# CORRELATIONS BETWEEN MULTIPARTICLE CUMULANTS AND MEAN TRANSVERSE MOMENTUM IN SMALL COLLISION SYSTEMS WITH THE CMS DETECTOR

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(Vanderbilt University)
for the CMS Collaboration

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# INTRODUCTIONS

In heavy ion collisions:

- Final state anisotropic flow is from hydrodynamic response to initial geometry anisotropy
- Mean $p_T$ ($[p_T]$) reflects the strength of radial flow push, which is related to the initial fireball energy density
- The correlations between $v_n$ and $[p_T]$ probe the fluctuations of the initial density profile

$$\rho(v_n^2, [p_\mathrm{T}]) = \frac{\mathrm{cov}(v_n^2, [p_\mathrm{T}])}{\sqrt{\mathrm{var}(v_n^2)}\sqrt{\mathrm{var}([p_\mathrm{T}])}}$$

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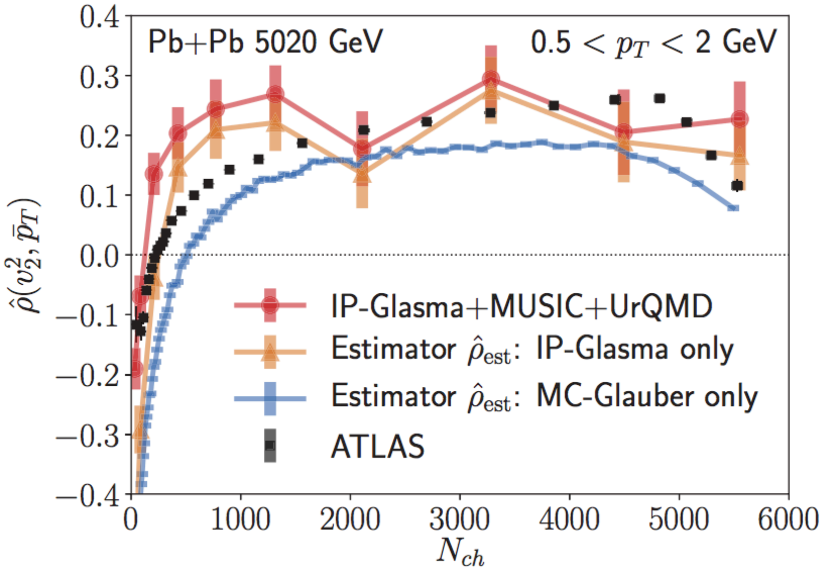


Phys. Rev. C 102, 034905 (2020)

Sensitive to the degree of sub-nucleon fluctuations

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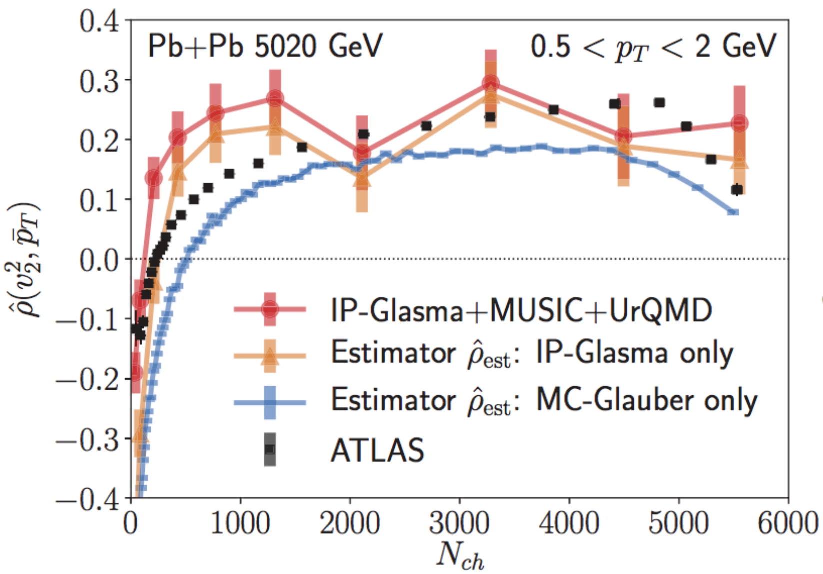


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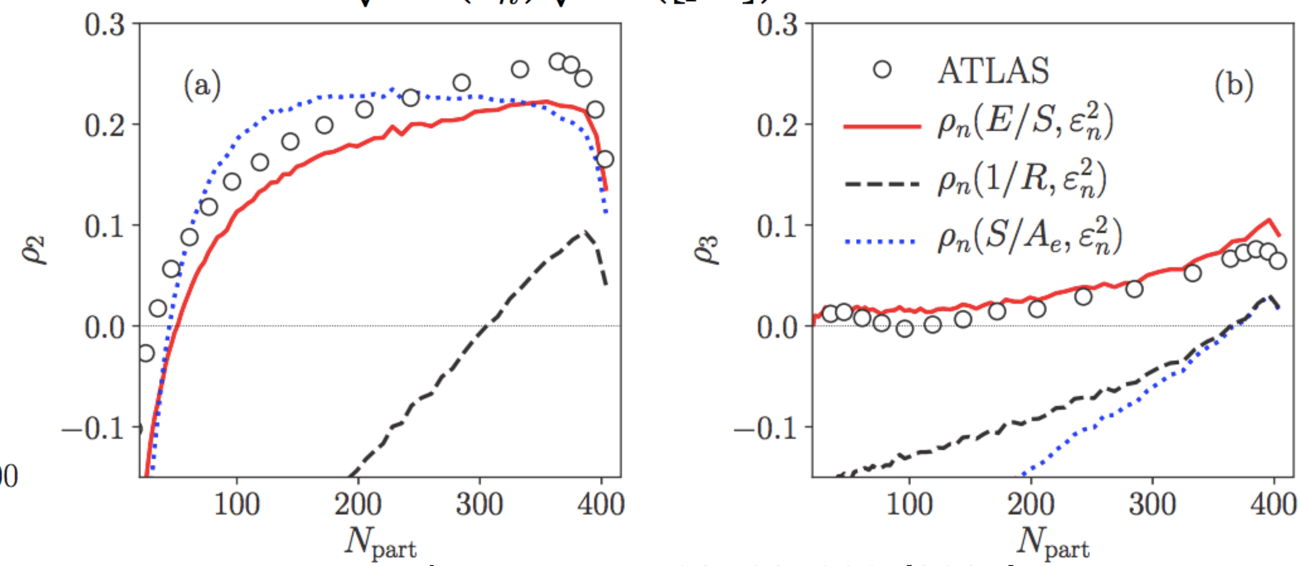
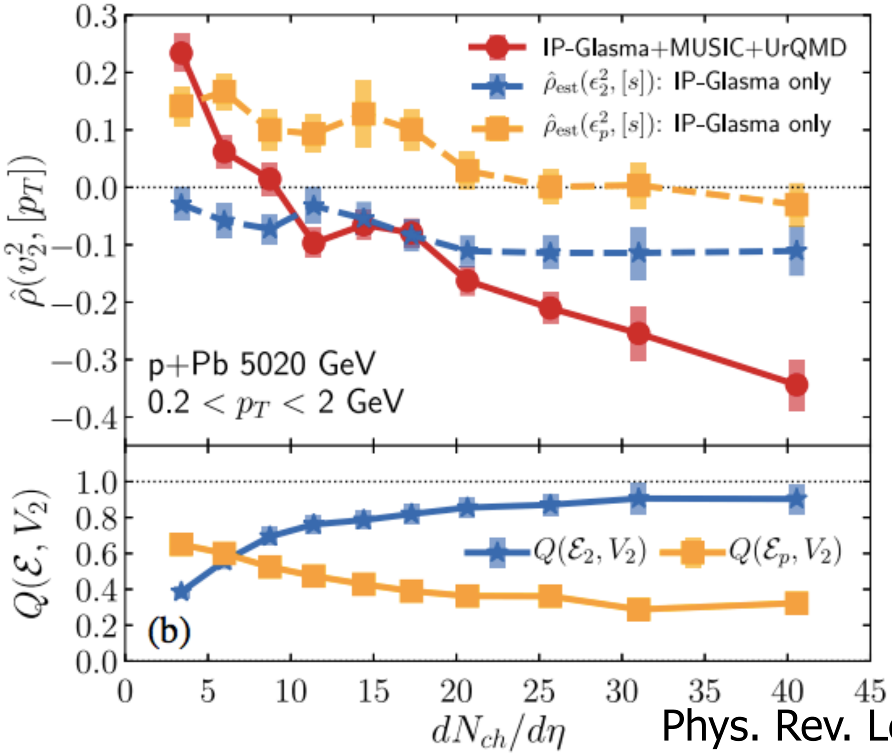


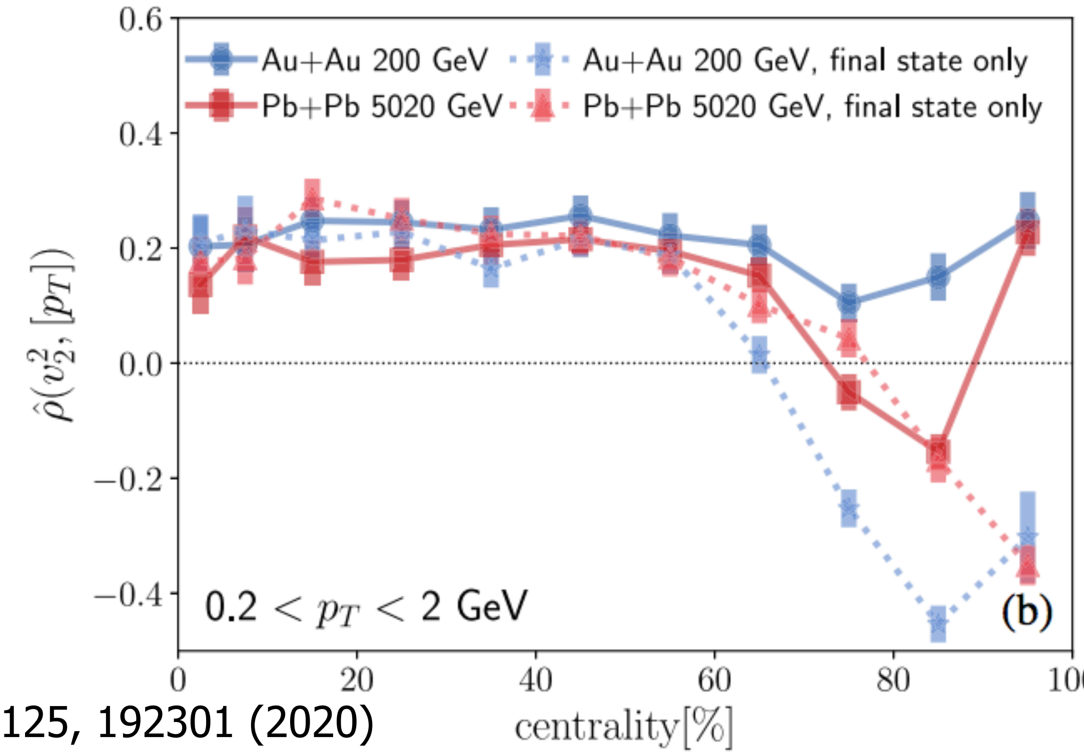

Phys. Rev. C 103, 024909 (2021)

Sensitive to the degree of sub-nucleon fluctuations

The mechanism driving the correlations can be traced back to the initial density profile

# MOTIVATIONS FOR SMALL SYSTEMS (1)




Phys. Rev. Lett. 125, 192301 (2020)

- The correlations carry information about the origin of the observed momentum anisotropy
- No sign change at low multiplicity without initial $v_2$ from CGC

