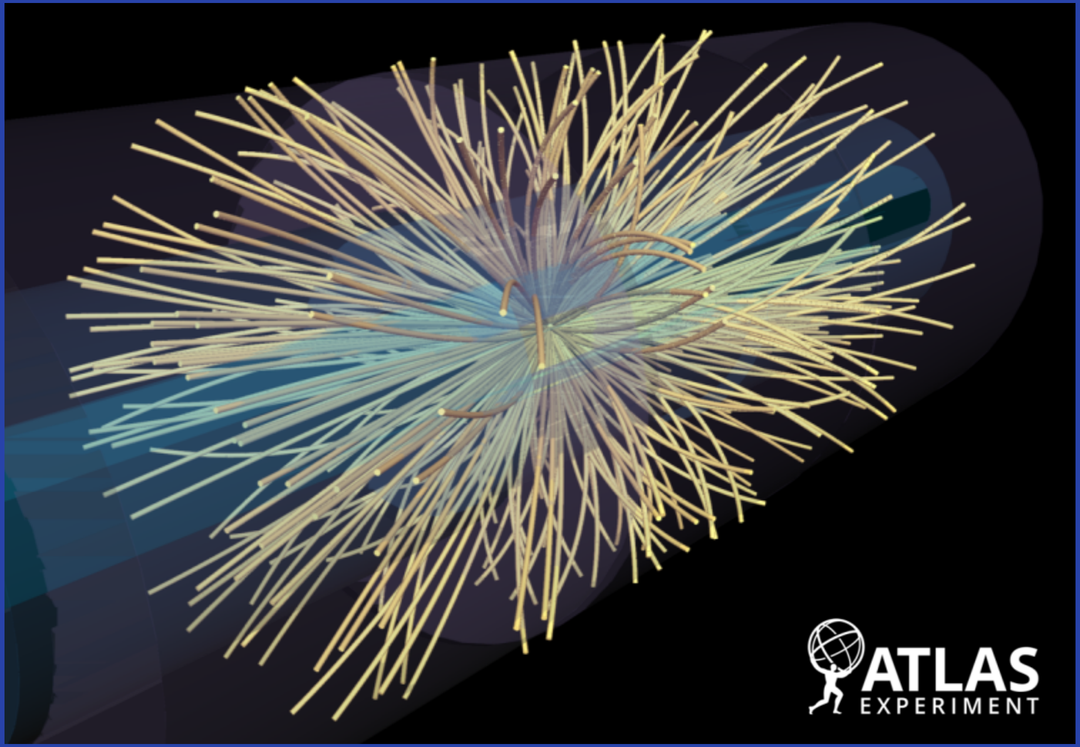
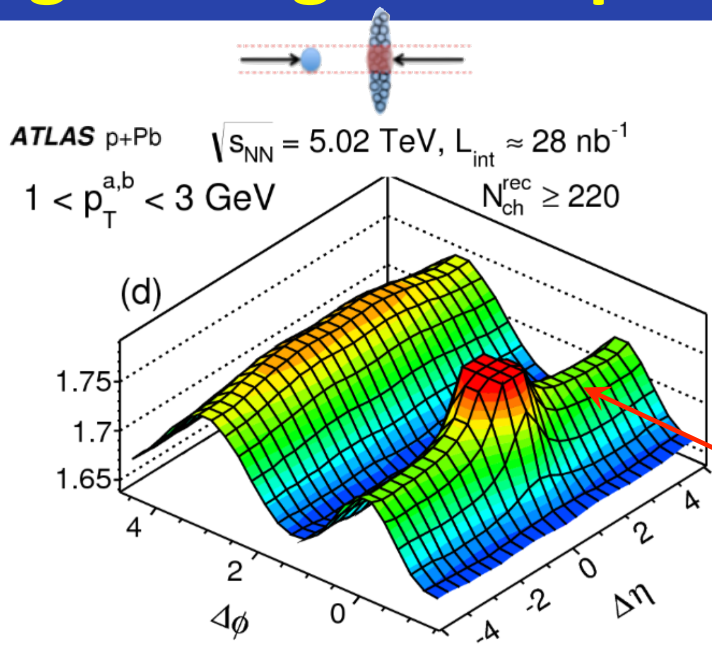
Recent ATLAS measurements of azimuthal anisotropies in pp and p+Pb collisions



Adam Trzupek on behalf of the ATLAS experiment
Institute of Nuclear Physics PAS, Kraków, Poland

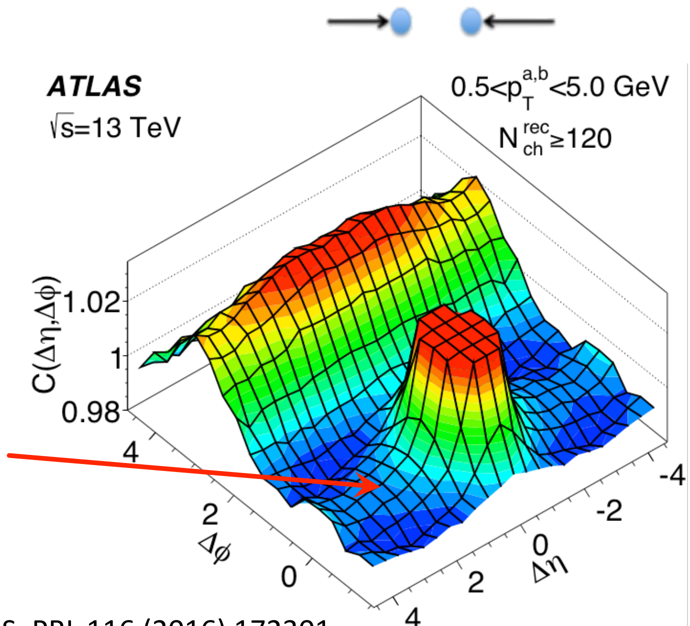
XLVII International Symposium on Multiparticle Dynamics
ISMD 2017
Tlaxcala City, Mexico, September 11-15, 2017

Ridge in High Multiplicity pp and p+Pb Collisions



ATLAS, PRC 90,044906 (2014)

ridge



ATLAS, PRL 116 (2016) 172301

p+Pb ridge

pp ridge

Strongly interacting QGP in small systems?

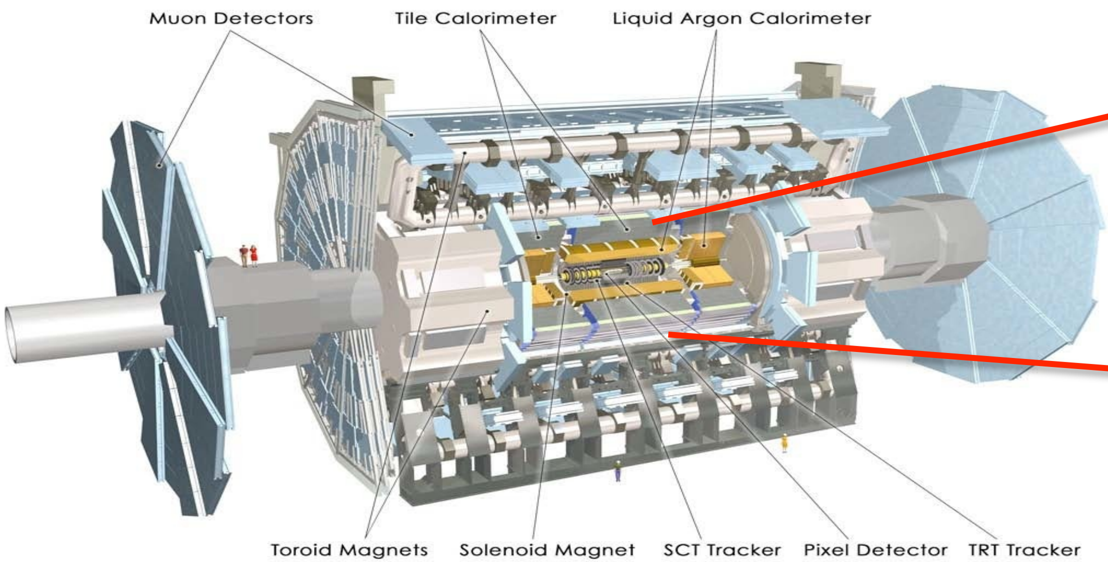
Recent results on small systems:

