LHCPhysics
Belgrade, 22 - 26 May 2023

Flow and correlations measurements in small and large systems

Highlights from ALICE, CMS, and ATLAS

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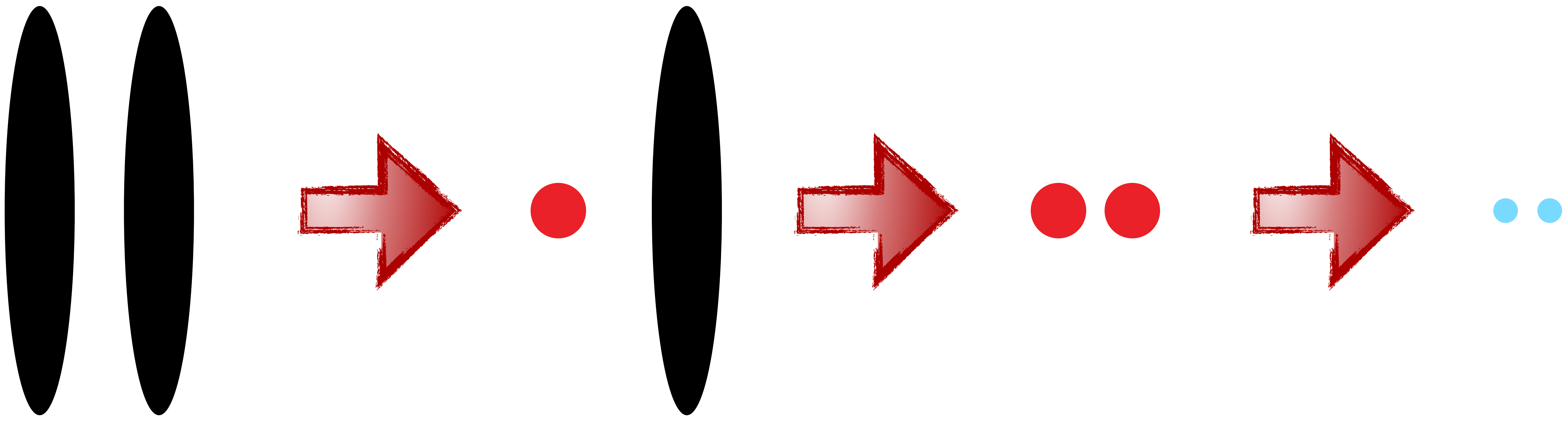
Westfälische Wilhelms-Universität,Münster

LHCP, 22.05.2023

From large to small systems

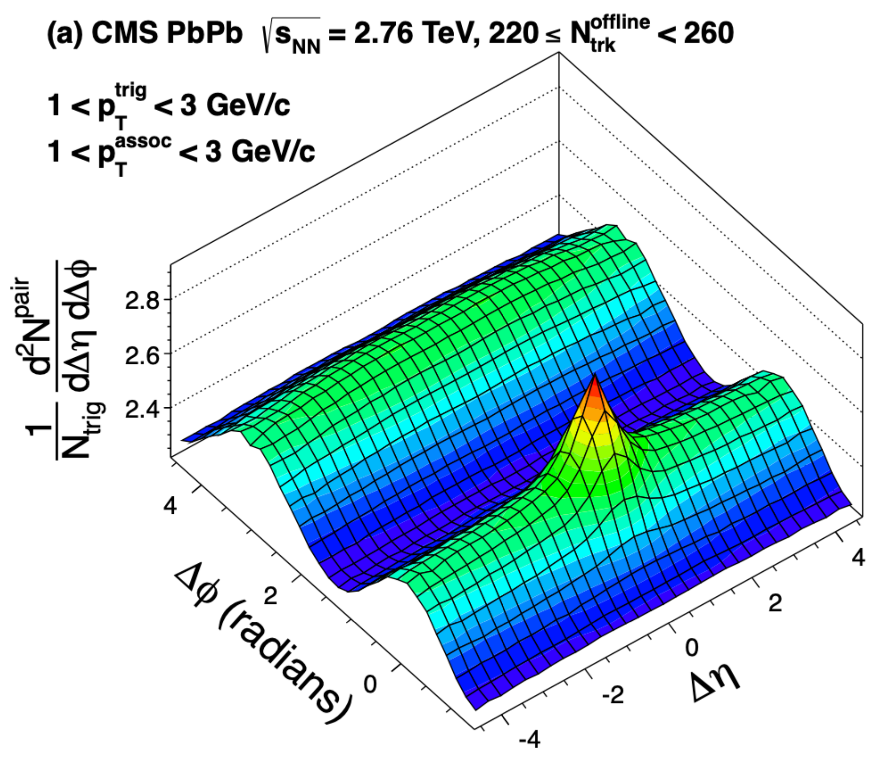


Pb—Pb

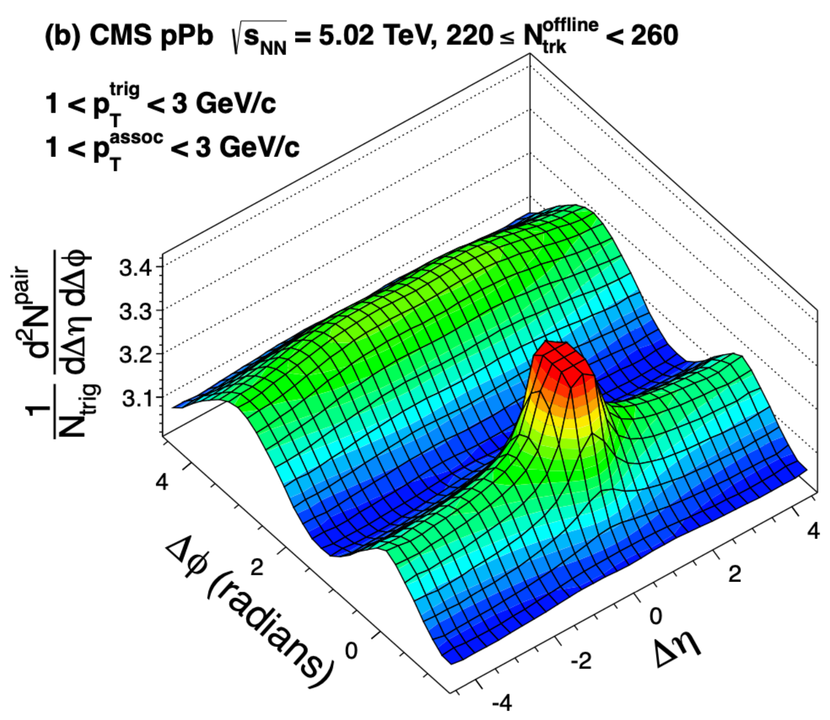
p—Pb

pp

$(e^{+}e^{-})$



Phys. Lett. B 724 (2013) 213



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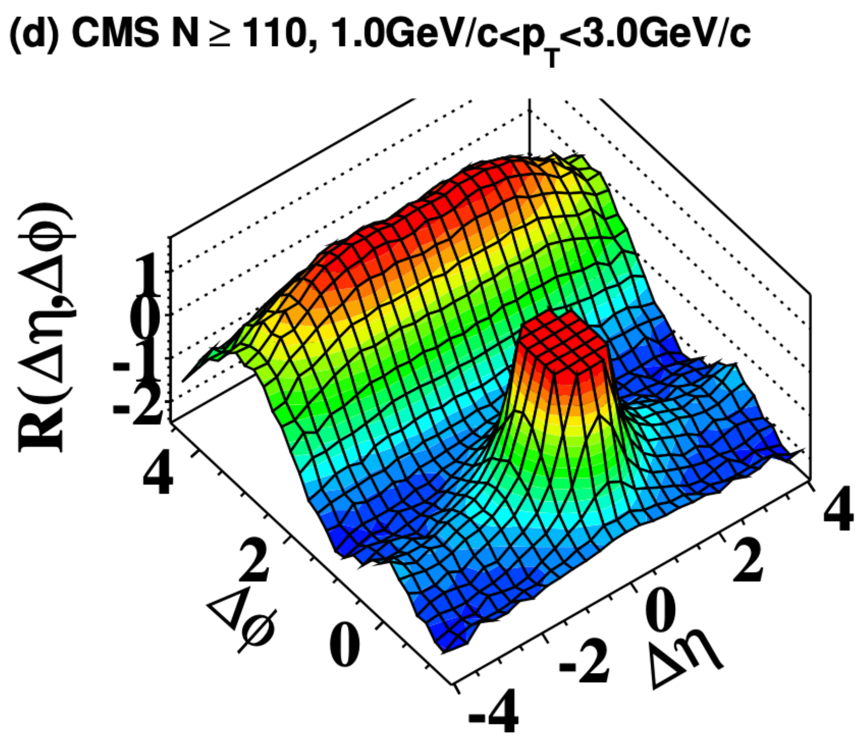
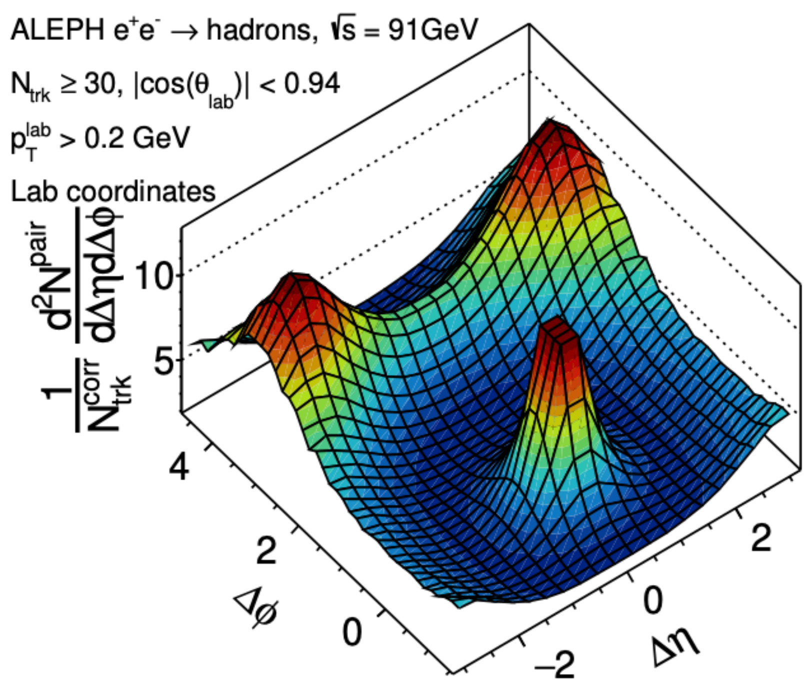
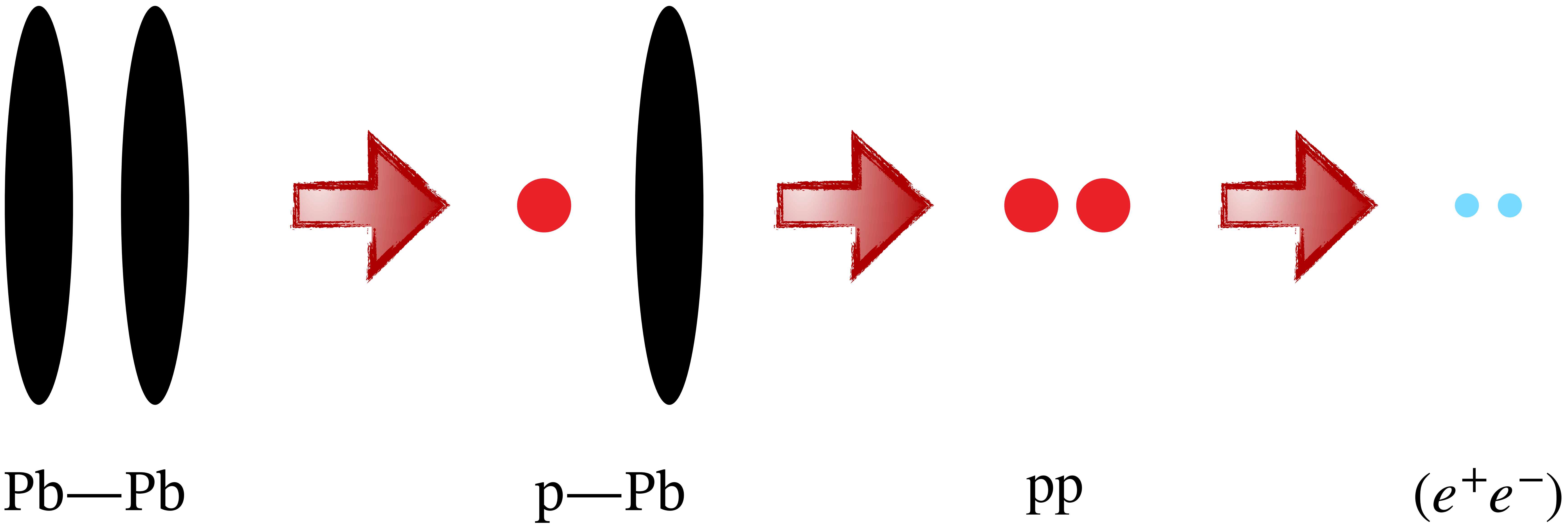


JHEP 1009:091,2010



Phys. Rev. Lett. 123, 212002 (2019)

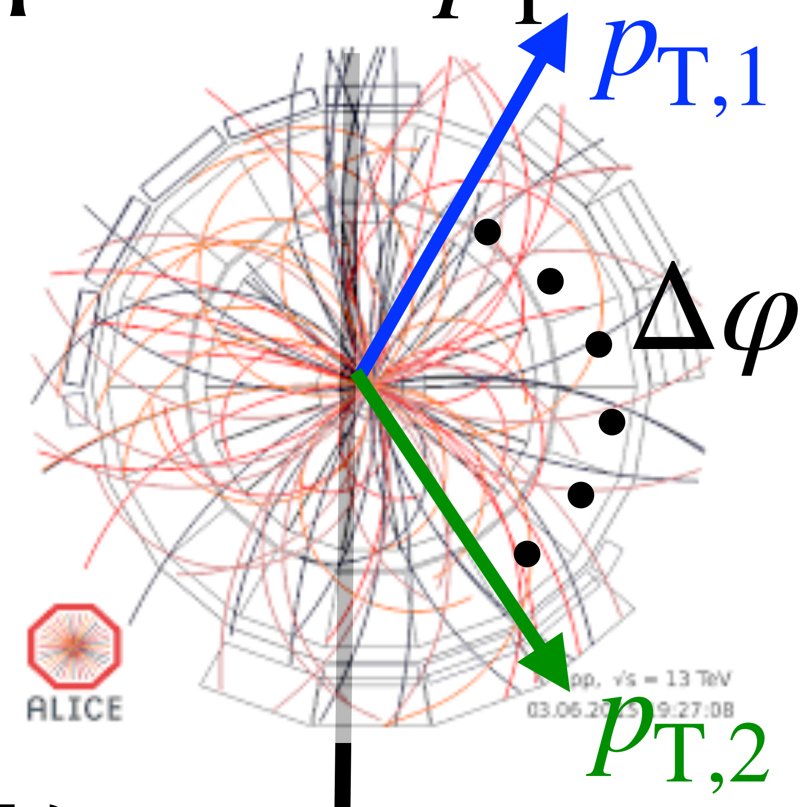
From large to small systems



- What are the properties of the QGP medium, mechanisms of parton energy loss and hadronisation?
- What is the origin of collective-like behaviour in small collisions systems?
- What is the lower limit of the collective-like behaviour?

Correlation functions

Soft particles $p_T < 2$ GeV/c

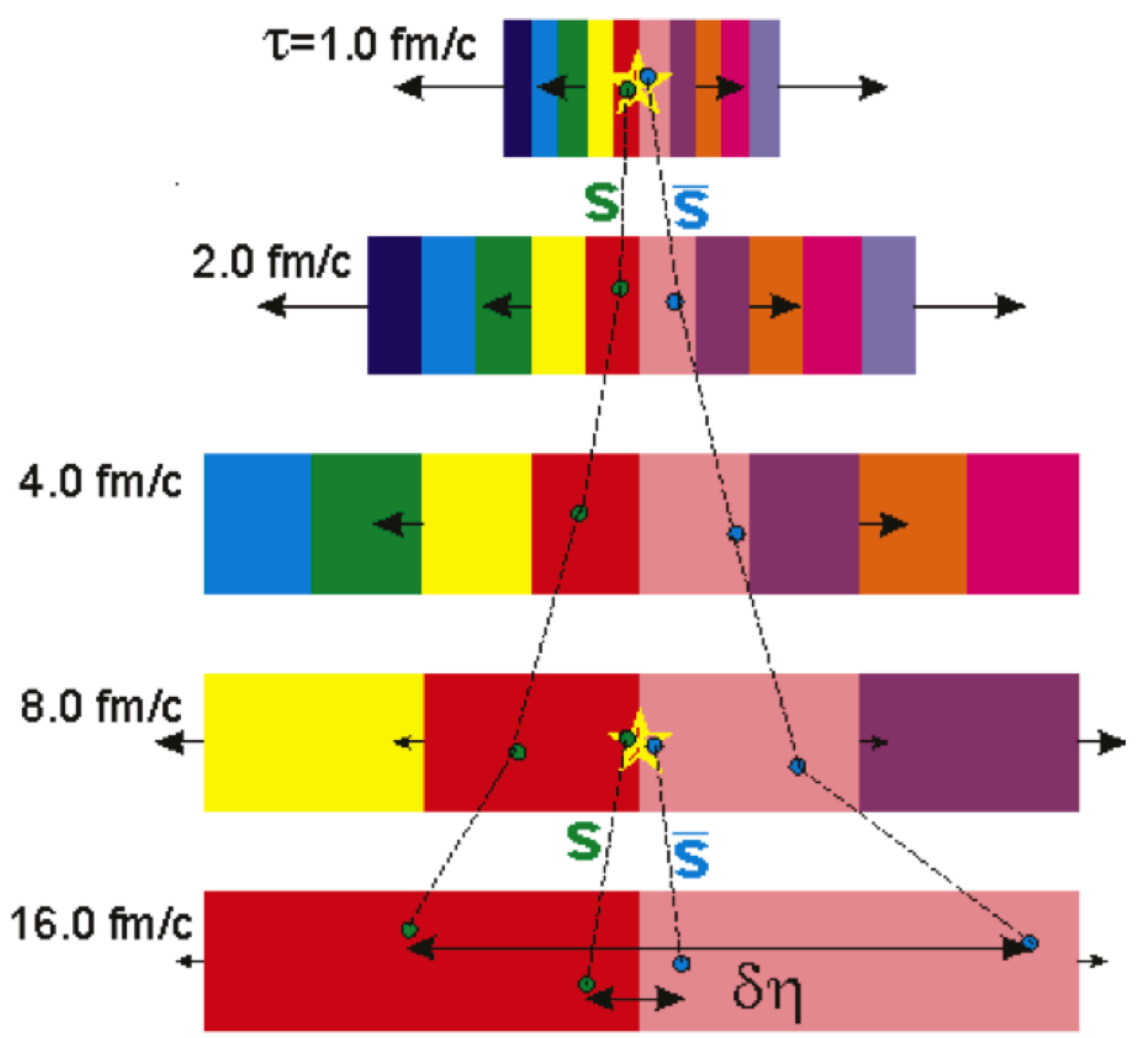


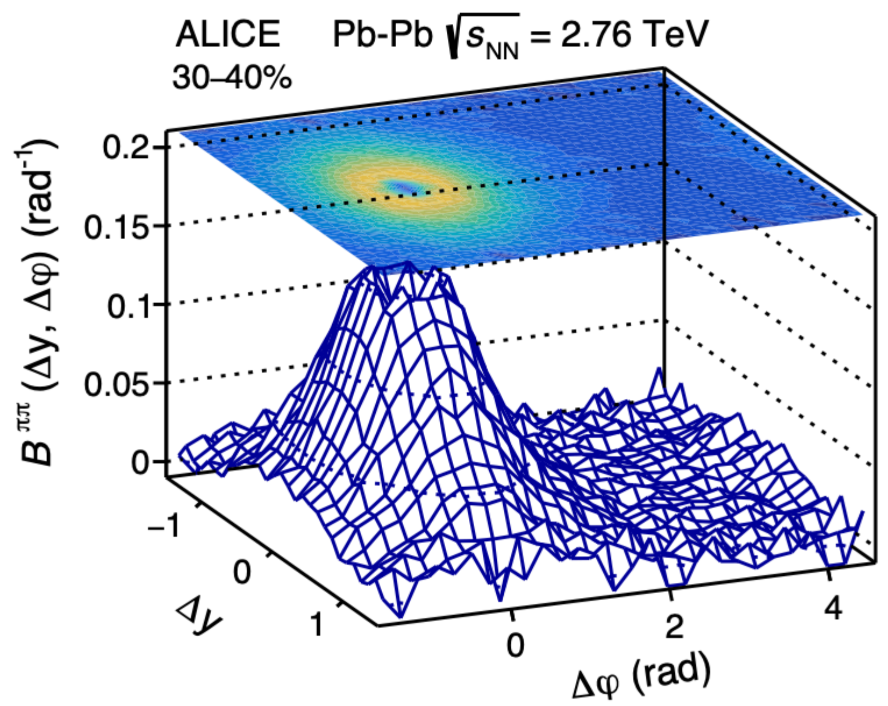
Balance function

- Measure of balancing charges

$$R_2^{\alpha\beta} = \frac{\rho_2^{\alpha\beta}}{\rho_1^{\alpha}\rho_1^{\beta}} - 1$$

$$B^{\alpha\beta} = \frac{1}{2}\left\{\rho_1^{\beta^-}\left[R_2^{\alpha^+\beta^-} - R_2^{\alpha^-\beta^-}\right] + \rho_1^{\beta^+}\left[R_2^{\alpha^-\beta^+} - R_2^{\alpha^+\beta^+}\right]\right\}$$





Phys.Lett.B 833 (2022) 137338

G_2

- Sensitive to momentum current correlations

$$G_2 = \frac{1}{\langle p_{T,1}\rangle\langle p_{T,2}\rangle}\left[\frac{\int_\Omega p_{T,1}p_{T,2}\rho_2(p_1,p_2)\mathrm{d}p_{T,1}\mathrm{d}p_{T,2}}{\int_\Omega \rho_1(p_1)\mathrm{d}p_{T,1}\int_\Omega \rho_2(p_2)\mathrm{d}p_{T,2}} - \langle p_{T,1}\rangle\langle p_{T,2}\rangle\right]$$

- Charge independent:

