

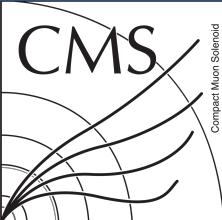
# Latest news on collectivity in high multiplicity p-p collisions at CMS

Maxime Guilbaud<sup>(1)</sup>

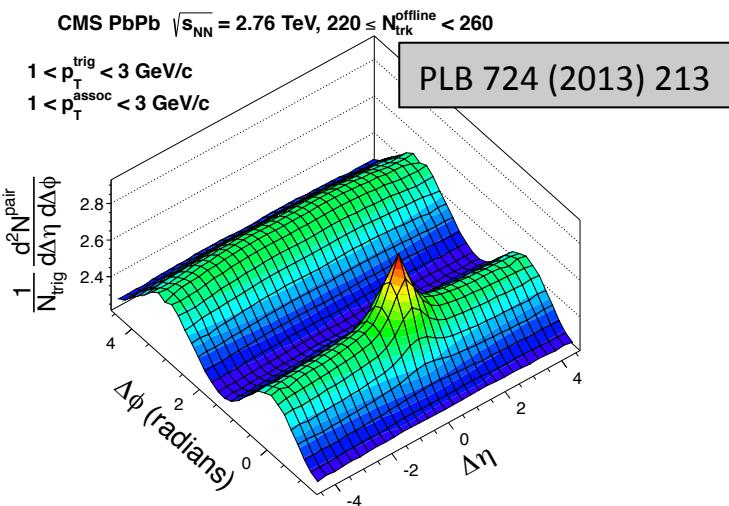
*On behalf of the CMS collaboration*

*(1) RICE University, Houston TX*





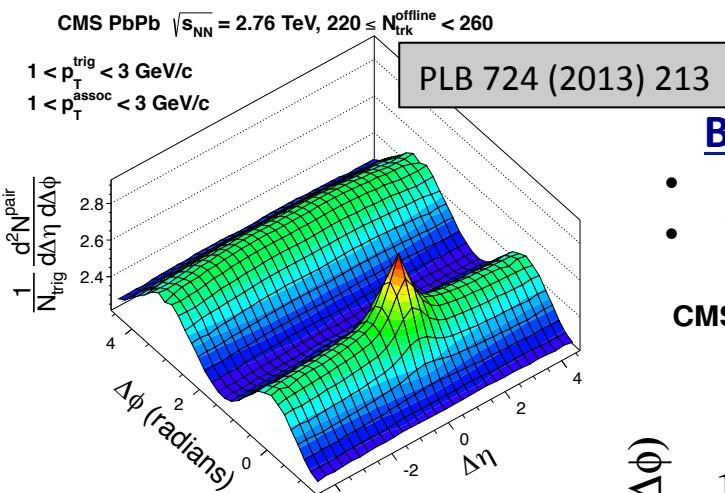
# A bit of history ...



## Double ridge in Pb-Pb:

- Perfect fluid property of QGP
- Geometry + fluctuation

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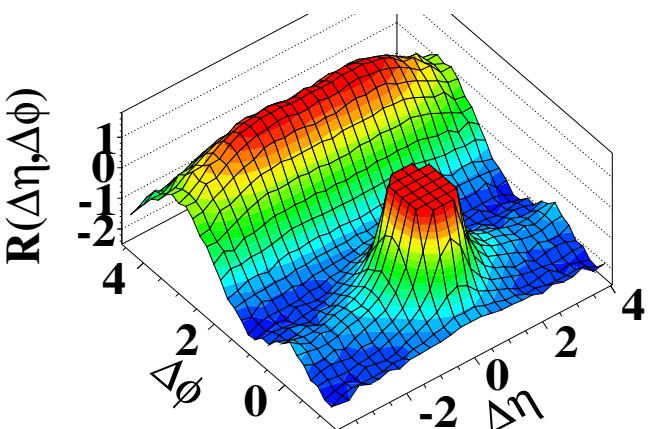
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## Breaking news in 2010 ...

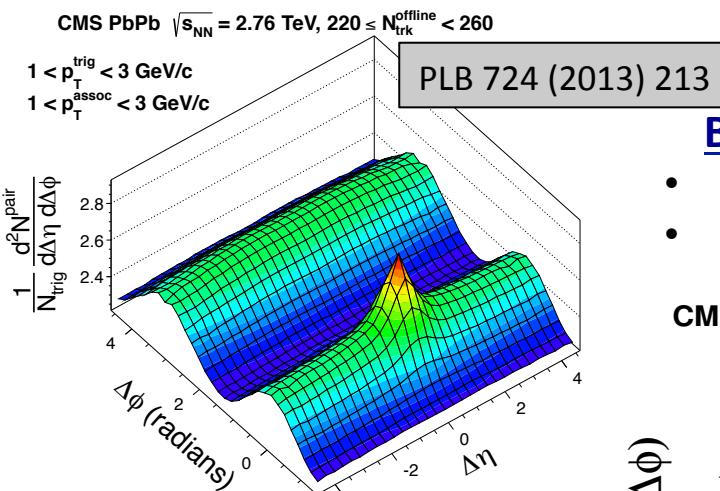
- Ridge visible in p-p data
- Where does it come from?

CMS  $N \geq 110$ ,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



J. High Energy Phys. 09 (2010) 091

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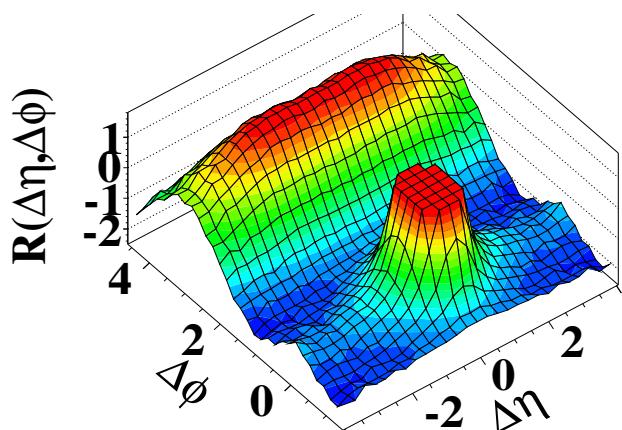
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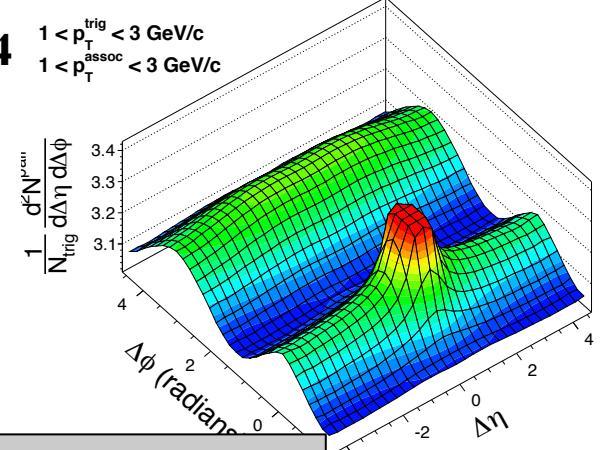


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## ... and also observed in p-Pb

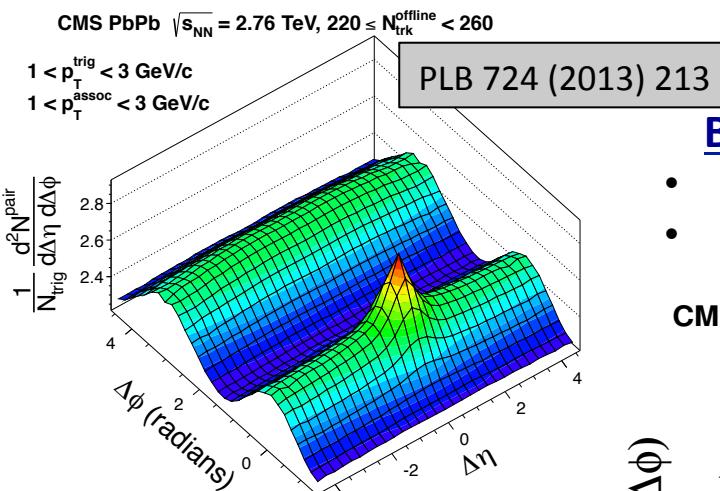
- QGP droplet? Something else?

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



PLB 724 (2013) 213

# A bit of history ...



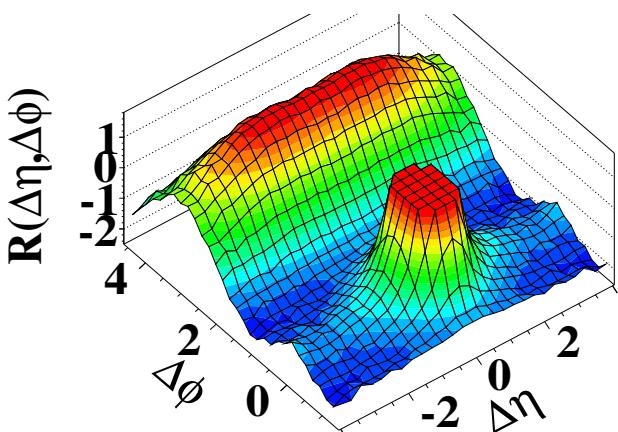
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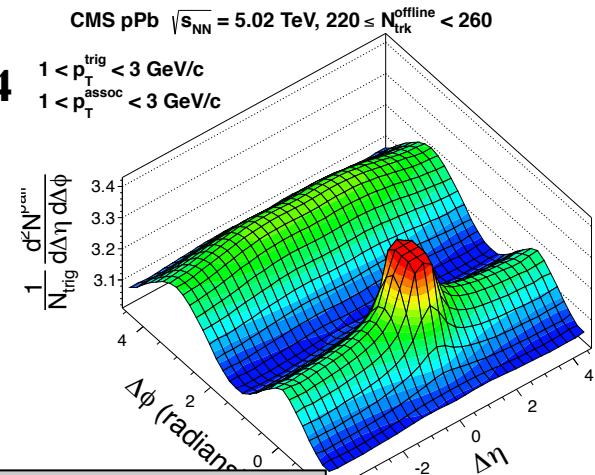
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PLB 724 (2013) 213

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

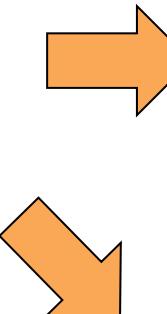
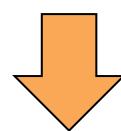
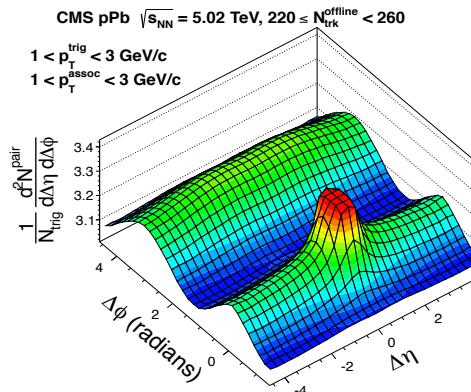
# Collectivity in small system: the p-Pb case



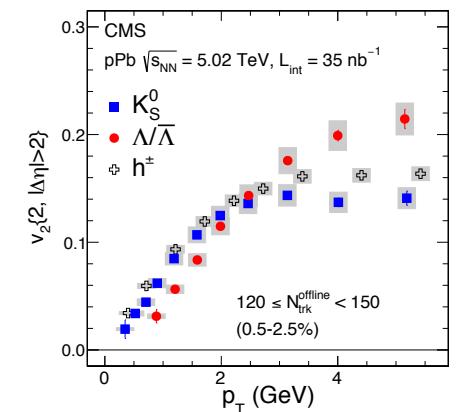
Extensive study on the Ridge nature was performed in p-Pb

❖ Similar feature to the Pb-Pb case were observed

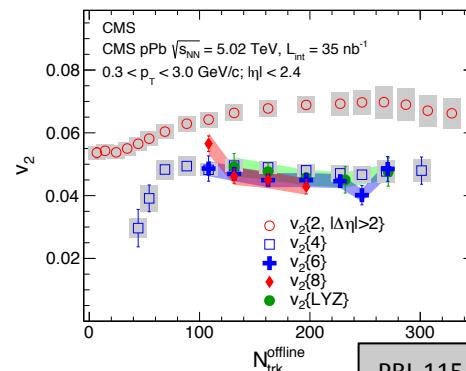
- Multi-particle cumulant analysis
- Measurement of higher Fourier harmonics
- $v_n$  of identified particle



PLB 742 (2015) 200 Mass ordering

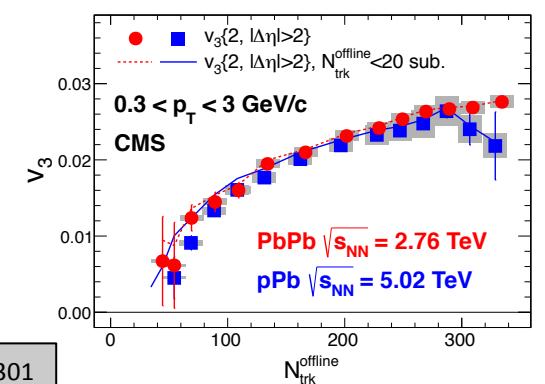


$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$



PRL 115 (2015) 012301

PLB 724 (2013) 213  $v_3$  Similar to Pb-Pb



# Collectivity in small system: the p-Pb case



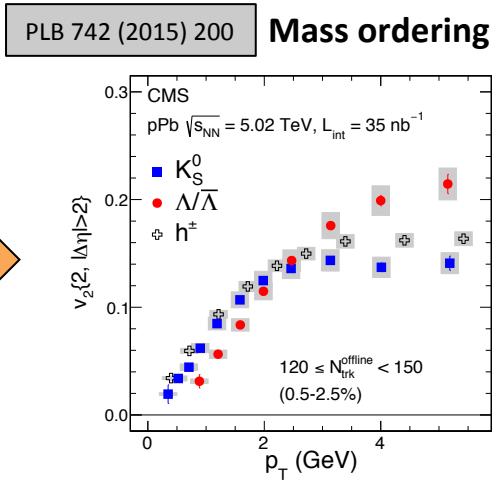
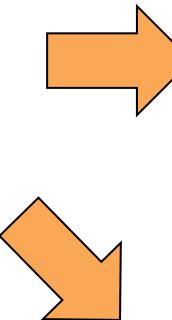
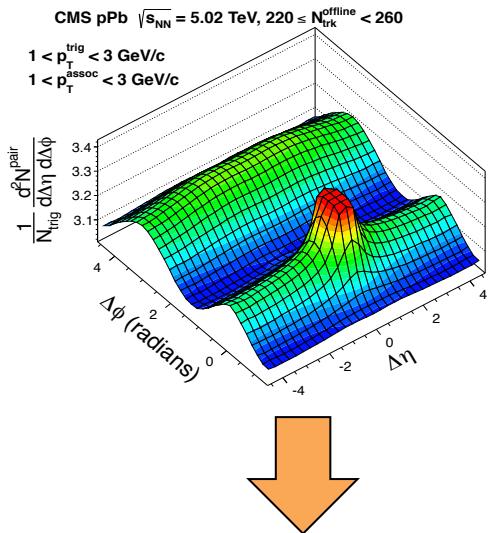
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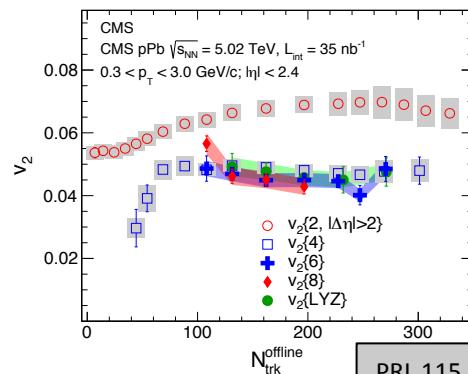
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❖ What do we learn?

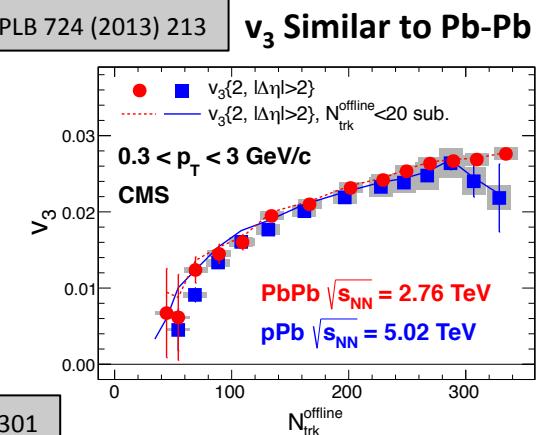
- Collective effect
- Fluctuation driven
- Clear mass ordering for  $V^0$

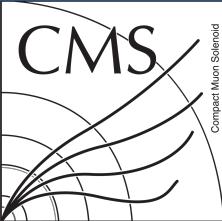


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PRL 115 (2015) 012301





# What are the possible explanations?

**As it is a collective effect, the interpretation is restricted to mainly two different pictures**

- ❖ Initial state interactions (CGC, ...)
- ❖ Initial state fluctuations + final state interactions (hydrodynamic, ...)

