WPCF2018

Measurement of long range azimuthal correlations in proton-proton and proton-lead collisions with ATLAS

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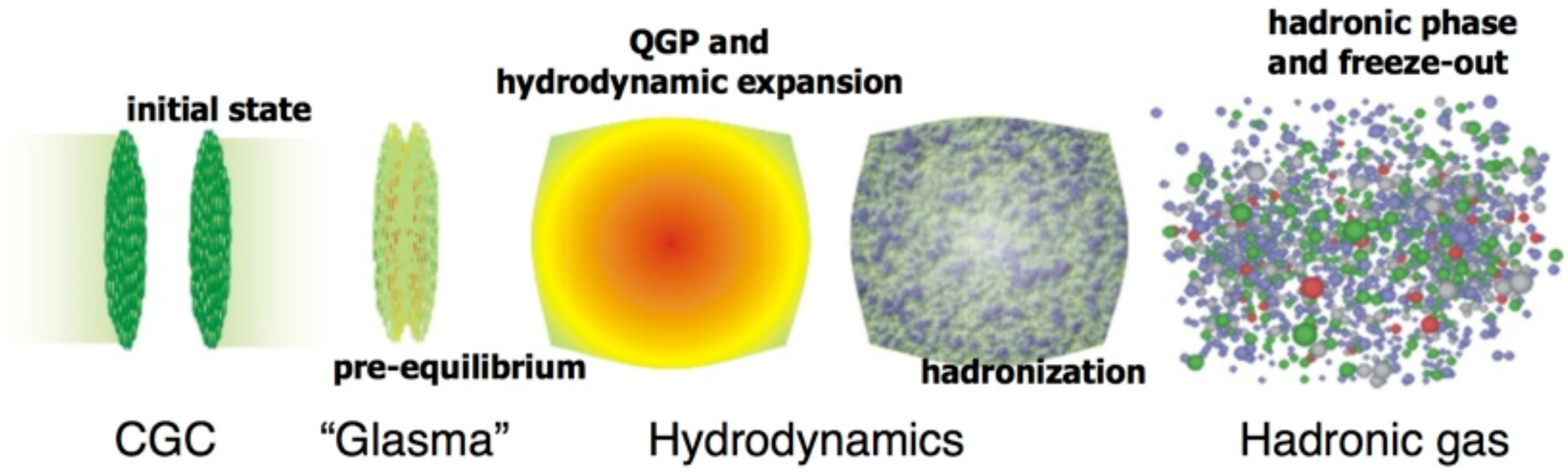
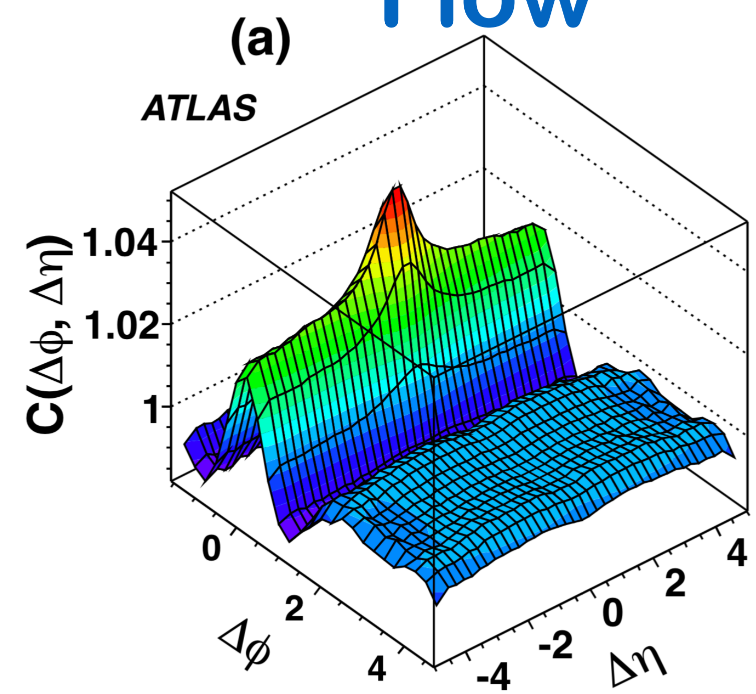
Stony Brook University

For the ATLAS Collaboration

23rd May, 2018

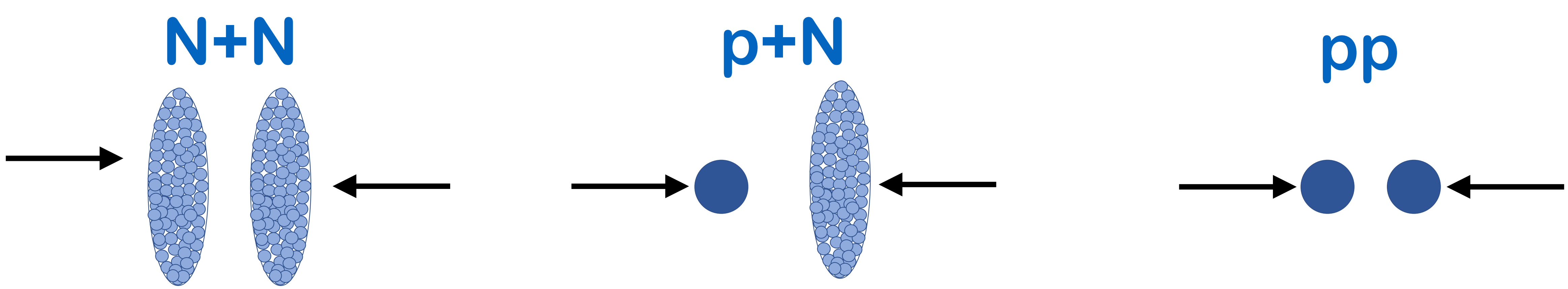
Large vs Small system





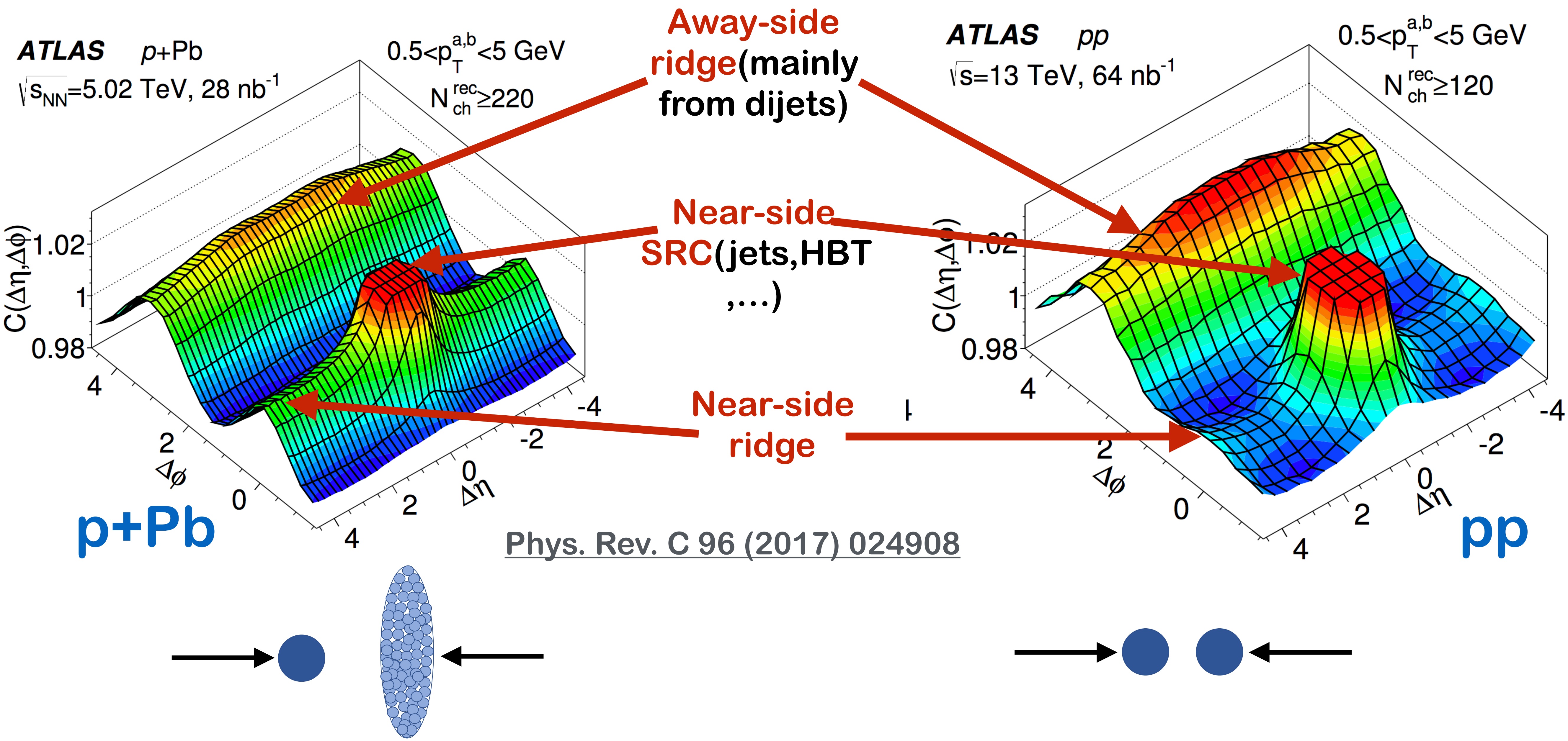
Phys.Rev. C 86 (2012) 014907

- N+N - QGP formation and collective expansion
- **Will the picture be same in small system???**



- Relatively very small created medium in p+Pb and pp
- **Expectation - No QGP and collective expansion in small system!!!**

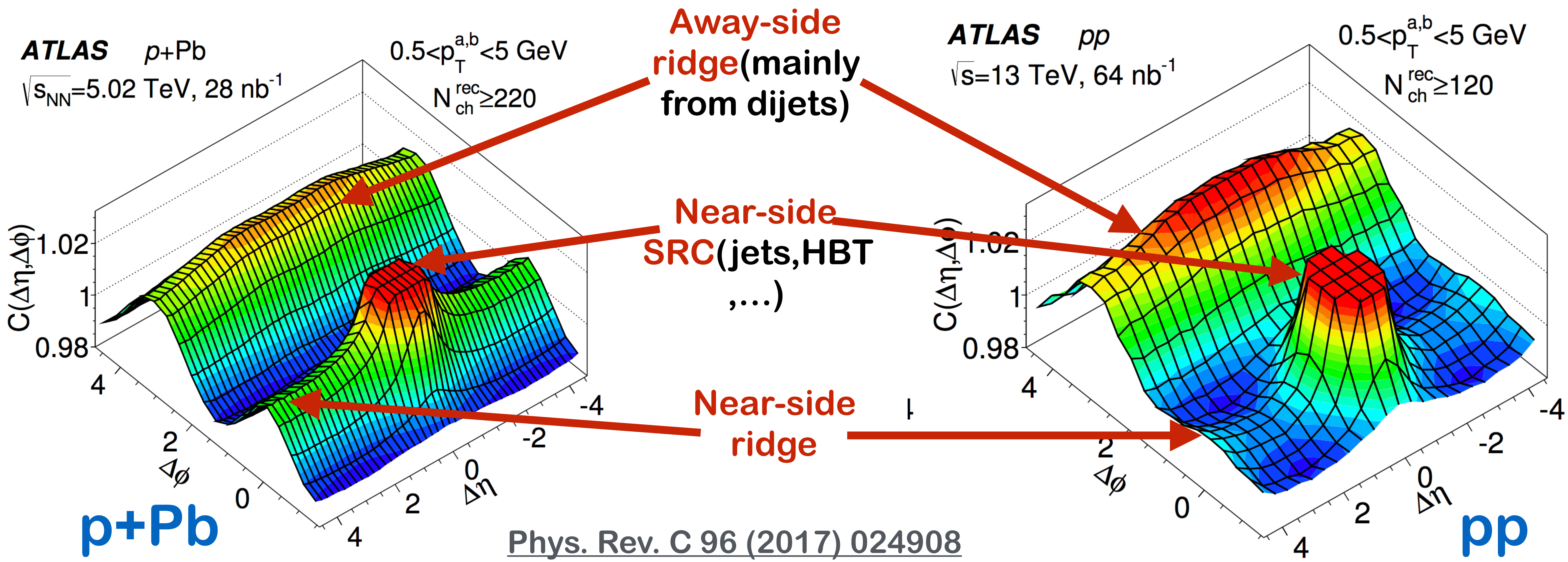
Ridge in Small System



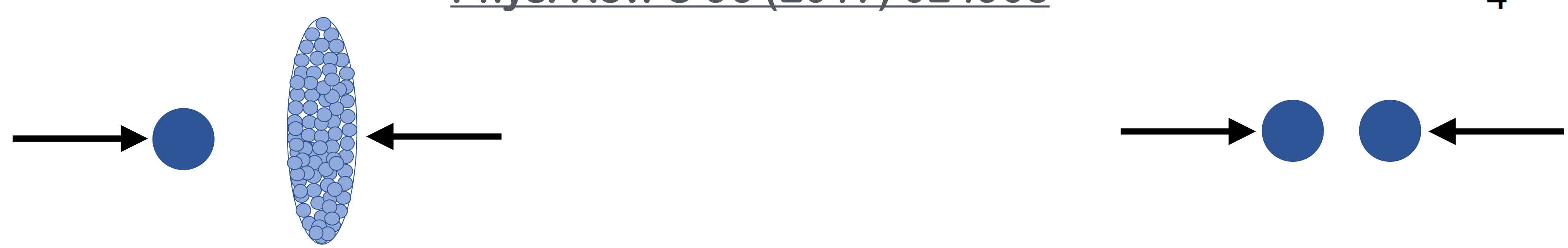
Phys. Rev. C 96 (2017) 024908

- Long-range azimuthal correlation observed in both pp and p+Pb
- Both system show near-side and away-side ridge

Ridge in Small System



Phys. Rev. C 96 (2017) 024908

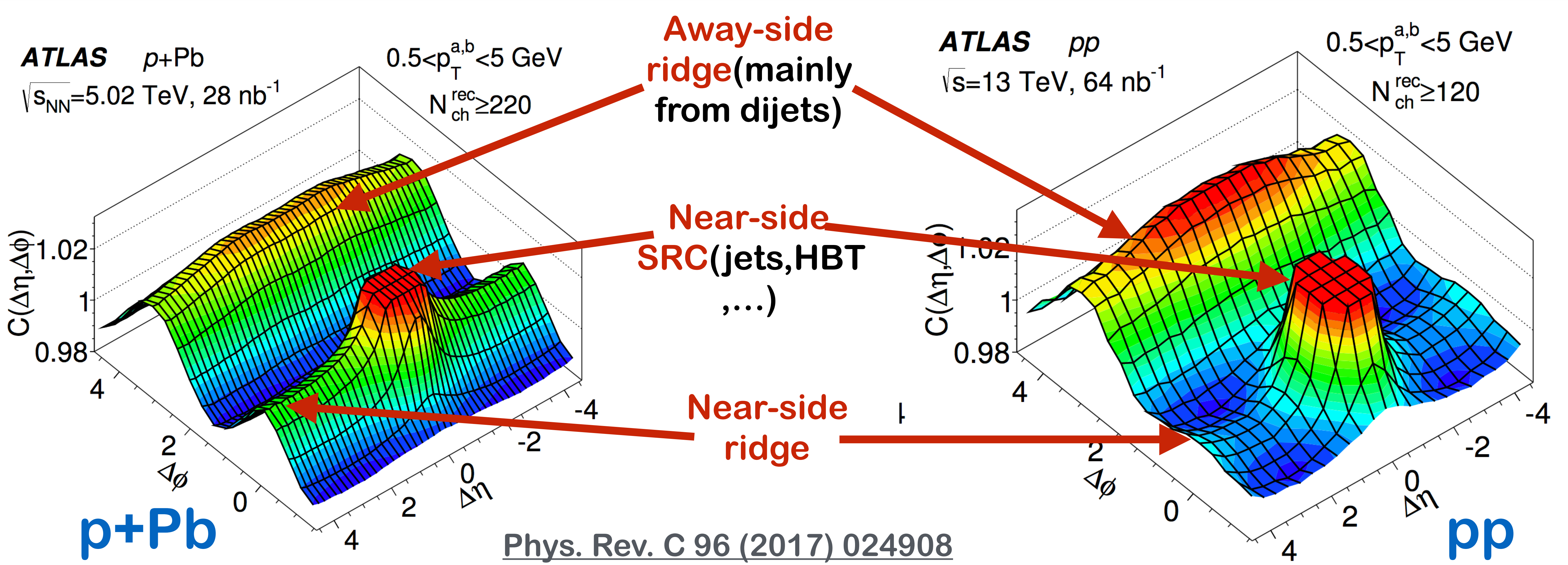


- Long-range azimuthal correlation observed in both pp and p+Pb
- Both system show near-side and away-side ridge

Is QGP droplet present in small system? How to turn off QGP?

What's the underlying physics?

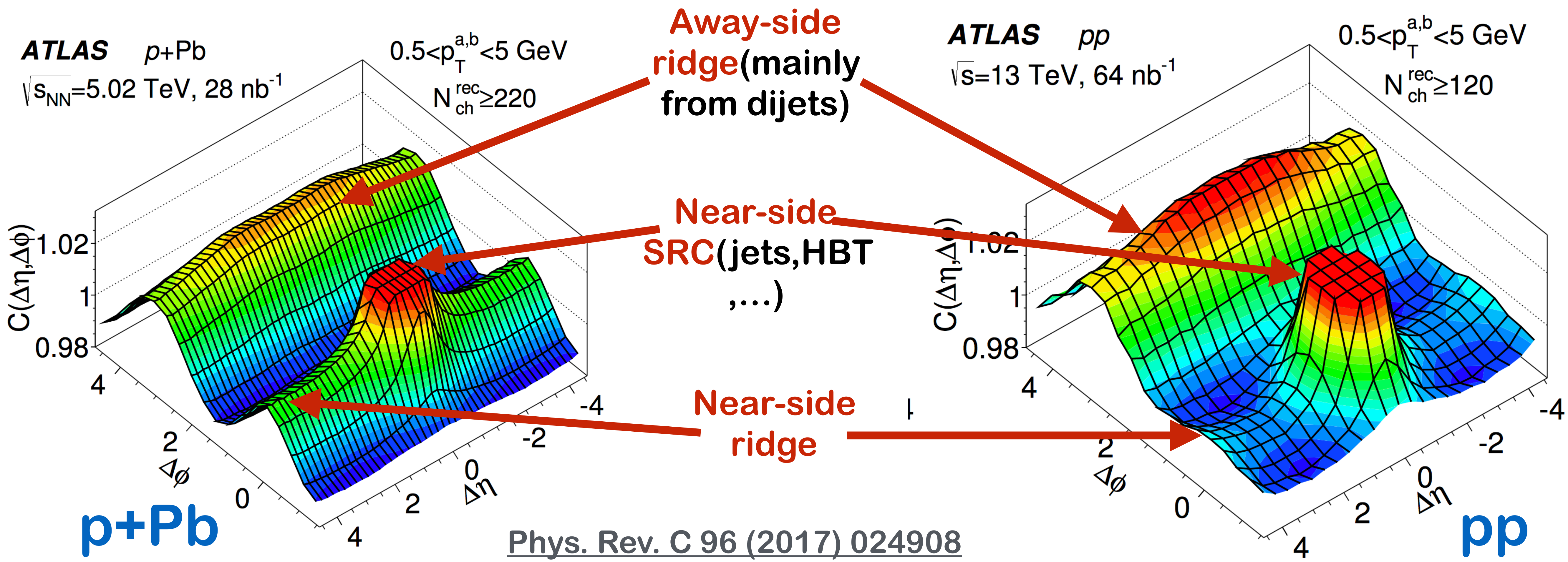
Non-flow in Ridge



Phys. Rev. C 96 (2017) 024908

- Non-Flow can contribute to both SRC(decays,single jets,HBT,etc) and LRC(dijets)
- Detailed investigation of the correlation and non-flow is very important

Non-flow in Ridge



Phys. Rev. C 96 (2017) 024908

- Non-Flow can contribute to both SRC(decays,single jets,HBT,etc) and LRC(dijets)
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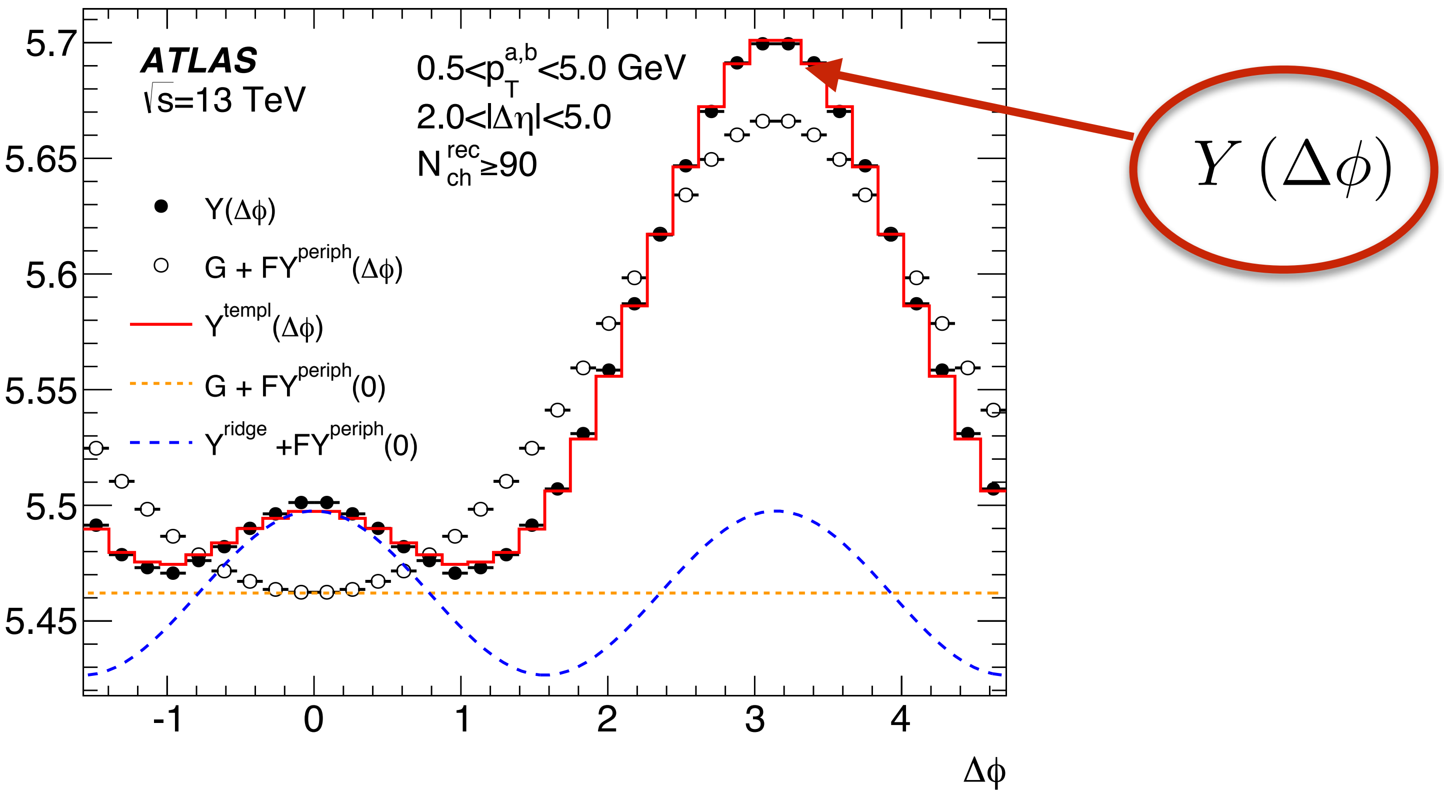
How to remove non-flow? Is there collectivity in small system?