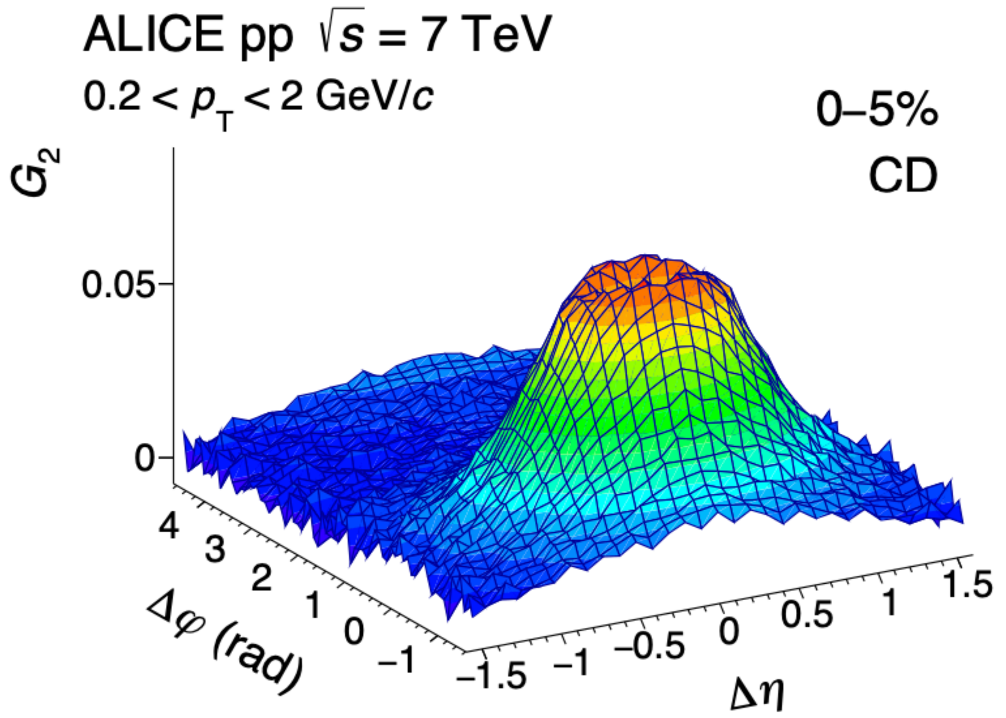
$$G_2^{CI} = \frac{1}{2}(G_2^{US} + G_2^{LS})$$

- Charge dependent:

$$G_2^{CD} = \frac{1}{2}(G_2^{US} - G_2^{LS})$$

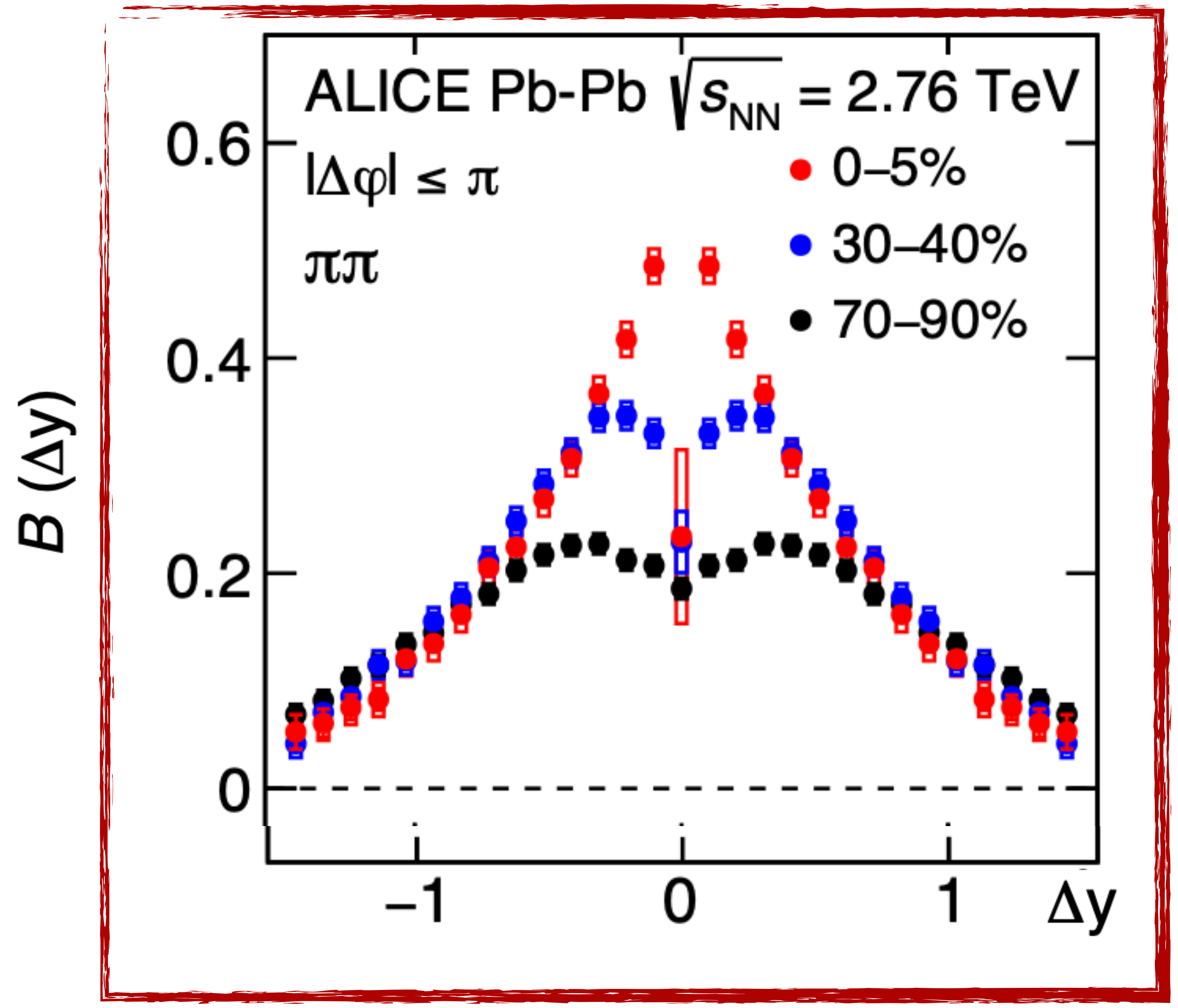
Like sign pairs (+ +) (- -)

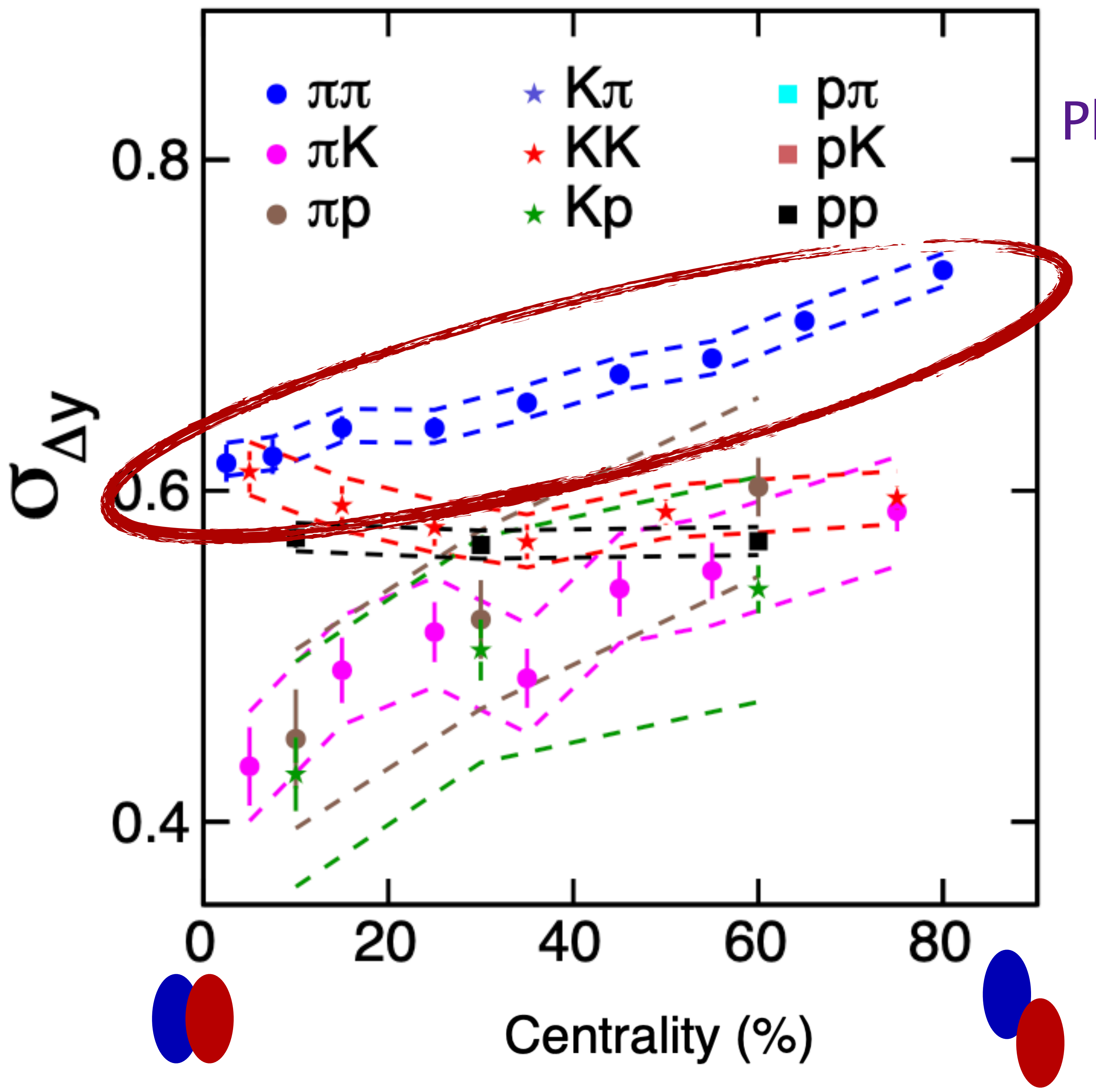
Unlike sign pairs (+ -)



arXiv:2211.08979

Balance function: Identified hadrons

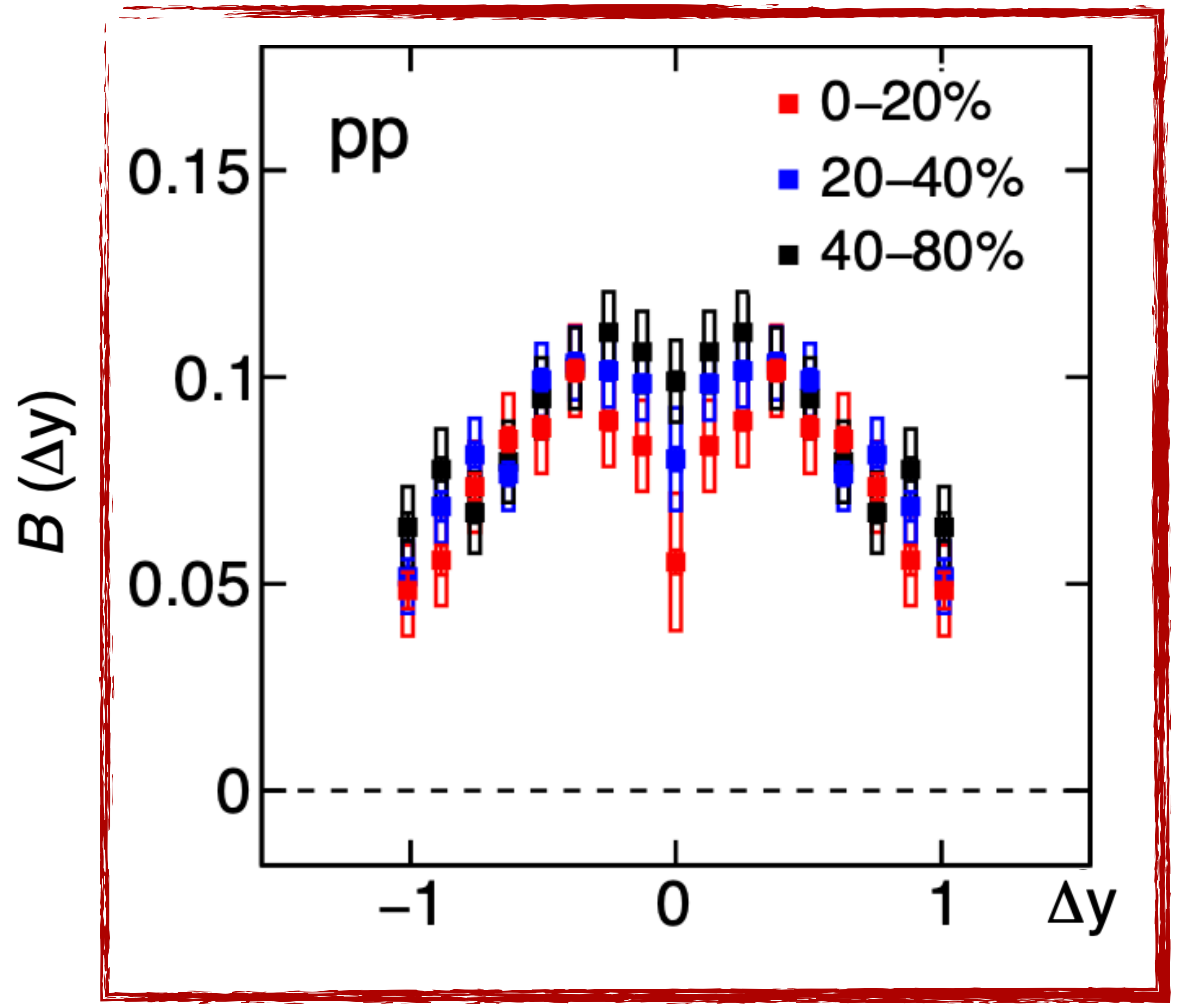


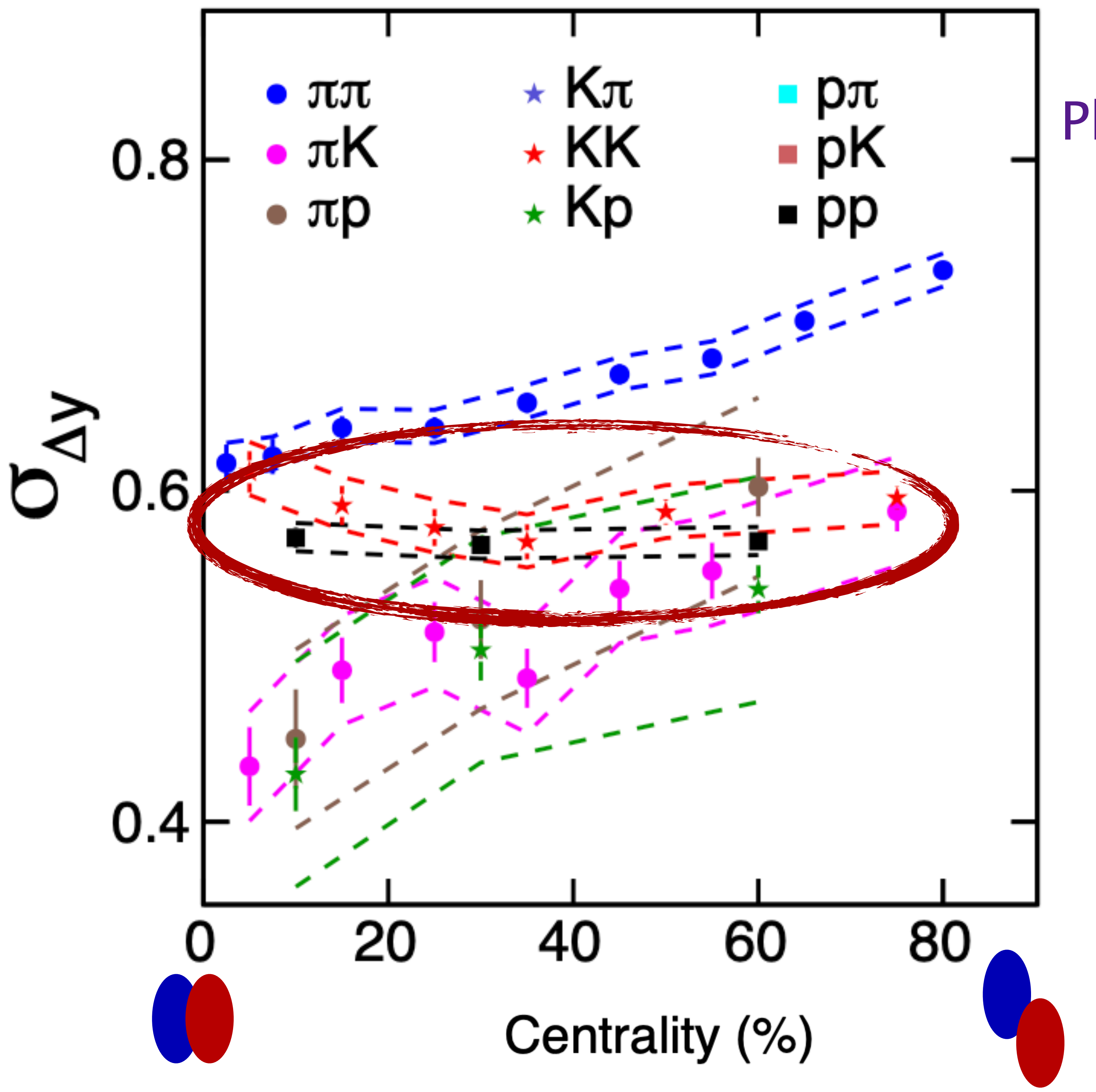


Phys.Lett.B 833 (2022) 137338

- Measure of balancing charges
- $BF_{\pi\pi}$ - narrow in central collision - **coalescence?**

Balance function: Identified hadrons

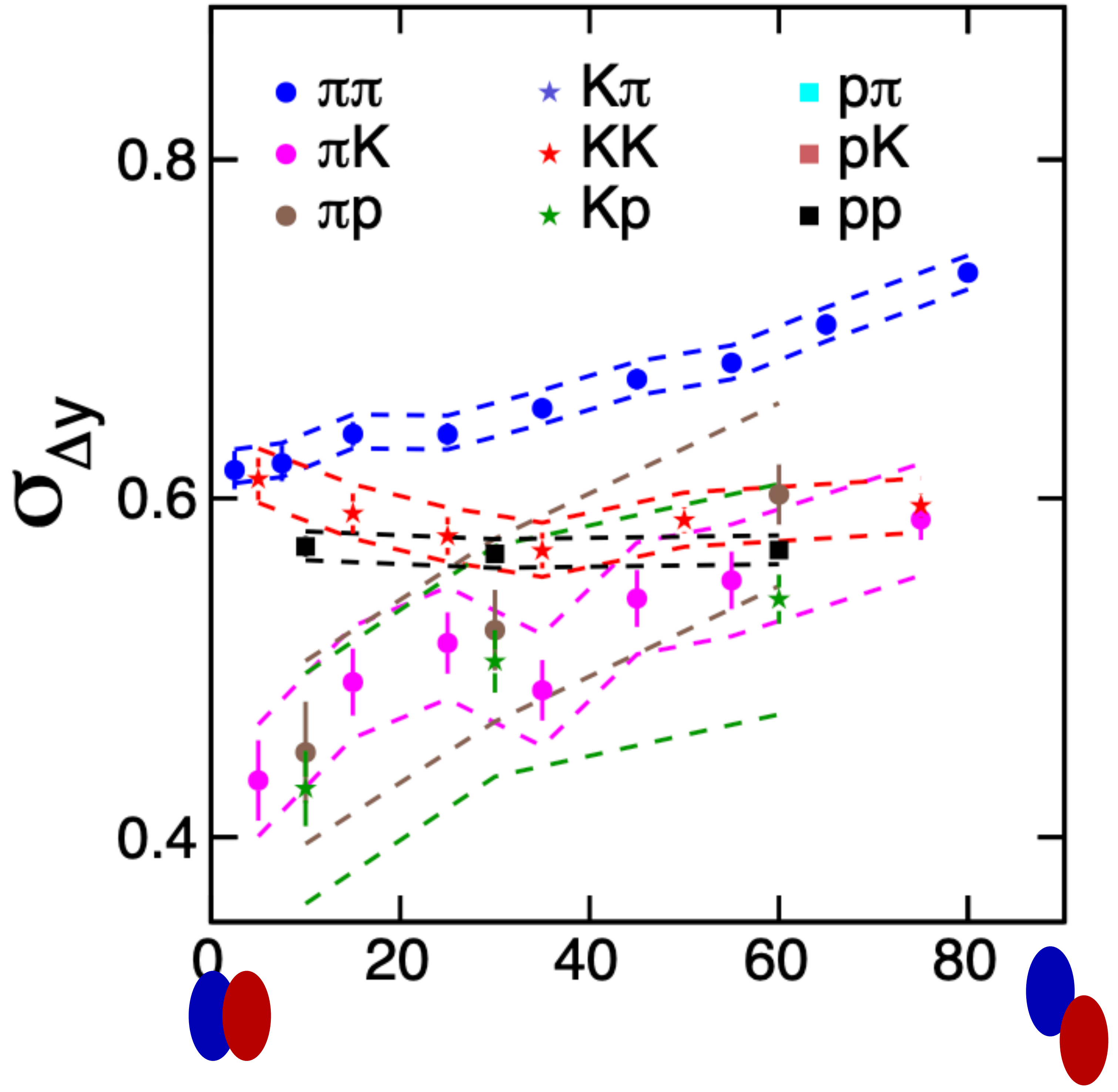


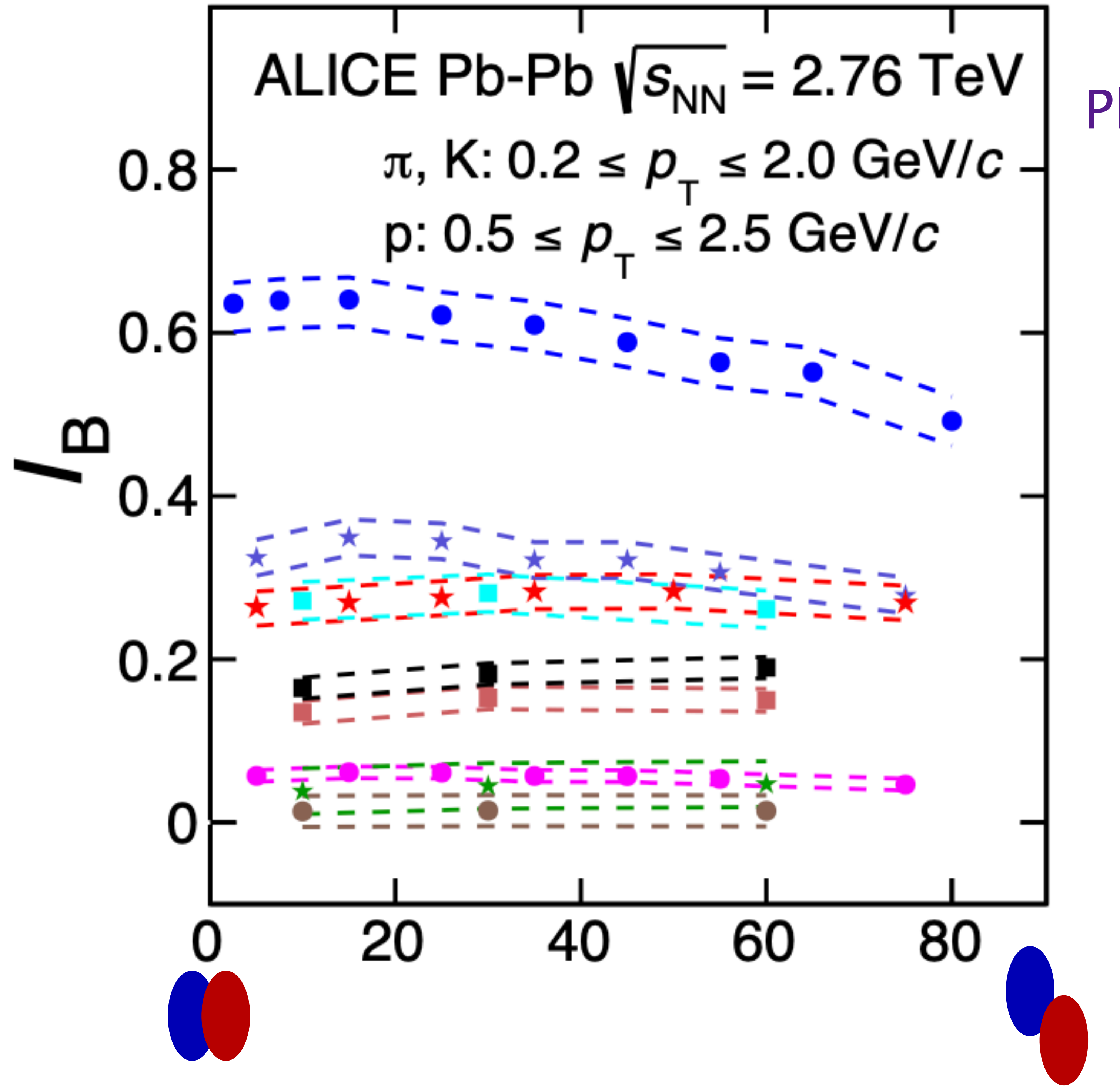


Phys.Lett.B 833 (2022) 137338

- Measure of balancing charges
- BF_{pp}- wider than acceptance, no dependence on multiplicity
  - **Early stage production?**

