CMS

ATLAS EXPERIMENT

ALICE

LHCb

The limits of QGP-like effects towards smaller systems

from Pb-Pb down to pp and fixed-target collisions

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

LHCP 2023, Belgrade - 23rd May 2023

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Relativistic AA collisions: the QGP

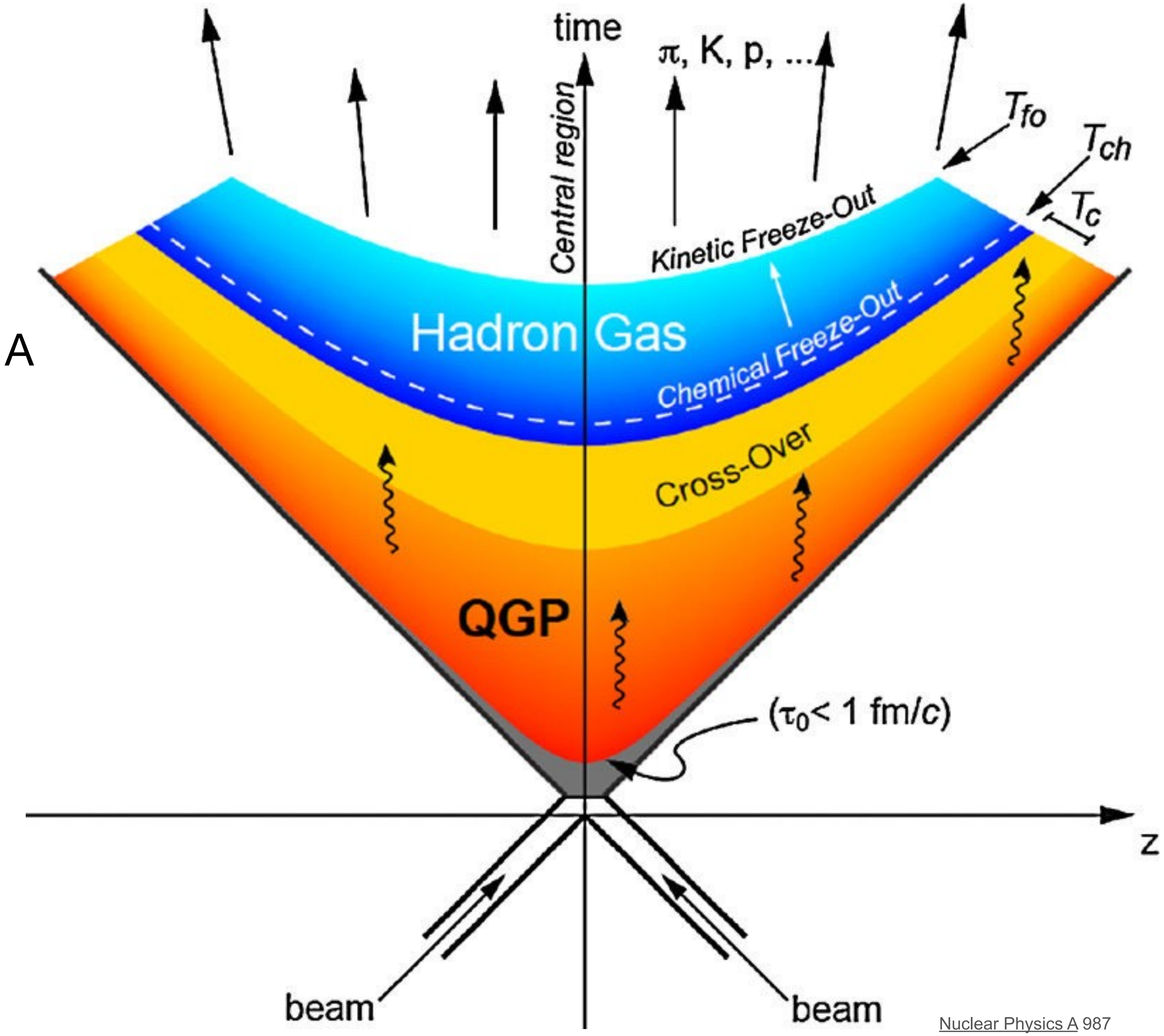
Initial state: collision of two Lorentz-contracted nuclei

- Fast thermalization → $\tau \approx 1$ fm/c
- Phase transition (cross-over) to hadron gas (T_c = 156.5 +/- 1.5 MeV P. Steinbrecher et al. Nucl. Phys. A 982 (2019) 847)

  → Color confinement: **hadronization**
- Chemical freeze-out ($T_{ch} \approx$ 153 MeV)

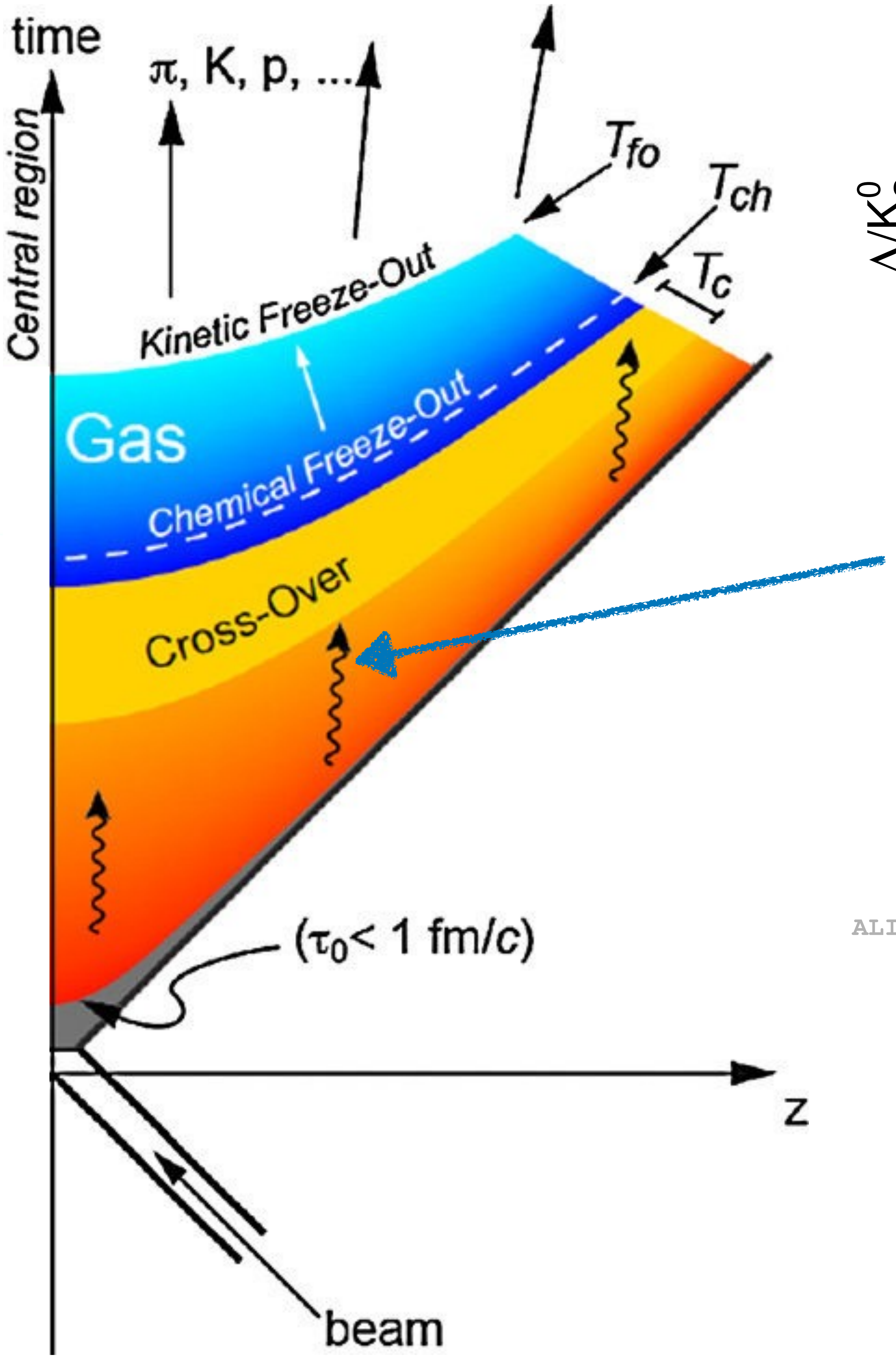
  → inelastic collisions stop: **particle abundances fixed**
- Kinetic freeze-out ($T_{fo} \approx$ 100 MeV)

  → elastic collisions stop: **particle spectra fixed**
- Particles fly towards detectors

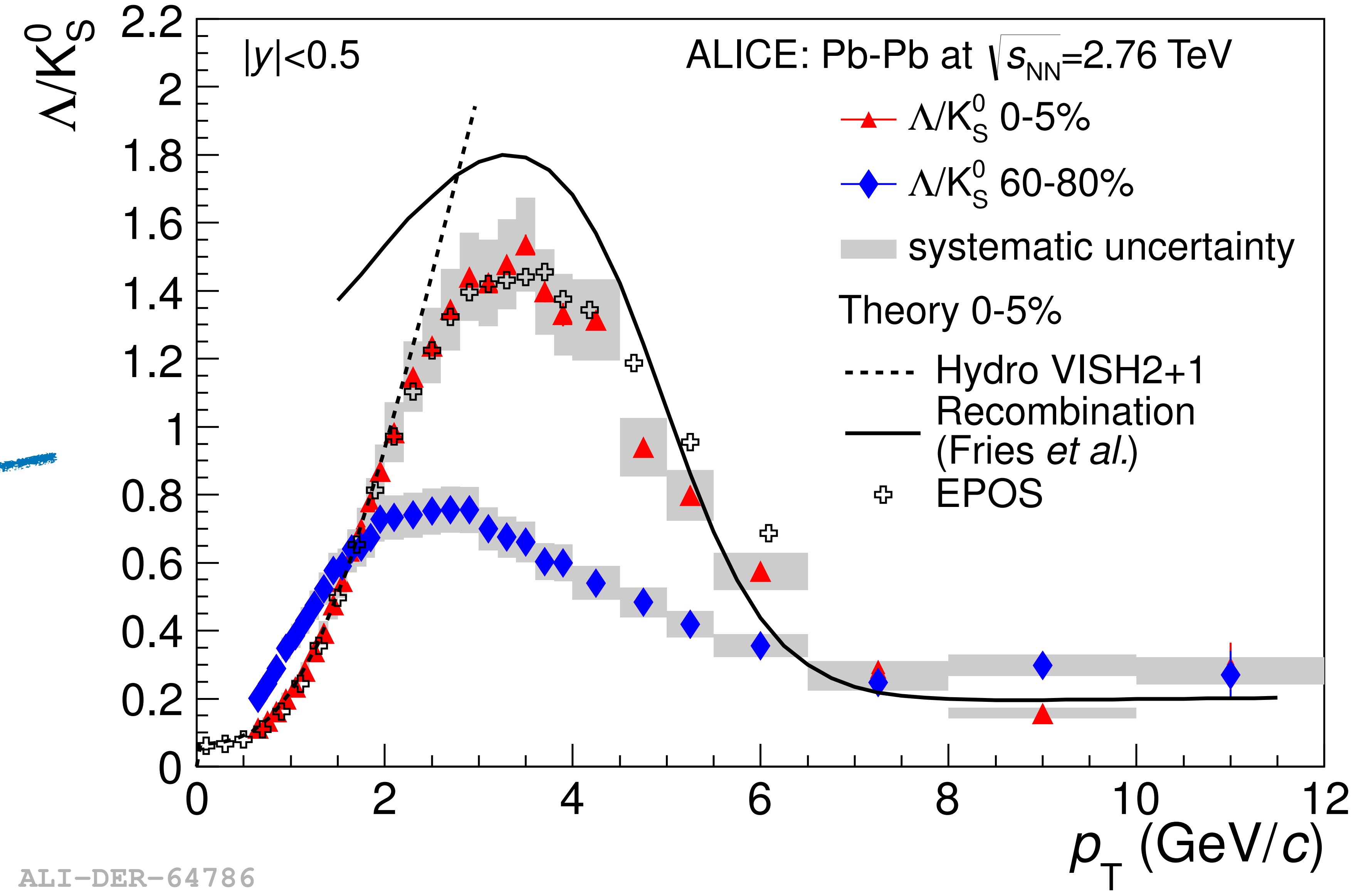


Nuclear Physics A 987

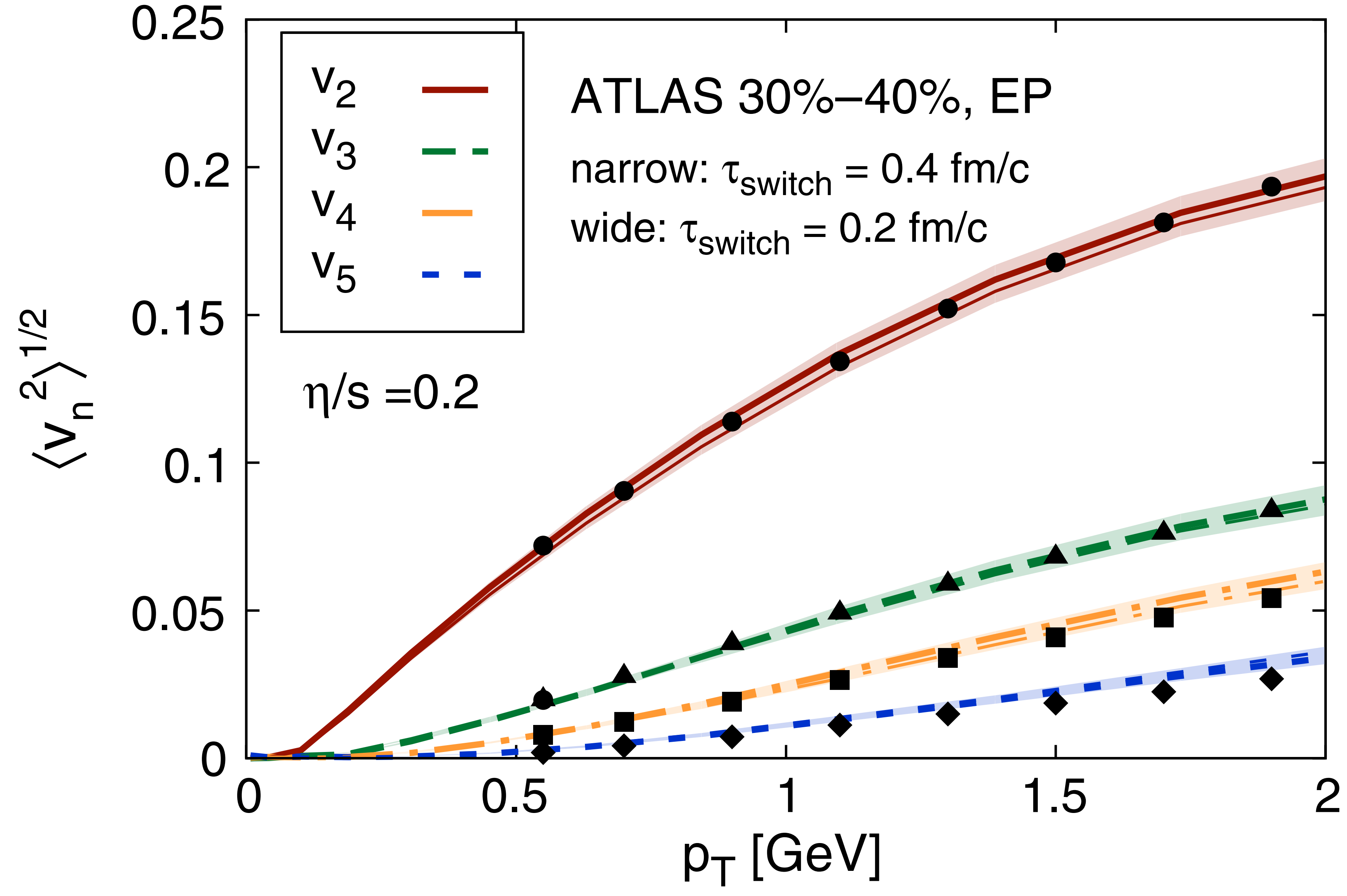
QGP in AA collisions



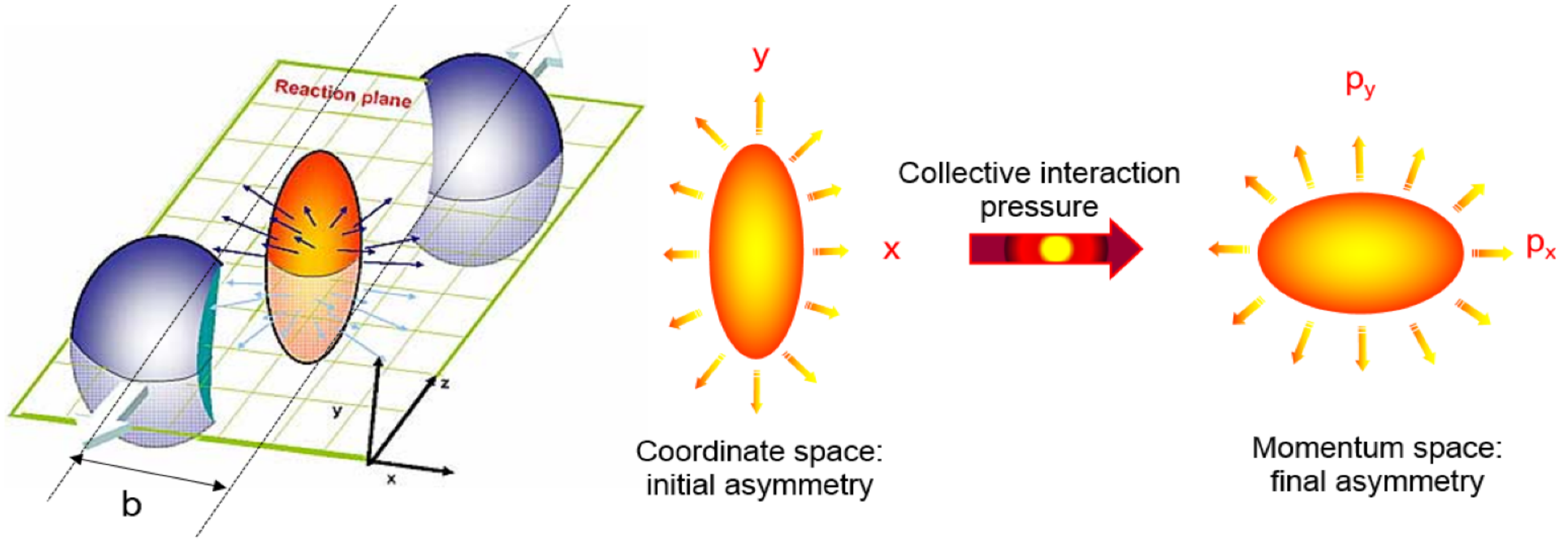
PRL 111 (2013) 222301



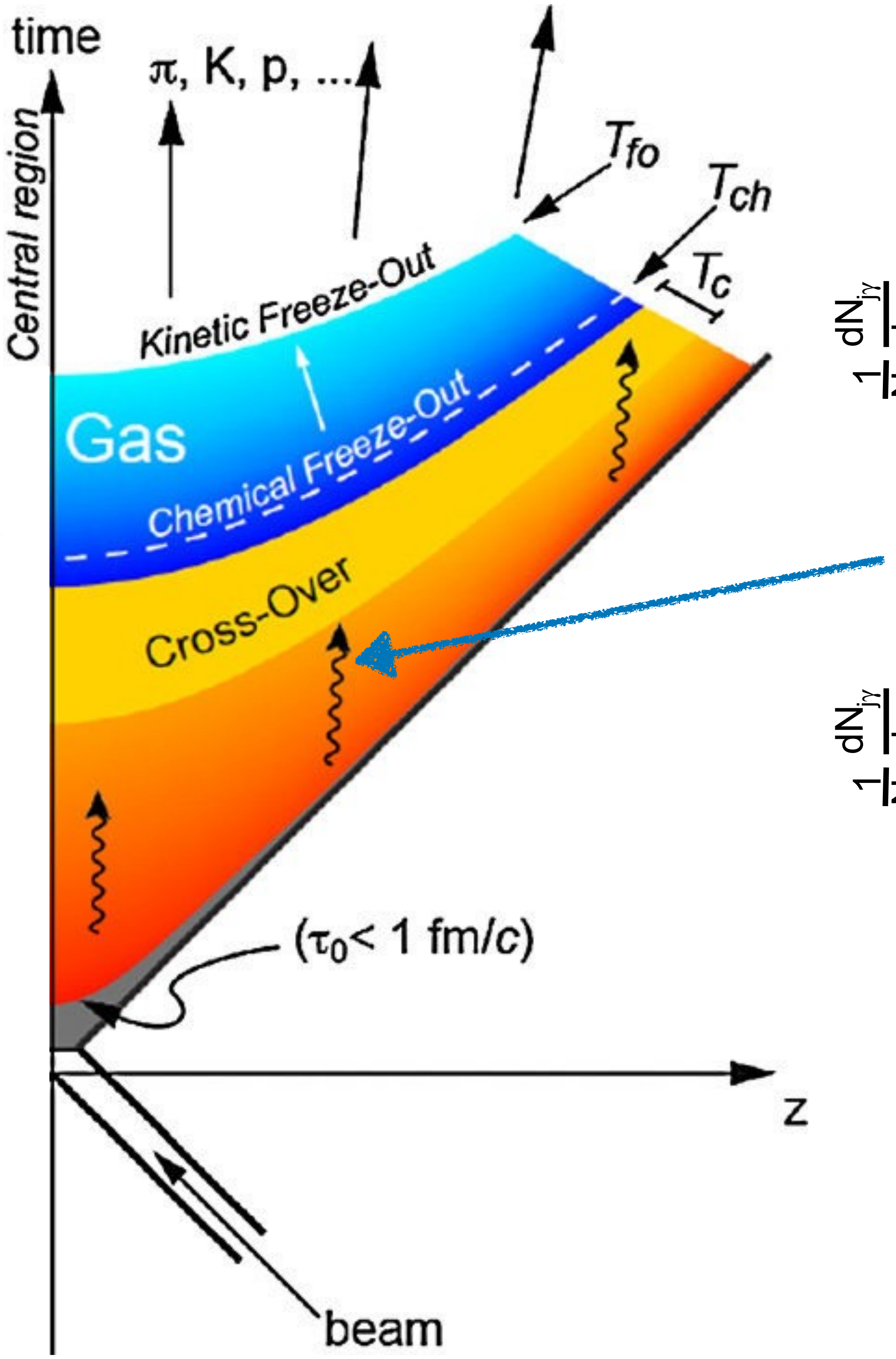
C. Gale et al. PRL 110 (2013) 012302



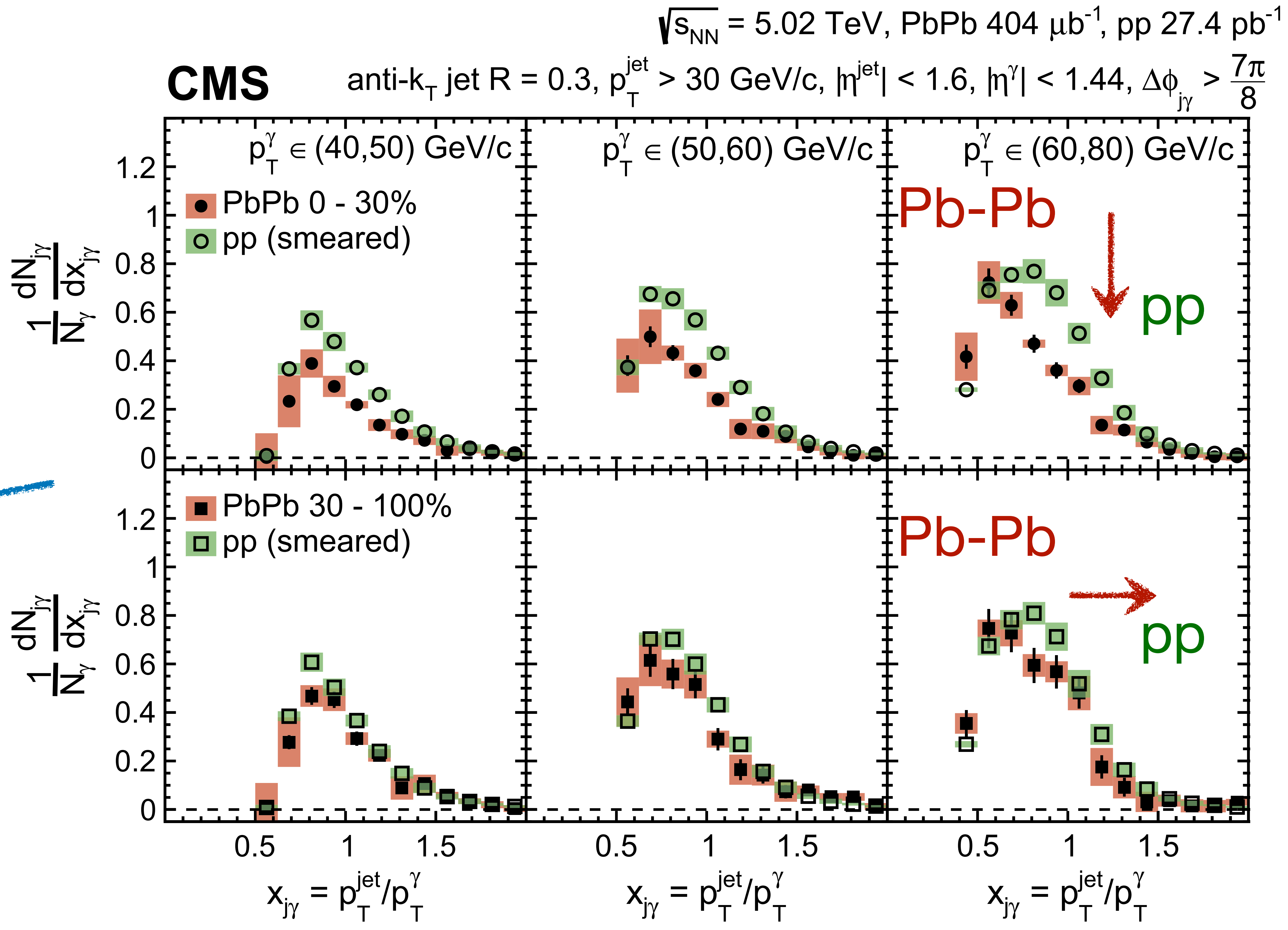
Collectivity: radial and anisotropic flow described by hydro models



