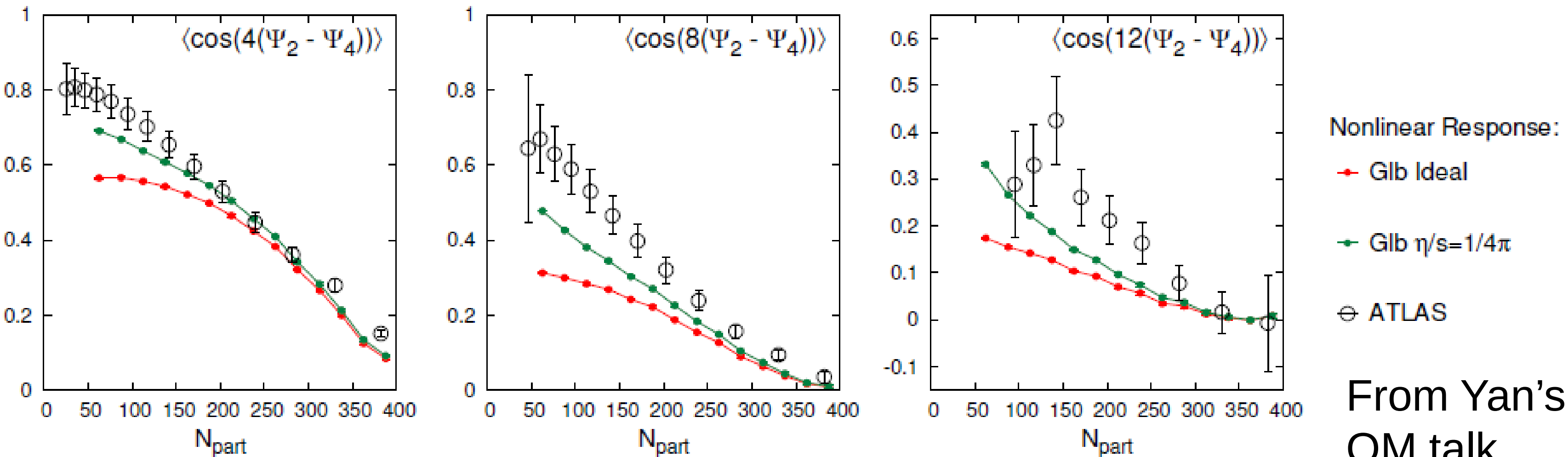
– Observed correlations can be partially attributed to the fluctuations in the initial geometry, but may also arise during the dynamical evolution of the created system

Event plane correlations



- **Correlations can be generated dynamically via hydrodynamic evolution**
  - Qiu and Heinz, arXiv:1208.1200
  - **Teaney and Yan, arXiv:1206.1905**

$$\underbrace{\text{Initial correlations}}_{\text{Initial state(cumulants)}} + \underbrace{\text{Flow response}}_{\text{Linear \& \underline{Non-linear}}} = \underbrace{\text{Reaction place correlations}}_{\text{Final state}}$$



From Yan's QM talk

Elliptic flow fluctuations

- Extracted from 2- and 4-particle cumulants

$$\frac{\sigma_2}{\langle v_2 \rangle} \approx \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$

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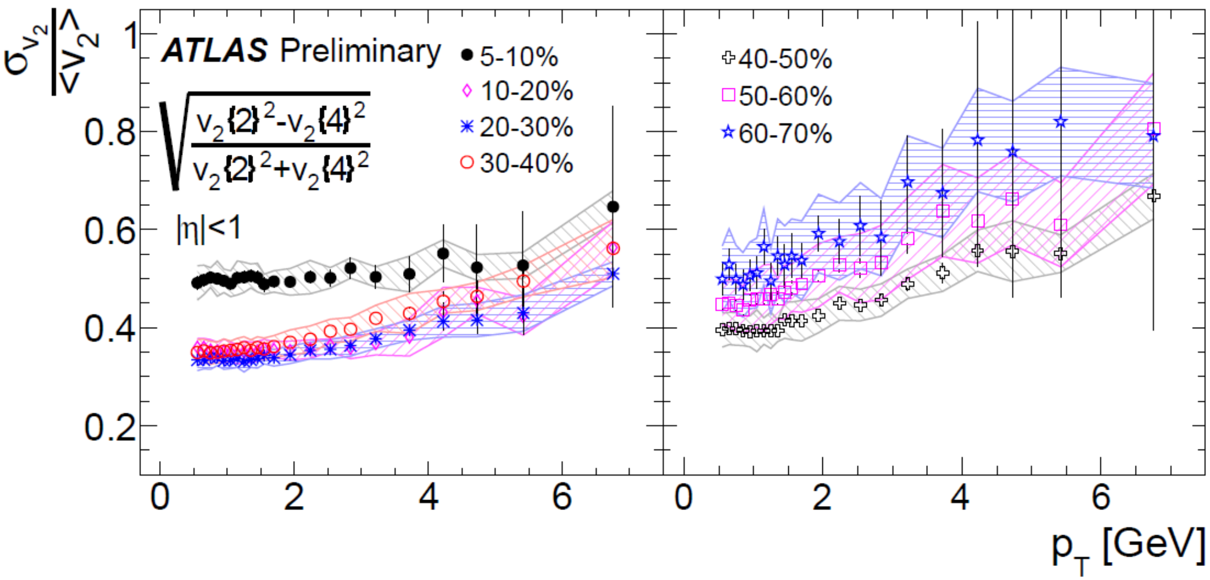
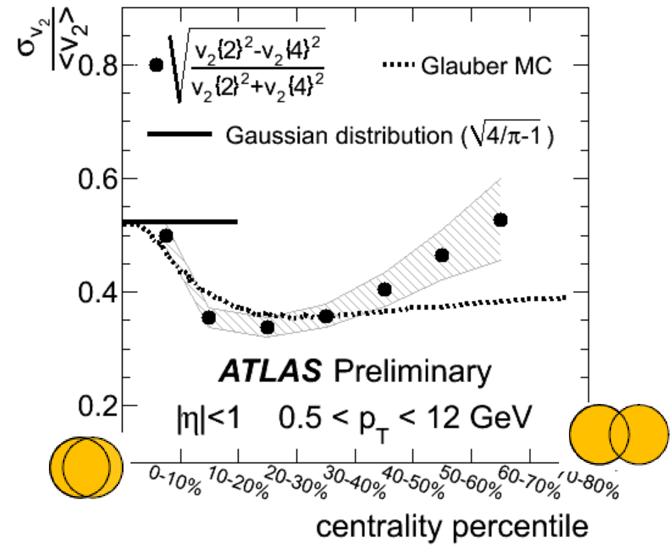
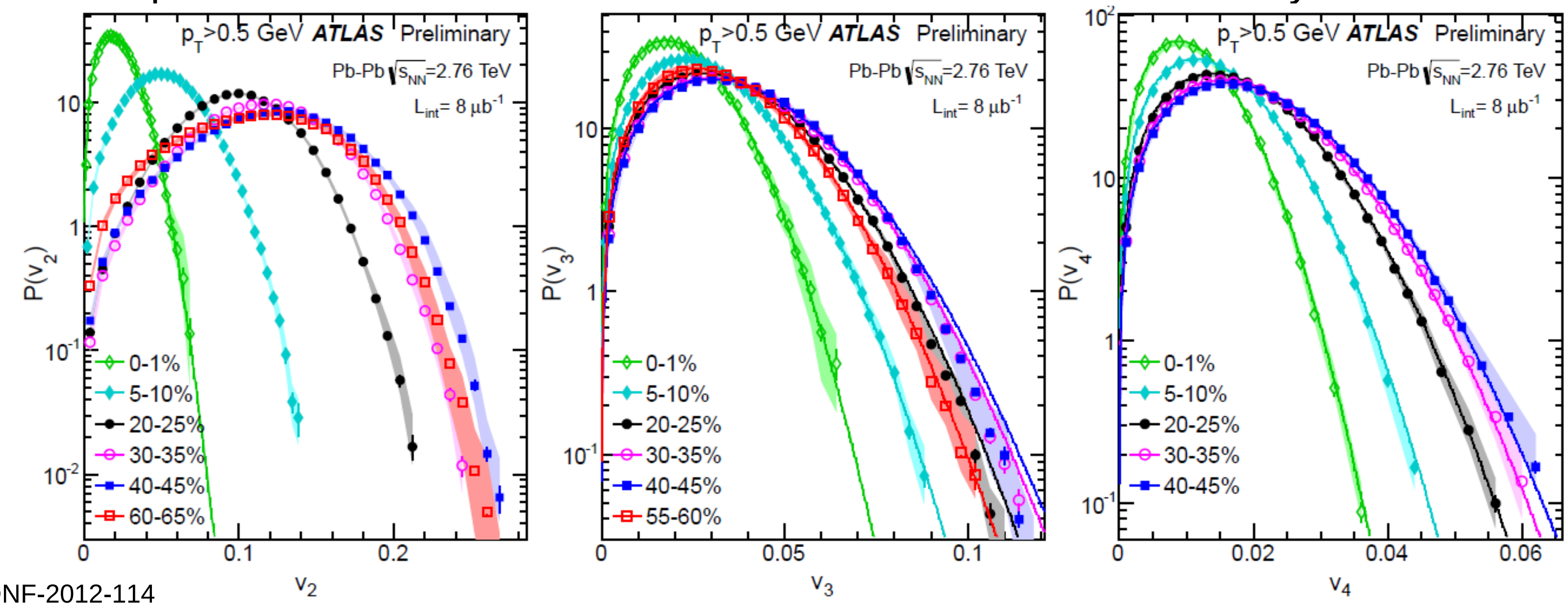




- weak p_T dependence for p_T < 2 GeV across all centralities;
- in 5-10% central p_T-independence holds up to higher p_T
- for p_T-integrated v_2, $\sigma_2/\langle v_2 \rangle$ comparable to Glauber model except for peripheral collisions
  (Glissando, W. Broniowki, M. Rybczynski, and P. Bozek, GLISSANDO: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

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



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- **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

Flow harmonics fluctuations

$$\frac{\sigma_{v_n}}{< v_n >}$$

for three p_T ranges:

$0.5 < p_T < 1$ GeV

$p_T > 0.5$ GeV

$p_T > 1$ GeV

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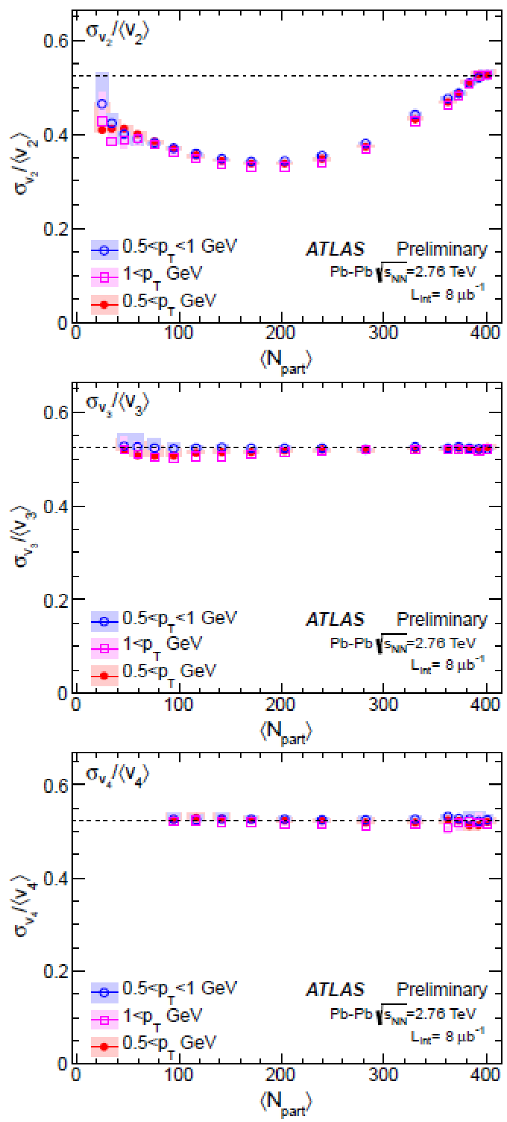


- **dotted lines show Gaussian limit**

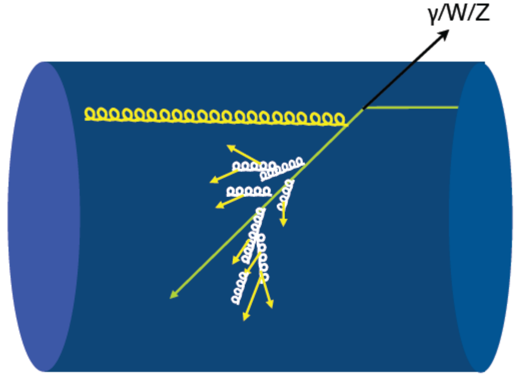
$$\frac{\sigma_n}{< v_n >} = \sqrt{\frac{4}{\pi} - 1} \approx 0.523$$

- **no p_T dependence in the above p_T ranges**
- **$\sigma_{v2}/<v_2>$ shows strong centrality dependence**
- **$\sigma_{v3}/<v_3>$ and $\sigma_{v4}/<v_4>$ centrality-independent, consistent with the value expected from Gaussian**
- **Compared to eccentricity distributions from Glauber and CCG (KLN) models:**
  - **Glauber better describes the data**
  - **Both models fail to describe shapes of v_n distributions in peripheral collisions**

Electroweak probes

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

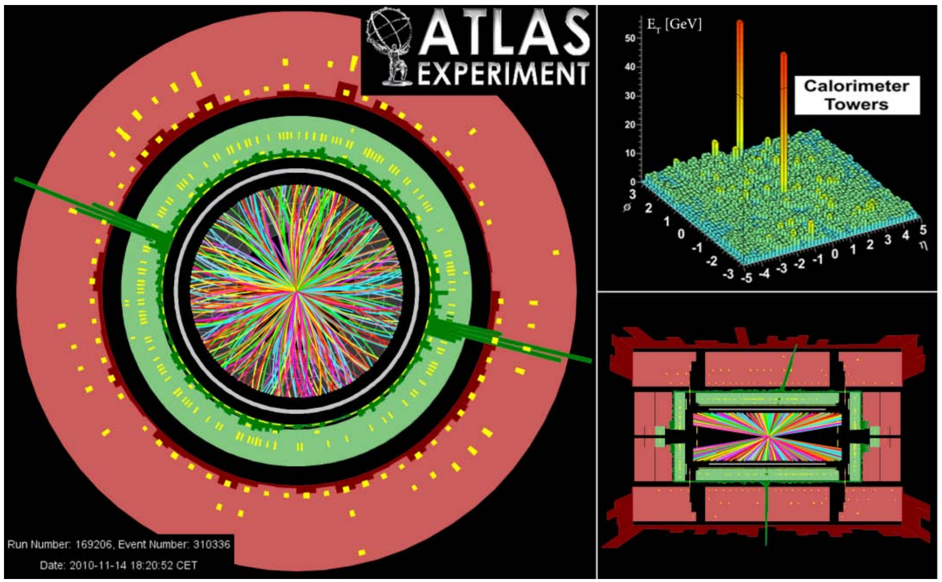
should obey OCD factorization (scaling with N_{coll})



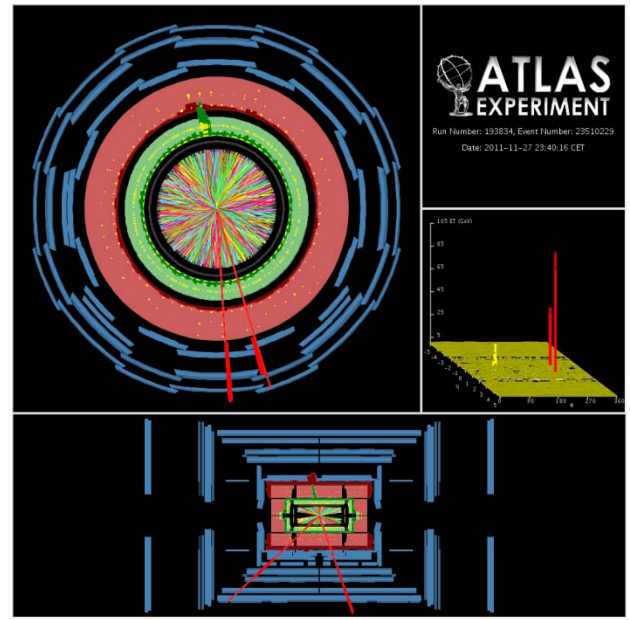
- **Measurements of Z/W/γ production in Pb+Pb provide constraints on the nuclear PDF**
- **Z/W/γ bosons can be used as a reference**
- **Production of Z/W/γ in association with jets provides a handle for understanding the parton energy loss in medium**

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

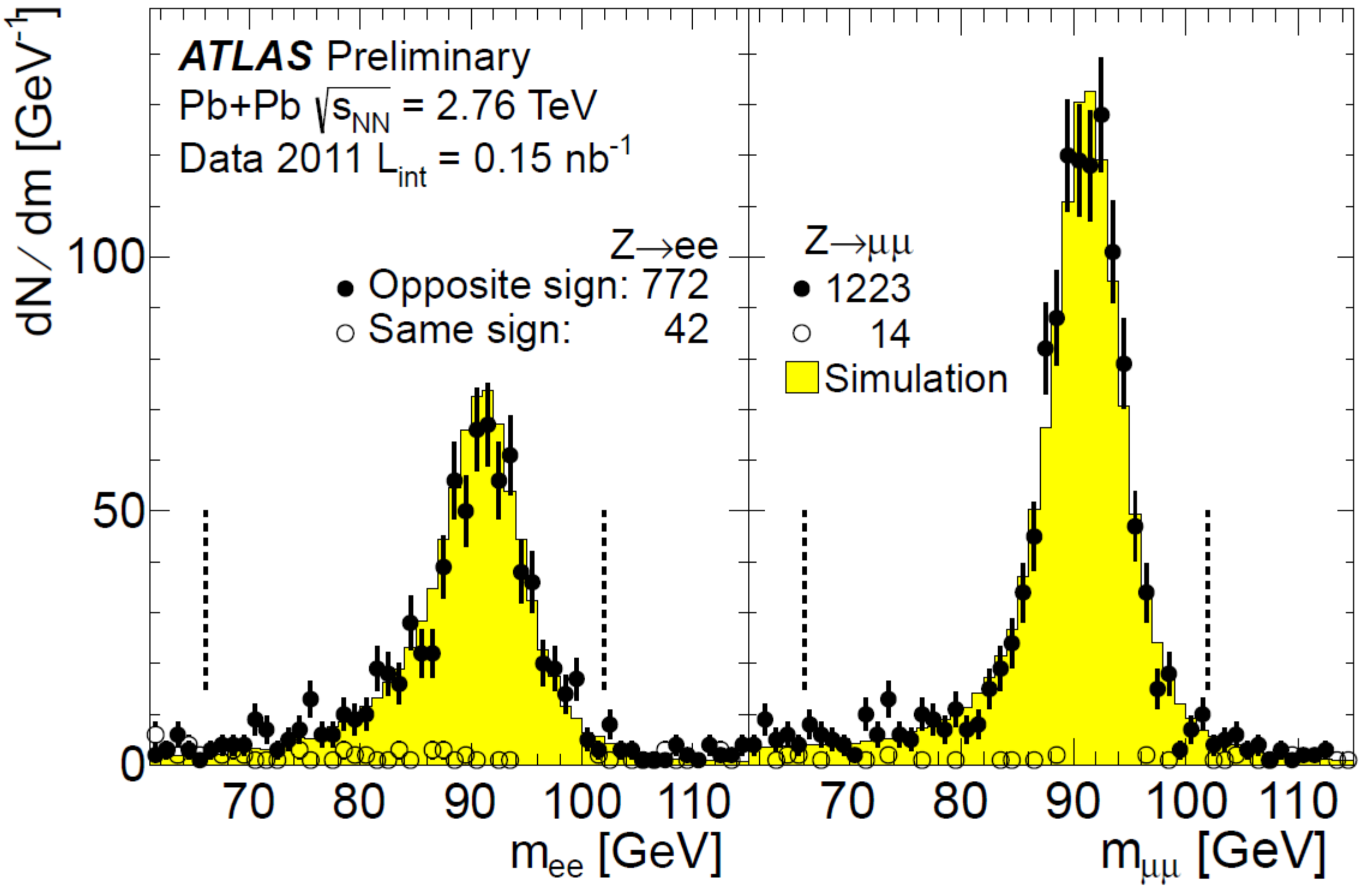
$Z \rightarrow e^+e^-$ candidate



$Z \rightarrow \mu^+\mu^-$ candidate



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



Electron selection

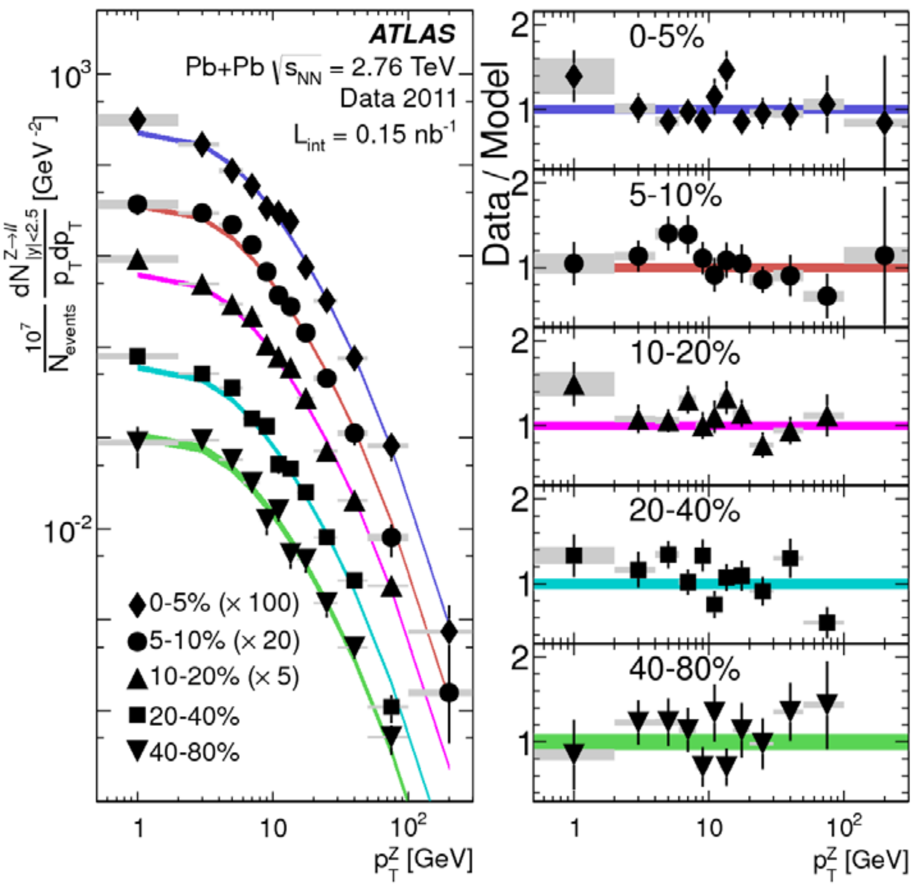
- E_T >20 GeV
- $|\eta|$<2.5
- Shower shape and energy cuts
- Subtraction of the UE energy