Balance function: Identified hadrons

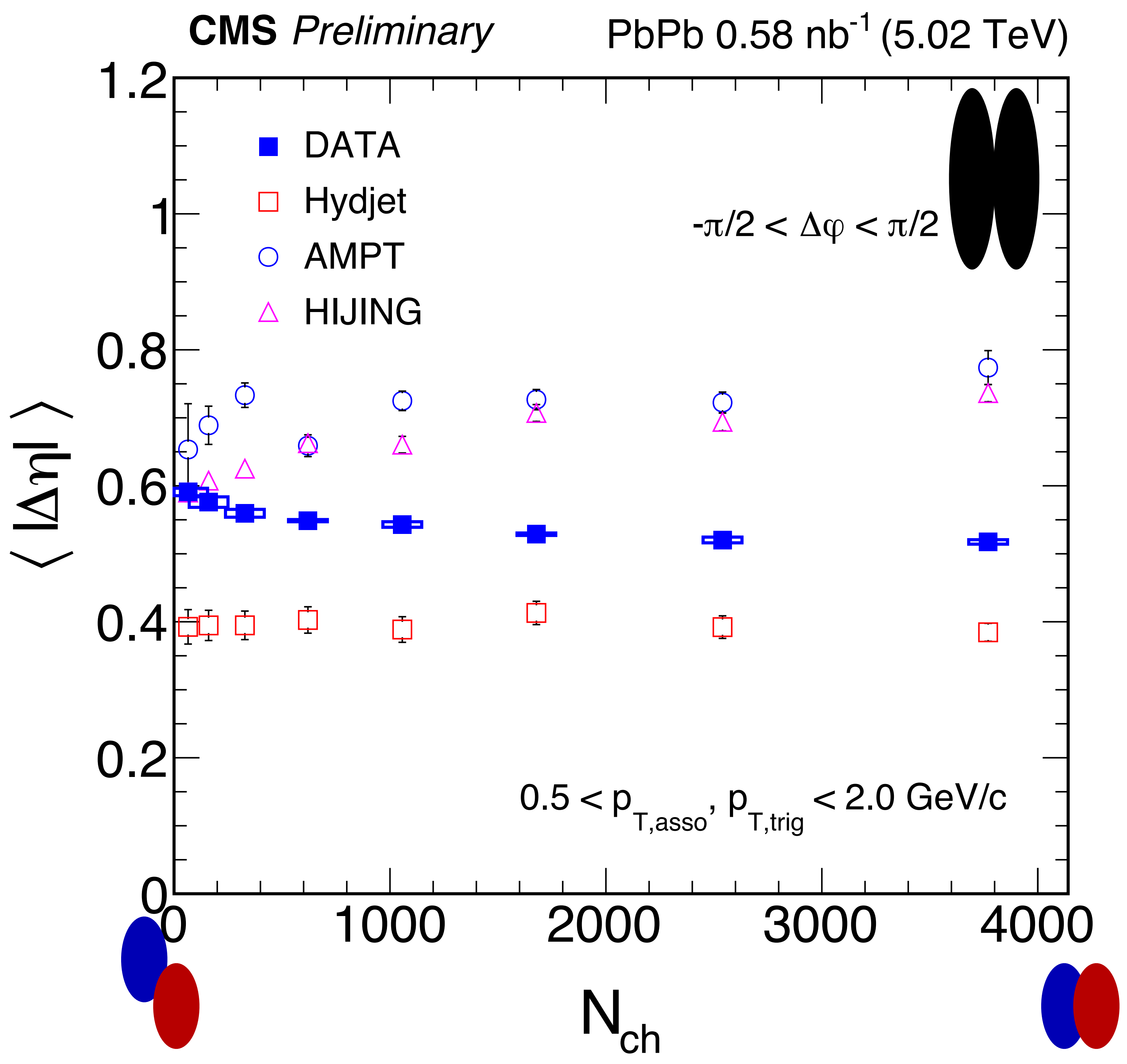


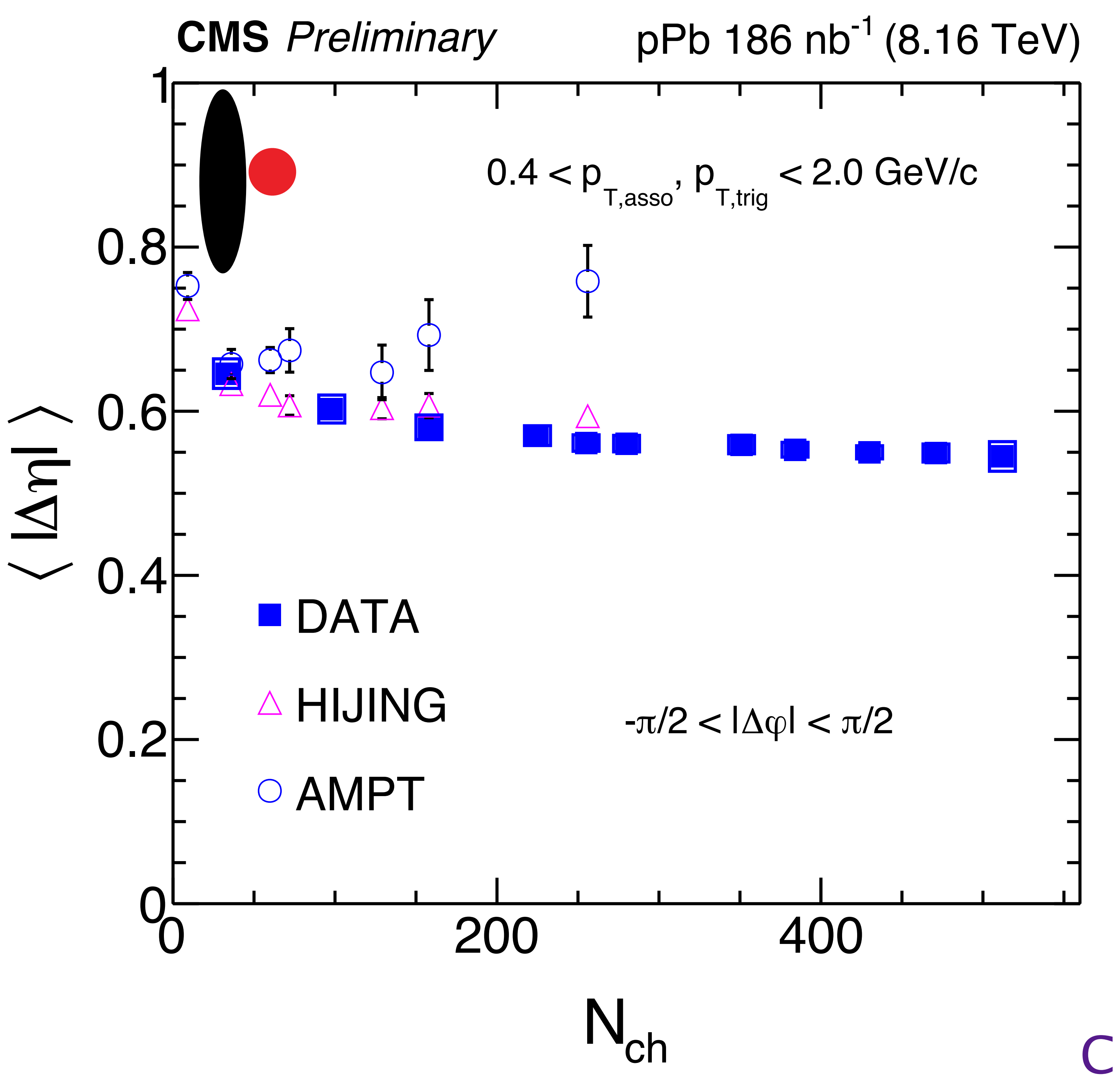


Phys.Lett.B 833 (2022) 137338

- Pairing fractions not dependent on centrality, except $I^{\pi\pi}$ ⇒ quantitative **characterisation of the hadronisation of the QGP**

Balance function: Charged hadrons

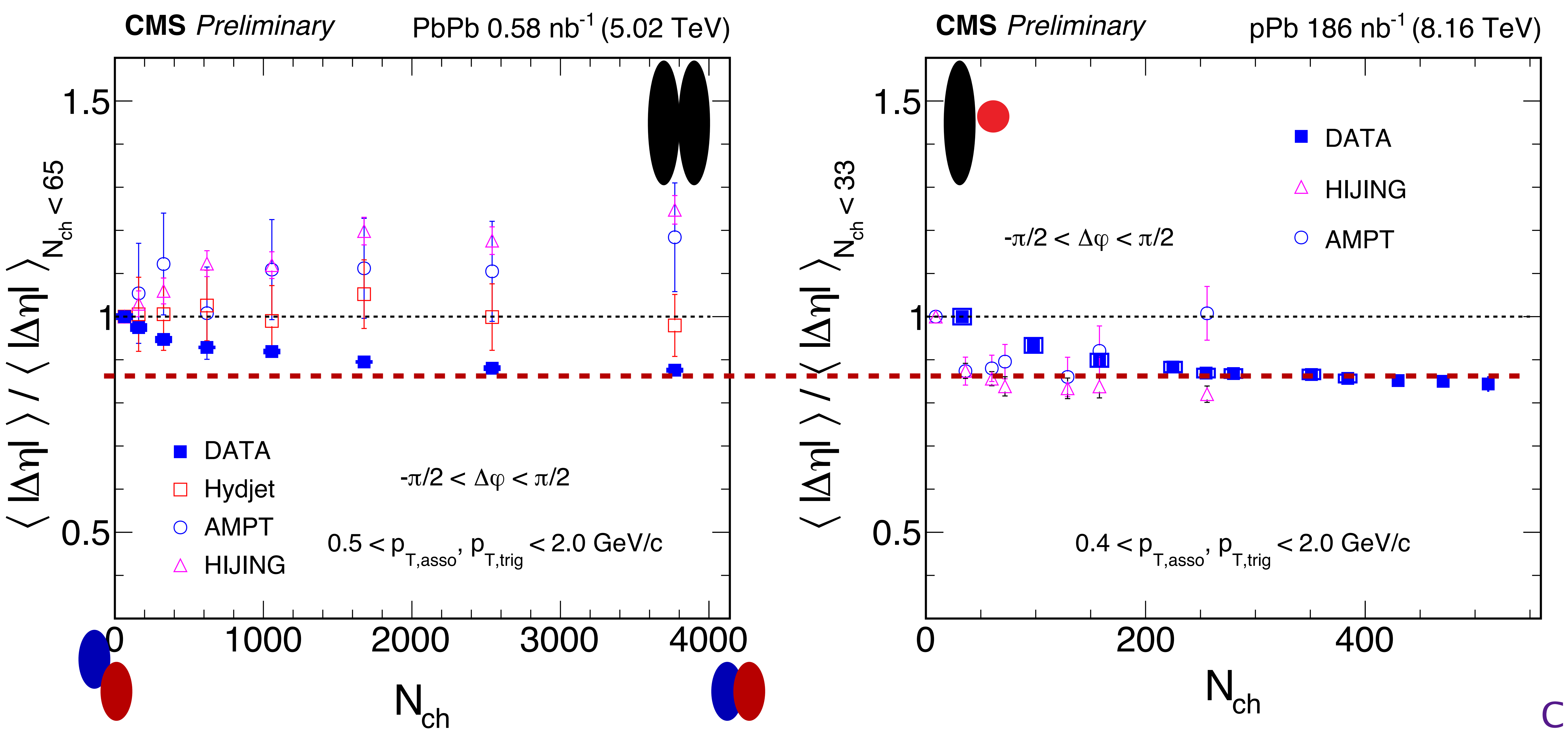




CMS-PAS-HIN-21-017

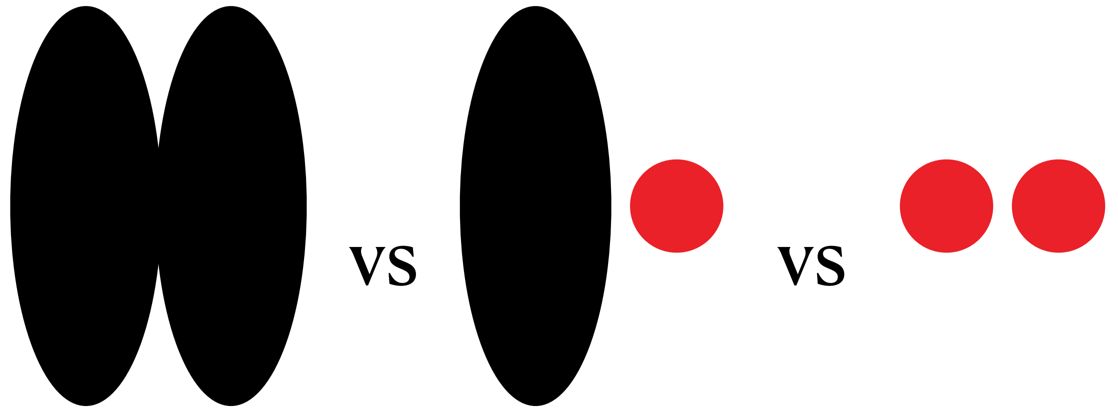
- Narrowing of width of BF towards central collisions
  - Radial flow, late particle production (coalescence)
- Similar behaviour in p—Pb collisions

Balance function: Charged hadrons



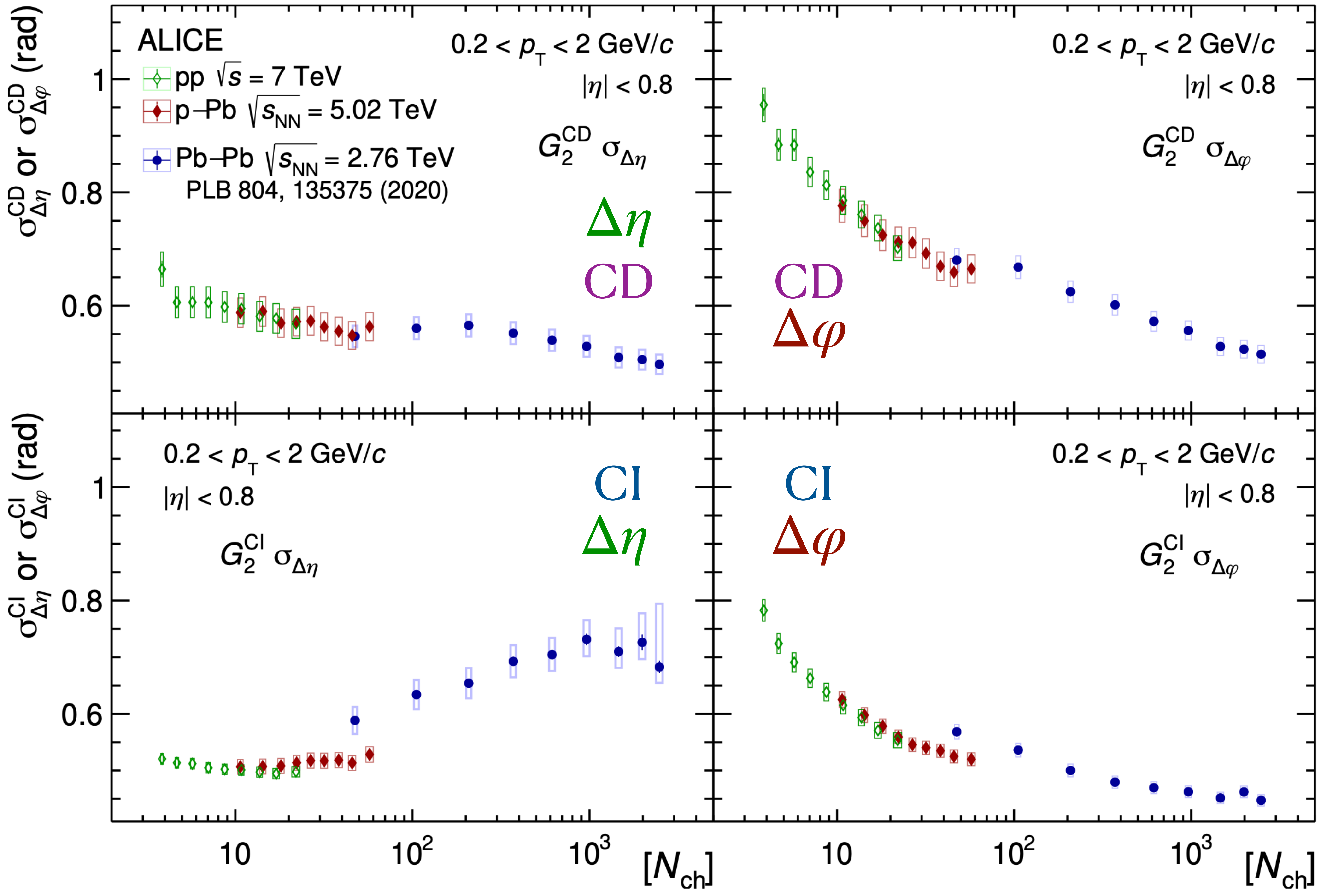
CMS-PAS-HIN-21-017

- Similar trends in p—Pb and Pb—Pb collisions
  - Consistent with the delayed hadronisation, **support collectivity** in p—Pb collisions
  - Models cannot describe data perfectly, though provide better description in $\Delta\varphi$



G_2

$$G_2 = \frac{1}{\langle p_{T,1}\rangle\langle p_{T,2}\rangle}\left[\frac{\int_\Omega p_{T,1}p_{T,2}\rho_2(p_1,p_2)dp_{T,1}dp_{T,2}}{\int_\Omega \rho_1(p_1)dp_{T,1}\int_\Omega \rho_2(p_2)dp_{T,2}} - \langle p_{T,1}\rangle\langle p_{T,2}\rangle\right]$$



- G_2^{CI} - sensitive to momentum current correlations
  - Affected by mini-jets, radial flow etc.
- G_2^{CD} - driven by hadronic decays, radial flow

arXiv:2211.08979

G_2

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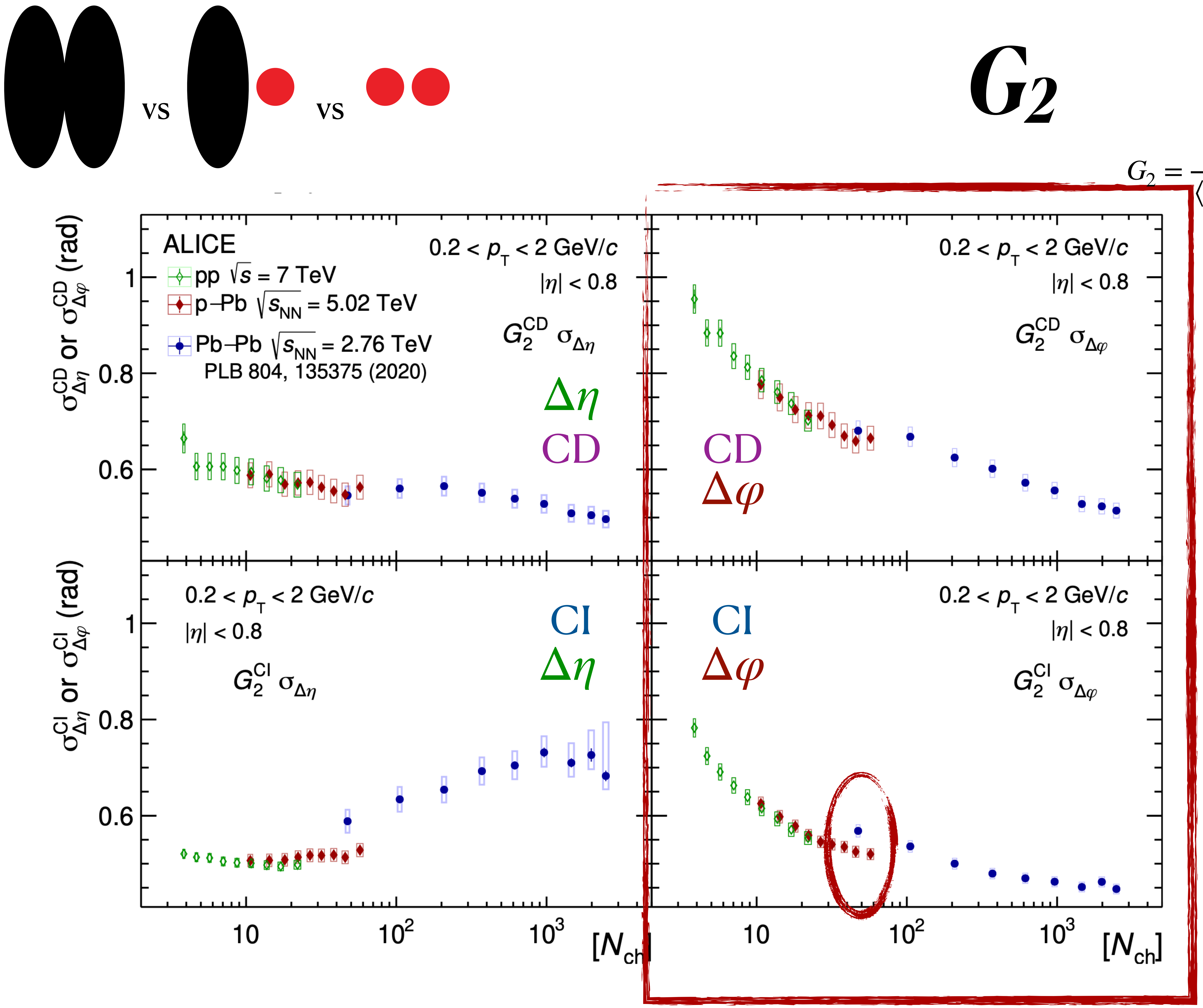
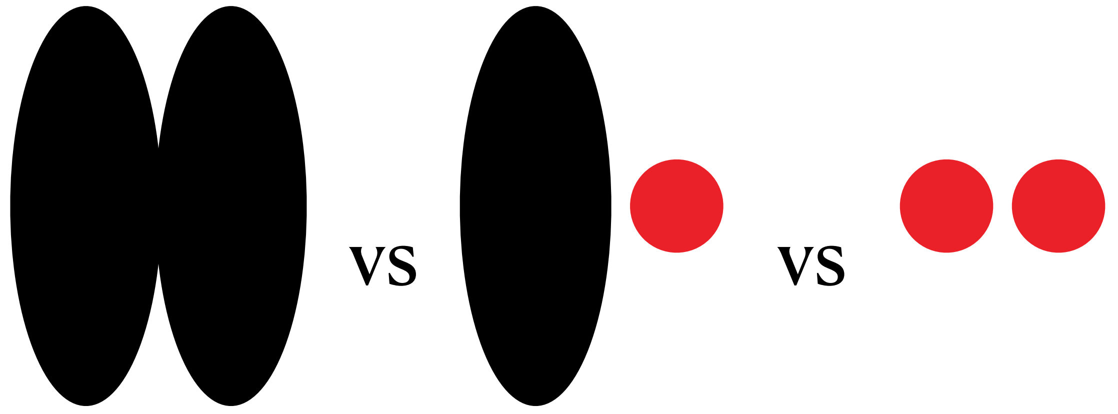


