

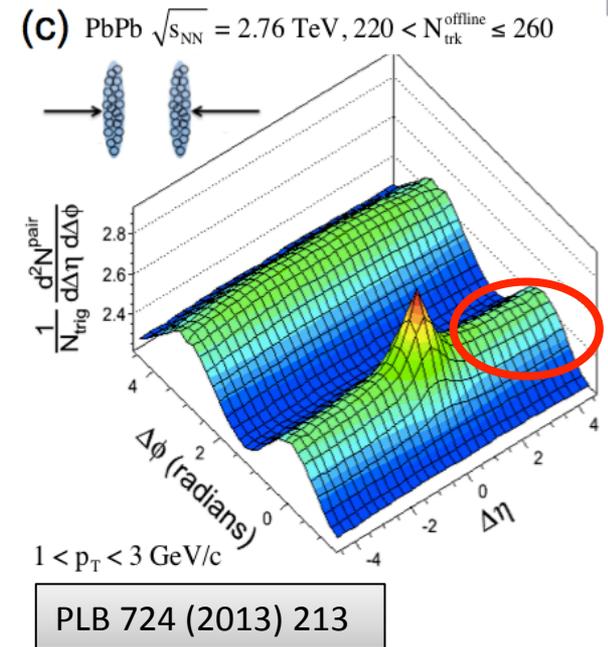
Collective “flow” in high multiplicity p-p collisions at CMS

Zhenyu Chen (Rice University)

For the CMS Collaboration

LHCP conference, Lund – June 14 (2016)

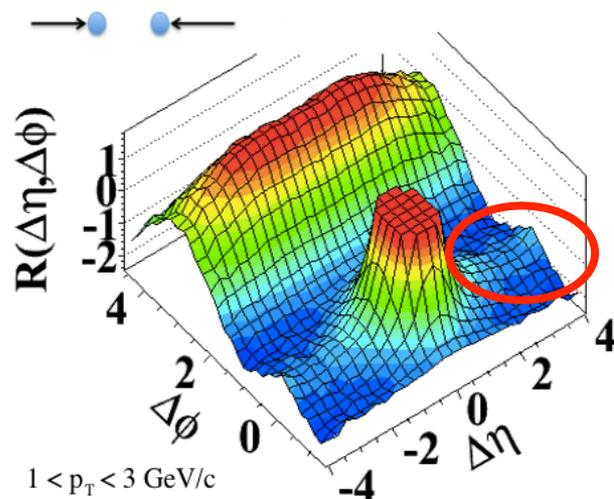
Long-range “ridge” – from large to small



Perfect fluid property of “QGP” in AA collisions

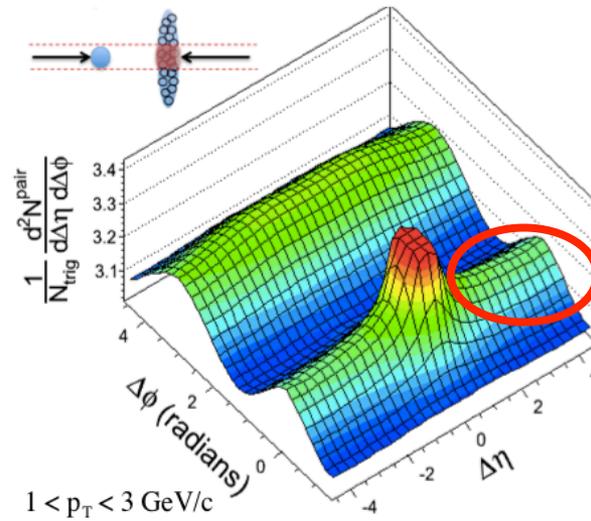
Long-range “ridge” – from large to small

(a) $pp \sqrt{s} = 7 \text{ TeV}, N_{\text{trk}}^{\text{offline}} \geq 110$



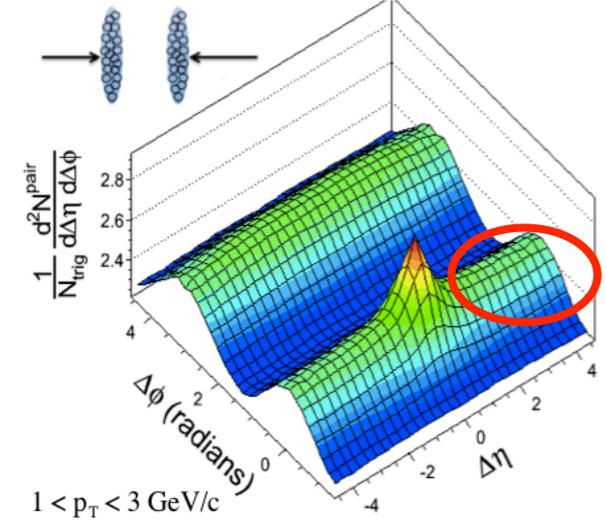
JHEP 09 (2010) 091

(b) $pPb \sqrt{s_{NN}} = 5.02 \text{ TeV}, 220 < N_{\text{trk}}^{\text{offline}} \leq 260$



PLB 724 (2013) 213

(c) $PbPb \sqrt{s_{NN}} = 2.76 \text{ TeV}, 220 < N_{\text{trk}}^{\text{offline}} \leq 260$



PLB 724 (2013) 213

What is the origin of the long range near side correlation in small system?

“ridge” in pPb – collective “flow”

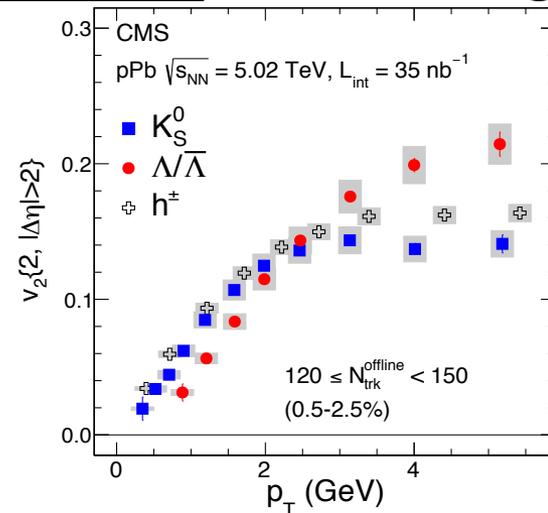
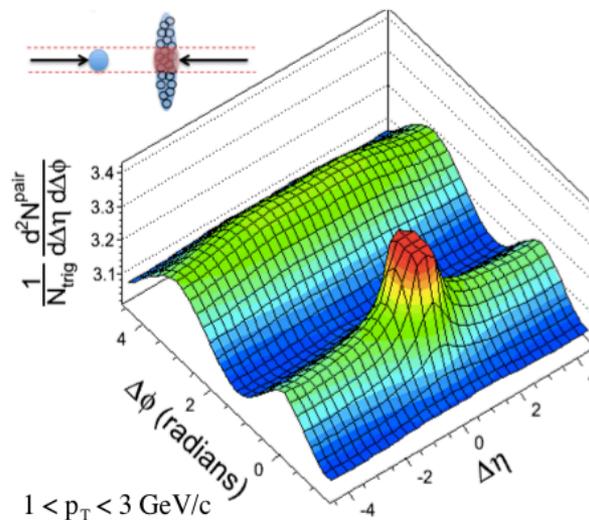
Similar feature to the AA case were observed

- ❖ Collective effect
- ❖ Clear mass ordering for V^0
- ❖ Larger “Radial flow”

(b) pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 < N_{trk}^{offline} \leq 260$

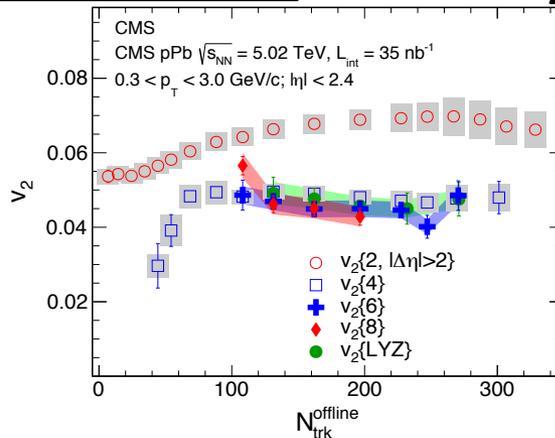
PLB 724 (2013) 213

Mass ordering



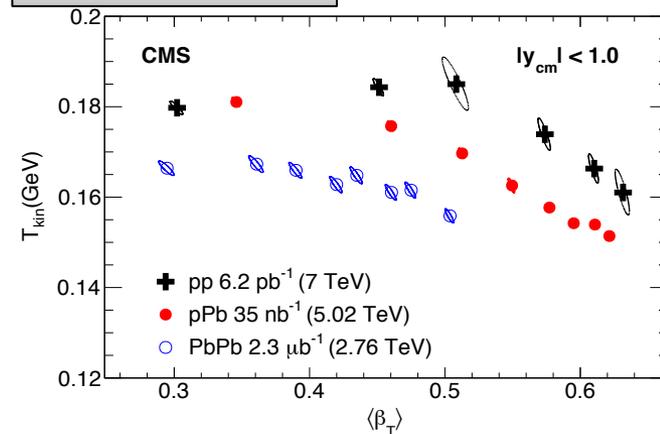
PRL 115 (2015) 012301

Collectivity



arXiv:1605.06699

“Radial flow”



“ridge” in pPb – collective “flow”

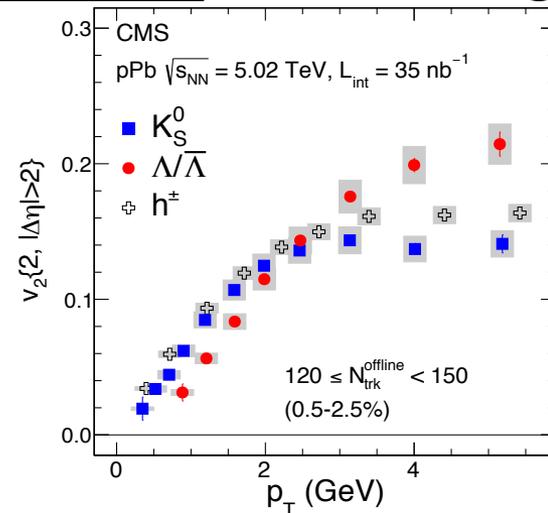
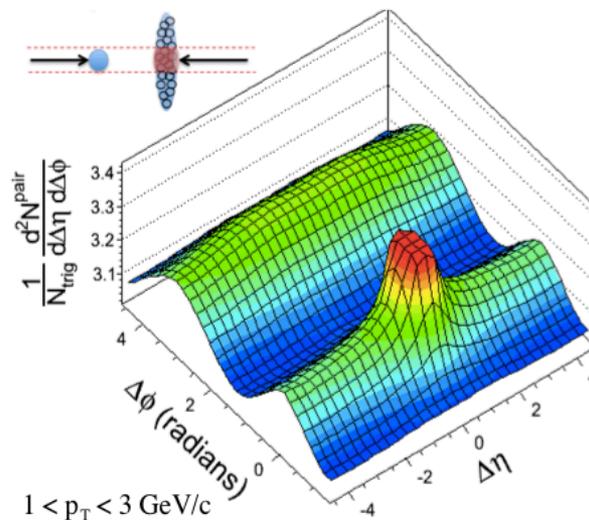
Similar feature to the AA case were observed

- ❖ Collective effect
- ❖ Clear mass ordering for V^0
- ❖ Larger “Radial flow”

(b) pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 < N_{trk}^{offline} \leq 260$

PLB 724 (2013) 213

Mass ordering

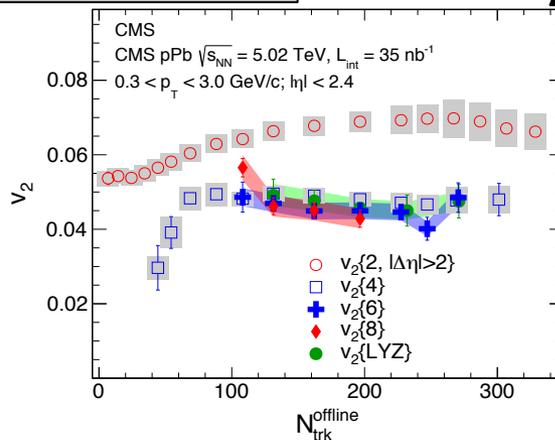


PRL 115 (2015) 012301

Collectivity

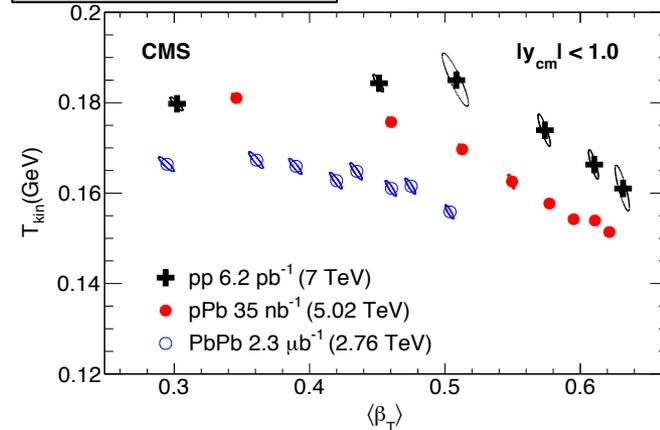
Possible interpretations

- ❖ Initial state interactions (CGC, ...)
- ❖ Final state interactions (hydrodynamic, ...)



arXiv:1605.06699

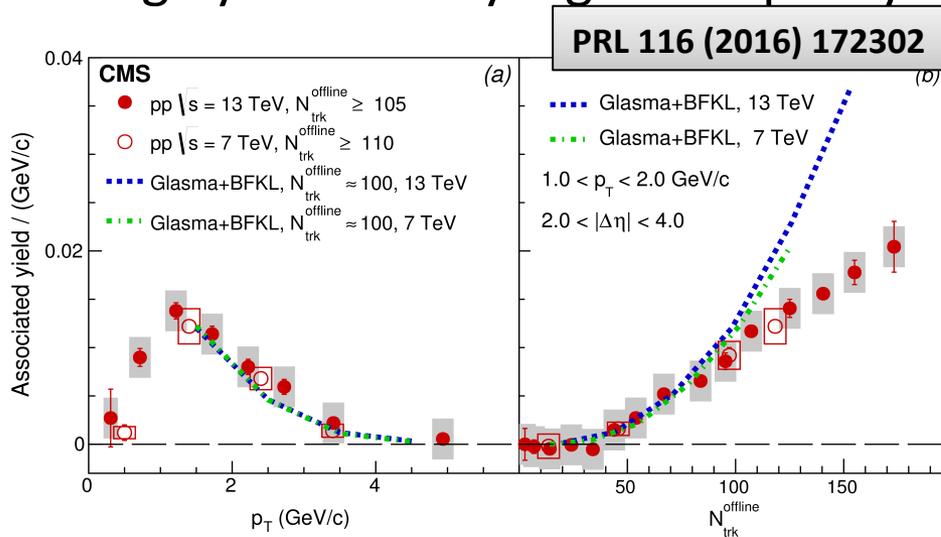
“Radial flow”