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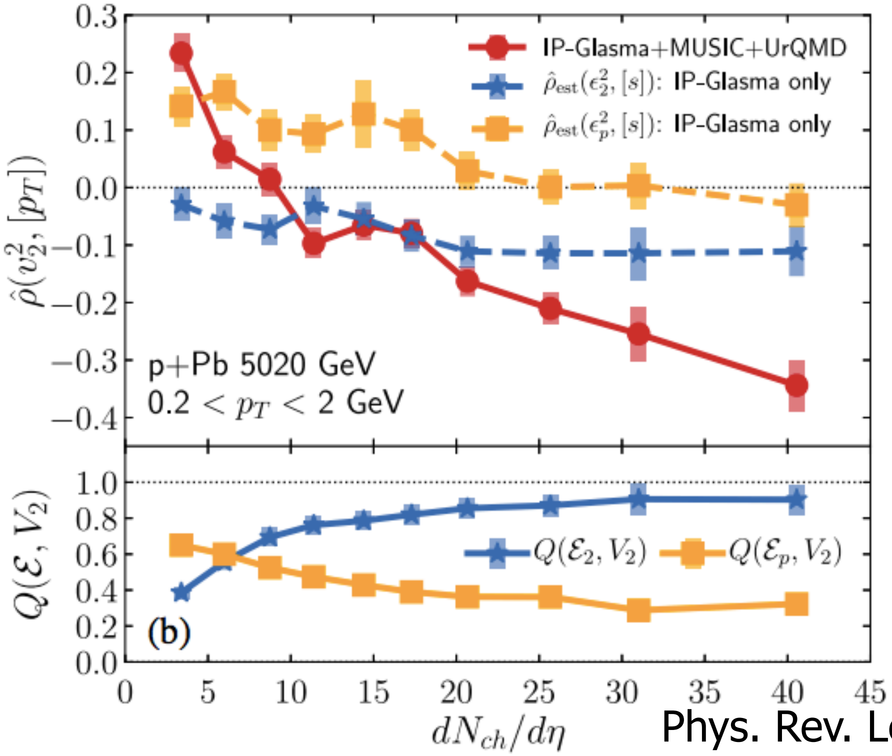


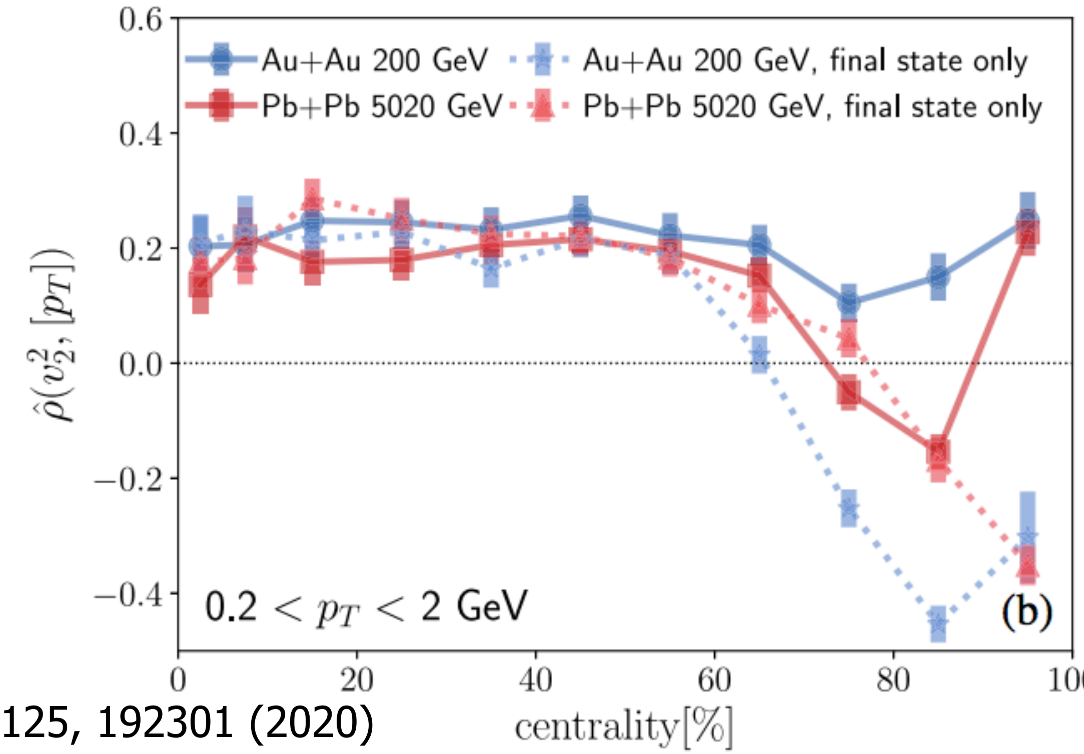


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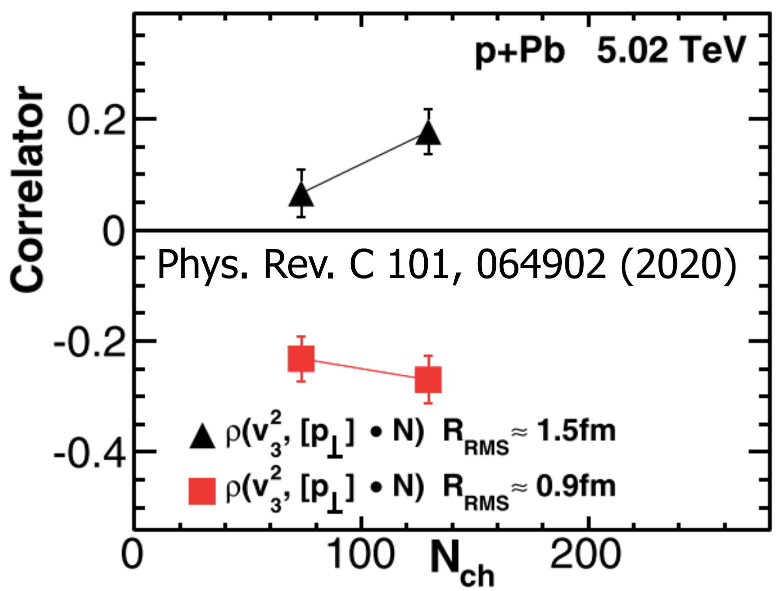
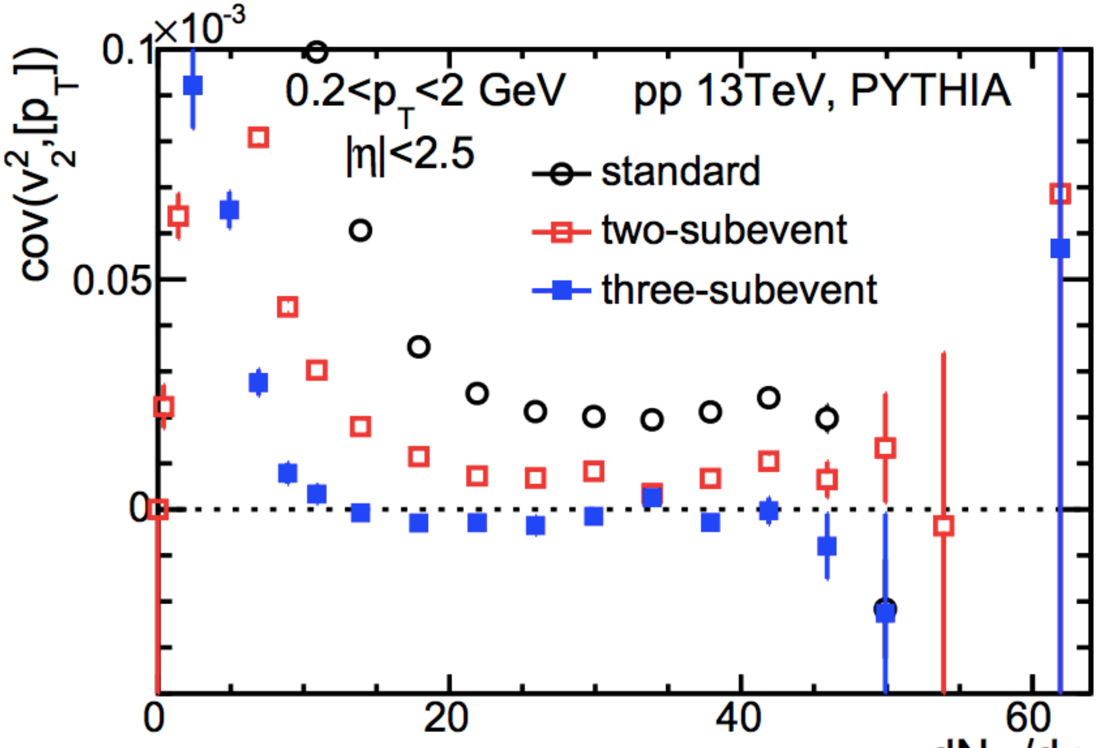


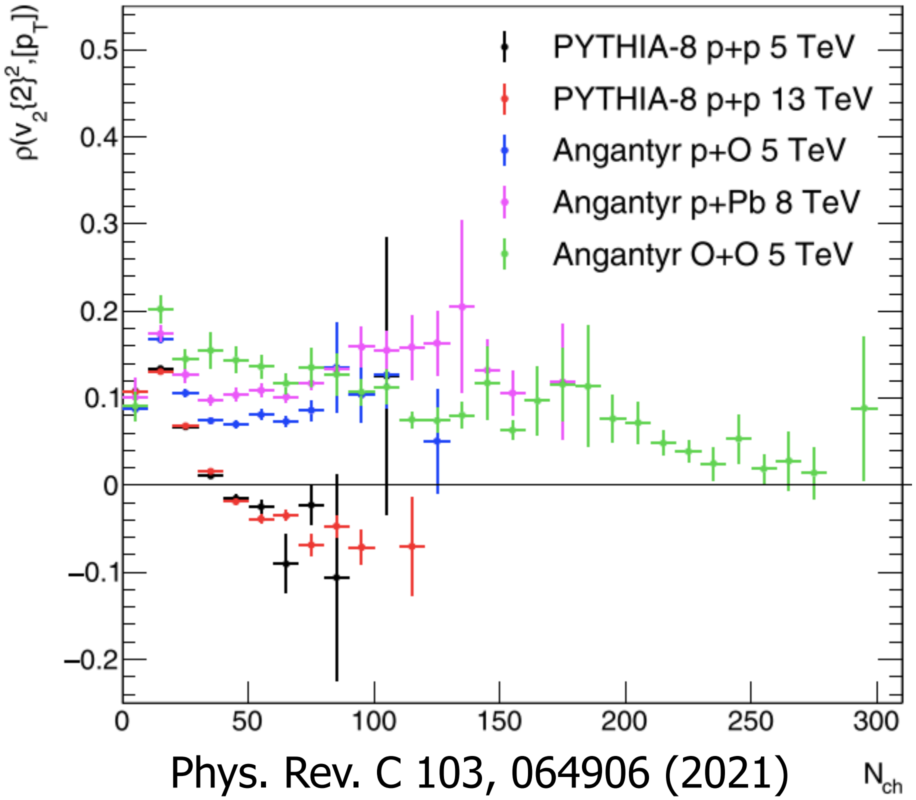

Phys. Rev. C 101, 064902 (2020)

- The correlations carry information about the origin of the observed momentum anisotropy
- No sign change at low multiplicity without initial $v_2$ from CGC
- Sensitive to the transverse size of the initial fireball

# MOTIVATIONS FOR SMALL SYSTEMS (2)




Phys. Lett. B 822 (2021) 136702



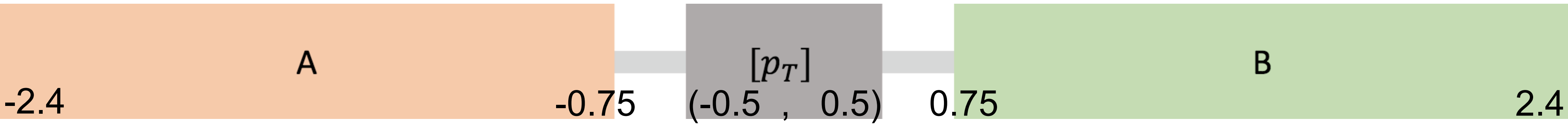

Phys. Rev. C 103, 064906 (2021)

- However, the correlations from PYTHIA alone have a sign change
- Nonflow has to be carefully subtracted
- Goal of this analysis:
    - Introduce a new variable to remove more nonflow
    - Search for sign change at lowest possible multiplicity in pp/pPb/PbPb collisions