- $\Delta\varphi$ - narrowing for both CI and CD
  - $\langle p_T \rangle$ vs. Mult. increasing in small systems
  - Difference in p—Pb and Pb—Pb - different system size

arXiv:2211.08979



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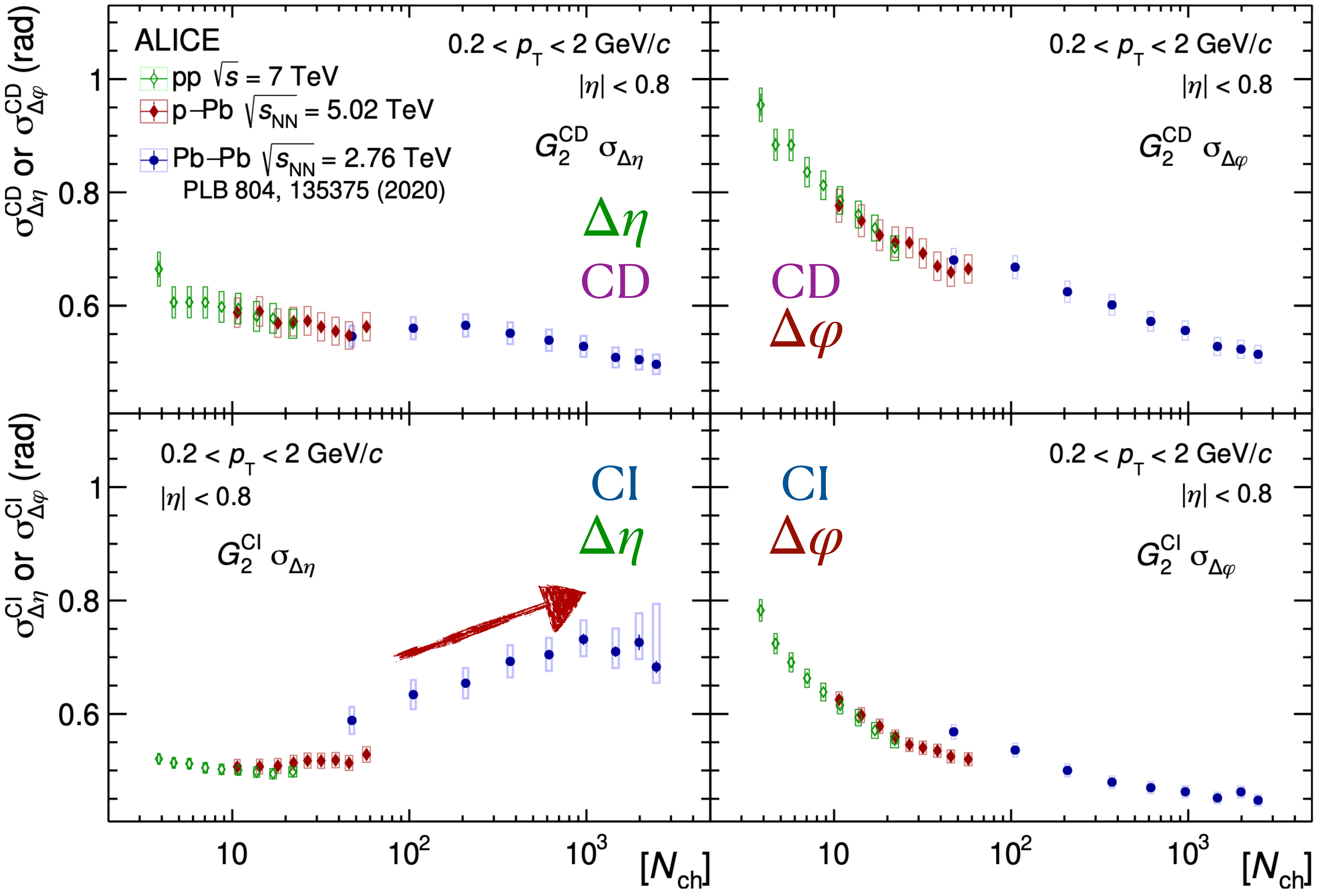
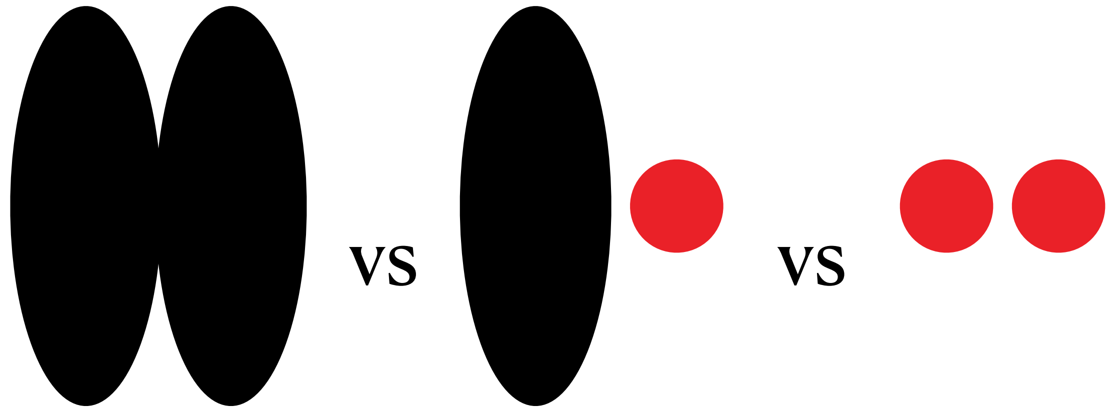


- $\Delta\eta$ CI - different for all three systems
  - Pb—Pb - increase 24% - viscous effects of long-lived QGP with small η/s

arXiv:2211.08979



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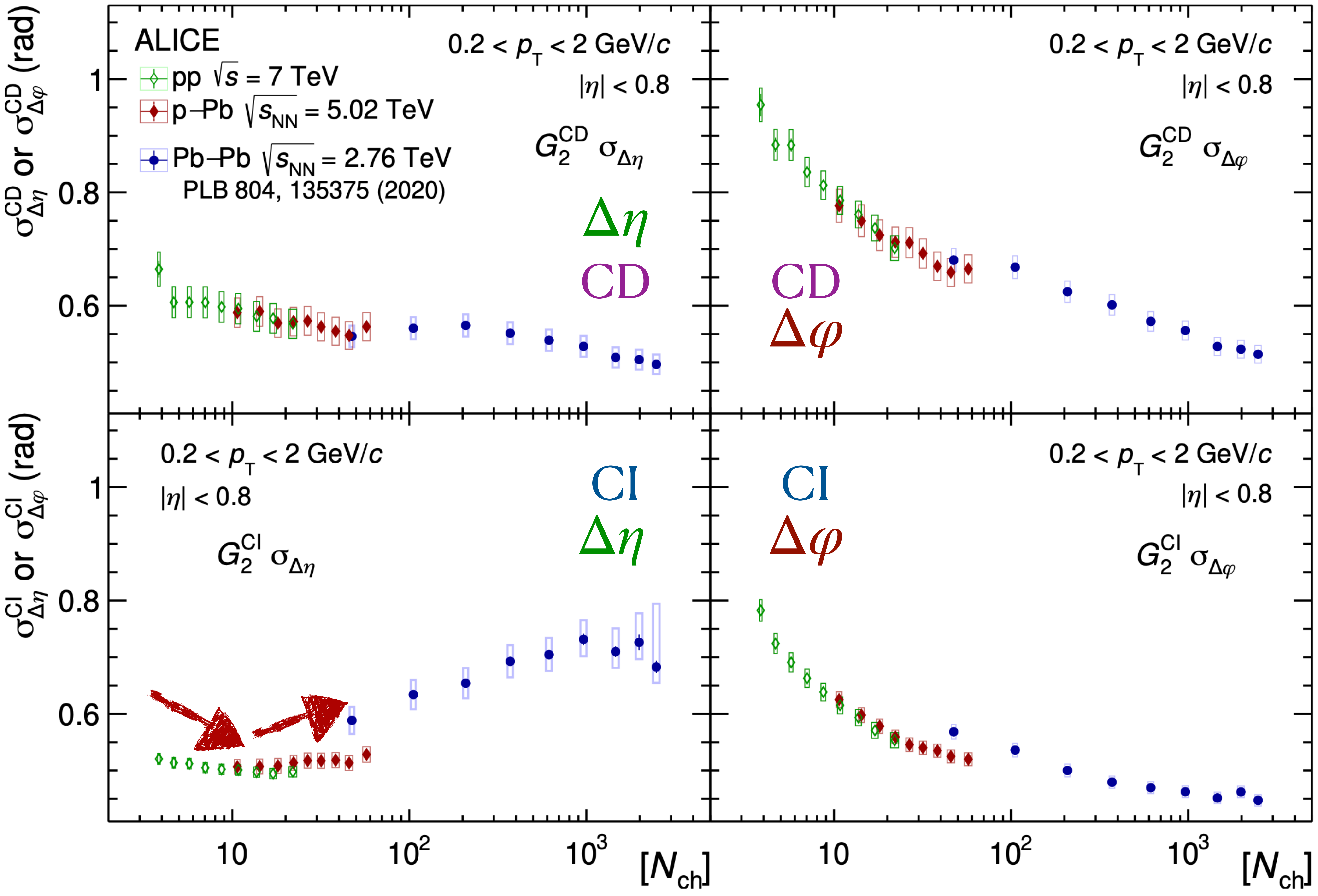

- $\Delta\eta$ CI - different for all three systems
  - Pb—Pb - increase 24% - viscous effects of long-lived QGP with small η/s
  - pp - slight decrease, p—Pb slight increase
    - **Too small for viscous forces to equilibrate?**
    - Different explanations?

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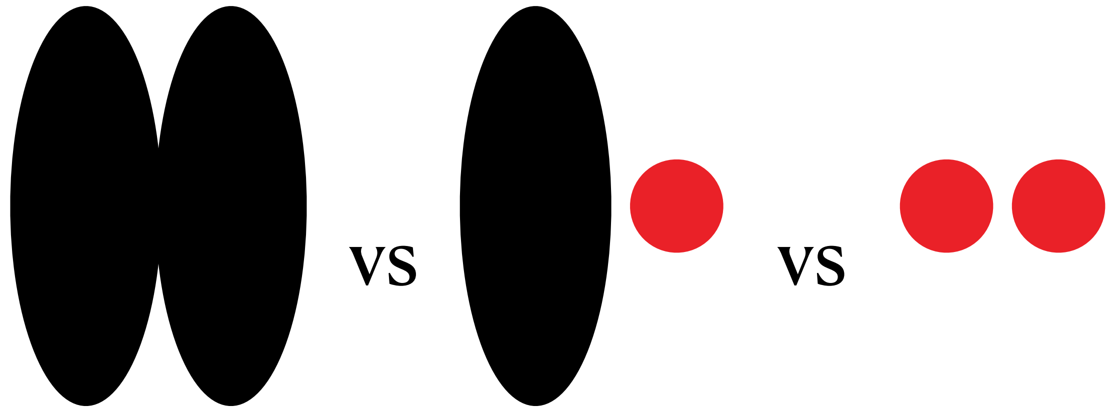
G_2



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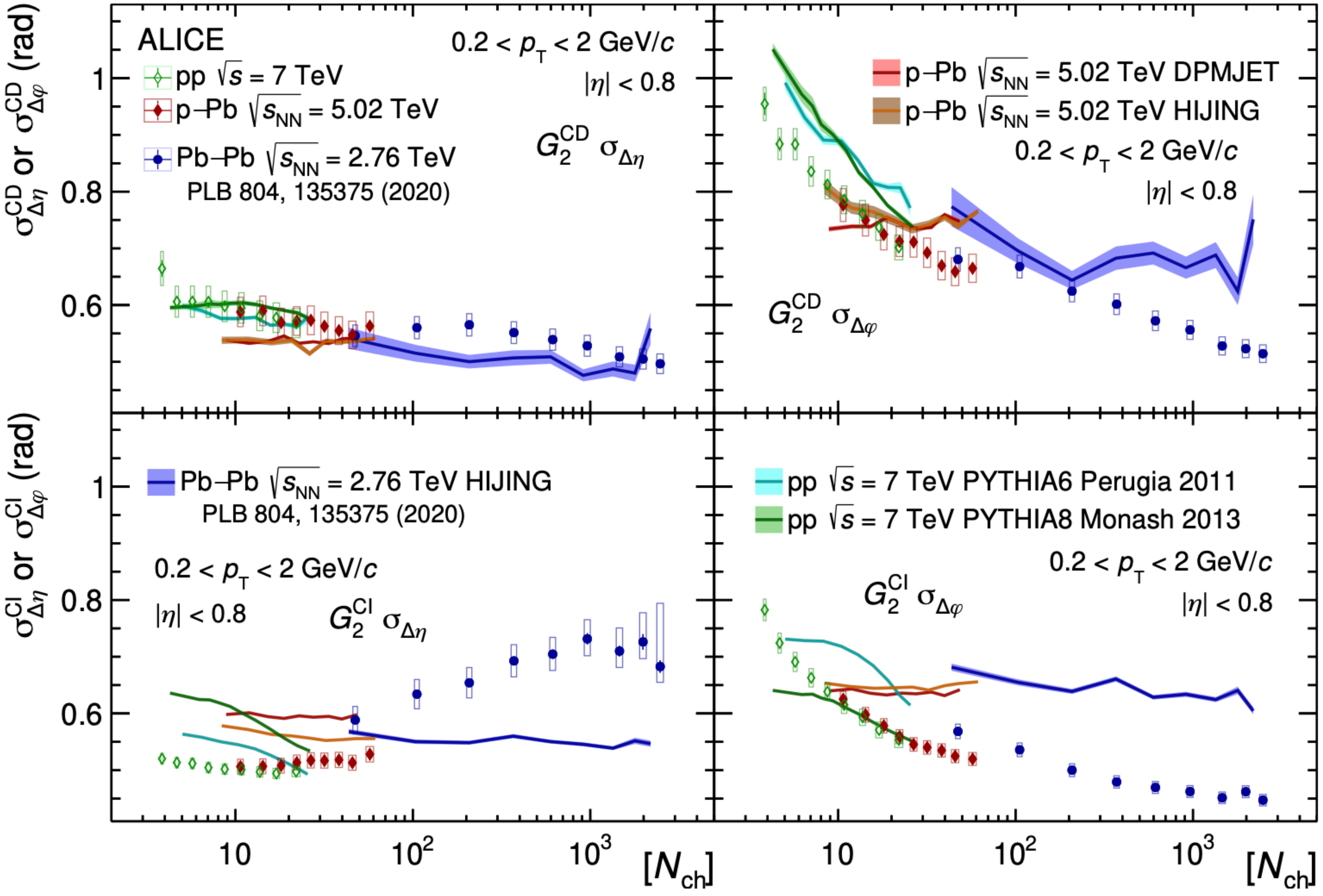
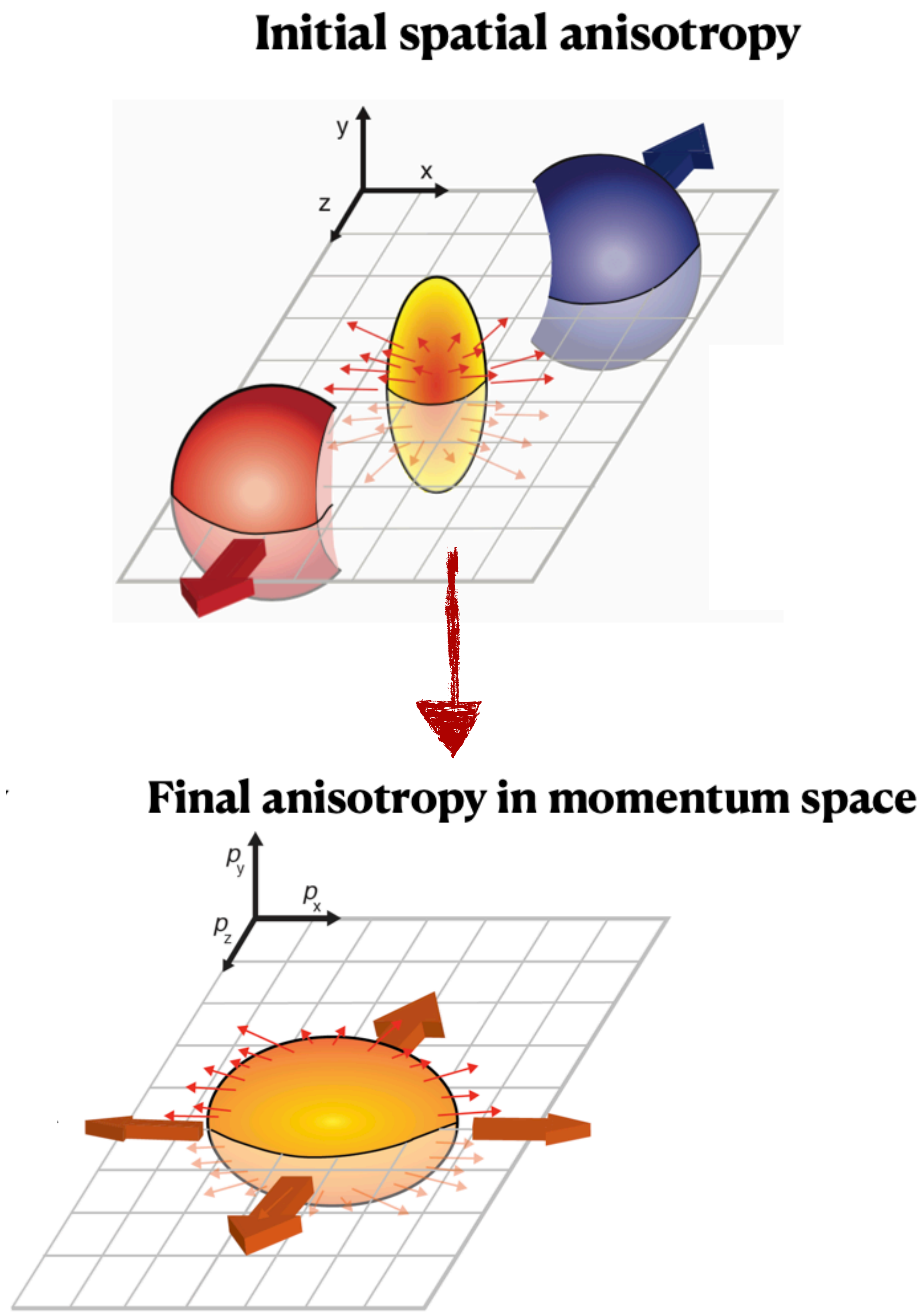


- $\Delta\eta$ CI - different for all three systems
  - Pb—Pb - increase 24% - viscous effects of long-lived QGP with small η/s
  - pp - slight decrease, p—Pb slight increase
    - Too small for viscous forces to equilibrate?
    - Different explanations
      - Models without collective effects do not describe data

arXiv:2211.08979

Anisotropic flow



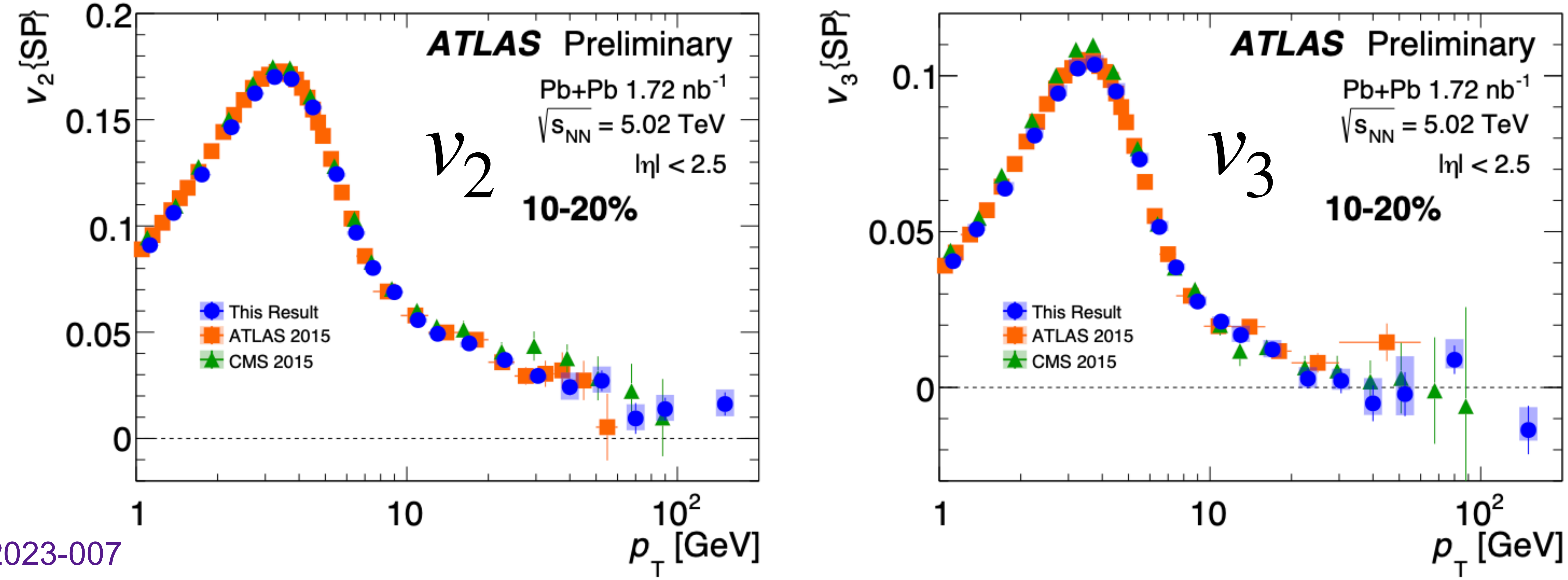
- Reflects the conversion of the initial-state spatial anisotropy into final-state anisotropies in momentum space
- Anisotropy in distribution of final-state particles:

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$$

$$v_n = \langle \cos(n(\varphi - \psi_n)) \rangle$$

- Initial conditions and transport properties of the created medium (low p_{T})
- Initial geometry affects energy loss of hard hadrons (high p_{T})