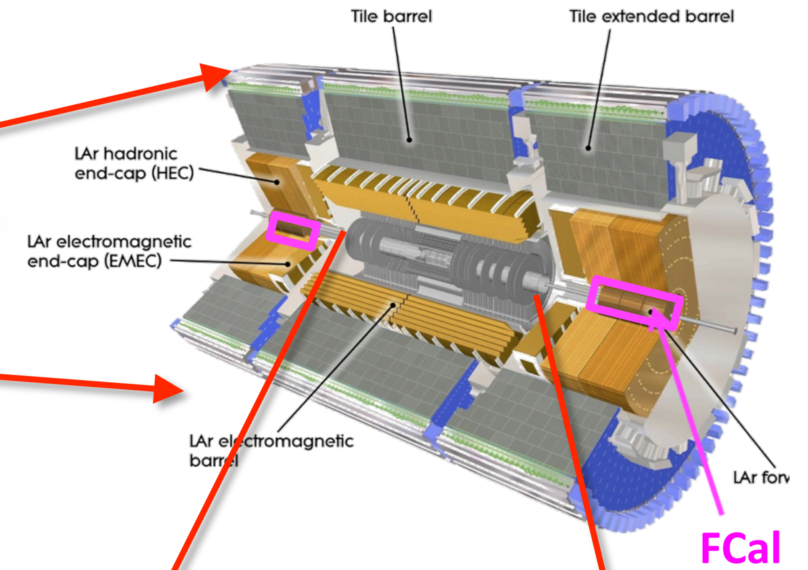
PRC 96 (2017) 024908 – v_n in 5.02 and 13TeV pp and 5.02TeV pPb (2PC)

ATLAS-CONF-2017-006 – charged hadron & muon v_2 in 8.16TeV pPb (2PC)

EPJC 77 (2017) 428, arXiv:1708.03559 – v_n from cumulants in 5.02 and 13 TeV pp, 5.02 TeV p+Pb and low-multiplicity 2.76 TeV Pb+Pb

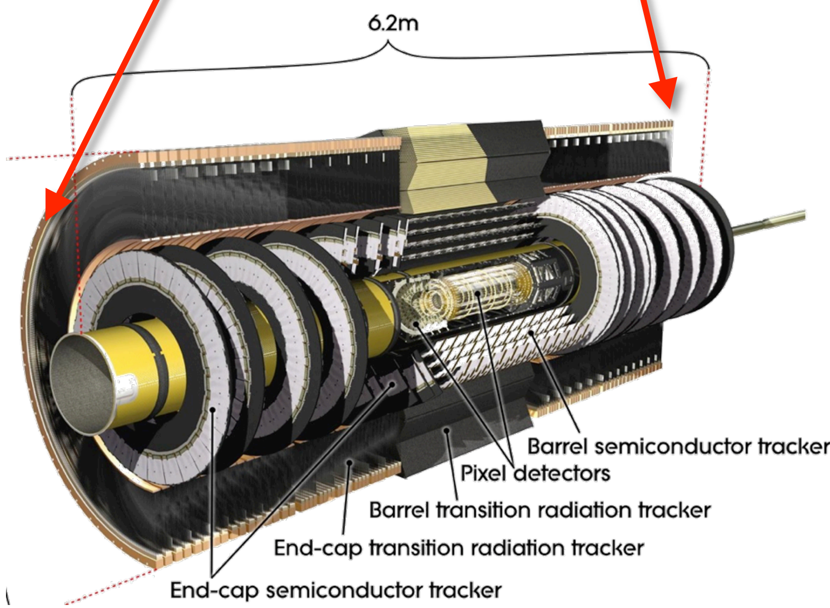
ATLAS Detector





Three main subsystems:

- Inner Detector (ID)–tracking |η|<2.5
- Calorimetry – |η|<4.9
  - FCal 3.1<|η|<4.9
- Muon Spectrometer - |η|<2.7



Fast trigger systems:

- Level 1 (L1)
- High Level Trigger (HLT)

Two-particle Correlations (2PC)

Two-particle correlation function:

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

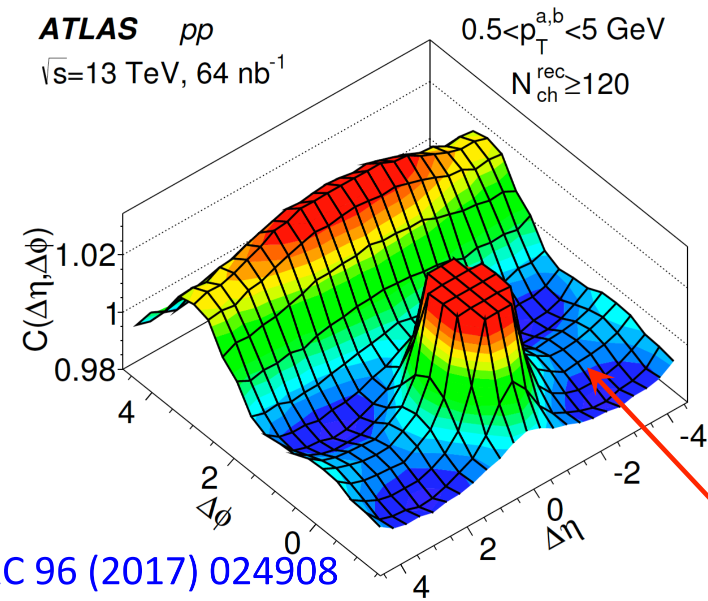
S and B are the same and mixed event pairs distributions. B corrects for detector effects

Per-trigger particle yield

$$Y(\Delta\phi) = \left(\frac{\int_{-\pi/2}^{3\pi/2} B(\Delta\phi) d\Delta\phi}{N^a \int_{-\pi/2}^{3\pi/2} d\Delta\phi} \right) C(\Delta\phi)$$

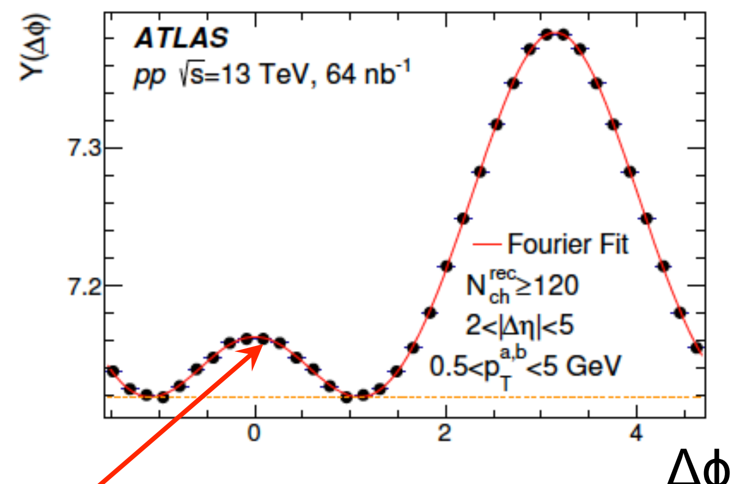
The average number of associated particles per trigger particle in Δφ bin

- Data samples: 13 TeV pp (64 nb^{-1}), for 5.02 TeV pp (170 nb^{-1}) and 5.02 TeV p+Pb (28 nb^{-1})



PRC 96 (2017) 024908

|Δη|>2



ridge

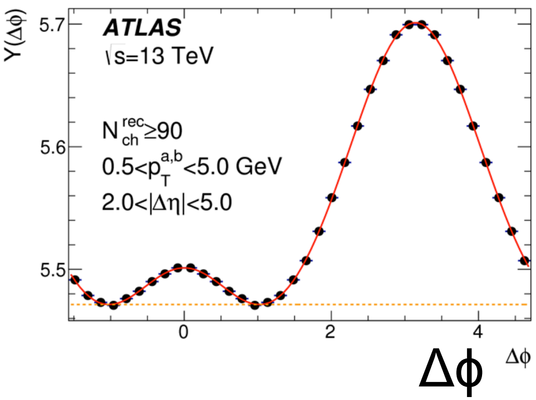
N_{ch}^{rec} – number of reconstructed tracks with p_T>0.4 GeV

Template-fitting Method

To separate the ridge from other correlations (e.g. dijets), ATLAS developed a template fitting procedure (PRL 116, 172301 (2016))

Template fit function (with 2 free parameters $v_{n,n}$, F):

$$Y^{templ}(\Delta\phi) \quad = \quad Y^{ridge}(\Delta\phi) \quad + \quad F\,Y^{periph}(\Delta\phi)$$



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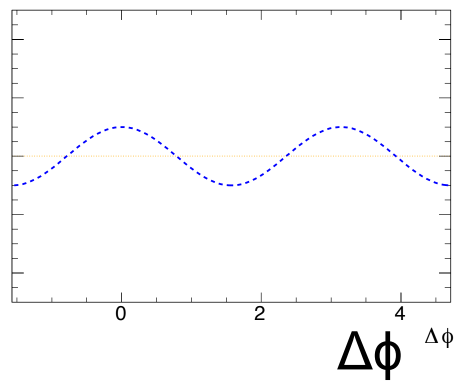

