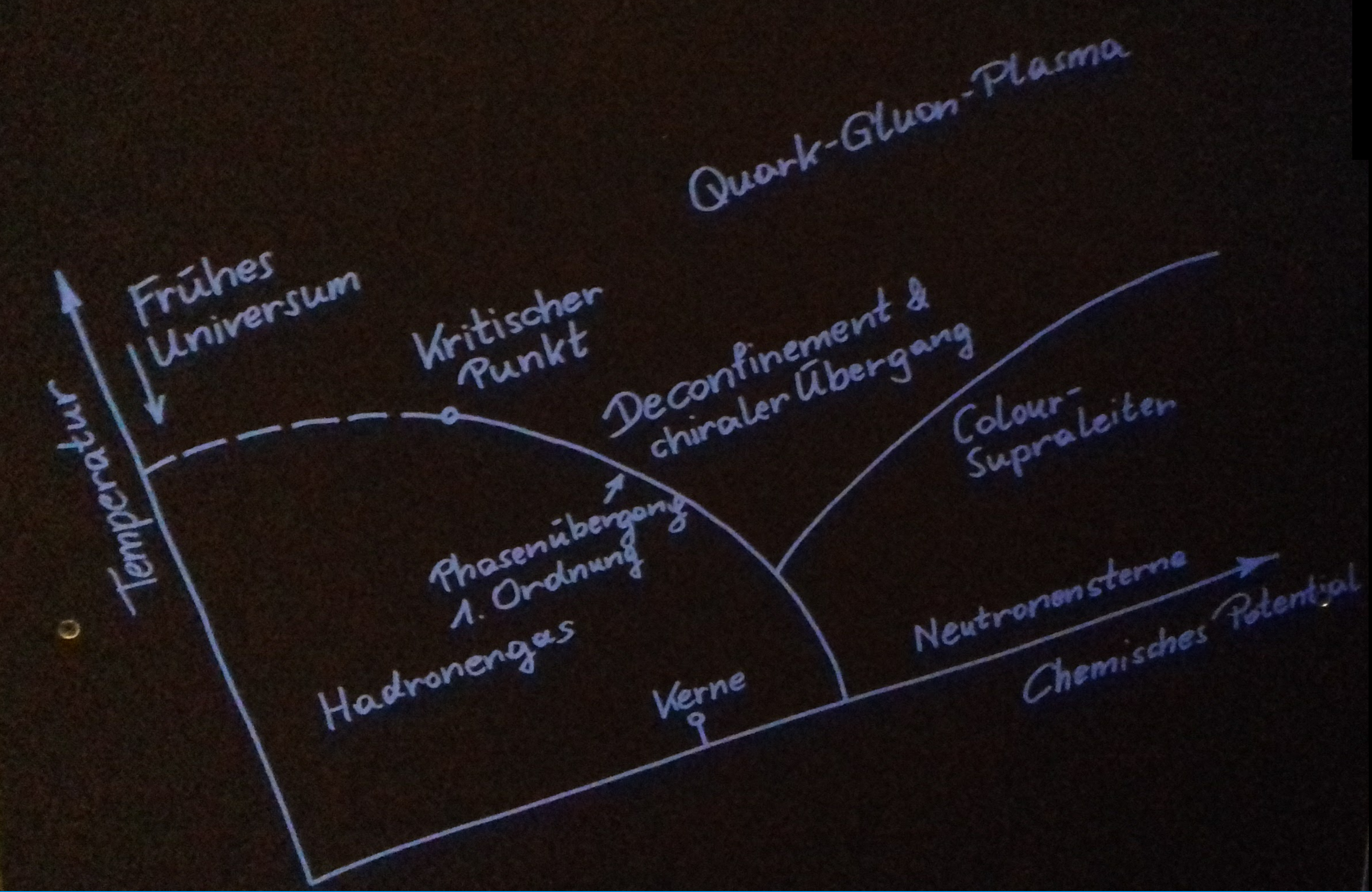
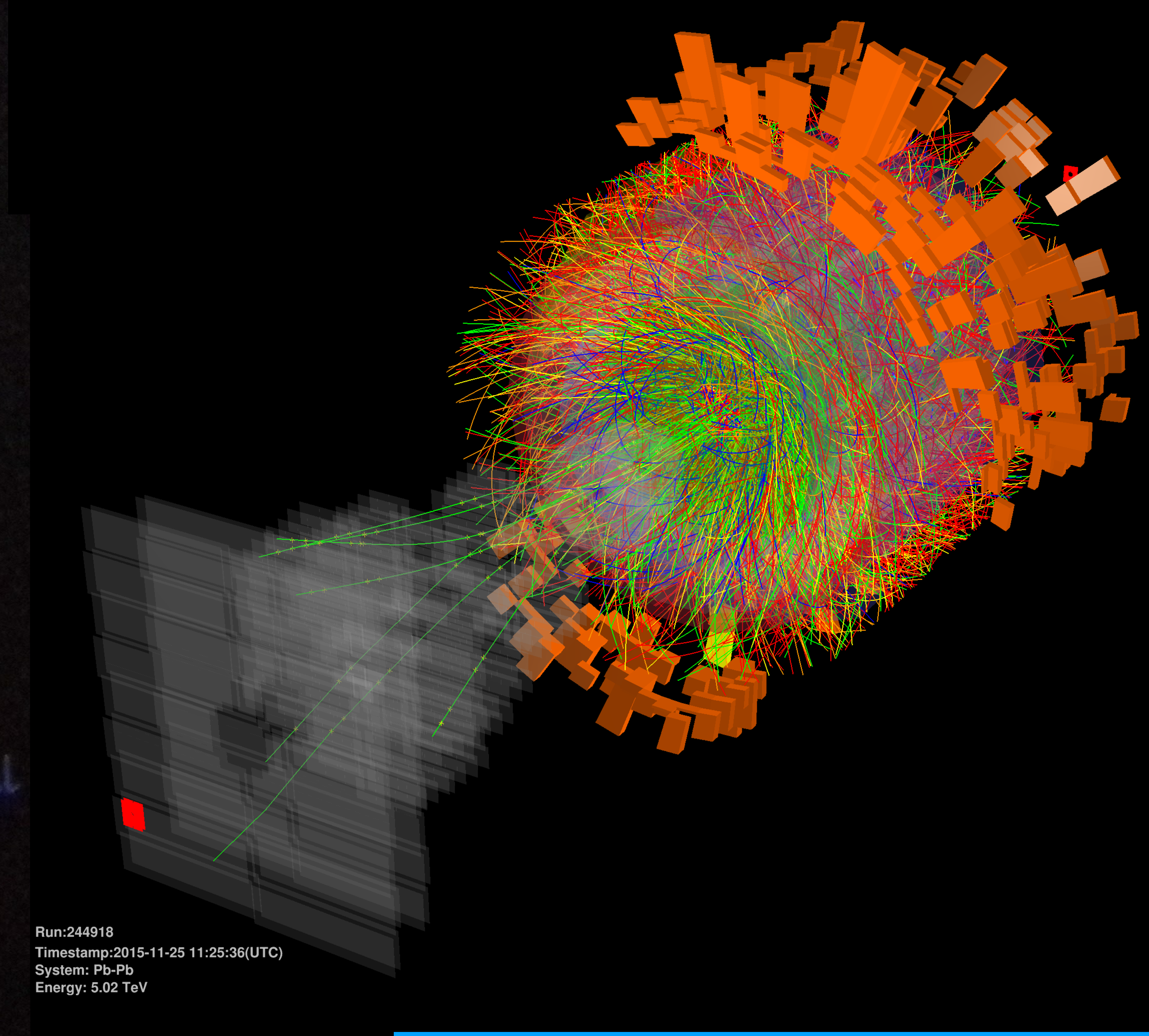
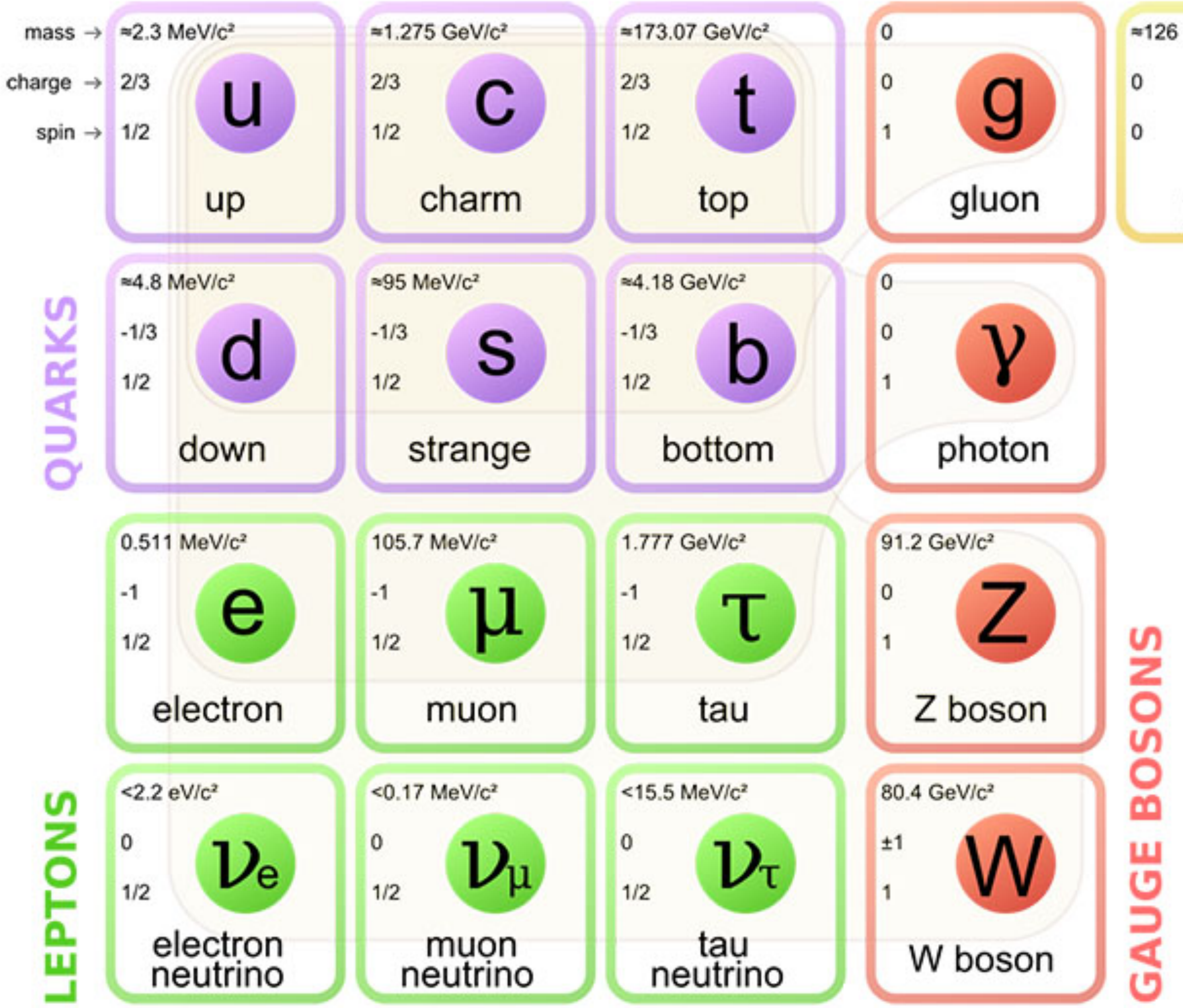


