Collective phenomena in pp collisions at CMS

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For the CMS Collaboration

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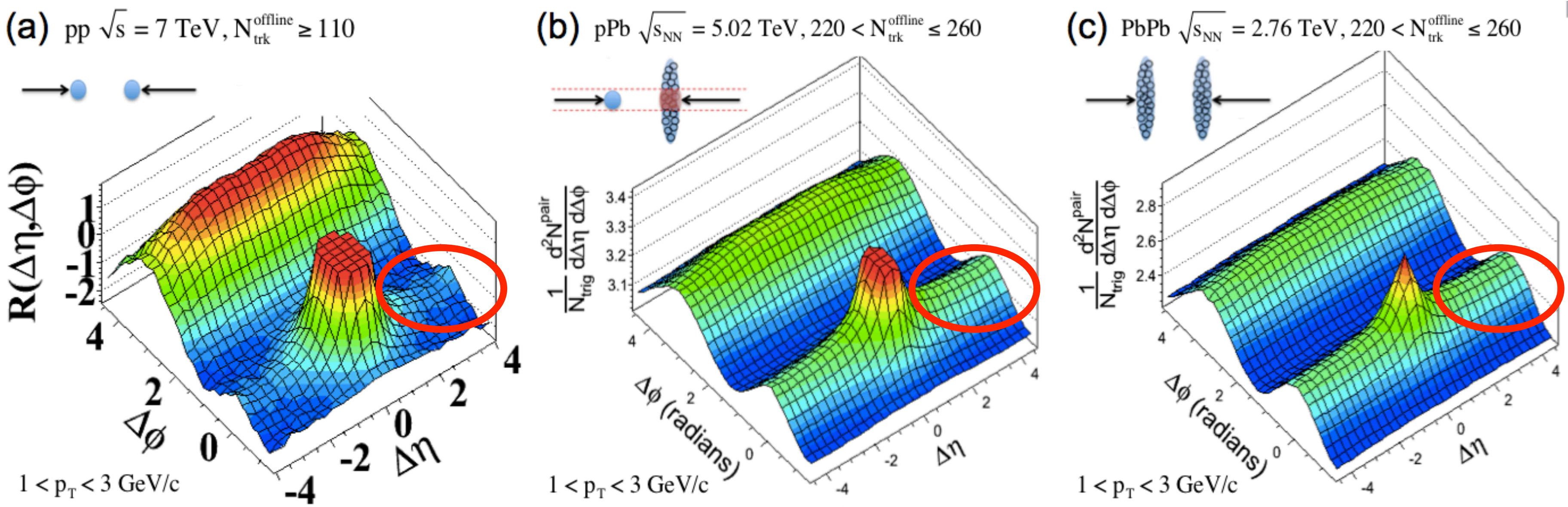
Oct 7 (2015)

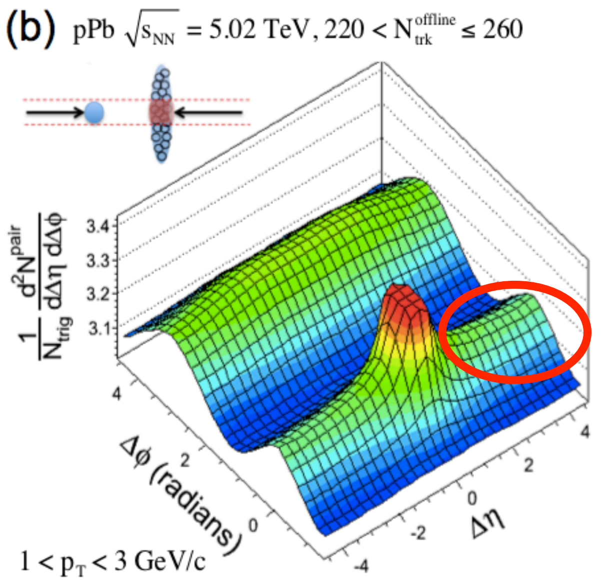
Long-range "ridges" at LHC



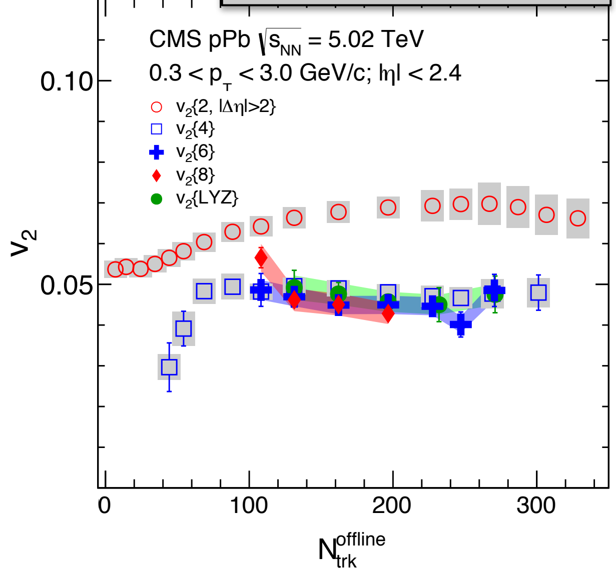
JHEP 09 (2010) 091 | PLB 724 (2013) 213 | PLB 724 (2013) 213

- The "ridge" seen in all systems at the LHC!
  - Hydrodynamic flow origin in PbPb collision.
  - What about small systems?

Long-range “ridge” in pPb



PRL 115 (2015) 012301



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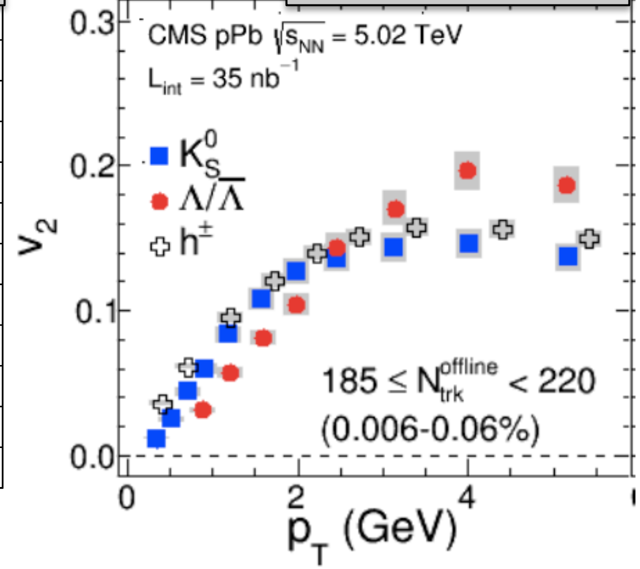
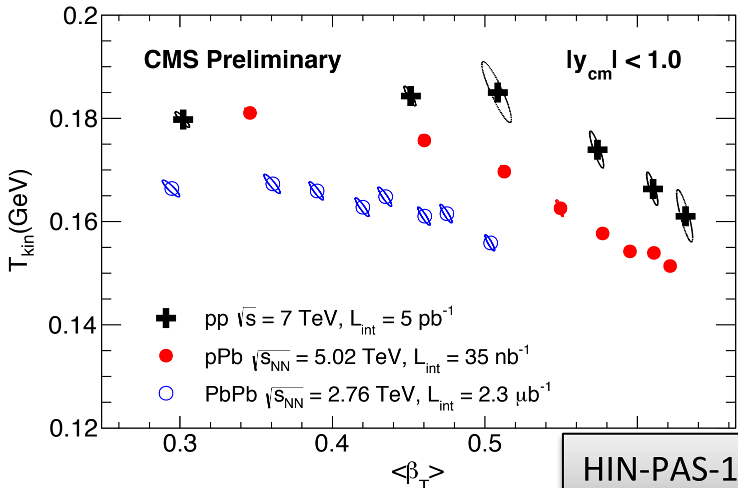
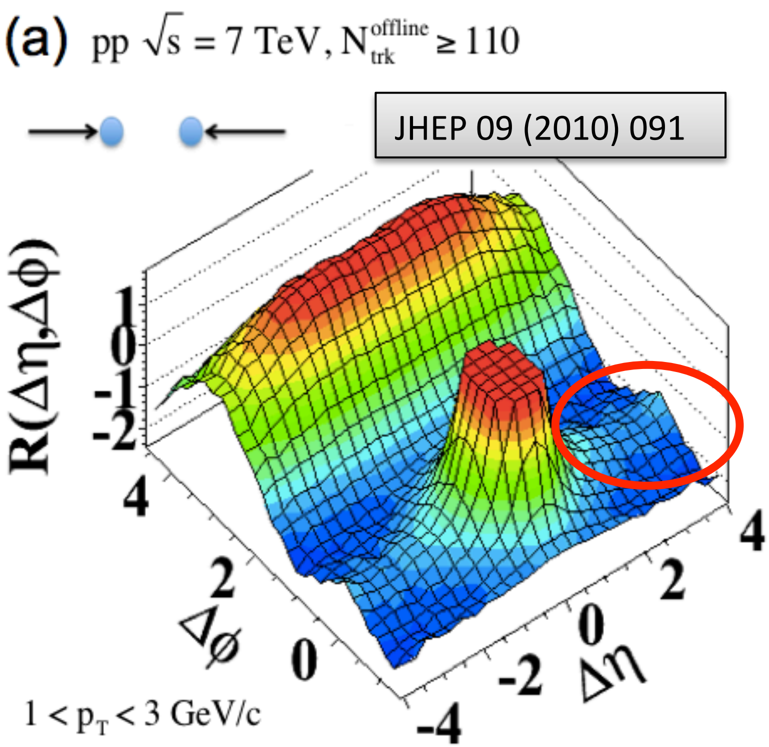


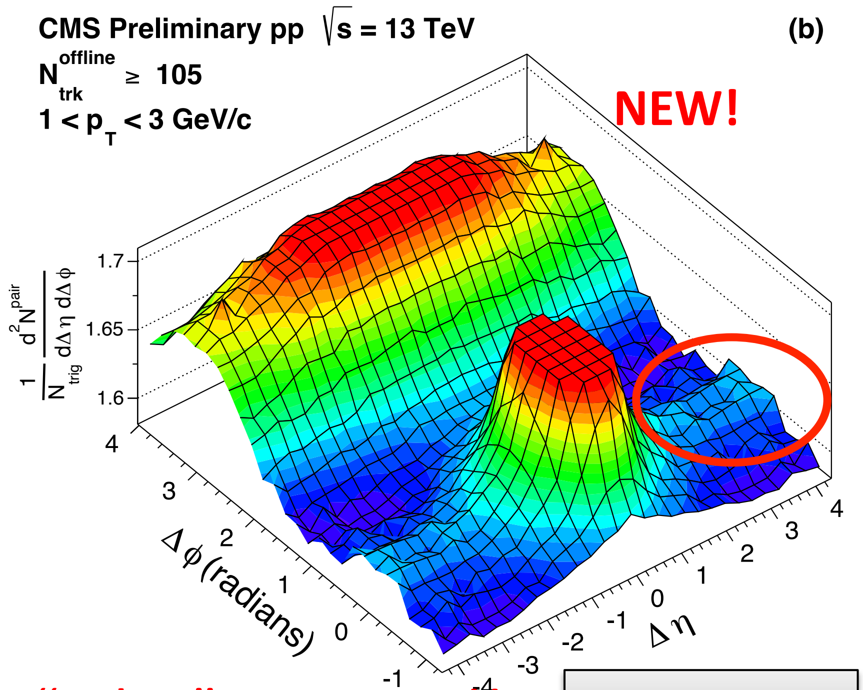


HIN-PAS-15-006

- Collectivity!
- Mass ordering!
- “Radial flow”!

Long-range "ridge" in pp

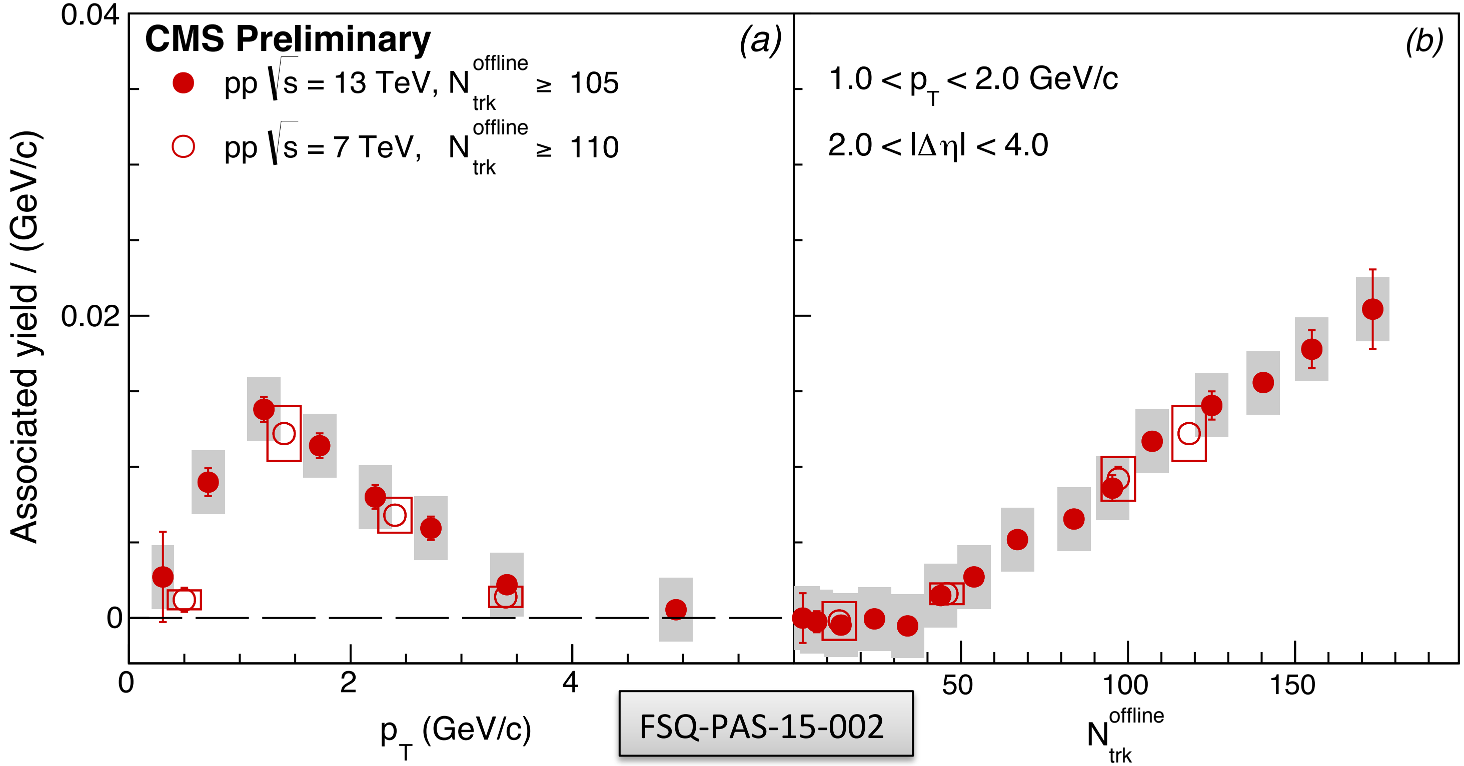




"ridge" at 13TeV!!

