Stony Brook University | The State University of New York

Long-range collectivity in small systems

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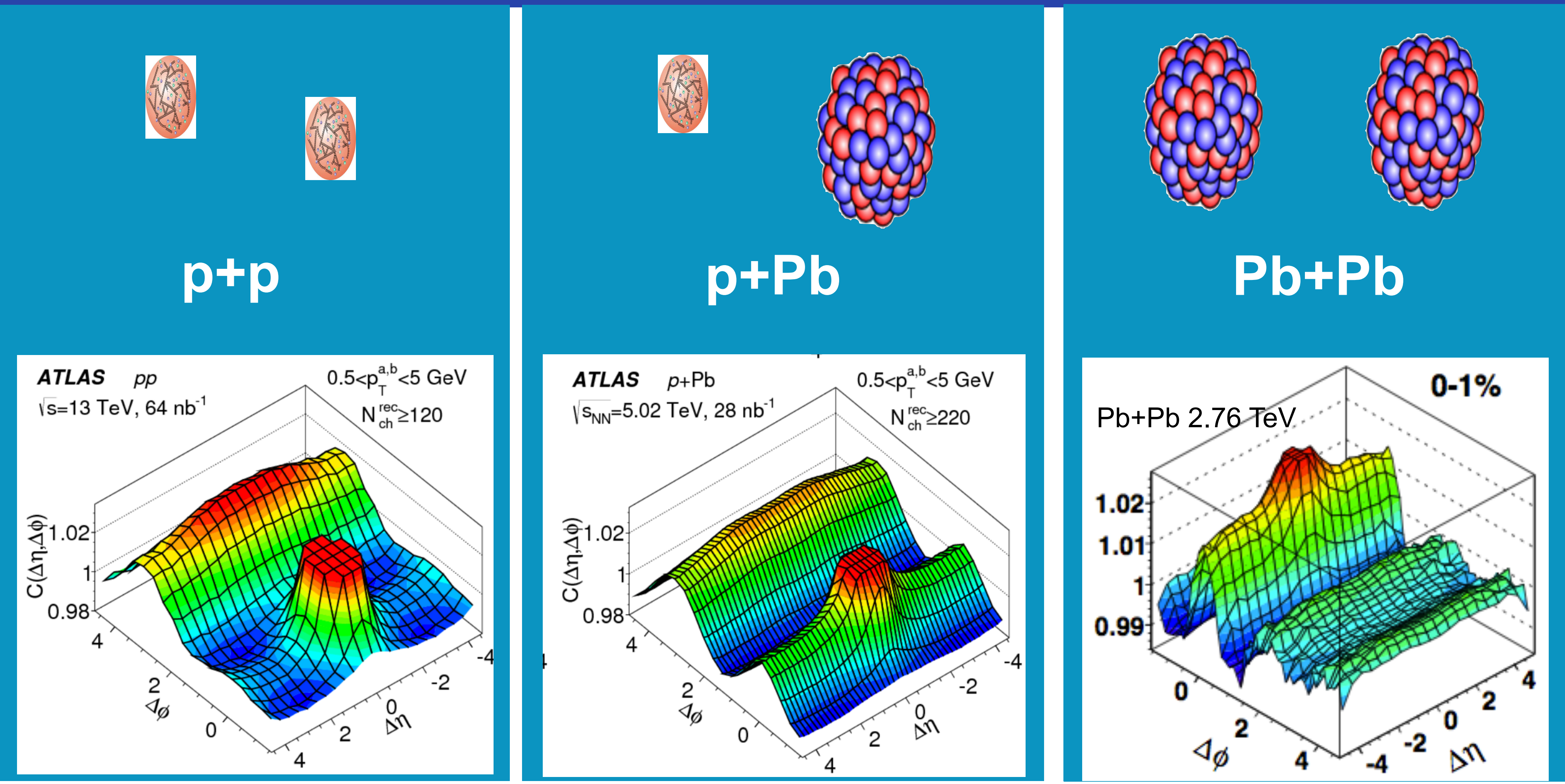
Stony Brook University and BNL

Second international workshop on Collectivity in Small Collision Systems (CSCS2018)

https://indico.cern.ch/event/689516/

Long-range collectivity in different systems

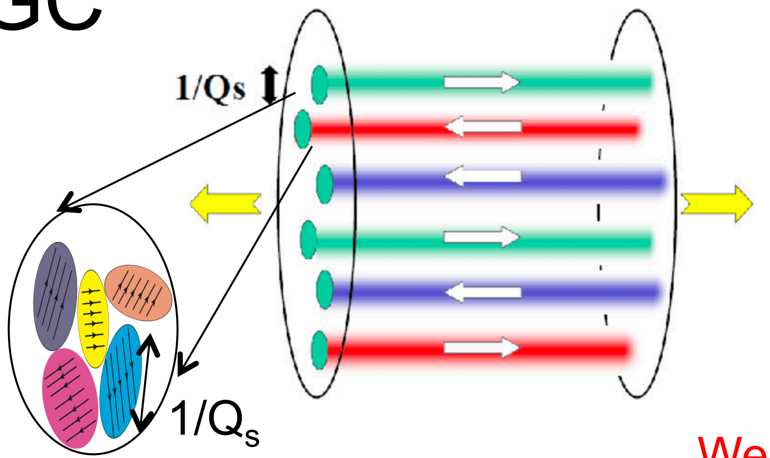


- Long-range correlation in momentum space comes
  - directly from early time t~0 (CGC)
  - or it is a final state response to spatial fluctuation at t=0 (hydro/transport).

What is the timescale for emergence of collectivity?

Examples of initial vs final state scenarios

CGC



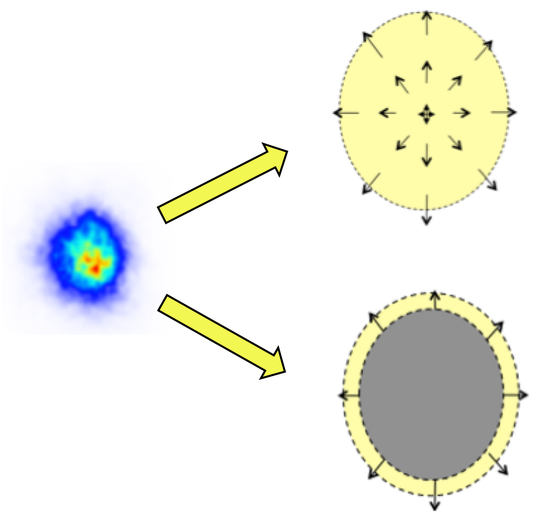
Domain of color fields of size $1/Q_s$, each produce multi-particles correlated across full η.

Uncorr. between domains, strong fluct. in Q_s

More domains, smaller v_n, more Q_s fluct, stronger v_n

Well motivated model framework, lack systematic treatment

Hydro or escape



Pressure driven

Single/few hit

Hot spots (domains) in transverse plane, ~ boost-invariant geometry shape

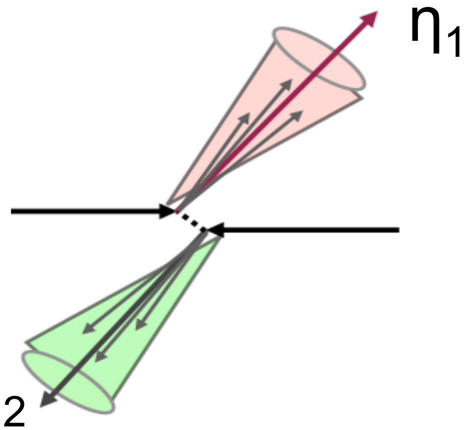
Expansion or interaction of hot spots generate collectivity

v_n depends on distribution of hot spots (ε_n) and space-time dynamics in the final state

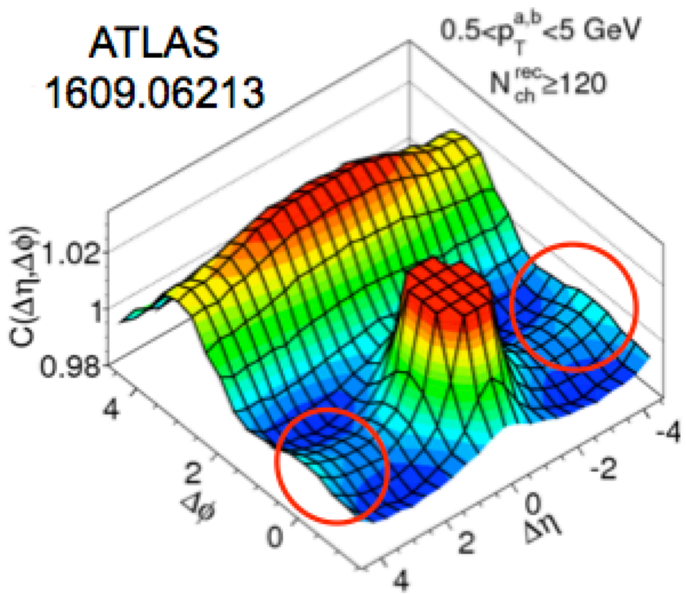
Ongoing debate: hydro from many scatterings ? non-hydro transport from a few scattering?

Non-flow vs long-range collectivity

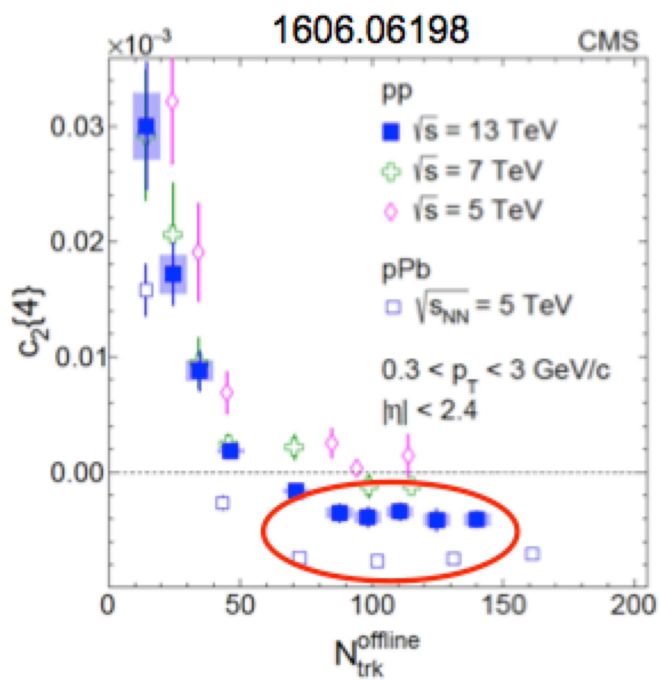
Dominating non-flow is jets and dijets, which are confined in **one or two η regions**



Features of long-range ridge:



Long-range in η



Multi-particle (3,4,5..) signal

Simultaneous correlations between multiple η ranges

Observables for long-range ridge: correlation

- Single particle distribution

$$\frac{dN}{d\phi} = N\left[1+2\sum_n \mathrm{v}_n \cos n\left(\phi-\Phi_n\right)\right] = N\left[\sum_{n=-\infty}^{\infty} V_n e^{in\phi}\right]$$

Flow vector:

$$\boldsymbol{V}_n = v_n e^{in\Phi_n}$$

- Multi-particle correlations

$$\left\langle \frac{dN_1}{d\phi}\frac{dN_2}{d\phi}..\frac{dN_m}{d\phi}\right\rangle \Rightarrow \left\langle\left\langle e^{i(n_1\phi_1+n_2\phi_2+\ldots+n_m\phi_m}\right\rangle\right\rangle = \left\langle V_{n_1}V_{n_2}\ldots V_{n_m}\right\rangle \quad n_1+n_2+\ldots+n_m=0$$

$$\Downarrow$$

$$\left\langle v_{n_1}v_{n_2}..v_{n_m}\cos(n_1\Phi_{n_1}+n_2\Phi_{n_2}+..+n_m\Phi_{n_m})\right\rangle$$

- Examples:

2PC $\quad \langle\langle\{2\}_n\rangle\rangle = \langle\langle \mathrm{e}^{in(\phi_1-\phi_2)}\rangle\rangle = \langle v_n^2\rangle$

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

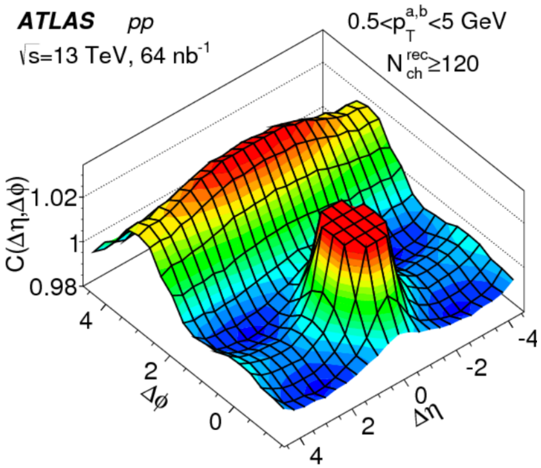
4PC $\quad \langle\langle\{4\}_{n,m}\rangle\rangle = \langle\langle \mathrm{e}^{in(\phi_1-\phi_2)+im(\phi_3-\phi_4)}\rangle\rangle = \langle v_n^2 v_m^2\rangle$

3PC $\quad \langle\langle\{3\}_n\rangle\rangle = \langle\langle \mathrm{e}^{in(\phi_1+\phi_2-2\phi_3)}\rangle\rangle = \langle v_n^2 v_{2n}\cos 2n(\Phi_n-\Phi_{2n})\rangle$

Observables for long-range ridge: cumulants

N-particle cumulant = N-particle correlation – lower-order correlations

Two-particle cummlants



$$c_n\{2\} = \langle\langle\{2\}_n\rangle\rangle = \langle v_n^2\rangle$$

=> coefficients of two-particle correlation function

$$\frac{dN}{d\Delta\phi} \propto 1 + 2\sum_n \langle v_n^2\rangle \cos(n\Delta\phi)$$

Four-particle cumulants

$$c_n\{4\} = \langle\langle\{4\}_n\rangle\rangle - 2\langle\langle\{2\}_n\rangle\rangle^2 = \langle v_n^4\rangle - 2\langle v_n^2\rangle^2$$ Probe $p(v_n)$

$$\mathrm{sc}_{n,m}\{4\} = \langle\langle\{4\}_{n,m}\rangle\rangle - \langle\langle\{2\}_n\rangle\rangle\langle\langle\{2\}_m\rangle\rangle = \langle v_n^2 v_m^2\rangle - \langle v_n^2\rangle\langle v_m^2\rangle$$ Probe $p(v_n, v_m)$

Three-particle cumulants

$$\mathrm{ac}_n\{3\} = \langle\langle\{3\}_n\rangle\rangle = \langle v_n^2 v_{2n}\cos 2n(\Phi_n - \Phi_{2n})\rangle$$ Probe $p(\Phi_n, \Phi_m)$

Observables for long-range ridge: cumulants

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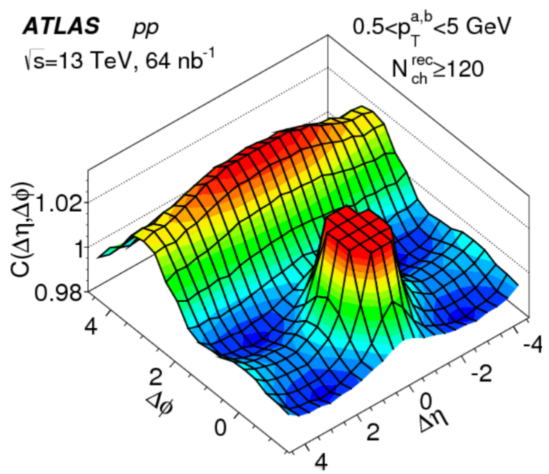

Four-particle cumulants

$$c_n\{4\} = \langle\langle \{4\}_n \rangle\rangle - 2\langle\langle \{2\}_n \rangle\rangle^2 = \langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2$$ Probe $p(v_n)$

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Three-particle cumulants

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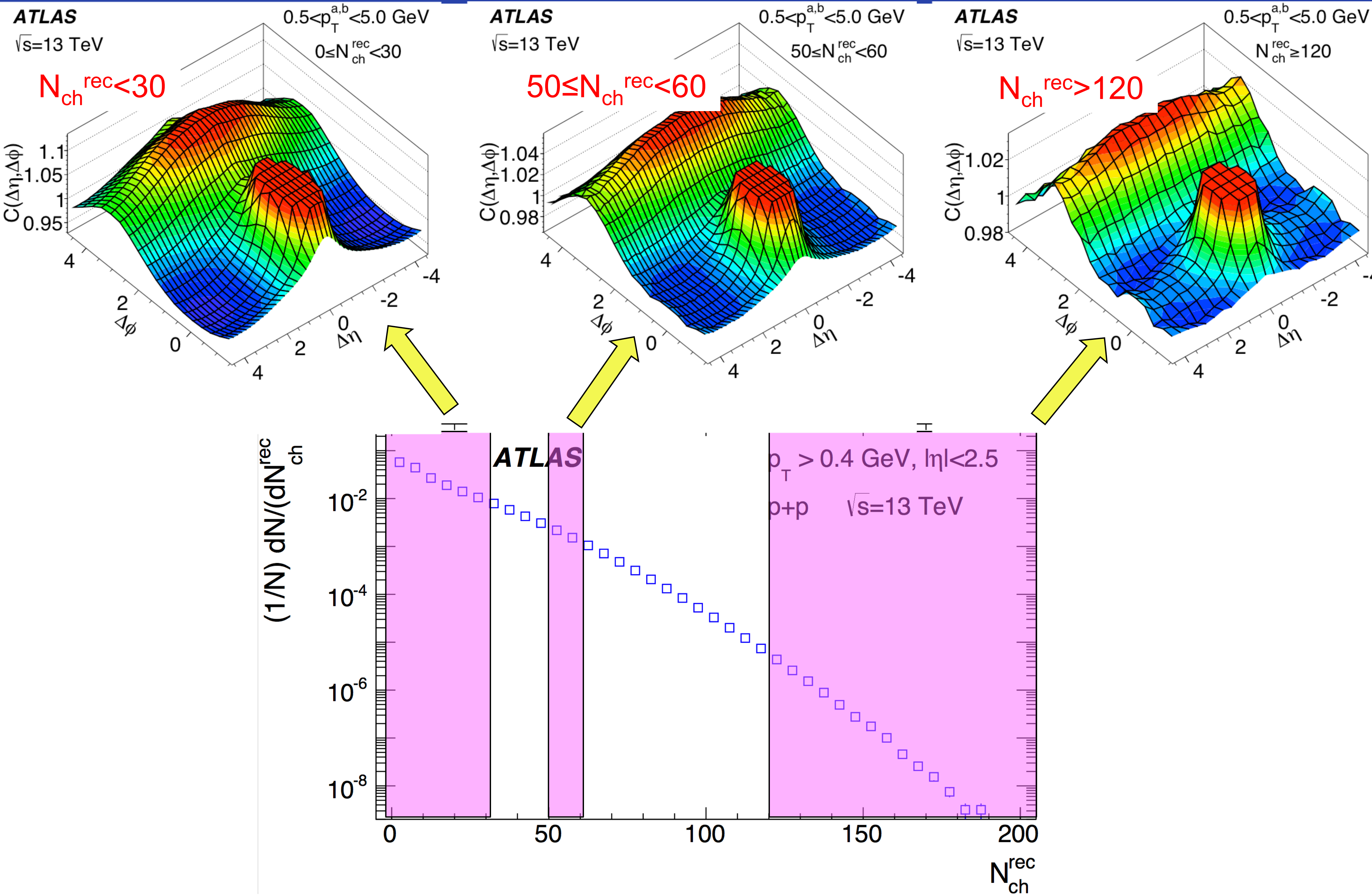
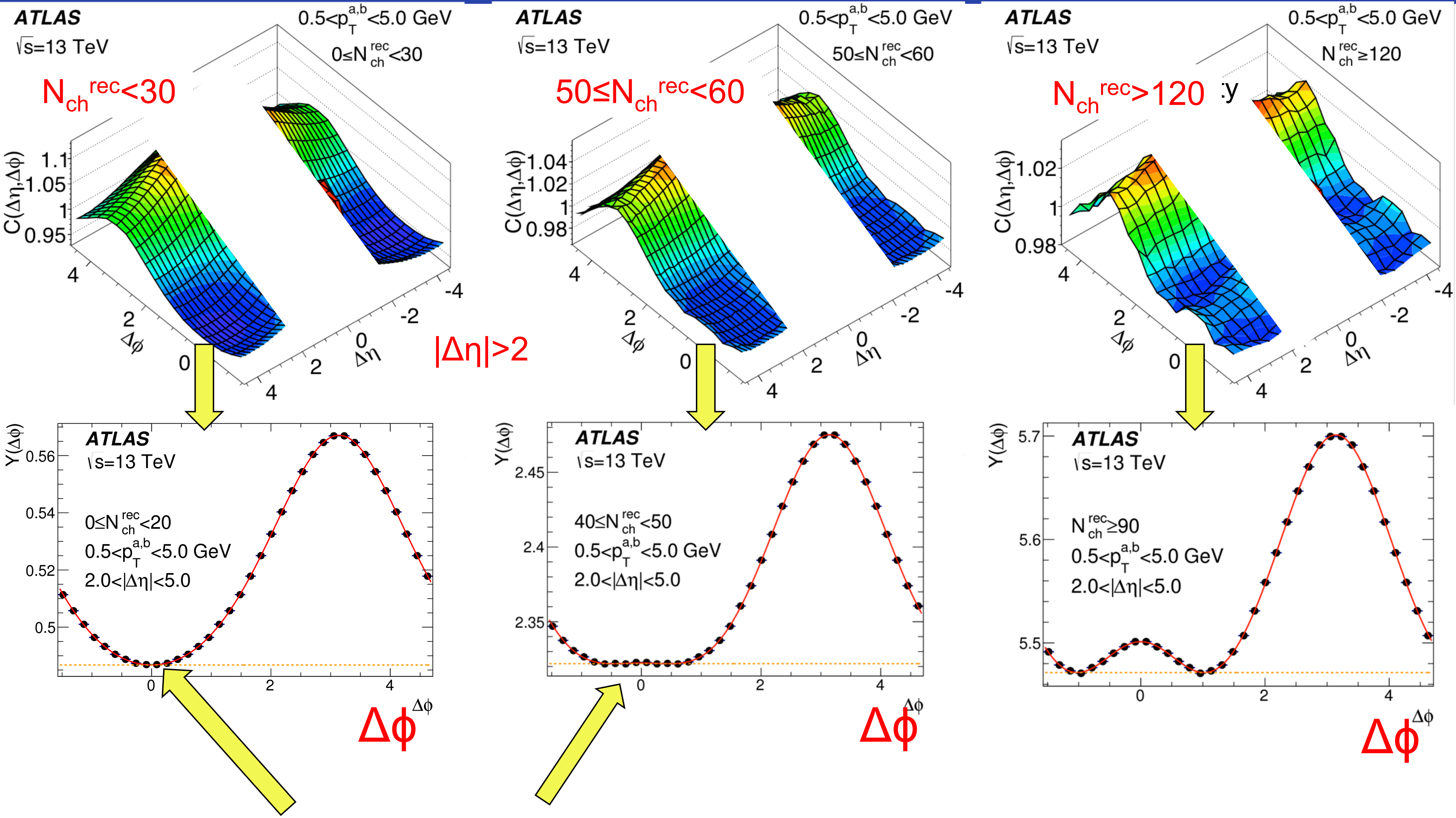
The “hidden” pp ridge