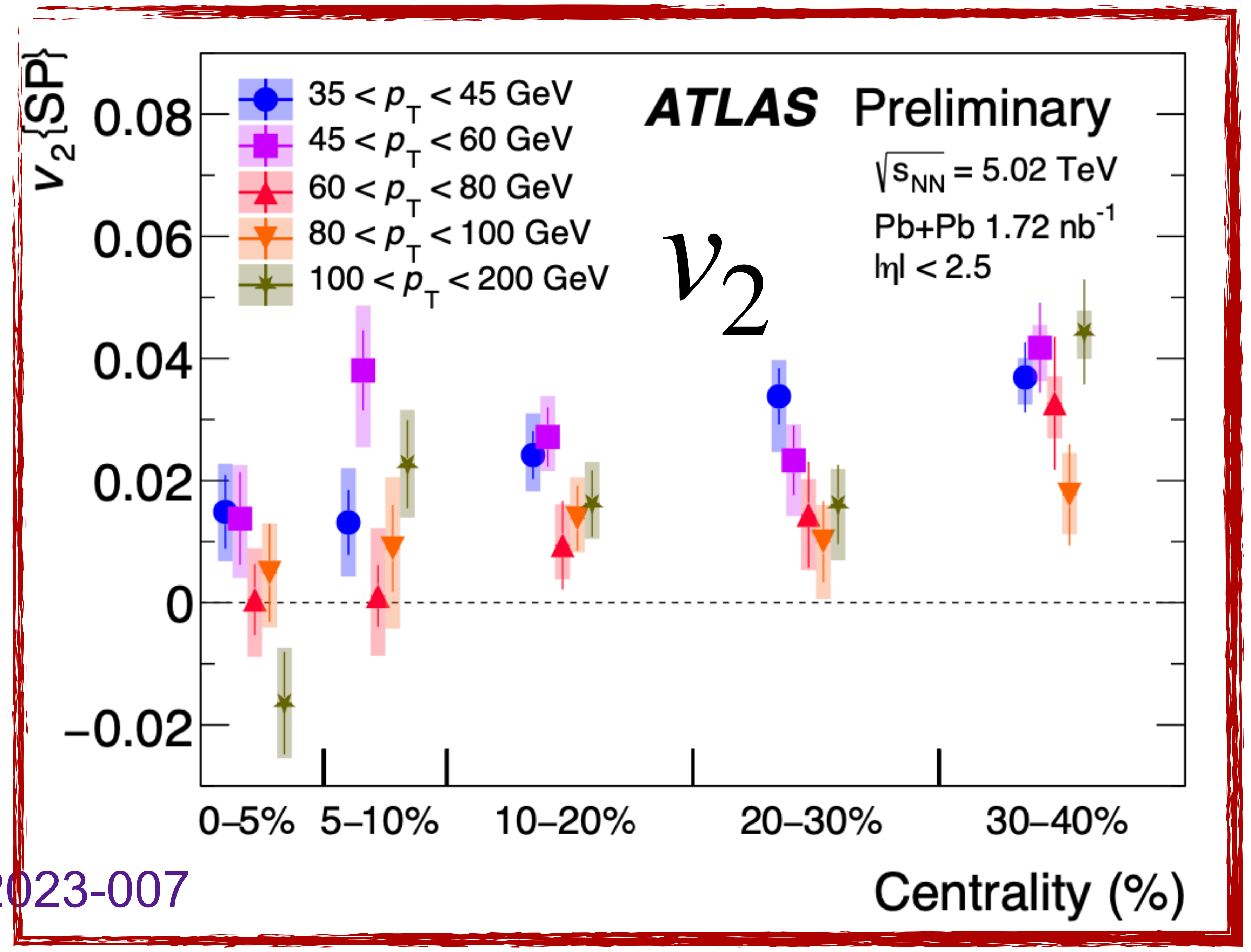
v_n up to high p_T in Pb—Pb

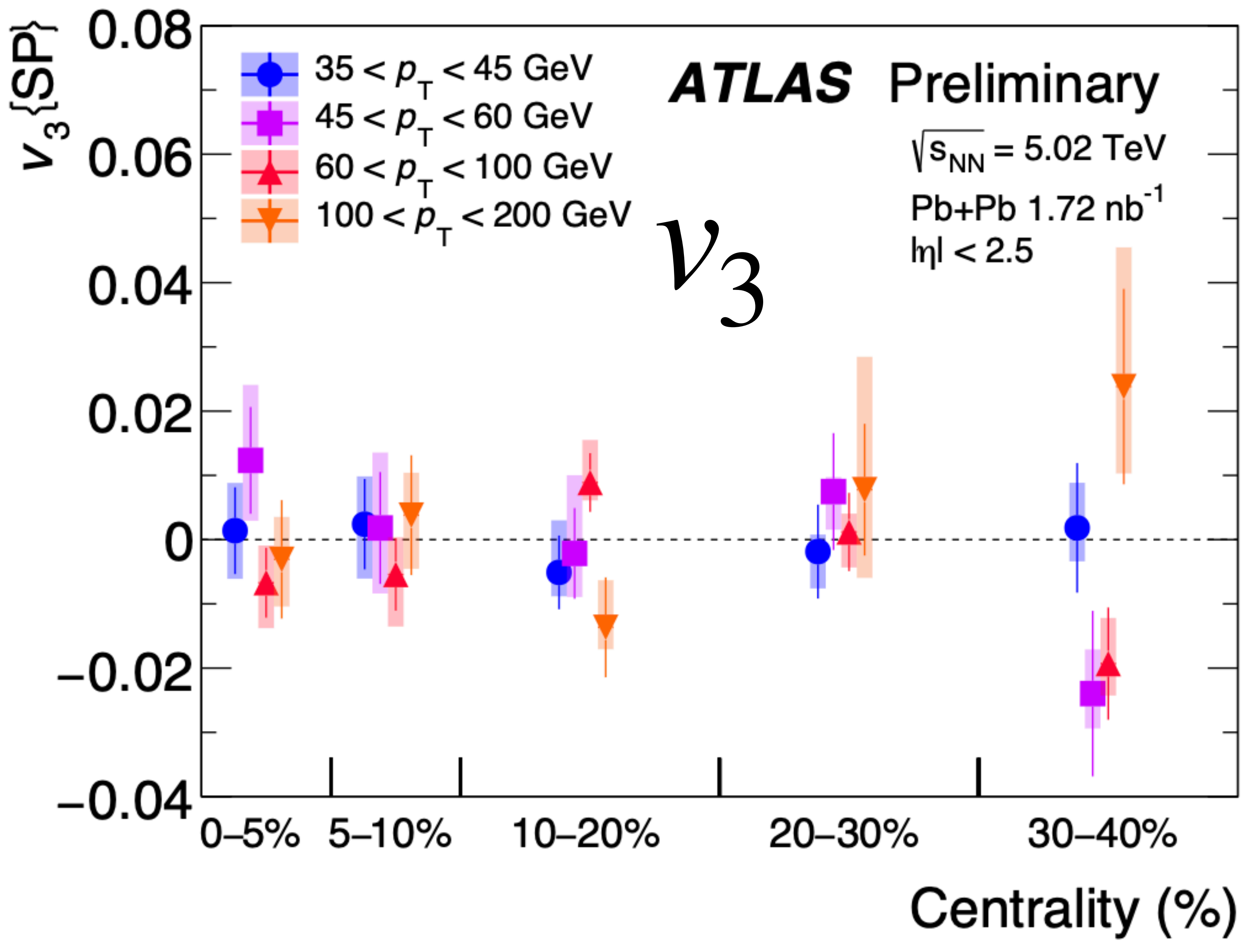


ATLAS-CONF-2023-007

- First measurement of Fourier coefficients up to $p_T = 200$ GeV/c
- Compatible with previous measurements
  - Decreased uncertainties

v_n up to high p_T in Pb—Pb

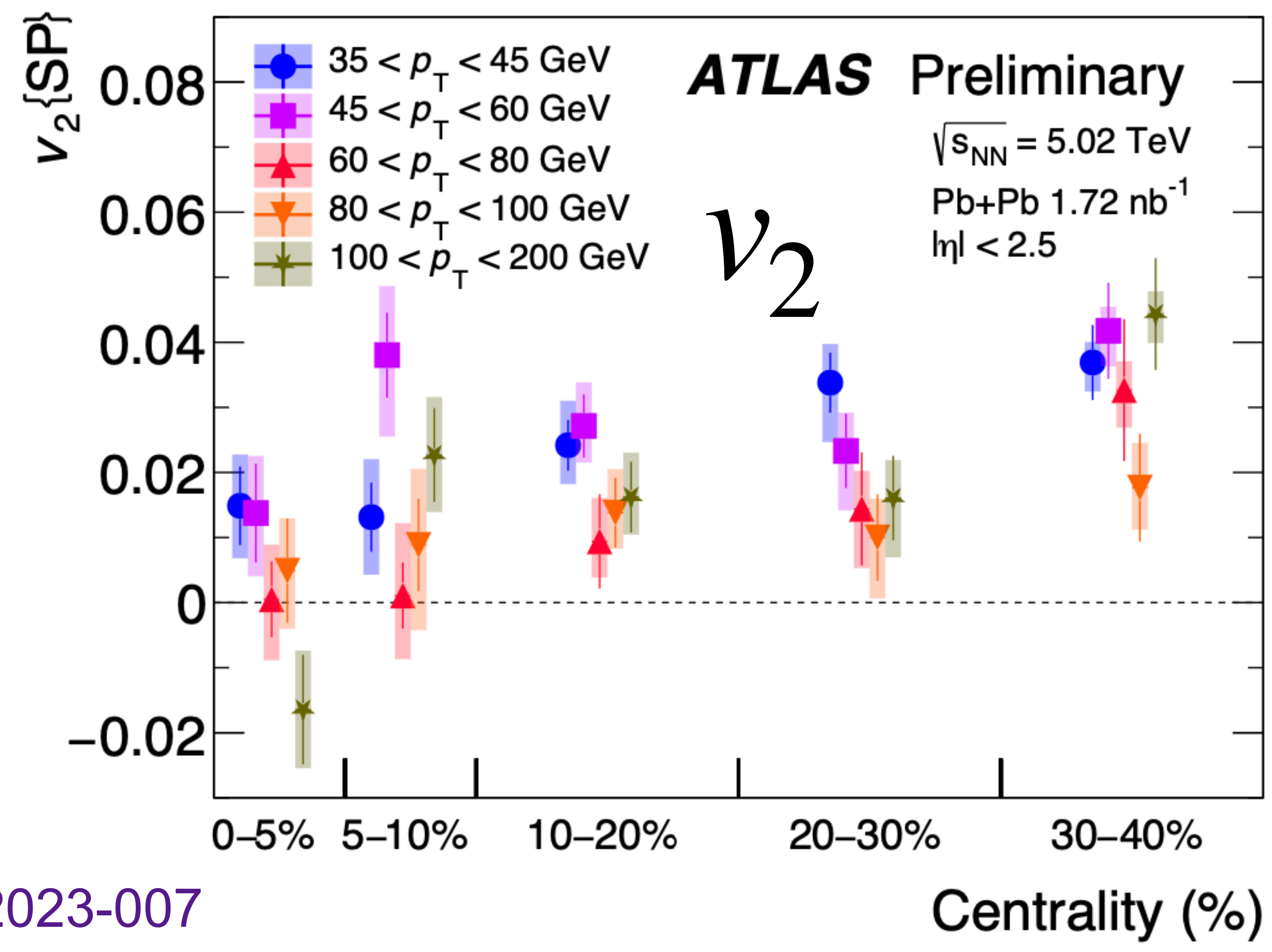


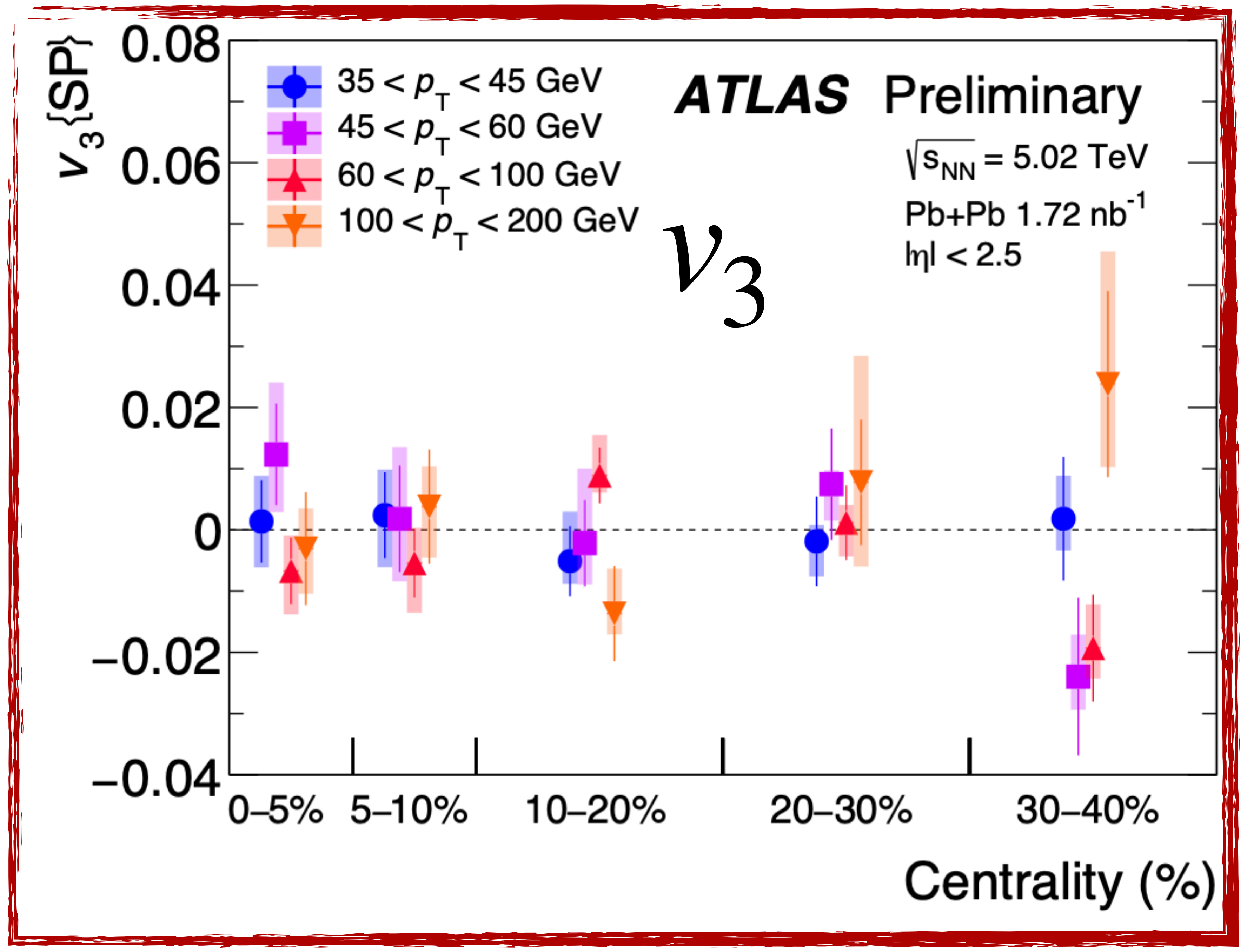


ATLAS-CONF-2023-007

- Non-zero v_2 at high p_T
  - Increasing towards semicentral collisions
  - **Hard hadrons influenced by initial geometry**

v_n up to high p_T in Pb—Pb

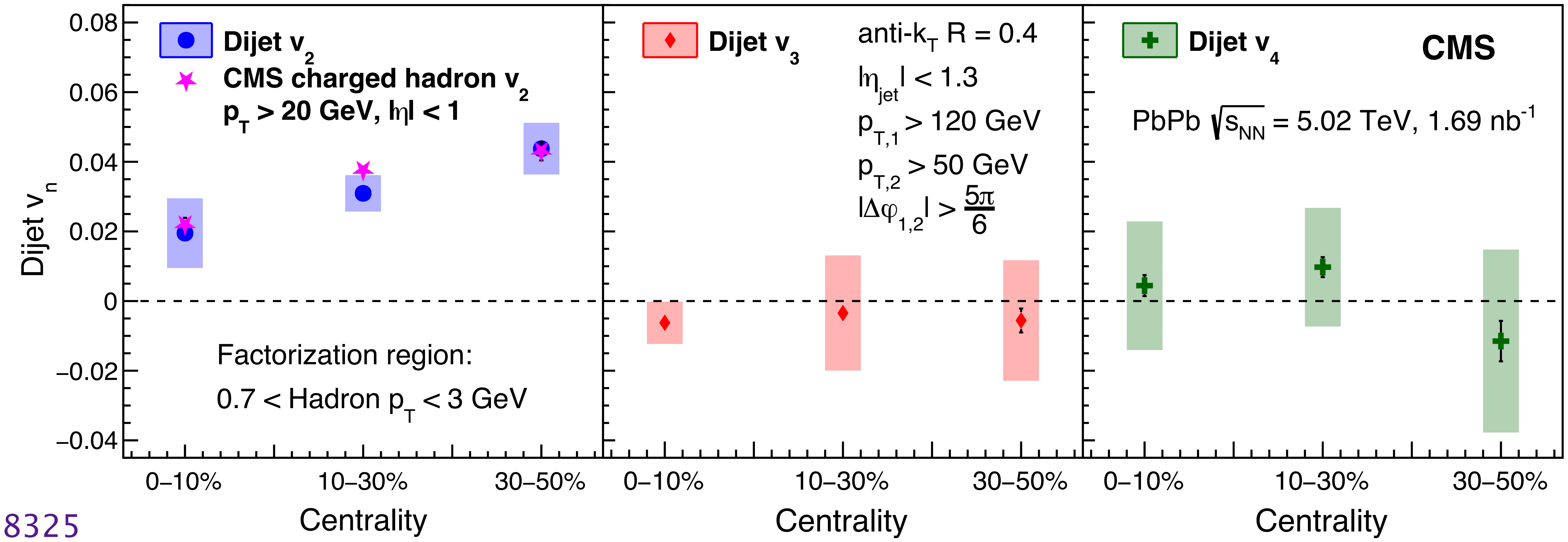




ATLAS-CONF-2023-007

- Non-zero v_2 at high p_T
  - Increasing towards semicentral collisions
  - Hard hadrons influenced by initial geometry
- v_3 at high p_T compatible with zero
  - **Hard hadrons not influenced by initial fluctuations**

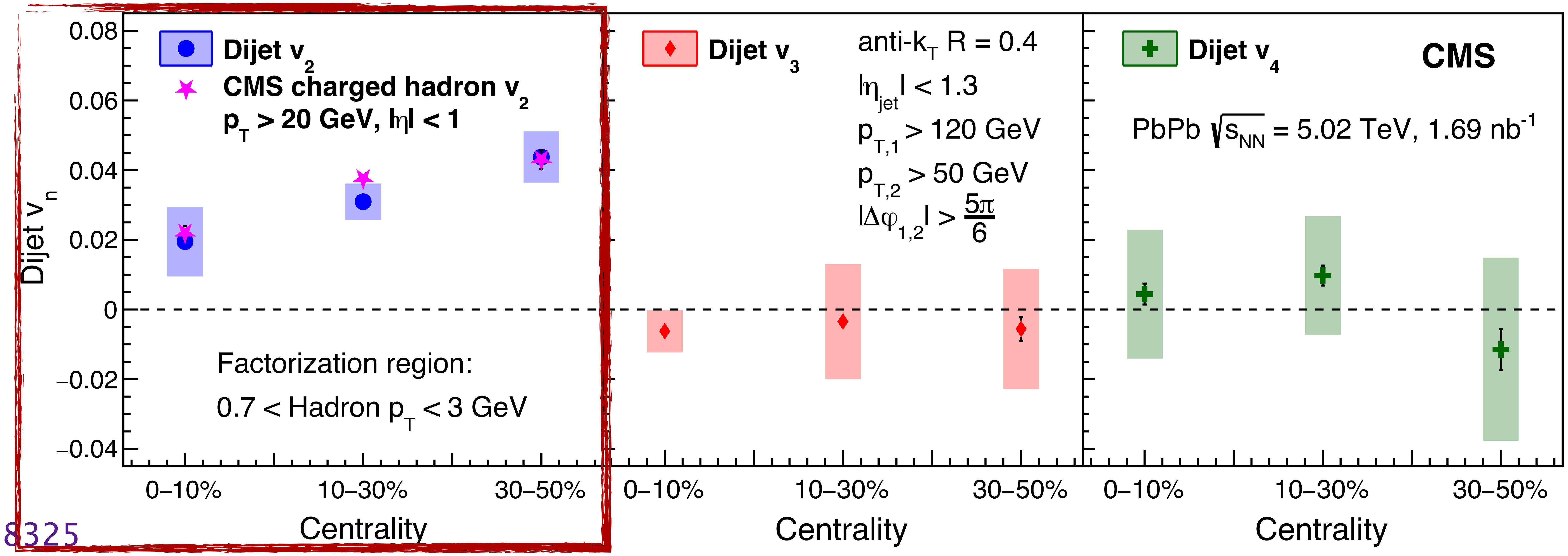
v_n of dijets (Pb—Pb)



arXiv:2210.08325

- Fourier coefficients of dijets measured with two-particle correlations

v_n of dijets (Pb—Pb)



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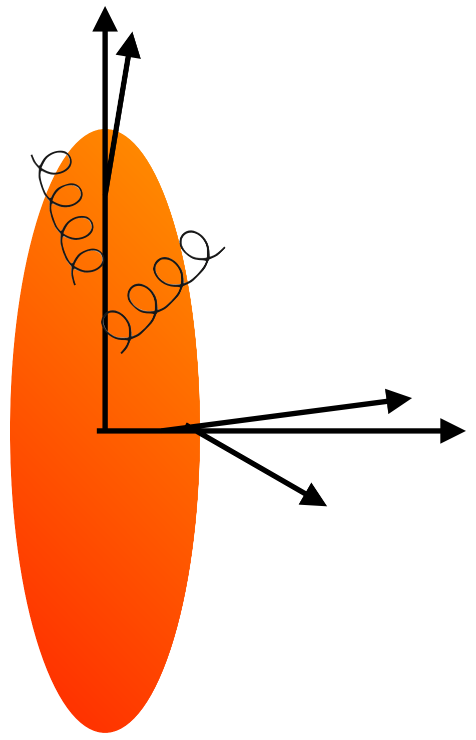
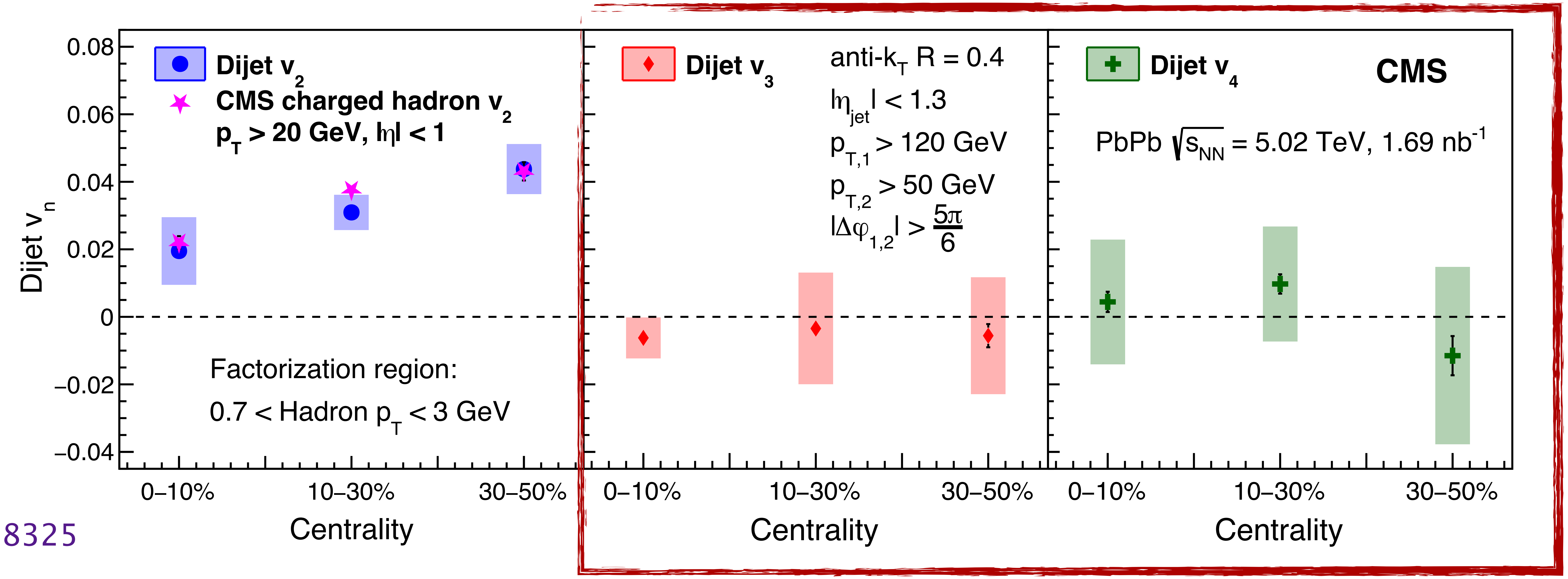


