Recent results on jets and collective phenomena in ALICE experiment

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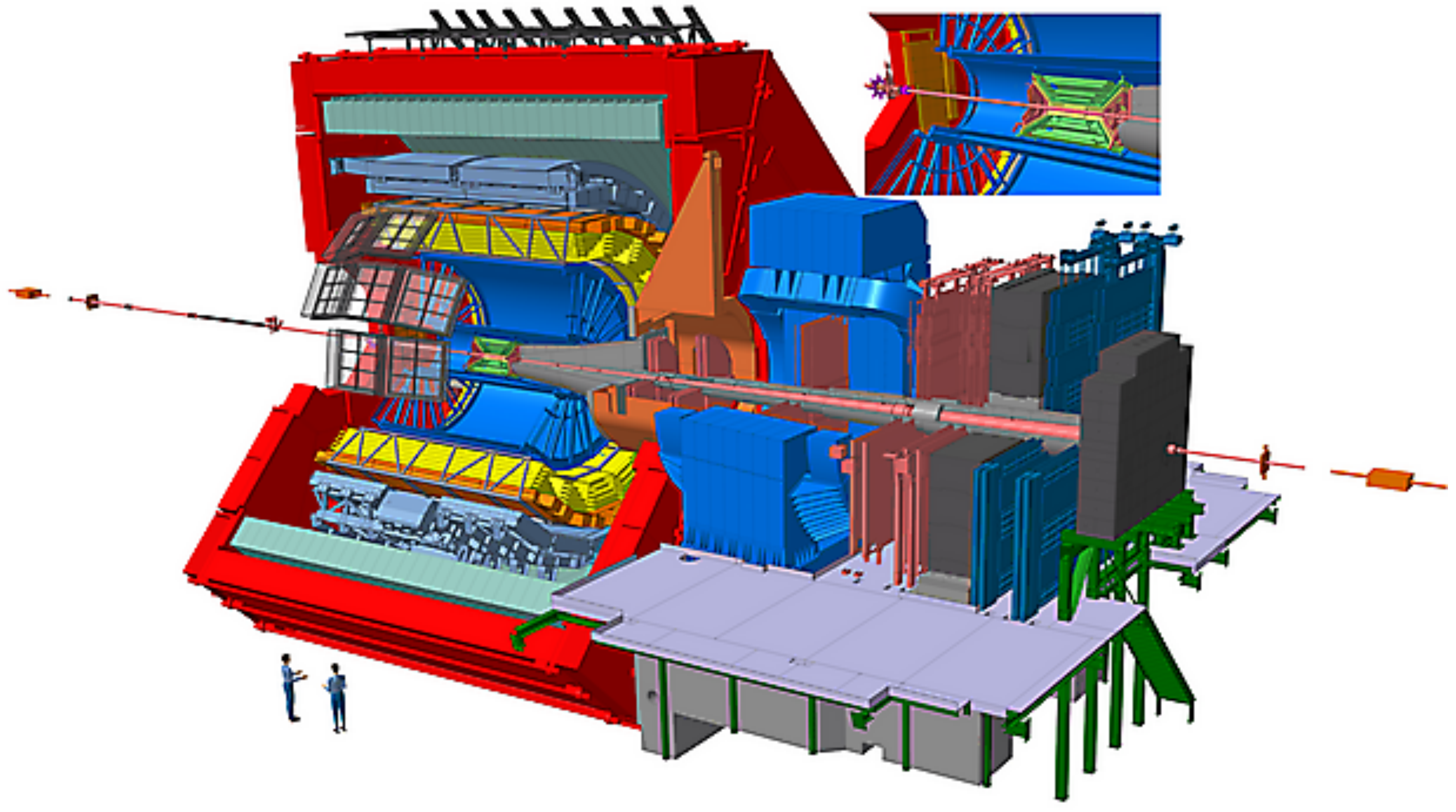
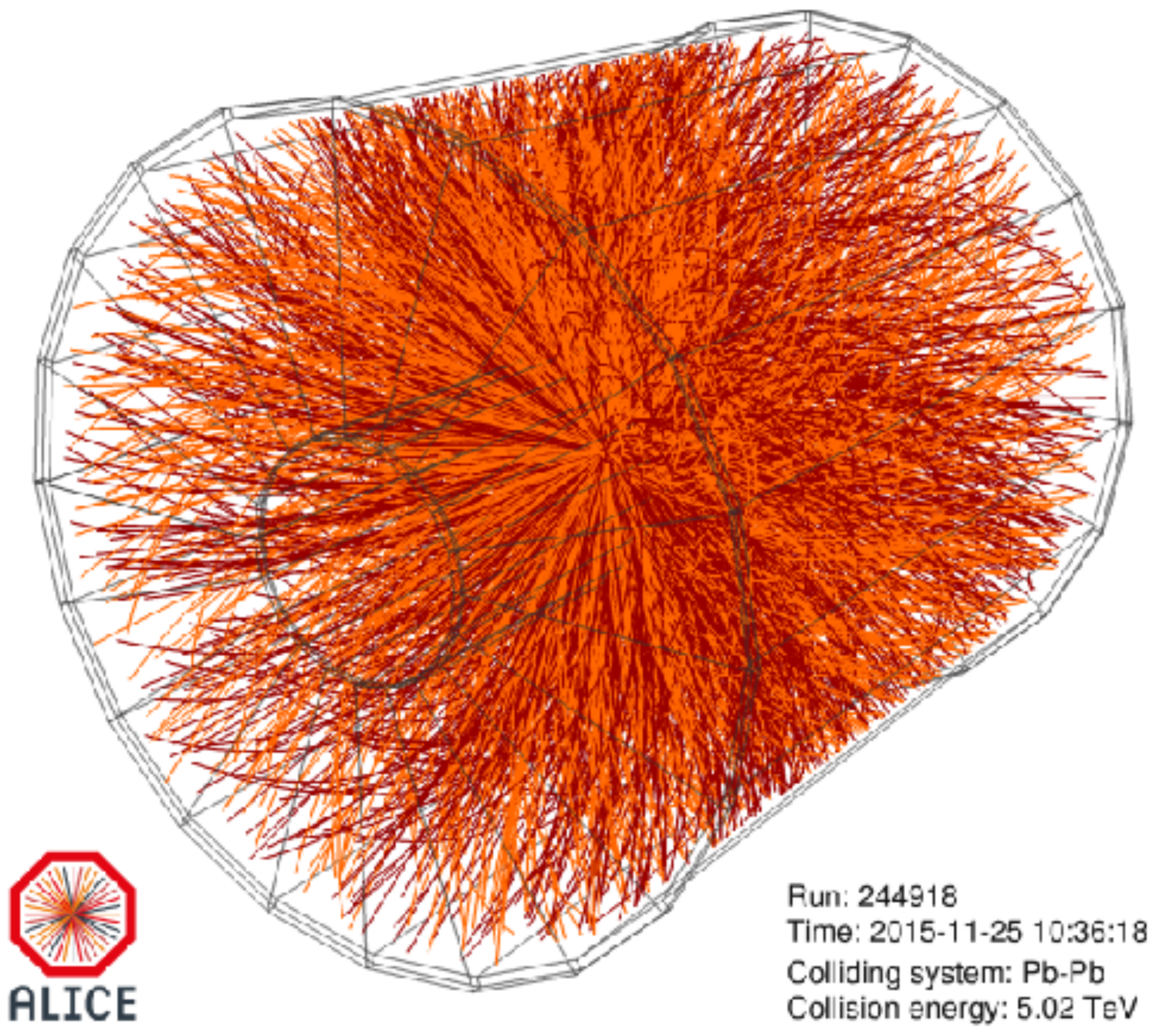
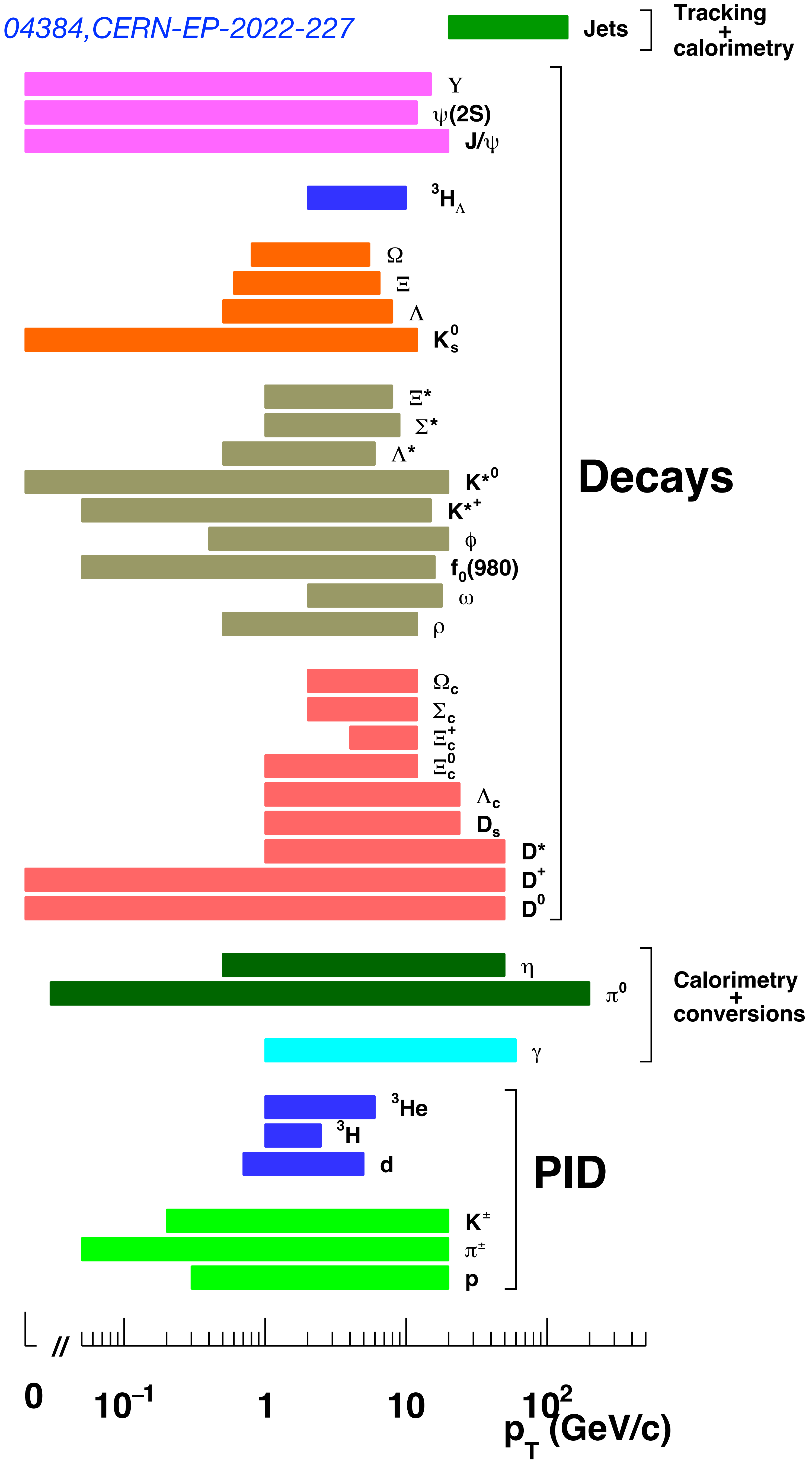
ALICE experiment at the LHC





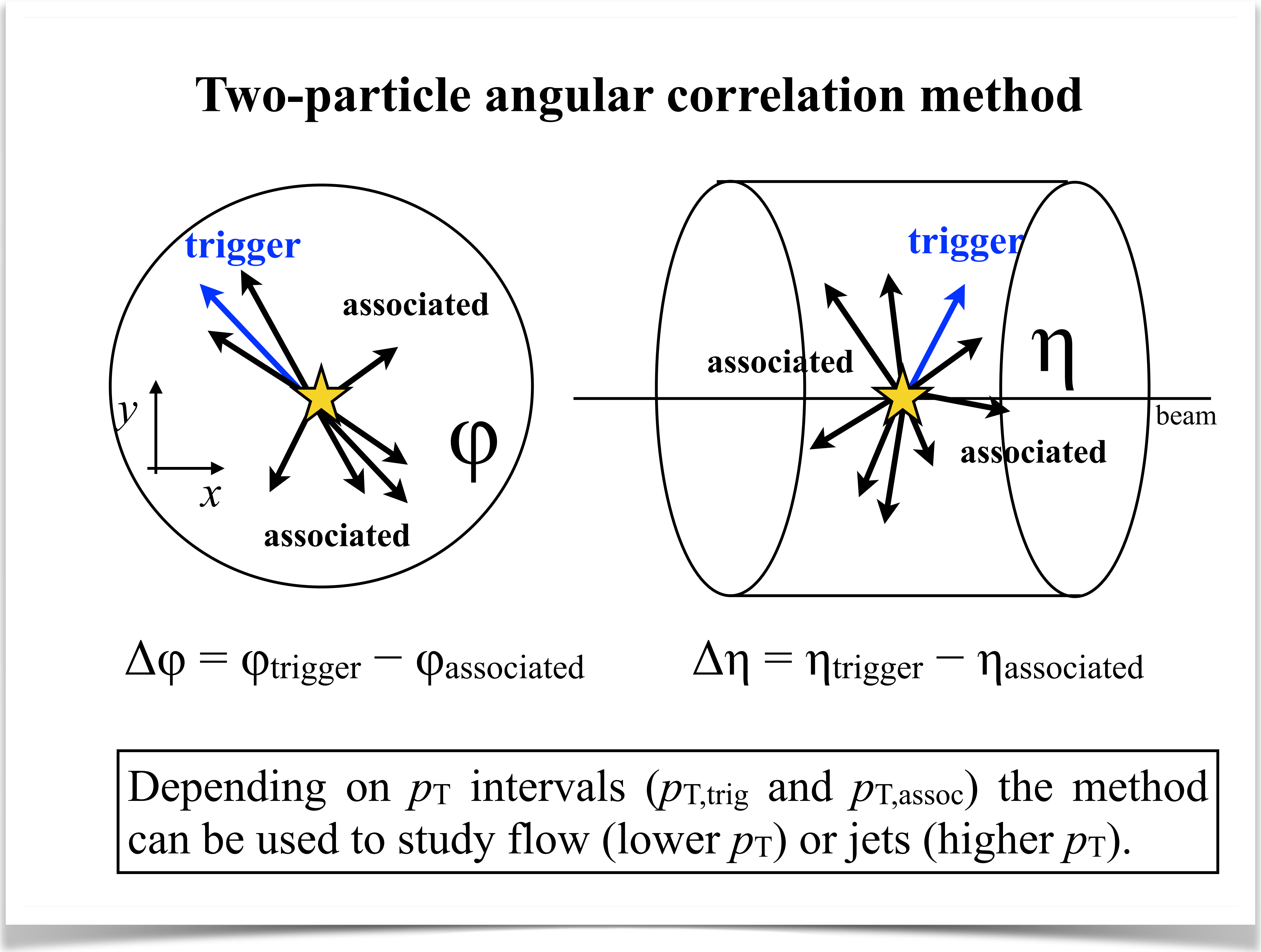
ALICE, arXiv:2211.04384,CERN-EP-2022-227



- dedicated to study the hot and dense nuclear matter in heavy-ion collisions
- crucial part of the physics programme is to study pp and p–Pb collisions
- excellent at particle identification and track reconstruction in high track density environment (central Pb–Pb) up to very low p_T (100 MeV/c in Run 2)