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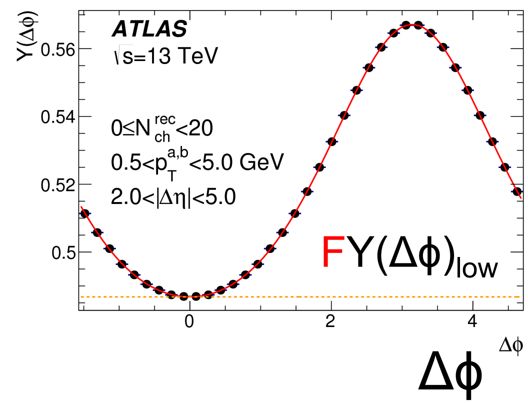


no ZYAM — $G\,(1 + 2\Sigma v_{n,n}\cos(n\Delta\phi))$ — no suppressed zero

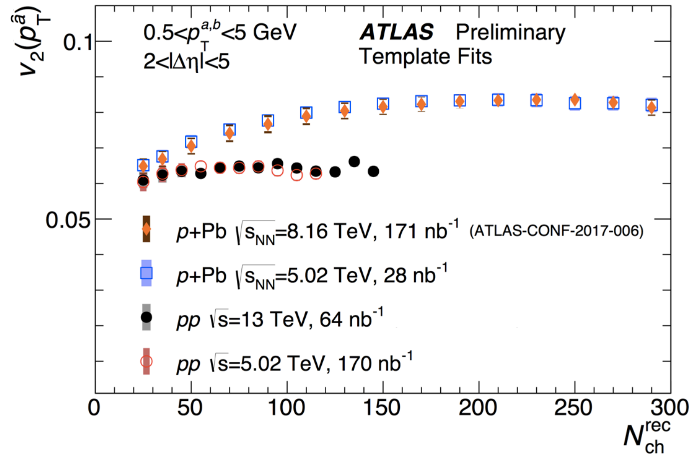
- Assumption: F Y^{periph} describes dijets correlations in full N_{ch}^{rec} range
- Y^{templ} successfully describes Y distributions
- The factorization works well in different N_{ch}^{rec} and p_T-ranges

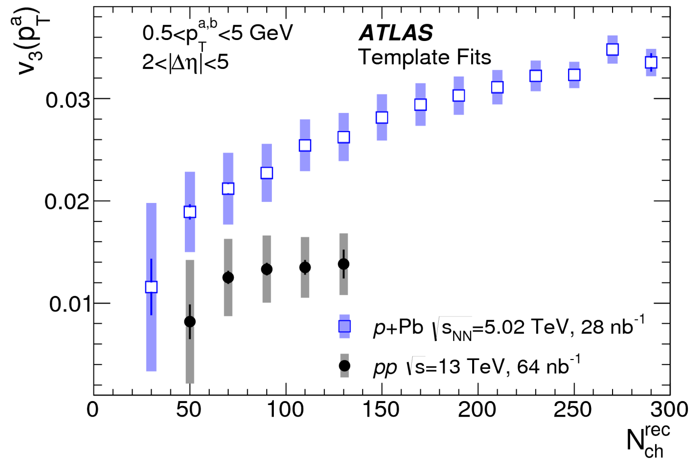
$$v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)\,v_n(p_T^b)$$

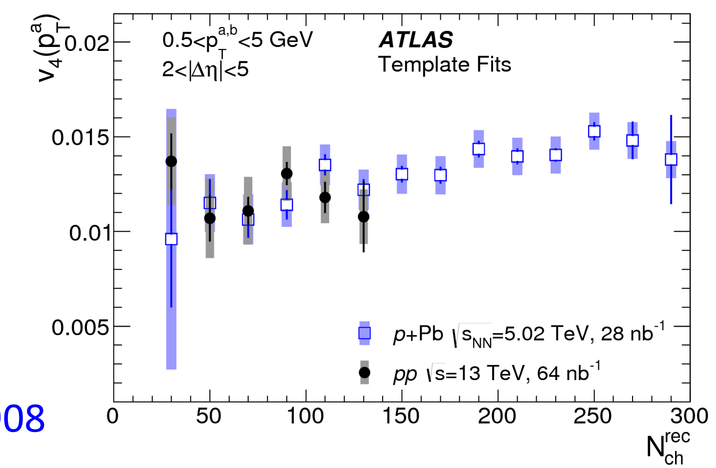
N_{ch} and Energy Dependence of v_2 ,v_3 , v_4 in pp and p+Pb

$$v_n(p_T^a) = \sqrt{v_{n,n}(p_T^a, p_T^b)}, \quad 0.5 < p_T^{a,b} < 5\,GeV$$

- v_n^{pp} have a weak dependence on N_{ch}
  - v_2 in 5.02 and 13 TeV pp collision agree
- v_n^{p+Pb} increase with N_{ch}^{rec}
  - v_2 in 5.02 and 8.16TeV pPb system agree
- v_n^{pp} and v_n^{p+Pb} are similar at low multiplicity







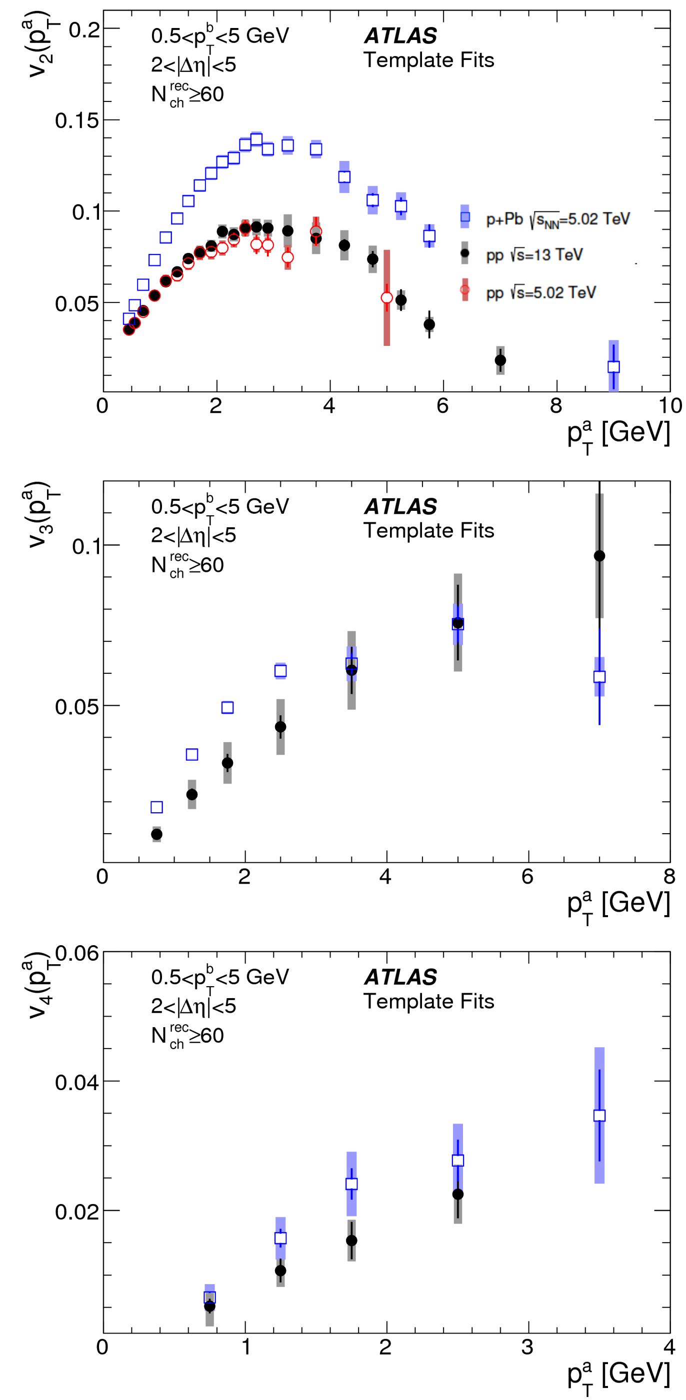
PRC 96 (2017) 024908

p_T Dependence of v_n

$$v_2(p_T^a) = v_{2,2}(p_T^a, p_T^b) \,/\, \sqrt{v_{2,2}(p_T^b, p_T^b)}$$

- $v_2(p_T)$ in pp and pPb collisions show a rise & fall,
  - Trend characteristic for collective flow observed in AA collisions
  - $v_2(p_T)$ in 5.02 and 13 TeV pp collisions agree

- $v_{3,4}(p_T)$ in pp and p+Pb collisions rise with p_T
  - faster increase for p+Pb system

