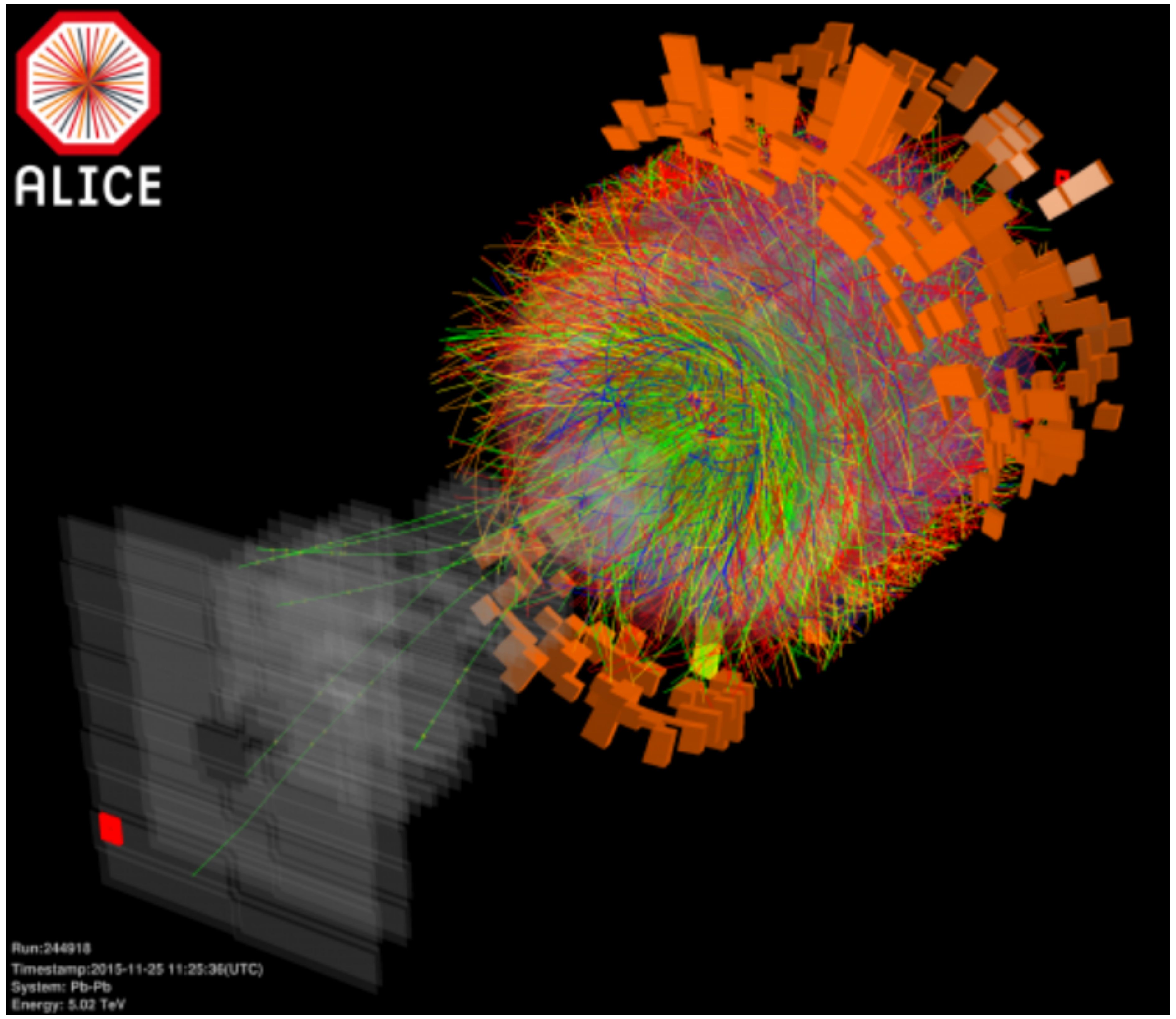
Studying the Quark Gluon Plasma (with ALICE) at the LHC

Current results and future plans

Marco van Leeuwen,
Nikhef, Utrecht University

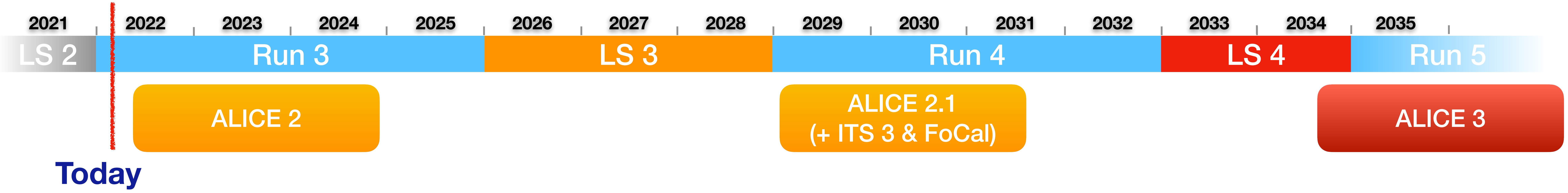
LIP seminar (online)
31 March 2022



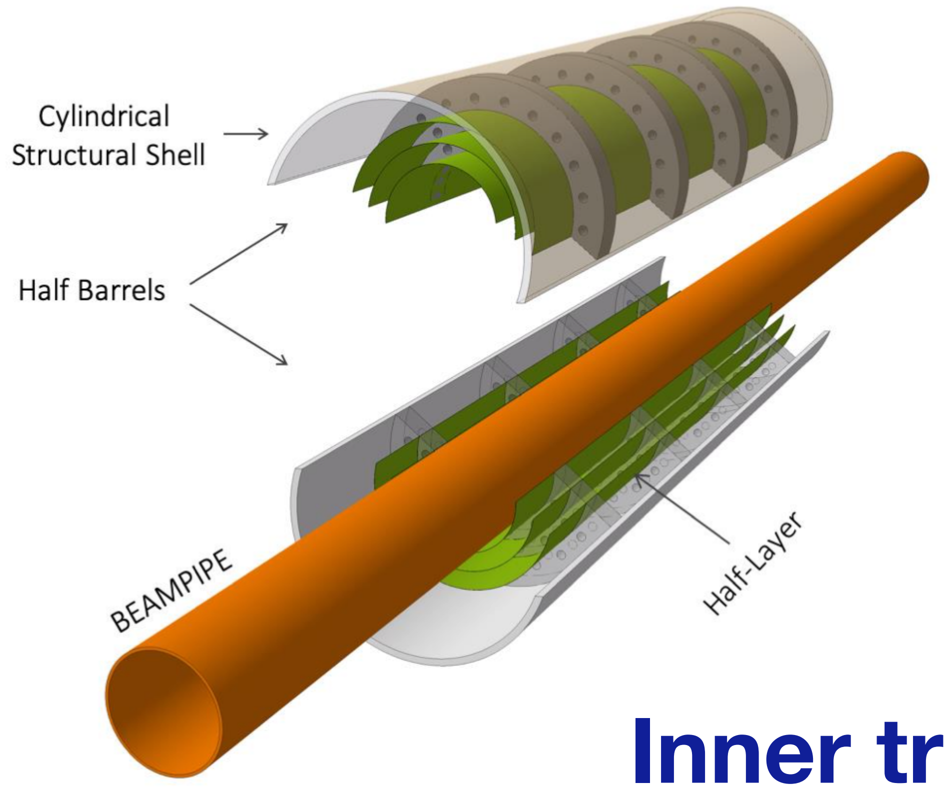
Physics Utrecht
EMMEΦ

Nikhef

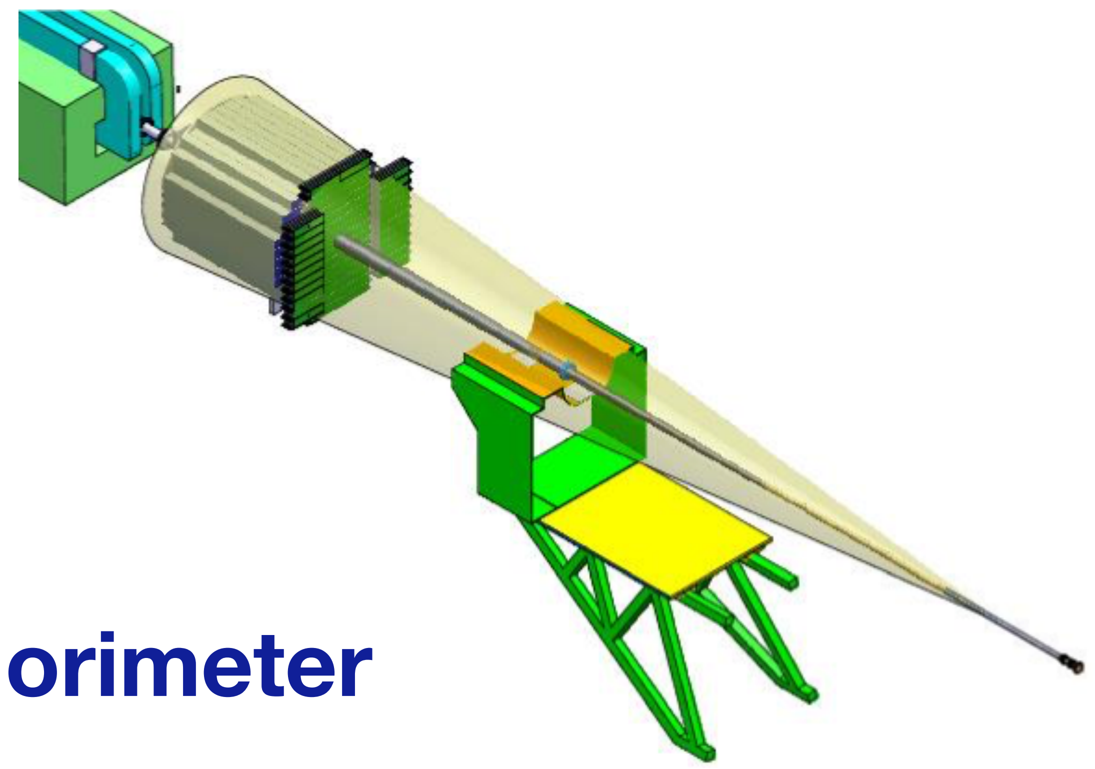
ALICE and LHC program time line



- ALICE installed **major upgrades for Run 3**
  - 50-100x larger data rate, better pointing resolution
  - commissioning ongoing; start of beams imminent
  - first heavy ion run: end of 2022
- Additional upgrades planned for Run 4
  - ITS 3: replace inner tracking layers and beam pipe
  - Forward Calorimeter
- … and beyond: ALICE 3



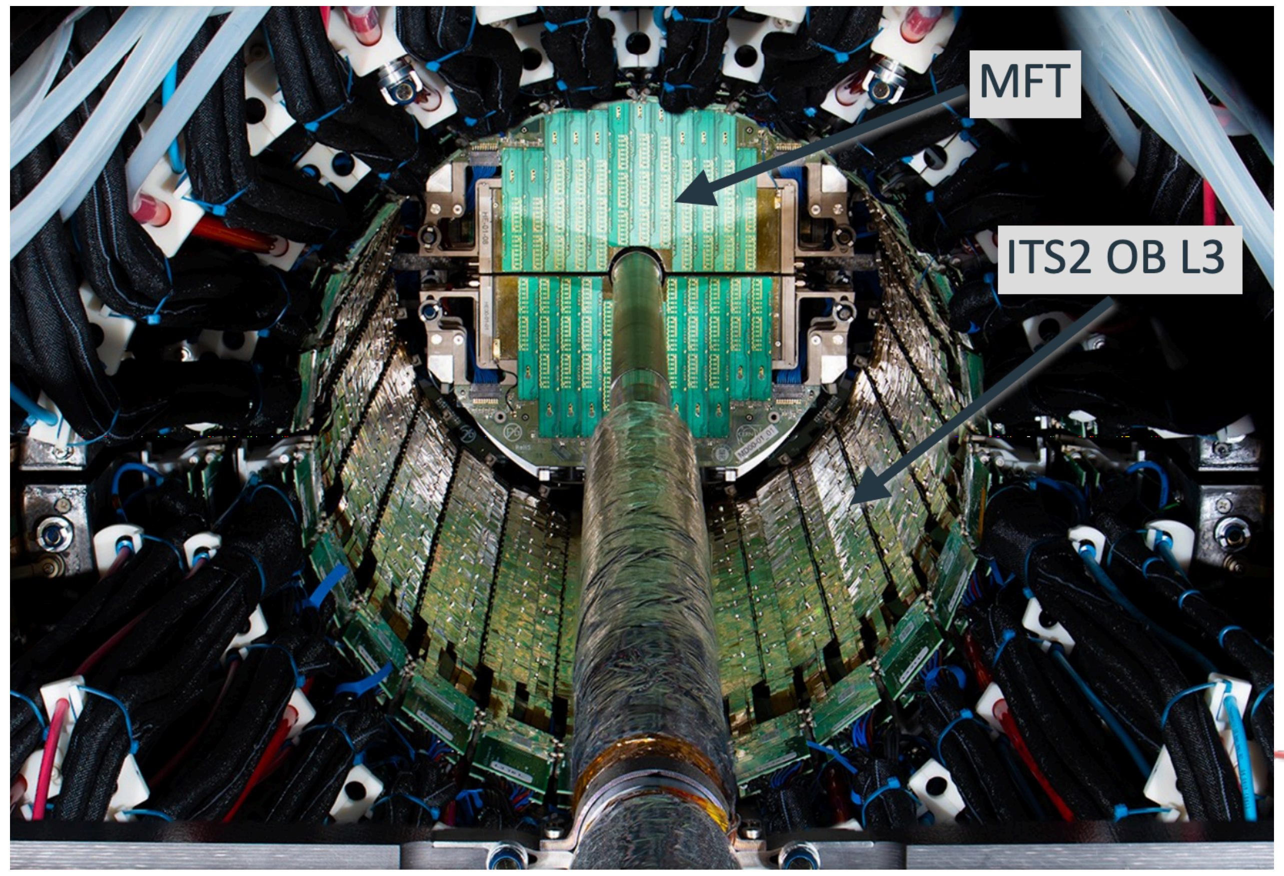
ITS 3
Inner tracker upgrade



Forward Calorimeter

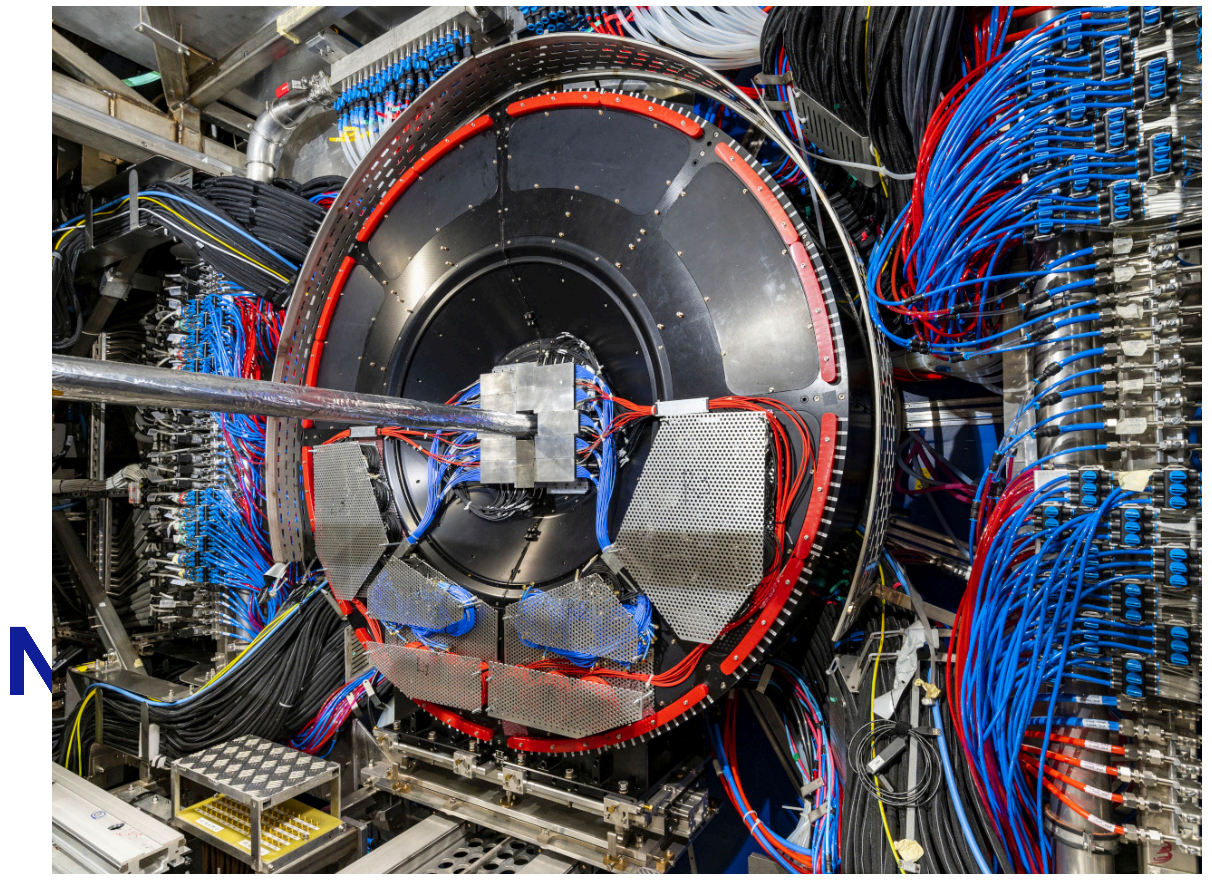
ALICE upgrades in Long Shutdown 2

New ITS and MFT

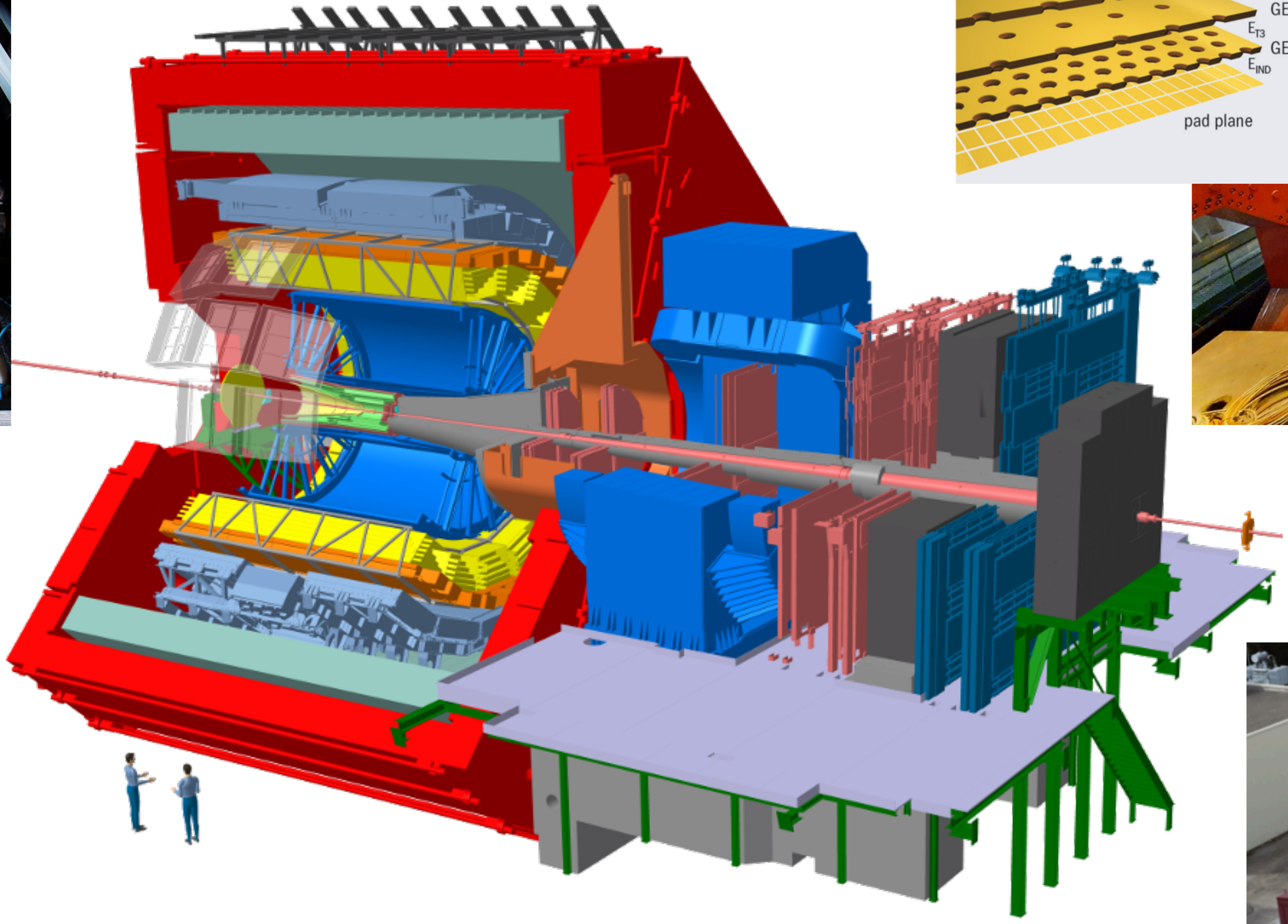


Full pixel detector
Improved spatial resolution

Fast Interaction Trigger



N



TPC: GEM readout

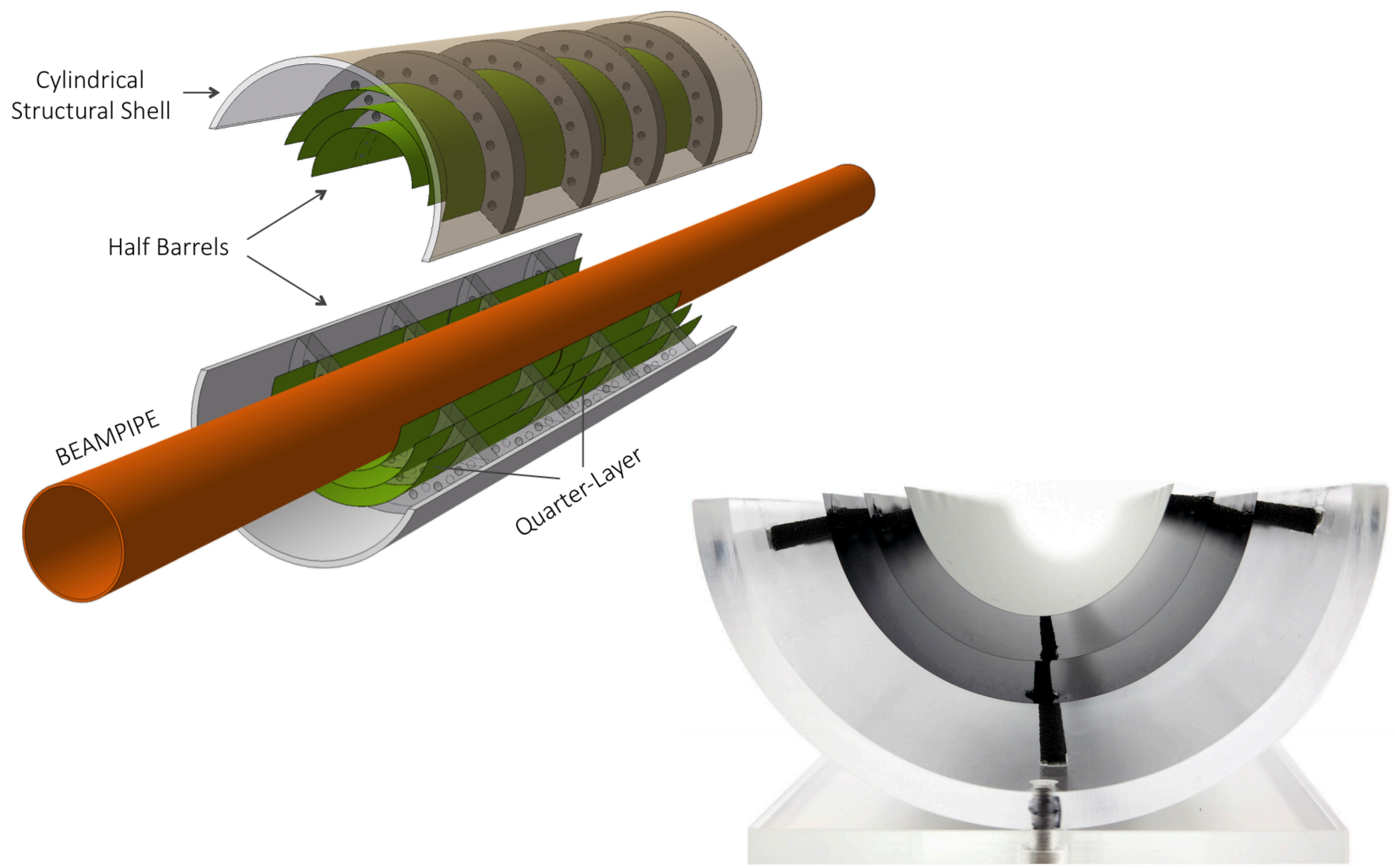
Continuous readout

Online event processing

Run 3/4: collect 13 nb^{-1} Pb-Pb: 50x more minimum bias data; 10x more triggered data

Future upgrades: ITS 3 and FoCal

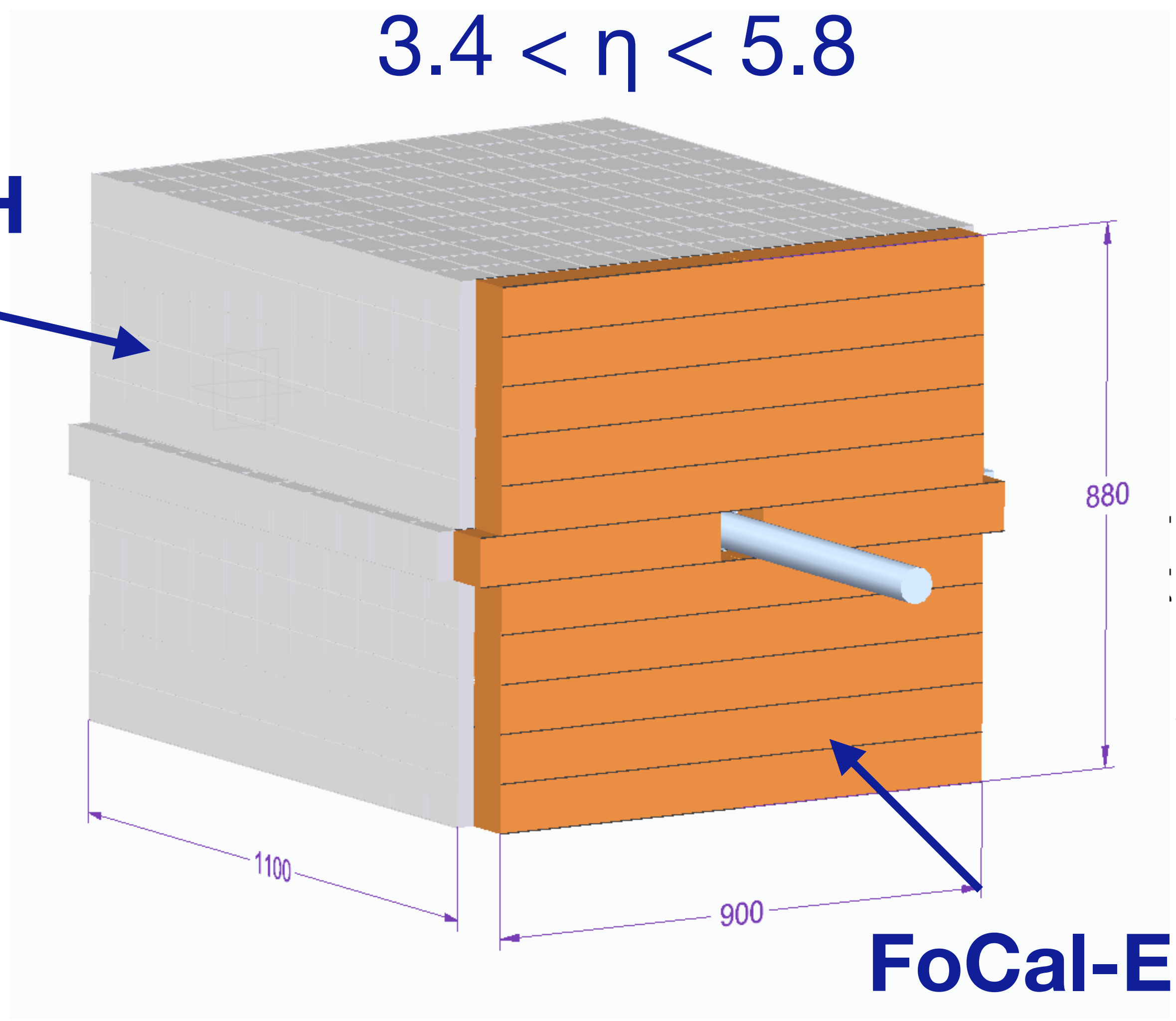
ITS 3: ultra-light, fully cylindrical tracking layers



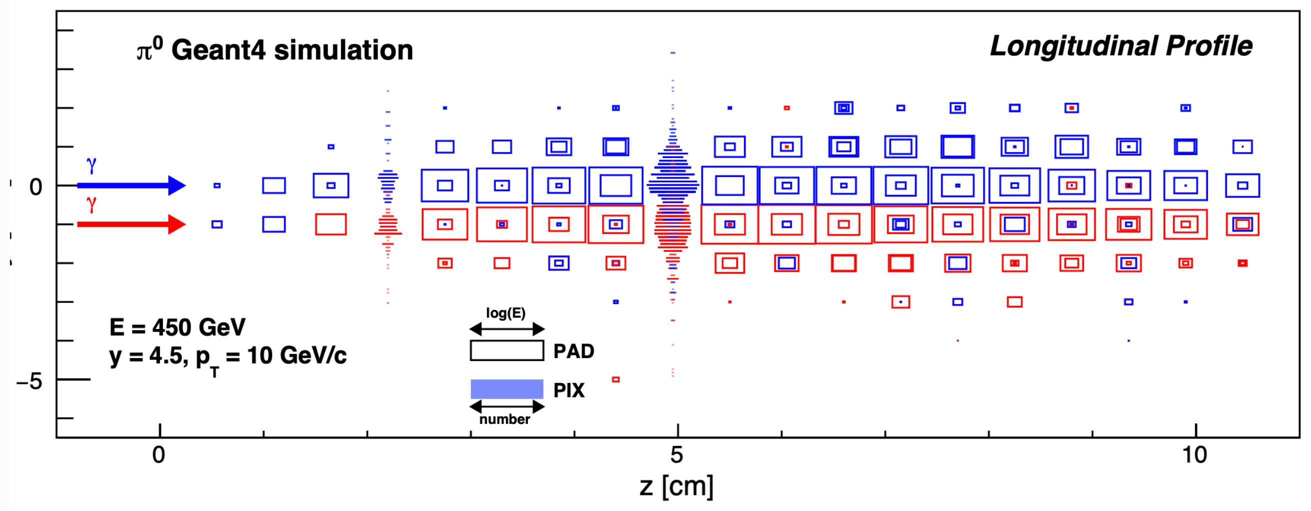
LoI: CERN-LHCC-2019-018

Improved performance for
- Heavy flavour reconstruction
- Di-lepton measurements

FoCal: high-granularity foward calorimeter



Longitudinal profile (2γ showers)



LoI: CERN-LHCC-2020-009

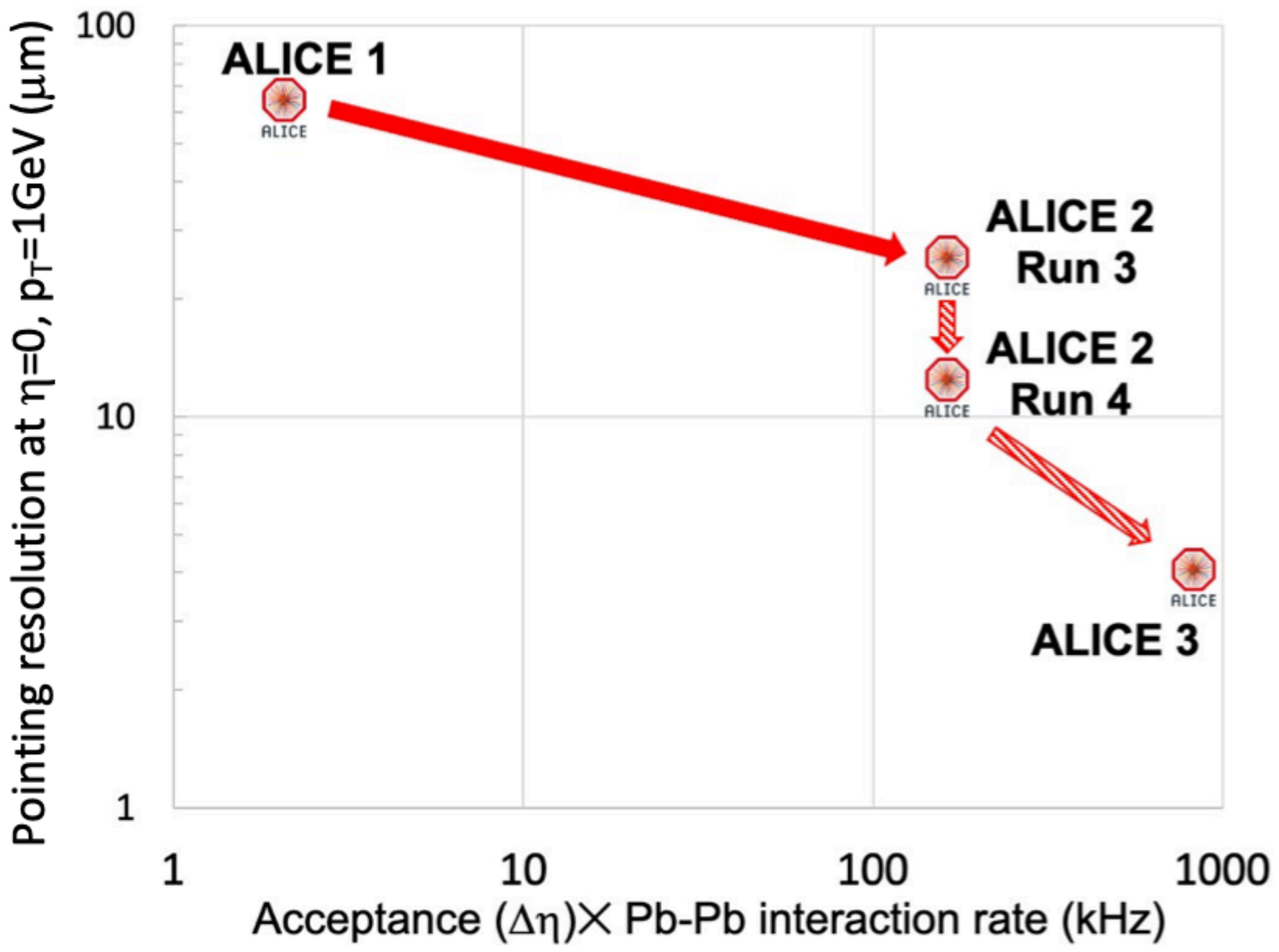
- High-granularity Si-W EM calorimeter for photons and π^0
- Small-x physics in pp and p-Pb
- Forward π^0 in Pb-Pb

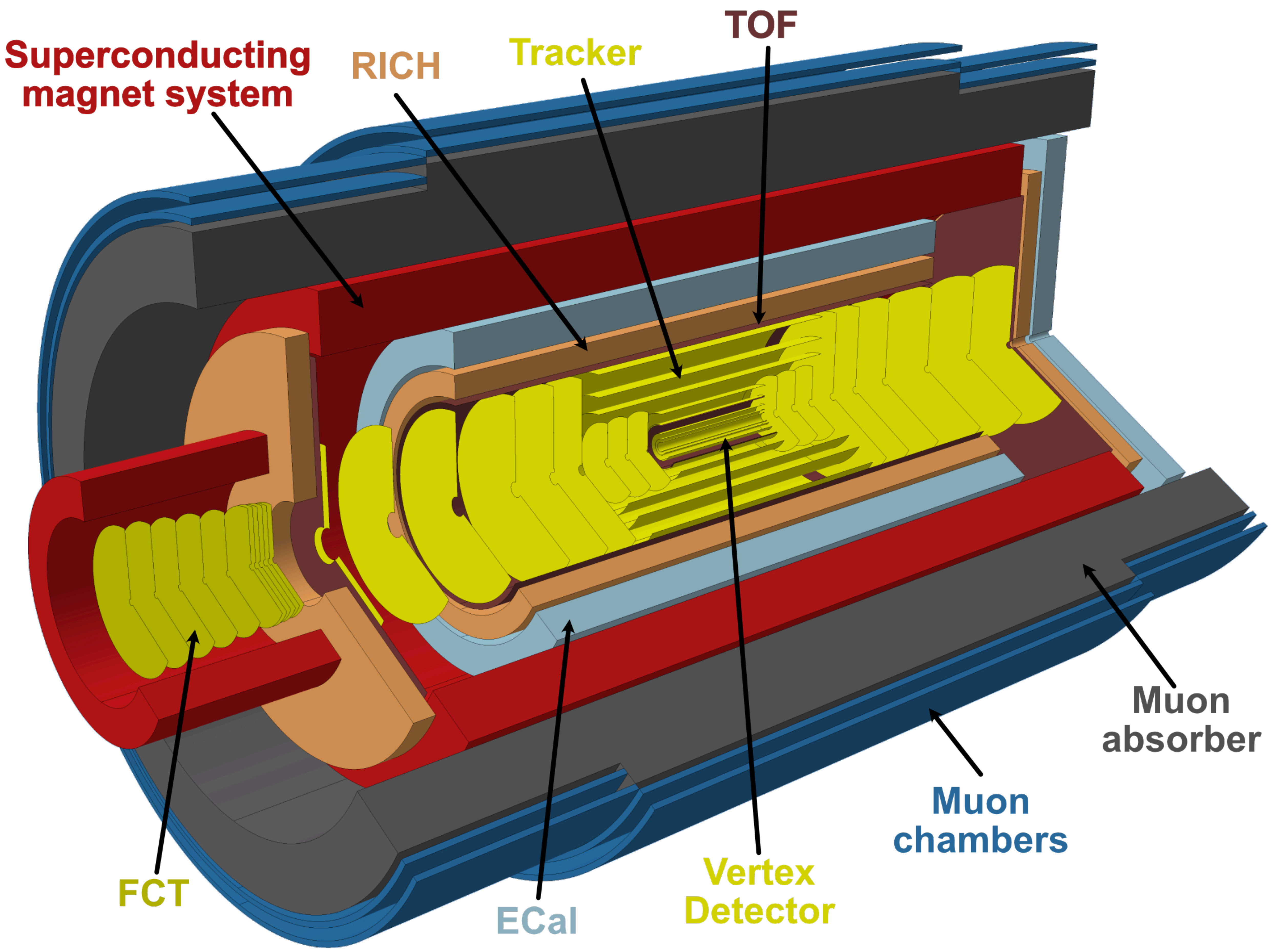
LHC Run 5 and 6: ALICE 3

- Compact all-silicon tracker with high-resolution vertex detector
- Particle Identification over large acceptance: muons, electrons, hadrons, photons
- Fast read-out and online processing

