Density dependent QCD effects in pp collisions

Unexpected Revelations and Valuable Insights at LHC energies

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Heavy Ion Physics and QGP

pp from the HI perspective

pp properties from an
intuitive pQCD perspective

collectivity in pp

challenges for yield measurements
enhancement patterns

insights for centrality selection
in p-Pb and Pb-Pb

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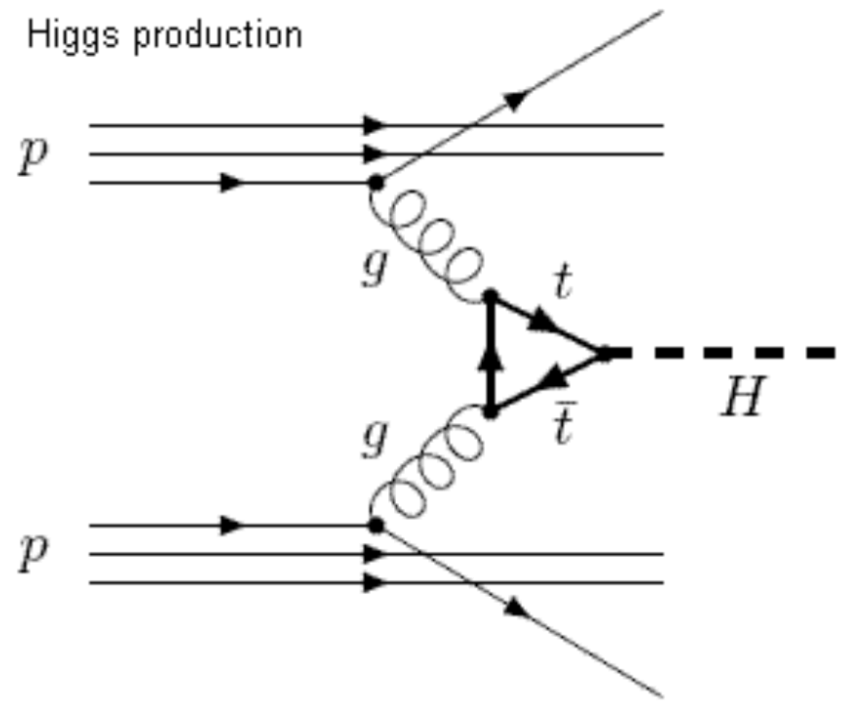
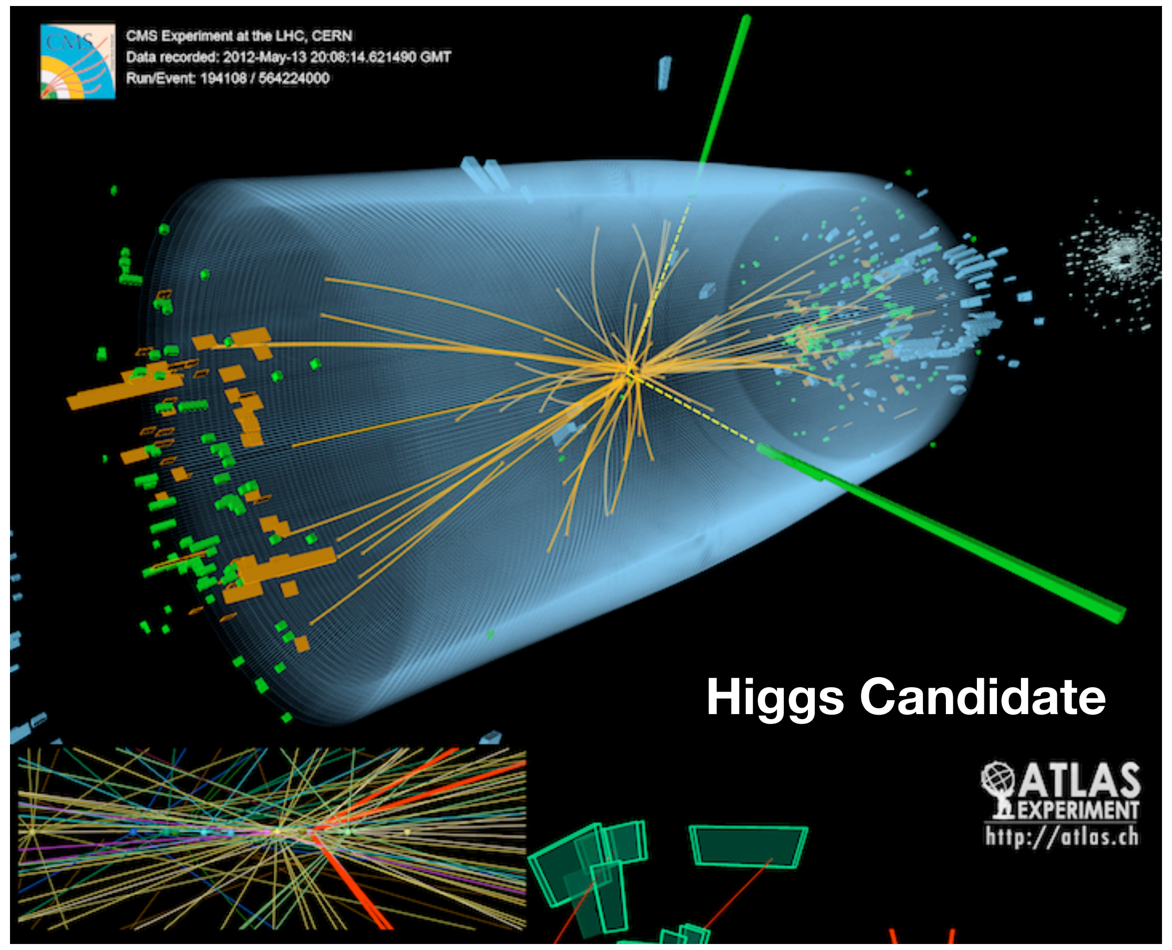
What is the nature of the Universe? What is it made of?

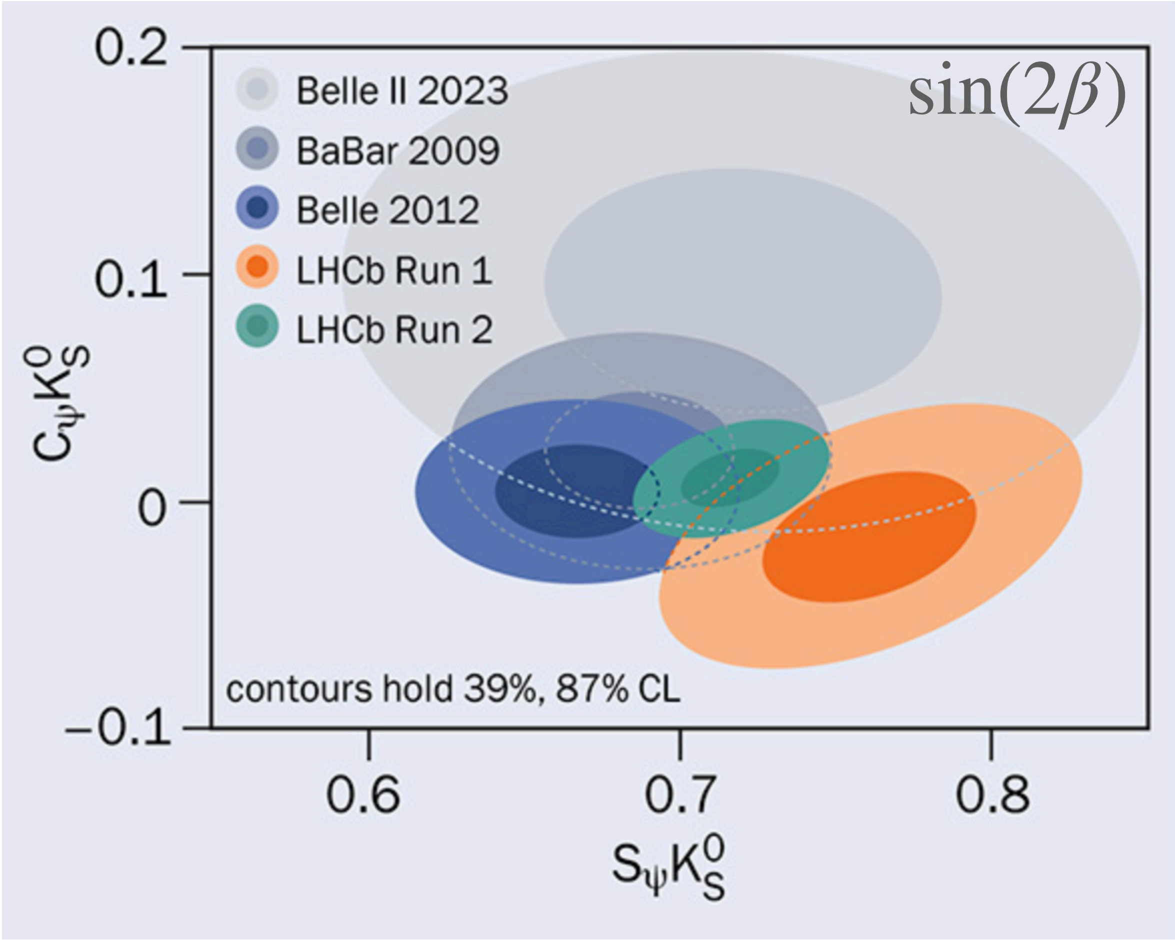
LHC



Exploratory: Particle Searches

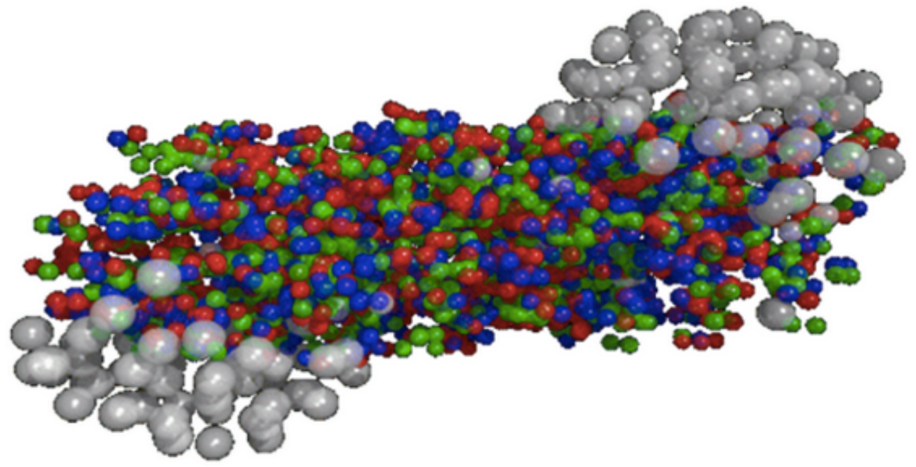


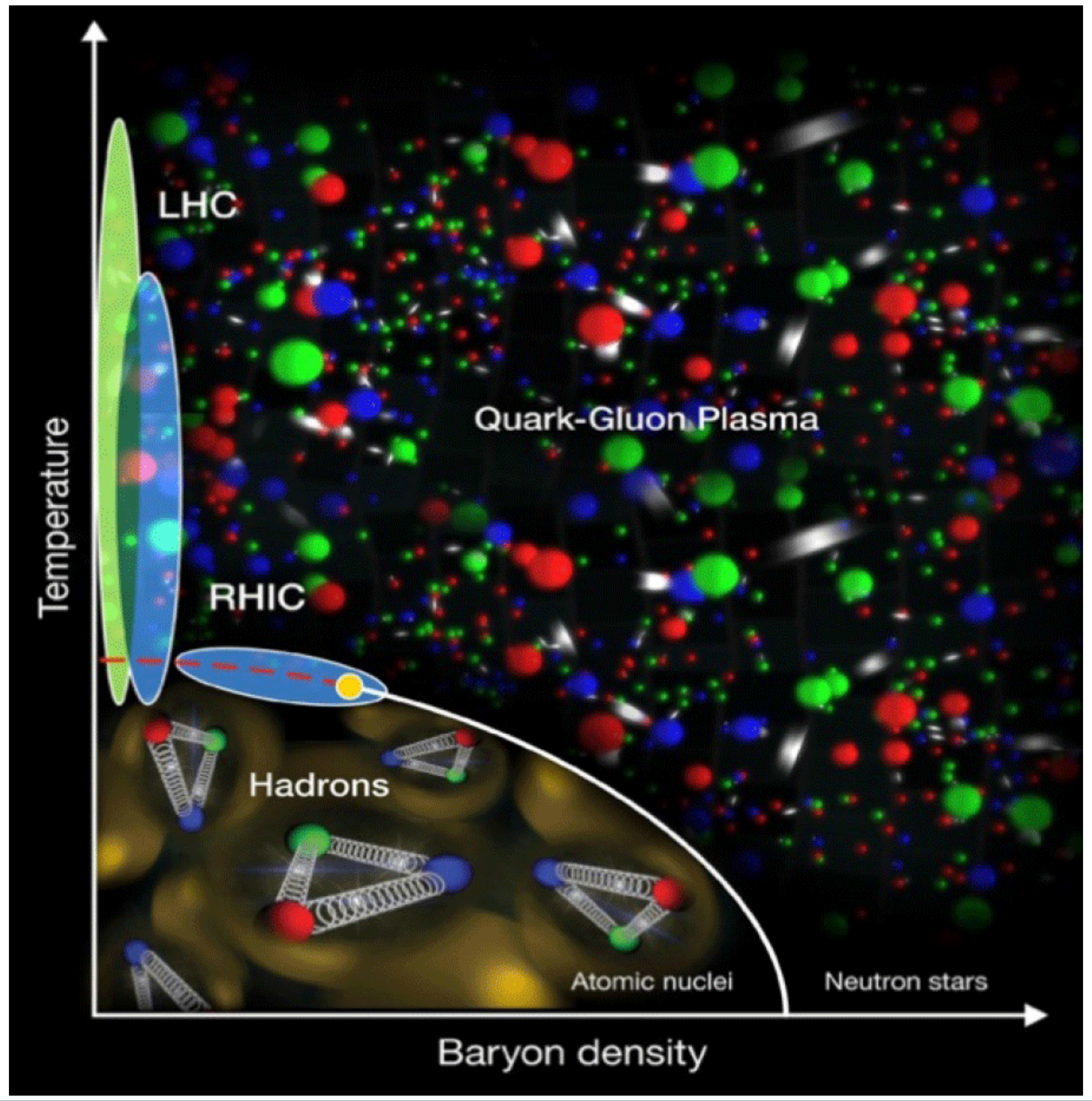
Precision Measurements ("b-factory")



Our quest is not complete without …

… Study **matter** under extreme conditions (T, ρ) with ultra-relativistic heavy ion collisions





Quantum Chromo Dynamics (QCD) predicts phase transition to Quark Gluon Plasma (QGP)

Matter under extreme conditions

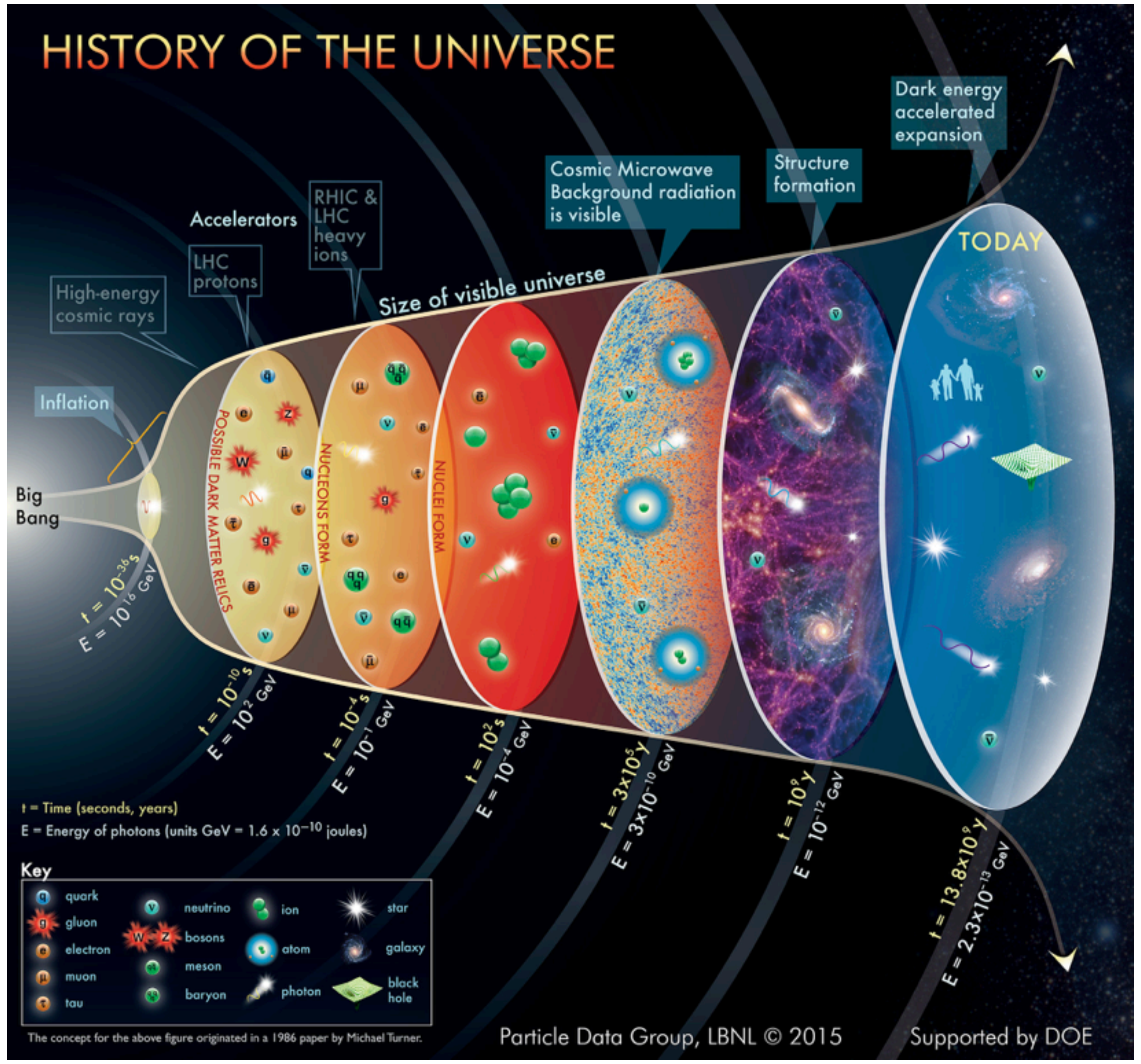
High temperatures: $4{\cdot}10^{12}$ K

(10^5 x temperature in interior of sun)

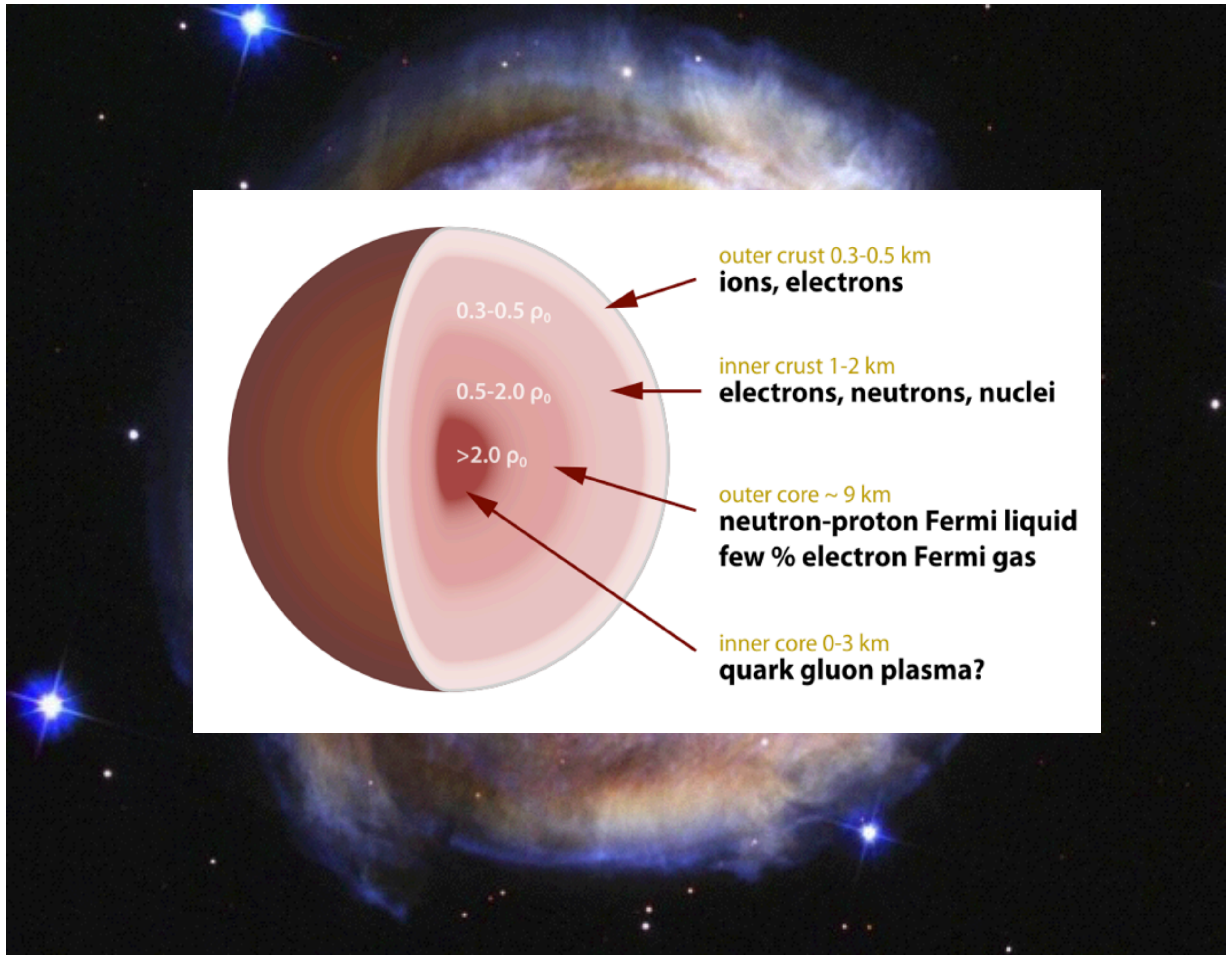
High pressure / density 10^{34} Pa

(road roller placed on the area of the size of a proton)

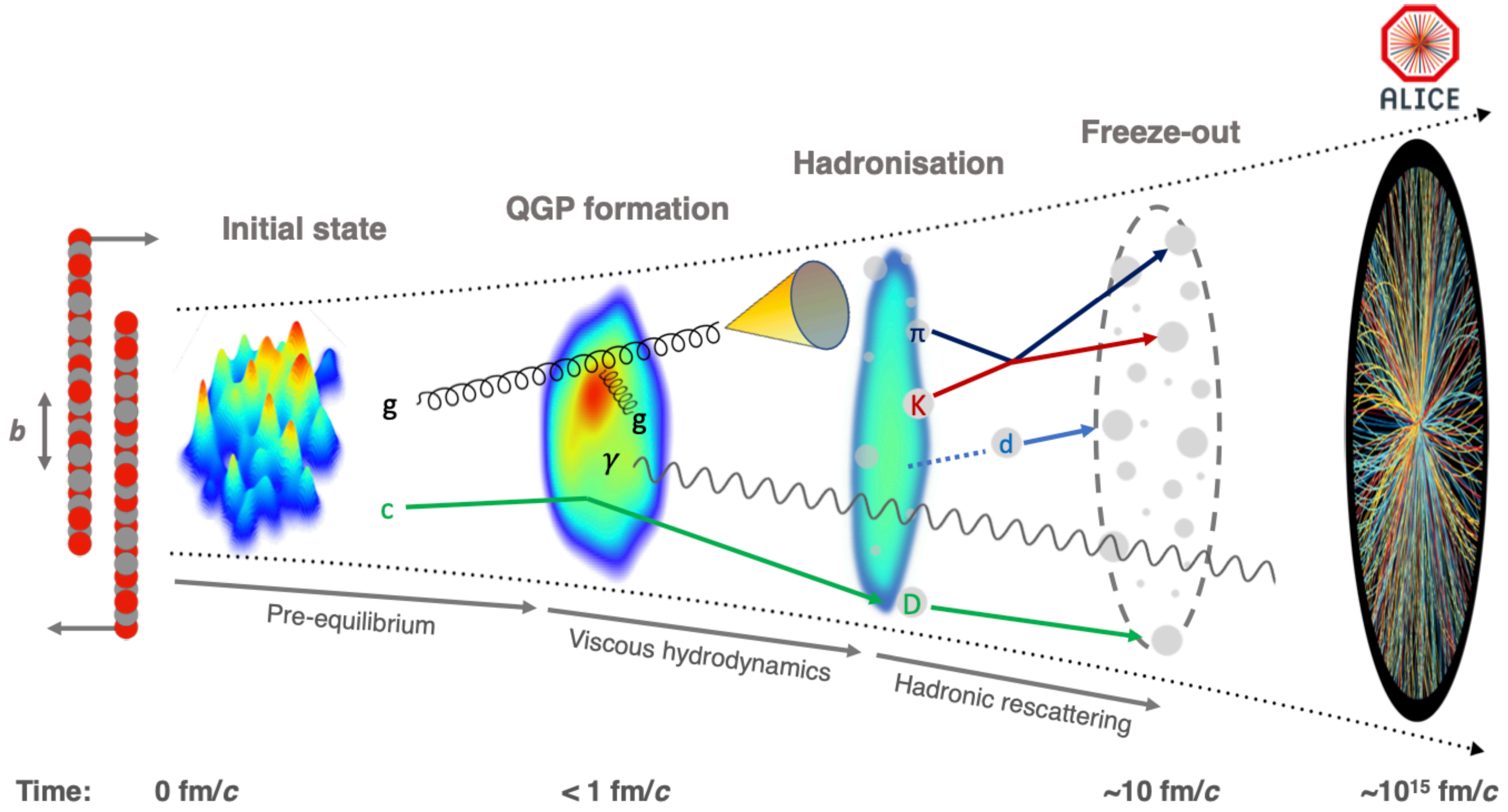
QGP phase ~10 μs after Big Bang

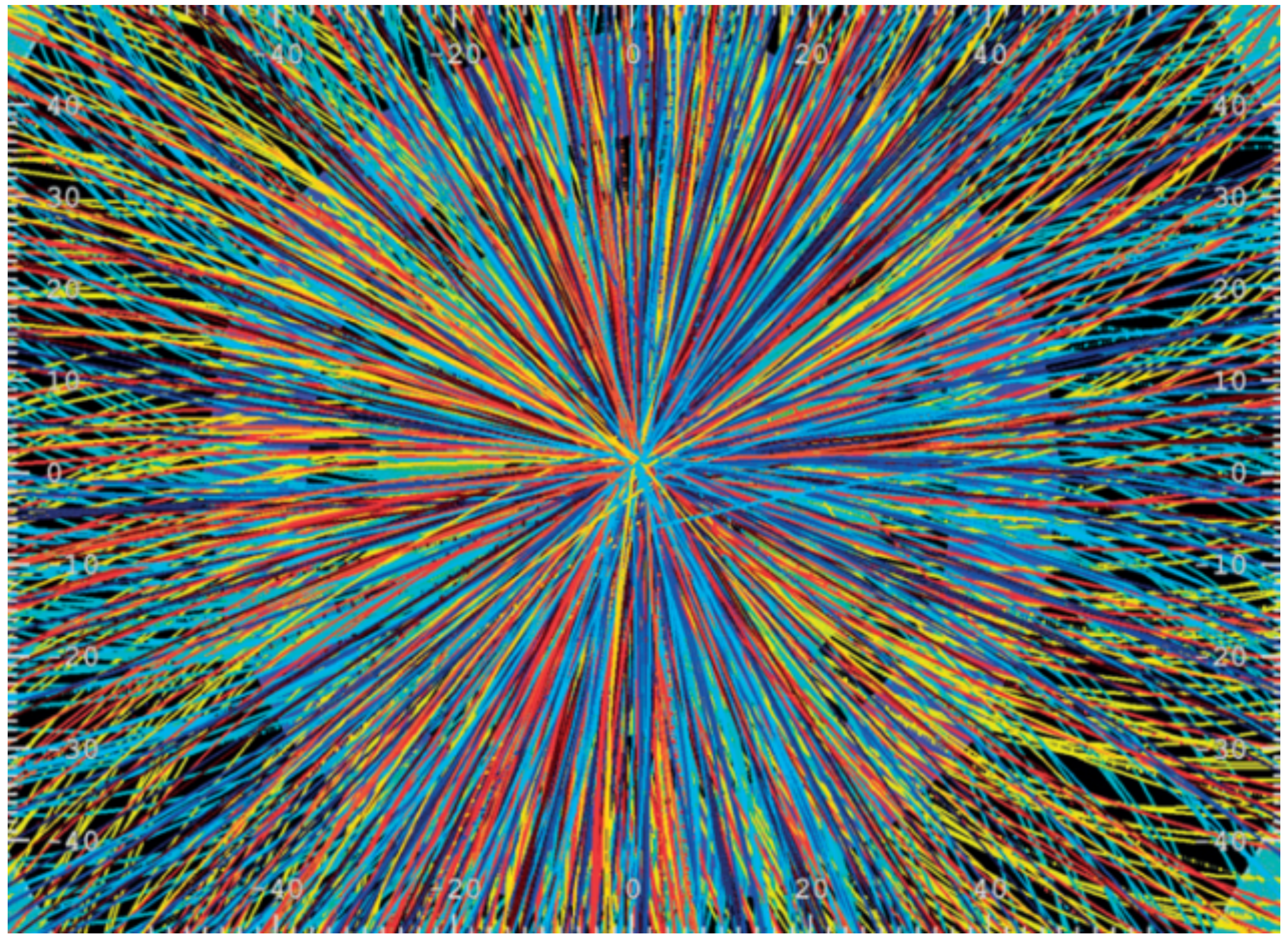


Neutron star



QGP created in HI collision is ephemeral



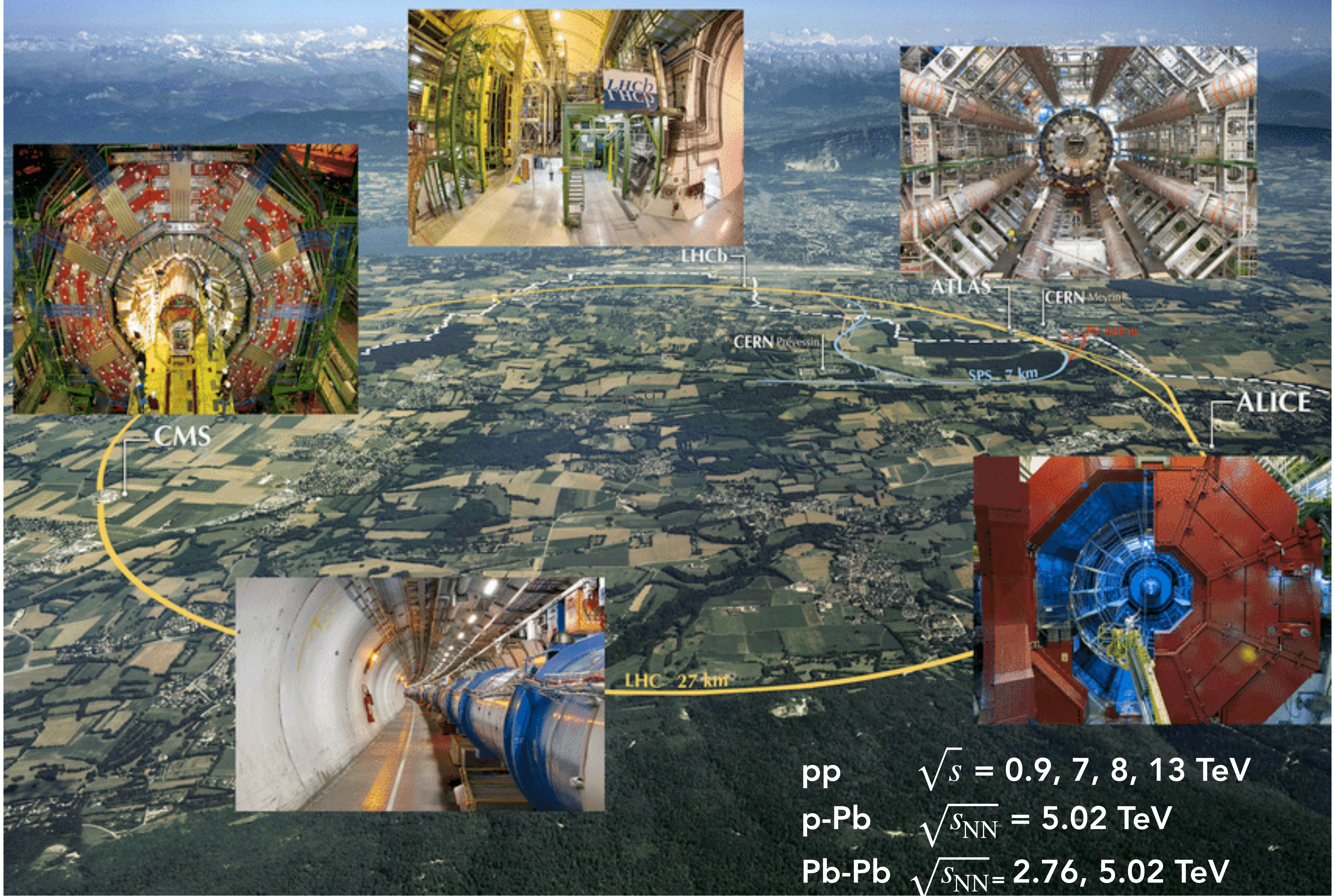


at LHC: $\frac{dN_{ch}}{d\eta} \approx 2000$ (in central collisions)

- In HI collision QGP produced under "explosive conditions"
  - Matter evolving through several phases
  - QGP phase lasts only 10^{-23} s
  - **Only final state particles are directly observable as messengers of the earlier phases … and there are many of them …**

4 large LHC experiments participate in Pb-Pb programme

about 1 month per year dedicated to HI physics



pp $\sqrt{s}$ = 0.9, 7, 8, 13 TeV

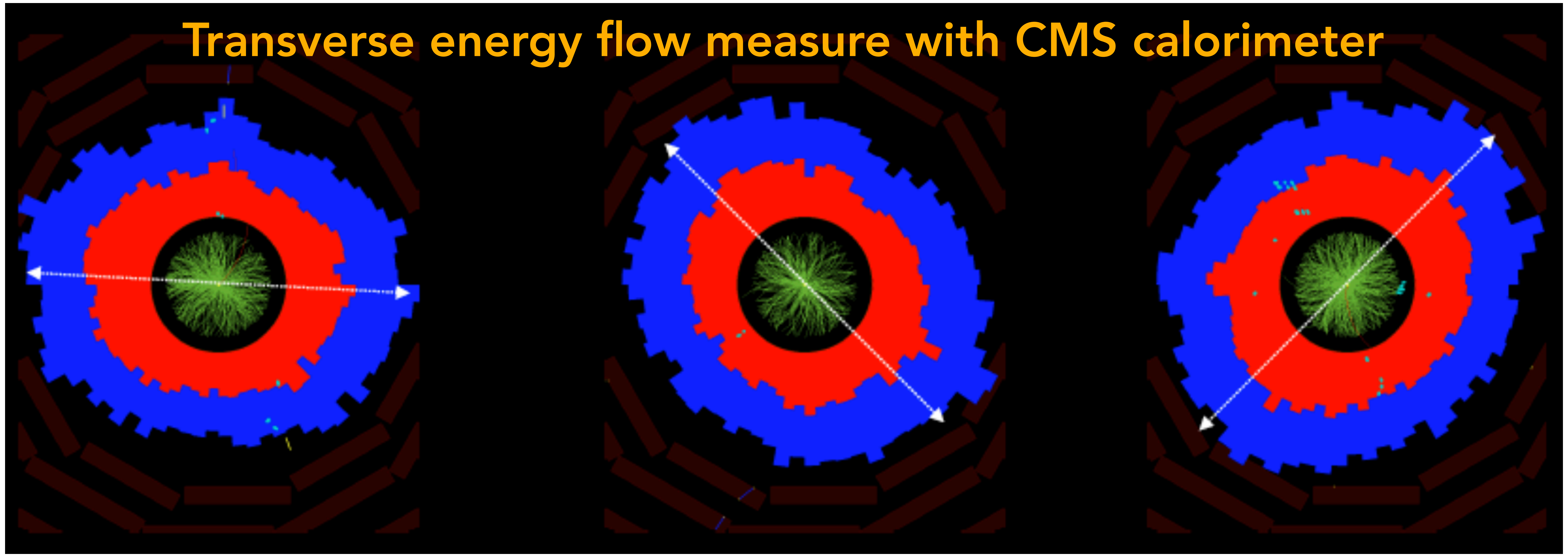
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Pb-Pb $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

QGP @ LHC: naked eye effects

Collective effects

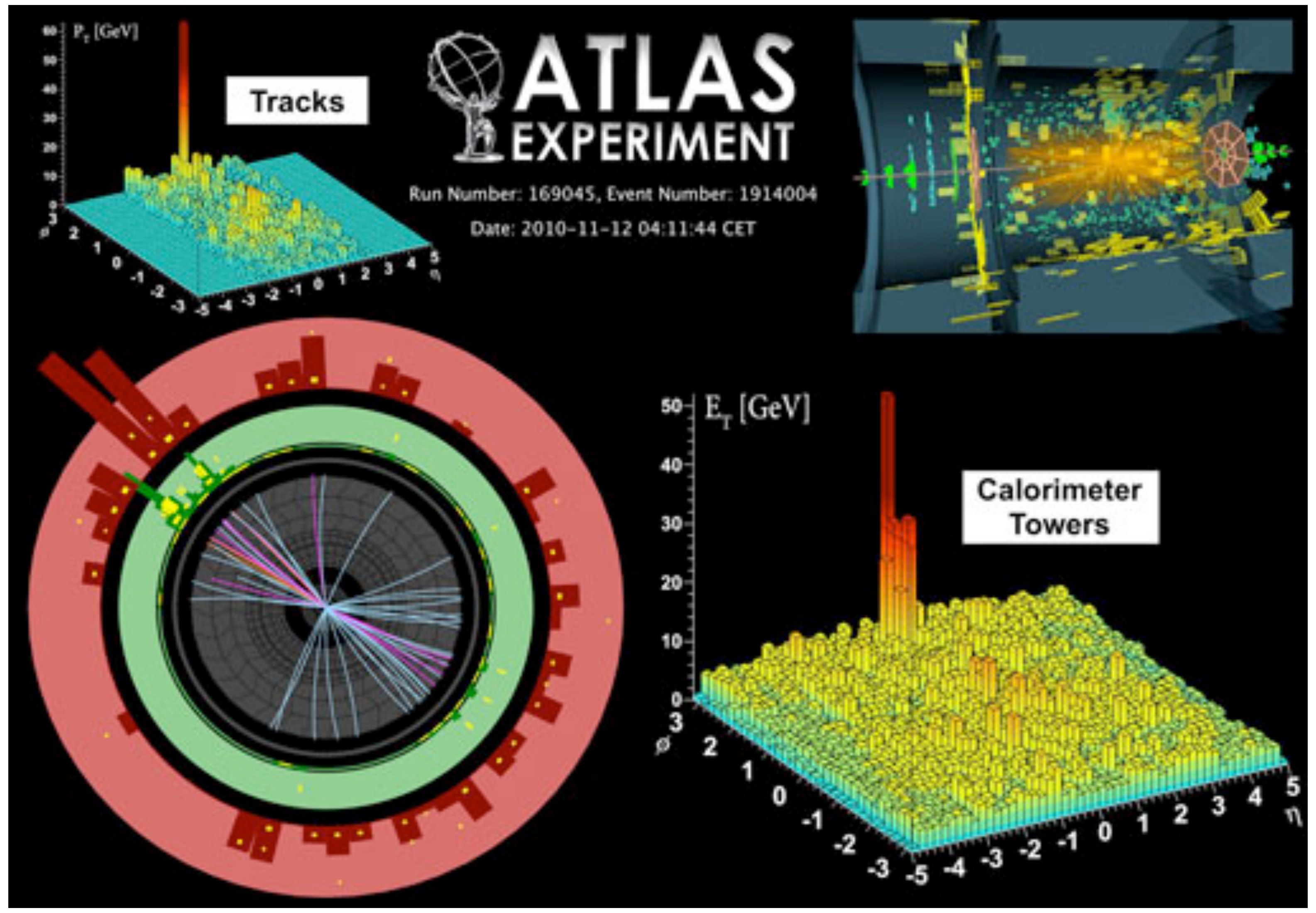
QGP: strongly coupled, low-viscosity



Jet quenching

QGP has strong effect on parton shower evolut

induced gluon radiation



And also:

- J/ψ enhancement in regions where the charm density is high ⇒freely roaming charm quarks
- Enhanced production of multi-strange baryons
- …

Allow to characterise the medium in terms of *T*, energy density, viscosity, diffusion parameter, …

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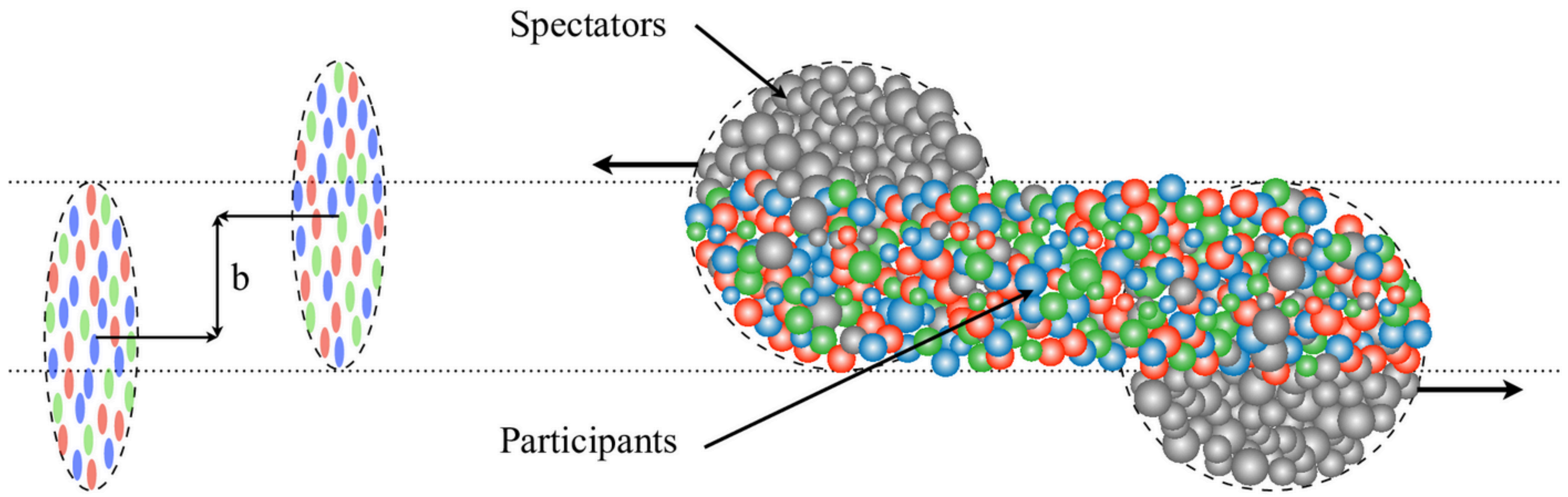
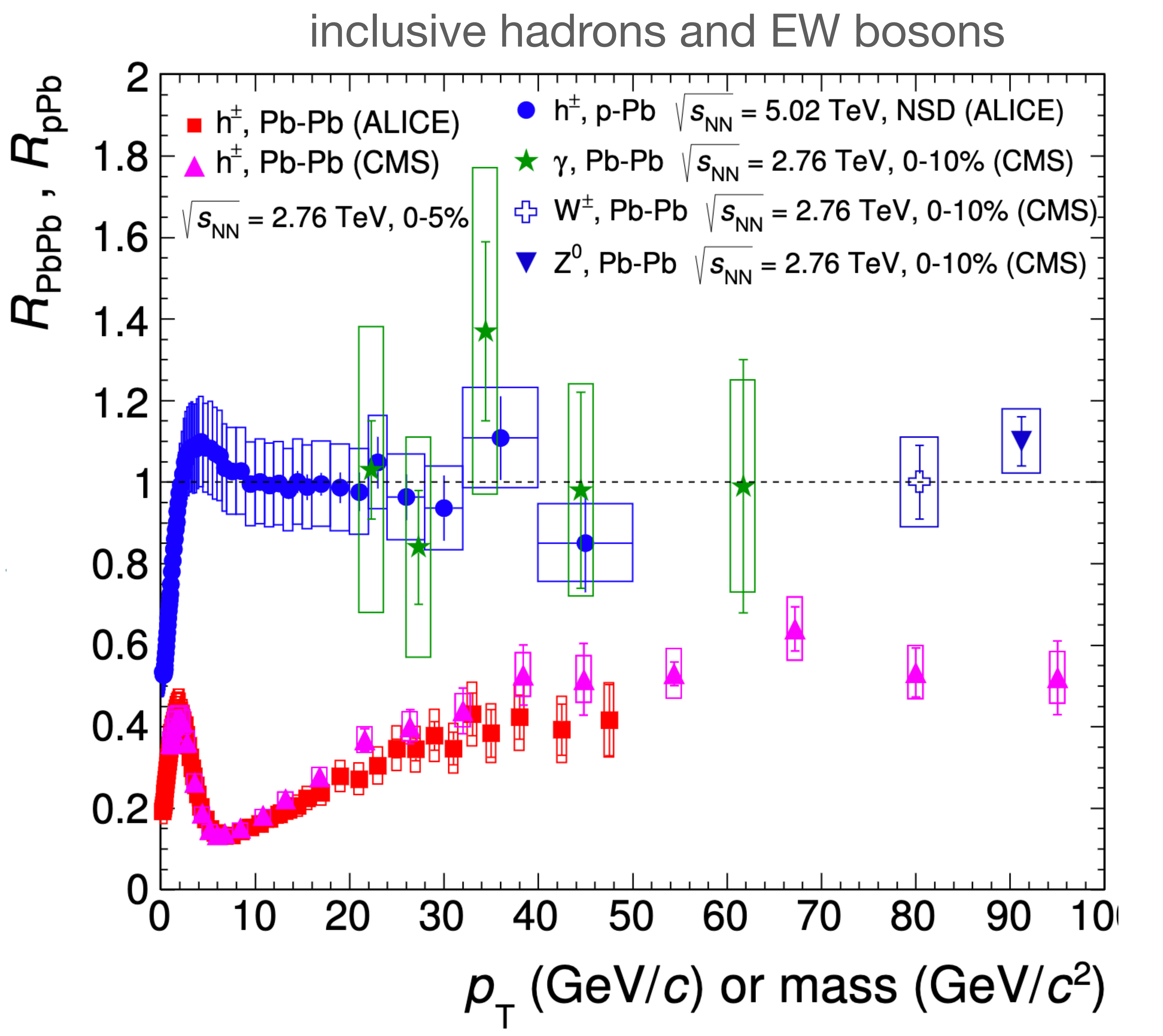
Rôle of pp physics: a reference

Nuclear modification factor R_{AA}

$$R_{AA}(p_T) = \frac{\frac{d\sigma^{cent}_{PbPb}}{dp_T}}{N_{col}\frac{d\sigma^{cent}_{pp}}{dp_T}}$$

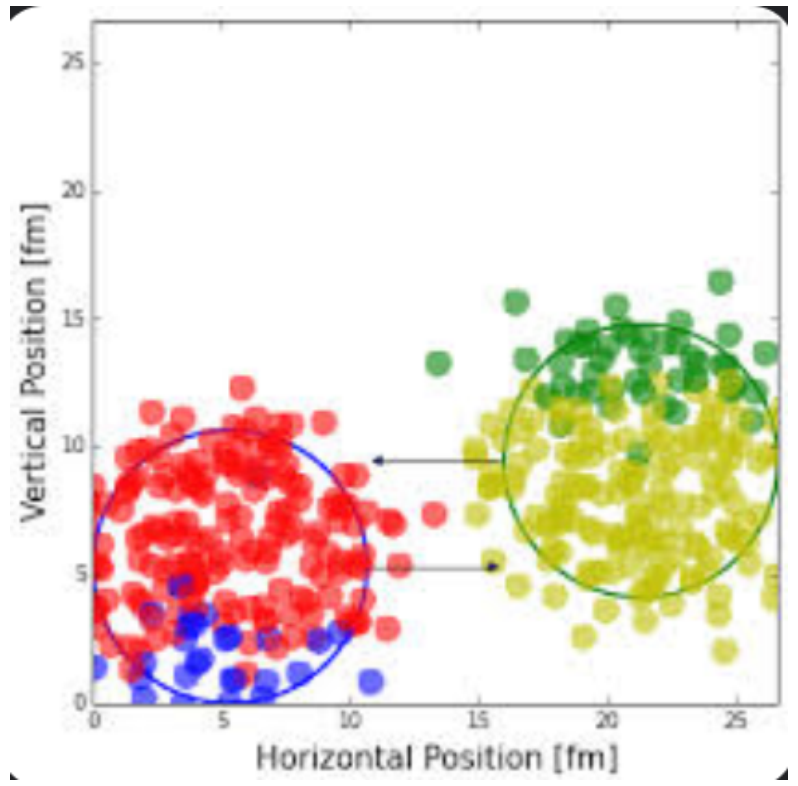
- Centrality class (cent): on average N_{col} binary nucleon-nucleon collisions
- Reference corresponds to incoherence superposition of N_{col} pp collisions
- Assume R_{AA} = 1 without any nuclear effects.