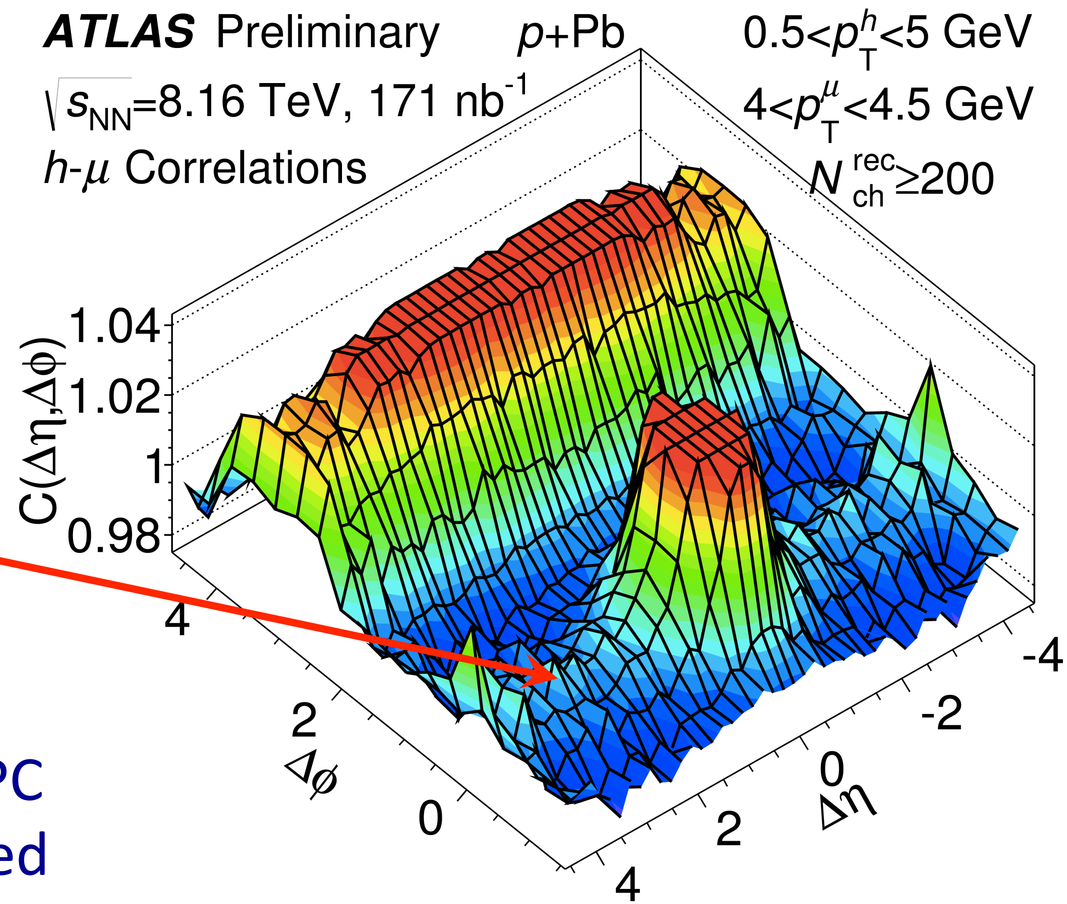


PRC 96 (2017) 024908

Muon-hadron Correlations in 8.16TeV pPb Collisions

- Elliptic flow of heavy flavor muons was measured in 2.76 TeV in Pb+Pb collsions (ATLAS-CONF-2015-053)
  - Interaction of heavy flavor quarks (c/b) with QGP

- Clear ridge is seen in the correlation function, C, of charged particles (mostly hadrons) and muons pairs in high-multiplicity 8.16 TeV p+Pb collisions



To extract the muon v_2 the 2PC template fitting method is used

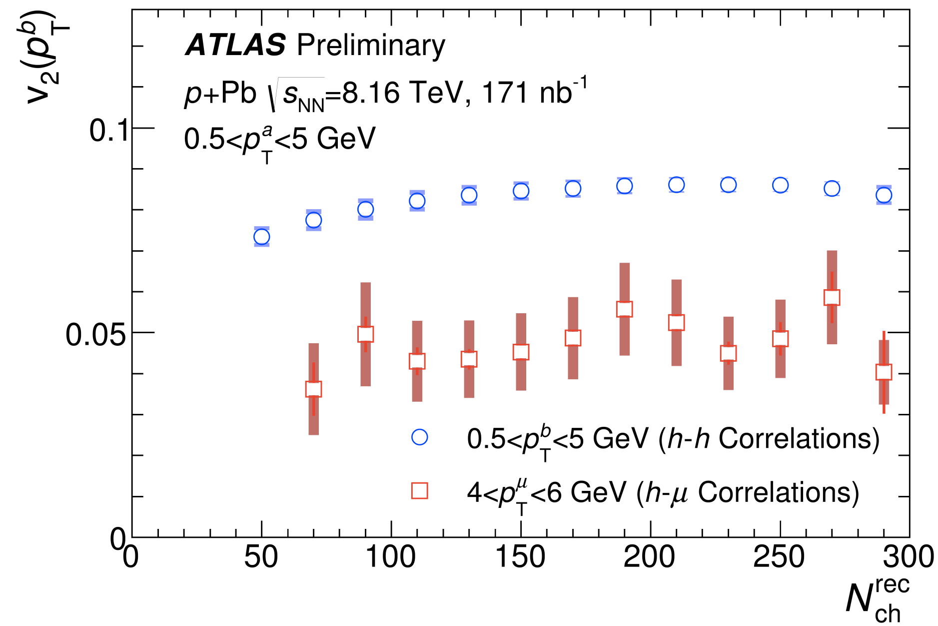
ATLAS-CONF-2017-006

Heavy Flavor Muon v_2^μ in 8.16 TeV p+Pb Collisions

N_{ch}^{rec} - dependence:

$v_2^\mu \approx 0.6\ v_2^h$

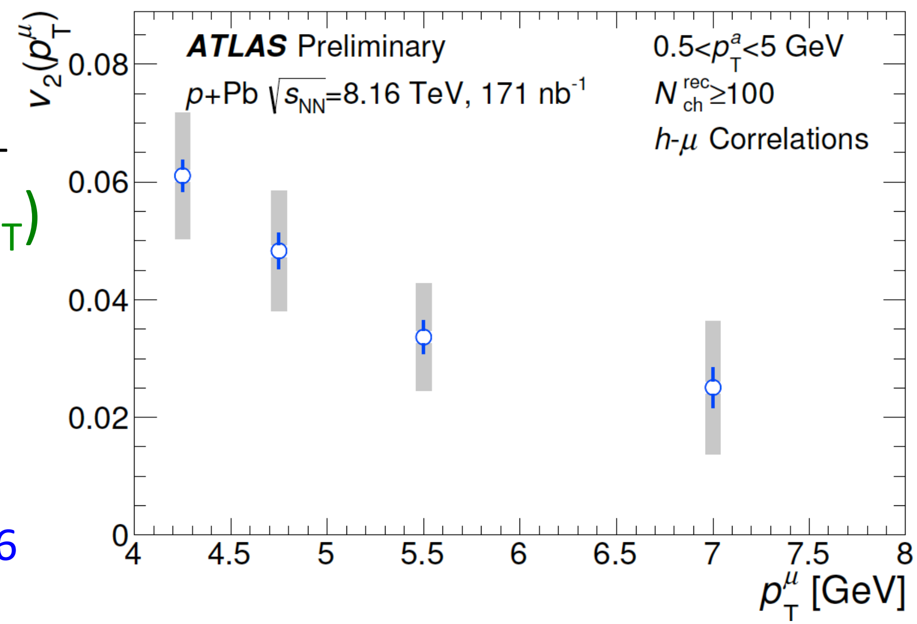
v_2^μ is constant as a function of event multiplicity



p_T - dependence, $N_{ch}^{rec} \geq 100$:

v_2^μ decreases with increasing p_T

- Similar trend to hadron $v_2(p_T)$



ATLAS-CONF-2017-006

Multi-particle Correlations (EPJC 77 (2017) 428)

- To directly explore collectivity in small systems, multi-particle correlations were measured in 5.02 and 13 TeV pp, 5.02 TeV p+Pb and low-multiplicity 2.76 TeV Pb+Pb collisions (k=1,2,3,4):

$$\left\langle corr_n\{2k\}\right\rangle \equiv \left\langle e^{in\left[(\varphi_1-\Phi_n)+..-(\varphi_{k+1}-\Phi_n)-...\right]}\right\rangle = \left\langle \cos[n(\varphi_1+...-\varphi_{k+1}-....)]\right\rangle = \left\langle v_n^{2k}\right\rangle$$

- Using cumulants suppresses “non-flow” correlations, e.g.