The “hidden” pp ridge



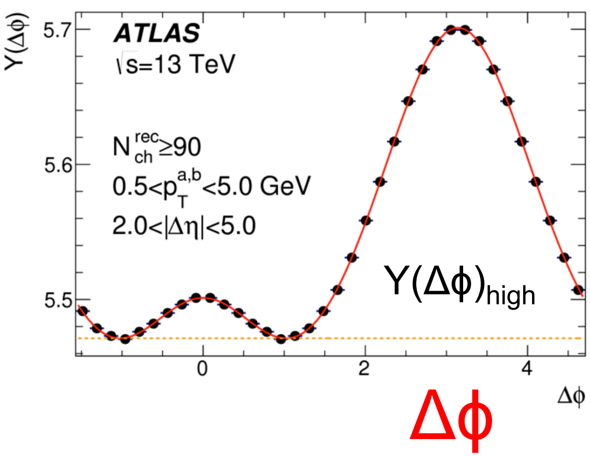
Ridge could be masked by away-side

The "hidden" pp ridge

Low multiplicity bin: $N_{ch}^{rec}<20$

Observation: $Y(\Delta\phi)^{\text{cent}} \approx F\, Y(\Delta\phi)^{\text{peri}} + G + A_2 \cos 2\Delta\phi$

Other harmonics much smaller



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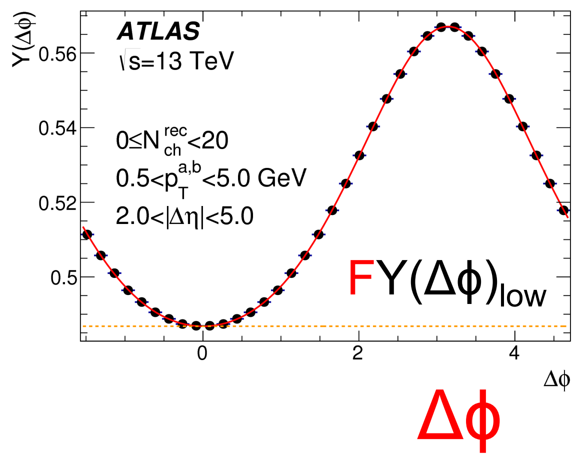

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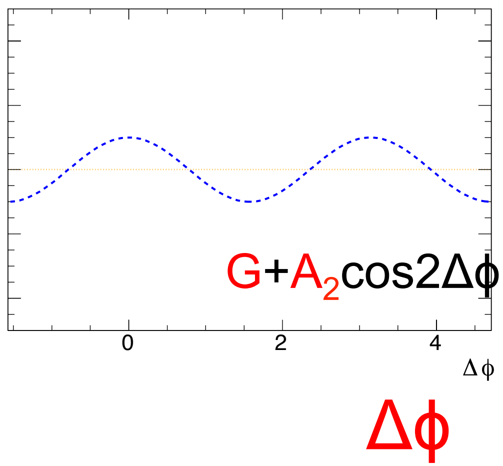
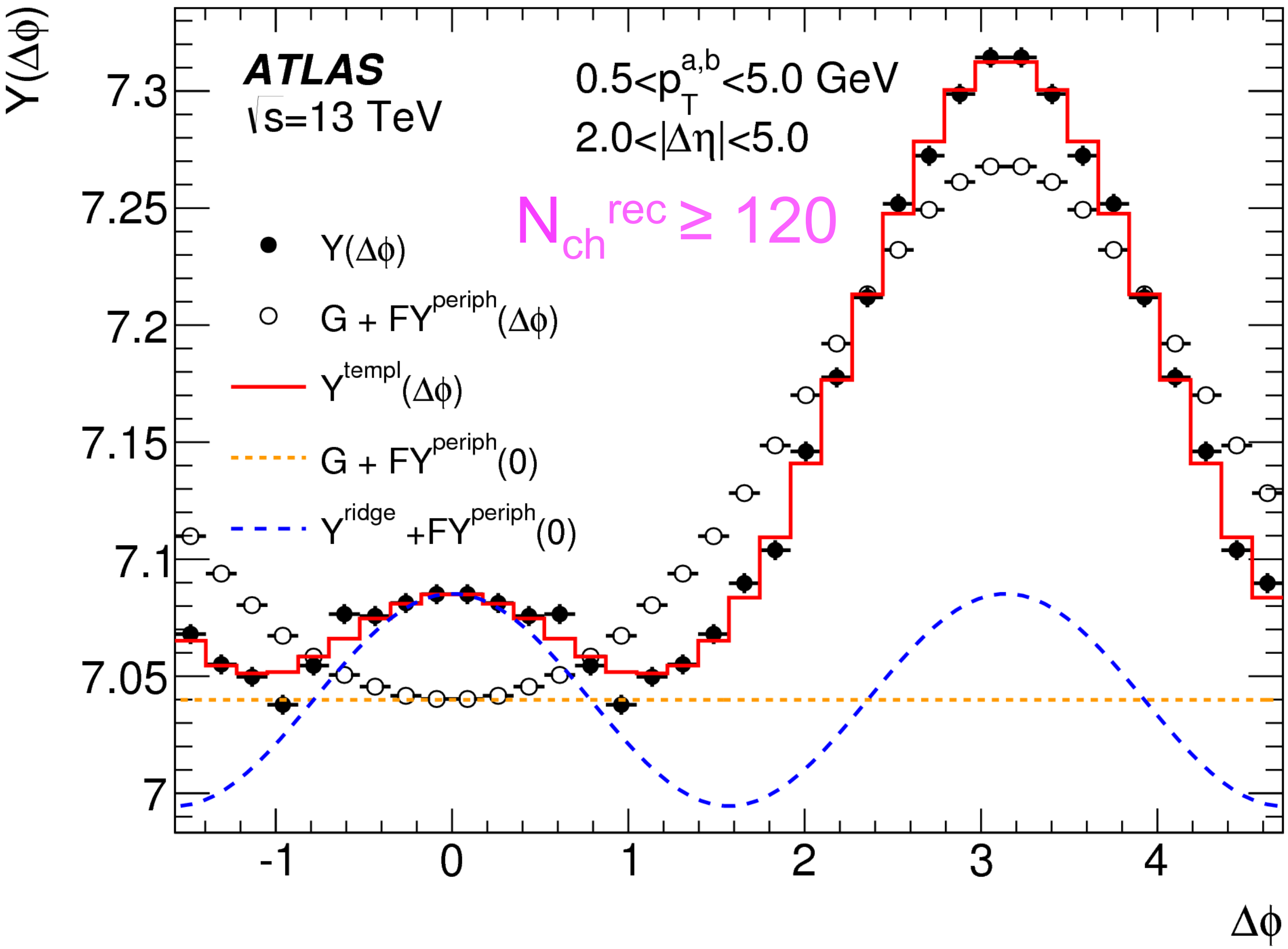




Assume away-side jet correlation unmodified

Narrowing of away Y(Δϕ) due to cos2Δϕ component

$$Y(\Delta\phi)^{\rm cent} \approx F\, Y(\Delta\phi)^{\rm peri} + G + A_2 \cos 2\Delta\phi$$

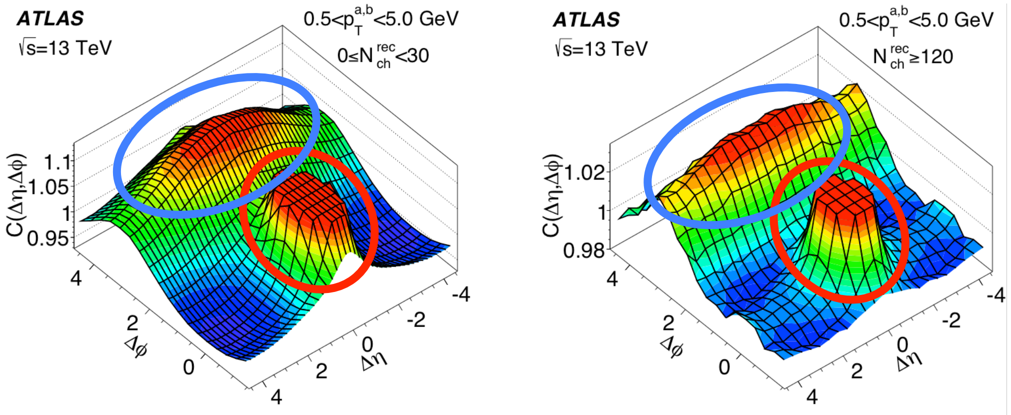
$$= F\, Y(\Delta\phi)^{\rm peri} + G\left(1 + 2v_2\{2,\mathrm{tmp}\}^2 \cos 2\Delta\phi\right)$$

Template fit v_n $= \frac{A_2}{2G}$

How to define scale factor F?

- Observation: $Y(\Delta\phi)^{\mathrm{cent}} = F\, Y(\Delta\phi)^{\mathrm{peri}} + G + A_2 \cos 2\Delta\phi + A_3 \cos 3\Delta\phi \ldots$

- F determined via
  - Scale near-side short-range peak
    - ATLAS/CMS/STAR
  - Scale away-side jet
    - ATLAS



$$F = \begin{cases} Y_{\mathrm{Jet}}^{\mathrm{Near}}(\mathrm{cent}) \big/ Y_{\mathrm{Jet}}^{\mathrm{Near}}(\mathrm{peri}) \\ Y_{\mathrm{Jet}}^{\mathrm{Away}}(\mathrm{cent}) \big/ Y_{\mathrm{Jet}}^{\mathrm{Away}}(\mathrm{peri}) \end{cases}$$

How to define scale factor F?

- Observation: $Y(\Delta\phi)^{\text{cent}} = F\, Y(\Delta\phi)^{\text{peri}} + G + A_2 \cos 2\Delta\phi + A_3 \cos 3\Delta\phi \ldots$

- F determined via
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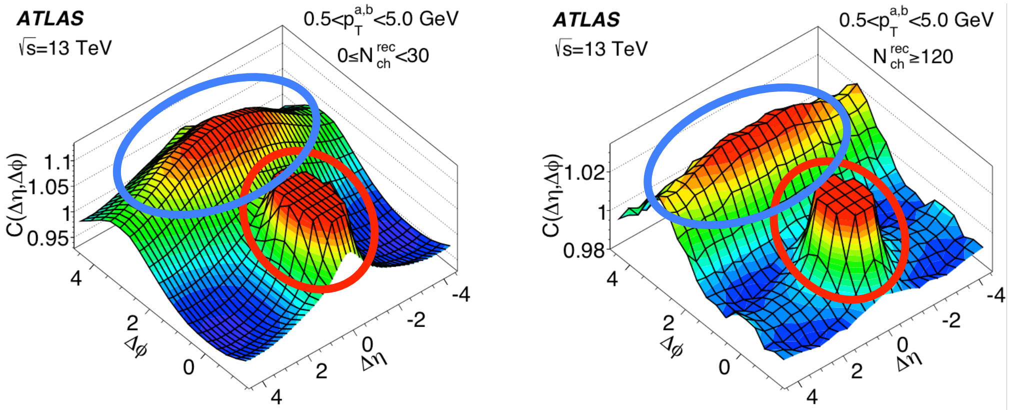
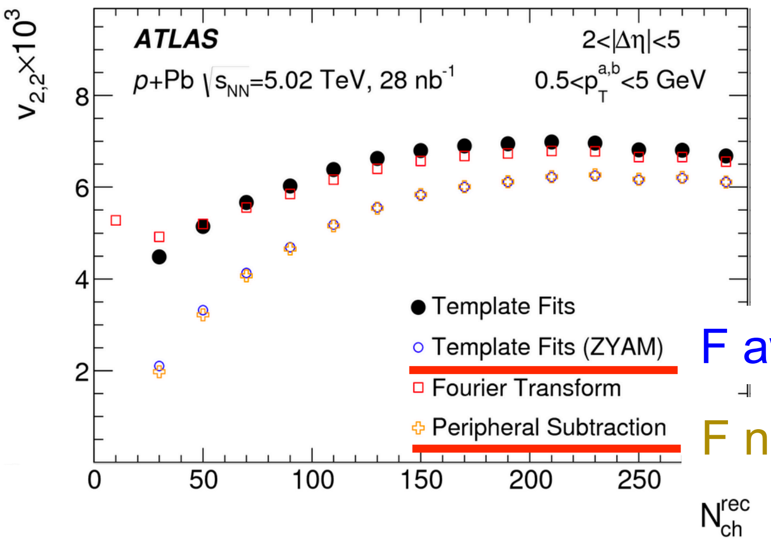


$$F = \begin{cases} Y_{\text{Jet}}^{\text{Near}}(\text{cent}) \big/ Y_{\text{Jet}}^{\text{Near}}(\text{peri}) \\ Y_{\text{Jet}}^{\text{Away}}(\text{cent}) \big/ Y_{\text{Jet}}^{\text{Away}}(\text{peri}) \end{cases}$$



F away-side jet

F near-side jet

Method for F make little difference for v_n! (not true at RHIC)

How to define v_n: "Template fit" method

- Observation: $Y(\Delta\phi)^{\mathrm{cent}} = F\, Y(\Delta\phi)^{\mathrm{peri}} + G^{\mathrm{tmp}} + A_2 \cos 2\Delta\phi + A_3 \cos 3\Delta\phi \ldots$

$$\boxed{v_n^2\{2,\mathrm{tmp}\} = \frac{1}{2}\frac{A_n}{G^{\mathrm{tmp}}}} \qquad = F\, Y(\Delta\phi)^{\mathrm{peri}} + G^{\mathrm{tmp}}\left(1 + 2\sum_{n=2}^{\infty} v_n\{2,\mathrm{tmp}\}^2 \cos n\Delta\phi\right)$$

Template fit v_n

- Each distribution should contain a jet and flow component

$$Y(\Delta\phi)^{\mathrm{cent}} = Y(\Delta\phi)^{\mathrm{cent}}_{\mathrm{jet}} + G^{\mathrm{cent}}\left(1 + 2\sum_{n=2}^{\infty} v_n\{2,\mathrm{cent}\}^2 \cos n\Delta\phi\right)$$

$$Y(\Delta\phi)^{\mathrm{peri}} = Y(\Delta\phi)^{\mathrm{peri}}_{\mathrm{jet}} + G^{\mathrm{peri}}\left(1 + 2\sum_{n=2}^{\infty} v_n\{2,\mathrm{peri}\}^2 \cos n\Delta\phi\right)$$

- Therefore $\boxed{v_n\{2,\mathrm{tmp}\}^2 = \frac{v_n\{2,\mathrm{cent}\}^2 - \alpha v_n\{2,\mathrm{peri}\}^2}{1-\alpha}, \alpha = \frac{F\, G^{\mathrm{peri}}}{G^{\mathrm{tmp}} + F\, G^{\mathrm{peri}}}}$

$$\rightarrow v_n\{2,\mathrm{cent}\}^2 = v_n\{2,\mathrm{tmp}\}^2 - (1-\alpha)\left(v_n\{2,\mathrm{tmp}\}^2 - v_n\{2,\mathrm{peri}\}^2\right)$$

If flow has no N_{ch} dependence $\quad v_n\{2,\mathrm{peri}\} = v_n\{2,\mathrm{cent}\}$

$v_n\{2,\mathrm{tmp}\}$ represents the true flow!

How to define v_n: "Peripheral sub." method

- Observation: $Y(\Delta\phi)^{\mathrm{cent}} = F\, Y(\Delta\phi)^{\mathrm{peri}} + G^{\mathrm{tmp}} + A_2 \cos 2\Delta\phi + A_3 \cos 3\Delta\phi \ldots$

$$\boxed{v_n^2\{2,\mathrm{tmp}\} = \frac{1}{2}\frac{A_n}{G^{\mathrm{tmp}}}} \qquad = F\, Y(\Delta\phi)^{\mathrm{peri}} + G^{\mathrm{tmp}}\left(1 + 2\sum_{n=2}^{\infty} v_n\{2,\mathrm{tmp}\}^2 \cos n\Delta\phi\right)$$

Template fit v_n

- Each distribution should contain a jet and flow component

$$Y(\Delta\phi)^{\mathrm{cent}} = Y(\Delta\phi)^{\mathrm{cent}}_{\mathrm{jet}} + G^{\mathrm{cent}}\left(1 + 2\sum_{n=2}^{\infty} v_n\{2,\mathrm{cent}\}^2 \cos n\Delta\phi\right)$$

$$Y(\Delta\phi)^{\mathrm{peri}} = Y(\Delta\phi)^{\mathrm{peri}}_{\mathrm{jet}} + G^{\mathrm{peri}}\left(1 + 2\sum_{n=2}^{\infty} v_n\{2,\mathrm{peri}\}^2 \cos n\Delta\phi\right)$$

- Therefore $\boxed{v_n\{2,\mathrm{tmp}\}^2 = \frac{v_n\{2,\mathrm{cent}\}^2 - \alpha v_n\{2,\mathrm{peri}\}^2}{1-\alpha}, \alpha = \frac{F\, G^{\mathrm{peri}}}{G^{\mathrm{tmp}} + F\, G^{\mathrm{peri}}}}$

- Include peripheral pedestal in flow definition via ZYAM

$\rightarrow$ $Y(\Delta\phi)^{\mathrm{cent}} = F\, Y(\Delta\phi)^{\mathrm{peri}}_{\mathrm{jet}} + G^{\mathrm{tmp}} + FG^{\mathrm{peri}} + A_2 \cos 2\Delta\phi + \ldots$

  - v_n defined as $\boxed{v_n^2\{2,\mathrm{sub}\} = \frac{1}{2}\frac{A_n}{G + FG^{\mathrm{peri}}} \equiv v_n\{2,\mathrm{cent}\}^2 - \alpha v_n\{2,\mathrm{peri}\}^2}$

The two differ by a simple factor 1-α

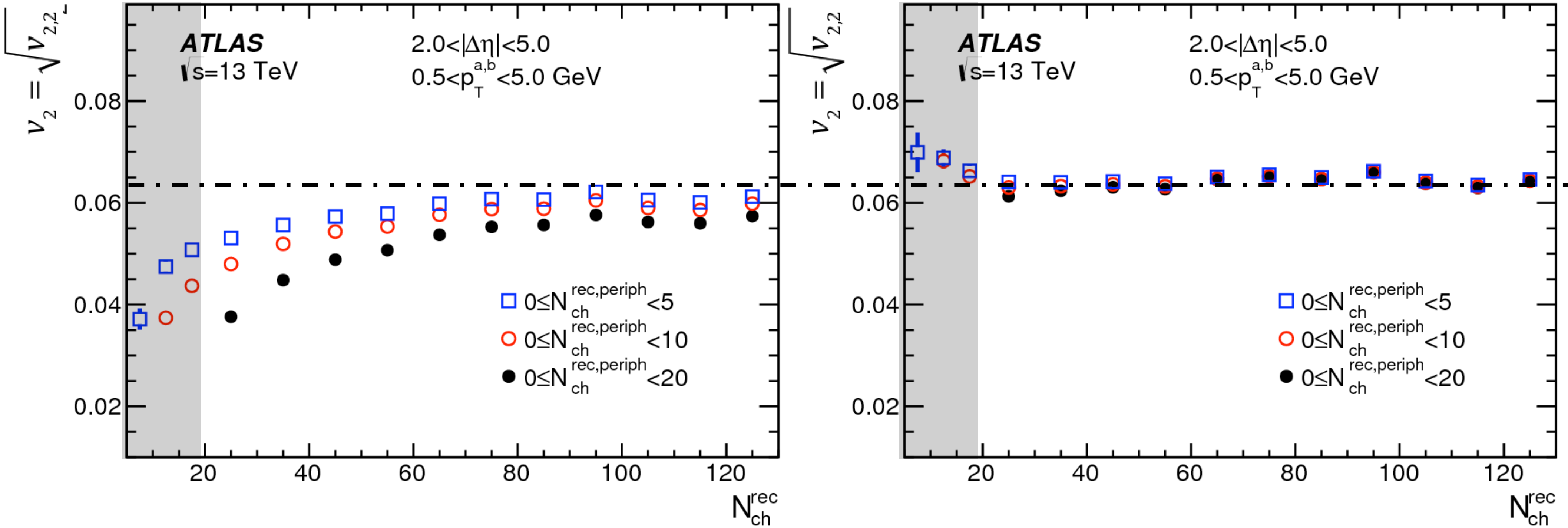
Compare the two approaches arxiv:1509.04776

Include pedestal

$$v_{2,2} = v_{2,2}^{cent} - a v_{2,2}^{peri}$$

Not include pedestal

$$v_{2,2} = \frac{v_{2,2}^{cent} - a v_{2,2}^{peri}}{1-a}$$



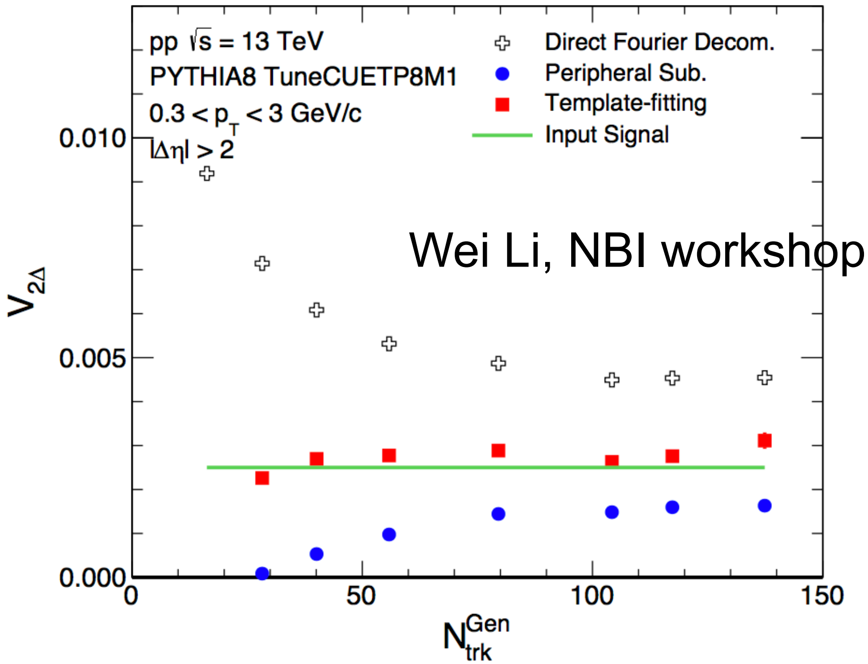
cos2Δϕ component has weak N_{ch} dependence in pp!