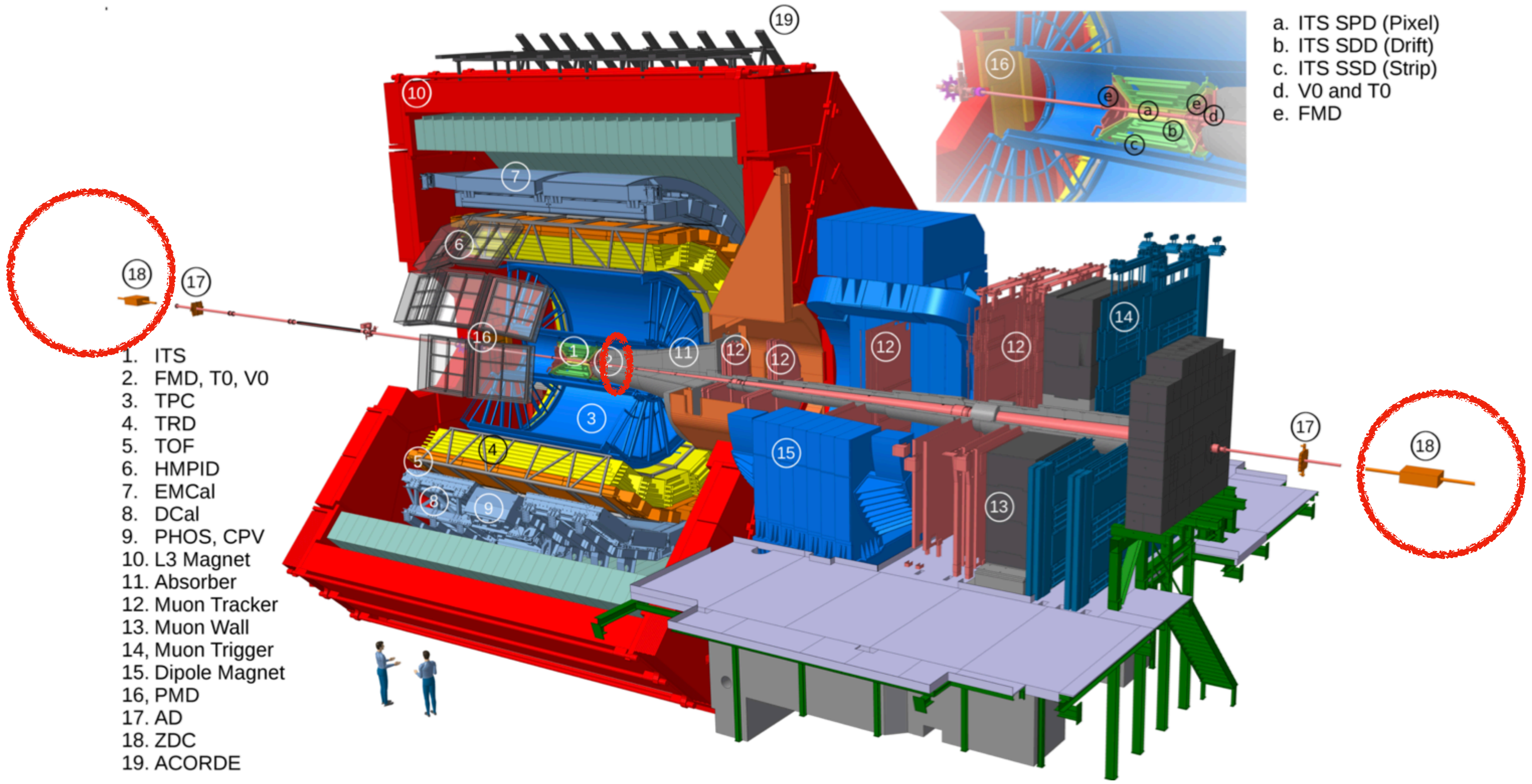


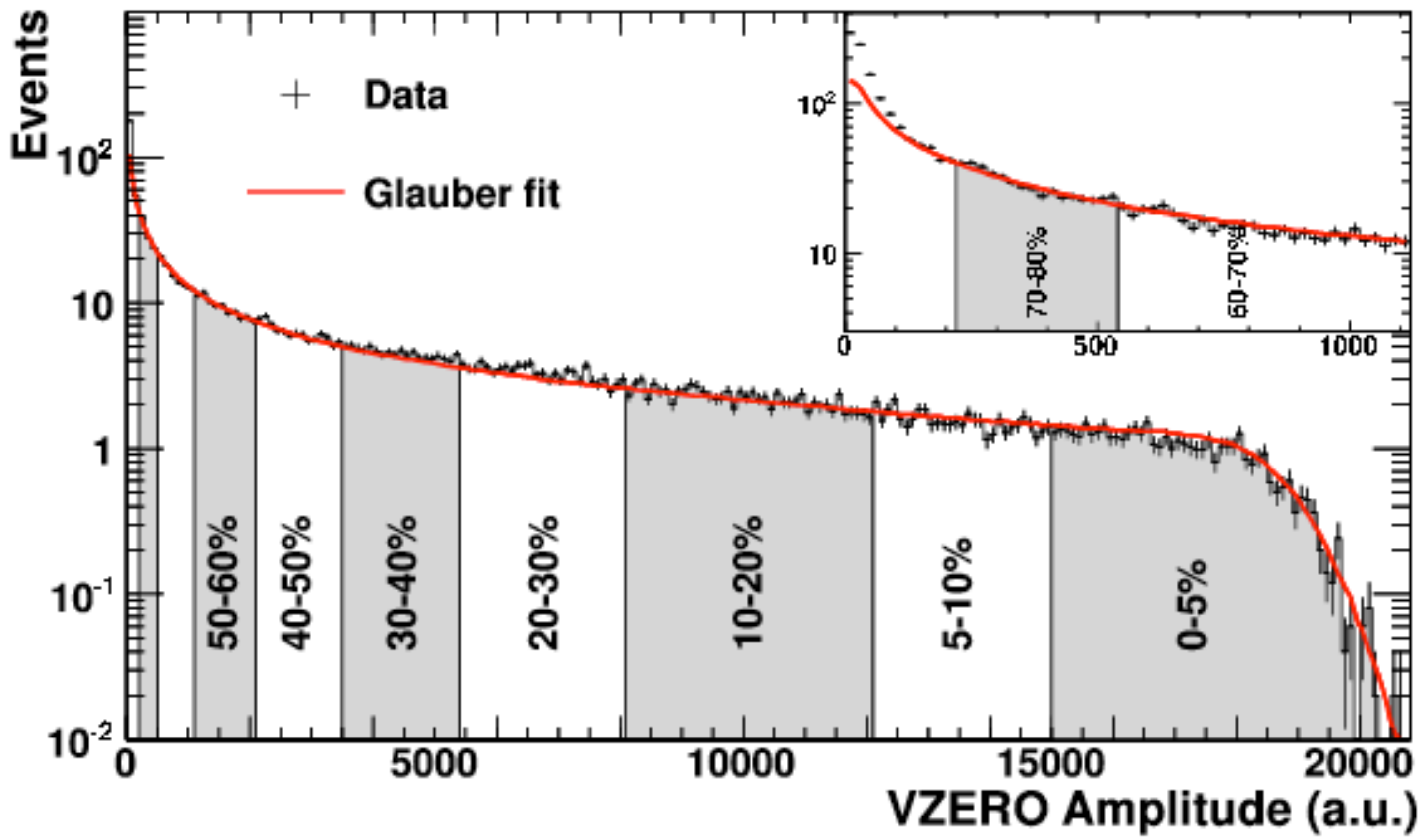


Centrality and the rôle of pp-physics

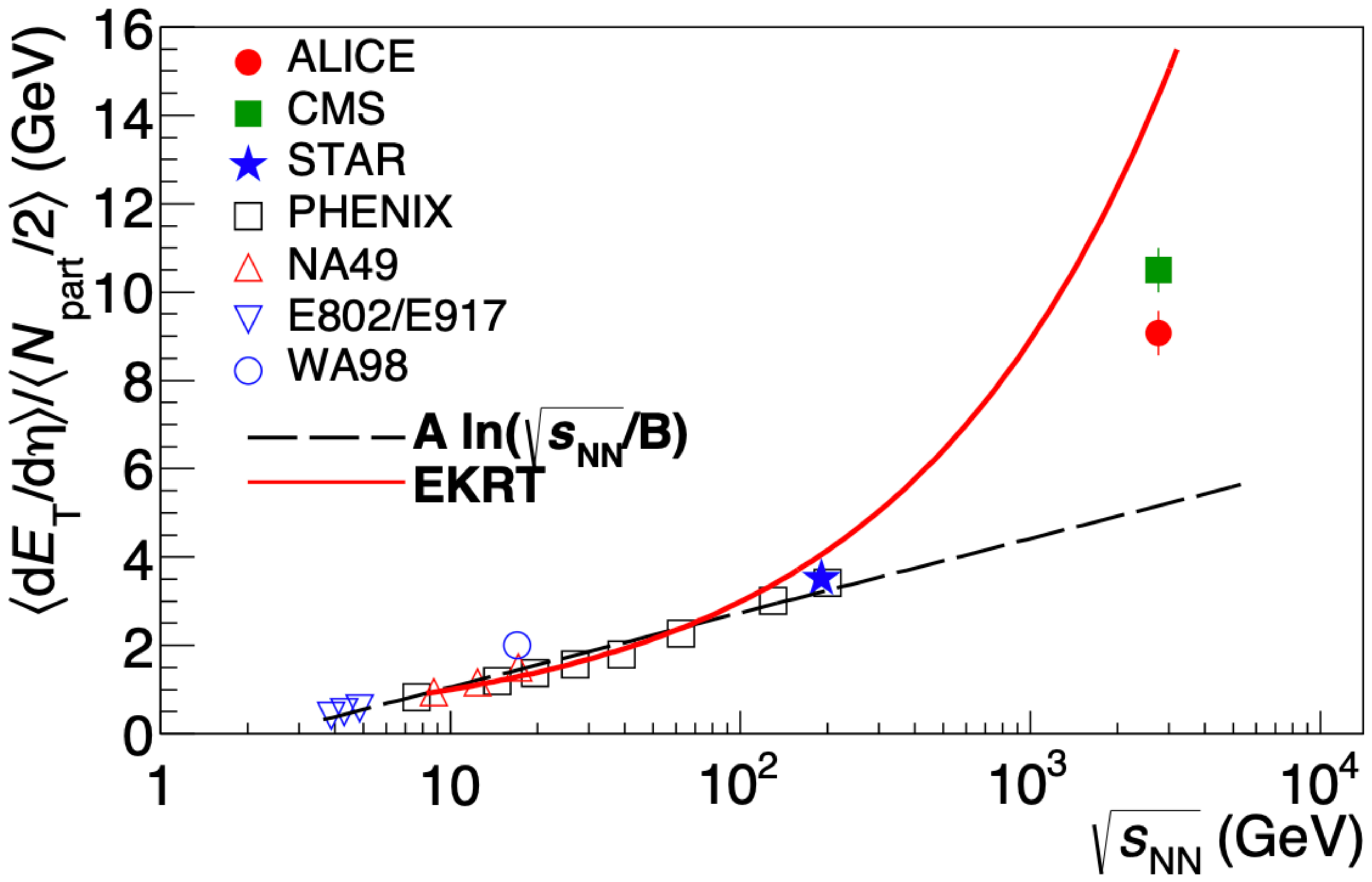
- Centrality is determined experimentally via multiplicity or summed energy measurement.
- Link to impact parameter measurement via Glauber model fit
- Fit accounts for fluctuations of multiplicity per nucleon-nucleon (pp, nn) collision
    - Better understanding of these fluctuations from study of pp collisions







More than a reference: high density QCD with pp collisions?



- From Bjorken estimate for energy density

$$\epsilon_i \approx \frac{3}{2}\frac{1}{1\ \mathrm{fm}\ \pi R_N^2 A^{\frac{2}{3}}}\langle E_\mathrm{T}\rangle\frac{\mathrm{d}N_\mathrm{ch}}{d\eta} = \frac{3}{2}\frac{1}{1\ \mathrm{fm}\ \pi R_N^2 A^{\frac{2}{3}}}\langle\frac{\mathrm{d}E_\mathrm{T}^\mathrm{ch}}{d\eta}\rangle$$

- In central Pb-Pb collisions
  - Average ≈14 GeV/fm^3
  - Core density ≈ 21 GeV/fm^3

Day One Proton-Proton Physics with the ALICE Central Detector

ALICE 2000-28
Internal Note / PHY
24 November 2000

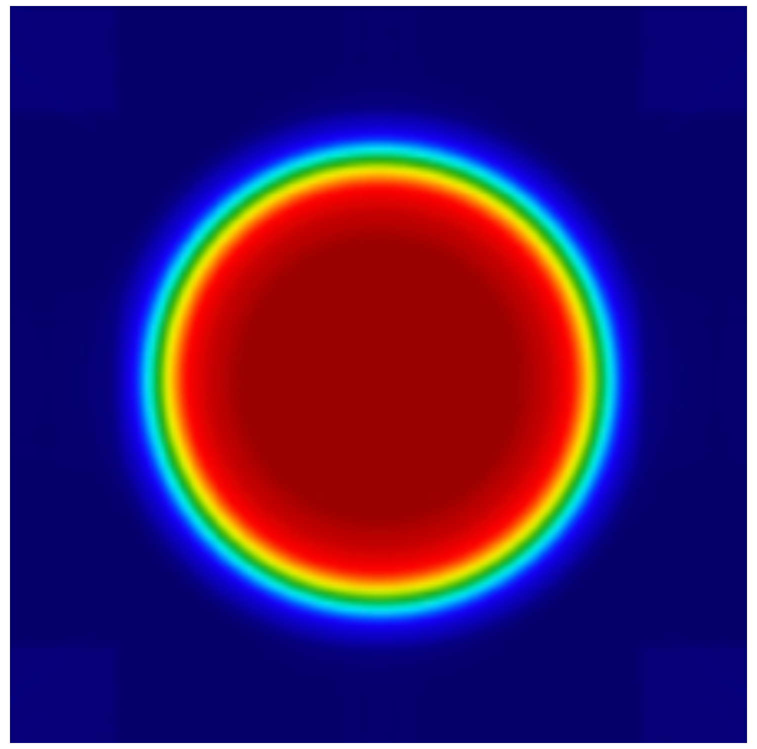
P. Giubellino, S. Kiselev, W. Klempt, A. Morsch, G. Paic, J.-P. Revol and K. Safarik

Table 6: Comparison of average kinematic parameters for pp and Pb-Pb collisions.

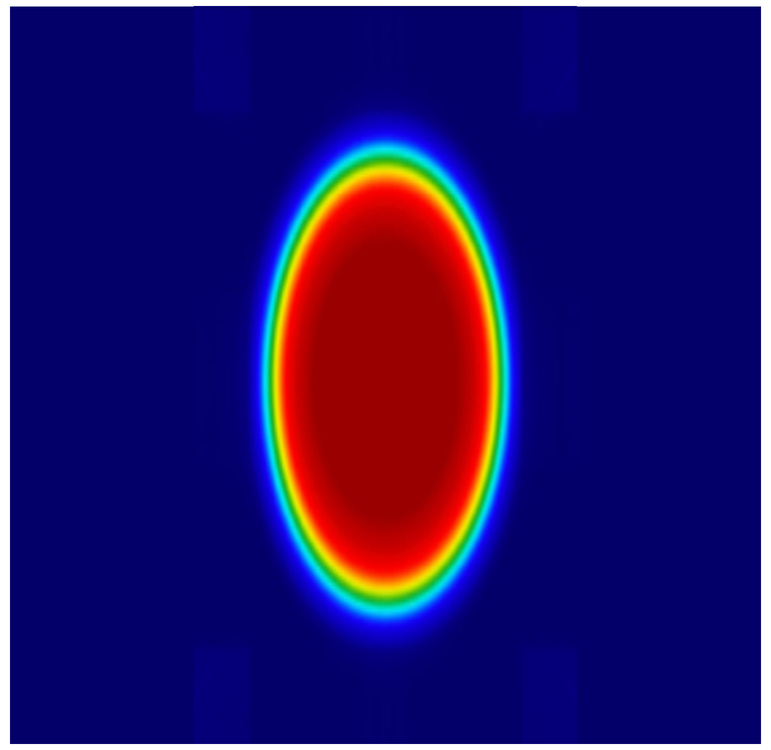
	<E> (MeV)	$\frac{dN_{ch}}{dy}$	V_i (fm^3)	ε_i (GeV/fm^3)
p$\bar{\text{p}}$ (√s = 630 GeV)	400	4	4.5	0.5
p$\bar{\text{p}}$ (√s = 1.8 TeV)	400	5.3	4.5	0.7
pp (√s = 14 TeV)	500	7	4.5	1.2
Au-Au (RHIC)	500	650–850 [1]	153	3.1–4.1
Pb-Pb (LHC)	500	2000–8000	159	10–38

We can see that going from the CERN proton-antiproton collider to the LHC in proton mode, the average energy density does not change very much (Table 6), going from 0.5 to 1.2 GeV/fm^3. However, we should be able to observe events up to 10 times the average charged particle multiplicity, which will provide energy densities of 12 GeV/fm^3, comparable to those of heavy-ion collisions.

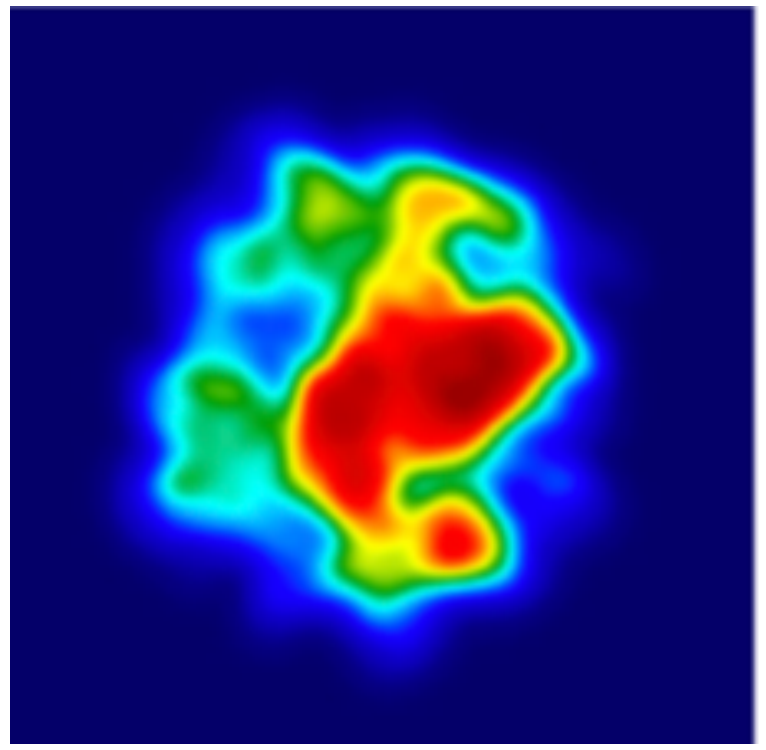
Initial conditions and collective motion (flow)



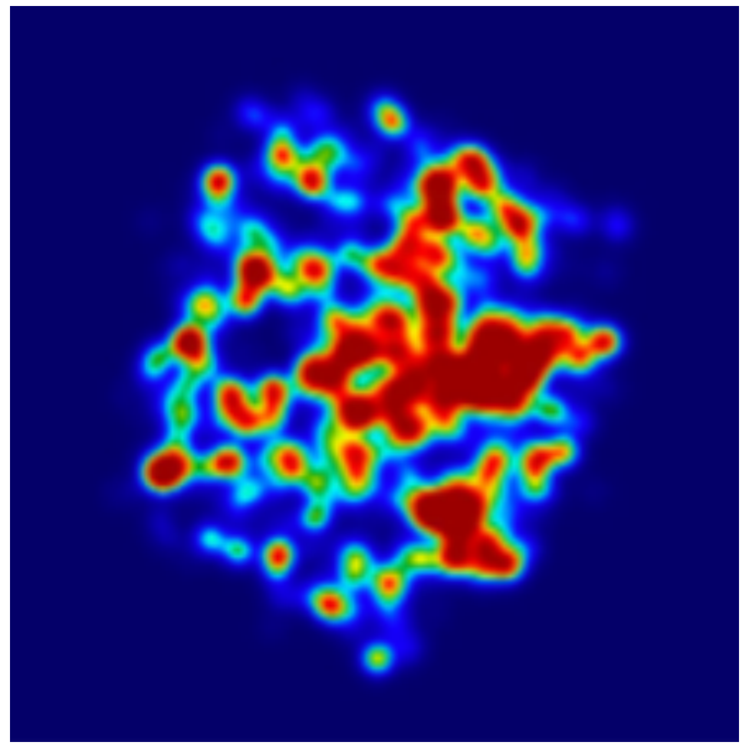
isotropic pressure gradients



smooth initial conditions ($\mathcal{O}(5\ \mathrm{fm})$)
elliptic flow

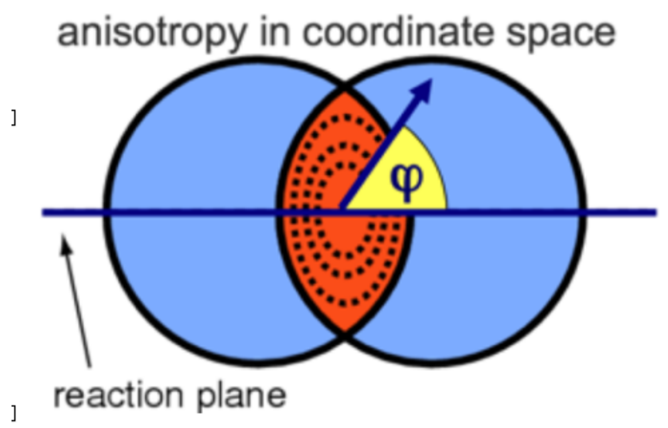


fluctuations of nucleon positions ($\mathcal{O}(1\ \mathrm{fm})$)
higher harmonics

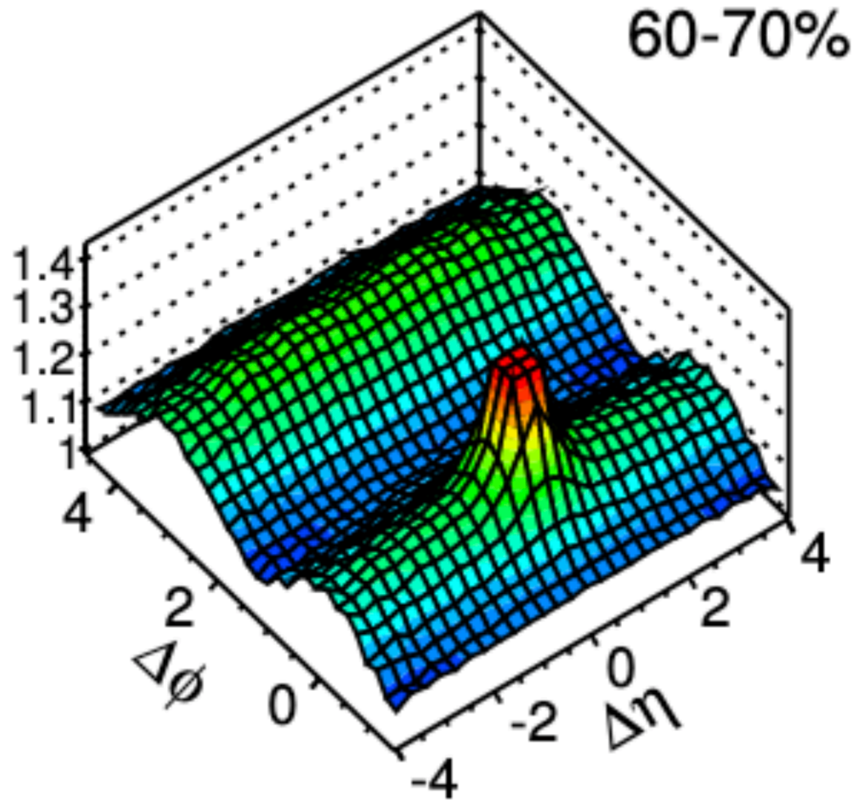


sub-fm fluctuations

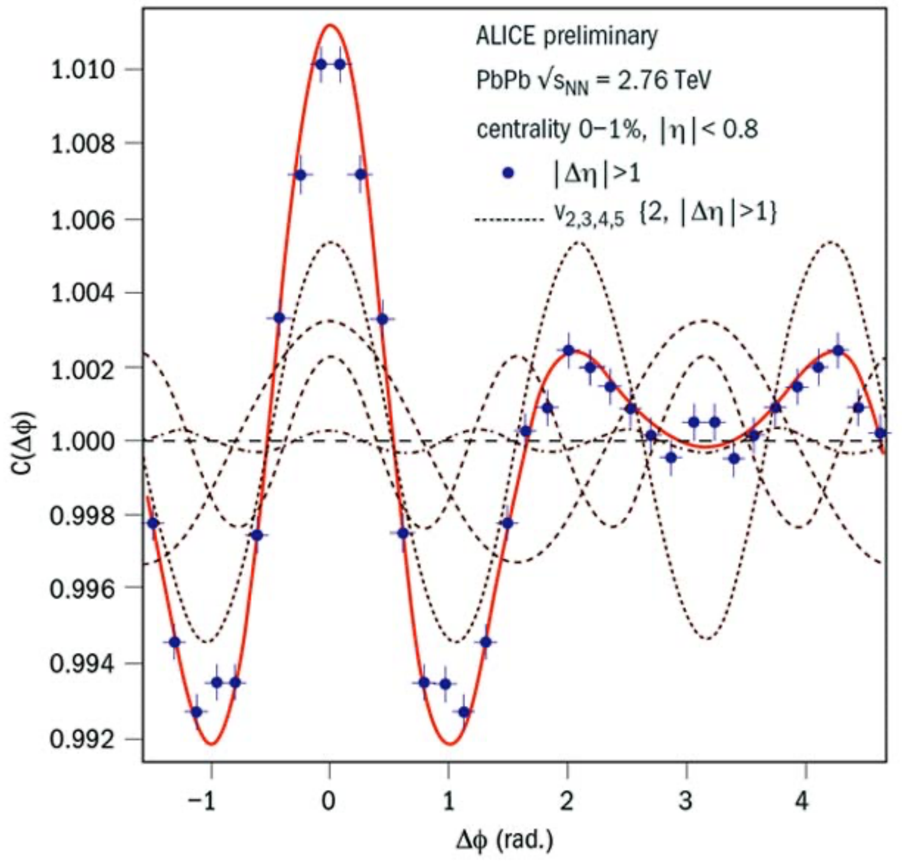
present also in pp!

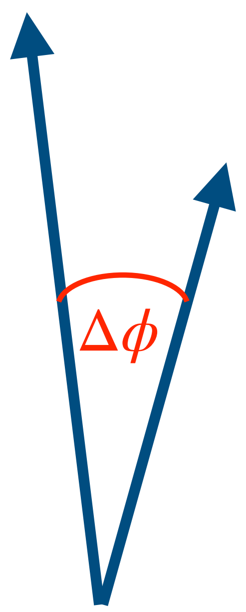


$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^3N}{p_T dp_T dy}\left[1 + \sum_{1}^{\infty} v_n \cos\left(n(\varphi - \Psi_n)\right)\right]$$



CMS, https://arxiv.org/pdf/1201.3158.pdf

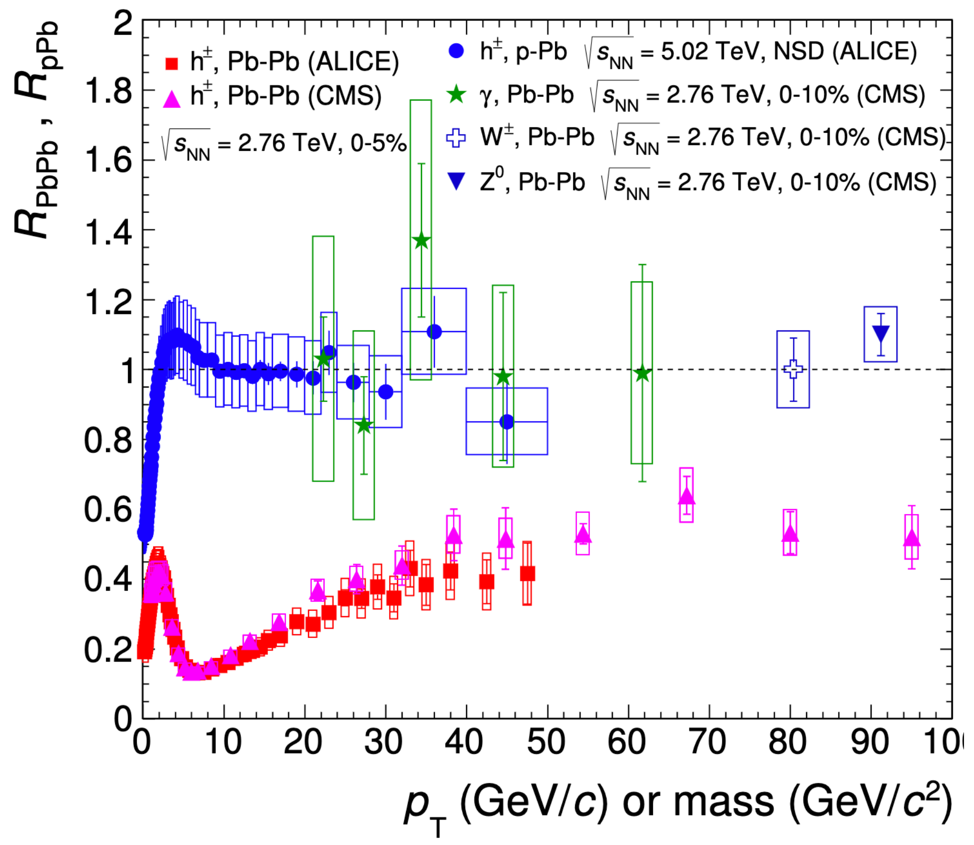




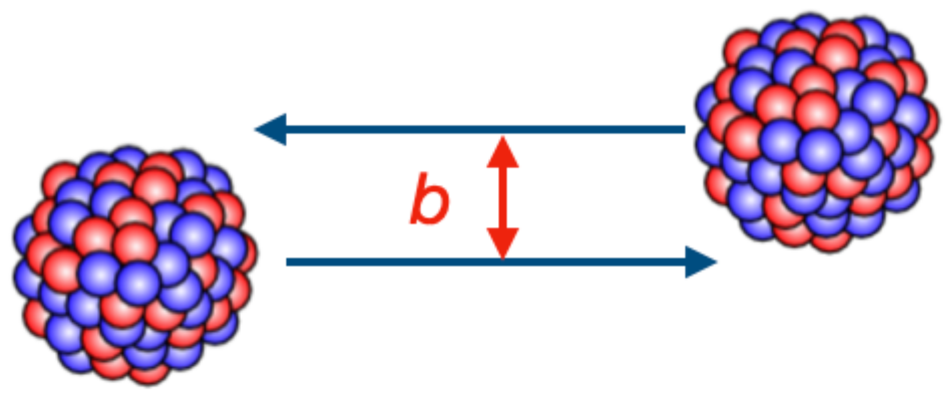
Medium shows a very strong response to the initial shape of overlap region

Summary: Interest in pp from HI perspective

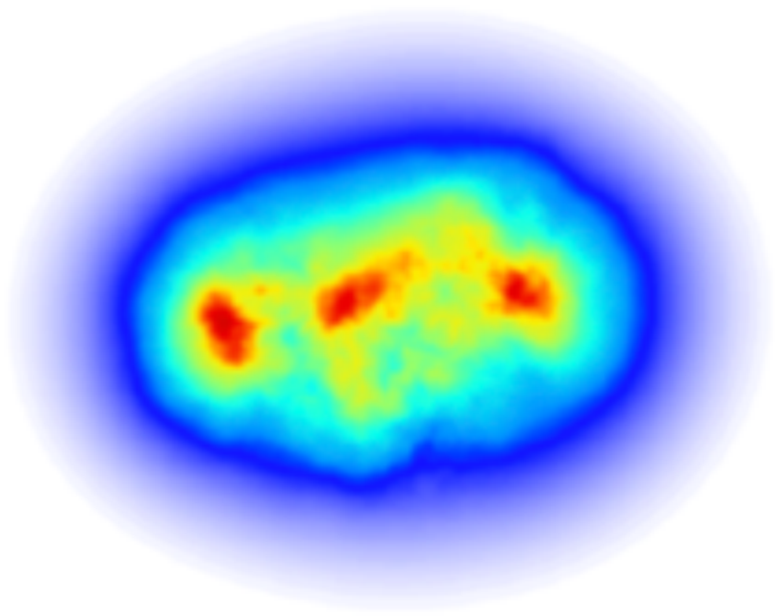
reference system



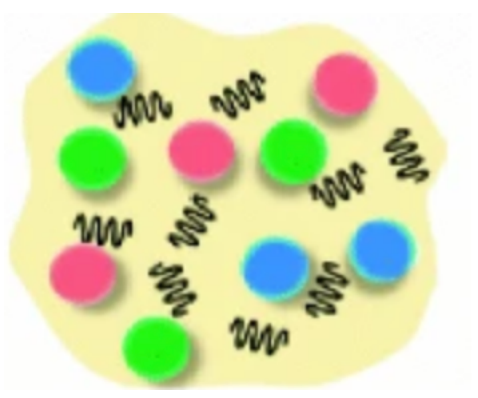
improve understanding of centrality selection

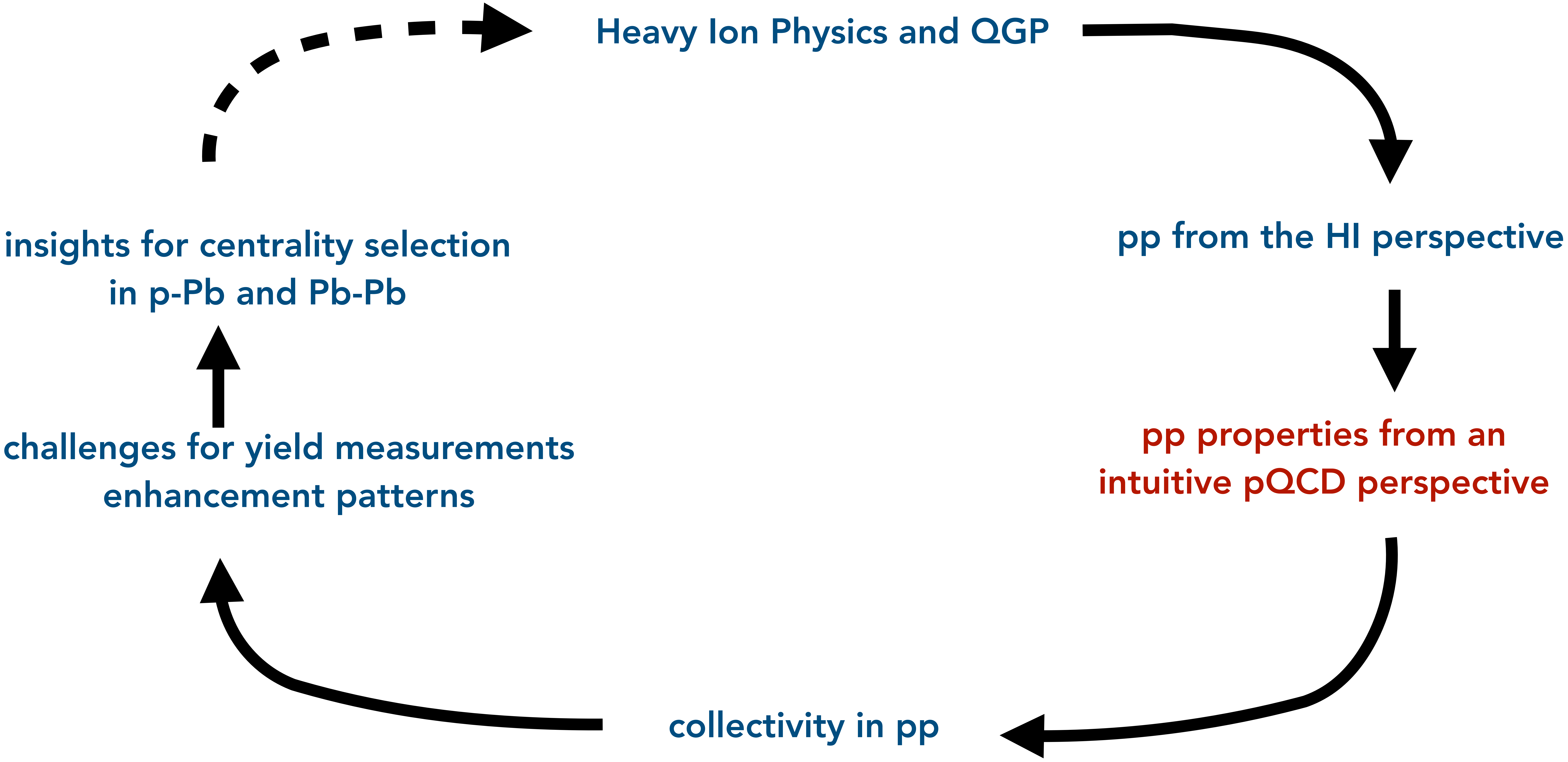


sub-fm fluctuations



laboratory for high-density QCD?