Long-range correlations in heavy-ion collisions

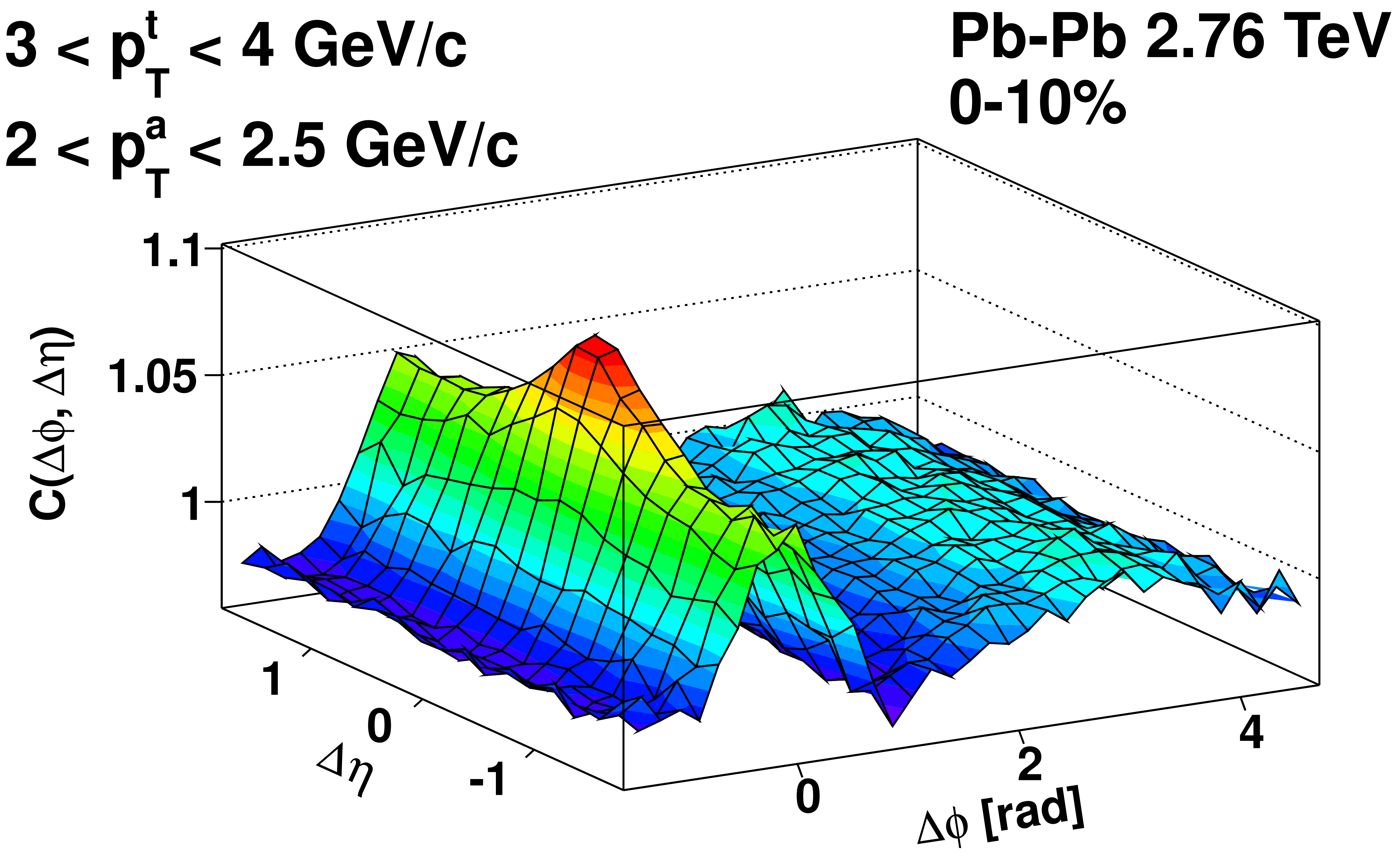
- long-range, near-side correlations (large Δη and small Δϕ) in Pb–Pb connected to hydrodynamic expansion of the quark-gluon plasma



Two-particle angular correlation method

$\Delta\varphi = \varphi_{\mathrm{trigger}} - \varphi_{\mathrm{associated}}$ $\Delta\eta = \eta_{\mathrm{trigger}} - \eta_{\mathrm{associated}}$

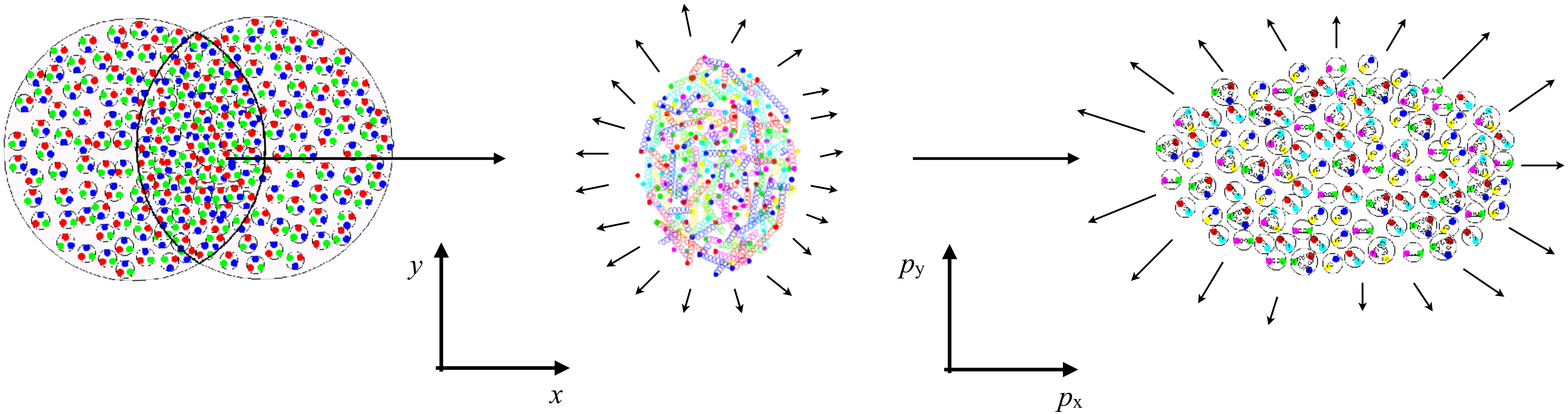
Depending on p_{T} intervals ($p_{\mathrm{T,trig}}$ and $p_{\mathrm{T,assoc}}$) the method can be used to study flow (lower p_{T}) or jets (higher p_{T}).



ALI-PUB-14107

ALICE, Physics Letters B 708 (2012) 249-264

Azimuthal anisotropy in heavy-ion collisions



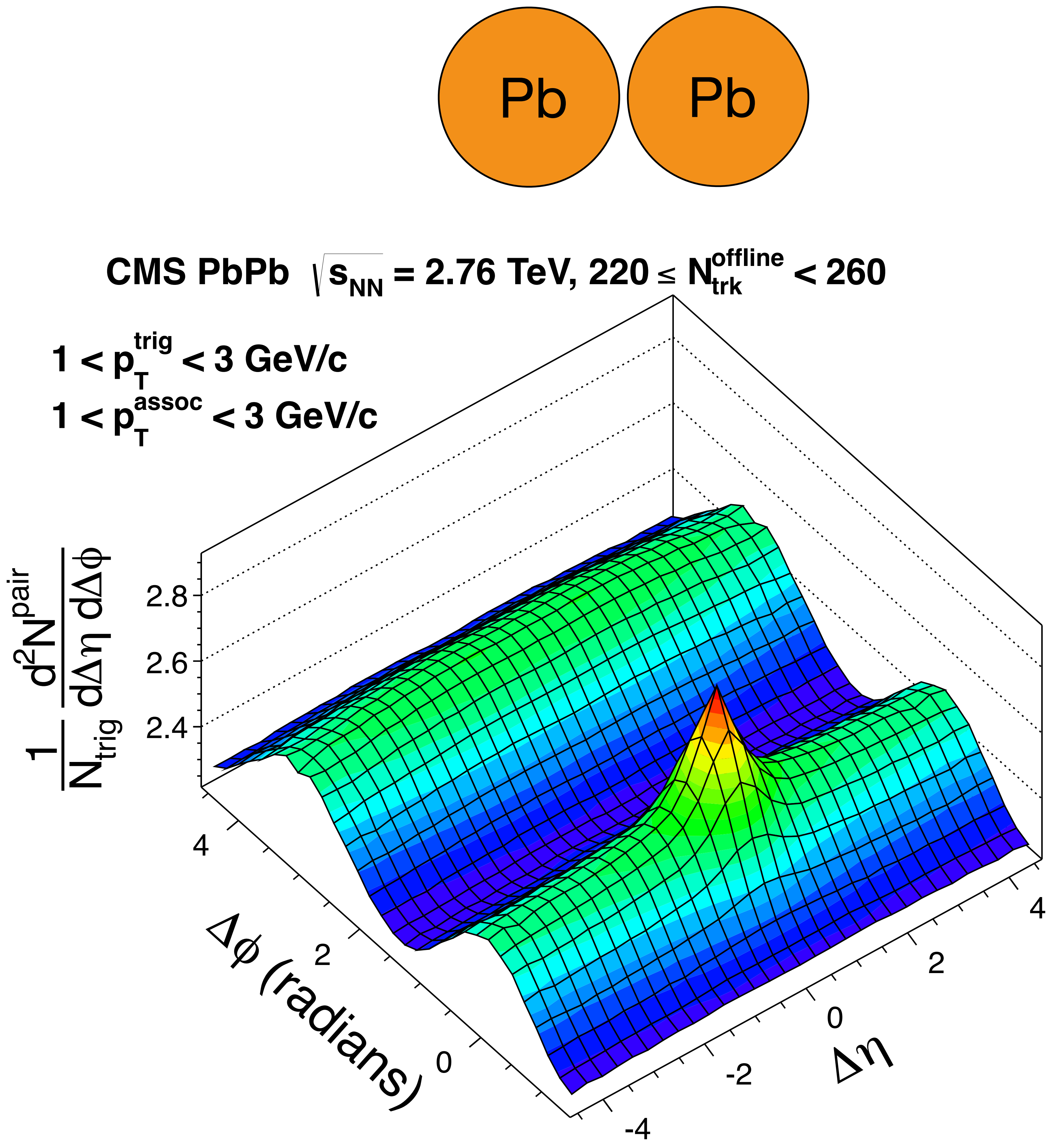
- initial spatial asymmetry of partonic matter leads to azimuthal momentum space anisotropy in hadron distribution due to different pressure gradients
- anisotropy can be quantified by second Fourier coefficient of the particle distribution (i.e. v_2 a.k.a. elliptic flow)
- "lumpiness" of the fireball (due to fluctuations of the initial energy density profile of the colliding nucleons) can give rise to higher harmonics (v_n, n=3,4,..)

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + 2\sum_{n=1}^{\infty} v_n(p_T, y)\cos[n(\phi - \Psi_R)]\right)$$

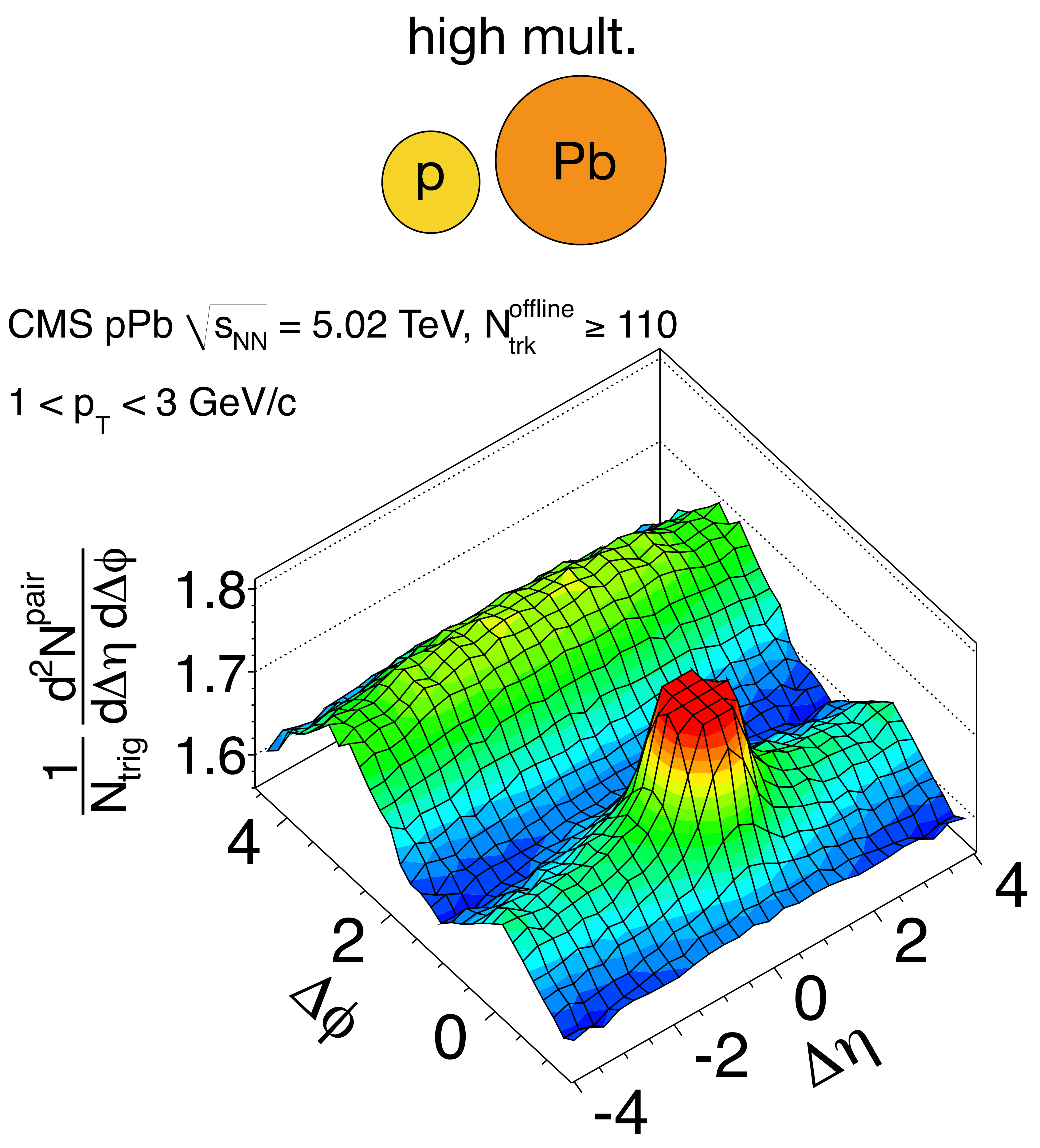
$$v_n(p_T, y) = \langle\cos[n(\phi - \Psi_R)]\rangle$$

Ψ_R - reaction plane angle

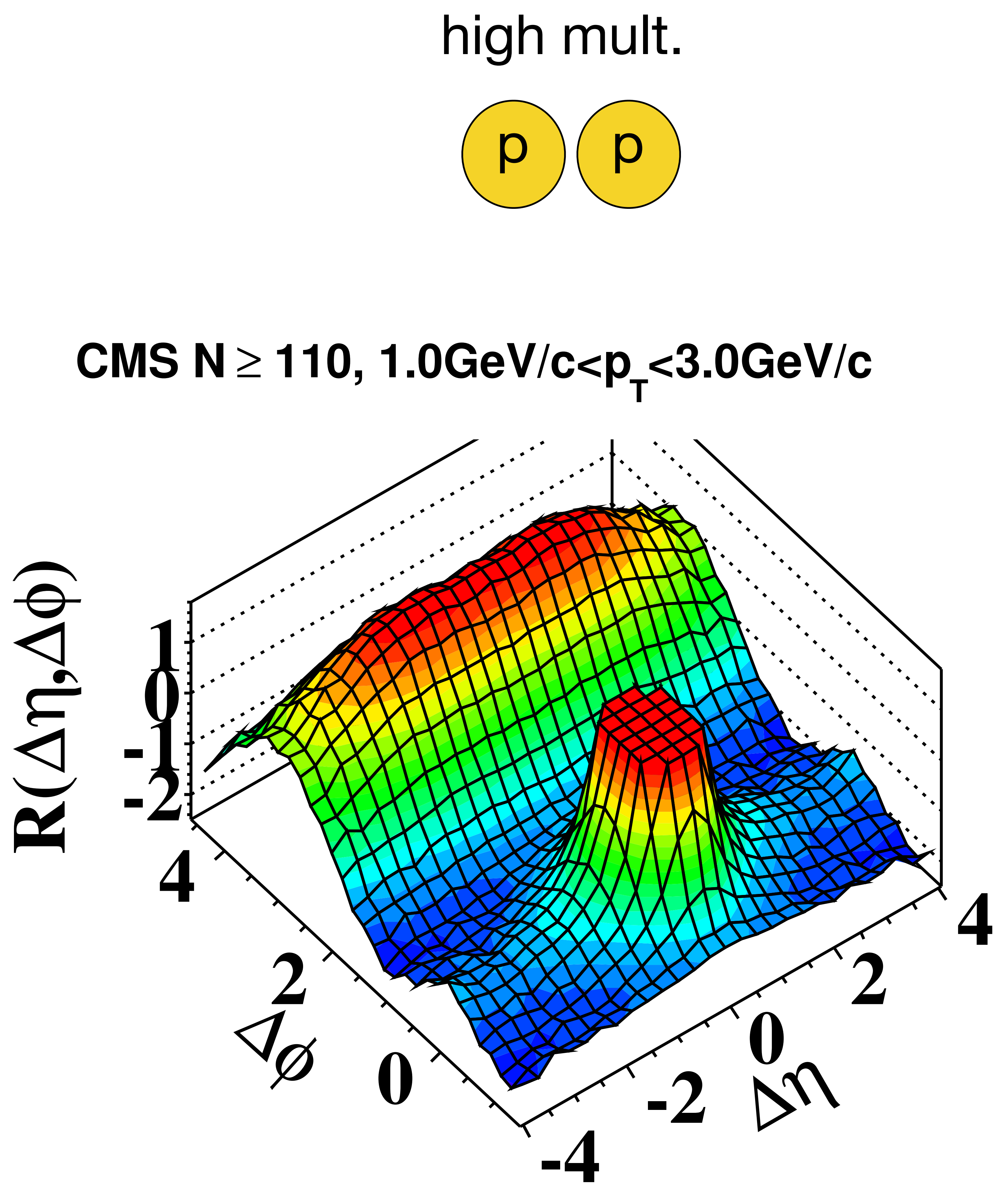
Long-range correlations in small systems