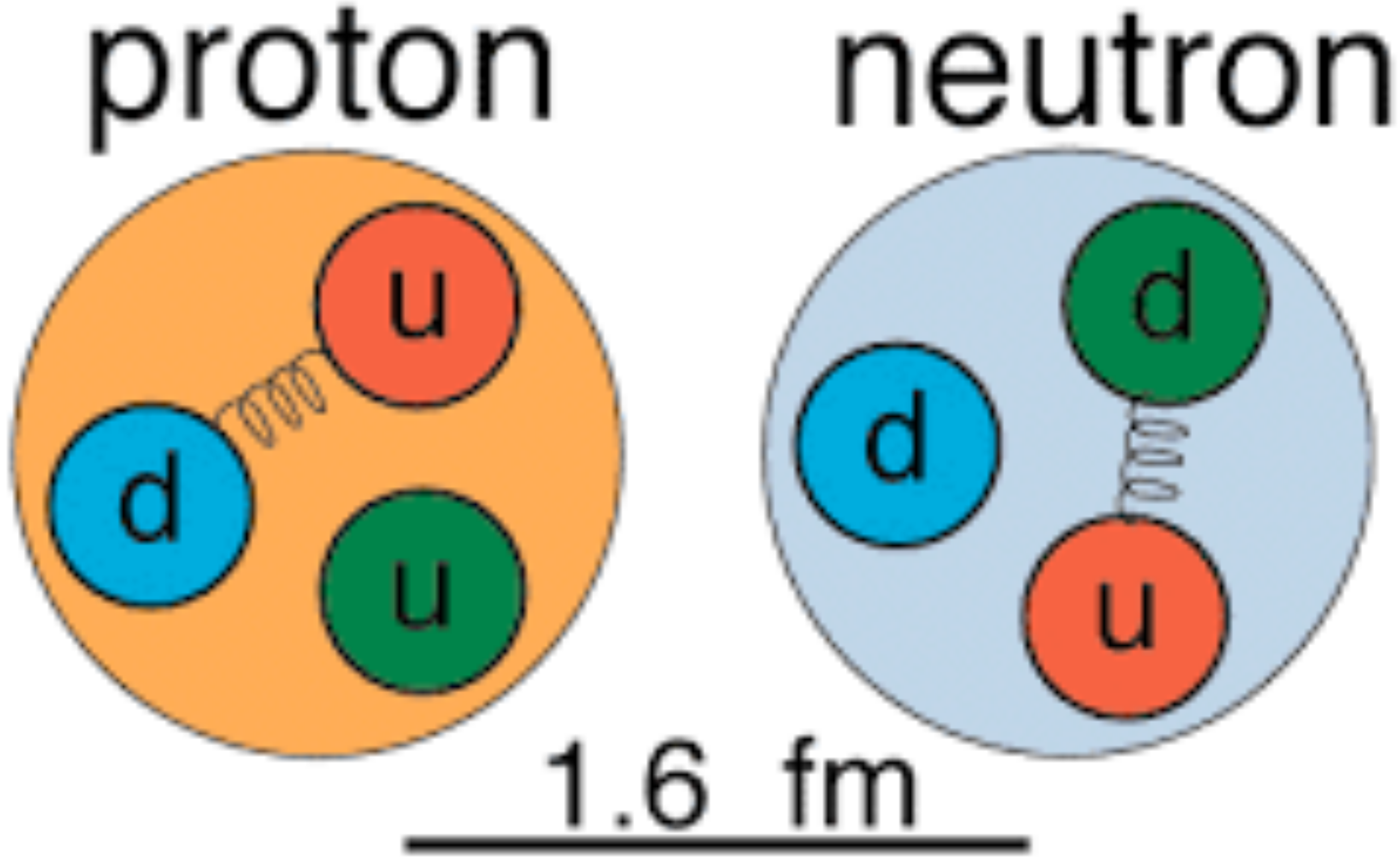


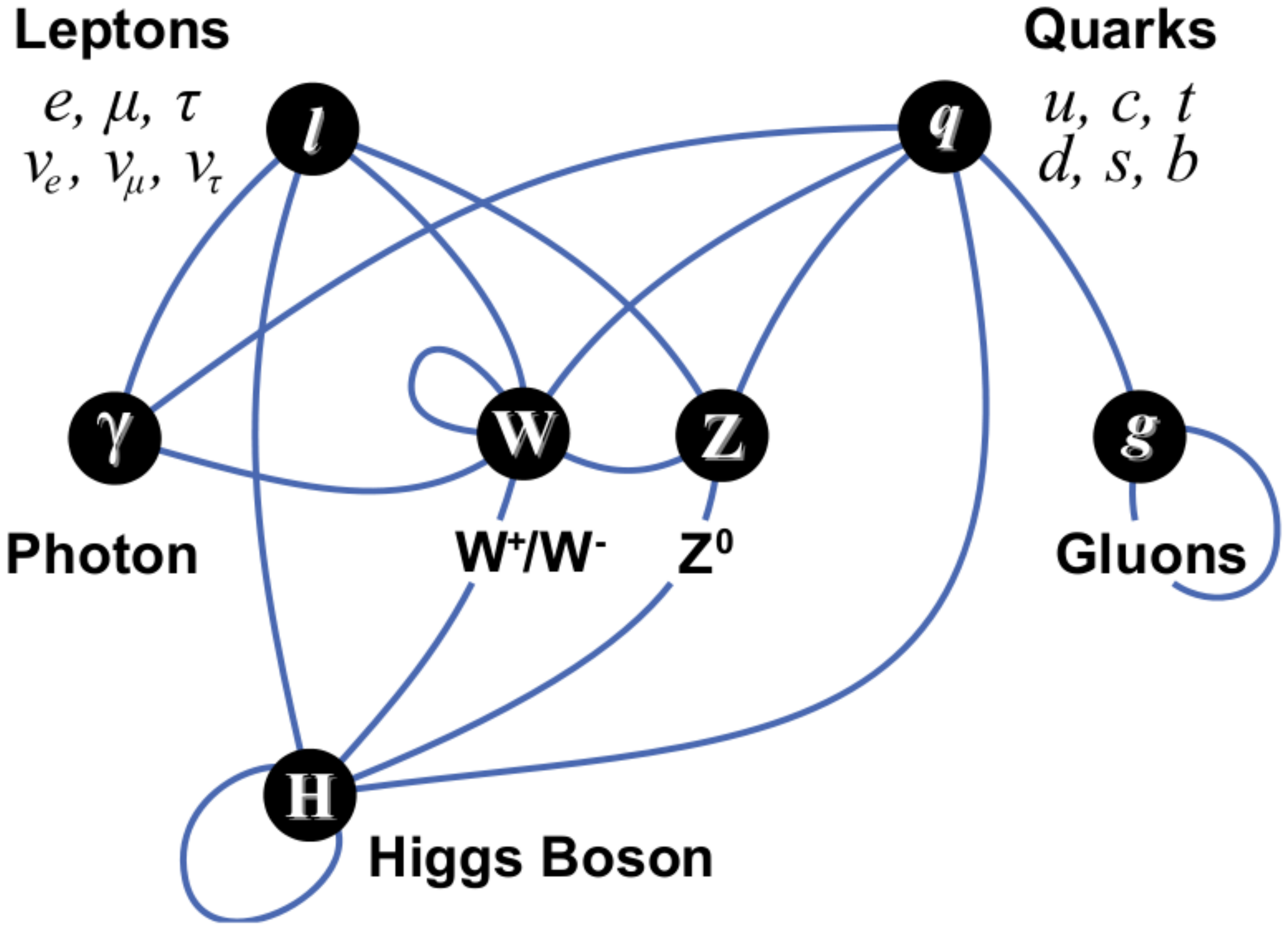
Xiaoming Zhang

Brief introduction of ultra-relativistic heavy-ion collisions

Standard model particles





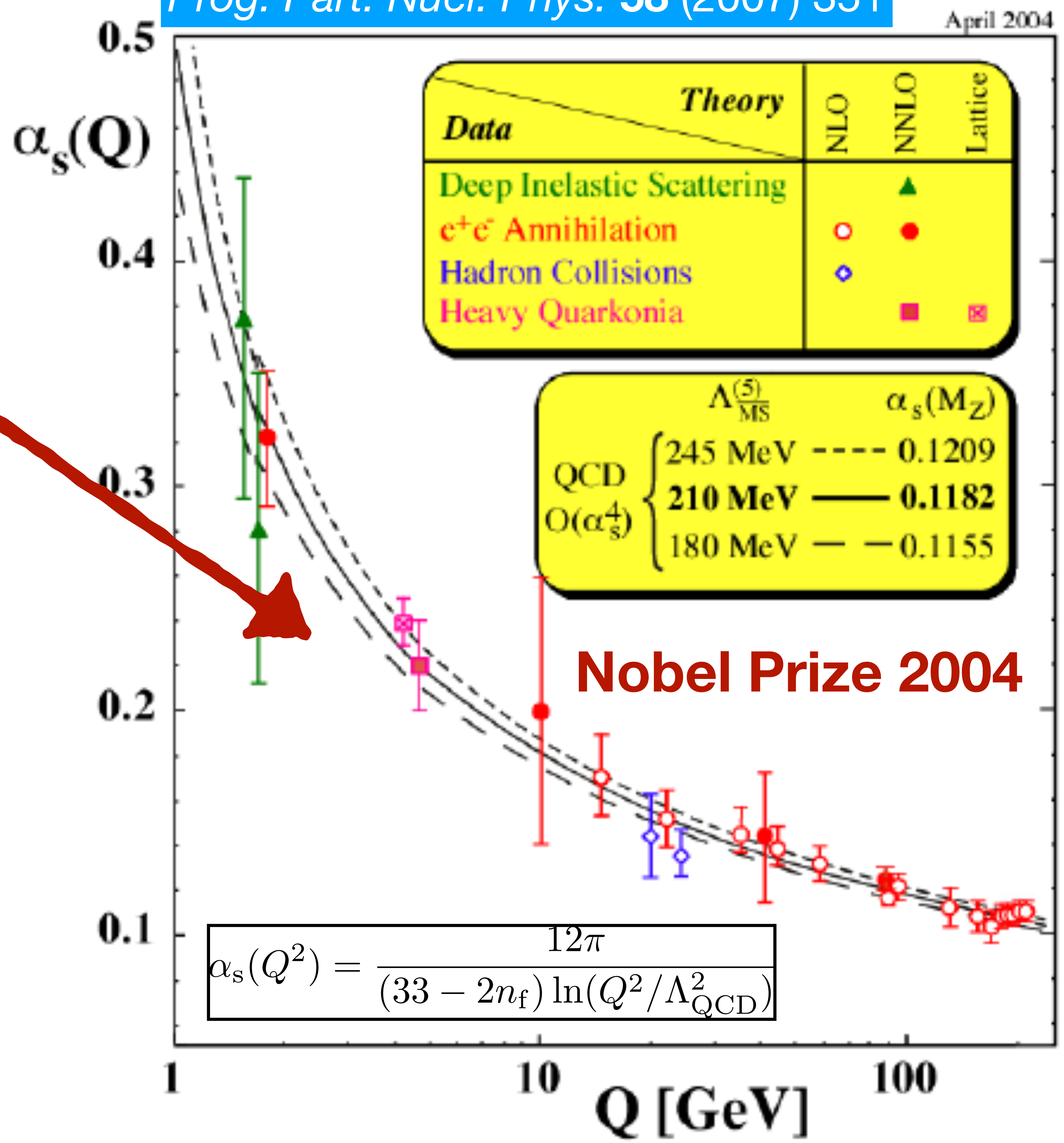


Strong nuclear force

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

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

Prog. Part. Nucl. Phys. **58** (2007) 351



Nobel Prize 2004

Strong nuclear force

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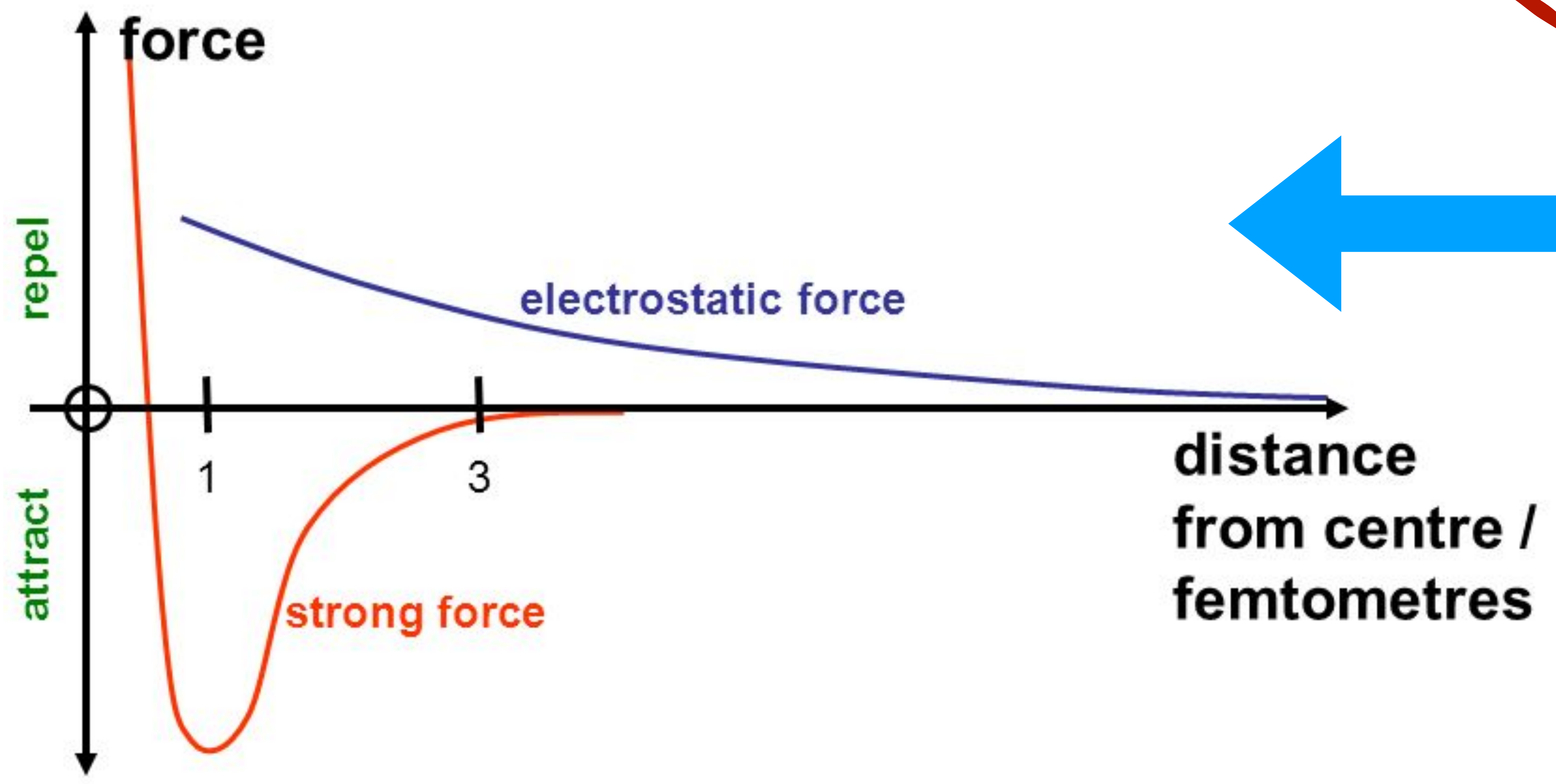
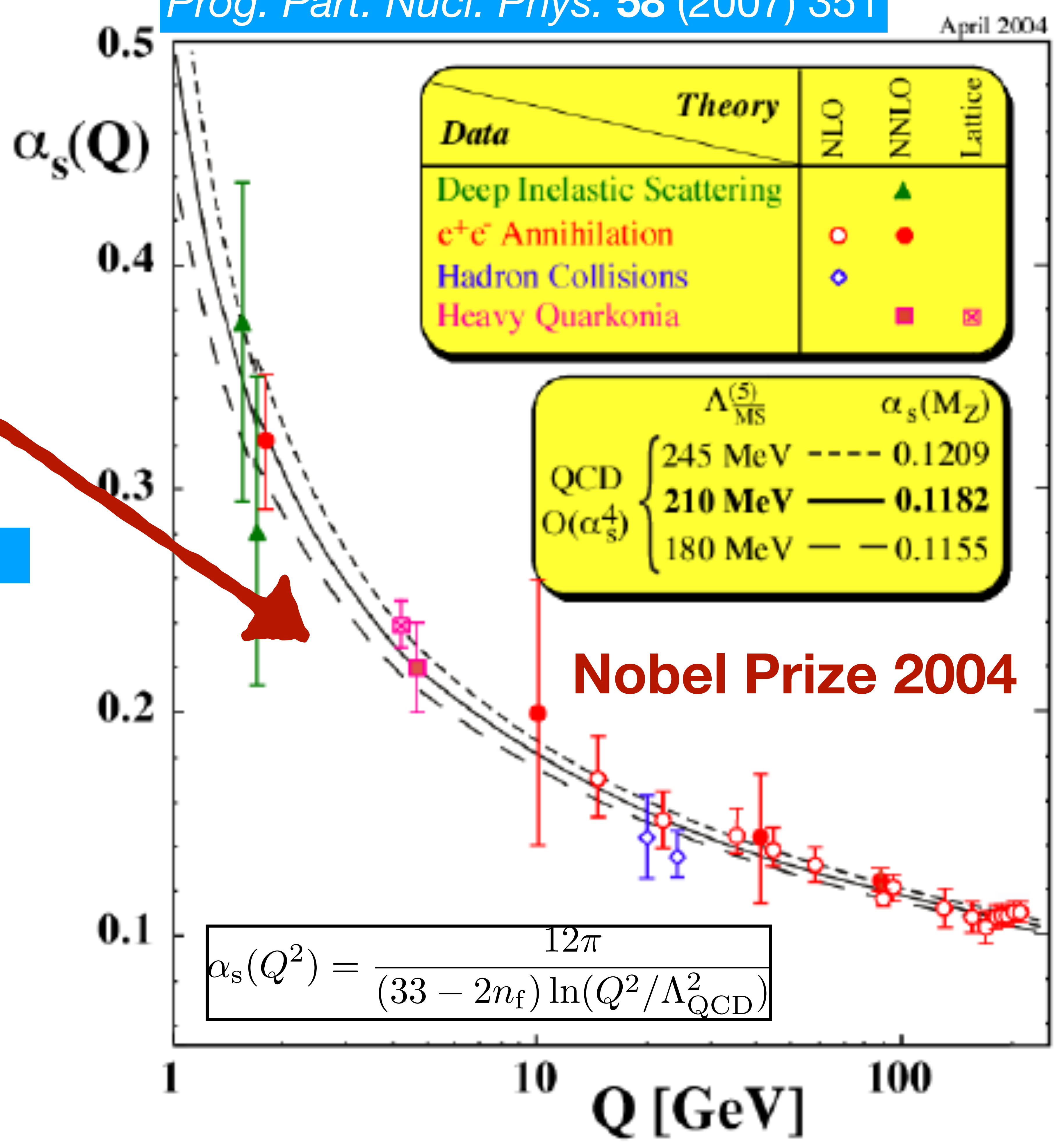


Prog. Part. Nucl. Phys. **58** (2007) 351



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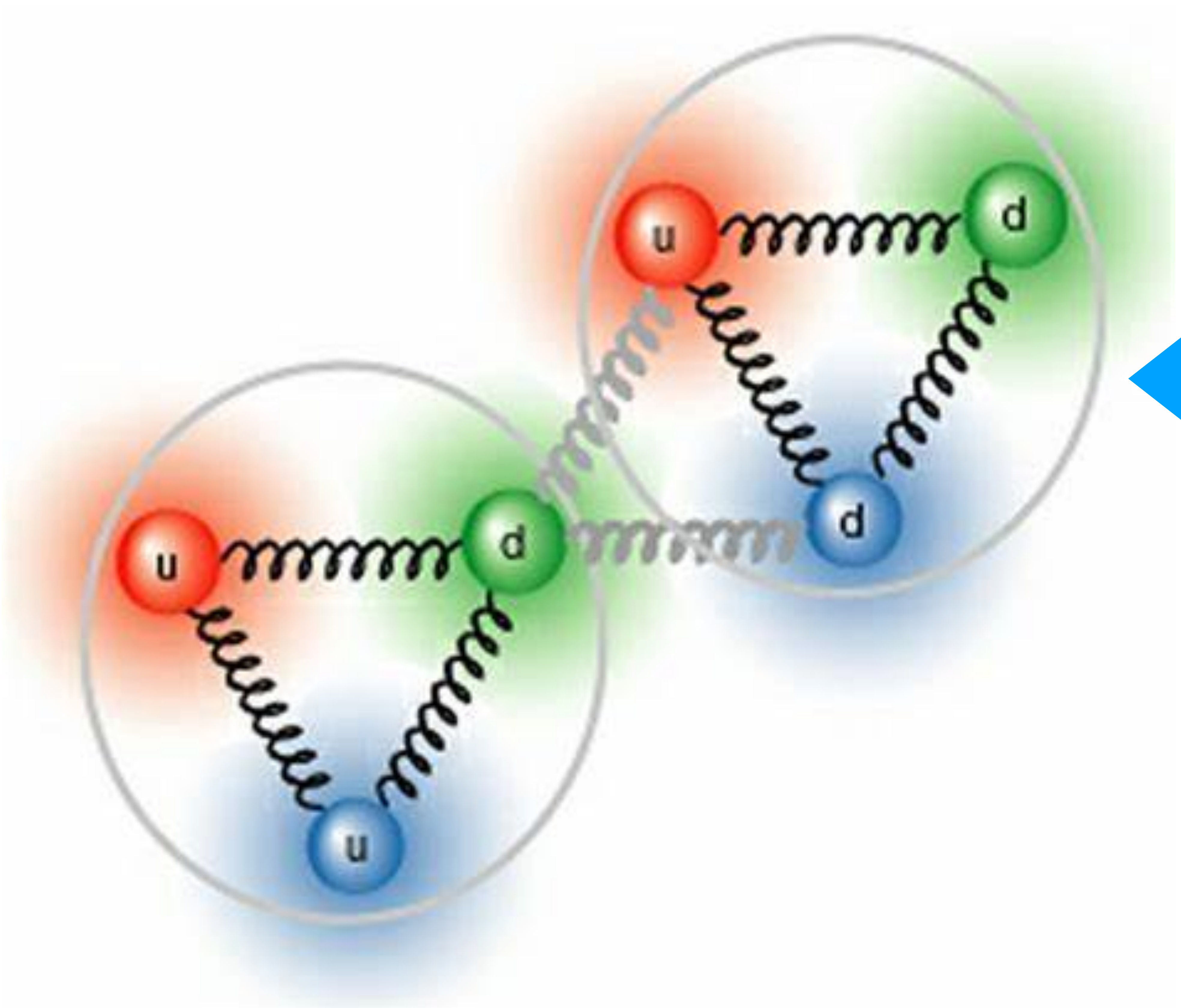
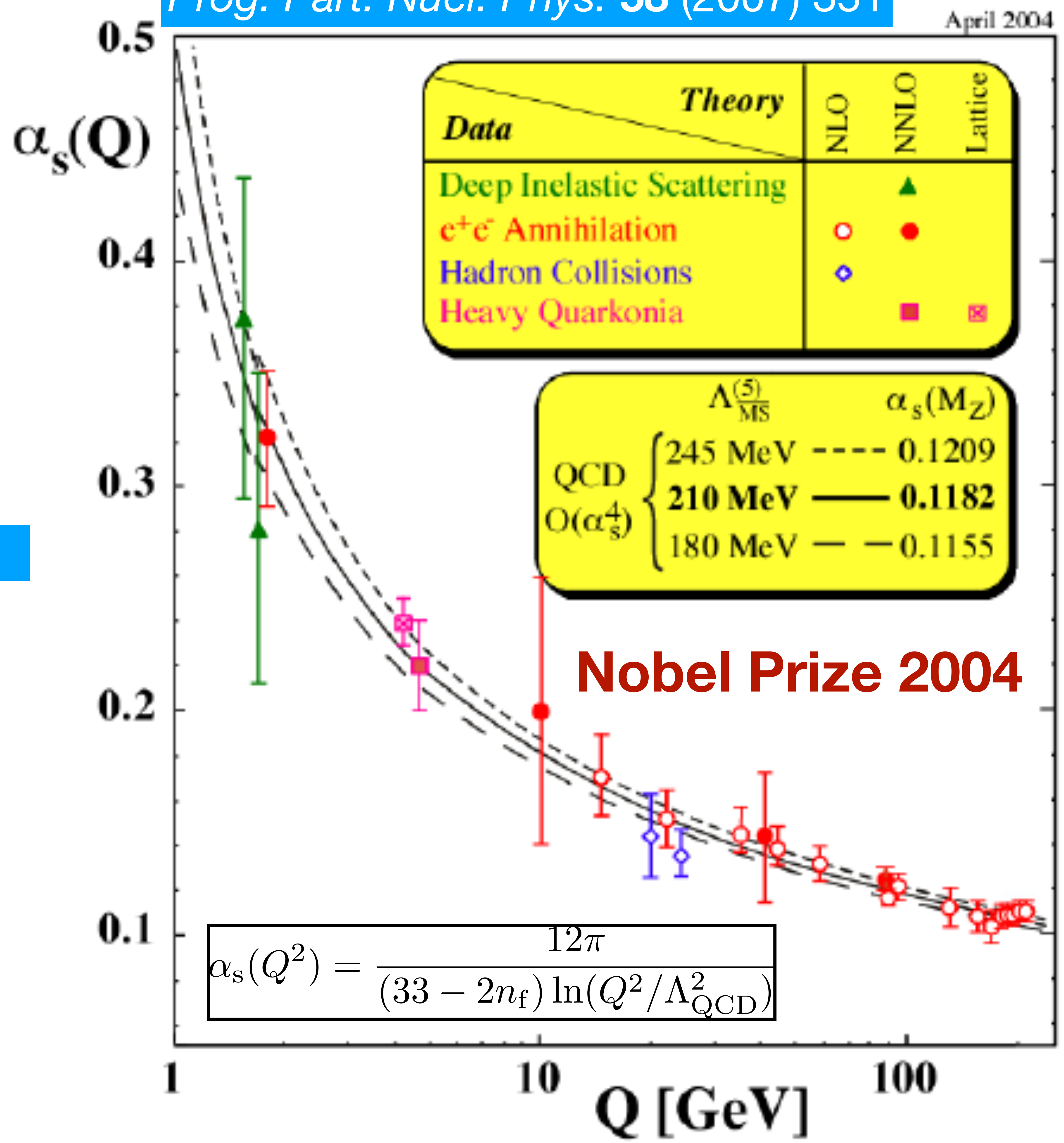