Improved Template Fit

Template Fit

Phys. Rev. C 96 (2017) 024908



Improved Template Fit

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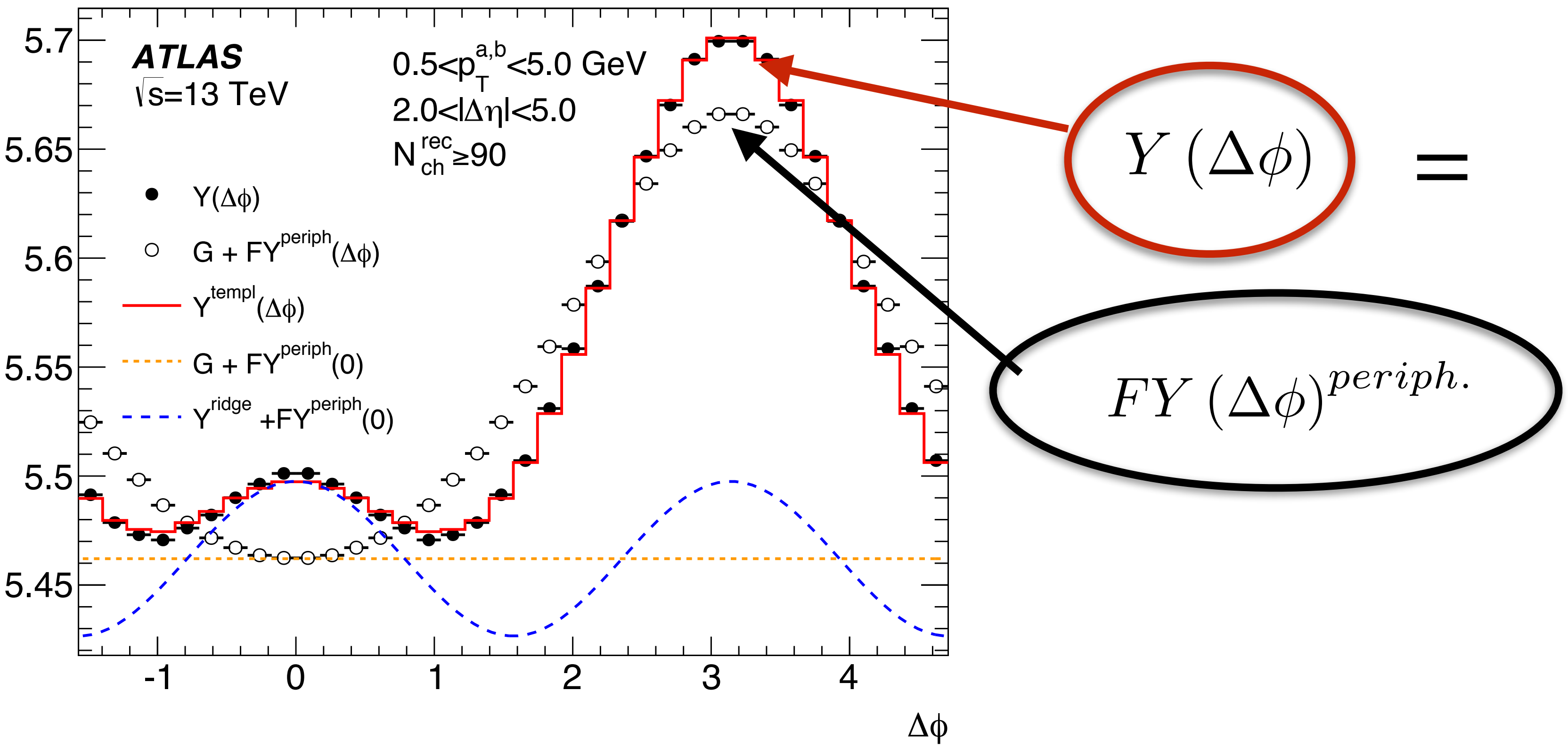
Phys. Rev. C 96 (2017) 024908



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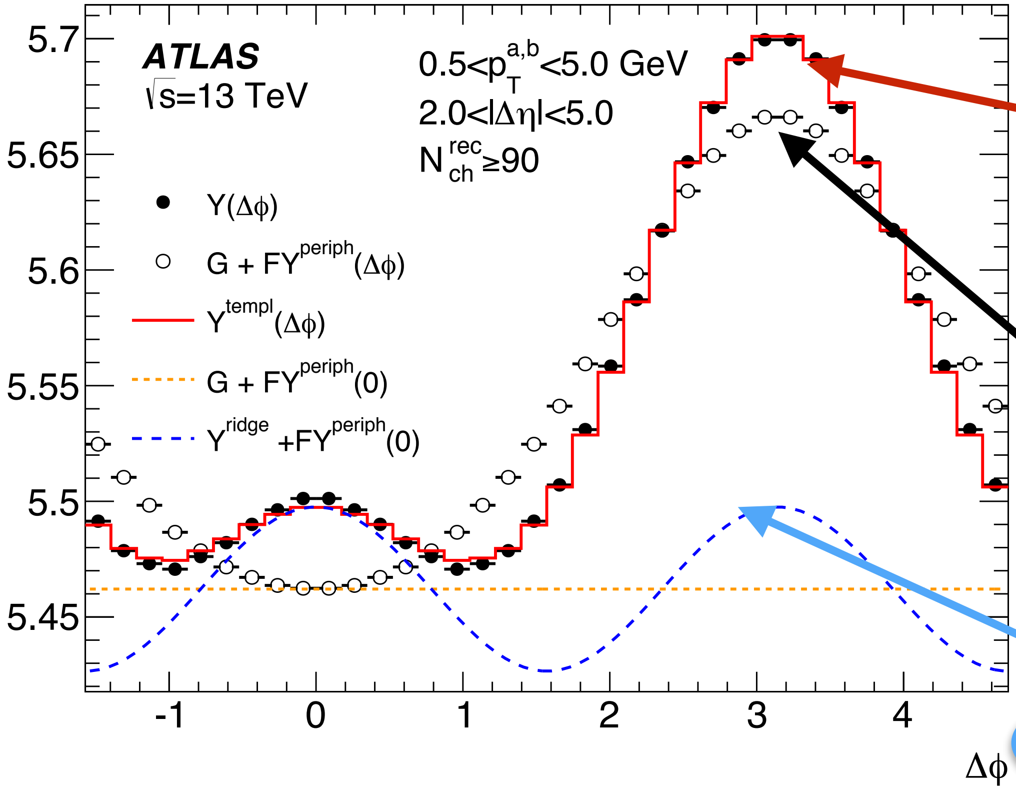
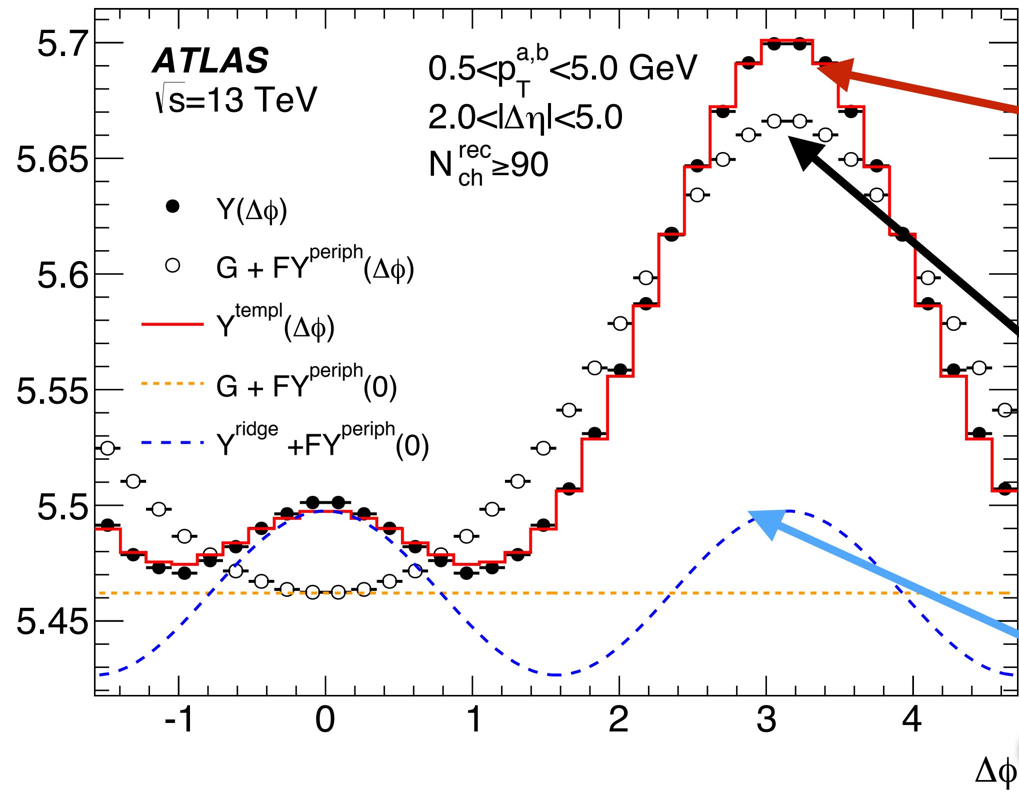


$$Y\left(\Delta\phi\right) = FY\left(\Delta\phi\right)^{periph.} + G^{templ.}\left(1 + 2\sum_{n=2}^{\infty} v_n\{2, templ.\}^2 cos\, n\Delta\phi\right)$$

Improved Template Fit

Template Fit

Phys. Rev. C 96 (2017) 024908



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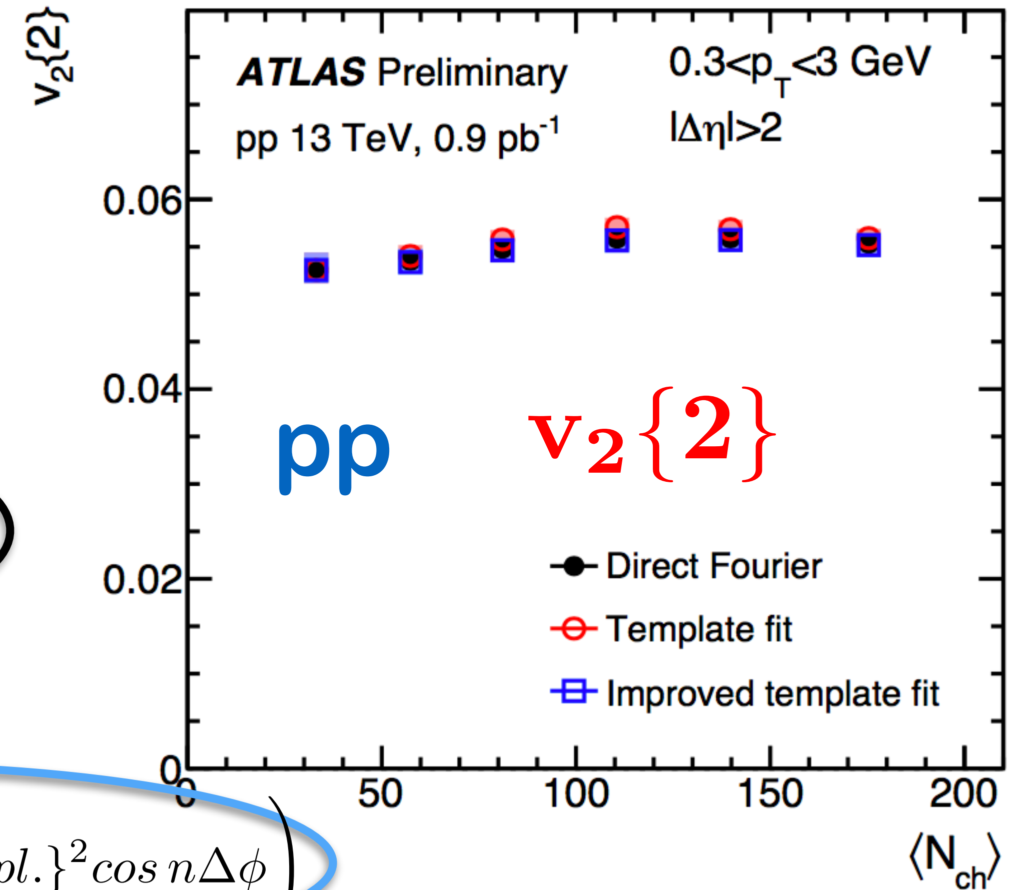

Improved Template Fit

- Bias - $v_n\{2\}^2$ can change with N_{ch}

$$v_n\{2\}^2 = v_n\{2,templ.\}^2 - \frac{FG^{periph.}}{G^{cent}}\left(v_n\{2,templ.\}^2 - v_n\{2,periph.\}^2\right)$$

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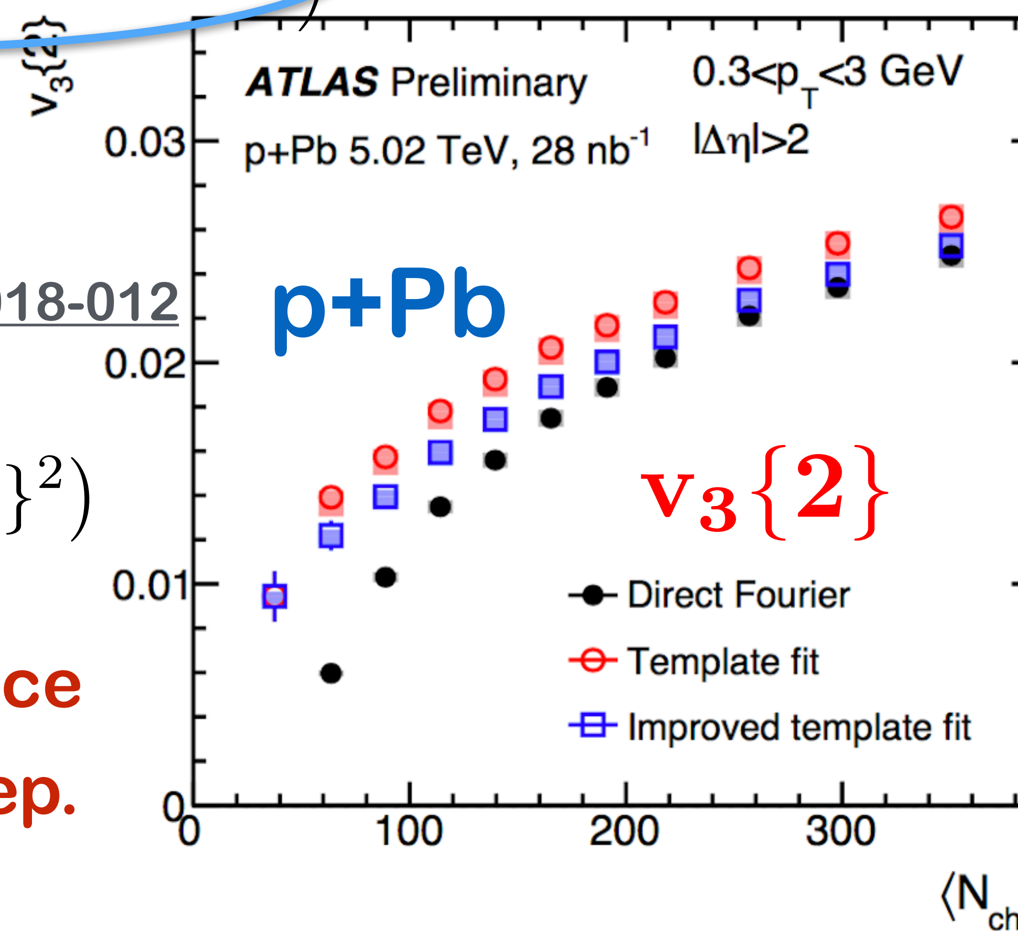
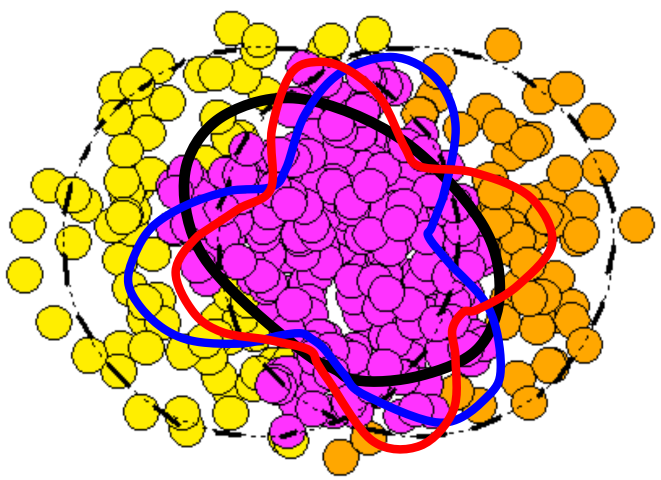
- **Small impact on $v_2\{2\}$ - weak N_{ch} dependence**
- **Significant difference in $v_3\{2\}$ - strong N_{ch} dep.**



Multi-particle Cumulants and Fluctuations

- **Flow fluctuates from event to event -**
  - Initial geometry
  - Hydro-evolution
  - Hadronic interactions



Multi-particle Cumulants and Fluctuations

- **Flow fluctuates from event to event -**
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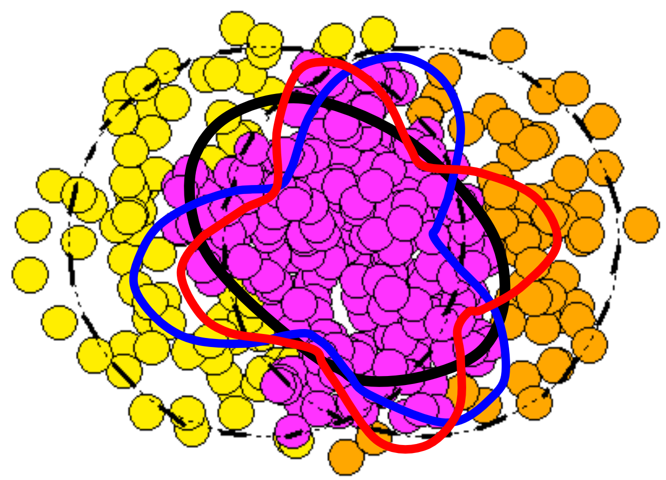
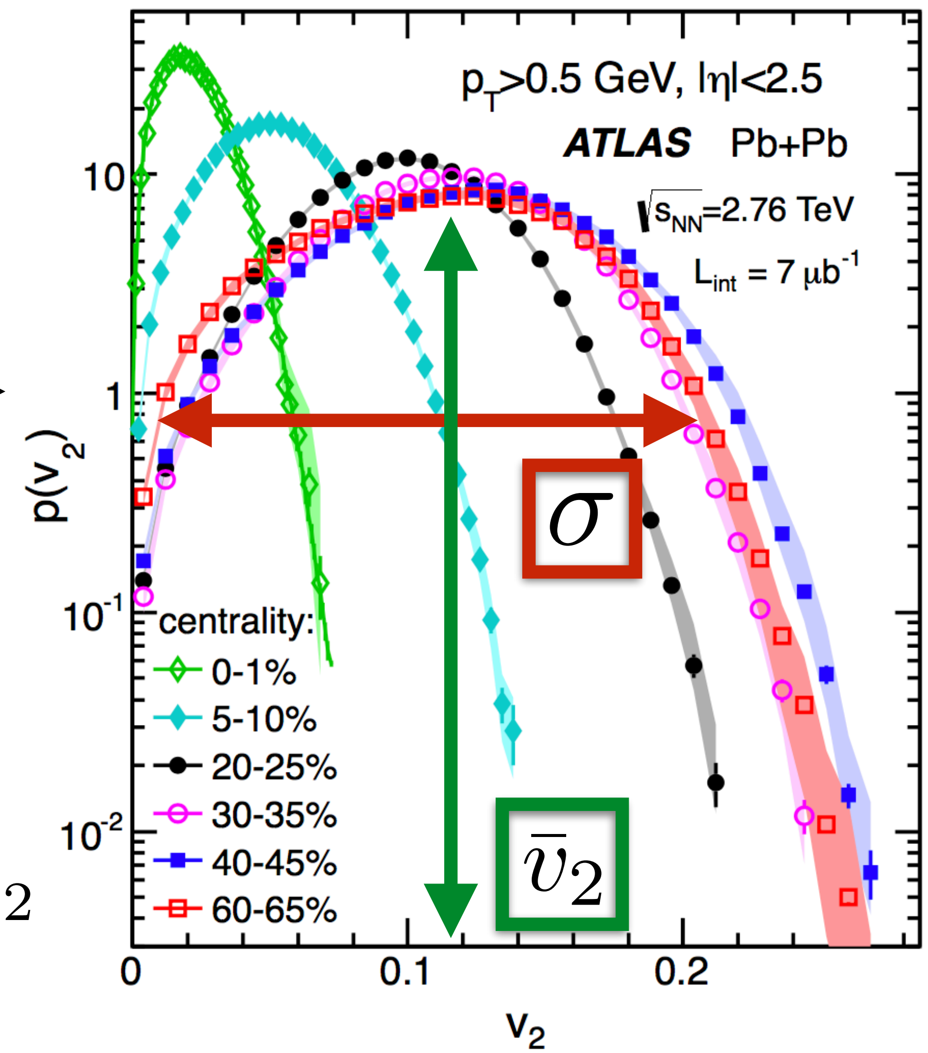
- **Cumulants :**
  - Global nature of correlation
  - Suppress non-flow
  - Measure $p(v_n)$



$$\langle\{4\}_n\rangle = \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle$$

$$c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2$$



- Reference flow : $v_n\{4\} = \sqrt{-c_n\{4\}}$
- For Gaussian flow fluctuations :

$$v_n\{2\} = \sqrt{\bar{v}_n + \sigma^2} \qquad v_n\{4\} = \sqrt{\bar{v}_n - \sigma^2} = v_n\{6\} = v_n\{8\}, \ldots.$$