CMS, PLB 724 (2013) 213



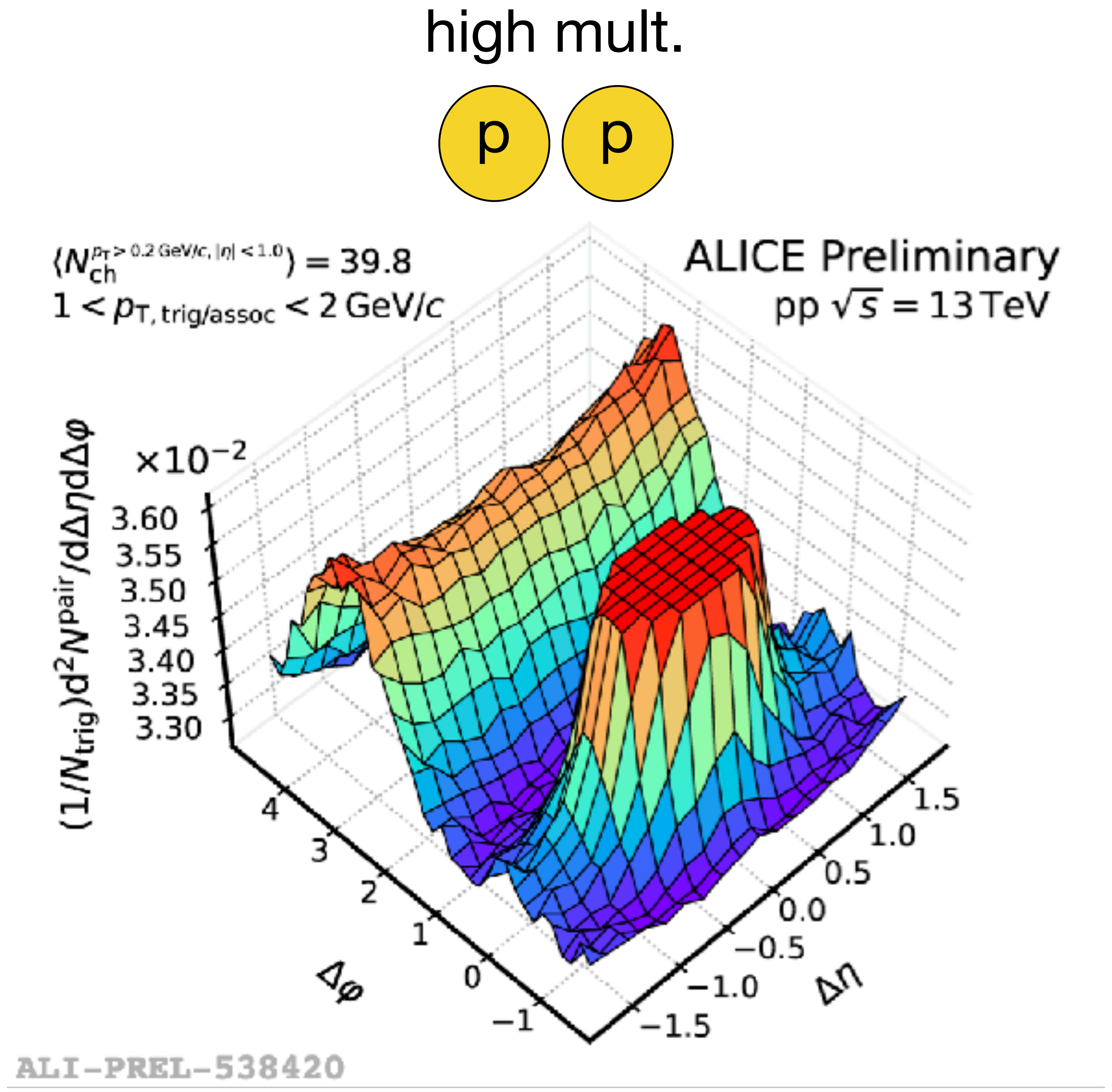
CMS, PLB 718 (2013) 795



CMS, JHEP 09 (2010) 091

- structures from two-particle correlations previously connected to collectivity in Pb–Pb collisions visible also in p–Pb and pp

Long range correlations in small systems - is there a limit?



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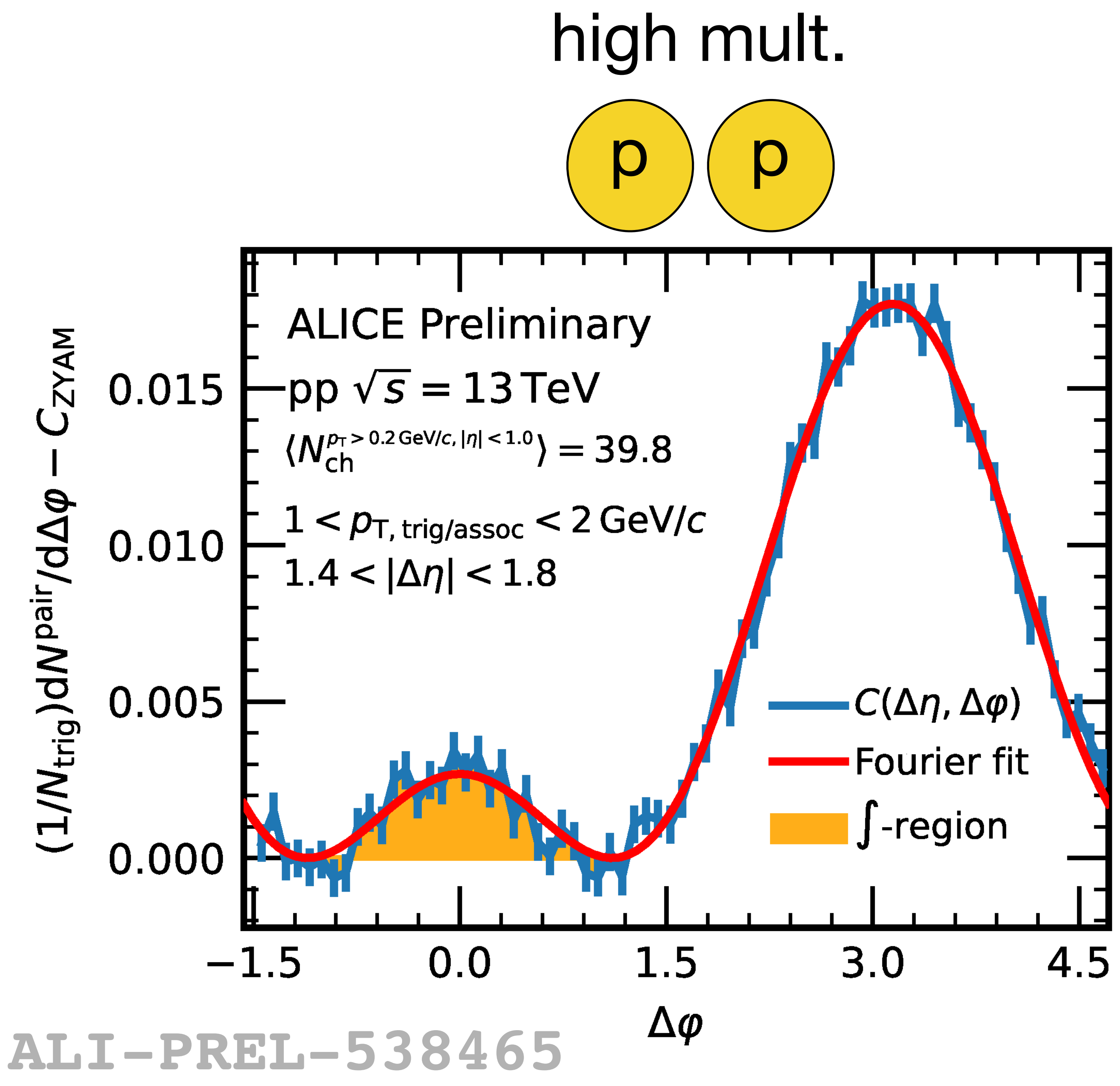

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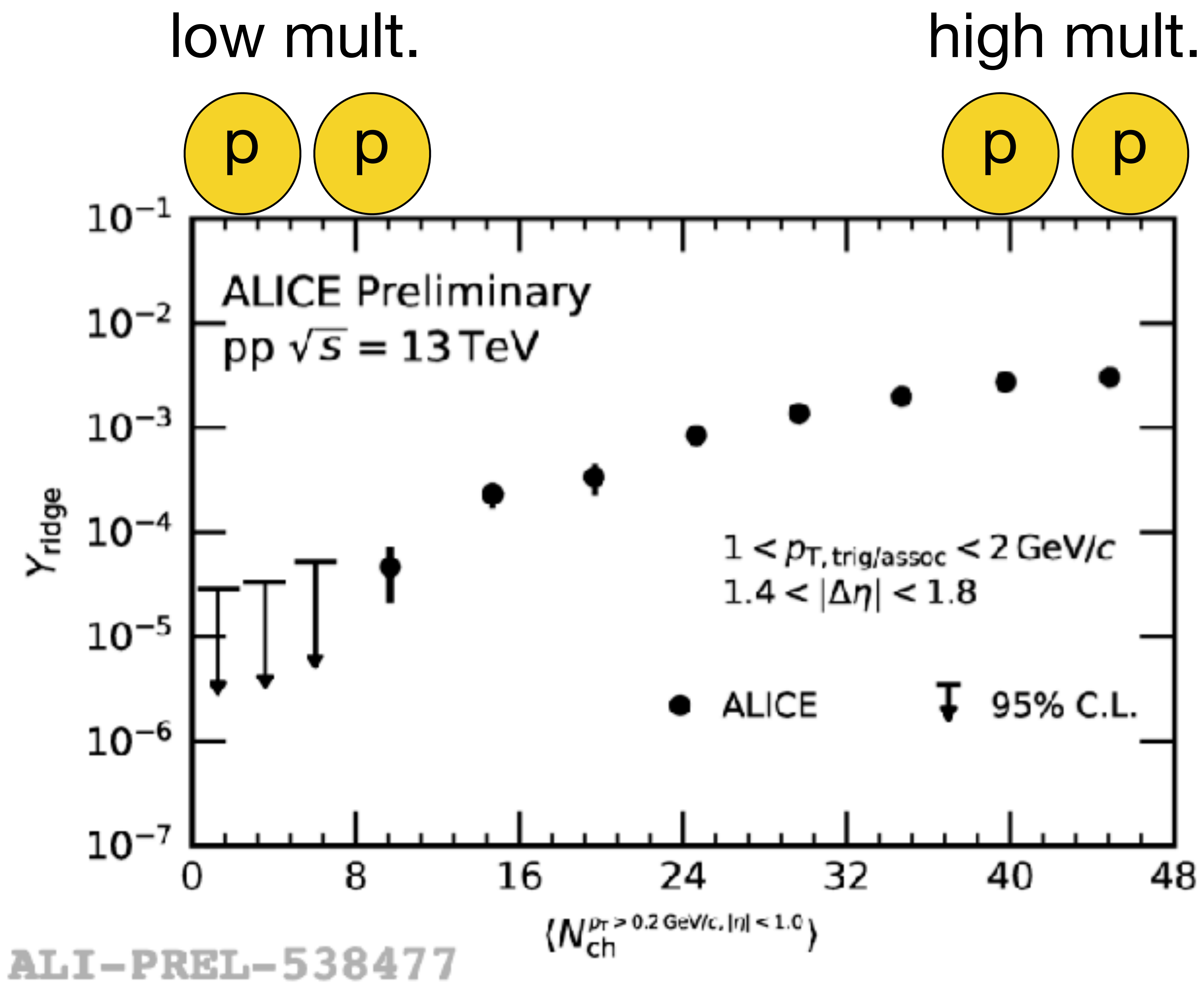
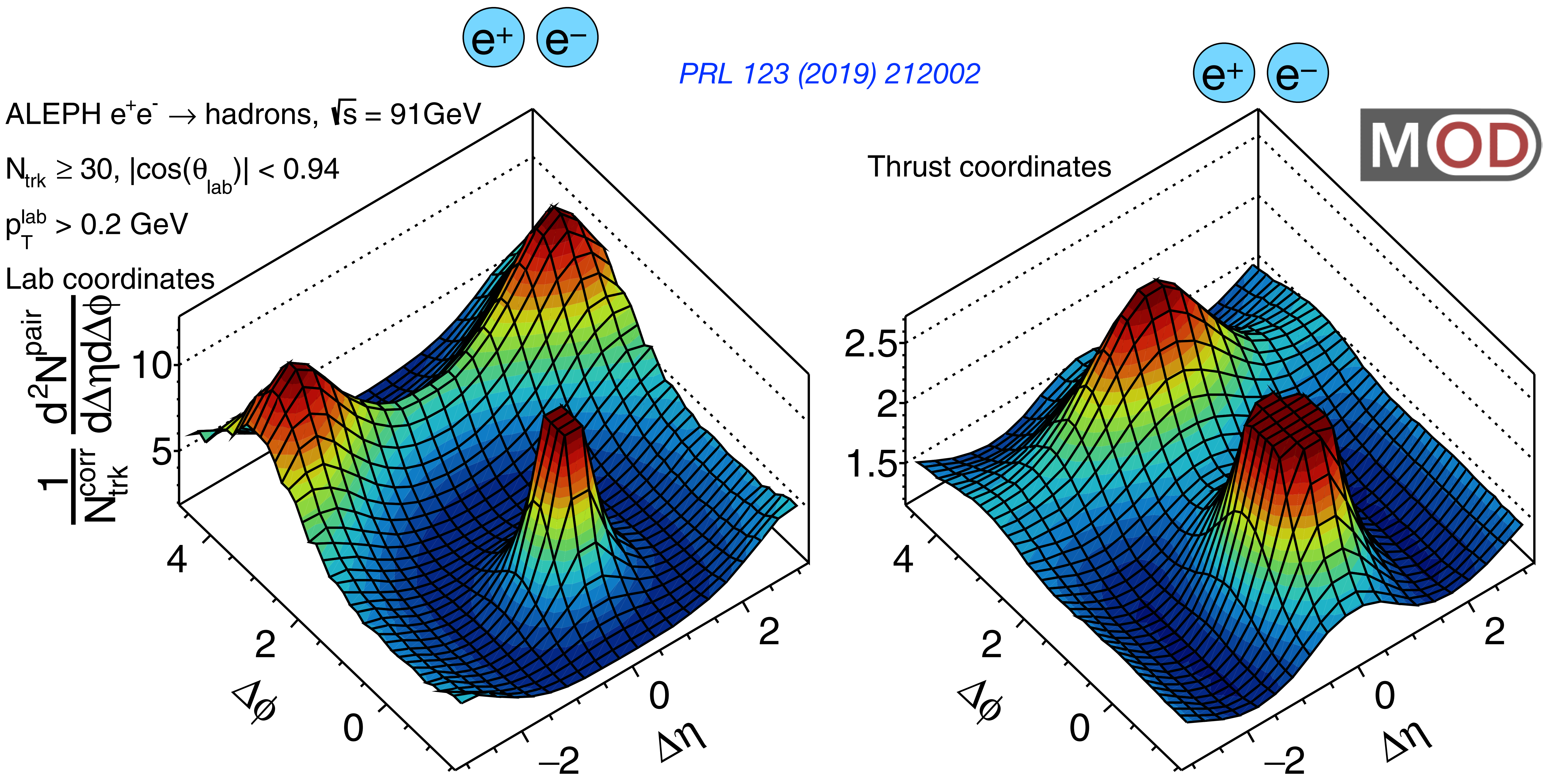
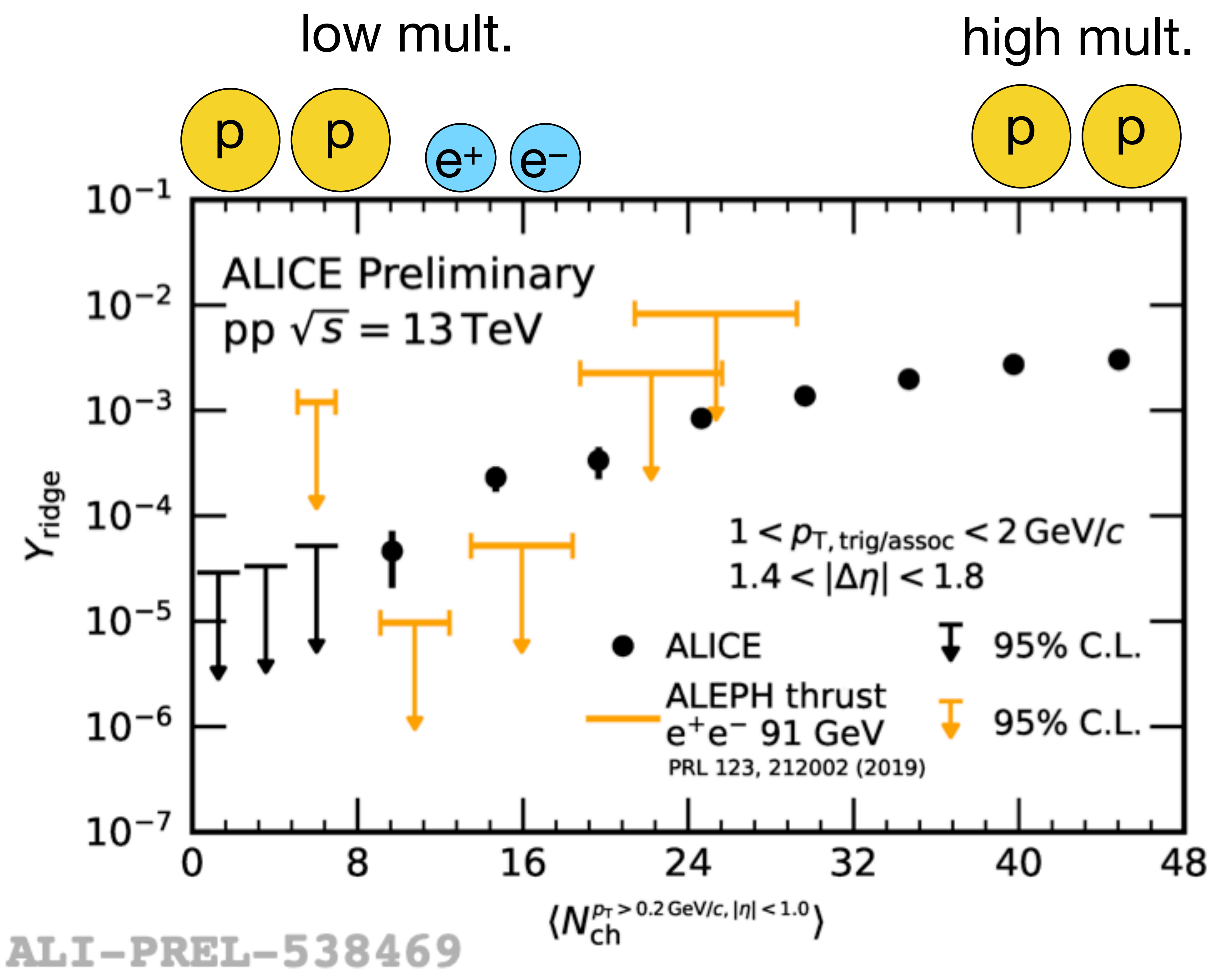