Improvement of pointing resolution and effective statistics

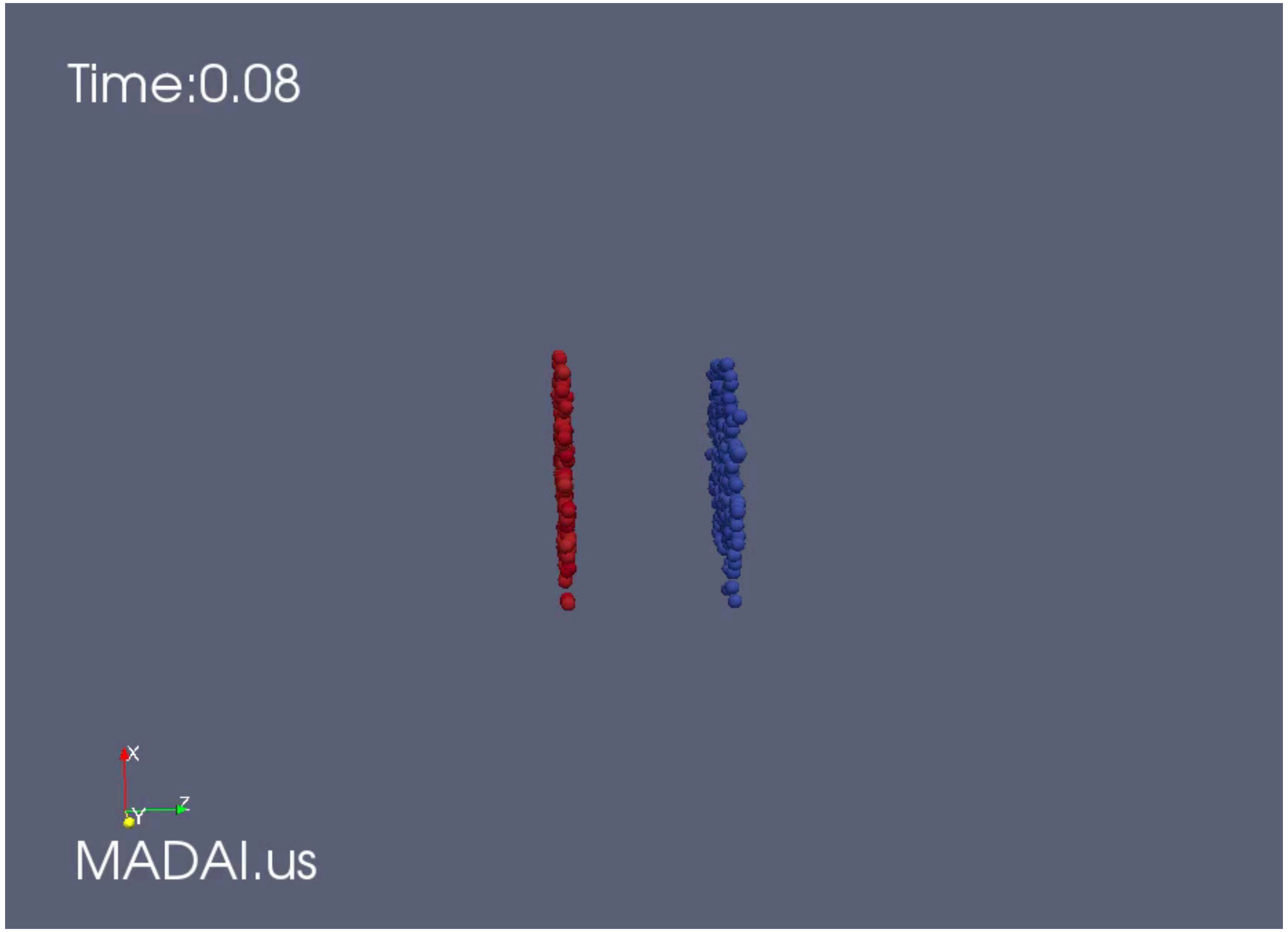
For LHC Run 5 & 6





Letter of Intent: LHCC-2022-009

Heavy ion collisions: Little Bangs

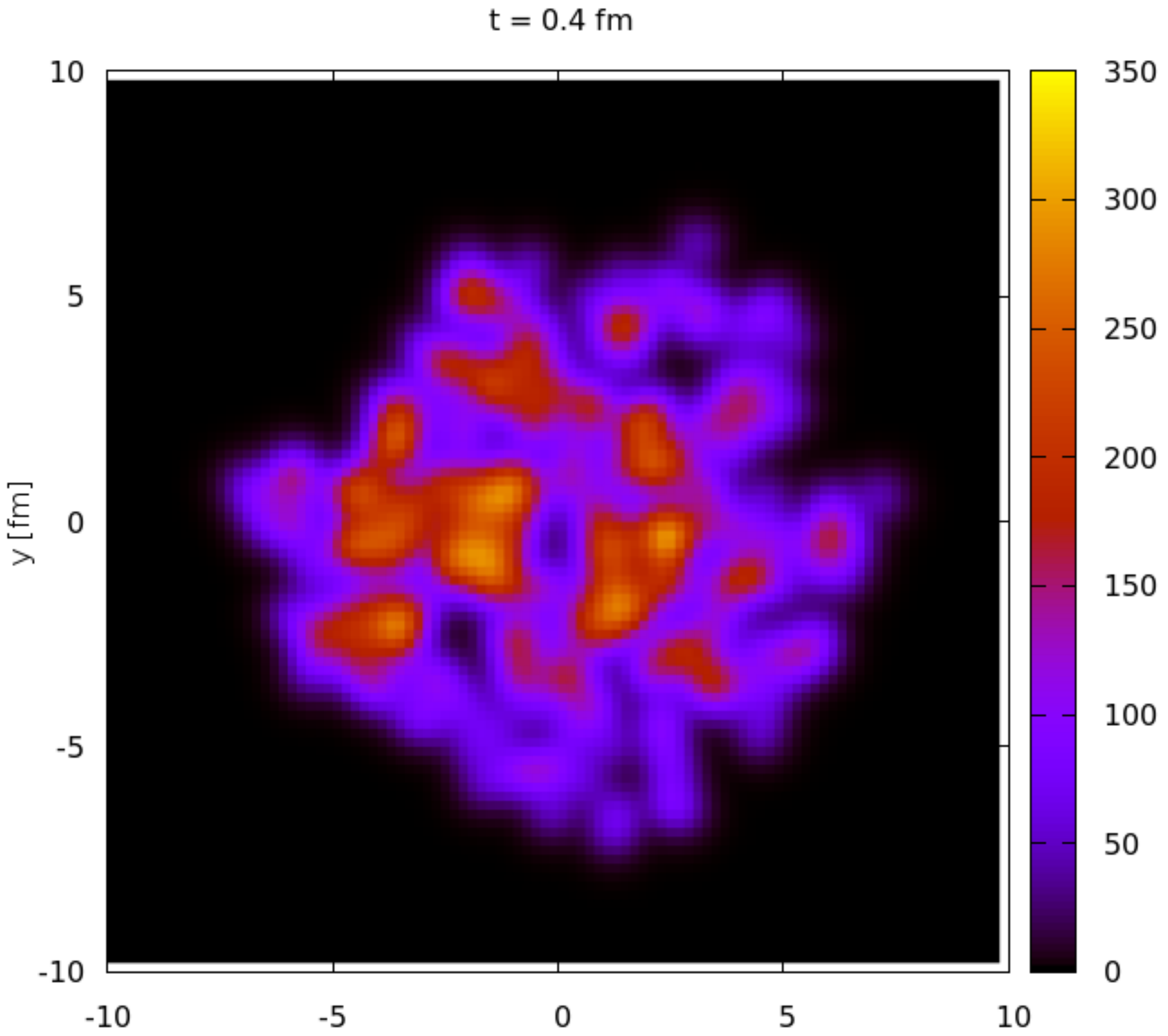


MADAI

Stages of the collision: initial stages — QGP/fluid stage — hadron formation (freeze out)

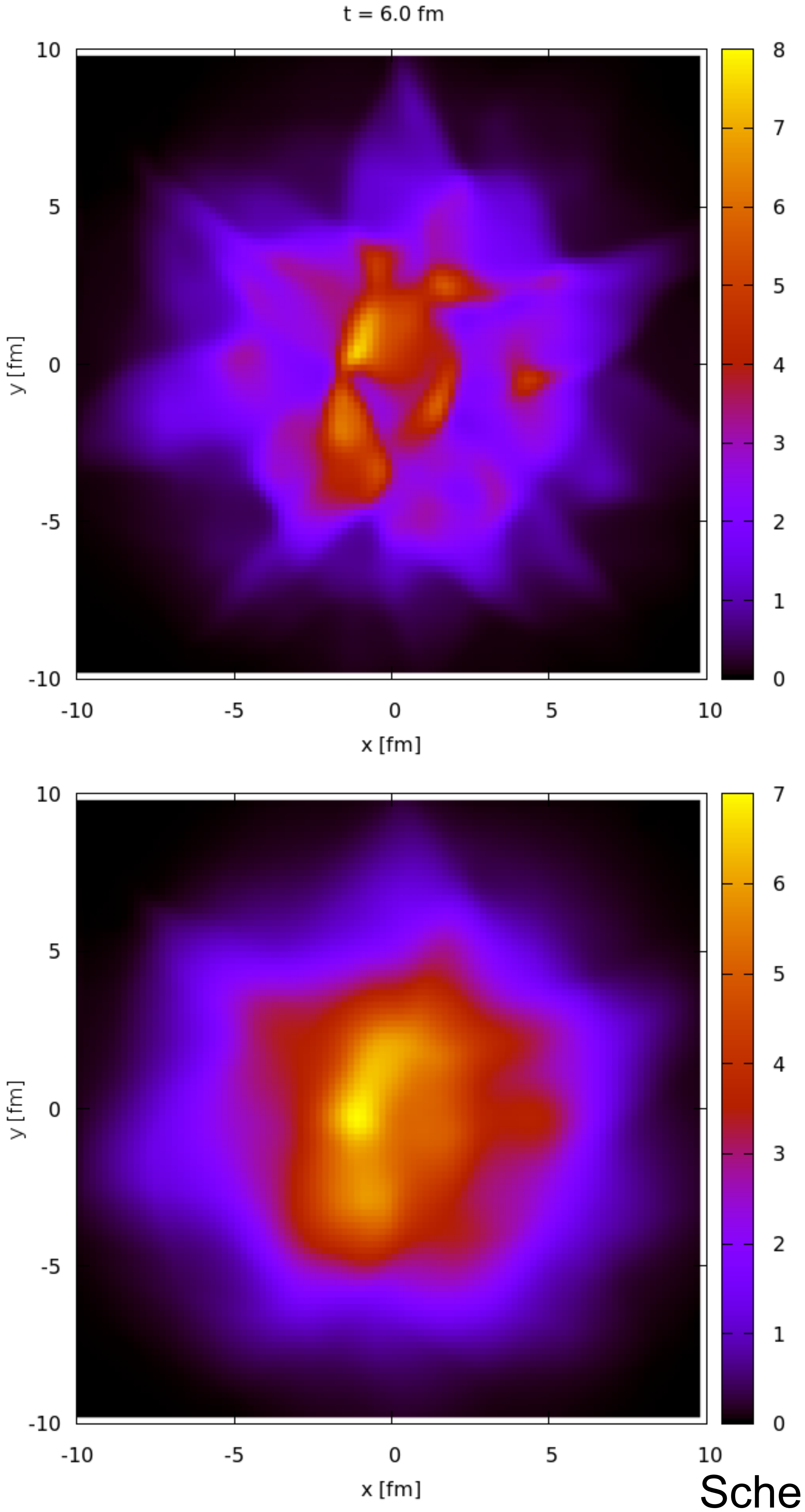
‘Little Bang’: recreate primordial matter in the laboratory

Azimuthal anisotropy: initial and final states



No viscosity
$\eta/s = 0$

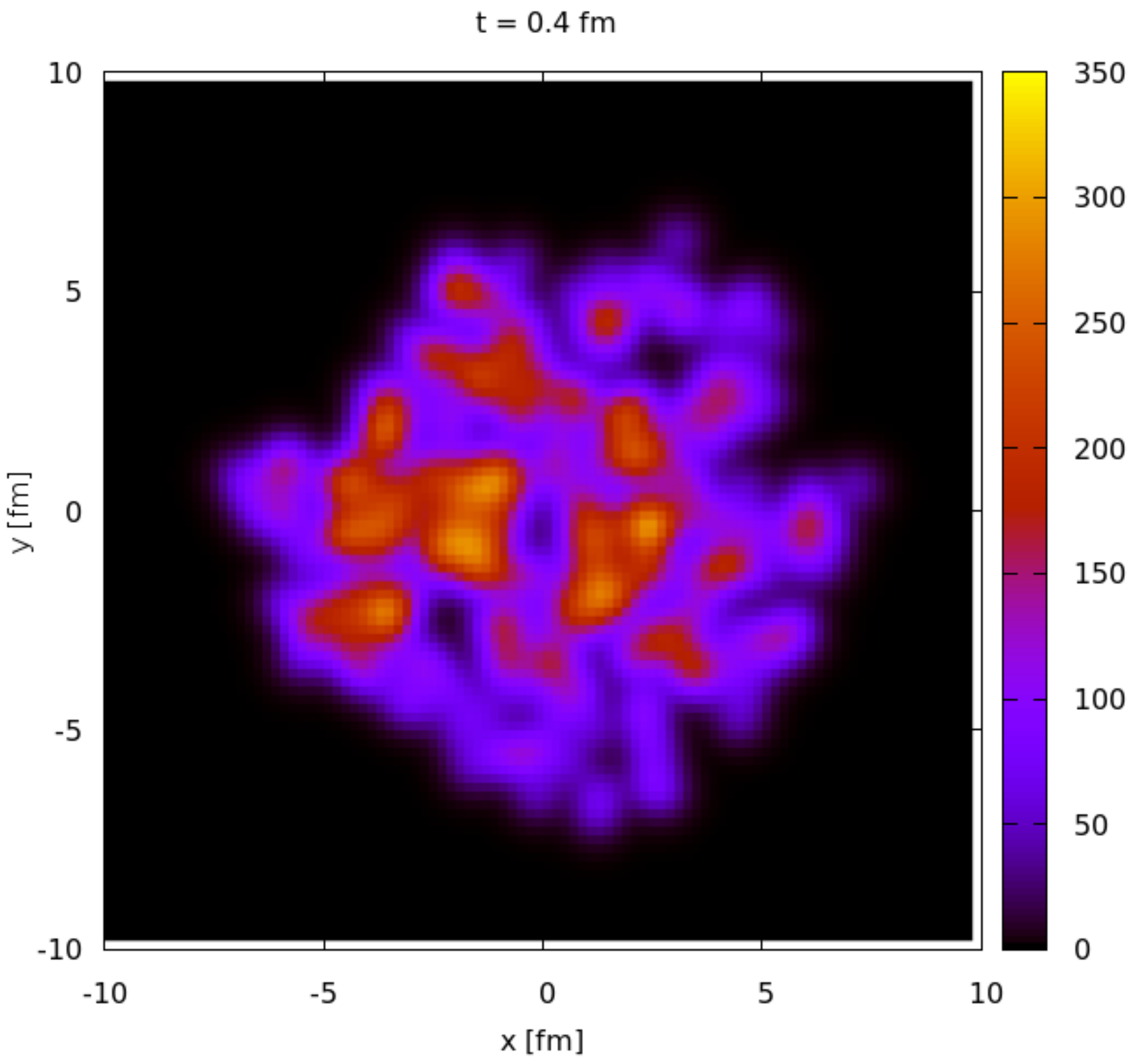
$\eta/s = 0.16$
Low viscosity



Pressure gradients: expansion of the QGP
Initial state spatial anisotropies ε_n: non-uniform expansion

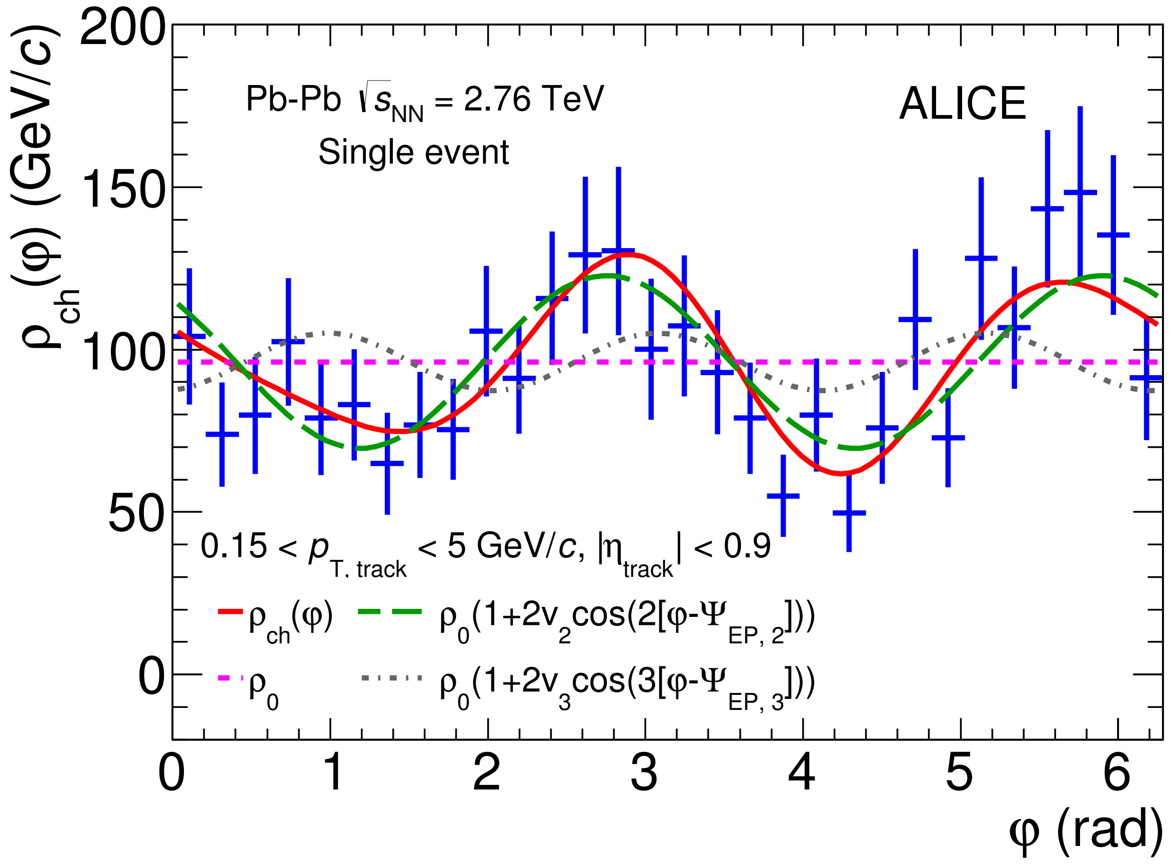
Schenke and Jeon,
Phys.Rev.Lett.106:042301

Azimuthal anisotropy: initial and final states



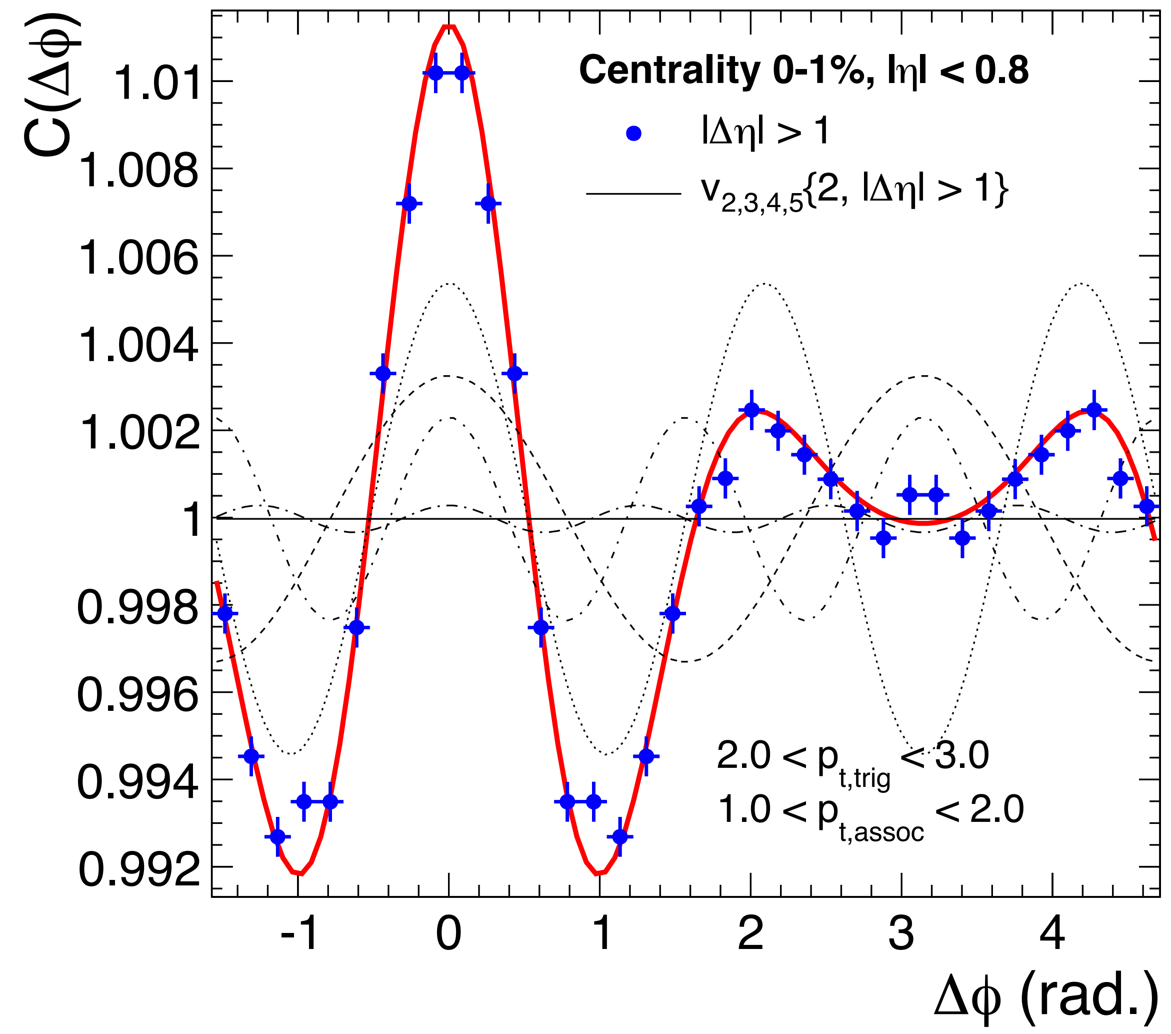
Initial state spatial anisotropies ε_n are transferred into final state momentum anisotropies v_n by pressure gradients, flow of the Quark Gluon Plasma

Azimuthal distribution single event



ALICE, PLB 753, 511

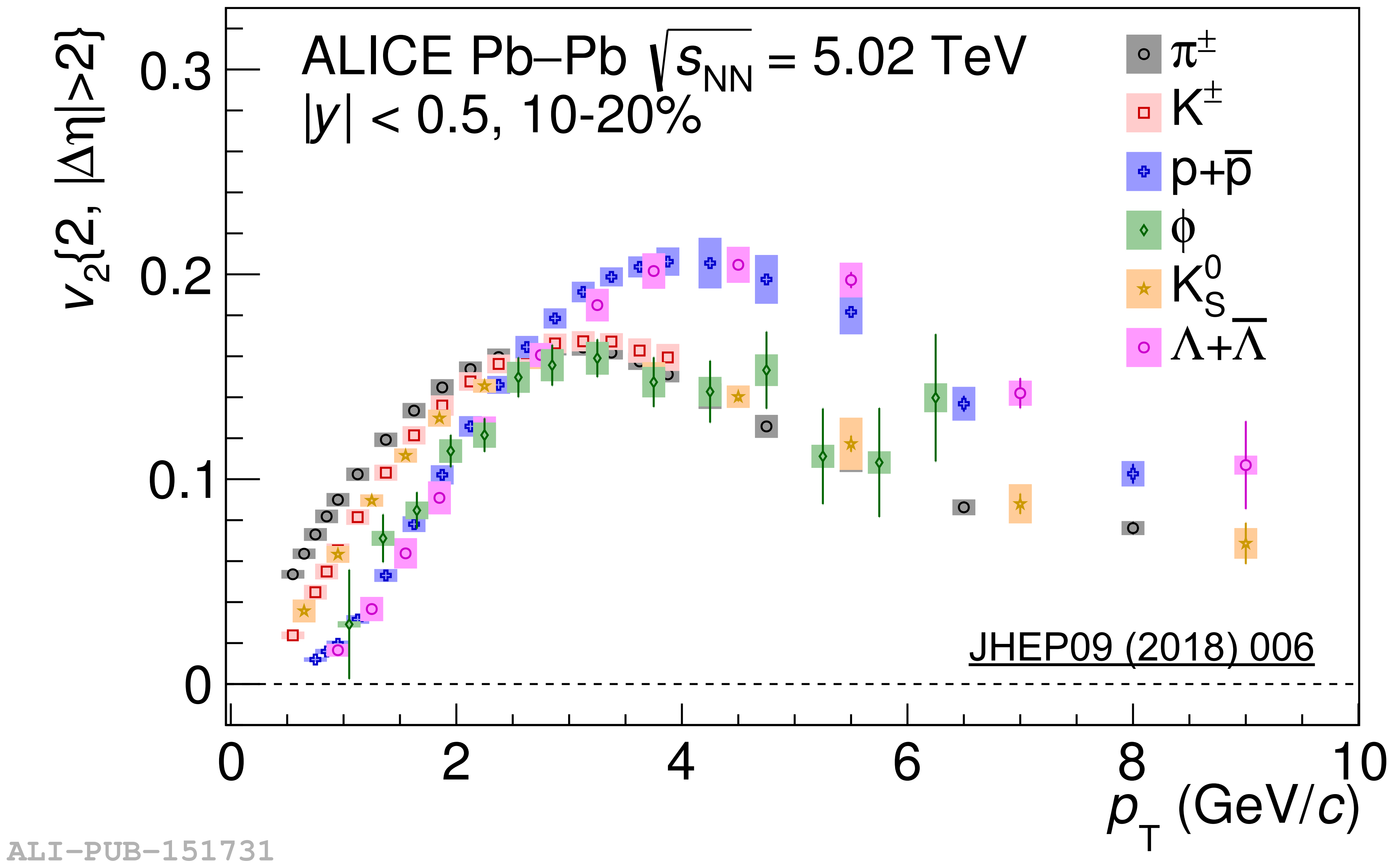
Sum over many events



ALICE PRL. 107, 032301

Anisotropic flow: initial state and QGP expansion

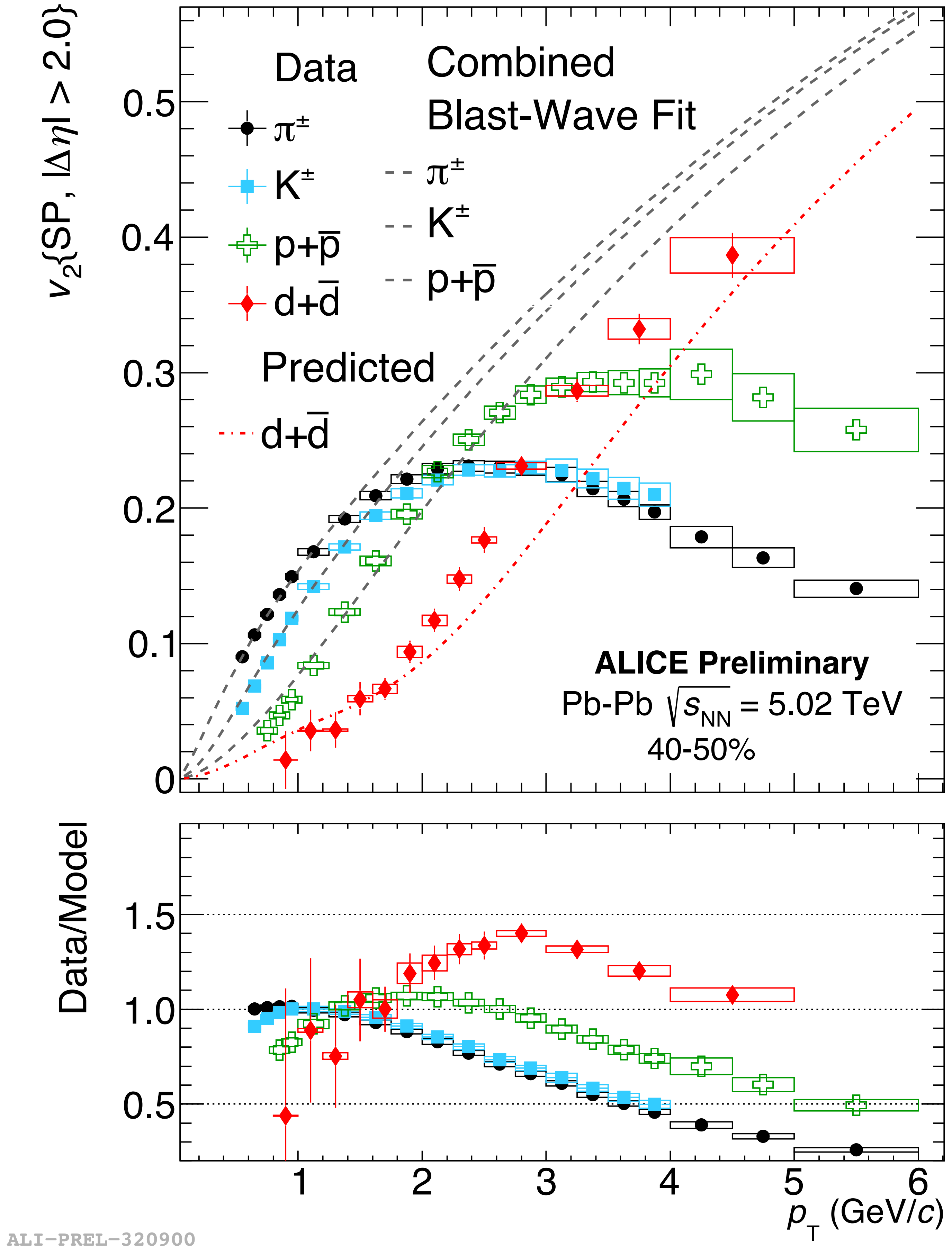
Elliptic flow v_2



ALI-PUB-151731

Mass-dependence of v_2 measures flow velocity

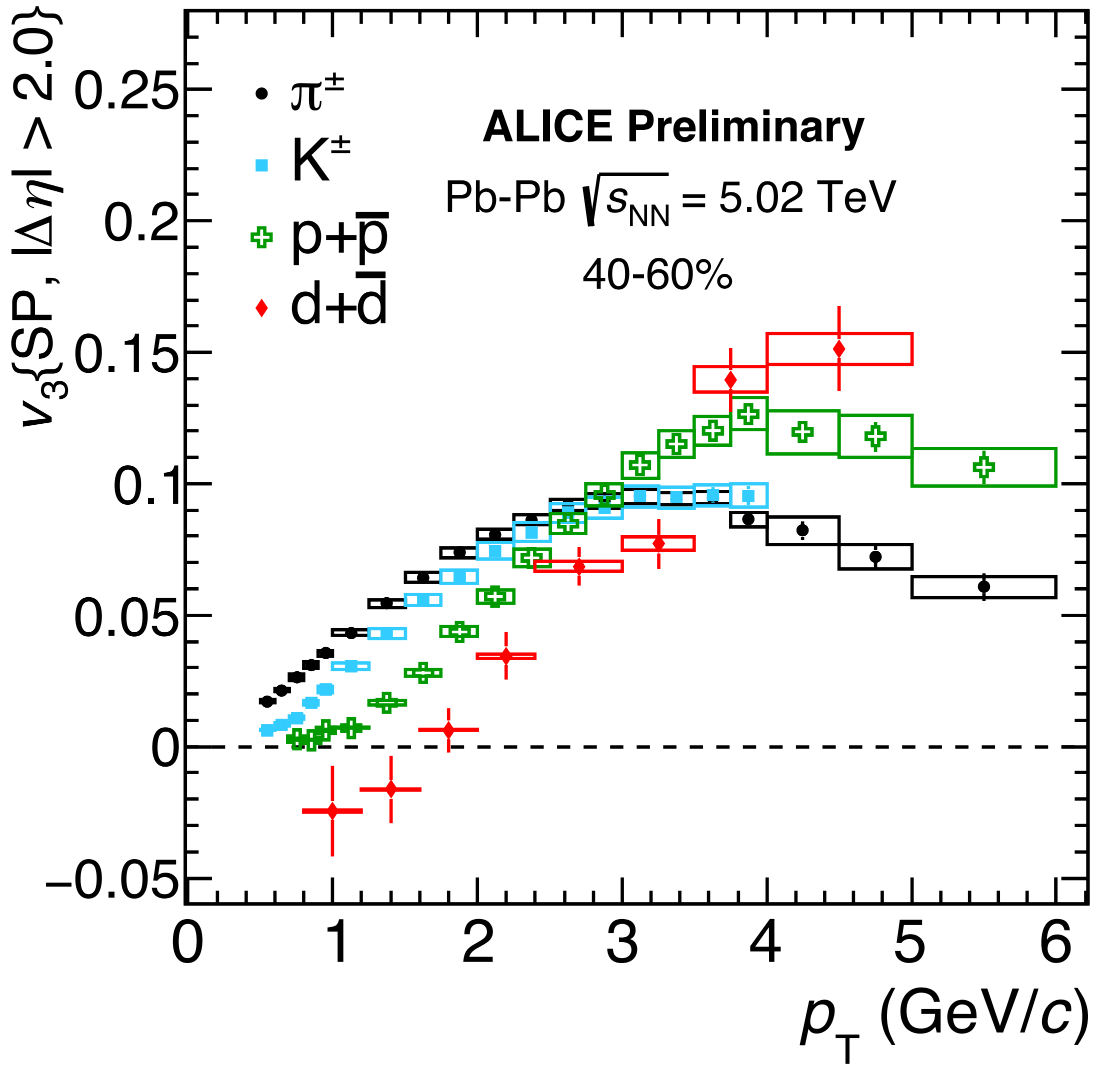
v_2 of deuterons



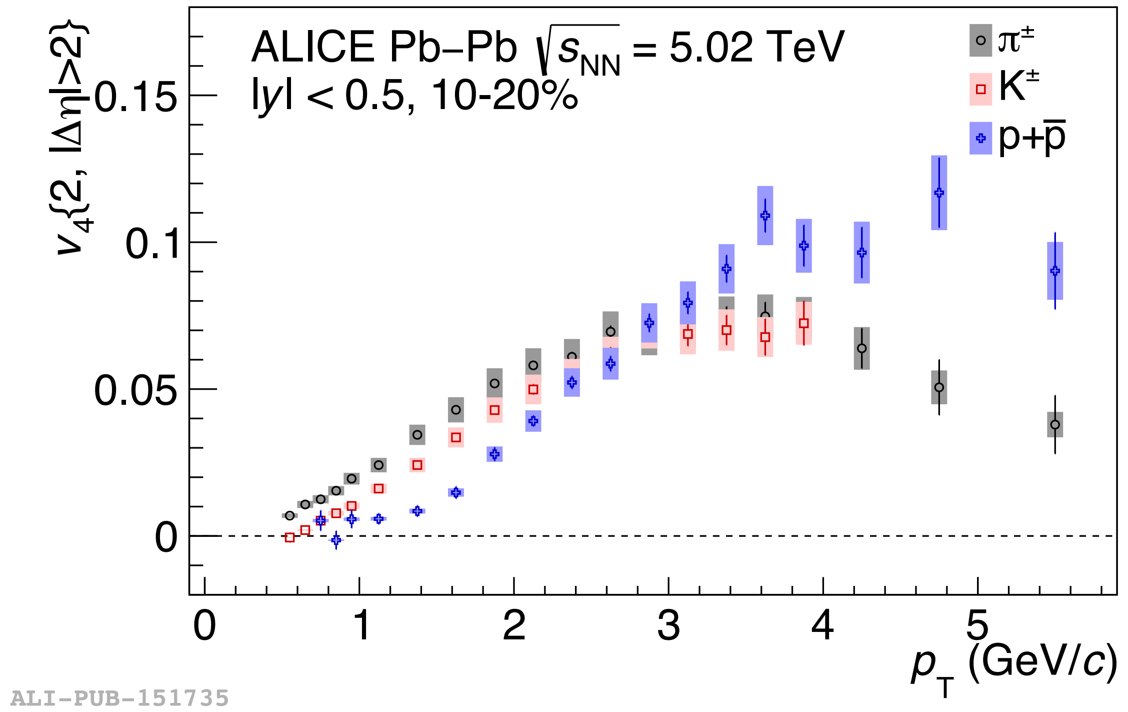
ALI-PREL-320900

Even nuclei flow !