Correcting for residual bias in Template fit

- When v_n does change with N_{ch}, temp-fit results in a small bias

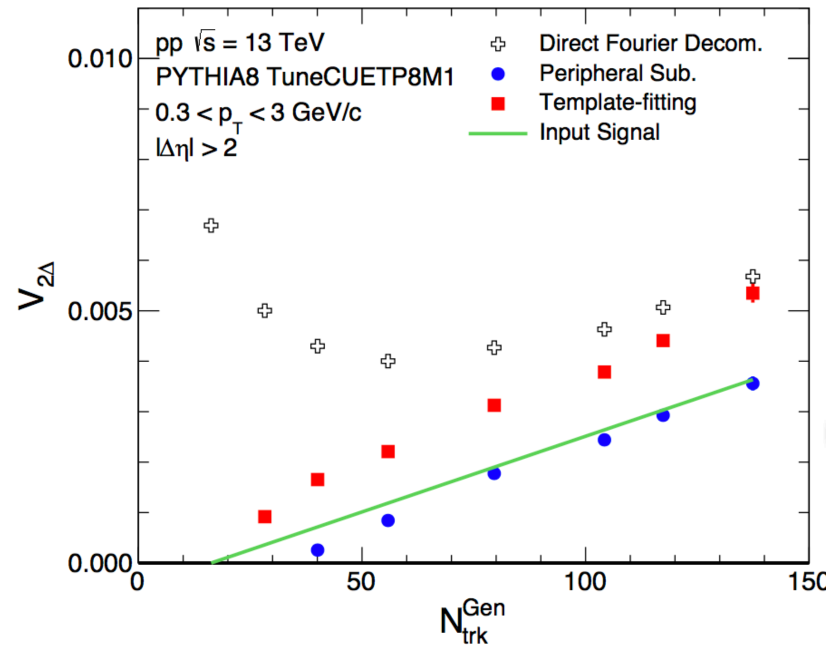
Flat v_2 vs N_{trk}

Temp. fit works better



Rising v_2 vs N_{trk}

Peri. sub. works better



$$\alpha = \frac{F\,G^{\rm peri}}{G^{\rm tmp} + F\,G^{\rm peri}}$$

- This bias can be mostly corrected:

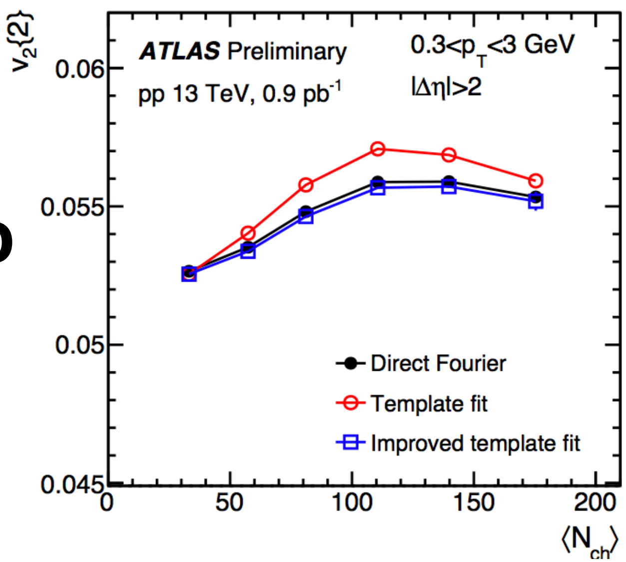
$$v_n\{2,\mathrm{cent}\}^2 = v_n\{2,\mathrm{tmp}\}^2 - (1-\alpha)\left(v_n\{2,\mathrm{tmp}\}^2 - v_n\{2,\mathrm{peri}\}^2\right)$$

by using v_n in 2nd N_{ch} bin as estimate for true v_n\{peri\}

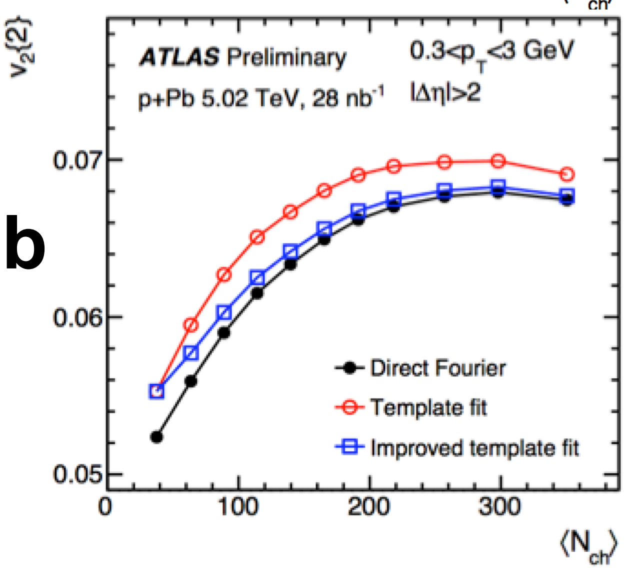
Improved template fit performance

- The corrected v_2 are similar but smaller than direct Fourier

pp



pPb



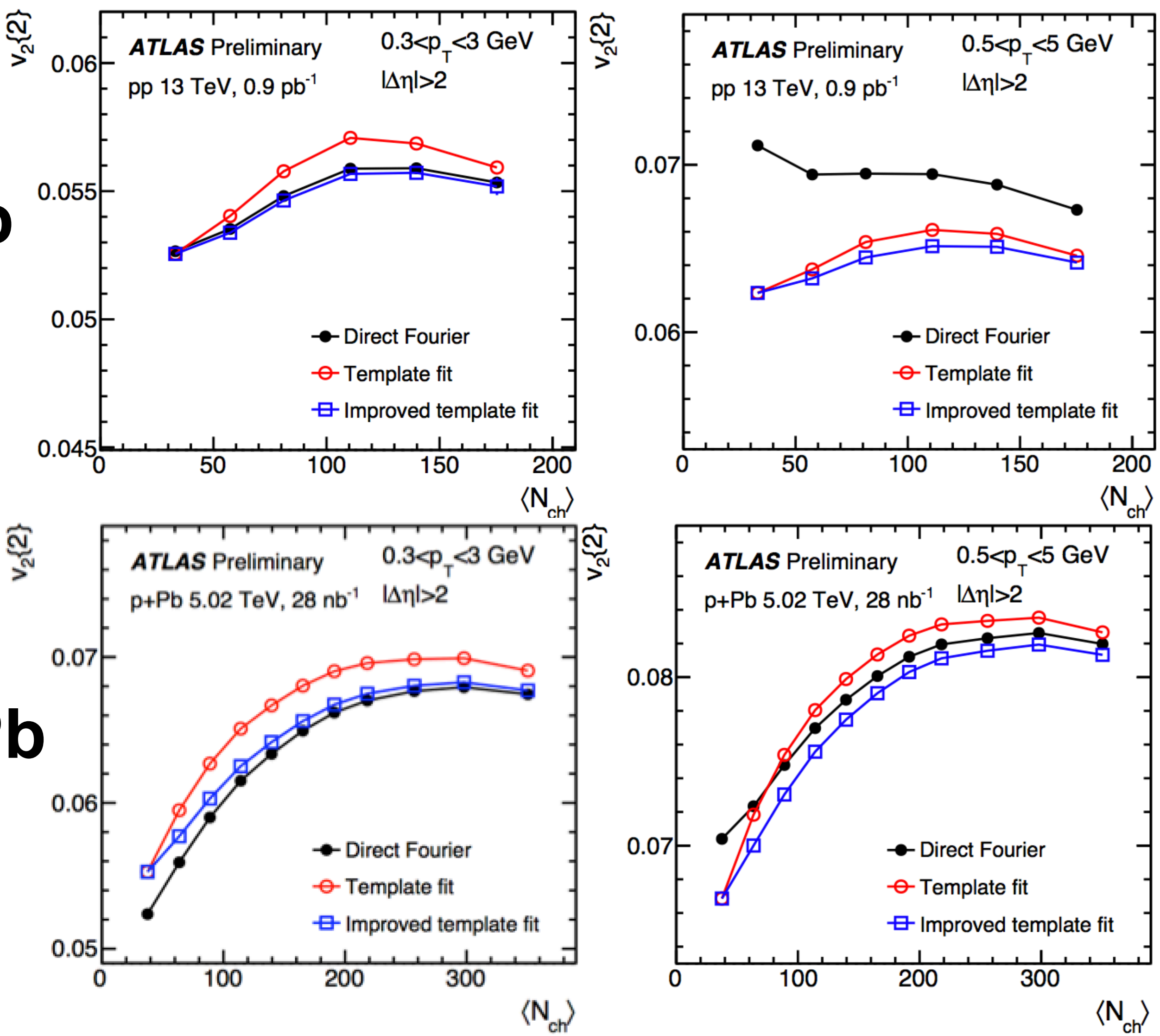
Improved template fit performance

- The corrected v_2 are similar but smaller than direct Fourier
- For higher p_T, where jet is larger, corrected v_2 < direct Fourier v_2

The trend of v_2 at low N_{ch} in pp?

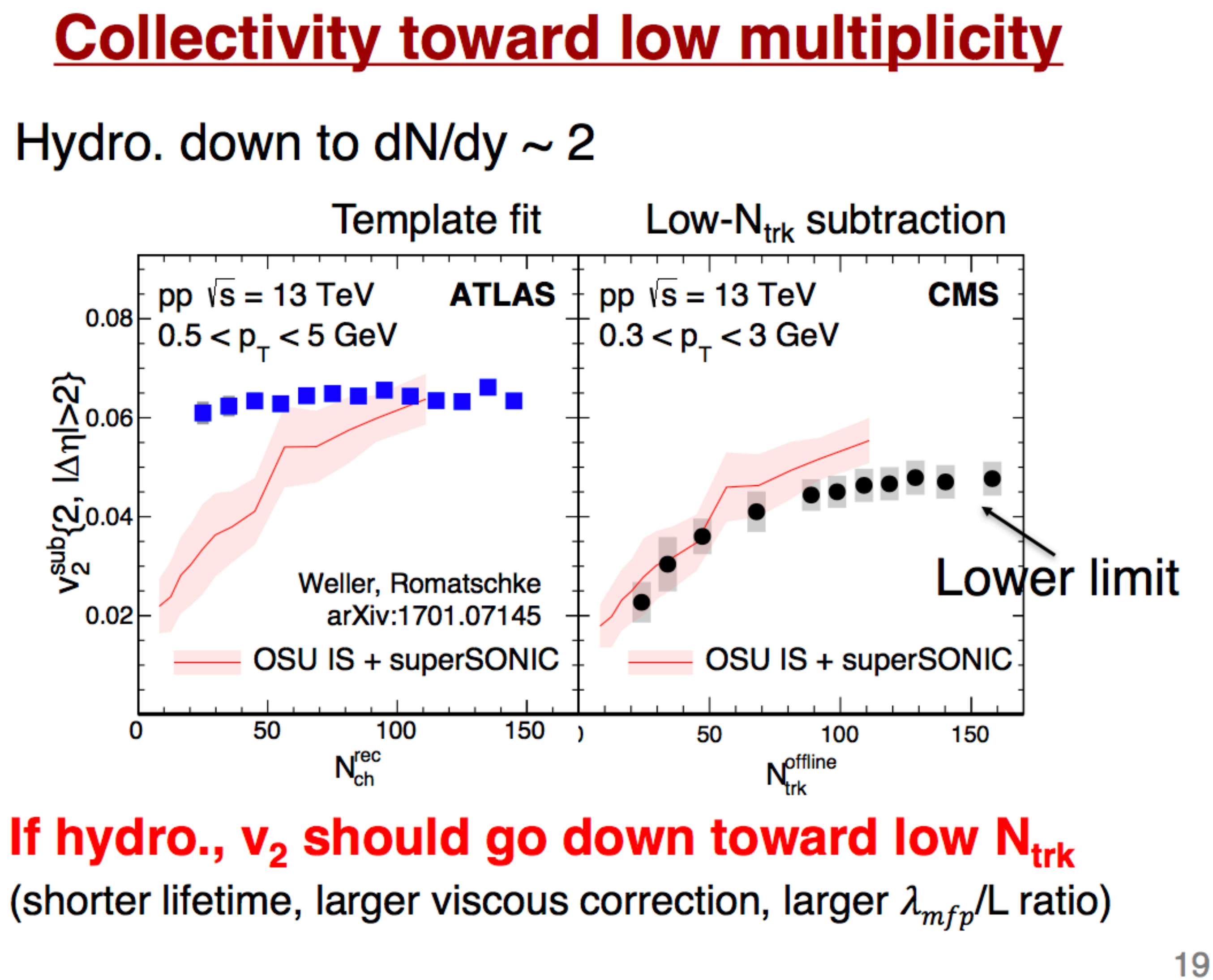
pp

pPb



What is the trend of v_2 at low N_{ch} in pp?

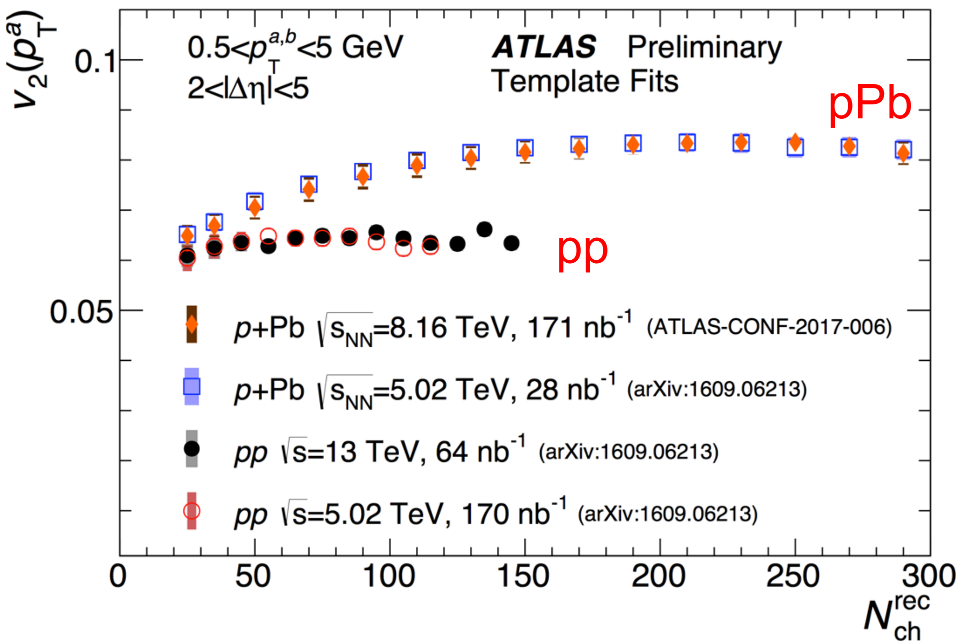
Wei Li, NBI workshop

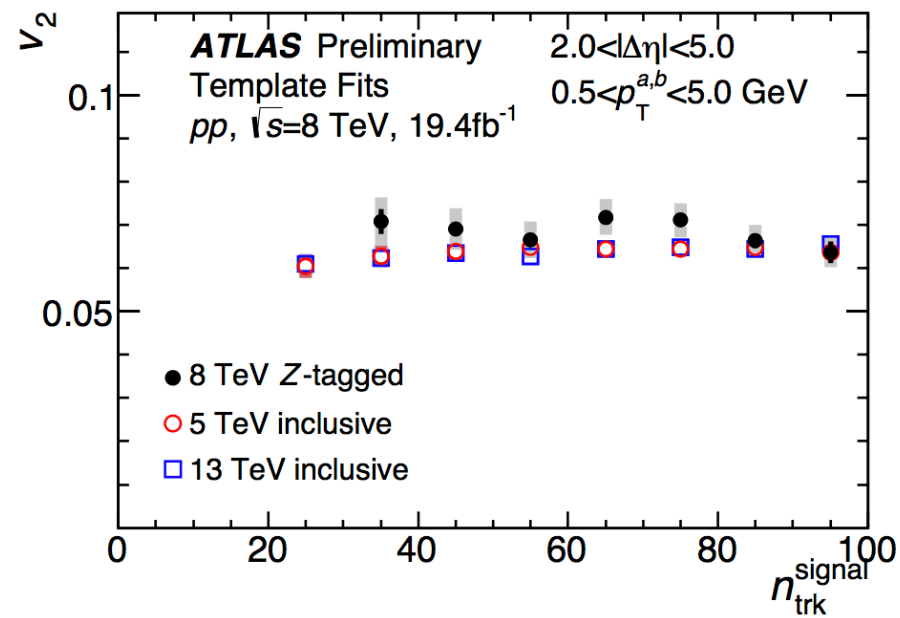


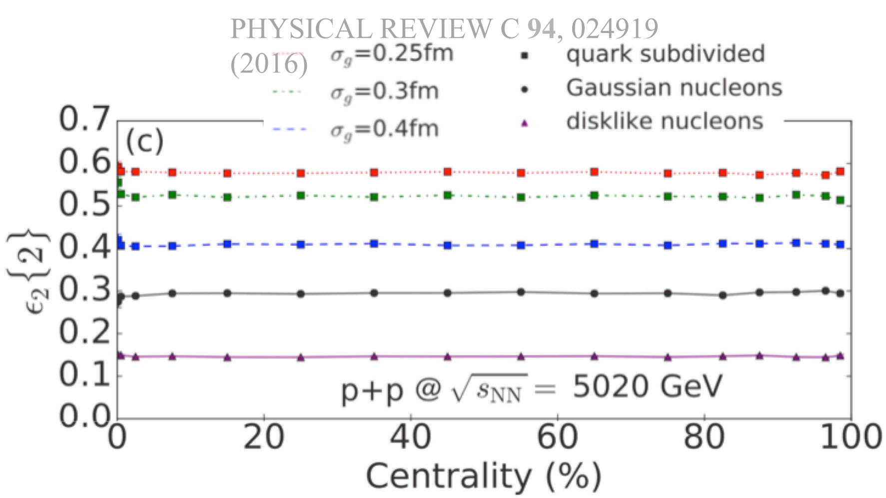
My answer: v_2 in pp is ~ constant with N_{ch}

How to understand this?

- Clear geometry effects seen in pPb
- But not seen in pp HMT or large-Q^2 events (with Z boson tag)







N_{ch} is not a good indicator of centrality!

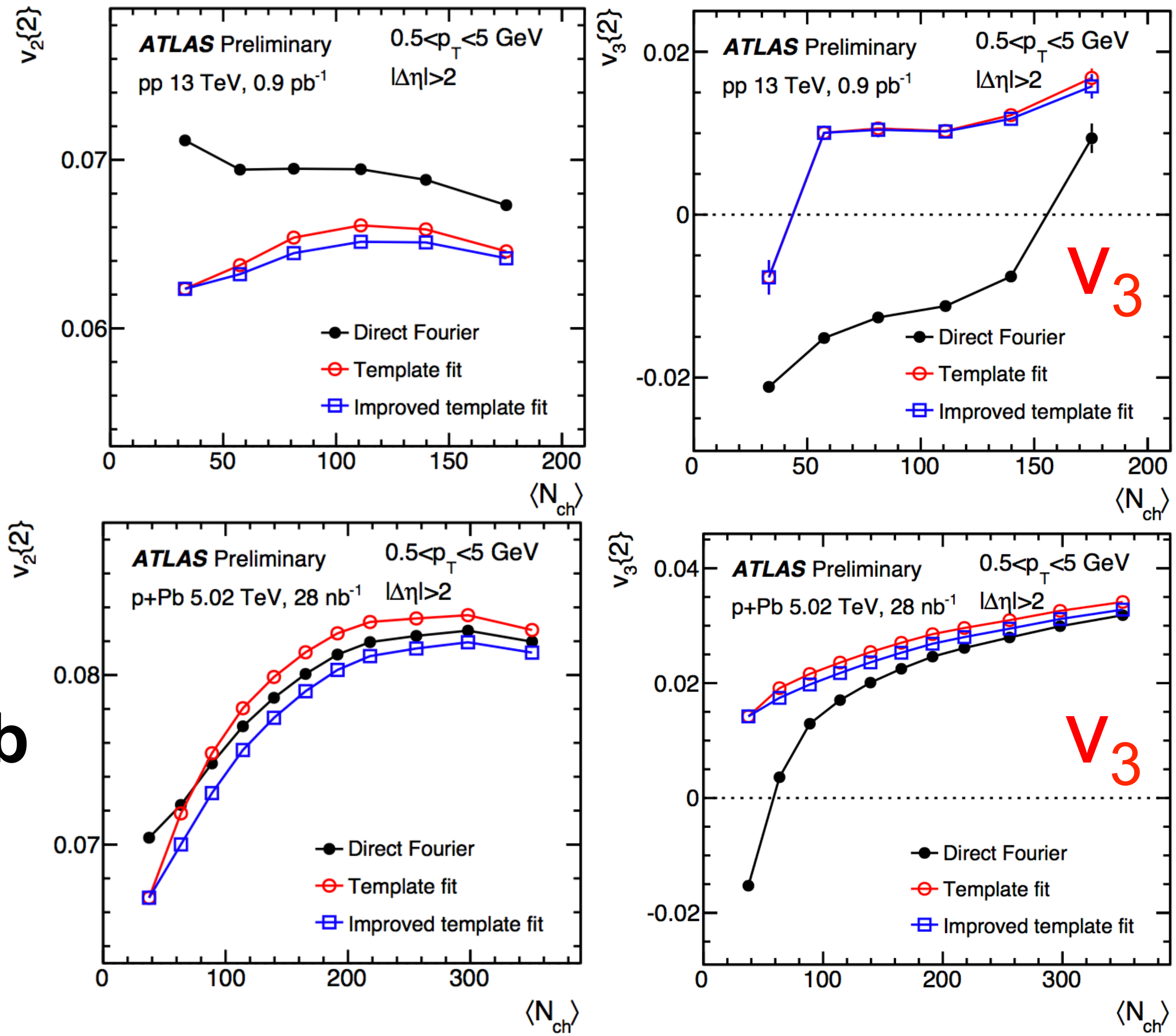
Multiplicity fluctuation in the final state mixes events from different impact parameters!

What about template fit for v_3 and v_4?

- The corrected v_3 are very different from direct Fourier

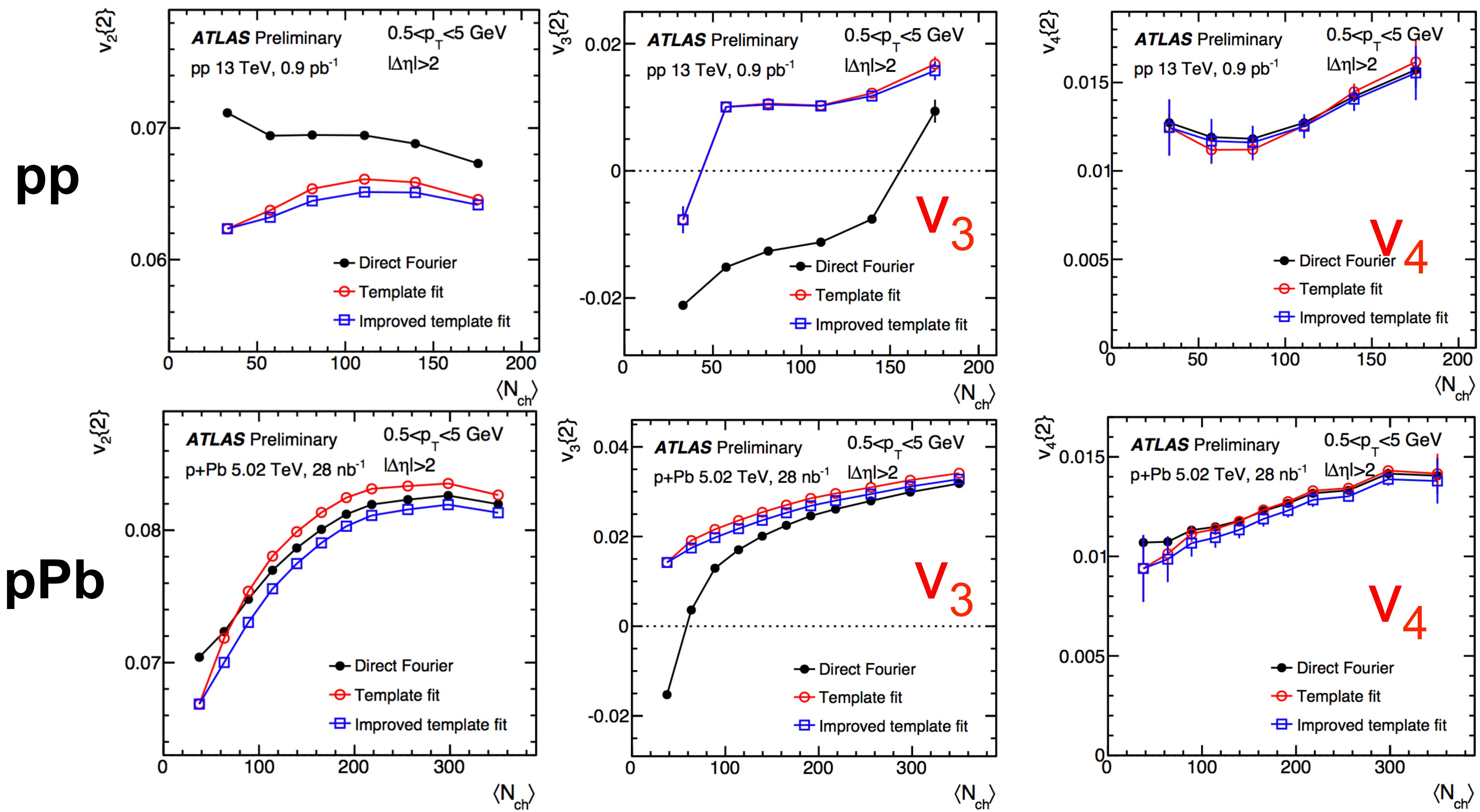
pp

pPb



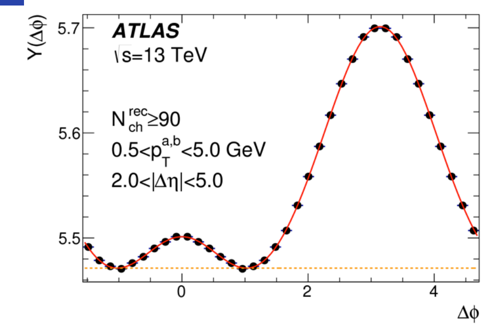
What about template fit for v_3 and v_4?

