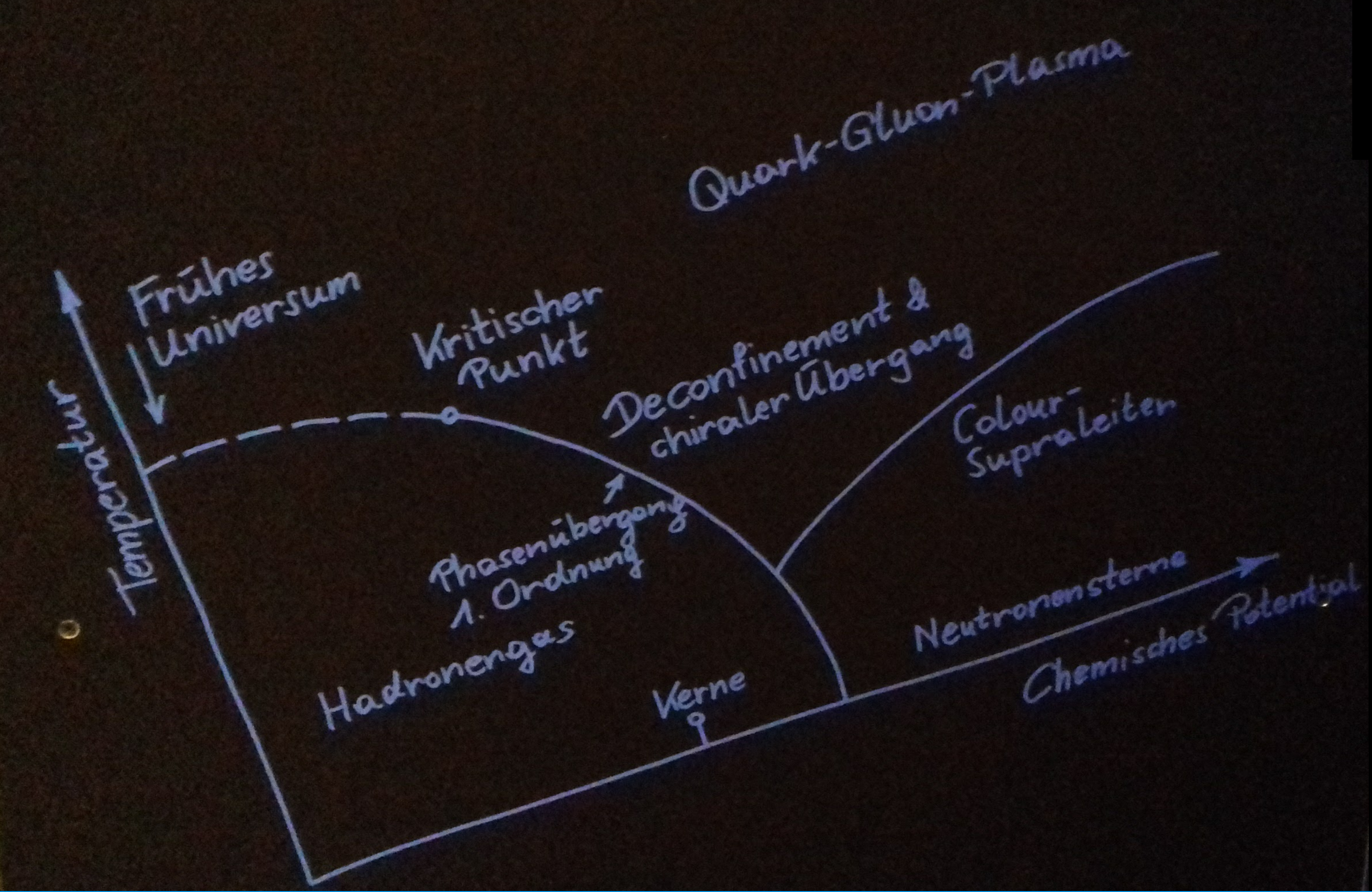
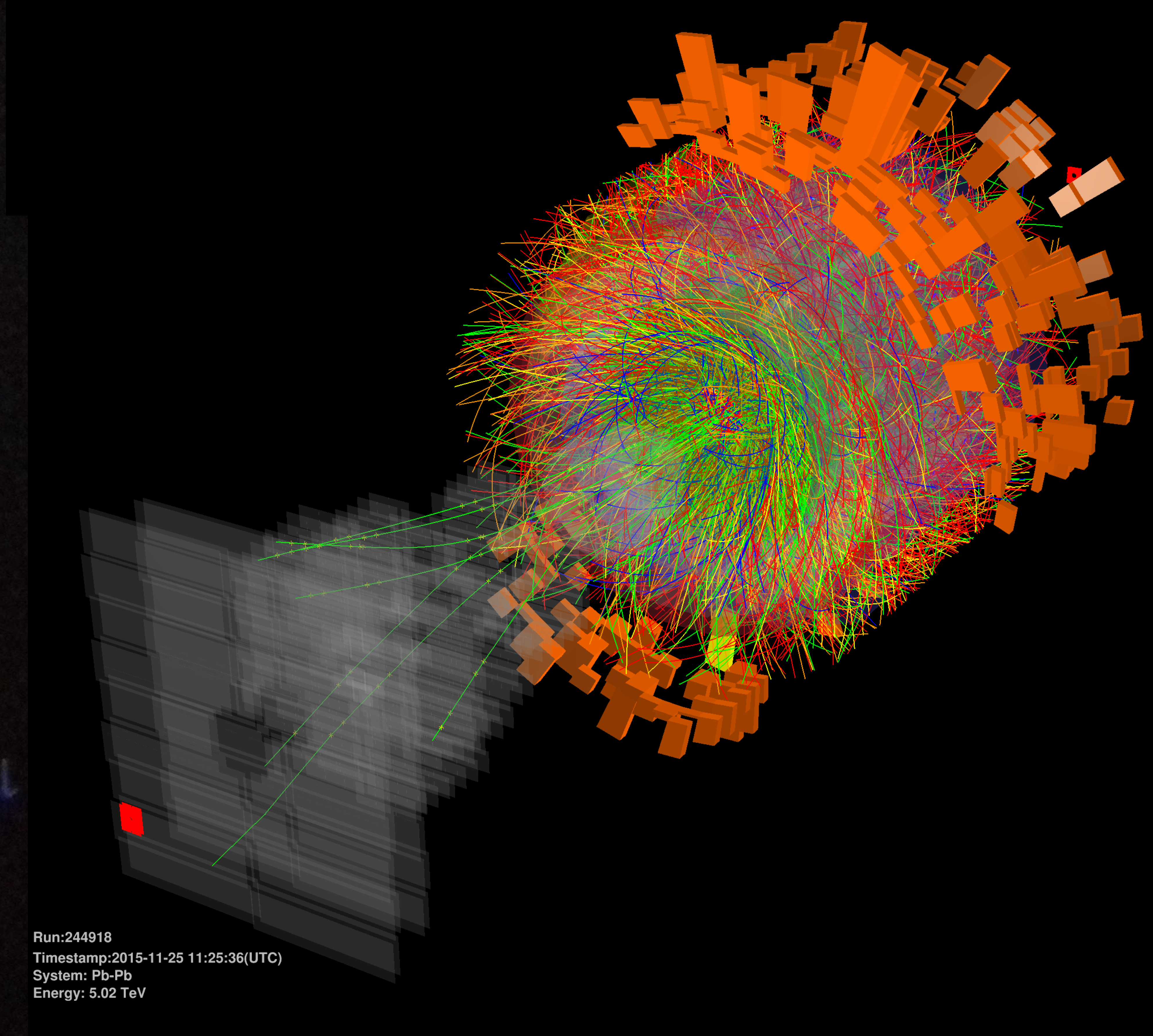
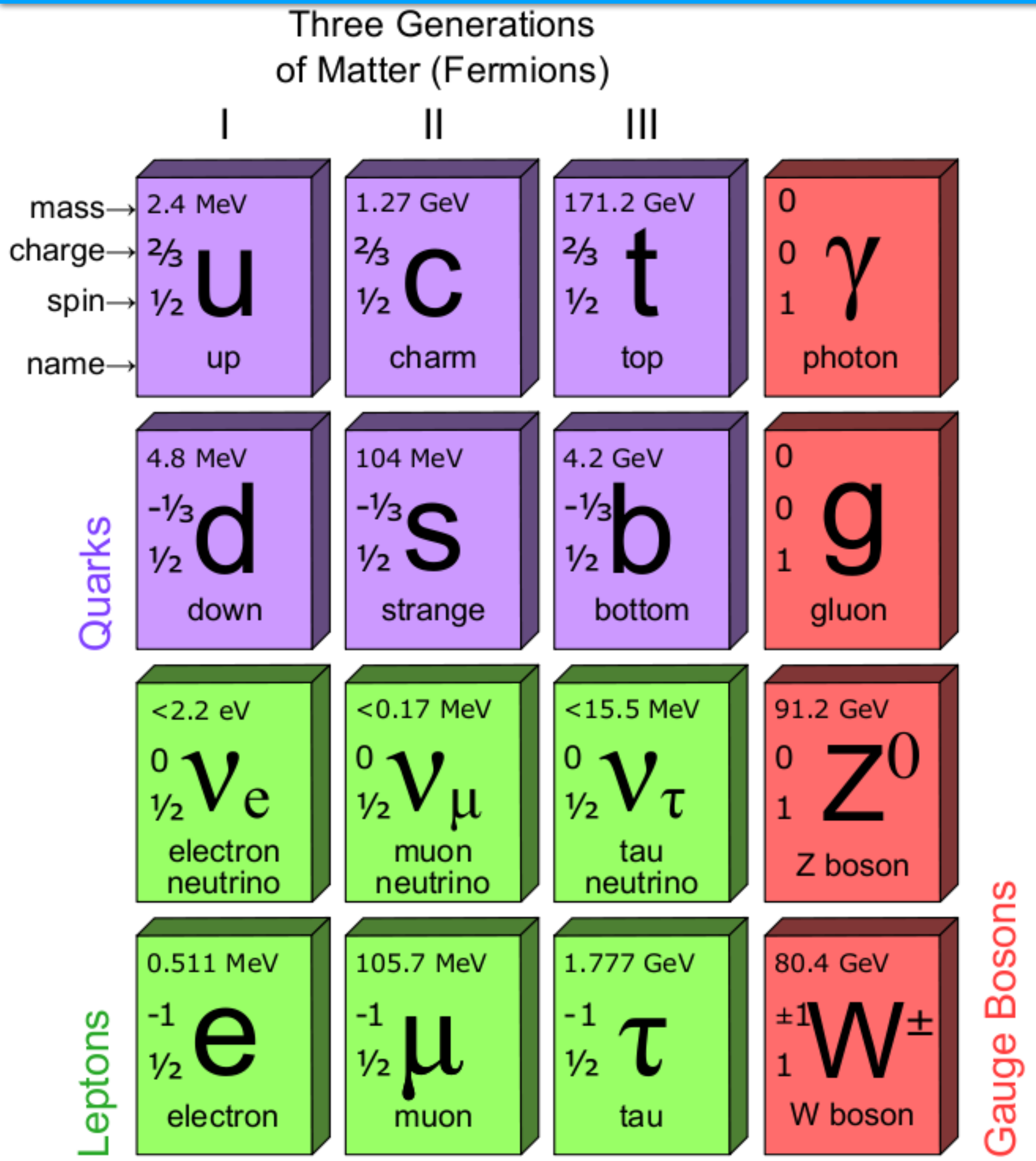


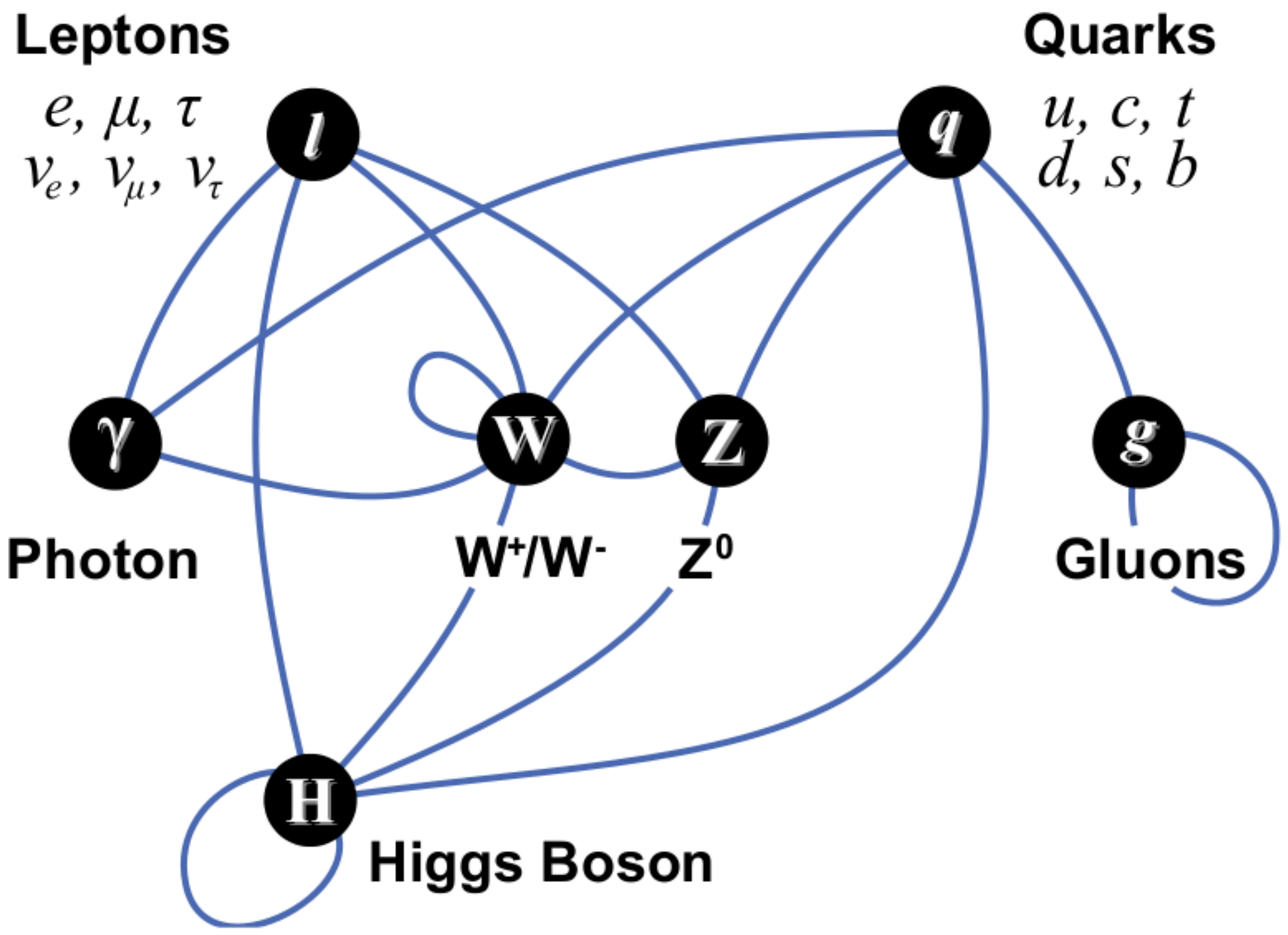


Xiaoming Zhang

Brief introduction to the physics of ultra-relativistic heavy-ion collisions

Standard model





Properties of the strong interaction

$$\mathcal{L} = \sum_q \overline{\psi}_{q,a}(i\gamma^\mu \partial_\mu \delta_{ab} - g_{\mathrm{s}} \gamma^\mu t^C_{ab} \mathcal{A}^C_\mu - m_a \delta_{ab}) \psi_{q,b} - \frac{1}{4} F^A_{\mu\nu} F^{A,\mu\nu}$$

Properties of the strong interaction

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$$F^A_{\mu\nu} = \partial_\mu \mathcal{A}^A_\nu - \partial_\nu \mathcal{A}^A_\mu - g_\mathrm{s} f_{ABC}\mathcal{A}^B_\mu \mathcal{A}^C_\nu$$

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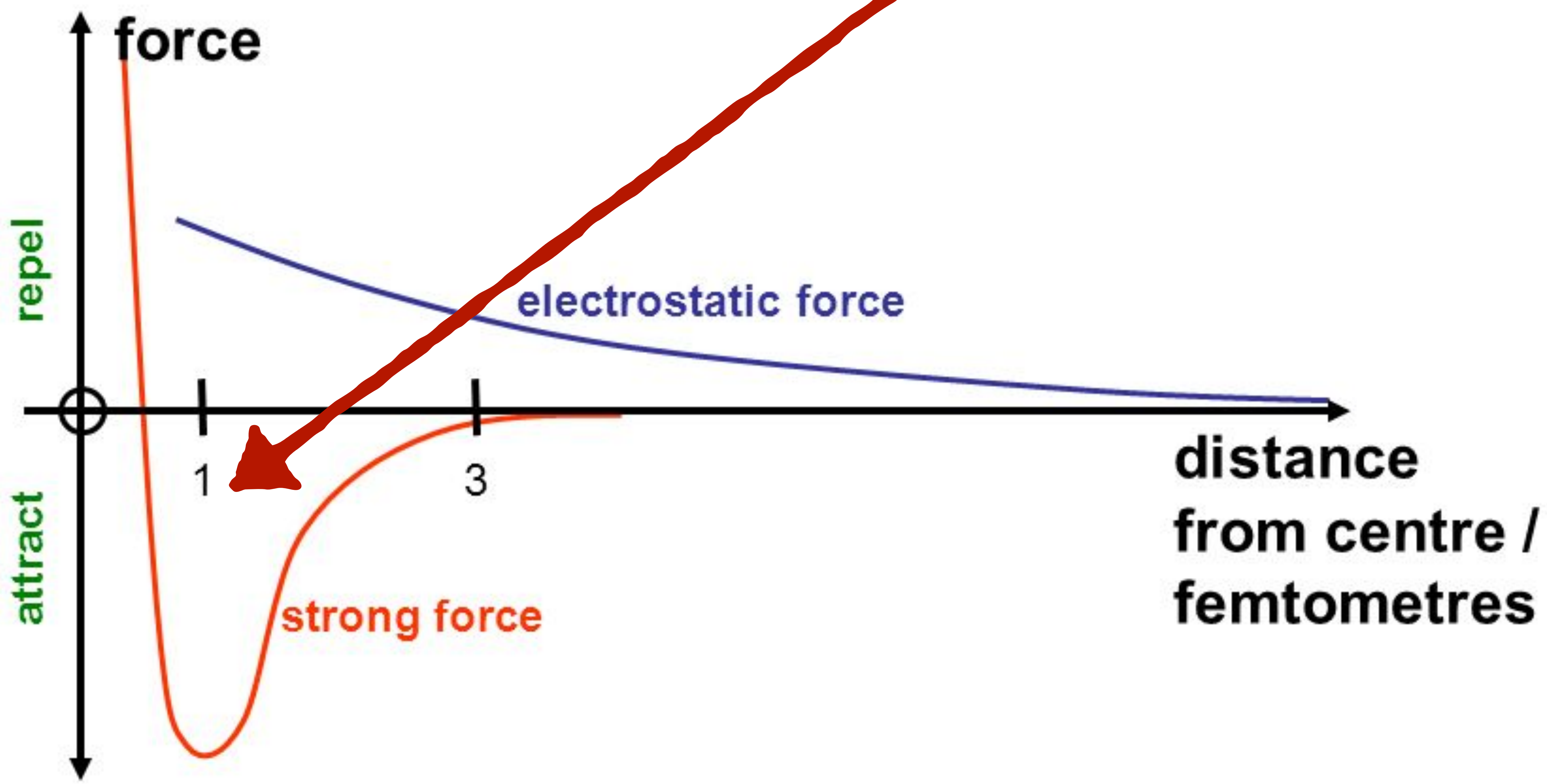

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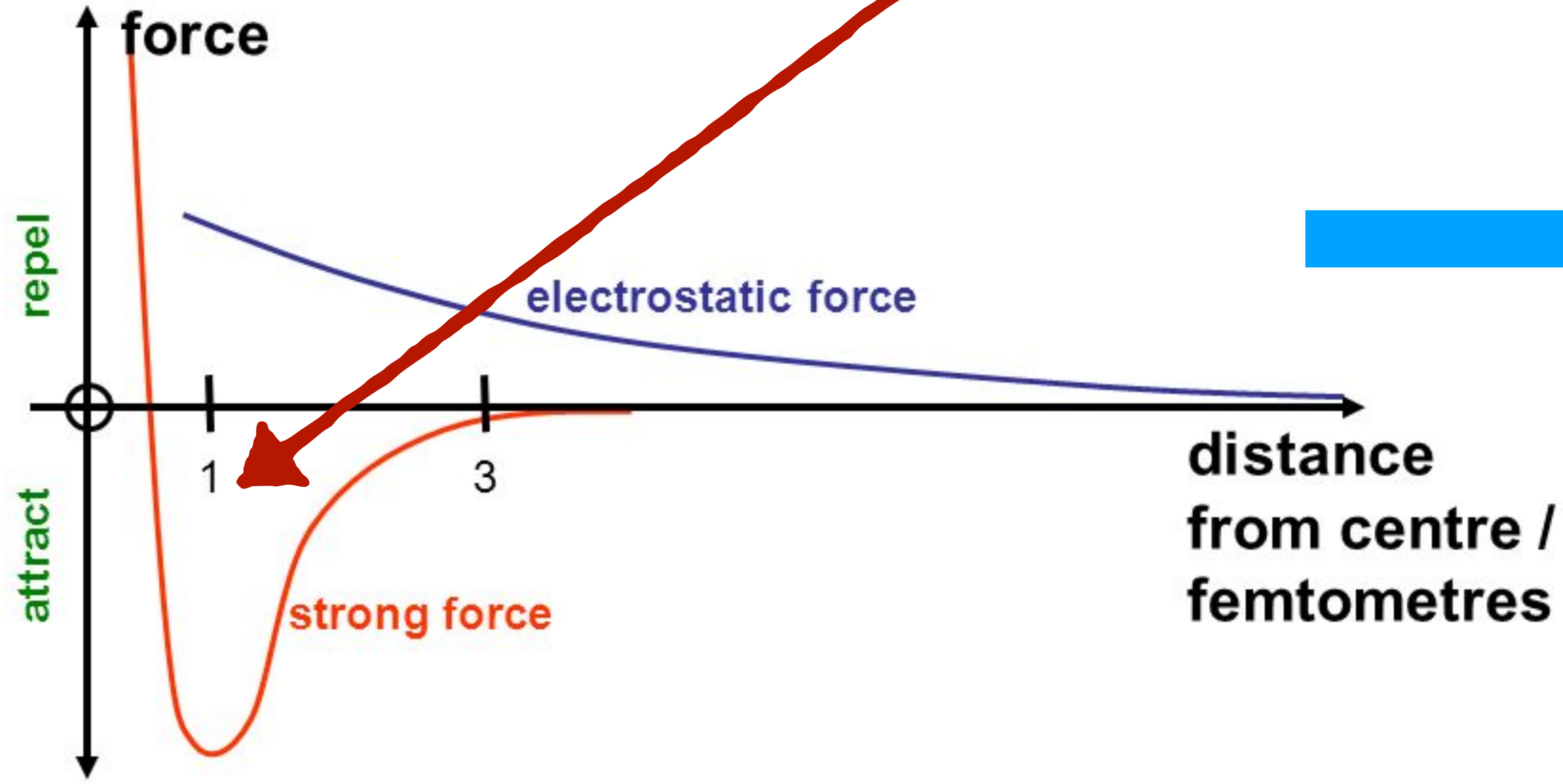
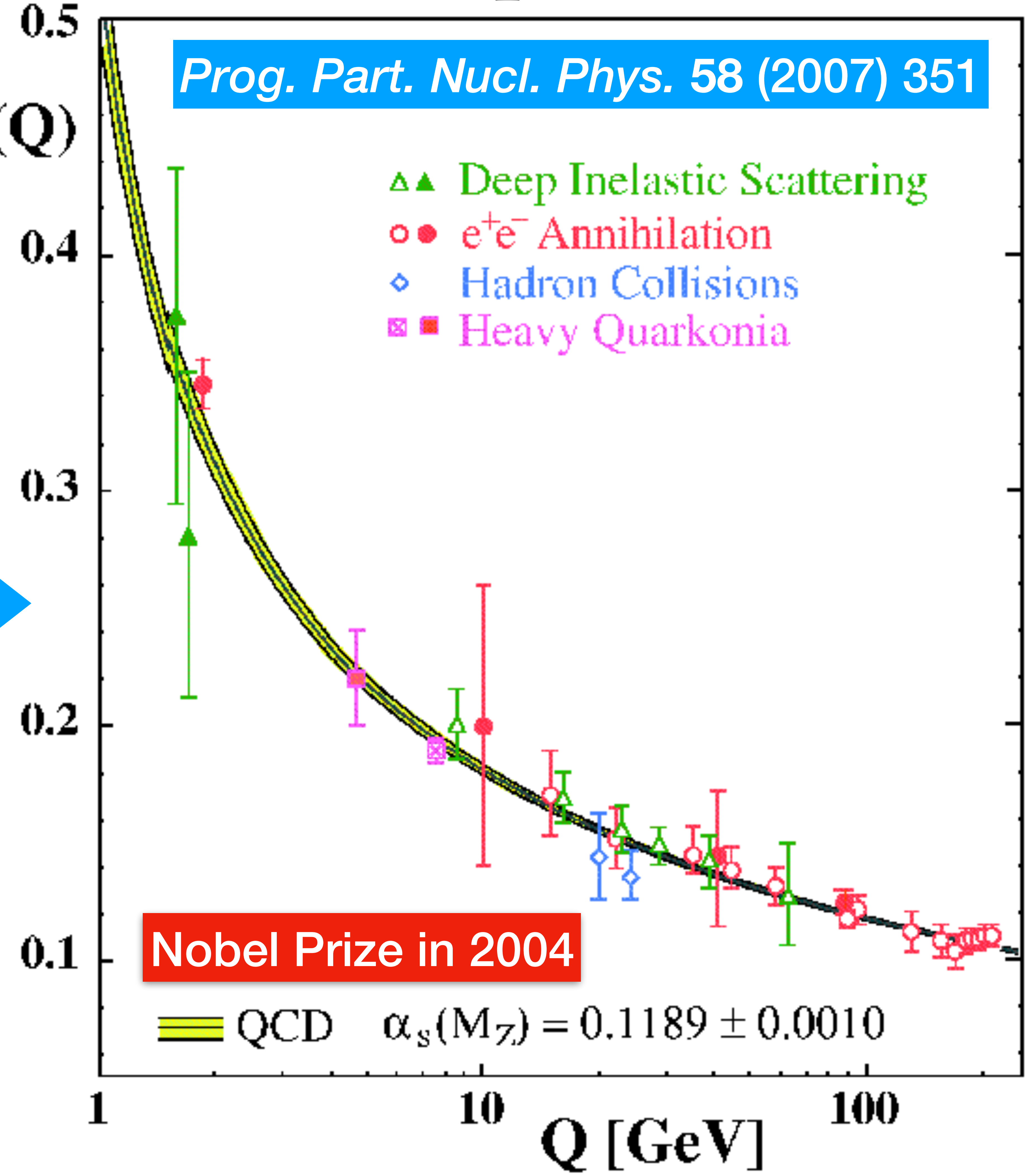
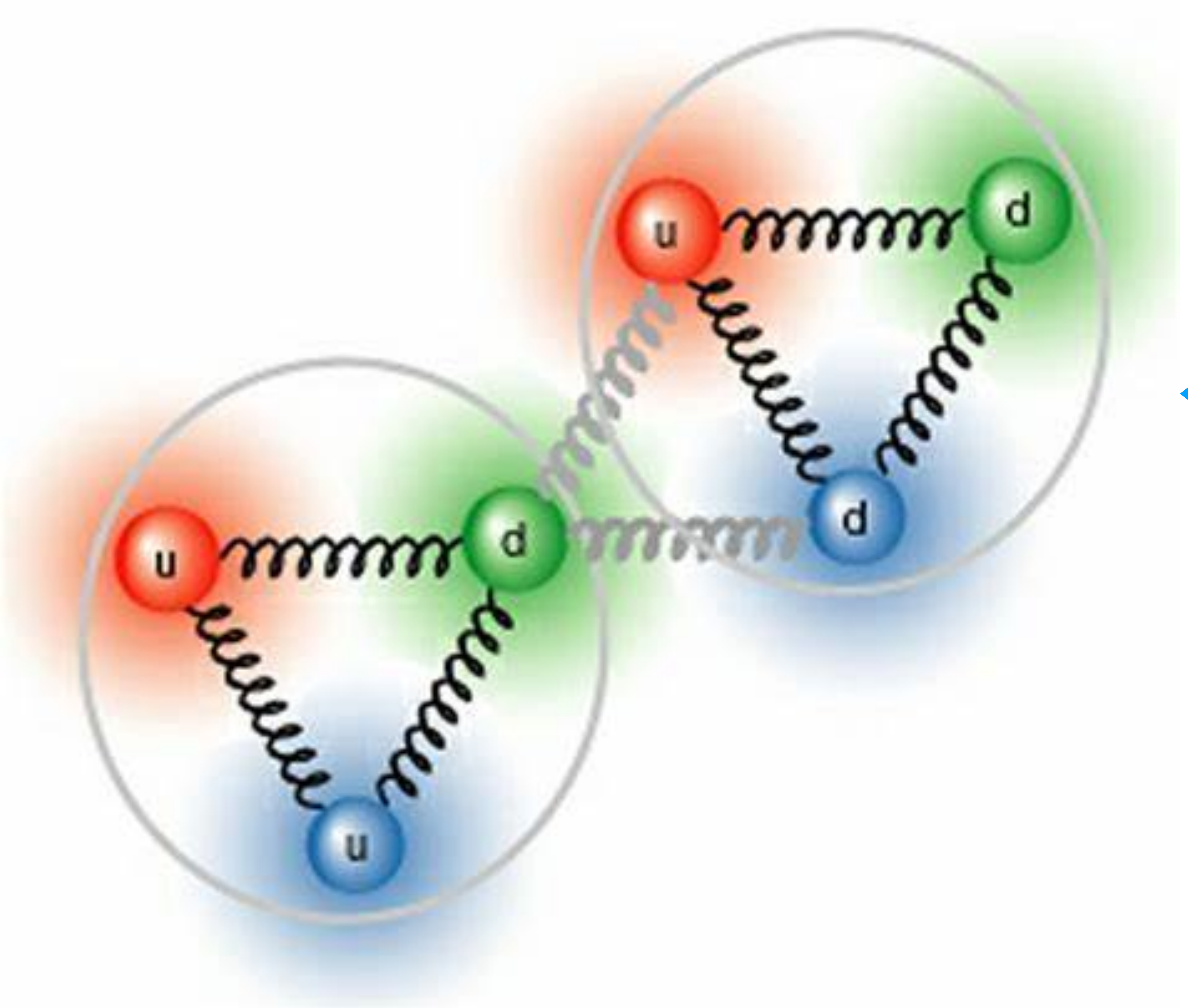


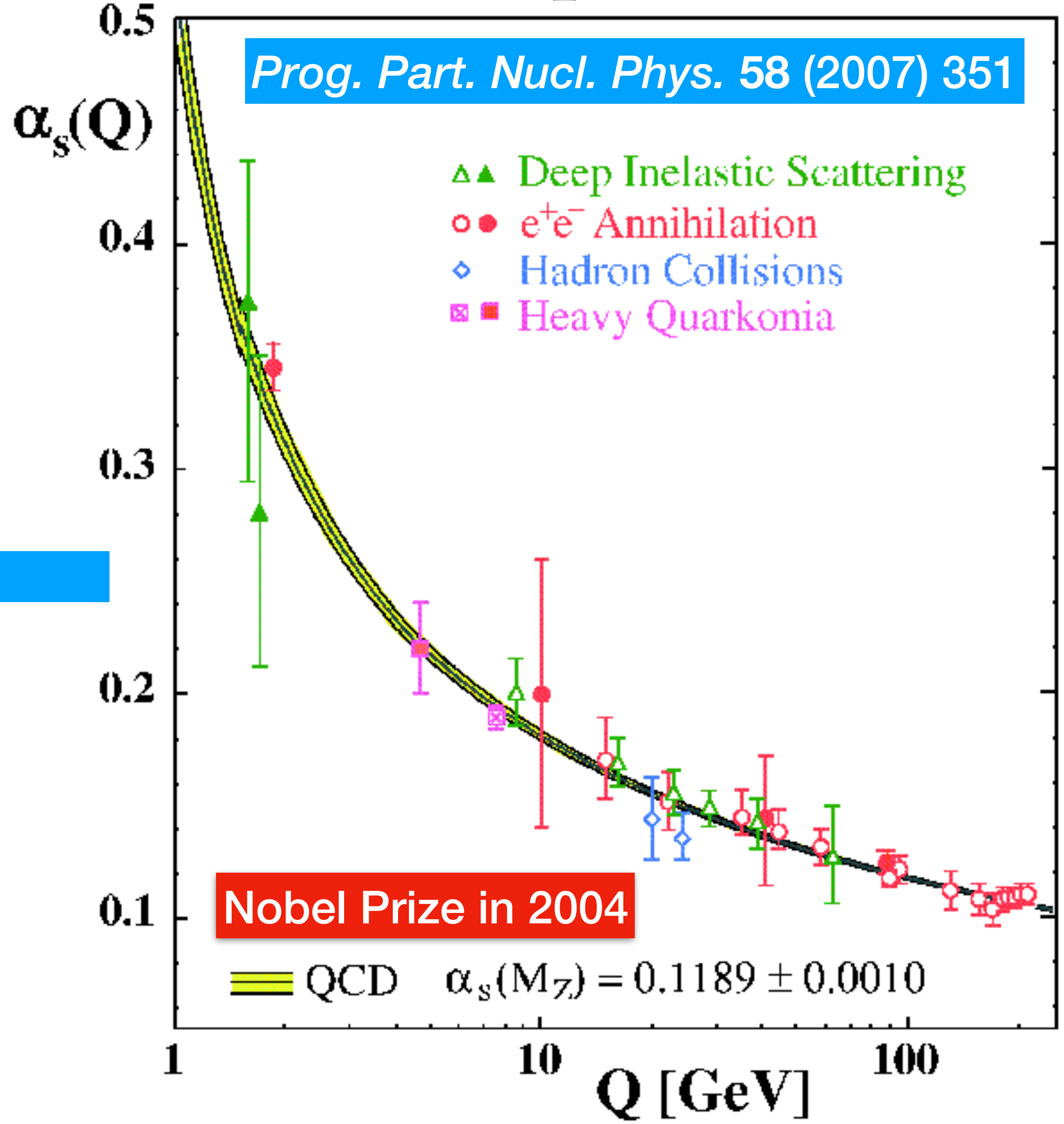


Properties of the strong interaction

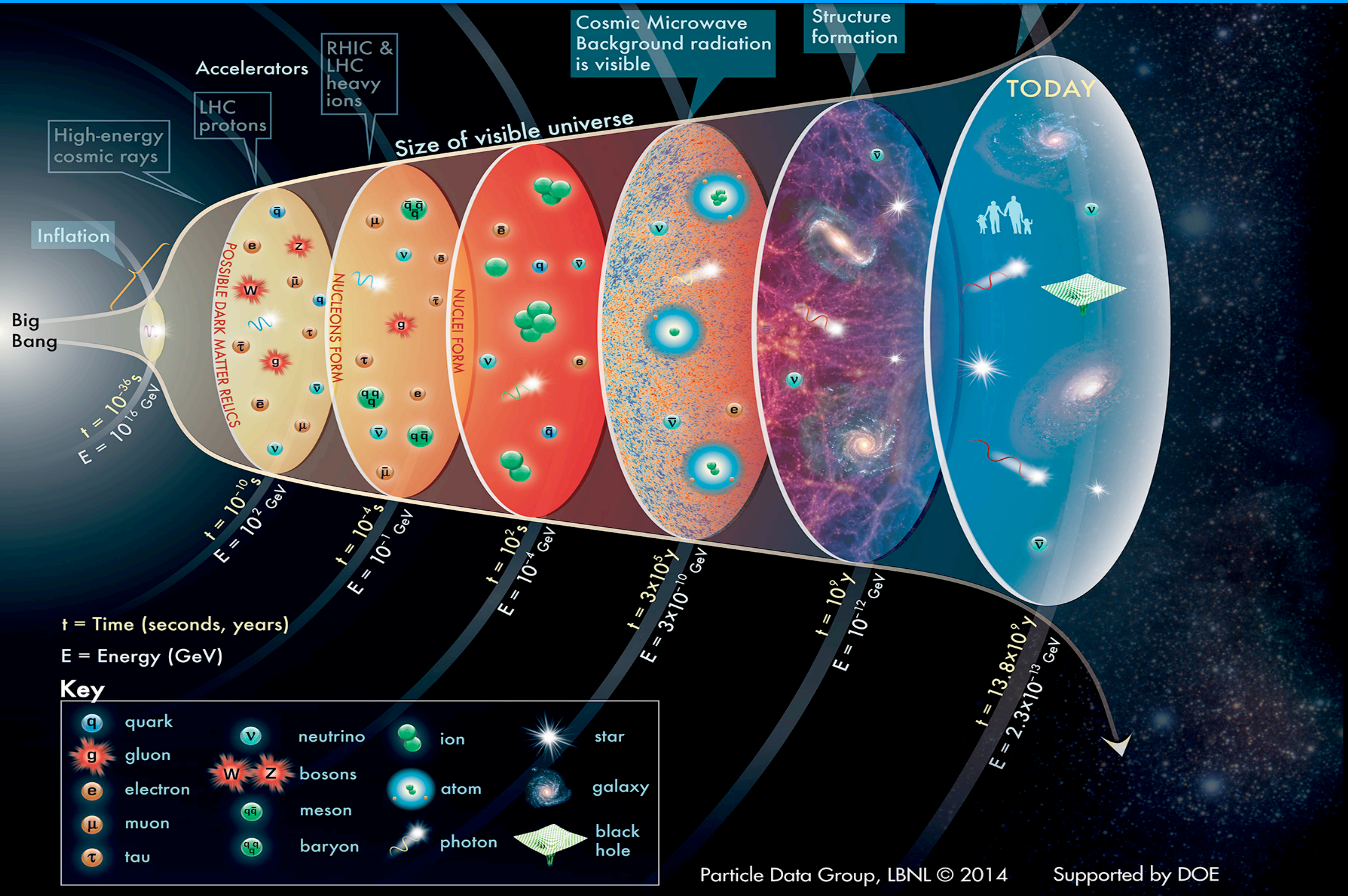
$$\mathcal{L} = \sum_q \overline{\psi}_{q,a}(i\gamma^\mu\partial_\mu\delta_{ab} - g_s\gamma^\mu t^C_{ab}\mathcal{A}^C_\mu - m_a\delta_{ab})\psi_{q,b} - \frac{1}{4}F^A_{\mu\nu}F^{A,\mu\nu}$$

$$F^A_{\mu\nu} = \partial_\mu\mathcal{A}^A_\nu - \partial_\nu\mathcal{A}^A_\mu - g_s f_{ABC}\mathcal{A}^B_\mu\mathcal{A}^C_\nu$$