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Fluctuations in the initial state is probably what matter the most in small systems

- ❖ Initial state fluctuations has to be very well understood
- ❖ Main incertitude comes from the proton fluctuations

**p-Pb and of course p-p collisions can help to constrain these fluctuations**

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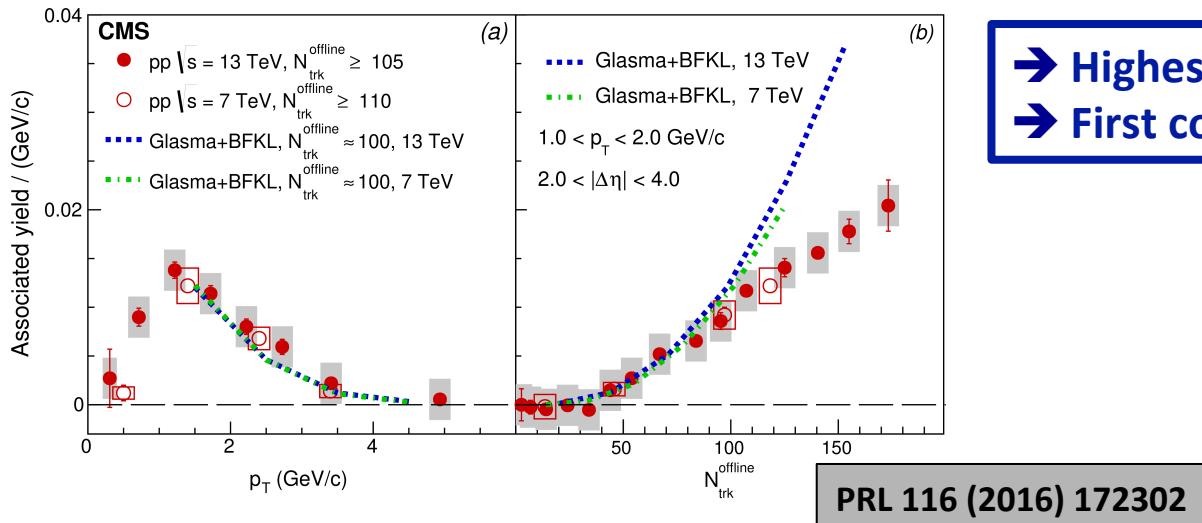
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**What about the Ridge in p-p collisions? What is new?**

# Status of p-p ridge studies

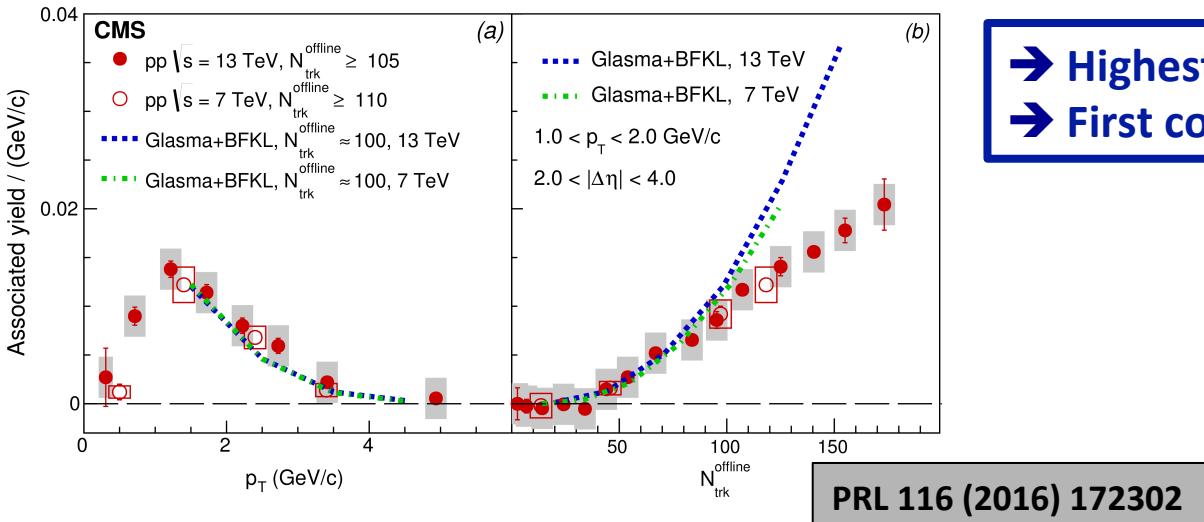
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→ Highest multiplicity reached so far  
 → First comparison with model (CGC)

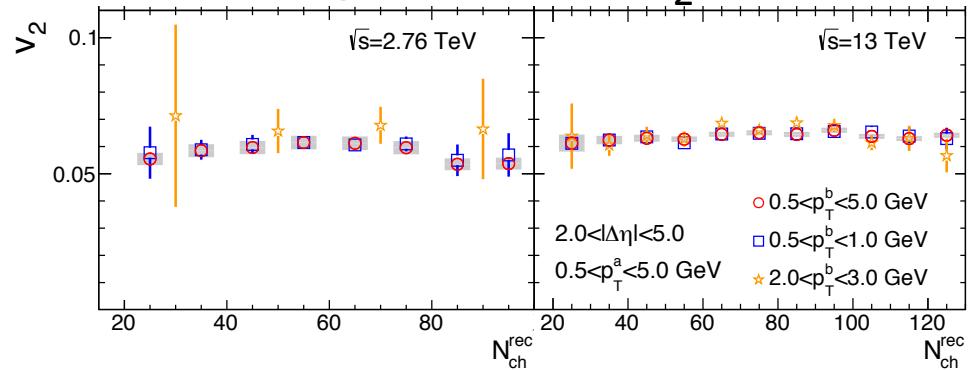
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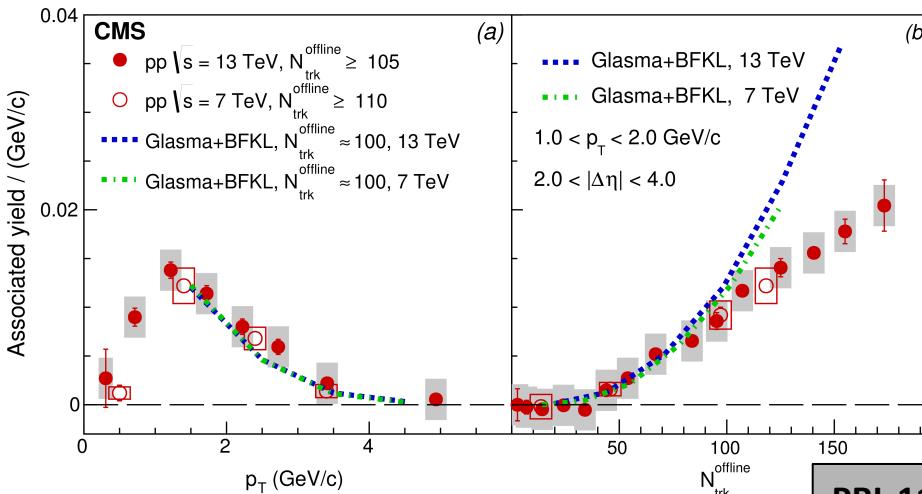


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**PRL 116 (2016) 172301**

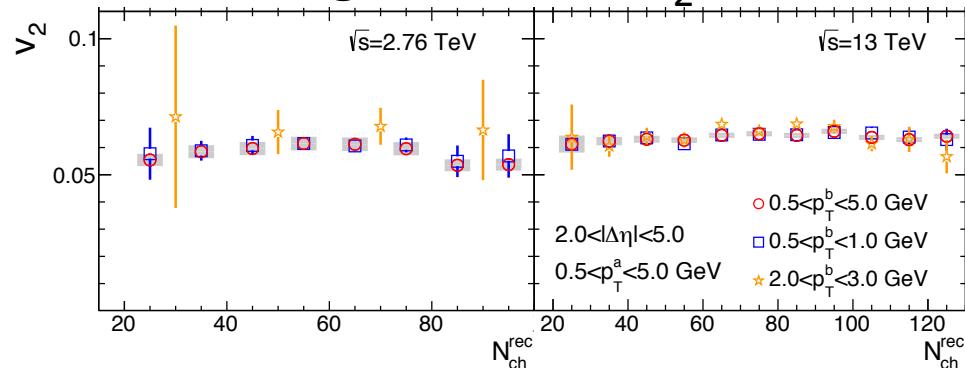
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Origin of the ridge?  
 → Detailed study of  $v_2$  and higher harmonics needed

# What are we trying to address?

- 1) Does the ridge arise from a collective behavior in p-p?
- 2) Mass ordering for identified particles as in p-Pb and Pb-Pb?
- 3) Can we understand better fluctuations in the IS in p-p collisions?

# Long range dihadron correlations: technique

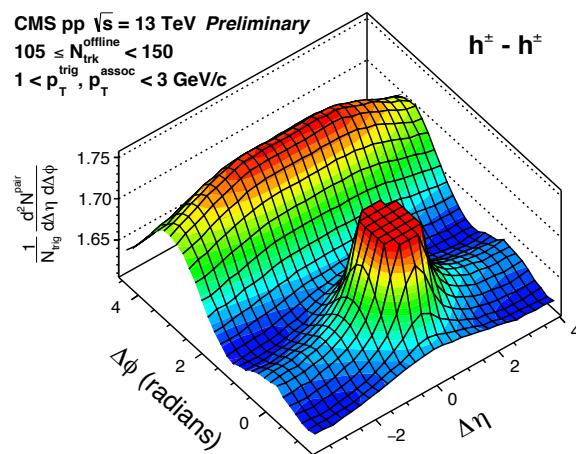


- ❖  $V_{n\Delta}$  coefficients extracted using a Fourier fit

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

- ❖ Single  $v_n$  coefficients are computed with:

$$v_n(p_T^{\text{trg}}) = \frac{V_{n\Delta}(p_T^{\text{trg}}, p_T^{\text{ref}})}{\sqrt{V_{n\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}}, \quad n = 2, 3.$$



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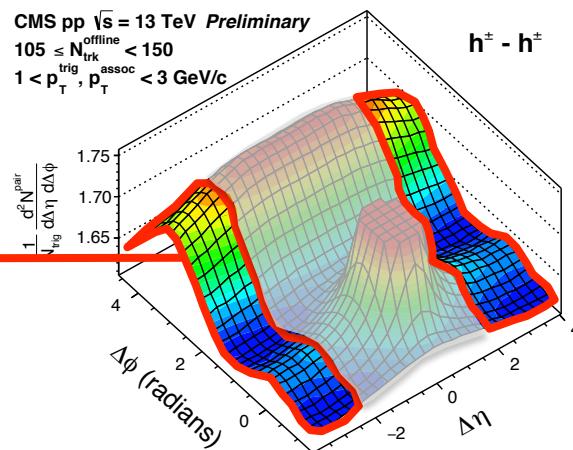
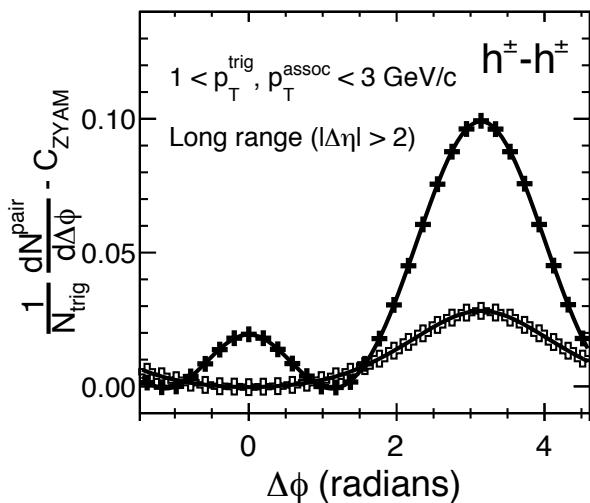


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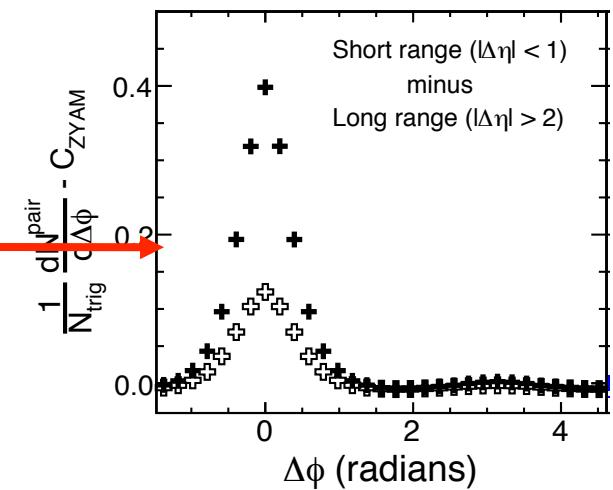
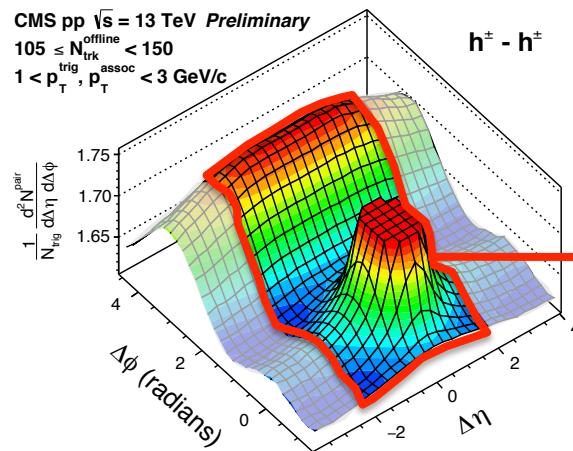
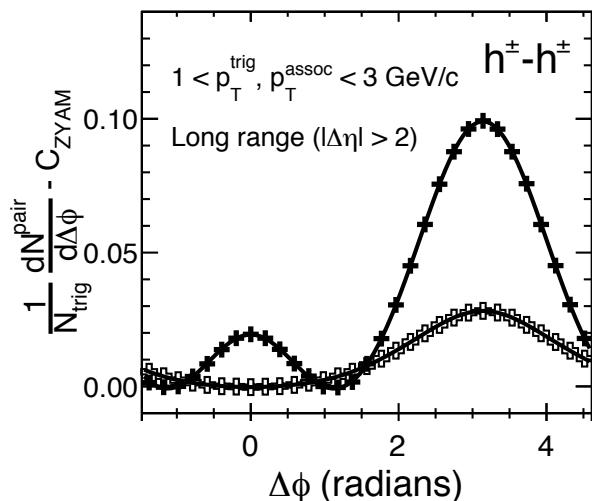
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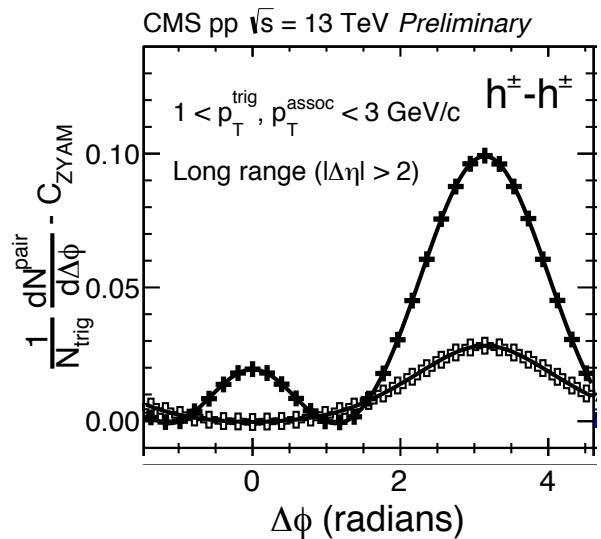
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# Long range dihadron correlations: low multiplicity subtraction



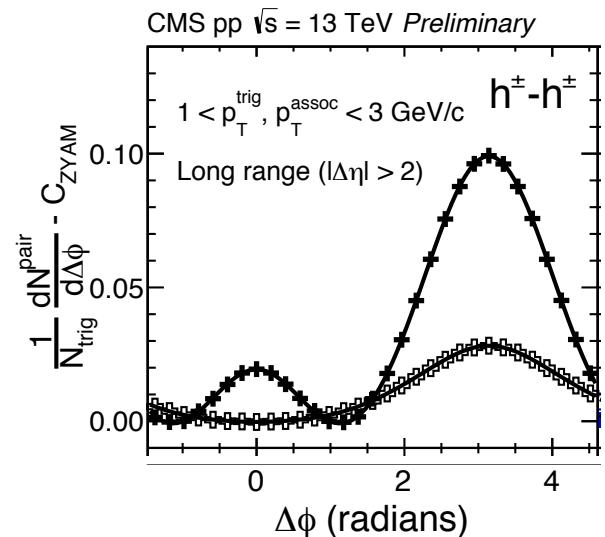
- ❖ Low multiplicity subtraction is applied on  $V_{n\Delta}$ 
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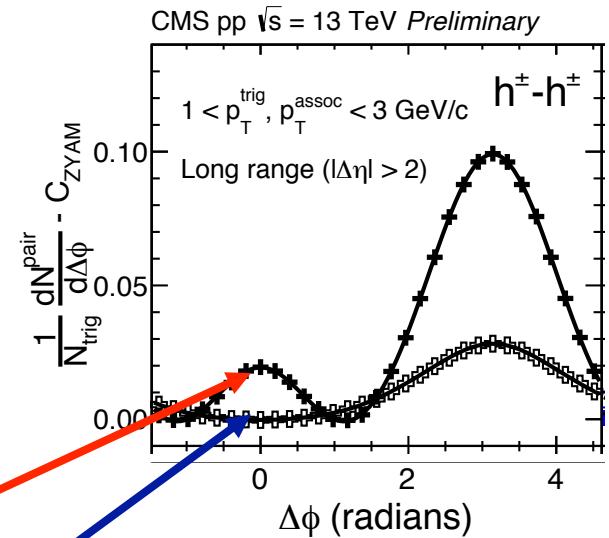
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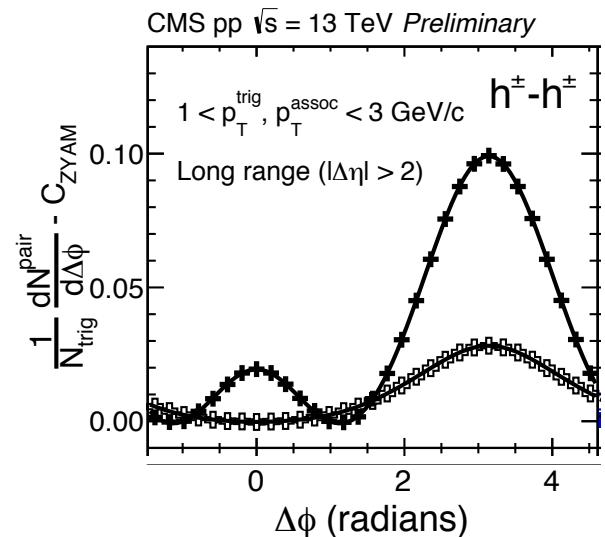


