Physics of heavy-ion collisions at the highest energy frontier

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online

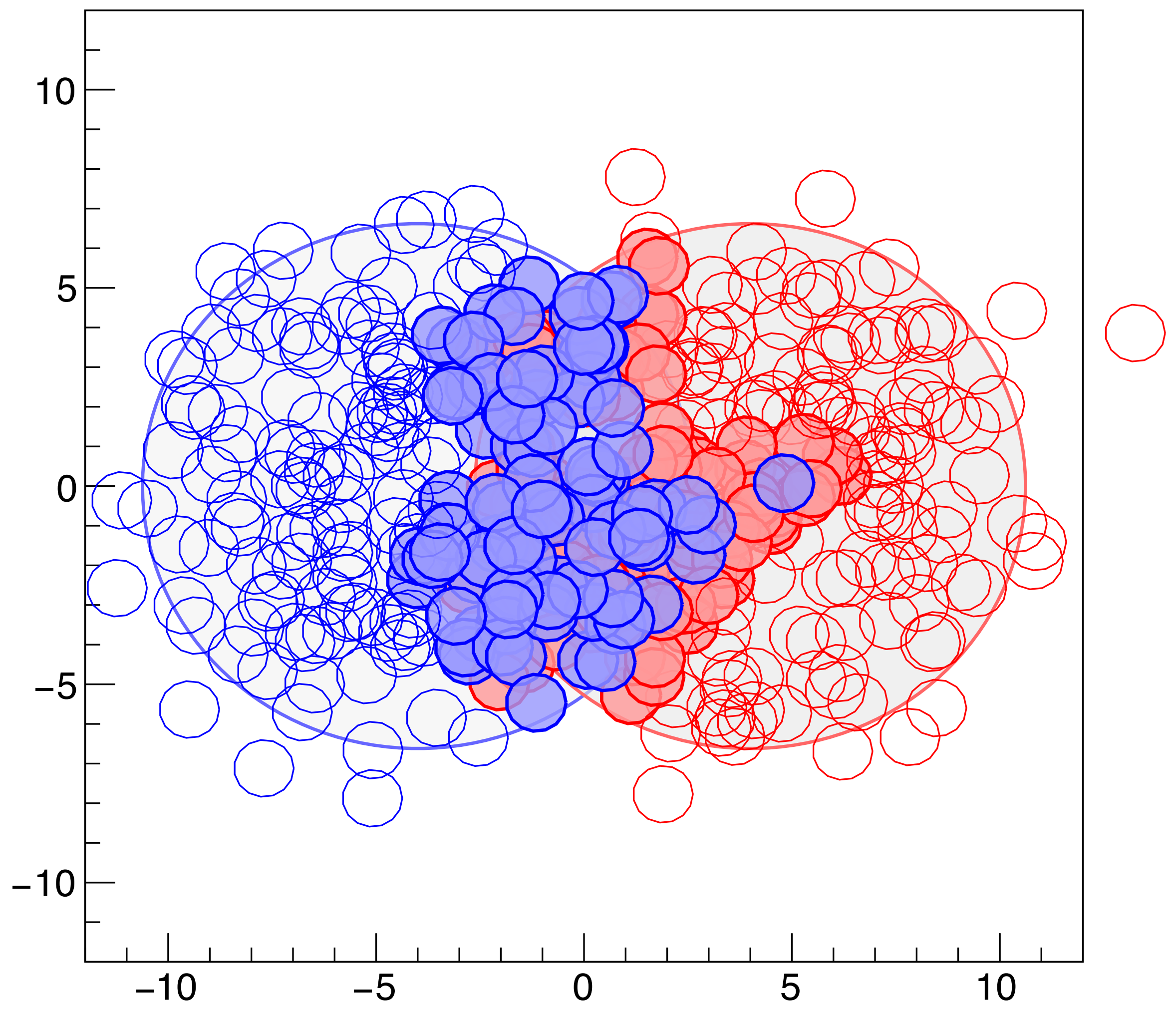
Disclaimer: had to be selective, some areas are not covered

Nikhef

Physics Utrecht
EMMEΦ

Heavy Ion Physics: many-body QCD systems

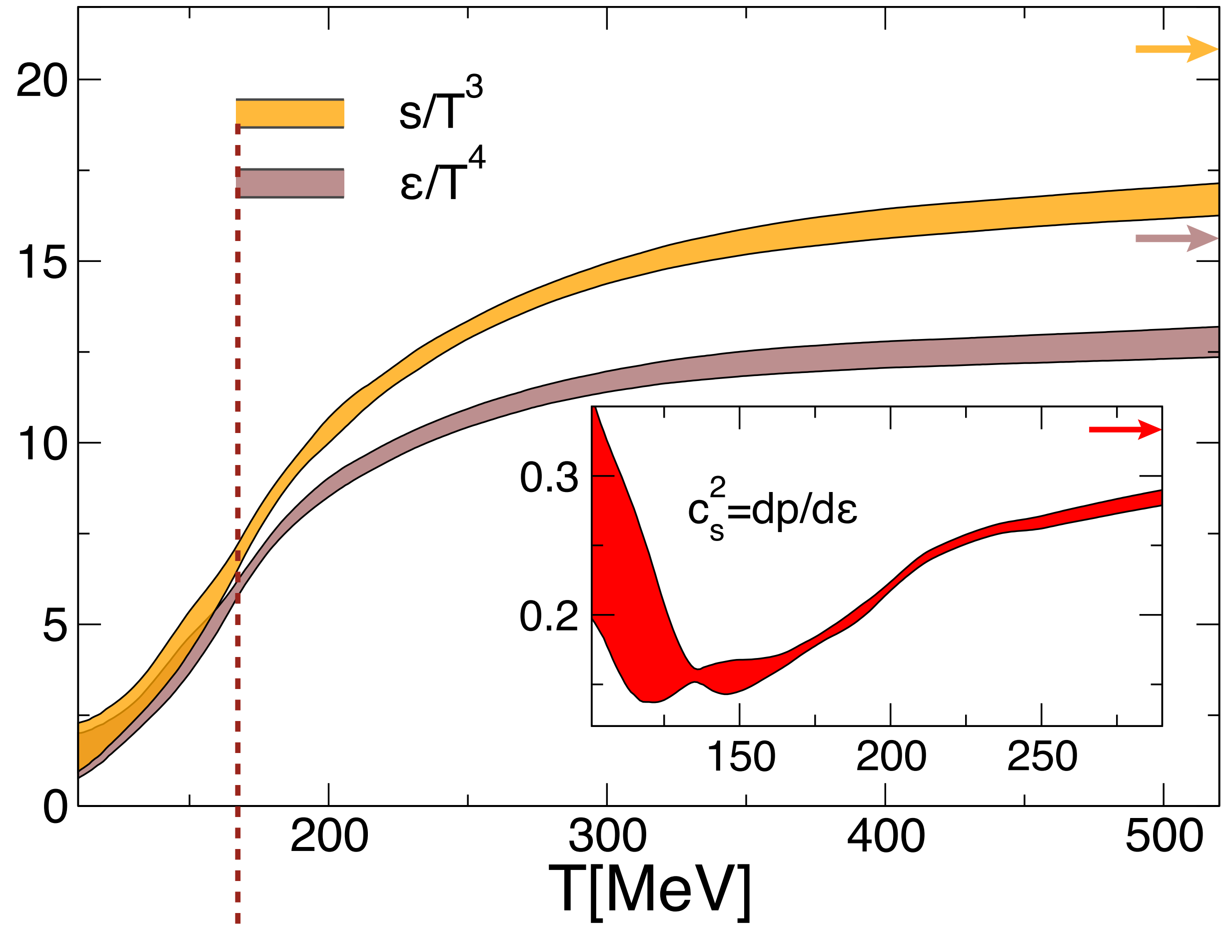
Initial state



Spatial and momentum distributions of incoming partons

Phase transition

Lattice QCD

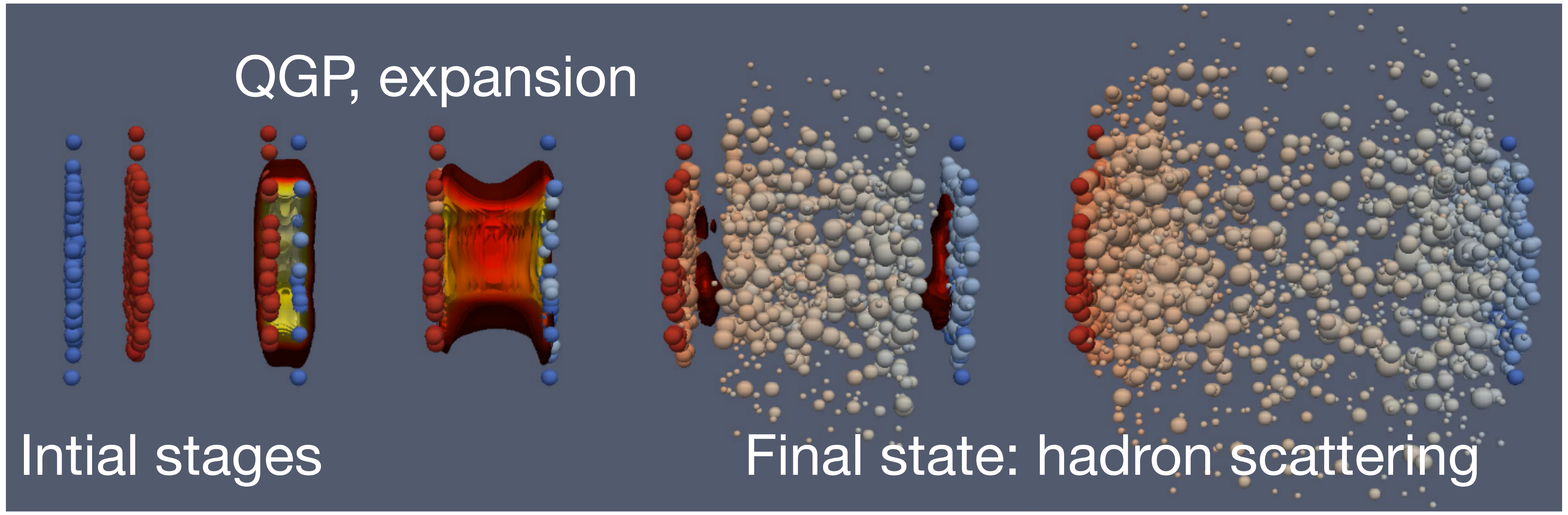


Borsanyi et al, PLB 730, 99

$T_c \approx 150$ MeV

$$\varepsilon \propto gT^4$$

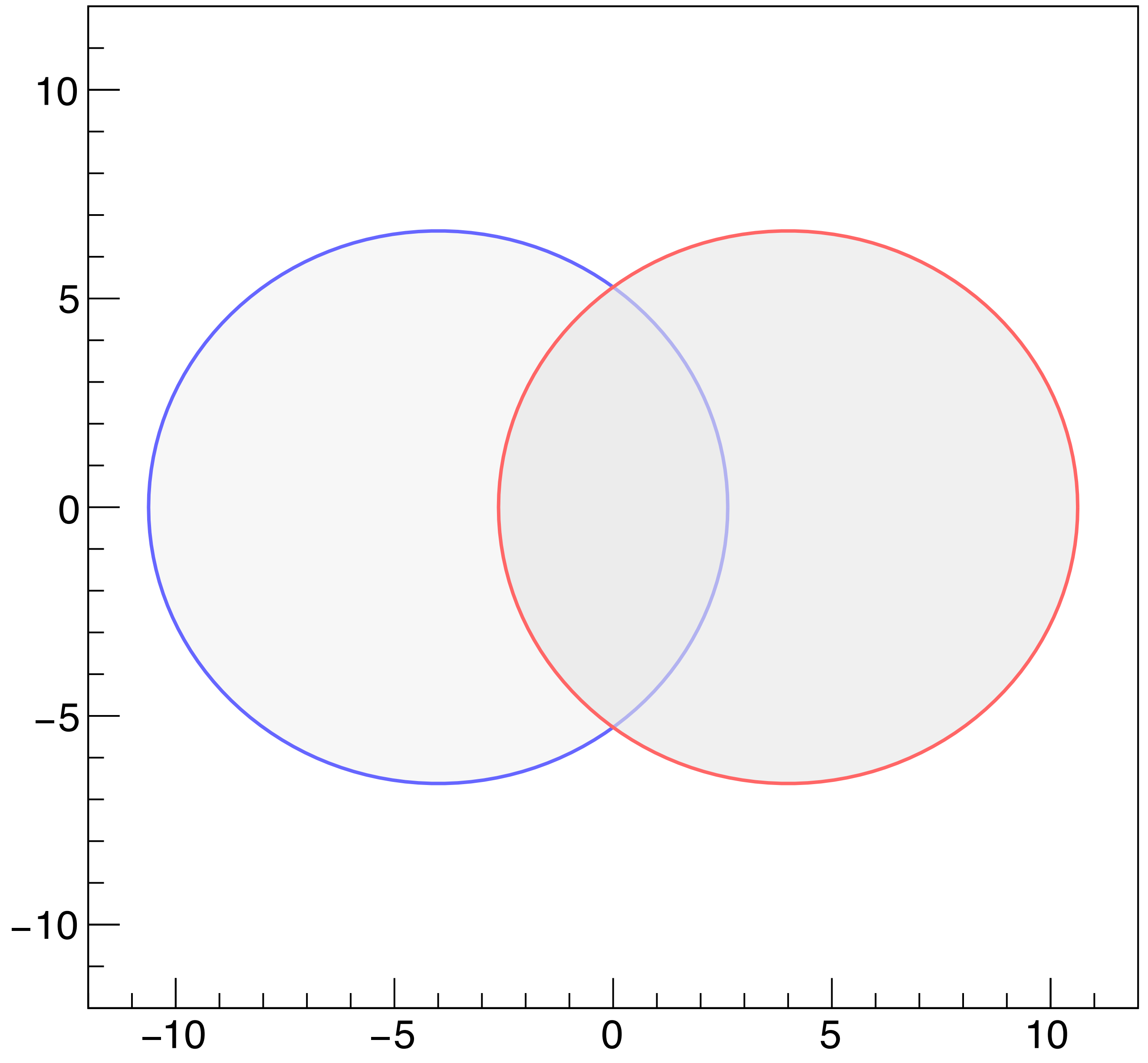
g: degrees of freedom



- **Properties of equilibrium matter**: equation of state, transport coefficients
- **Dynamics**: hadronisation, interactions of partons with the medium

Azimuthal anisotropy: initial and final states

MC event: location of nucleons



Characterise shape by harmonics:

$$\varepsilon_n = \frac{\sum r^2(\cos^2 n\varphi + \sin^2 n\varphi)}{\sum r^2}$$

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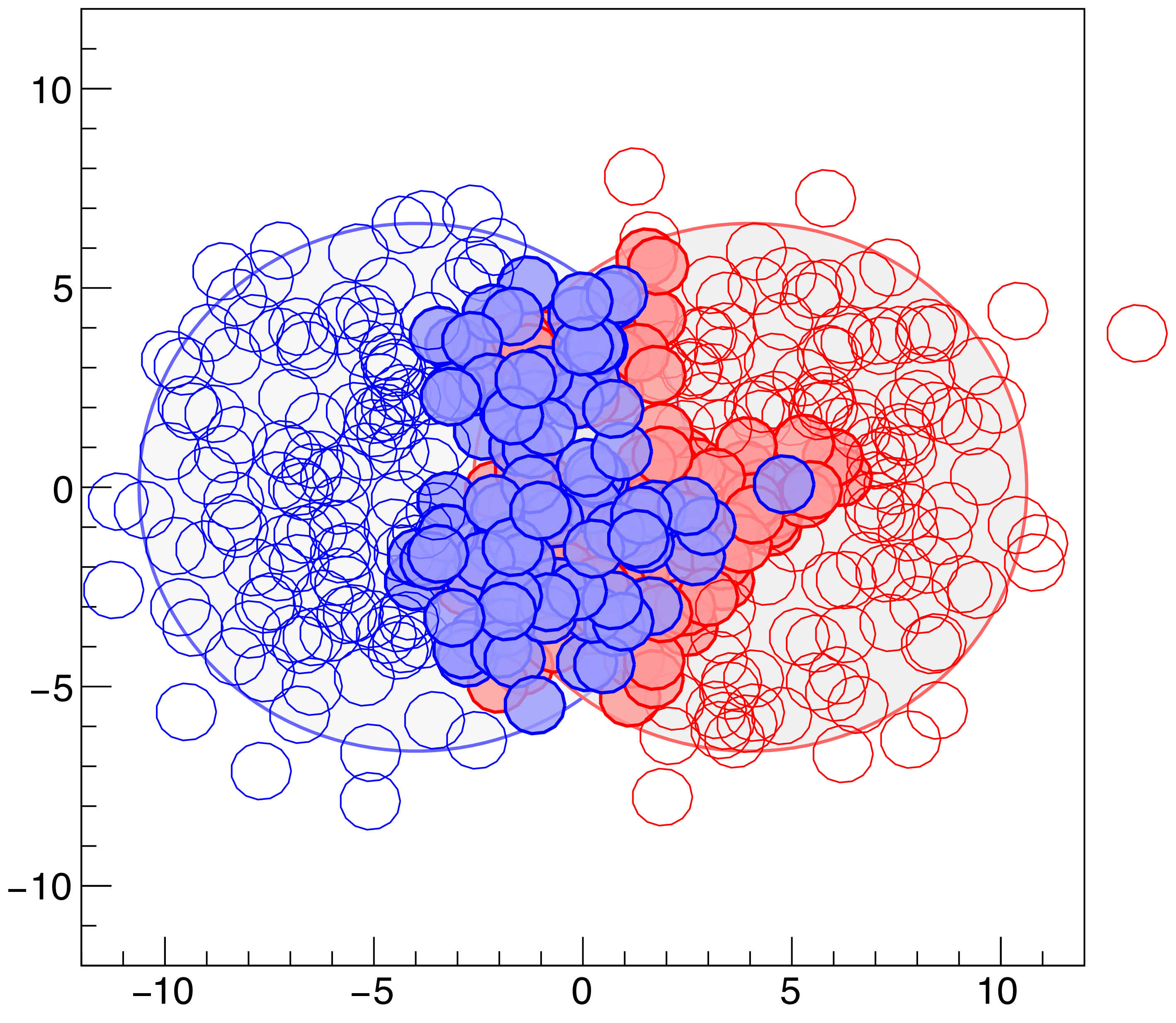

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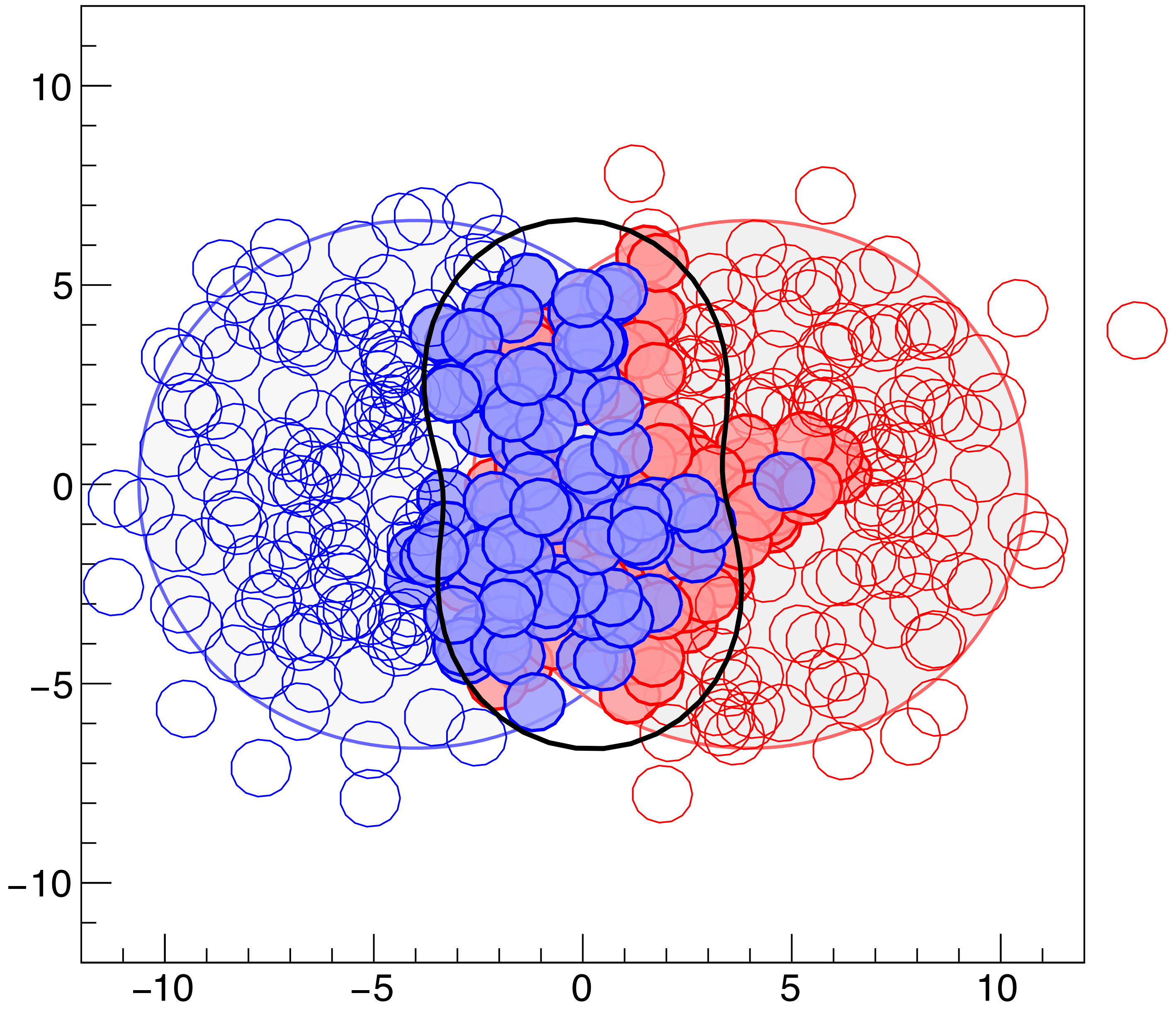

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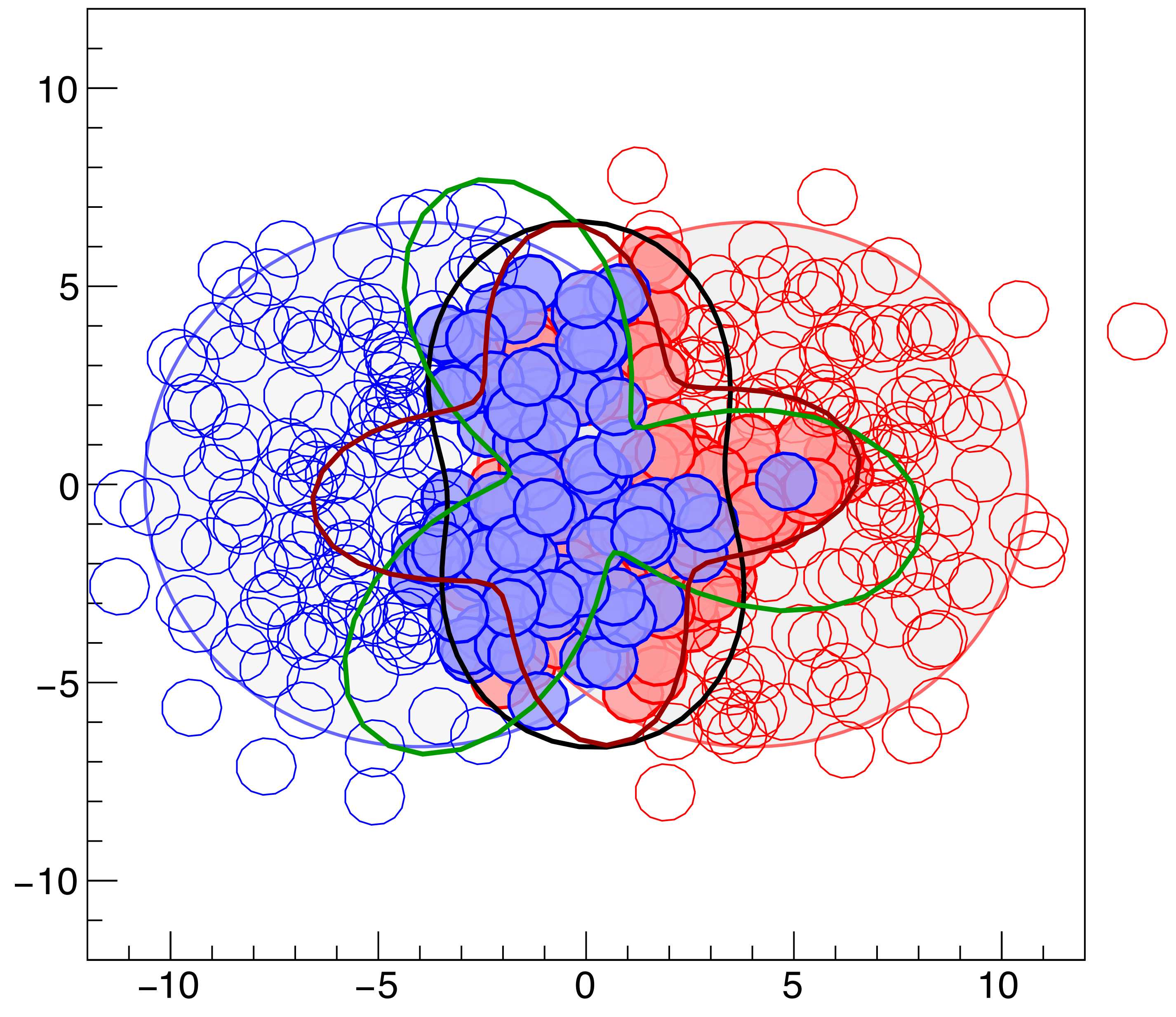

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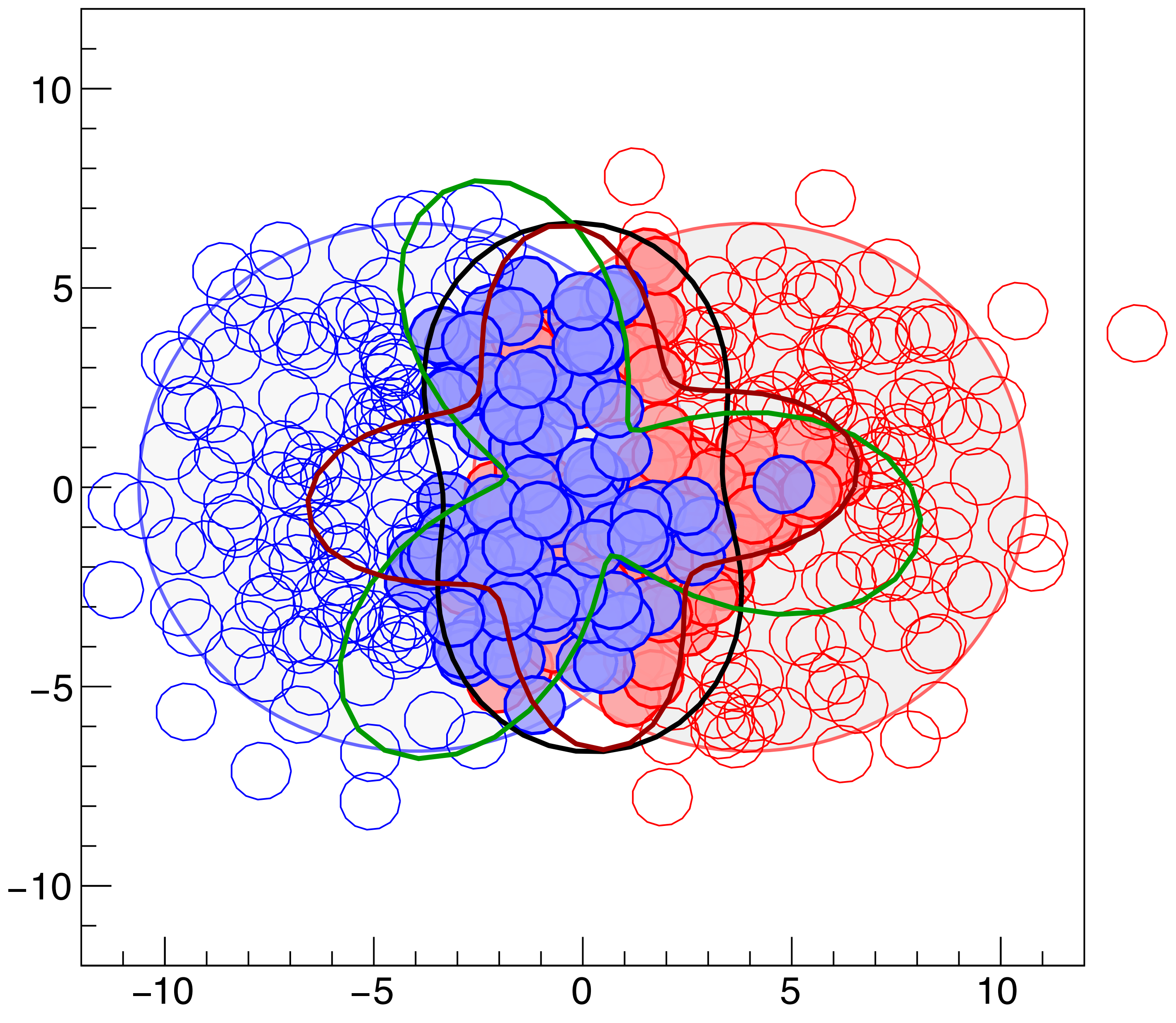
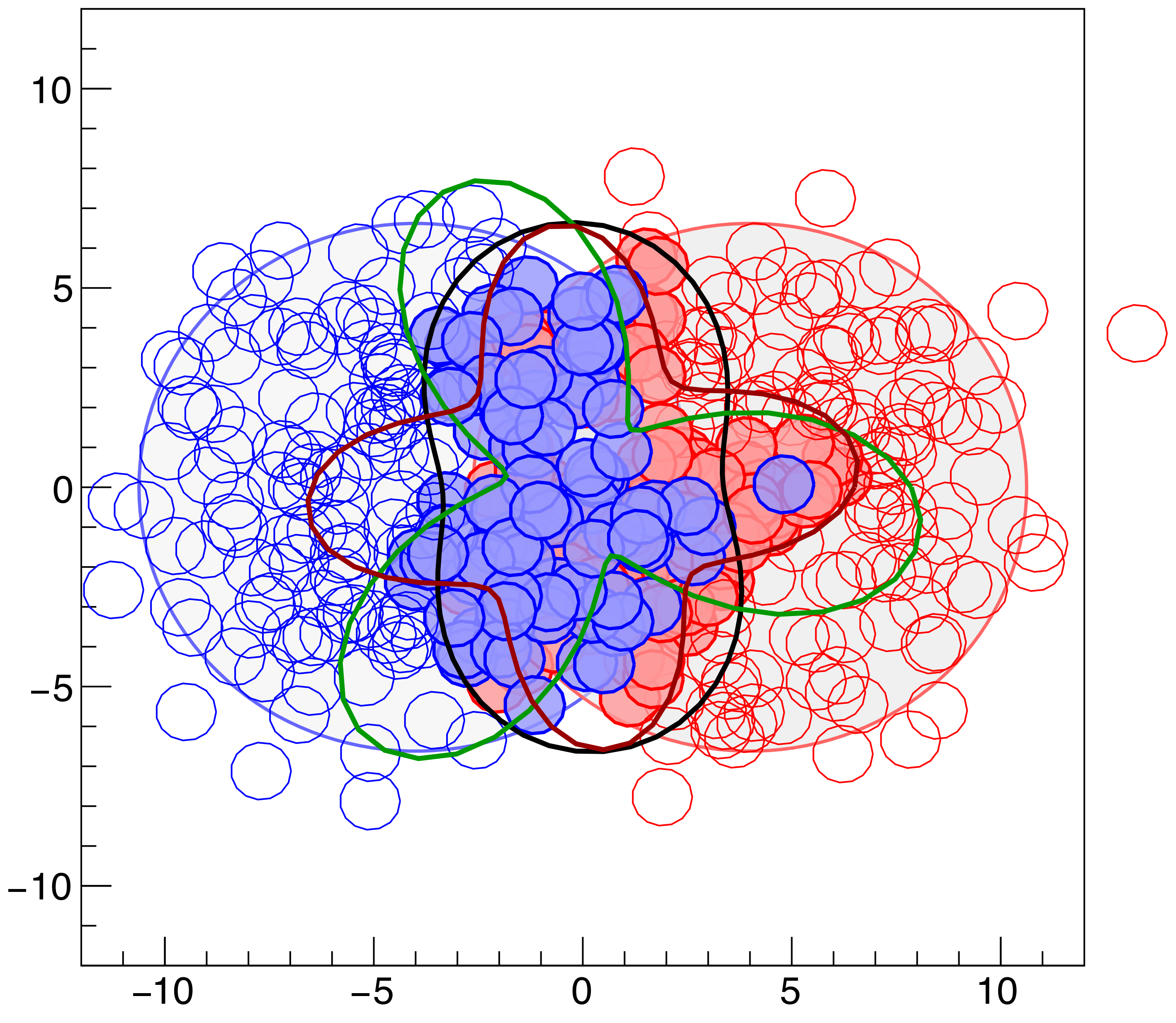


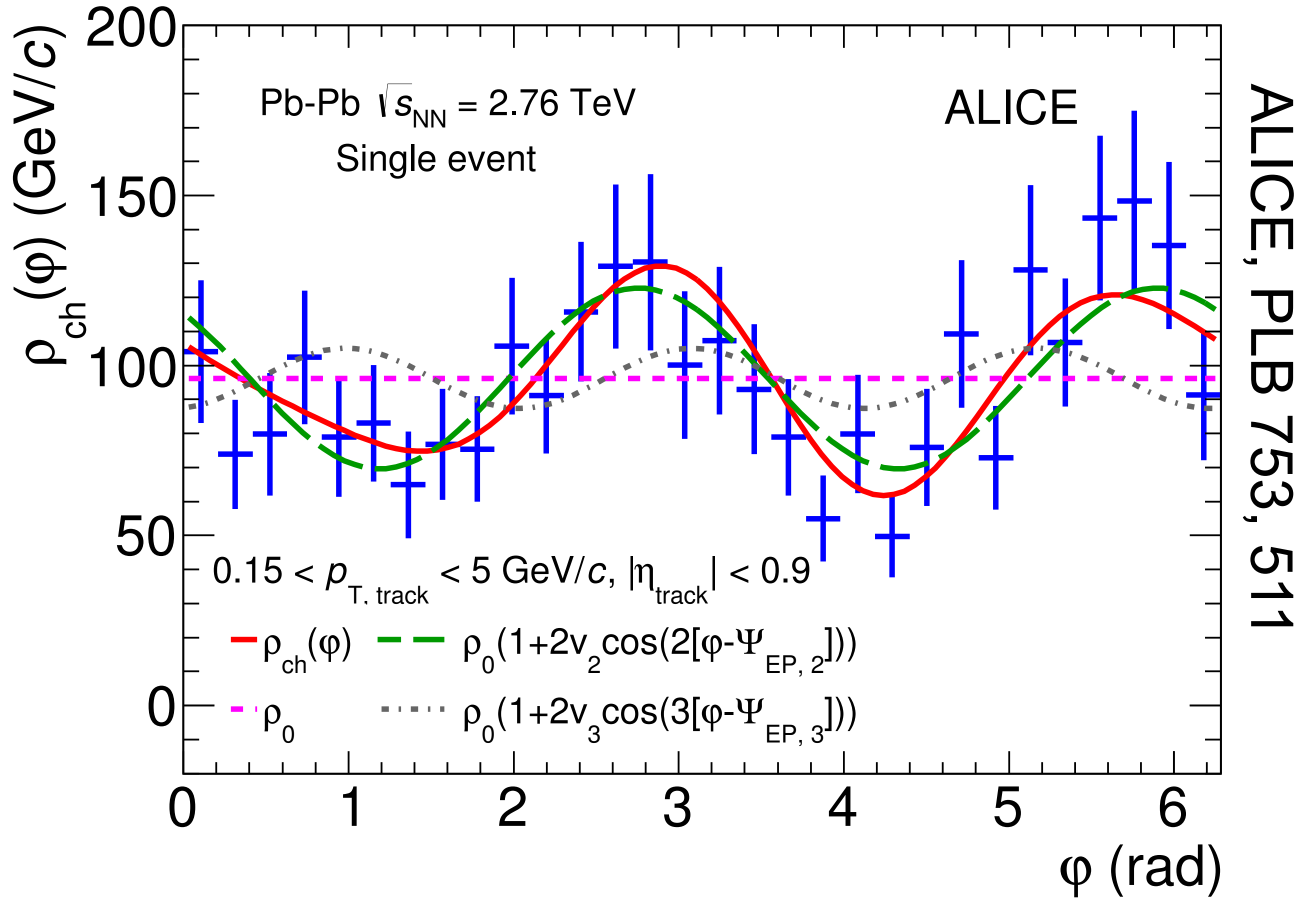
Initial state spatial anisotropies ε_n are transferred into
final state momentum anisotropies v_n
by pressure gradients, flow of the Quark Gluon Plasma

Azimuthal anisotropy: initial and final states

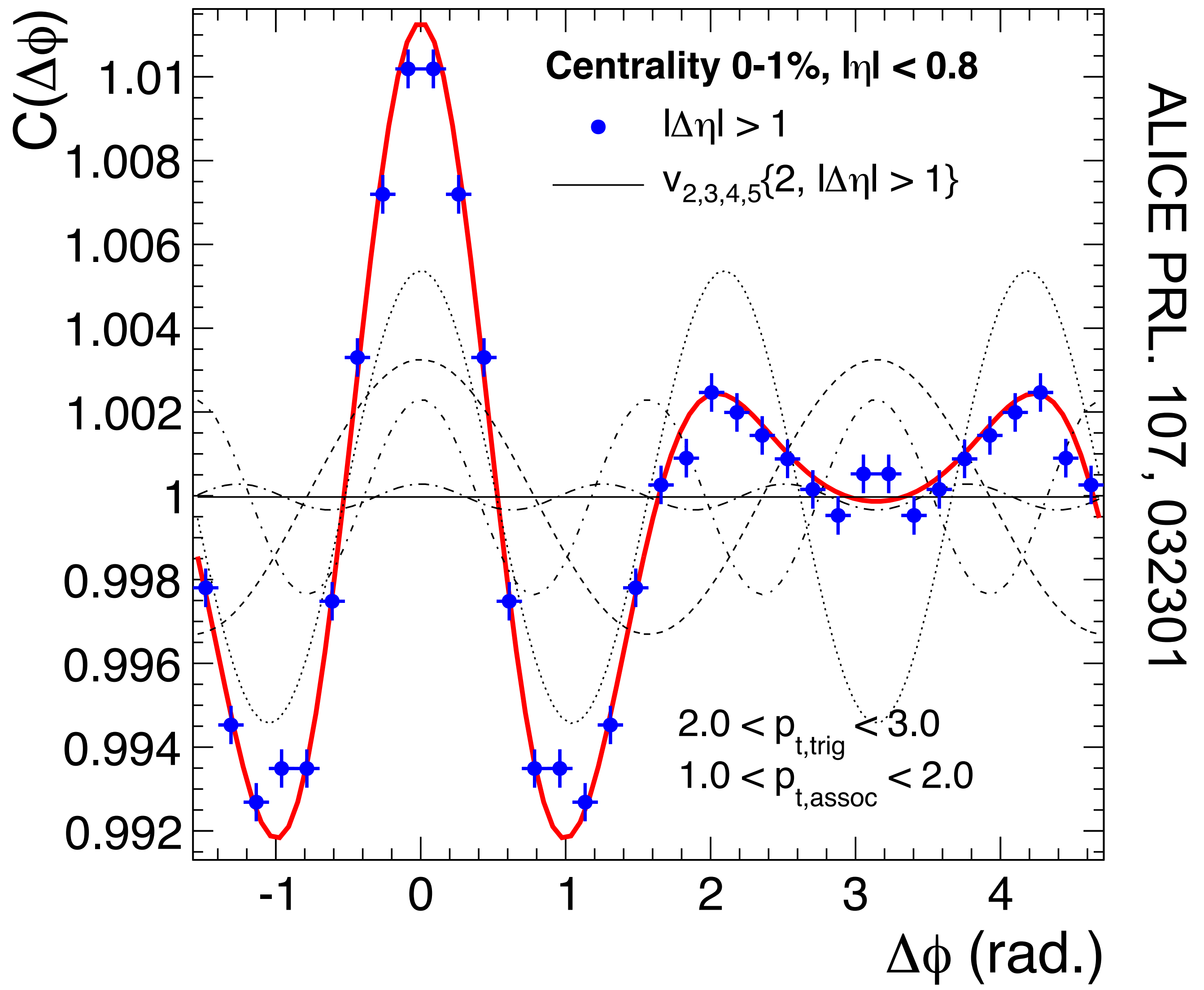
MC event: location of nucleons



Azimuthal distribution single event



Sum over many events



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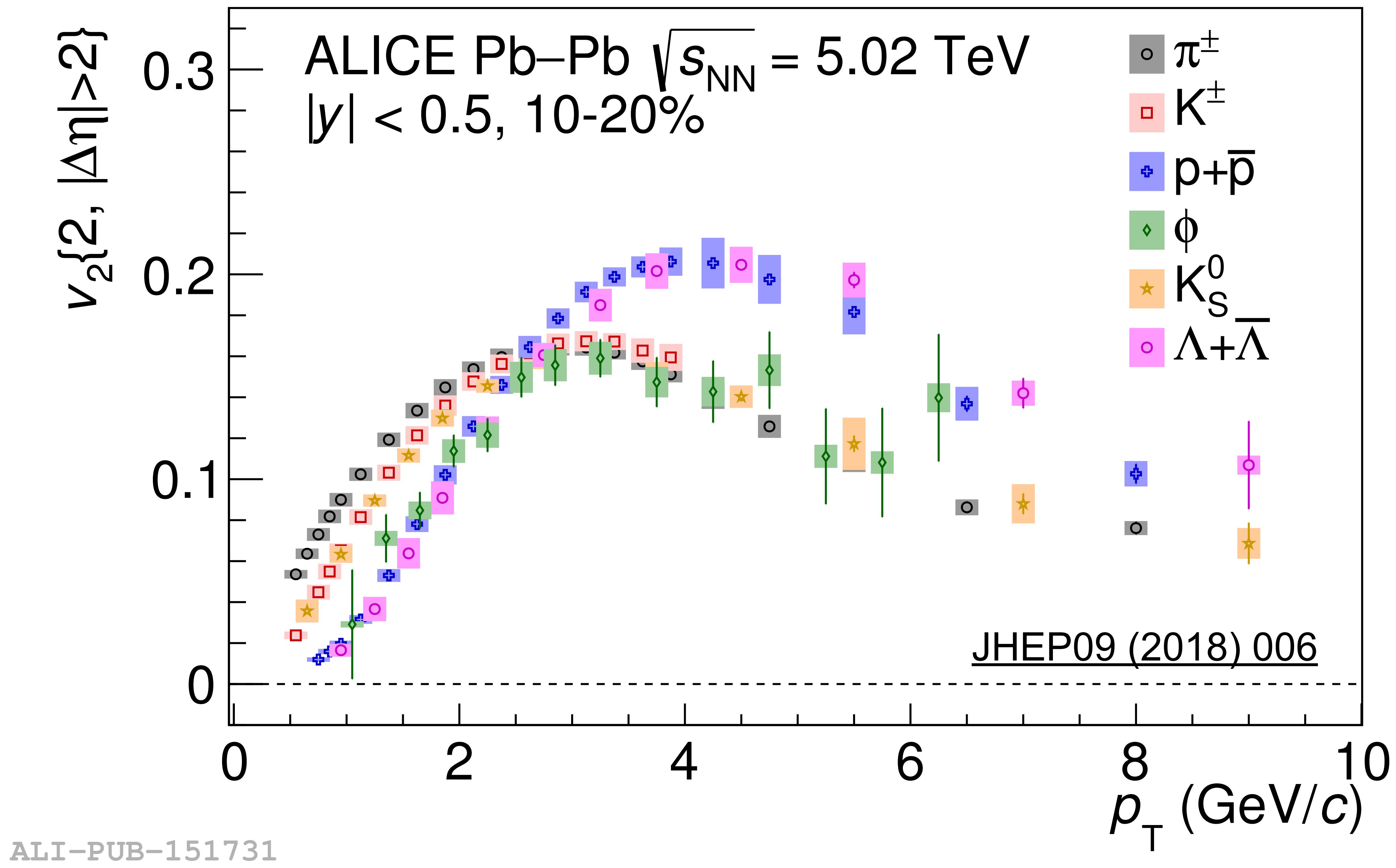
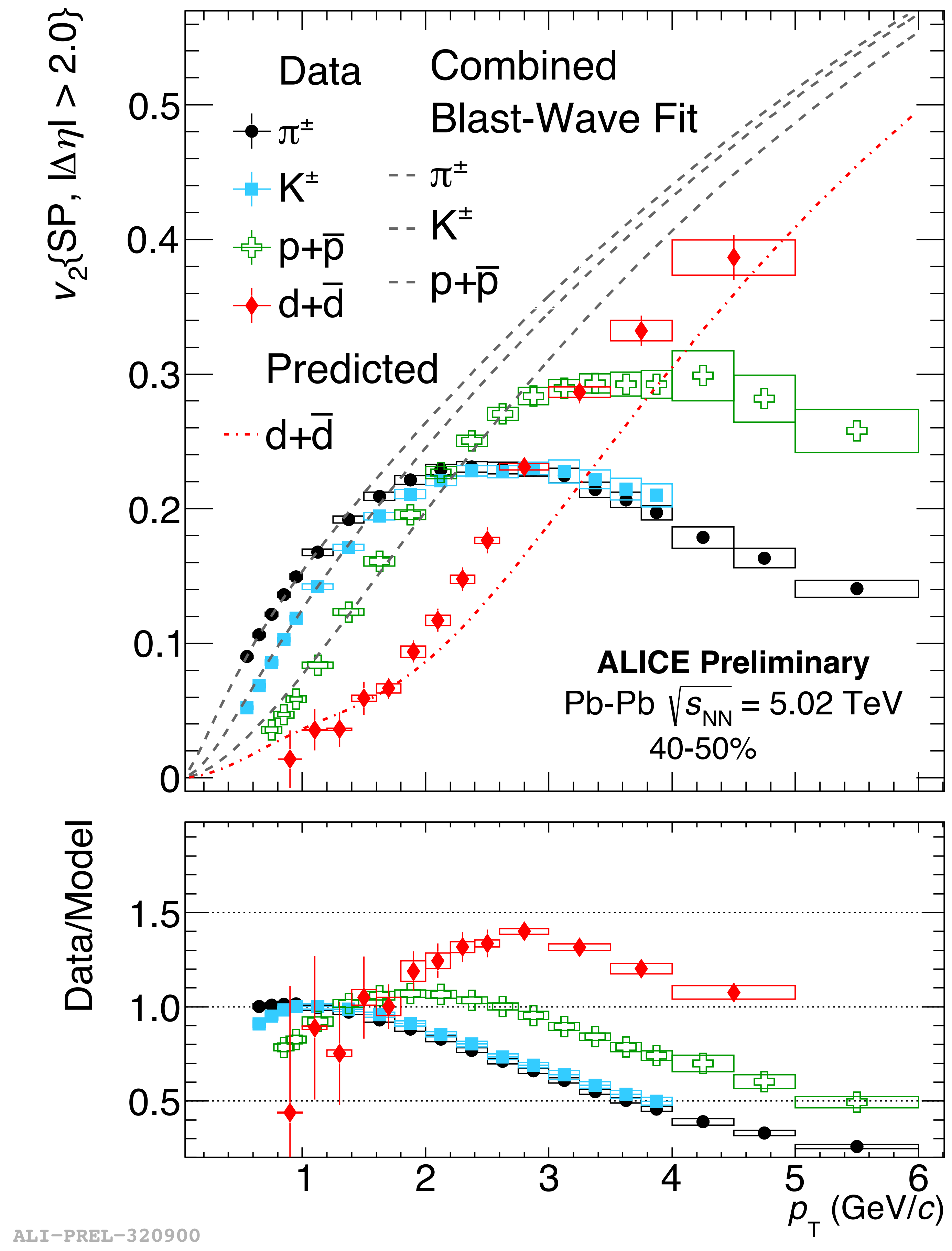
Anisotropic flow: initial state and QGP expansion

elliptic flow v_2



v_2 of deuterons



Mass-dependence of v_2 measures flow velocity

Even nuclei flow !