- The corrected v_3 are very different from direct Fourier
- The corrected v_4 are similar to direct Fourier (reflect NL from v_2^2)

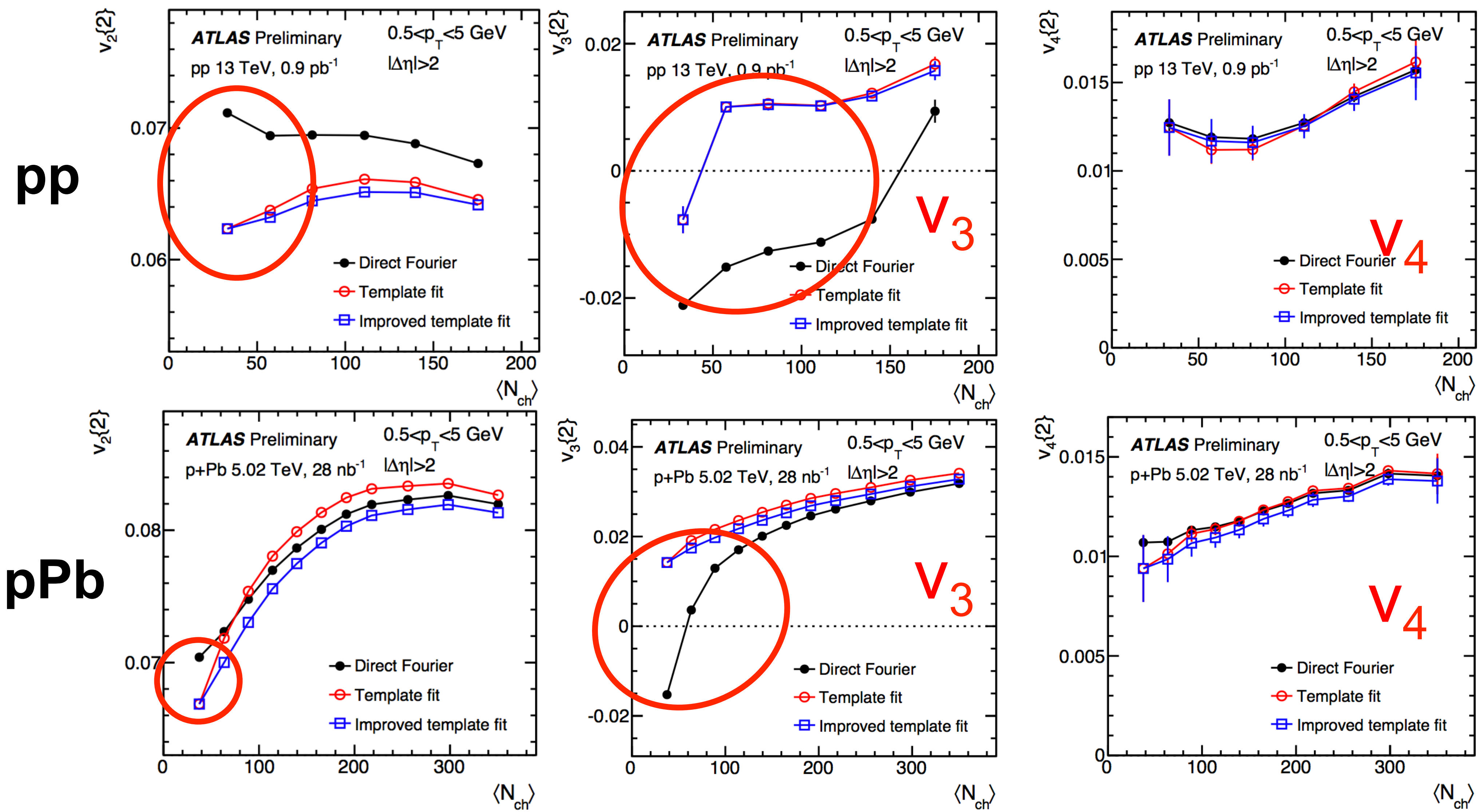


Bias from the away-side jet

- A peak at $\Delta\phi \sim \pi$ contribute +signal for even harmonics and -signal for odd harmonics

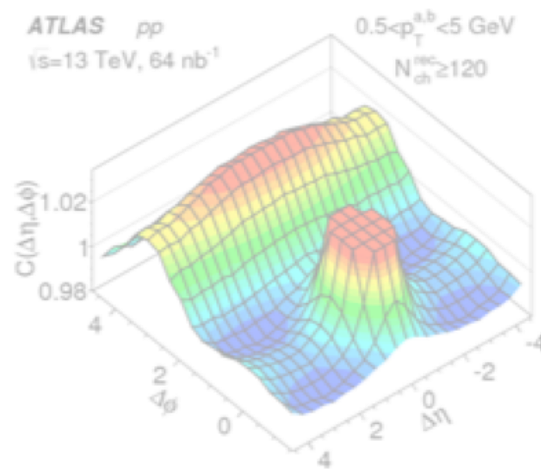


$v_{2,2}\{jet\}, v_{4,4}\{jet\}\ldots>0$; $v_{1,1}\{jet\}, v_{3,3}\{jet\}\ldots<0$



Observables for long-range ridge: cumulants

Two-particle cummlants



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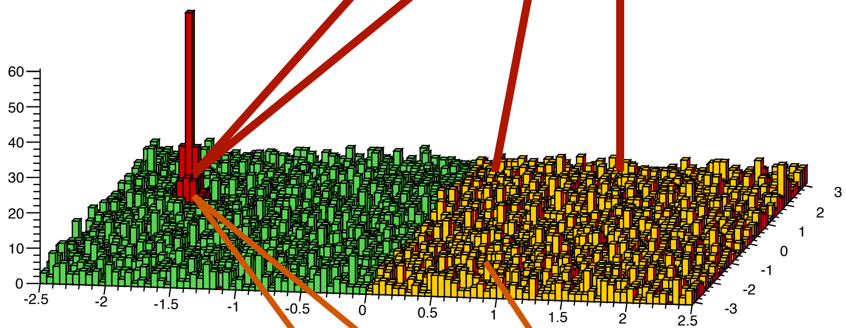
$$\mathrm{sc}_{n,m}\{4\} = \langle\langle \{4\}_{n,m} \rangle\rangle - \langle\langle \{2\}_n \rangle\rangle \langle\langle \{2\}_m \rangle\rangle = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle$$ Probe $p(v_n, v_m)$

Three-particle cumulants

$$\mathrm{ac}_n\{3\} = \langle\langle \{3\}_n \rangle\rangle = \langle v_n^2 v_{2n} \cos 2n(\Phi_n - \Phi_{2n}) \rangle$$ Probe $p(\Phi_n, \Phi_m)$

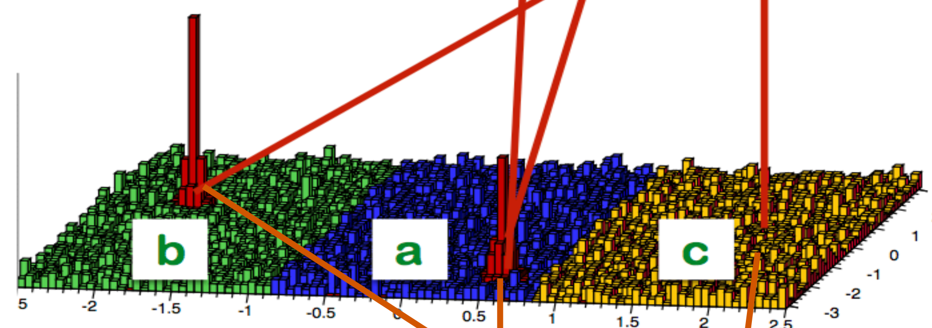
Suppress non-flow via subevent cumulants

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



$$\langle\{3\}_n\rangle_{2a|b} = \left\langle e^{i(n\phi_1^a+n\phi_2^a-2n\phi_3^b)}\right\rangle$$

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



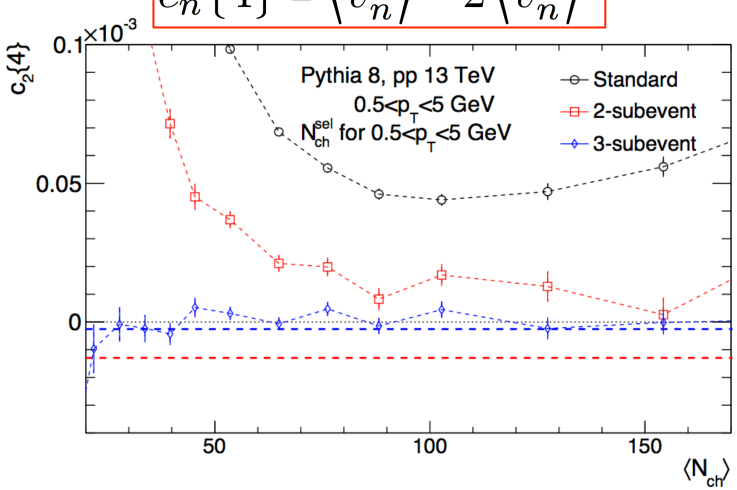
$$\langle\{3\}_n\rangle_{a,b|c} = \left\langle e^{i(n\phi_1^a+n\phi_2^b-2n\phi_3^c)}\right\rangle$$

2-subevent removes intra-jet corr.

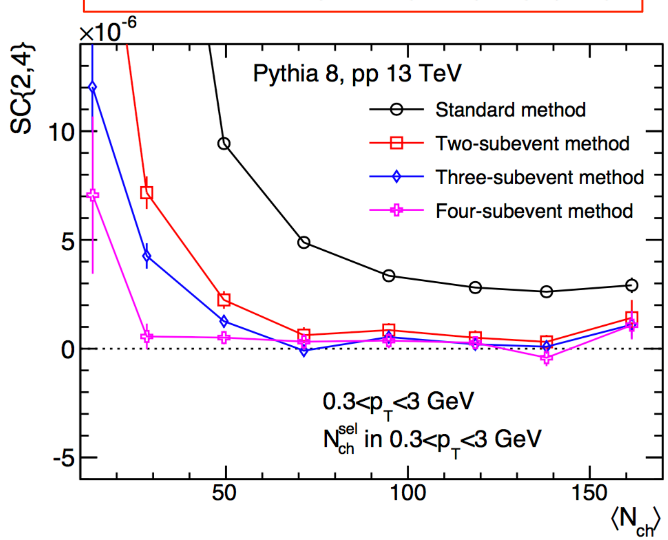
3- or 4-subevent removes inter-jet corr.

Performance validated in PYTHIA: 1701.03830, 1710.07567

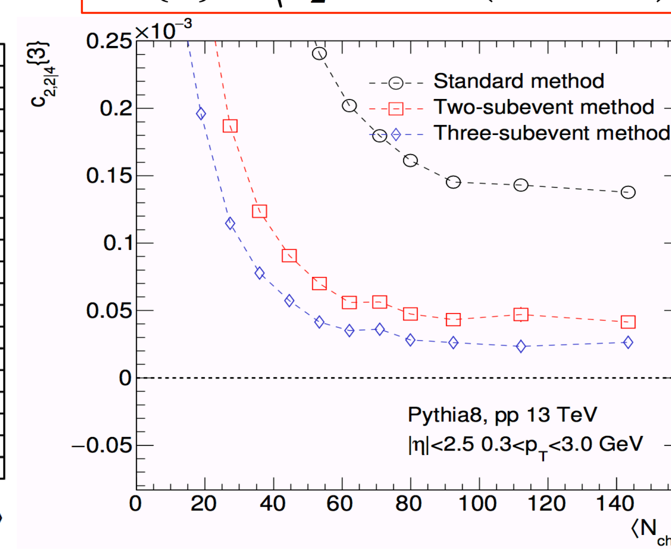
$\boxed{c_n\{4\} = \left\langle v_n^4\right\rangle - 2\left\langle v_n^2\right\rangle^2}$



$\boxed{sc_{2,4}\{4\} = \left\langle v_2^2 v_4^2\right\rangle - \left\langle v_2^2\right\rangle\left\langle v_4^2\right\rangle}$

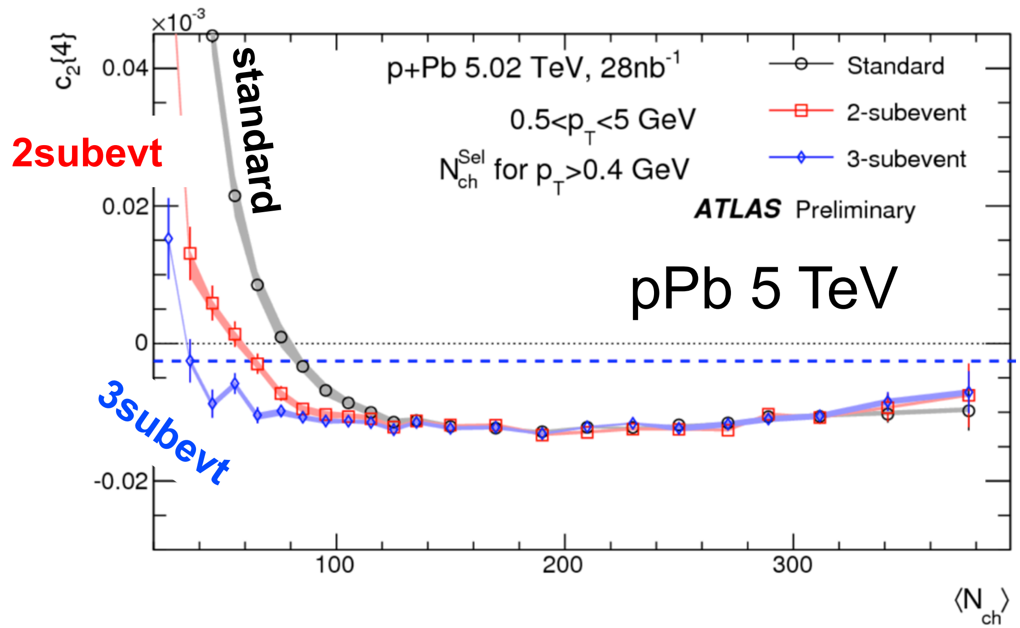


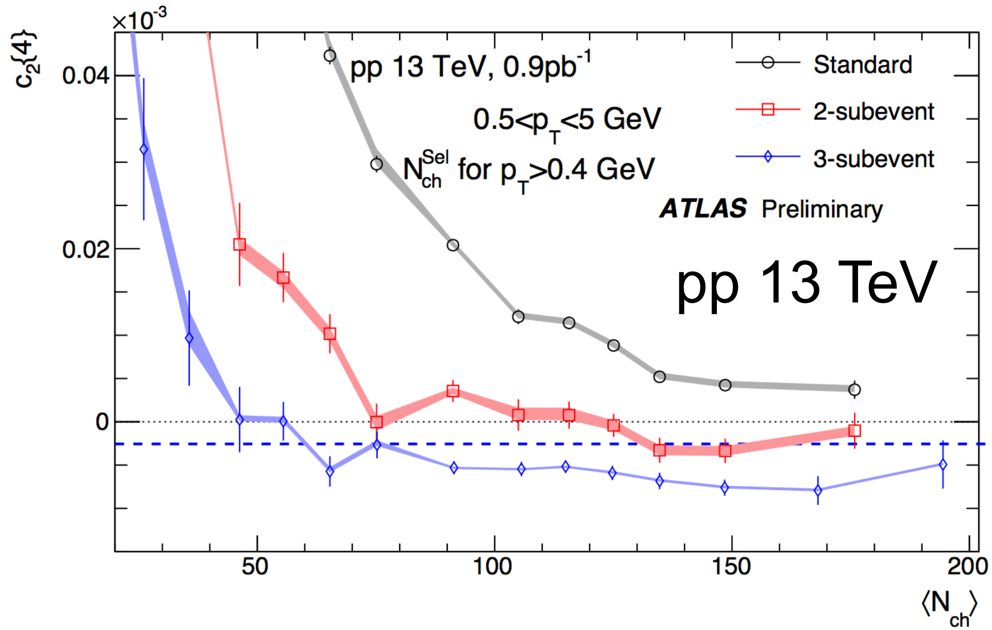
$\boxed{ac_2\{3\} = \left\langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\right\rangle}$



$c_2\{4\}$ from different methods in data

- pPb: methods consistent for N_{ch}>100, but split below that
- pp: Only subevent method gives negative $c_2\{4\}$ in broad N_{ch} range

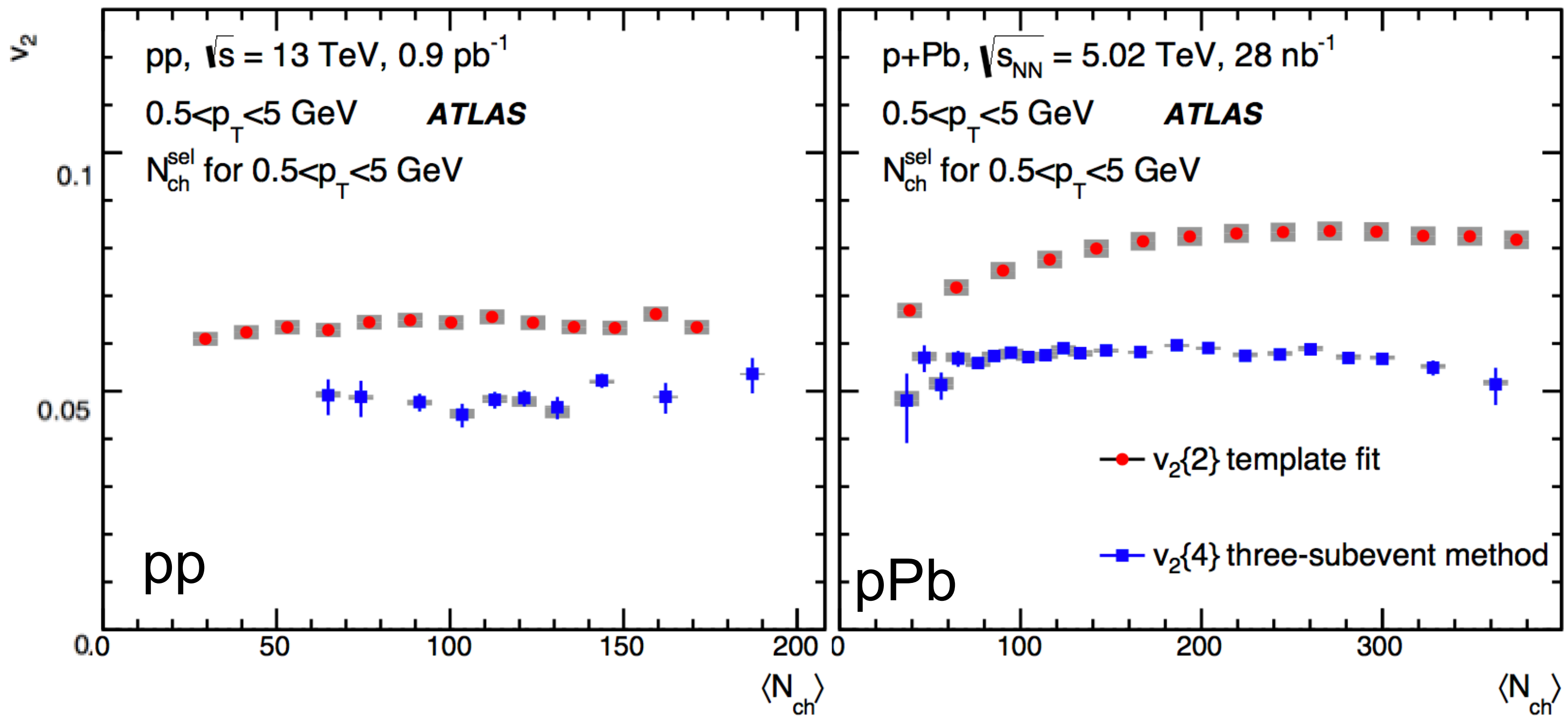




Direct evidence of significant collectivity down to very low N_{ch}

$v_2\{4\}$ vs. $v_2\{2\}$

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



- $v_2\{4\}_{\text{three-sub}} < v_2\{2\}_{\text{temp-fit}}$ as expected

PRL112,082301(2014)

- Fluc. of ε_2 (therefore v_2) is driven by fluc. of independent sources
  - N_s can be estimate from $v_2\{4\}/v_2\{2\}$ $\quad \dfrac{v_2\{4\}}{v_2\{2\}} \approx \dfrac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}} = \left[\dfrac{4}{(3+N_s)}\right]^{1/4}$

Relate to the initial geometry

1708.03559

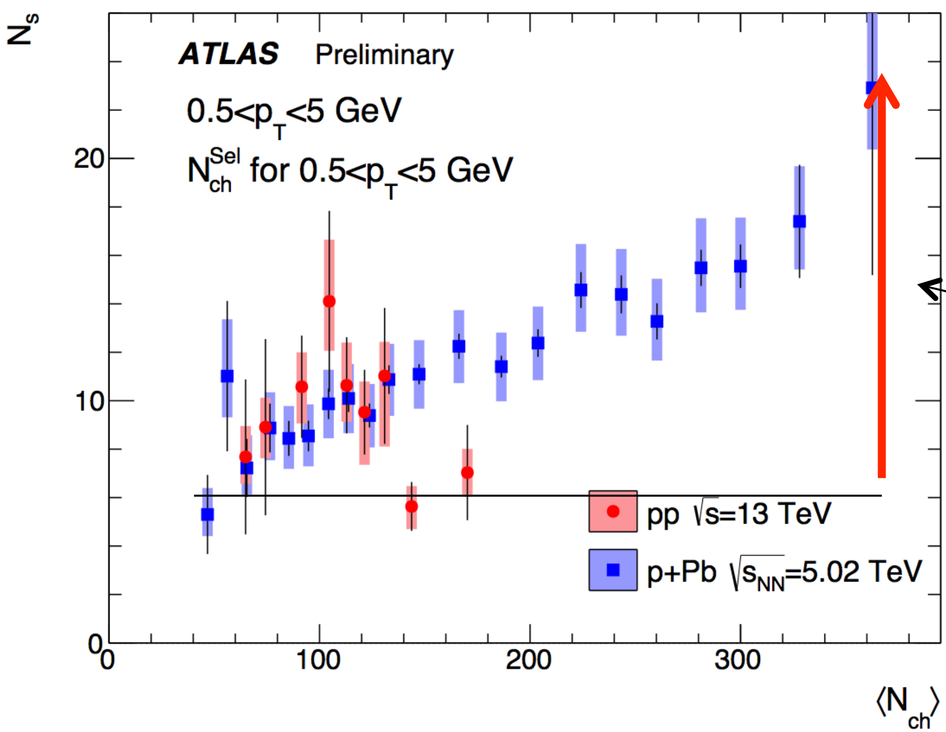
Sources driving the transverse flow

$$\frac{v_2\{4\}}{v_2\{2\}} \approx \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}} = \left[\frac{4}{(3+N_s)}\right]^{1/4}$$