v_3



v_4

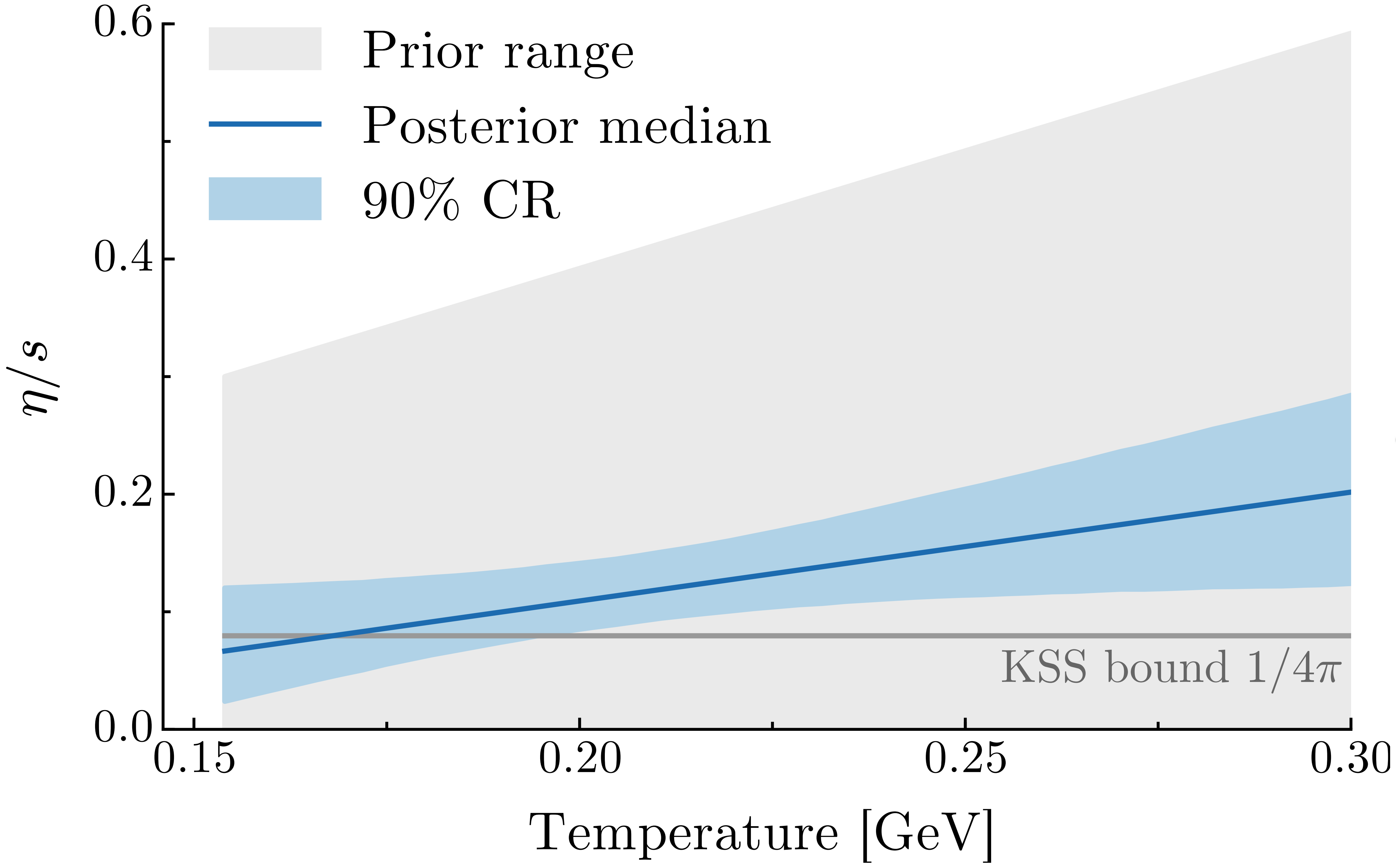


ALI-PUB-151735

A global fit to anisotropic flow: main results

J. E. Bernhard et al, arXiv: 1605.03954

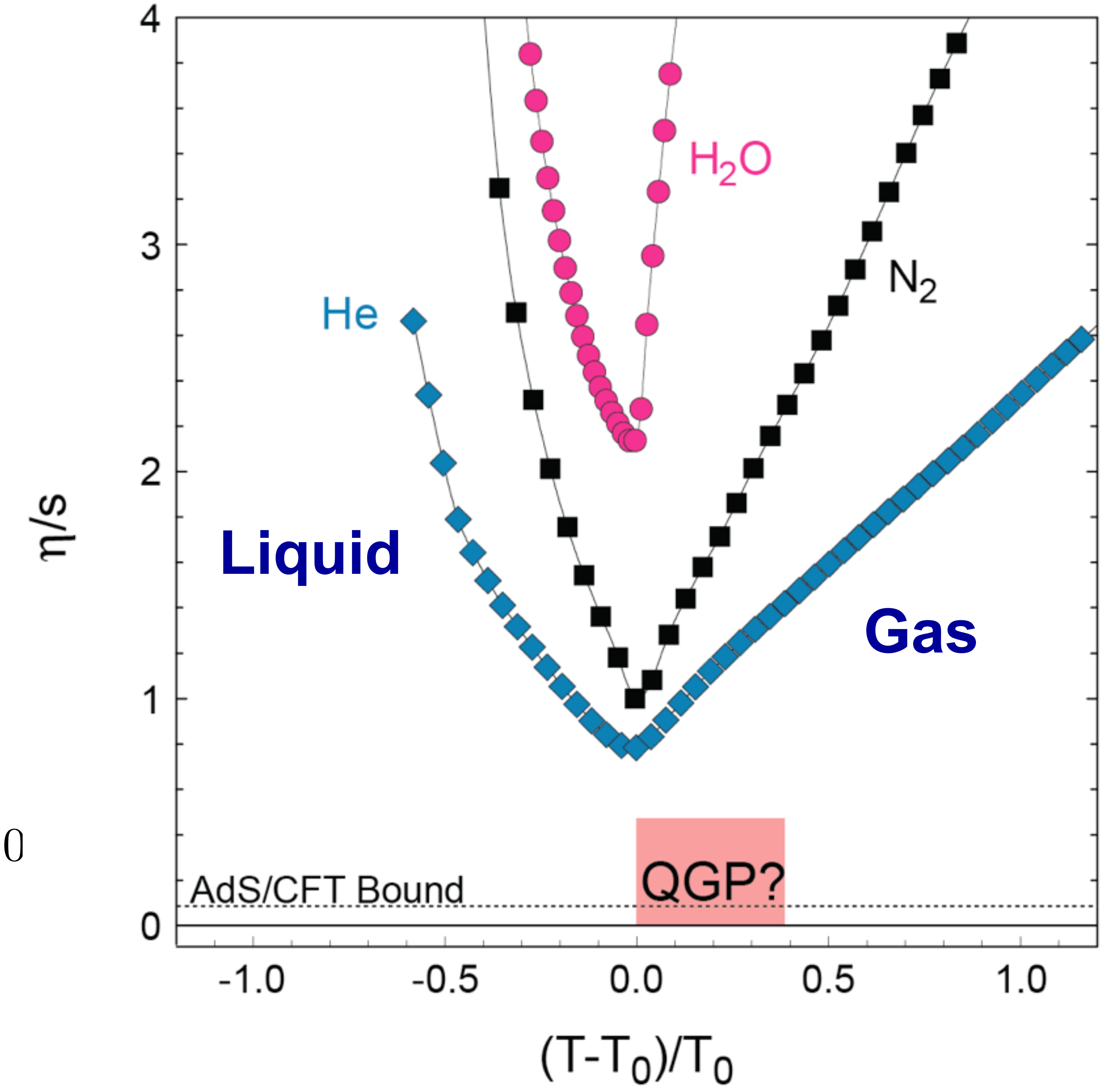
Viscosity of the QGP



Global fit to large data set:
constrains initial state geometry and
transport properties at the same time

Viscosity close to lower bound

Comparison to common liquids



QGP has a very small 'specific viscosity'

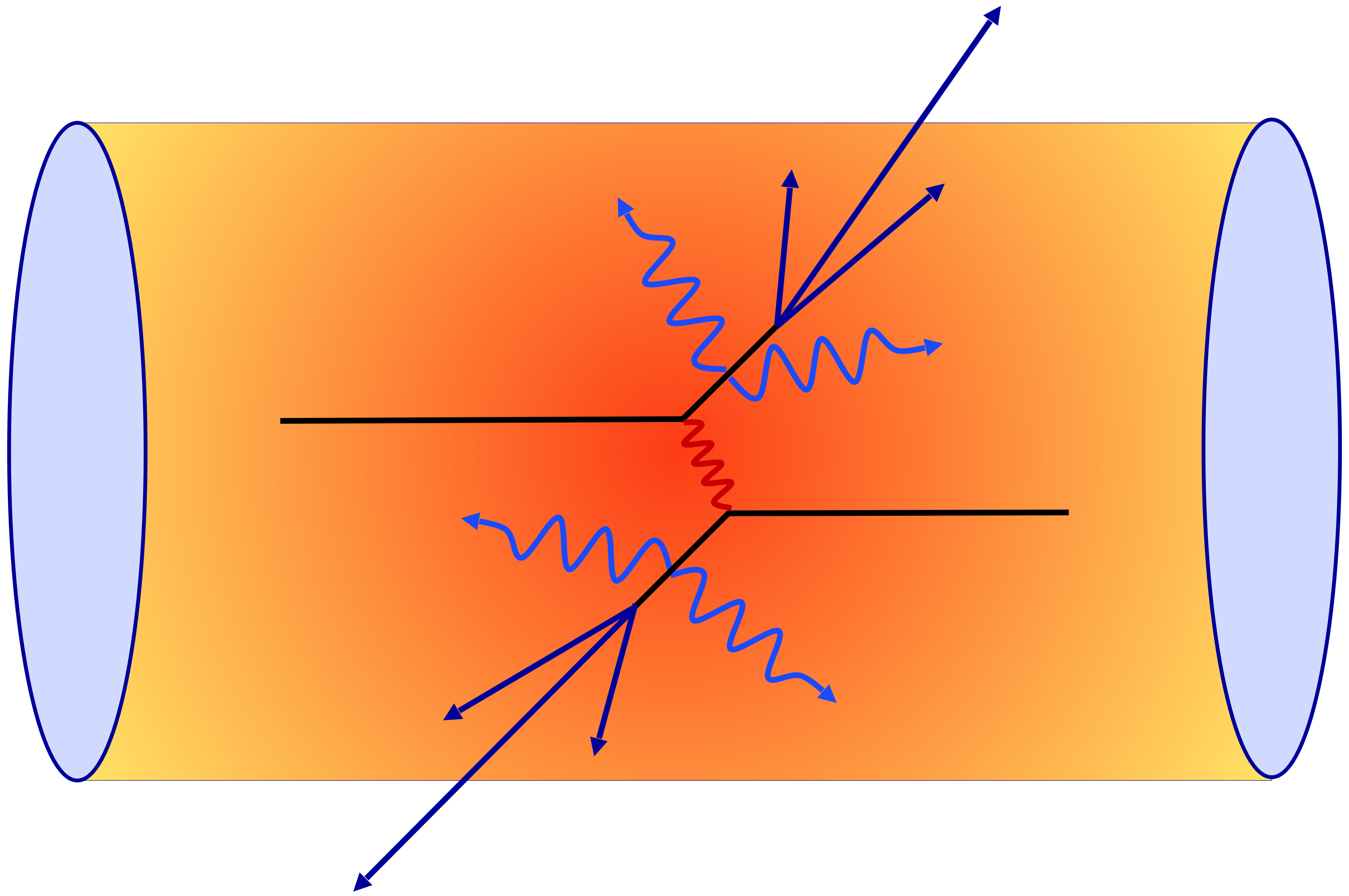
Messengers of the Plasma: soft and hard processes

Soft probes: particles produced by the QGP

Azimuthal anisotropy

Light-flavour particle ratios

Thermal radiation



Hard scattering products probe the QGP as they propagate out

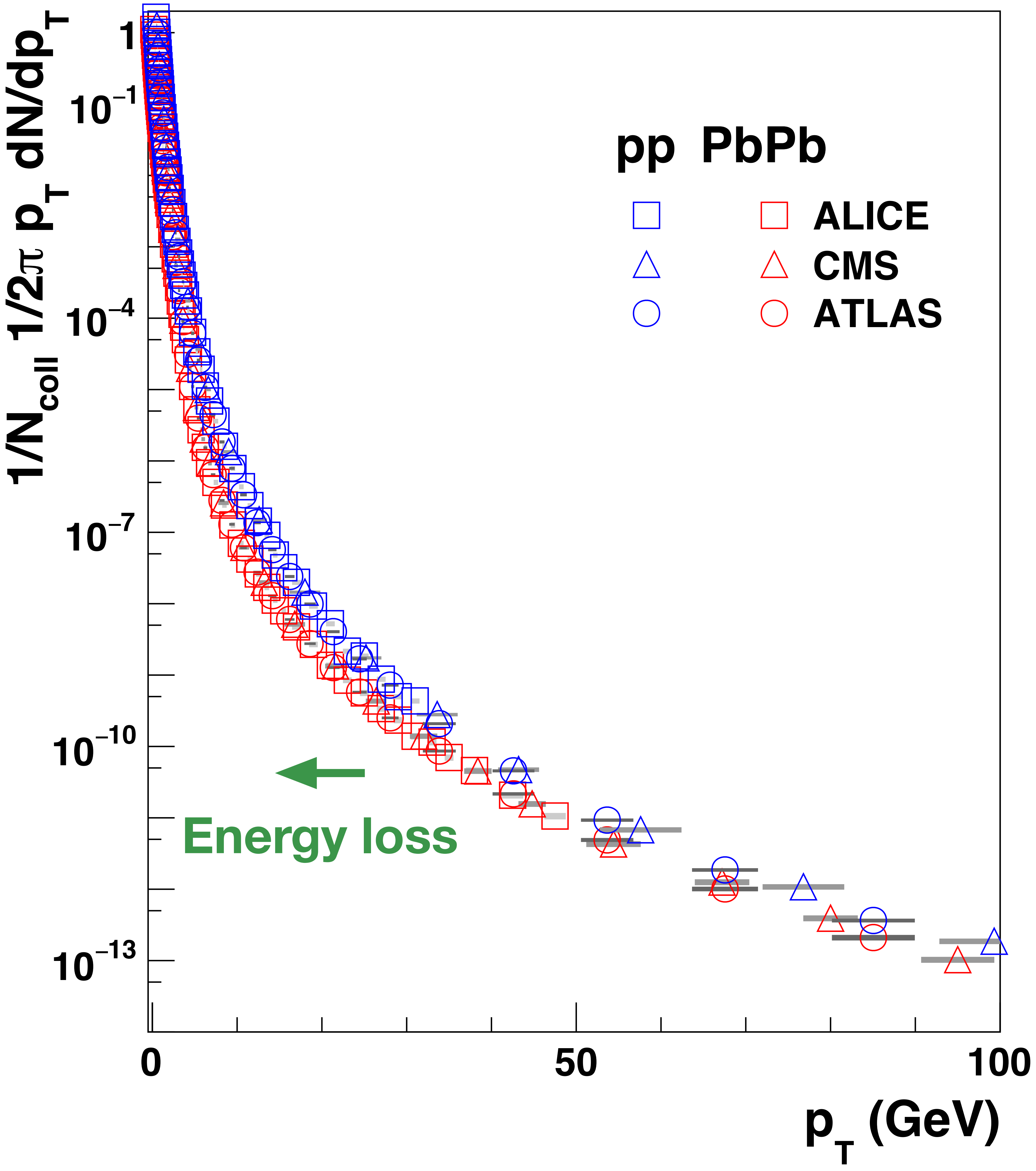
Heavy quarks charm and beauty:

- *m* >> *T*: Only produced in initial hard scattering
- Flavour conserved during evolution

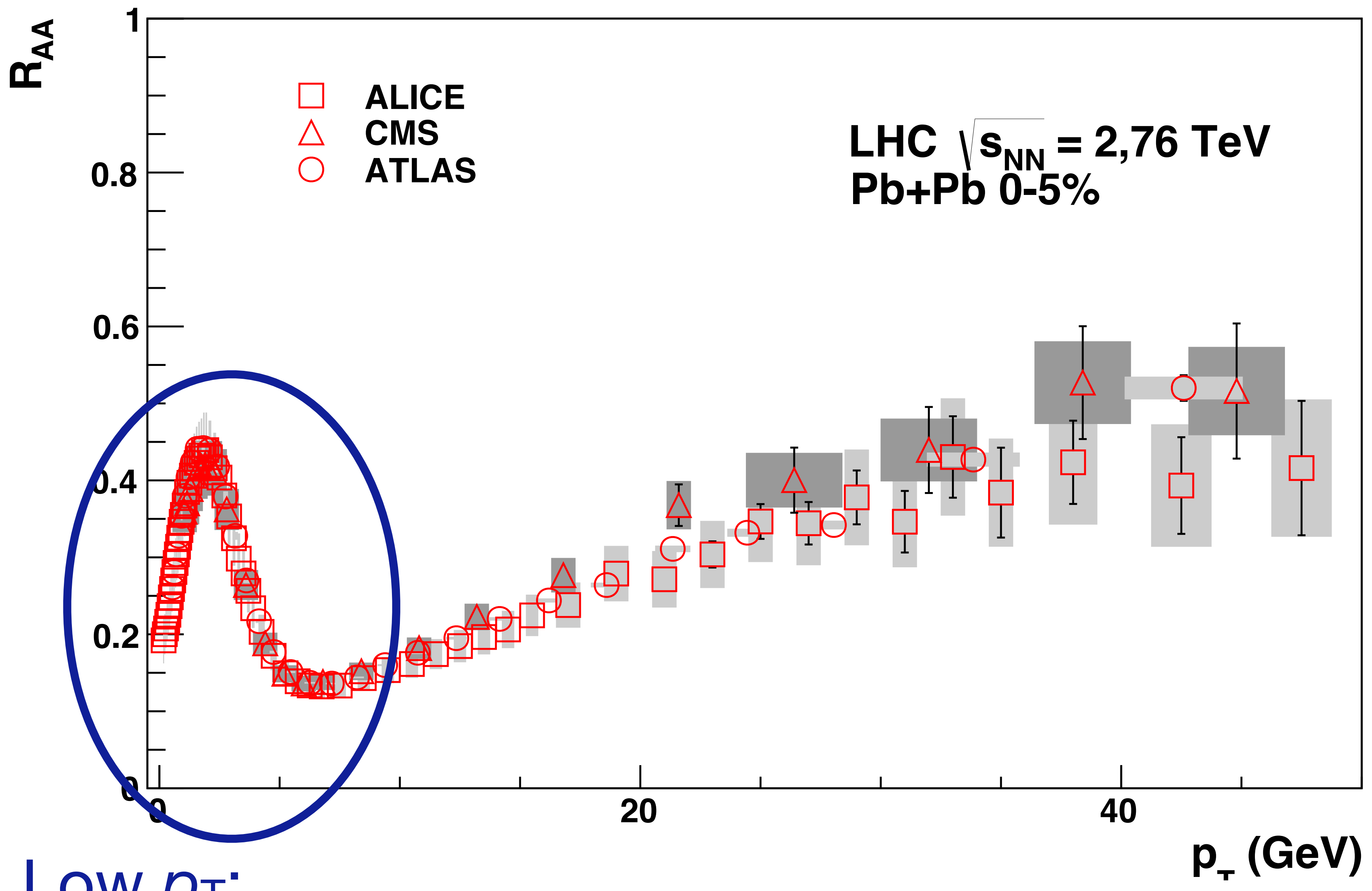
Nuclear modification: Pb+Pb

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

Charged particle p_T spectra

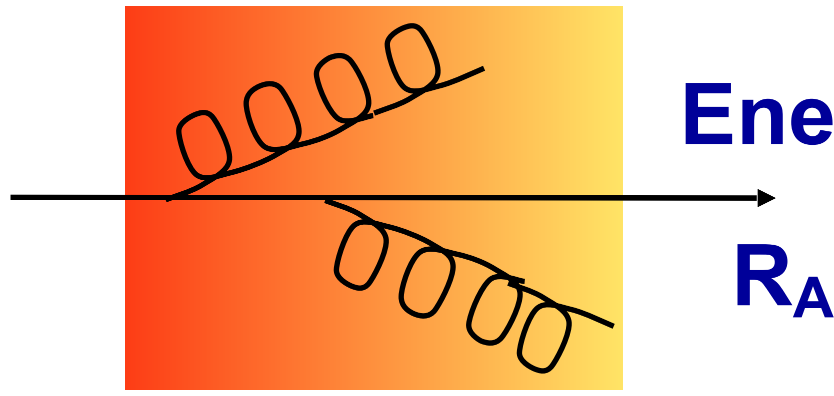


Nuclear modification factor



Low p_T:
soft production,
N_{part} scaling

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



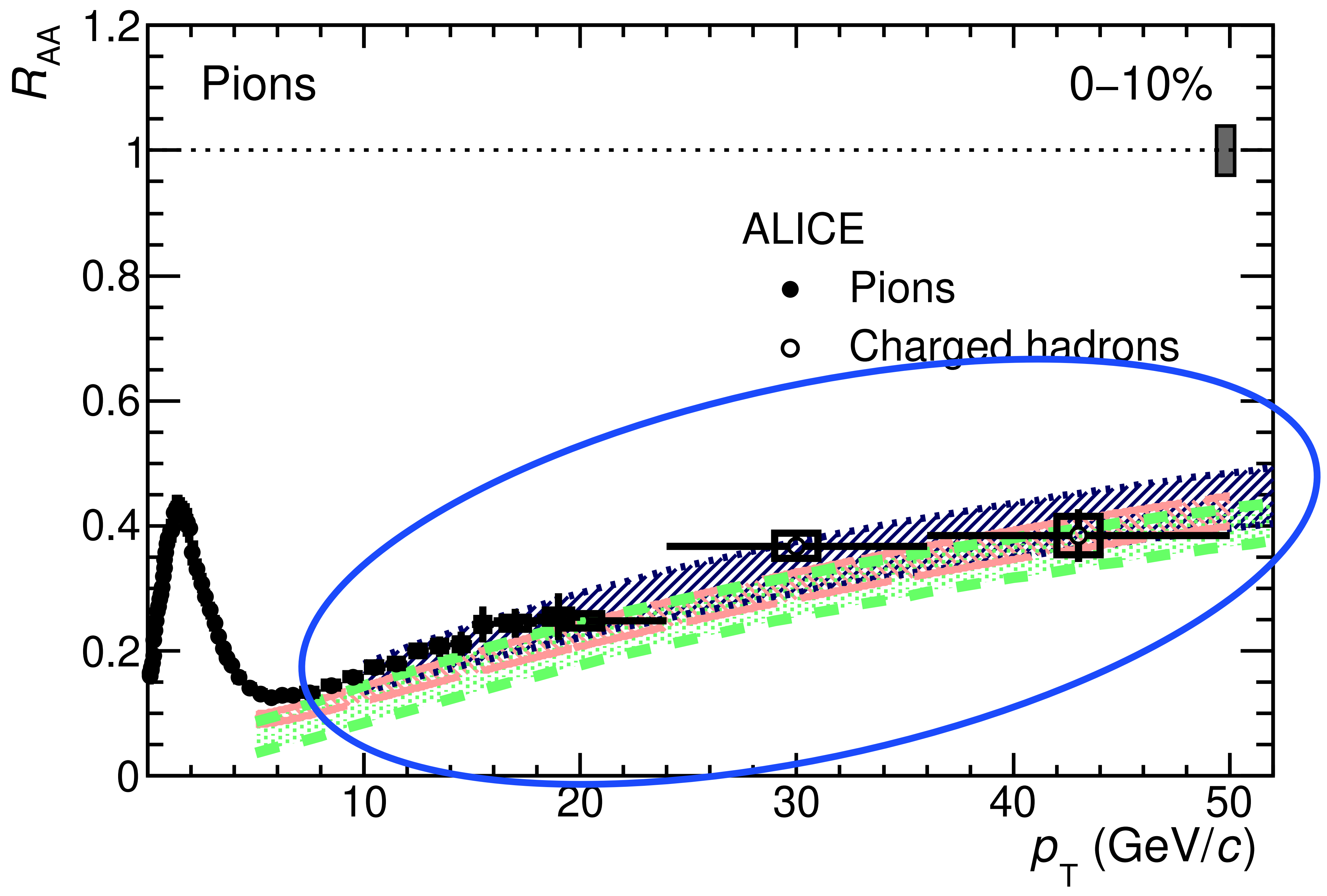
Energy loss

$R_{AA} < 1$

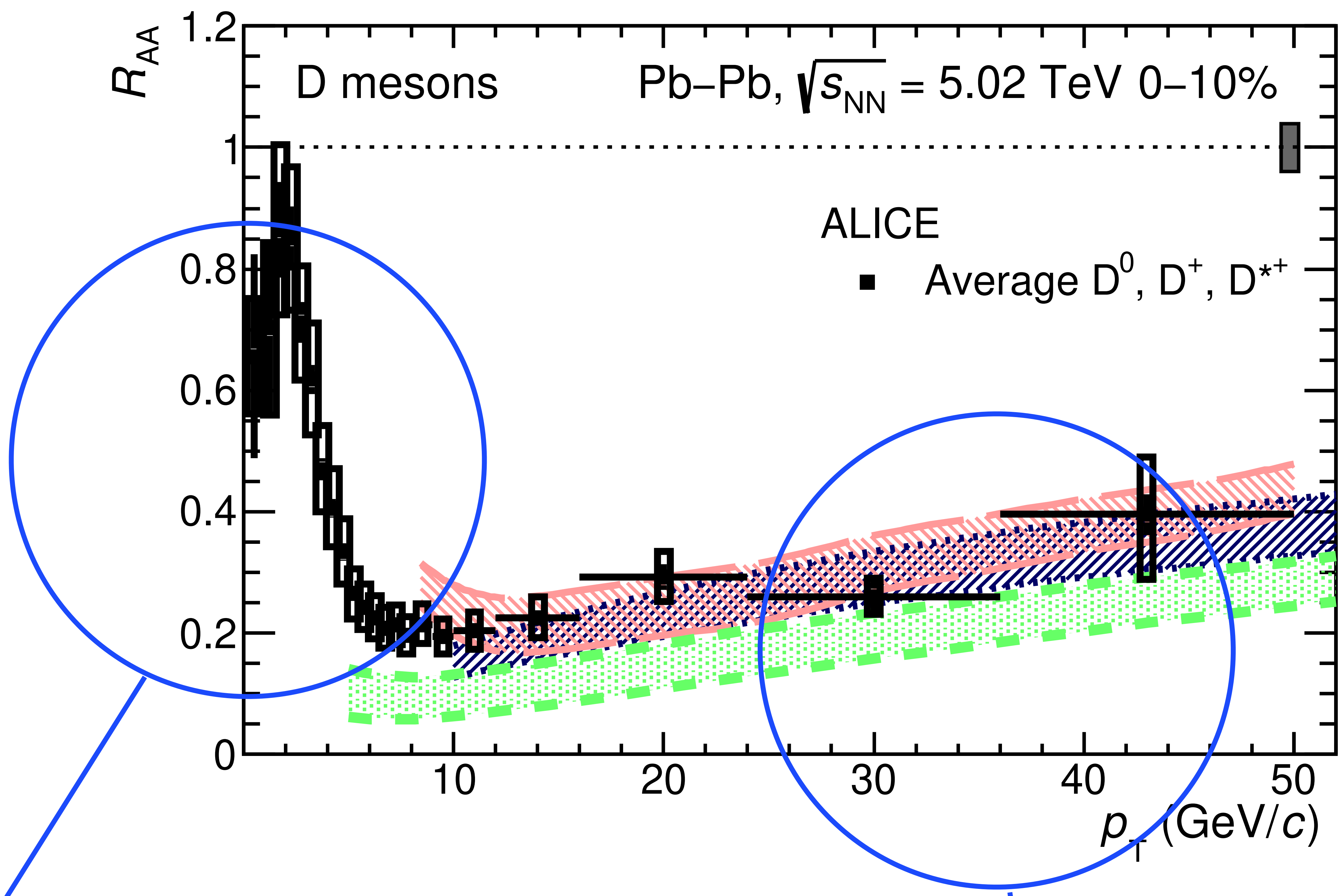
Pb+Pb: clear suppression ($R_{AA} < 1$): parton energy loss

Nuclear modification factor: light and heavy quarks

Light flavour: pions, charged particles



Heavy flavour: D mesons



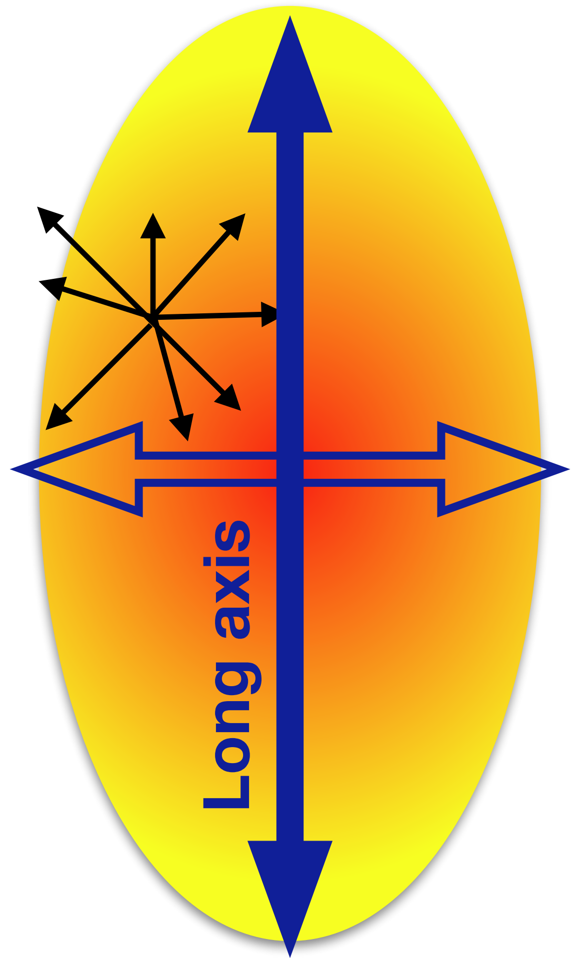
Low p_T: no change/enhancement:
charm conservation + energy loss

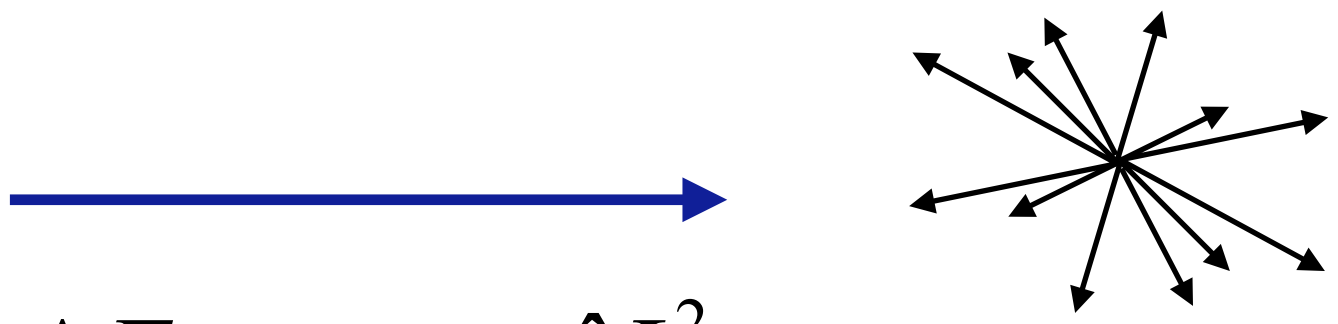
High-p_T suppression:
due to energy loss/thermalisation

ALICE, JHEP 01 (2022) 174

Heavy quark azimuthal anisotropy

Nuclear overlap non-central collisions





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

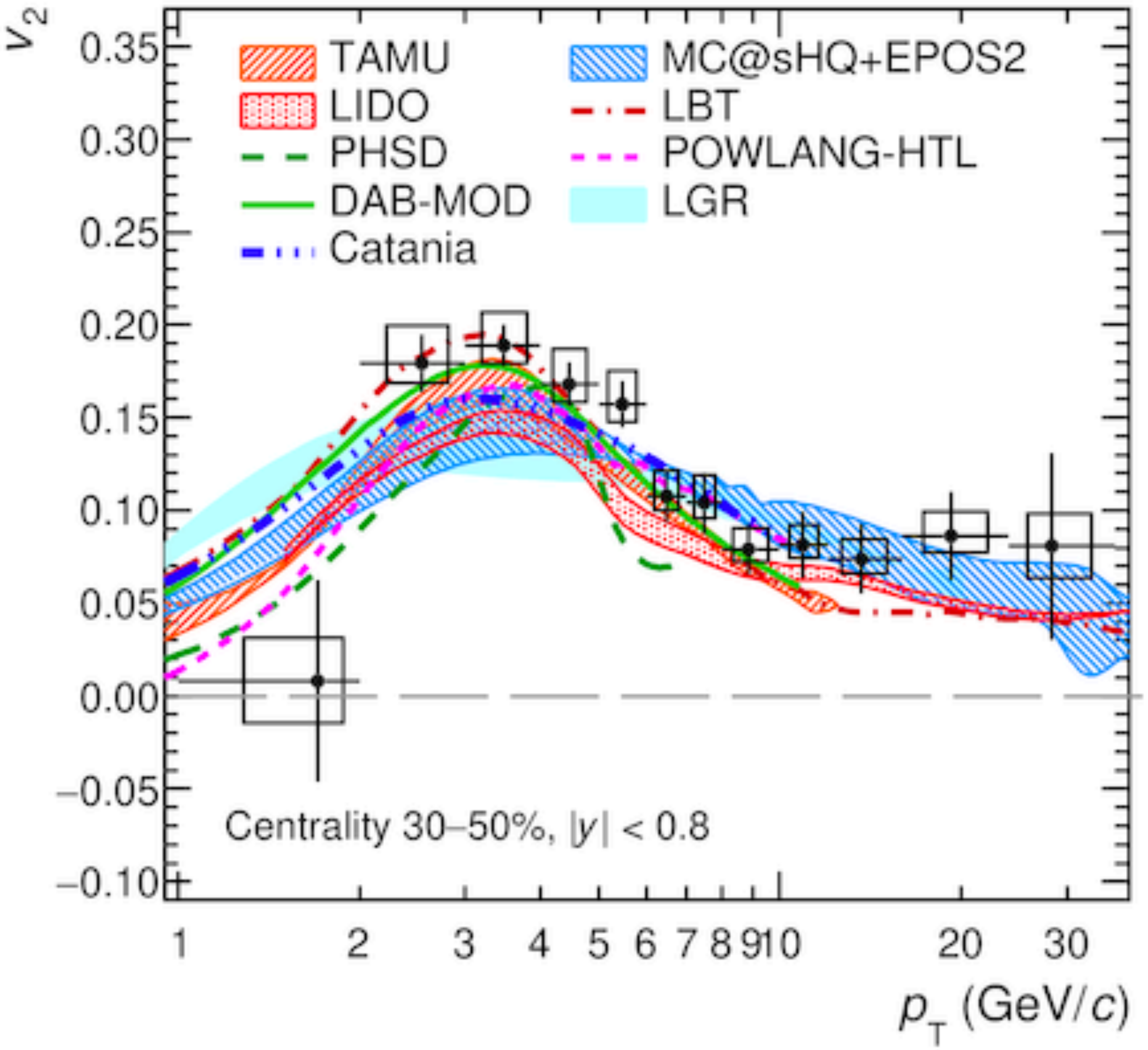
Anisotropy generated by energy loss differences

Initial production is isotropic

Azimuthal anisotropy v_2:

$$\frac{dN}{d\phi} \propto 1 + 2\,v_2 \cos 2(\varphi - \psi)$$

D meson elliptic flow v_2



JHEP 01 (2022) 174

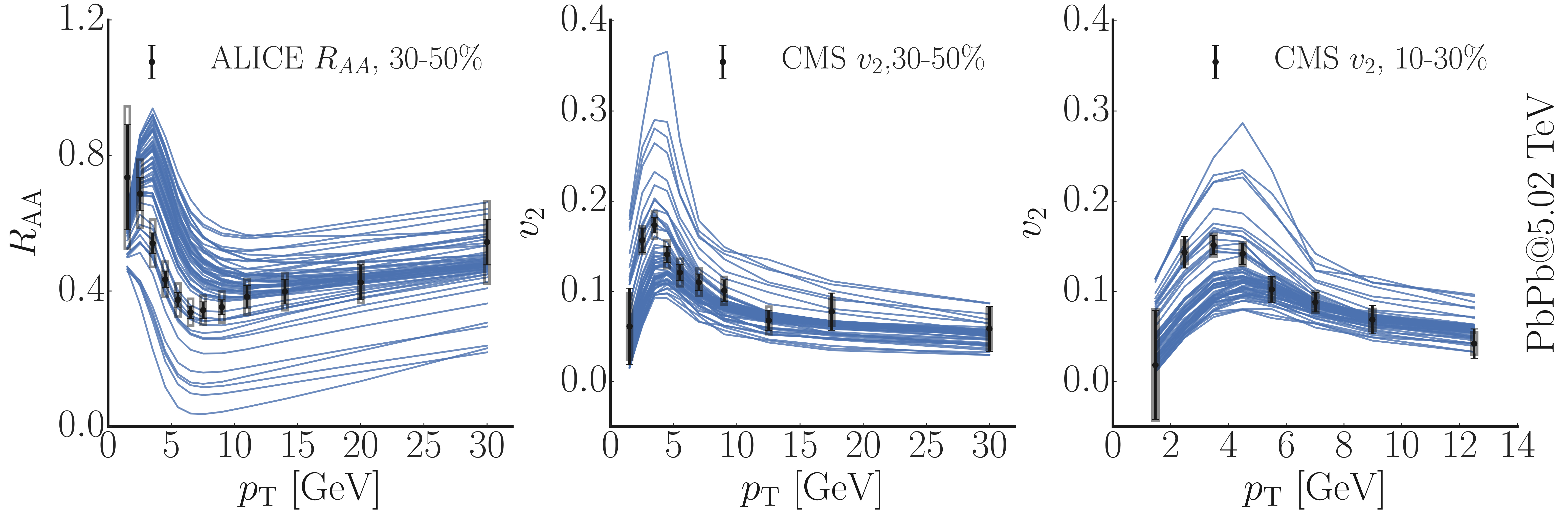
Azimuthal anisotropy:

Full effect generated by interactions

Determining the transport coefficients

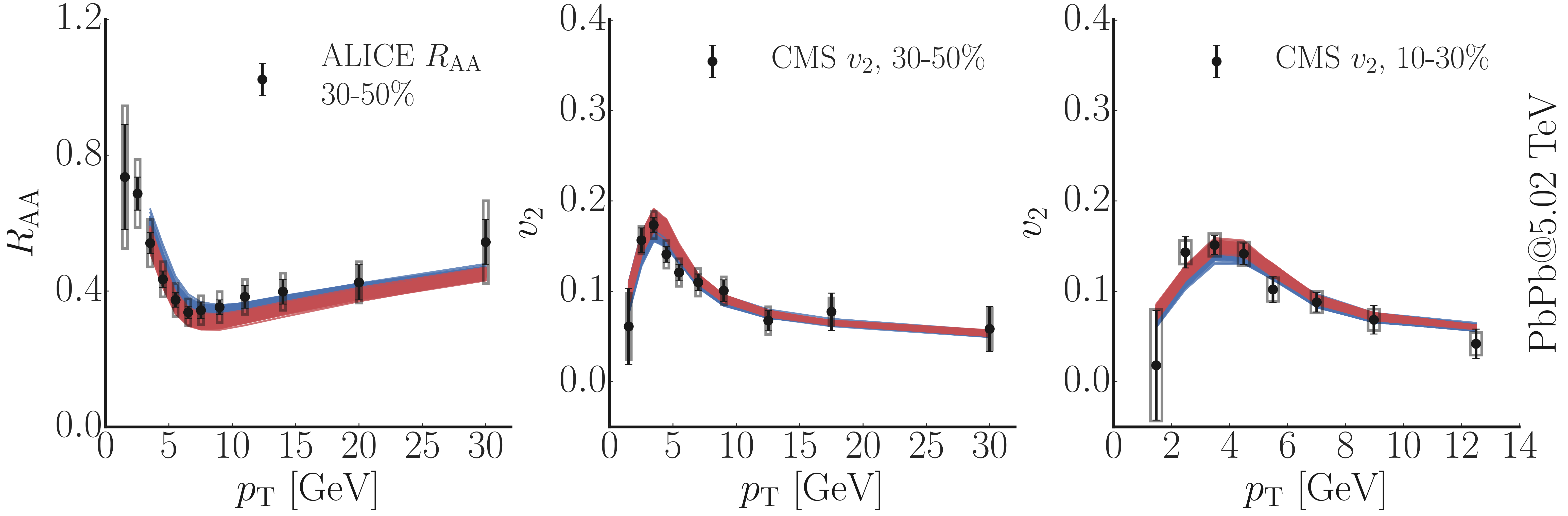
Run model for different parameter settings