- Collectivity in even smaller system?
- Hydro flow at the smallest scale?
- Other contenders? E.g. Color Glass Condensate glasma

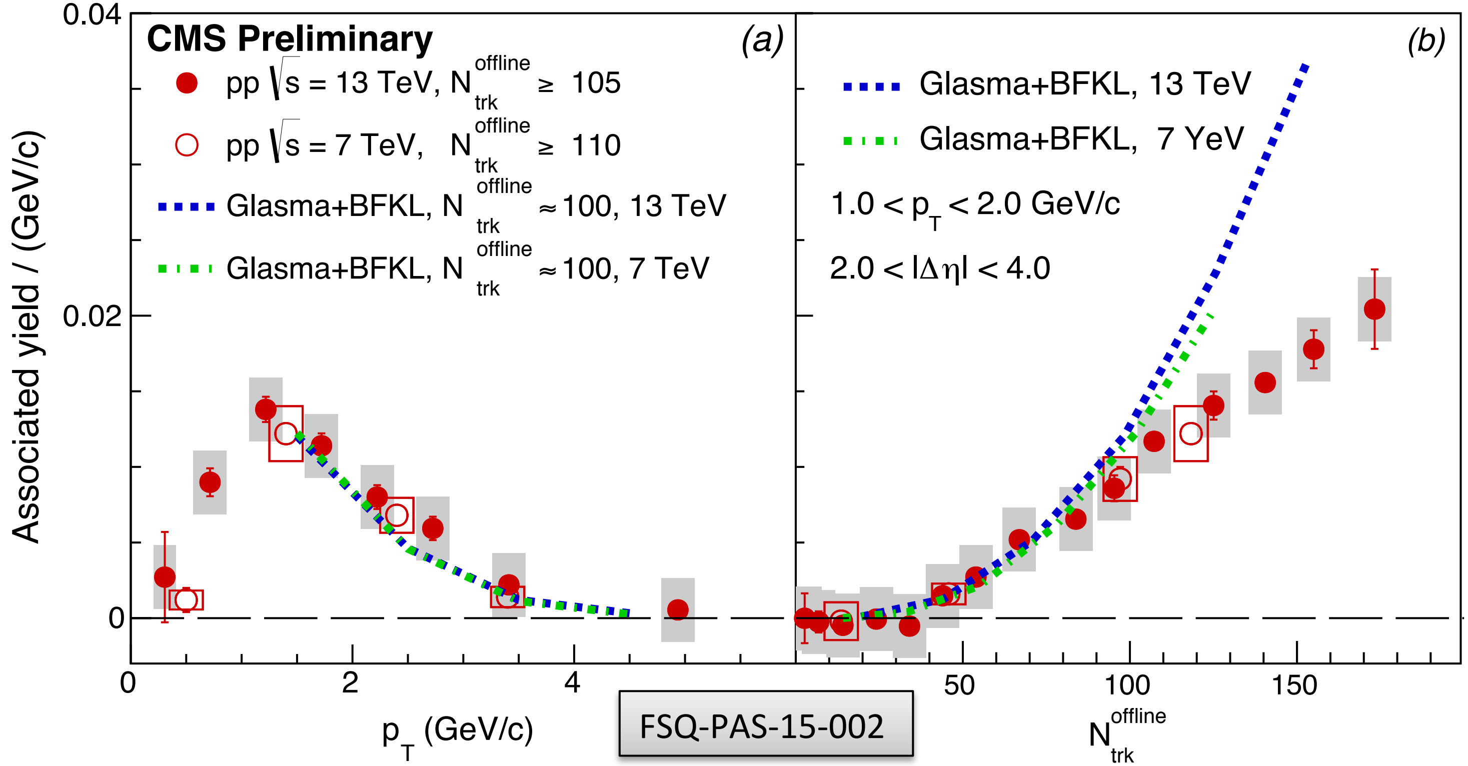
Long-range "ridge" in pp



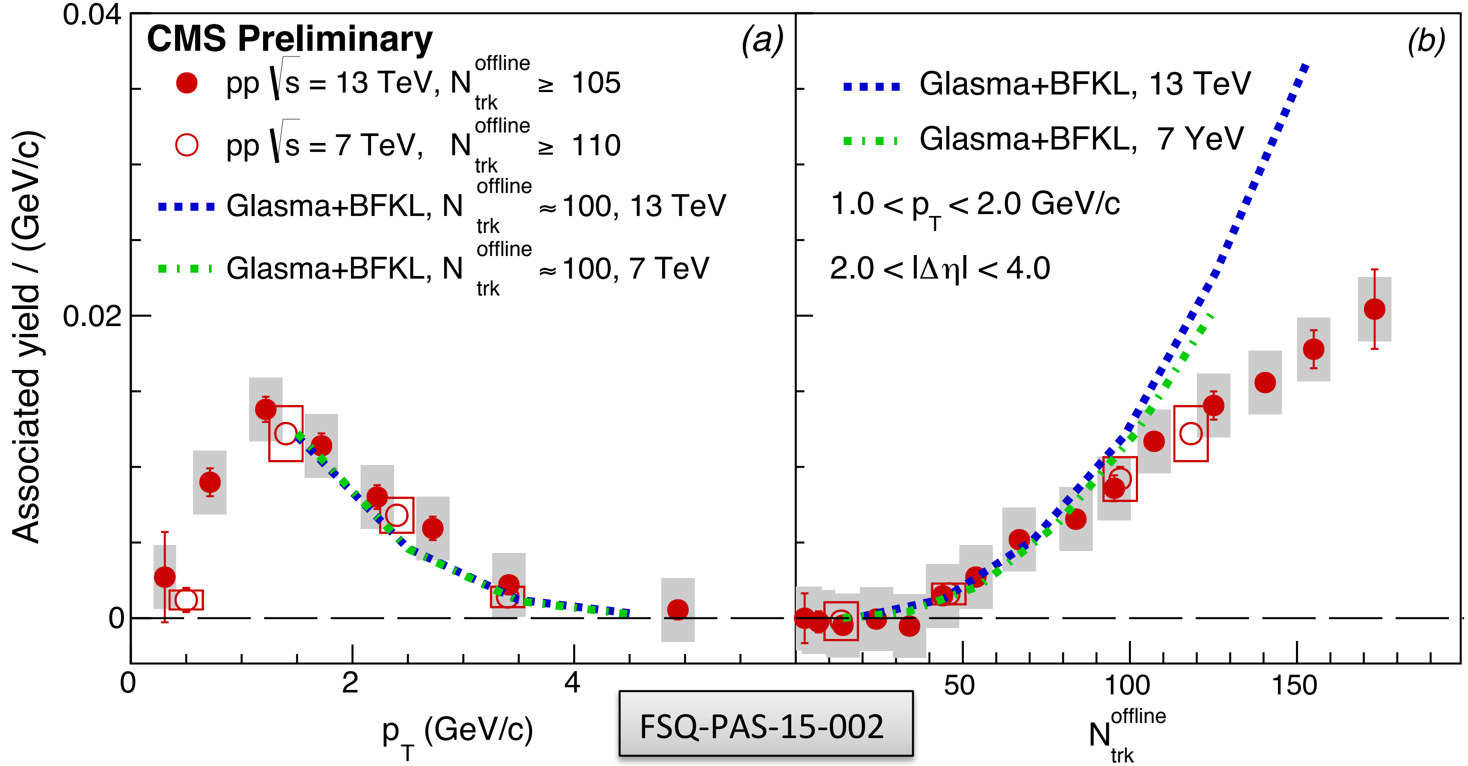
FSQ-PAS-15-002

- No collision energy dependence

Long-range "ridge" in pp



- No collision energy dependence
- CGC overshoots at high multiplicity
- Hydro calculations?

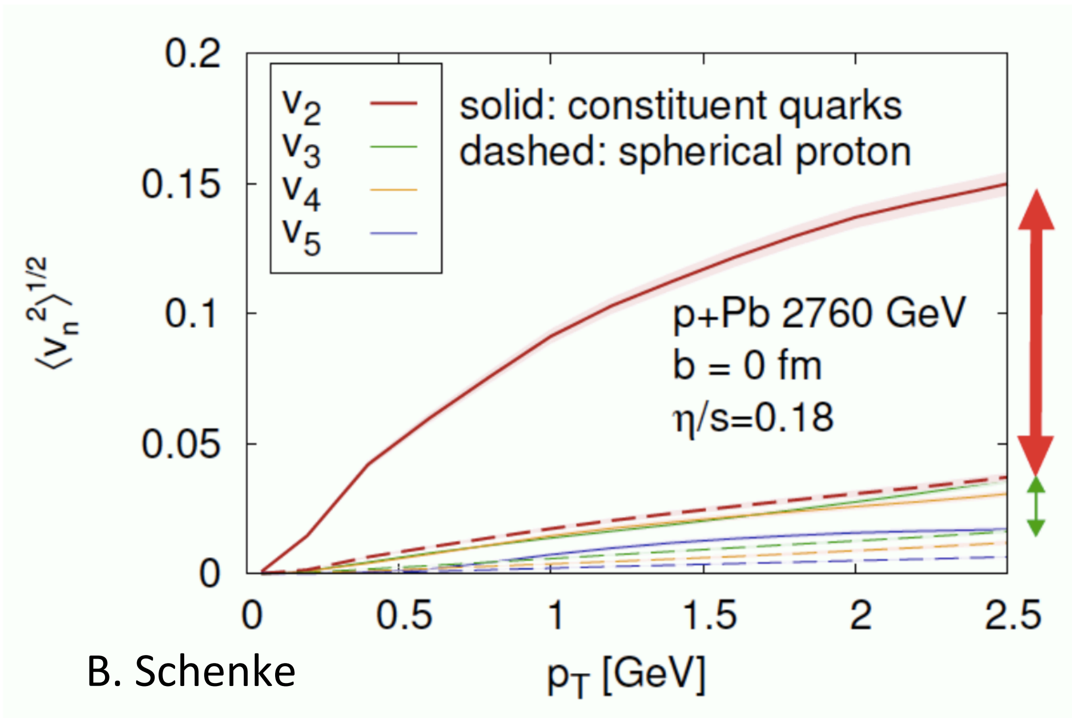


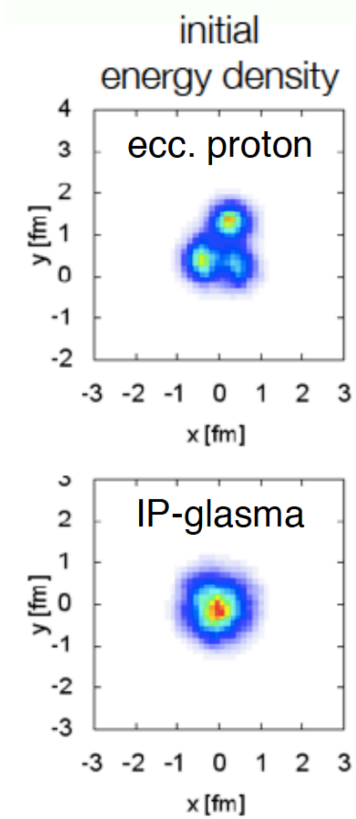
FSQ-PAS-15-002

- What about v_2, v_3 in pp?
- Particle species dependence?
- Is it collectivity?

Probe of proton shape fluctuation

- In pA, hydro calculation limited by **proton shape**



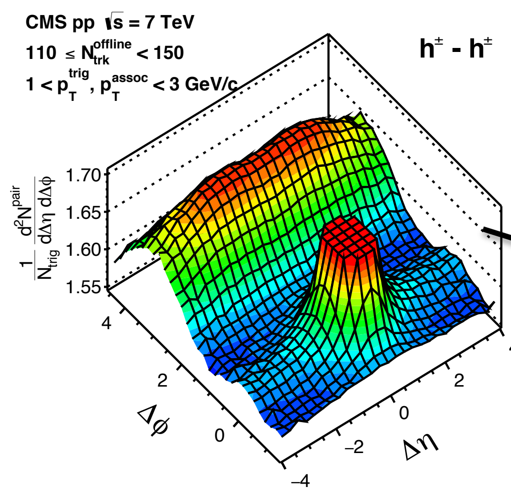


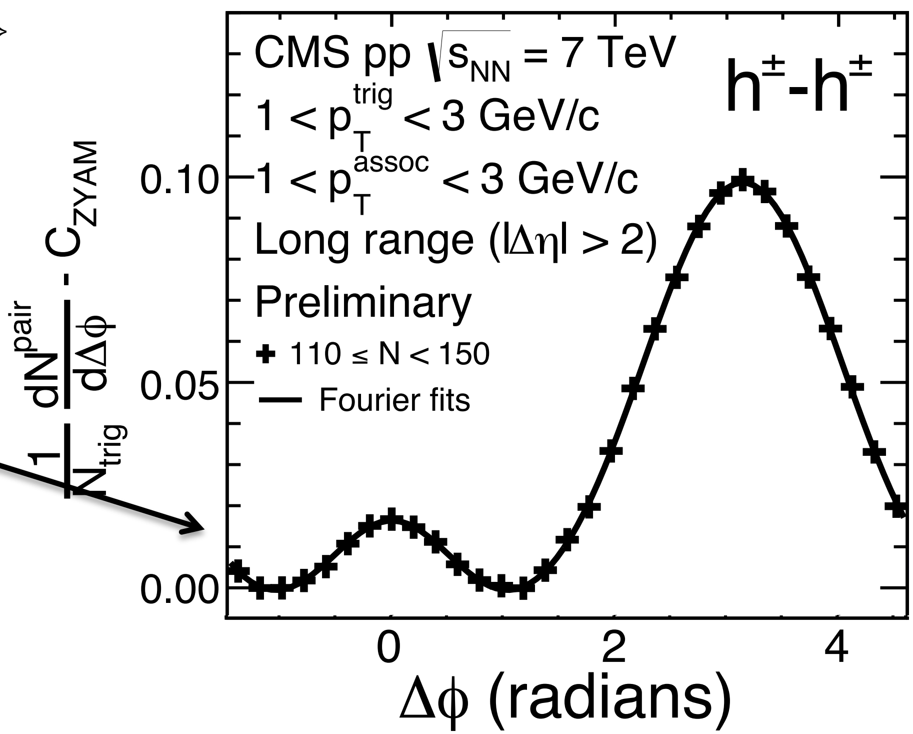
- pp collision provides **exclusive** probe of proton shape fluctuation at very short time scale!

v_n extraction

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

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

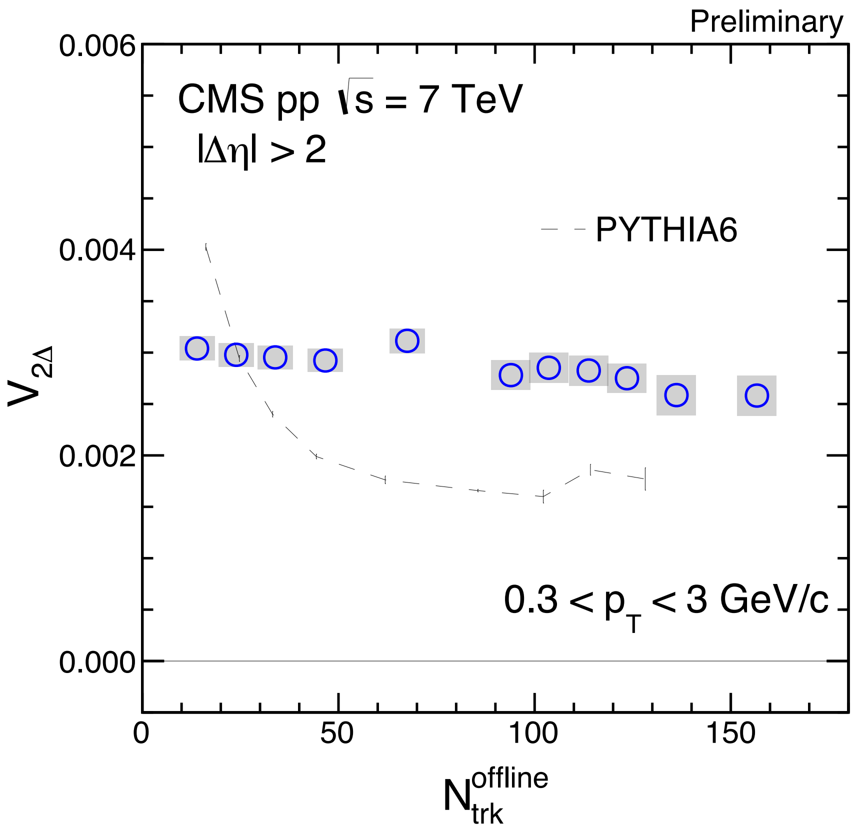




- Assume factorization:

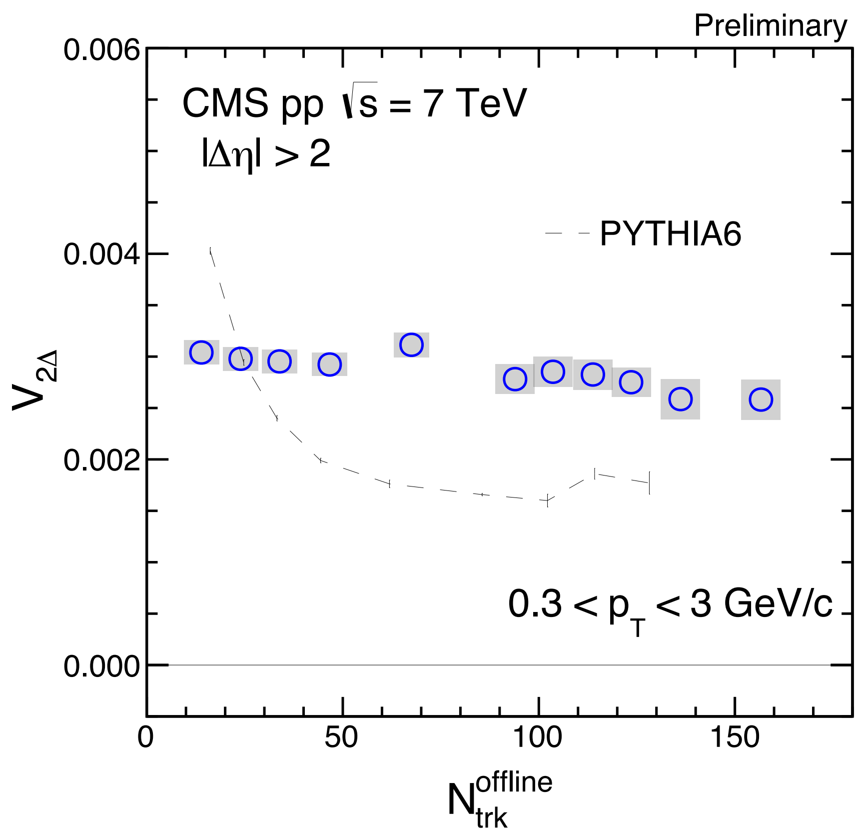
$$v_n\{2,|\Delta\eta|>2\}(p_T) = \frac{V_{n\Delta}(p_T, p_T^{ref})}{\sqrt{V_{n\Delta}(p_T^{ref}, p_T^{ref})}}$$

