Heavy Ion results from ATLAS experiment

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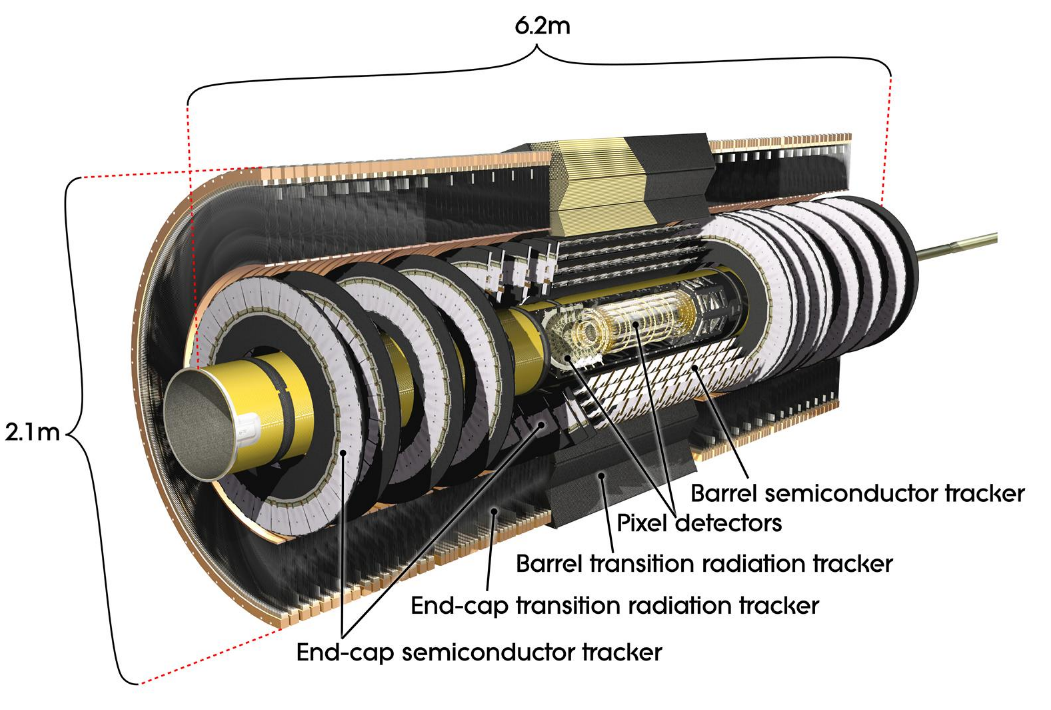
for the **ATLAS collaboration**
Institute of Nuclear Physics
Polish Academy of Sciences

XXII Cracow EPIPHANY Conference
on the Physics in LHC Run2
7-9 January 2016

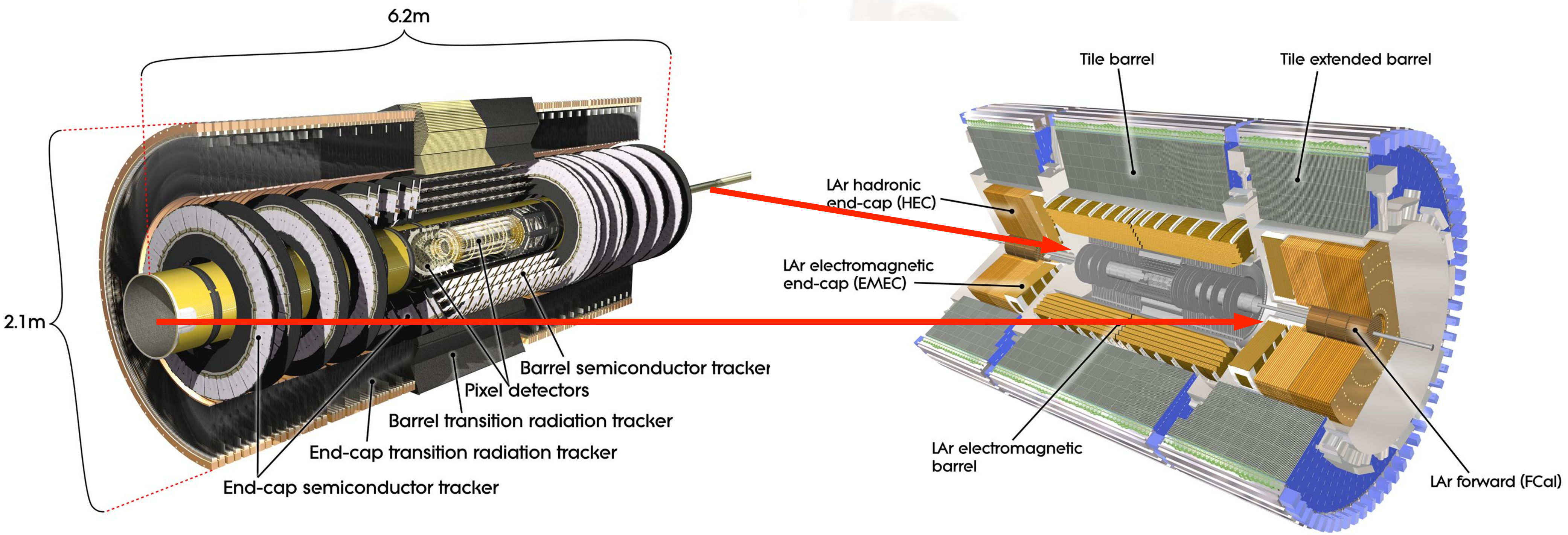
ATLAS detector



Three main subsystems:

- Inner detector – tracking
- Calorimetry
- Muon Spectrometer

ATLAS detector



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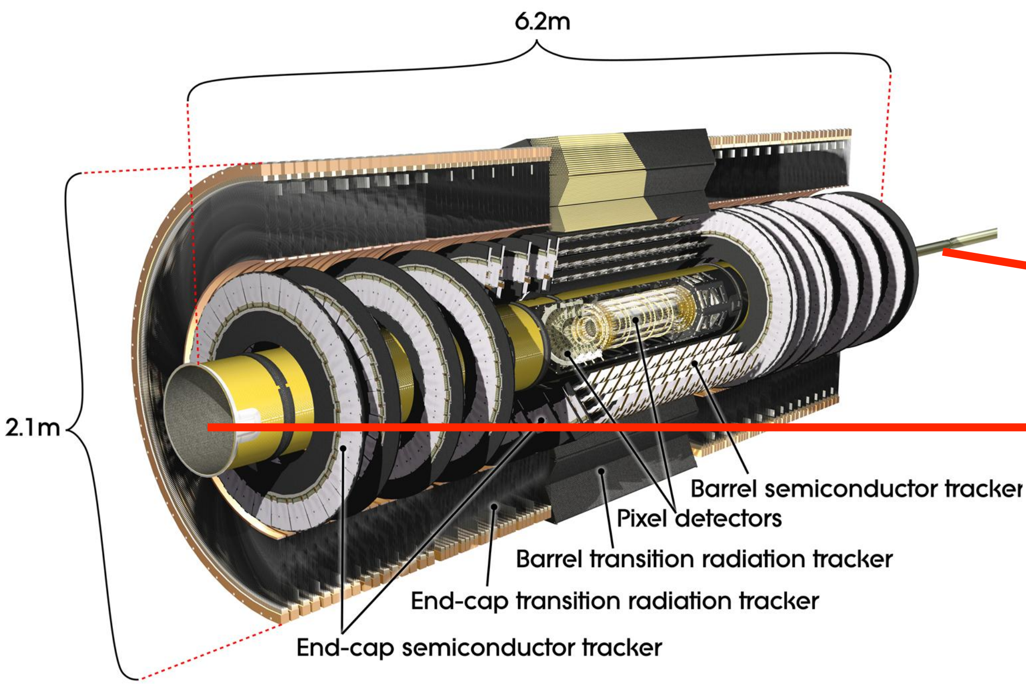

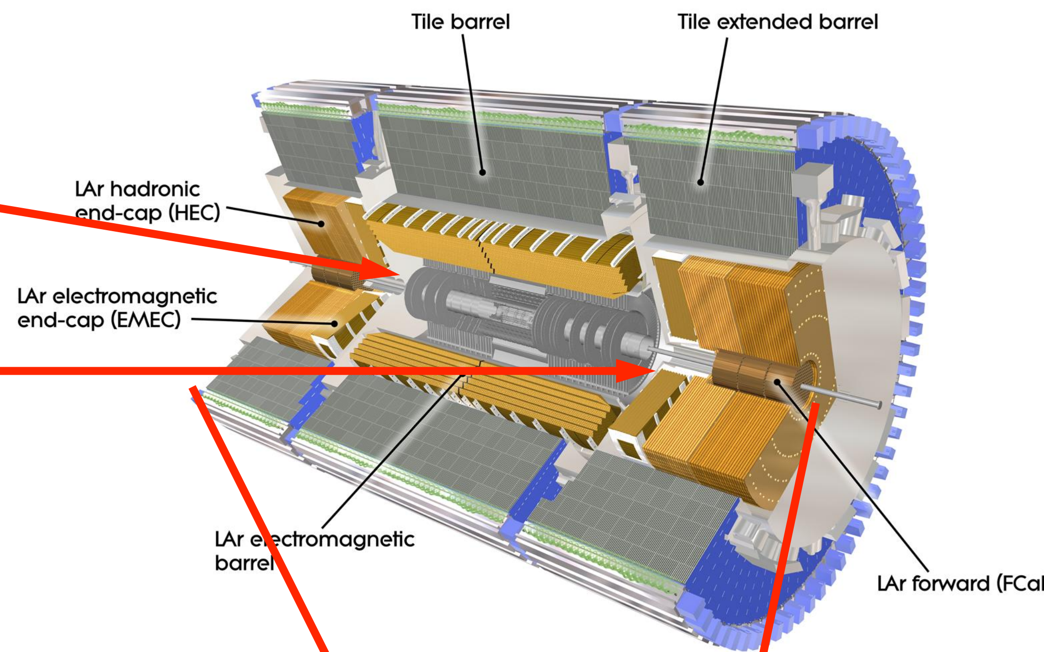

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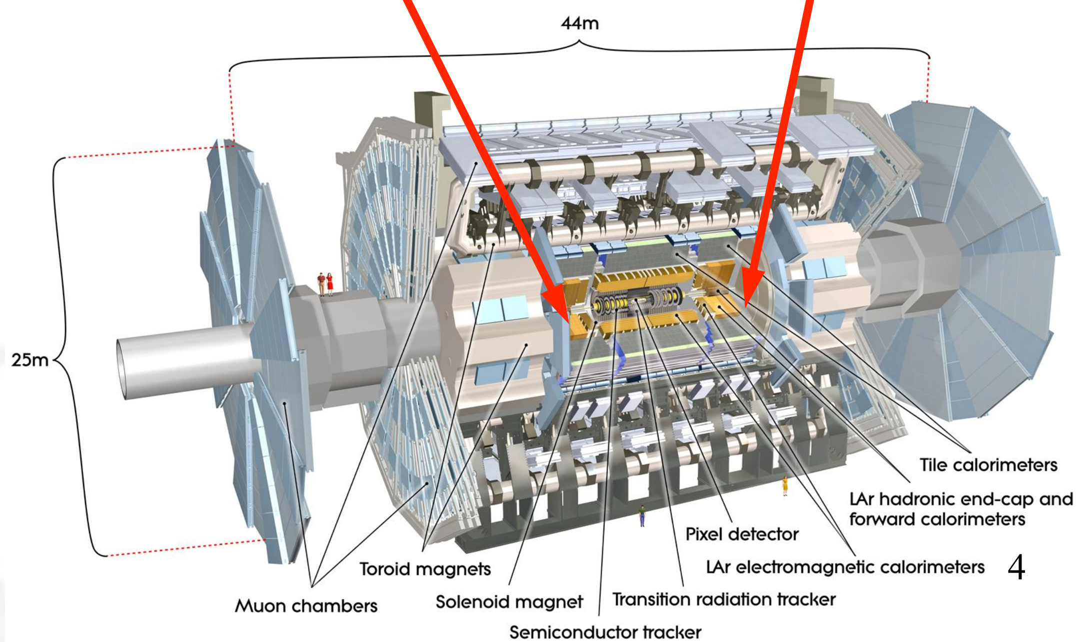
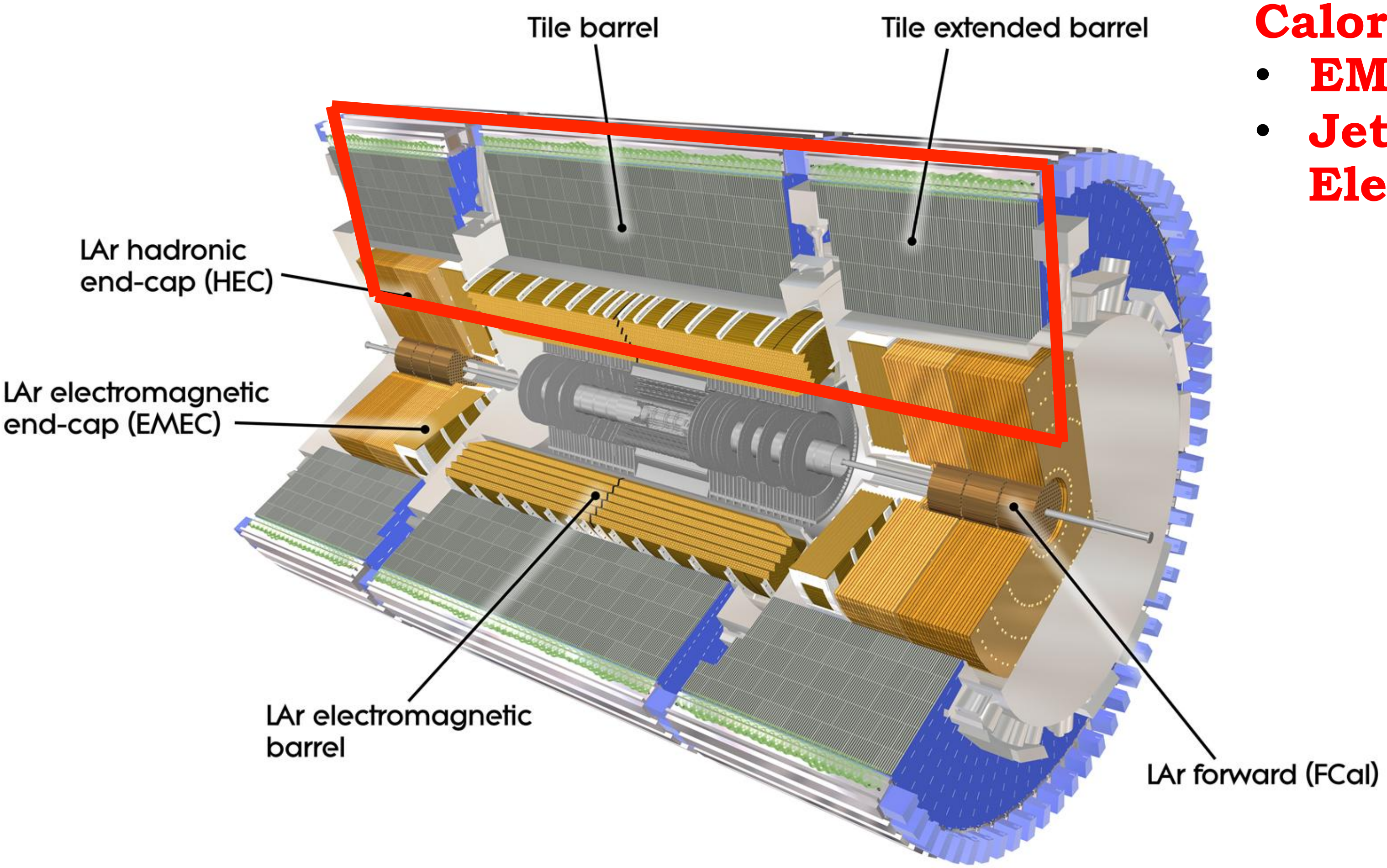


