Heavy Ions physics in ATLAS

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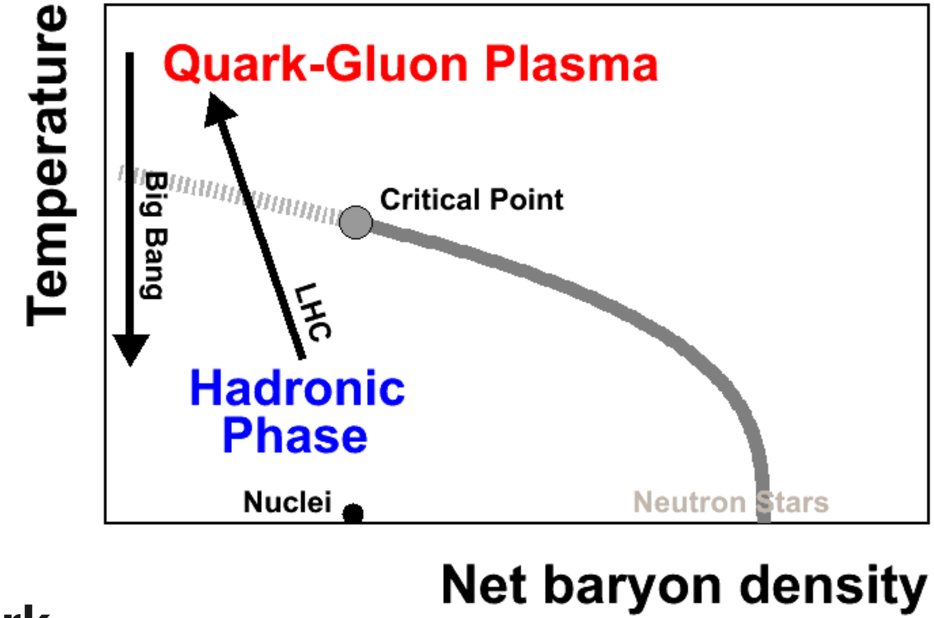
for the ATLAS Collaboration

Nucleus-nucleus collisions



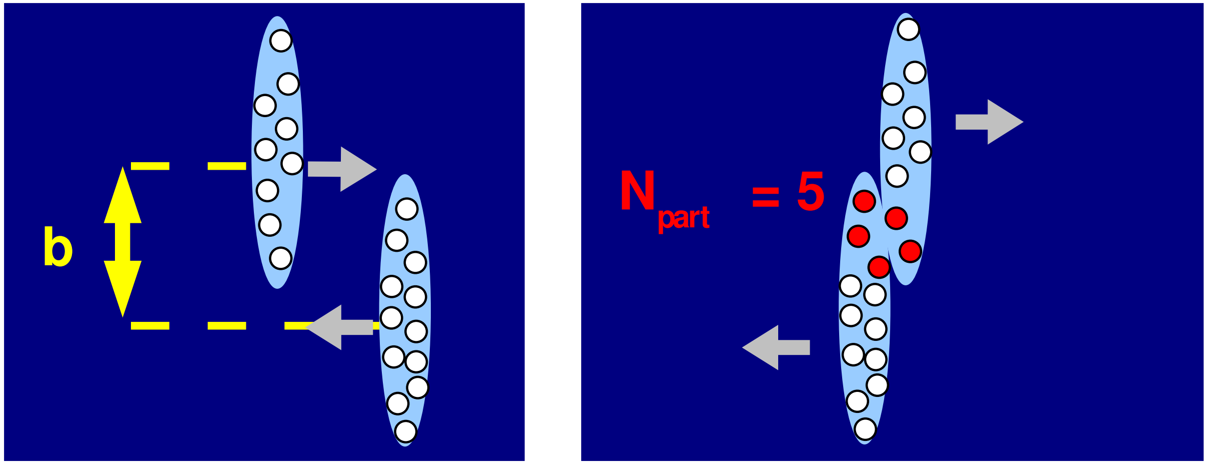
Study of the CQD phase diagram

Properties of the strongly interacting Quark-Gluon Plasma created in PbPb collisions:

- the initial volume, its fluctuations and the evolution of the system (azimuthal correlations studies)
- interactions of the partons with the QGP (jets suppression, correlations with photons and Z bosons)

First results from pPb collisions - an outline

Nucleus-nucleus collision - definitions

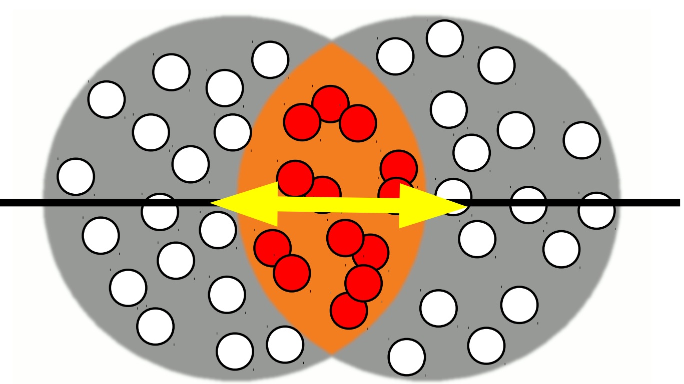


Side view

Parameters describing the centrality of the collision:

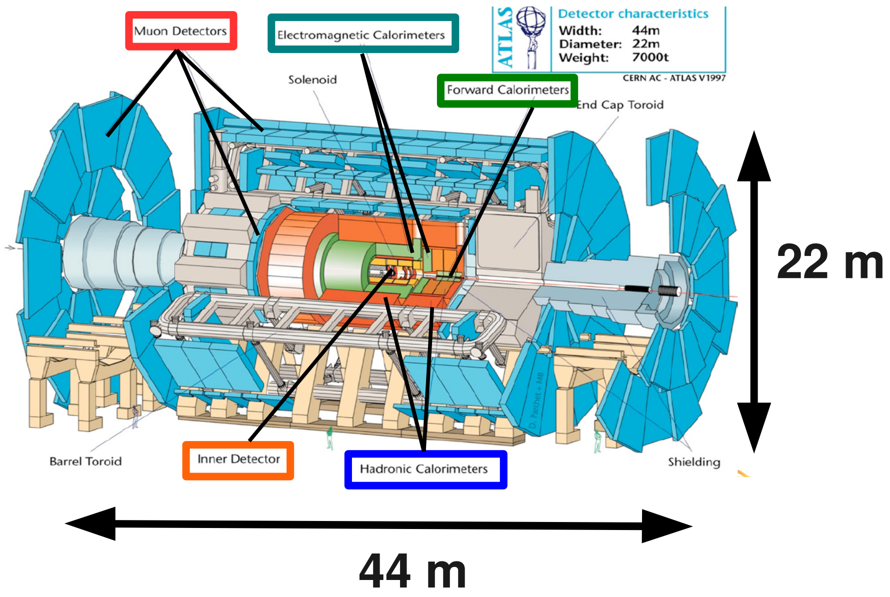
- b - geometrical impact parameter
- N_{part} - number of nucleons participating in the collision
- N_{coll} - number of nucleon-nucleon collisions
- centrality bin or class as percentage of the events, using an observable monotonically related to the above parameters

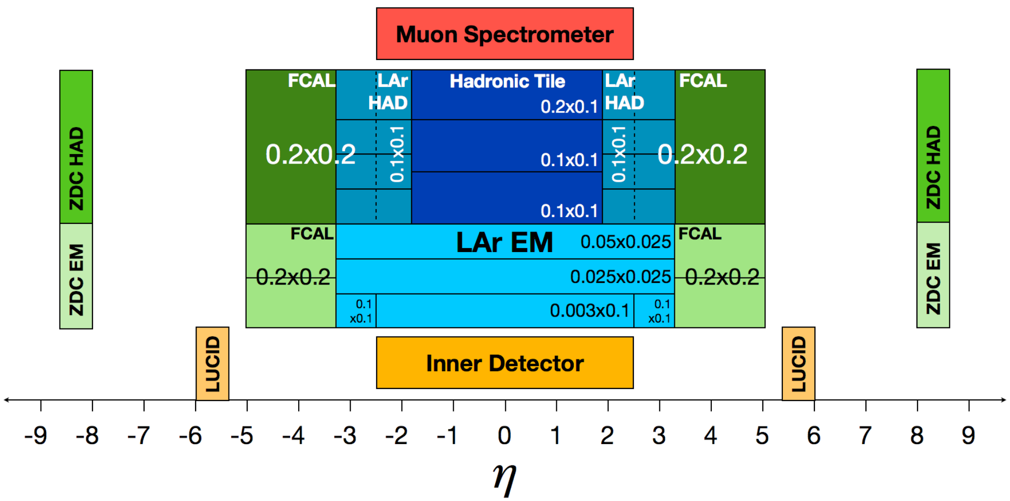
Event plane



"Along the beam" view

The ATLAS detector

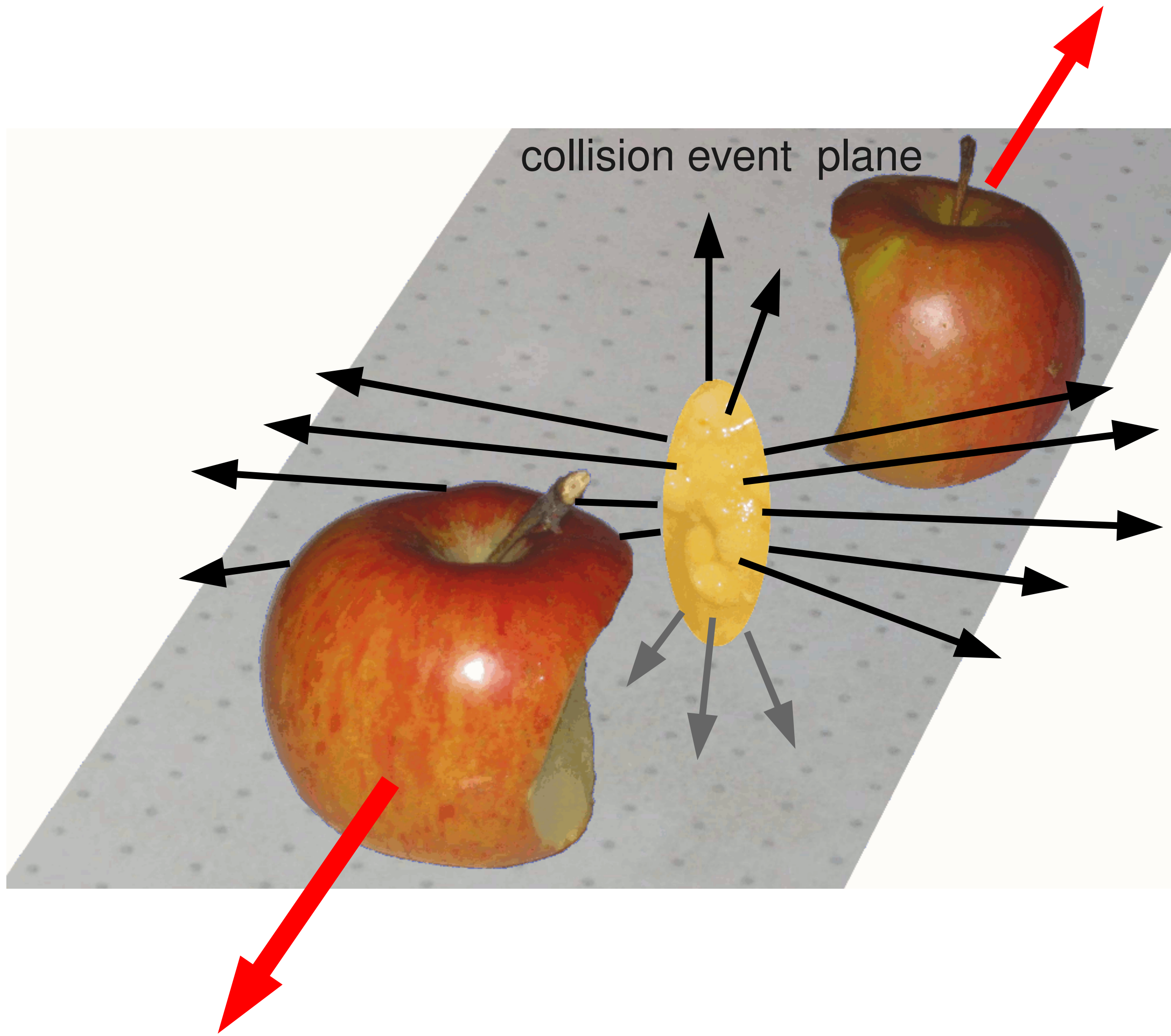


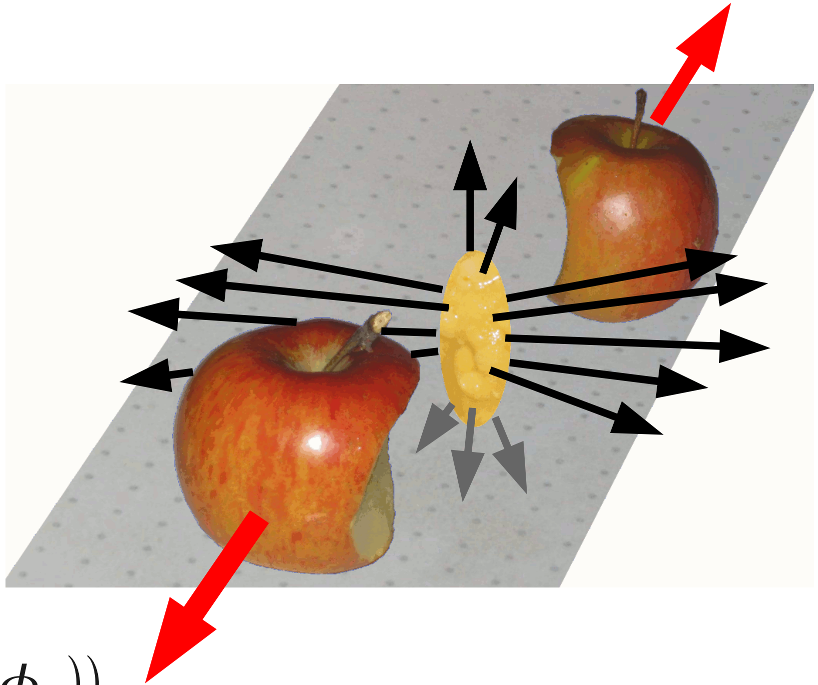


Inner detector	$\lvert\eta\rvert<2.5$	track reconstruction
Calorimeter	$\lvert\eta\rvert<3.2$	jet reconstruction
Forward Calorimeter	$3.1<\lvert\eta\rvert<4.9$	centrality determination
Muon spectrometer	$\lvert\eta\rvert<2.7$	muon reconstruction

Flow and other azimuthal correlations in PbPb collisions

Collective flow - definitions





Event plane method

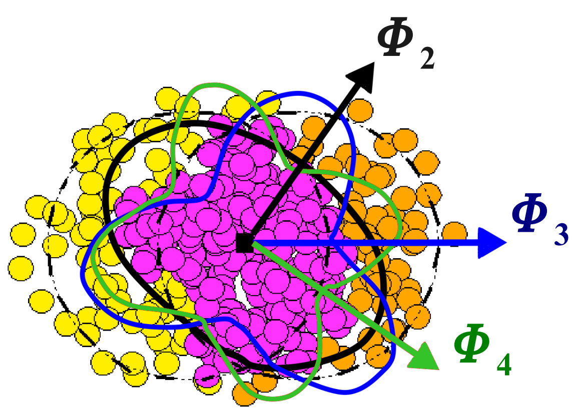
$$\frac{dN}{d\phi} \sim 1+2\sum_{n=1}^{\infty} v_n(p_T,\eta)\cos(n(\phi-\Phi_n))$$