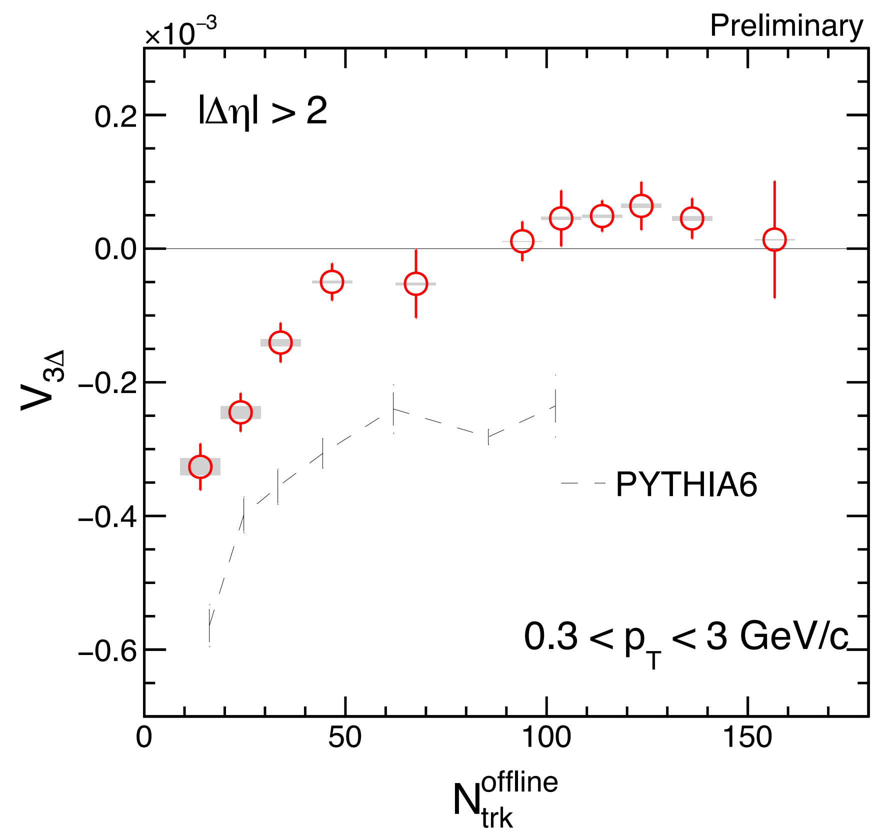
$V_{2\Delta}$ vs. multiplicity



- Data & MC difference → contribution other than jet correlation

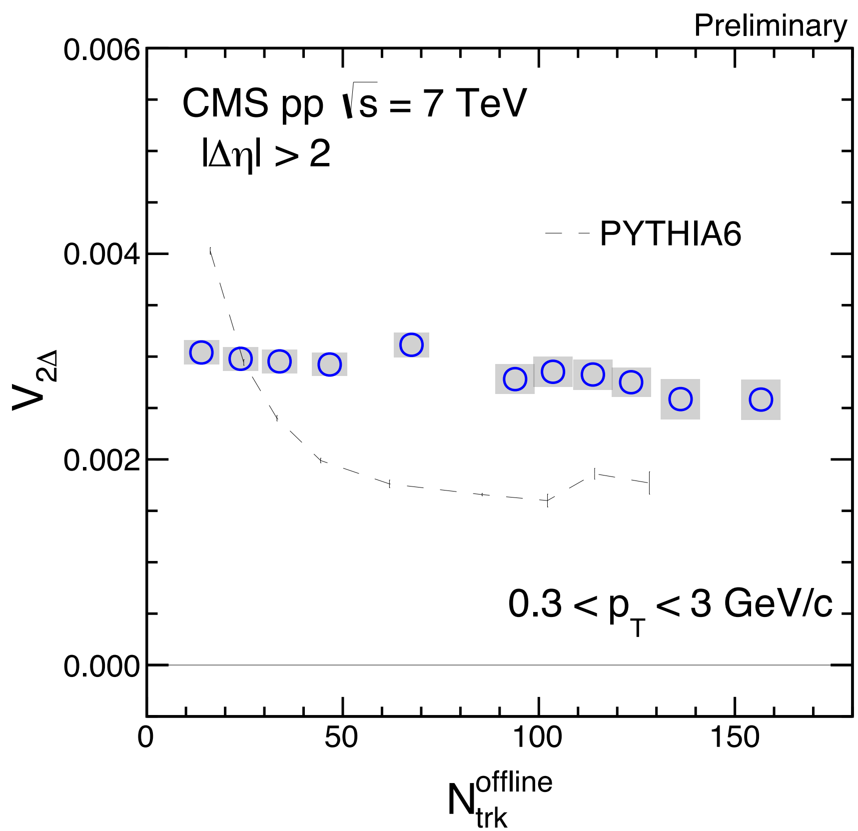
$V_{2\Delta}$, $V_{3\Delta}$ vs. multiplicity

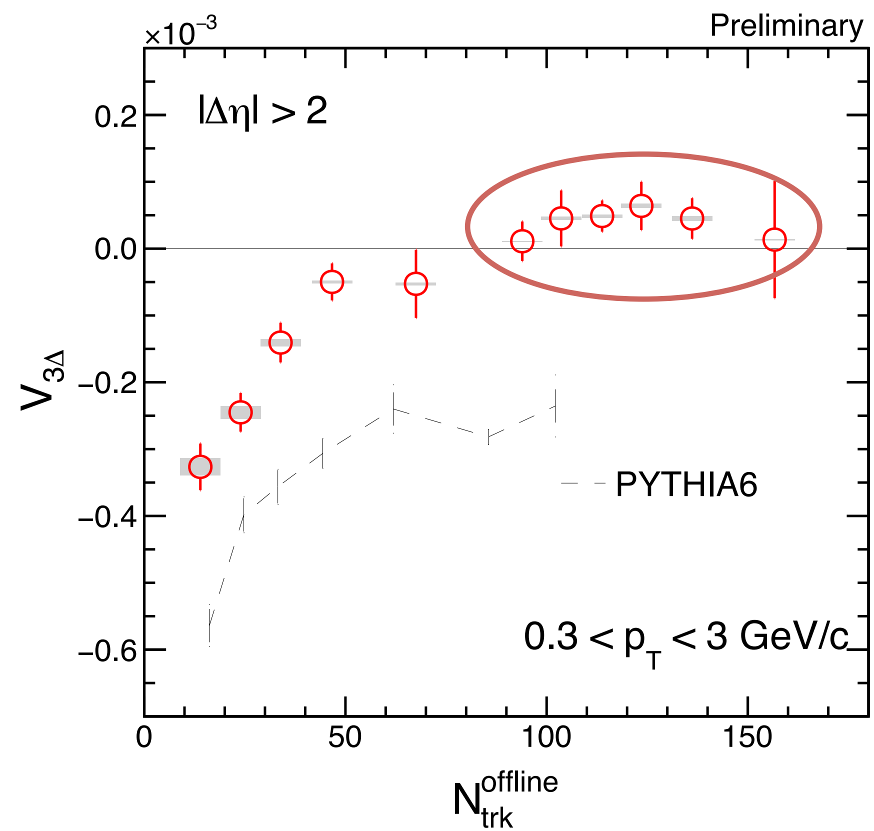




- Data & MC difference → contribution other than jet correlation

$V_{2\Delta}$, $V_{3\Delta}$ vs. multiplicity

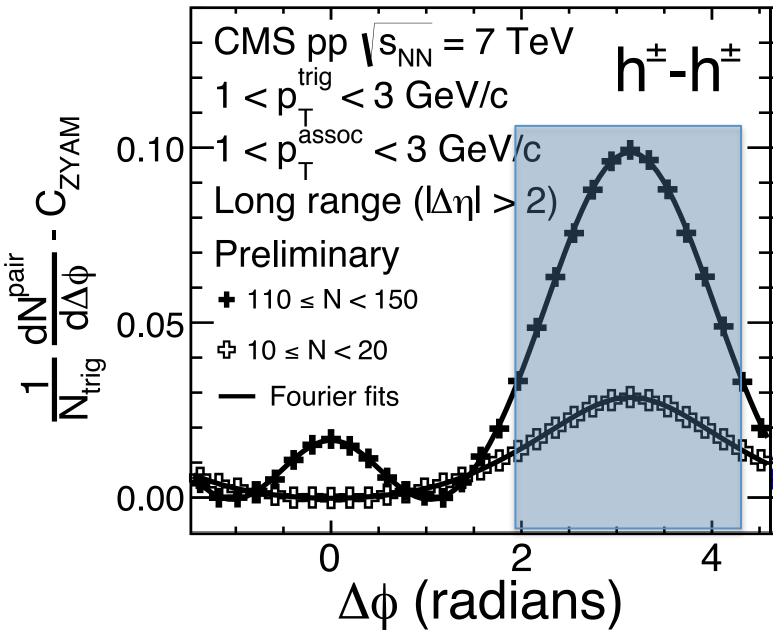


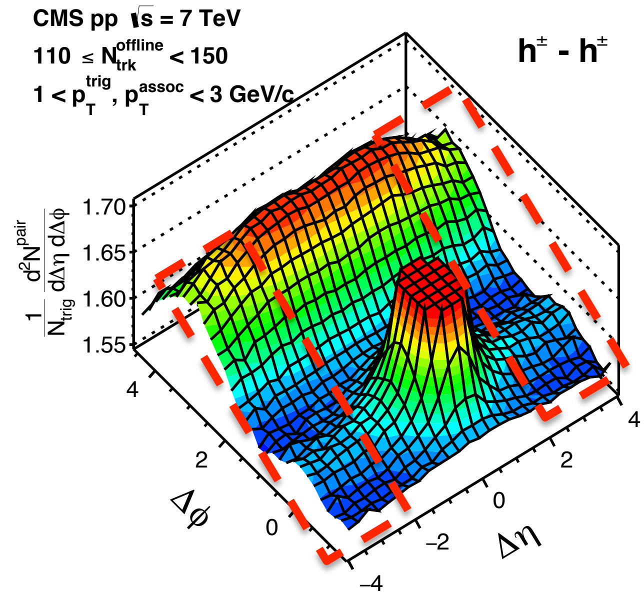


- Data & MC difference → contribution other than jet correlation
- **Positive $V_{3\Delta}$ → brand new phenomena!**

Correction for jet contribution

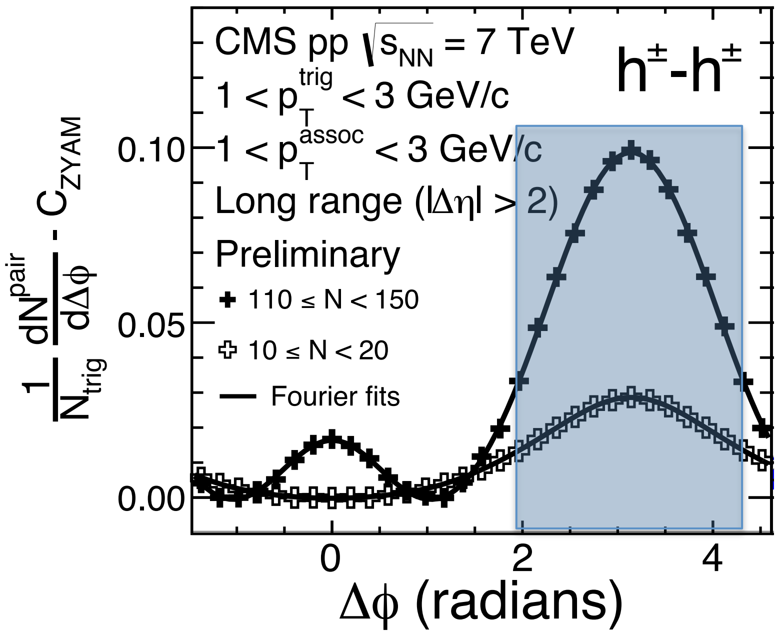
- Back-to-back jet correlation on the away side

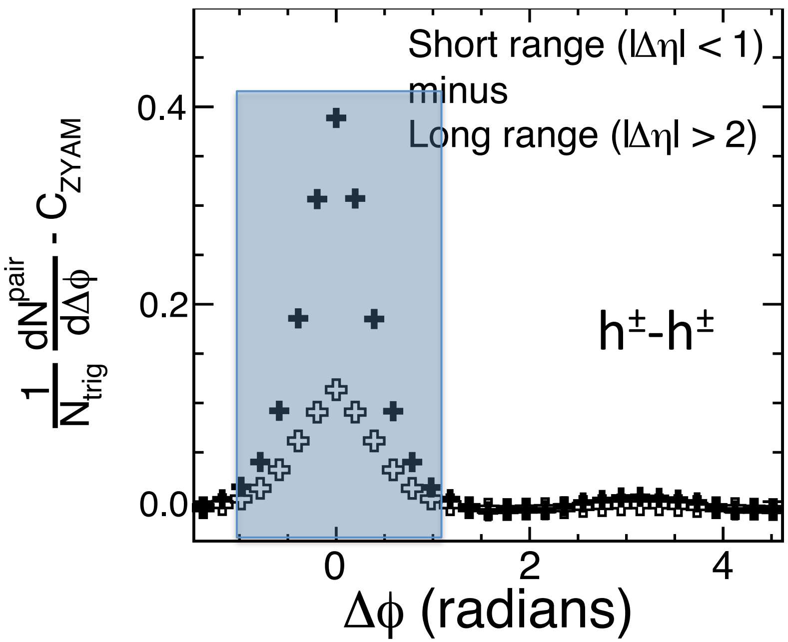




Correction for jet contribution

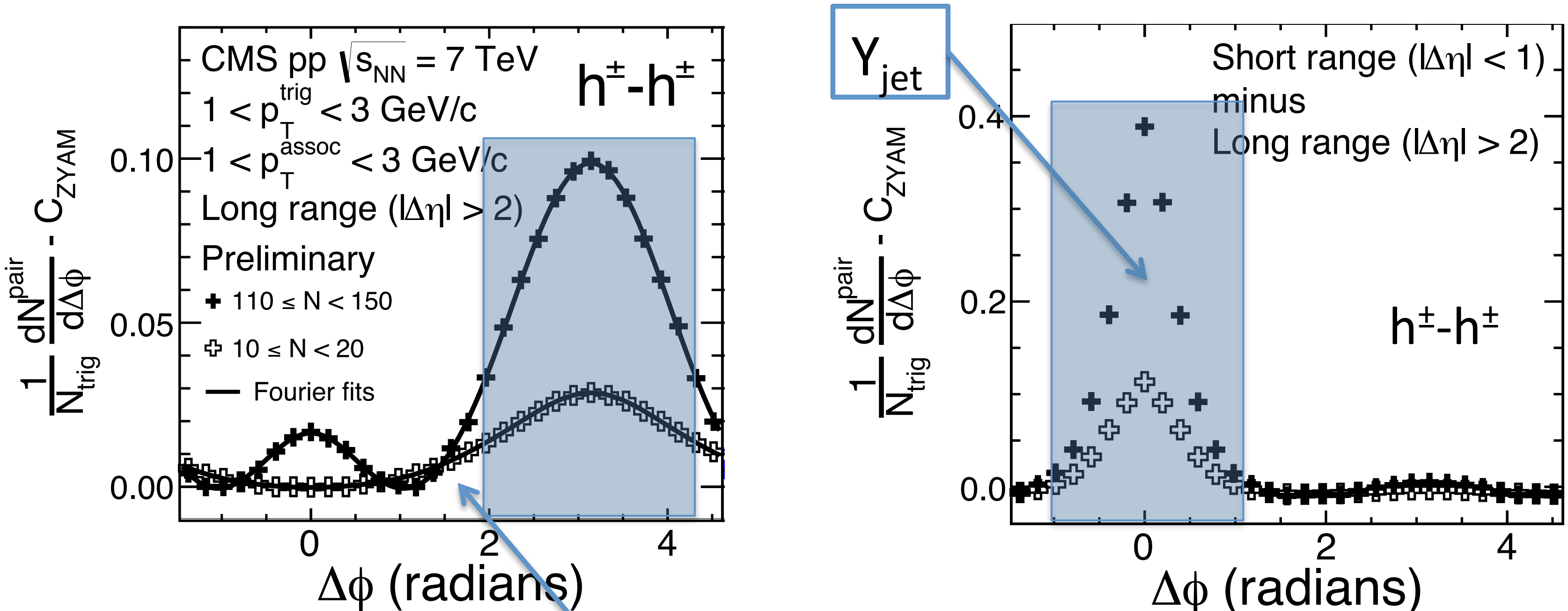
- Correlation between away and near-side jet contribution





Correction for jet contribution

- Bias to more jet contribution when selecting high multiplicity

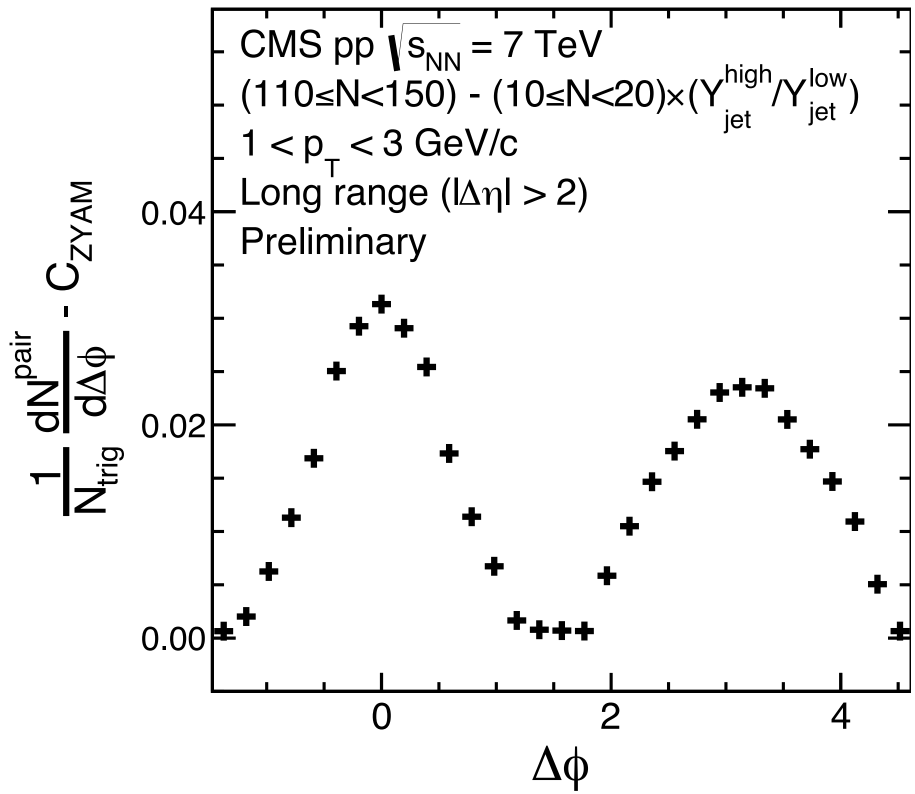


- Calibrating the bias by near-side jet yield Y_{jet}, low multiplicity subtraction to remove jet contribution:

$$V_{n\Delta}^{sub} \times N_{assoc}^{high} = V_{n\Delta}^{high} \times N_{assoc}^{high} - V_{n\Delta}^{low} \times N_{assoc}^{low} \times \frac{Y_{jet}^{high}}{Y_{jet}^{low}}$$