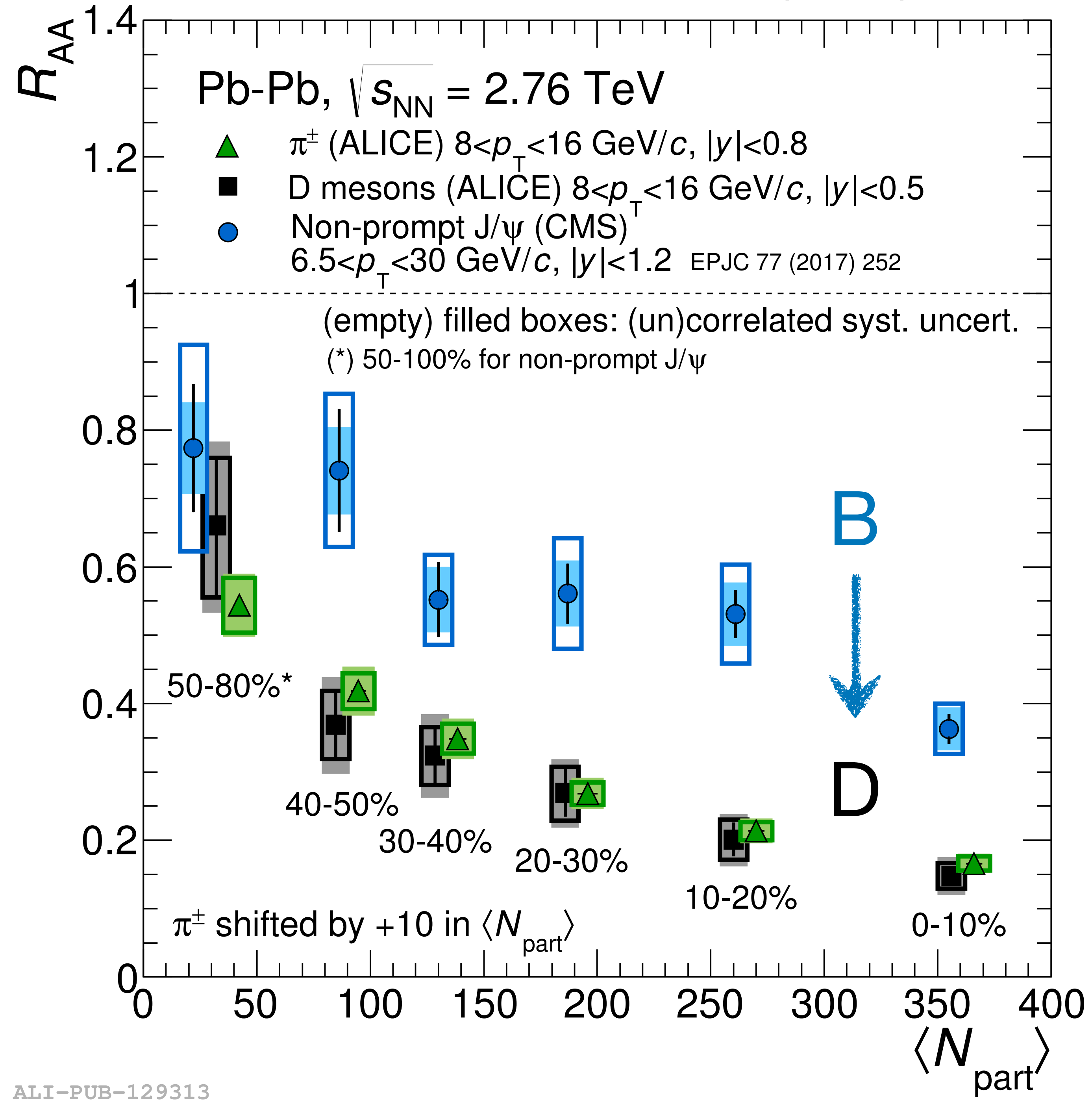
QGP in AA collisions



CMS PLB 785 (2018) 14



ALICE JHEP 1511 (2015) 205



Partonic energy loss: jet quenching and energy loss hierarchy $\rightarrow R^{\pi}_{AA} \sim R^{D}_{AA} < R^{B}_{AA}$

- Non prompt J/ψ produced from B decays

$$R_{AA} = \frac{1}{\langle N_{Coll}\rangle}\frac{d^2N/dydp_T|_{AA}}{d^2N/dydp_T|_{pp}}$$

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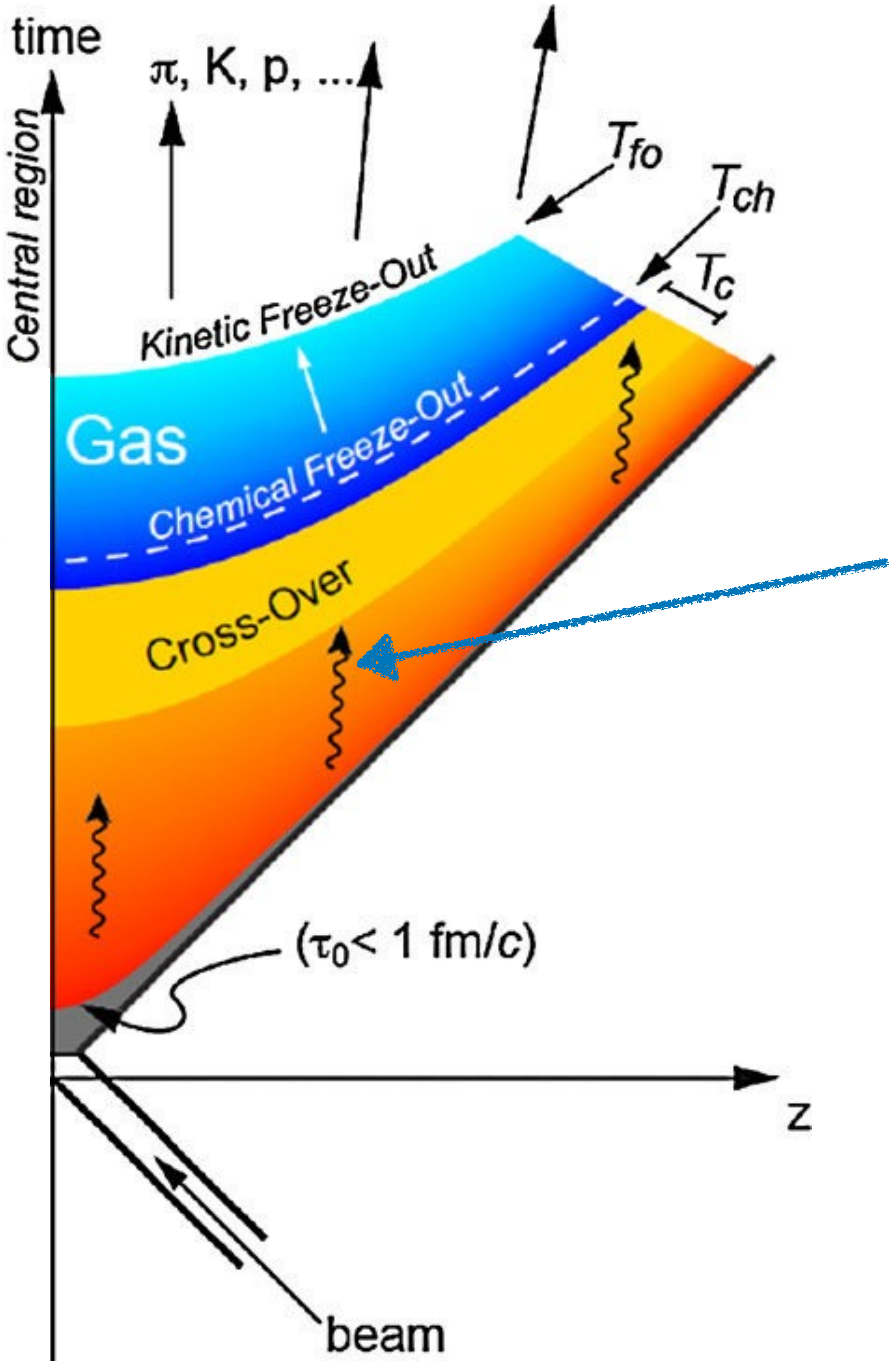
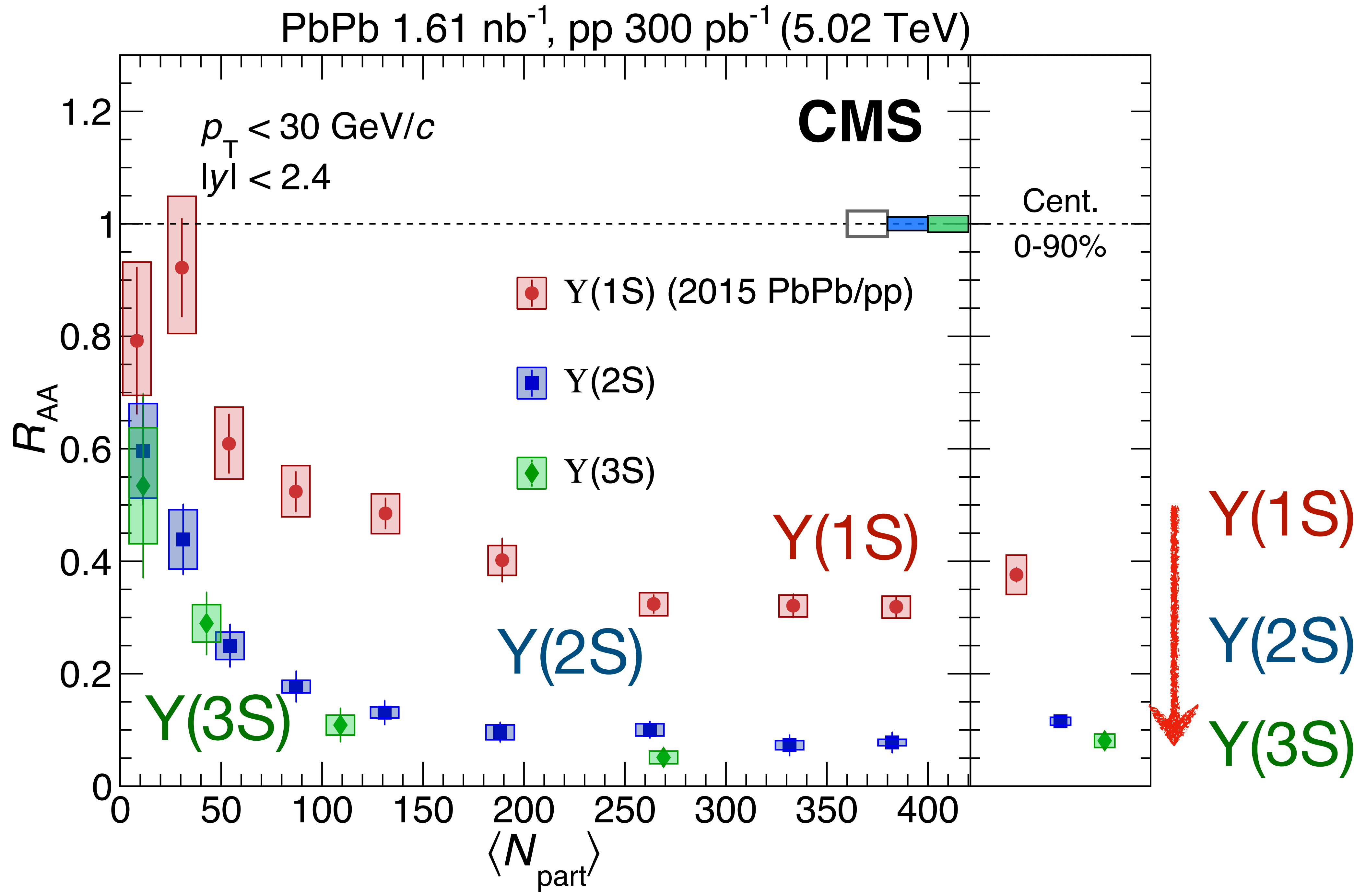
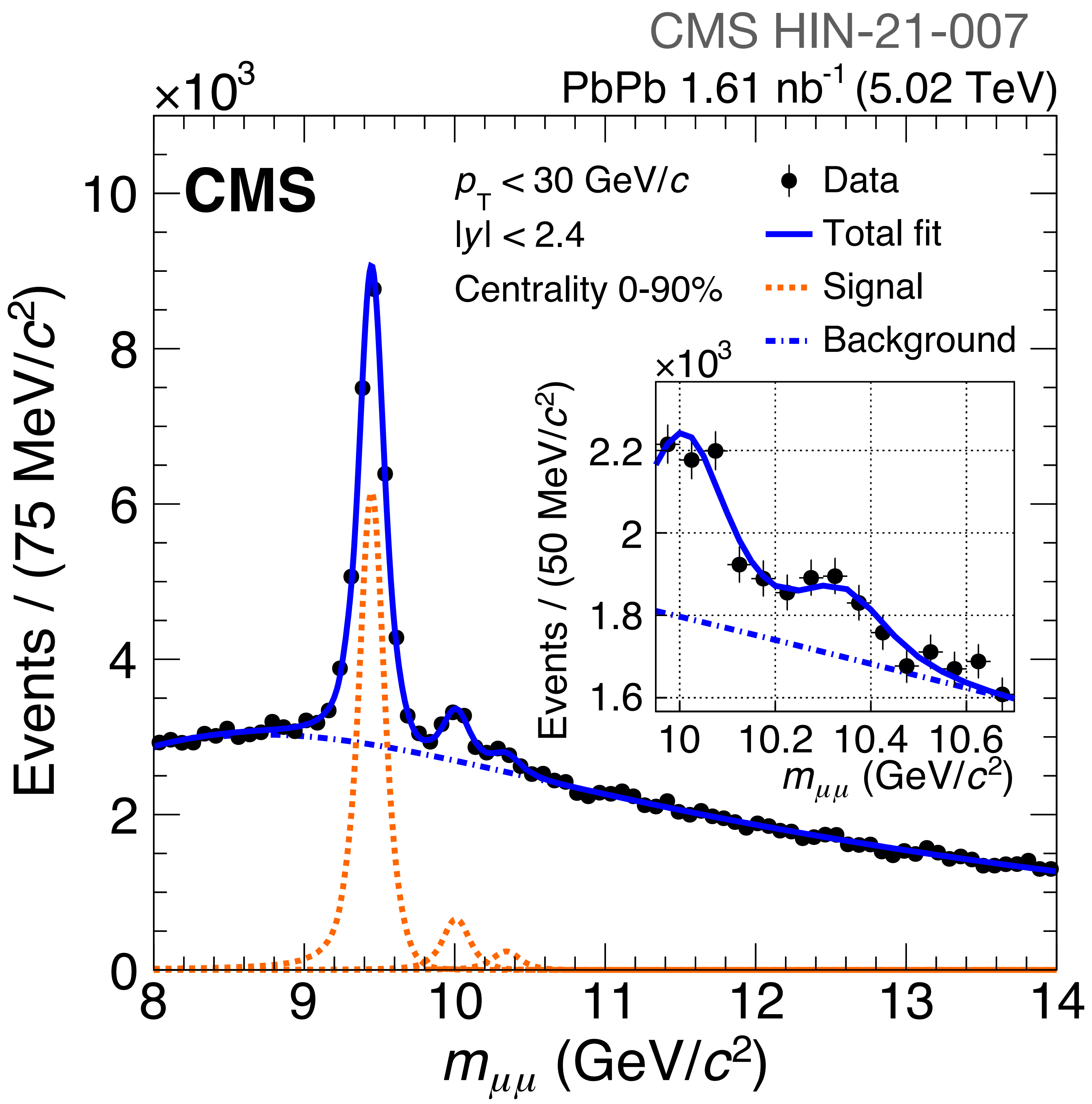
QGP in AA collisions