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

Two-particle correlations method

$$\frac{dN}{d(\phi_a-\phi_b)} \sim 1+2\sum_{n=1}^{\infty} v_{n,n}(p_T^a,p_T^b)\cos(n(\phi_a-\phi_b))$$

$$v_{n,n} = \langle\cos(n(\phi_a-\phi_b))\rangle$$

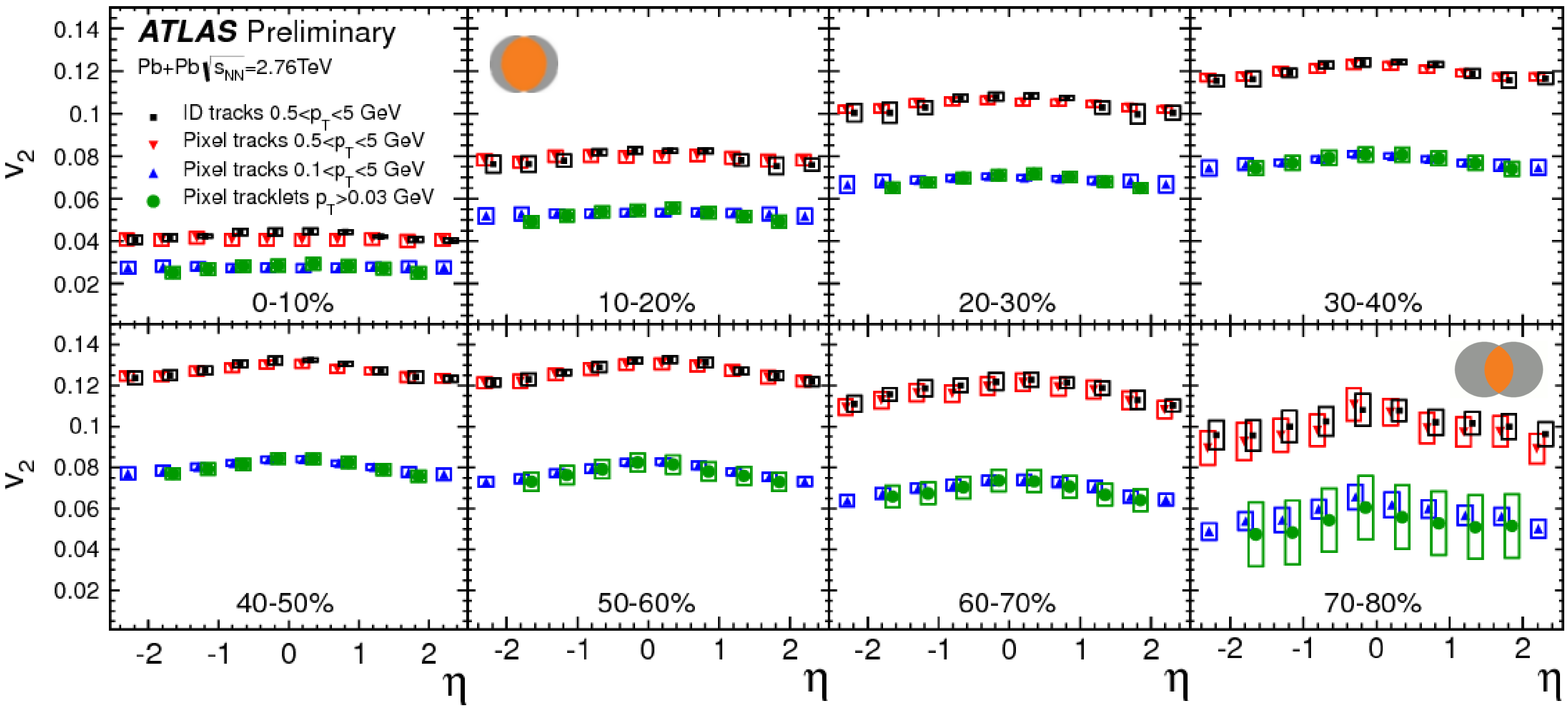


for flow: $v_{n,n}(p_T^a,p_T^b) = v_n(p_T^a)v_n(p_T^b)$

Cumulants from 2k-particle correlations

$$\langle corr_n\{2k\}\rangle = \langle\exp(i\,n(\phi_1+\ldots+\phi_k-\phi_{k+1}+\ldots+\phi_{2k}))\rangle$$

Dependence on pseudorapidity

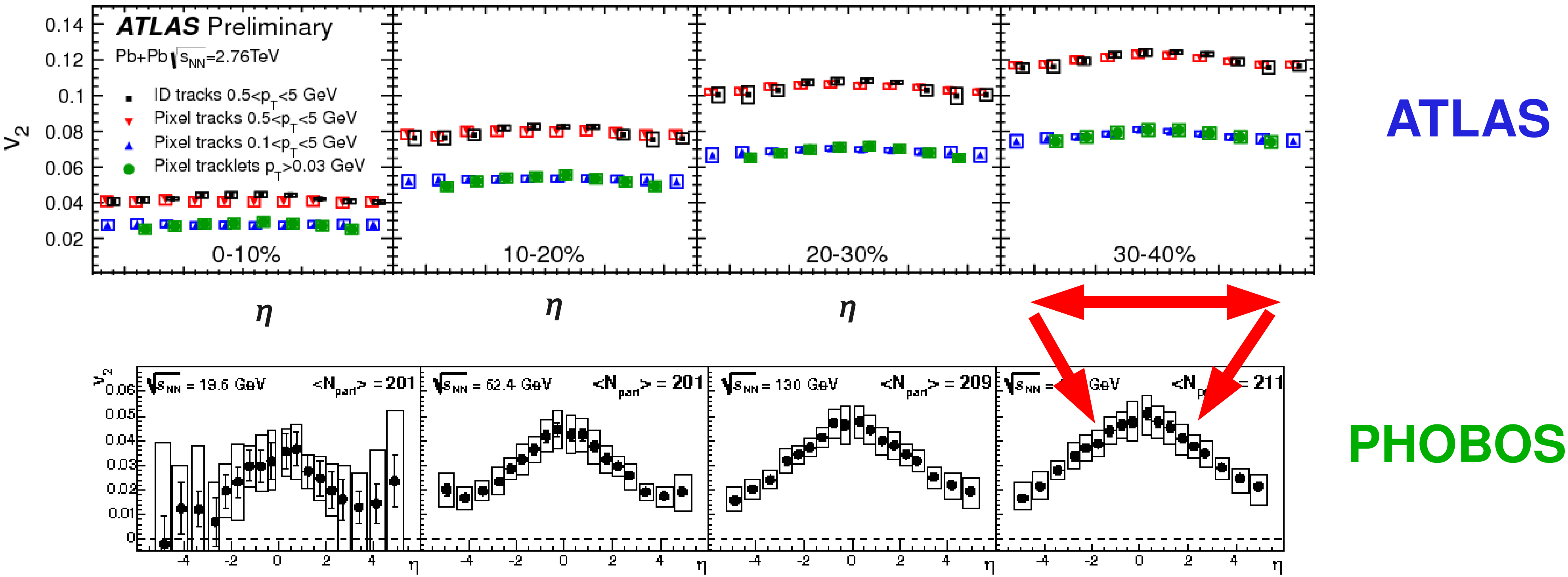


Elliptic flow:

- **increases for peripheral collisions**
- **only weakly depends on pseudorapidity for all centralities**

ATLAS-CONF-2012-117.

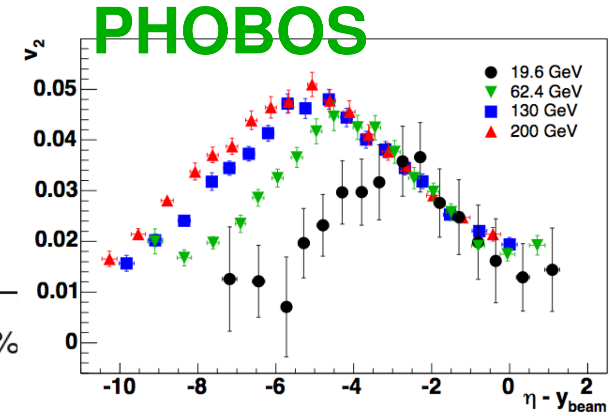
Dependence on pseudorapidity



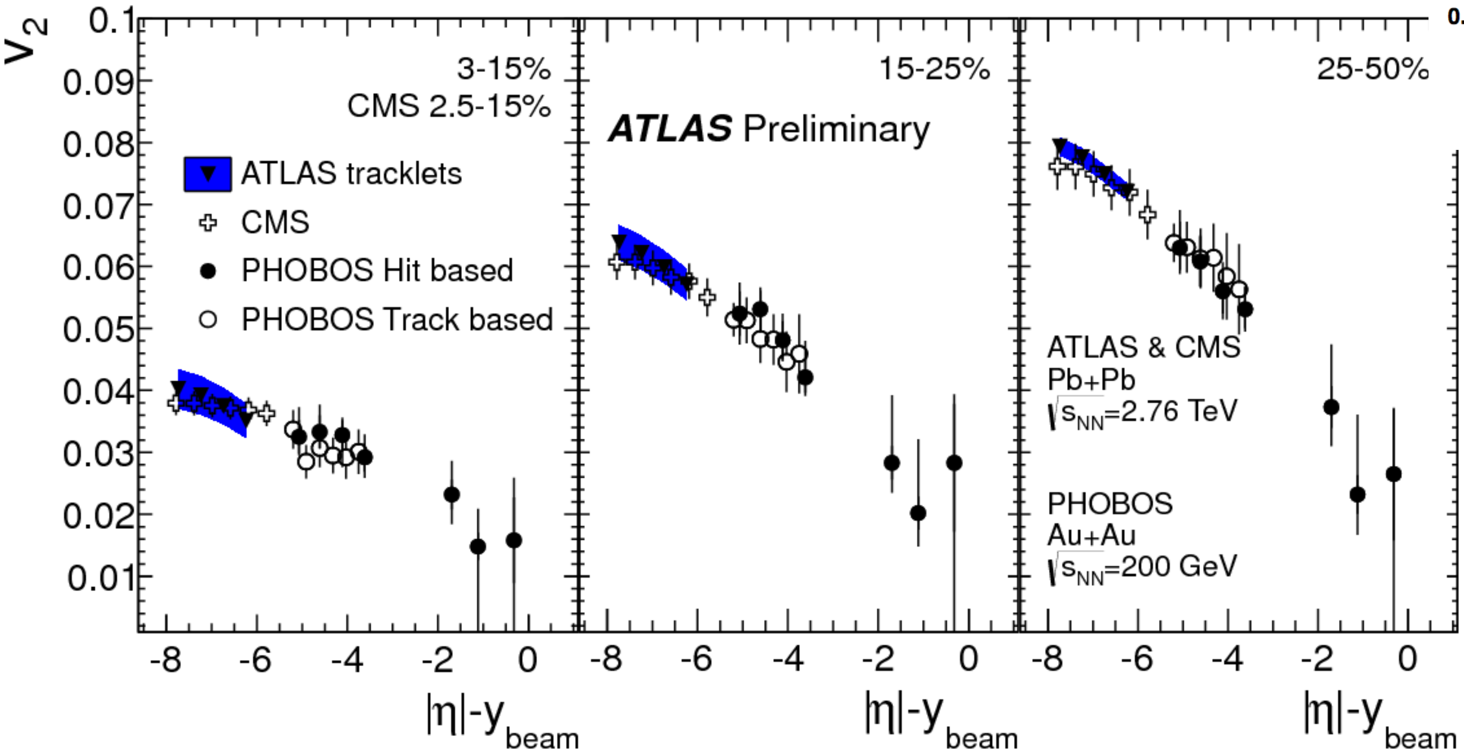
ATLAS observes small (~10%) variation of the elliptic flow in $|\eta|<2.5$ range but these results are not contradicting triangular shape of pseudorapididty dependence observed at RHIC.

ATLAS-CONF-2012-117.
PHOBOS, Phys. Rev. Lett. 94 (2005) 122303.

Collective flow - elliptic flow v_2



Dependence on pseudorapidity

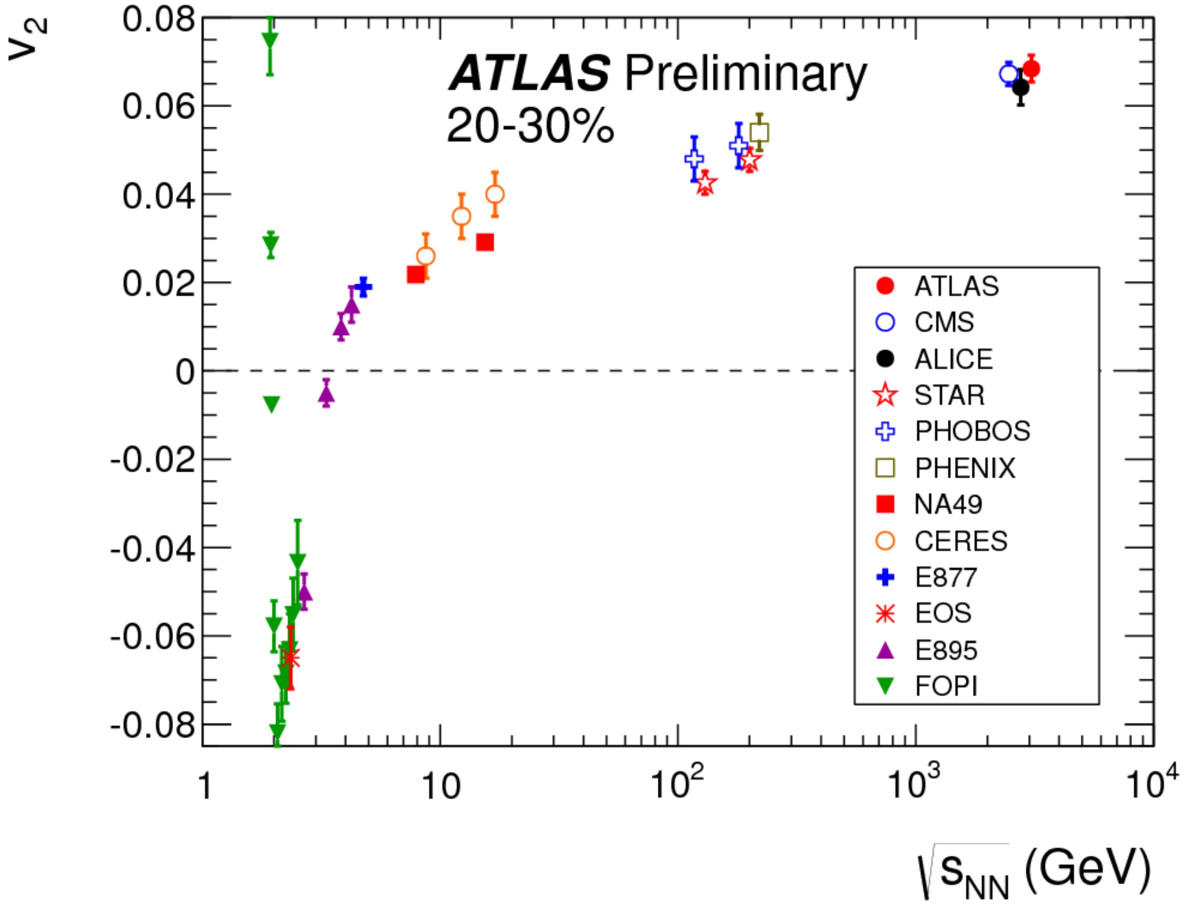


Extended longitudinal scaling

Elliptic flow η distribution shifted by the rapidity of the beam scales in the collision energy range from 19 to 2760 GeV

ATLAS-CONF-2012-117.
PHOBOS, Phys. Rev. Lett. 94 (2005) 122303.

Dependence on the collision energy

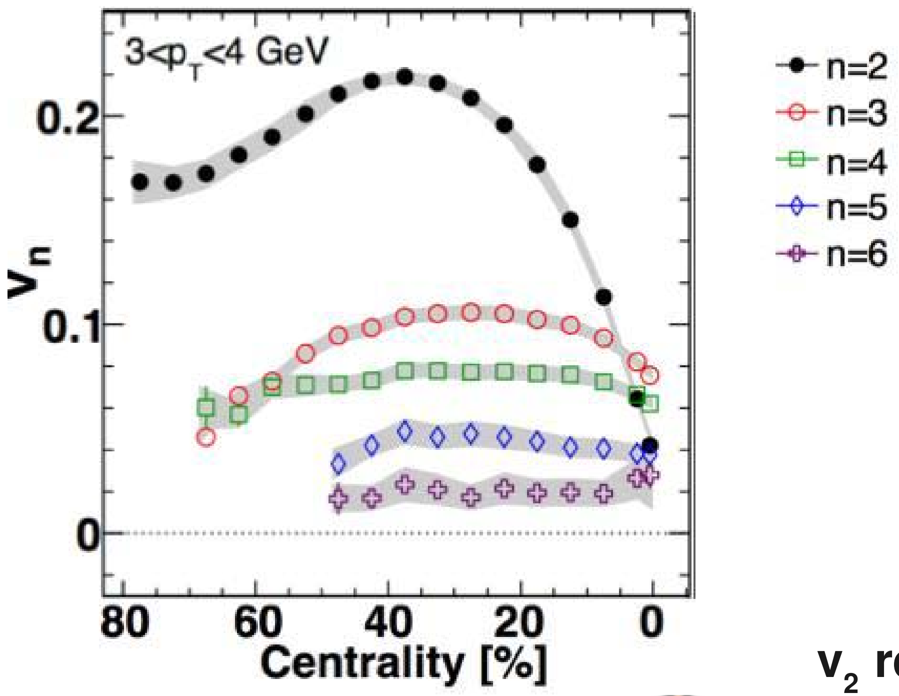


Elliptic flow values moderately increase in the collision energy range from 10 to 2760 GeV.

At lower energies, when the interactions involving spectator parts of the nuclei are important, v_2 is changing rapidly, from positive to negative and then again to positive values.

ATLAS-CONF-2012-117.