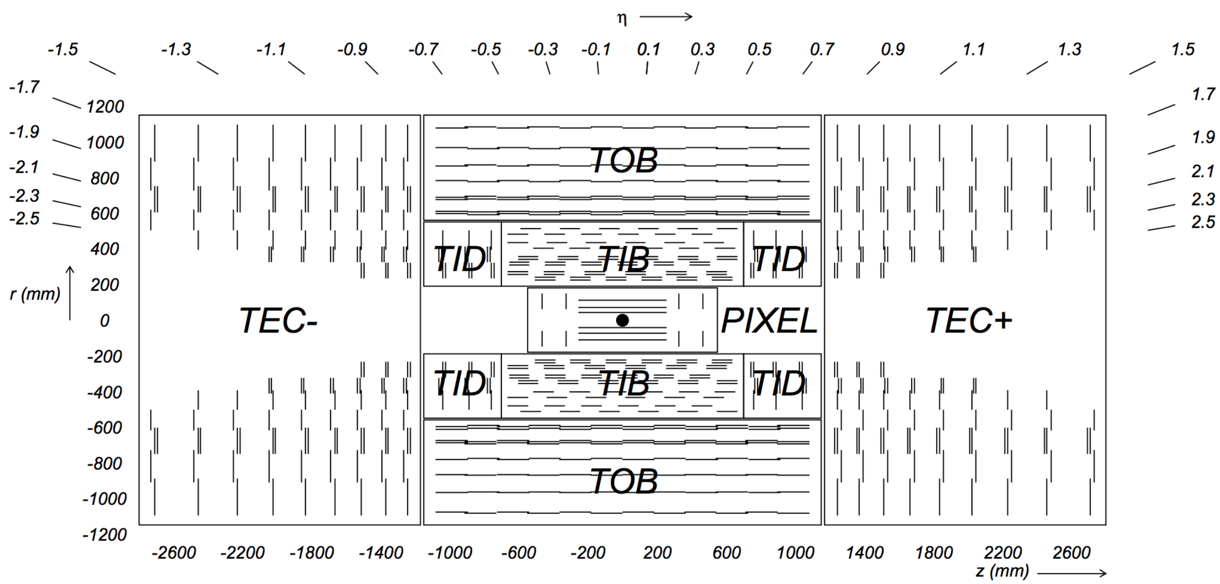
# ANALYSIS METHOD (1)

$$\rho(v_2^2, [p_\mathrm{T}]) = \frac{\mathrm{cov}(v_2^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_2^2)_{dyn}}\sqrt{\mathrm{Var}([p_\mathrm{T}])_{dyn}}} \quad (1)$$

$$\rho(c_2\{2\}, [p_\mathrm{T}])$$




Subevents A and B are used for calculation of $c_2\{2\}$; $|\eta|<0.5$ for $[p_\mathrm{T}]$




CMS Silicon Tracker, JINST 3 (2008) S08004

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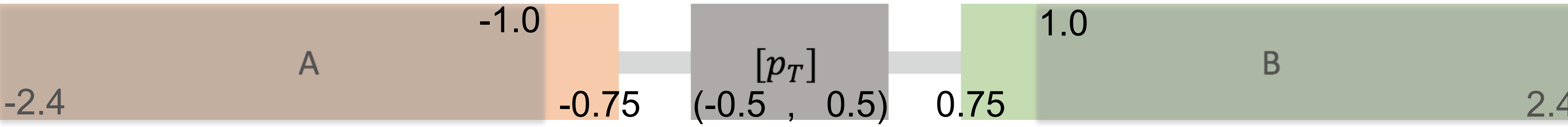


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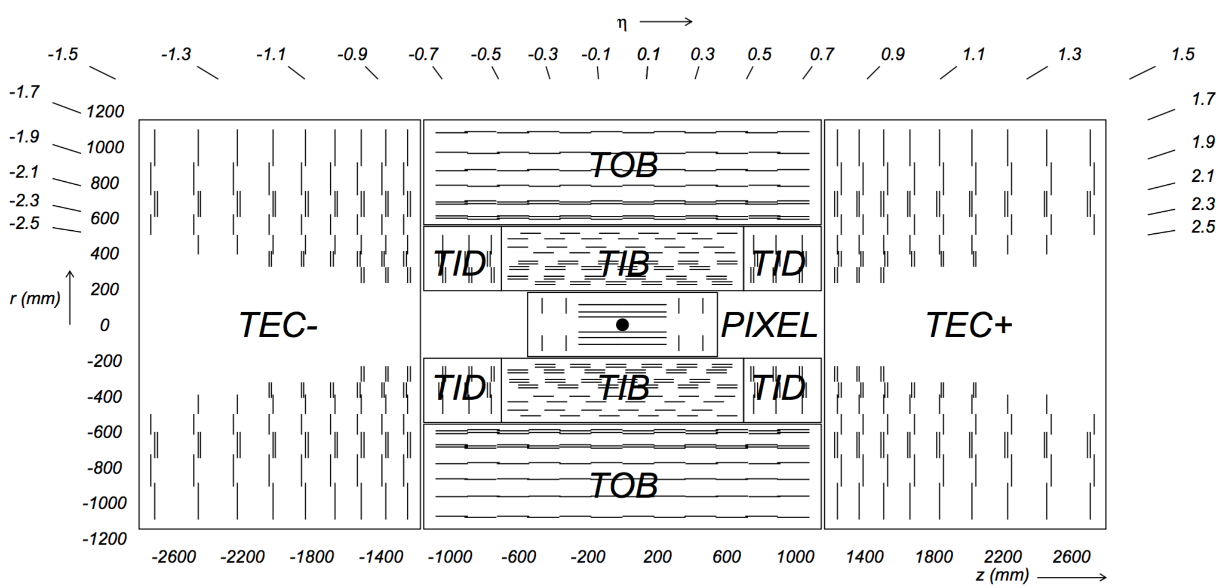


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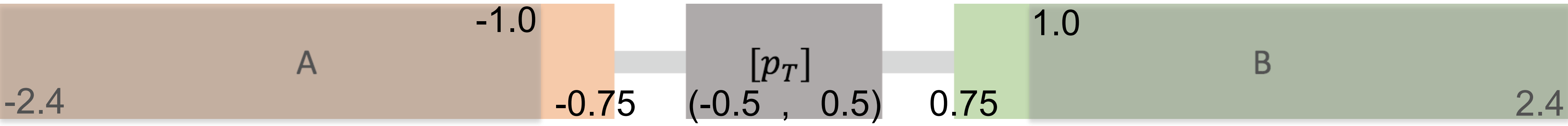



Subevents A and B are used for calculation of $c_2\{2\}$; $|\eta|<0.5$ for $[p_T]$

Covariance between $c_2\{2\}$ and $[p_T]$:

$$\mathrm{cov}(c_2\{2\}, [p_\mathrm{T}]) = \Re\mathfrak{e}\left\langle \sum_{a,b} \exp^{2i(\phi_a-\phi_b)} \left([p_\mathrm{T}] - \langle [p_\mathrm{T}] \rangle\right) \right\rangle \quad (2)$$

Dynamic variance of $c_2\{2\}$:

$$\mathrm{Var}(c_2\{2\})_{\mathrm{dyn}} = \langle\langle 4\rangle\rangle - \langle\langle 2\rangle\rangle^2 \quad (3)$$

Variance of $[p_T]$ from dynamic $[p_T]$ fluctuation $c_k$:

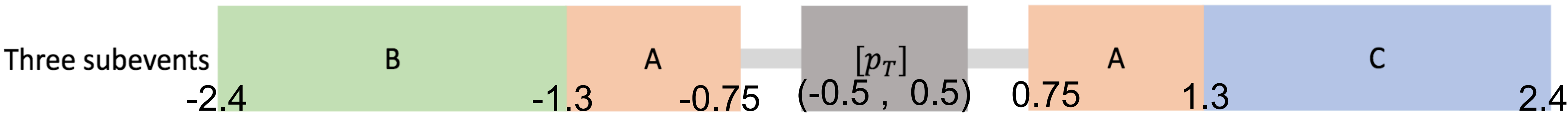
$$c_k = \left\langle \left[ (p_{\mathrm{T}i} - \langle [p_\mathrm{T}] \rangle)(p_{\mathrm{T}j} - \langle [p_\mathrm{T}] \rangle) \right] \right\rangle \quad (4)$$

# ANALYSIS METHOD (2)

$$\rho(v_2^2, [p_\mathrm{T}]) = \frac{\mathrm{cov}(v_2^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_2^2)_{dyn}}\sqrt{\mathrm{Var}([p_\mathrm{T}])_{dyn}}} \quad (1)$$

Extend and study the new variable to remove more nonflow

$$\rho(c_2\{2\}, [p_\mathrm{T}]) \rightarrow \rho(c_2\{4\}, [p_\mathrm{T}])$$




$c_2\{4\}$ is analyzed with three subevent method

$$c_2\{4\}_{3\text{-sub}} = \langle 4\rangle_{a,a|b,c} - 2\langle 2\rangle_{a|b}\langle 2\rangle_{a|c}$$

Phys. Rev. C 96, 034906 (2017)

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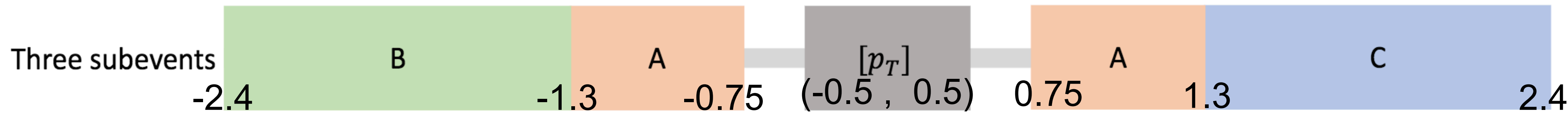


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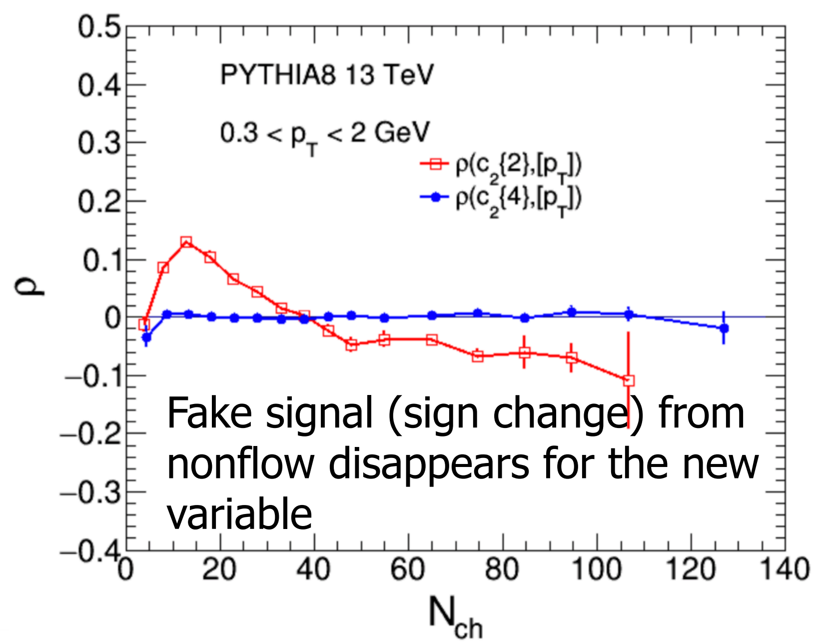


# Observables in this analysis

- This analysis focuses on small systems
- It is the first paper to :
  - use multiparticle correlations for flow when correlating with $[p_T]$
  - explore the correlator with different $\eta$ gaps to study nonflow effects
  - measure $v_3$ - $[p_T]$ correlations in small systems
  - include measurements in pp collisions