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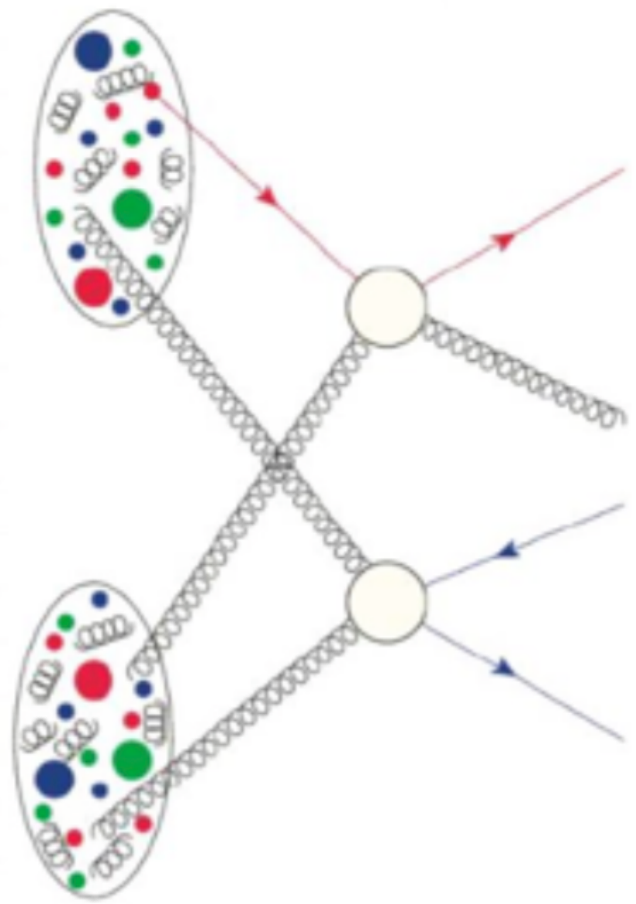
High density pp at LHC from pQCD perspective

- Straightforward interpretation of pQCD $\sigma_{2\to2} > \sigma_{tot}$
- Number of 2→2 scatterings per event assuming naïve **factorization**:

$$\langle n_{2\to2} \rangle = \frac{\sigma_{2\to2}}{\sigma_{tot}}$$

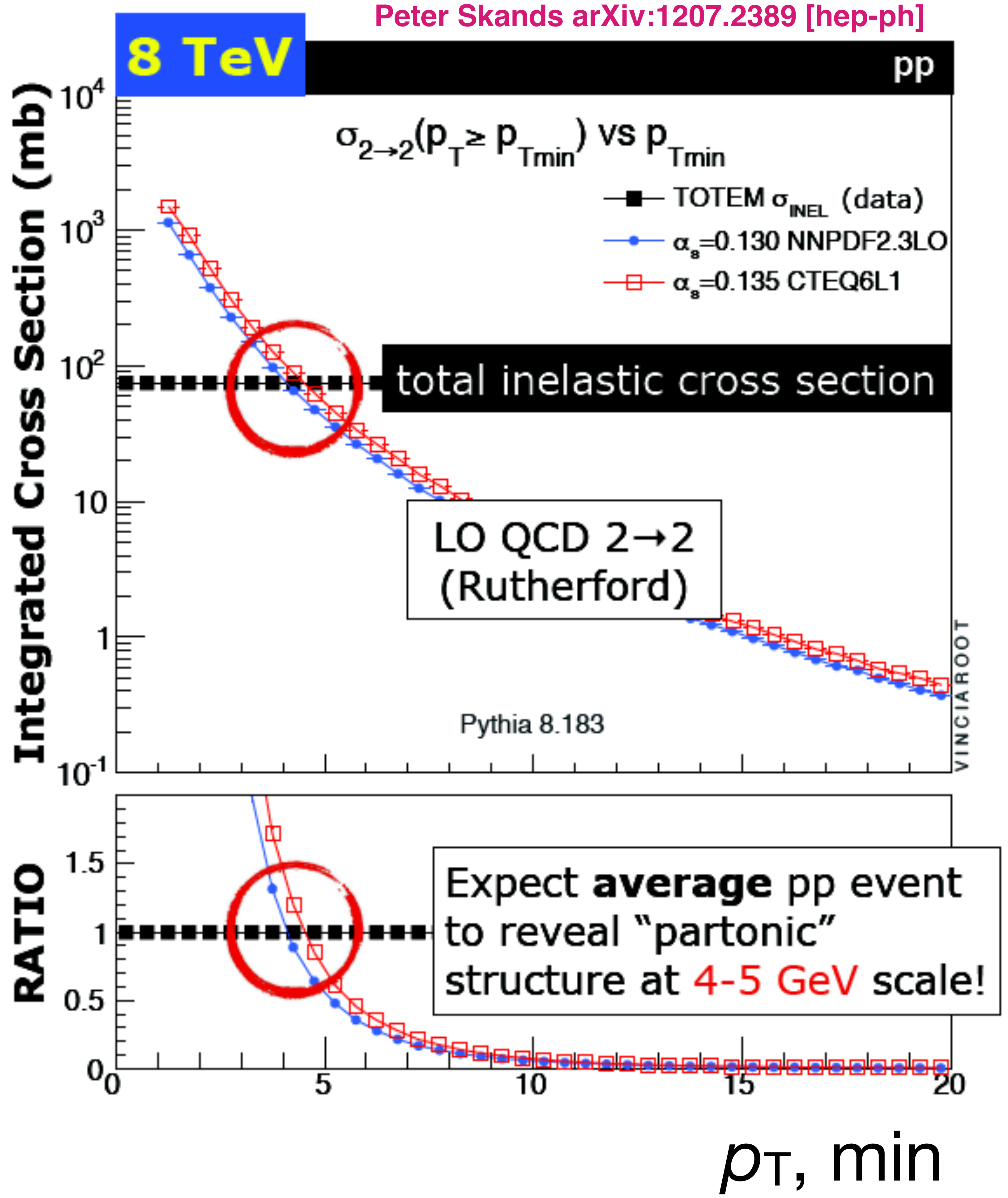
$$P_n = \frac{\langle n_{2\to2} \rangle^n}{n!} e^{-\langle n_{2\to2} \rangle}$$



At LHC multiple hard scatterings at perturbative scales

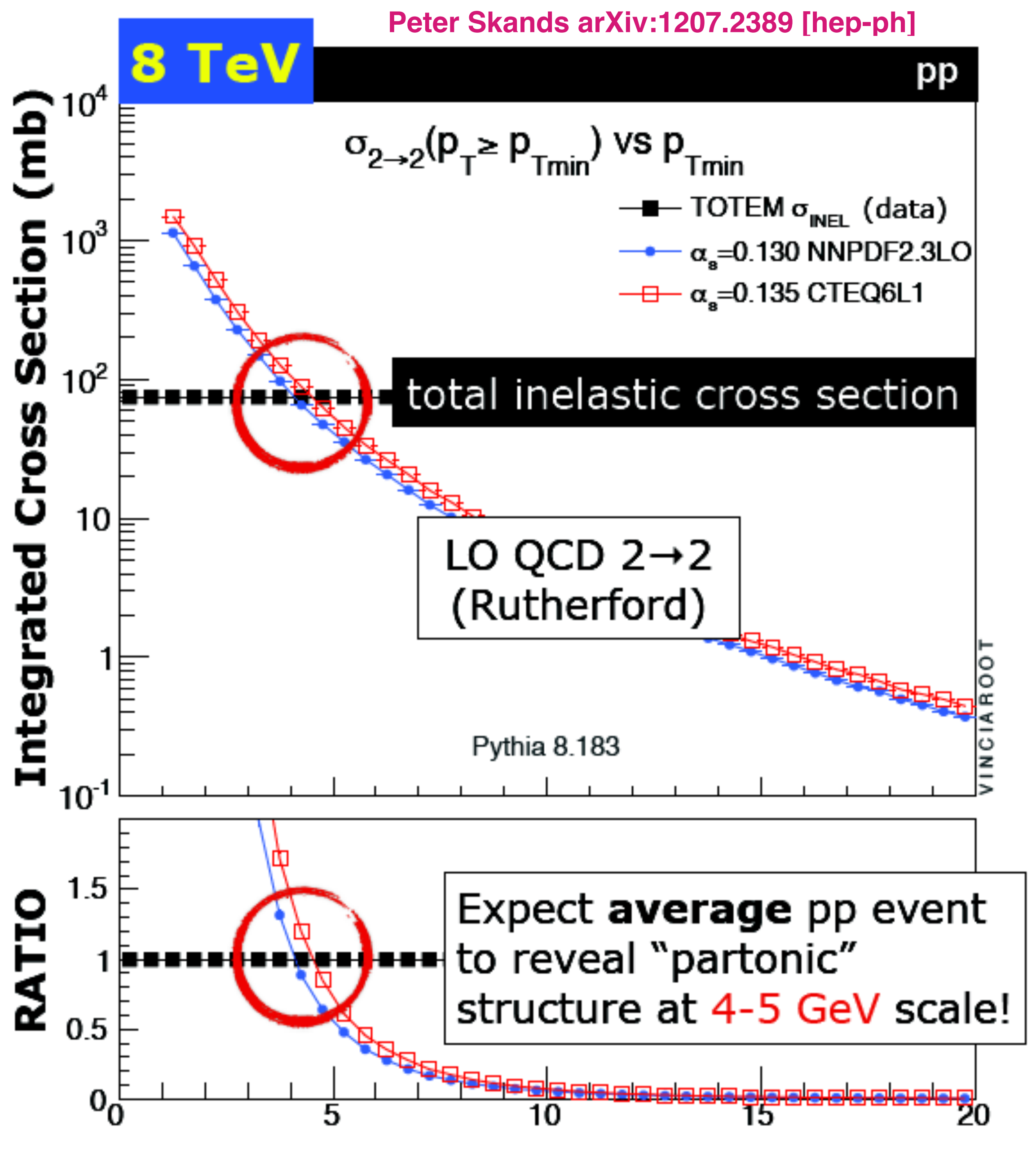
~5 per minimum bias collision

Integrated hard cross-section above cut-off p_{Tmin}



The low-p_T limit

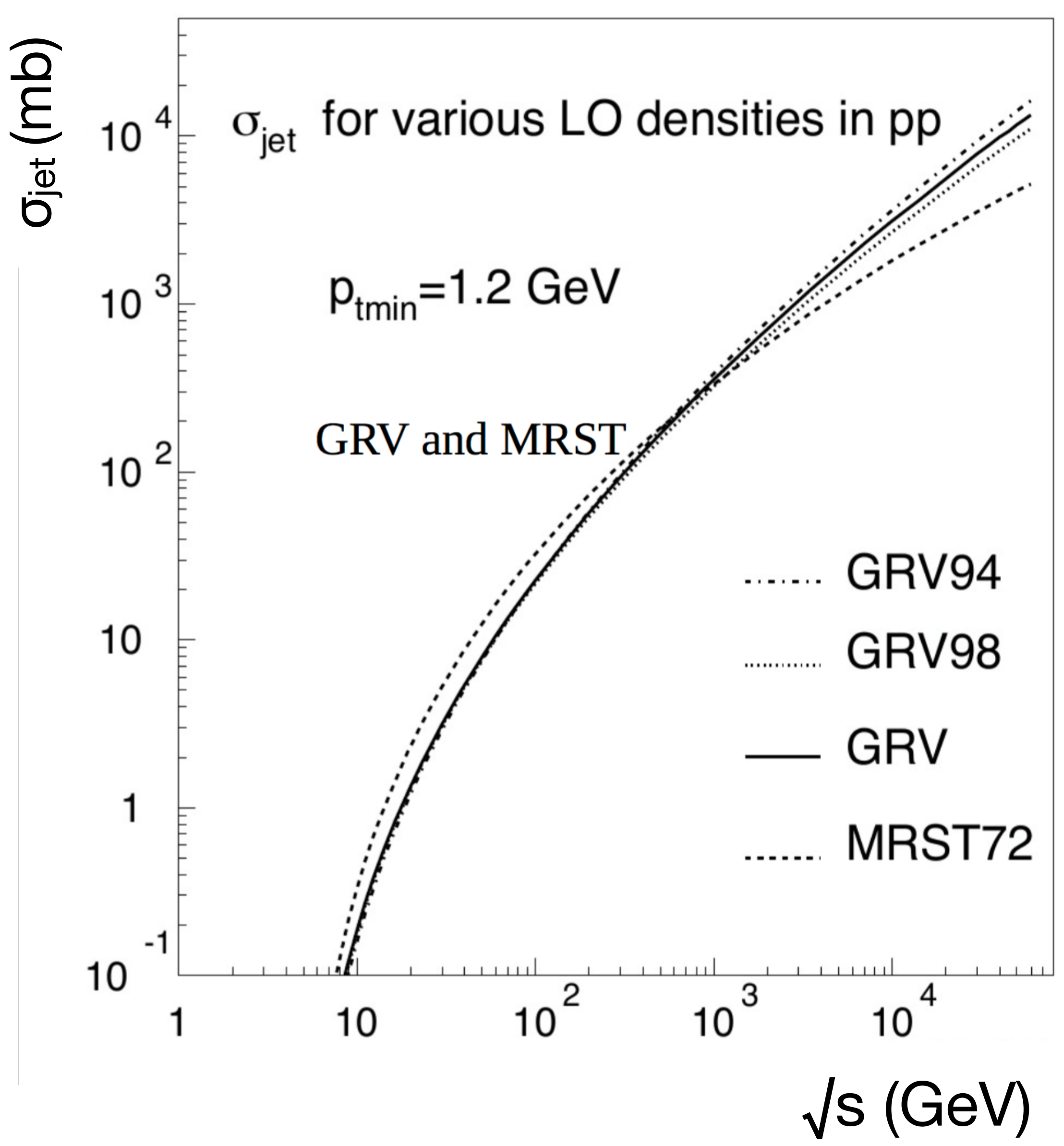
Integrated hard cross-section

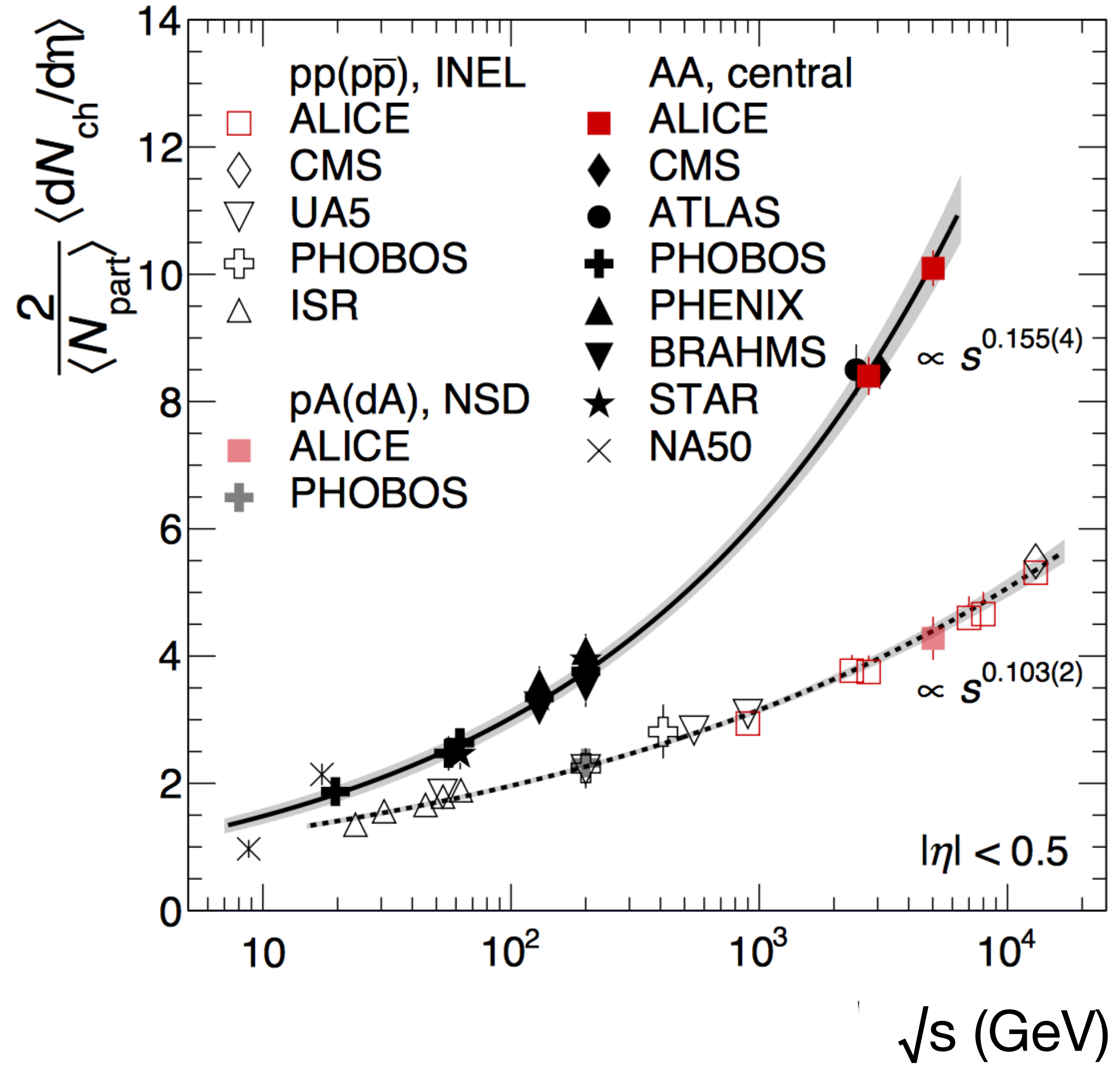


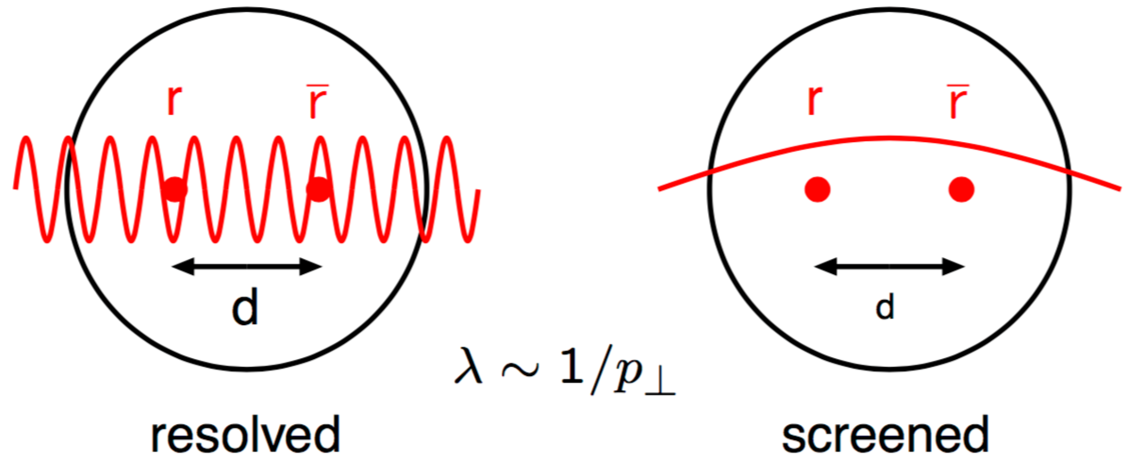
$\sqrt{s}$ = 10 - 10 TeV

σ_{hard} x 10^5

pp: N_{ch} x 4 AA: x10

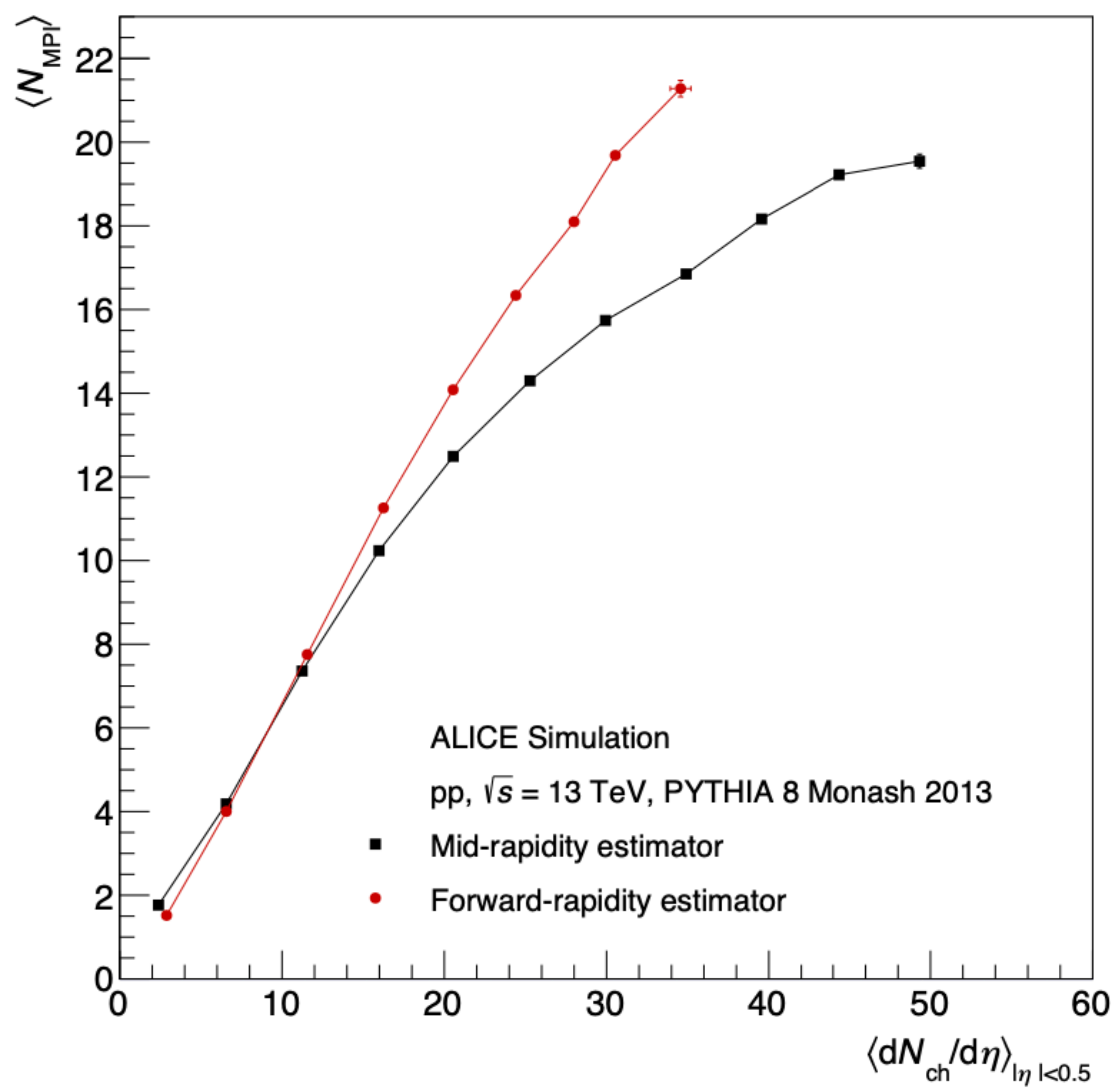


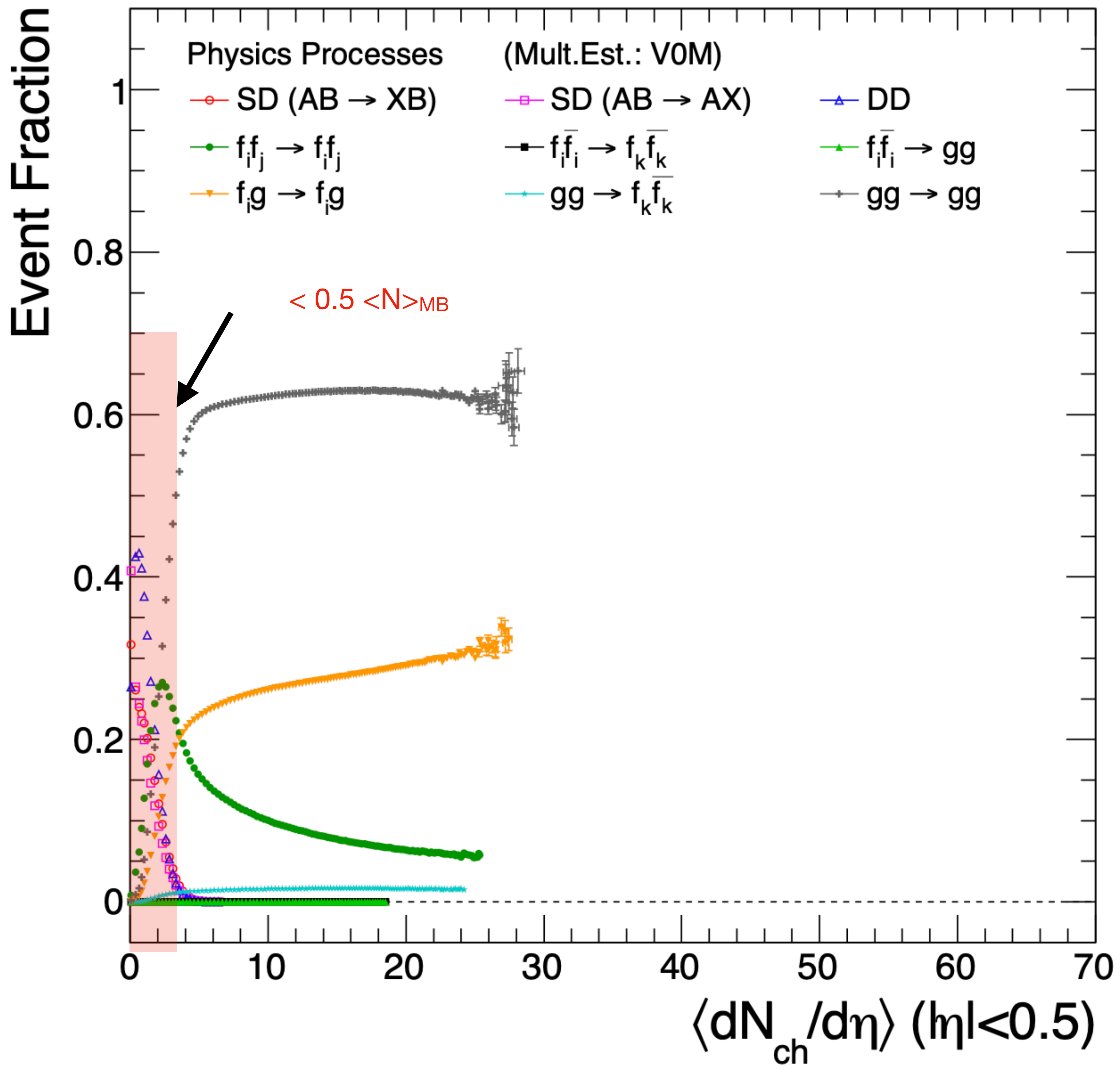




- Factorisation breaks for $n_{2\to2}$ large in area $\propto 1/p_T^2$
  - Damping of hard cross-section at low p_T (Pythia) $\sigma(\hat{p}_T) \to \sigma(\hat{p}_T)\frac{\hat{p}_T^4}{(\hat{p}_{T0}^2 + \hat{p}_T^2)^2}; \; \hat{p}_{T0} \approx 1.5 - 2$ GeV
  - "Natural" transition in models like EPOS
  - Decrease of cross-section does not necessarily imply change of kinematics
    - 2-2 topologies seen down to low p_T

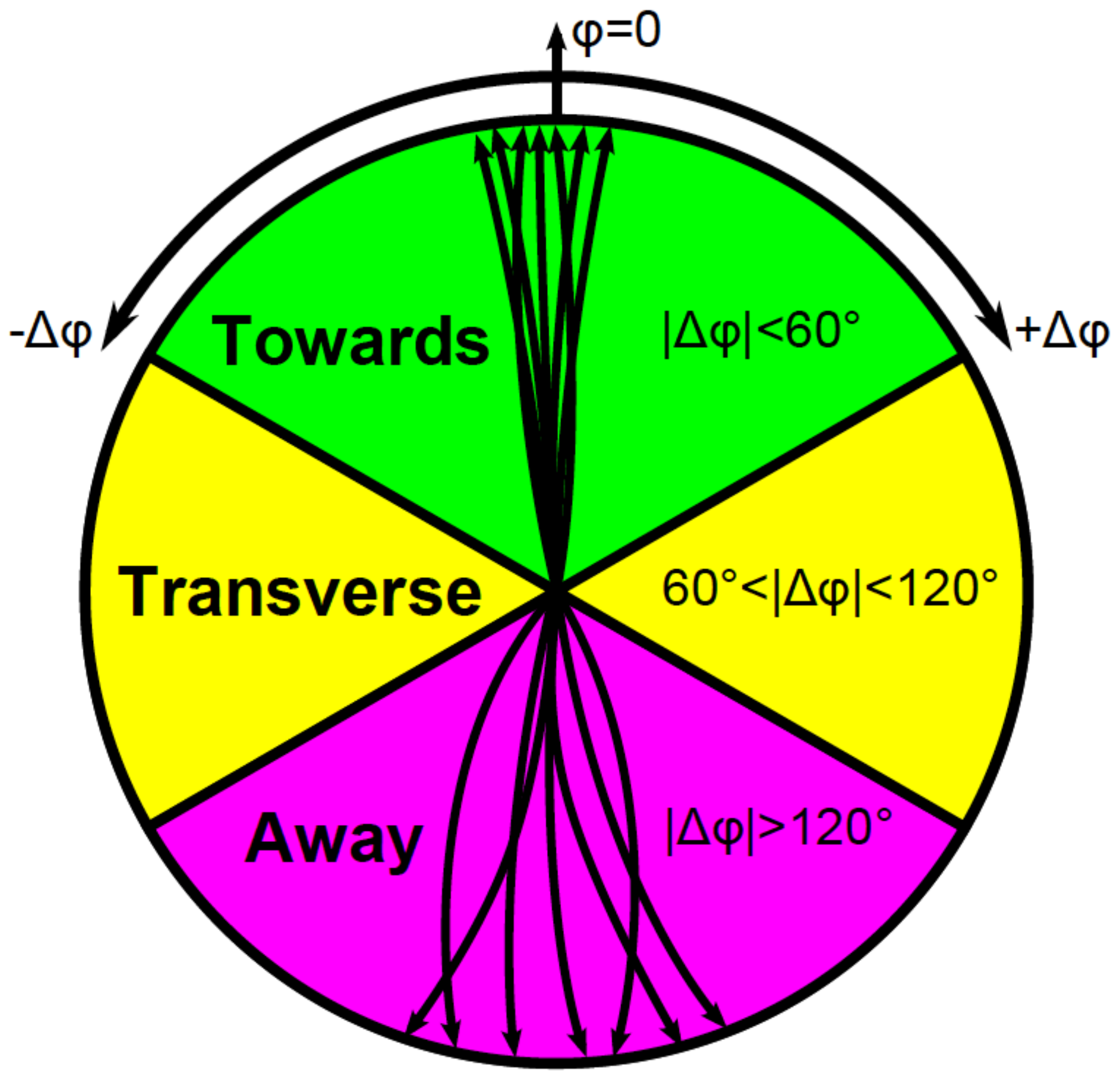
Multiplicity as a proxy for number of MPI (?)

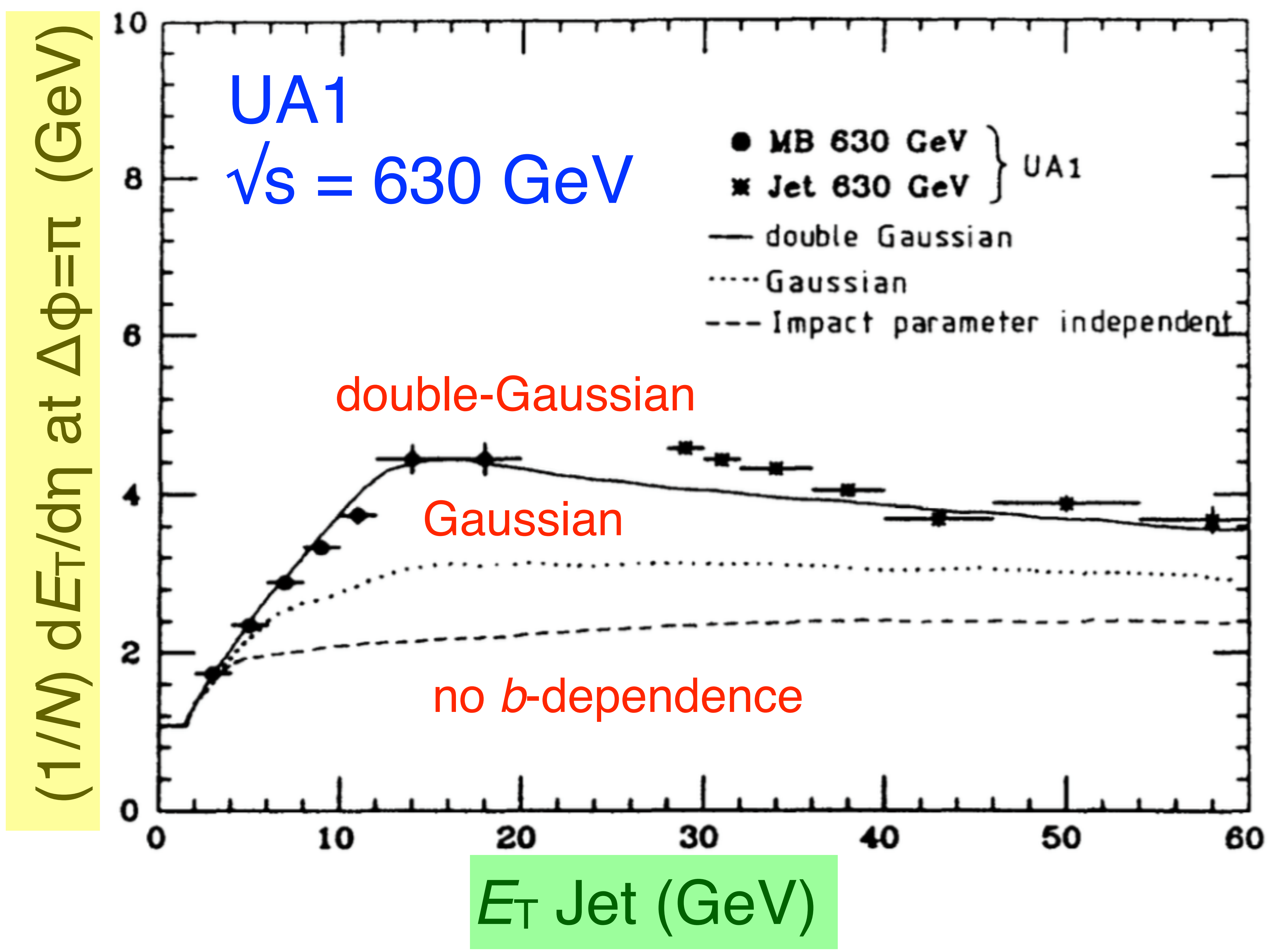




- Caveat at at low multiplicity
  - Smaller number of MPI, but also veto on single parton-parton scattering
  - Increased importance of non-perturbative processes (diffraction, …), very model dependent
  - Some strong effects (decrease of Ω/π) observed in this region.

Underlying Event of hard process = Minimum Bias?



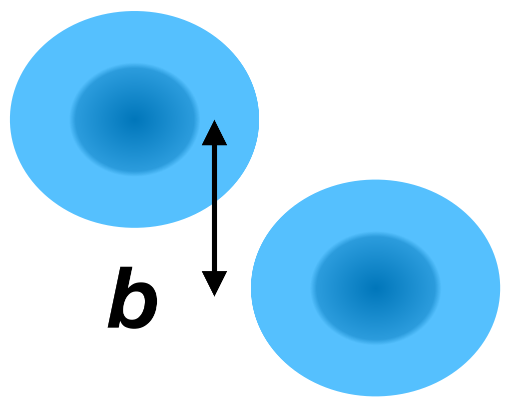


"jet pedestal"

- High p_T objects bias towards smaller *b* where probability for additional interactions is larger increased UE activity.
- Constrain in MPI models radial parton distribution in proton

Number of hard scatterings depends on matter overlap:

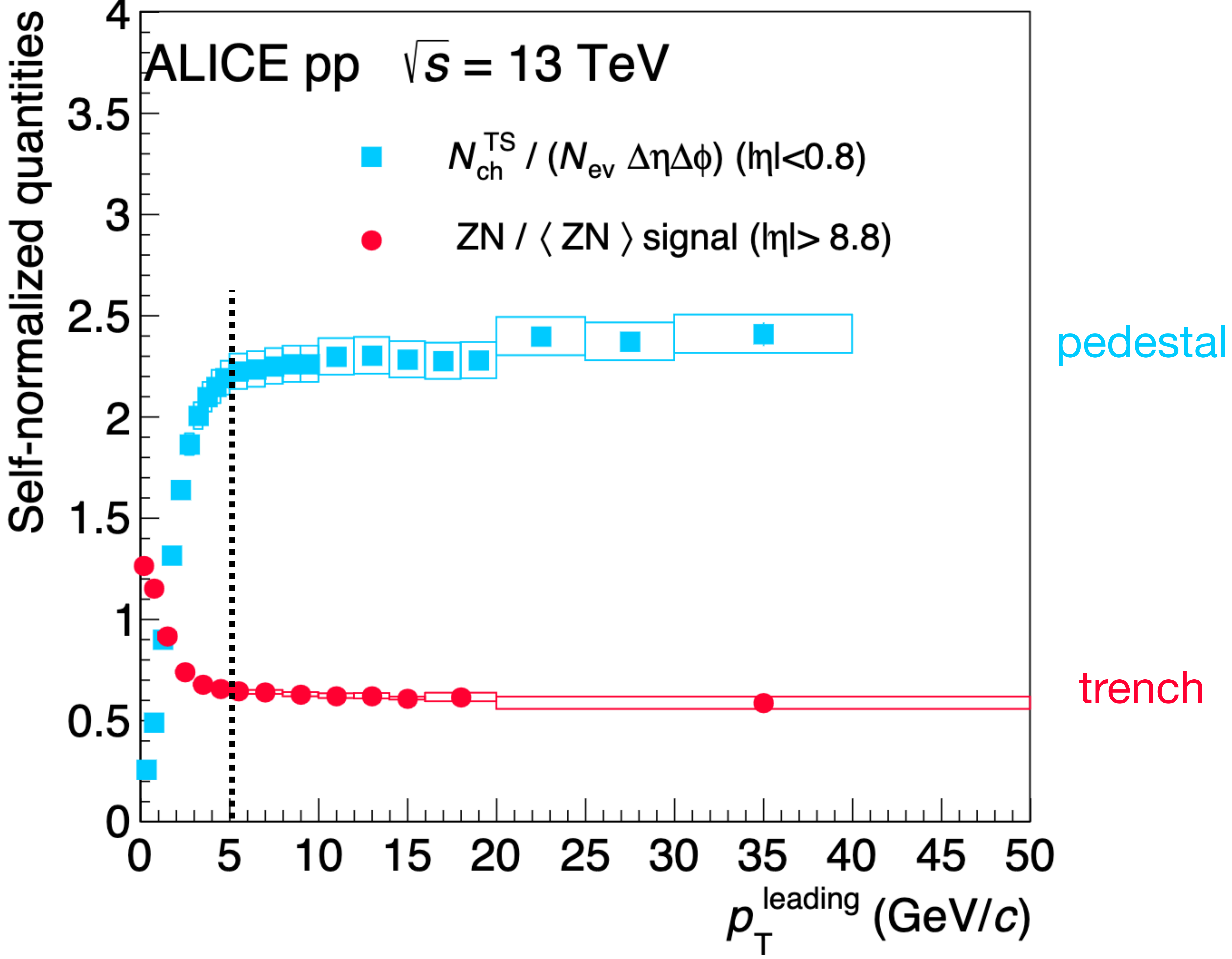
$$\langle n^{\text{hard}} \rangle = T_{\text{pp}}(b)\sigma_{\text{hard}}$$



Pedestal unambiguously related to initial state

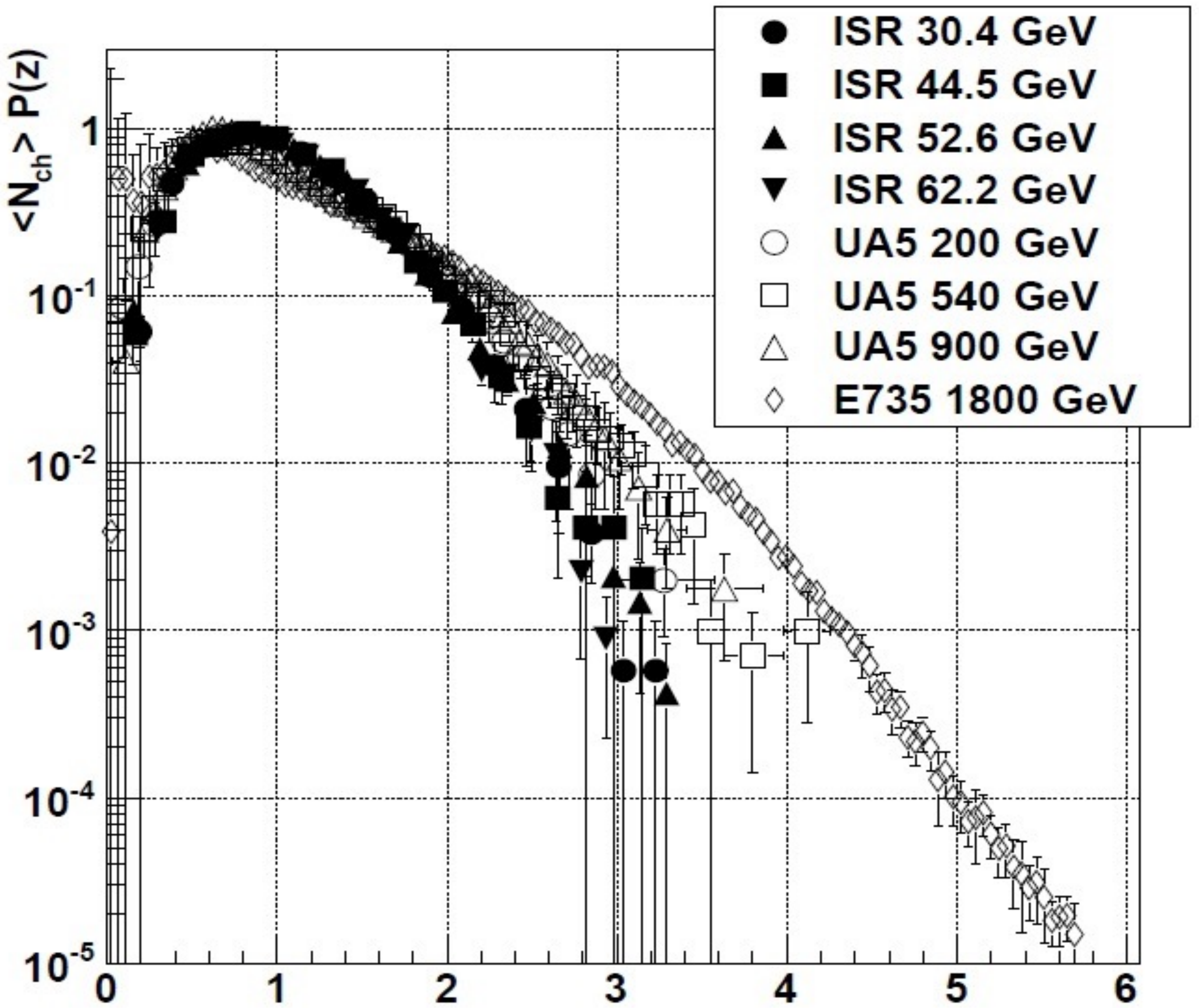
Correlation between 0-deg energy and leading particle tag