Correction for jet contribution

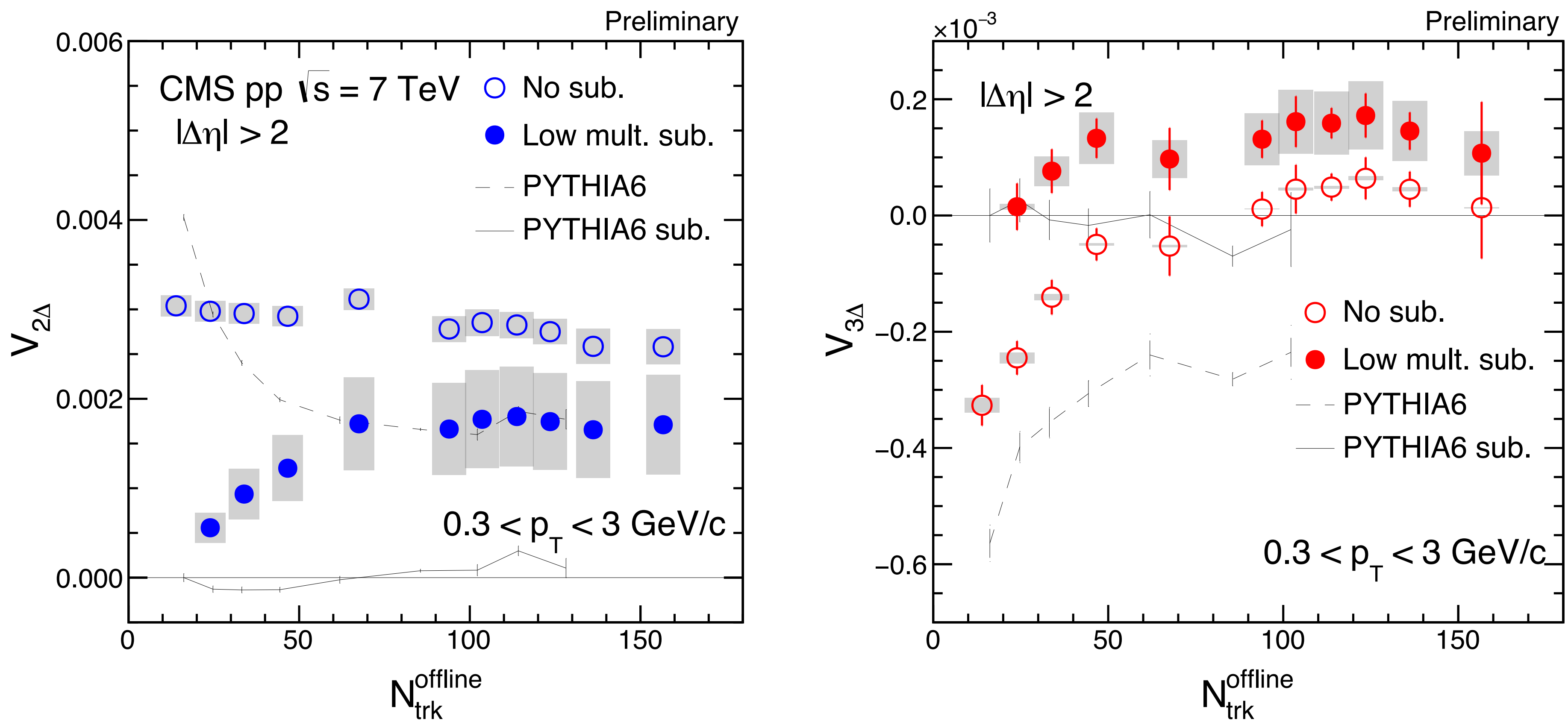
- After low multiplicity subtraction



$V_{n\Delta}$ after subtraction:
$V_{1\Delta}^{sub} \approx 0.0003$
$V_{2\Delta}^{sub} \approx 0.0042$
$V_{3\Delta}^{sub} \approx 0.0008$

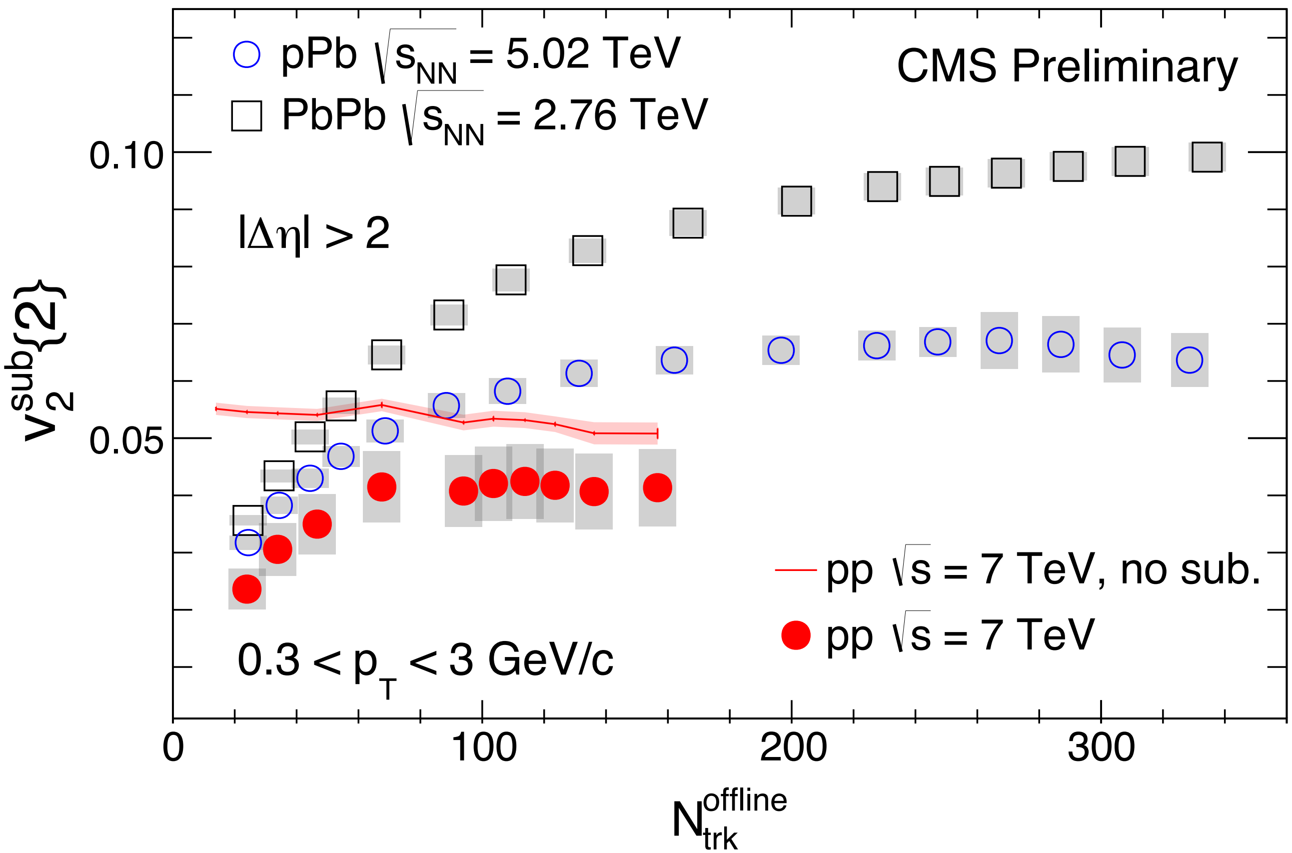
- "Double ridge" structure similar to pPb and PbPb

$V_{2\Delta}$, $V_{3\Delta}$ vs. multiplicity



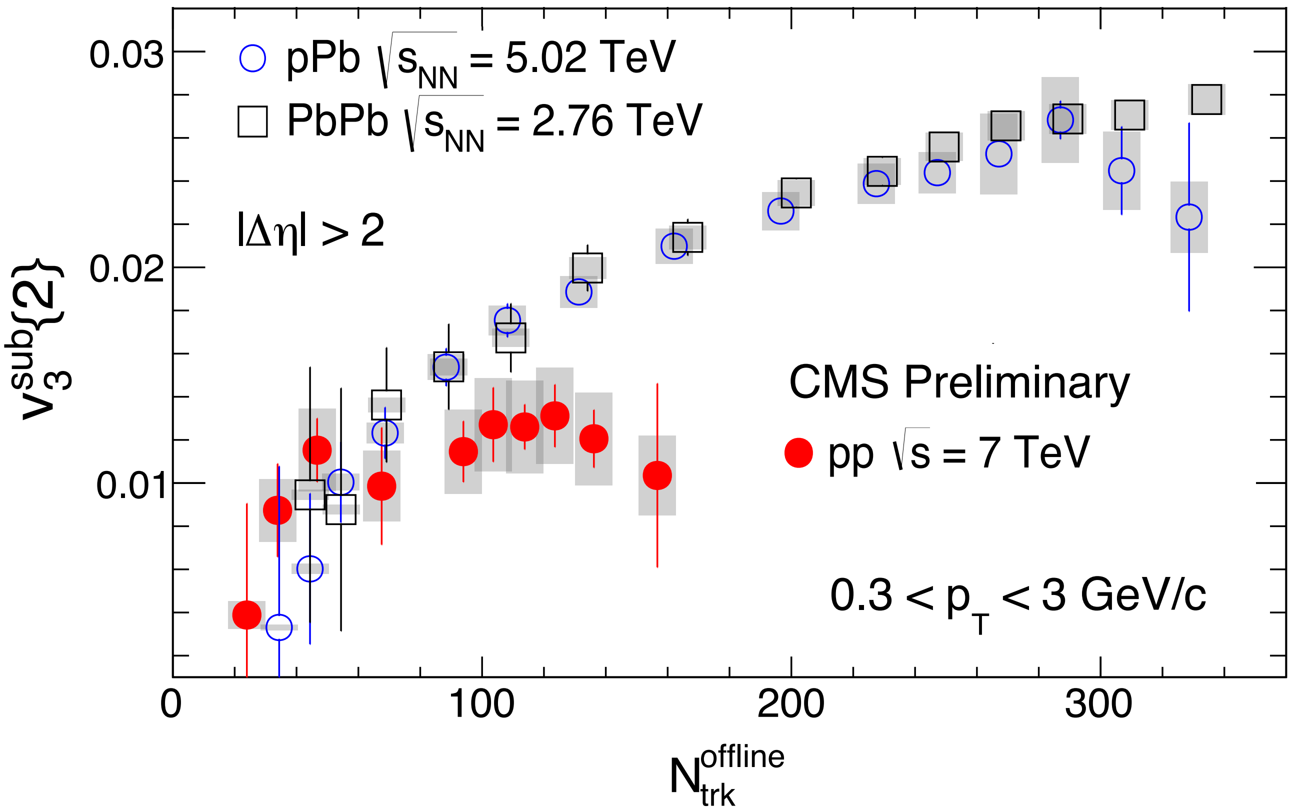
- $V_{2\Delta}$, $V_{3\Delta}$ become relative constant at high multiplicity
- Low multiplicity subtraction works well for jet correlation (MC)

v_2 vs. multiplicity



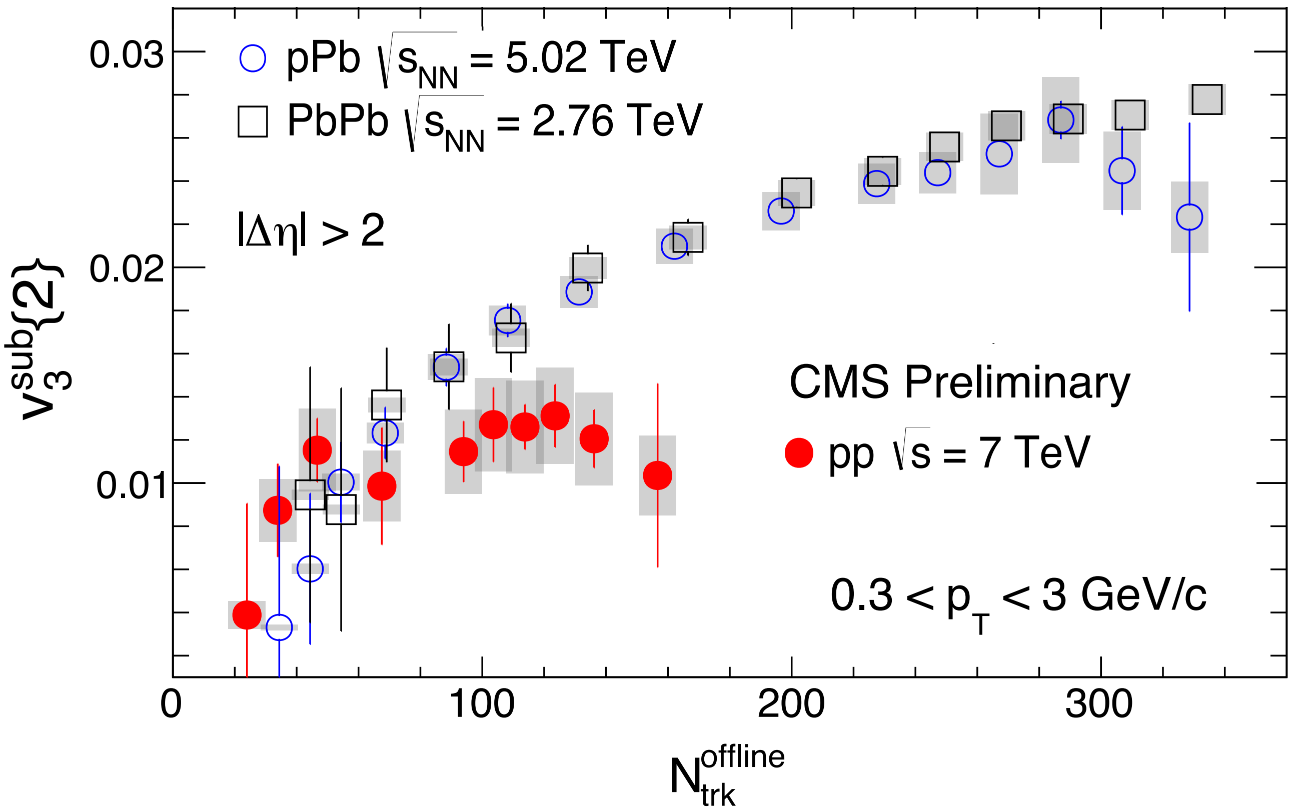
- $v_2(pp) \approx 4\%$ at high multiplicity
- $v_2(pp) < v_2(pPb) < v_2(PbPb)$

v_3 vs. multiplicity



- $v_3(pp) \approx 1.2\%$ at high multiplicity
- Trend of deviation from $v_3(pPb)$ & $v_3(PbPb)$ at high multiplicity