ALI-PREL-538477

- long-range two-particle correlations measured by ALICE up to the smallest multiplicities with very high precision
- **non-zero ridge yield** even for events with low multiplicities

Long-range correlations in small systems - comparison to e$^+$e$^-$ collisions

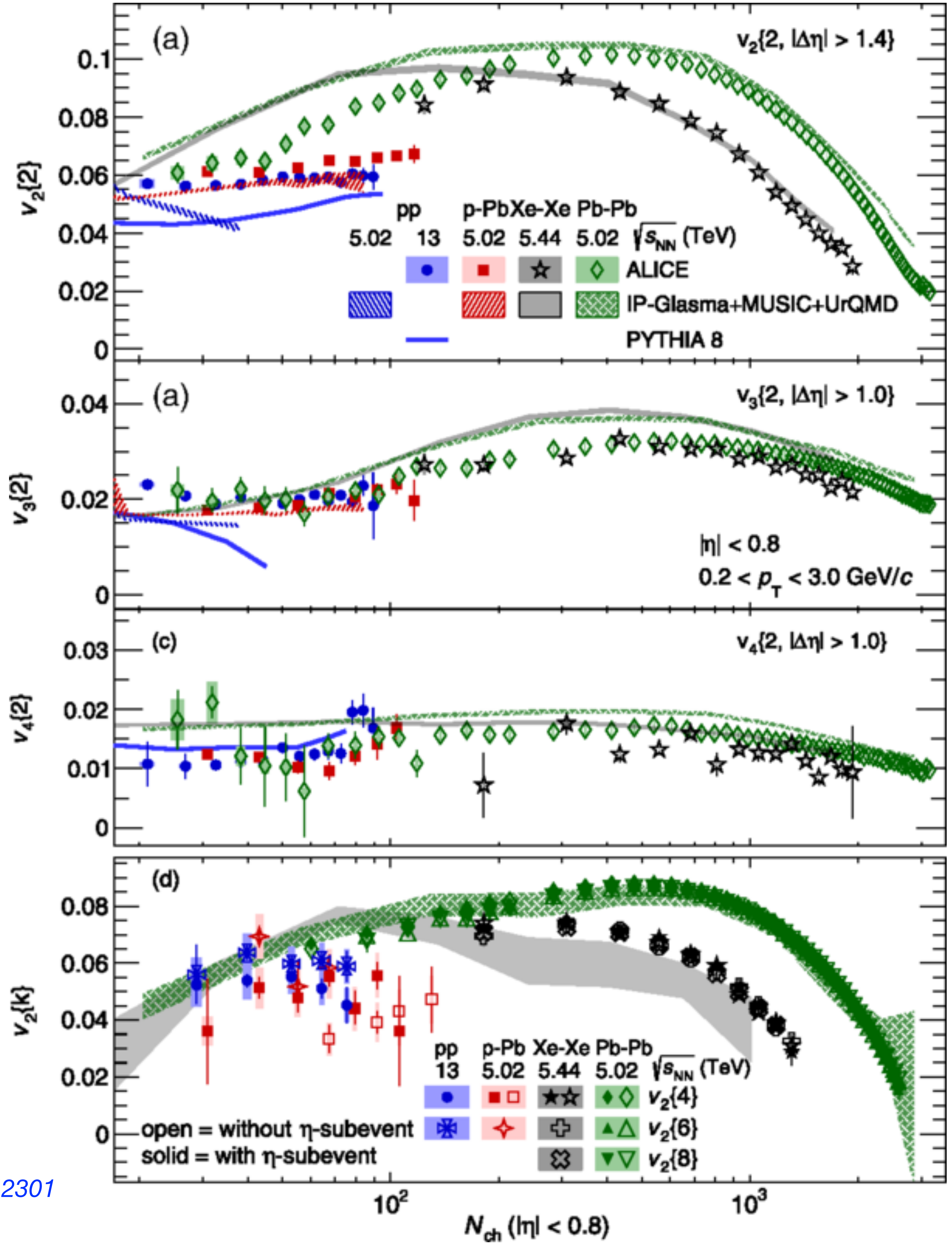




- the cleanest environment (e$^+$e$^-$) does not show any significant ridge structure at $\Delta\phi = 0$
- **ridge yields in pp higher** than yields (upper limits) in (e$^+$e$^-$) at the same multiplicities (10, 15)

Flow in Pb–Pb, Xe–Xe, p–Pb and pp collisions

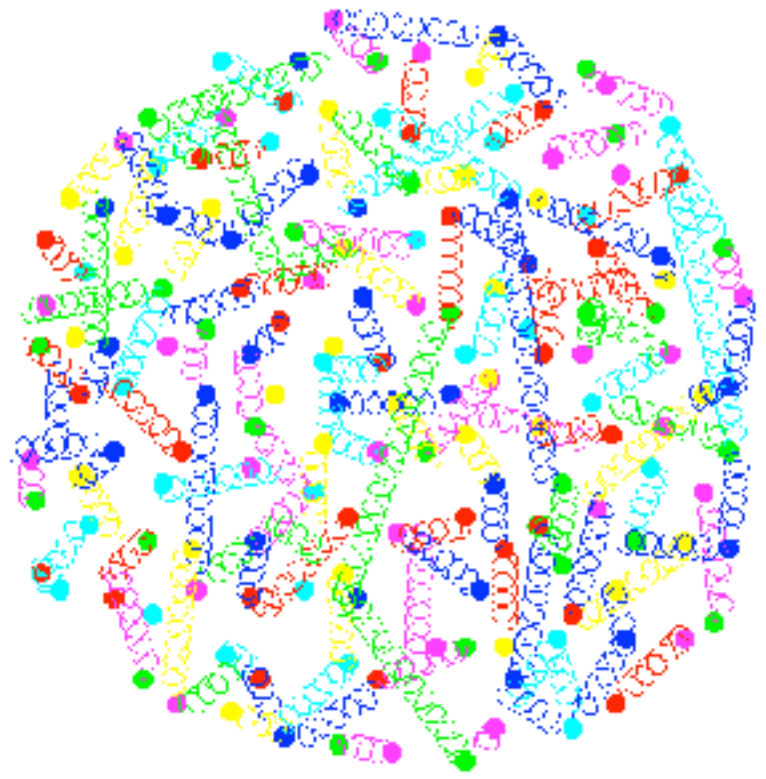
- similar multiplicity dependence of v_n in pp and p–Pb collisions to that observed in large systems
  - anisotropic flow is created as a response to initial geometry via final state interactions of produced matter
- non-zero flow coefficients using multiparticle correlations in pp and p–Pb collisions, compatible with those in large systems
  - presence of long-range and multiparticle correlations —> collectivity
- data cannot be described by purely non-flow based models
- hydrodynamic calculations show qualitative agreement with Pb–Pb, Xe–Xe and p–Pb collisions, while they fail for pp collisions



ALICE, PRL 123 (2019) 142301

Strangeness enhancement

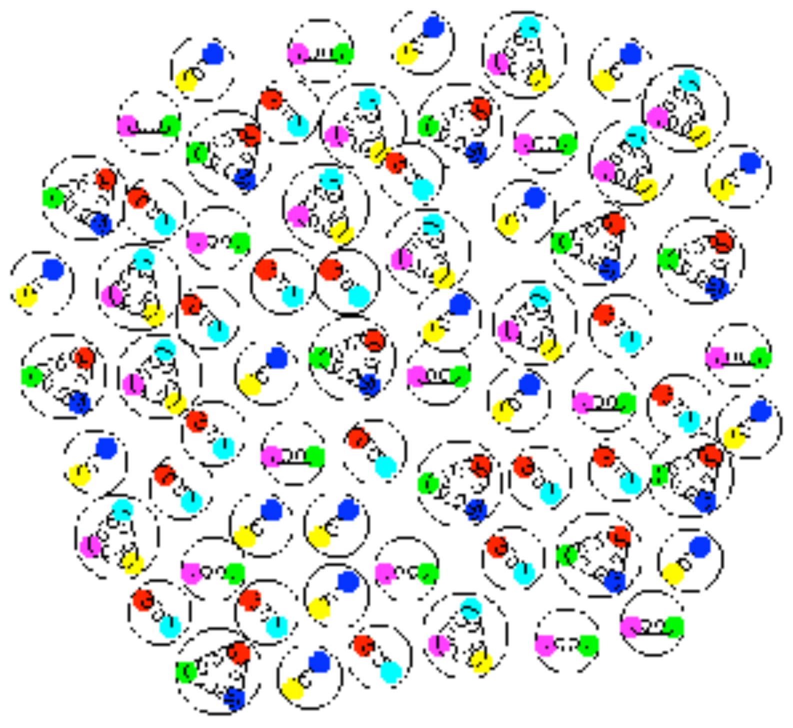
quark-gluon plasma



$$g + g \rightarrow \boxed{s} + \bar{s}$$
$$g + g \rightarrow \boxed{s} + \bar{s}$$
$$q + \bar{q} \rightarrow \boxed{s} + \bar{s}$$

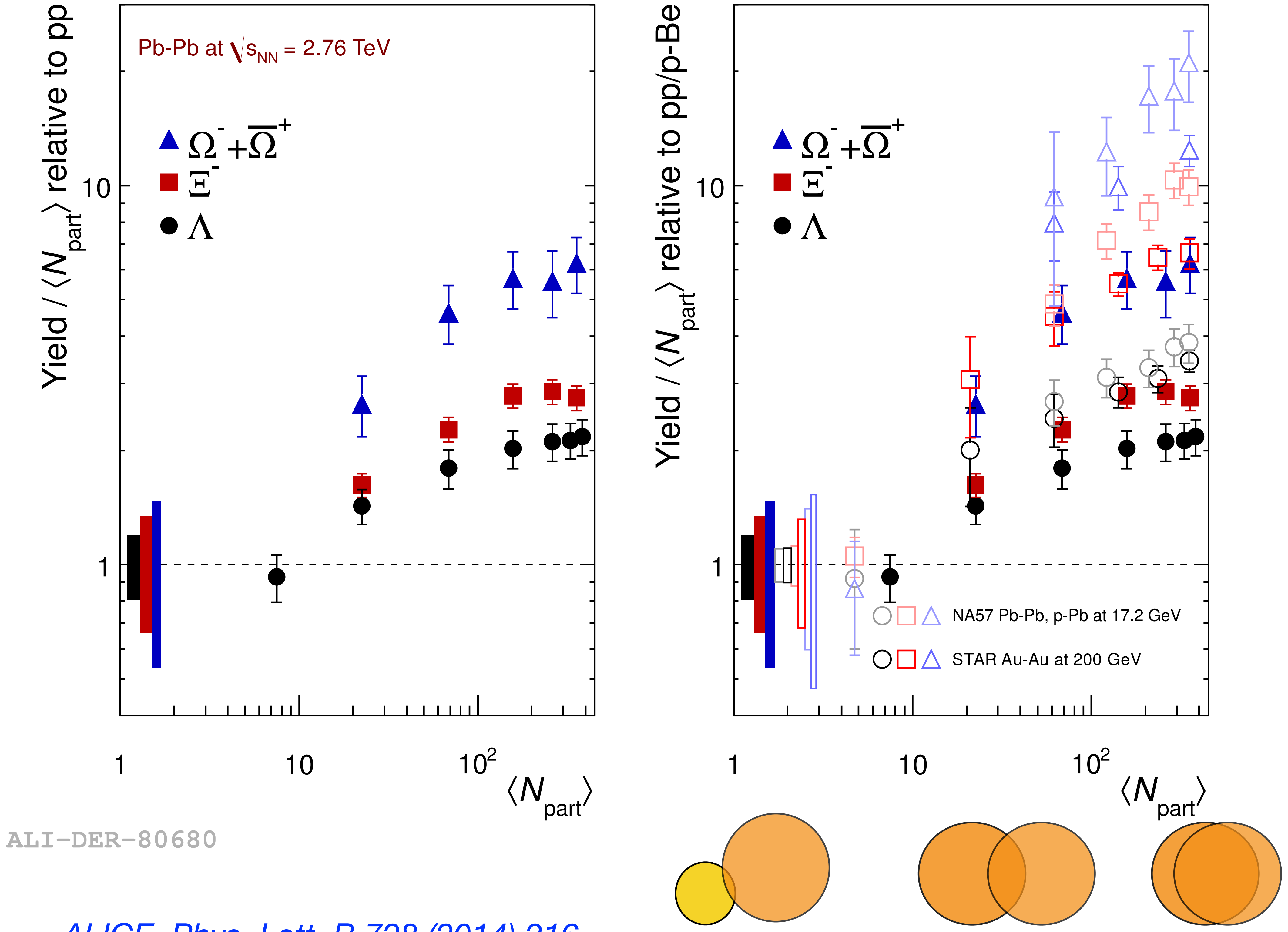
$$\Omega^{-}(sss)$$

hadron gas



$$p + \pi^{-} \rightarrow \Lambda^{0} + K^{0}$$
$$\Lambda^{0} + \pi^{-} \rightarrow \Xi^{-} + K^{0}$$
$$\Xi^{-} + \pi^{0} \rightarrow \Omega^{-} + K^{0}$$

$$\Omega^{-}$$



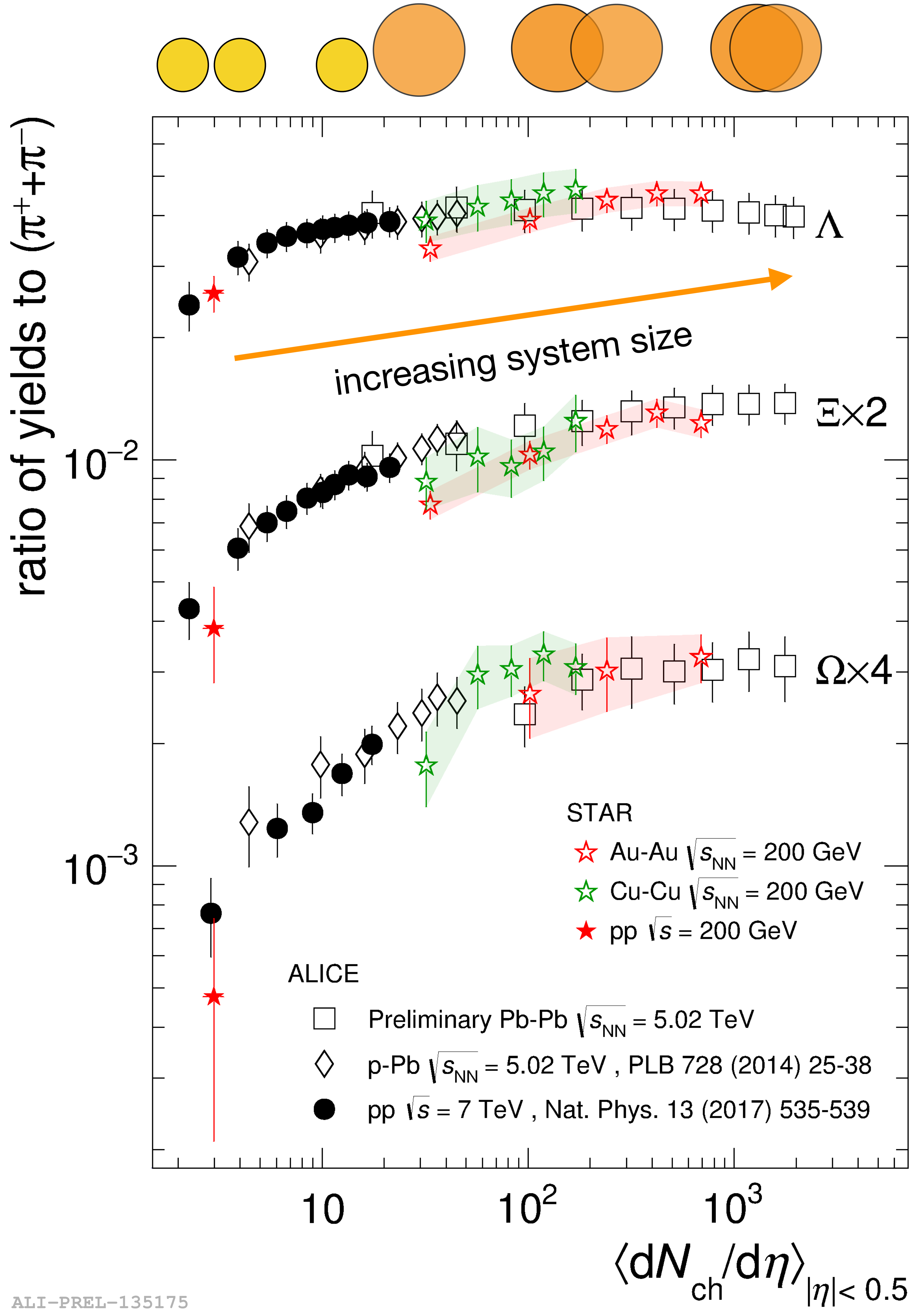
ALICE, Phys. Lett. B 728 (2014) 216

- production of strange quarks in QGP should be energetically favoured and faster than production in hadron gas *[J. Rafelski, B. Müller, Phys. Rev. Lett. 48 (1982) 1066–1069]*