⇒ interpolate with Gaussian process emulator



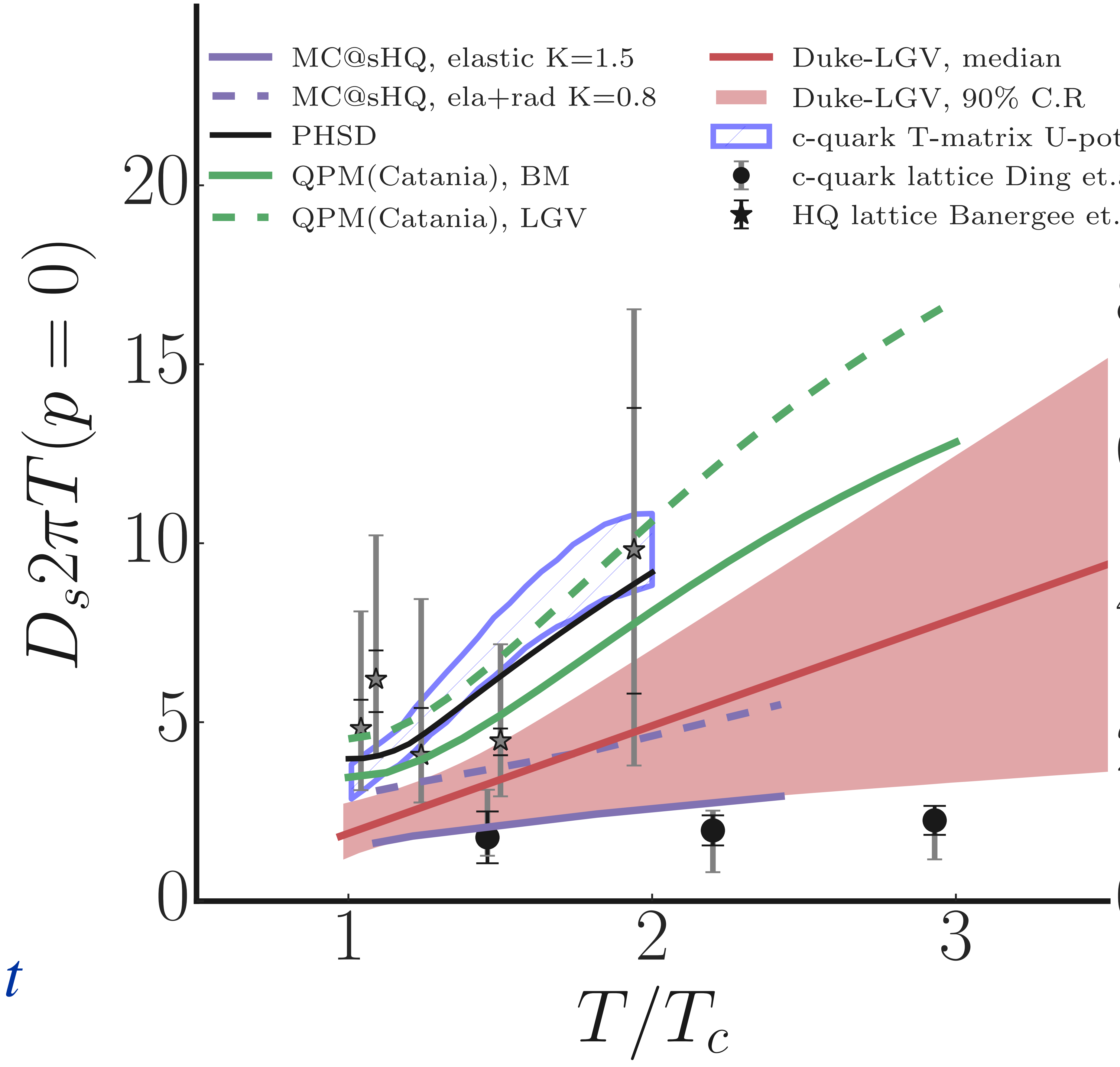
Posterior

Range of model settings that agree with data



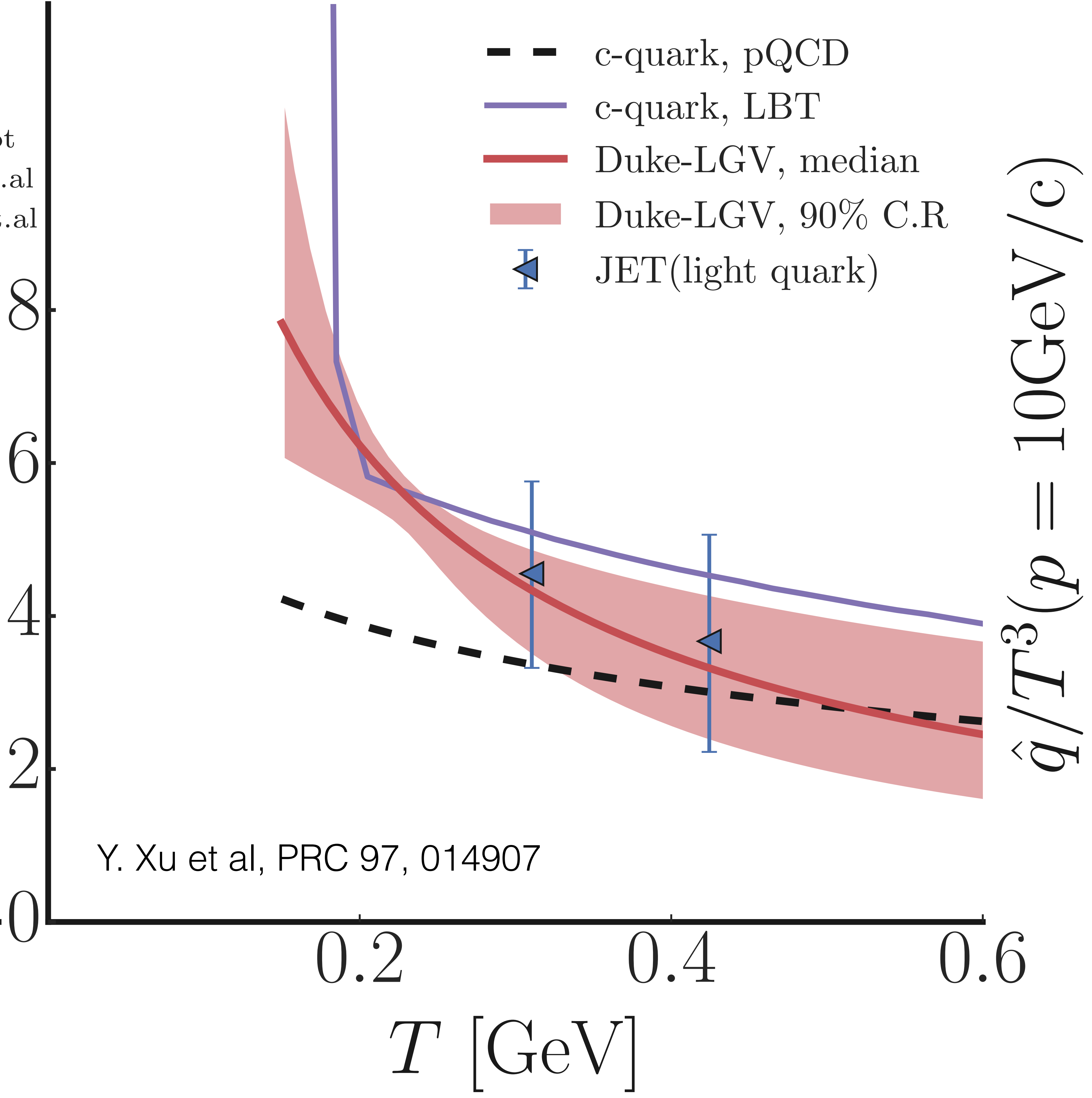
Heavy flavor transport coefficient: Bayesian fit

Diffusion coefficient D_s



$$\langle r^2 \rangle = 6\, D_s\, t$$

Transport coefficient $\hat{q}$



Y. Xu et al, PRC 97, 014907

$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

Data constrain transport properties of the QGP

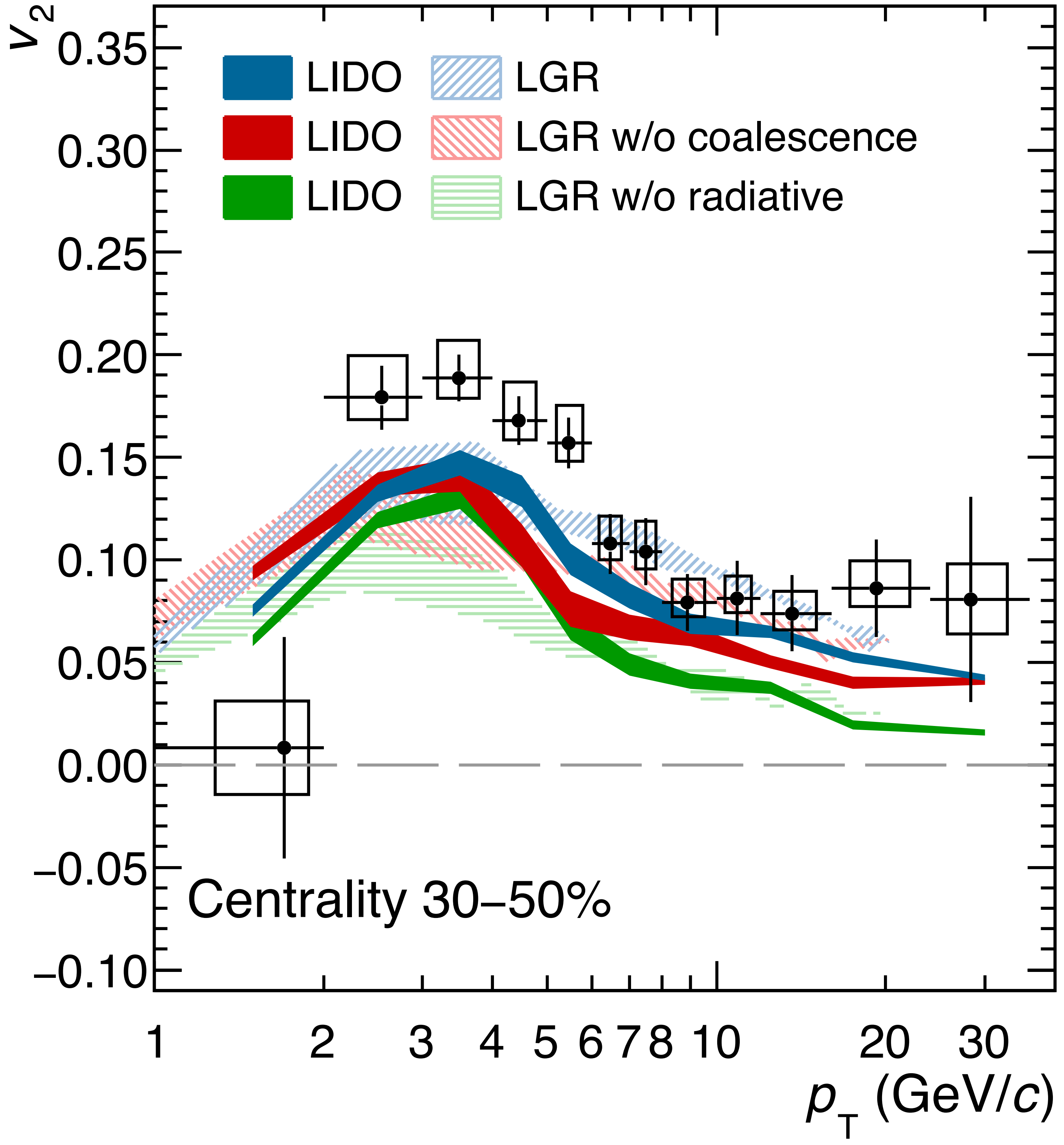
Results agree with lattice QCD/pQCD expectations

Heavy quark transport: some open questions

Nuclear modification and v_2 of light and heavy flavour qualitatively understood

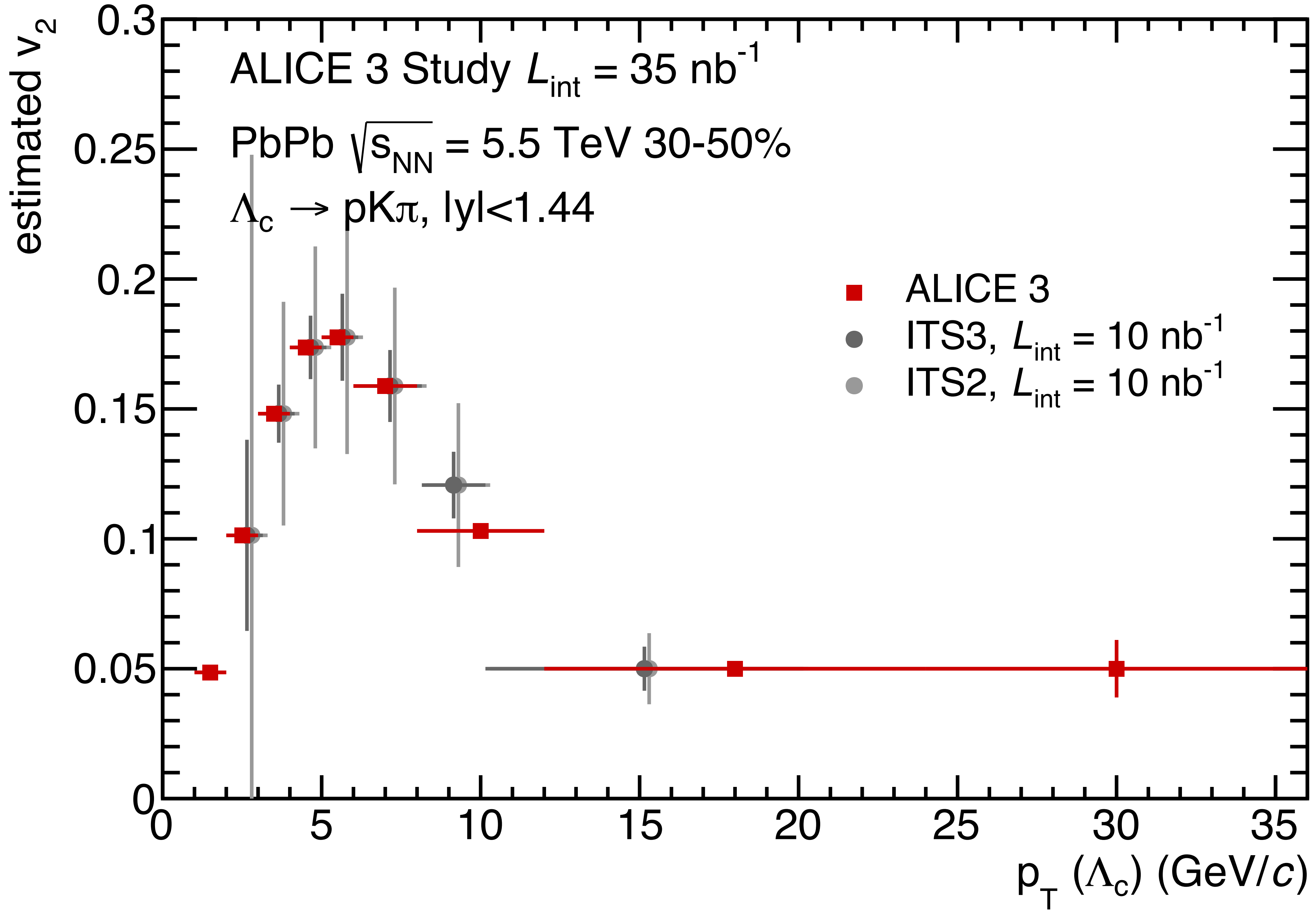
Some open questions remain:

- **Interplay/relation between**:
  - Diffusion/drag: **elastic processes** — dominant at low p_T
  - **Inelastic processes**: gluon radiation — dominant at high p_T
- Approach to **thermalisation**:
  - Large charm $v_2 \Longrightarrow$ close to thermalisation?
  - Expect larger thermalisation time for beauty
  - **Role of hadronisation**: dependence on light quark v_2 via quark coalescence?

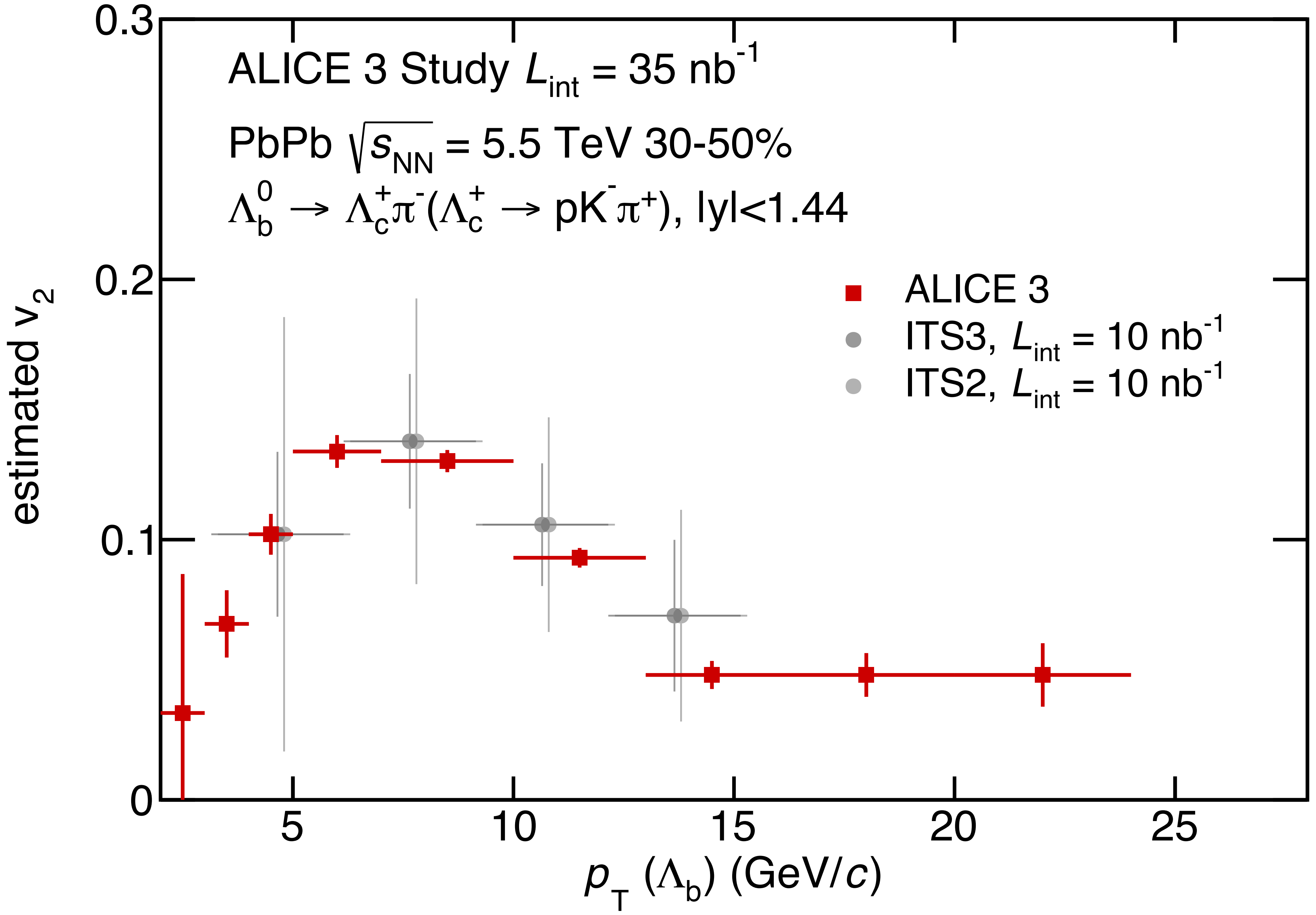


Heavy flavour transport: performance for run 3 and beyond

Λ_c v_2 performance



Λ_b v_2 performance



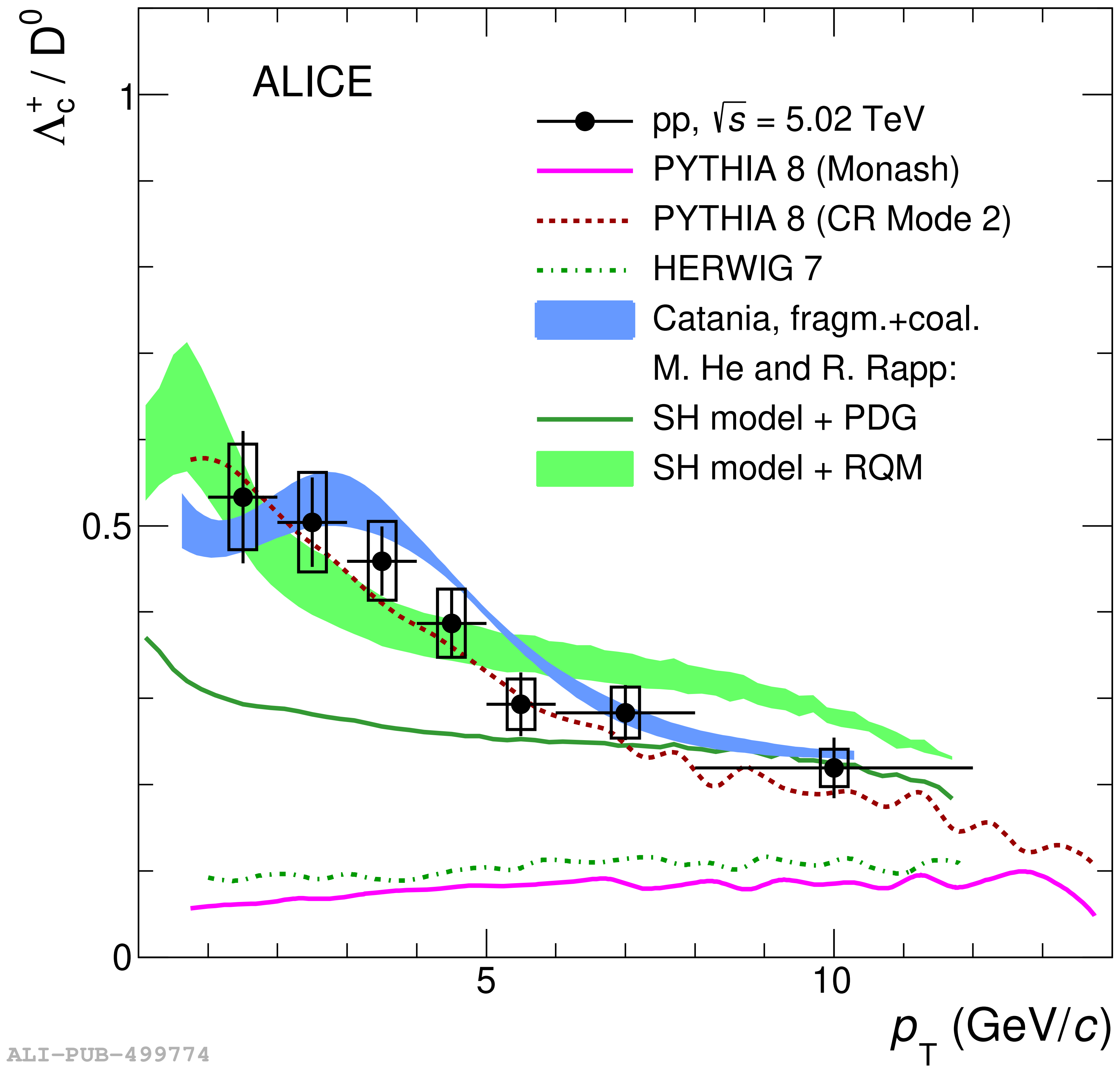
- Heavy quarks: access to quark transport at hadron level
  - Expect beauty thermalisation slower than charm — smaller v_2
- Run 3 and 4: measure Λ_c v_2; large uncertainty for Λ_b
- ALICE 3: precision measurements Λ_c and Λ_b v_2

relaxation time

$$\tau_Q = (m_Q/T)\, D_s$$

Hadronisation and baryon production

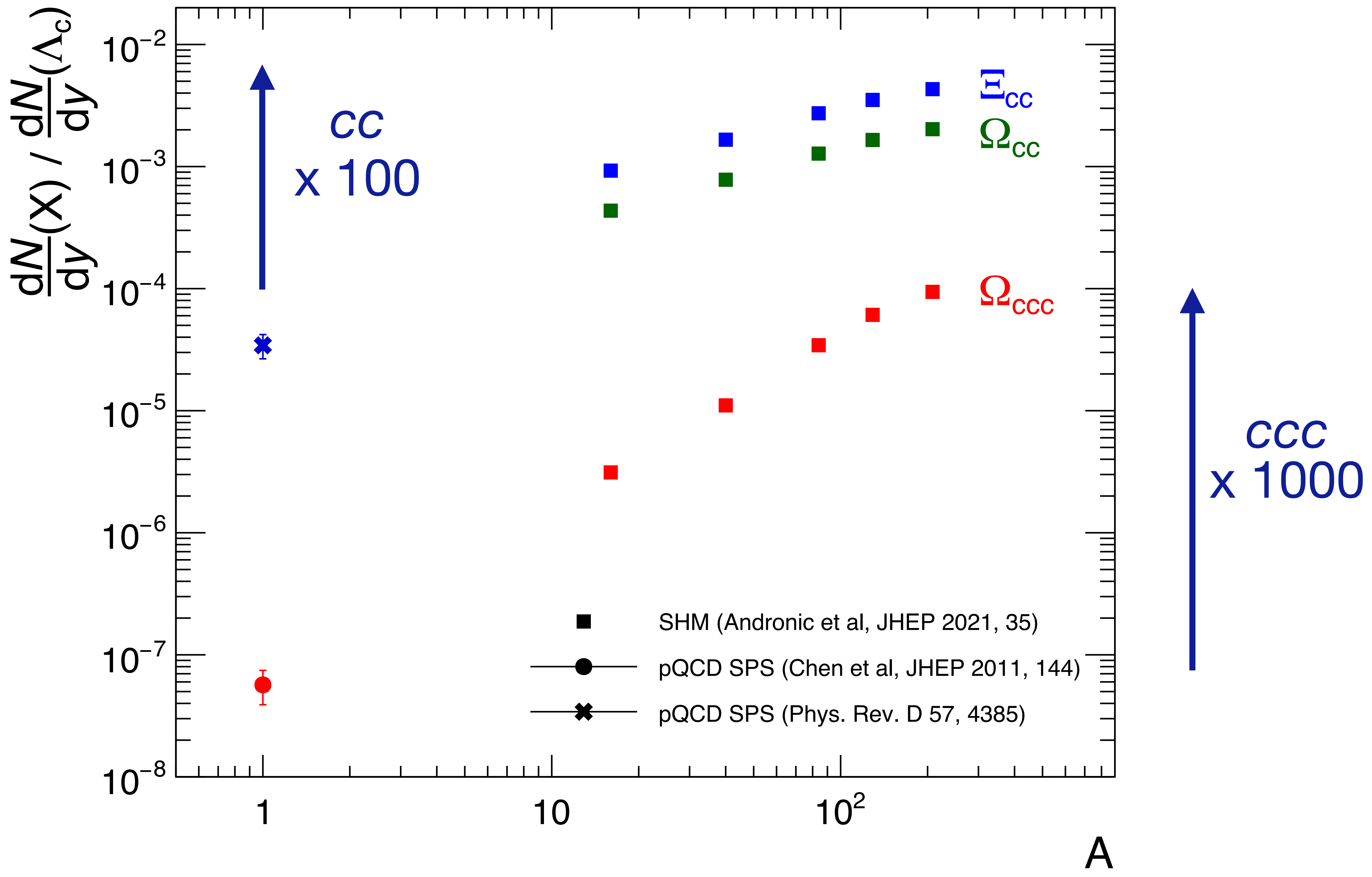
Charm baryon/meson ratio



ALICE, PRL 127, 202301

Charm baryon production enhanced in pp, AA compared to e^+e^-

Multi-charm baryon yields

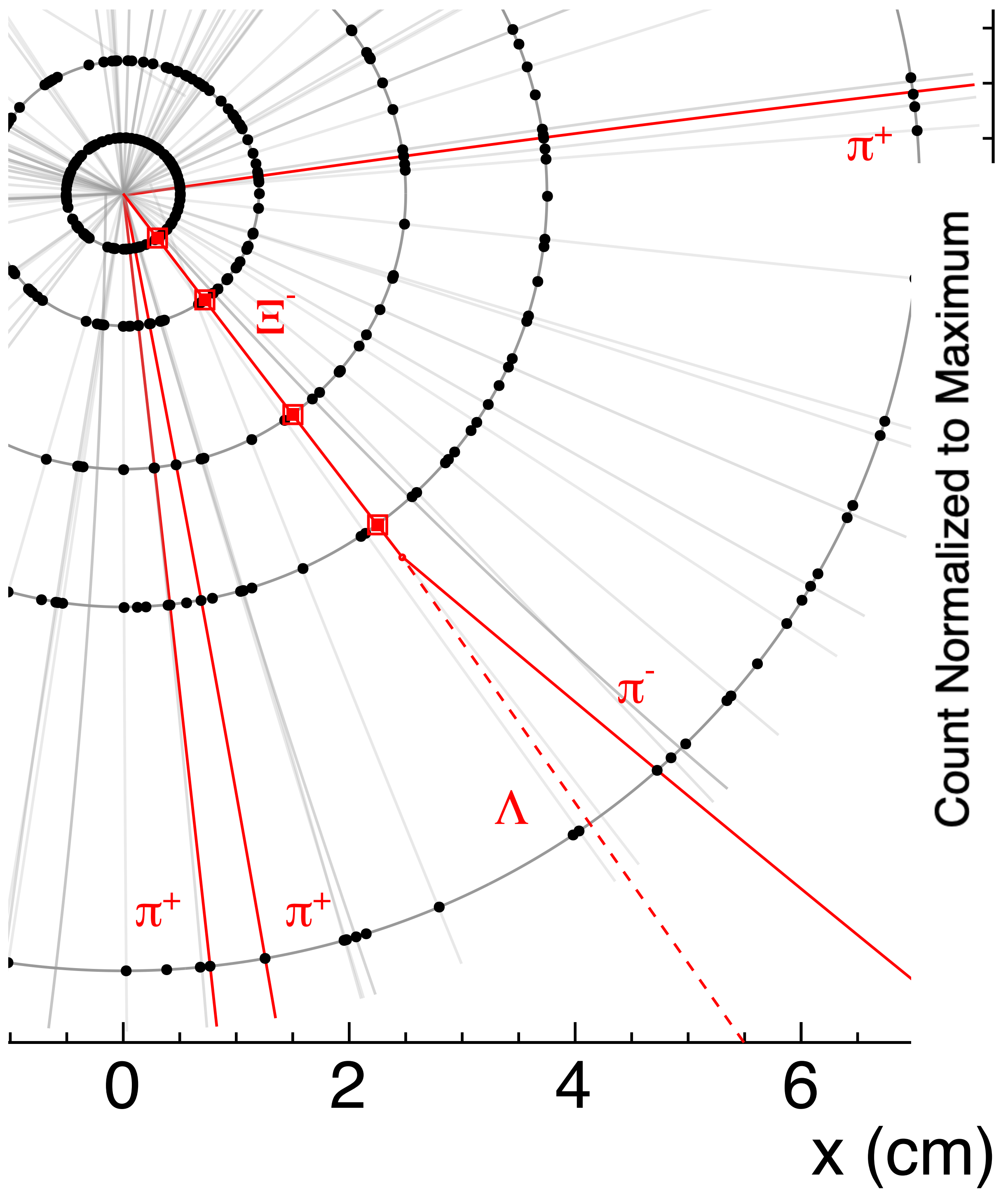


Multi-charm baryons: unique probe

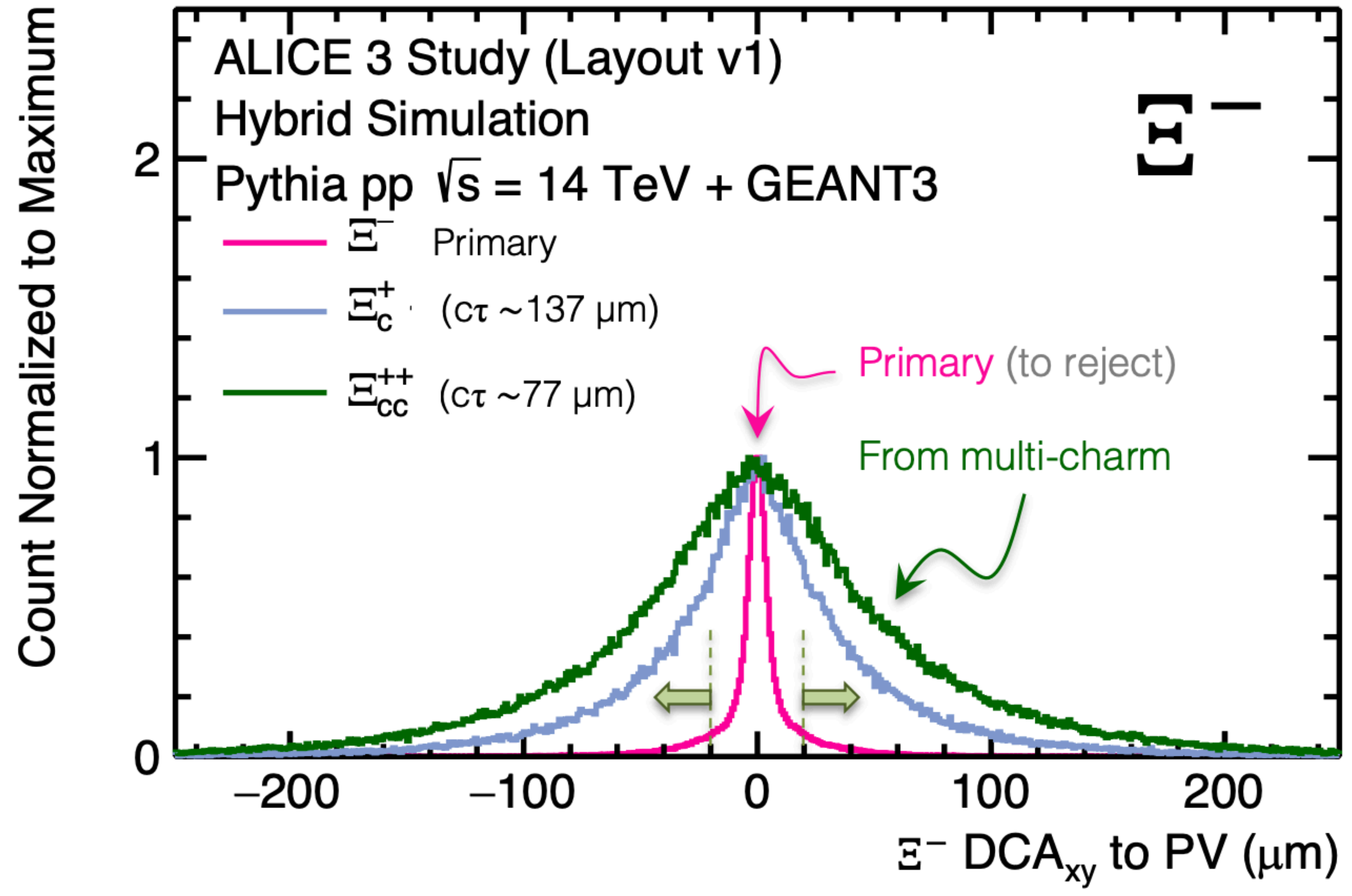
- Large expected enhancement
- Theoretically clean: charm quarks conserved

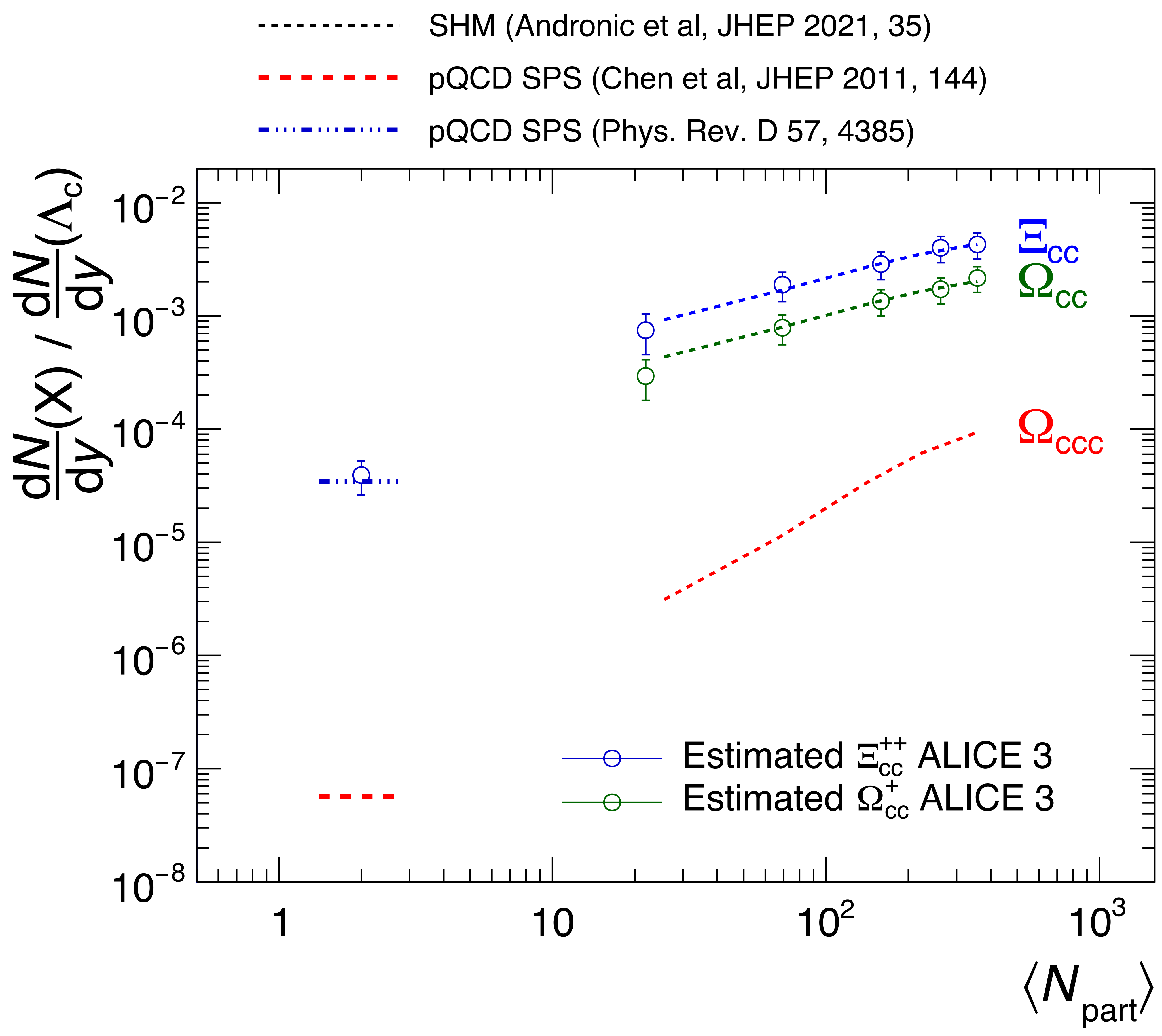
Multi-charm baryon detection

New technique: strangeness tracking



Impact parameter of Ξ





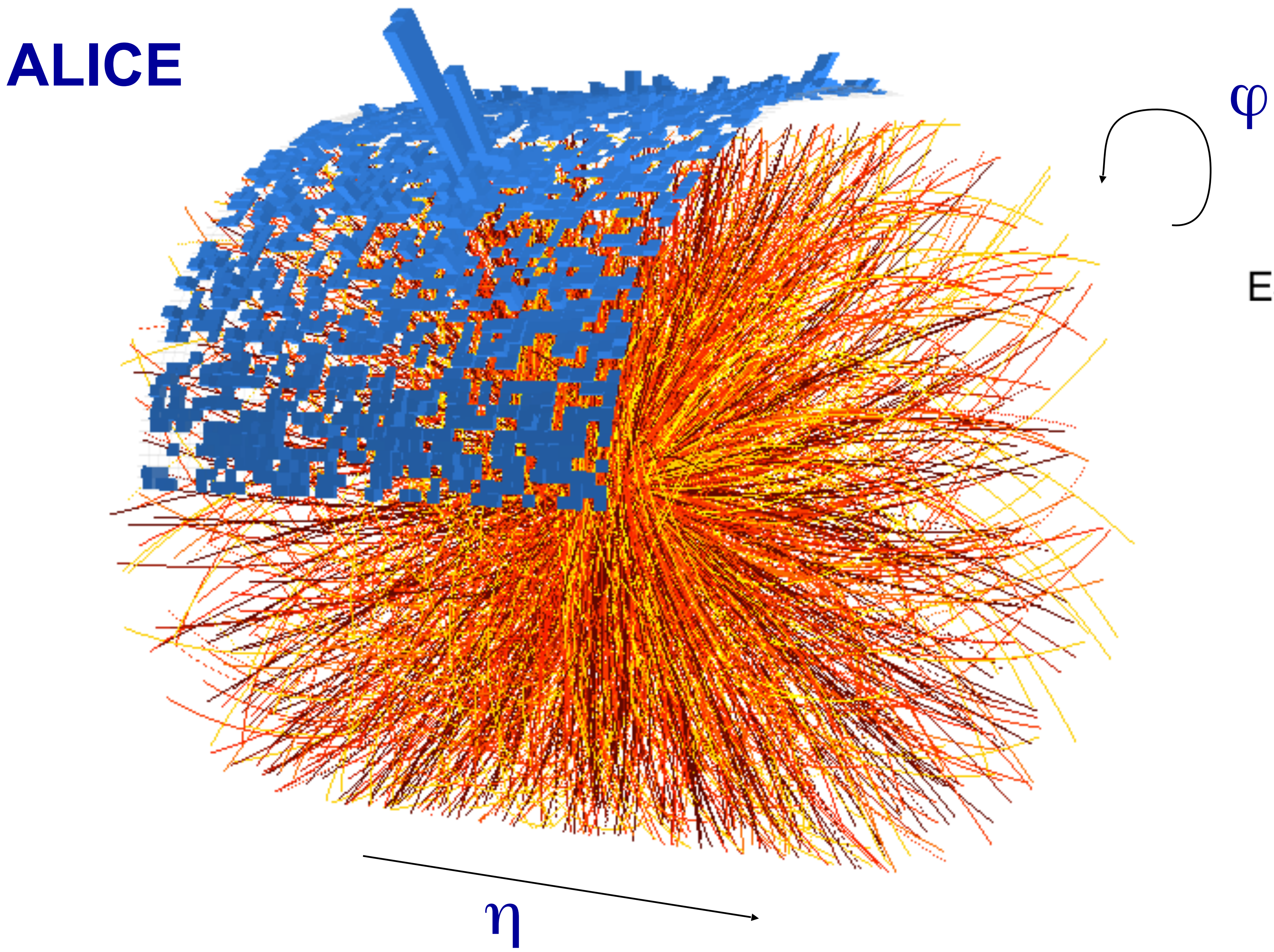
Pointing of Ξ baryon provides high selectivity