ALICE, Phys. Rev. C 91 (2015) 064905



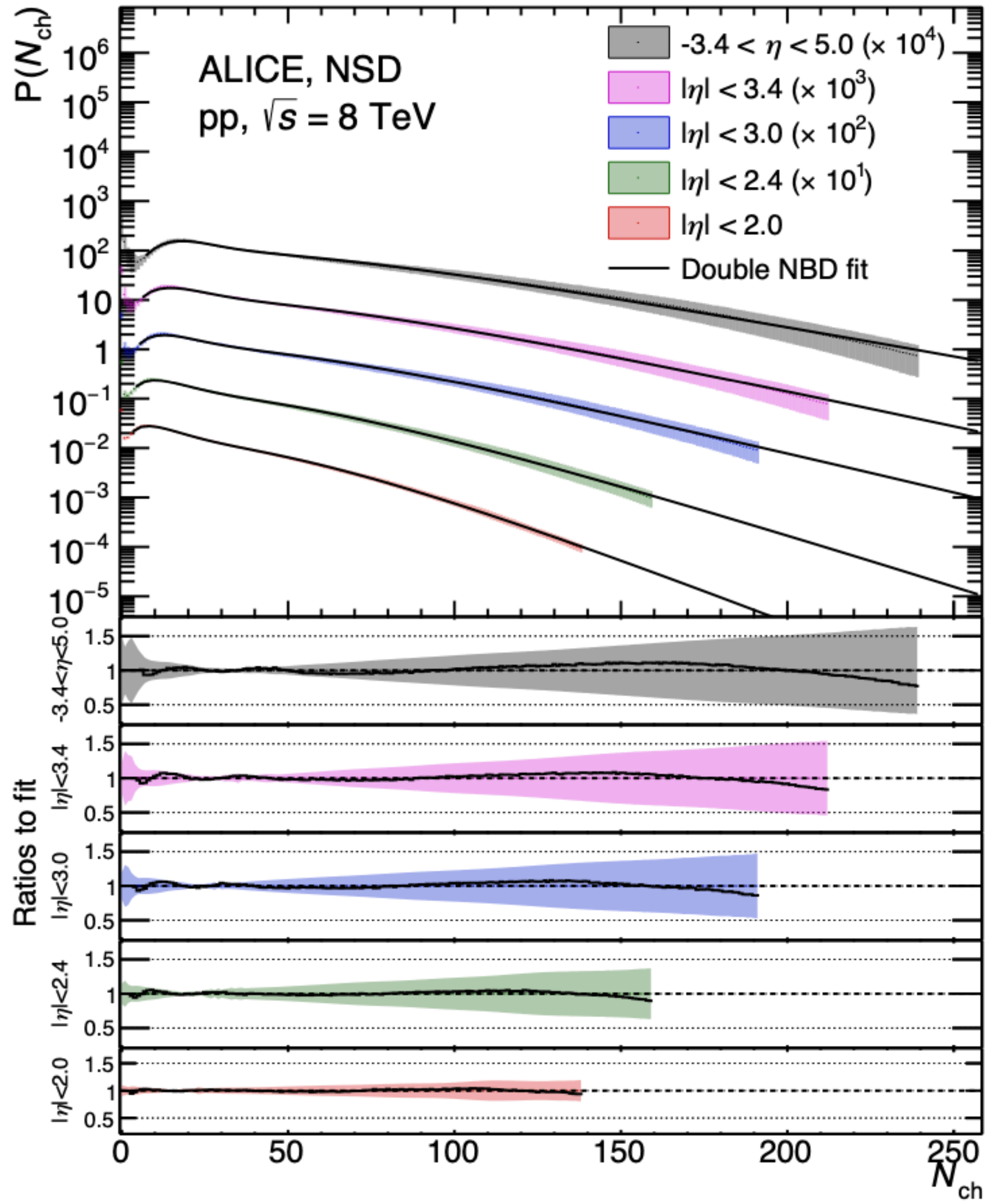
Correlations of signals separated by 8 units of rapidity proof that an initial state effect is observed

Centrality explains also deviation from KNO scaling



"self normalised" $z = N_{ch}/\langle N_{ch}\rangle$

Eur. Phys. J. C 77 (2017) 852



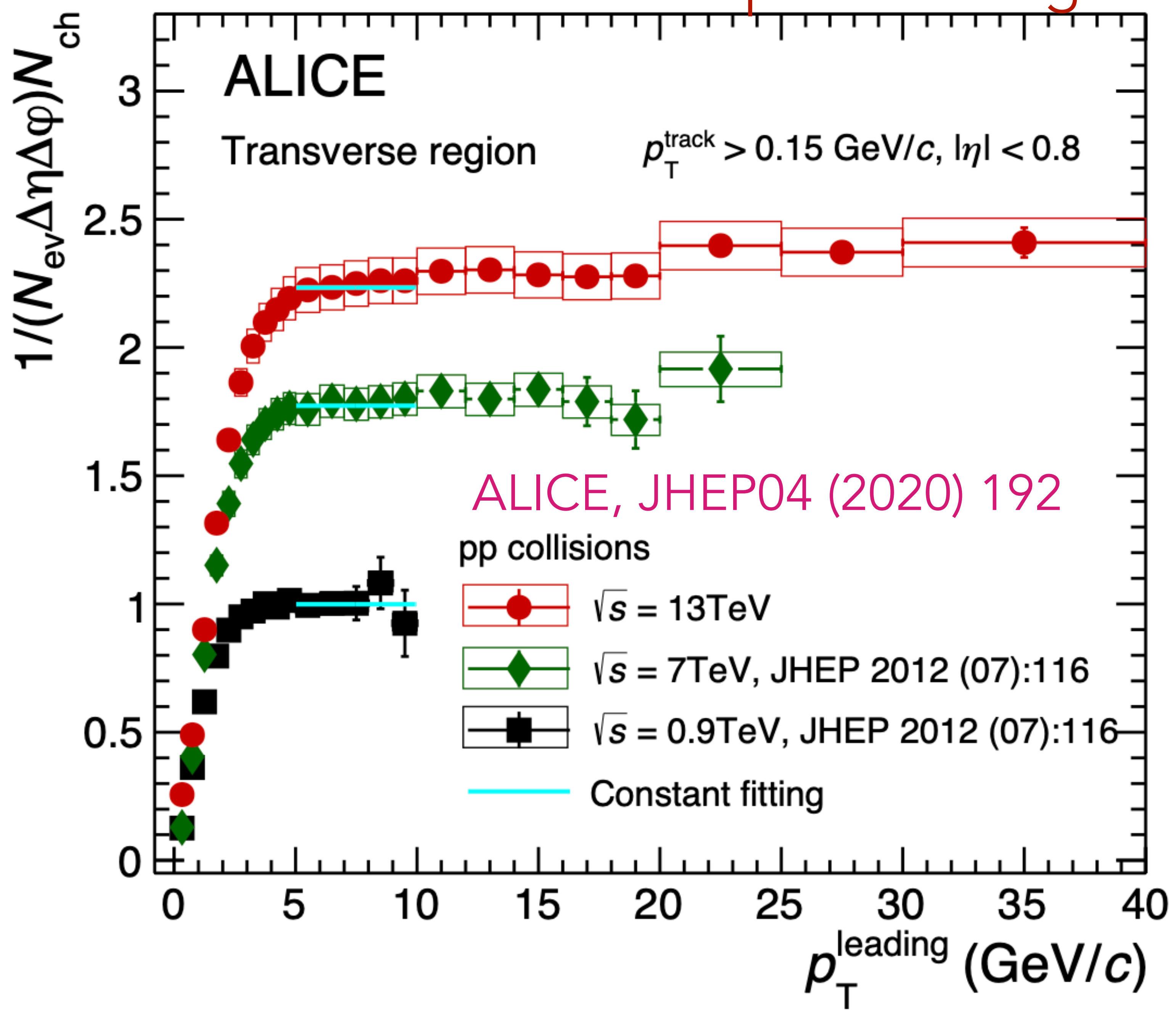
Deviation from KNO scaling for √s > 200 GeV

Fluctuations beyond Poissonian production of ancestors and their fragmentation.

Double Negative Binomial Distribution (NBD) provide could description of data

Fluctuations and pedestal are related

normalized pedestal hight

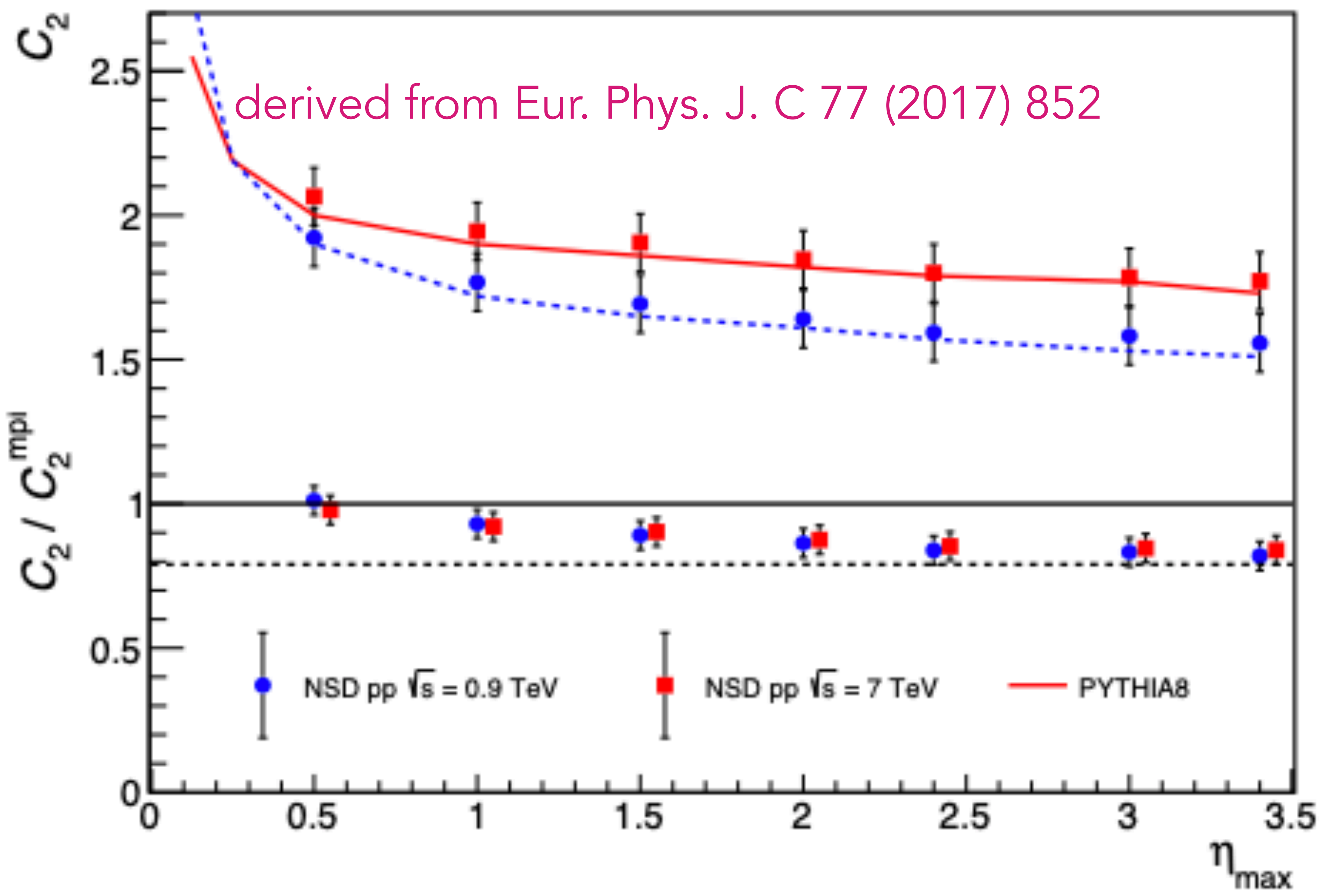


2.4 x MB

2.1 x MB

2 x MB

normalized moments



$$C_2 = \frac{\langle N^2 \rangle}{\langle N \rangle^2}$$

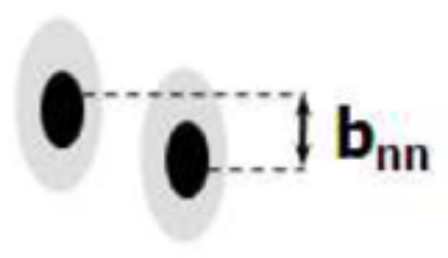
- Jet Pedestal and multiplicity fluctuations increase with $\sqrt{s}$
- They are similar in size, when properly normalised
- Relation via impact parameter fluctuations

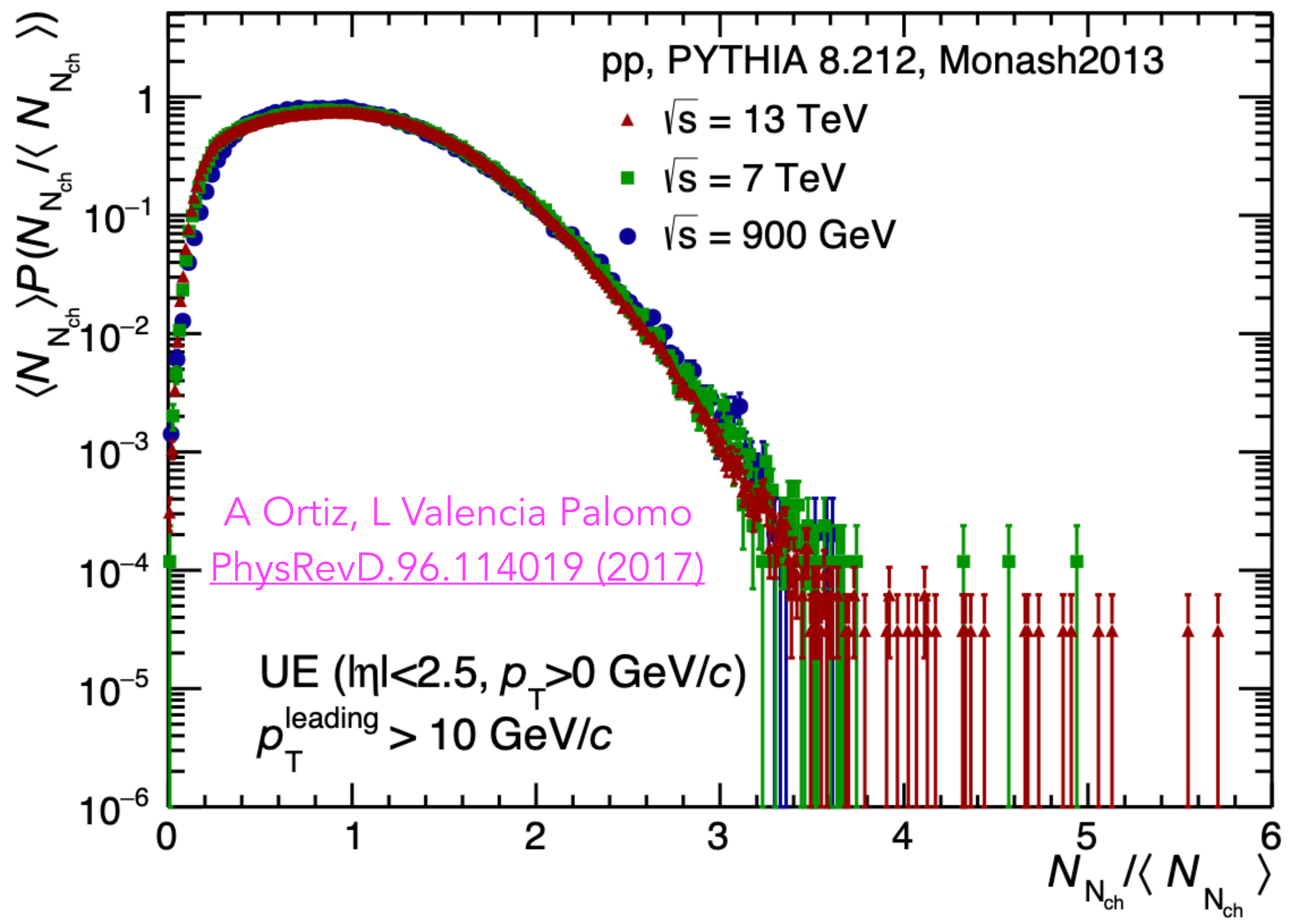
Fluctuations and pedestal are related

- Multiplicity fluctuations and jet pedestal effect are linked via impact parameter fluctuations.
  - In case hard yield proportional to (unbiased) multiplicity estimator

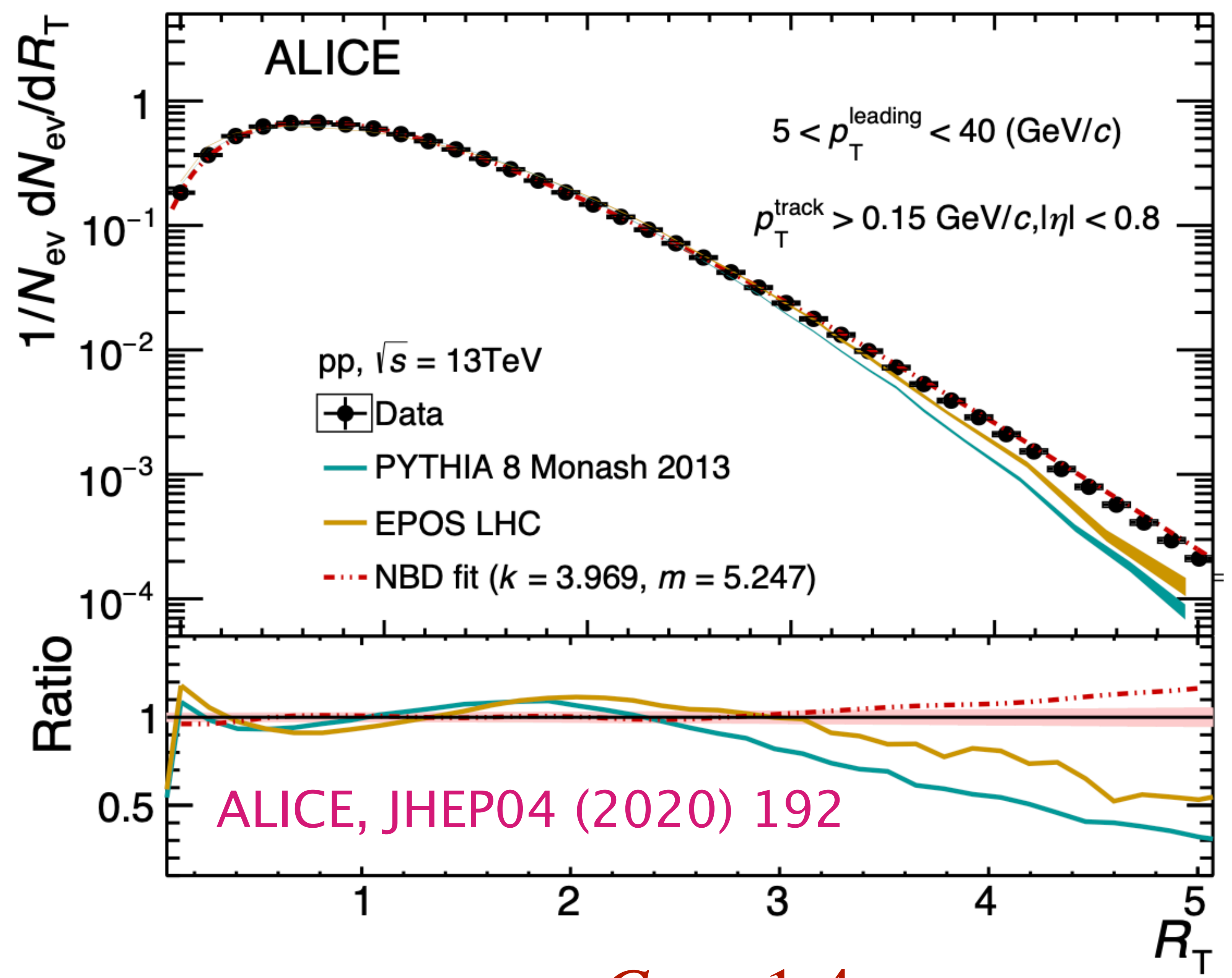
    $\langle Y \rangle / \langle Y \rangle_{MB} \propto \langle N \rangle / \langle N \rangle_{MB}$

  - $\langle N_{pedestal} \rangle / \langle N_{MB} \rangle = C_2 = \langle N_{MB}^2 \rangle / \langle N_{MB} \rangle^2 \approx 2$
- Since impact parameter more constrained also expect
  - $C_2^{pedestal} \approx C_3^{MPI} / (C_2^{MPI})^2 \approx 1.4 < C_2^{MB}$





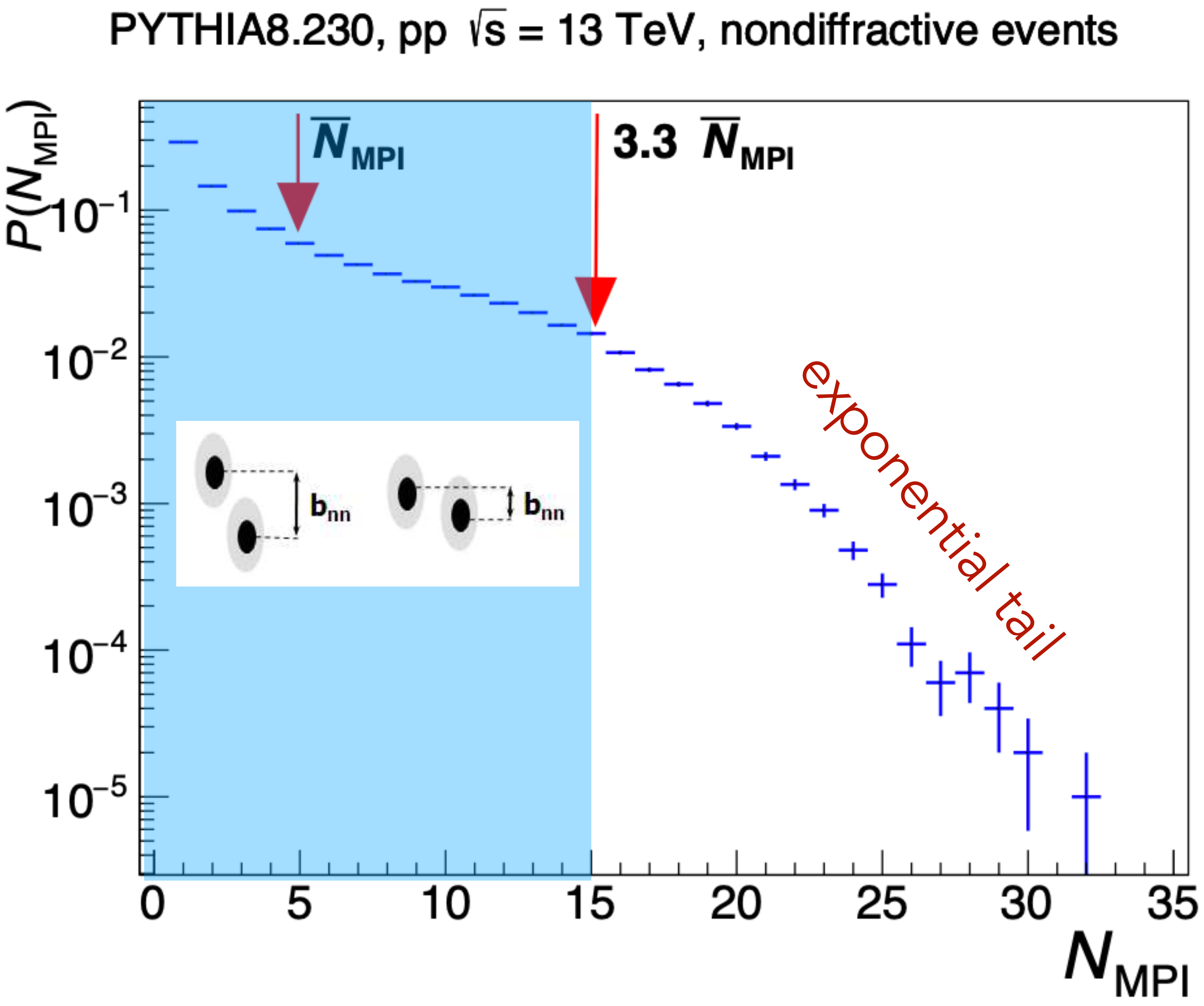
Multiplicity fluctuations inside pedestal region



$C_2 \approx 1.4$

and well described by NBD

Origin of high multiplicity events

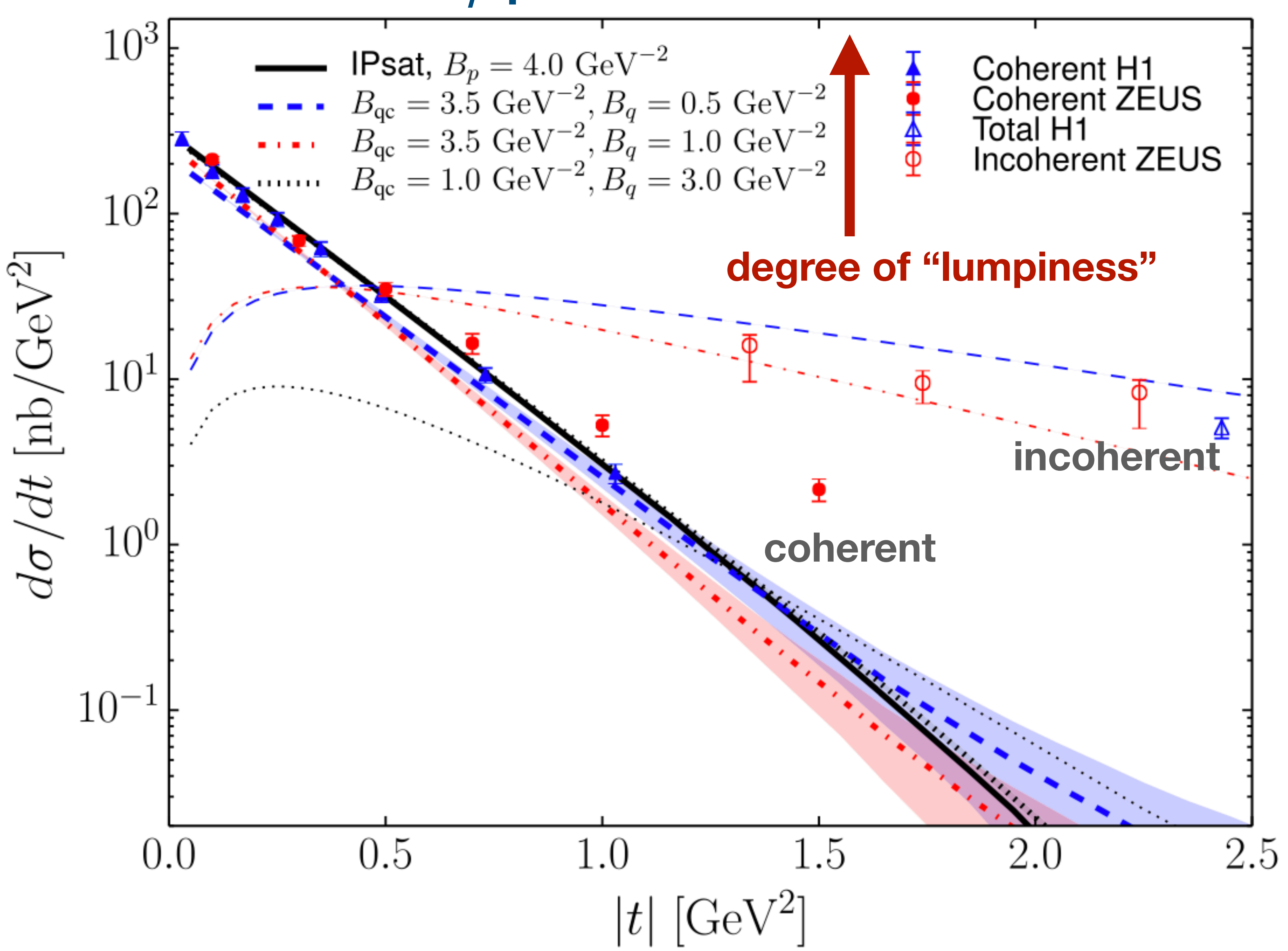


- Very high multiplicity events are not anymore explained by impact parameter fluctuations
- Mainly statistical fluctuations ?

e-p: The lumpiness of the proton

H. Mantysaari and B. Schenke, Phys. Lett. B772 (2017) 832

diffractive J/ψ production



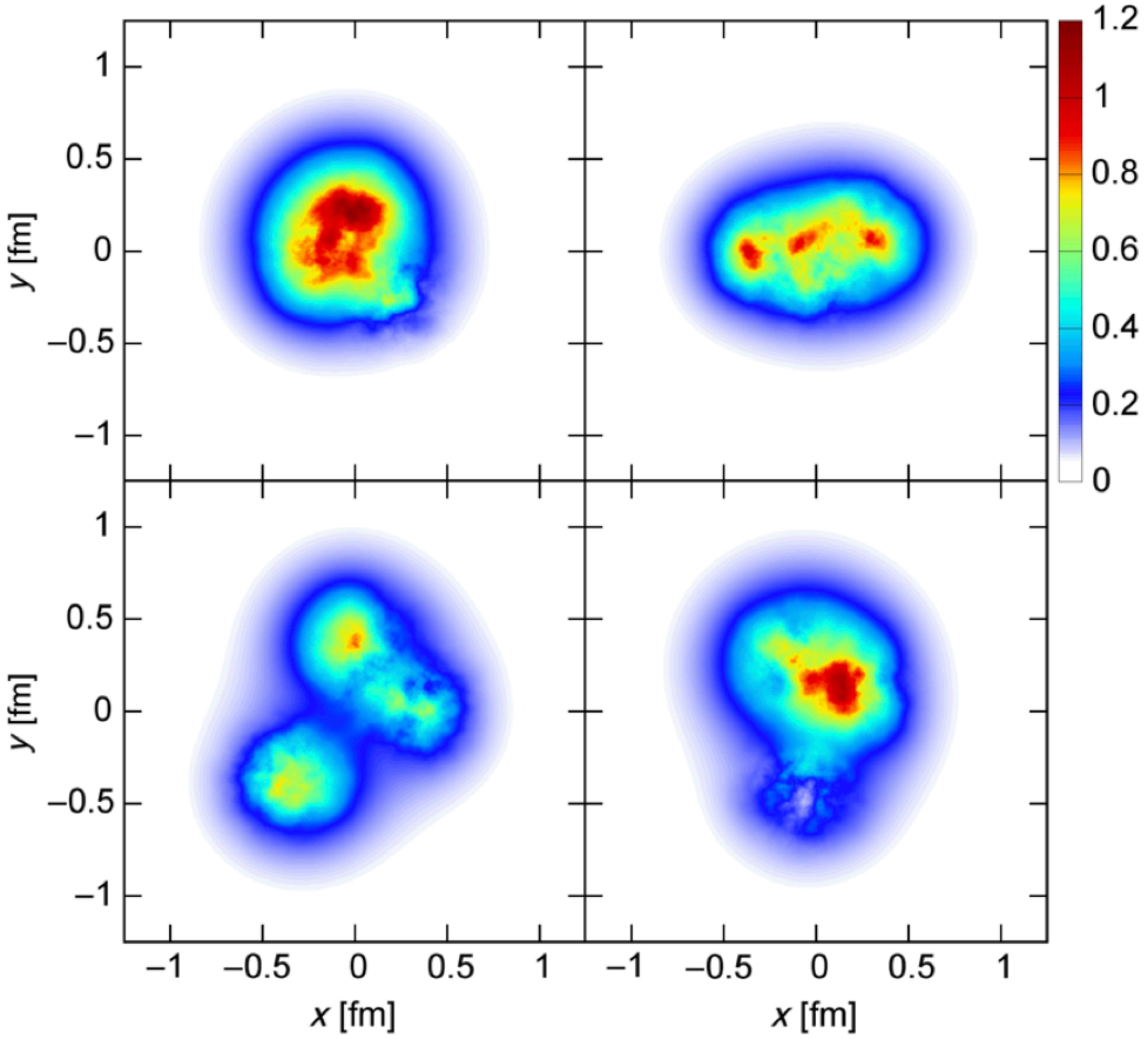


FIG. 3. Four configurations of the proton in the IP-Glasma model at $x \approx 10^{-3}$, represented by $1 - \mathrm{Re}(\mathrm{Tr}V)/N_c$.

Incoherent cross section is extremely sensitive to the degree of geometric fluctuations of the proton.

Additional fluctuations?

Eur. Phys. J. C 77 (2017) 852

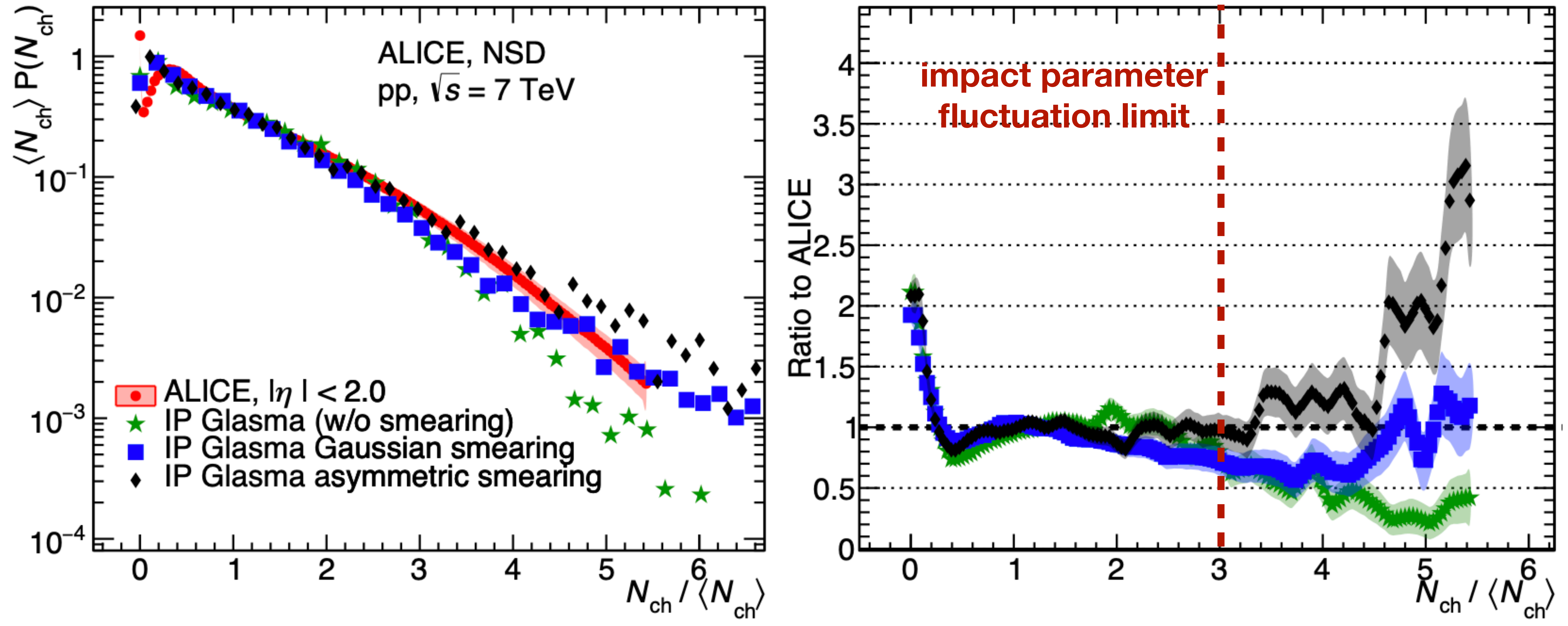
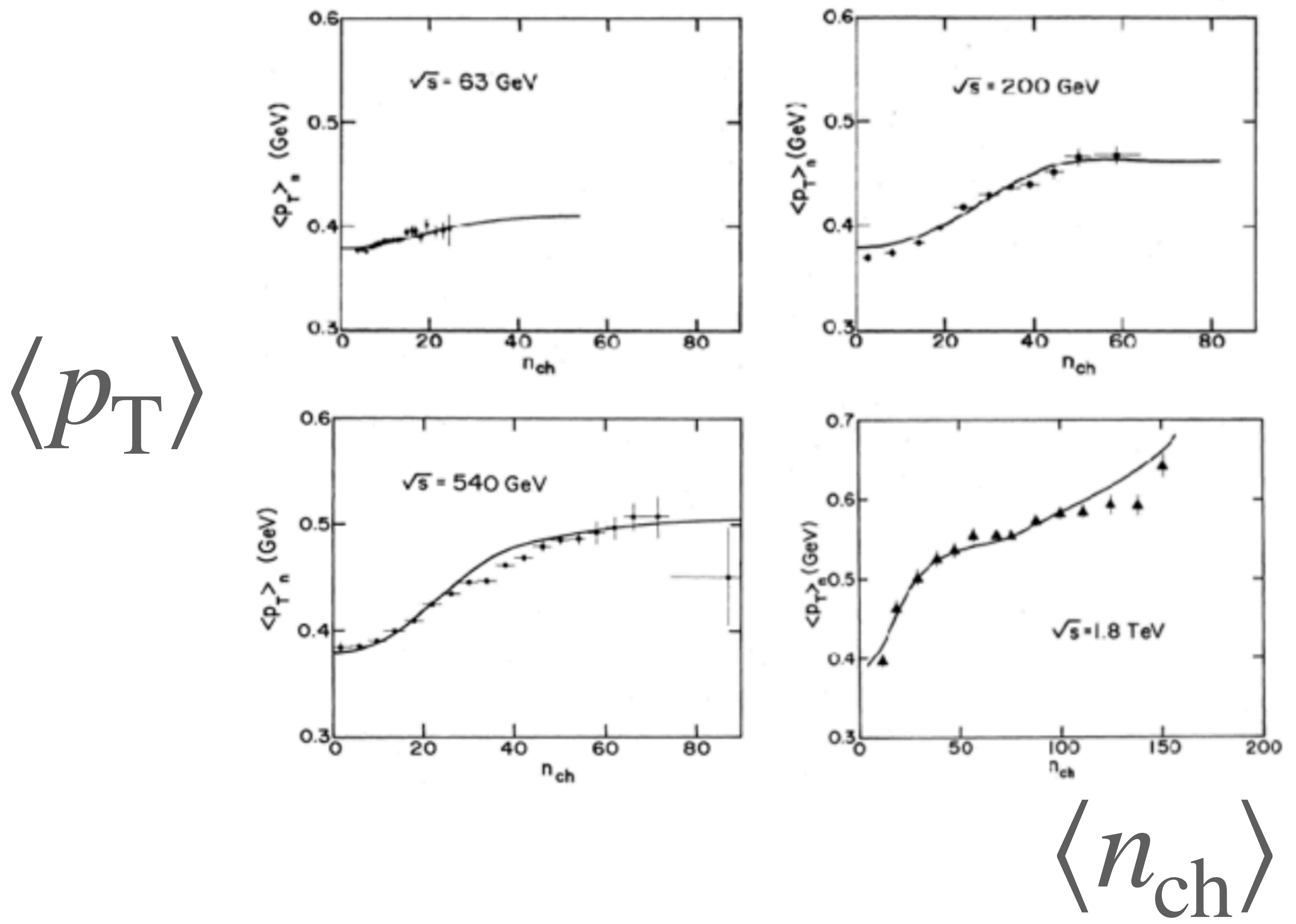


Figure 8: Charged-particle multiplicity distributions for pp collisions at $\sqrt{s} = 7$ TeV compared to distributions from the IP-Glasma model with the ratio between Q_s and the color charge density either fixed (green stars), allowed to fluctuate with a Gaussian (blue squares) [12] or with additional fluctuations of proton saturation scale (black diamonds) [13].

Are the tails of the multiplicity distribution sensitive to fluctuations beyond the impact parameter limit?