# Results

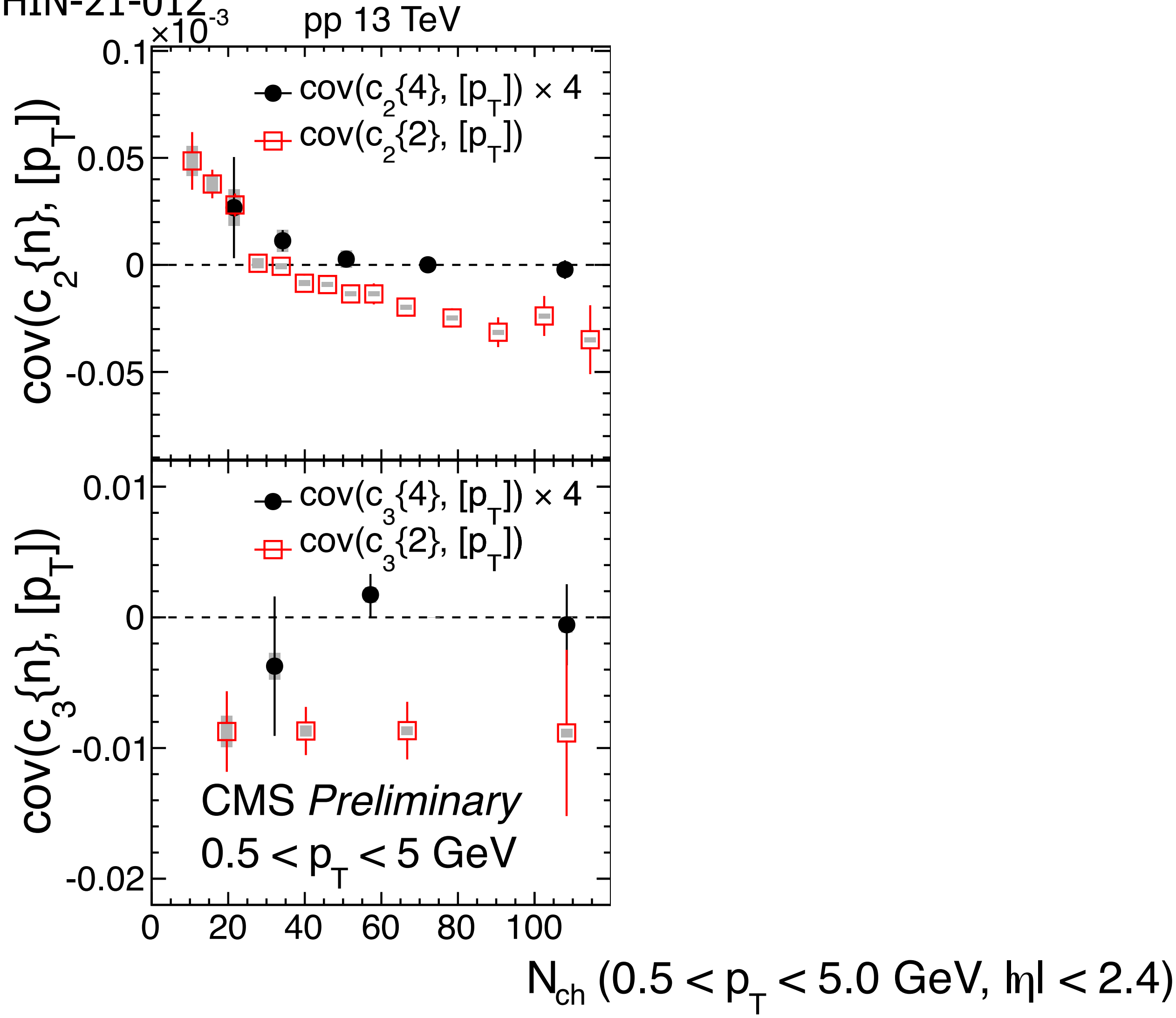
Results are presented as a function of $N_{ch}$, which is defined in $0.5<p_T<5.0$ GeV, $|\eta|<2.4$, and corrected for tracking efficiency

# RESULTS FOR COVARIANCE

CMS-PAS-HIN-21-012

n=2

n=3




- Clear sign change for pp collisions with $c_2\{2\}$
- No sign change at low $N_{ch}$ using multiparticle correlations with current statistics
- The sign of the normalized correlator is determined by the covariance

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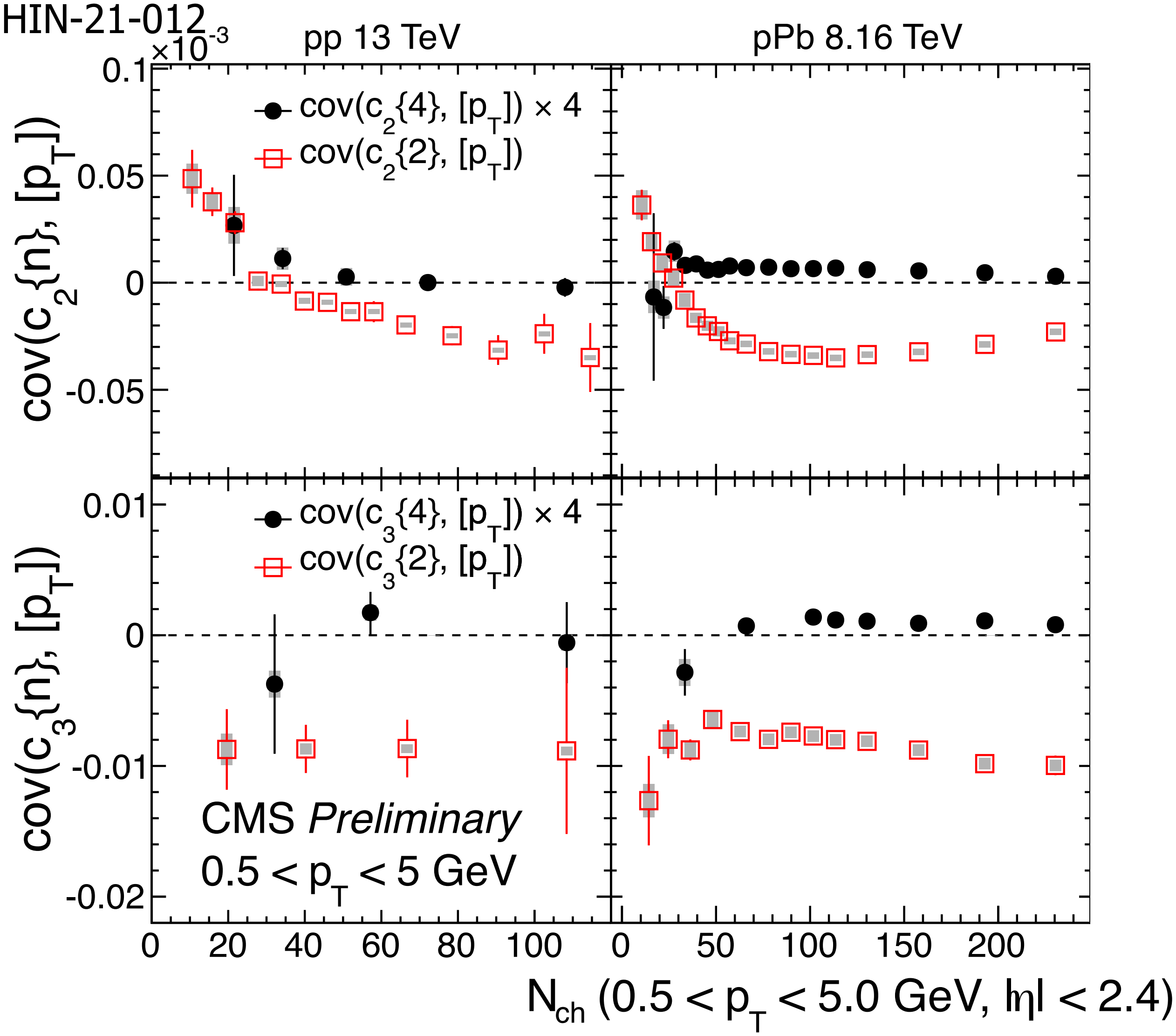


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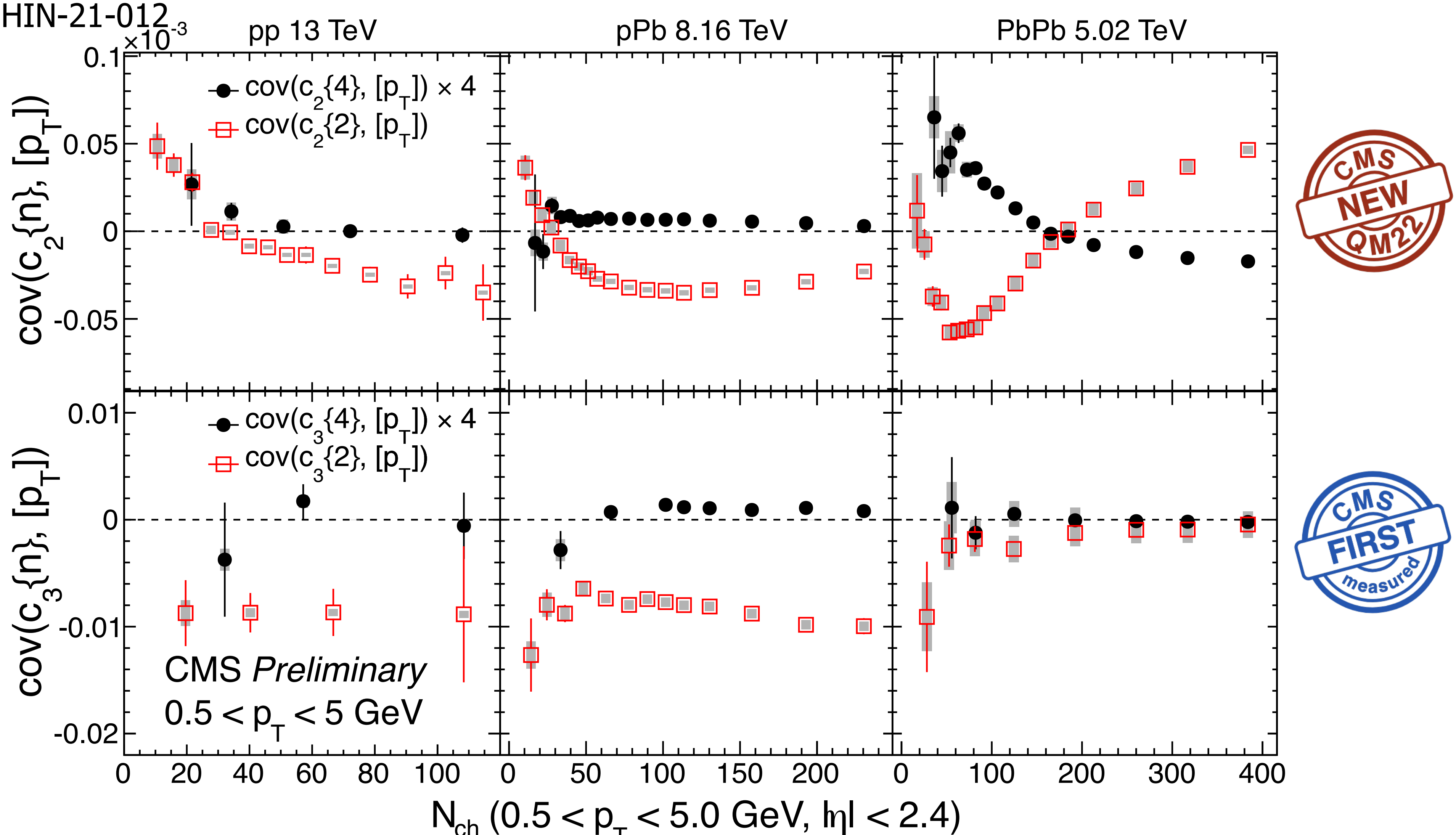