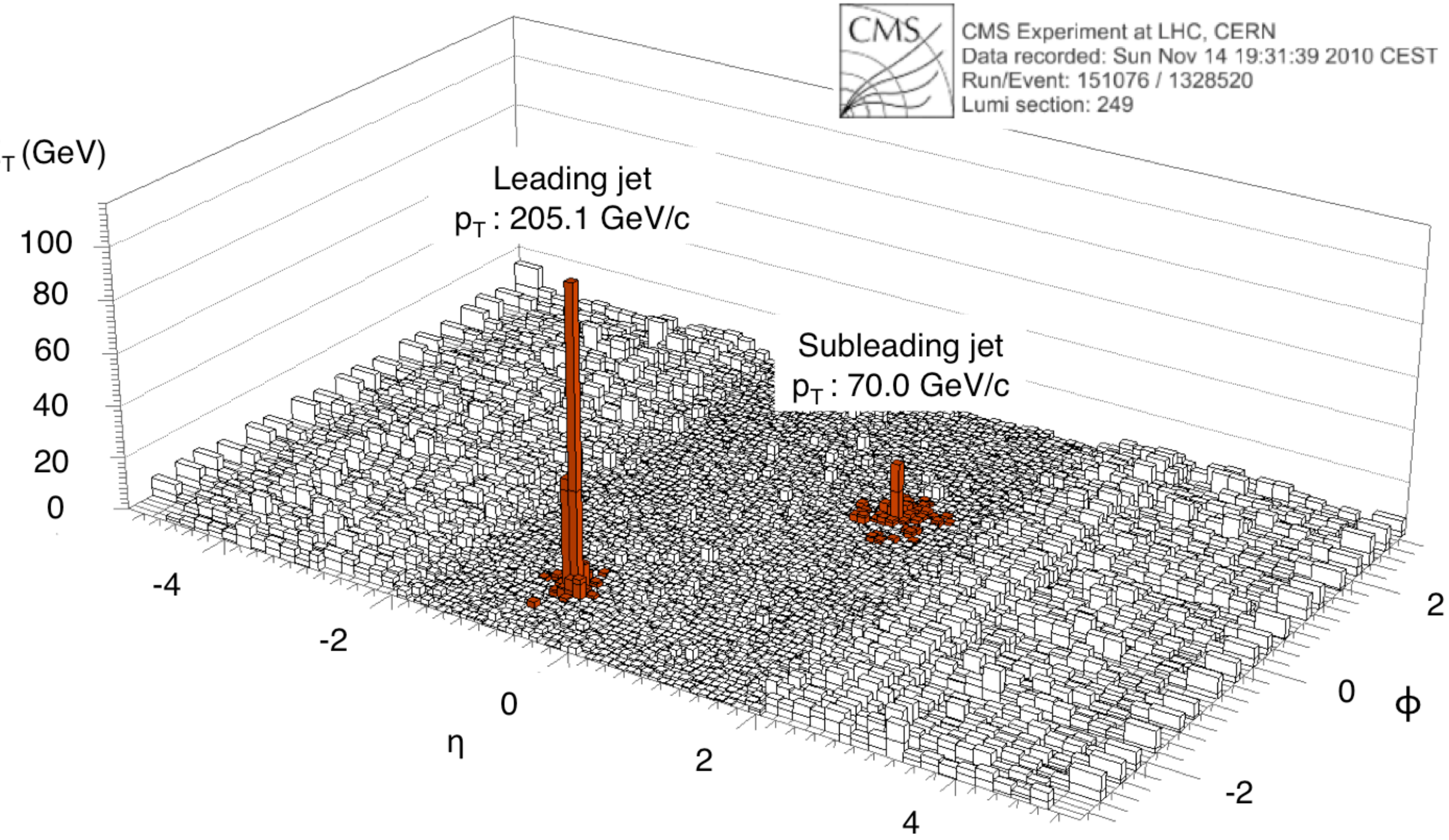
$$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} + \pi^{+} \qquad \Xi_c^{+} \rightarrow \Xi^{-} + 2\pi^{+}$$

Large enhancements: unique sensitivity to thermalisation and hadronisation dynamics

Unique access in Pb-Pb collisions with ALICE 3

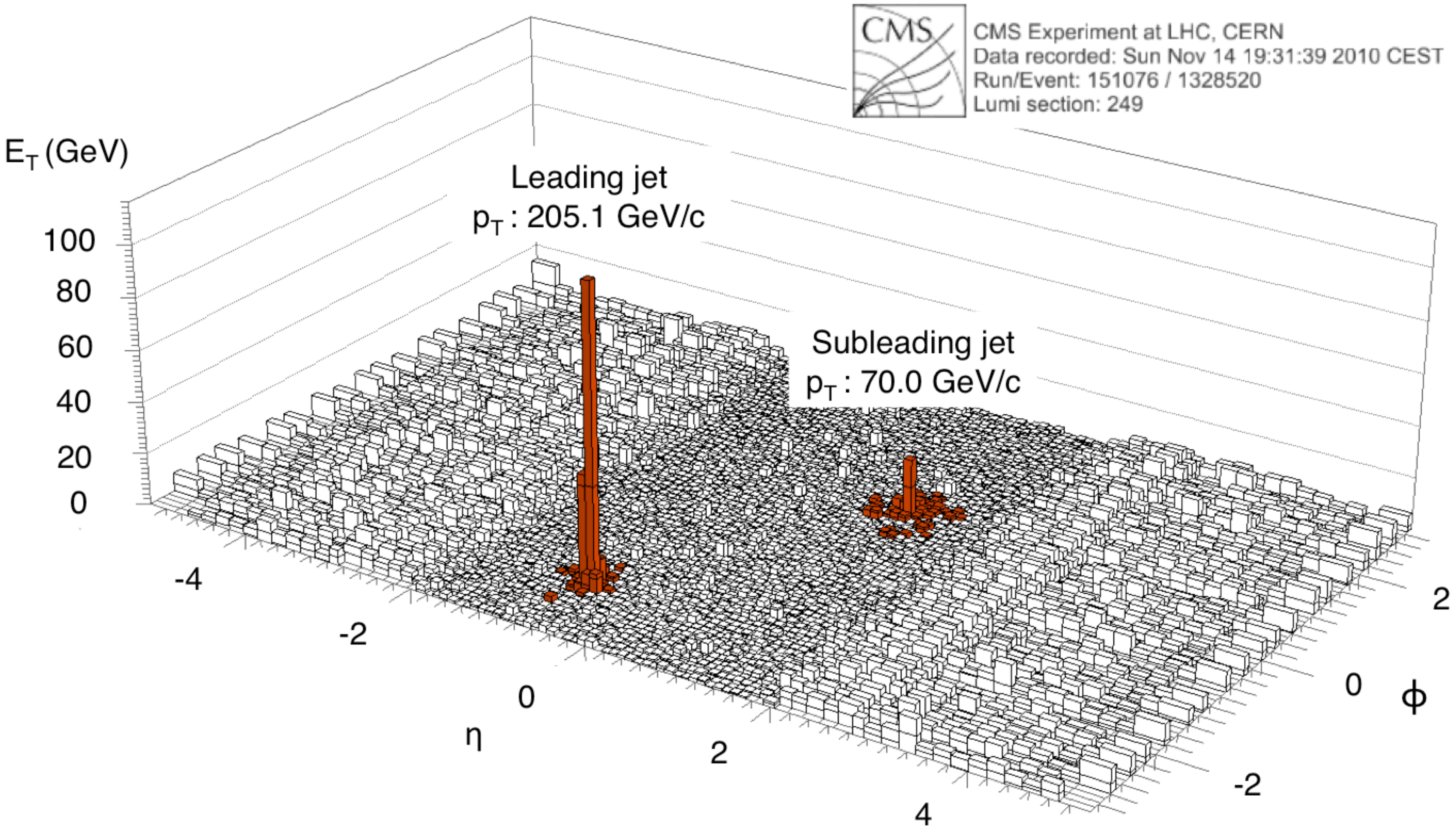
Probing the QGP with jets at LHC





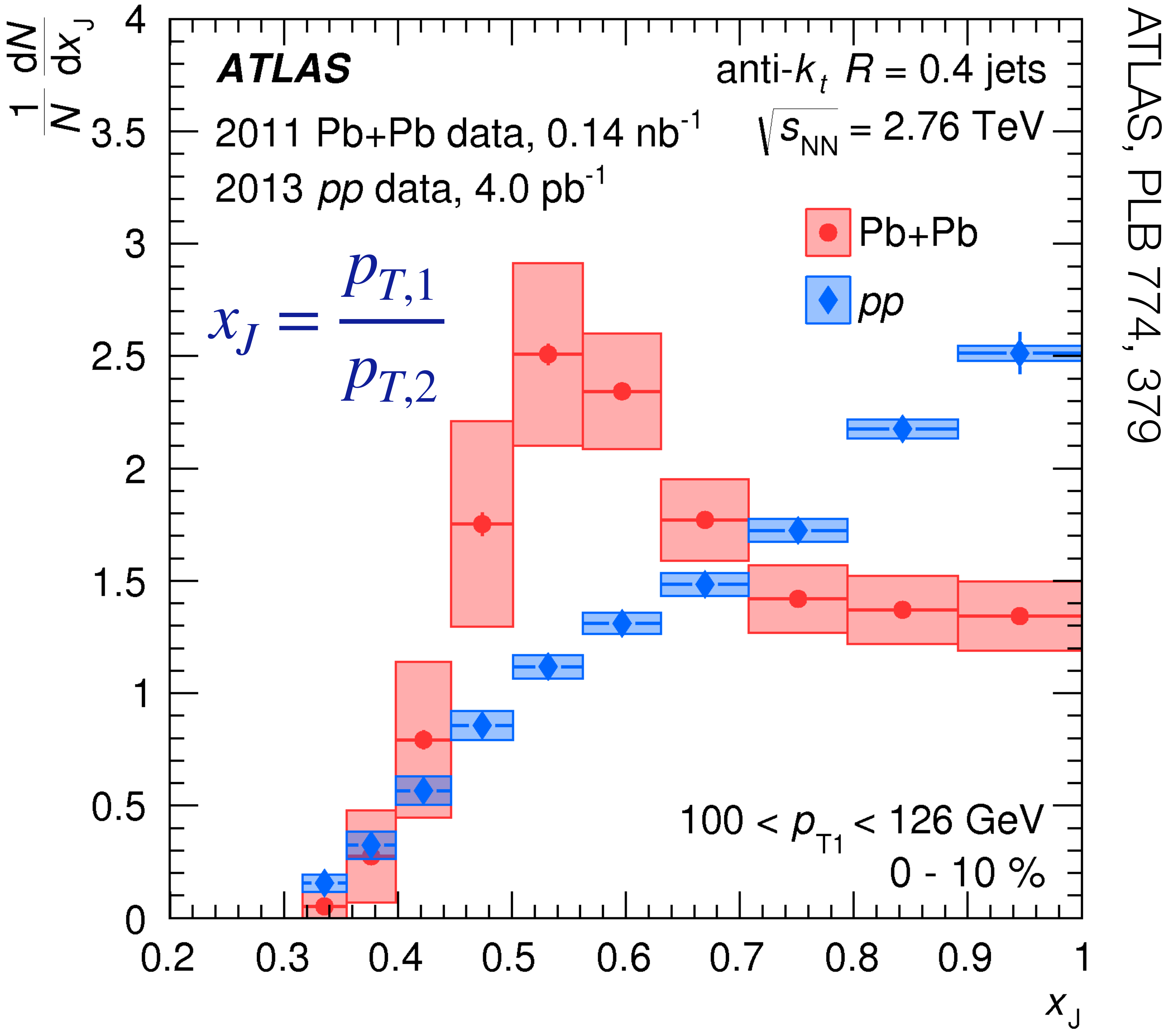
Very clear signals at high p_T: jets stand out above uncorrelated ‘soft’ background

Energy loss: di-jet asymmetry



Single event: p_T not balanced!

Energy fraction of second jet



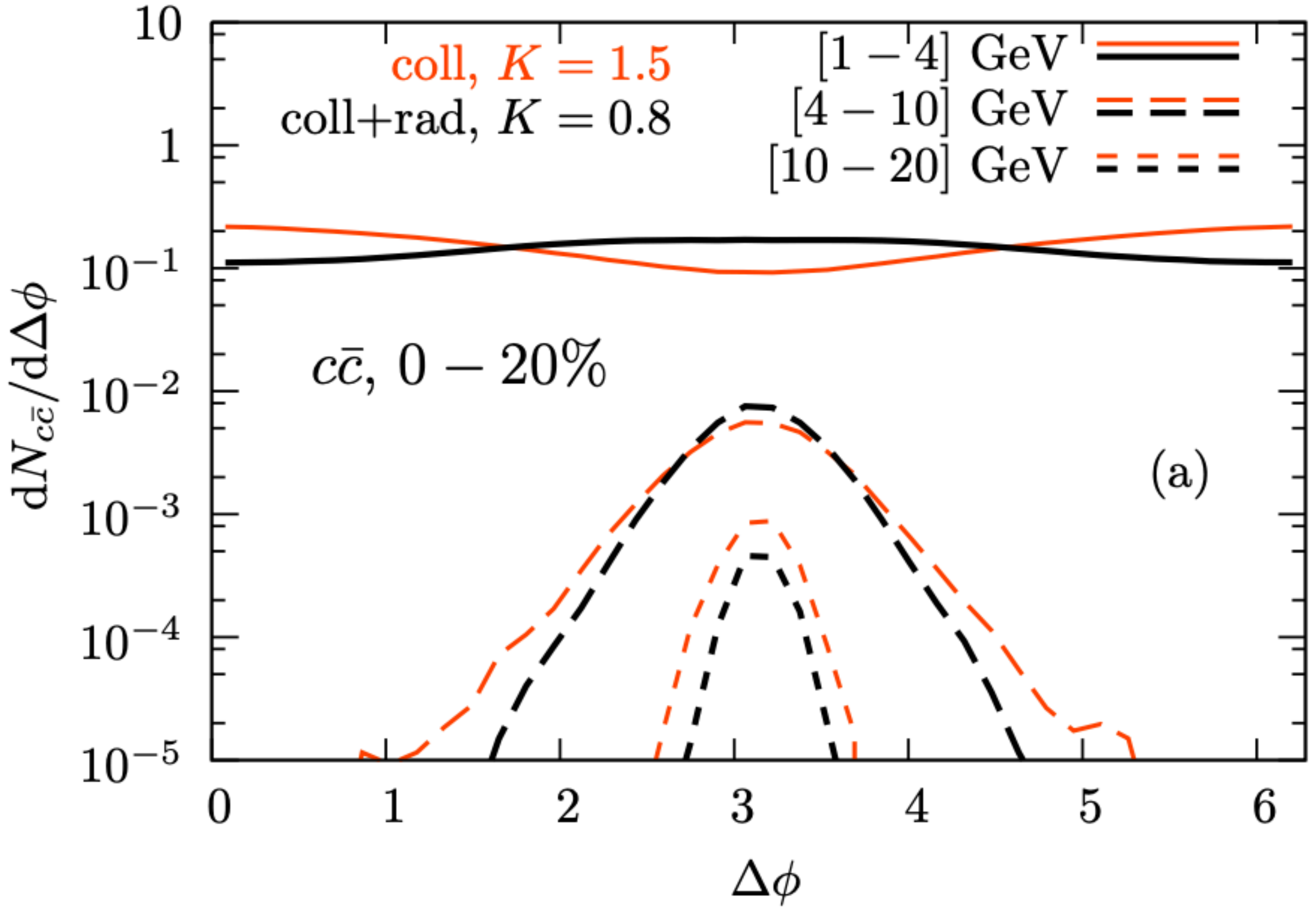
ATLAS, PLB 774, 379

pp: peak at 1 — balanced jets
PbPb: shift towards lower values

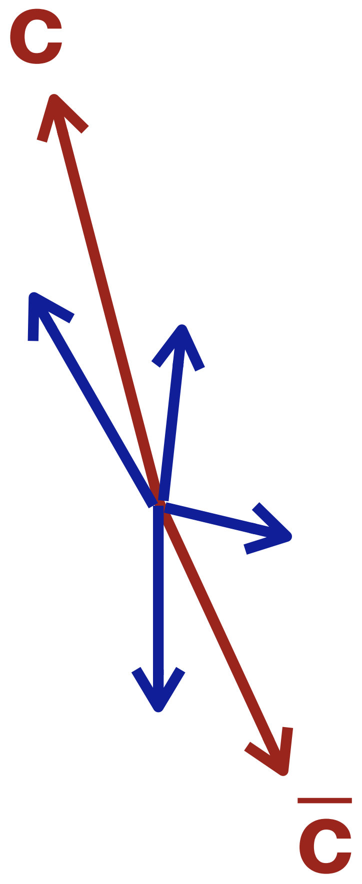
Di-jet energy imbalance: jets lose energy as they propagate through the plasma

In-medium broadening: $D\bar{D}$ azimuthal correlations

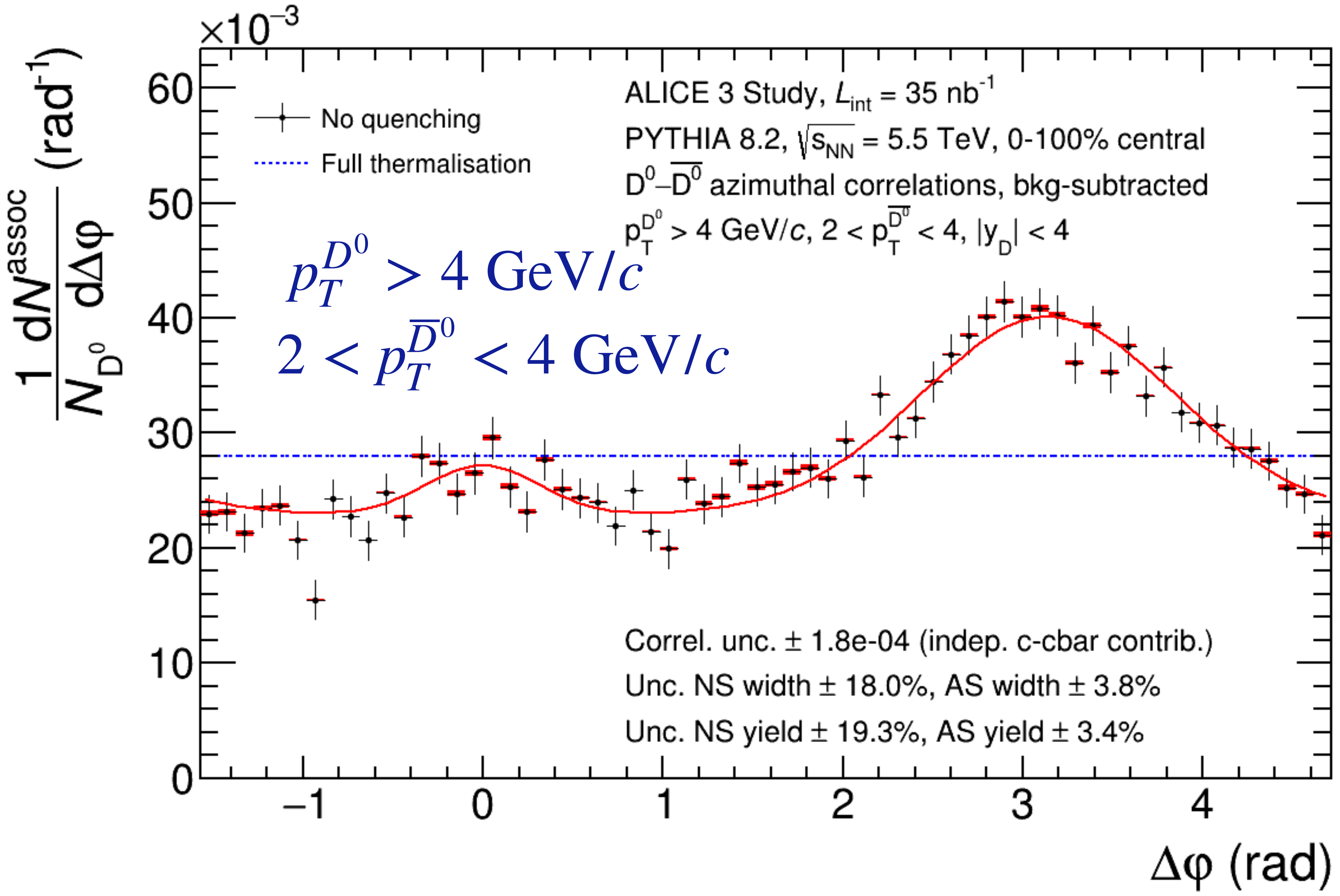
Charm azimuthal correlations



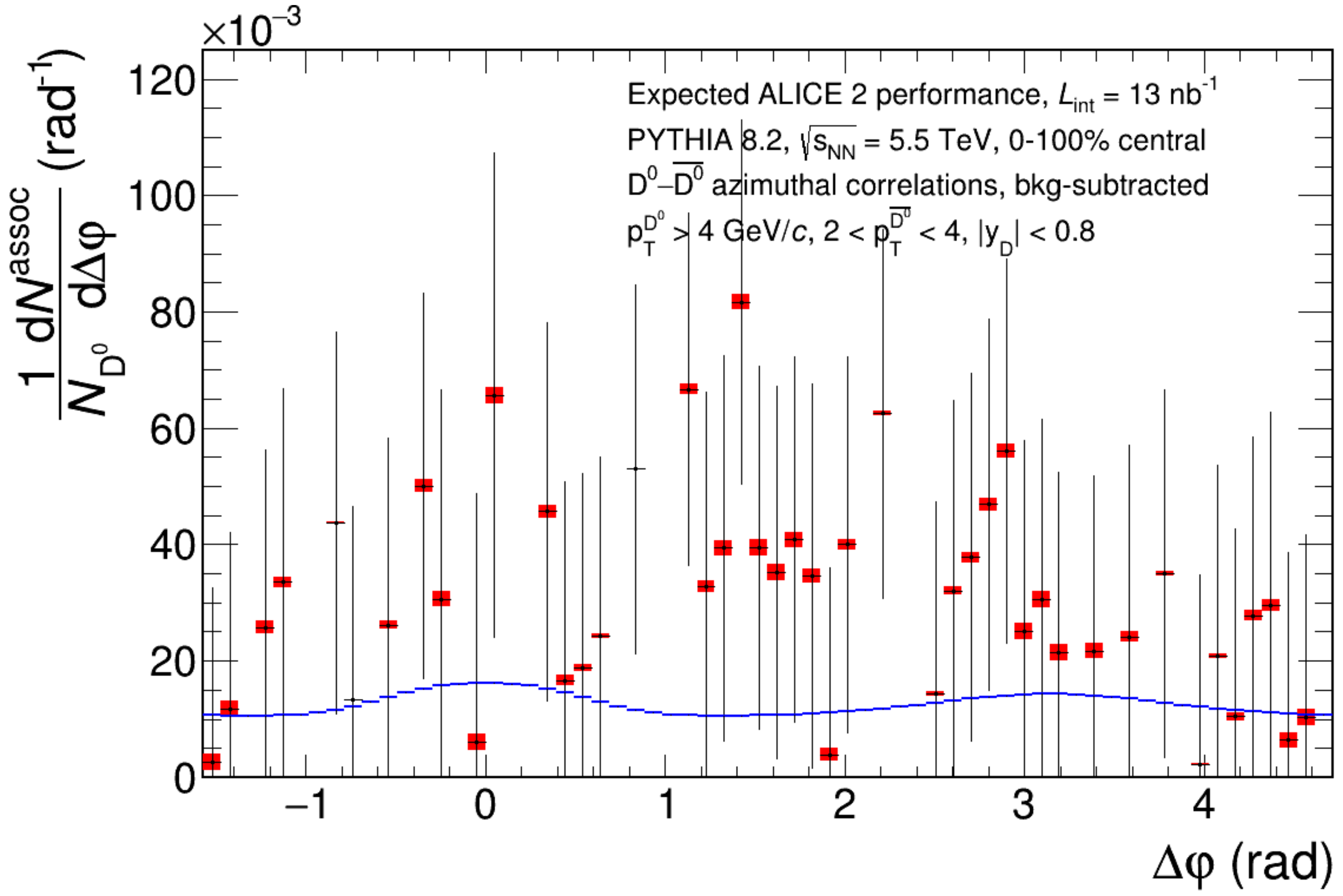
M Nahrgang et al, PRC 90, 024907



ALICE 3 projection: $D\bar{D}$ correlations



ALICE Run 3 + 4 projection



- **Angular decorrelation directly probes QGP scattering**
  - Signal strongest at low p_T
- Very challenging measurement:
  need good purity, efficiency and η coverage
  → ALICE 3

Direct photon production

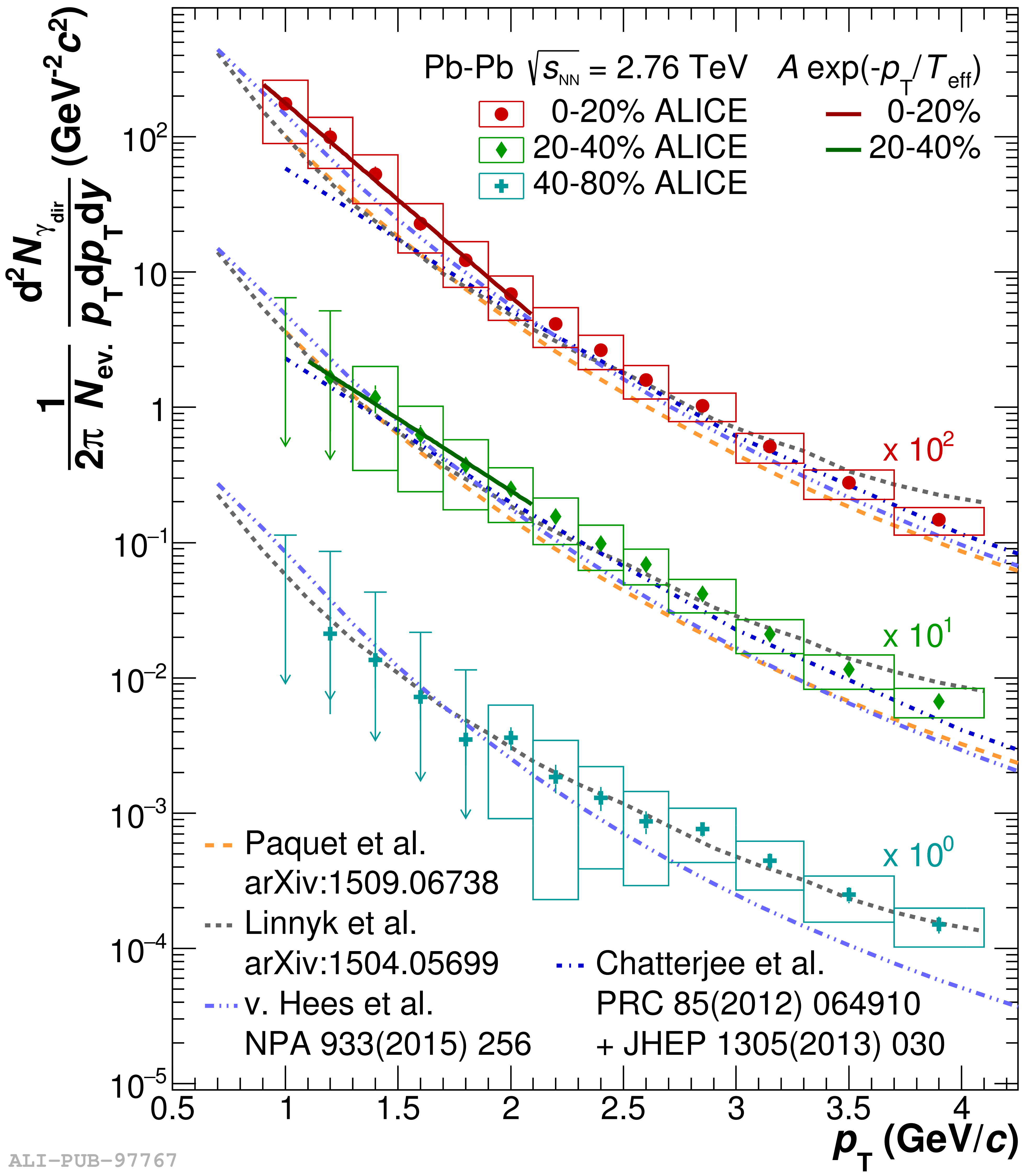
Large background: decay photons from π^0, η, …

⇒ Challenging measurement

Main sources:

- High p_T: hard scattering; quark-gluon Compton process
- Low p_T: thermal radiation

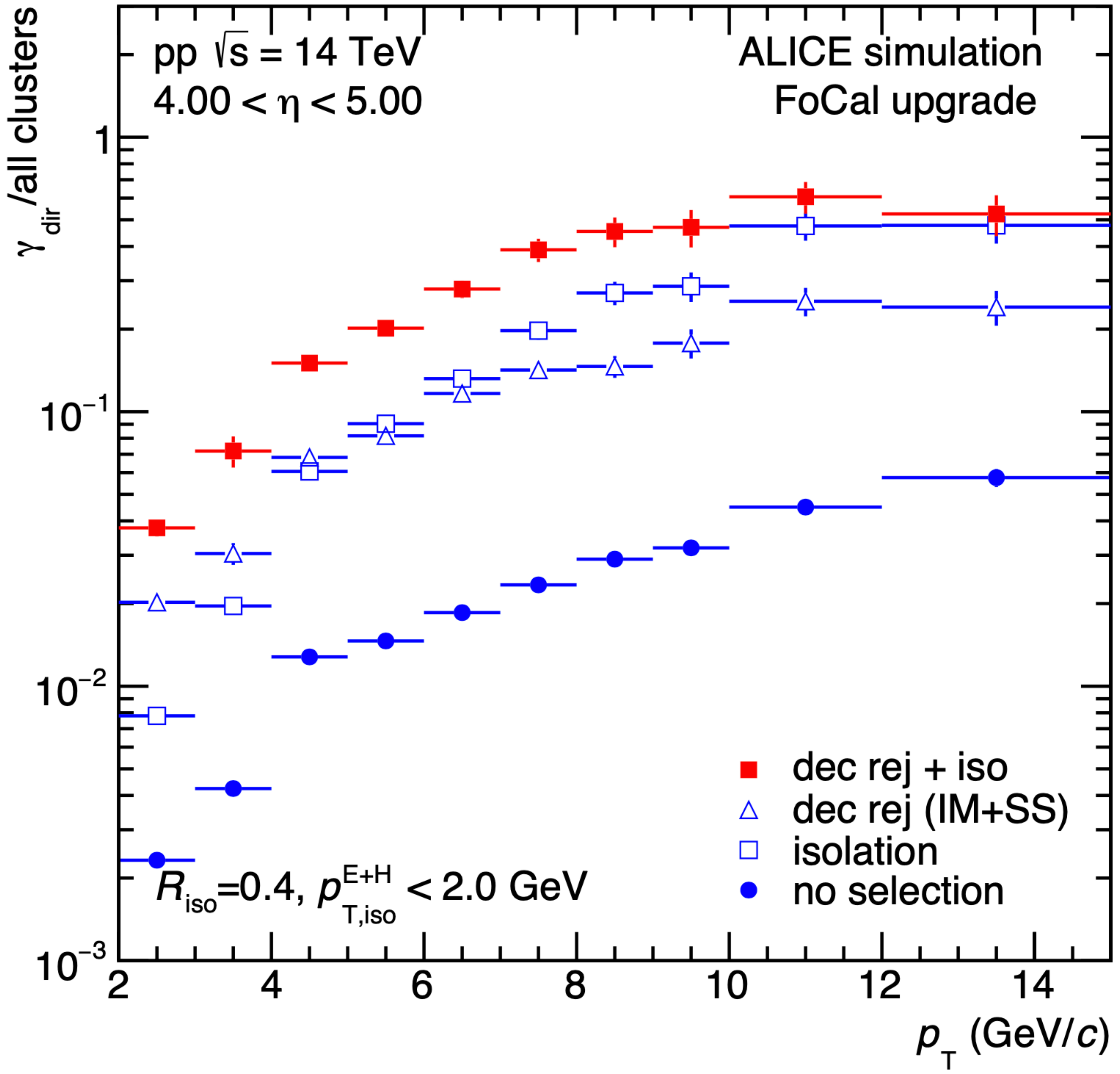
Hint of excess at low p_T in central collisions
Limited by systematic uncertainties



ALICE, PLB 754, 235

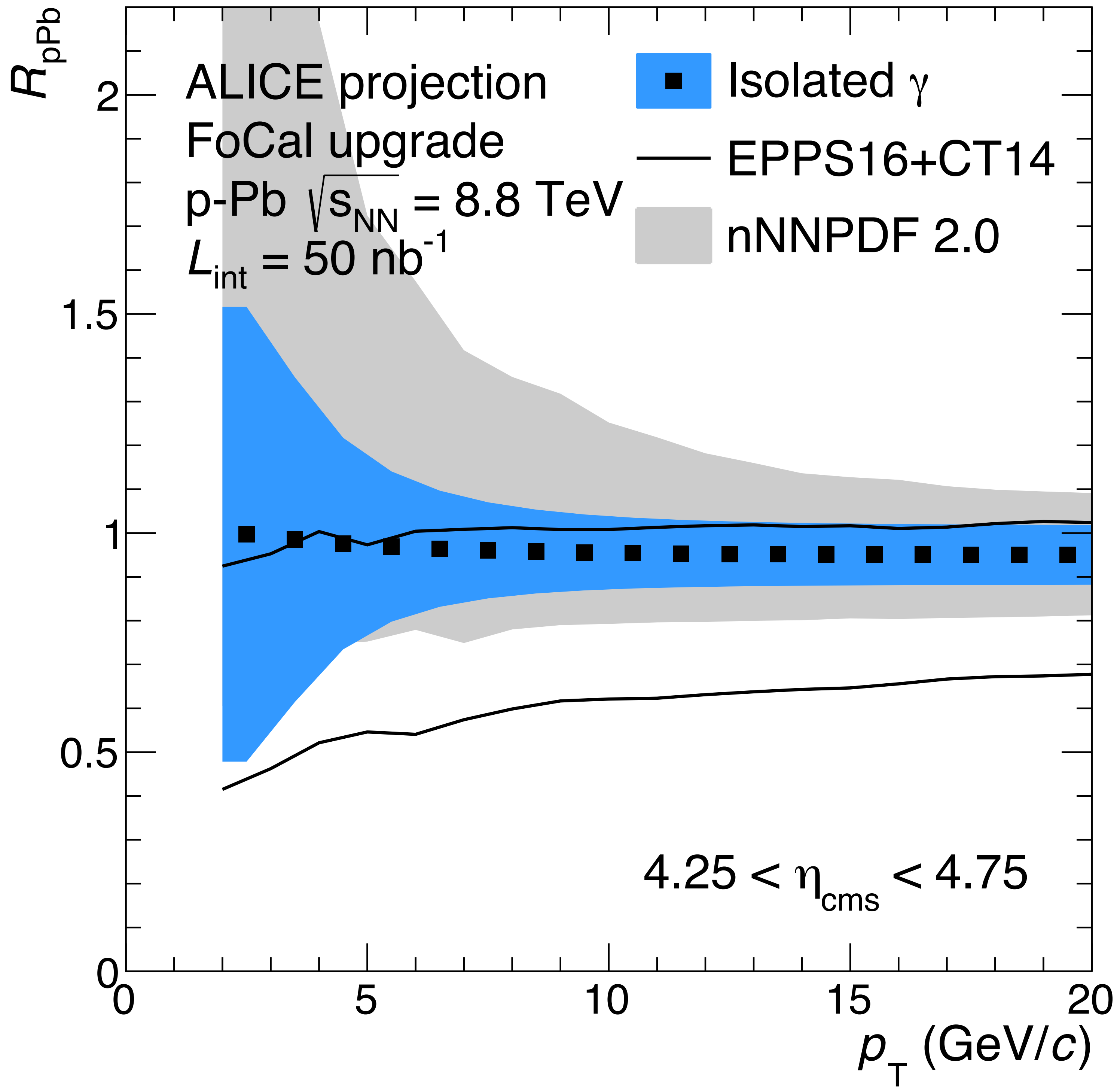
Forward photons with FoCal

Signal photon fraction



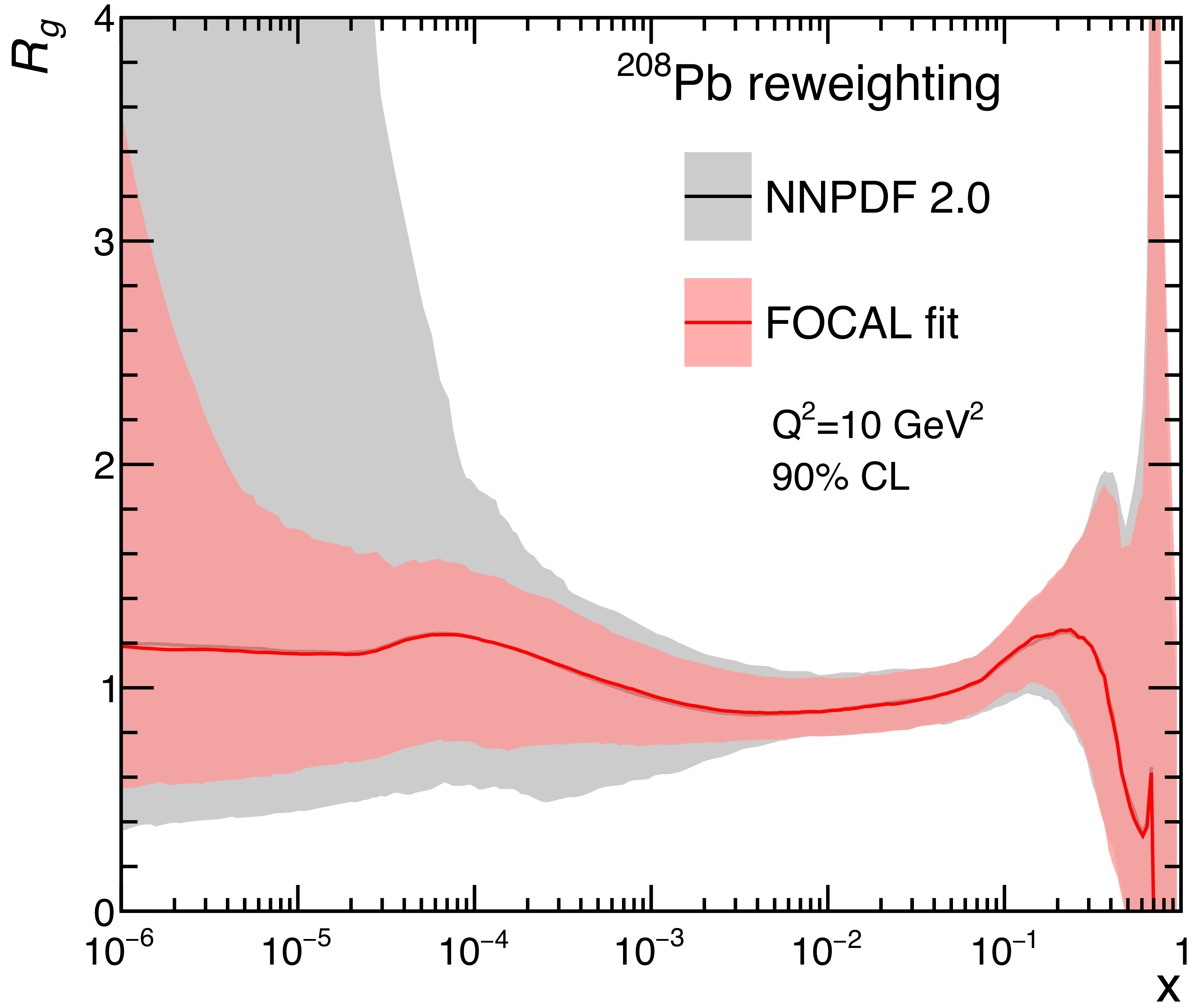
High granularity to
reject decay background