- Fourier coefficients of dijets measured with two-particle correlations
- Non-zero v_2:
  - **More jets observed coplanar with event plane**
    - Less energy loss → higher chance to pass selection criteria

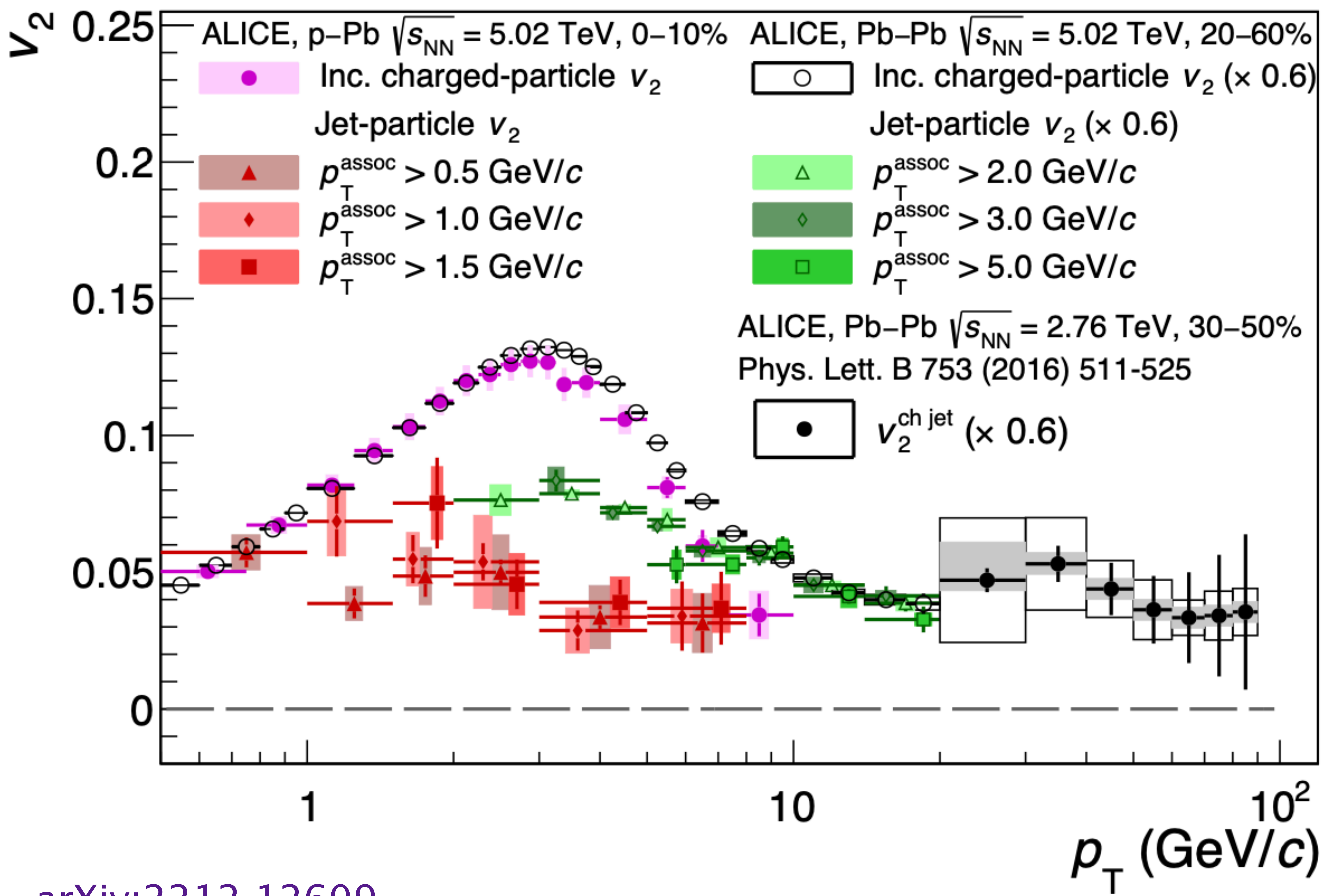
v_n of dijets (Pb—Pb)



arXiv:2210.08325

- Fourier coefficients of dijets measured with two-particle correlations
- Non-zero v_2:
  - **More jets observed coplanar with event plane**
    - Less energy loss → higher chance to pass selection criteria
- v_3, v_4 compatible with zero:
  - The fluctuations in the initial state **do not impact** the azimuthal distributions of dijets

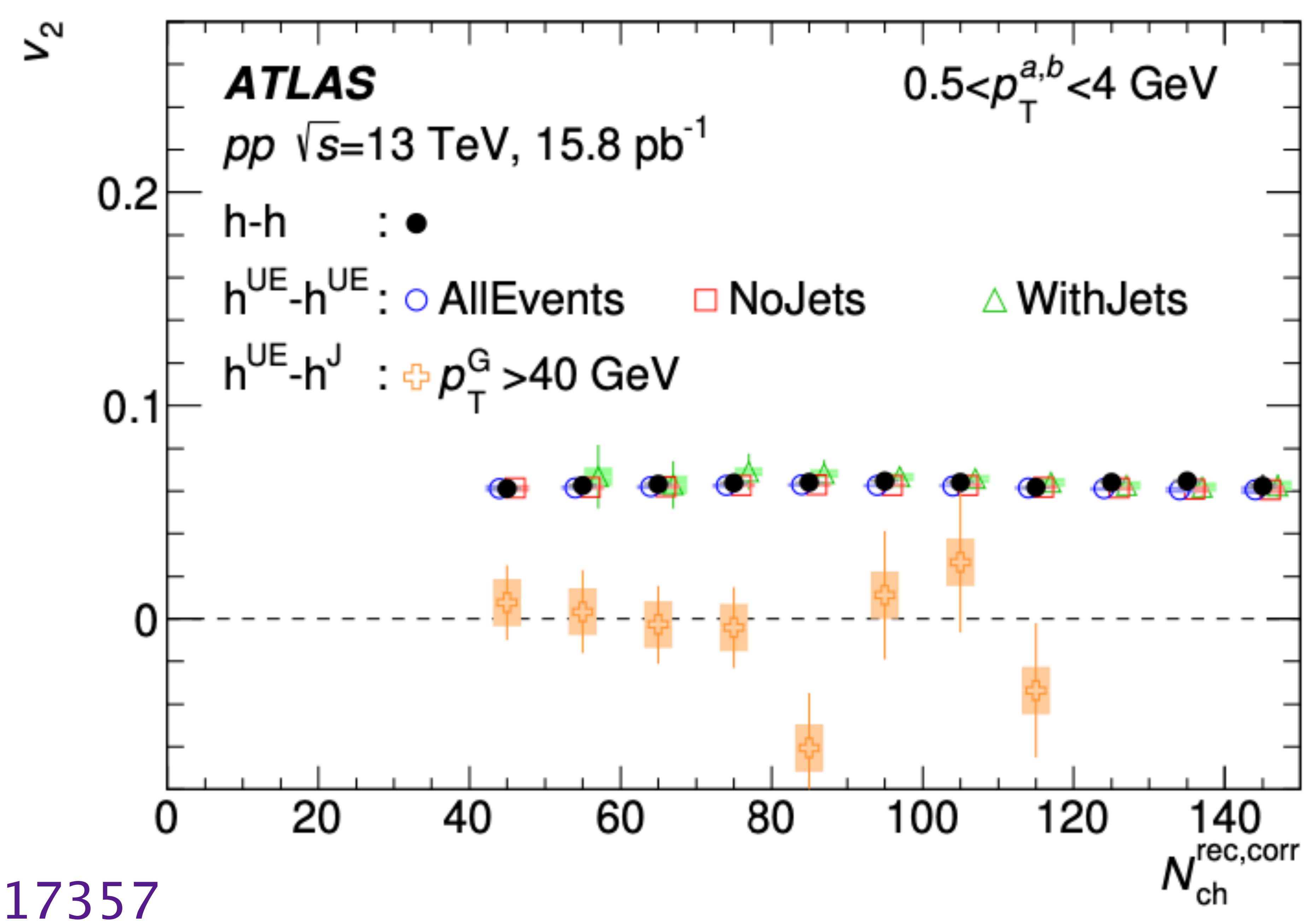
v_2 of particles in jets (p—Pb, Pb—Pb)

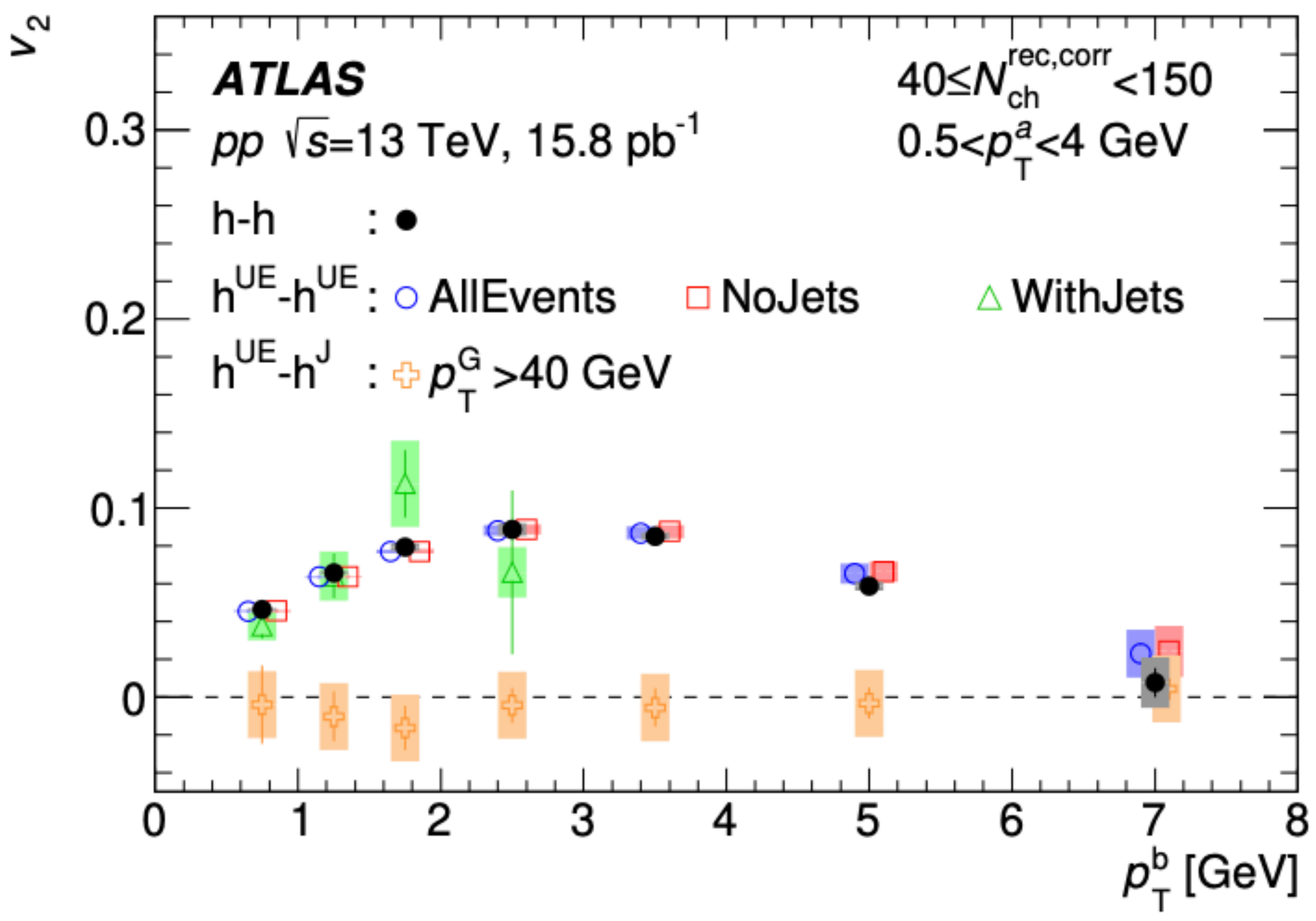


arXiv:2212.12609

- **Non-zero jet v_2** in p—Pb and Pb—Pb collisions
  - Smaller magnitude than inclusive v_2
  - No dependence on p_T^{assoc}
  - At high p_T - similar magnitude as in Pb—Pb
- v_2 driven by the non- equilibrium anisotropic parton escape mechanism

v_2 of particles in jets (pp)

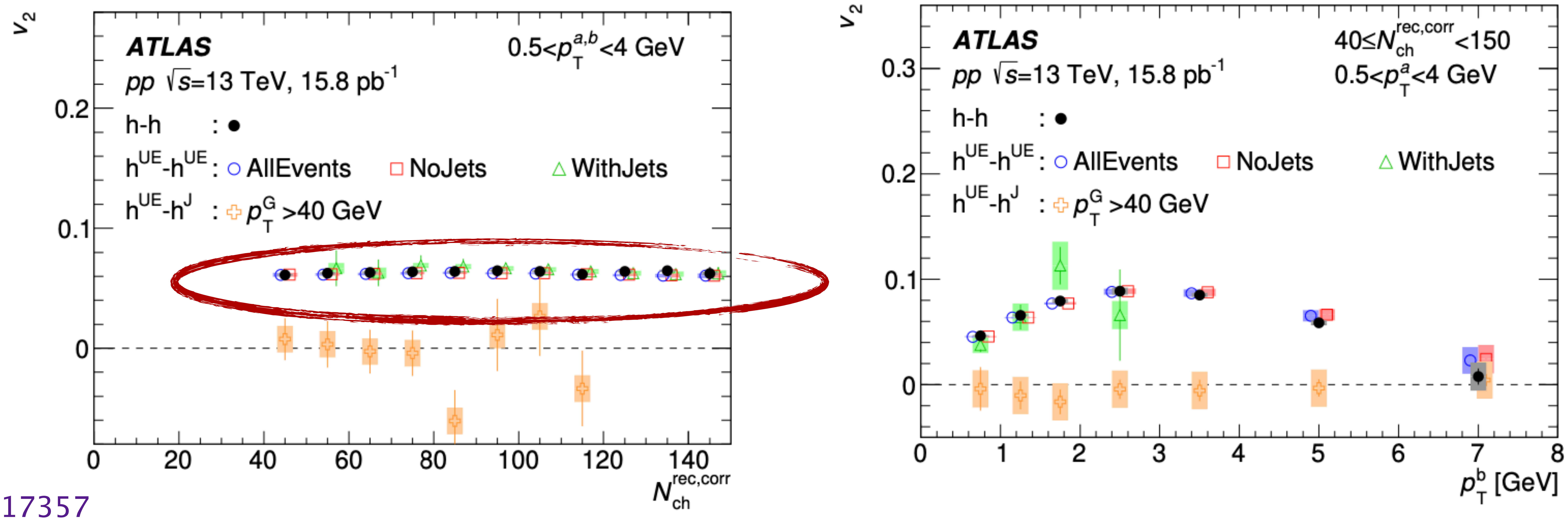




arXiv:2303.17357

- Study of influence of jets on inclusive v_2 and jet v_2 - origin of v_n in pp?
- h^{UE} separated by $\Delta\eta > 1$ from jet with $p_T > 15$ GeV/c
- h^J constituents of jets

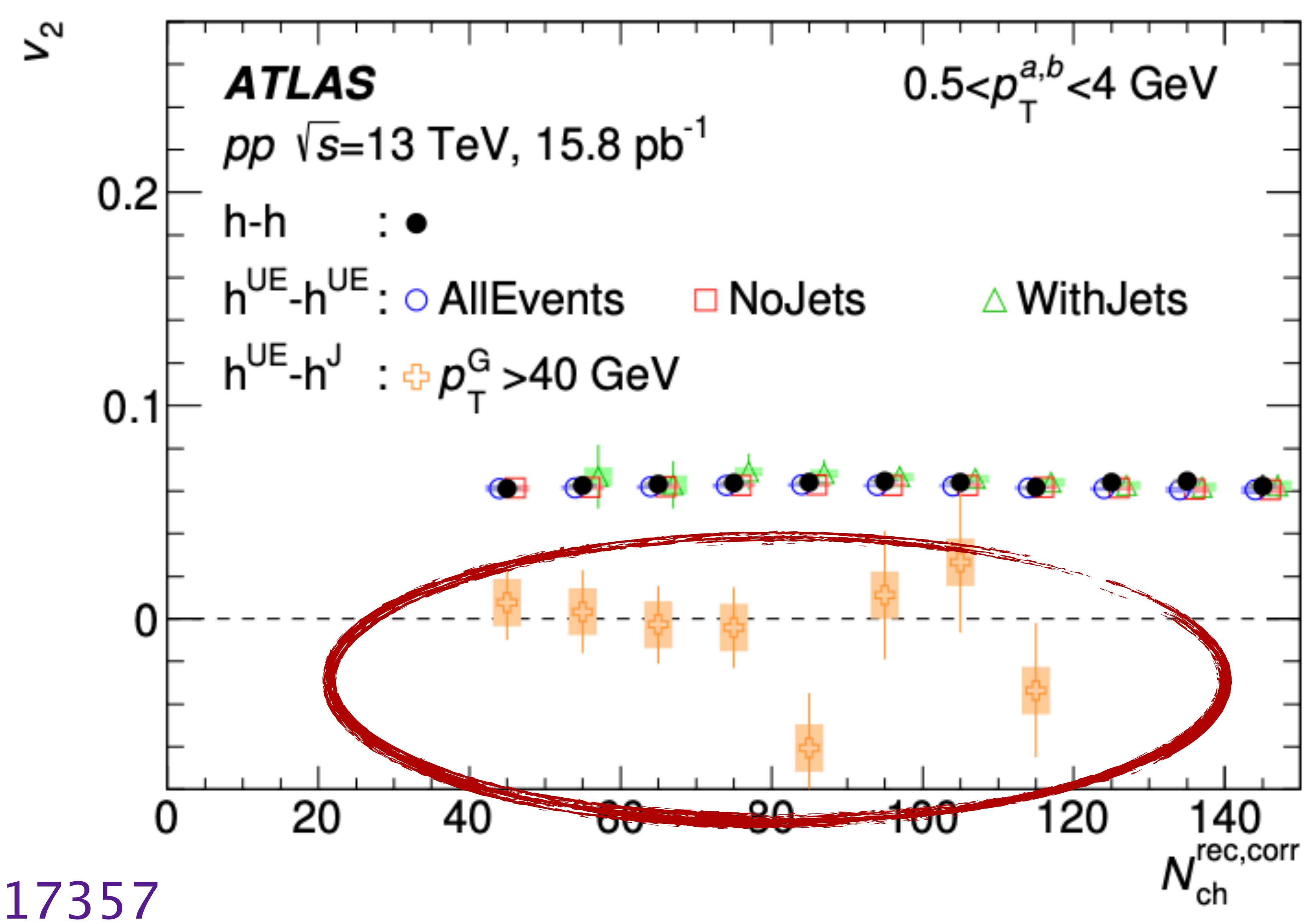
v_2 of particles in jets (pp)

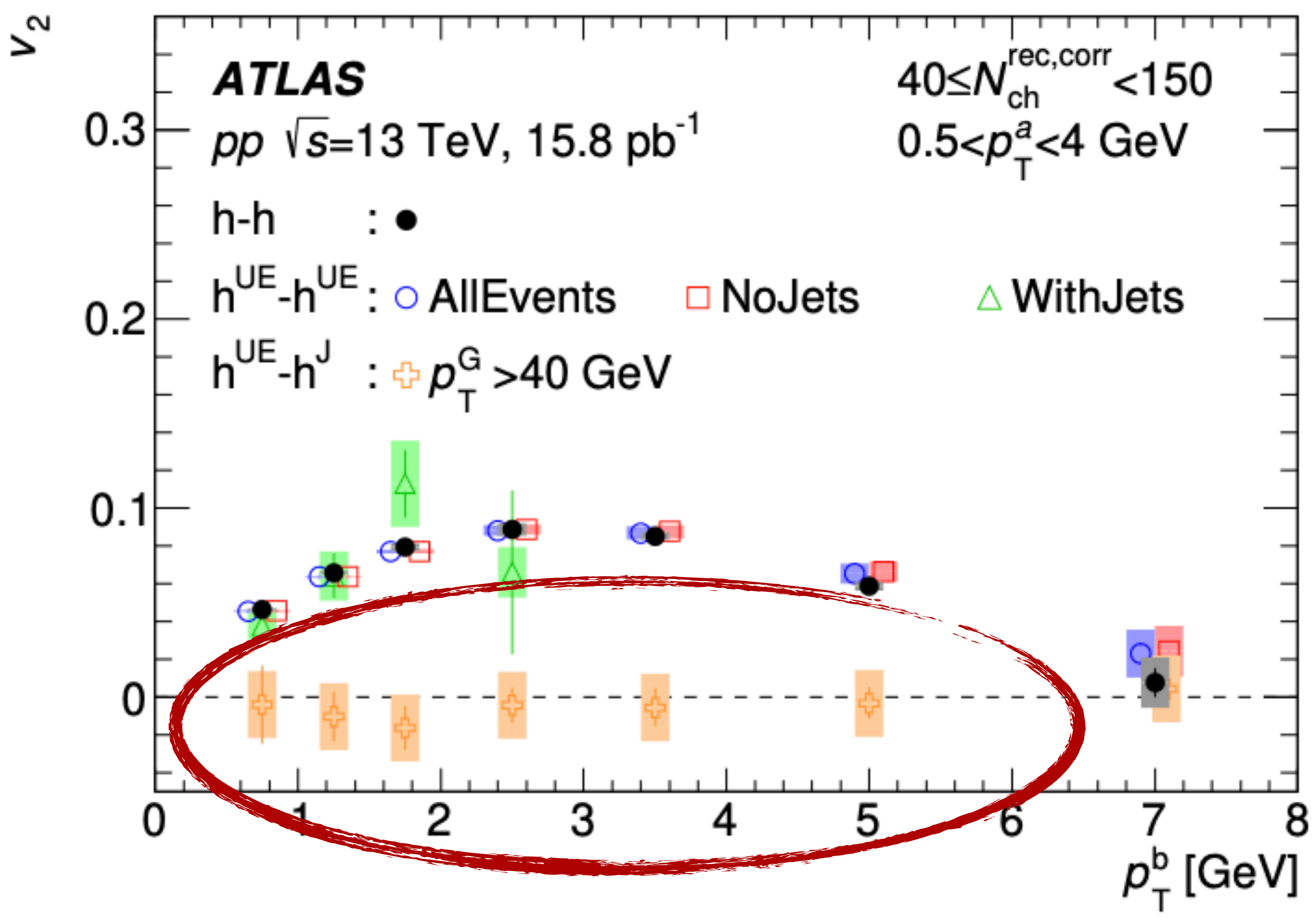


arXiv:2303.17357

- **Presence of a jet with $p_T > 15$ GeV/c does not influence the v_2 of h^{UE}**
  - No multiplicity dependence

v_2 of particles in jets (pp)