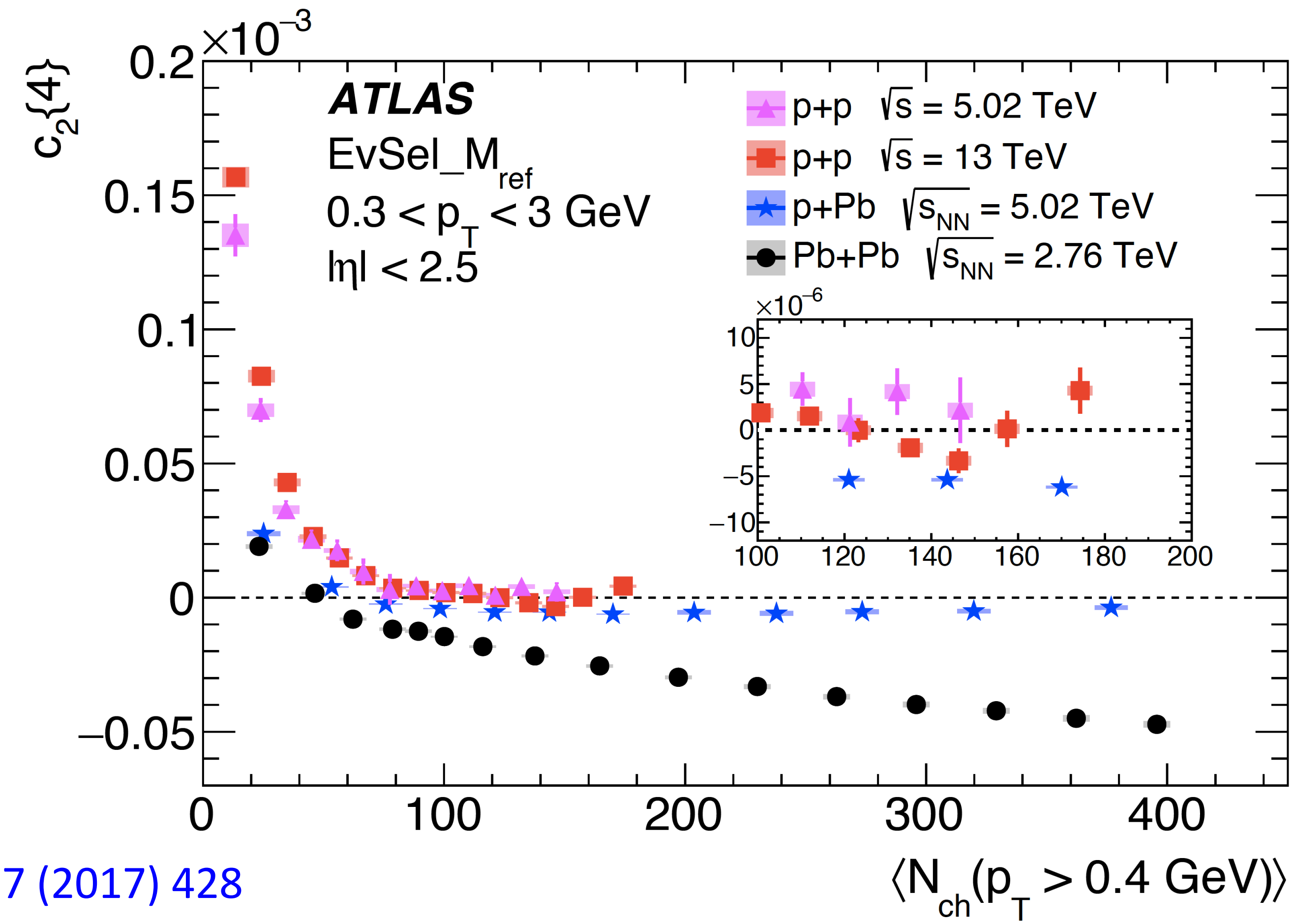
$$c_n\{4\} = \left\langle corr_n\{4\}\right\rangle - 2\left\langle corr_n\{2\}\right\rangle^2 \qquad v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

negative

  - Negative $c_n\{4\}$ allows for v_n calculations (sign of collectivity)

- Averaging of cumulants over events was performed in unit bins of the number of reference particles (event selection $EvSel\_M_{ref}$)
  - Results for different systems are compared in a common variable $<N_{ch}(p_T > 0.4\ GeV)>$ (corrected for efficiency)

Multiplicity and System Size Dependence of $c_2\{4\}$



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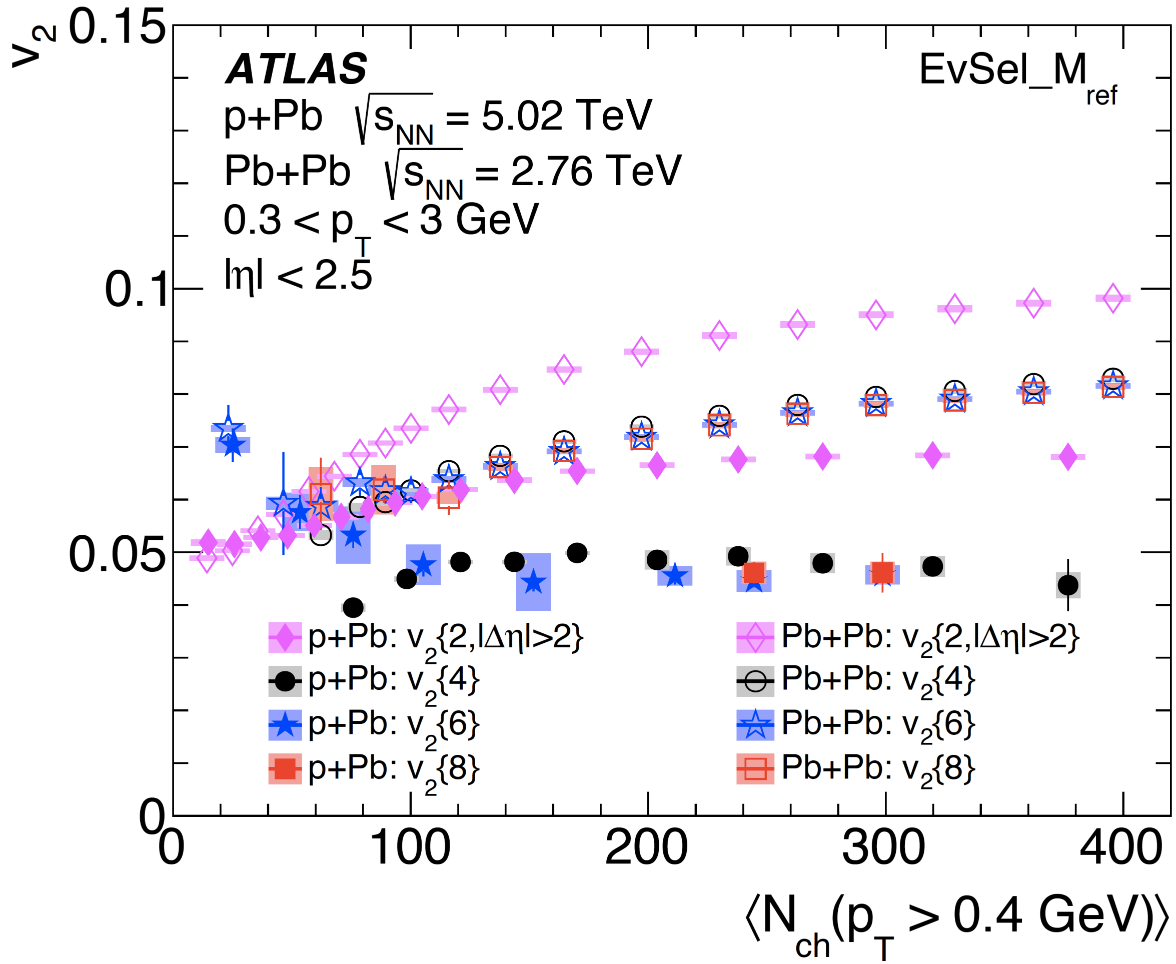
- $c_2\{4\}$ cumulant for 5.02 and 13 TeV pp is positive
- For p+Pb and Pb+Pb collisions, for $c_2\{4\} < 0$
- For N_{ch}>100: $|c_2\{4\}|_{pp} < |c_2\{4\}|_{pPb} < |c_2\{4\}|_{PbPb}$

Elliptic Flow v_2 in p+Pb and Pb+Pb

$v_2\{2k\}$ of multi particle cumulants (k=1,2,3,4) provide important information on initial-state anisotropy