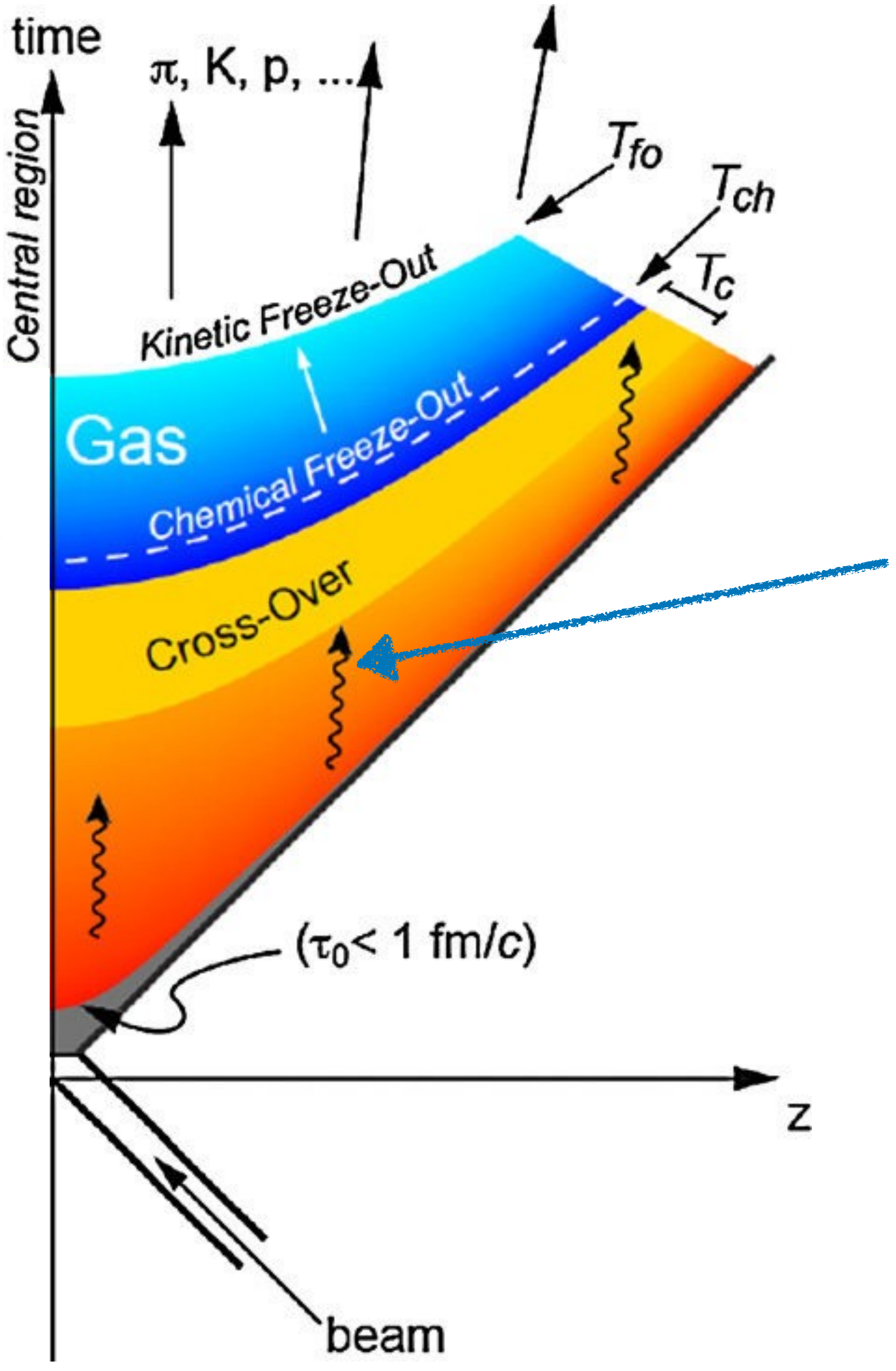


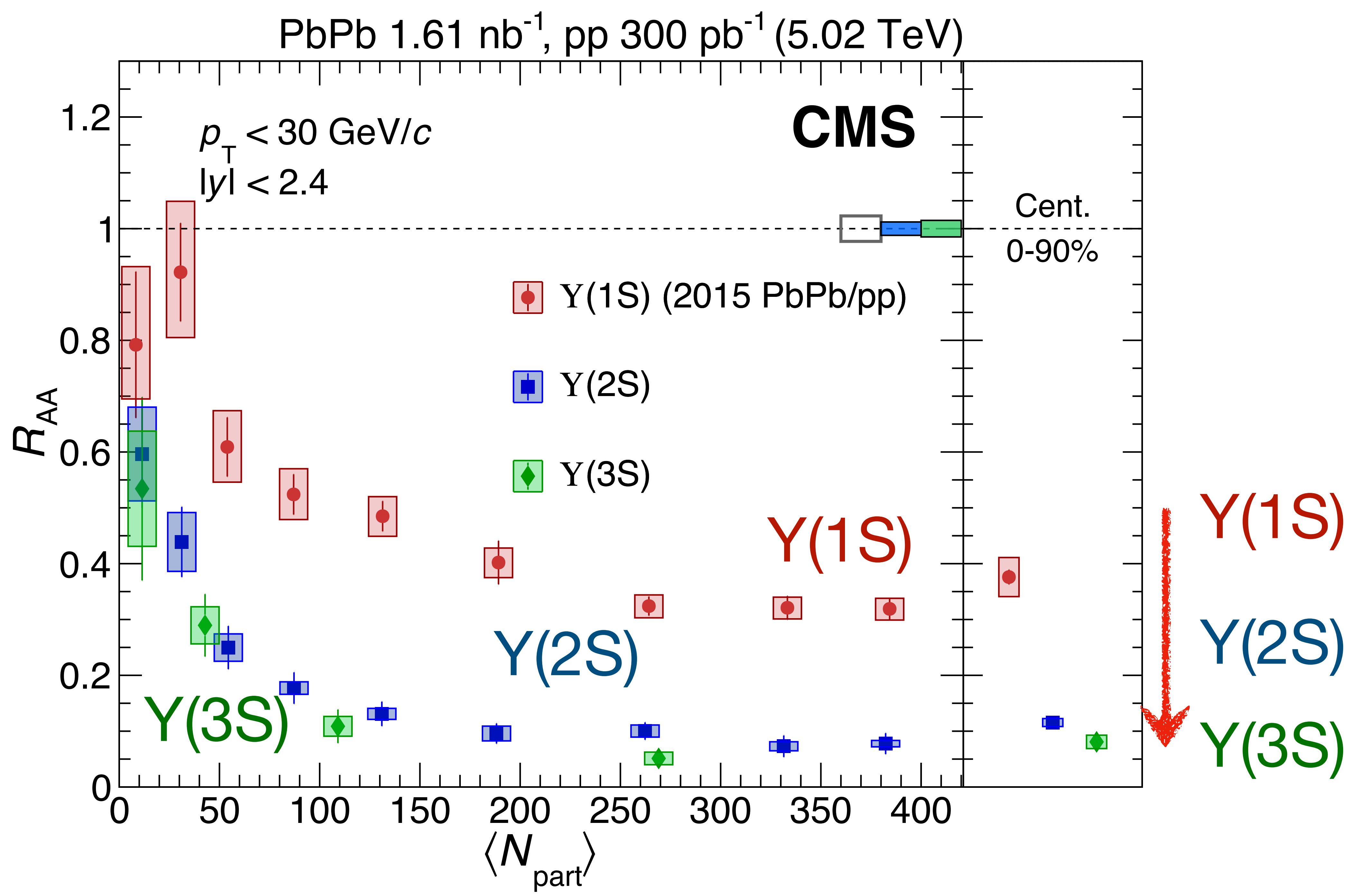


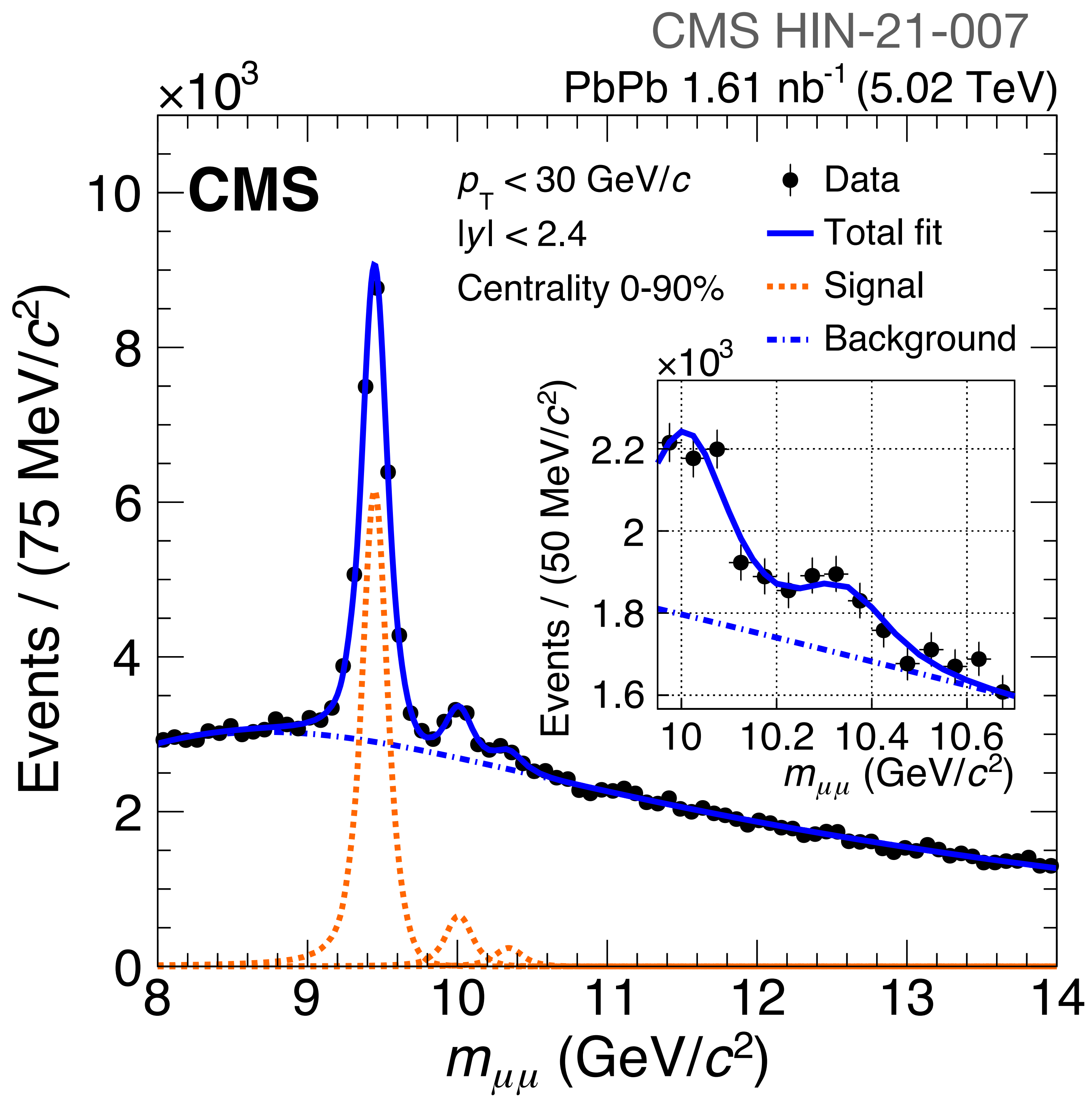


Suppression of quarkonium: increases from peripheral to central AA collisions

QGP in AA collisions







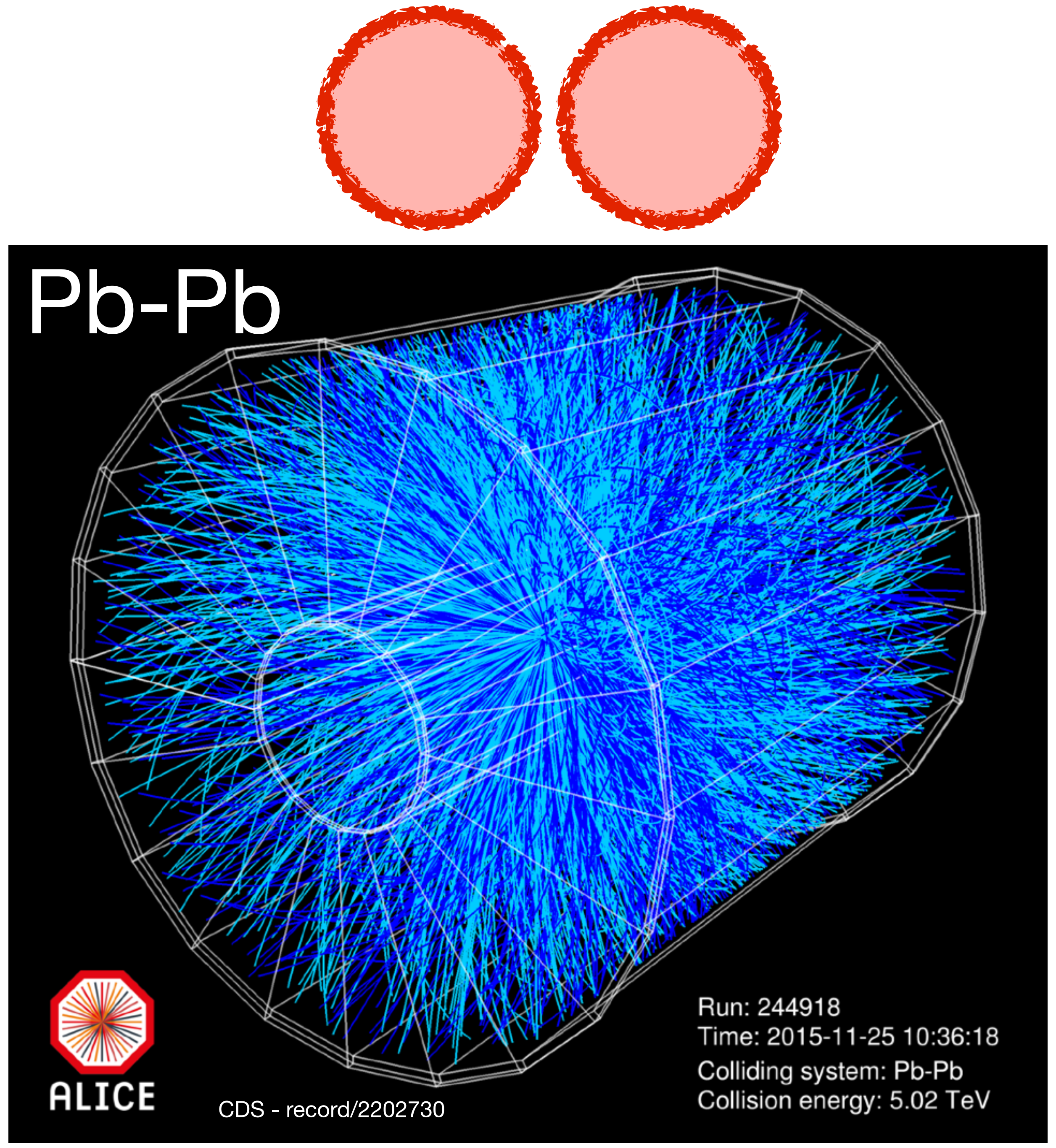
Suppression of quarkonium: increases from peripheral to central AA collisions

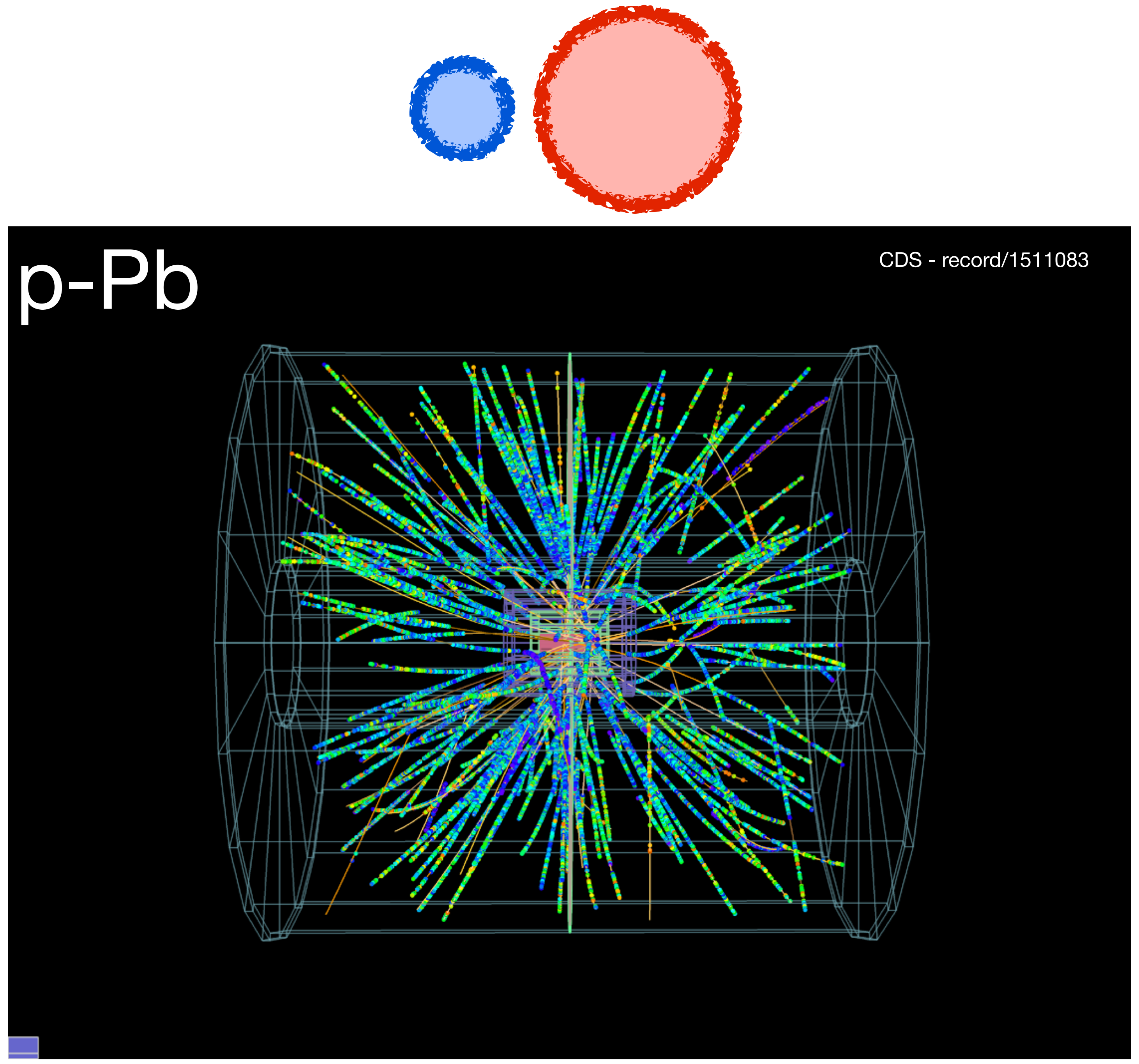
Compelling evidence of QGP formation putting together SPS, RHIC and LHC results!

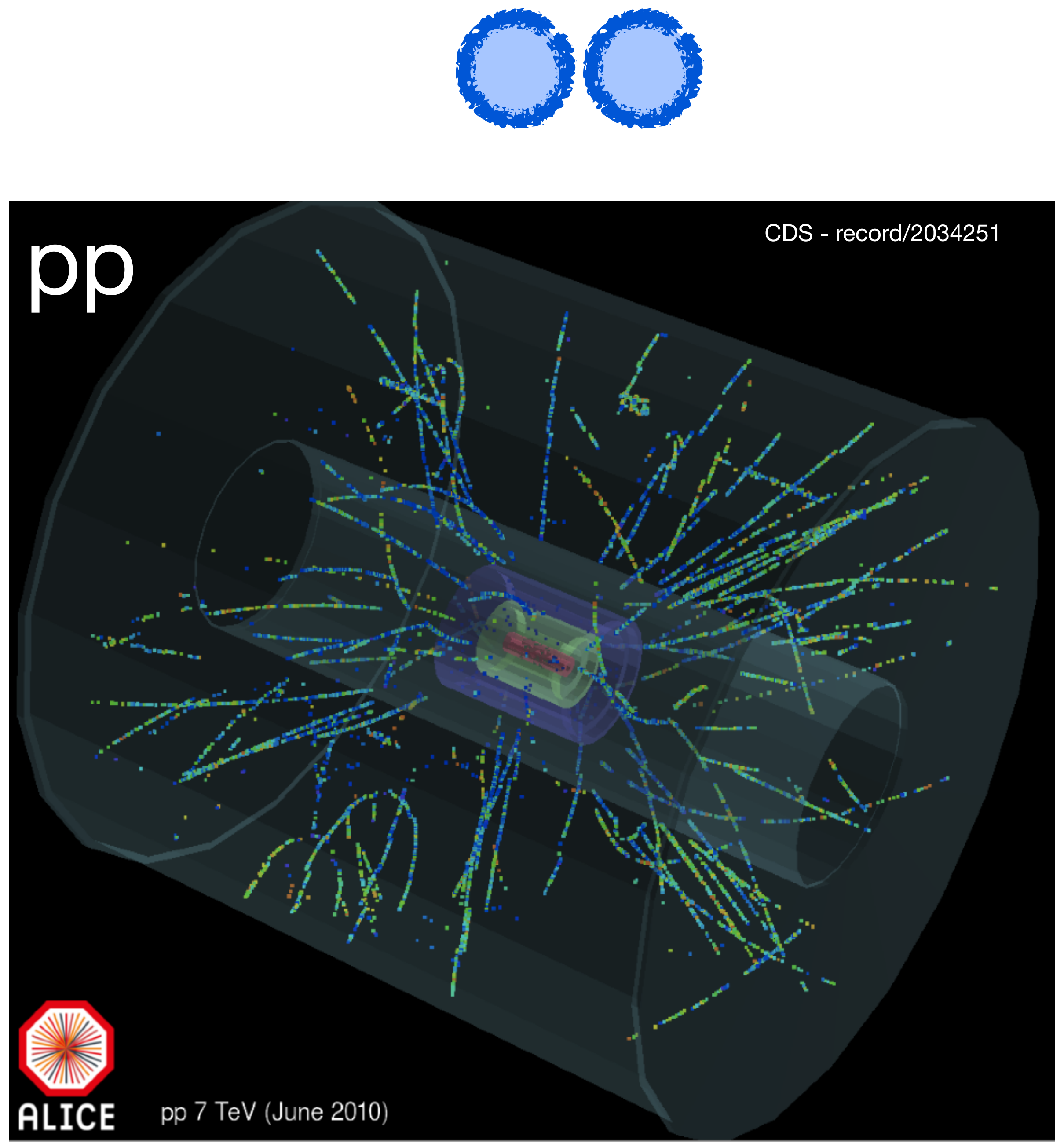
A. Timmins Quark-gluon plasma properties from LHC data 22 May 2023, 18:15

Pre LHC: pp, pA and AA

- **At the LHC:** QGP is formed in AA collisions → clear signatures (e.g. flow, strangeness enhancement, nuclear modification factor, jet suppression, ...)
- p—Pb → control experiment, disentangle cold nuclear matter effects
- pp collisions → reference for Pb—Pb







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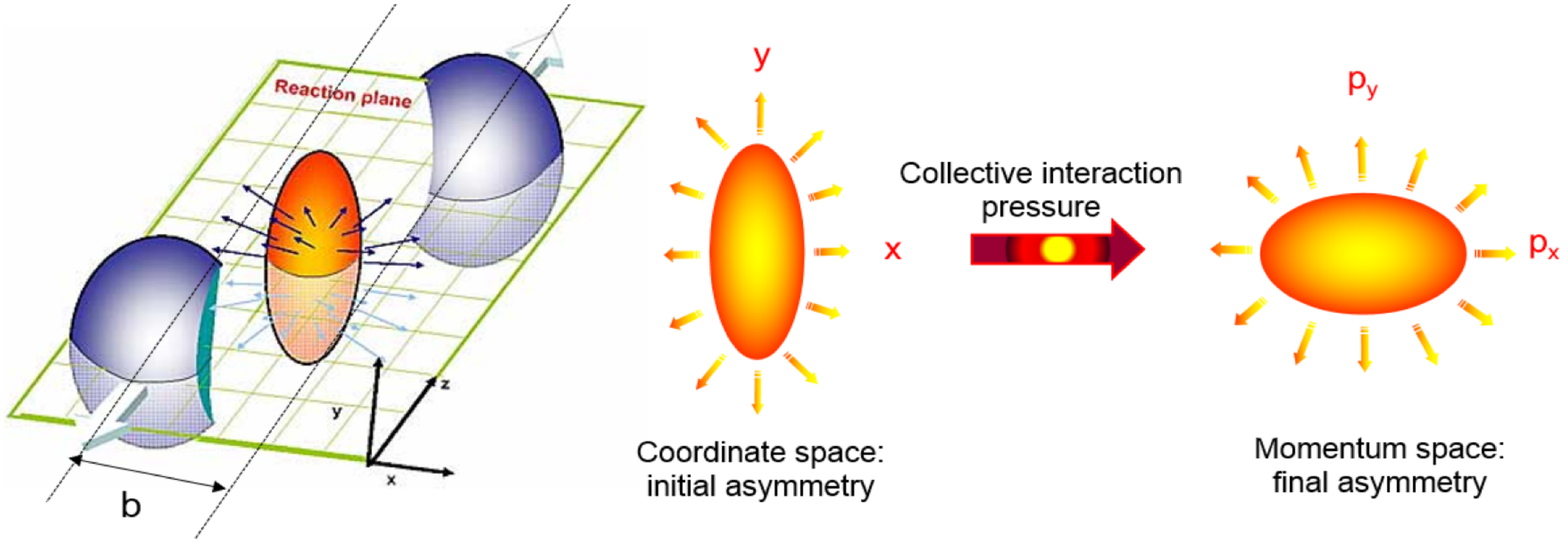
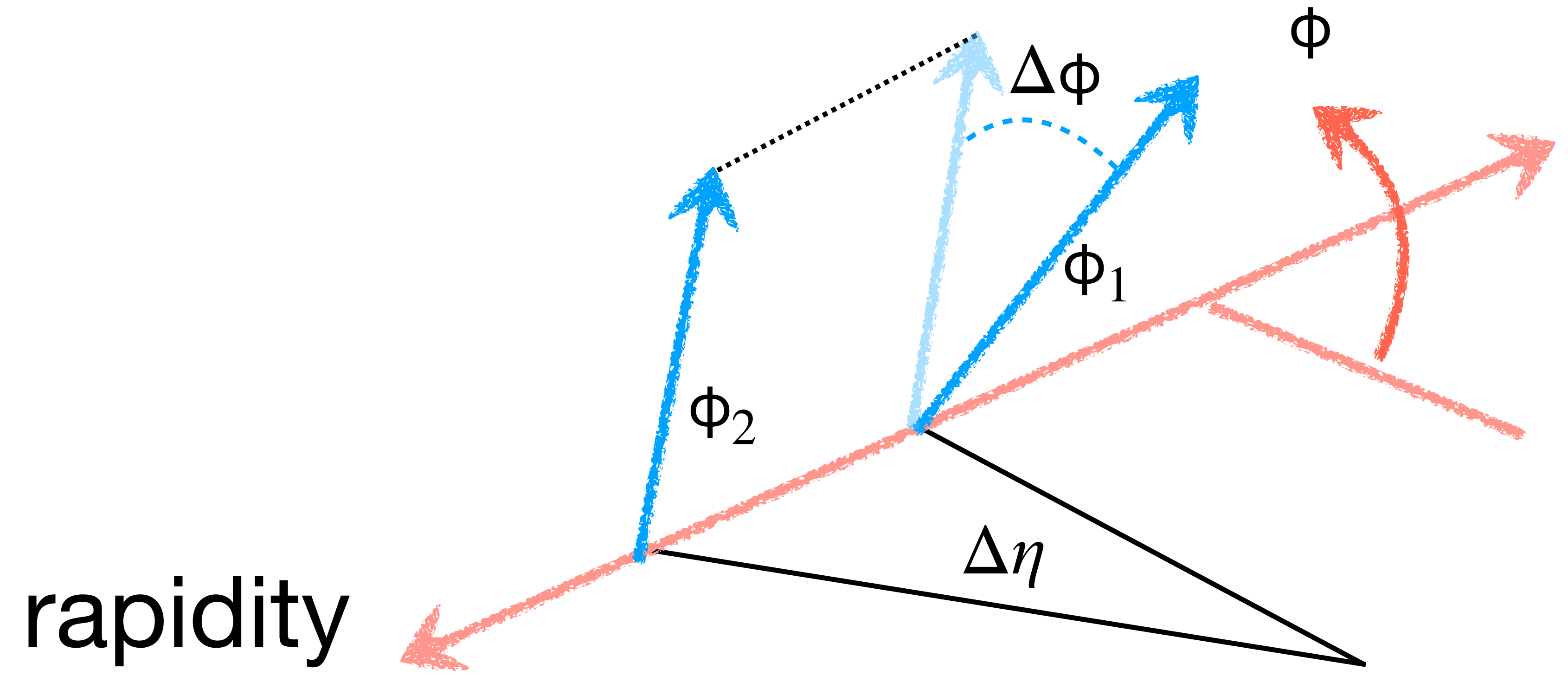
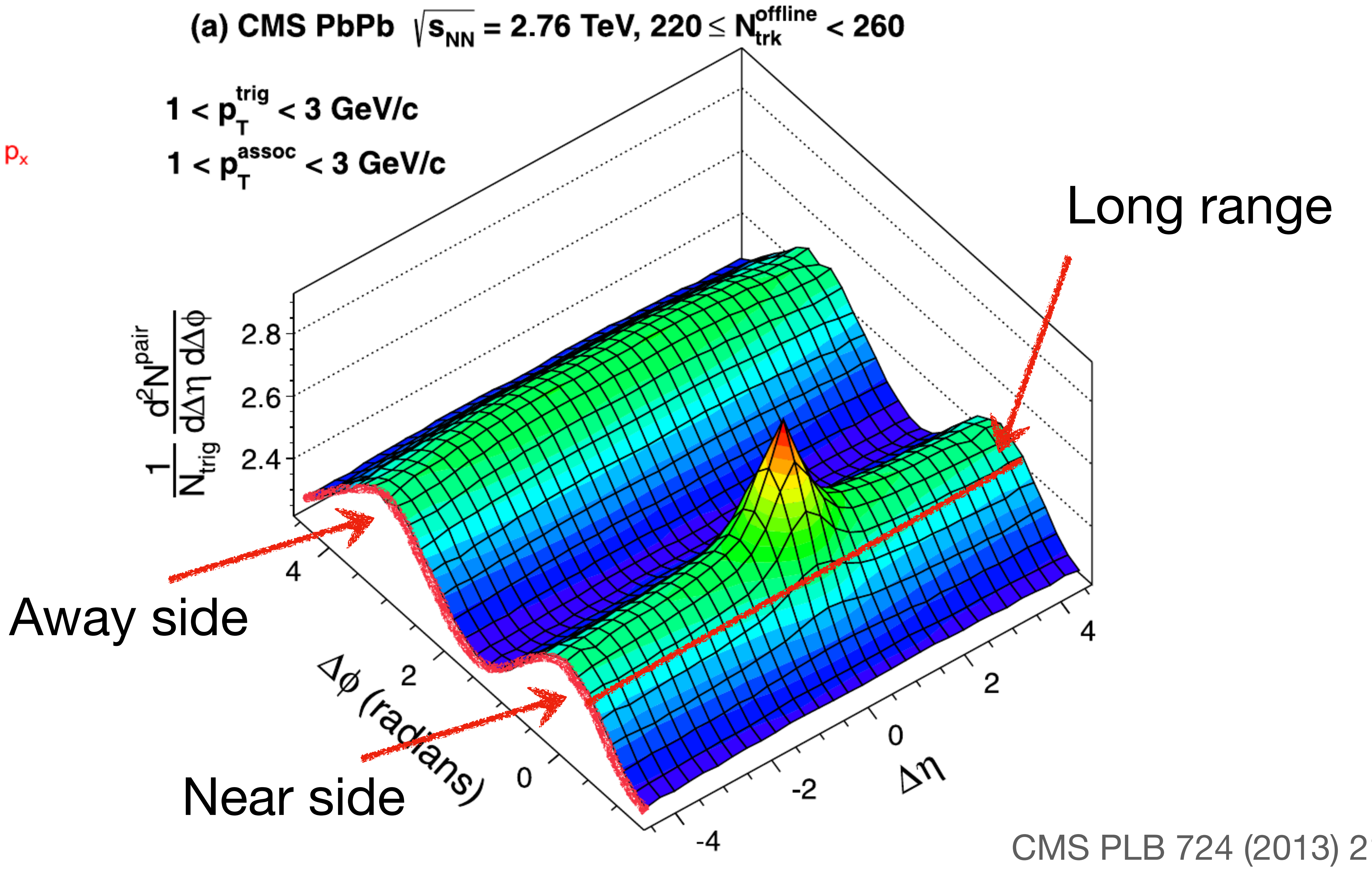
Collective evolution: two particle correlation

- Collective expansion translates into **long range** modulation of particle emission **in azimuth**