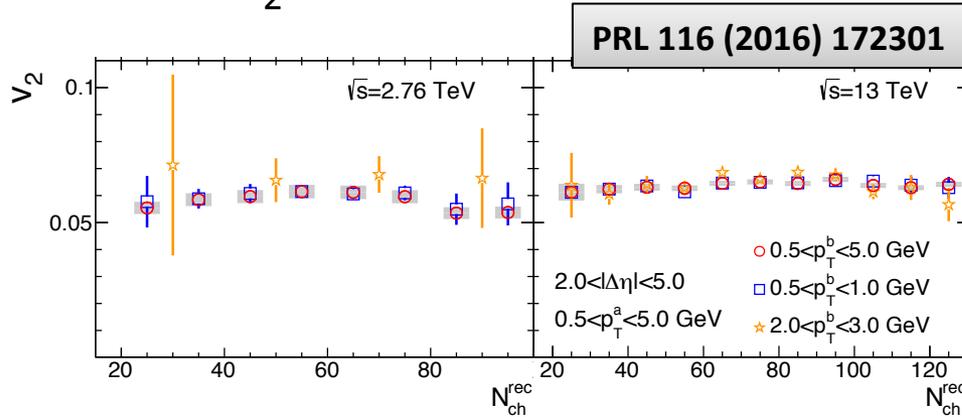
“ridge” in pp – first steps



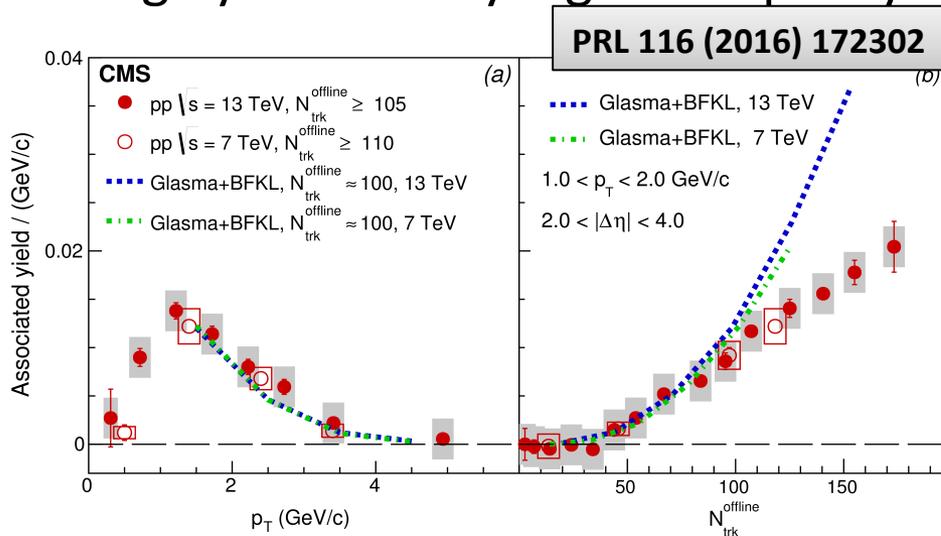
❖ Ridge yield to very high multiplicity



❖ ATLAS v_2 with new method



❖ Ridge yield to very high multiplicity

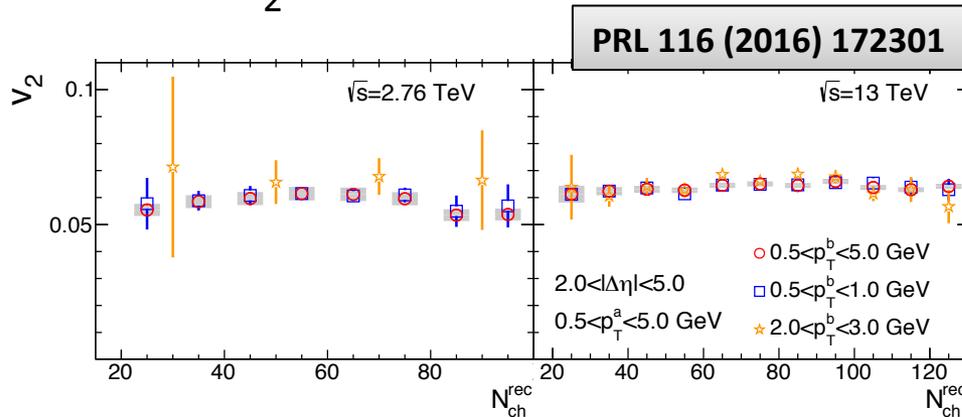


Yet to explore: Origin of the ridge?

Detailed studies needed for

- v_2 and higher harmonics
- Particle species dependence
- Multi-particle correlation

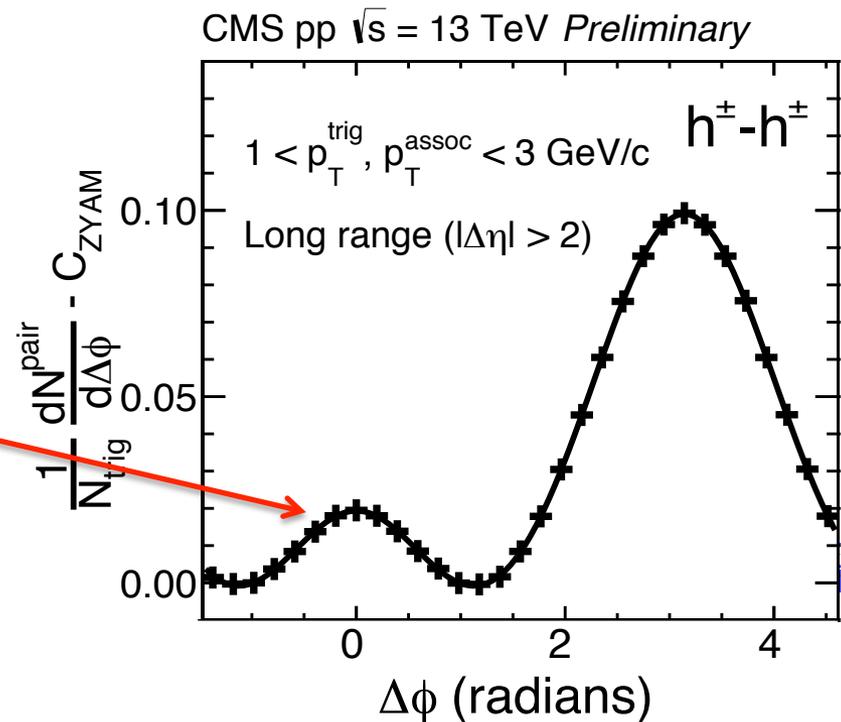
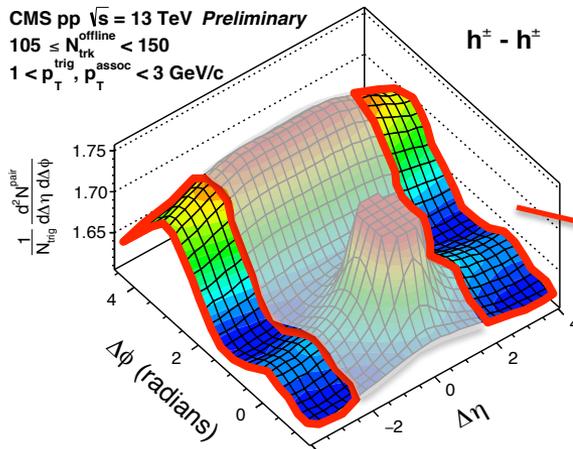
❖ ATLAS v_2 with new method



Two-particle correlations - v_n extraction

- Two particle correlation functions projected in ridge range ($|\Delta\eta| > 2$), fit by Fourier decomposition to get $V_{n\Delta}$:

$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi} \left\{ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right\}$$



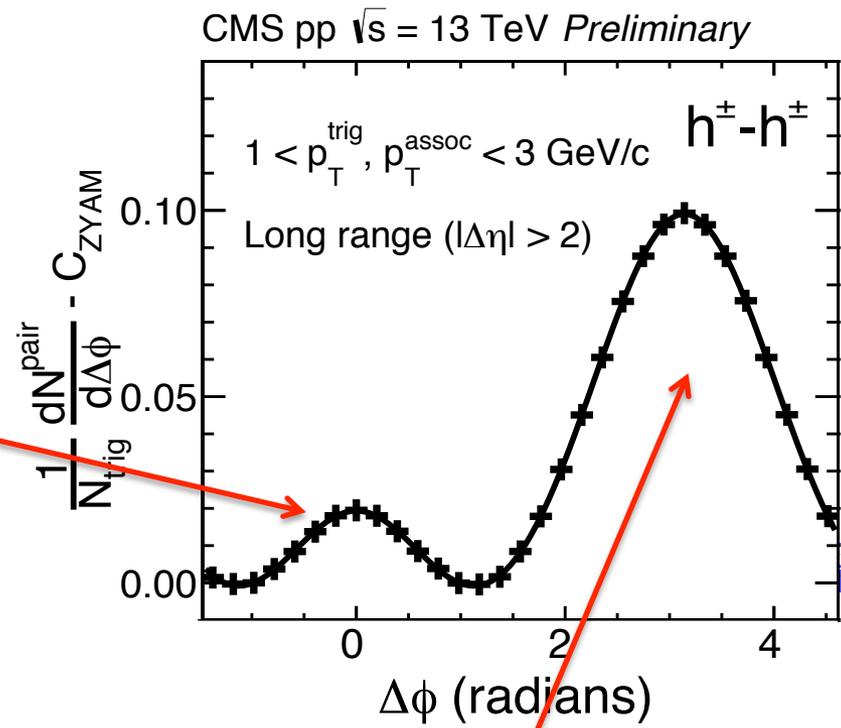
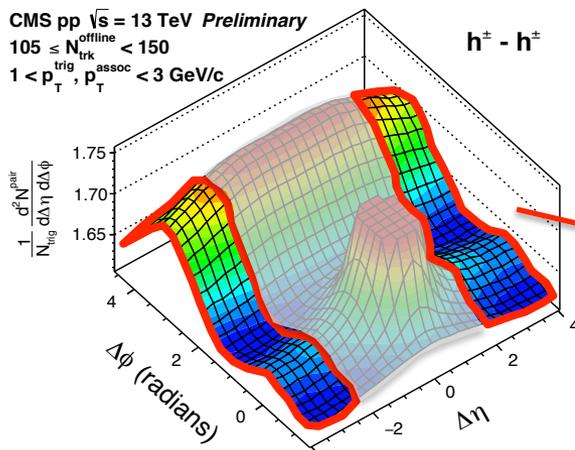
- Single particle harmonics:

$$v_n(p_T^{trig}) = \frac{V_{n\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n\Delta}(p_T^{assoc}, p_T^{assoc})}}, n = 2, 3$$

Two-particle correlations - v_n extraction

- Two particle correlation functions projected in ridge range ($|\Delta\eta| > 2$), fit by Fourier decomposition to get $V_{n\Delta}$:

$$\frac{1}{N_{trig}} \frac{dN^{pair}}{d\Delta\phi} = \frac{N_{assoc}}{2\pi} \left\{ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right\}$$

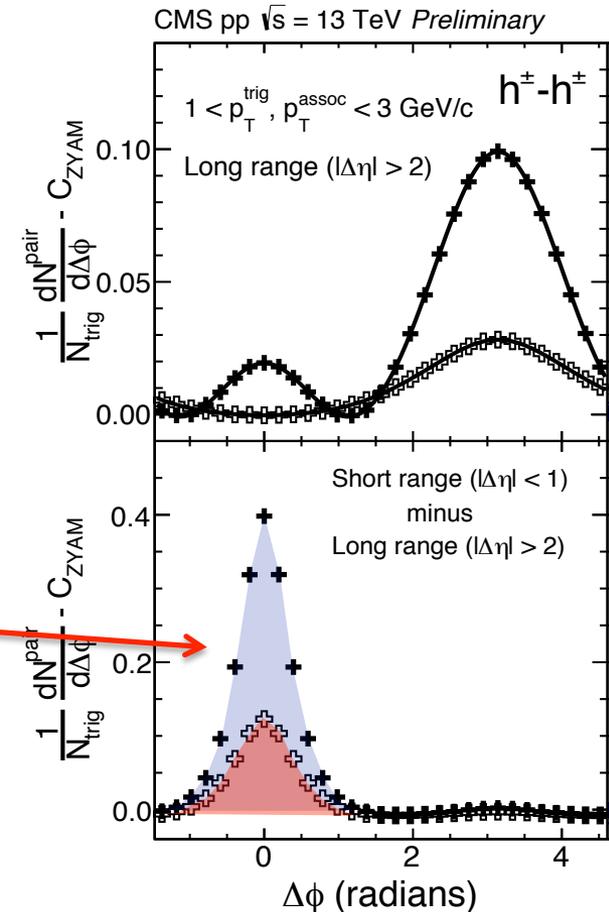
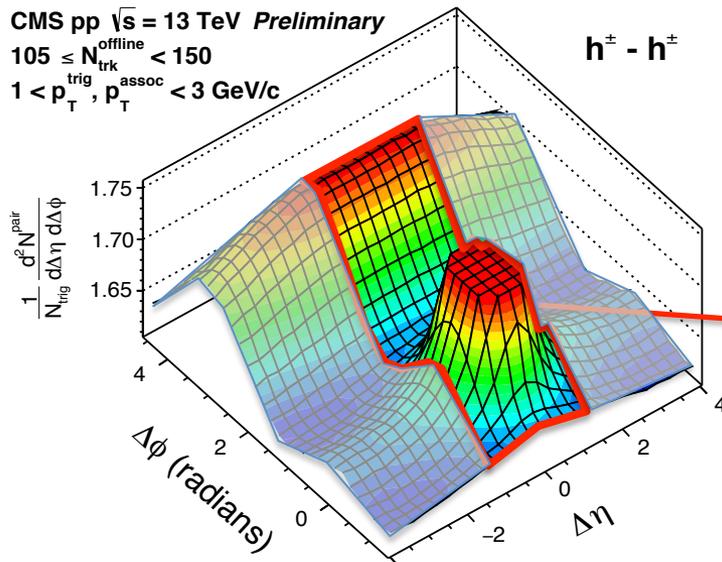


Back-to-back jet contribution

- Single particle harmonics:

$$v_n(p_T^{trig}) = \frac{V_{n\Delta}(p_T^{trig}, p_T^{assoc})}{\sqrt{V_{n\Delta}(p_T^{assoc}, p_T^{assoc})}}, n = 2, 3$$

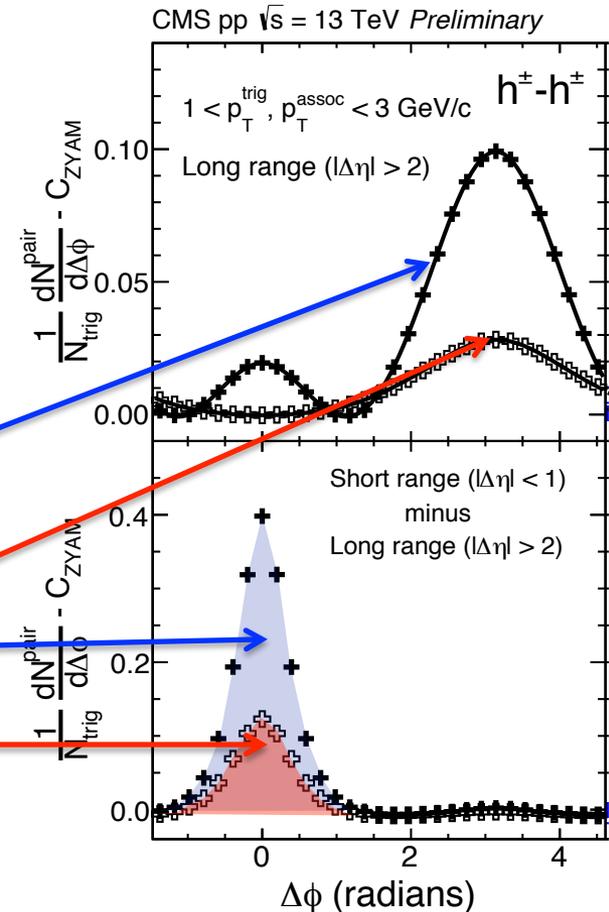
- ❖ Low multiplicity subtraction on $V_{n\Delta}$
 - Assume jet-induced correlations at away-side proportional to near-side jet yield



Correction for jet contribution

- ❖ Low multiplicity subtraction on $V_{n\Delta}$
 - Assume jet-induced correlations at away-side proportional to near-side jet yield
 - Assume $v_2^{\text{collective}}(N_{\text{trk}}^{\text{offline}} < 20) = 0$