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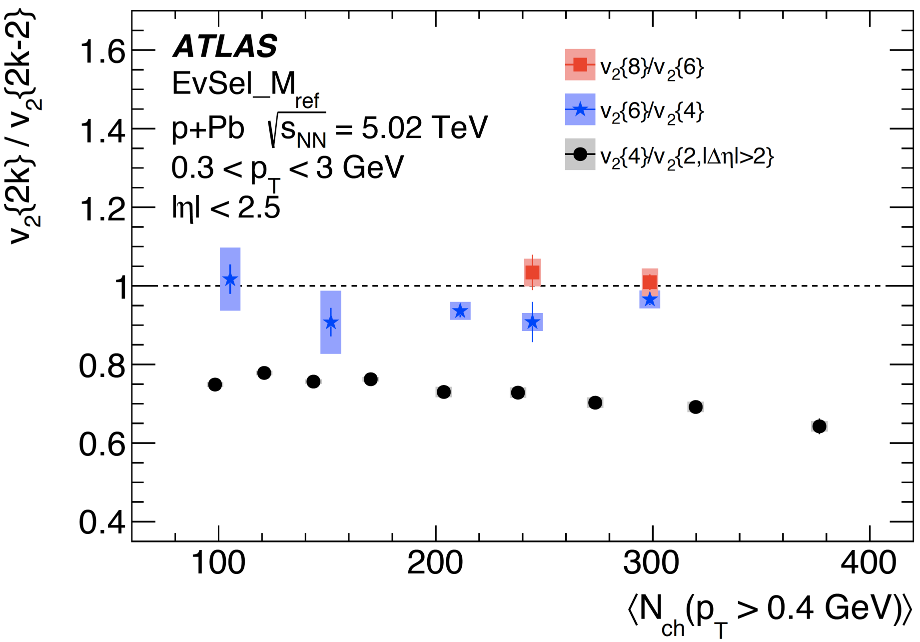
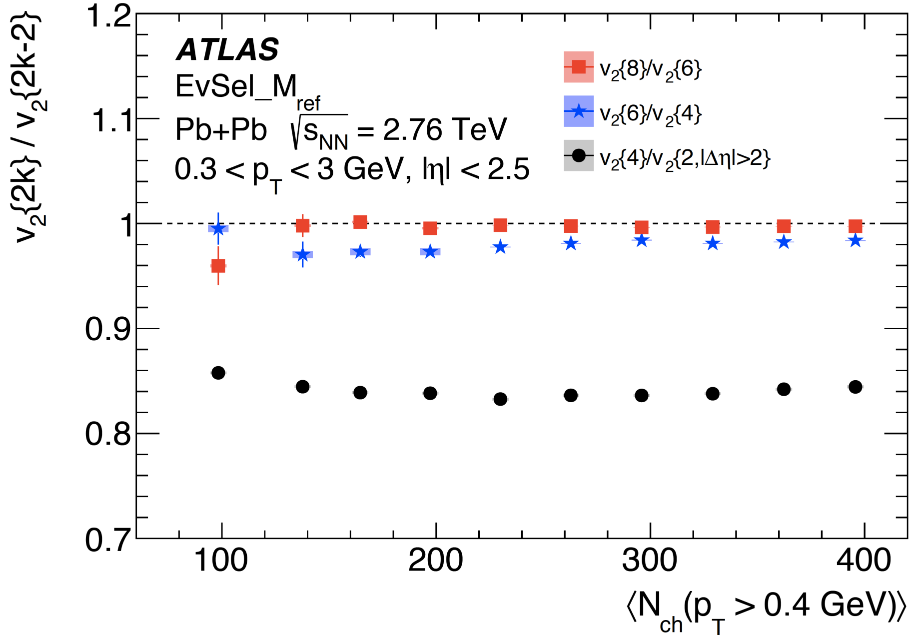
- v_2 harmonics are larger for Pb+Pb than for p+Pb
- $v_2\{4\}$, $v_2\{6\}$ and $v_2\{8\}$ are similar for p+Pb as well as for Pb+Pb

Ratios: $v_2\{8\}/v_2\{6\}$, $v_2\{6\}/v_2\{4\}$, $v_2\{4\}/v_2\{2,|\Delta\eta|>2\}$

5.02 TeV p+Pb



2.76 TeV Pb+Pb



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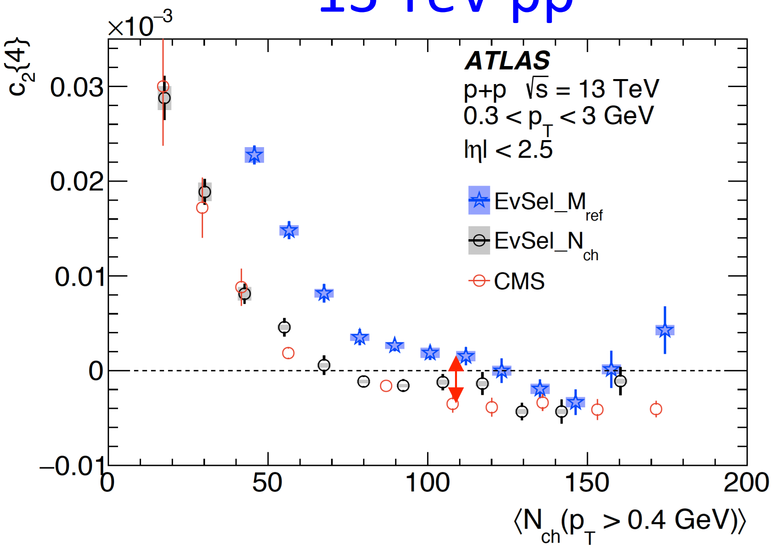
- For Pb+Pb collisions the ratios are independent of N_{ch}, for N_{ch} >120
  - $v_2\{6\}/v_2\{4\}$, $v_2\{8\}/v_2\{6\}$ are close to 1 but $v_2\{6\}/v_2\{4\} < v_2\{8\}/v_2\{6\}$
- $v_2\{4\}/v_2\{2,|\Delta\eta|>2\} \approx 0.85$ (0.7) for Pb+Pb (p+Pb) collisions
  - Significant fluctuations in the initial geometry in both systems (Li Yan and Jean-Yves Ollitrault, PRL 112 (2014) 082301)

Comparison to Other Results

13 TeV pp



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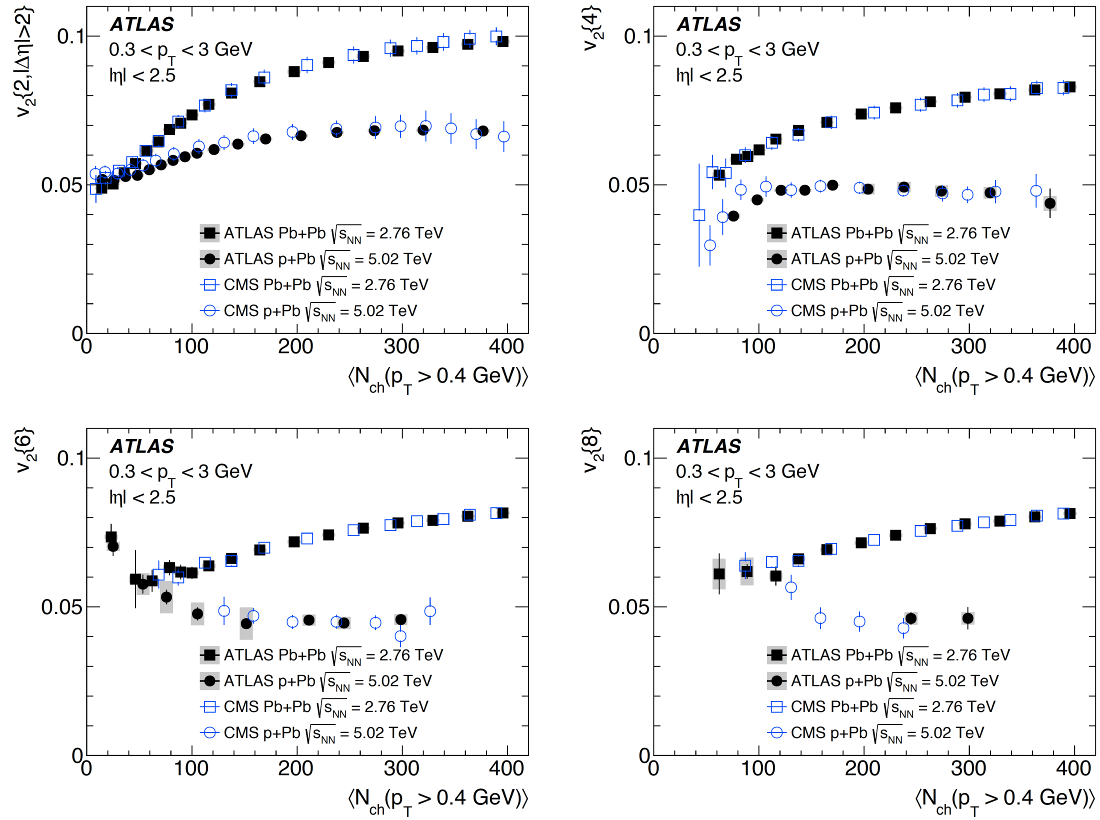
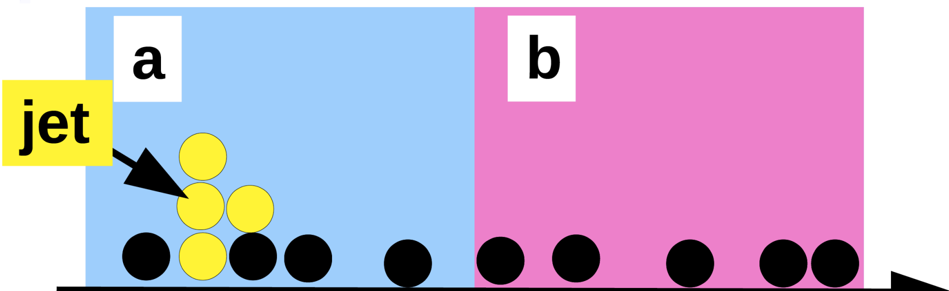


