Correlations and Fluctuations in Small Systems from LHC

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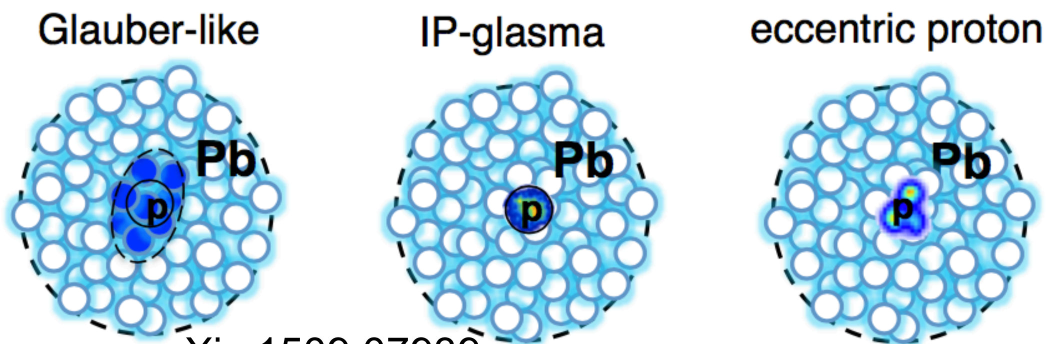
BNL NY, 7-10 June, 2016

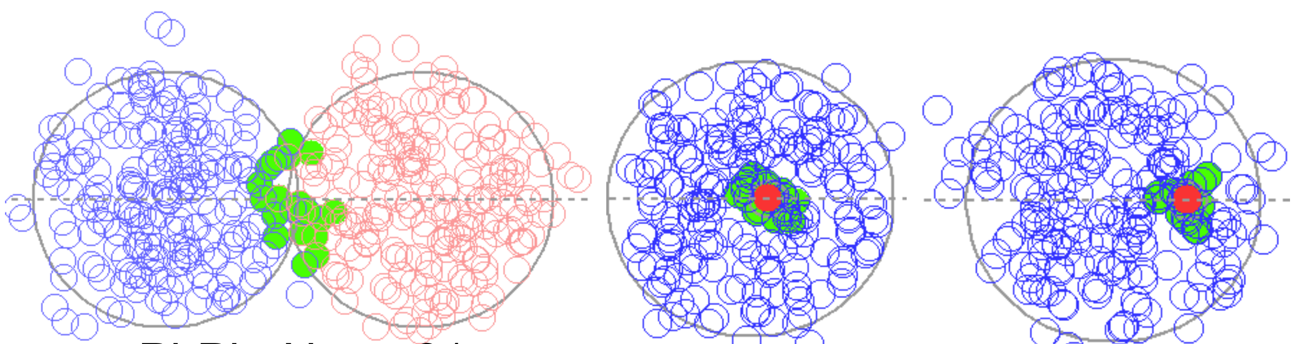
Small systems

Small systems at LHC: pp, pPb and peripheral PbPb

What are the properties of the “matter” produced in small systems? Are they different from larger systems?



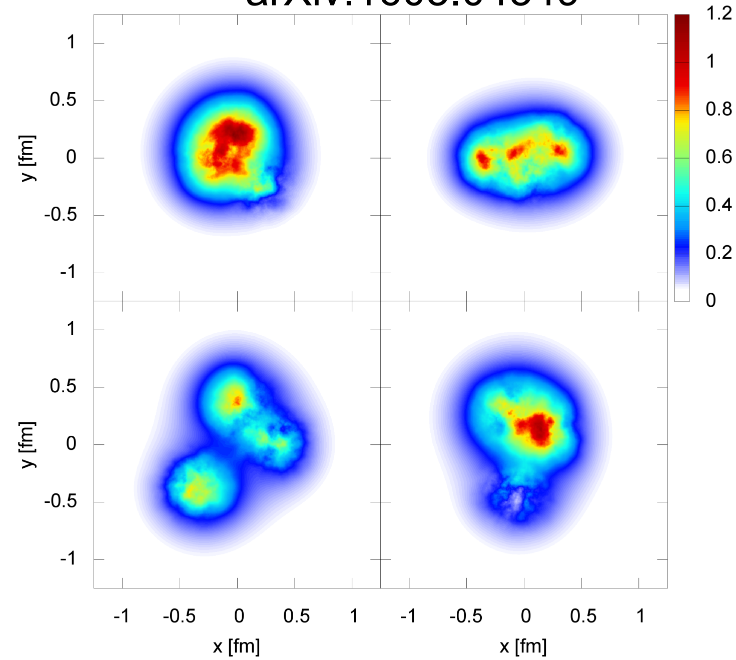
arXiv:1509.07939



PbPb, N_{part} =21

pPb, N_{part} =21

arXiv:1603.04349



proton, IP-Glasma

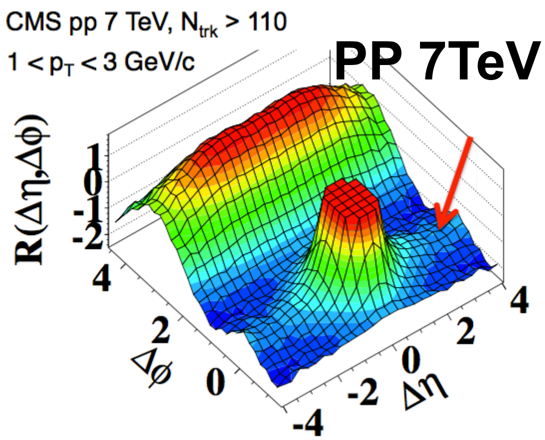
Various initial state configurations

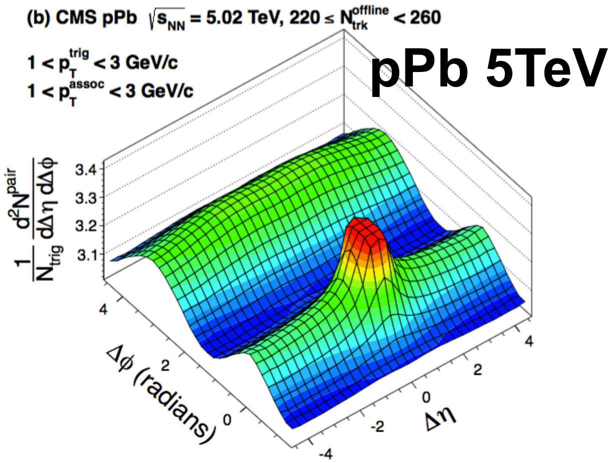
Correlations and fluctuations

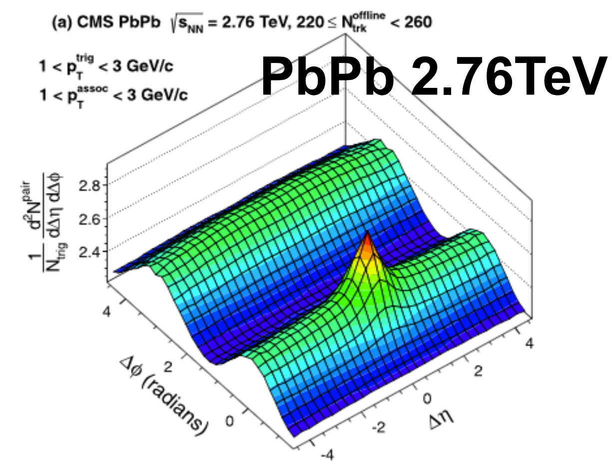
- Ridge
  - ➢ Collision energy, multiplicity and p_T dependence
- v_2 and Higher Harmonics
  - ➢ Peripheral subtraction; template fitting method
  - ➢ Collision energy, multiplicity and p_T dependence
- Multi-particle Correlations
  - ➢ Multi-particle Cumulants; $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$ and $v_2\{all=LYZ\}$
- Identified Particle v_n
  - ➢ Mass ordering
- v_n Factorization Breaking
  - ➢ Lumpiness of the initial states