Tests hydrodynamical description, freeze-out models

Anisotropic flow: initial state and QGP expansion

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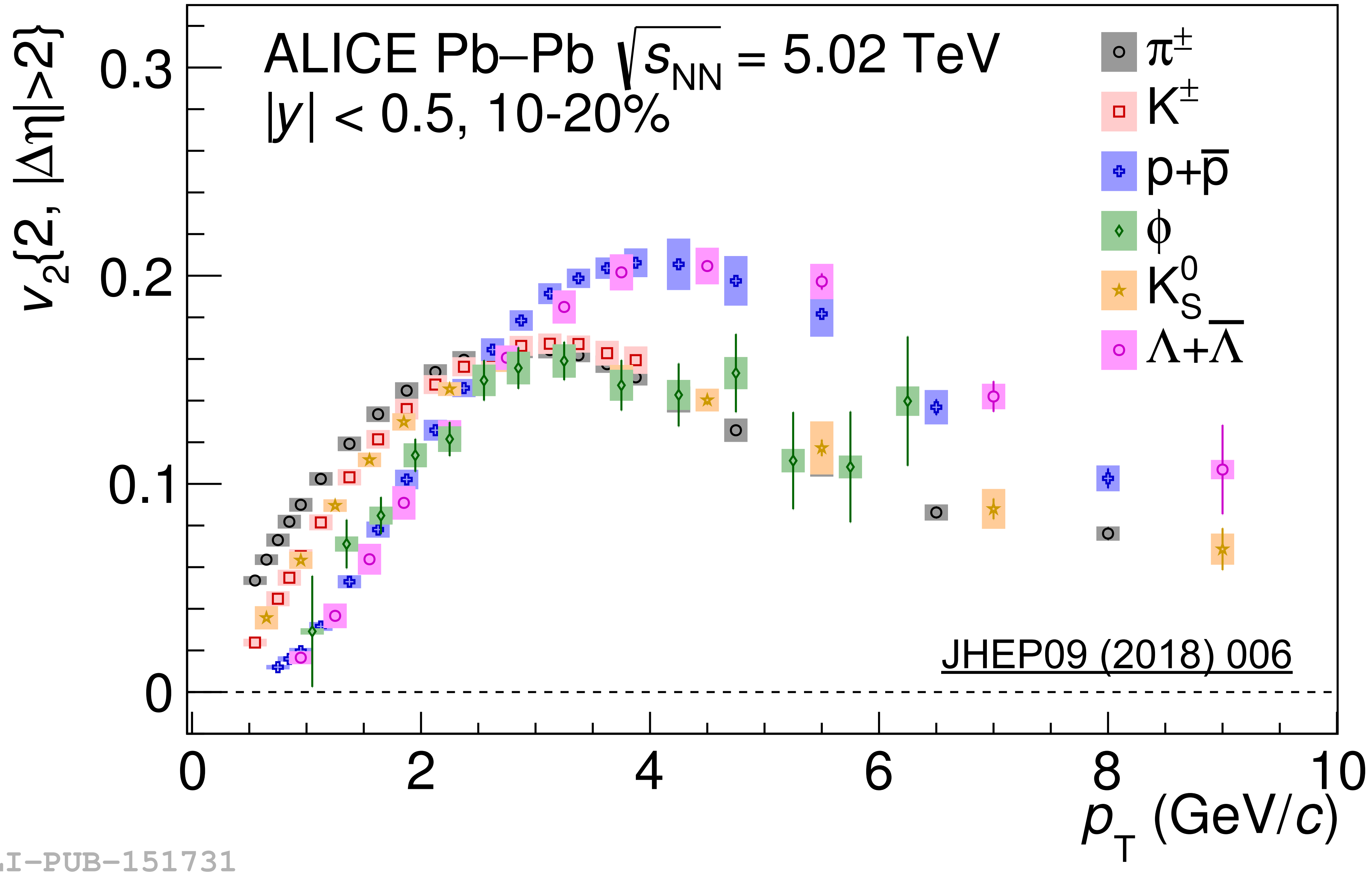

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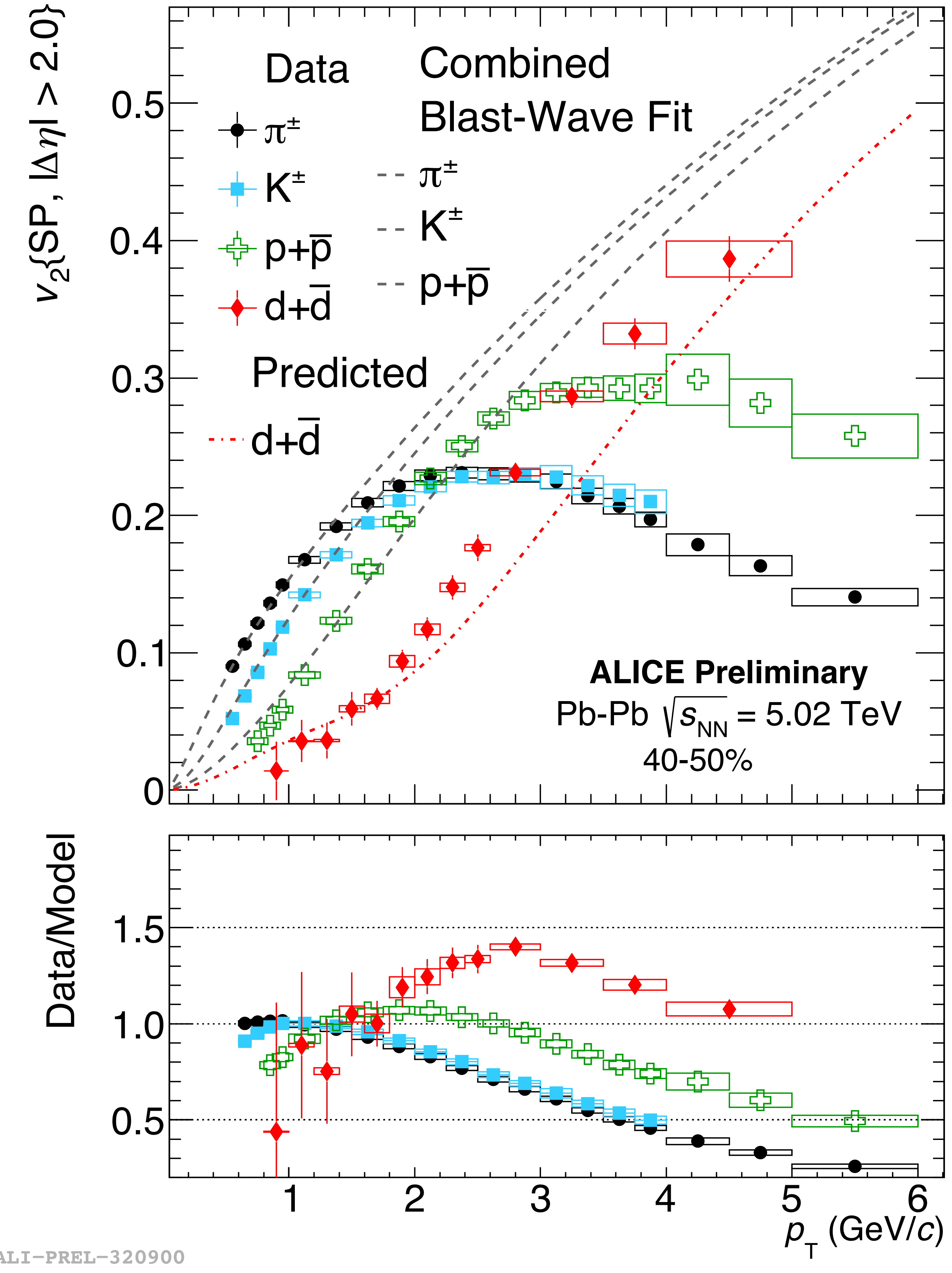
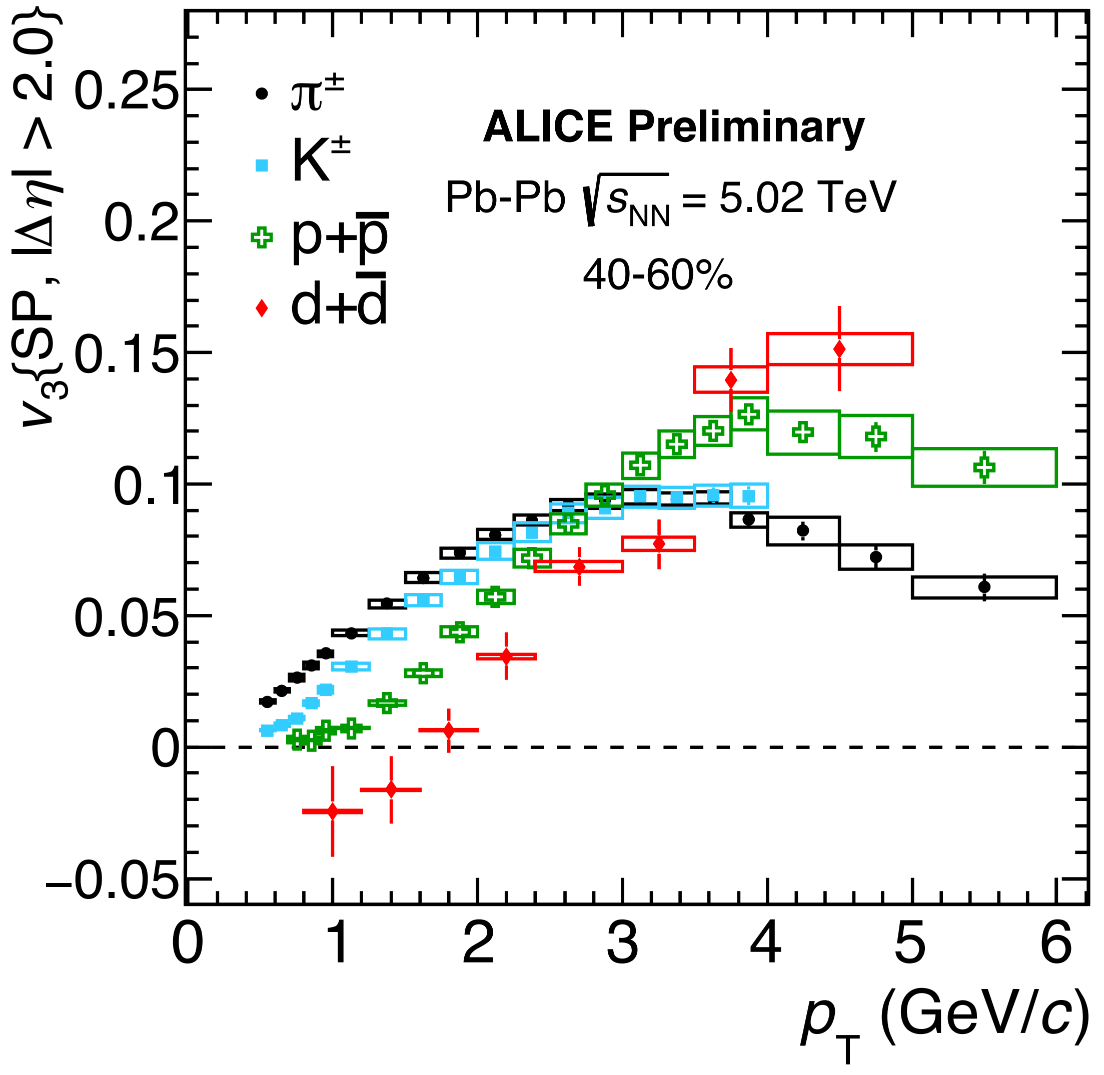
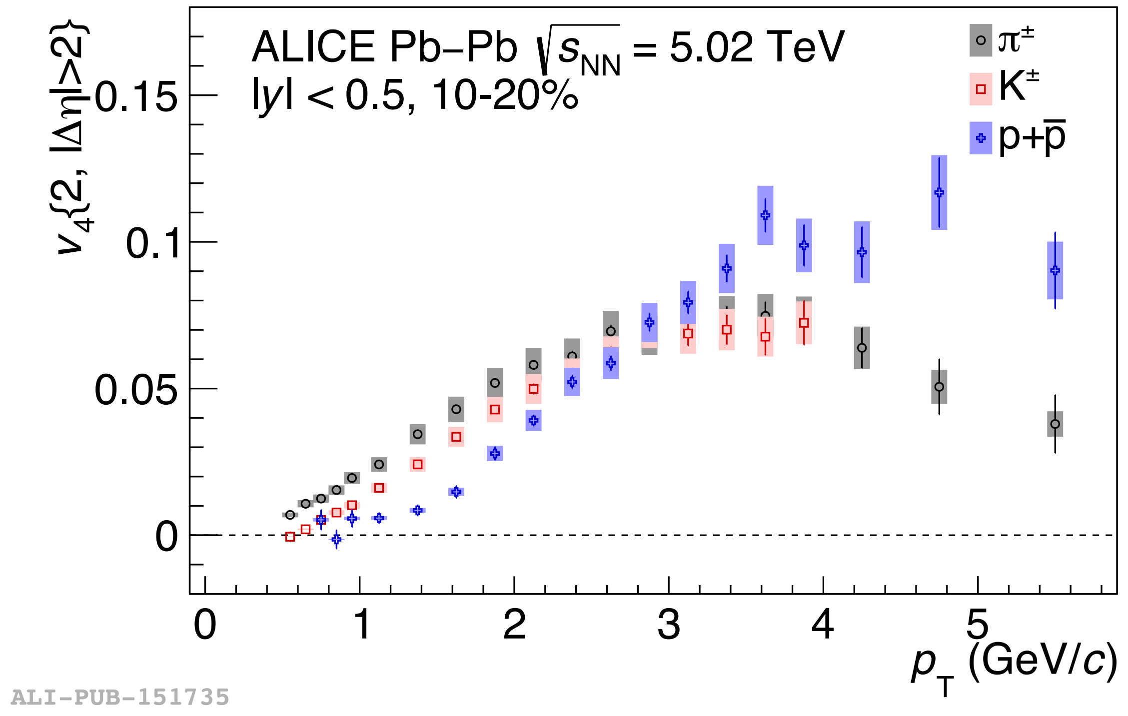


Even nuclei flow !

v_3



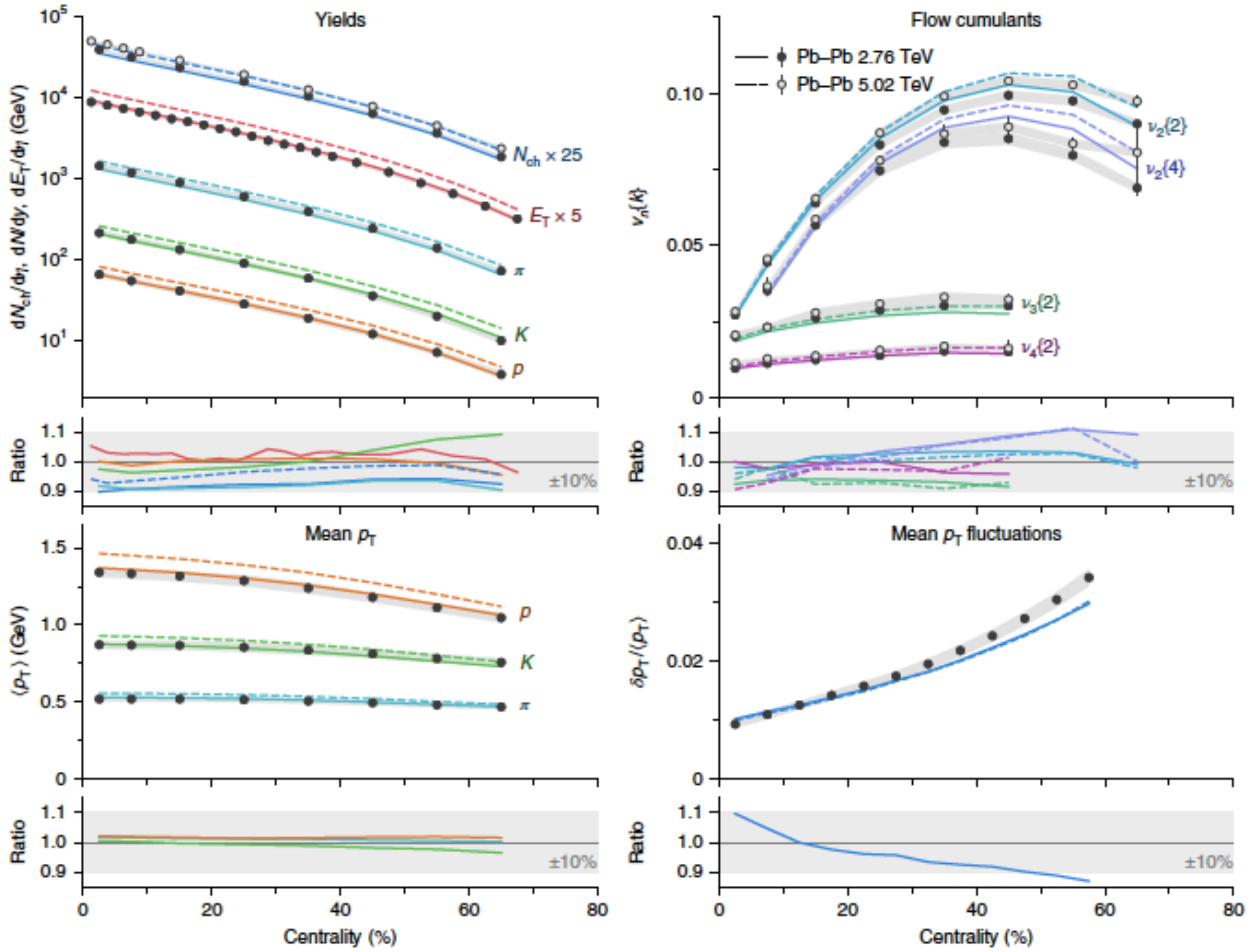
v_4



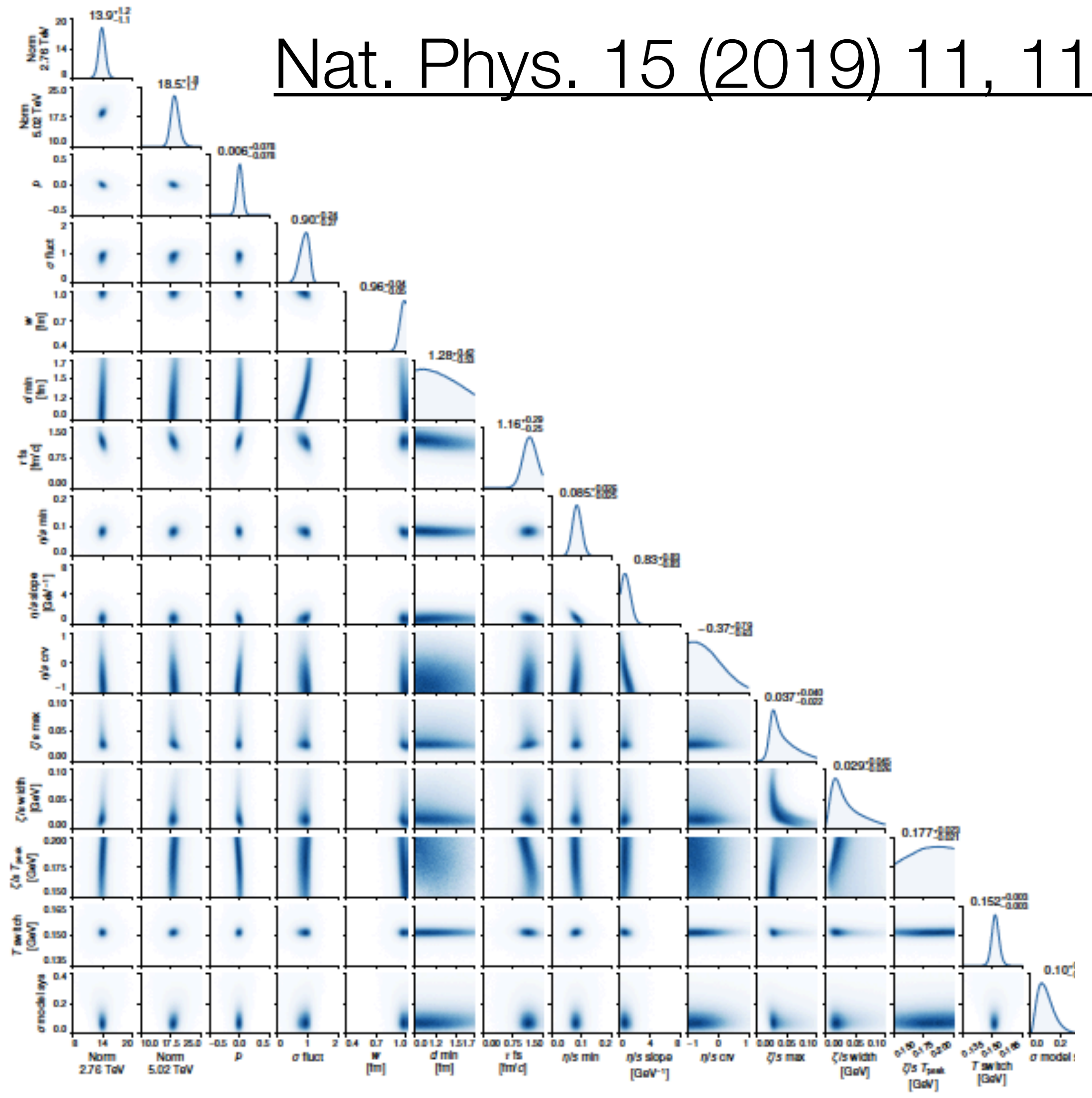
Tests hydrodynamical description, freeze-out models

Challenge: constrain both initial geometry and QGP properties

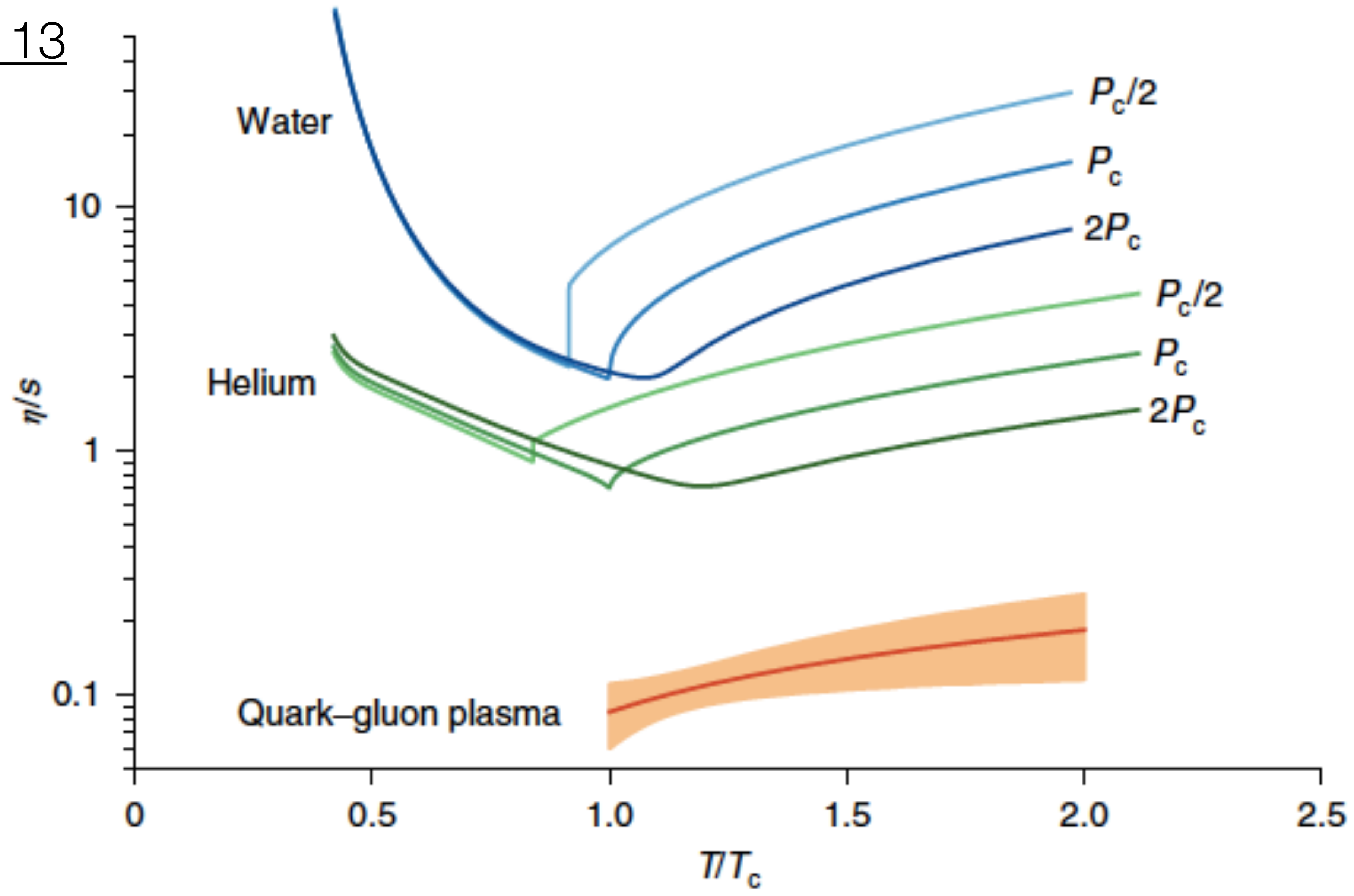
Input data compared to model curves



Nat. Phys. 15 (2019) 11, 1113



Shear viscosity η vs *T*

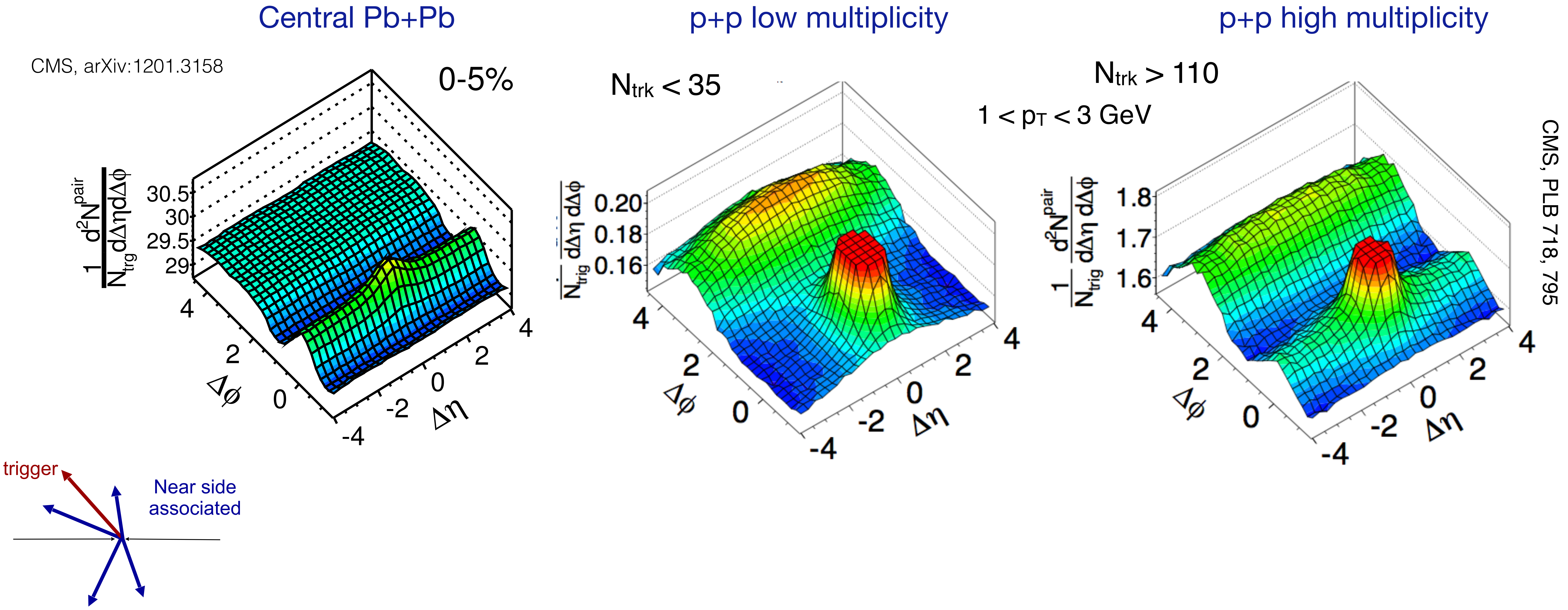


Need multiple inputs to constrain system:
Multiplicity, mean p_T, v_2, v_3

Total 14 model parameters
constrained by data

QGP has very small shear viscosity:
short mean free path, strong interactions

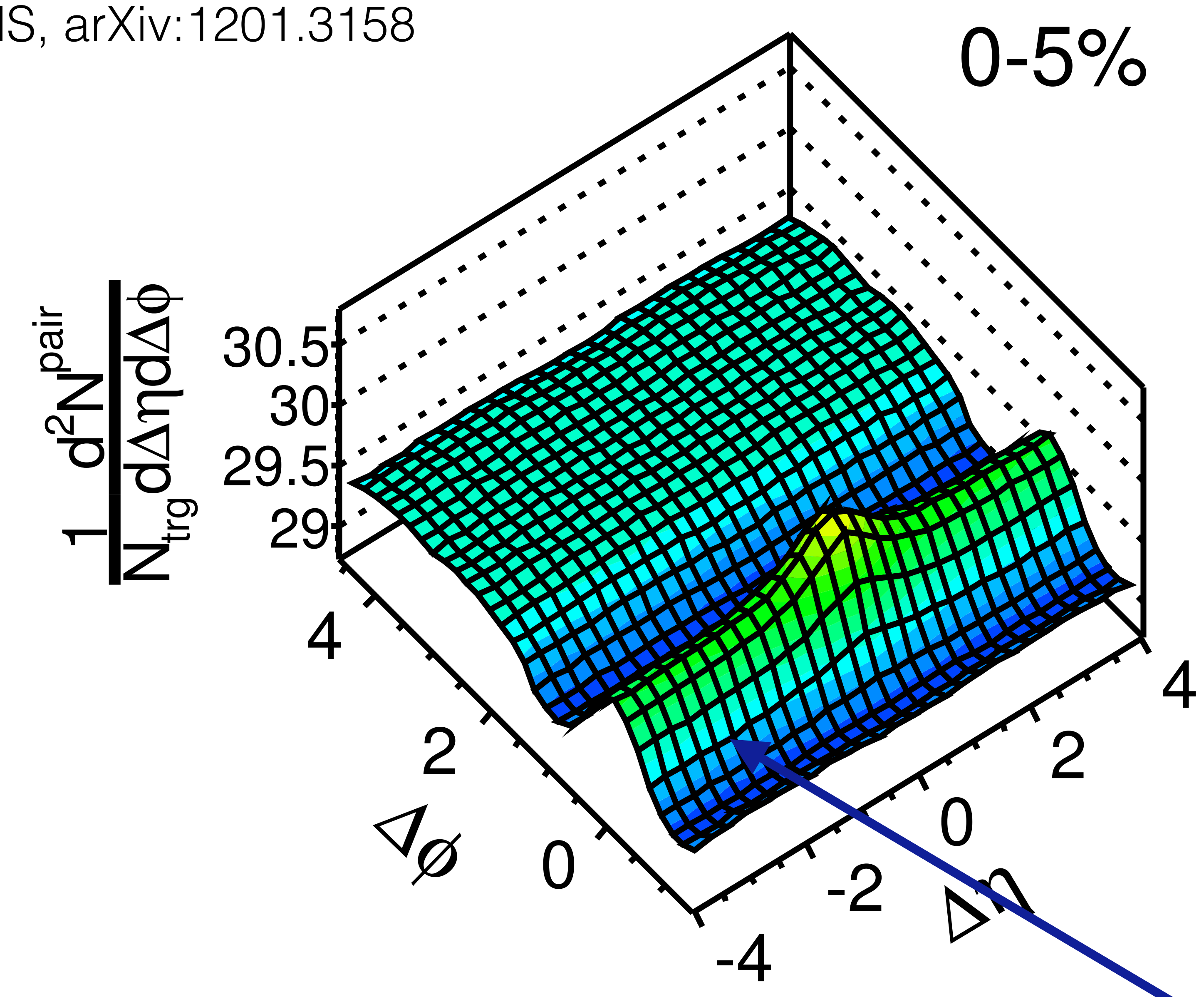
Azimuthal anisotropy in pp collisions



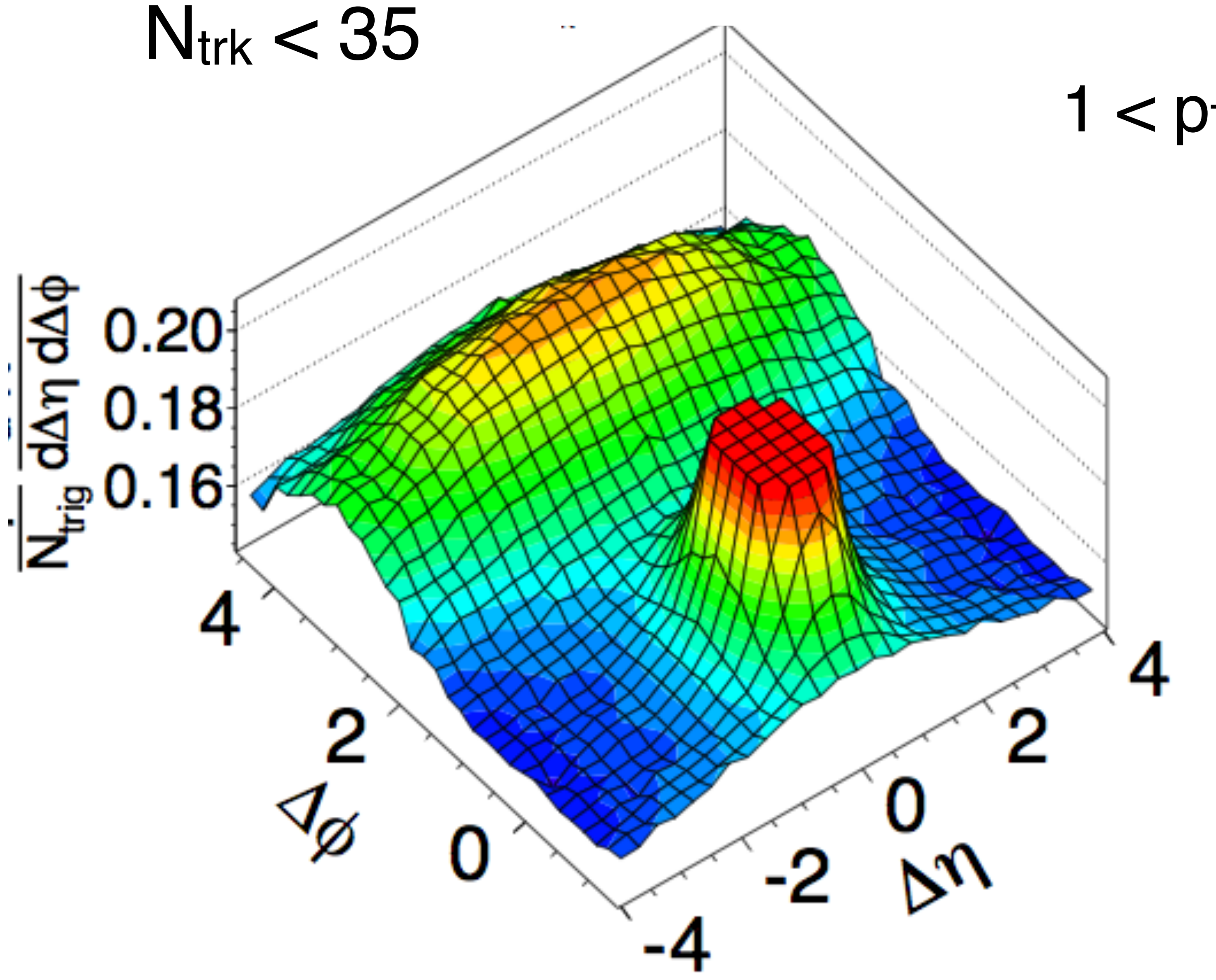
Azimuthal anisotropy in pp collisions

Central Pb+Pb

CMS, arXiv:1201.3158



p+p low multiplicity



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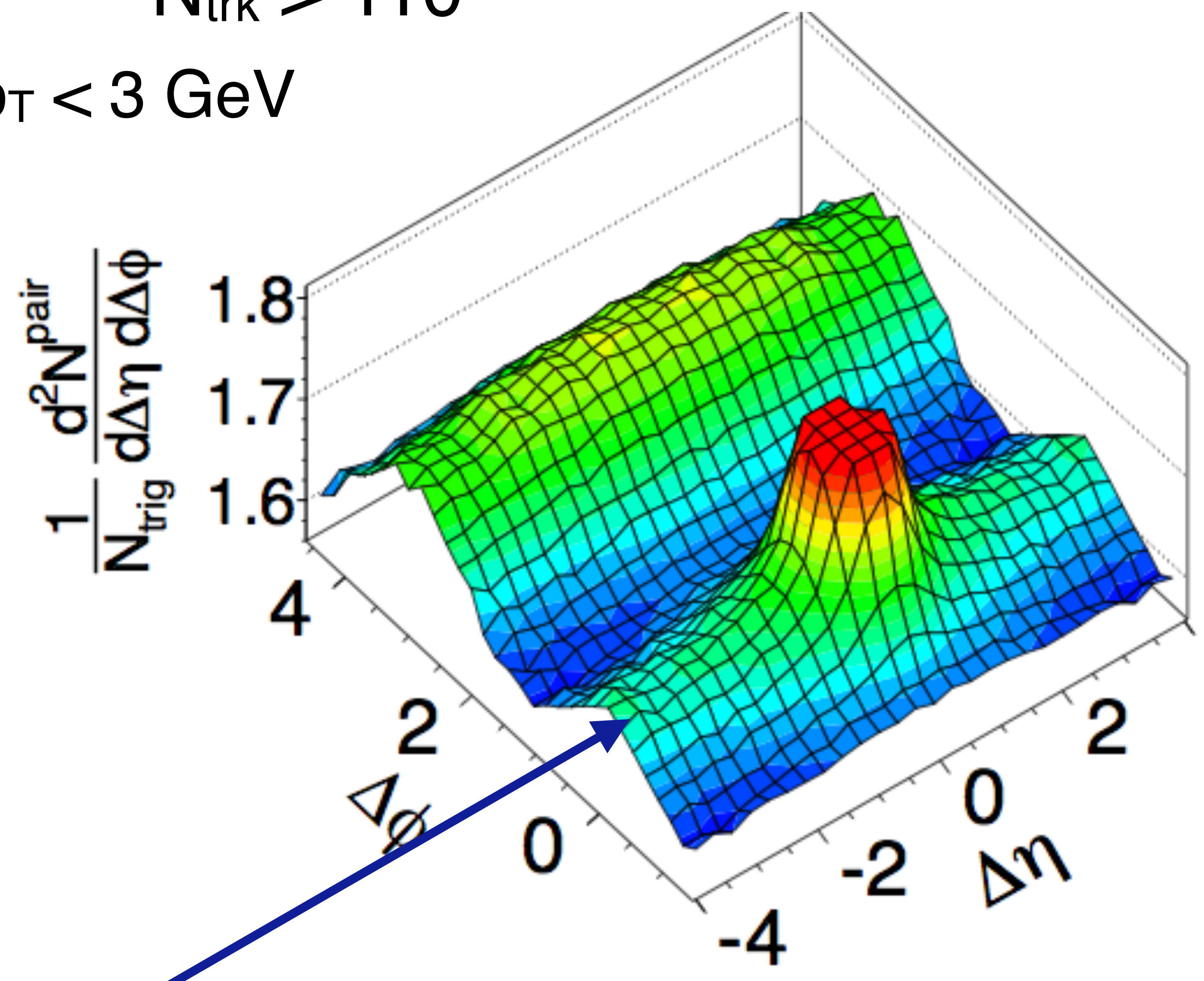
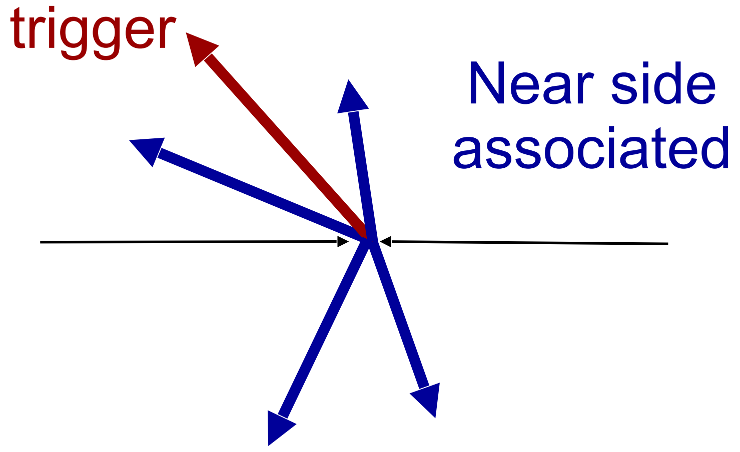


CMS, PLB 718, 795

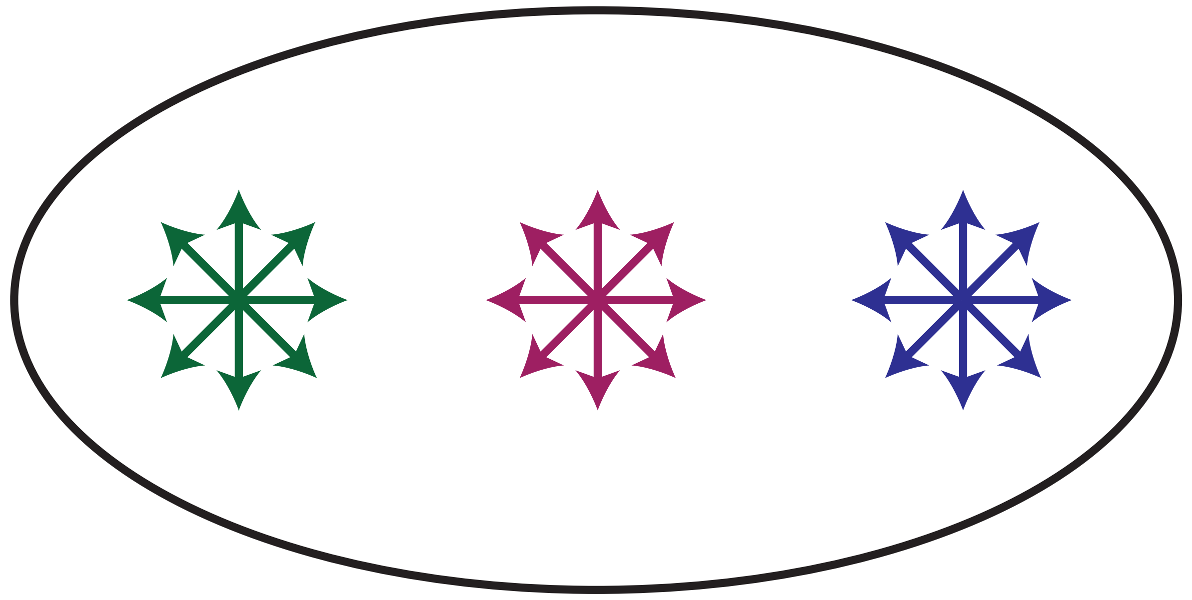


Near-side long range correlation: indicates early time - global origin

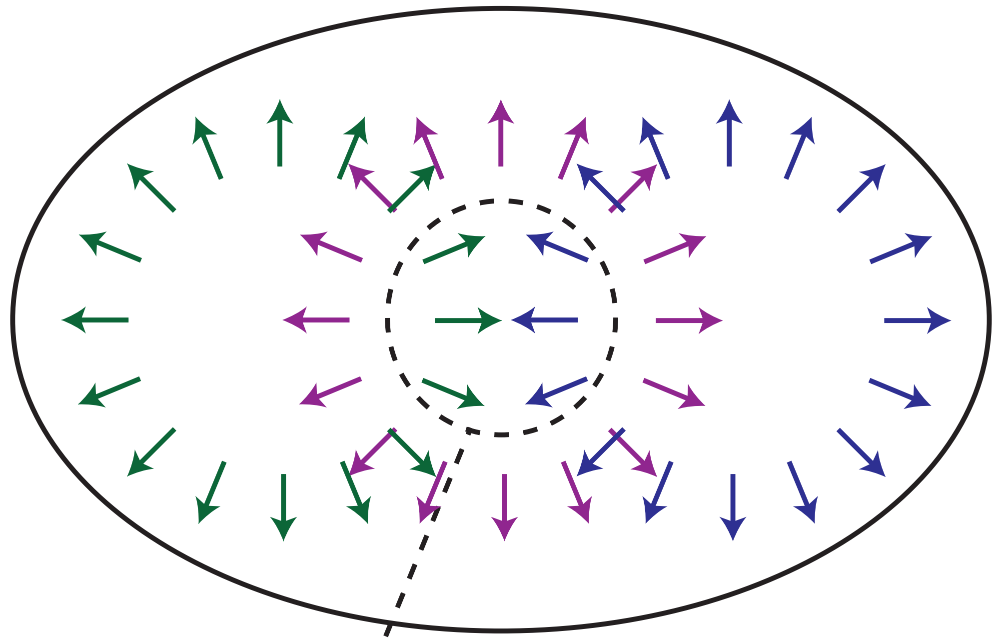
Seen in both p-p and Pb-Pb: non-trivial initial spatial distributions also in pp?

Building up azimuthal anisotropy with few scatterings

Can you have flow with a few scatterings?
'anisotropic escape' mechanism

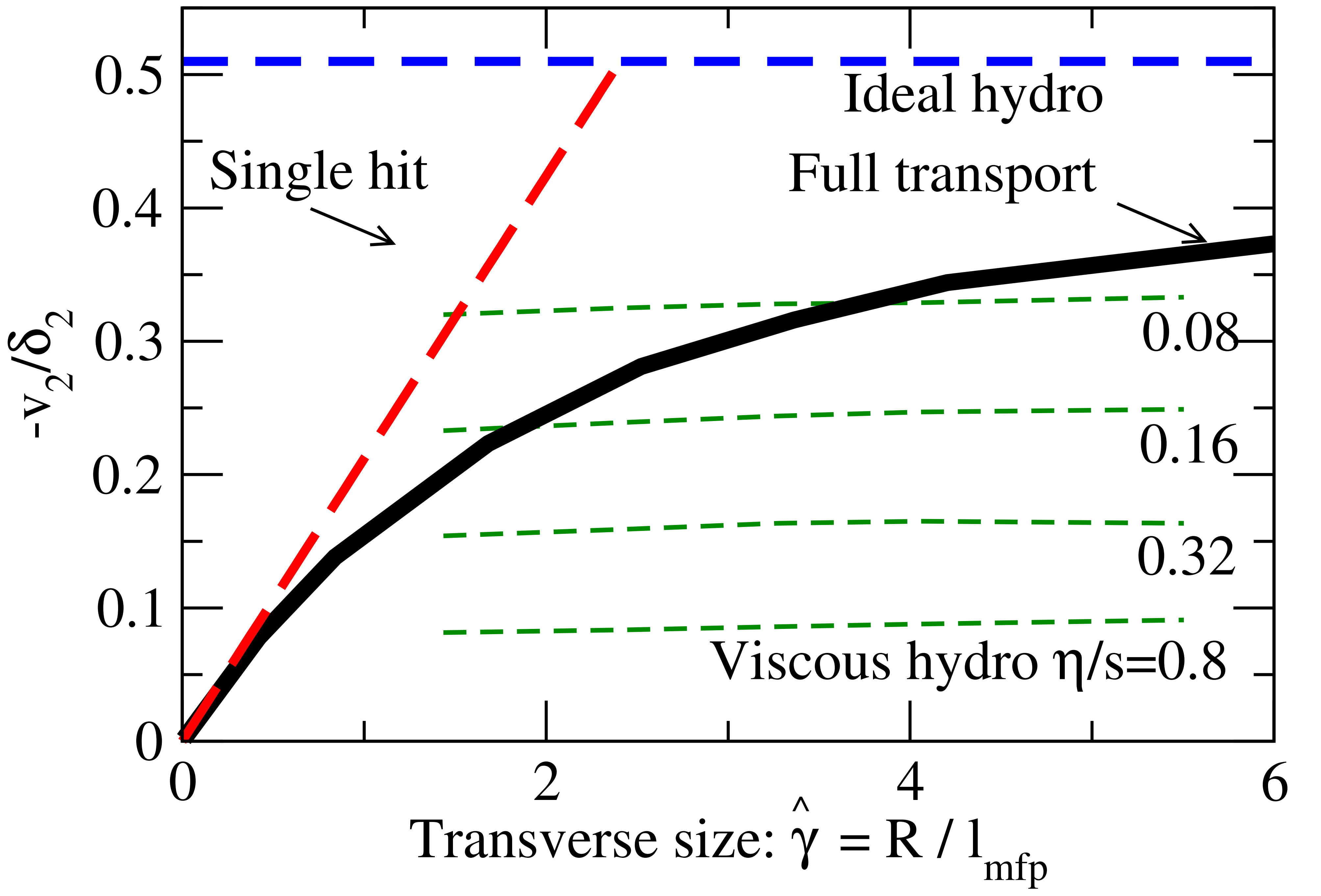


Initially isotropic momentum distribution



Kurkela, Wiedemann, Wu, arXiv:1803.02072

Kurkela, Wiedemann, Wu, arXiv:1805.04031



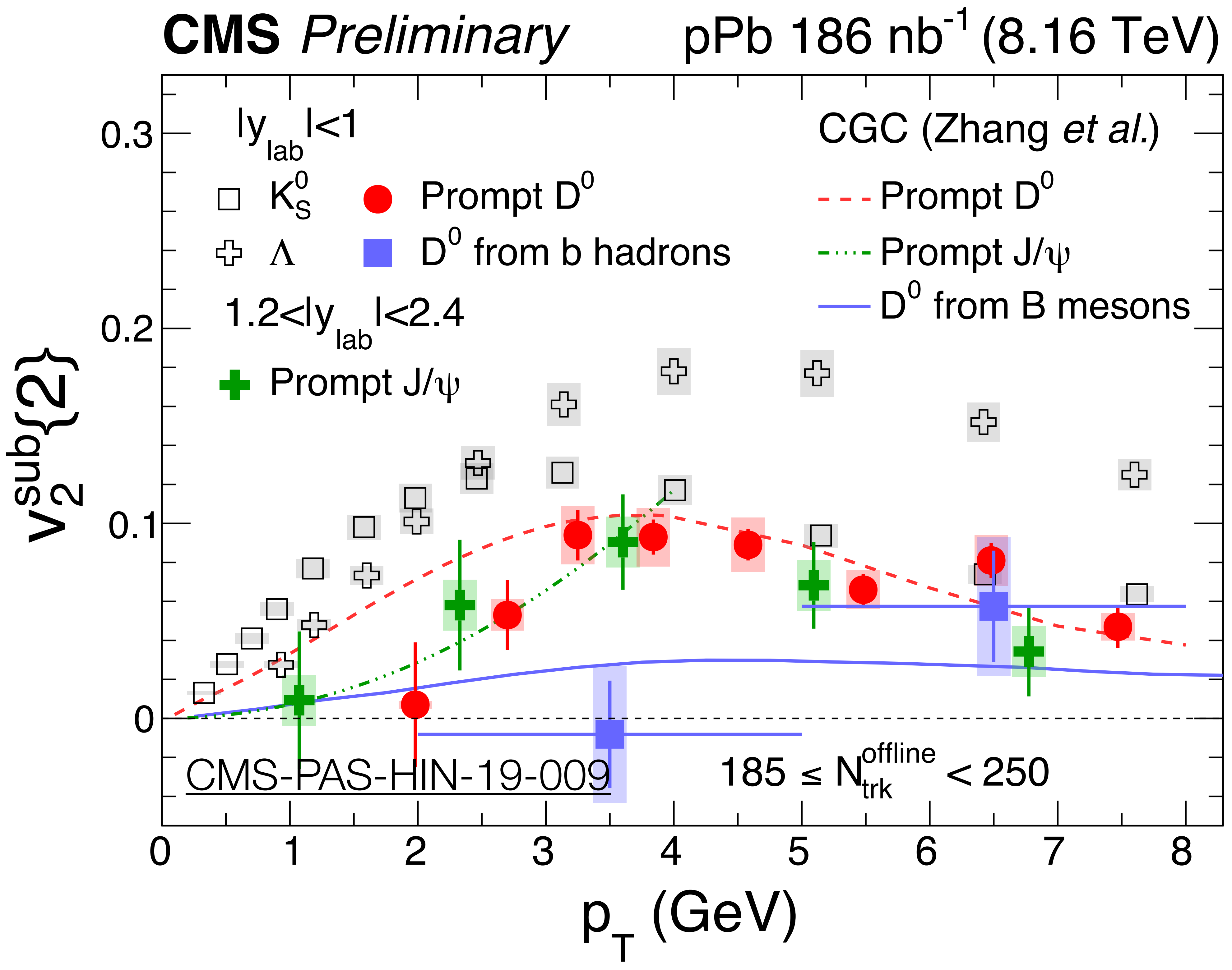
Scattering randomises directions; more scatterings to 'out-of-plane'

Anisotropic density converted
into anisotropic momentum distribution by few scatterings

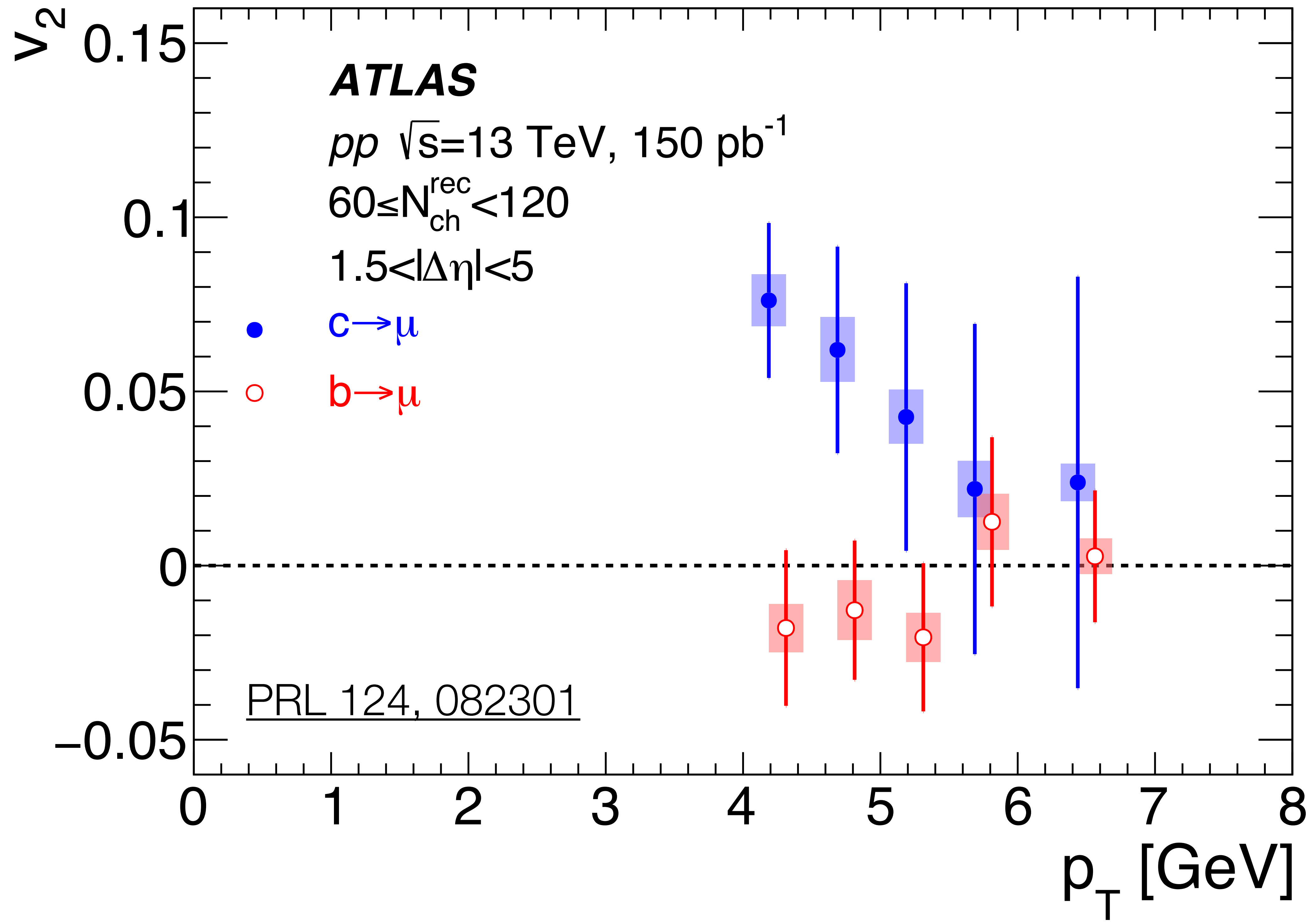
Small systems: 'single hit' kinetic transport equal to full hydro

Small system flow: recent results

Light in heavy flavor v_2 in p-Pb



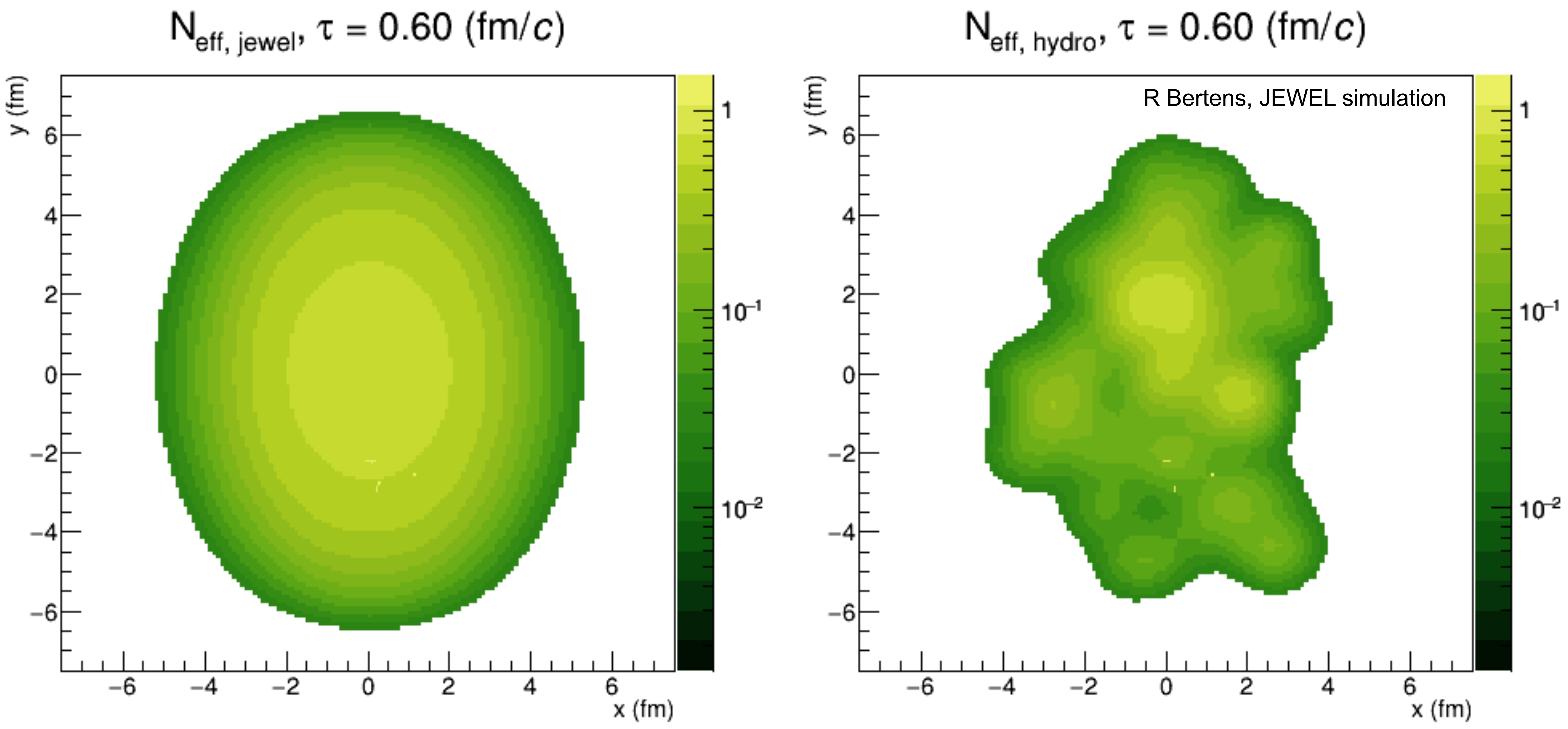
Heavy flavour decay muons: charm and beauty



Significant asymmetry for charm. Beauty v_2 compatible with 0

Mass effect? Formation time?