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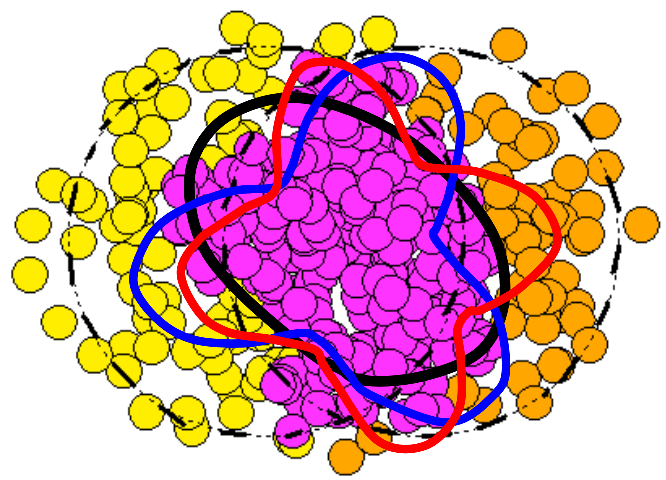

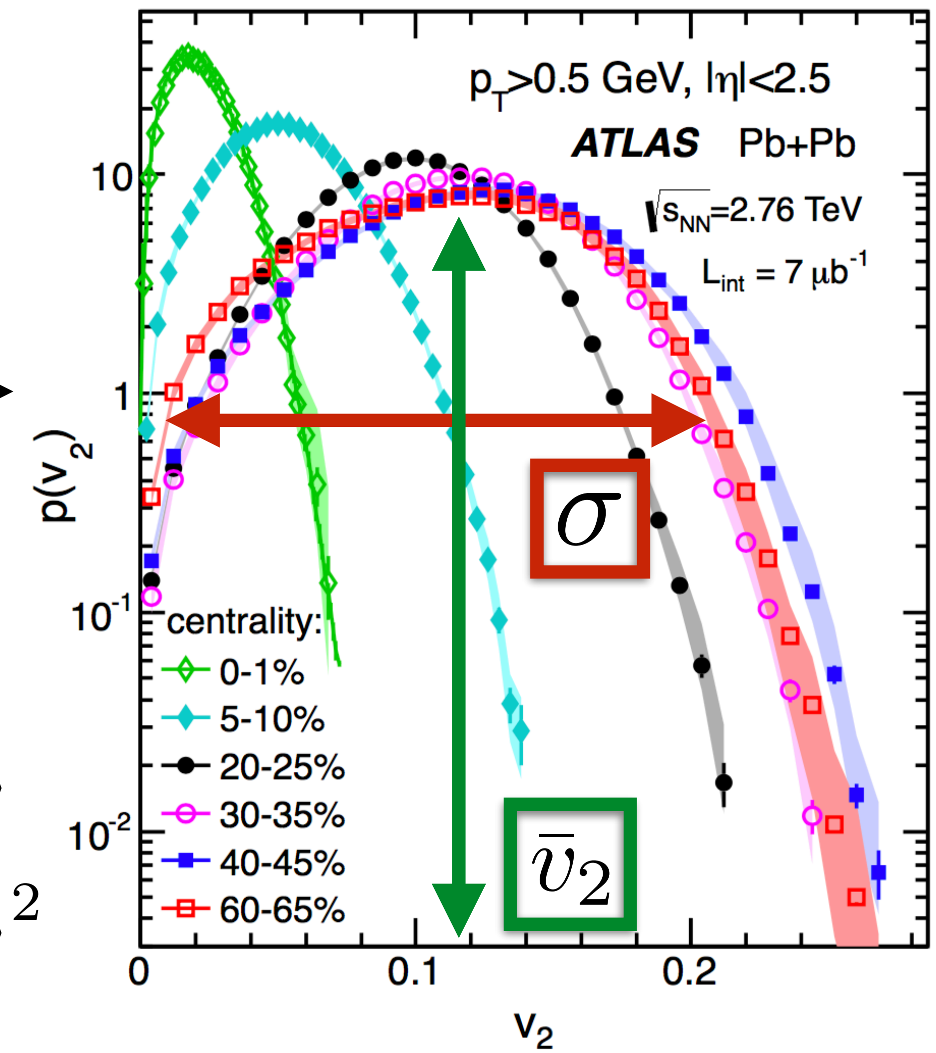

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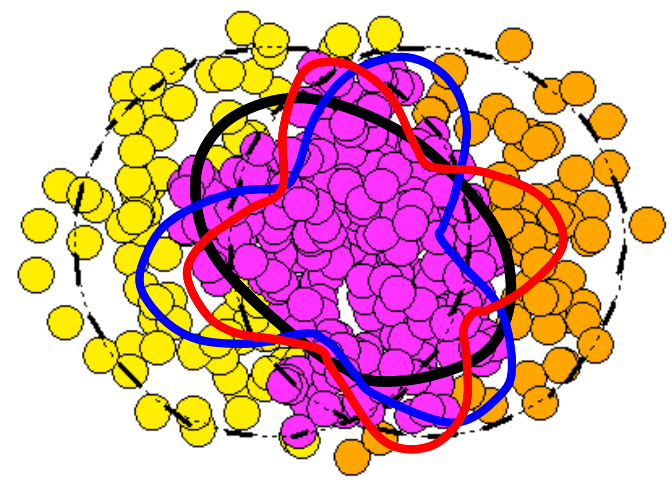

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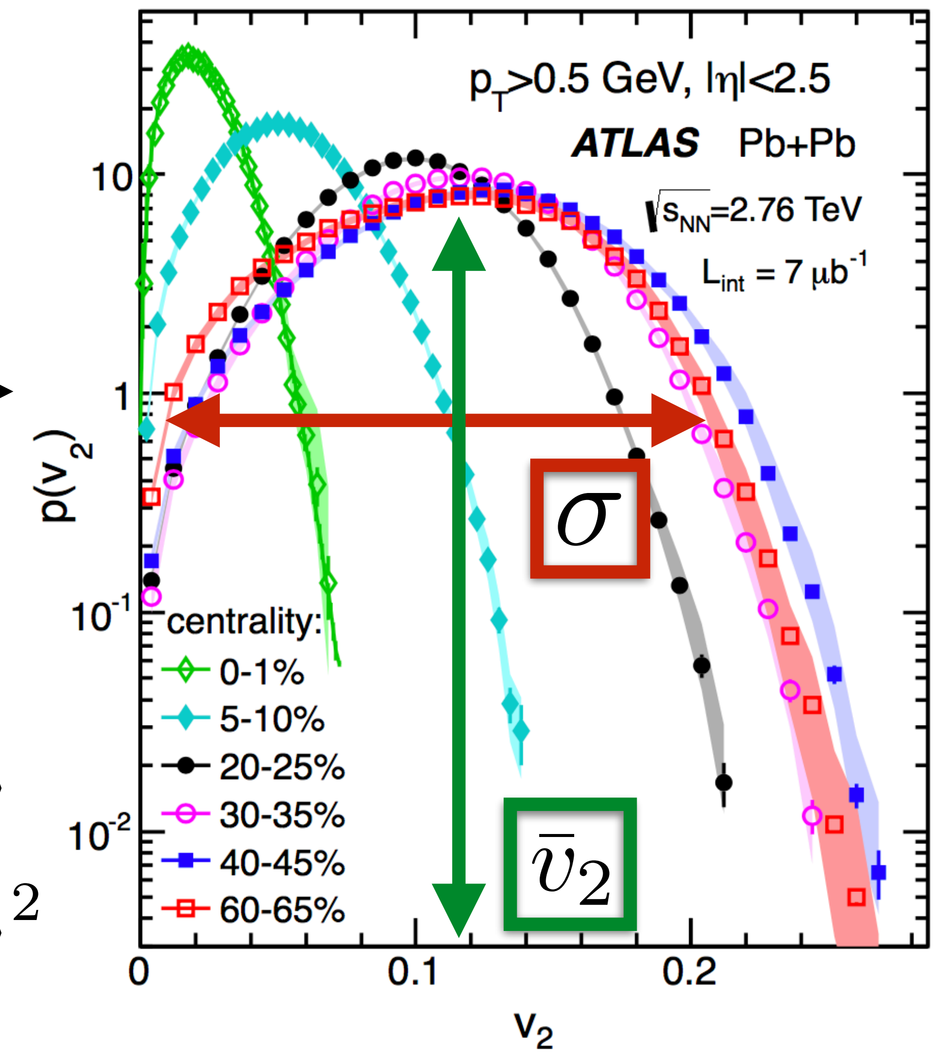

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- **Signature of Collectivity :**

$$\boxed{c_n\{4\} < 0 \quad \& \quad v_n\{2\} > v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}}$$

Cumulant Observables

- 4-particle cumulant : $\langle \{4\}_n \rangle = \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle$ $\quad c_n\{4\} = \langle\langle \{4\}_n \rangle\rangle - 2\langle\langle \{2\}_n \rangle\rangle^2$
- Mixed harmonics Correlation : correlation among different flow harmonics

Symmetric Cumulant

$$\langle \{4\}_{n,m} \rangle = \langle e^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)} \rangle$$

$$sc_{n,m}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle - \langle\langle \{2\}_n \rangle\rangle \langle\langle \{2\}_m \rangle\rangle$$

$$sc_{n,m}\{4\} = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$

Asymmetric Cumulant

$$\langle \{3\}_n \rangle = \langle e^{i(n\phi_1+n\phi_2-2n\phi_3} \rangle$$

$$ac_n\{3\} = \langle\langle \{3\}_n \rangle\rangle$$

$$ac_n\{3\} = \langle v_n^2 v_{2n} \, cos\, 2n(\Phi_n - \Phi_{2n}) \rangle$$

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$sc_{n,m}\{4\} = \langle\langle\{4\}_{n,m}\rangle\rangle - \langle\langle\{2\}_n\rangle\rangle\langle\langle\{2\}_m\rangle\rangle$	$ac_n\{3\} = \langle\langle\{3\}_n\rangle\rangle$
$sc_{n,m}\{4\} = \langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$	$ac_n\{3\} = \langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n})\rangle$

- **Results** :
  - p+Pb low Nch $c_2\{4\}$ has wrong sign
  - pp $c_2\{4\}$ dominated by **non-flow**
  - **No Collectivity in pp?**

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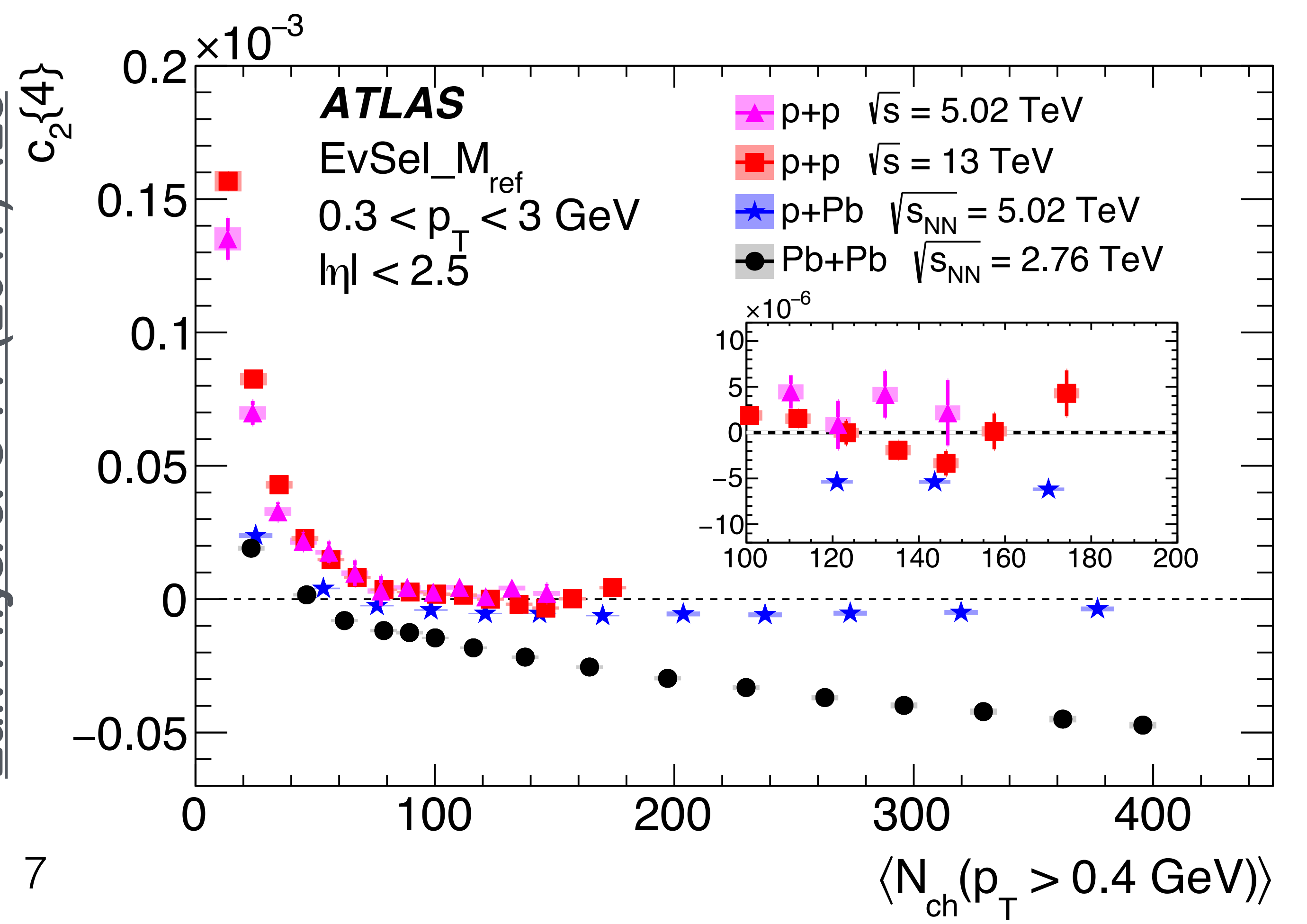
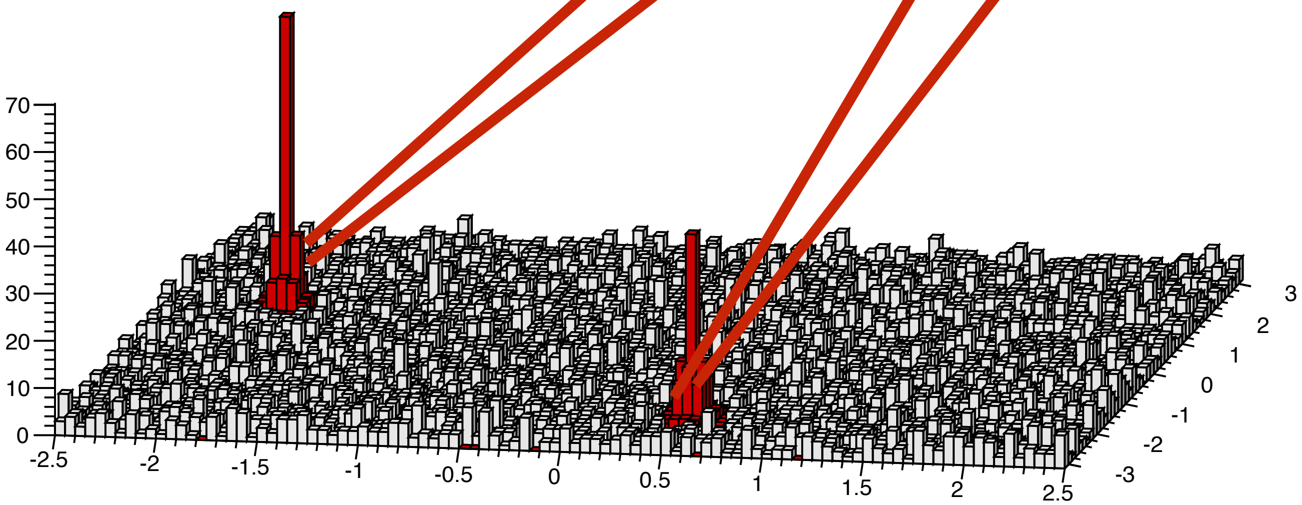


Subevent Method for Cumulants

- Subevents in pseudorapidity used to remove non-flow correlations

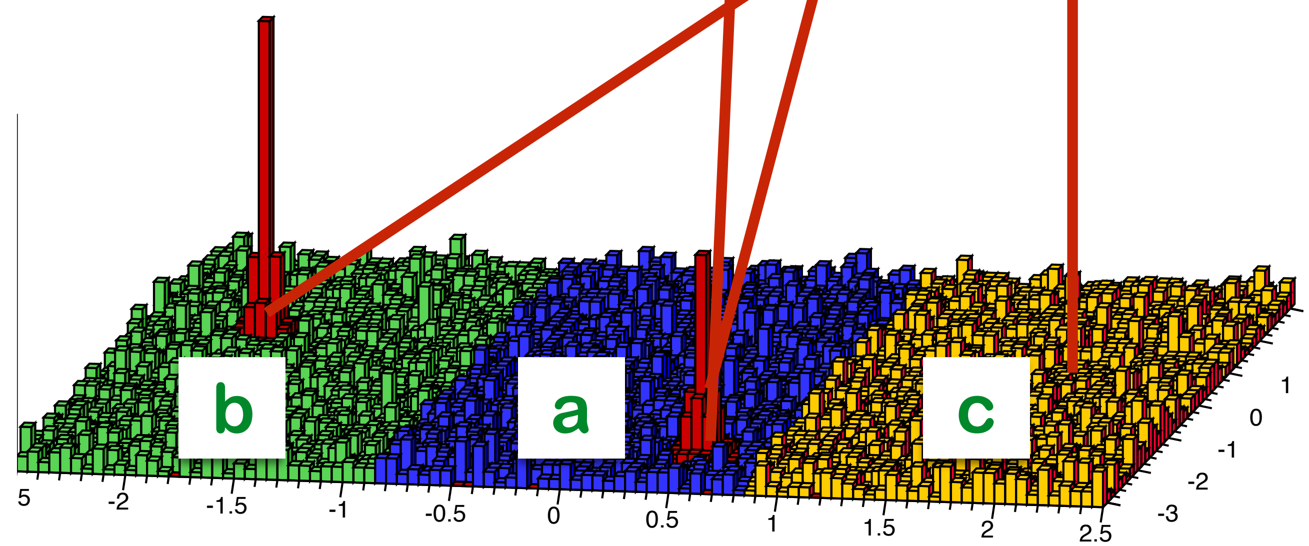
Standard

$$\langle\{4\}_n\rangle = \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\rangle$$



3 Subevents

$$\langle\{4\}_n\rangle_{2a|b,c} = \langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)}\rangle$$



- 2-subevent removes **intra-jet** and 3-subevent removes **inter-jet** correlations

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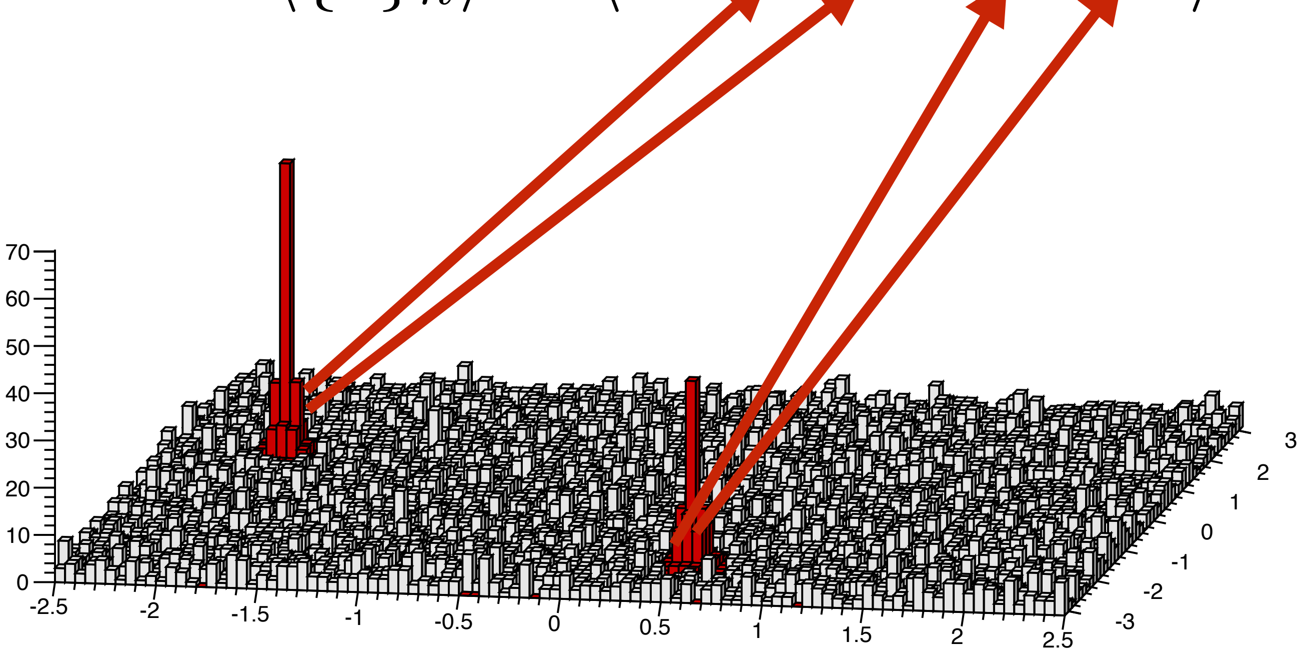