Ridge observed in every system

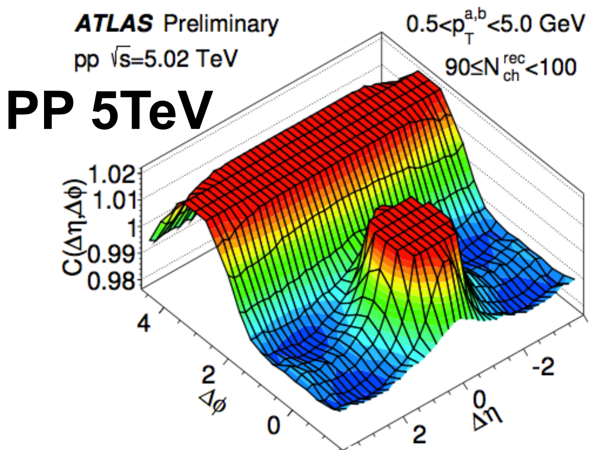
CMS

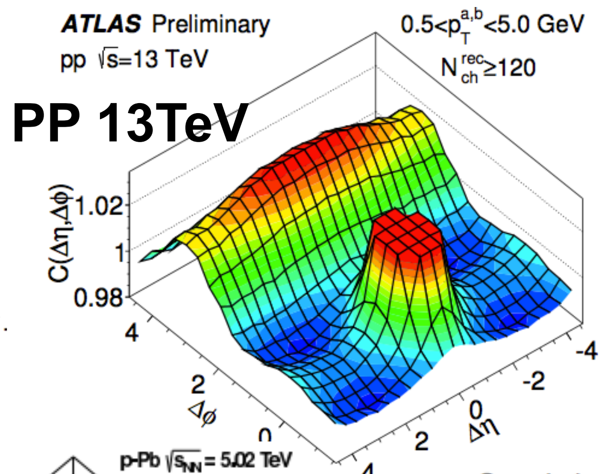


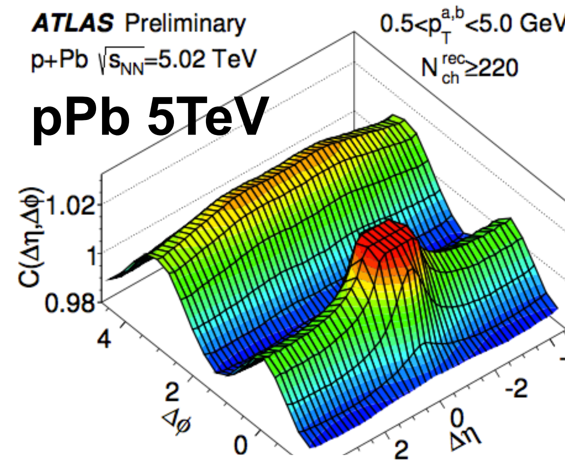




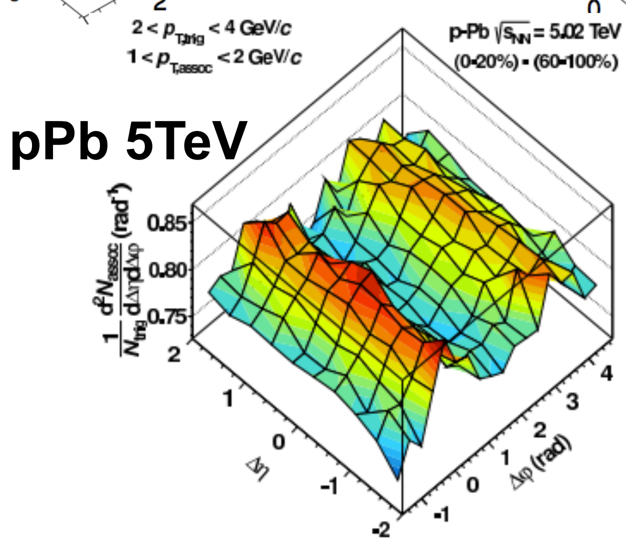
ATLAS

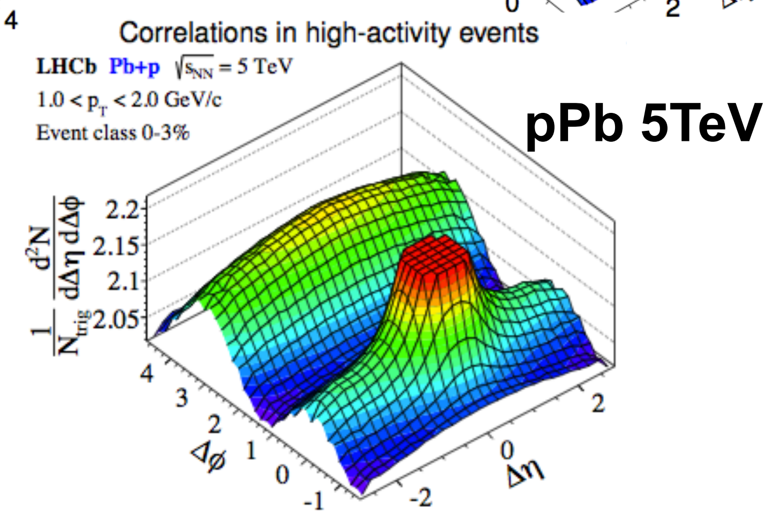




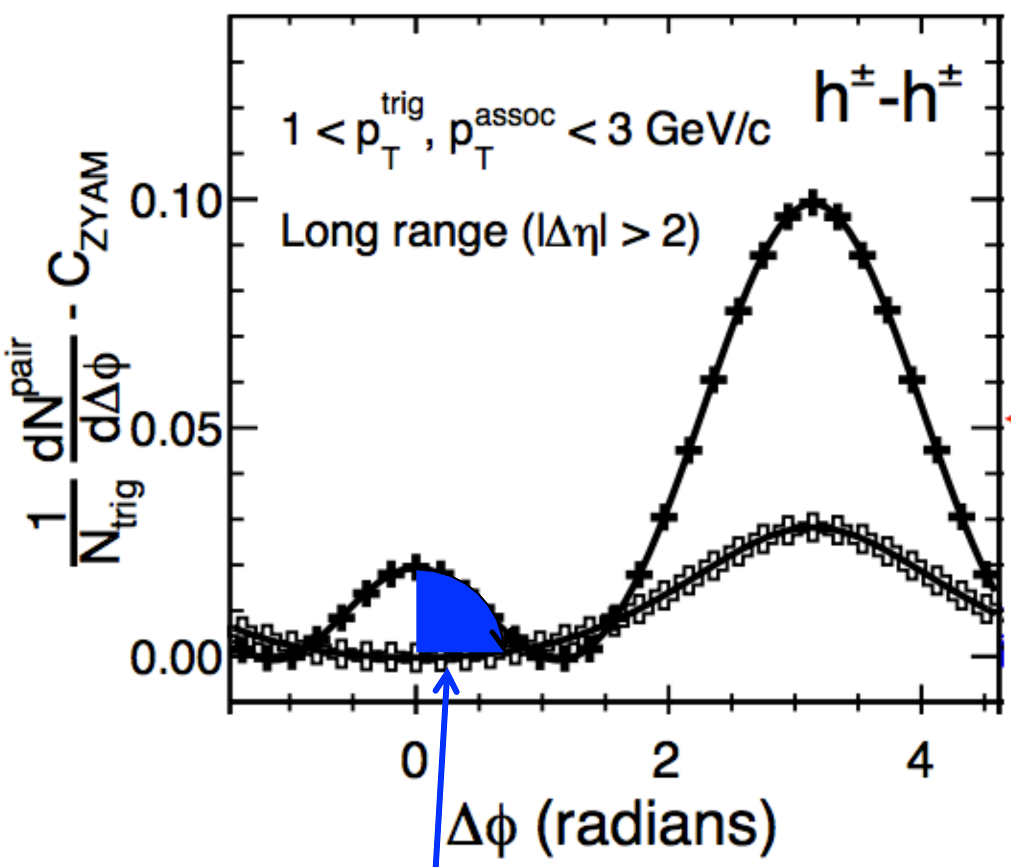


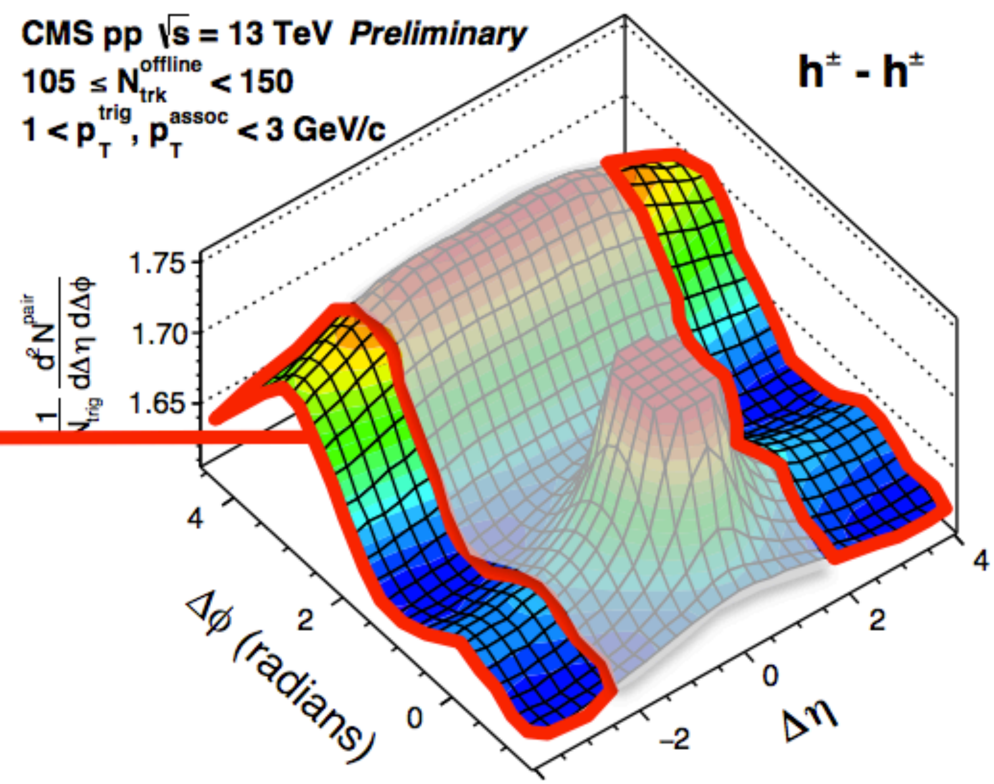
ALICE and LHCb





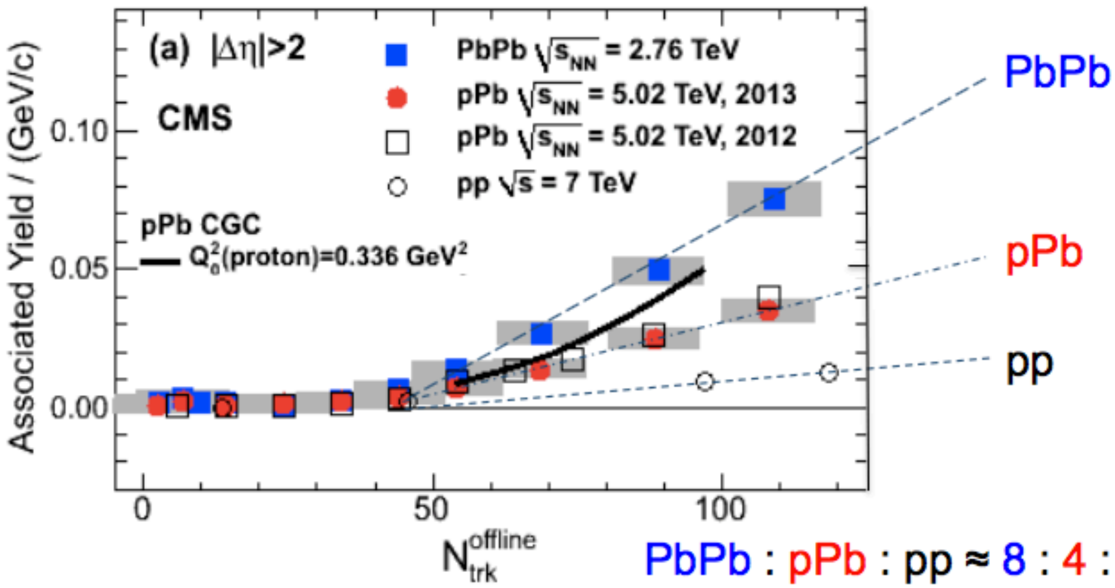
Ridge yield



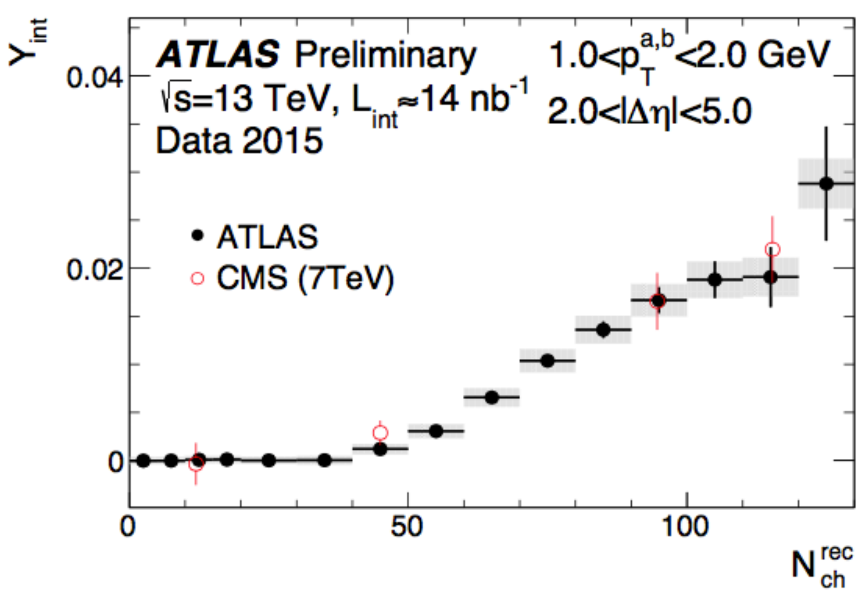


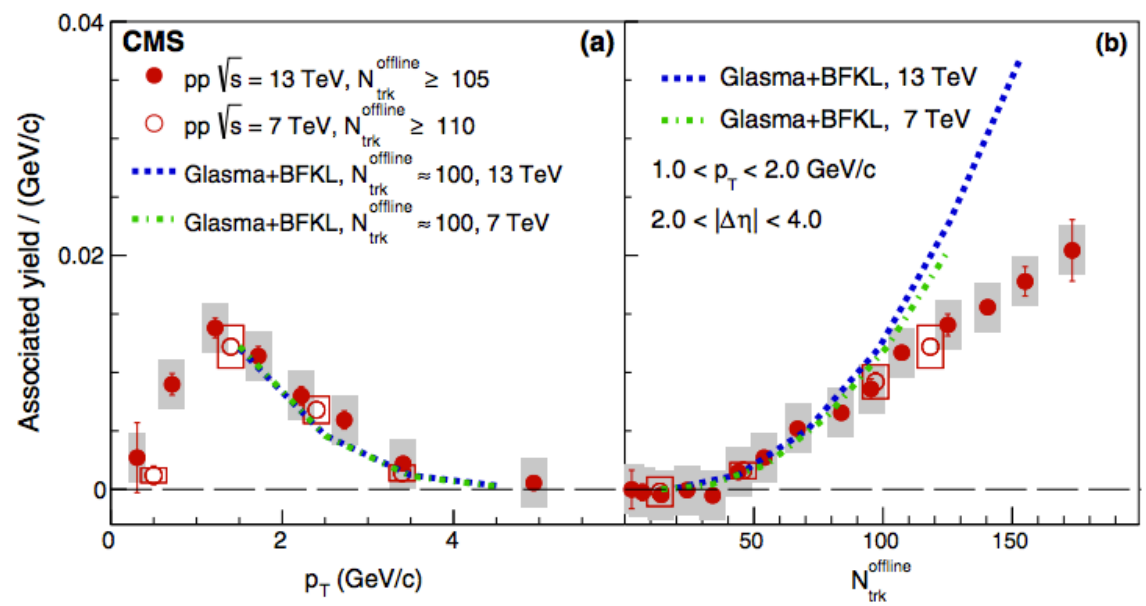
Ridge yield

Ridge yield in different systems



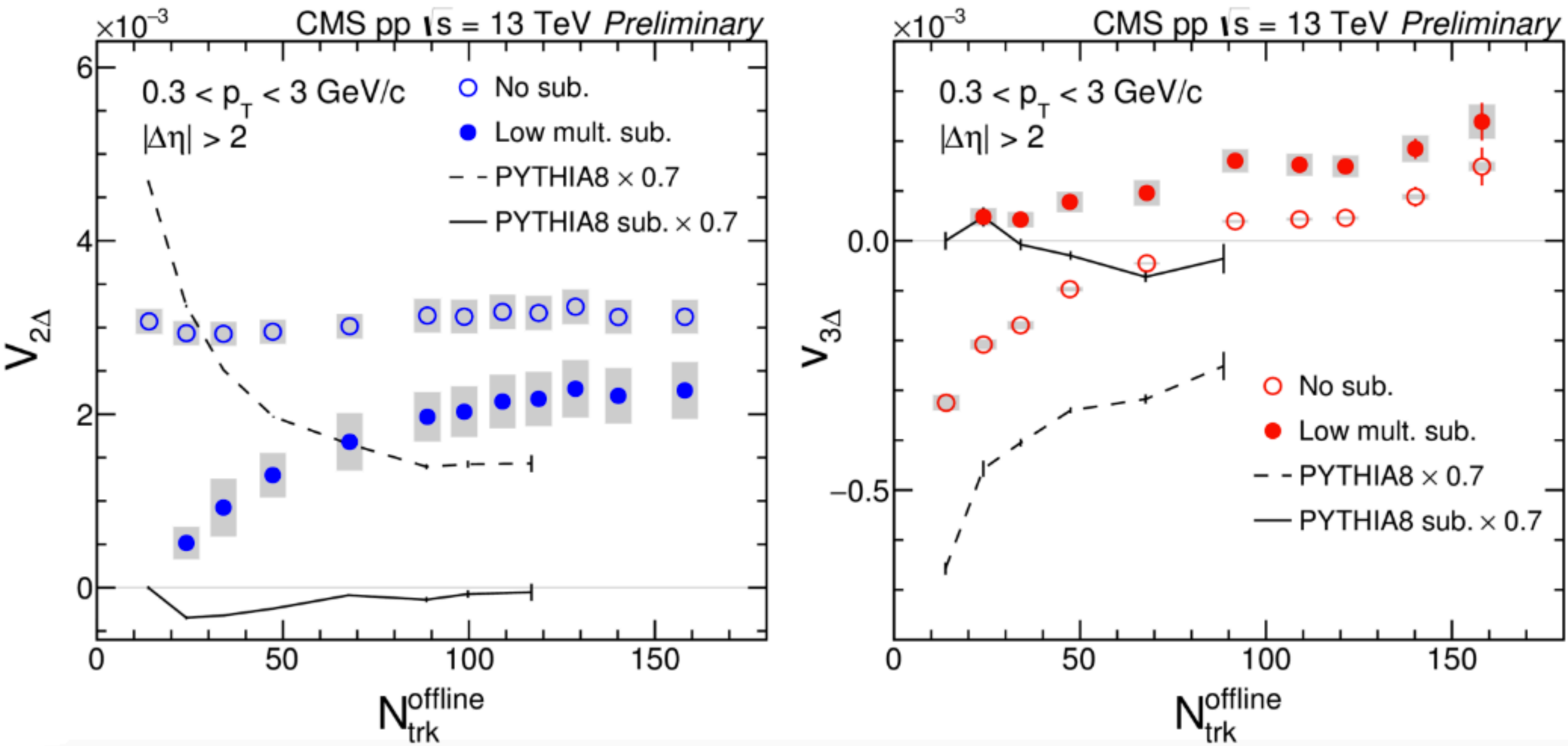
PbPb : pPb : pp ≈ 8 : 4 : 1





Ridge yield weekly depends on center of mass energy in pp collisions

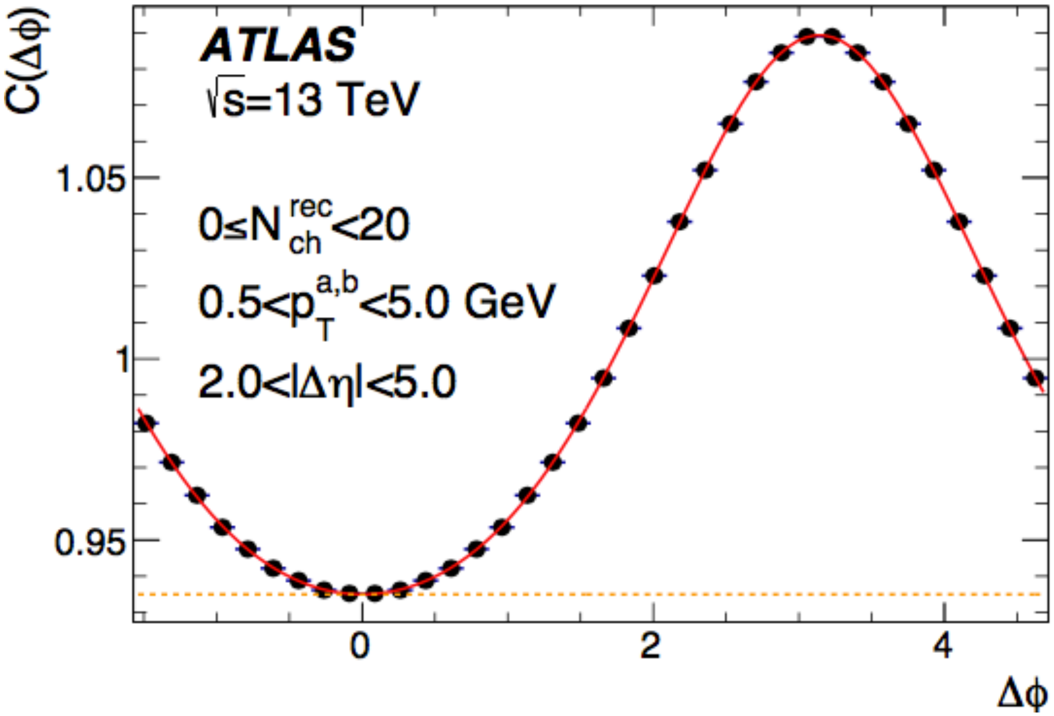
V_n and peripheral subtraction in CMS

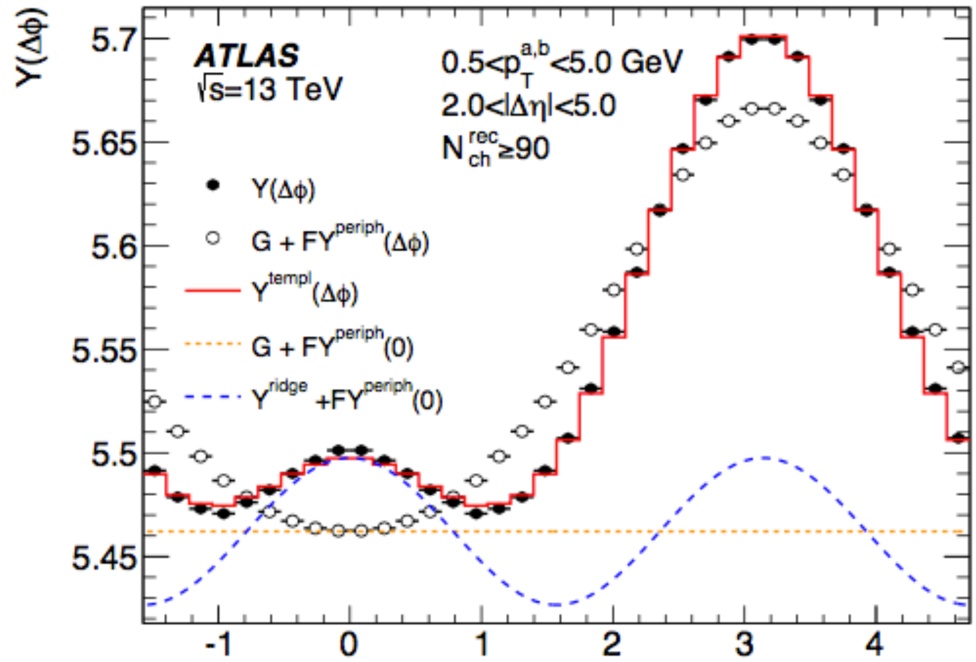


$$V_{n\Delta}^{\mathrm{sub}} = V_{n\Delta} - V_{n\Delta}(10 < N_{\mathrm{trk}}^{\mathrm{offline}} < 20) \times \frac{N_{\mathrm{assoc}}(10 < N_{\mathrm{trk}}^{\mathrm{offline}} < 20)}{N_{\mathrm{assoc}}} \times \frac{Y_{\mathrm{jet}}}{Y_{\mathrm{jet}}(10 < N_{\mathrm{trk}}^{\mathrm{offline}} < 20)}$$