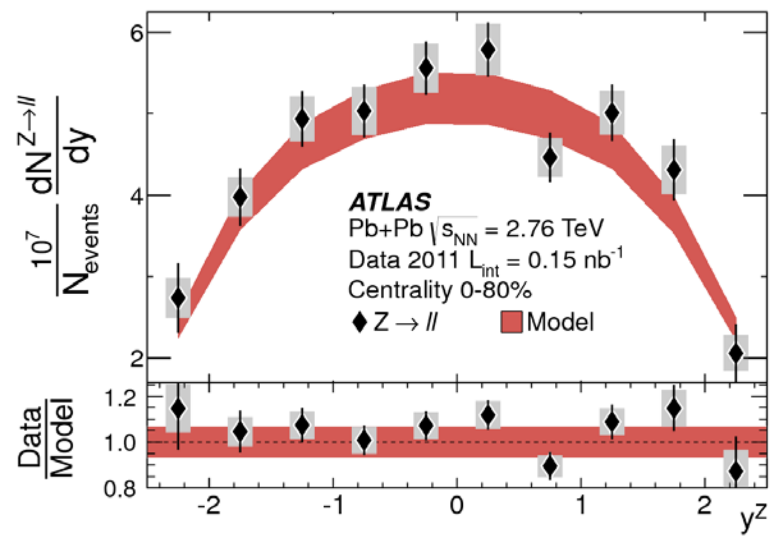
Muon selection:

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

p_T and y distributions of Z bosons

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



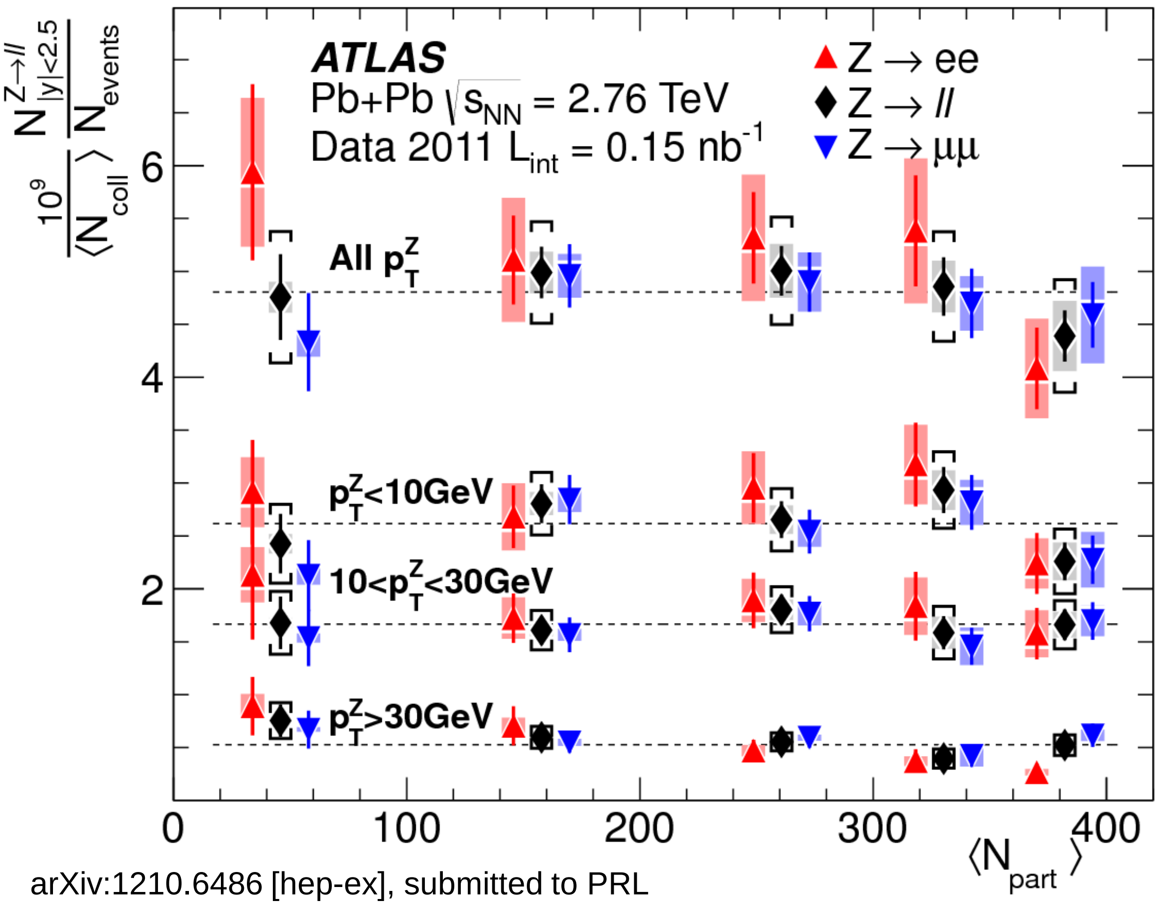


p_T and y distributions consistent with Pythia simulations for pp with NNLO cross section × $\langle T_{AA} \rangle$

arXiv:1210.6486 [hep-ex], submitted to PRL

Centrality dependence of Z's production

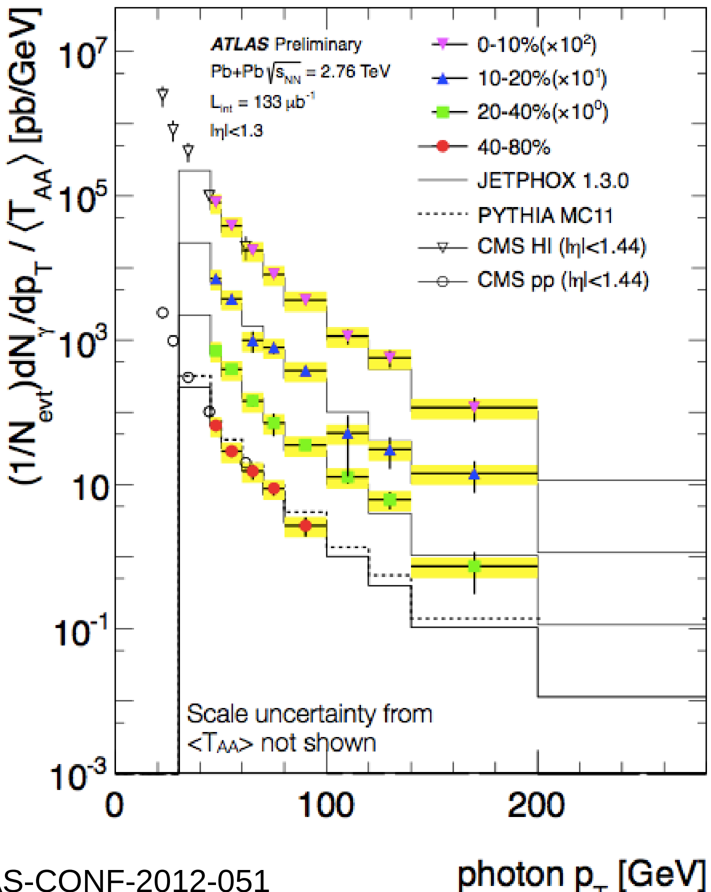
$Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$



arXiv:1210.6486 [hep-ex], submitted to PRL

Yields consistent with N_{coll} scaling

Prompt photon production



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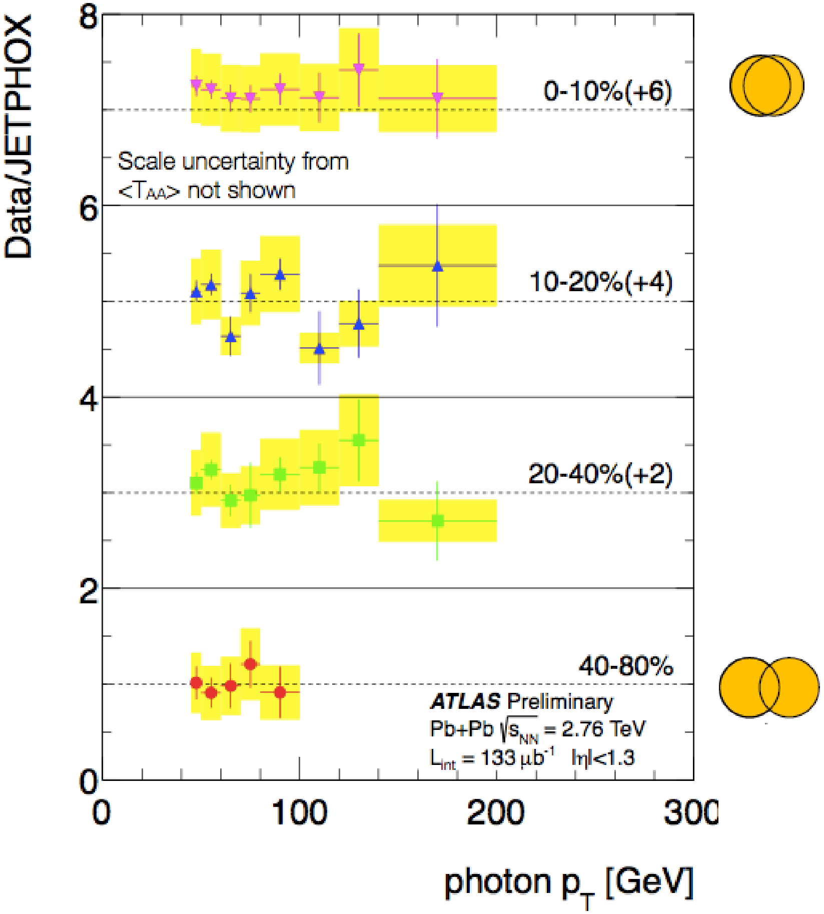