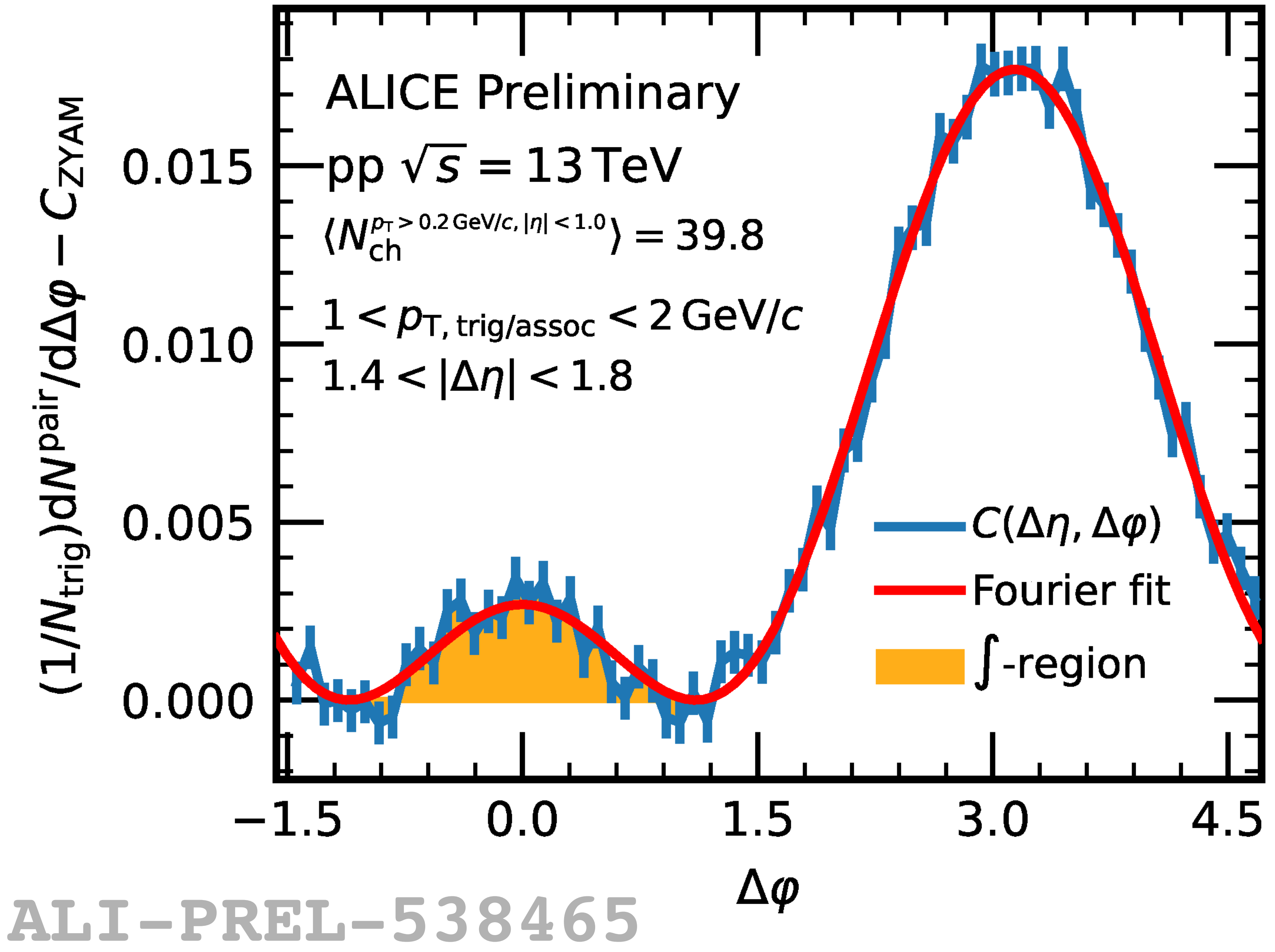


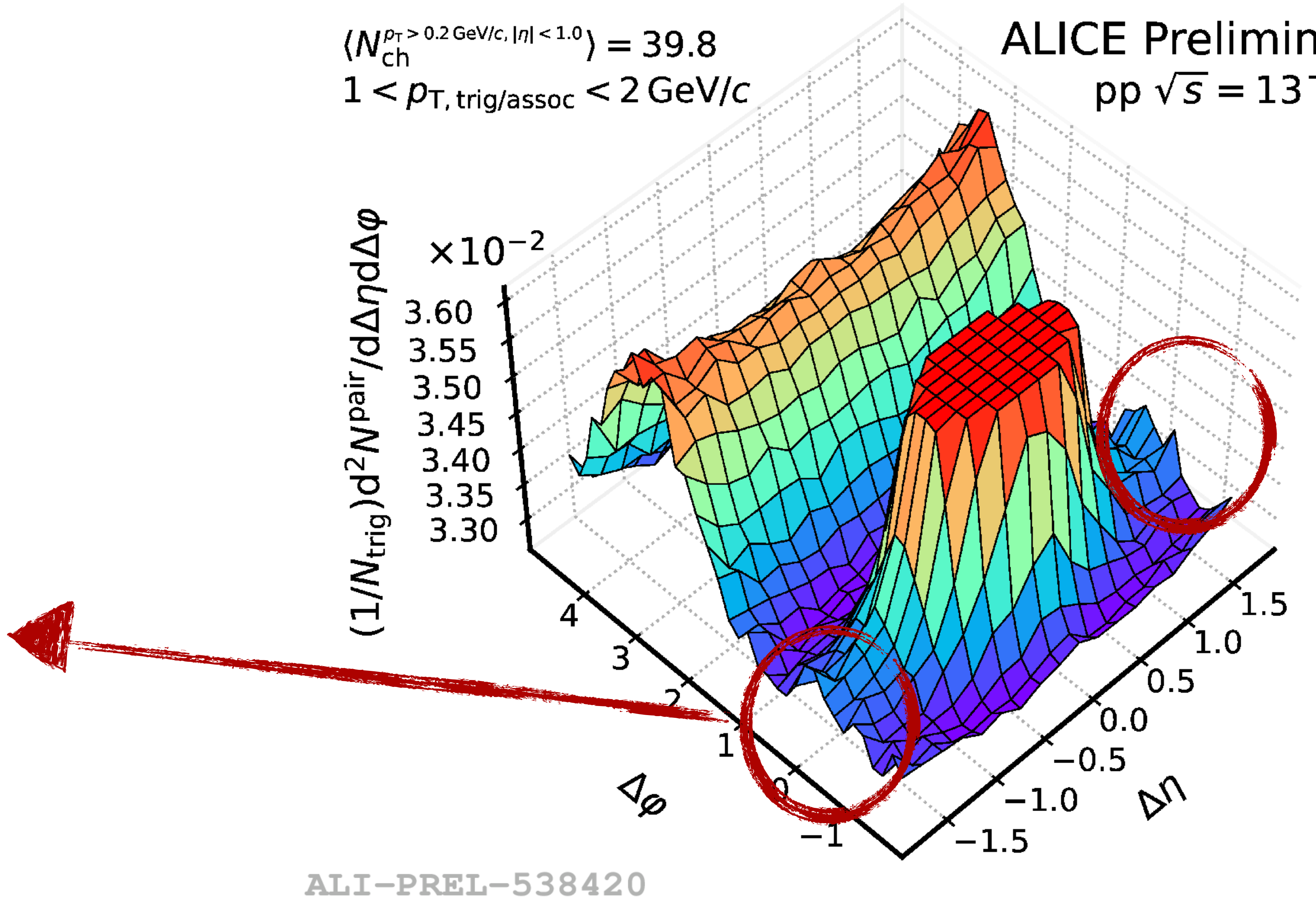


arXiv:2303.17357

- Presence of a jet with $p_T > 15$ GeV/c does not influence the v_2 of h^{UE}
  - No multiplicity dependence
- v_2 of h^J compatible with zero
  - **The inclusive v_2 is not driven by jet fragmentation, but rather by bulk**
  - **The collective system is too small to influence jets - no energy loss**

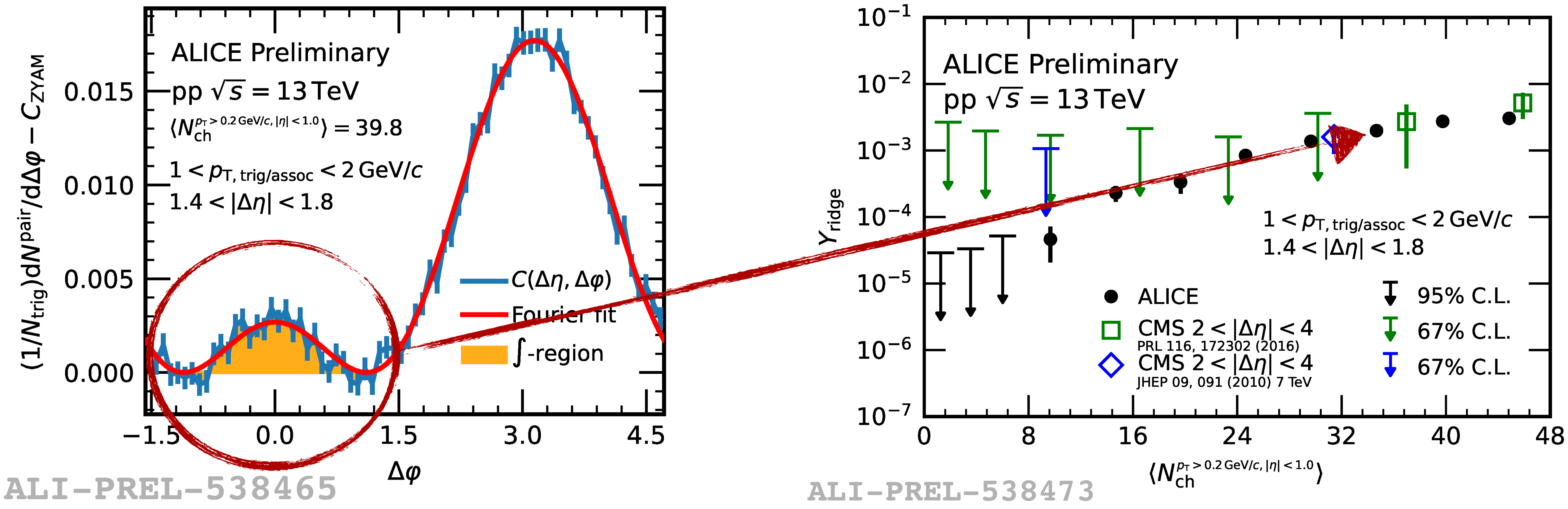
Limit of collectivity in small systems





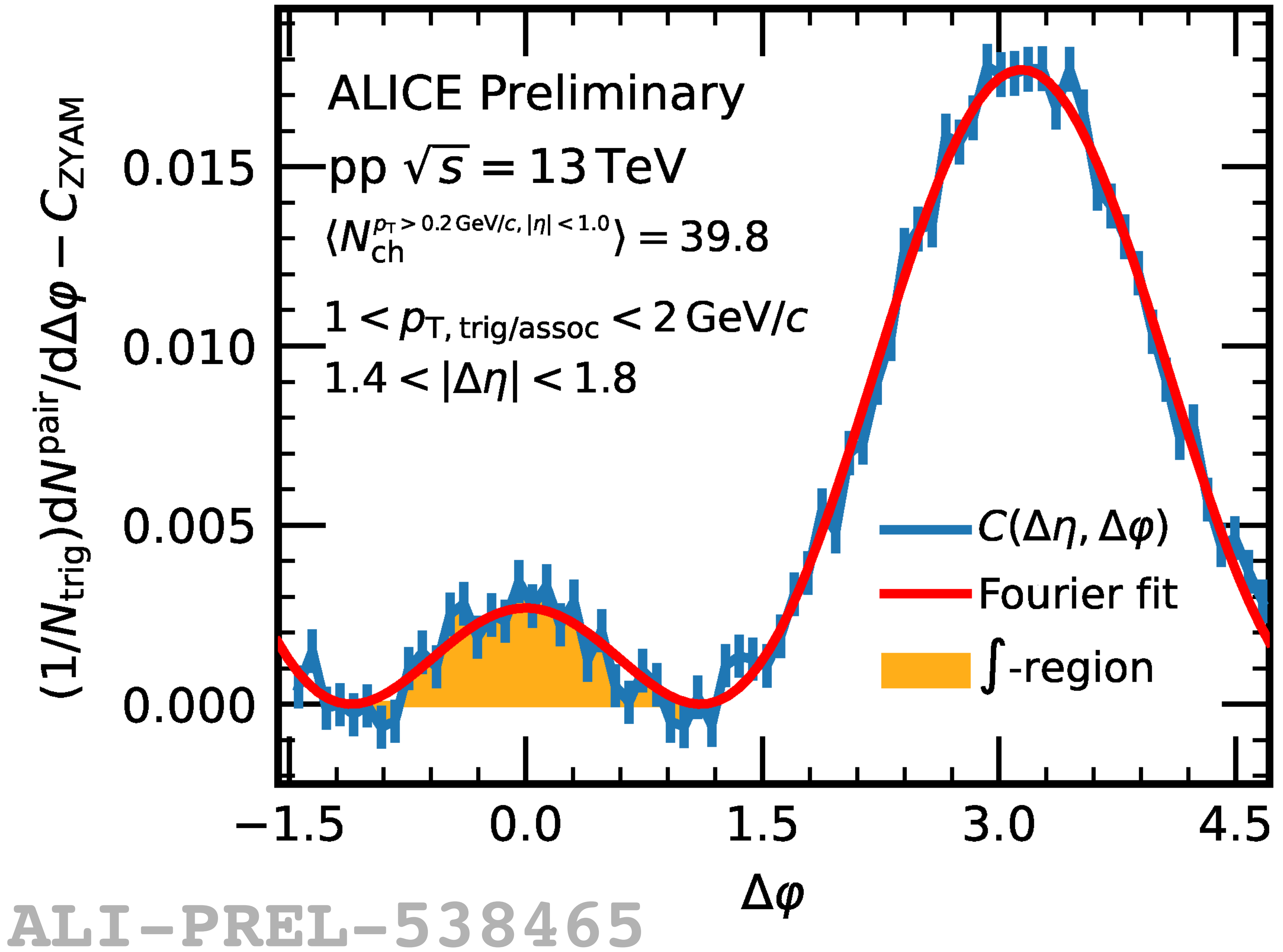
- Long-range two-particle correlations measured up to the smallest multiplicities

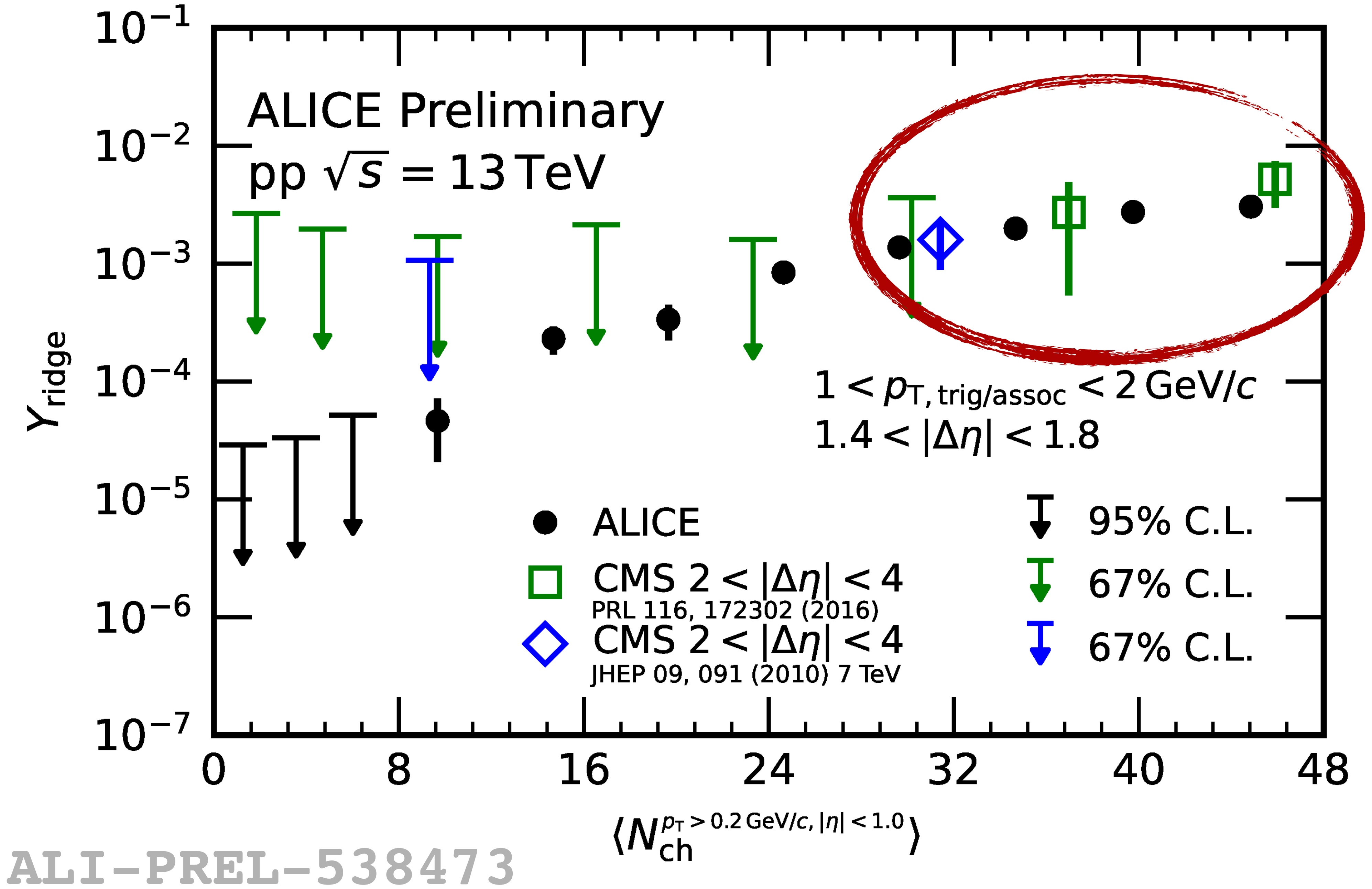
Limit of collectivity in small systems



- Integrated ridge yield as a function of multiplicity calculated with great precision

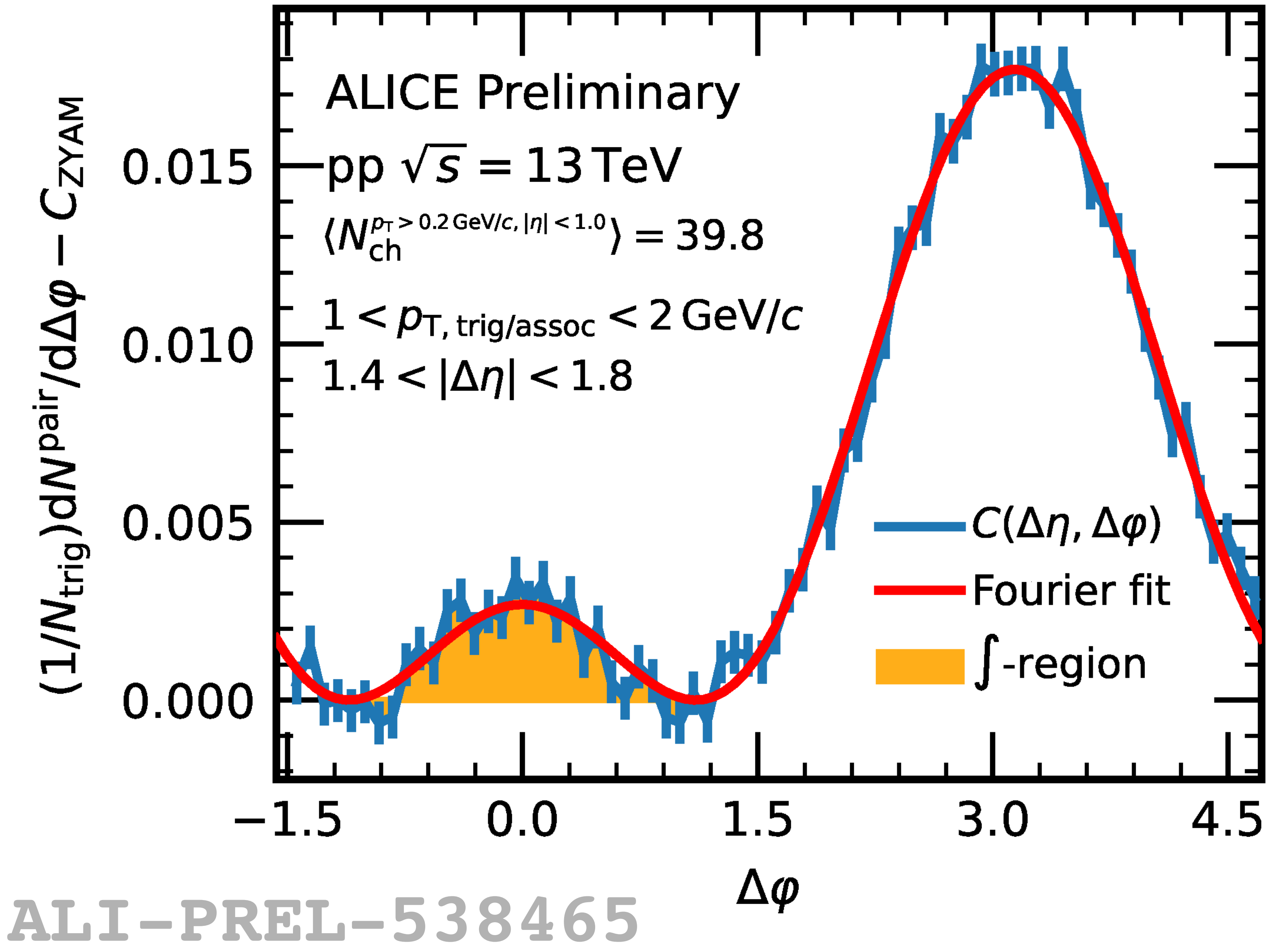
Limit of collectivity in small systems

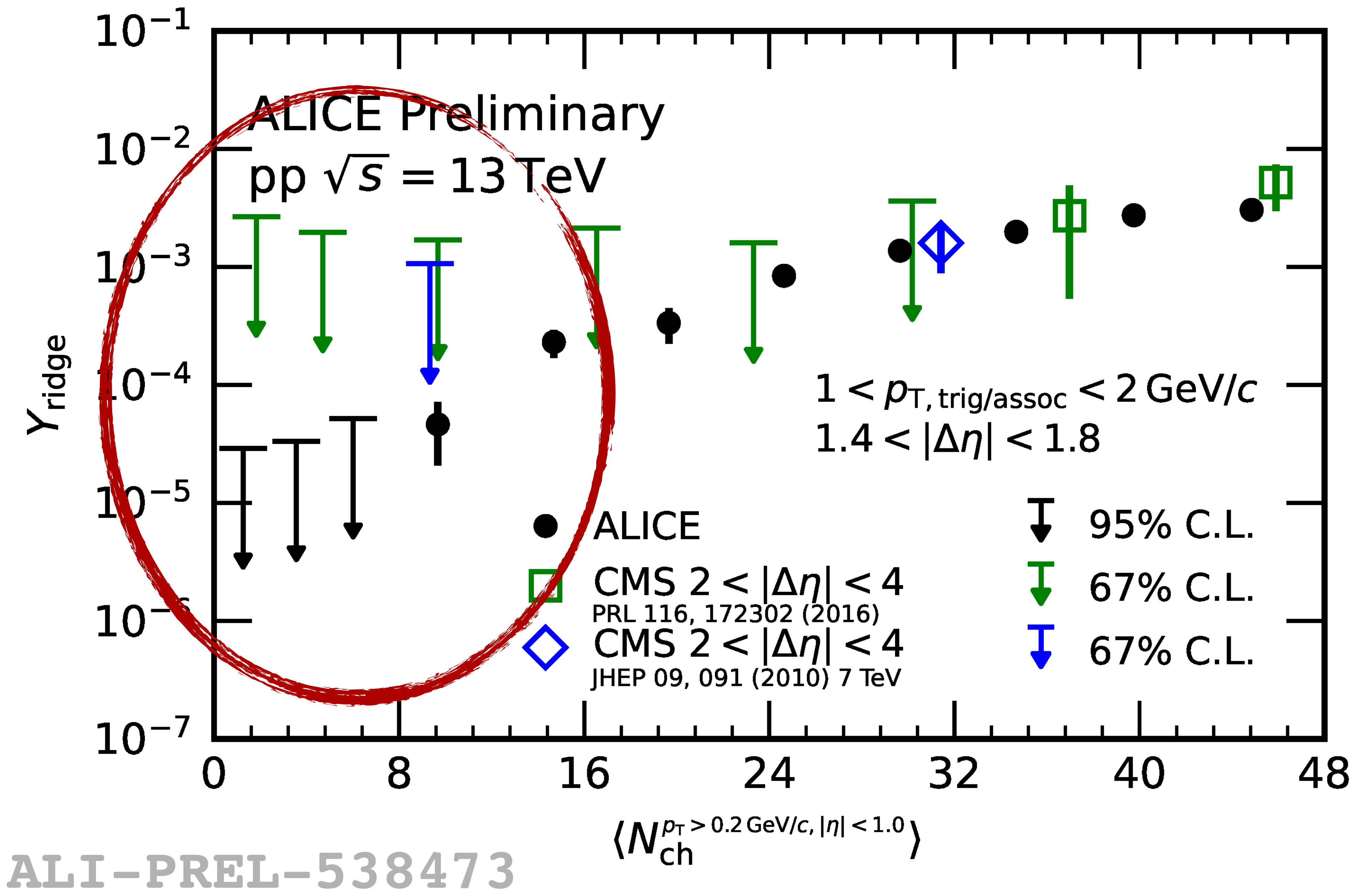




- Integrated ridge yield as a function of multiplicity calculated with great precision
  - At $N_{ch} > 30$ **compatible with CMS** measurement