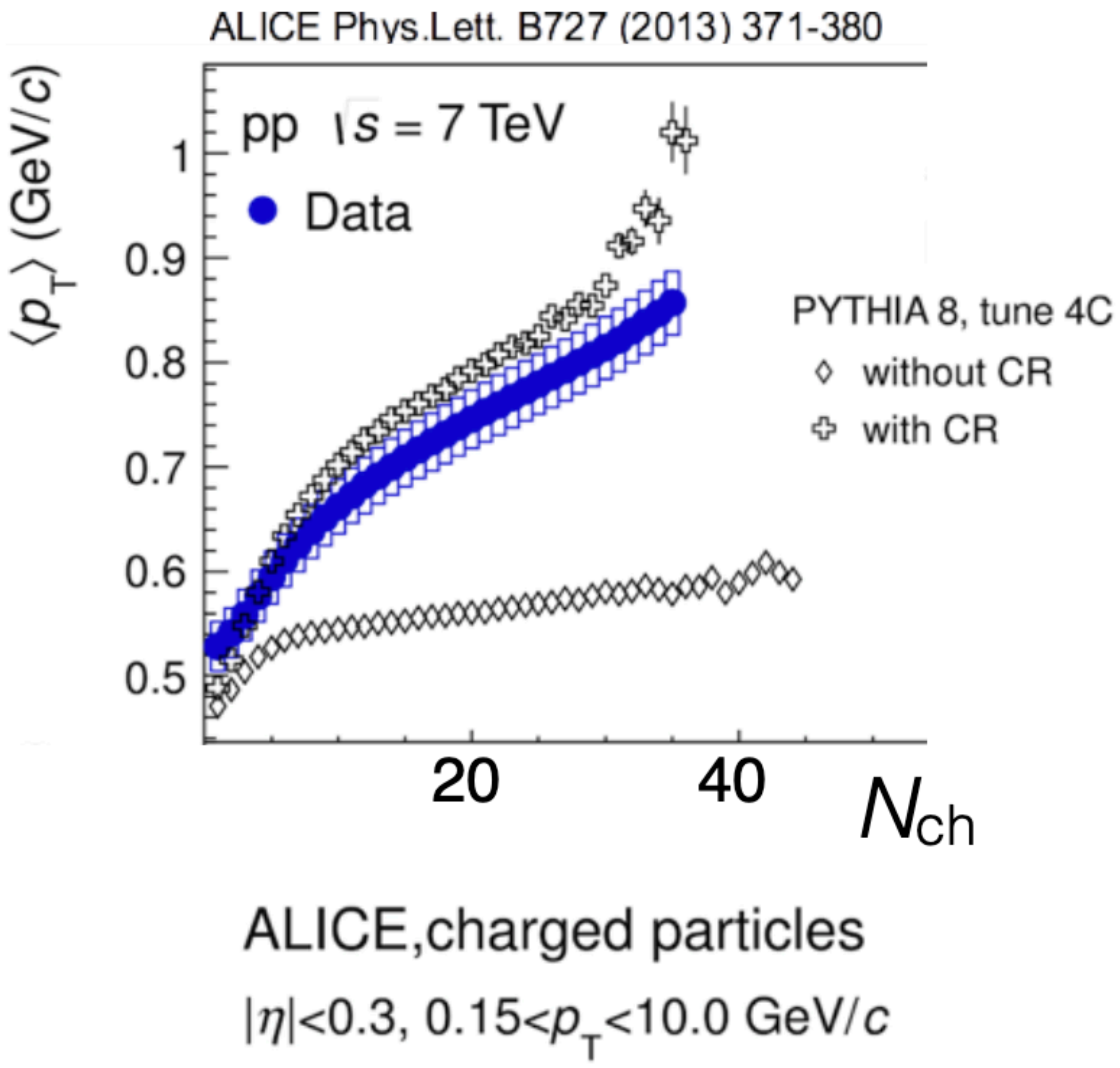
Two components model: Hard-Soft Transition

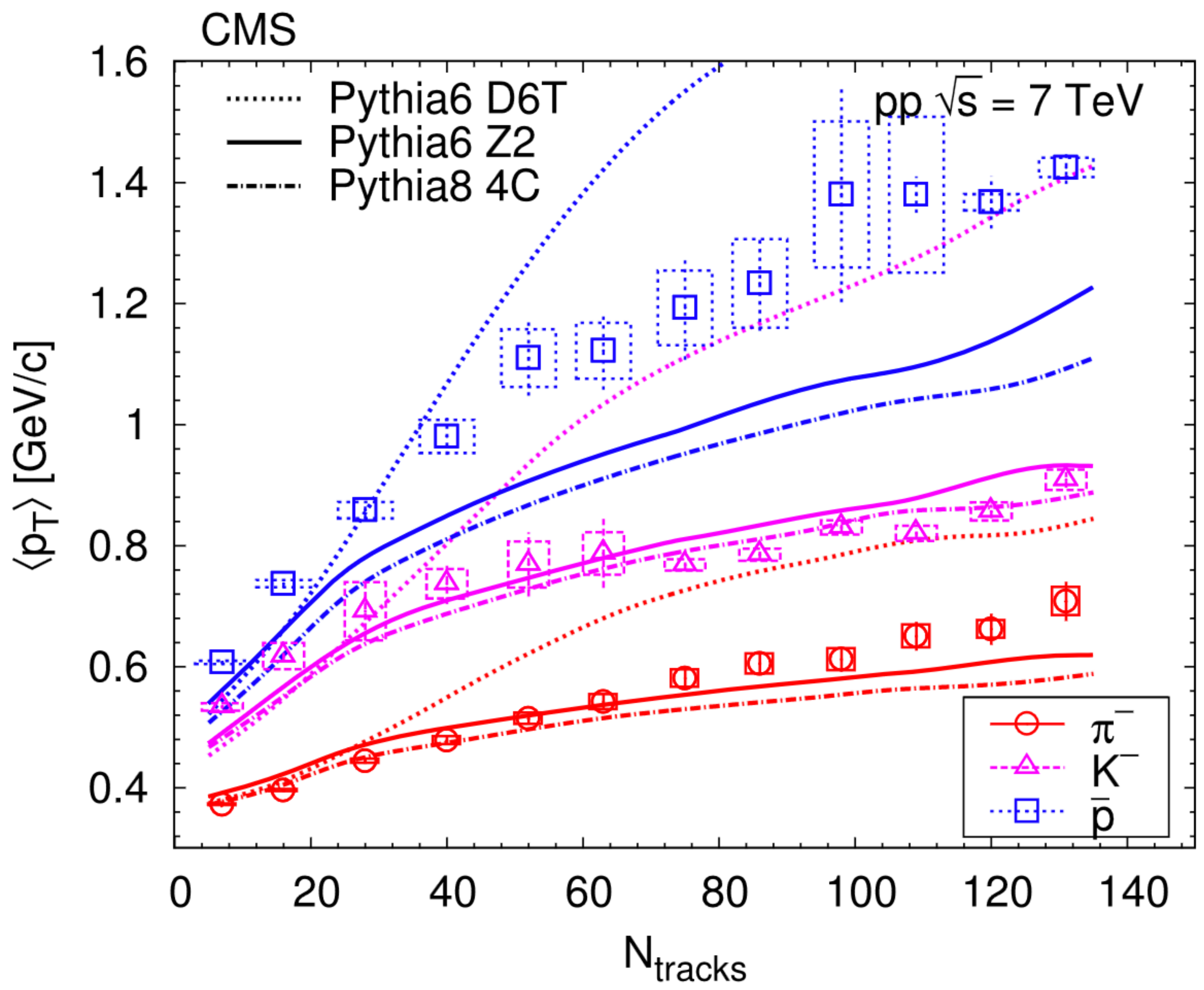
XN Wang and R Hwa (Phys.Rev. D39 (1989) 187)

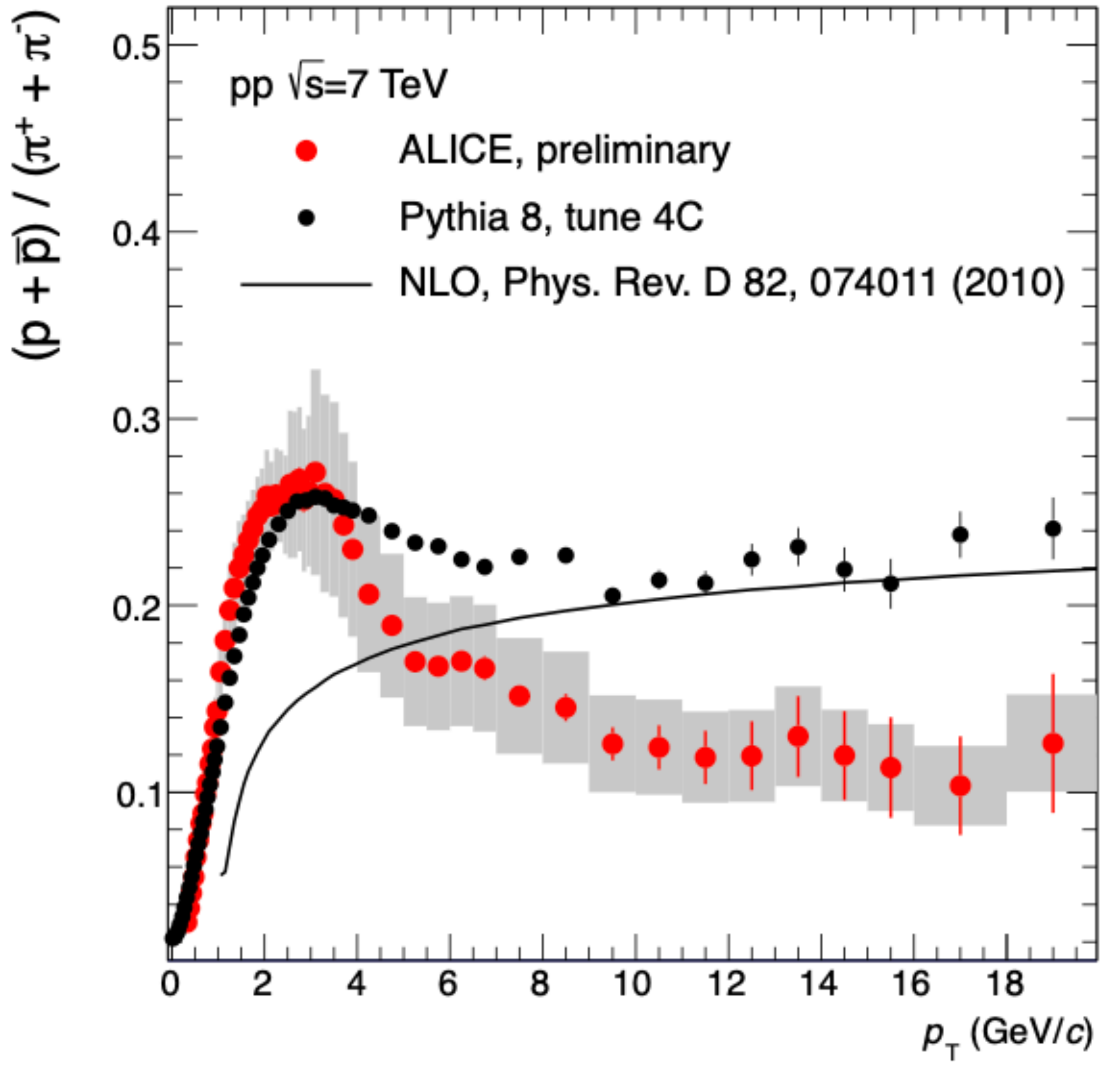


- two component model hard + soft
- expect "ledge effect"
  - 1st ledge: increasing dominance of hard processes
  - 2nd ledge: jet fragments contribute to multiplicity ⇒ fragmentation and parton-p_T bias

More than hard/soft transition







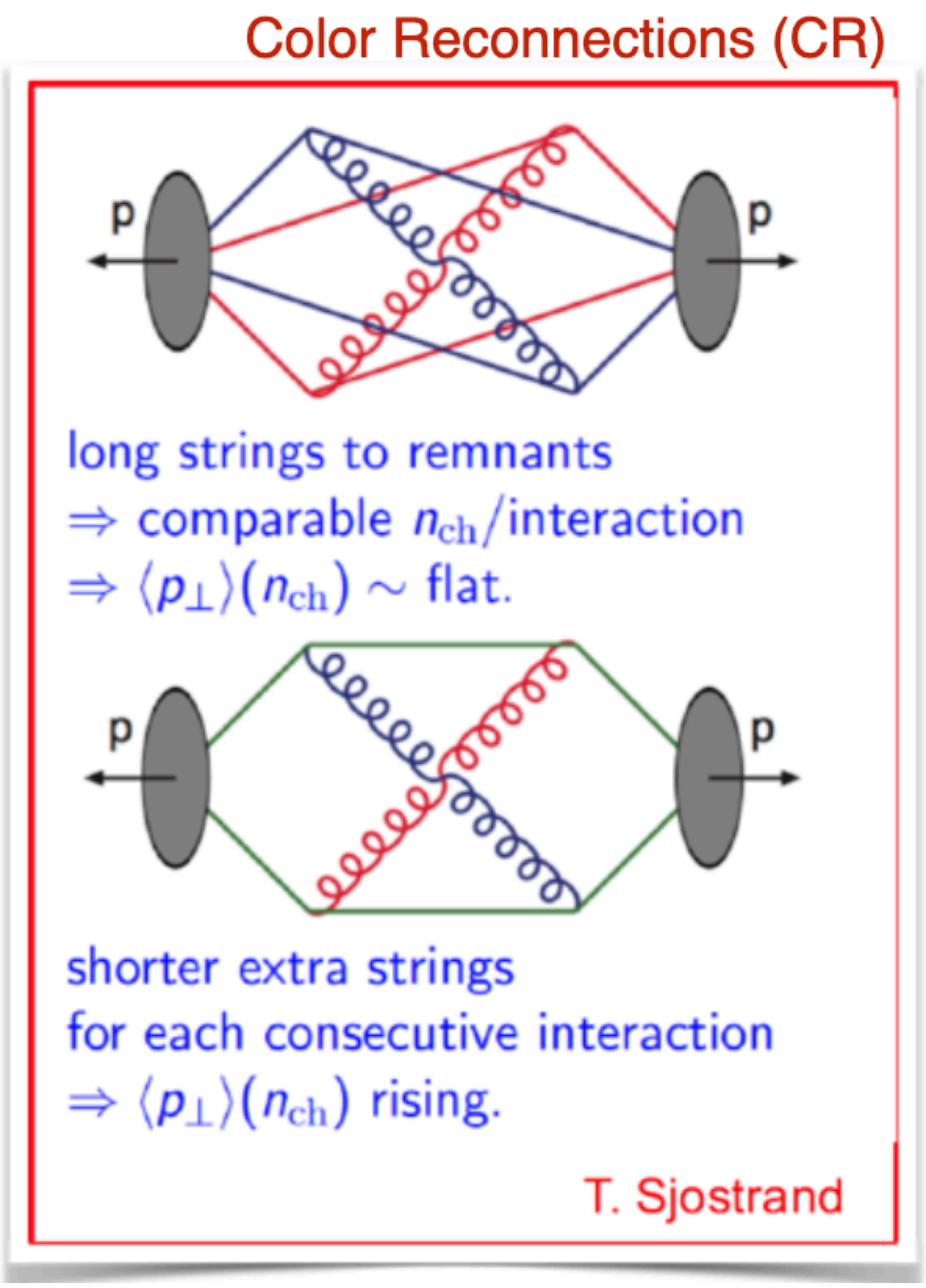
Effects stronger than the soft/hard transition

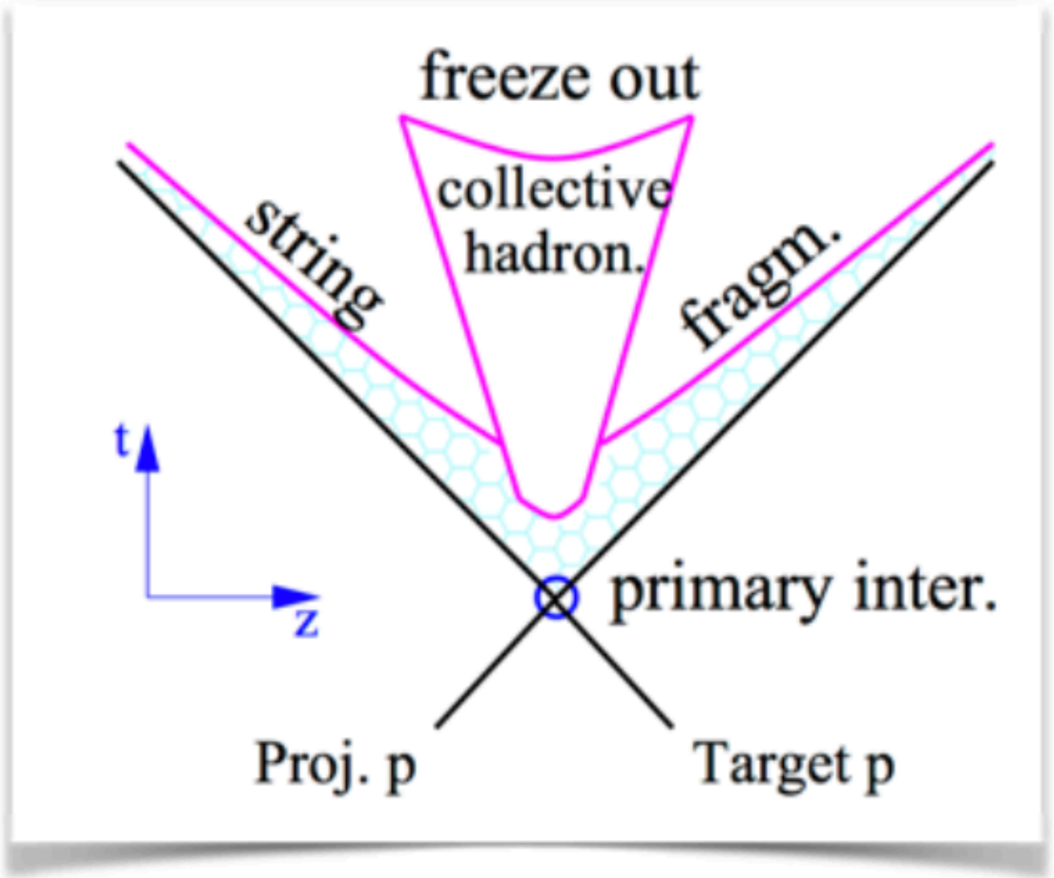
Clear mass dependence

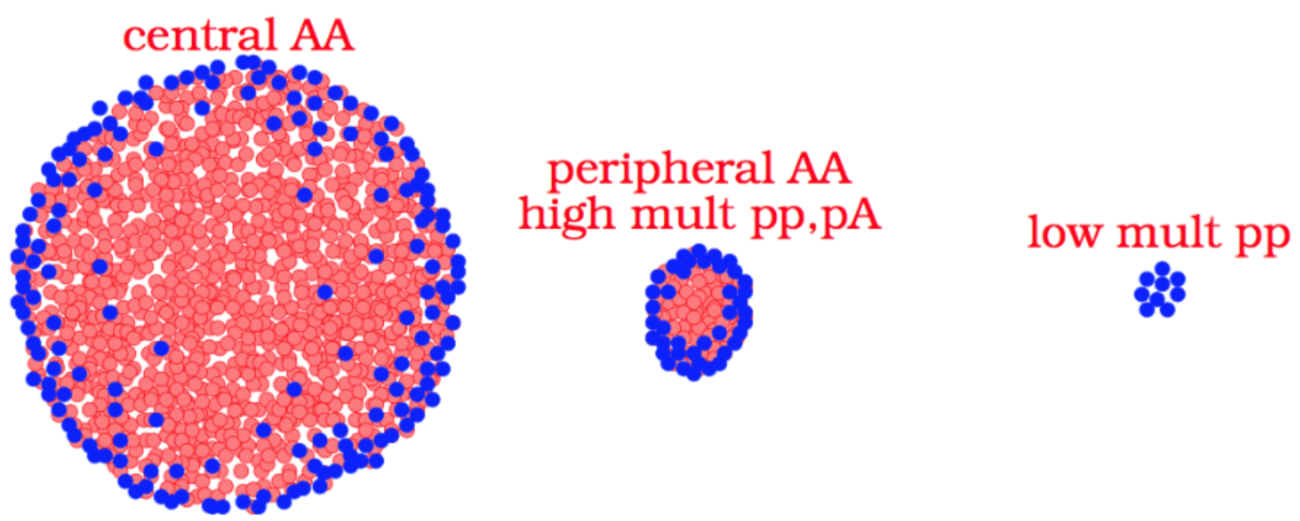
A Ortiz, P Christiansen, E Cuautle, I Maldonado, G Paic, PRL 111 042001 (2013)

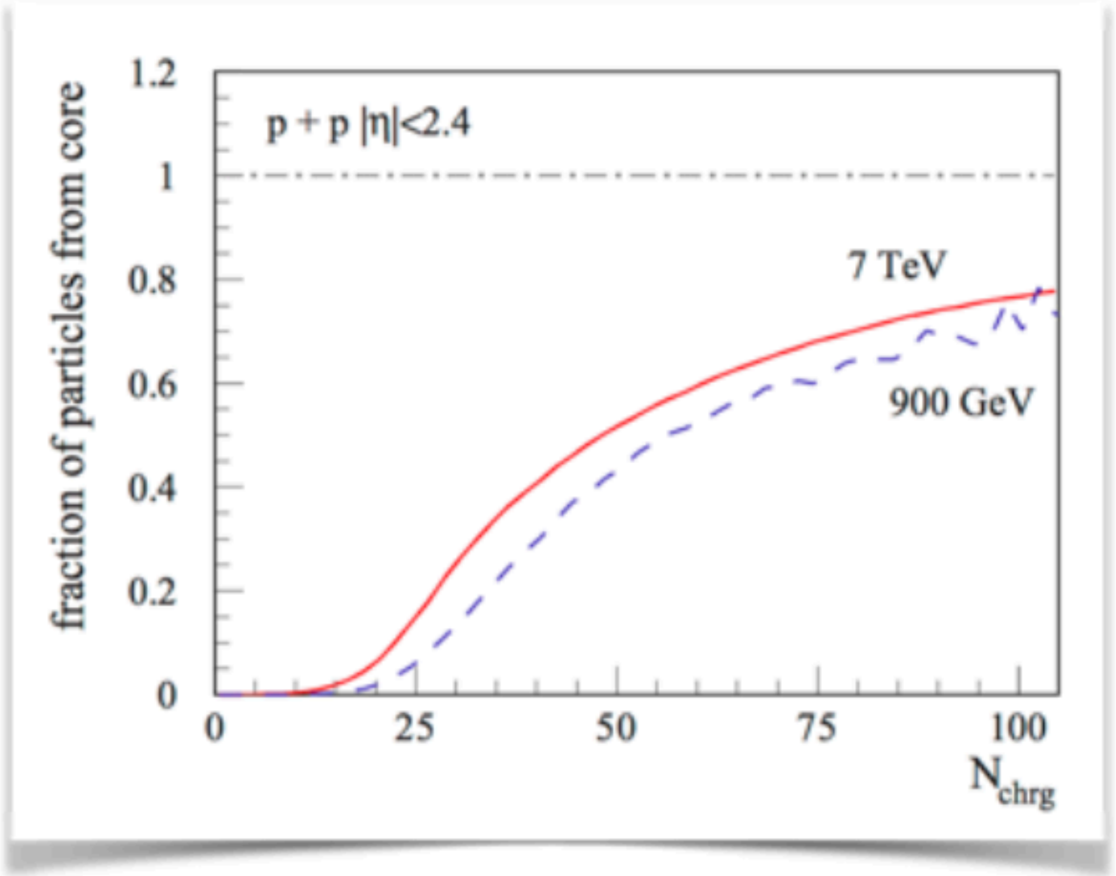
PYTHIA with coherence between strings (color reconnection) produces effects that resemble collective effects in PbPb

Collective effects in Pythia and EPOS



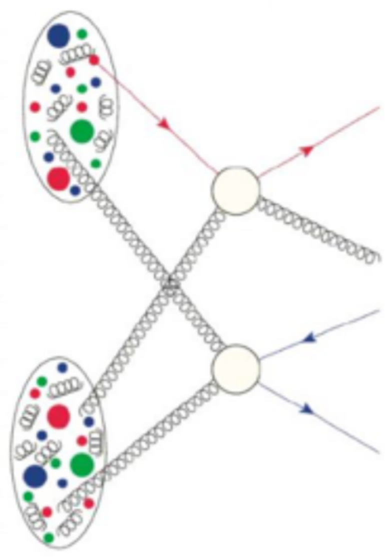




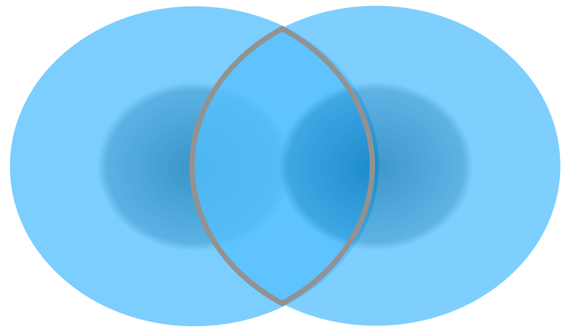


- Corona: string decays
- Core: hydrodynamic evolution and statistical decays

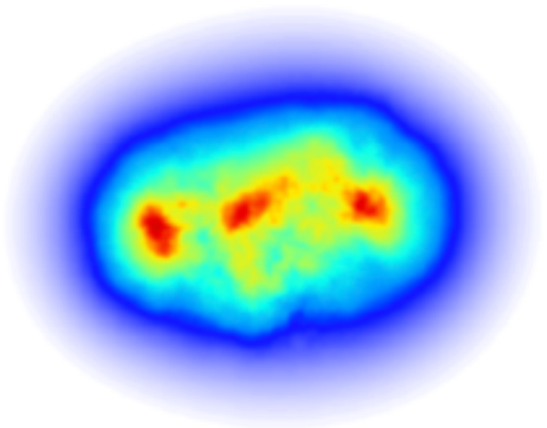
Basic pp physics so far …



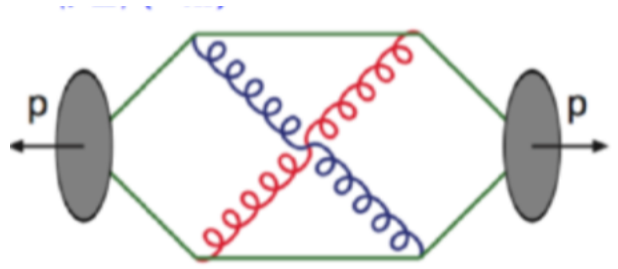
At LHC, multiple partonic interactions at pQCD scale



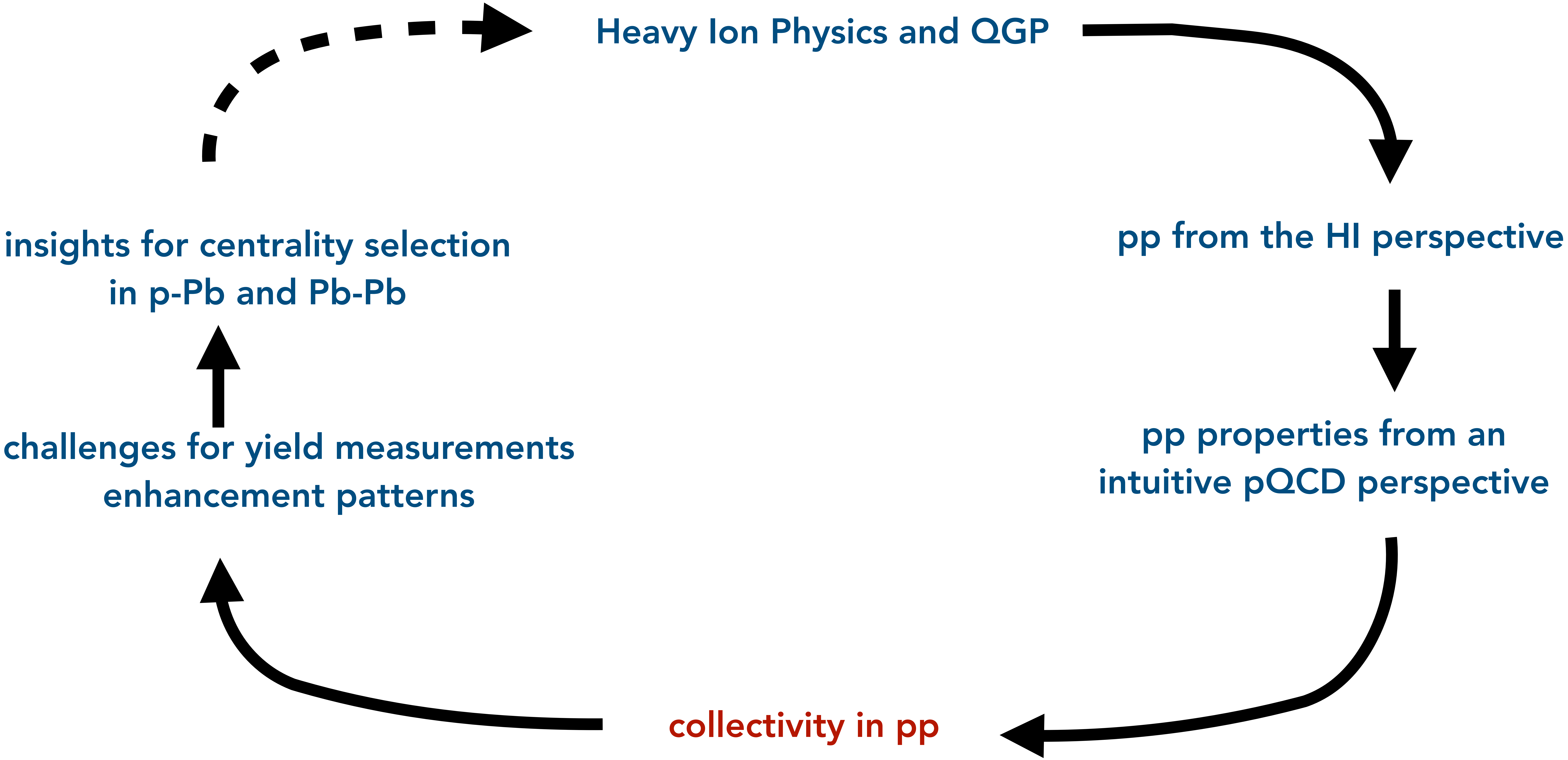
Centrality dependent effects until about 3xMin Bias multiplicity



Sub-fm density fluctuations inside proton and in collision region



Evidence for interactions between partons produced in initial collision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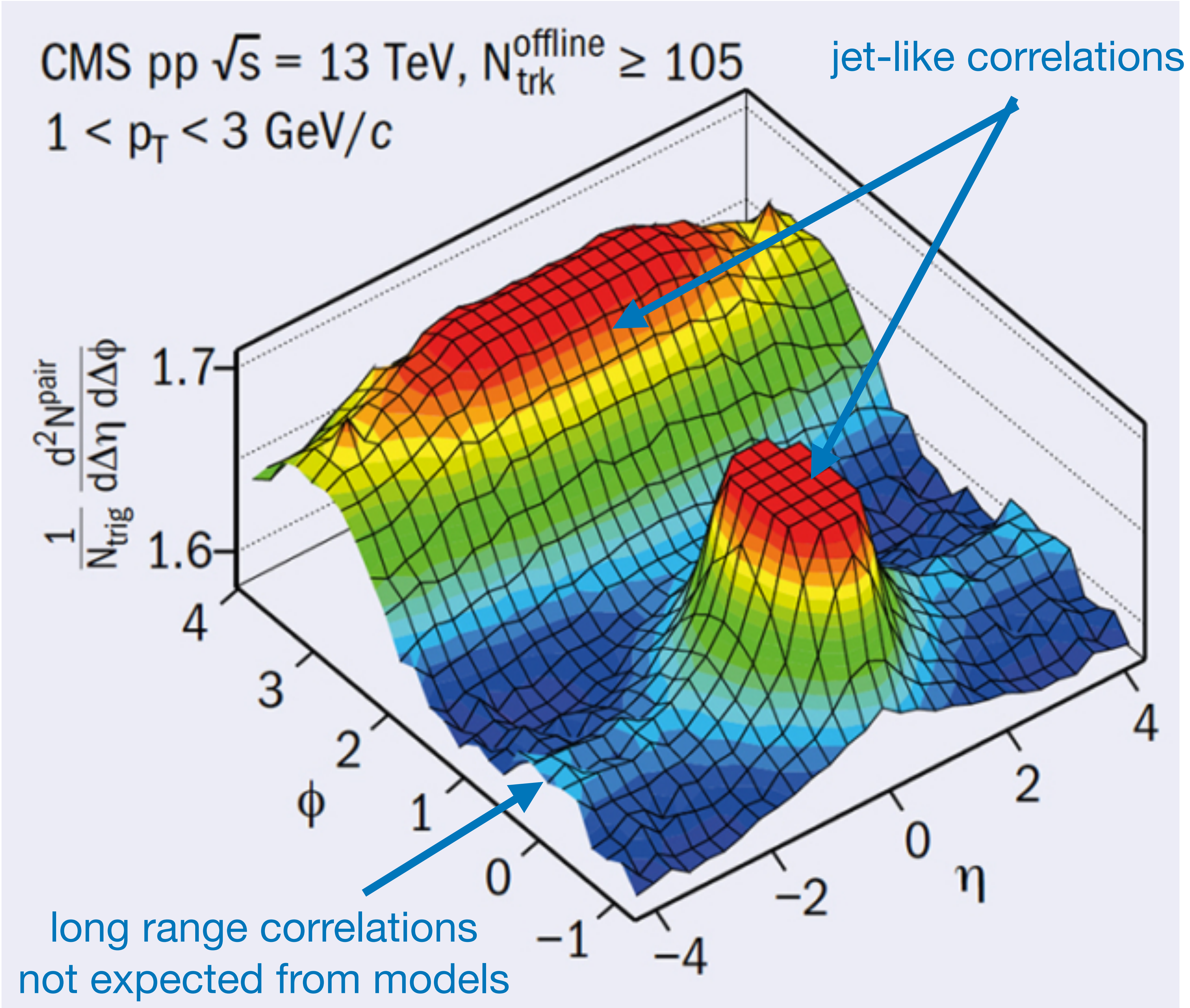
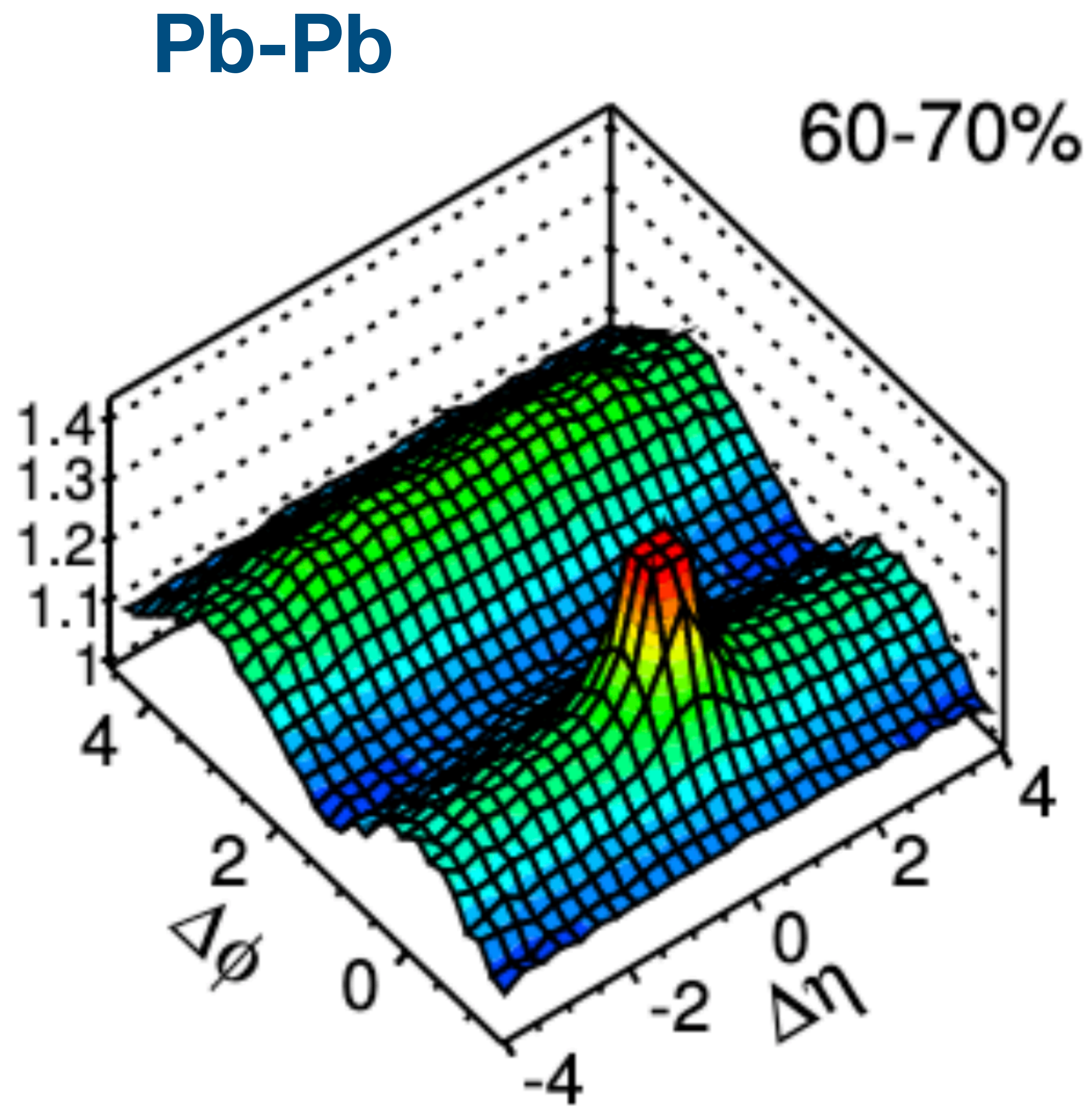
Long range $\Delta\eta$ correlations in pp: "Ridge"

STRONG INTERACTIONS | NEWS

CMS observes long-range correlations in pp collisions at 13 TeV

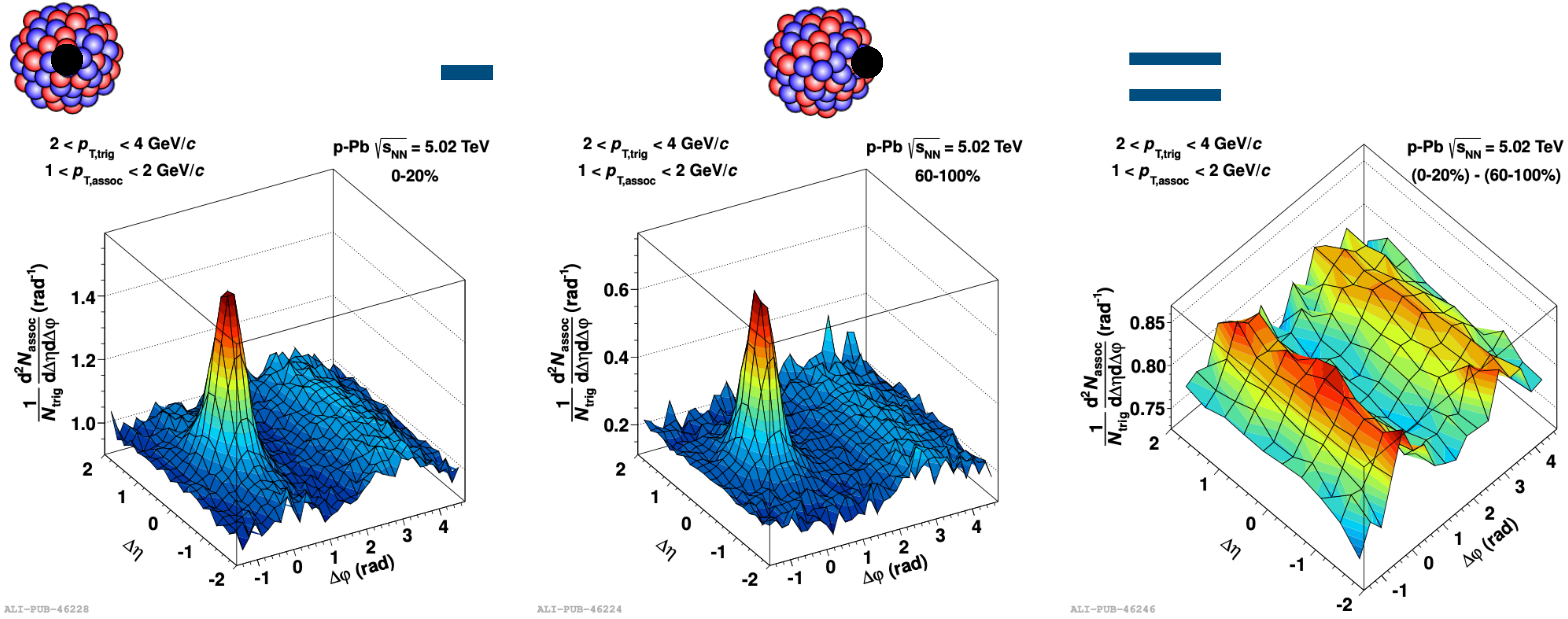
28 October 2015





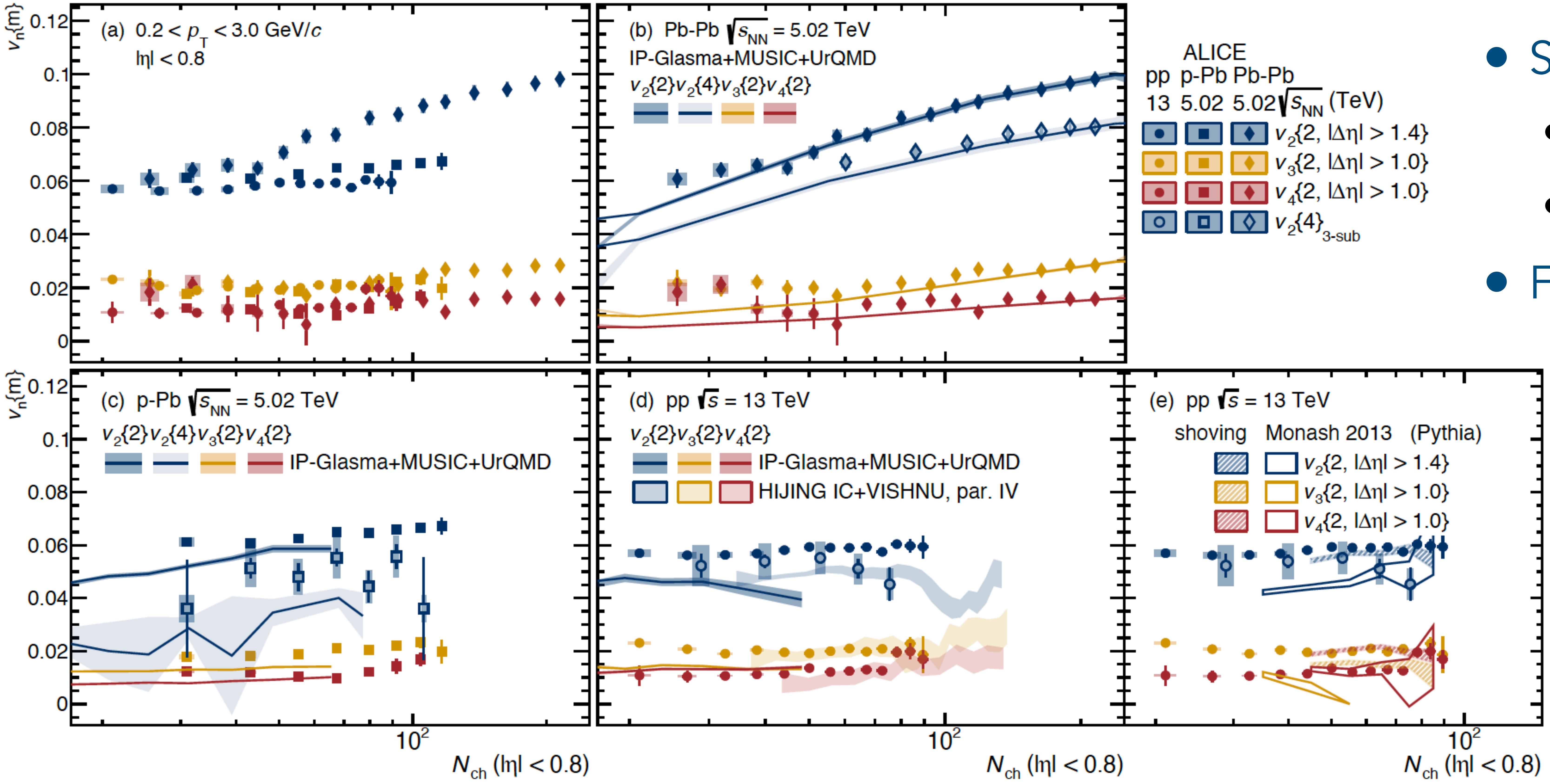
- Striking similarity with Pb-Pb where effect is associated to QGP formation
- However, at that point not excluded that jet-like correlations play a rôle.

p-Pb: removal of jet-like correlations



- Jet-like correlation removed by subtracting correlations in peripheral collisions
- Results in cos($2\Delta\phi$)-modulation constant in $\Delta\eta$

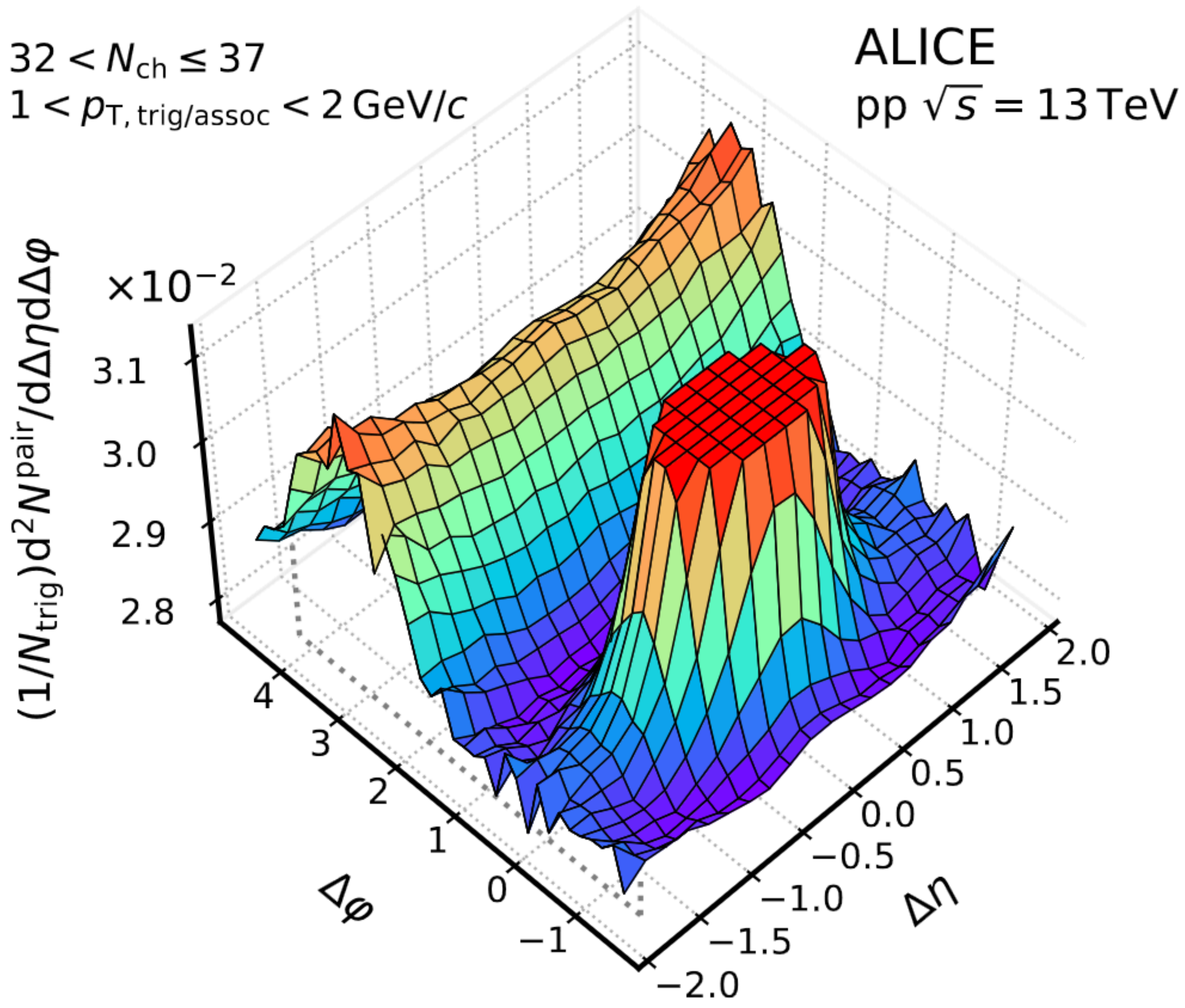
Collectivity in pp?