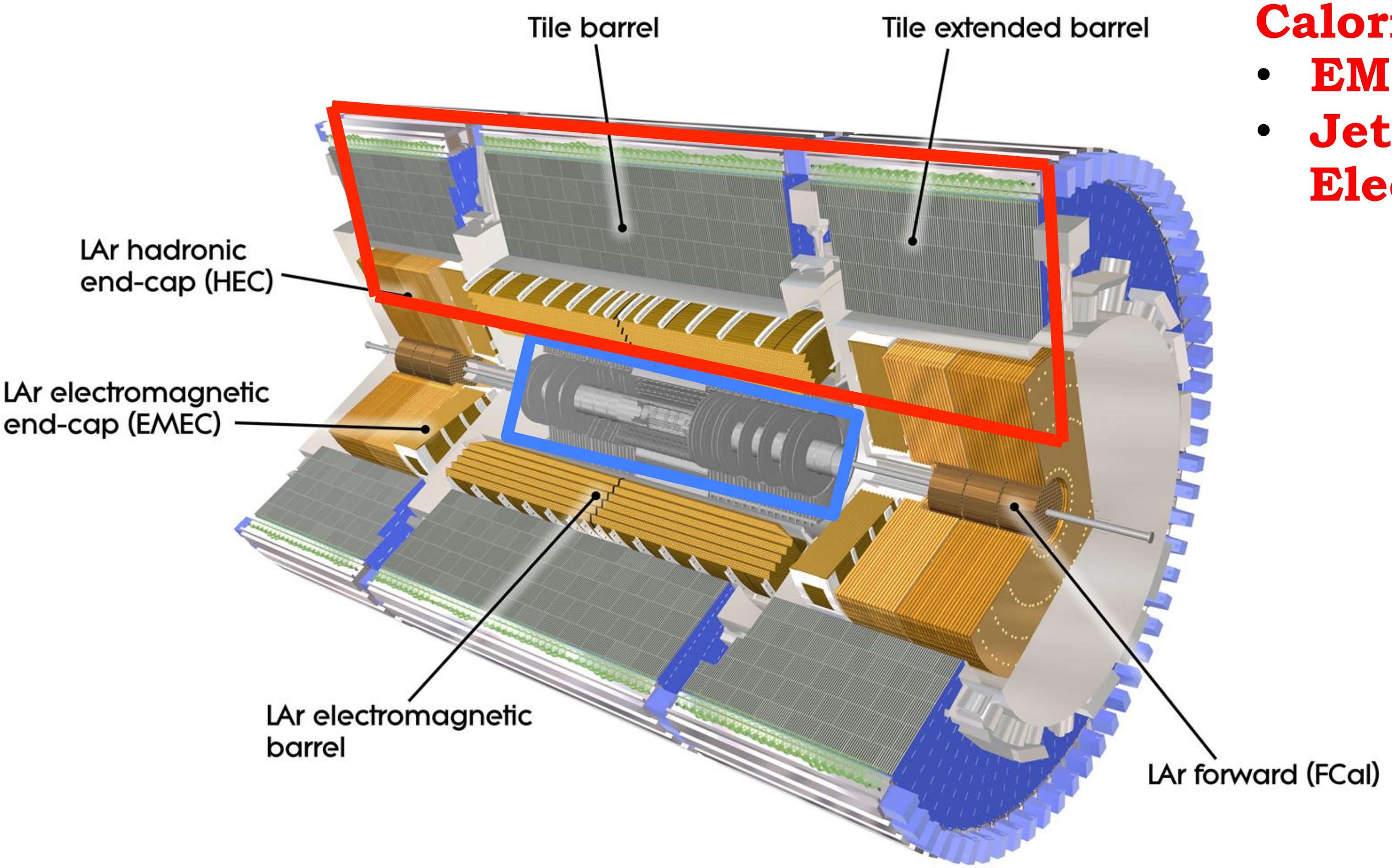
ATLAS detector



Calorimetry

- **EM & HCal $|\eta| < 3.2$**
- **Jets, Photons, Electrons**

ATLAS detector



Calorimetry
- **EM & HCal $|\eta| < 3.2$**
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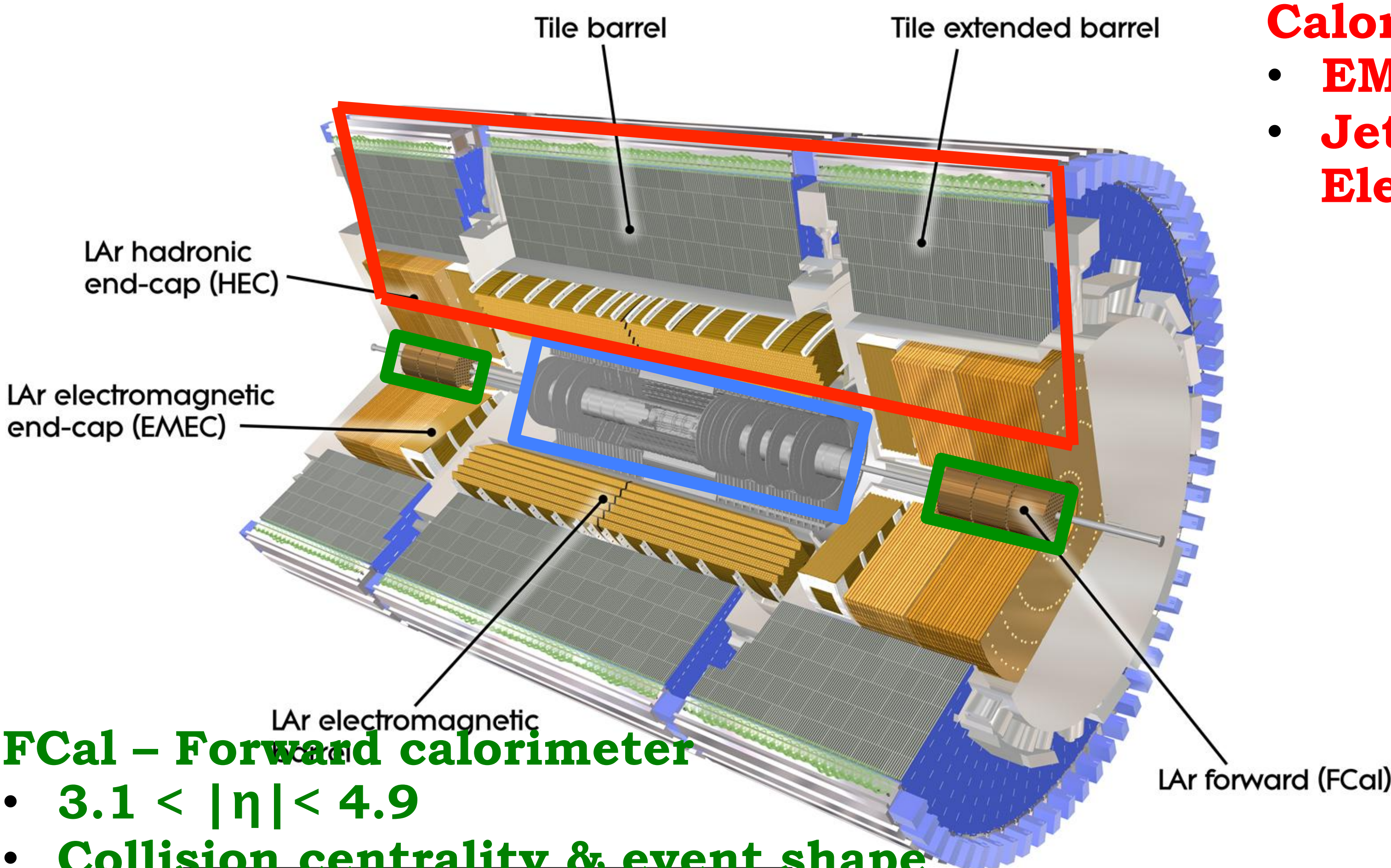
Inner detector – tracking
- **pT > 0.5 GeV & $|\eta| < 2.5$**
- **Charged hadrons spectra**
- **Correlations**

ATLAS detector



Calorimetry
- **EM & HCal |η| < 3.2**
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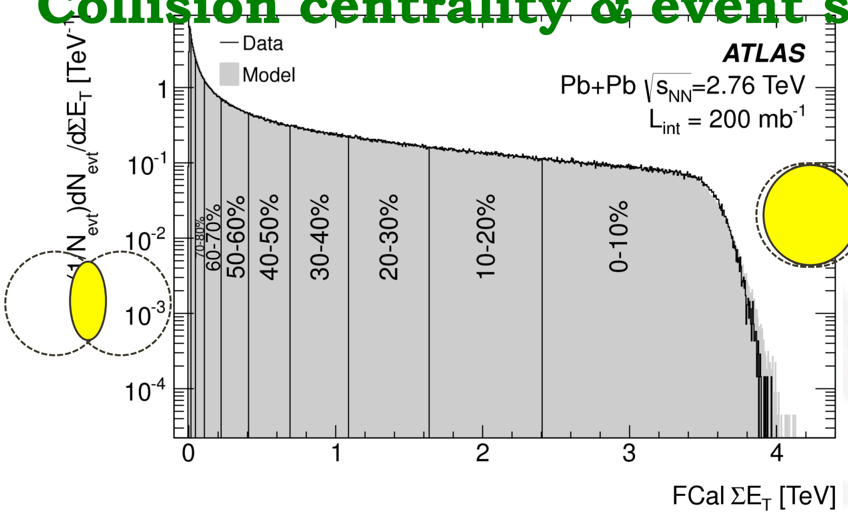
FCal – Forward calorimeter
- **3.1 < |η|< 4.9**
- **Collision centrality & event shape**



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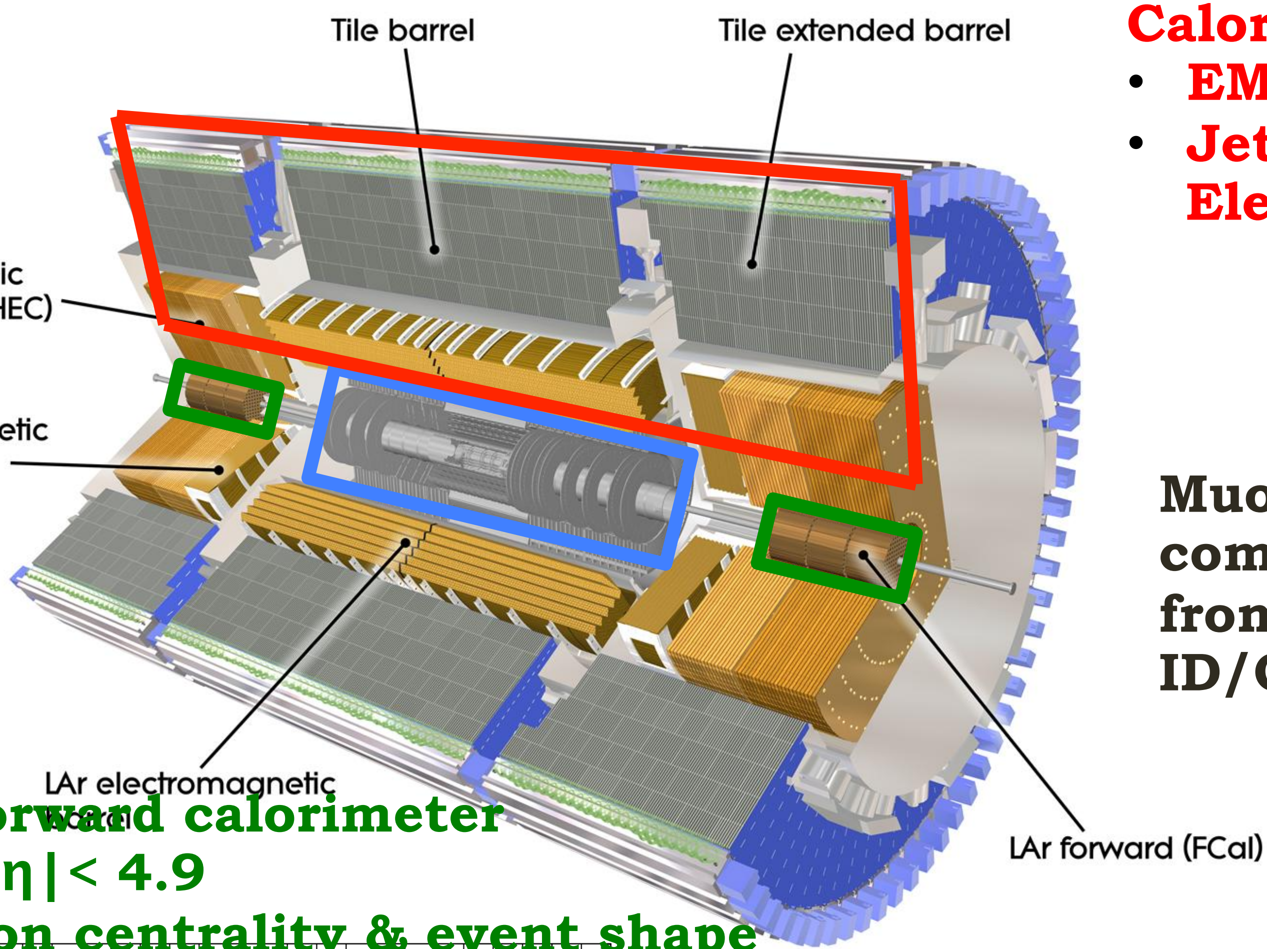

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- **EM & HCal |η| < 3.2**
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Muons reconstruction - combined information from ID/Calo/MS

FCal – Forward calorimeter
- **3.1 < |η|< 4.9**
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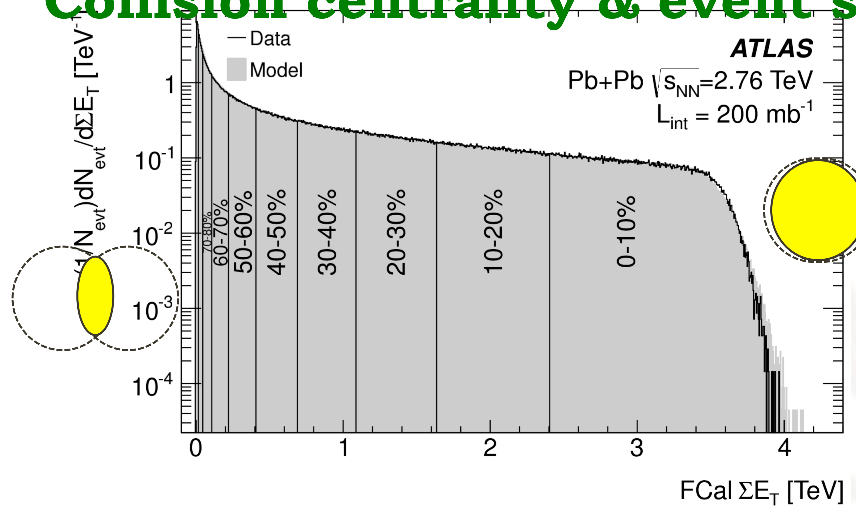


Inner detector – tracking
- **pT > 0.5 GeV & |η| < 2.5**
- **Charged hadrons spectra**
- **Correlations**

Datasets & physics goals

Datasets collected in 2010-2015

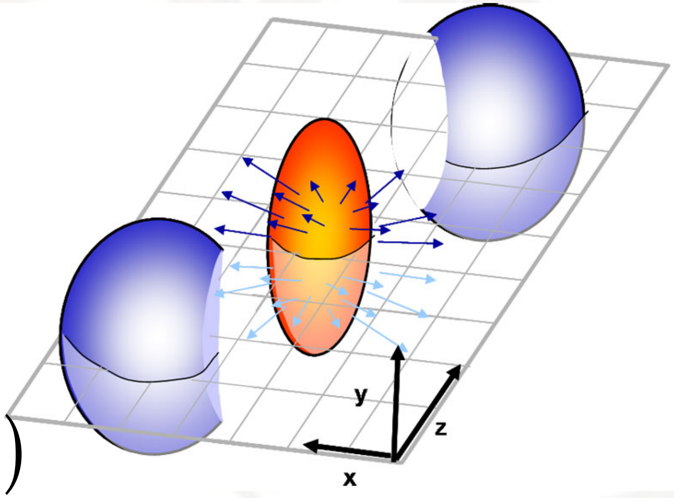
Pb+Pb	@ 2.76 TeV	2010 & 2011	160 μb^{-1}
Pb+Pb	**@ 5.1 TeV**	**2015**	**680 μb^{-1}**
p+Pb	@ 5.02 TeV	2013	28 nb^{-1}
p+p	@ 2.76 TeV	2013	4 pb^{-1}
p+p	**@ 13 TeV**	**2015**	
p+p	**@ 5 TeV**	**2015**	**27 pb^{-1}**

28 papers & 49 public conference notes
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

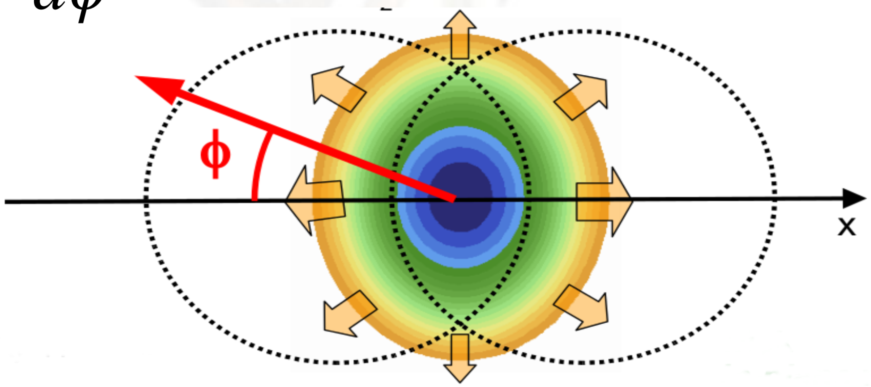
Study the strongly coupled QGP using soft and hard probes by

- Collective response of the plasma to the initial conditions
- Modification of the energetic parton shower in the plasma
- Calibrate observed phenomena to p+Pb and p+p collisions

Study of the QGP with collective flow



$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_2)$$



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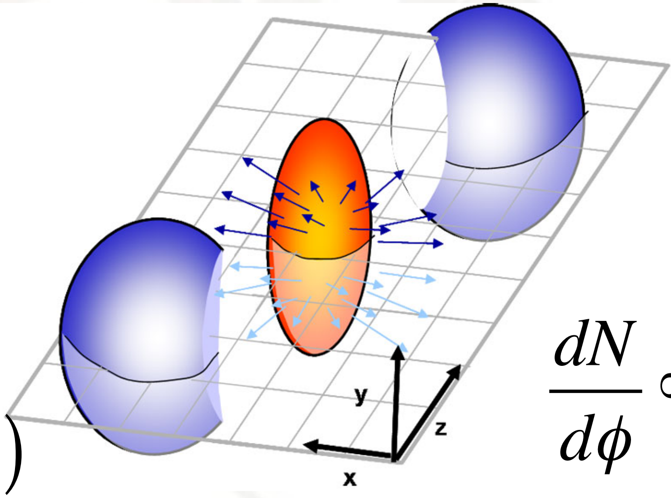

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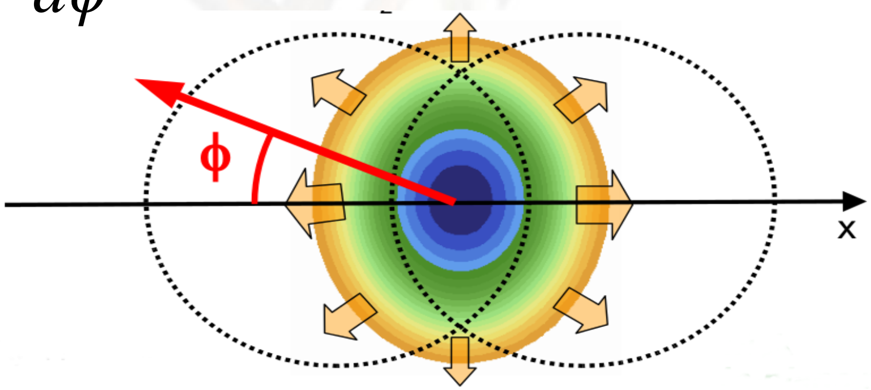
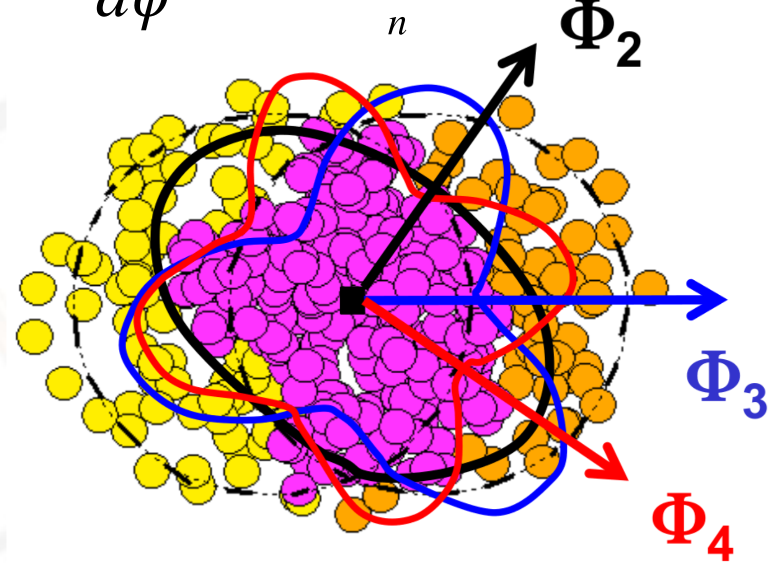


$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$

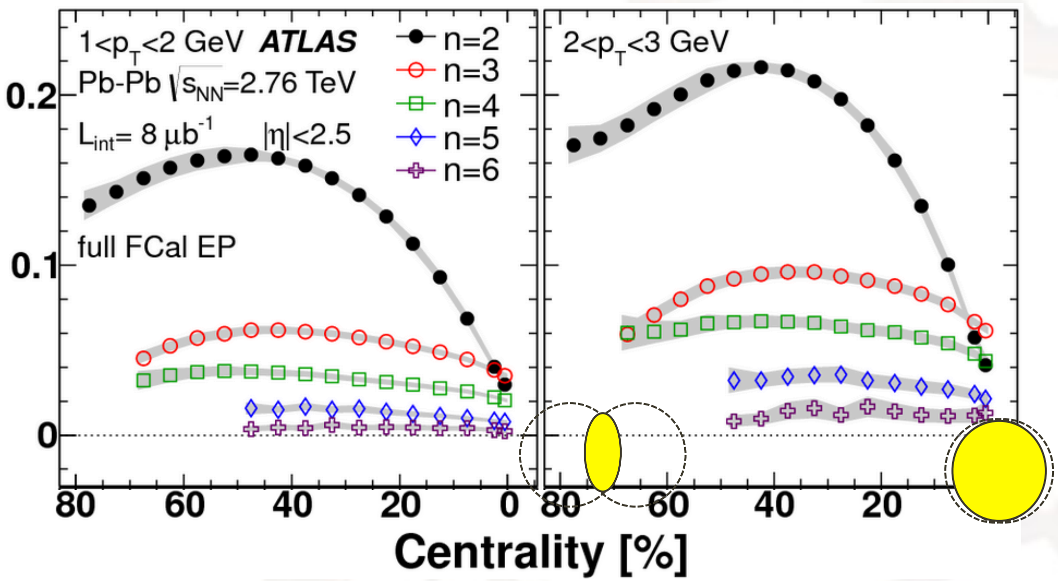


vn harmonics sensitive to initial shape of the interaction region & viscosity of the QGP