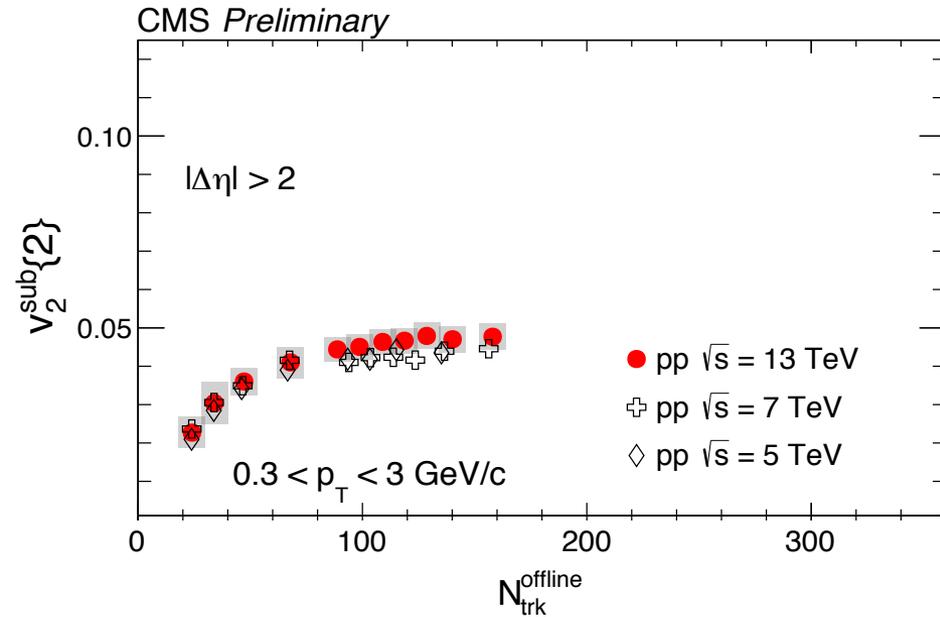
$$V_{n\Delta}^{\text{sub}} \times N_{\text{assoc}}^{\text{high}} = V_{n\Delta}^{\text{high}} \times N_{\text{assoc}}^{\text{high}} - V_{n\Delta}^{\text{low}} \times N_{\text{assoc}}^{\text{low}} \times \begin{matrix} \gamma_{\text{jet}}^{\text{high}} \\ \gamma_{\text{jet}}^{\text{low}} \end{matrix}$$



Two-particle correlations: v_2 & v_3 vs. multiplicity



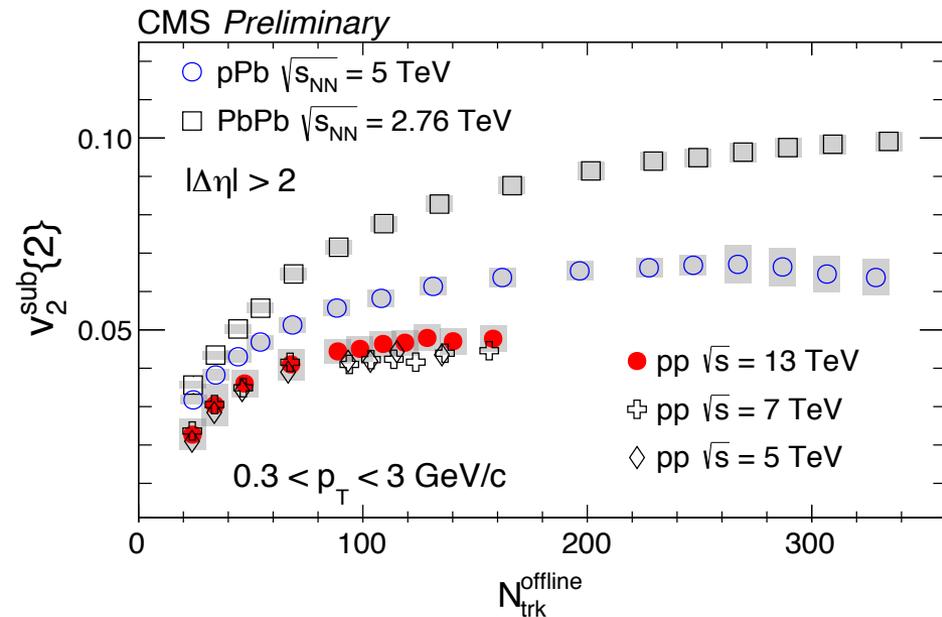
- ◆ v_2 :
 - No energy dependence observed



Two-particle correlations: v_2 & v_3 vs. multiplicity



- ❖ v_2 :
 - No energy dependence observed
 - Similar shape as p-Pb and Pb-Pb
 - Smaller than bigger system
- Similar effect involved with different magnitude?**



Two-particle correlations: v_2 & v_3 vs. multiplicity

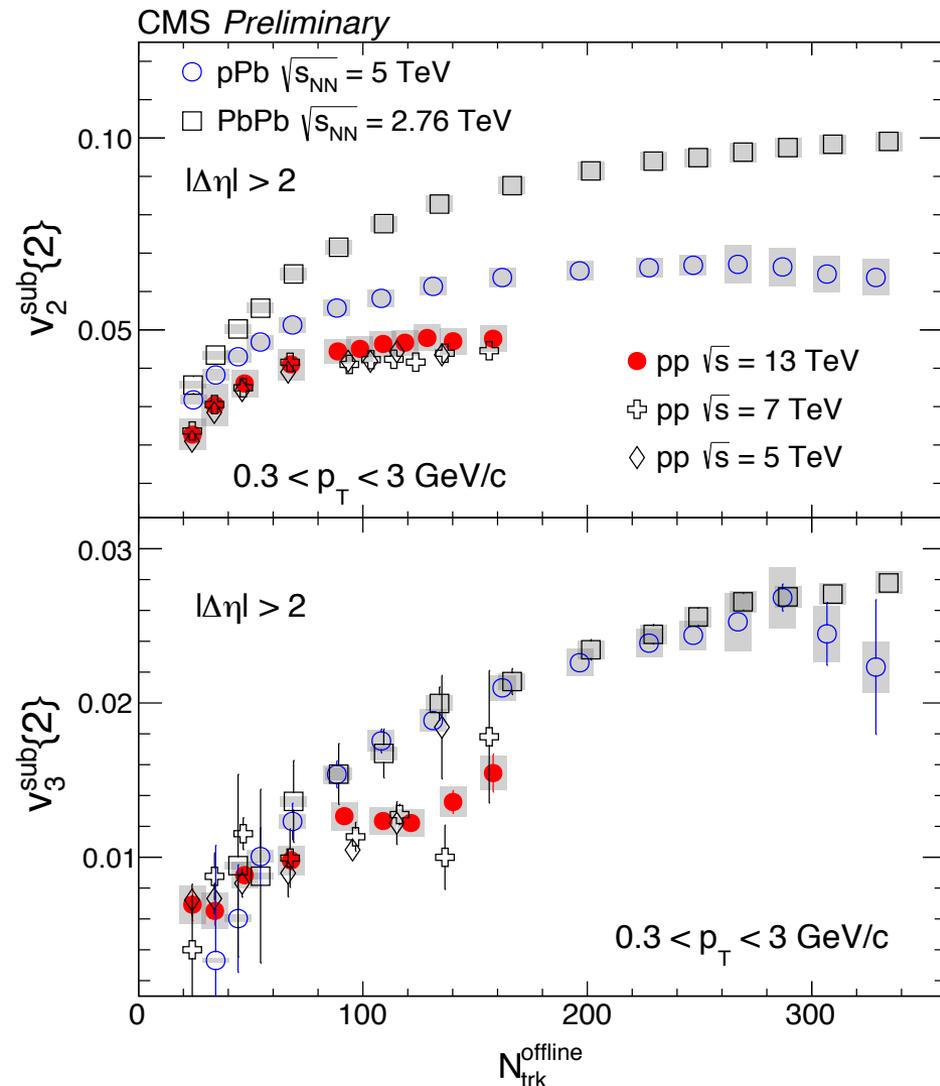


- ❖ v_2 :
 - No energy dependence observed
 - Similar shape as p-Pb and Pb-Pb
 - Smaller than bigger system

Similar effect involved with different magnitude?

- ❖ v_3 :
 - No energy dependence observed
 - Different from p-Pb and Pb-Pb

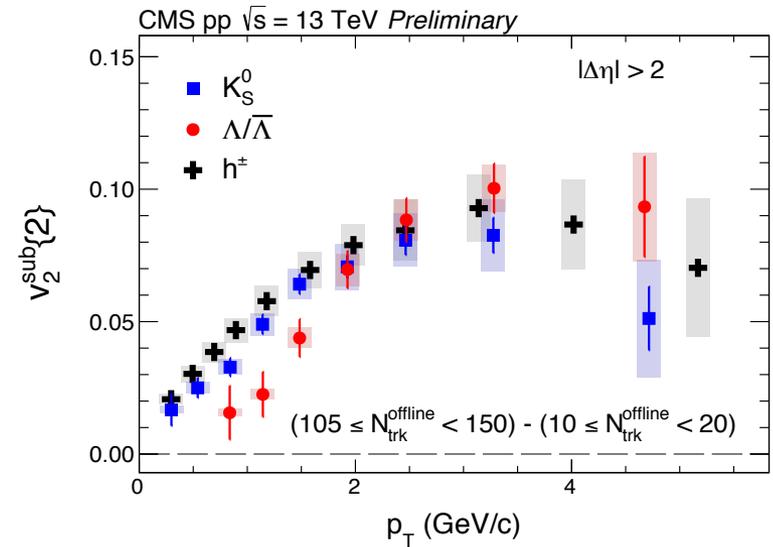
Difference in initial state fluctuations?



Two-particle correlations: v_2 vs. p_T

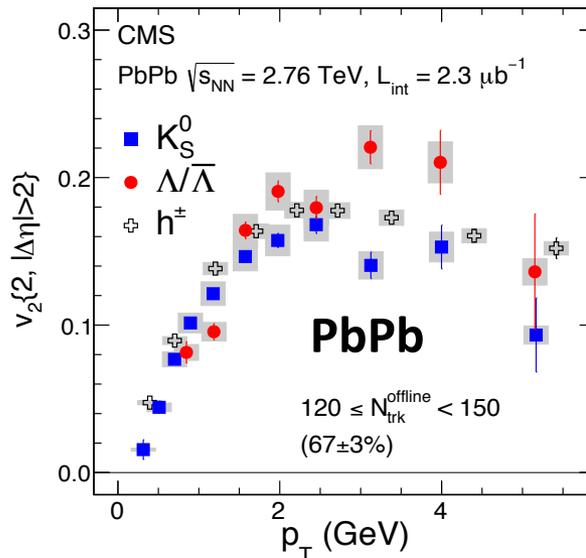
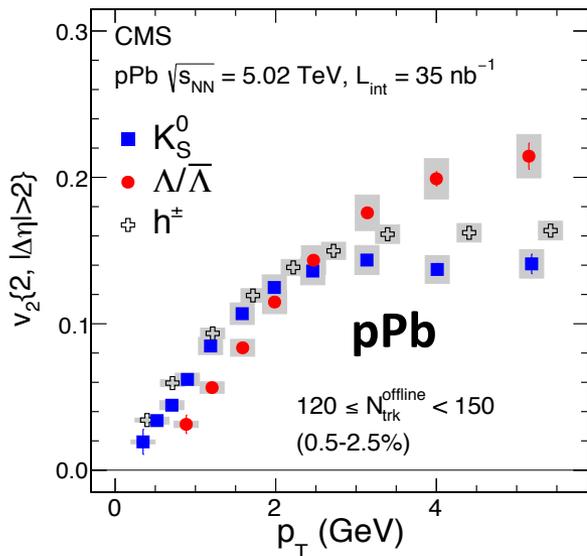
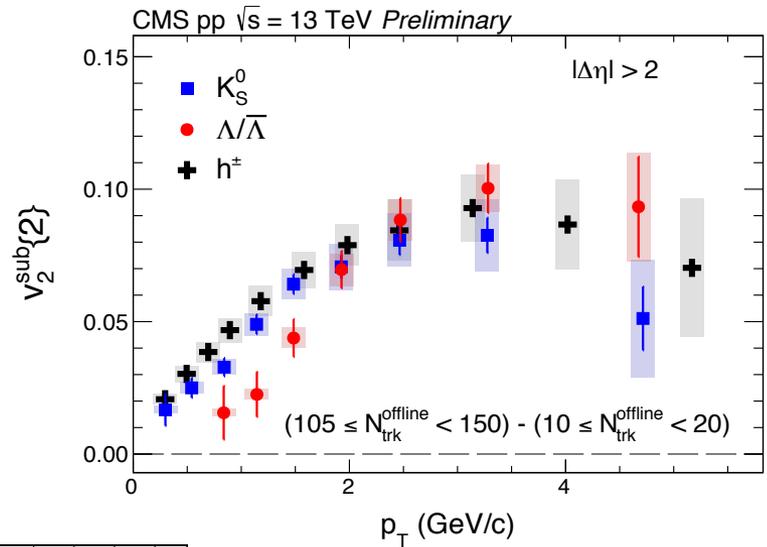


❖ Clear mass ordering up to 2 GeV/c



Two-particle correlations: v_2 vs. p_T

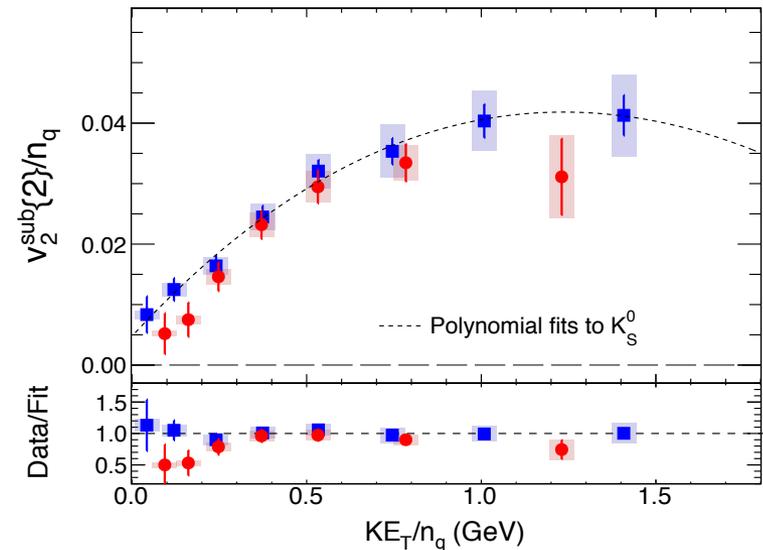
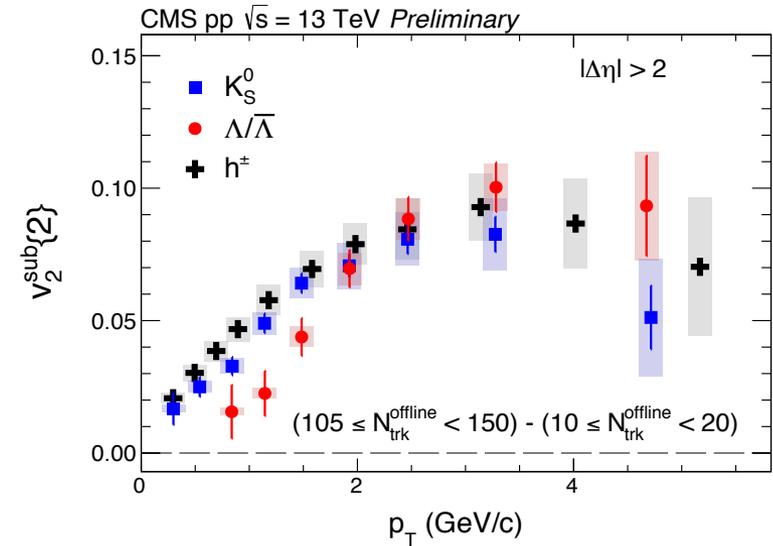
- ❖ Clear mass ordering up to 2 GeV/c
 - ❖ Similar to pPb and PbPb
- Similar origin?**



Two-particle correlations: v_2 vs. p_T



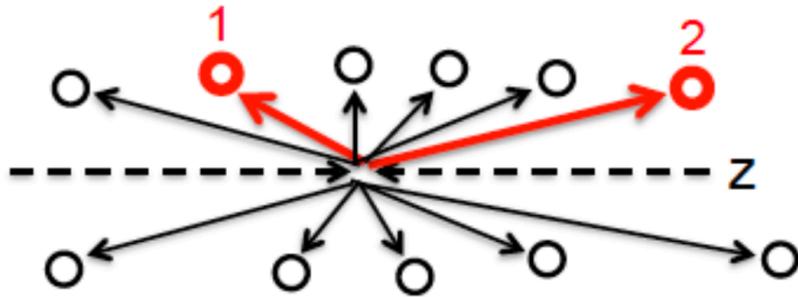
- ❖ Clear mass ordering up to 2 GeV/c
- ❖ Similar to pPb and PbPb
Similar origin?
- ❖ Number of **Constituent Quark** scaling observed in pp
Quark degree of freedom?