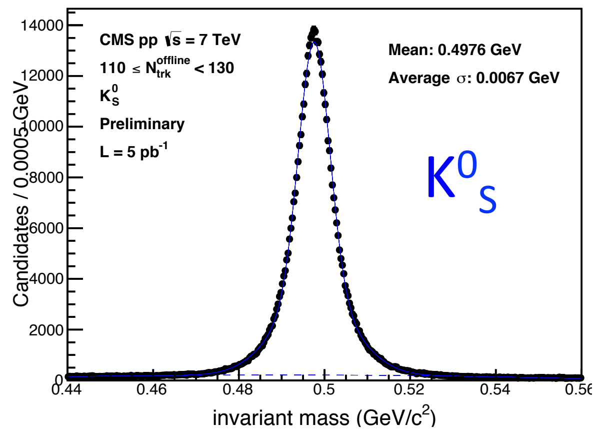
v_3 vs. multiplicity

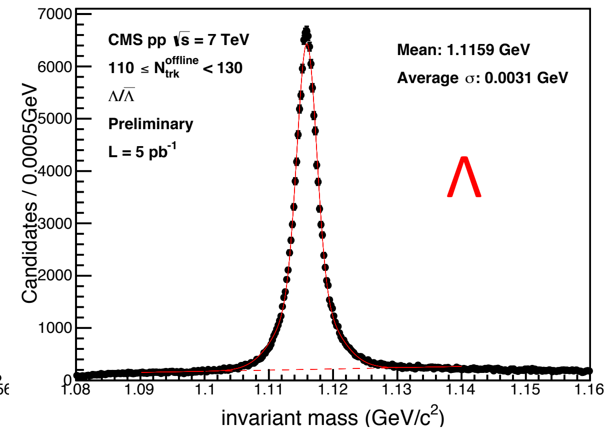


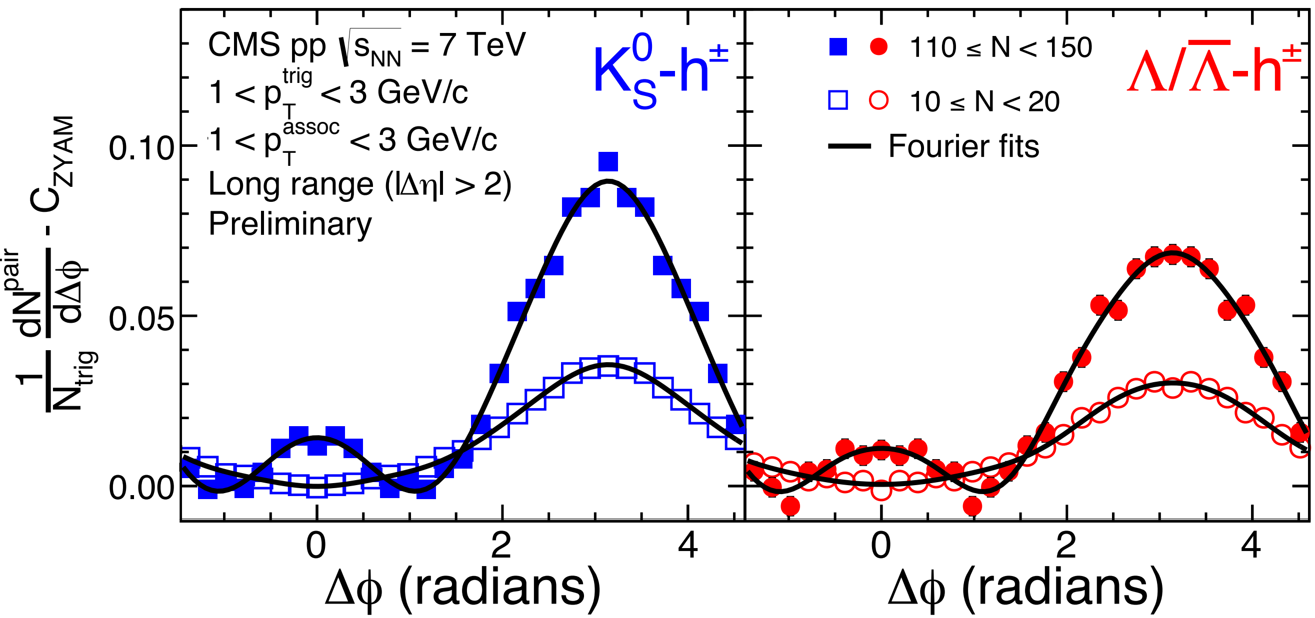
- v_3(pp) ≈ 1.2% at high multiplicity
- Trend of deviation from v_3(pPb) & v_3(PbPb) at high multiplicity
- **More constraints on the proton shape**

V^0 correlation

- Topological V^0 reconstruction
  - $K^0_S \rightarrow \pi^+\pi^-$
  - $\Lambda \rightarrow p^+\pi^-$

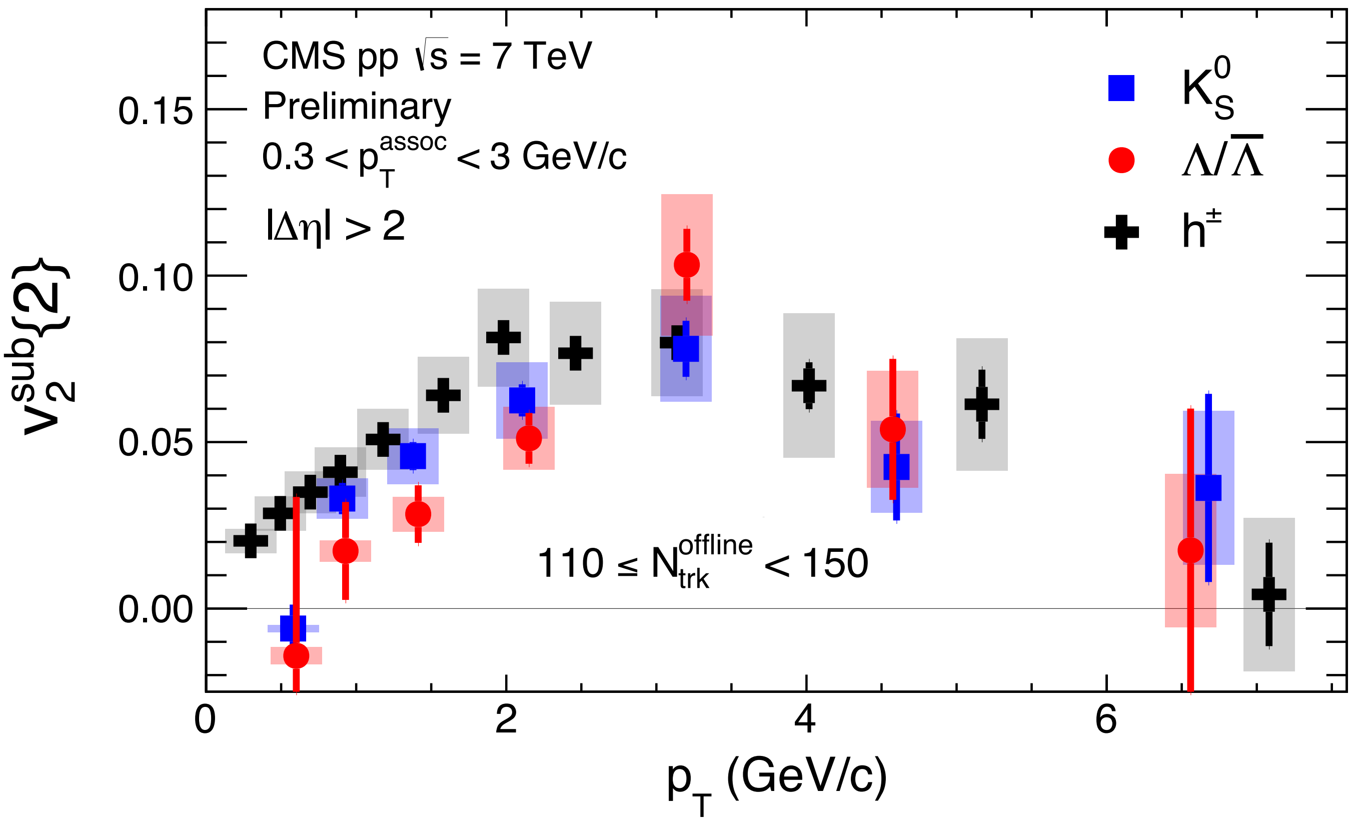






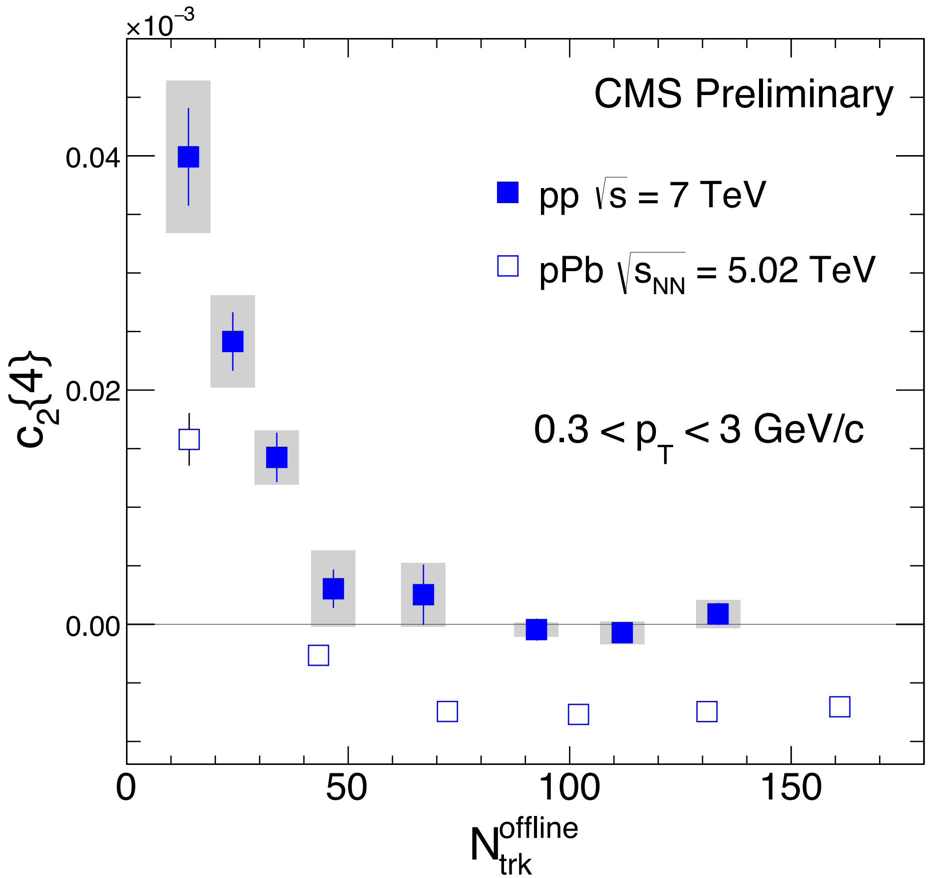
Similar correlation as charge hadron

PID v_2 vs. p_T



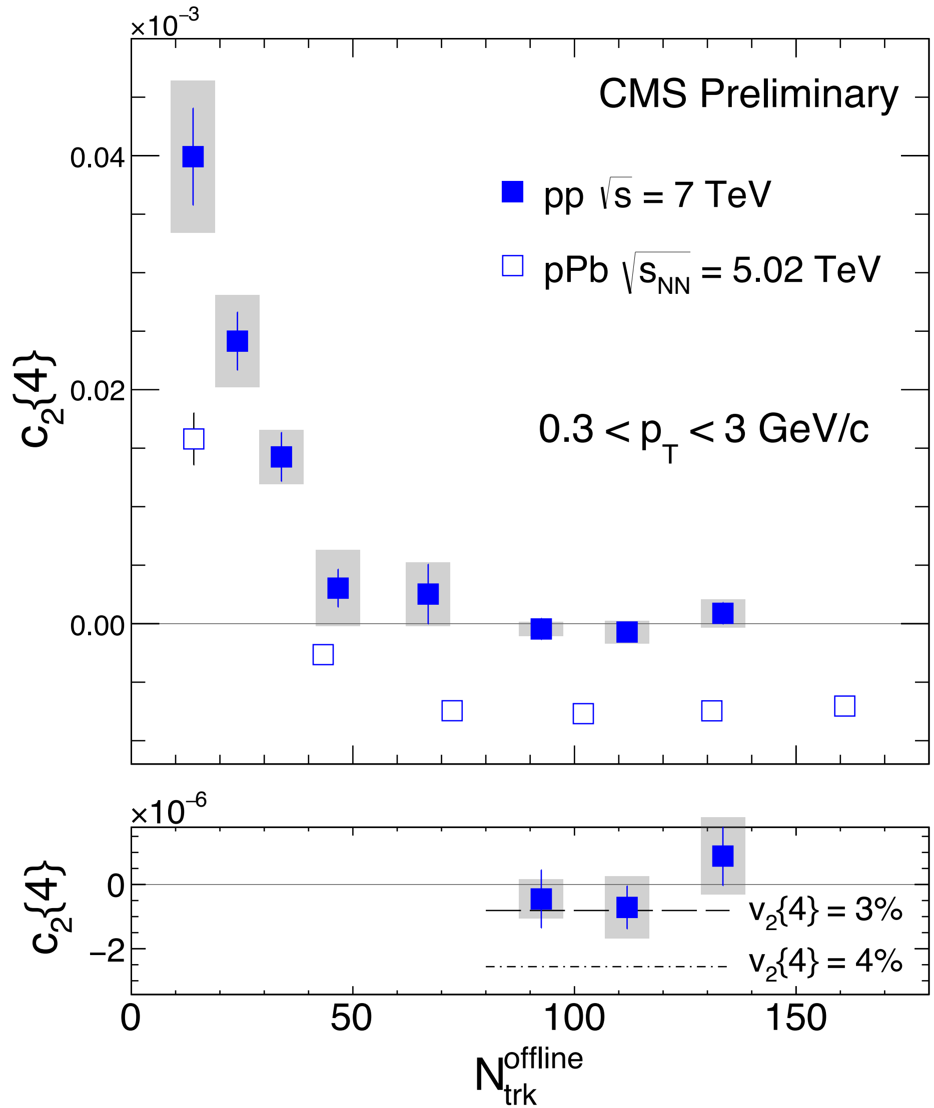
- No mass dependence of v_2 from jet correlation at low multiplicity
- **Mass ordering in low p_T region at high multiplicity**

4-particle correlation: collectivity?



- Q-cumulant 4-particle correlation
  $$\langle\langle 4\rangle\rangle \equiv \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle$$
  $$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2$$
  related to v_2 as
  $$v_2\{4\}^4 = -c_2\{4\}$$
- $c_2\{4\}$ decrease with multiplicity, same behavior as in pPb

4-particle correlation: collectivity?



- Q-cumulant 4-particle correlation
  $$\langle\langle 4 \rangle\rangle \equiv \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \right\rangle\right\rangle$$
  $$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$
  related to v_2 as
  $$v_2\{4\}^4 = -c_2\{4\}$$
- $c_2\{4\}$ decrease with multiplicity, same behavior as in pPb
- Indication of negative $c_2\{4\}$ at high multiplicity, stay tuned!

Summary

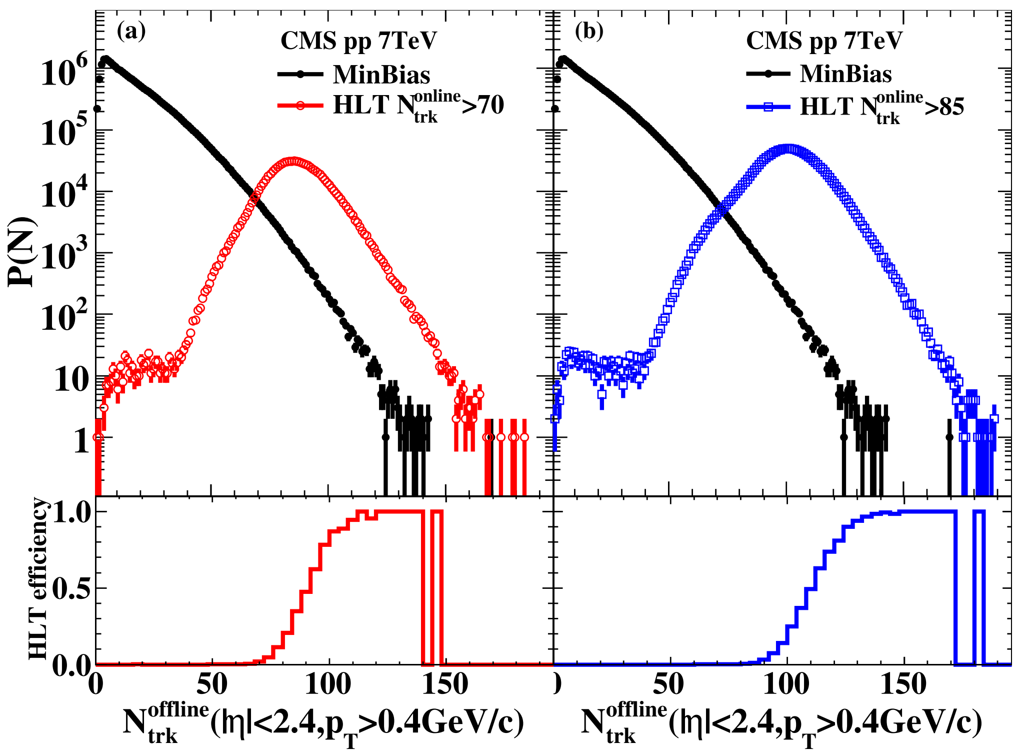
Presented the second-order (v_2) and third-order (v_3) anisotropy of charge hadron, K^0_S and Λ for high multiplicity pp collisions