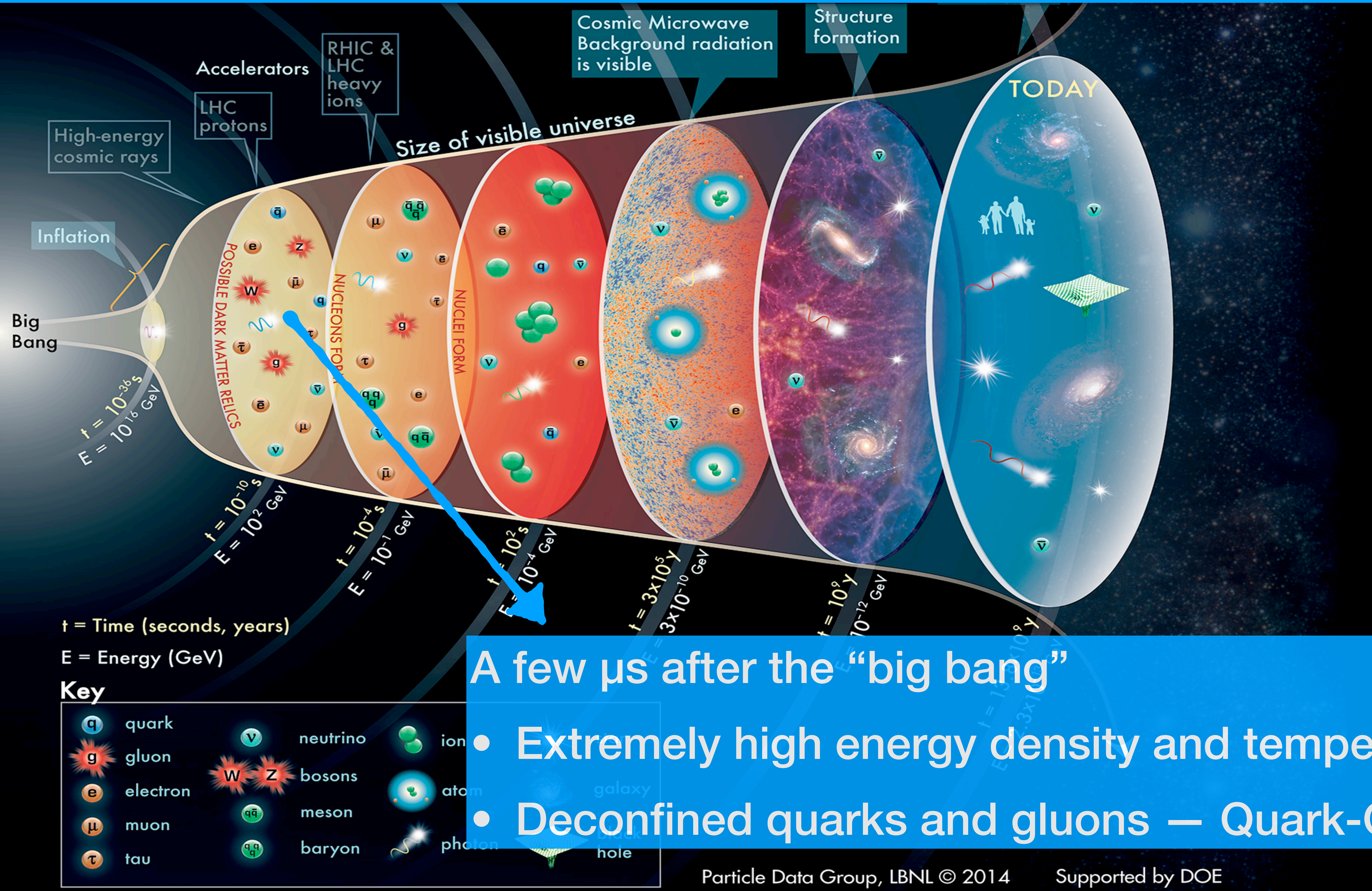




History of the universe



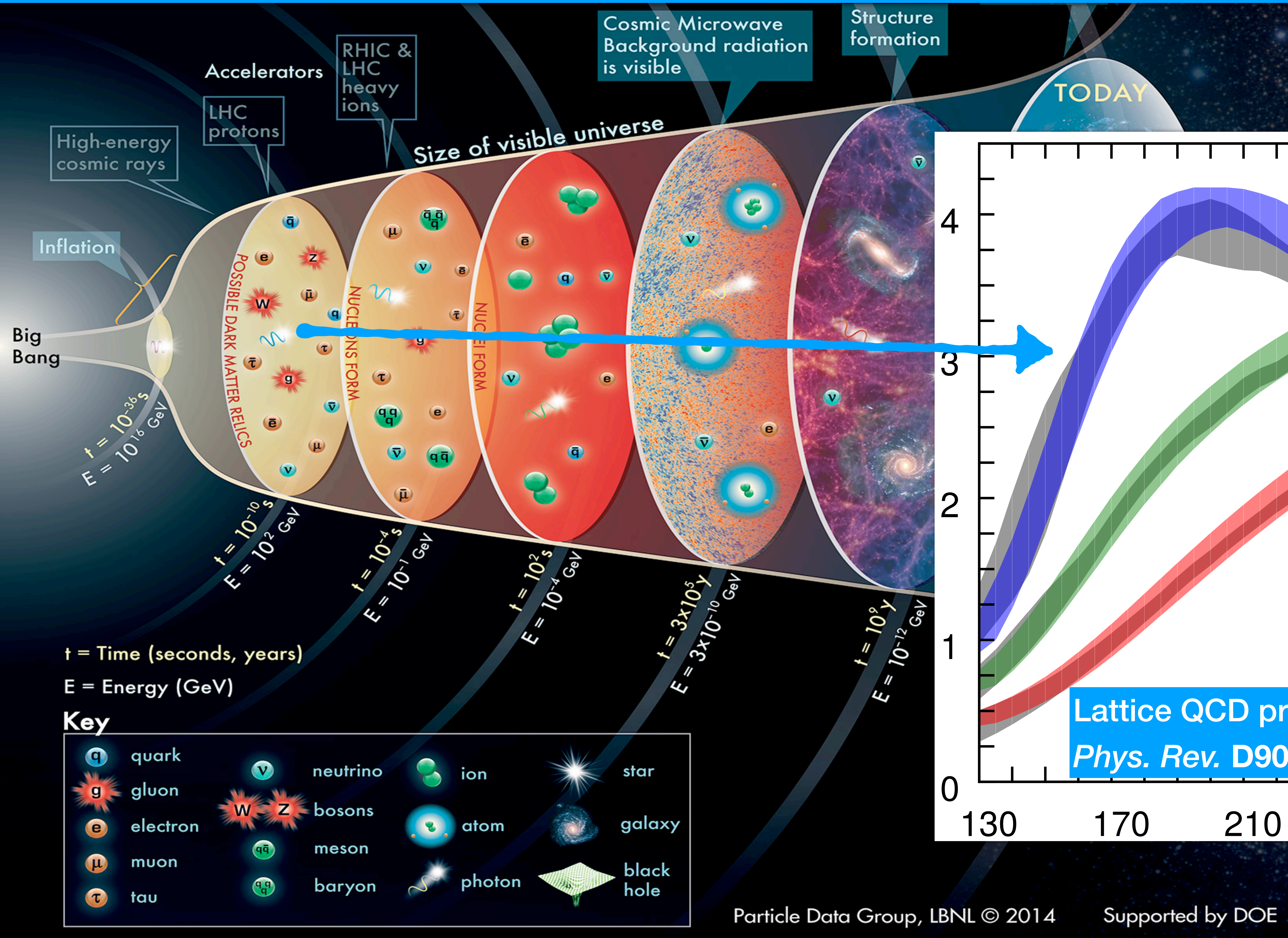
History of the universe

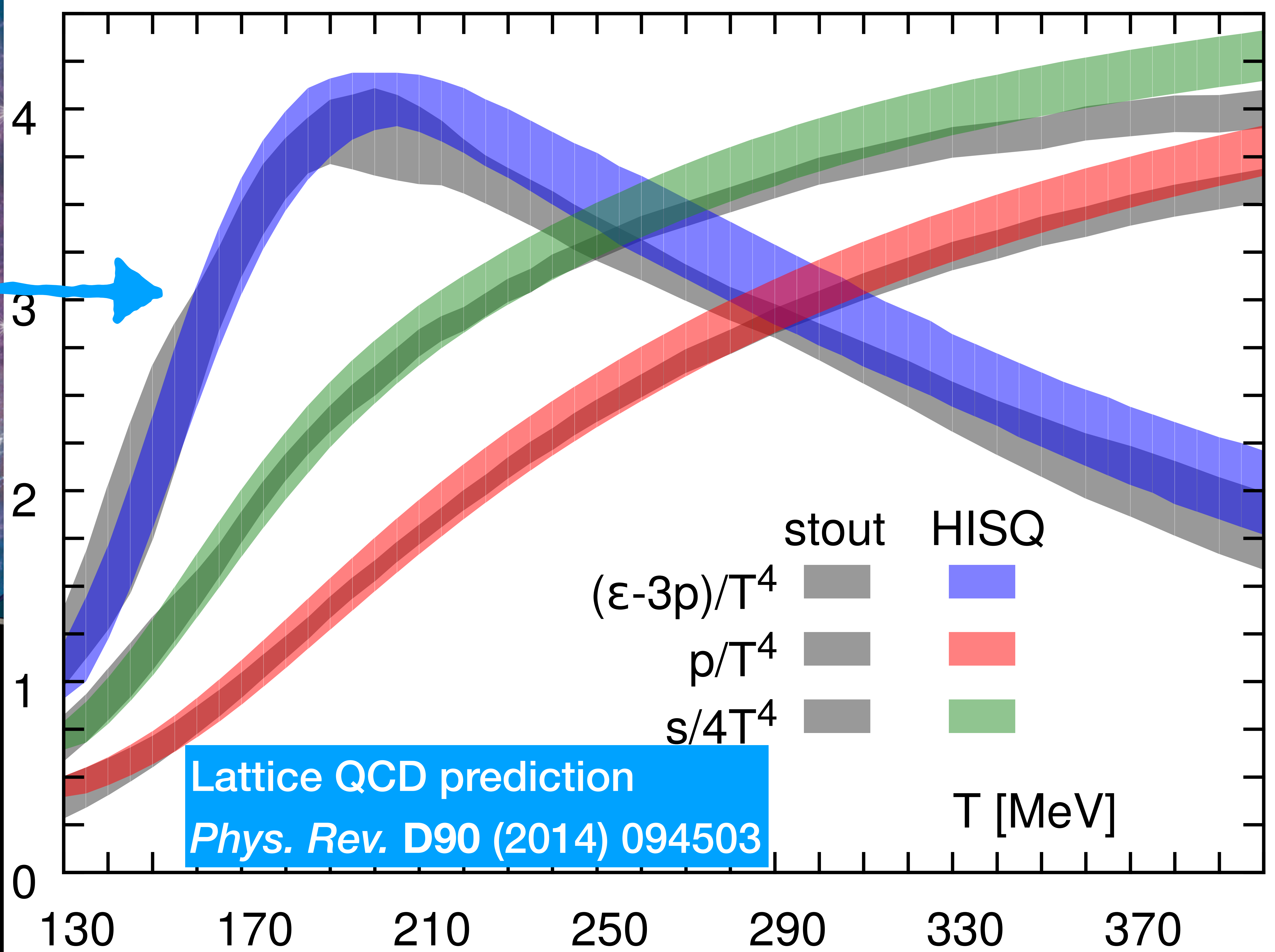


A few μs after the “big bang”

- Extremely high energy density and temperature
- Deconfined quarks and gluons — Quark-Gluon Plasma (QGP)

History of the universe





Lattice QCD prediction

Phys. Rev. **D90** (2014) 094503

Ultra-relativistic heavy-ion collisions

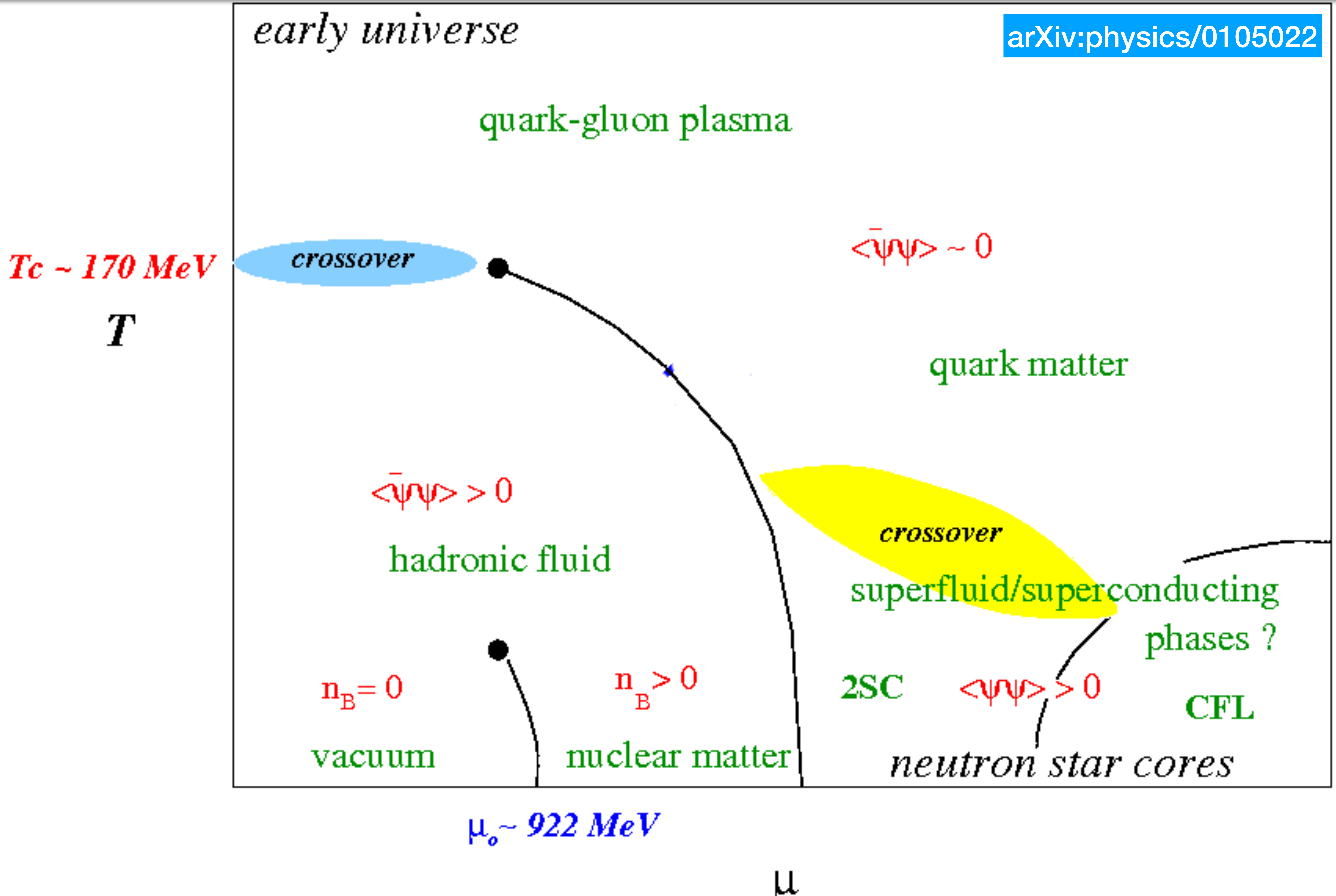
Ultra-relativistic heavy-ion collisions

“Small bang” — study of the QGP

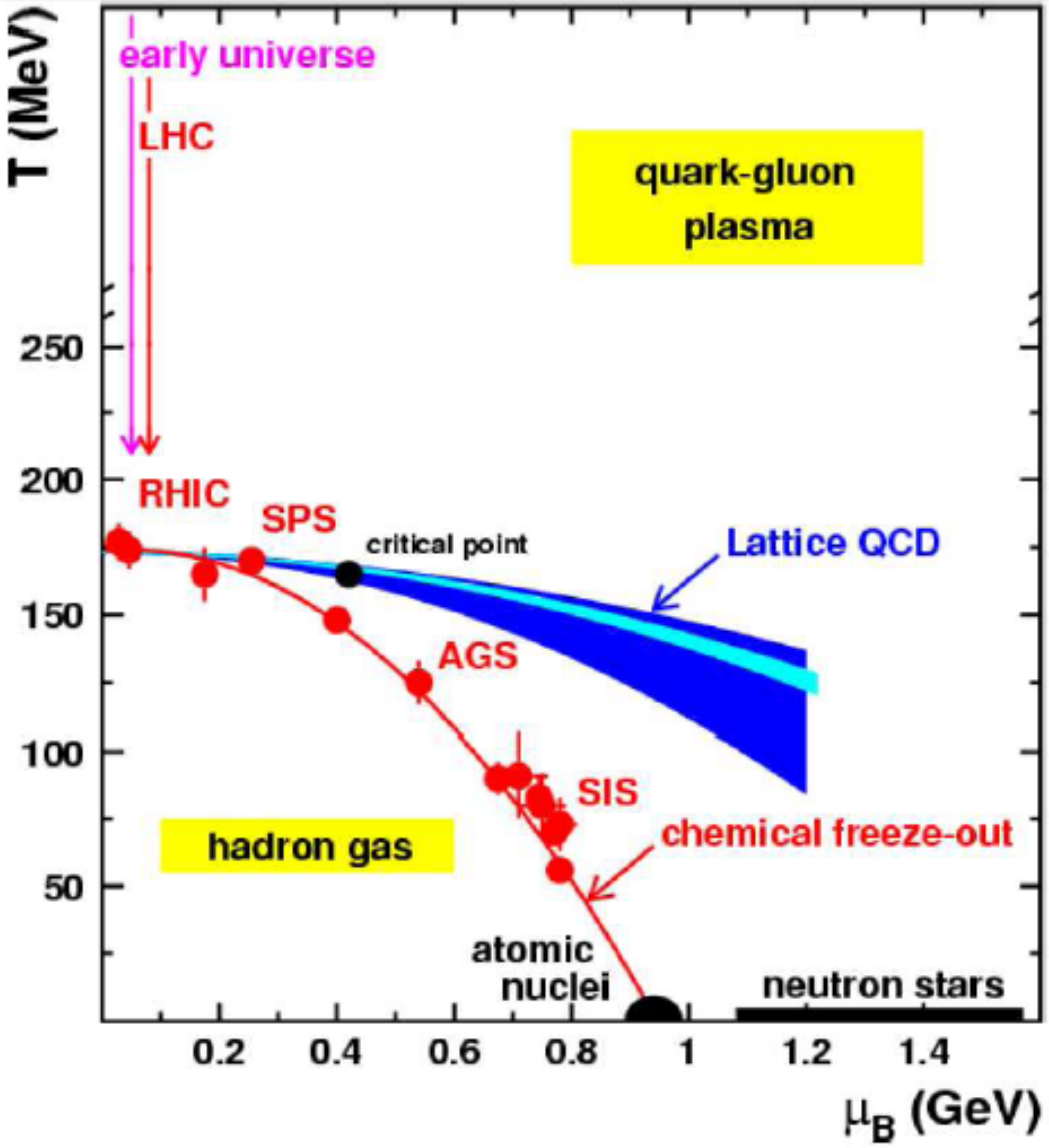
- History of the early universe
- Properties of the strongly interacting force under extreme conditions of temperature and energy density
- Deep layer structure of matter in the current universe

QGP signatures

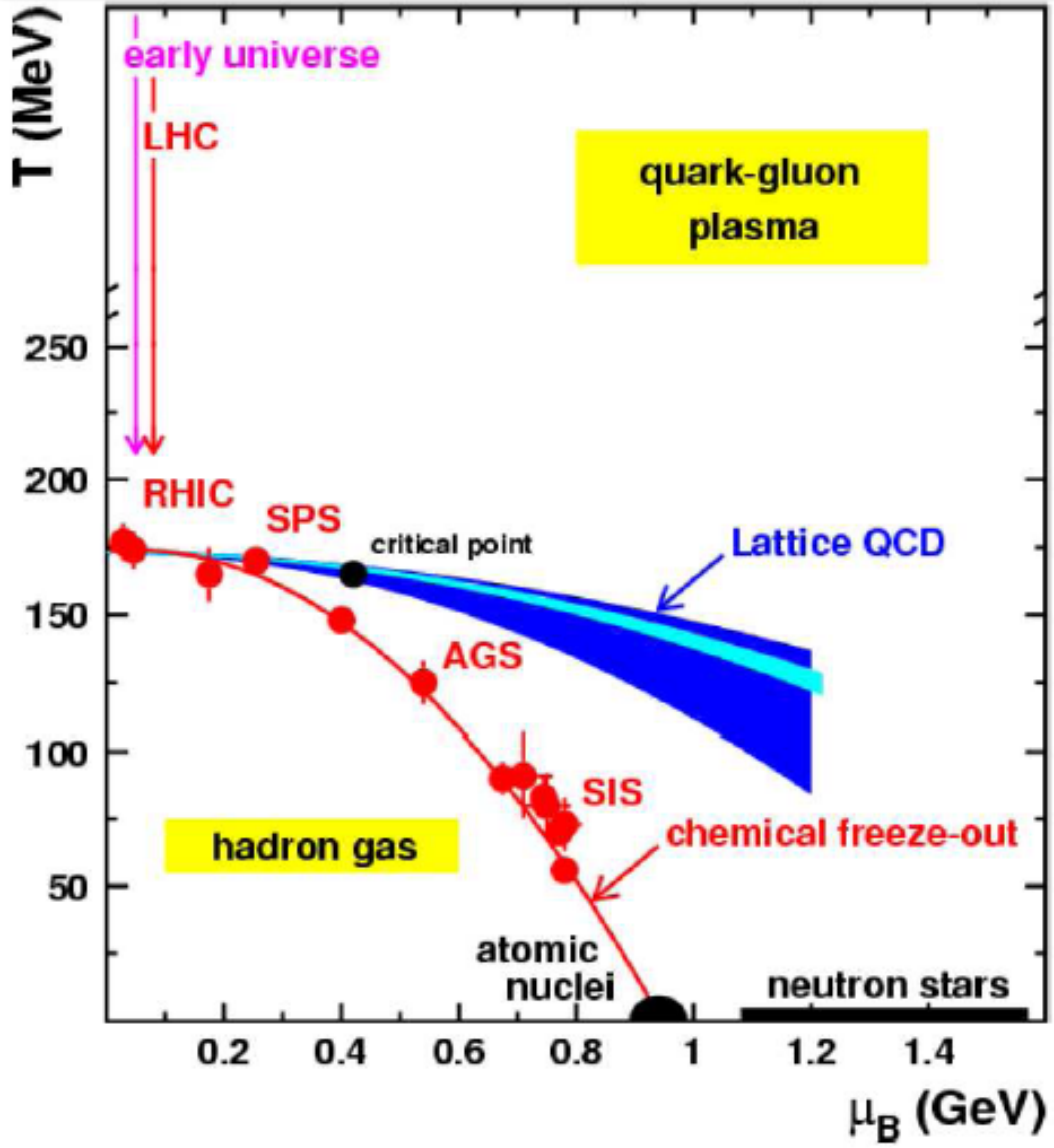
QCD phase diagram

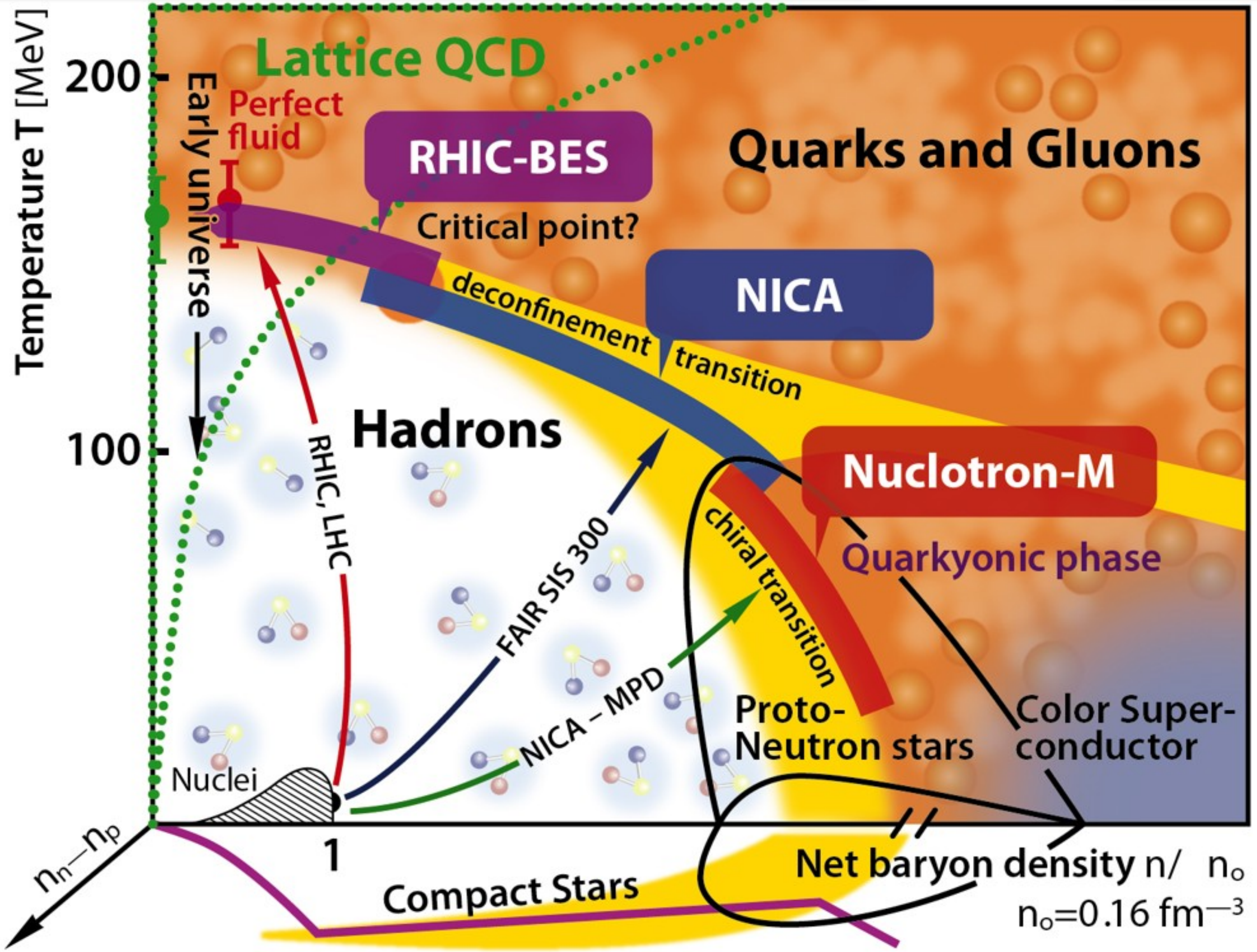


QGP factories



QGP factories

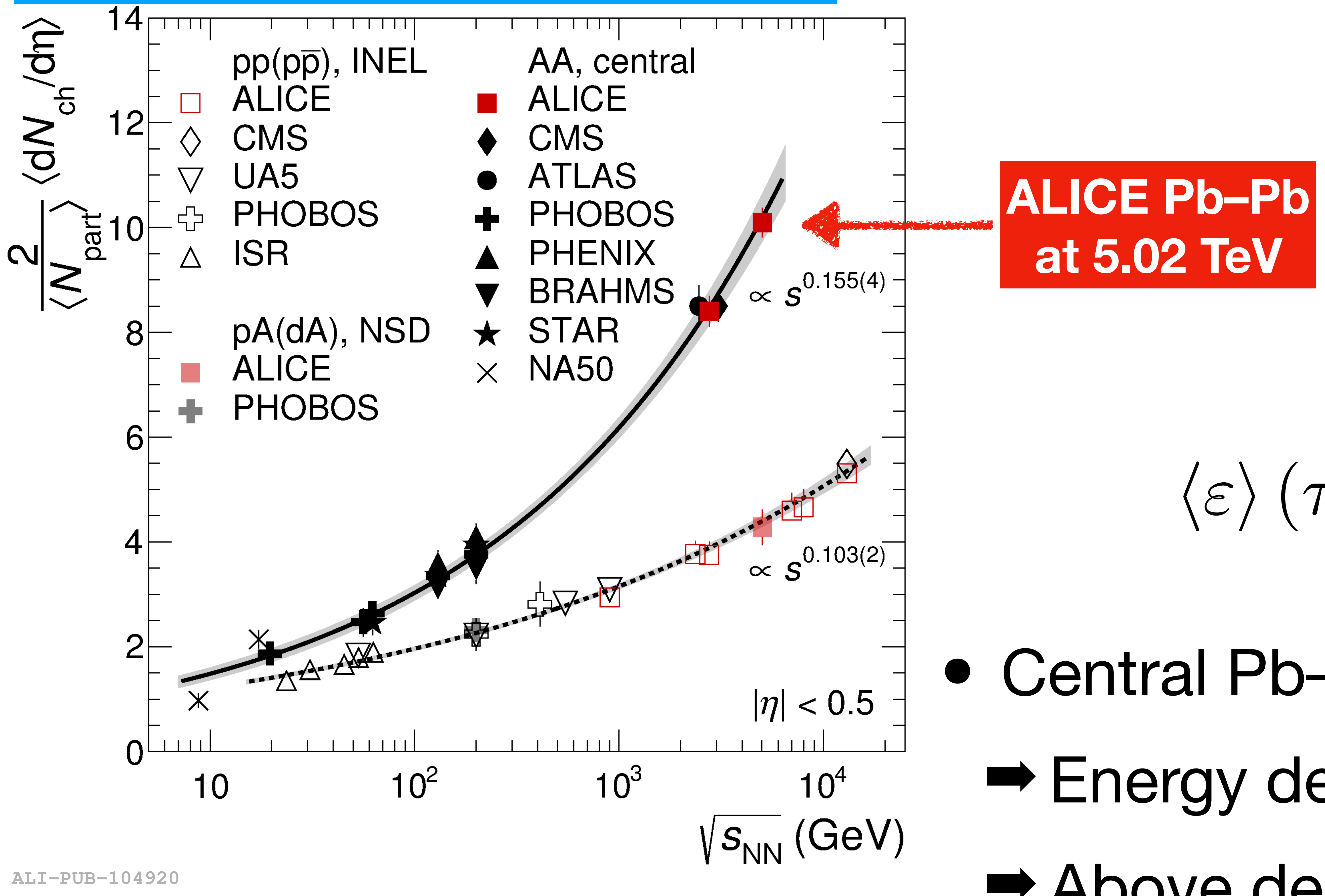




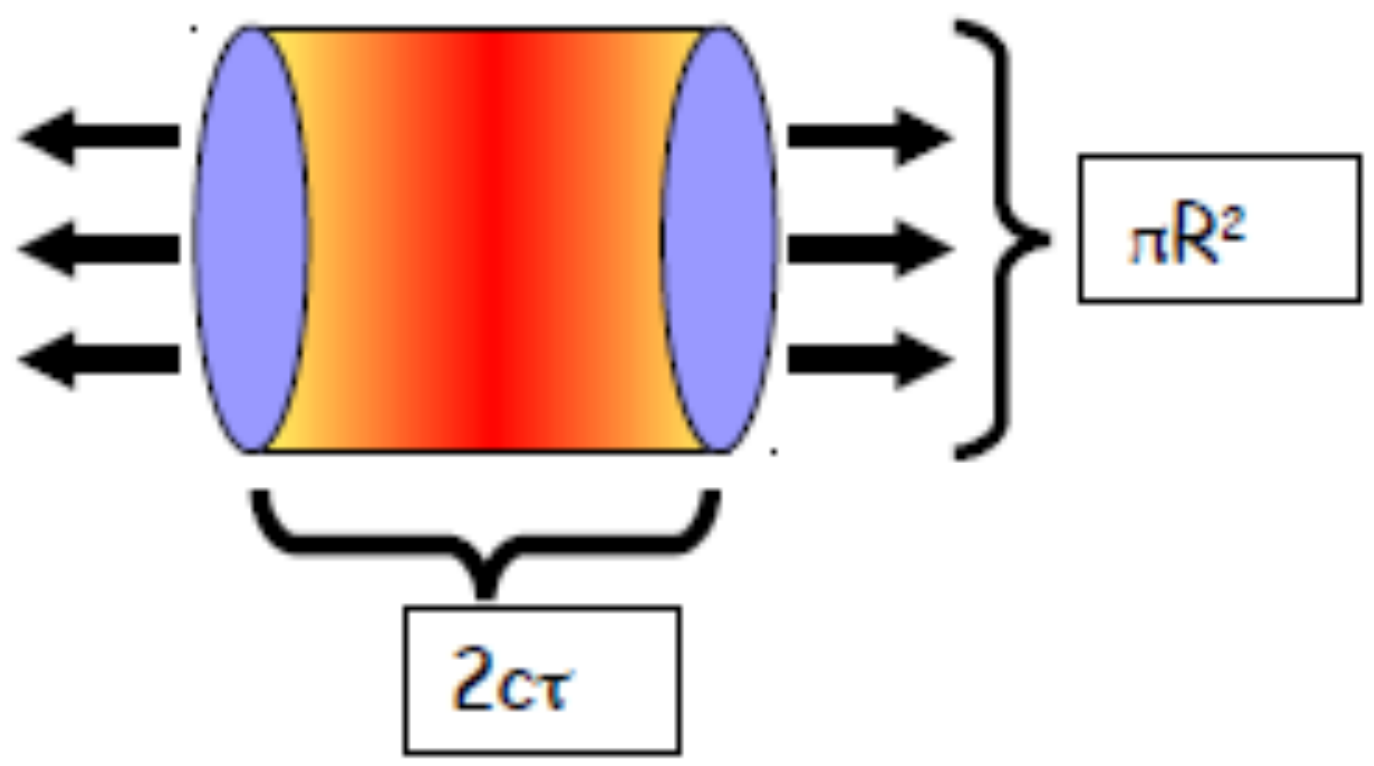
From the study of QGP signatures to that of the QCD phase diagram