Comparison of flow harmonics



event plane method

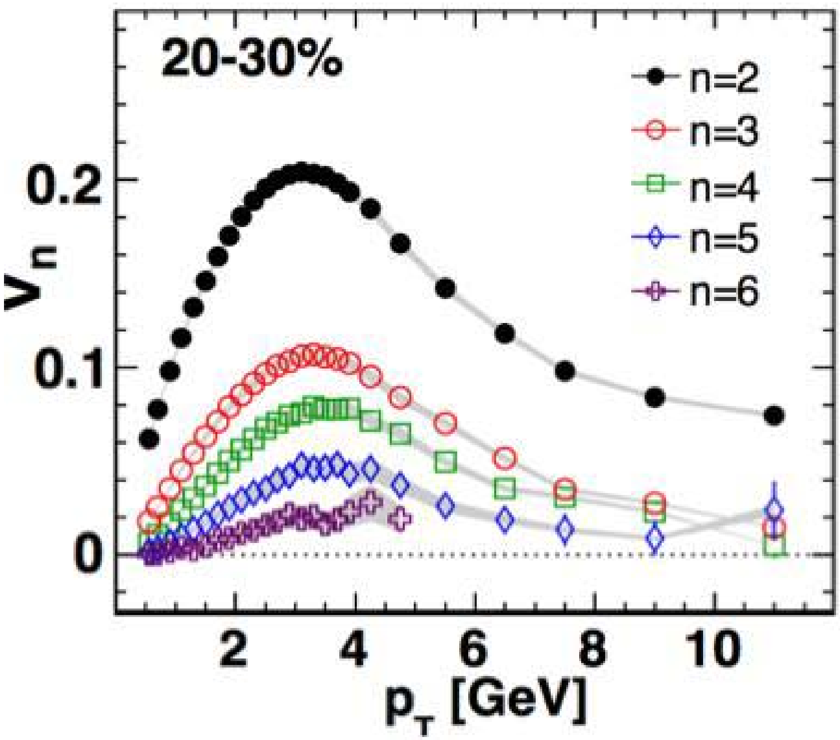
ATLAS, Phys.Rev C 86 (2012) 014907.

- v_2 is much larger than v_3 for 5-95% centrality range, it drops fast for the most central events
- generally v_n values decrease with increasing n
- v_n weakly depends on centrality for n=3-6
- maximum of the distribution decreases with n (for n>2)

v_2 reflects the degree of elongation of the interaction area, while the higher harmonics result from fluctuations of it

more details on flow harmonics in the talk by **Dominik Derendarz**

Comparison of flow harmonics



event plane method

Elliptic flow v2

- rapid rise to p_T ~ 2-3 GeV (hydrodynamic expansion)
- decrease in the p_T range 3-8 GeV (coalescence)
- weak dependence at high p_T (jet quenching)

Higher harmonics

- shape of v_n distributions similar for n=2-6
- maximum of the distribution decreases with n (for n>2)

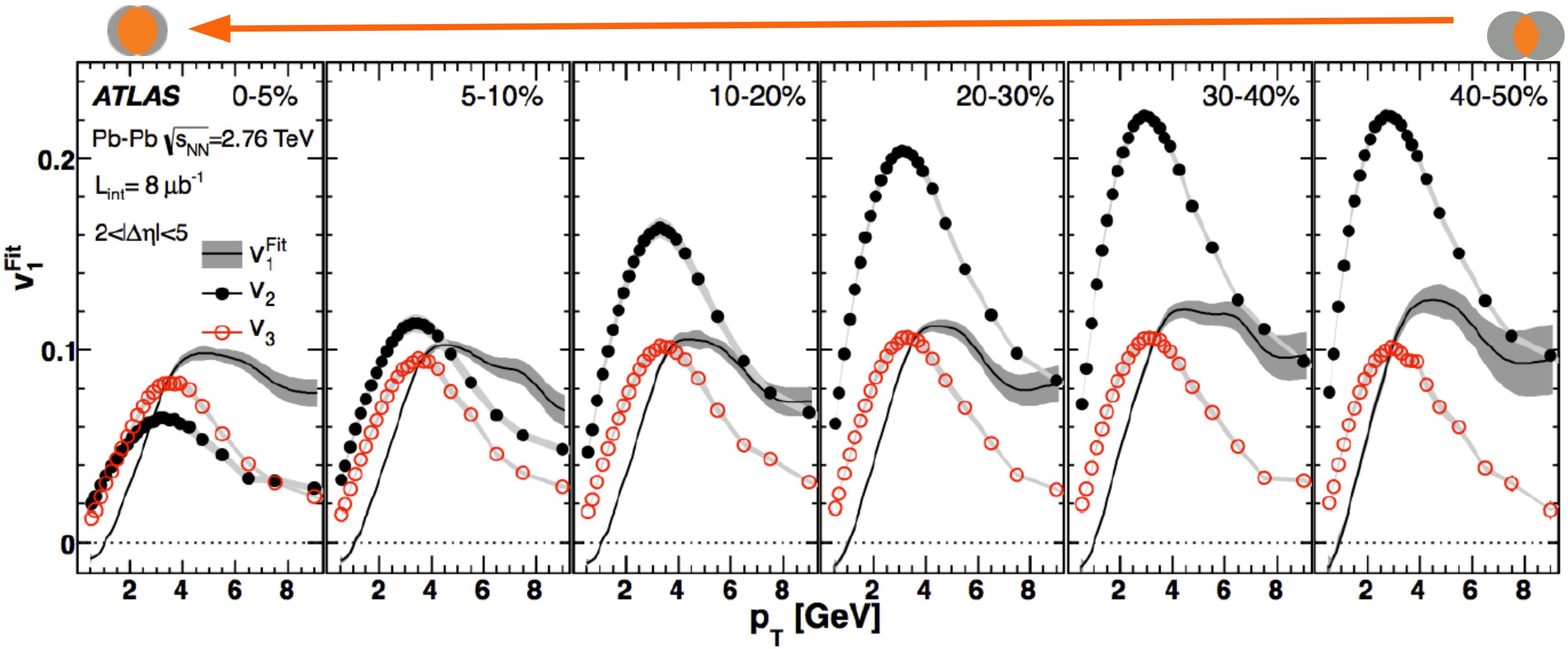
ATLAS, Phys.Rev C 86 (2012) 014907.

$$v_{1,1}^{2PC} = \langle \cos(\phi_a - \phi_b) \rangle$$

momentum conservation term

Directed flow

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



v_1 - from a fit to the above formula

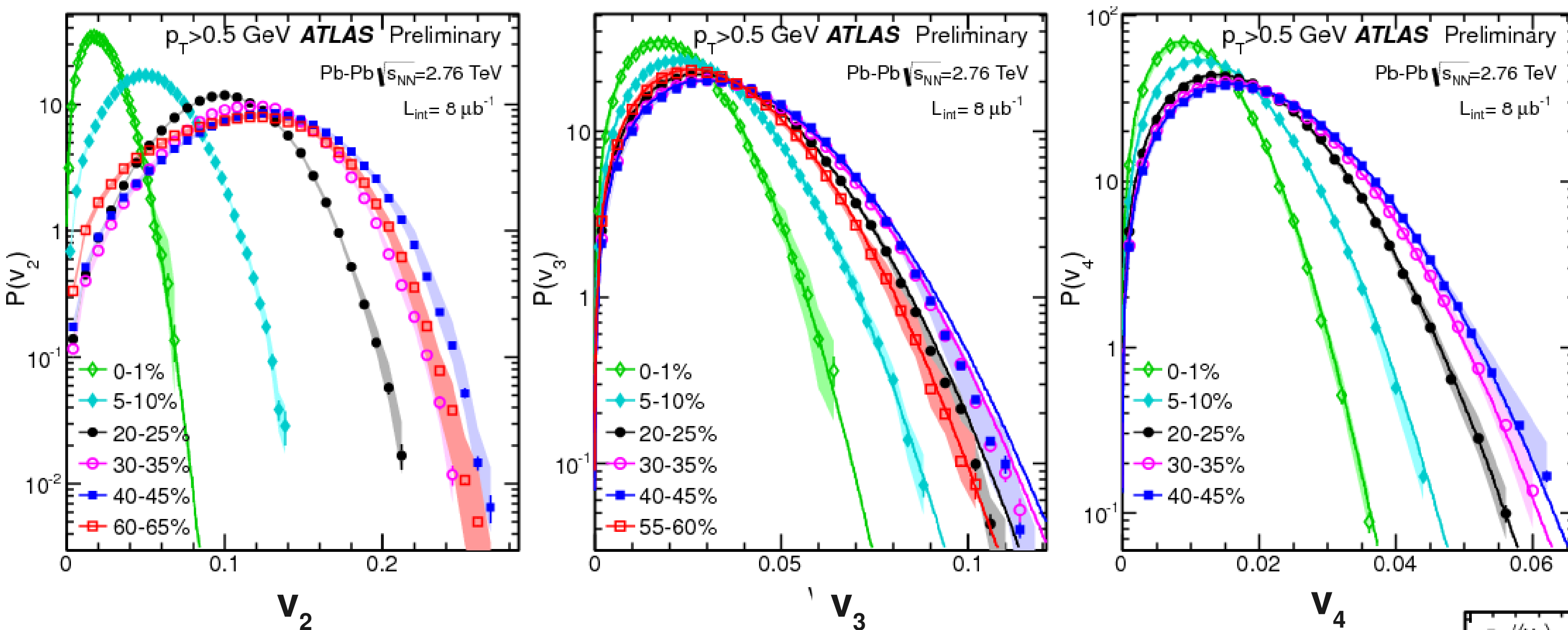
v_2, v_3 - event plane method

ATLAS, Phys.Rev C 86 (2012) 014907.

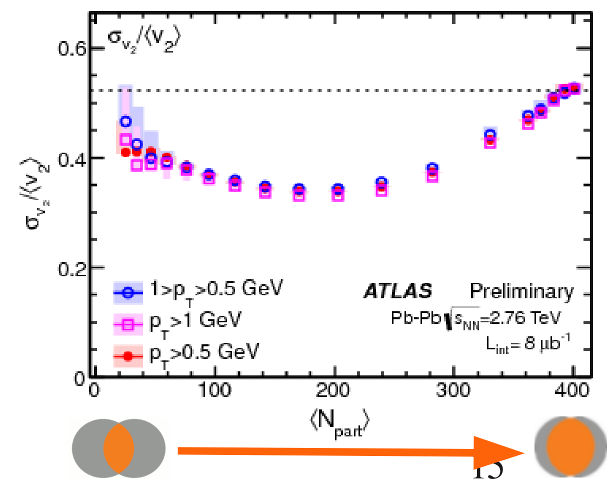
- **v_1 is negative for p_T<1 GeV**
- **centrality dependence much weaker (~10% change of the maximum) than for v_2, v_3**

Collective flow - fluctuations

Event-by-event flow harmonics distributions

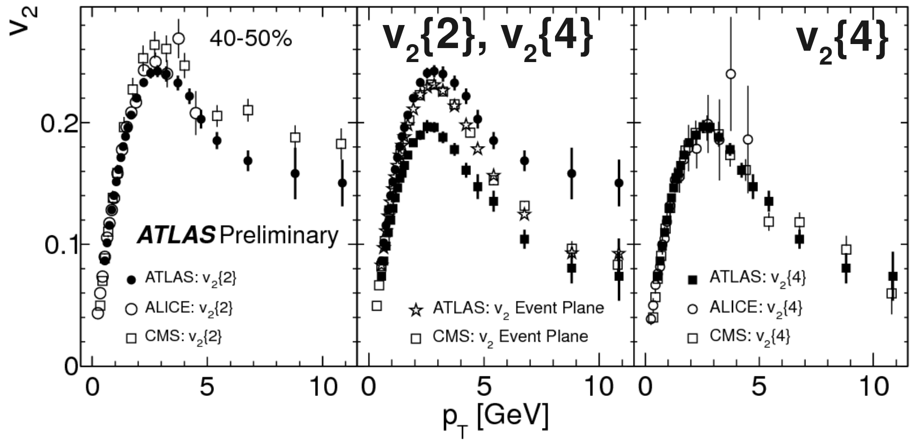


- v_n distributions are obtained from raw measurements by unfolding
- v_3 and v_4 are consistent with a 2D Gaussian distribution
- v_2 distributions, with exception of the most central events, are narrower, $\sigma_{v_2}/\langle v_2 \rangle$ is smaller than $\sqrt{\frac{4}{\pi}-1}$ expected for 2D Gaussian distribution



ATLAS-CONF-2012-114.

Elliptic flow from cumulants

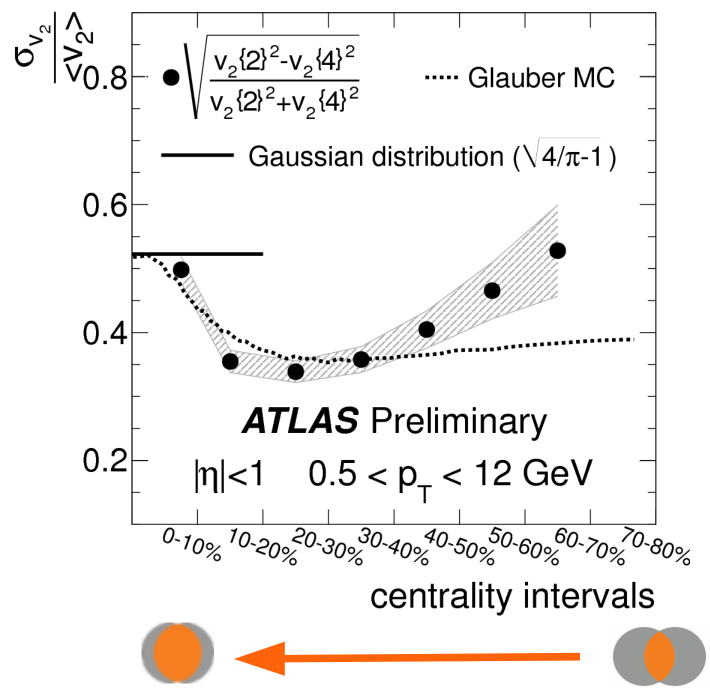


$v_2\{4\}$ cumulant from four-particle correlations, in which effects from two-particle correlations are cancelled, is significantly smaller than v_2 from two-particle correlations or from event plane method

more details on flow cumulants in the talk by **Dominik Derendarz**

Elliptic flow fluctuations from cumulants

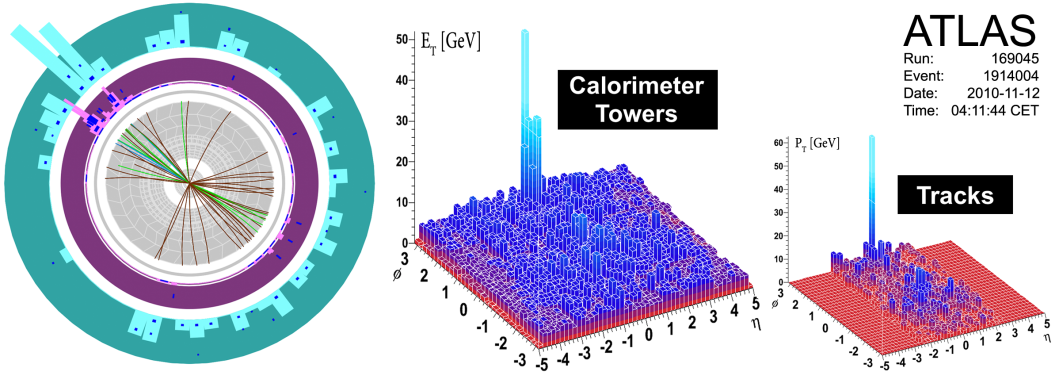
- **fluctuations averaged over p_T**
- **centrality dependence of fluctuations compared with predictions from the Glissando Glauber MC model** ***(W. Broniowki, M. Rybczynski, and P. Bozek, arXiv:0710.5731 [nucl-th])***
- **fluctuations obtained from cumulants provide an upper limit, as the $v_2\{2\}$ contains also non flow fluctuations.**



ATLAS-CONF-2012-118.