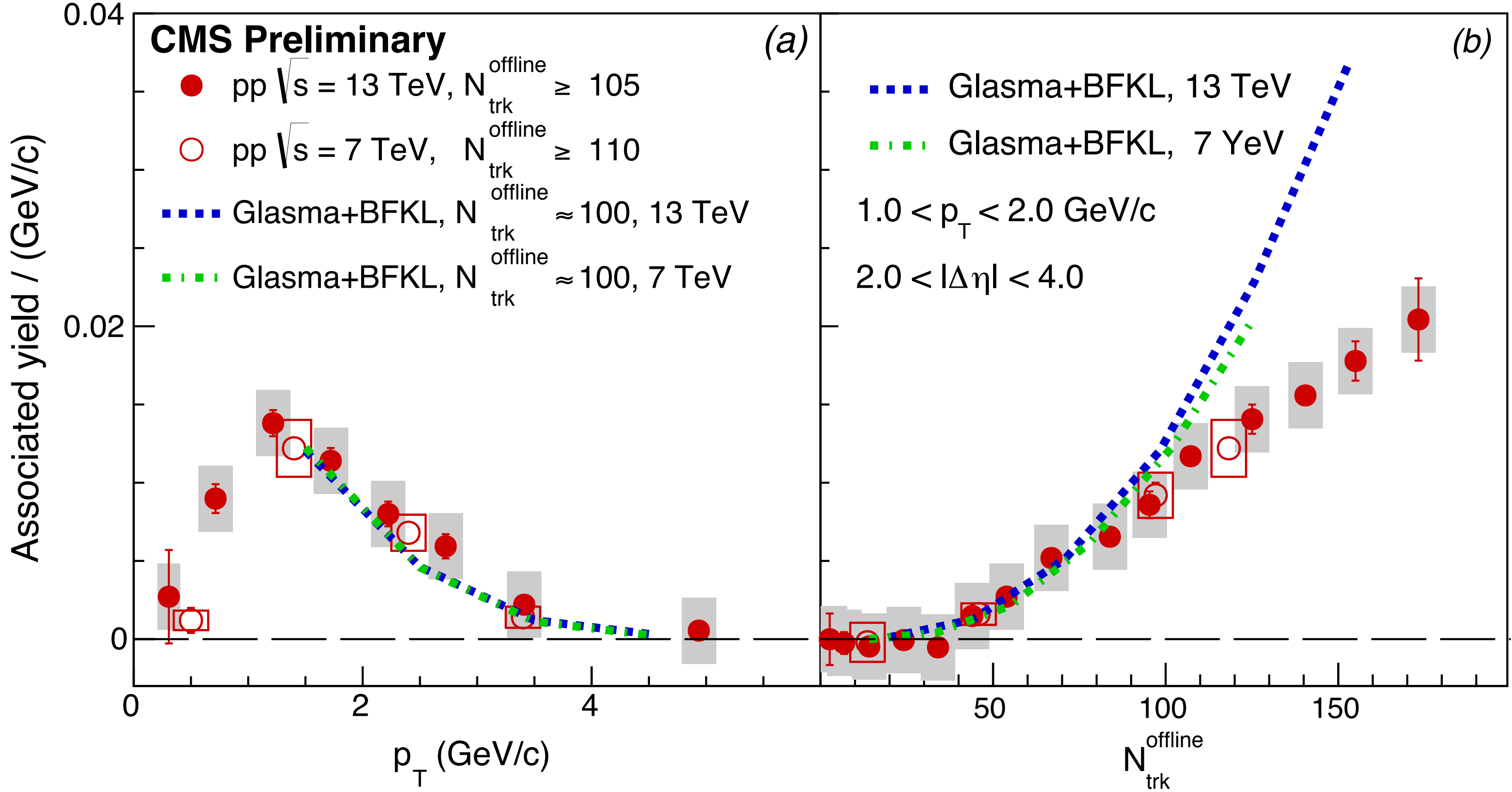
- Multiplicity dependent (charge hadron)
  - overall v_2(pp) < v_2(pPb) < v_2(PbPb)
  - v_3(pp) deviates from v_3(pPb & PbPb) at high multiplicity
- Transverse momentum dependent (PID)
  - Mass ordering clearly observed in low p_T region

Back up

Data sets, trigger

- 2010 pp, 6.2 pb^{-1}
- Triggers
  - High Multiplicity Trigger
  - Minimum Bias Trigger

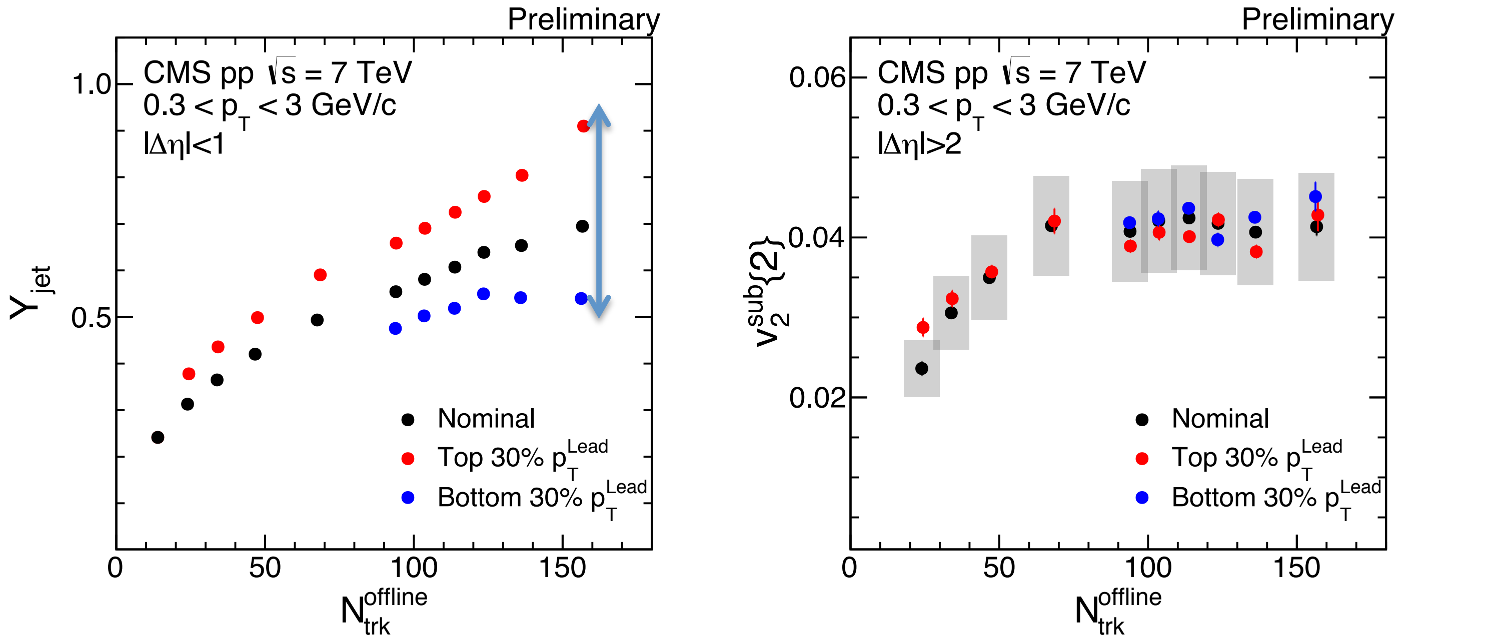




CMS Preliminary
(a)
(b)
pp √s = 13 TeV, N offline trk ≥ 105
pp √s = 7 TeV, N offline trk ≥ 110
Glasma+BFKL, N offline trk ≈100, 13 TeV
Glasma+BFKL, N offline trk ≈100, 7 TeV
Glasma+BFKL, 13 TeV
Glasma+BFKL, 7 YeV
1.0 < p_T < 2.0 GeV/c
2.0 < |Δη| < 4.0
Associated yield / (GeV/c)
0.04
0.02
0
2
4
50
100
150
p_T (GeV/c)
N offline trk

Validation of subtraction in data

- Systematic studies considering: from low to high multiplicity
  - Potential de-correlation between near and away side jet contribution
  - Potential change of jet distribution in Δη and Δϕ
- One overall test: cut leading particle p_T



- Subtraction robust against potential bias on jet mechanism

Validation of Subtraction in MC

- The subtraction procedure to remove jet contribution

$$V_{n\Delta}^{\mathrm{sub}} \times N_{\mathrm{assoc}}^{\mathrm{high}} = V_{n\Delta}^{\mathrm{high}} \times N_{\mathrm{assoc}}^{\mathrm{high}} - V_{n\Delta}^{\mathrm{low}} \times N_{\mathrm{assoc}}^{\mathrm{low}} \times \frac{Y_{\mathrm{jet}}^{\mathrm{high}}}{Y_{\mathrm{jet}}^{\mathrm{low}}}$$

- For purely jet correlation

  $V_{n\Delta}^{\mathrm{sub}} \times N_{\mathrm{assoc}}^{\mathrm{high}} =$ 0 expected,

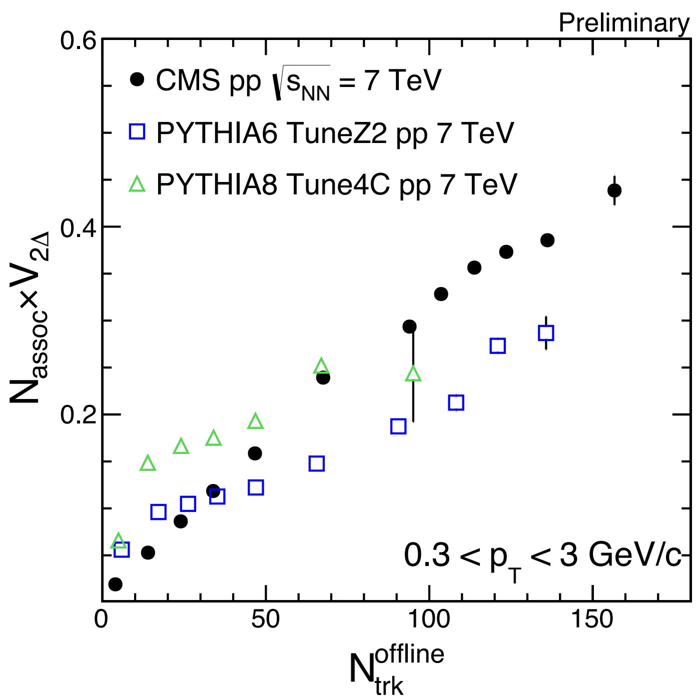
  which requires

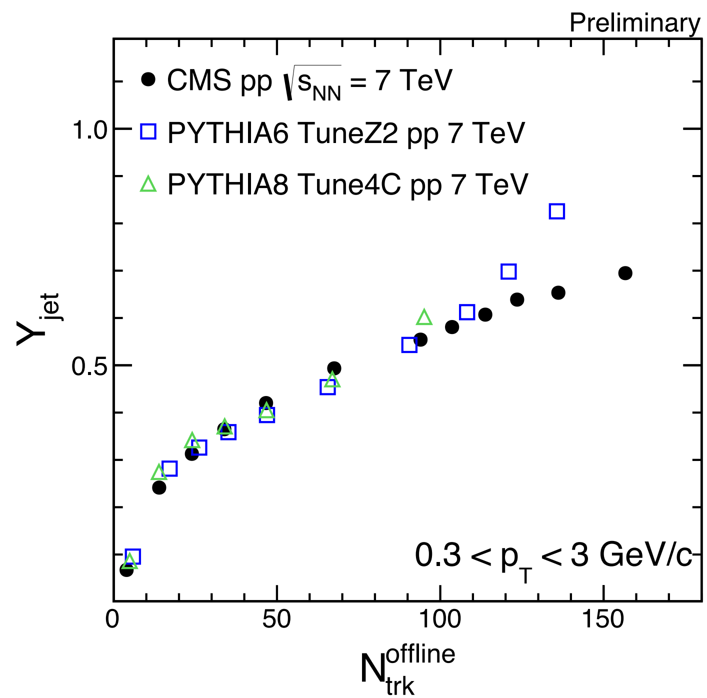
$$V_{n\Delta}^{\mathrm{high}} \times N_{\mathrm{assoc}}^{\mathrm{high}} = V_{n\Delta}^{\mathrm{low}} \times N_{\mathrm{assoc}}^{\mathrm{low}} \times \frac{Y_{\mathrm{jet}}^{\mathrm{high}}}{Y_{\mathrm{jet}}^{\mathrm{low}}}$$

$$\Downarrow$$

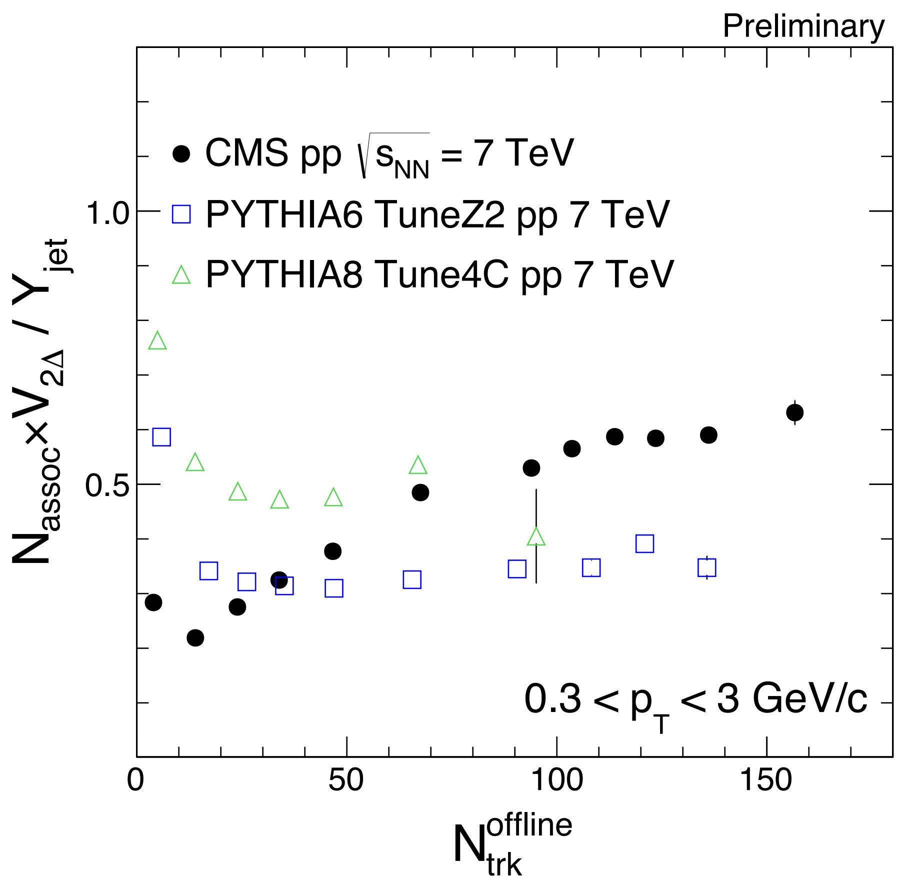
$$\frac{V_{n\Delta}^{\mathrm{high}} \times N_{\mathrm{assoc}}^{\mathrm{high}}}{Y_{\mathrm{jet}}^{\mathrm{high}}} = \frac{V_{n\Delta}^{\mathrm{low}} \times N_{\mathrm{assoc}}^{\mathrm{low}}}{Y_{\mathrm{jet}}^{\mathrm{low}}}$$