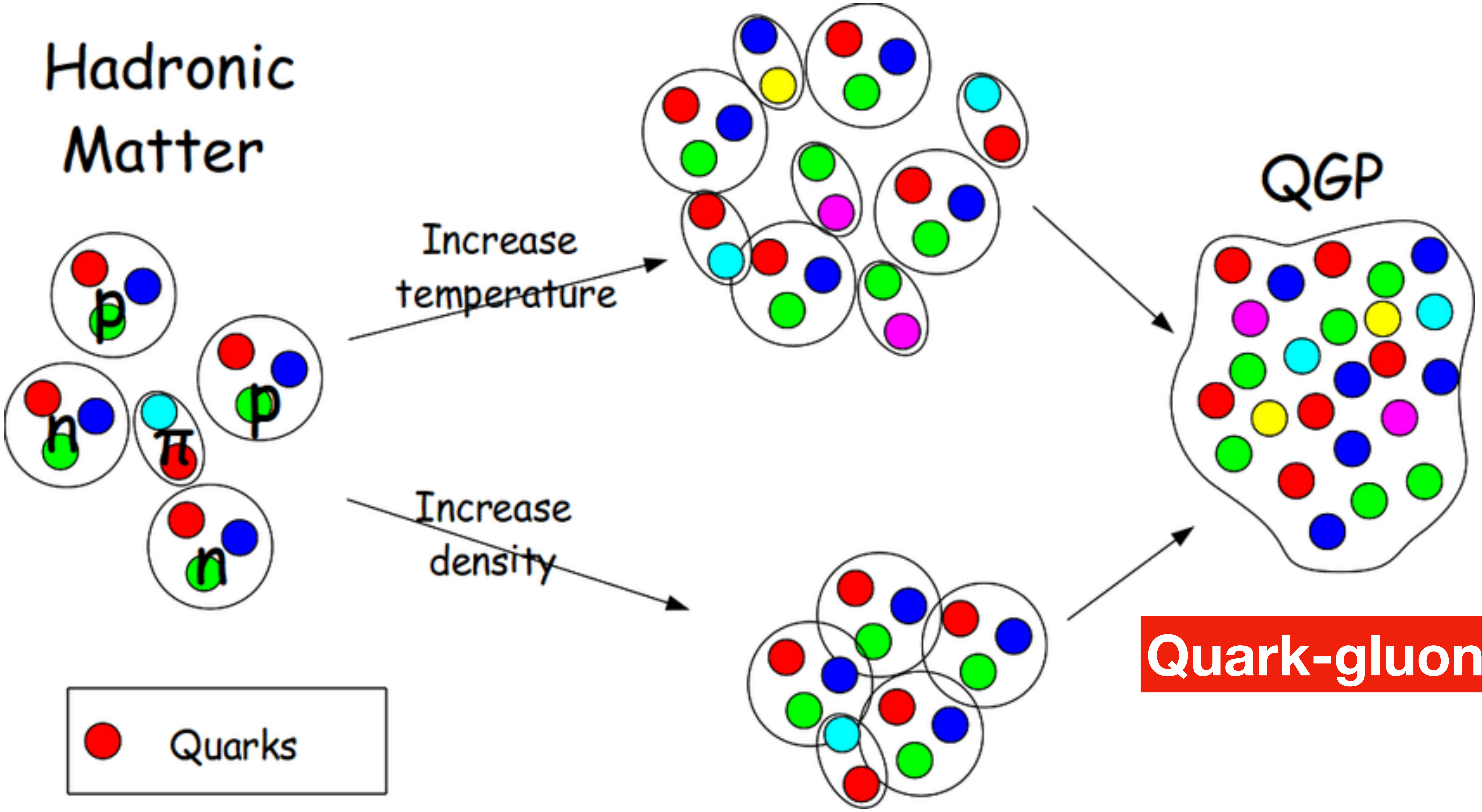
Prog. Part. Nucl. Phys. **58** (2007) 351



QCD phase transition

QCD running coupling constant

- Quark confinement and asymptotic freedom



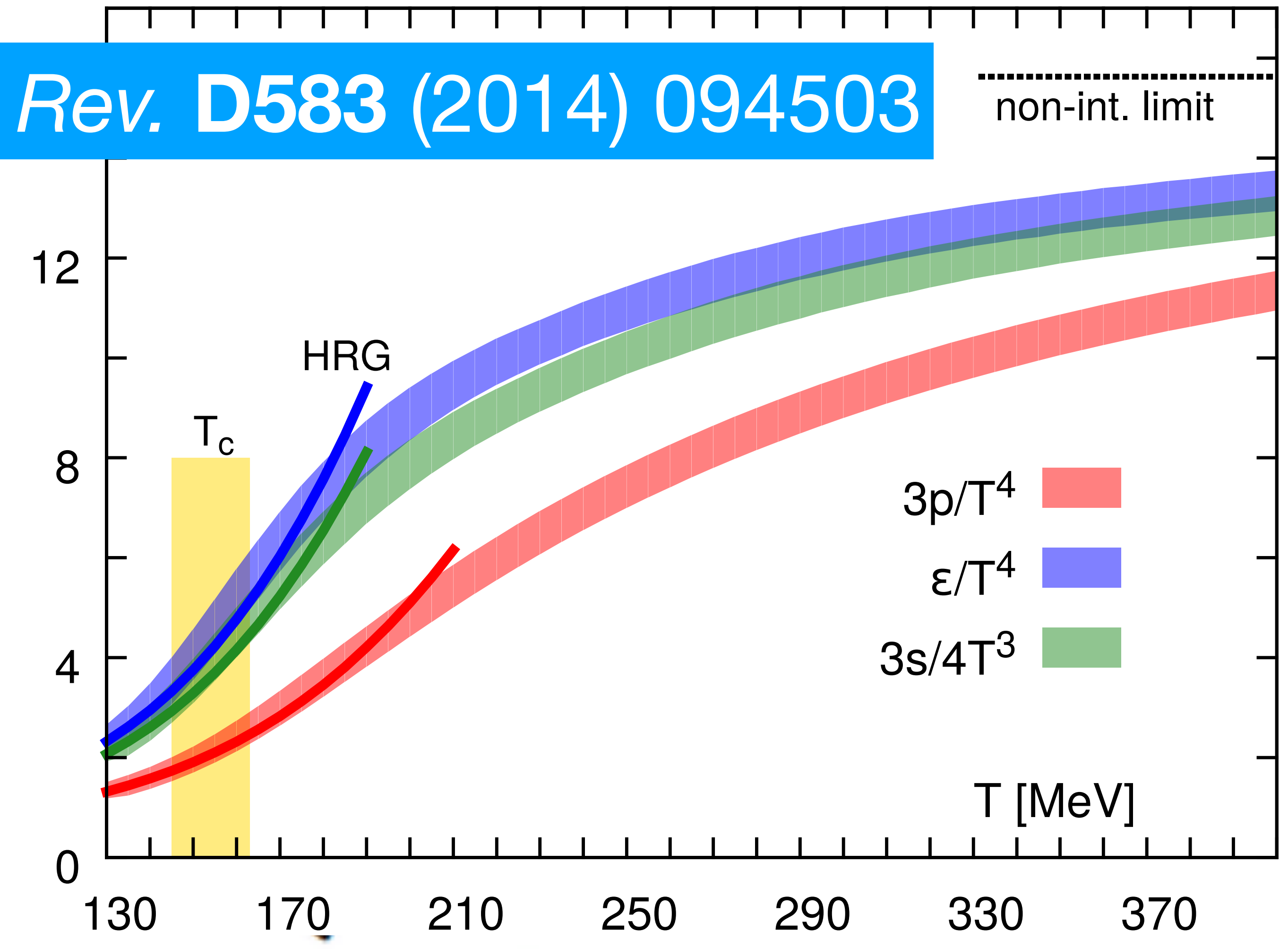
Quark-gluon plasma (QGP)