- For 13 TeV pp collisions CMS $c_2\{4\}$ is roughly consistent with ATLAS cumulant obained for event selection method, EvSel_N_{ch}, but it has a larger magnitude than $c_2\{4\}$ for the selection EvSel_M_{ref}
- For p+Pb and Pb+Pb collisions, ATLAS and CMS $v_2\{2,|\Delta\eta|>2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ agree very well

New Sub-event Cumulant Method

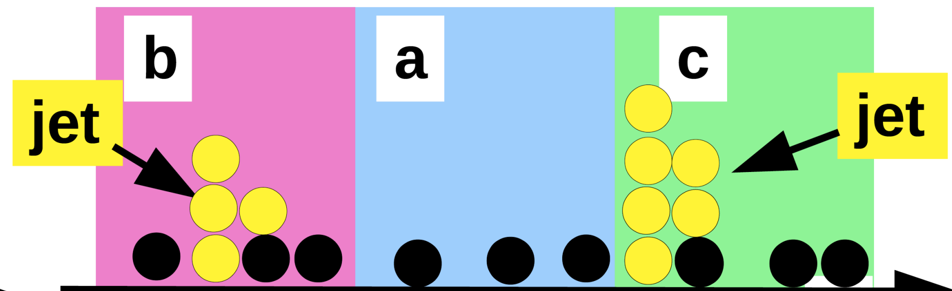
To lower contributions from "non-flow" in pp collisions, $c_n\{4\}$ is calculated for separate η intervals of correlated particles (sub-events)

2 sub-events method



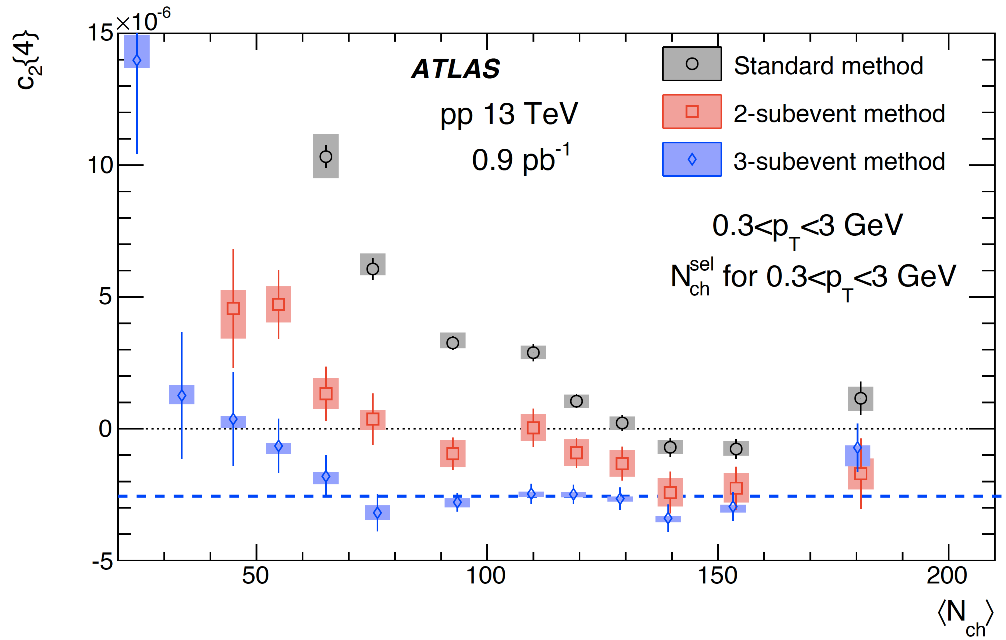
$$\langle \cos(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^b) \rangle \qquad \eta$$

3 sub-events method



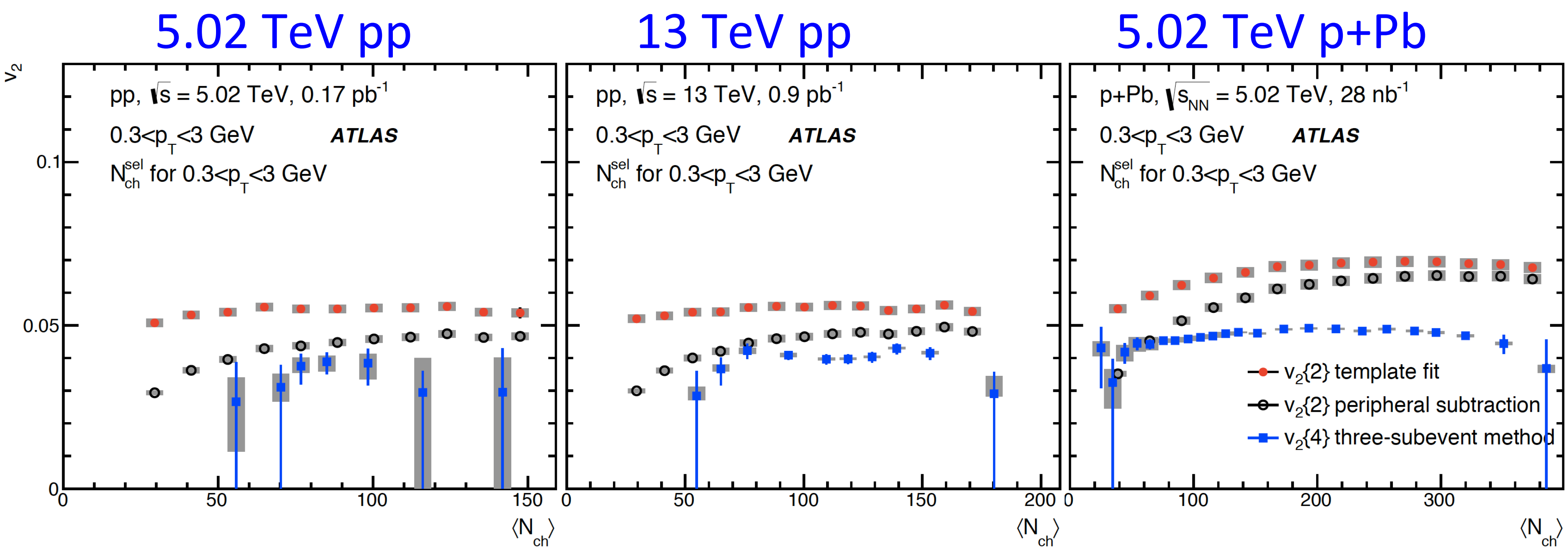
$$\langle \cos(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^c) \rangle \qquad \eta$$

- For N_{ch}>70, $c_2\{4\}$ from 2 or 3 sub-events is clearly negative
  - Sign of collectivity
  - Suppression of "non-flow"
- The new sub-event method is described in arXiv:1701.03830