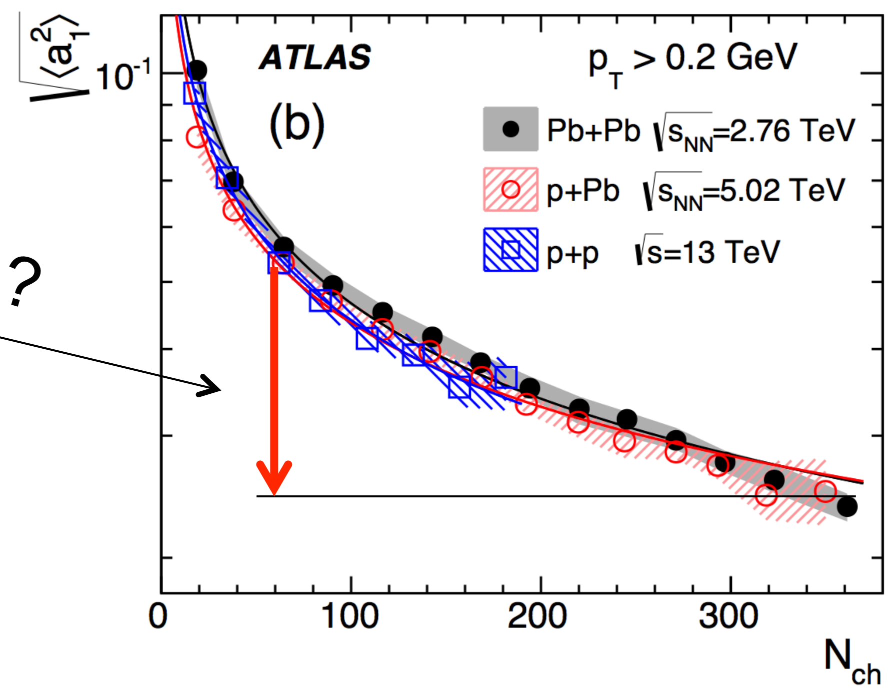
1606.08170

Source for particle production which drives FB multiplicity fluc.

$$\frac{N(\eta)}{\langle N(\eta)\rangle} \approx 1 + a_1\eta \quad a_1 \propto 1\Big/\sqrt{N_s}$$

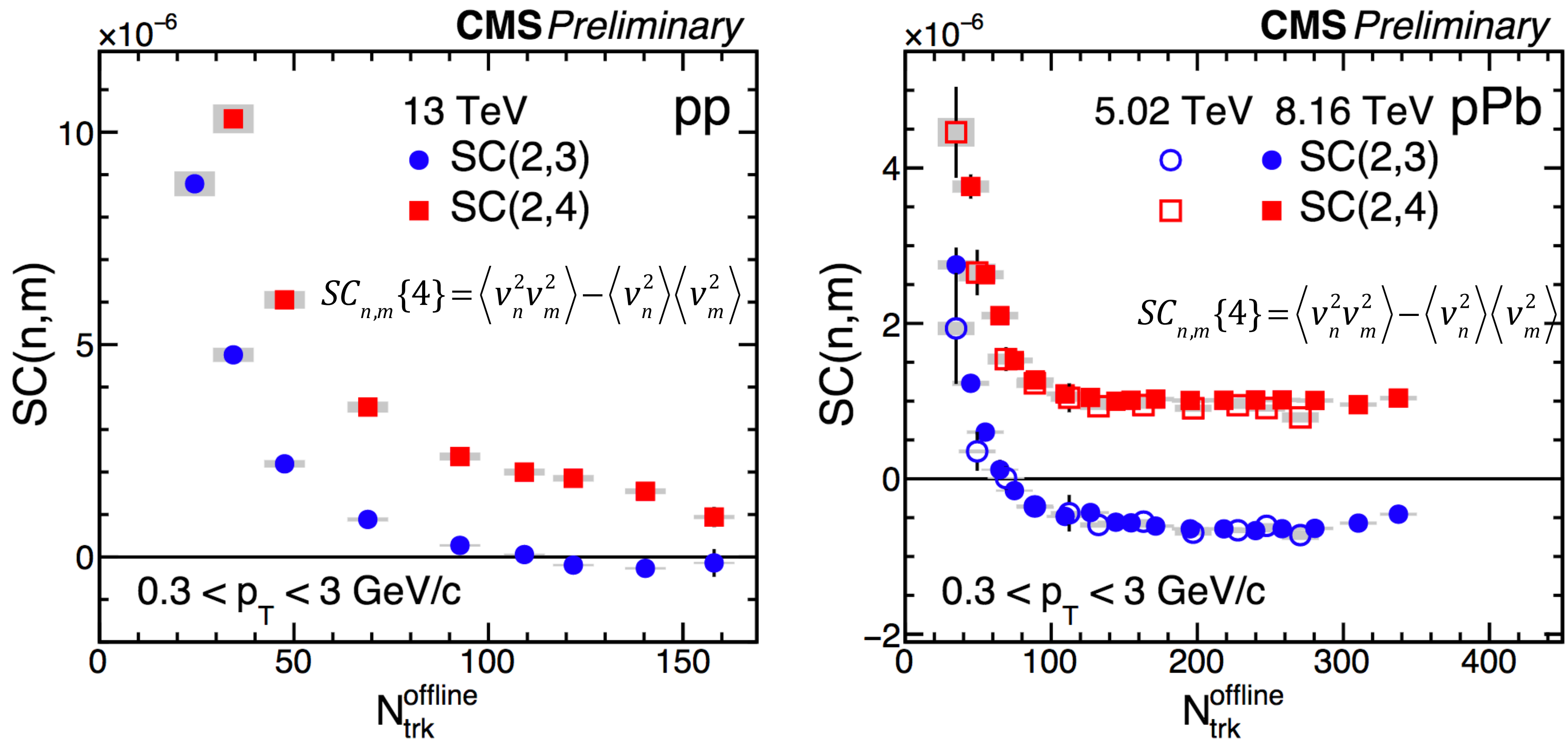


N_S ?



Are these two sources related?

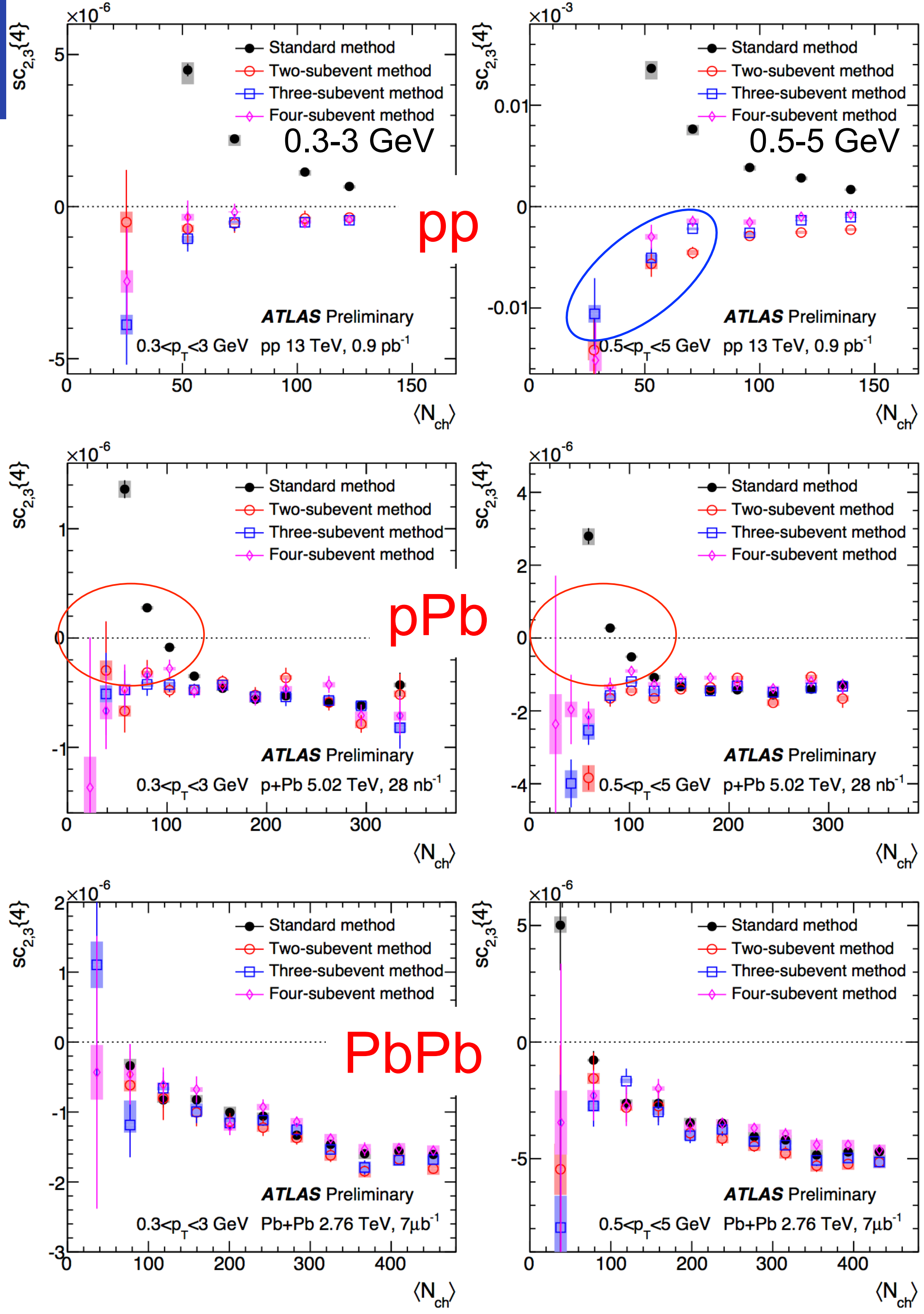
Symmetric cumulant: $sc_{2,3}\{4\}$ and $sc_{2,4}\{4\}$



- Naturally understood in hydrodynamics
  - $v_2 v_3$ reflects $\varepsilon_2\varepsilon_3$ anti-correlation, $v_2 v_4$ correlation reflects mode-mixing effects
- CGC can also qualitatively produce these trends 1705.00745
- But influence of non-flow need to be taken out.

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

- Non-flow dominate standard method in pp and low N_{ch} pPb
  - largely suppressed in subevent methods
- Little non-flow in PbPb
- Clear anti-correlation expected from $\varepsilon_2 - \varepsilon_3$ correlation
  - Similar to non-peripheral Pb+Pb collisions
- However, anti-correlation in low N_{ch} could also come from dijets (later)

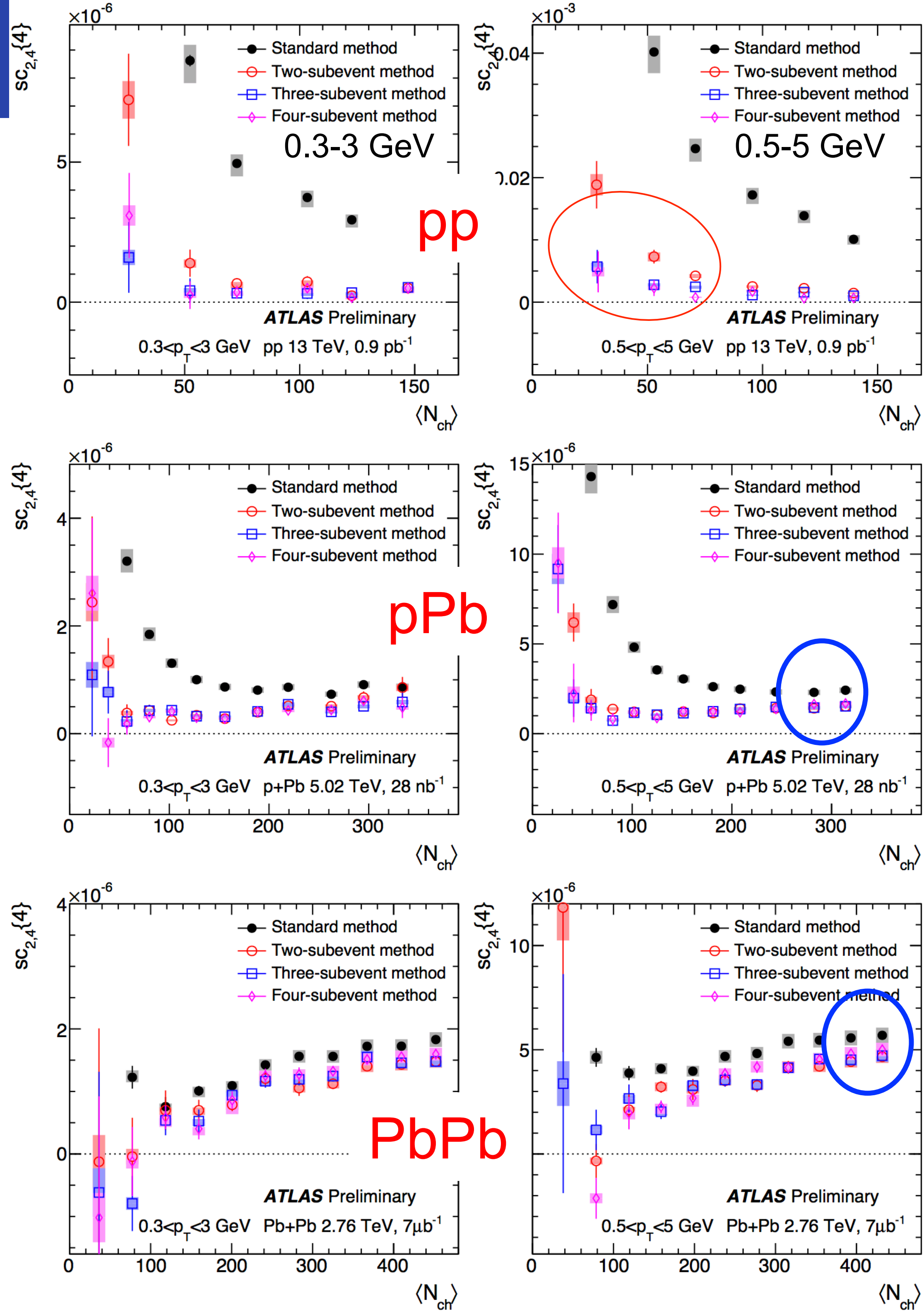


$sc_{2,4}\{4\}$

- Standard method has much larger non-flow in pp and pPb.
  - Subevent methods are closer, 2-sub still show some non-flow.
- Little non-flow in PbPb
- Positive correlation due to nonlinear effects

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

- Difference between standard & subevent at large N_{ch} in pPb and PbPb due to non-flow and flow decorrelation

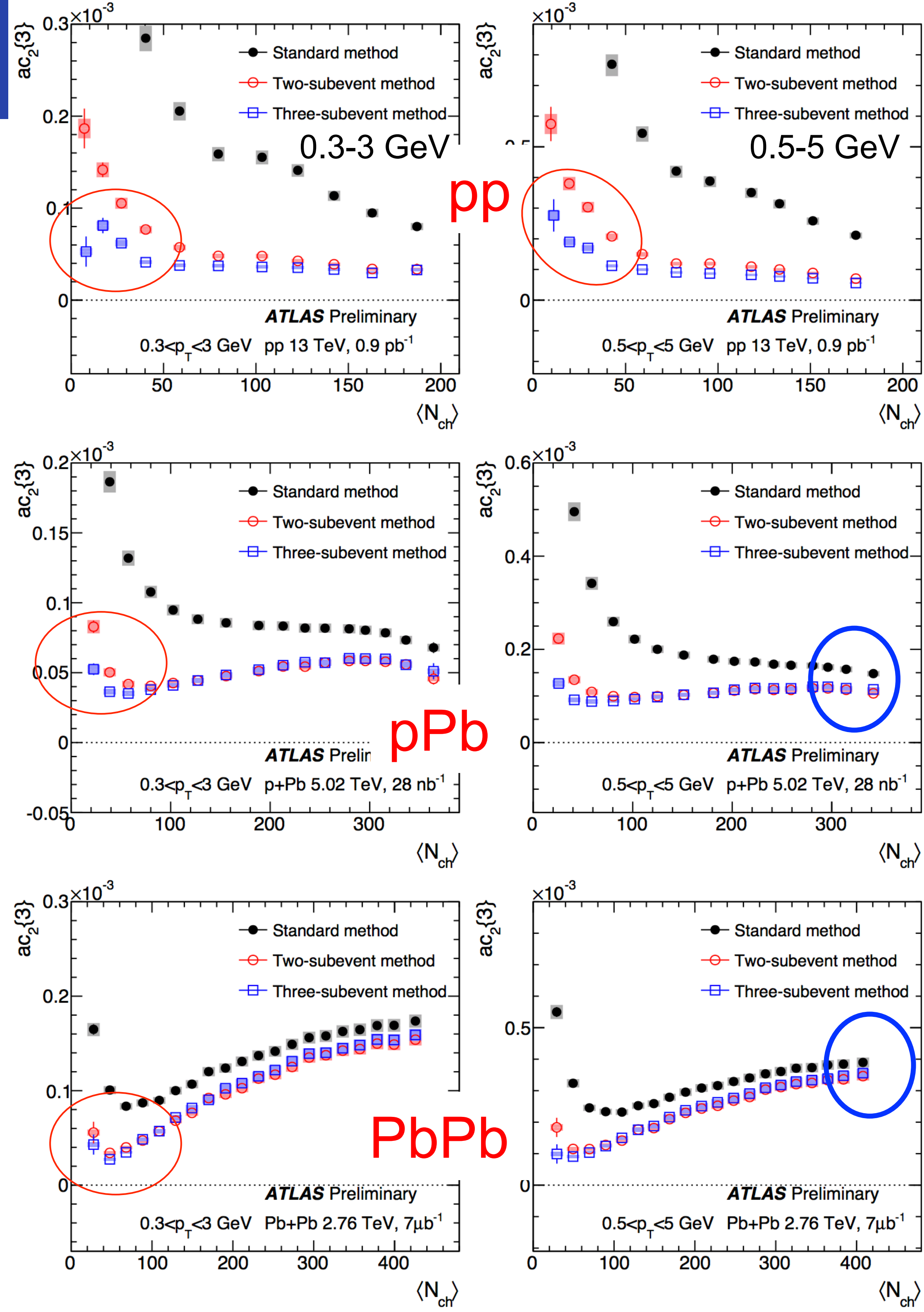


$ac_2\{3\}$

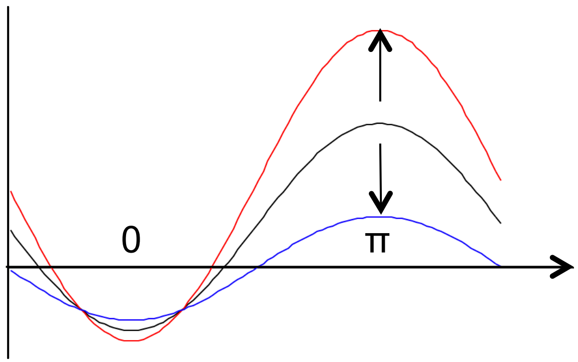
- Subevent method effectively suppress non-flow.
  - Small non-flow still present at low N_{ch}.
- Positive correlation due to nonlinear effects

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

- N_{ch} dep. of $ac_2\{3\}$ reflects N_{ch} dep. of v_2
  - Direct evidence of ~ cons v_2 in pp!
  - Rise and fall of v_2 with N_{ch} in pPb
- Difference between standard and subevent methods at large N_{ch} due to non-flow and flow decorrelations.



Symmetric cumulants from dijets?