- Jet correlation contributions removed
- V_n (N_{trk} < 20) = 0 by construction

ATLAS template fitting method





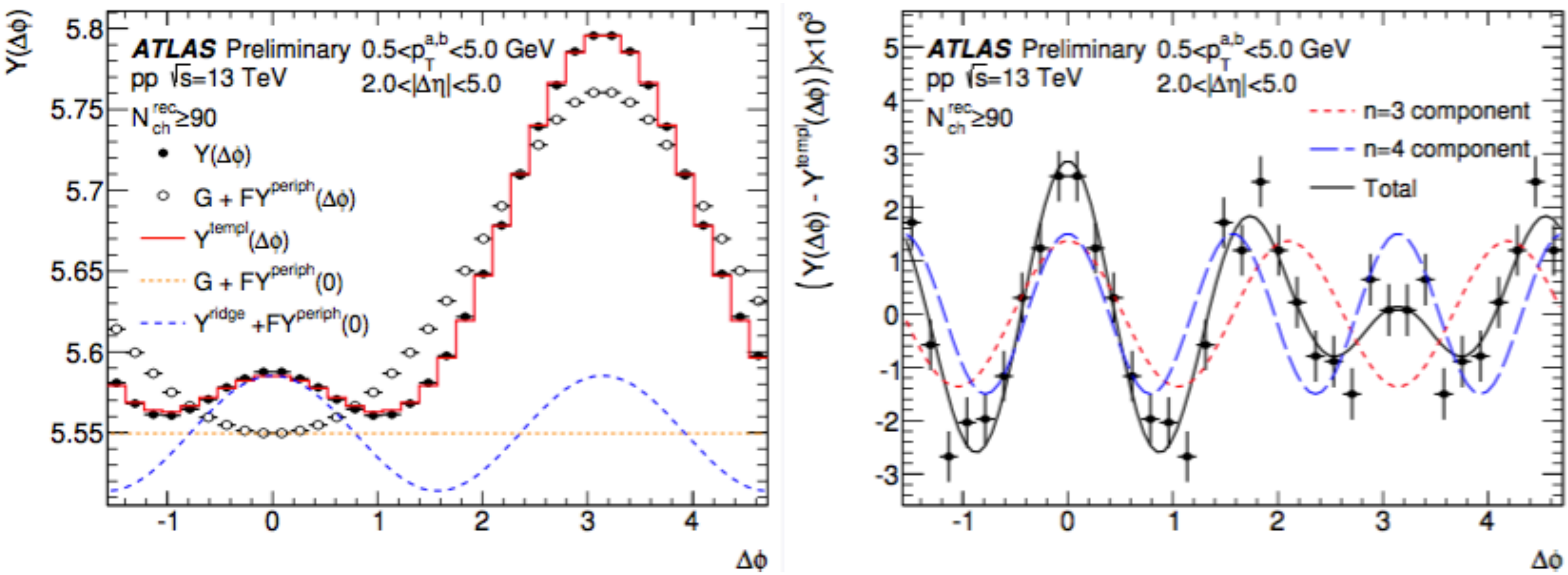
PhysRevLett.116.172301

Assumption: Correlation observed in high-multiplicity events is a linear combination of “hard” correlation seen in low-multiplicity events + cos(2Δφ) modulation

$$Y^{\text{templ}}(\Delta\phi) = FY^{\text{periph}}(\Delta\phi) + Y^{\text{ridge}}(\Delta\phi)$$

$$Y^{\text{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)]$$

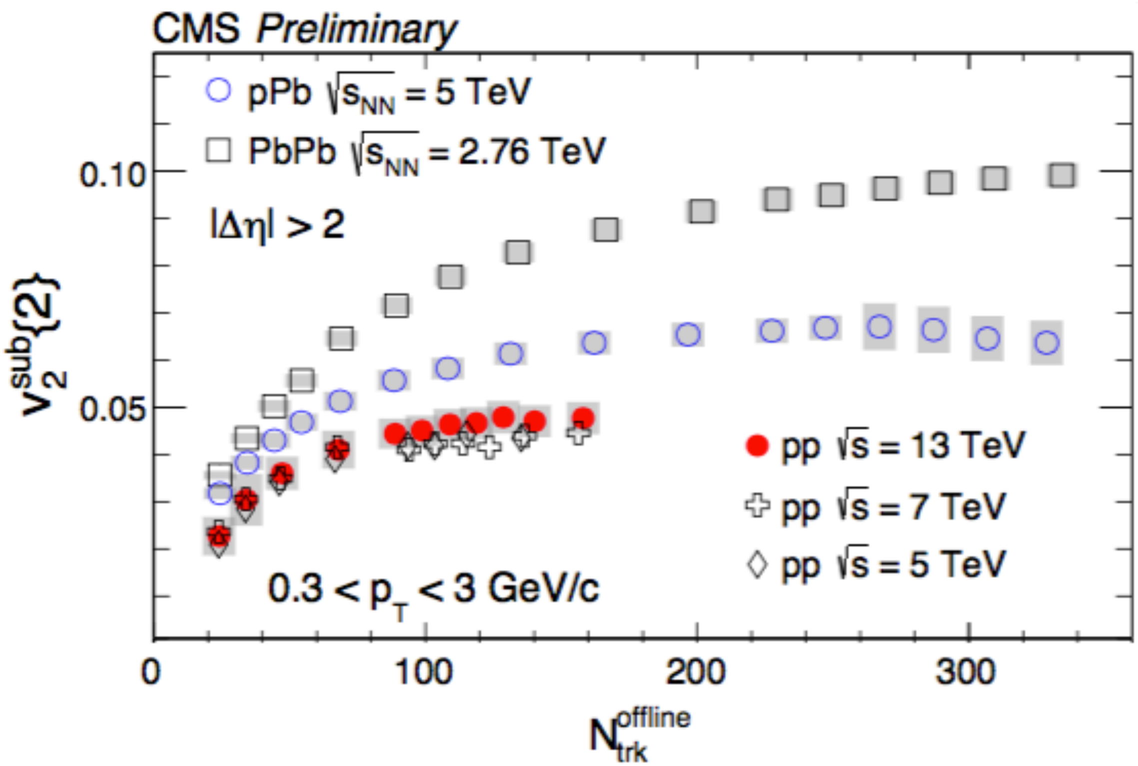
Template fitting with v_3 and v_4

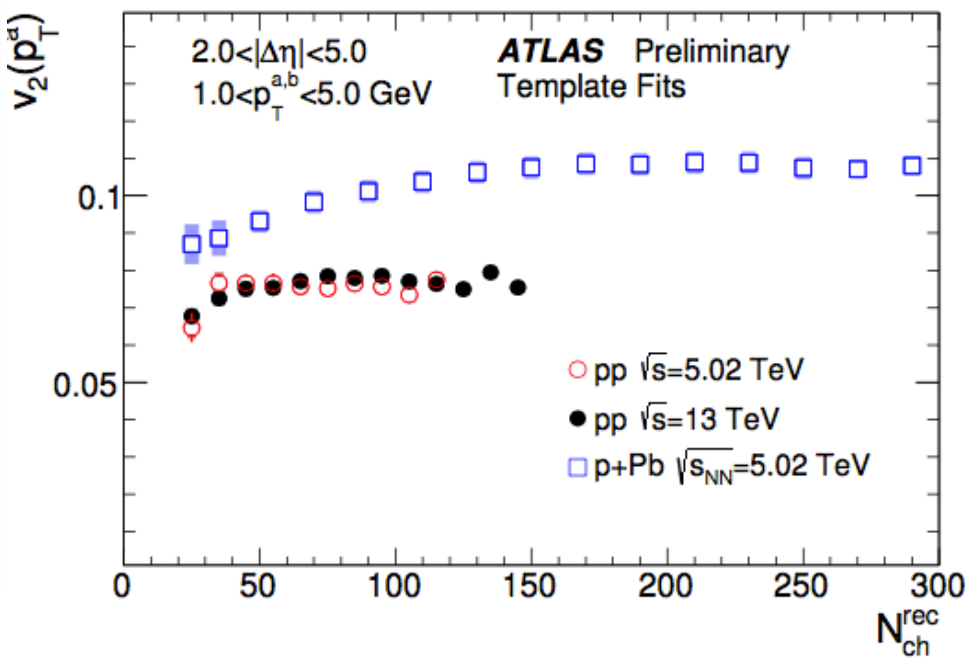


Observe clear higher harmonics

- Well described by sum of cos(3Δφ) and cos(4Δφ)

v_2 after peripheral subtraction

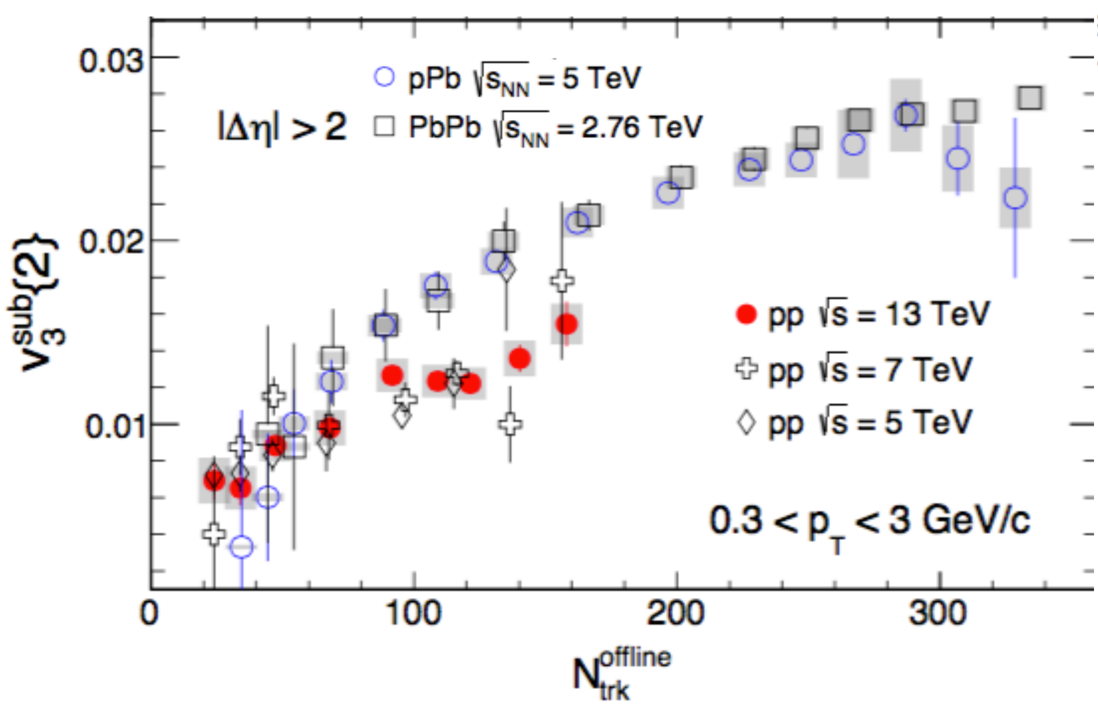


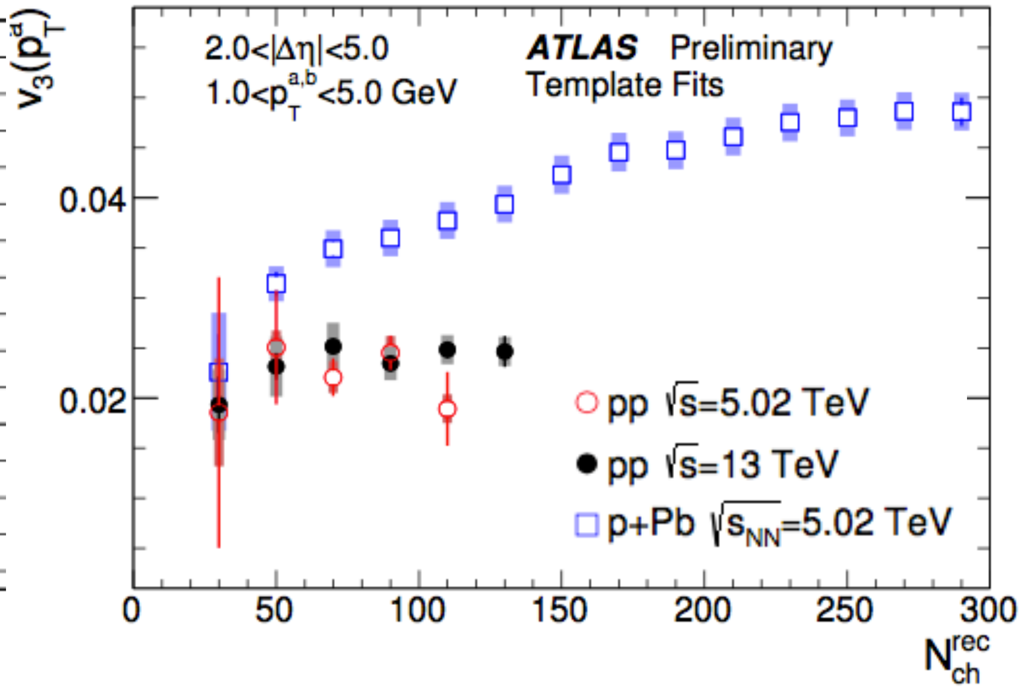


pp collisions:

- No energy dependence observed
- Similar shape as pPb and PbPb
- Smaller v_2 than in larger systems

v_3 after peripheral subtraction

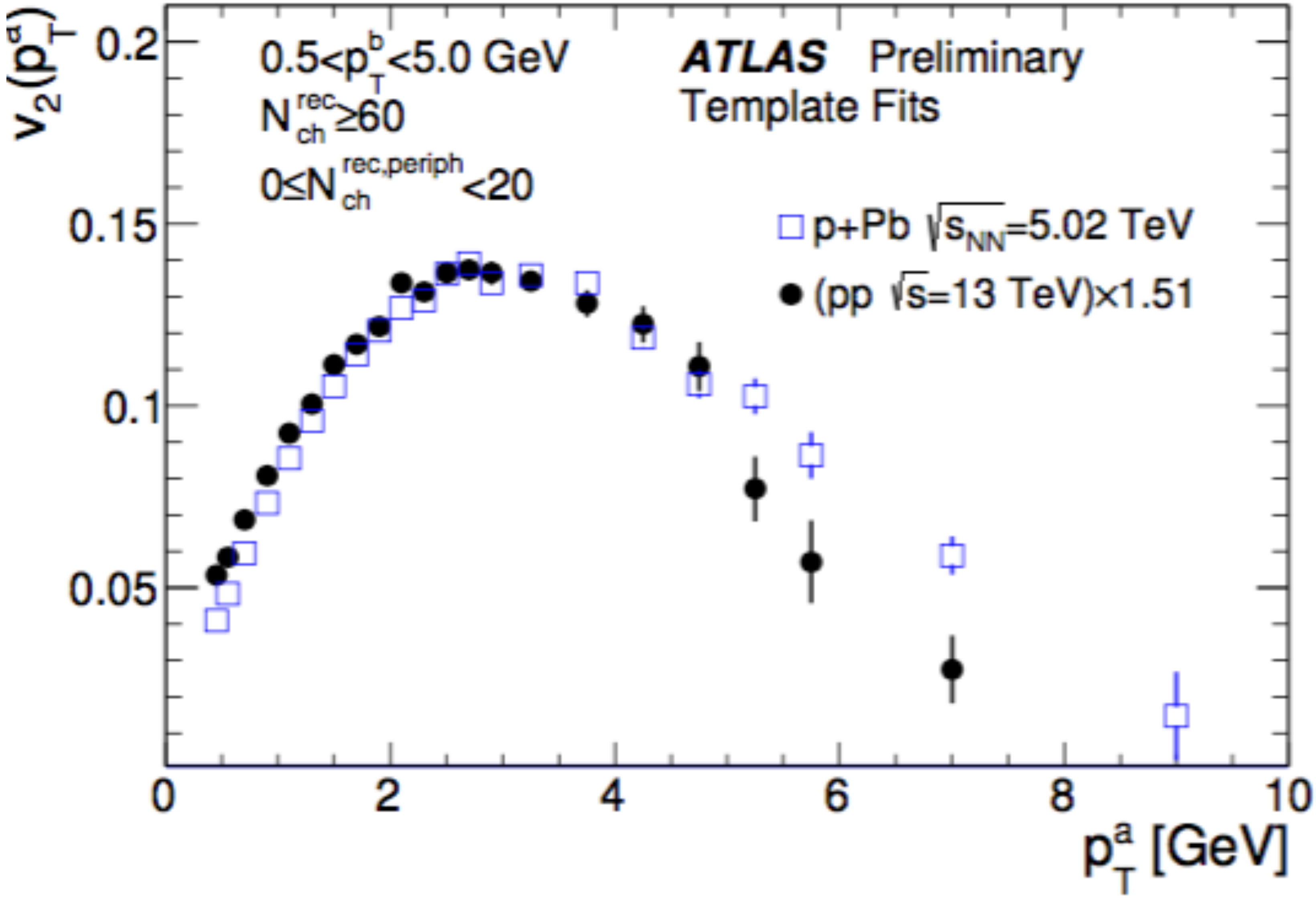




pp collisions:

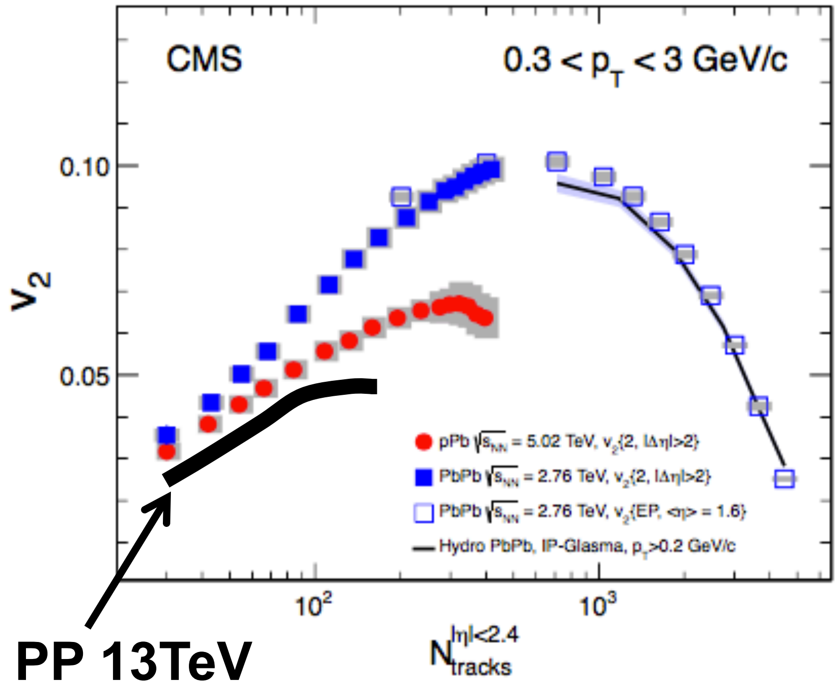
- No energy dependence observed
- Smaller than pPb and PbPb

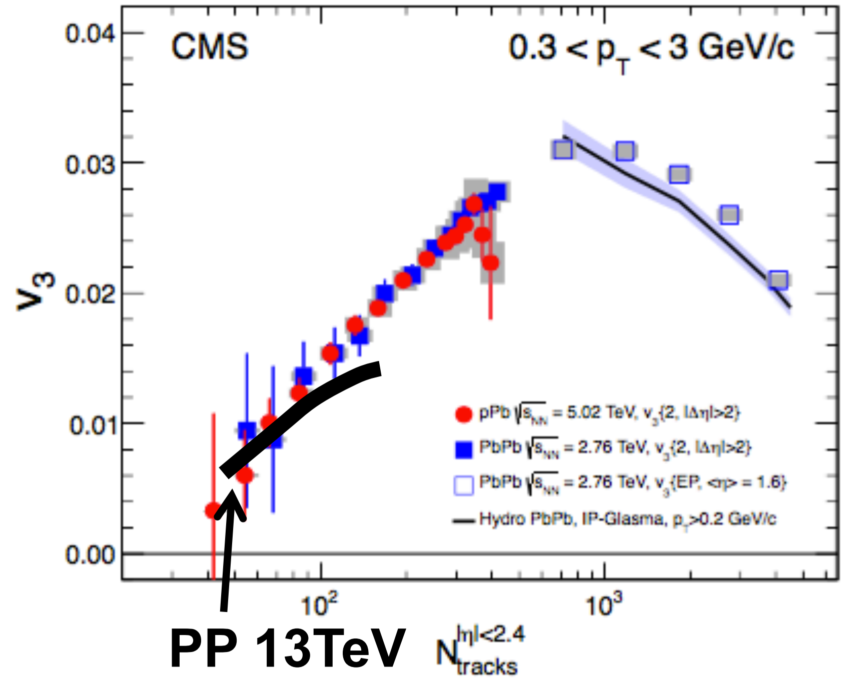
How different are pp and pPb ? $v_2(p_T)$ shape comparison



- Compare $v_2(p_T)$ in pPb with $1.51^*v_2(p_T)$ in pp
- pPb v_2 have the same trends vs p_T

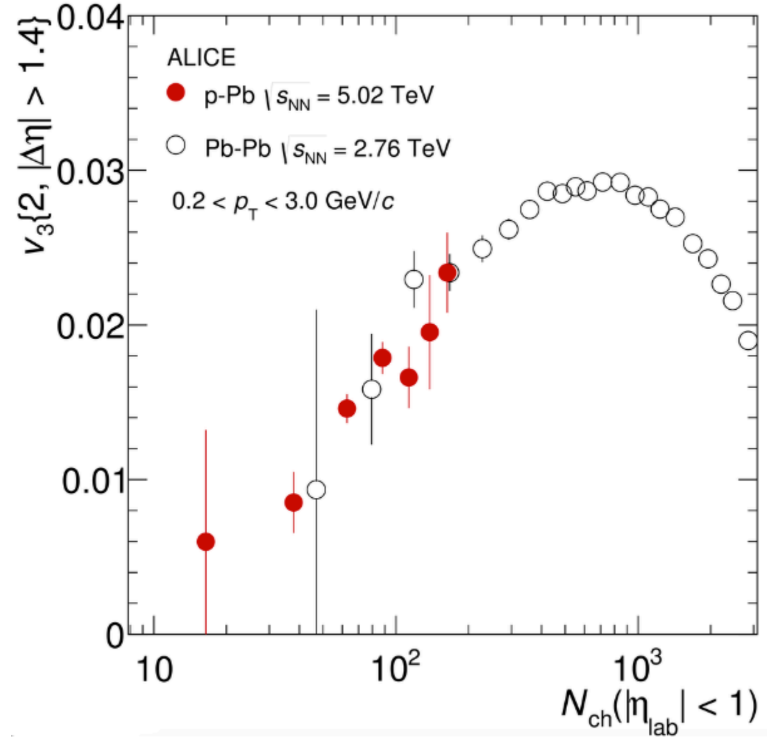
v_n in small and large systems





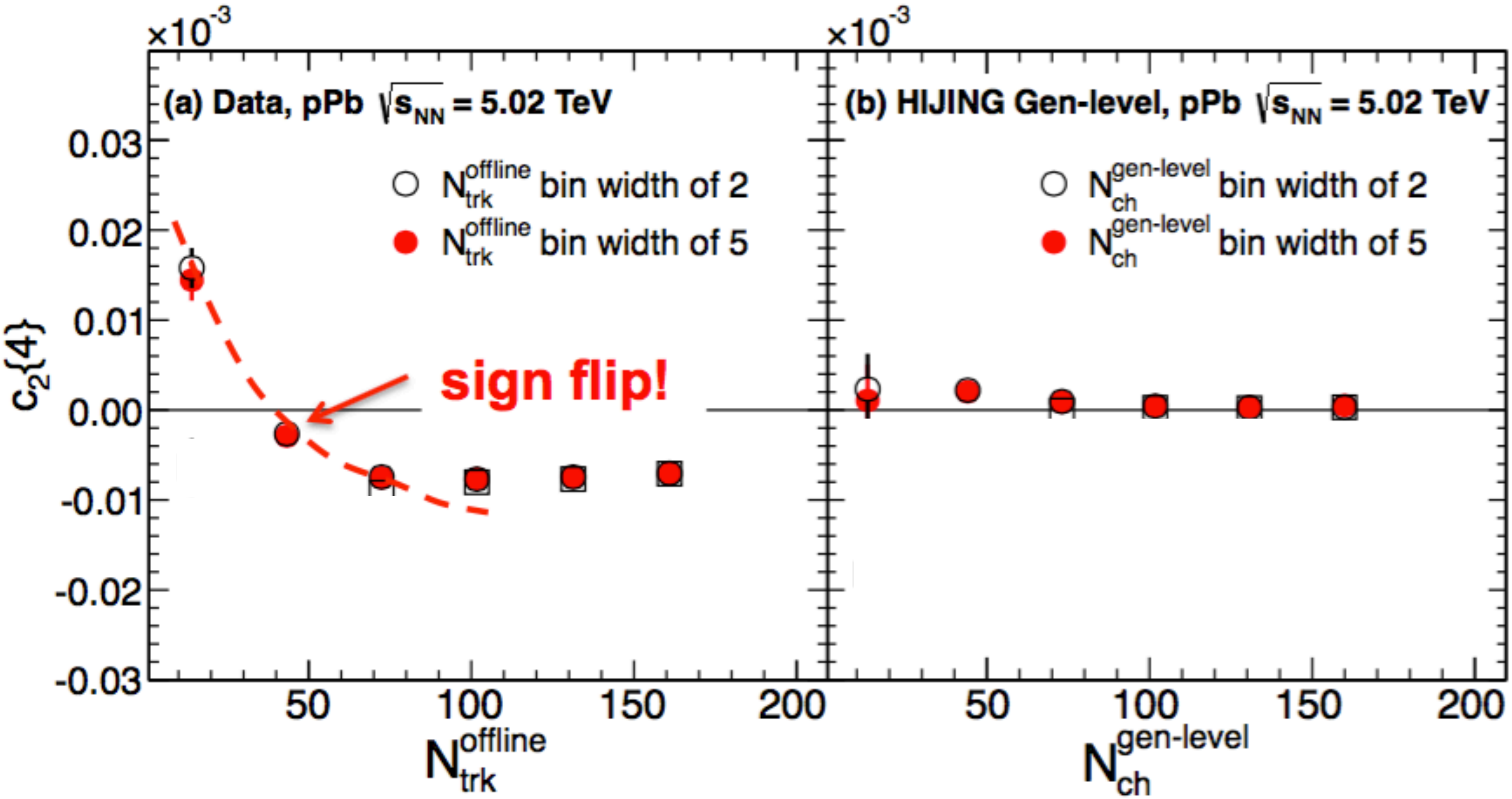
v_2: smaller in pp and pPb than in PbPb

v_3: Continuous evolution from “small” to “large” systems for pPb and PbPb, not for pp



Multi-particle Cumulant

$$\langle\langle 4\rangle\rangle = \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle, \quad c_2\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2$$