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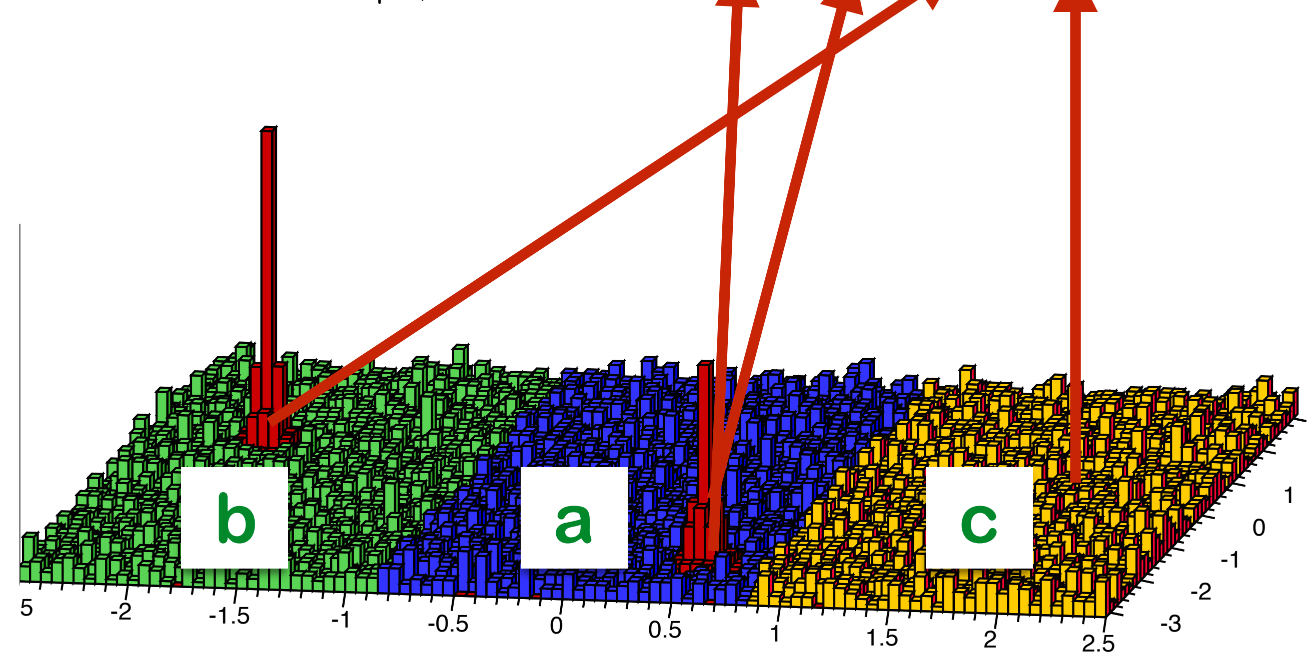

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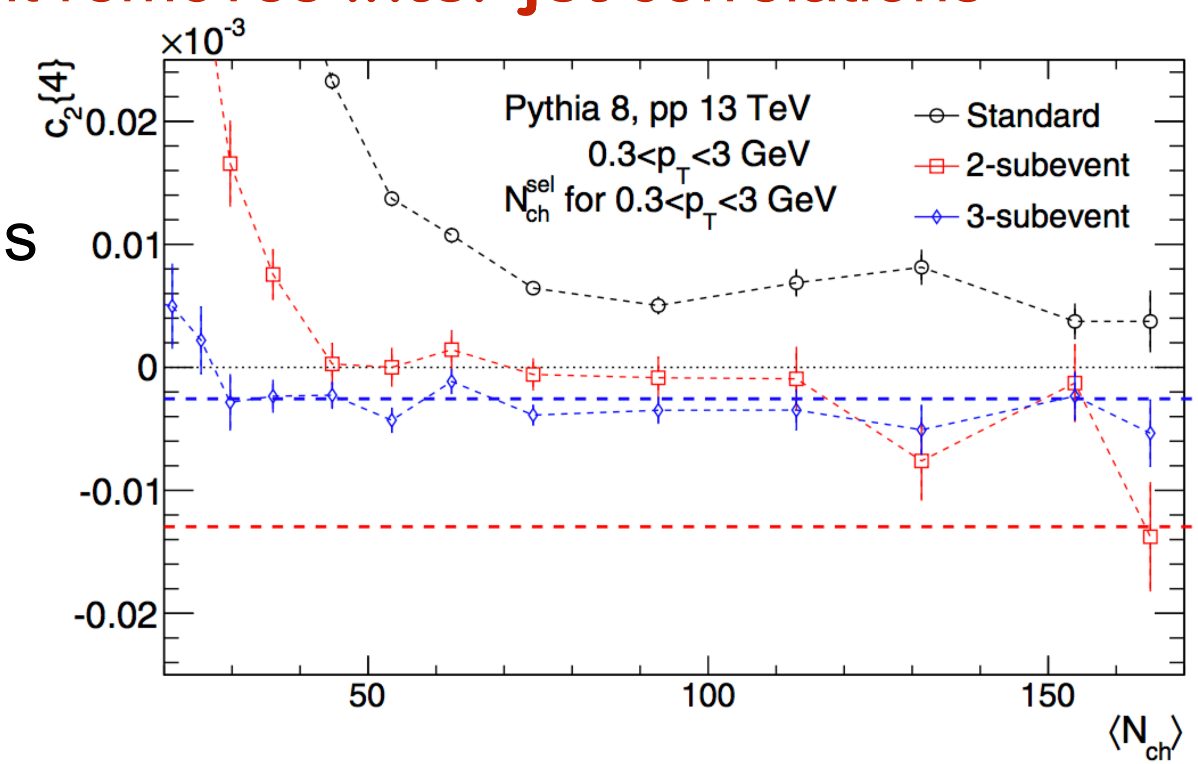
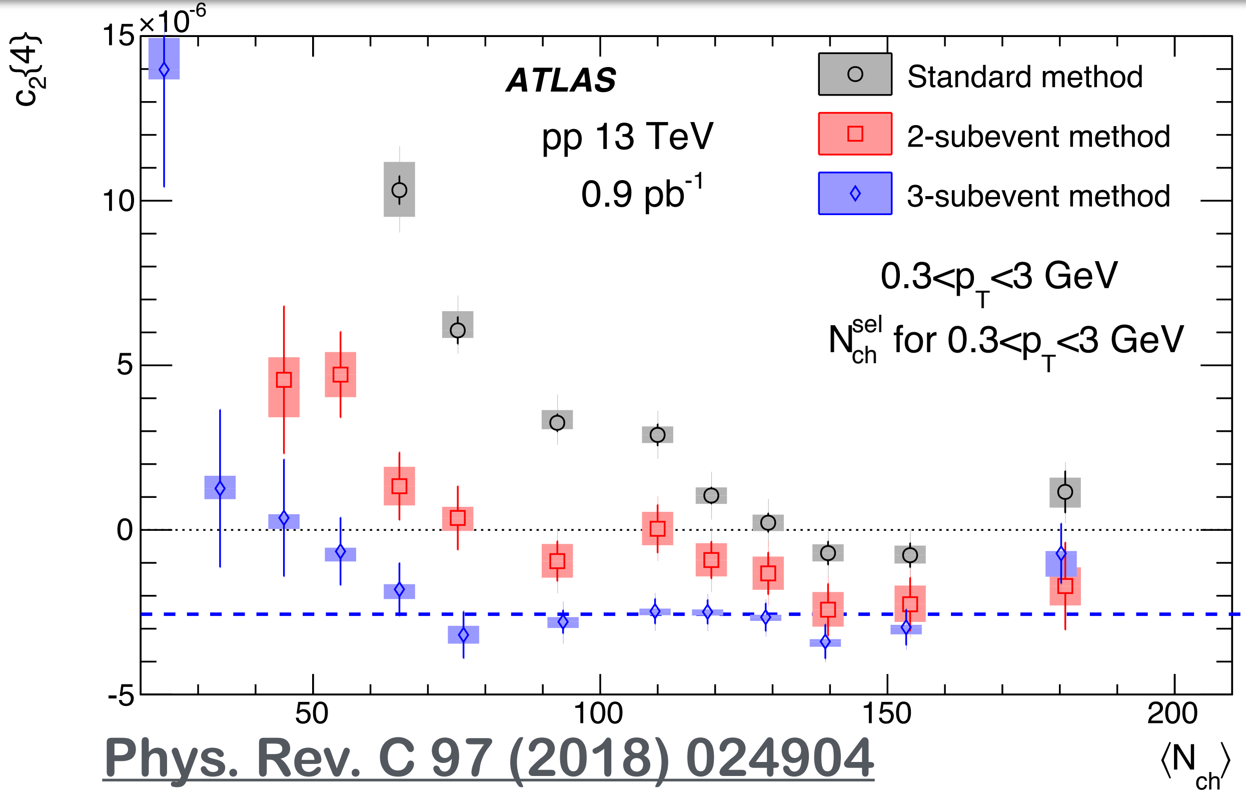
- Performance in Pythia - standard method fails to suppress non-flow



PHYSICAL REVIEW C 96, 034906 (2017)

Results : 4-Particle Cumulant

- Standard cumulant has positive $c_2\{4\}$
  - residual non-flow



Phys. Rev. C 97 (2018) 024904

Results : 4-Particle Cumulant

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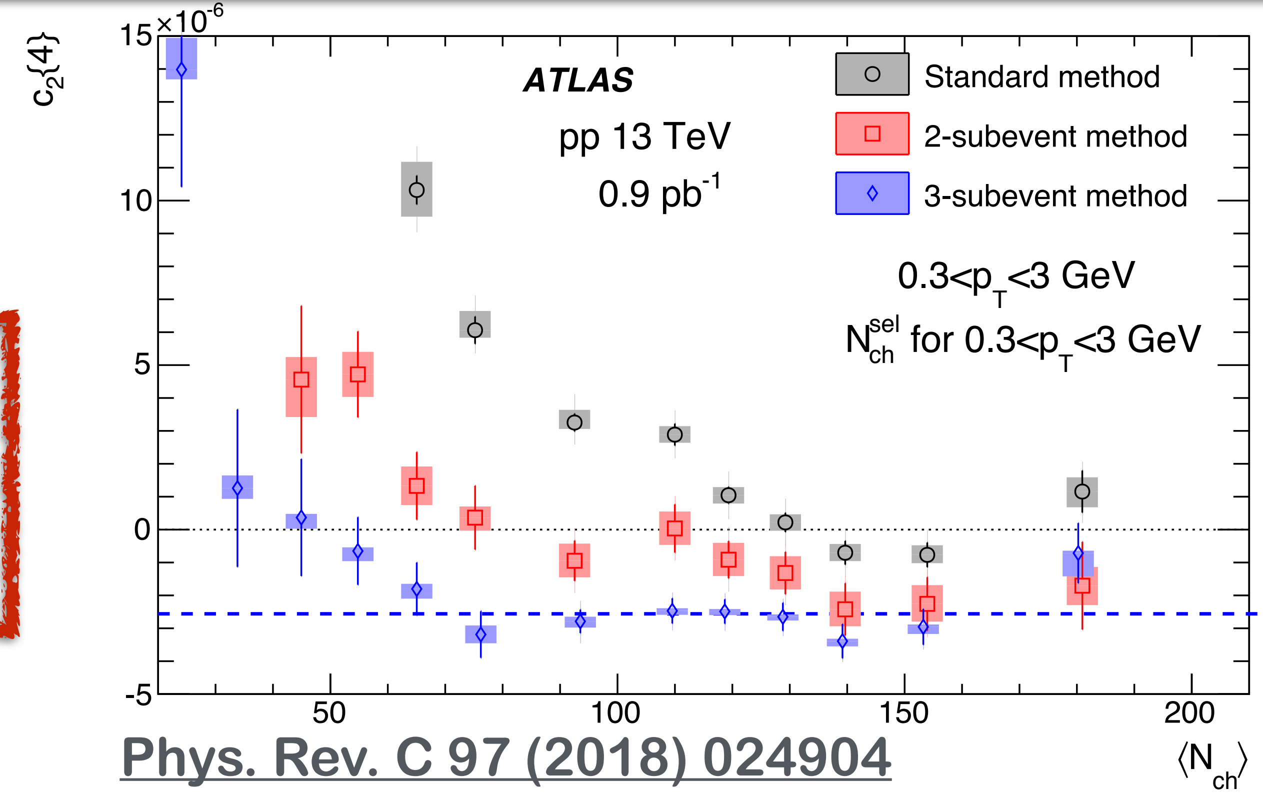
3 Subevent has the highest non-flow suppression and measures 4% flow down to 70 tracks



Phys. Rev. C 97 (2018) 024904

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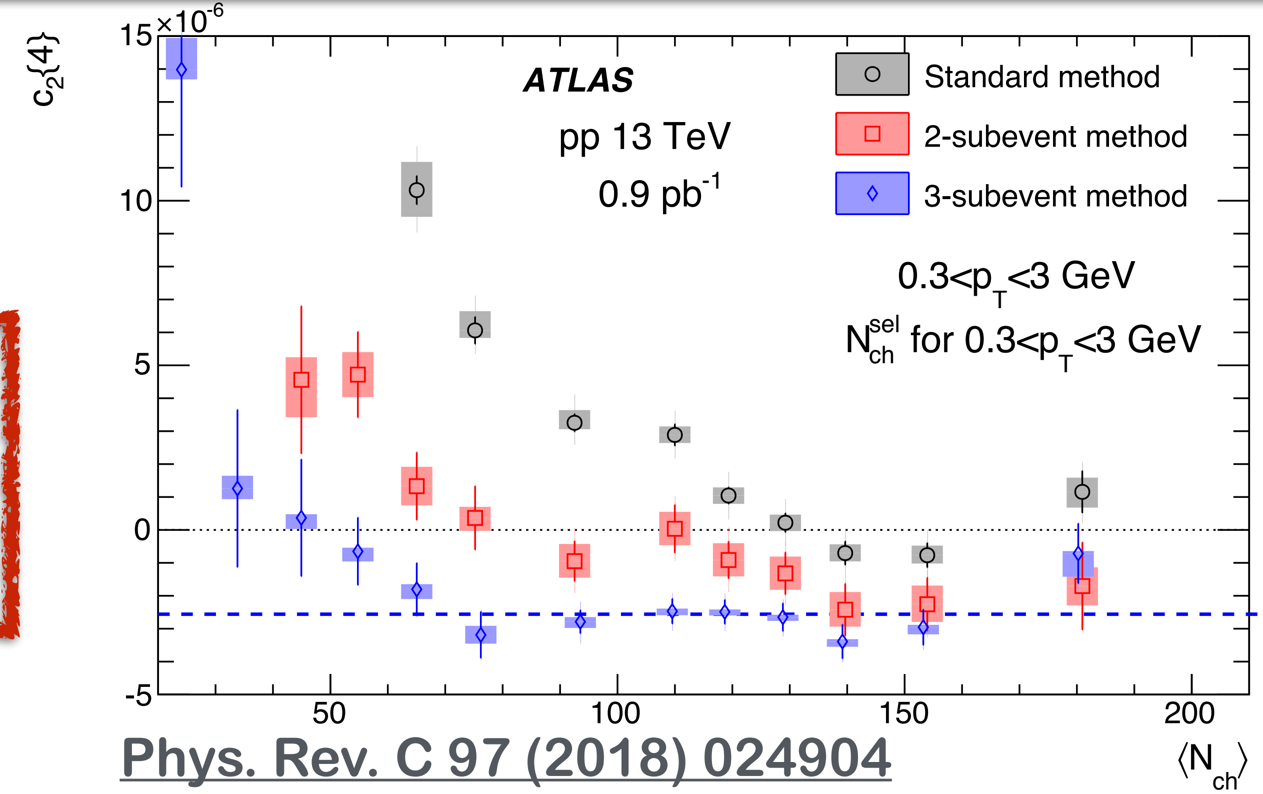
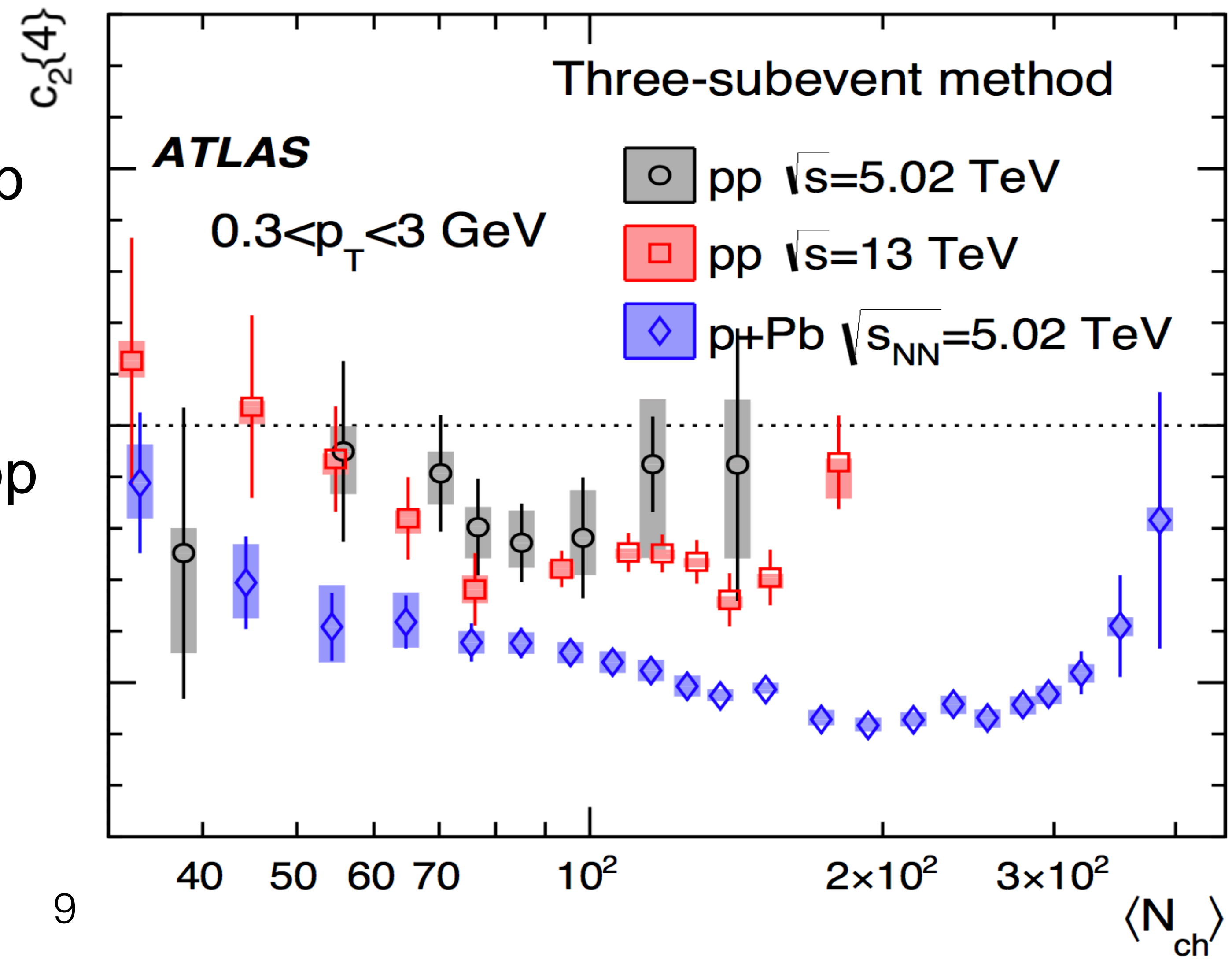


Phys. Rev. C 97 (2018) 024904

- System comparison - 3-Subevent
  - Non-flow suppression in both pp and p+Pb
  - Correct sign both pp and p+Pb
  - Weak energy dependence for pp