Jets in PbPb collisions

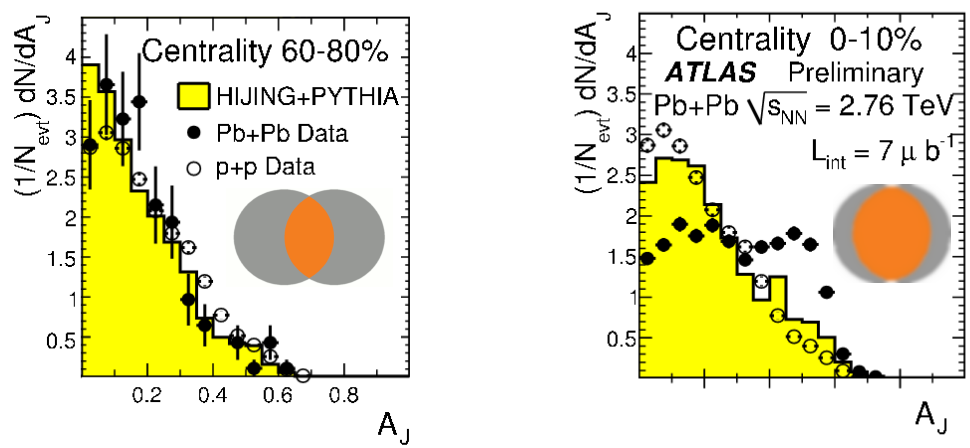
First result in 2010 - disappearance of one of jets



events with a single high energy jet in the most central PbPb collisions

Quantitative description of the jet suppression using dijet energy asymmetry

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



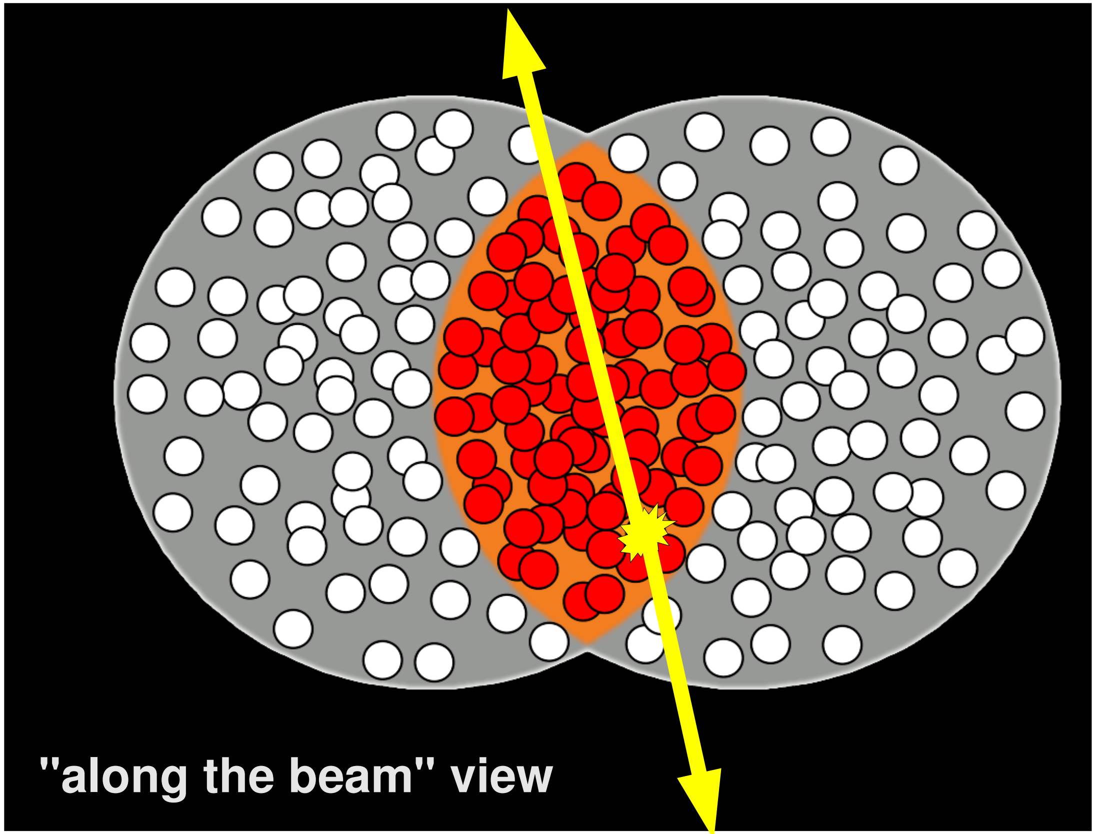
Asymmetry of jet energy in PbPb collisions at 2.76 TeV:

- **in peripheral collisions is similar to that in pp collisions**
- **becomes much larger for more central events**
- **angular correlations do not depend on centrality**

ATLAS, Phys. Rev. Lett. 105 (2010) 252303.
ATLAS-CONF-2011-075.

Jet Suppression

- jets are produced in pairs from energetic partons emerging from hard collisions of quarks or gluons
- in the strongly interacting matter created in PbPb collisions they loose energy depending on the traversed path length
- this effect can be observed also using particles with high transverse momenta



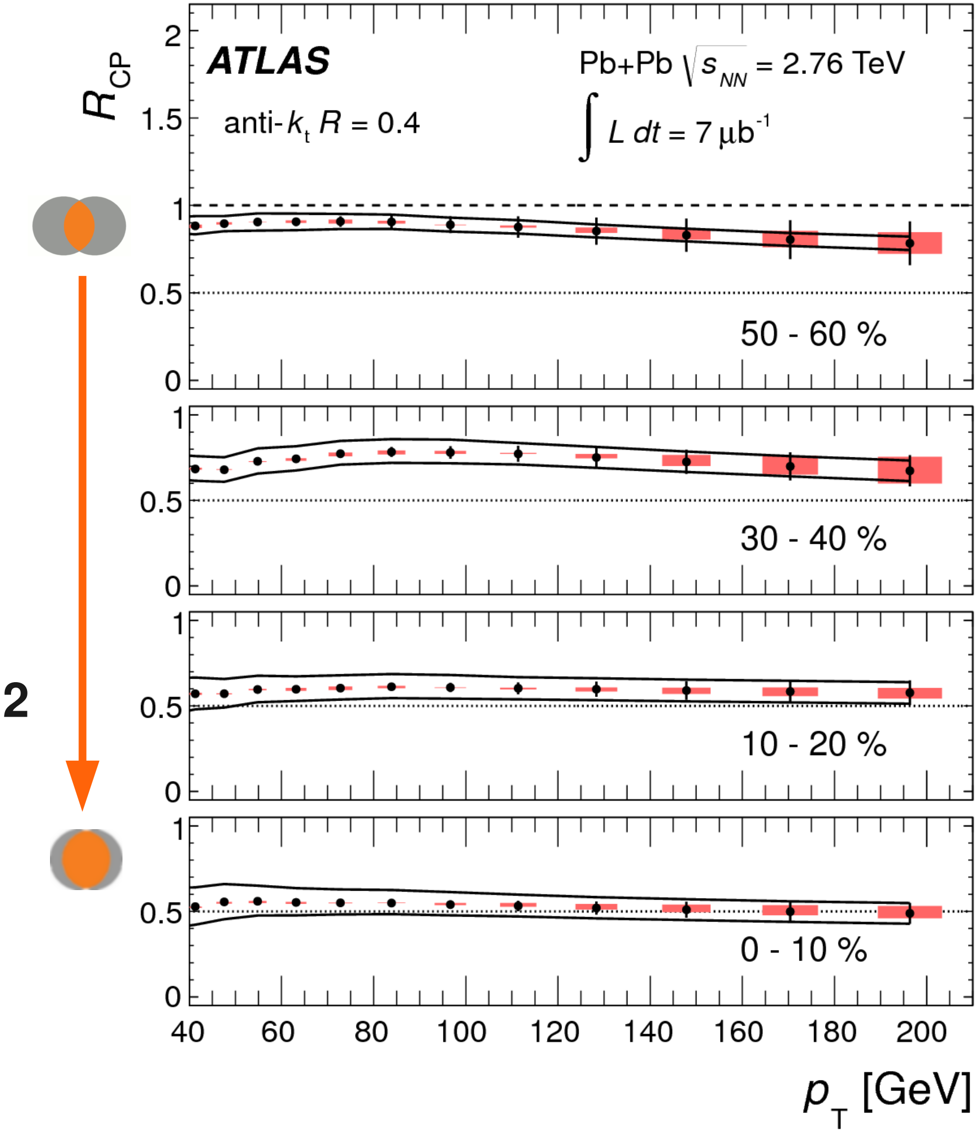
Questions:

- both partons are affected: what fraction of energy is lost by each parton on average?
- how the energy loss depends on the traversed path length?
- is the fragmentation of jets modified?
- what are the suppression patterns of jets with heavy quarks, of photons and electroweak bosons?

Central to peripheral ratio

$$R_{CP} = \frac{\frac{1}{N_{coll}^{centr}} \frac{1}{N_{ev}^{centr}} \frac{dN_{jet}^{centr}}{d\,p_T}}{\frac{1}{N_{coll}^{60-80\,\%}} \frac{1}{N_{ev}^{60-80\,\%}} \frac{dN_{jet}^{60-80\,\%}}{d\,p_T}}$$

- **in the most central sample the jet yields are 2 times smaller than in peripheral collisions**
- **weak dependence on jet p_T**

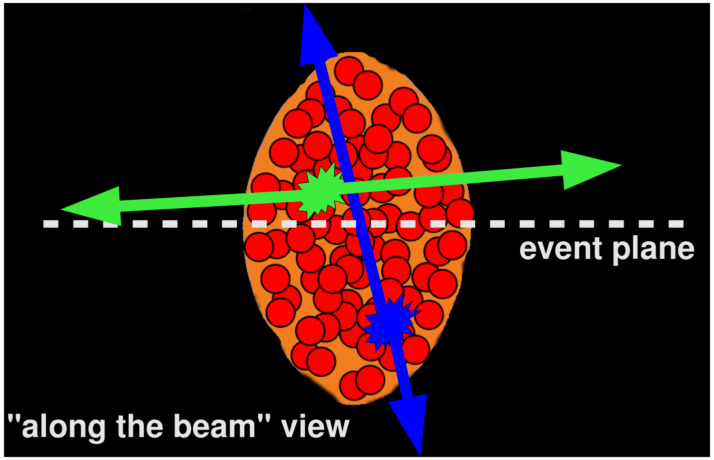


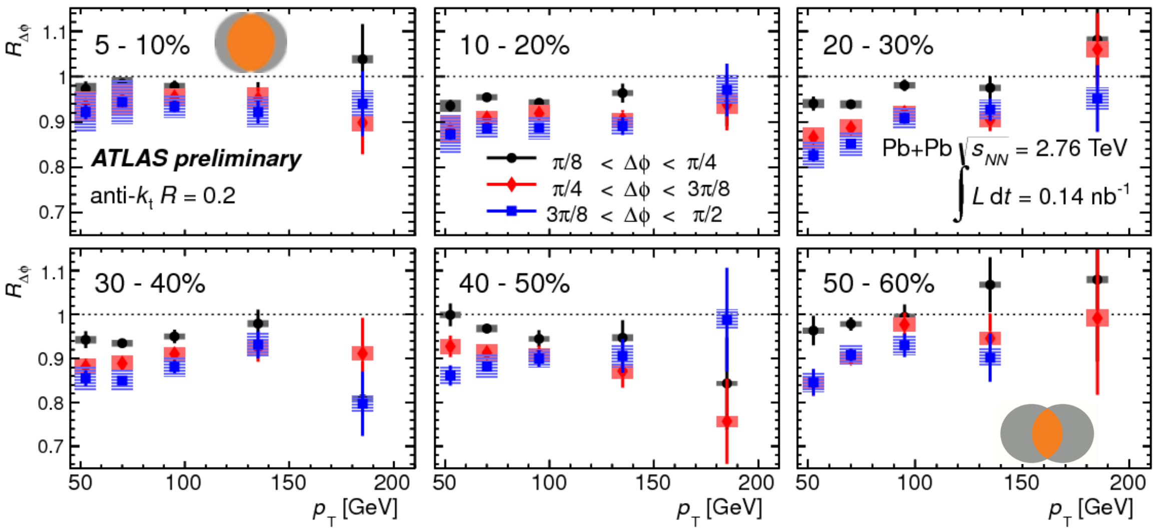
ATLAS, arXiv:1208.1967 hep-ex.

Azimuthal angle dependence

reflecting the path length dependence

$$R_{\Delta\phi} = \frac{\dfrac{d^2 N_{jet}}{d\,p_T\,d(\Delta\phi)}(\Delta\phi)}{\dfrac{d^2 N_{jet}}{d\,p_T\,d(\Delta\phi)}(\Delta\phi<\pi/8)}$$





$\Delta\phi$ - the angle between a jet and the event plane

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

ATLAS-CONF-2012-116.

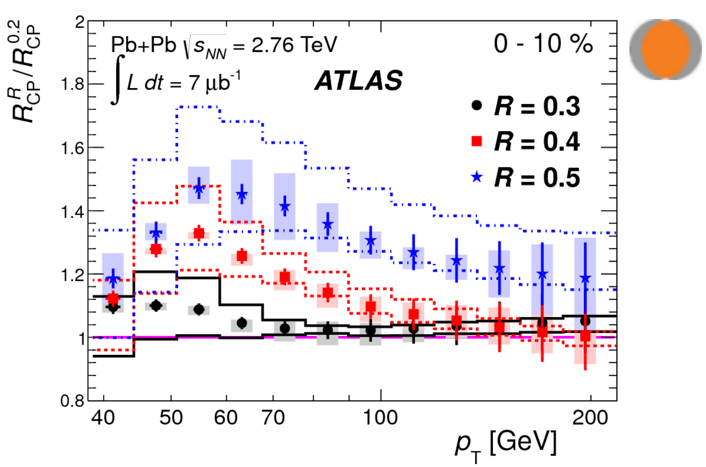
Central to peripheral ratio

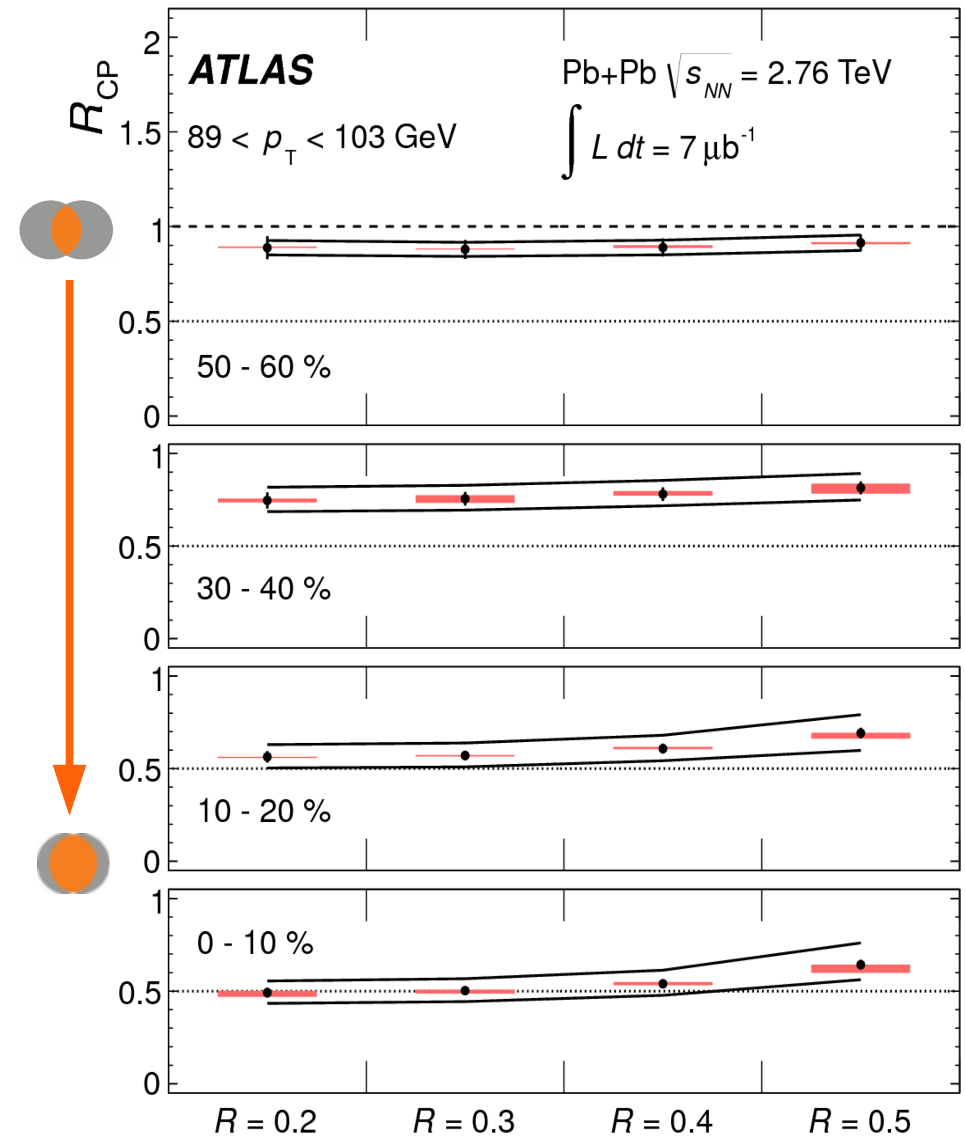
for different jet sizes

Dependence of jet suppression on the jet size parameter - largest suppression for jets with smallest size.

Energy of the jet is partially recovered by increasing the jet size.

$$\frac{R_{CP}^{R}}{R_{CP}^{R=0.2}}$$





ATLAS, arXiv:1208.1967 hep-ex.