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

Multi-particle Cumulant

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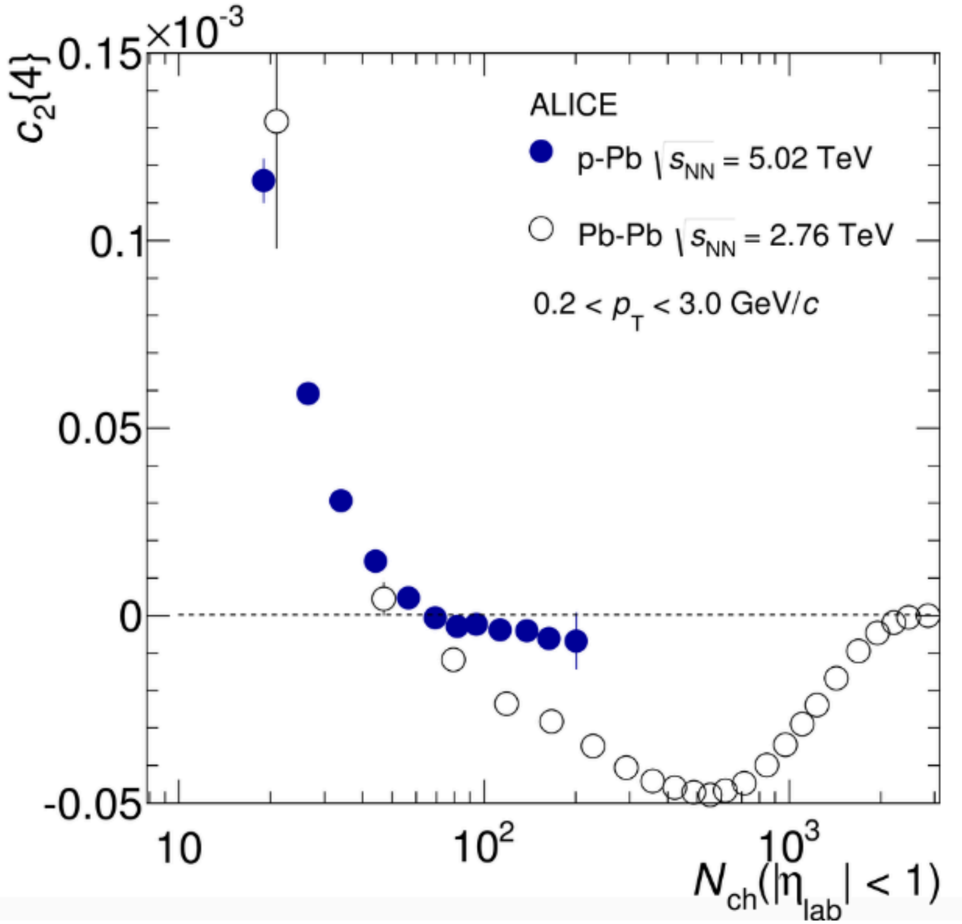
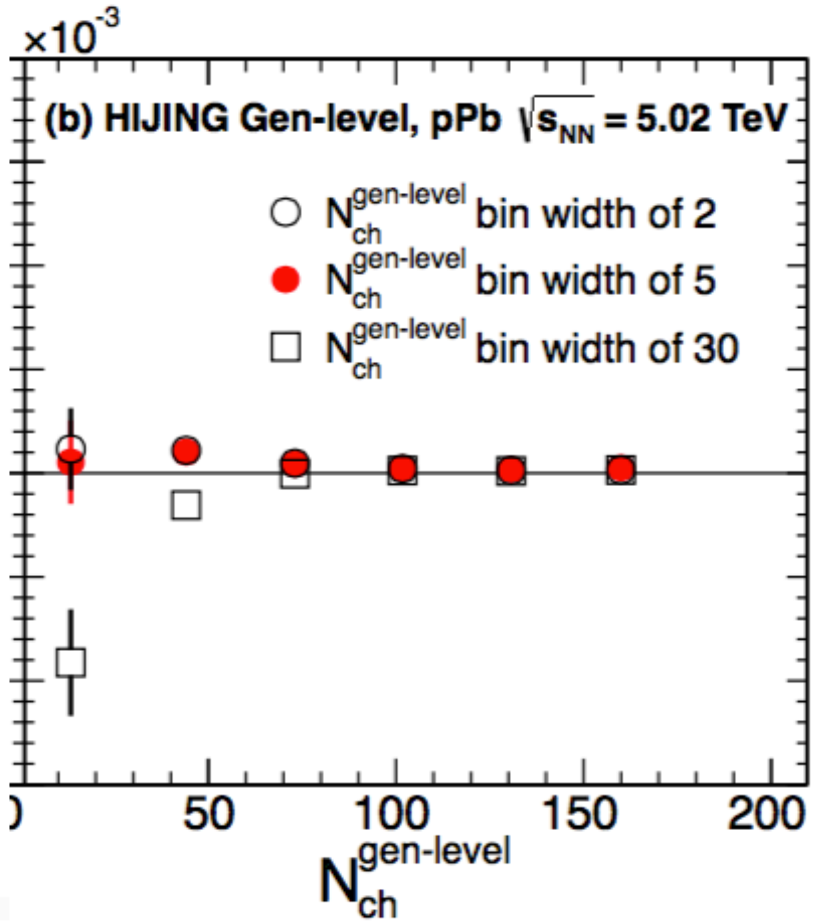
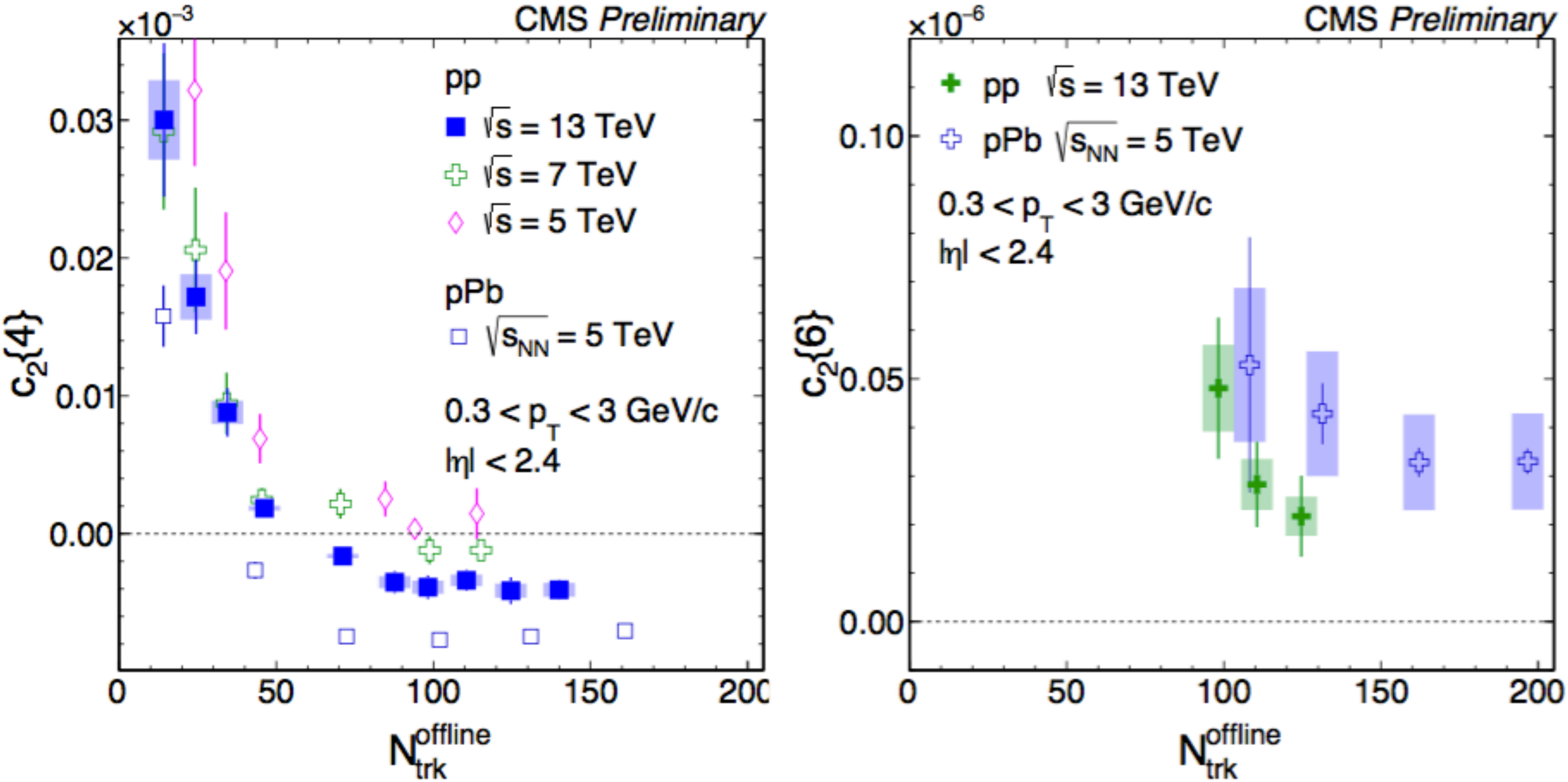




$$\boxed{v_2\{4\} = \sqrt[4]{-c_2\{4\}}}$$

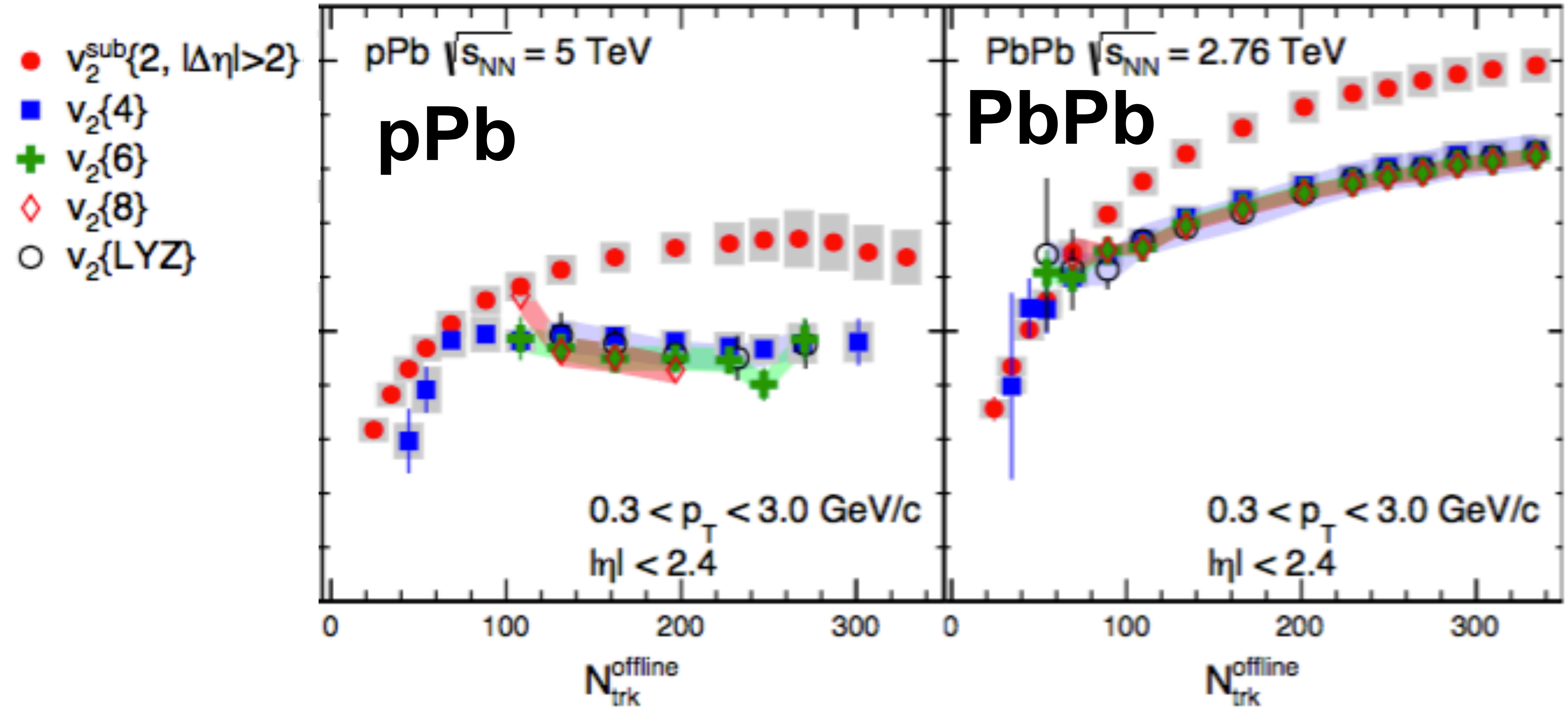
Multi-particle Cumulant: adding pp



- Clear signal observed in 13 TeV pp collisions
- Shape similar to pPb but with different magnitude

v_2 from Multi-particle Correlations

Phys. Rev. Lett. 115, 012301 (2015)



- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{all{=}LYZ\}$ in pPb and PbPb!
  - Strong evidence of collectivity! All particles correlated

v_2 from Multi-particle Correlations

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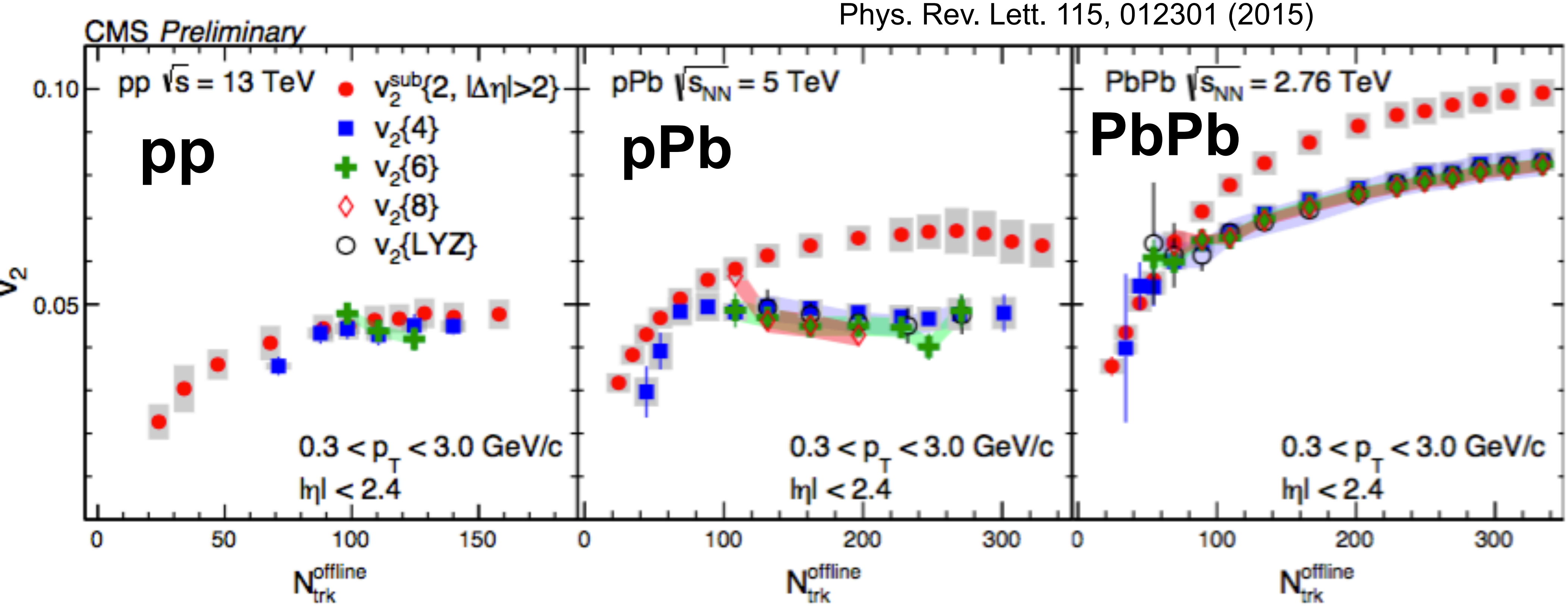
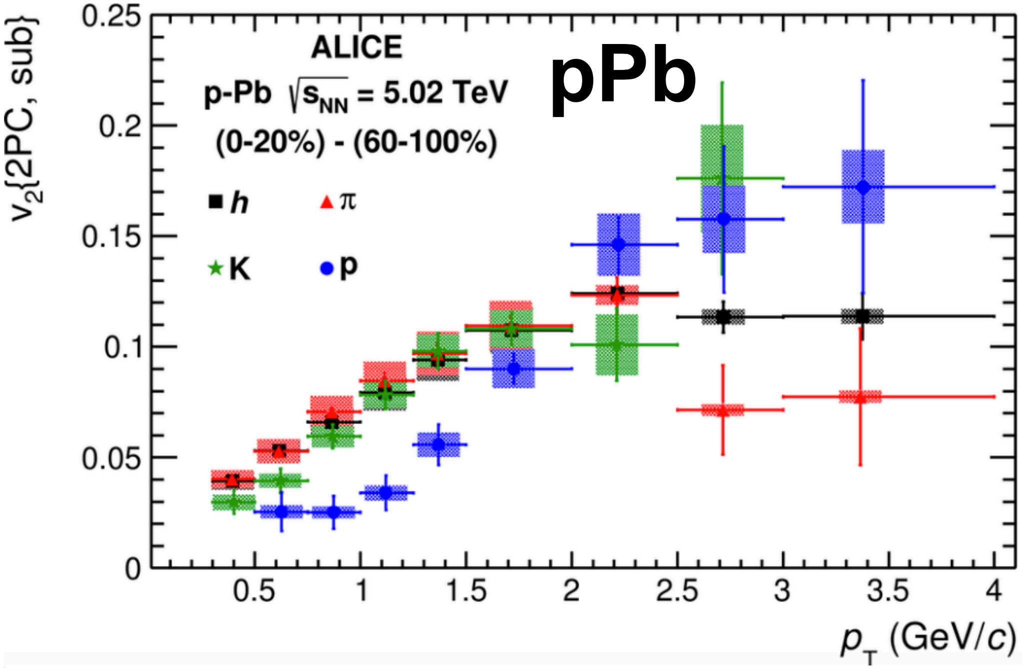
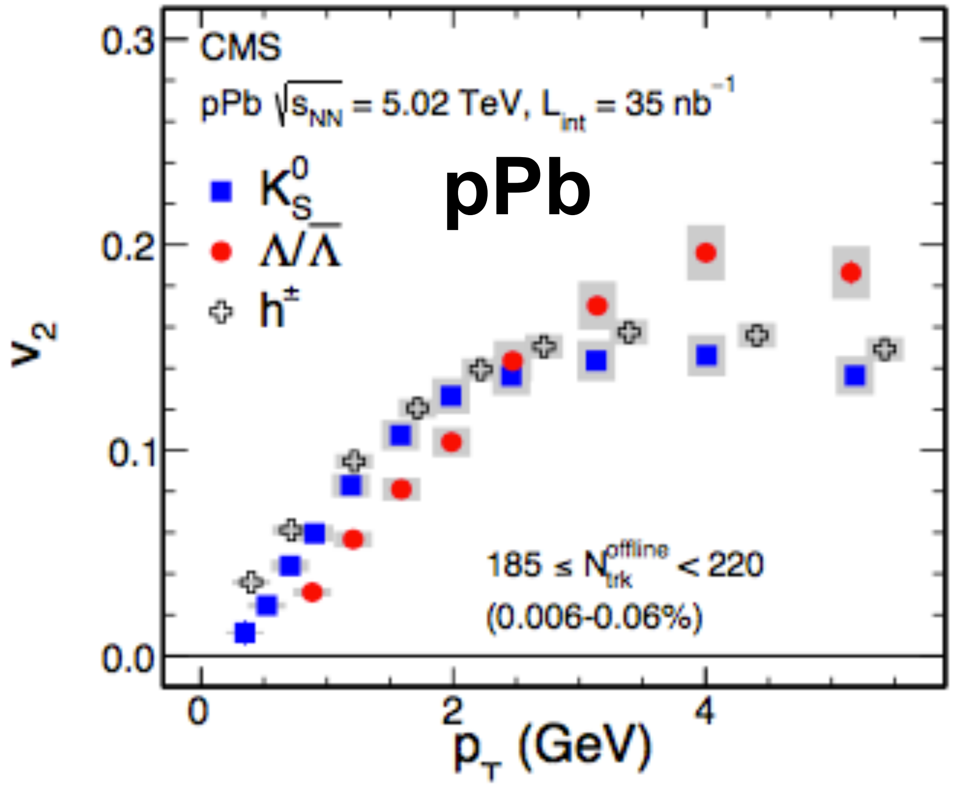