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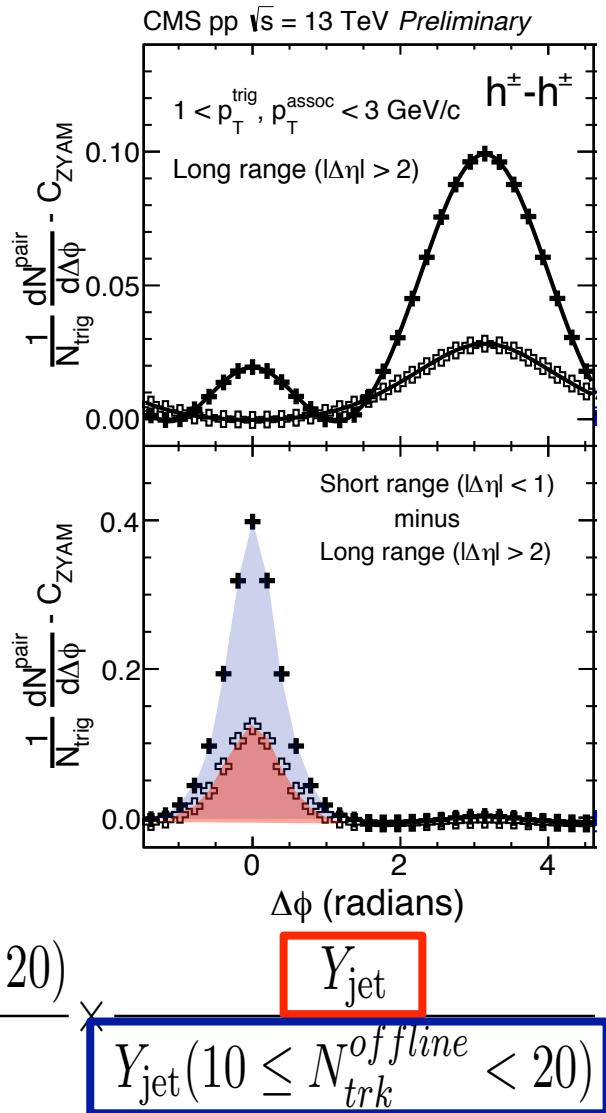


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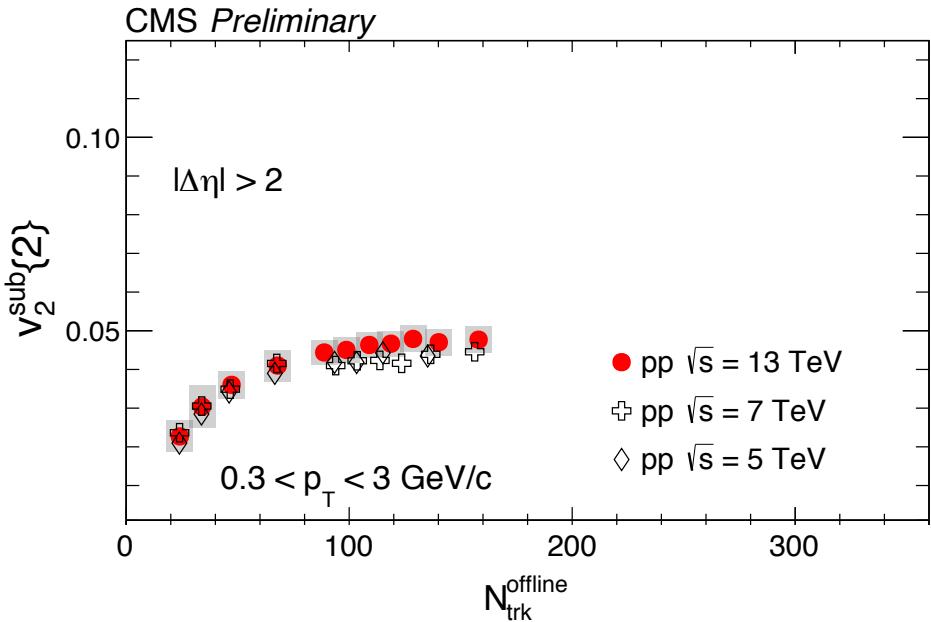


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# Long range dihadron correlations: $v_2$ & $v_3$ vs. multiplicity



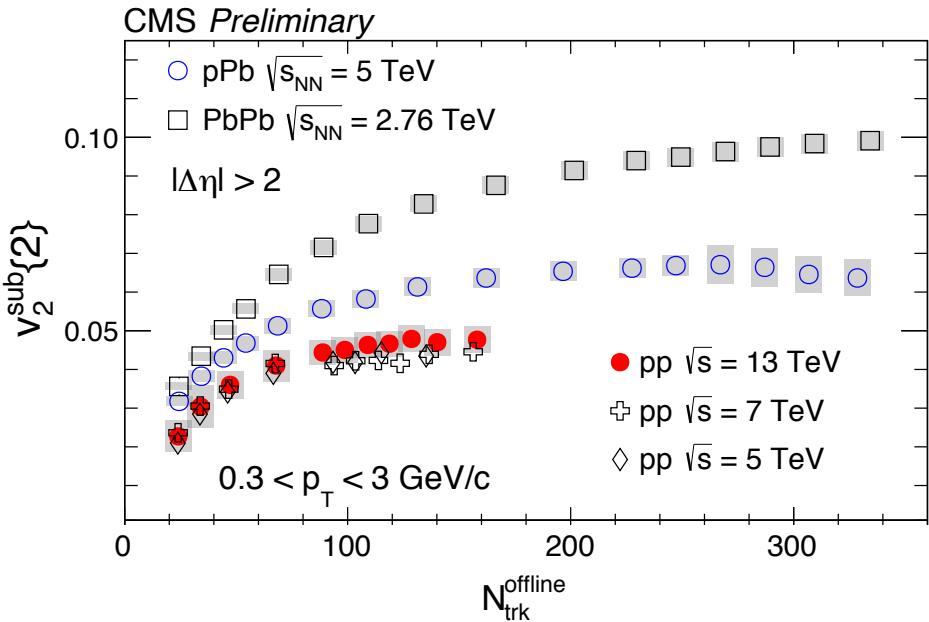
- ❖ Low multiplicity subtraction applied
- ❖  $v_2$ :
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# Long range dihadron correlations: $v_2$ & $v_3$ vs. multiplicity



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



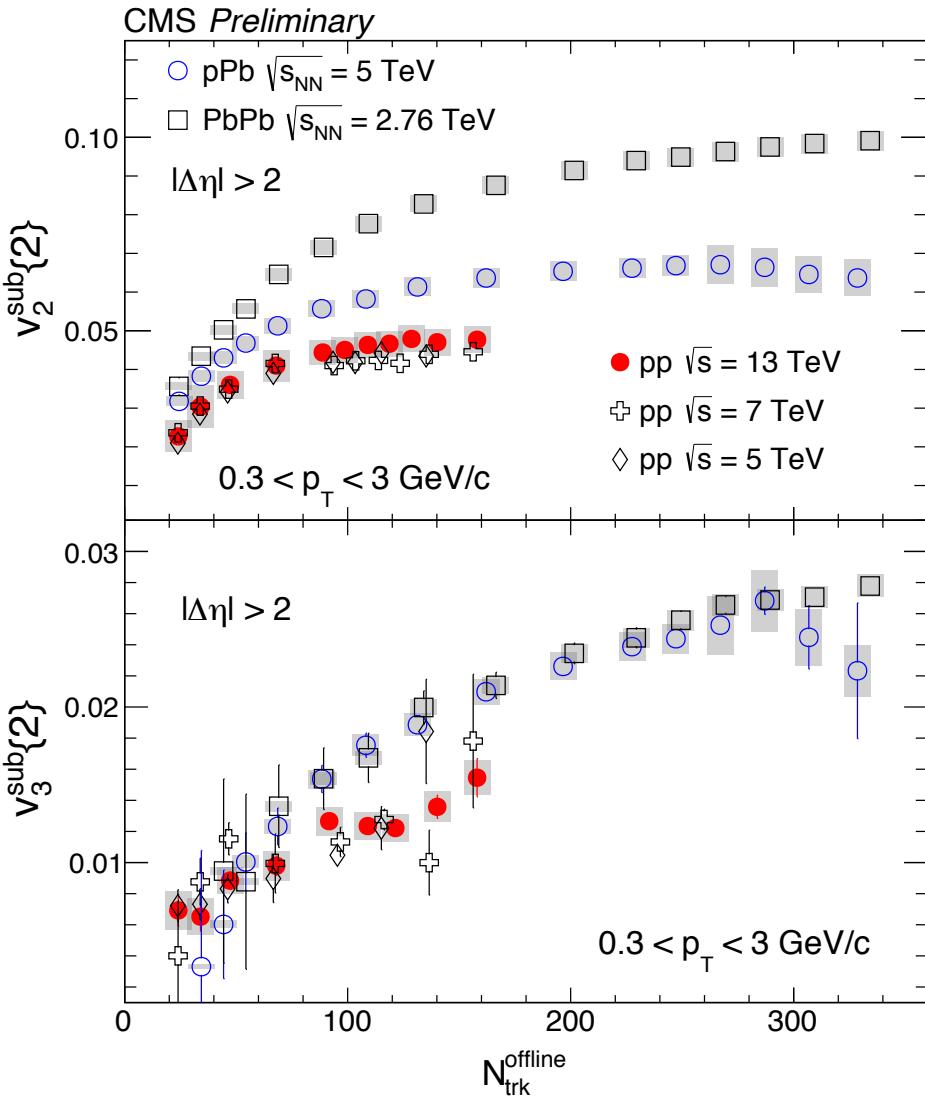
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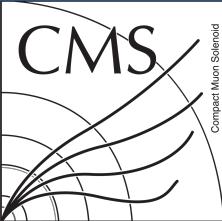


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**Similar effect involved with different magnitude?**
- ❖  $v_3$ :
  - No energy dependence observed
  - Different from p-Pb and Pb-Pb

**Difference in initial state fluctuations?**

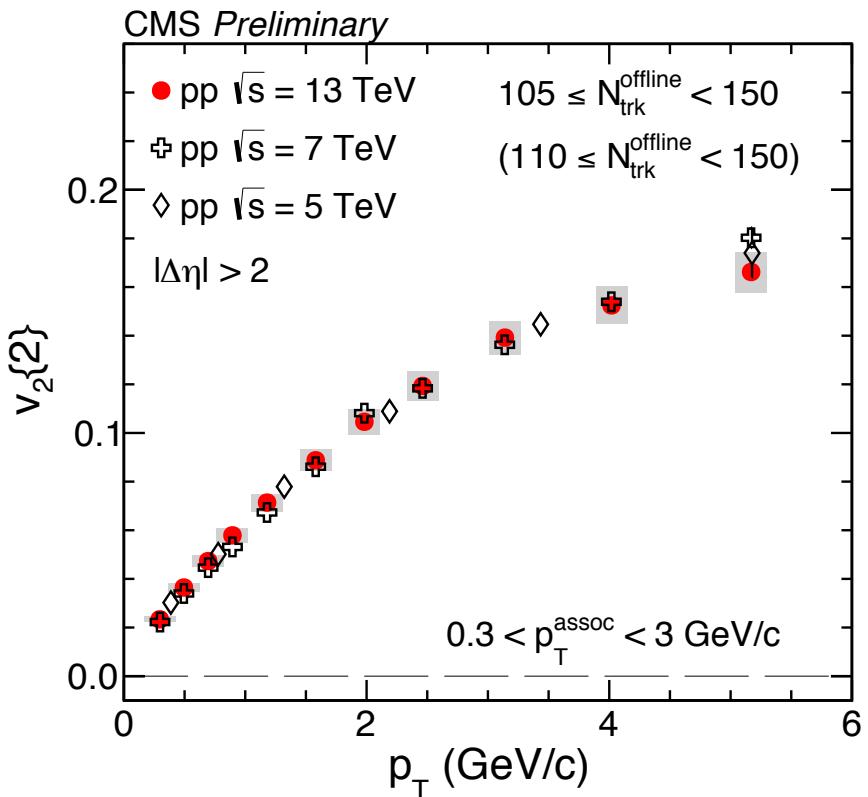




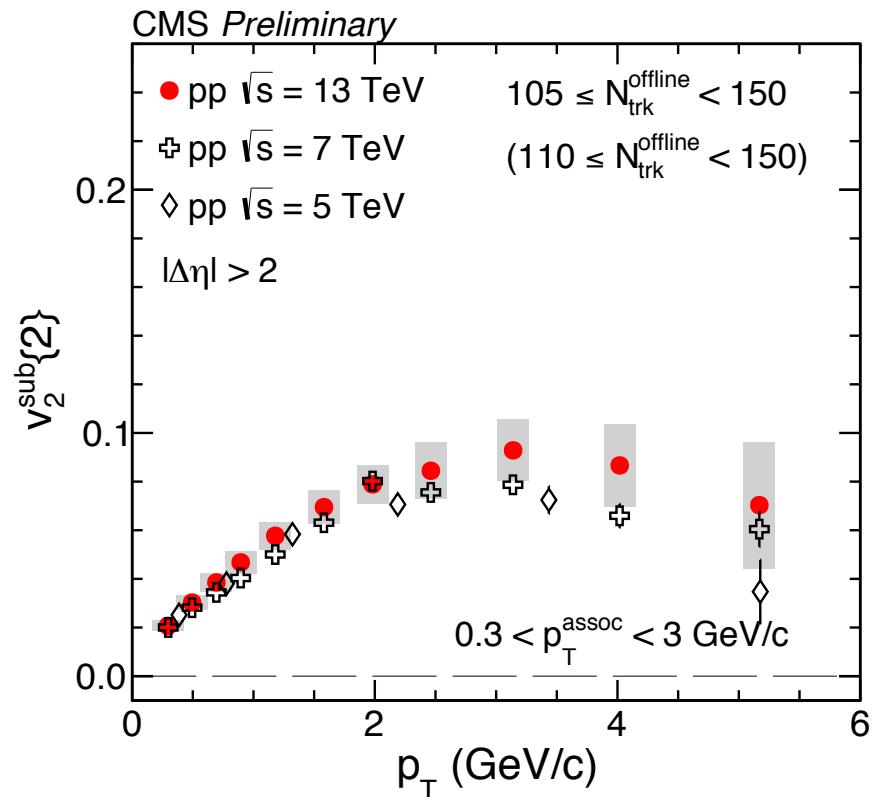
# Long range dihadron correlations: $v_2$ & $v_3$ vs. $p_T$



## Before low multiplicity subtraction



## After low multiplicity subtraction



No energy dependence observed within systematics before or after peripheral subtraction

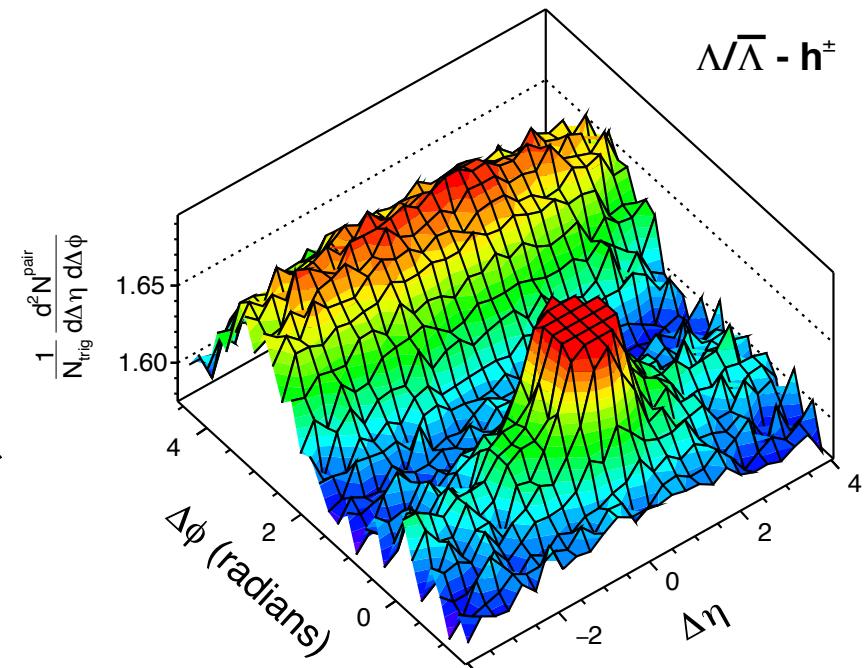
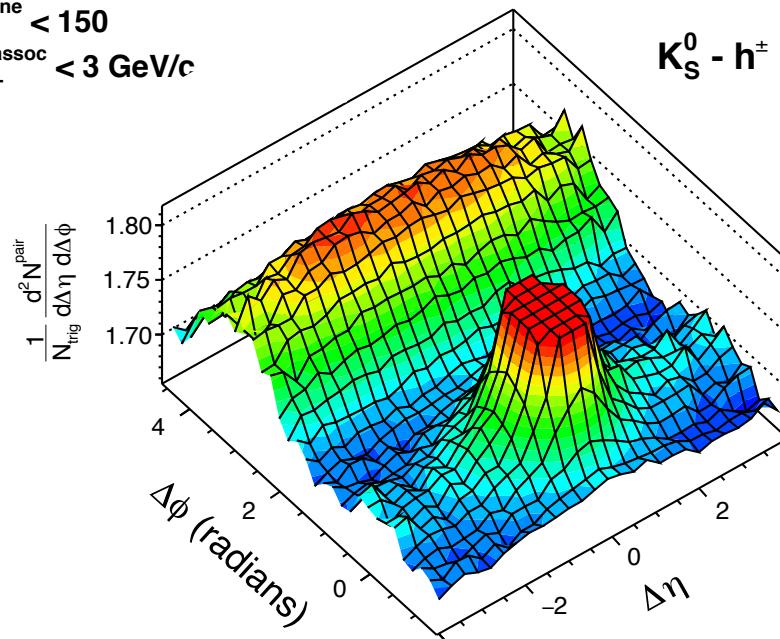
# Identified particles ( $V^0$ ) long range correlations: double ridge



- ❖ Ridge structure also observed for  $V^0$

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

$105 \leq N_{\text{trk}}^{\text{offline}} < 150$   
 $1 < p_T^{\text{trig}}, p_T^{\text{assoc}} < 3 \text{ GeV}/c$