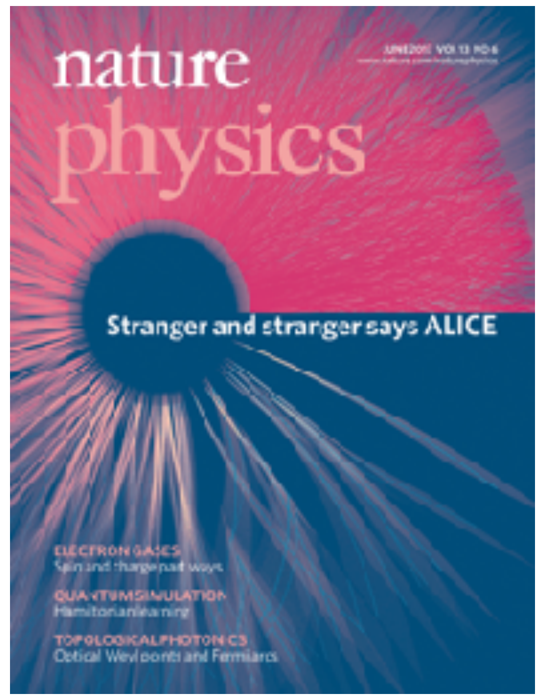
- experimental variable based on comparison of strange hadron production in nucleus-nucleus collision with nucleon-nucleon (or nucleon-nucleus) collision - strangeness enhancement confirmed

Strangeness enhancement

- N_{part}-scaling does not hold at LHC energies - a different experimental variable is used: **ratio to pion production** as a function of multiplicity
- remarkable overlap of p–Pb and peripheral Pb–Pb with Cu–Cu and Au–Au - even for 25 times smaller energy (RHIC) the strangeness production is similar!
- a smooth transition from pp to central Pb–Pb - seems the only parameter needed to estimate strangeness production is **multiplicity**



Strangeness enhancement



ALICE, Nature Physics 13 (2017) 535

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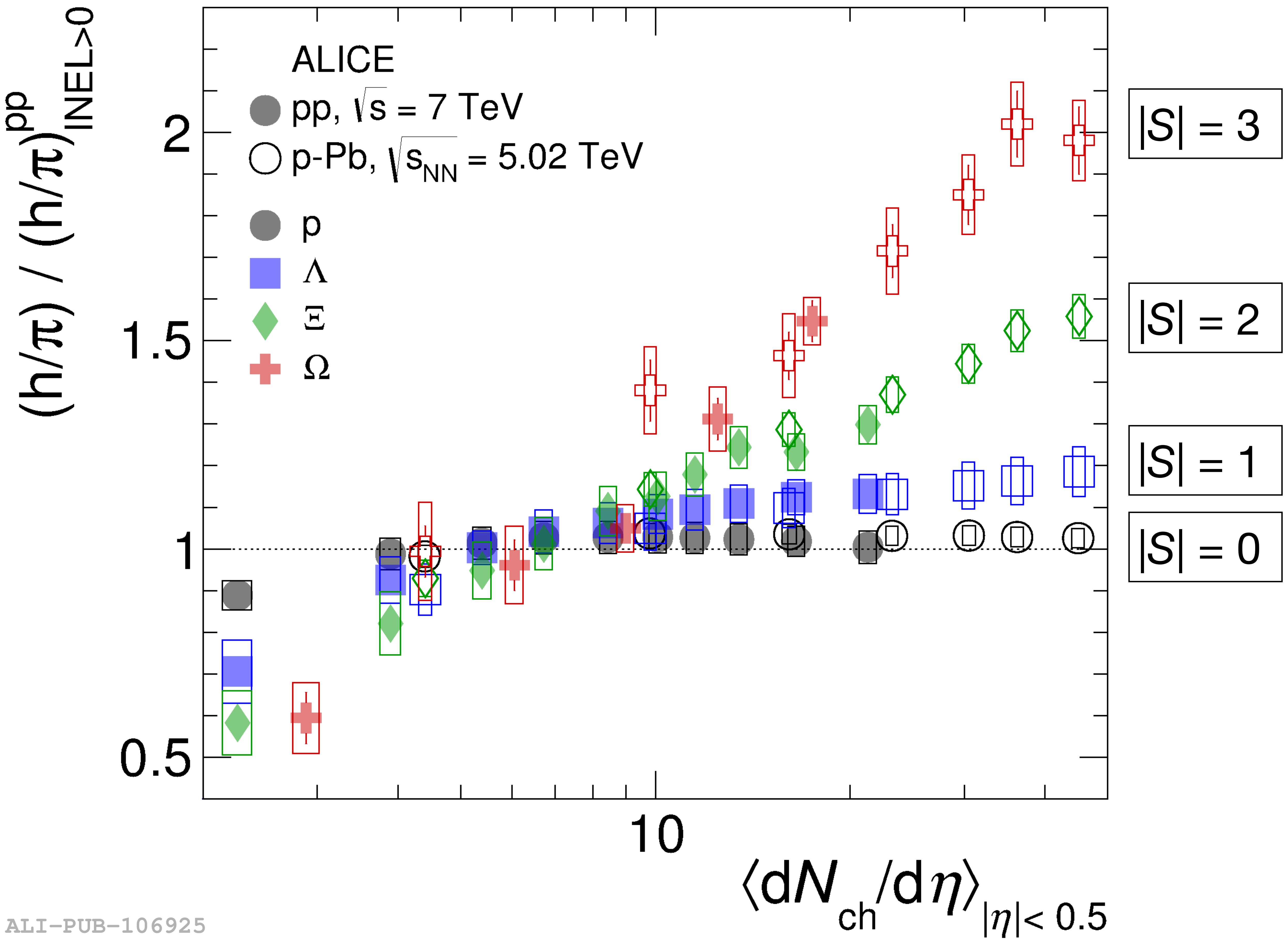
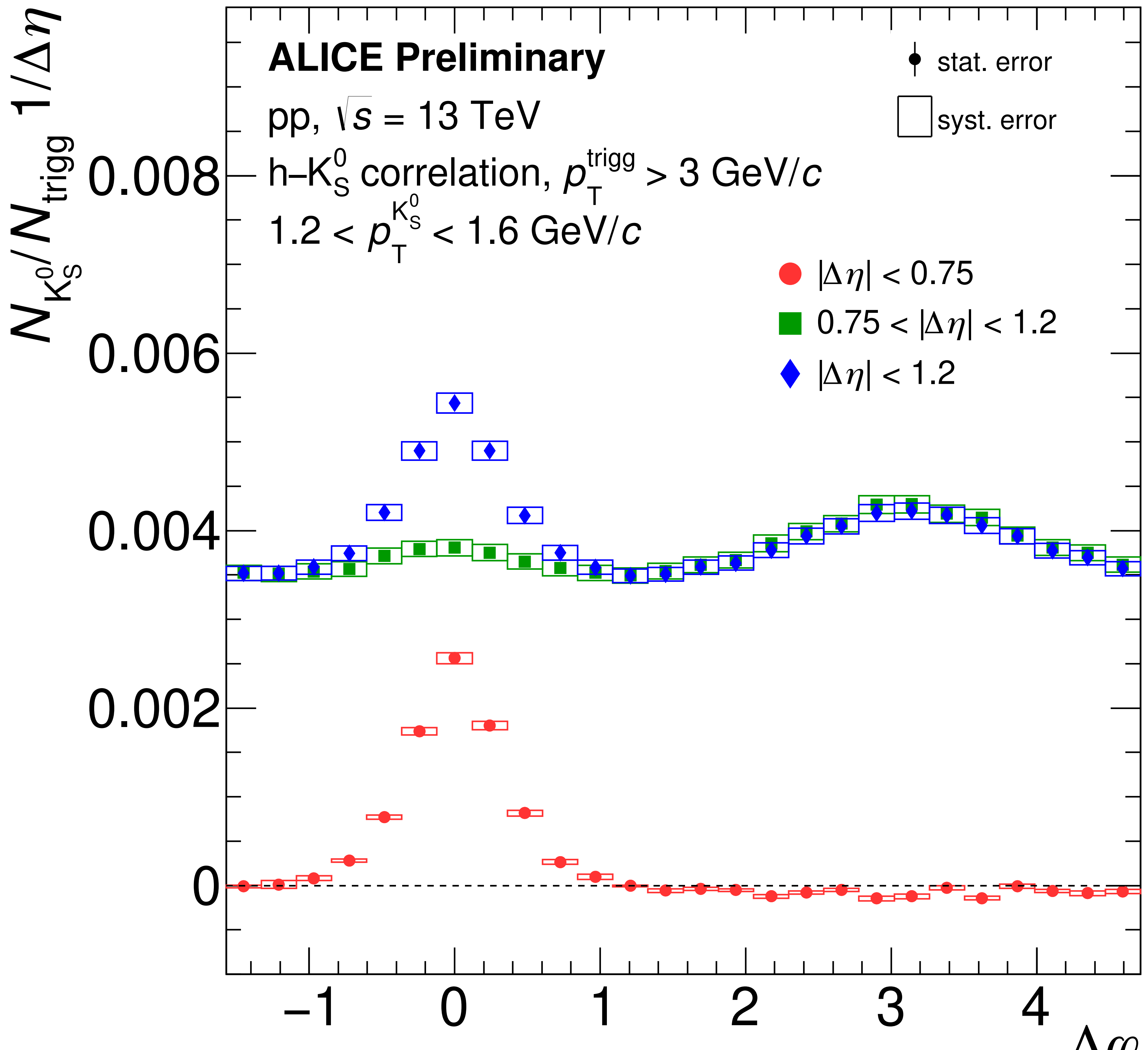
- a smooth transition from pp to central Pb–Pb - seems the only parameter needed to estimate strangeness production is **multiplicity**
- hierarchy of the enhancement determined by the hadron strangeness!

What are the roles of jet/underlying event in strangeness production in high-multiplicity pp or p–Pb collisions?