Probing the QGP: Hard probes



High p_T > 5 GeV or so: hard scattering, short formation time

Heavy flavor: large mass $m > \Lambda_{QCD}$, produced in **early stage hard scattering**

Production understood; sample the **full time evolution** of the collision

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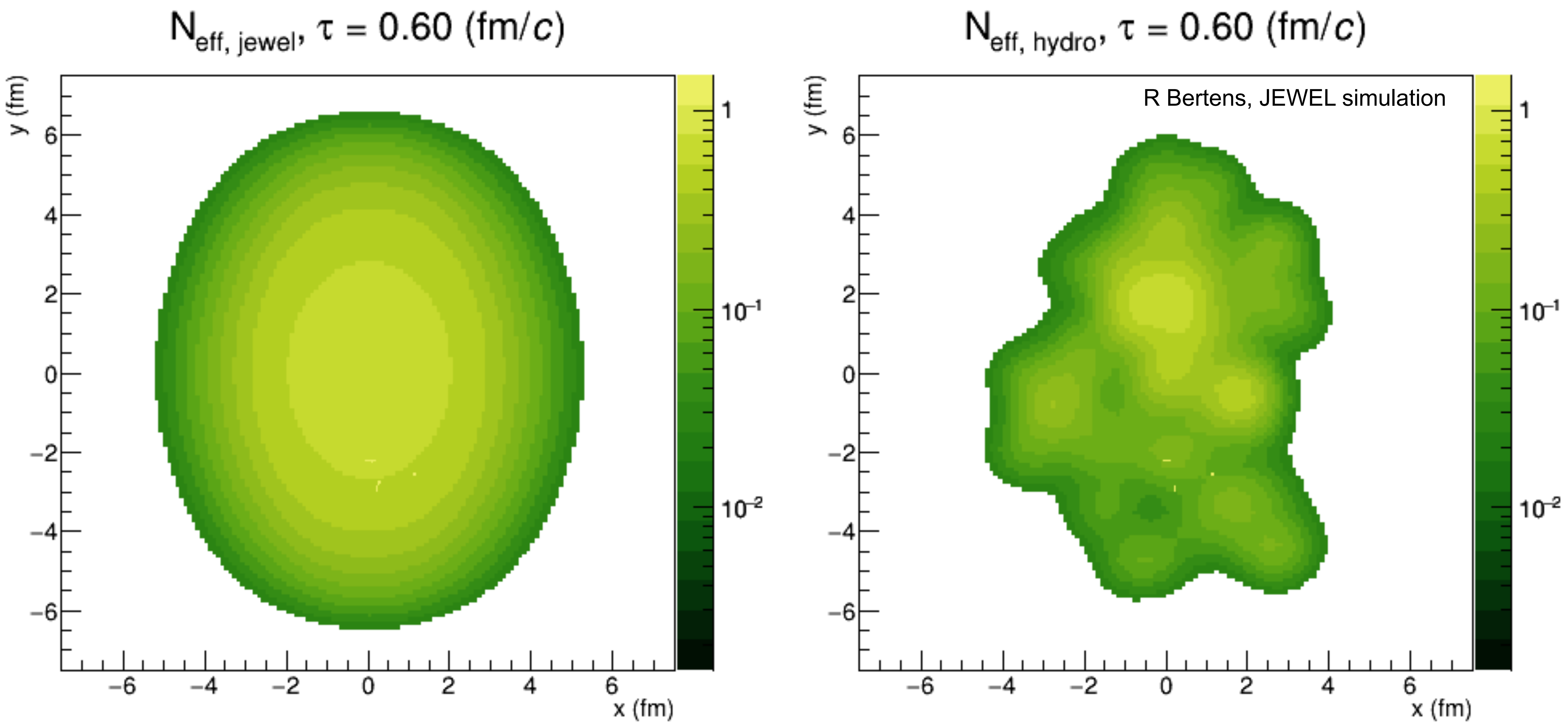

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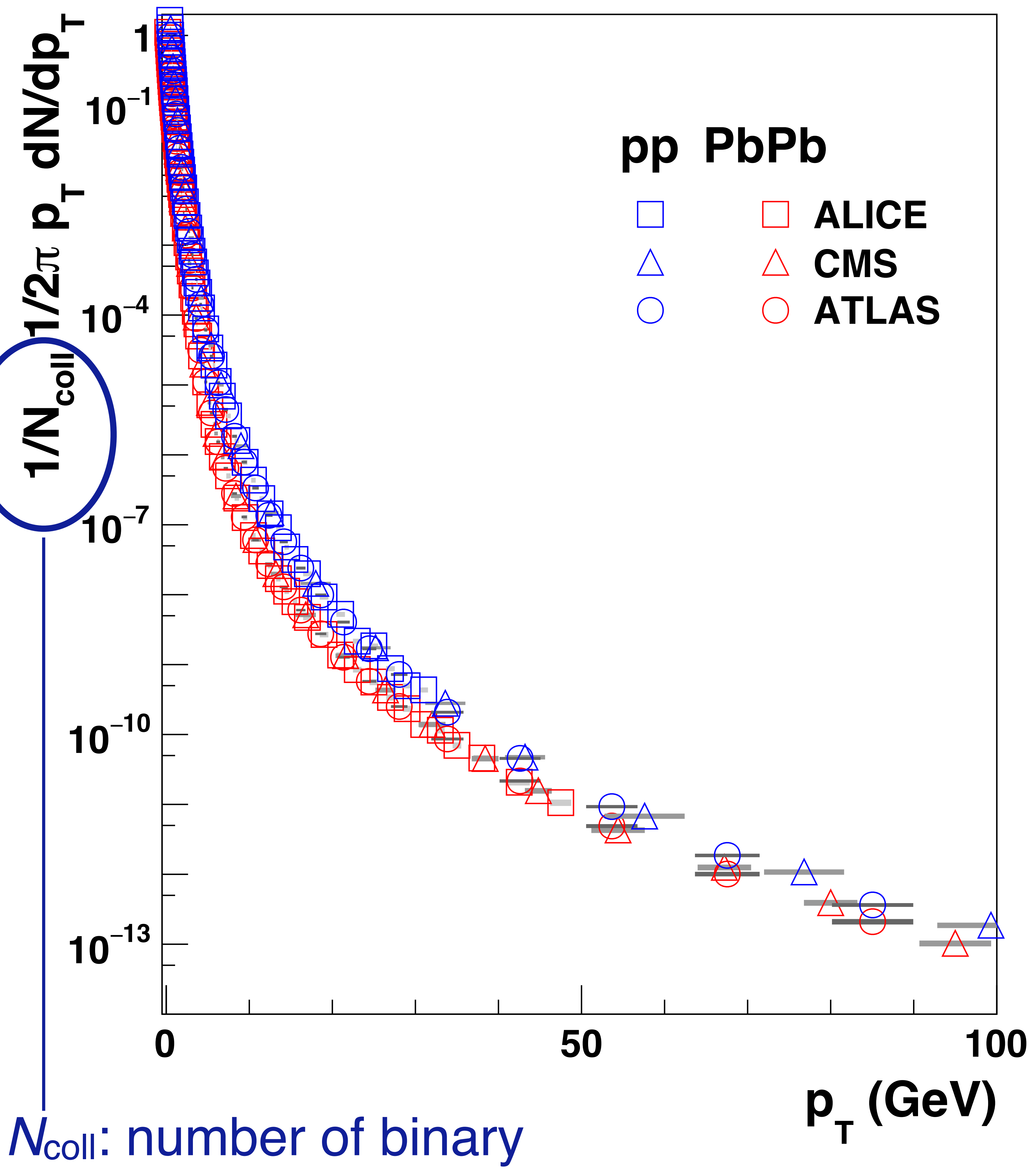
Nuclear modification: Pb—Pb

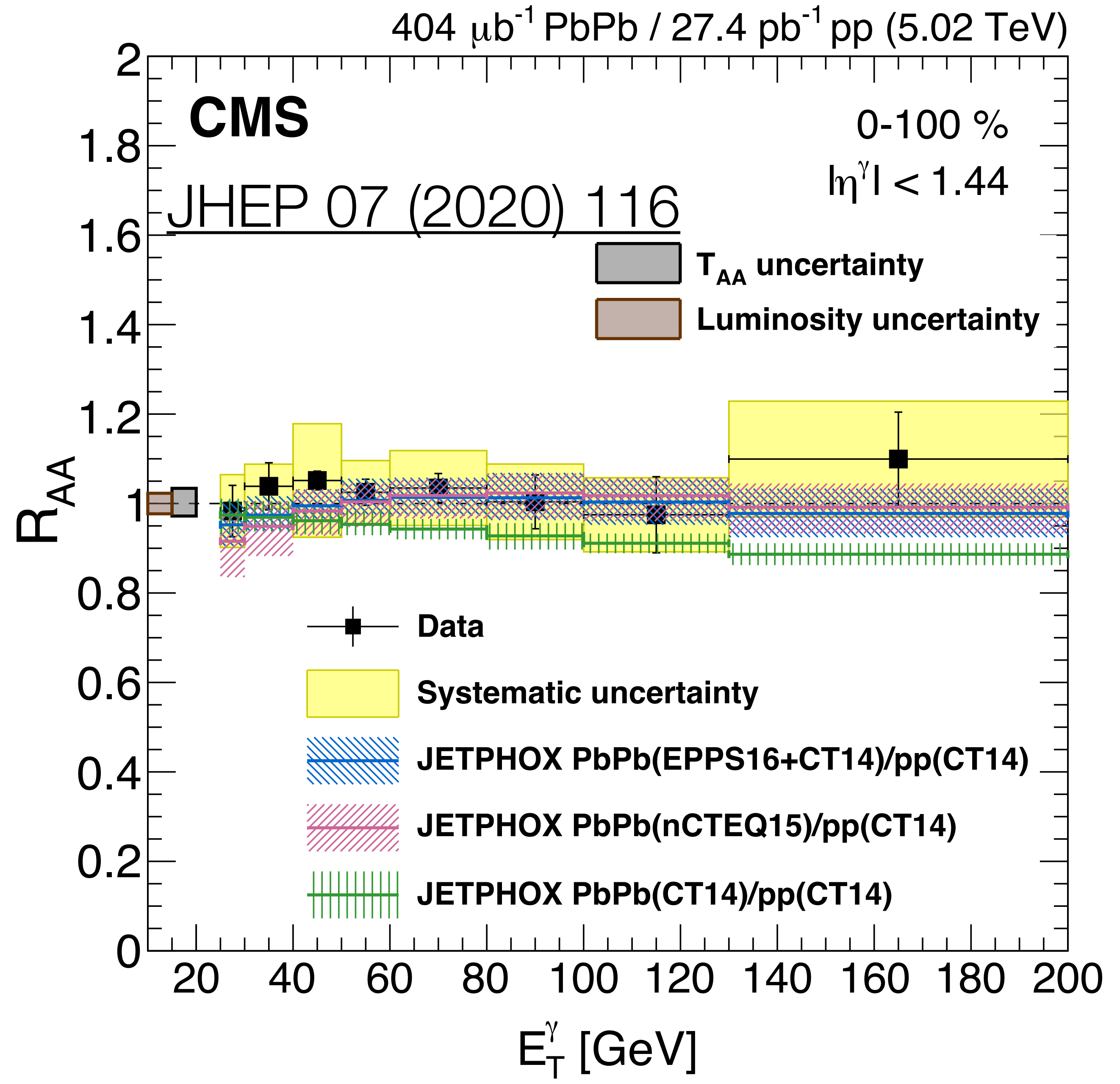
ALICE, PLB720, 52
CMS, EPJC, 72, 1945
ATLAS, arXiv:1504.04337

Charged particle p_T spectra



N_{coll}: number of binary nucleon-nucleon collisions

Direct isolations photons



No nuclear modification
Very weak interactions with QGP

$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$

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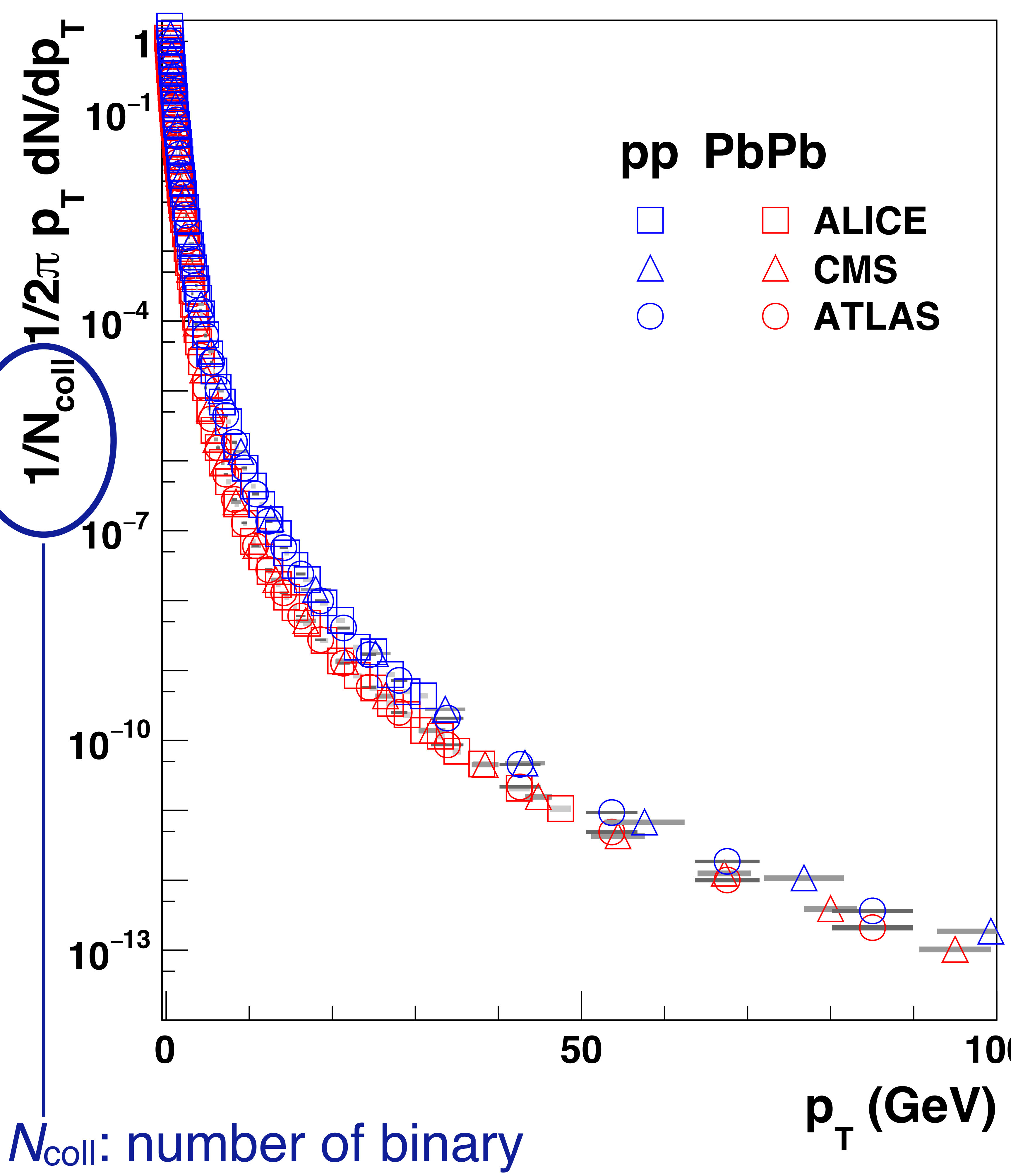

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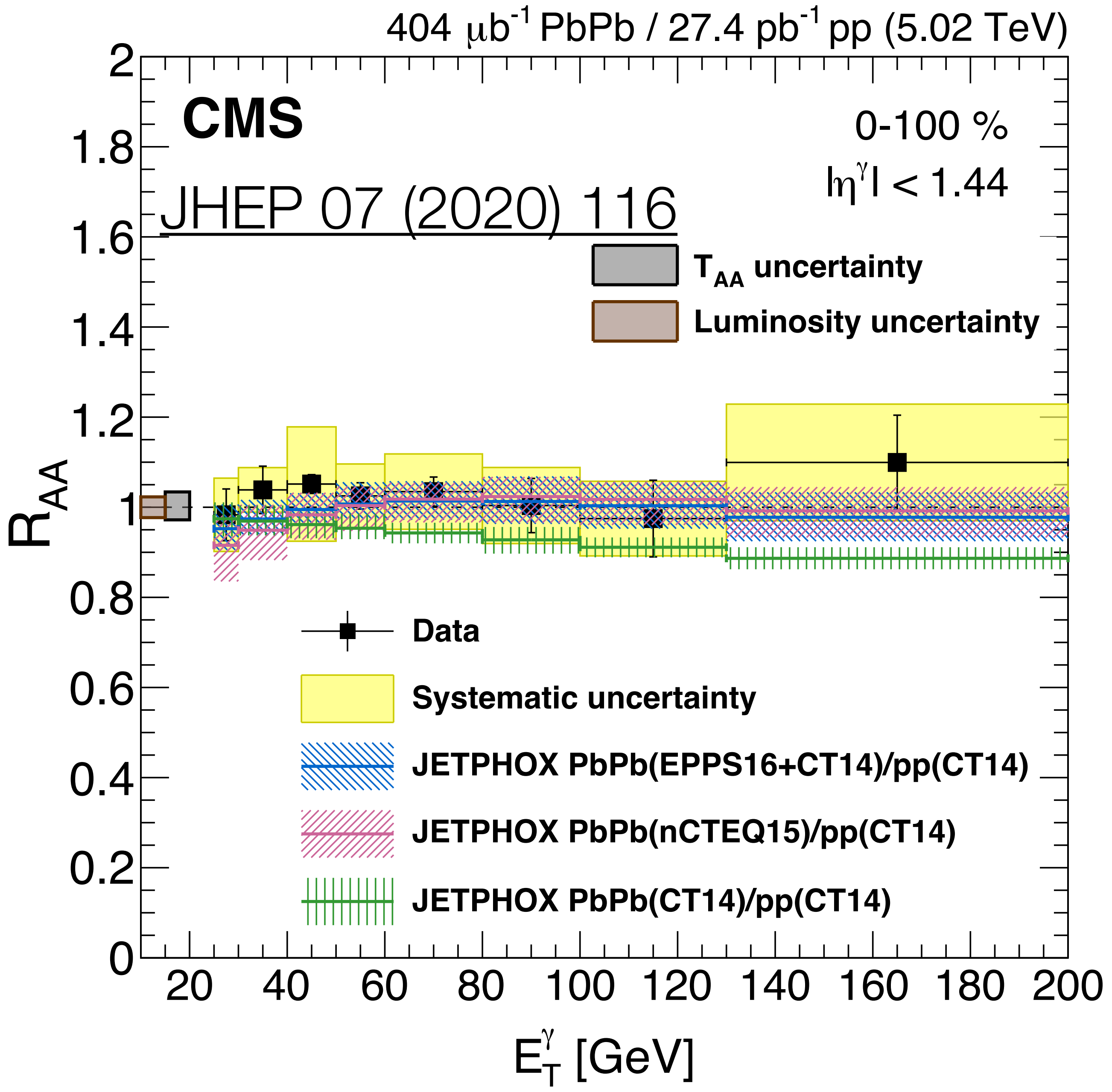

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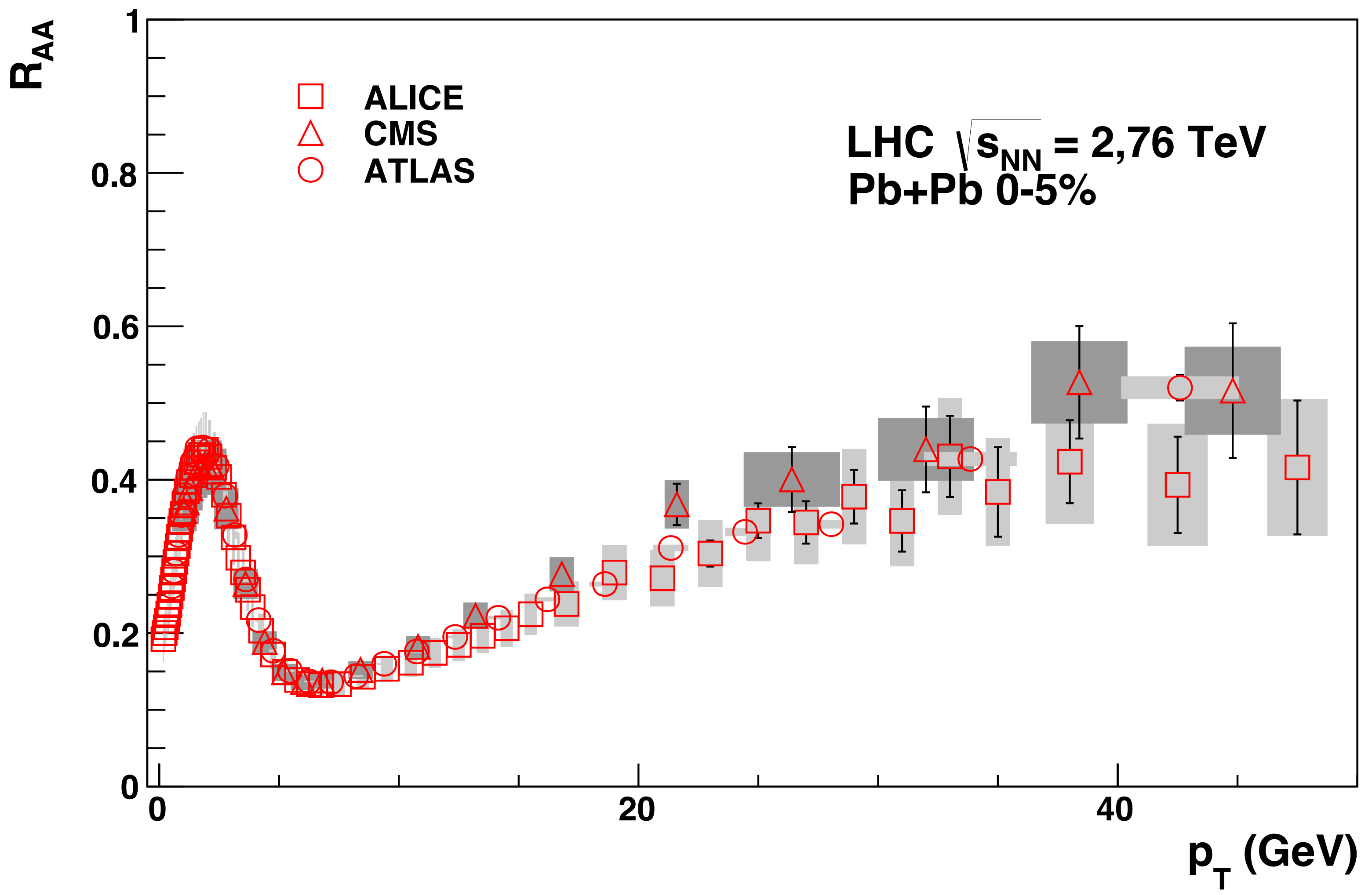
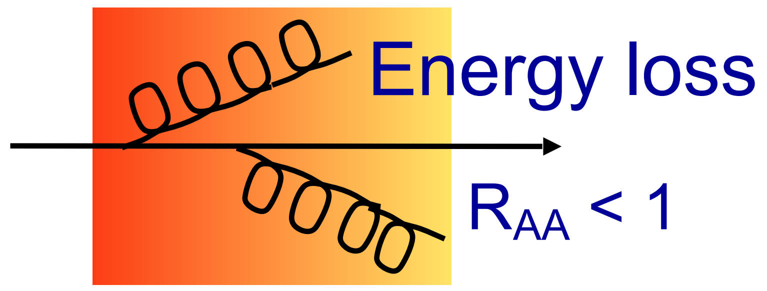
Nuclear modification: charged particles





Pb+Pb: clear suppression ($R_{AA} < 1$): parton energy loss

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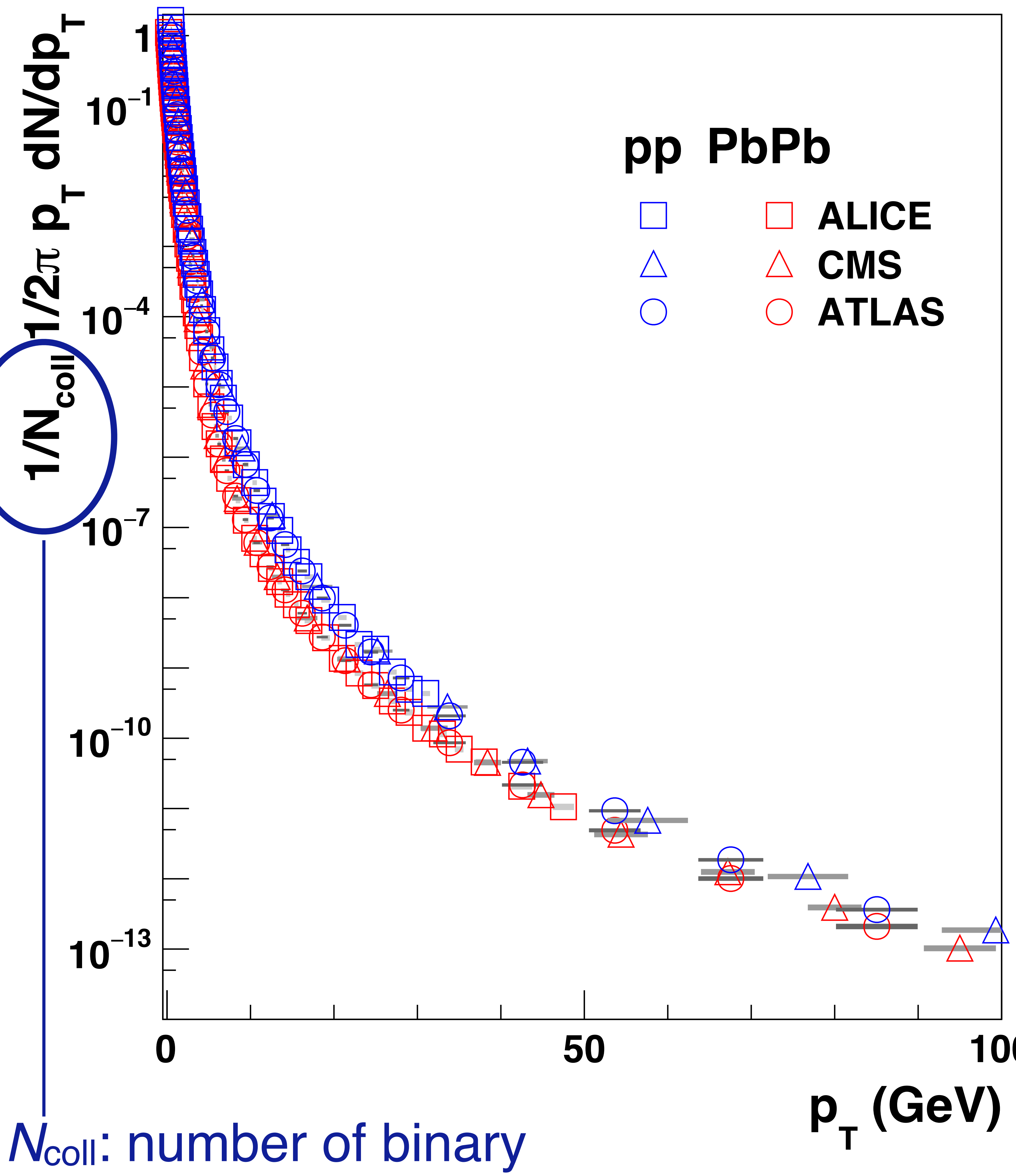

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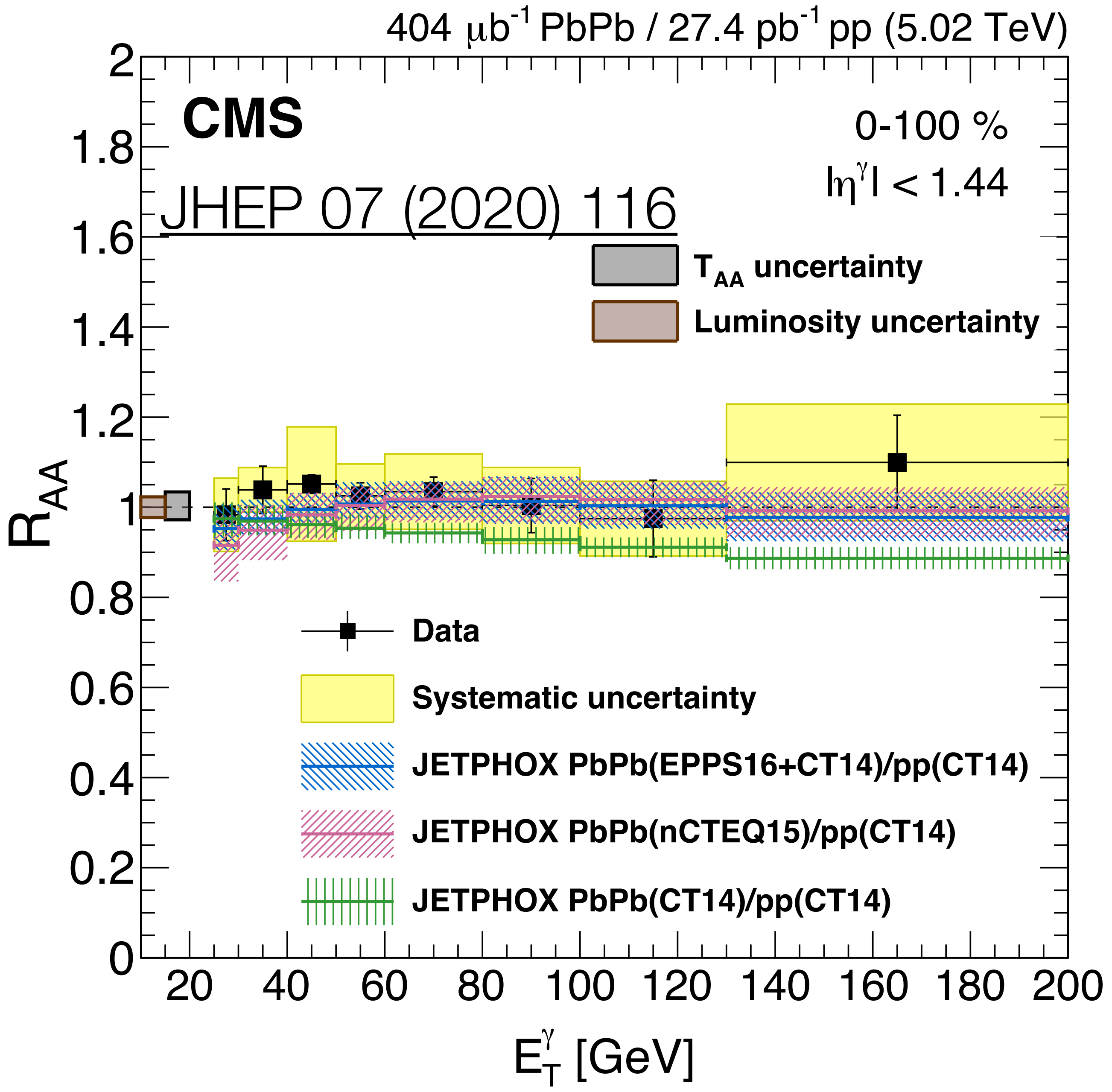

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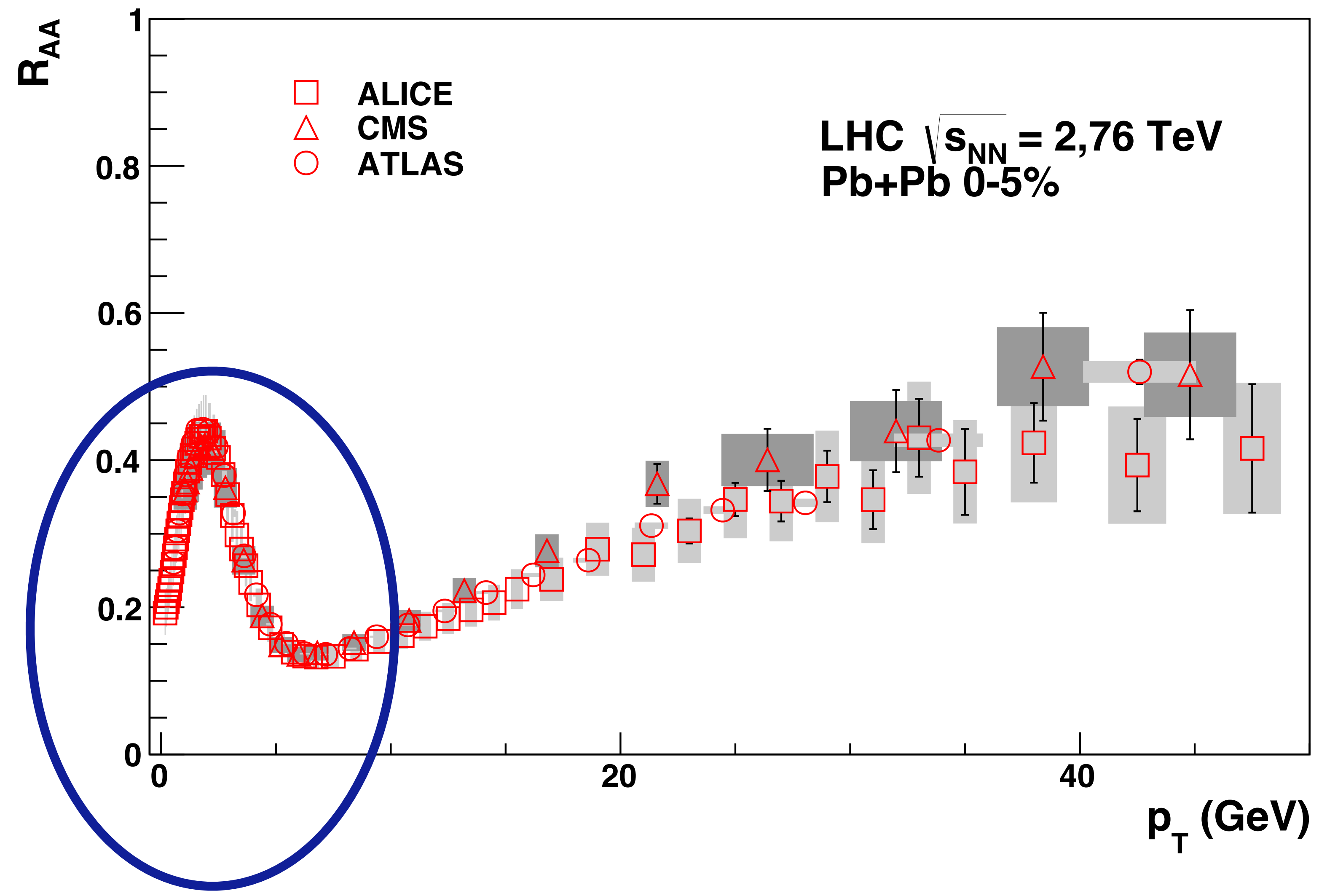
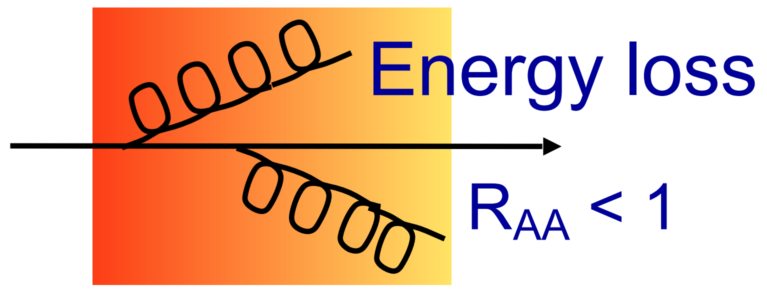


Low p_T:
soft production,
N_{part} scaling



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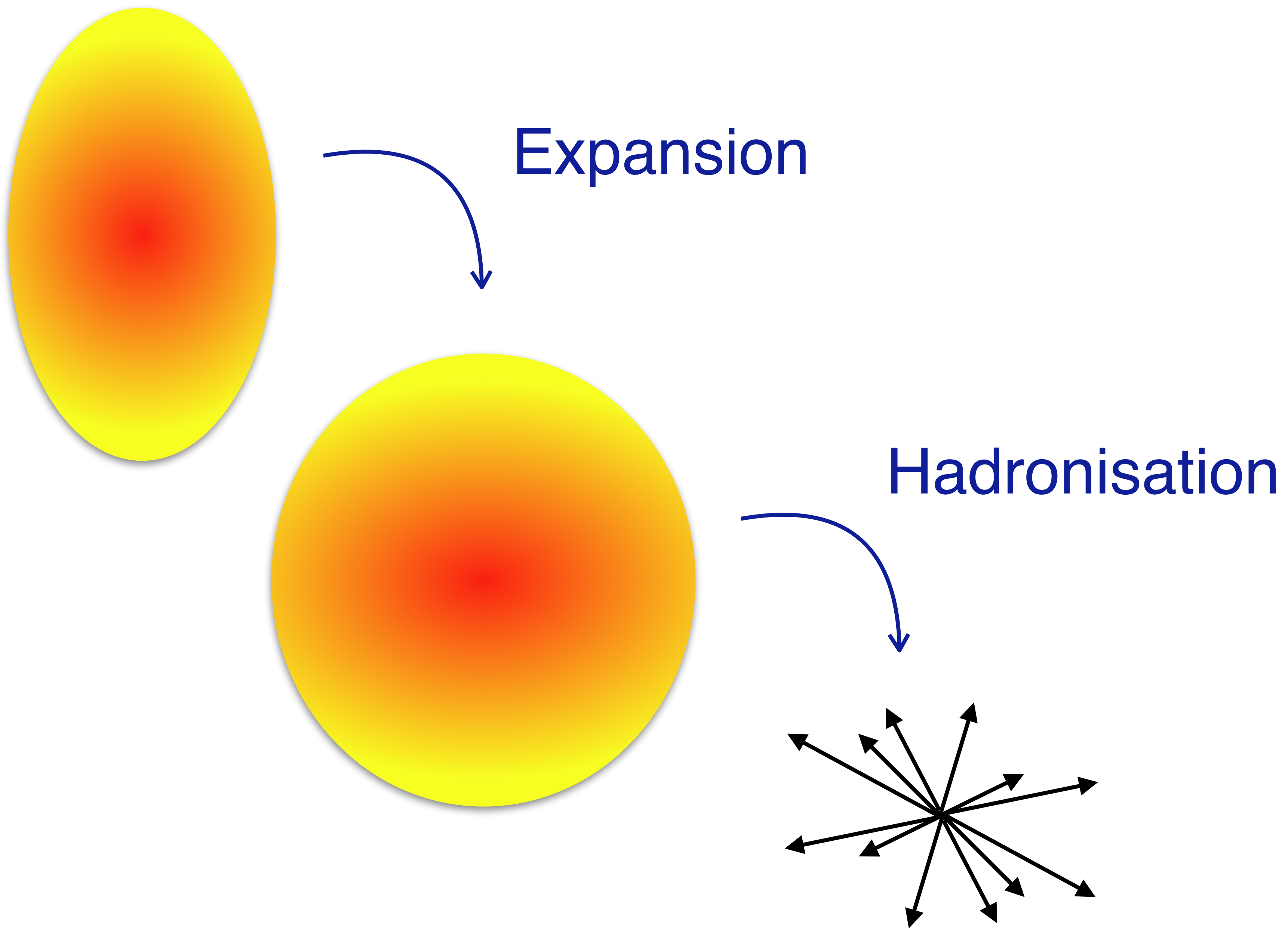
Azimuthal anisotropy: two mechanisms

Hydrodynamical expansion

Conversion of pressure gradients into momentum space anisotropy

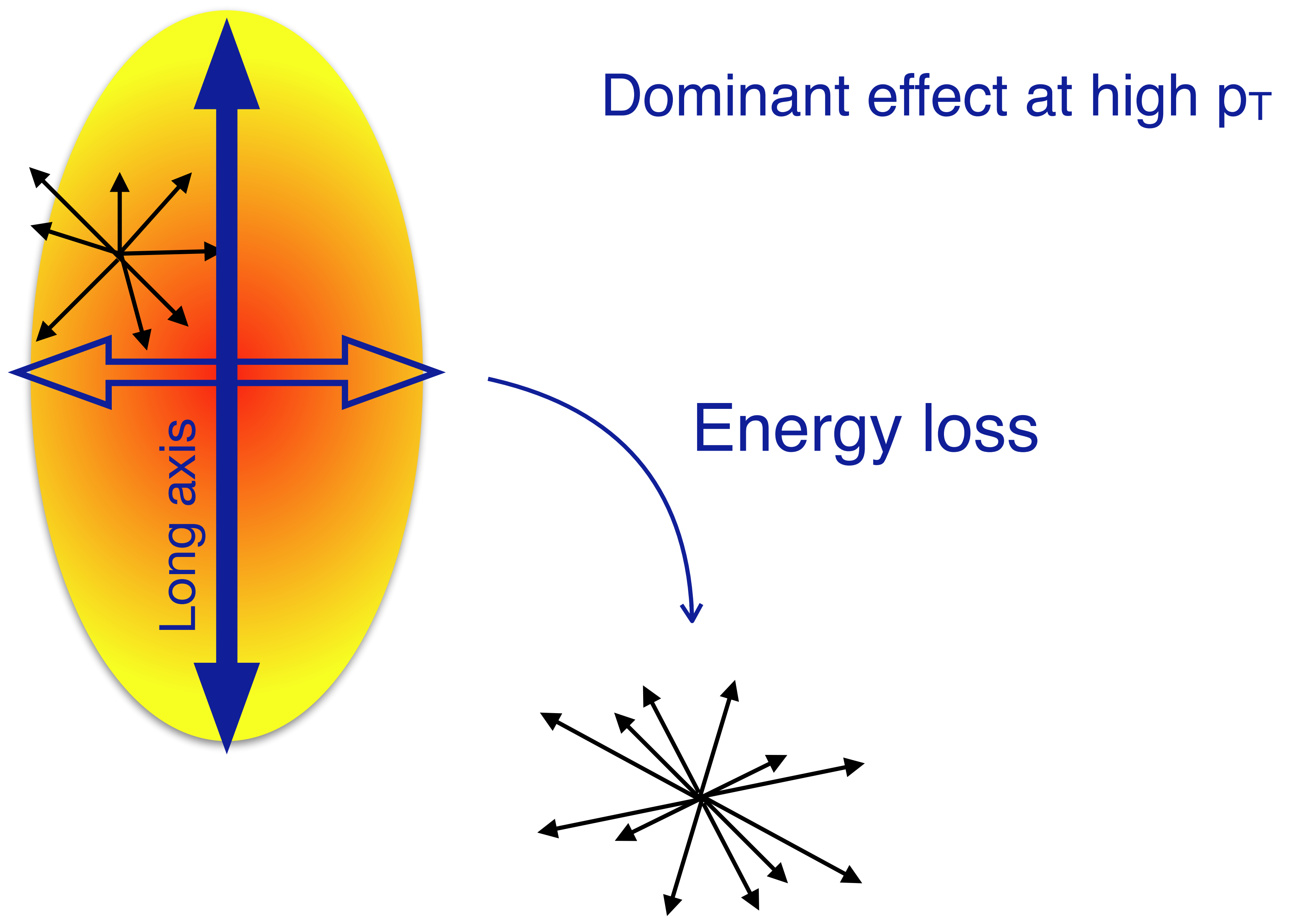


$$\nabla p = \rho \frac{d\vec{v}}{dt}$$

Dominant effect for late formation times:
light flavour at low p_T

Parton energy loss

Anisotropy due to energy loss and path length differences



More energy loss along long axis than short axis

$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Dominant effect for early formation times:
heavy flavour, high p_T probes

Heavy flavor energy loss: open charm

Nuclear modification factor:

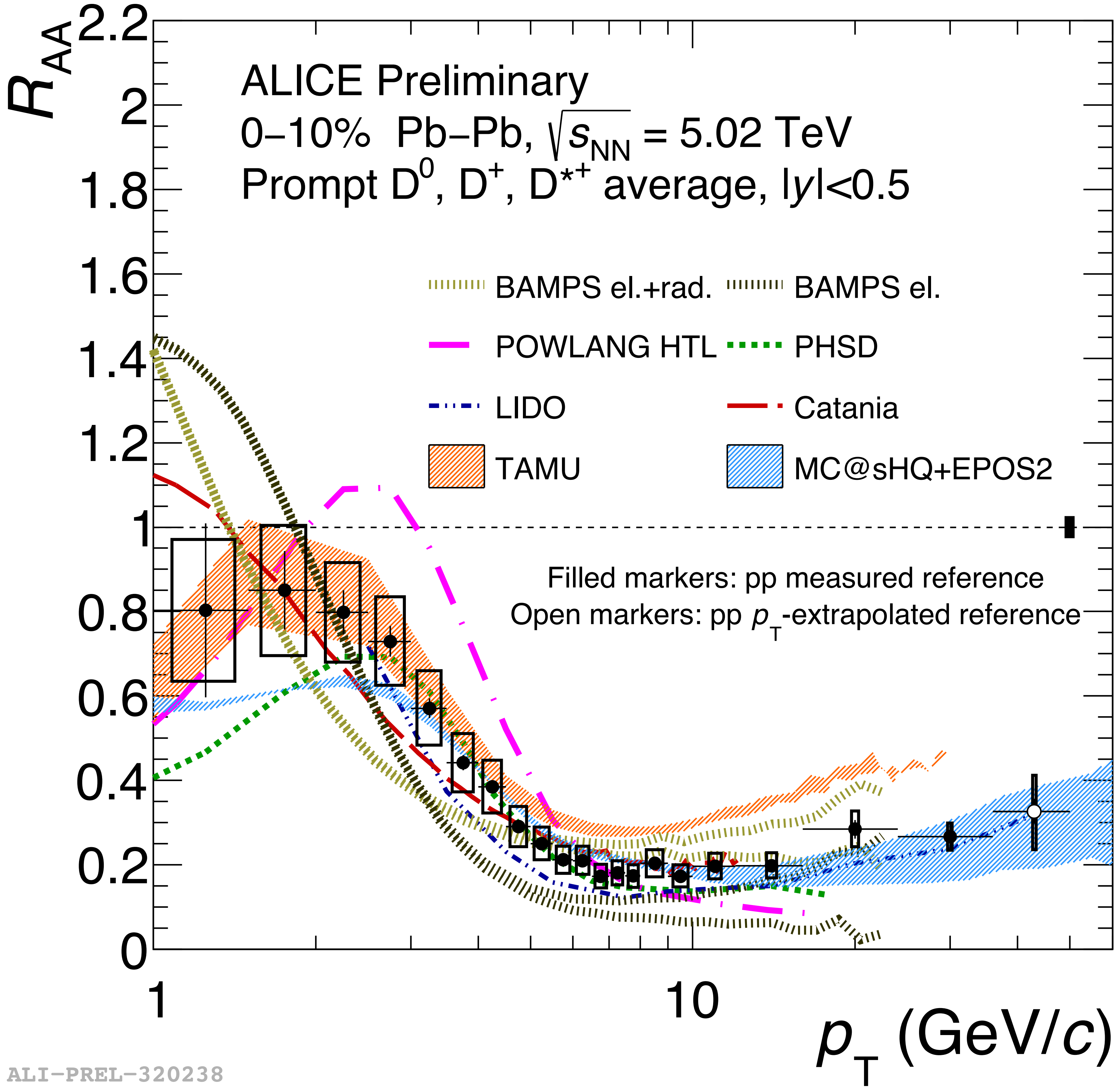
$$R_{AA} = \frac{dN^{AA}/dp_T}{T_{AA}\, d\sigma^{pp}/dp_T}$$

ratio of p_T spectra

$R_{AA} < 1$, charm quarks lose energy in the QGP

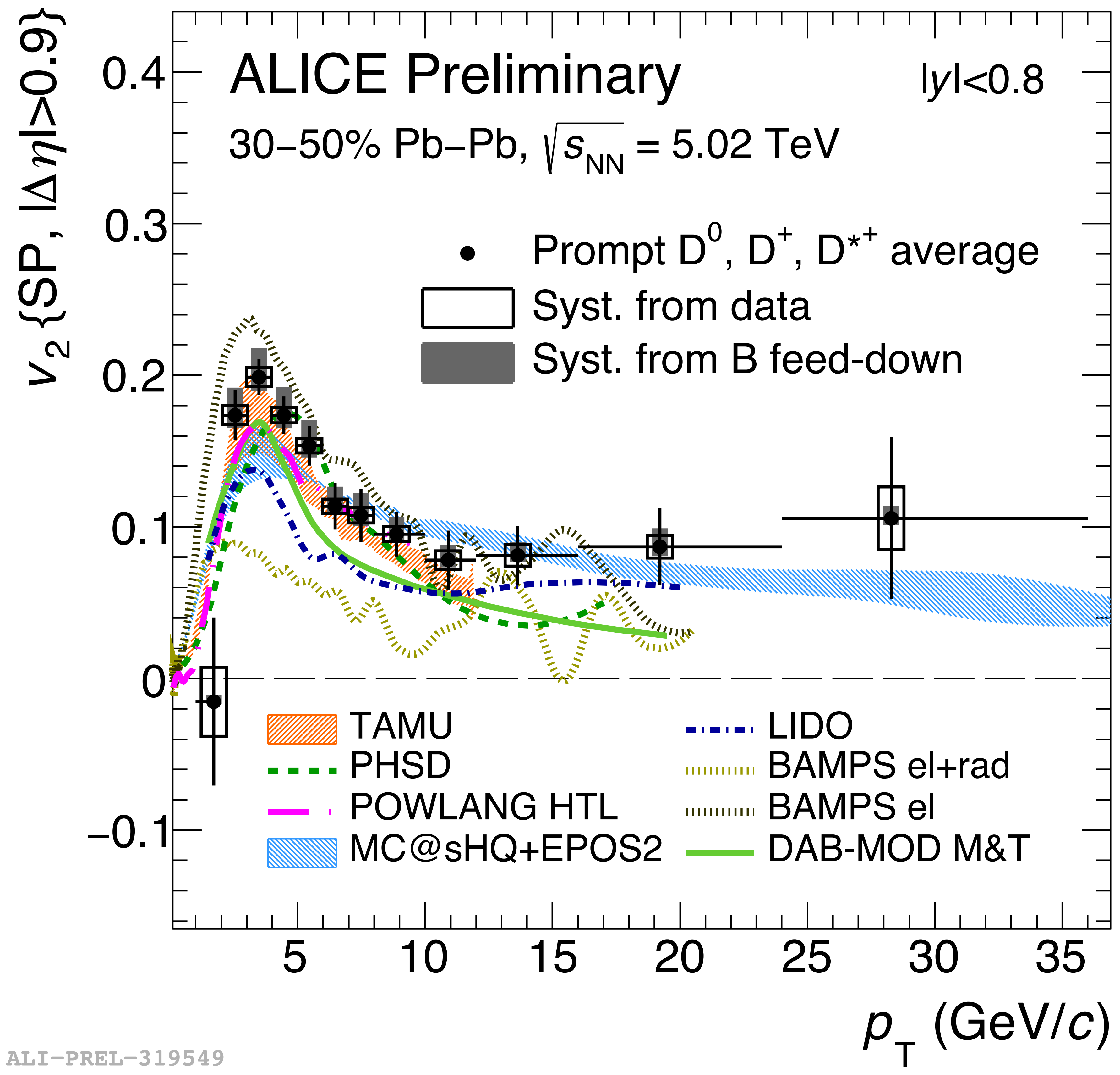
Different mechanisms

Nuclear modification factor of D mesons



Low p_T: mostly elastic collisions, diffusion
High p_T: mostly radiative loss

Elliptic flow v_2

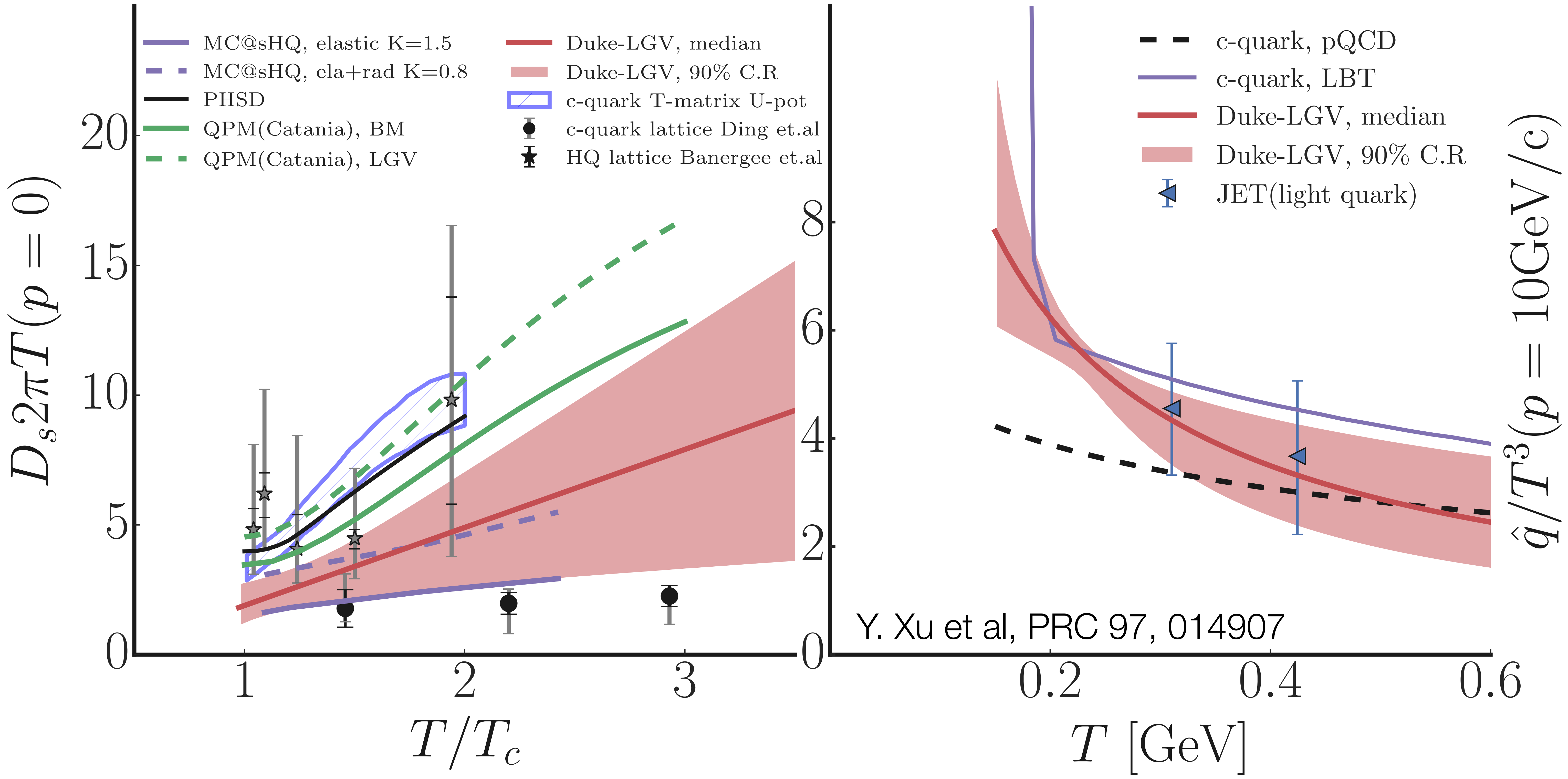


Large v_2 due to diffusion, energy loss

Heavy flavour transport coefficients

Diffusion coefficient
governs low momenta

Transport coefficient
governs high momenta



Data provide significant constraints on *T*, *p* dependence of $\hat{q}$ and D_s

Heavy flavour transport coefficients

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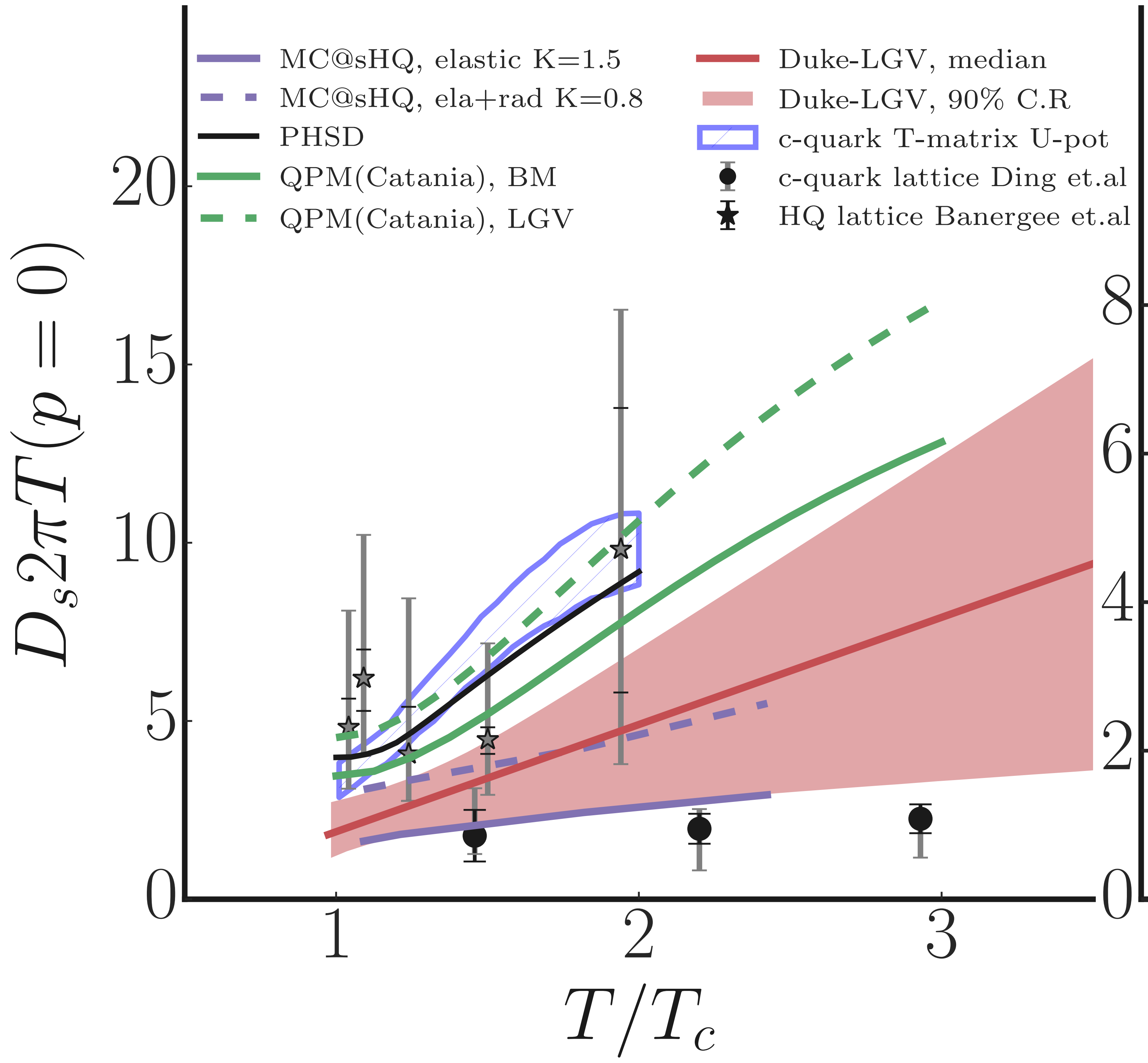