Jets - fragmentation

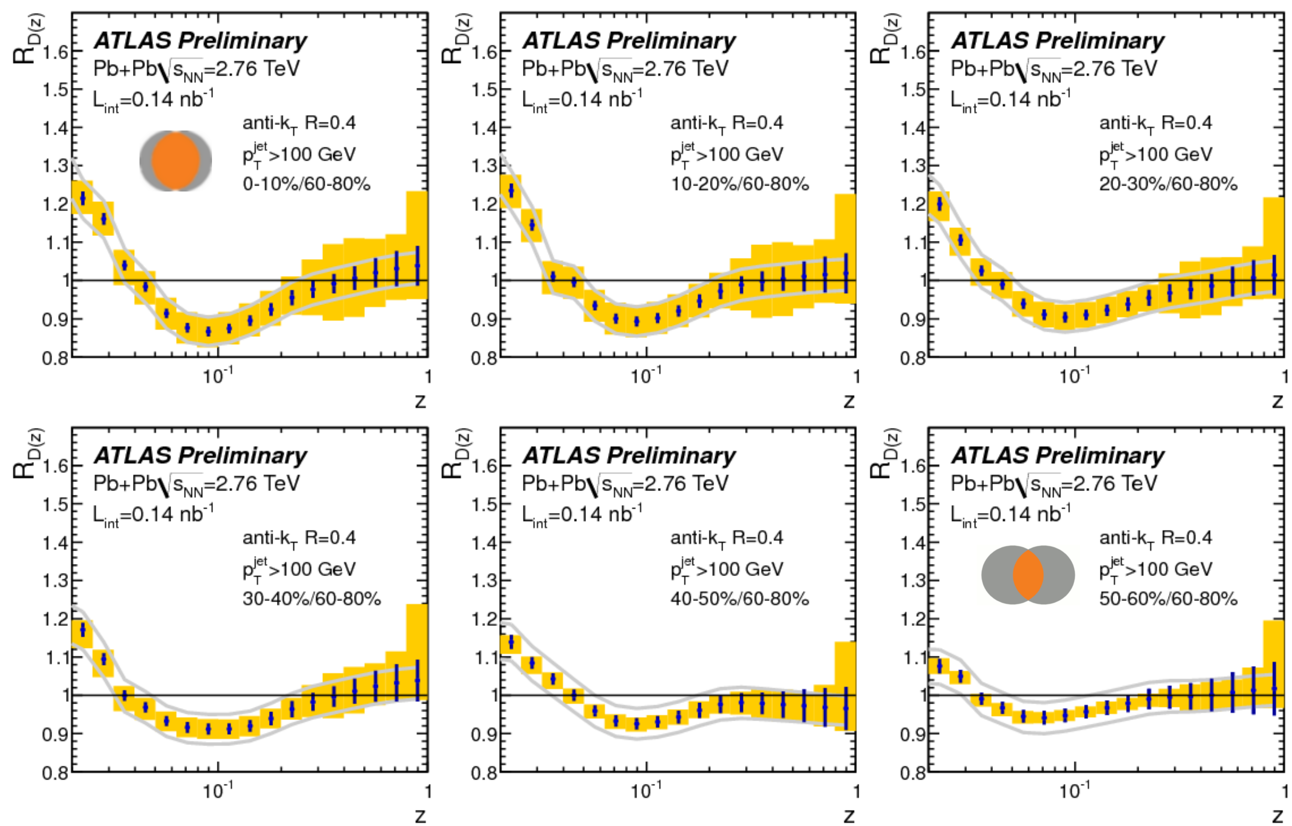
Fragmentation function

$$z = \frac{p_T^{ch}}{p_T^{jet}} \cos(\Delta R)$$

ΔR represents the angle between particle and jet direction

$$R_{D(z)} = \frac{D(z)_{centr}}{D(z)_{60-80\%}}$$

- **no change for z ≈ 1**
- **R<1 for 0.05<z<0.2**
- **R>1 for z<0.03**



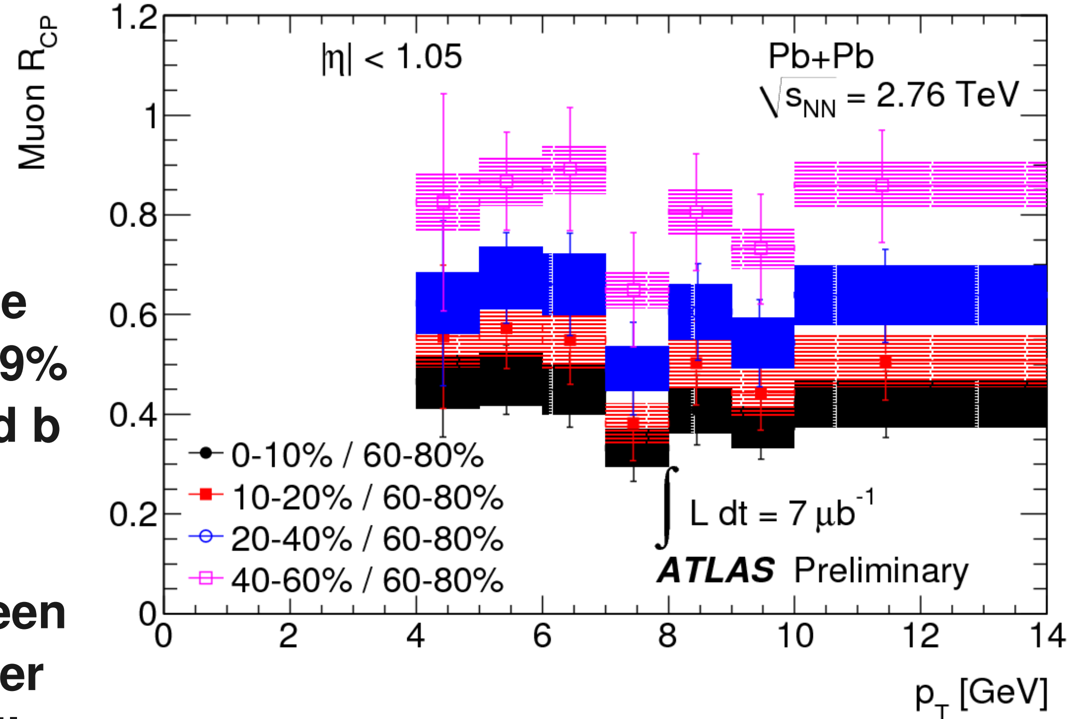
ATLAS-CONF-2012-115.

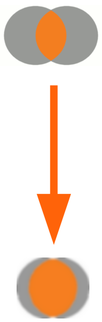
Muon R_{CP}

$$R_{CP} = \frac{\frac{1}{N_{coll}^{centr}} \frac{1}{N_{ev}^{centr}} \frac{dN_{\mu}^{centr}}{d\,p_T}}{\frac{1}{N_{coll}^{60-80\,\%}} \frac{1}{N_{ev}^{60-80\,\%}} \frac{dN_{\mu}^{60-80\,\%}}{d\,p_T}}$$

Muons in the 4 < pT < 14 GeV range used in this analysis originate in 99% from semi-leptonic decays of c and b quarks.

Suppression by a factor of 2 between 0-10% and 60-80% centrality, weaker than for charged hadrons and similar to jets suppression.





ATLAS-CONF-2012-050.

Photons and Z bosons

- matter created in the heavy collisions strongly interacts with energetic partons (quarks and gluons) created in hard processes, but photons and products of leptonic decays of Z bosons penetrate it freely and leave it unaffected
- momenta of "penetrating probes" can be used as a measure of the initial momentum of associated jets

ATLAS-CONF-2012-050.

Photon-jet correlations

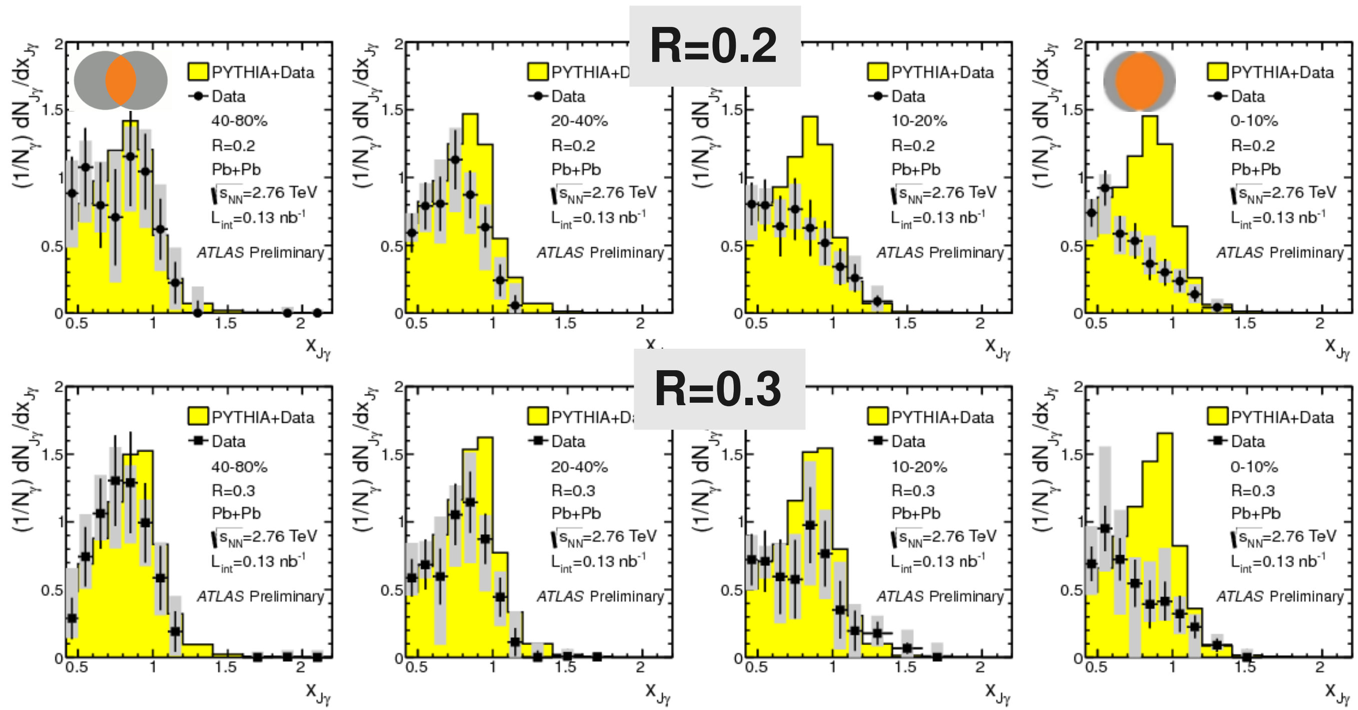
pair: photon - jet produced in the processes:

$qg \rightarrow q\gamma$ **or** $qq \rightarrow g\gamma$

E_γ 60-90 GeV, $|\eta|<1.2$

γ-jet separation $\Delta\phi > 7\pi/8$

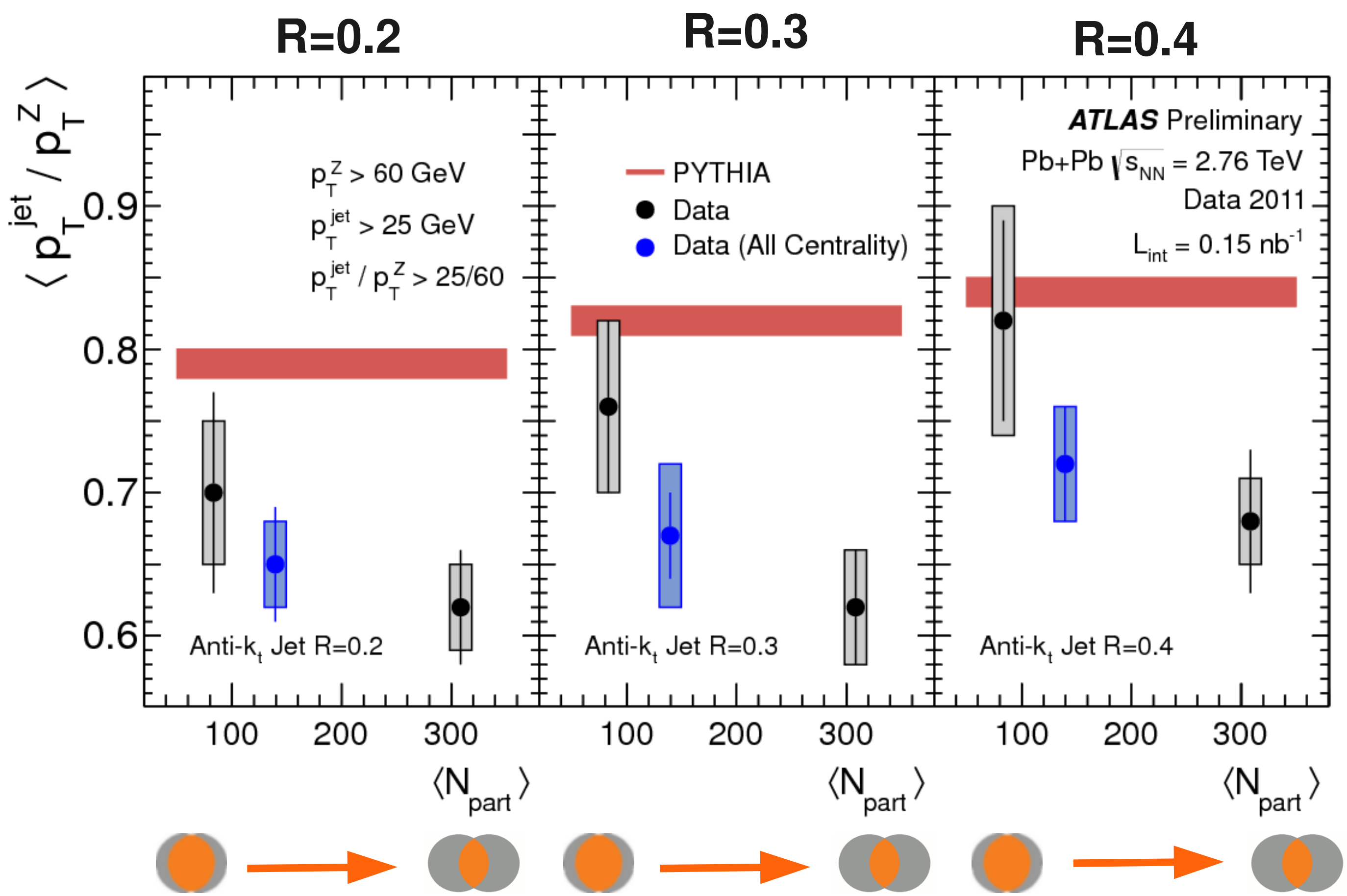
$$X_{J_\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$



correlations similar to PYTHIA predictions in peripheral collisions
momenta of jets shifted to lower values in the central collisions

ATLAS-CONF-2012-051.

Z boson - jet correlations



p_T of the Z boson used as a measure of the original momentum of the jet

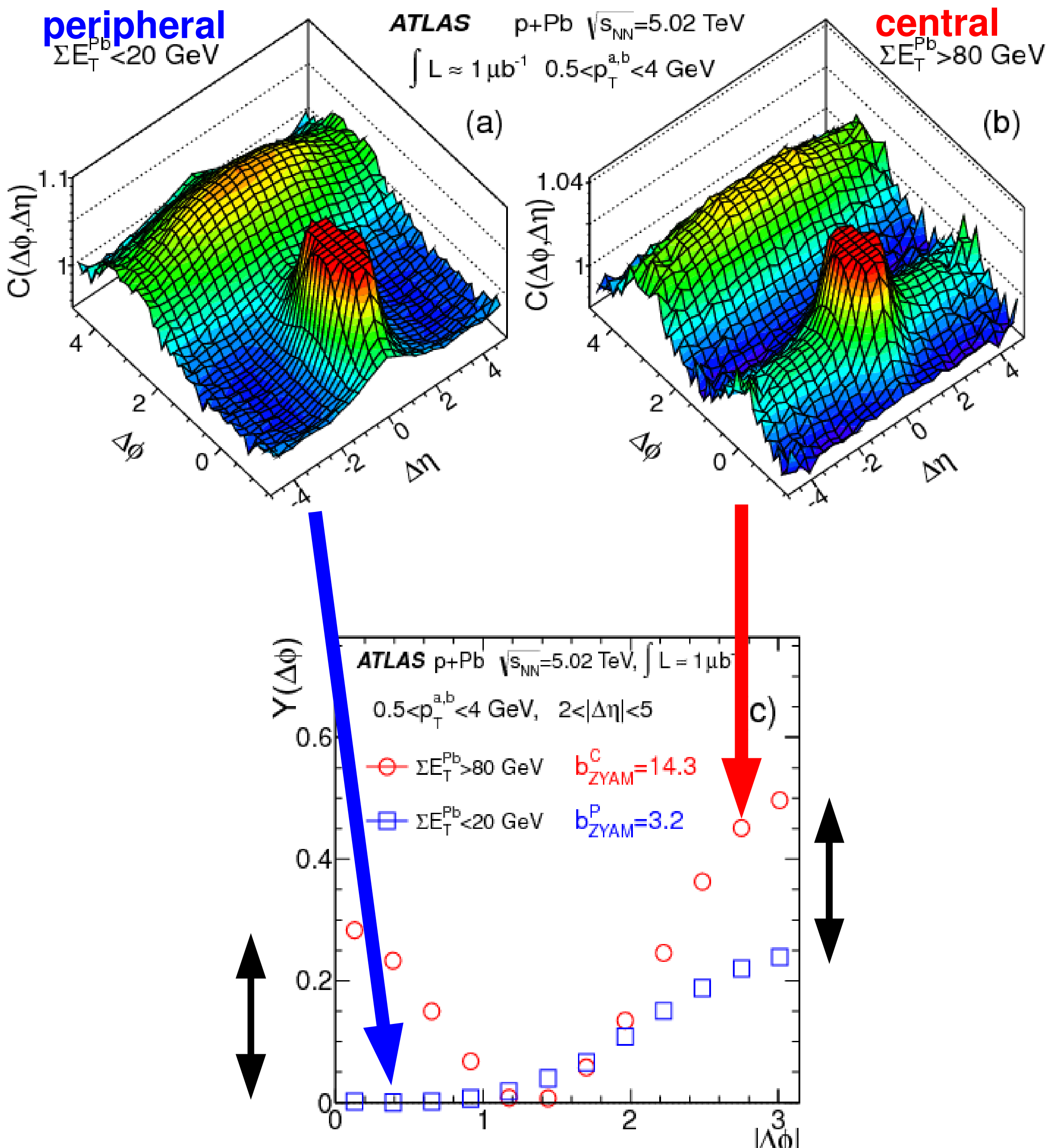
the final p_T of jet is lower than predicted by PYTHIA model (without jet energy loss) and indicates the level of jet suppression

lower statistics than for photon-jet correlations, but the same trend

ATLAS-CONF-2012-119.