Charged particle multiplicity

ALICE *Phys. Rev. Lett.* 116 (2016) 222302



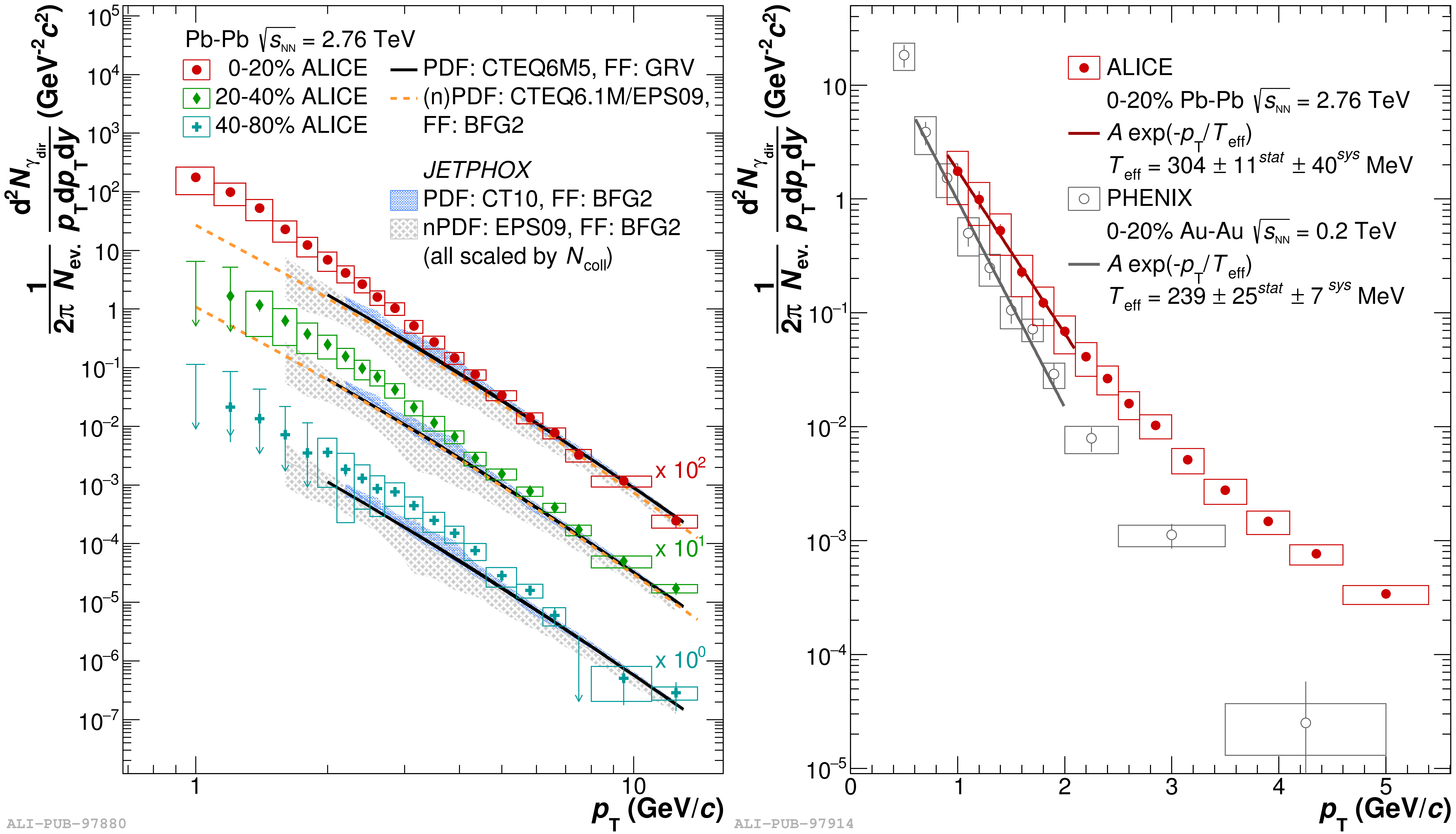
Bjorken estimate:



$$\langle \varepsilon \rangle (\tau) = \frac{1}{\tau \pi R^2} \frac{dE_T}{dy} \longleftrightarrow dN/d\eta$$

- Central Pb–Pb collisions at 5.02 TeV dN/dη ~ 2000
  - ➡ Energy density ε ~18 GeV/fm³
  - ➡ Above deconfinement transition (~1 GeV/fm³)
- ALICE: Pb–Pb at 5.02 TeV — highest energy so far
  - ➡ For 0–5% most central collisions, confirms trend from lower energies

Temperature of the QGP

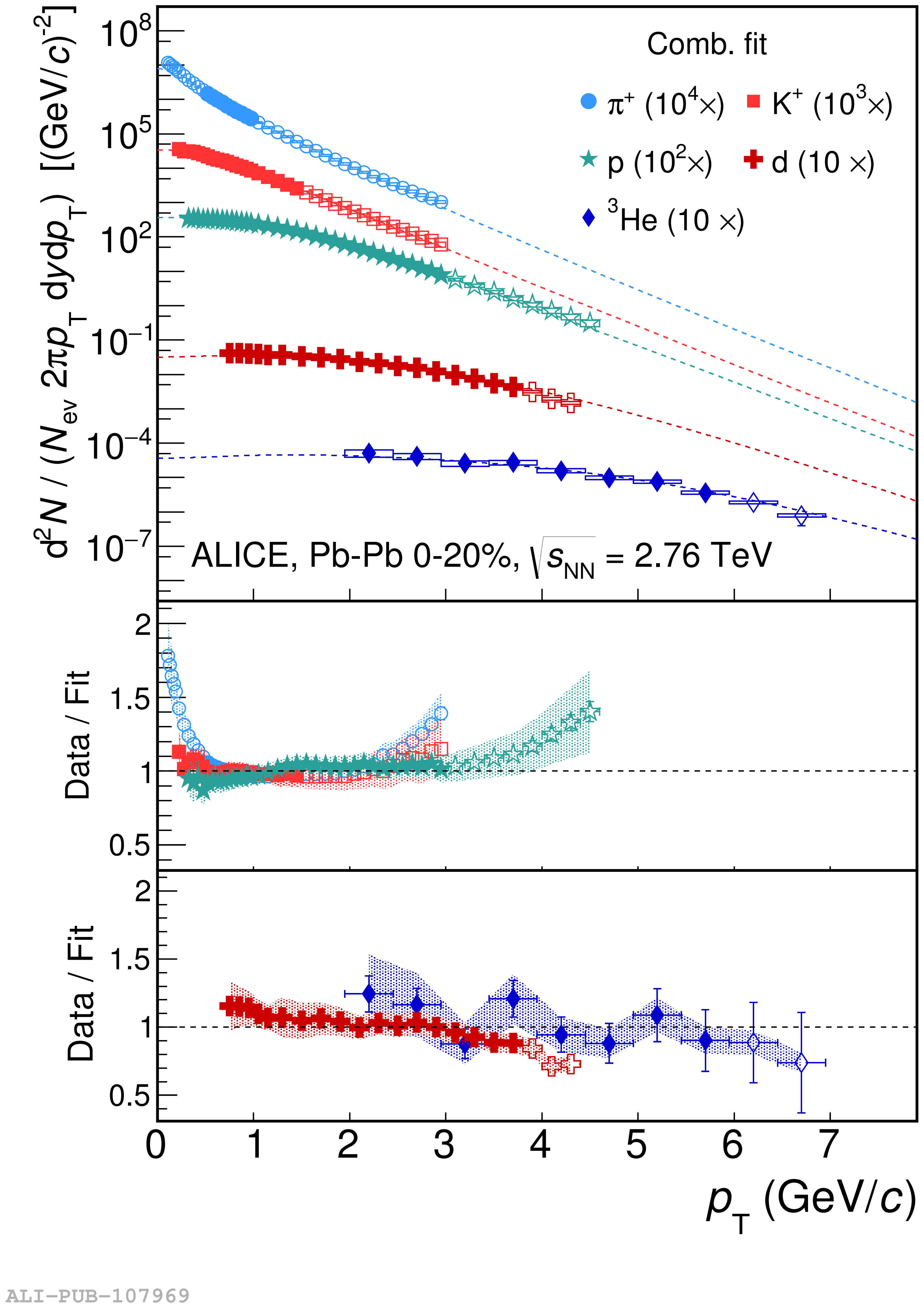


- Low-p_T: 2.6σ excess w. r. t. models in 0–20% central — thermal contribution
- T_{eff} = 304 ± 11(stat.) ± 40 (syst.) MeV in central collisions — way above T_c ~ 170 MeV
- 30% higher than at RHIC (Au–Au at $\sqrt{s_{NN}}$=200 GeV)

ALICE *Phys. Lett.* B754 (2016) 235

Particle production

ALICE *Phys. Rev.* C93 (2015) 024917



Blast-wave model: simplified hydrodynamic model with 3 parameters

- β_T: radial expansion velocity
- T_{kin}: kinetic freeze-out temperature
- n: velocity profile

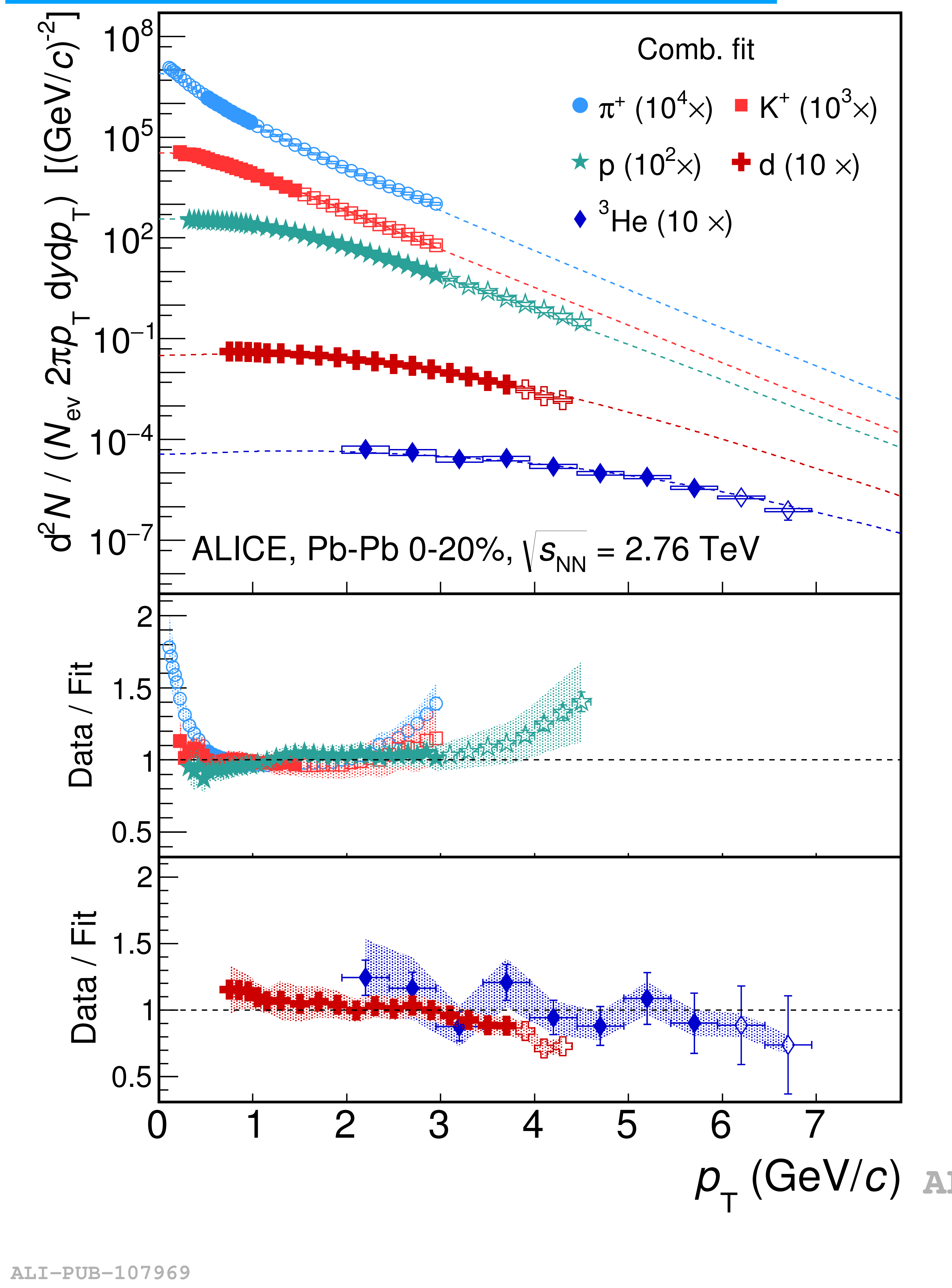
$$E\frac{d^3N}{dp^3} \propto \int_0^R m_T I_0\left(\frac{p_T \sinh(\rho)}{T_{Kin}}\right) K_1\left(\frac{m_T \cosh(\rho)}{T_{Kin}}\right) r\, dr$$

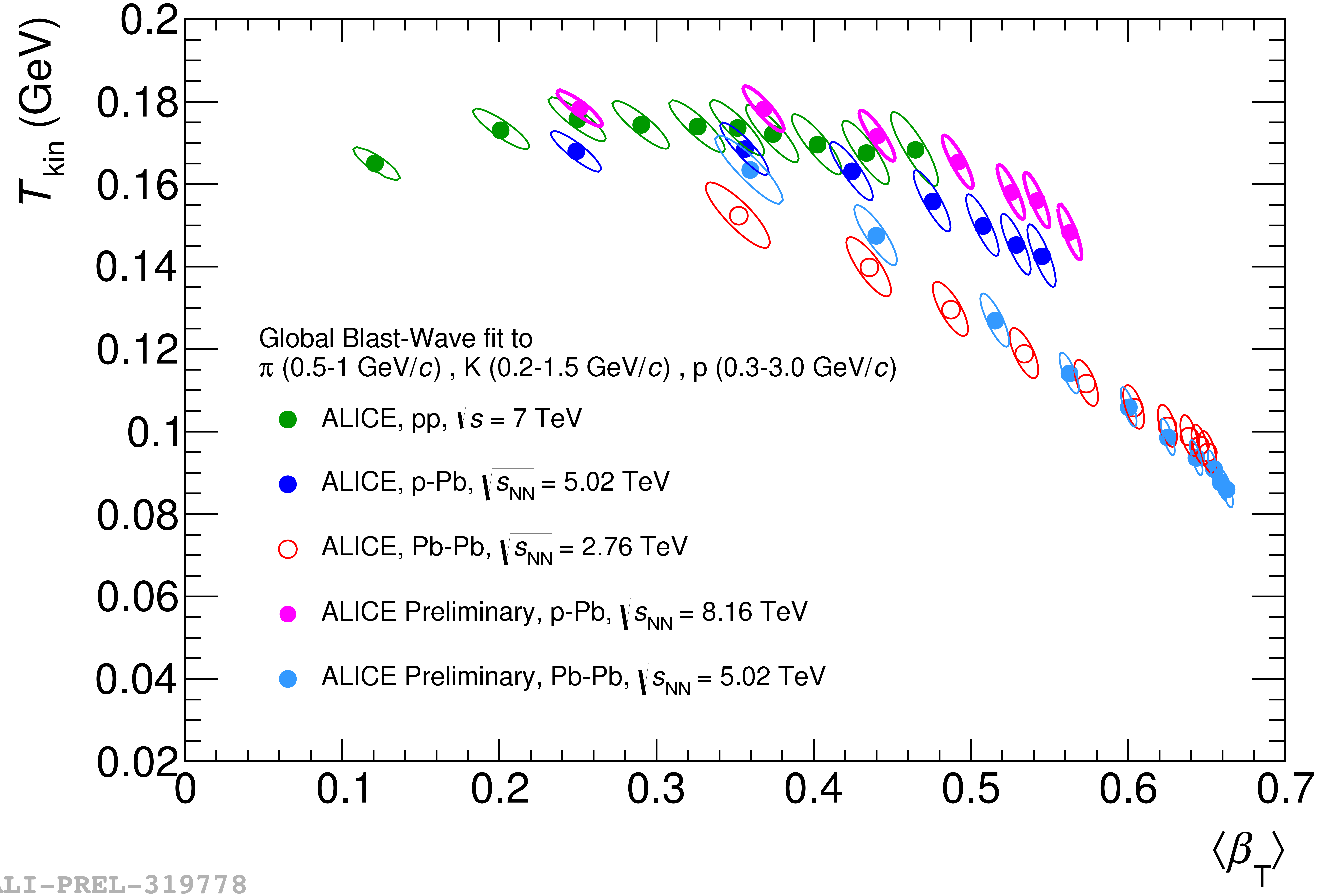
$$m_T = \sqrt{m^2 + p_T^2} \qquad \rho = \tanh^{-1}(\beta_T) \qquad \beta_T = \beta_s \left(\frac{r}{R}\right)^n$$

Schnedermann, Sollfrank and Heinz Phys. Rev. C 48, 2462

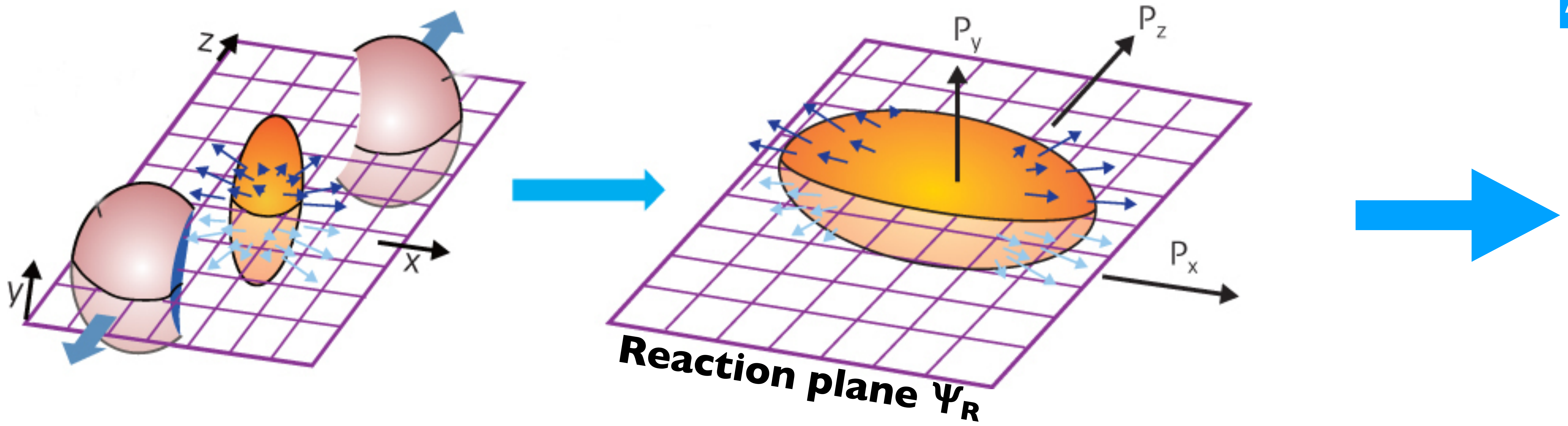
Particle production

ALICE *Phys. Rev.* C93 (2015) 024917

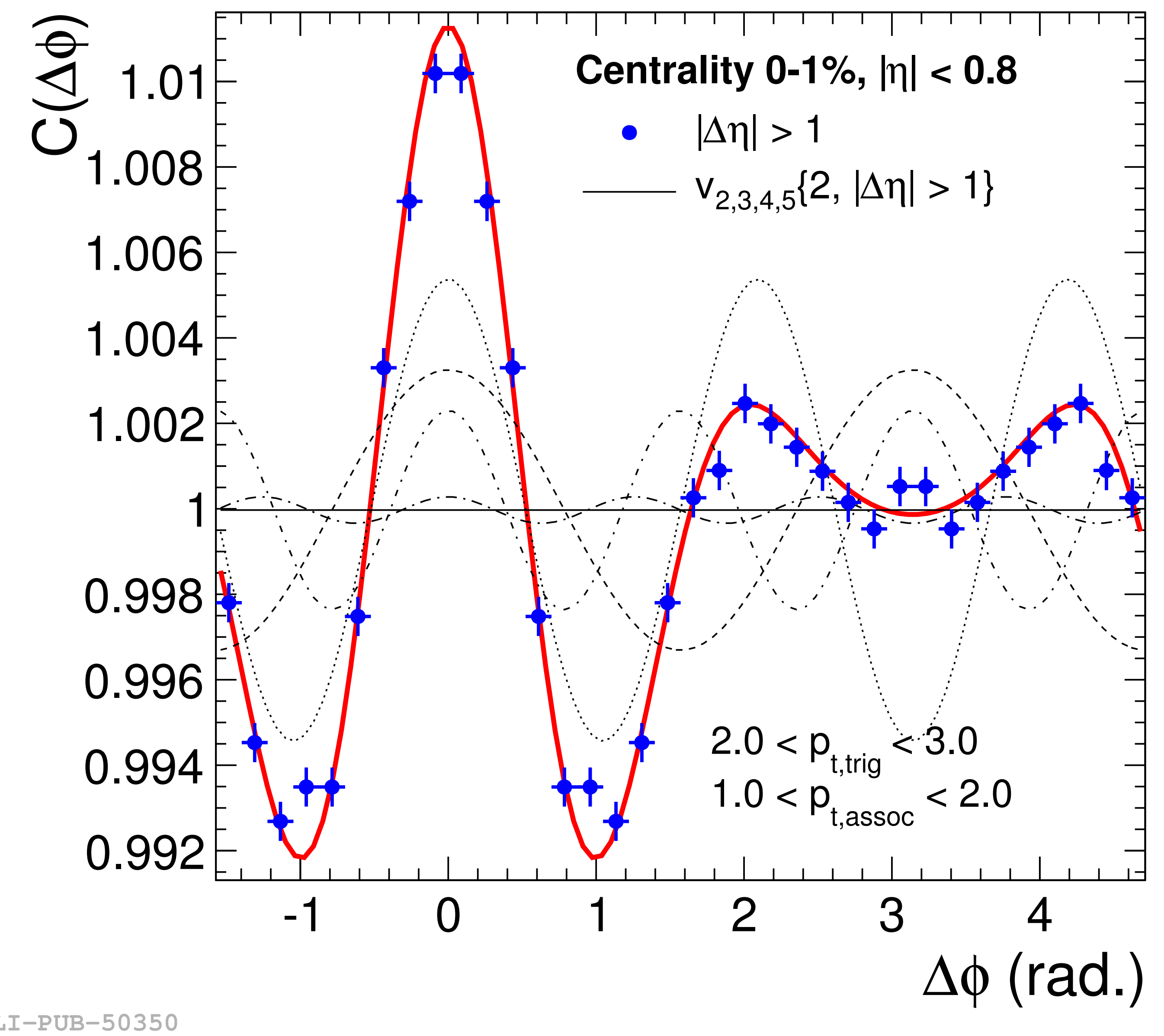




Azimuthal anisotropy



ALICE *Phys. Rev. Lett.* 107 (2013) 032301

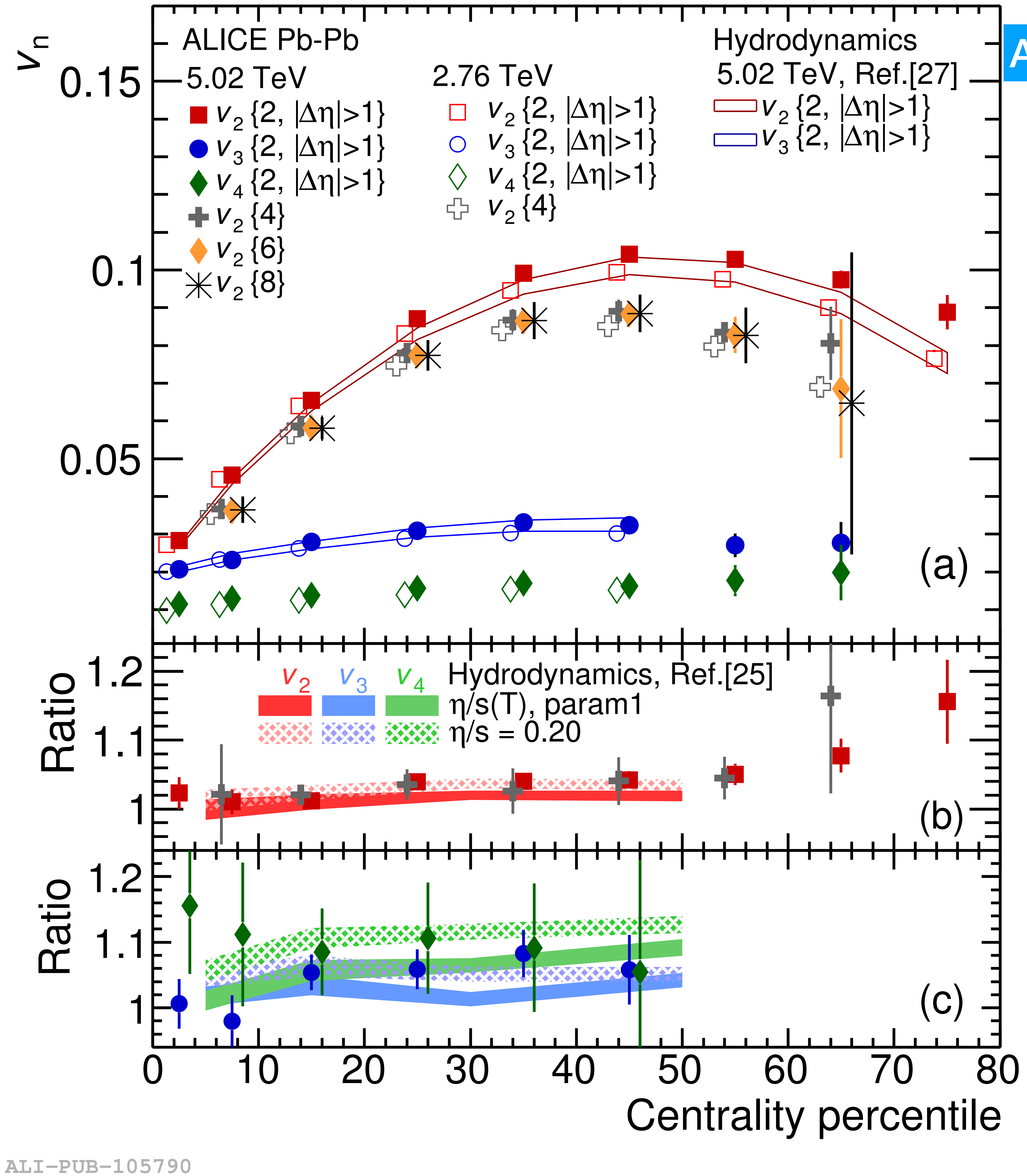


ALI-PUB-50350

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

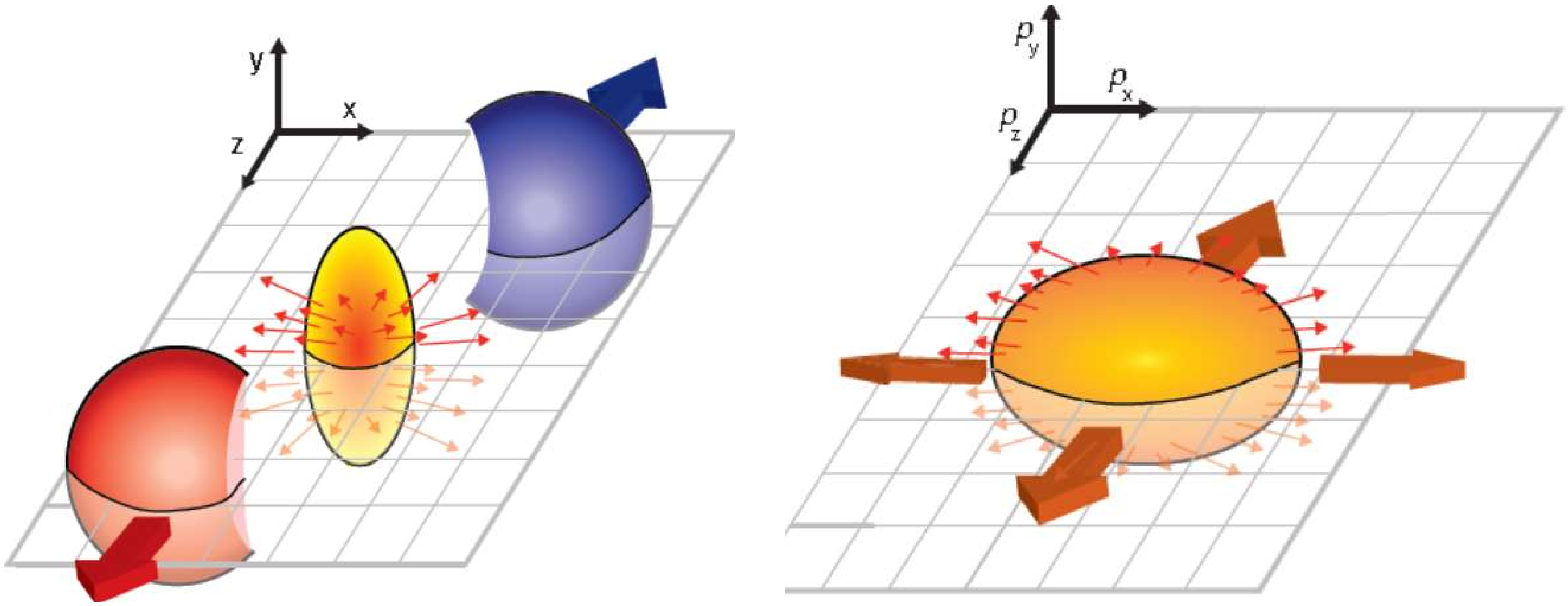
- Quantify anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP}) — coefficients v_2, v_3, v_4… v_n
- Elliptic flow (v_2): spatial anisotropy — pressure gradients leads to momentum anisotropy — hydrodynamics
- Higher order flow: bring additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

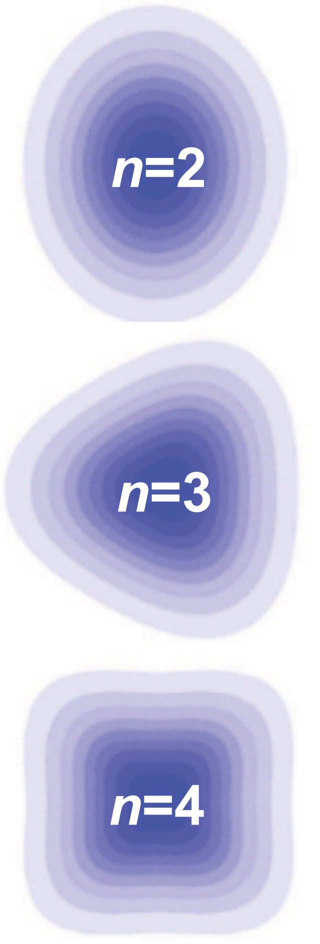
Azimuthal anisotropy



ALICE *Phys. Rev. Lett.* **116** (2016) 132302

$$v_n = < \cos n(\varphi - \Psi_{\mathrm{RP}}) >$$





Measurements support a low value for η/*s* ~0.2

Hard probes: medium tomography

- Produced in the early stage of heavy-ion collisions
  - ➡ Experience the full evolution of the QCD medium, and interact with particles in the medium and loss energy
- Efficient probes for understanding the transport properties of the medium

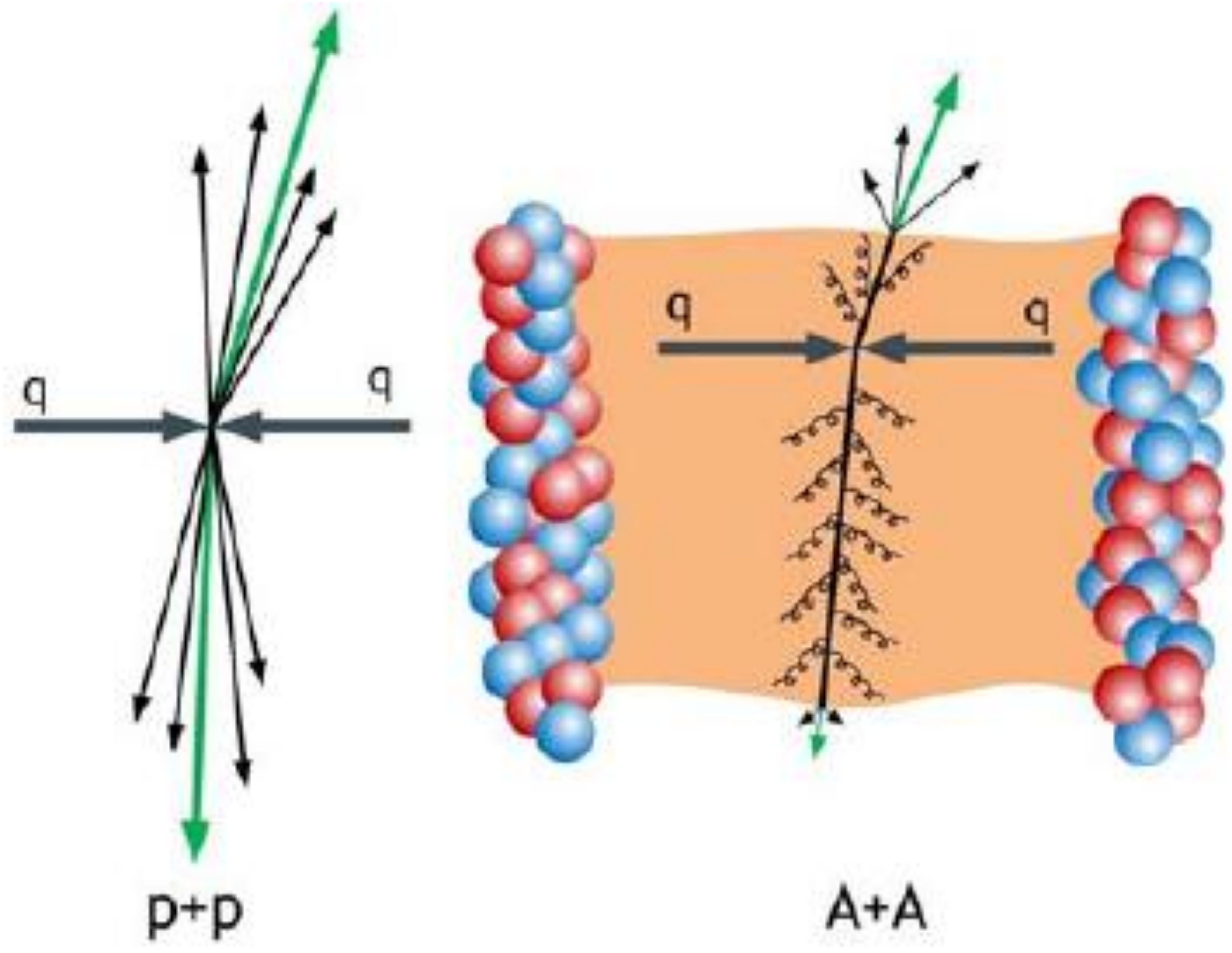
Nuclear modification factor: R_{AA} — sensitive to the presence of the medium