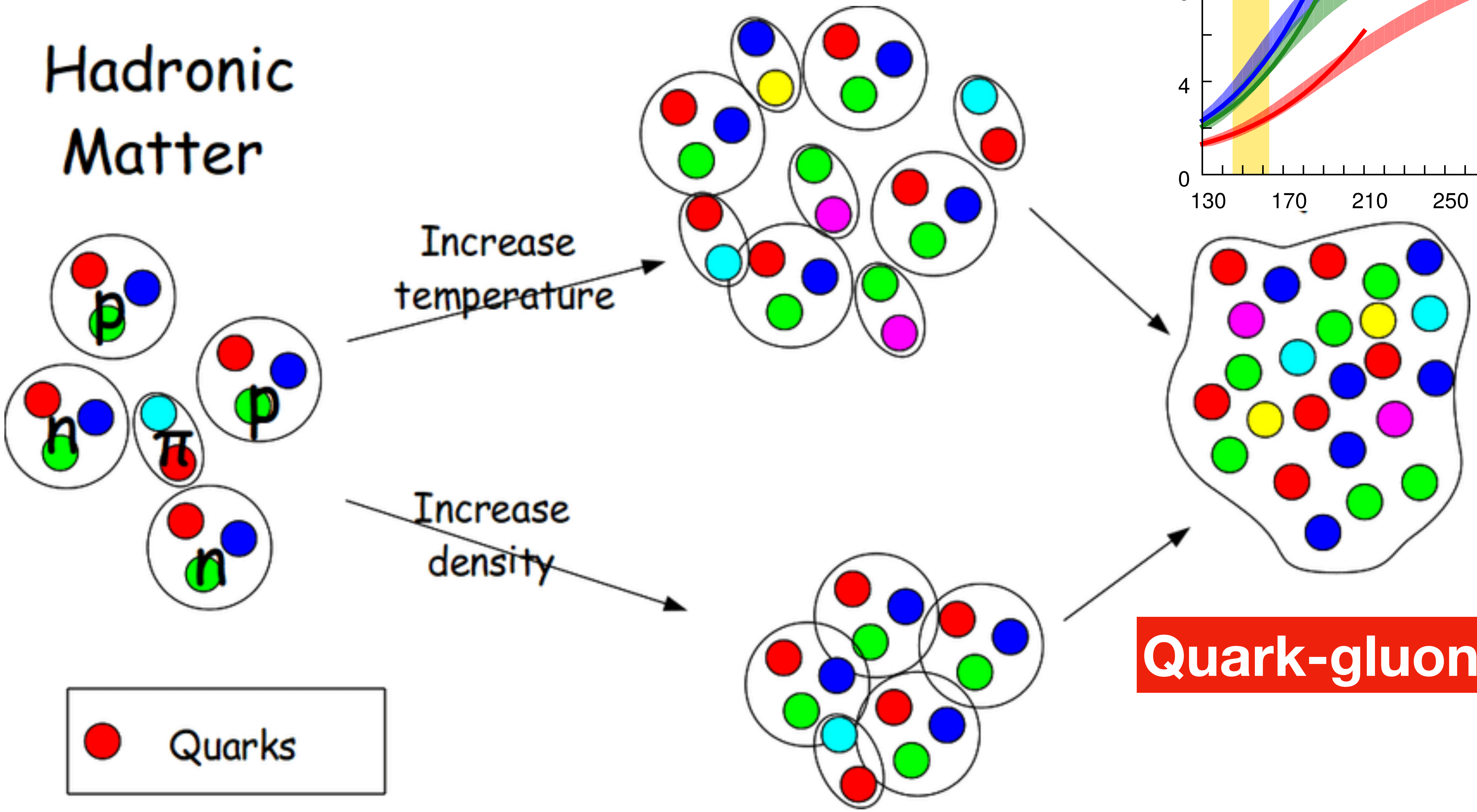
QCD phase transition

QCD running coupling constant

- Quark confinement and asymptotic freedom

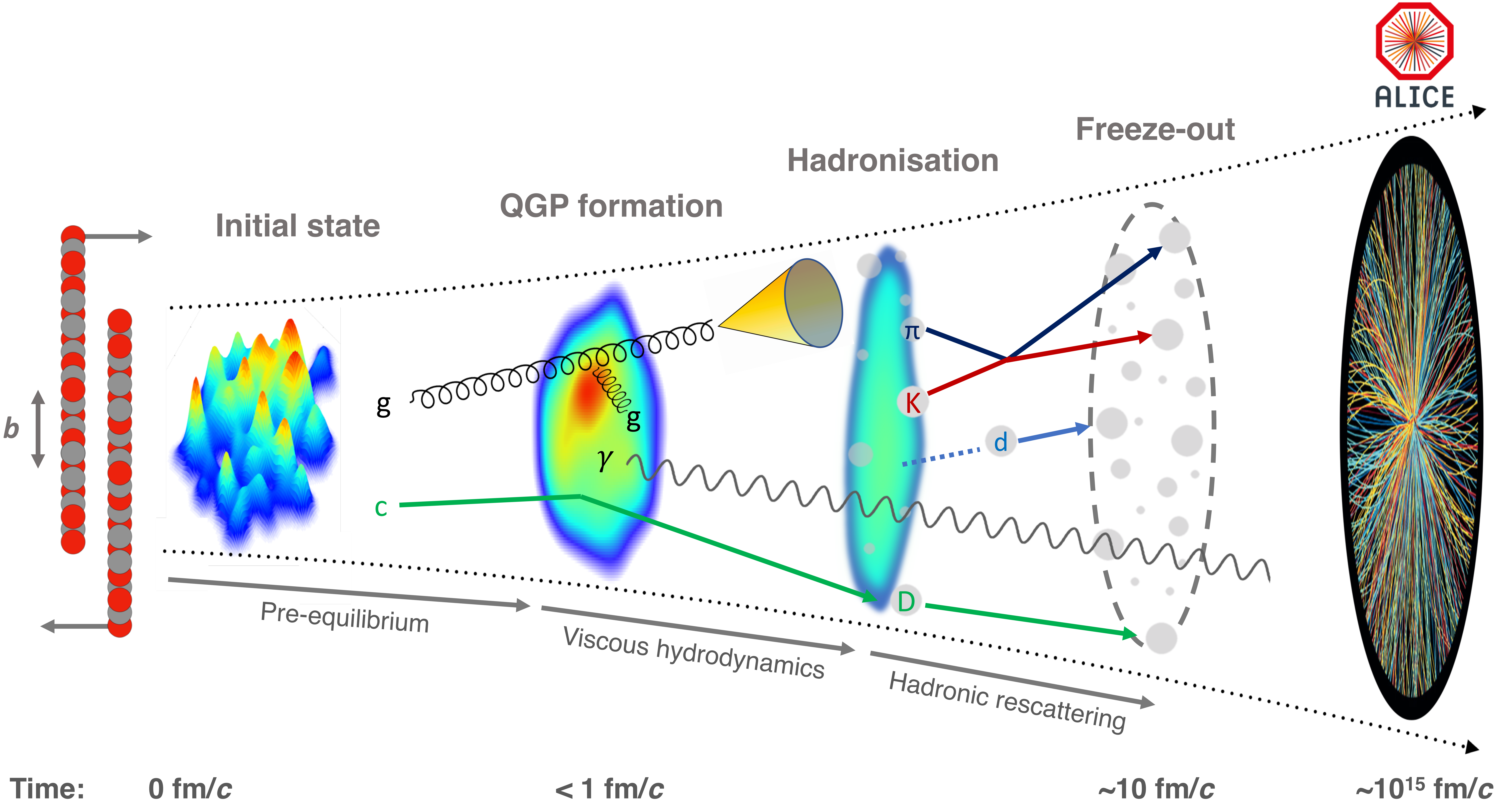
Phys. Rev. **D583** (2014) 094503



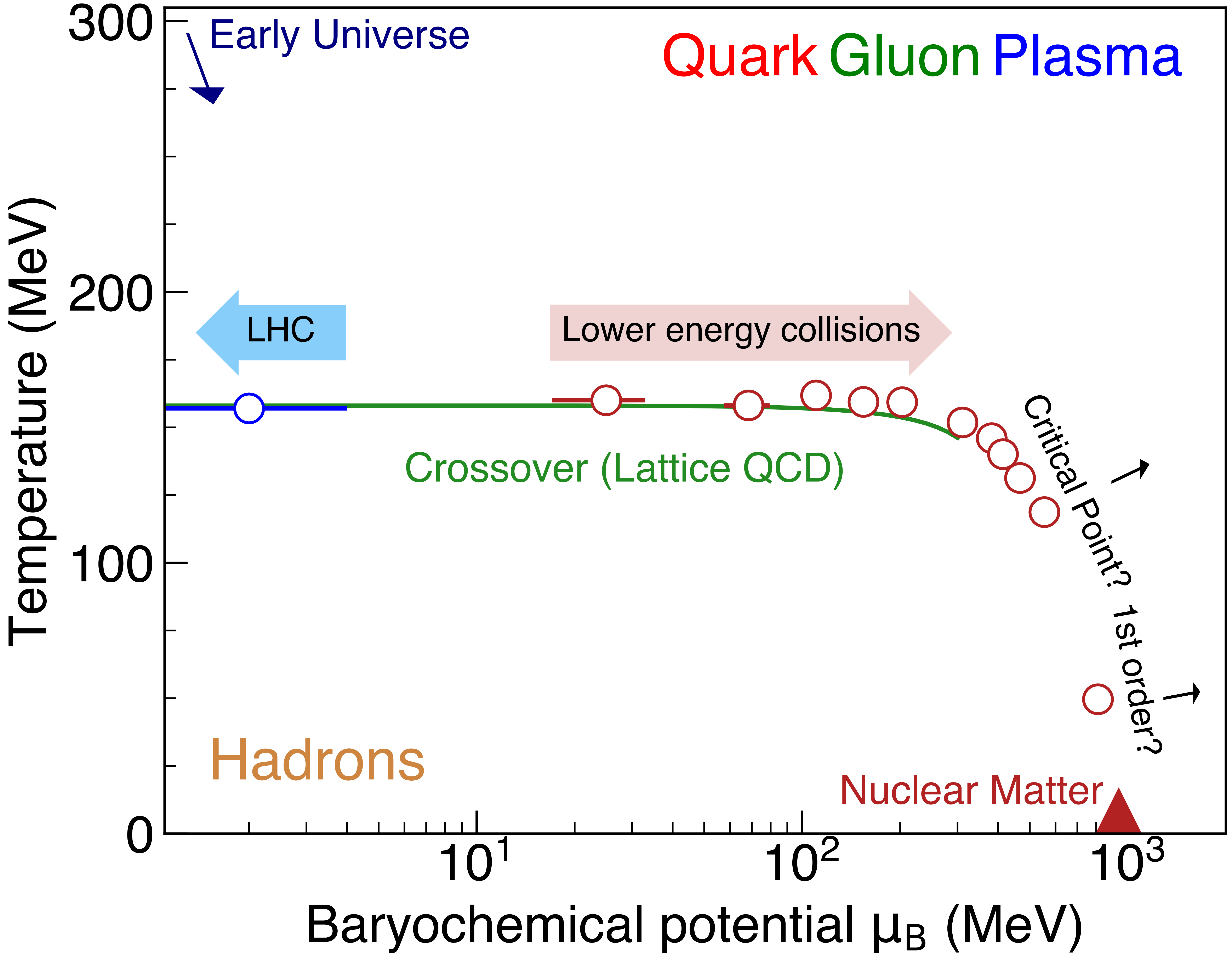


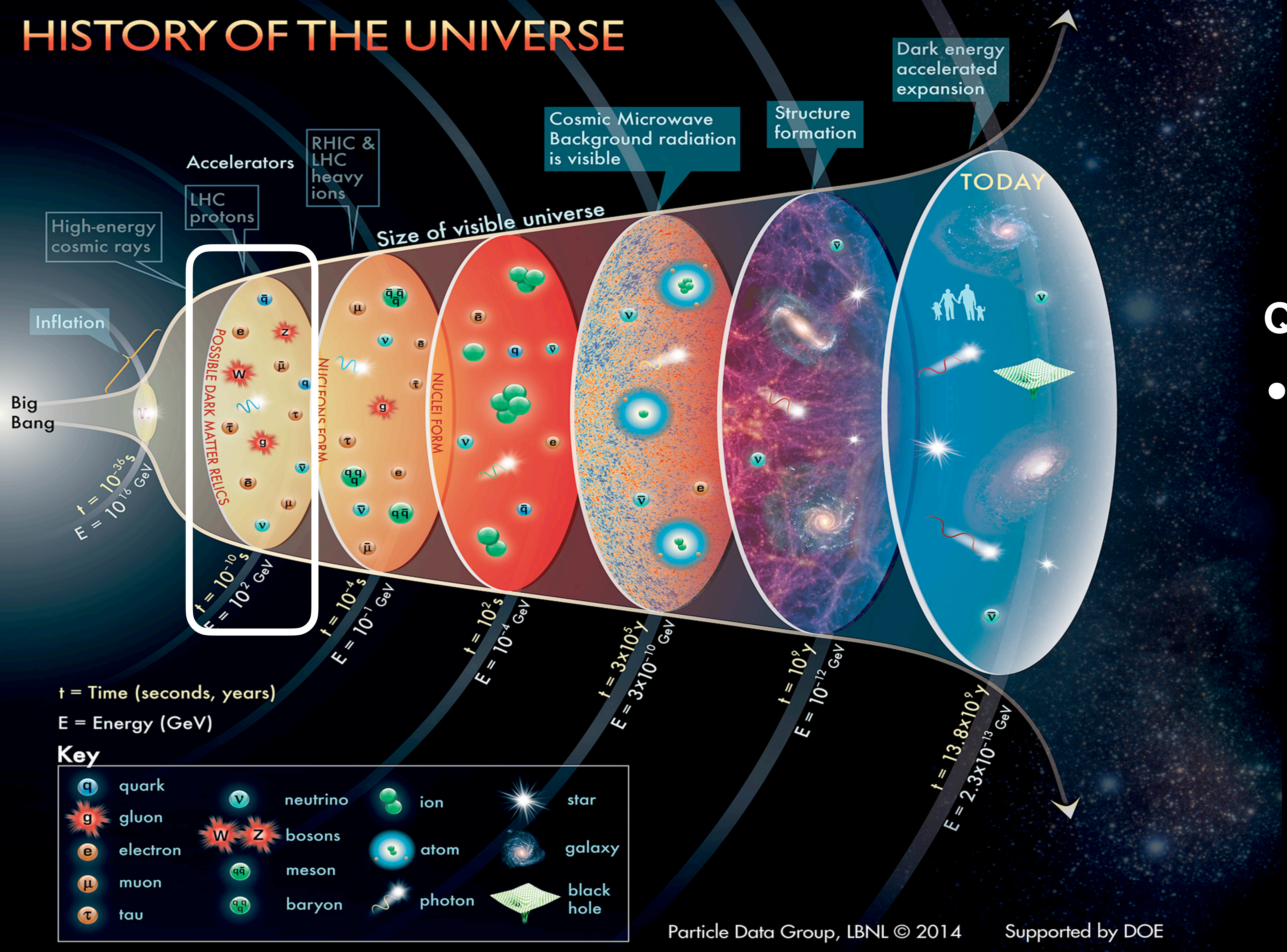
Quark-gluon plasma (QGP)

Heavy-ion collisions



QCD phase diagram



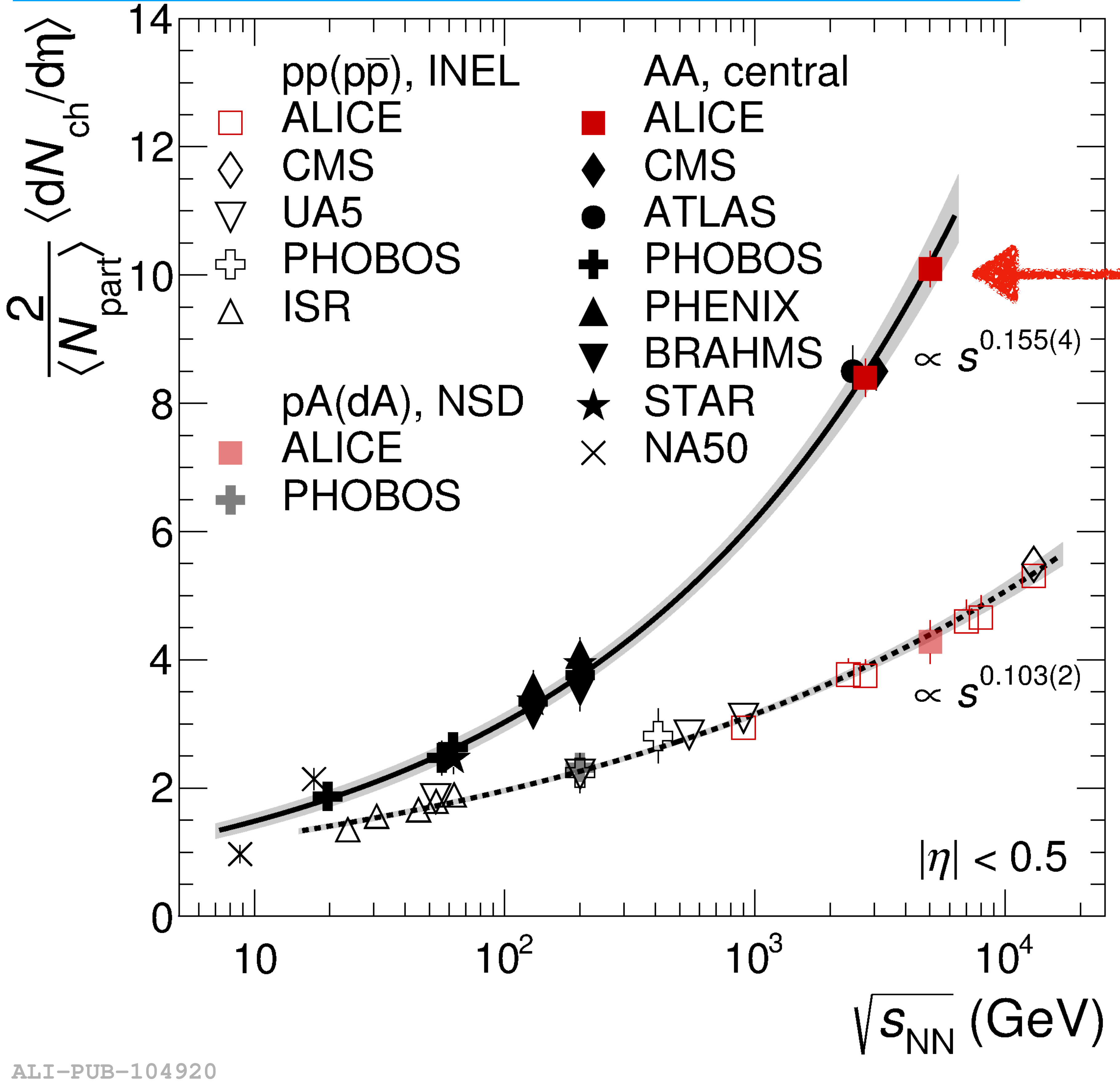


Quark-gluon plasma

- The earliest known state of matter in the Universe

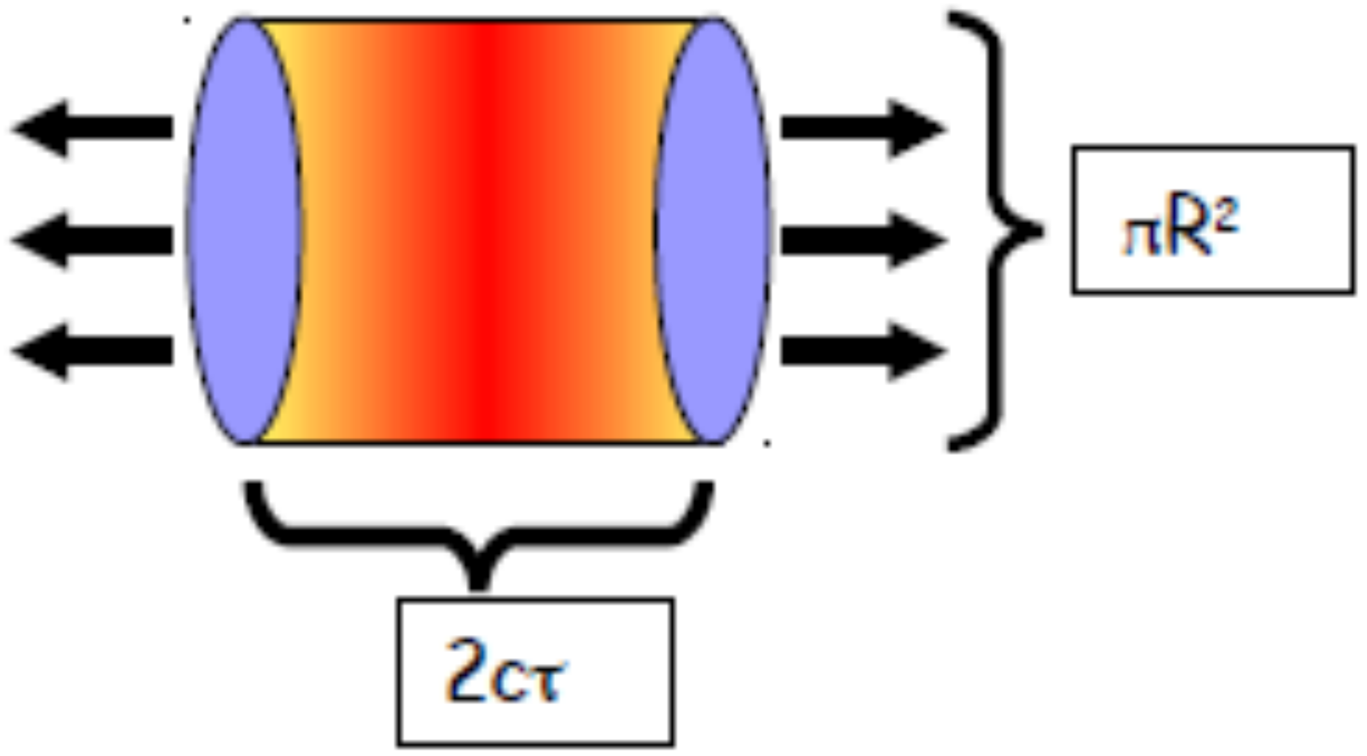
Charged-particle multiplicity

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



ALICE Pb–Pb at 5.02 TeV

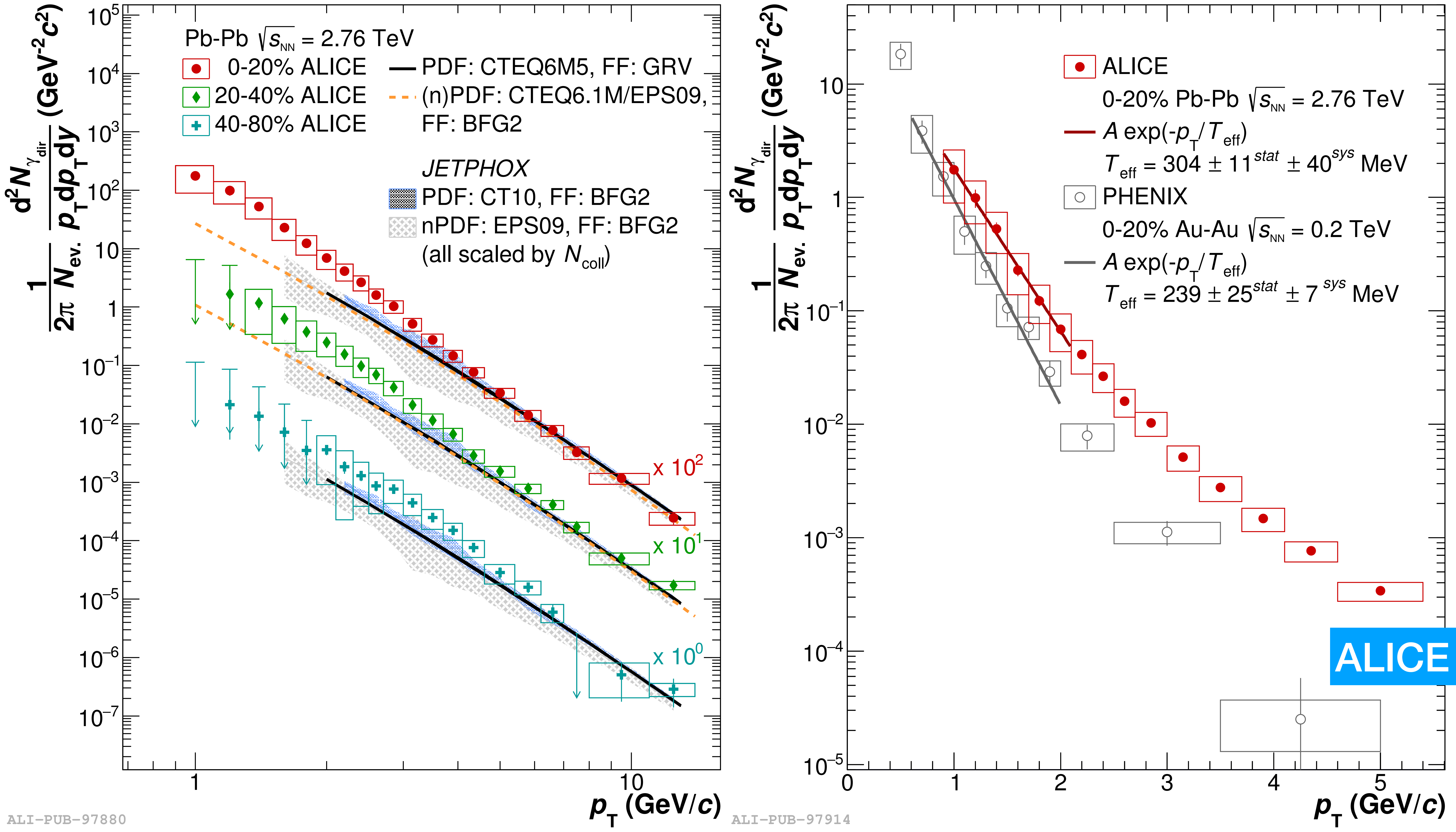
Bjorken estimate:



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

- 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

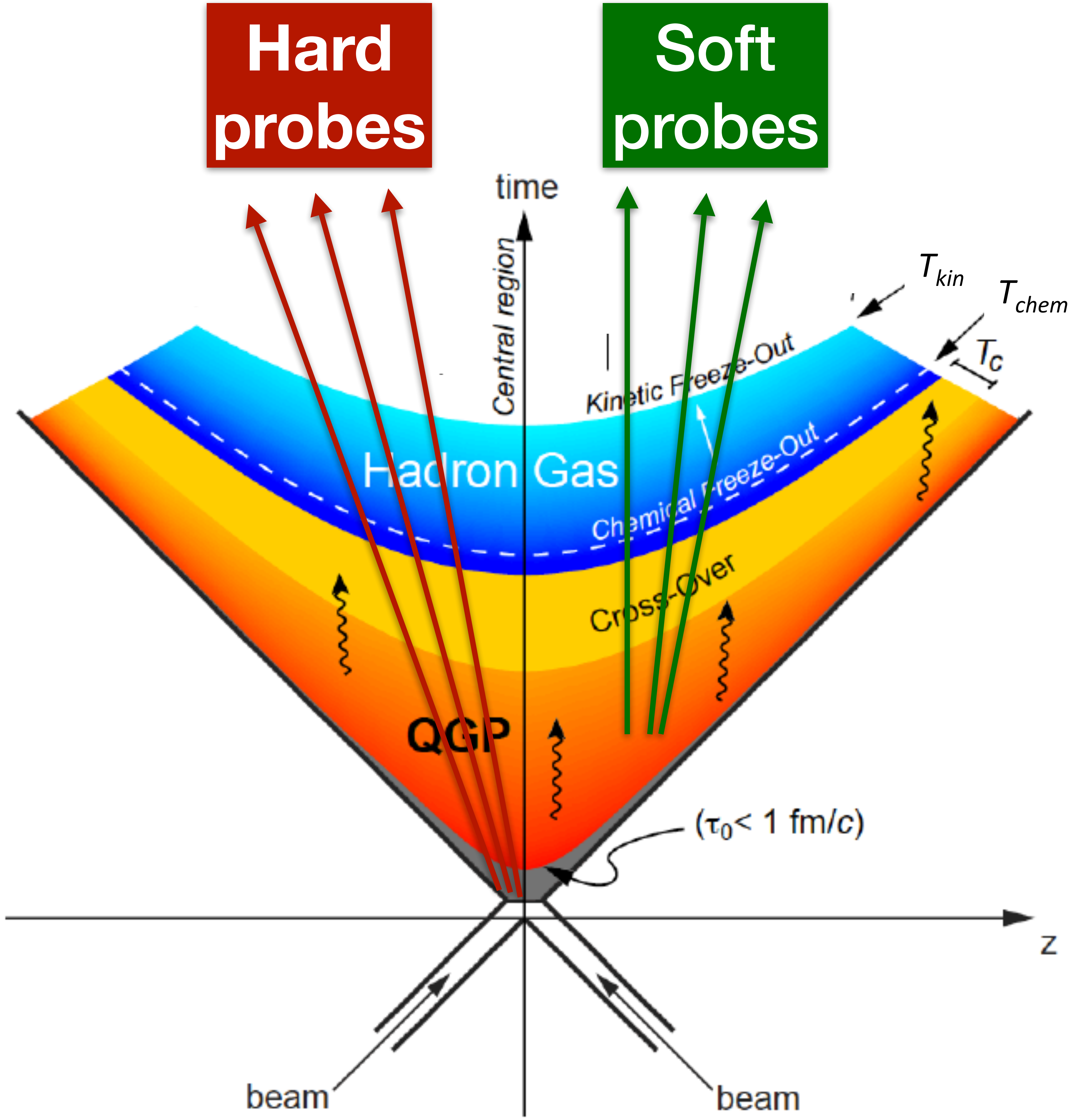
Temperature of the QGP



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

- 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

QGP signatures



Heavy-ion collisions probe the strongly-interacting matter — the quark-gluon plasma (QGP) under extreme conditions of high temperature and energy density

Hard probes created at initial stage of the collision

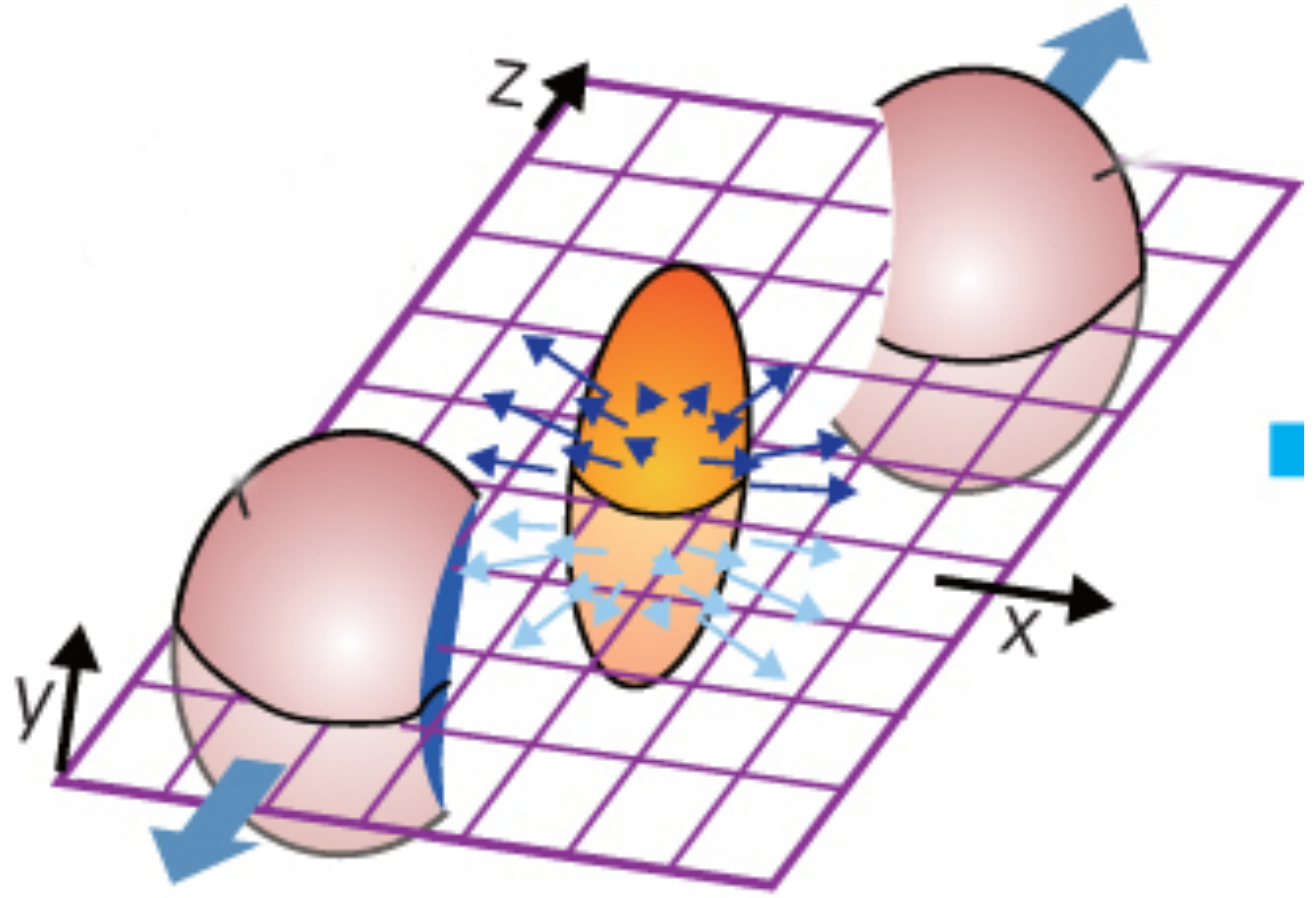
➡ QGP tomography

Soft probes created in the “fireball”