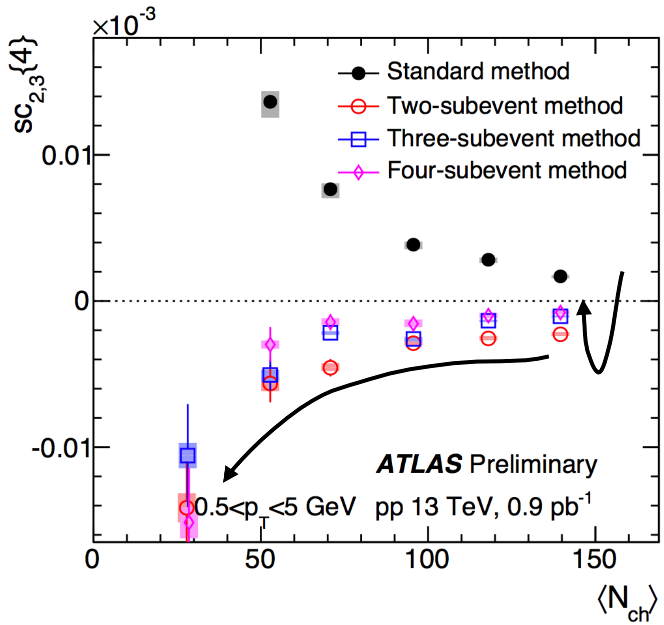


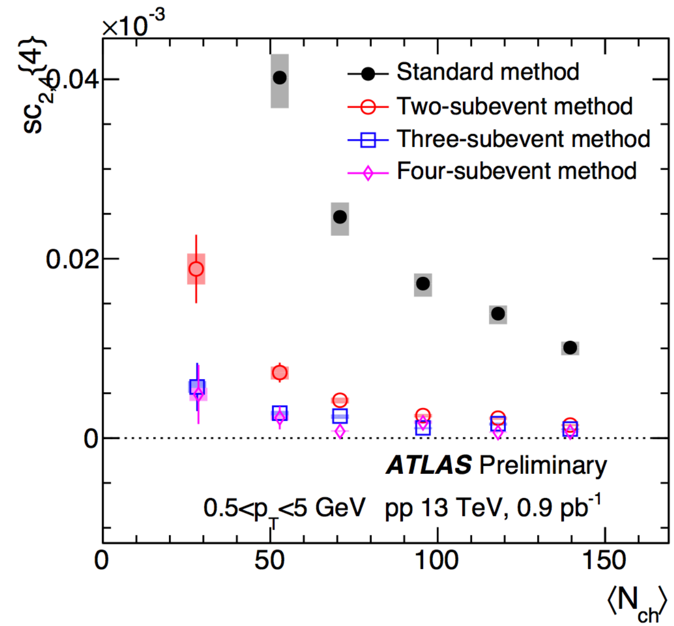
Away peak increase v_2^2, v_4^4 and decrease v_1^2, v_3^2..➔

EbyE fluc. of dijets give anti-corr. v_2v_3 and corr for v_2v_4

$$\mathrm{sc}_{2,3}\{4\} = \left\langle v_2^2 v_3^2 \right\rangle - \left\langle v_2^2 \right\rangle \left\langle v_3^2 \right\rangle \qquad \mathrm{sc}_{2,4}\{4\} = \left\langle v_2^2 v_4^2 \right\rangle - \left\langle v_2^2 \right\rangle \left\langle v_4^2 \right\rangle$$

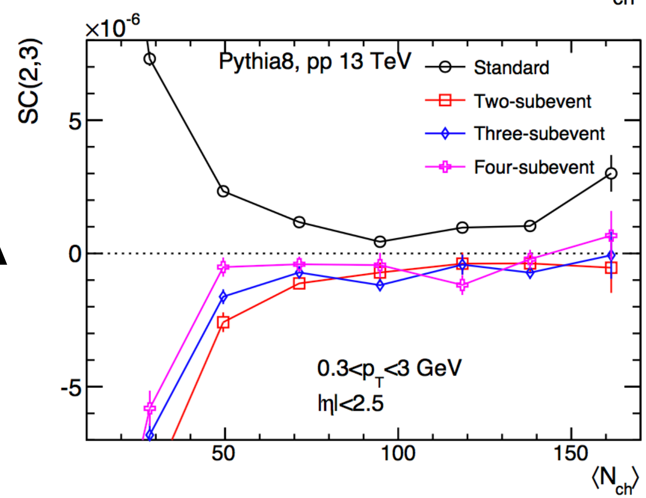
pp data

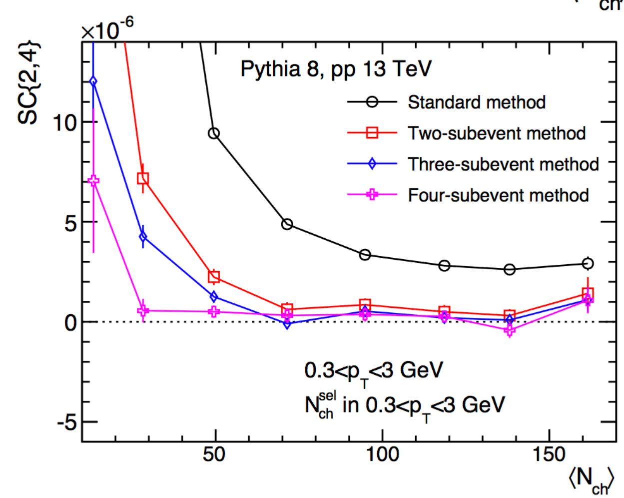




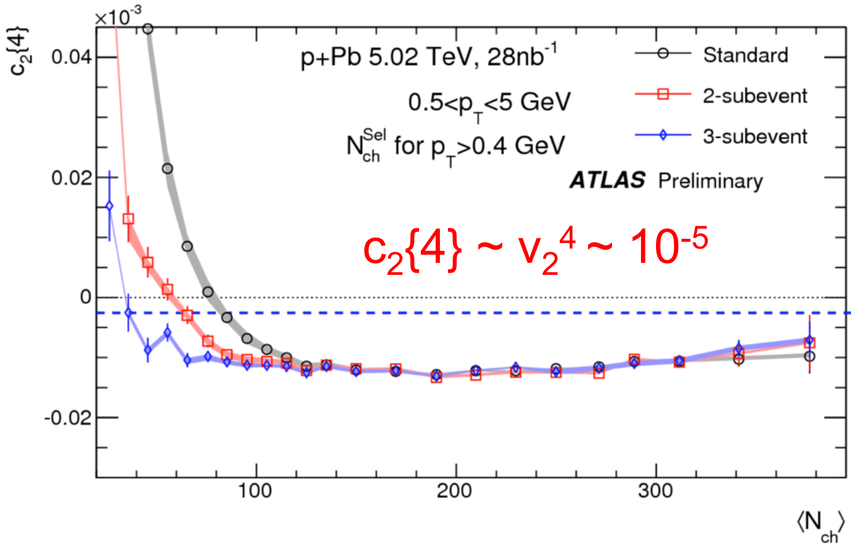
Part of the anti-correlation between v_2 & v_3 clearly due to dijet

PYTHIA



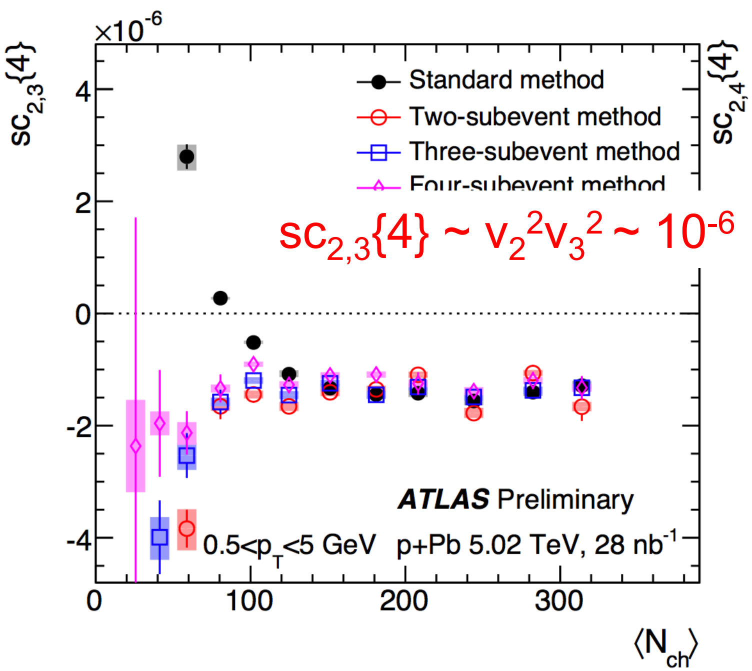


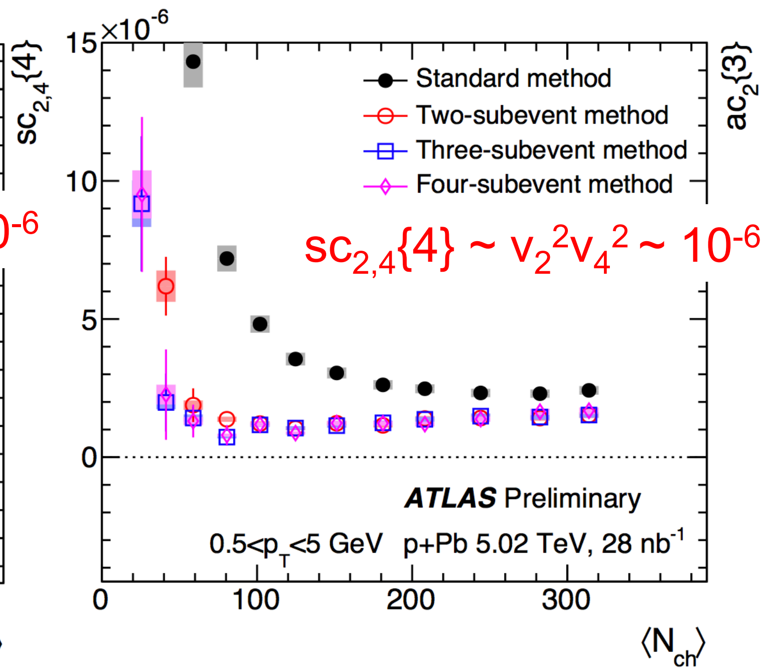
Signal strength comparison

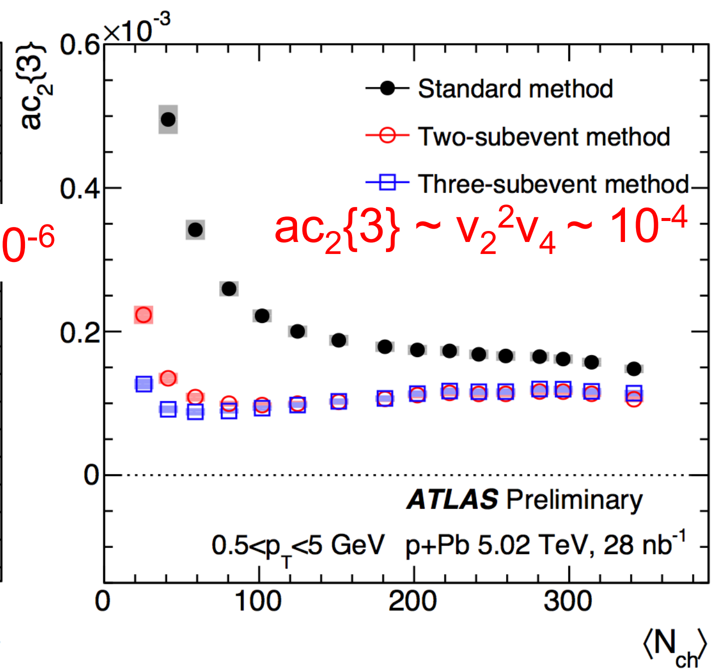


Three-particle correlation has much larger signal than four-particle correlation!

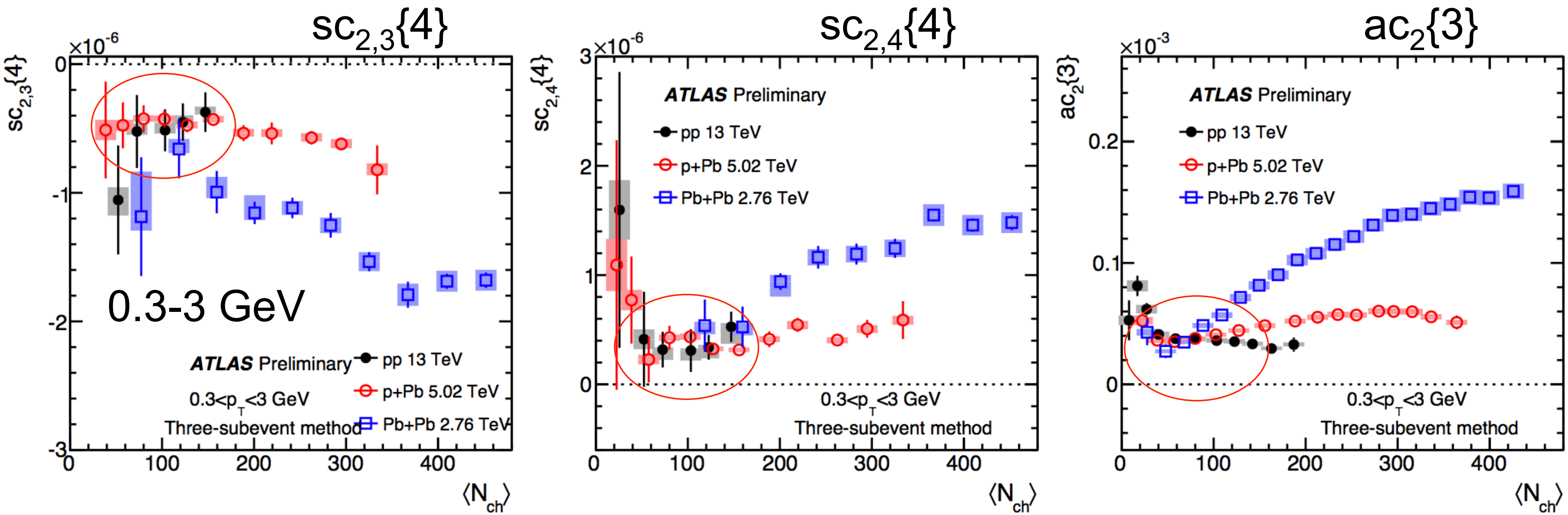
$ac_2\{3\}$ is factor 50 larger than $sc_{2,4}\{4\}$, while effectively suppressing non-flow!







pp, pPb, PbPb on same plot



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

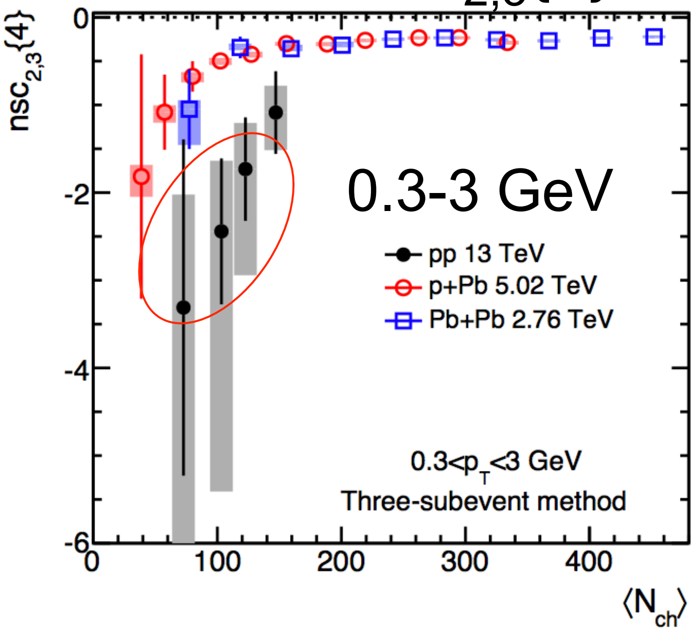
$sc_{2,4}\{4\} = \left\langle v_2^2 v_4^2 \right\rangle - \left\langle v_2^2 \right\rangle \left\langle v_4^2 \right\rangle$

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

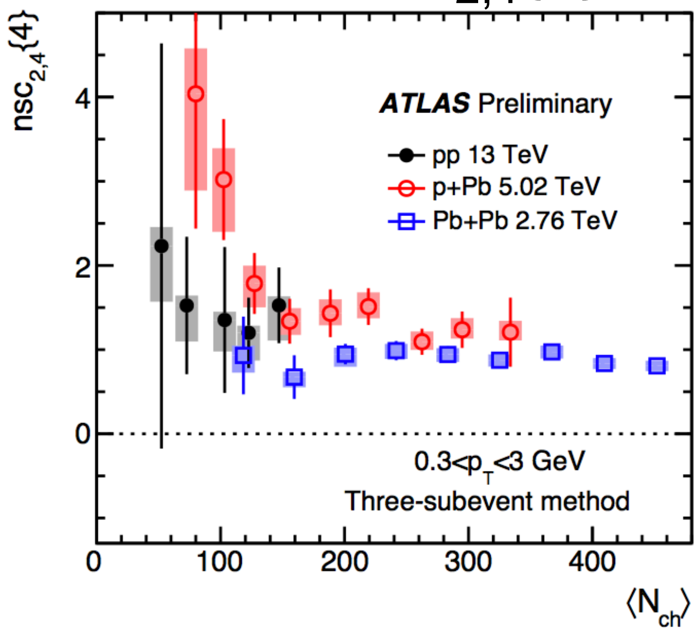
- In the N_{ch} region covered by pp, $0<N_{ch}<160$:
  - $sc_{2,3}\{4\}$ and $sc_{2,4}\{4\}$ are similar among different systems
  - $ac_2\{3\}$ has much better precision, reveal fine splitting pp<pPb<PbPb
- At larger N_{ch} region, $N_{ch}>160$:
  - Magnitude of sc and ac are larger in PbPb than pPb
  - Reflecting the N_{ch} dependence of $v_2\{2\}$

Comparison of normalized cumulants

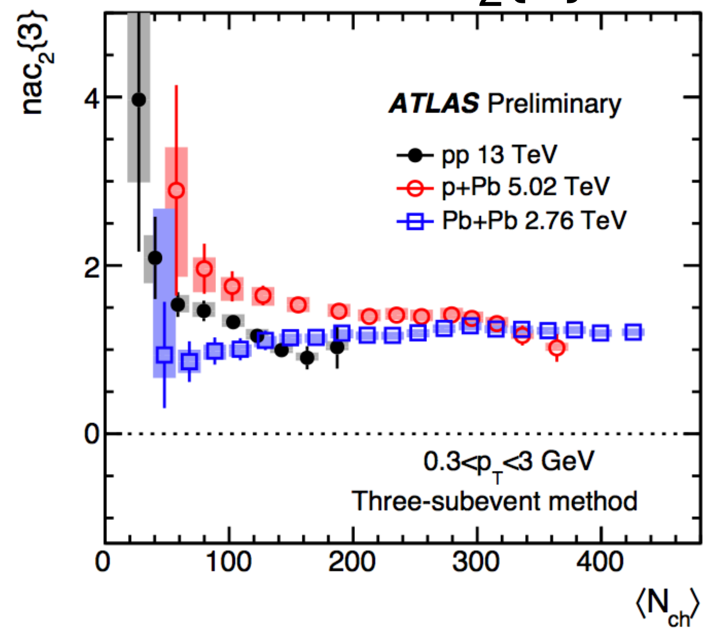
$nsc_{2,3}\{4\}$



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



$nac_2\{3\}$



$$\mathrm{nsc}_{2,3}\{4\} = \frac{\langle v_2^2 v_3^2 \rangle}{\langle v_2^2 \rangle \langle v_3^2 \rangle} - 1$$

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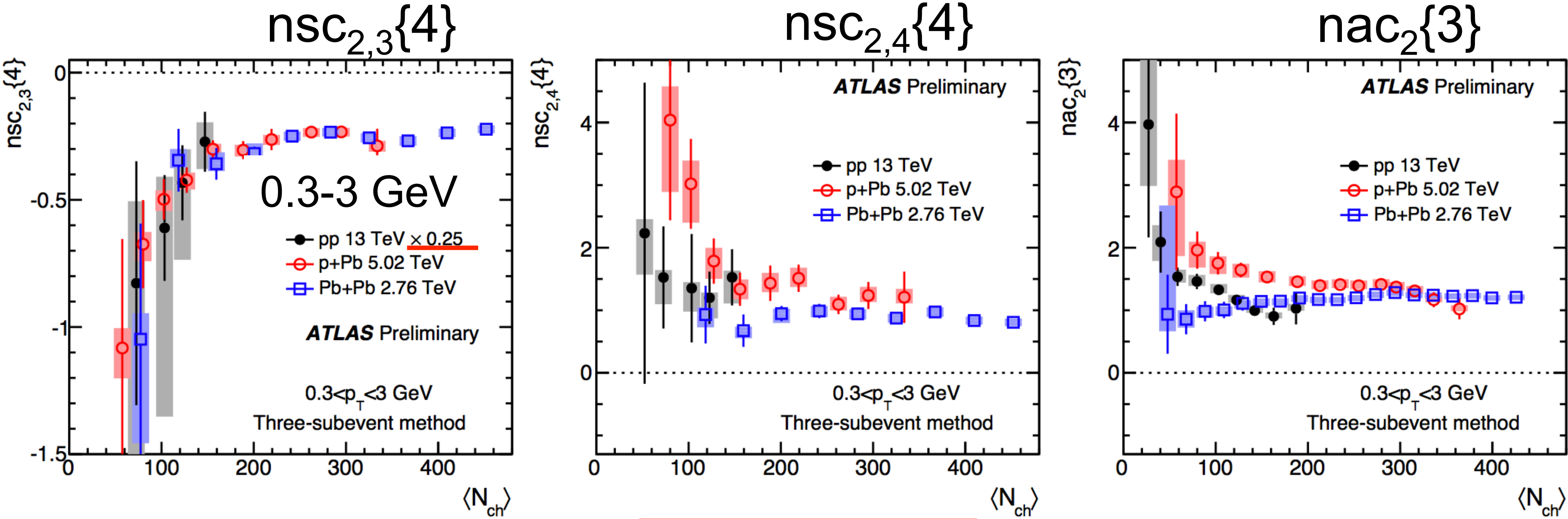
$$\mathrm{nac}_2\{3\} = \frac{\langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4) \rangle}{\langle v_2^2 \rangle \sqrt{v_4^2}}$$

- The normalization removes most of the N_{ch} dependence!
- Strength are similar between all systems!
  - But see 20-30% fine splitting at low N_{ch}.

- $sc_{2,3}$: the pp values is x4 larger in magnitude than other systems
  - The v_3 in pp from template fit is x2 too small

Comparison of normalized cumulants



$$\mathrm{nsc}_{2,3}\{4\} = \frac{\langle v_2^2 v_3^2\rangle}{\langle v_2^2\rangle\langle v_3^2\rangle} - 1$$

$$\mathrm{nsc}_{2,4}\{4\} = \frac{\langle v_2^2 v_4^2\rangle}{\langle v_2^2\rangle\langle v_4^2\rangle} - 1$$

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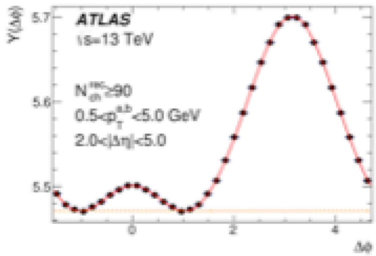
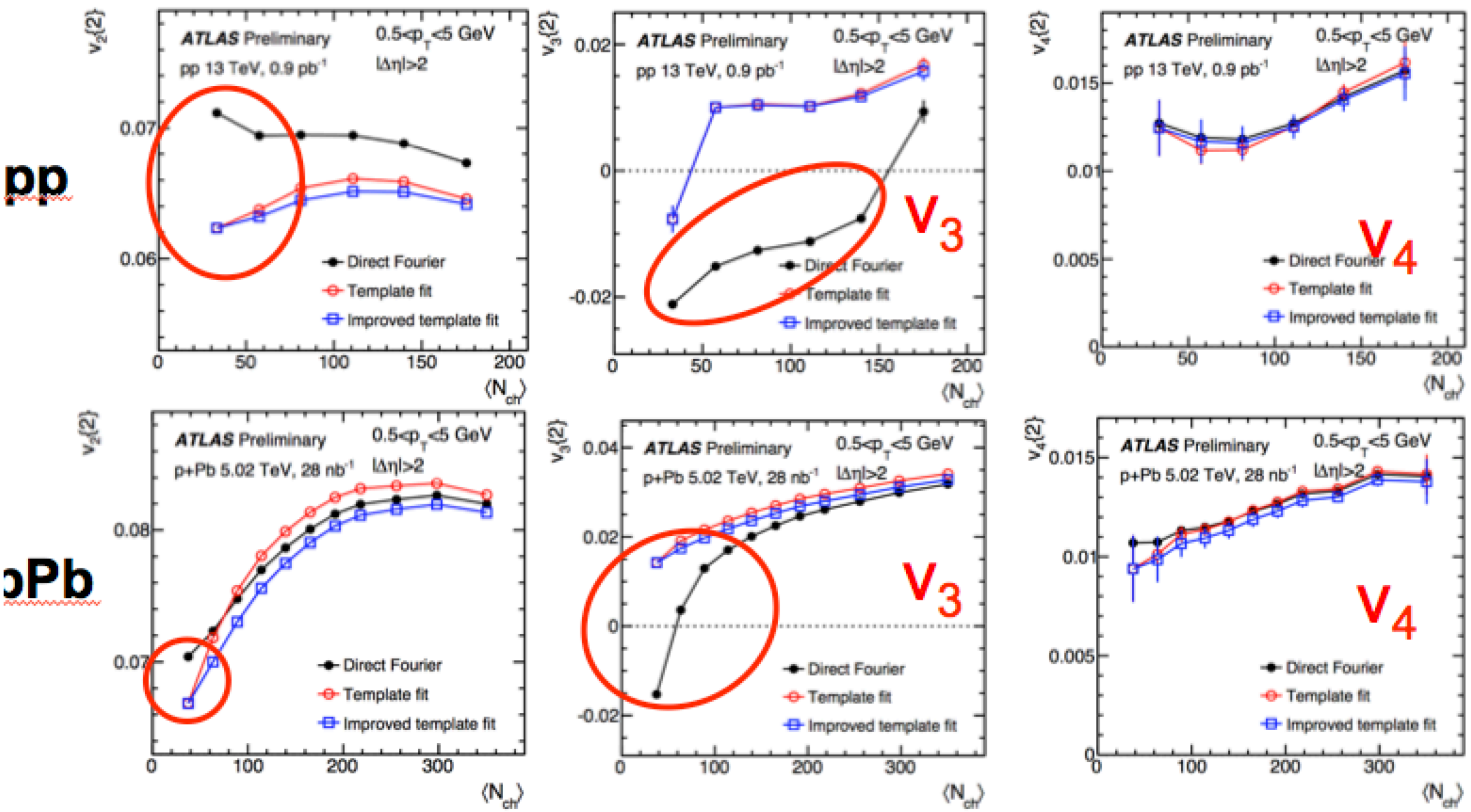
Bias from away-side jet to v_3^2