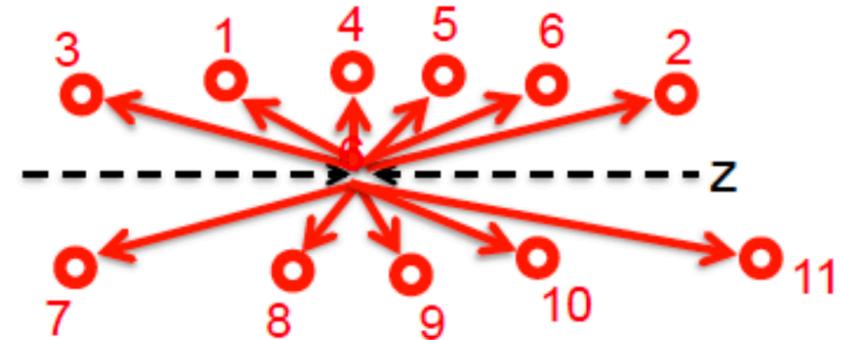
Multi-particle correlations: Collectivity



Two-particle correlation



Multi-particle correlation



Multi-particle (>2) cumulants:

$$\langle\langle 6 \rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)} \rangle\rangle$$

$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9 \cdot \langle\langle 4 \rangle\rangle \langle\langle 2 \rangle\rangle + 12 \cdot \langle\langle 2 \rangle\rangle^3$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

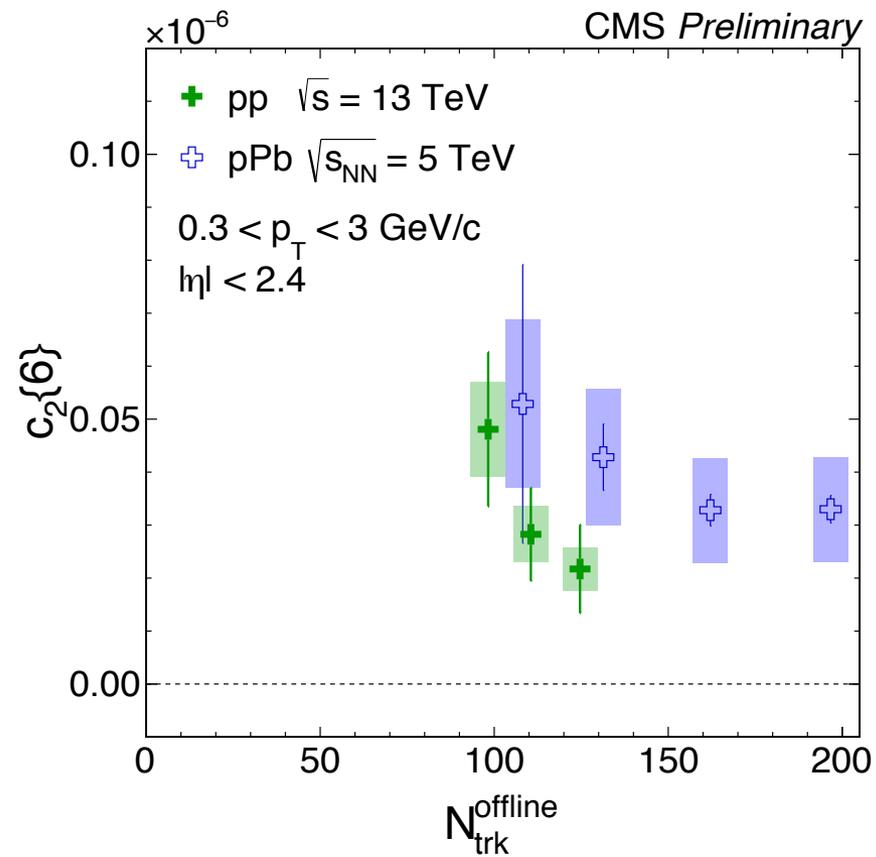
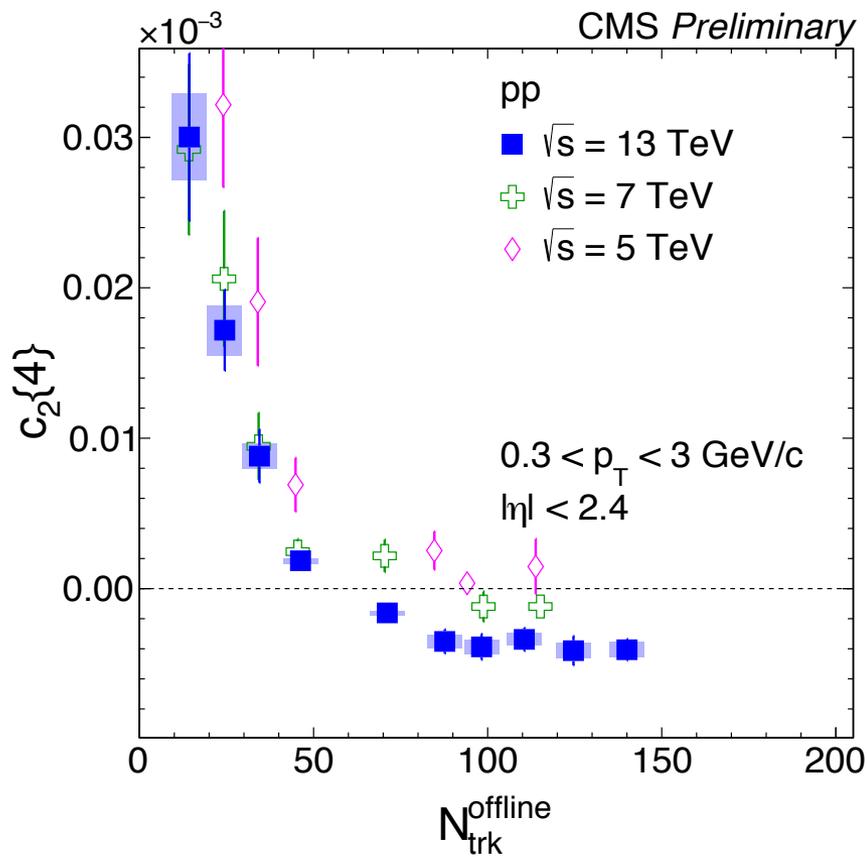
$$v_n\{6\} = \sqrt[4]{\frac{1}{4}c_n\{6\}}$$

Q-cumulant, PRC 83 (2011) 044913

$v_n\{4\} \approx v_n\{6\} \approx \dots \rightarrow$ system is collective

- ❖ 4- and 6-particle cumulant measured at different energies

Clear signal observed in 13 TeV sample!





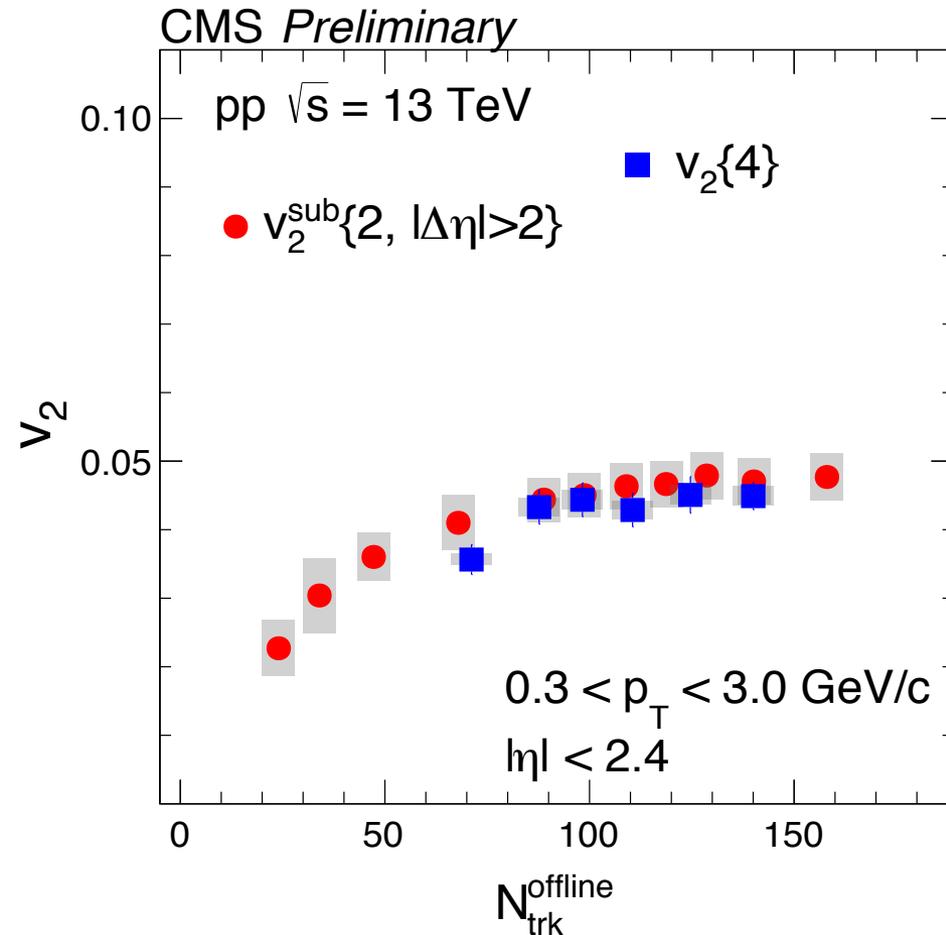
❖ Multi-particle cumulant results compared to $v_2\{2\}$

- Probe collectivity

$$v_2\{4\} = \sqrt[4]{-c_n\{4\}},$$

❖ Comparison between $v_2\{2\}$, $v_2\{4\}$

- $v_2\{2\} \approx v_2\{4\}$





❖ Multi-particle cumulant results compared to $v_2\{2\}$

- Probe collectivity

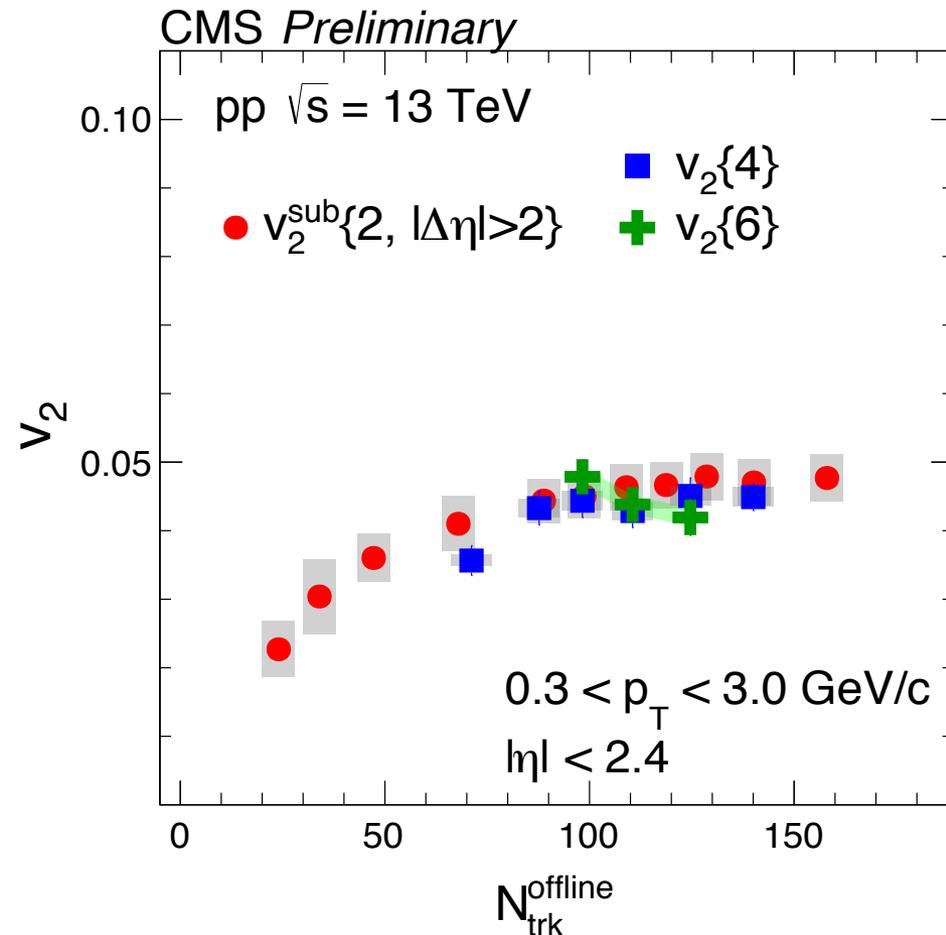
$$v_2\{4\} = \sqrt[4]{-c_n\{4\}},$$

$$v_2\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}},$$

❖ Comparison between $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$:

- $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$

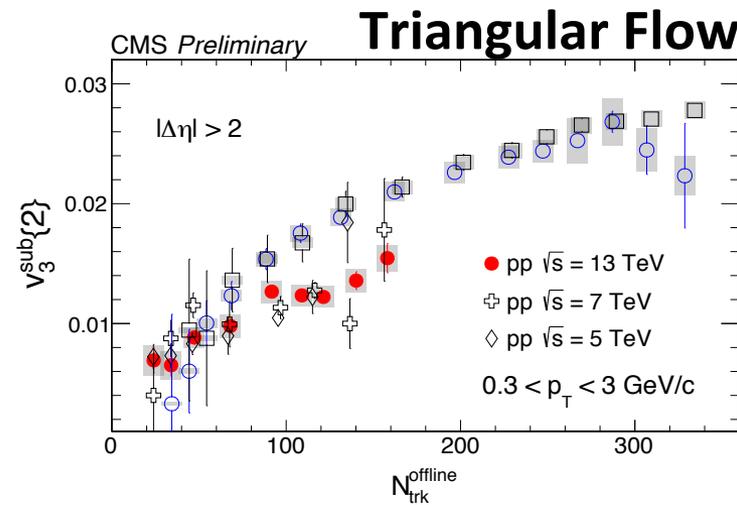
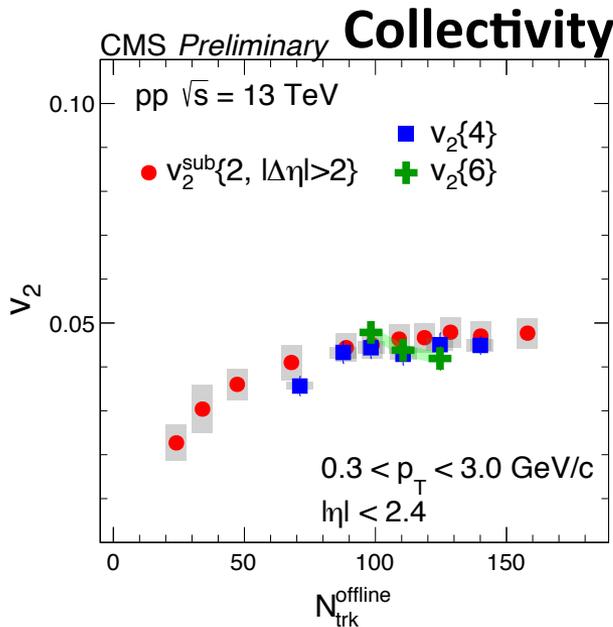
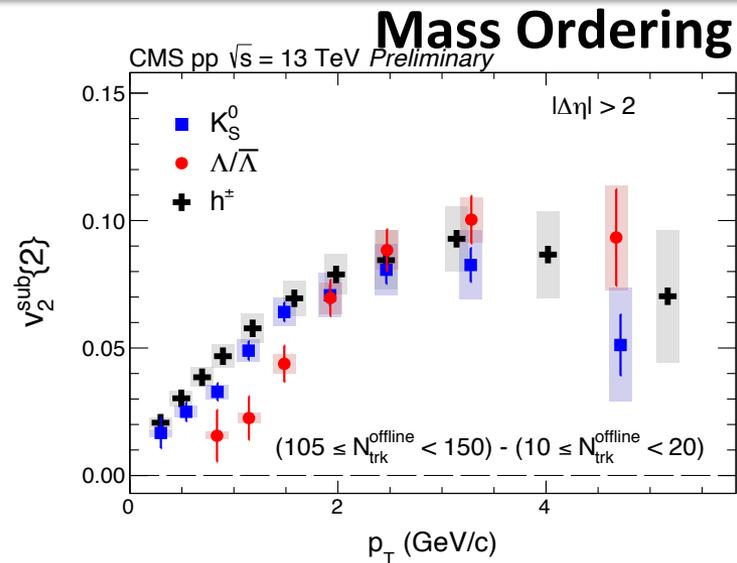
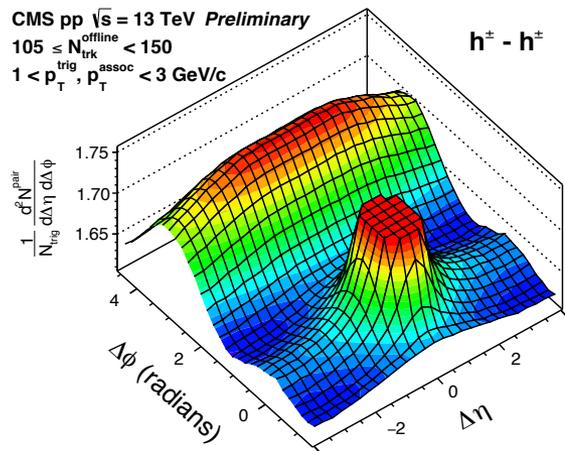
➔ **Collectivity!**



Similar feature to the AA and pPb case were observed

- ❖ Higher harmonics
- ❖ Collective effect
- ❖ Clear mass ordering for V^0

Strong constrains on interpretation of the correlations

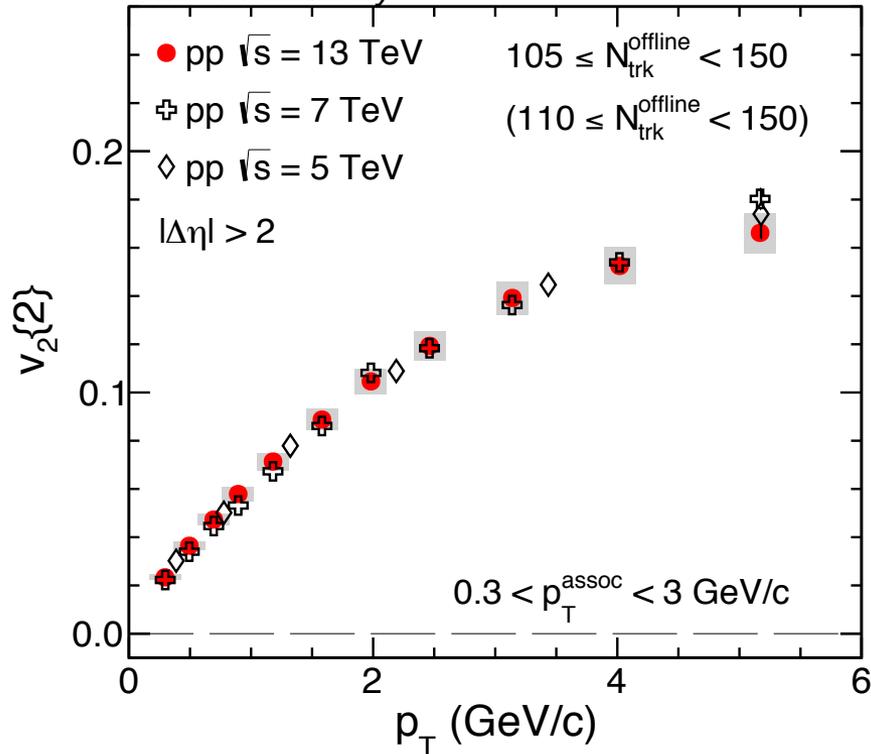


BACKUP



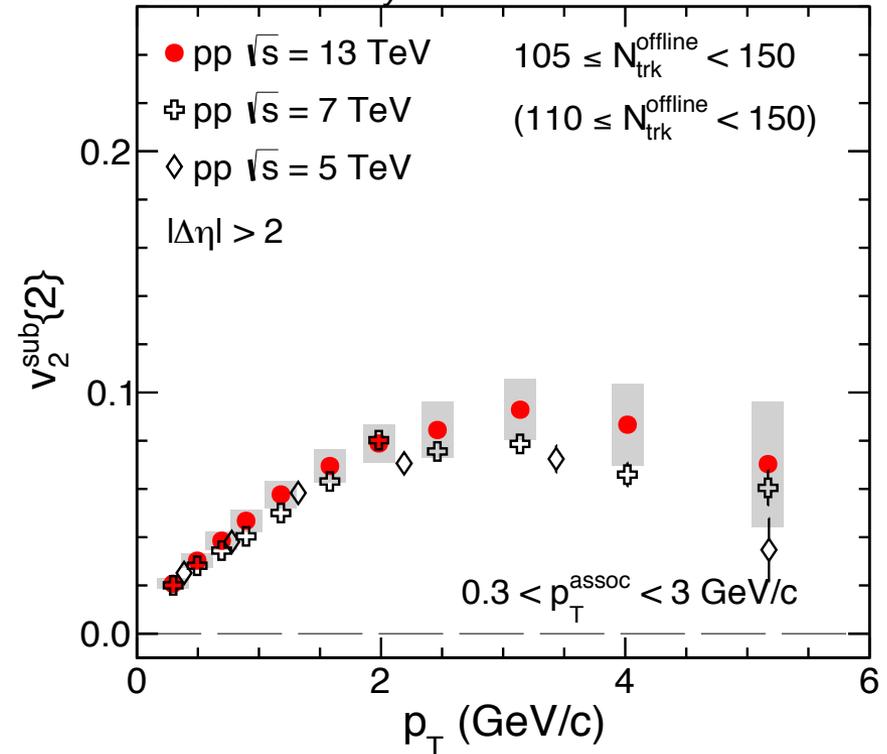
Before low multiplicity subtraction

CMS Preliminary



After low multiplicity subtraction

CMS Preliminary



No energy dependence observed within systematics before or after peripheral subtraction

Identified particles (V^0) long range correlations: double ridge

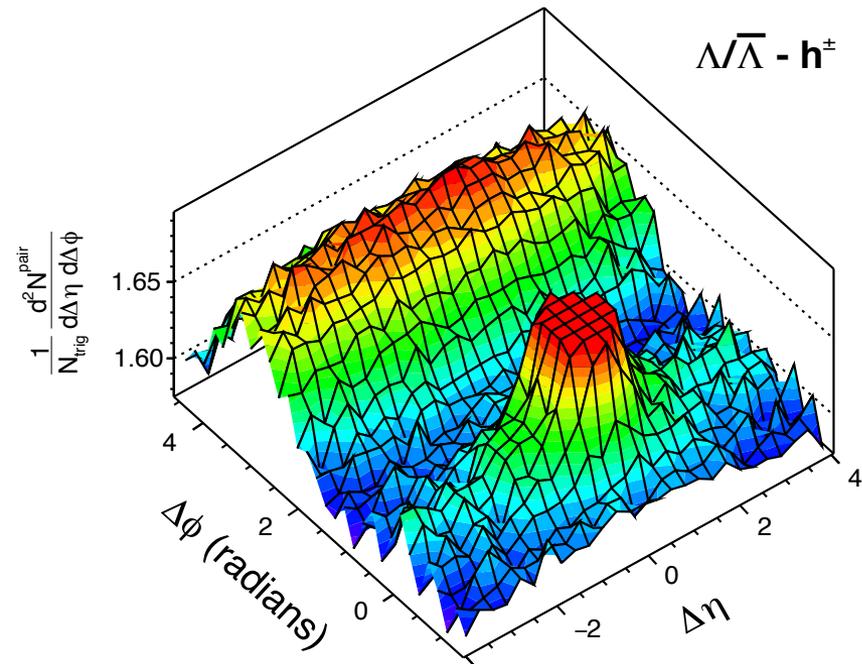
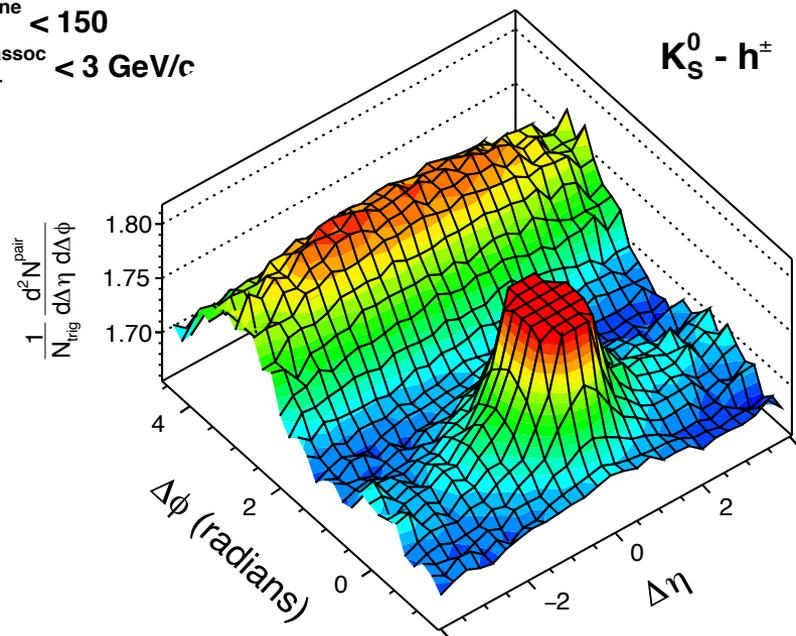


❖ Ridge structure also observed for V^0

CMS pp $\sqrt{s} = 13$ TeV Preliminary

$105 \leq N_{\text{trk}}^{\text{offline}} < 150$

$1 < p_{\text{T}}^{\text{trig}}, p_{\text{T}}^{\text{assoc}} < 3$ GeV/c



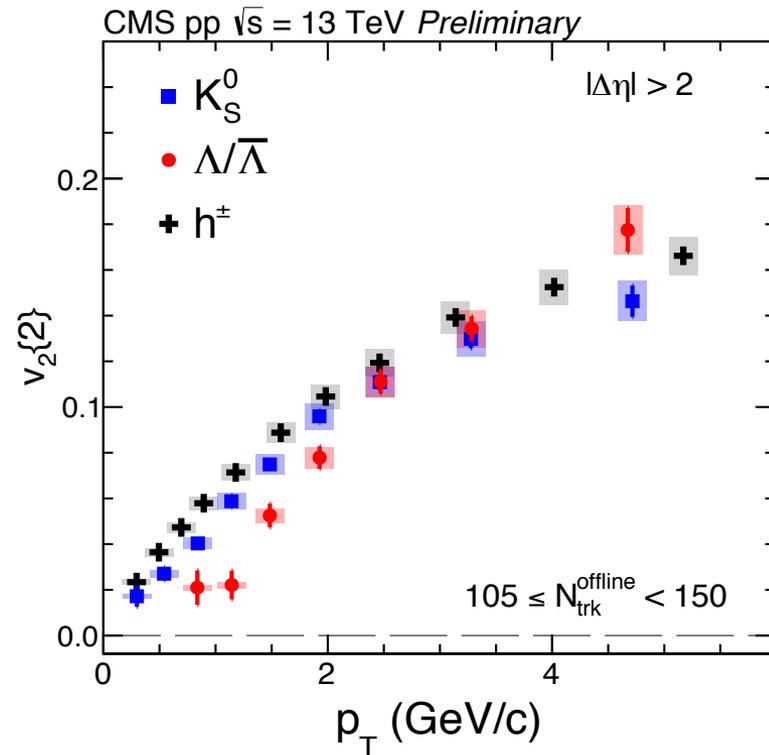
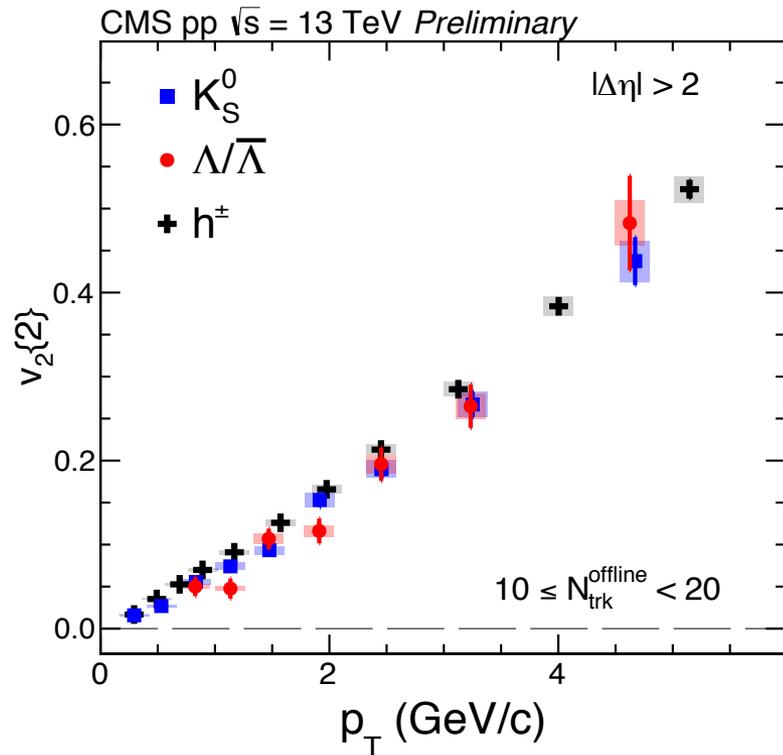
Does K^0 and Λ shows a mass ordering in p-p collisions?