Projected photon uncertainties



High precision direct photon
measurement down to low p_T

Projected PDF uncertainties

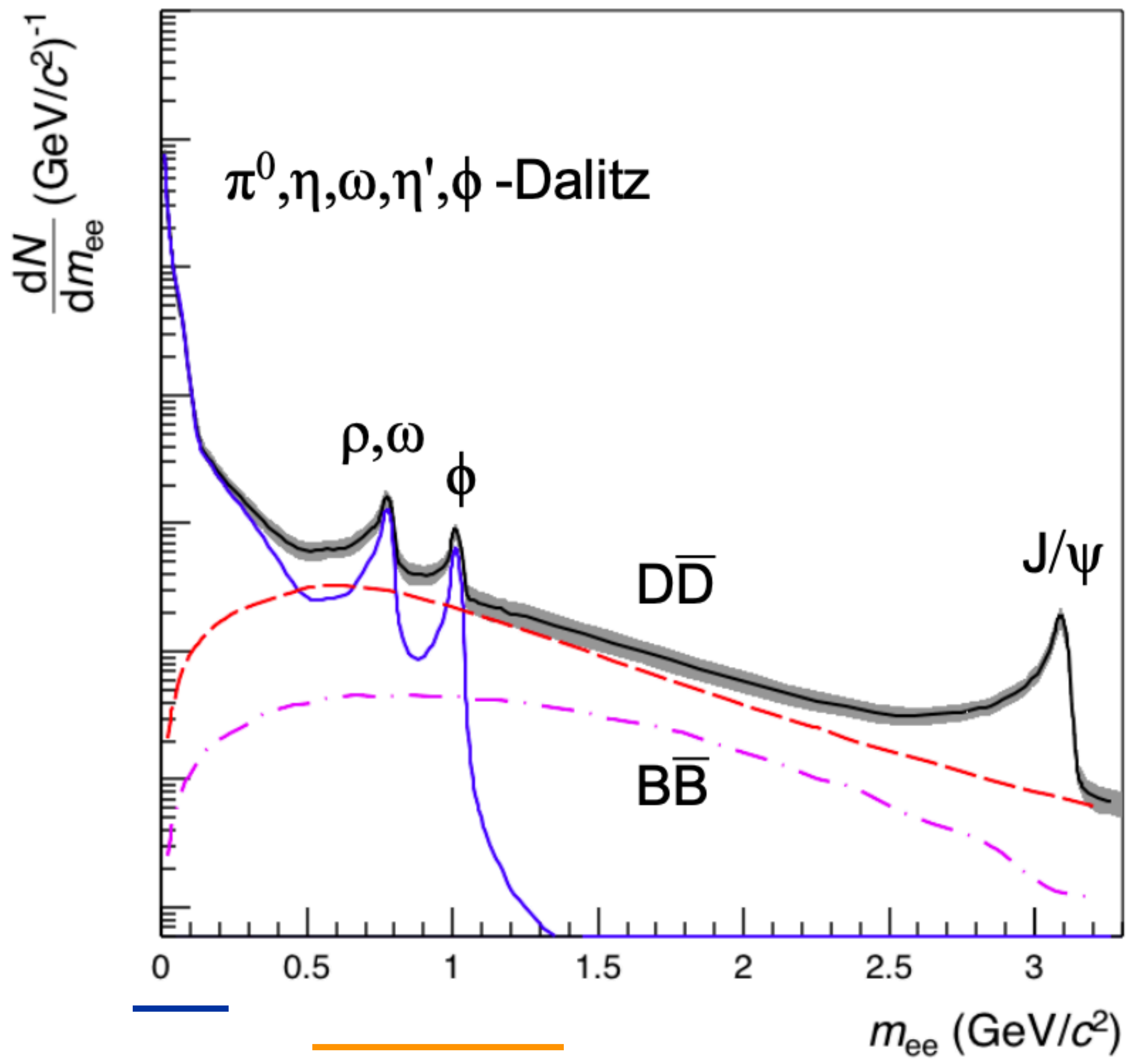


Constrain gluon density in nuclei
over a broad range:
$x \sim 10^{-5}$ - 10^{-2} at small Q^2

Di-lepton emission: virtual photons

- Virtual photons e^+e^- pairs
- Vector meson spectral functions sensitive to chiral symmetry restoration
- $m_{ee} > 1\ \mathrm{GeV}/c^2$ removes light flavour decay background
- Remaining background: heavy flavour pairs

Di-lepton mass distribution



Very low mass:
π_0 decay background
conductivity

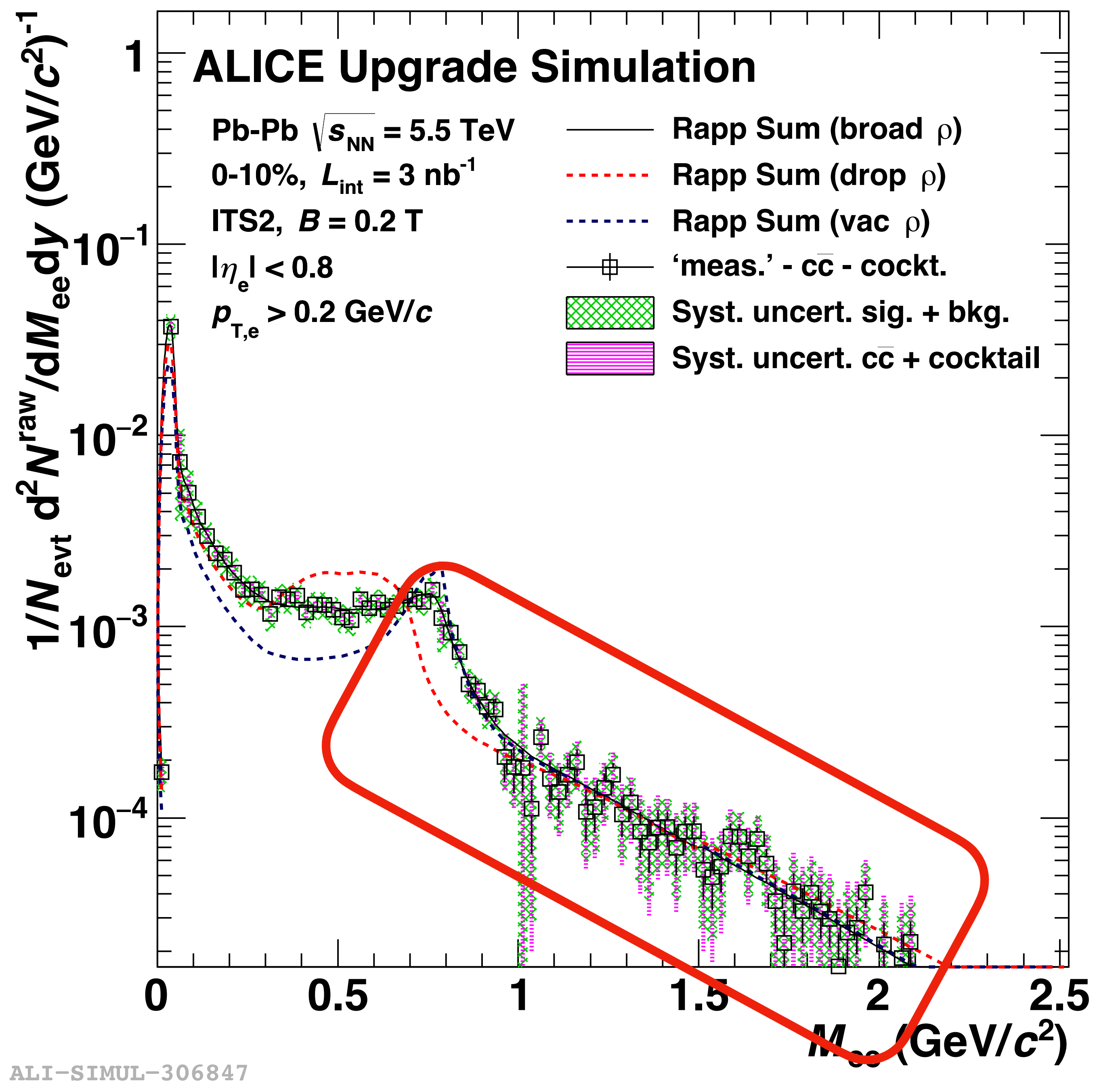
ω/φ region:
chiral symmetry and
ρ-a$_1$ mixing

Large mass:
thermal emission,
early times

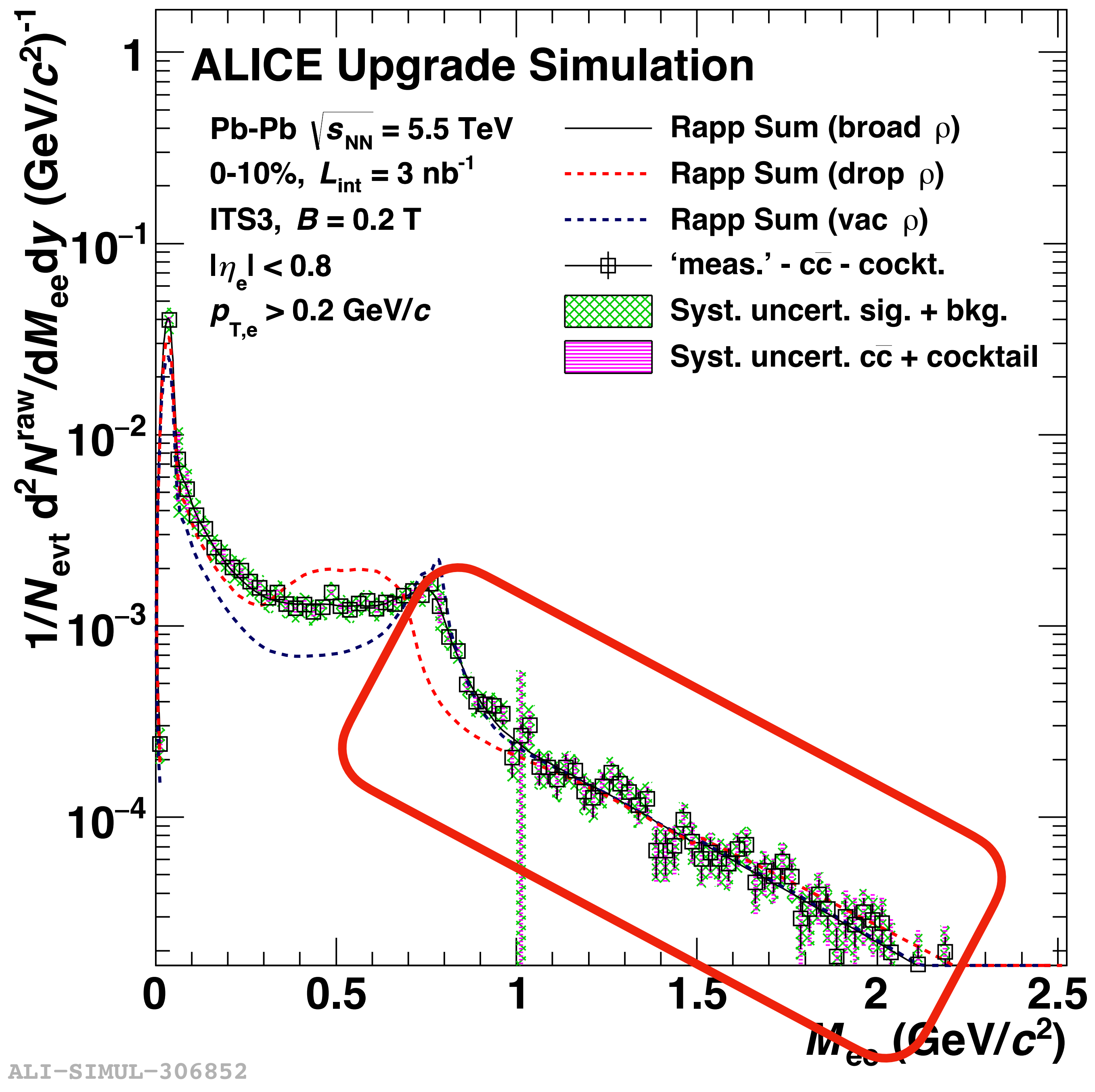
Run 3 and 4: temperature of the QGP

Di-electron spectra

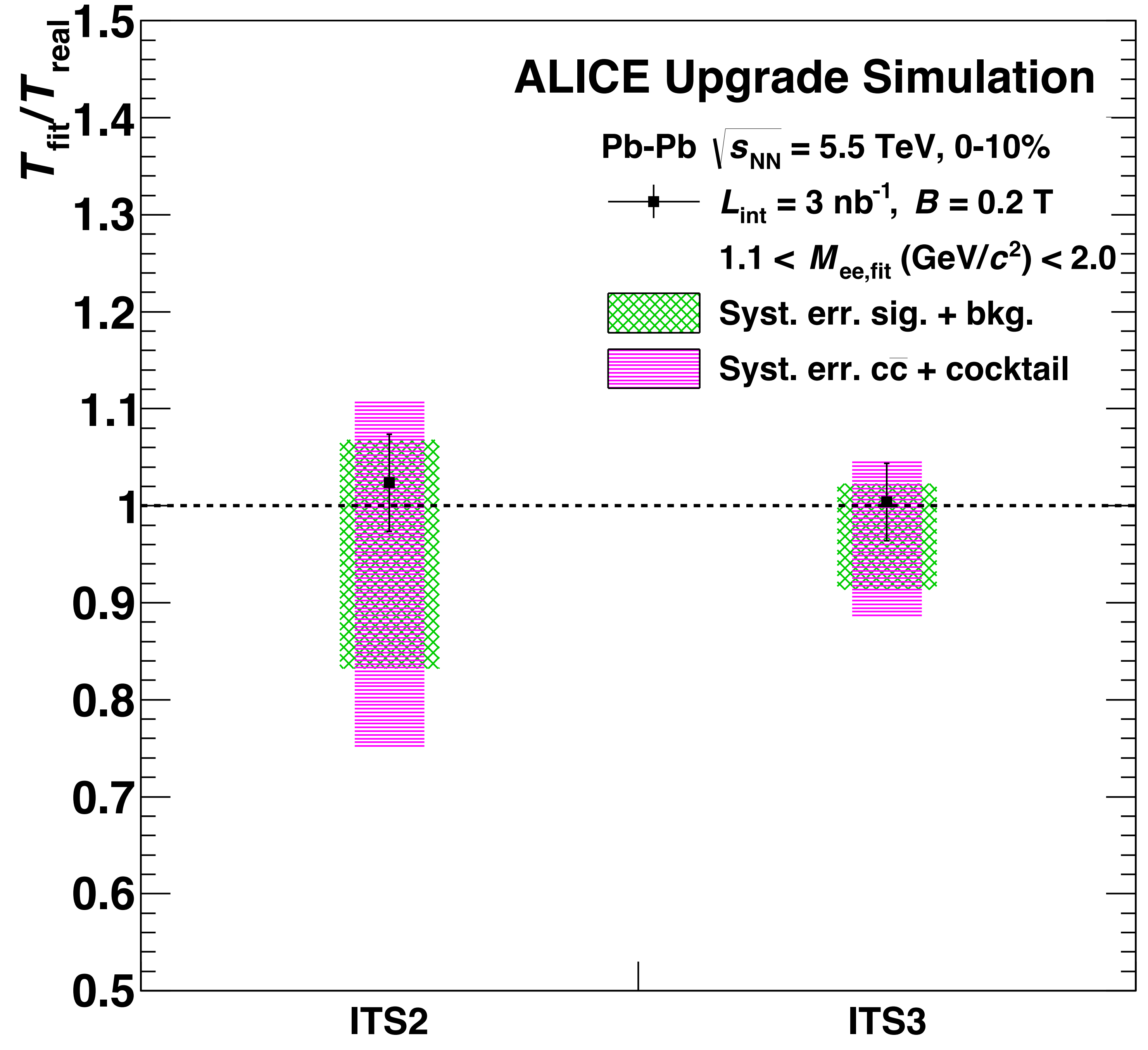
Upgraded ITS



ITS3



Di-lepton temperature fit



Dielectron measurements require:

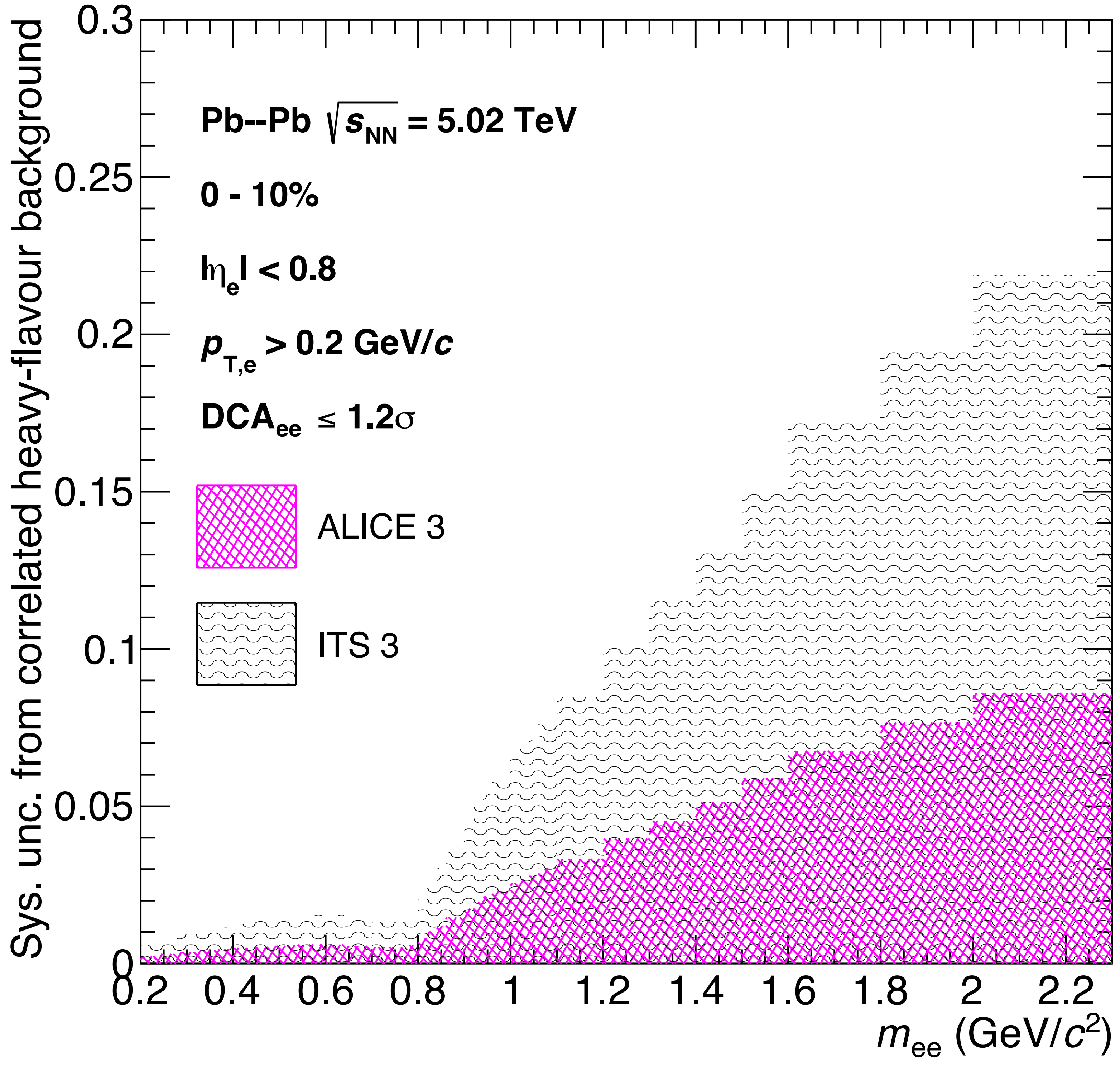
- Excellent PID
- Low material budget to limit conversion background
- Good pointing resolution: reject heavy flavour backgrounds

First measurements at LHC: Run 3 and 4

ITS3 improves systematic uncertainty on *T* by a factor 2

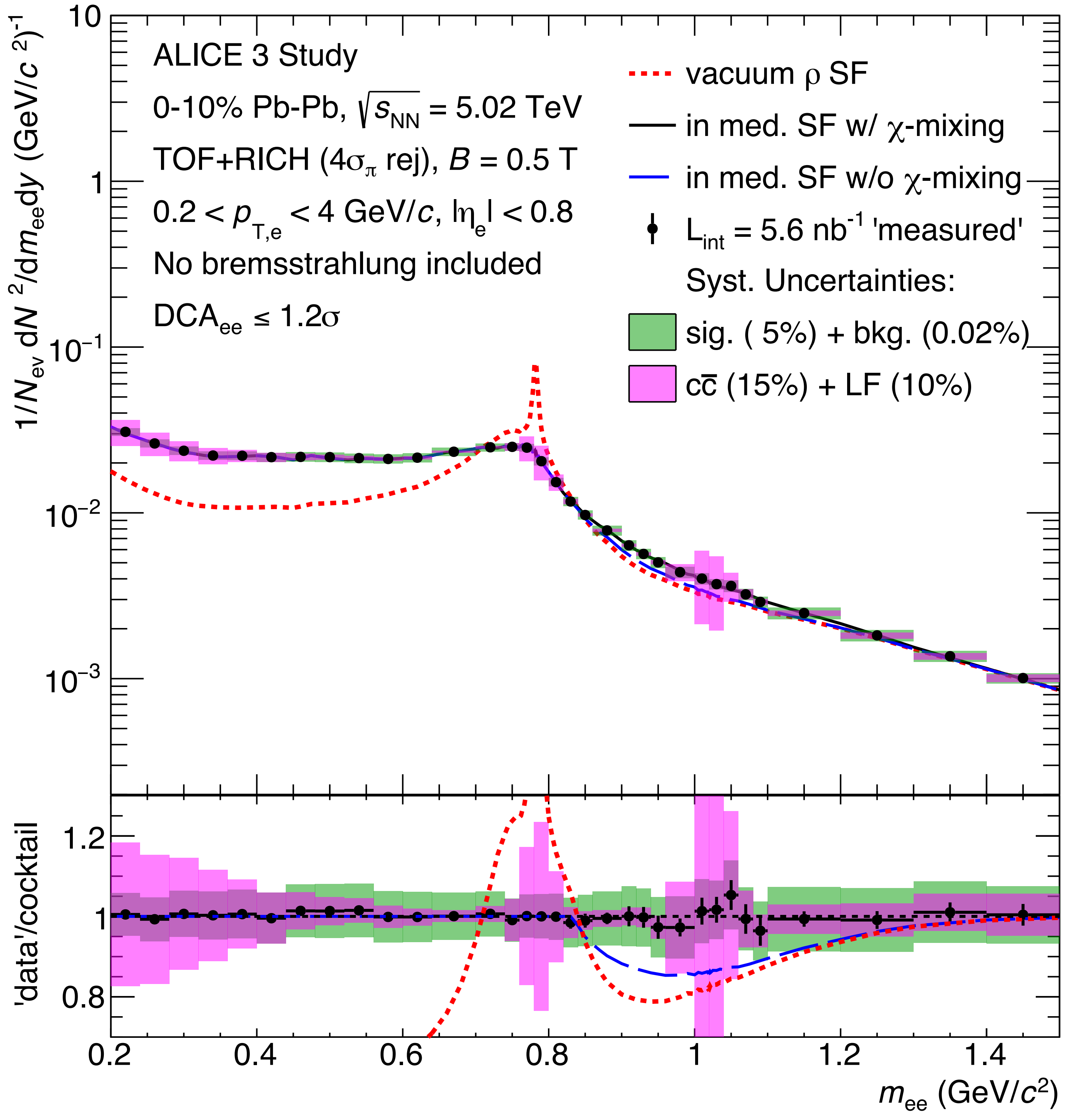
Dielectrons: chiral symmetry and thermal emission

Relative syst uncertainty from HF decay bkg



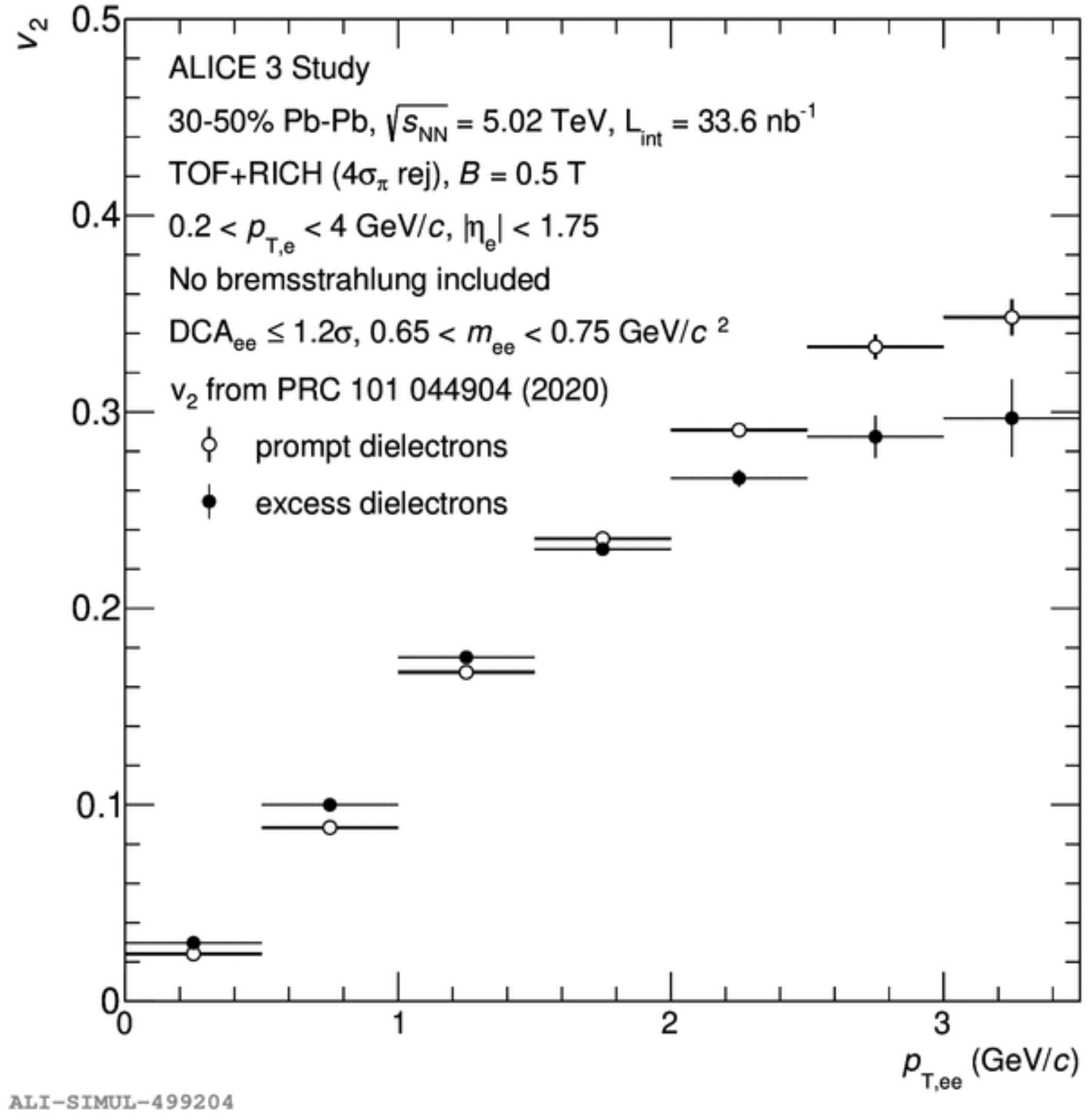
- HF decays produce correlated background
- Large for $m_{ee} \gtrsim 1\,\mathrm{GeV}/c^2$
- Improved rejection in ALICE 3

ALICE 3 mass spectrum



High precision:
access $\rho - a_1$ mixing

Dielectron v_2



Excellent precision for dilepton v_2 vs p_T in different mass ranges
→ time evolution of emission

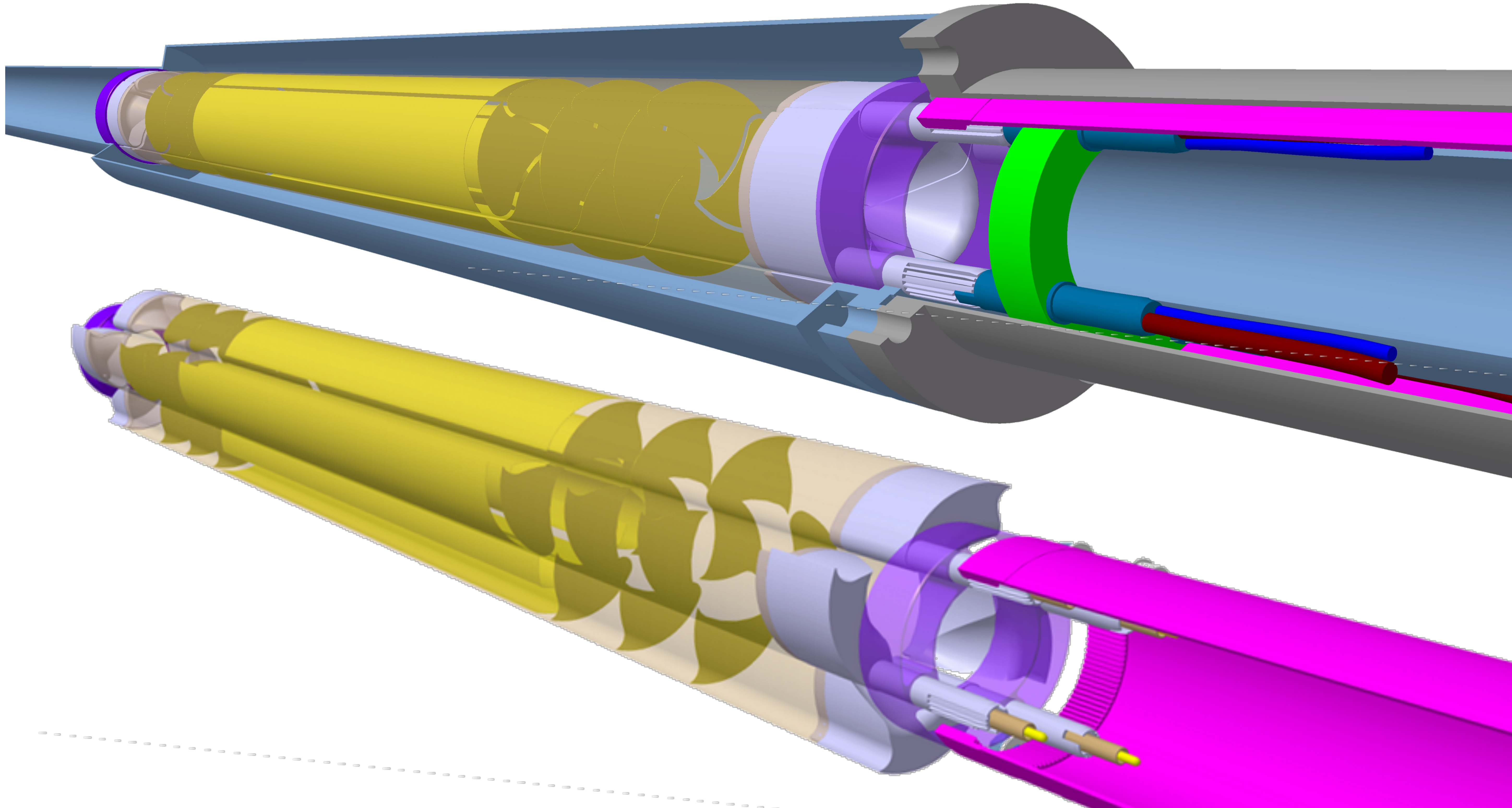
Conclusion

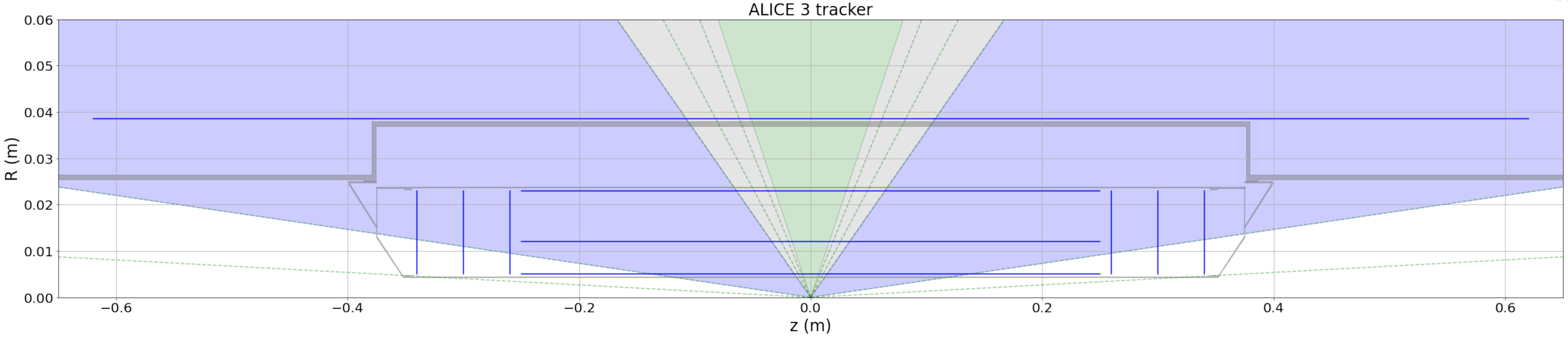
- **Heavy-ion collisions allow to study properties of bulk QCD**
- **Large azimuthal asymmetry for light and heavy flavours**
  - The QGP at LHC has a viscosity close to the lower bound
  - Charm diffusion and approach to thermalisation
- **Large energy loss for high-momentum probes**
  - Radiative and collisions energy loss
  - Transport properties in line with lattice QCD and pQCD expectations
- **Much more to come in Run 3 and beyond**
  - Temperature of the QGP before hadronisation from dielectron emission
  - Understanding heavy quark thermalisation
  - Impact of hadronisation on main observables
  - ….