$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

QCD medium

QCD vacuum

- $R_{AA} = 1$, if there is no medium modification

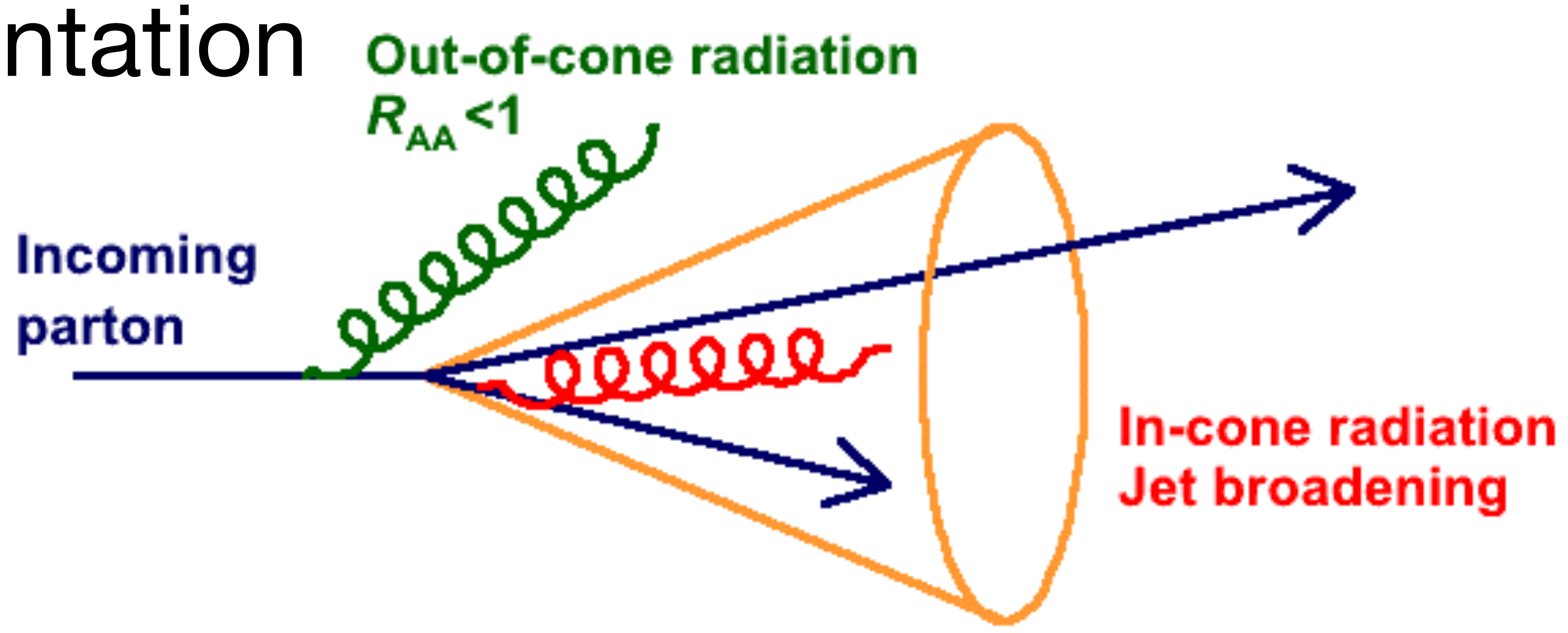


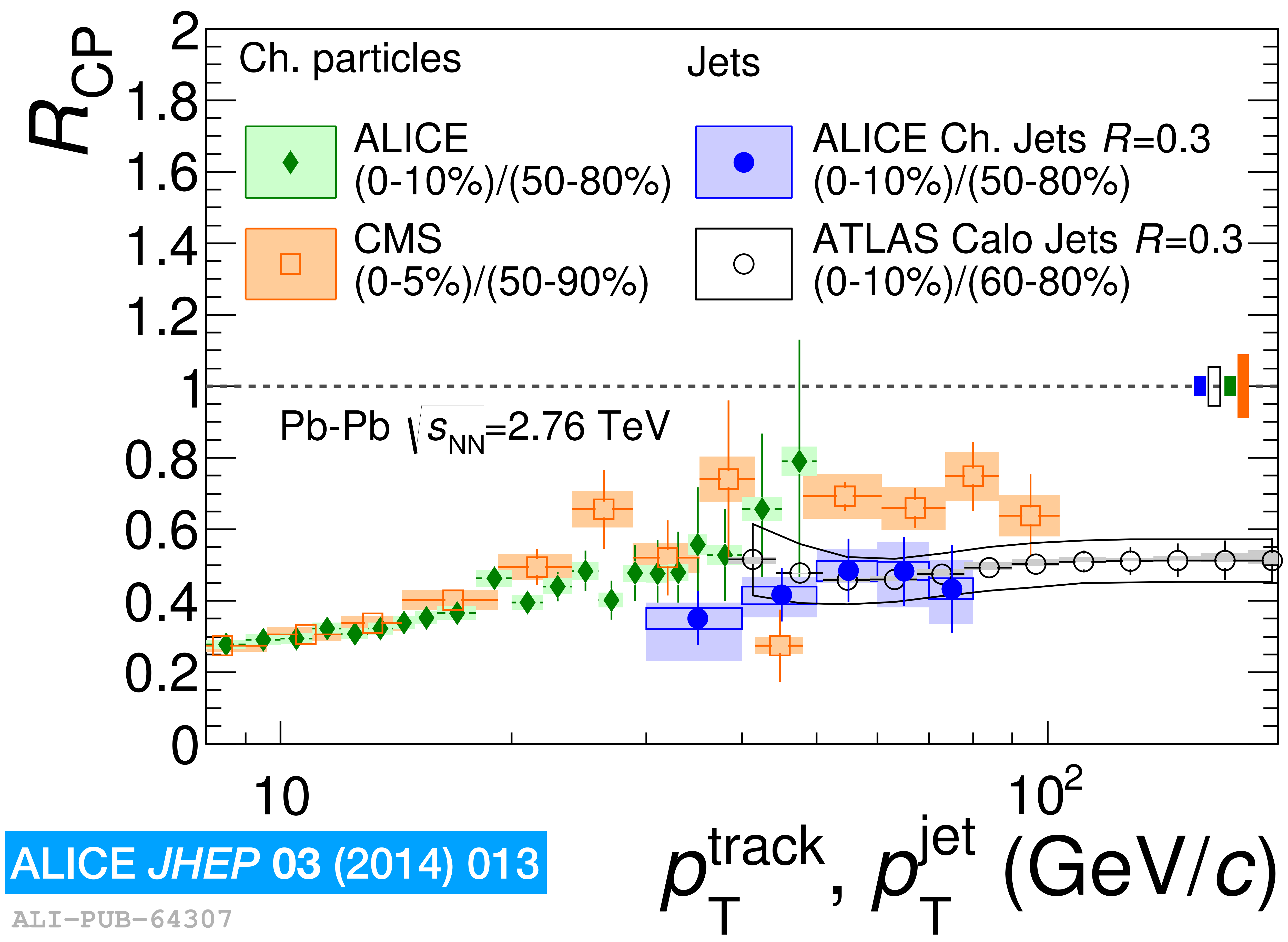
Shopping list

- High p_T particles, jets
- Open heavy flavours, quarkonia (J/ψ, ψ'… Y…)

R_{AA} of charged particles and jets

- Jet: a spray of particles from hard parton fragmentation
  - ➡ Get closer access to parton energy



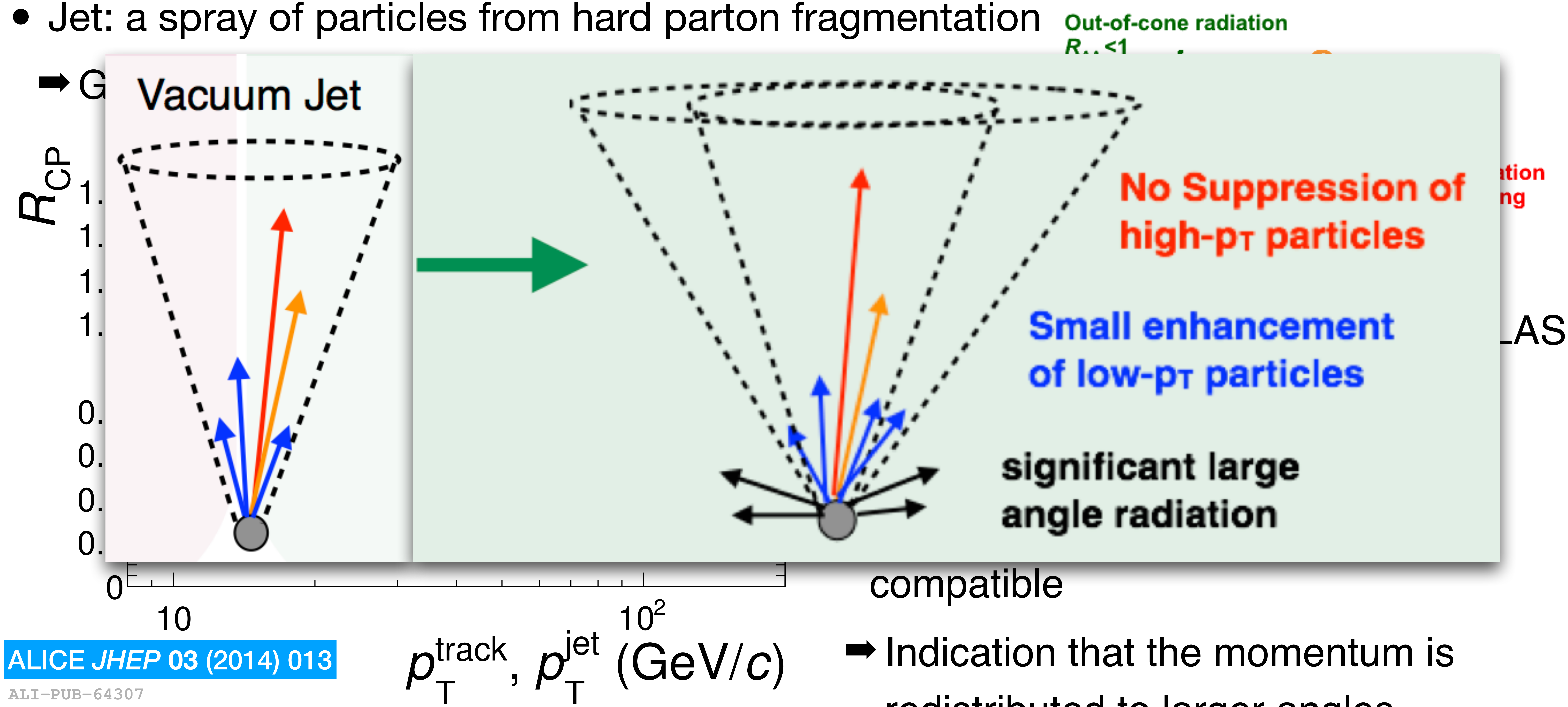


ALICE *JHEP* 03 (2014) 013

- Agreement between ALICE and ATLAS
  - ➡ Contribution of low momentum jet fragments to jet energy is small
- R_{CP} of jets and single hadrons are compatible
  - ➡ Indication that the momentum is redistributed to larger angles

R_{AA} of charged particles and jets

- Jet: a spray of particles from hard parton fragmentation
  - ➡ G



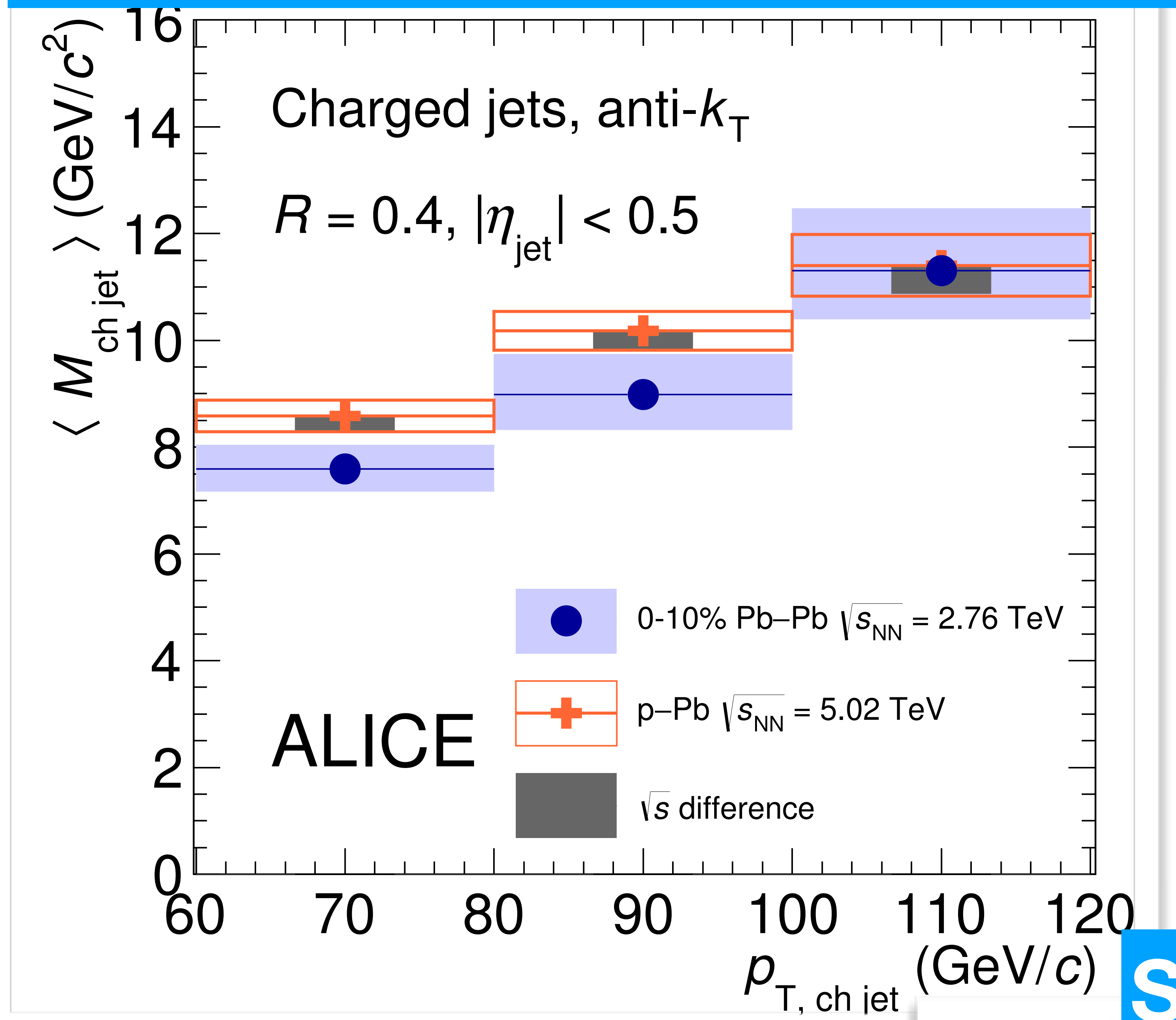
AS

compatible

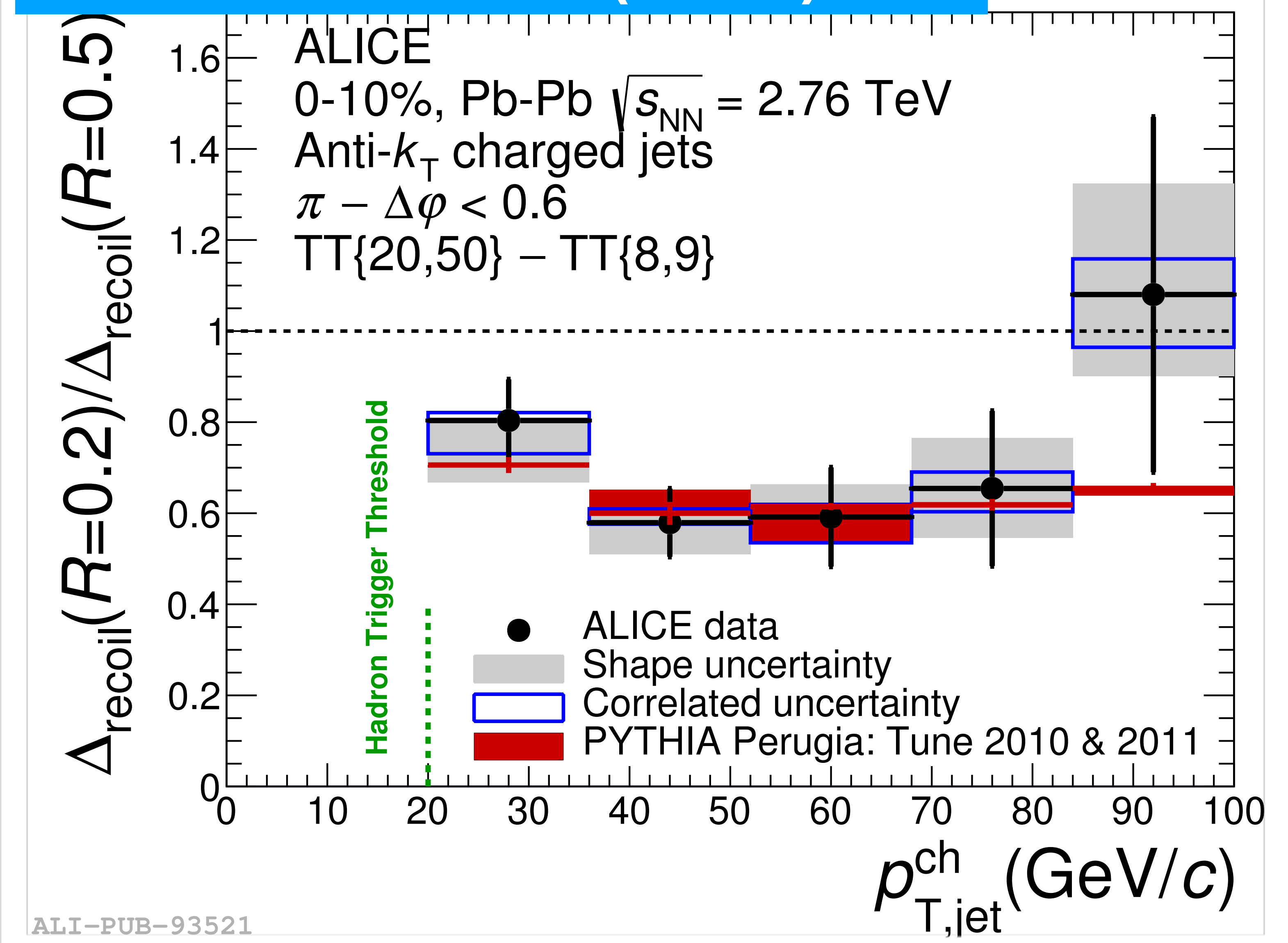
➡ Indication that the momentum is redistributed to larger angles

Differential jet measurements

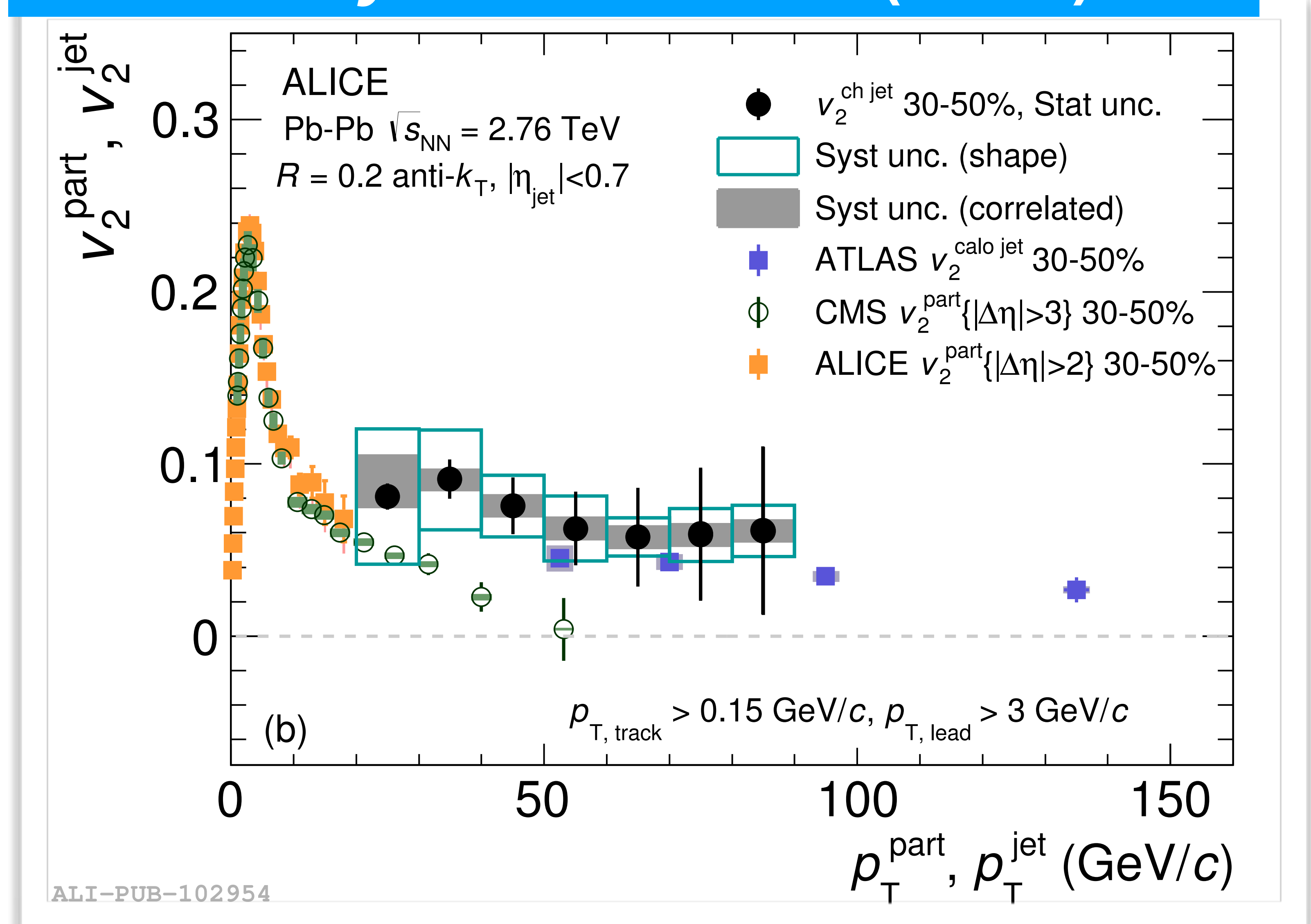
ALICE *Phys. Lett.* B776 (2018) 249



ALICE *JHEP* 09 (2015) 170

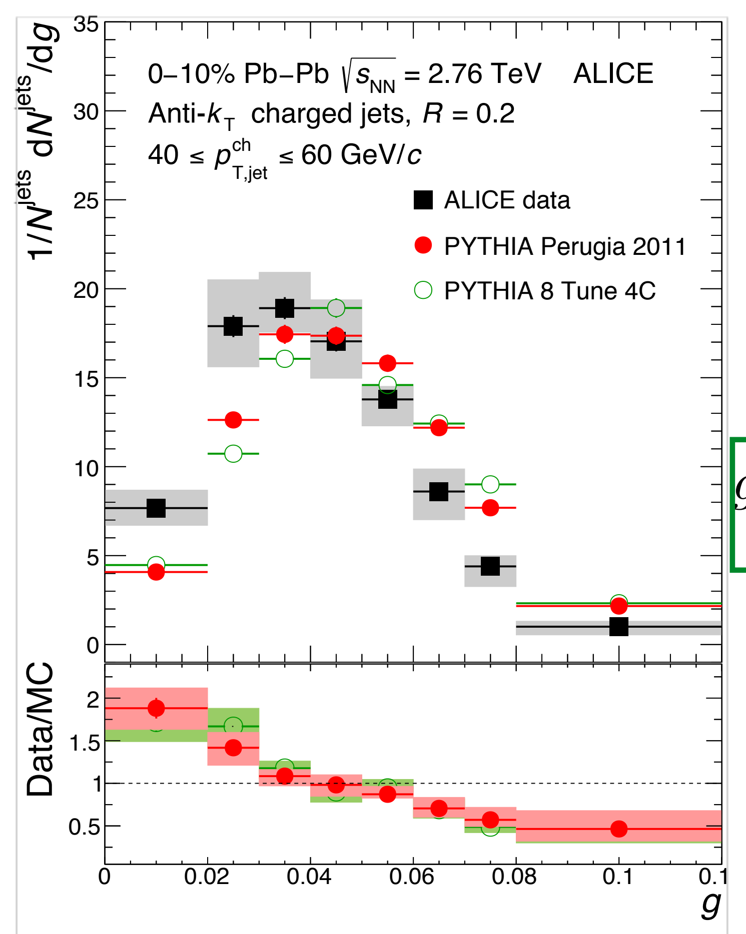


ALICE *Phys. Lett.* B753 (2016) 511



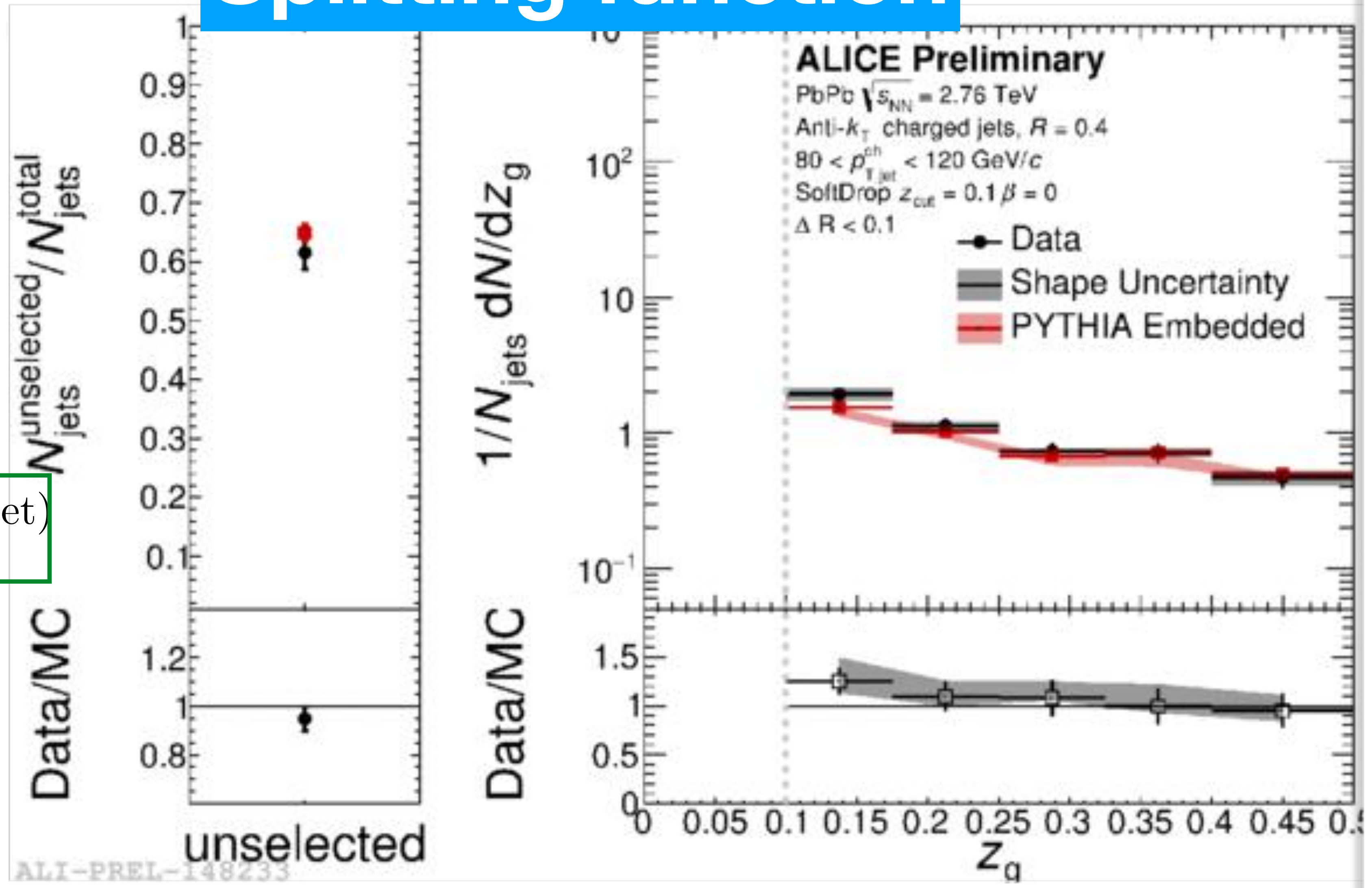
ALICE *JHEP* 10 (2018) 139

Profile

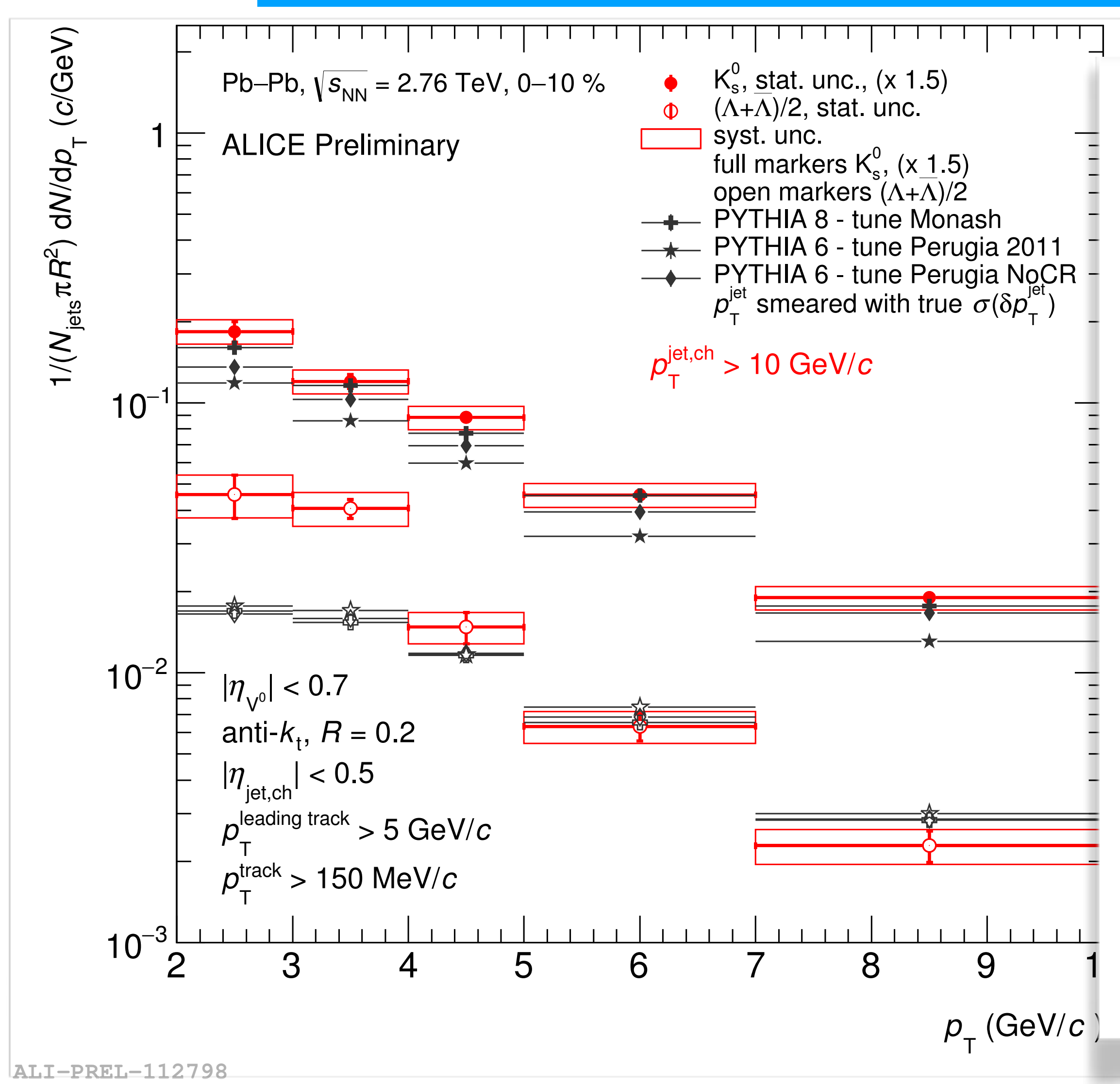


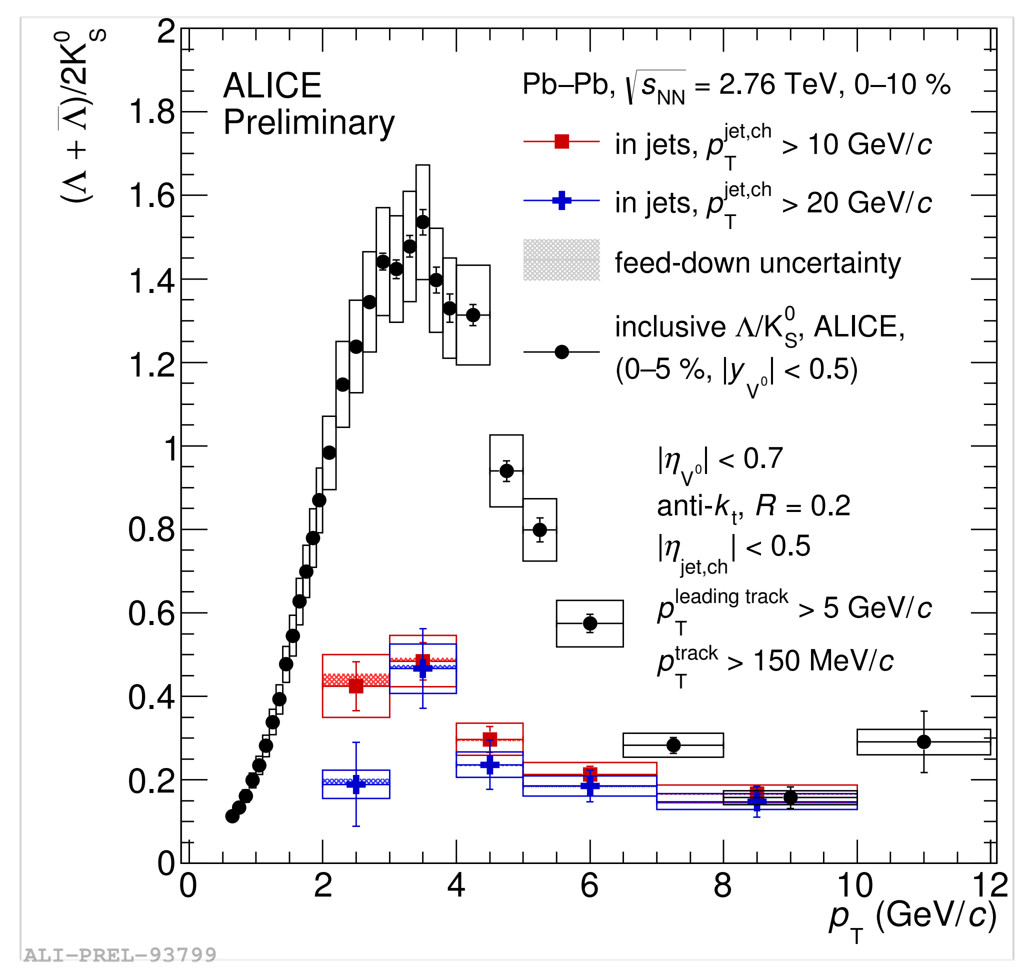
$$g = \sum_{i \in \mathrm{jet}} \frac{p_{\mathrm{T},i}}{p_{\mathrm{T,jet}}} \Delta R(i, \mathrm{jet})$$

Splitting function



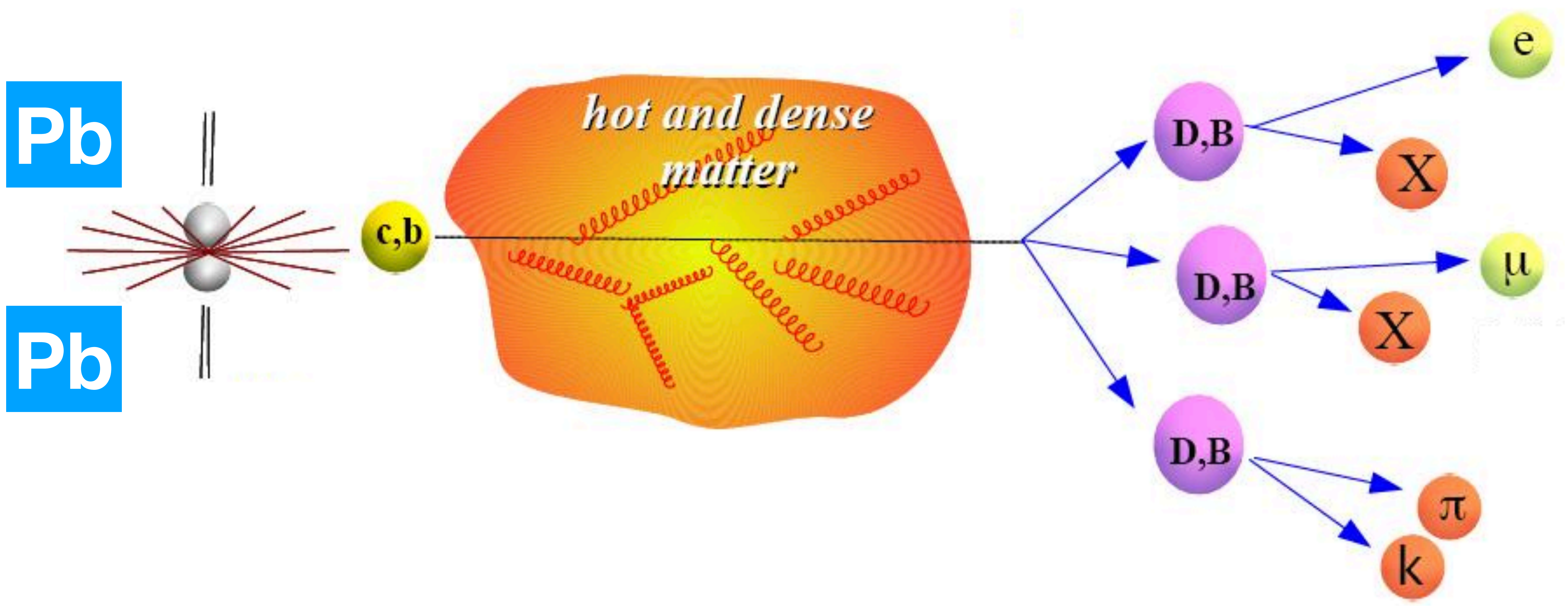
Strangeness production in jets





Heavy flavours in the QCD Medium

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)



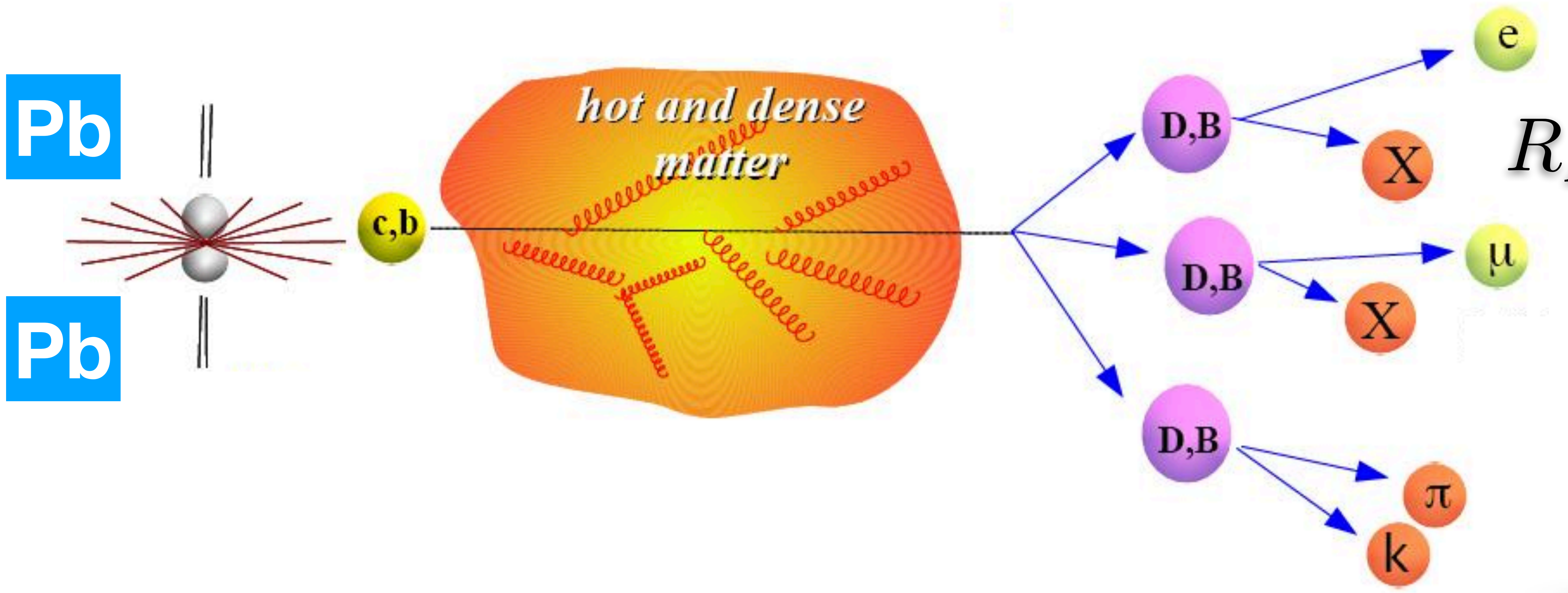
Total charm cross section in HIC is expected to scale w. r. t. the number of binary collisions in pp-like collisions

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

- Produced in initial hard scatterings (high Q^2) at the early stage of heavy-ion collisions: $\tau_{c/b}$ ~0.01 — 0.1 fm/c < τ_{QGP} (~0.3 fm/c)
- Production cross section calculable with pQCD (m_c, $m_b \gg \Lambda_{QCD}$)
- Experience the entire evolution of the QCD medium — probe transport properties of the deconfined medium

Heavy flavours in the QCD Medium

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)



$$R_{\mathrm{AA}}(p_{\mathrm{T}}) = \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{< T_{\mathrm{AA}} > \mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

QCD medium

QCD vacuum

$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

➡ R_{AA}(light hadron) < R_{AA}(D) < R_{AA}(B) ?