- A peak at $\Delta\phi \sim \pi$ contribute +signal for even harmonics and -signal for odd harmonics



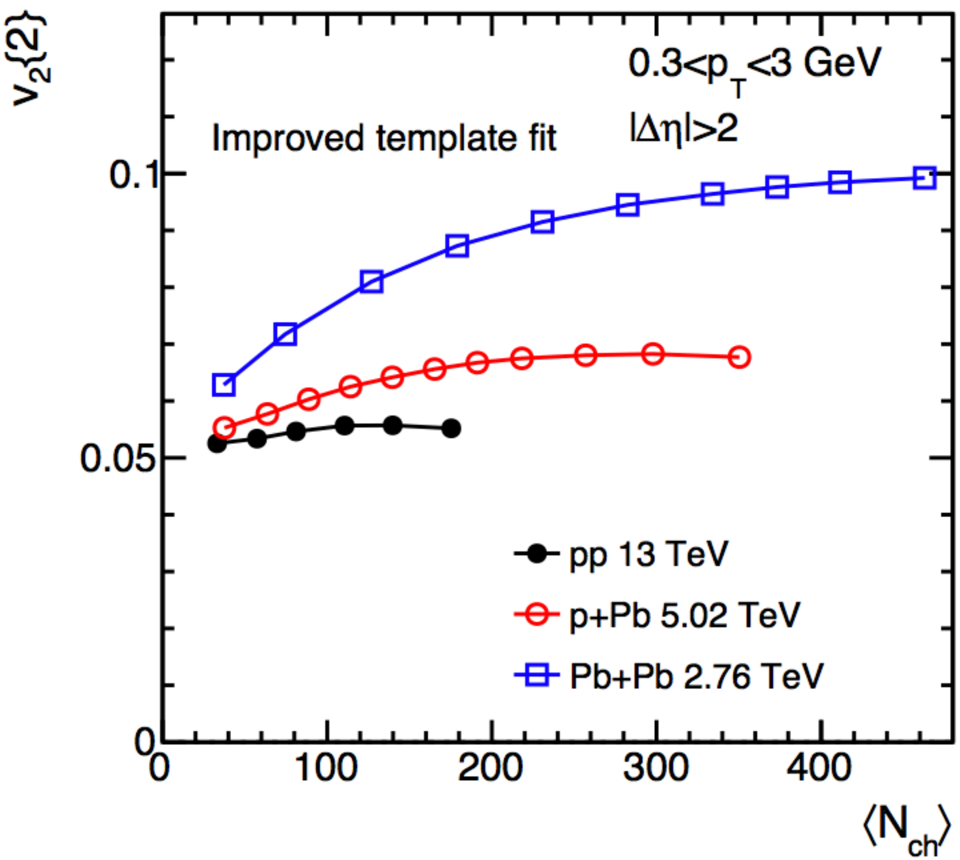
$v_{2,2}\{jet\}, v_{4,4}\{jet\}\ldots>0;\ v_{1,1}\{jet\}, v_{3,3}\{jet\}\ldots<0$

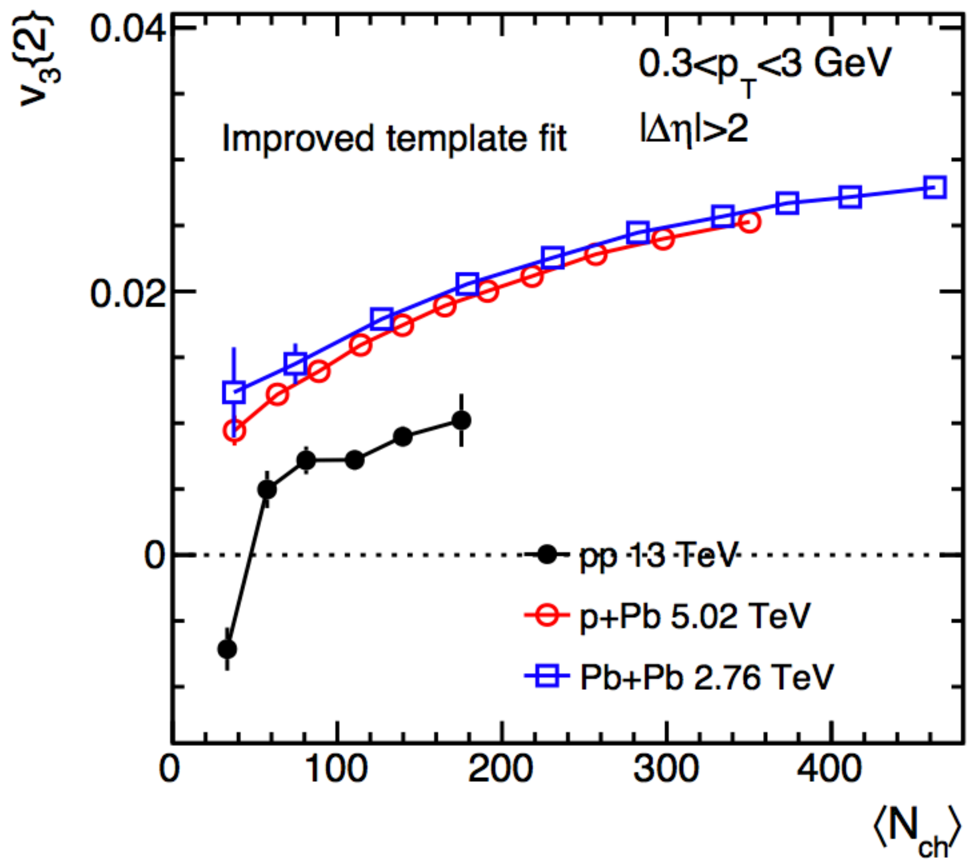


Even after large correction, the template-fit method still significantly underestimate the v_3

v_2 and v_4 are fine since the correction due to away-side jet are small

v_2 and v_3 from different systems





v_2 hierarchy reflect the average geometry effects

v_3, driven by fluctuations, clearly are underestimated in pp

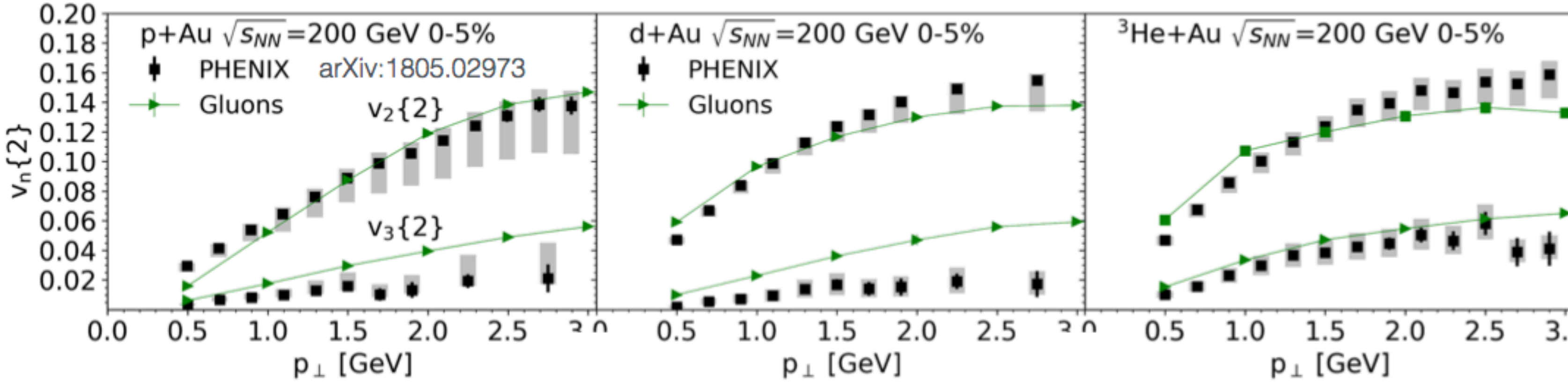
Discussions

Current status of initial state model

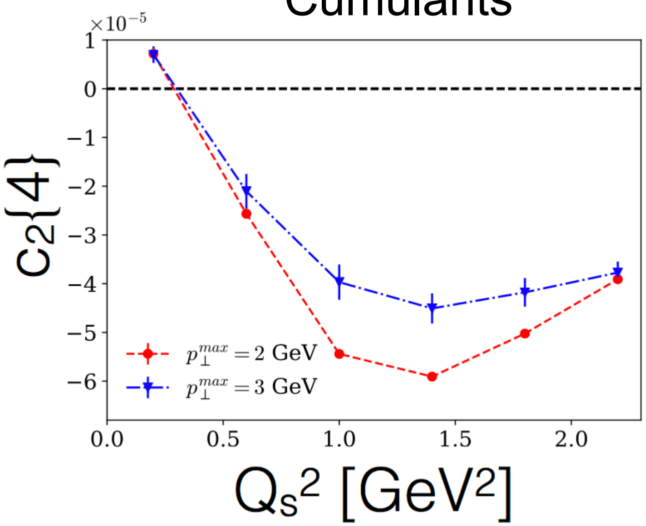
Initial state momentum anisotropy model “describe” most pA data?

Mark Mace ECT 2018, QM2018

RHIC p+Au, d+Au, ^{3}He+Au scan

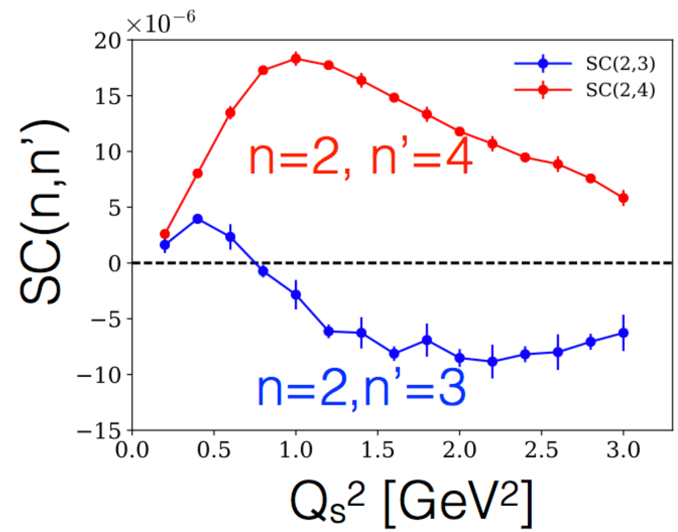


Cumulants



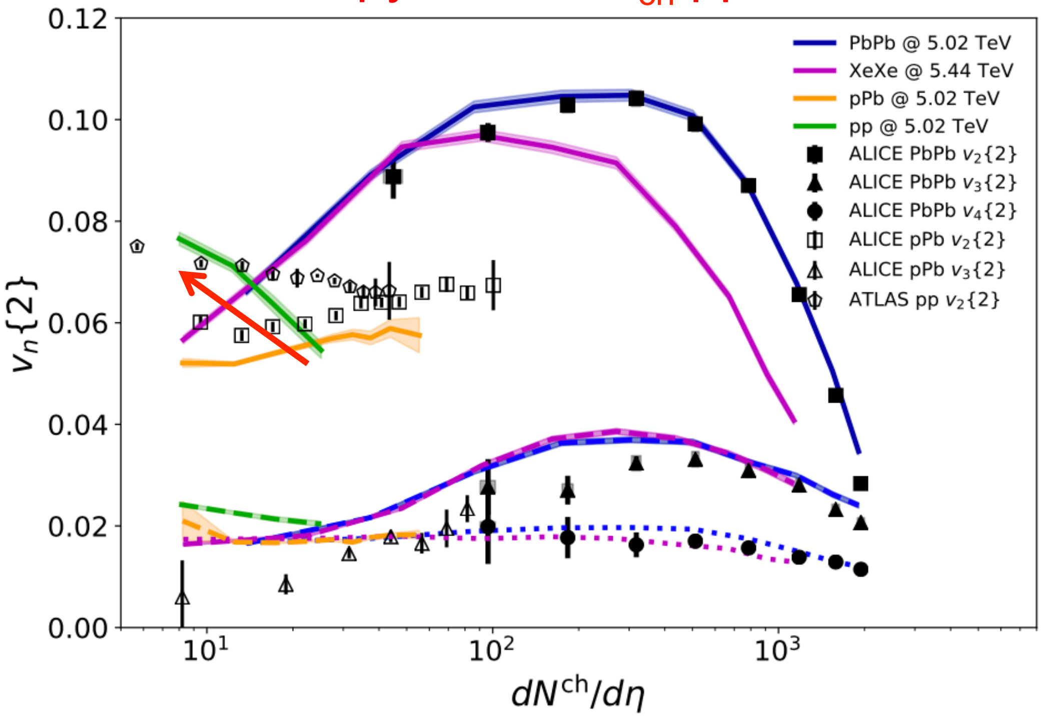
Dusling, MM, Venugopalan PRD 97 (2018)

Symmetric cumulants

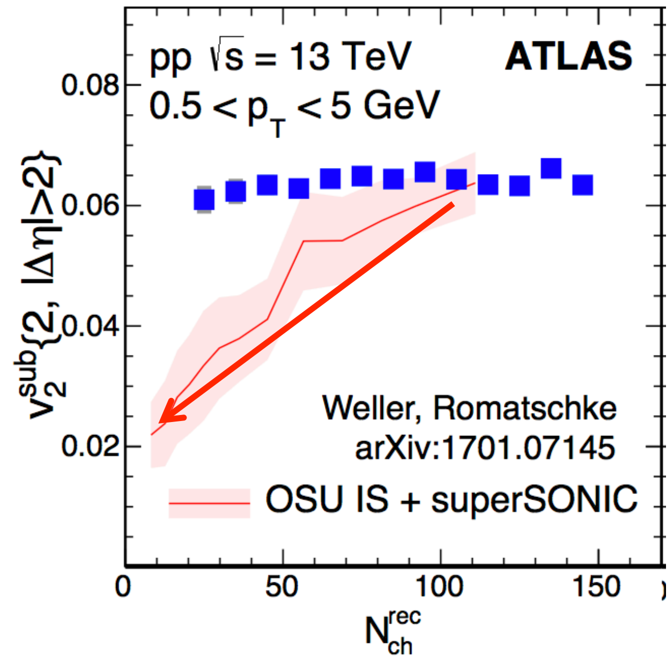


Initial state vs final state in pp

CGC predicts more momentum anisotropy for low N_{ch} pp



hydro predicts more less anisotropy for low N_{ch} pp



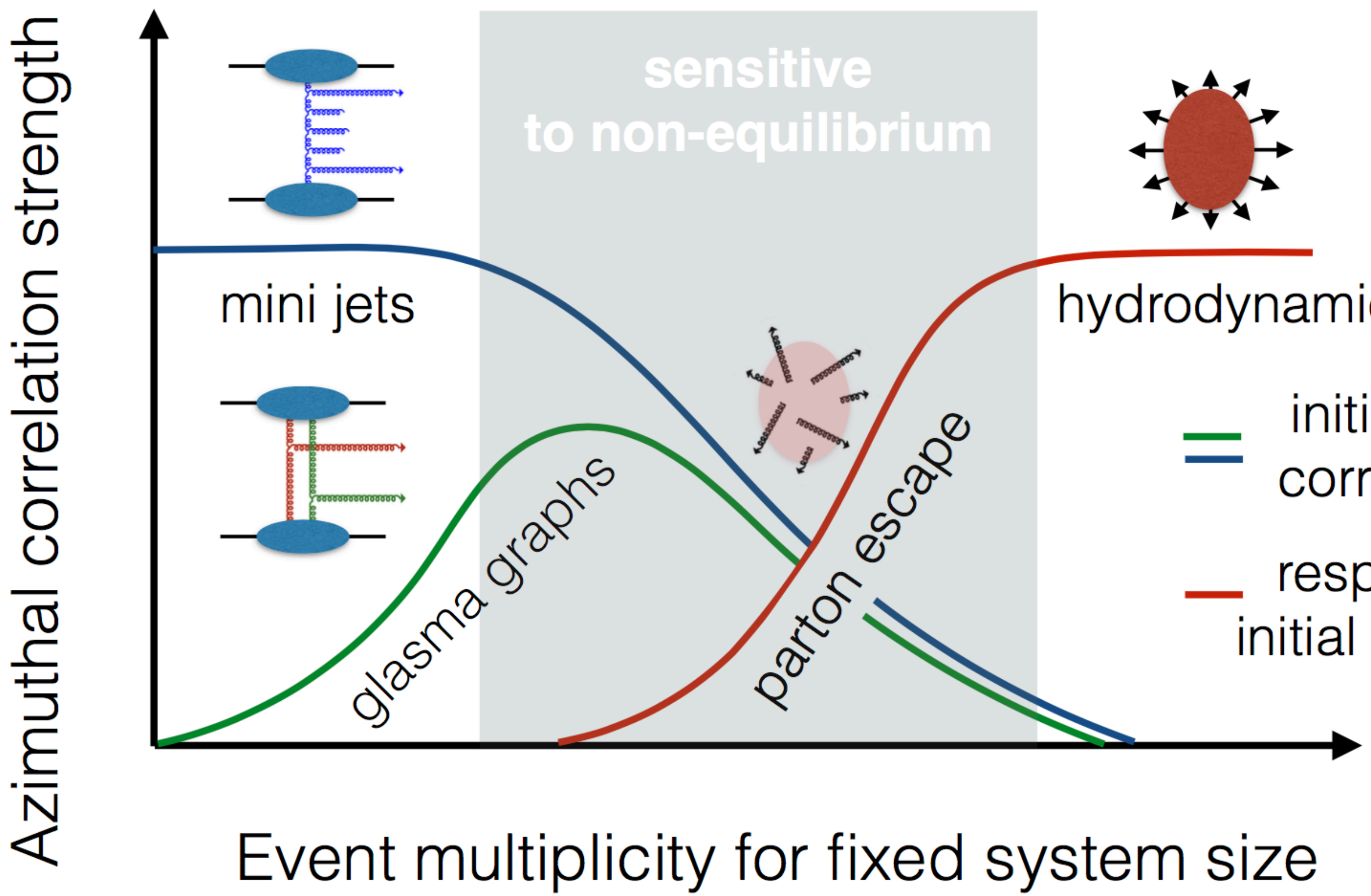
Truth could be somewhere in between?

What is the time-scale for the collectivity?

Initial anisotropy
CGC

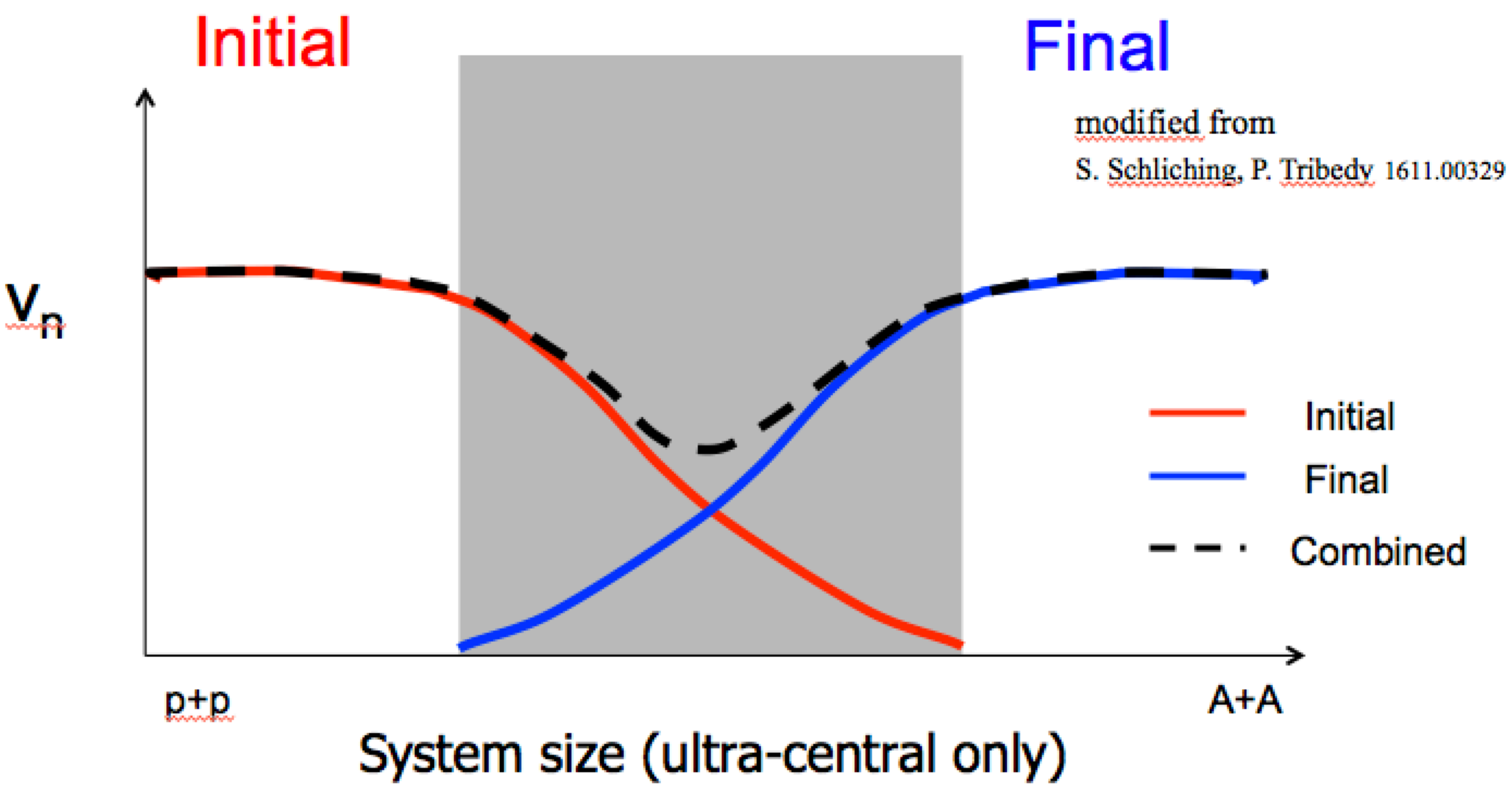
Single-hit transport

Multi-hit hydrodynamics



Presence of both initial and final state scenarios?