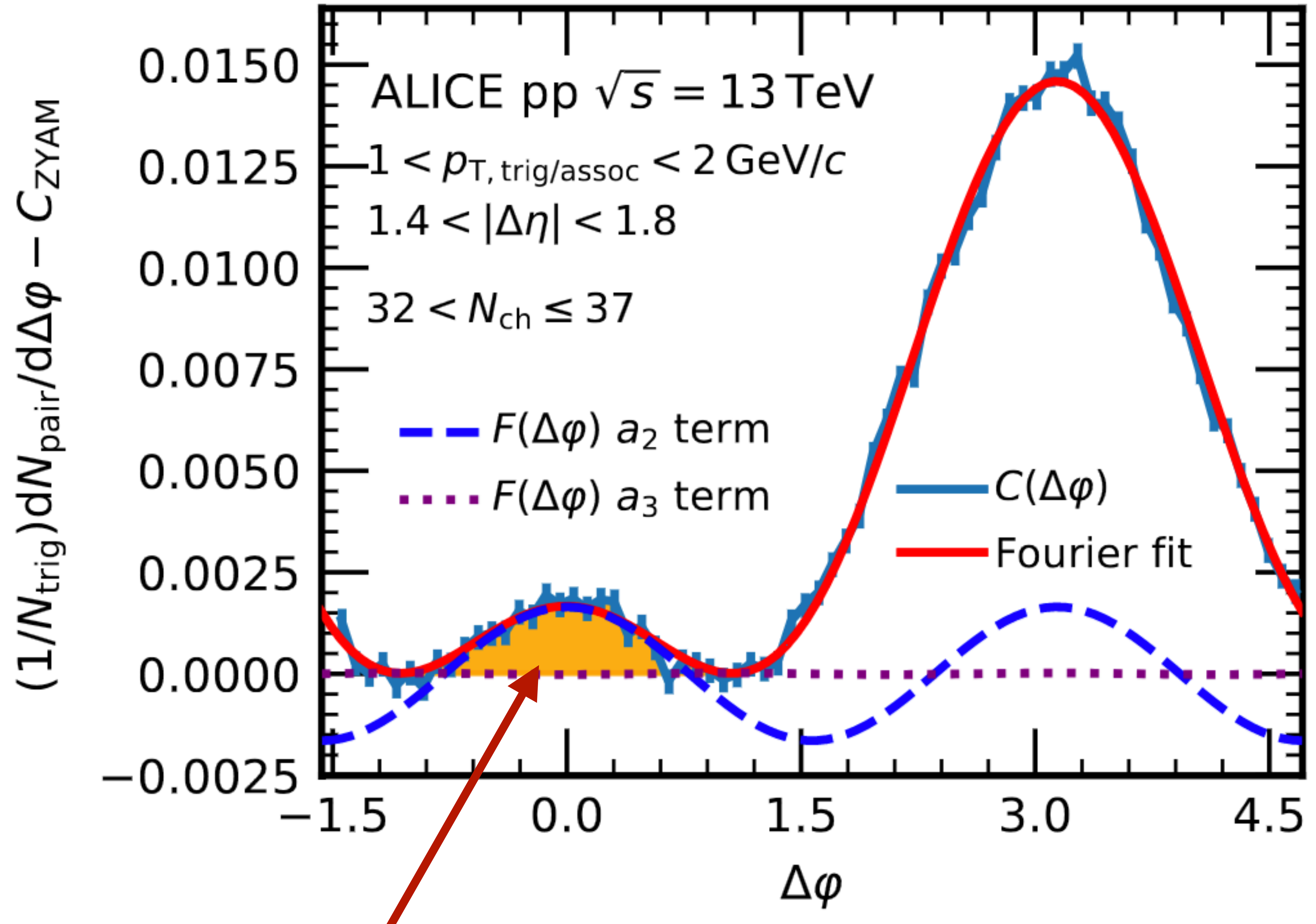
- Suppression of jet-like effects
  - via > 2-particle correlations: $v_2\{4\}$
  - rapidity gaps: $\Delta\eta > 1, 1.4$
- Finite higher order harmonics: v_3, v_4

- Hydrodynamic-like description seems to be favoured, particularly at high N_{ch}
- Initial state effects from initial gluon momentum correlations may play a rôle at low N_{ch}

Ridge in low-multiplicity pp

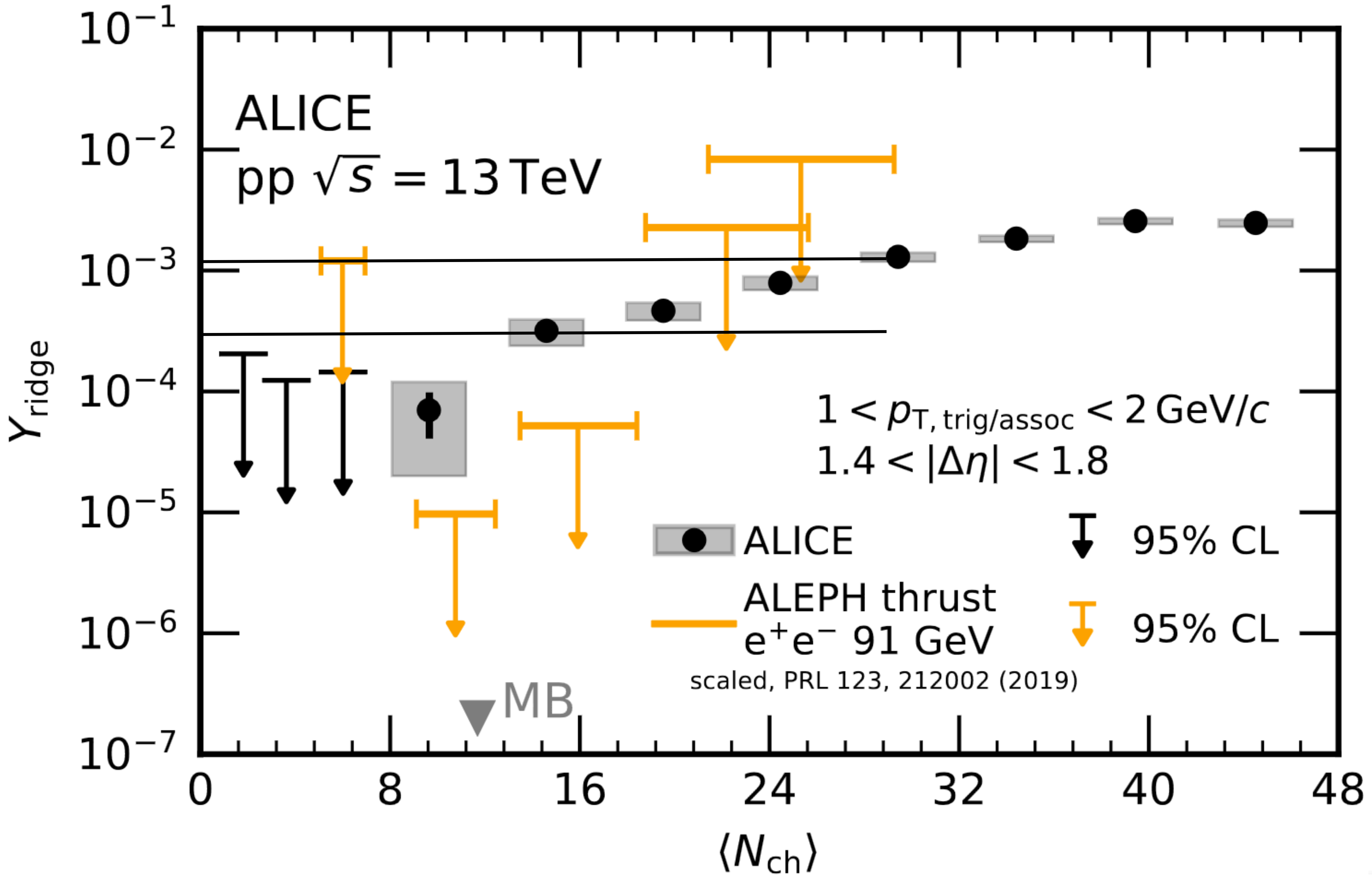


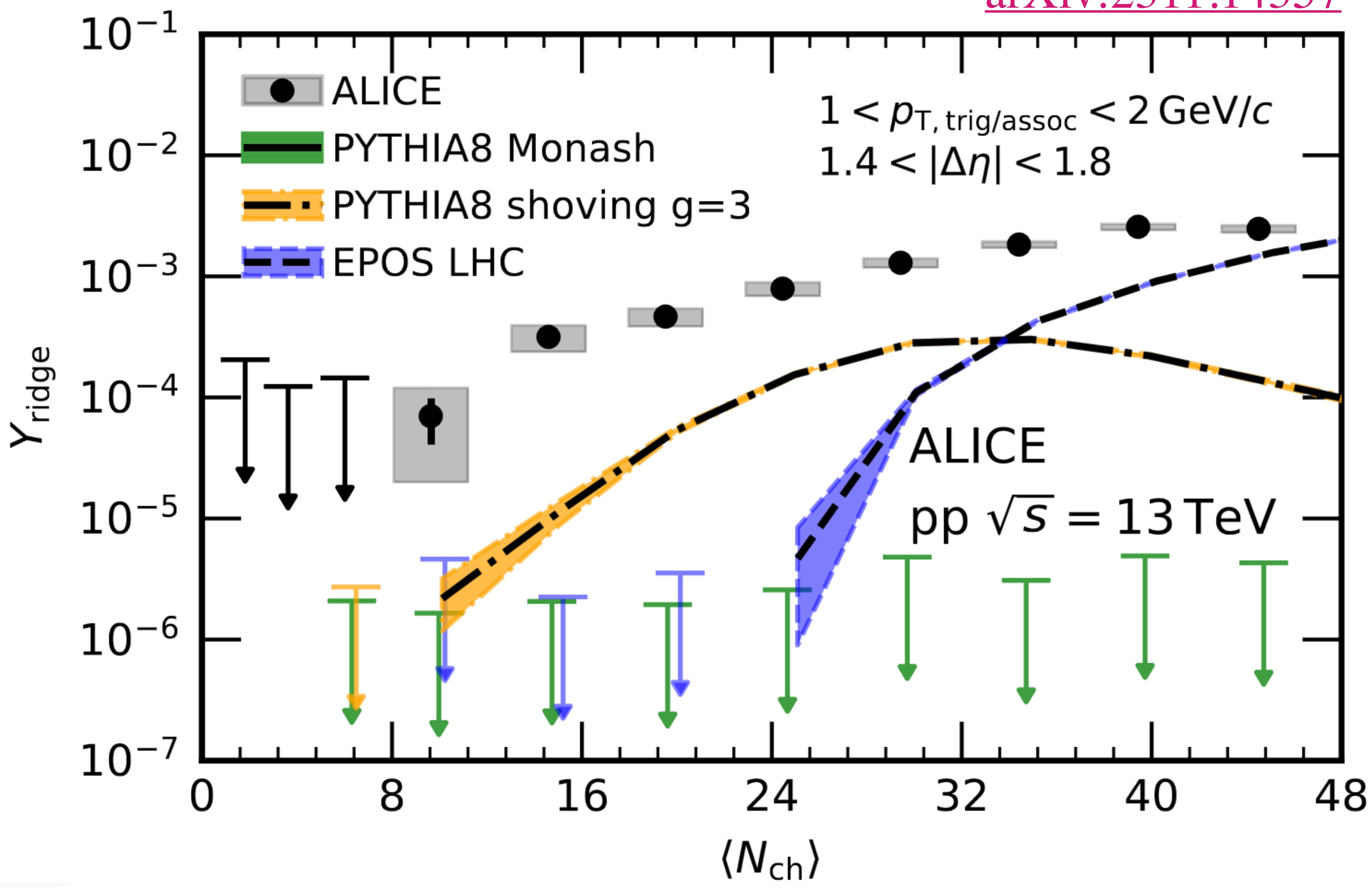
arXiv:2311.14357



Comparison with e^+e^- data and models

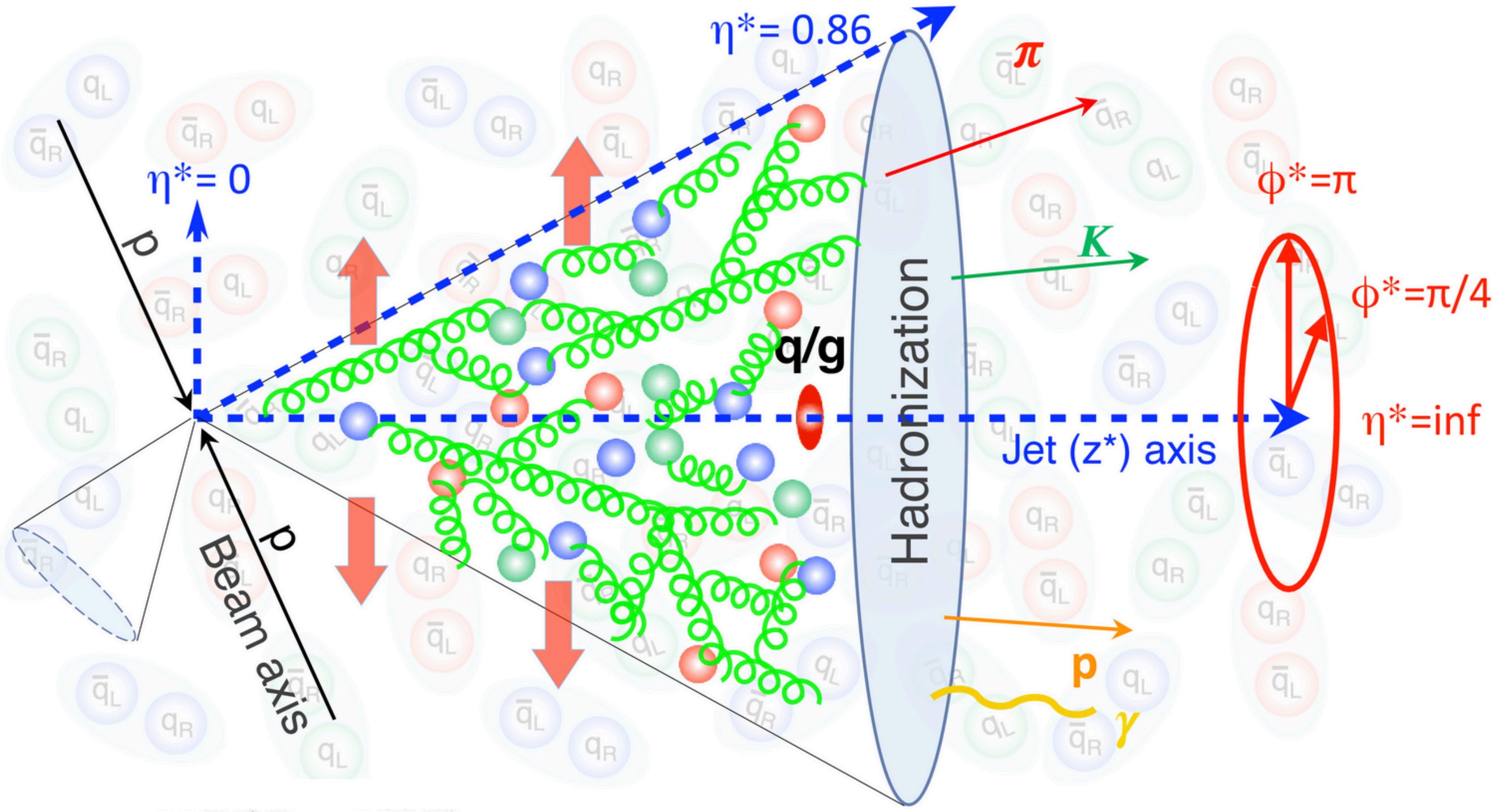
arXiv:2311.14357



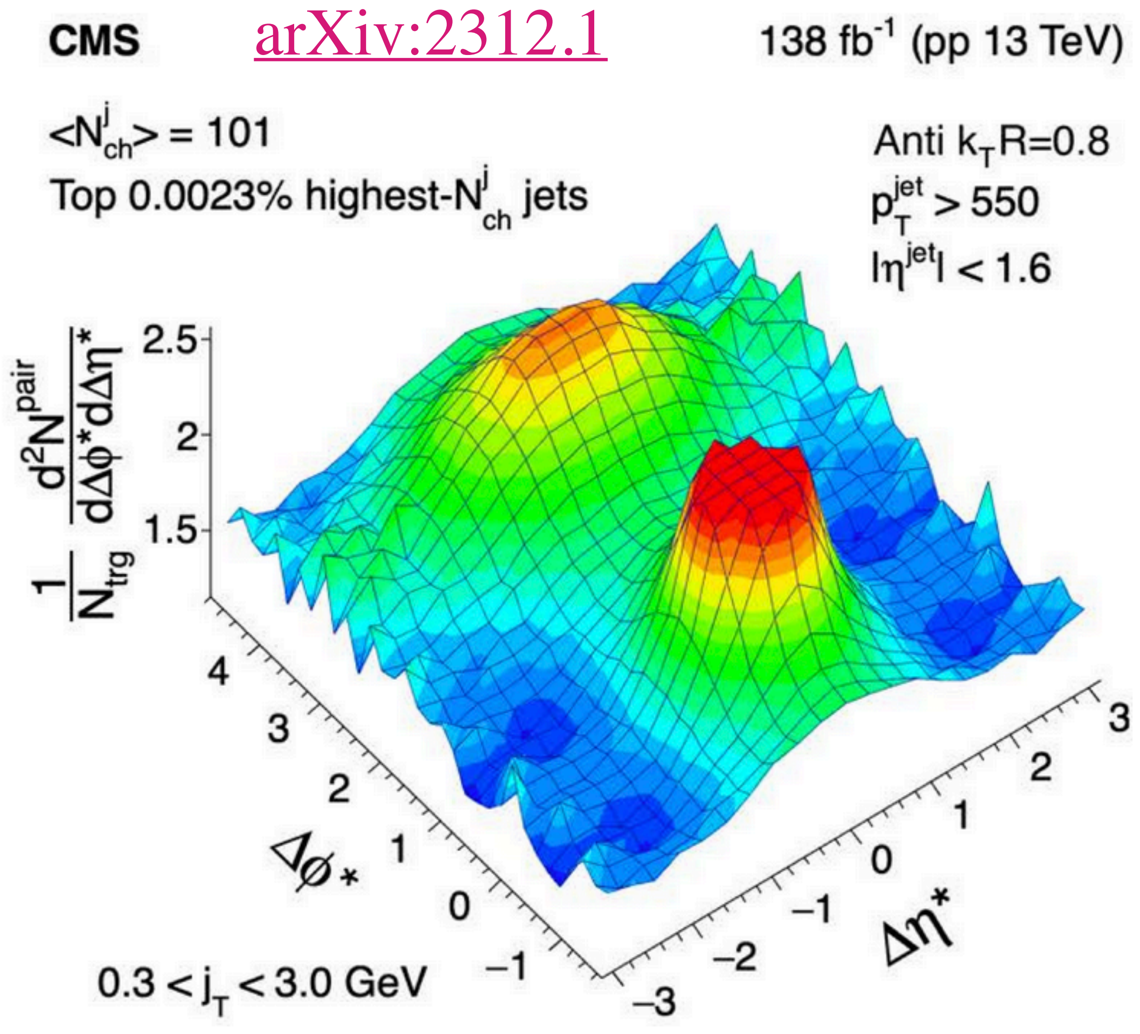


- Non-zero yield at multiplicity at low multiplicities equivalent to e^+e^-
- Substantially larger than limits established in
- Yield not reproduced by Pythia and EPOS, but consistent with const. v_2??

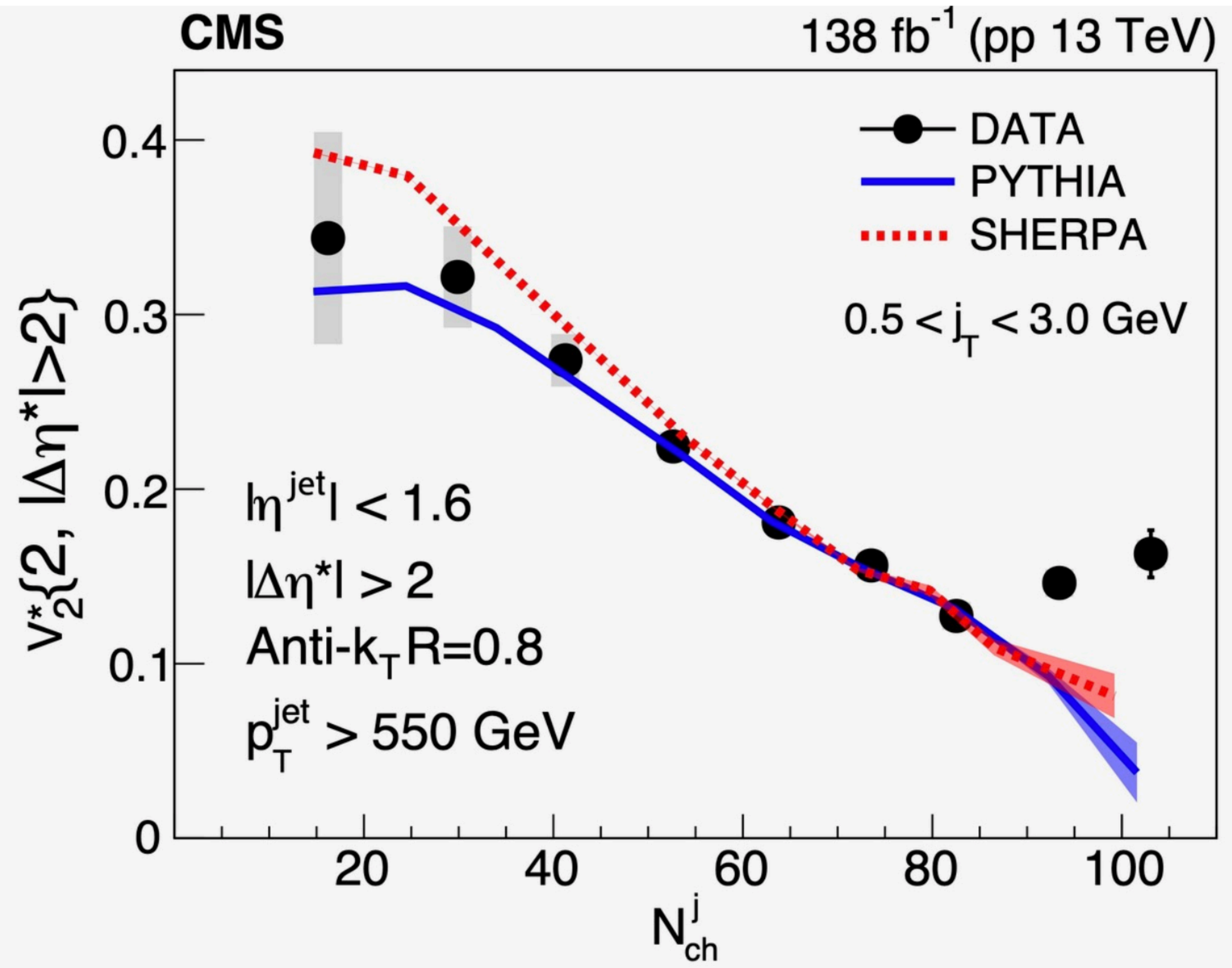
Flow inside jets?



arXiv:2312.1



arXiv:2312.1



v_2-R_{pPb} Puzzle

- Challenge for models (v_2-R_{pPb} puzzle): v_2>0 at high p_T and R_{pPb}~1 including charm and jets …
- Described by CGC but would also expect $v_2(\Upsilon)$ > 0 (not observed)
  - However, open b-hadrons and Y have v_2 compatible with 0
- Charm v_2 > 0 even in pp

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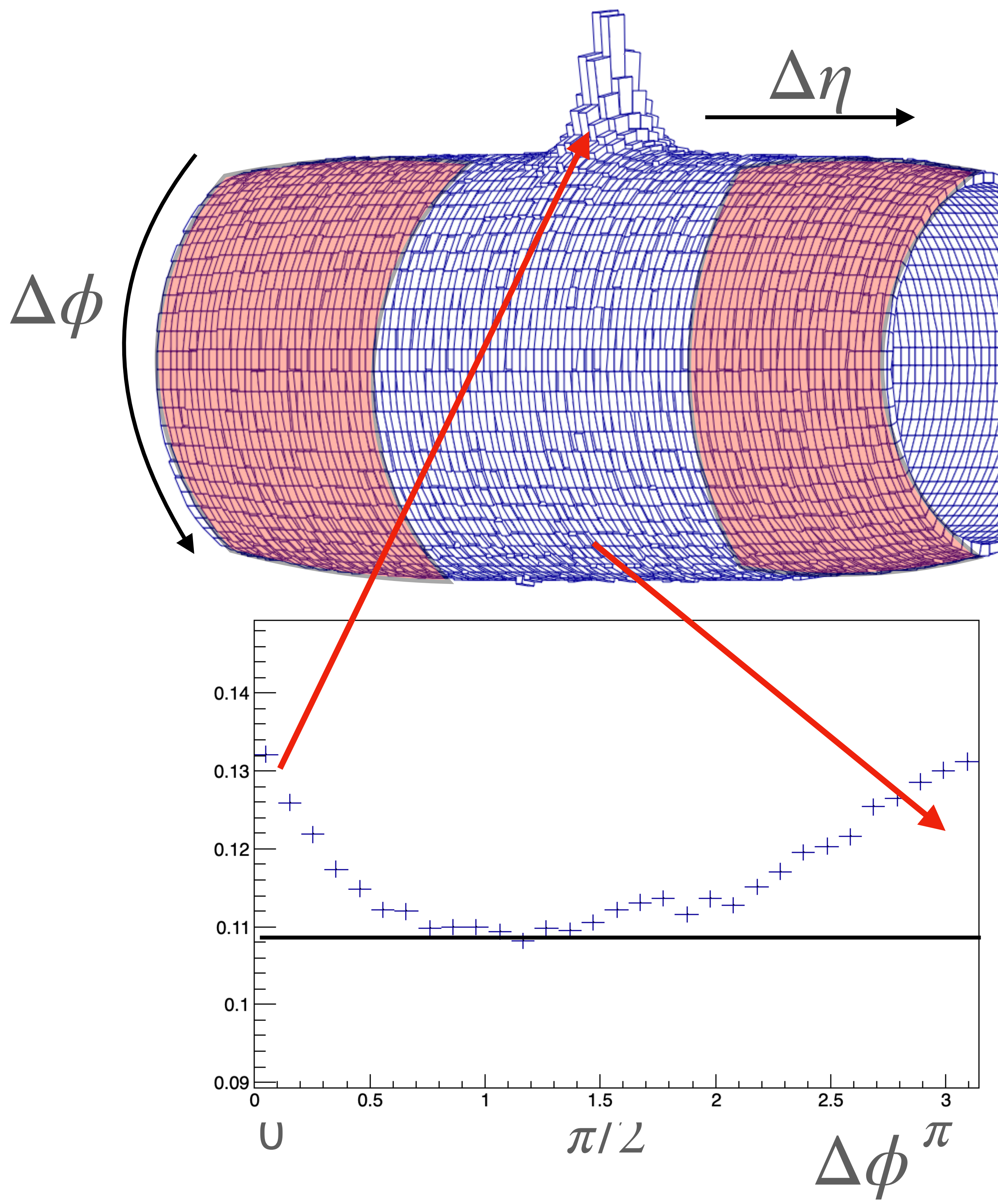
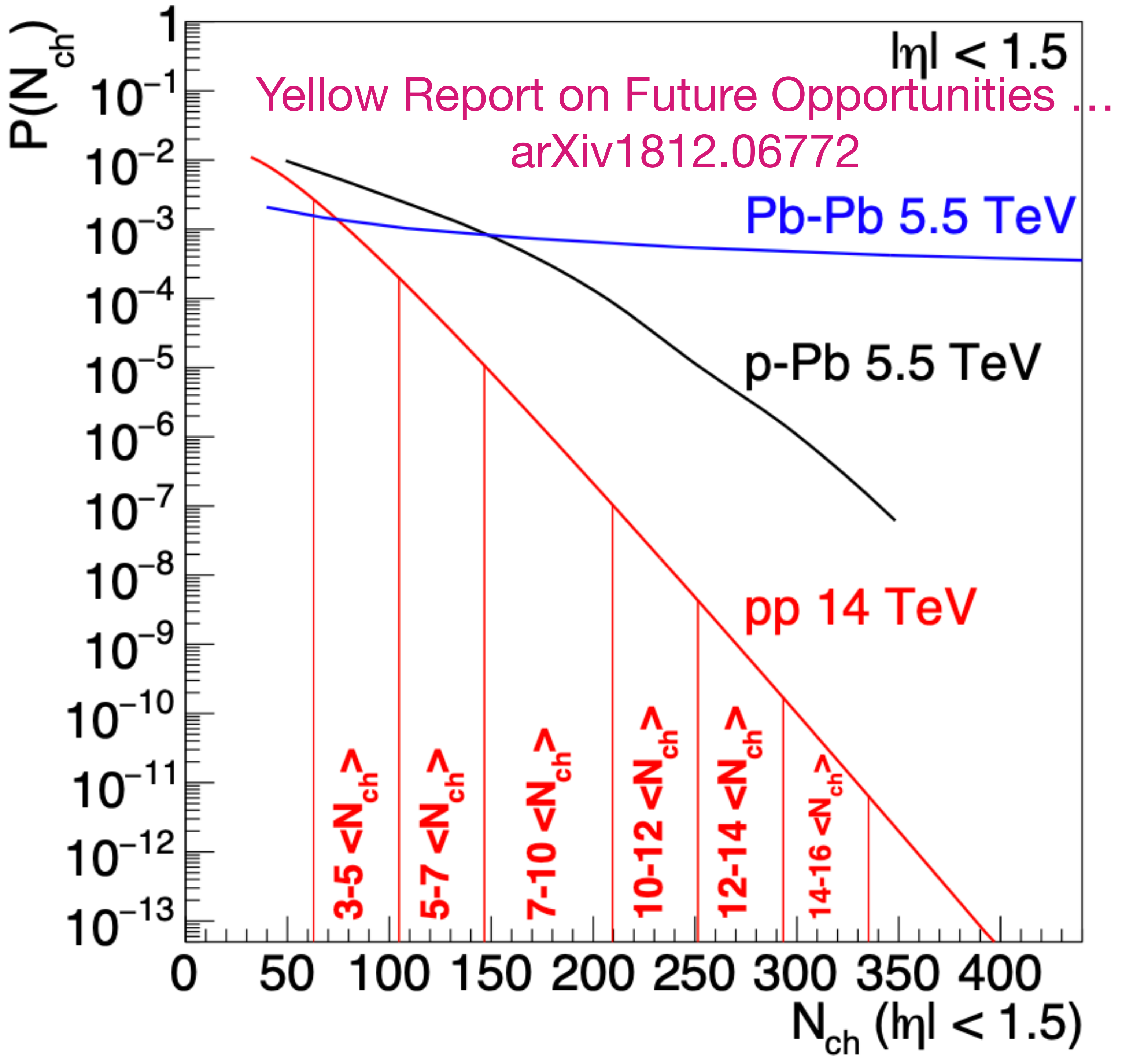
Challenge: Auto-correlation Bias





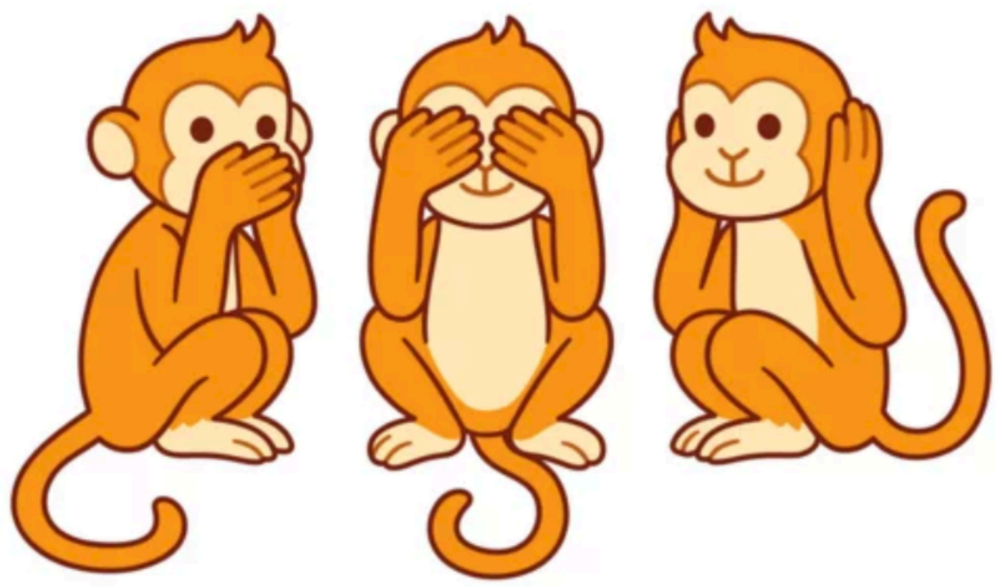
- Autocorrelation bias from N_{cor} particles correlated with the signal production (*Y*) contributing to the total multiplicity.

$$pp \rightarrow Y + N = (Y + N_{\rm cor}) + N_{\rm uncor}$$

- Main contribution from $\Delta\phi \approx 0$ (near-side) and $\Delta\phi \approx \pi$ (away-side, spread over $\Delta\eta$).