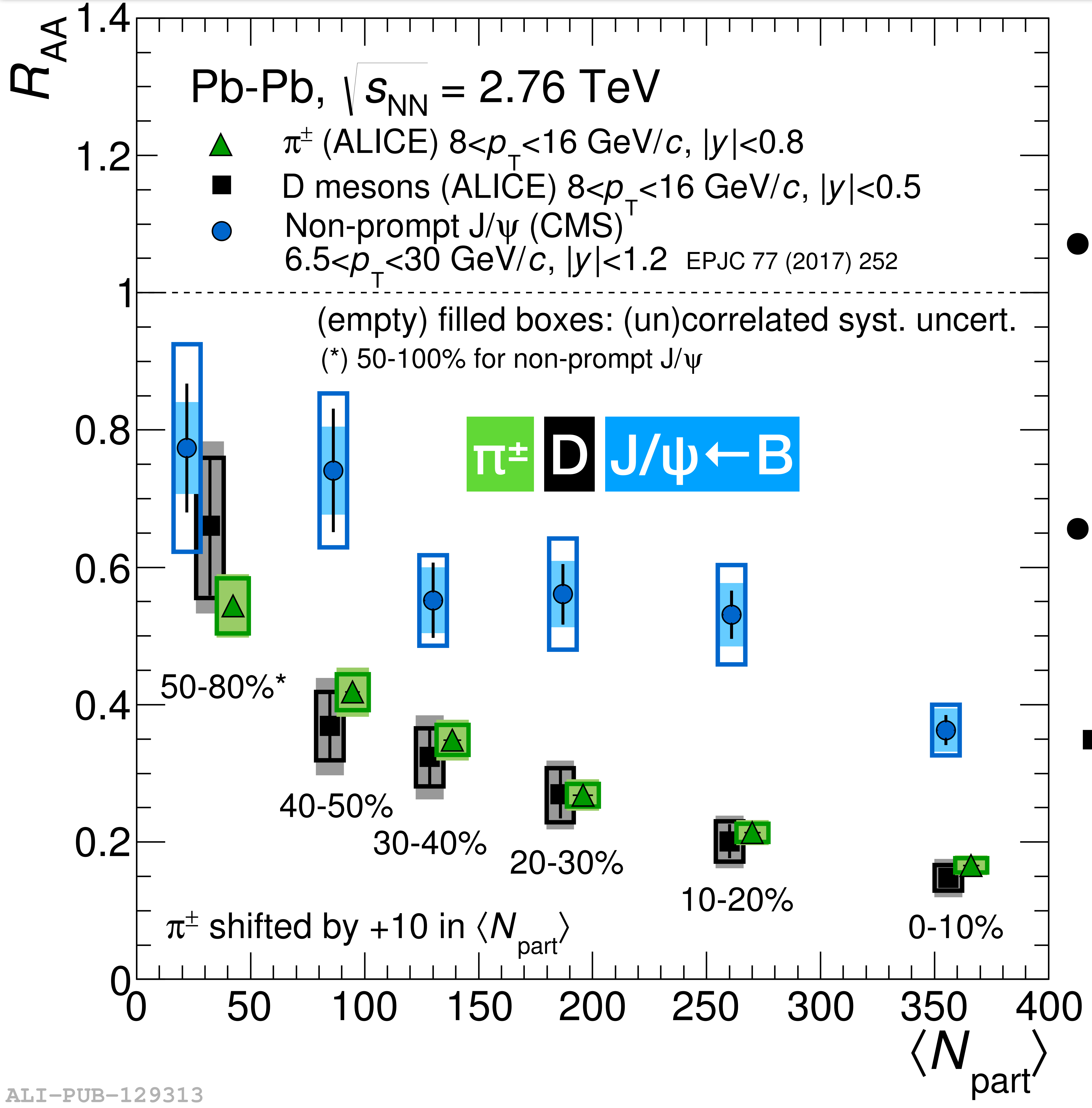
Nuclear modification factor (R_{AA}): heavy quark in-medium energy loss

- Elastic (radiative) vs. inelastic (collisional) processes
- Color charge (Casimir factor) and mass (eg dead-cone effect) dependence

Medium modification of heavy-flavour hadron production

- Hadronization via coalescence may modify the D_s^+ / non-strange D and Λ_c / D ratios

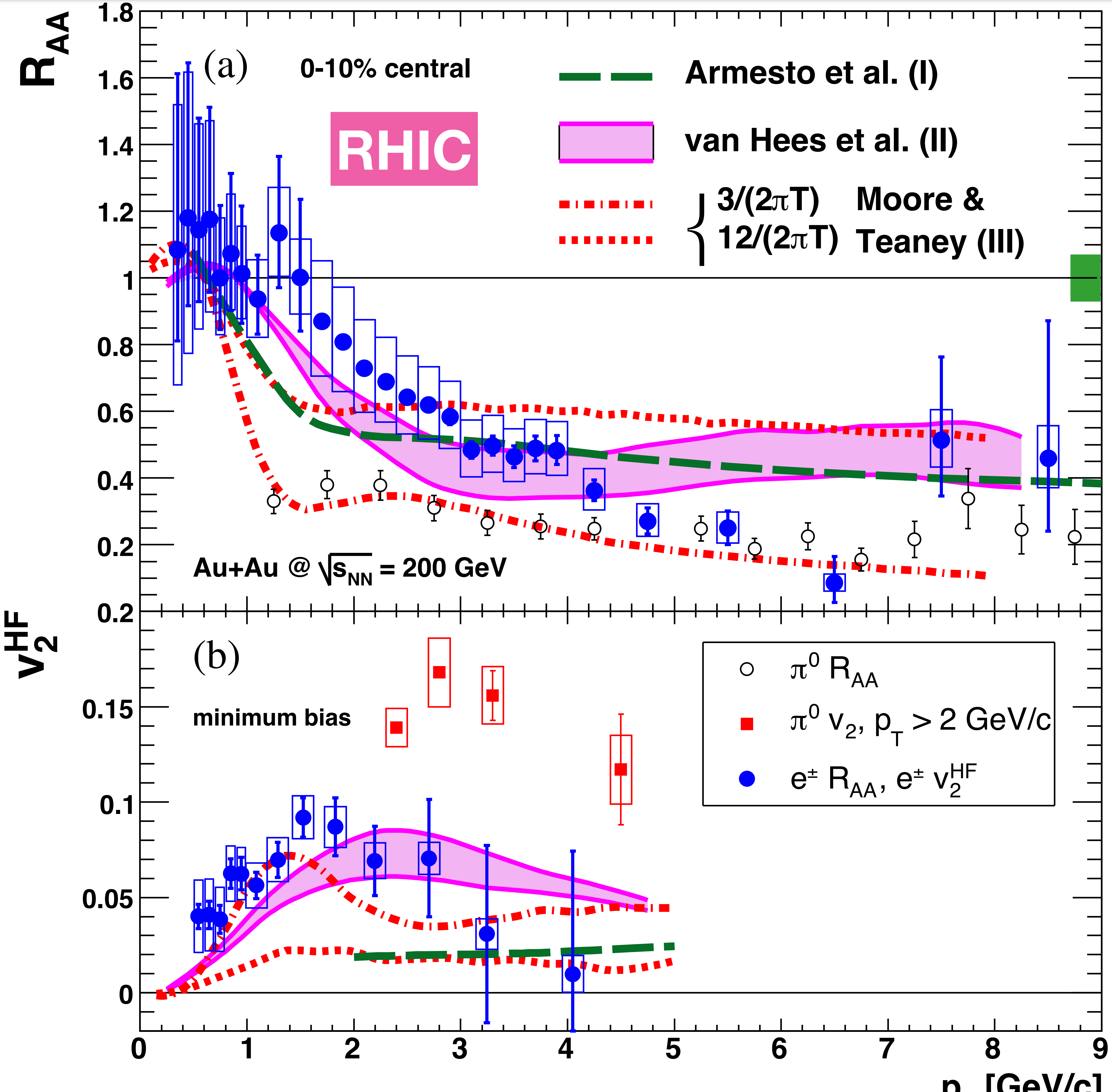
Heavy quark energy loss

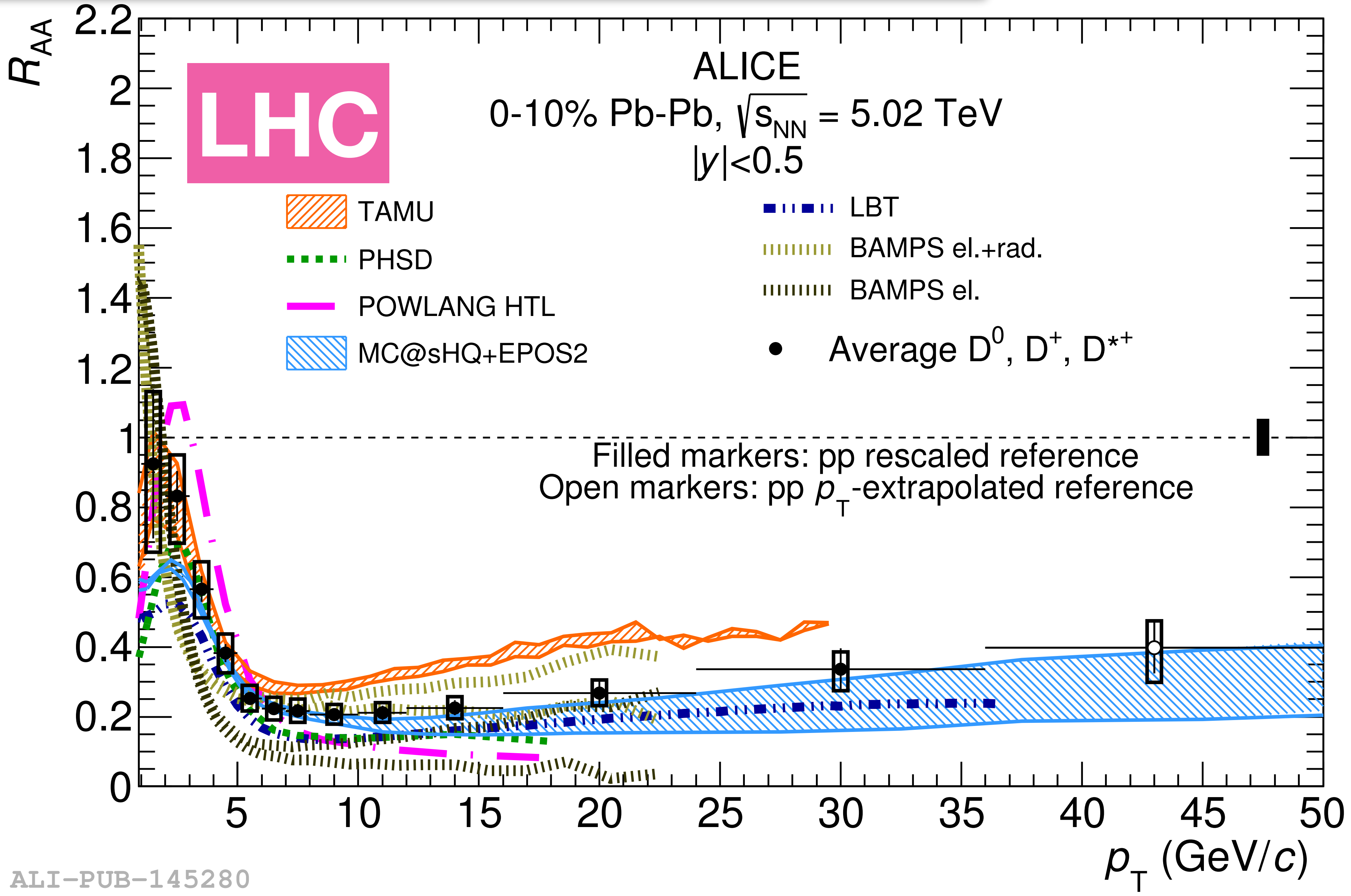


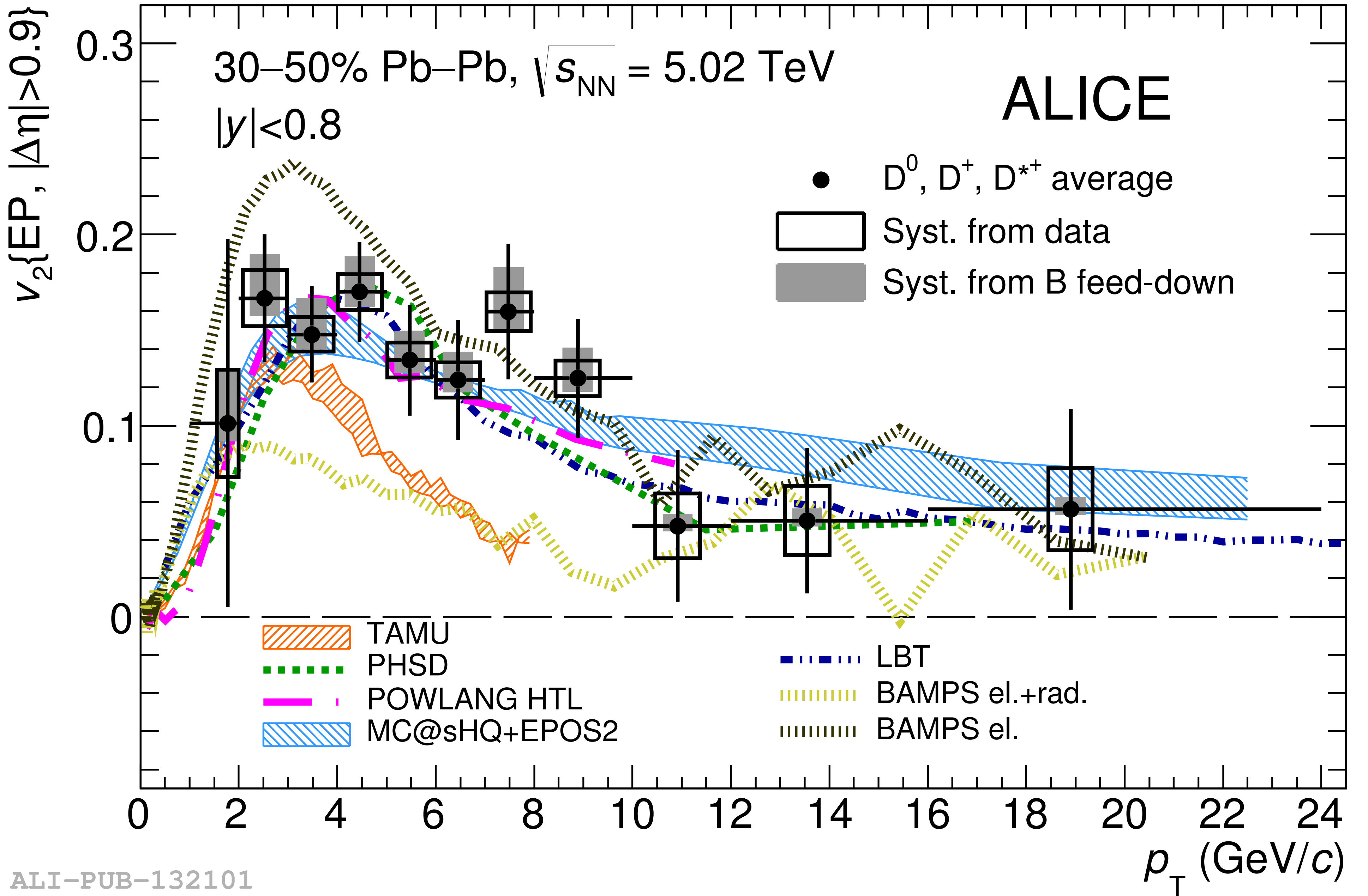
- Indication of R_{AA}(D) < R_{AA}(J/ψ←B) at the LHC
- R_{AA} of open heavy-flavour particles at the RHIC — hint of R_{AA}(D) < R_{AA}(B)

➡Indication of mass dependence of heavy-quark energy loss: $\Delta E_c > \Delta E_b$

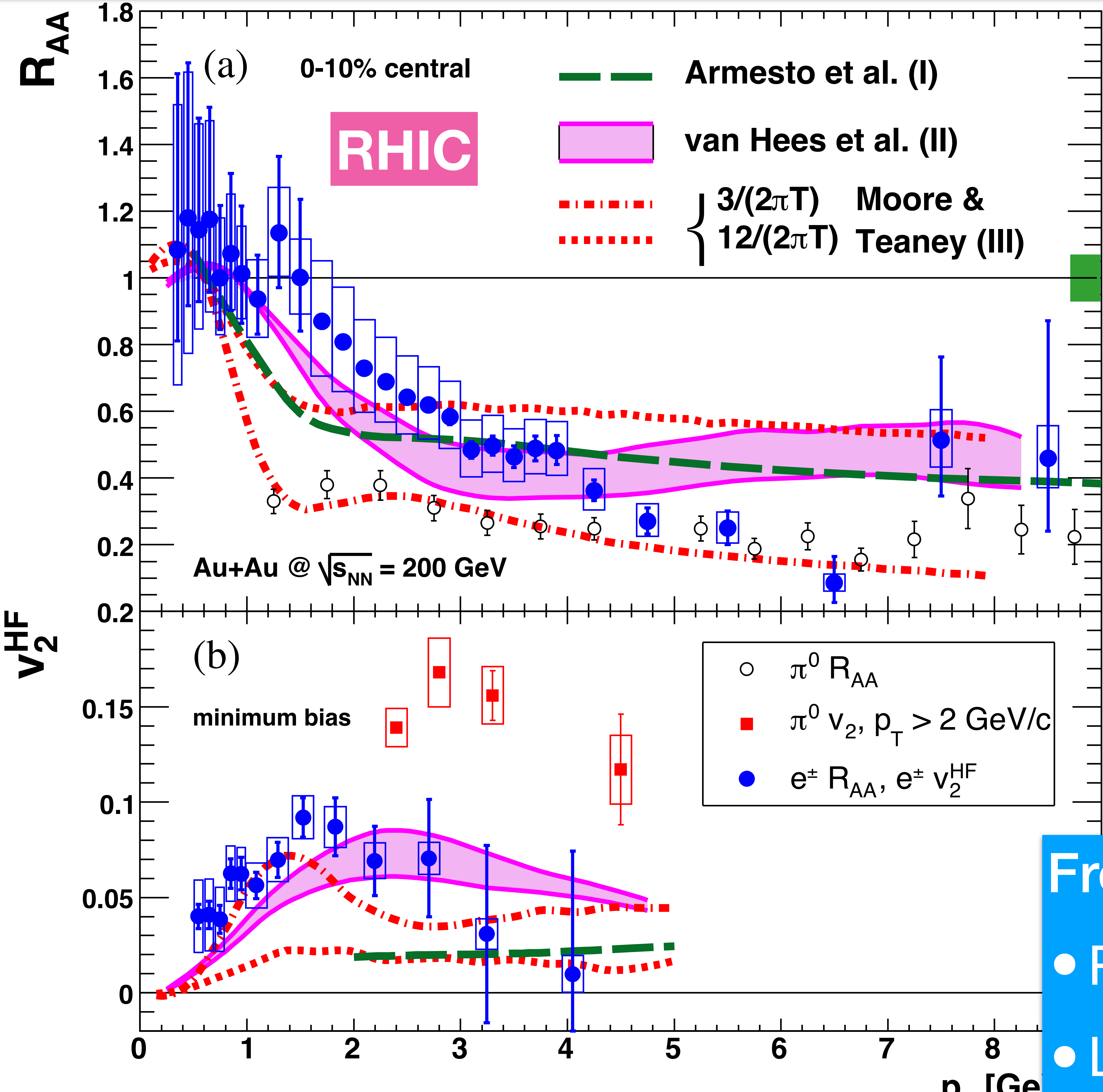
Heavy quark transport properties

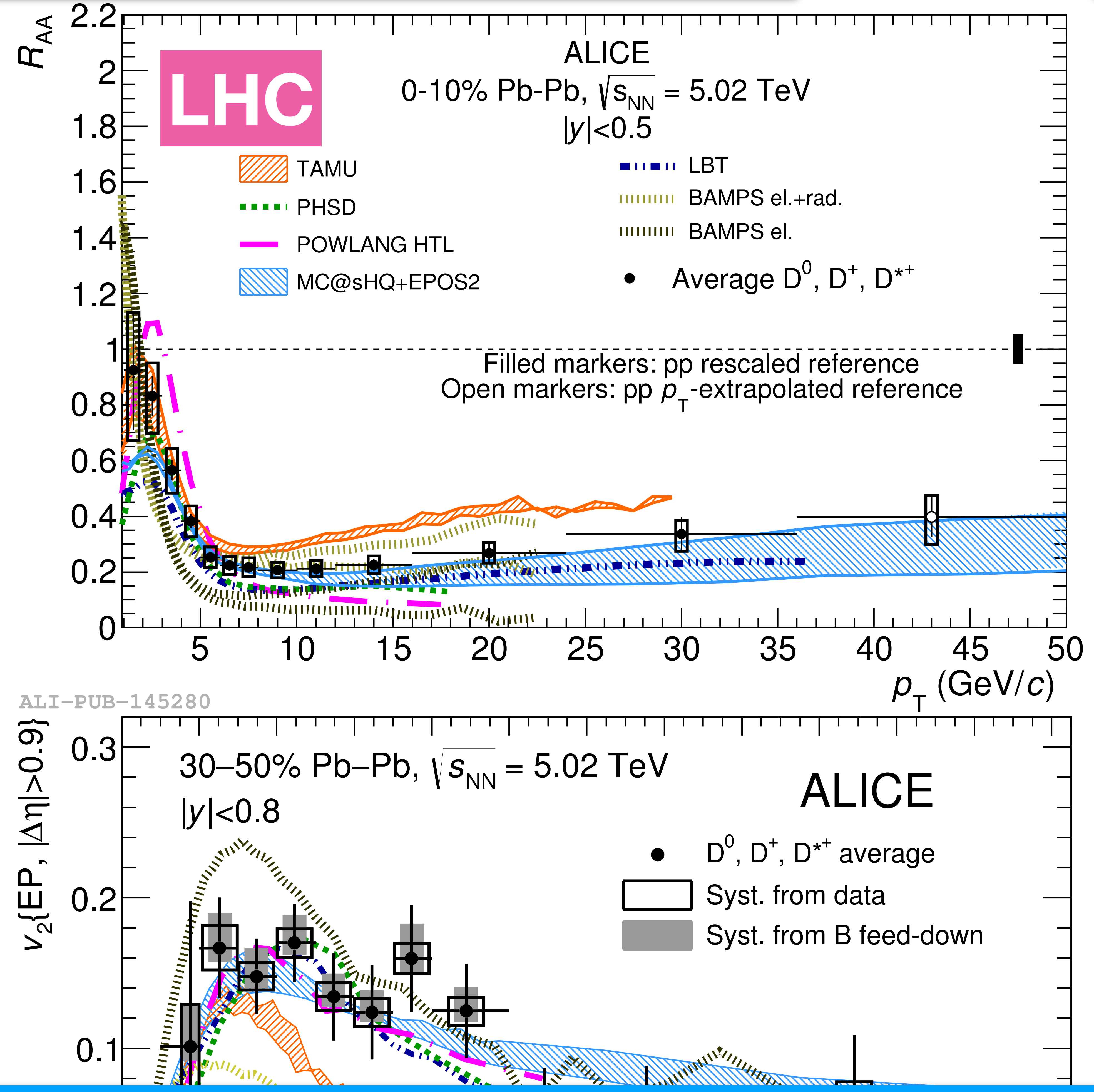






Heavy quark transport properties

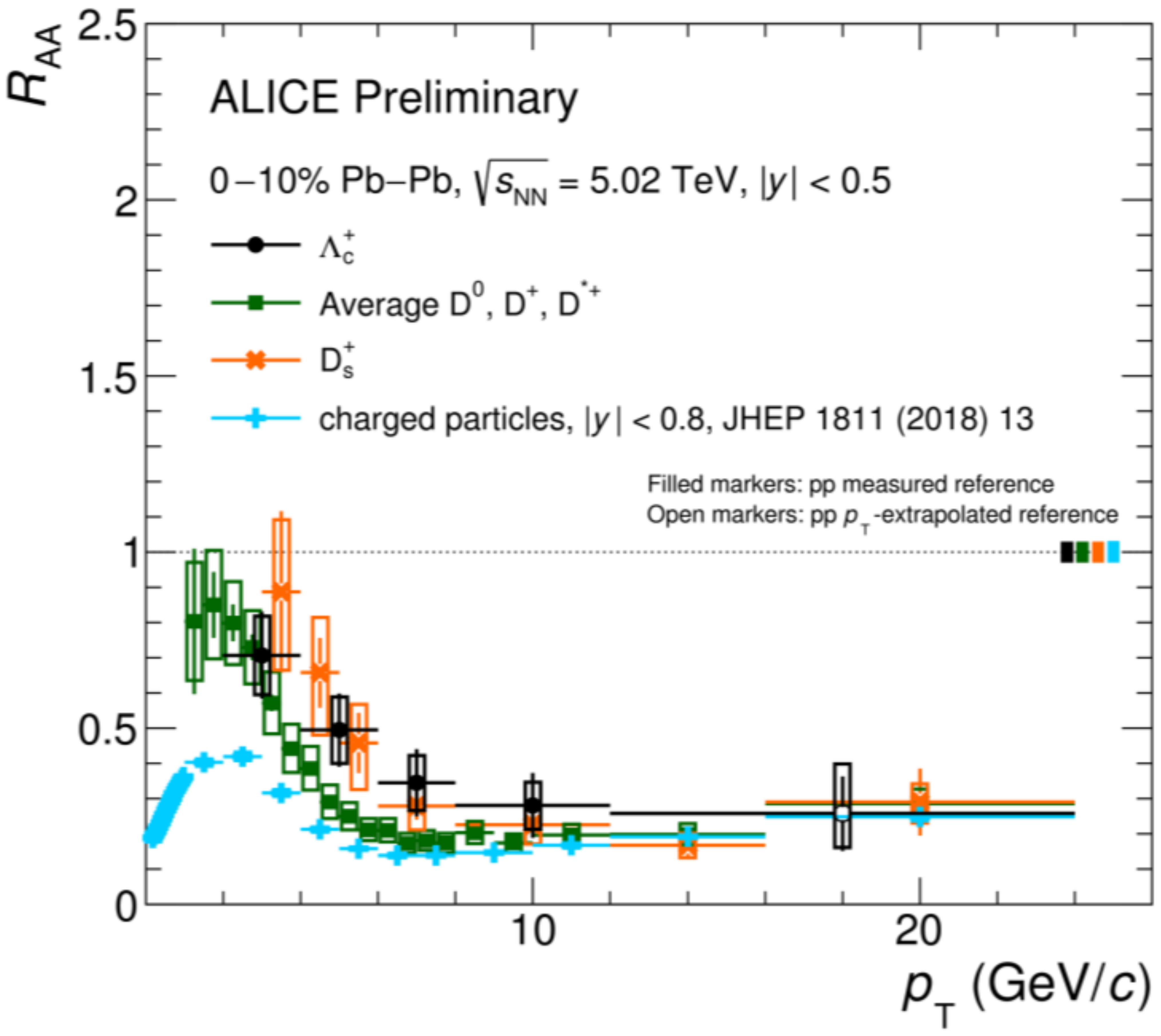




FromHeavy quark diffusion coefficient

- RHIC: (4 – 6) / $2\pi T$ for $0.2 < T < 0.4$ GeV
- LHC: (1.5 – 7) / $2\pi T$ for $T = T_c$

Charmed baryon production



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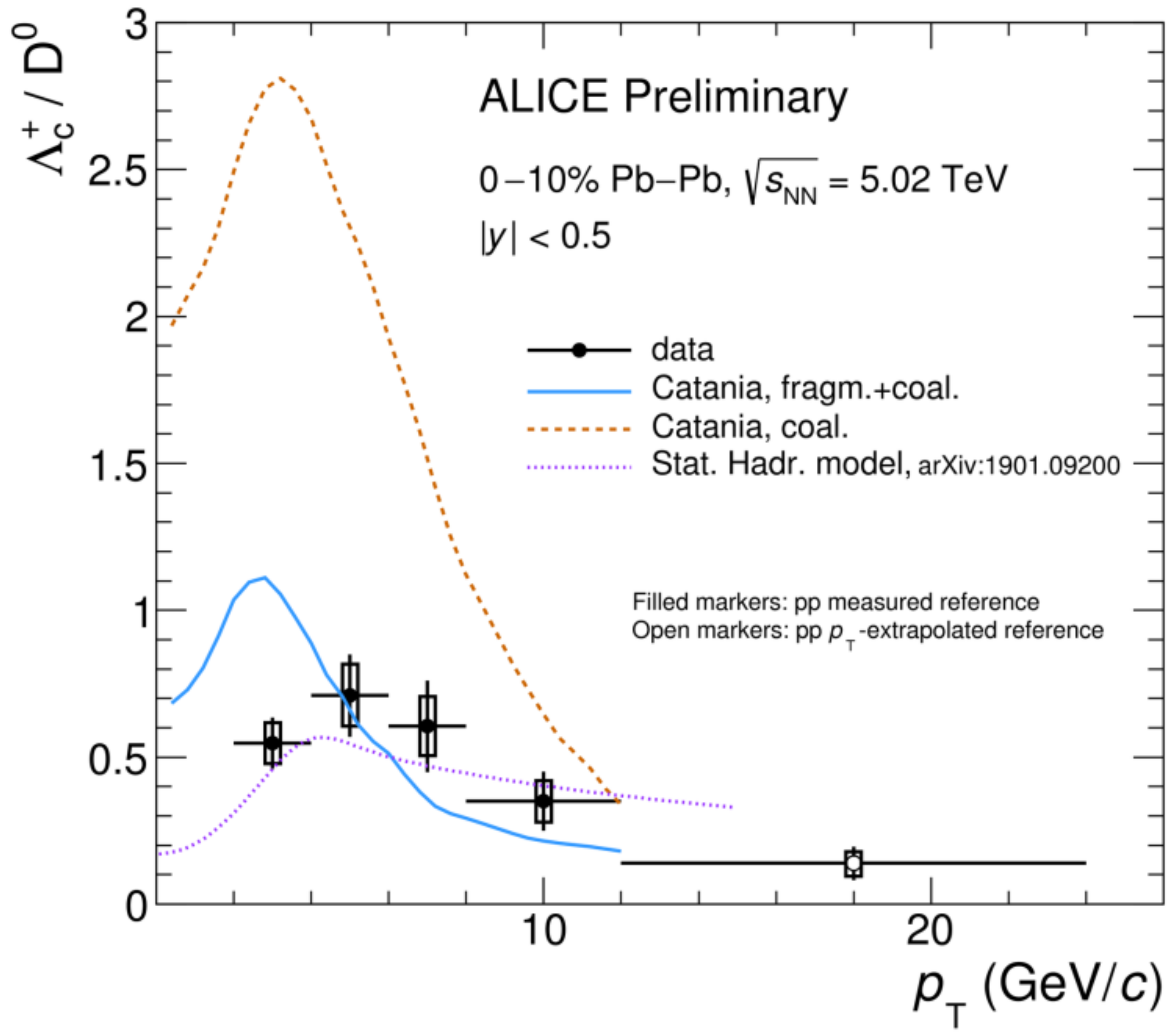