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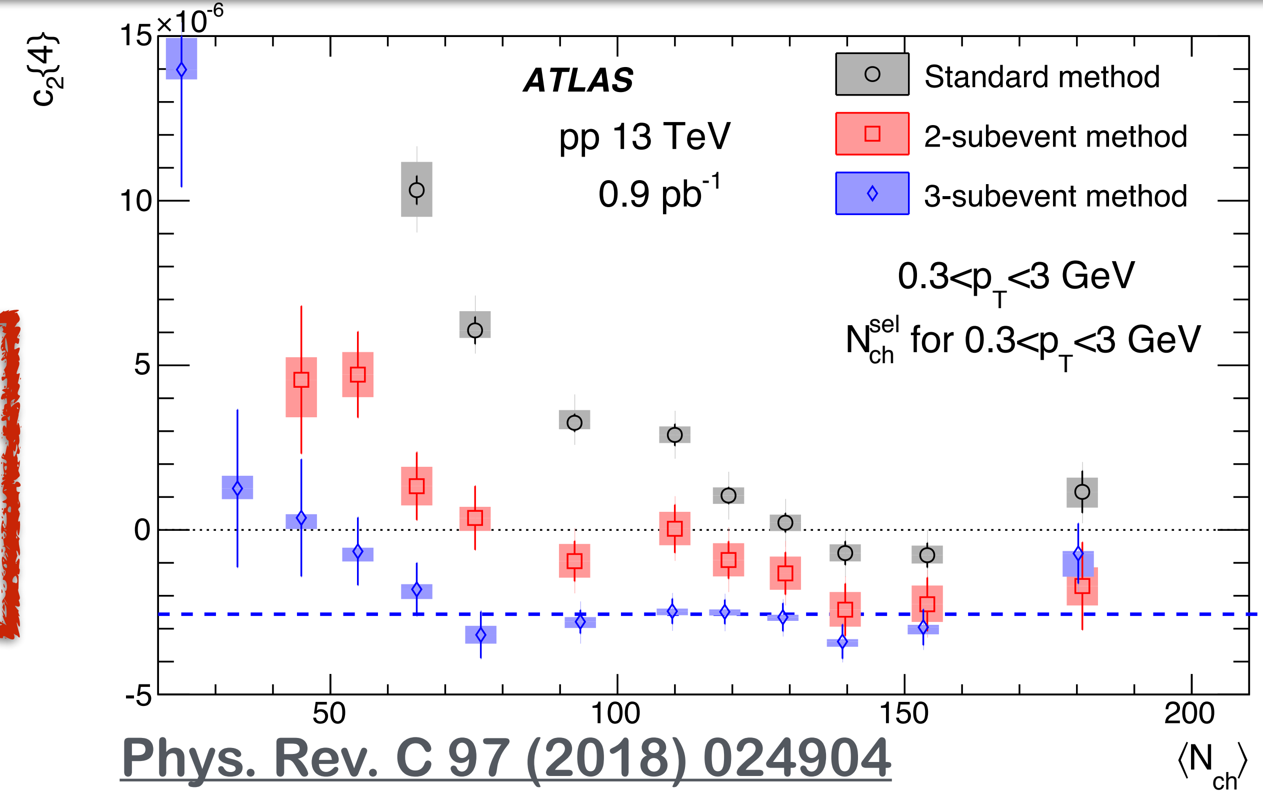

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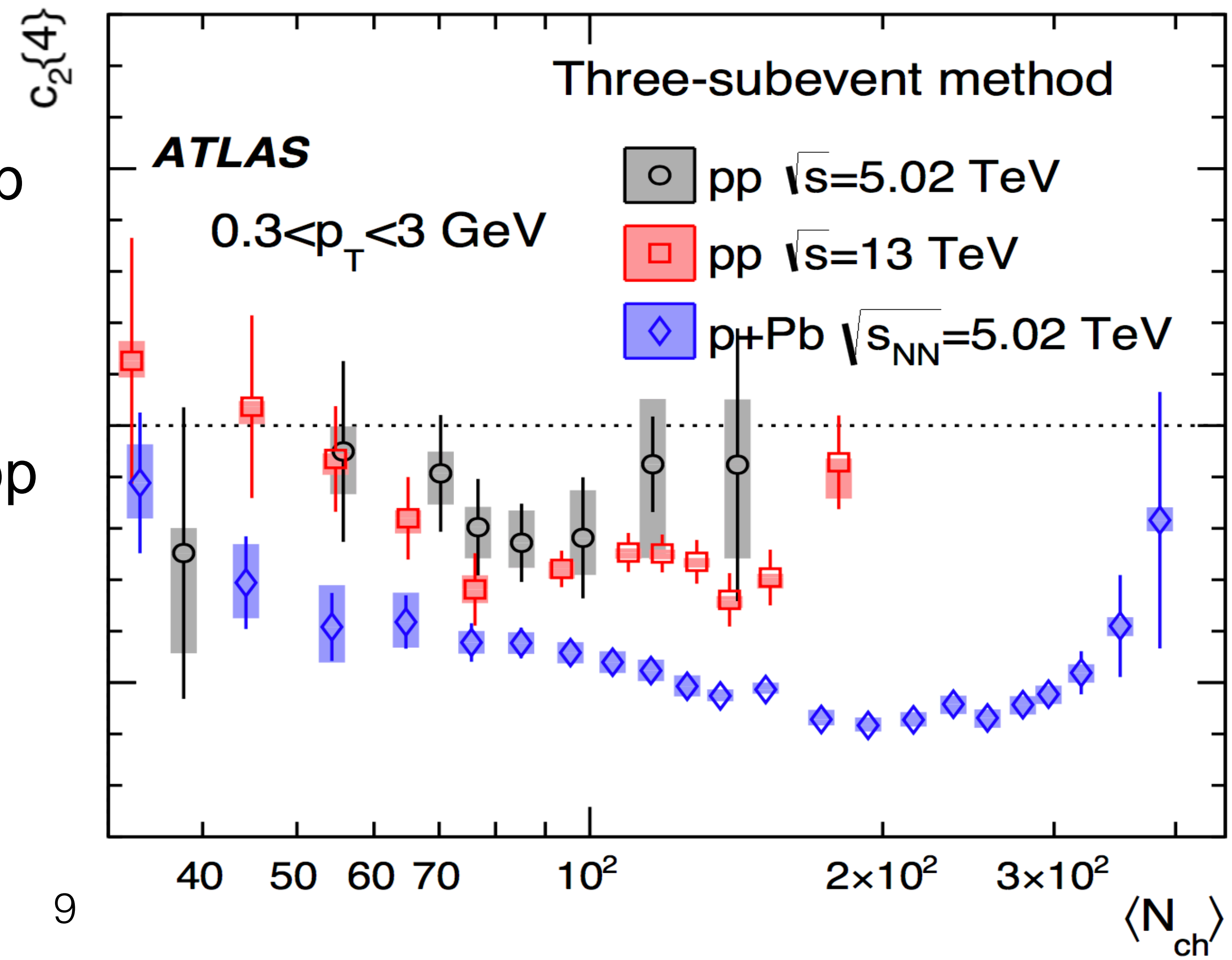
pp also shows signs of collectivity

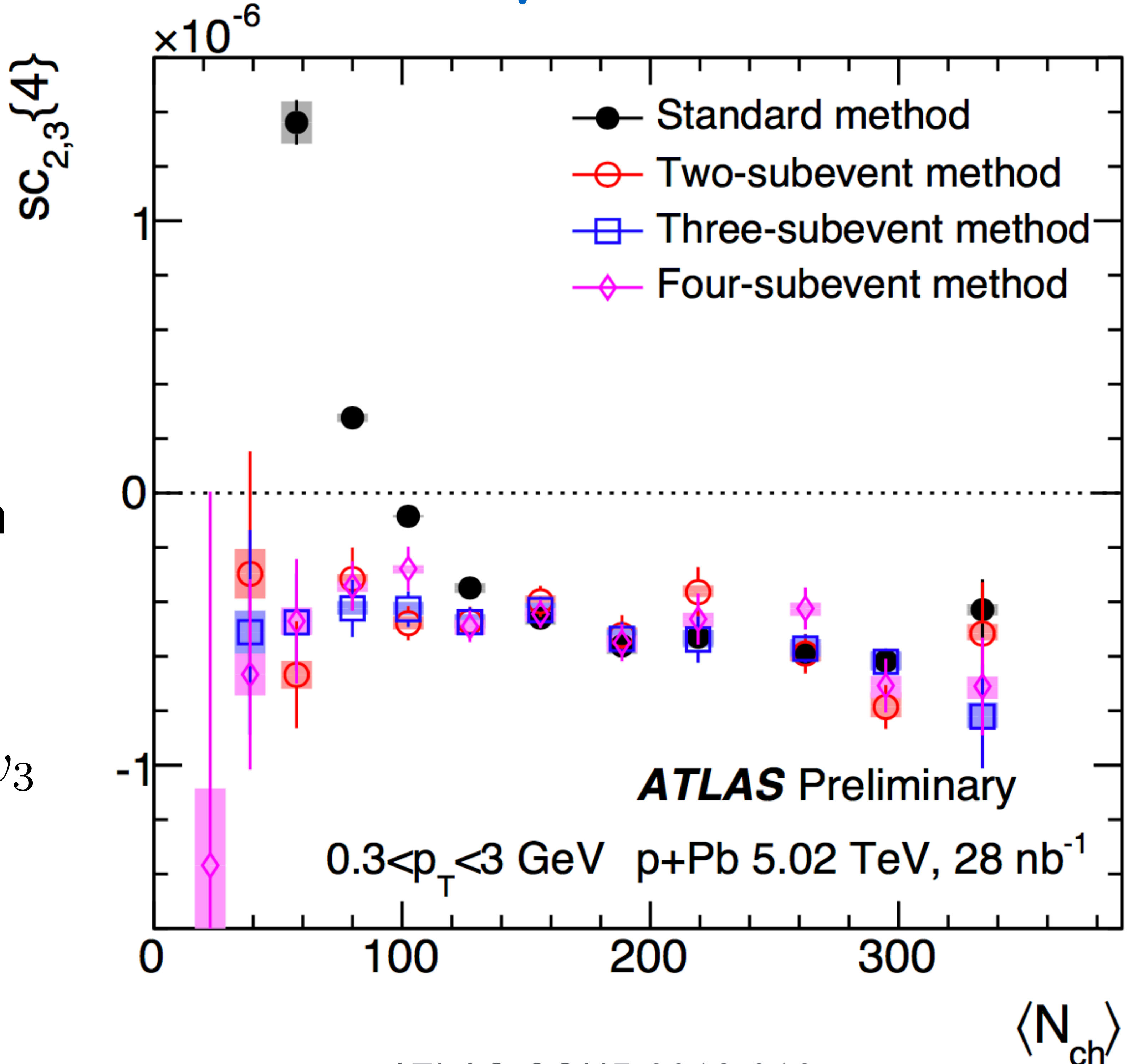


Symmetric Cumulant (2,3)

$$\mathbf{sc_{2,3}\{4\} = \langle v_2^2 v_3^2\rangle - \langle v_2^2\rangle\langle v_3^2\rangle}$$

- At high N_{ch} - all consistent
- N_{ch} <140 - Standard method non-flow dominated
- Non-flow largely suppressed in sub-event method
- **Anti-correlation of v_2 and v_3 in subevent method**

p+Pb



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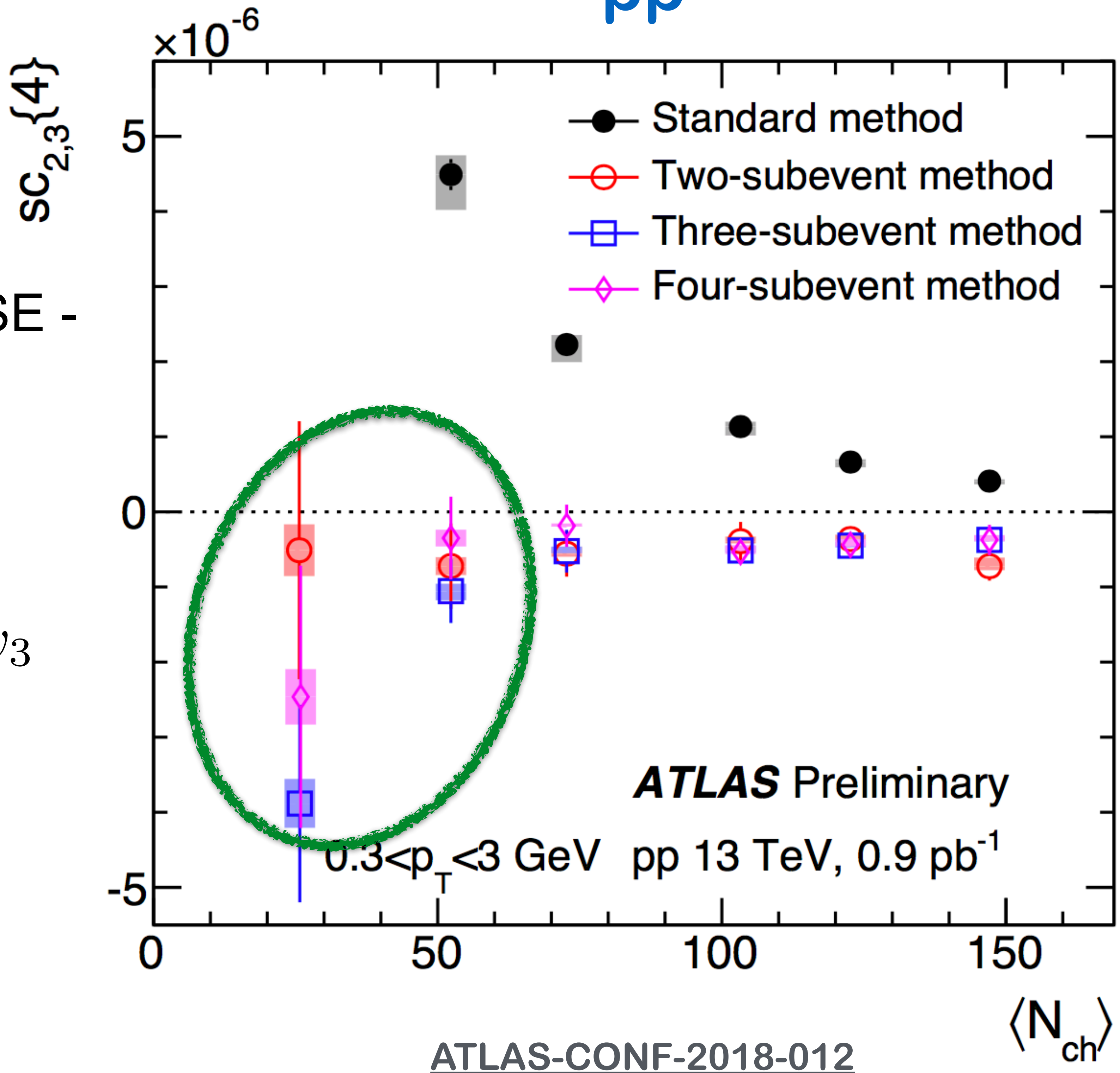
- All N_{ch} - Standard method non-flow dominated
- Difference in 2SE and 3SE/4SE - Residual non-flow in 2SE
- 3SE and 4SE consistent
- **Anti-correlation of v_2 and v_3 in subevent method**

pp



ATLAS-CONF-2018-012

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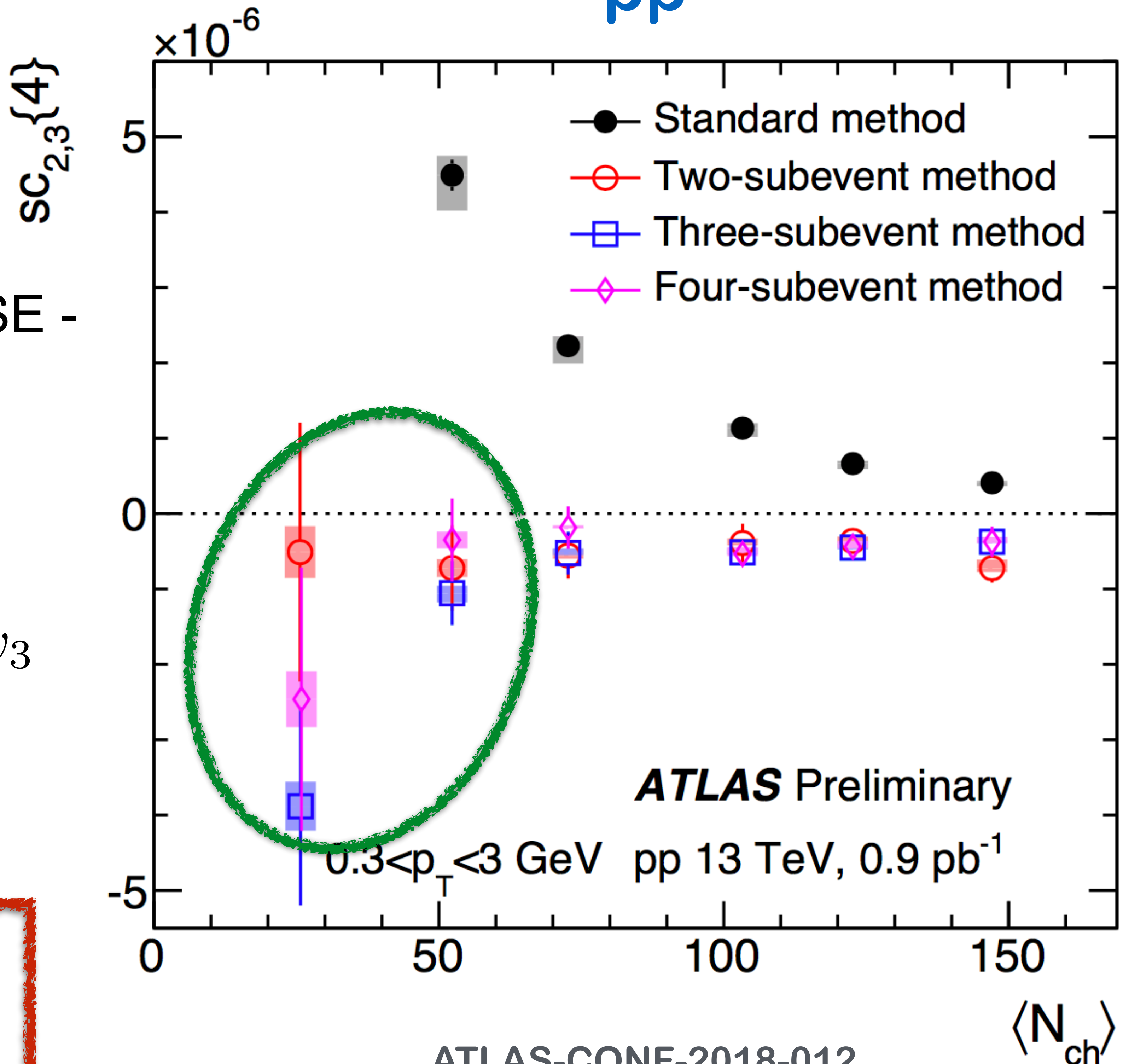
3 Subevent method best choice for non-flow removal

pp



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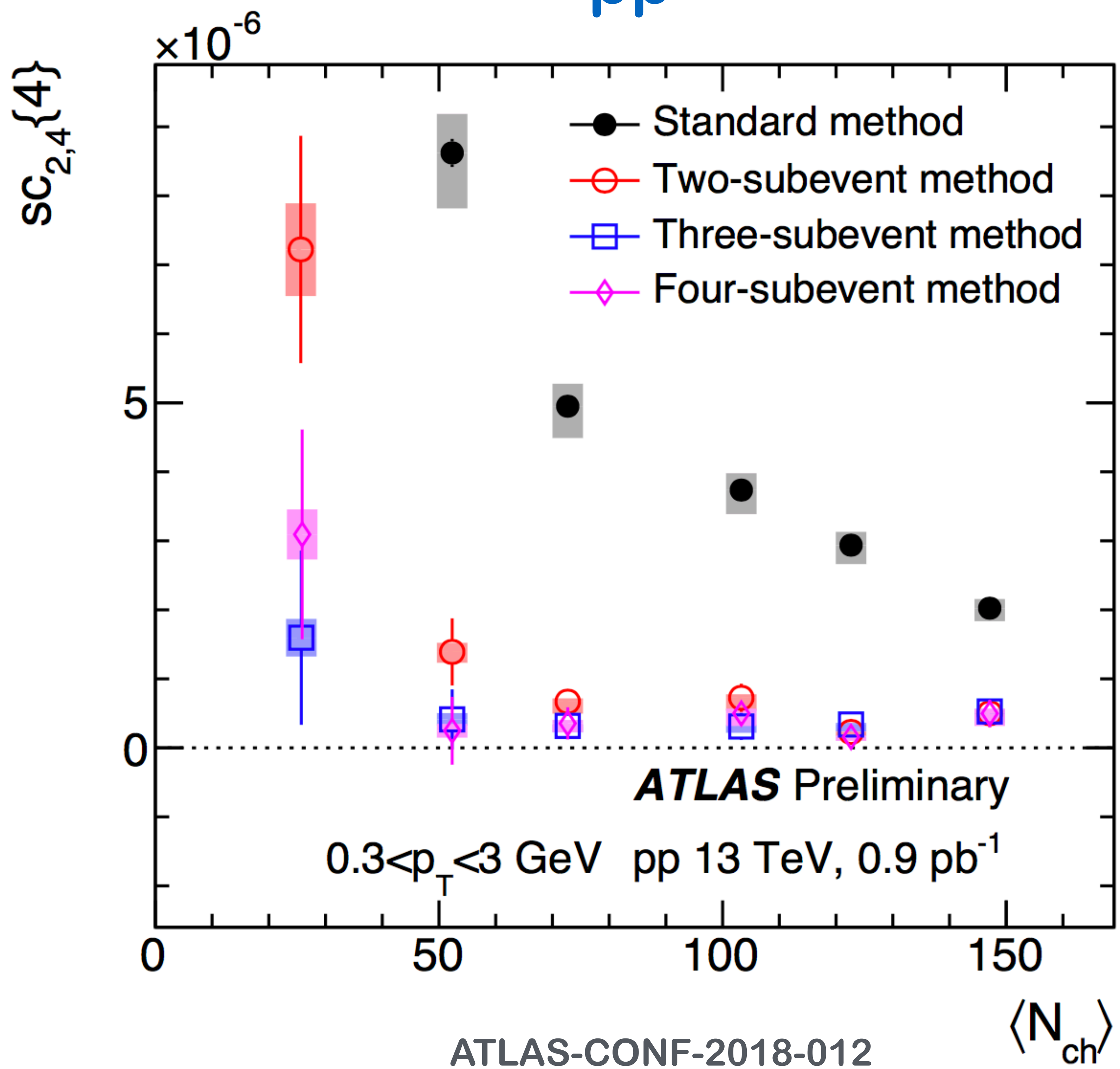
- Standard method non-flow dominated
- Residual non-flow in 2SE
- **Positive correlation between v_2 and v_4 is observed in all methods**
- Manifestation of non-linear effects

$$v_4 = v_{4L} + \chi_2 v_2^2$$

pp



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- Standard method non-flow dominated
- **Positive correlation between v_2 and v_4 is observed in all methods**
- Standard and subevent cumulants dont converge even at high Nch
- **Possible flow decorrelations effects?** v_4 shows stronger decorrelation than v_3