Transport coefficient
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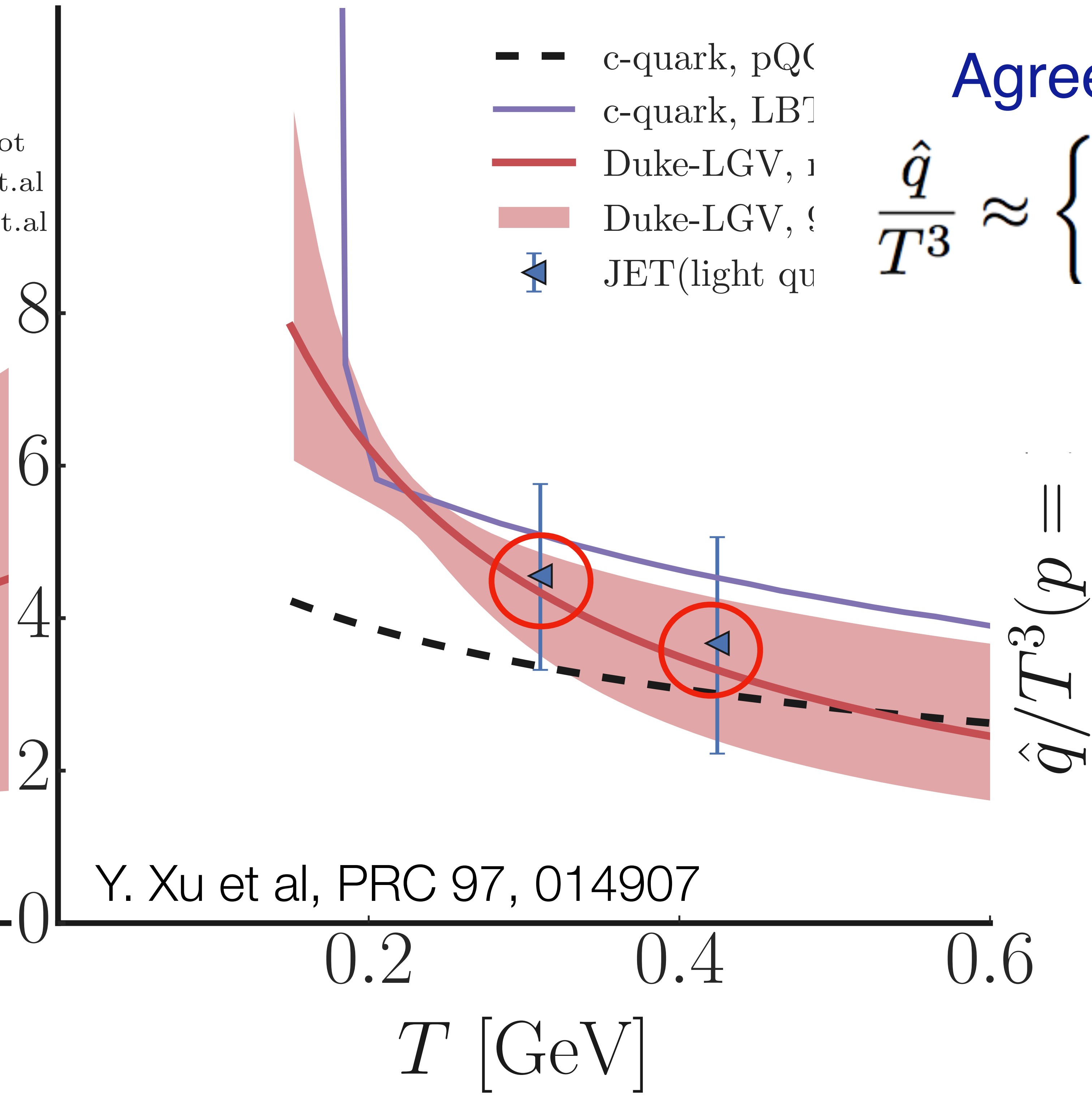


Agrees with light flavour:

$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC,} \\ 3.7 \pm 1.4 & \text{at LHC,} \end{cases}$$

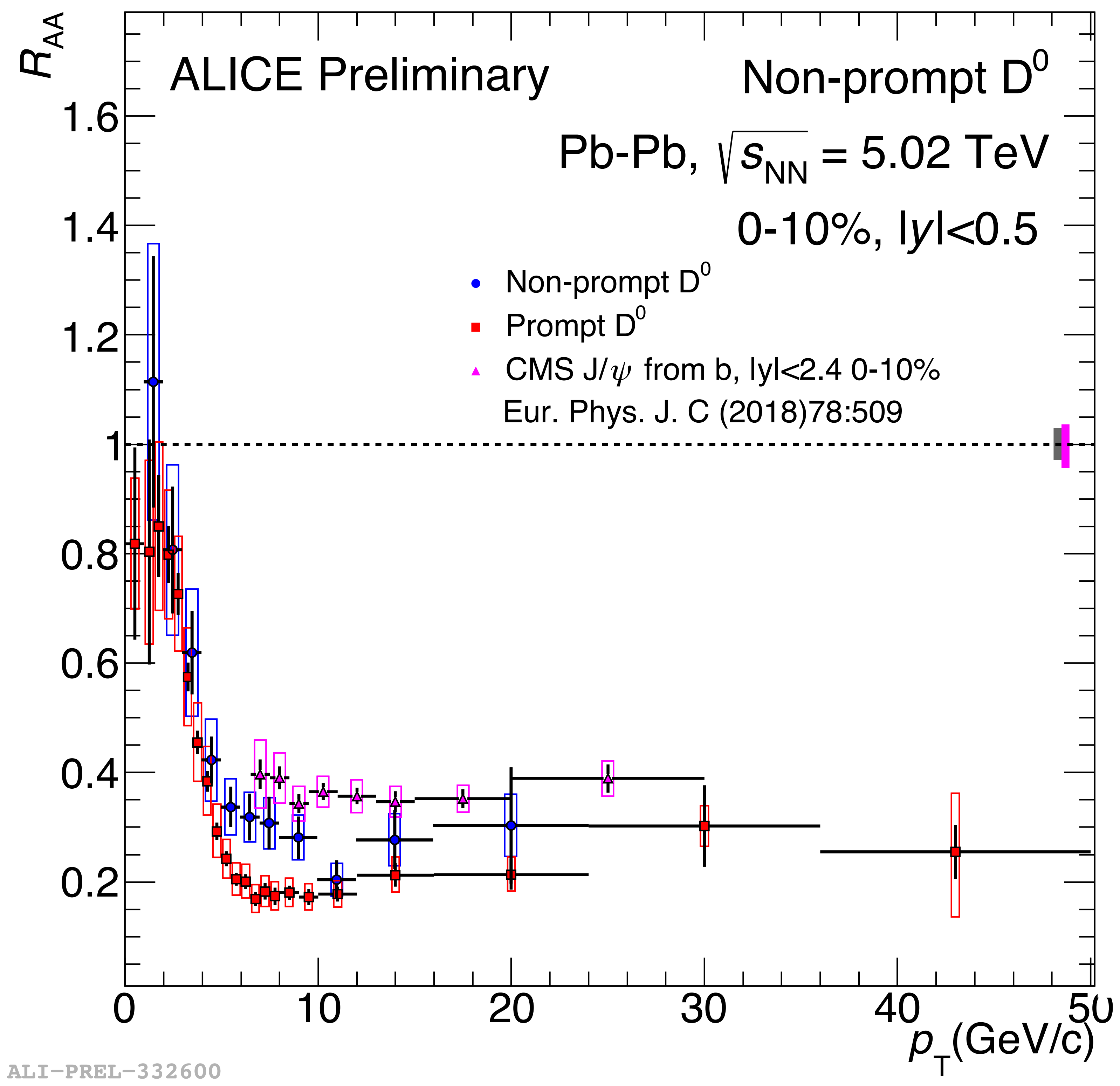
Burke et al, JET Collaboration, PRC 90, 014909

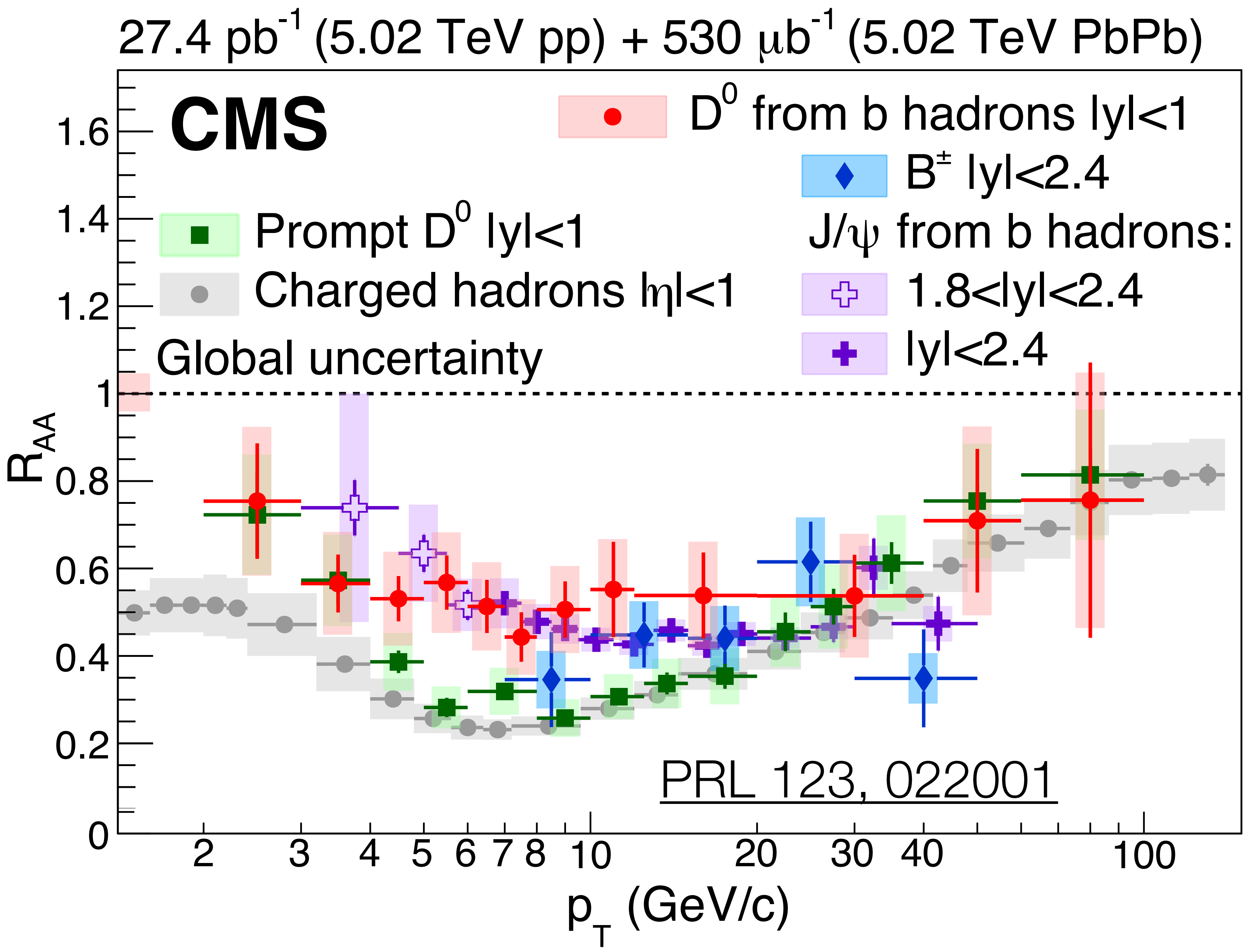
Data provide significant constraints on T, p dependence of $\hat{q}$ and D_s

A consistent understanding of light and heavy flavour transport, medium expansion is emerging

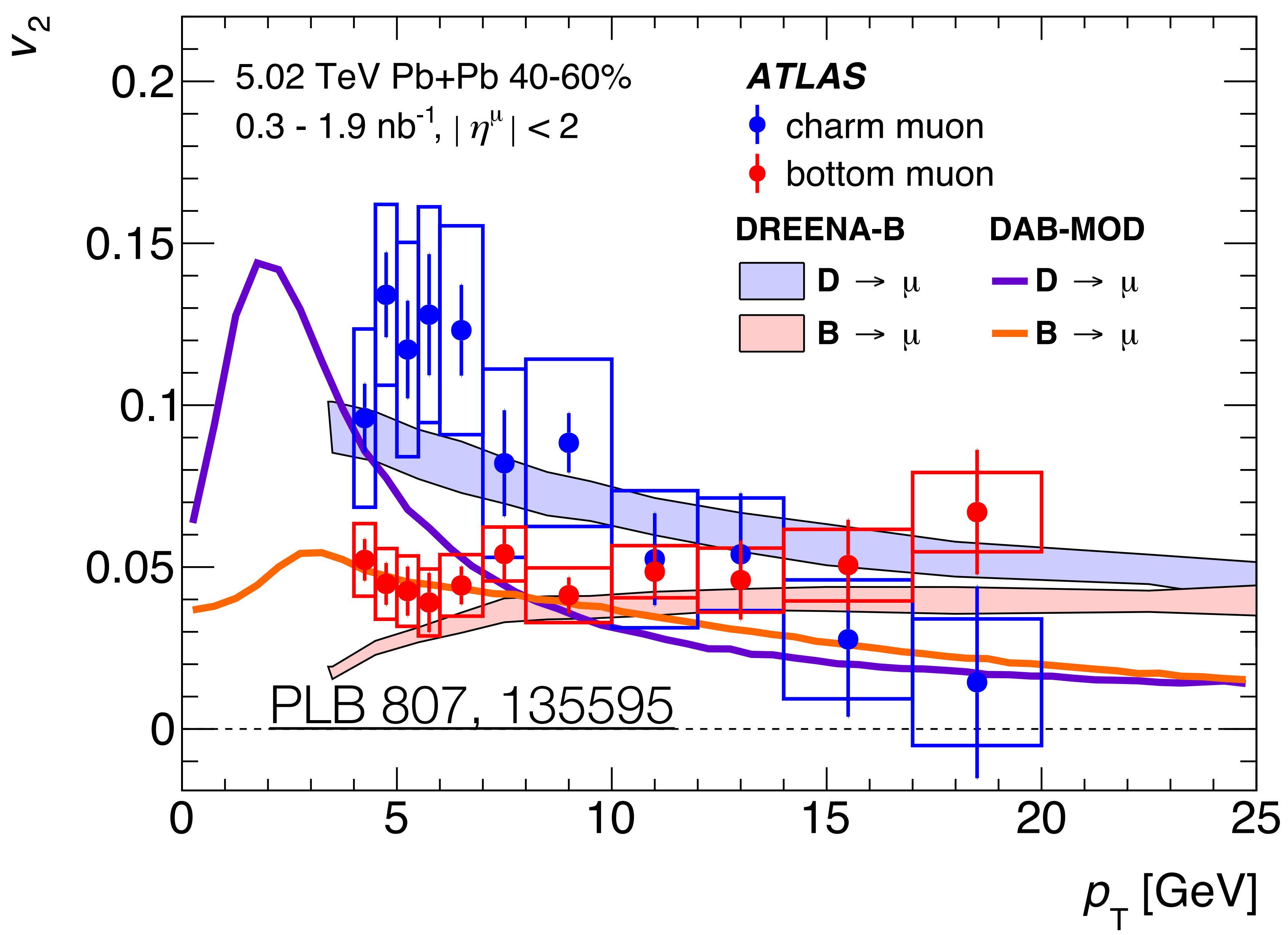
Understanding e-loss: mass dependence charm and beauty

Prompt D mesons (charm) and non-prompt (beauty decays)



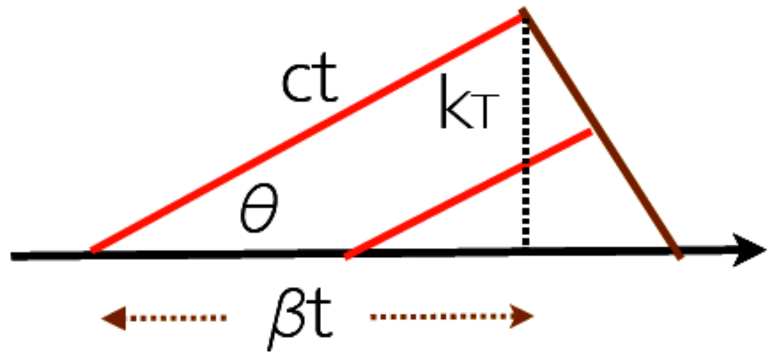


Charm and beauty decay muons



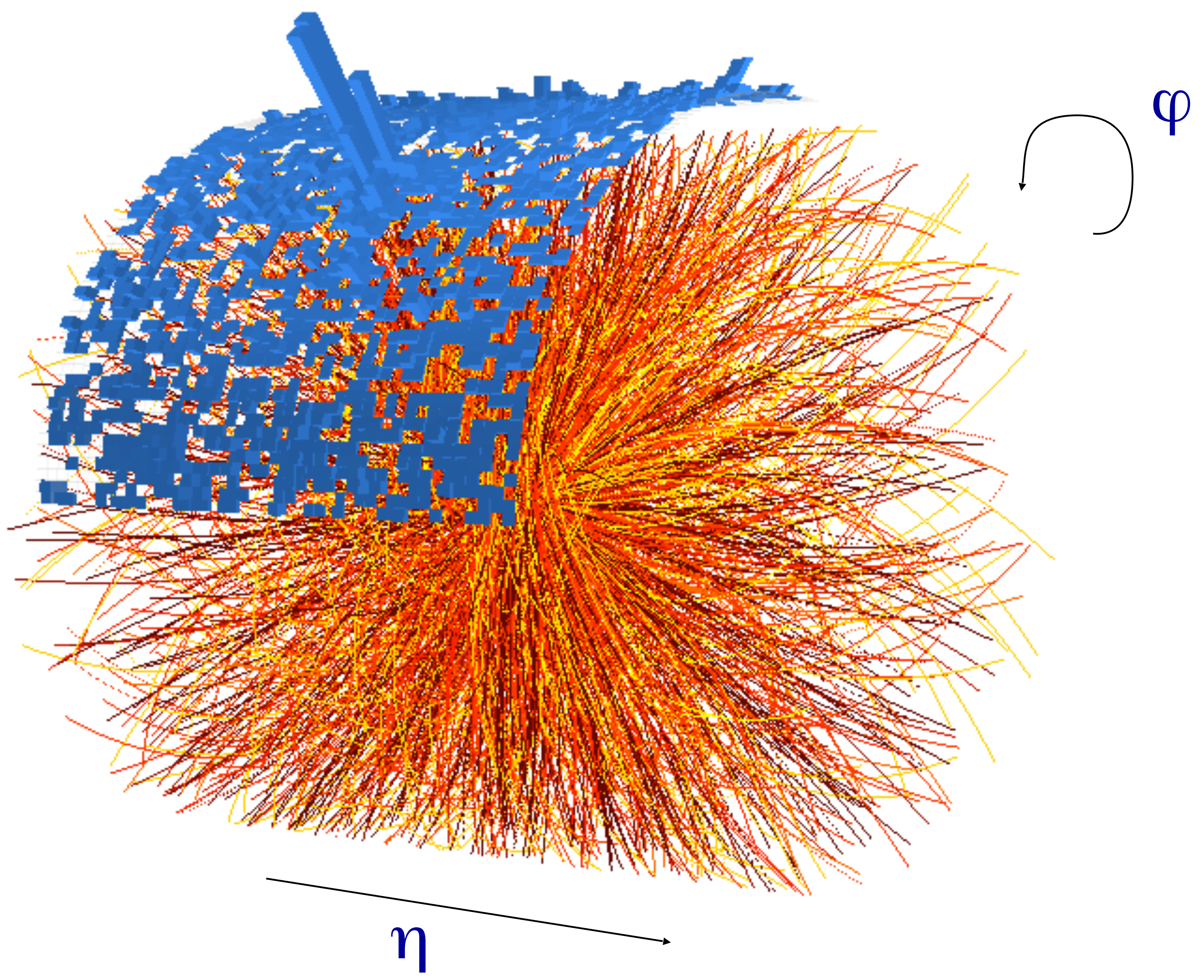
Non-prompt charm from beauty decays shows smaller suppression

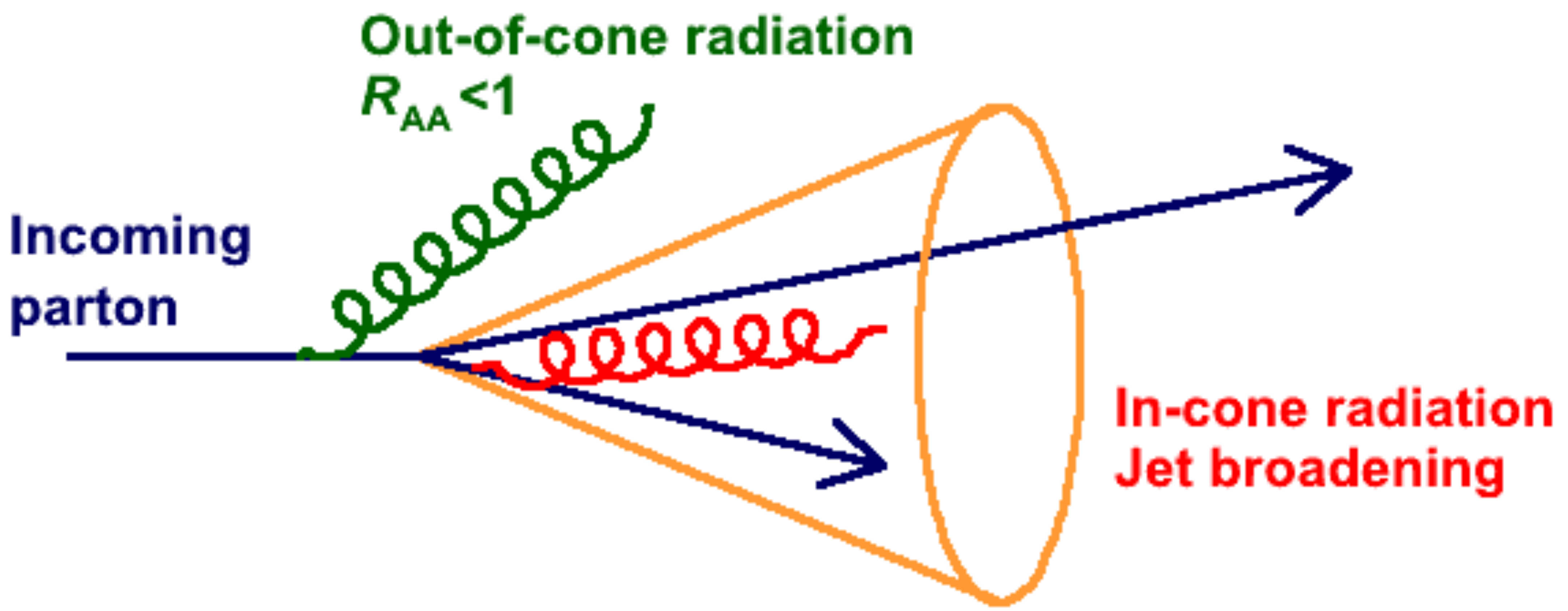
Beauty shows smaller v_2:
smaller energy loss



Dead cone effect: induced gluon radiation suppressed for v < c
Visible for charm, beauty at low p_T

Jets in heavy ion collisions



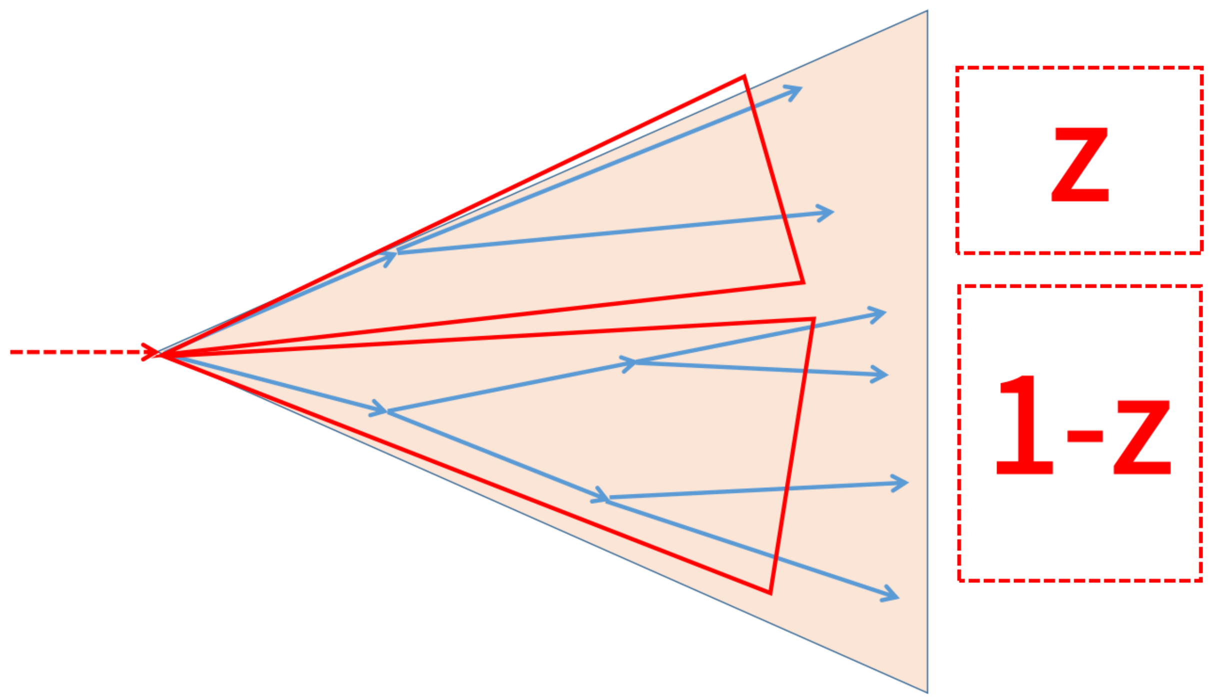


Motivation: understand energy loss dynamics

Very clear signals at high p_T: jets stand out above uncorrelated soft background

Jet physics with pp collisions: dead cone effect

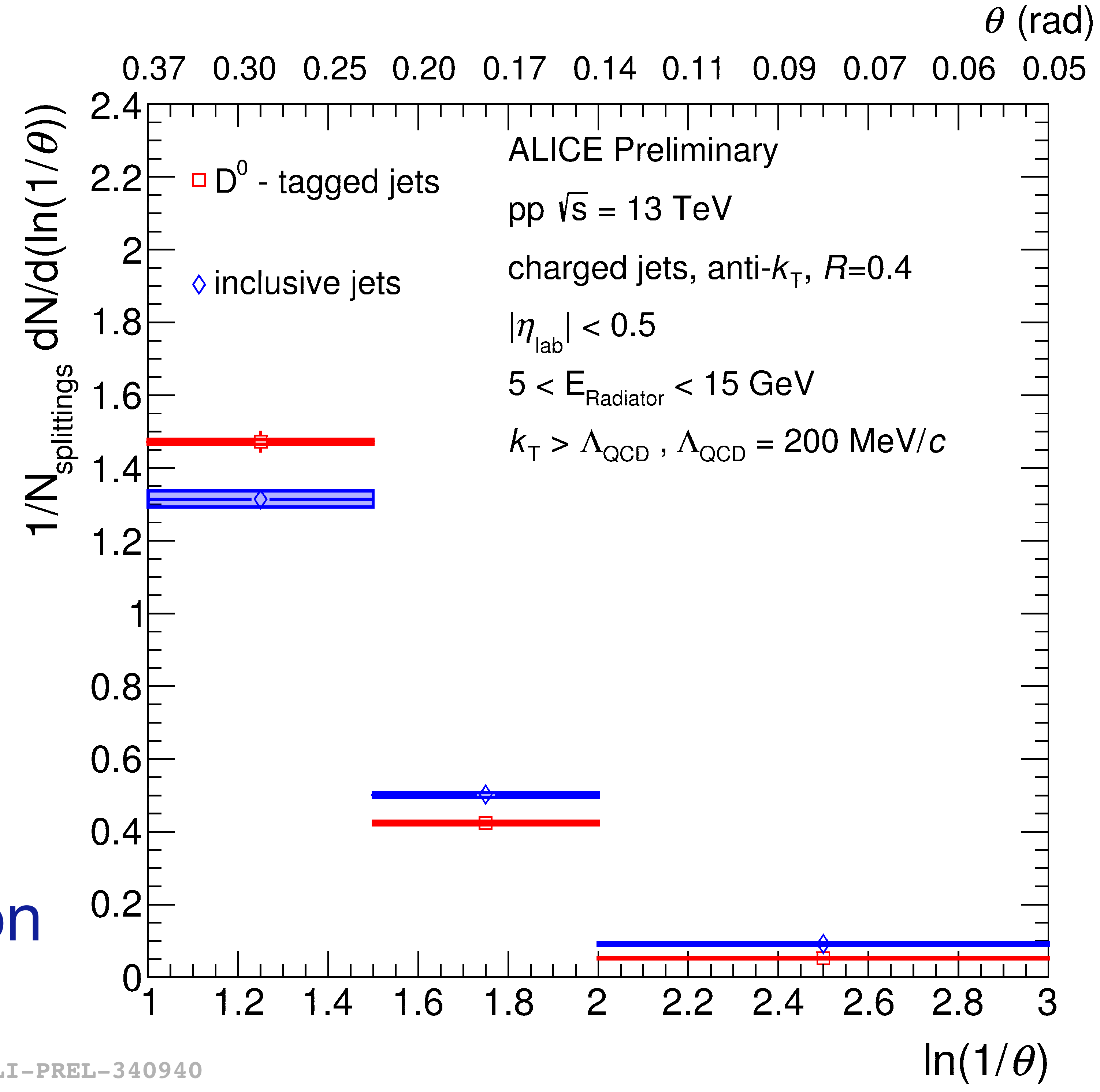
Jet structure from declustering + grooming:



This study: follow prongs with a charm meson

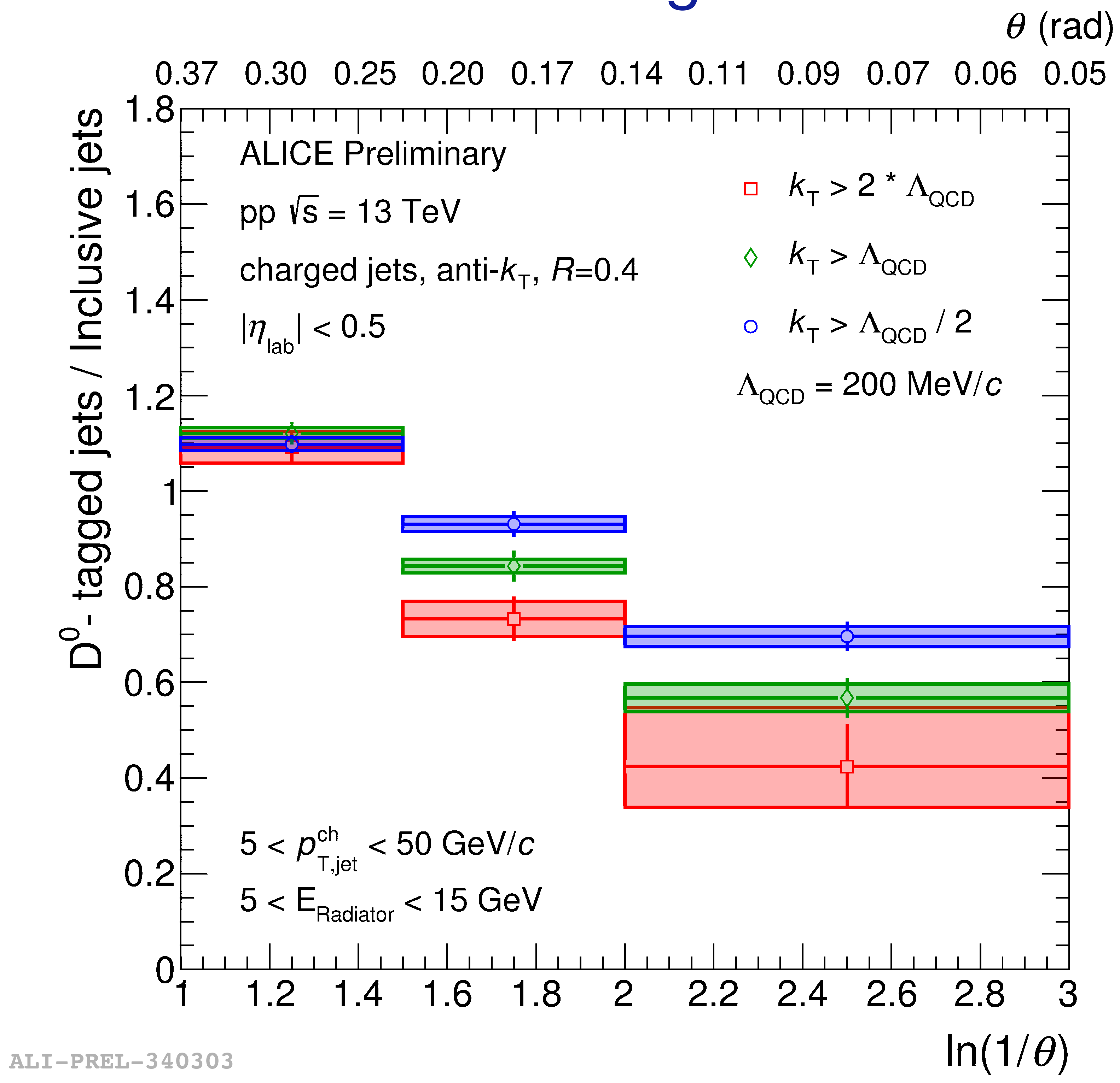
Cunqueiro and Ploskon, *PRD* 99, 074027

Angular distribution of SD splittings



Opening angle ←

Ratio charm to light flavour



Opening angle ←

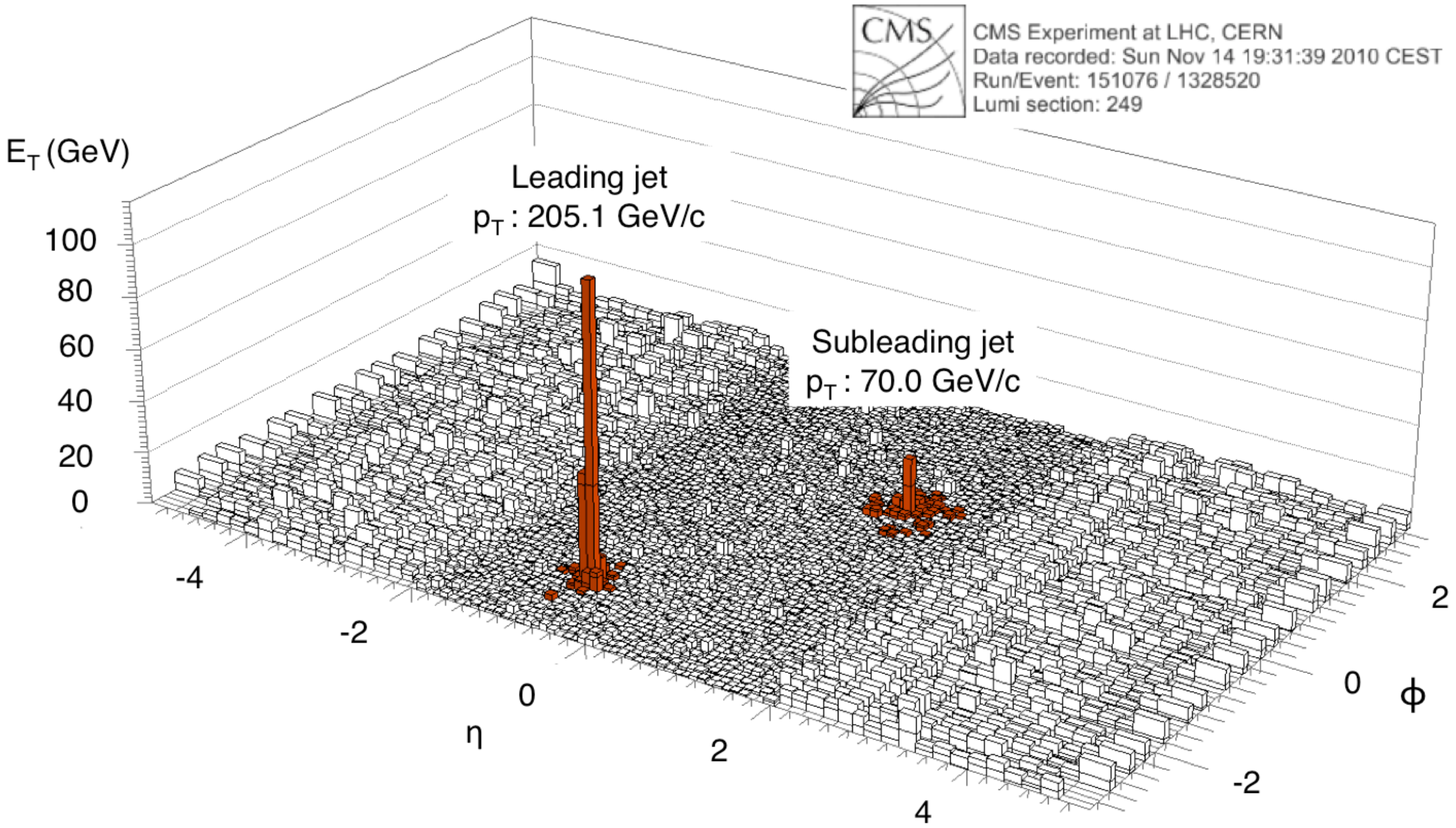
Comparing charm to light flavour splittings: suppression at small angle — dead cone effect

Part of a broader program — productive exchange of ideas between pp and heavy-ion community

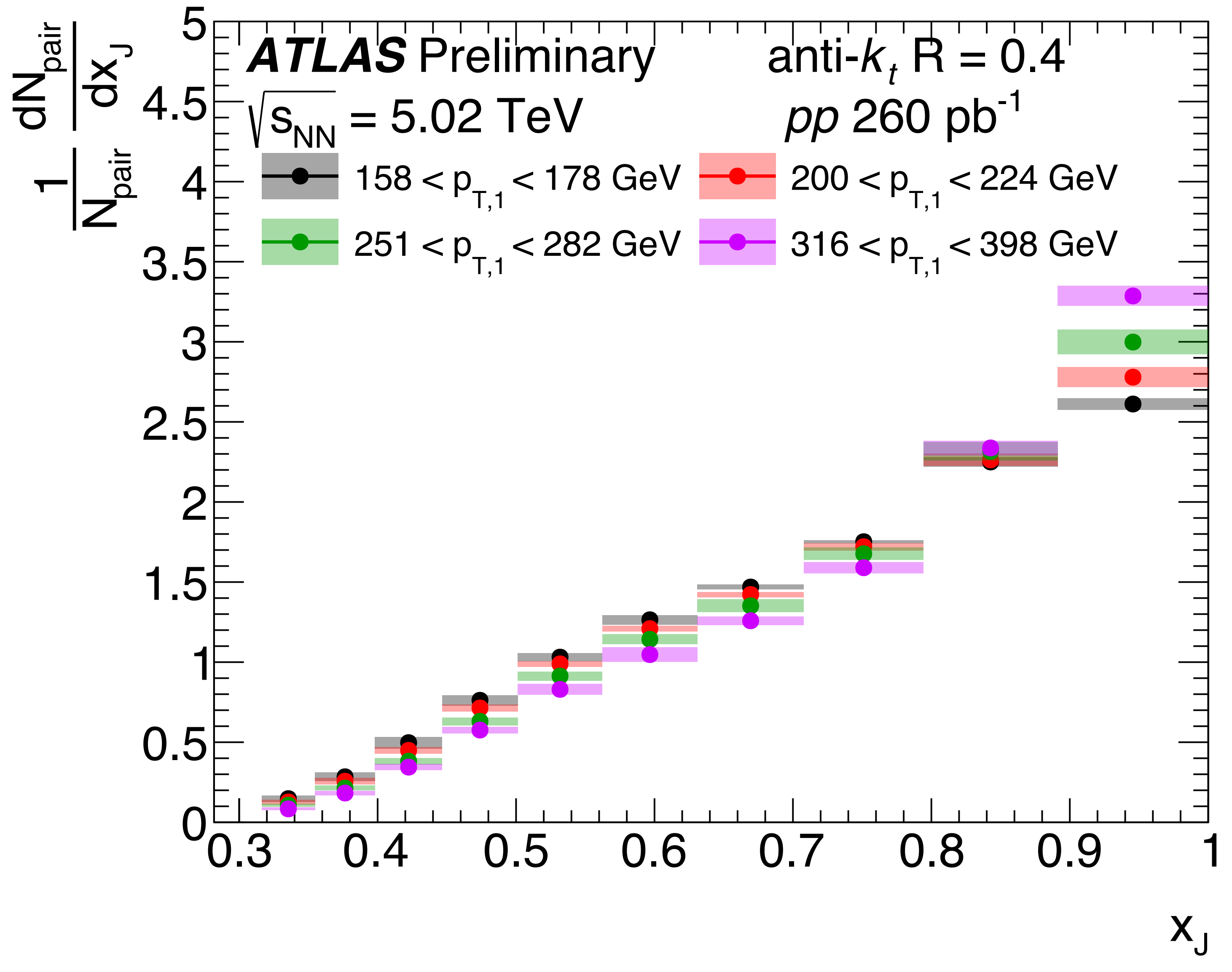
Energy loss: di-jet asymmetry

Subleading jet energy fraction $x_J = \frac{p_{T,1}}{p_{T,2}}$

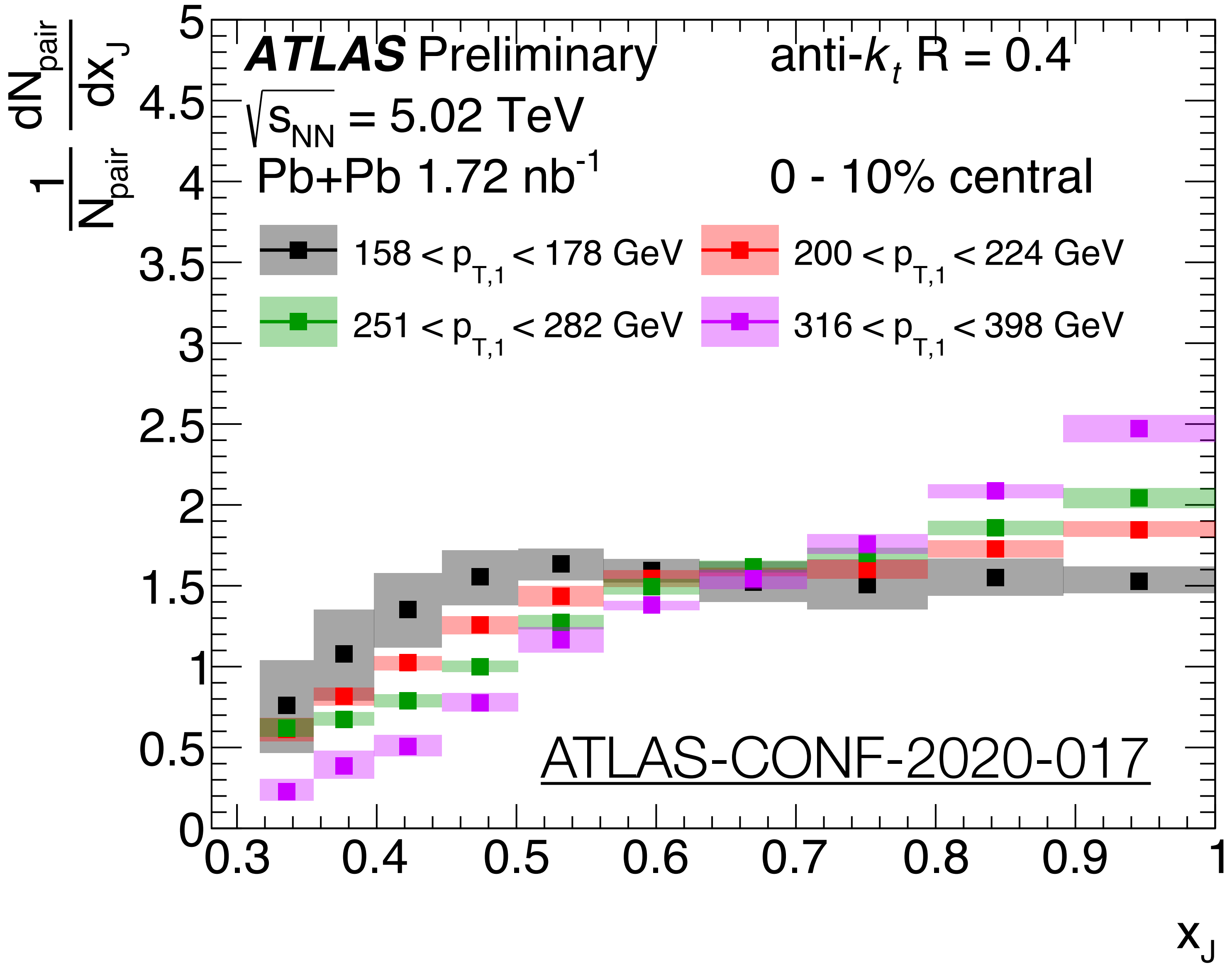
Transverse energy map of 1 event



proton-proton collisions



Pb-Pb collisions



Use p_T balance to measure energy loss
i.e. transport of energy outside jet cone

Pb—Pb distribution shifted to lower energies: energy loss due to interactions

(relative) strength of effect depends on jet energy:
fraction of energy loss decreases with $p_{T,\text{jet}}$

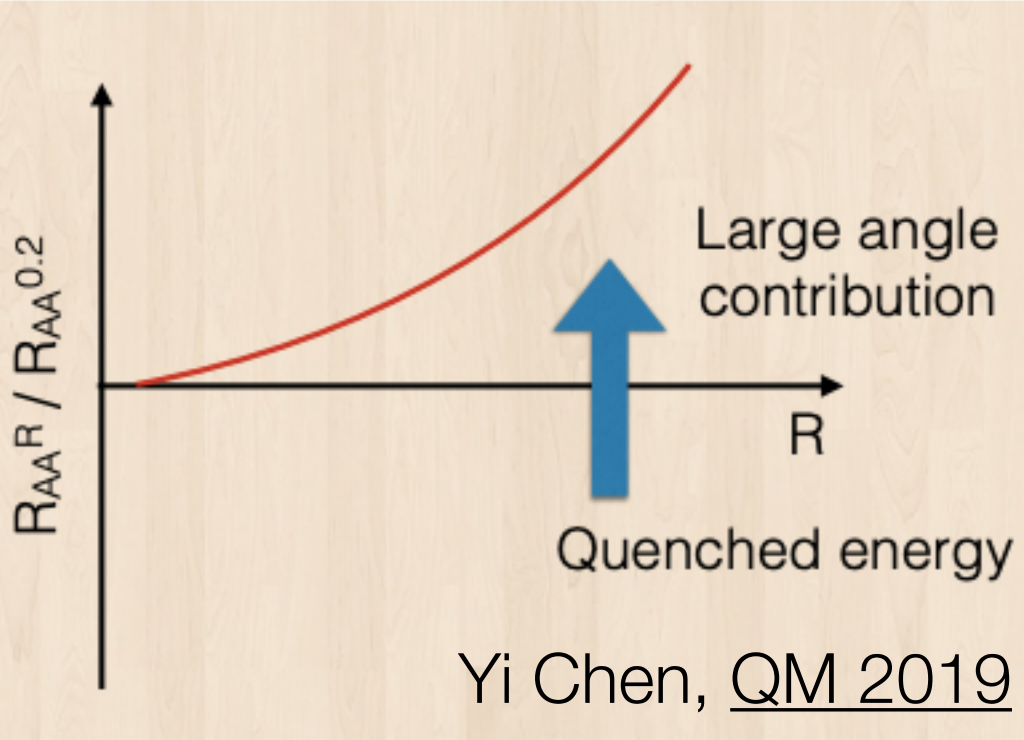
Qualitatively in line with bremmsstrahlung expectation $\frac{dE}{dx} \propto \ln(E)$

Strong coupling: $\frac{dE}{dx} \propto E$

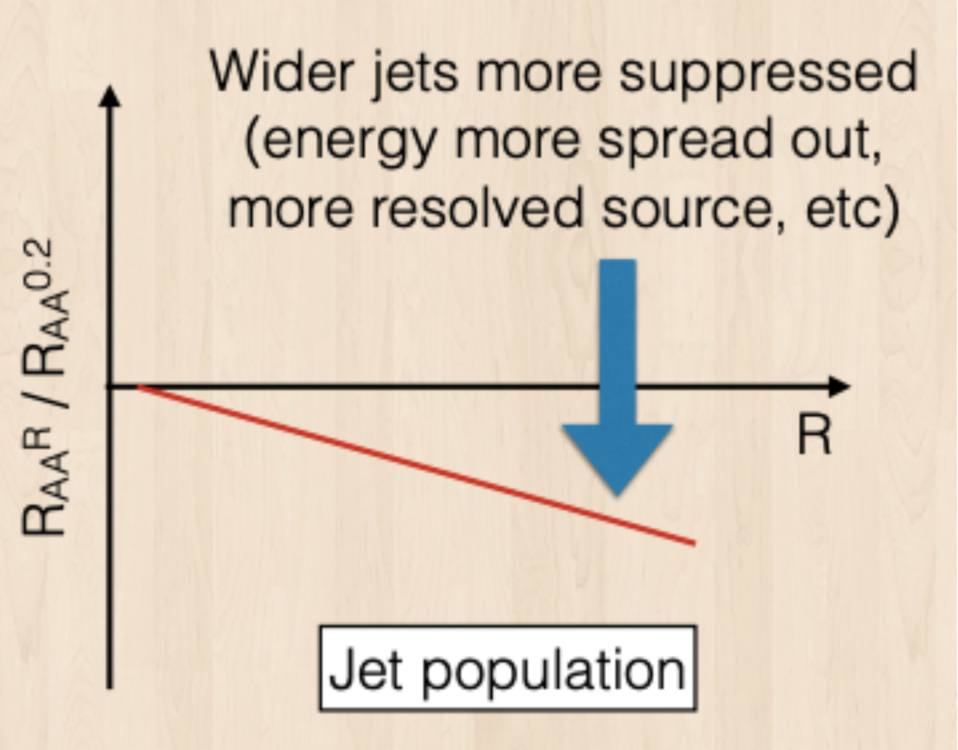
Chesler and Rajagopal, *PRD* 90, 025033

Where does the radiation go: R_{AA} vs R_{jet}

Two competing effects?