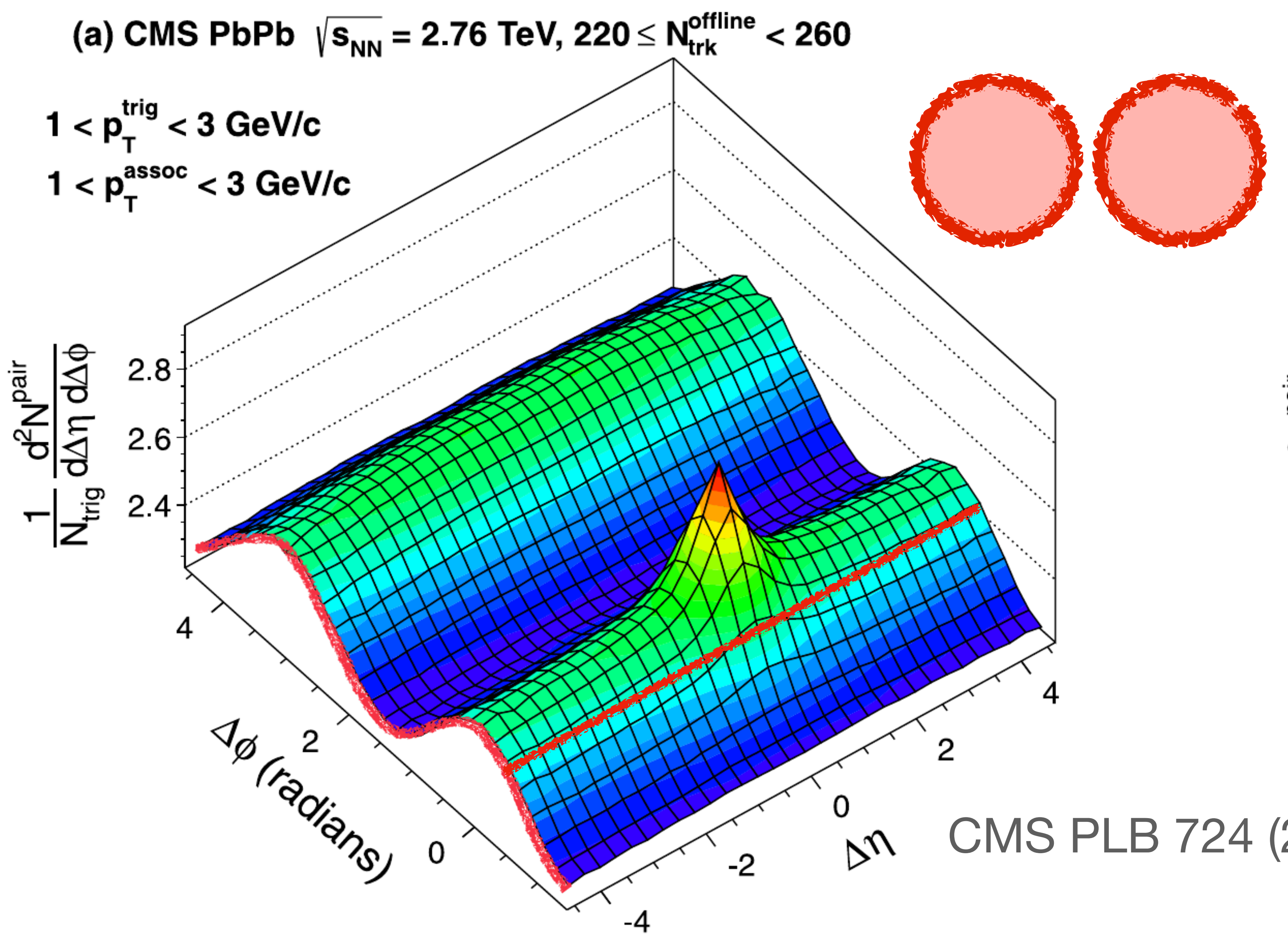




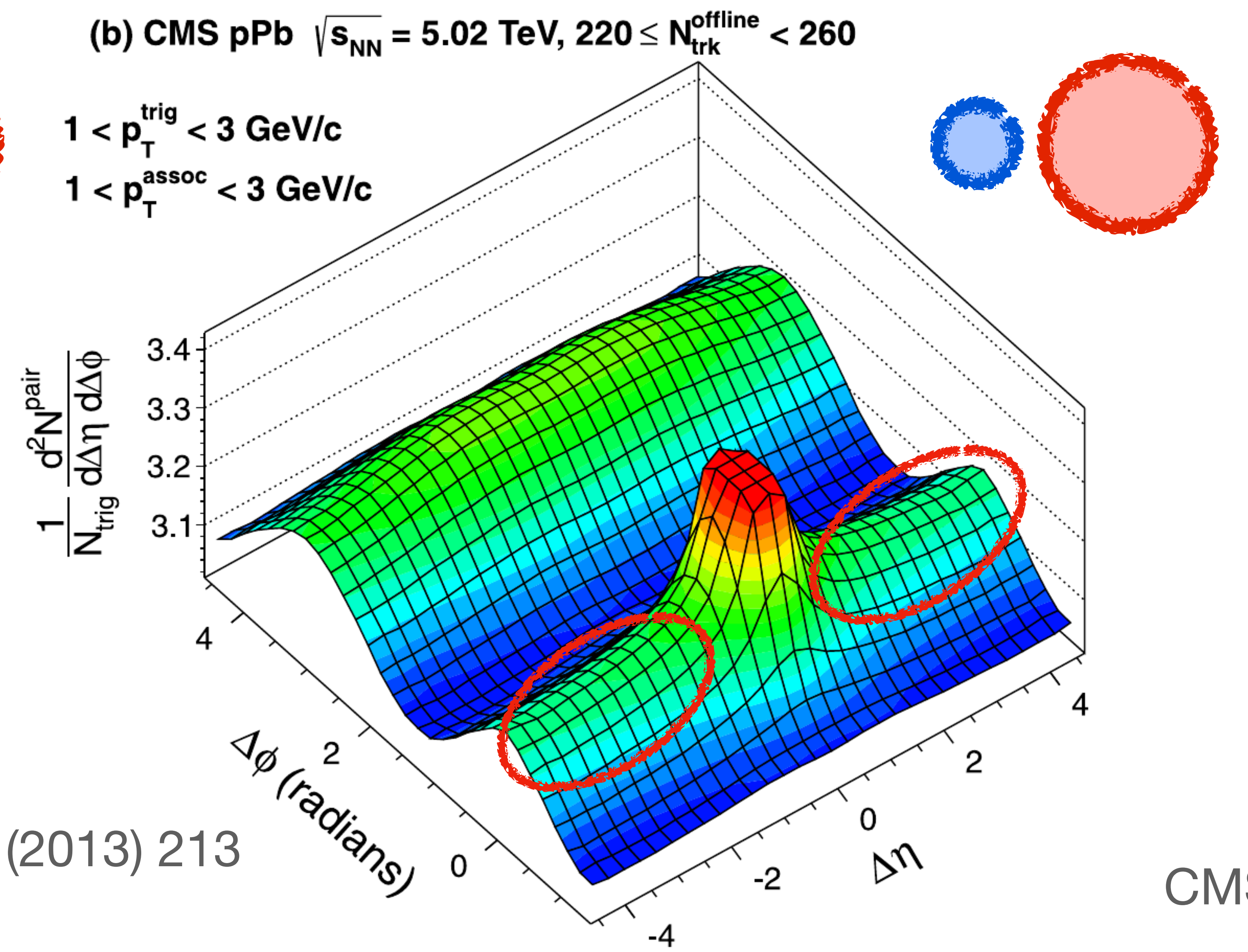
CMS PLB 724 (2013) 213

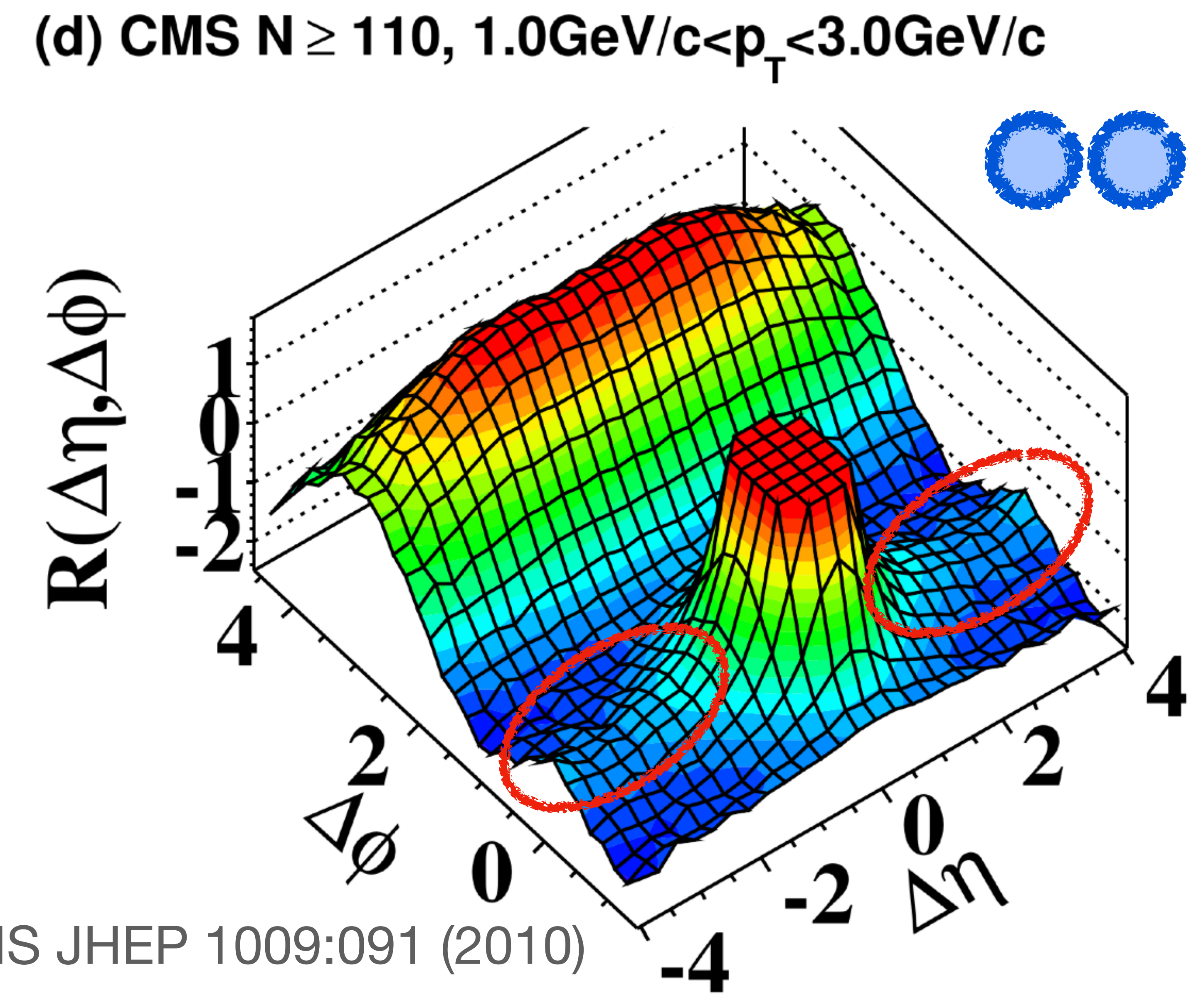
Collective evolution holding until pp?

- Collective expansion translates into **long range** modulation of particle emission **in azimuth**
- Also observed in p-Pb and pp → "small systems" is born
- Collective expansion also at play? Under which conditions does this not happen?



CMS PLB 724 (2013) 213





CMS JHEP 1009:091 (2010)

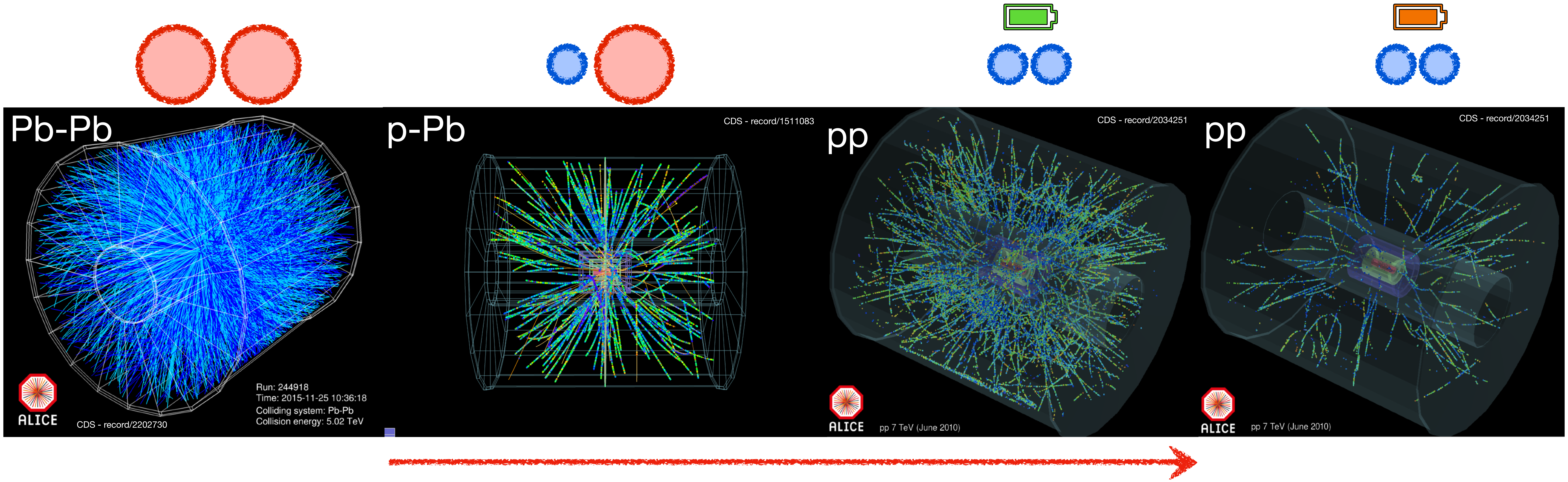
Decreasing systems size

Small systems post LHC

- Tentative definition: "system a priori too small to show characteristics of heavy ion physics and however in which we observe them" → **small systems are defined from AA**

- **Nota bene:** with this definition a system "too small" is not defined a priori → sometimes a final state looking like a large system, at least for charged particle multiplicity

- Minimum Bias pp **still holds as the reference** → high-multiplicity events ~ O(10^{-4}) of the total cross section



Decreasing systems size

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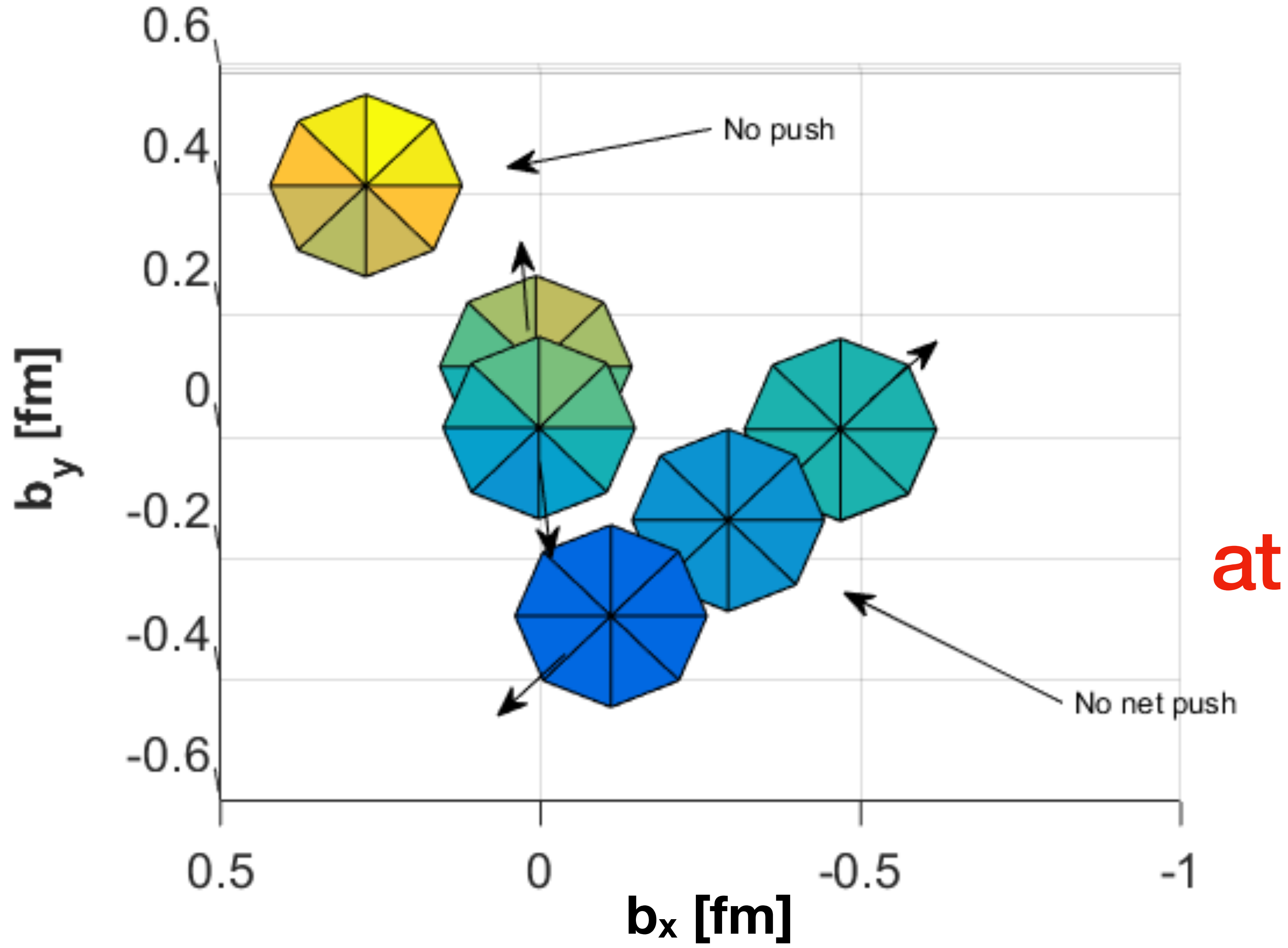
Collective motion in small systems

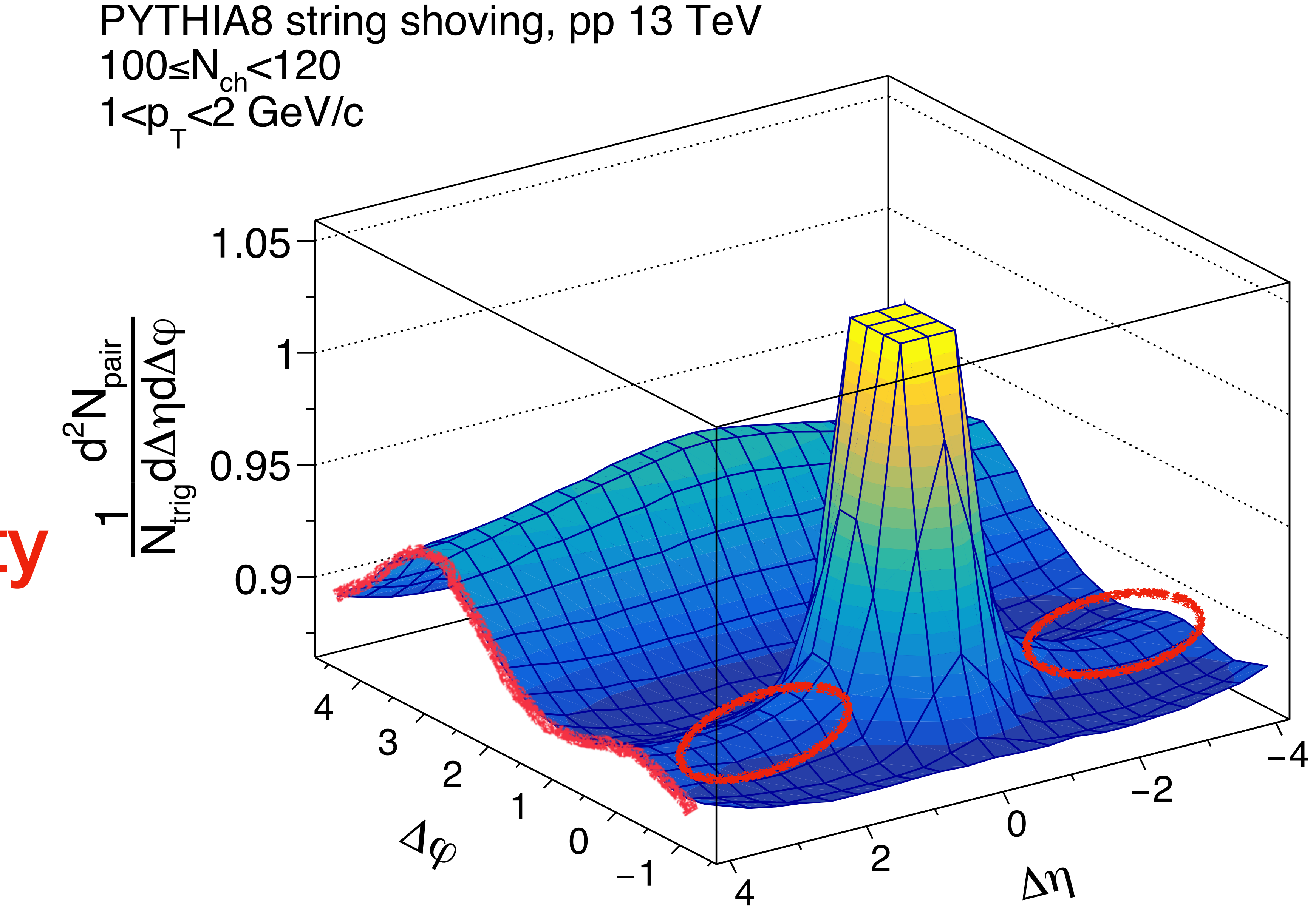
- High multiplicity → many partonic interactions → many color strings → color string shoving!

String shoving leads to collective motion



C. Bierlich et al.
MCnet-16-48, LU-TP 16-64

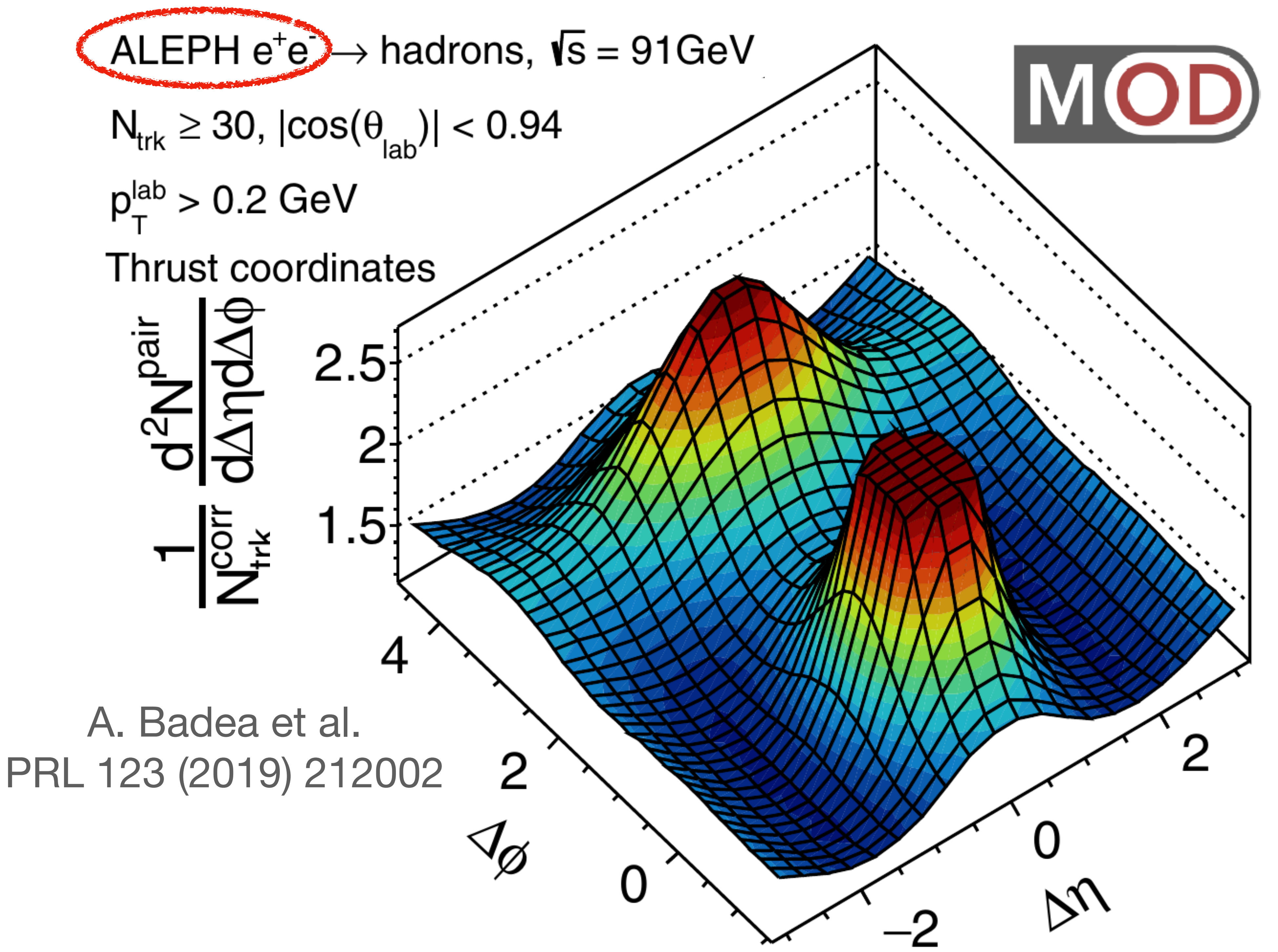
at high multiplicity

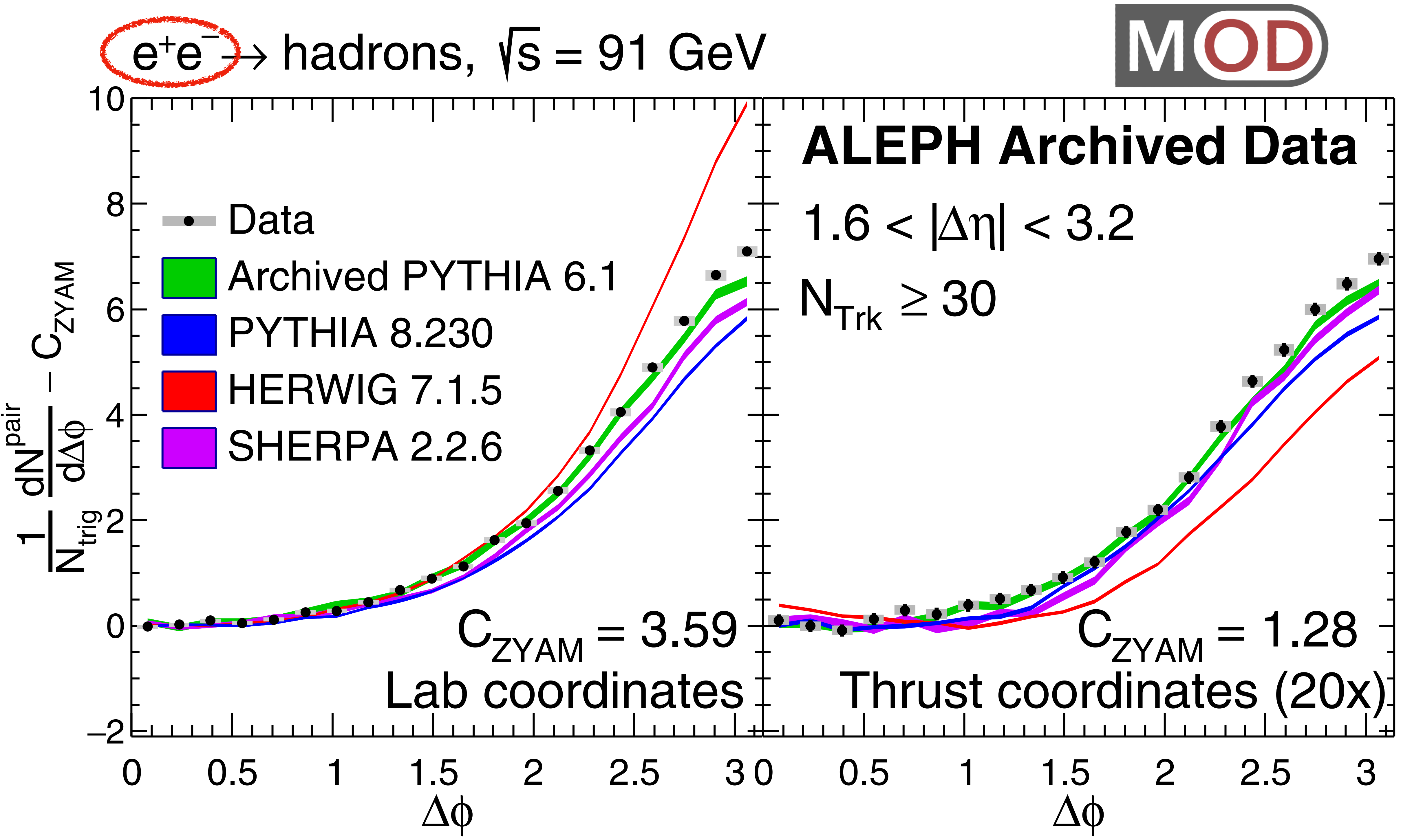


J. Kim et al.
arXiv:2108.09686

- PYTHIA with string shoving can reproduce long range angular correlation
- Explains presence in high-multiplicity hadron-hadron collisions

Breaking down of the collective evolution?