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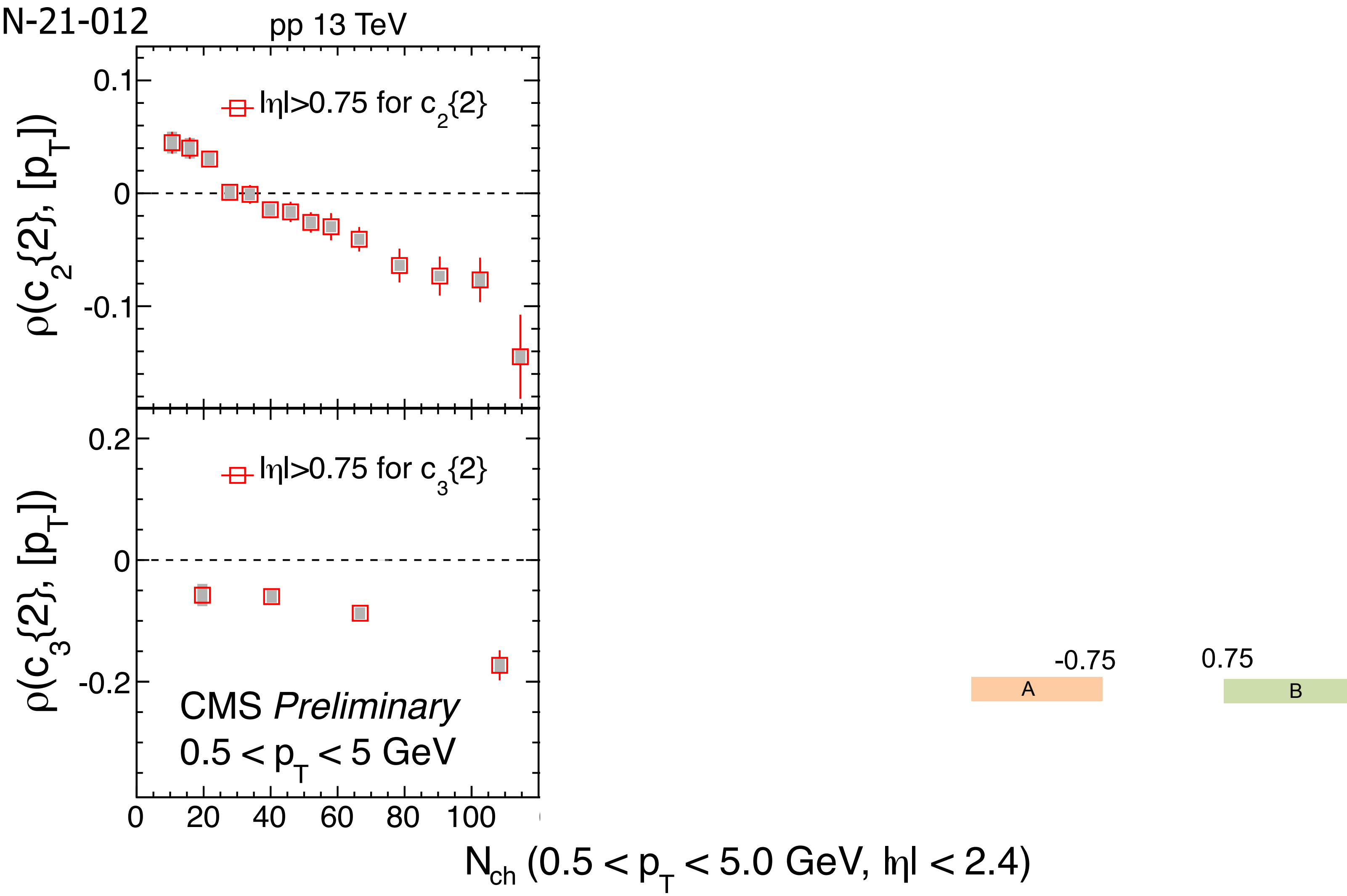


- Apparent sign change for $\rho(c_2\{2\}, [p_T])$ in pp collisions

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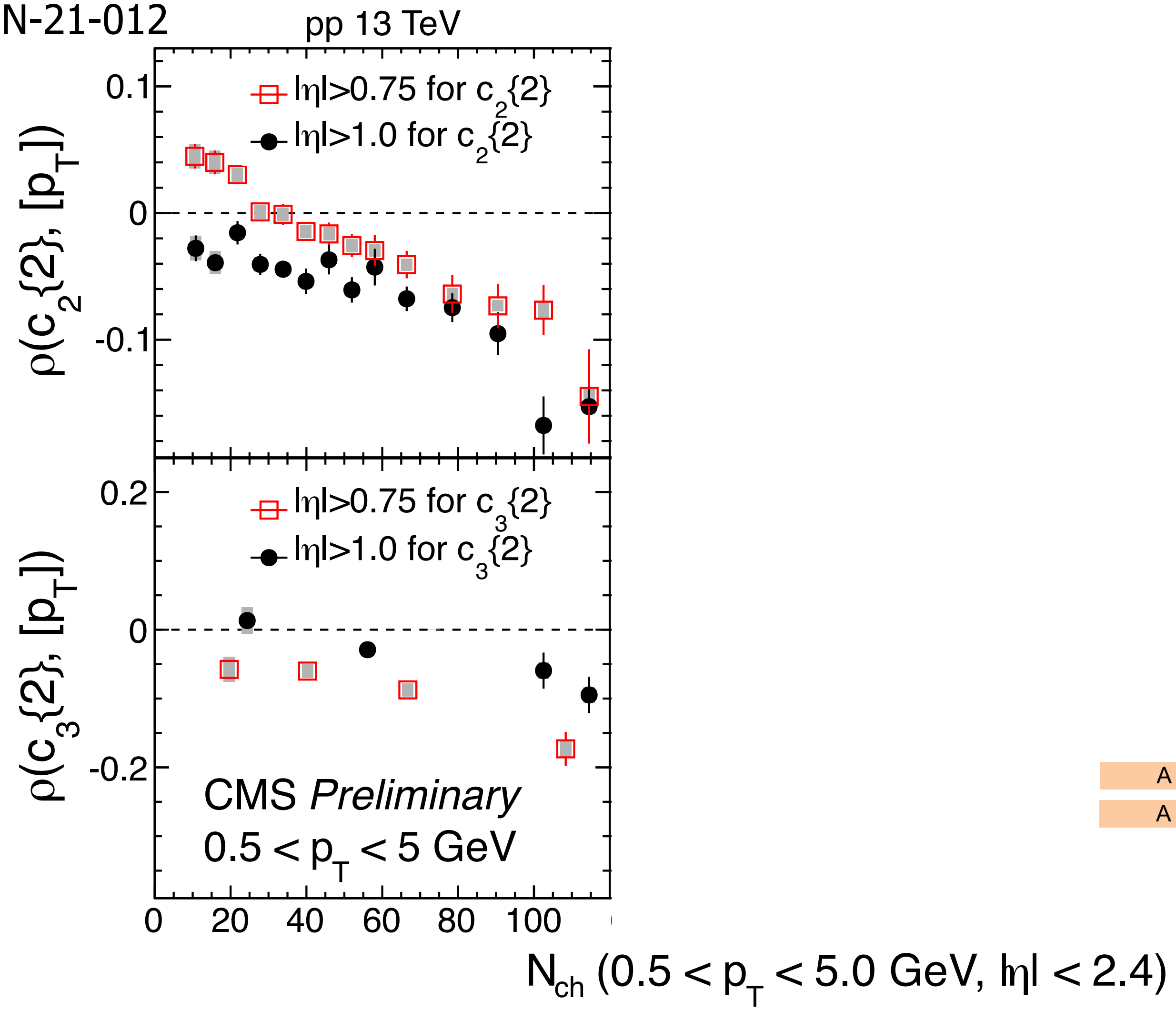


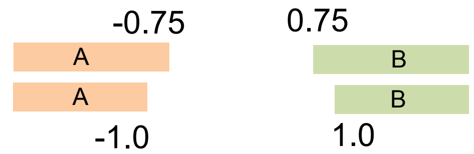


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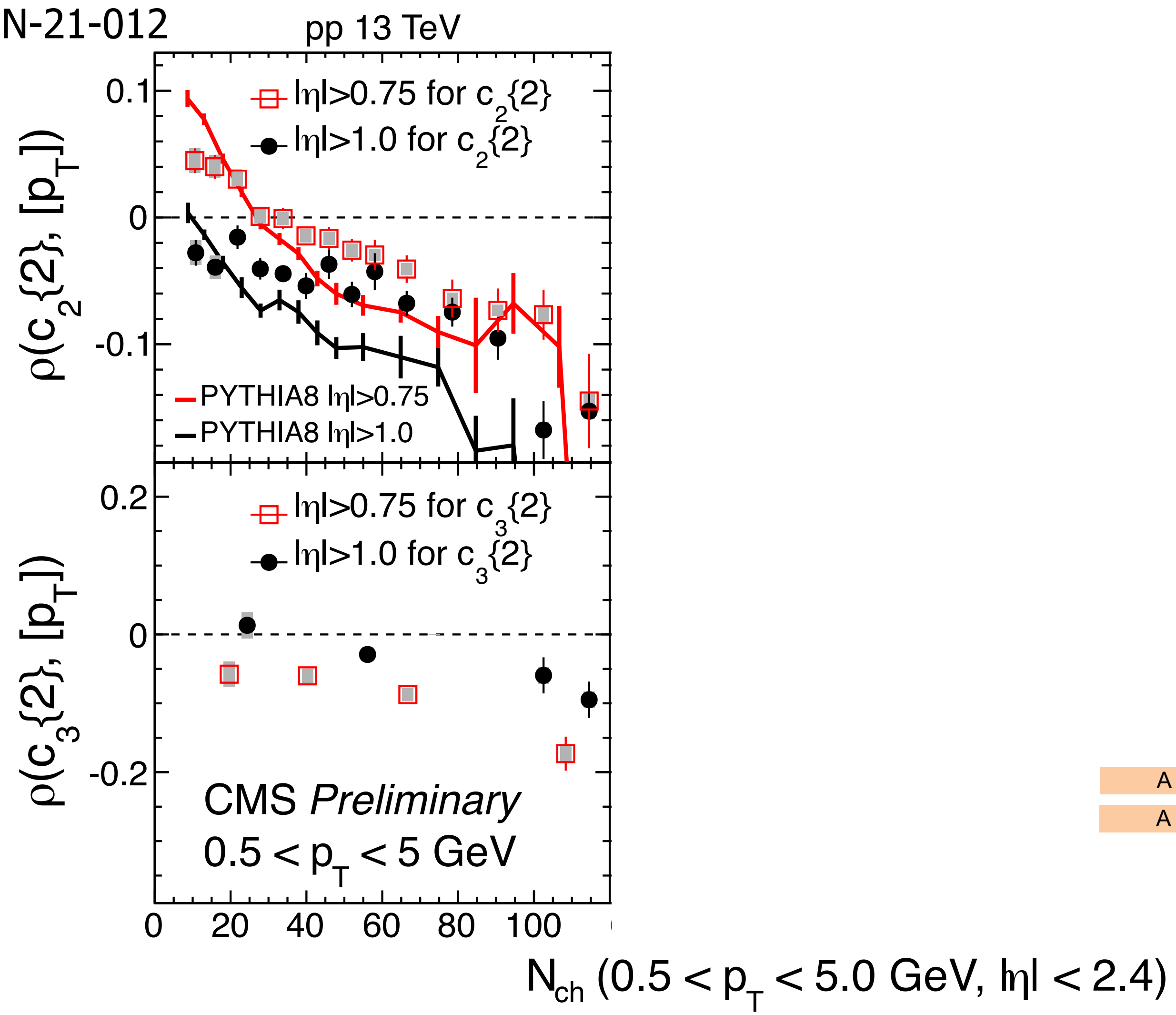


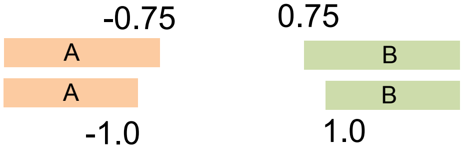


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- Also true for PYTHIA8 events