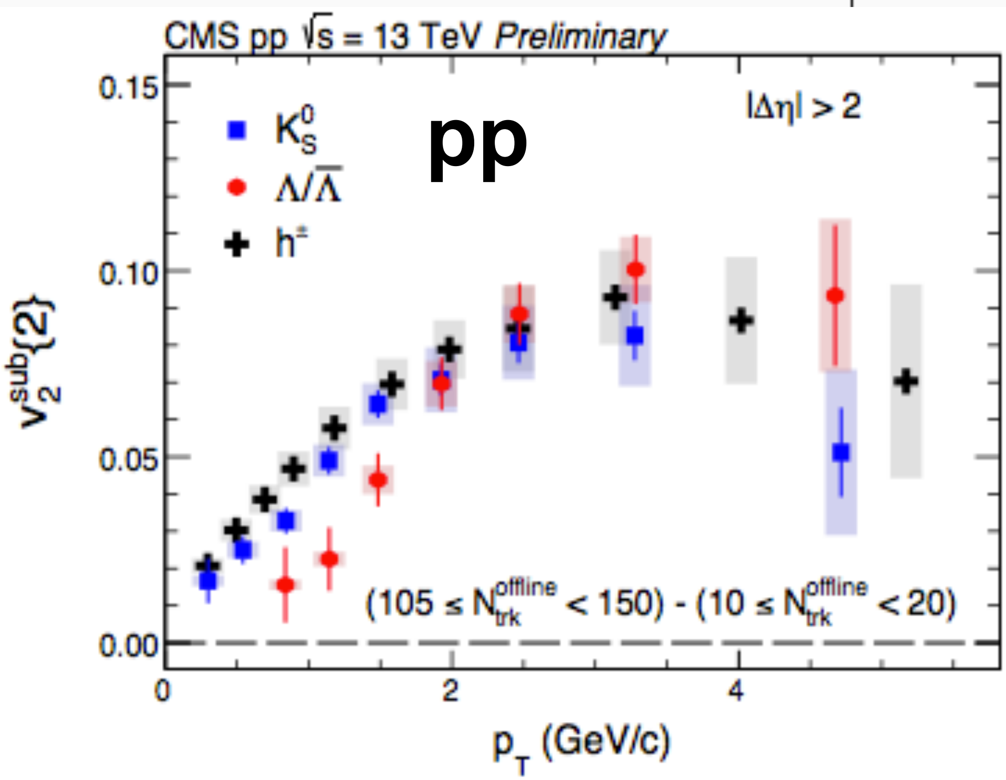
- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{all=LYZ\}$ in pPb and PbPb!
  - Strong evidence of collectivity! All particles correlated

- $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$ in pp at 13 TeV! Collectivity?

Identified Particle v_2

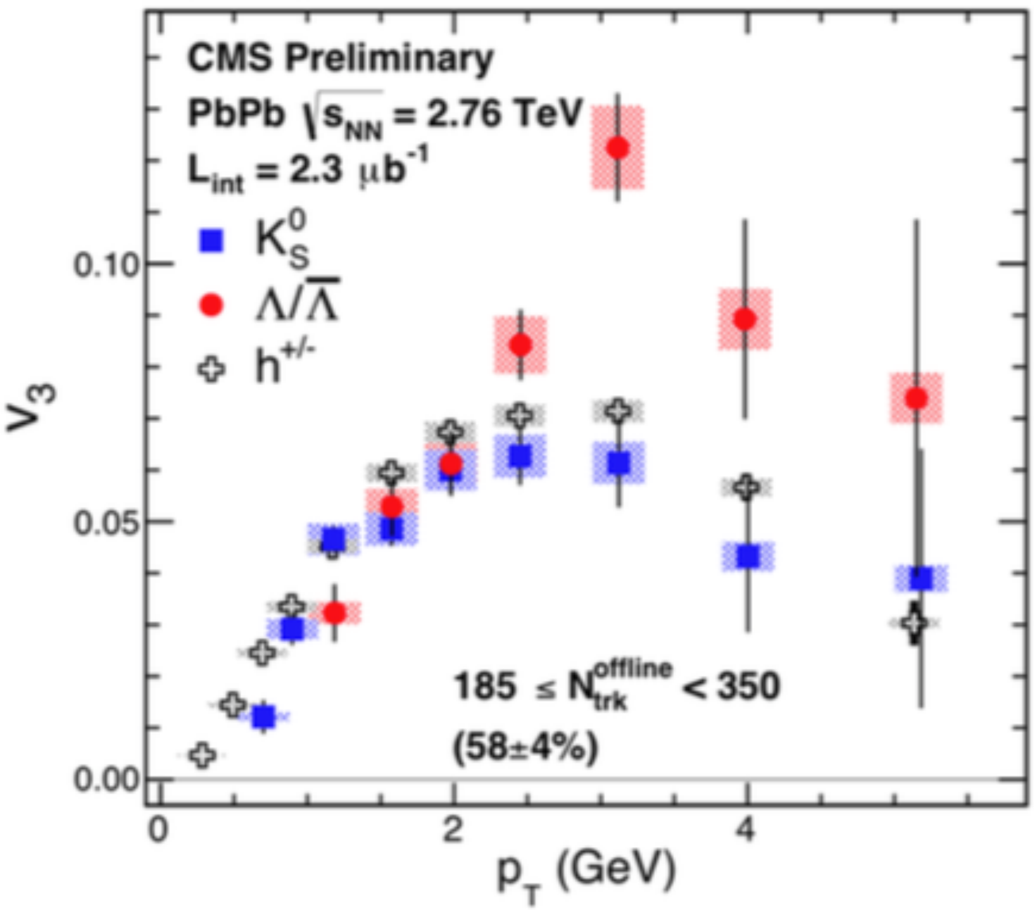


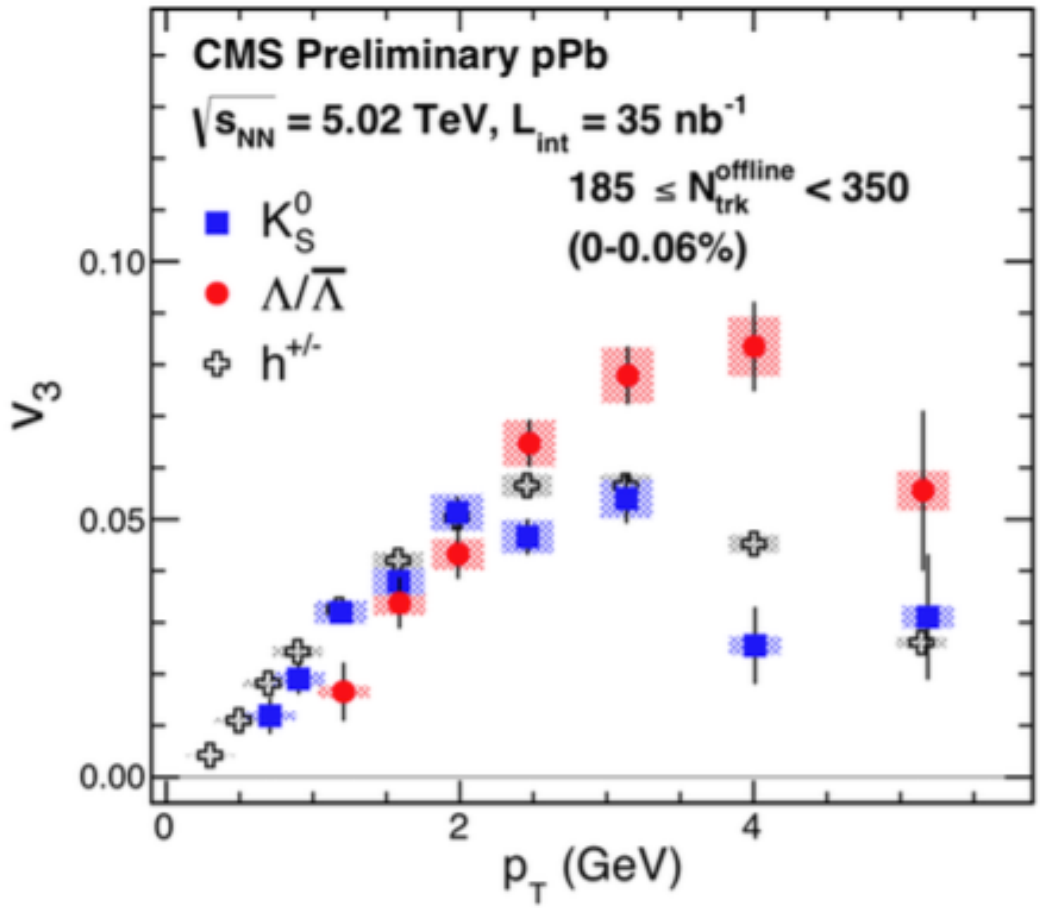




- Clear mass ordering observed up to 2 GeV/c
- Features similar to those seen in “large” systems

Identified Particle v_3





Mass ordering observed up to 2 GeV/c

v_n Factorization Breaking

Initial state fluctuations

⇓

Lumpiness of the initial state geometry

⇓

p_T and η dependent $\Psi_n(p_T, \eta)$

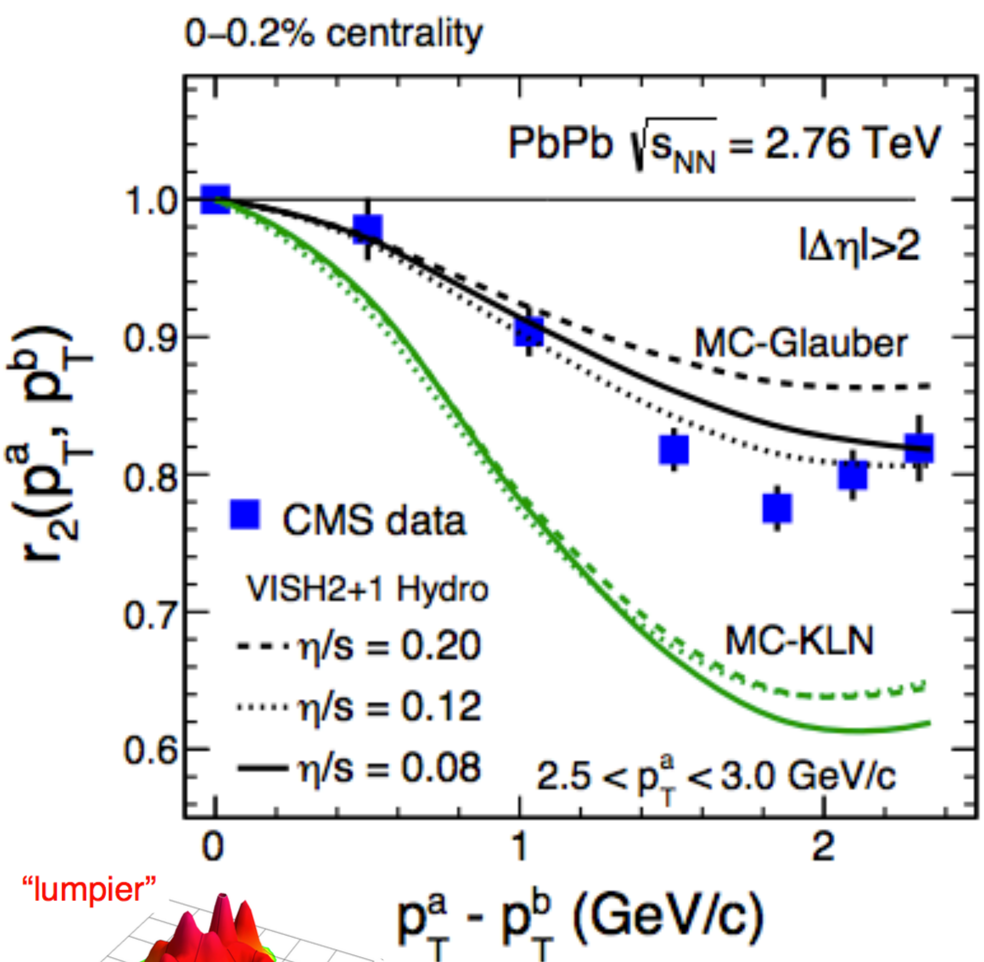
⇓

$$V_{n\Delta}(p_T^a,\eta^a;p_T^b,\eta^b) \neq v_n(p_T^a,\eta^a)\times v_n(p_T^b,\eta^b)$$

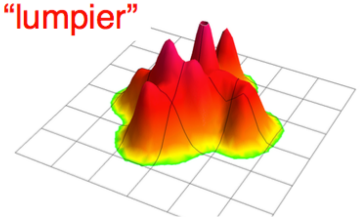
(two-particle) (single-particle)