Strangeness enhancement in small systems



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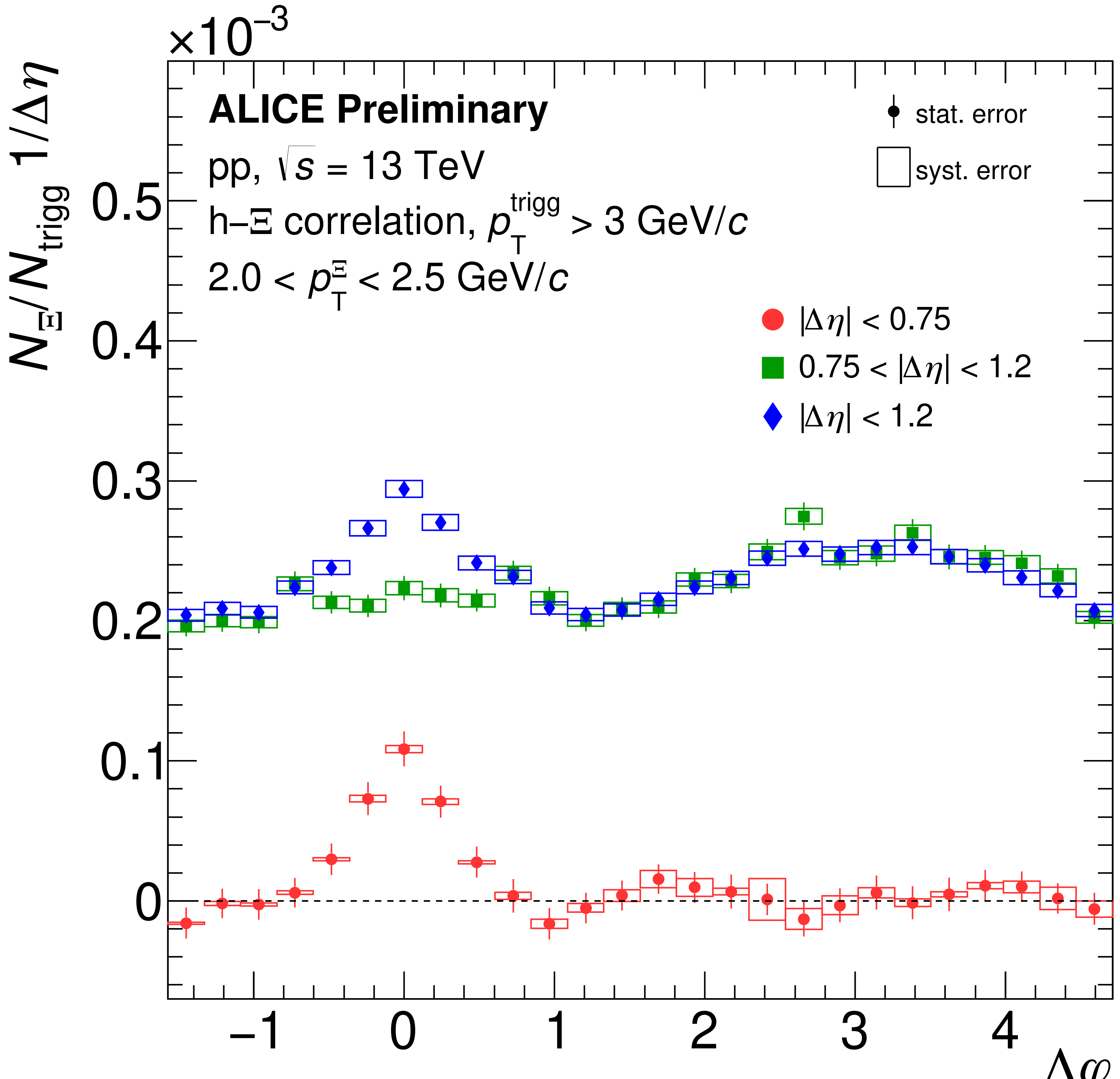
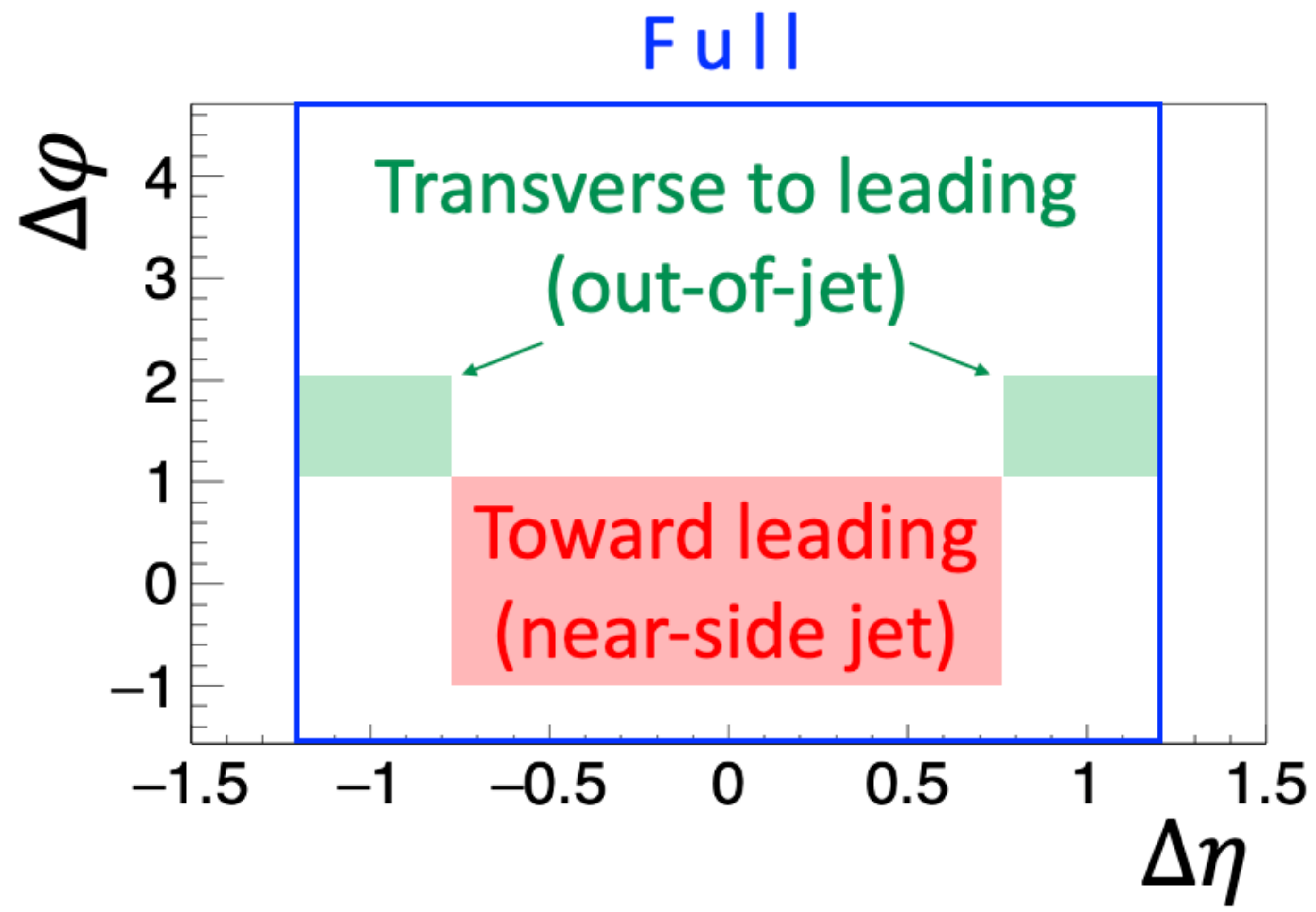
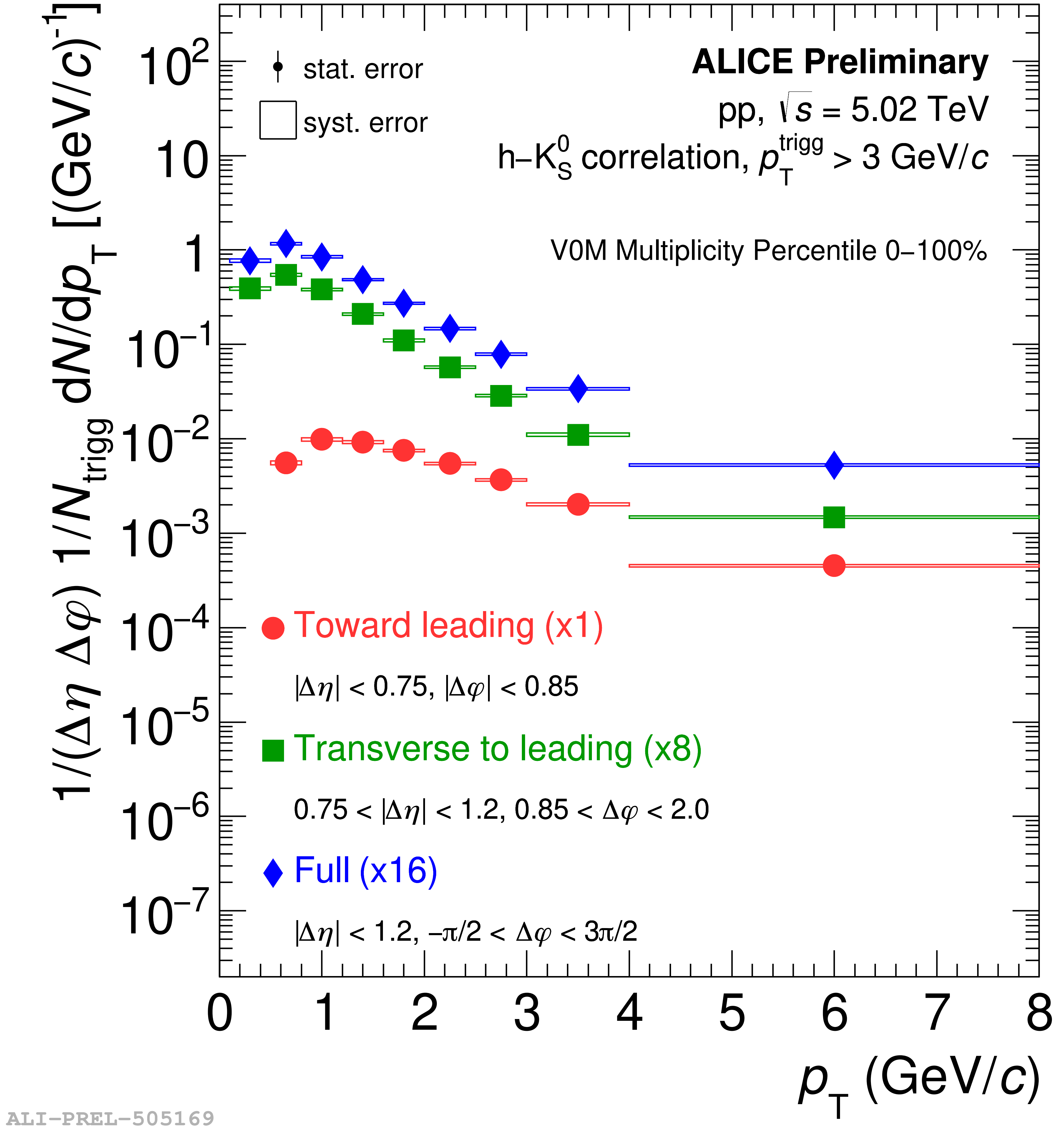


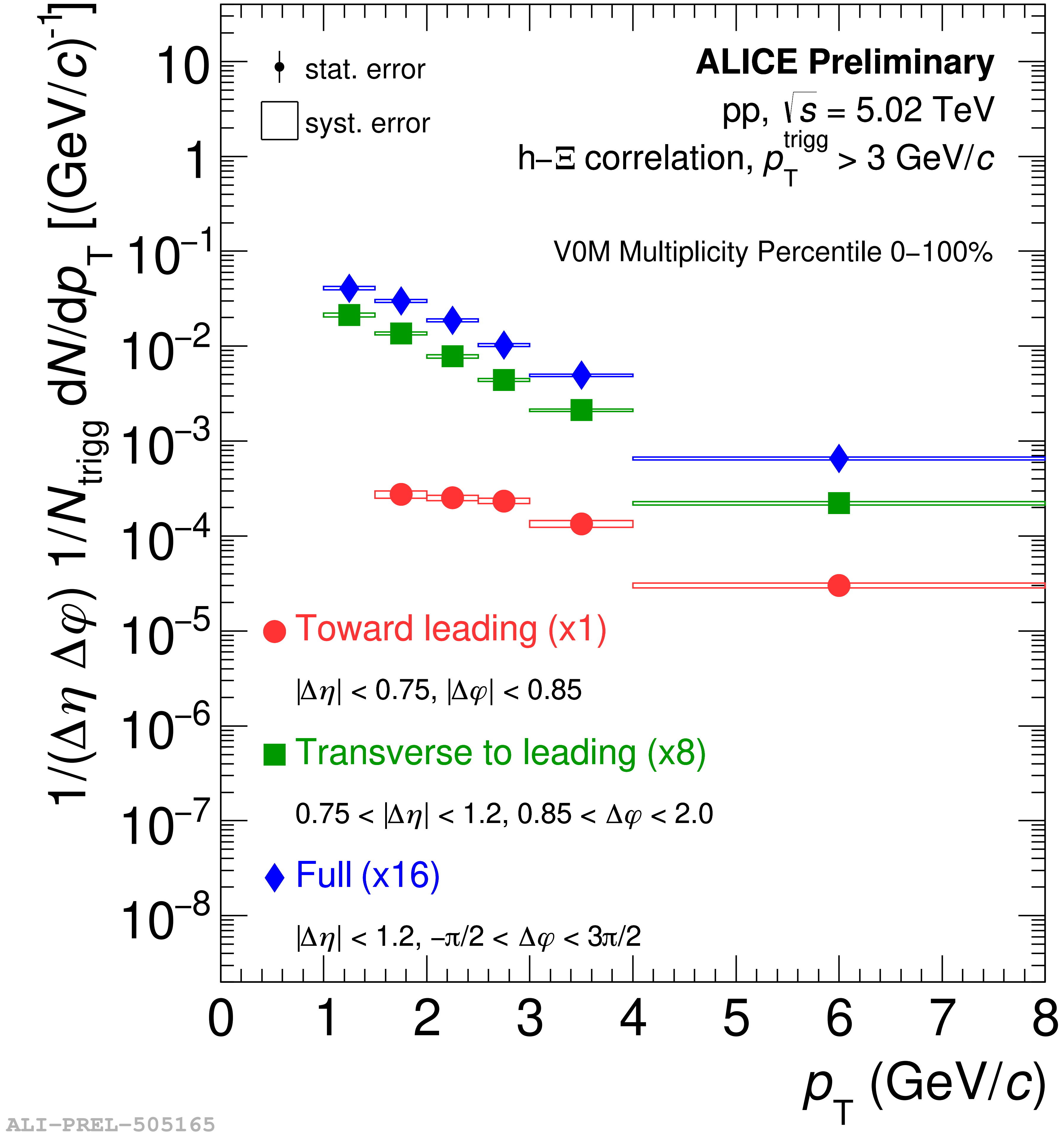
ALI-PREL-366825



- trigger particle (jet axis proxy) - charged hadron with highest p_T in event & $p_T > 3$ GeV/c
- associated particles: identified strange hadrons

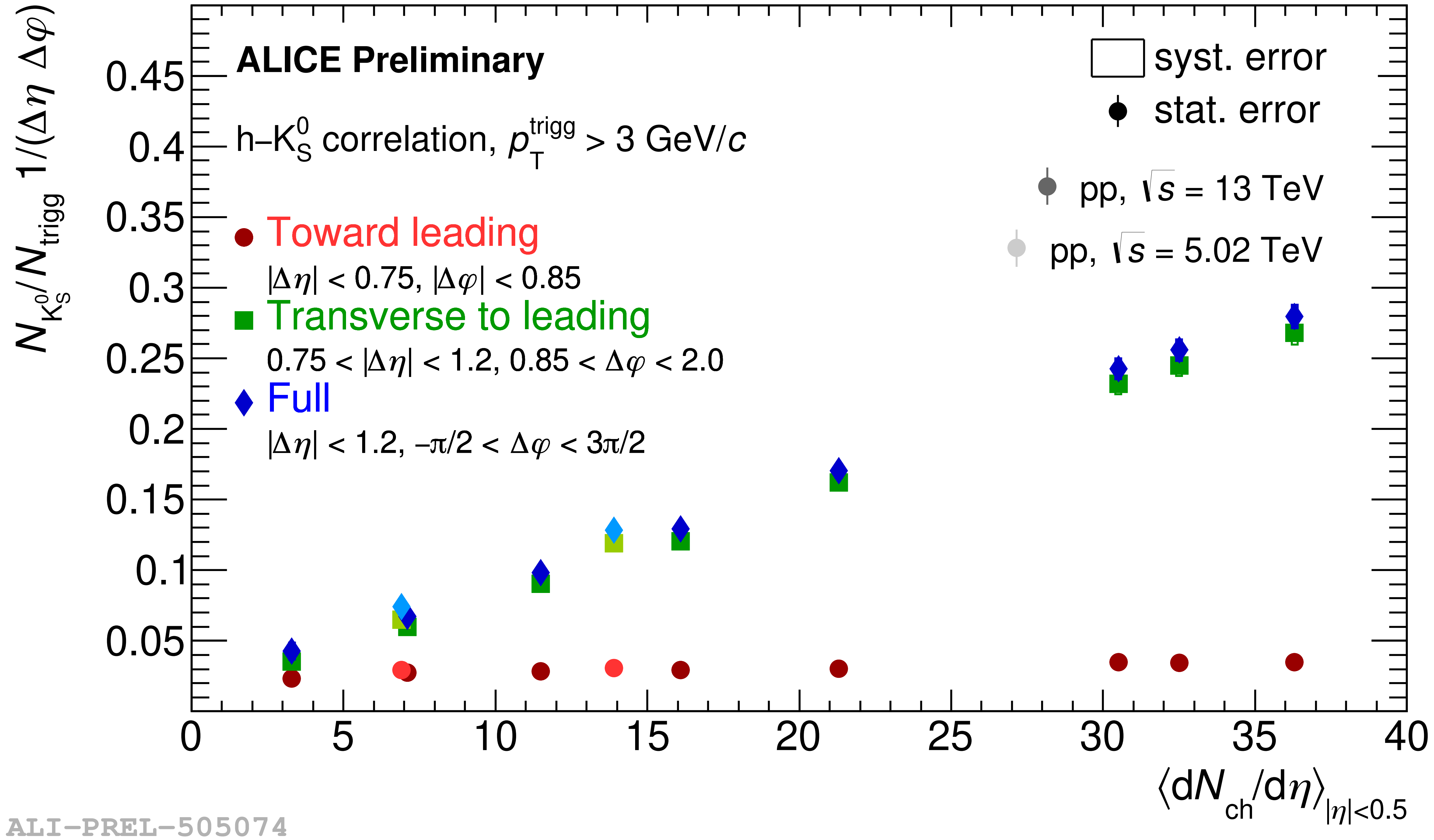
Strangeness enhancement in small systems



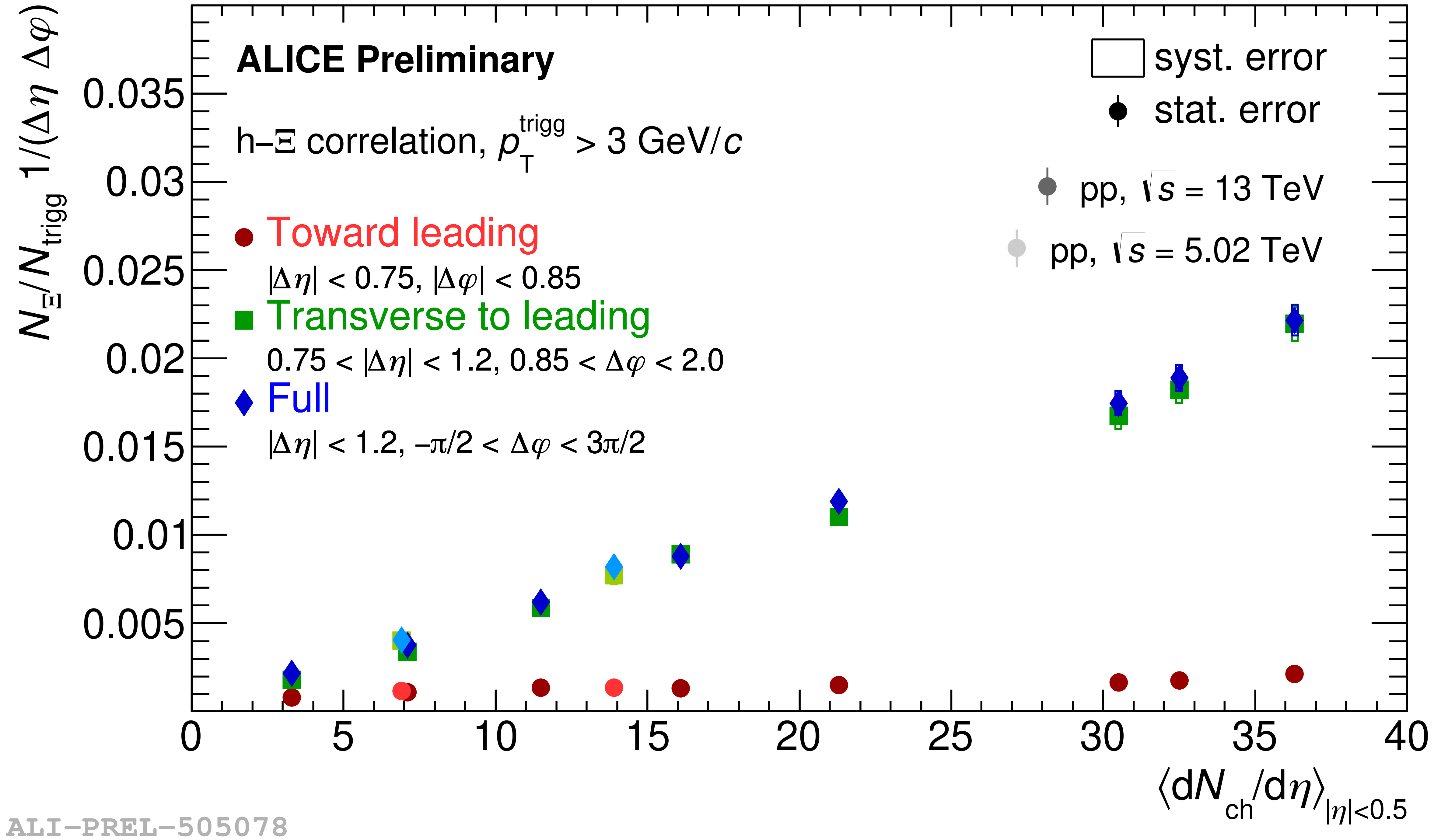


- toward-leading spectra of strange hadrons harder than transverse-to-leading spectra or full spectra
- same behaviour also for different multiplicity classes and different collision energy (13 TeV)