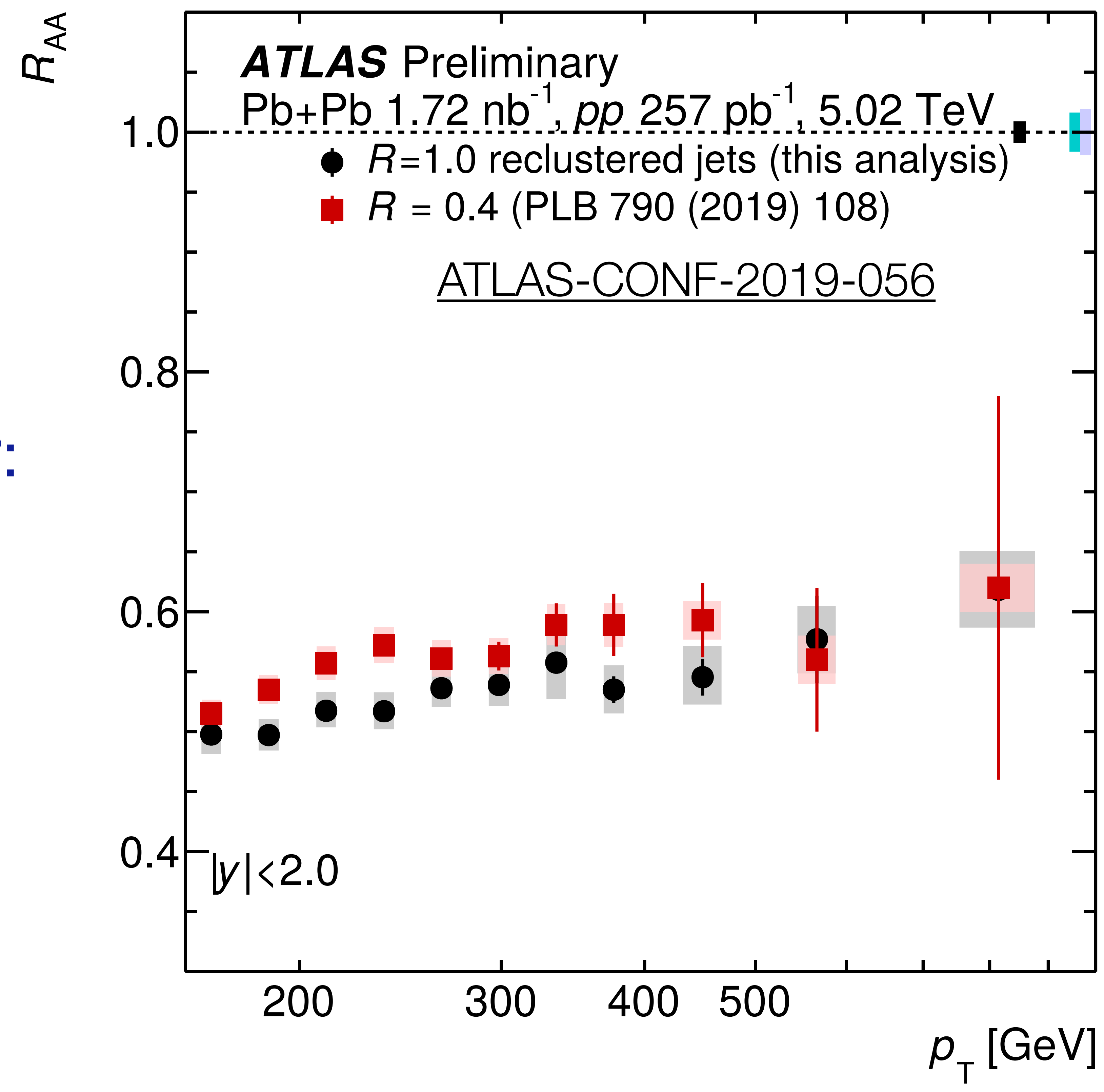
Lost energy appears at large R: increase of R_{AA}



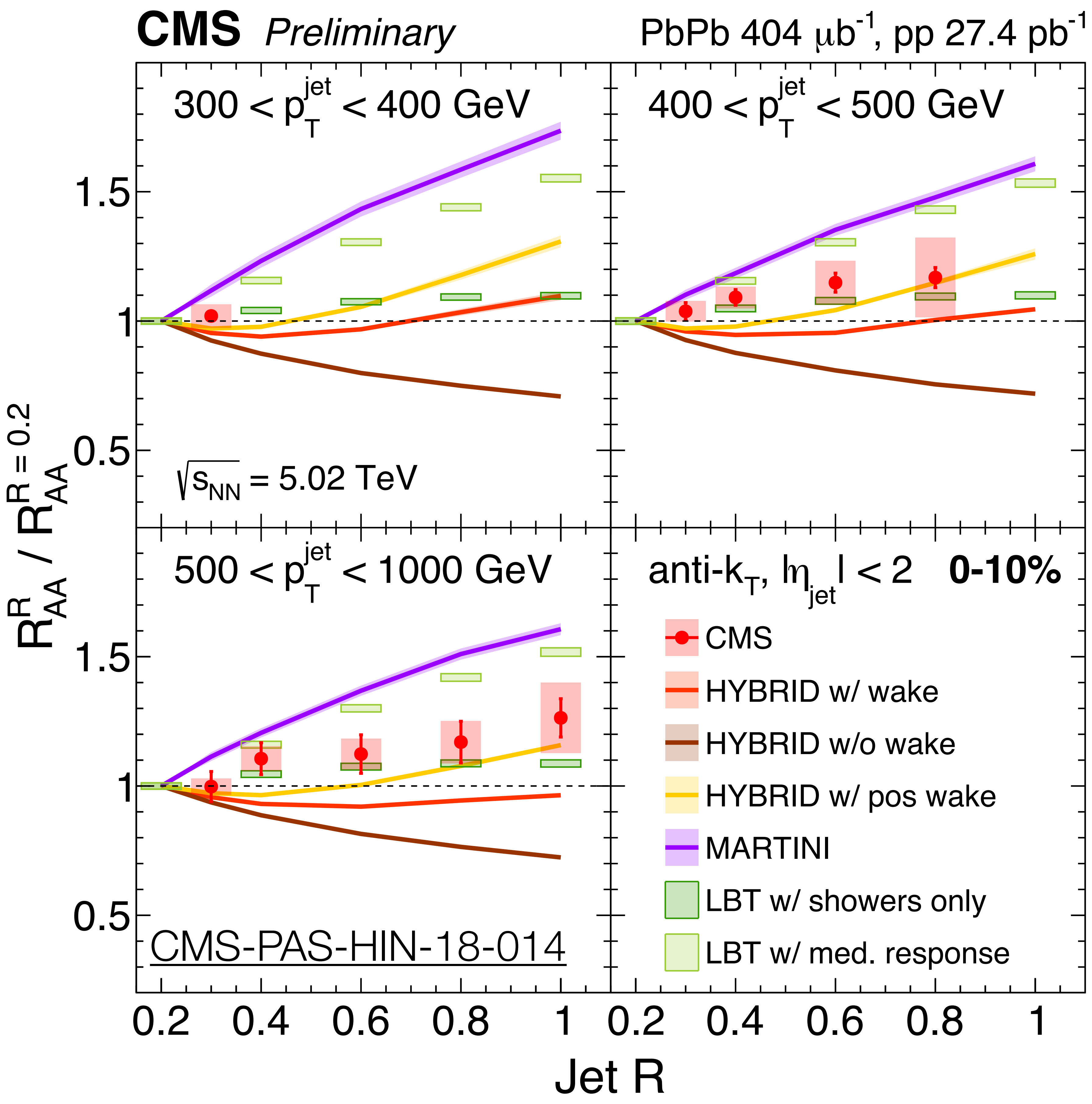
Large jets lose more energy (more sources) decrease of R_{AA}

Caselderrey-Solana et al, *JHEP* 01 (2020) 044

Nuclear modification factor for R_{jet} = 0.4 and 1.0

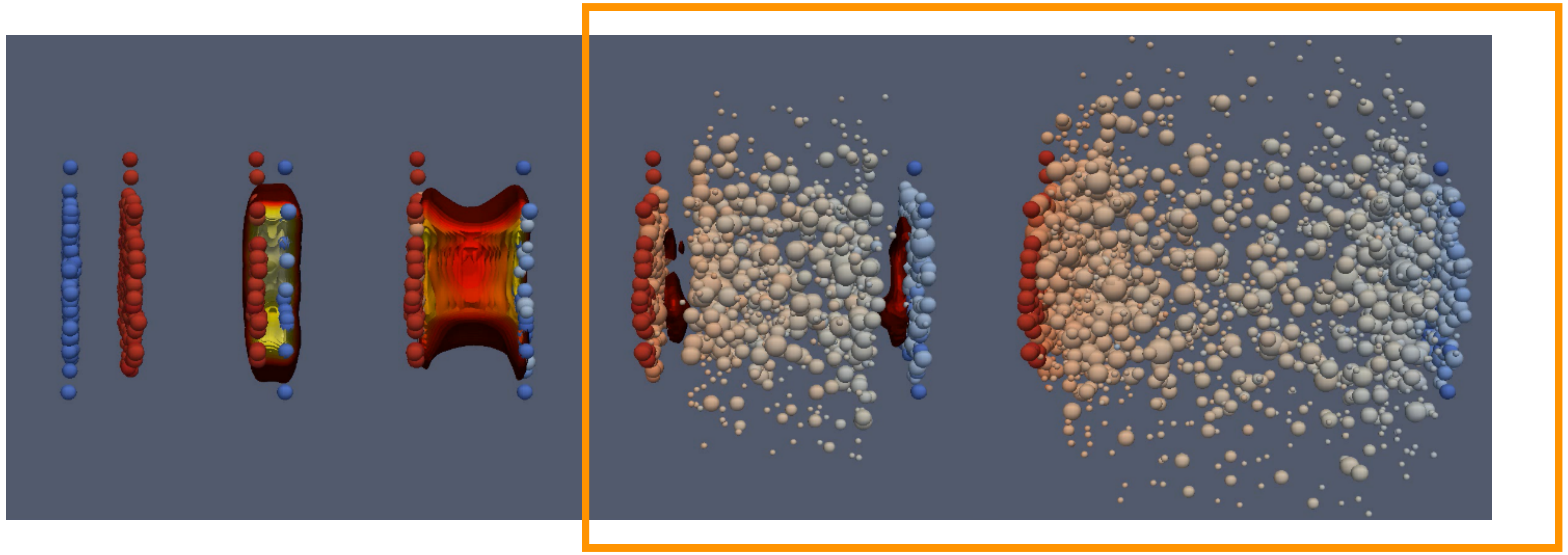


Jet R_{AA} vs R_{jet}



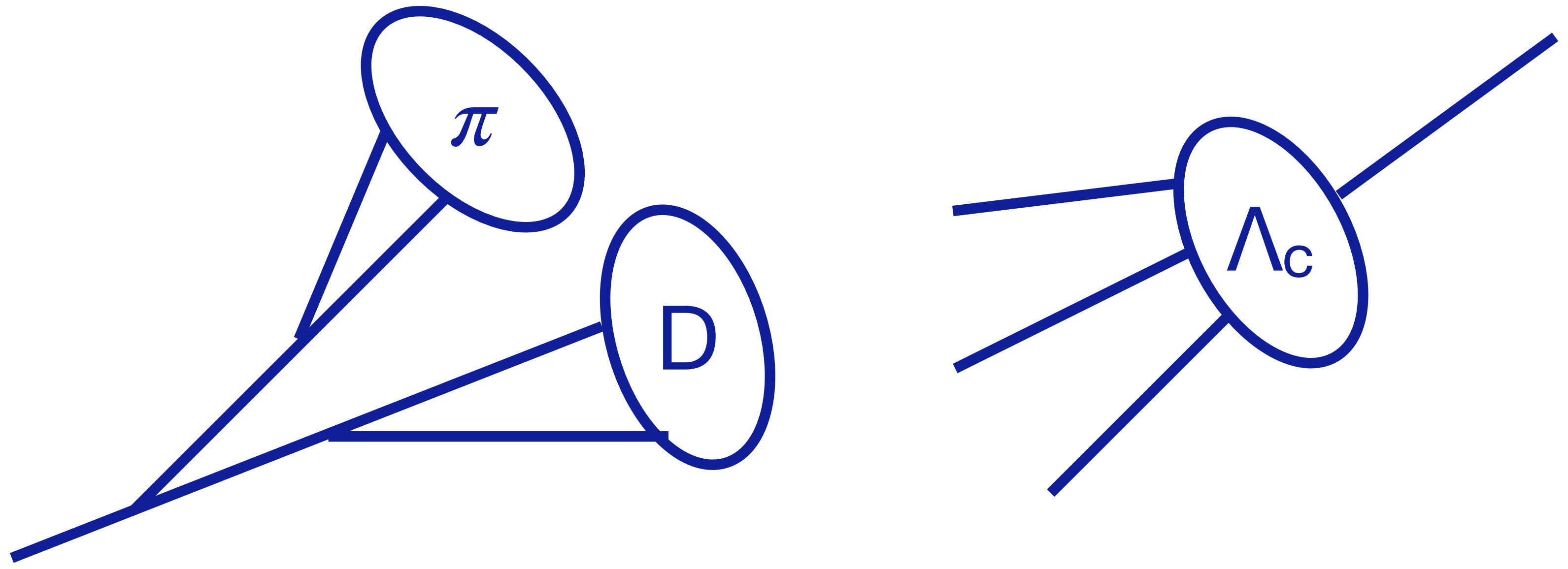
Net result: only modest increase of R_{AA} with larger R_{jet}

Final state: hadronisation and rescattering



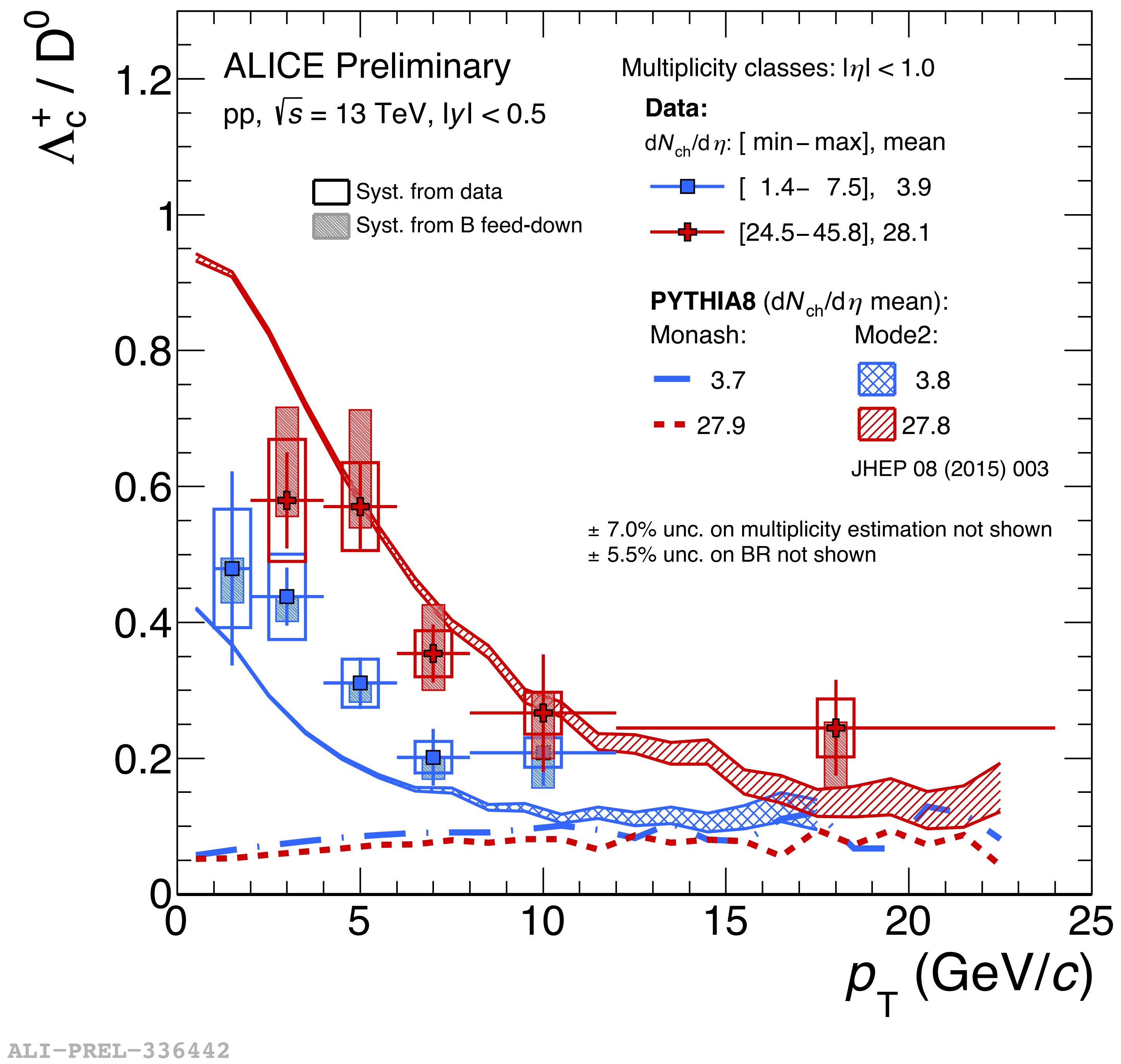
Fragmentation

Coalescence

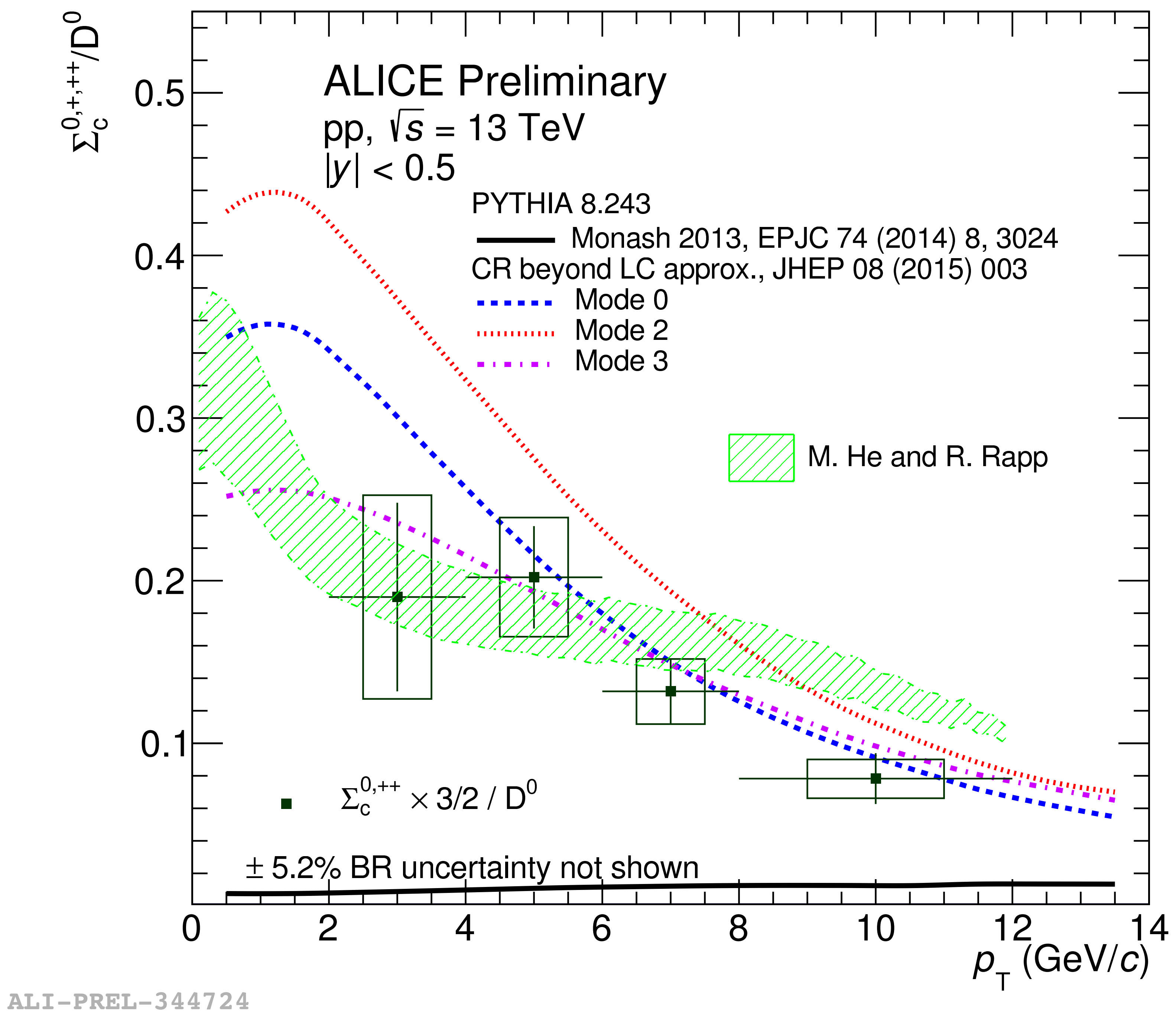


Heavy flavor baryon production

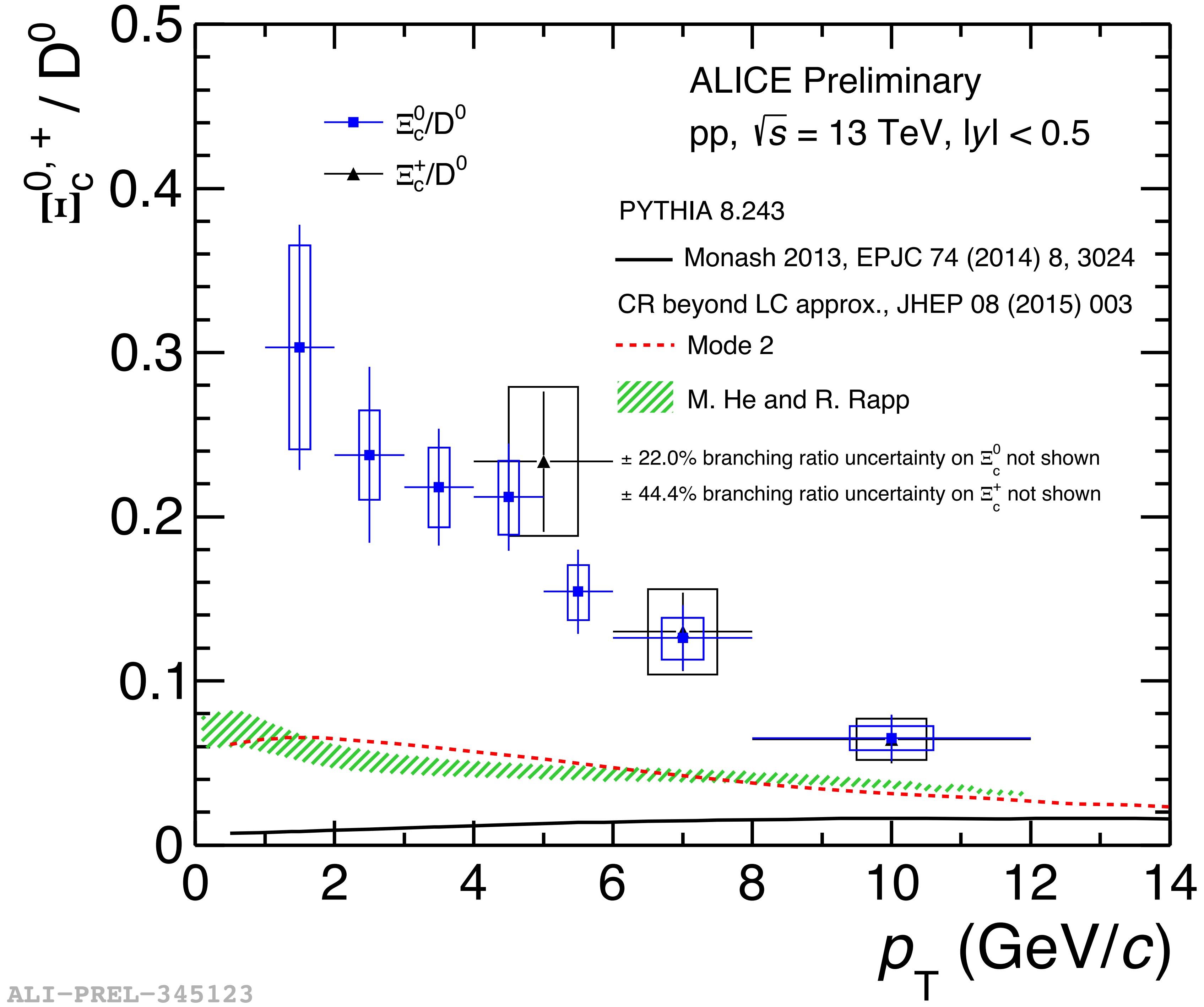
Λ_c(udc)/D^0



Σ_c(uuc,ddc)/D^0



Ξ_c(usc,dsc)/D^0



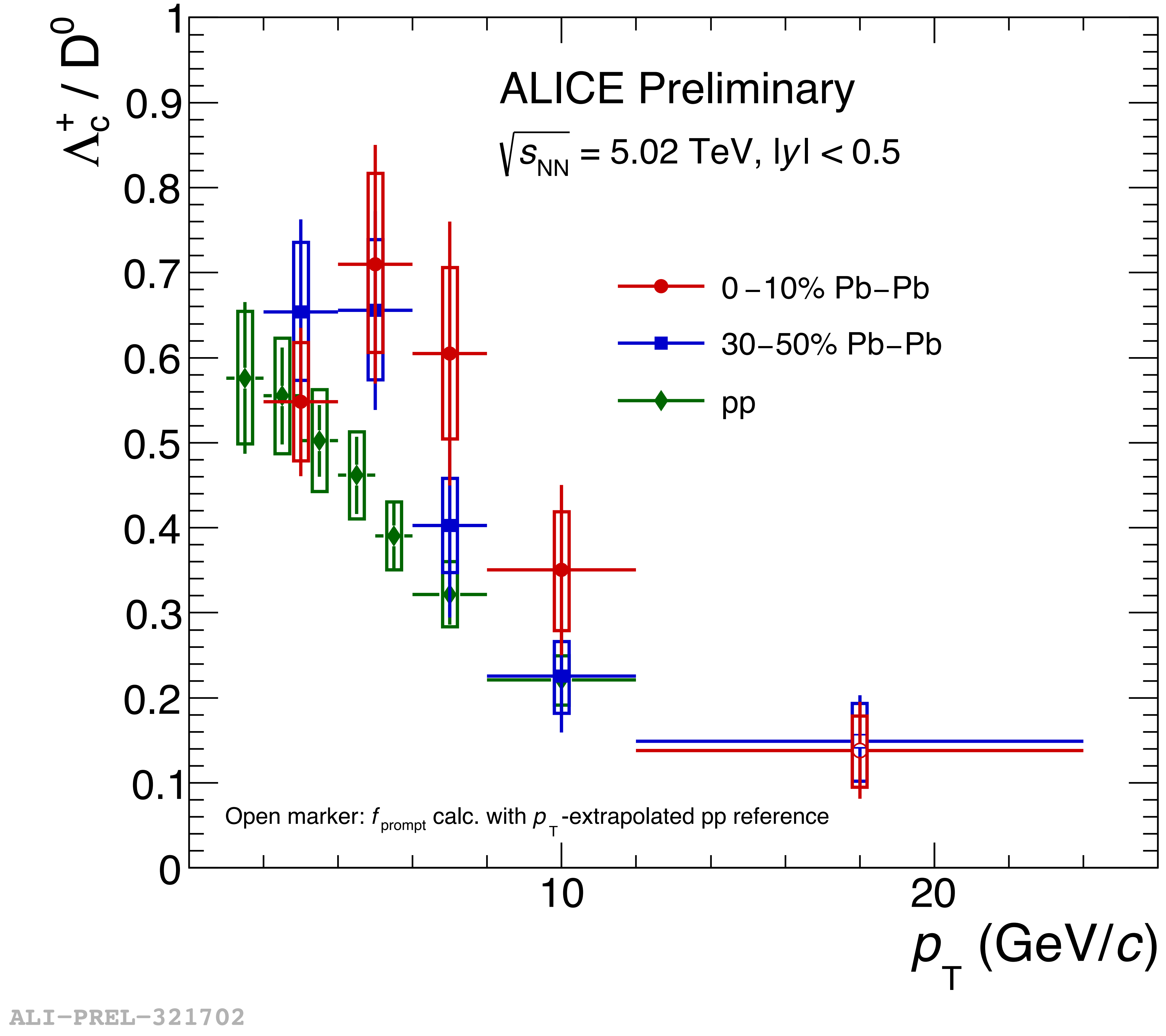
Charmed baryon/meson ratios much larger in pp than e^+e^- (at $p_T < 10$ GeV)

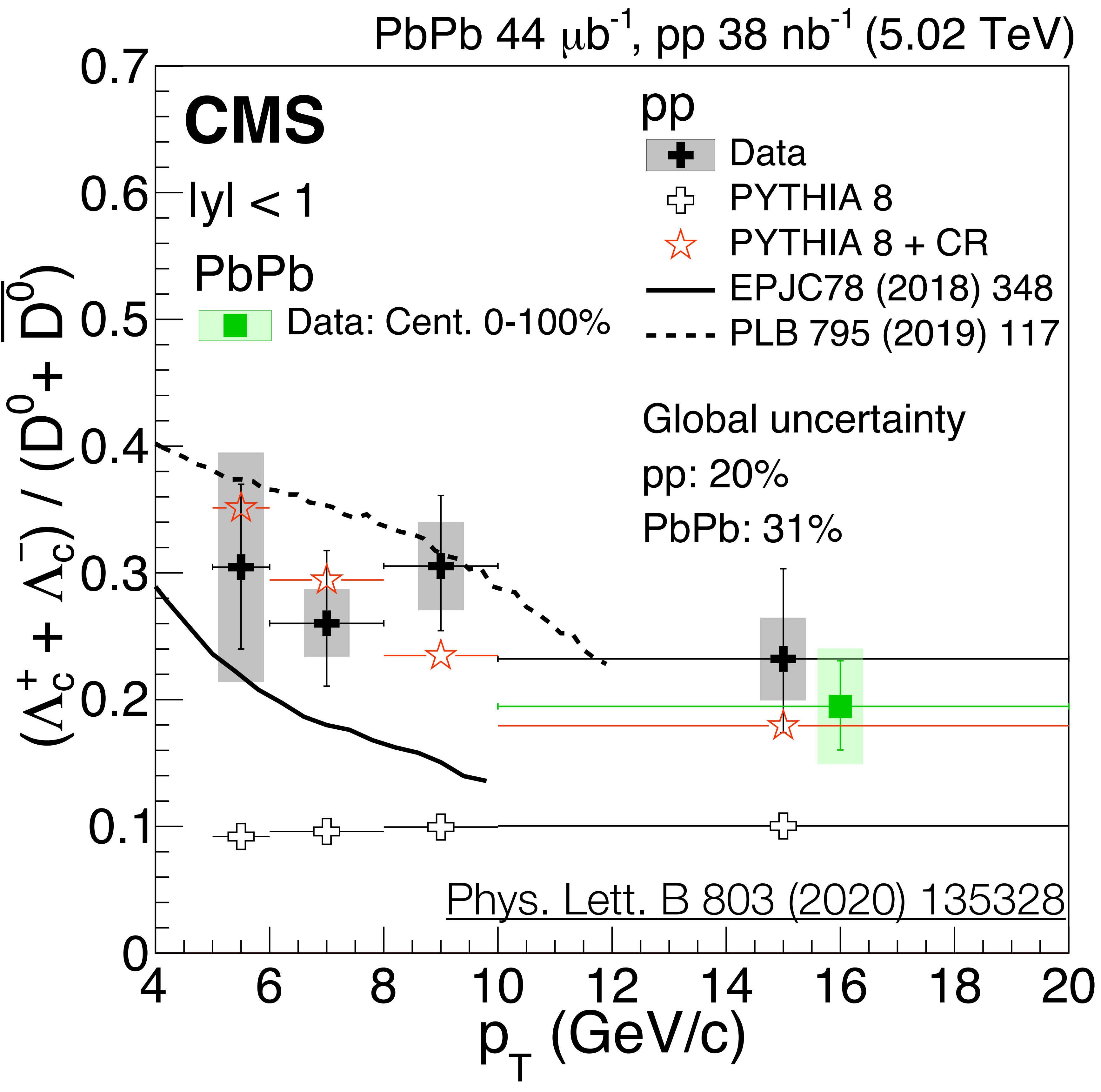
Not expected: universal fragmentation

Other mechanisms: color reconnection, coalescence, others?

~1/3 of c quarks end up in baryons in pp at LHC vs ~6% in e^+e^-

Λ_c production in Pb-Pb collision



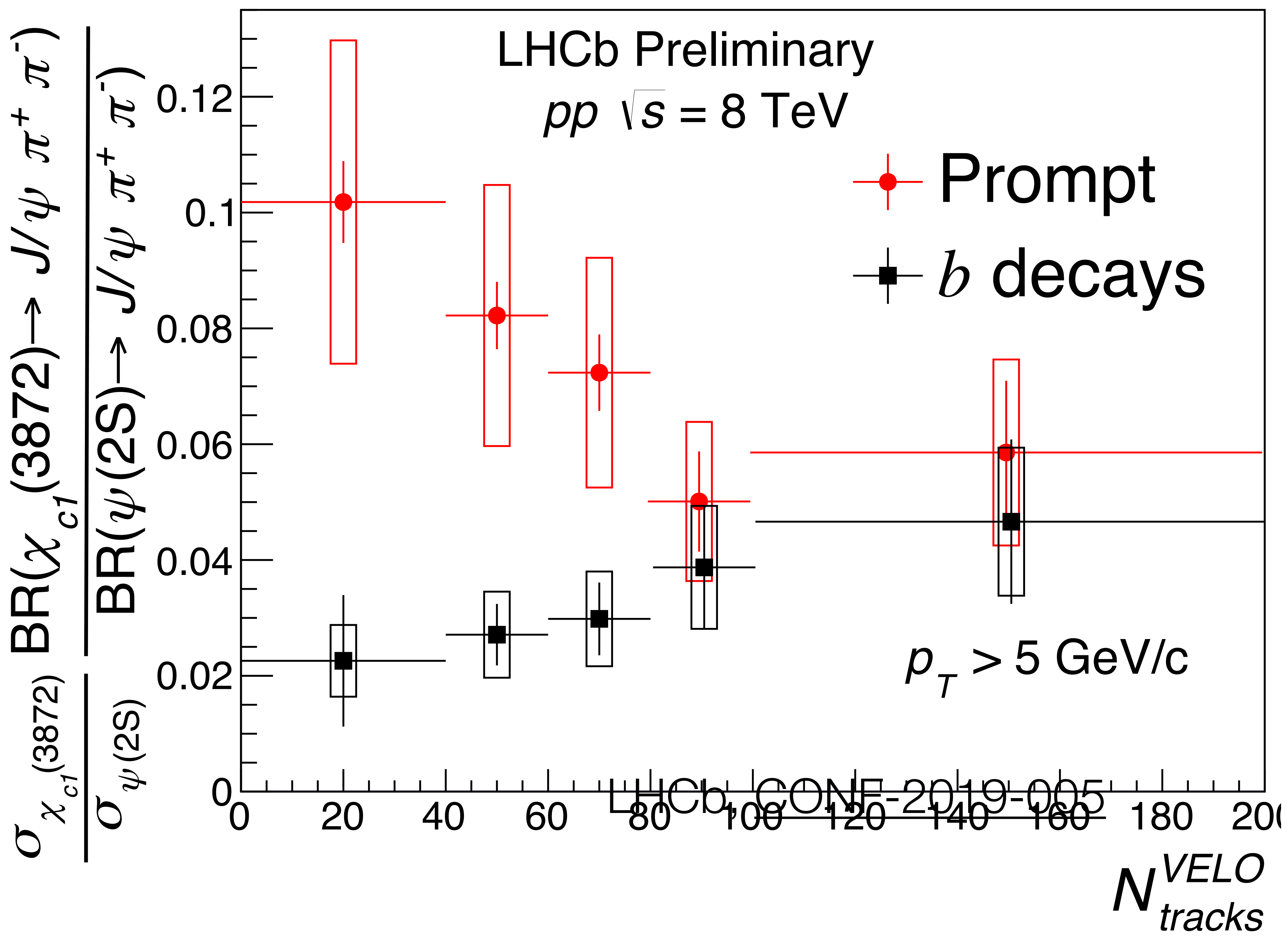


Baryon enhancement in Pb-Pb collisions similar to pp

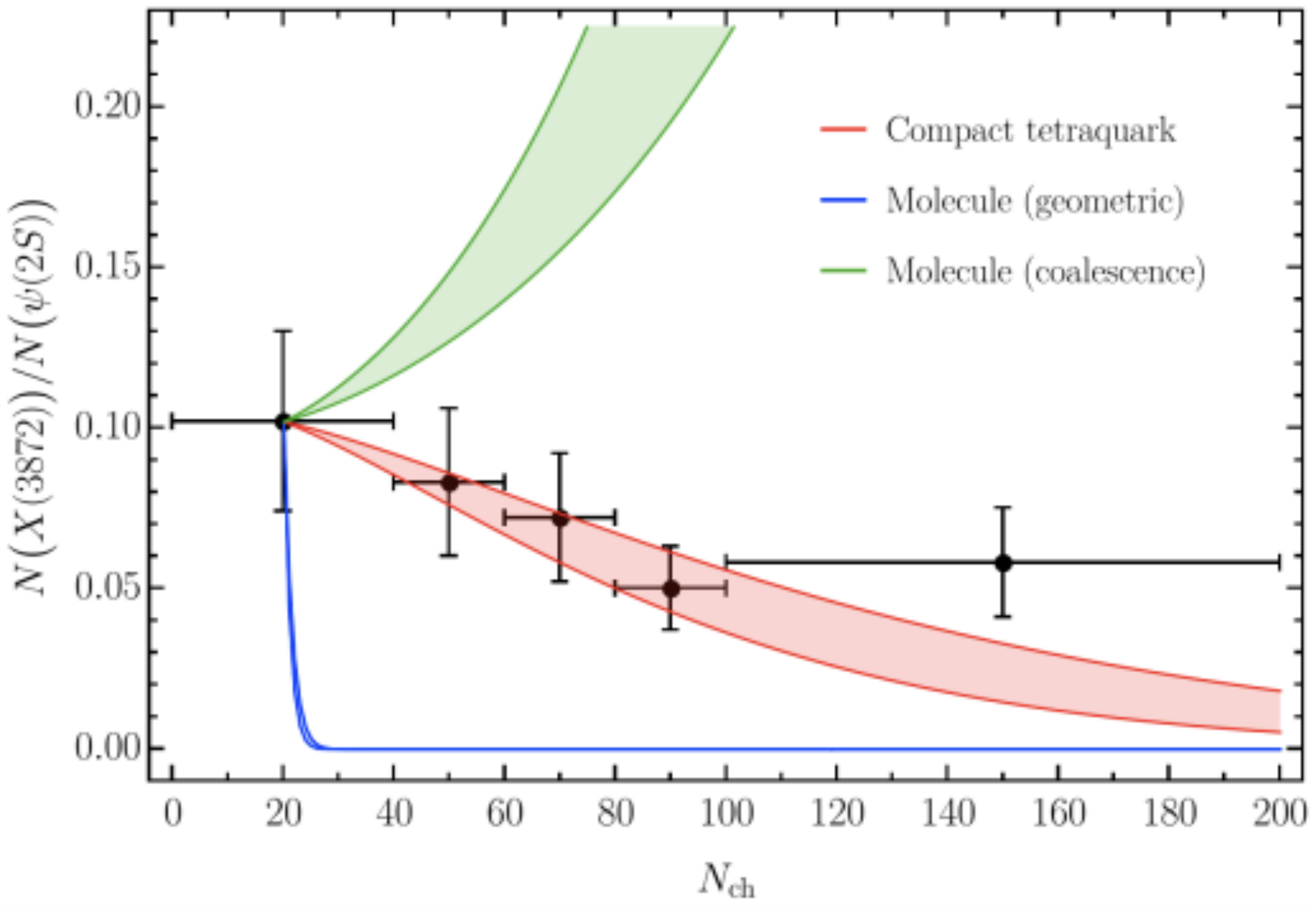
In line with expectations from coalescence models?

Taking it one step further: $\chi_{c1}(3872)$

Prompt and non-prompt $\chi_{c1}(3872)$ in pp

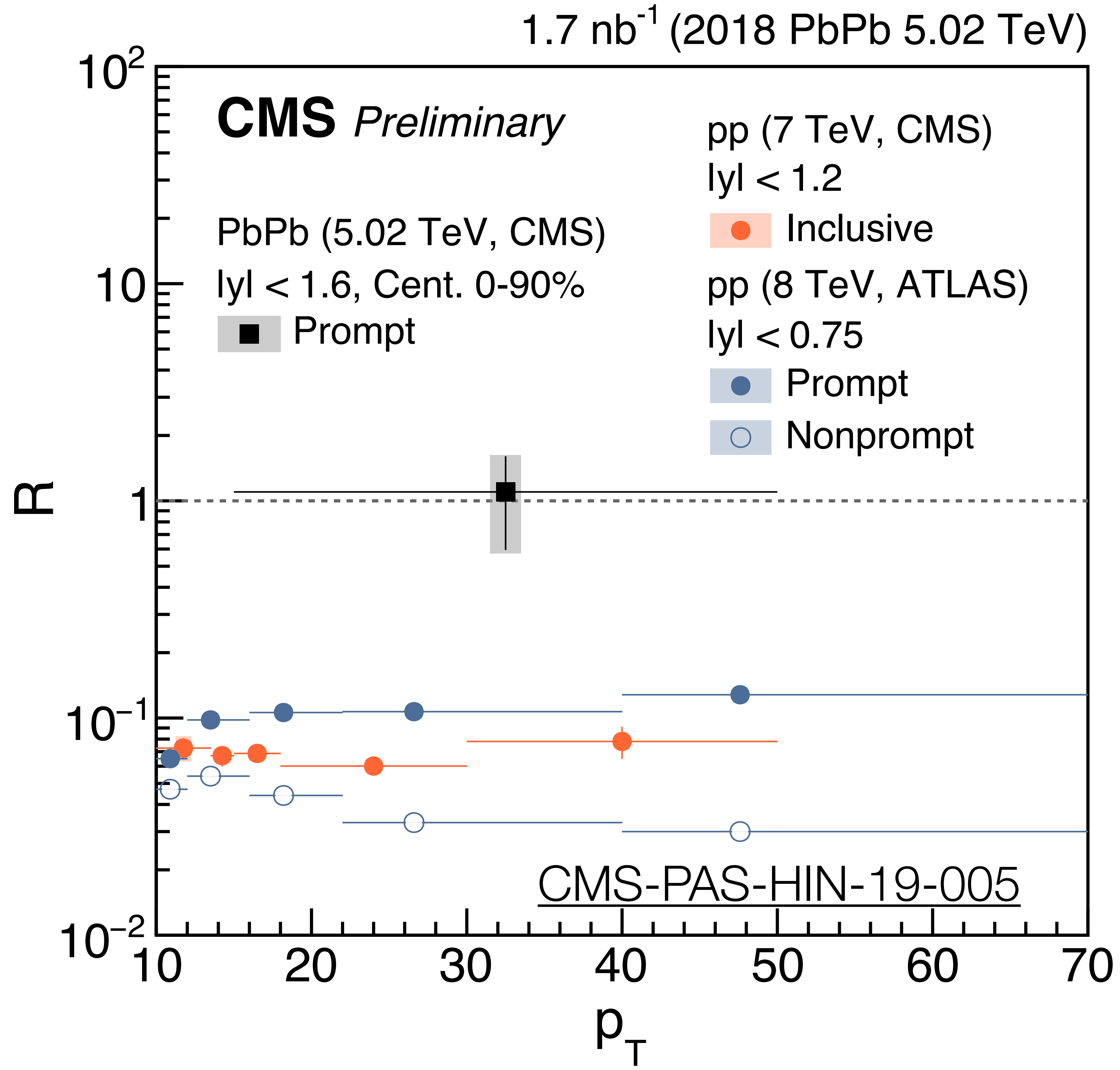


Coalescence model

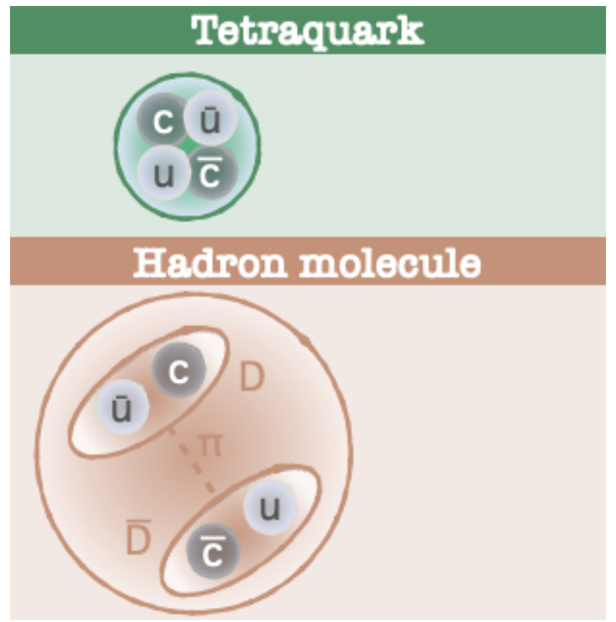


Esposito et al, arXiv:2006.15044

pp and Pb-Pb



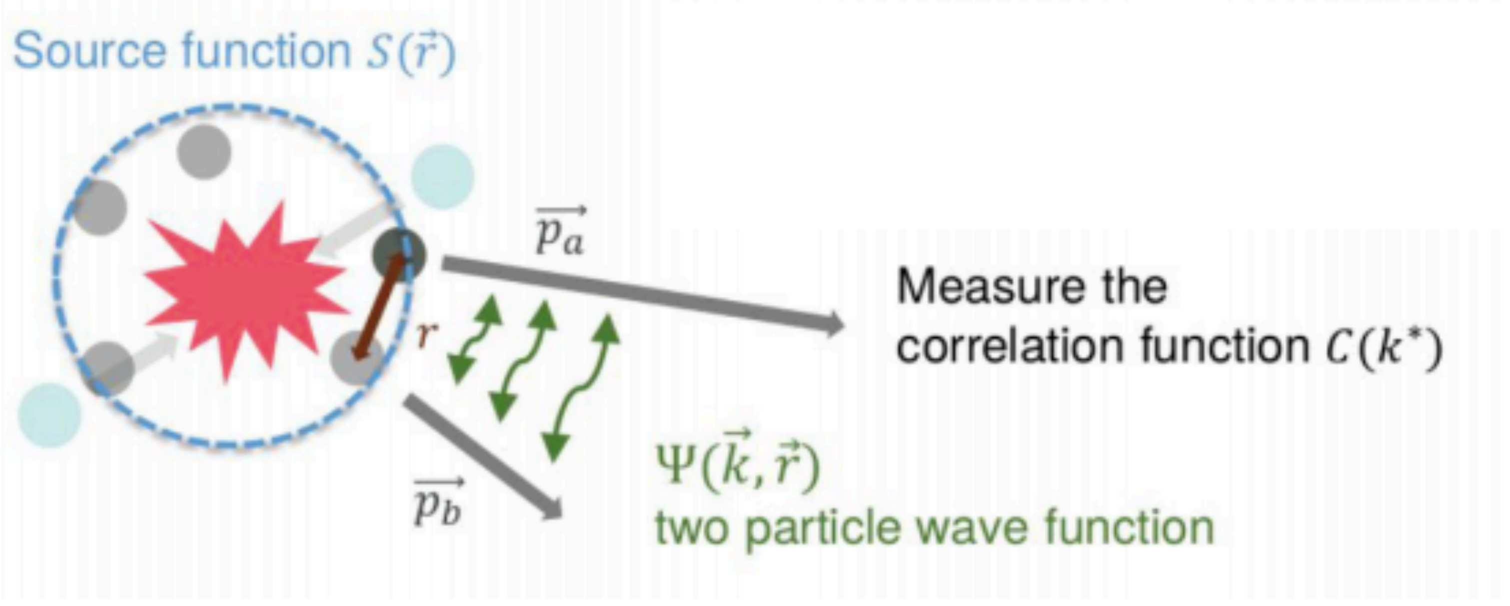
Hint of larger increase in Pb-Pb?



Production rates could also shed light on structure: coalescence cross section, rate different for molecular state ?

Coalescence rates determined by system size and hadron size

Probing final state interactions with correlations



Experimental definition ***Theoretical definition***

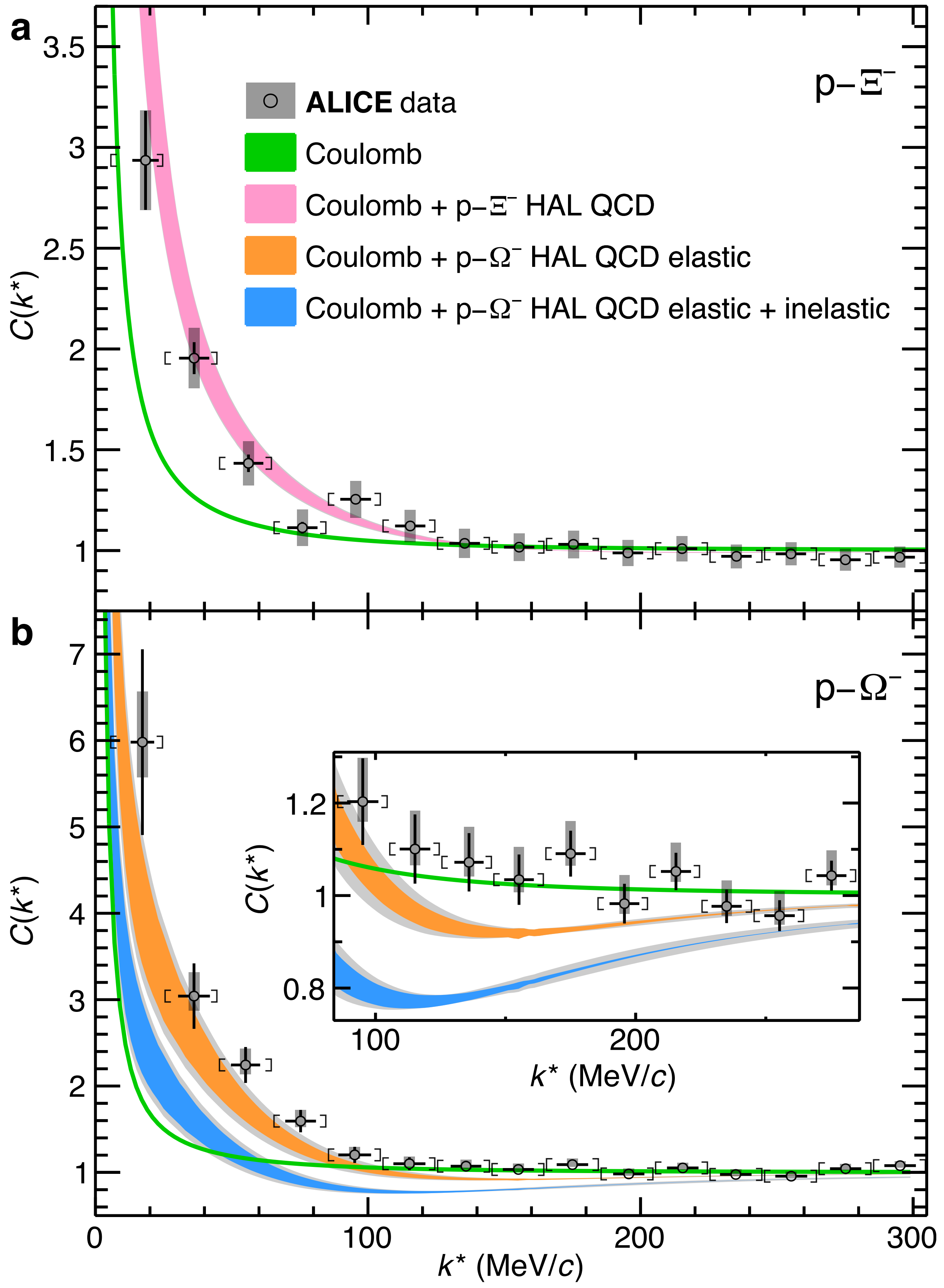
$$C(k^*) = \mathcal{N}\frac{N_{\mathrm{Same}}(k^*)}{N_{\mathrm{Mixed}}(k^*)} = \int S(\vec{r})\left|\Psi(\vec{k}^*,\vec{r})\right|^2 \mathrm{d}^3\vec{r} \xrightarrow{k^*\to\infty} 1$$

>1 : **Attractive** Interaction

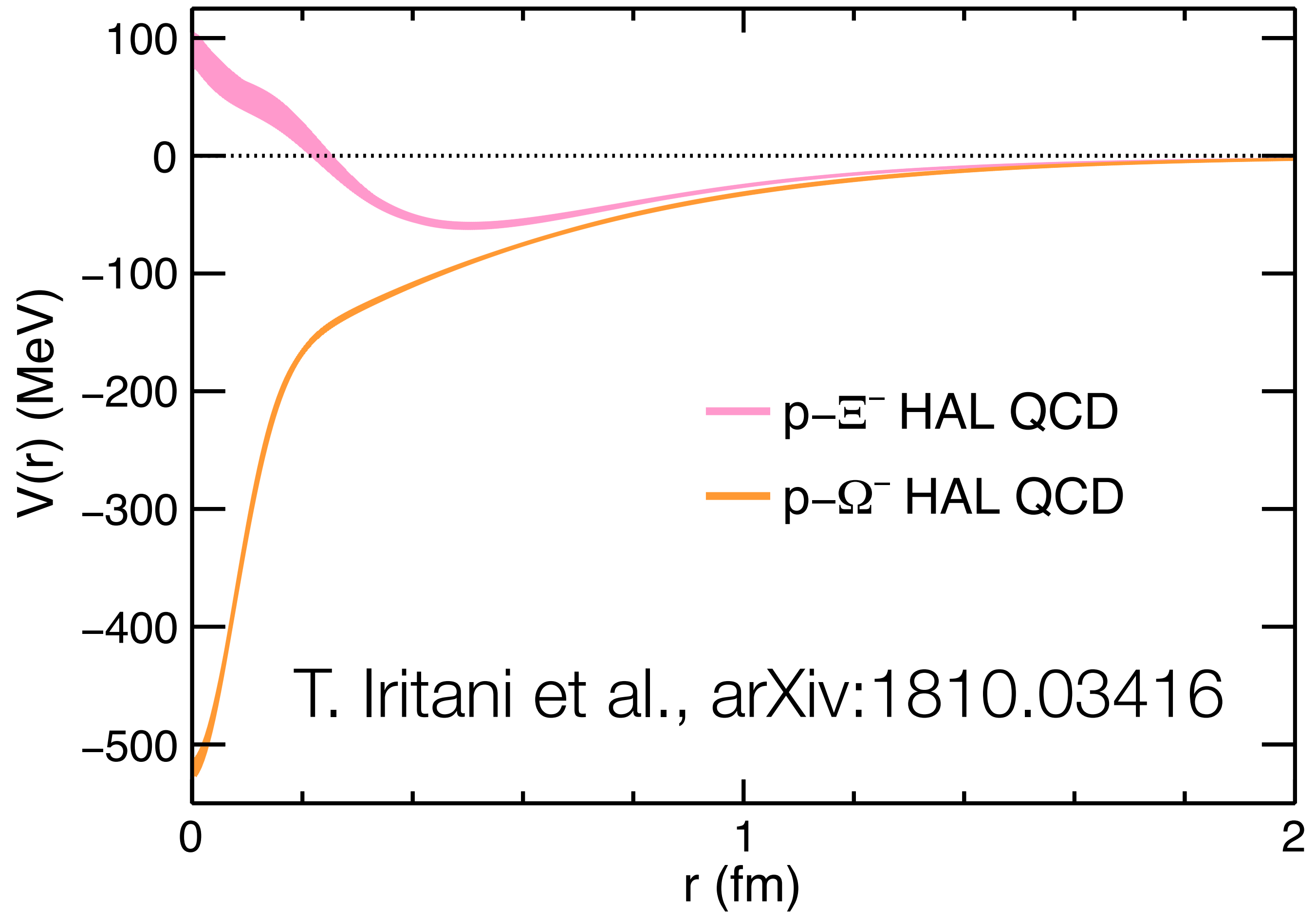
<1: **Repulsive** Interaction

Relative distance / reduced momentum in the rest frame of the pair

p - Ξ, p - Ω correlations



ALICE, arXiv:2005.11495



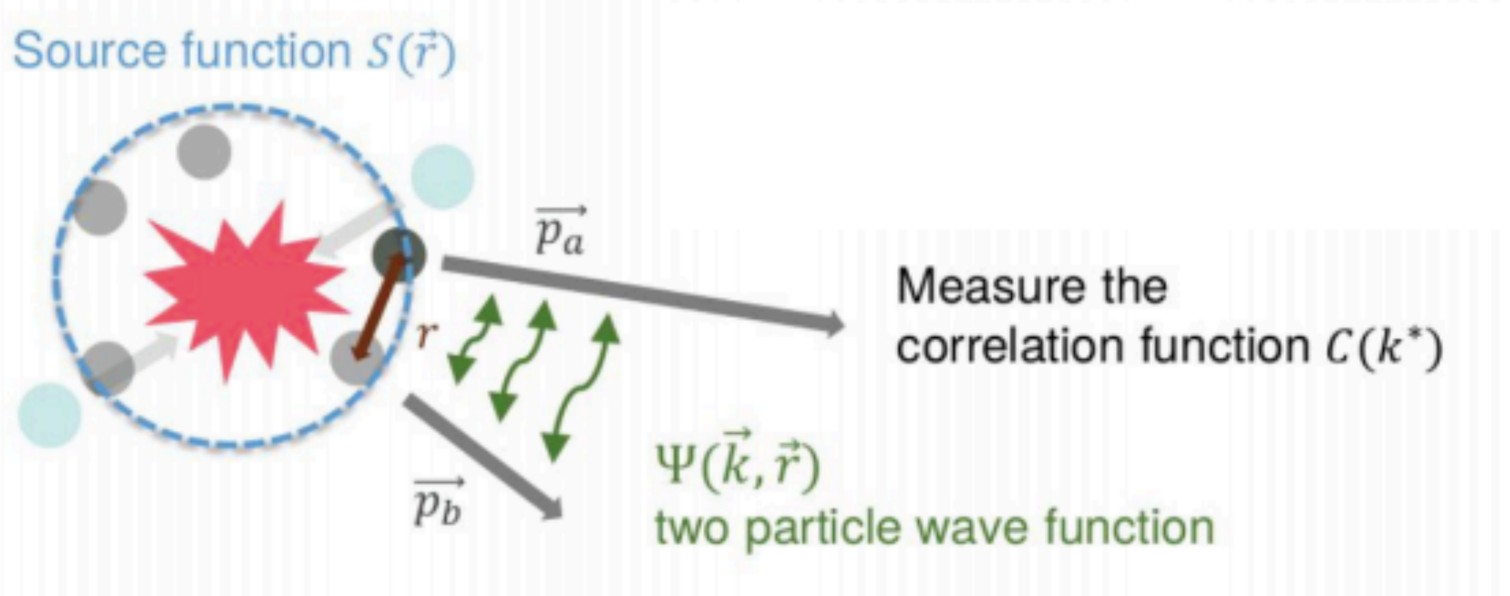
Data agree with HAL (lattice) QCD potential