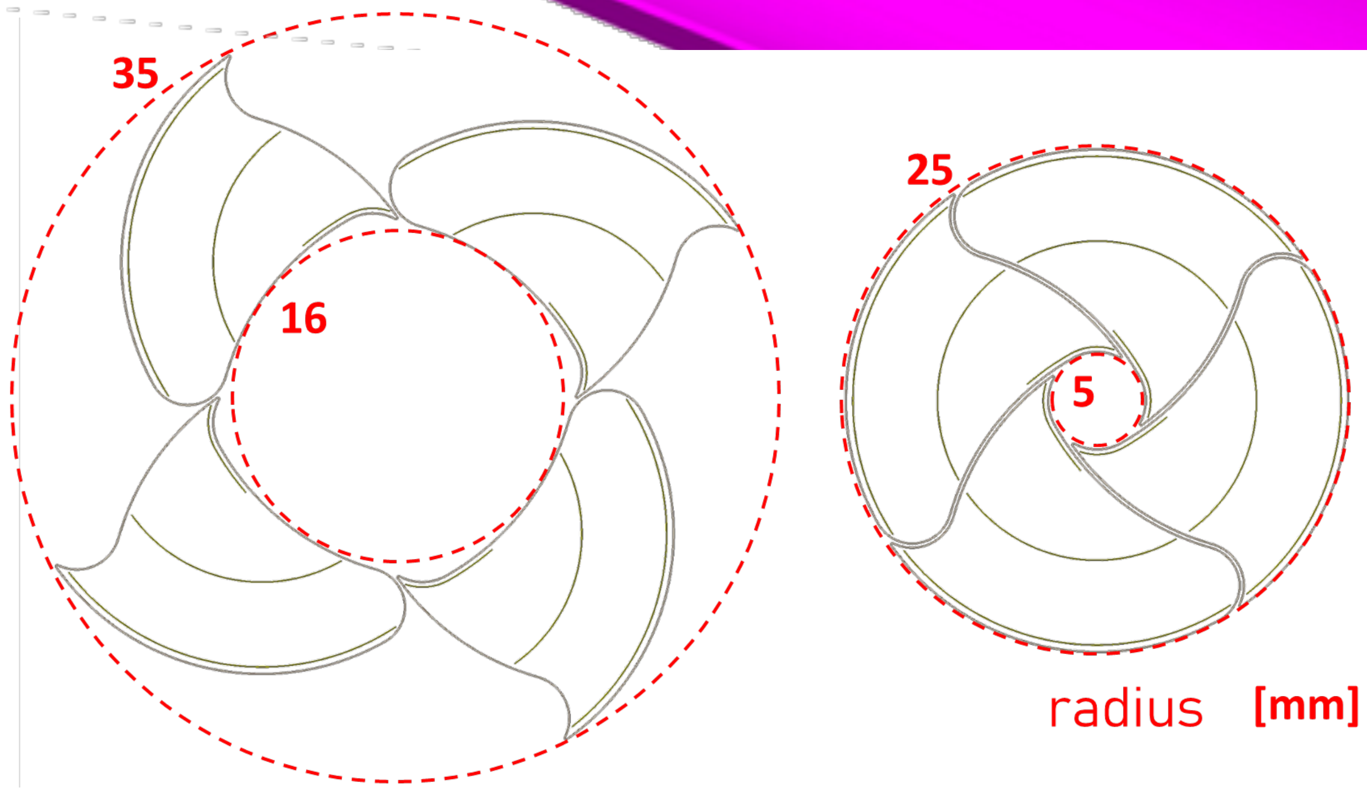
Extra slides

ALICE 3 Vertex Detector

- **Conceptual study of iris tracker**
    - wafer-sized, bent MAPS
    - rotary petals for secondary vacuum thin walls to minimise material
- Challenging design: **R&D programme** on mechanics, cooling, radiation tolerance



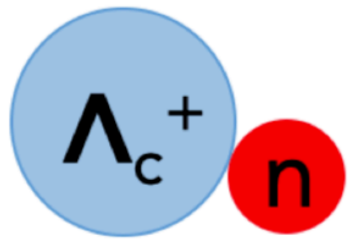




Nuclear states: charm-deuteron

anti-triton

anti-hyper-triton

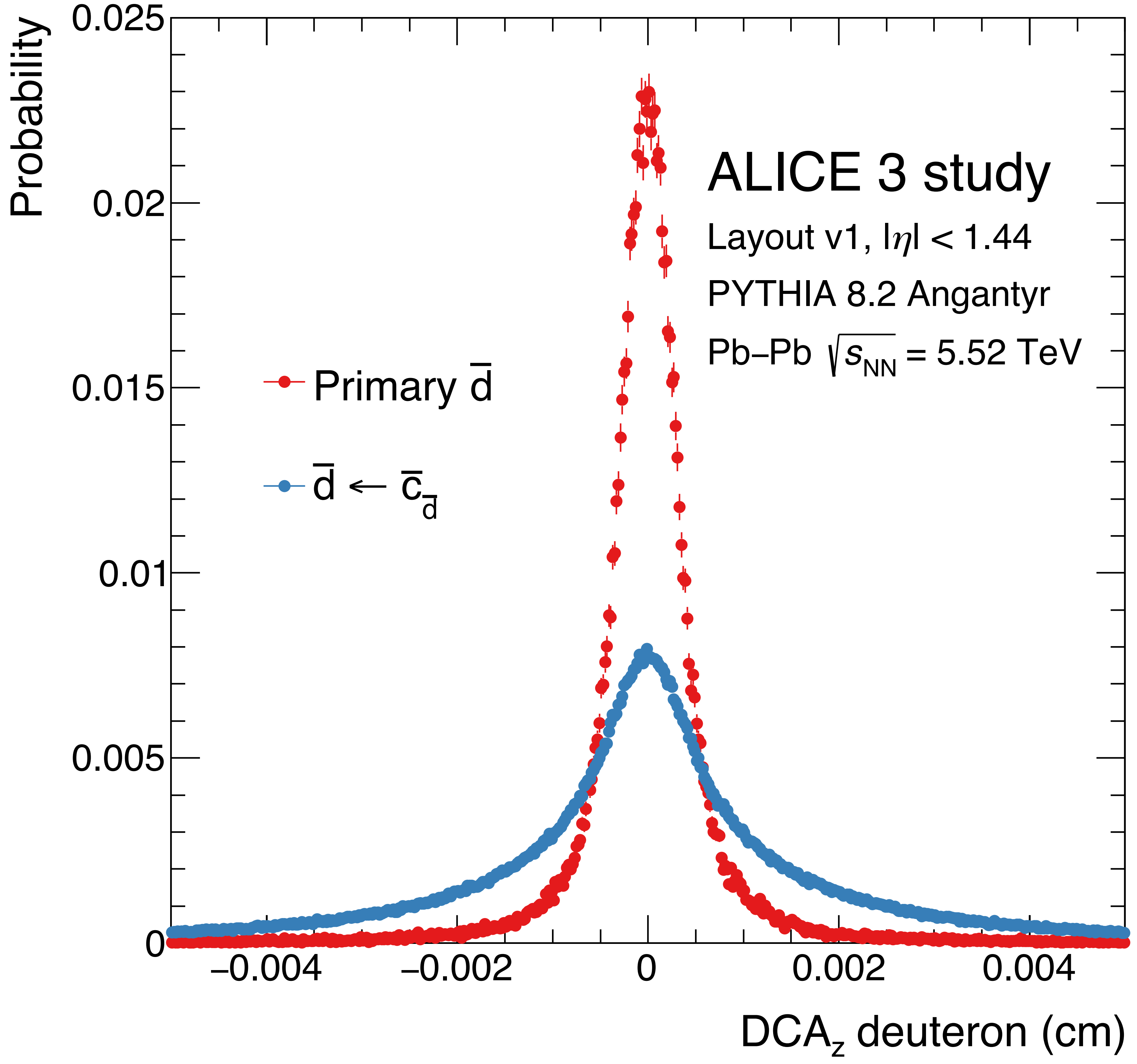


c-deuteron

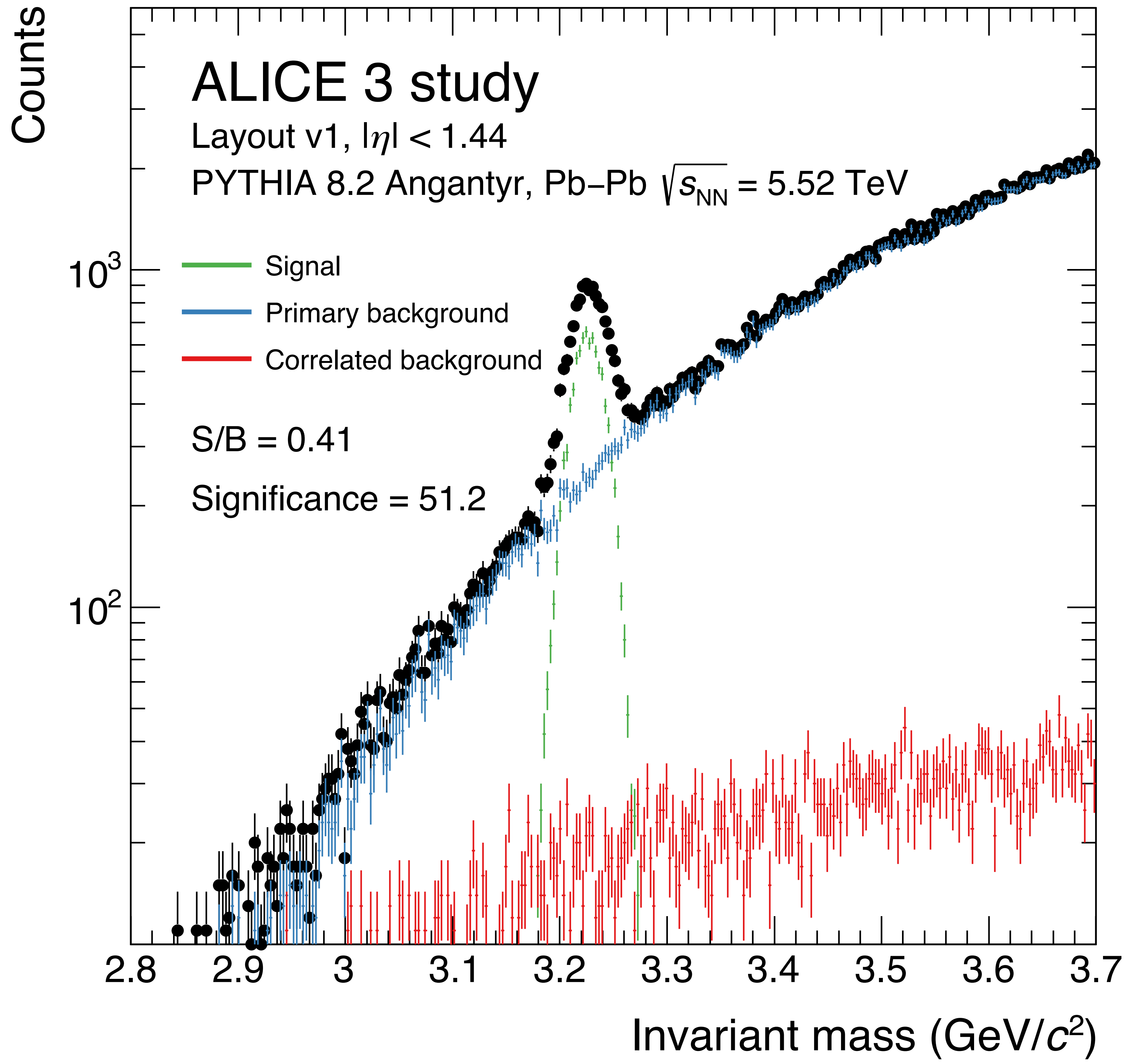
Decay channel:

$$c_d \to d + K^- + \pi^+$$

Impact parameter distributions



Invariant mass distribution



Unique sensitivity to undiscovered charm-nuclei: charm-deuteron and higher nuclear states

Hadron formation

- **Multi-charm baryons**: unique probe of hadron formation
  - Require **production of multiple charm quarks**
  - Single-scattering contribution very small (unlike e.g. J/ψ)
- Statistical hadronisation model:
  very large enhancement in AA
  - Charm out of equilibrium: yields scale with g_c^n for *n*-charm states
  - How is thermalisation approached microscopically?

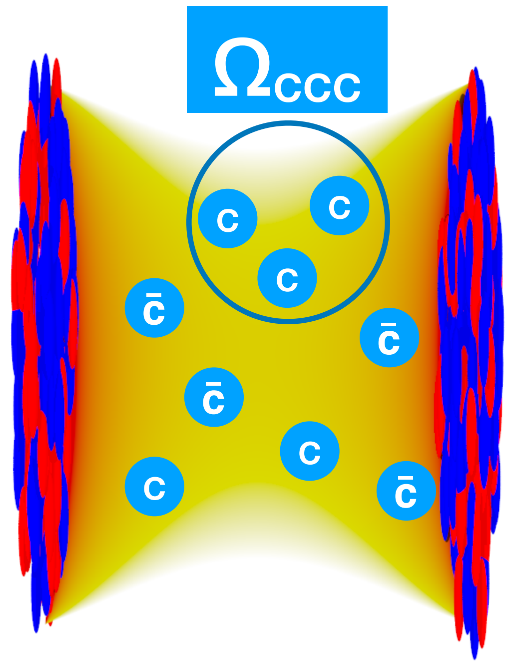
Measure additional states to test physical pictu

Single and double-charm baryons: Λ_c, Ξ_c, Ξ_{cc}, Ω_{cc}

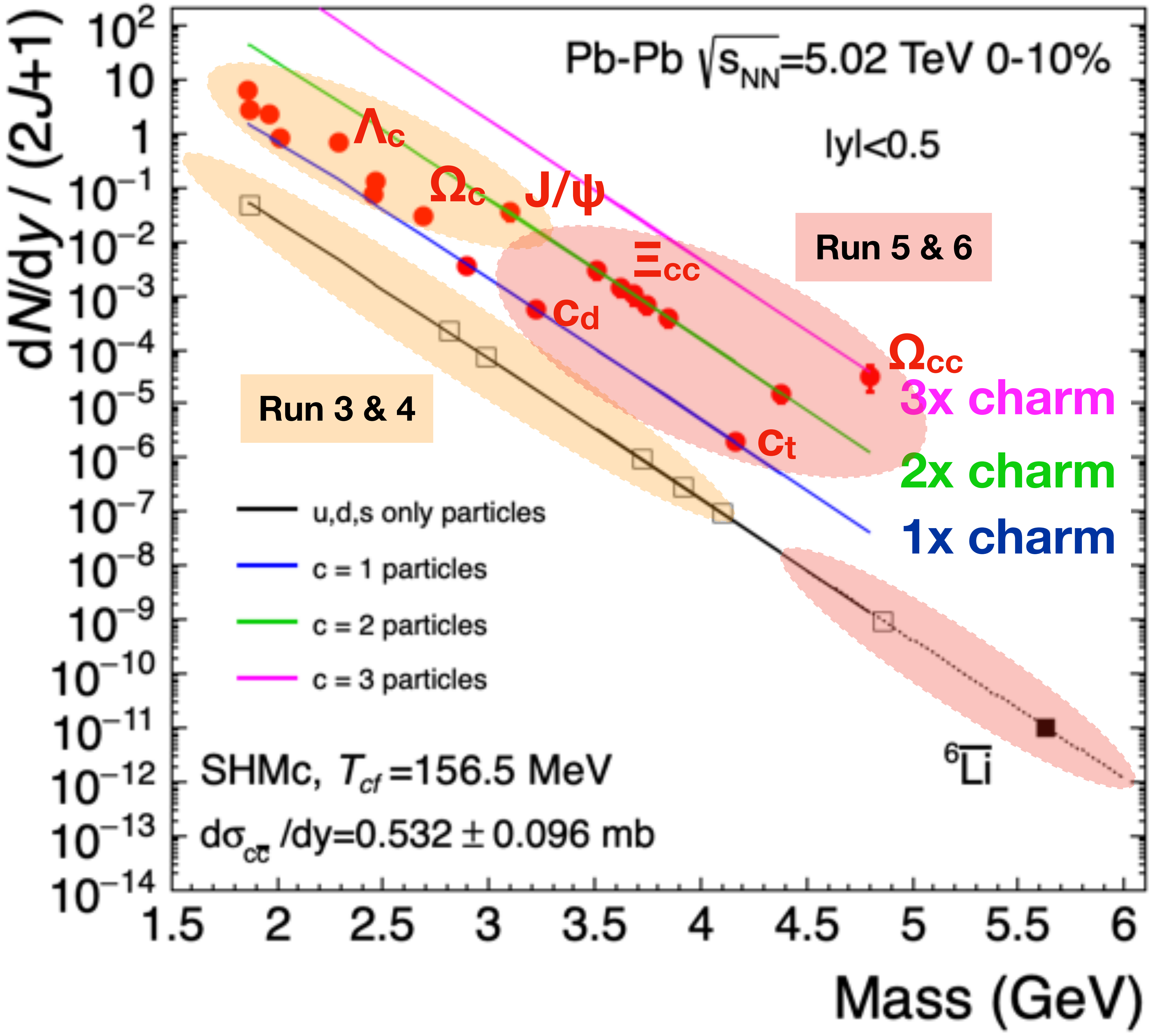
Multi-flavour mesons: B_c, D_s, B_s, …

Tightly/weakly bound states J/ψ, $\chi_{c1}(3872)$, T^+_{cc}

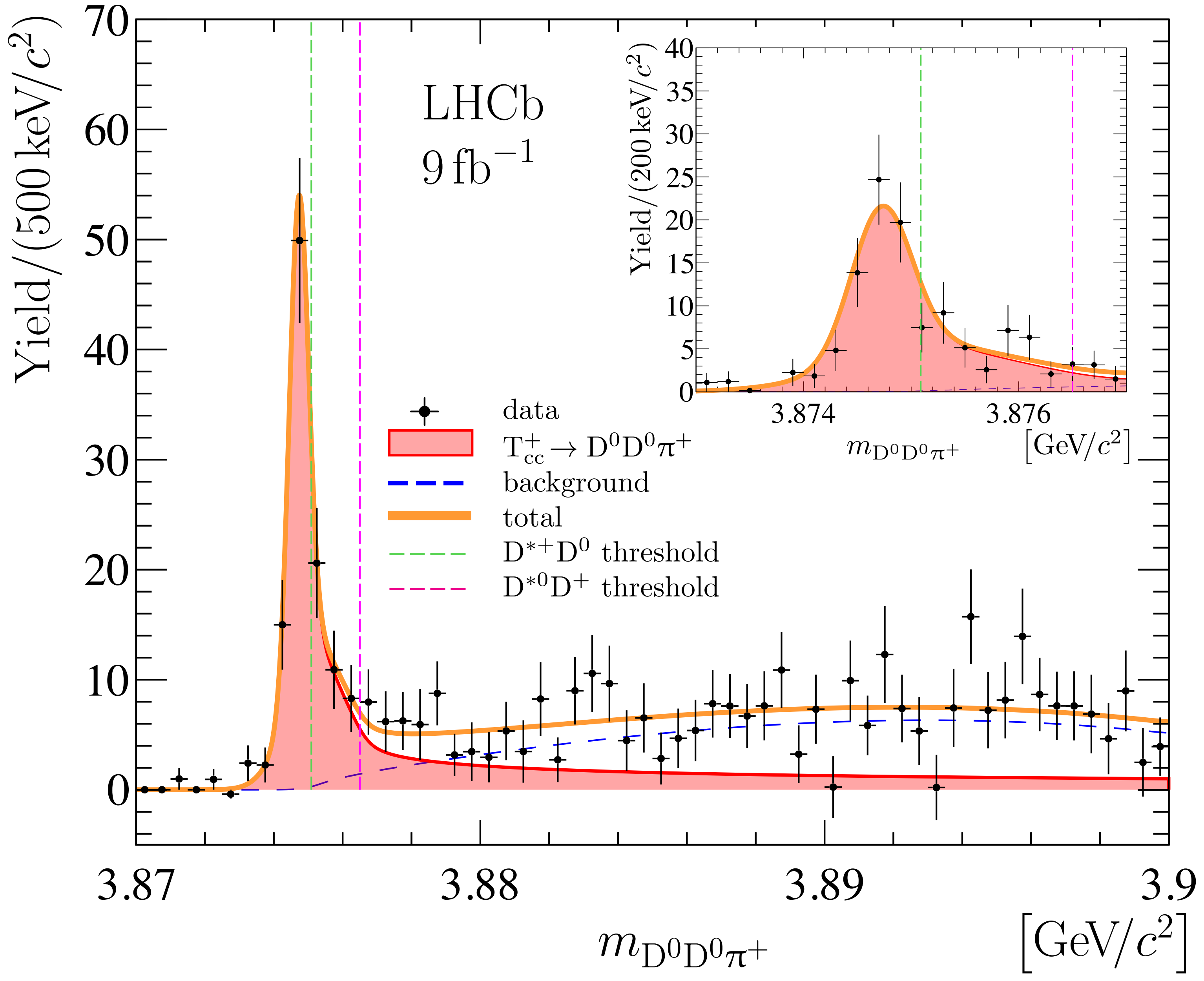
Large mass light flavour particles: nuclei

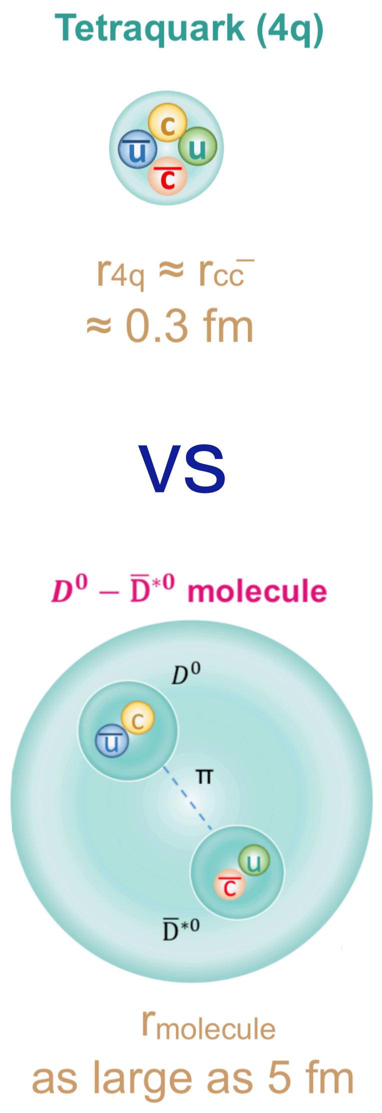


Hadron yields in statistical hadronisation model



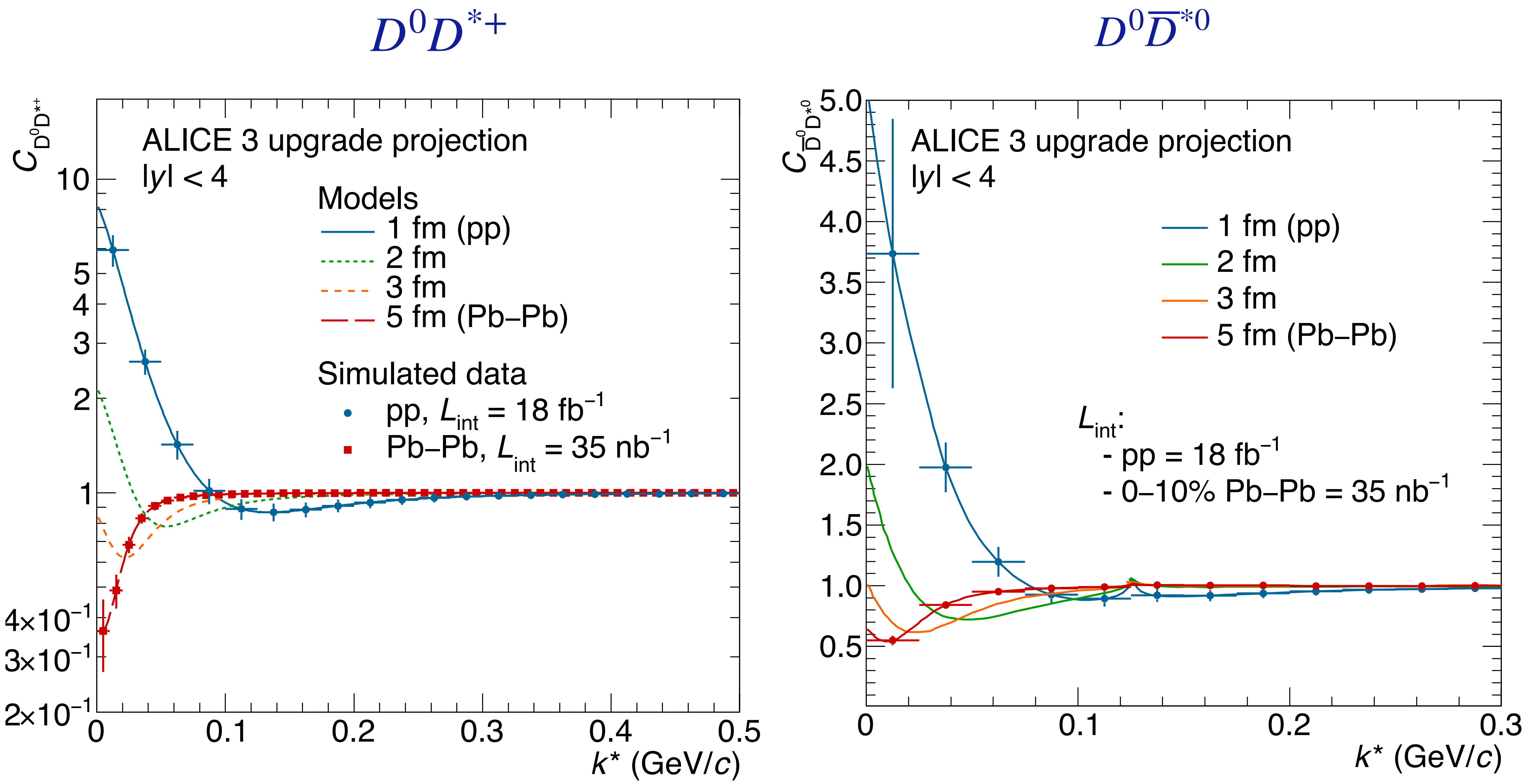
DD* momentum correlations





- Several exotic heavy flavour states identified
- Loosely bound meson molecule or tightly bound tetraquark?
- Study binding potential with final state interactions ‘femtoscopic correlations’

DD* momentum correlation

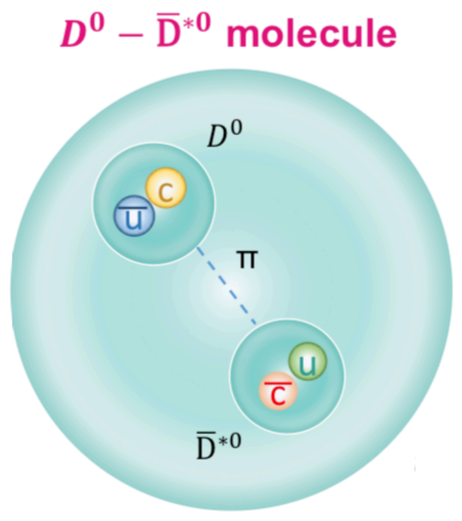


D^0D^{*+}: nature of T_{cc}^+

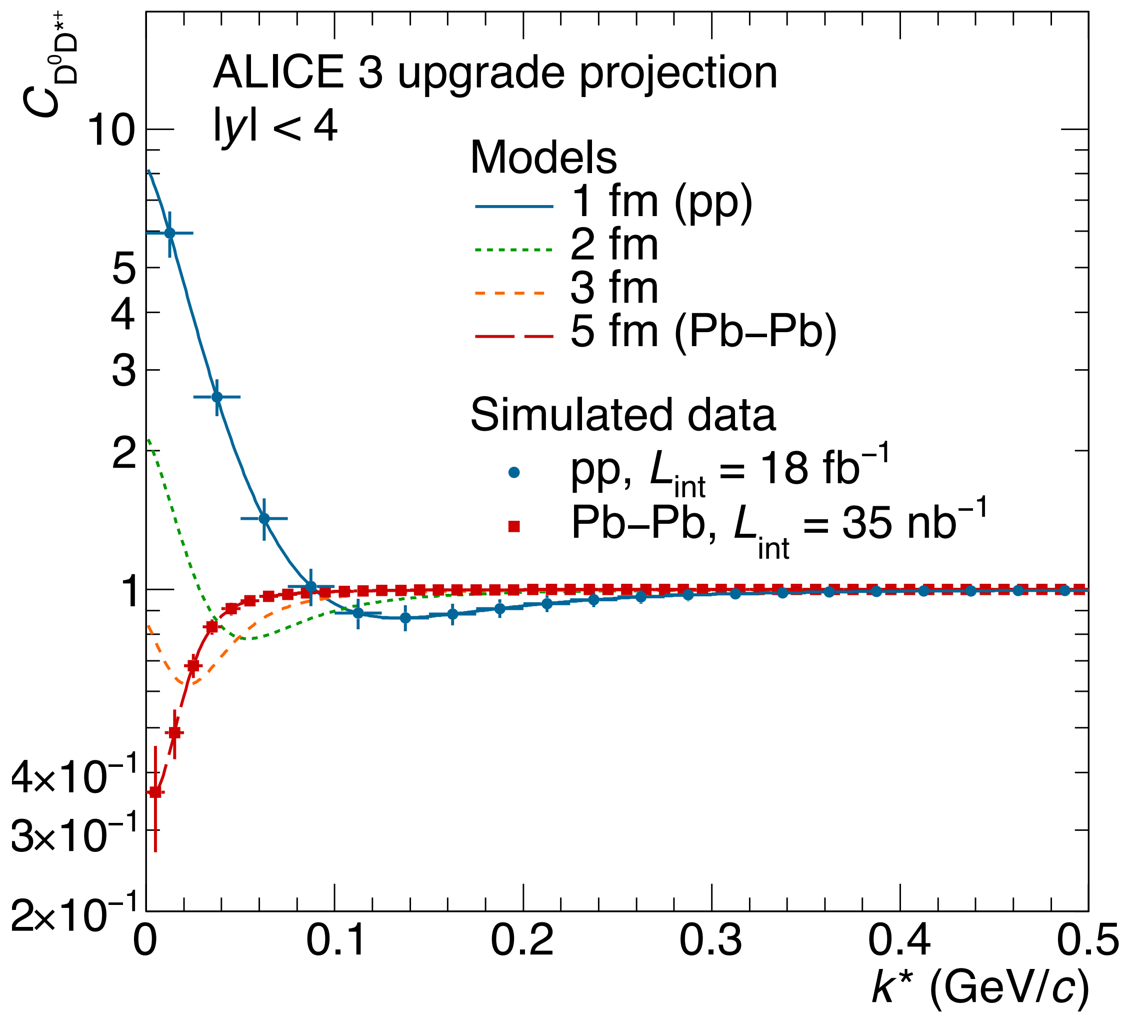
$D^0\overline{D}^{*0}$: nature of $\chi_{c1}(3872)$

Exotic bound states

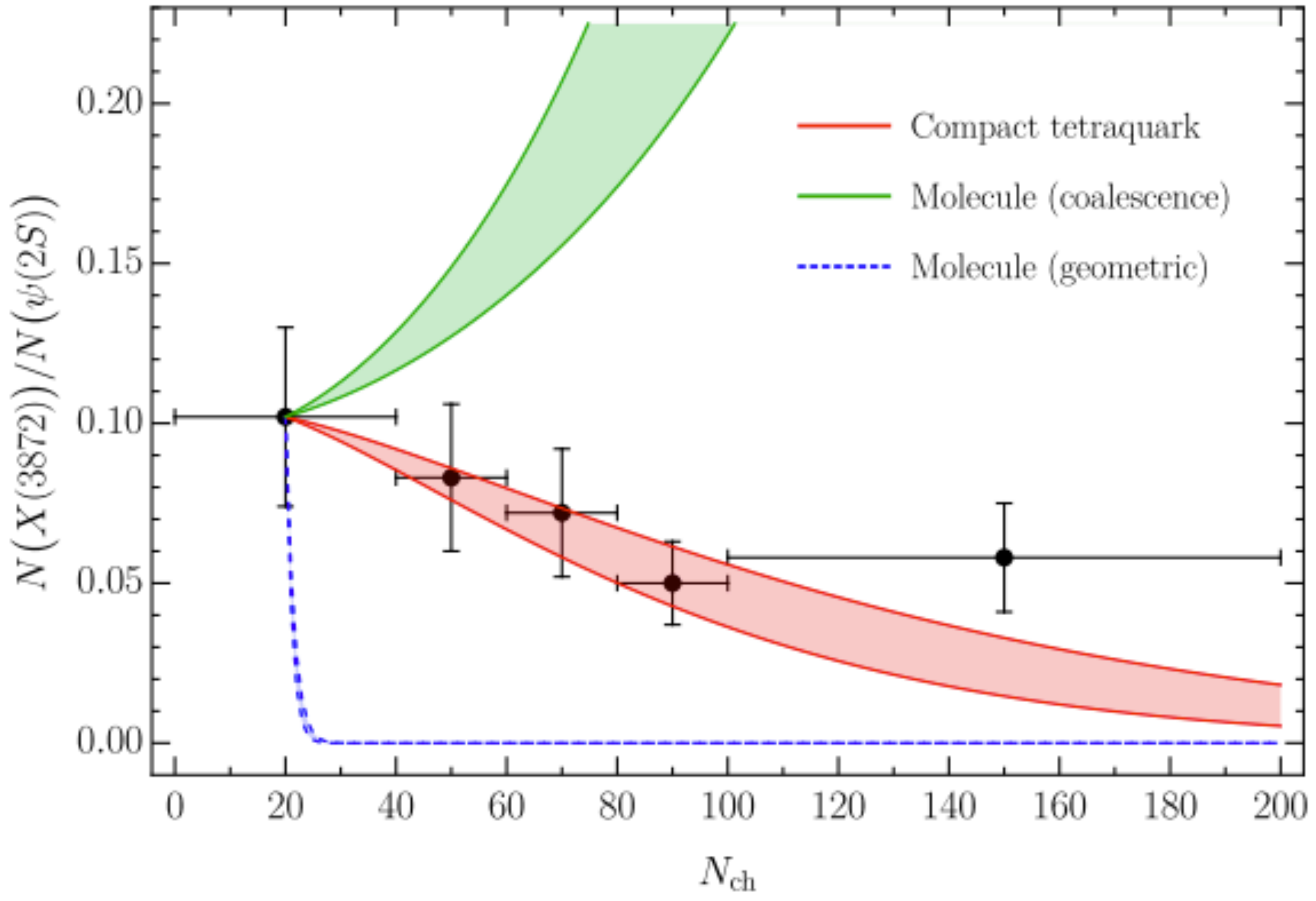
D^0D^{*+}: nature of T_{cc}^+



r_{molecule} as large as 5 fm

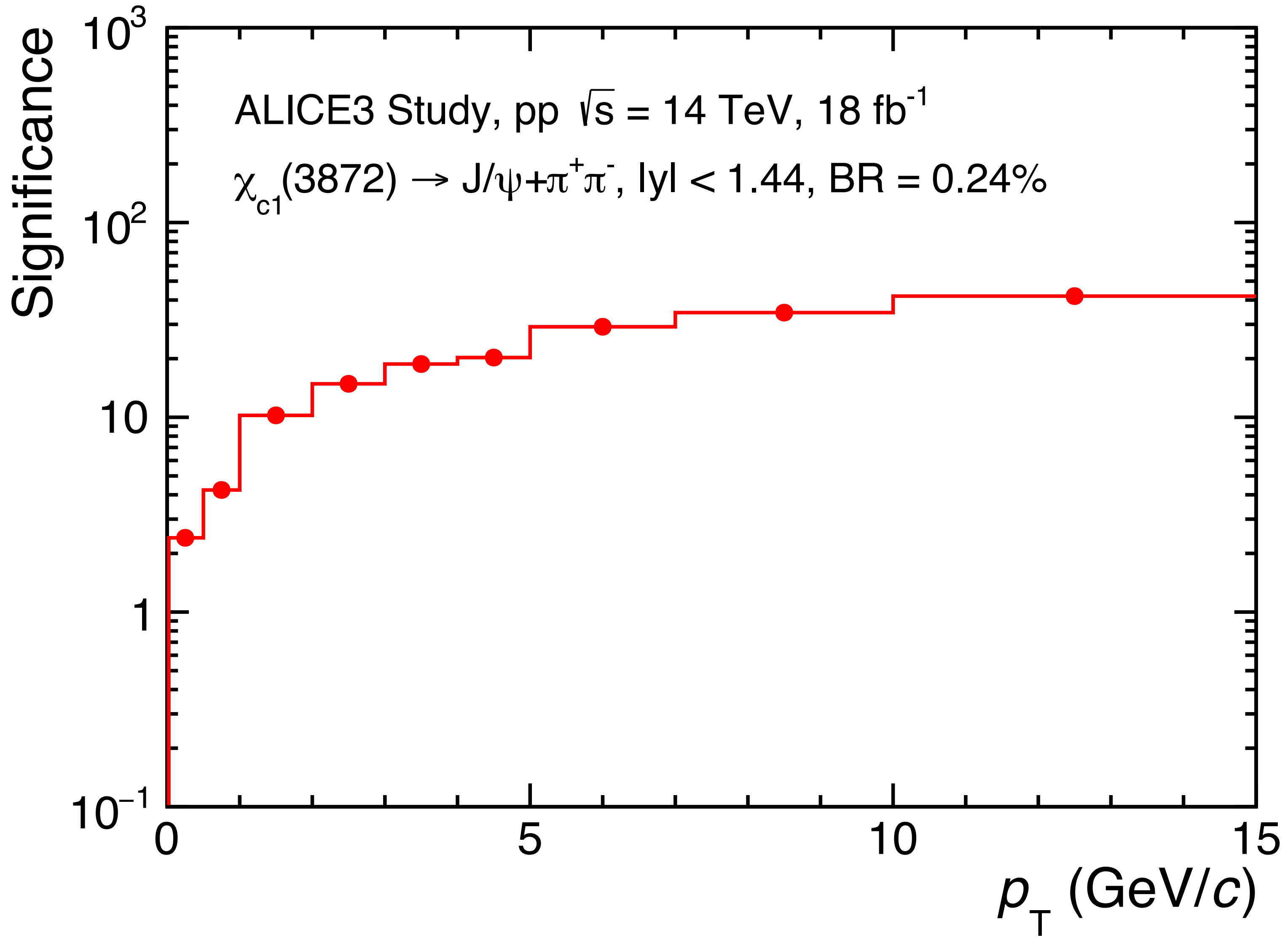


Dissociation and regeneration vs multiplicity



A Esposito et al, *EPJ.C* 86, 669

$\chi_{c1}(3872)$ significance (pp)



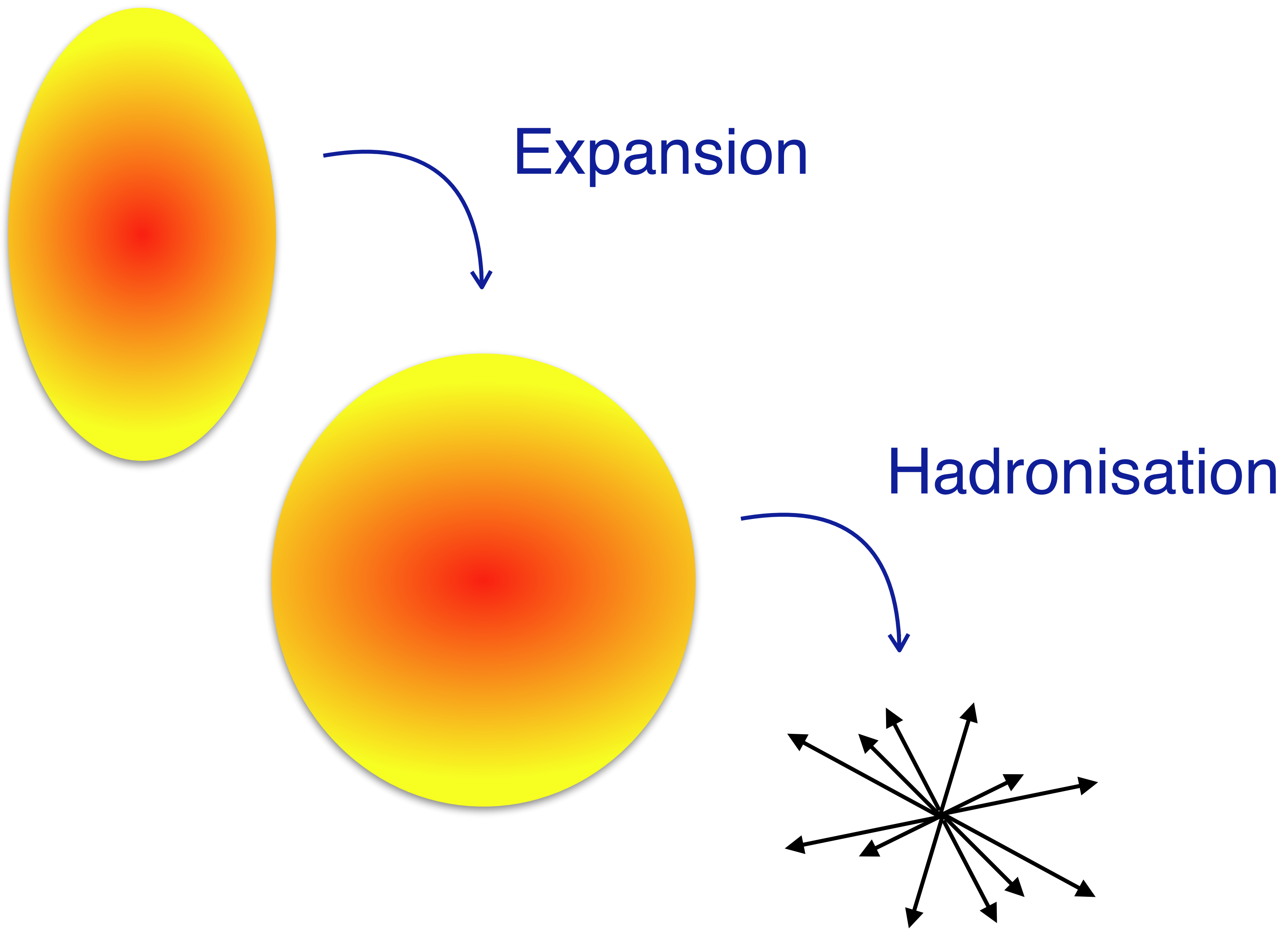
Requires:
muon ID down to 1.5 GeV/*c*

- Exotic states: $\chi_{c1}(3872)$, T_{cc}^+, …
  - Include double charm states, potentially weakly-bound states
  - **Investigate structure** with femtoscopic momentum correlations
  - Understand **dissociation and regeneration in QGP**