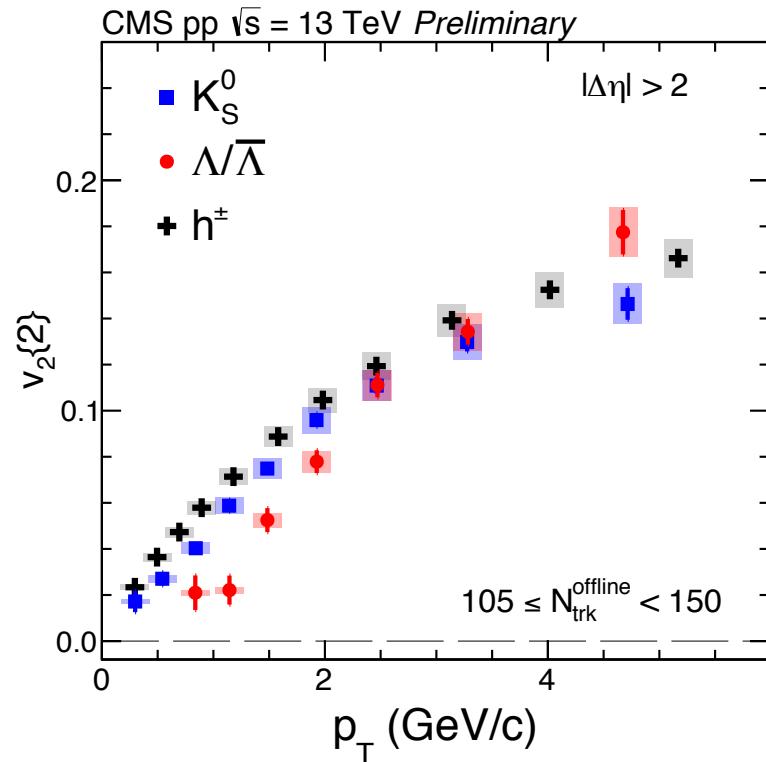
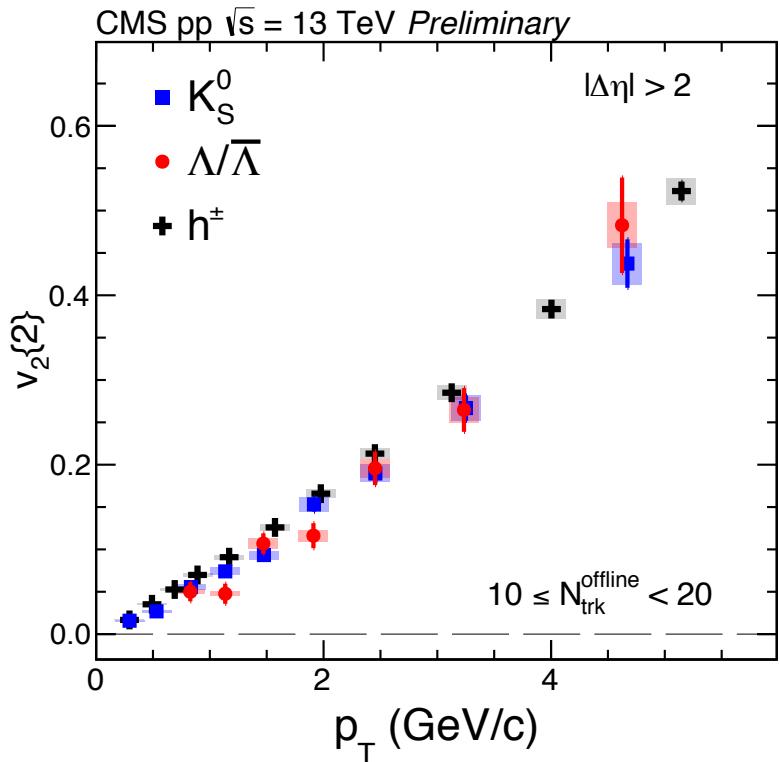
Does  $K^0$  and  $\Lambda$  shows a mass ordering in p-p collisions?

# 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

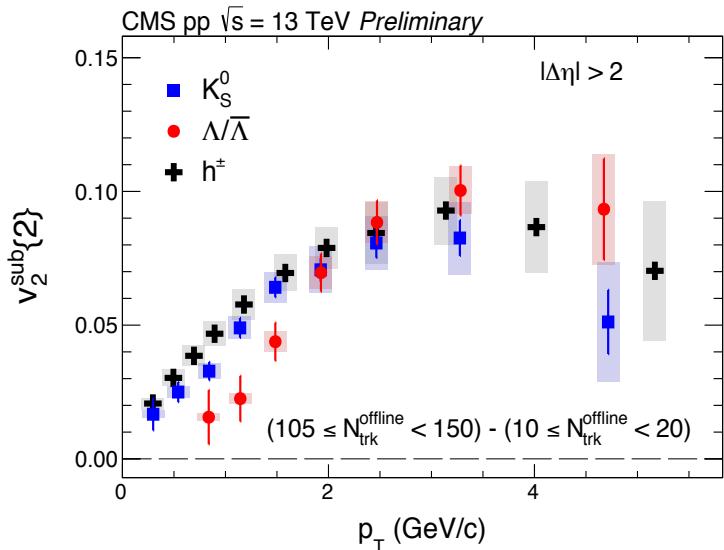


**Similar pattern to what is observed in p-Pb and Pb-Pb? Similar origine?**

# Identified particles ( $V^0$ ) long range correlations: mass splitting



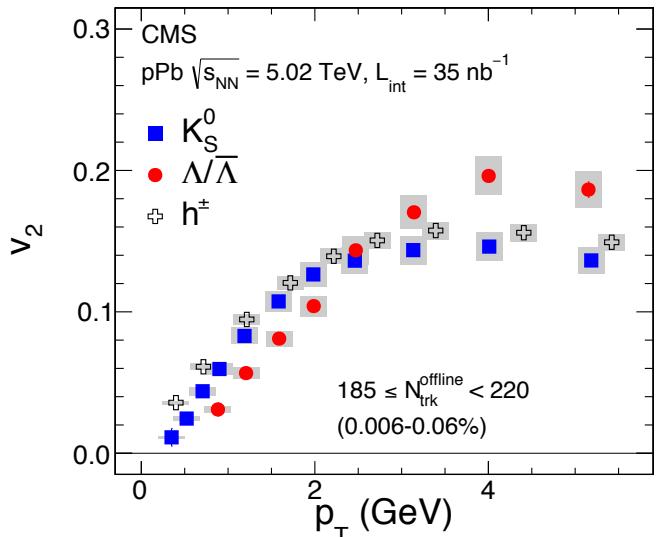
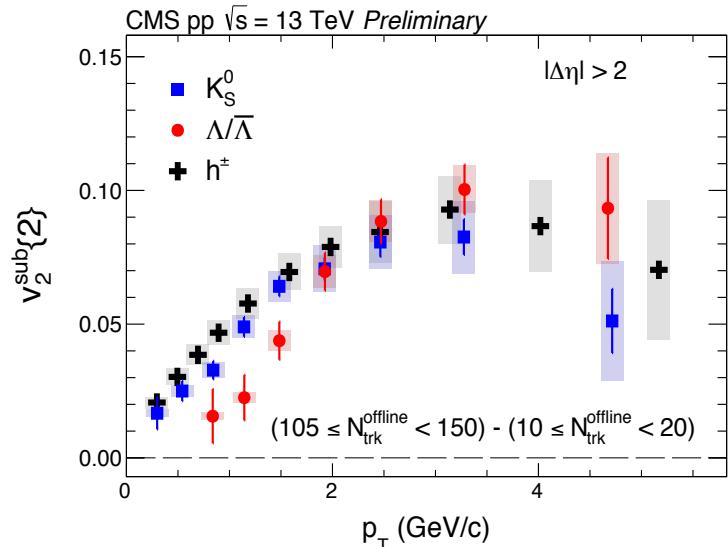
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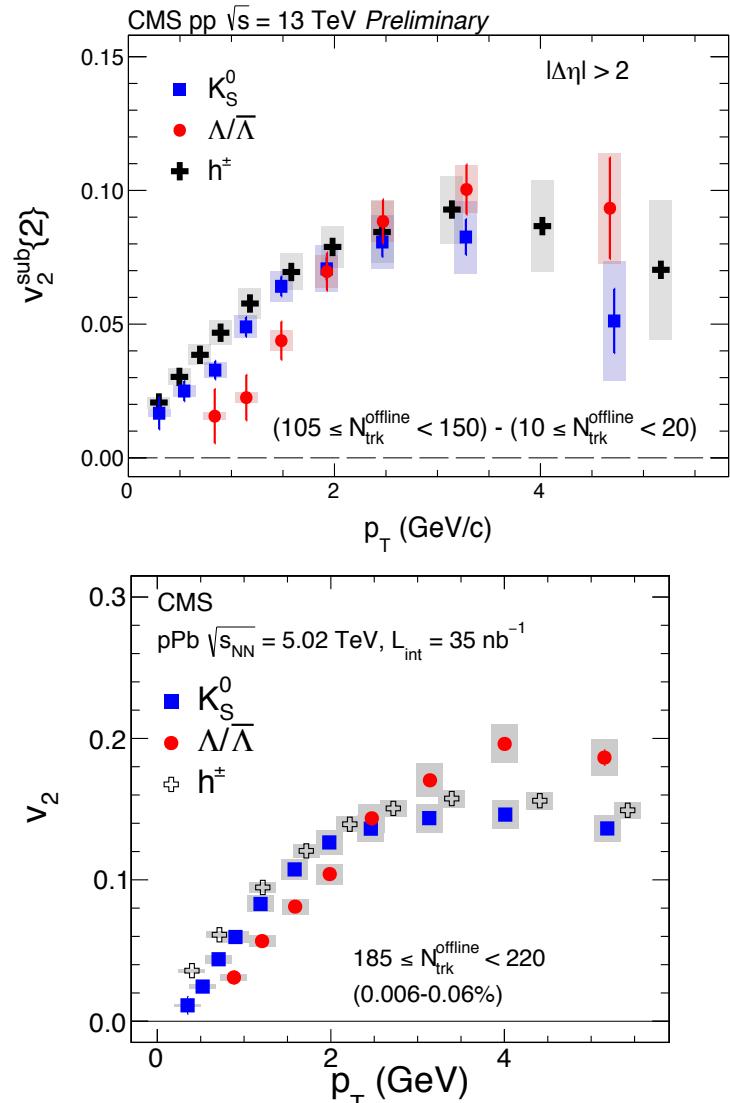
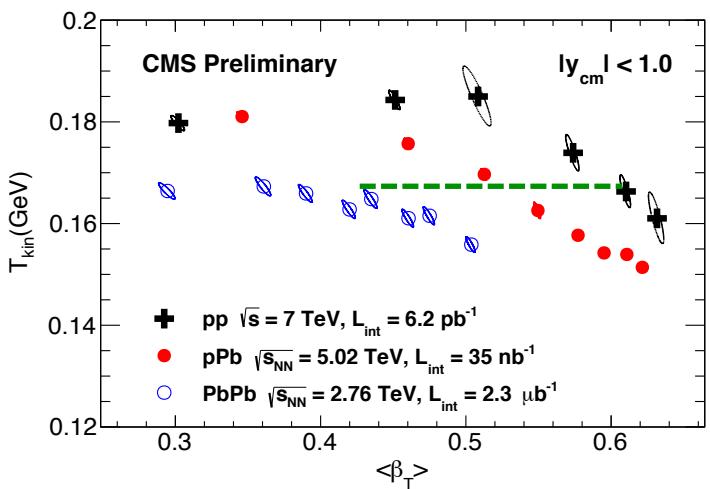
- ❖ Low multiplicity subtraction applied
- ❖ Clear mass splitting observed up to 2 GeV/c
- ❖ Clearer effect in p-p than in p-Pb (or Pb-Pb)
- ❖ **Where does this come from?**



# Identified particles ( $V^0$ ) long range correlations: mass splitting



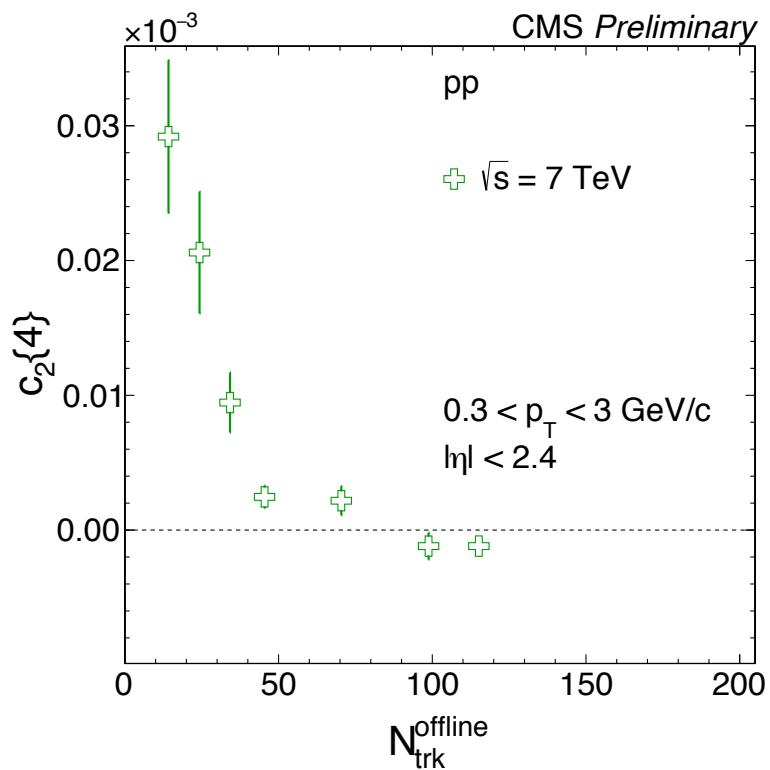
- ❖ Low multiplicity subtraction applied
- ❖ Clear mass splitting observed up to 2 GeV/c
- ❖ Clearer effect in p-p than in p-Pb (or Pb-Pb)
- ❖ **Where does this come from?**
  - Connected to radial flow
  - p-p is a more explosive system



# Is it collective?

**Goal:** Probe the collective nature of the “Ridge” in p-p collisions

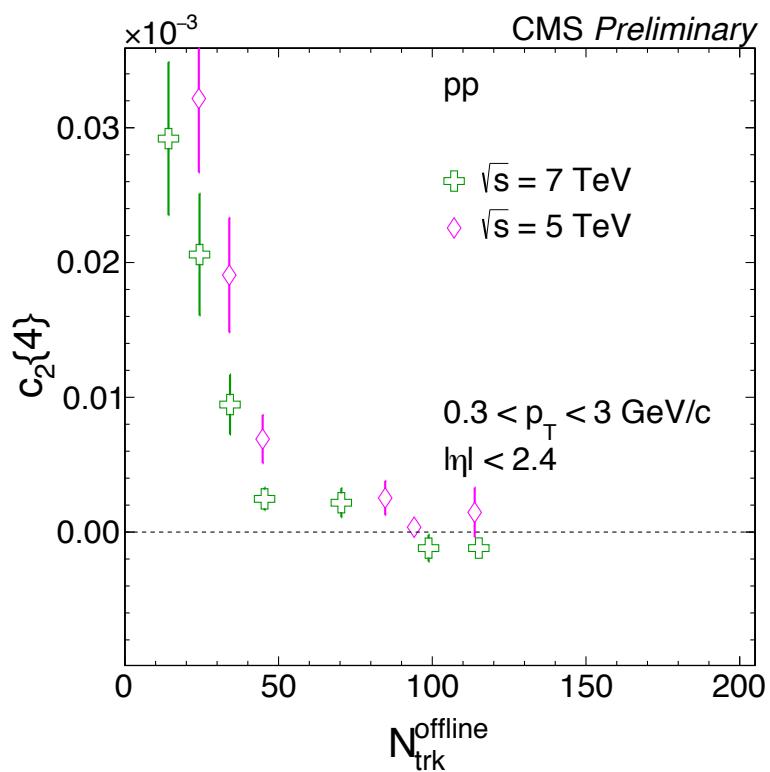
- 4- and 6-particle cumulant distributions were measured at different energies



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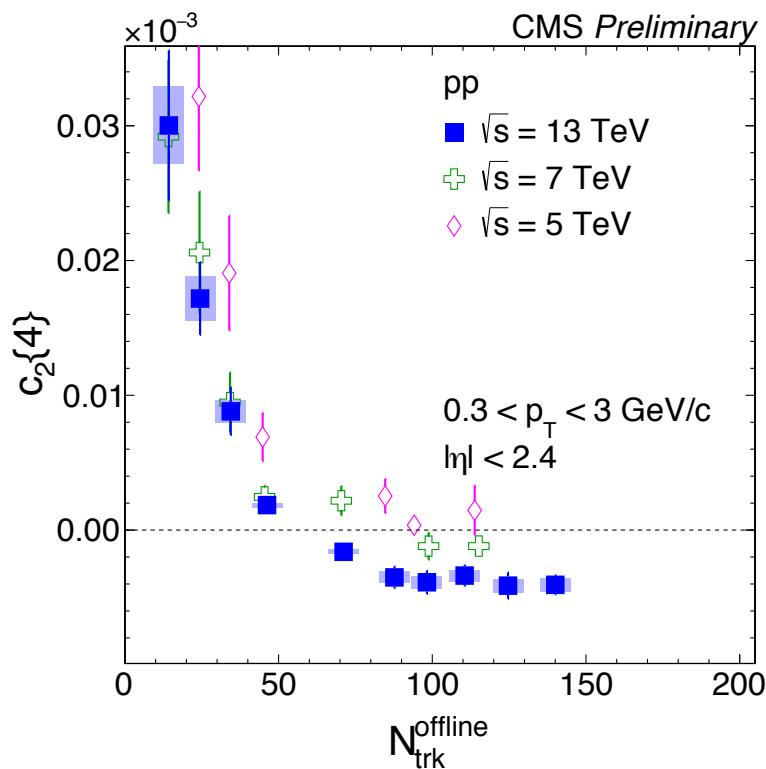


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**Clear signal observed in 13 TeV sample!**