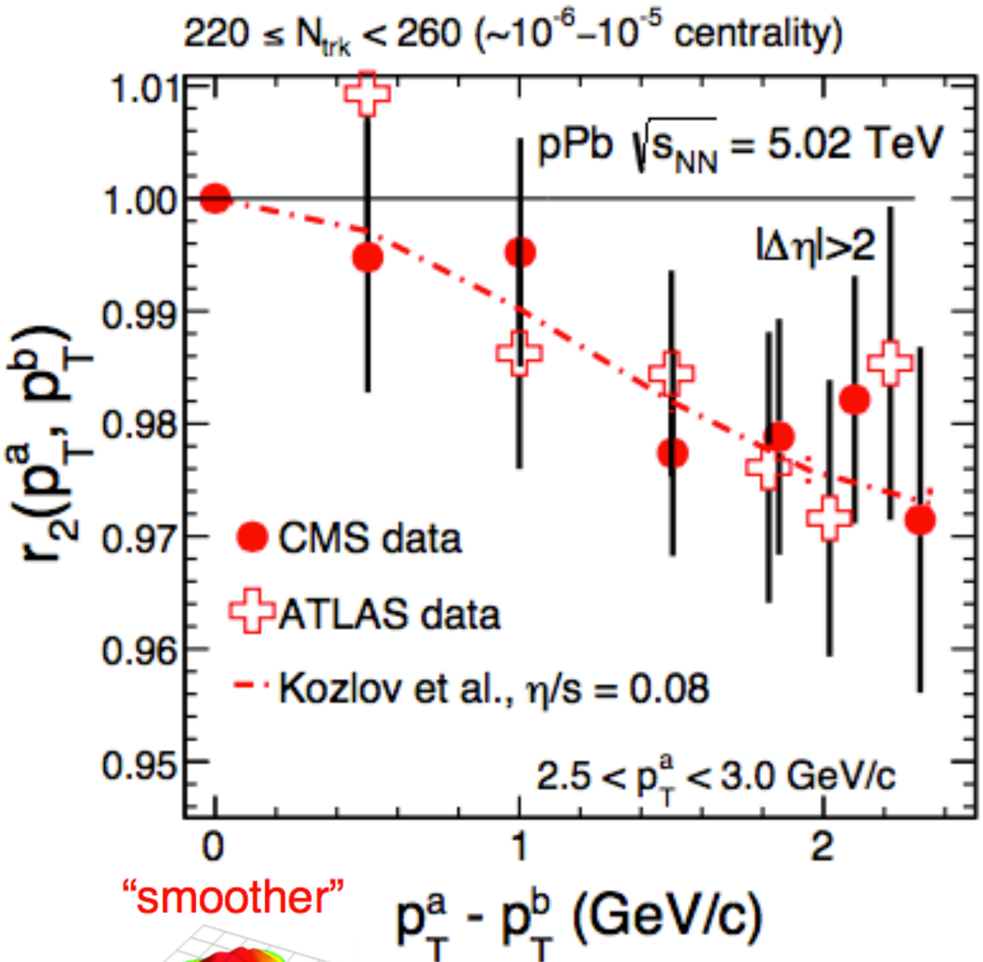
Sensitive to

v_2 Factorization Breaking in p_T

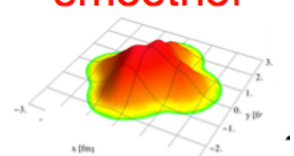


"lumpier"





"smoother"



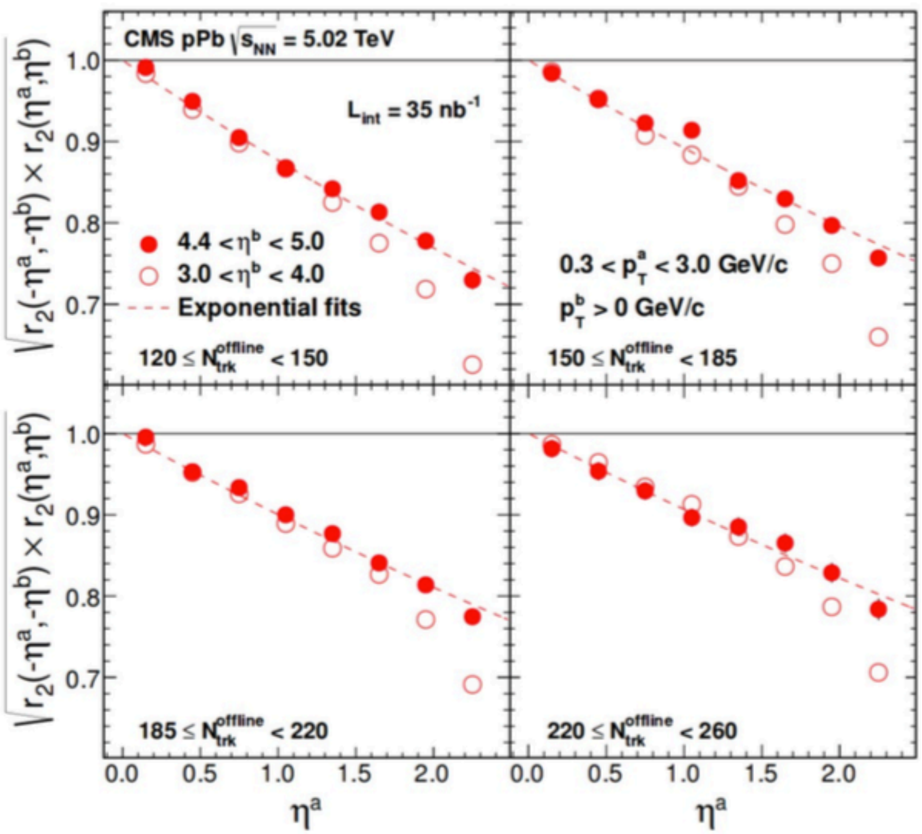
$$r_n(p_T^a, p_T^b) \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)}\sqrt{V_{n\Delta}(p_T^b, p_T^b)}}$$

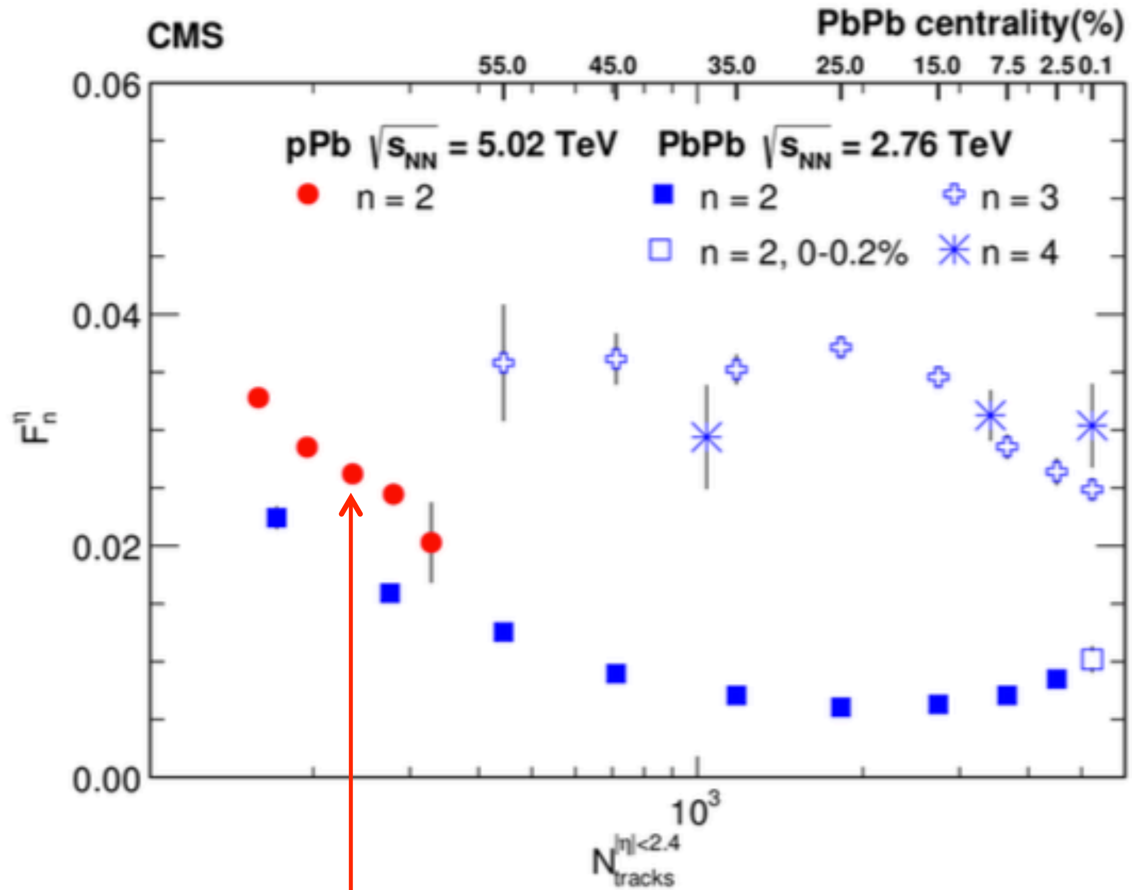
$$\sim \left\langle \cos[n(\Psi_n(p_T^a) - \Psi_n(p_T^b))] \right\rangle$$

Much less breaking in pPb than in central PbPb

v_n Factorization Breaking in η

$$r_n(\eta^a,\eta^b) = e^{-2F_n^\eta \eta^a} \approx 1 - 2F_n^\eta \eta^a$$





- Factorization breaking in both “small” and “large” systems
- Observe larger decorrelation in η for pPb

$$\sqrt{r_n(\eta^a,\eta^b) \times r_n(-\eta^a,-\eta^b)} \approx \sqrt{\frac{\langle\cos[\Psi_n(-\eta^a) - \Psi_n(\eta^b)]\rangle}{\langle\cos[\Psi_n(\eta^a) - \Psi_n(\eta^b)]\rangle} \frac{\langle\cos[\Psi_n(\eta^a) - \Psi_n(-\eta^b)]\rangle}{\langle\cos[\Psi_n(-\eta^a) - \Psi_n(-\eta^b)]\rangle}}$$

$$\sim \langle \cos[n(\Psi_n(\eta^a) - \Psi_n(-\eta^a))] \rangle$$

Summary

- No obvious difference between small and large systems
  - ✓ Ridge yield
  - ✓ v_2 and higher harmonics
  - ✓ Muliti-particle correlations
  - ✓ Identified particle of v_n
  - ✓ v_n factorization breaking
- Is QGP produced in small systems?
  - o Need more theoretical studies
  - o New measurements?

Backup

ATLAS and CMS method

Assumption: Correlation observed in high-multiplicity events is a linear combination of "hard" correlation seen in low-multiplicity events + cos(2Δφ) modulation

$$Y^{\mathrm{templ}}(\Delta\phi) = FY^{\mathrm{periph}}(\Delta\phi) + Y^{\mathrm{ridge}}(\Delta\phi) \qquad (1)$$

$$Y^{\mathrm{ridge}}(\Delta\phi) = G[1 + 2v_{2,2}\cos(2\Delta\phi)] \qquad (2)$$

Data suggests that Y^{periph} contains a hard component and a soft component:

$$Y^{\mathrm{periph}}(\Delta\phi) = Y^{\mathrm{hard}}(\Delta\phi) + G_0[1 + 2v_{2,2}^{0}\cos(2\Delta\phi)] \qquad (3)$$

CMS peripheral subtraction method subtract: $2FG_0 v_{2,2}^{0}\cos(2\Delta\phi)$ Reduced v_2

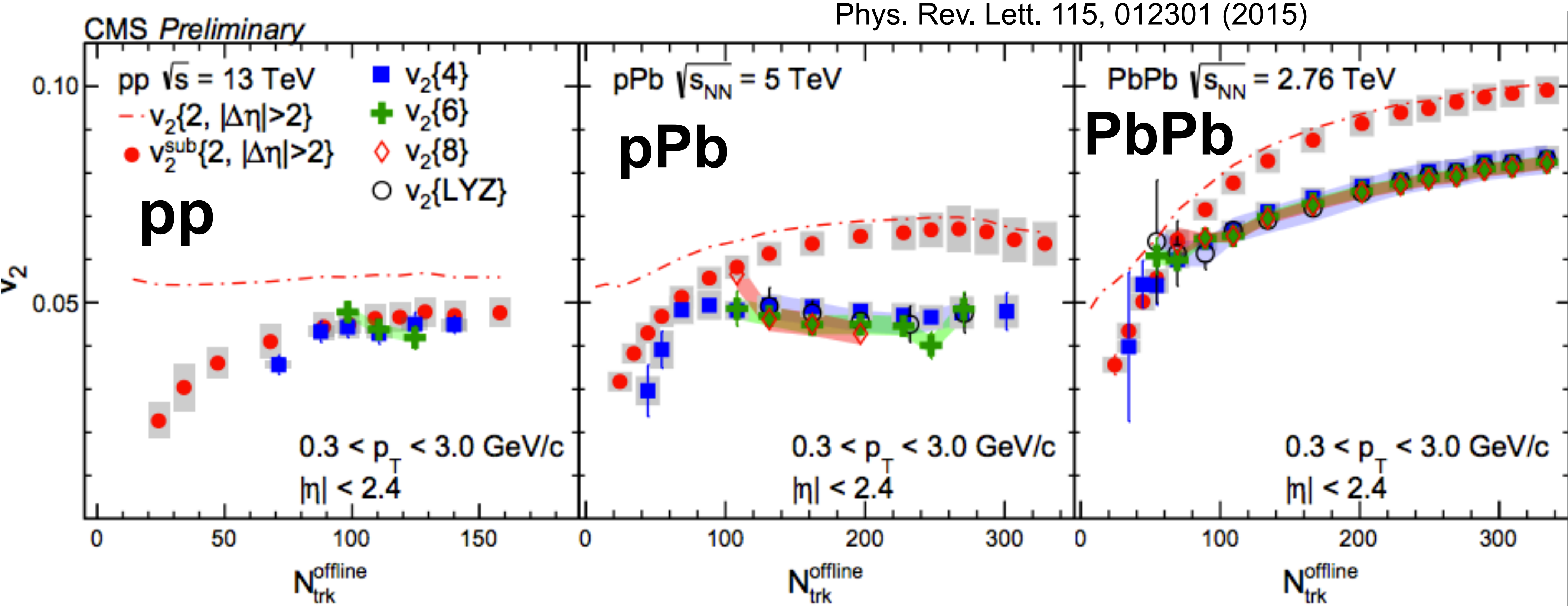
ATLAS template fitting method subtract: $FG_0[1 + 2v_{2,2}^{0}\cos(2\Delta\phi)]$

Reduced G in (2), less impact on v_2 .

Can be interpreted as correlation w.r.t. a subset of particles?

v_2 from Multi-particle Correlations

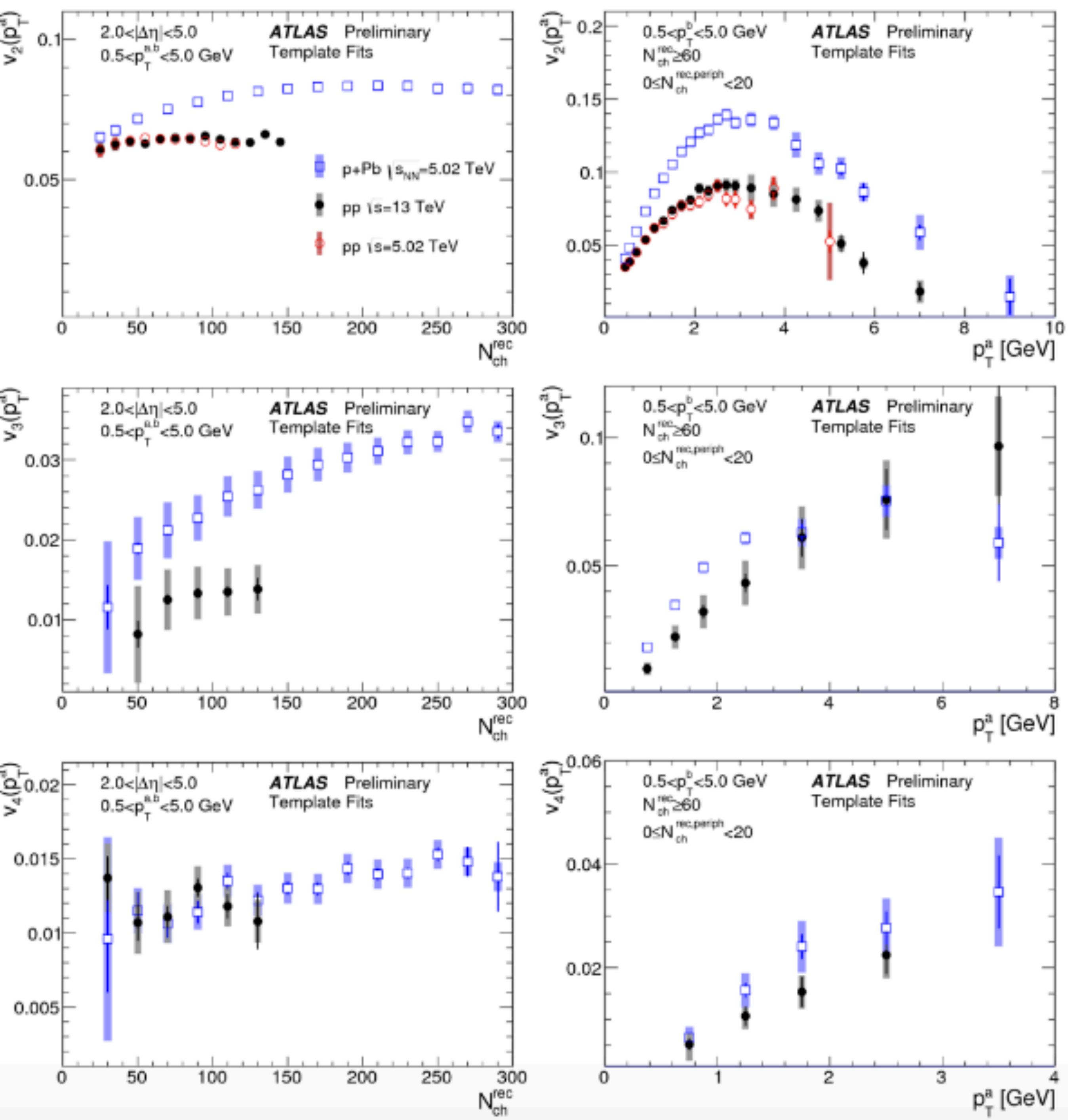
Phys. Rev. Lett. 115, 012301 (2015)