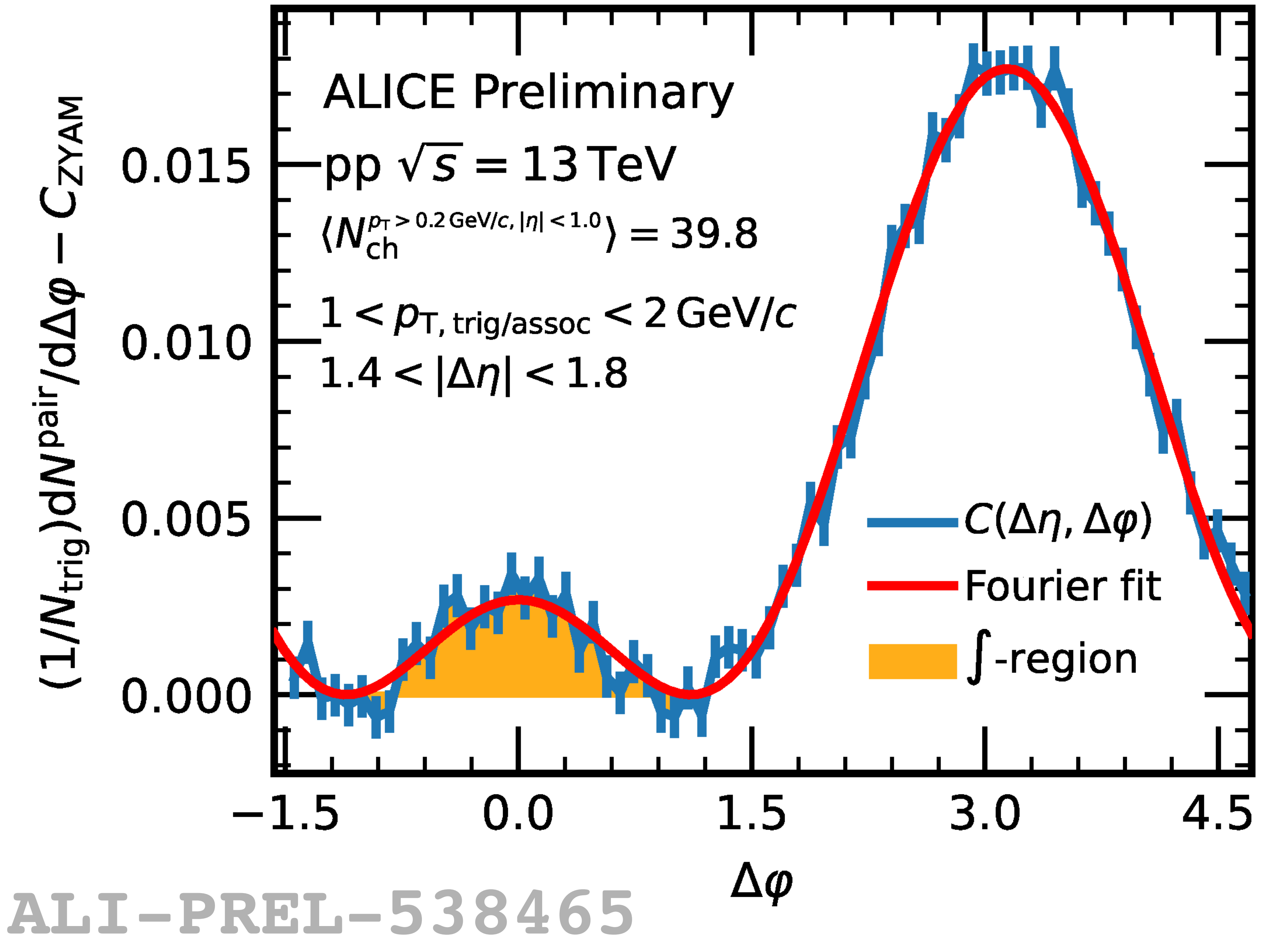
Limit of collectivity in small systems

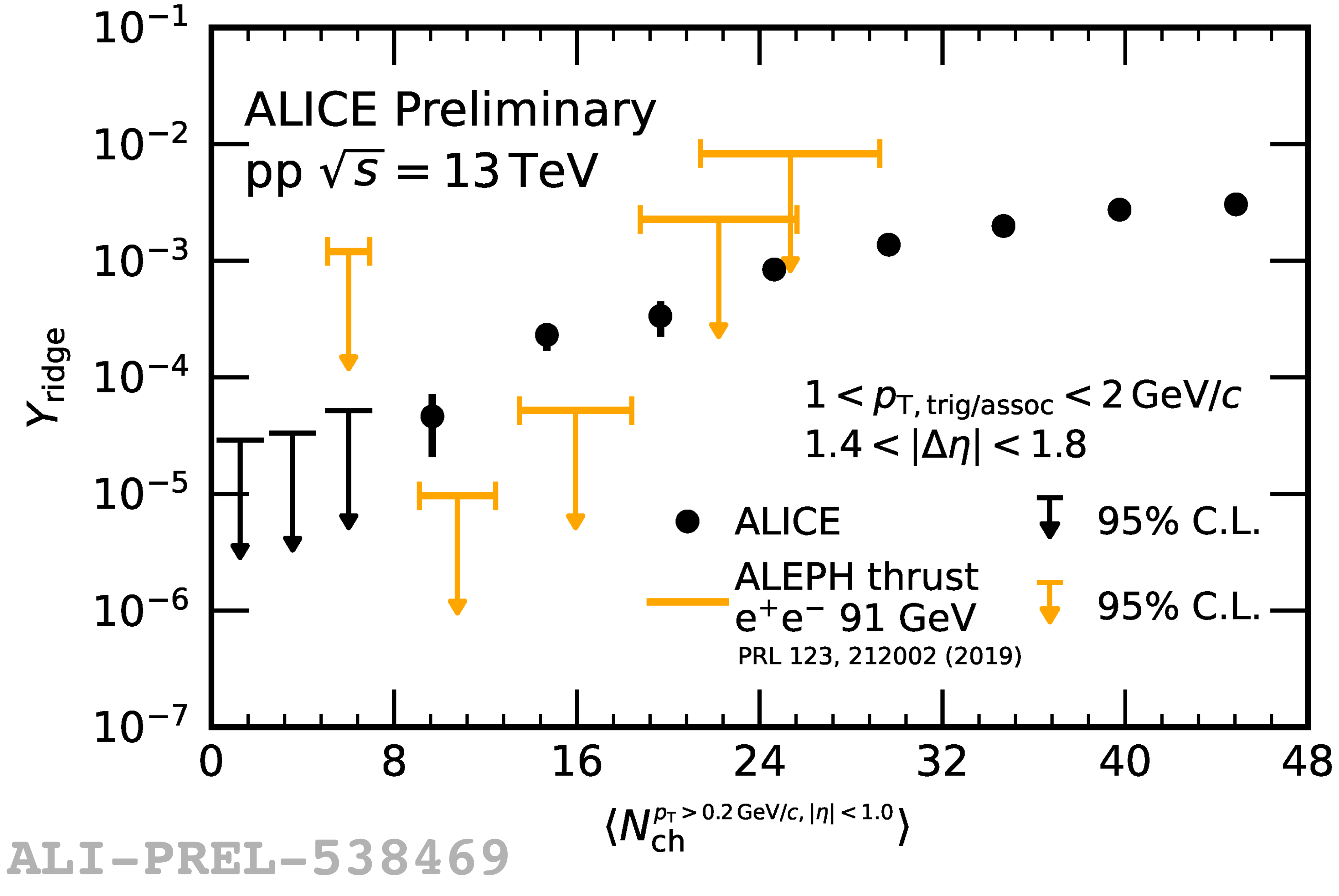




- Integrated ridge yield as a function of multiplicity calculated with great precision
  - At $N_{ch} > 30$ **compatible with CMS** measurement
  - At lower multiplicities - increased precision

Limit of collectivity in small systems





- Comparison with e^+e^- collisions
  - $Y^{pp} > Y^{ee}$ **for** $\langle N_{ch} \rangle \approx 15$ **with** 3σ
  - First quantitative comparison between pp and e^+e^- collisions
  - New insight to processes contributing to the long-range ridge

Conclusion

- **Large systems**
  - Deconfined medium with small η/s
  - Late production of pions via coalescence, hint of early production of protons
  - v_2 of jets and jet particles induced by path length dependent energy loss
- **Small systems**
  - Collectivity supported by narrowing of the peak width of BF and G_2 correlation functions of low p_T hadrons and non-zero v_2
    - Viscous forces do not have time to equilibrate the system
  - v_2 in pp collisions not driven and not influenced by jet fragmentation
  - Significant ridge yield in pp down to $\langle N_{ch} \rangle \approx 10$, larger than in e^+e^-

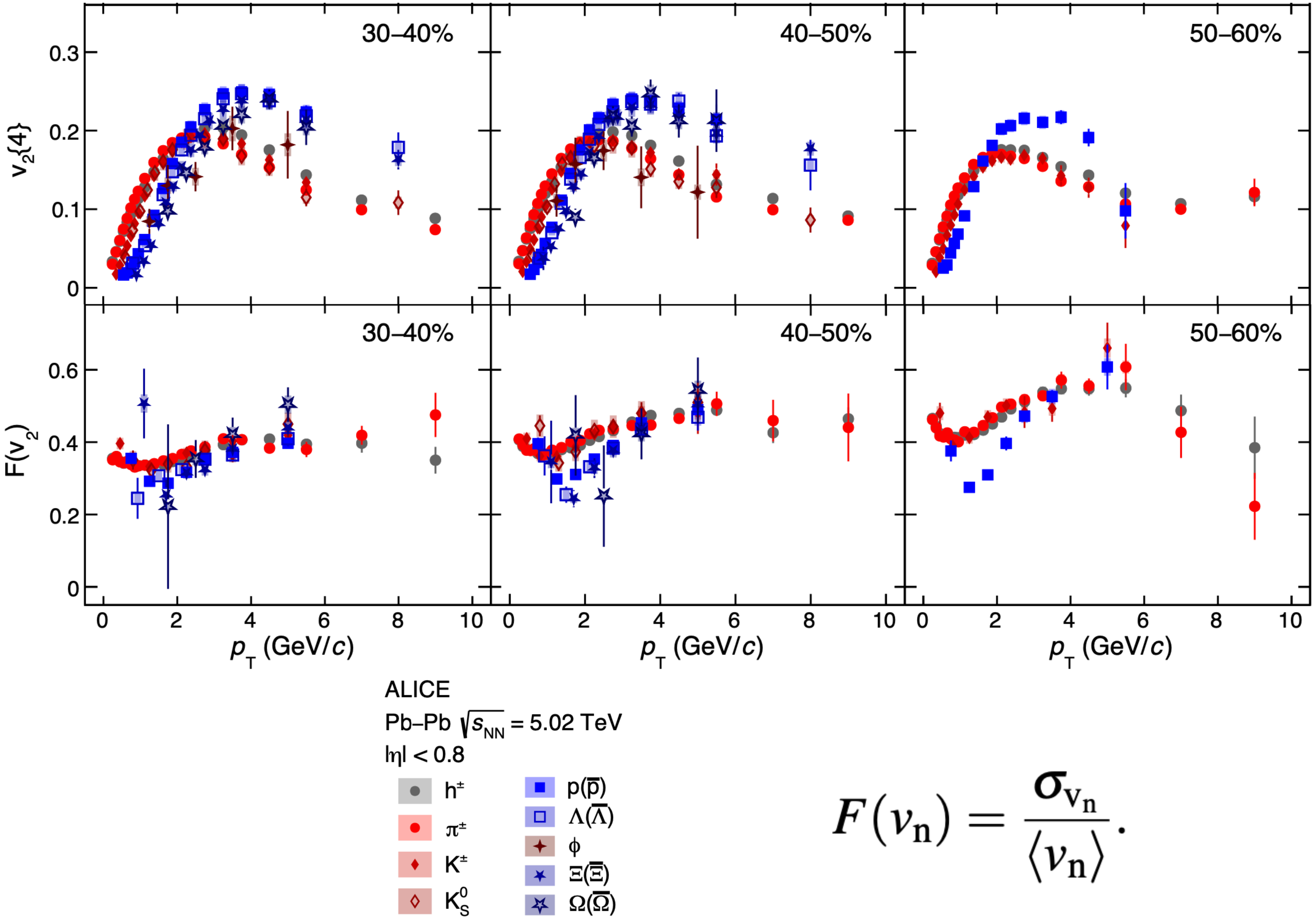
Thank you for your attention!

Questions

More results

PID flow in Pb-Pb

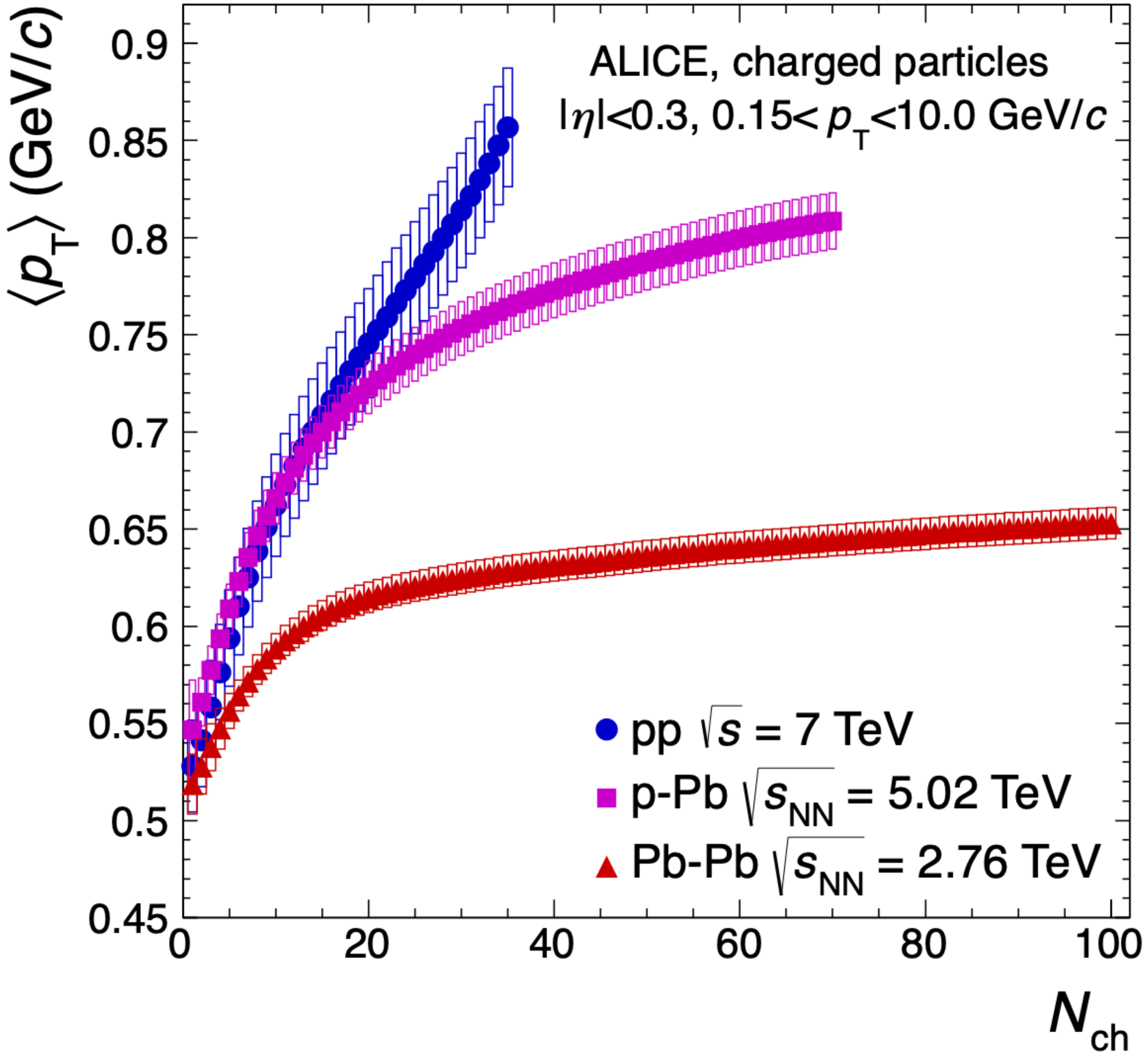
arXiv:2206.04587

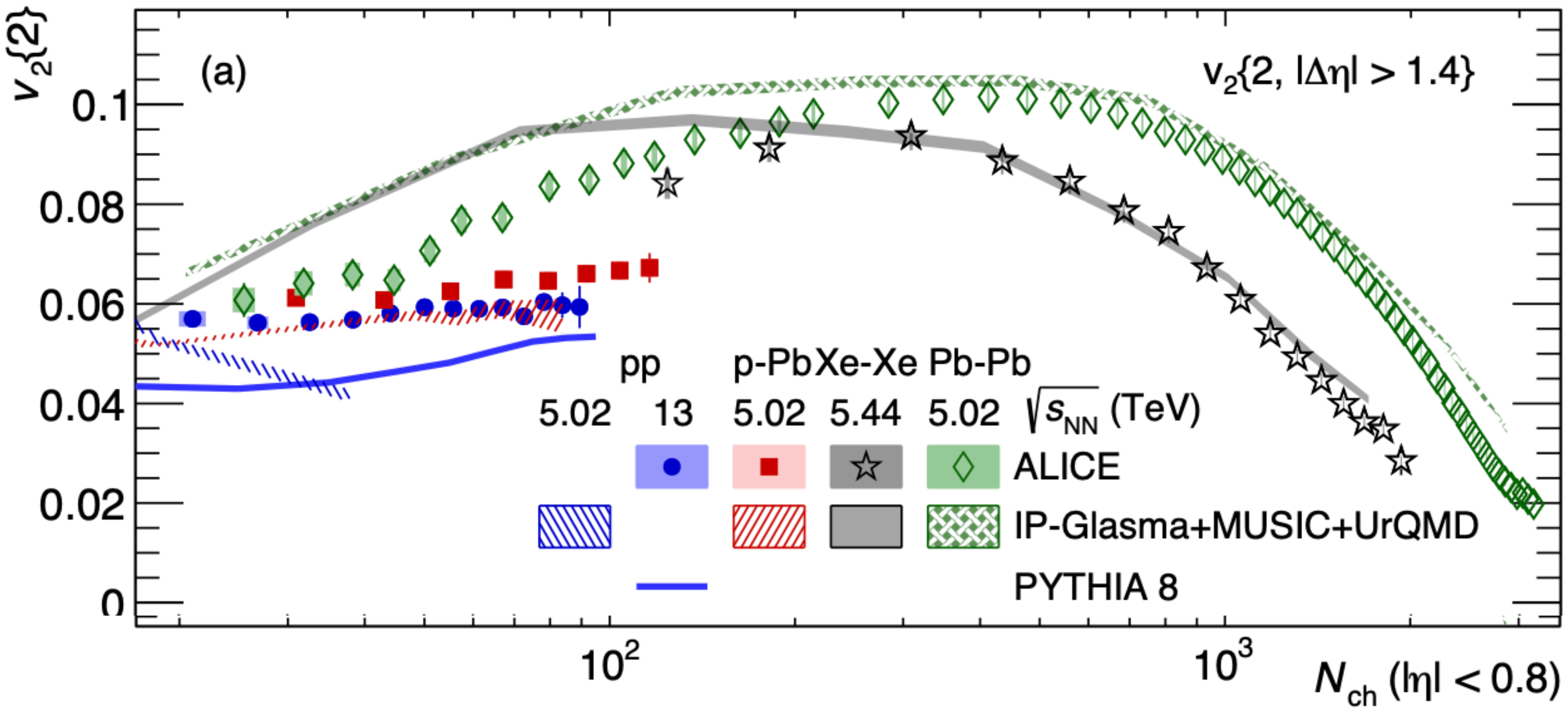


- First p_T-differential v_2 measurements using four-particle cumulants for identified particles
- In the intermediate p_T range, - $v_2\{4\}$ for baryons is larger than that for mesons by about 50%
- $F(v_2)$ - an apparent splitting between baryons and mesons for centrality above 30% ⇒ a significant role for final-state interactions in developing this observable

$$F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}.$$

Back up


ALICE, charged particles
|η|<0.3, 0.15< p_T<10.0 GeV/c
pp $\sqrt{s}$ = 7 TeV
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
$\langle p_T \rangle$ (GeV/c)
N_{ch}
0.45
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0
20
40
60
80
100



v2{2}
(a)
v2{2, |Δη| > 1.4}
0.1
0.08
0.06
0.04
0.02
0
pp
p-Pb
Xe-Xe
Pb-Pb
5.02
13
5.02
5.44
5.02
√sNN (TeV)
ALICE
IP-Glasma+MUSIC+UrQMD
PYTHIA 8
10^2
10^3
Nch (|η| < 0.8)