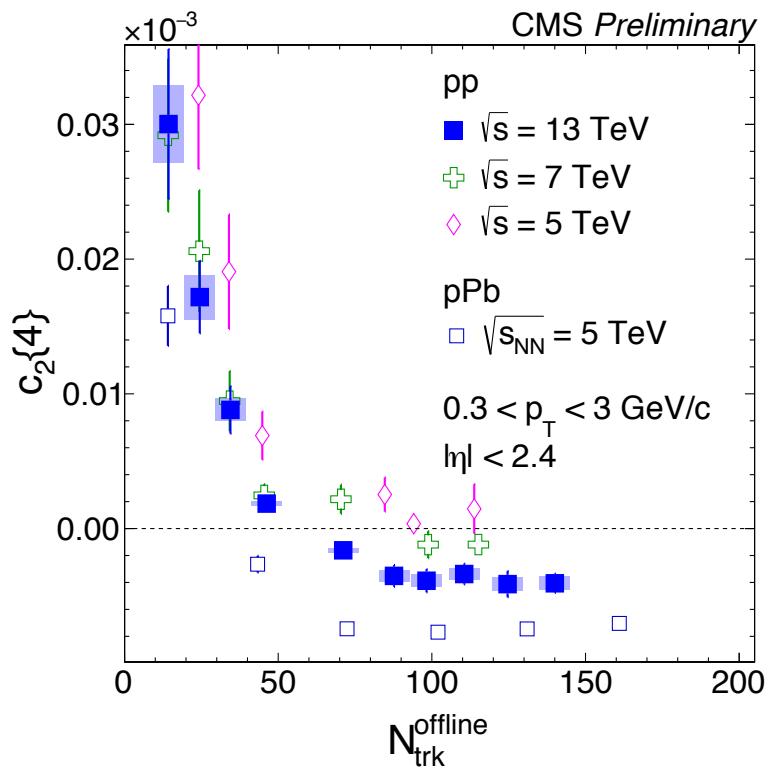


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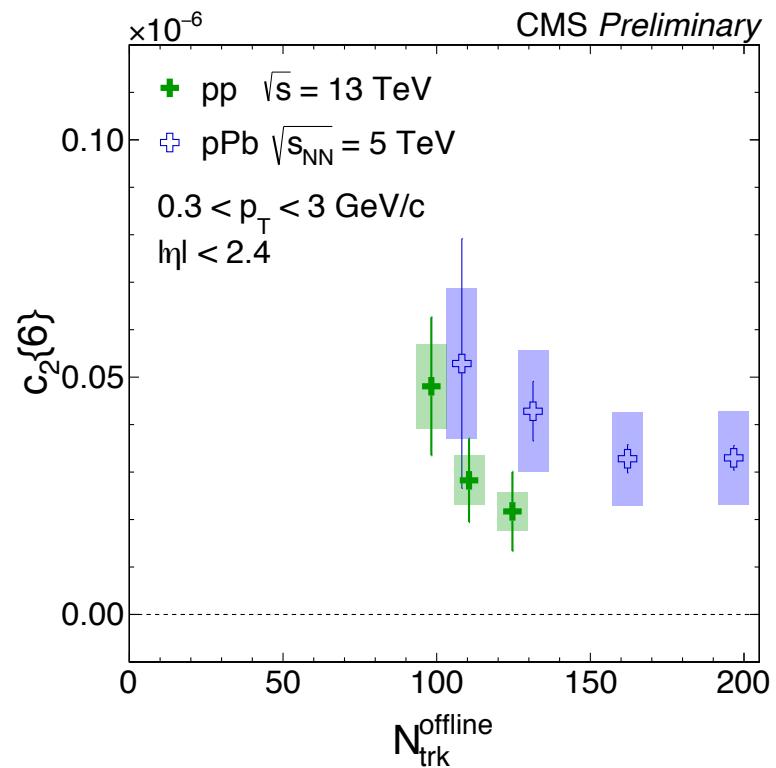
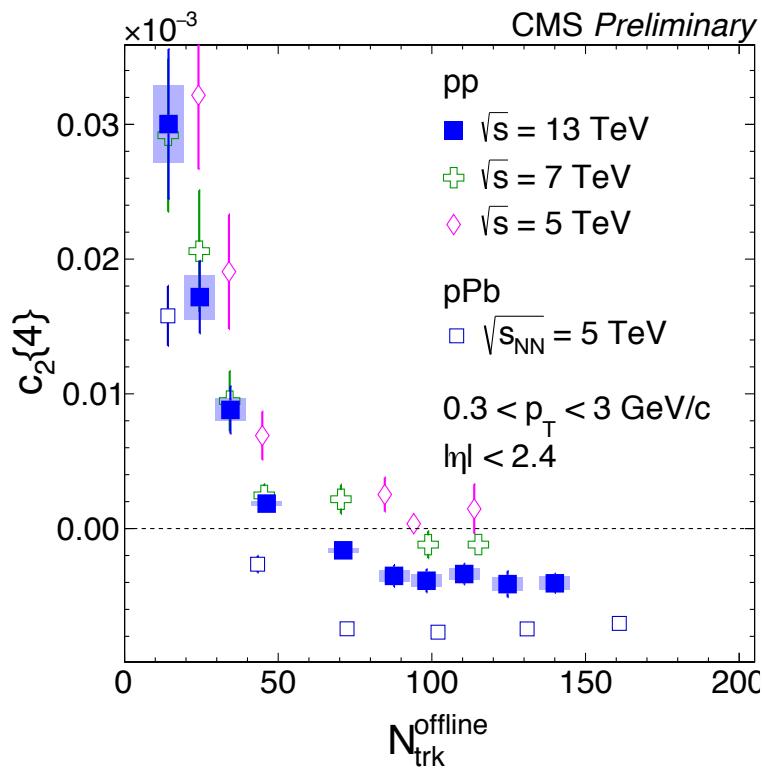


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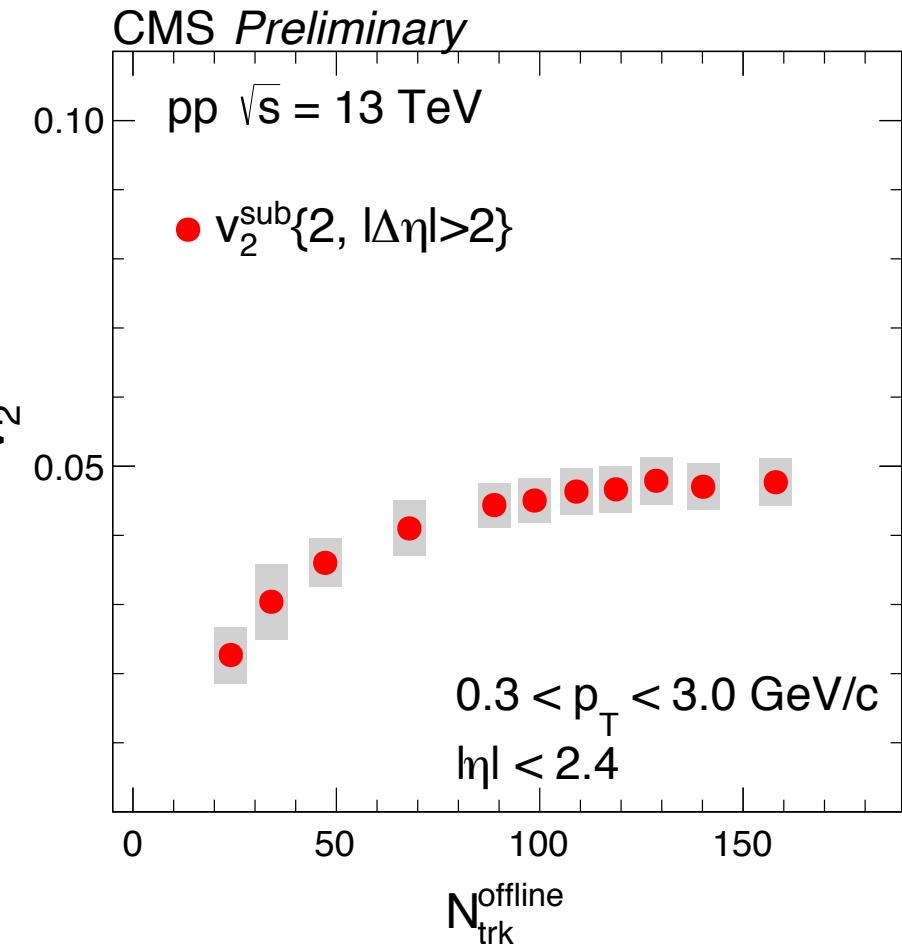
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- ❖ Multi-particle cumulant results compared to  $v_2\{2\}$



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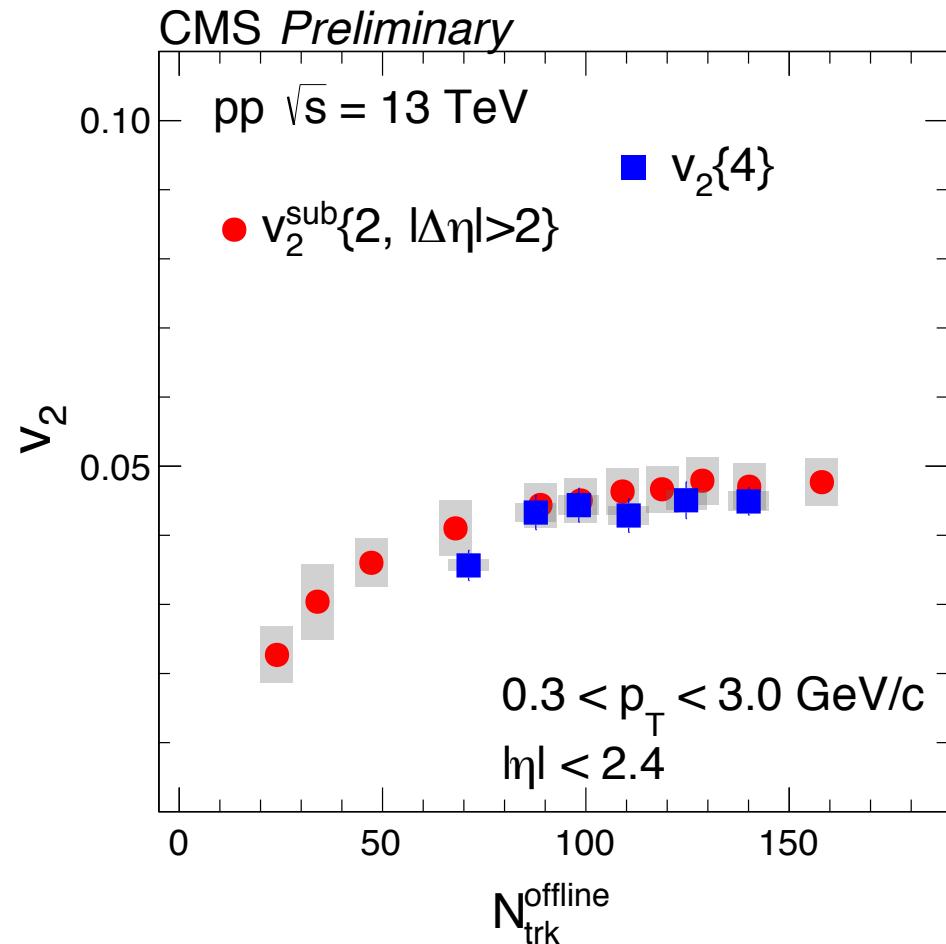
- ❖ Multi-particle cumulant results compared to  $v_2\{2\}$

- Probe collectivity

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

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

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



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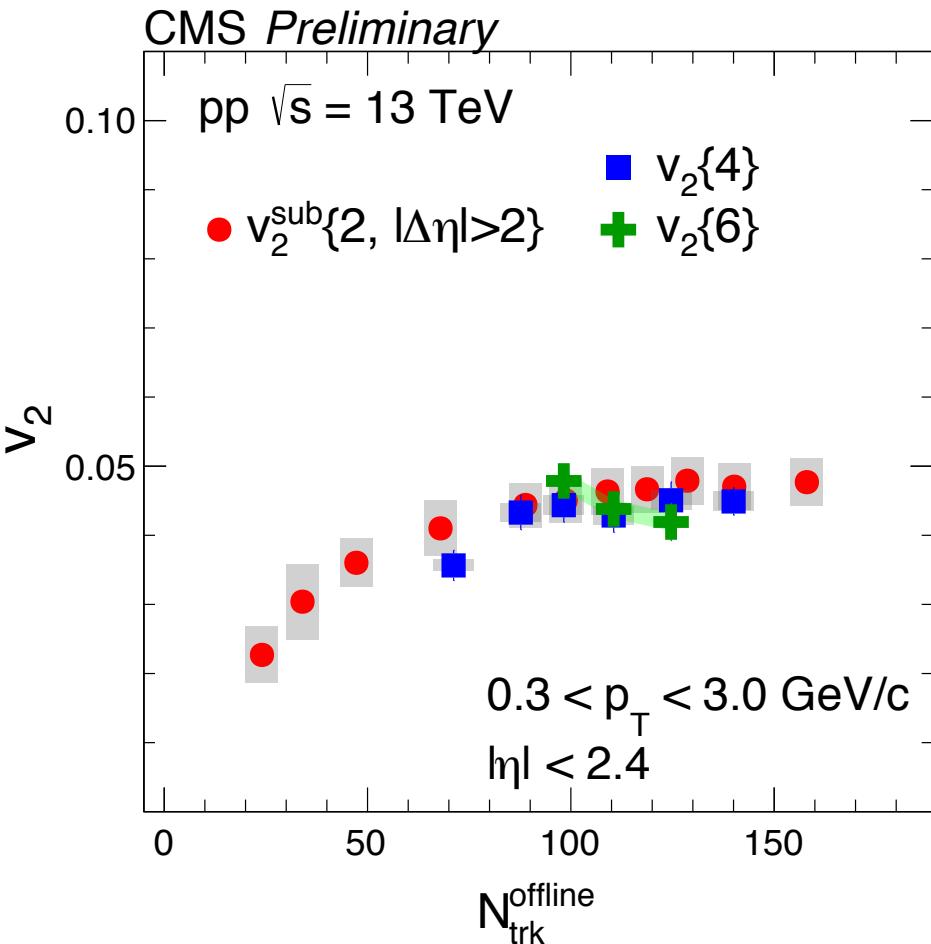
$$v_2\{4\} = \sqrt[4]{-c_n\{4\}},$$

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

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

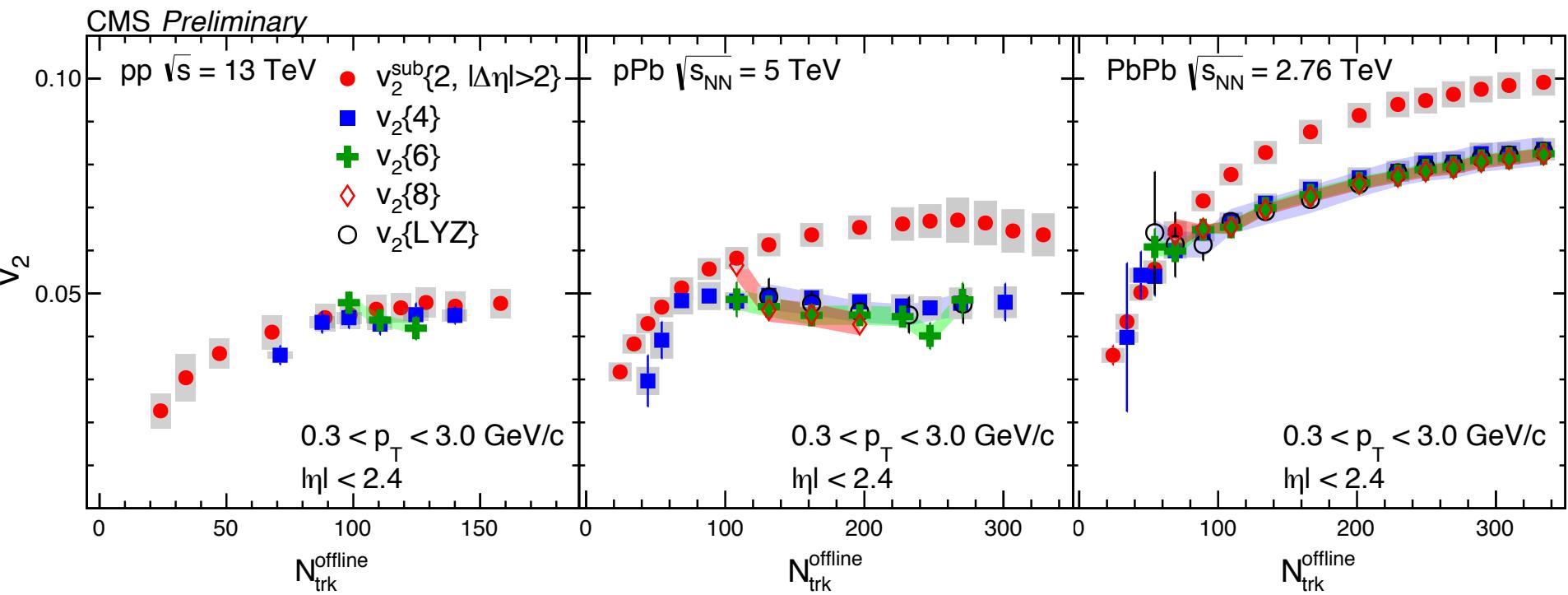
- $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$

→ Collectivity!