Slides from 1st small system workshop

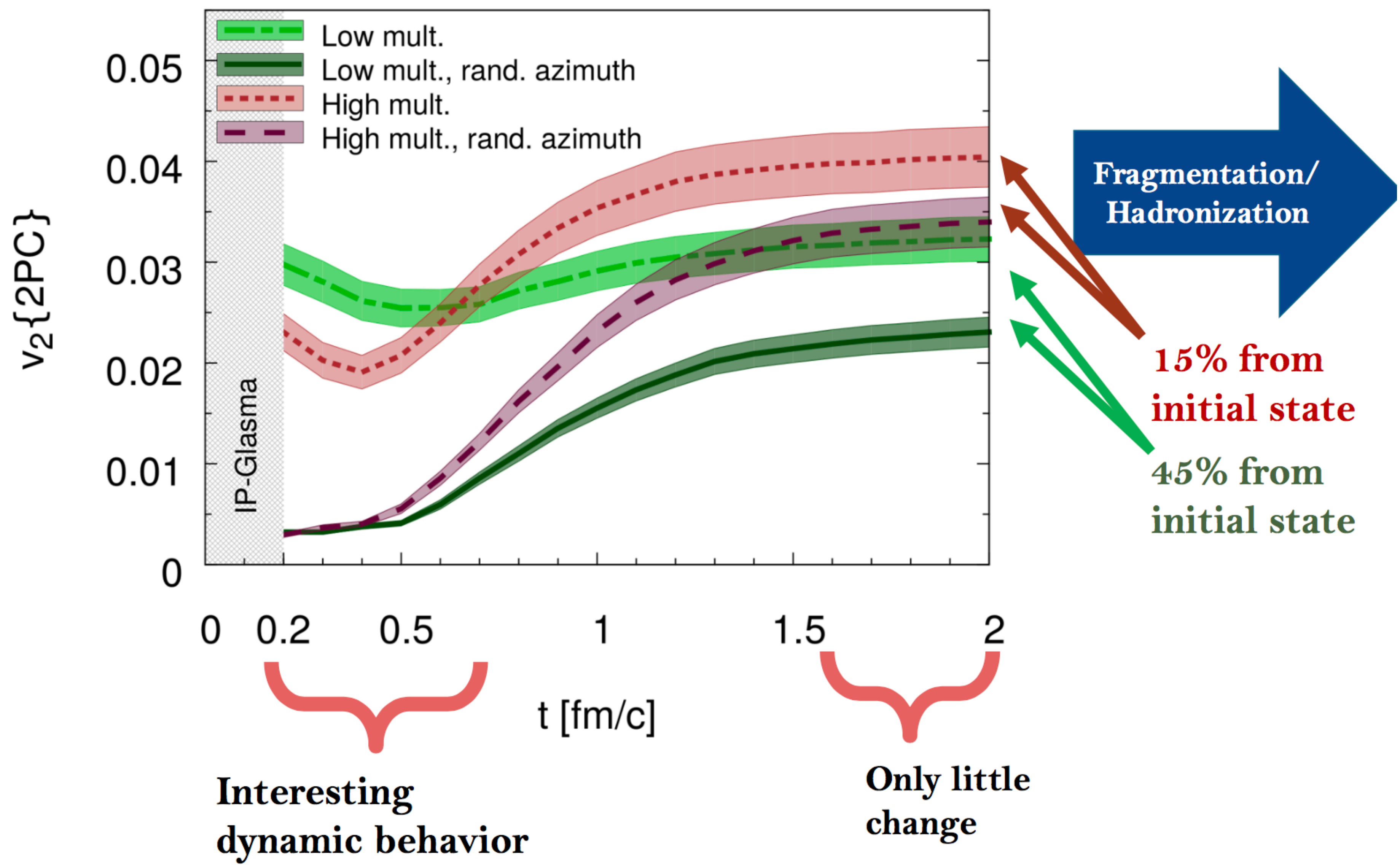


Phases of collectivity from CGC and hydro are unrelated

→ a minimum of total v_n at certain system size?

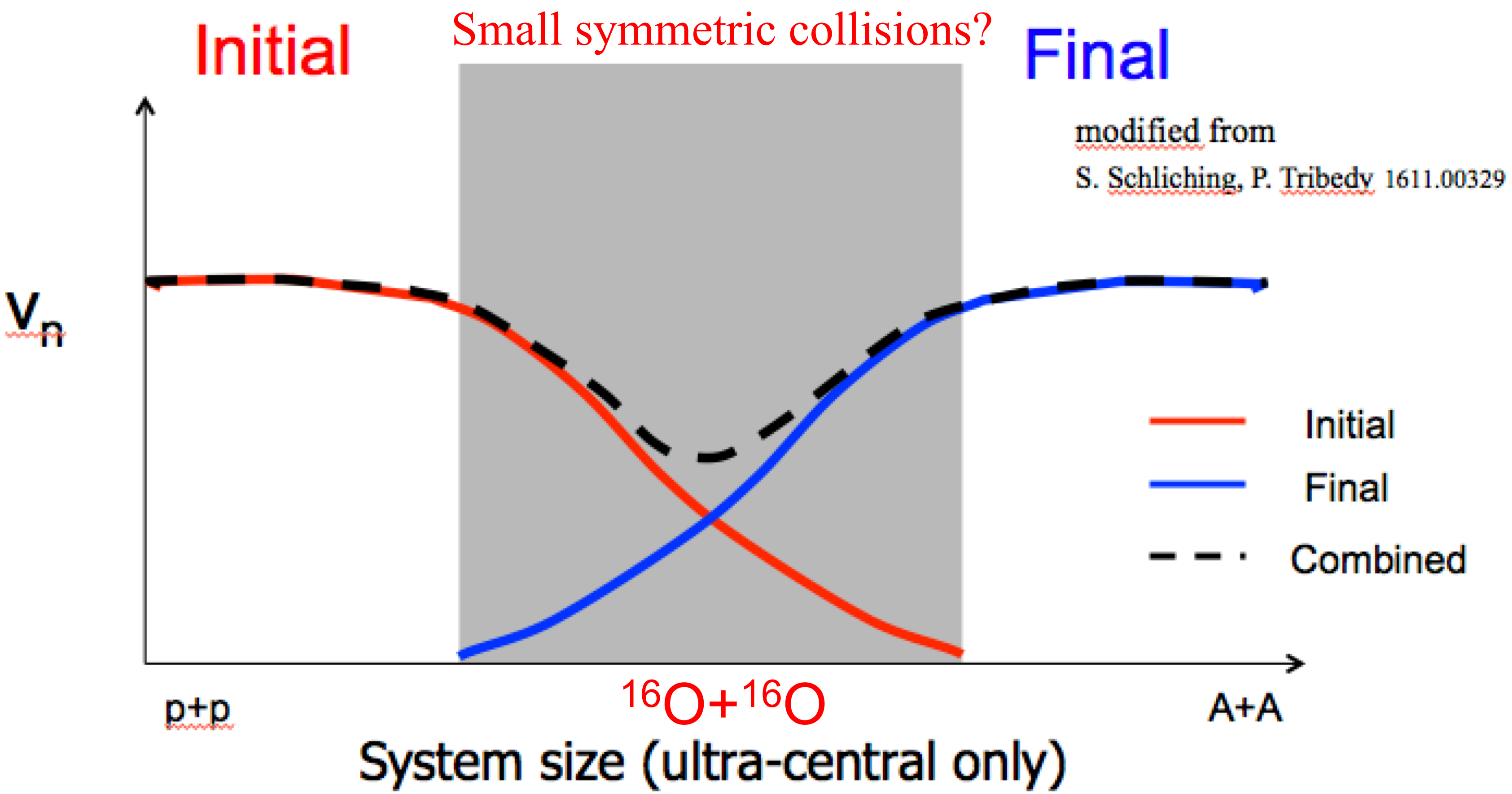
Presence of both initial and final state scenarios?

Calculations from Moritz Greif QM2018



Presence of both initial and final state scenarios?

Slides from 1st small system workshop

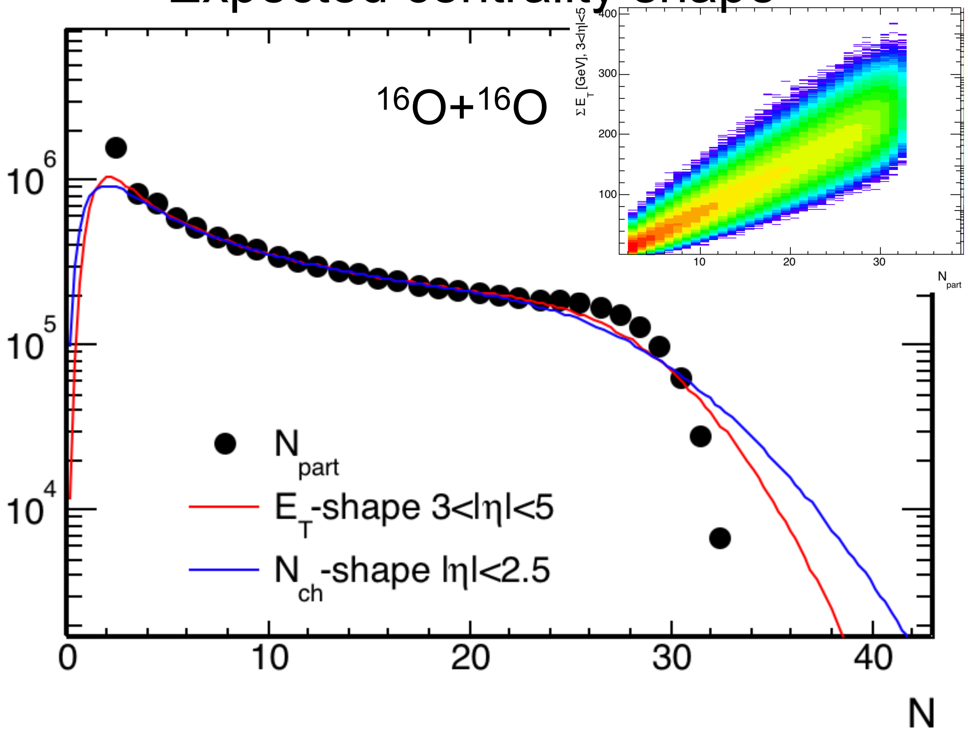


Phases of collectivity from CGC and hydro are unrelated

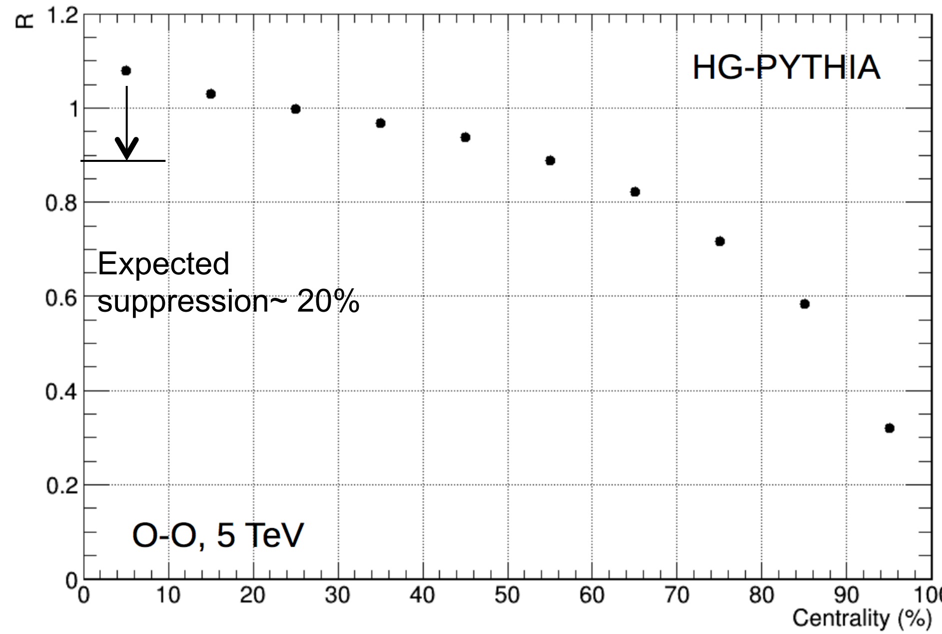
→ a minimum of total v_n at certain system size?

O+O collisions?

Expected centrality shape



Expected centrality bias on R_{AA}



- Centrality shoulder allow selection of initial geometry N_{part} & ε_2
- System is small enough such that both CGC and escape maybe important
- System is large enough to see jet quenching, 32 N_{part} ~ 55-60% PbPb
  - Also search in minbias OO, N_{part} ~ 11
- Clear advantage over asymmetric systems pA, dA, He_3A

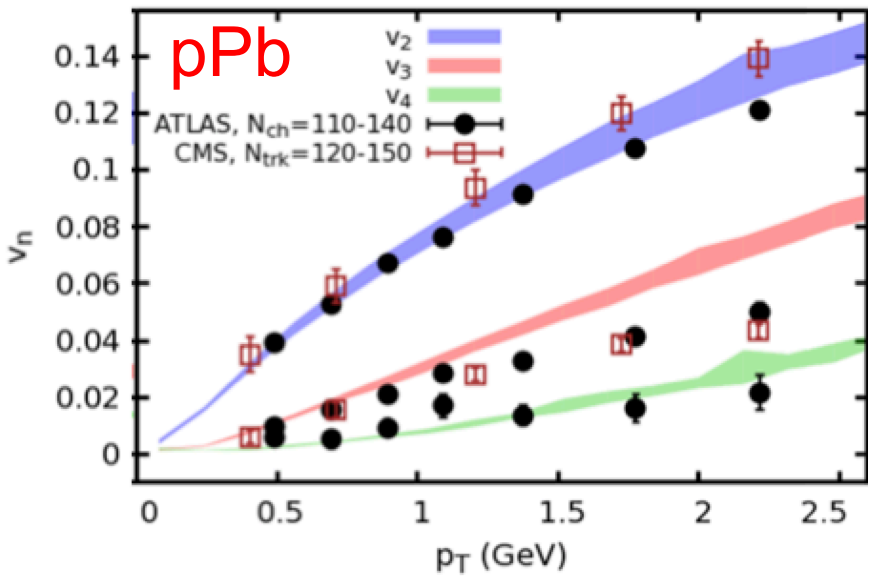
Four birds one stone?: CGC, escape, hydro, jet quenching.

Hydrodynamics vs non-hydro escape

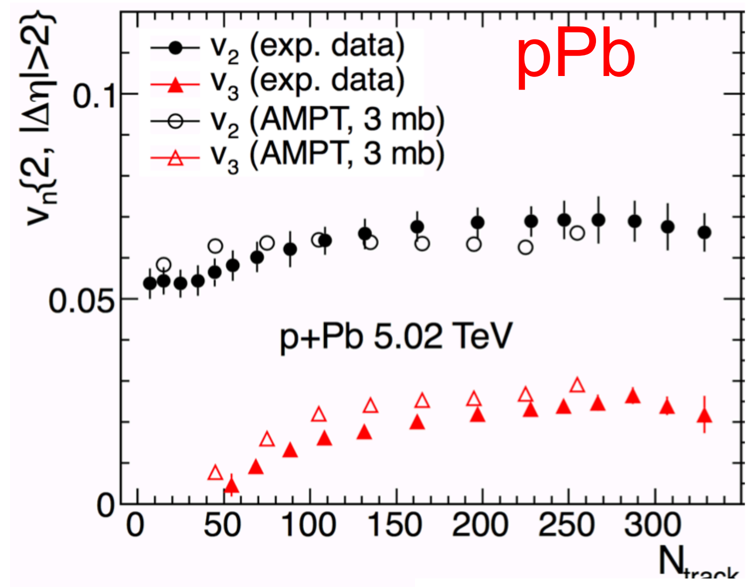
P. Romatschke, R. Weller 1701.07145

L.He, T.Edmonds, Z.Lin, F.Liu, D. Molnar and F. Wang 1502.05572, G. Ma and A Bzdak 1406.2804

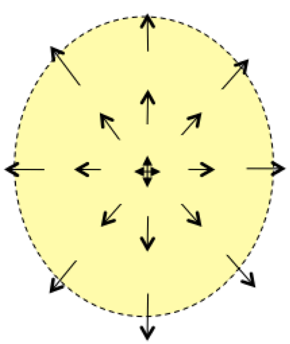
Hydrodynamics



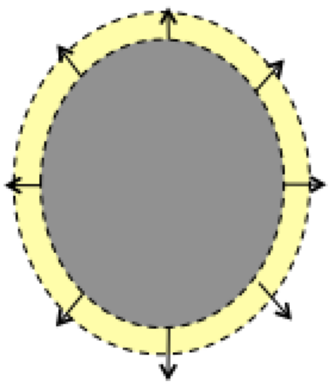
AMPT transport



Pressure driven



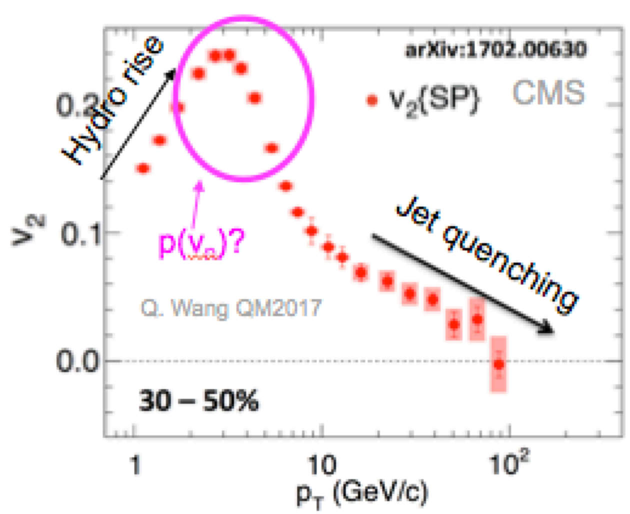
Anistropic escape

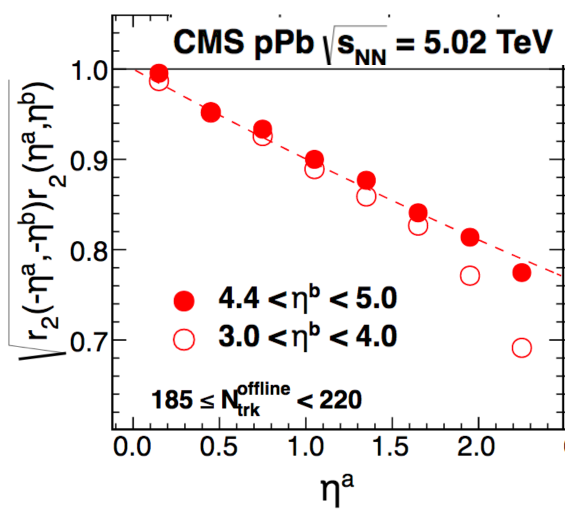


Space-time dynamics should be very different
How to distinguish the two experimentally?

Searching for non-hydrodynamic mode

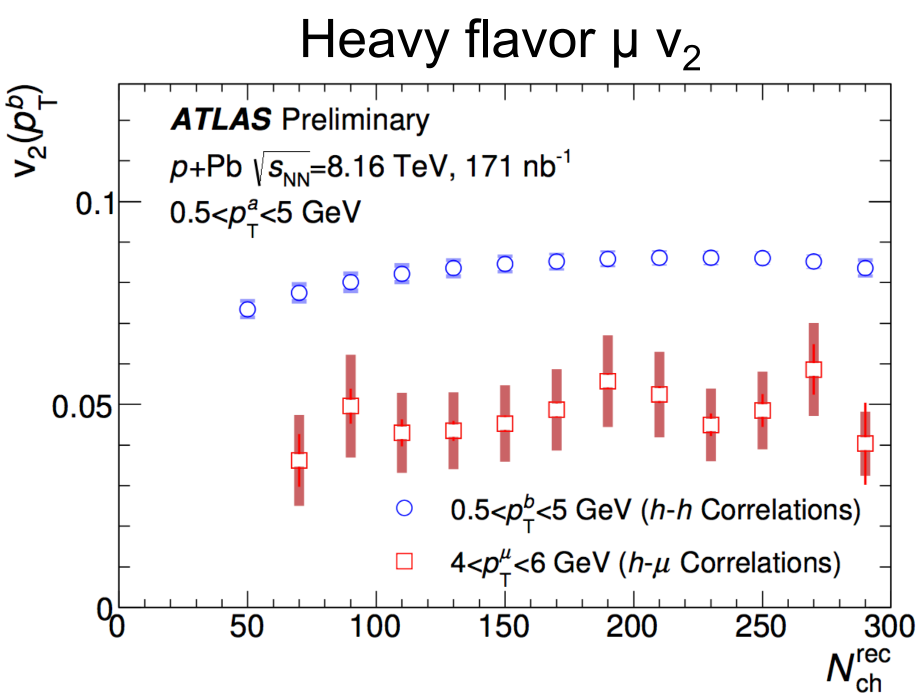
- Different relation between low p_T flow & high-p_T quenching
  - Hallmark of $v_n(p_T)$ rise and fall maybe weaker in few hit transport?
- Factorization breaking in p_T and η should be different
  - Hydro maybe better aligned with geometry.
- The $p(v_n)$ and flow cumulants ratios could be different
  - Geometry response may not the only source for flow fluctuations.
  - Event-shape engineering would also be useful (doable in pPb, O+O).

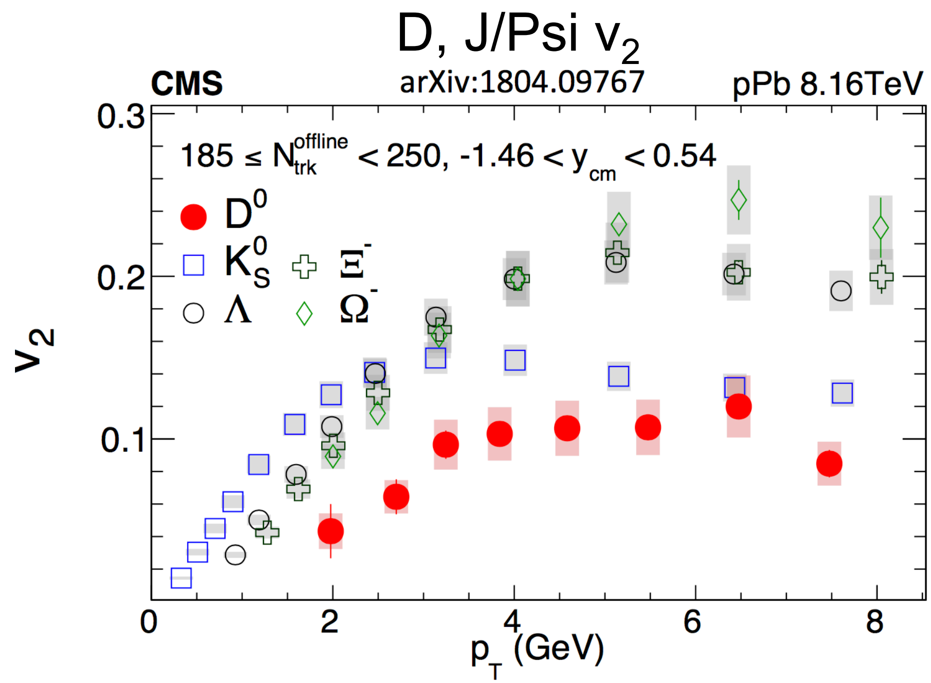




Search for systematic failure of gradient expansion of hydrodynamics

Origin of heavy flavor flow





Challenging for initial state and escape models?

- Relies on the same assumption that non-flow is unmodified in high-multiplicity events, i.e ties with lack of jet quenching.
  - Mini-jet decay kinematics different from charge hadrons….
- Need examine multi-particle long-range nature of heavy quarks
  - 3- or 4- particle cumulants with subevent methods would be convincing.

Summary

- Comprehensive study of nature of the two- and multi-particle correlation of the long-range ridge in small systems
- Two-particle correlation
  - Systematics of the away-side non-flow subtraction is understood.
  - v_2, v_4 ~ independent of N_{ch} in pp collisions, down to very small N_{ch}.
  - v_3 is underestimated due to large negative contribution from away-jet.
- Three- and four-particle correlations
  - Method based on 3 or 4 η-separated subevents are needed to suppress non-flow
  - Neg. $c_2\{4\}$ to low N_{ch}, $v_2\{4\}$ indep. of N_{ch} in pp and pPb
  - $sc_{n,m}\{4\}$and $ac_2\{3\}$ show anti-corr. for v_2 & v_3 and positive corr. for v_2 & v_4.
  - Normalized quantities show similar corr strength for different collision system.
- Important inputs to distinguish initial vs final state scenarios, but more inputs are needed.
  - Search for jet quenching is crucial: symmetric small systems
  - Search for non-hydrodynamic behavior.