- Larger initial shape fluctuation lead to larger vn's
- Small viscosity ensure efficient transport of the initial shape (fluctuation) to the final state

Differential measurements of vn harmonics

PRC 86, 014907 (2012)



- v_n harmonics measured in the broad centrality, p_T & η range
- Different sensitivity to v_n's fluctuations of the different measurement methods
- Provides constraint to the hydro models

Differential measurements of vn harmonics

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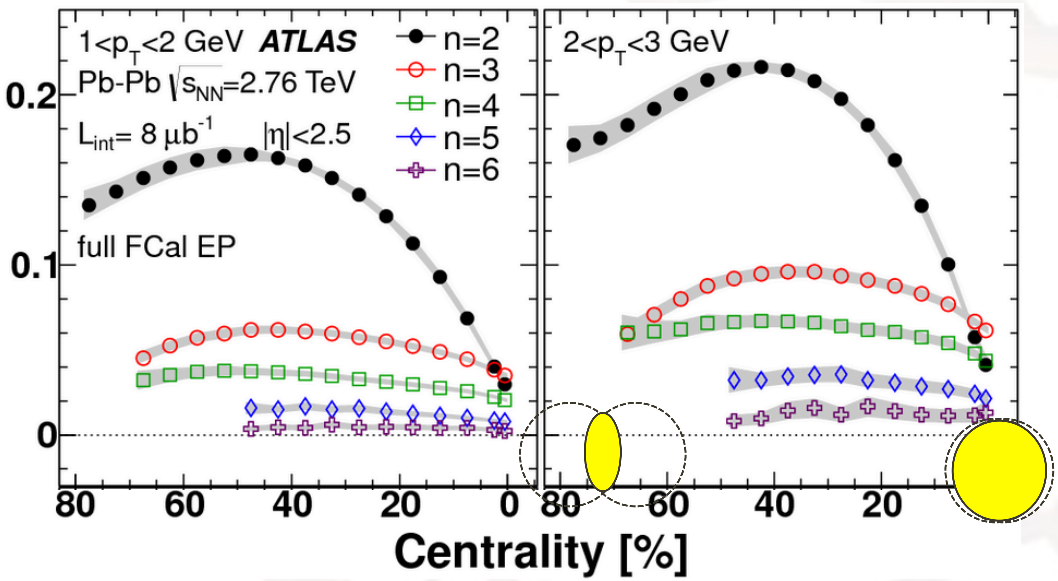
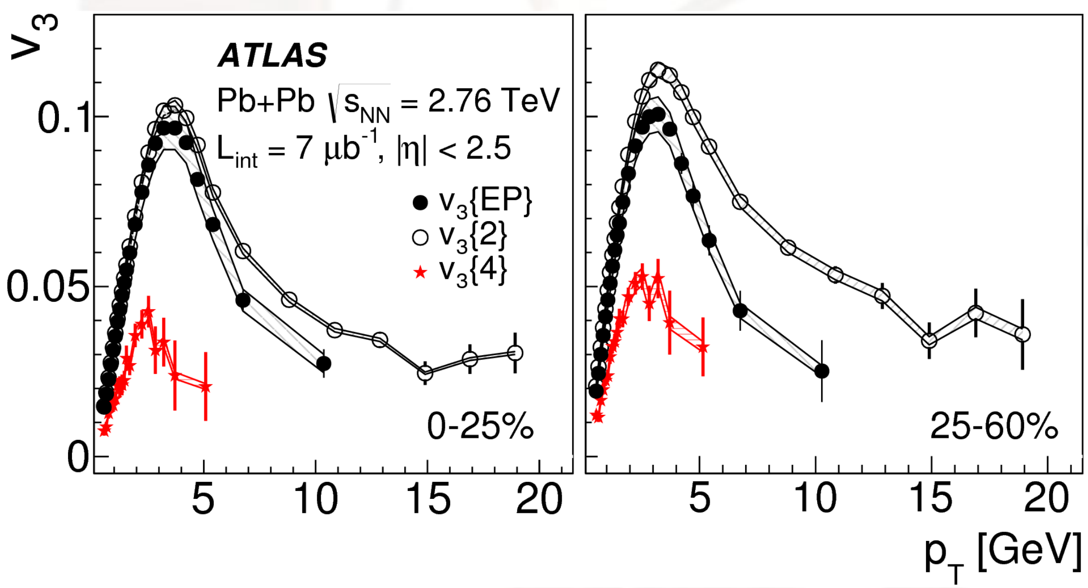


EPJC (2014) 74: 3157



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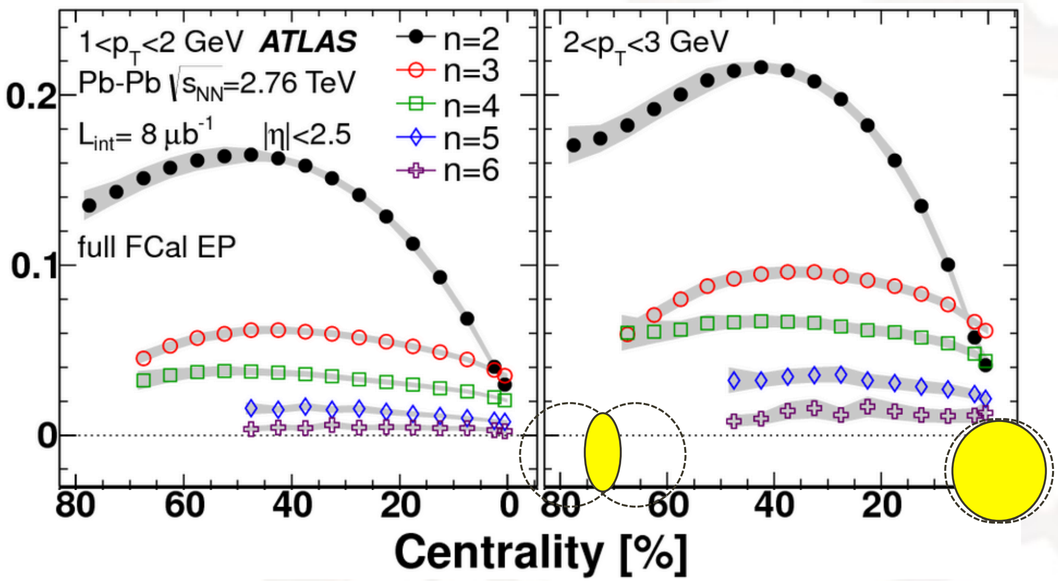

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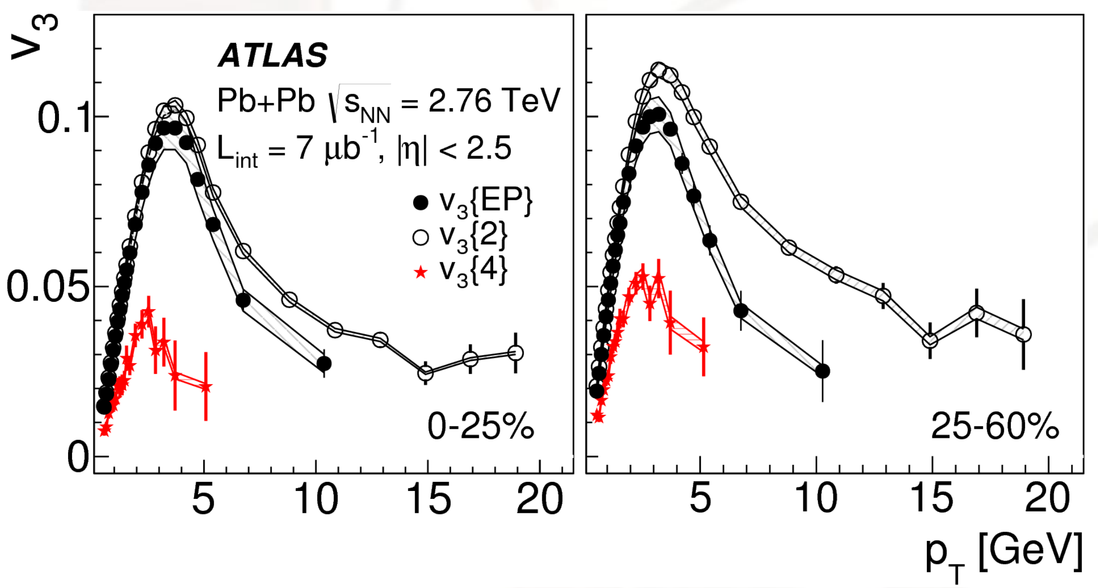
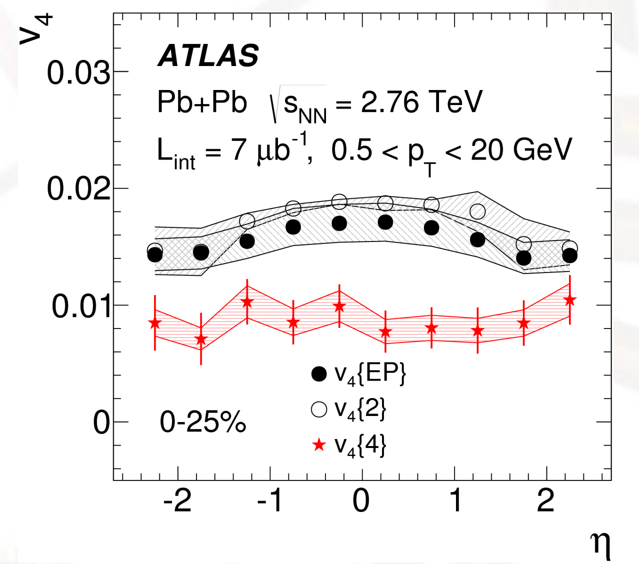
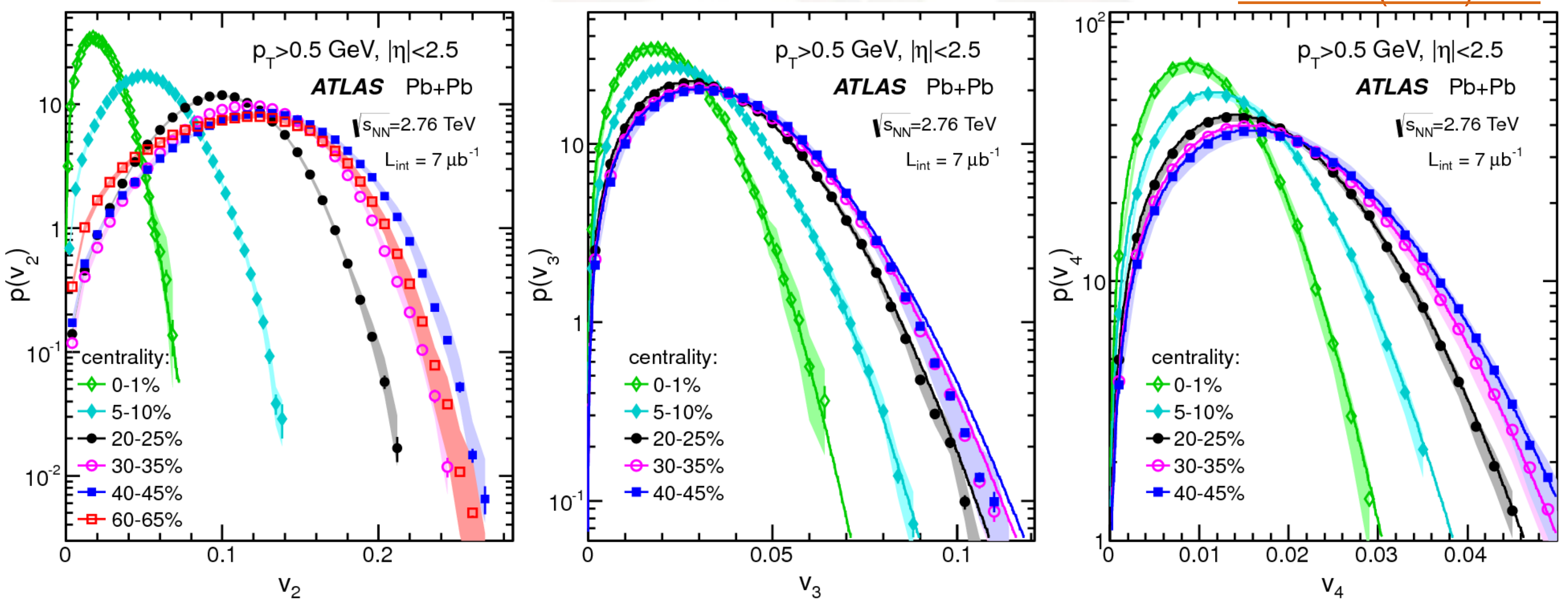
More details in K. Burka talk tomorrow 3:12pm





Event by event flow harmonics

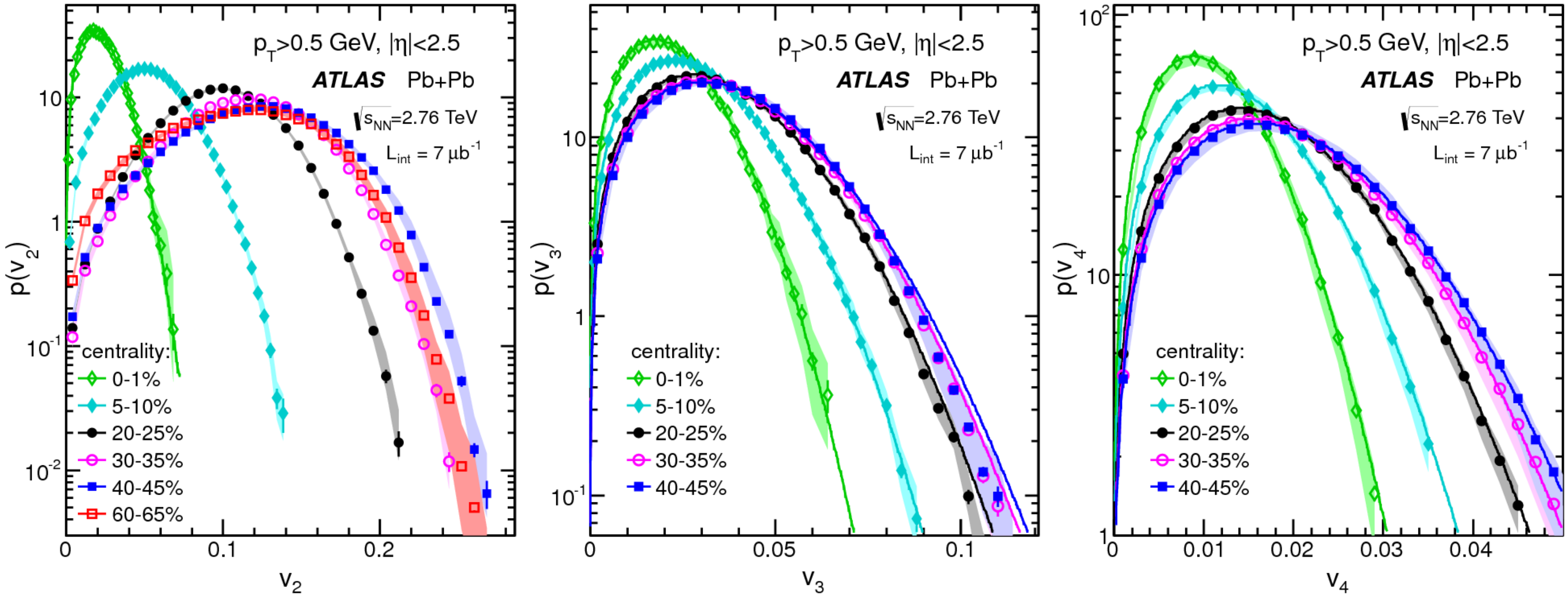
JHEP 11 (2013) 183



- Unfolded probability distributions of the EbyE vn's - new observables (also EbyE event plane angles correlations)
- Impose even stronger constraint on the hydro models

Event by event flow harmonics

JHEP 11 (2013) 183



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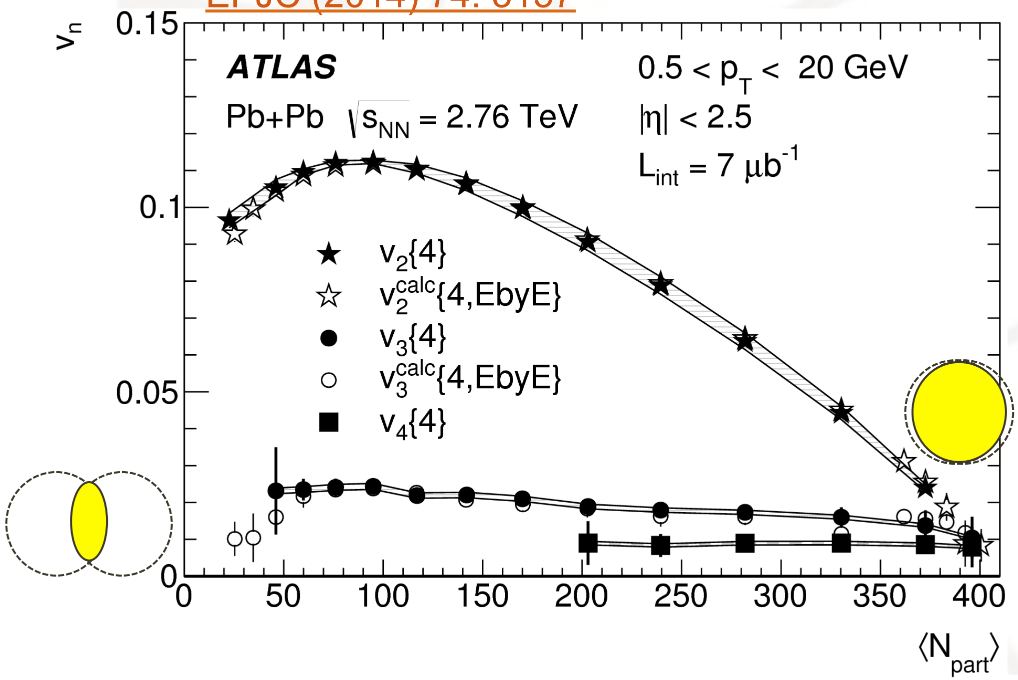


- Unfolded probability distributions of the EbyE vn's - new observables (also EbyE event plane angles correlations)
- Impose even stronger constraint on the hydro models
- Very good consistency between cumulant and EbyE measurement