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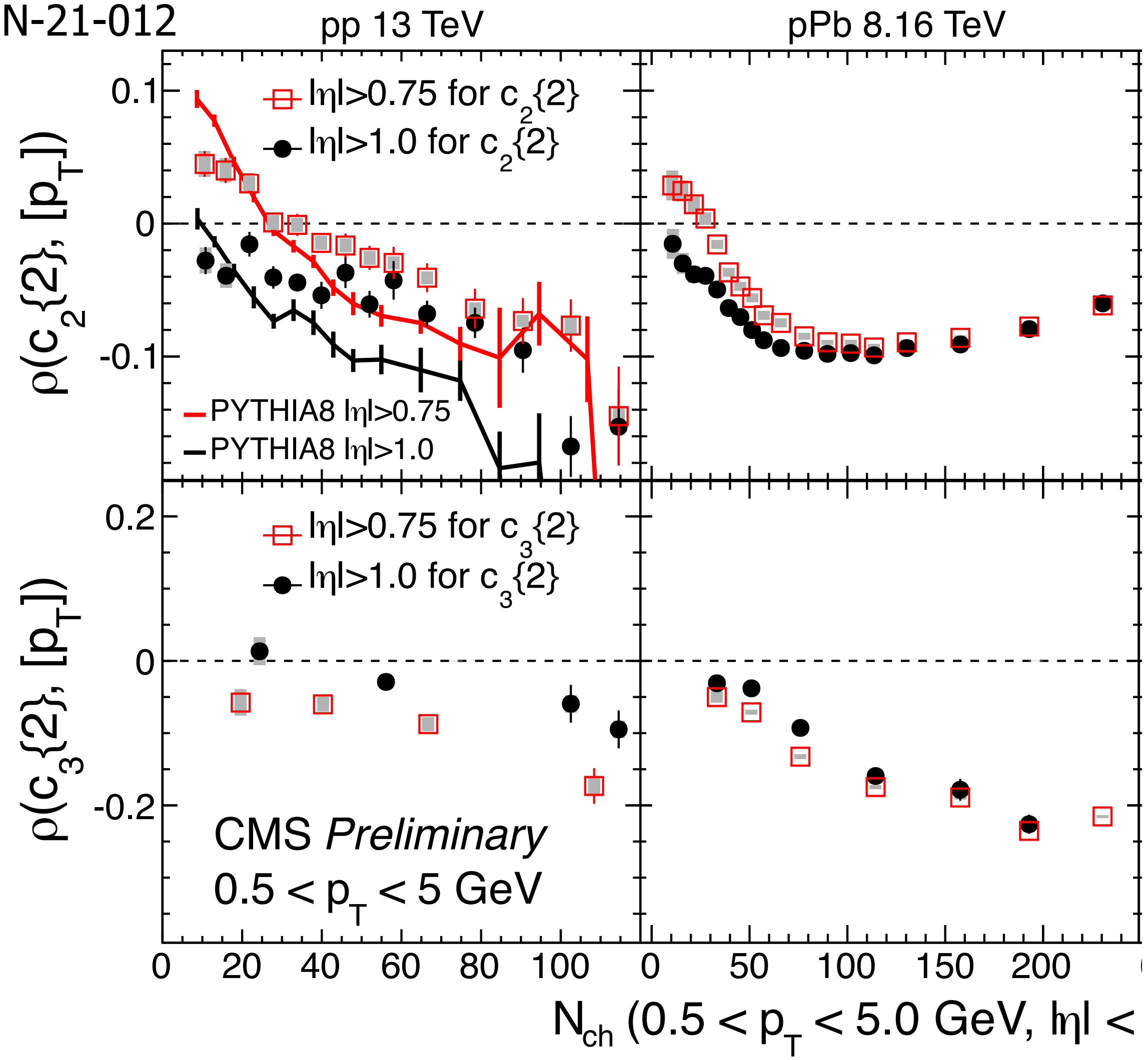


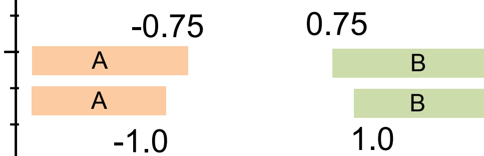


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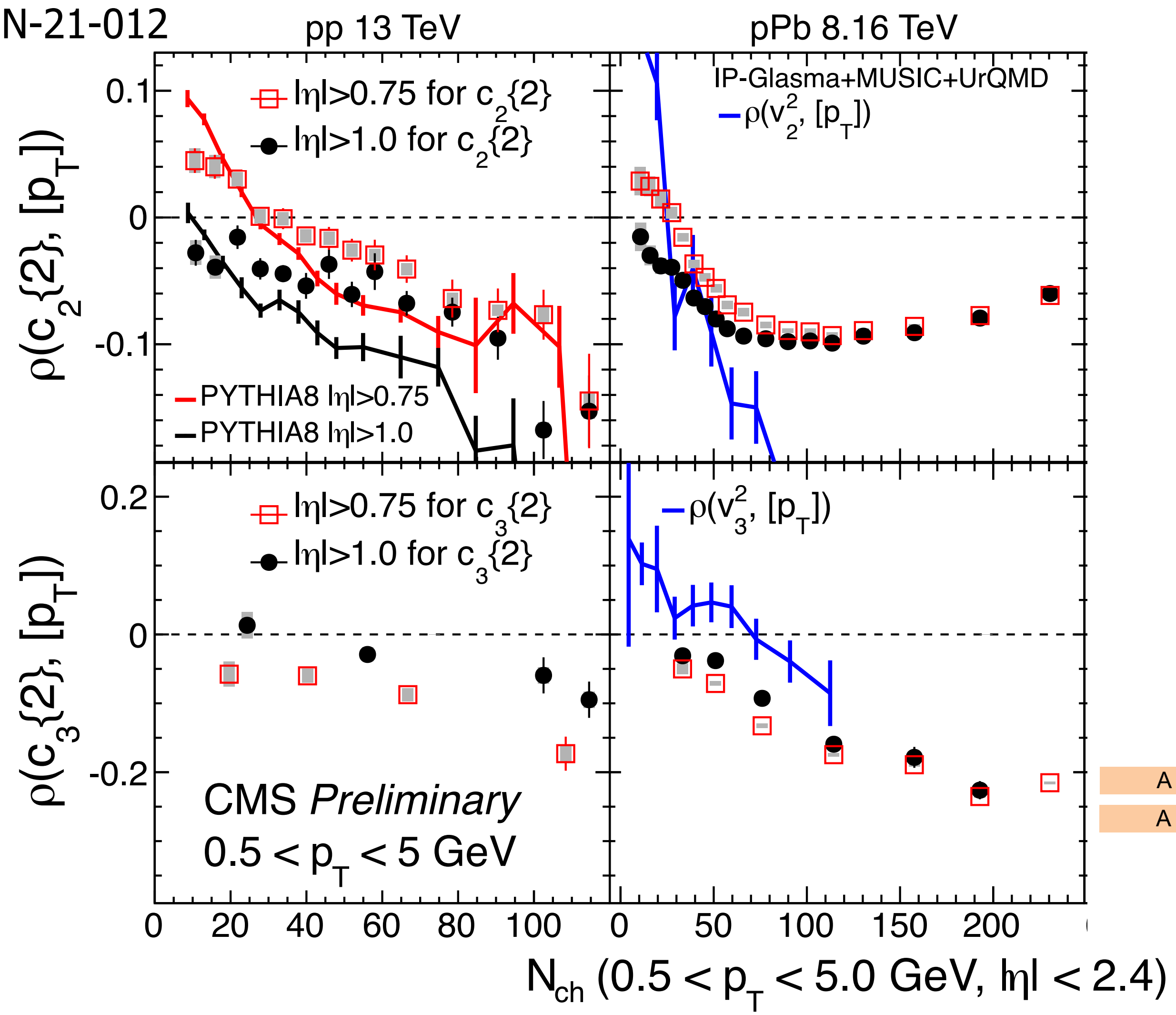


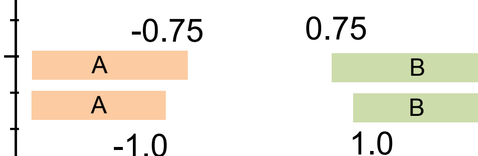


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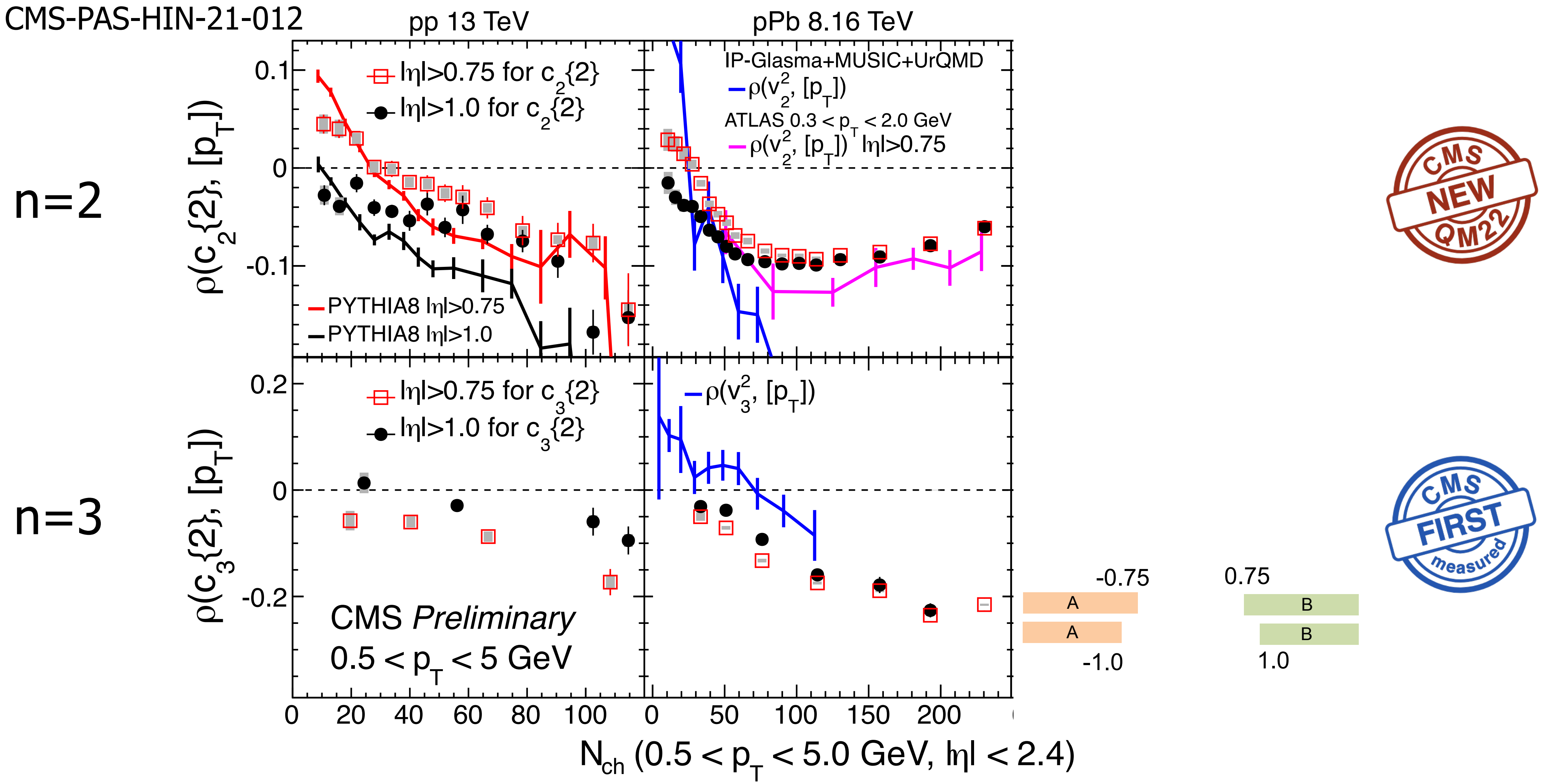