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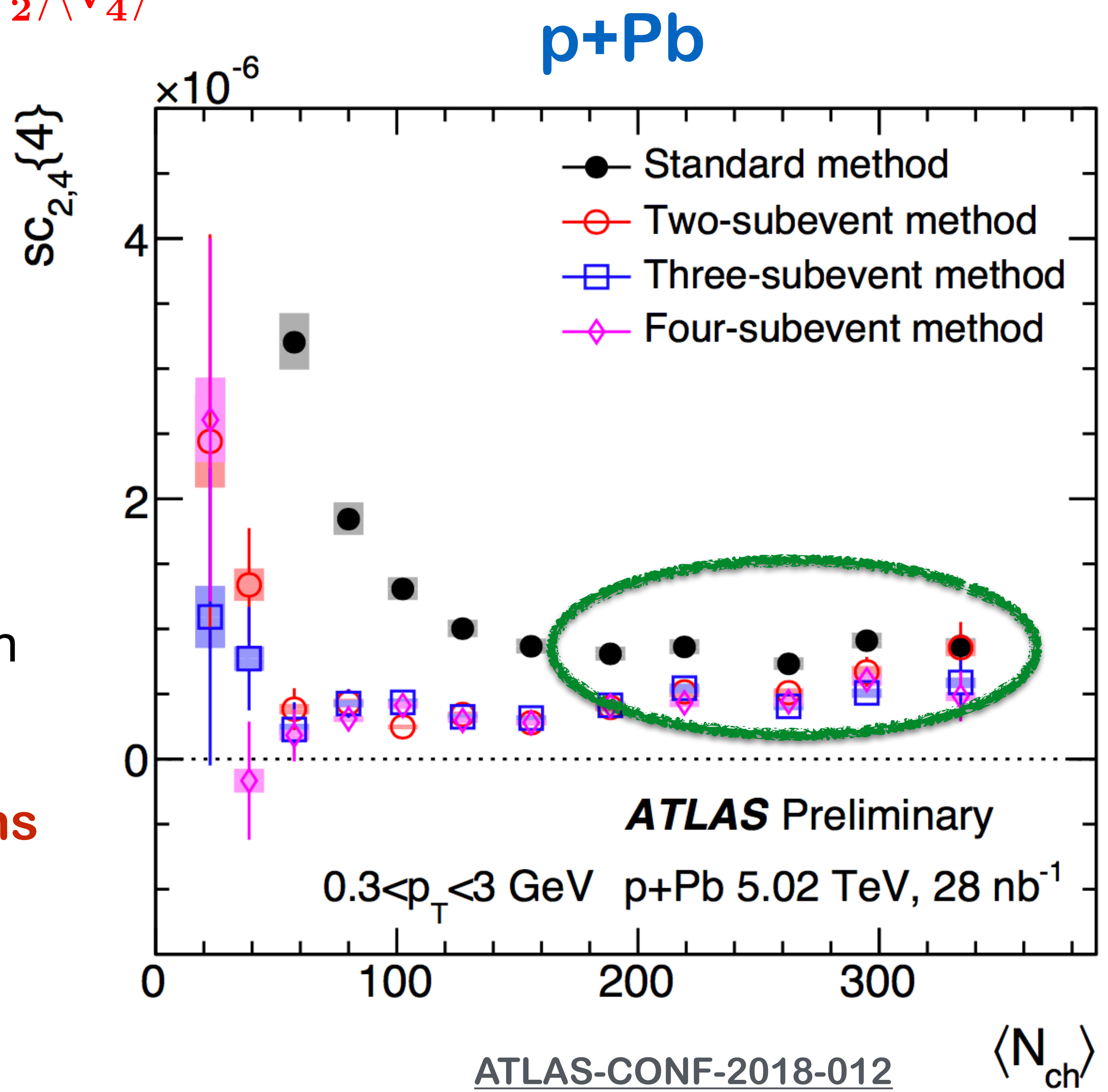

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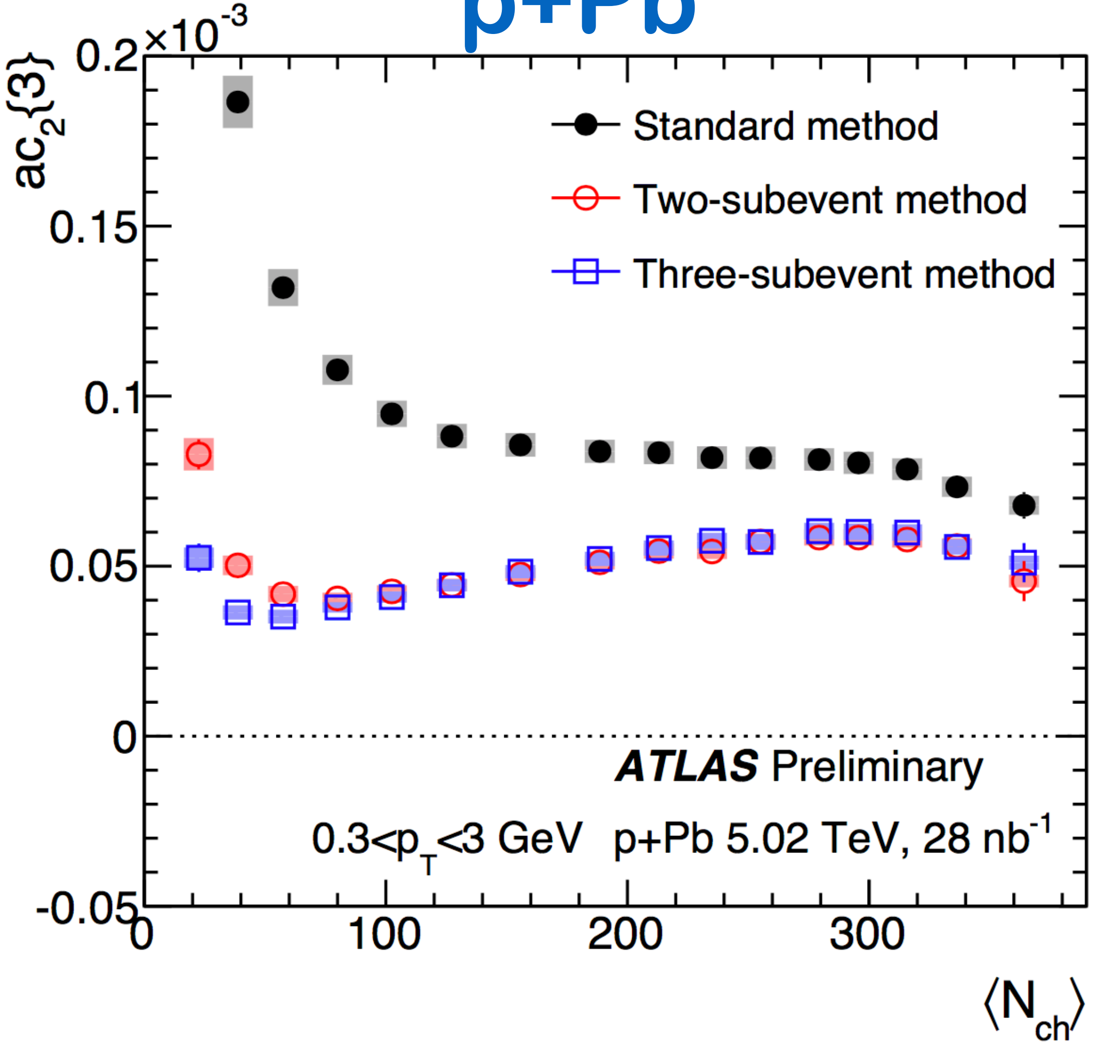
Asymmetric Cumulant

ATLAS-CONF-2018-012

$$\mathrm{ac_2\{3\}} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\rangle$$

p+Pb



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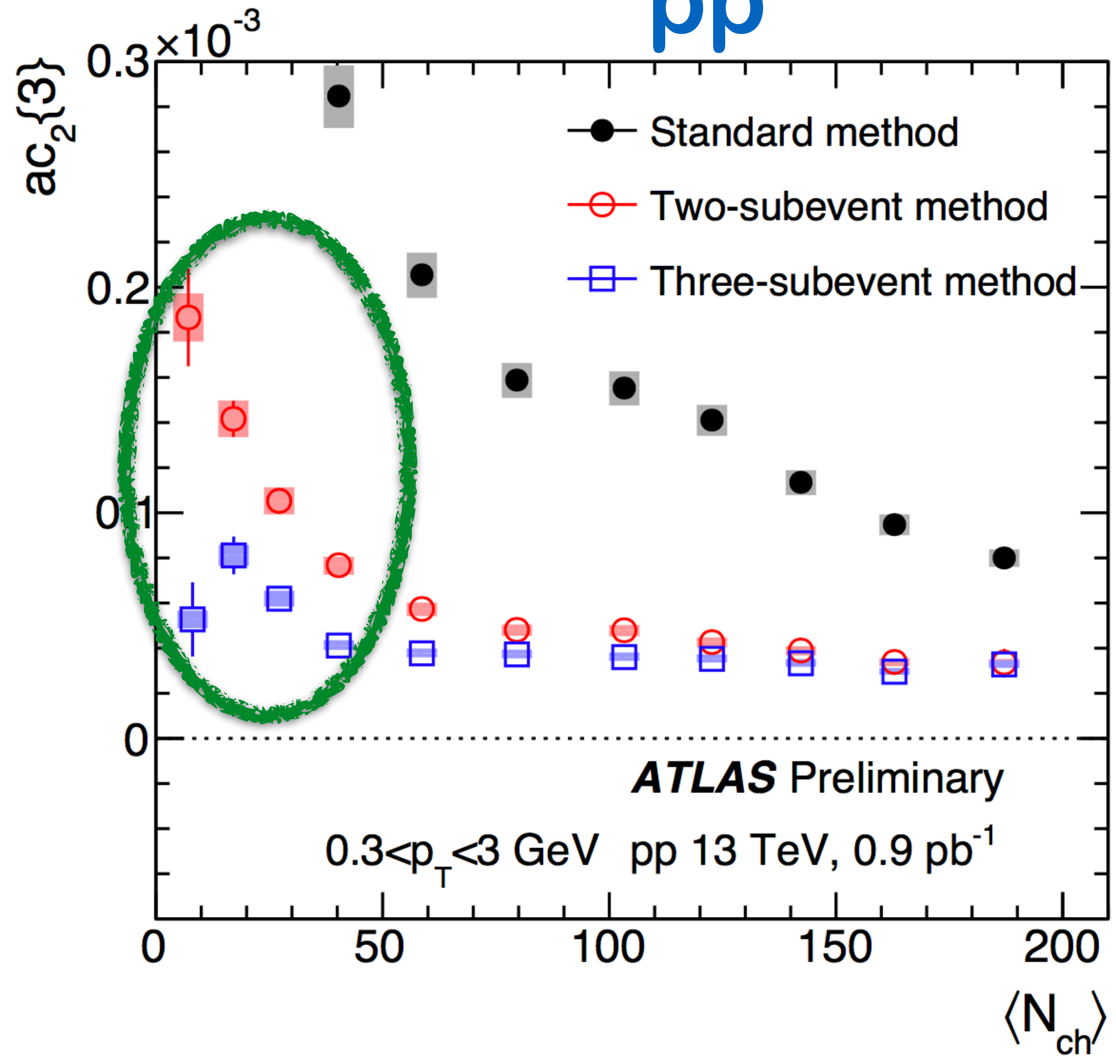

- Positive correlation is observed in all systems and all methods
- Residual non-flow in 2SE

Asymmetric Cumulant

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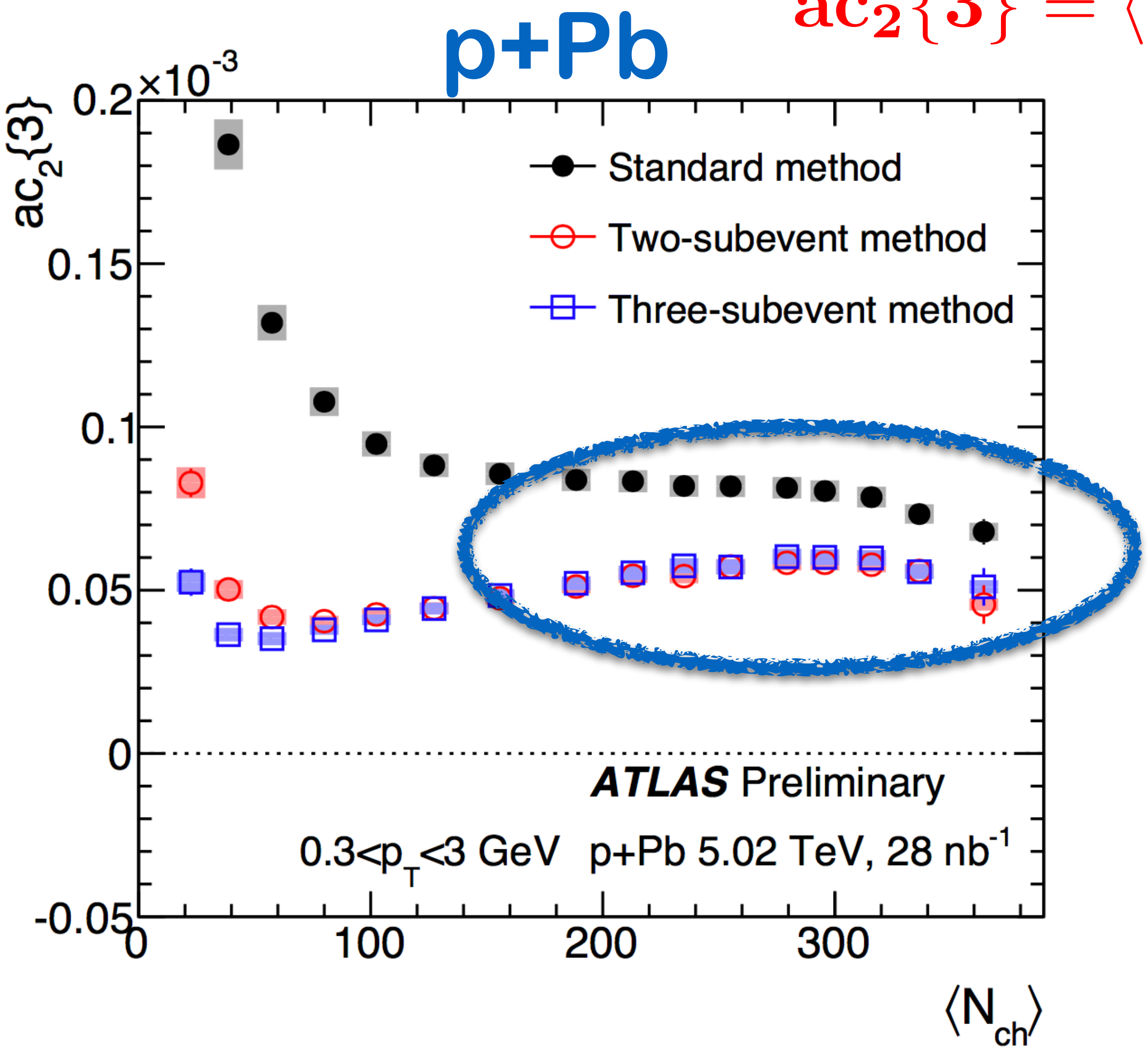
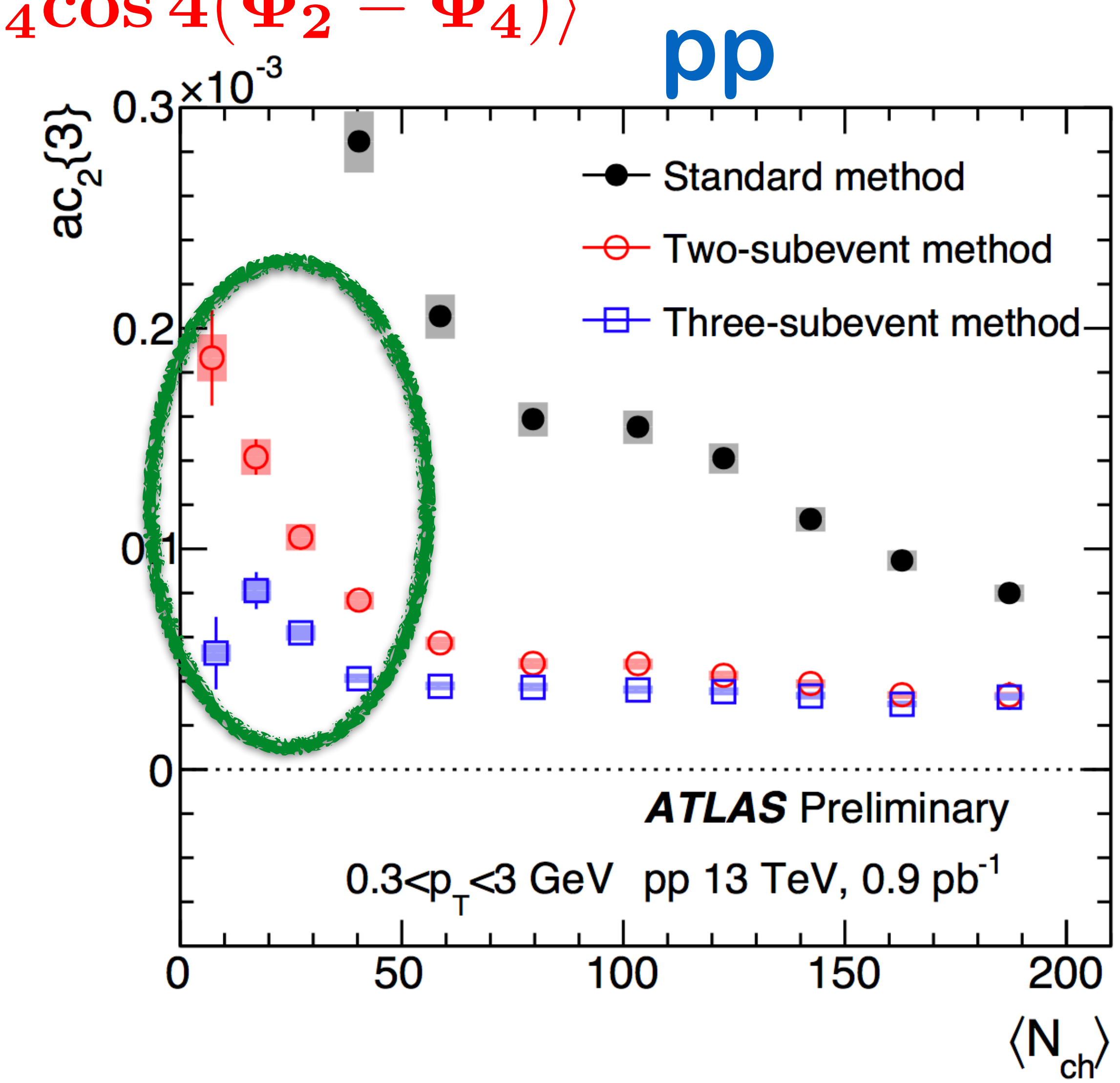
$$ac_2\{3\} = \langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle$$





- Positive correlation is observed in all systems and all methods
- Residual non-flow in 2SE
- Standard and subevents dont converge even at high N_{ch} - **Flow decorrelation?** Eur. Phys. J. C 76 (2018) 142
- **Higher signal thus better statistical precision than symmetric cumulants**