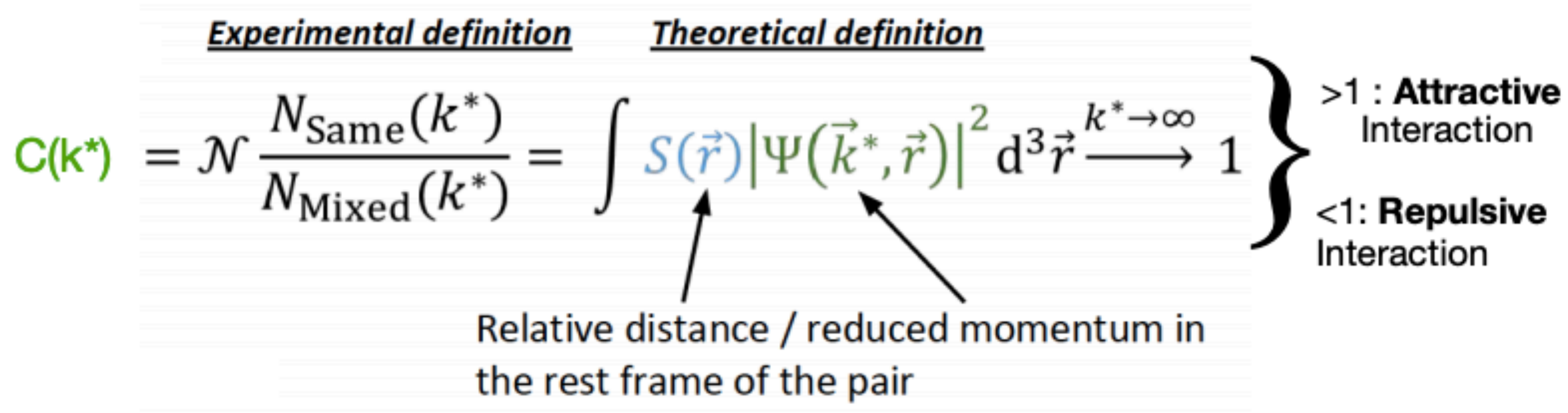
Role of inelastic channels to be confirmed

Final state momentum correlations ‘femtoscopy’ sensitive to:
- Space-time **distribution of production points**
- **Interactions** and quantum statistics

Connections to hadron physics, neutron star Equation of State

Probing final state interactions with correlations





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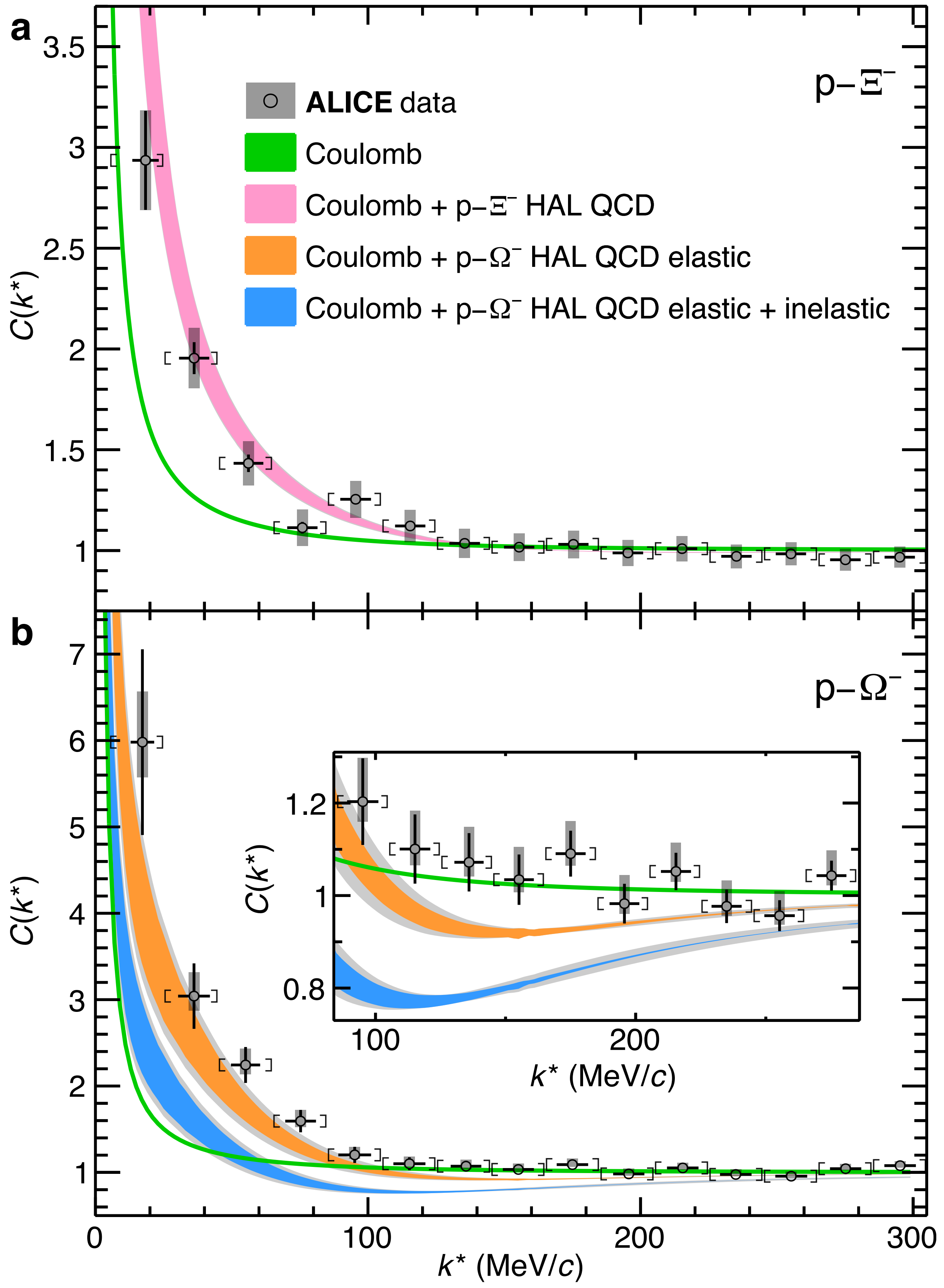
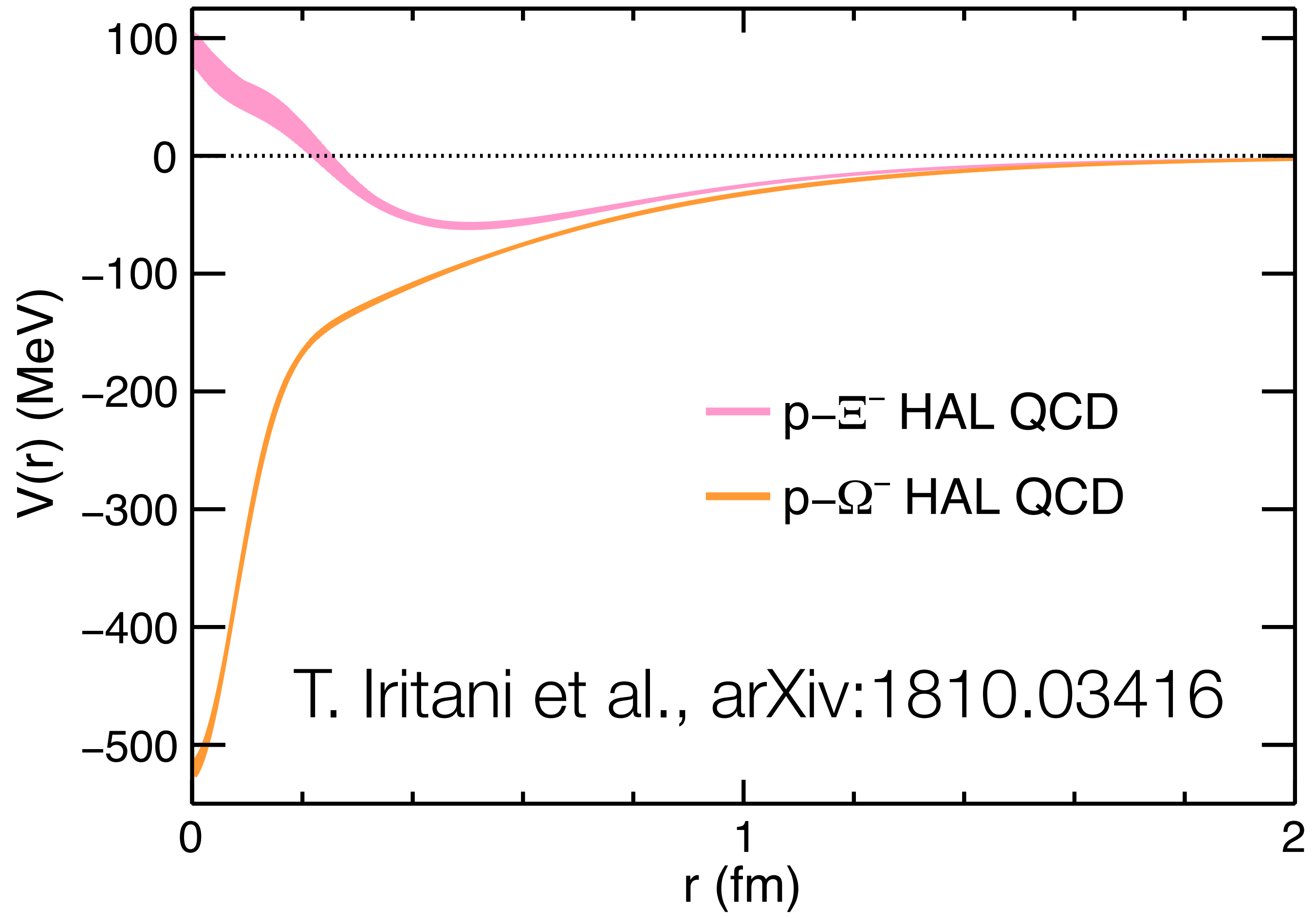


ALICE, arXiv:2005.11495



Data agree with HAL (lattice) QCD potential

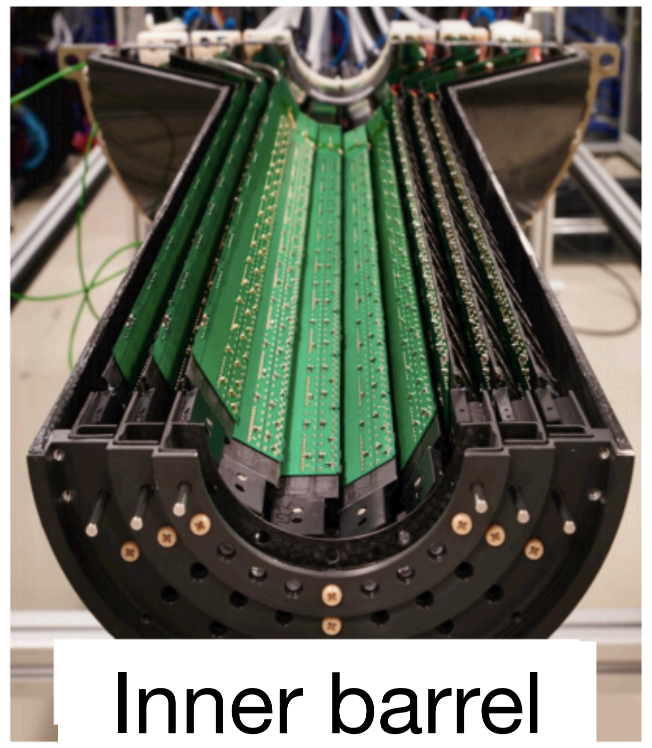
Role of inelastic channels to be confirmed

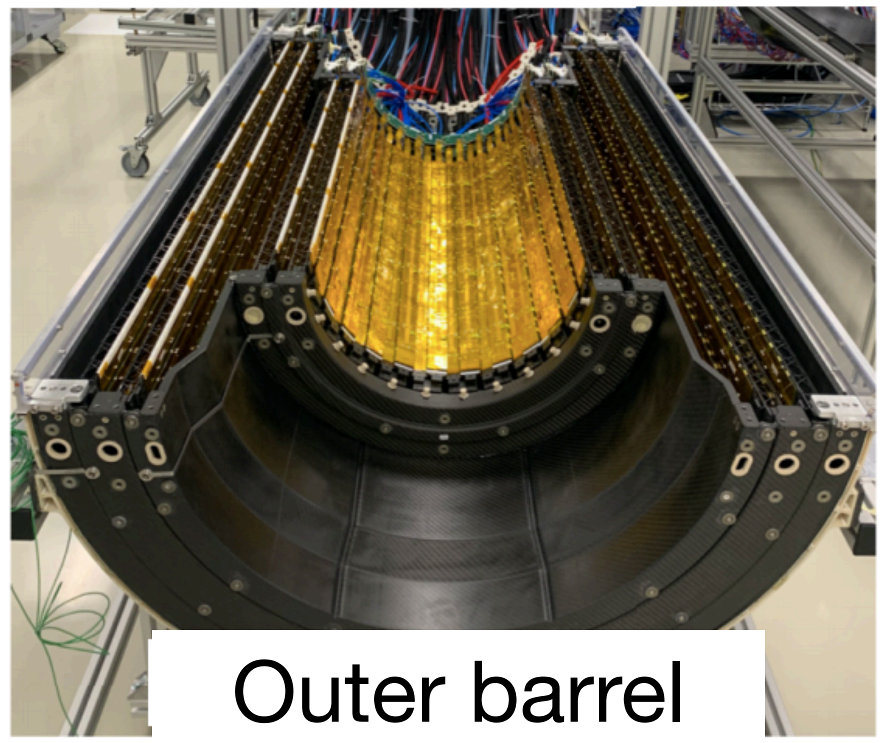
Tool to measure interaction potentials of unstable particles

Connections to hadron physics, neutron star Equation of State

Future plans: ongoing upgrades in LS2

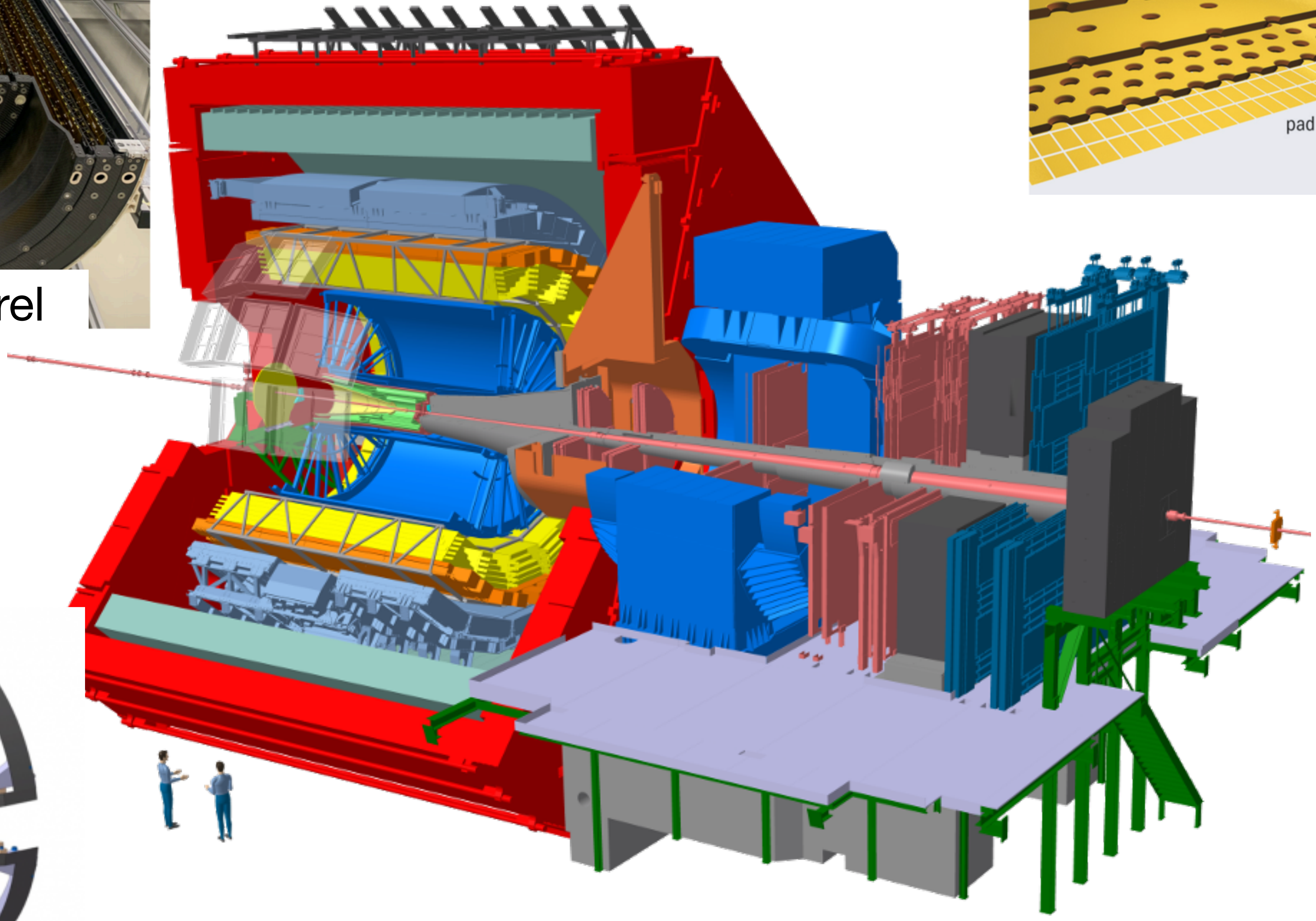
New ITS



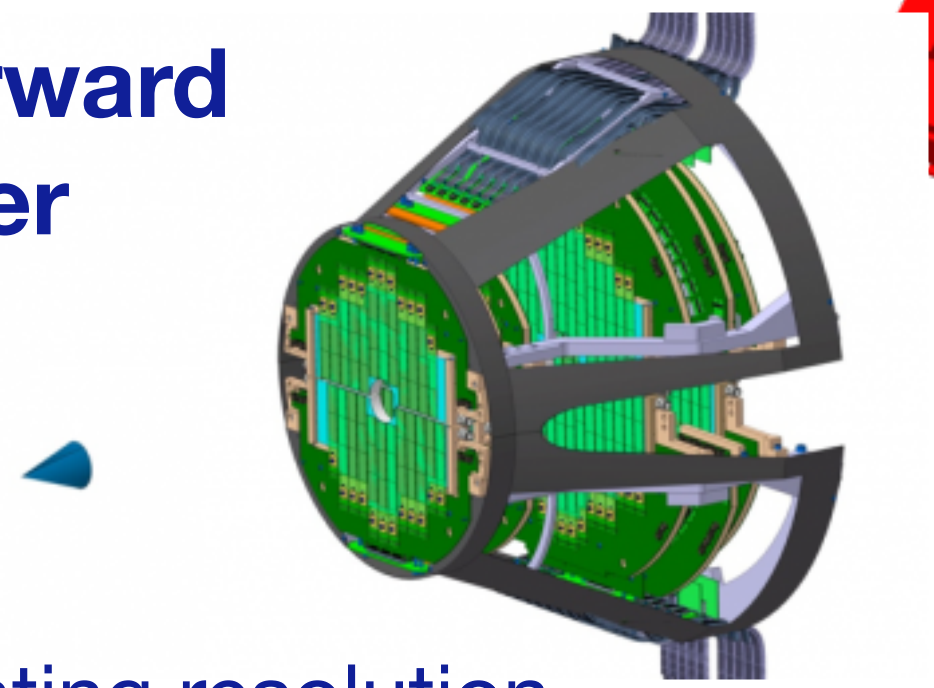


Full pixel detector
Improved read-out rate,
spatial resolution

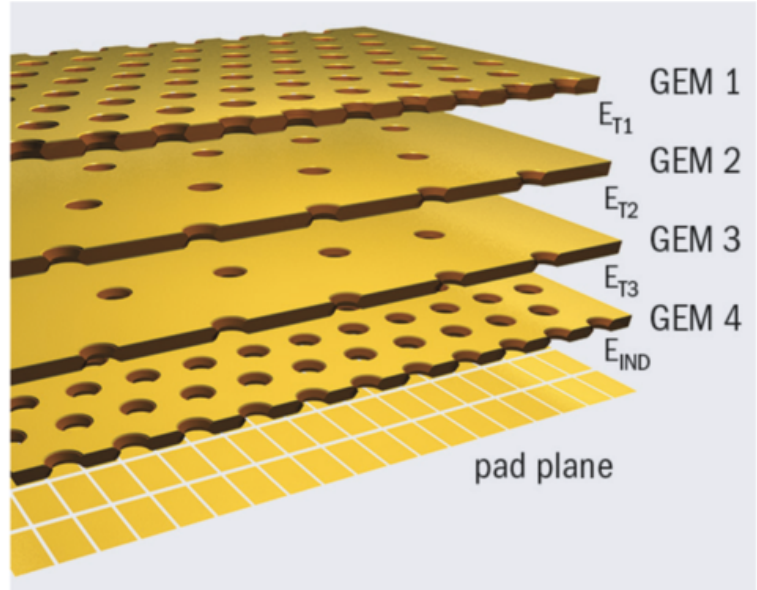
ALICE upgrades



Muon Forward Tracker



Improved pointing resolution
for muons



TPC: GEM readout

Continuous readout
Higher rates

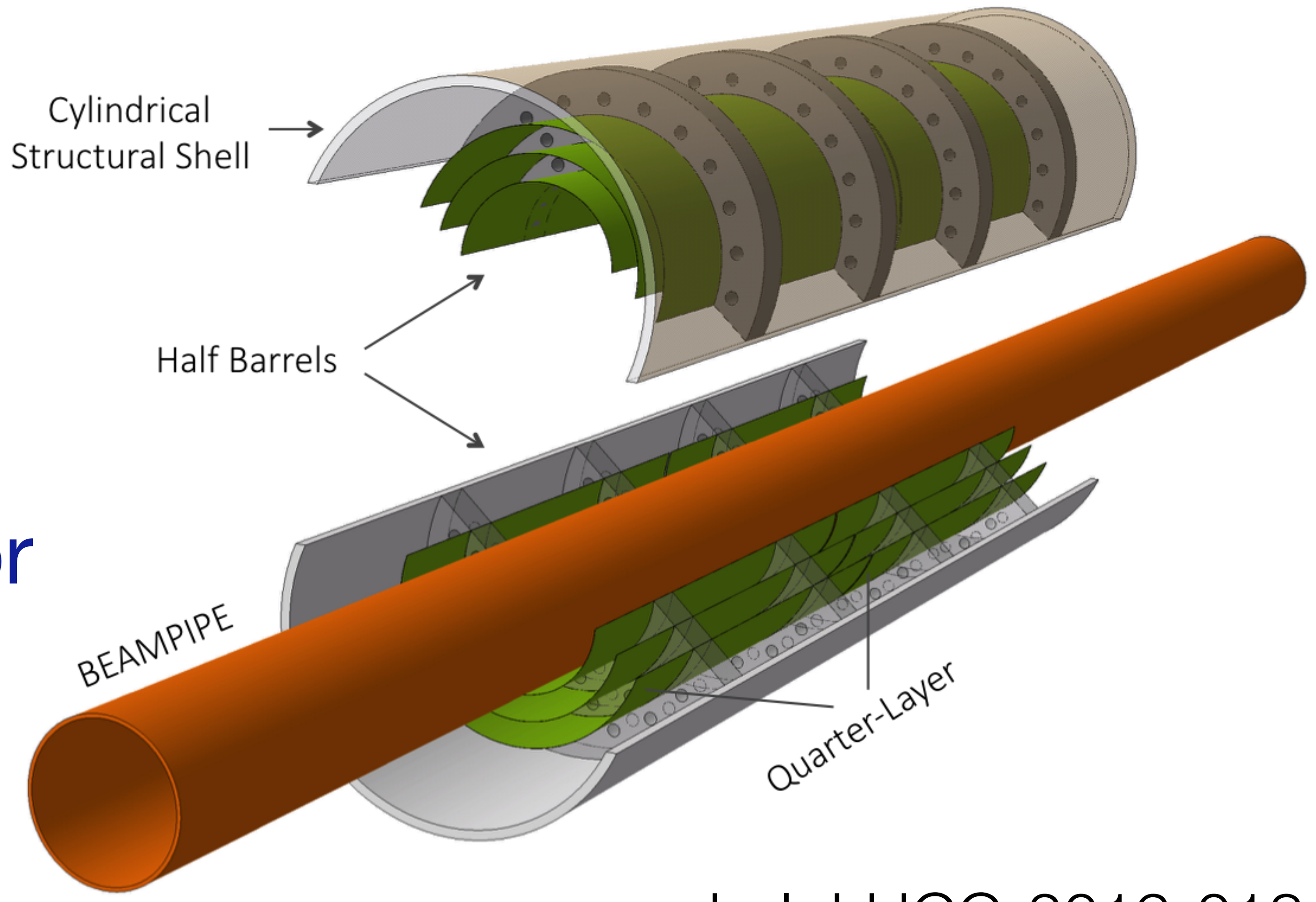
Upgraded readout and online processing

Run 3 and 4: higher luminosity; collect 13 nb^{-1} Pb—Pb:
~ 10x improvement over run 2; factor 50-100x for minimum bias in ALICE

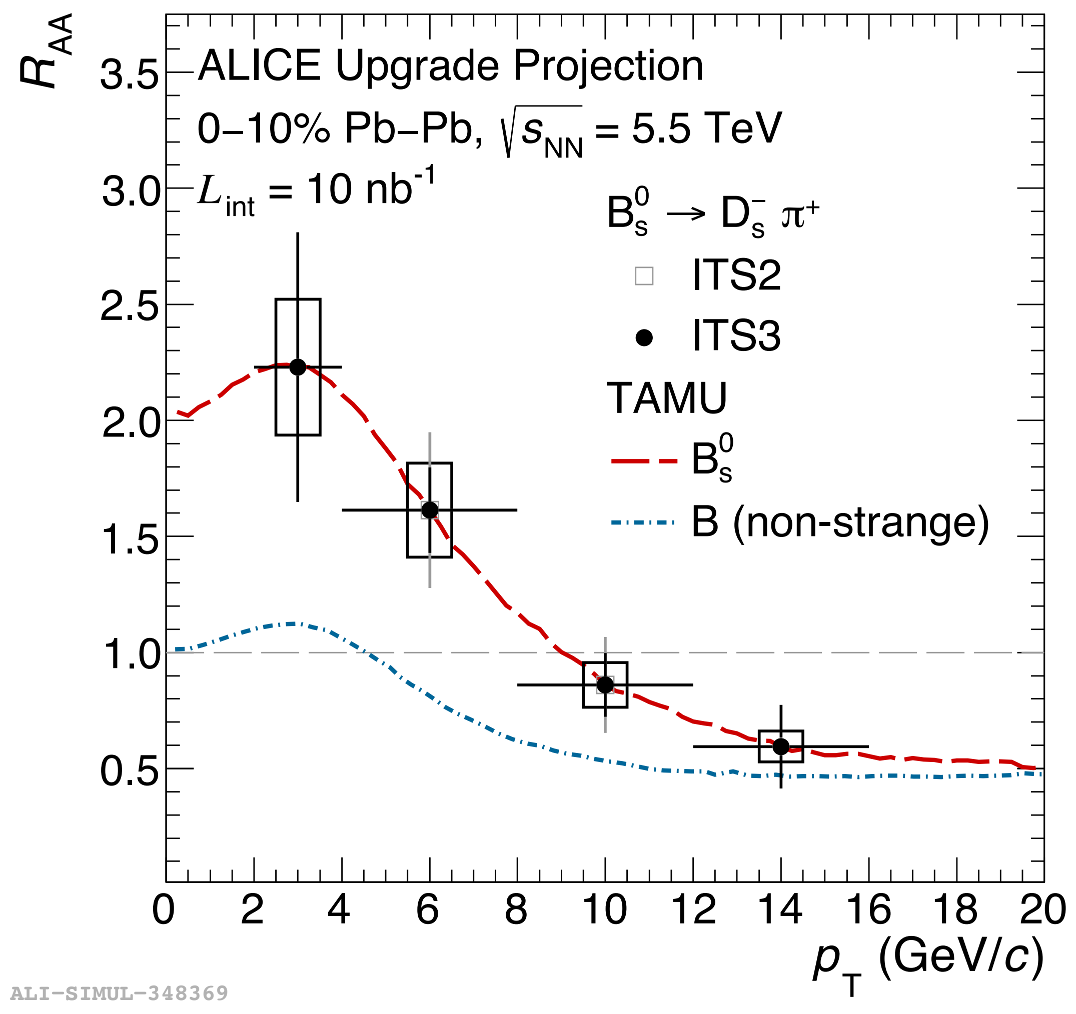
Future upgrades: Long Shutdown 3 (2025)

ALICE ITS3: Ultra-thin tracker

- Lower background for di-electrons
- Improved pointing resolution for heavy flavor



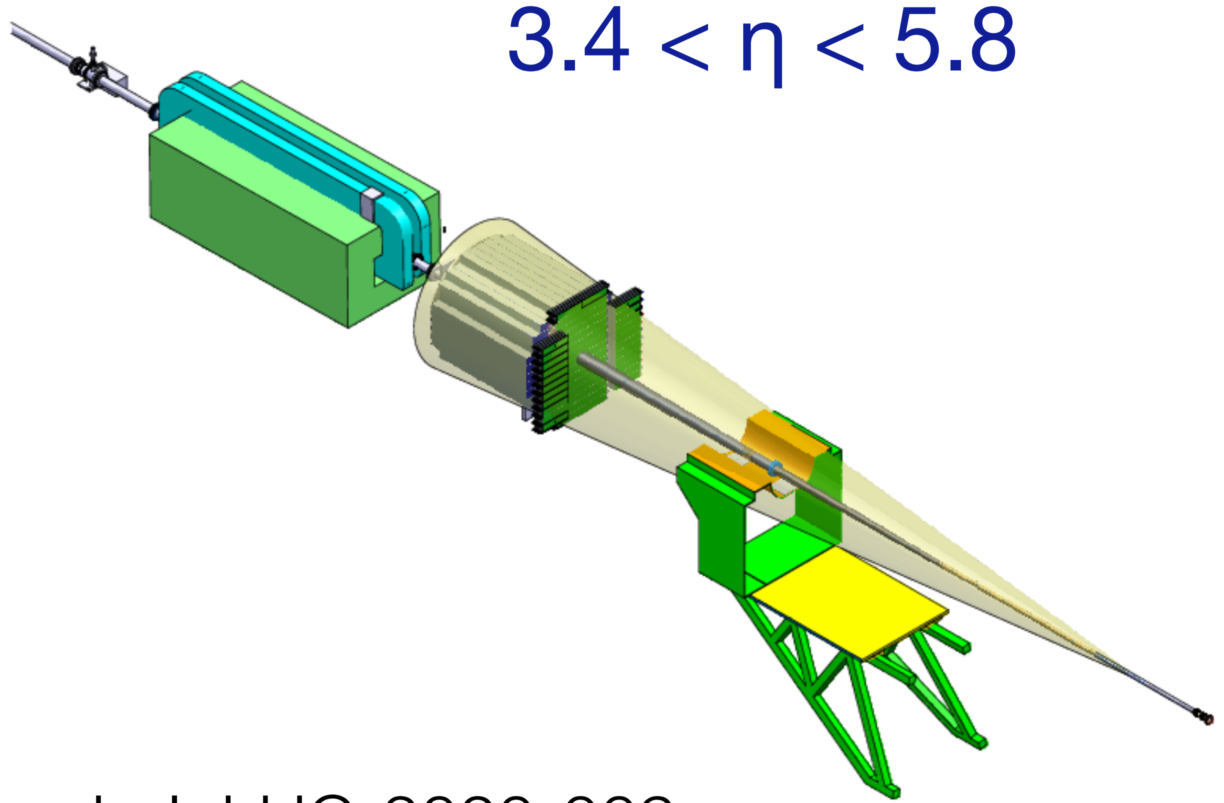
LoI: LHCC-2019-018



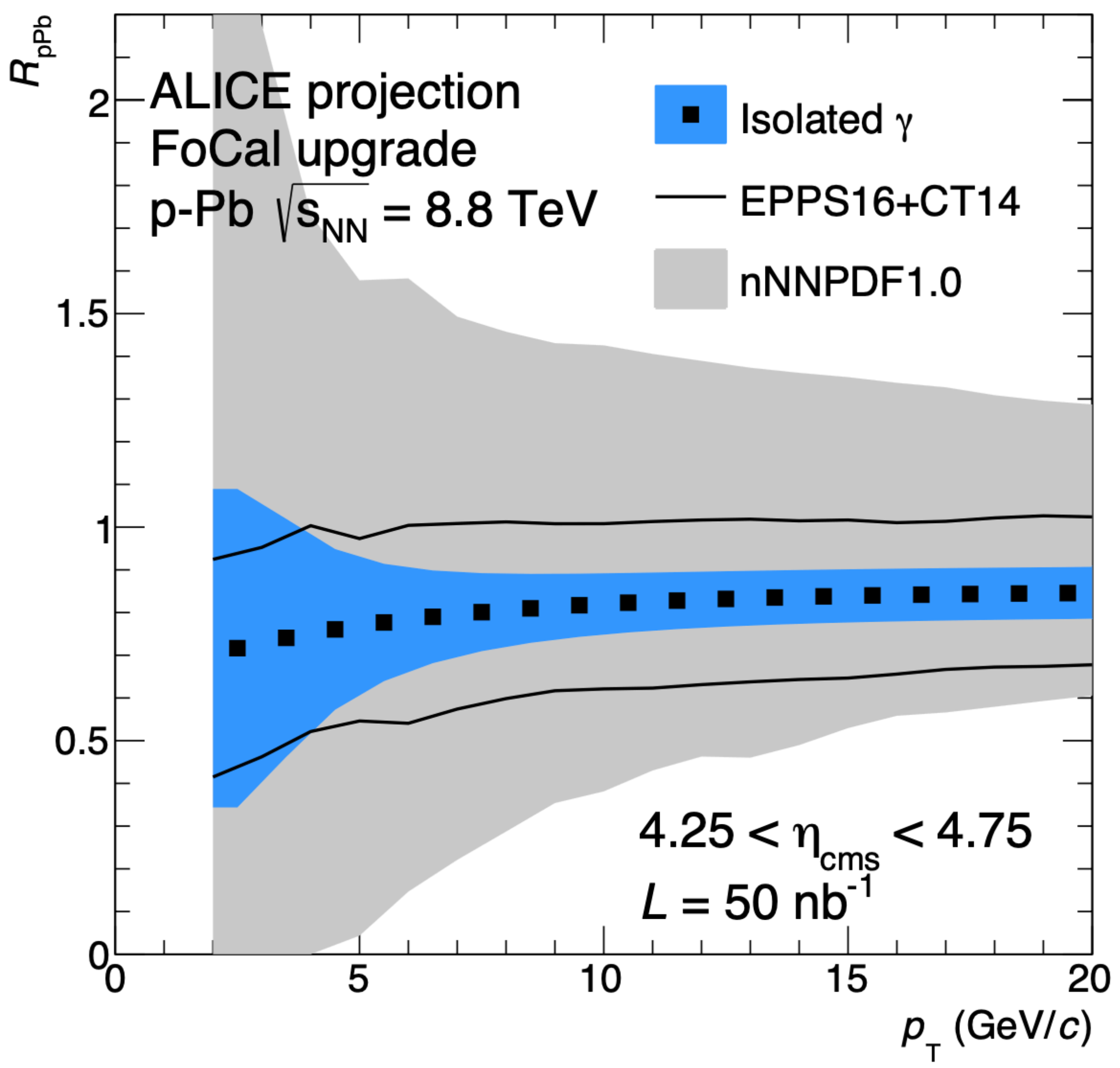
ALICE Forward Calorimeter

- Very high granularity γ/π^0 separation
- Access to small-x gluon density; Color Glass Condensate effects

3.4 < η < 5.8



LoI: LHC-2020-009



ATLAS+CMS: various upgrades for HL-LHC

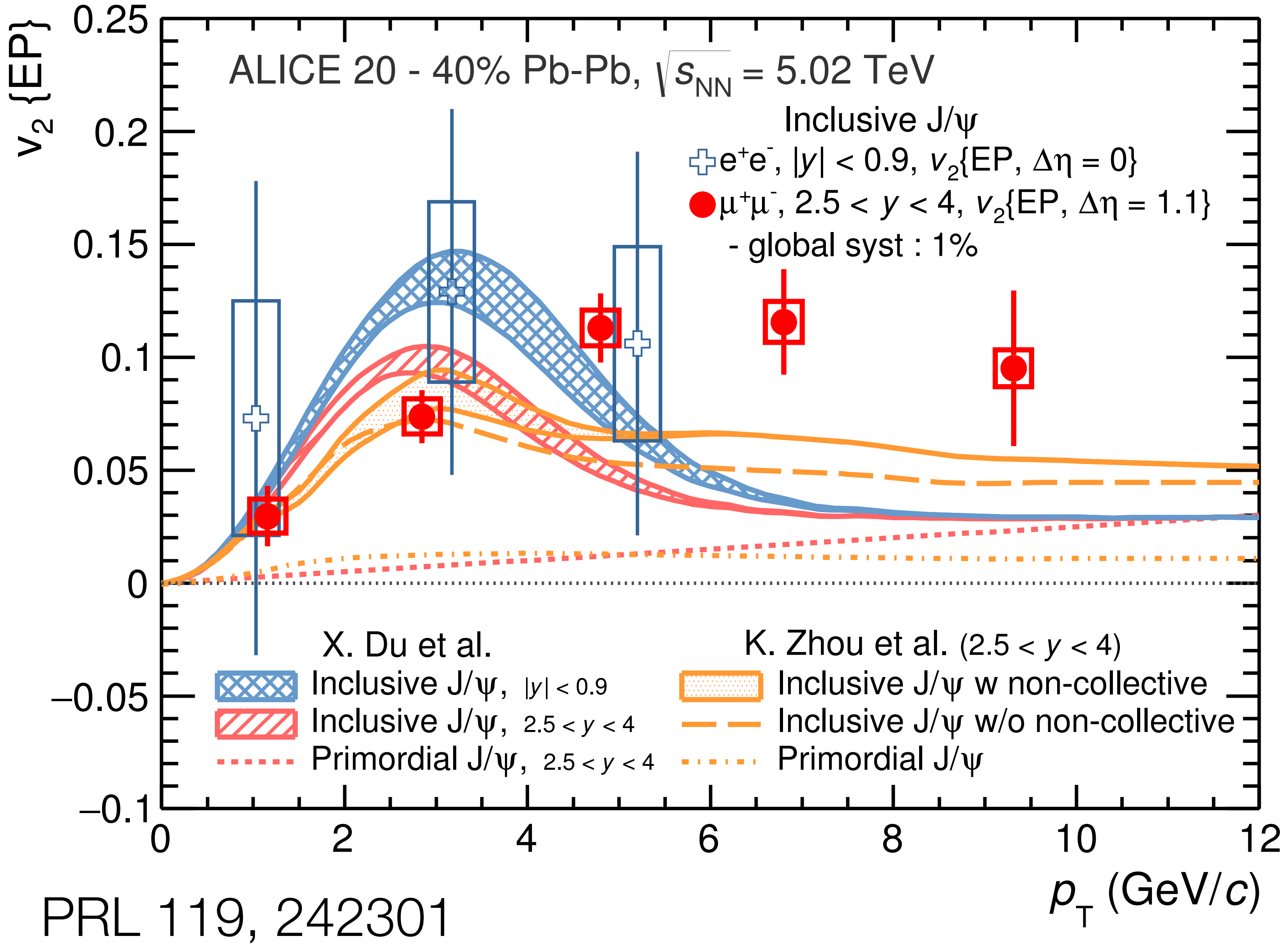
Summary/conclusions

- Heavy-ion collisions explore and measure properties of QGP matter
  - Viscosity
  - Transport coefficients for high-p_T partons and heavy quarks
  - Theoretical multi-observable analyses becoming available:
    test theoretical understanding while determining key parameters
  - Azimuthal anisotropy in small systems: explore ‘few-collision’ limit
- Jets in heavy ion collisions: dynamics of parton energy loss
  mass, energy dependence, opening angle/resolution scales
- Hadronisation: charm baryon formation not fully understood
- Laboratory for hadron interaction measurements

Thank you for your attention!

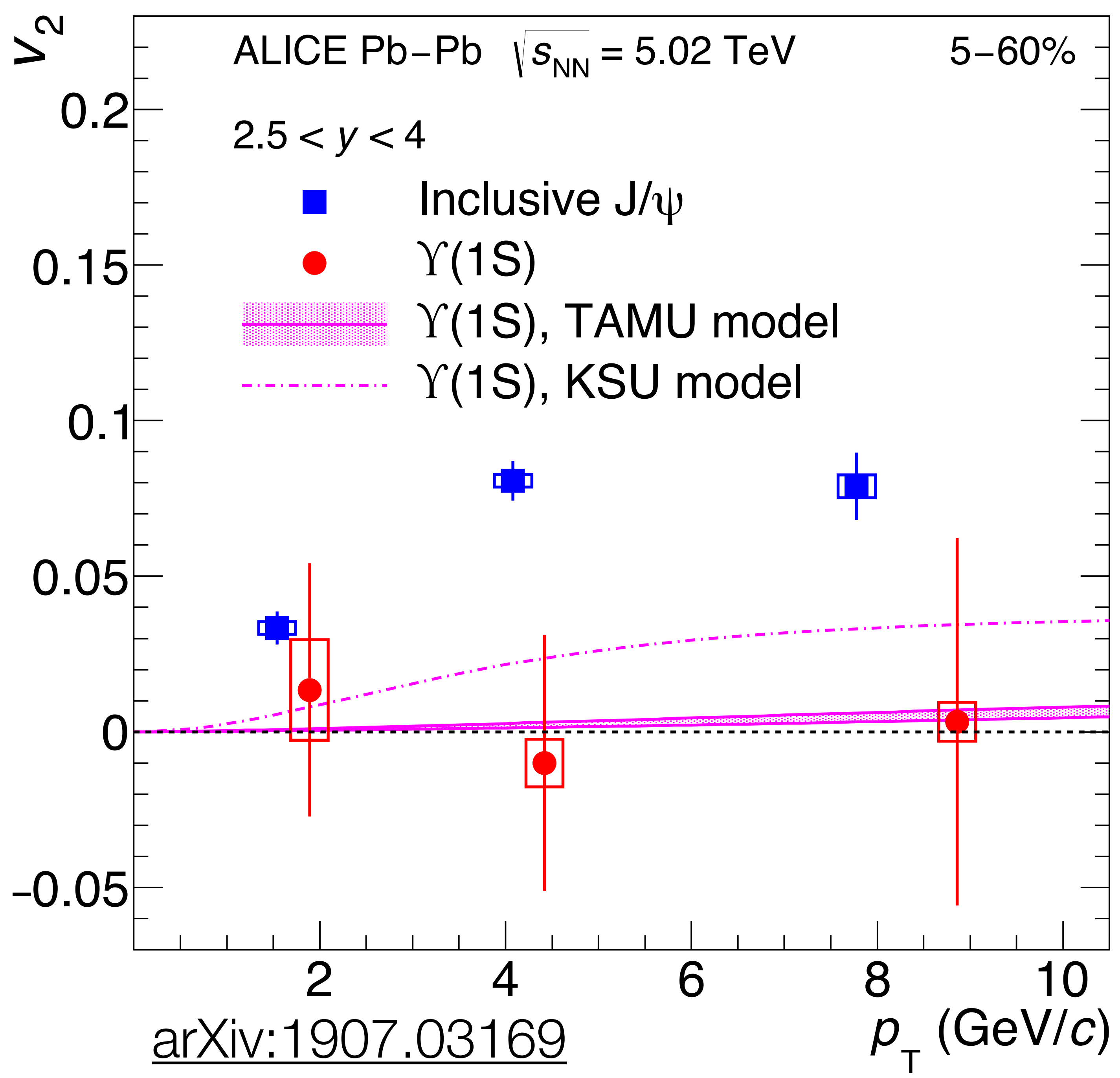
J/ψ and Upsilon v_2

J/ψ v_2



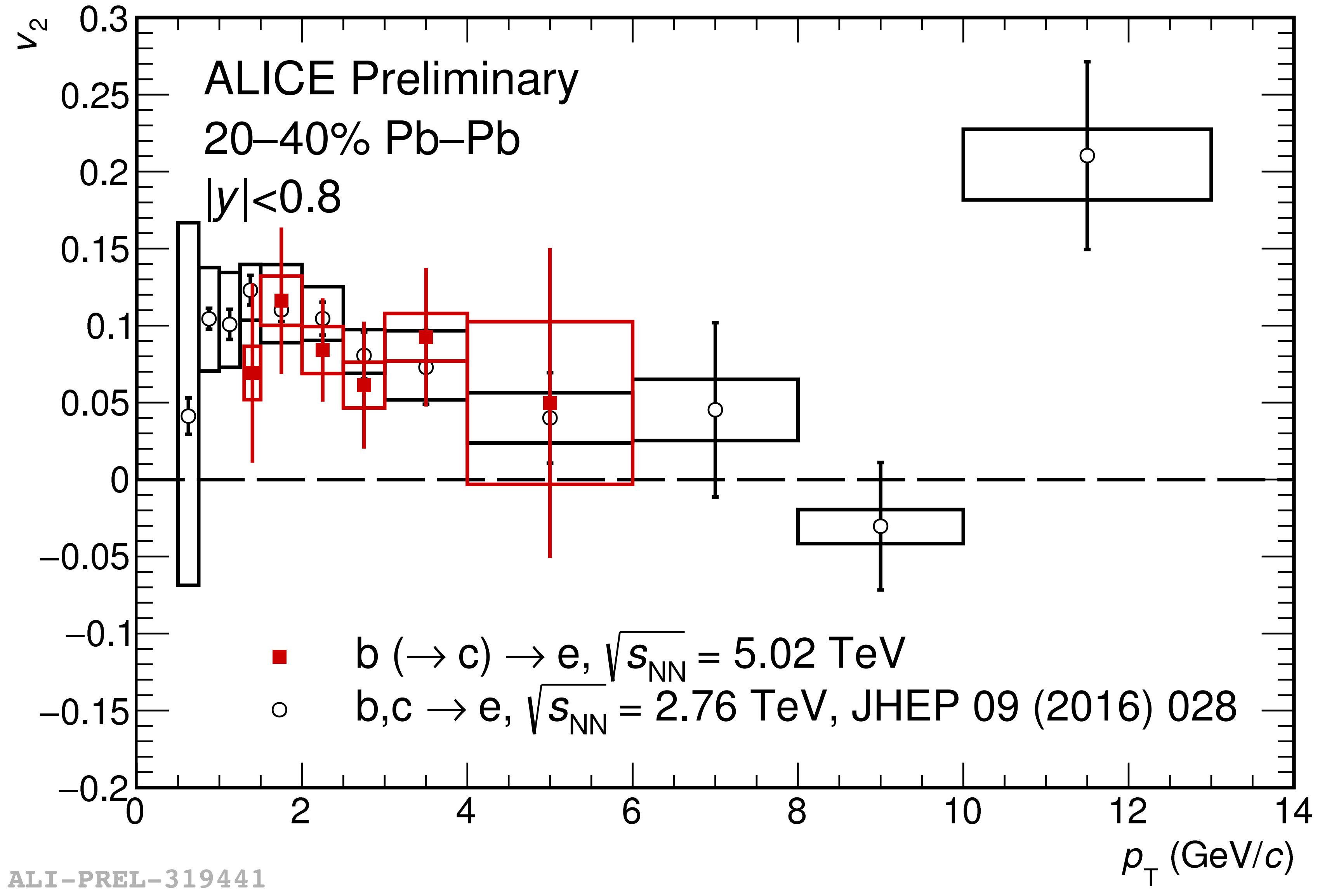
PRL 119, 242301

ϒ v_2



arXiv:1907.03169

Electrons from charm, beauty decays



Mechanism:

- Low p_T: charm quark energy loss and recombination
- High p_T: radiative energy loss of di-quark?