Event shape engineering

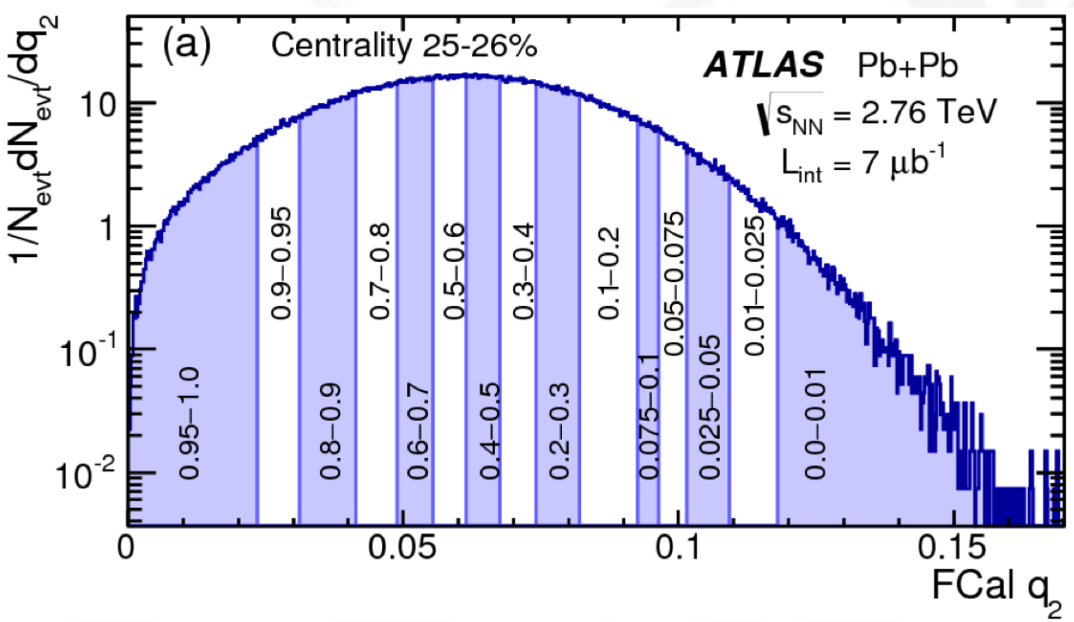
- 1st order event shape selection: Centrality (Sum E_T FCal)
  system size

- 2nd order event shape selection: ellipticity by v_2^{obs}
  system shape

- 2nd order event shape selection: triangularity v_3^{obs}
  system shape

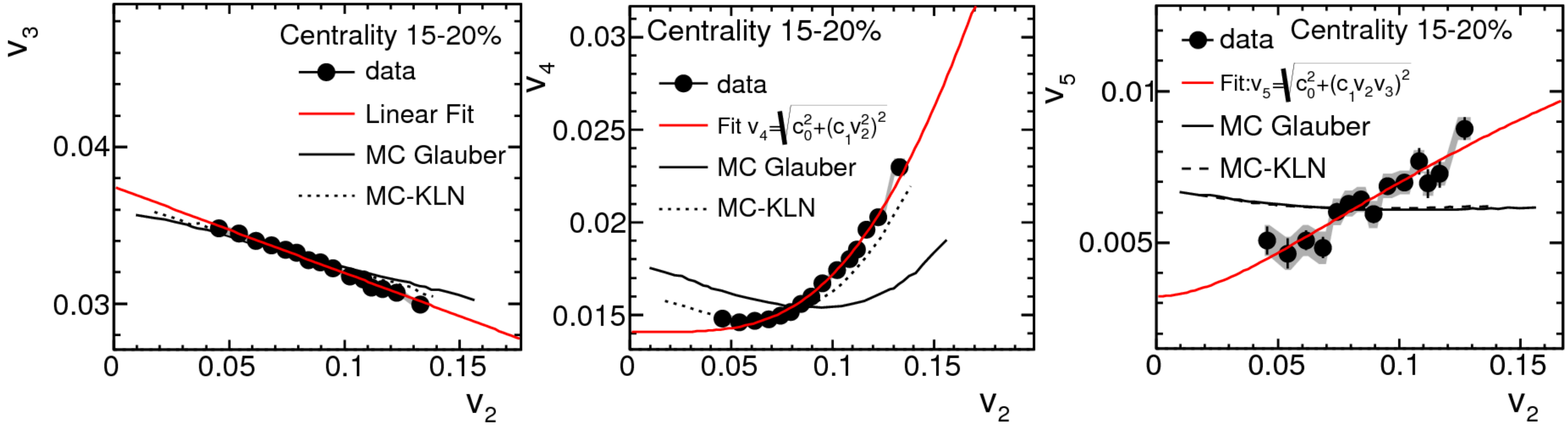
- Selecting events with the same geometric size but different ellipticity

PRC 92 (2015) 034903



Event shape engineering

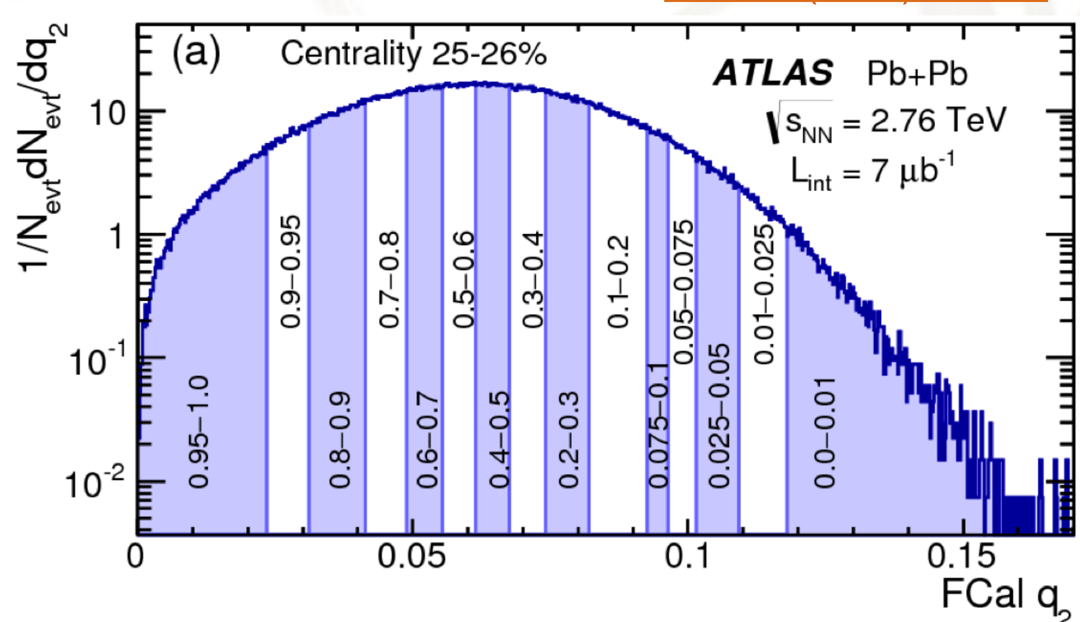
Correlation between v2 and higher order flow harmonics



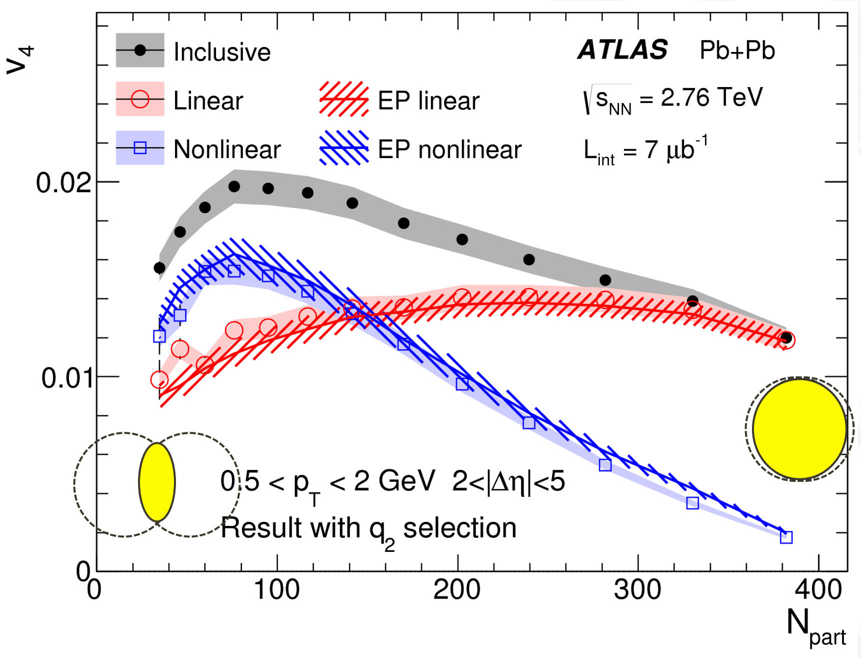
Fit with a two component function with linear and non-linear response terms

PRC 92 (2015) 034903

- Selecting events with the same geometric size but different ellipticity



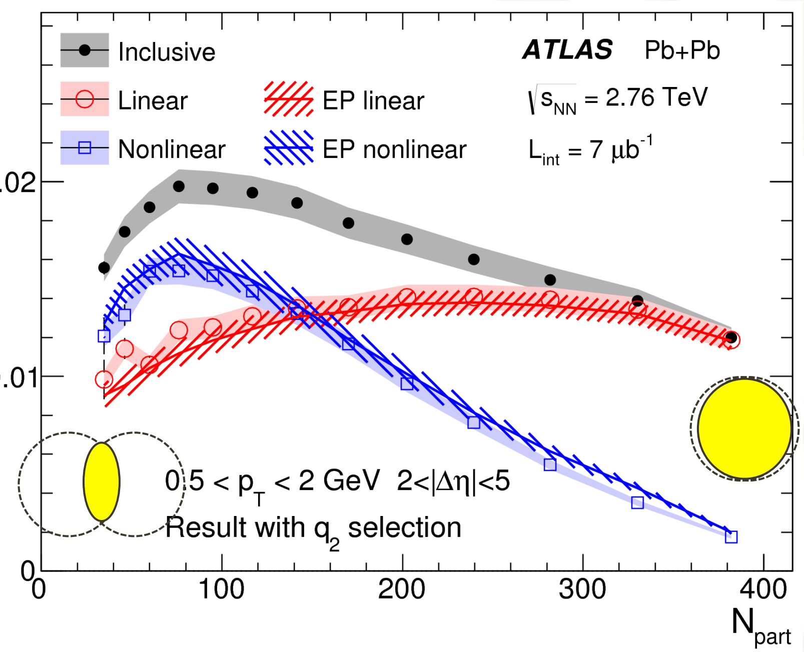
Eccentricity scaling



- Separate “linear” and “non-linear” components
- Linear component has weak centrality dependence, non-liner component has strong centrality dependence
- Consistent with results from event plane correlations

Eccentricity scaling

PRC 92 (2015) 034903



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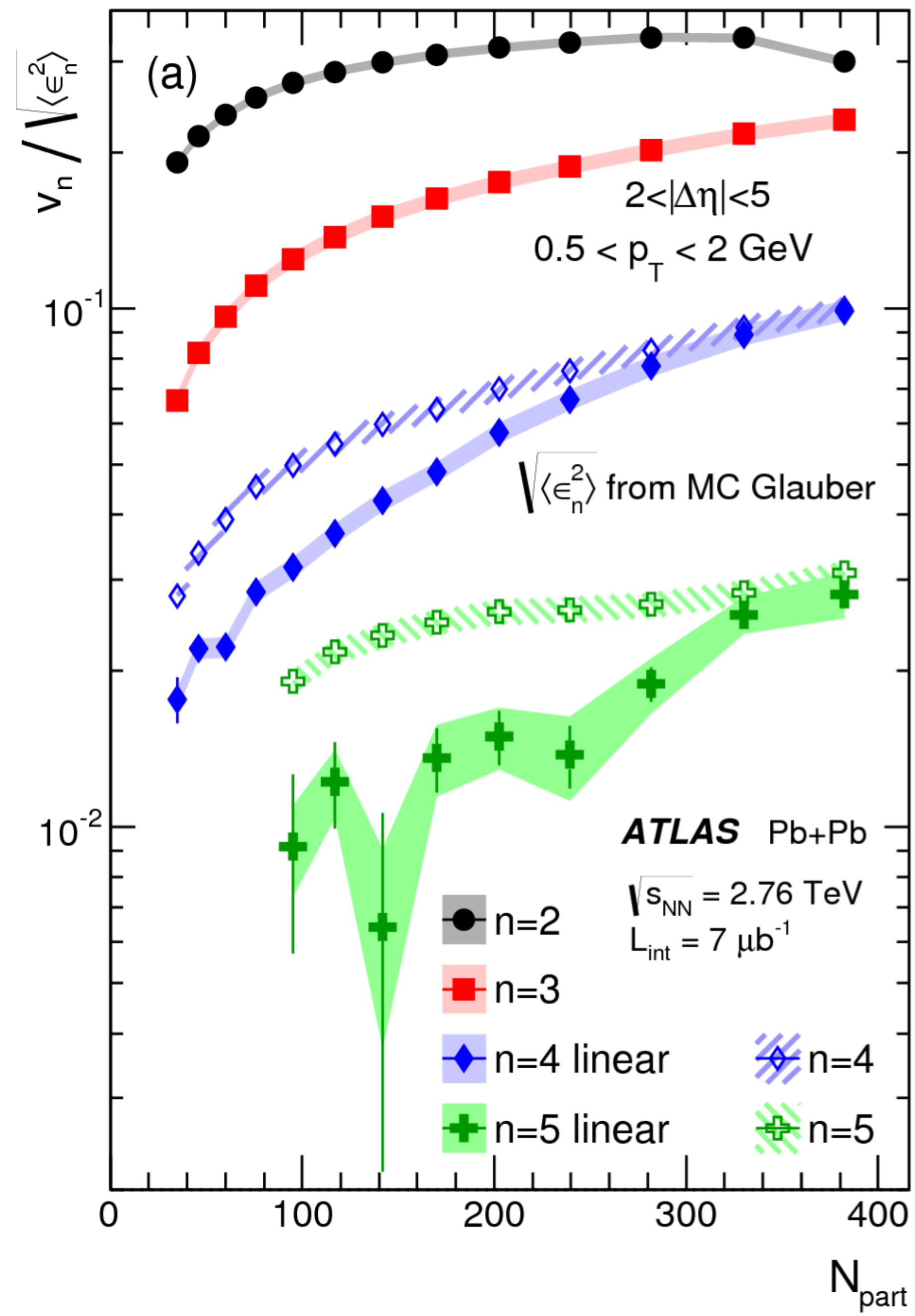
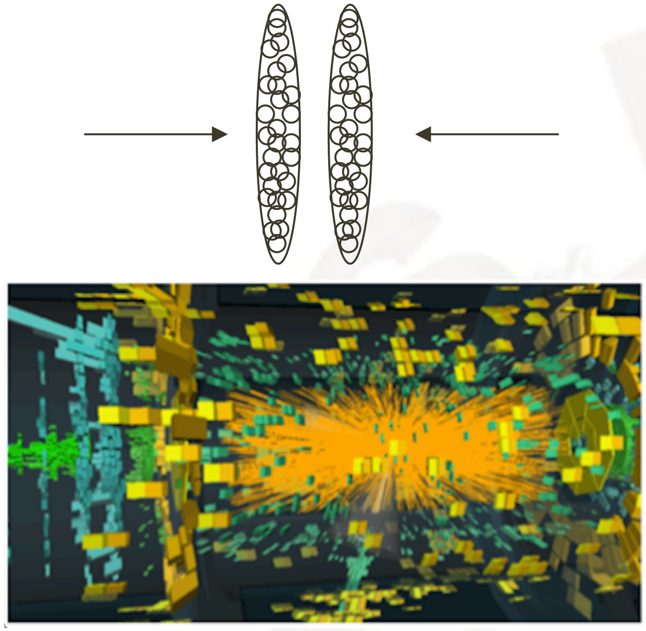
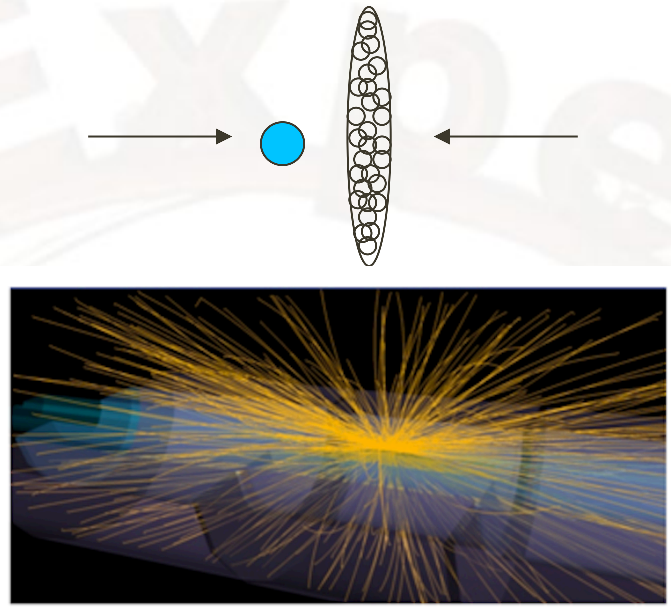


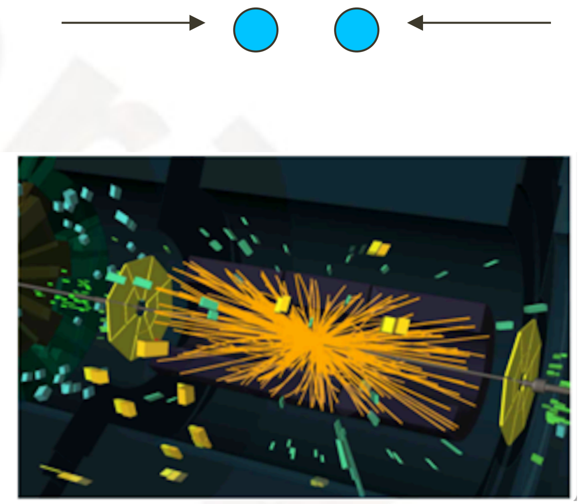
Flow in small systems



~30000 particles*



~1000 particles*

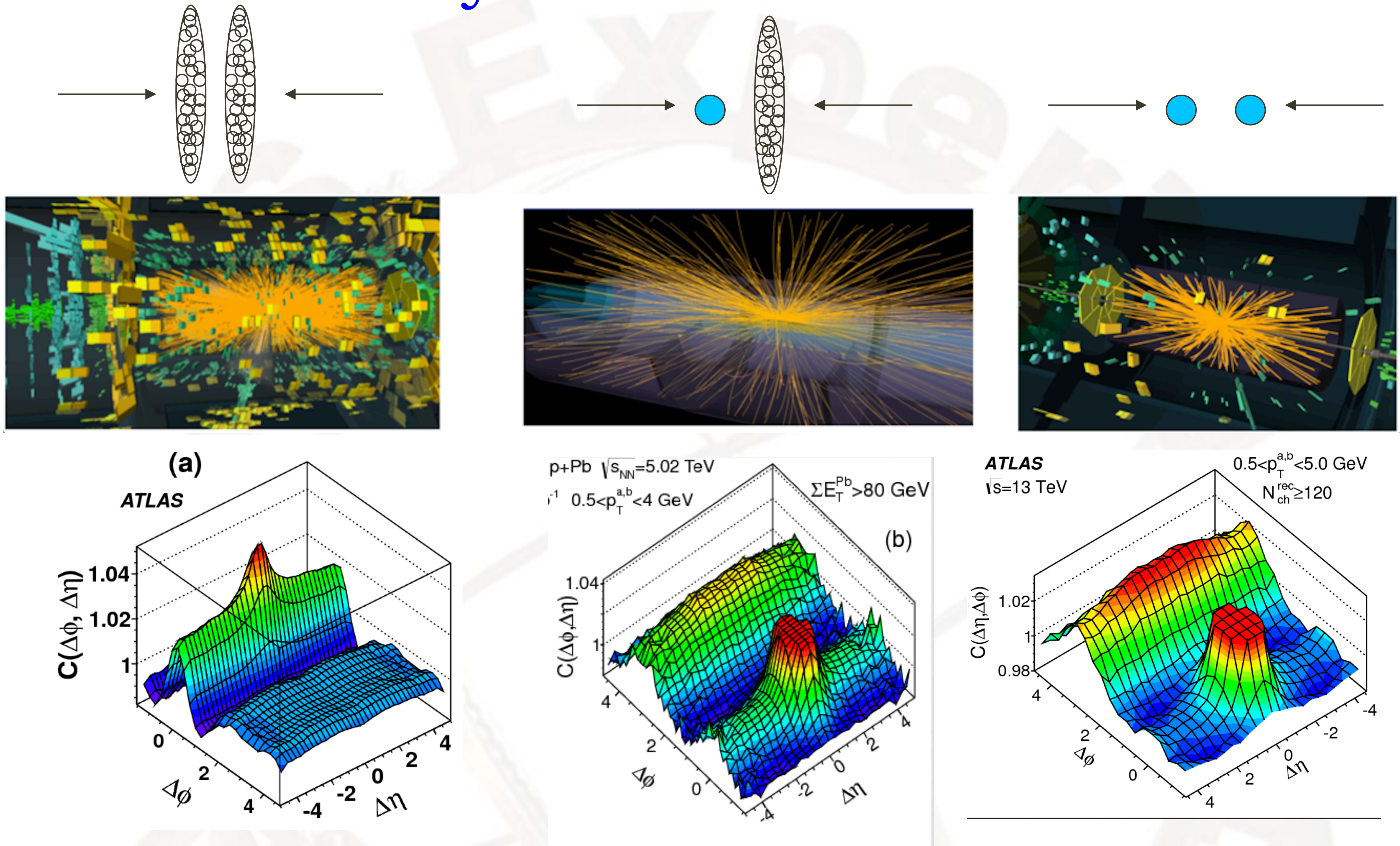


~150 particles*

What is the smallest droplet of the QGP created in these collisions?