- No significant long range correlation is found in e^+e^- collisions around $\Delta\phi = 0$

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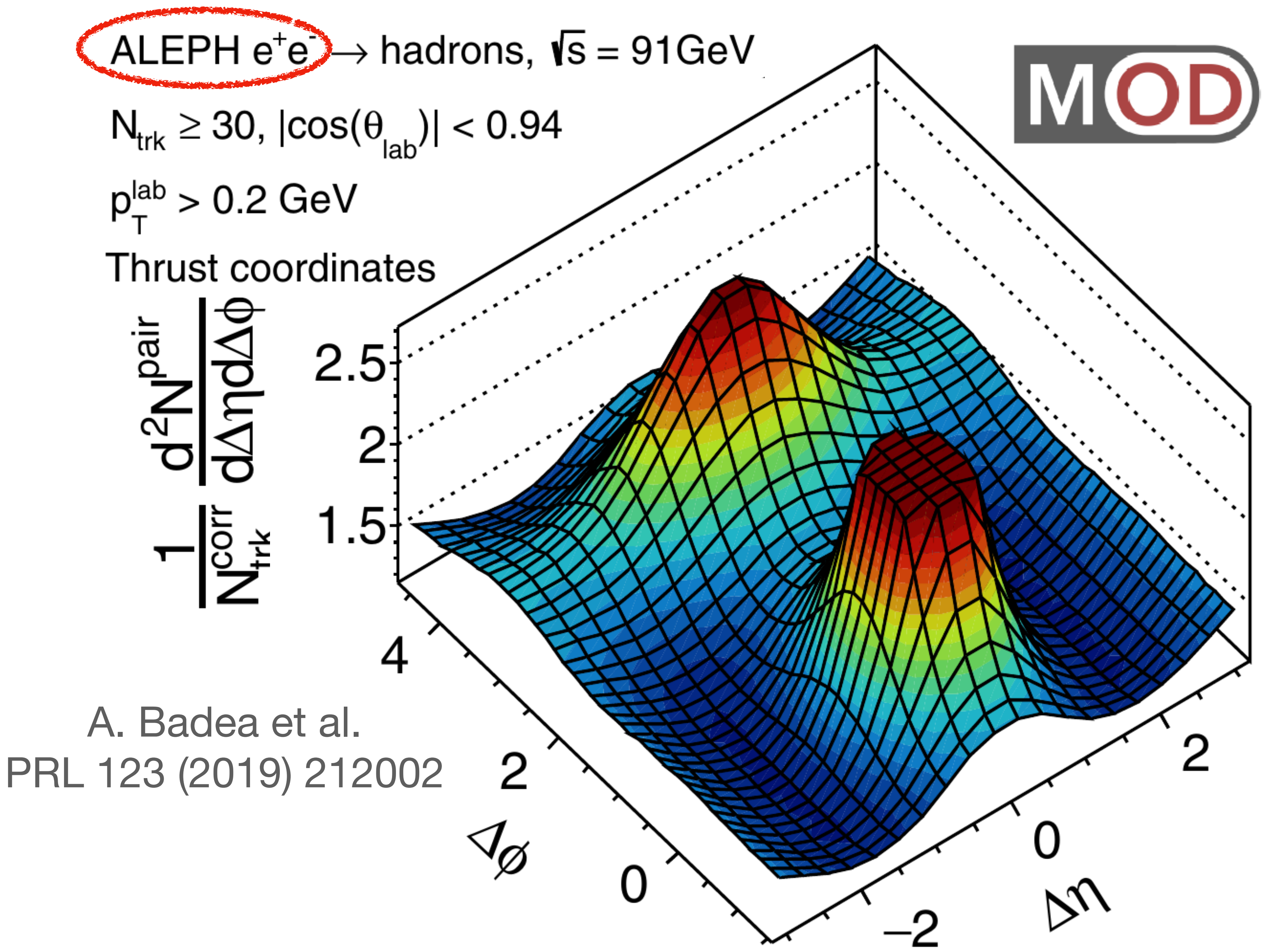
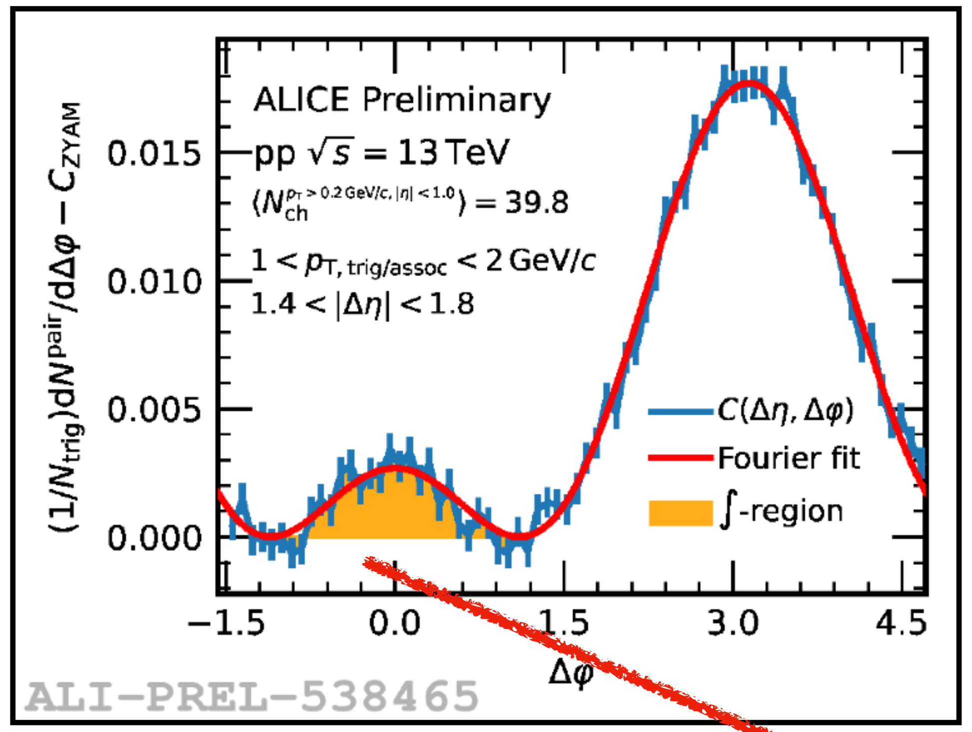
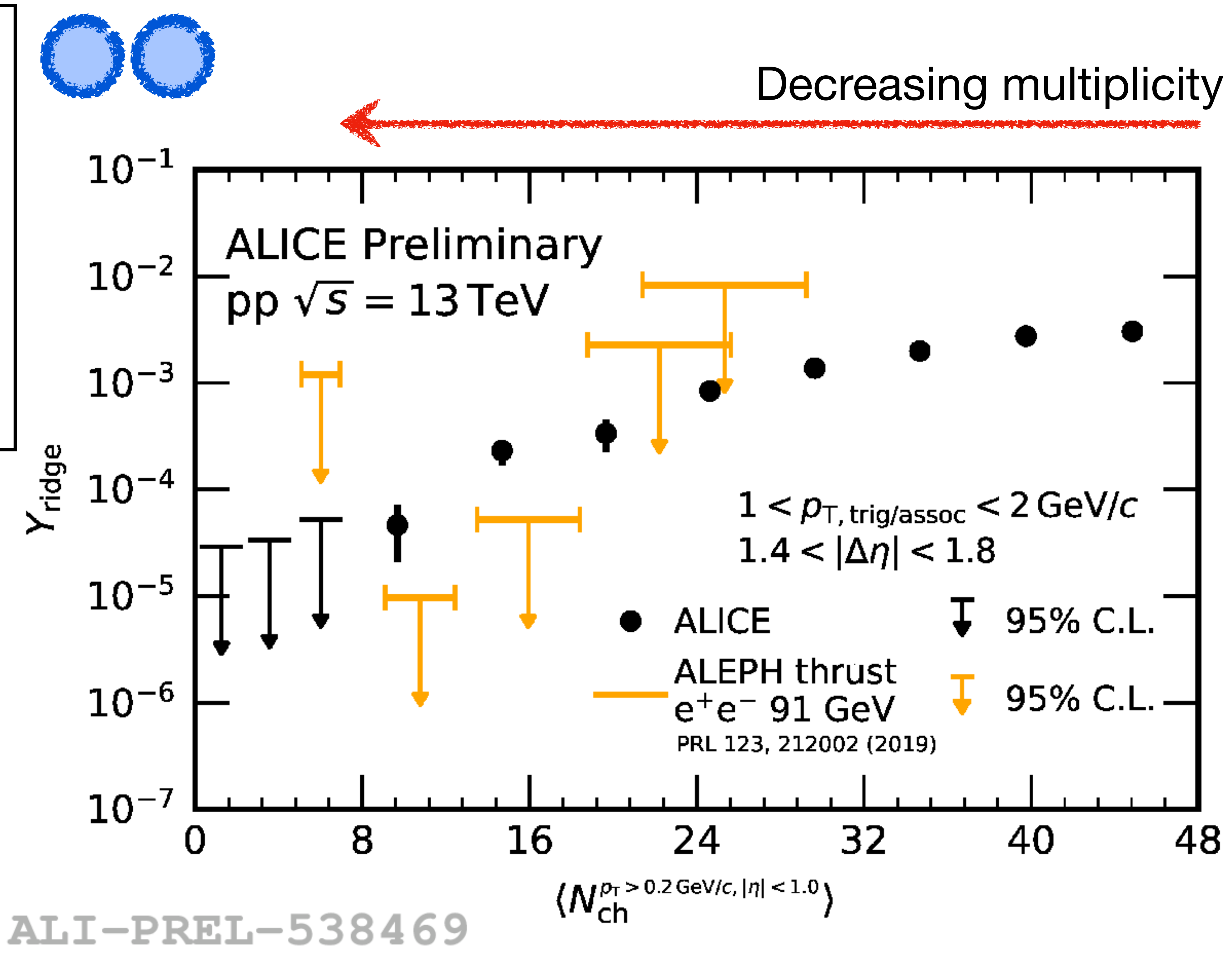
And at the LHC?



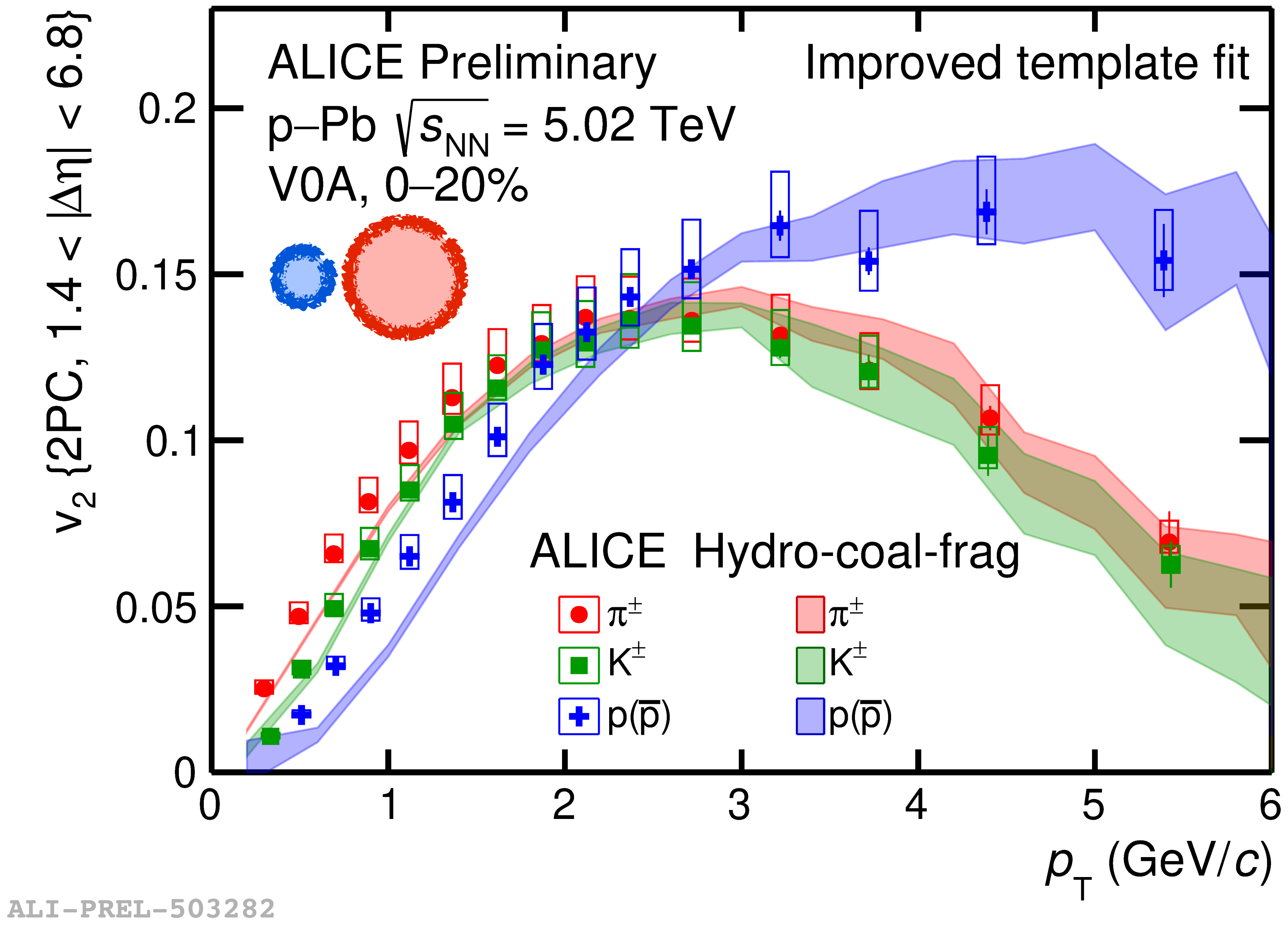


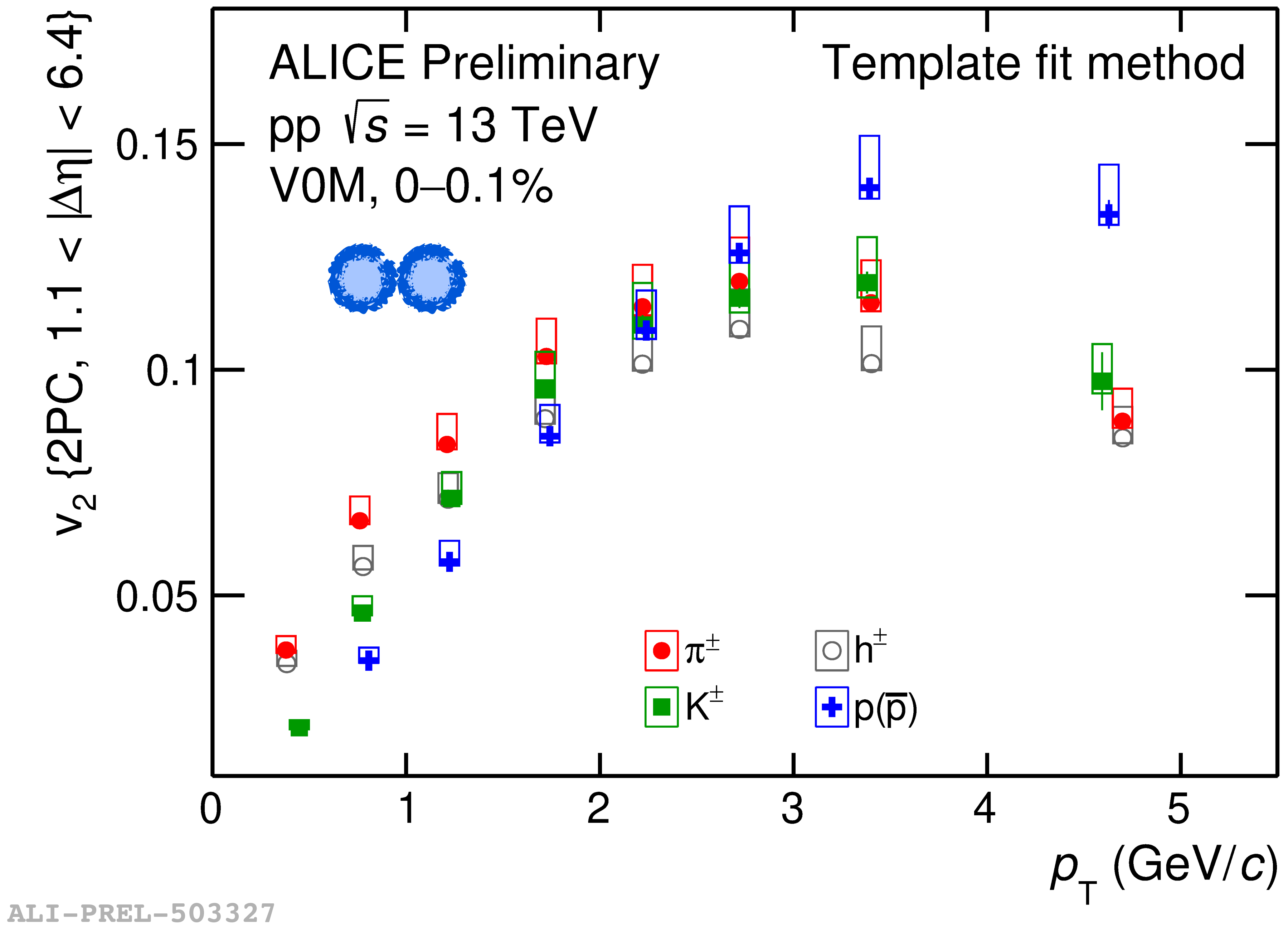
$$Y_{ridge} = \int \Delta\phi$$



- No significant long range correlation is found in e+e- collisions around $\Delta\phi = 0$
- At the LHC we can lower the multiplicity in pp collisions
  - Correlation in pp is larger than that of e+e- at similar multiplicity

Anisotropic flow of identified particle





- ***v_2* > 0 in small systems:**
  low p_T → consistent with mass ordering
  intermediate p_T → particle type grouping

- Described by hydro with quark coalescence and jet fragmentation

$v_2 > 0$ implies some energy loss **yet no jet quenching? → to be solved!**

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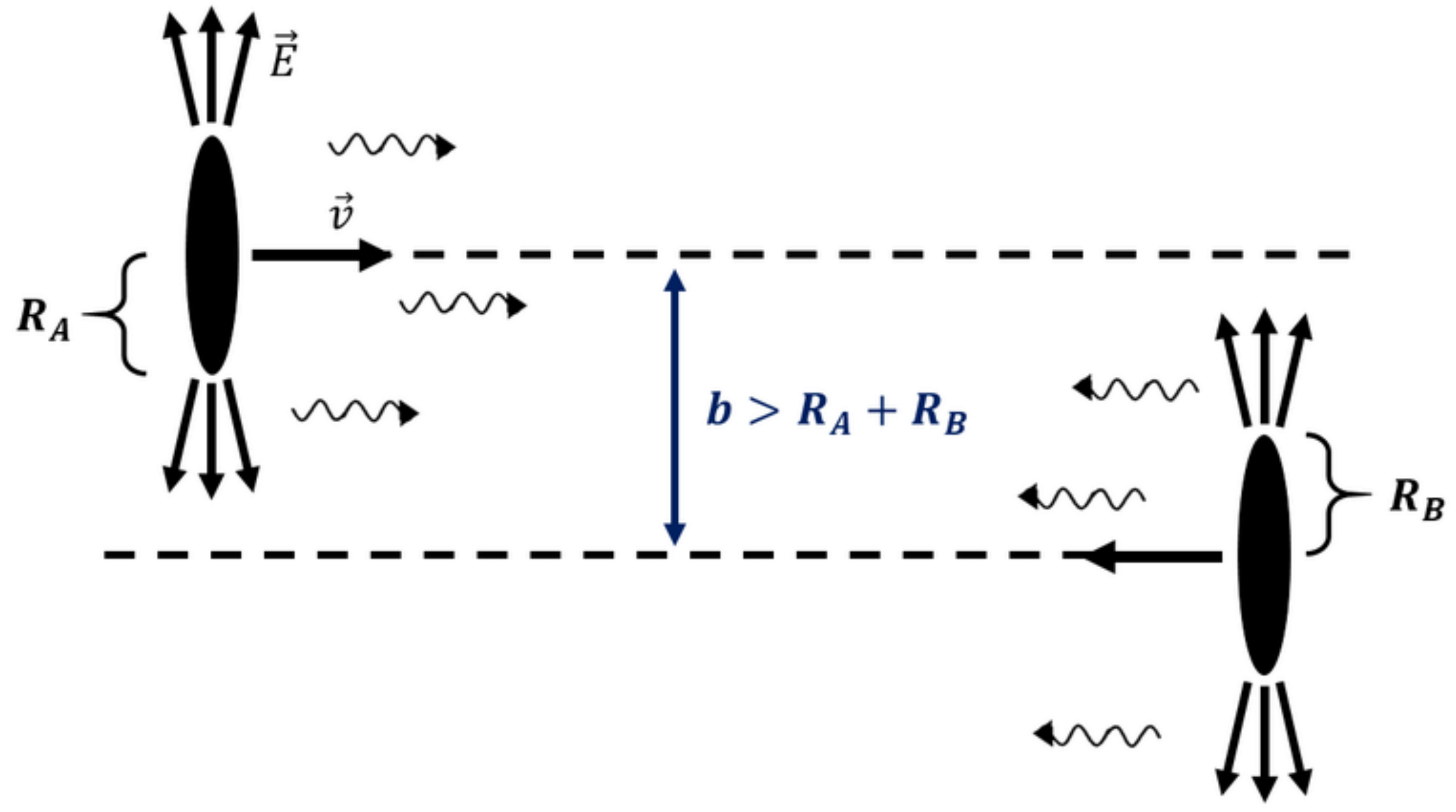
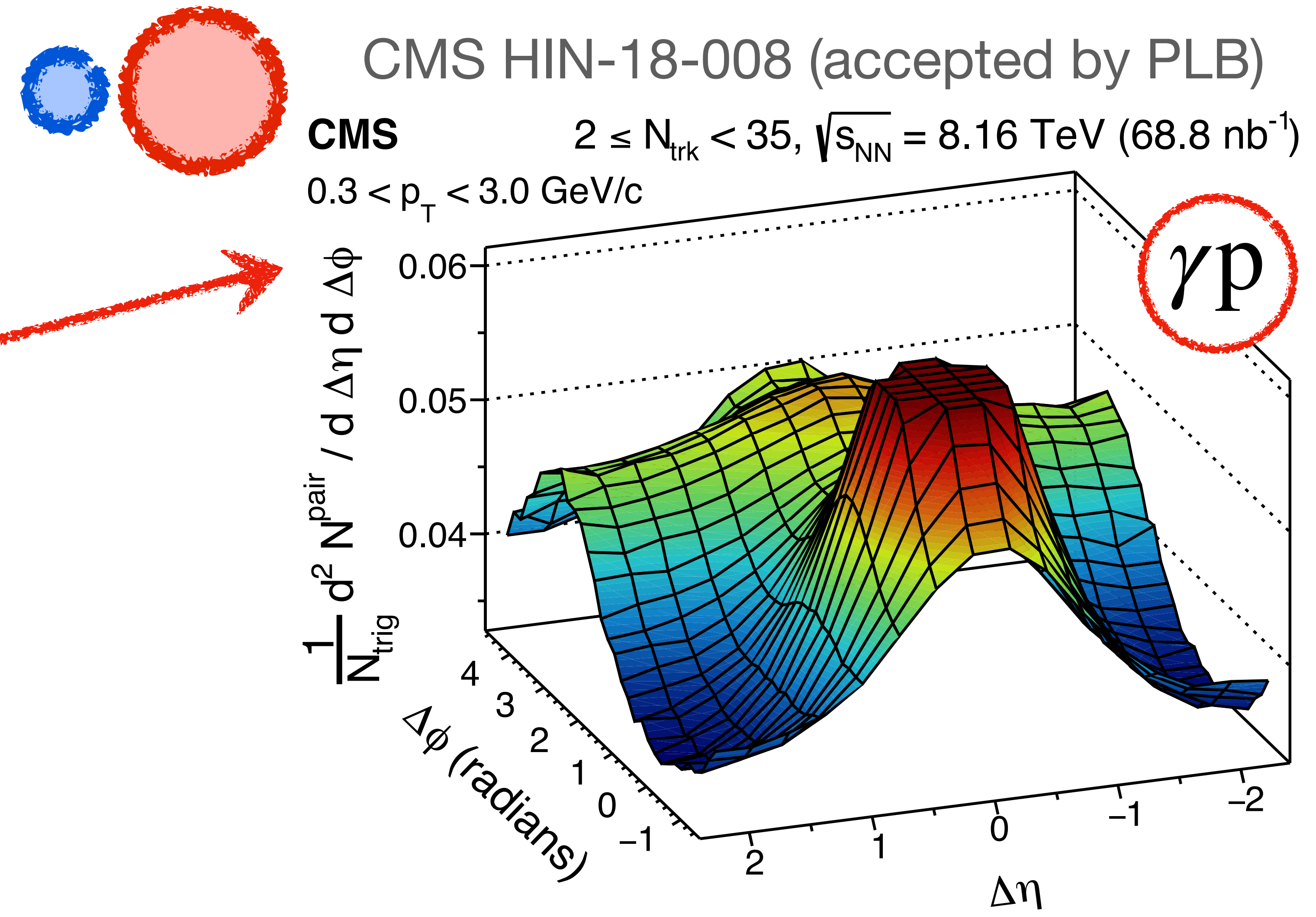
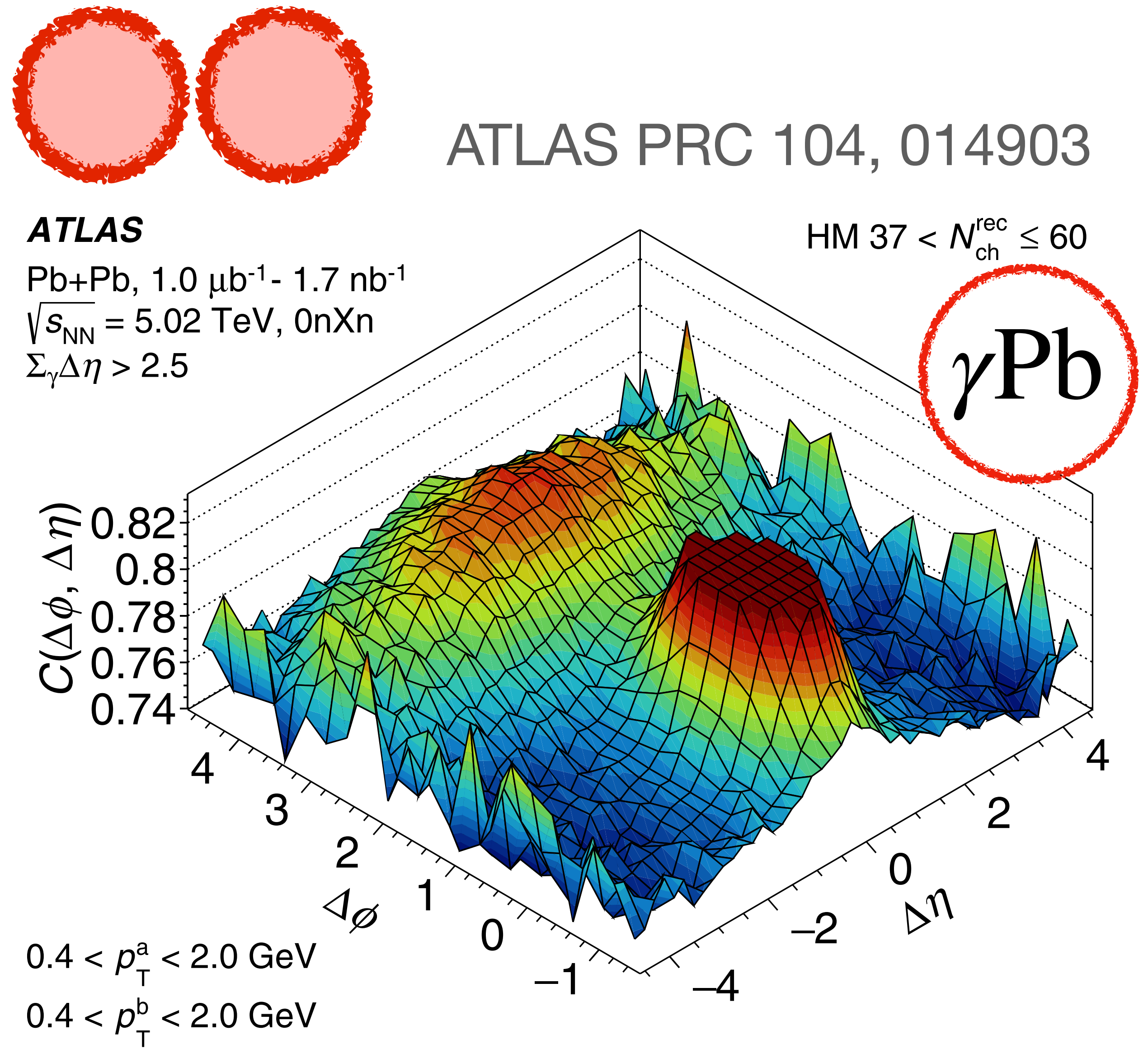
Going smaller at the LHC: UPCs