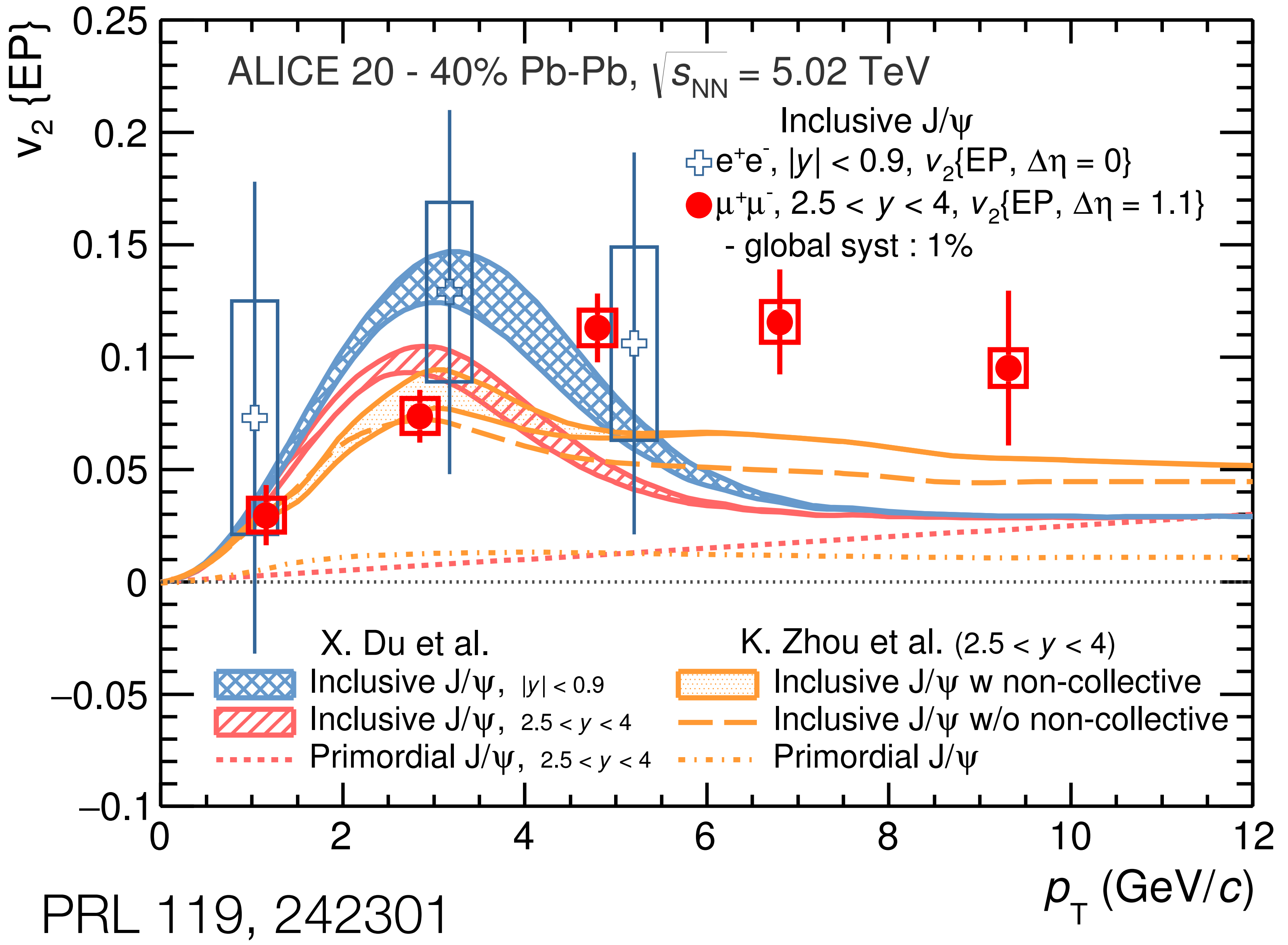
Upsilon v_2 smaller than J/ψ

No recombination

Open charm and beauty: similar v_2

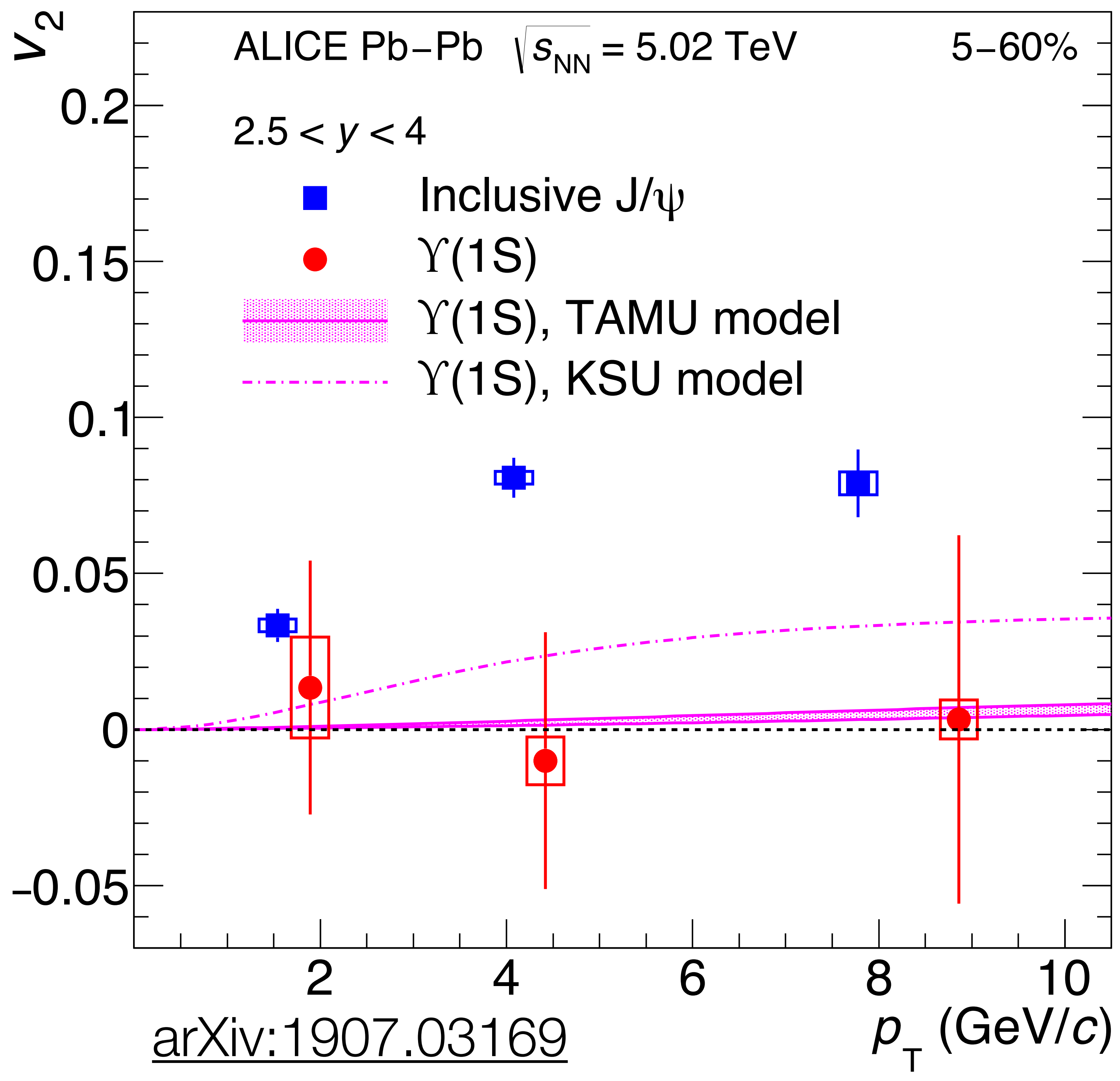
J/ψ and Upsilon v_2

J/ψ v_2



PRL 119, 242301

ϒ v_2



arXiv:1907.03169

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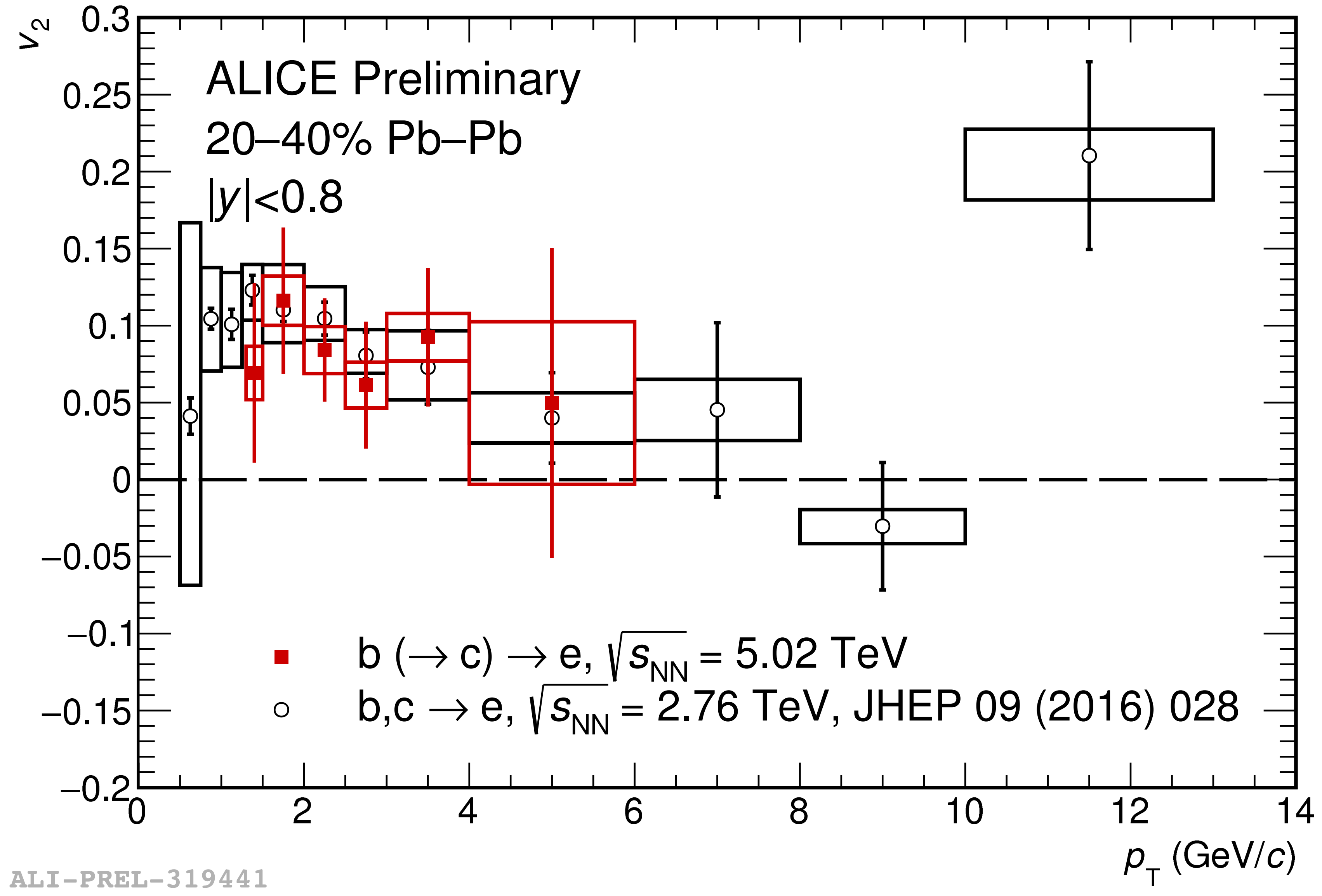

Mechanism:

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Upsilon v_2 smaller than J/ψ

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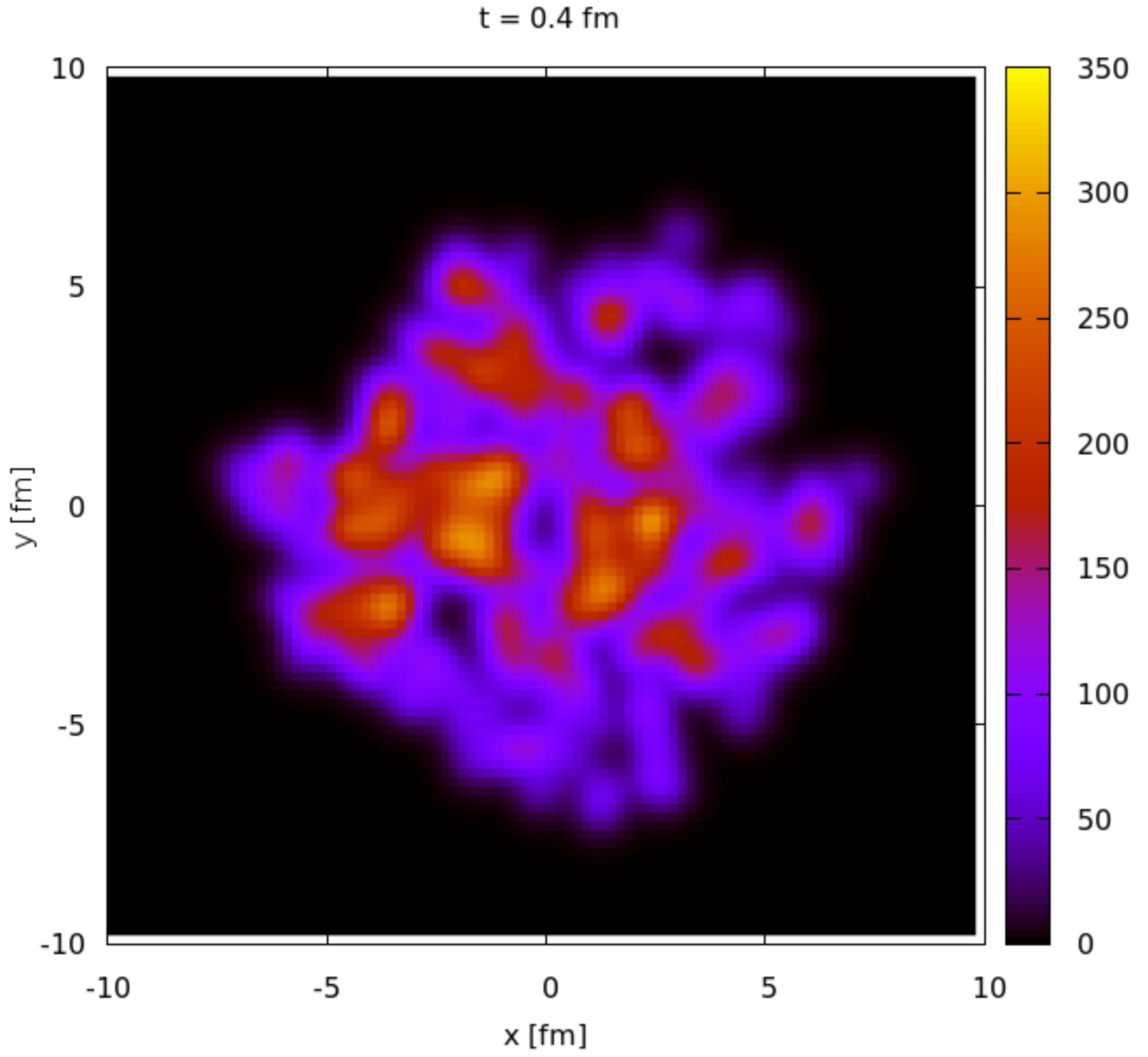
Open charm and beauty: similar v_2

Suggests different mechanism (contributions) for open and hidden charm interactions

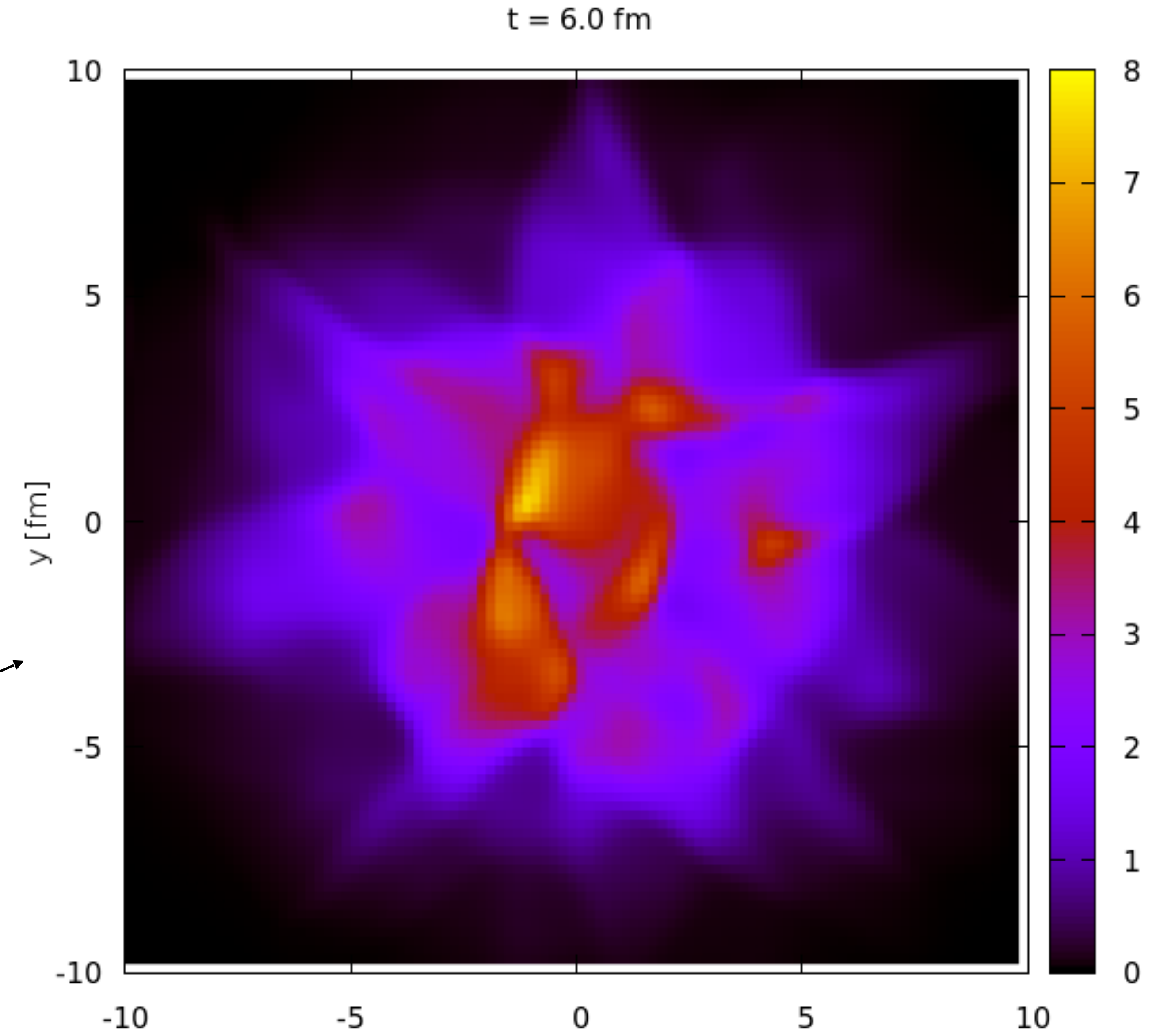
Higher harmonics and viscosity

Schenke and Jeon, Phys.Rev.Lett.106:042301

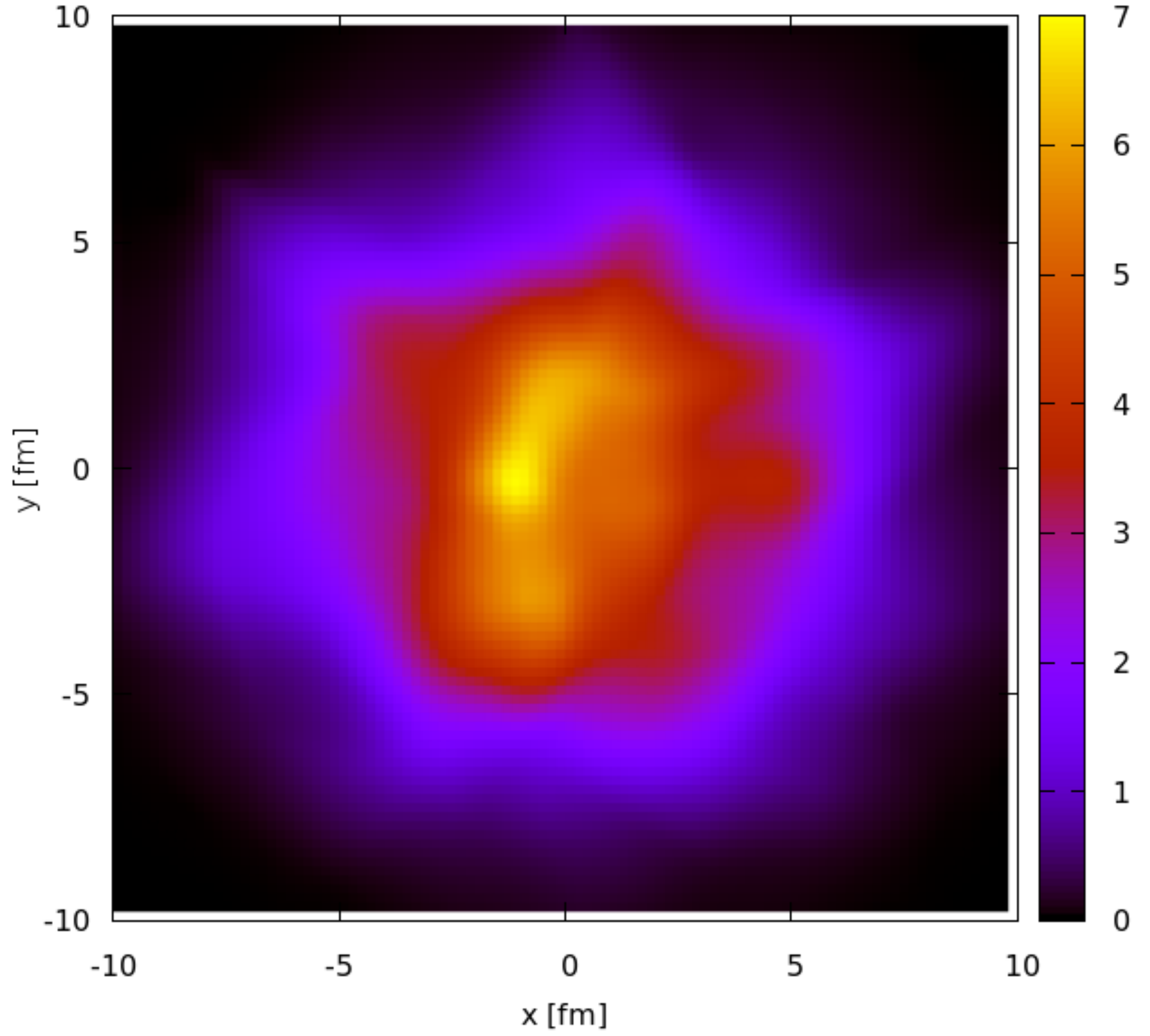
In general: initial state is ‘lumpy’



$\eta/s = 0$



$\eta/s = 0.16$

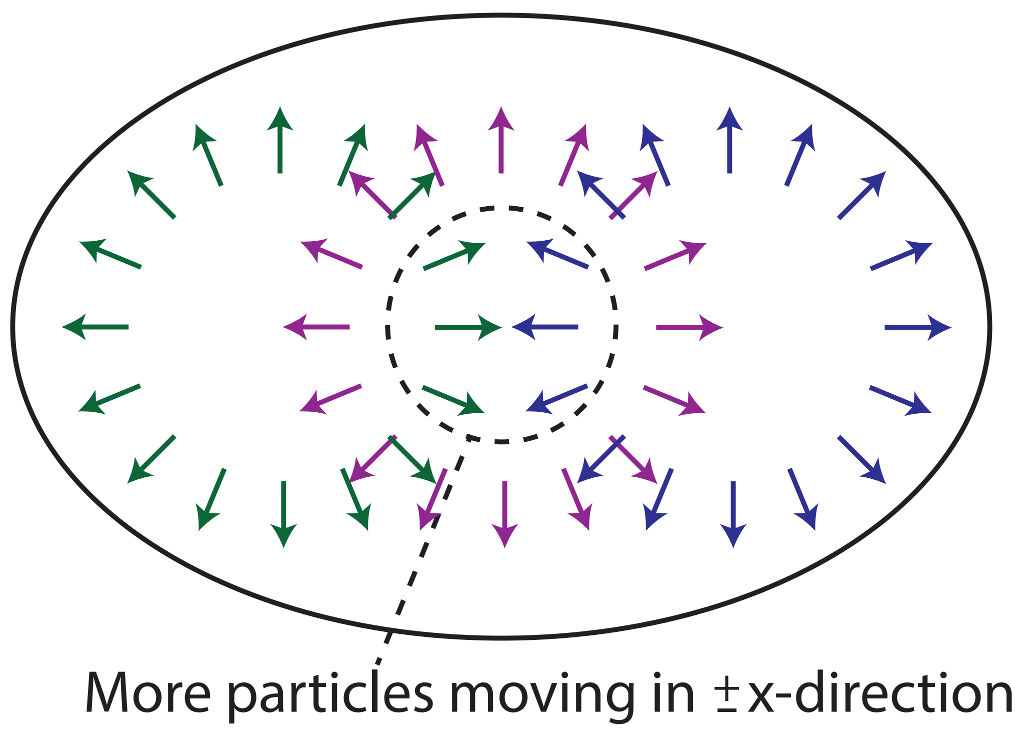


How much of this is visible in the final state, depends on shear viscosity η

and a number of other model parameters

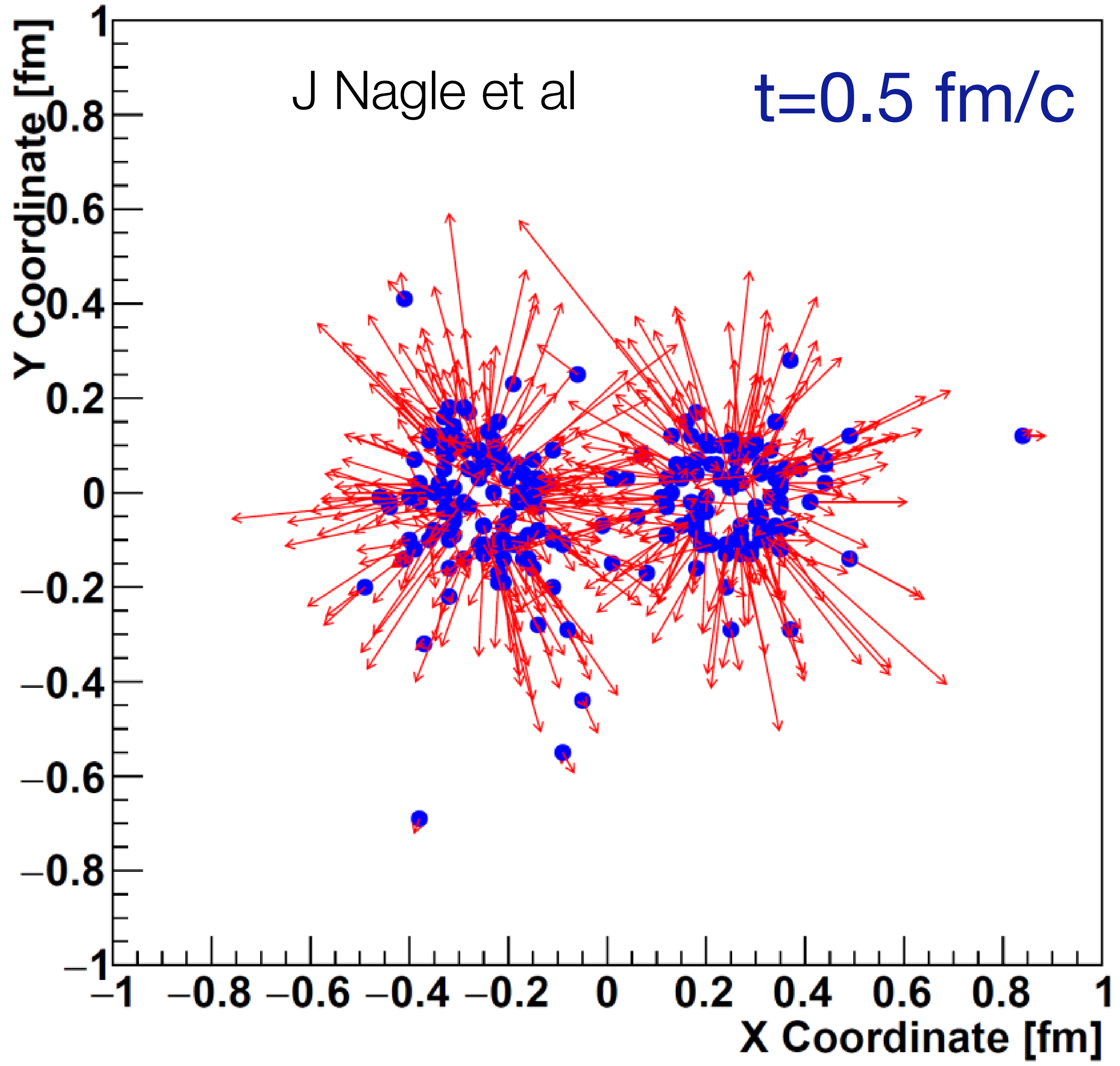
Flow without a liquid

Can you have flow with a few scatterings?
'anisotropic escape'



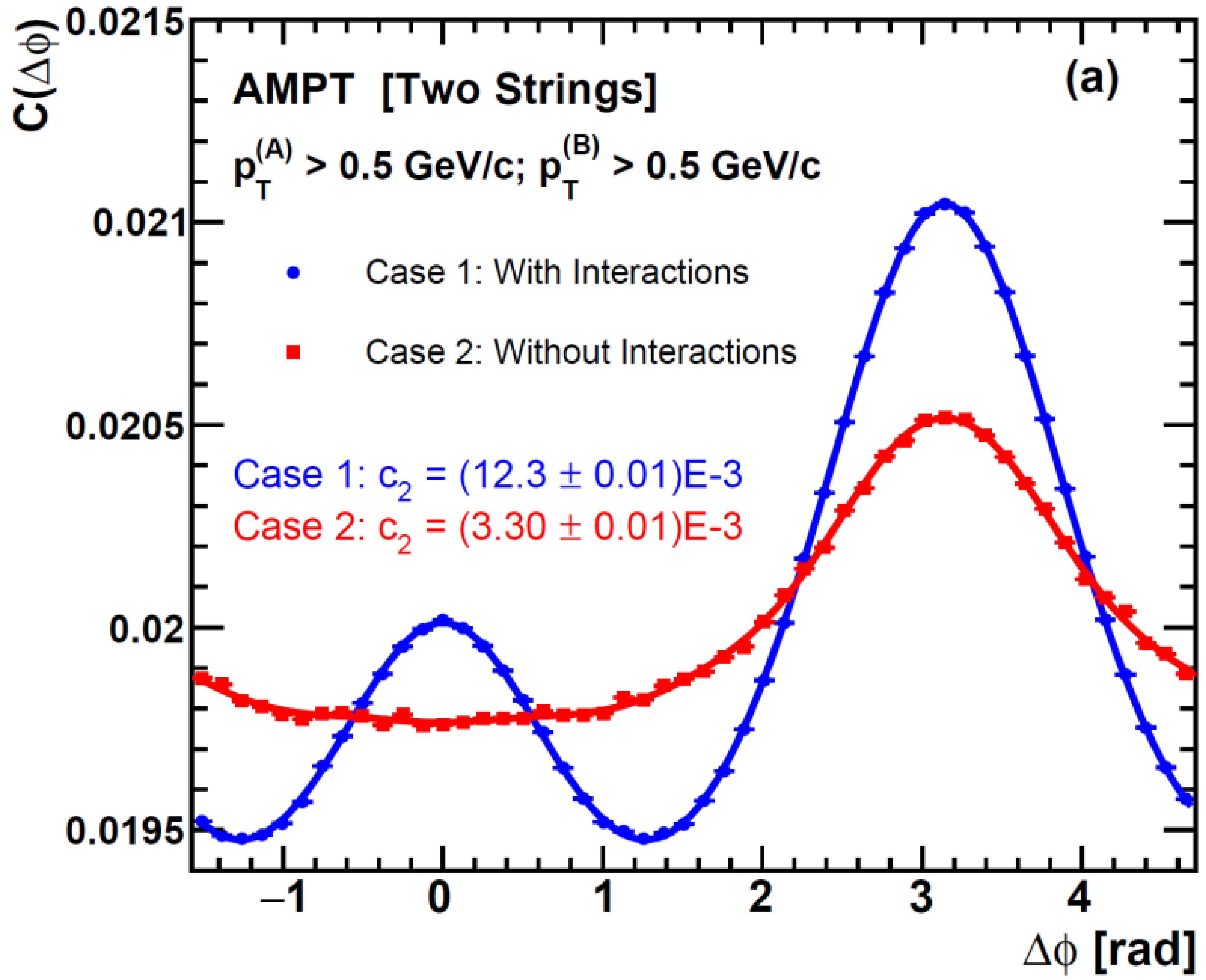
Kurkela, Wiedemann, Wu, arXiv:1803.02072

Two parallel strings



Formation time is important

Two-particle correlations



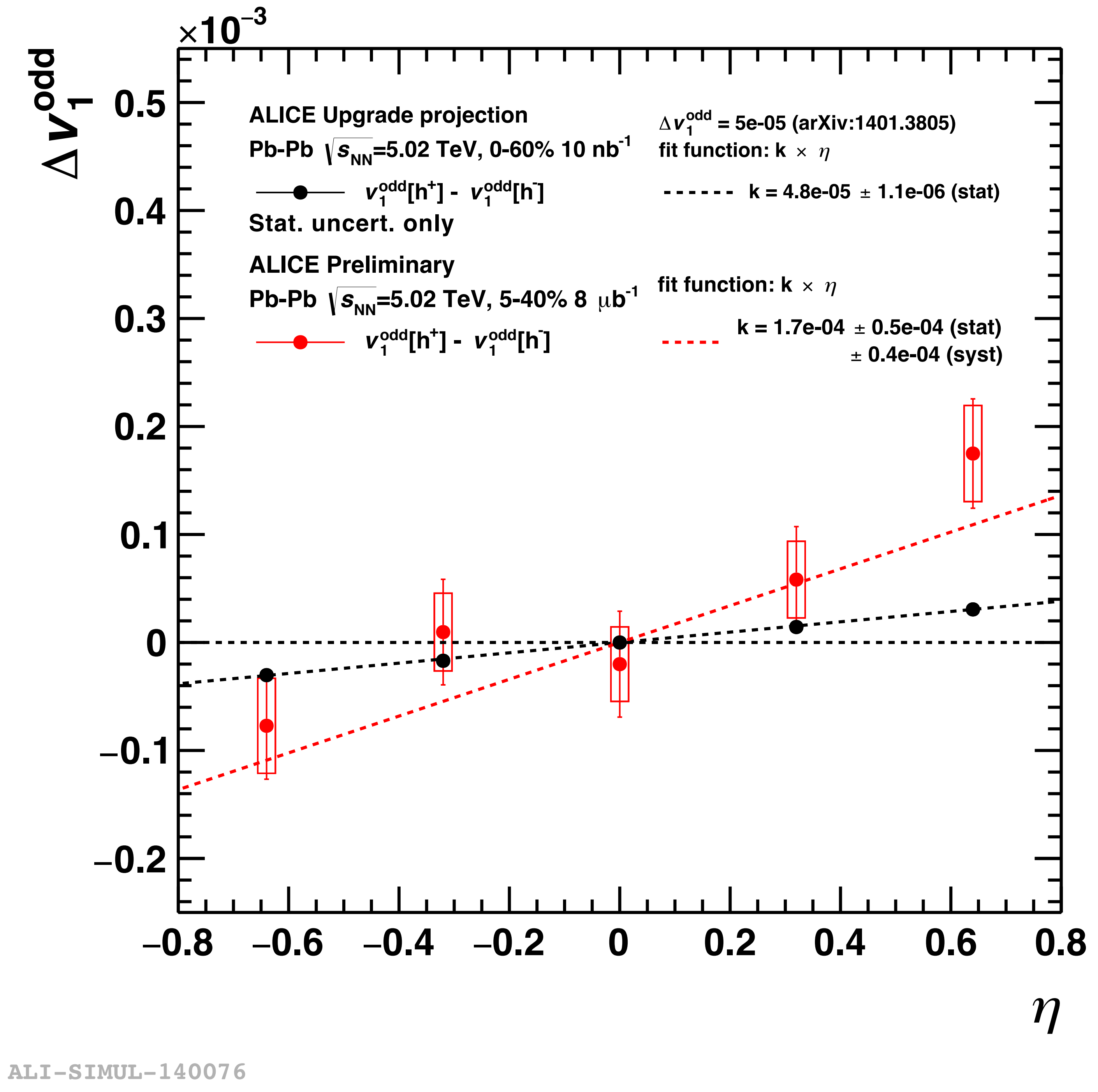
Shows a clear signal
in a transport calculation

ALICE upgrade goals and performance

ALICE-PUBLIC-2019-001

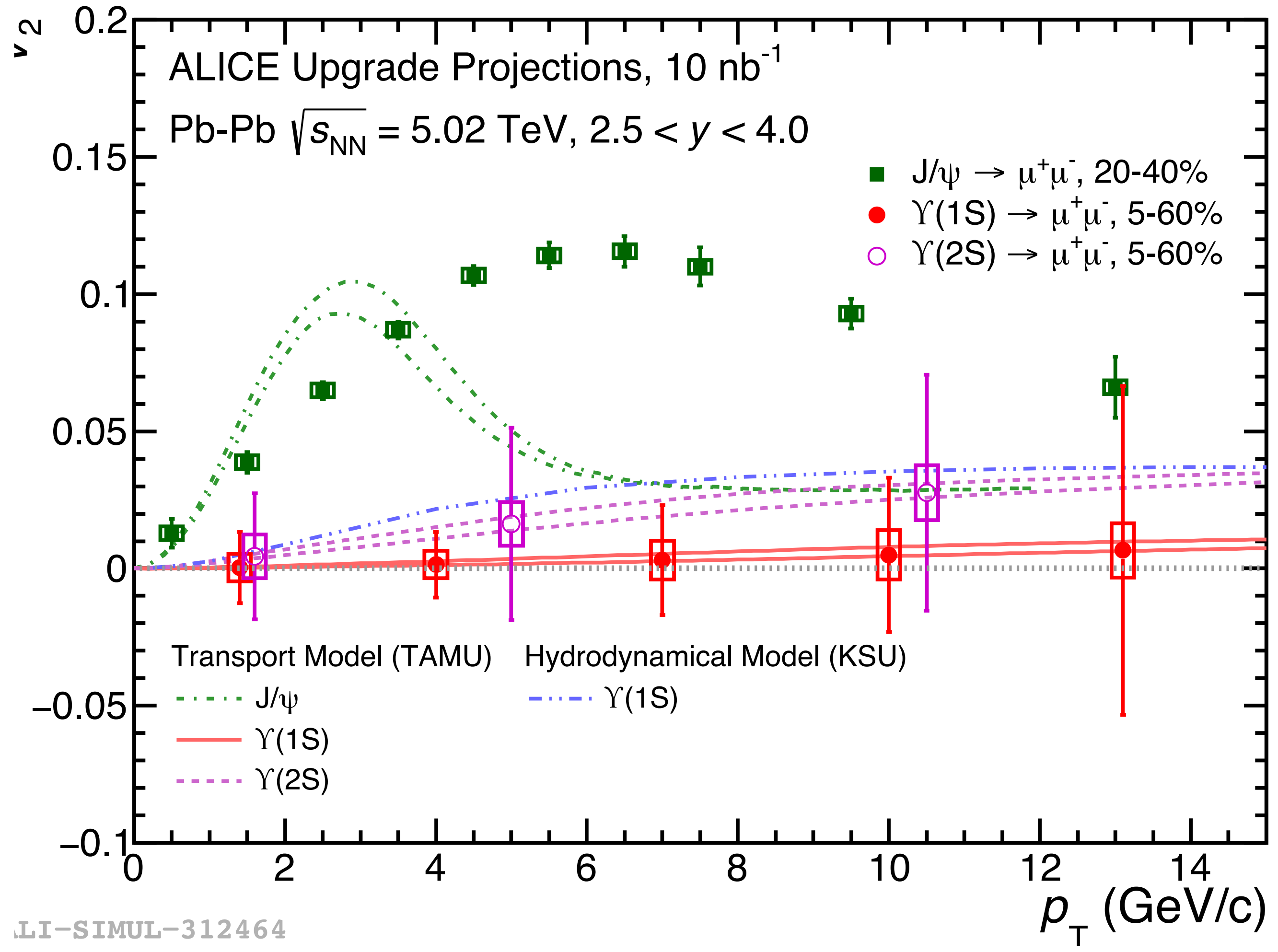
HL-LHC WG5 report

Charge dependent v_1

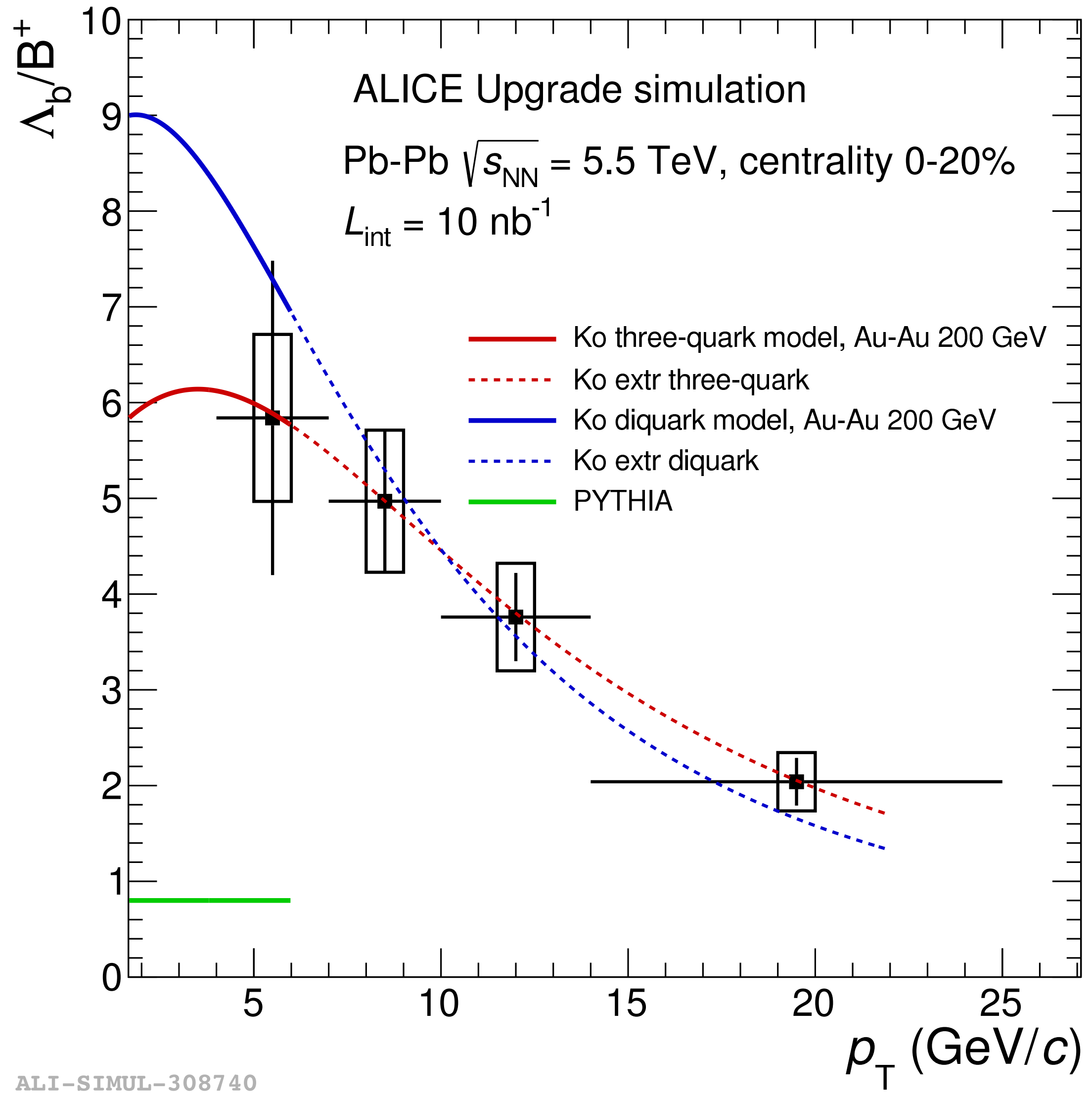


Initial state magnetic fields

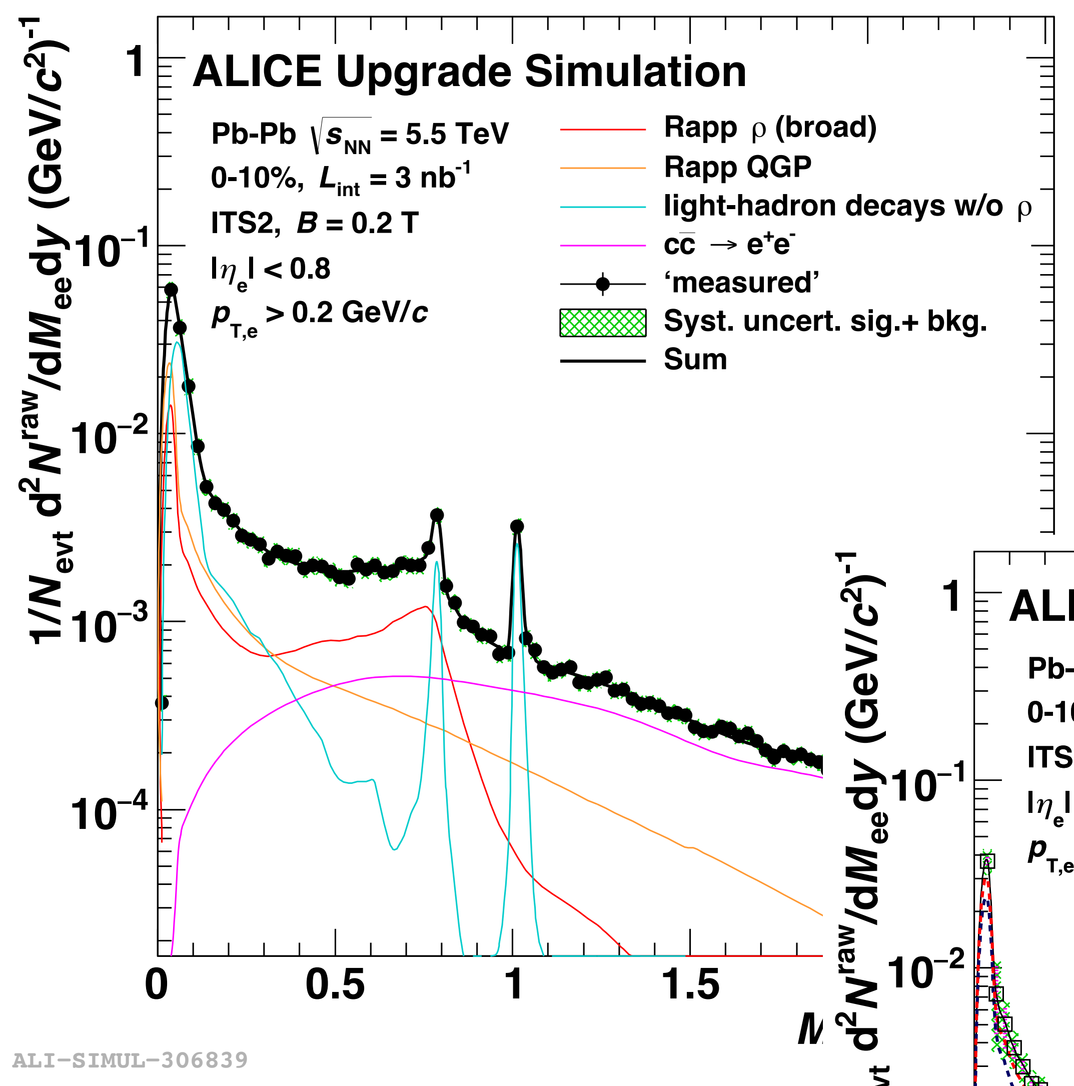
J/ψ and ϒ v_2

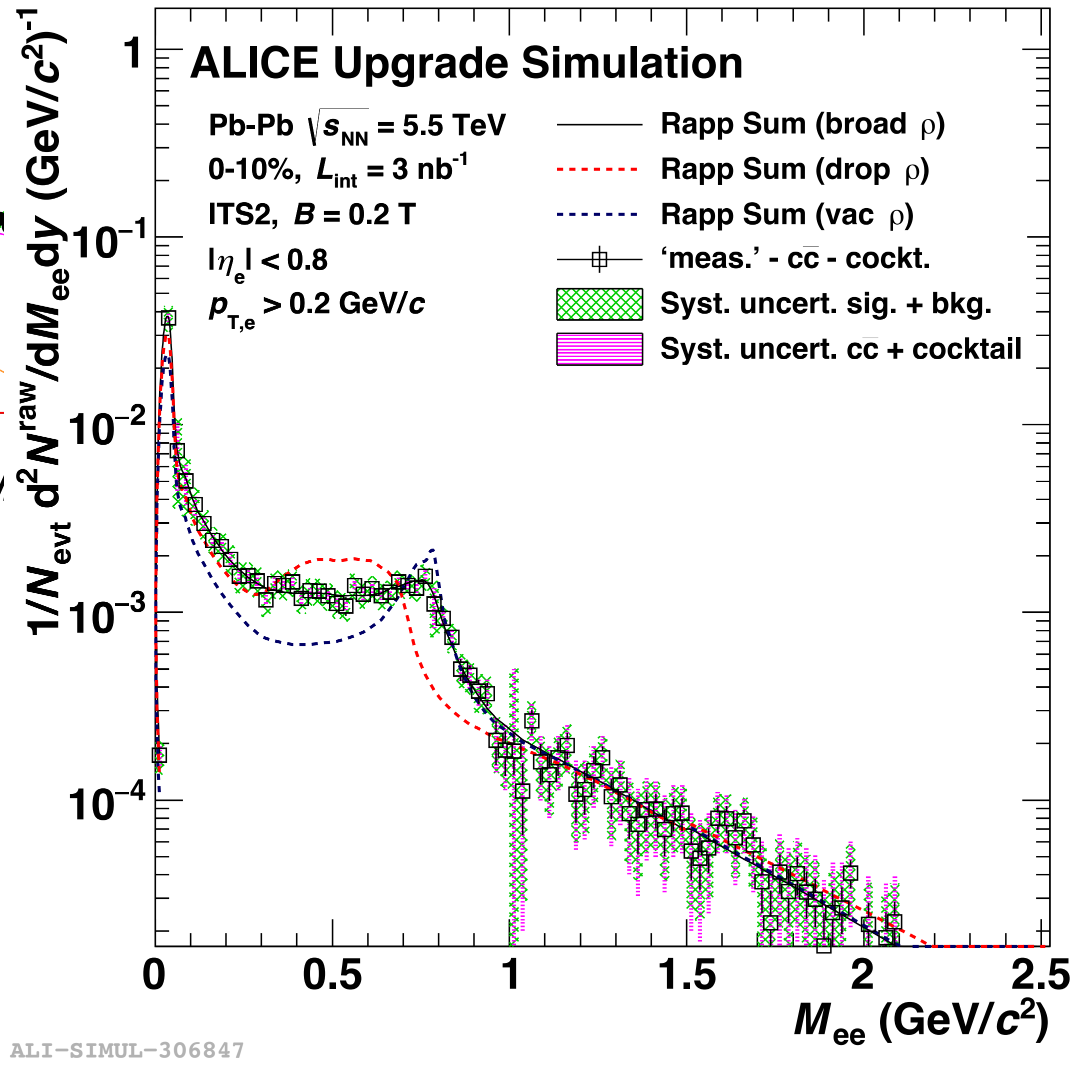


Λ_b and B mesons



Dileptons



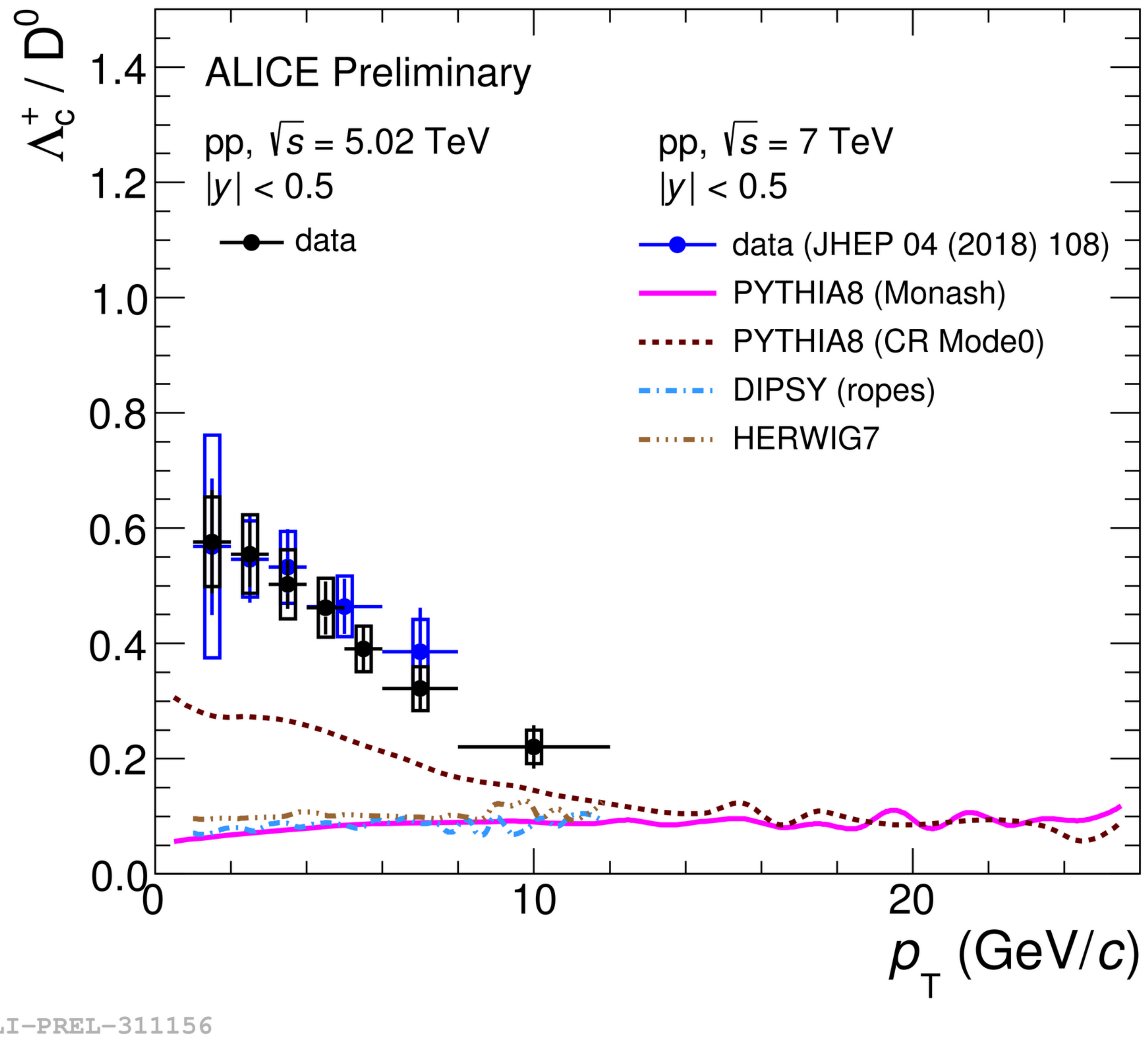


Thermal radiation

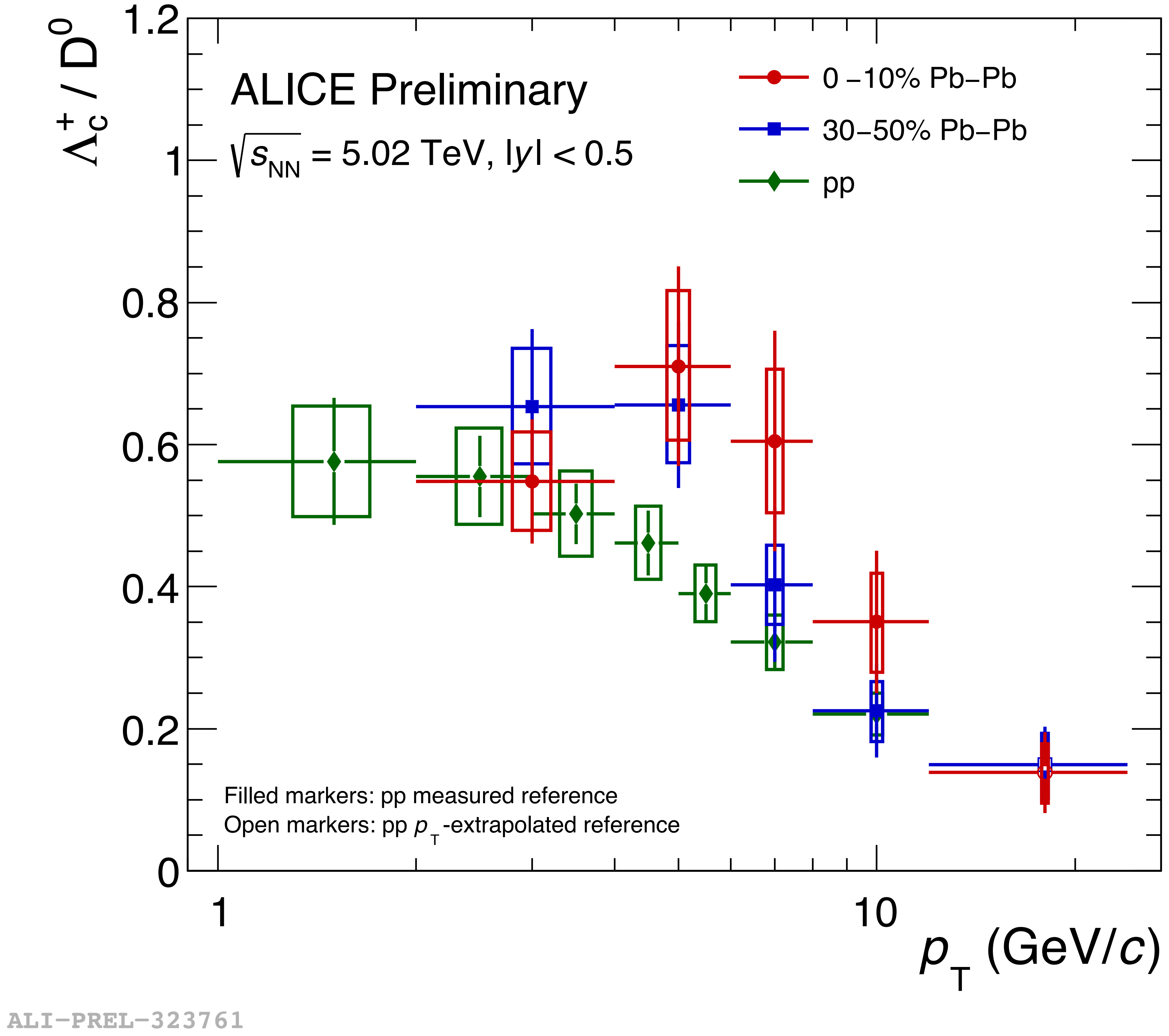
…and much more…

Λ_c production in pp and Pb-Pb

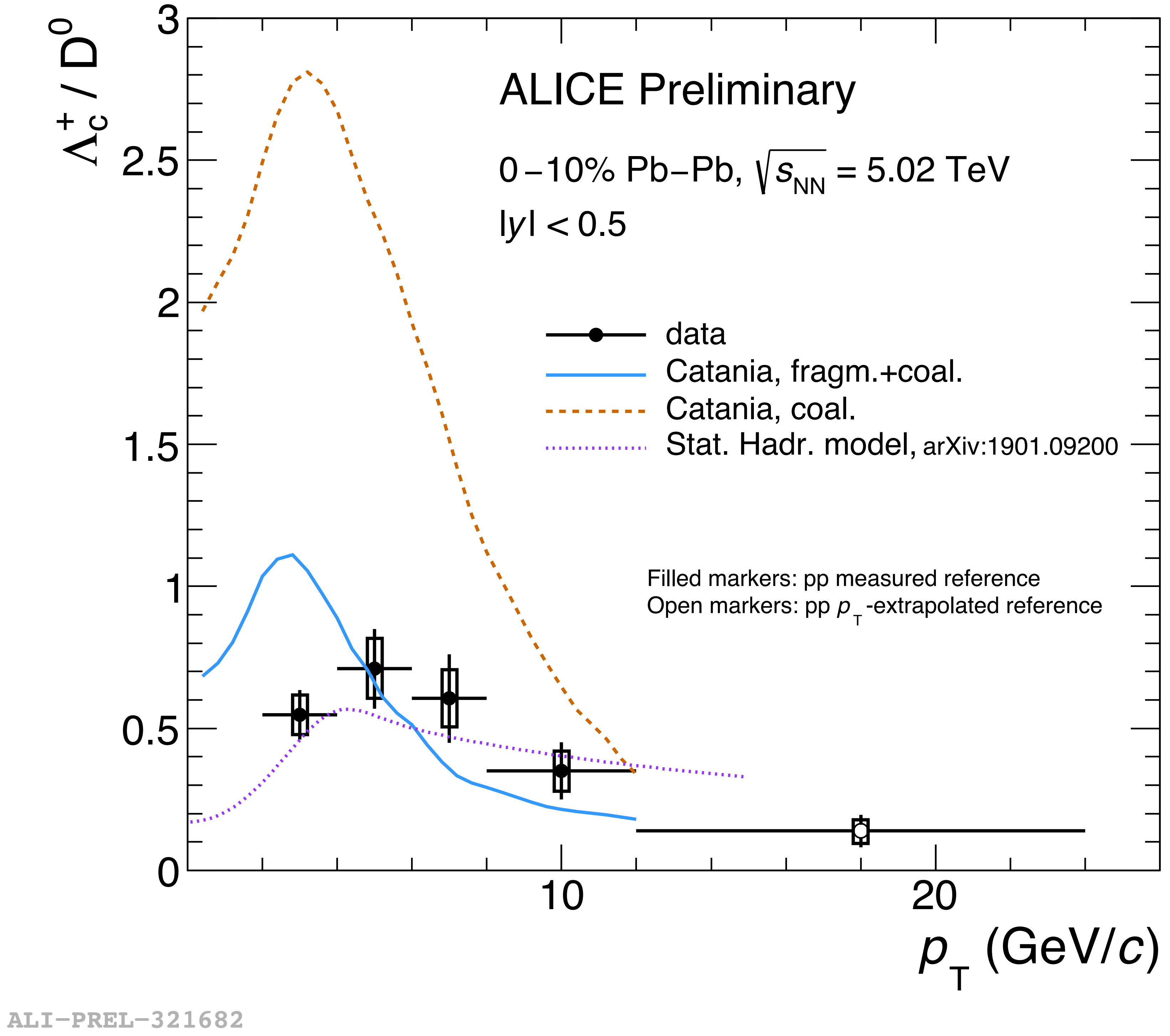
Λ_c/D in pp



Λ_c/D in pp, Pb-Pb



Λ_c/D in Pb-Pb



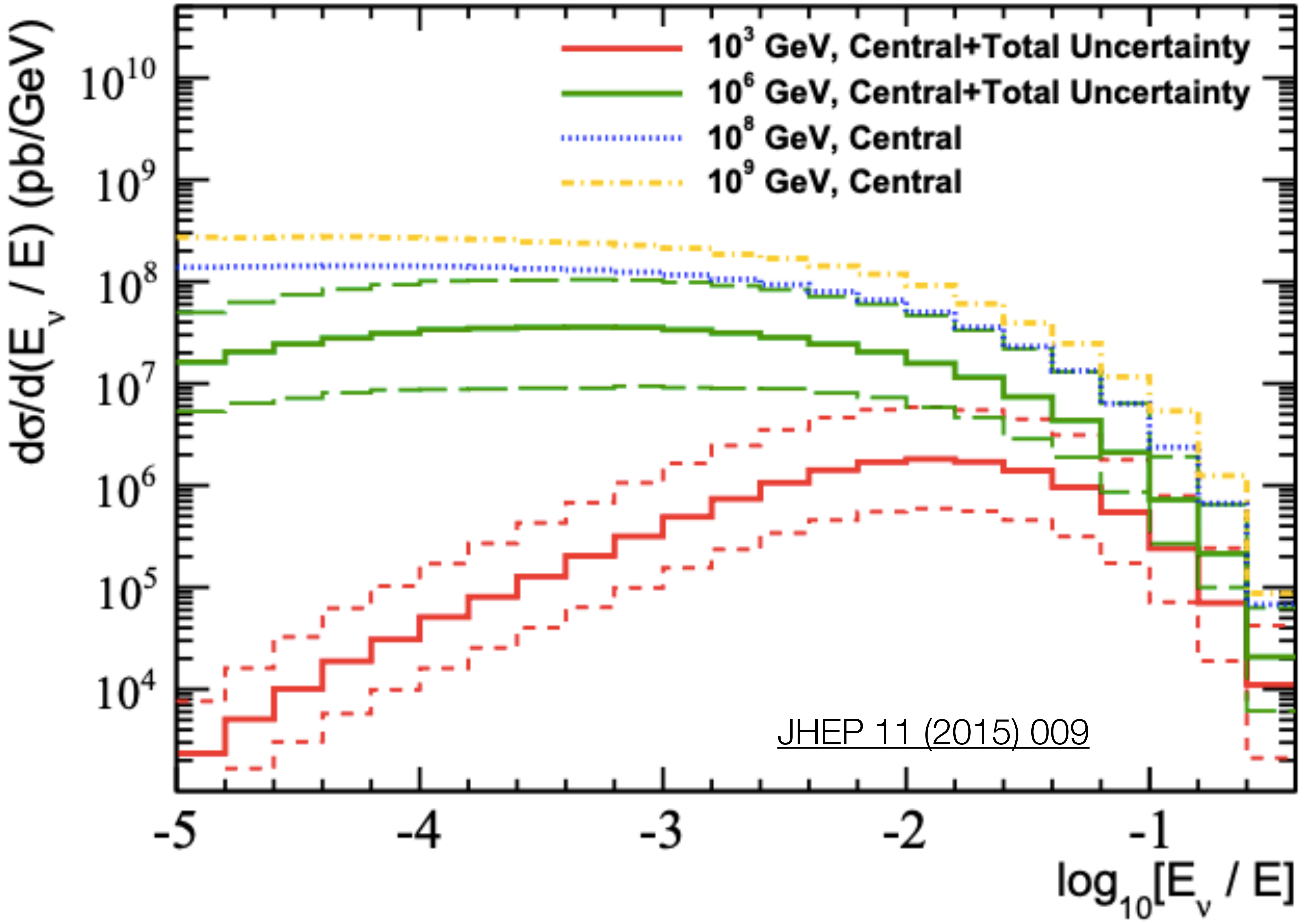
Λ_c/D^0 in pp significantly larger than expected from e^+e^-

New result: Λ_c in Pb-Pb; Λ_c/D similar or slightly larger than in pp

Does hadronisation by recombination play a role? Or 'just' fragmentation?