➡ Fingerprint of the QGP evolution

Collective properties

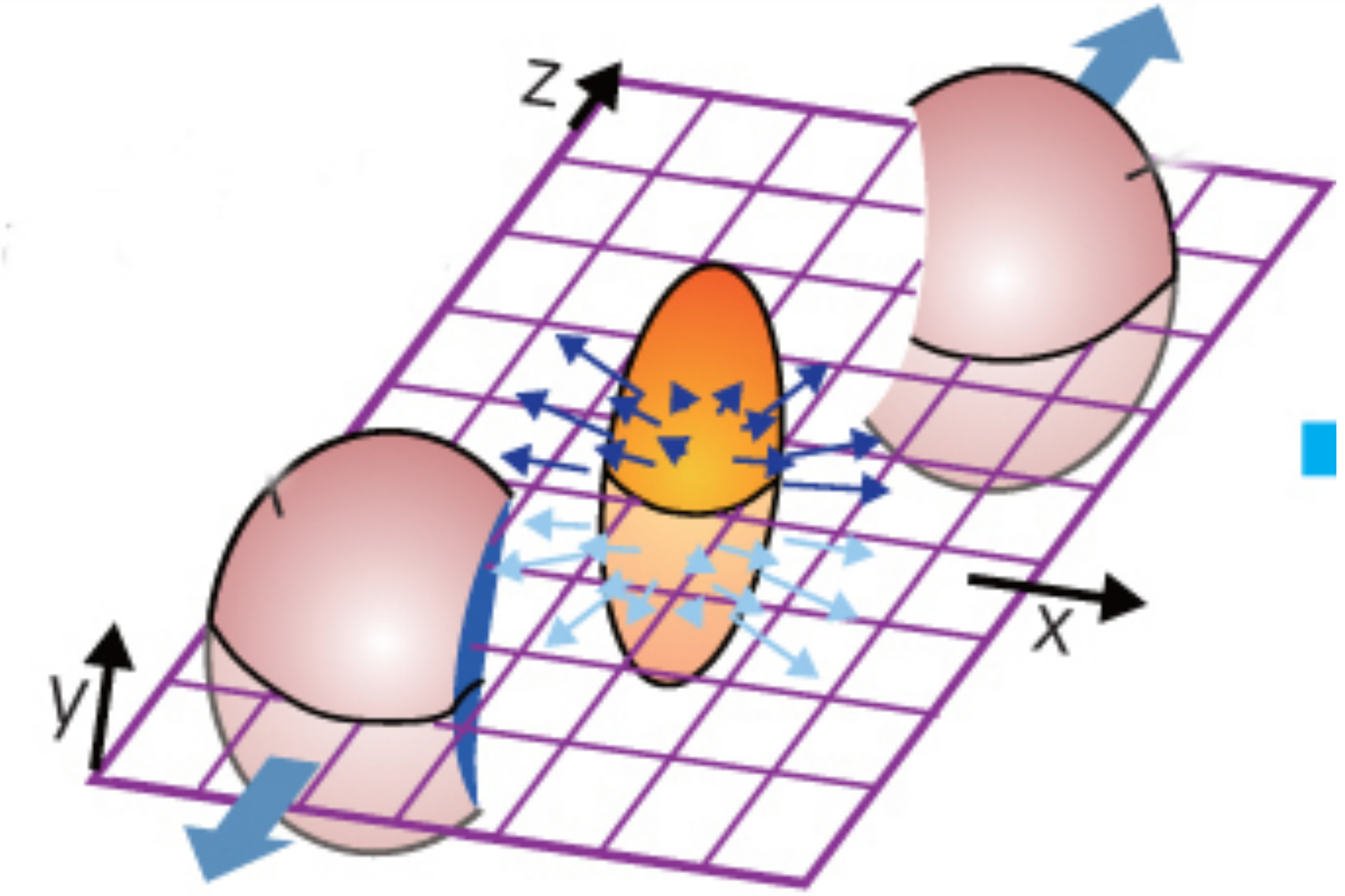
Collective expansion

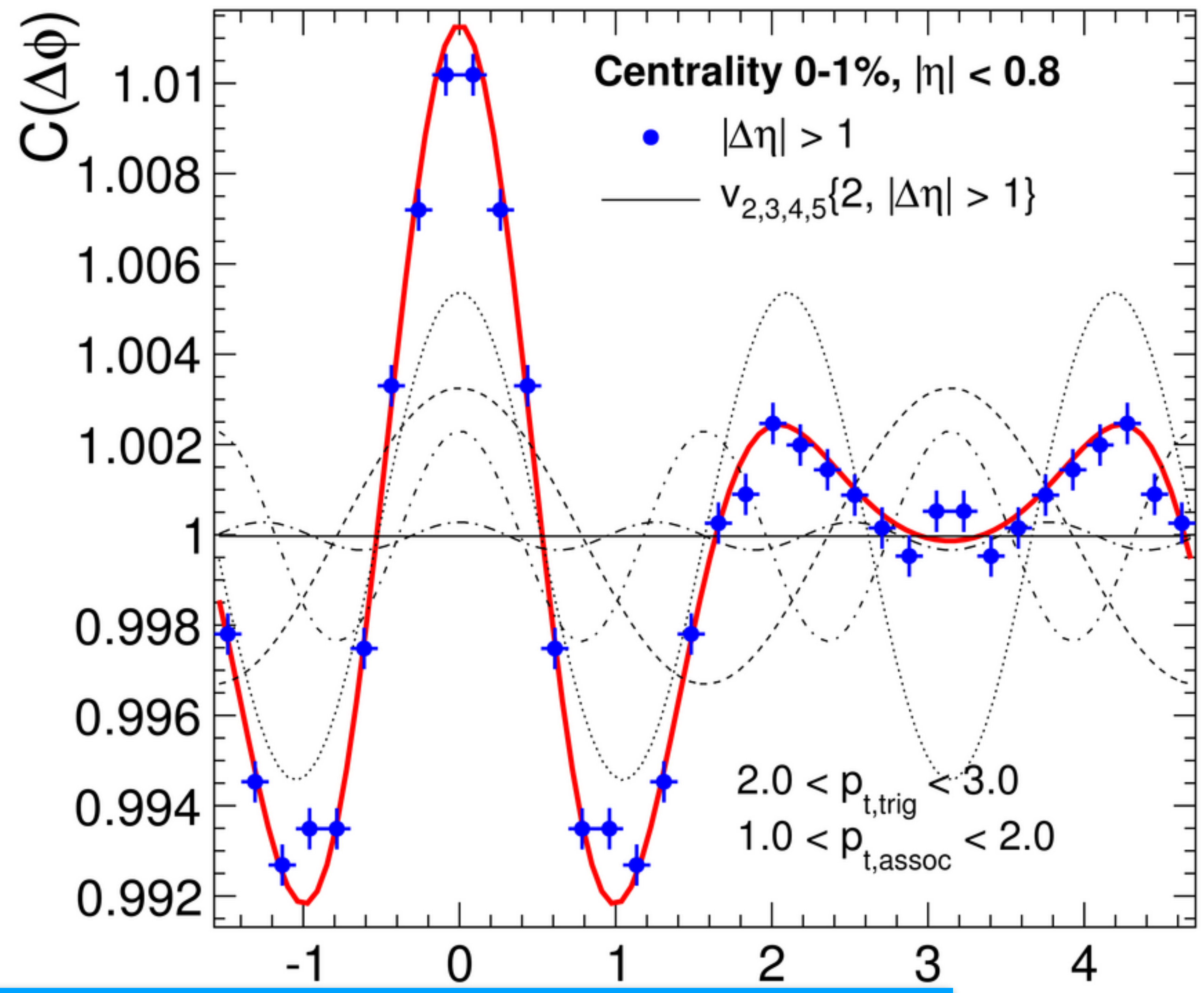


Anisotropy flow

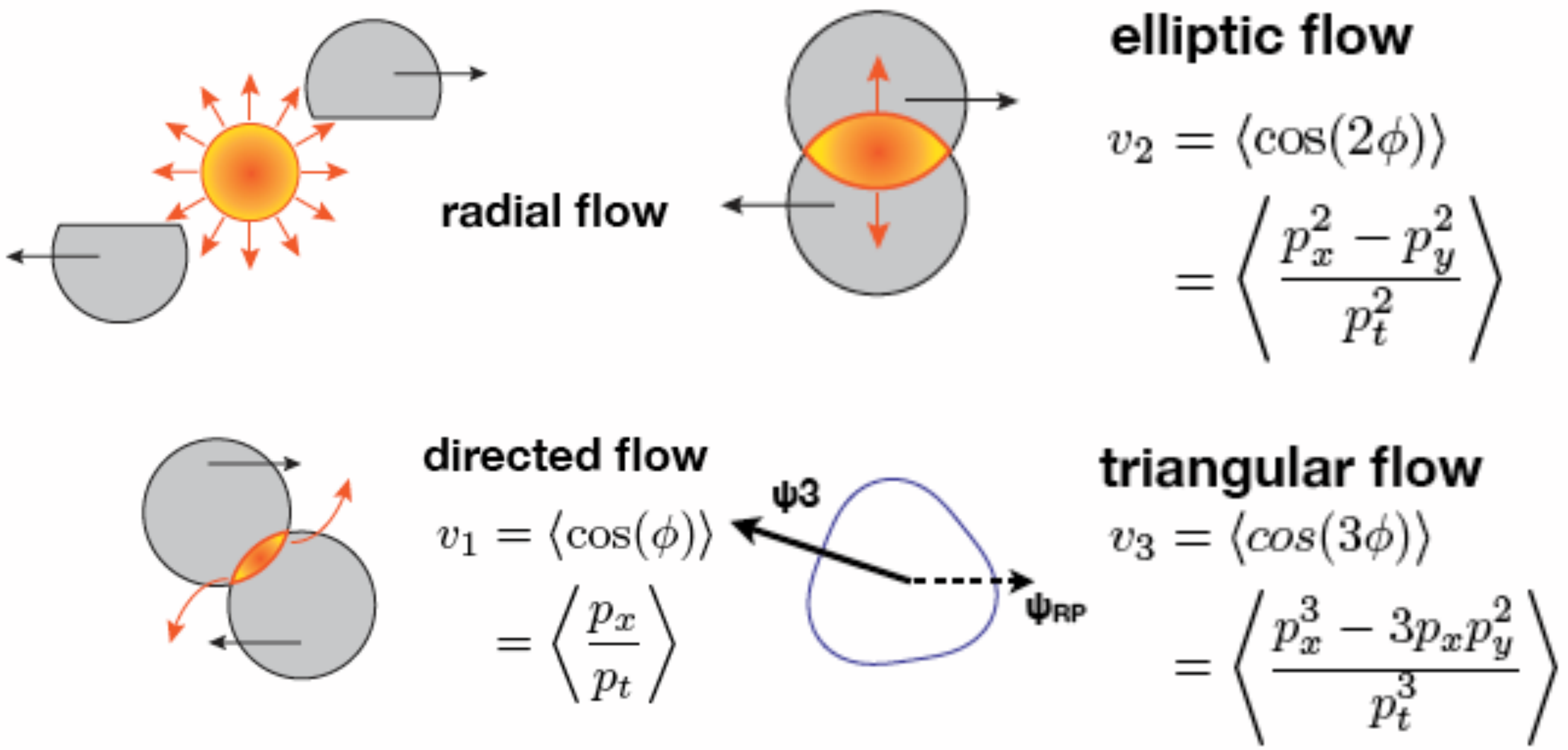
Collective expansion — results in complex azimuthal structure of final state particles

➡ Interactions in medium, access to medium properties, e.g. viscosity, equation of state





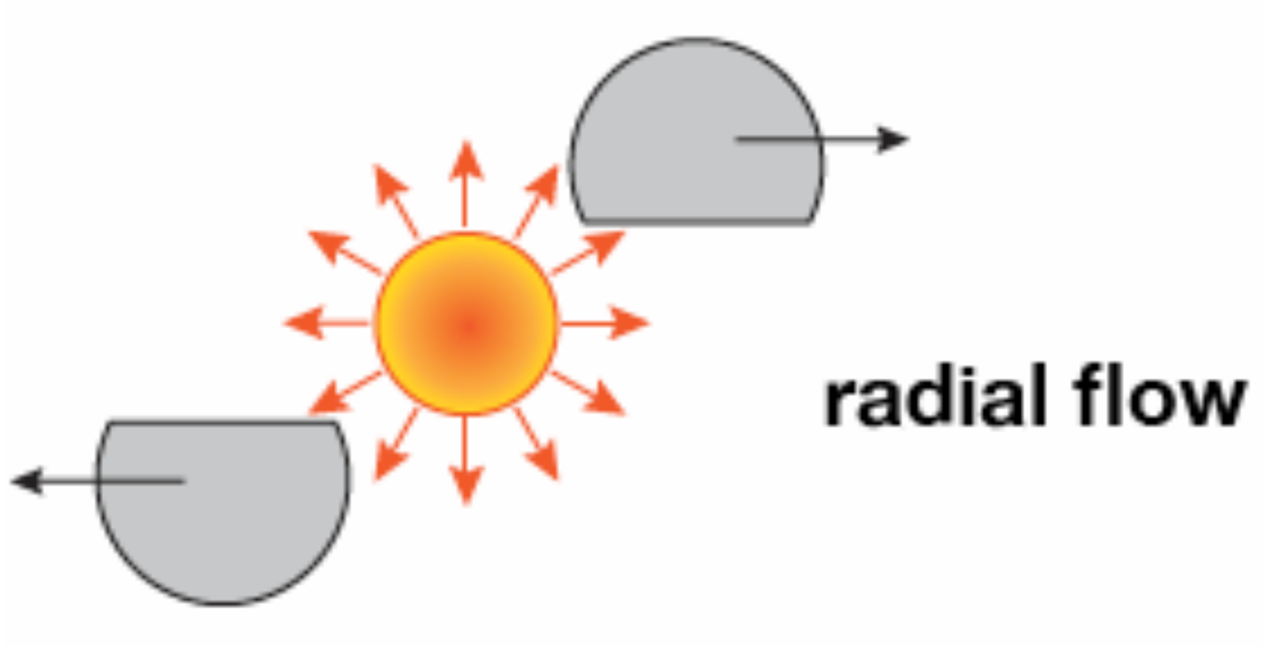
ALICE *Phys. Rev. Lett.* 107 (2011) 032301



Radial flow

Collective expansion

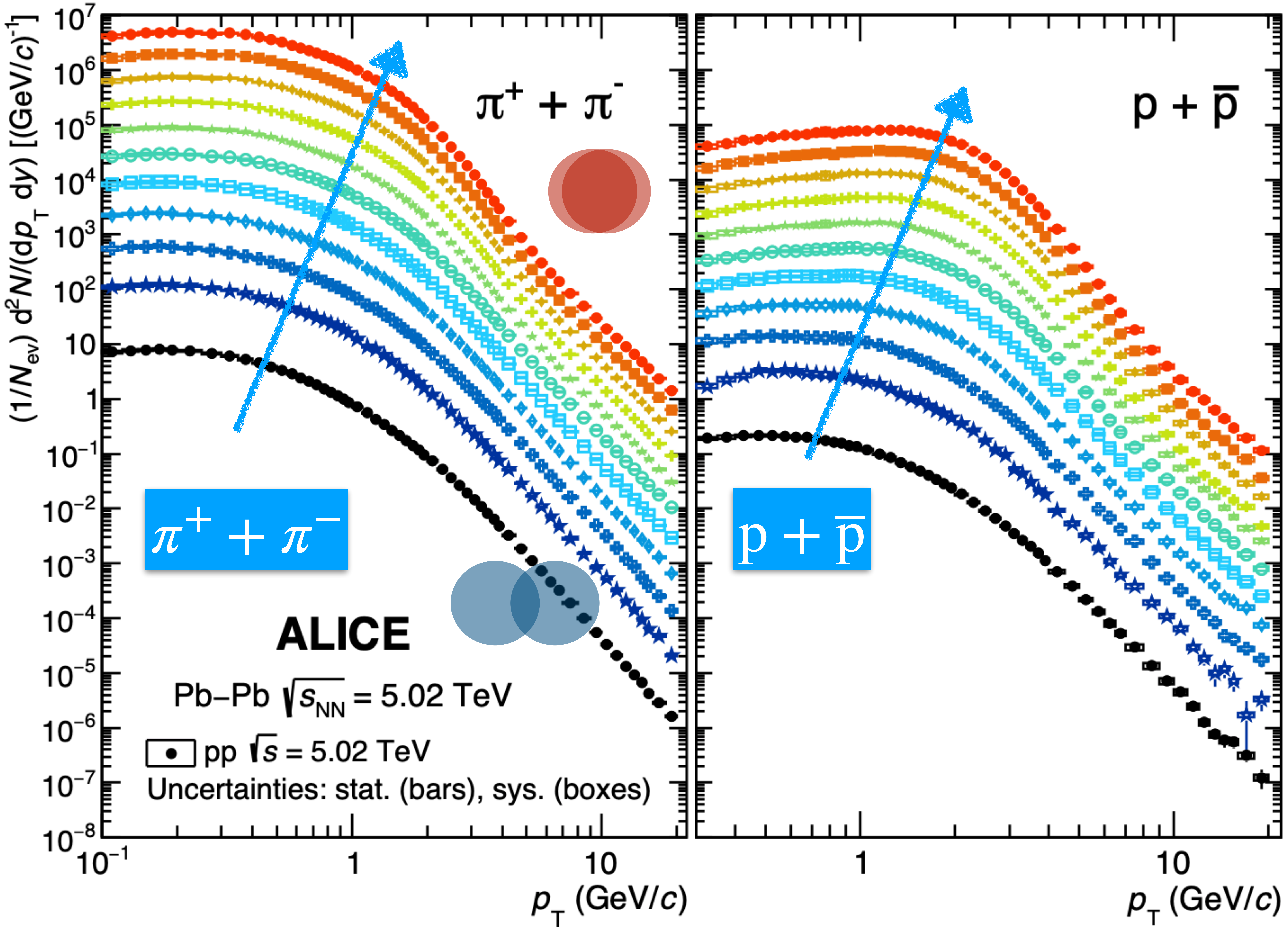
➡ "Zero order" — radial flow



➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

***p_0*: initial momentum**
***β*: flow velocity**
***m*: particle mass**

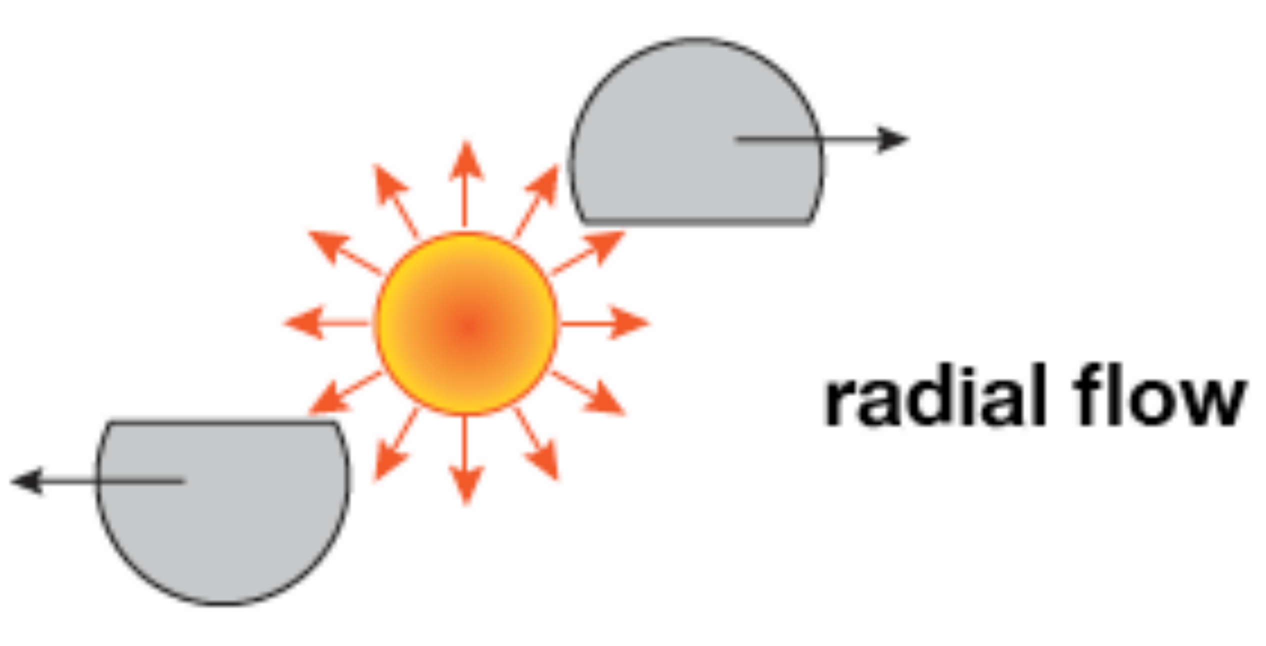


ALICE *Phys. Rev.* C101 (2020) 044907

Radial flow

Collective expansion

- ➡ "Zero order" — radial flow

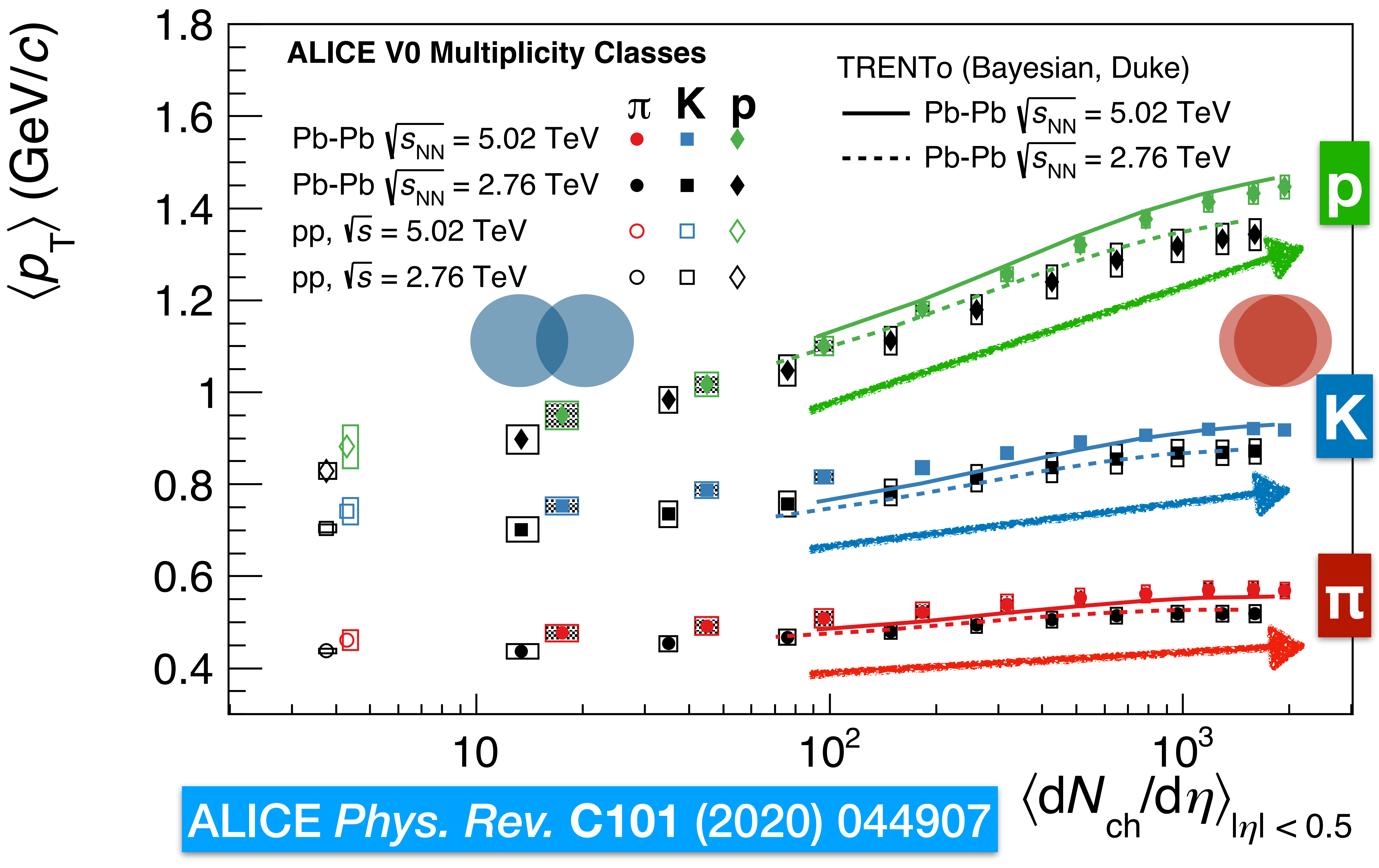


- ➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

p_0: initial momentum
β: flow velocity
m: particle mass

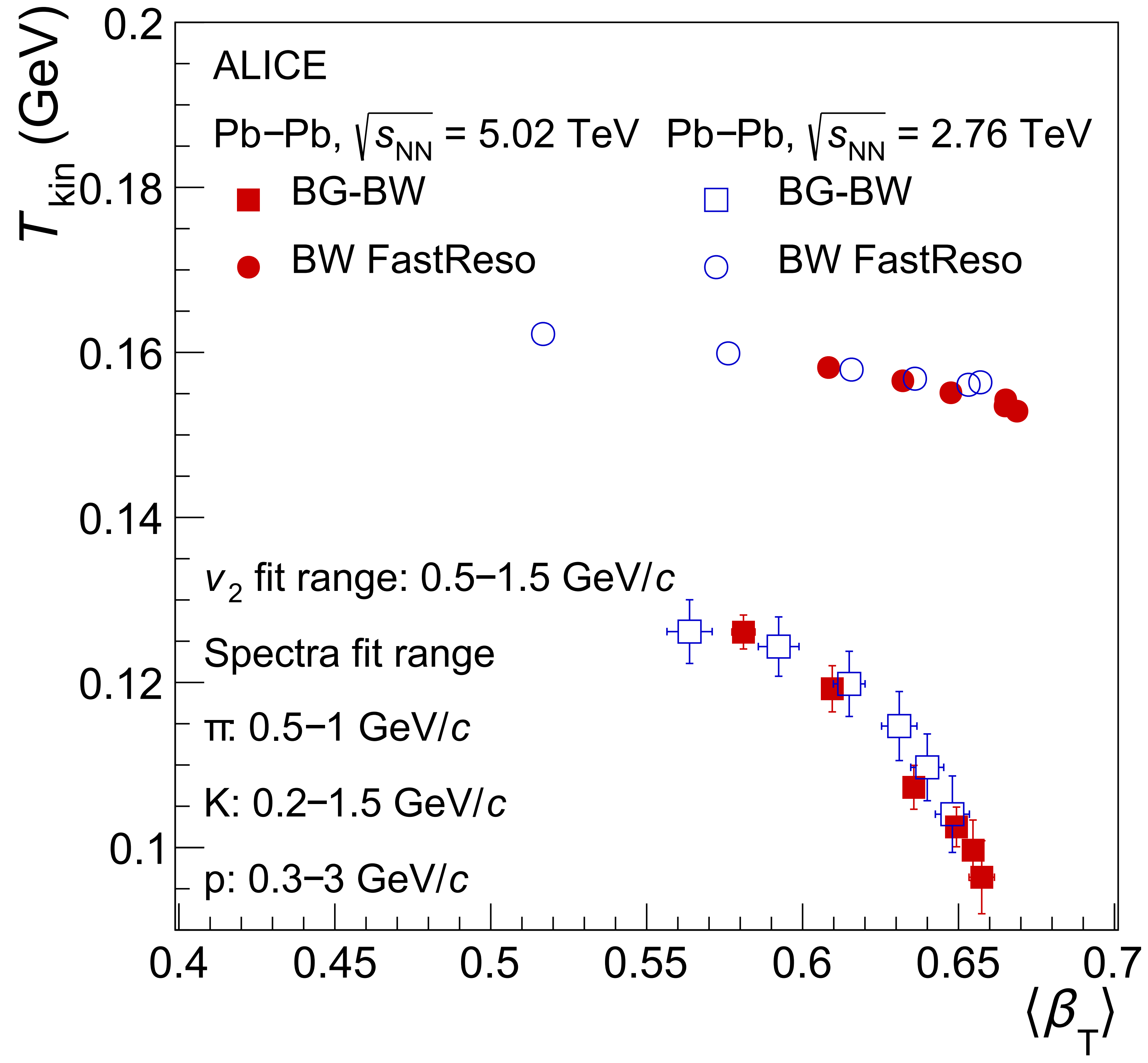
- ➡ More pronounced in central collisions