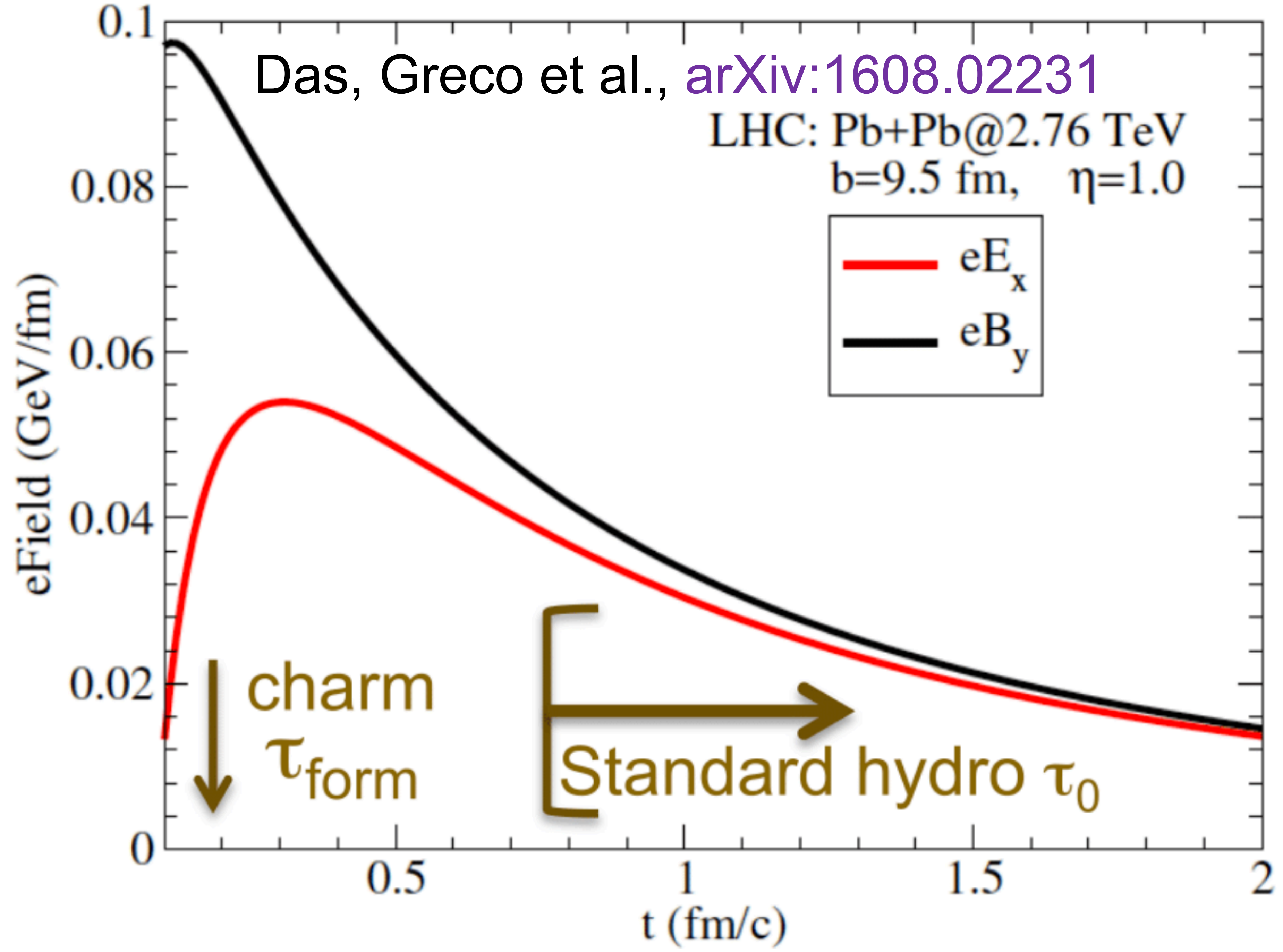
ALI-PREL-321682

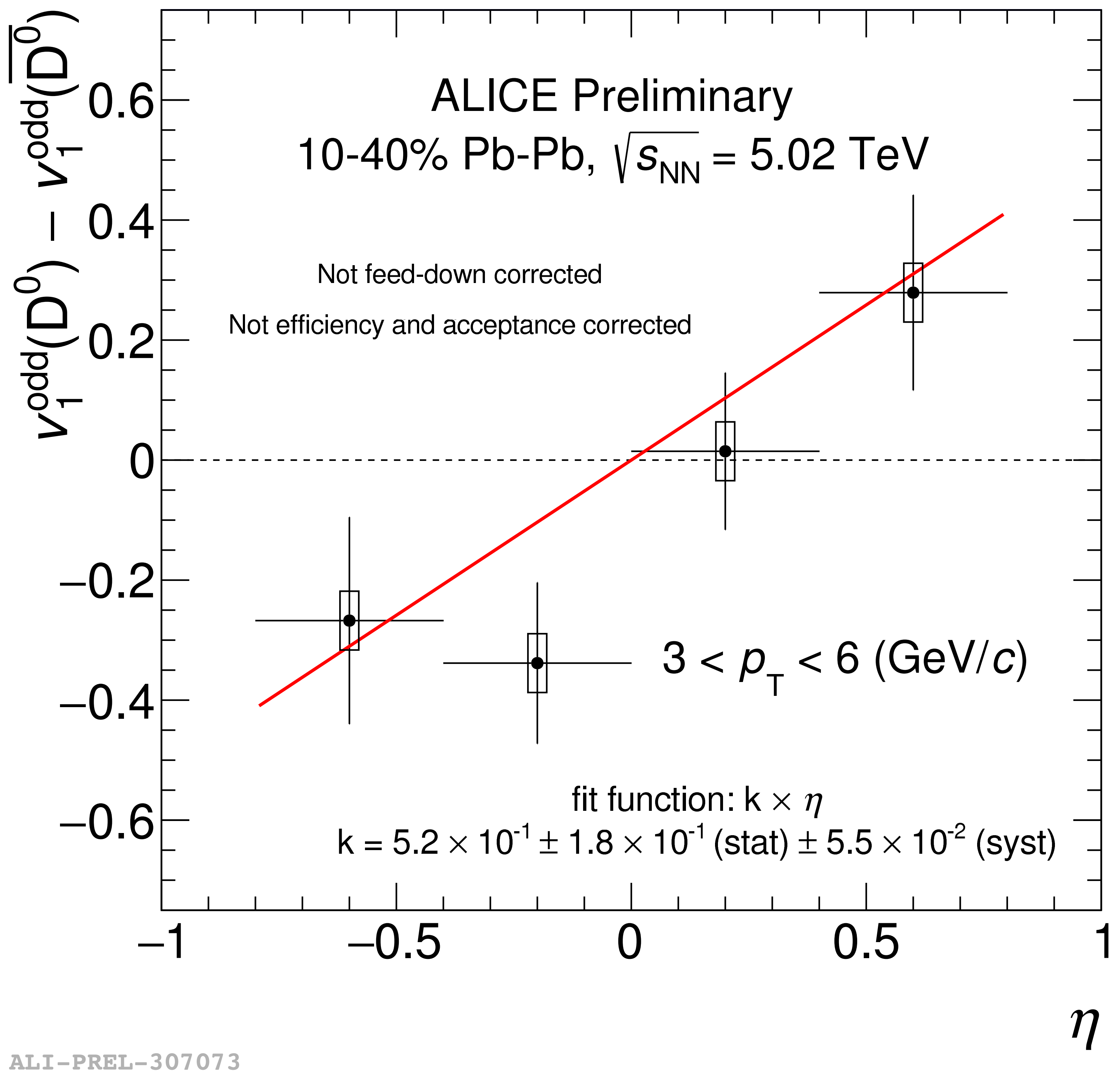
- New Λ_c R_{AA} in 2018 Pb–Pb data, similar suppression as D_s^+
- Hint of higher Λ_c / D^0 ratio in Pb–Pb collisions than small systems

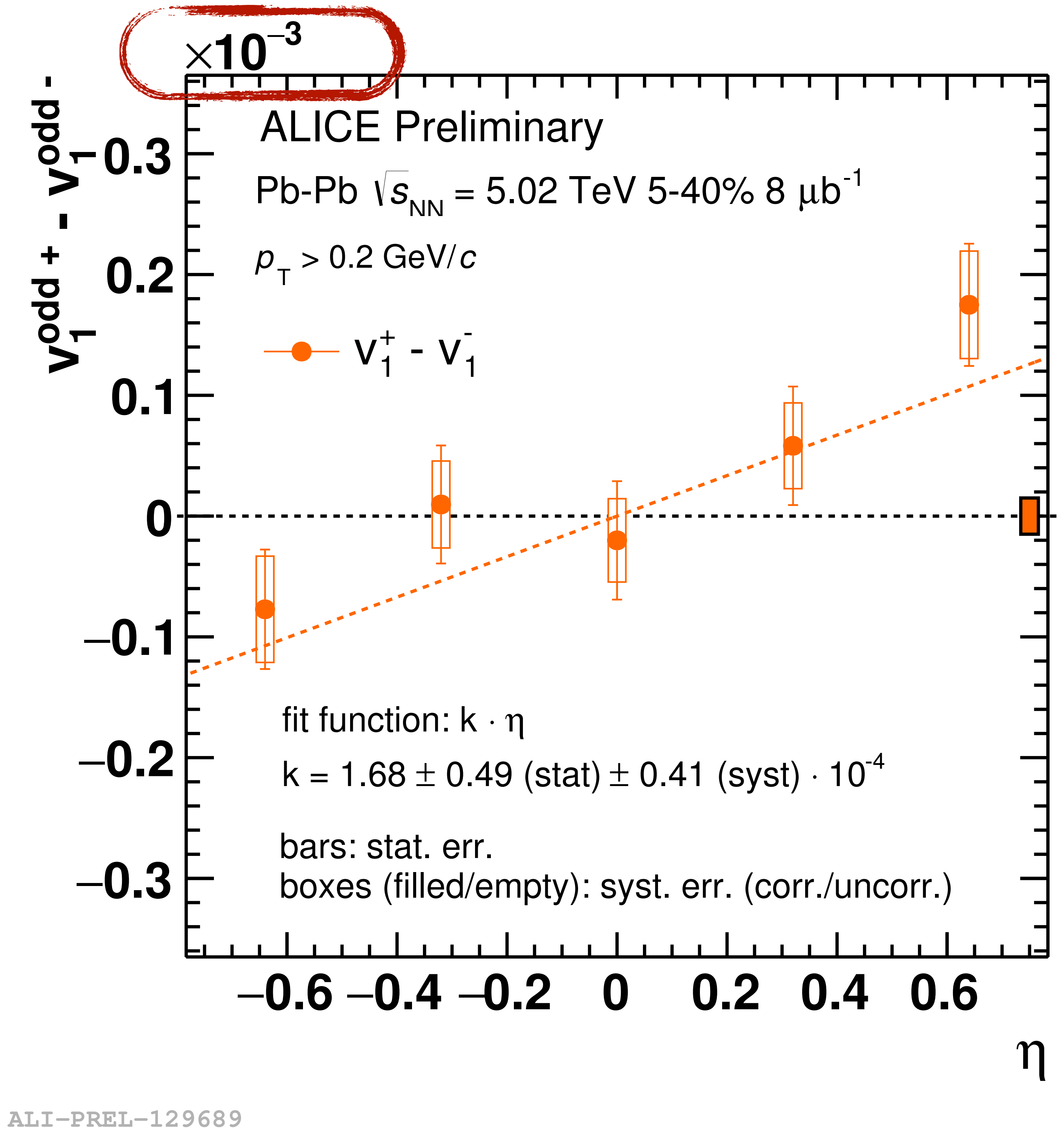
➡ Described by model including both coalescence and fragmentation

Direct flow of open charm

- Sensitive to the early time EM fields in the collisions
  - ➡ Provide constraint for CME related physics
- Charm dragged by tilted bulk
  - ➡ Larger v_1 for D mesons, probe the longitudinal profile of the initial matter





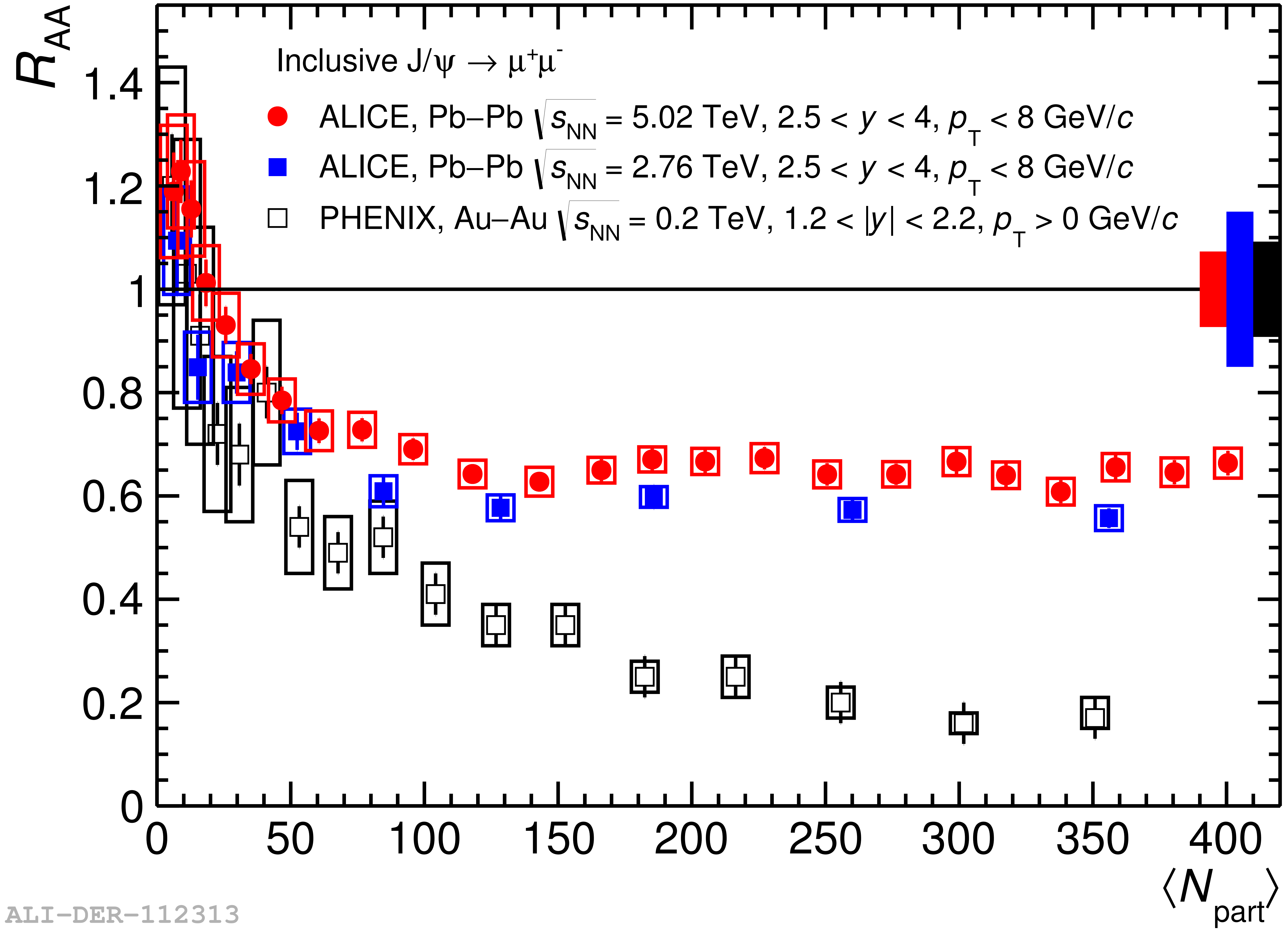


Hint of positive slope with a significance of 2.7σ at low p_T

Similar trend observed for charged particles, but different magnitude

J/ψ production in Pb–Pb collisions

ALICE *Phys. Lett.* B766 (2017) 212



- Suppression is insensitive on centrality in central and semi-central collisions
- Recombination plays important roles on J/ψ production on top of the Debye screening at the LHC energies

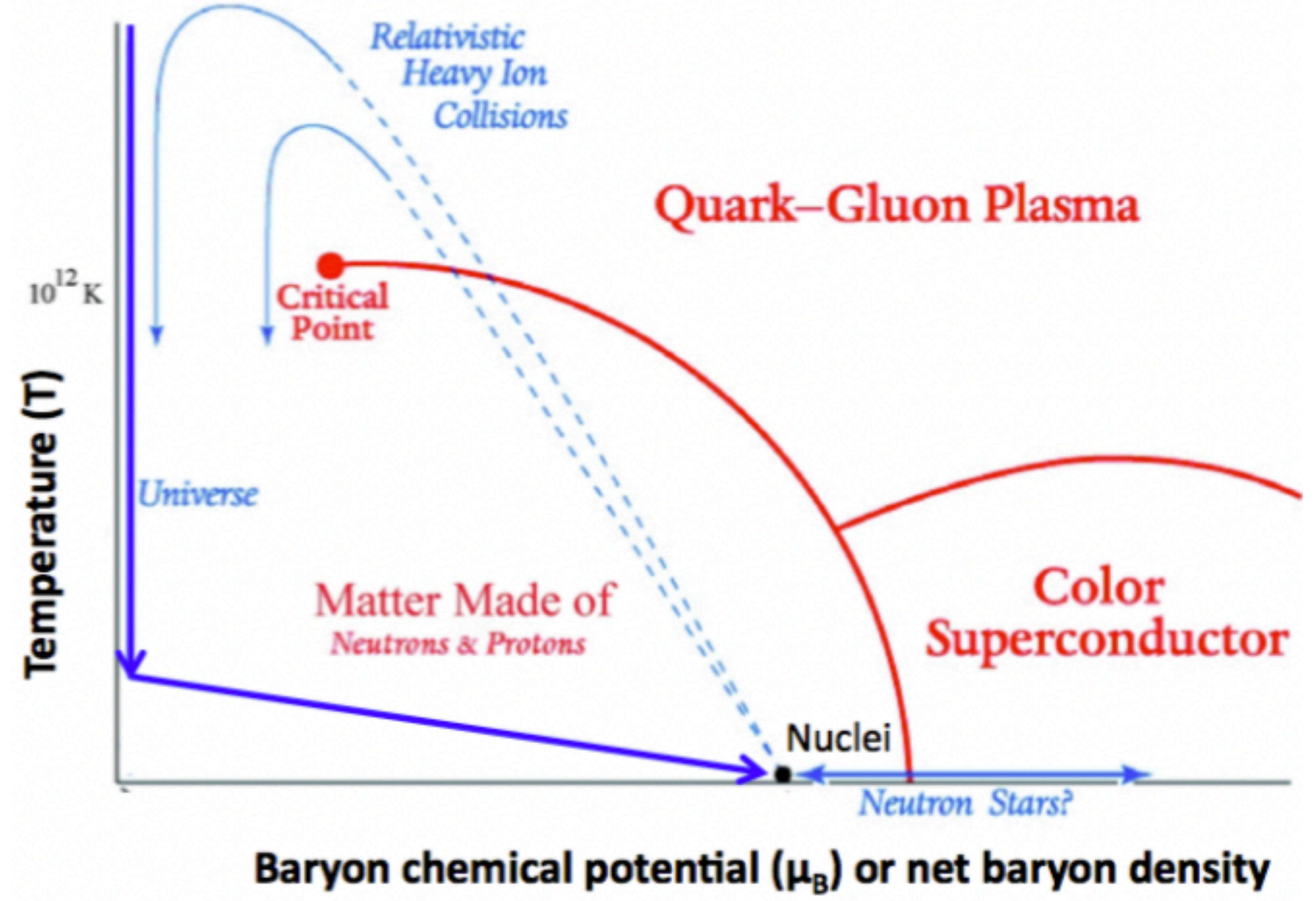
The "pre-LHC" paradigm

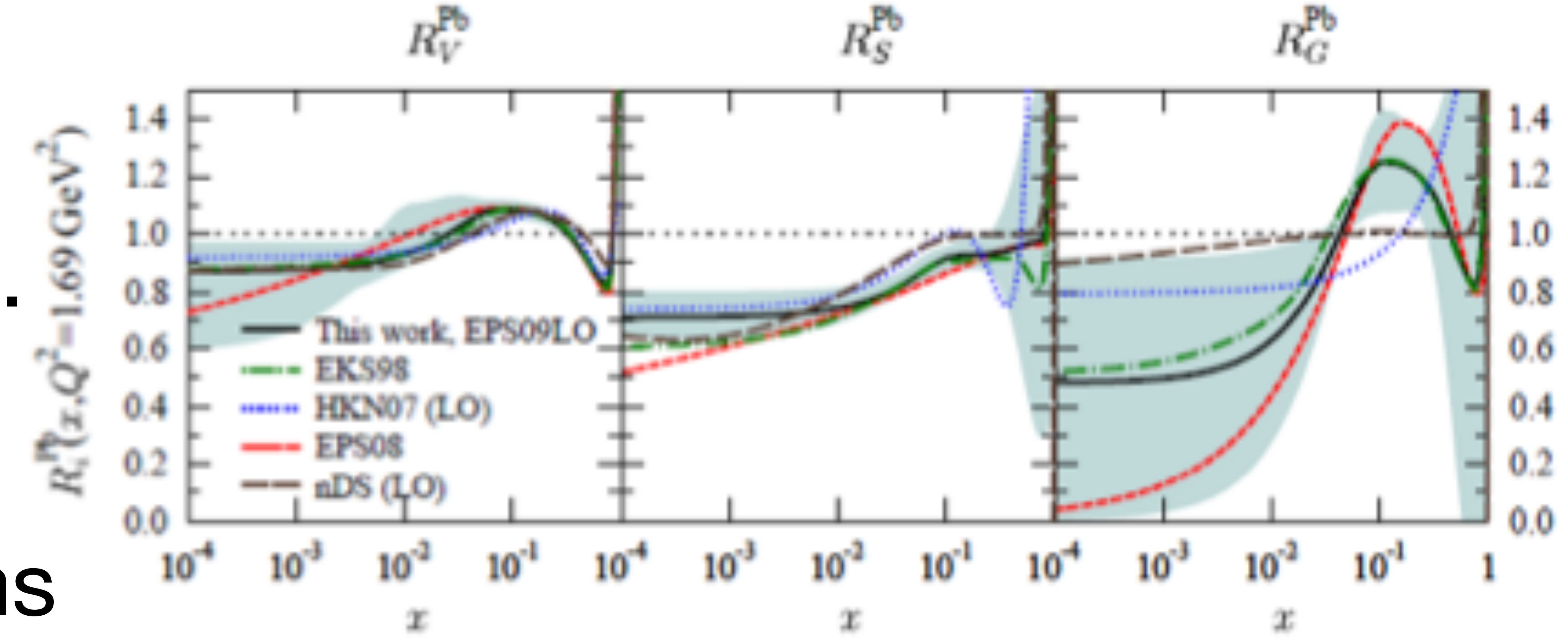
Heavy-ion collisions

- Probe in details the properties of high density and temperature nuclear matter
  - ➡ Hot nuclear matter effects — the QGP

Control experiment

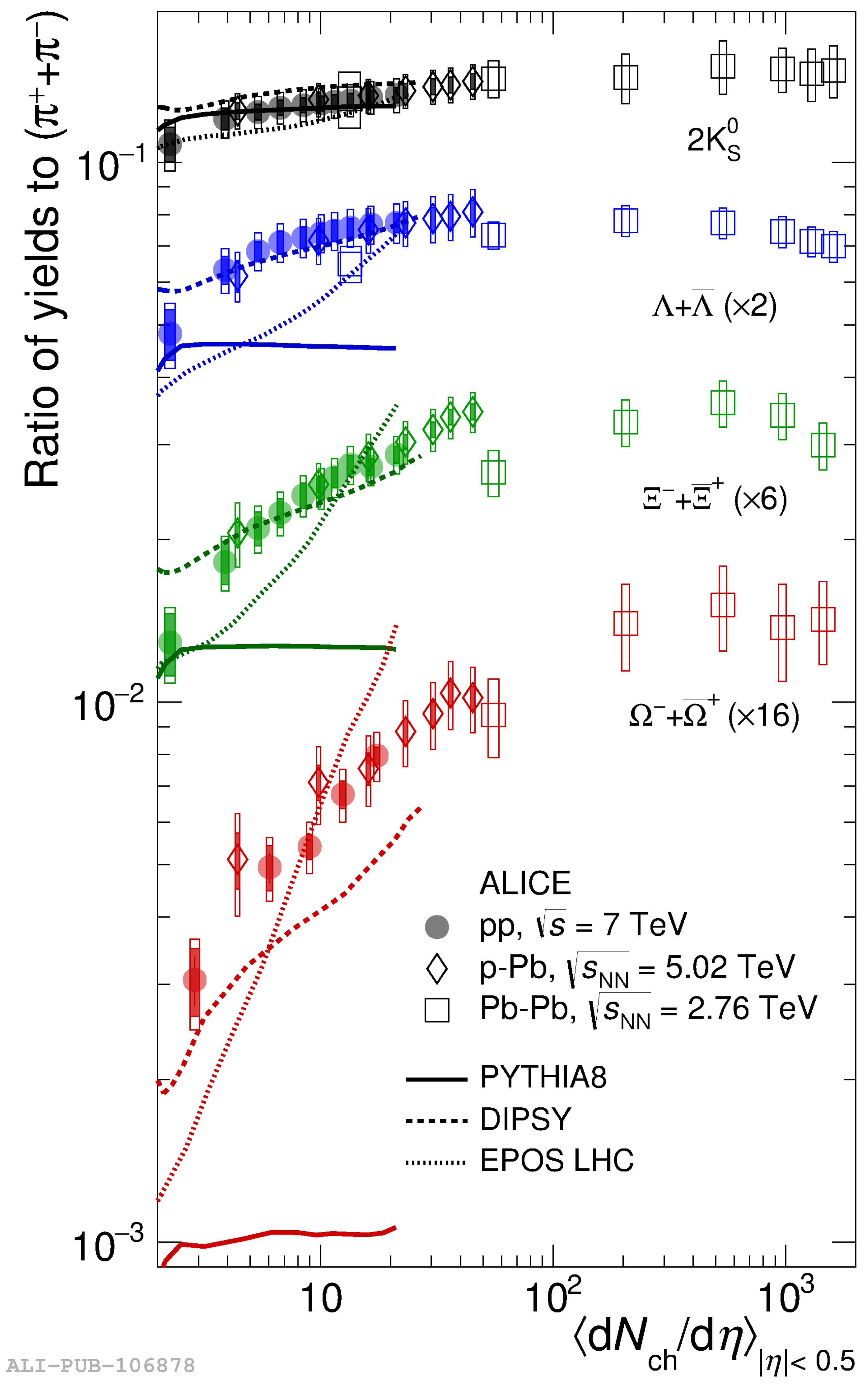
- p–Pb collisions: investigation of cold nuclear matter (CNM) effects
  - ➡ nPDF, Saturation, Color Glass Condensate…
- pp collisions
  - ➡ Important baseline to compare other systems
  - ➡ Test pQCD calculations at TeV domain, parton hadronization in vacuum





The "Pandora box"

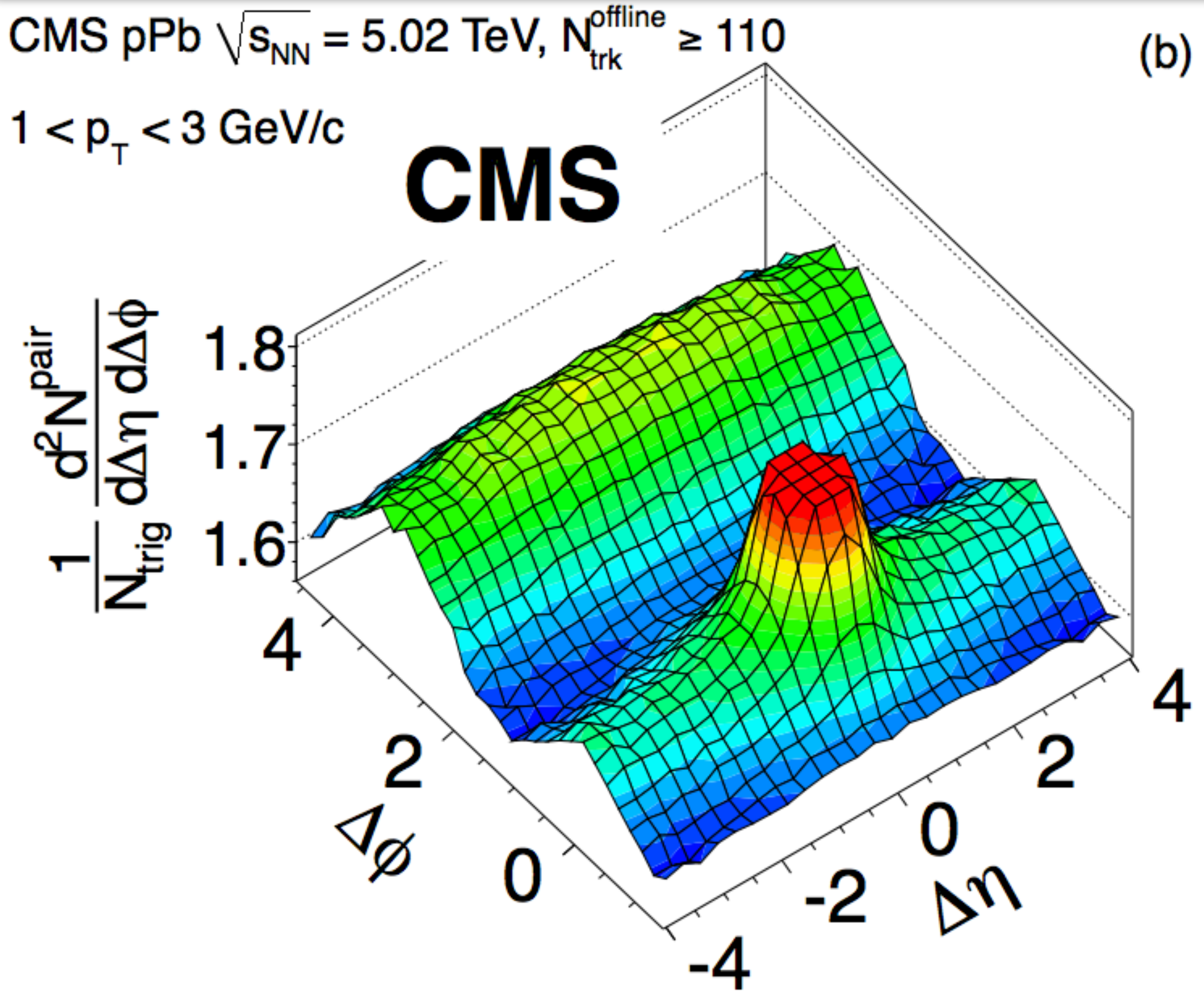
ALICE *Nature Physics* **13 (2017) 535**

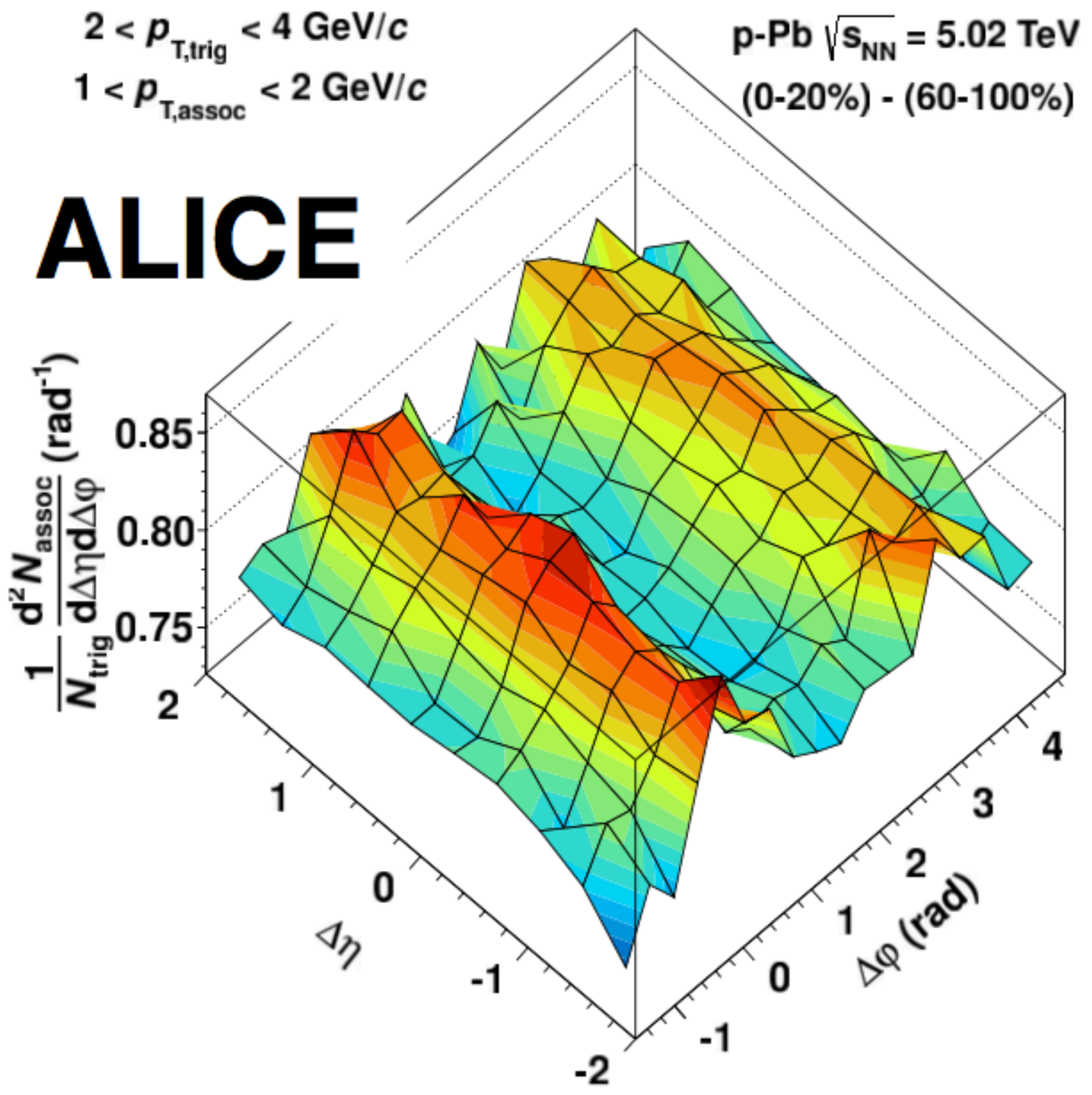


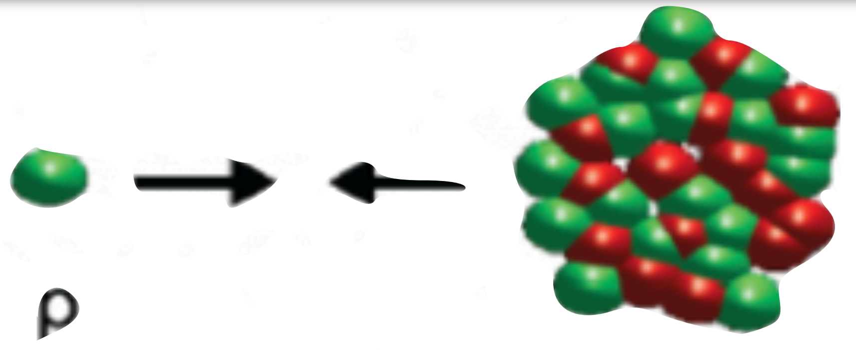
- Smooth evolution of particle production from small to large systems vs charge multiplicity
  - ➡ Strangeness enhancement considered defining feature of heavy-ions — now seen in high-multiplicity pp / p–Pb!

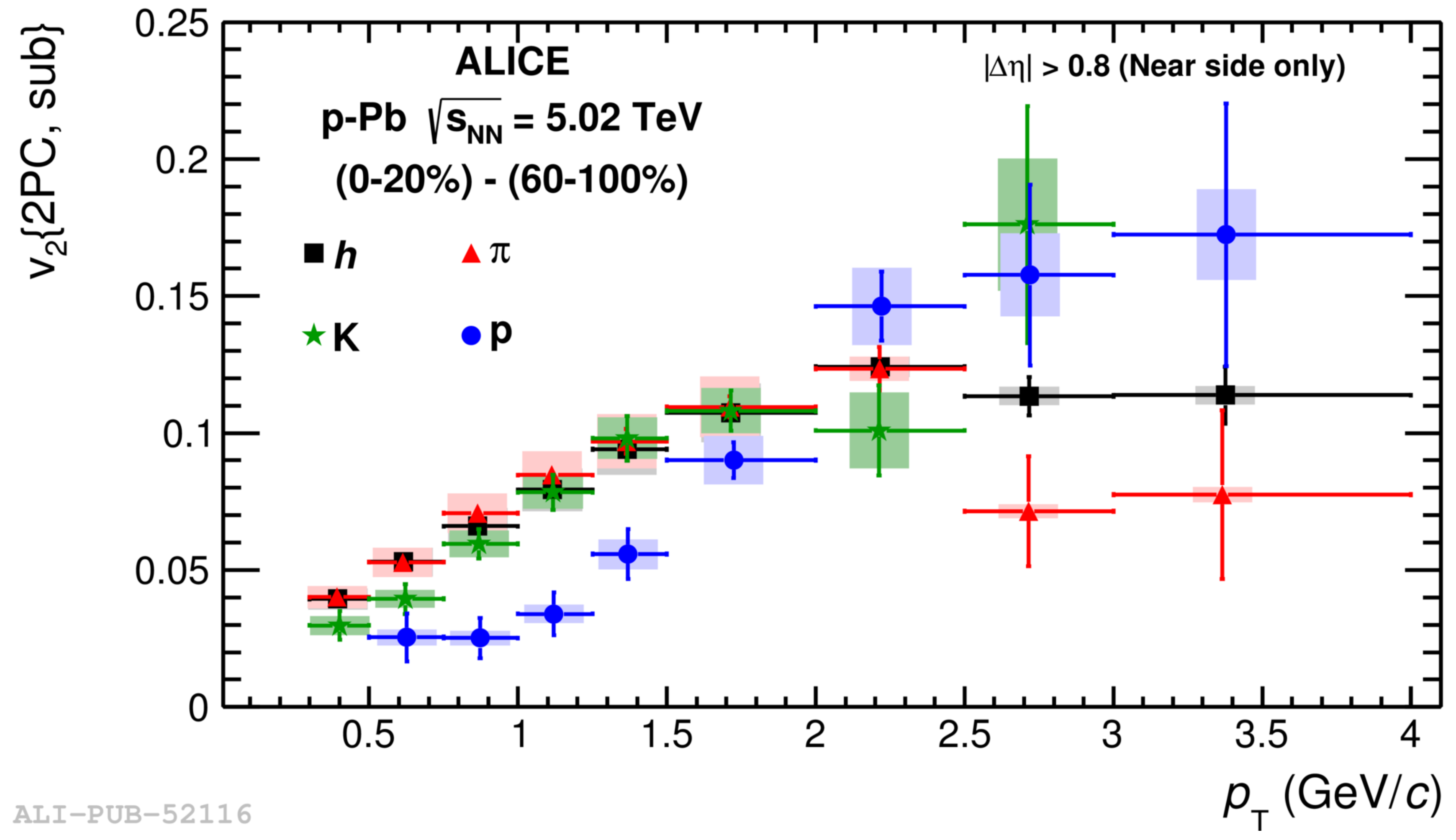
- Where all this comes from?
  - ➡ Initial stages effects?
  - ➡ Better understanding of the observables we use in heavy-ion for small systems?
  - ➡ Common mechanism of particle production?
  - ➡ Final state effects?