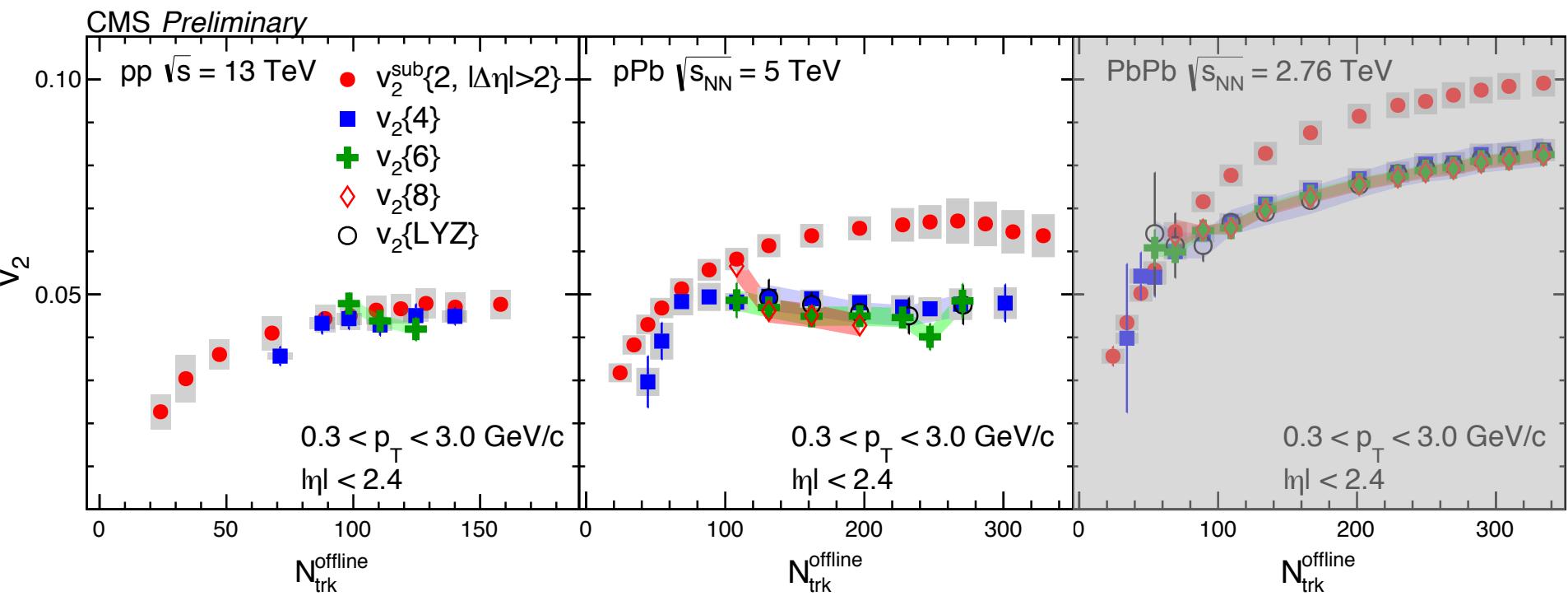
# Comparison across different systems of $v_2\{2\}$ , $v_2\{4\}$ and $v_2\{6\}$



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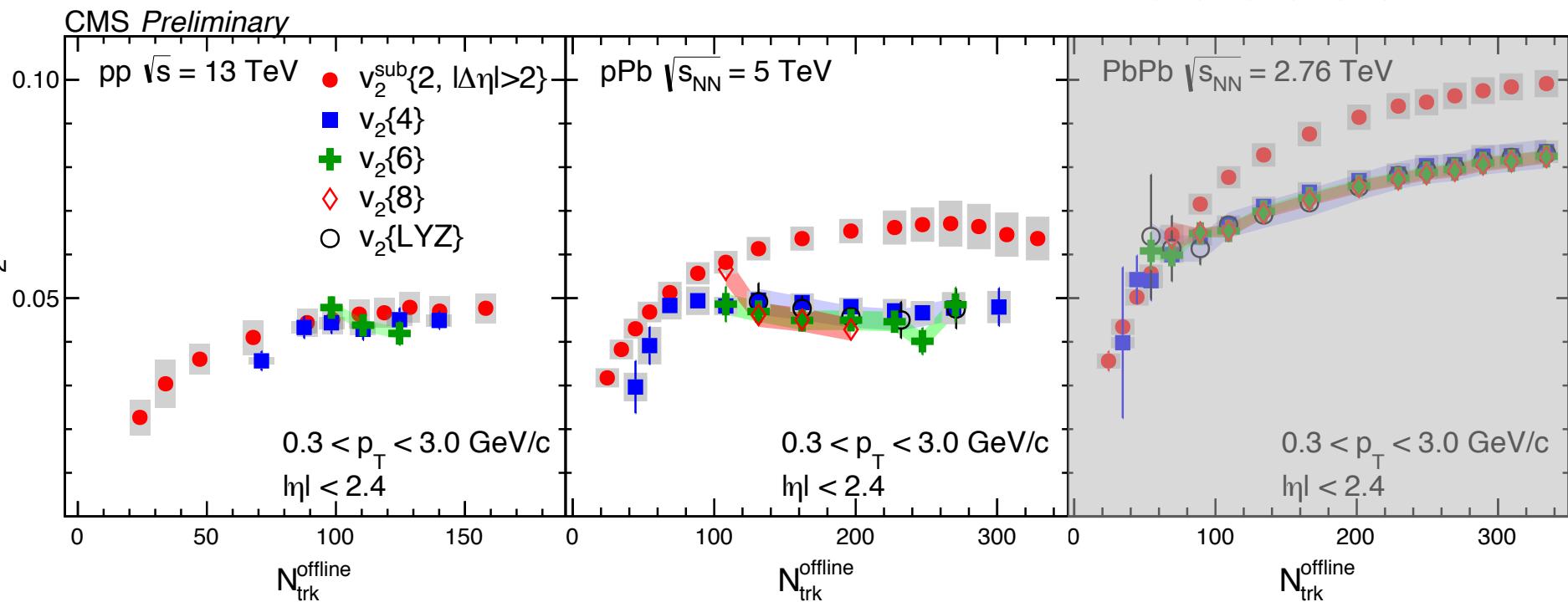
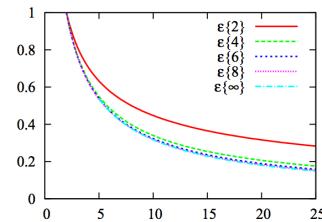
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  - $v_2\{2\}/v_2\{4\}$  (p-p)  $\leq v_2\{2\}/v_2\{4\}$  (p-Pb) → Related to IS fluctuations



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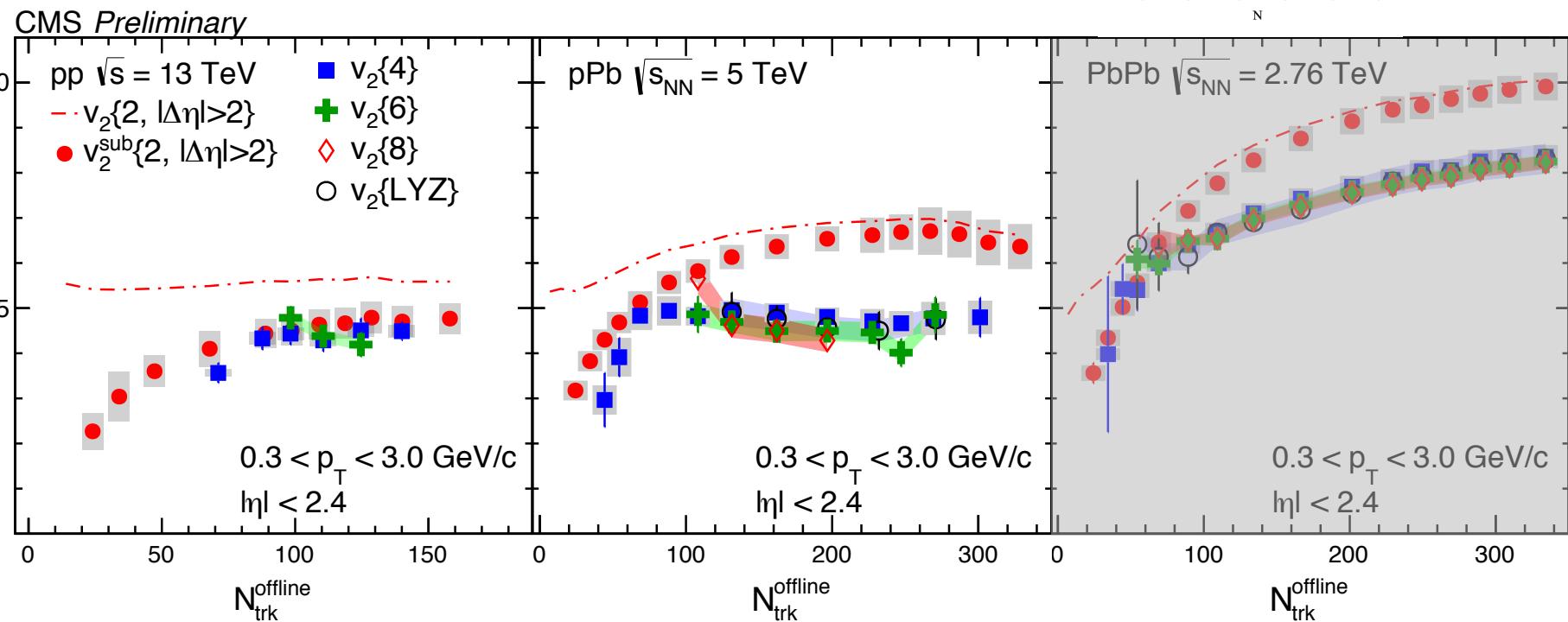
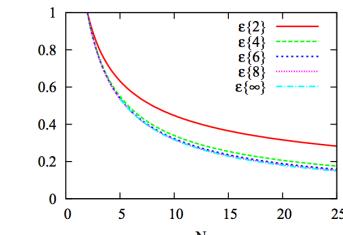
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- ❖ One possible explanation: [\*\*PRL 112 \(2014\) 082301\*\*](#)
  - smaller  $v_2\{2\}/v_2\{4\}$  → Less IS fluctuating sources



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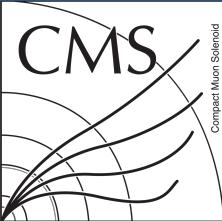


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  - smaller  $v_2\{2\}/v_2\{4\}$  → Less IS fluctuating sources
  - Still true before subtraction → Upper limit



# Summary

- ❖ A clear long-range near-side structure is observed in p-p collisions at high-multiplicity
- ❖ Significant  $v_2$  and  $v_3$  are measured with CMS at 5, 7 and 13 TeV using dihadron correlations and low-multiplicity subtraction technique
  - Similar shape for  $v_2$  as p-Pb but smaller magnitude
  - $v_3$  is different from p-Pb and Pb-Pb: suggest that initial state fluctuations in p-p and bigger systems have different patterns
  - Clear mass ordering is observed
- ❖  $v_2\{4\}$  and  $v_2\{6\}$  were measured at high multiplicity
  - **Results indicate that the Ridge in p-p is collective!**
  - **May provide important insight of the initial state fluctuations of the proton**

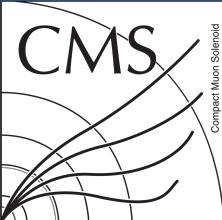


# Outlook (I)

**As in p-Pb, it is a collective effect, the interpretation is restricted to mainly two different pictures**

- ❖ Initial state interactions (CGC, ...)
- ❖ Initial state fluctuations + final state interactions (hydrodynamic, ...)

**Need of theoretical inputs in high multiplicity p-p collisions**



# Outlook (I)

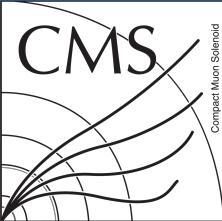
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- ❖ Can we constrain the proton initial state fluctuations?



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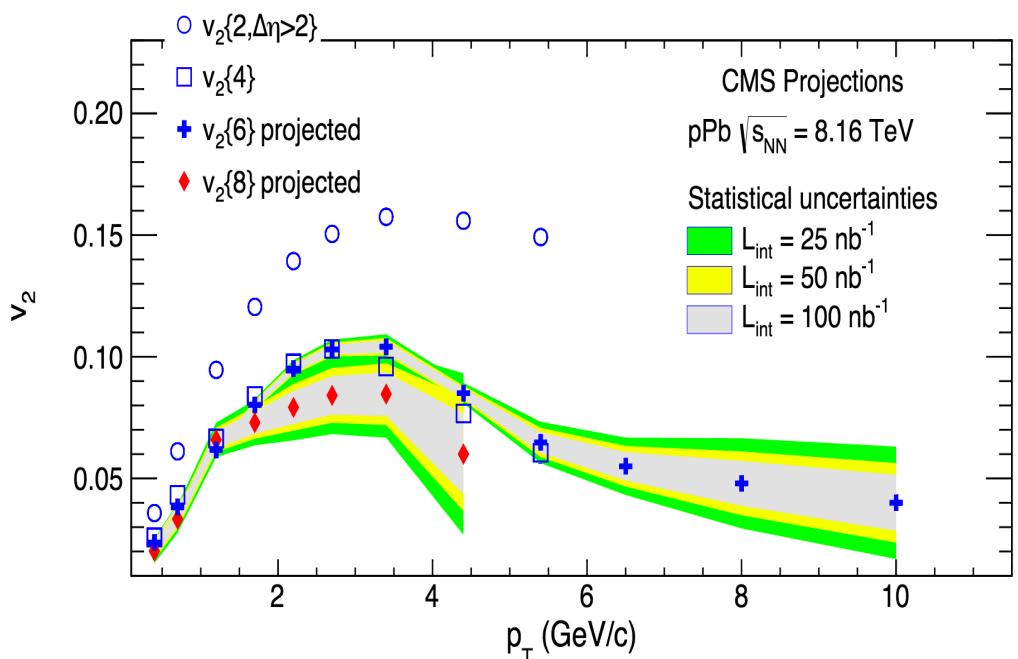
- ❖ Less fluctuating sources
- ❖ Can we constrain the proton initial state fluctuations?

**More results on small systems will come with the Run-2 p-Pb run this year!!!**

# Outlook (II)

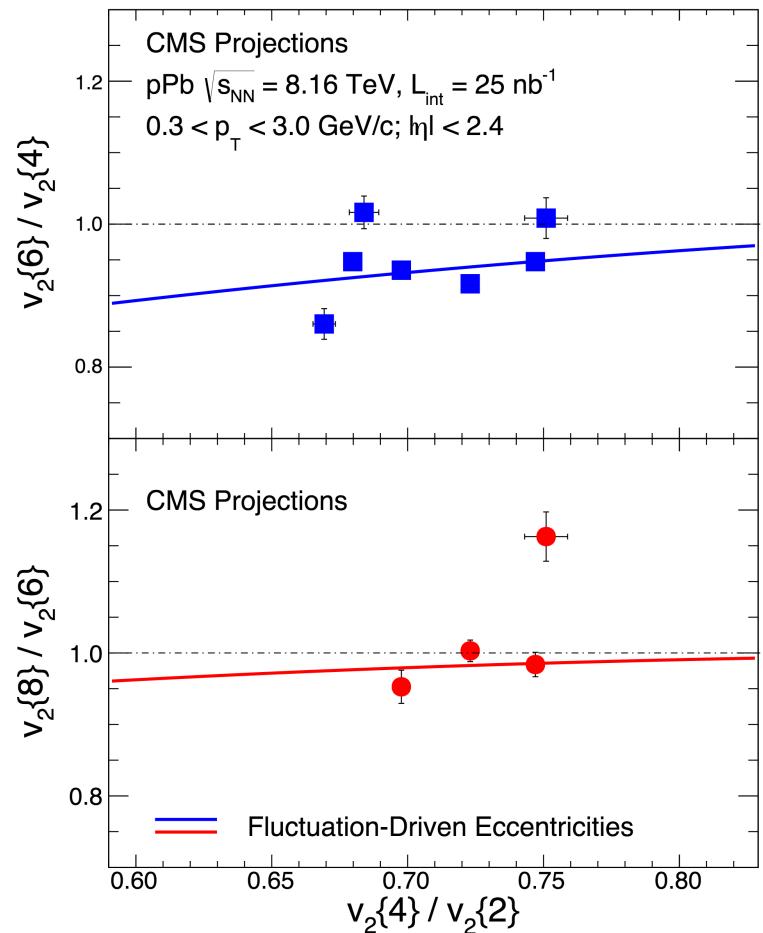
→ Extend measurements to higher  $p_T$ :

- Collectivity
- Jet quenching



[LPC meeting](#)

→ More constrains on IS fluctuations



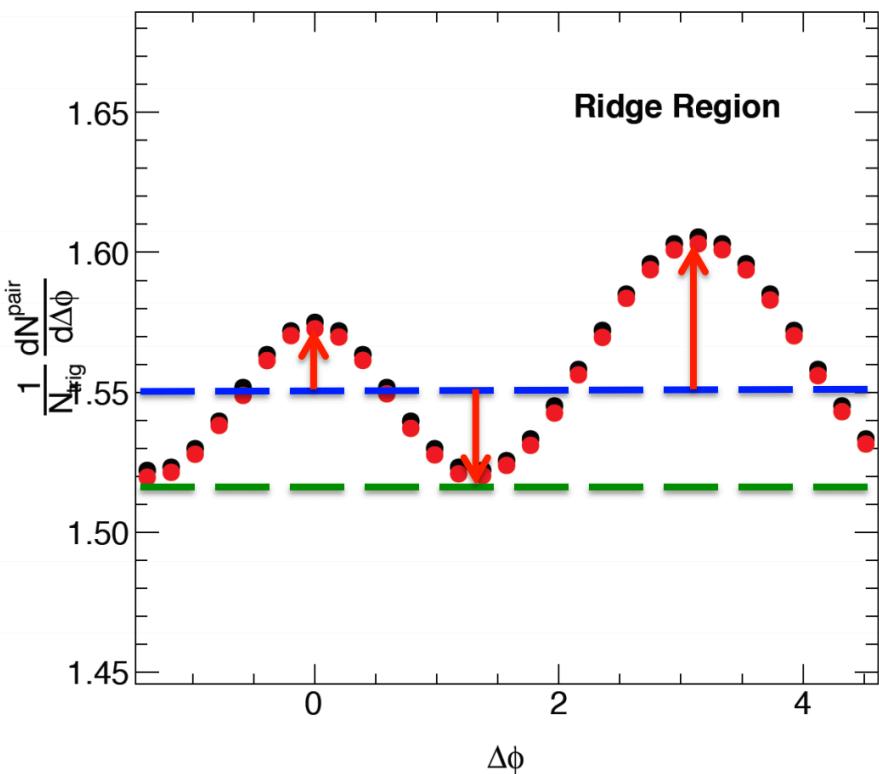


# BACKUP

# ATLAS and CMS method comparison

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*



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

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

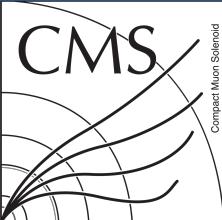
**Baseline of the correlation:**

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  $N \downarrow$

then  $V_{n\Delta} \uparrow$



# ATLAS and CMS method comparison

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

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

$$G = N^{HM} - F.N^{LM}$$

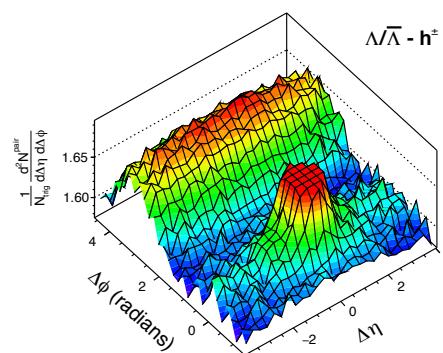
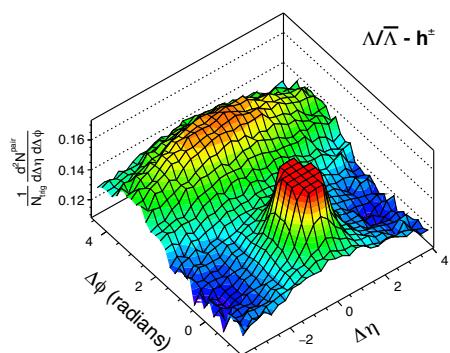
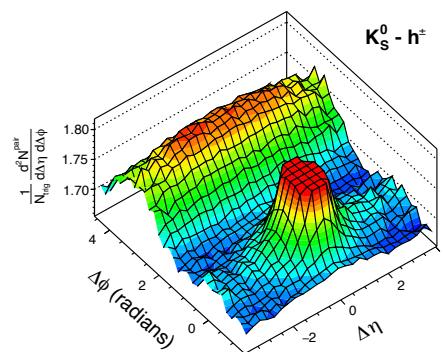
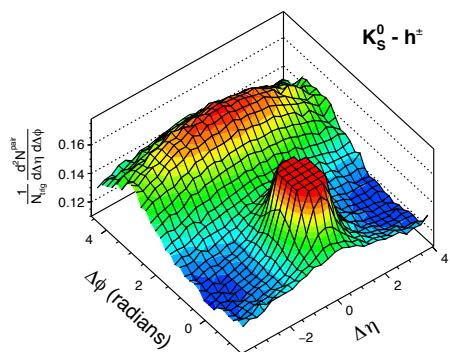
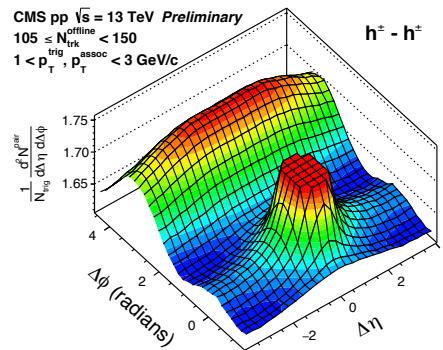
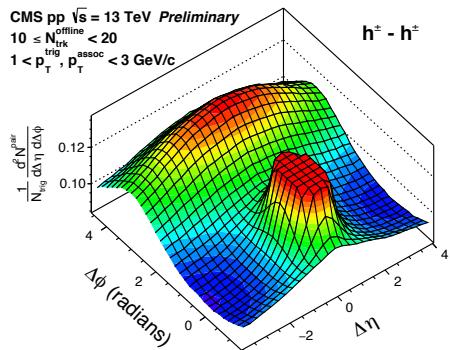
$$G.V_2^{\text{ridge}} = N^{HM}.V_2 - F.N^{LM}.V_2^{LM}$$