Identified particles (V^0) long range correlations: v_2



❖ Before jet correlation subtraction:

- $v_2\{2\}$ consistent for all particles at low multiplicity
- Clear ordering for $p_T < 2.5$ GeV/c at high multiplicity

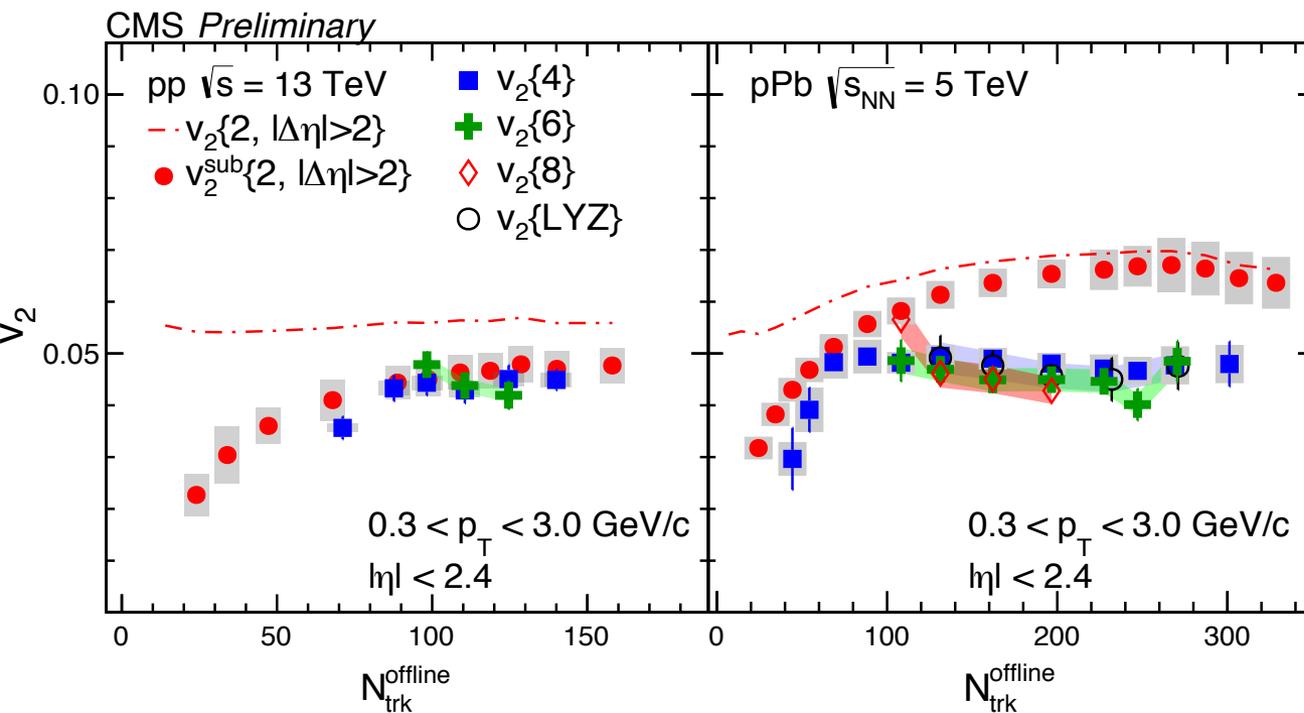


Similar pattern to what is observed in p-Pb and Pb-Pb? Similar origin?

Comparison across different systems of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$



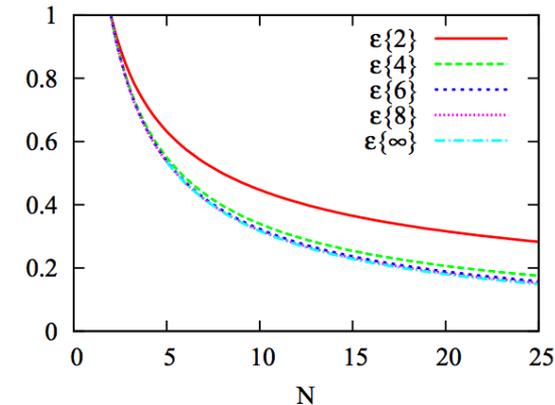
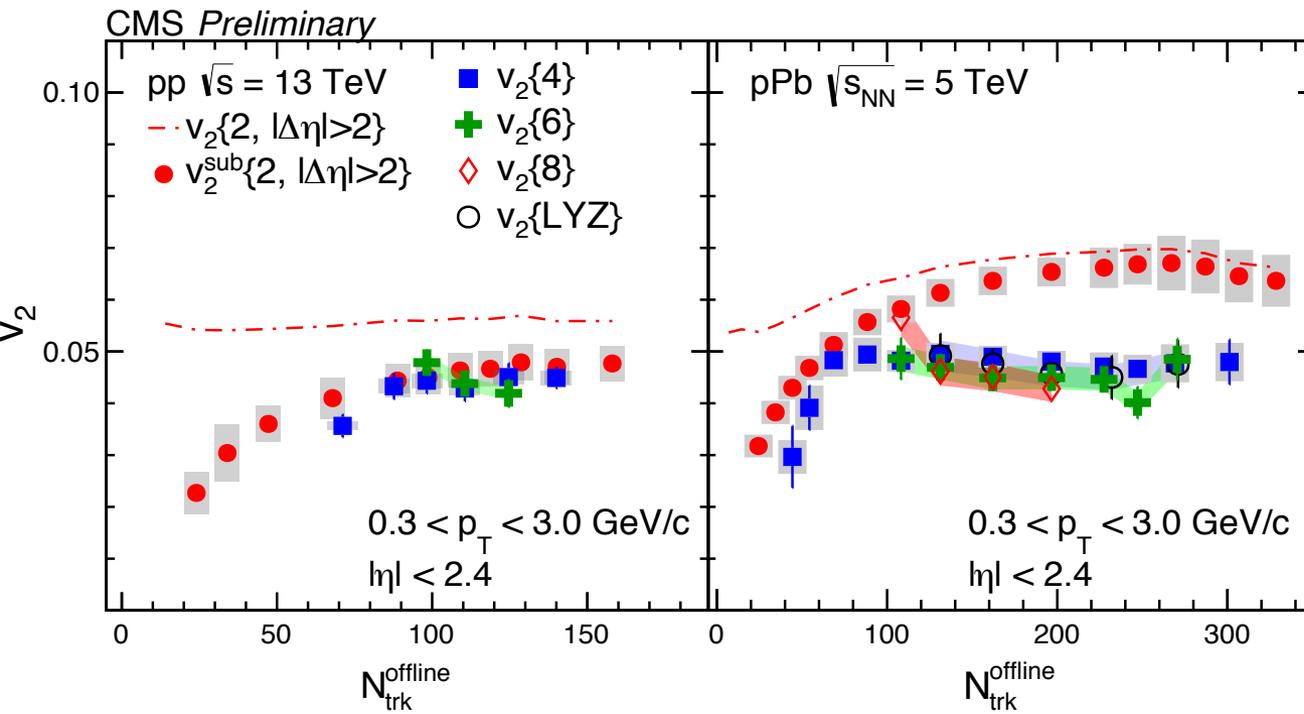
- ❖ Comparison between $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ in p-p and p-Pb:
 - $v_2\{2\}/v_2\{4\}$ (p-p) \leq $v_2\{2\}/v_2\{4\}$ (p-Pb) \rightarrow **Related to Initial State fluctuations**
 - Still true **before subtraction** \rightarrow **Upper limit**



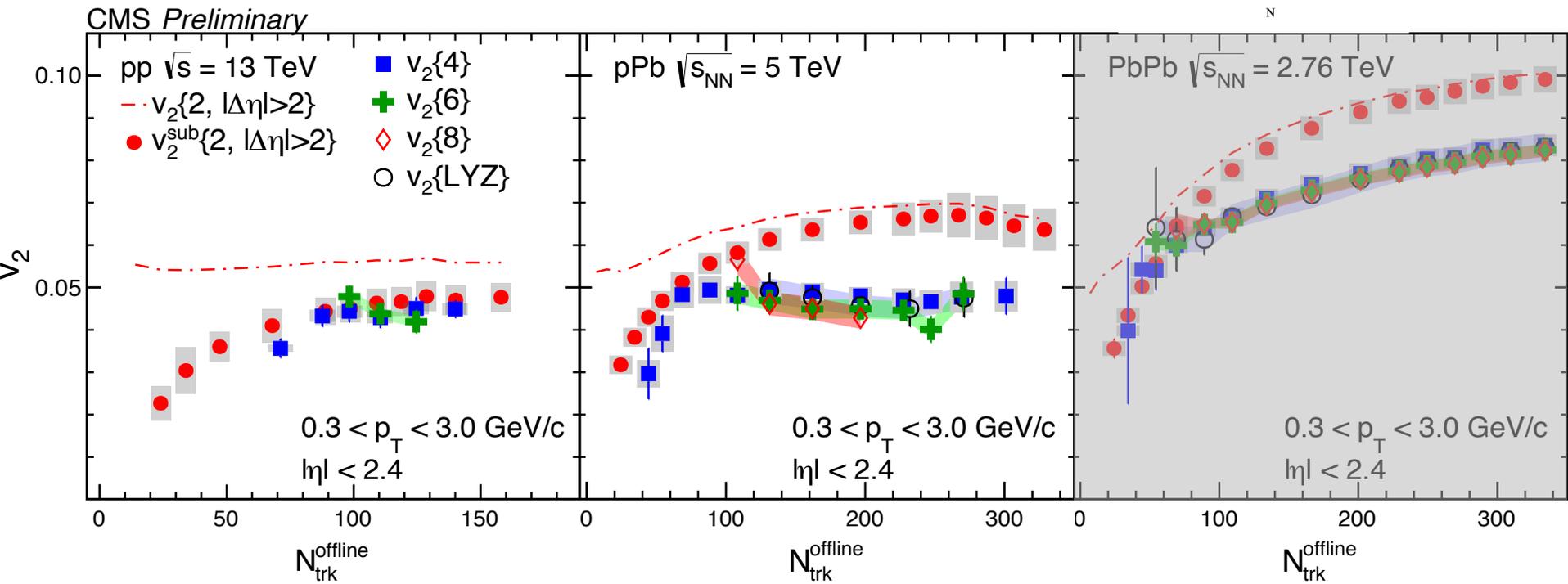
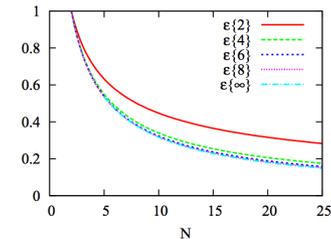
Comparison across different systems of $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$



- ❖ Comparison between $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ in p-p and p-Pb:
 - $v_2\{2\}/v_2\{4\}$ (p-p) \leq $v_2\{2\}/v_2\{4\}$ (p-Pb) \rightarrow **Related to Initial State fluctuations**
 - Still true **before subtraction** \rightarrow **Upper limit**
- ❖ One possible explanation: [PRL 112 \(2014\) 082301](#)
 - smaller $v_2\{2\}/v_2\{4\}$ \rightarrow **Less IS fluctuating sources**



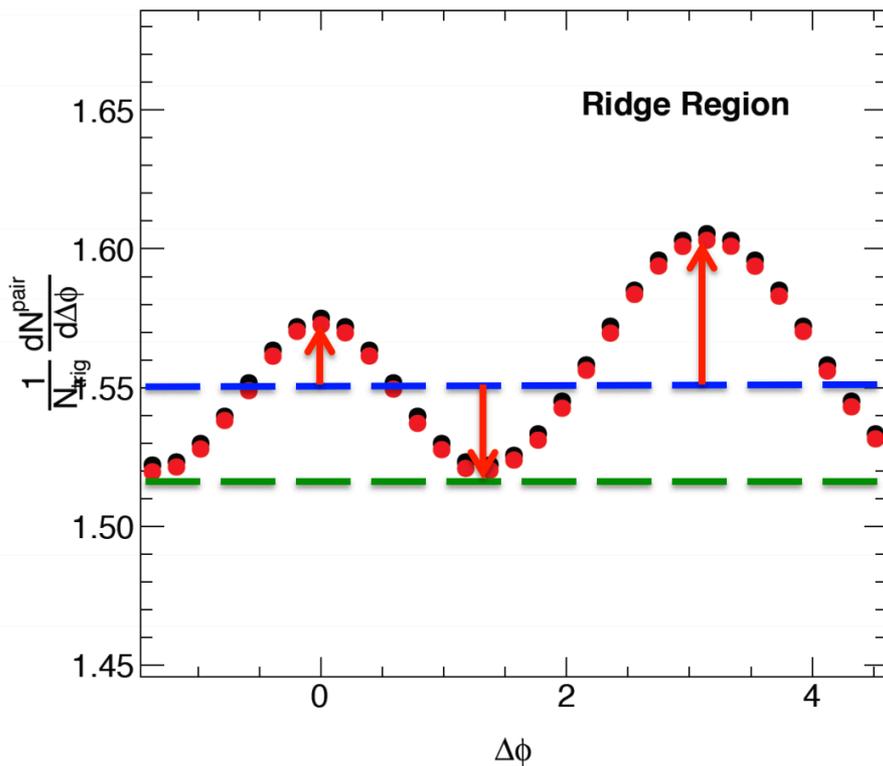
- ❖ Comparison between $v_2\{2\}$, $v_2\{4\}$ and $v_2\{6\}$ in p-p and p-Pb:
 - $v_2\{2\}/v_2\{4\}$ (p-p) \leq $v_2\{2\}/v_2\{4\}$ (p-Pb) \rightarrow **Related to IS fluctuations**
- ❖ One possible explanation: [PRL 112 \(2014\) 082301](#)
 - smaller $v_2\{2\}/v_2\{4\}$ \rightarrow **Less IS fluctuating sources**
 - Still true **before subtraction** \rightarrow **Upper limit**





Fundamental difference between ATLAS and CMS method:

Subtract or not the combinatoric pedestal in the correlation function of low multiplicity from those of high multiplicity



$$\Upsilon(\Delta\phi) = N \left\{ 1 + \sum_n 2V_{n\Delta} \cos(n\Delta\phi) \right\}$$

$$= \boxed{N} + \boxed{N \sum_n 2V_{n\Delta} \cos(n\Delta\phi)}$$

Baseline of the correlation:
Related to number of pairs involved in the correlation

Amplitude of sinusoidal modulation

if $N \sum_n 2V_{n\Delta} \cos(n\Delta\phi) = cste$ and $N \searrow$
then $V_{n\Delta} \nearrow$

ATLAS and CMS method comparison

$$\Upsilon^{HM}(\Delta\phi) = F\Upsilon^{LM}(\Delta\phi) + \Upsilon^{Ridge}(\Delta\phi)$$

$$N^{HM} \left\{ 1 + \sum_n 2V_{n\Delta}^{HM} \cos(n\Delta\phi) \right\} = FN^{LM} \left\{ 1 + \sum_n 2V_{n\Delta}^{LM} \cos(n\Delta\phi) \right\} + G \left\{ 1 + \sum_n 2V_{n\Delta}^{ridge} \cos(n\Delta\phi) \right\}$$

$$G = N^{HM} - F \cdot N^{LM}$$

$$G \cdot V_2^{ridge} = N^{HM} \cdot V_2 - F \cdot N^{LM} \cdot V_2^{LM}$$

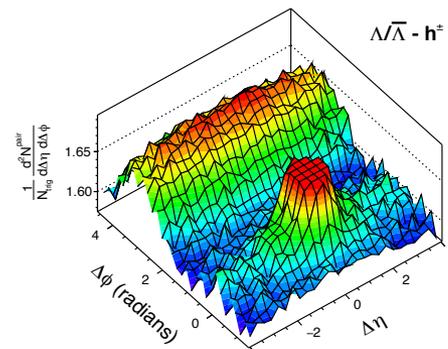
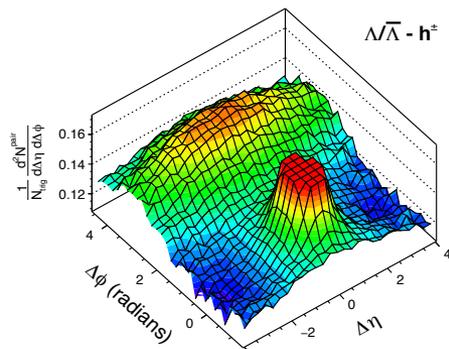
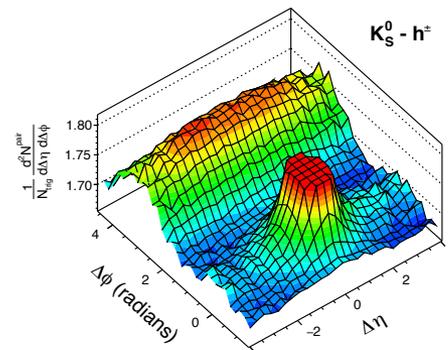
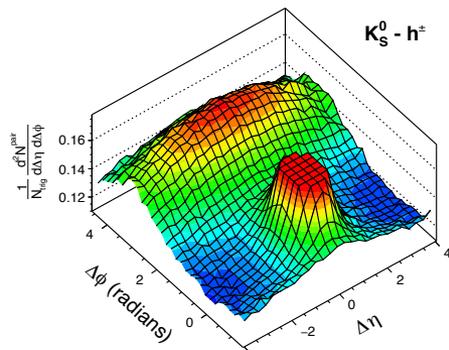
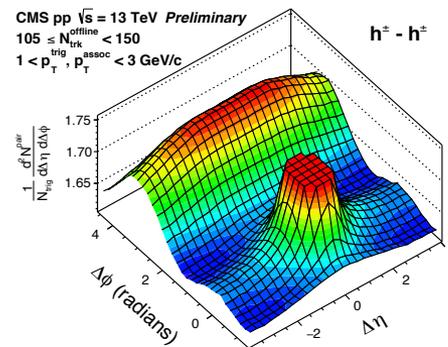
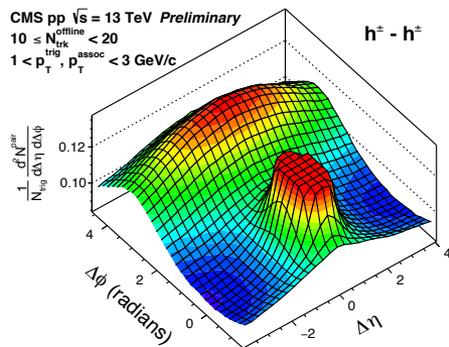
if $N \sum_n 2V_{n\Delta} \cos(n\Delta\phi) = cste$ and $N \Downarrow$
 then $V_{n\Delta} \Uparrow$