Strangeness enhancement in small systems



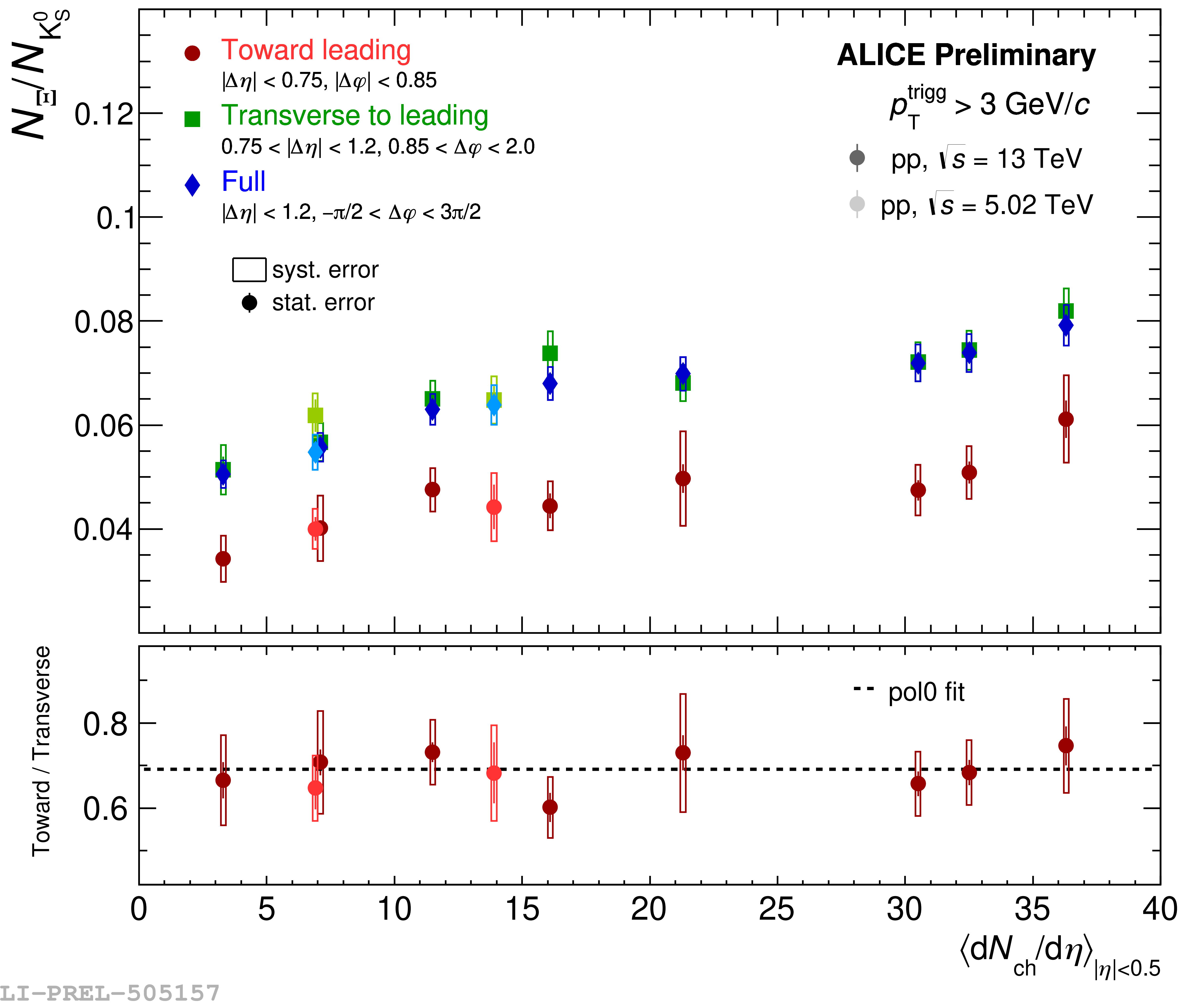
ALI-PREL-505074



ALI-PREL-505078

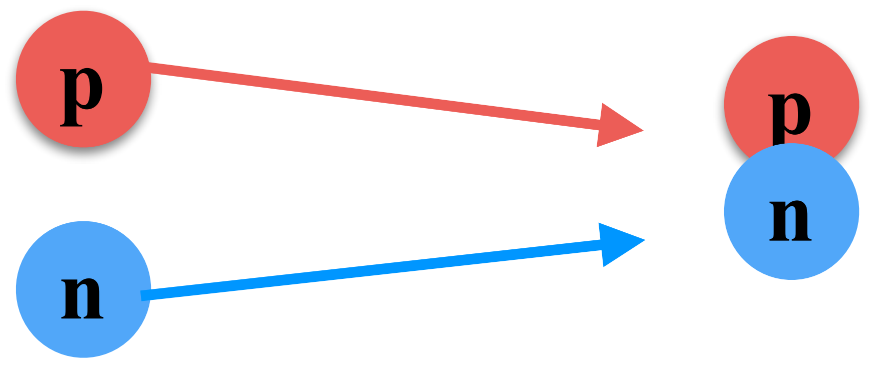
- strange hadron yields from transverse-to-leading and full samples increase with multiplicity and they are consistent with each other - **the increase is driven by soft processes**
- no difference in trends for different collision energies
- toward-leading yields do not depend on multiplicity (or depend very mildly)

Strangeness enhancement in small systems



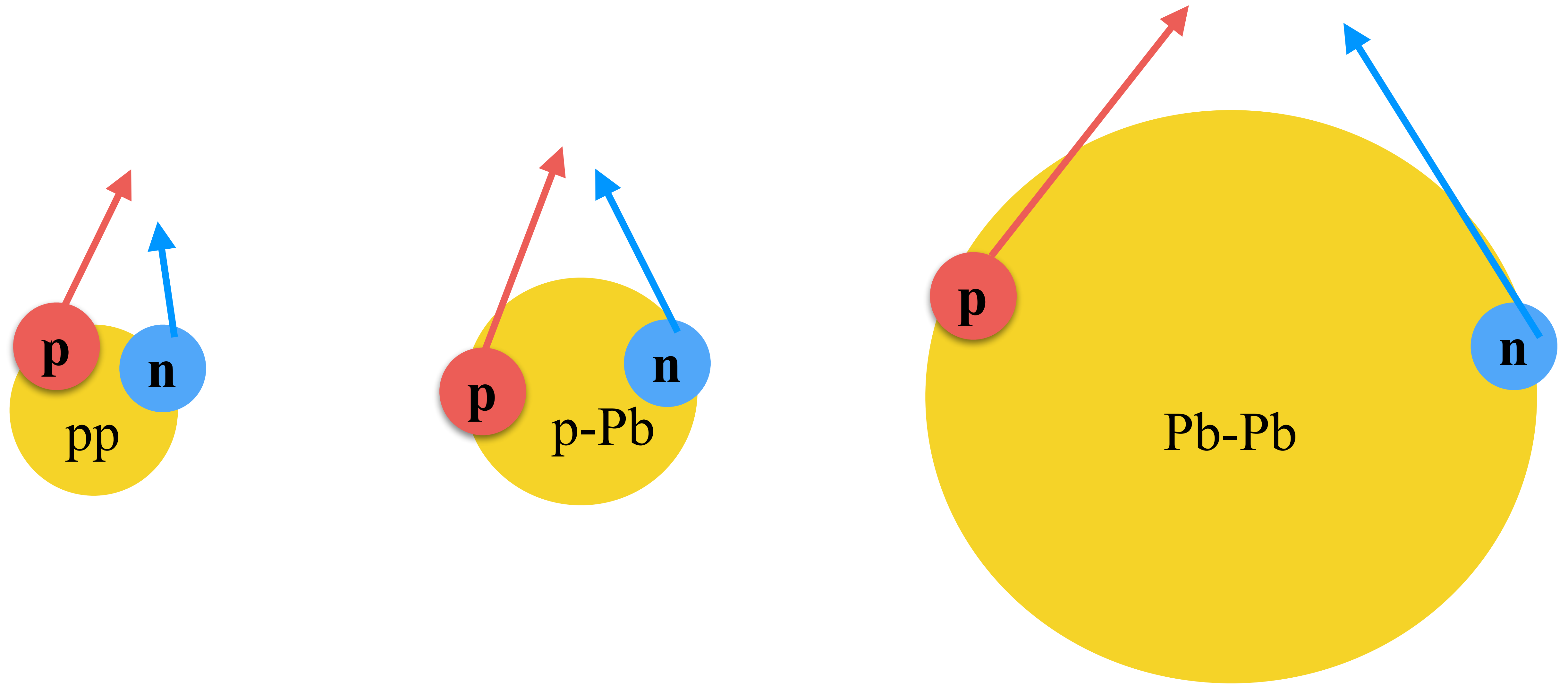
- transverse-to-leading and full yield ratios show an enhancement as a function of multiplicity (resembling the enhancement of the inclusive strangeness production w.r.t. pions) - can be attributed to the strangeness difference: Ξ^- vs. K^0_S ($|\Delta S|=1$)
- toward-leading contributes less to the enhancement
- transverse-to-leading and toward-leading trends **are compatible**

Deuteron production



$$B_2 = \left(\frac{1}{2\pi p_\mathrm{T}^\mathrm{d}} \frac{\mathrm{d}^2 N_\mathrm{d}}{\mathrm{d}y \mathrm{d}p_\mathrm{T}^\mathrm{d}} \right) \Bigg/ \left(\frac{1}{2\pi p_\mathrm{T}^\mathrm{p}} \frac{\mathrm{d}^2 N_\mathrm{p}}{\mathrm{d}y \mathrm{d}p_\mathrm{T}^\mathrm{p}} \right)^2$$

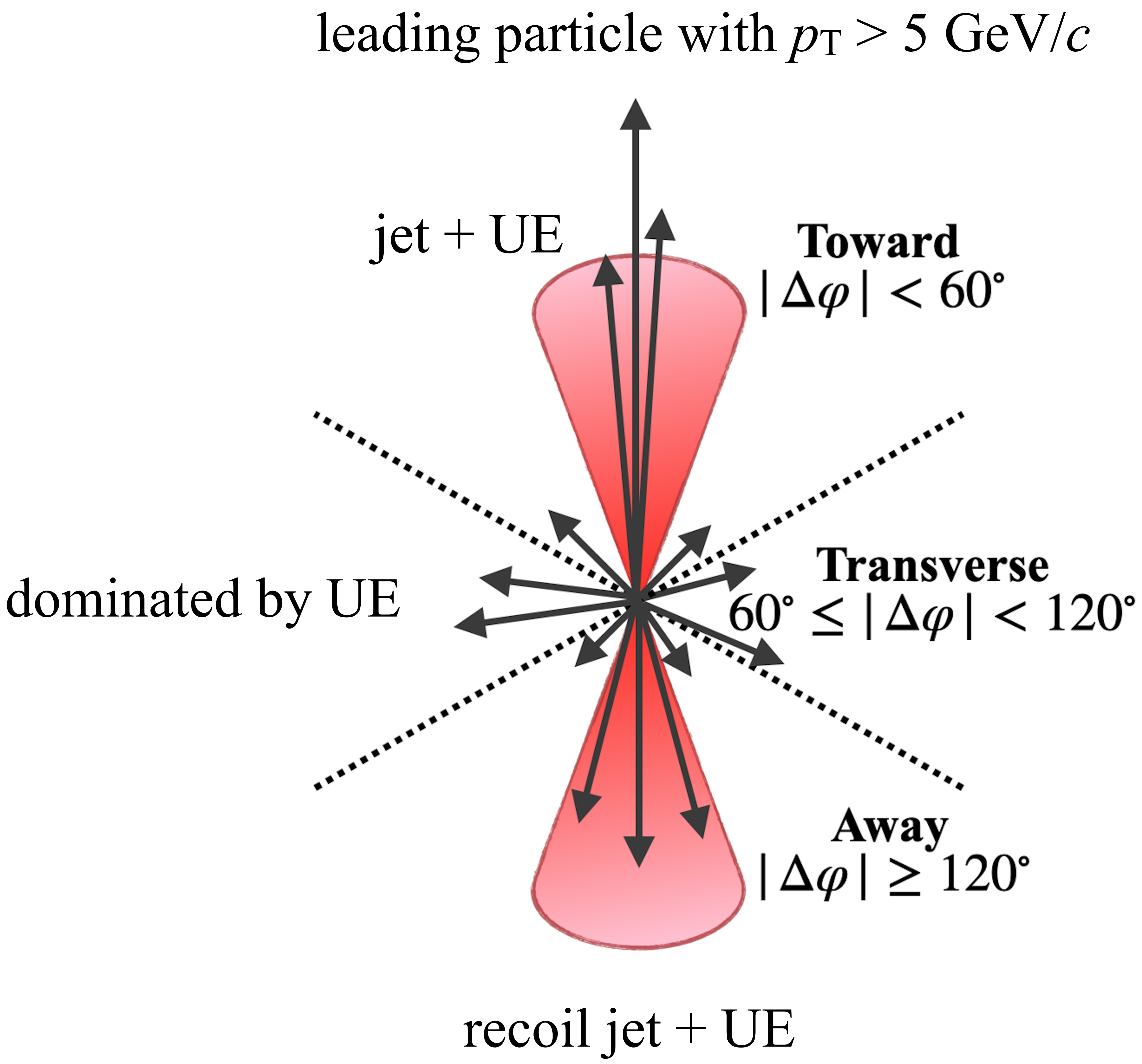
- if proton and neutron are close in phase space and match the spin state, they can form the deuteron *[S. T. Butler et al., Phys. Rev. 129 (1963) 836]*
- the parameter B_2 quantifies the probabiliby of the coalescence
- small collision systems ideal for studying coalescense - the phase space smaller than in heavy-ion collisions - the coalescence should be more probable