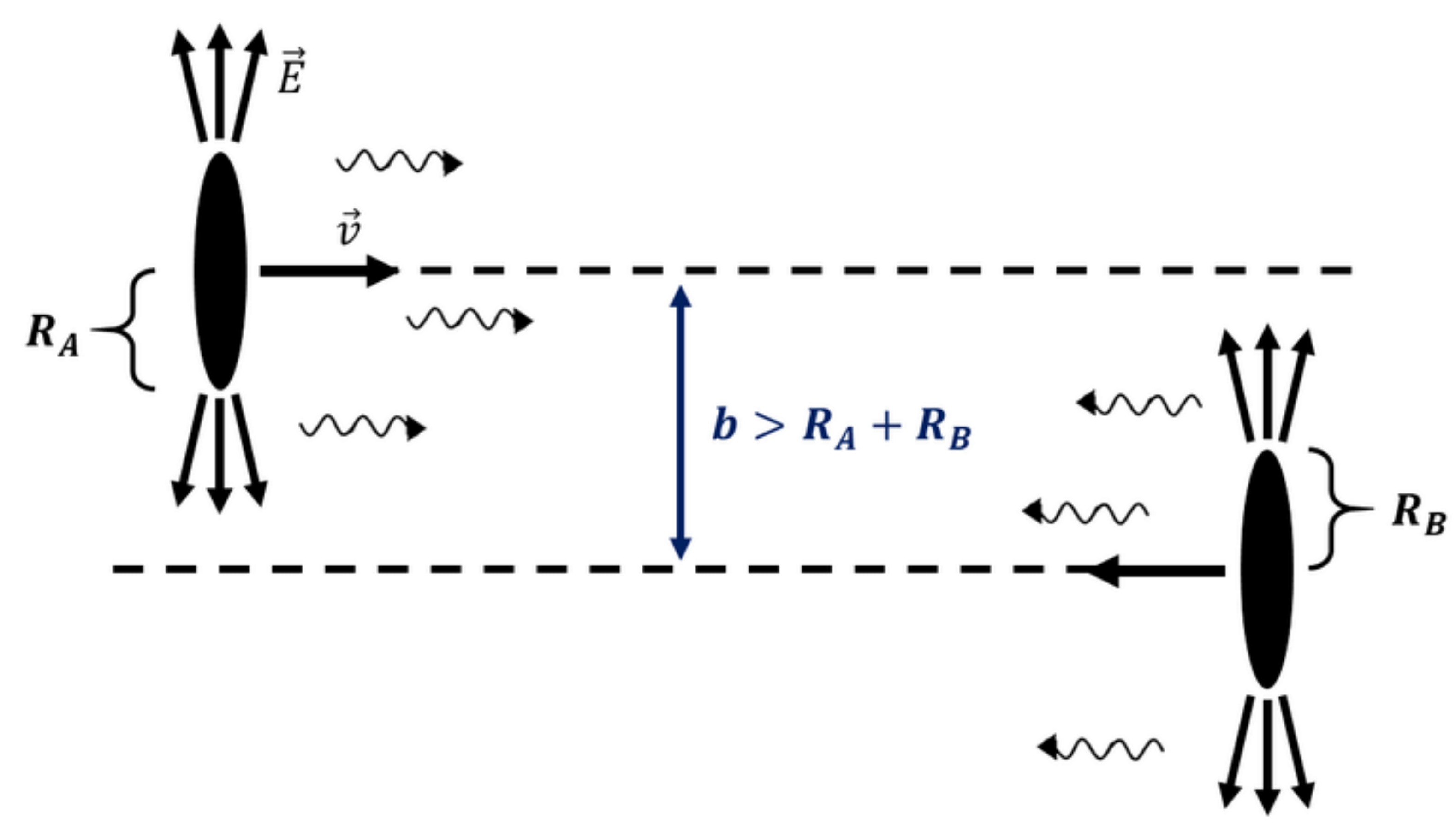


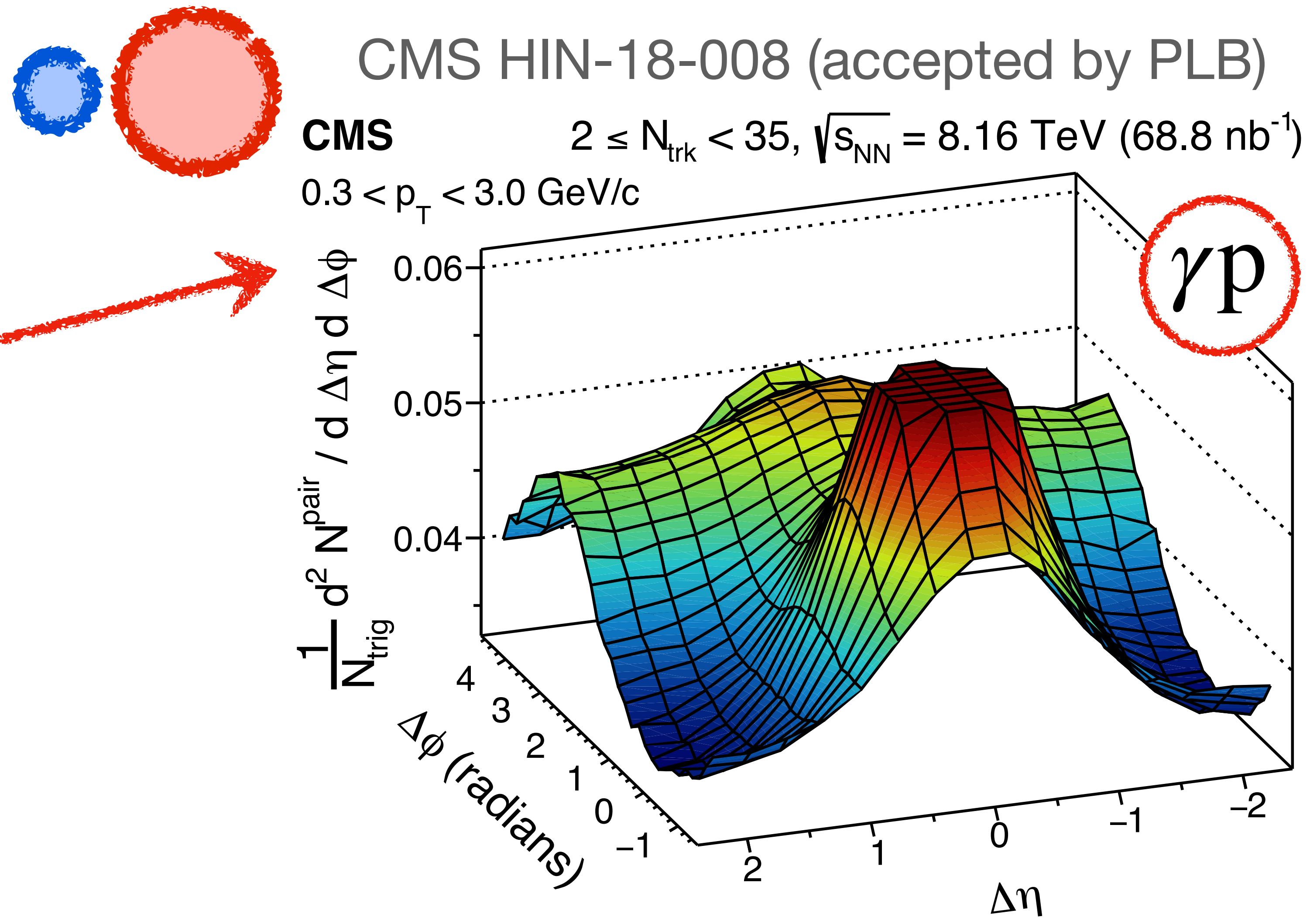


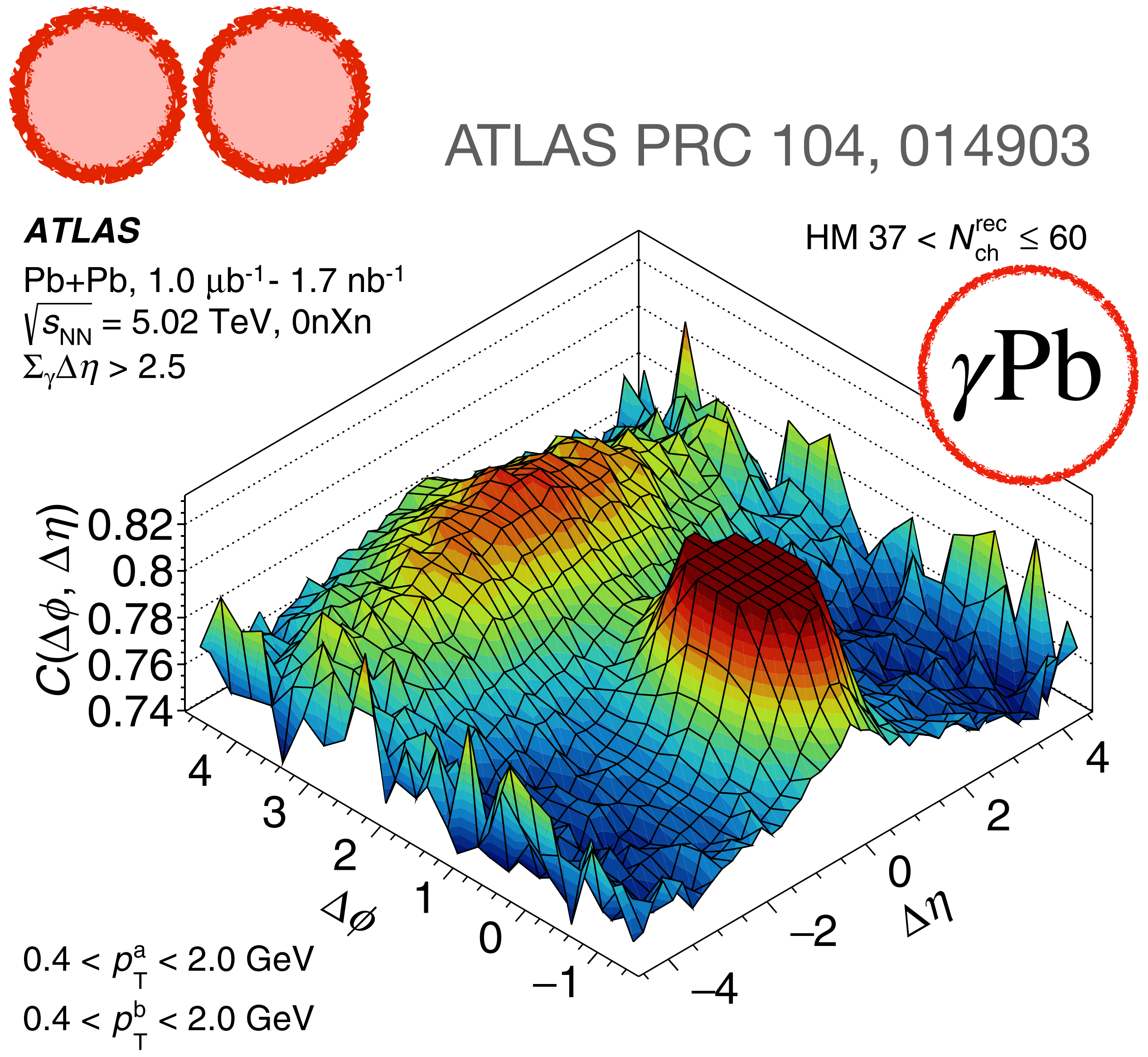


- Coulomb fields of moving charges equivalent to a flux of photons boosted to high energies
  - γ energies of $\sim$ 10s GeV with a 2.5 TeV Pb beam
- High multiplicity events → no clear near side ridge

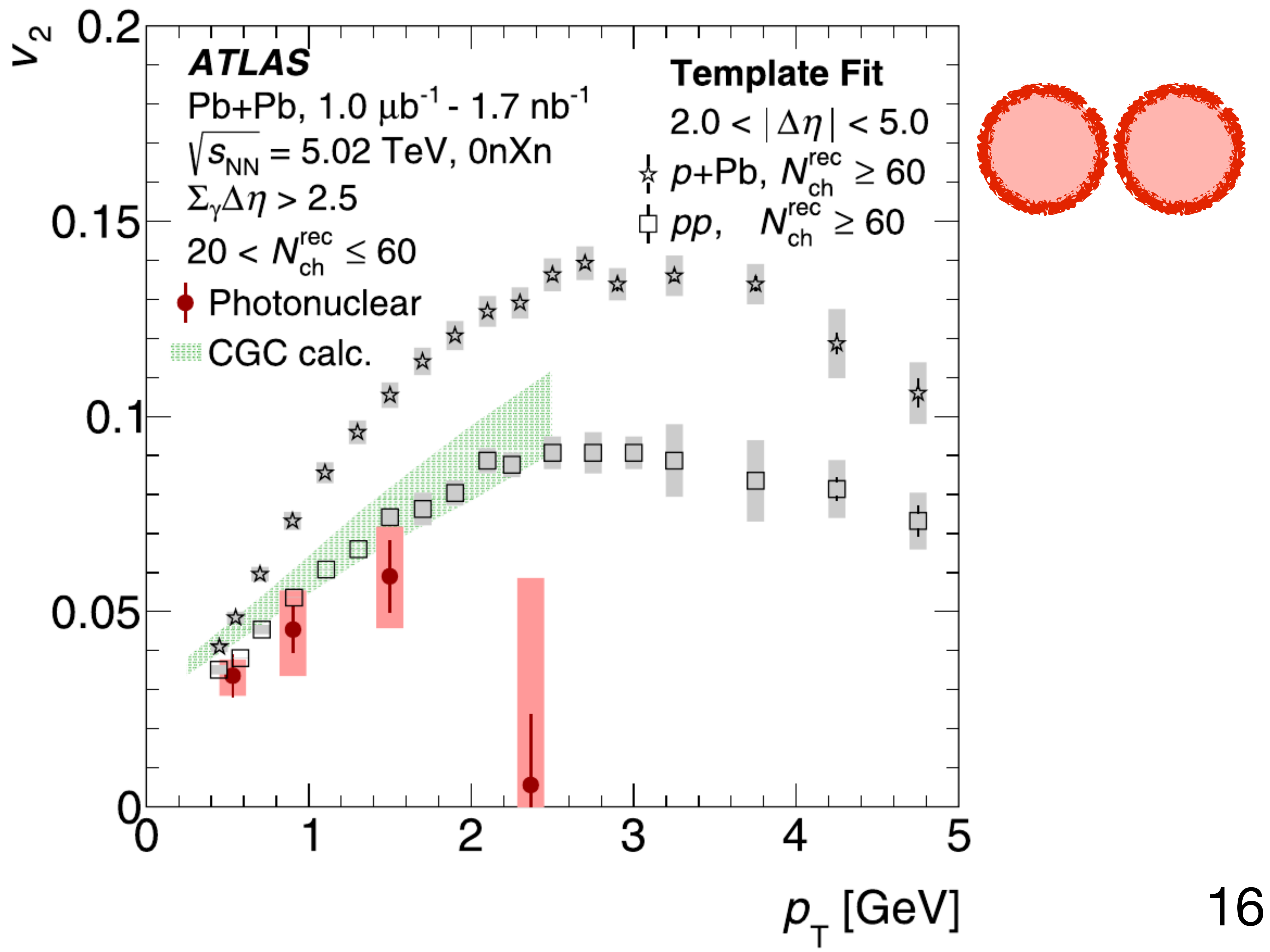
Going smaller at the LHC: UPCs







- Coulomb fields of moving charges equivalent to a flux of photons boosted to high energies
  - γ energies of $\sim$ 10s GeV with a 2.5 TeV Pb beam
- High multiplicity events → no clear near side ridge
- **Non-zero v_2** but lower than hadron-hadron collisions!
- Caveat: v_2 coefficients vulnerable to (residual) non-flow



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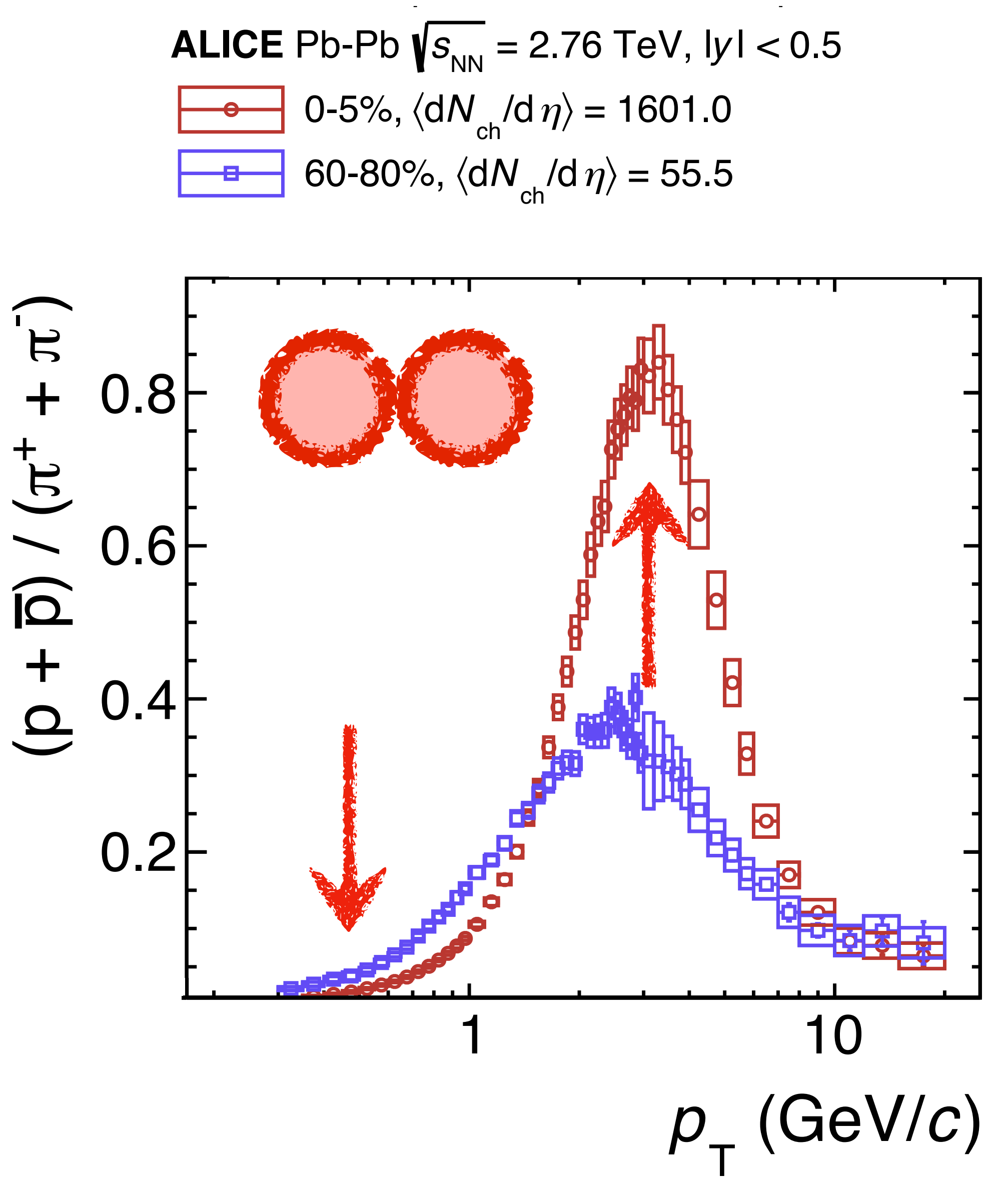
"Baryon-to-meson"



- In Pb-Pb collisions mass-dependent hardening of the spectra

  low-p_T depletion

  intermediate-p_T enhancement

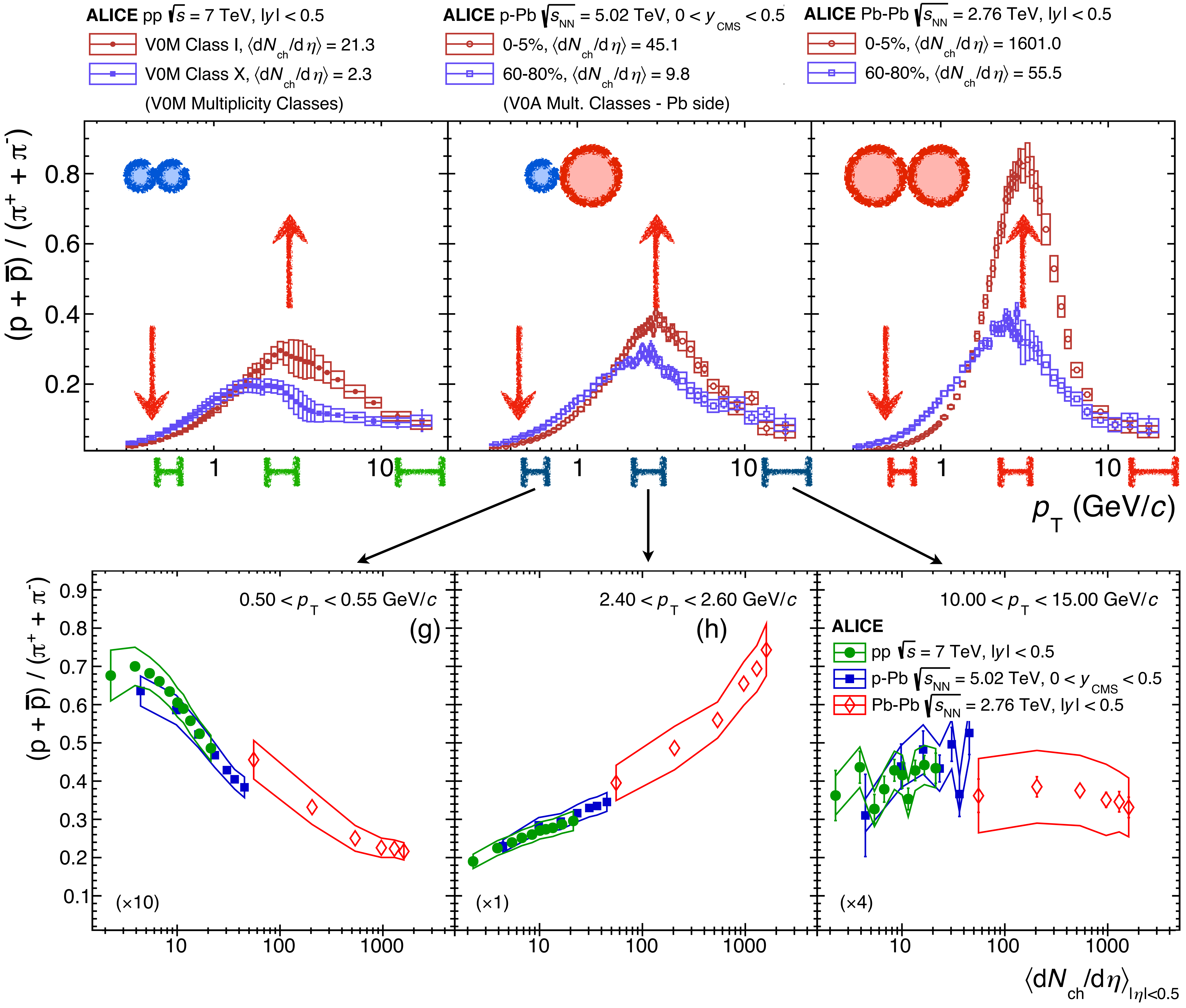
- protons are shifted towards higher momenta