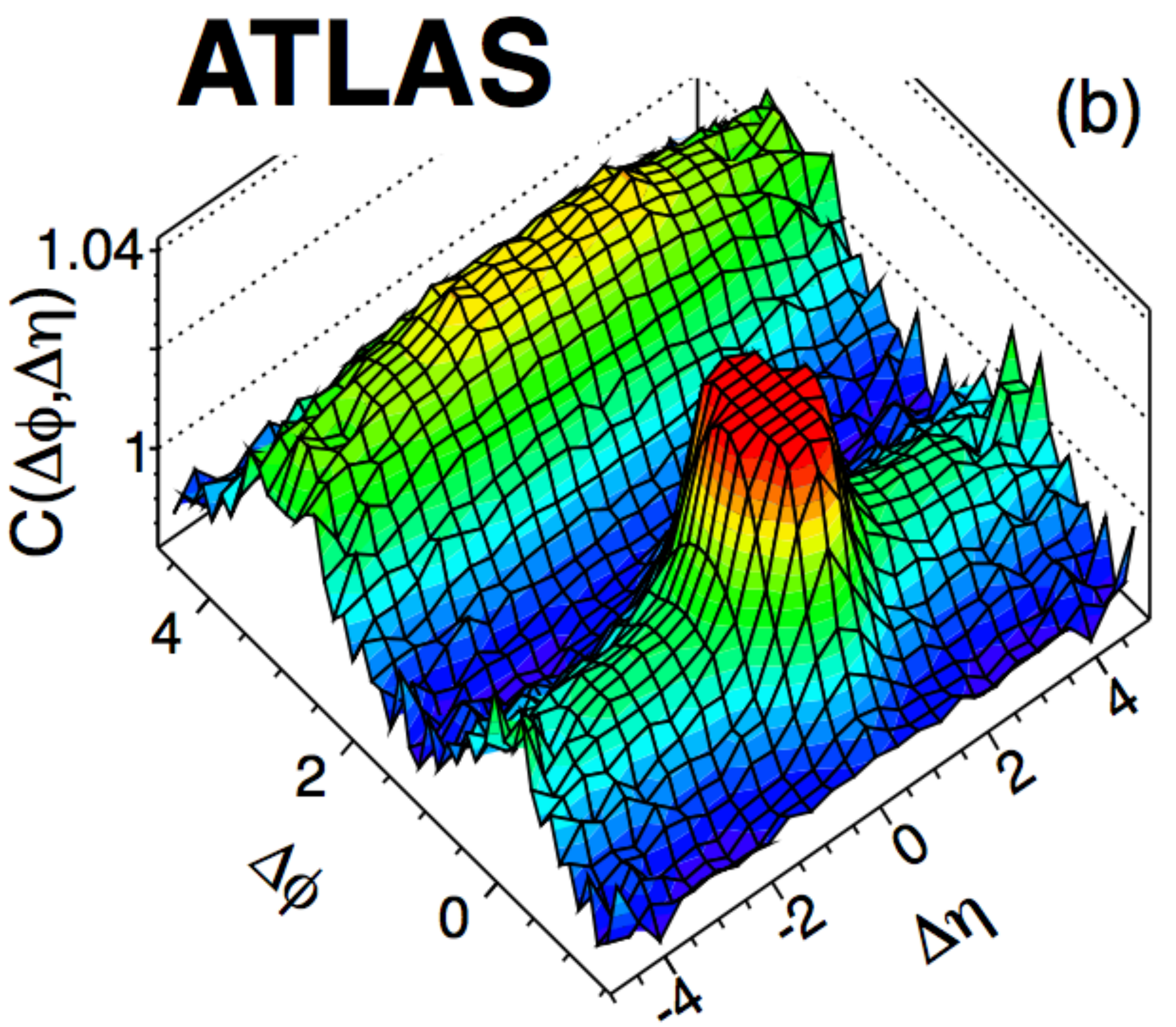
Particle production in small systems

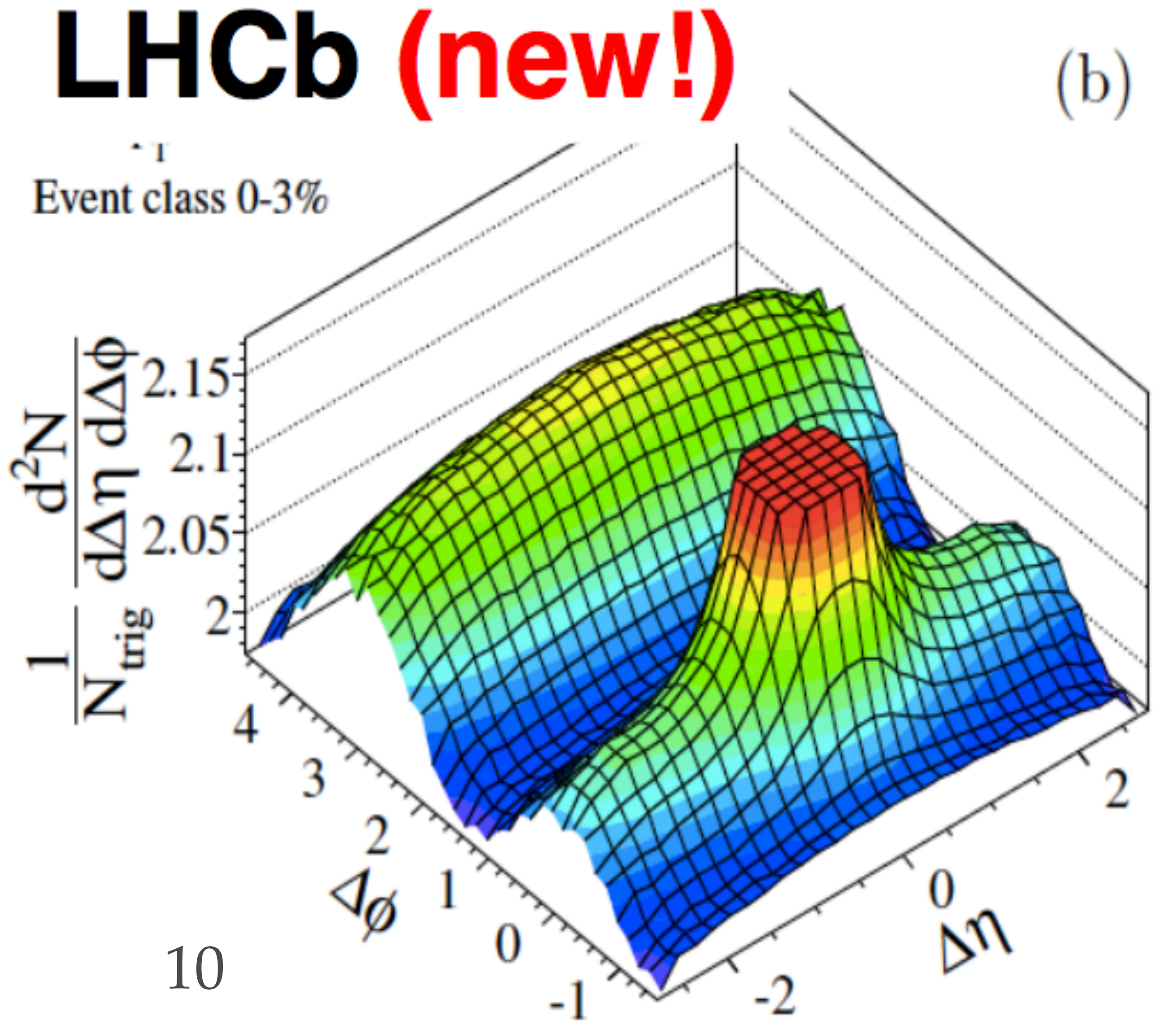


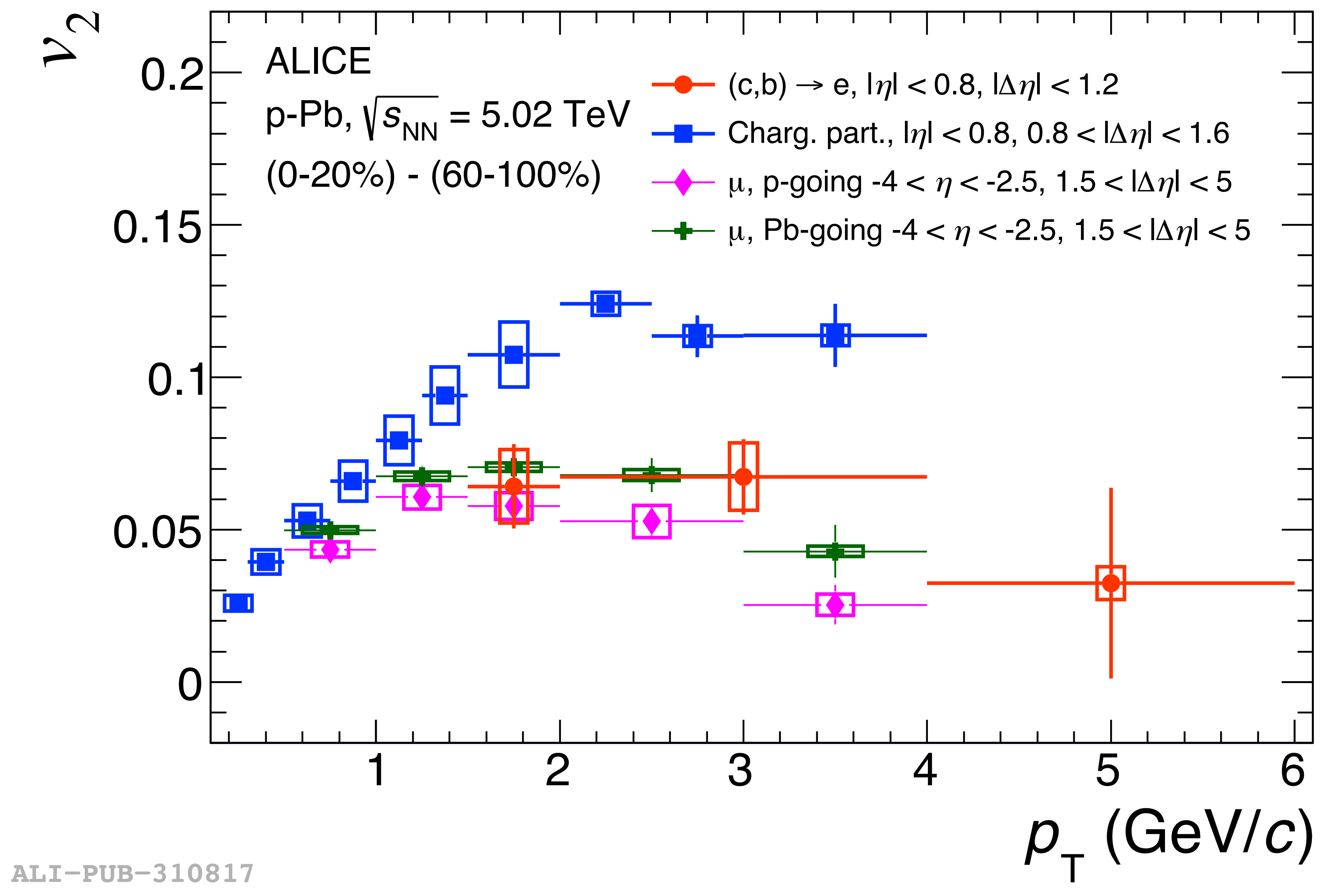






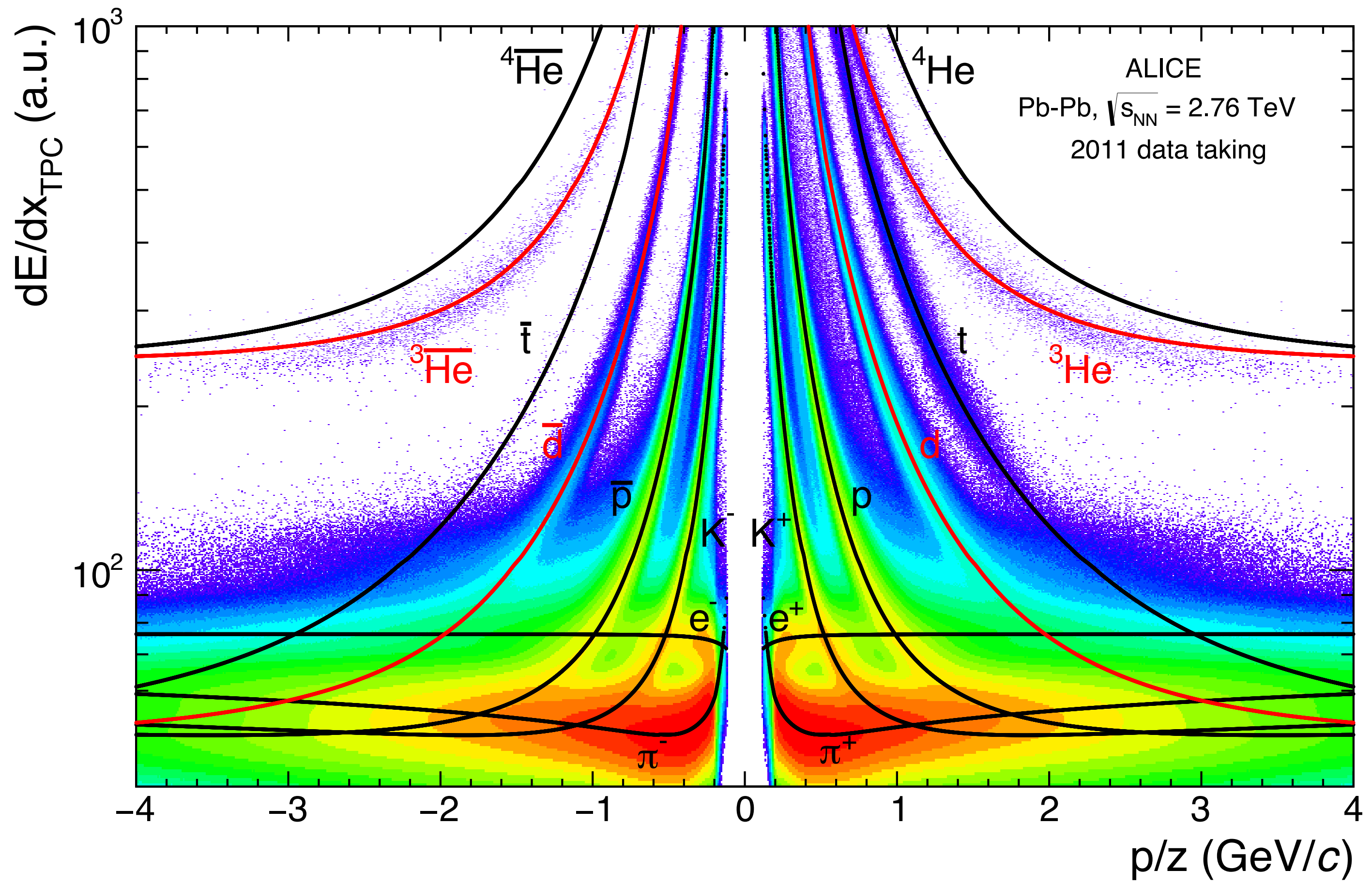


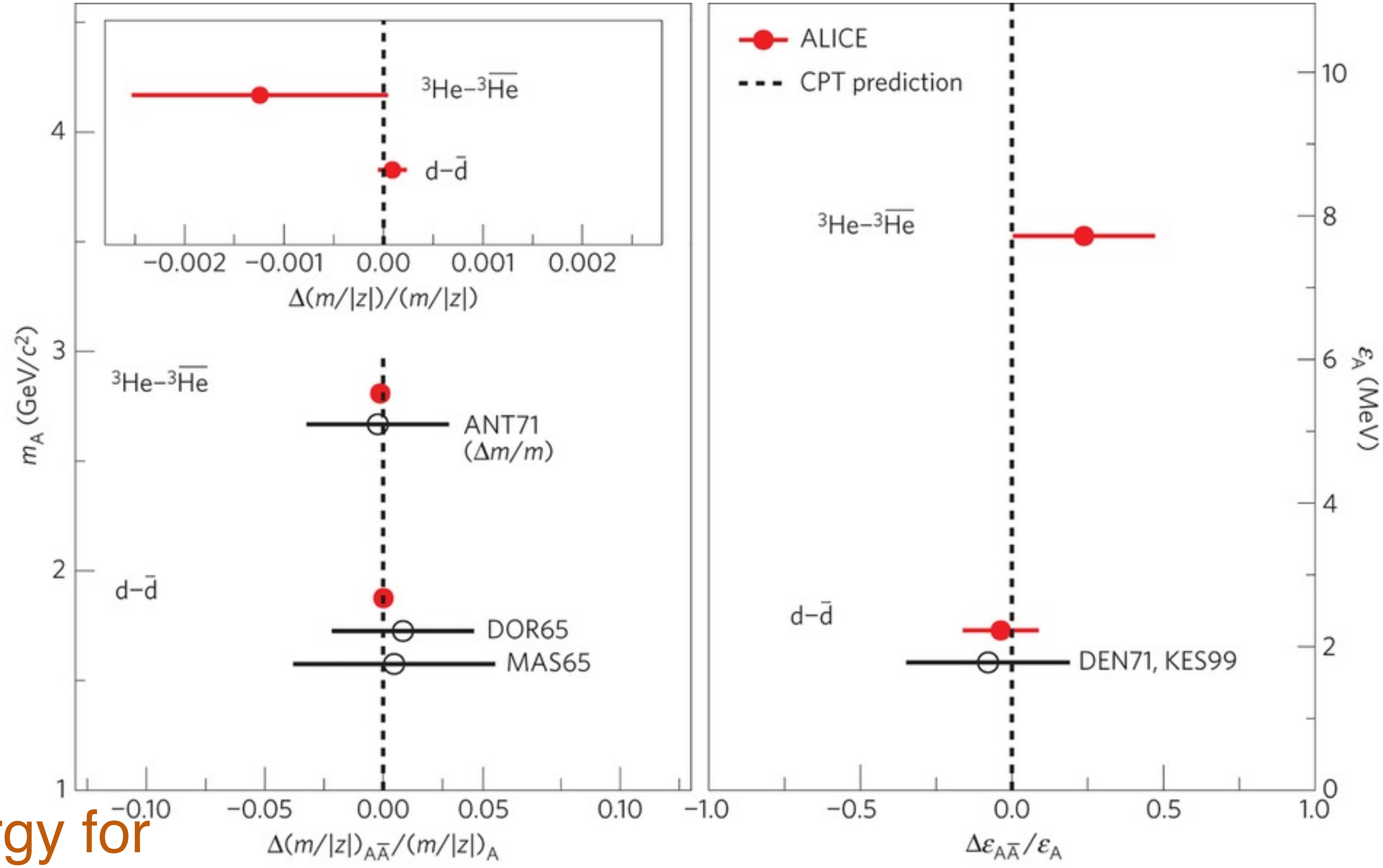




Mass Difference of (Anti-)nuclei

- Test of CPT invariance of residual nuclear force by measuring mass difference in the nuclei sector (^{3}He and deuterons)



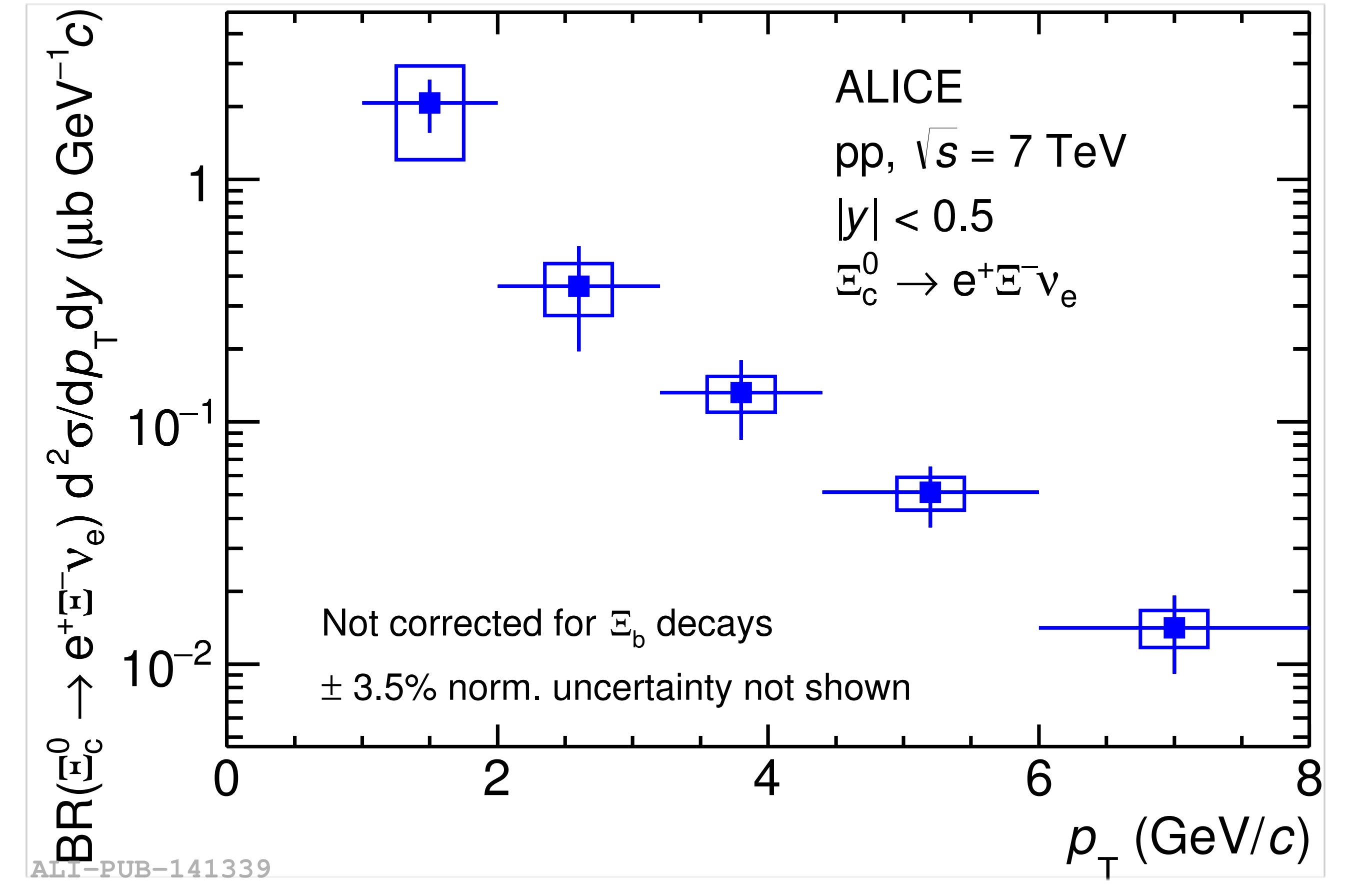


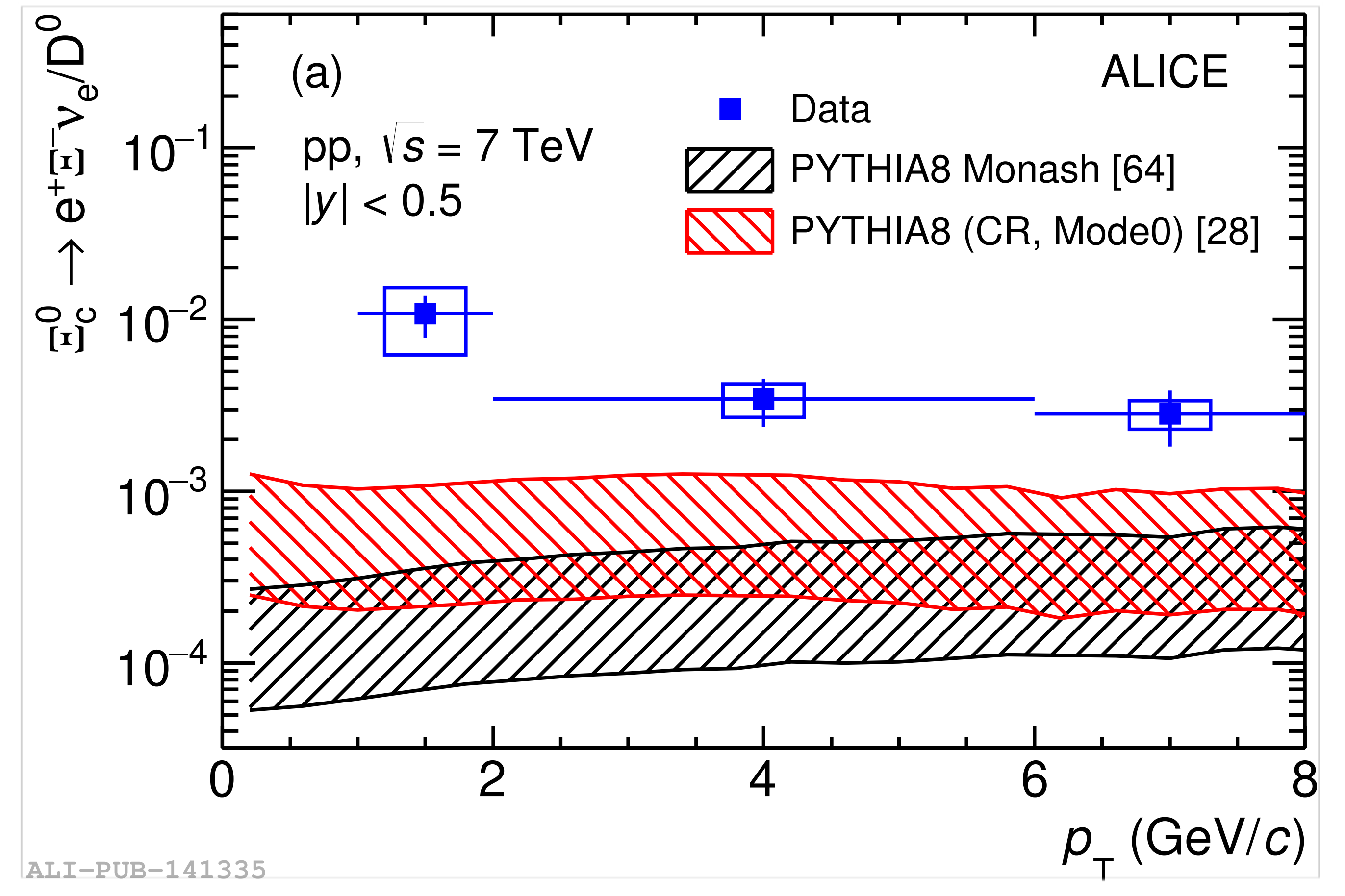
ALICE *Nature Physics* 11 (2017) 811

- Improved by one to two orders of magnitude compared to earlier measurements
- First measurement of binding-energy for (anti-)^{3}He
- Confirms CPT invariance for light nuclei