Validation of Subtraction in MC

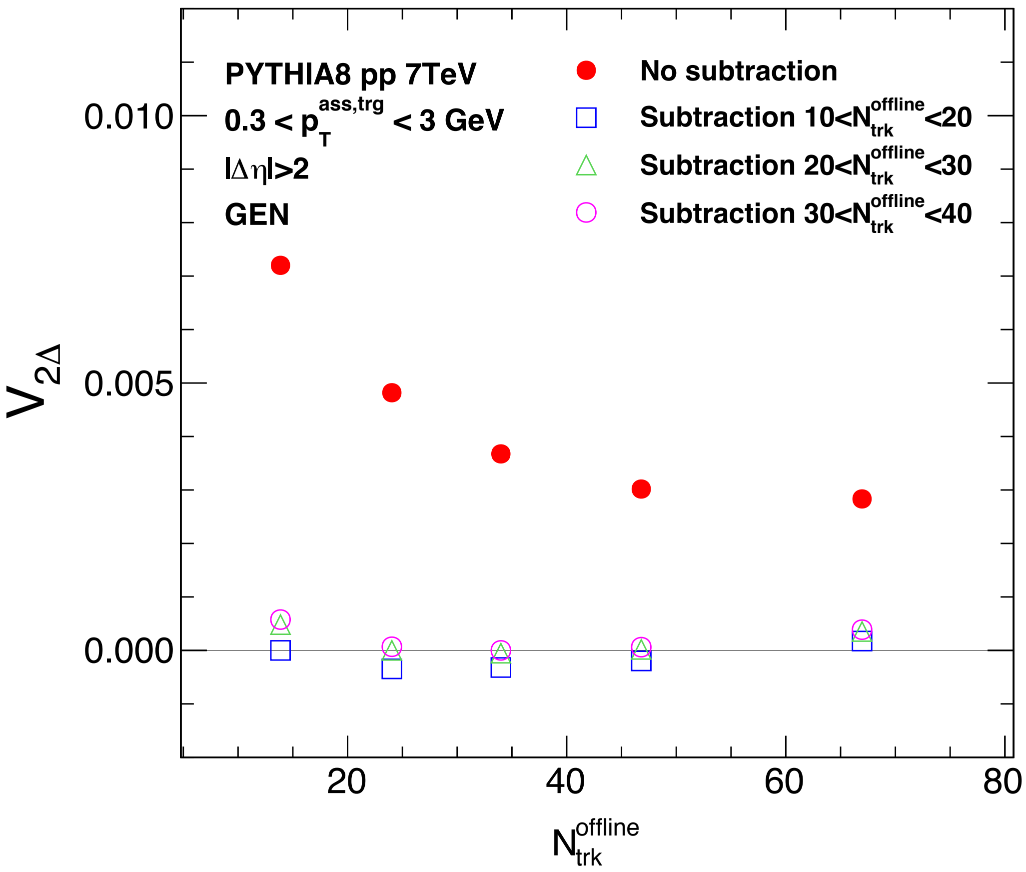




Validation of Subtraction in MC

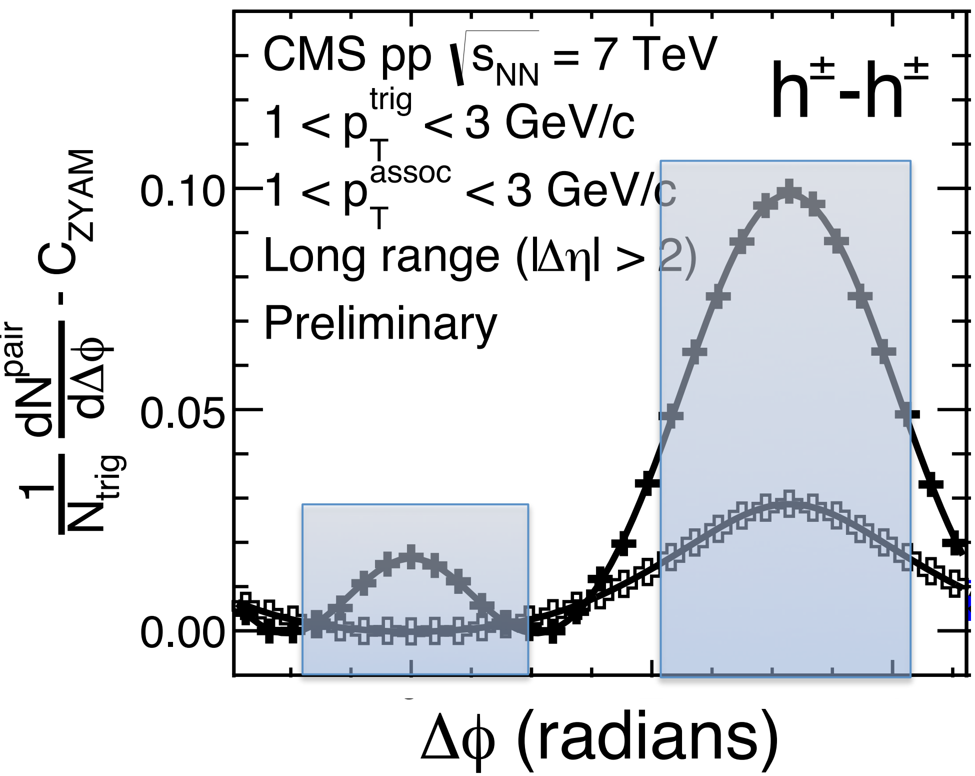


Validation of Subtraction in MC



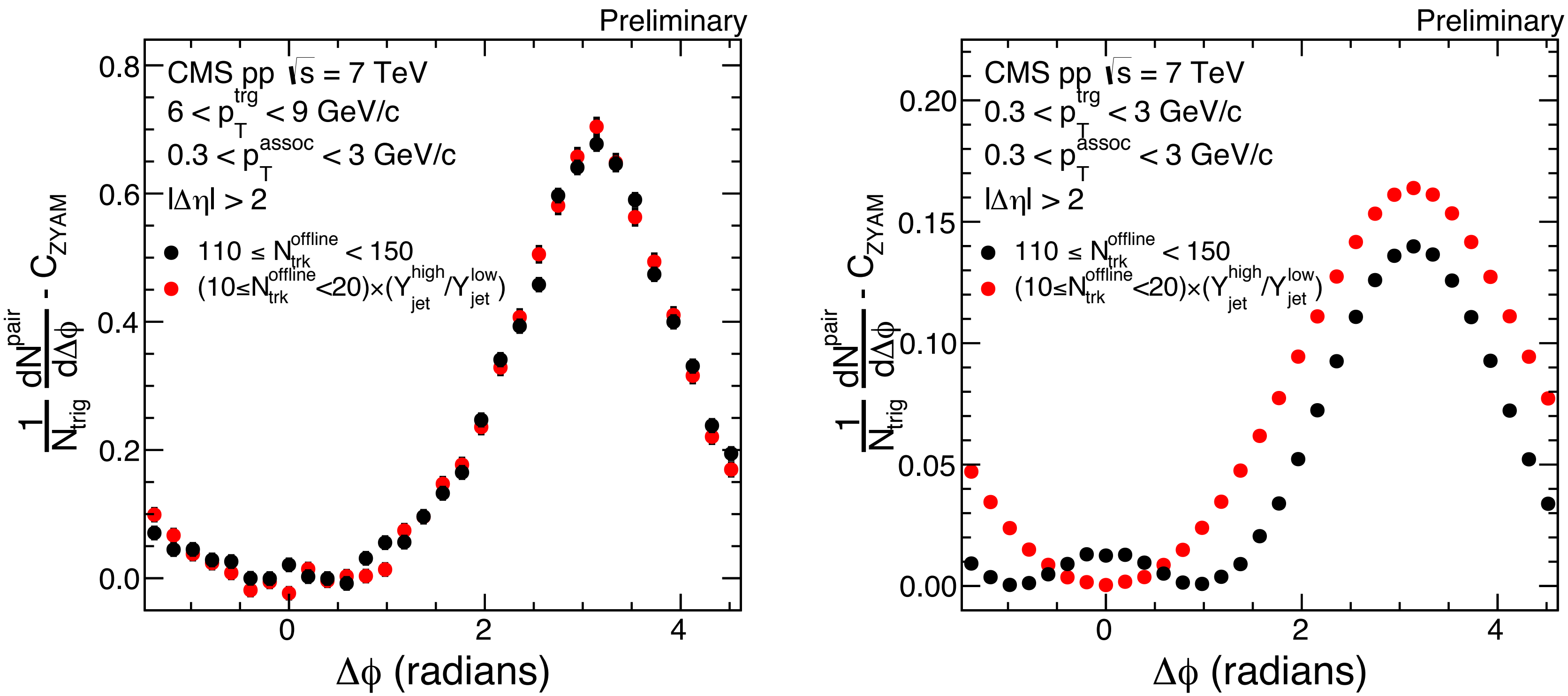
Potential de-correlation between near and away side jet contribution

- Jet yield used in subtraction estimated by long-rang ($|\Delta\eta|>2$) away side ($|\Delta\phi|>2\pi/3$) yield minus near side yield ($|\Delta\phi|<\pi/3$).