Yields scaled by T_{AA} and compared to JETPHOX predictions

Ratio: Data/JETPHOX ≈ 1 (~R_{AA})

Electroweak probes: Summary

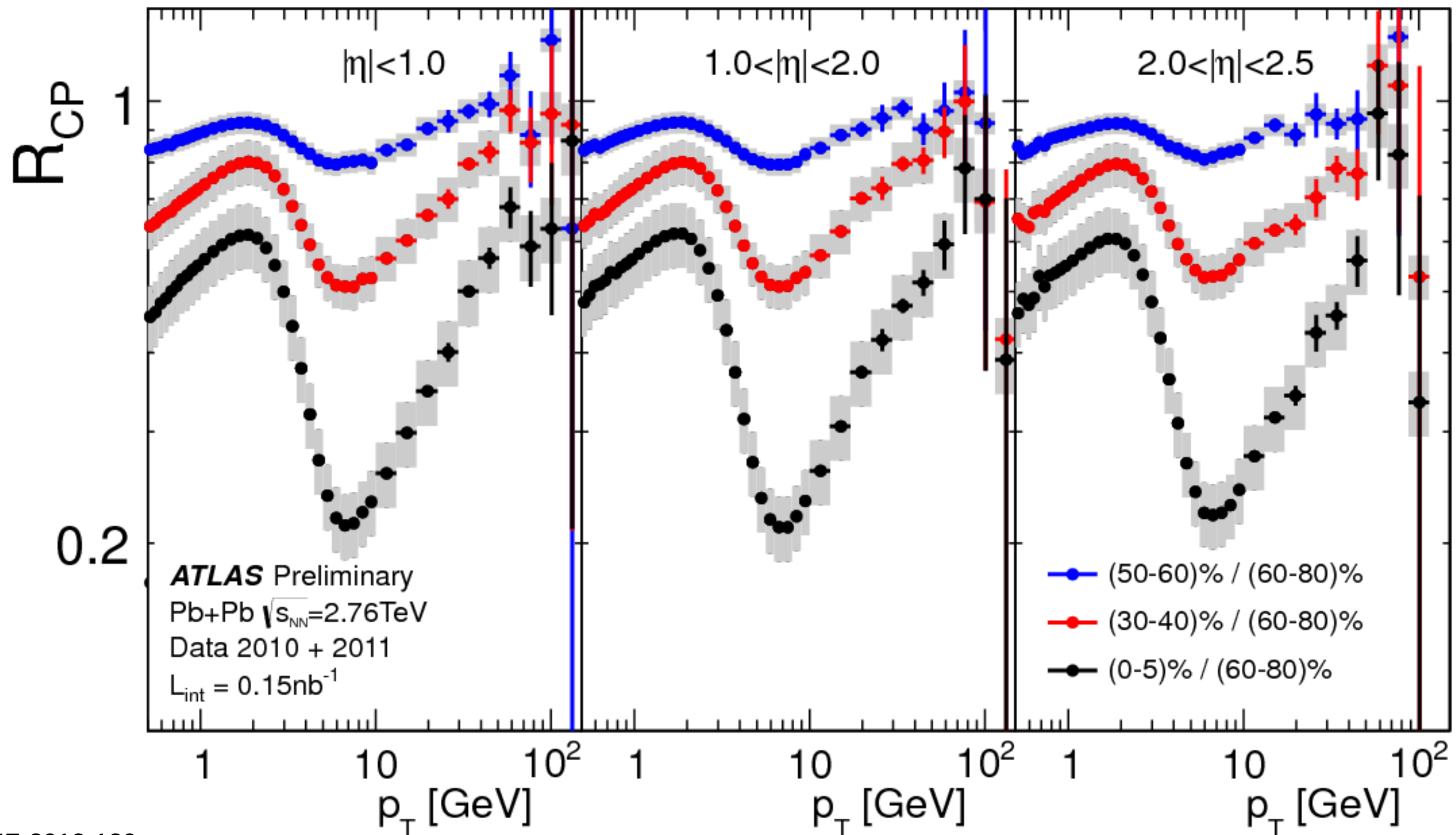
- Z, γ yields scale with N_{coll}
  - No significant violation of QCD factorization
- Using N_{coll} as a normalization of AA spectra is justified

Medium-sensitive probes

- Charged hadron production
- Heavy quark production
- Jet studies

Suppression of high-p_T hadrons

R_{CP}=(Yield/N_{coll})$_{cent}$/(Yield/N_{coll})$_{60-80\%}$ **out to p_T=150 GeV**



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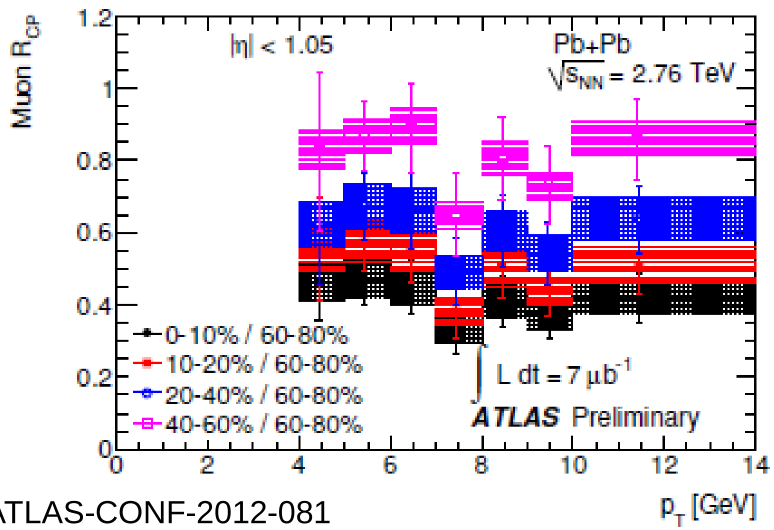
Strong suppression (R_{CP}≈0.2) at ~7 GeV in central collisions
No η dependence observed

Open heavy flavour production

- **b→μ.. & c→μ..** - studied via semileptonic decays to muons
  - template fitting method
  - $4 < p_T < 14$ GeV, $|\eta|<1.05$



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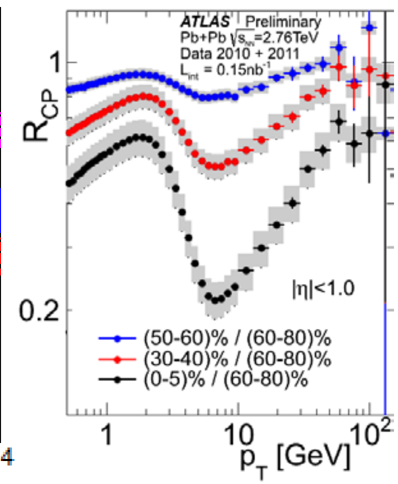
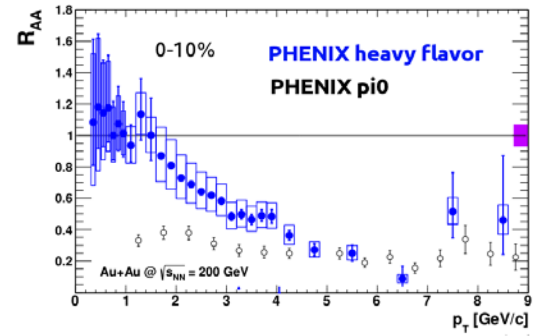
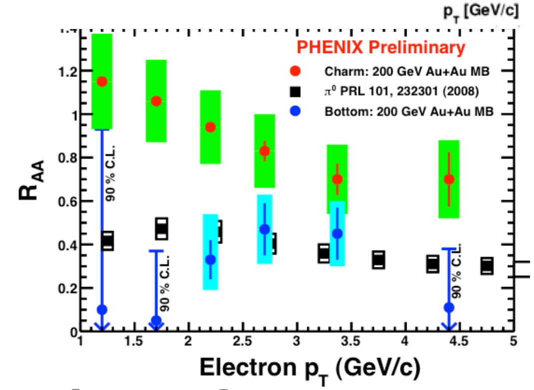


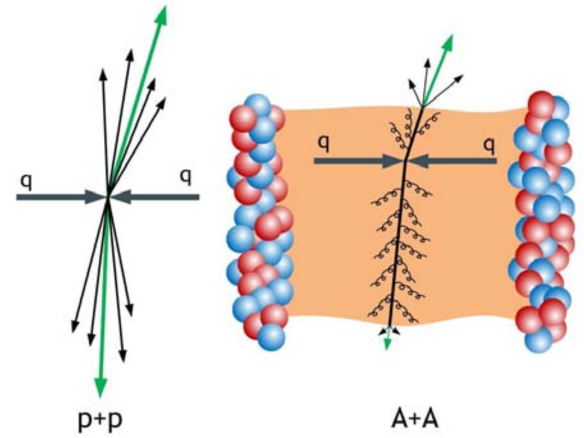
RHIC





- 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 HF electron results
- At RHIC b→e.. more suppressed than c→e…?!