*Raw number of charged particles (integrated over entire phase space) produced in events with high activity

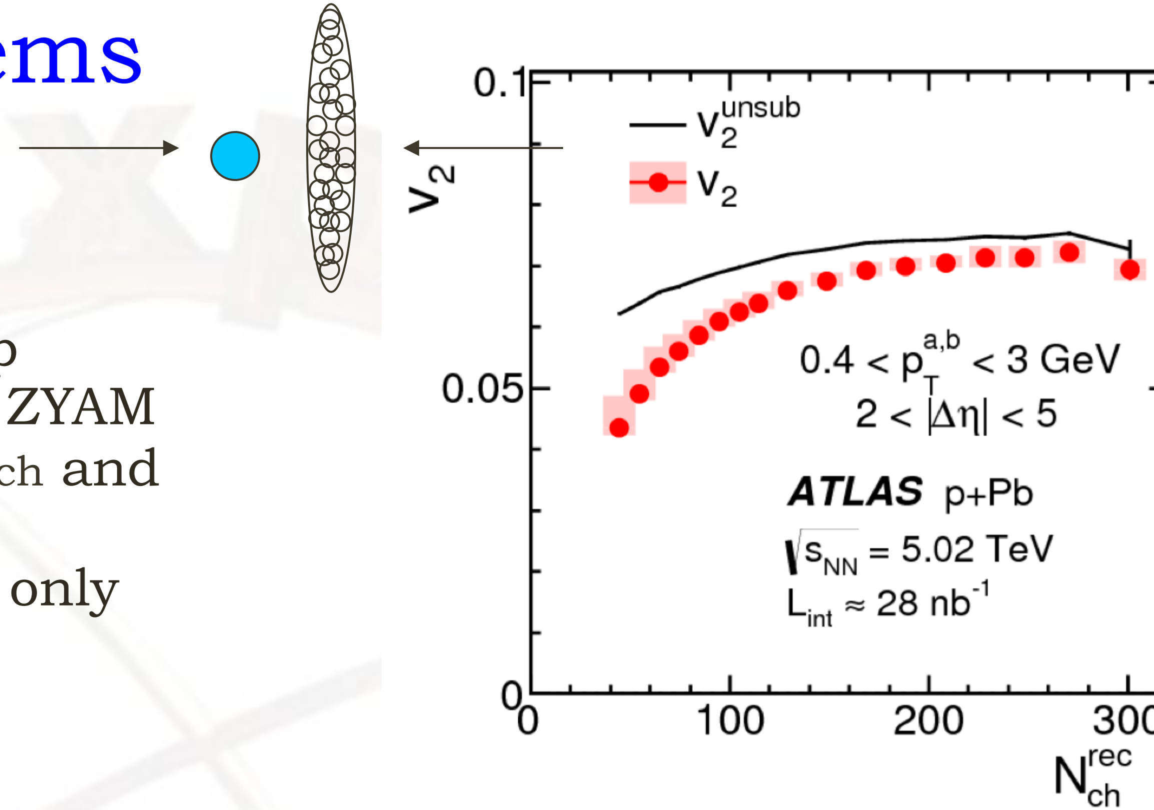
Flow in small systems



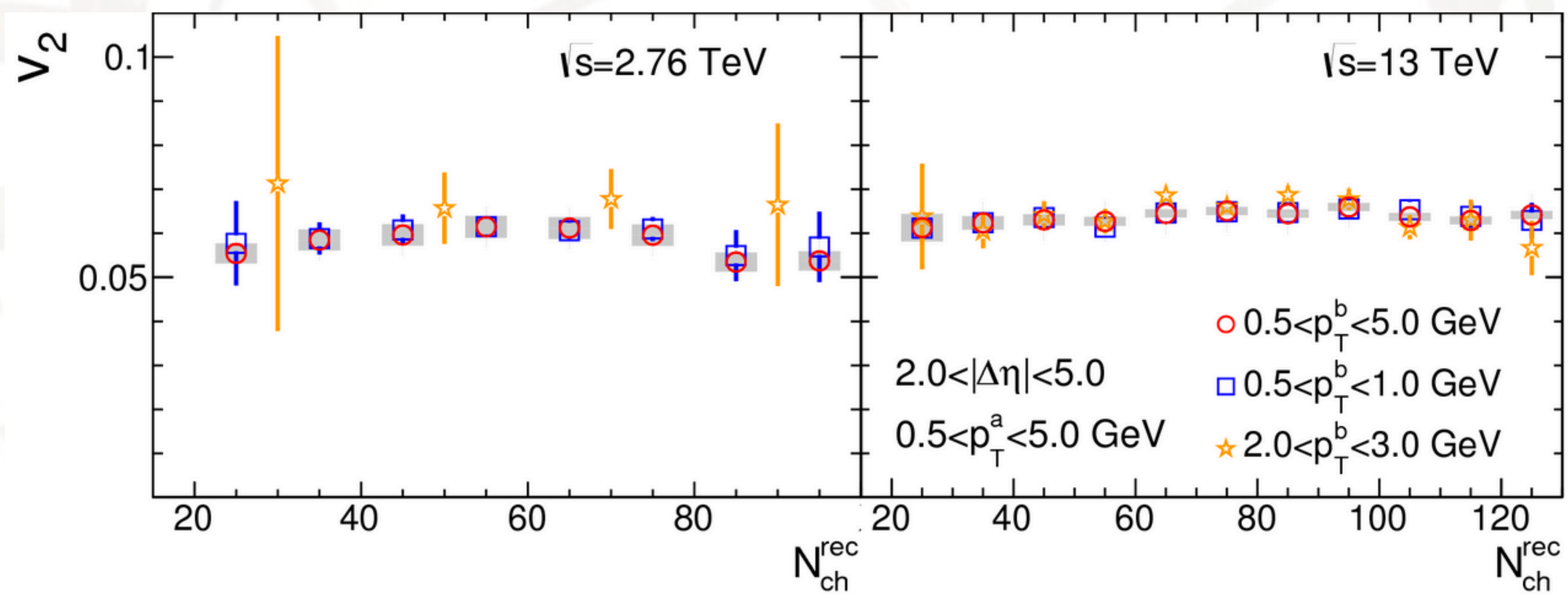
p+Pb and p+p collisions reveal collective/flow like behavior

Flow in small systems

- Measurement of two-particle correlation in p+Pb and p+p
- New method (template) for p+p measurement reduces bias in ZYAM
- Weak trend as a function of Nch and beam energy
- Phenomenon not restricted to only high multiplicity events



arXiv:1509.04776



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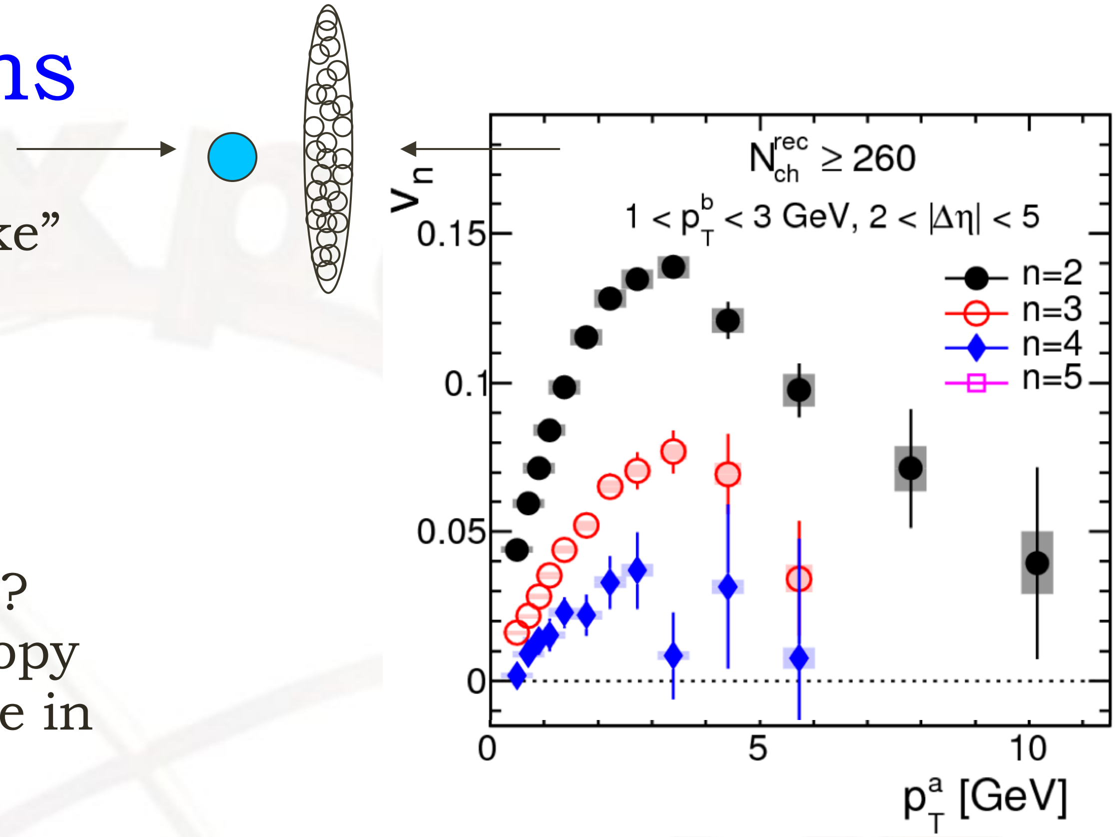
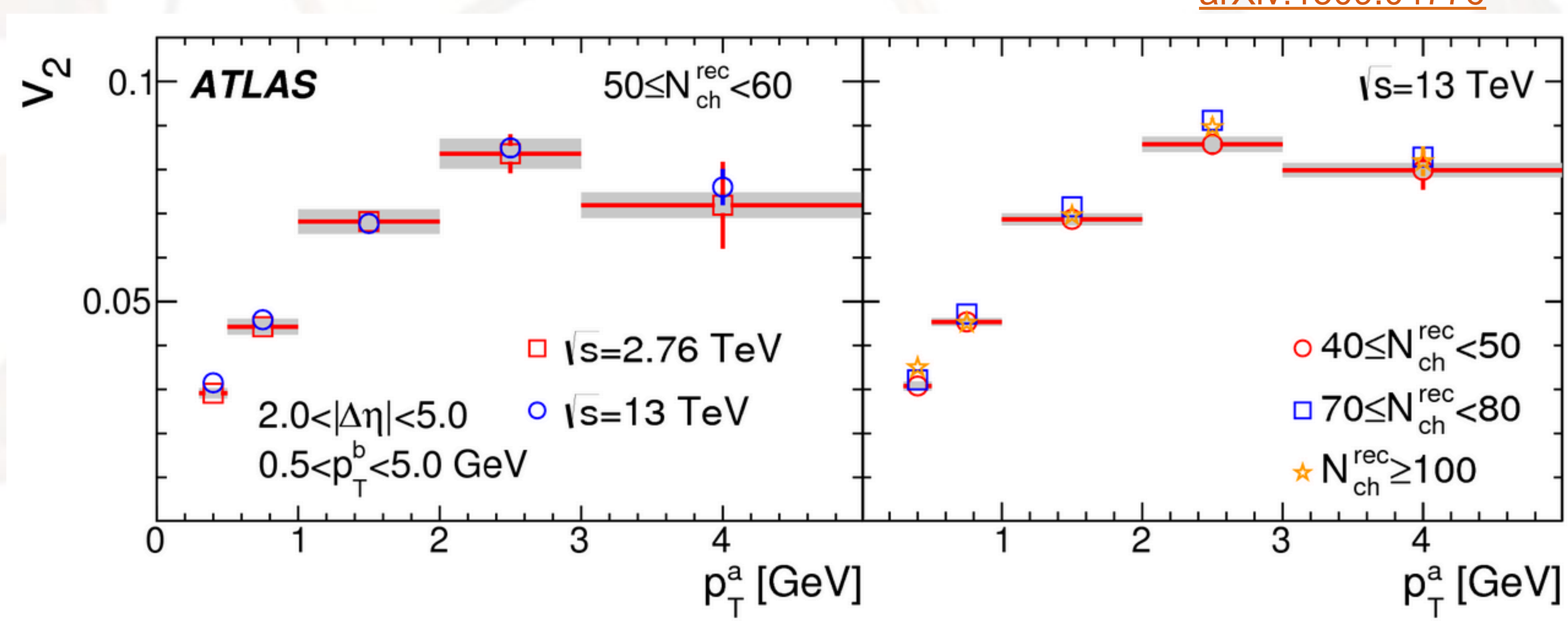


- Characteristic "hydrodynamic like" pT dependence

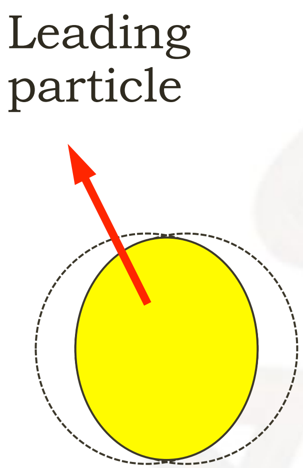
Open questions:

- Does the observation of the collectivity in NN imply any quantitative consequences in AA?
- Is the final state particle anisotropy a reflection of the initial state like in AA?

arXiv:1509.04776



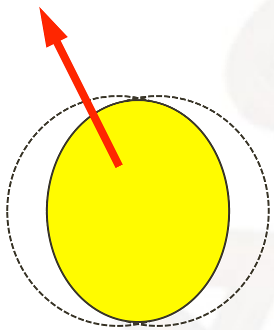
Study of the QGP with hard probes



JHEP09 (2015) 050

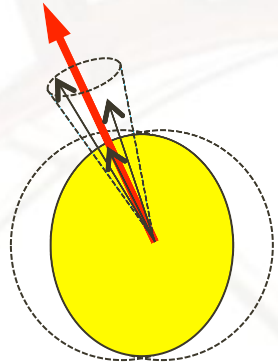
Study of the QGP with hard probes

Leading particle



JHEP09 (2015) 050

Jet sub-structure



PLB 739 (2014) 320-342
Updated in
ATLAS-CONF-2015-055
ATLAS-CONF-2015-022 (pPb)

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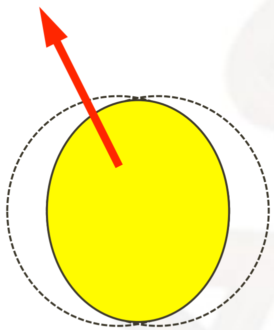

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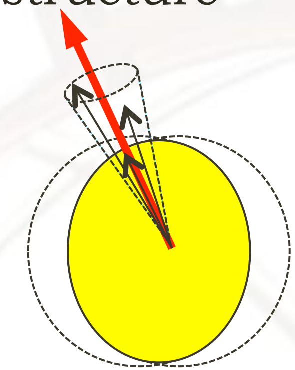

PLB 739 (2014) 320-342
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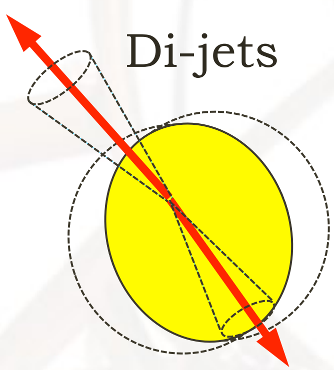
Di-jets



PRL 105 (2010) 252303
Updated in
ATLAS-CONF-2015-052

Study of the QGP with hard probes

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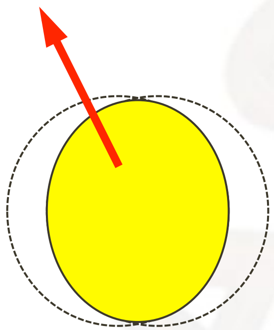

JHEP09 (2015) 050

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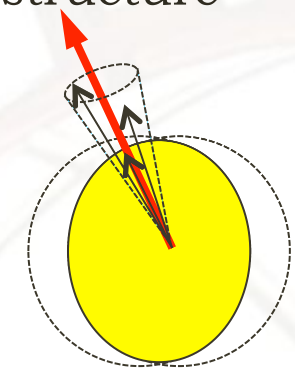

PLB 739 (2014) 320-342
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ATLAS-CONF-2015-055
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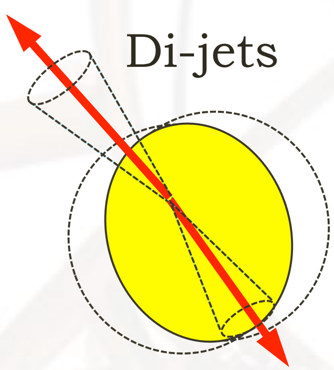
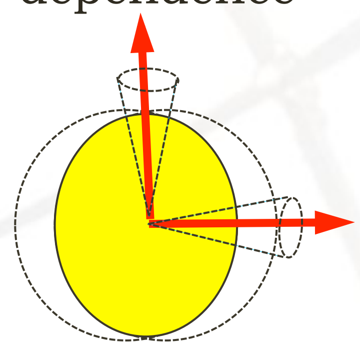


PRL 105 (2010) 252303
Updated in
ATLAS-CONF-2015-052

Path-length dependence



PRL 111, 152301 (2013)
ATLAS-CONF-2015-052

Study of the QGP with hard probes

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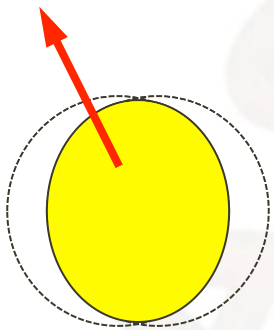

JHEP09 (2015) 050

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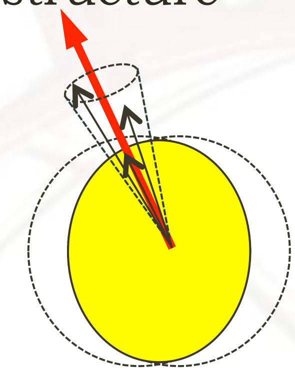
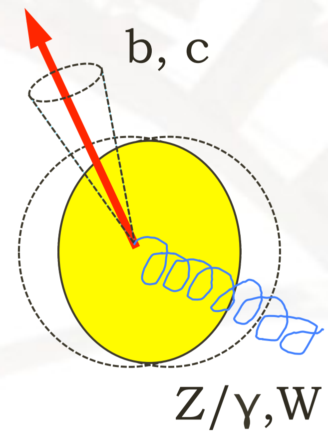