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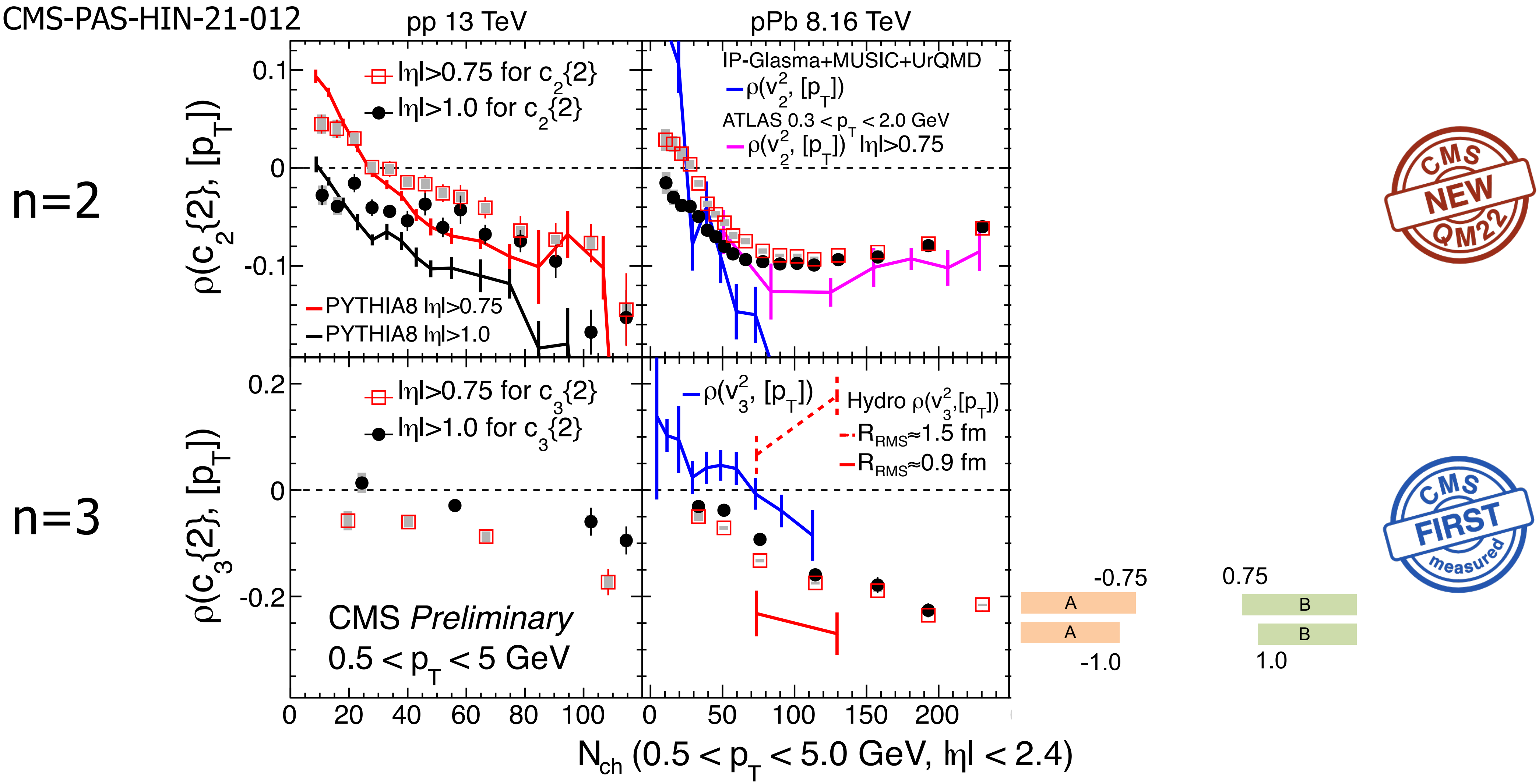


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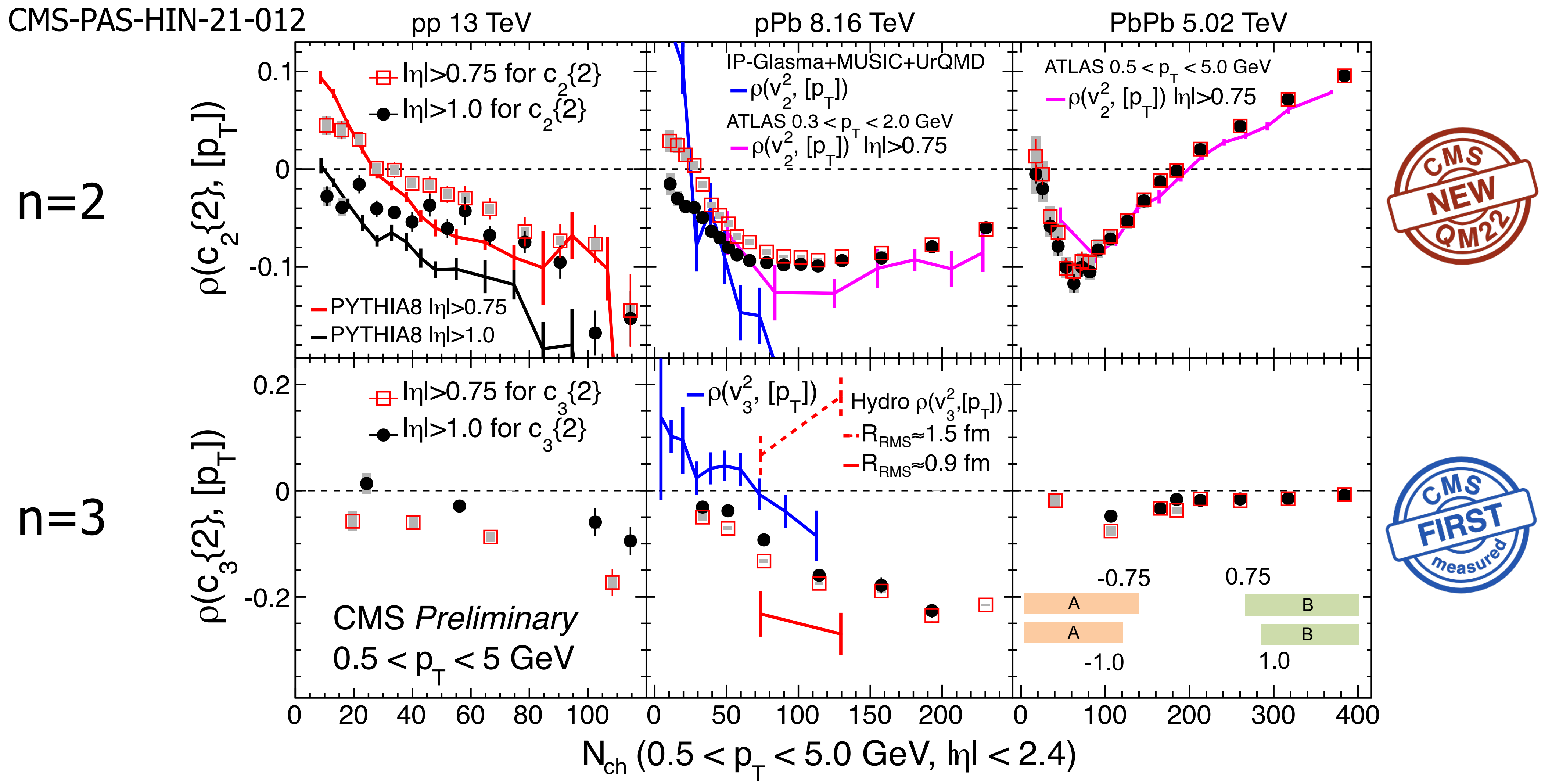


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# SUMMARY

- For the first time, the correlations between $[p_T]$ and cumulants from both two- and four-particle correlations in small systems are presented
- Apparent sign change is observed for $\rho(c_2\{2\}, [p_T])$ in pp and pPb
- However, no sign change is observed with larger η gap in $c_2\{2\}$
    - ATLAS default is $|\eta|>0.75$, with $|\Delta\eta|>1.5$
    - ALICE default is $|\eta|>0.4$, with $|\Delta\eta|>0.8$
    - CMS is studying both $|\eta|>0.75$ ($|\Delta\eta|>1.5$) and $|\eta|>1.0$ ($|\Delta\eta|>2.0$)
- After removing more nonflow with both two- and four-particle correlation cumulants, there is no evidence of CGC in data
- These high-precision data and the observables employing multiparticle correlations should provide new insight into the origin of azimuthal anisotropy in small collision systems

# Backup

# ANALYSIS METHOD (3)

$$\rho(v_2^2,[p_\mathrm{T}]) = \frac{\mathrm{cov}(v_2^2,[p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_2^2)}\sqrt{\mathrm{Var}([p_\mathrm{T}])}} \quad (1)$$

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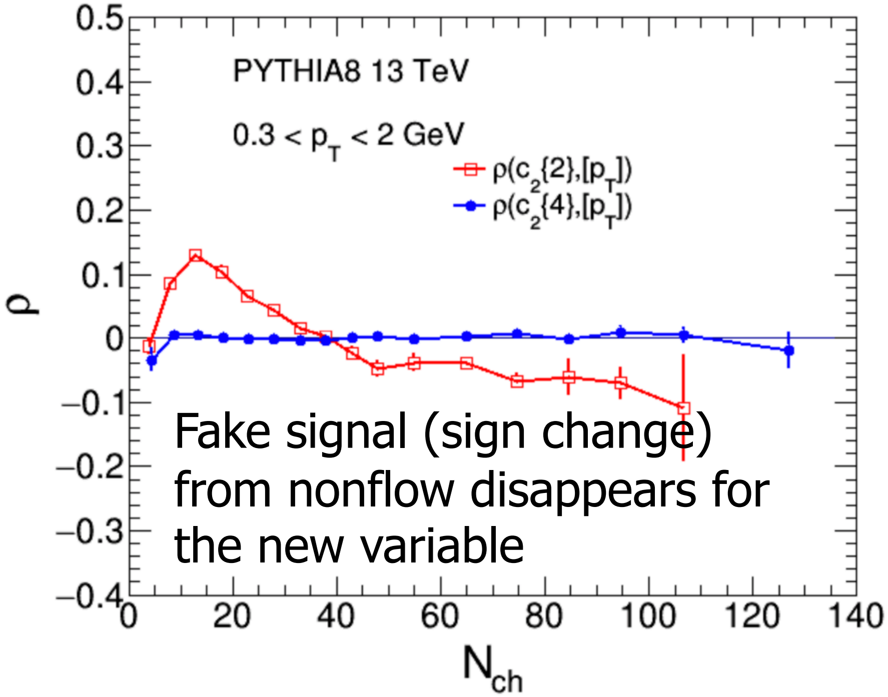
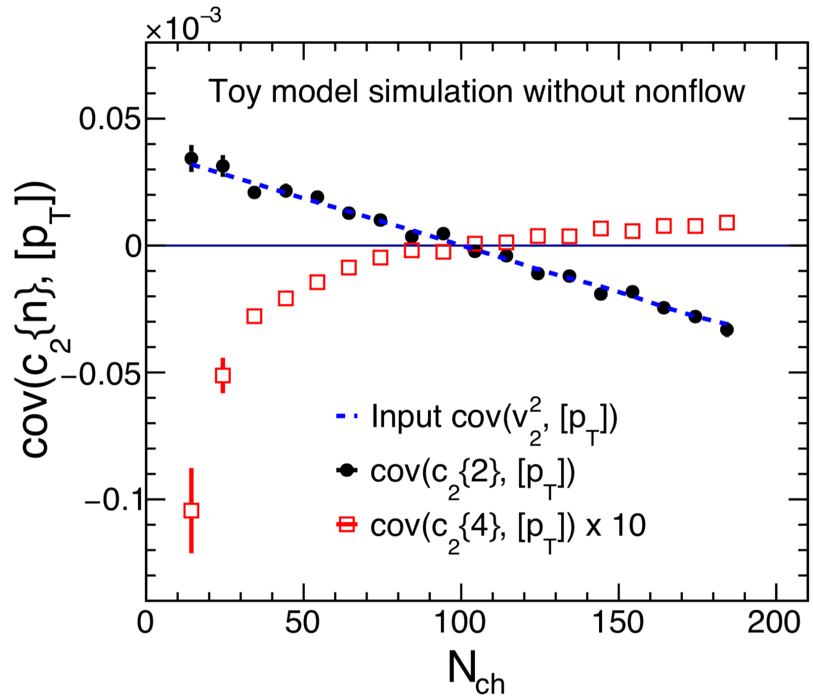


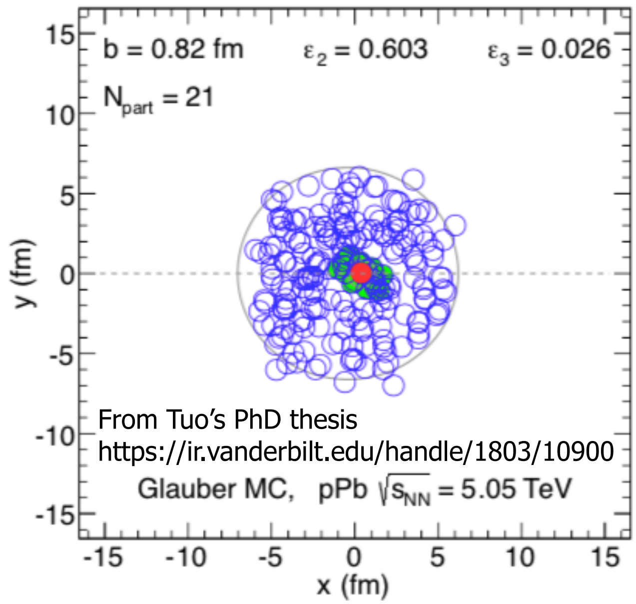



# DYNAMIC FLOW FLUCTUATIONS

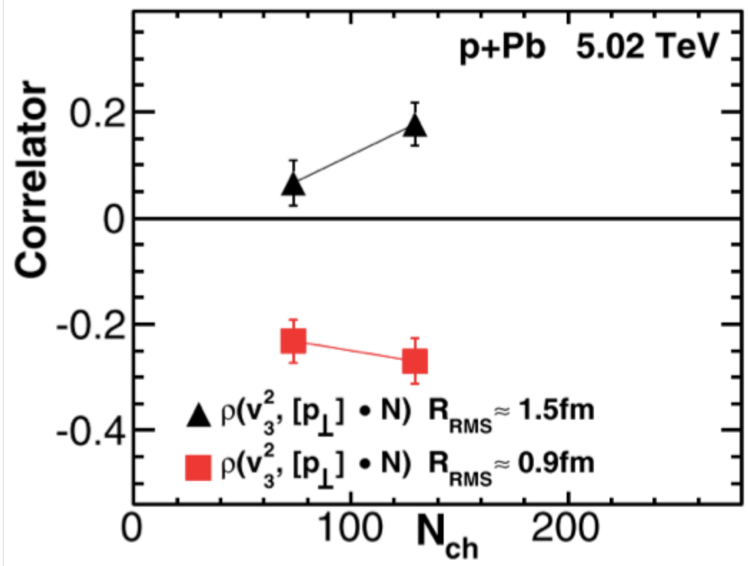
Keeping $\mathrm{cov}(c_2\{4\}, [p_T])$ but drop $\rho(c_2\{4\}, [p_T])$ in this analysis