G smaller than N^{HM} , $V_2 \Uparrow$
Smaller G can be interpreted as correlation wrt a subset of particle

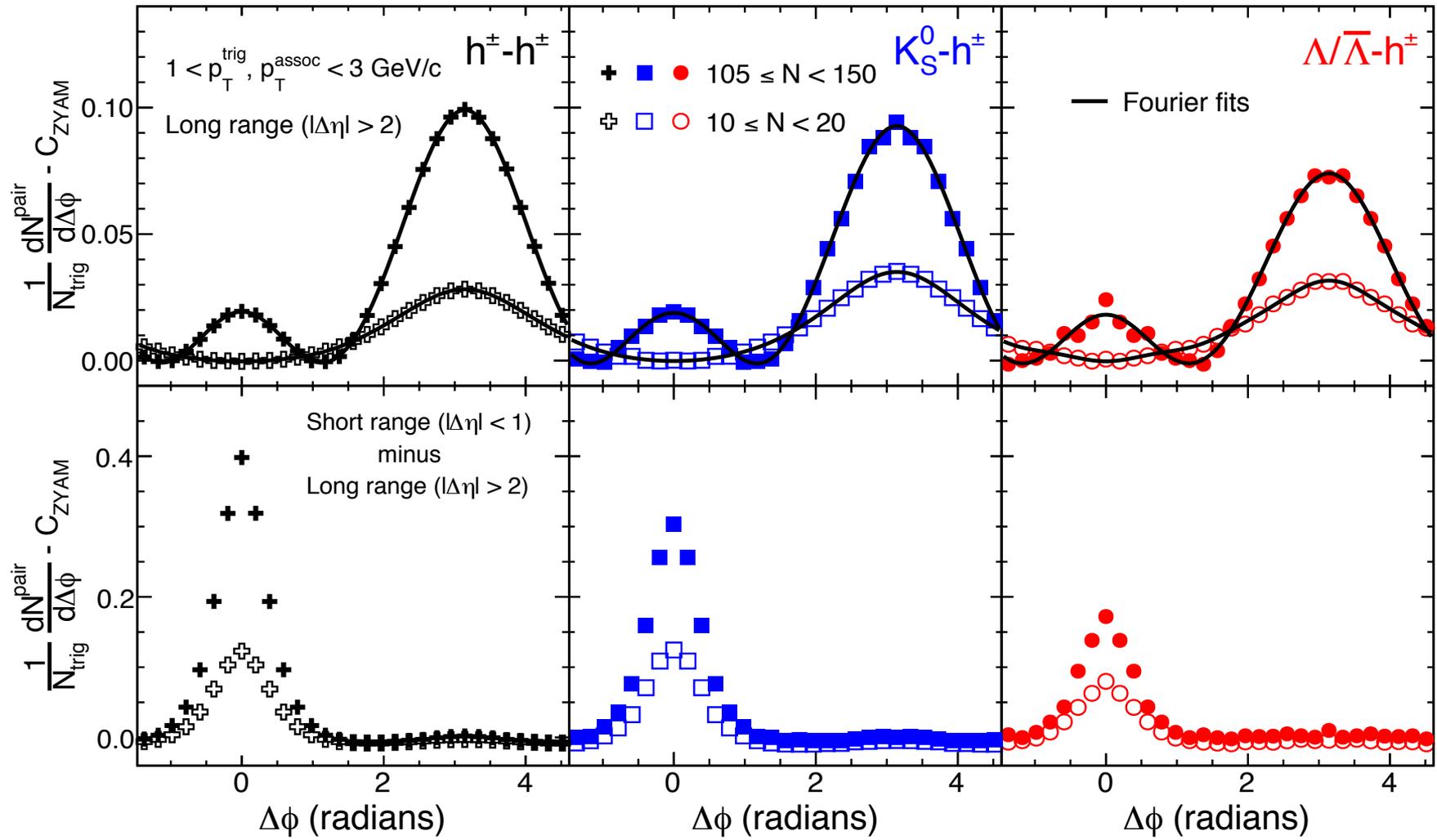
HM: High Multiplicity
LM: Low Multiplicity

2D correlation functions



1D correlation functions

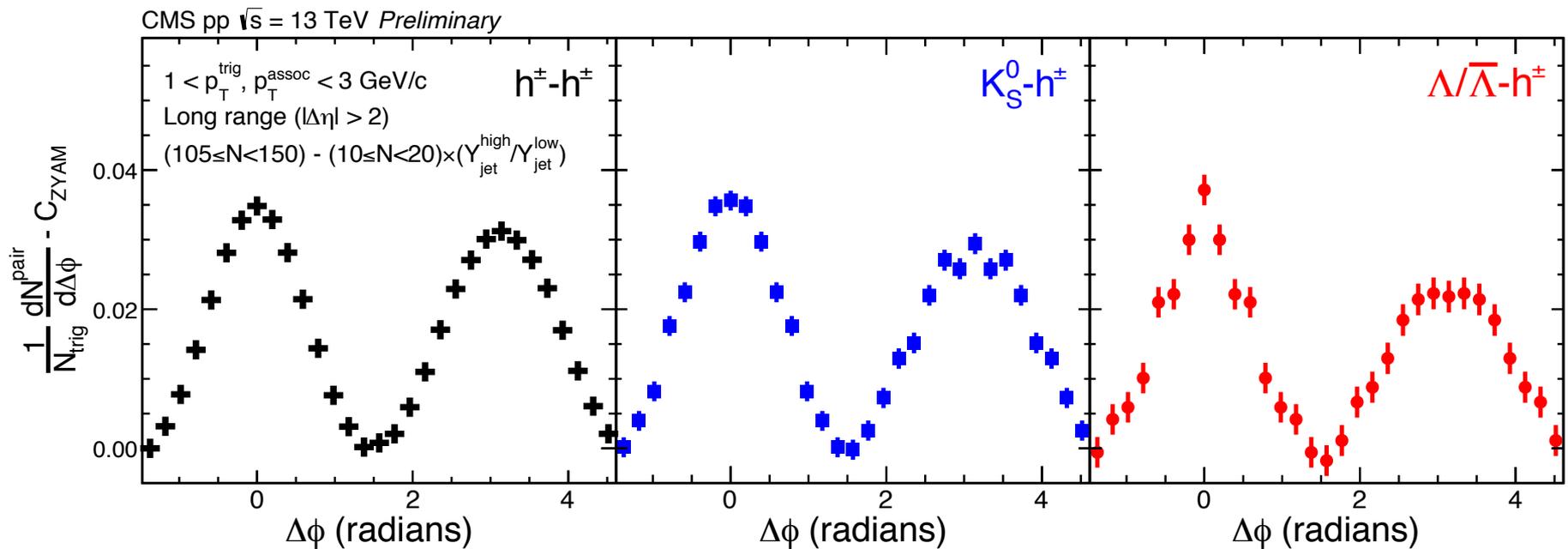
CMS pp $\sqrt{s} = 13$ TeV Preliminary



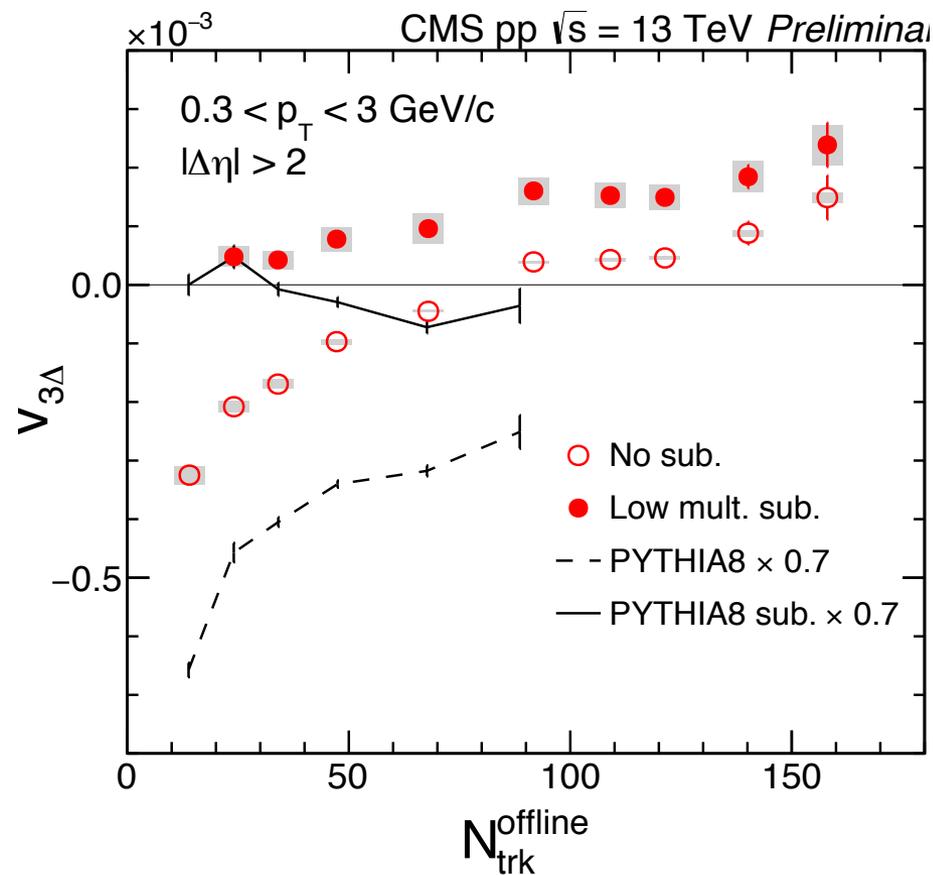
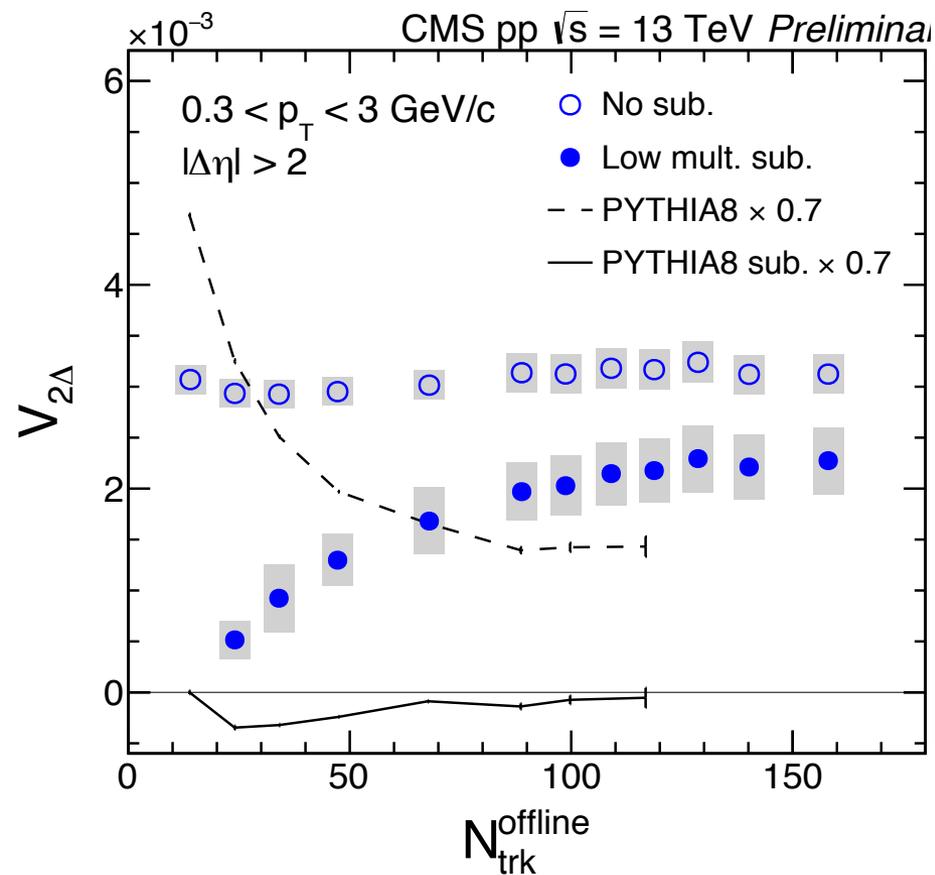
Identified particles (V^0) long range correlations: double ridge



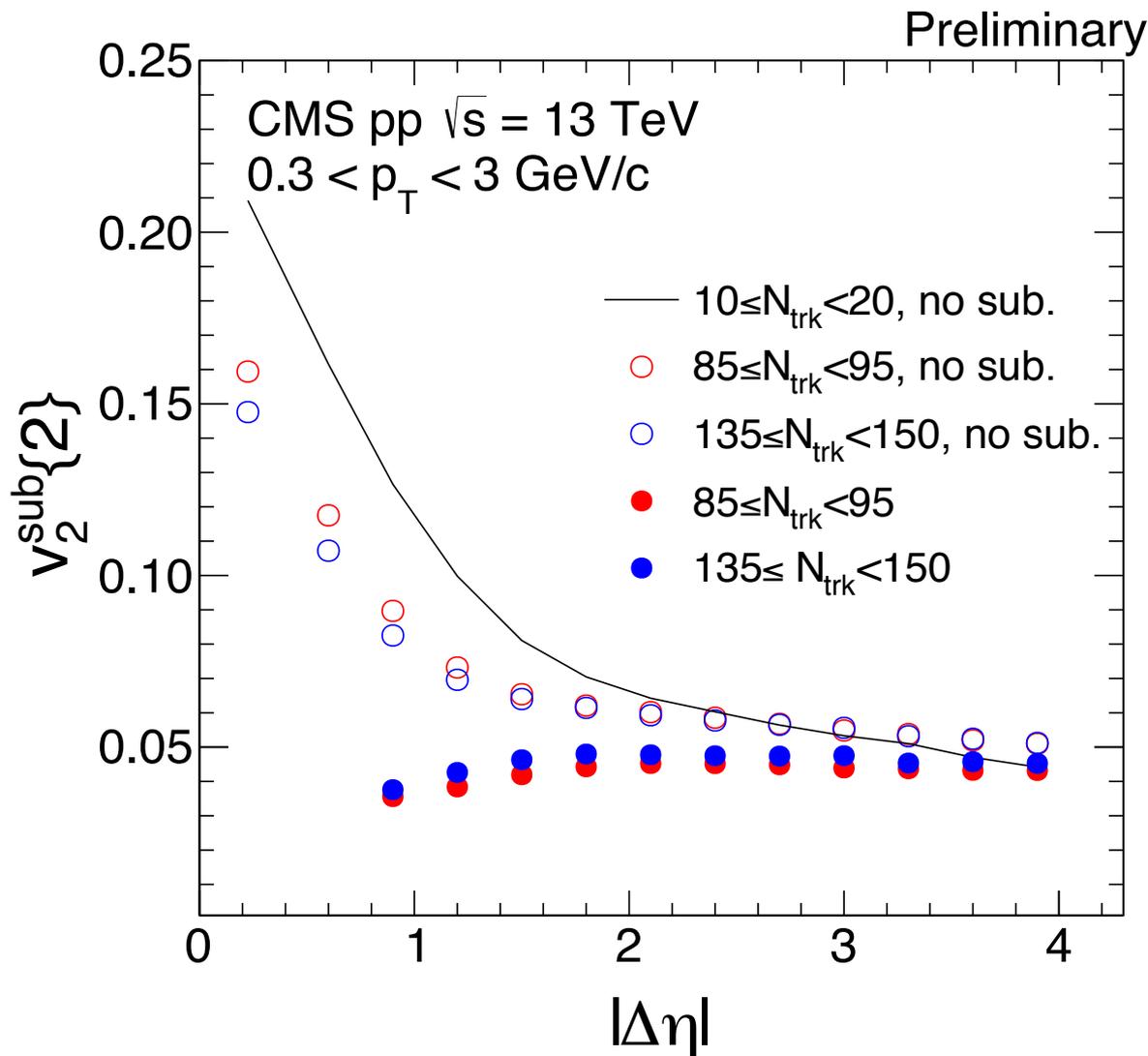
- ❖ Clear double ridge structure also observed for V^0 after subtracting jet correlations