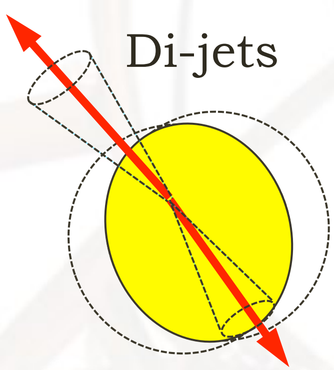
PLB 739 (2014) 320-342
Updated in
ATLAS-CONF-2015-055
ATLAS-CONF-2015-022 (pPb)

Flavor & color dependence



PRL 110, 022301 (2013)
PRC 92 (2015) 044915
EPJC (2015) 75:23
ATLAS-CONF-2015-056
arXiv:1506.08552
ATLAS-CONF-2015-050
PRC 92 (2015) 034904
PLB 697 (2011) 294-312
ATLAS-CONF-2015-023

Di-jets



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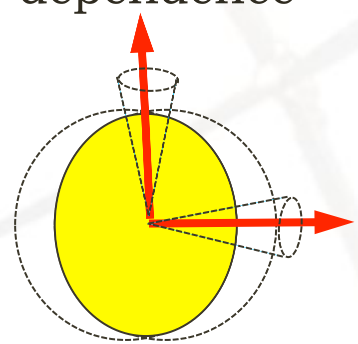
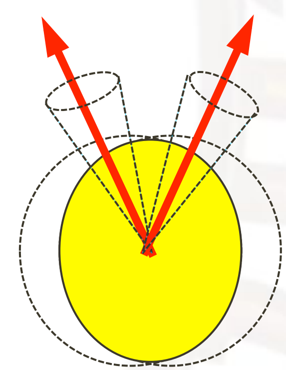


PRL 111, 152301 (2013)
ATLAS-CONF-2015-052

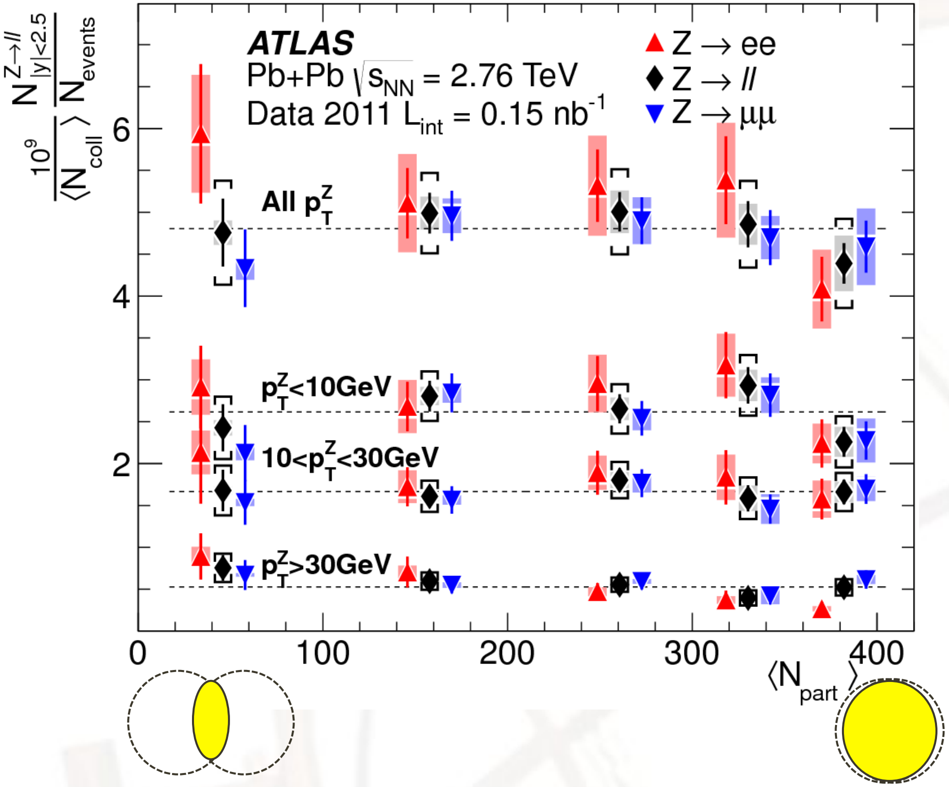
Nearby jet



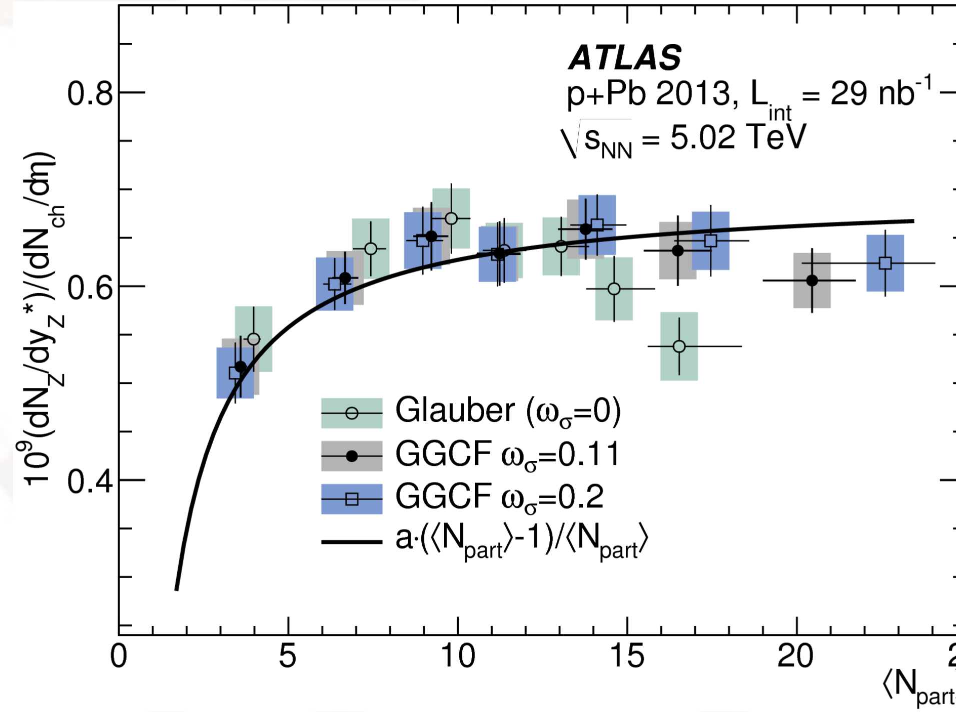
arXiv:1512.00197

Z boson production

PRL 110, 022301 (2013)



PRC 92 (2015) 044915



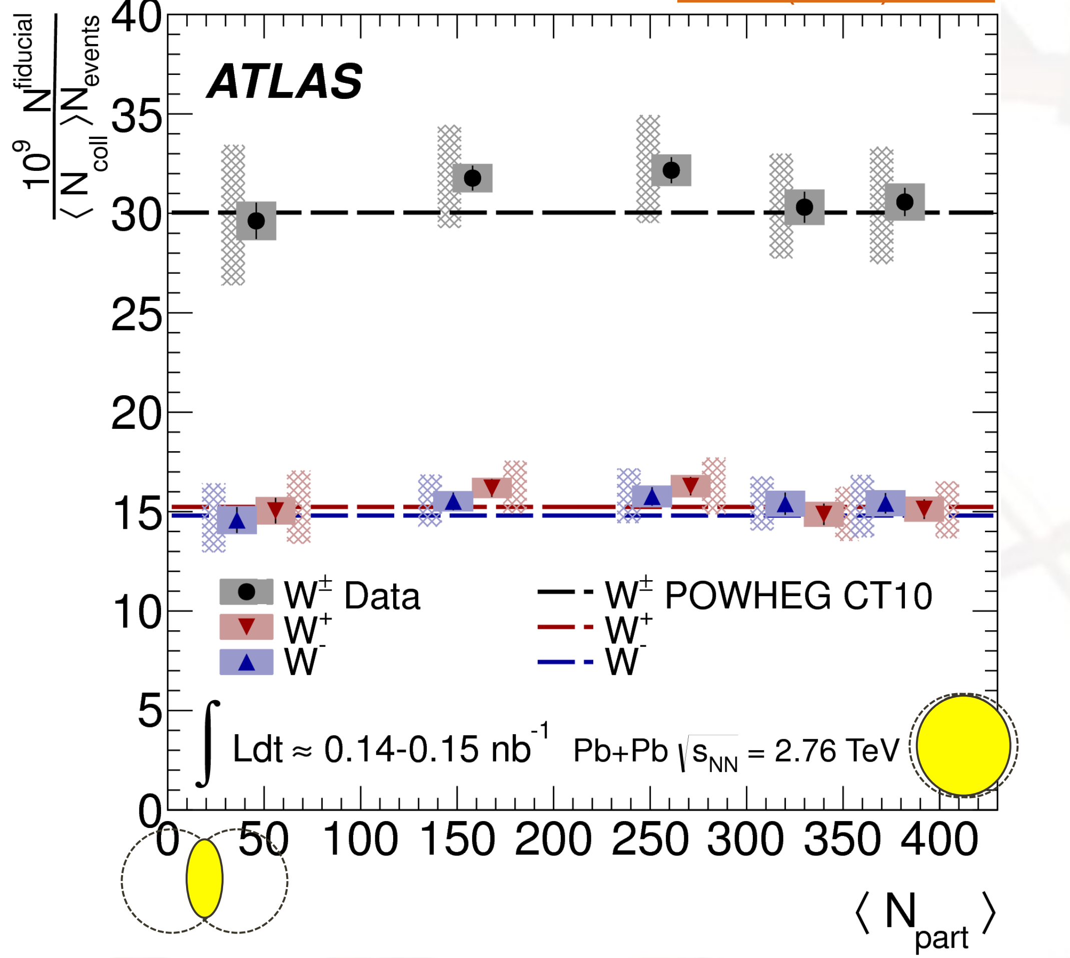
- No centrality dependence
- Can be used as a calibration tool to investigate energy loss of color object created in association with Z boson

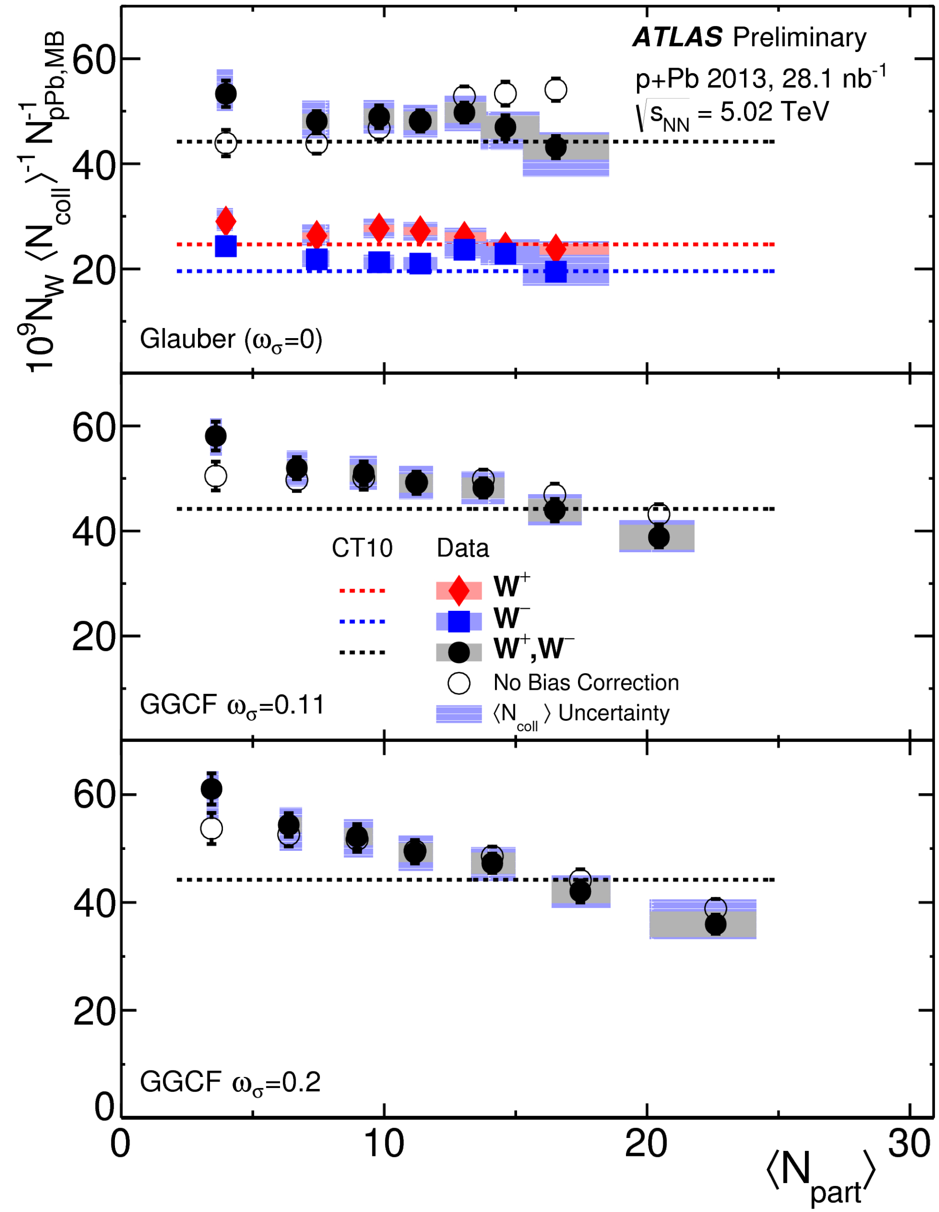
- Z boson production used to test Glauber model extension for fluctuations of the underlying nucleon-nucleon cross section

W bosons production

ATLAS-CONF-2015-056

EPJC (2015) 75:23

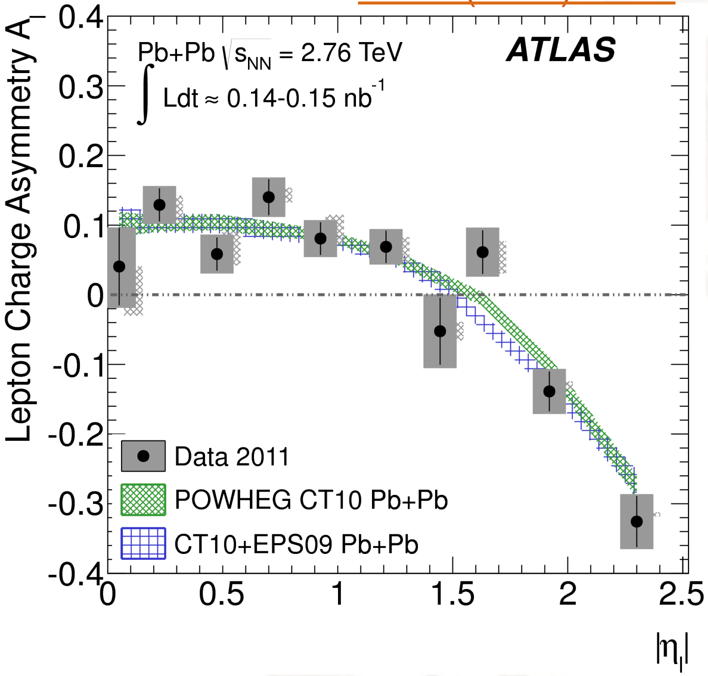




- No centrality dependence of the W production
- Glauber model extension for fluctuations of the underlying nucleon-nucleon cross section in pPb

Initial conditions – parton distributions

EPJC (2015) 75:23



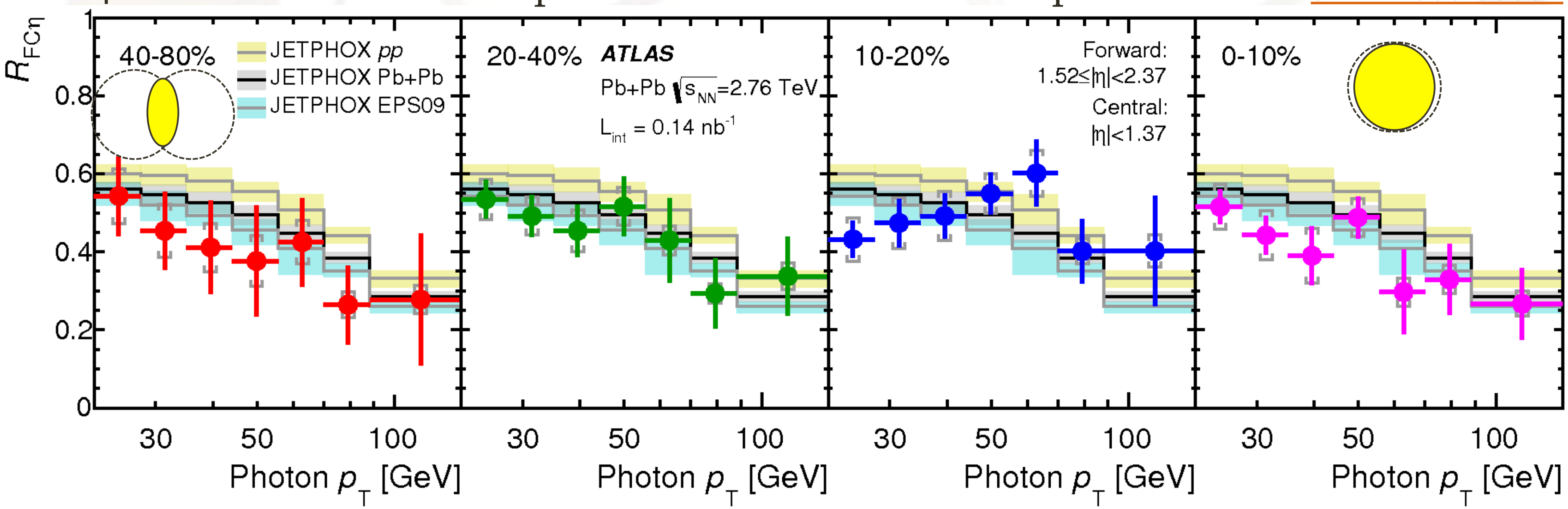
$$A_l = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}}$$

A_l sensitive to nuclear modification of PDF + spin conservation in W boson production

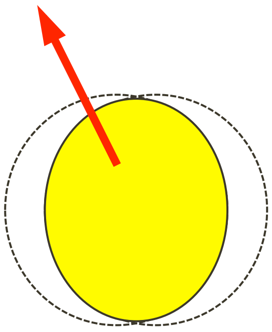
No sensitivity for nuclear modifications within the experimental precision of Run1 Pb+Pb data