Azimuthal anisotropy: two mechanisms

Hydrodynamical expansion

Conversion of pressure gradients into momentum space anisotropy



Expansion

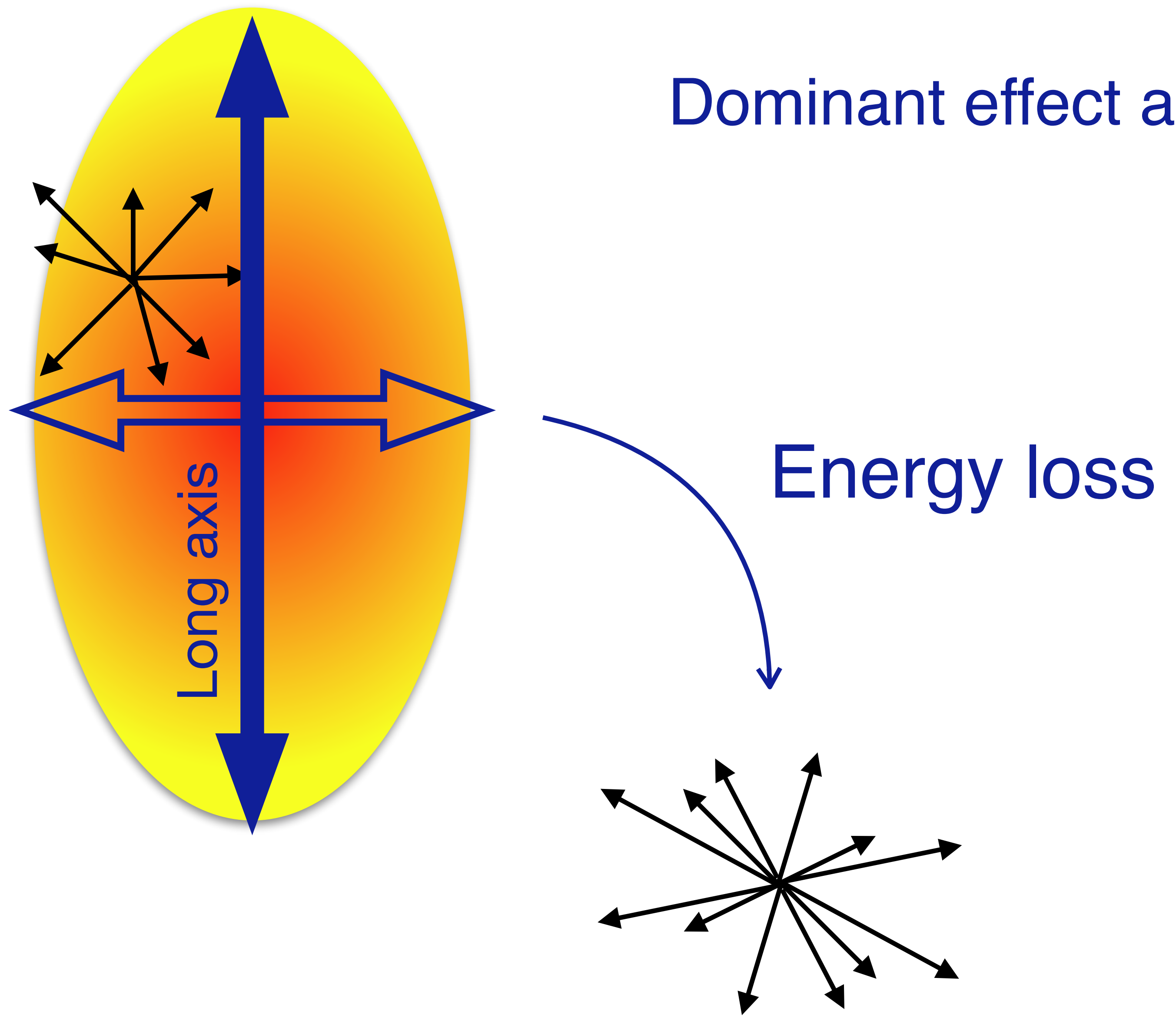
Hadronisation

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

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

Parton energy loss

Anisotropy due to energy loss and path length differences



Dominant effect at high p_T

Energy loss

More energy loss along
long axis than short axis

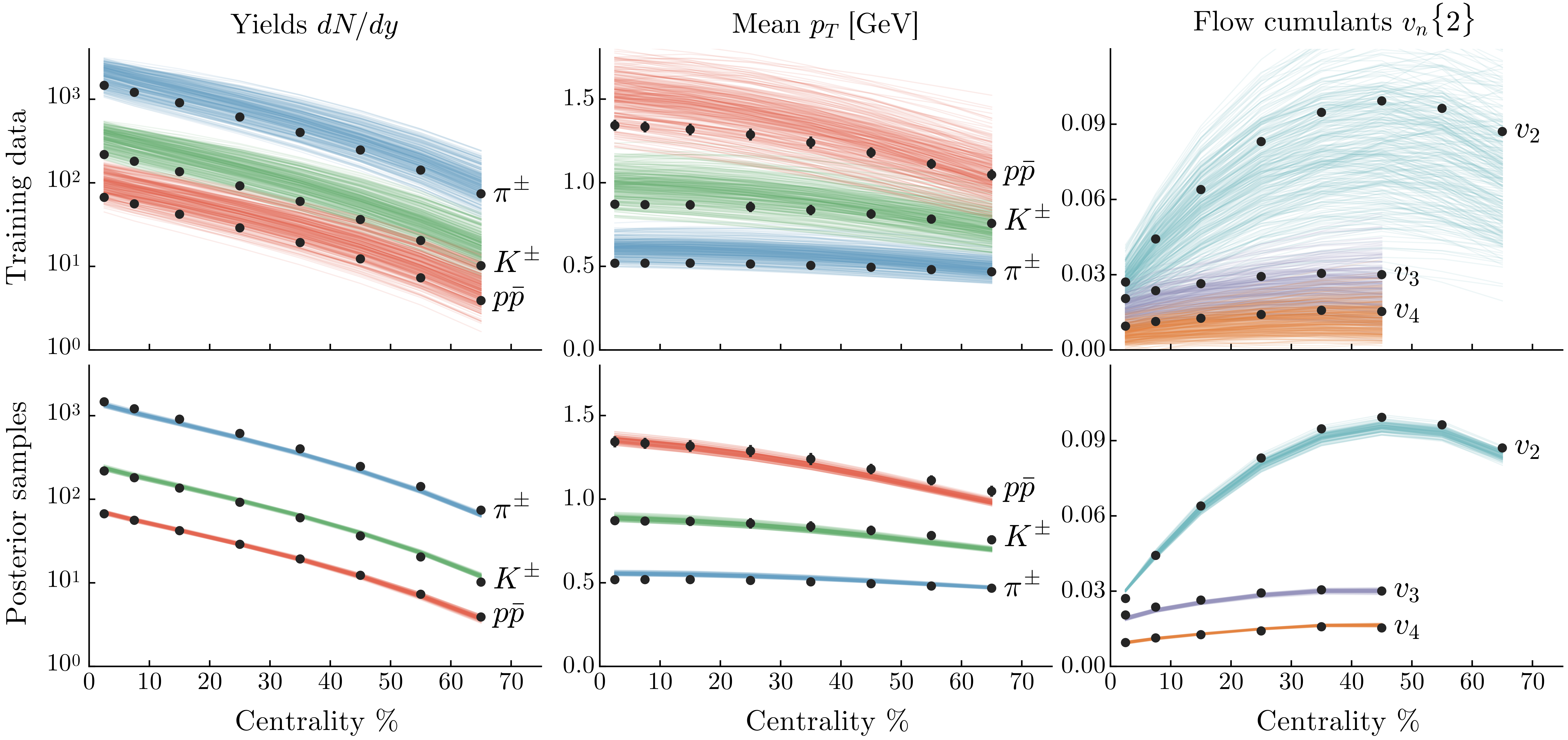
$$\Delta E_{med} \sim \alpha_s \hat{q} L^2$$

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

Azimuthal anisotropy global fit: input

J. E. Bernhard et al, arXiv: 1605.03954

Experimental input: yields, mean p_T and harmonic flow vs p_T



Model: initial anisotropies + medium response

Explores a large parameter space to investigate reliability/robustness of the modeling

Parton interactions in the medium: Collisional + radiative

Different formulations exist in literature — use this as an example

Y. Xu et al, PRC 97, 014907

'Improved Langevin model':

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi} + \vec{f}_g.$$

Drag

(often not used/present in light flavour models)

Thermal force

Radiative loss

(fluctuations are modelled as well)

Transport coefficients:

$$\begin{cases} \frac{d}{dt}\left\langle p\right\rangle \equiv -\eta_D \left\langle p\right\rangle, \\ \frac{1}{2}\frac{d}{dt}\left\langle (\Delta p_T)^2\right\rangle \equiv \kappa_T, \\ \frac{d}{dt}\left\langle (\Delta p_z)^2\right\rangle \equiv \kappa_L. \end{cases}$$

Drag

Transverse and longitudinal momentum diffusion

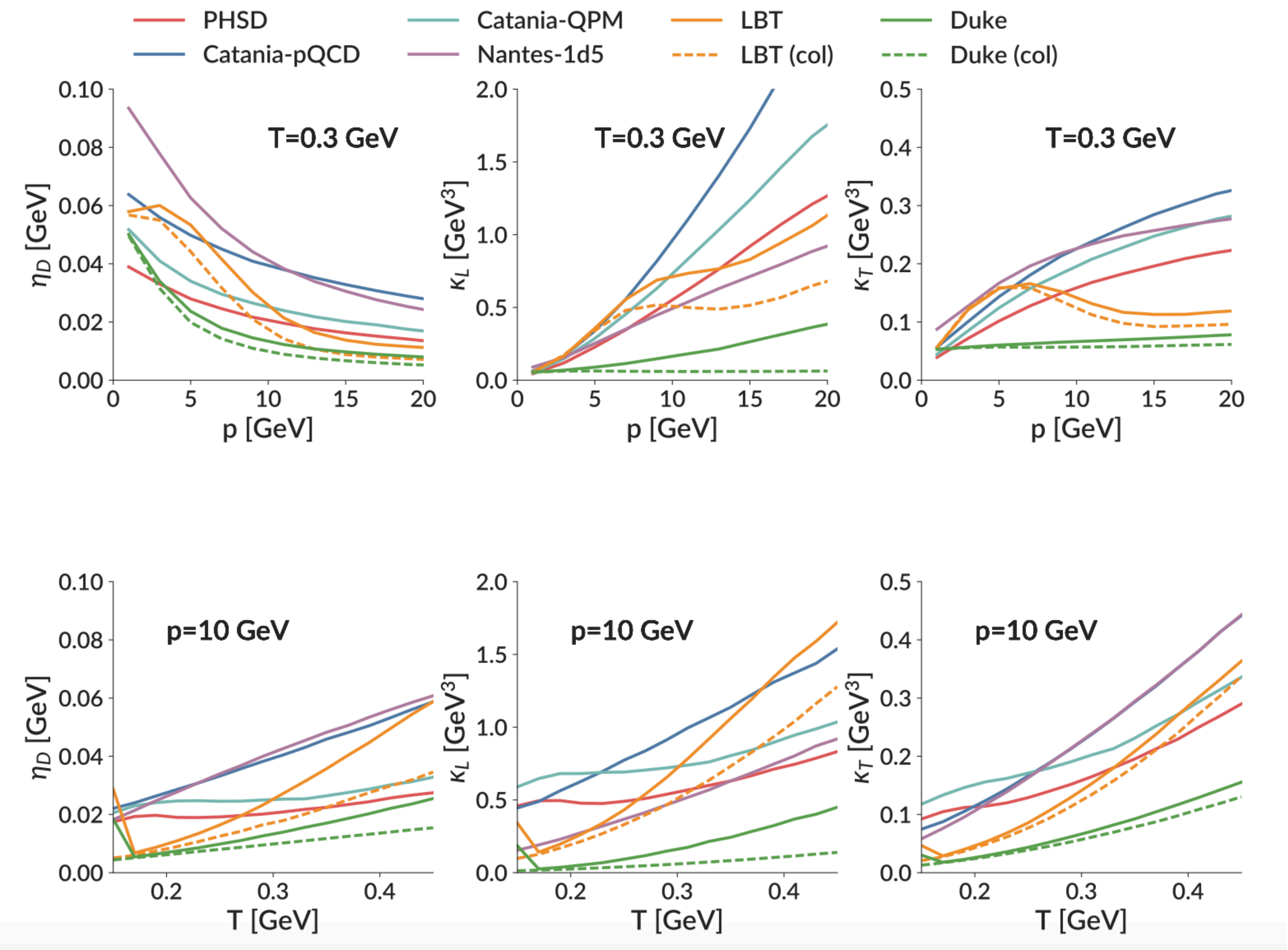
Over time: approach thermalisation
'limiting behaviour'

Mass and momentum dependence of transport coefficients

Heavy quark spatial diffusion coefficient D_s

$$\langle r^2 \rangle = 6\, D_s\, t$$

Mass independent, limit $p \to 0$



Rapp et al, arXiv:1803.03824

Xu, Y and Bass, S er at, PRC 99, 1, 014902

Other key quantities do depend on mass:

Relaxation time $\tau_Q = (m_Q/T)\, D_s$

Drag coefficient $\gamma = \dfrac{T}{m_Q\, D_s}$

⇒ Beauty thermalises more slowly than charm

Beauty vs charm: important handle on understanding phenomenology

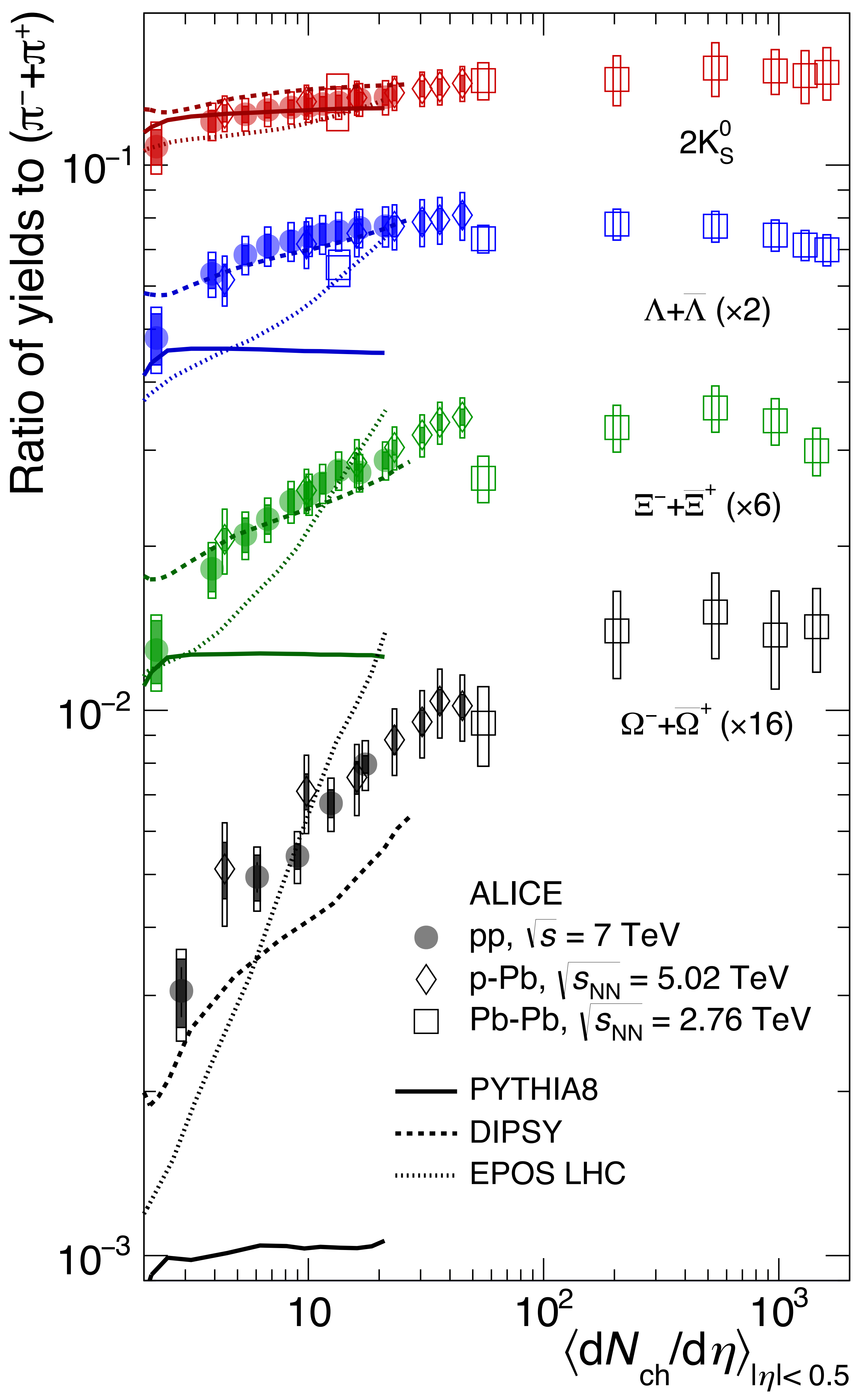
Hadronisation and baryon production

Fraction of strange hadrons increases
with multiplicity

Large effect for multi-strange Ξ and Ω

Similar enhancement in PbPb
has been interpreted as thermalisation;
global equilibration of the strangeness yield.
Are they related?

particle yields in multiplicity bins



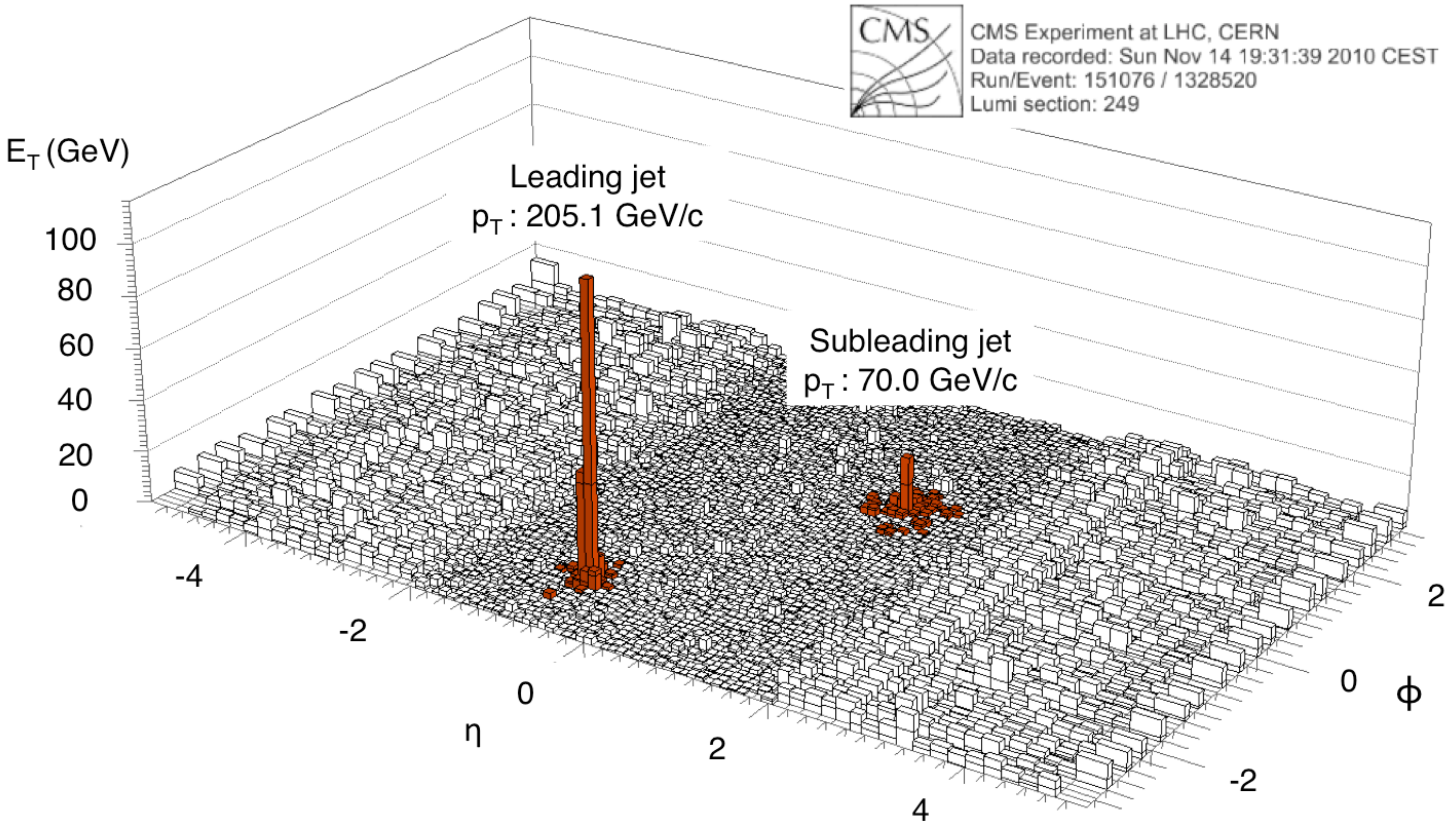
ALICE, arXiv:1606.07424, arXiv:1307.6796, arXiv:1512.07227

Nature Physics

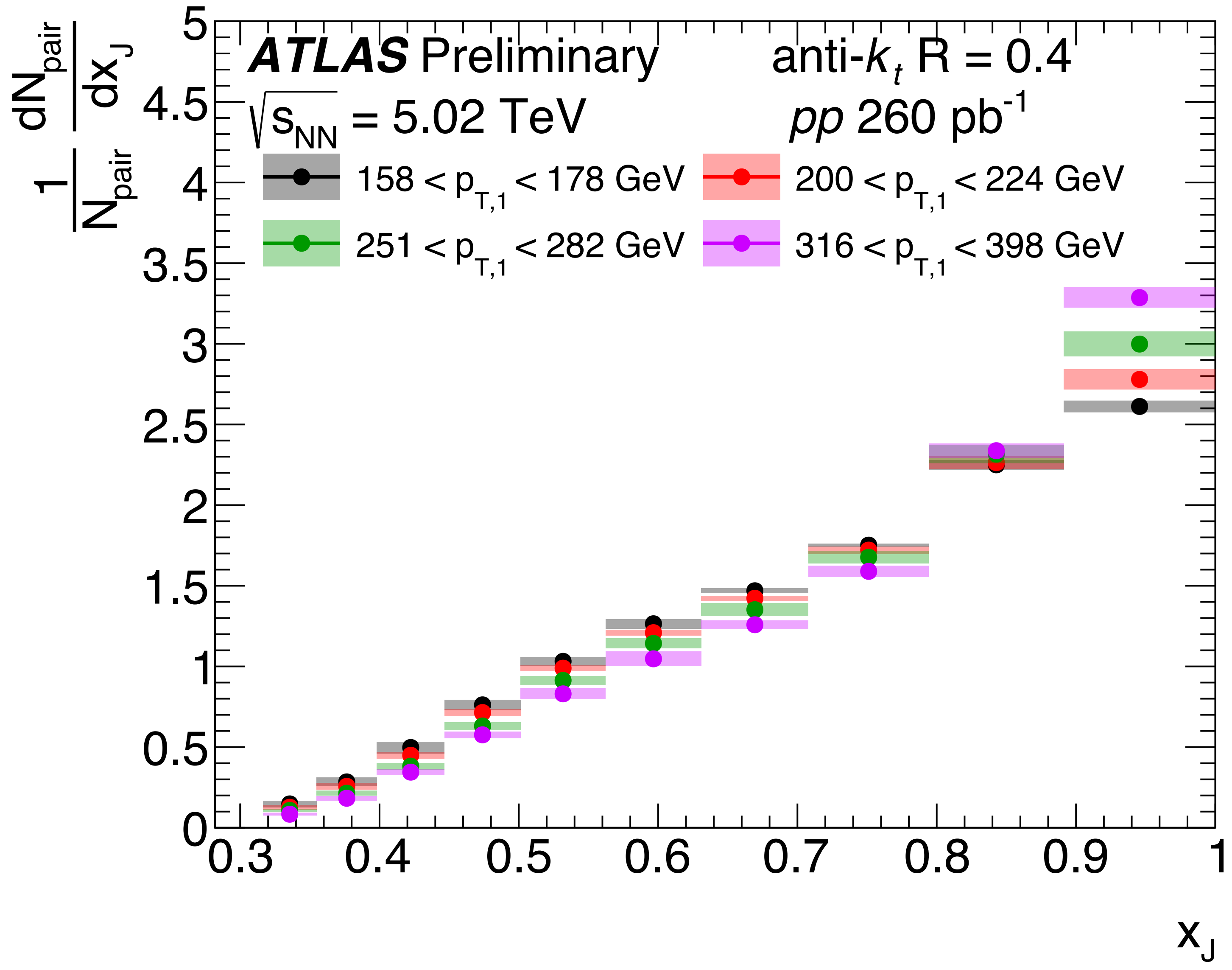
Energy loss: di-jet asymmetry

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

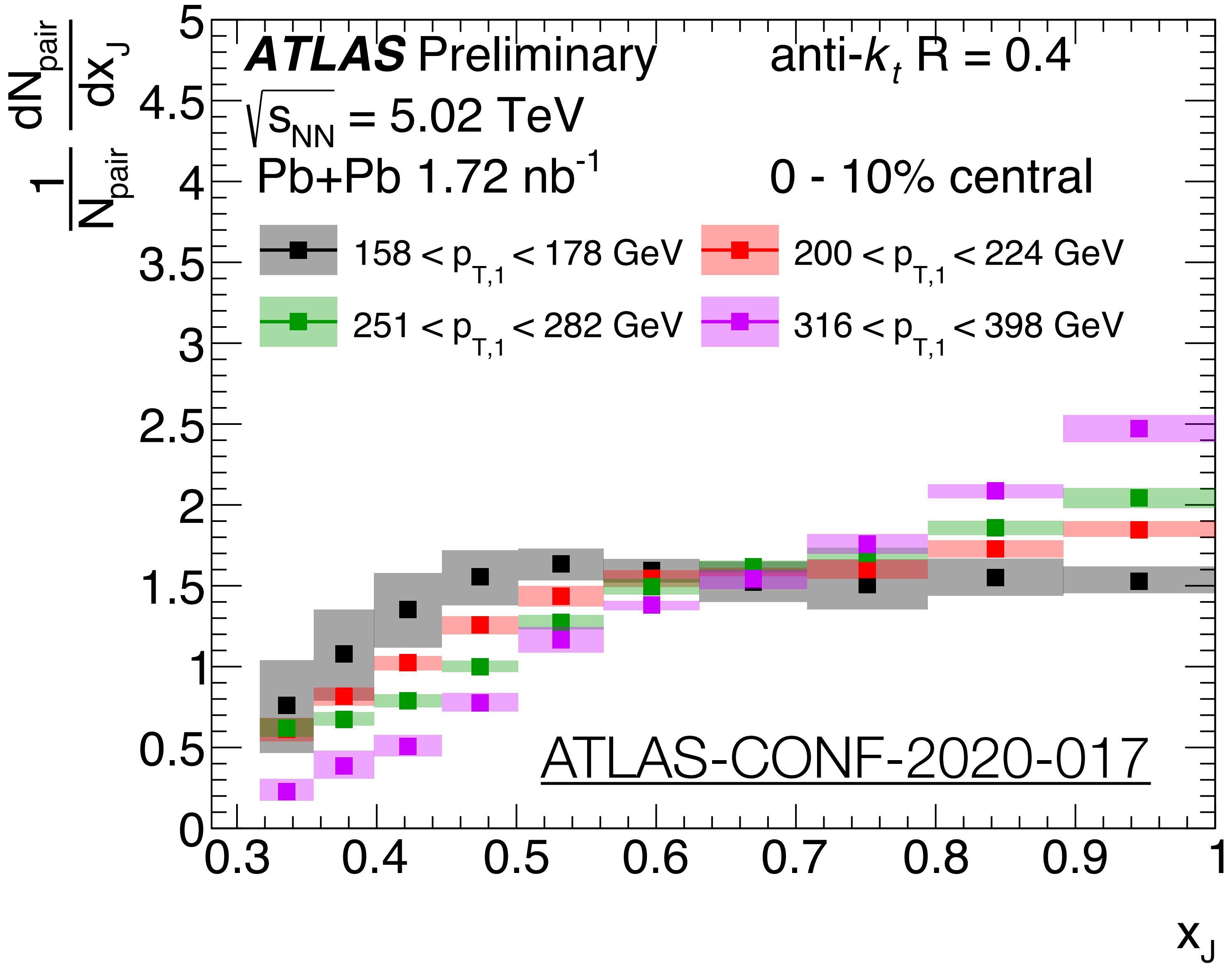
Transverse energy map of 1 event



proton-proton collisions



Pb-Pb collisions



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

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

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

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

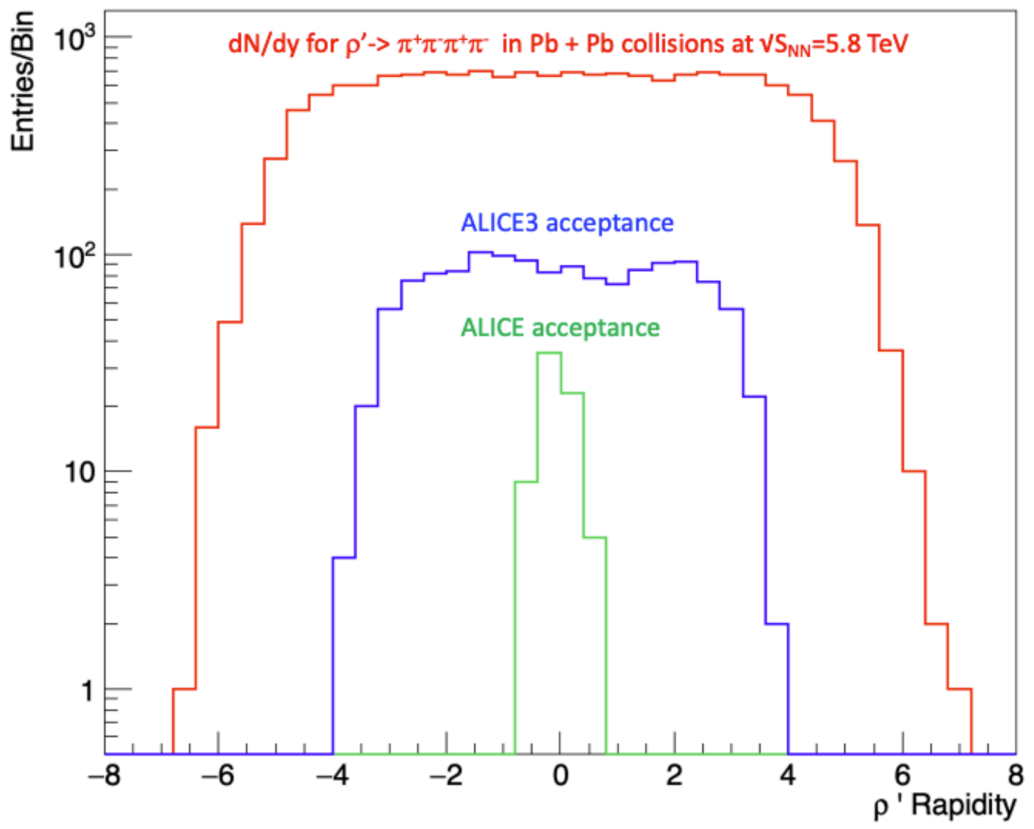
Strong coupling: $\frac{dE}{dx} \propto E$

Chesler and Rajagopal, *PRD* 90, 025033

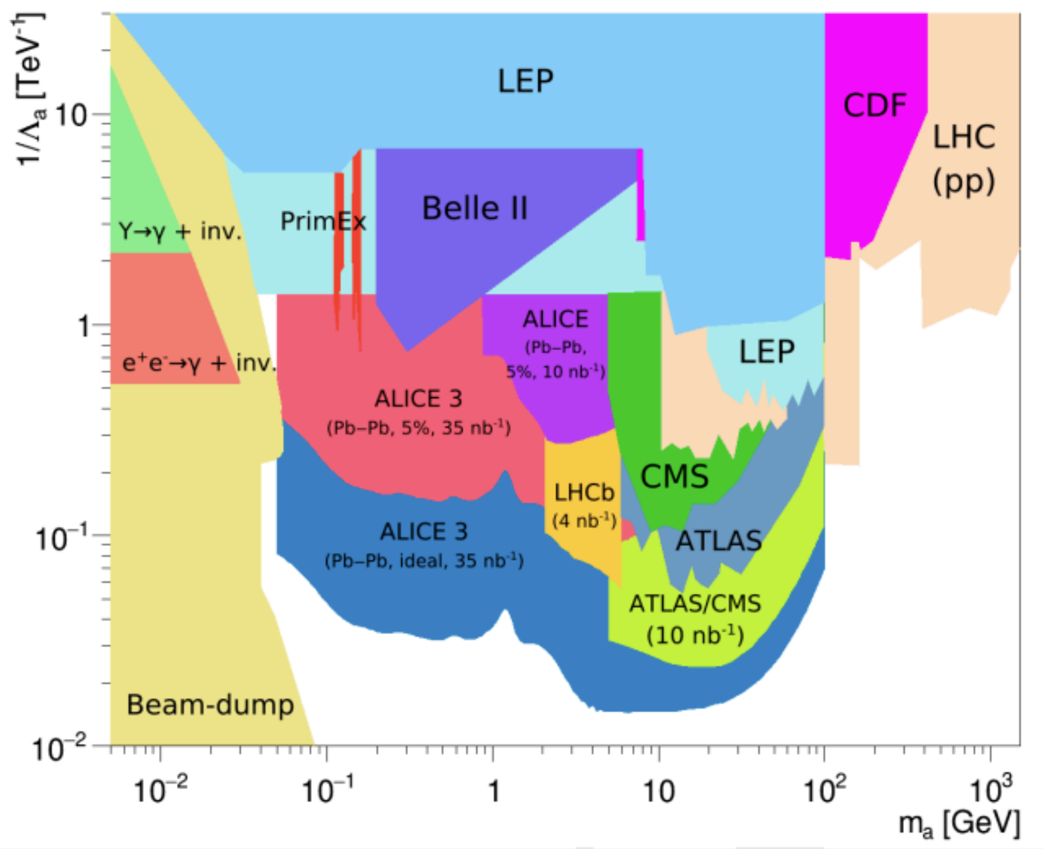
ALICE 3 Physics motivation cont’d

- Jet quenching
- Electrical conductivity
  with very low p_T dileptons
- Small collision systems:
  collectivity, MPIs, rare events
- Ultra-soft photons: Low’s theorem
- Resonance production in UPC
- ALP search in $\gamma\gamma$
- $\overline{\Lambda}_b \rightarrow {}^3\,\overline{\mathrm{He}}$ decays

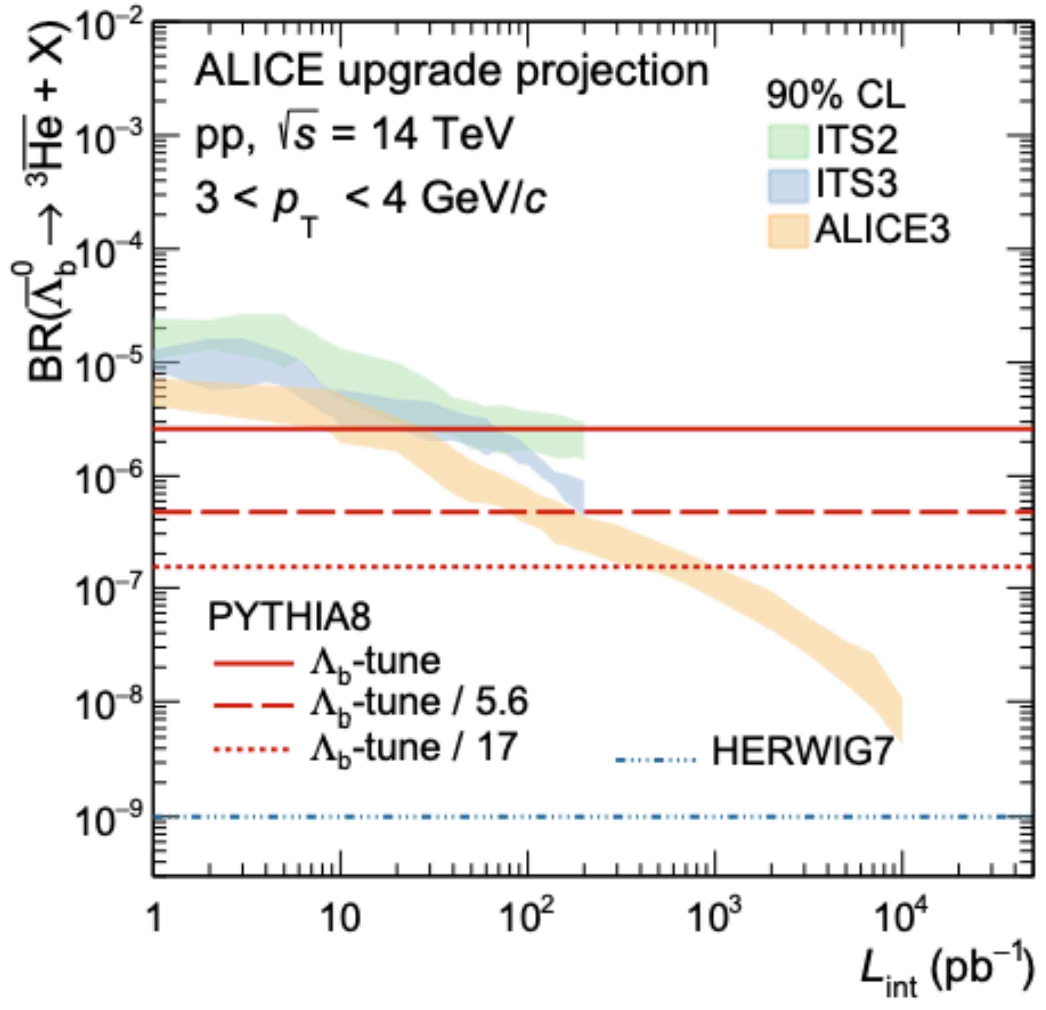
ρ’ acceptance



ALP search



$\overline{\Lambda}_b \rightarrow {}^3\,\overline{\mathrm{He}}$



Ultra-soft photons