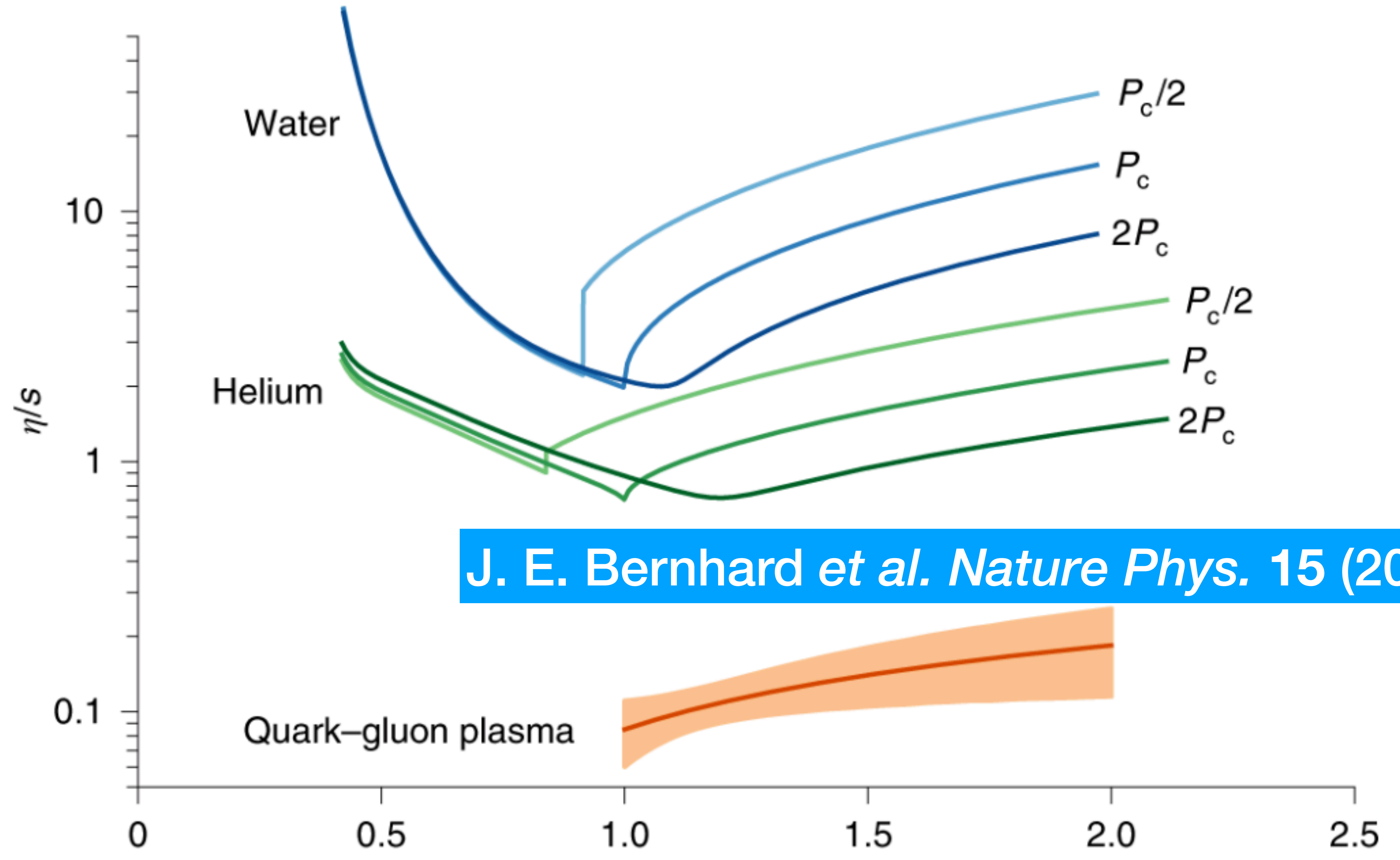


ALICE *Phys. Rev.* C101 (2020) 044907

QGP properties

- Measurements described by viscous hydrodynamics considering low viscosity (η/s)
- Bayesian estimation using RHIC and the LHC data: QGP ×10 less viscosity than any other form of matter —“perfect” liquid

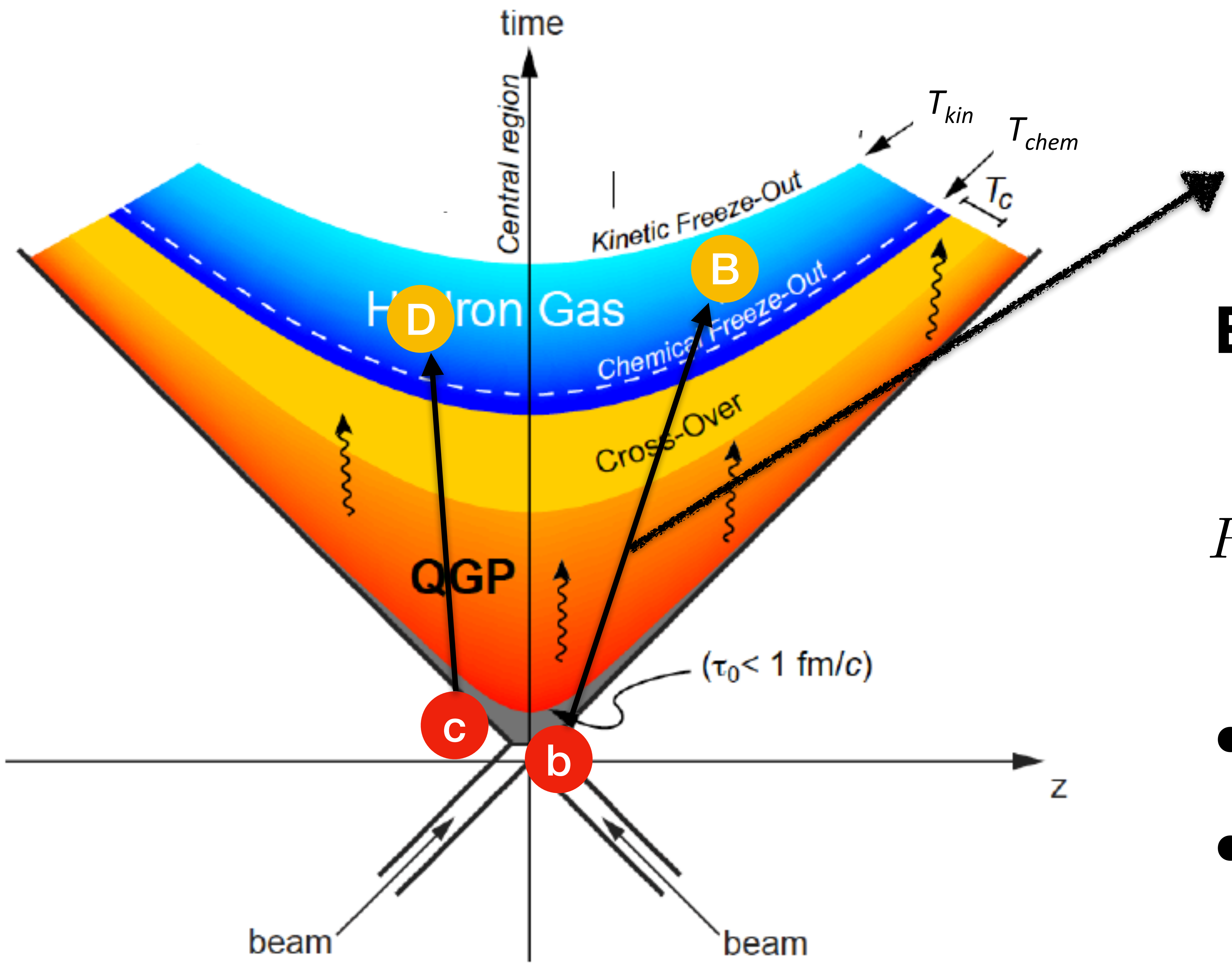


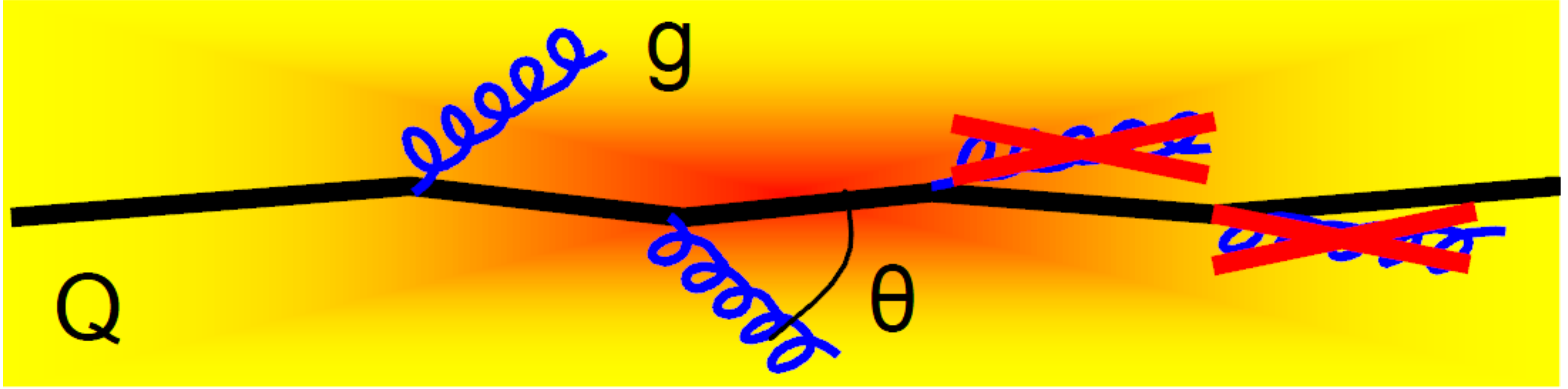


J. E. Bernhard *et al. Nature Phys.* 15 (2019) 1113

Heavy quark: QGP tomography

Heavy quarks (charm and beauty): produced at the early stage of the collisions before the QGP creation





Energy loss in QGP medium

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

QCD medium

QCD vacuum

- R_{AA} = 1 if no medium effect
- Radiative vs. collisional energy loss

Heavy quark: QGP tomography

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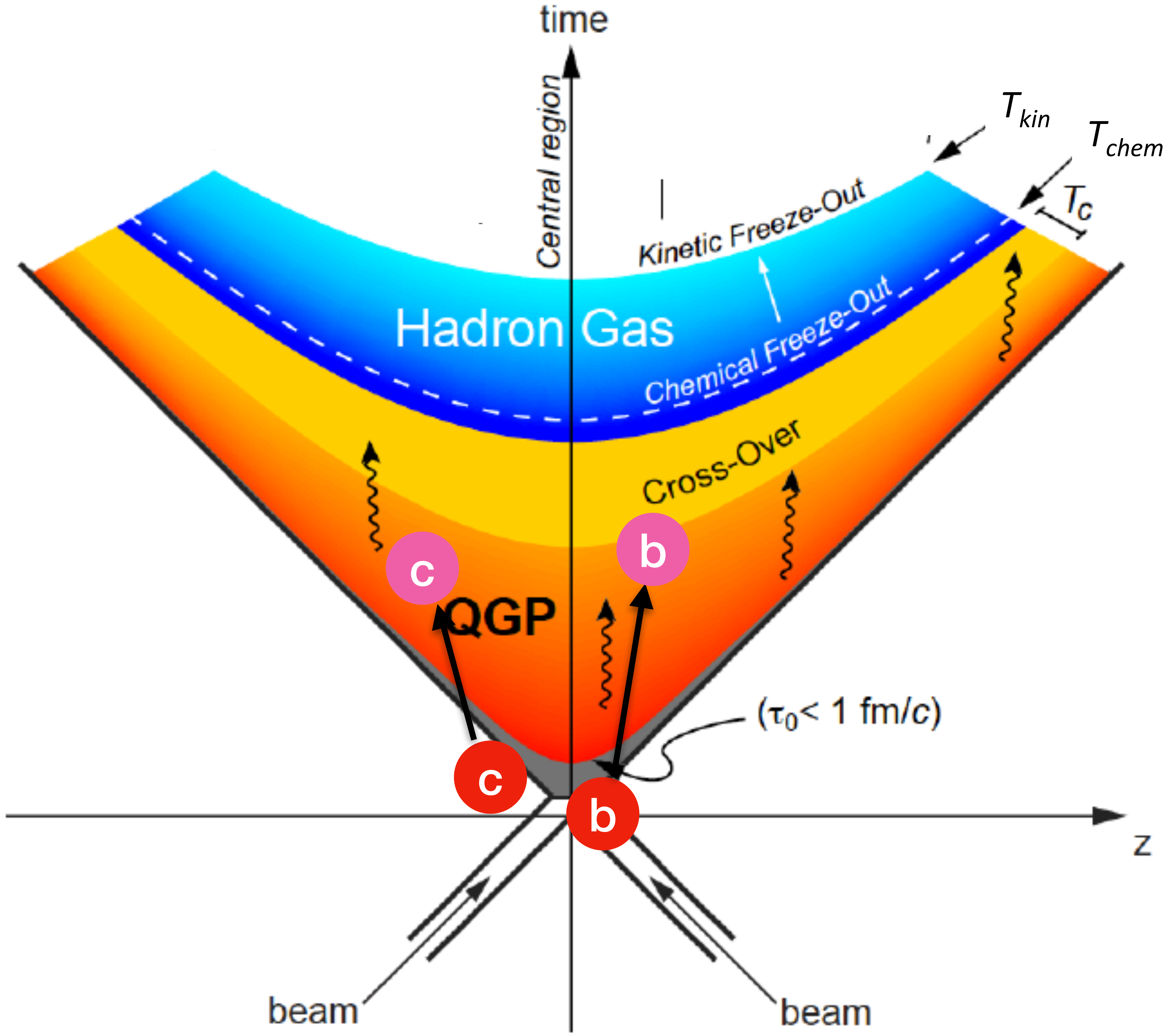
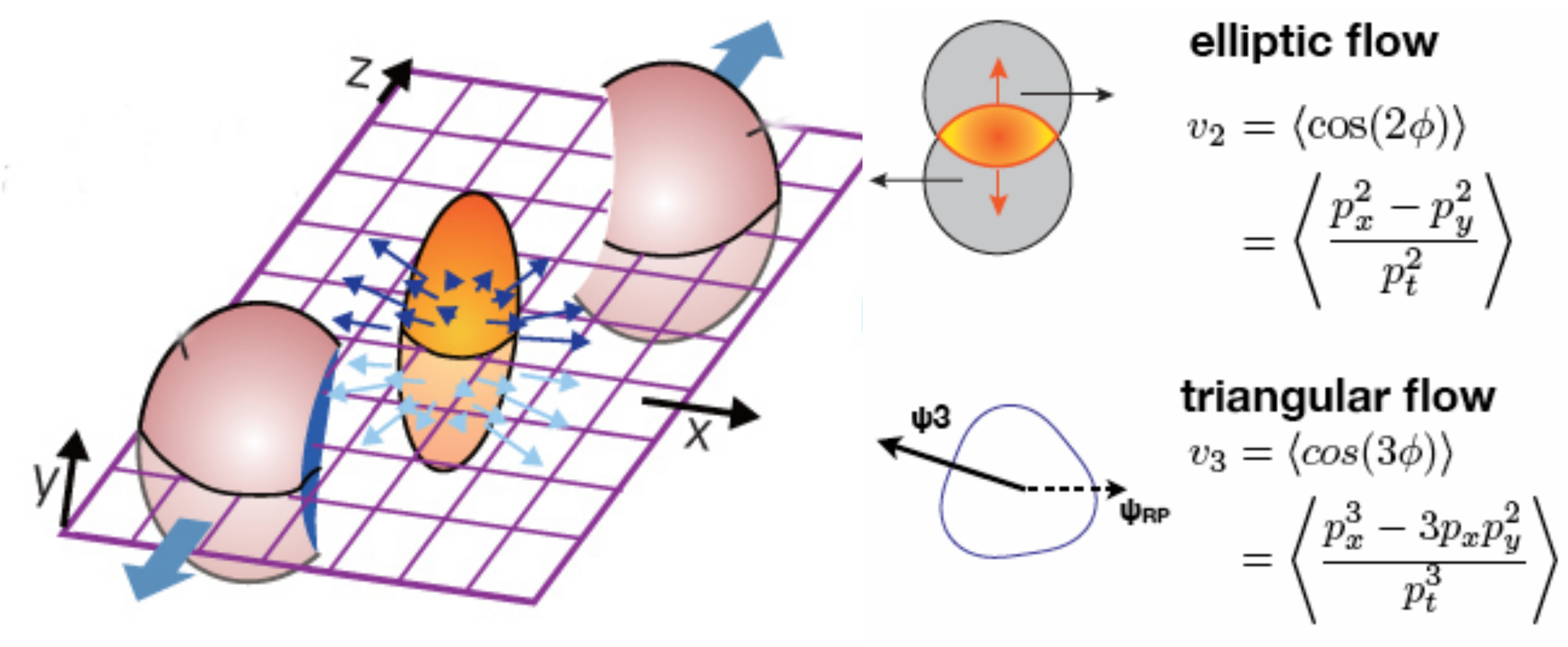