RFCη - forward-to-central production ratio of direct photons

arXiv:1506.08552



Nuclear modification factor for high p_T particles and jets - PbPb

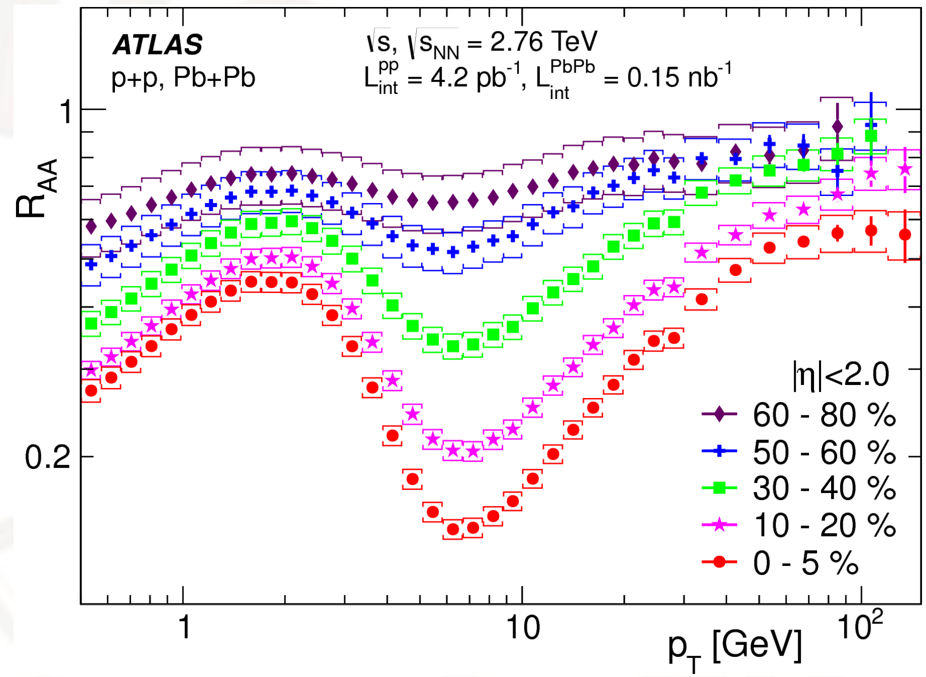


In medium energy loss leads to suppression in leading particle and jet yield

$$R_{AA} = \frac{dN^{cent}/dp_T}{\langle T_{AA}^{cent} \rangle d\sigma^{pp}/dp_T}$$

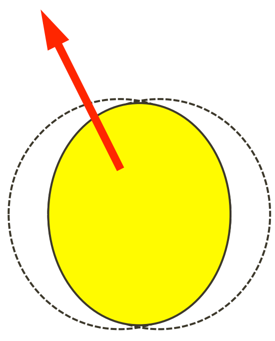
$$\langle T_{AA}^{cent} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{pp}$$

JHEP09 (2015) 050



|y|

Nuclear modification factor for high p_T particles and jets - PbPb



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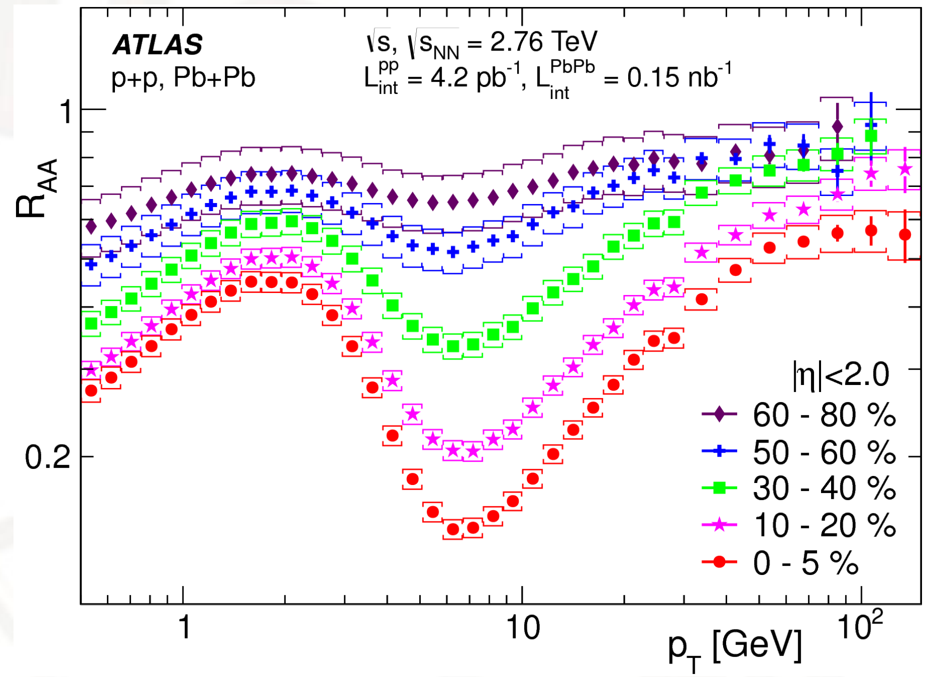
$$R_{AA} = \frac{dN^{cent} / dp_T}{\langle T_{AA}^{cent} \rangle d\sigma^{pp} / dp_T}$$

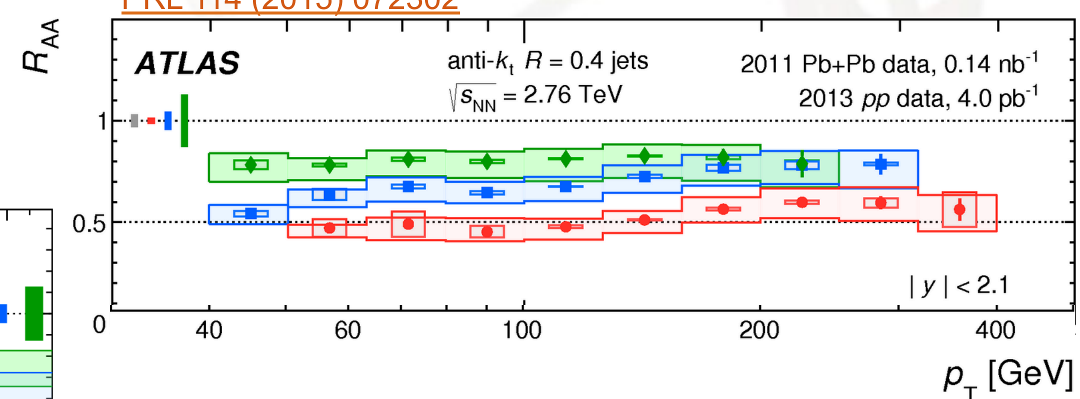
$$\langle T_{AA}^{cent} \rangle = \langle N_{coll} \rangle / \sigma_{inel}^{pp}$$

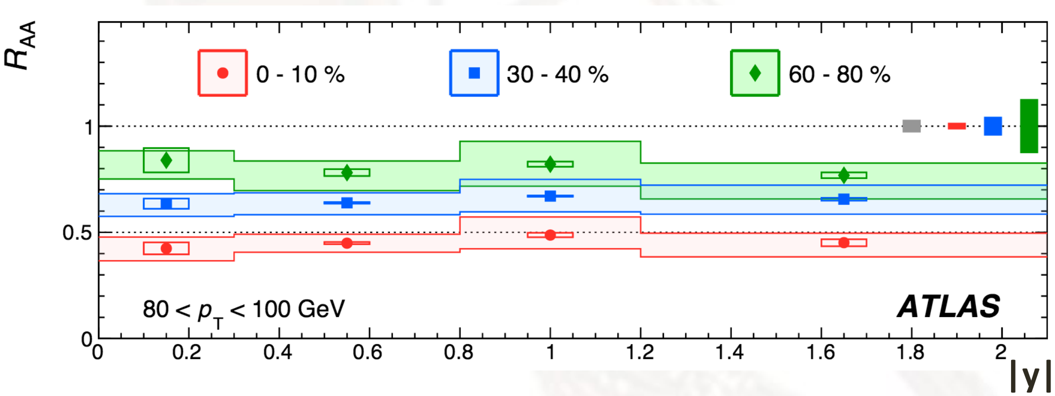
- Suppression of the factor of 2 in the most central collisions
- Measured up to 400 GeV, for the first time possible hints of the increase of RAA with pT
- RAA shows little dependence on y

JHEP09 (2015) 050

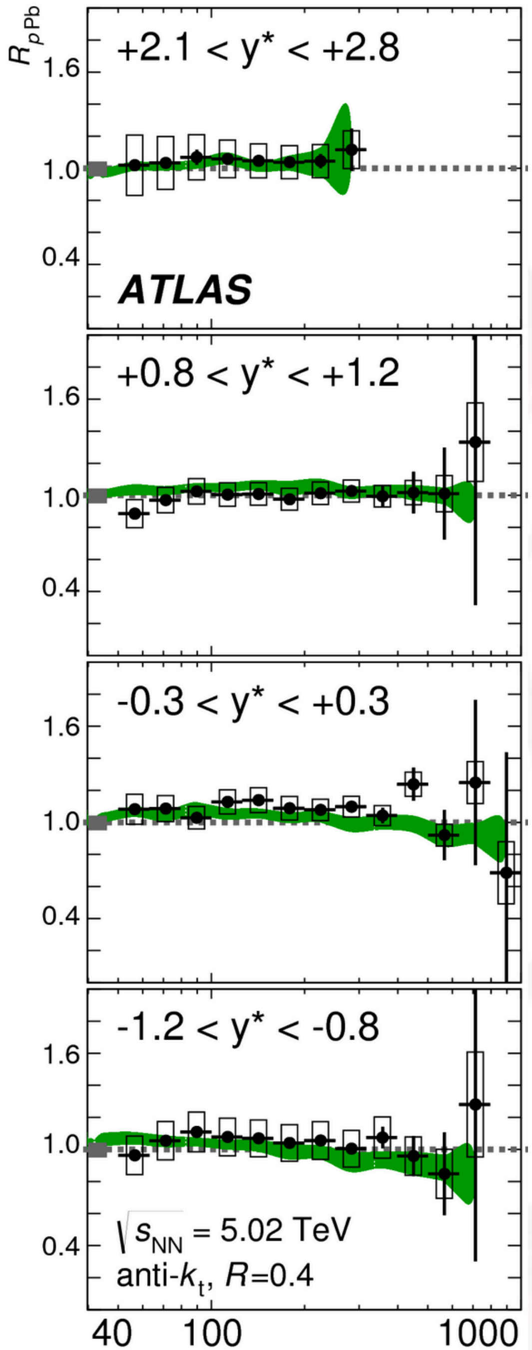


PRL 114 (2015) 072302



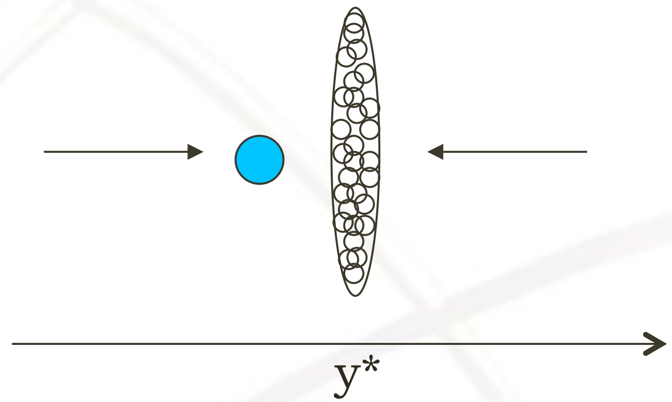


Nuclear modification factor for high p_T particles and jets - pPb

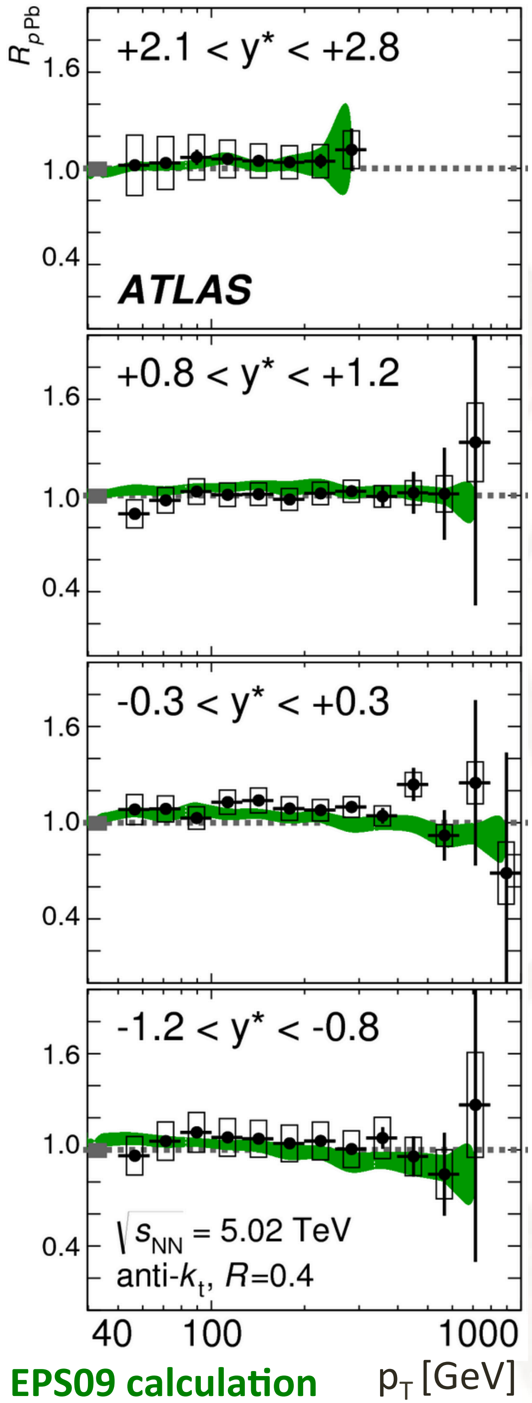


EPS09 calculation

No large deviations observed in the inclusive R_{pPb}



Nuclear modification factor for high p_T particles and jets - pPb



EPS09 calculation

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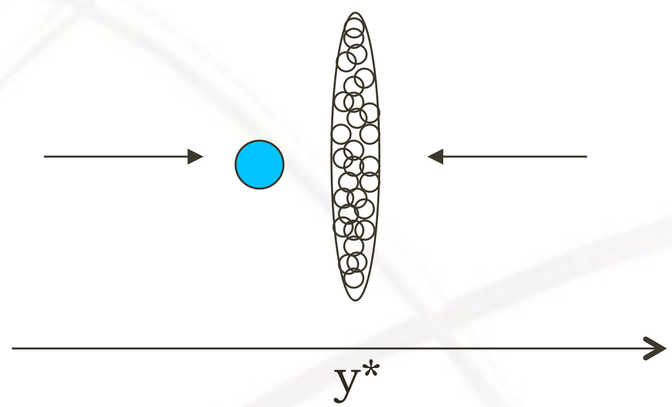
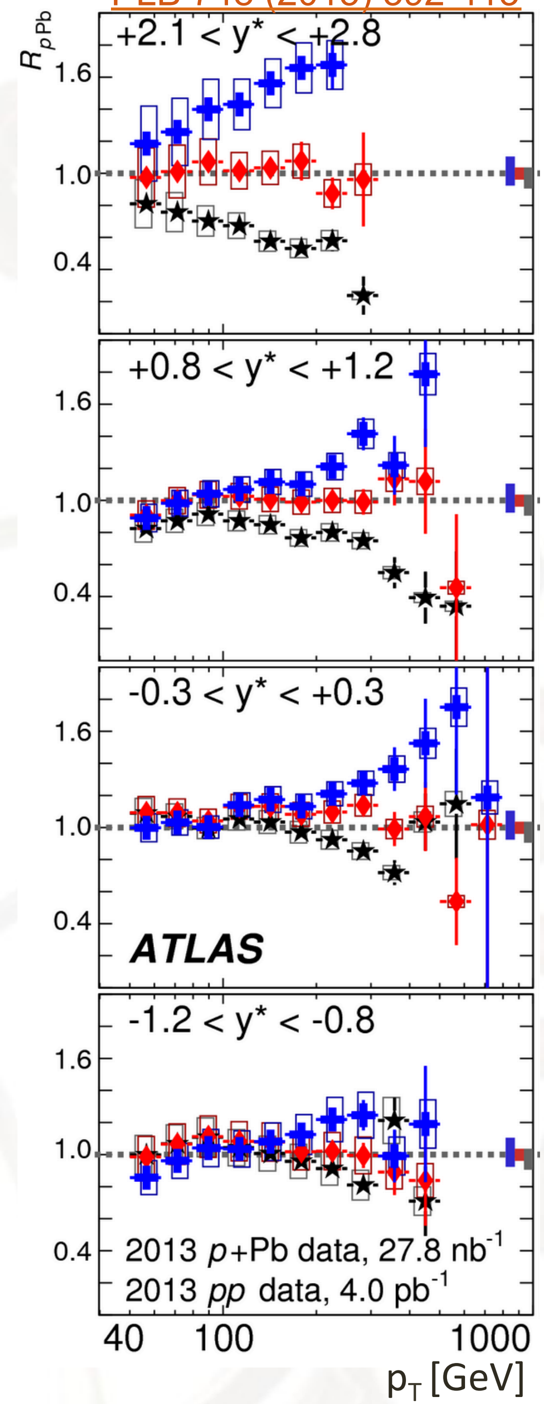


At large energy see correlation between hard scattering and total event activity

Suggestive that geometric size of proton correlated with x of hard scattering

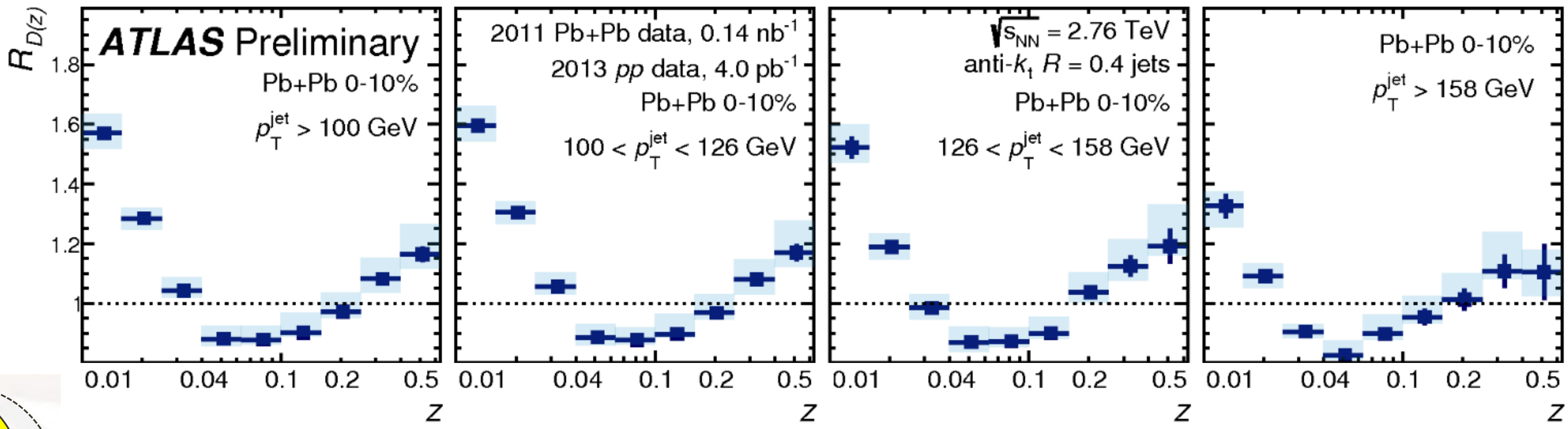
PLB 748 (2015) 392-413

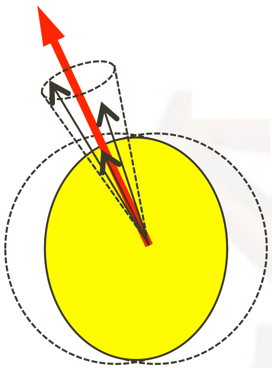


0-10%
20-30%
60-90%

Modification of the jet sub-structure

ATLAS-CONF-2015-055





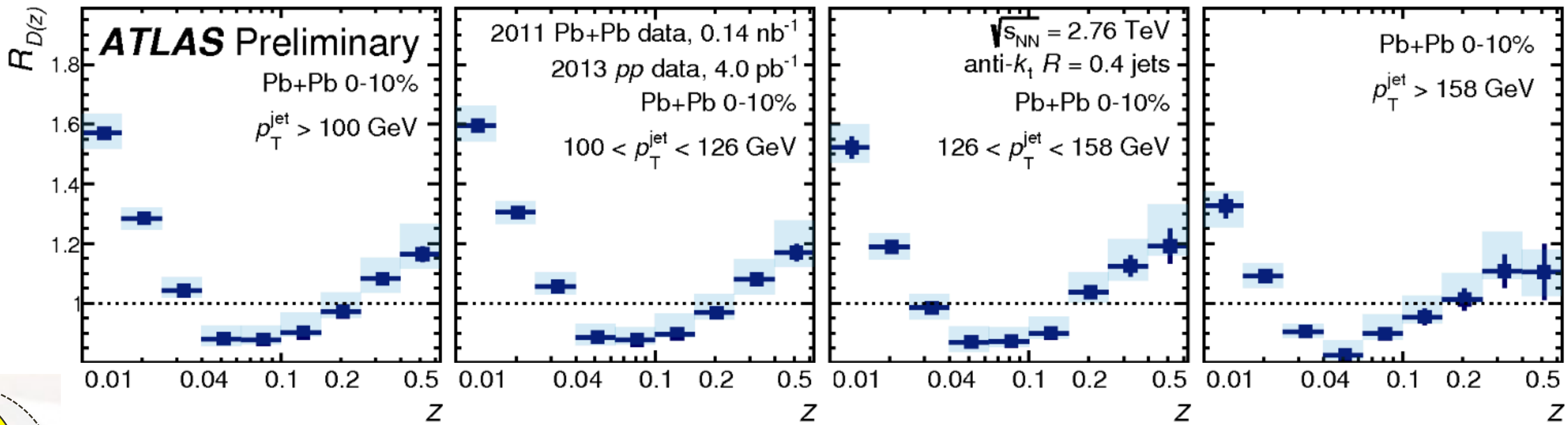
Significant modifications at high *z* observed in updated result in Pb+Pb