pPb collisions

"Ridge" in two-particle correlations in pPb collisions



ATLAS, arXiv:1212.5198 [hep-ex]

$$C(\Delta\phi,\Delta\eta) = \frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)}$$

two distinct centralities of pPb collisions, selected by E_T ranges:

peripheral $\sum E_T$<20 GeV

central $\sum E_T$ > 80 GeV

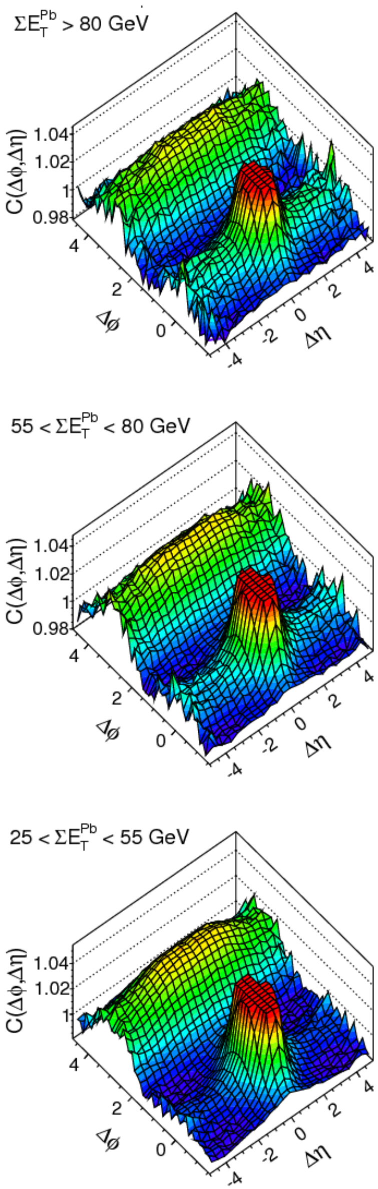
per trigger yield

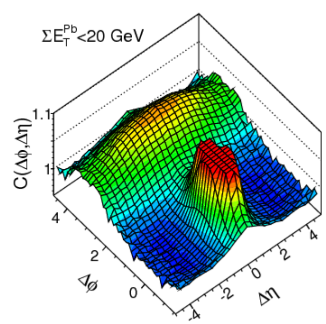
$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi)\,d(\Delta\phi)}{\pi N_a}\right) C(\Delta\phi) - b_{ZYAM}$$

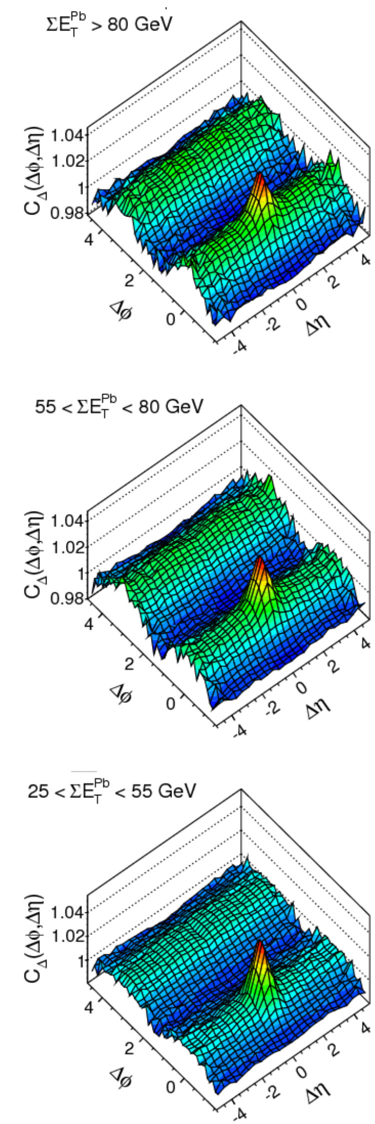
$B(\Delta\phi, \Delta\eta)$ and $C(\Delta\phi, \Delta\eta)$ are integrated in the range **$2 < |\Delta\eta| < 5$**

Difference between points for large and small $\sum E_T$ is similar near $\Delta\phi = 0$ and $\Delta\phi = \pi$

Subtraction of recoil contribution







recoil contribution

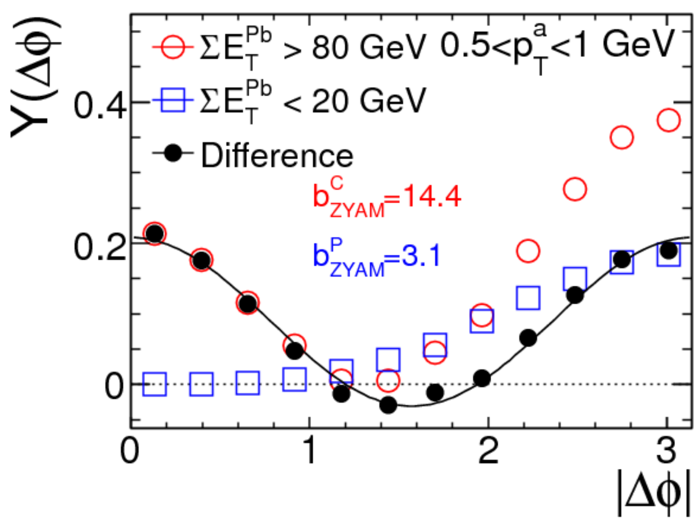
(peripheral collisions)

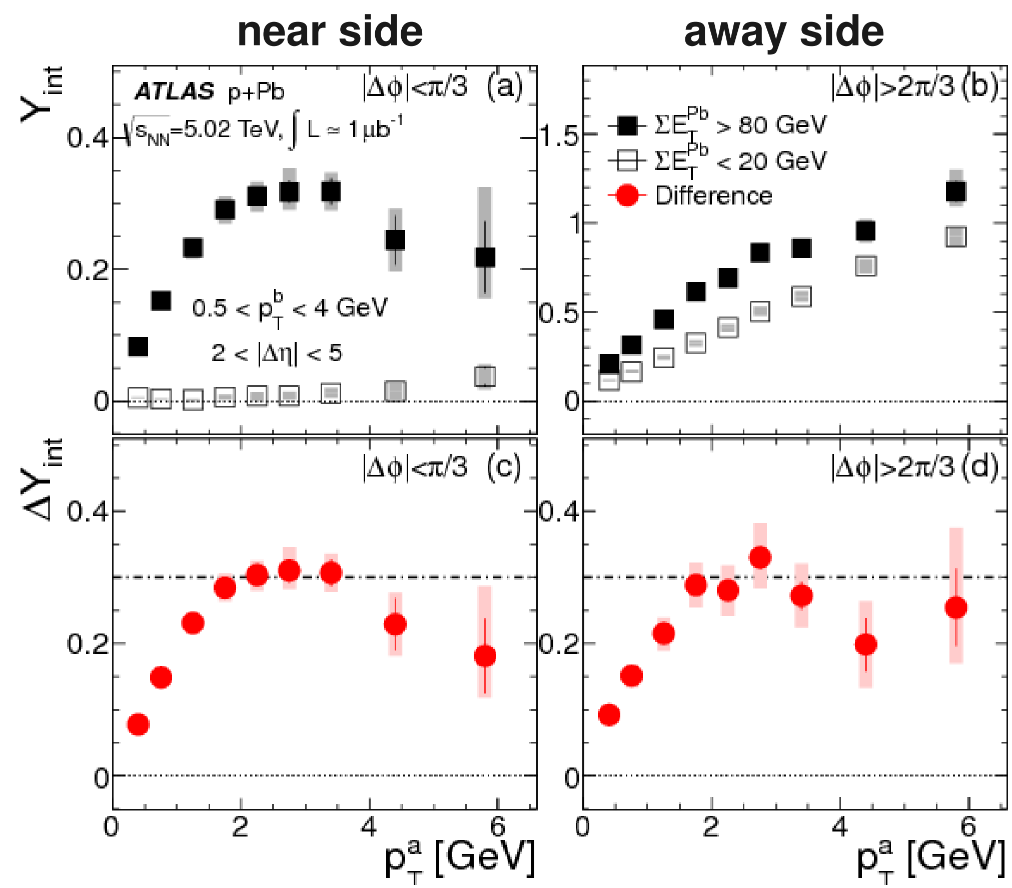
ATLAS, arXiv:1212.5198 [hep-ex]
ATLAS, HION-2012-13

"Ridge" in two-particle correlations in pPb collisions

Difference of per trigger yields

$$Y(\Delta\phi)_{central} - Y(\Delta\phi)_{peripheral} \sim a_0 + 2a_2\cos 2\Delta\phi$$





Yield can be described as a **recoil contribution** plus a **cos(2$\Delta\phi$) component**

The yield difference as a function of p_T is the same in the near and away side.

ATLAS, arXiv:1212.5198 [hep-ex]

more details in the talk by
Bartłomiej Żabiński

Summary

Azimuthal correlations in PbPb collisions

- measurements of flow harmonics v_n, n=1, ..., 6
- ($|\eta|$<2.5, p_T > 0.03 GeV)
- cumulant harmonics $v_2\{2\}$ and $v_2\{4\}$
- cumulants and event-by-event harmonics used to quantify flow fluctuations and in comparisons with models

Jets in PbPb collisions

- suppression of jet yields in central collisions by a factor of 2
- 15% difference of jet suppression for jets perpendicular and parallel to event plane
- jet size dependence of suppression
- jet fragmentation independent of centrality for large z, but shows suppression at z=0.1 and enhancement for very low z

Studies of high-p_T particles

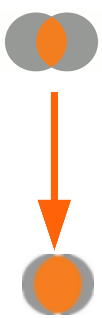
- from muons analysis - suppression for c and b quarks similar to all jets
- no suppression for photons and Z bosons
- momentum of jets correlated with γ or Z bosons shifted to lower values

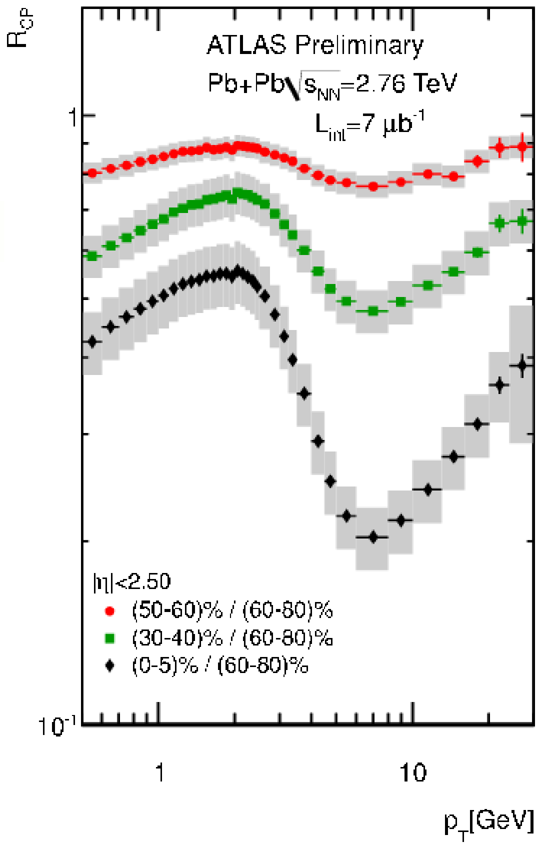
New results from pPb collisions

- in the central events a $\cos(2\Delta\phi)$ modulation component extracted from two-particle correlations

Backup

Charged particle R_{CP}



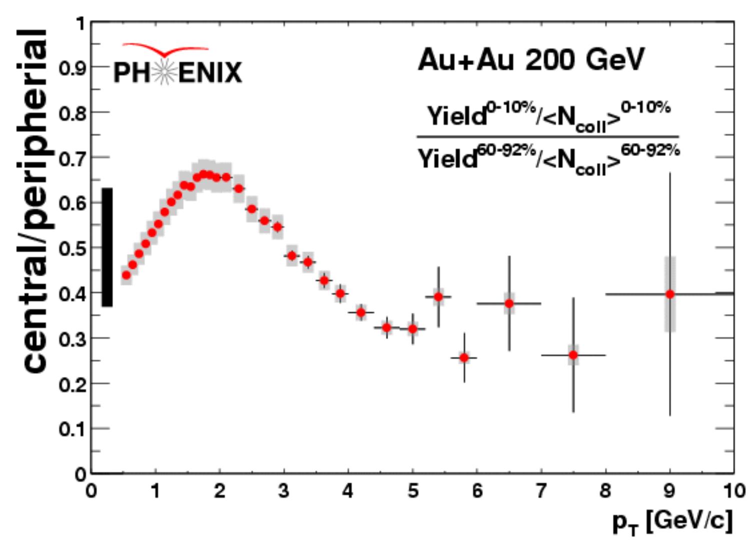


$$R_{CP} = \frac{\frac{1}{N_{coll}^{centr}} \frac{1}{N_{ev}^{centr}} \frac{d^2 N^{centr}}{d\eta\, dp_T}}{\frac{1}{N_{coll}^{60-80\%}} \frac{1}{N_{ev}^{60-80\%}} \frac{d^2 N^{60-80\%}}{d\eta\, dp_T}}$$

ATLAS-CONF-2011-079.

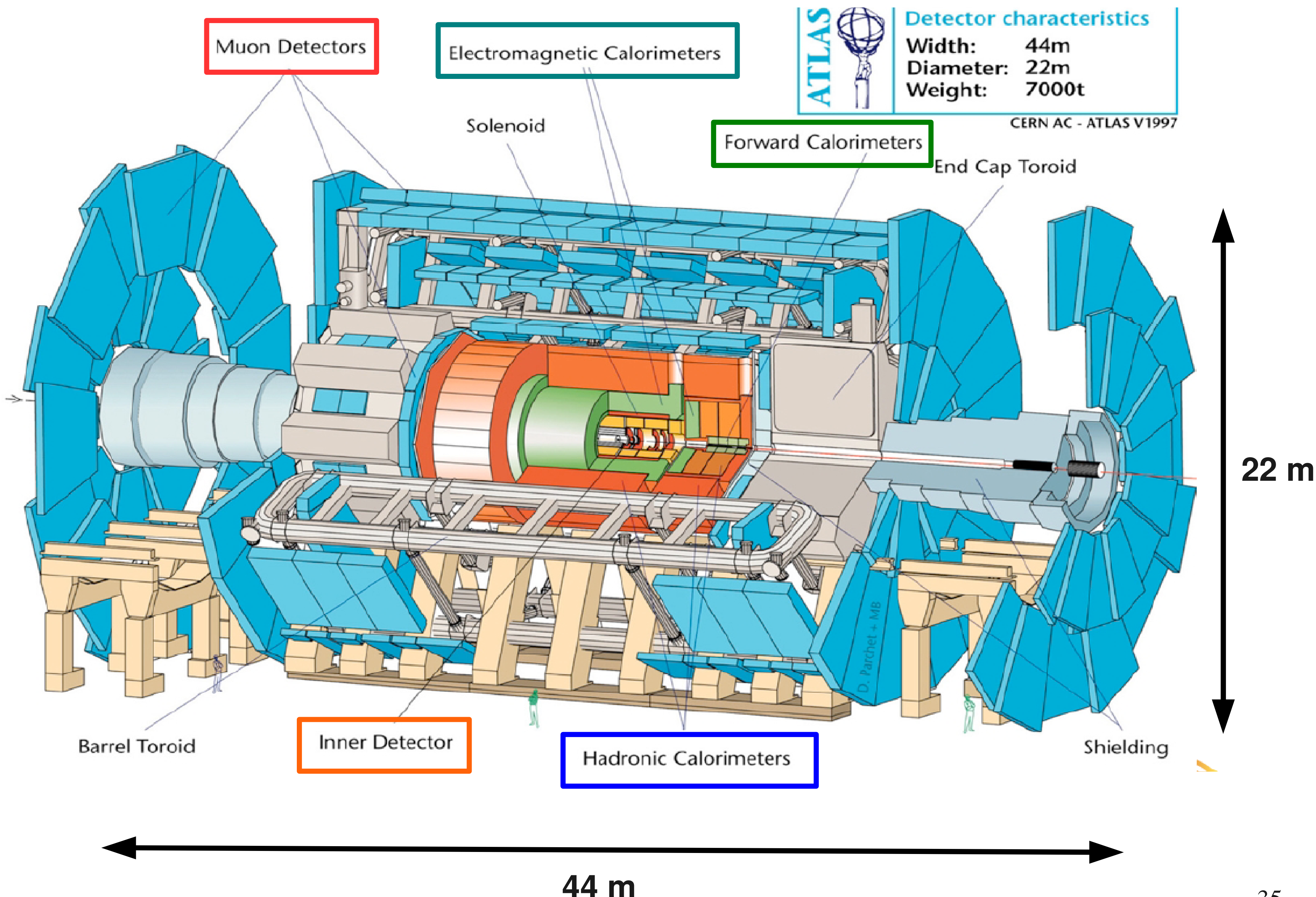
Charged particle yield ratios in PbPb collisions at 2.76 TeV:

- **R_{CP} drops between 2-7 GeV to the values observed at RHIC**
- **above 7 GeV R_{CP} increases reaching 0.5 for the most central collisions**

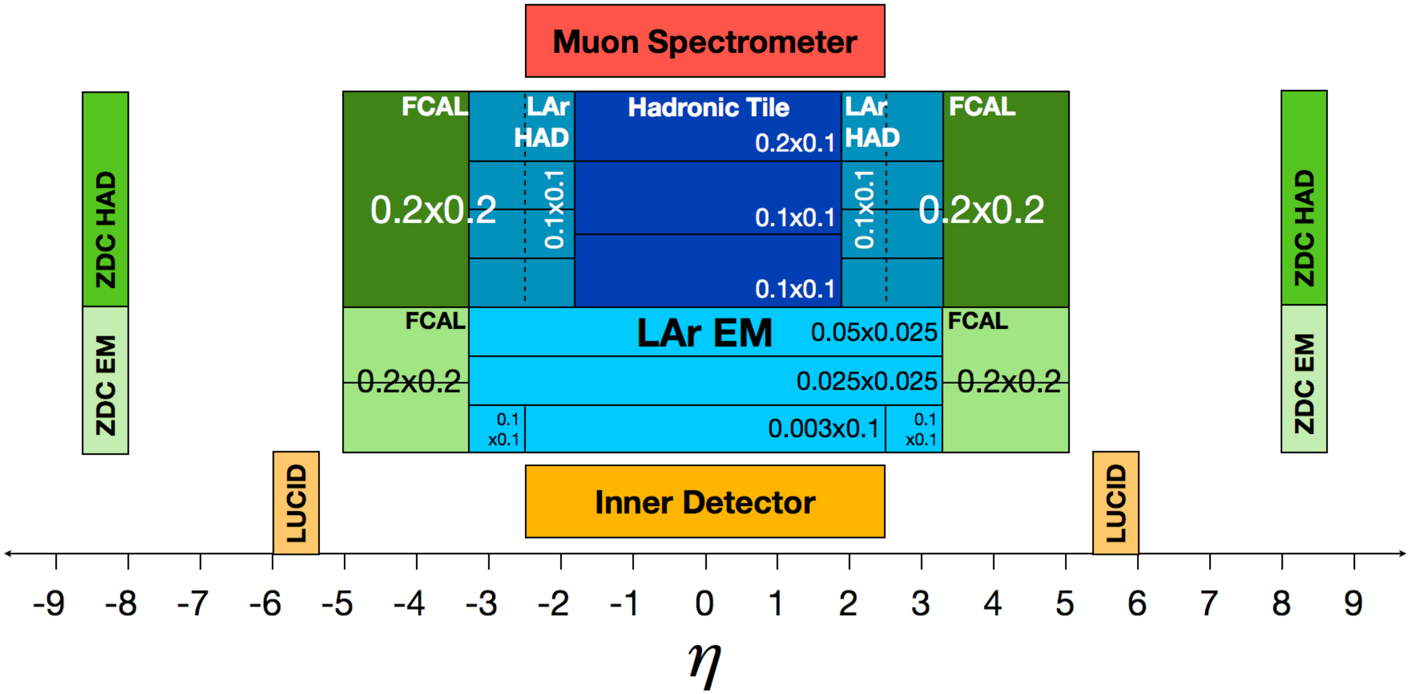


PHENIX, Phys. Rev. C69 (2004) 034910.