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

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

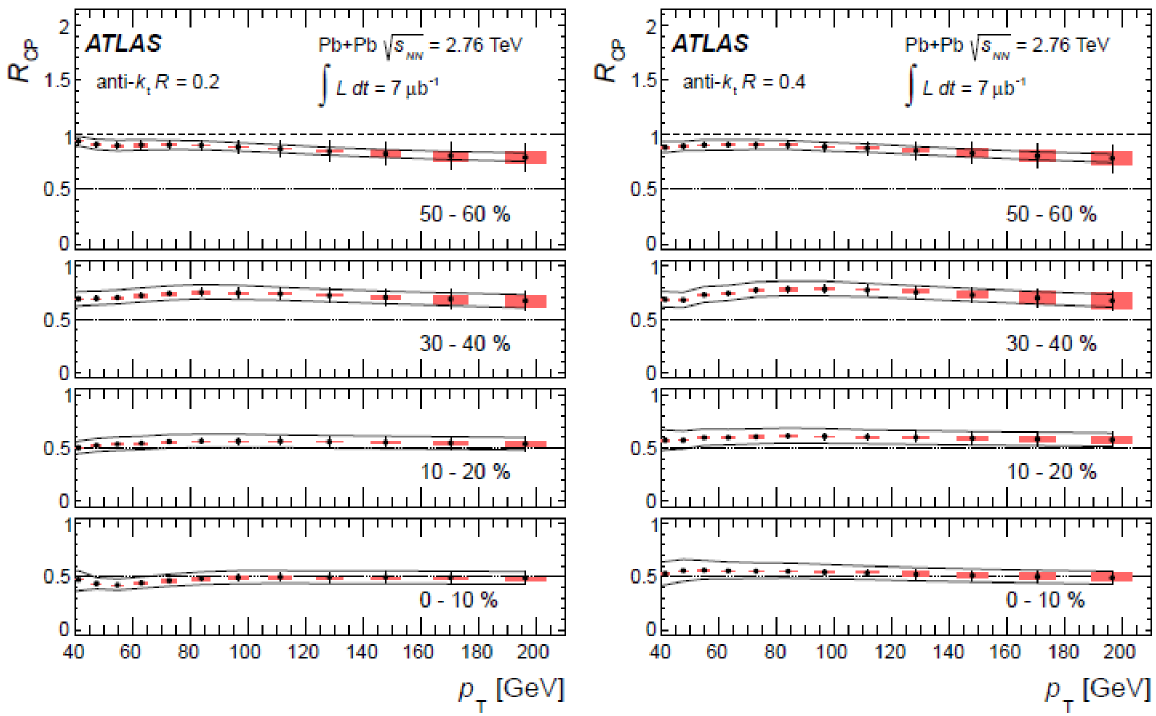
First LHC result on jet suppression

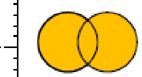
Unfolded p_T spectra

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

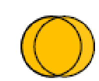
peripheral reference: 60-80%

R=0.2





R=0.4

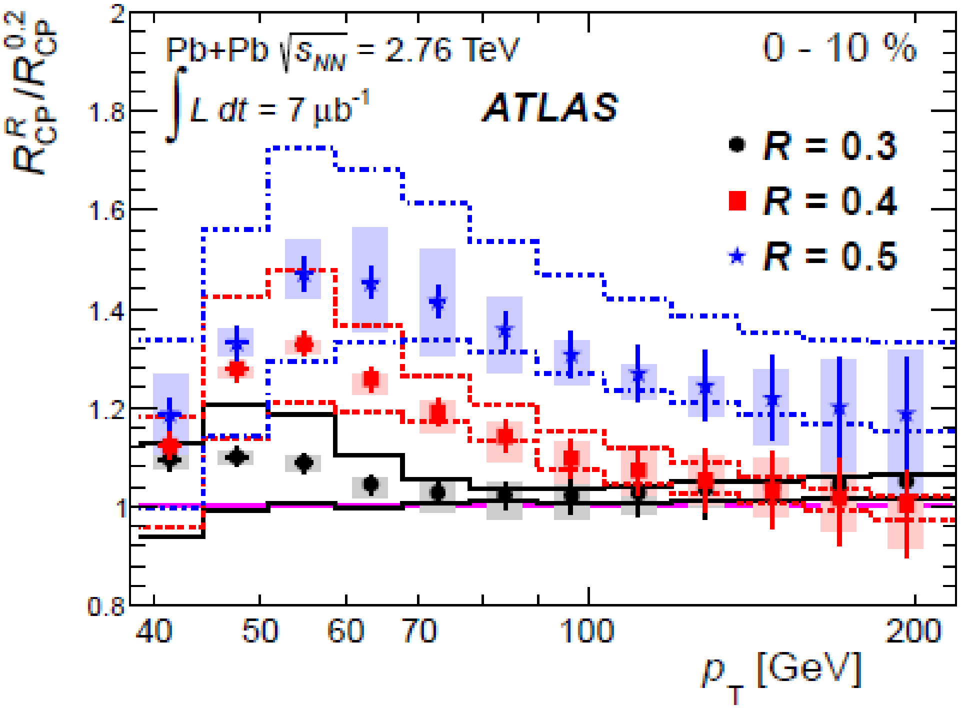


- **A factor of ~2 suppression in 0-10% most central collisions**
- **Suppression independent of jet p_T**

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

→A weaker suppression is observed for larger jet radius parameters

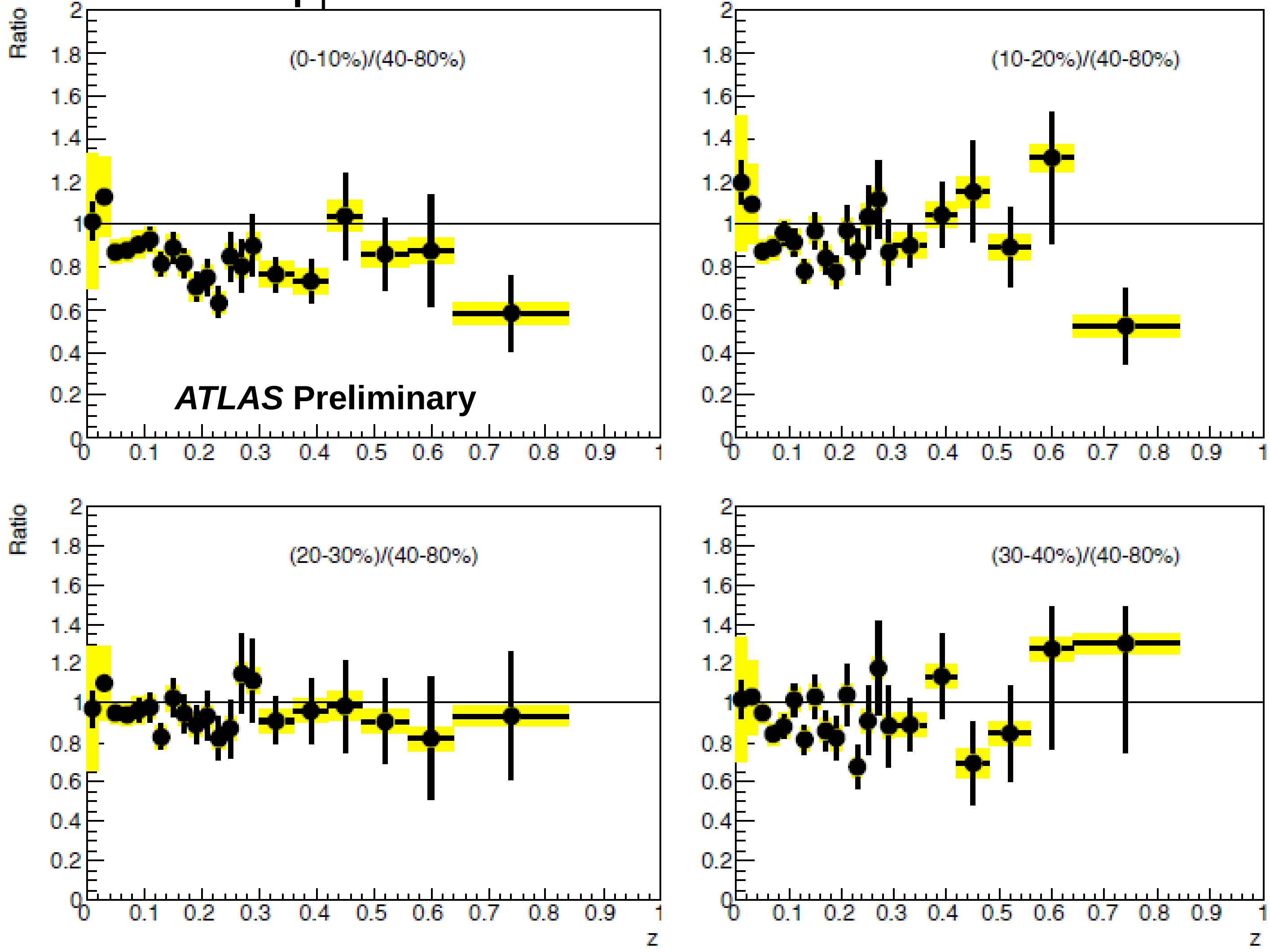
Weaker dependence is observed in 10-20% centrality bin

No dependence on the jet radius is seen for more peripheral collisions

Jet fragmentation at QM'2011

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

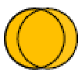
$R_{D(z)} \equiv D(z)_{cent} / D(z)_{40-80\%}$

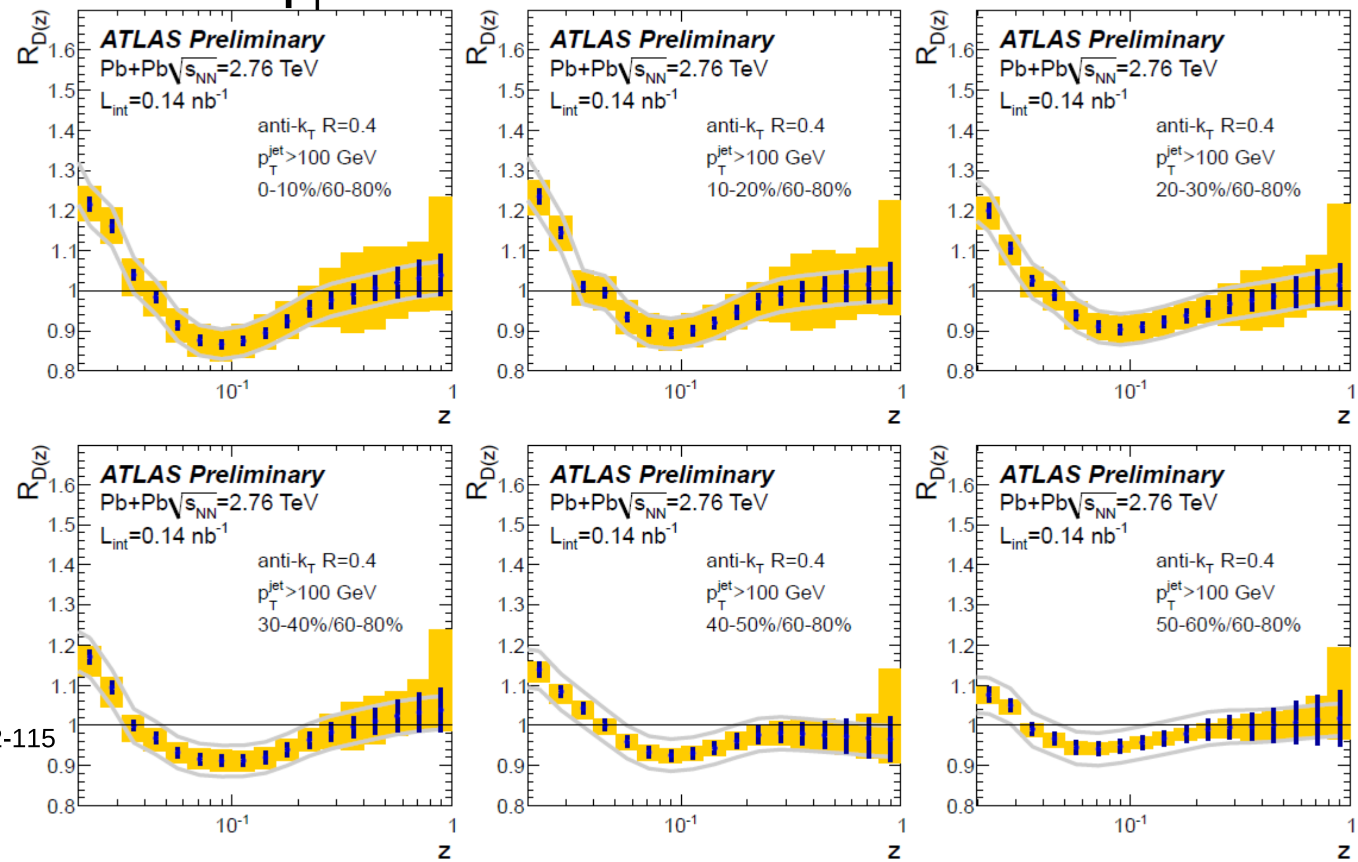


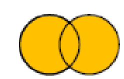
Data 2010

Jet fragmentation

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







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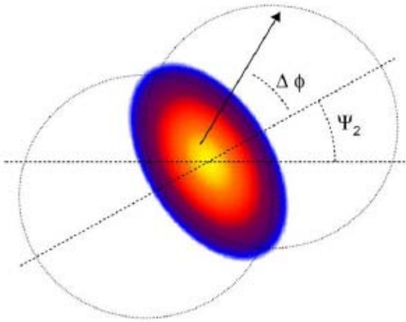
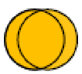
- Enhancement at low z, suppression at z≈0.1
- No modification at high z
- Similar results found for R=0.2 and 0.3 jets