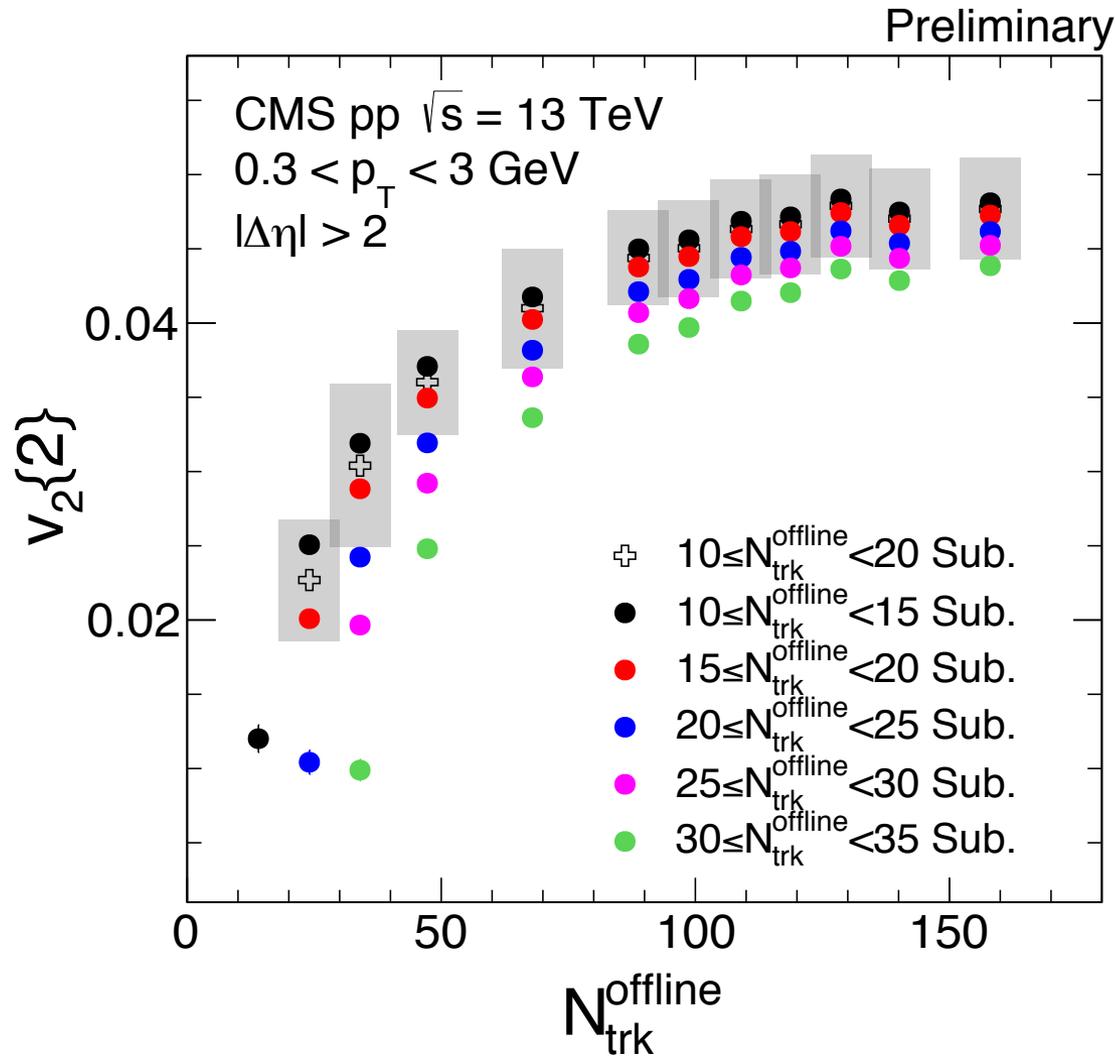
$V_{2\Delta}$ subtraction and MC closure



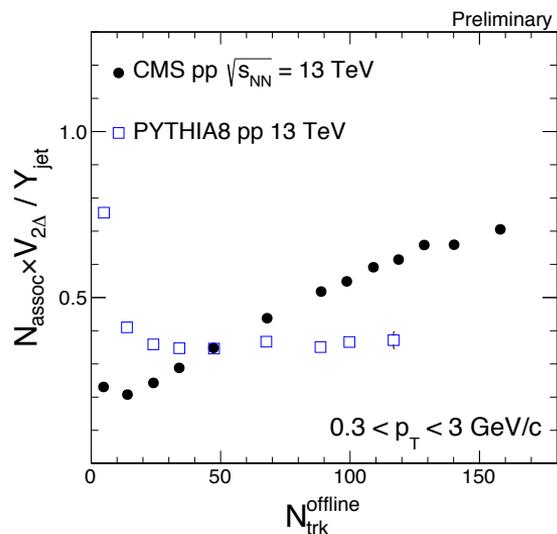
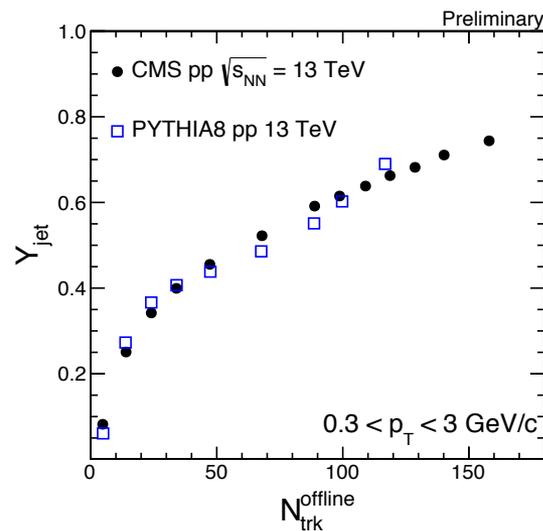
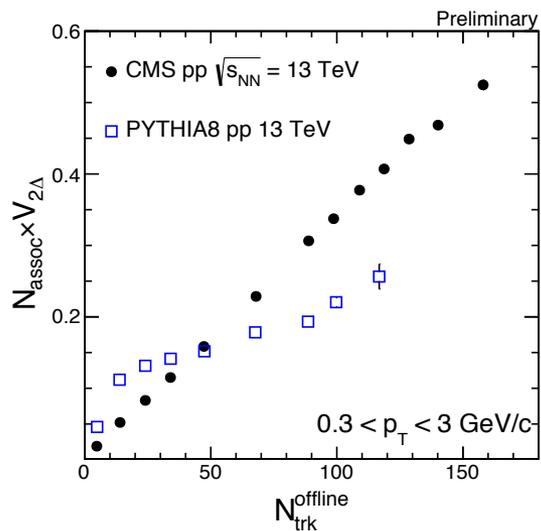
$\Delta\eta$ dependence of $v_2\{2\}$



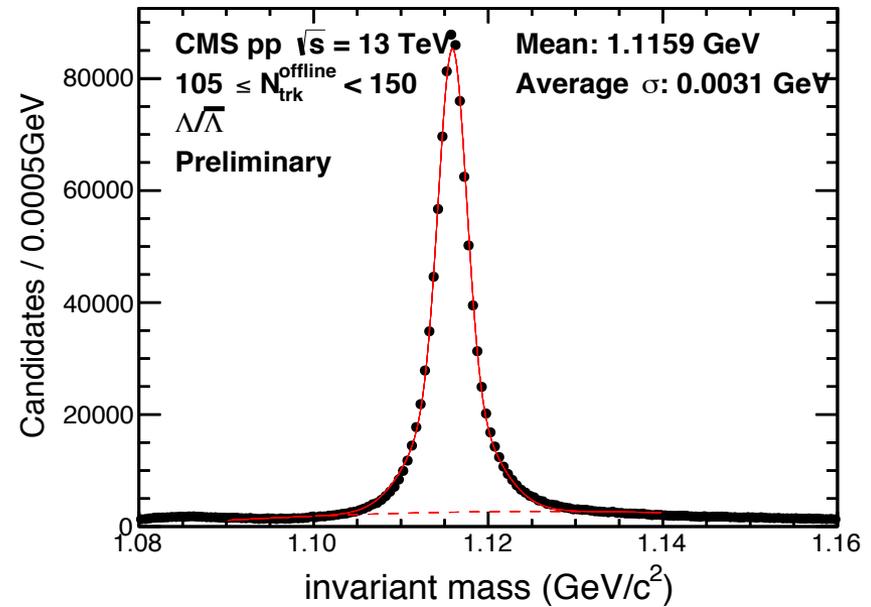
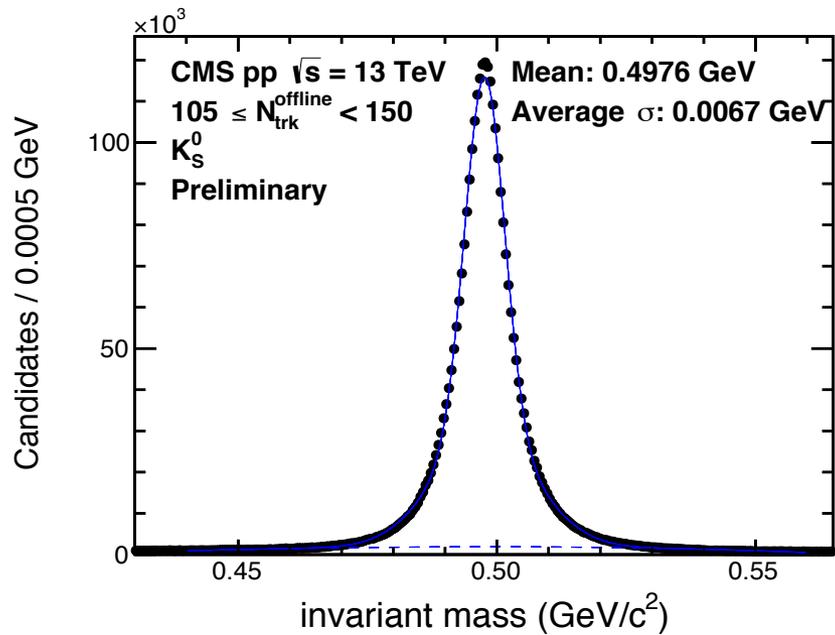
Subtraction as a function of multiplicity for $v_2\{2\}$



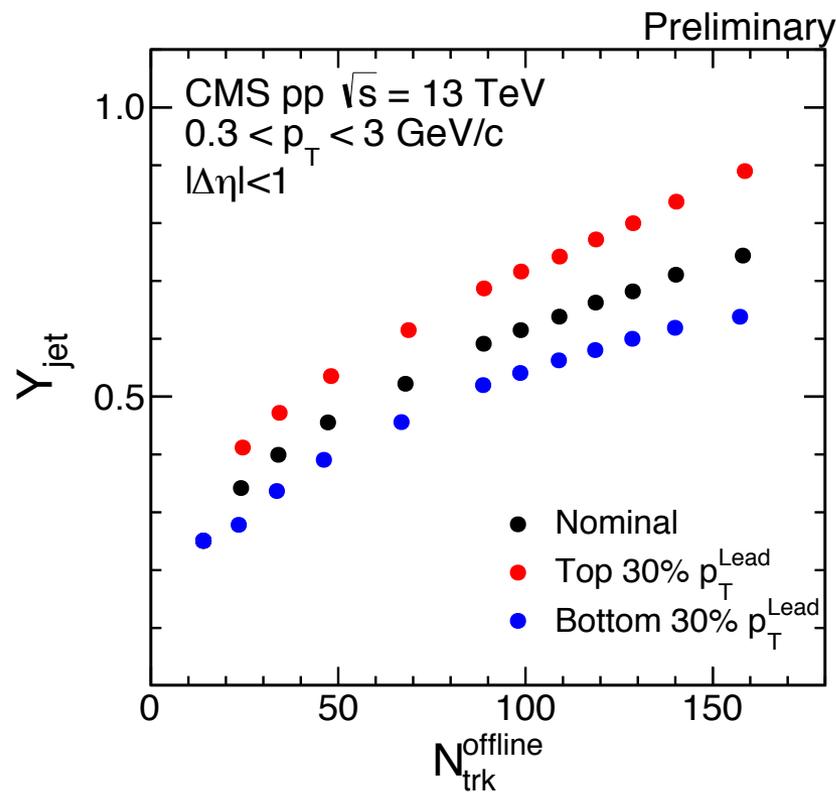
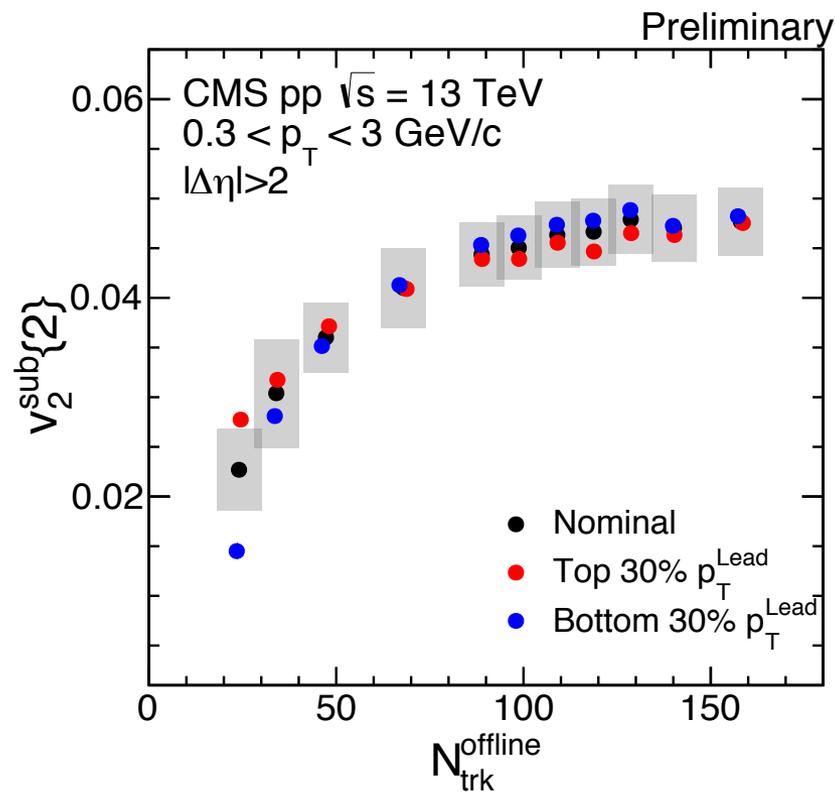
MC comparison with PYTHIA



V^0 mass fits



Jet subtraction test



Multi-particle correlations: Collectivity



- ❖ Multi-particle cumulant results compared to $v_2\{2\}$