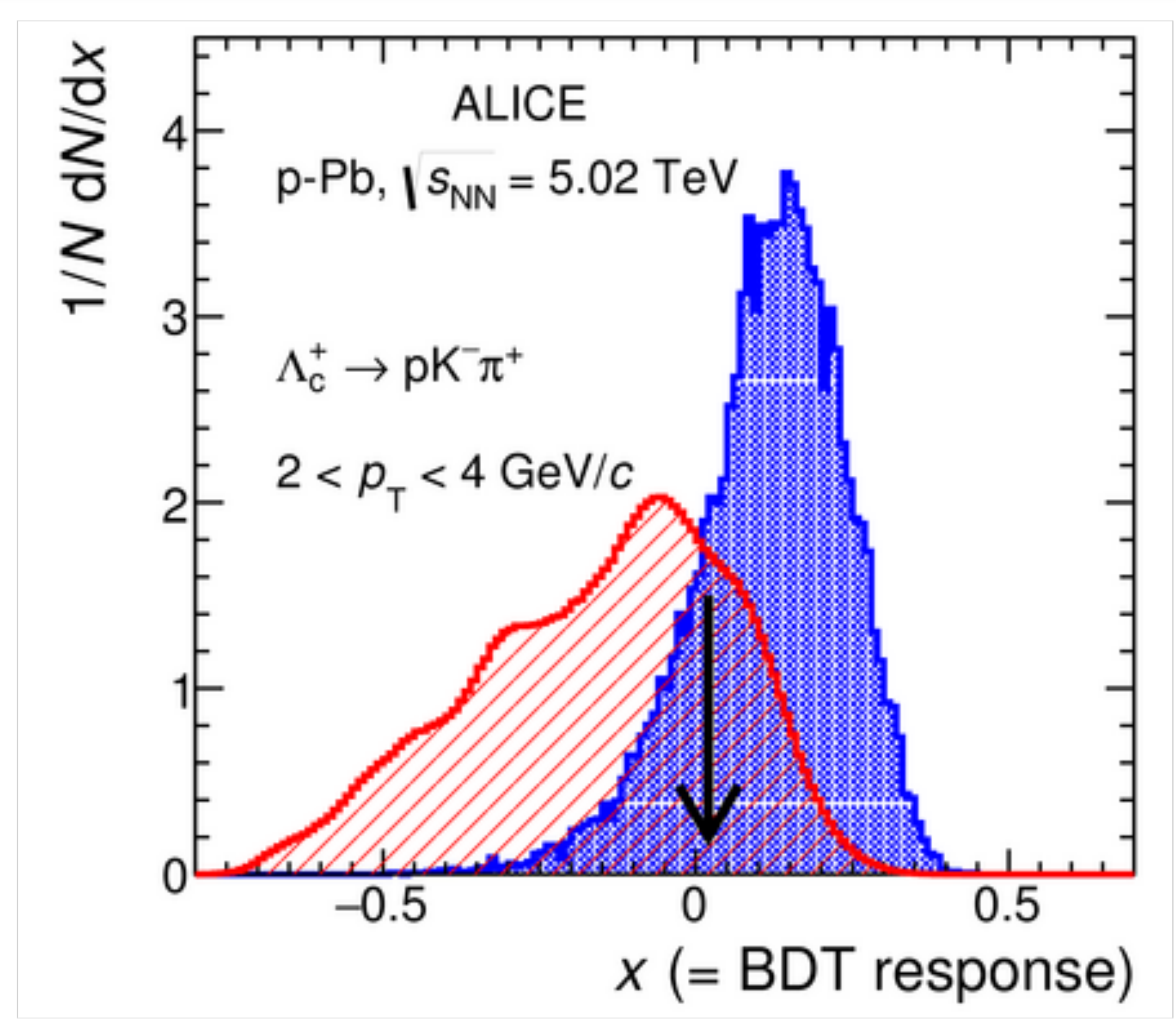
More rare probes…

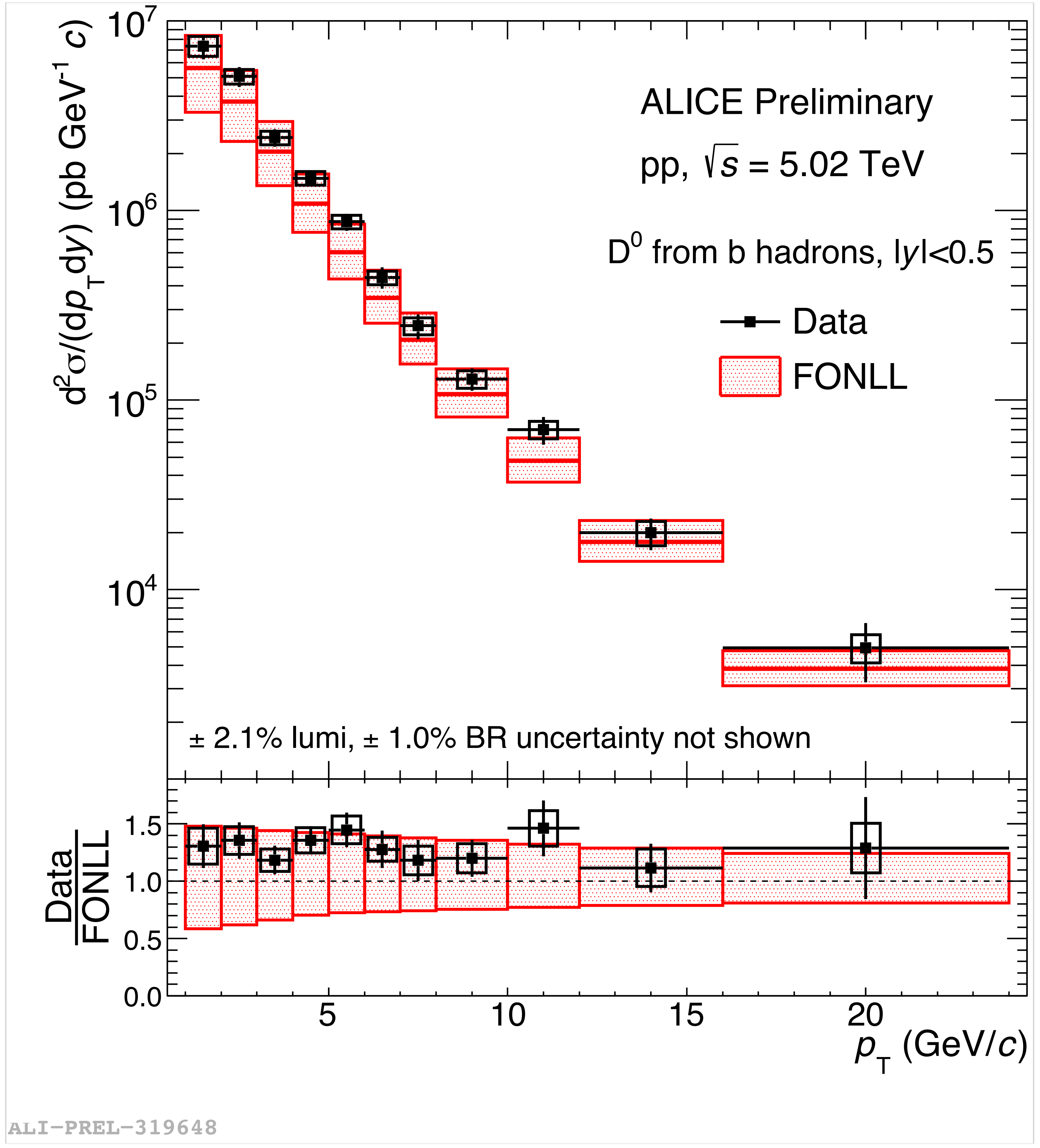
ALICE *Phys. Lett.* B781 (2018) 8





ALICE *JHEP* 04 (2018) 108

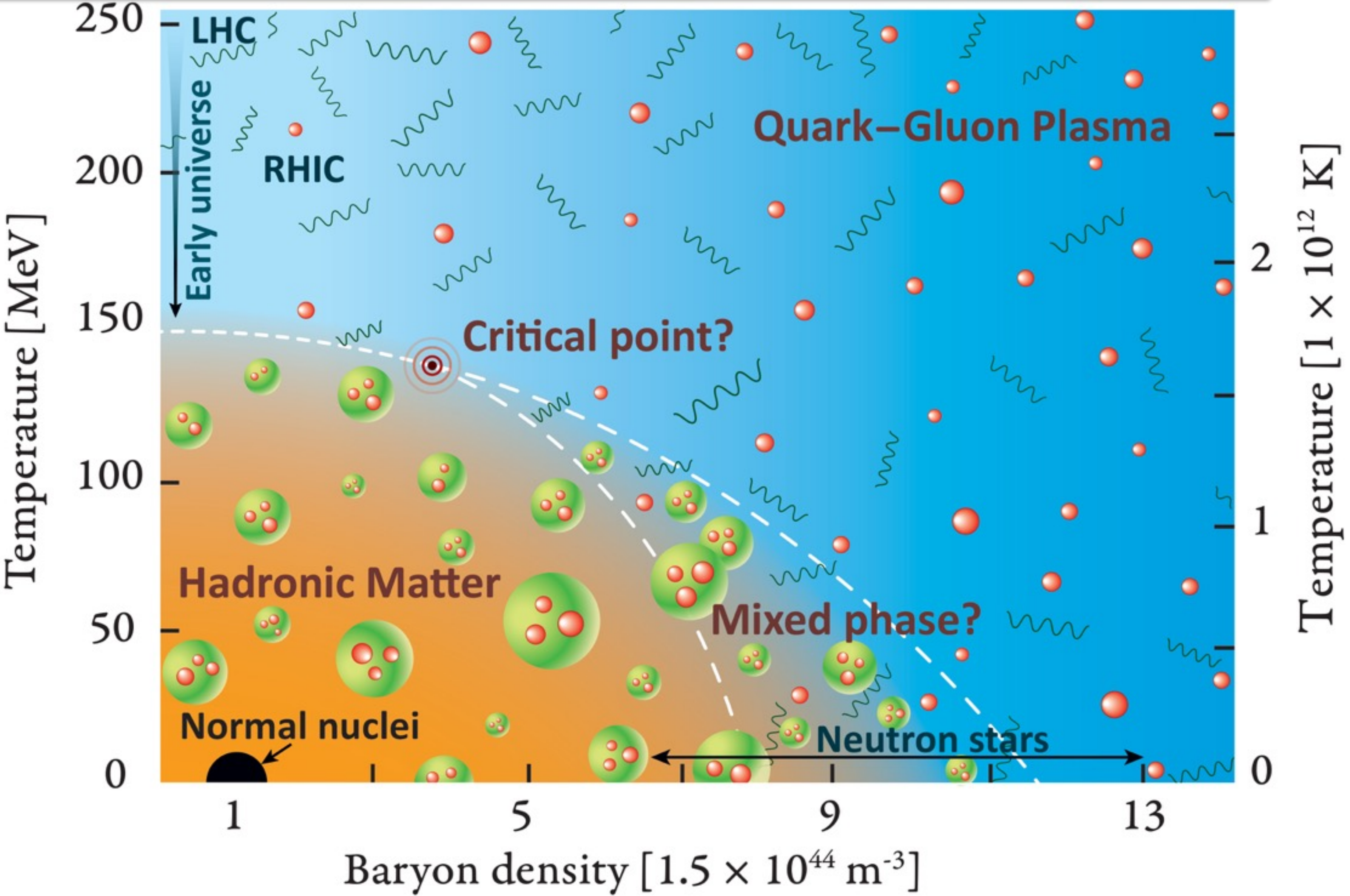




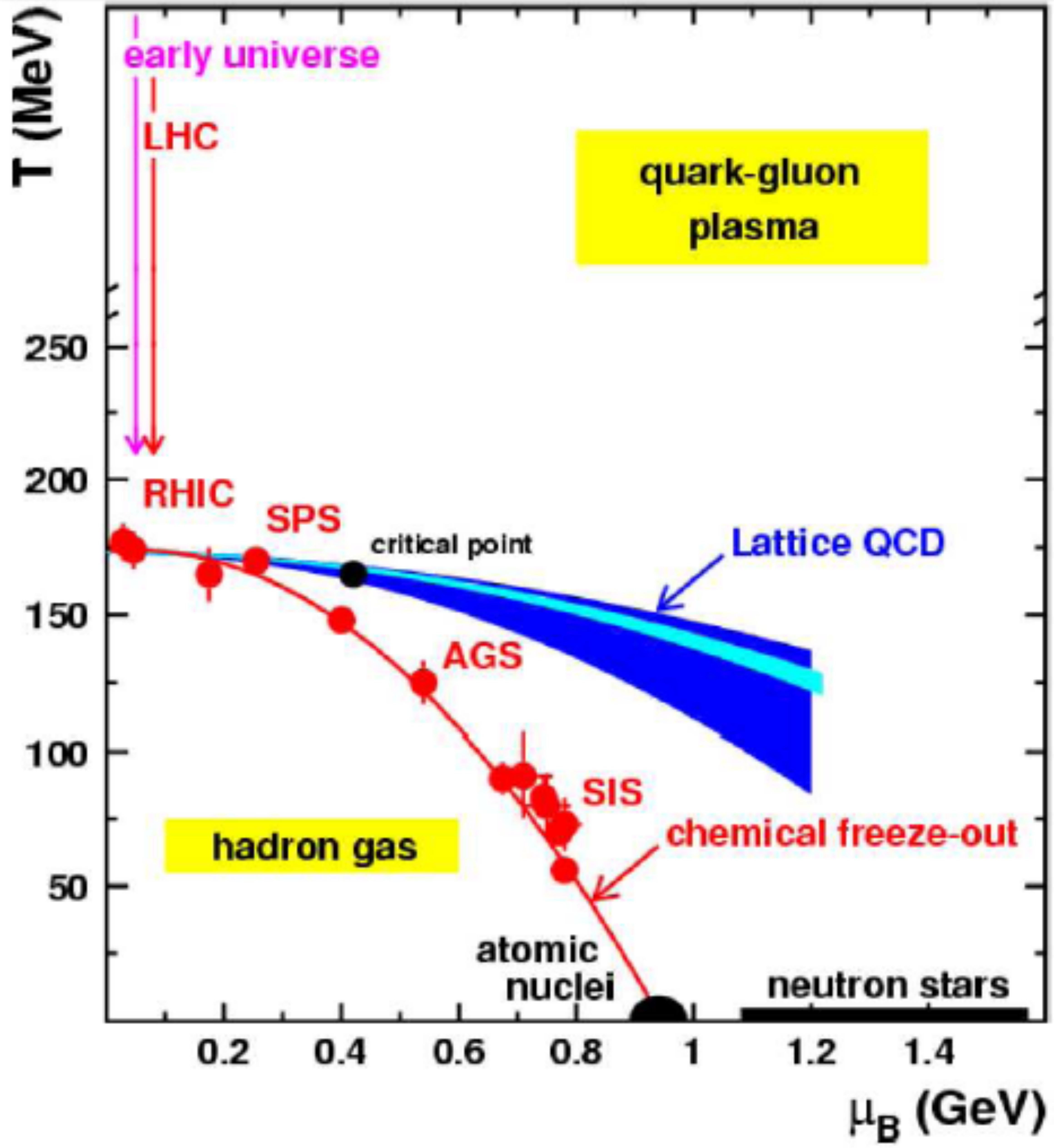
- **Study of rare probes, non-prompt D mesons, Σ_c, Ξ_c… are on the road**
- **Exploring new techniques, such as machine learning…**

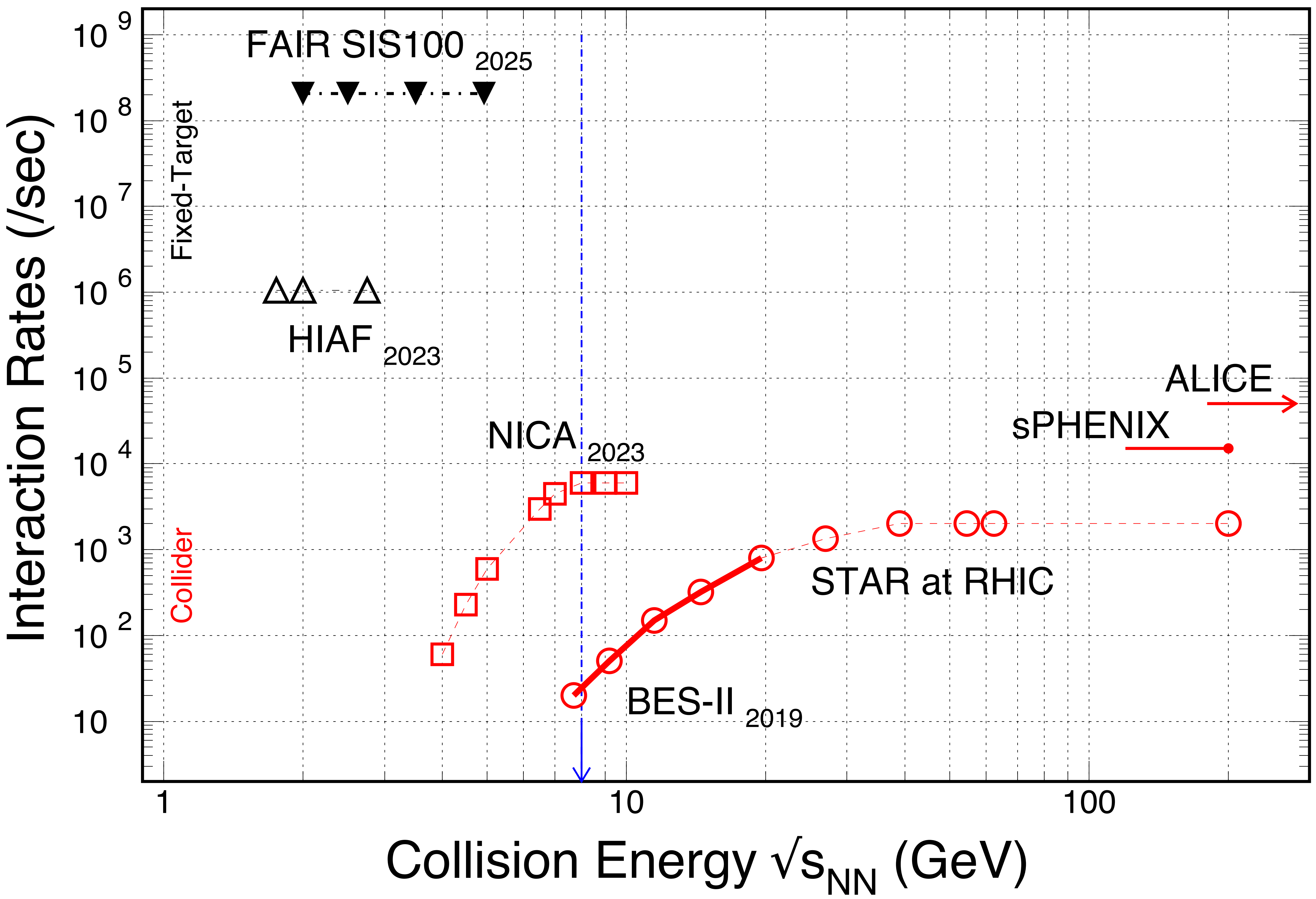
Backup

QCD phase diagram



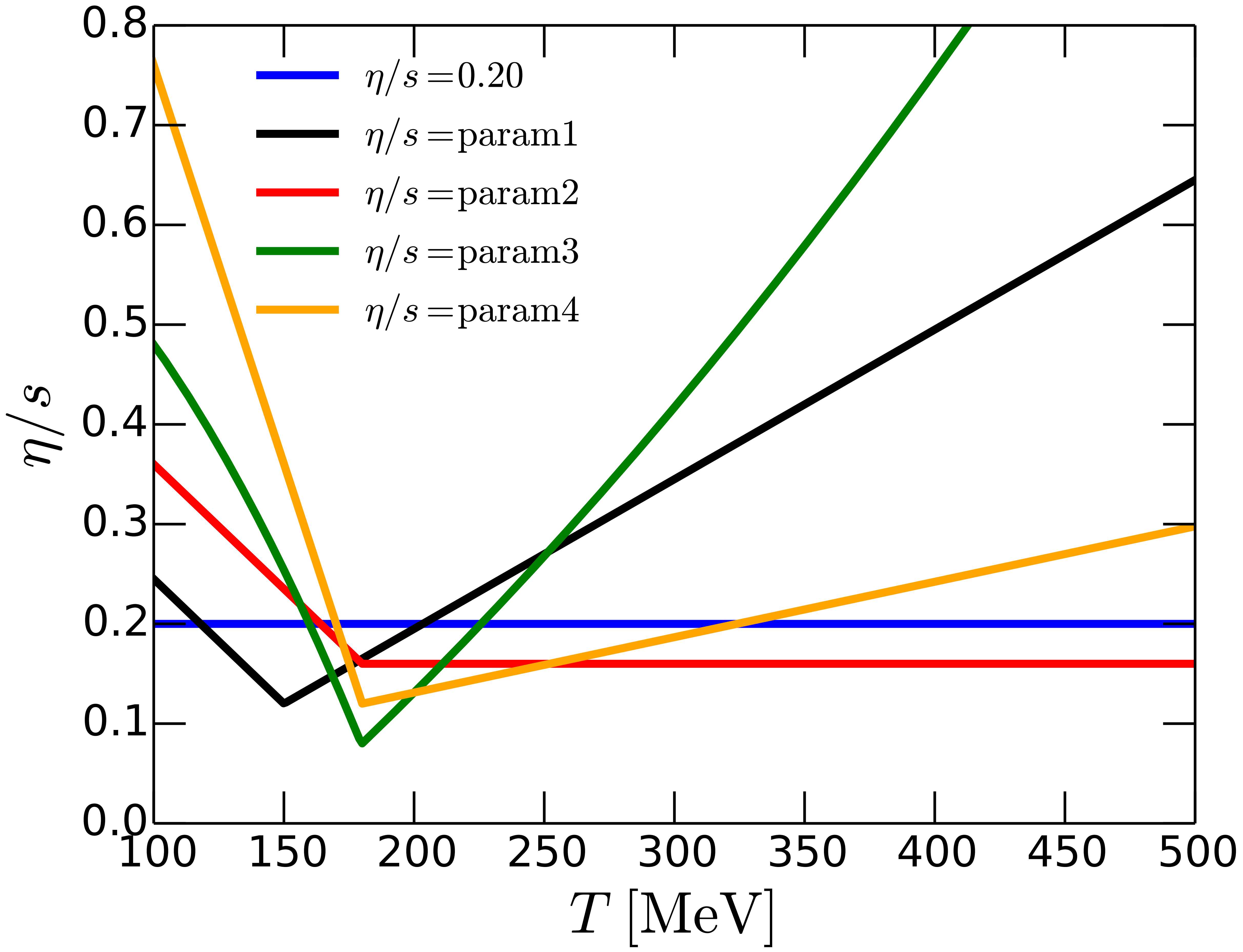
QGP factories



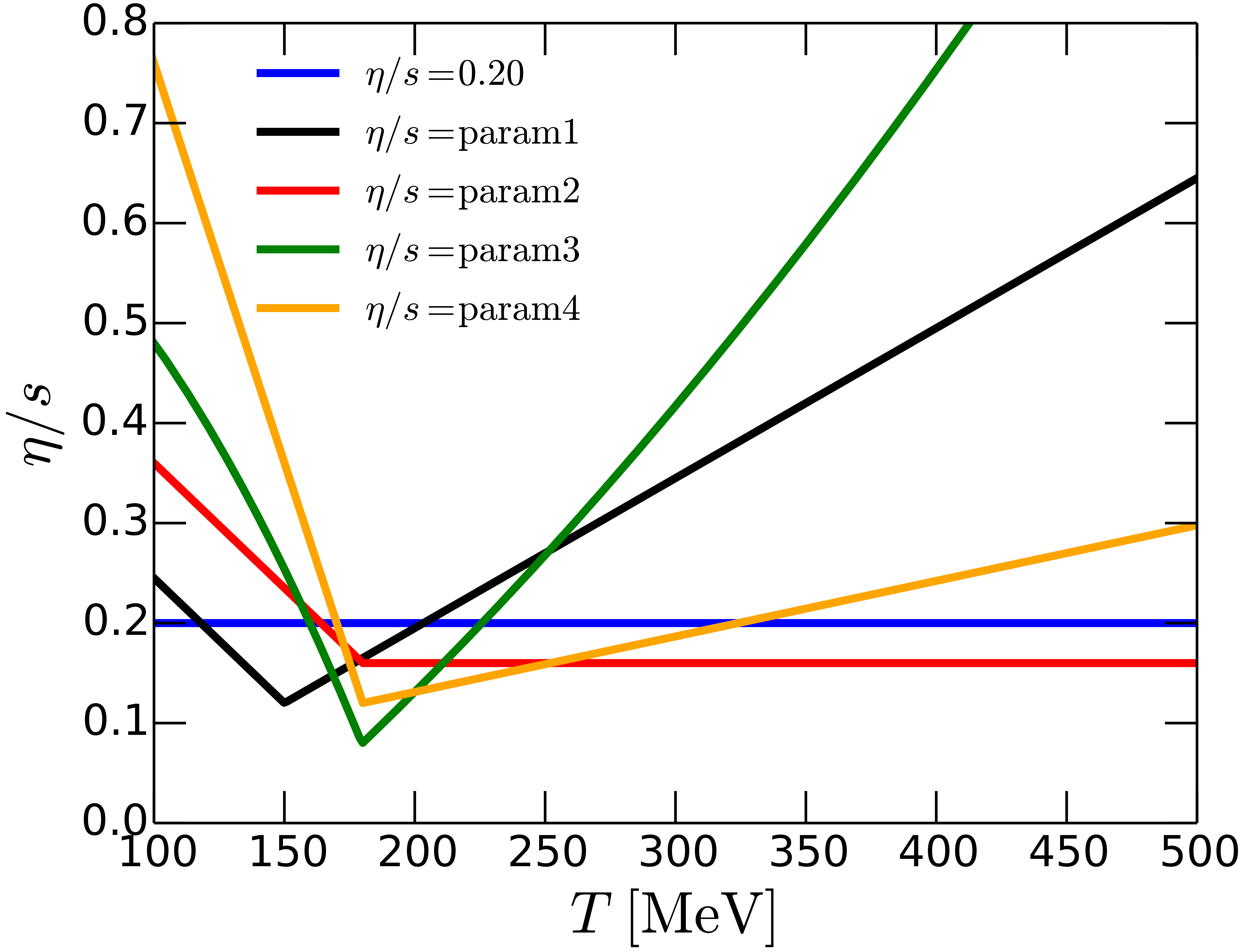


From study of the QGP signatures to that of the QCD phase diagram

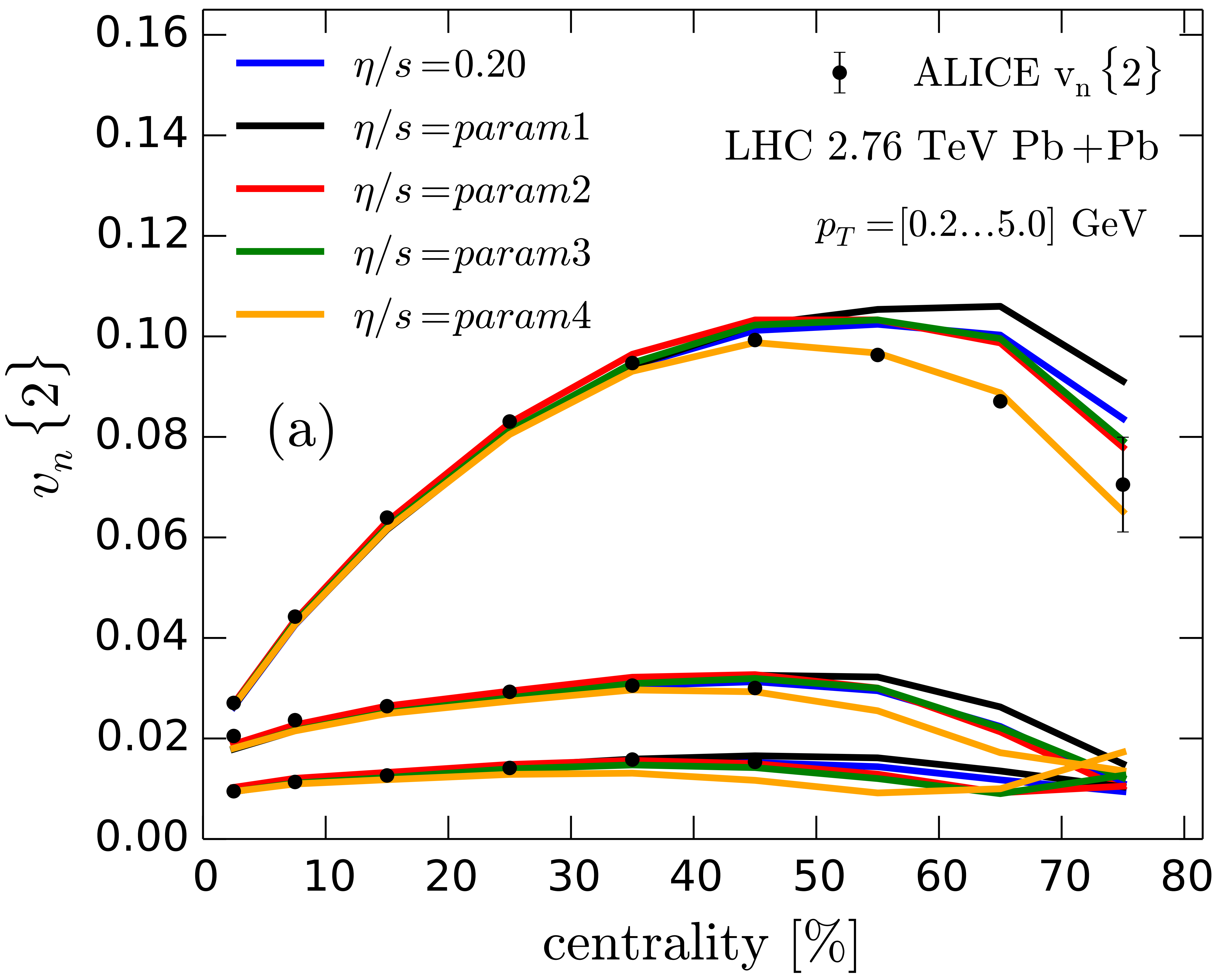
Flow harmonics correlations



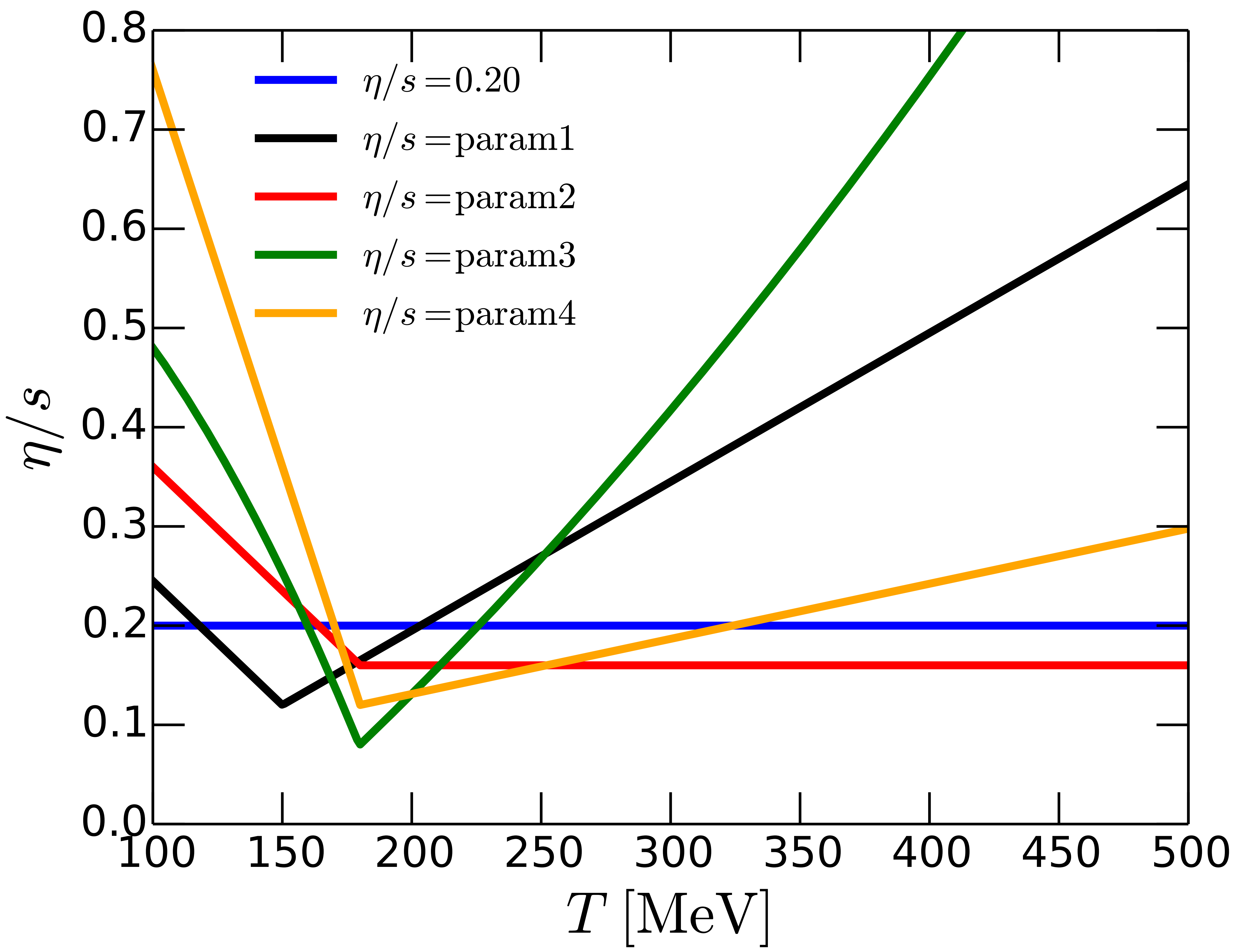
Flow harmonics correlations



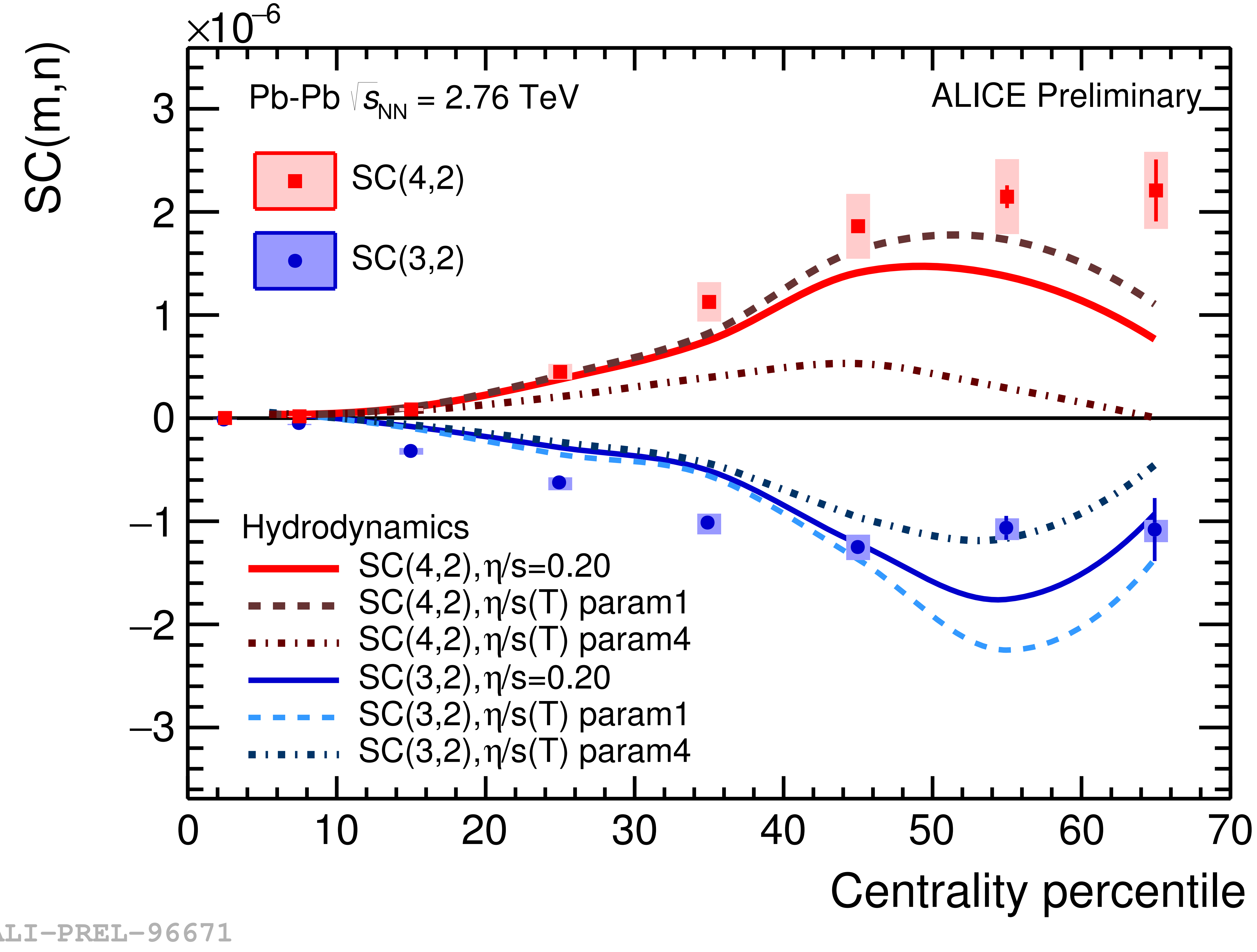
ALICE *Phys. Rev. Lett.* 107 (2011) 032301

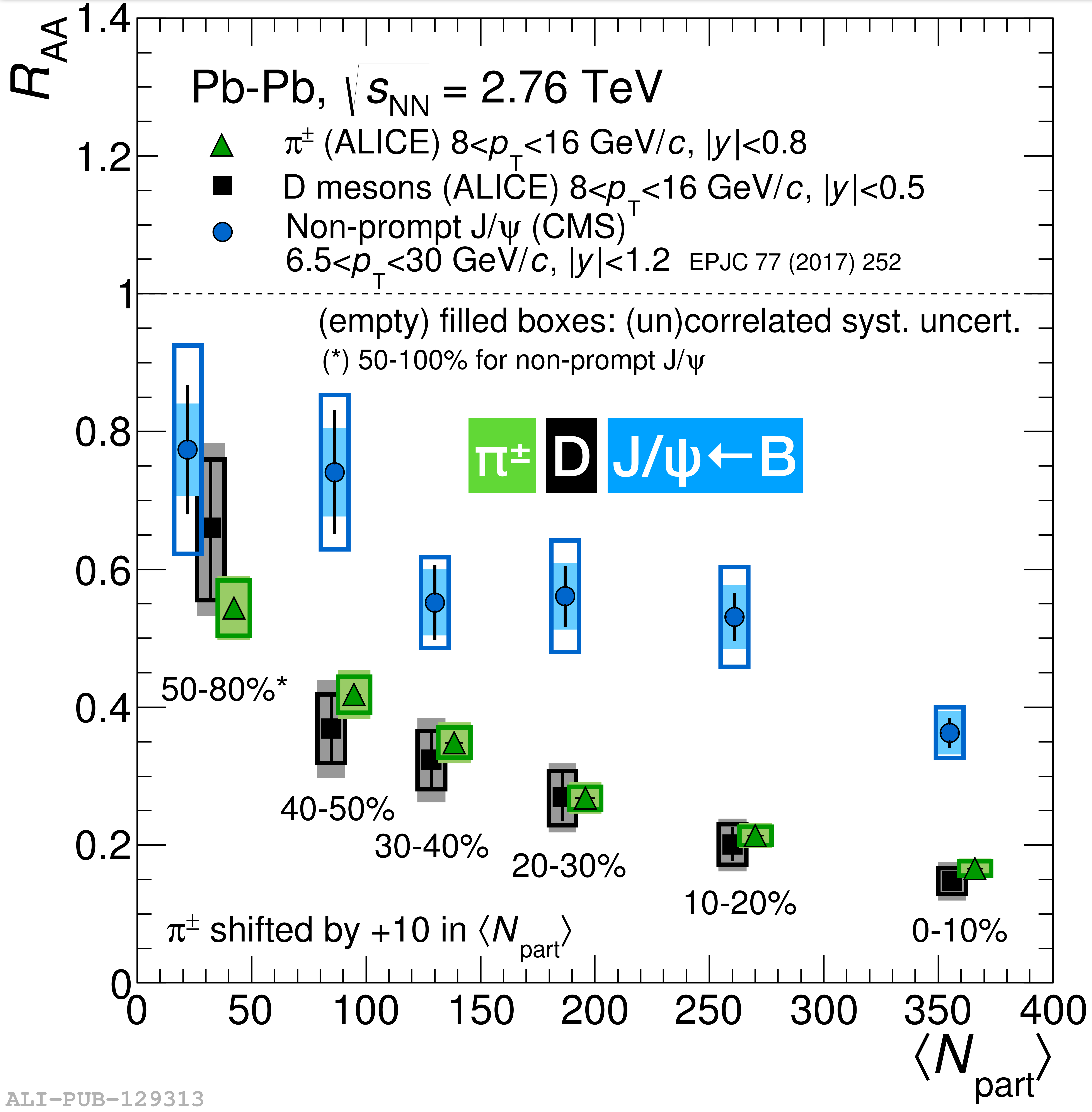


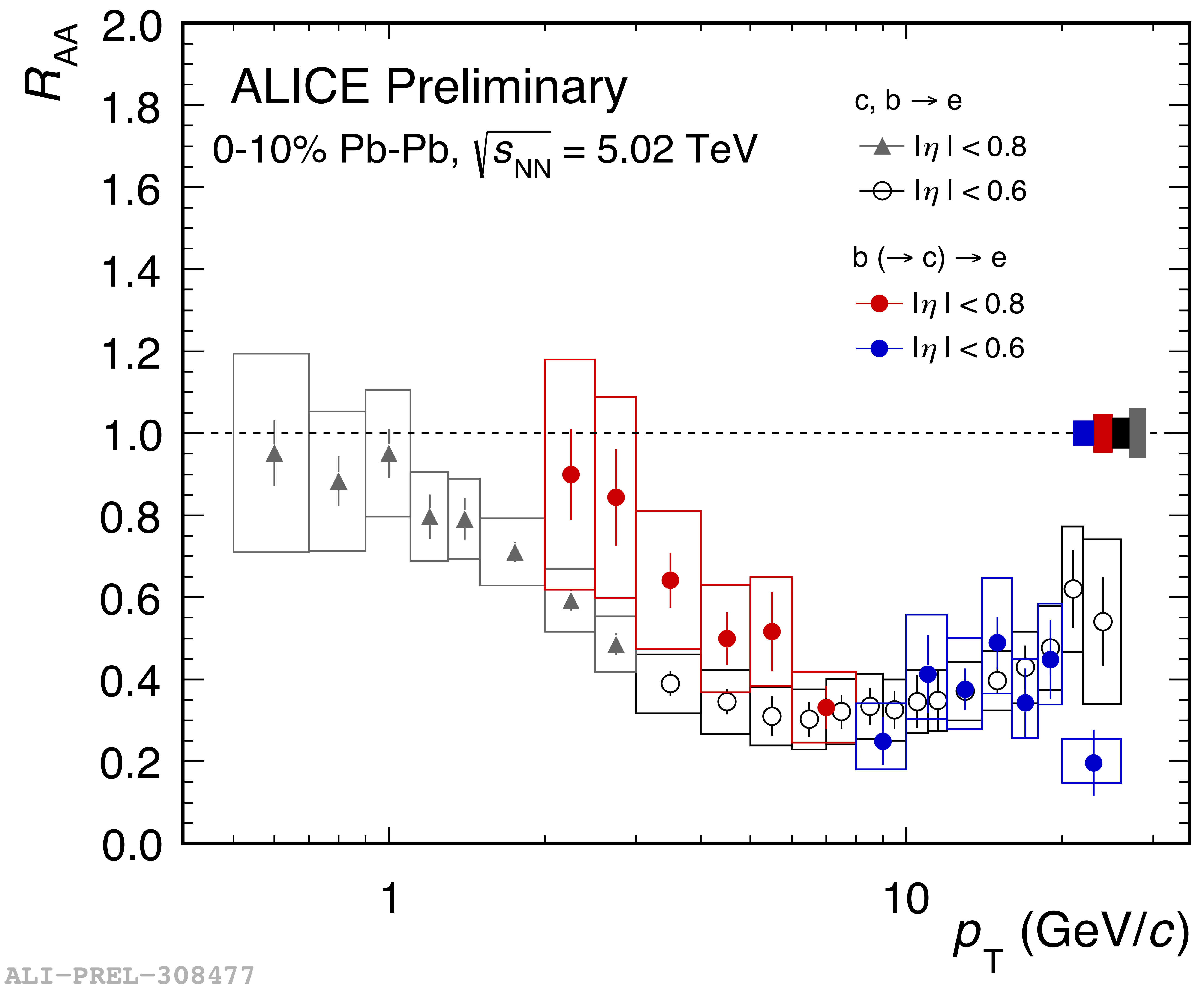
Flow harmonics correlations



$$SC(m,n) = < v_m^2 v_n^2 > - < v_m^2 >< v_n^2 >$$




Pb-Pb, √sNN = 2.76 TeV
π± (ALICE) 8<pT<16 GeV/c, |y|<0.8
D mesons (ALICE) 8<pT<16 GeV/c, |y|<0.5
Non-prompt J/ψ (CMS) 6.5<pT<30 GeV/c, |y|<1.2 EPJC 77 (2017) 252
(empty) filled boxes: (un)correlated syst. uncert.
(*) 50-100% for non-prompt J/ψ
π± D J/ψ←B
50-80%*
40-50%
30-40%
20-30%
10-20%
0-10%
π± shifted by +10 in ⟨Npart⟩
RAA
⟨Npart⟩
ALI-PUB-129313


ALICE Preliminary
0-10% Pb-Pb, √sNN = 5.02 TeV
c, b → e
|η| < 0.8
|η| < 0.6
b (→ c) → e
|η| < 0.8
|η| < 0.6
RAA
pT (GeV/c)
ALI-PREL-308477

Particle production in small systems

ALICE *Phys. Rev. Lett.* **122 (2019) 072301**