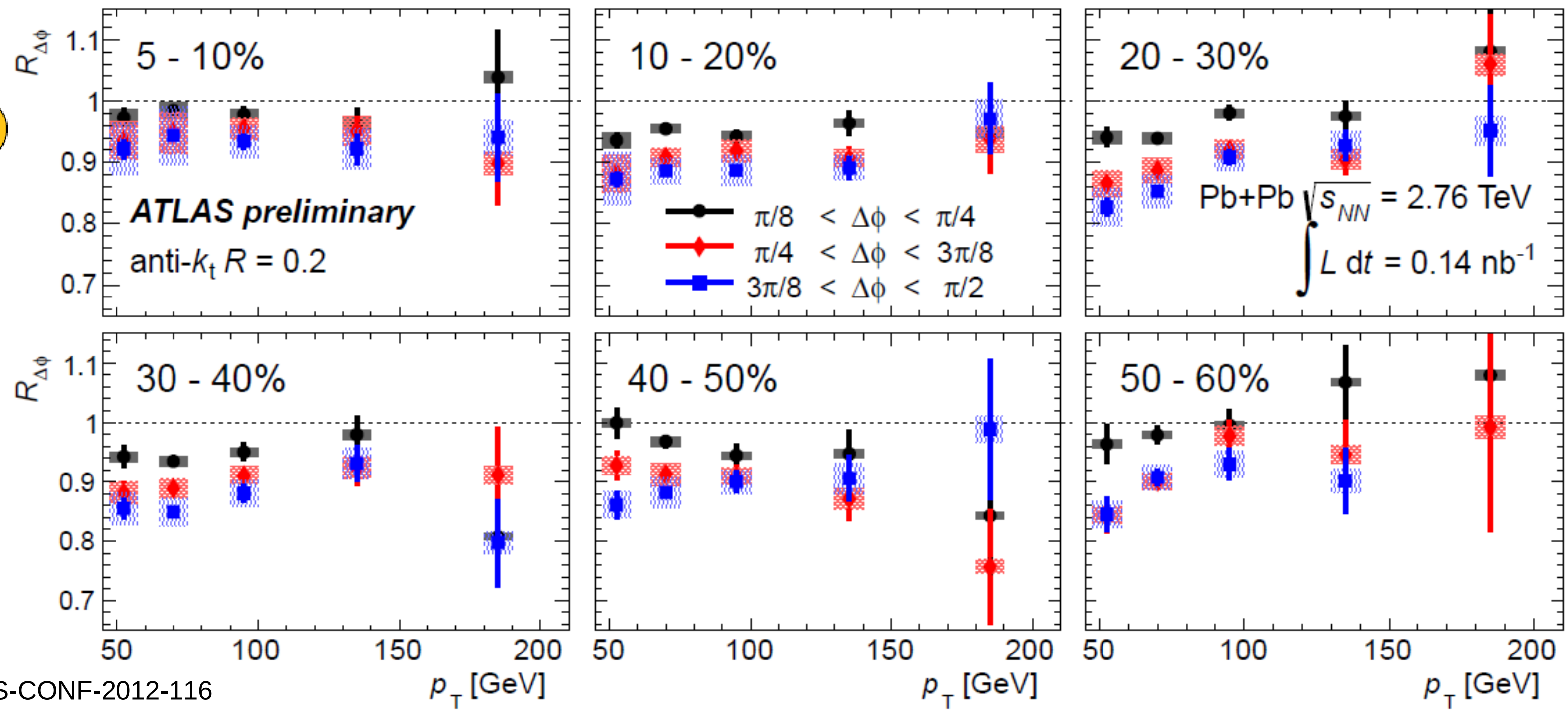
Azimuthal dependence of jet yields

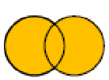
- **Path length dependence of jet suppression**
- **Ratios of yields in different slices of $\Delta\phi = \phi^{jet} - \Phi_2(\Psi_2)$**



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







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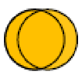
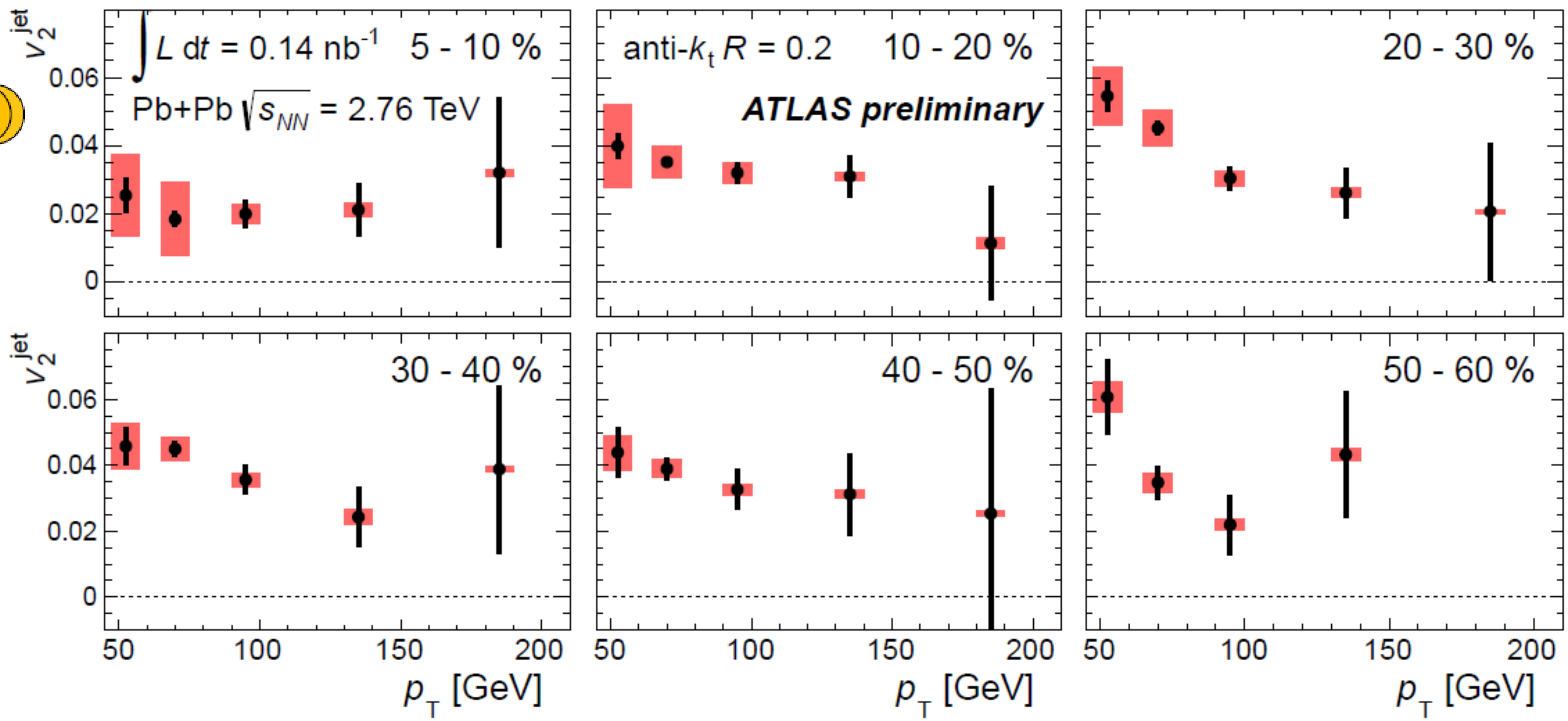
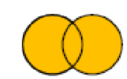
– **Yields are reduced by about 15% for $3\pi/8<\Delta\phi<\pi/2$ relative to $0<\Delta\phi<\pi/8$**

Jet v_2

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

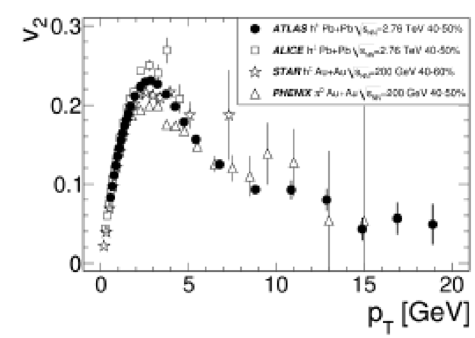






Charged hadrons

Phys. Lett. B707 (2012) 330-348



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

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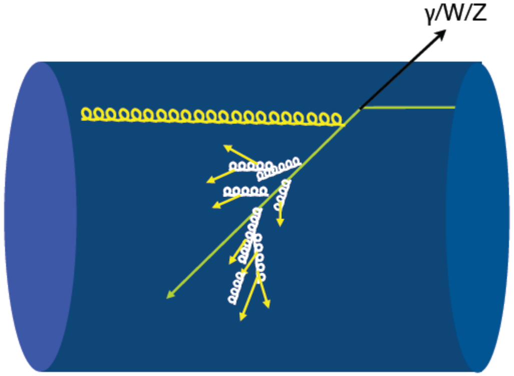
γ, Z – jet correlations

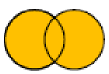
Modification of the jet energy relative to the probe not affected by the medium