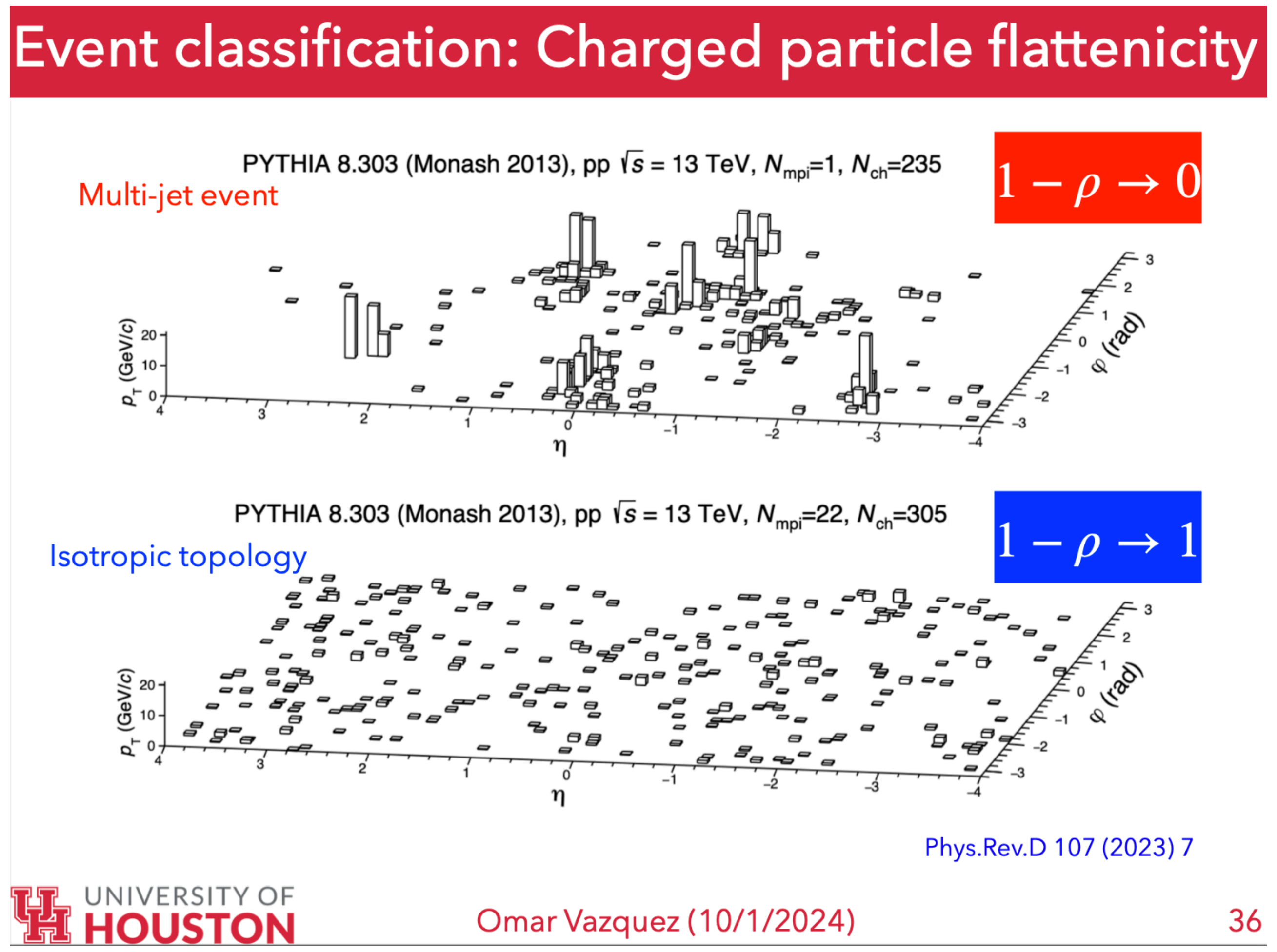
How to meet the challenge

Deny

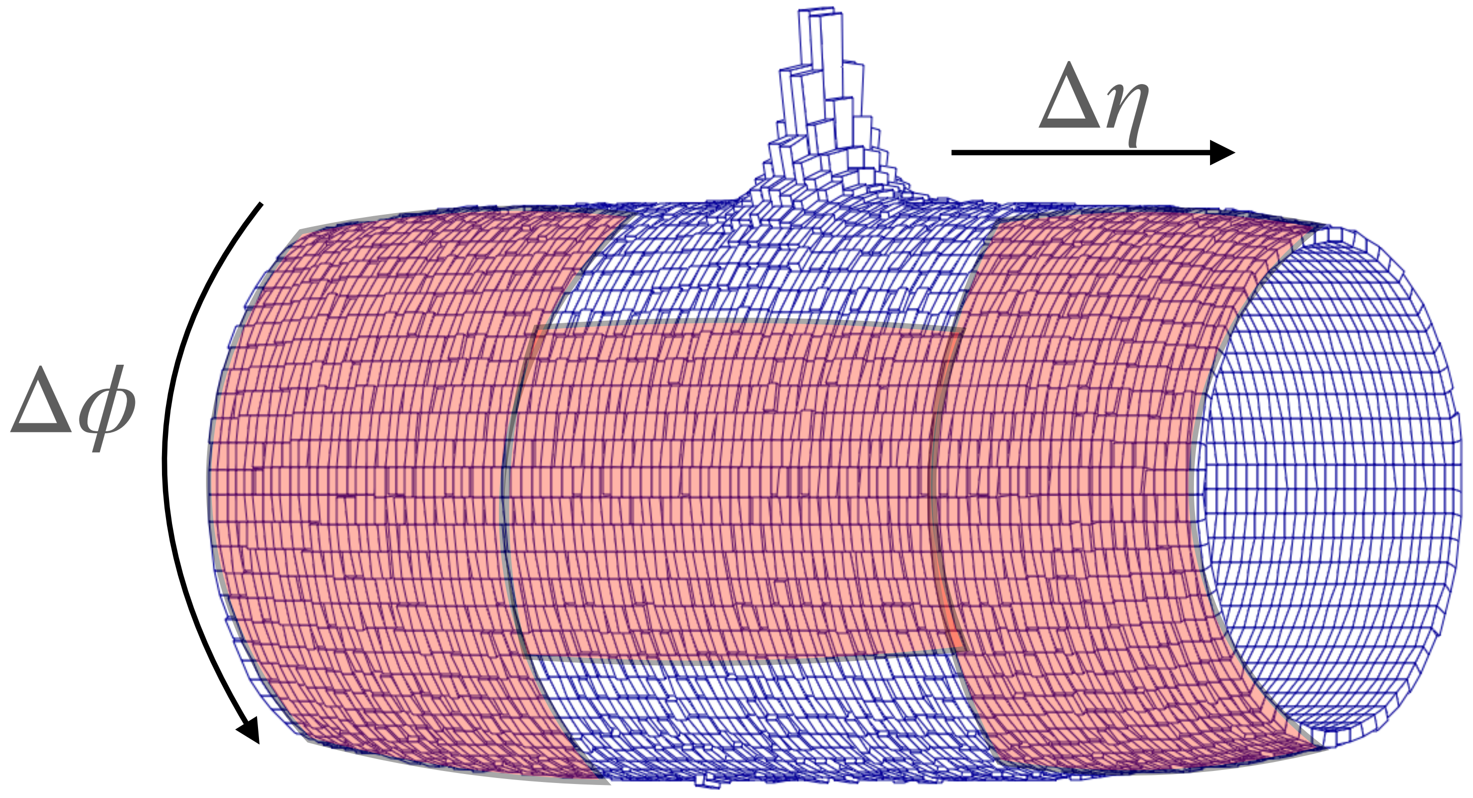


Accept

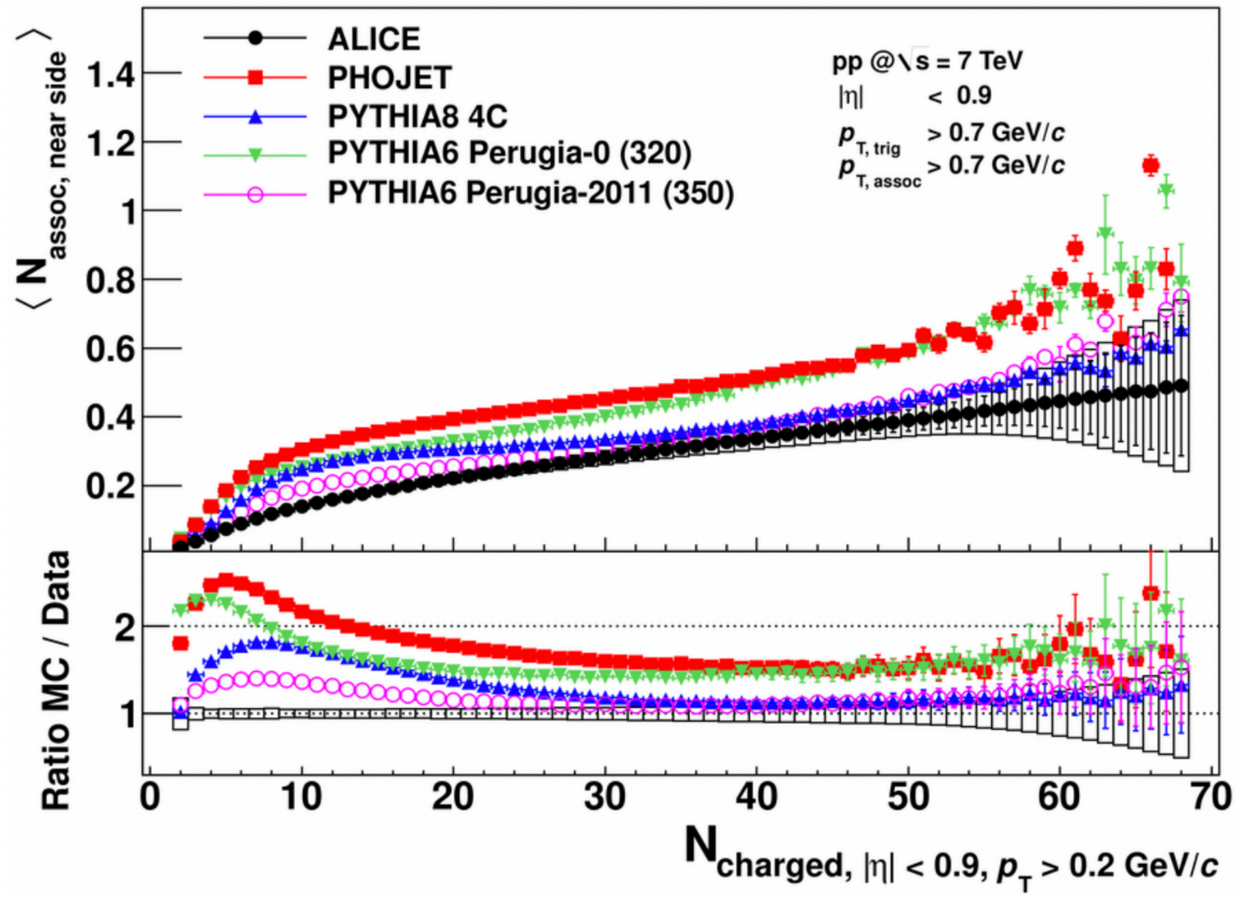
Event Classification



Rapidity gap, Transverse Region

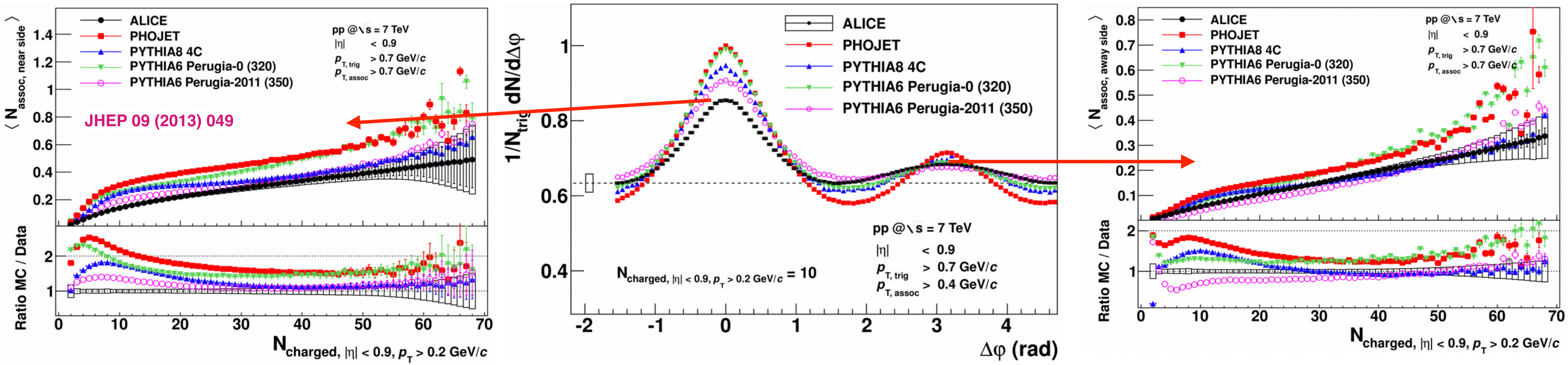


Embrace



Measure multiplicity dependence and correlations for the same observable

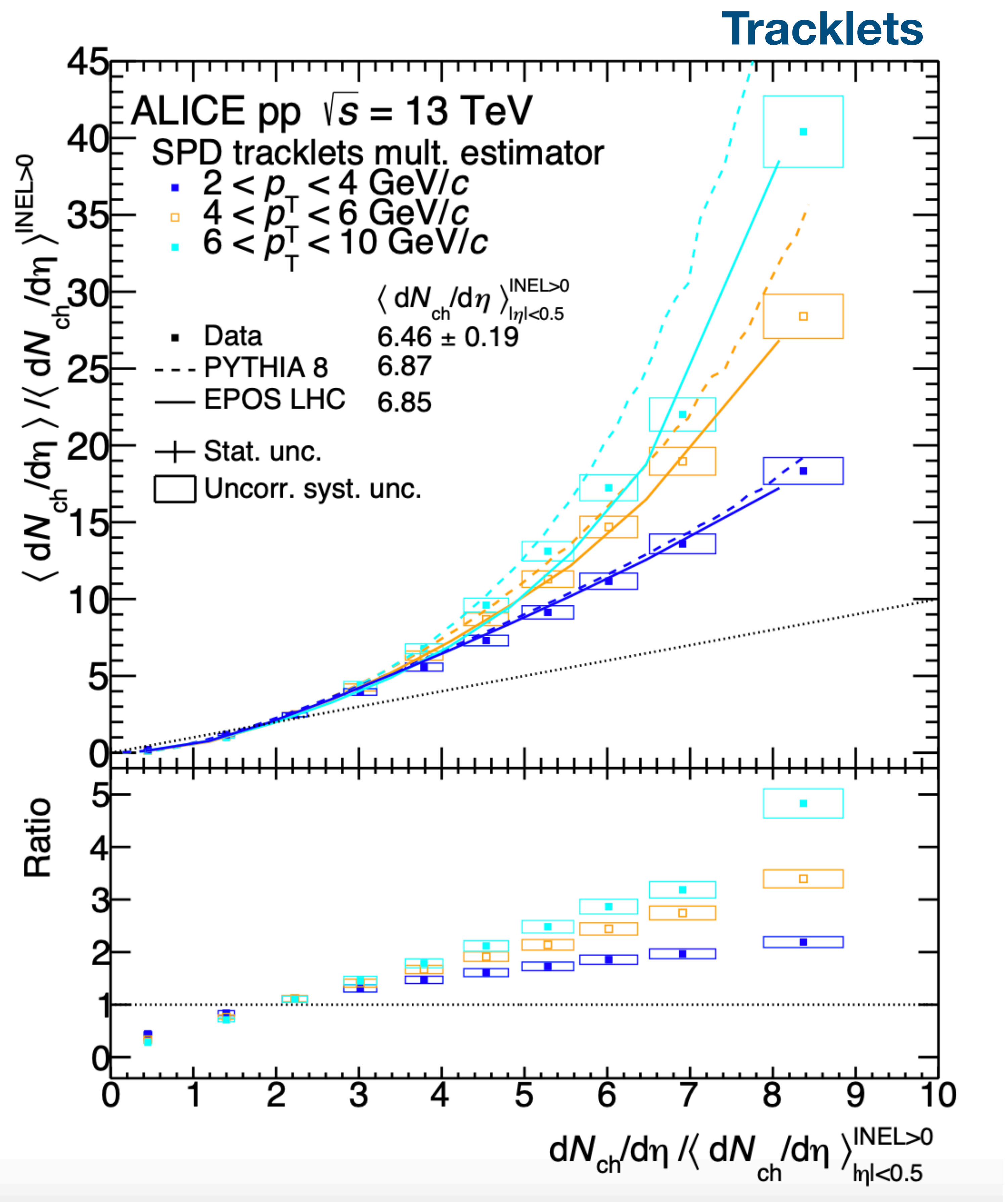
Direct investigation of multiplicity bias

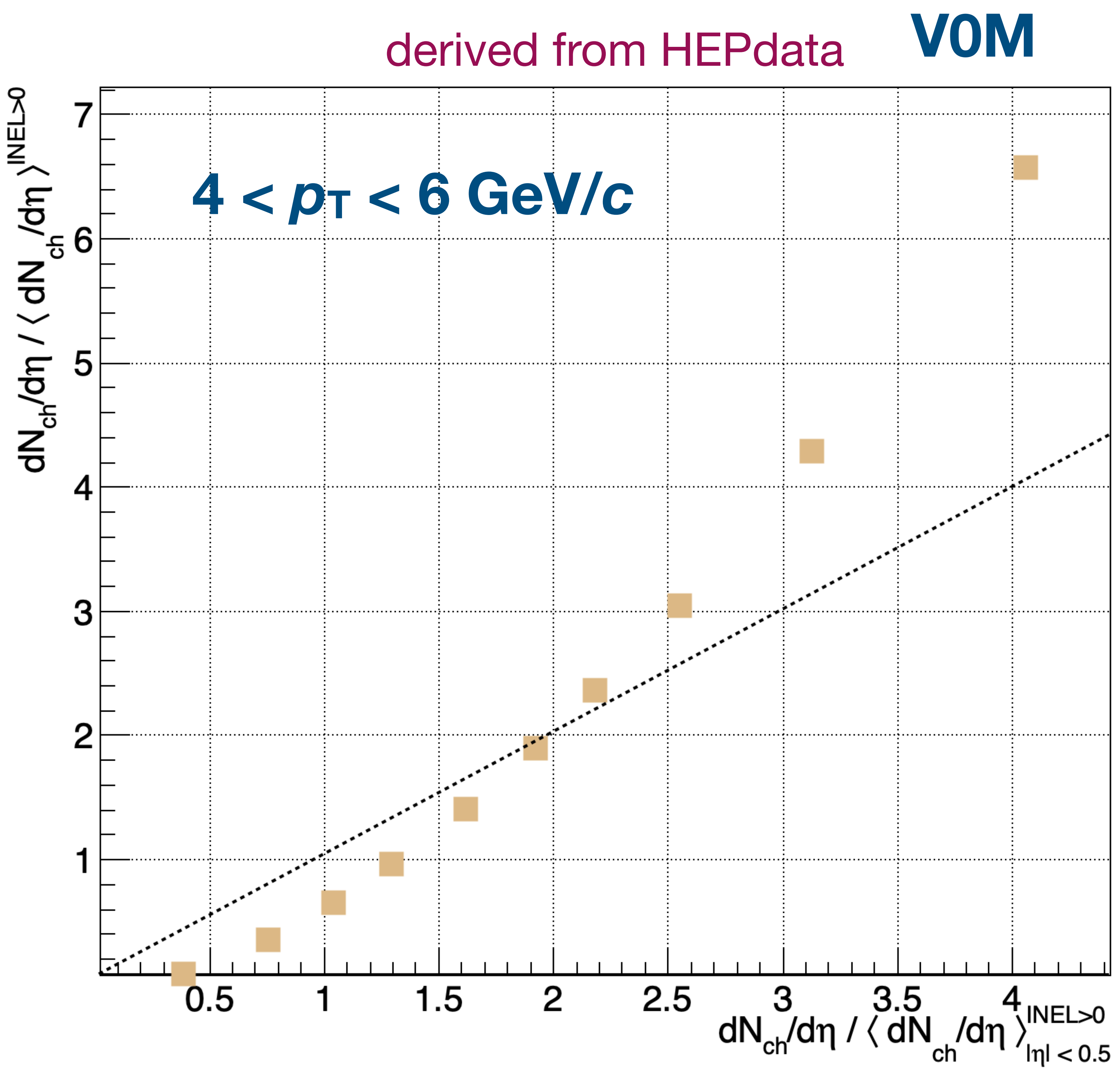


- 2 → 2 semi-hard back-to-back topologies persist down to low p_T
  - Strong increase of correlated particle production with multiplicity
  - At HM: correlated with p_T > 0.7 GeV/c particle on average > 1 additional particle produced
- It would be interesting to repeat the analysis
  - For different multiplicity/event shape estimators (“flattenicity”)
  - For the Underlying event of a hard process (which is often assumed to be “soft”)

Charged particle yields as a function of multiplicity

self-normalized ratios
N/⟨N⟩, Y/⟨Y⟩

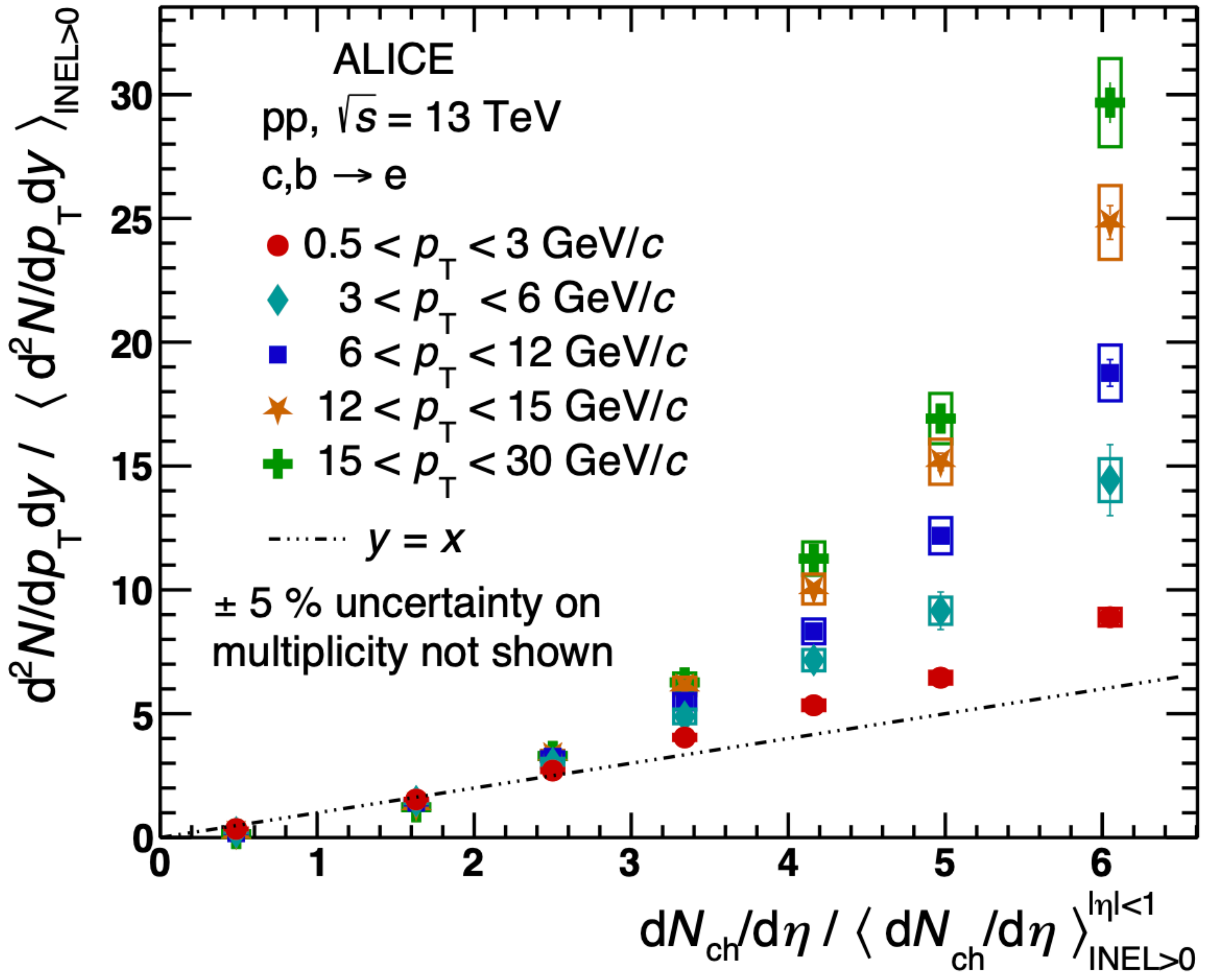


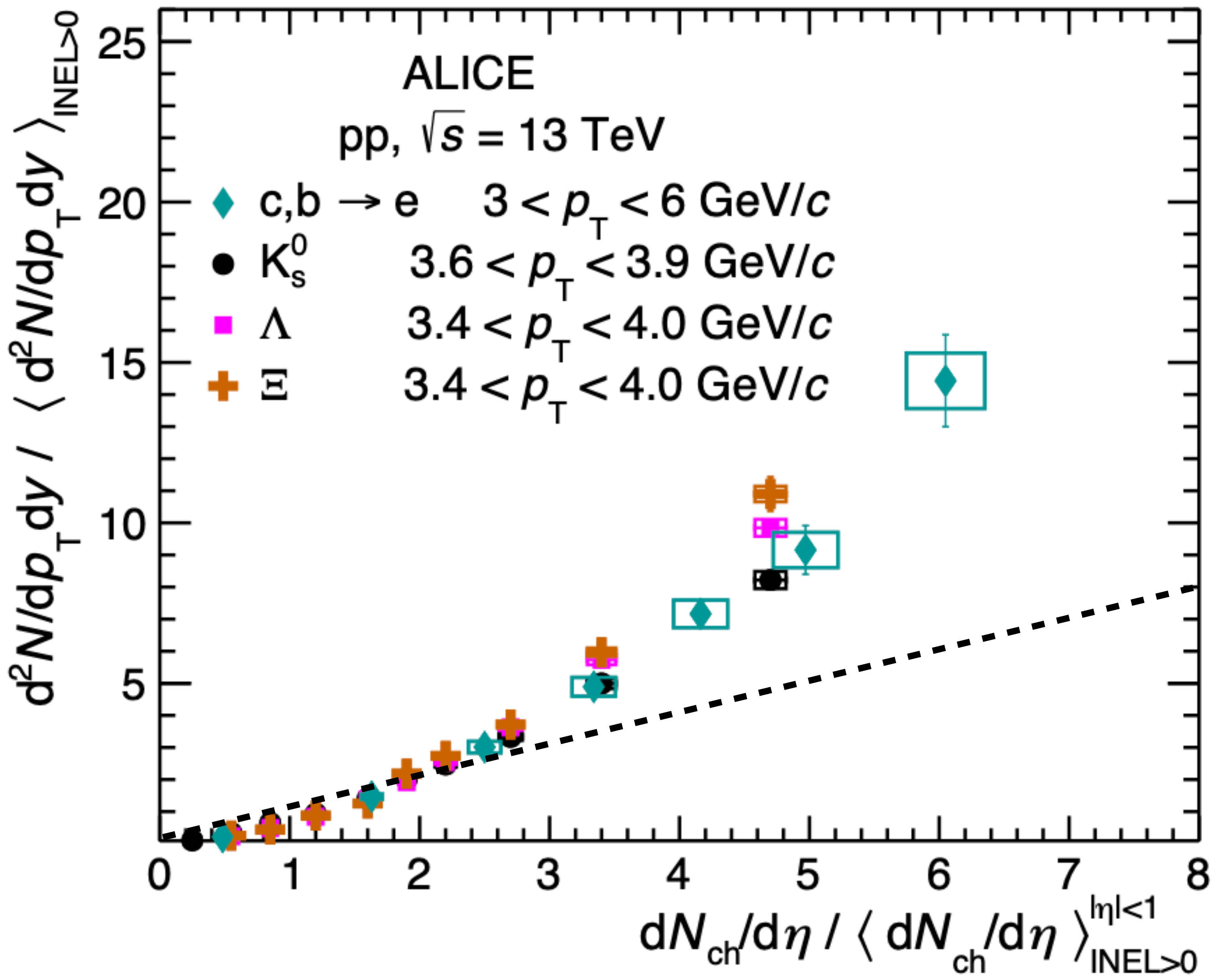


- Strong non-linear increase of yields with multiplicity
- Measuring particles and multiplicity (V0M) in separated η regions does not change the picture

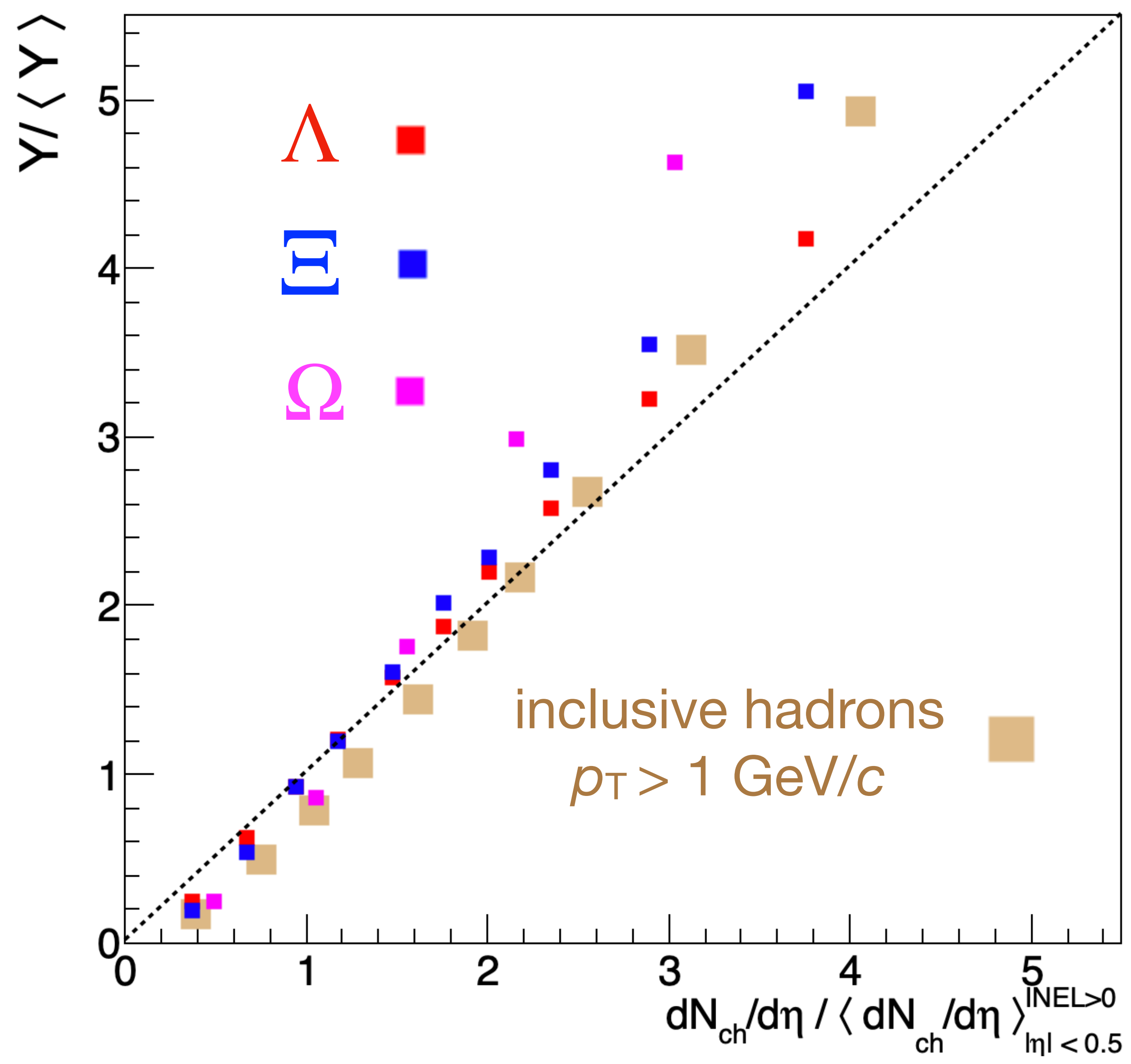
Particle species and p_T-dependence

inclusive HF electrons vs multiplicity arXiv2303.13349



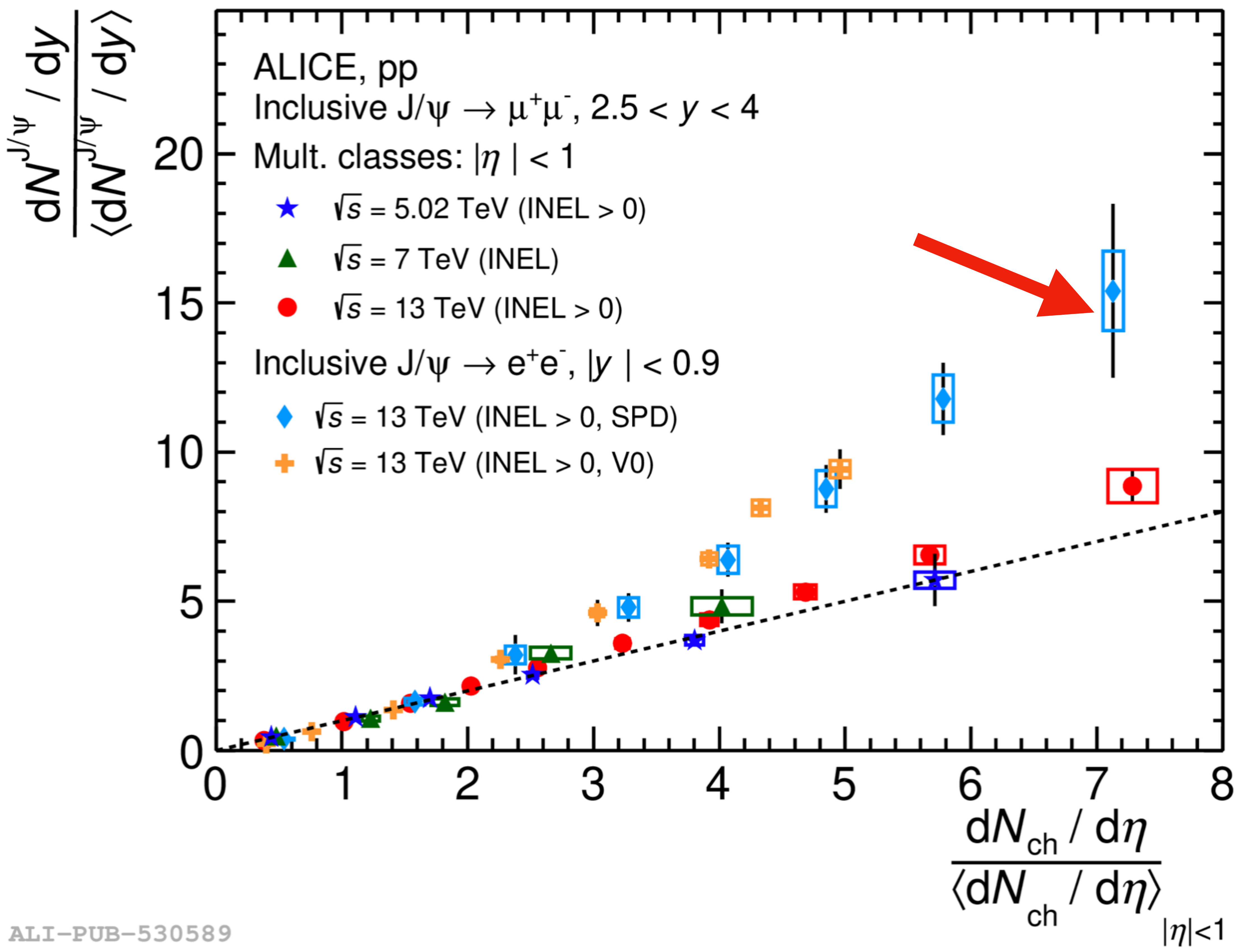


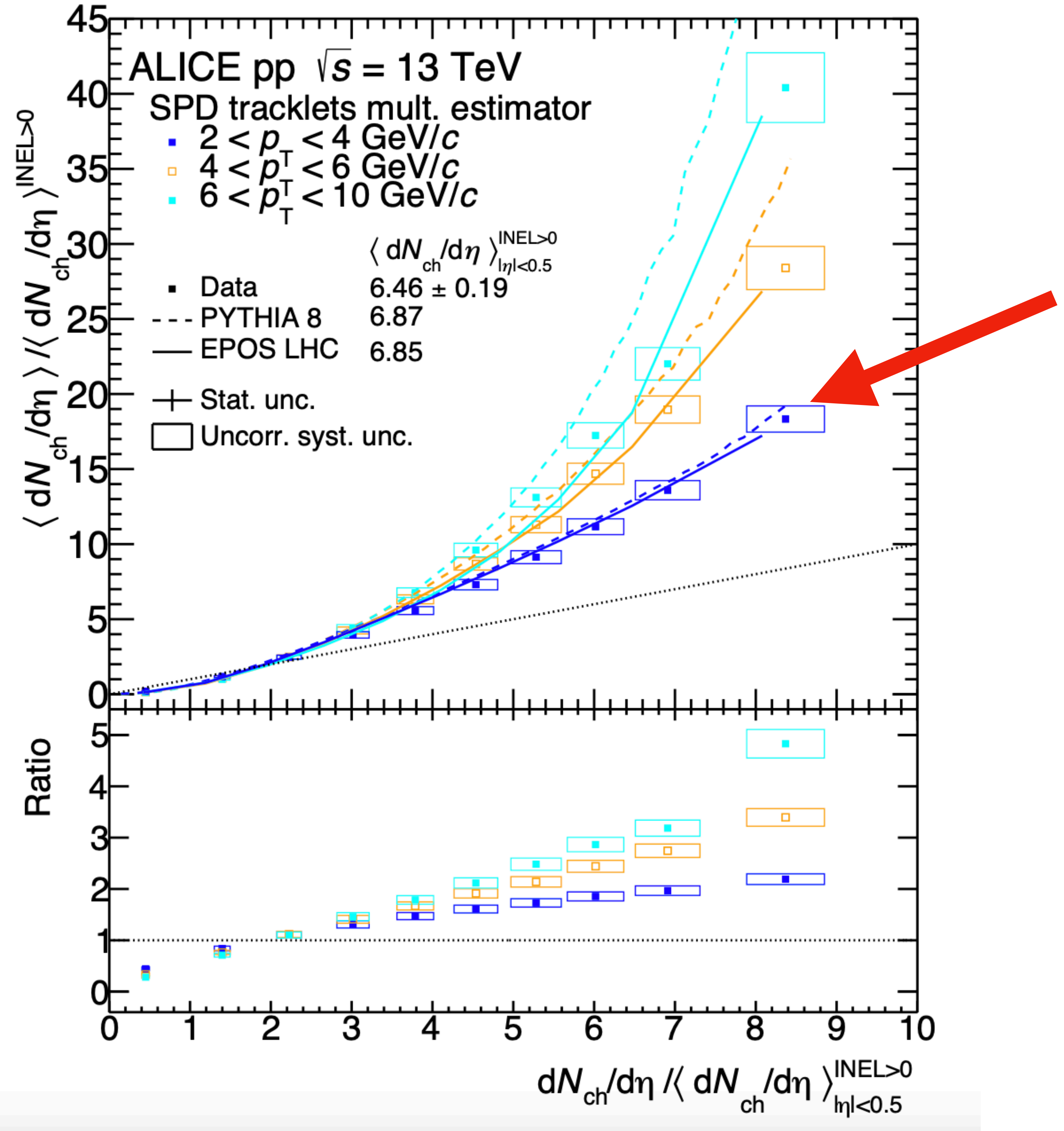
derived from HEPdata



- Clear dependence on hardness and no dependence on particle species at high p_T
  - In general attributes to auto-correlation bias
- While for multi-strange baryons (low p_T, integrated yields) the effect is interpreted as "strangeness enhancement"
  - Strangeness content dependence
  - Has similarities with low p_T inclusive particle production

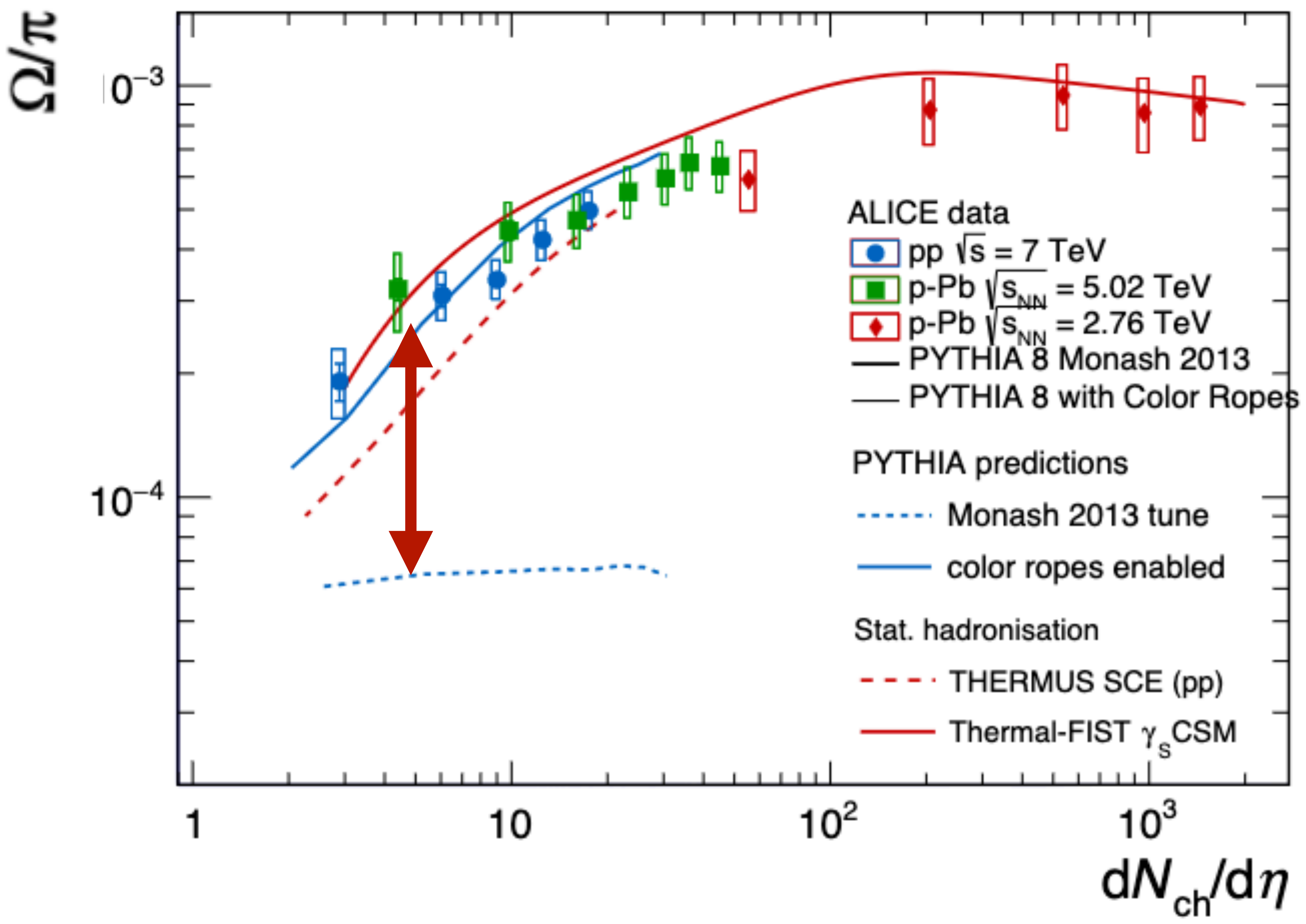
Inclusive J/ψ production vs multiplicity

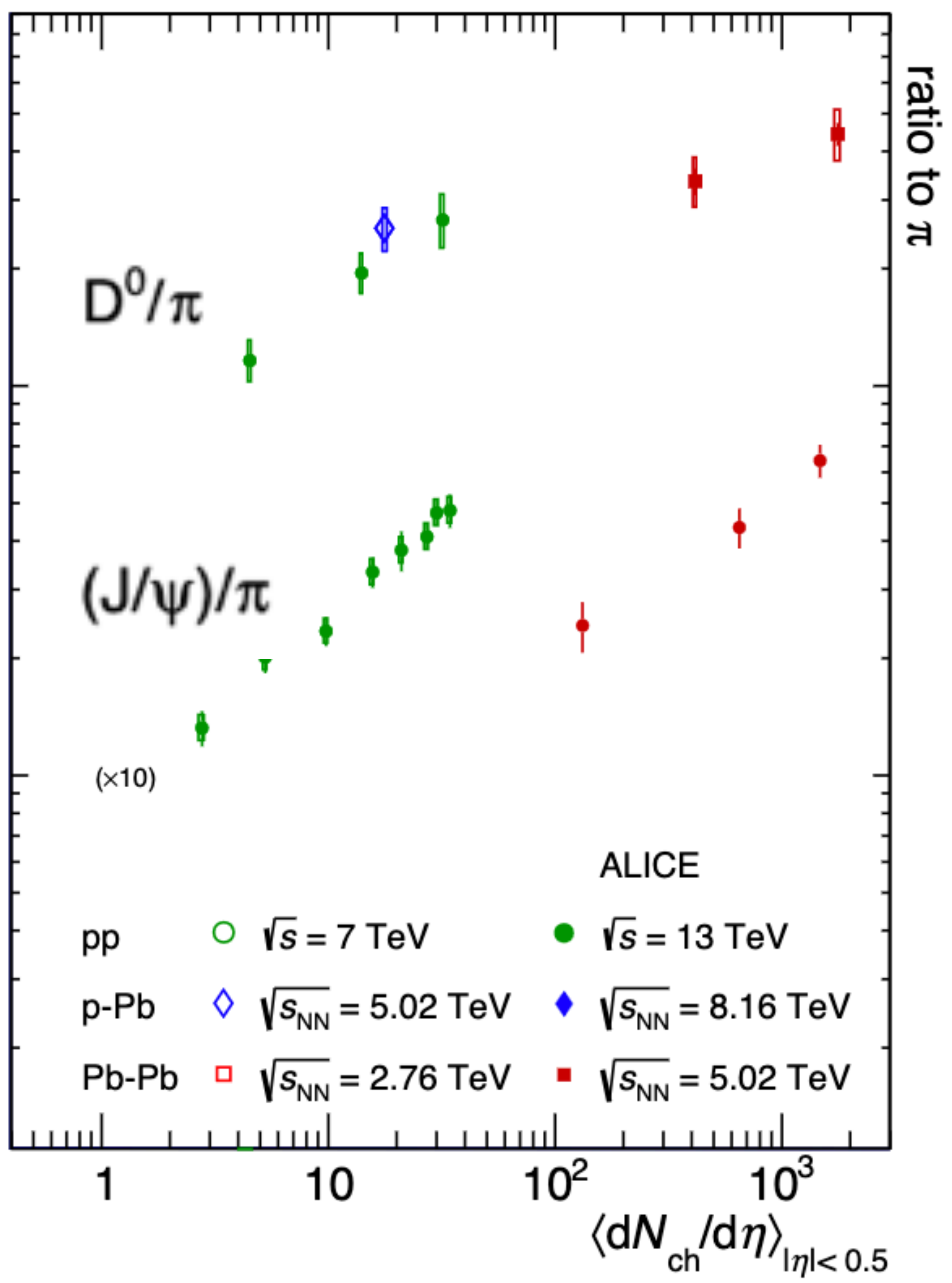




- At central rapidity J/ψ similar to inclusive particle production at same Q^2
- Puzzling: almost linear dependence for forward J/ψ production
  - Multiplicity determined in central region
  - Similar rapidity gap between J/ψ and multiplicity measurement

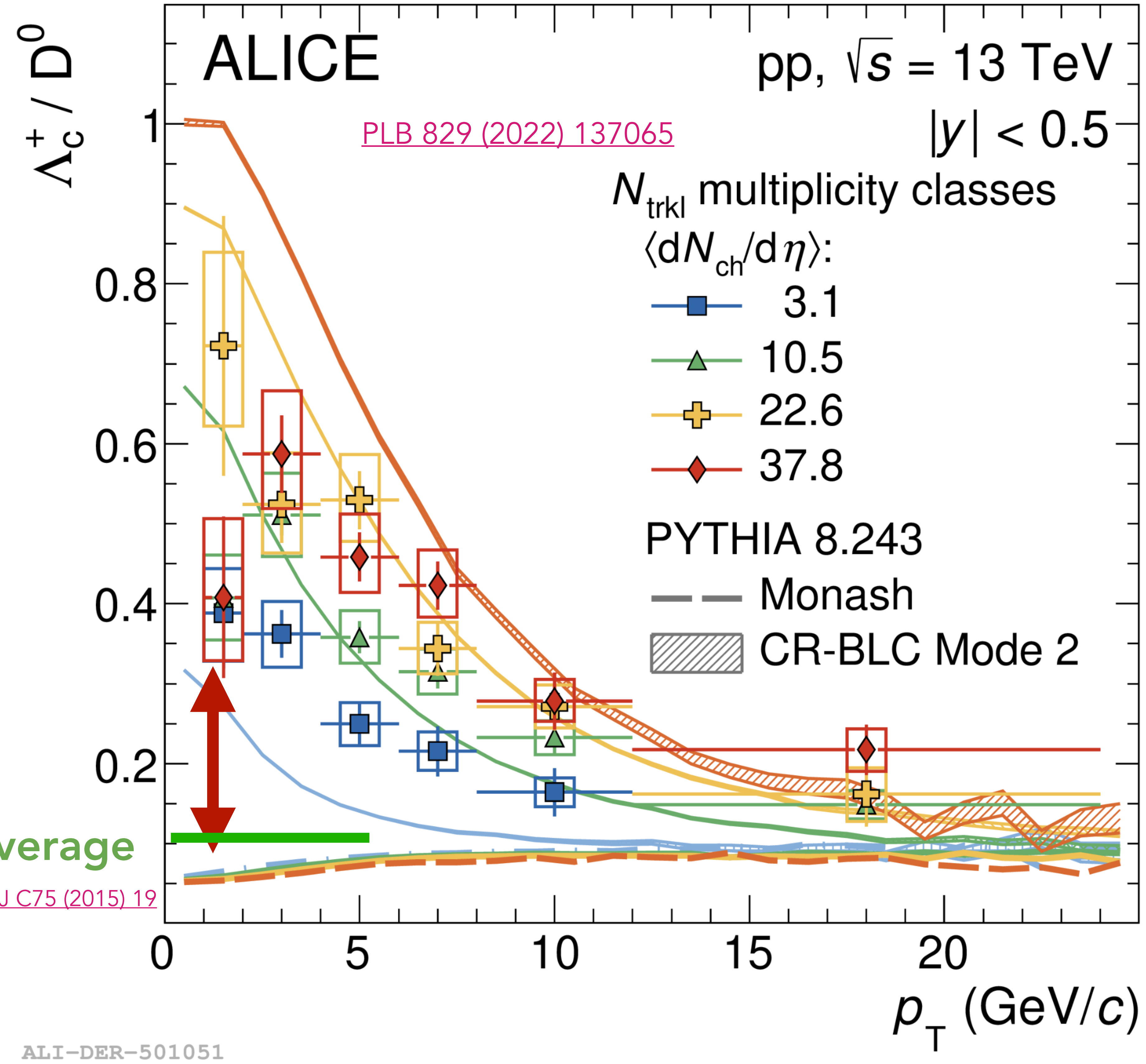
Particle ratios

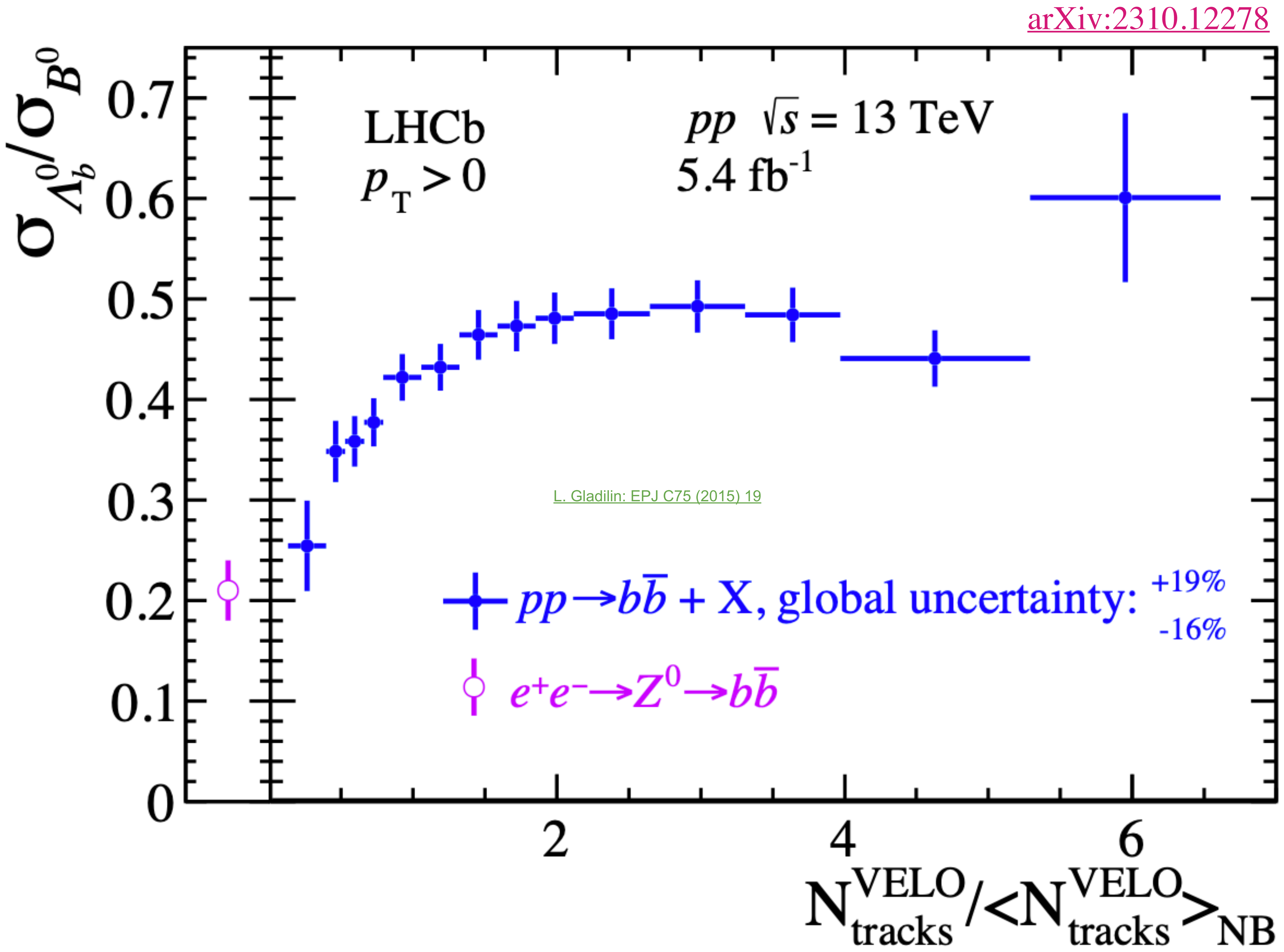




- Similar enhancement vs multiplicity pattern for Λ/π, Ξ/π, Ω/π, D/π, $J/\Psi/\pi$
- Λ/π, Ξ/π, Ω/π strong enhancement wrt e^+e expectation (universal fragmentation)
- strangeness enhancement?