if  $N \sum_n 2V_{n\Delta} \cos(n\Delta\phi) = \text{cste}$  and  $N \downarrow$   
then  $V_{n\Delta} \uparrow$

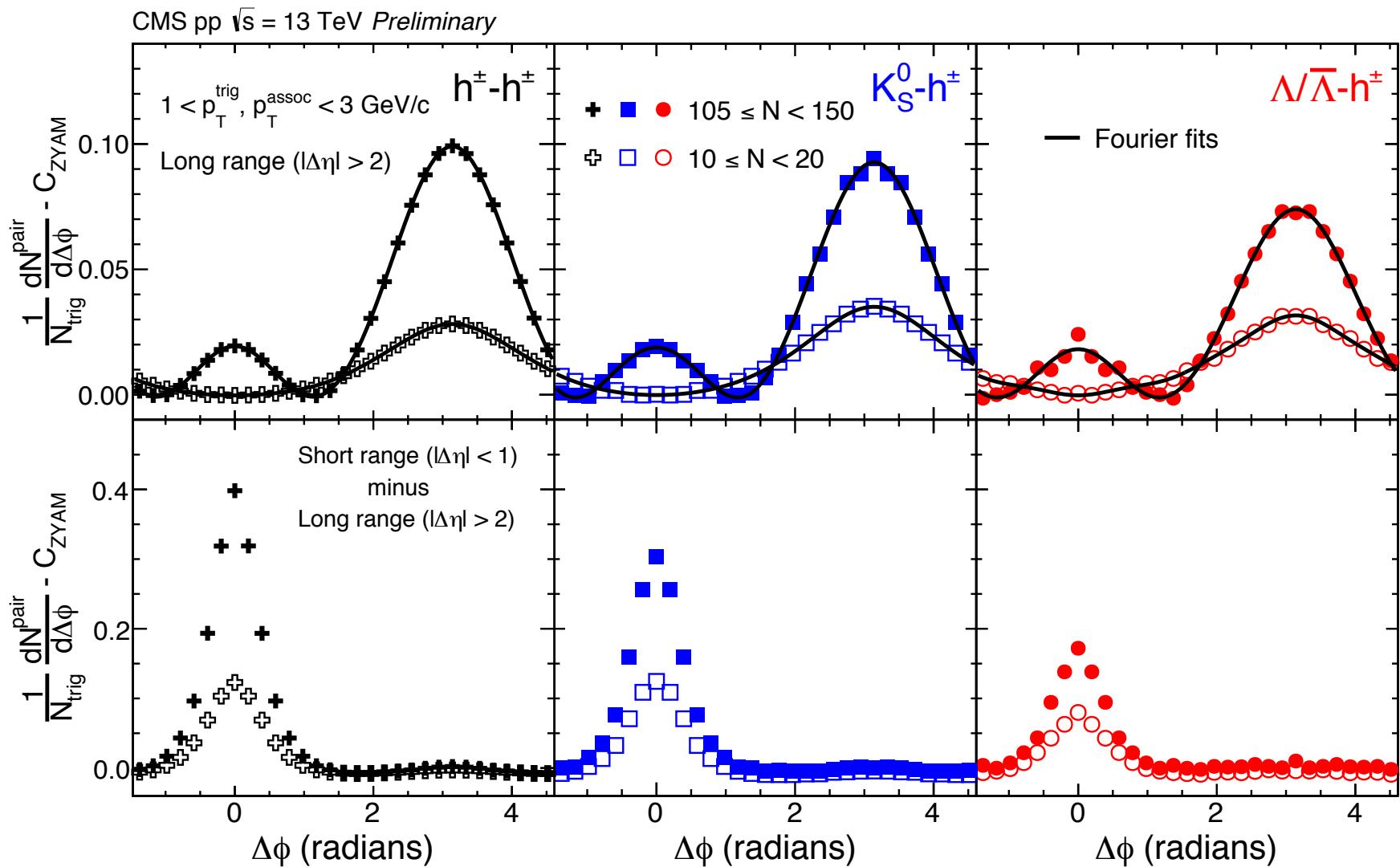
$G$  smaller than  $N^{HM}$ ,  $V_2 \uparrow$   
**Smaller  $G$  can be interpreted as correlation wrt a subset of particle**

**HM: High Multiplicity**  
**LM: Low Multiplicity**

# 2D correlation functions



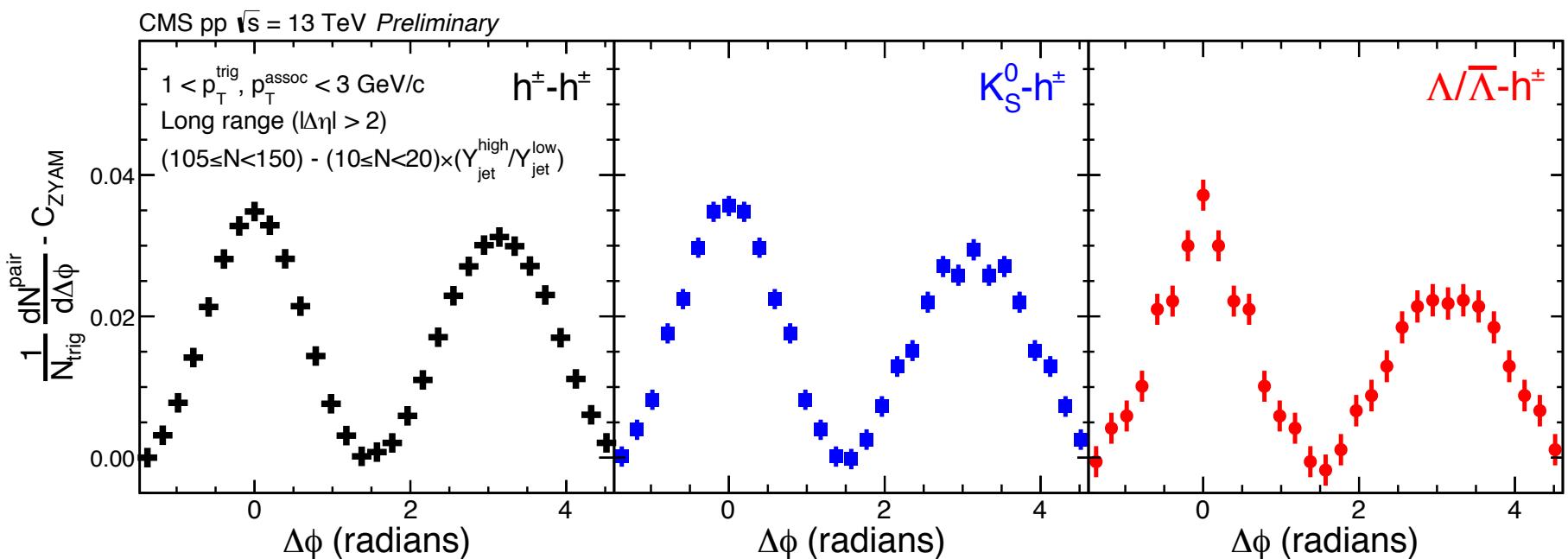
# 1D correlation functions

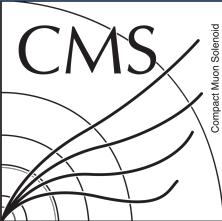


# Identified particles ( $V^0$ ) long range correlations: double ridge

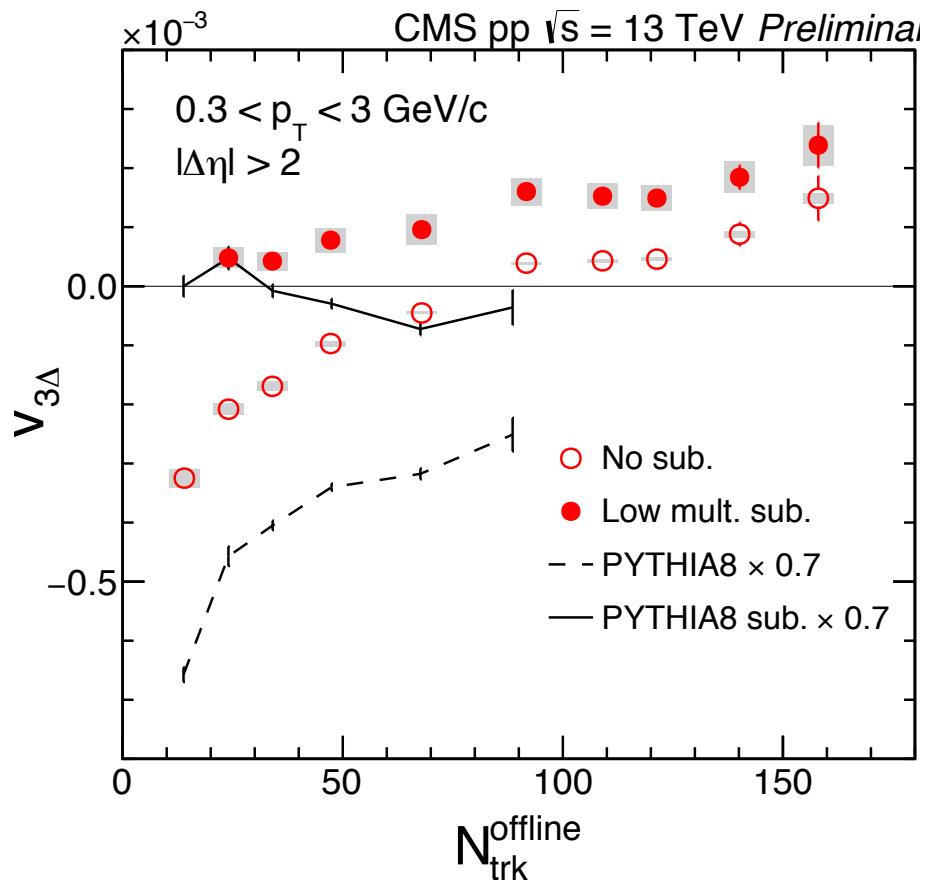
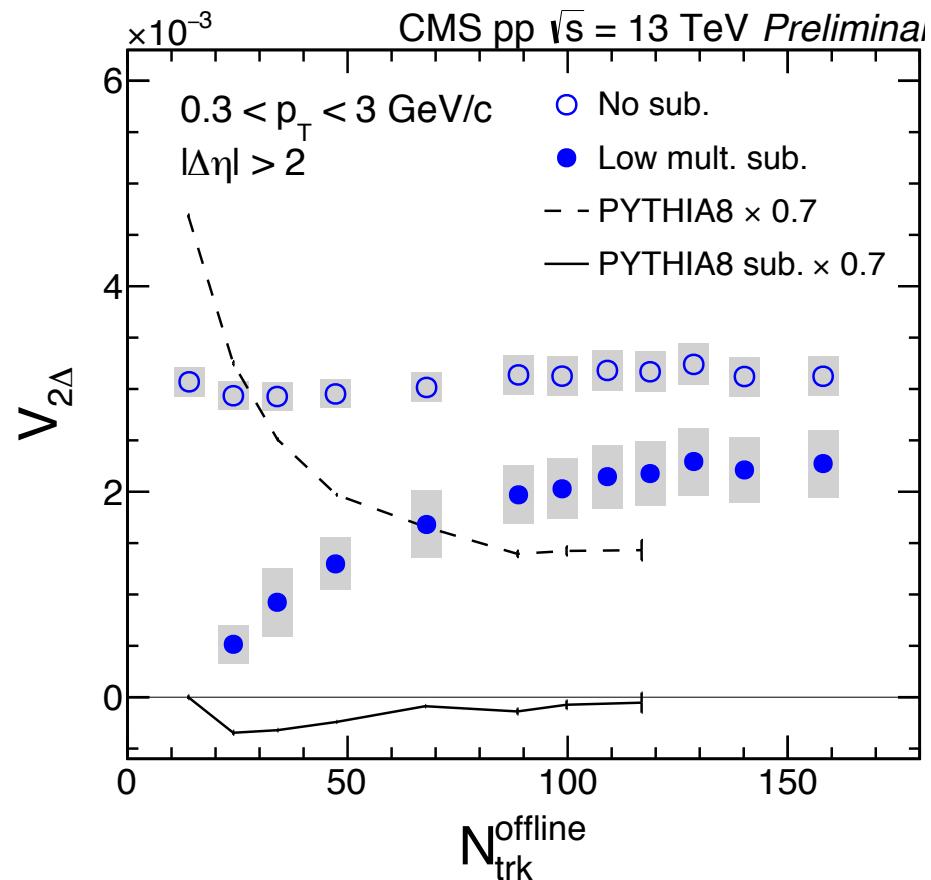


- ◆ Clear double ridge structure also observed for  $V^0$  after subtracting jet correlations