The ATLAS detector

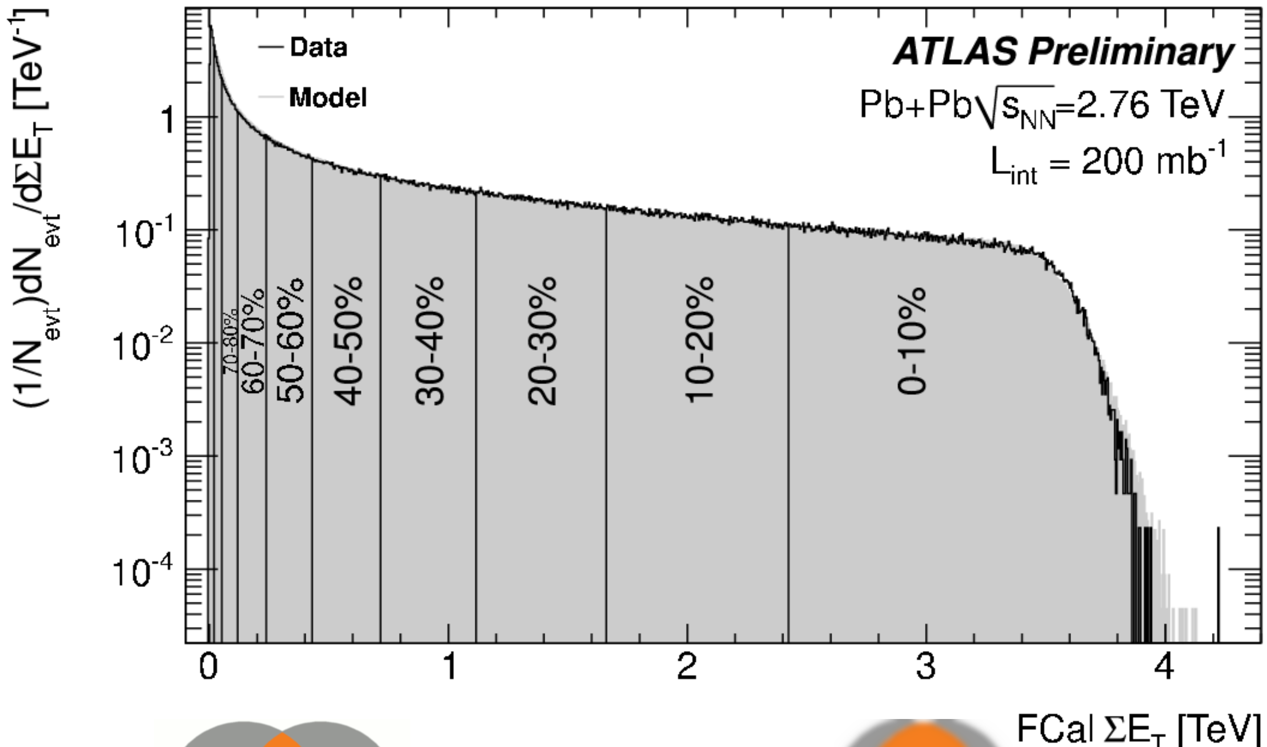


The ATLAS detector



Inner detector	$\|\eta\|<2.5$	track reconstruction
Calorimeter	$\|\eta\|<3.2$	jet reconstruction
Forward Calorimeter	$3.2<\|\eta\|<4.9$	centrality determination
Muon spectrometer	$\|\eta\|<2.7$	muon reconstruction

Centrality of PbPb collisions

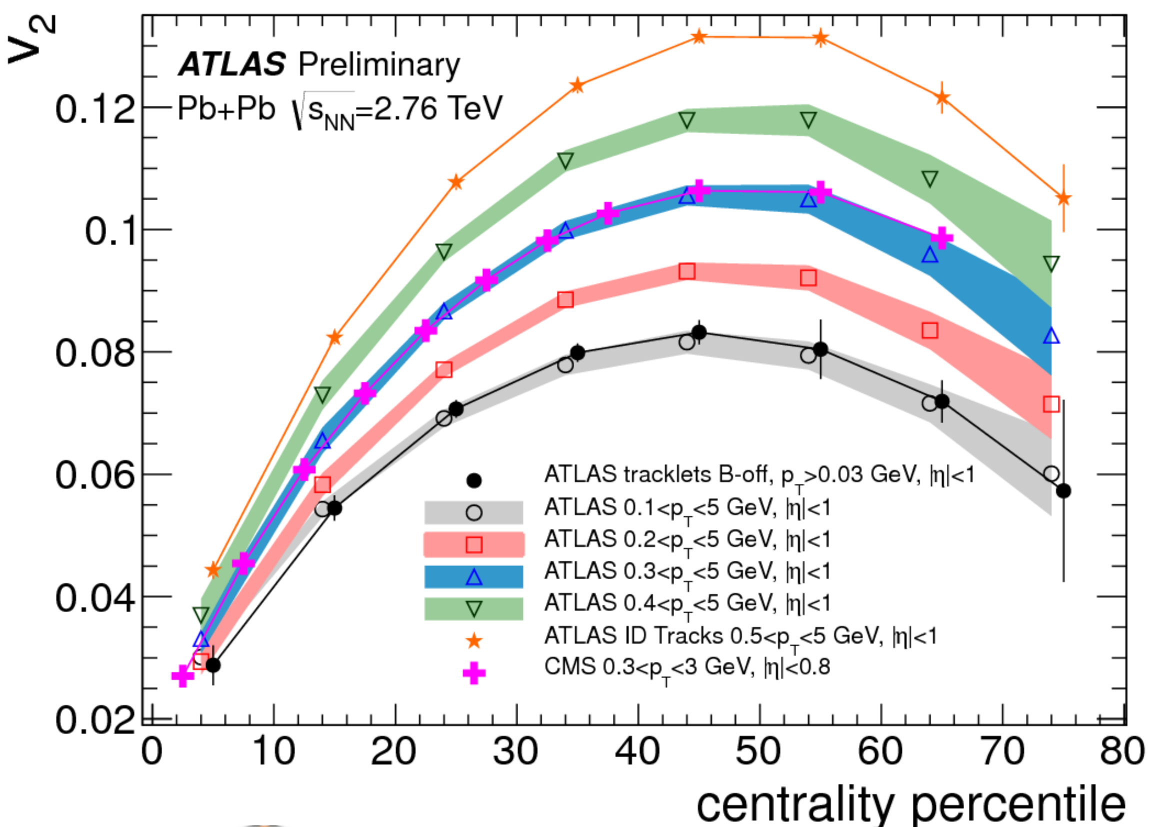


Distribution of the signals registered in the Forward Calorimeter (FCal) is divided into bins with the same number of events (10% of the total).

Fraction of the sampled non-Coulomb inelastic cross section after all trigger selection cuts is estimated to be 100% ±2%

Collective flow - elliptic flow v_2

Centrality dependence



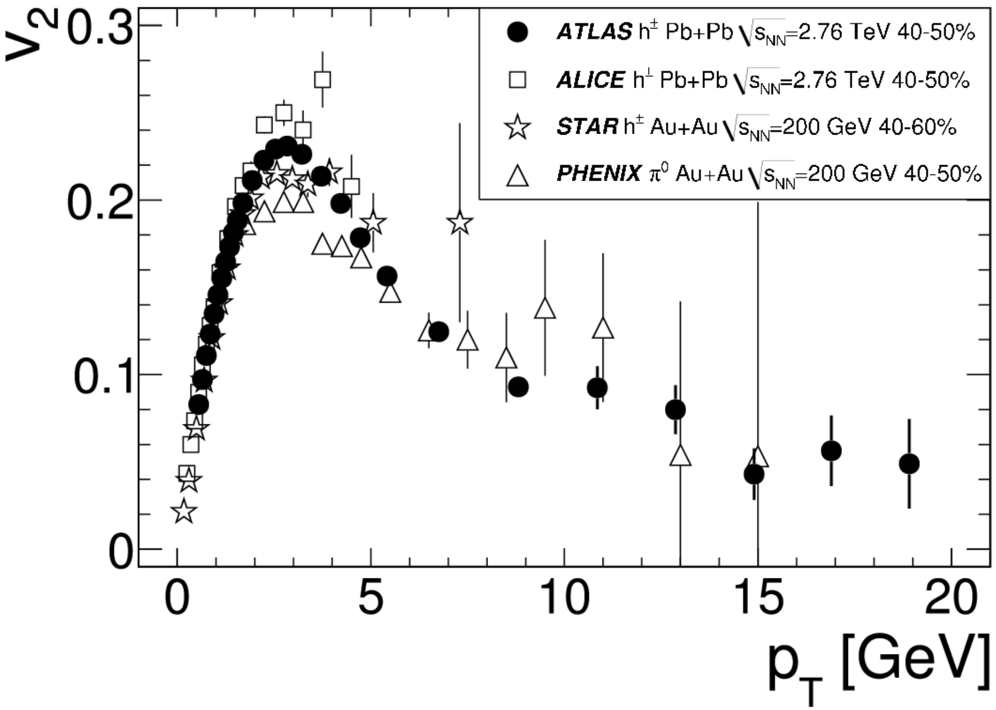
Integrated elliptic flow:

- **is small for central collisions (almost complete overlap area - symmetric shape)**
- **grows for peripheral collisions (overlap area - almond shape)**

Integrated flow depends on transverse momentum cut
(ATLAS has measured flow for particles with very small transverse momenta $p_T > 0.03$ GeV)

ATLAS-CONF-2012-117.

Dependence on transverse momentum



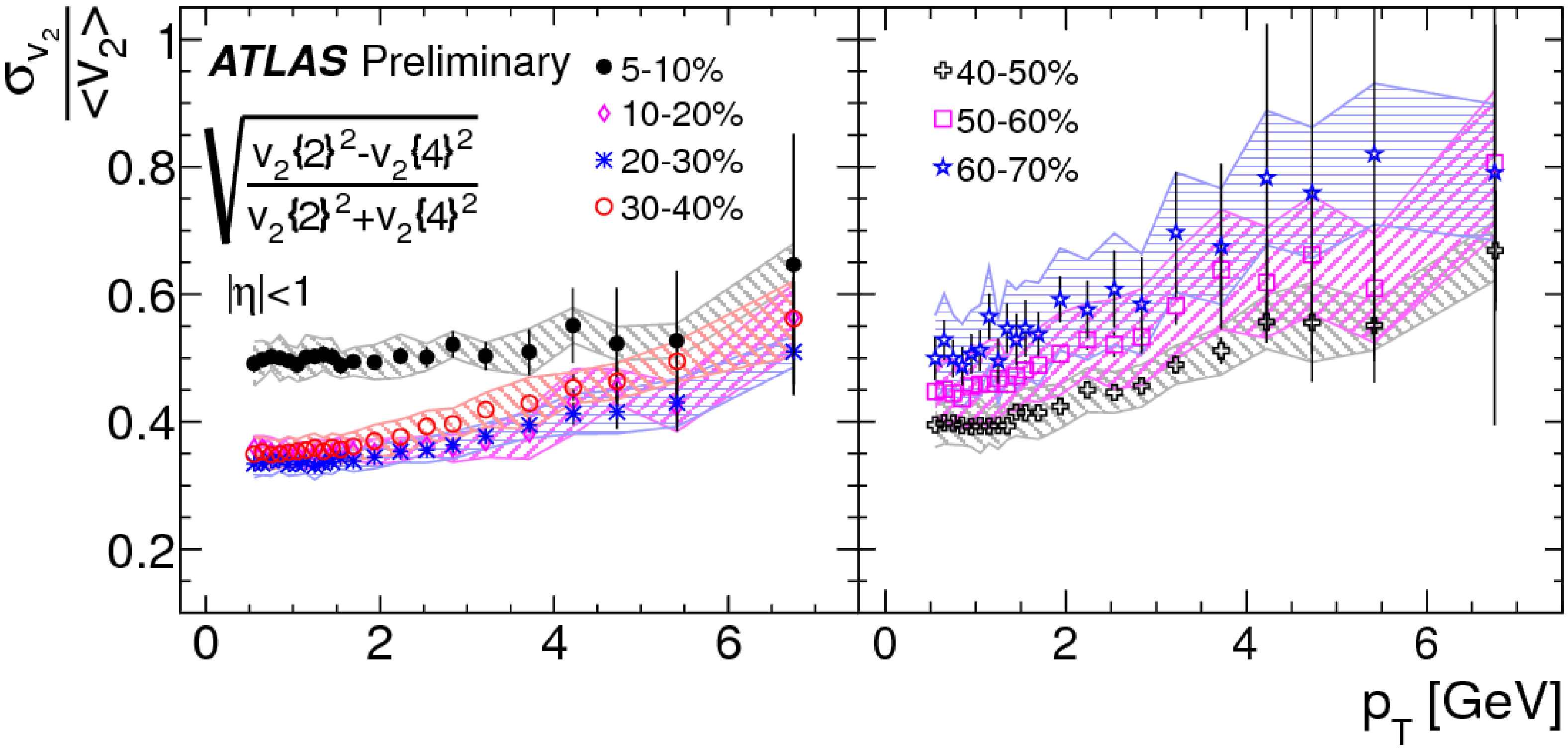
- **rapid rise to p_T ~ 2 GeV (hydrodynamic expansion)**
- **a maximum at p_T ~ 3 GeV**
- **decrease in the p_T range 3-8 GeV (coalescence)**
- **weak dependence at high p_T (jet quenching)**

Similar dependence at LHC and RHIC energies

ATLAS, Phys. Lett. B707 (2012) 330.

Collective flow - fluctuations

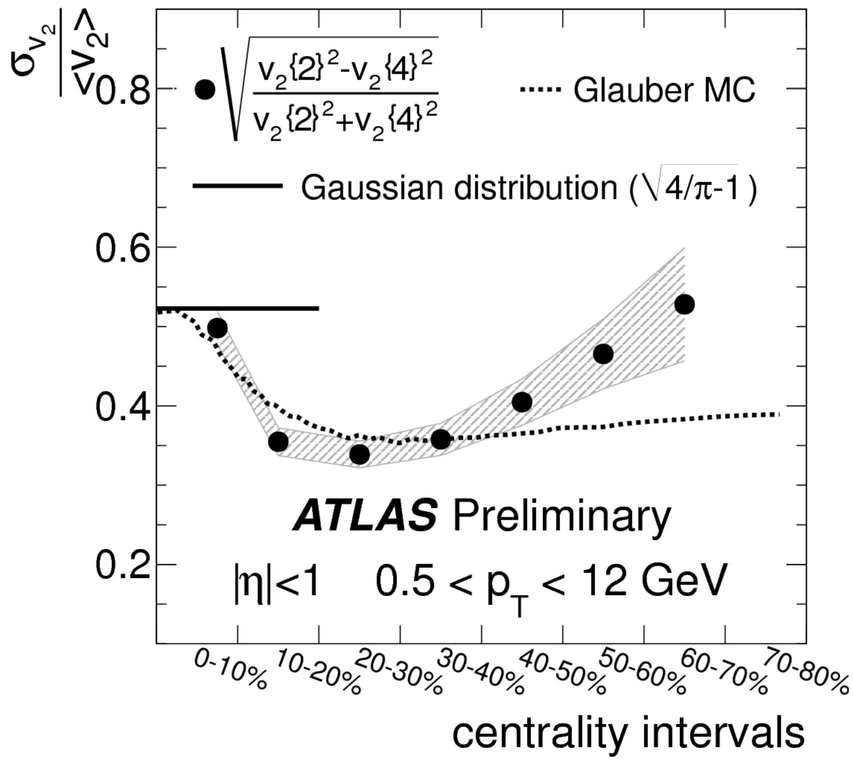
Elliptic flow fluctuations from cumulants $\frac{\sigma_{v_2}}{\langle v_2 \rangle} = \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$



- in the most central events, elliptic flow fluctuations independent of p_T; for other centralities weak dependence for p_T<2 GeV
- largest relative fluctuations are observed for the most peripheral and the most central events

ATLAS-CONF-2012-118.