Comparison to Other Methods

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$



arXiv:1701.03830

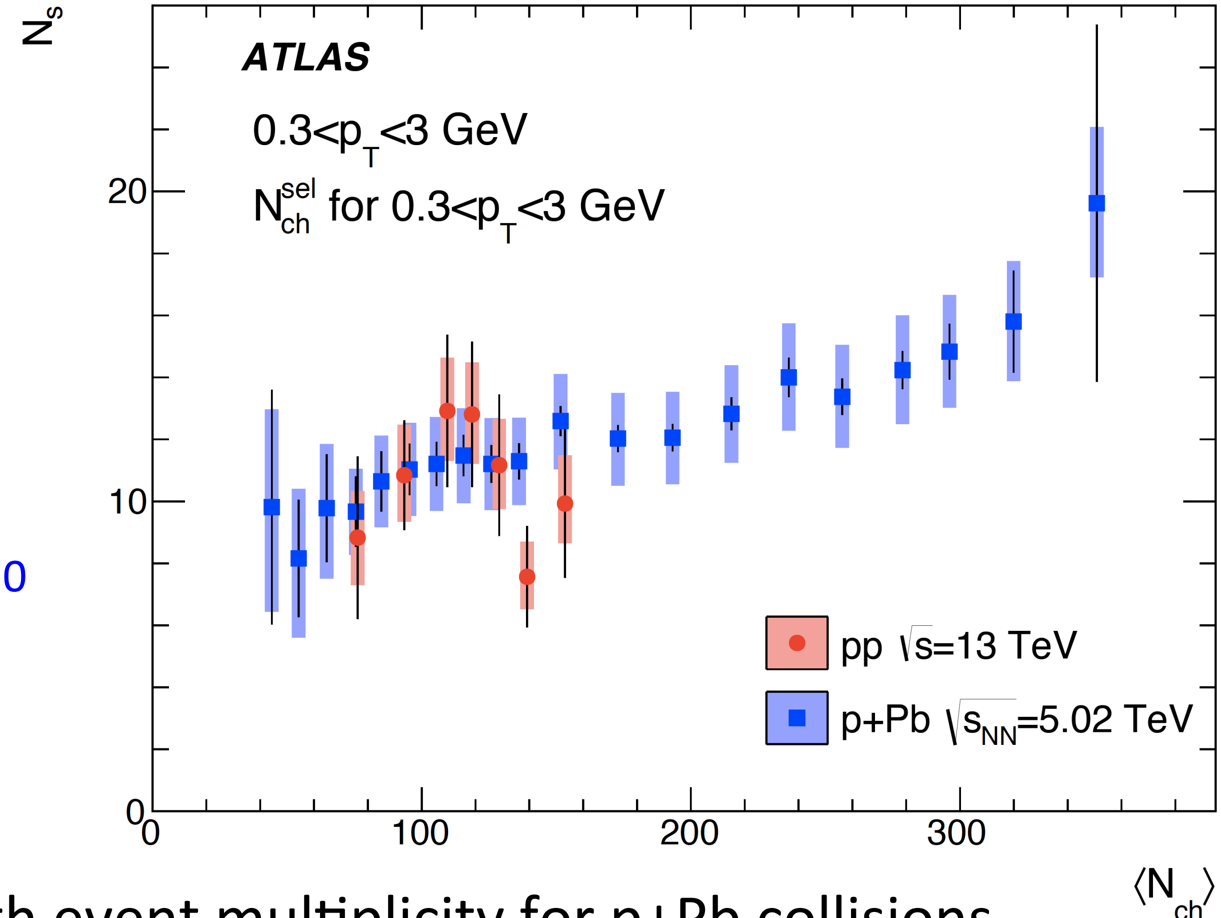
- $v_2\{4\}$, almost independent of N_{ch} in the three systems and very weak dependence on $\sqrt{s_{NN}}$ in pp collisions
- $v_2\{4\} < v_2\{2\}$ ➔ significant fluctuations in the initial geometry

Number of Particle Sources

Number of particle sources, N_s, estimated from transverse flow
(Li Yan and Jean-Yves Ollitrault, PRL 112 (2014) 082301)

$$\frac{v_2\{4\}}{v_2\{2\}} \approx \left[\frac{4}{(3+N_s)}\right]^{\frac{1}{4}}$$

arXiv:1701.03830



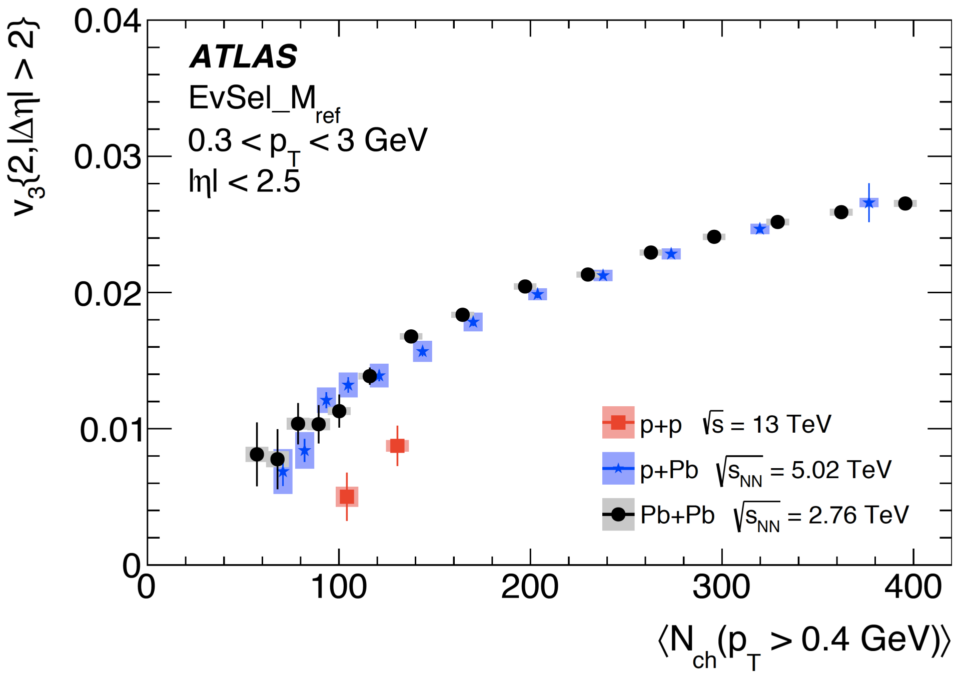
- N_s is increasing with event multiplicity for p+Pb collisions
- N_s in pp and p+Pb are similar in the common N_{ch} range

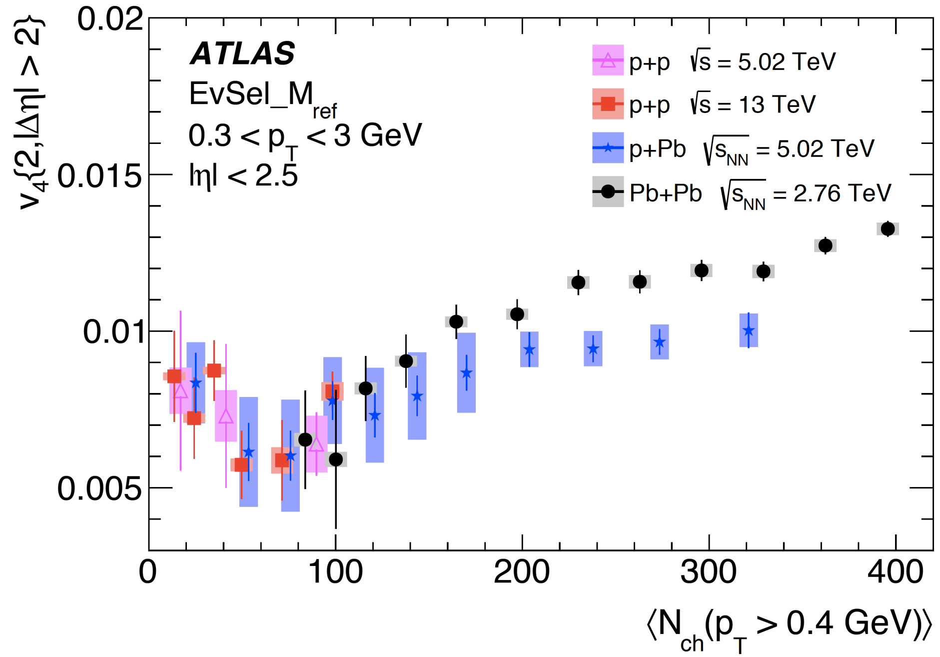
Summary

- Harmonics v_2, v_3 and v_4 were obtained from 2PC in 5.02 and 13 TeV pp, and in 5.02 and 8.16 TeV p+Pb collisions
  - v_n^{pp} are constant with multiplicity and energy
  - v_n^{p+Pb} increase with multiplicity and are constant with energy
  - Muon v_2^{p+Pb} is smaller than v_2 of charged hadrons by factor 0.6
- In 5.02 & 13TeV pp, multi particle cumulants, $c_2\{4\}$, are positive
  ➔ collective effects may be "hidden" by "non-flow" correlations
  - Sub-event cumulants method suppresses "non-flow" effects and allows to calculate $v_2\{4\}$ in pp collisions
  - $v_2\{4\}$ in pp and p+Pb are almost independent of N_{ch} and $\sqrt{s_{NN}}$
- In 5.02 TeV p+Pb and 2.76 TeV Pb+Pb collisions collectivity is supported by $v_2\{2,|\Delta\eta|>2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ measurements
  - $v_2\{4\}$, $v_2\{6\}$ $v_2\{8\}$ are similar and smaller than $v_2\{2,|\Delta\eta|>2\}$
    ➔ significant fluctuations in the initial geometry

v_3 and v_4 Harmonics

Two-particle correlations with pseudorapidity gap, |Δη|>2





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- $v_3\{2,|\Delta\eta|>2\}$ is similar for p+Pb and Pb+Pb collisions
- $v_3\{2,|\Delta\eta|>2\}^{pp} < v_3\{2,|\Delta\eta|>2\}$ for p+Pb and Pb+Pb collisions

- $v_4\{2,|\Delta\eta|>2\}$ is similar for p+Pb and Pb+Pb collisions, for $N_{ch}<120$
- For $N_{ch} > 120$: $v_4\{2,|\Delta\eta|>2\}^{pPb} < v_4\{2,|\Delta\eta|>2\}^{PbPb}$