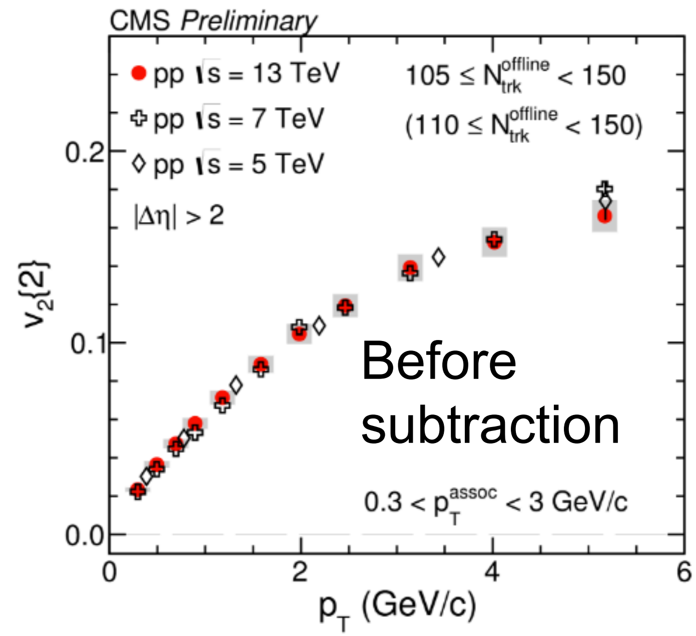


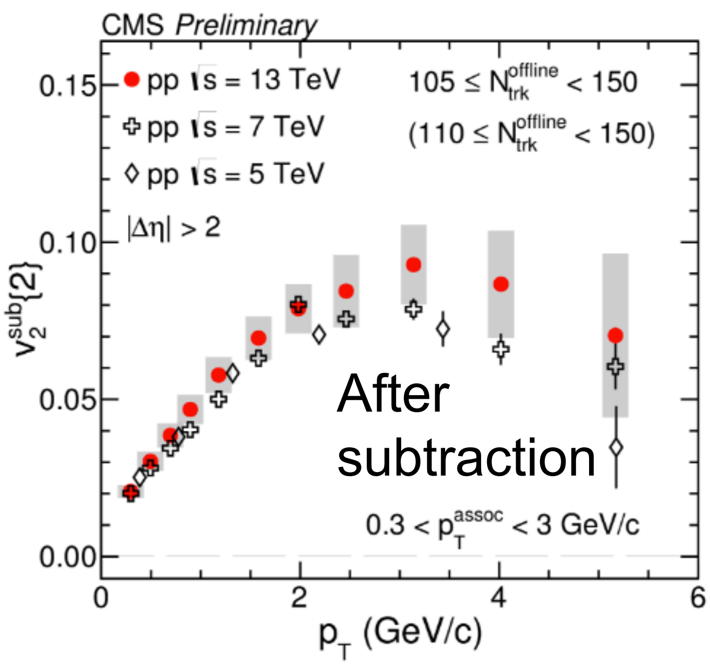
- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{all=LYZ\}$ in pPb and PbPb!
  - Strong evidence of collectivity! All particles correlated

- $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$ in pp at 13 TeV!

v_n in small systems



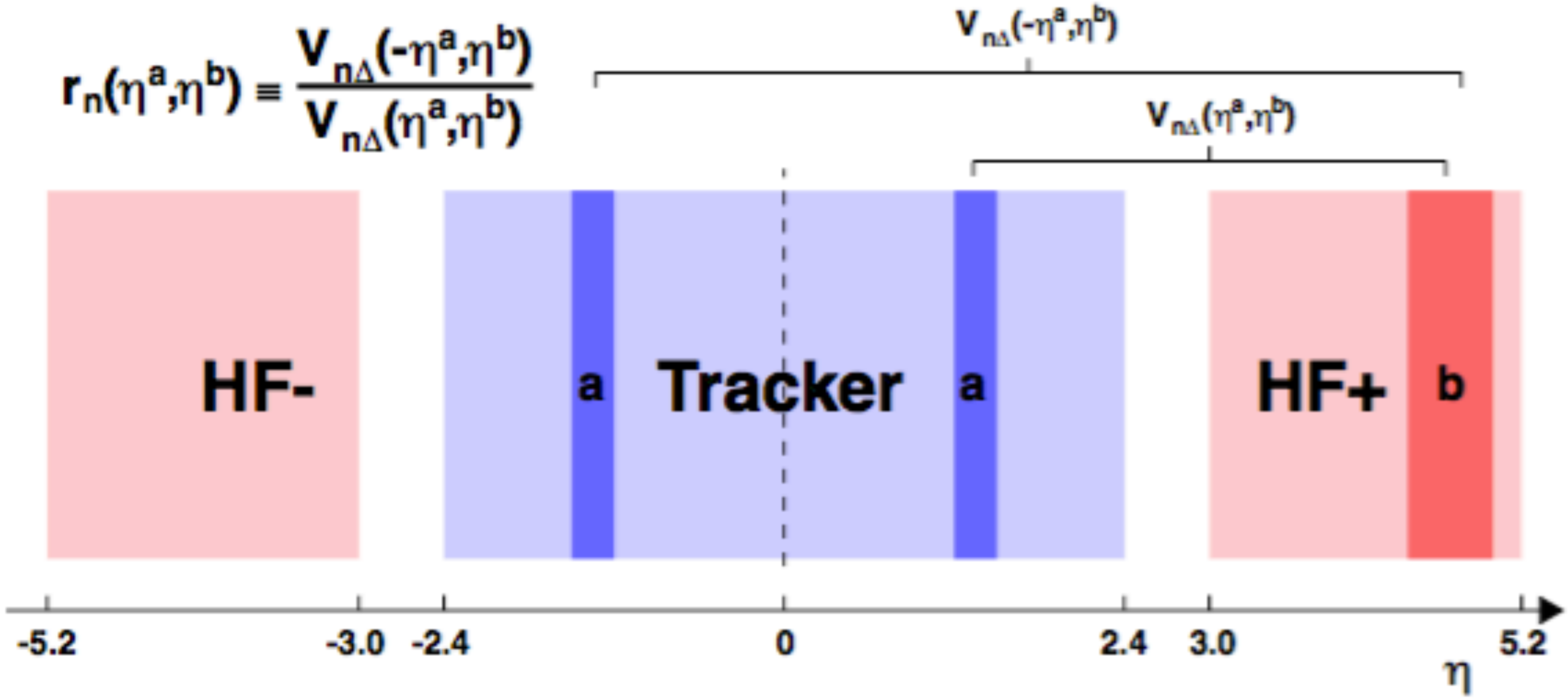




v_n Factorization Breaking in η

Redefine "factorization ratio": $V_{n\Delta}(\eta^a,\eta^b)=\langle\langle\cos[n(\phi^a-\phi^b)]\rangle\rangle$

$$r_n(\eta^a,\eta^b)\equiv\frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$



HF towers (tracks) weighted by E_T (p_T)

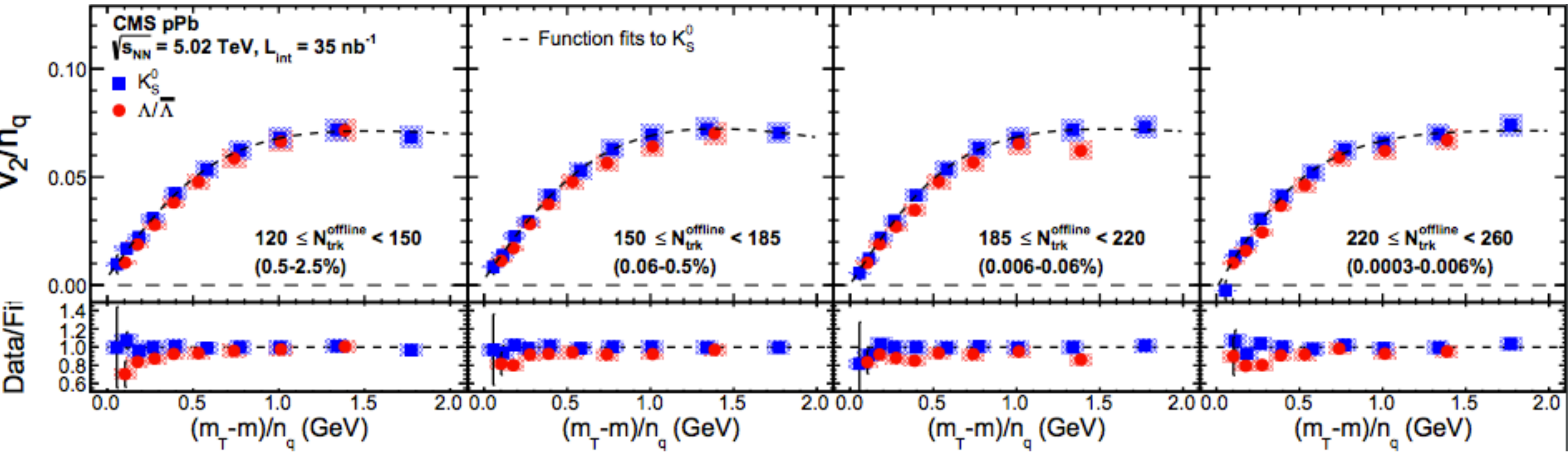
CMS, arXiv:1503.01692

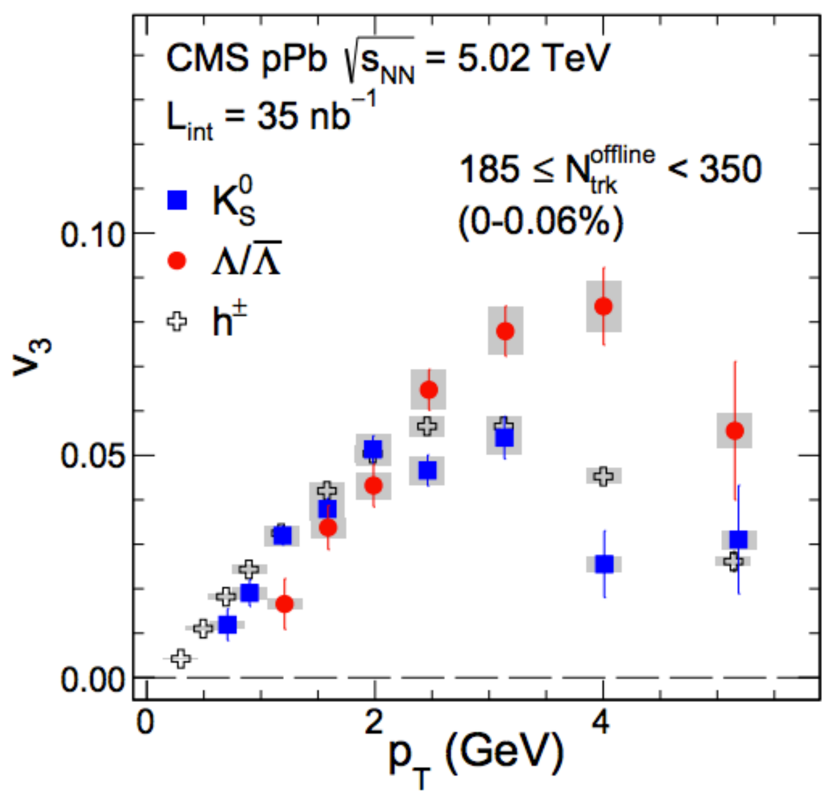
Ensure all pairs used have η gap > 2 units!

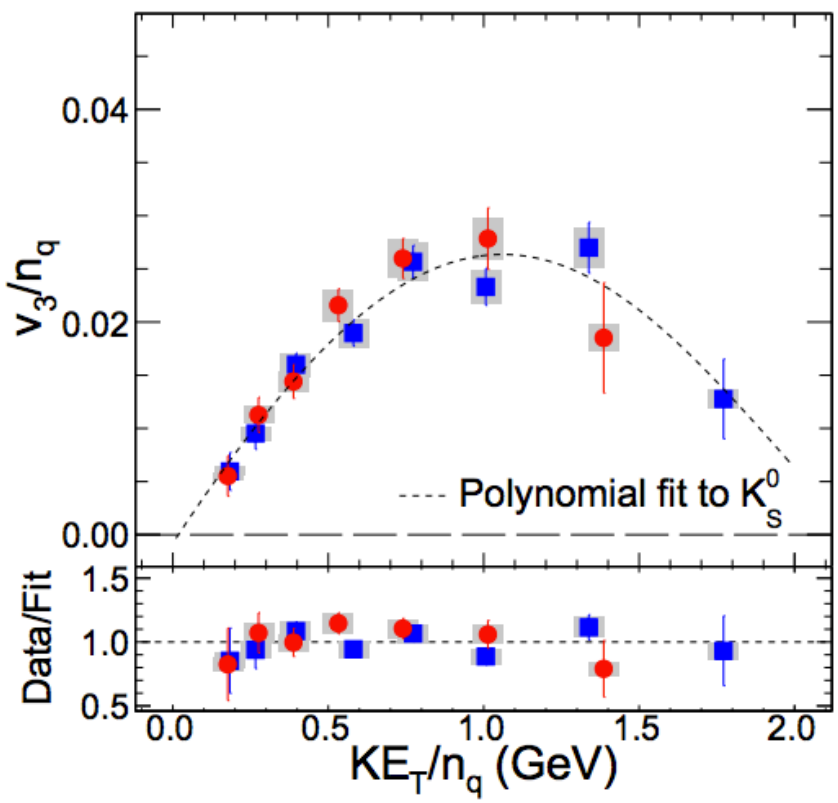
$$\sqrt{r_n(\eta^a,\eta^b)\times r_n(-\eta^a,-\eta^b)}\approx\sqrt{\frac{\langle\cos[\Psi_n(-\eta^a)-\Psi_n(\eta^b)]\rangle}{\langle\cos[\Psi_n(\eta^a)-\Psi_n(\eta^b)]\rangle}\frac{\langle\cos[\Psi_n(\eta^a)-\Psi_n(-\eta^b)]\rangle}{\langle\cos[\Psi_n(-\eta^a)-\Psi_n(-\eta^b)]\rangle}}$$

$$\sim\langle\cos[n(\Psi_n(\eta^a)-\Psi_n(-\eta^a))]\rangle \text{ in pPb}$$

Identified Particle v_n in pPb







Identified Particle v_2 in pp