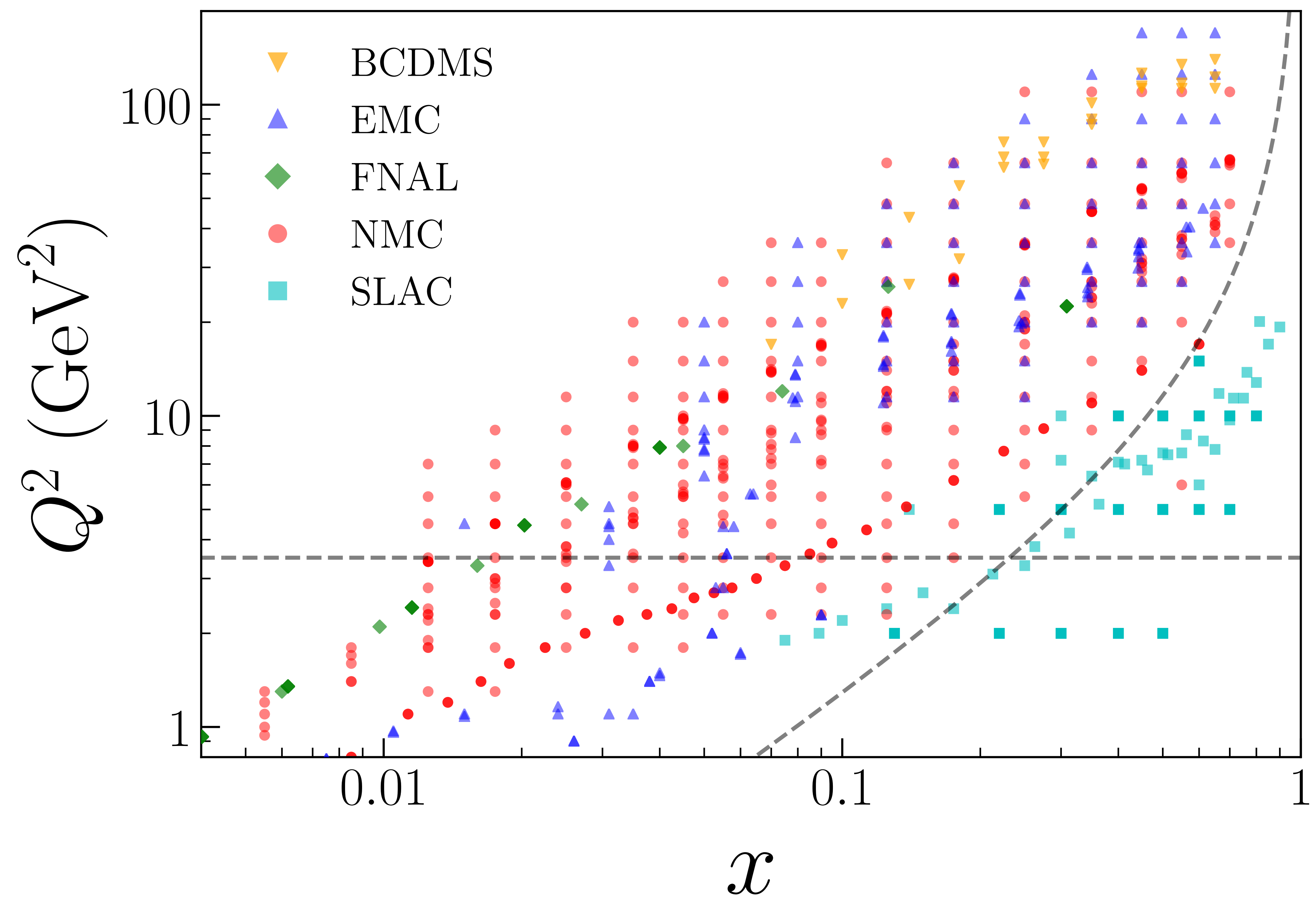
Connection to cosmic rays: nuclear PDFs

Impact of nuclear PDF uncertainty on (atmospheric) neutrino production



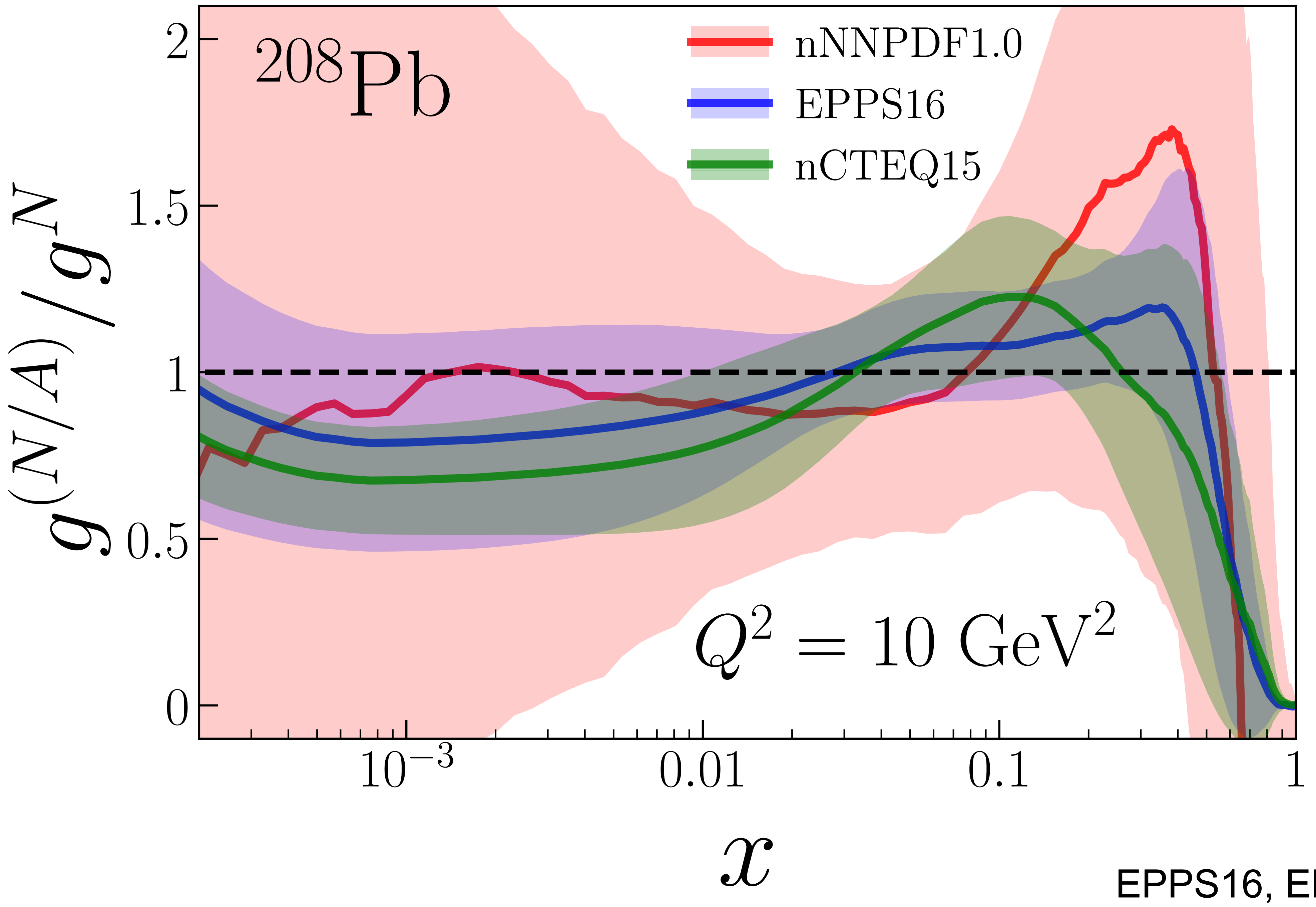
Uncertainties in Nuclear PDFs

Kinematic range of measurements



Kalek, Rojo and Ethier, EPJC 79, 471

Ratio of gluon density in nuclei to protons



EPPS16, EPJC 77, 163

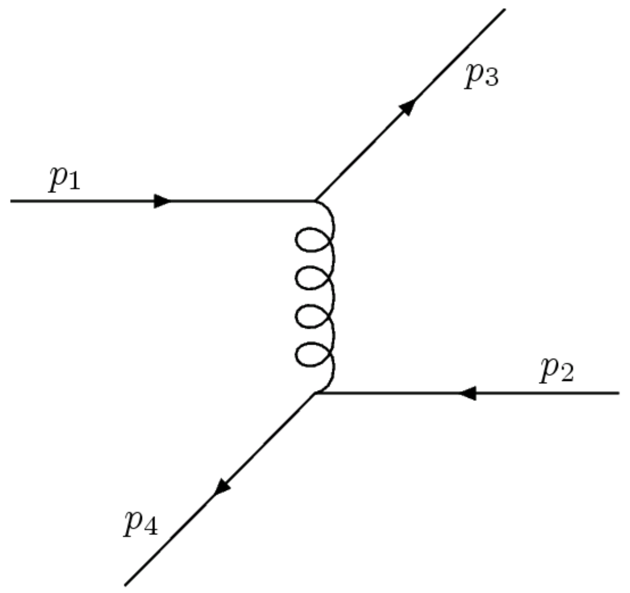
Large uncertainties on the gluon content of the nucleus at low x

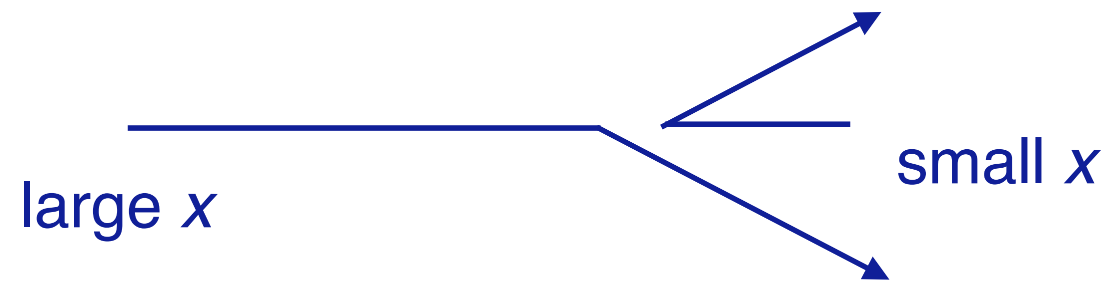
Hints of suppression 'shadowing' seen in old DIS data (NMC)

No/very few measurements available at low x

Reminder: how to get *x* and Q^2 in hadronic collisions

Leading order: 2→2 kinematics:

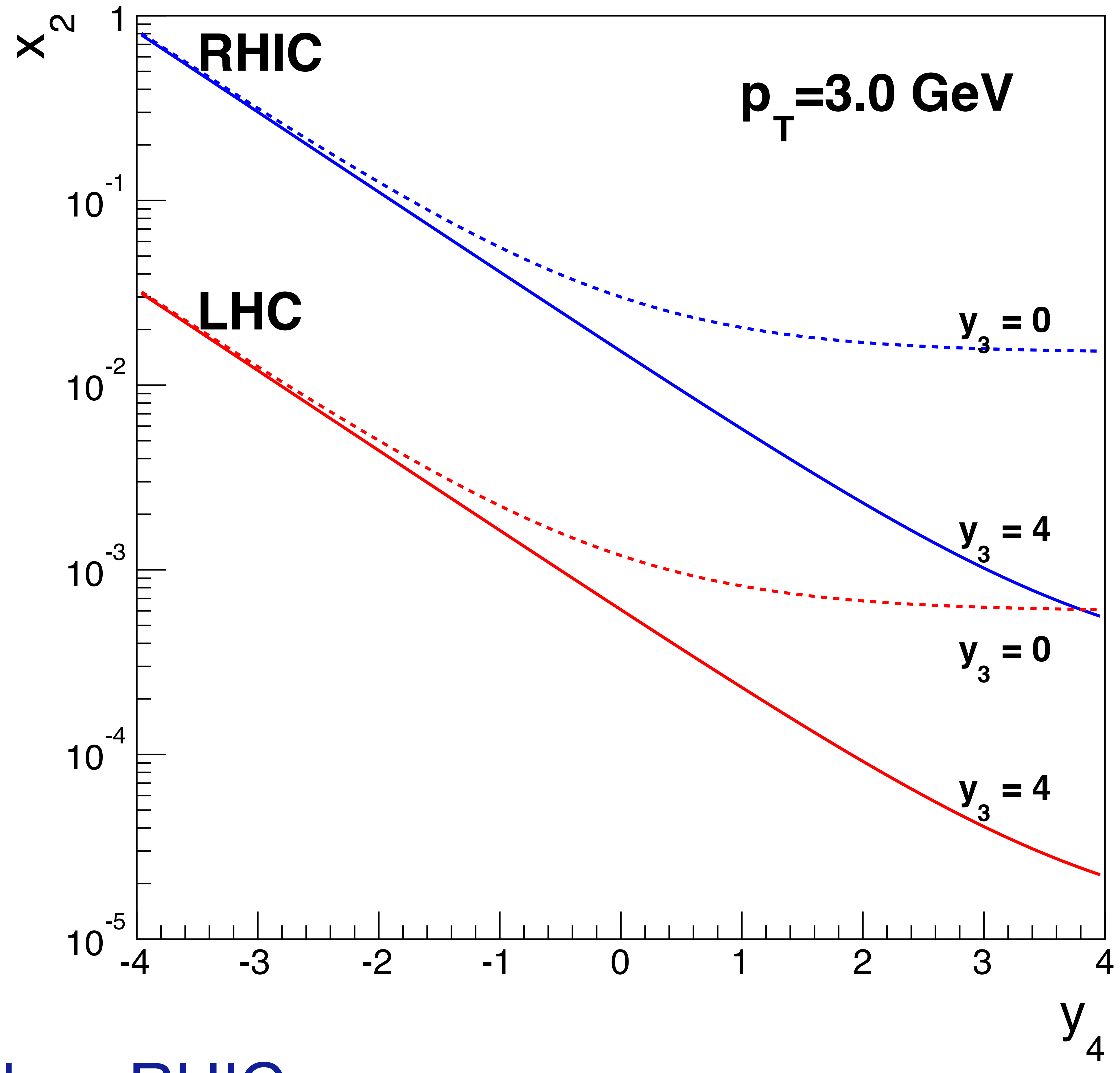




Forward rapidity is small *x*

$$x_2 \approx \frac{p_T}{\sqrt{s}} \left(e^{-y_3} + e^{-y_4}\right)$$

$Q \sim m_T$

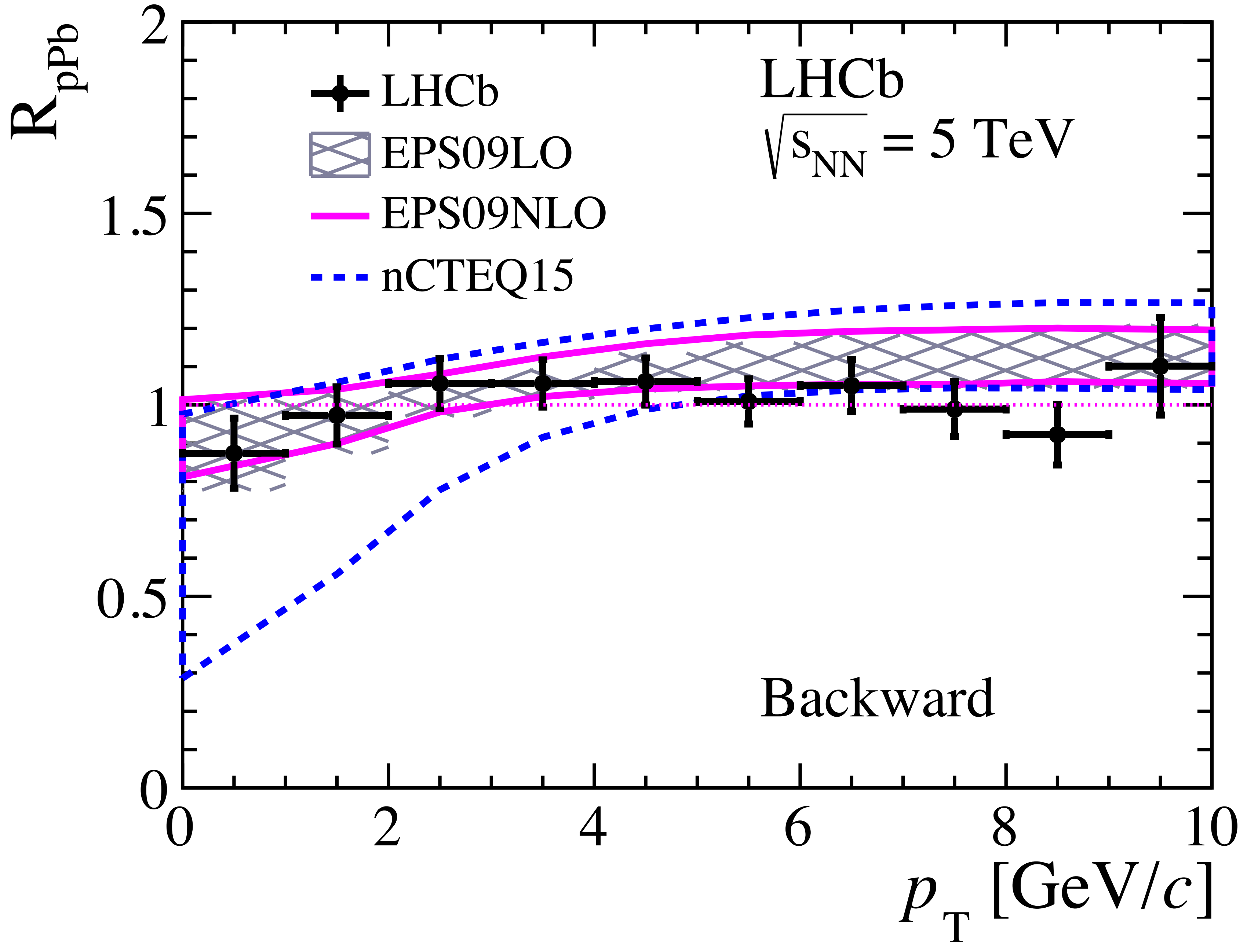


LHC probes lower *x* than RHIC

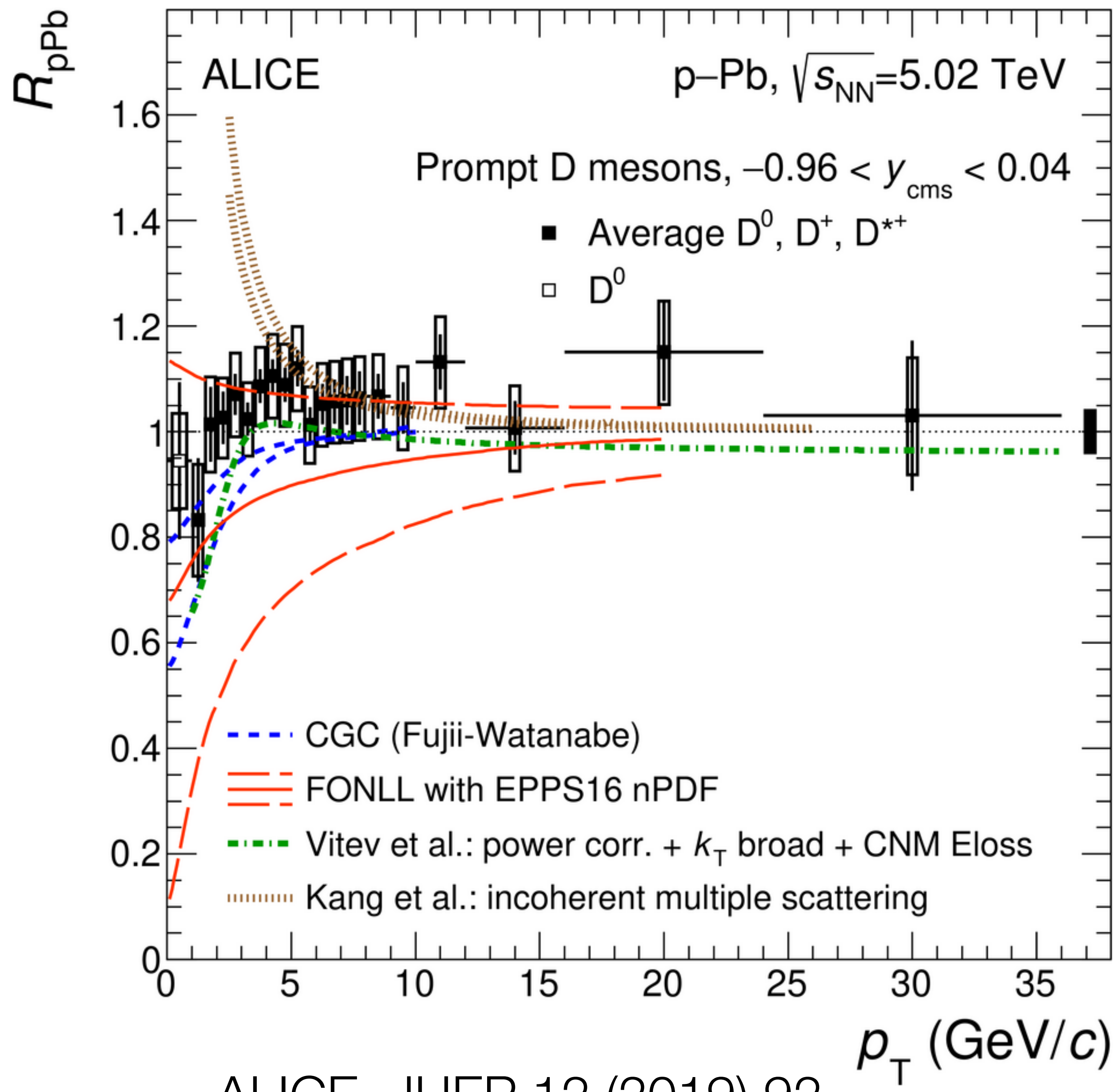
Mid-rapidity at LHC ≈ forward rapidity at RHIC

Open charm production vs rapidity at LHC

Backward rapidity: large x

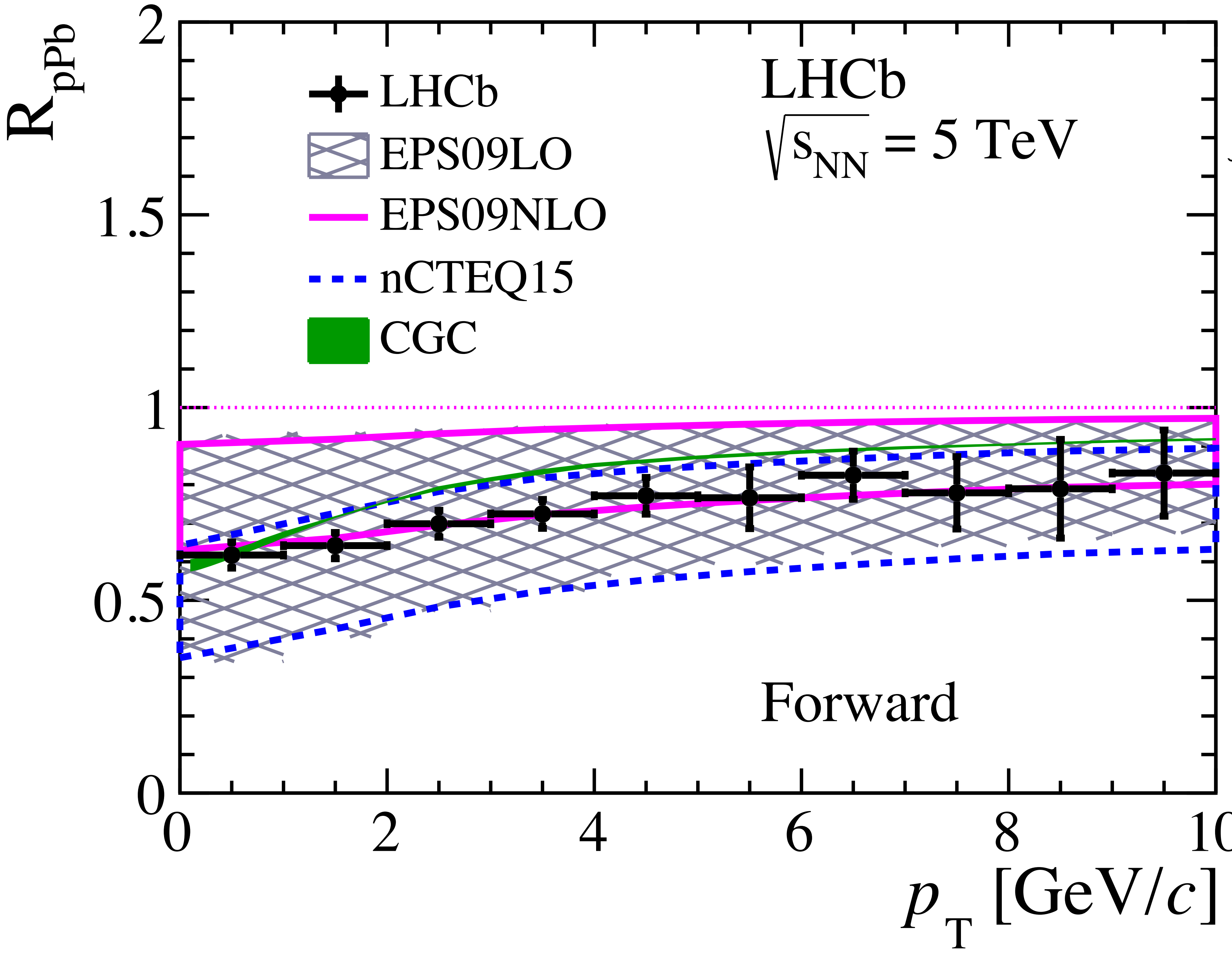


Mid-rapidity



ALICE, JHEP 12 (2019) 92

Forward rapidity: small x



LHCb, arXiv:1707.02750

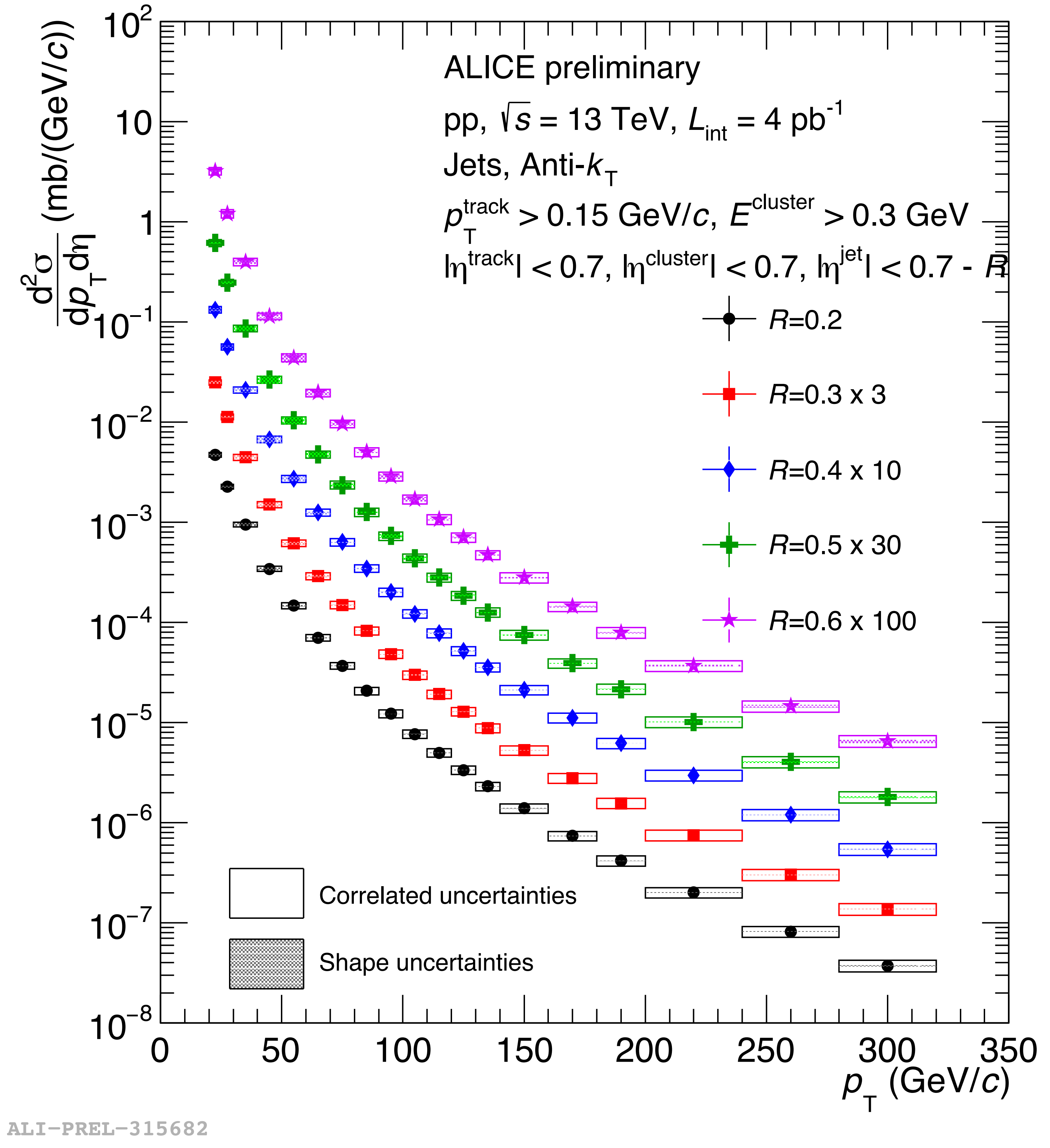
R_{pPb} ~ 1 at backward and mid-rapidity; below 1 at forward rapidity

Suppression mainly at small-x compatible with nuclear PDFs (shadowing) and CGC calculations

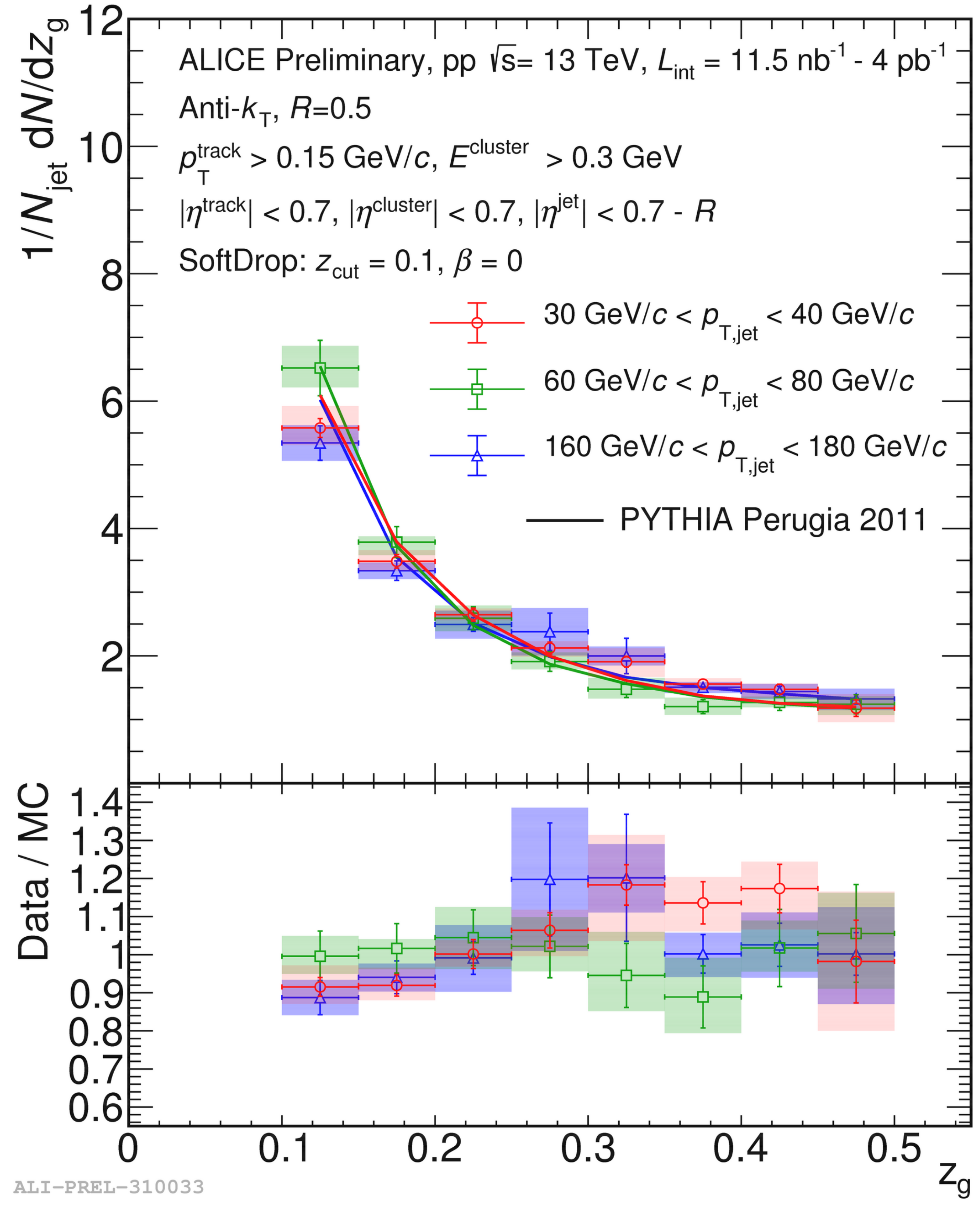
CGC: Decloue et al, PRD 91, 114005

Jets in pp collisions

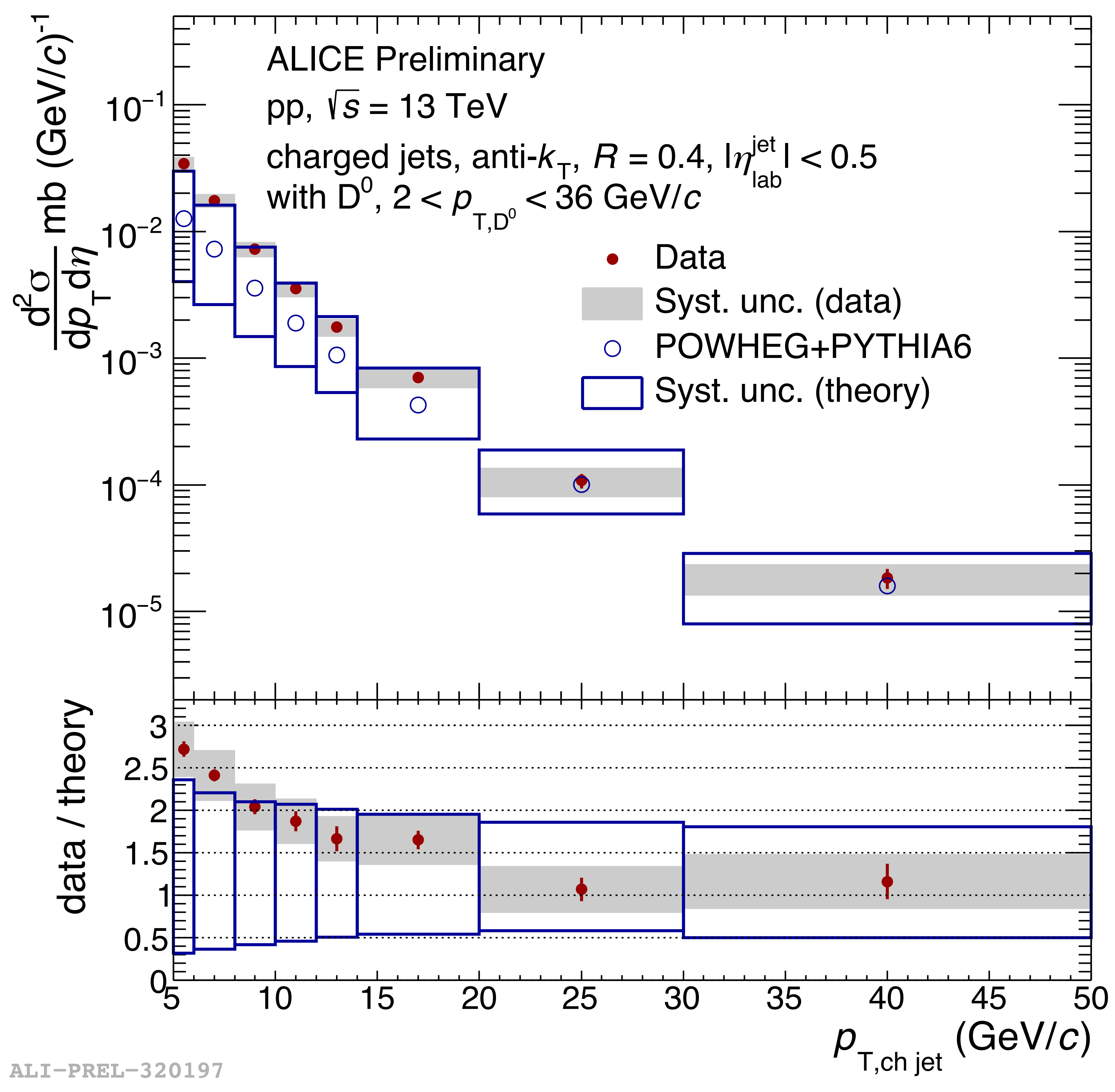
pp 13 TeV jet spectra



Soft drop momentum fraction



Charm jets

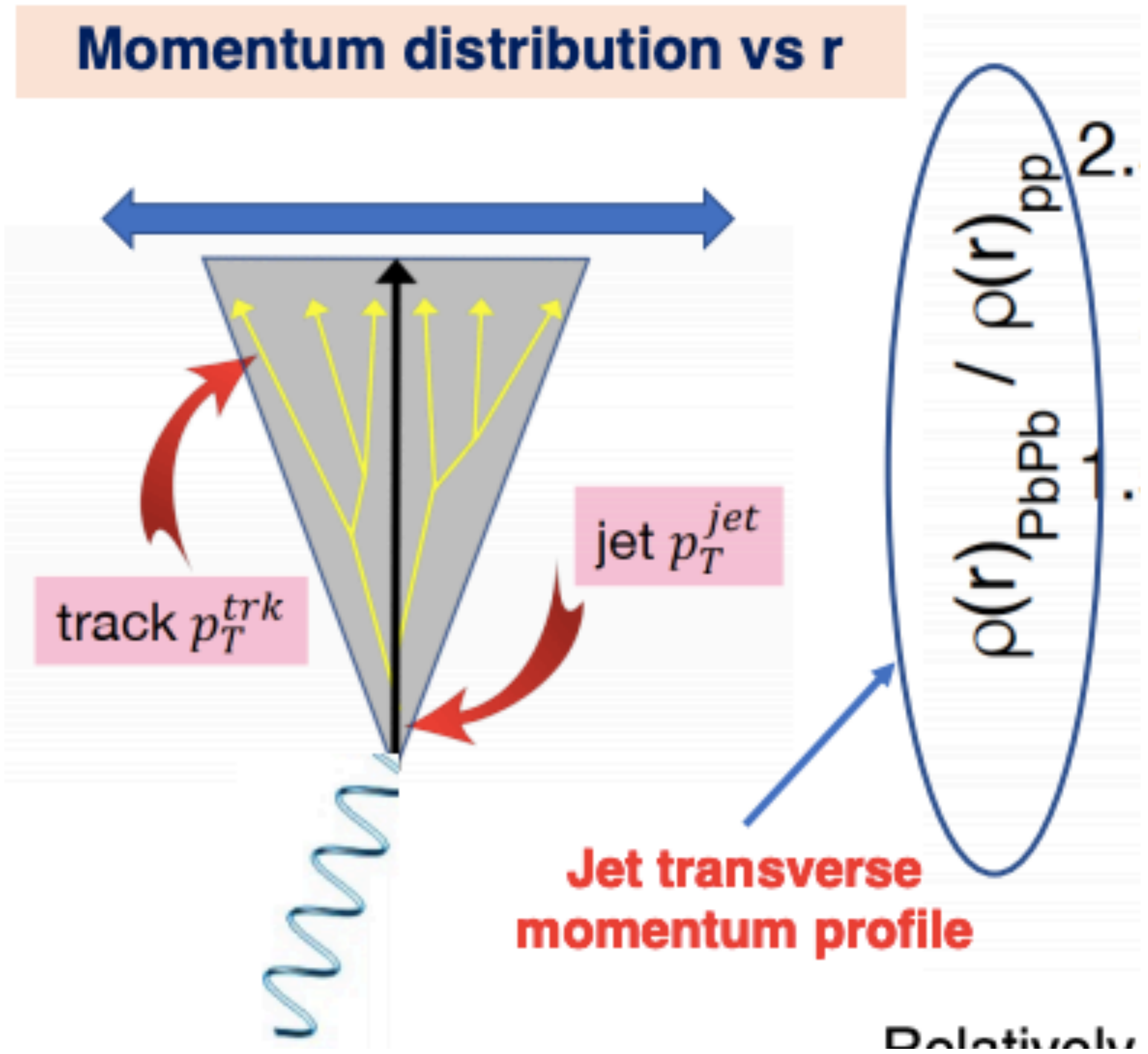


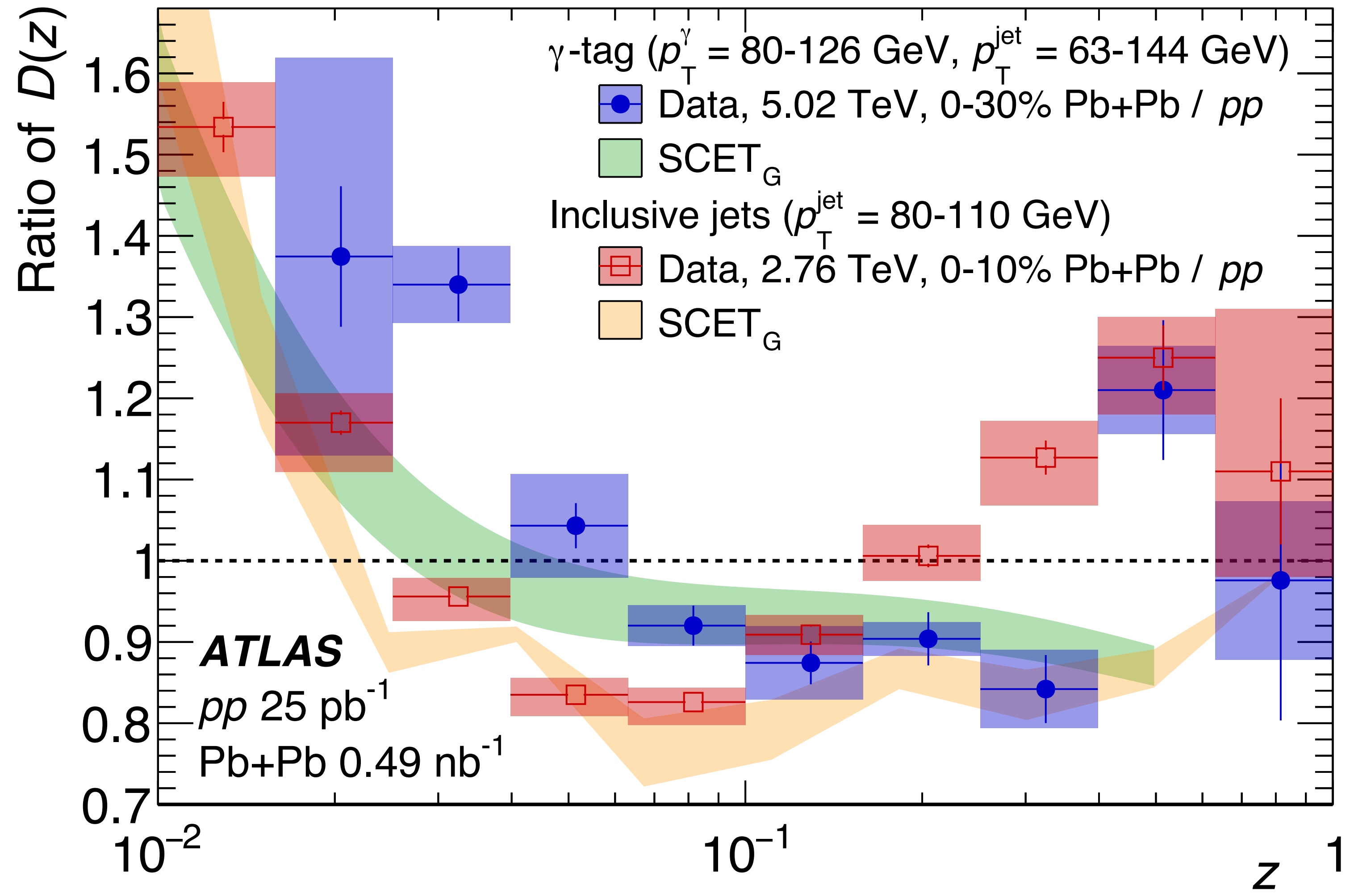
Important reference for Pb-Pb measurements: probe pQCD/parton showers and fragmentation in pp

Keeping track of the initial energy: gamma-jet

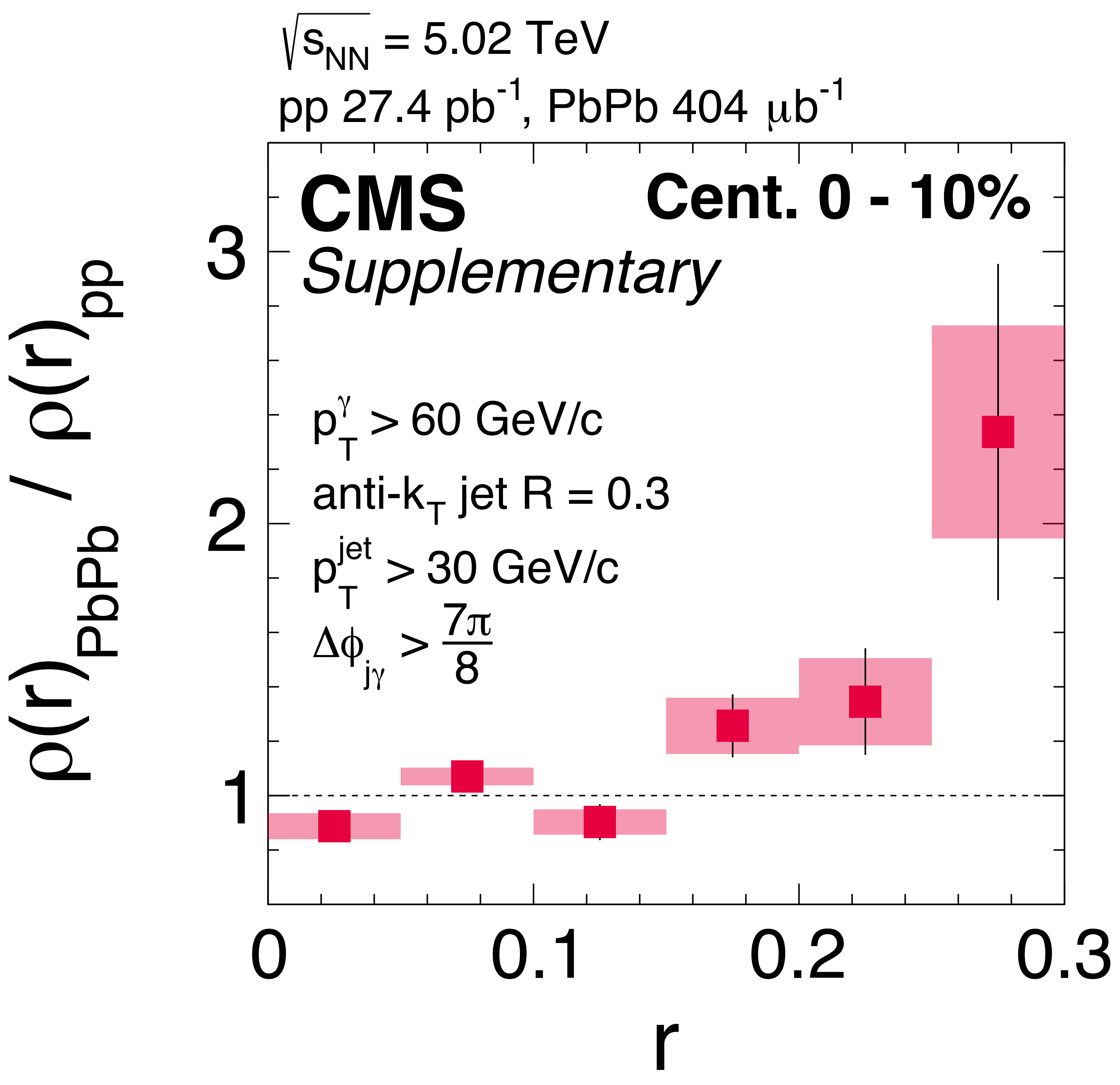
Recoil fragment distributions: γ-jet and di-jet

PRL 122 (2019) 152001





PRL 123, 042001



γ-jet: suppression at high z

di-jet: enhancement at large z

Different bias/selection

quark vs gluon jets