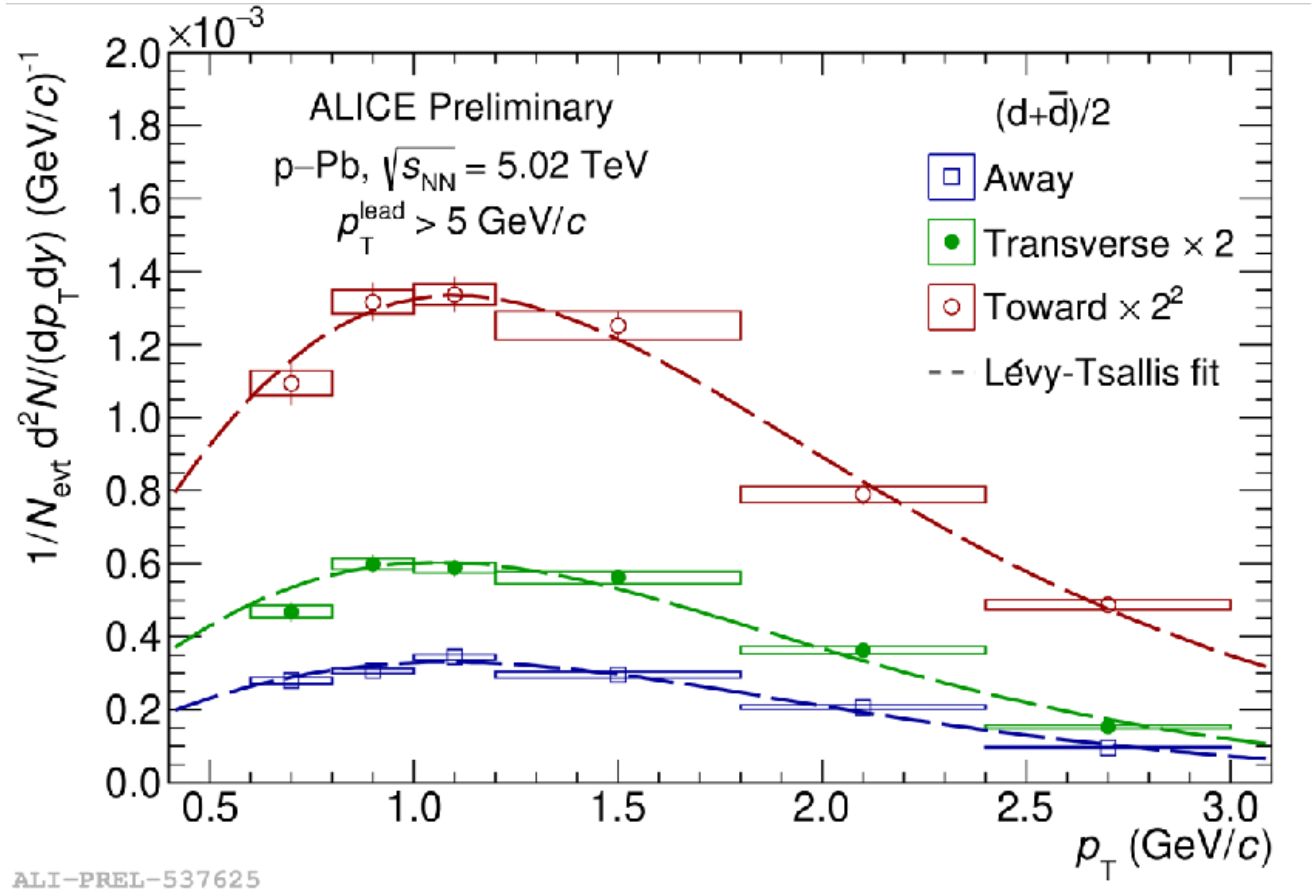


$$B_2\,(\mathrm{pp}) \quad > \quad B_2\,(\mathrm{p{-}Pb}) \quad > \quad B_2\,(\mathrm{Pb{-}Pb})$$

Deuteron production in jets

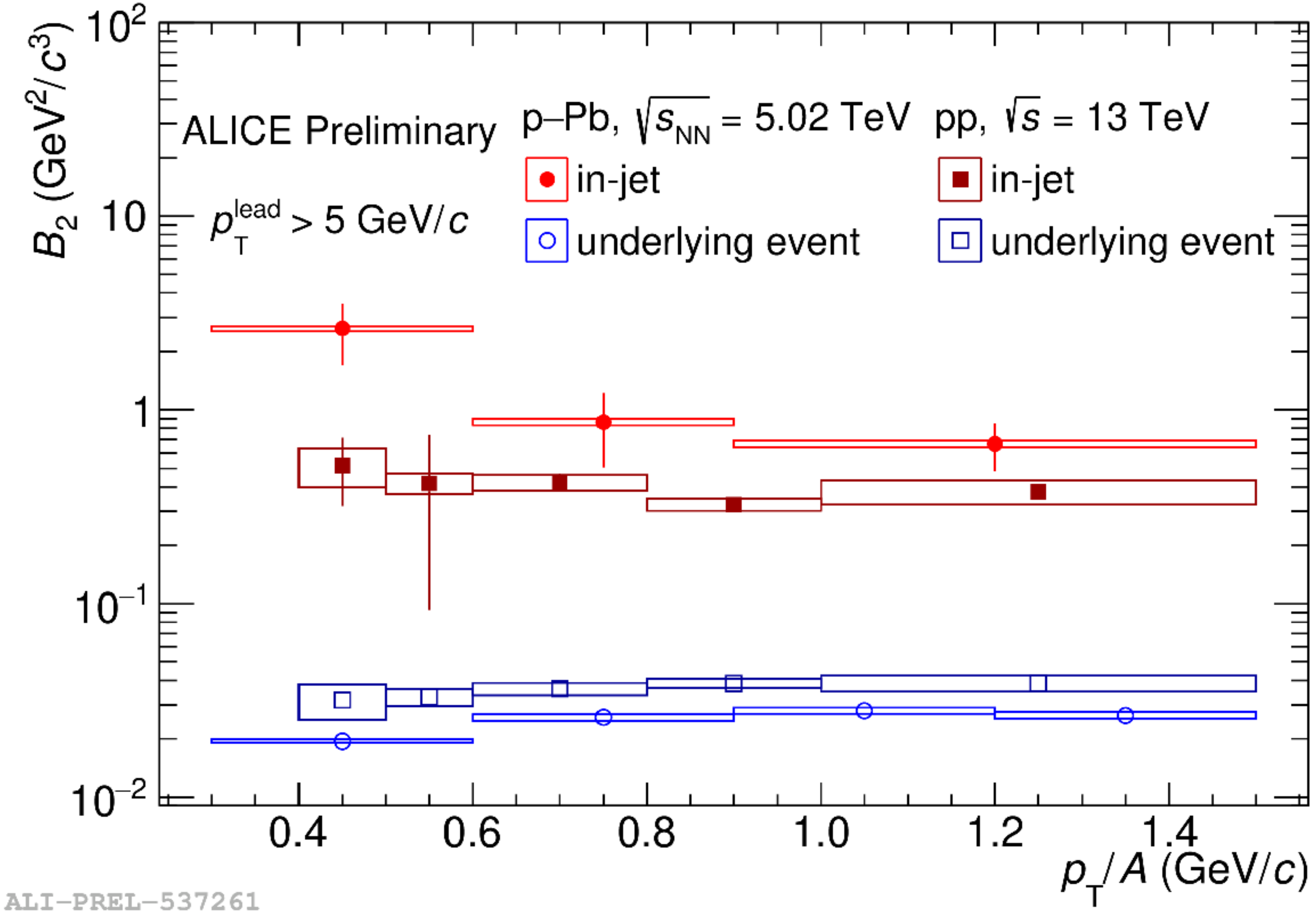
- phase-space distance between nucleons in jet smaller than in underlying event (UE) - naively the coalescence probability in jets should be enhanced w.r.t. underlying event





Martin, T., Skands, P. & Farrington, S. Eur. Phys. J. C 76, 299 (2016)
ALICE, arXiv:2301.10120

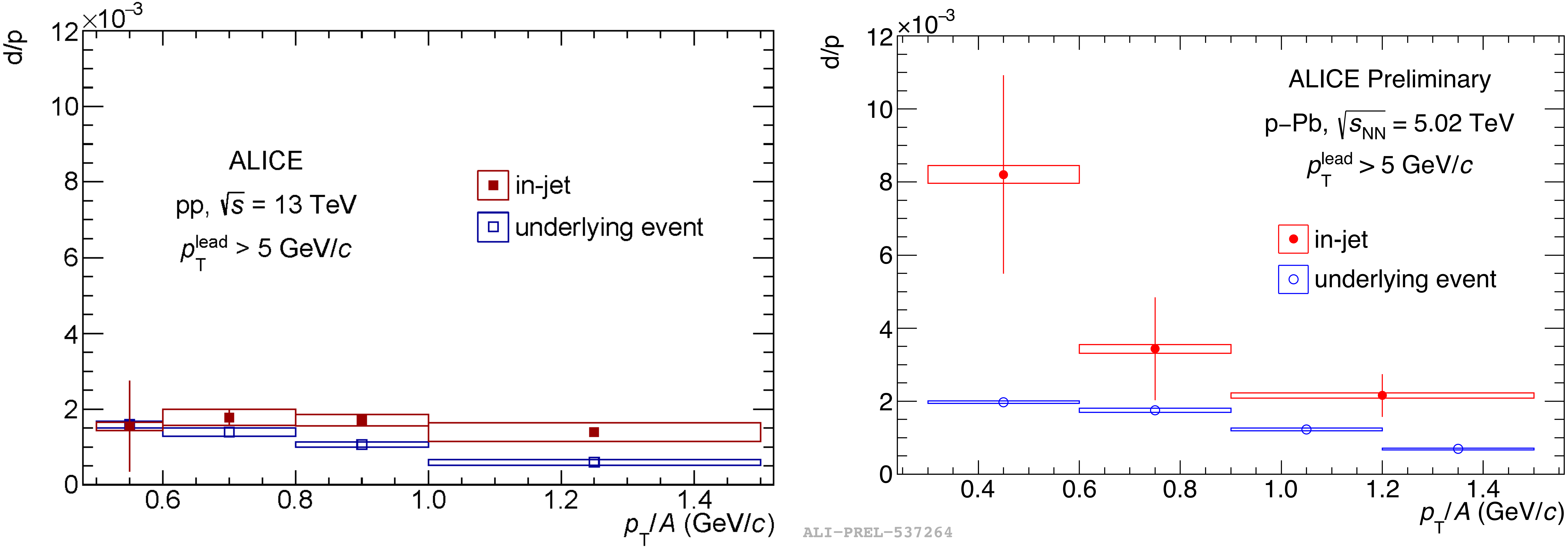
Deuteron production in jets



- in-jet = Toward - Transverse
- underlying event = Transverse
- B_2 **for jets larger than for UE** as predicted by coalescence model
- underlying event: B_2 for p–Pb smaller than for pp - source size is bigger in p-Pb
- in-jet: B_2 for **p–Pb larger(!) than for pp** - assuming same source size for the nucleons in jet, the nucleons are closer in phase-space in p–Pb jets than in pp jets
- could be the difference related to particle composition in jets (p–Pb vs. pp)?

Deuteron production in jets

ALICE, arXiv:2211.15204v1
ALICE, arXiv:2301.10120

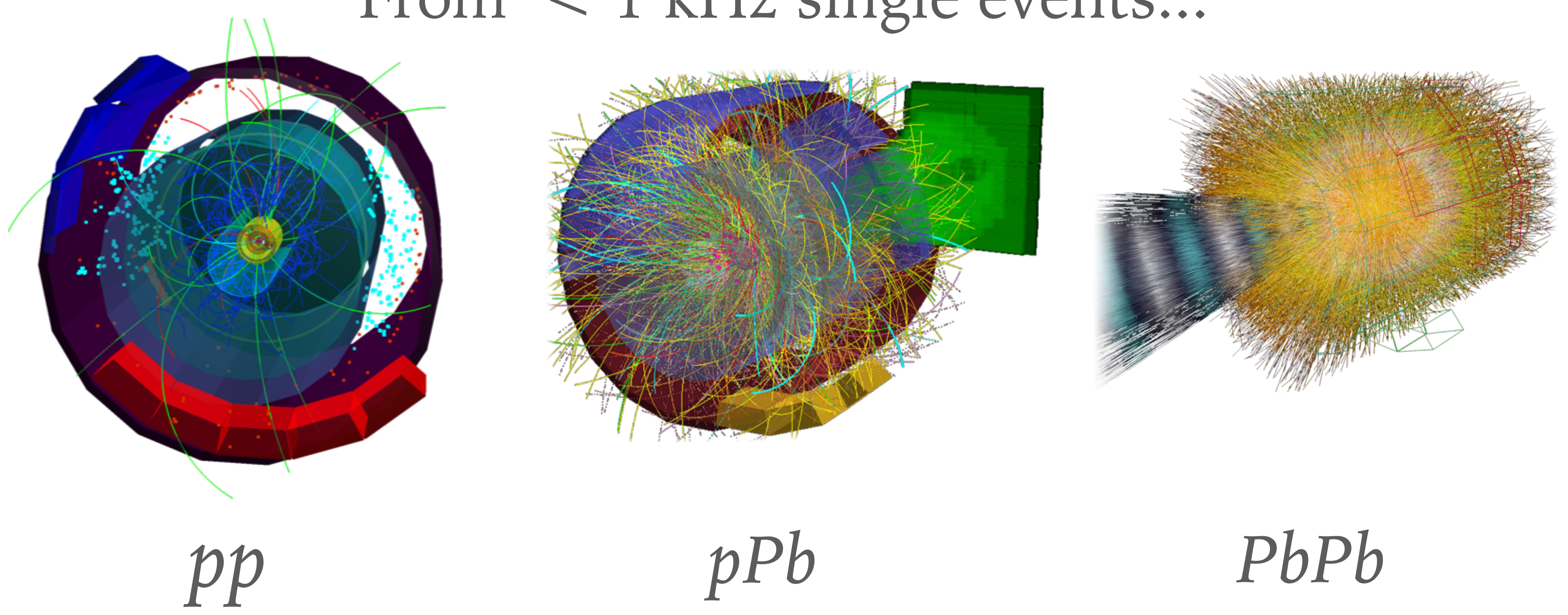


- d/p ratio for jets in p–Pb bigger than for the pp - different particle composition in the two collision systems?

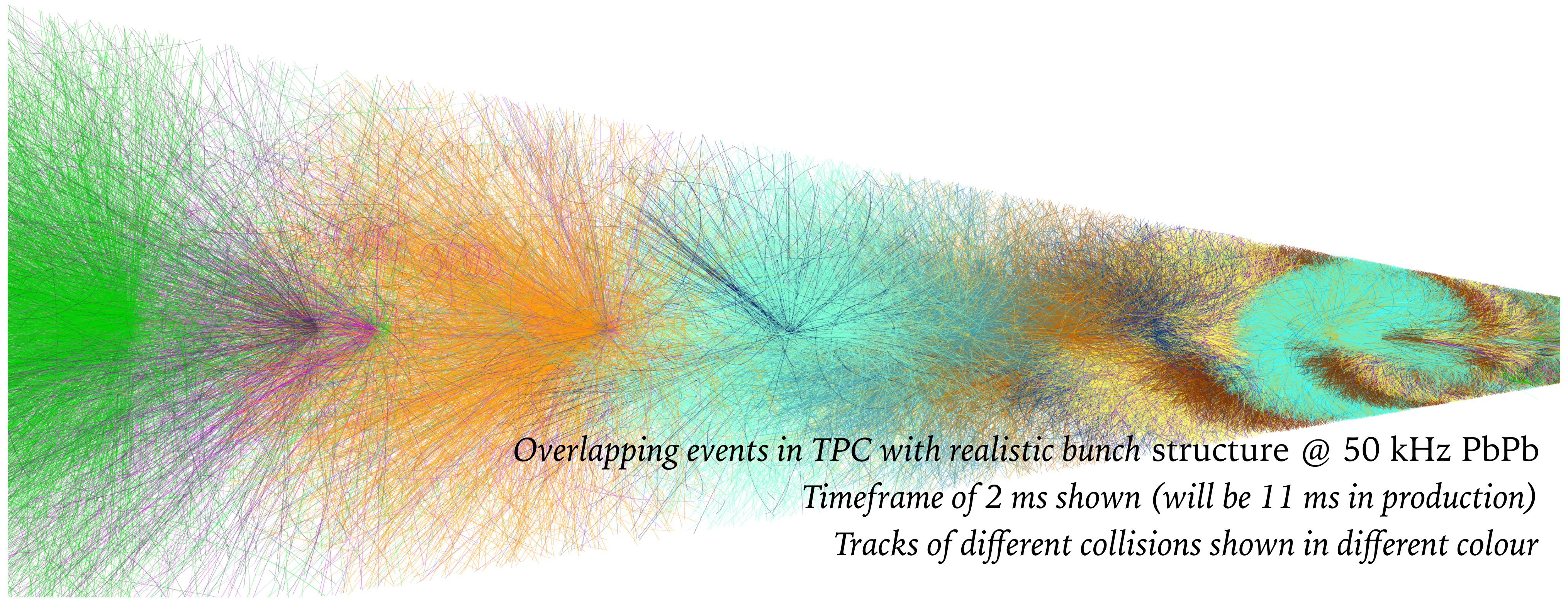
ALICE 2.0 in Run 3

- new Inner Tracking System - 7 pixel layers, first layer at 20 mm
- new Forward Muon Tracker - forward vertexing and tracking for muons
- new readout chambers of the TPC (Time Projection Chamber) based on GEM (Gas Electron Multipliers) technology
- new FIT (Fast Interaction Trigger) - interaction trigger, multiplicity estimator
- from < 1 kHz single events in Run 2 to 50 kHz of **continuous readout data** in Run 3
- building new reconstruction and analysis framework O^2 (Online/Offline) from scratch
- expected **50-100 times** more statistics for selected rare probes than in Run1+Run2

From < 1 kHz single events...



...to 50 kHz of continuous readout data.



Overlapping events in TPC with realistic bunch structure @ 50 kHz PbPb
Timeframe of 2 ms shown (will be 11 ms in production)
Tracks of different collisions shown in different colour

Summary

- **long-range correlations** (connected to the flow in Pb–Pb):
  - ➡ observed also in small systems
  - ➡ ridge yields in pp collisions bigger than the yields in e^+e^- (events with comparable multiplicity)
- **strangeness enhancement in small systems**:
  - ➡ out-of-jet processes give dominant contribution to strangeness enhancement in small systems
  - ➡ non-negligible contribution also from in-jet processes
- **deuteron production in jet and in underlying event**:
  - ➡ higher coalescence probability B_2 in jets than in underlying event
  - ➡ higher coalescence probability B_2 in jets in p–Pb than in jets in pp collisions
- stay tuned for the new Run 3 results