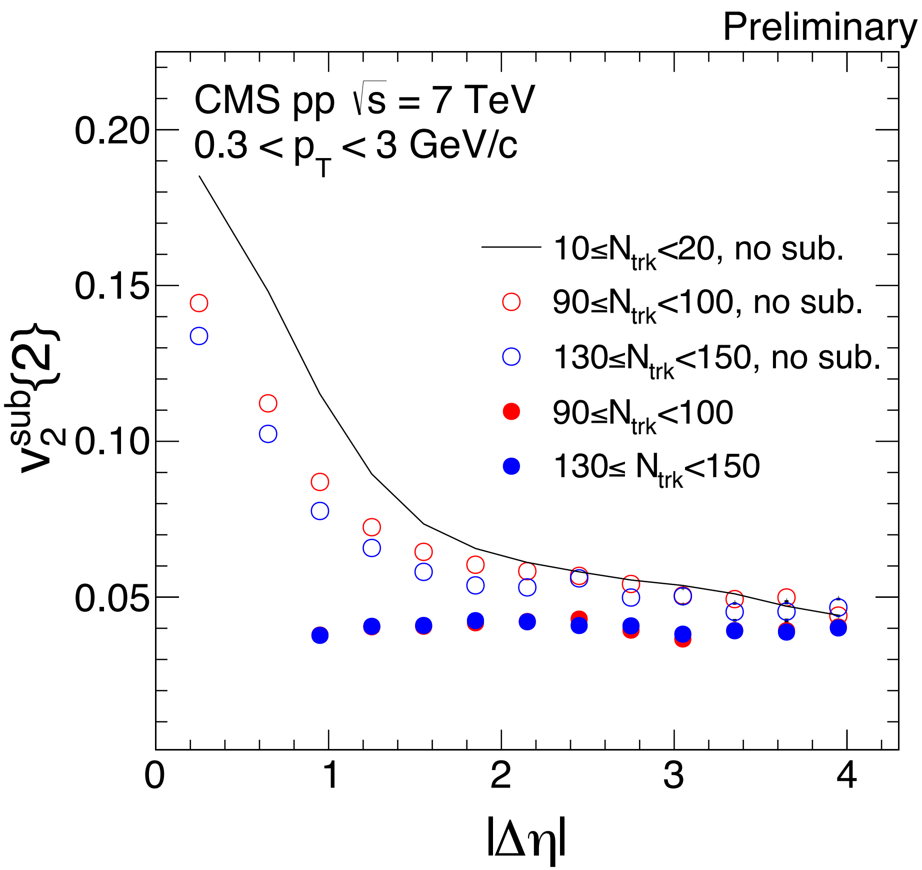


- Systematic uncertainty assigned

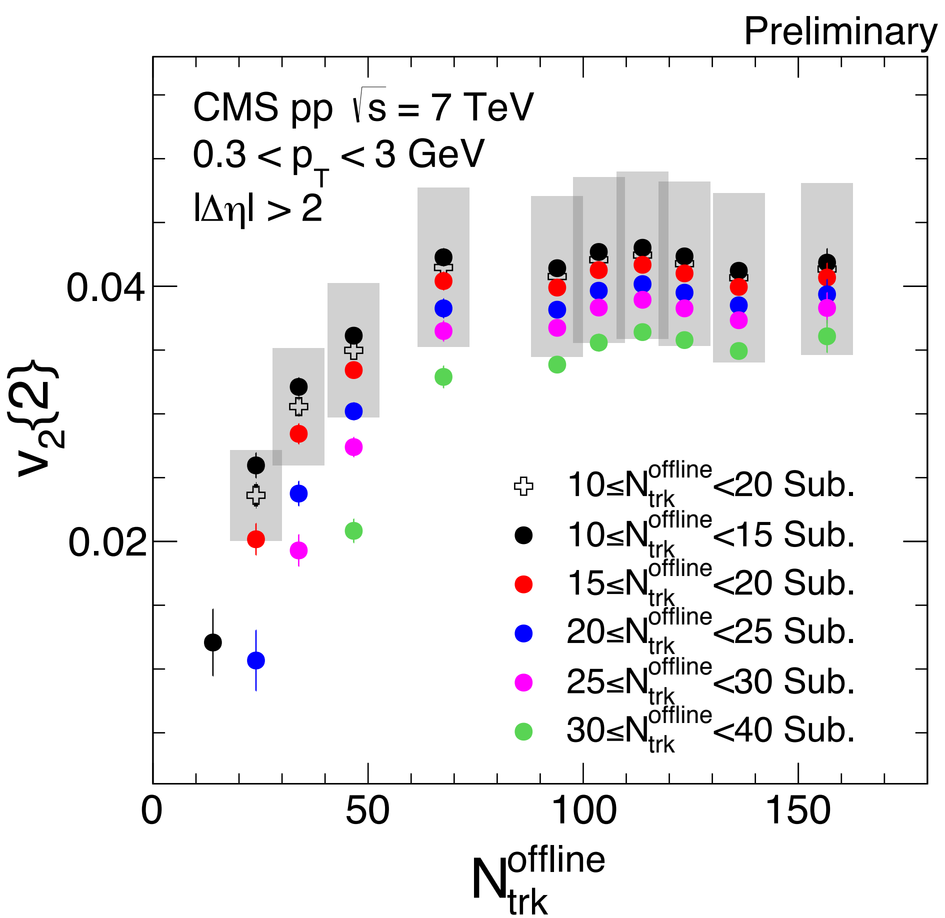
No bias on jet distribution in Δϕ



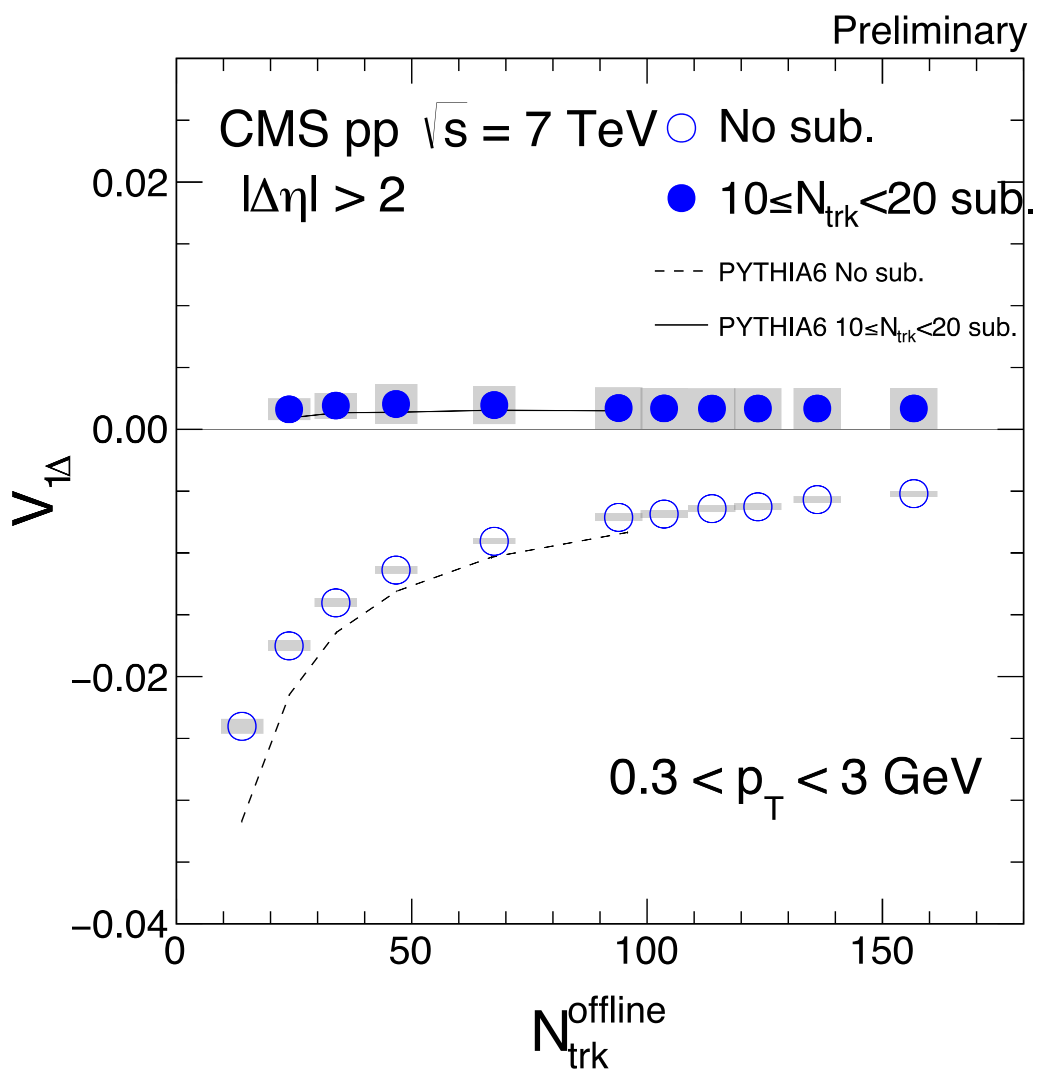
No bias on jet distribution in Δη



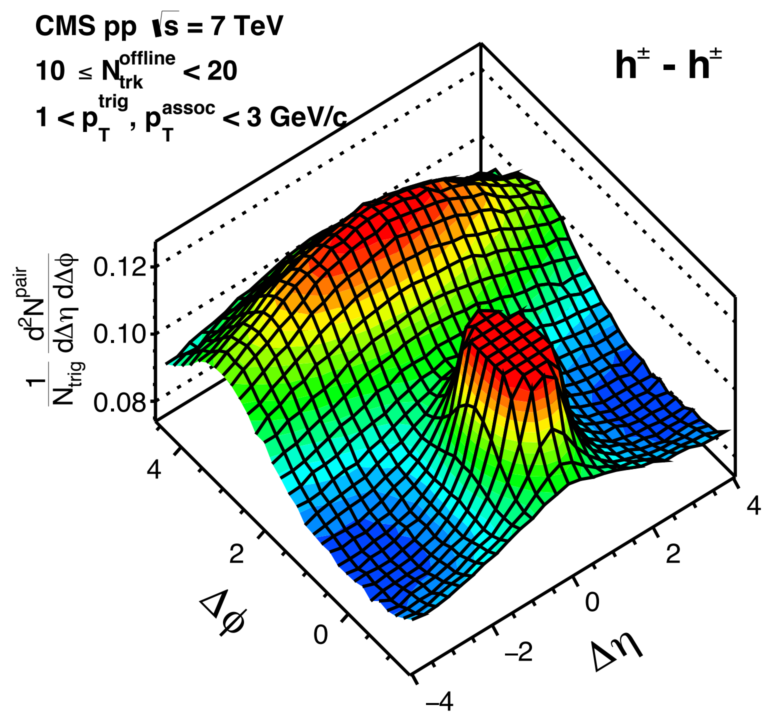
Test of Subtraction in data

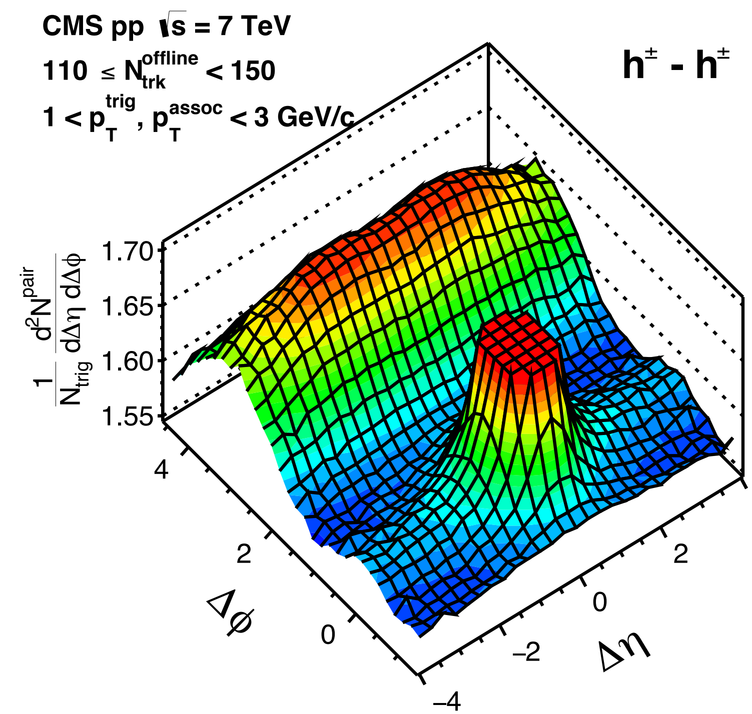


$V_{1\Delta}$ in data & MC



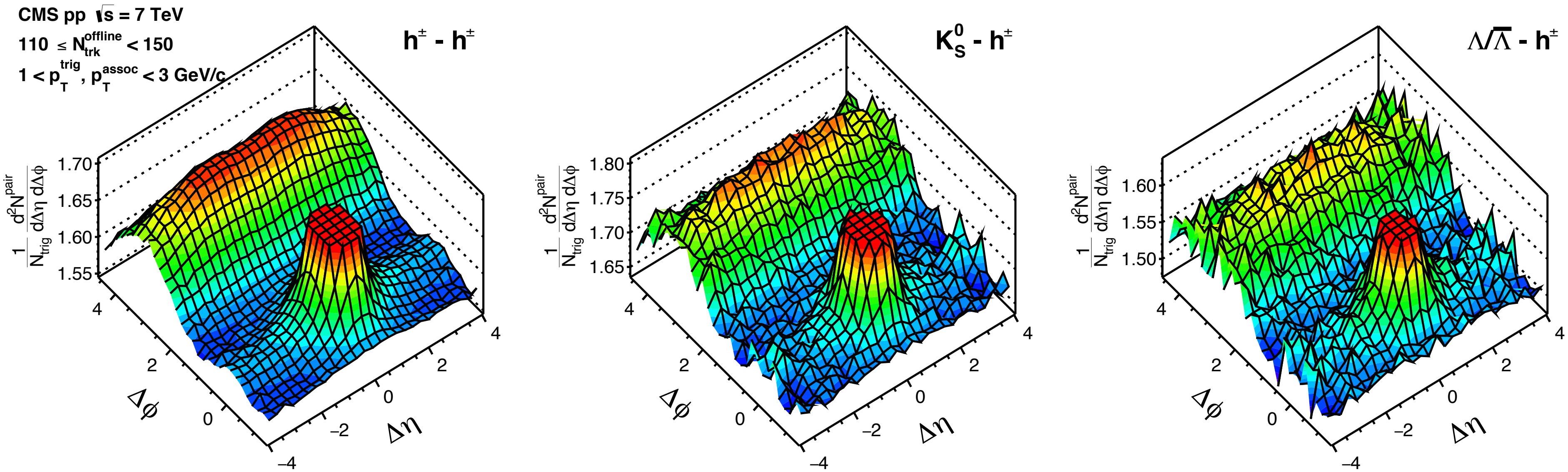
Two particle correlation function





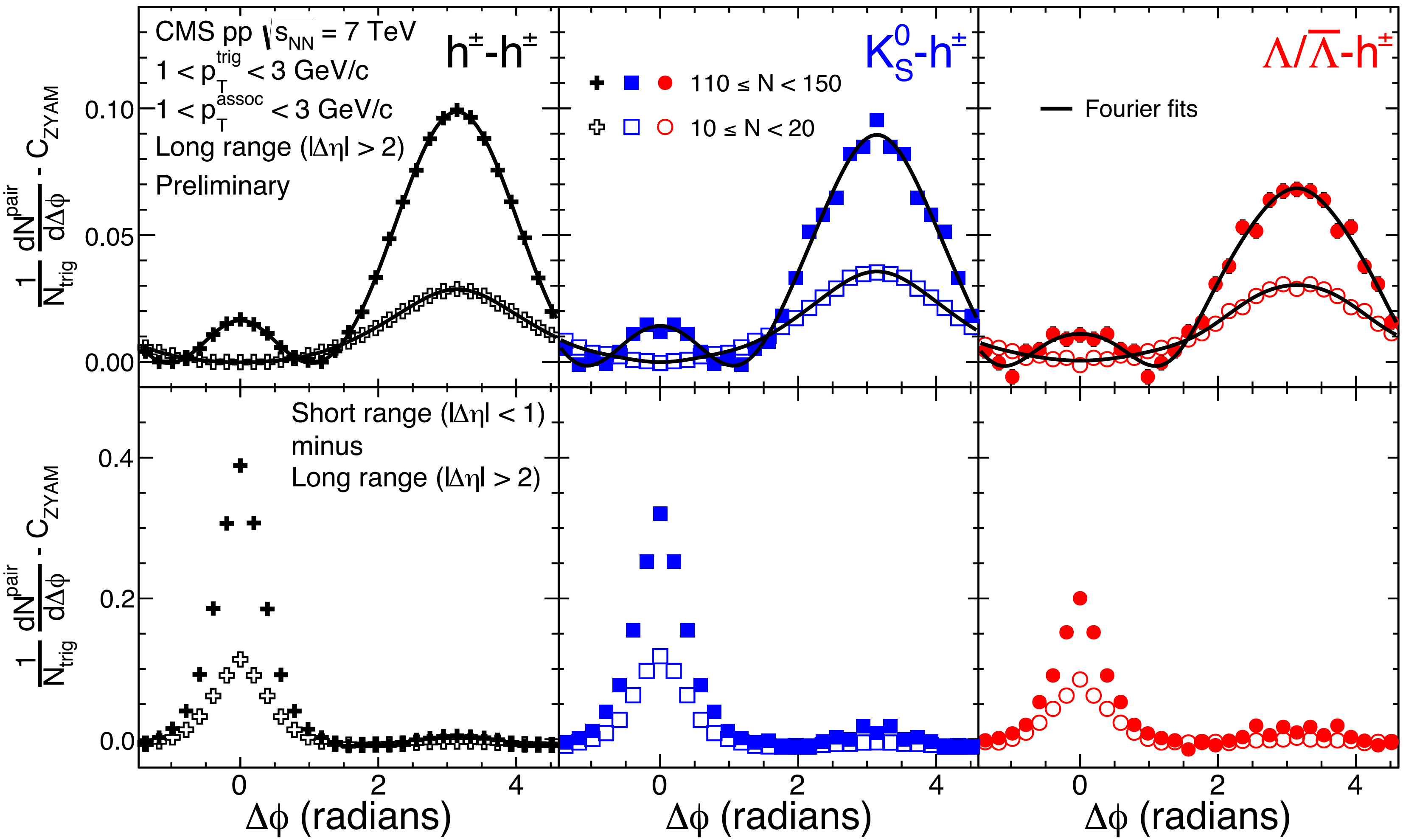
- Clear ridge at high multiplicity
- No ridge at low multiplicity

Two particle correlation function

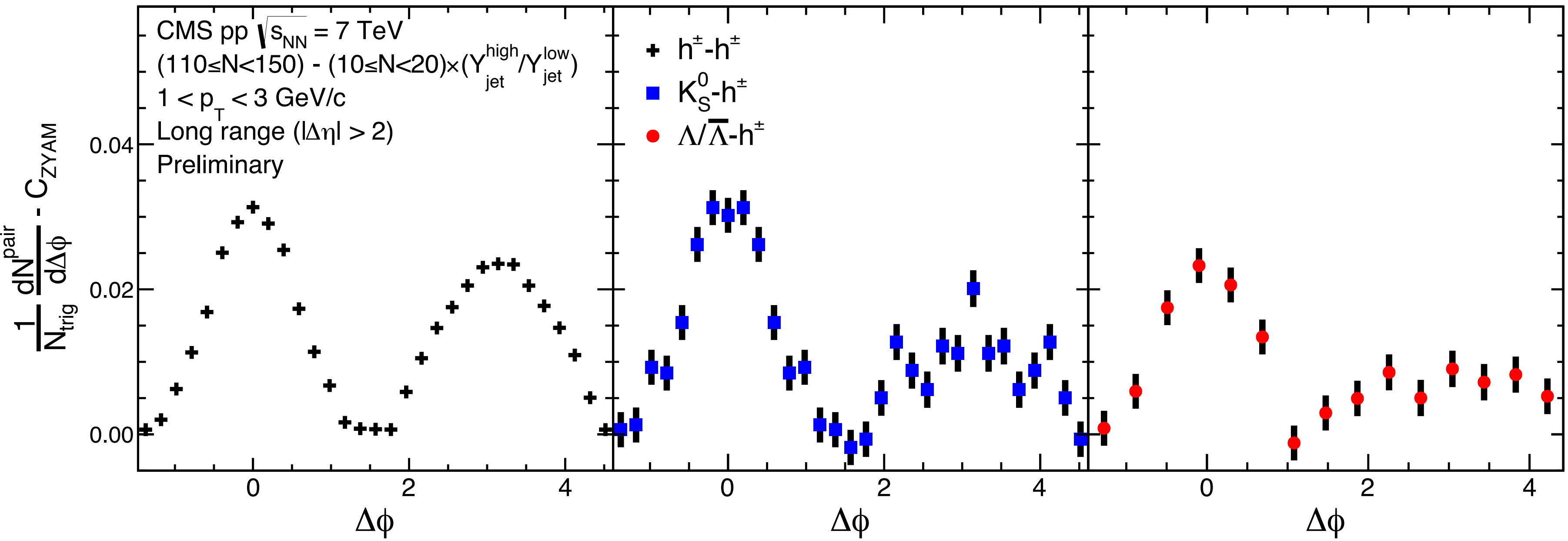


- Two particle correlation constructed for:
  - Charge hadron as both trigger and associated, $h^{\pm} - h^{\pm}$
  - K^0_S as trigger, charge hadron as associated, $K^0_S - h^{\pm}$
  - Λ as trigger, charge hadron as associated, $\Lambda - h^{\pm}$

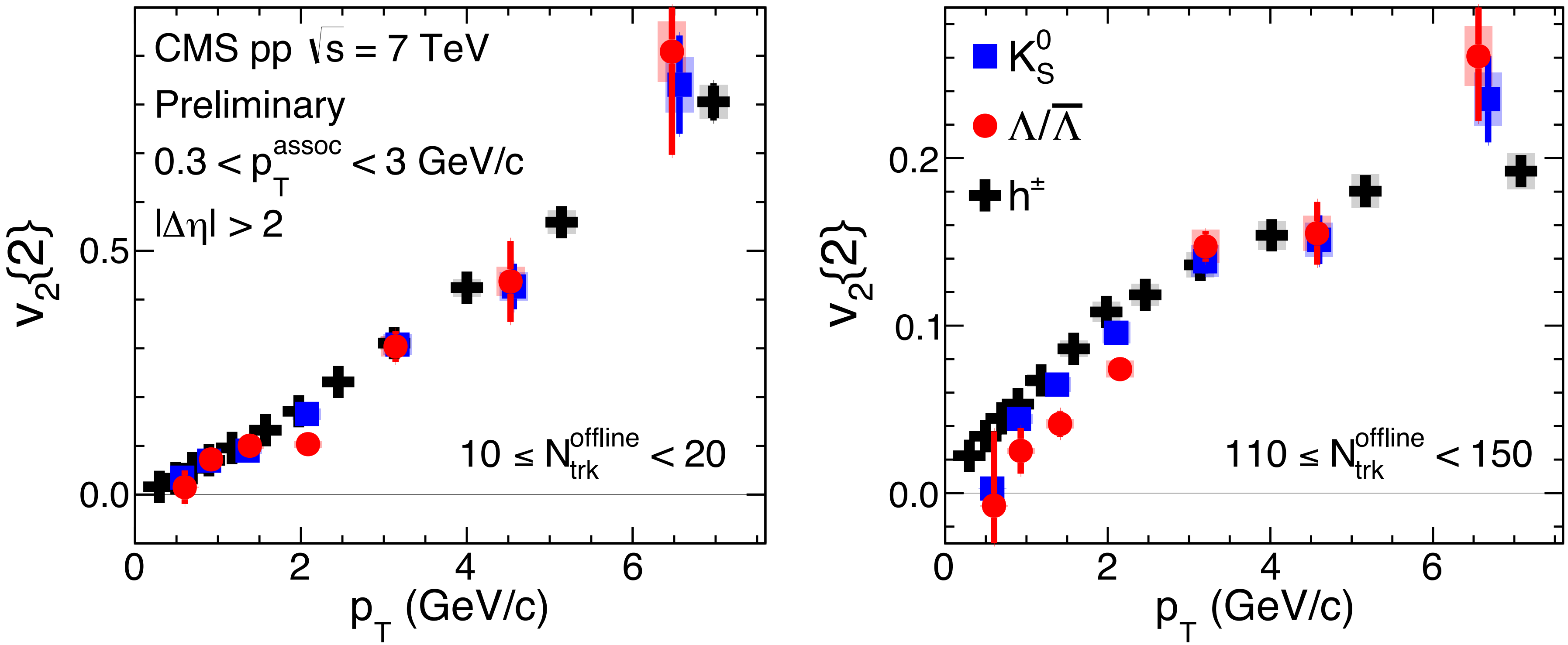
v_n extraction



Correction for jet contribution

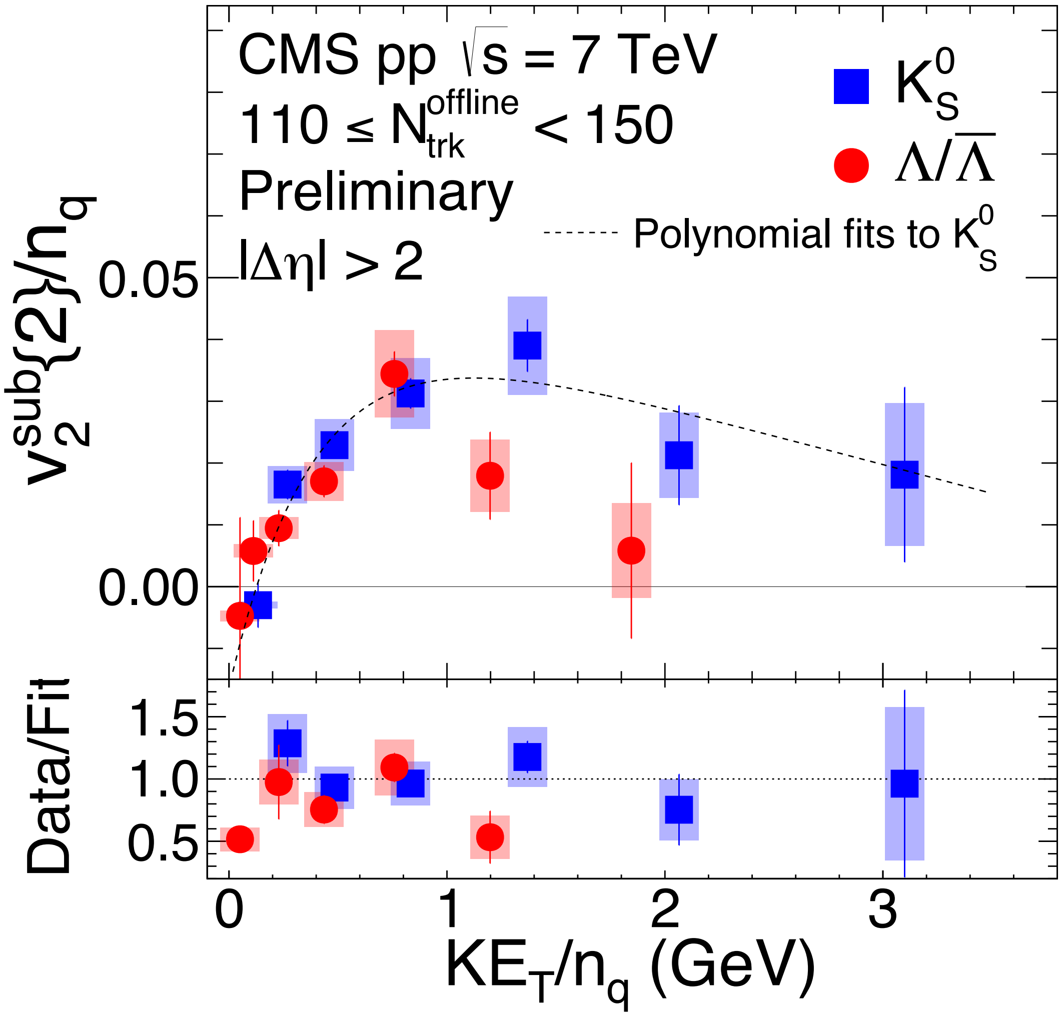


PID v_2 vs. p_T



- No mass dependence of v_2 from jet correlation at low multiplicity
- **Mass ordering** in low p_T region at high multiplicity

NCQ scaling in pp



Two particle correlation function after low multiplicity subtraction