- The reason is we are not 100% sure if the variance $\mathrm{Var}(c_2\{4\})_{dyn}$ in our new method is truly dynamic
- It may contain statistical fluctuations in our current method
- The measurement of $v_n$ fluctuation in small systems is a task our community has not accomplished. The event-by-event $v_n$ studies all stopped at 60-70% centrality in AA collisions

# HYDRODYNAMIC PREDICTION IN PPB FOR N=3




Average transverse size of the fireball in pPb collisions:
Is it close to $R_{RMS}$ = 1.5 fm or 0.9 fm?

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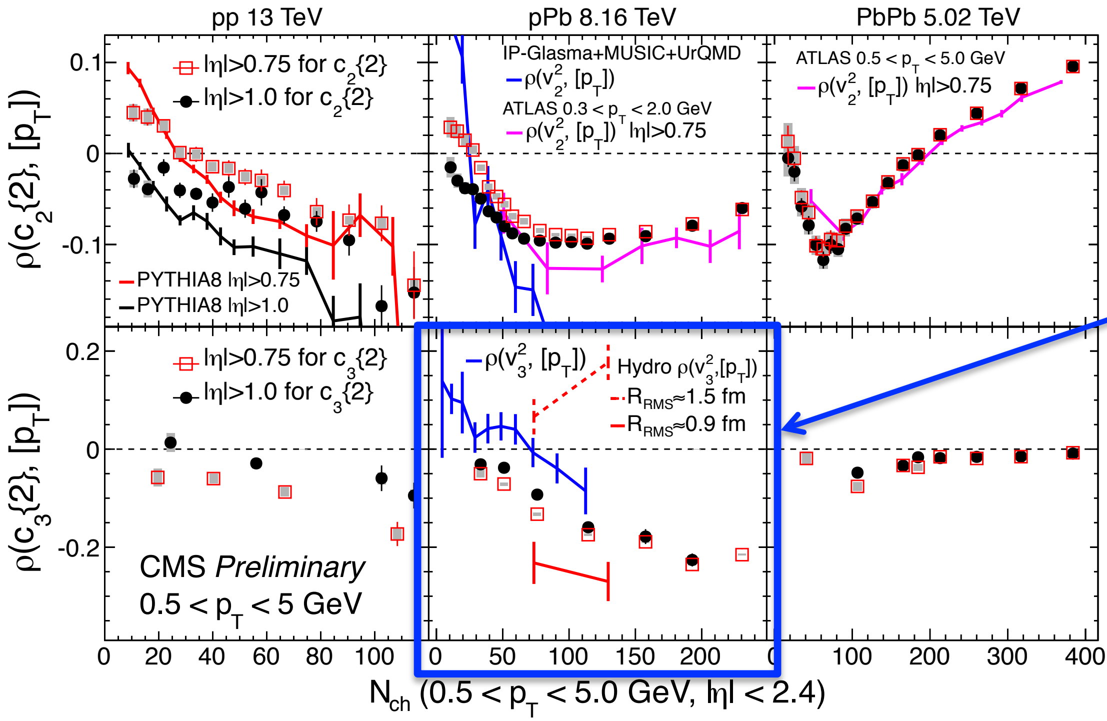



- The data are qualitatively better described by the smaller initial fireball

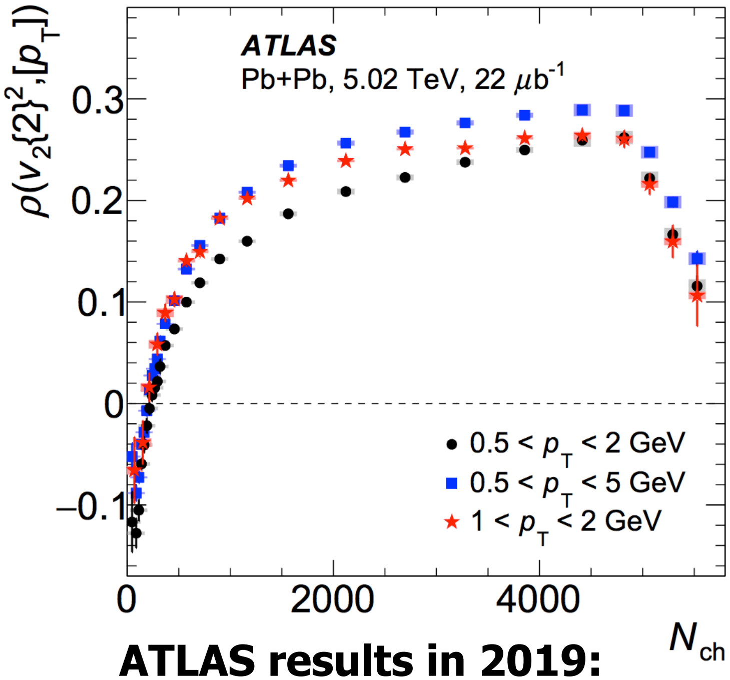
# MAPPING BETWEEN $N_{CH}$ AND $N_{TRK}^{OFFLINE}$

Table 1: Average multiplicity of reconstructed tracks per $N_{ch}^{rec}$ bin for $N_{ch}$ and $N_{trk}^{offline}$ in pp, pPb, and PbPb collisions. Uncertainties for the tracking efficiency corrected $N_{ch}$ are included.

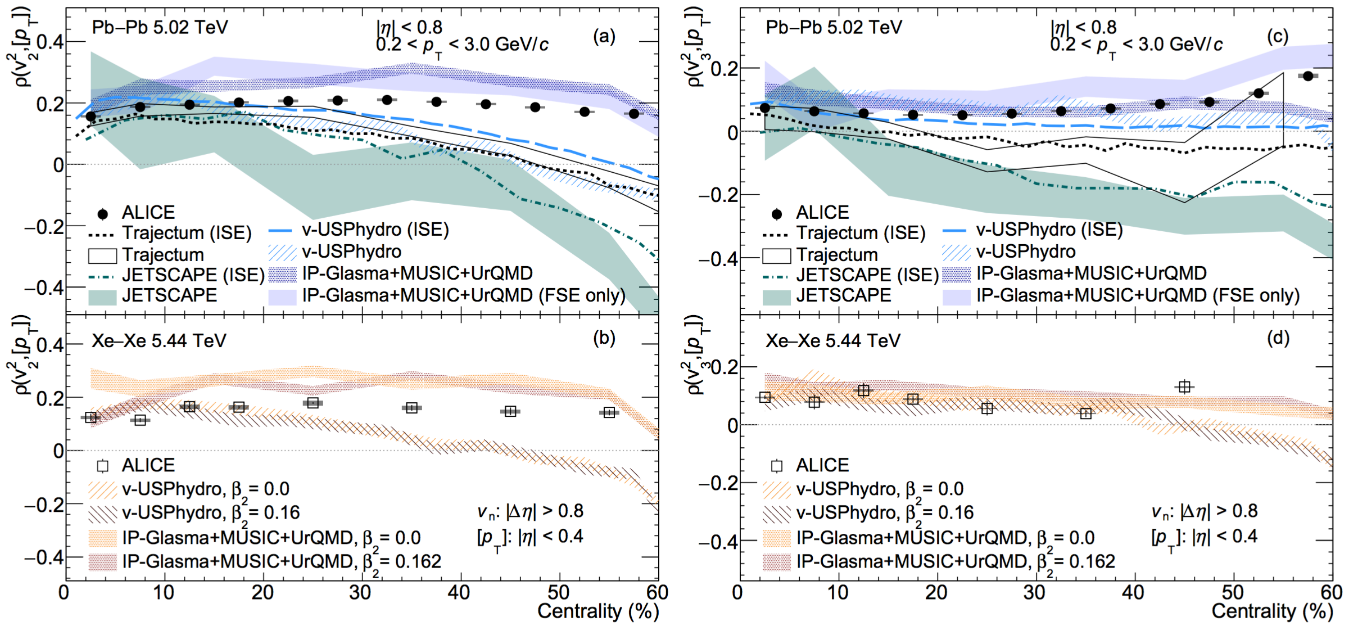
| | pp | | pPb | | PbPb | |
|---|---|---|---|---|---|---|
| $N_{ch}^{rec}$ range | $\langle N_{ch} \rangle$ | $\langle N_{trk}^{offline} \rangle$ | $\langle N_{ch} \rangle$ | $\langle N_{trk}^{offline} \rangle$ | $\langle N_{ch} \rangle$ | $\langle N_{trk}^{offline} \rangle$ |
| [0, 20) | 8±0.3 | 9 | 11±0.4 | 12 | 16±0.6 | 14 |
| [20, 40) | 34±1 | 34 | 36±1 | 36 | 57±2 | 48 |
| [40, 60) | 58±2 | 56 | 60±2 | 60 | 96±4 | 80 |
| [60, 80) | 82±3 | 78 | 83±3 | 82 | 135±5 | 112 |
| [80, 100) | 106±4 | 101 | 107±4 | 105 | 175±7 | 144 |
| [100, 150) | 132±5 | 125 | 140±6 | 137 | 240±10 | 197 |
| [150, 200) | | | 198±8 | 191 | 335±13 | 276 |
| [200, 250) | | | 256±10 | 246 | 434±17 | 353 |
| [250, 300) | | | | | 535±21 | 426 |

- The mapping table between $N_{ch}$ and $N_{trk}^{offline}$

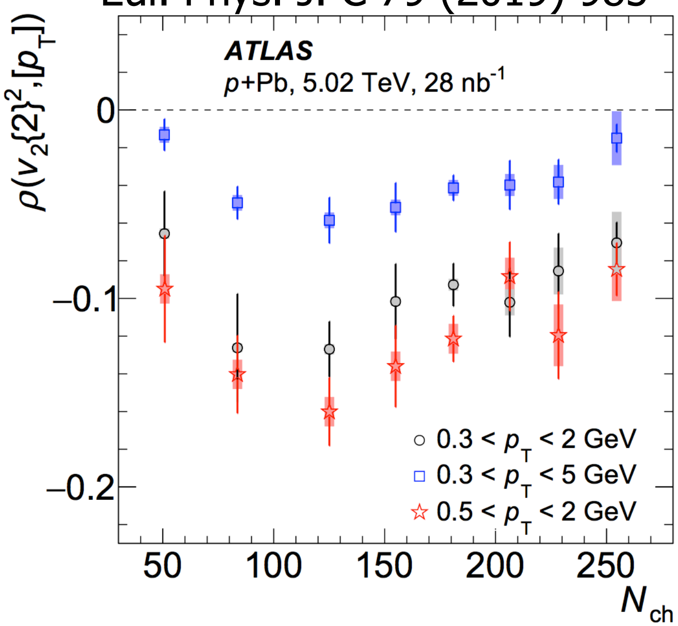
# EXISTING MEASUREMENTS




**ALICE:** arXiv:2111.06106 submitted to PRL




**ATLAS results in 2019:**
Eur. Phys. J. C 79 (2019) 985




- ATLAS results in pPb, PbPb, and XeXe collisions
- ALICE results in PbPb and XeXe collisions
- Some recent studies from STAR