  → interpreted as radial flow

  common velocity field ($p = m\gamma\beta$)

ALICE, PRC 99 (2019) 024906

"Baryon-to-meson"



- In Pb-Pb collisions mass-dependent hardening of the spectra

  low-p_T depletion

  intermediate-p_T enhancement

- protons are shifted towards higher momenta

  → interpreted as radial flow

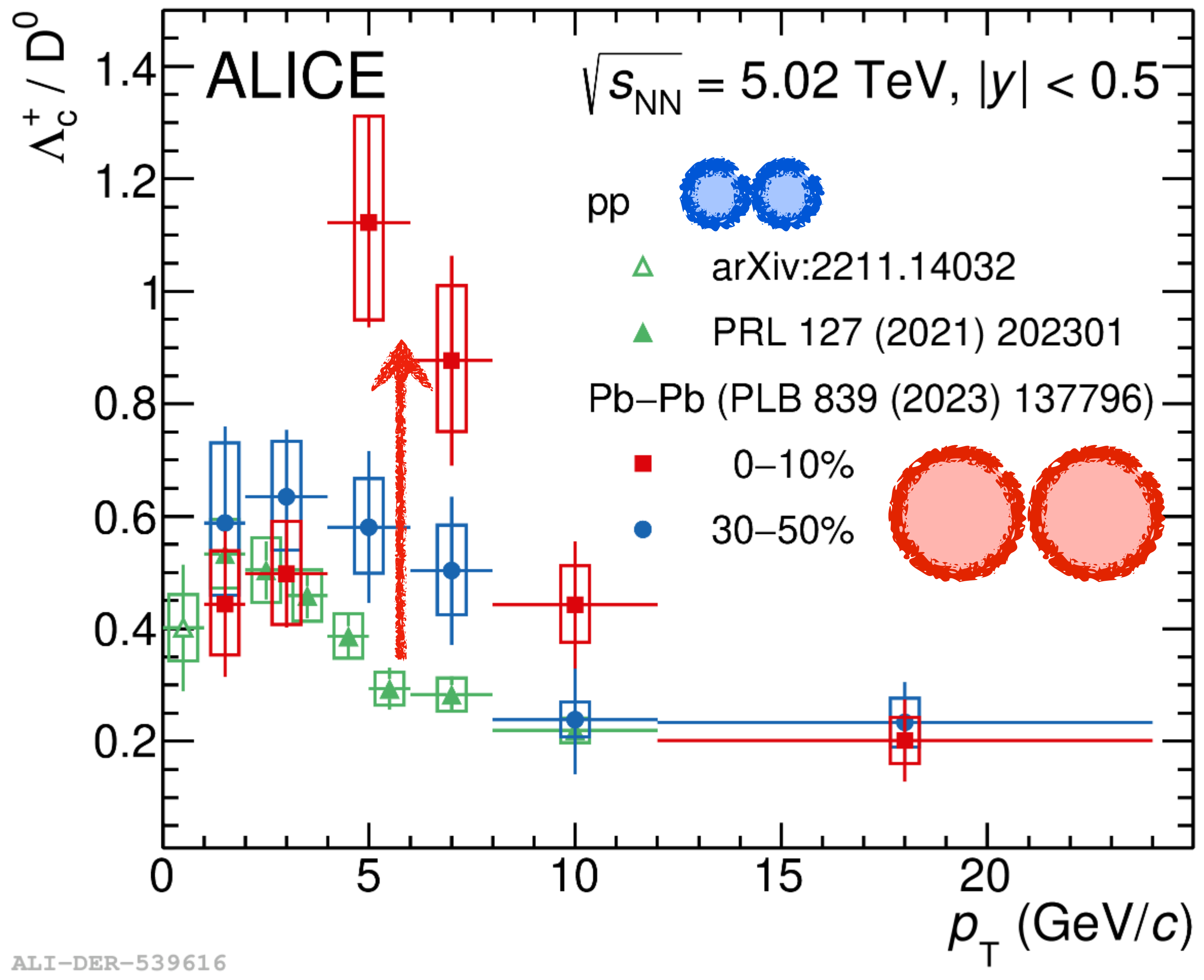
  common velocity field (p=m$\gamma\beta$)

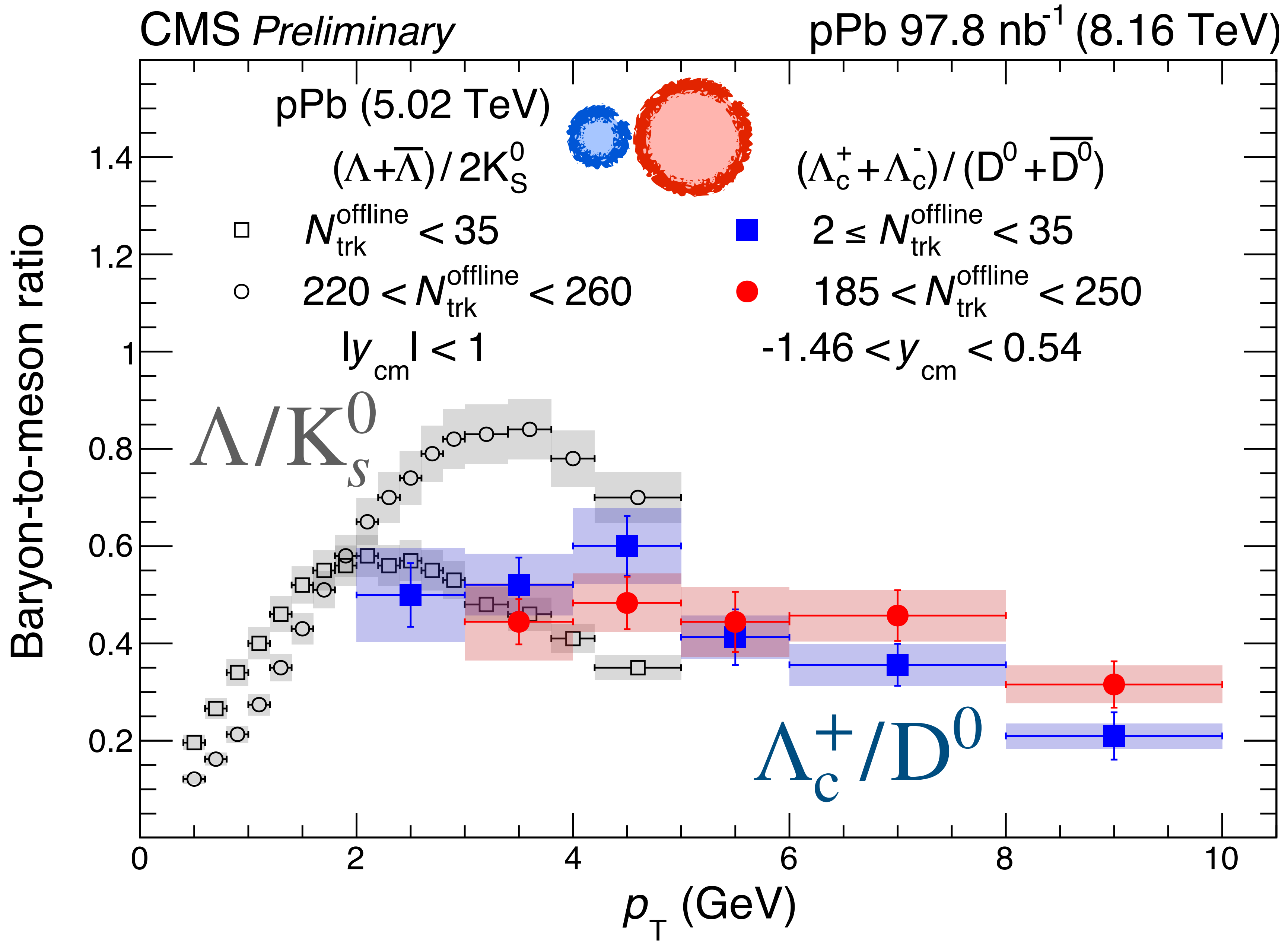
- Remarkable consistency across systems as a function of multiplicity
- high-p_T : recovery of universal behavior?

ALICE, PRC 99 (2019) 024906

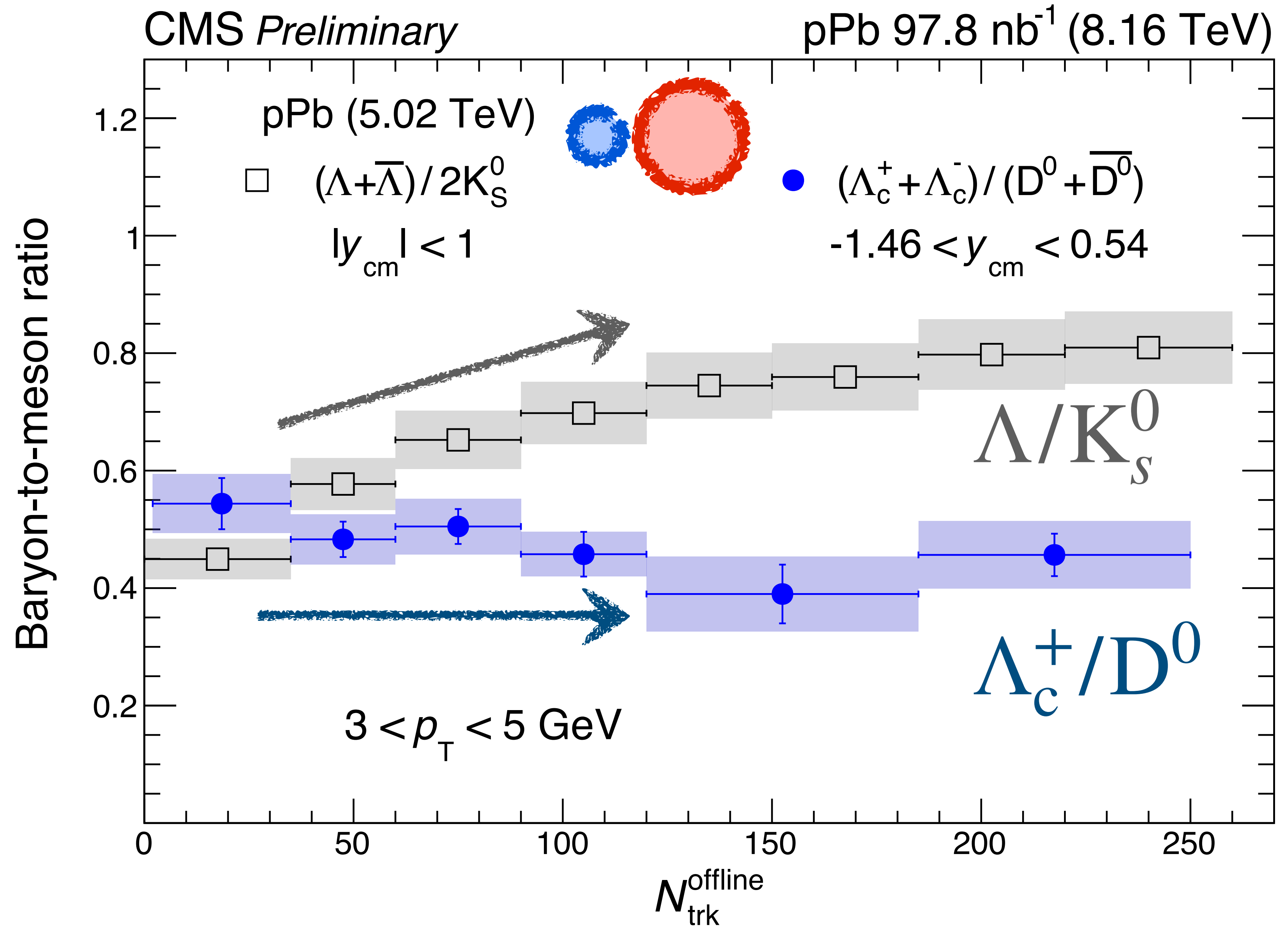
"Baryon-to-meson" ratio with HF probes

PLB 839 (2023) 13779





CMS-PAS-HIN-21-016

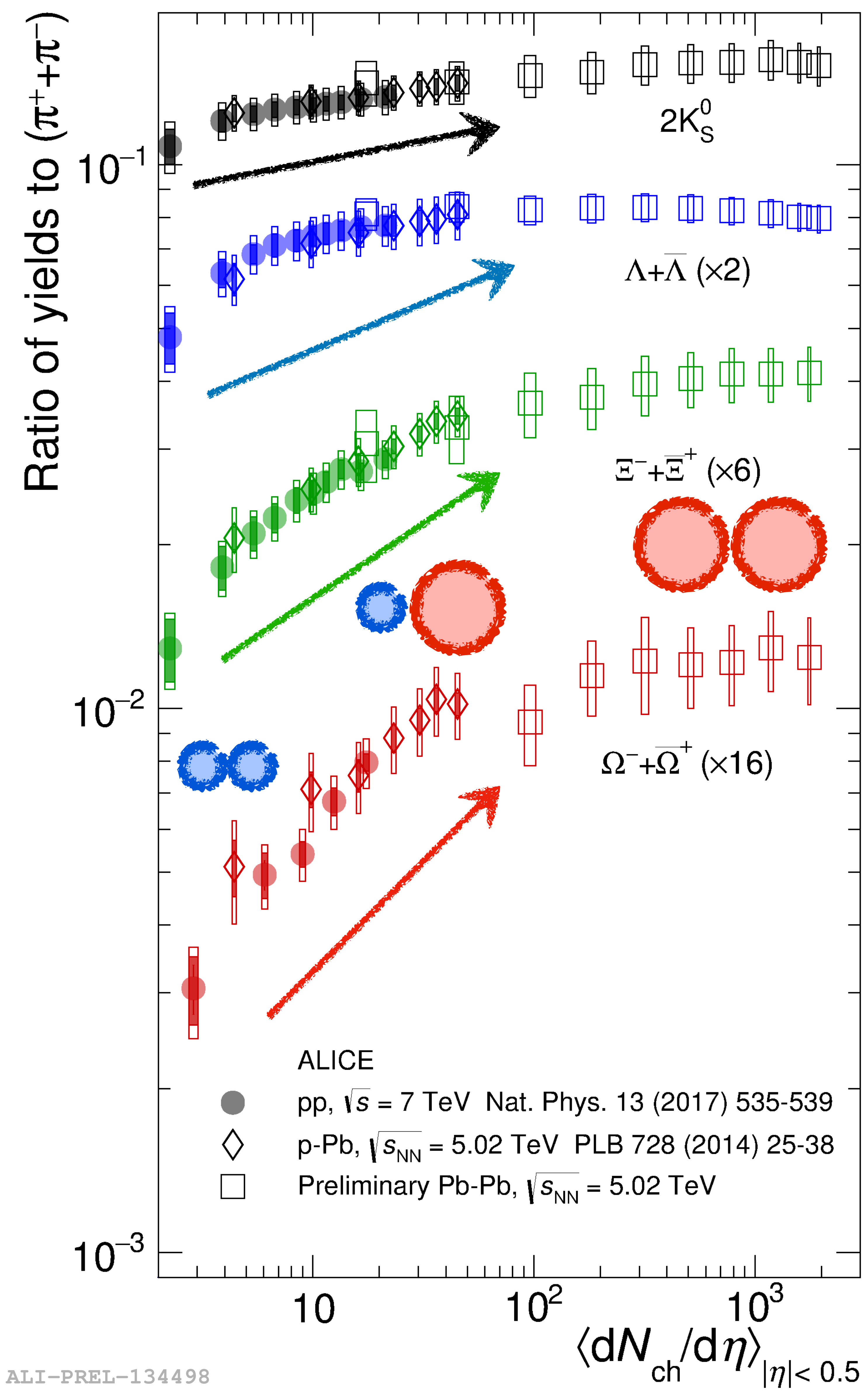


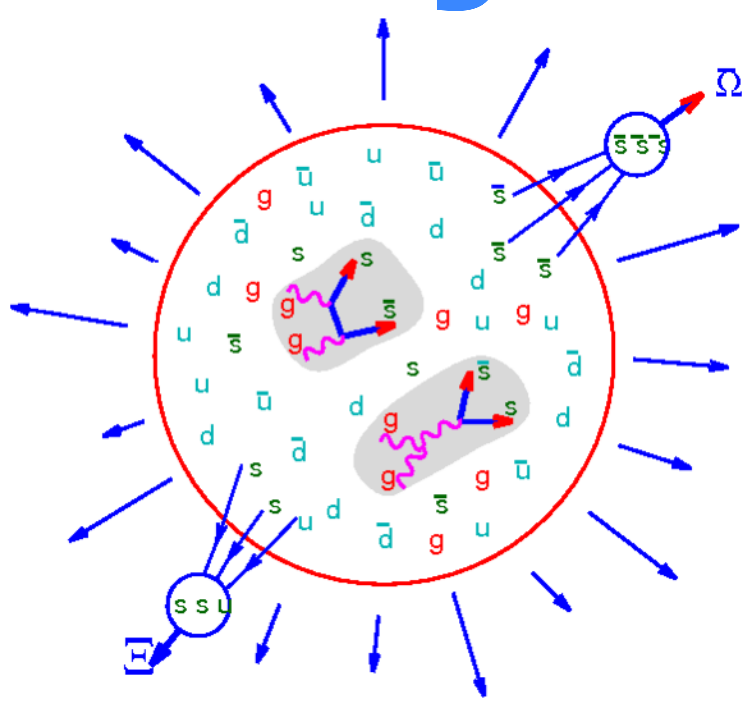
- Λ_c^+/D^0 **enhanced at intermediate p_T in central Pb-Pb collisions**
  (also measured up to high p_T CMS-PAS-HIN-21-004)

- Λ_c^+/D^0 **in p—Pb does not depend on the final-state multiplicity**
  → similar values observed in peripheral Pb-Pb collisions (LHCb-PAPER-2021-046)

  - Comparison to Λ/K_s^0 might indicate coalescence of heavy quarks saturates earlier than for light quarks in small systems

Strangeness enhancement in small systems





- One of the original traces of the QGP
  → thermal production via gluon fusion
- Enhanced production of strange hadrons wrt π
  → increasing with multiplicity
- Hierarchy with strangeness content: K^0_S < Λ(1s) < Ξ (2s) < Ω (3s)
- Strangeness increases with multiplicity following a universal trend

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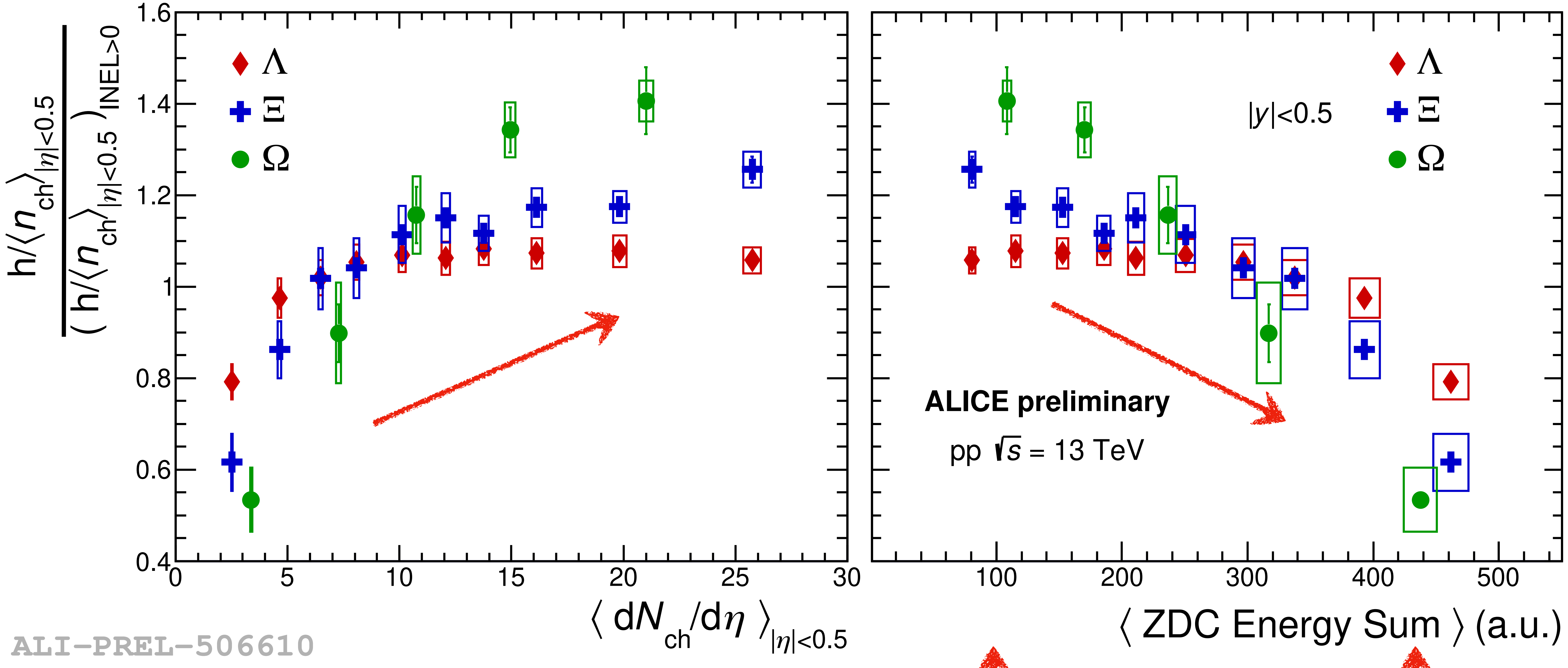
Strangeness enhancement: more differential

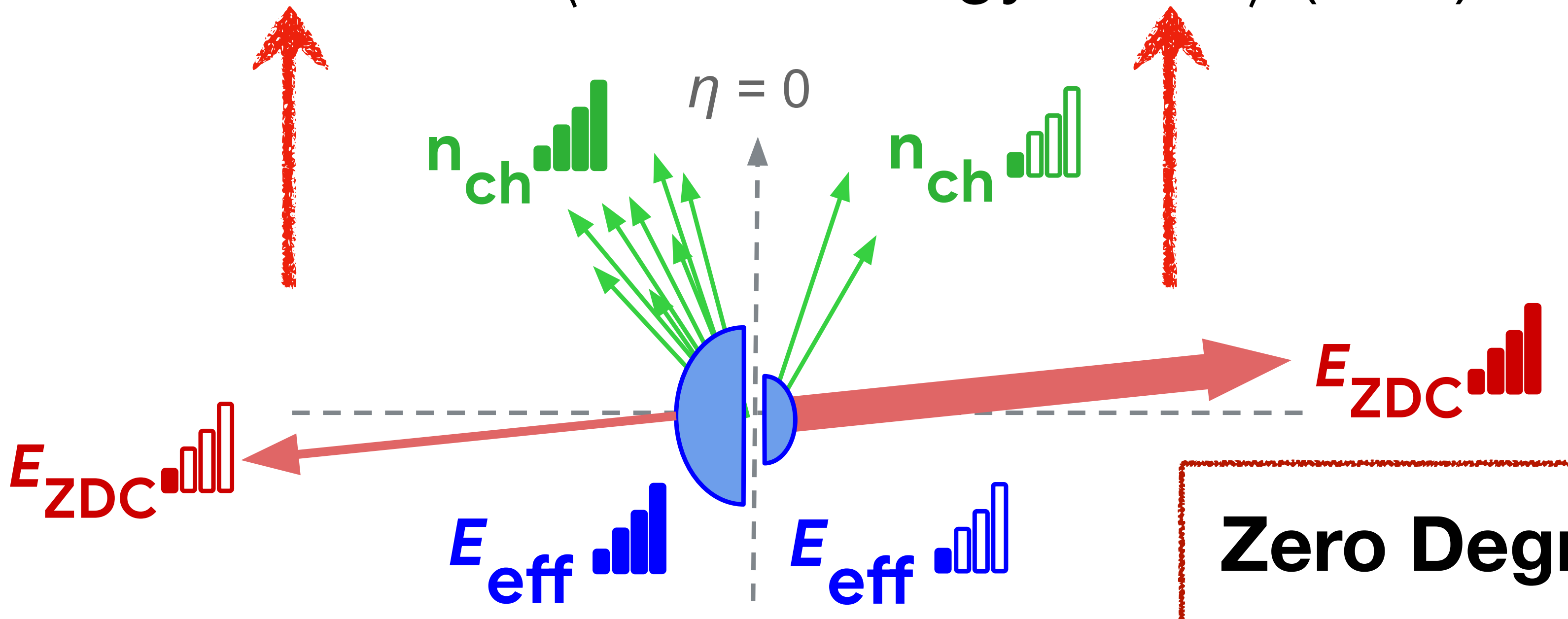
Relative strangeness production:

Increases with multiplicity at midrapidity



Decreases with forward energy

- Same hierarchy with strangeness content observe vs multiplicity and forward energy!
- Can we disentangle the effects?