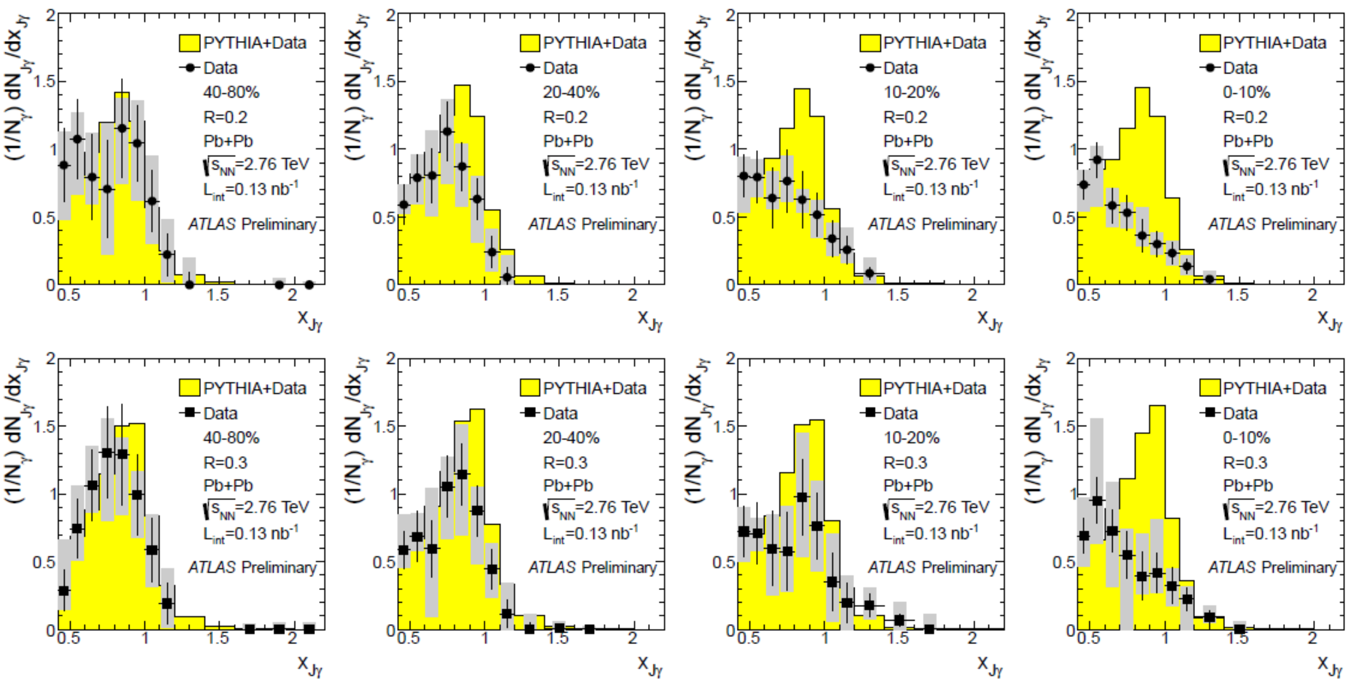


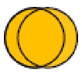
γ - jet correlations

- **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**

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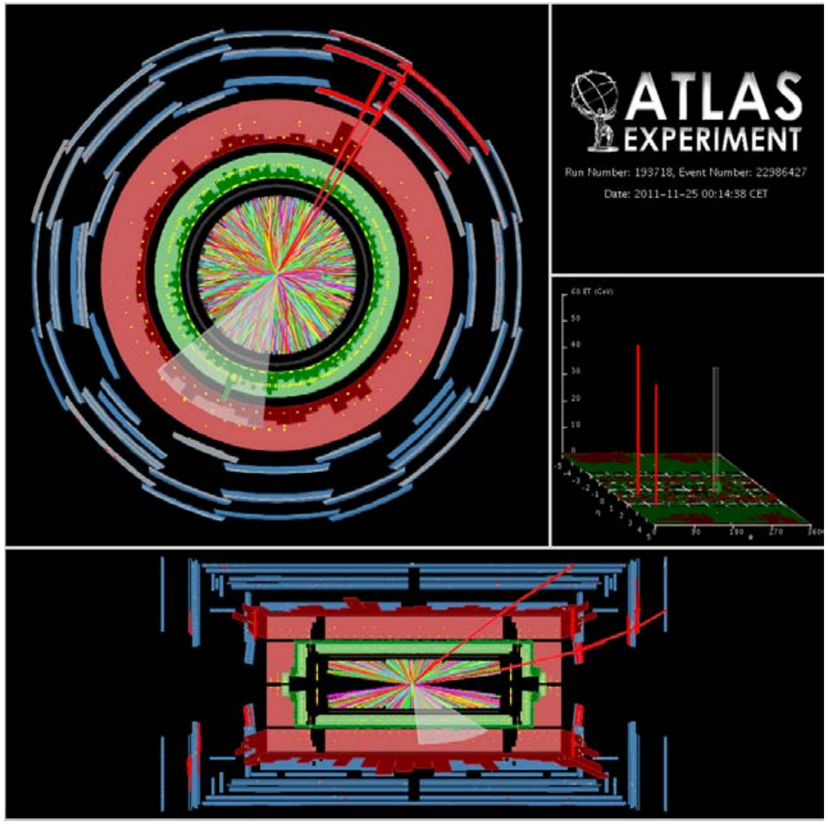
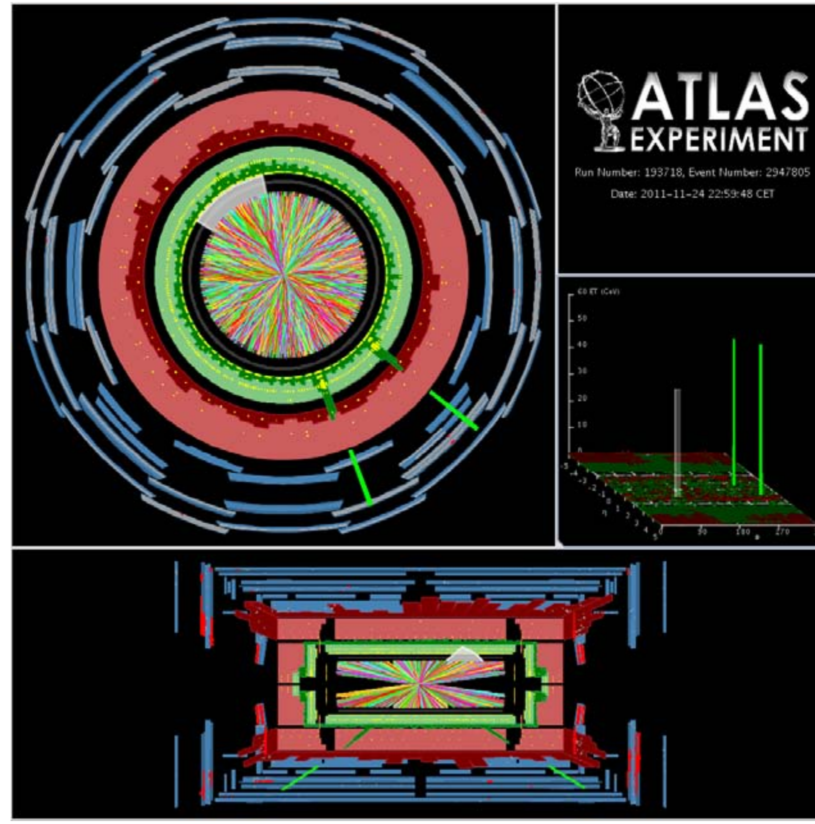
Z - jet correlations

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



$M_{\mu\mu}$=92.5 GeV
p_T(Z)=102 GeV
p_T(jet)=46.3 GeV

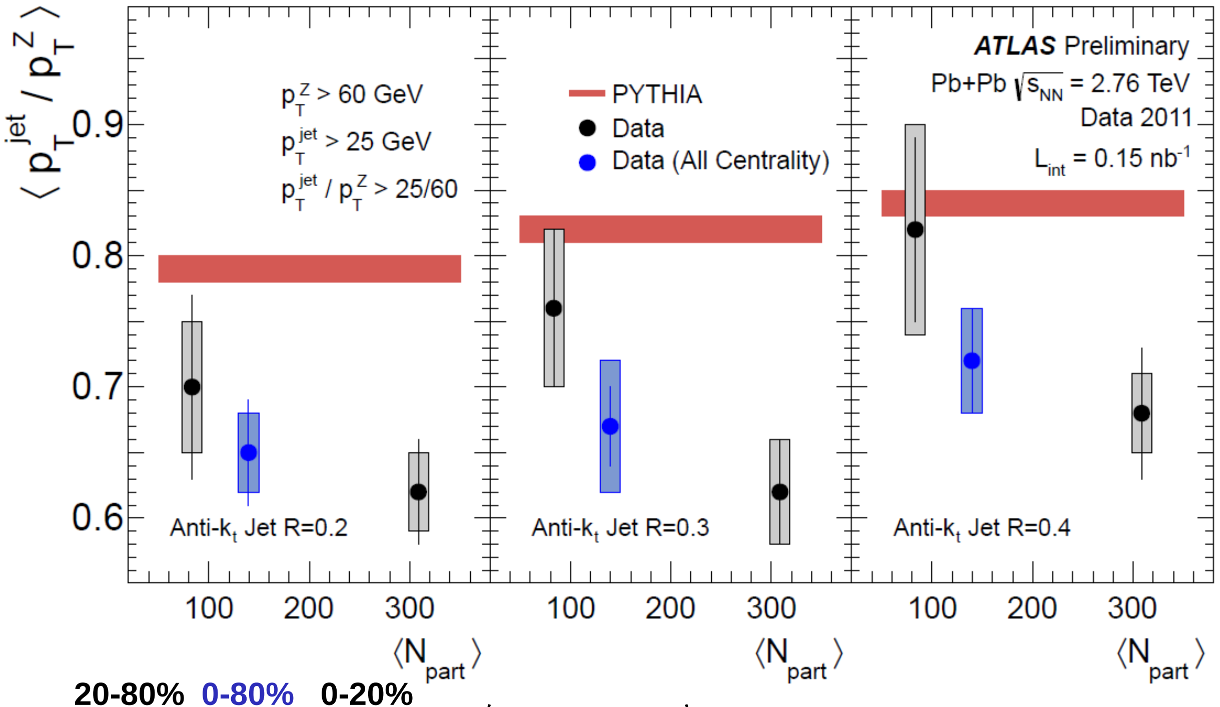
Z($\rightarrow e^+e^-$) - jet



M_{ee}=87.5 GeV
p_T(Z)=105 GeV
p_T(jet)=41.8 GeV

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 > $\pi/2$ → 37 events for L_{int}=0.15 nb^{-1}