System Size Dependence

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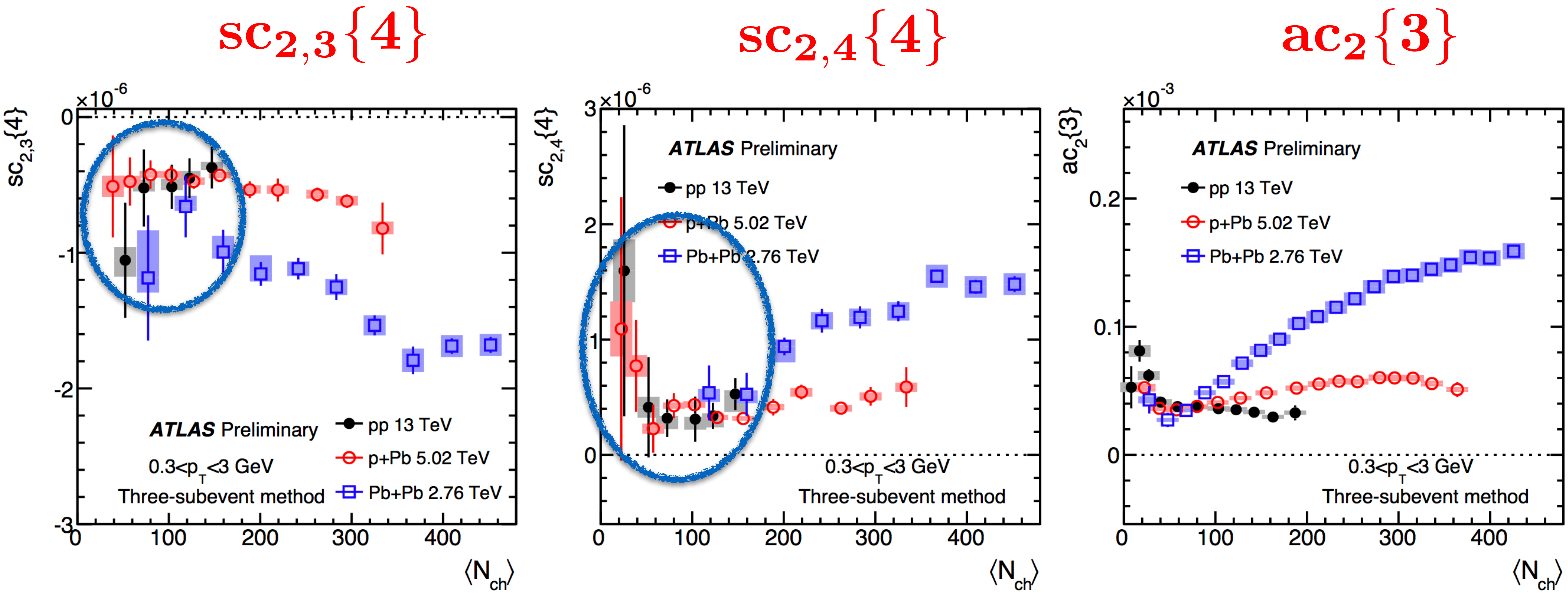
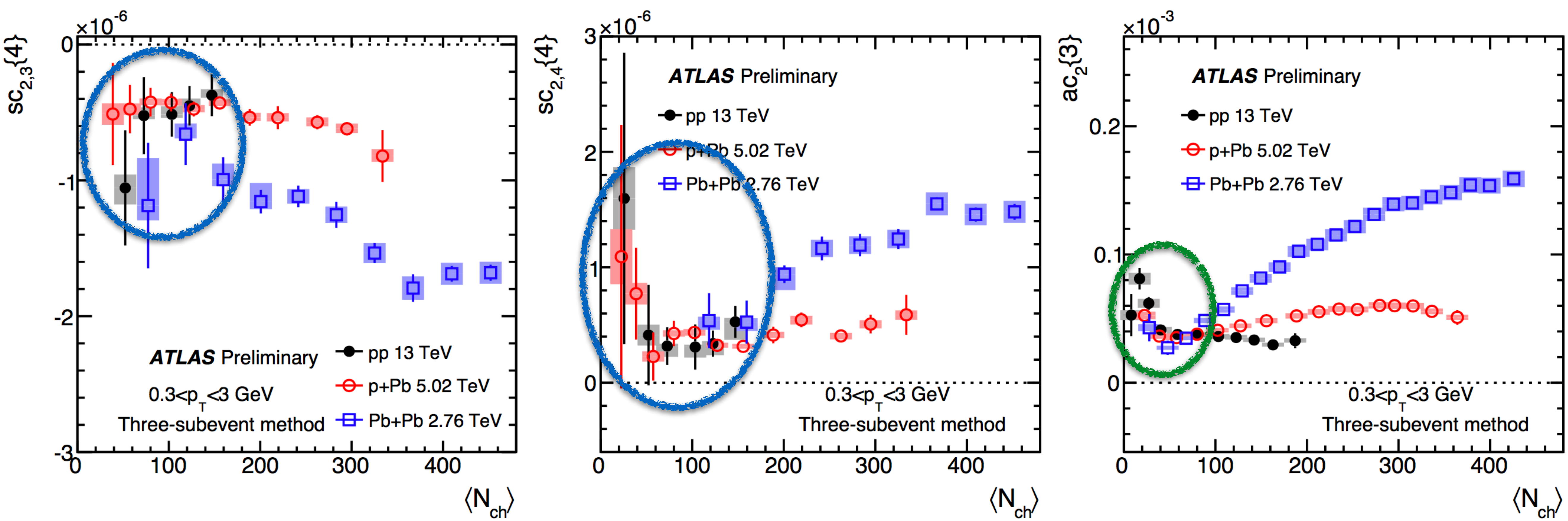


- Consistent results for symmetric cumulants N_{ch} range covered by pp
- For N_{ch} > 150, $sc_{23}\{4\}$ and $sc_{24}\{4\}$ signals are larger for Pb+Pb than p+Pb

System Size Dependence

ATLAS-CONF-2018-012

$sc_{2,3}\{4\}$ $sc_{2,4}\{4\}$ $ac_2\{3\}$



- Consistent results for symmetric cumulants N_{ch} range covered by pp
- For N_{ch} > 150, $sc_{23}\{4\}$ and $sc_{24}\{4\}$ signals are larger for Pb+Pb than p+Pb
- For N_{ch} > 100, $ac_2\{3\}$ in the three systems deviate from each other
- **Comparison not perfect - as different cumulants have different v_n**

Normalized Cumulant

- Normalised cumulants - remove dependence on harmonics magnitude and focus only on correlation strength

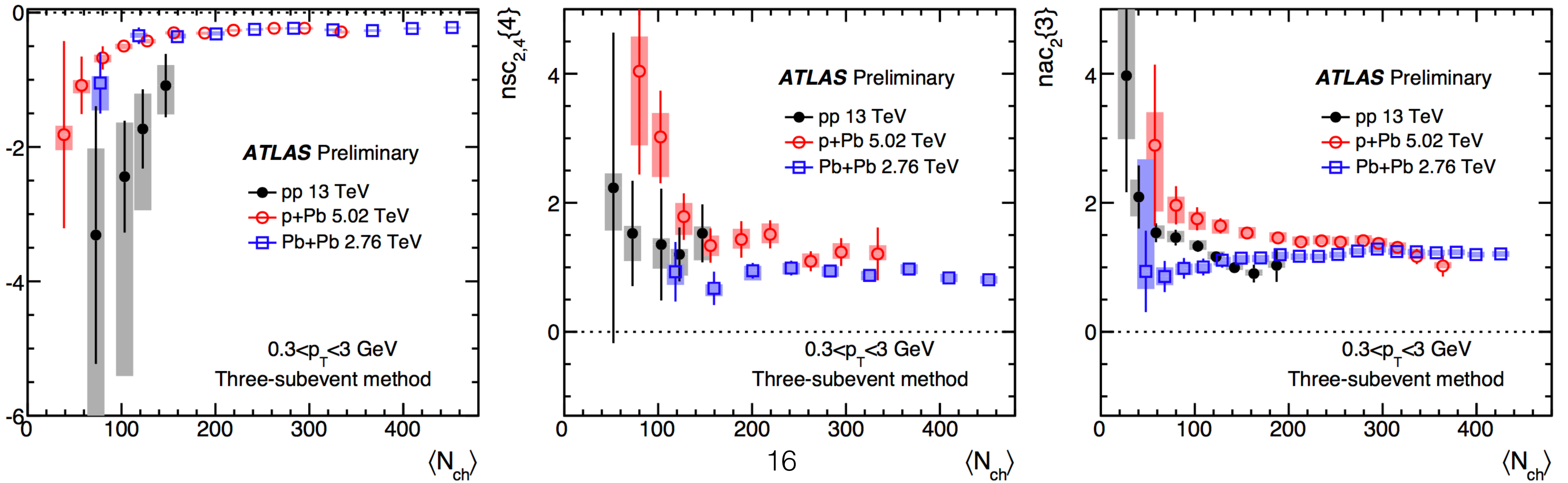
$$nsc_{2,3}\{4\} = \frac{sc_{2,3}\{4\}}{v_2\{2\}^2 v_3\{2\}^2} = \frac{\langle v_2^2 v_3^2 \rangle}{\langle v_2^2 \rangle \langle v_3^2 \rangle} - 1 \quad , \quad nsc_{2,4}\{4\} = \frac{sc_{2,4}\{4\}}{v_2\{2\}^2 v_4\{2\}^2} = \frac{\langle v_2^2 v_4^2 \rangle}{\langle v_2^2 \rangle \langle v_4^2 \rangle} - 1$$

$$nac_2\{3\} = \frac{ac_2\{3\}}{v_2\{2\}^2 \sqrt{v_4\{2\}^2}} = \frac{\langle v_2^2 v_4 cos4(\Phi_2 - \Phi_4) \rangle}{\langle v_2^2 \rangle \sqrt{\langle v_4^2 \rangle}}$$

- "Improved" template fit method - To obtain $v_n\{2\}^2$

ATLAS-CONF-2018-012

$\mathbf{nsc_{2,3}\{4\}}$ $\mathbf{nsc_{2,4}\{4\}}$ $\mathbf{nac_2\{3\}}$



Normalized Cumulant

- Normalization removes most of the N_{ch} dependence at N_{ch} >100!
- Signal strength similar in all systems at high N_{ch} but 20-30% difference at low N_{ch}

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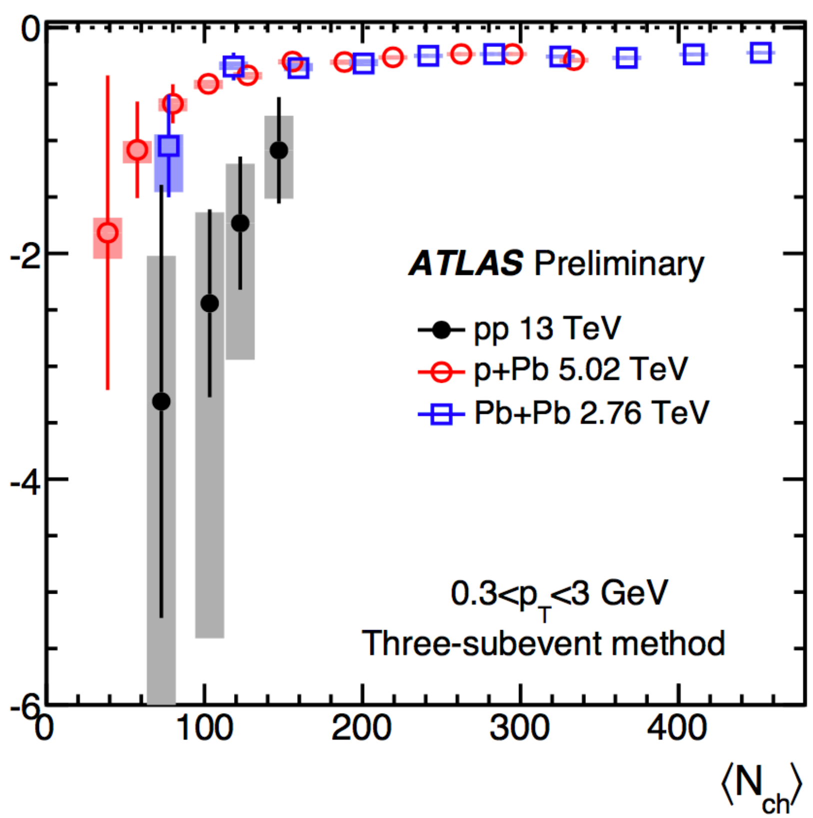
$\mathbf{nsc_{2,3}\{4\}}$



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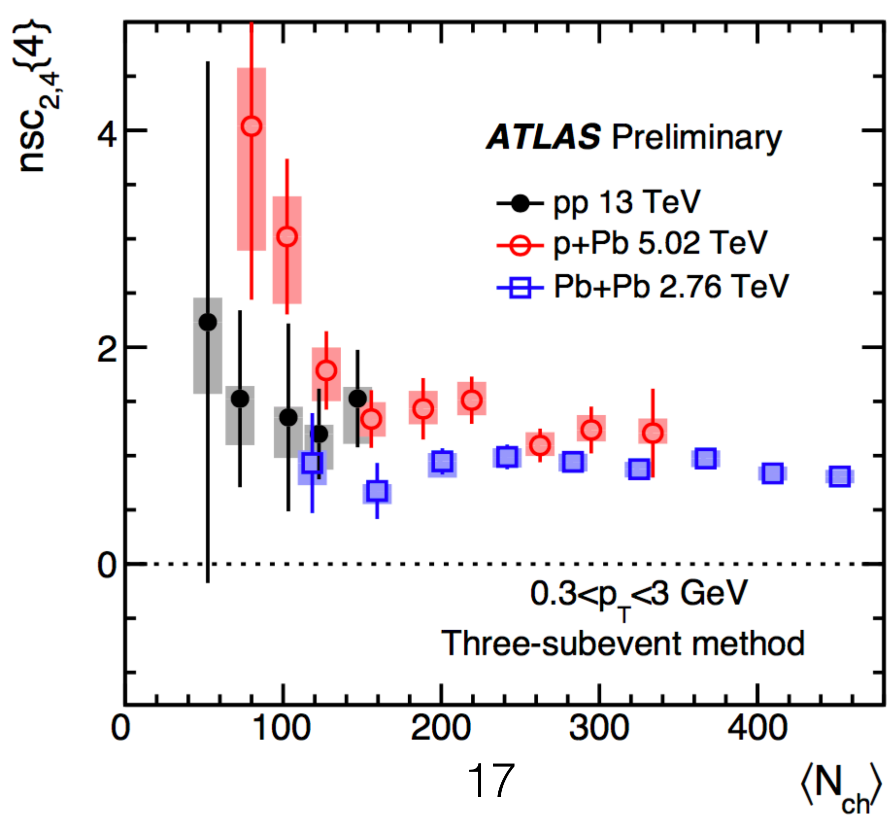
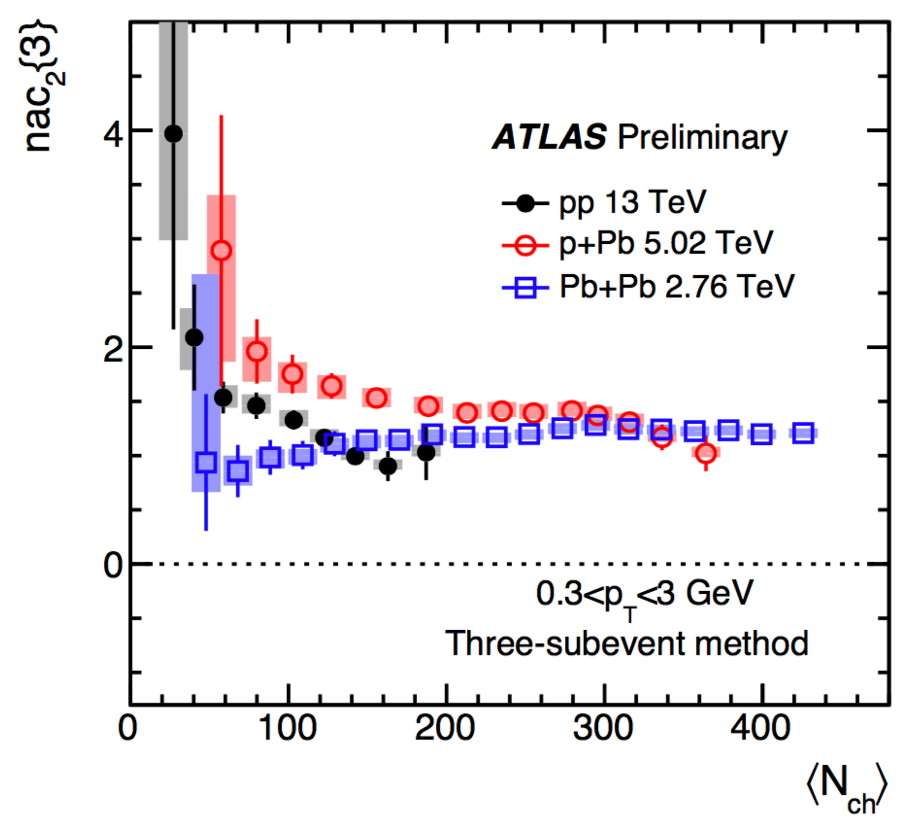


$\mathbf{nac_2\{3\}}$



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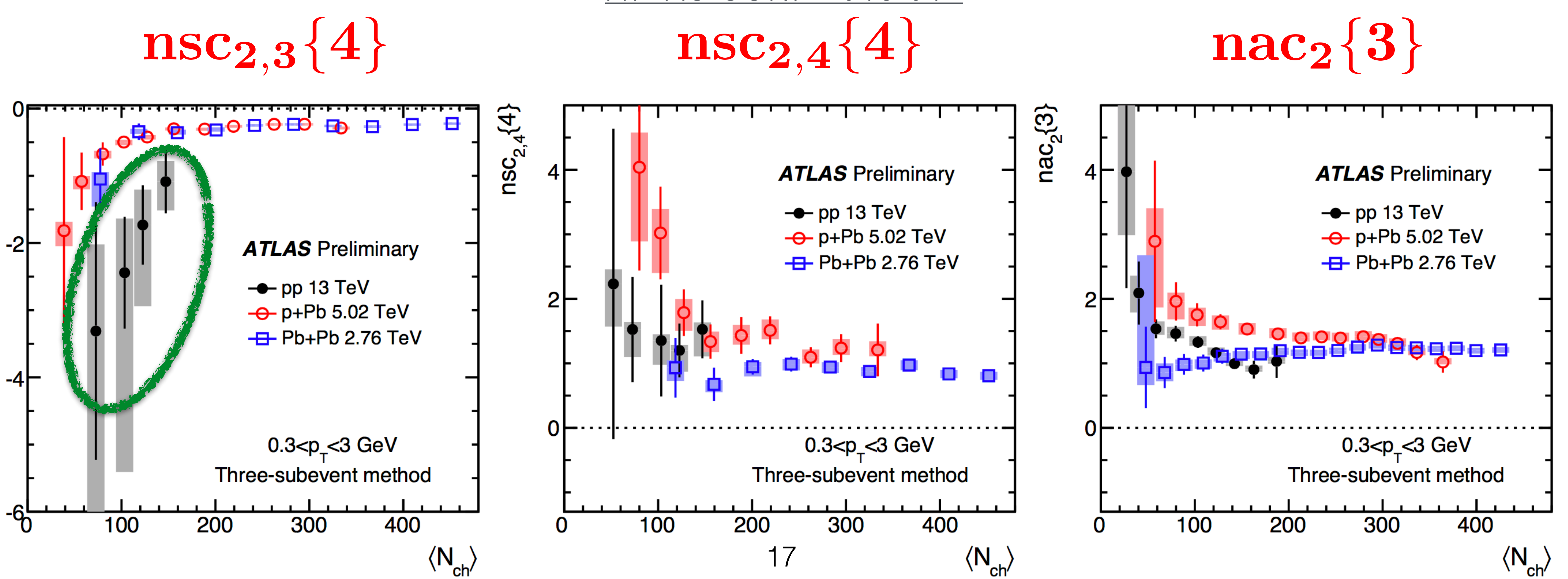

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Behaviour of mixed harmonics correlation is similar in small systems and large systems

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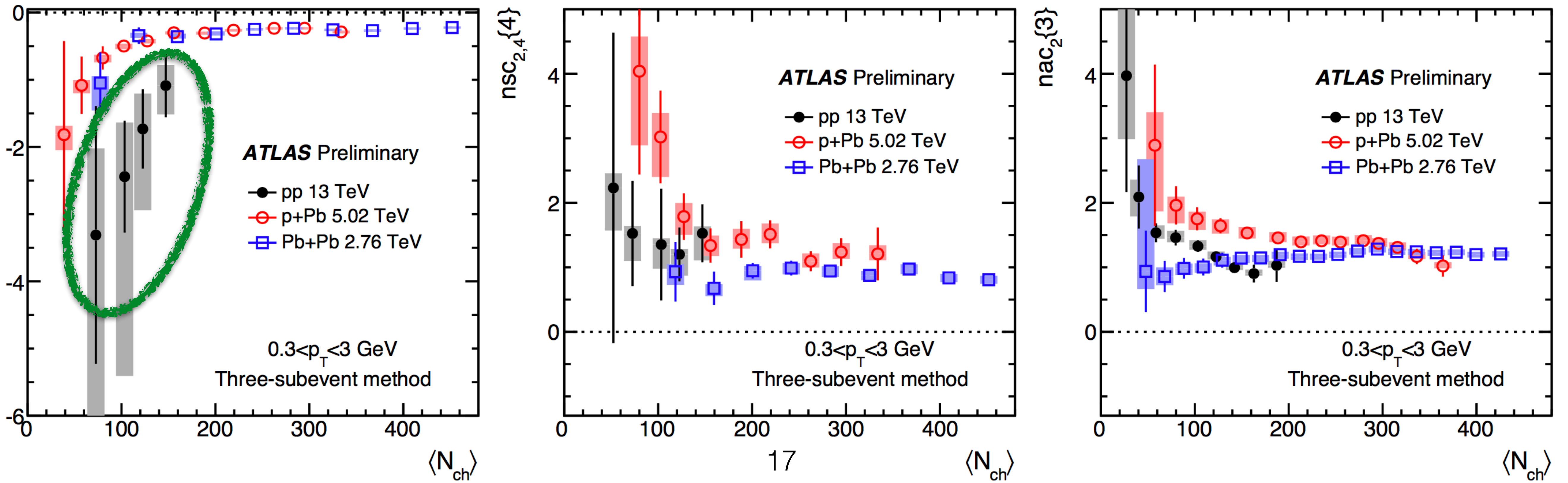
$\mathbf{nsc_{2,3}\{4\}}$ $\mathbf{nsc_{2,4}\{4\}}$ $\mathbf{nac_2\{3\}}$



Summary

- **Two-particle Flow :**
  - Improved Template Fit - corrects for fluctuating v_n with N_{ch}
  - Significant $v_2\{2\}$ for small system
- **Multi-particle Cumulants :**
  - Standard cumulant method dominated by non-flow
  - Three-subevent method removes non-flow
  - **Small system shows signs of collectivity**
- **Mixed Harmonics Correlation :**
  - Three-subevent method removes non-flow
  - Anticorrelation (v_2, v_3) and correlated (v_2, v_4)
  - **Normalised cumulants - similar strength across all systems**
  - Behaviour of small and large systems are similar

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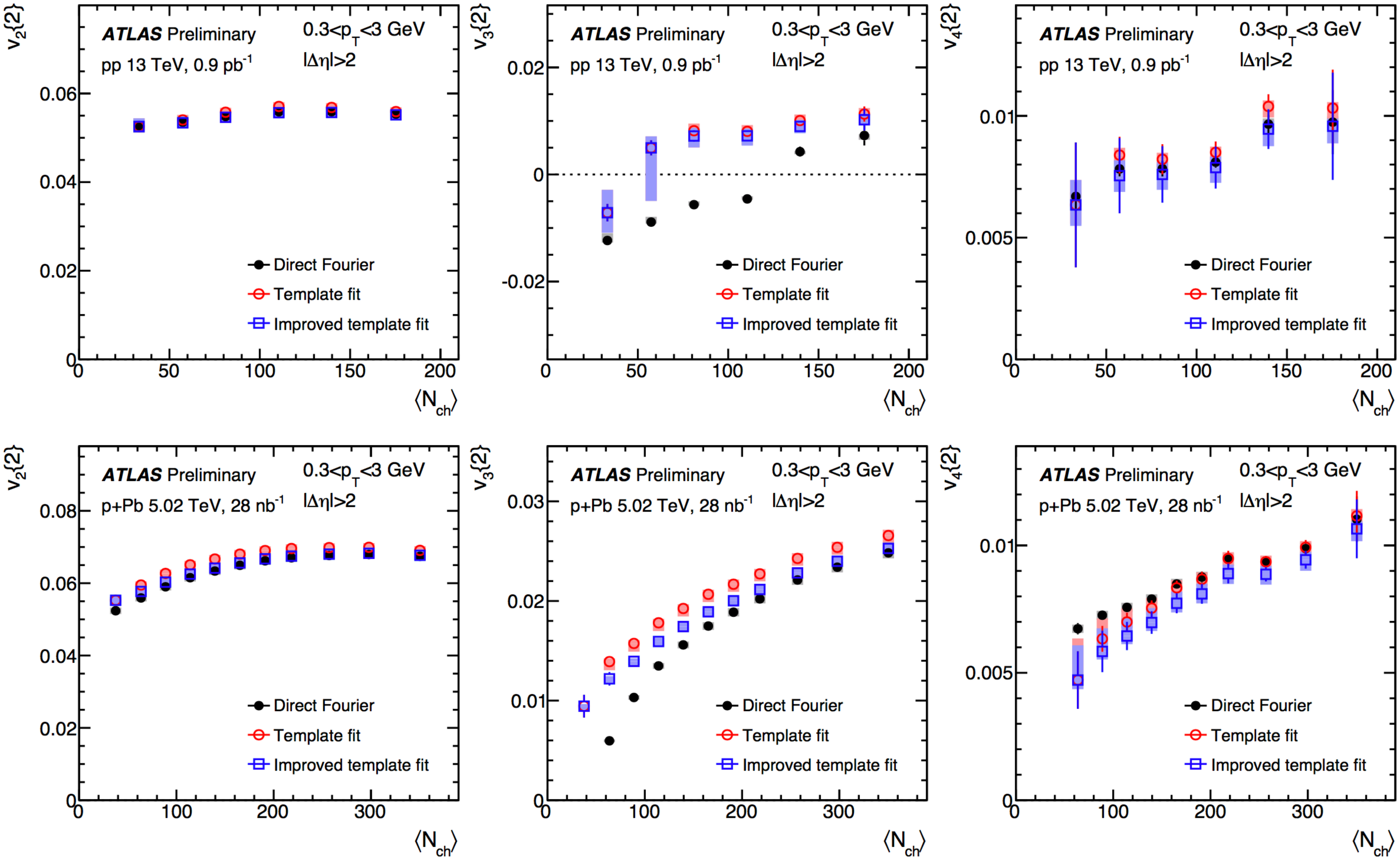
Strong evidence for long-range correlation and collectivity in small system. Can help constrain theoretical models.