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

$$z = \frac{p_T^{trk}}{p_T^{jet}} \cos \Delta R$$

Modification of the jet sub-structure

ATLAS-CONF-2015-055



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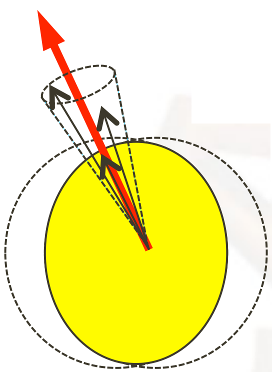
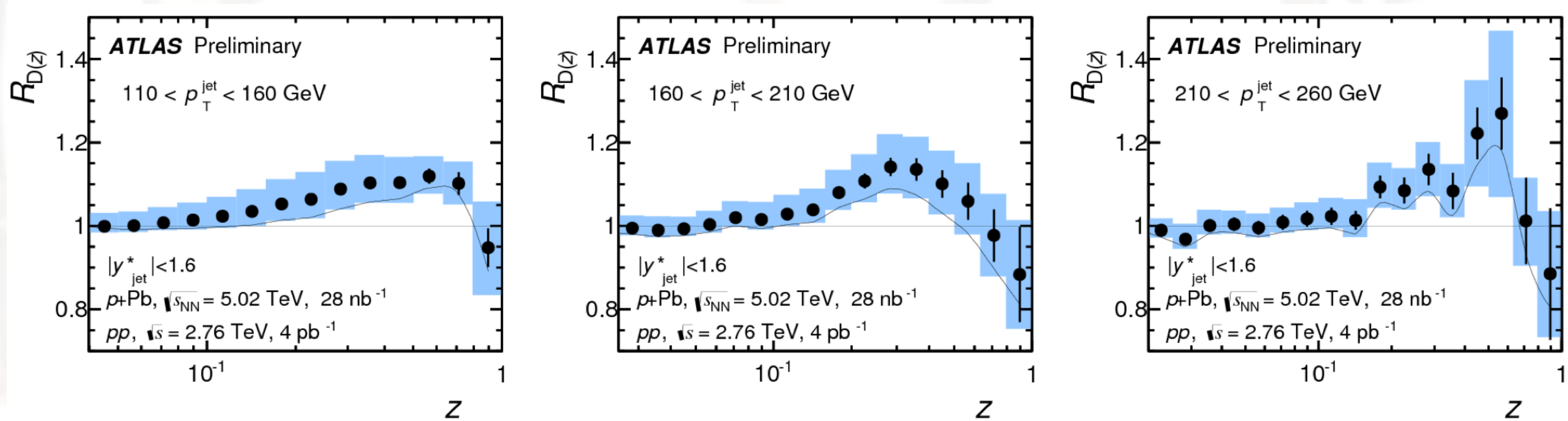


$$D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz}$$

$$z = \frac{p_T^{trk}}{p_T^{jet}} \cos \Delta R$$

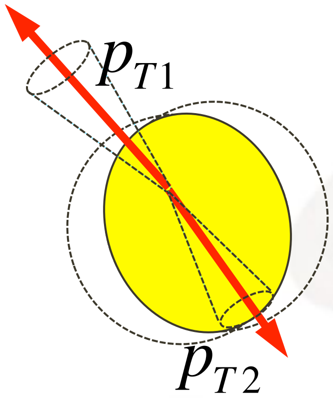
Modifications at high z in p+Pb?
5 TeV p+p reference from run2 crucial for this study.

ATLAS-CONF-2015-022



MC based extrapolation of p+p at 2.76 to 5.02 TeV

Di-jets asymmetry

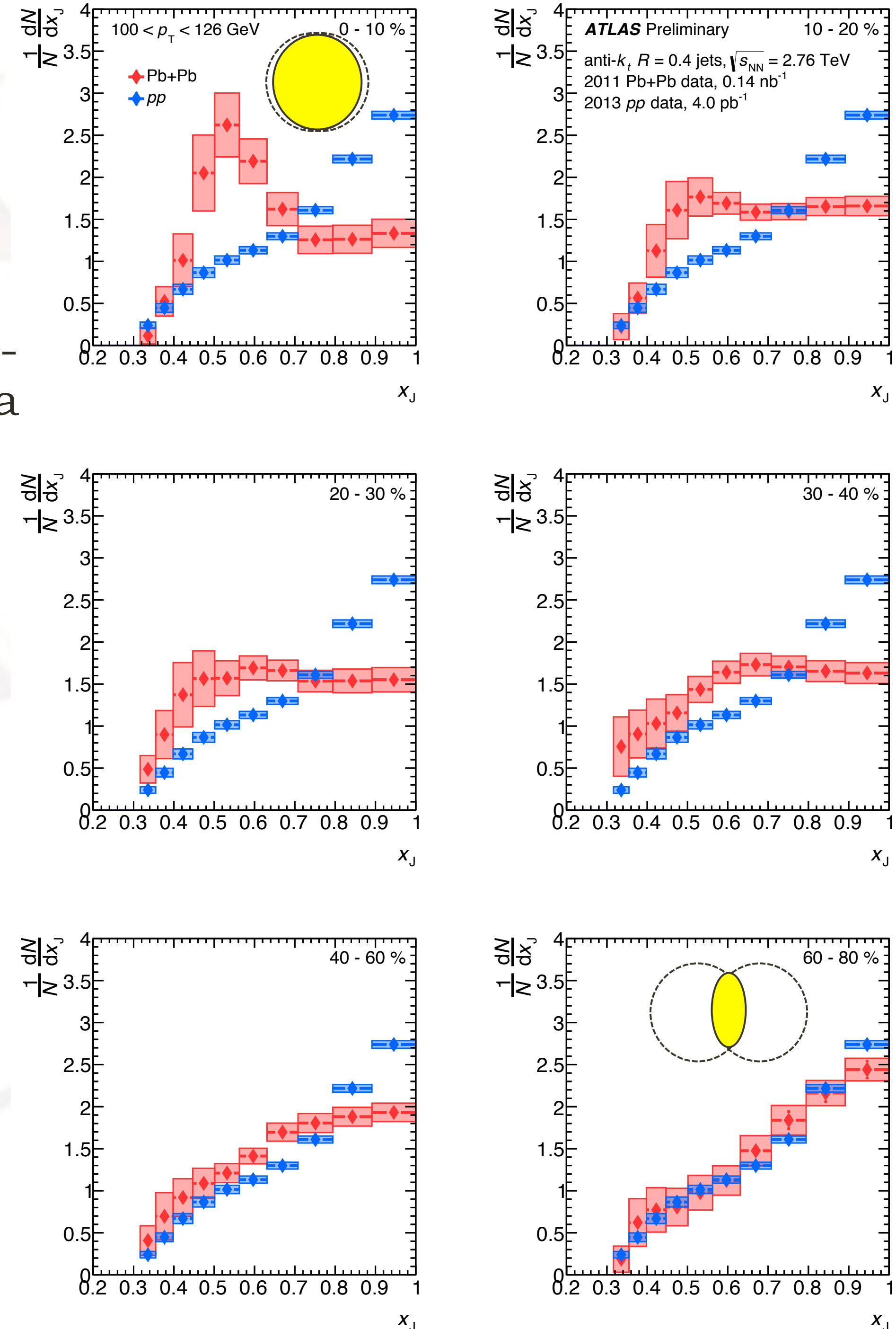


$$A_j = \frac{p_{T1} - p_{T2}}{p_{T1} + p_{T2}}$$

2D unfolding of di-jet (p_{T1},p_{T2}) spectra

$$x_j = \frac{p_{T2}}{p_{T1}}$$

Account for p_T migration and switch between p_{T1}&p_{T2}

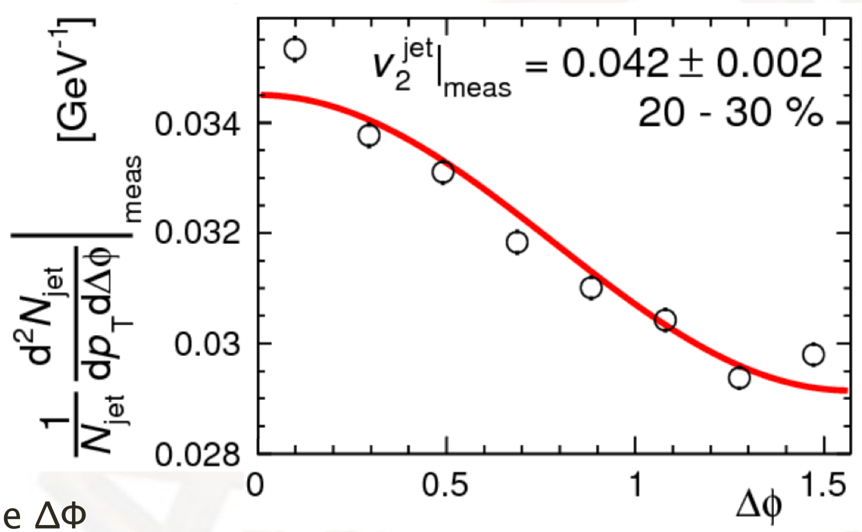


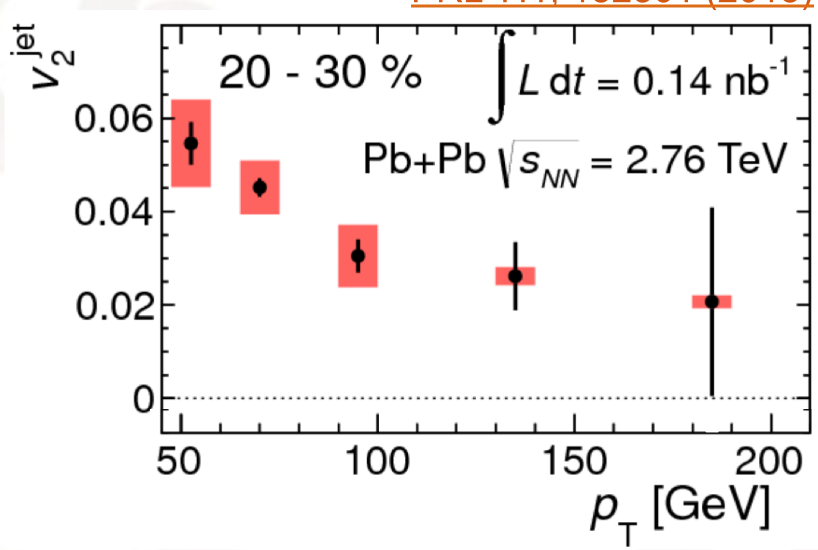
- In p+p most probable configuration is x_j~1 balanced di-jets
- In central Pb+Pb most probable configuration is x_j~0.5 – half of the jet energy is deposited in the medium

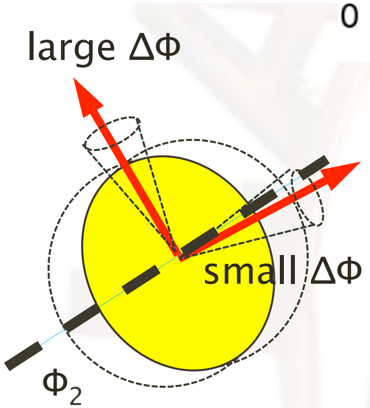
Can be directly compared with theory

Jet quenching path length dependence

PRL 111, 152301 (2013)





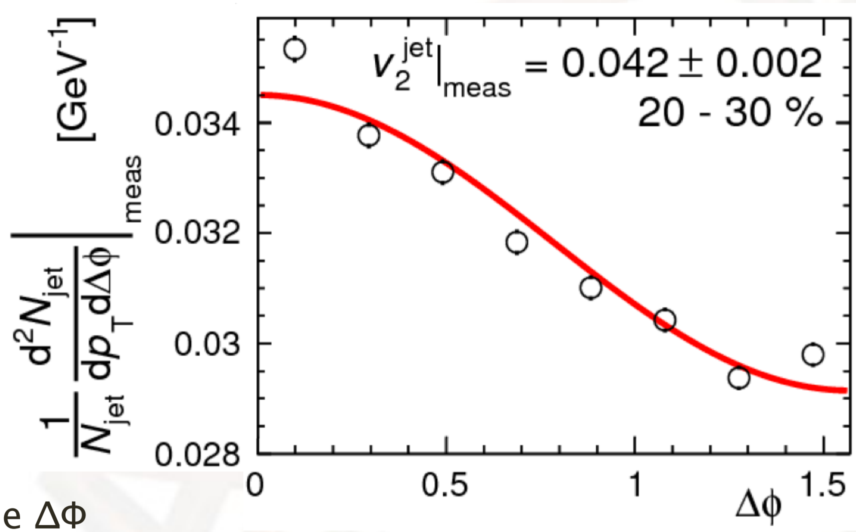


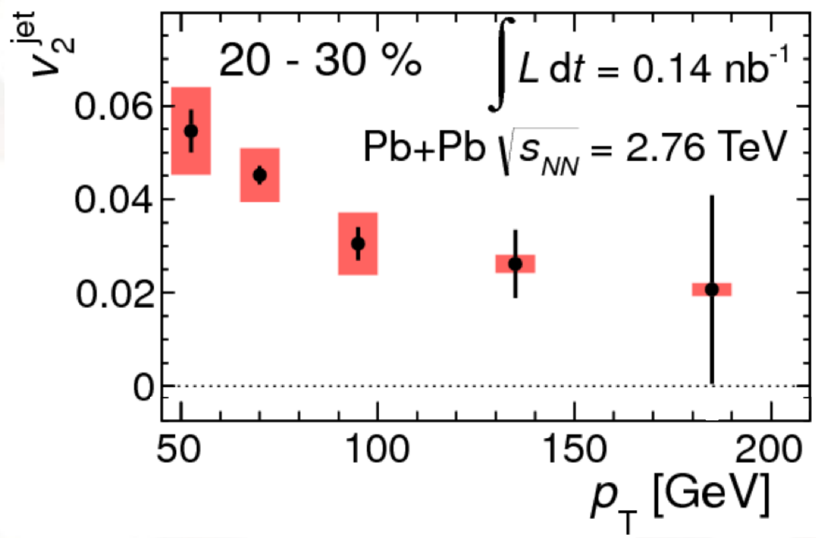
$$R_{AA}(\phi) = R_{AA}\left[1 + 2v_2 \cos 2\Delta\phi\right]$$

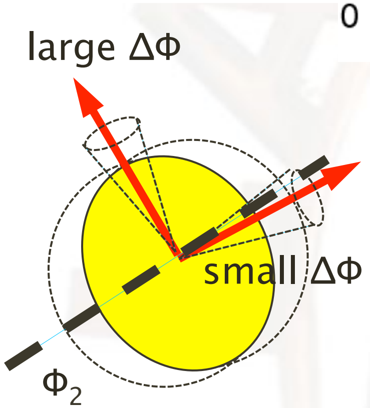
$$\Delta\phi = \phi_{jet} - \Phi_2$$

Jet quenching path length dependence

PRL 111, 152301 (2013)



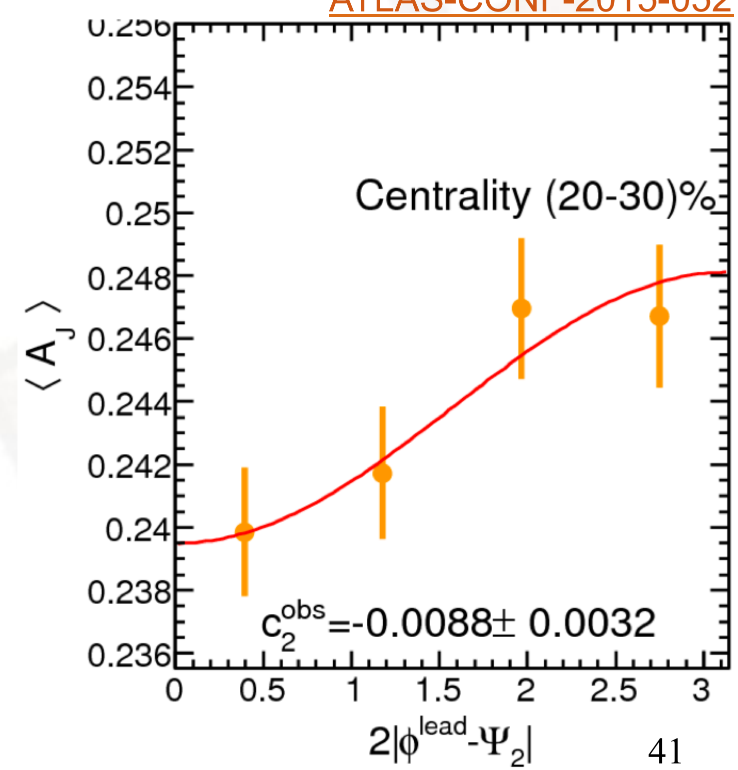




$$R_{AA}(\phi) = R_{AA}\left[1 + 2v_2 \cos 2\Delta\phi\right]$$

$$\Delta\phi = \phi_{jet} - \Phi_2$$

ATLAS-CONF-2015-052



- Decrease of jet v2 at high pT consistent smaller quenching (larger RAA at high pT)
- Very small, but significant anti-correlation between EP angle and <Aj>

Summary

- Many observables to study hydrodynamic response to EbyE fluctuating initial conditions
- Variety of measurements of vector bosons in both Pb+Pb and p+Pb do not reveal (yet) the modification of the nuclear parton distributions
- Jet probes of heavy ion collisions provide detailed information about the physics of jet-quenching
- Studding small collisions systems (p+Pb, p+p) reveal unexpected phenomena
  - Observed collectivity in the p+Pb and p+p collisions
  - Jets in p+Pb – proton size depends on x

Run2 data (Pb+Pb and p+p) will substantially help to understand the phenomena observed in Run1

$$N_{jet/W/Z/\gamma} = \boxed{L_{AA}\sigma_{AA}}_{\rightarrow jet/W/Z/\gamma}$$

Both factors higher in run 2