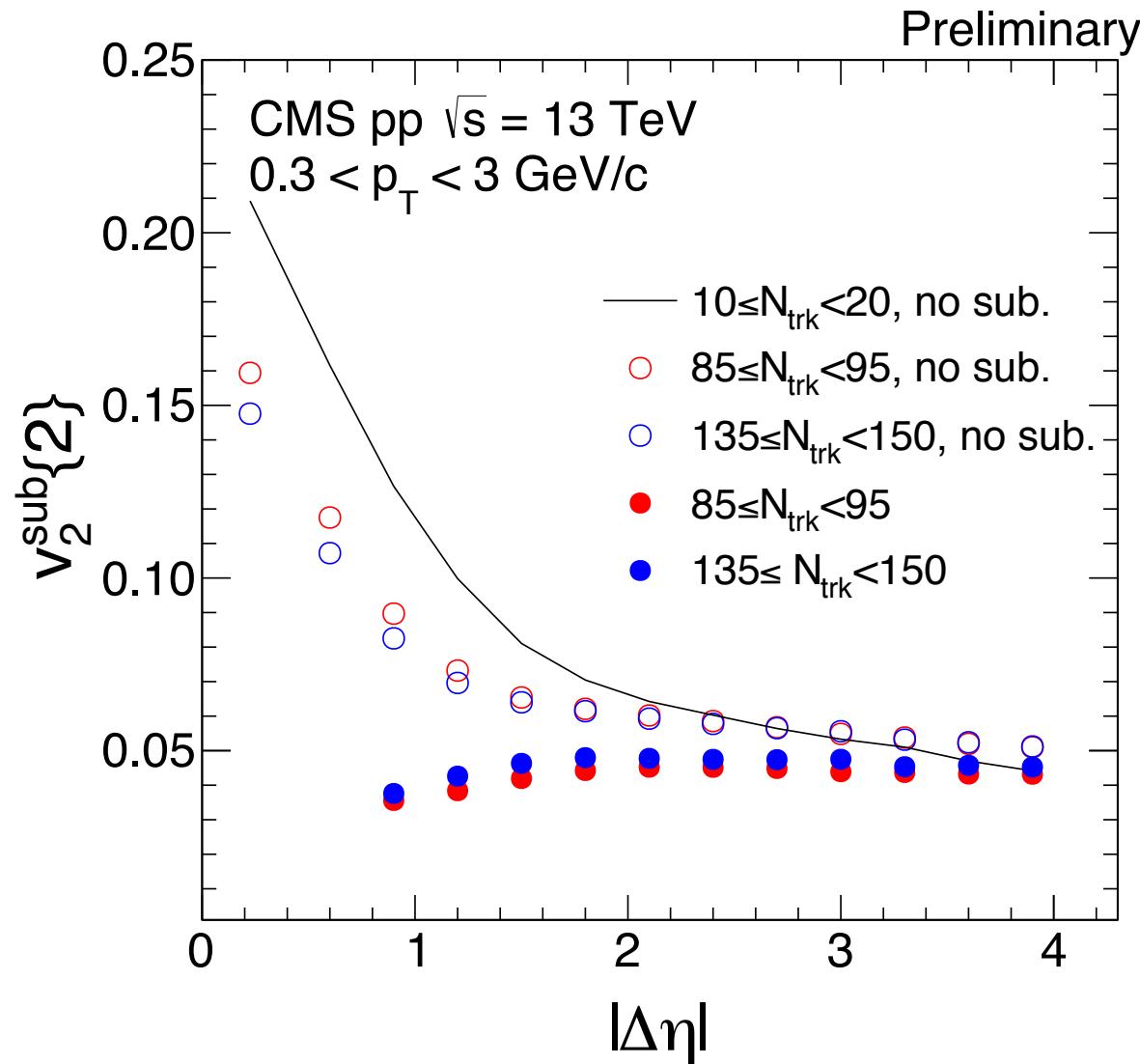




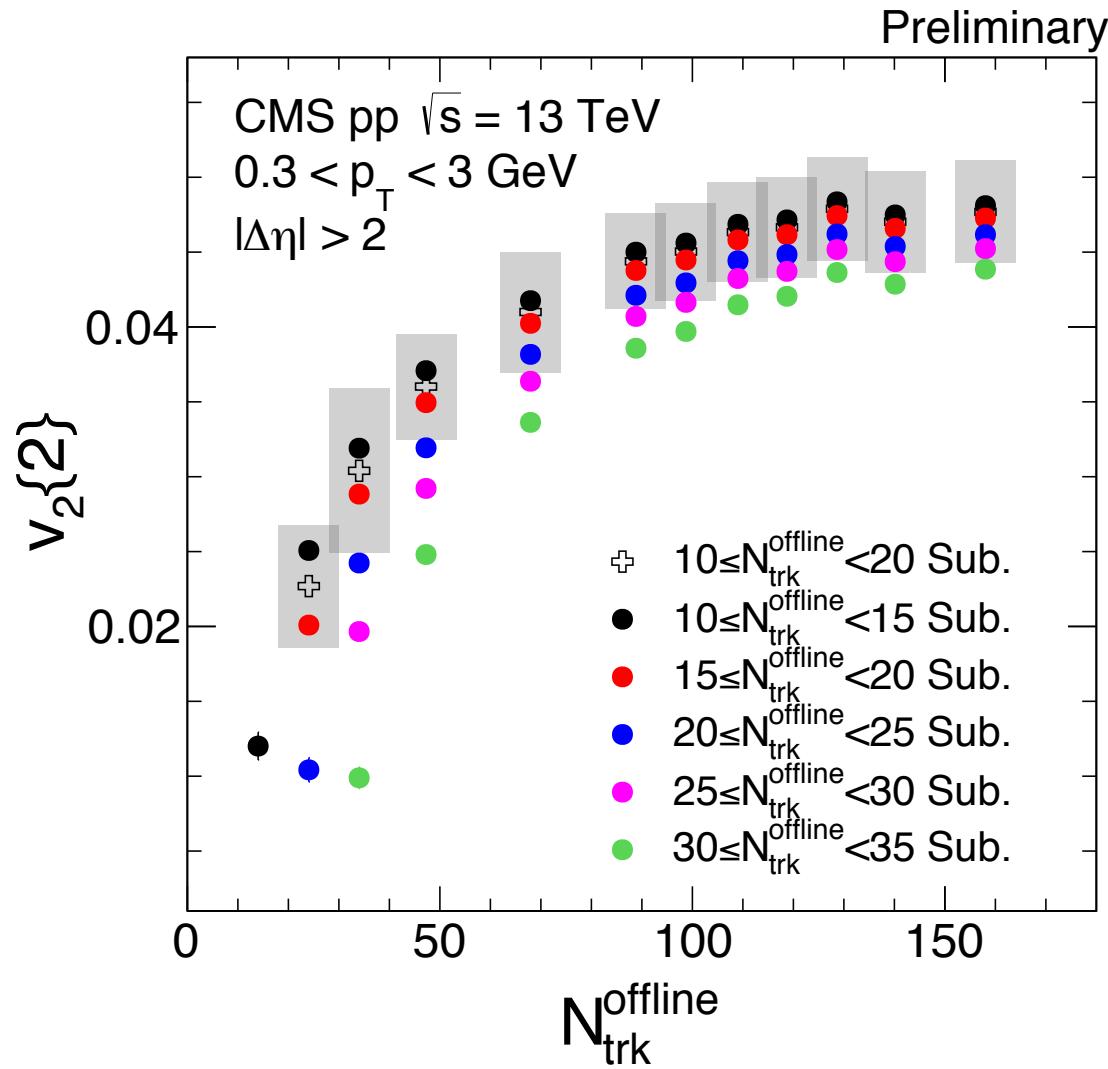
# $V_{2\Delta}$ subtraction and MC closure



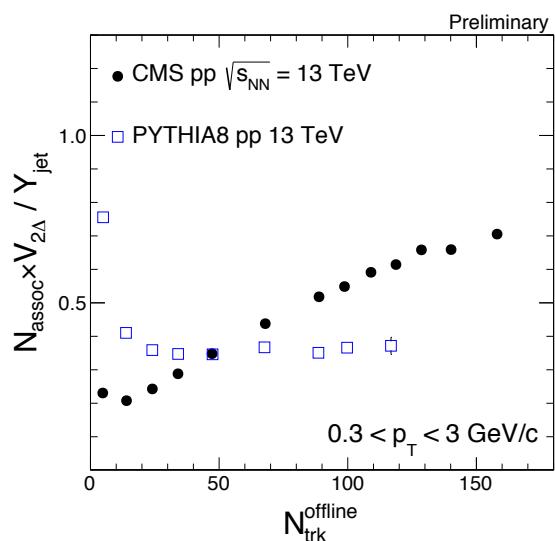
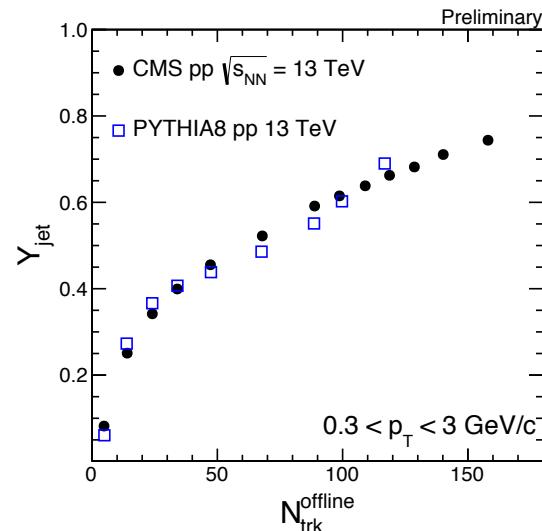
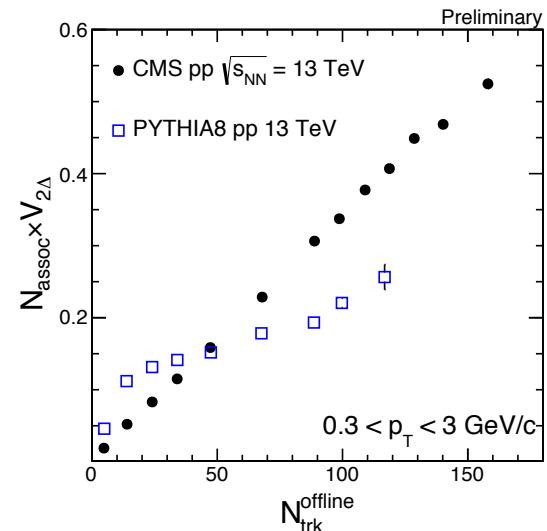
# $\Delta\eta$ dependence of $v_2\{2\}$



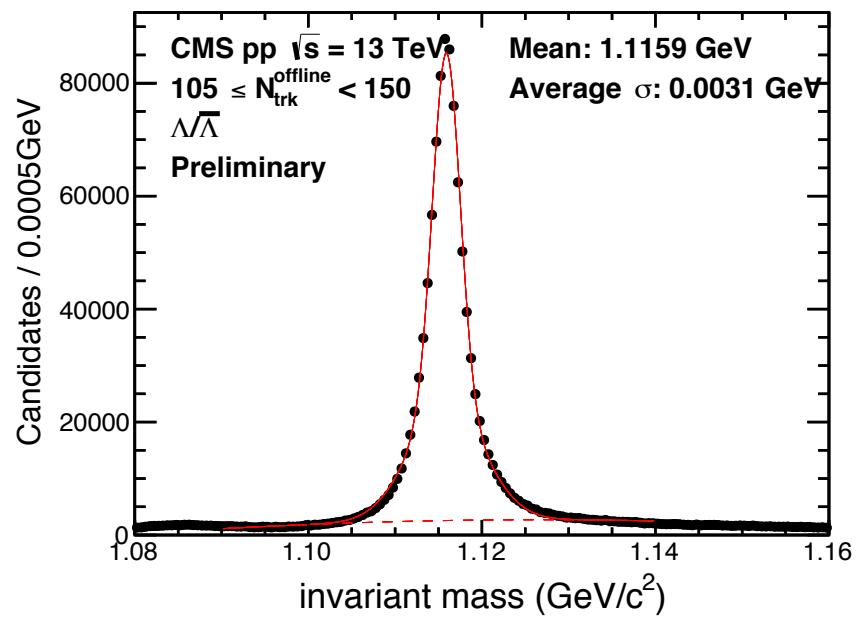
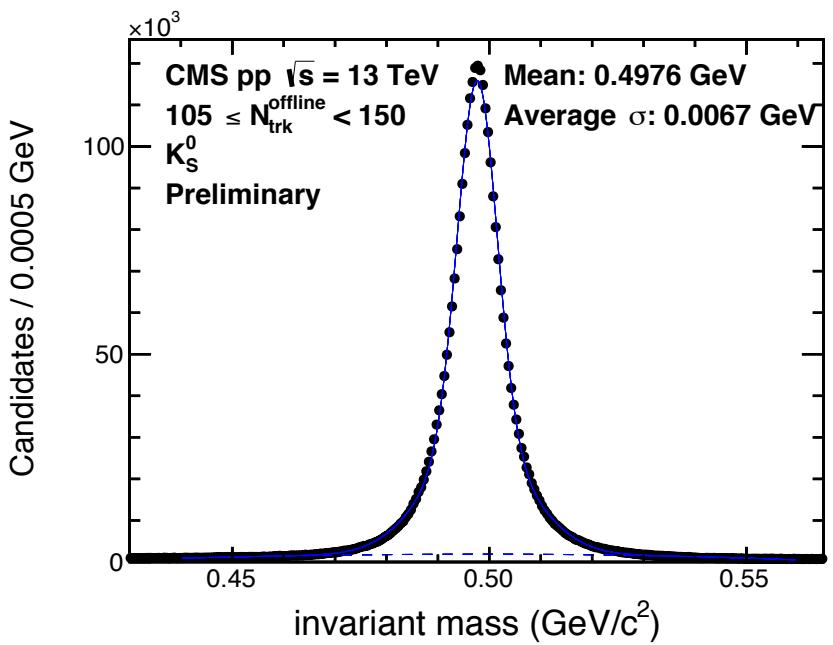
# Subtraction as a function of multiplicity for $v_2\{2\}$



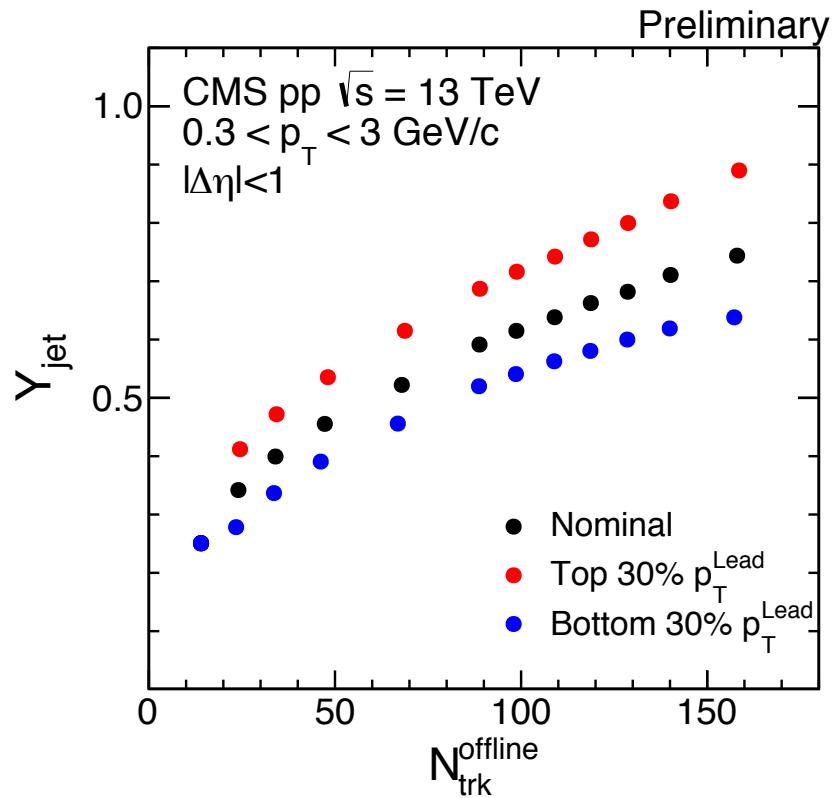
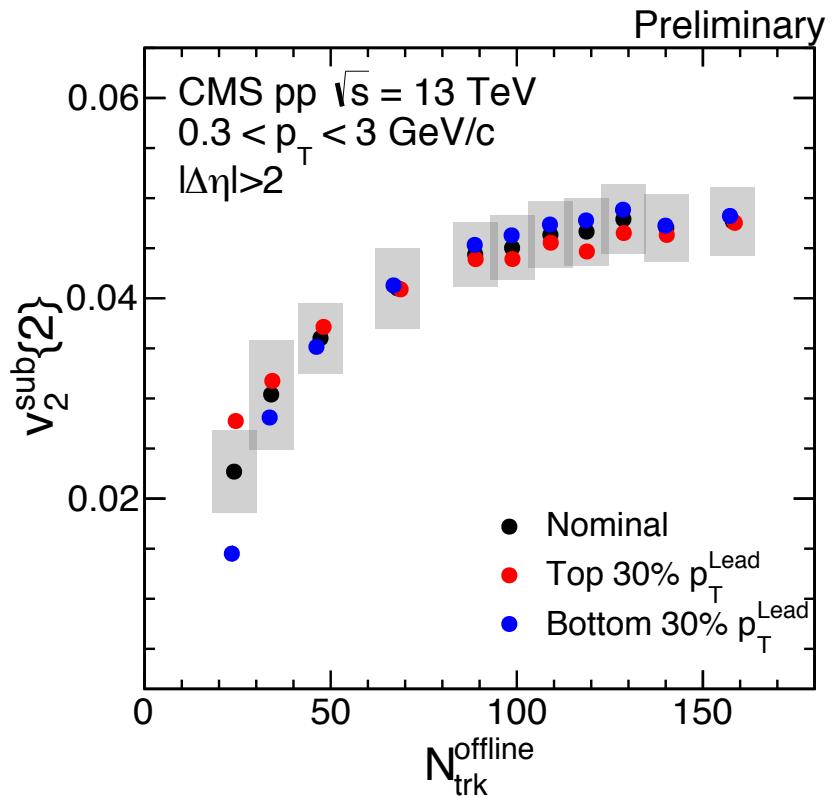
# MC comparison with PYTHIA



# $V^0$ mass fits



# Jet subtraction test

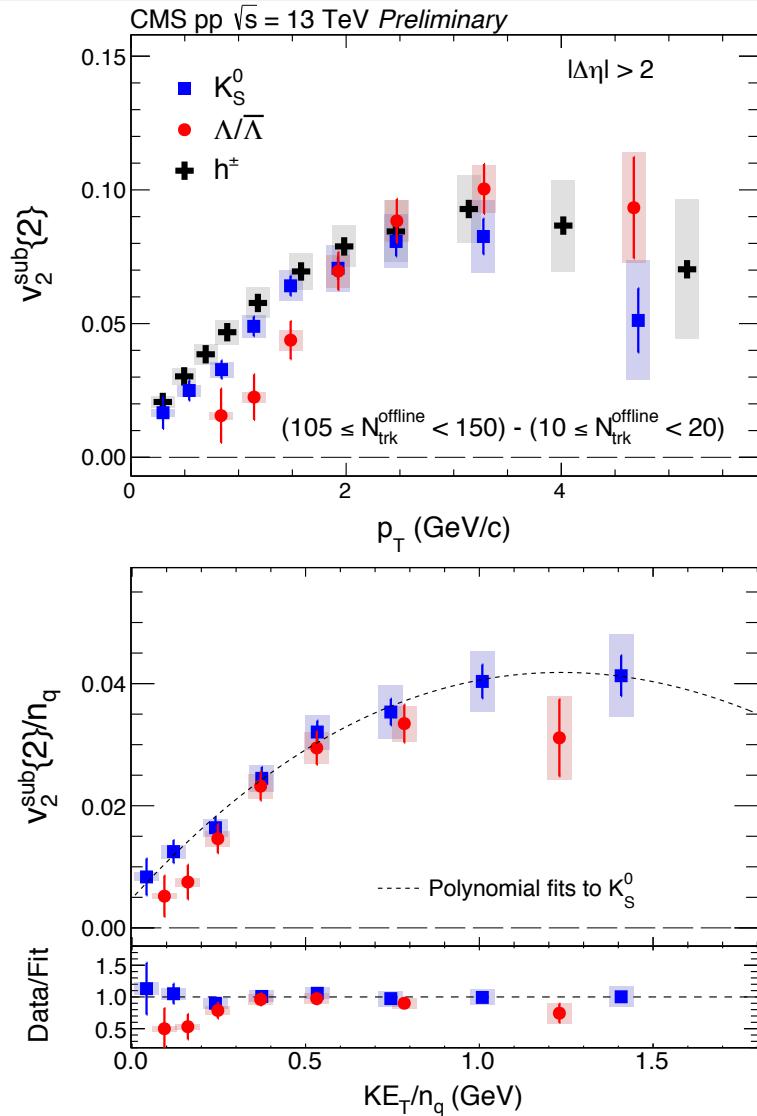


# NCQ scaling

- ❖ NCQ scaling stand for intermediate  $KE_T/n_q$
- ❖ Tension a low  $KE_T/n_q$  but statistical uncertainties are large

**How to explain this scaling?**

**What can we learn from that?**



# Number of fluctuating sources