Zero Degree Calorimeter (ZDC)
Forward calorimeters counting collision remnants

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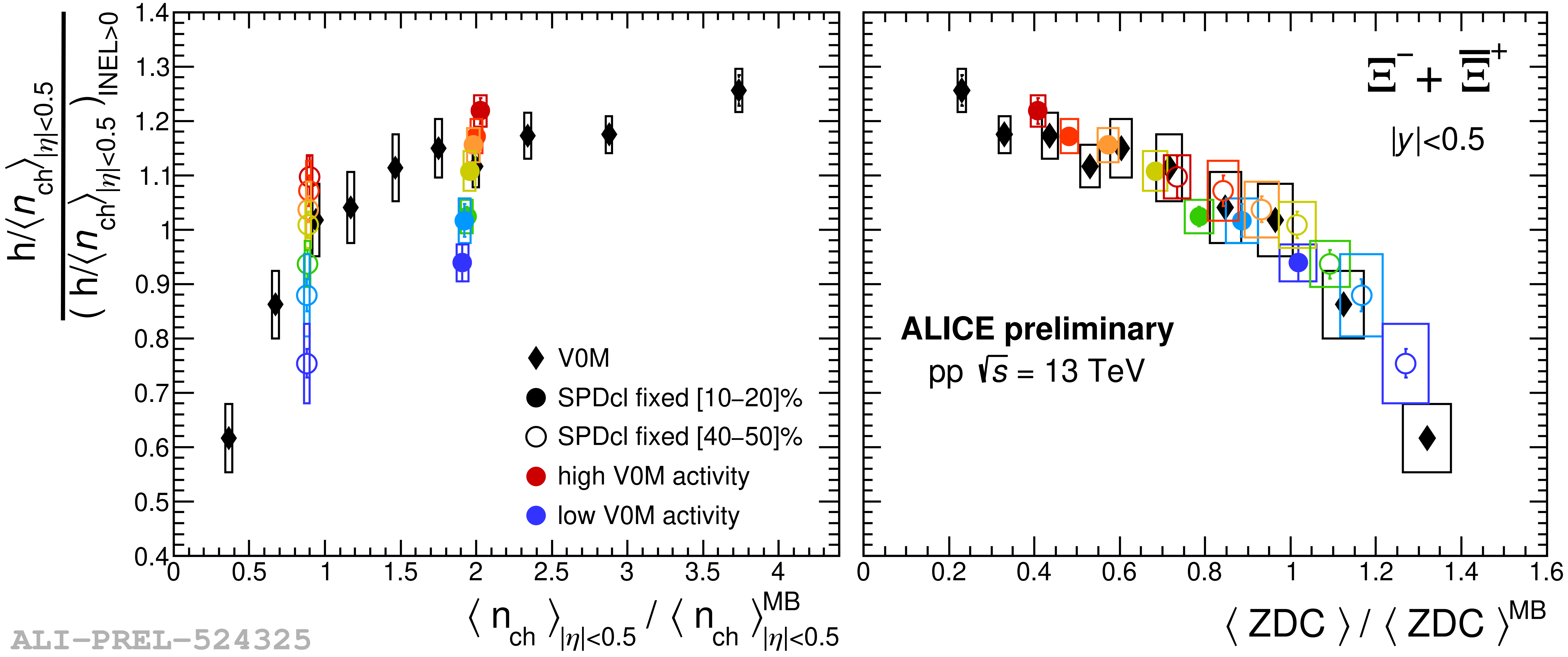
Strangeness enhancement: more differential

At fixed multiplicity:

Relative Ξ yield increase with forward activity



At fixed multiplicity:

Relative Ξ yield increase with decreasing energy

- Increase in the average fraction of strange hadrons with increasing multiplicity and decreasing ZDC energy

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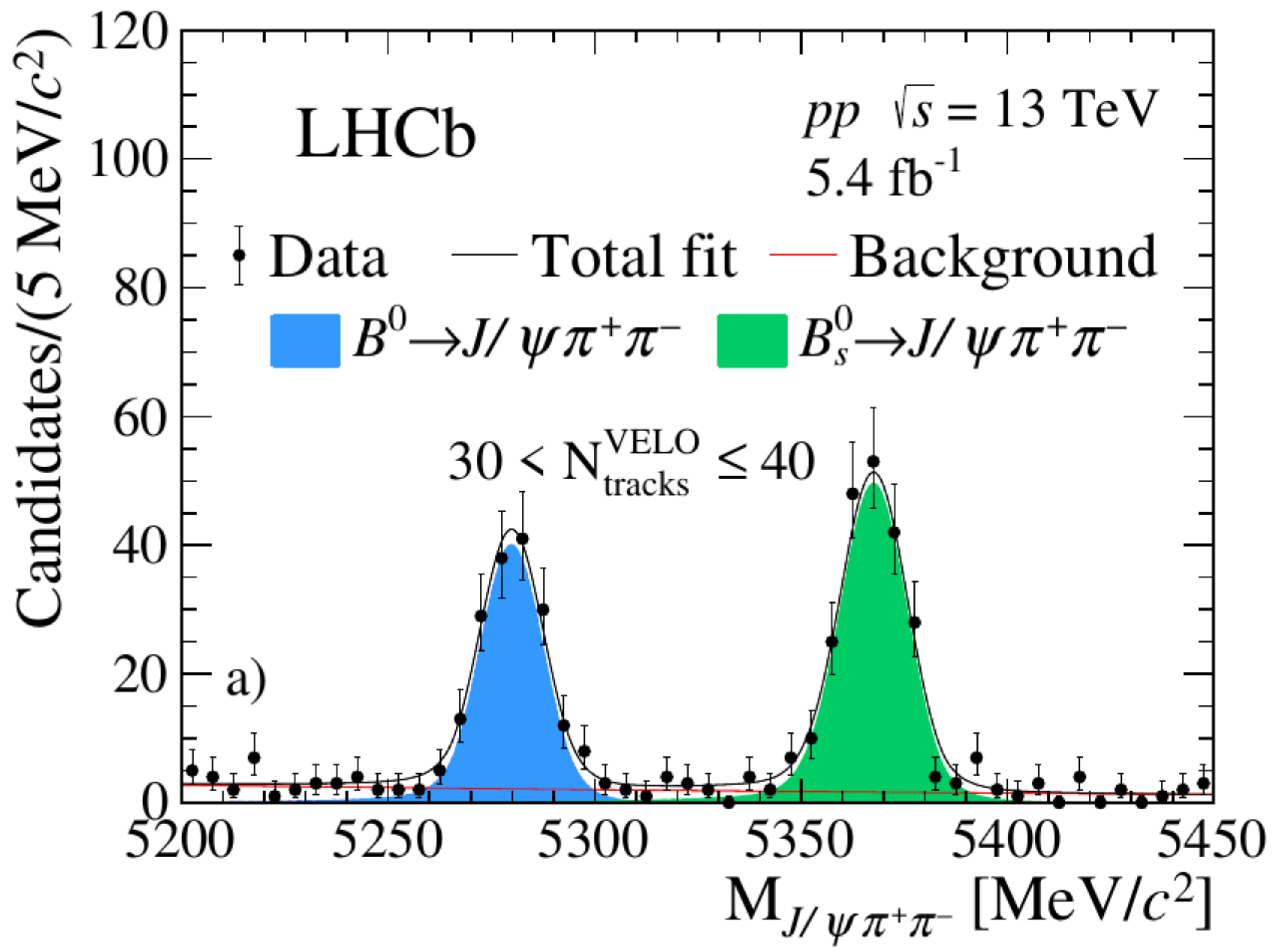
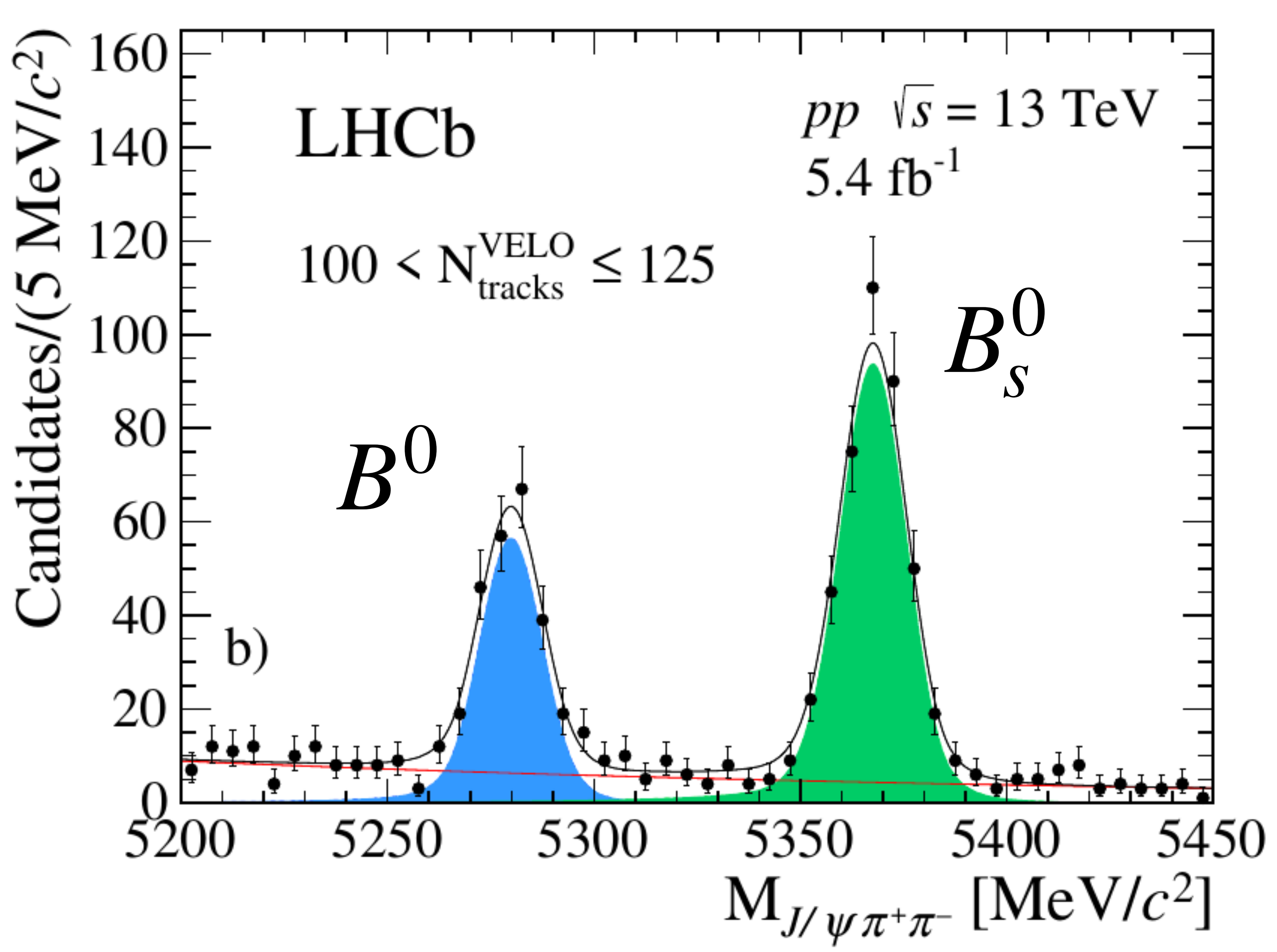
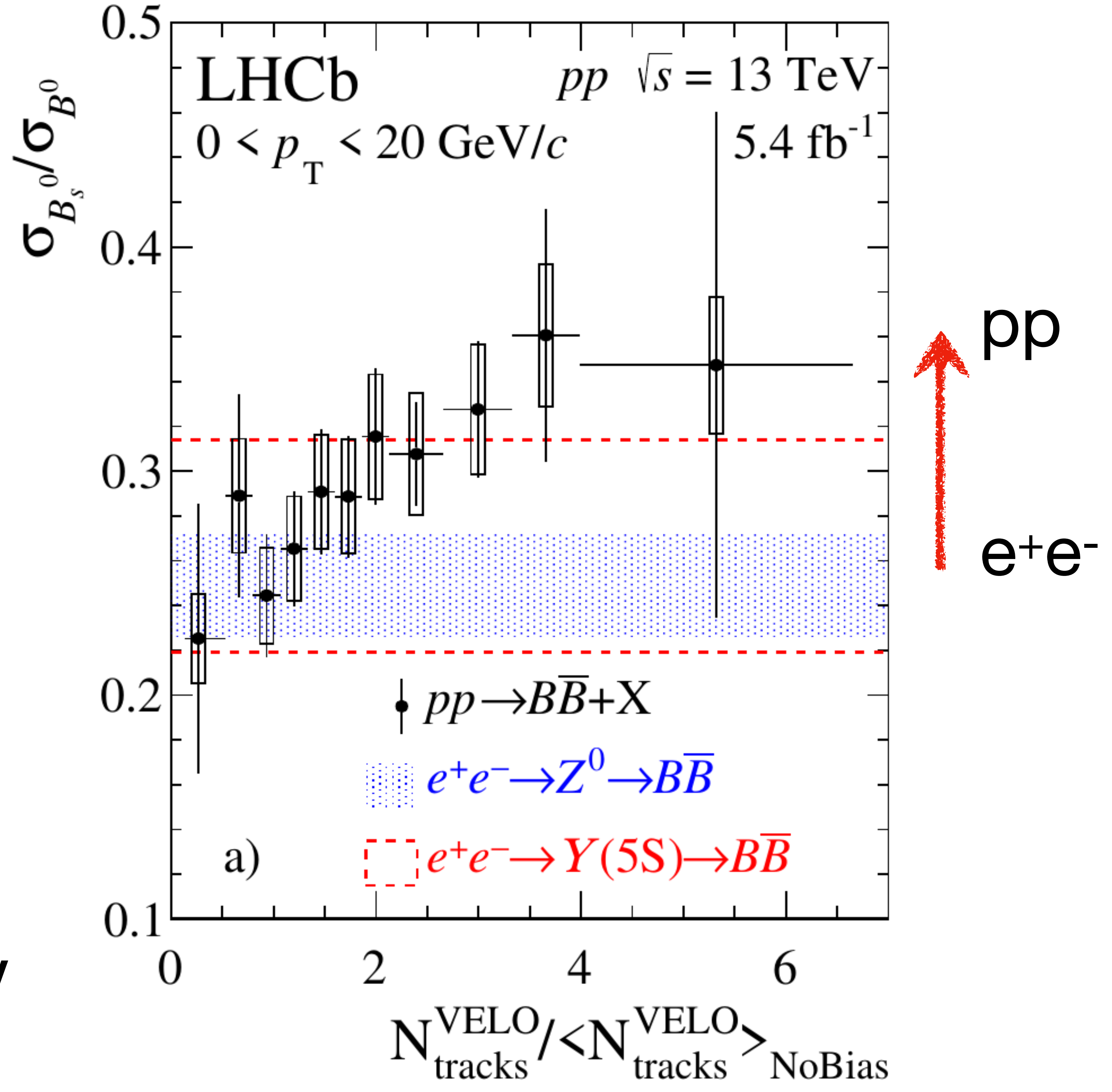
Strangeness enhancement with beauty?





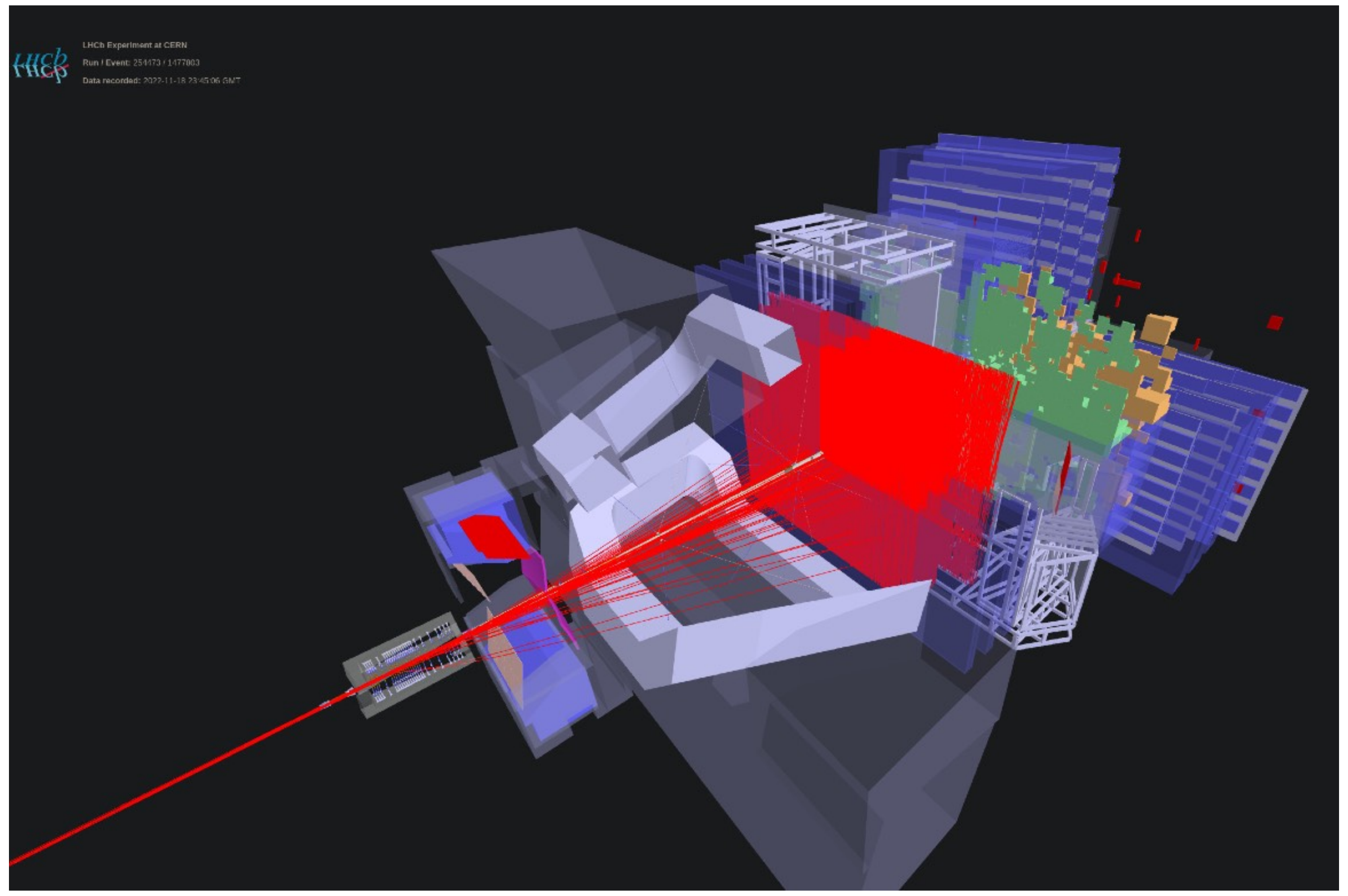
LHCb-PAPER-2022-001

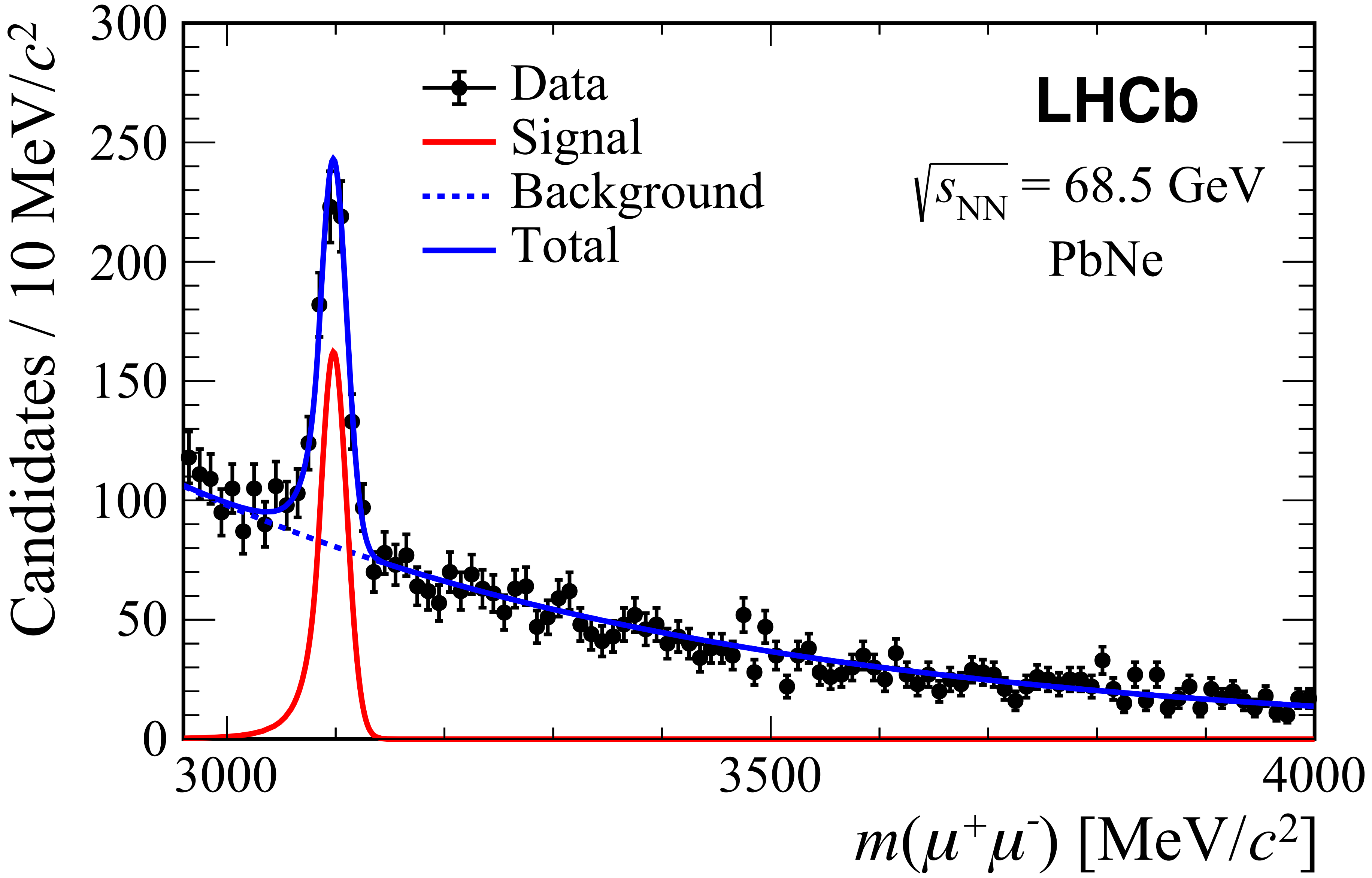


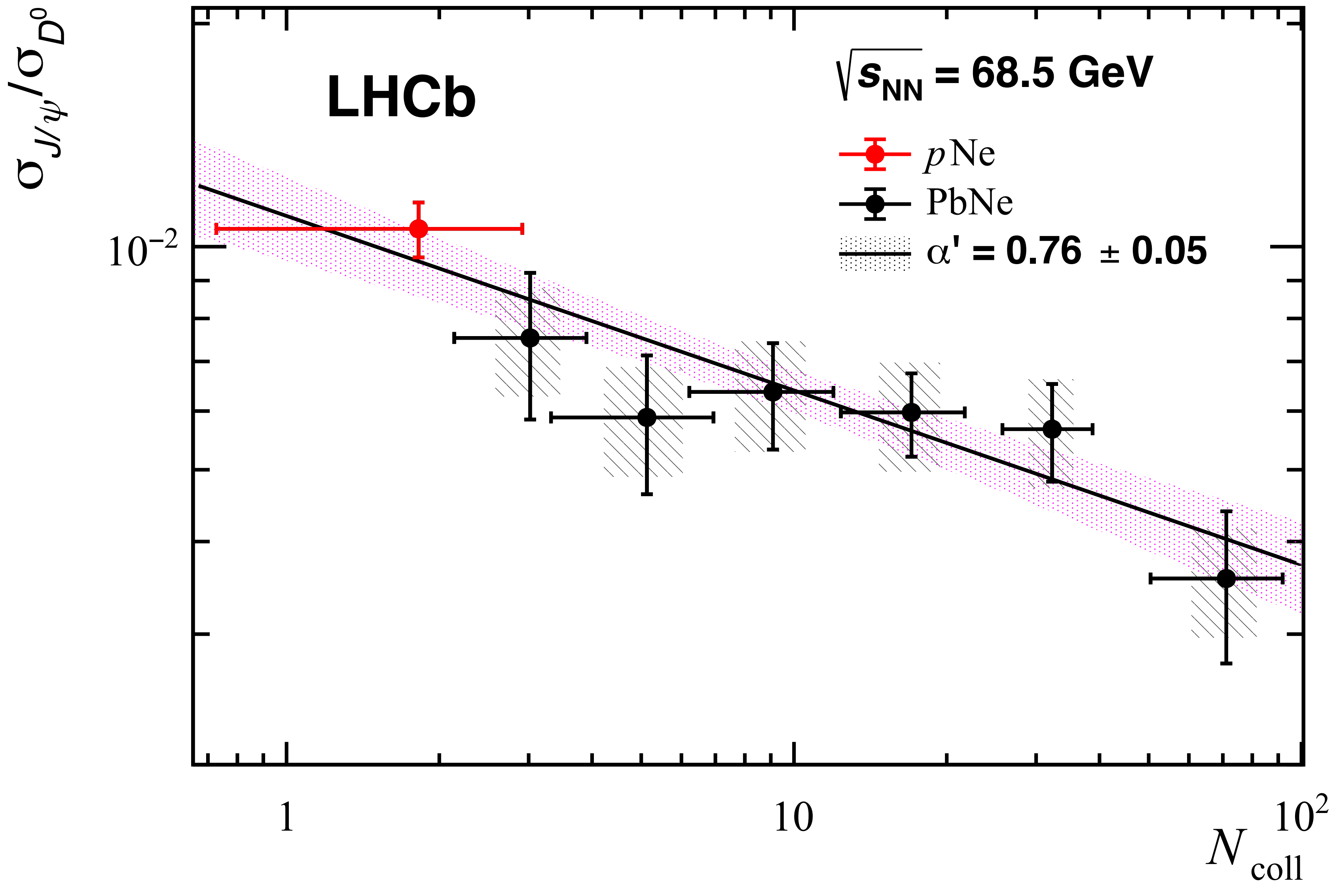
- Measurement of B_s^0 and B^0 at forward rapidity (2 < y < 5) in pp at 13 TeV
- **Significant increase in B_s^0/B_s^0 with multiplicity** when measured in the same rapidity range
- $b\bar{b}$ pair production at hadron colliders dominated by hard parton-parton interactions → set in the initial stages
- Possibly due to quark coalescence → enhanced B_s^0/B_s^0 ratio with increasing particle multiplicity

Smaller systems with fixed target

LHCB-PAPER-2022-011







- SMOG → unique opportunity to access pA and AA collisions with smaller nuclei at the LHC
- J/ψ showing no discontinuity from p—Ne to central Pb—Ne
- More data and more collision systems required to complete the picture
  - SMOG2 will be taking data in Run 3 → more nuclei, x1000 increase in luminosity

	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	~ 100 nb^{-1}	100 pb^{-1}
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
ψ(2S) yield	150	400k
Υ(1S) yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9$ GeV/c^2) Drell-Yan yield	5	20k

Z. Citron et al.
CERN-LPCC-2018-07

Conclusions

Small systems exhibit features typical of AA collisions

- Soft boundaries between small and large systems

Dynamics

- Correlations in the smallest systems (γp, γPb) show no long range effect but overall positive flow
- Precision measurements of identified hadron flow show mass effect in small systems
- Baryon-over-meson ratio showing universal evolution among systems in the LF sector

Hadrochemistry

- Strangeness enhancement observed in small systems with light and heavy flavors
- More differential measurements of the initial state effects on strangeness

Pushing the limits to understand small systems

Future data will help us in understanding $\rightarrow$ going smaller, more differential, larger

Crucial role of the LS2 upgraded detectors