Backup

Improved Template Fit



pp

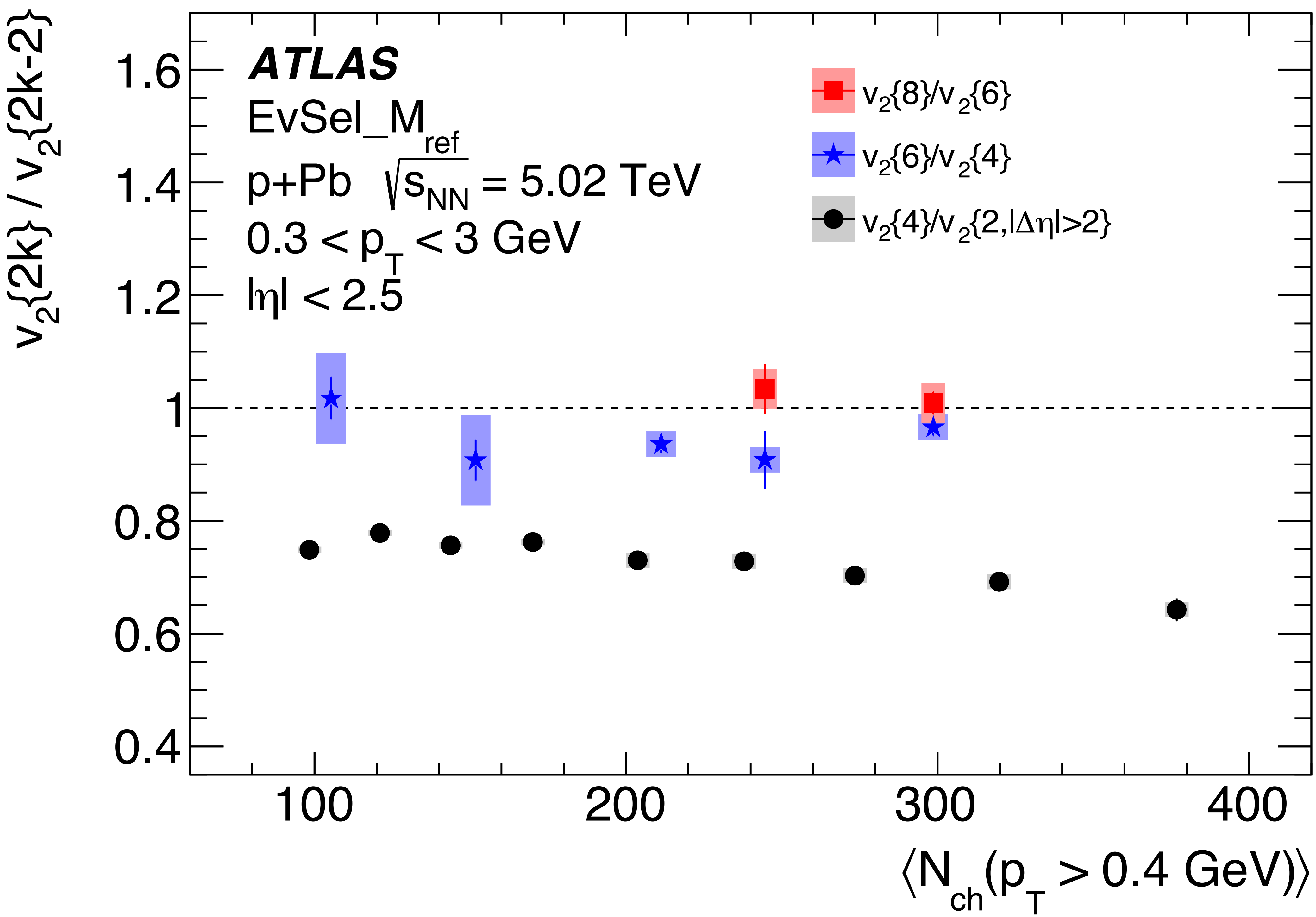
p+Pb

$v_2\{2\}$ $v_3\{2\}$ $v_4\{2\}$

Backup

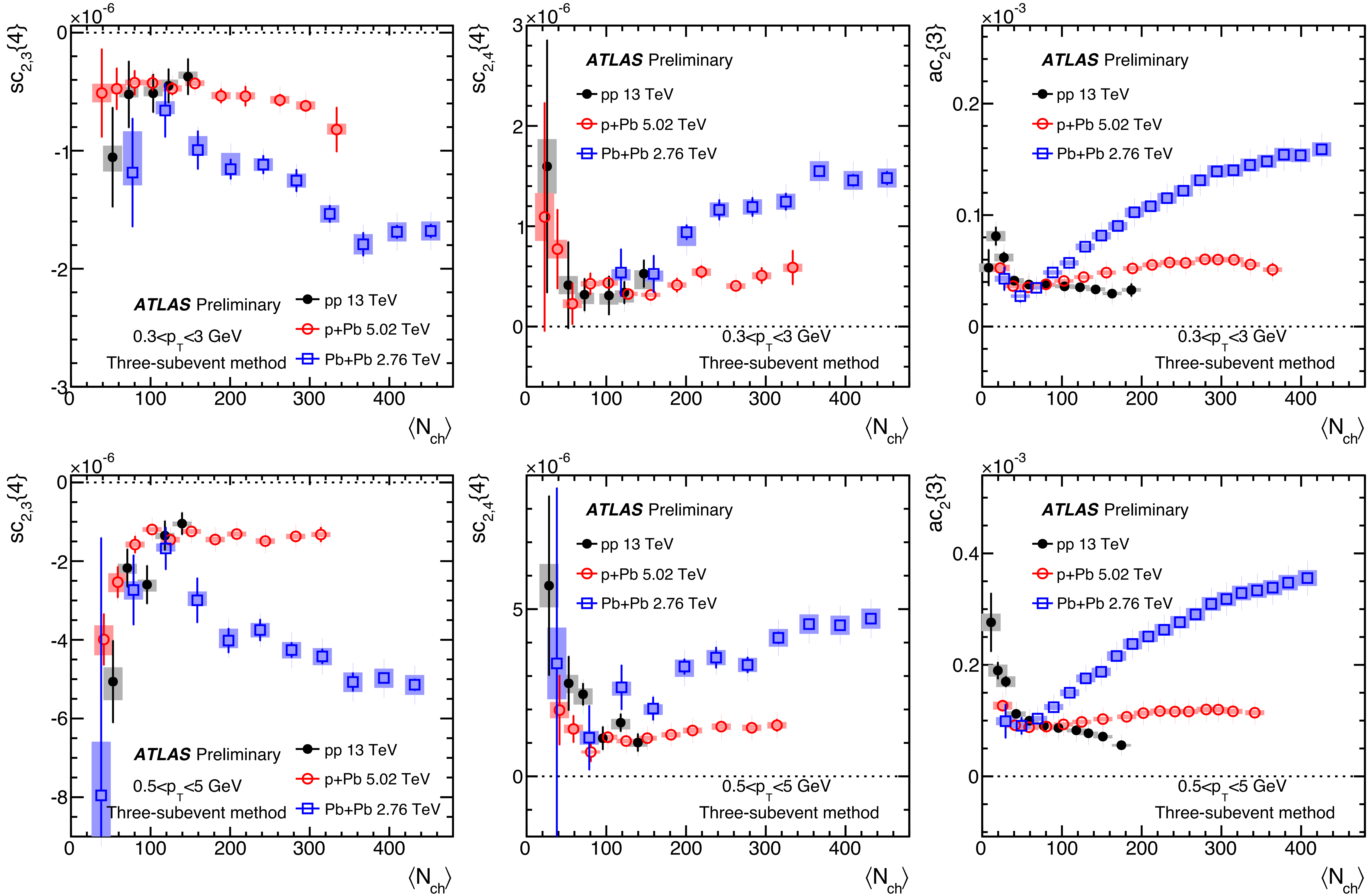
p+Pb Collectivity

Eur. Phys. J. C 77 (2017) 428



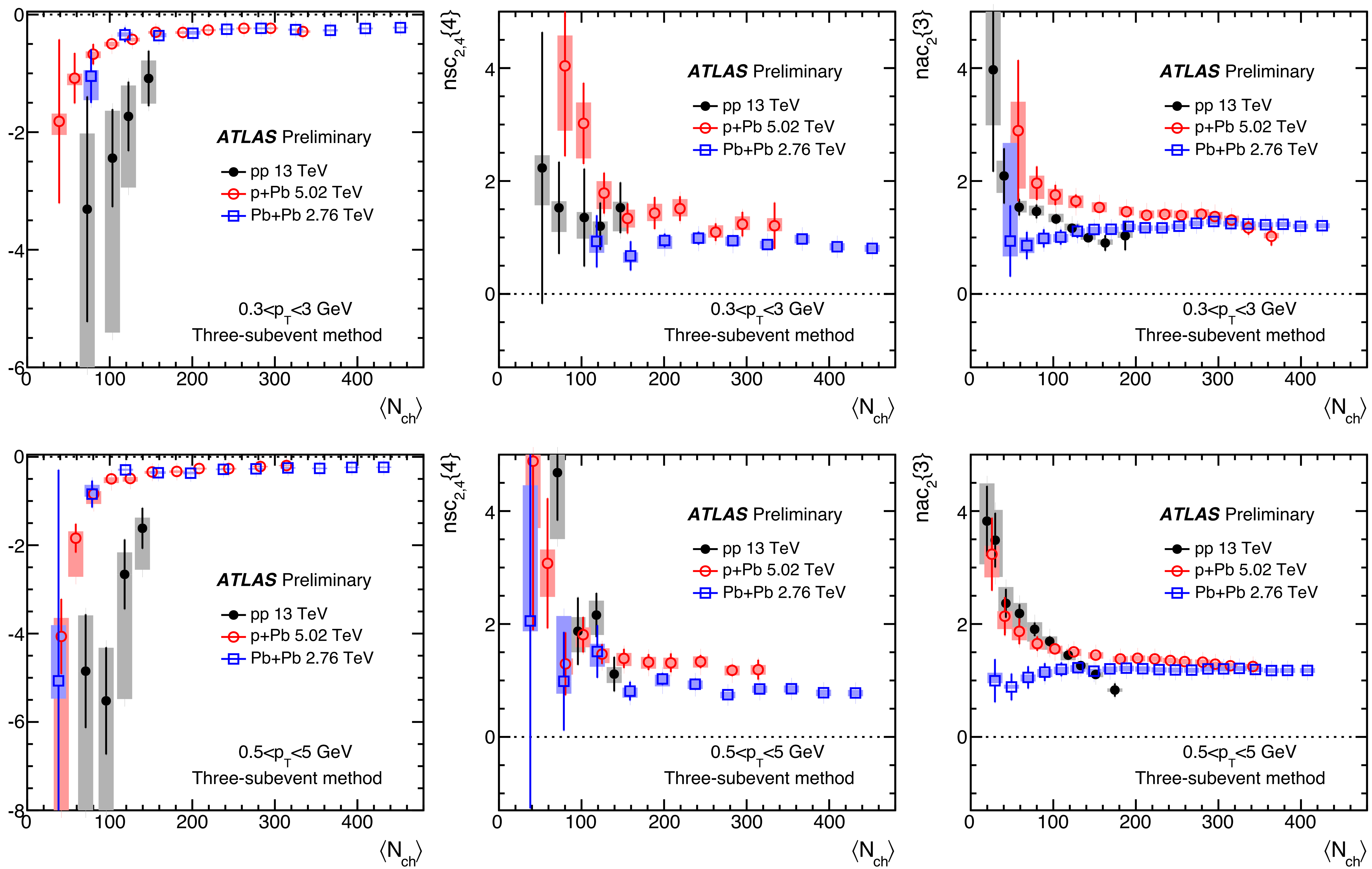
Backup

System dependence

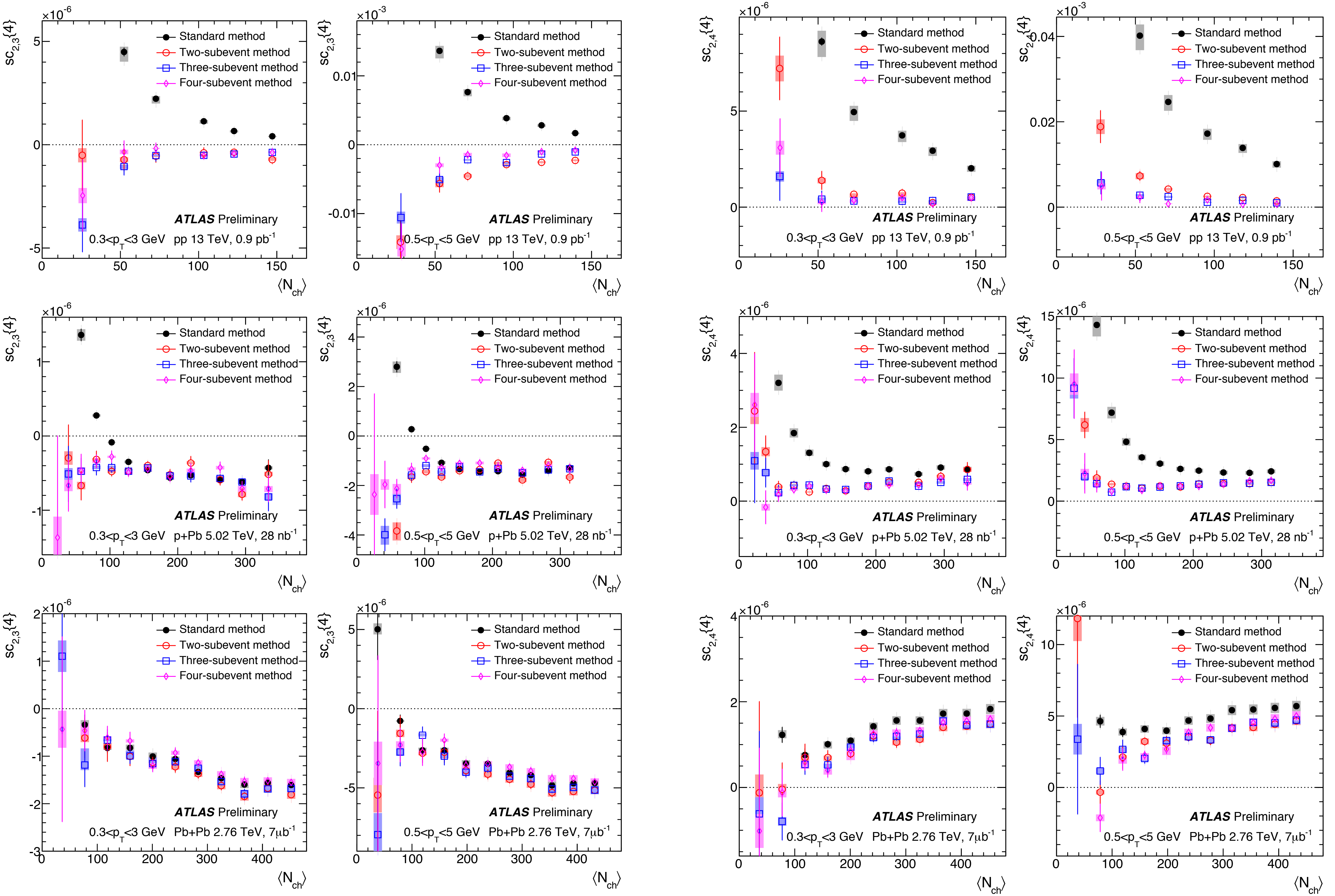


Backup

Normalised Cumulants



Backup



Standard method
Two-subevent method
Three-subevent method
Four-subevent method
ATLAS Preliminary
0.3<p_T<3 GeV pp 13 TeV, 0.9 pb^-1
0.5<p_T<5 GeV pp 13 TeV, 0.9 pb^-1
0.3<p_T<3 GeV p+Pb 5.02 TeV, 28 nb^-1
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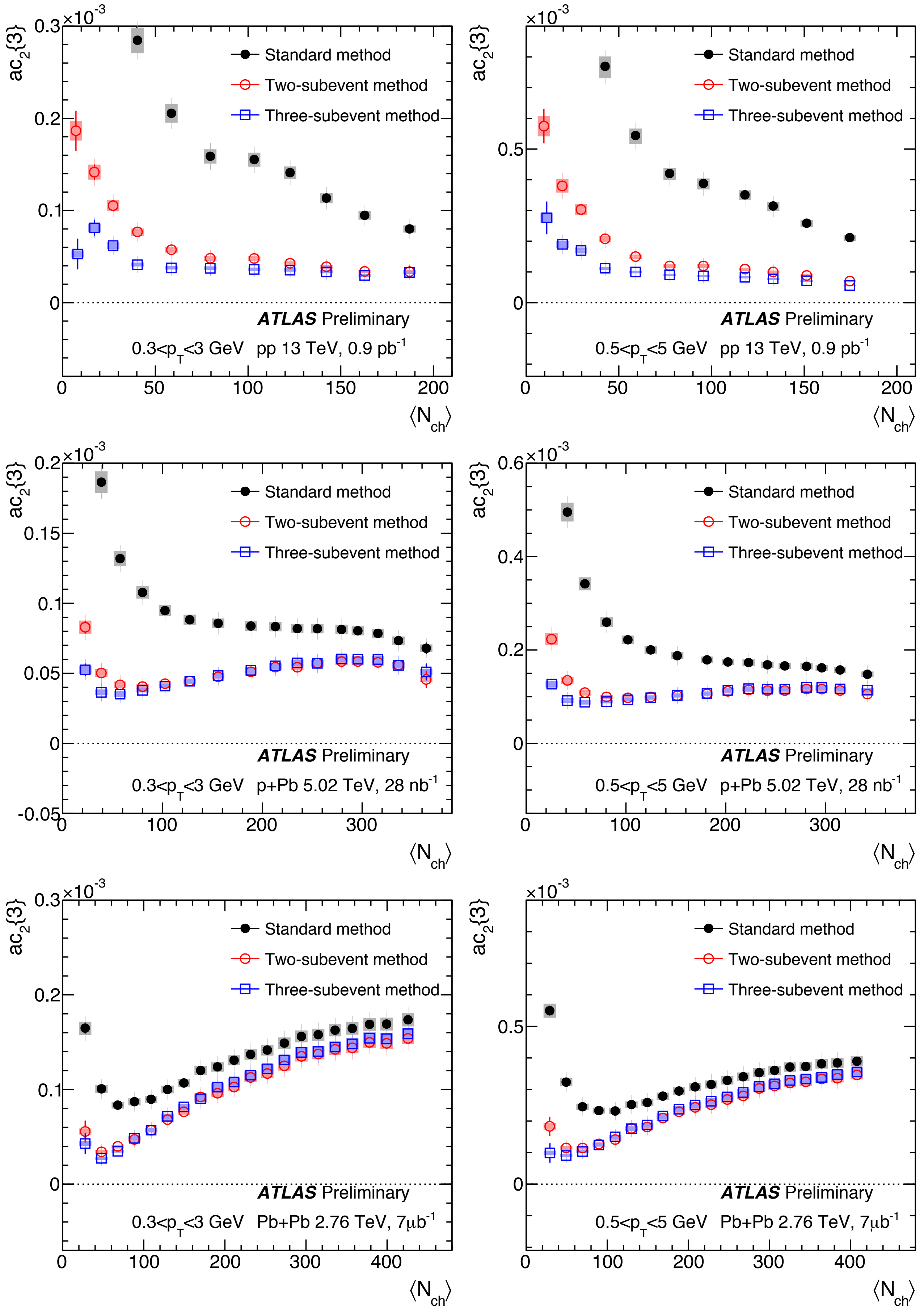
sc_2,3{4}
sc_2,4{4}
⟨N_ch⟩

Backup



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ac_2{3}
⟨N_ch⟩
×10^-3