Elliptic flow fluctuations from cumulants $\frac{\sigma_{v_2}}{\langle v_2 \rangle} = \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$



- fluctuations averaged over p_T
- centrality dependence of fluctuations compared with predictions from the Glissando Glauber MC model
  (*W. Broniowki, M. Rybczynski, and P. Bozek, arXiv:0710.5731 [nucl-th]*)
- fluctuations obtained from cumulants provide an upper limit, as the $v_2\{2\}$ contains also non flow fluctuations.

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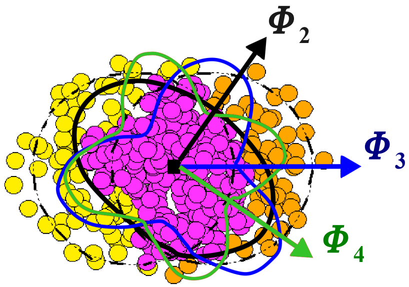
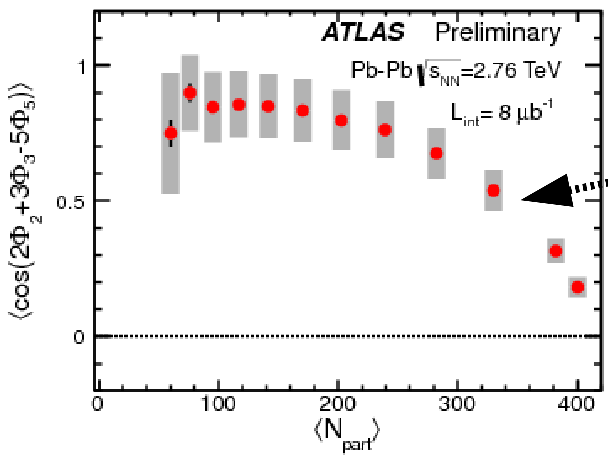
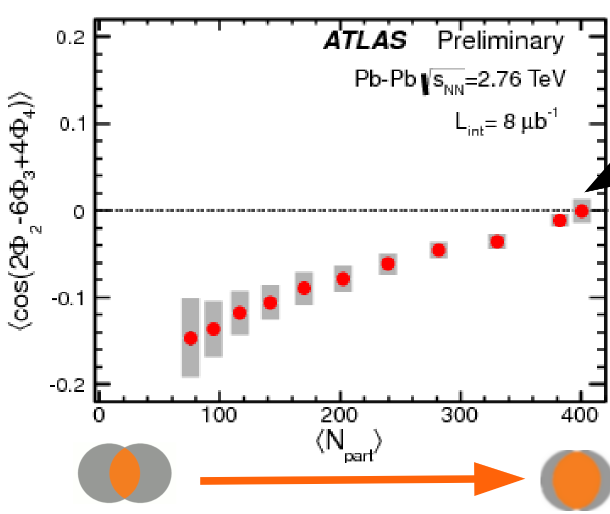
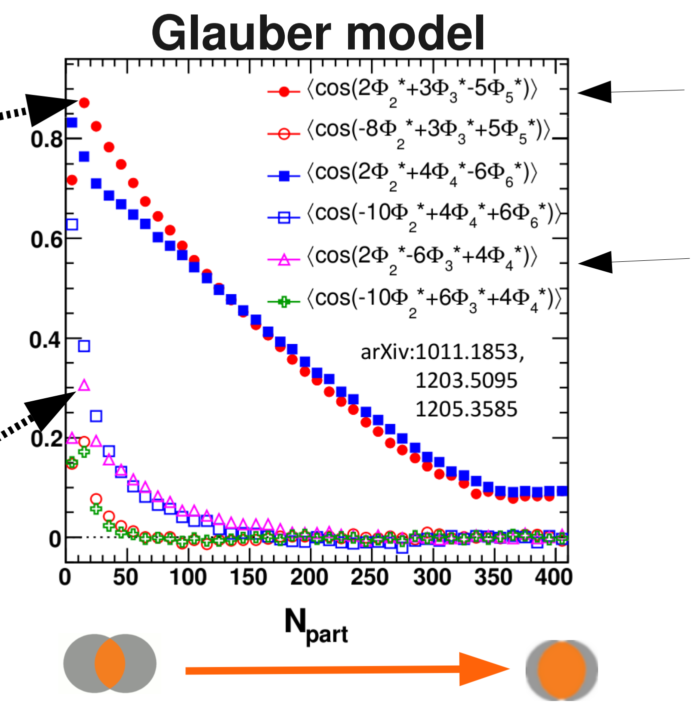
Collective flow - event plane correlations



Correlations between 2 or 3 event planes for flow harmonics are sensitive to non linear response of the medium to initial fluctuations



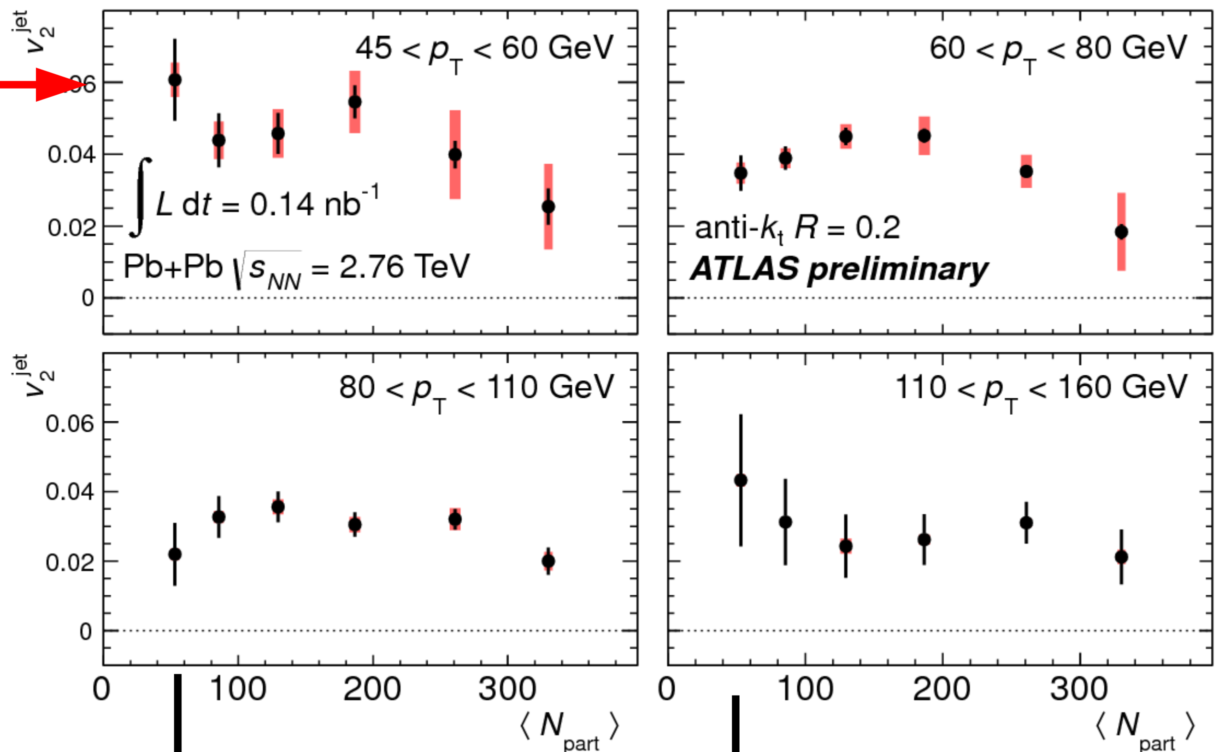




- **some correlations are qualitatively similar to Glauber model, but the other differ significantly**
- **both the initial geometry of the collision and dynamical evolution of the medium are important**

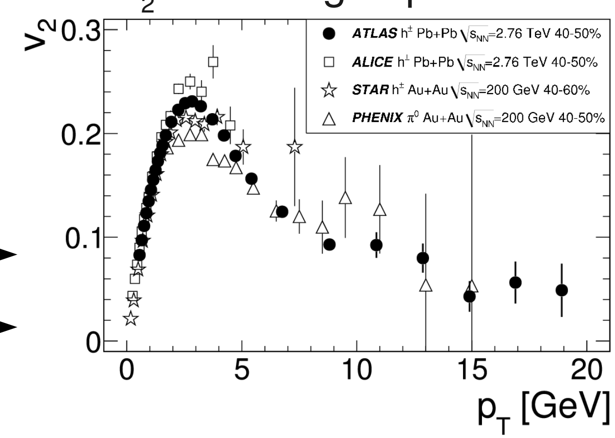
ATLAS-CONF-2012-049.

v_2 for jets



- $v_2 \leq 0.06$ for jets
- decrease of v_2 with p_T
- weak centrality dependence - decrease of v_2 for more central events is significant only at the lowest p_T

v_2 for charged particles

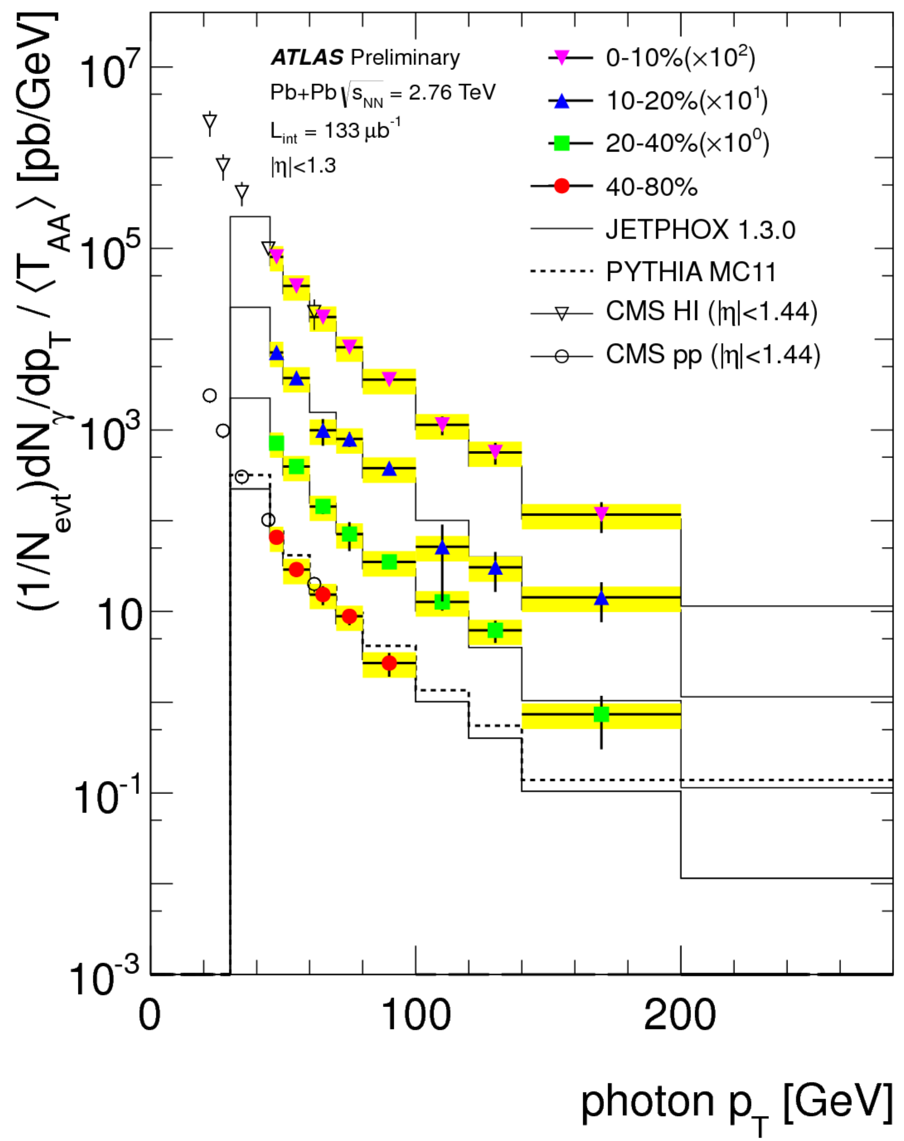


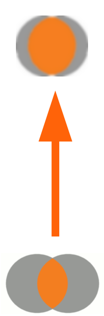
ATLAS-CONF-2012-116.
ATLAS, Phys. Lett. B707 (2012) 330.

Prompt photon yields

good agreement of the yields in PbPb collisions scaled by T_{AA} with the expectations from JETPHOX model.

No indication of suppression.





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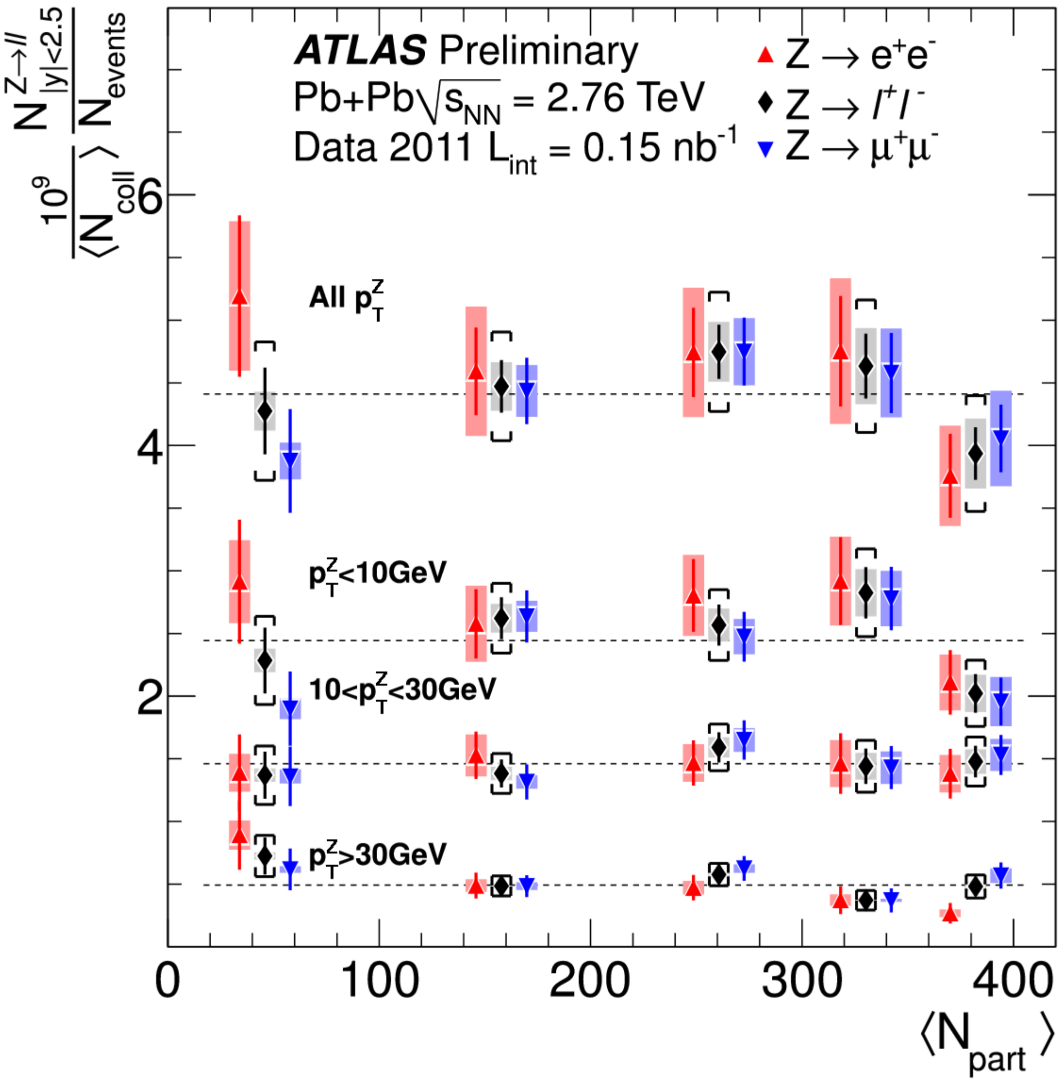
Z boson yields



Calculated using Z boson candidates:
772 in Z → ee channel
1223 in Z → μμ channel

within the measurement uncertainties, Z boson yields are proportional to the number of nucleon-nucleon collisions

No indication of suppression

ATLAS-CONF-2012-052.