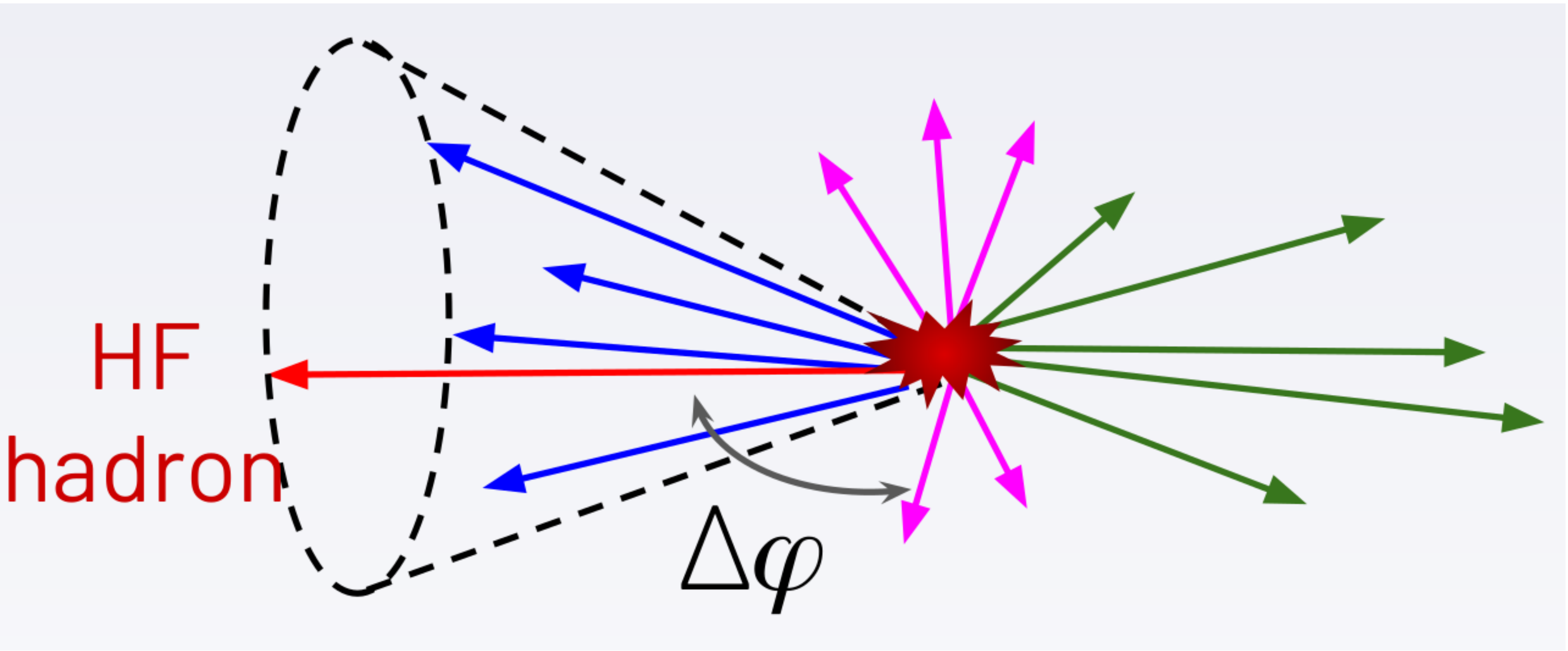
Charm and Beauty Baryon Enhancement

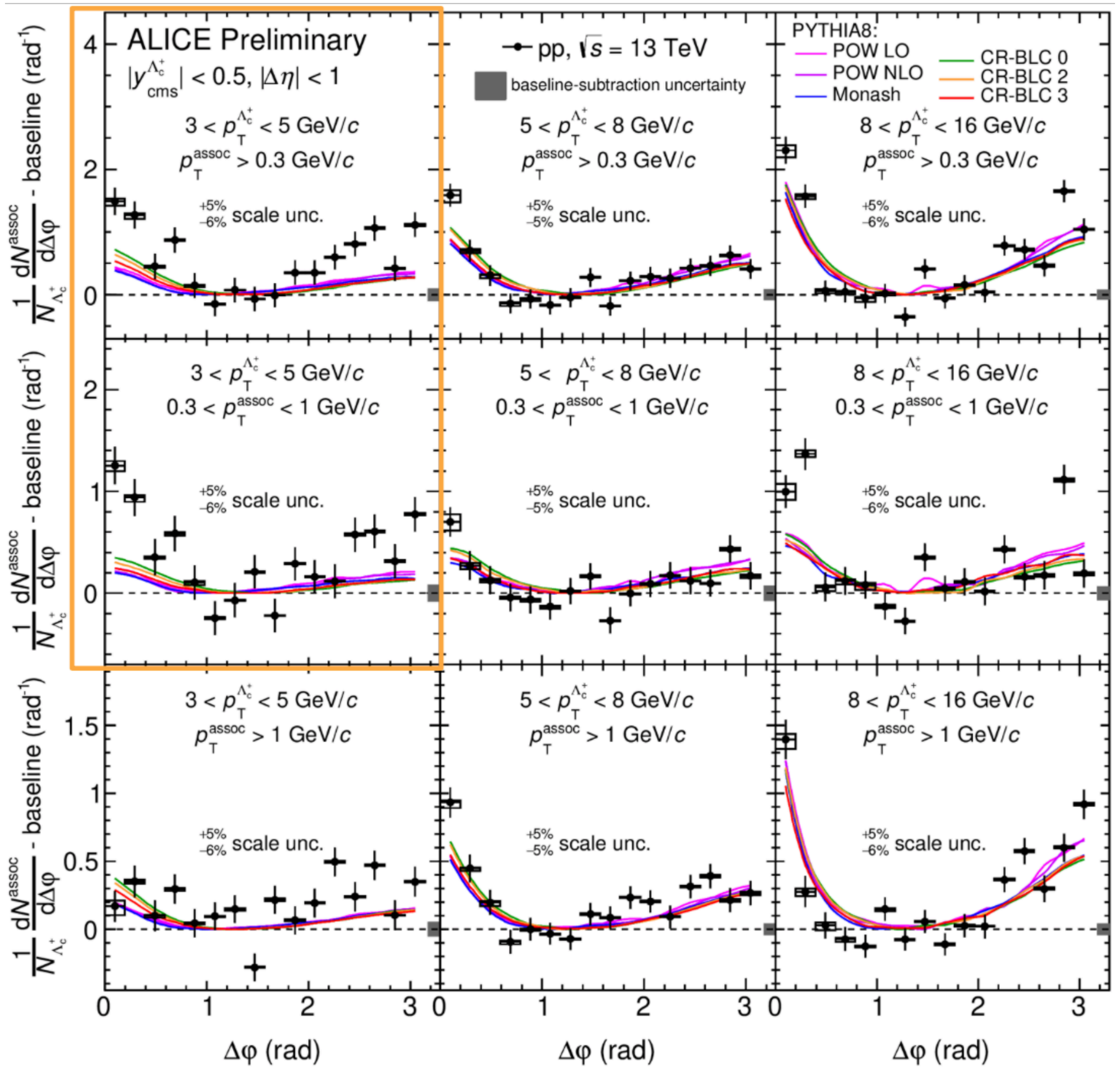




- Are we approaching e+e- like collisions at low multiplicity?
  - not obvious for Λ_c^+/D^0
  - interpretation of LHCb Λ_b^0/B^0 results depend very much on measurement at lowest multiplicity

Λ_c-charged particle correlation





Enhance near and away-side correlations: challenge for models that describe yield

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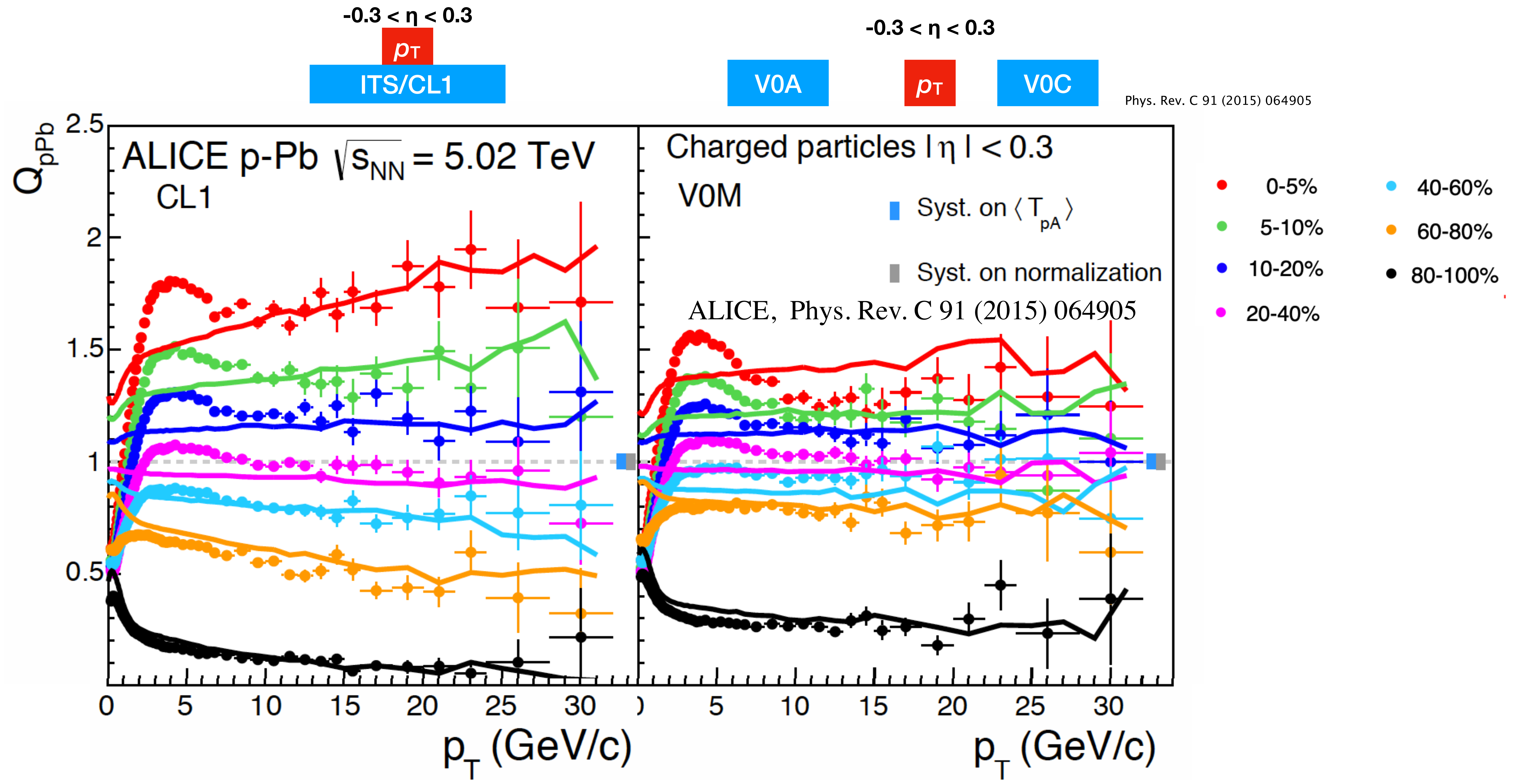
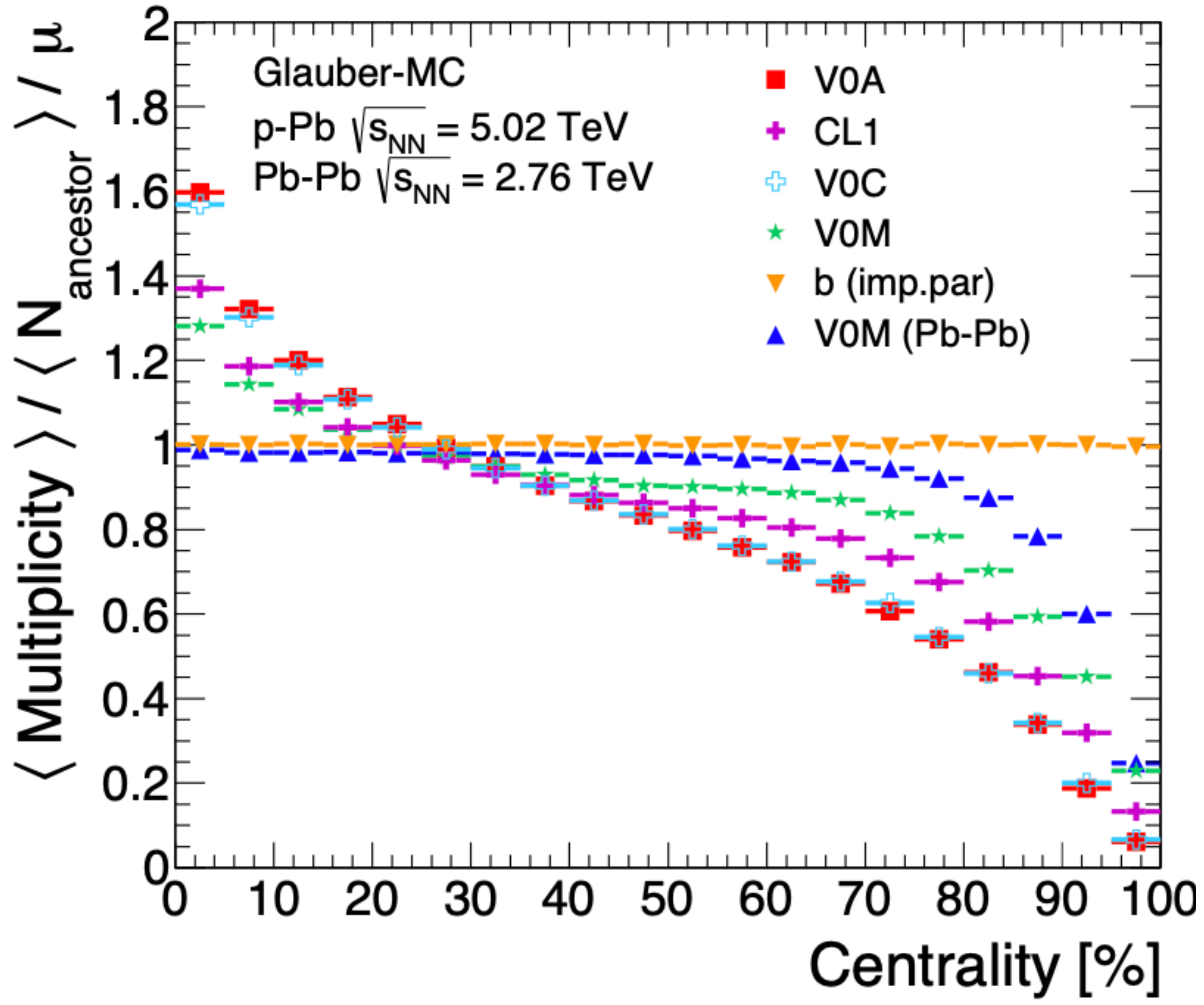
From pp to p-Pb



- Centrality from multiplicity in different η regions
  - N_{coll} with standard Glauber leads to large "spread" of Q_{pPb} (cent)

From pp to p-Pb

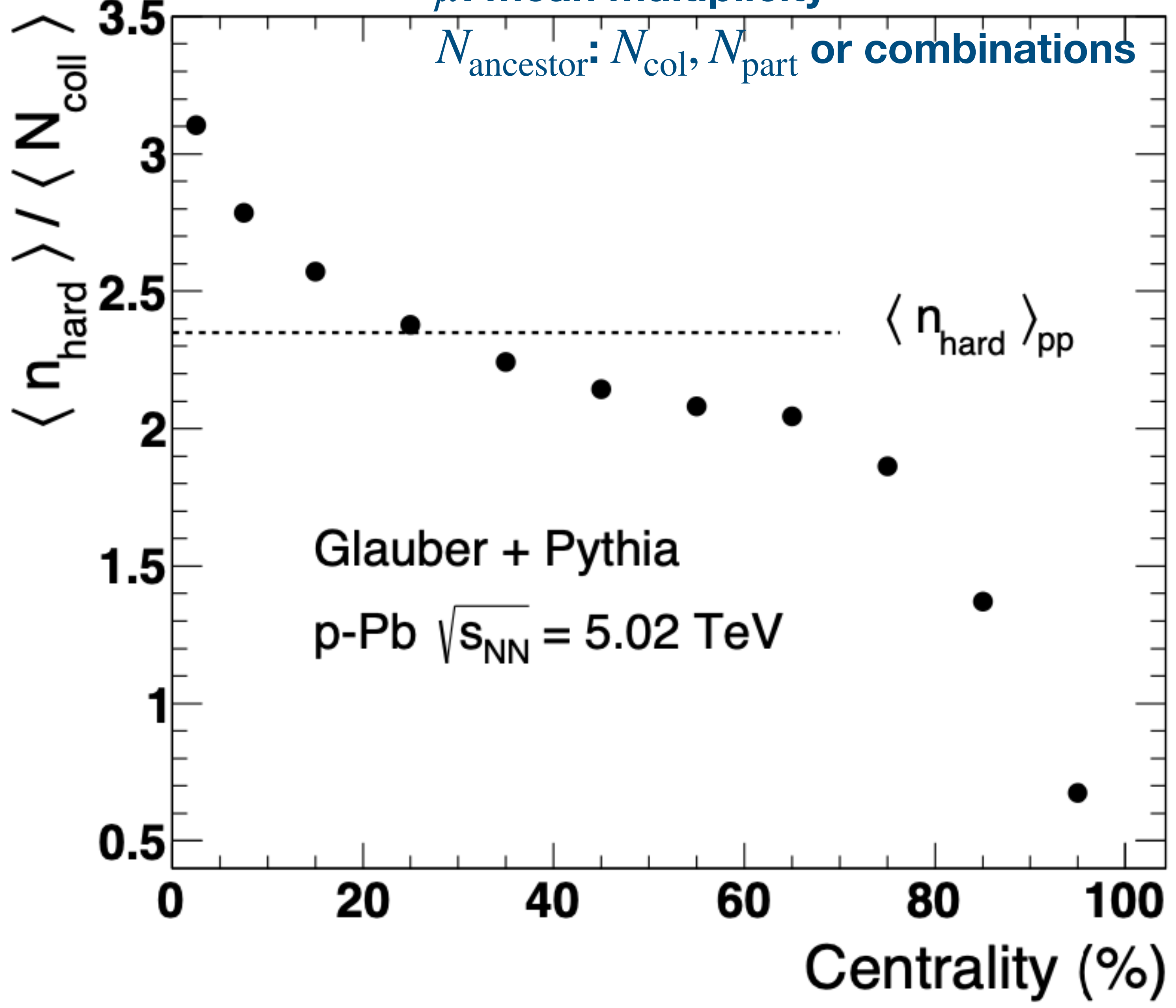
Multiplicity bias from Glauber fit



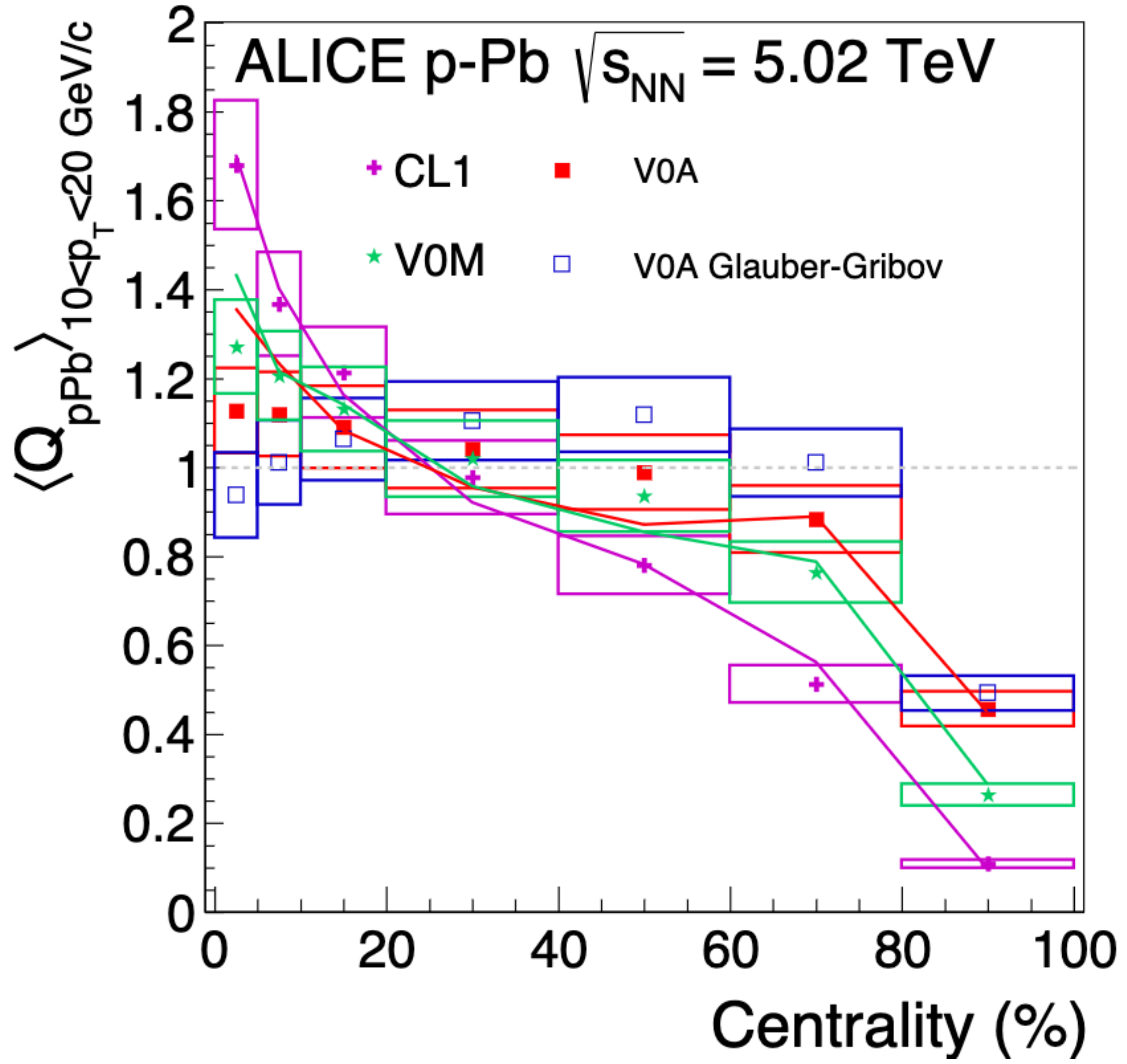
MPI model provides link between bias and hard scatterings

μ: **mean multiplicity**

$N_{\rm ancestor}$: $N_{\rm col}$, $N_{\rm part}$ **or combinations**



Glauber + MPI descibes data



ALICE, Phys. Rev. C 91 (2015) 064905

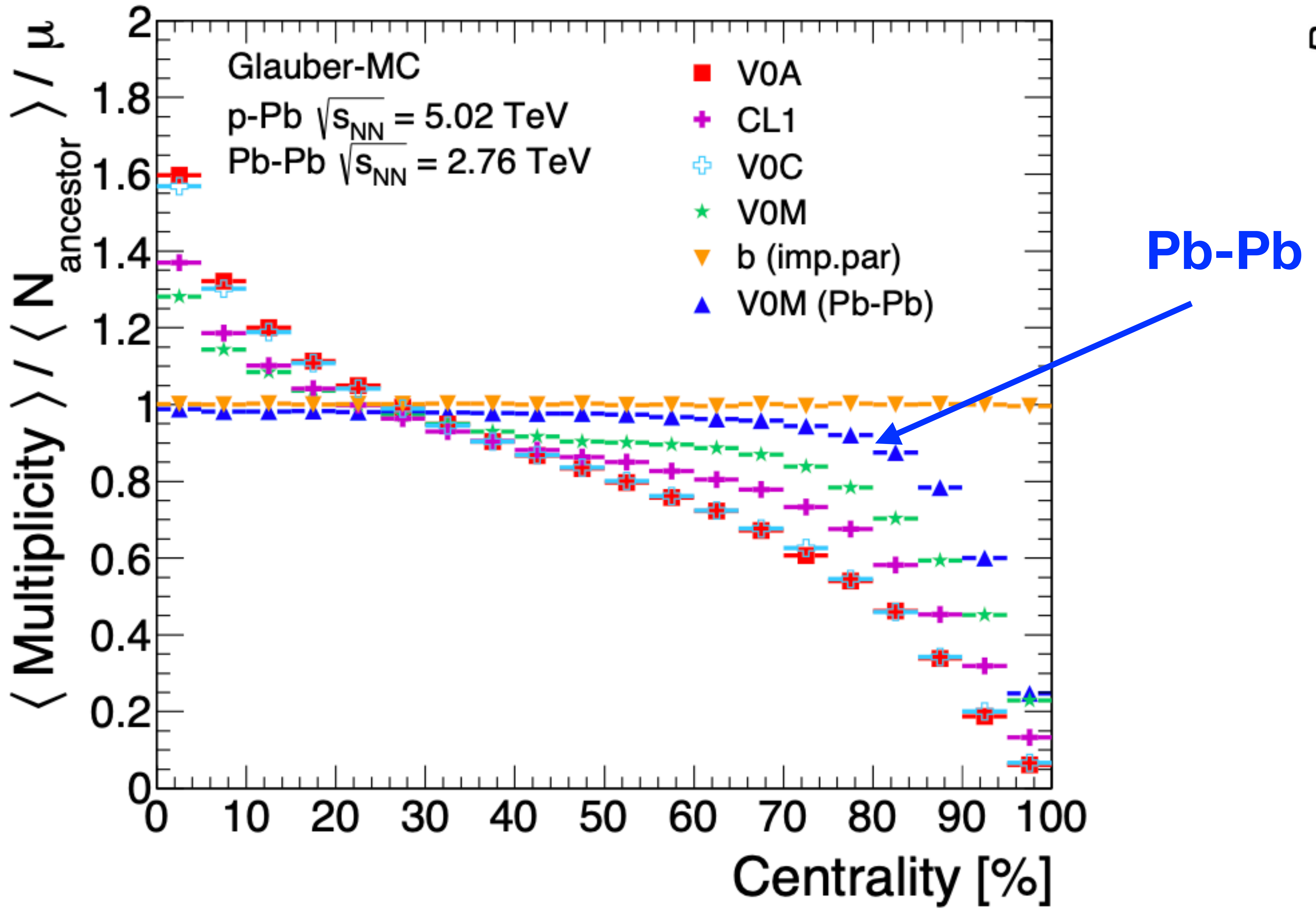
- Reason: Matter overlap not described by $N_{\rm coll}$ alone
  - need also overlap (impact parameter dependence) of individual N-N collisions
- Bias on N-N impact parameter
  - from pure phase space
  - multiplicity bias ("inverse" jet pedestal)
- Solution: ZN Pb-going centrality classes

QM2017 (D. Perepelitsa)

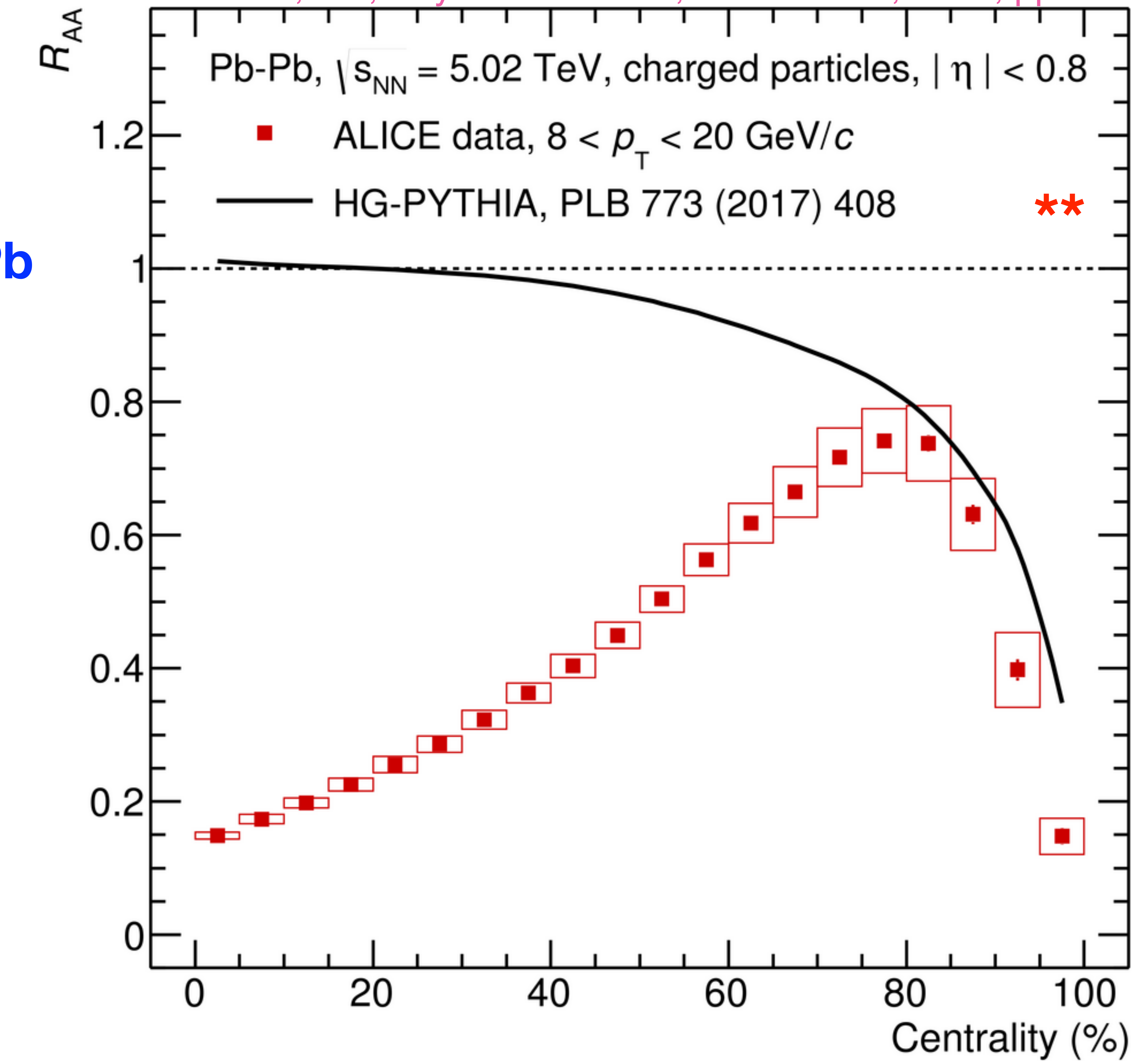
Indications of jet quenching in peripheral Pb-Pb ?

… to Pb-Pb

Multiplicity bias from Glauber fit



C Loizides, AM, Physics Letters B, Volume 773, 2017, pp. 408-411

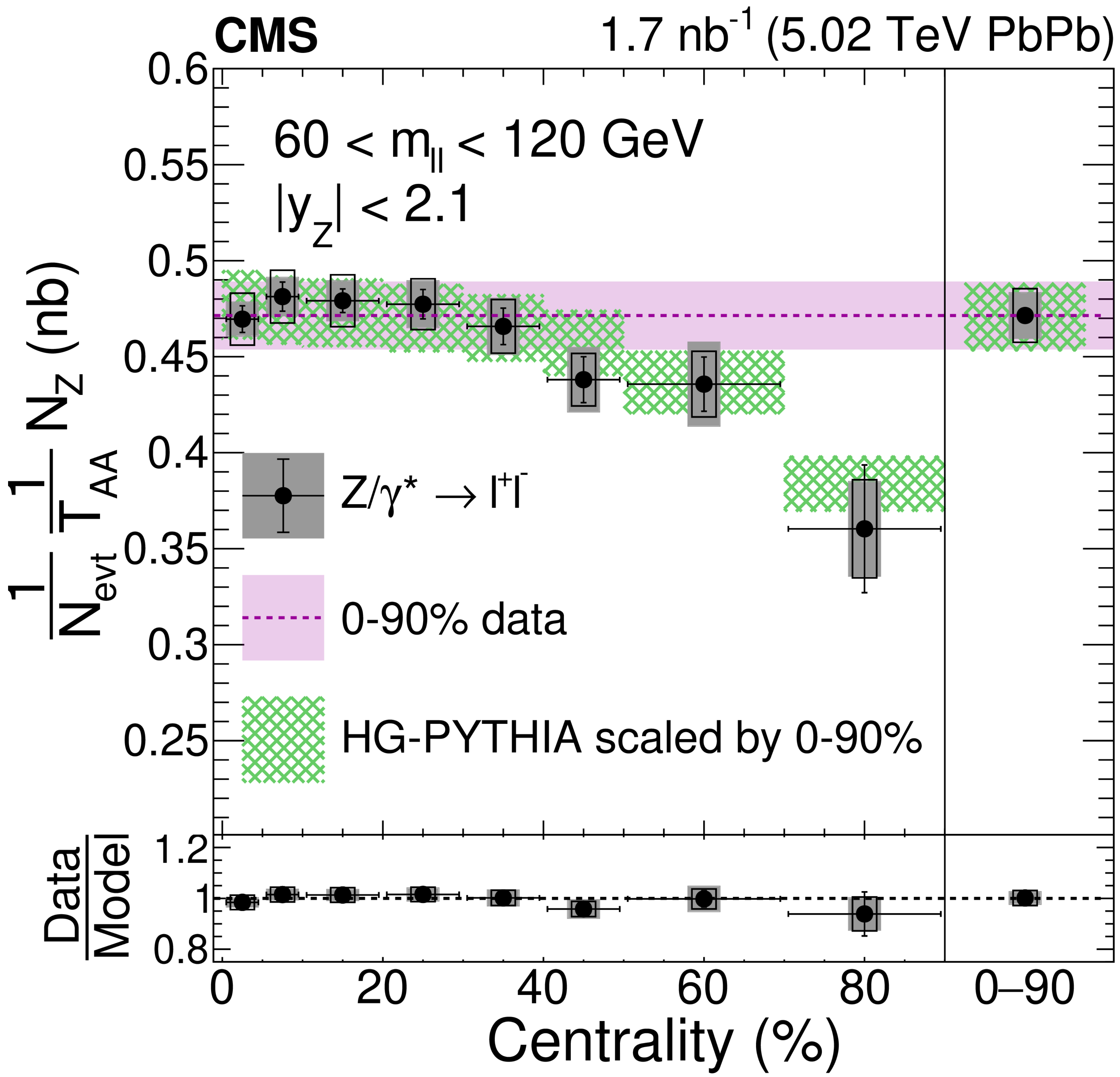


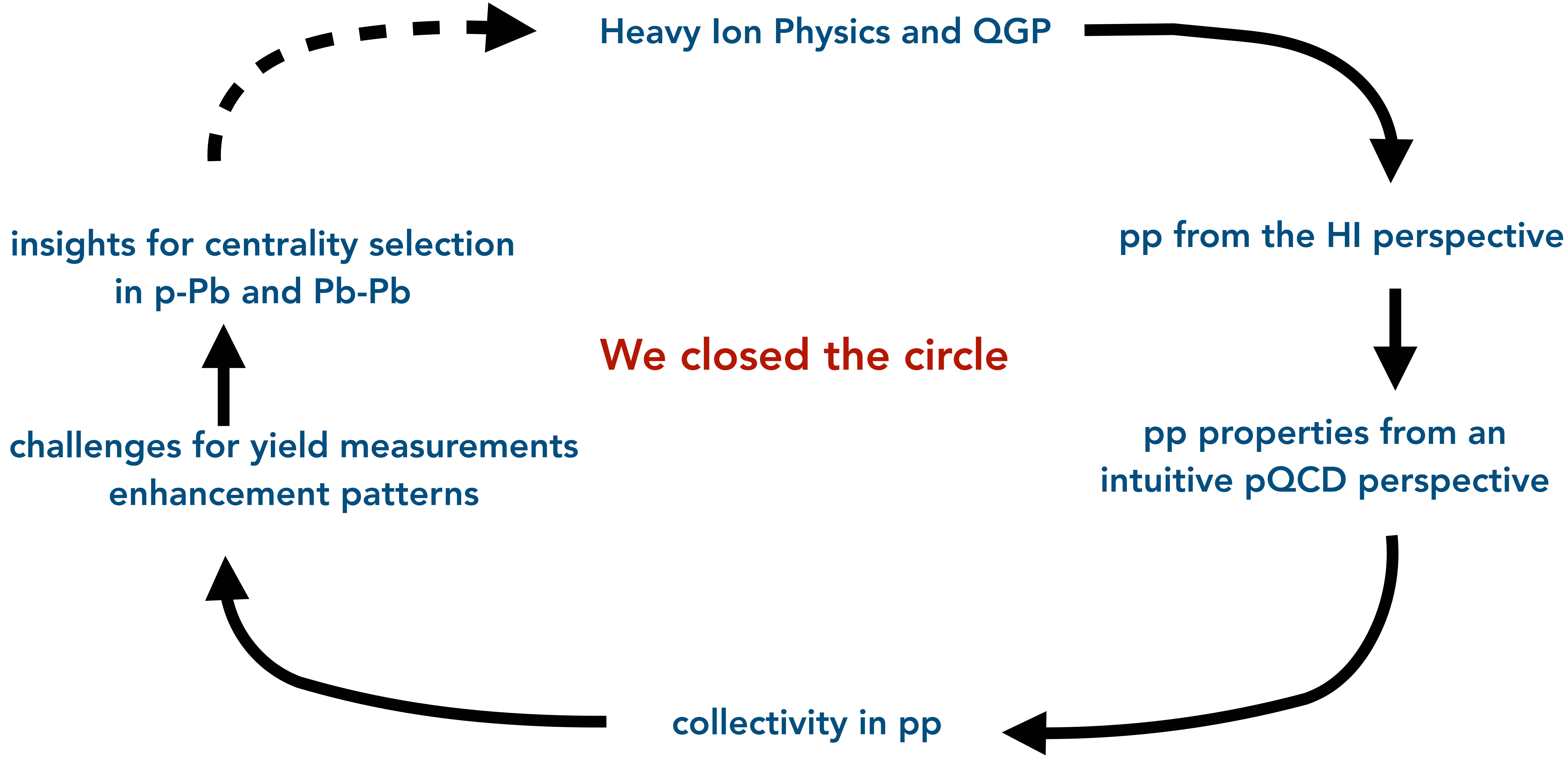
** HG-PYTHIA used to give credit to the original MPI-Glauber implementation in HIJING. In HIJING itself the MPI effects are masked by other nuclear effects.

Centrality dependent Z production in PbPb

- No quenching expected for Z
  - “calibrates” the Glauber reference

Phys. Rev. Lett. 127 (2021) 102002

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We closed the circle

Time to conclude …

- Starting off from the search of QGP-like effects in high density pp collisions one finds that flow-like signals and baryon enhancement are present even at lowest multiplicity
  - … but apparently not in even smaller systems (e^+e^-)
  - what is the reason for the difference: presence of the remnant protons?
- Huge chance: study of production processes in almost background free environment
- At high multiplicity (in the exponential tail)
  - mind possible biases
  - combine yield measurements with angular correlation studies and/or event shape observables
  - challenge models with more differential studies!
- Small systems including pp remain a dynamic and captivating field of study
  … many crucial contributions by ICN members