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

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

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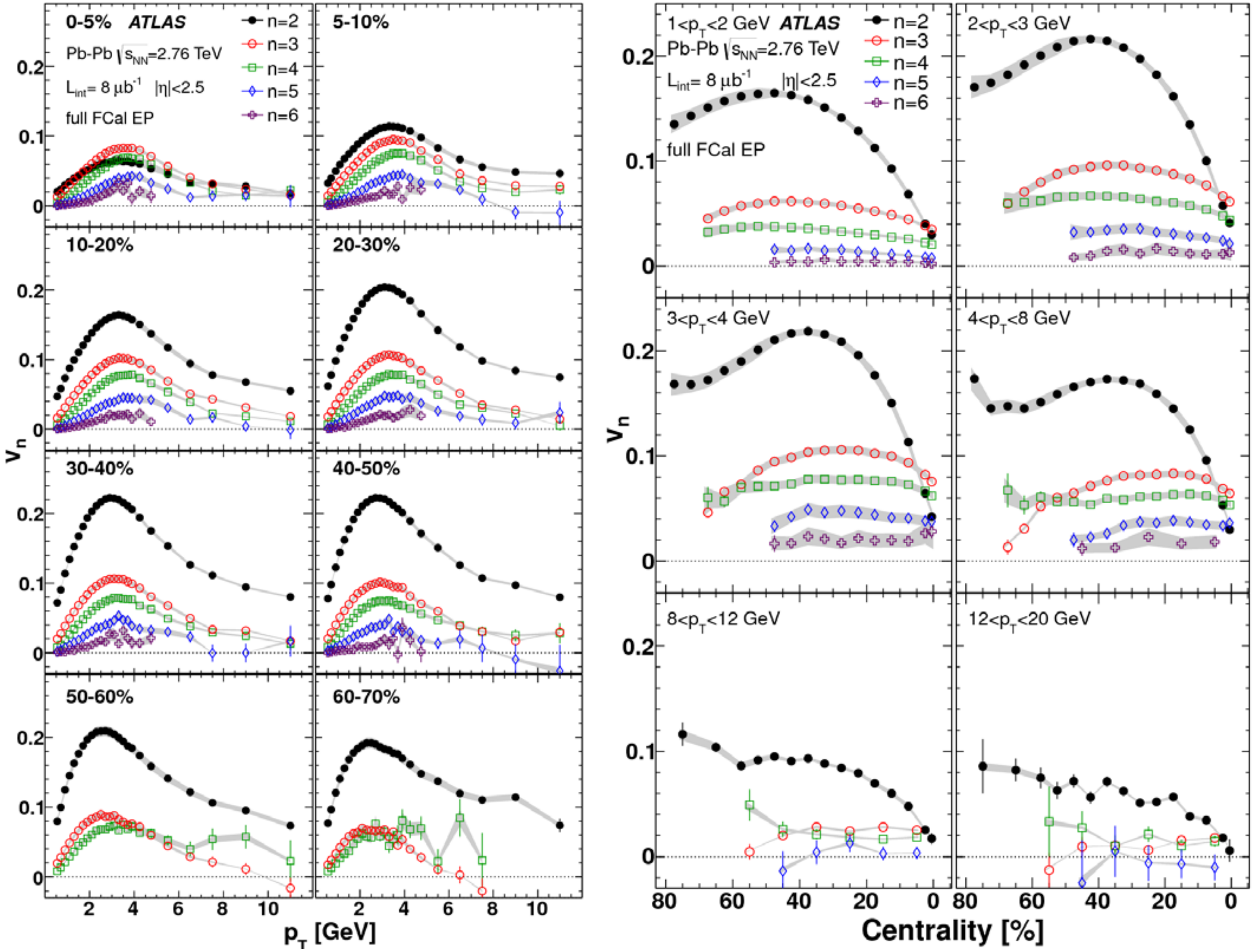
Summary

- **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



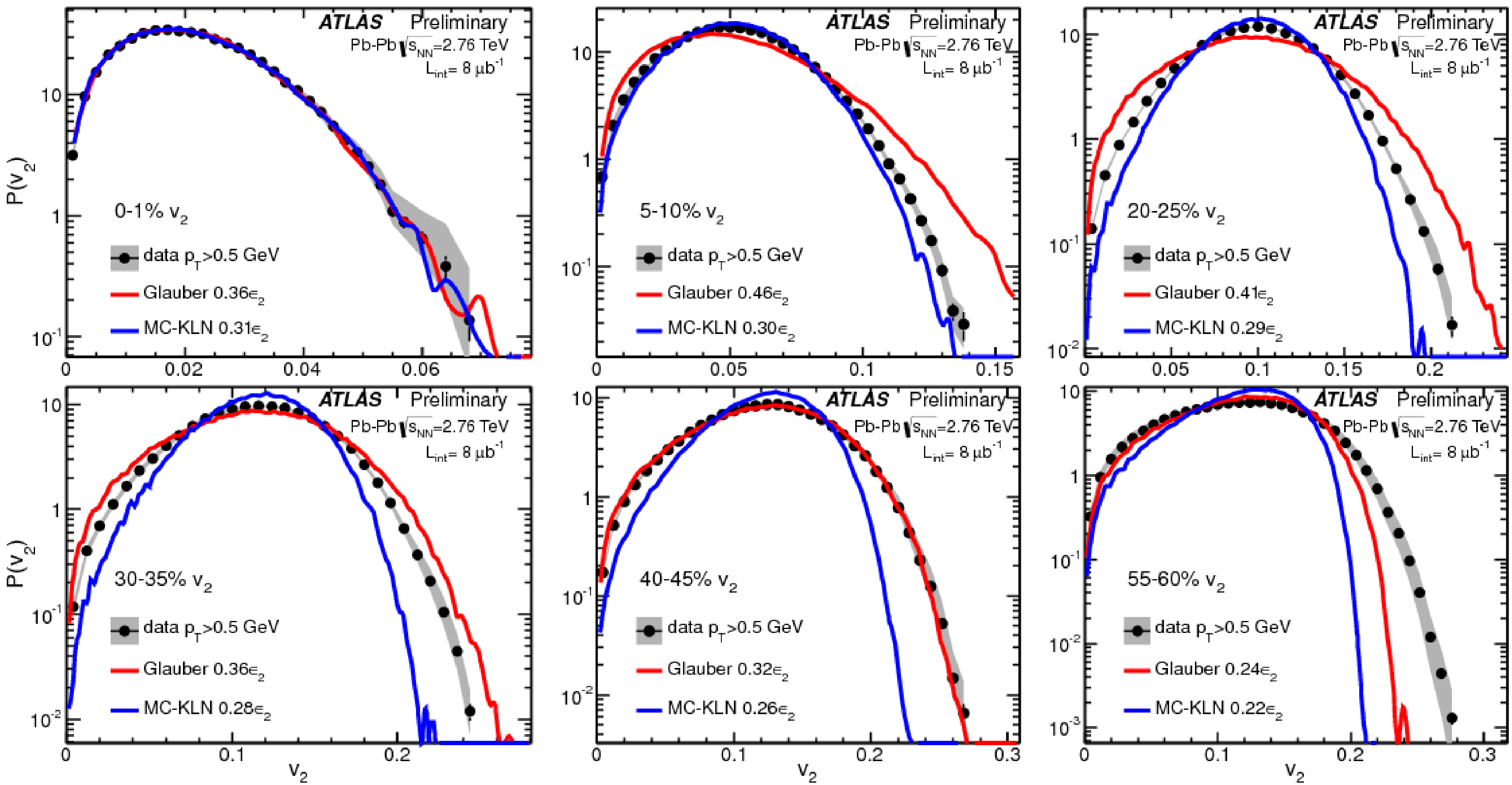
Similar p_T dependence for n=2-6 flow harmonics

Weak centrality dependence observed for v_3-v_6

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

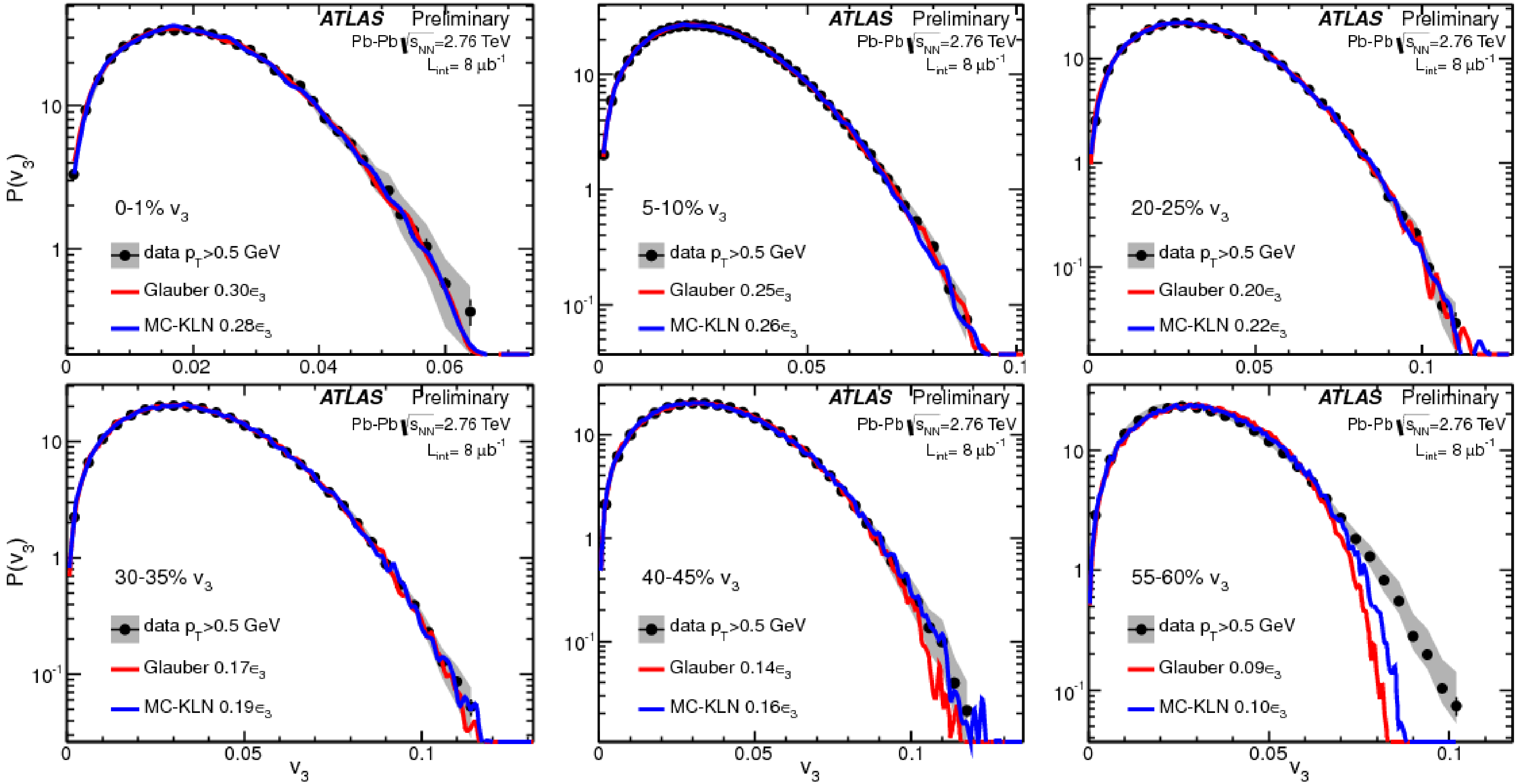
The EbE v_2 distributions compared with the eccentricity distributions from two initial geometry models: Glauber (red lines) and MC-KLN (blue lines)

Ann. Rev. Nucl. Part. Sci. 57, 205 (2007)   Phys. Rev. C 74, 044905 (2006)



The EbE v_3 distributions compared with the eccentricity distributions from two initial geometry models: Glauber (red lines) and MC-KLN (blue lines)

Ann. Rev. Nucl. Part. Sci. 57, 205 (2007)   Phys. Rev. C 74, 044905 (2006)



The EbE v_4 distributions compared with the eccentricity distributions from two initial geometry models: Glauber (red lines) and MC-KLN (blue lines)

Ann. Rev. Nucl. Part. Sci. 57, 205 (2007)   Phys. Rev. C 74, 044905 (2006)