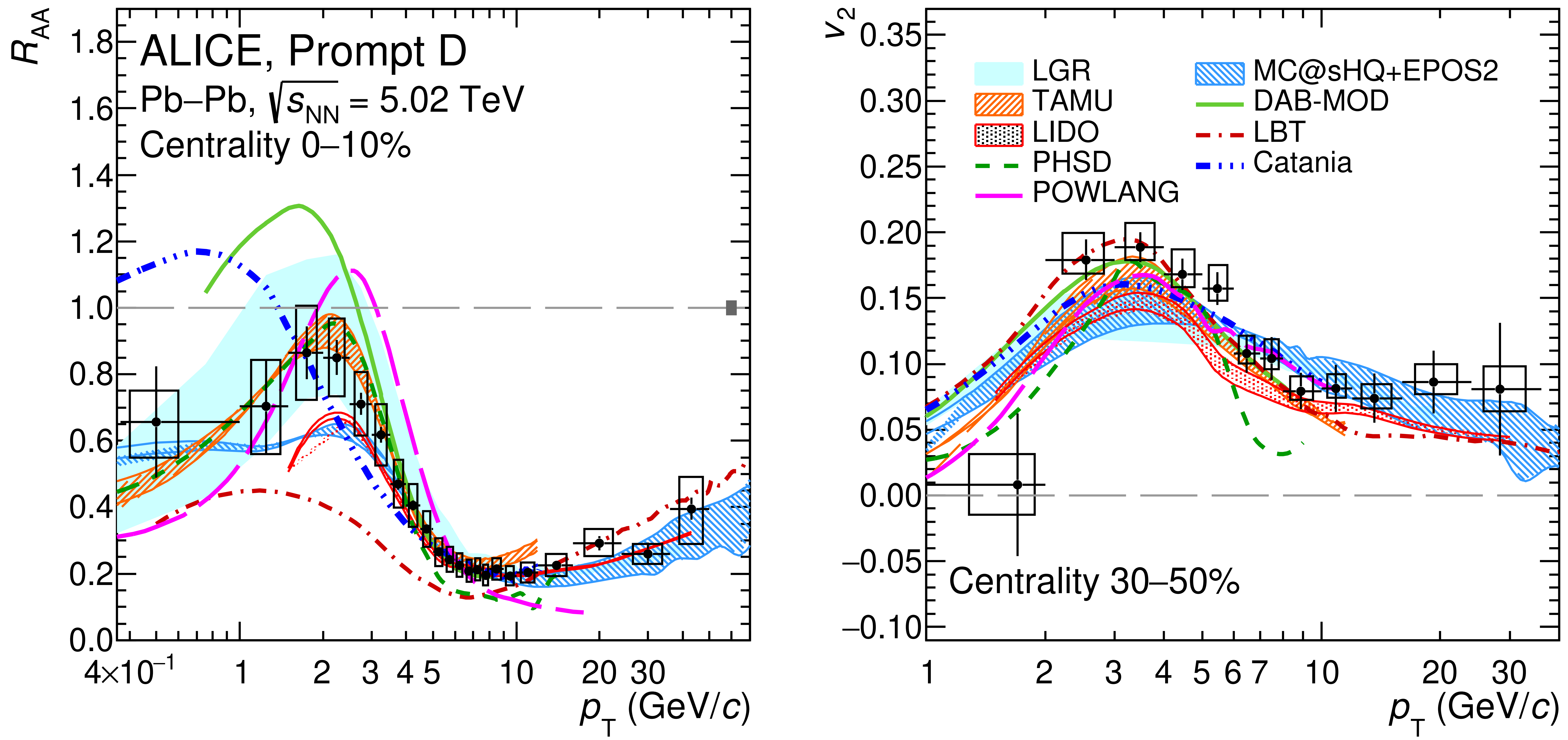
Collective expansion

➡ Anisotropic flow



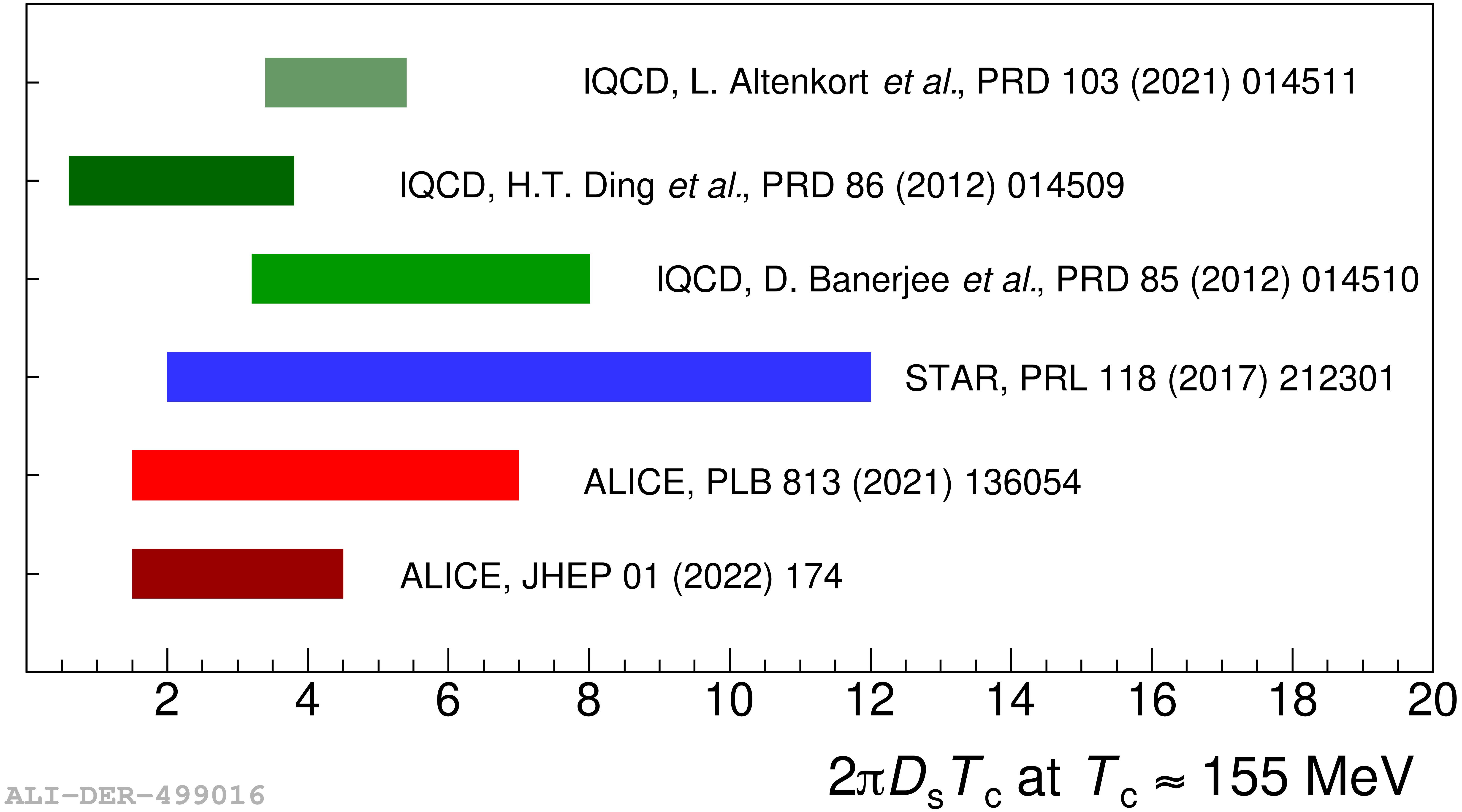
➡ Results in complex azimuthal structure of final state particles

Charm quark transport



- Most charm quark transport models able to describe both the R_{AA} and v_2
- Use to estimate the spatial diffusion coefficient *Ds*

Charm quark transport



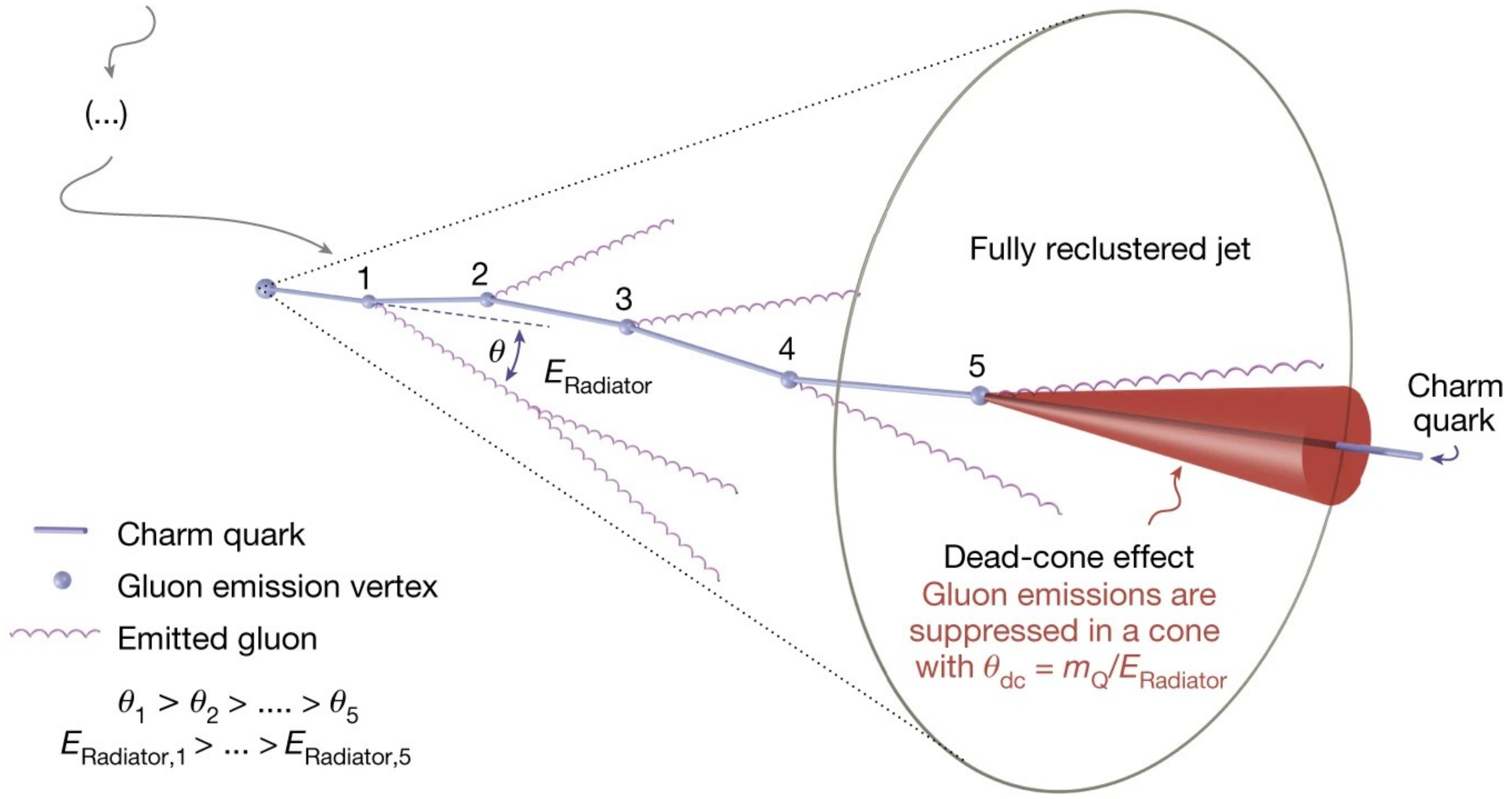
Diffusion coefficient D_s

- Almost independent of quark mass
- Characterization of the transport properties of the medium
- Constrains the specific shear viscosity η/s

The newest constraints from ALICE by combining D meson R_{AA} and v_2

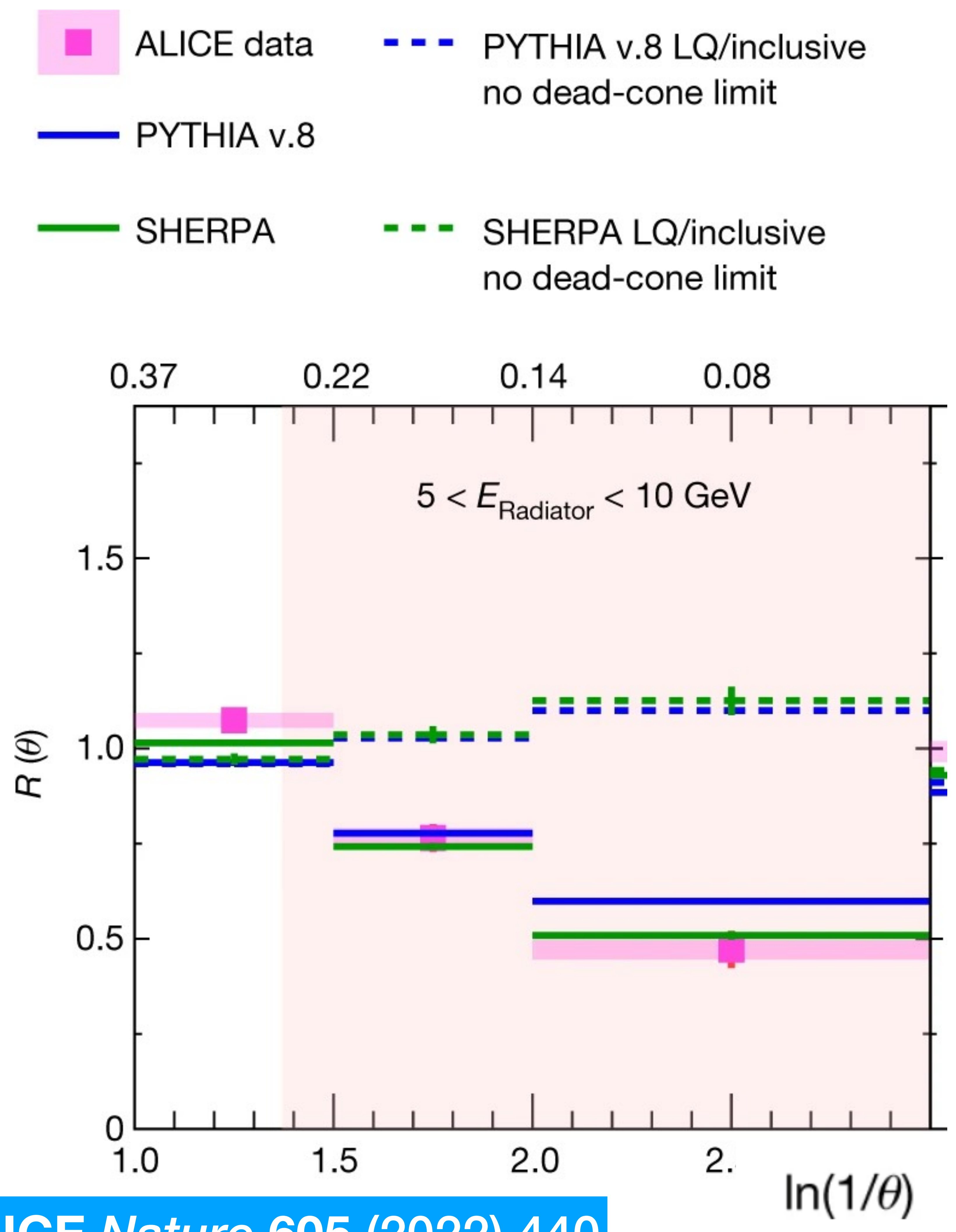
- $1.5 < 2\pi D_s(T) < 4.5$, $\tau_{charm} = (m_{charm} / T)\, D_s(T) = 3\text{–}9$ fm/c < $\tau_{medium} \approx 10$ fm/c
- Indicate charm may thermalize in the medium

Dead-cone of charm radiation



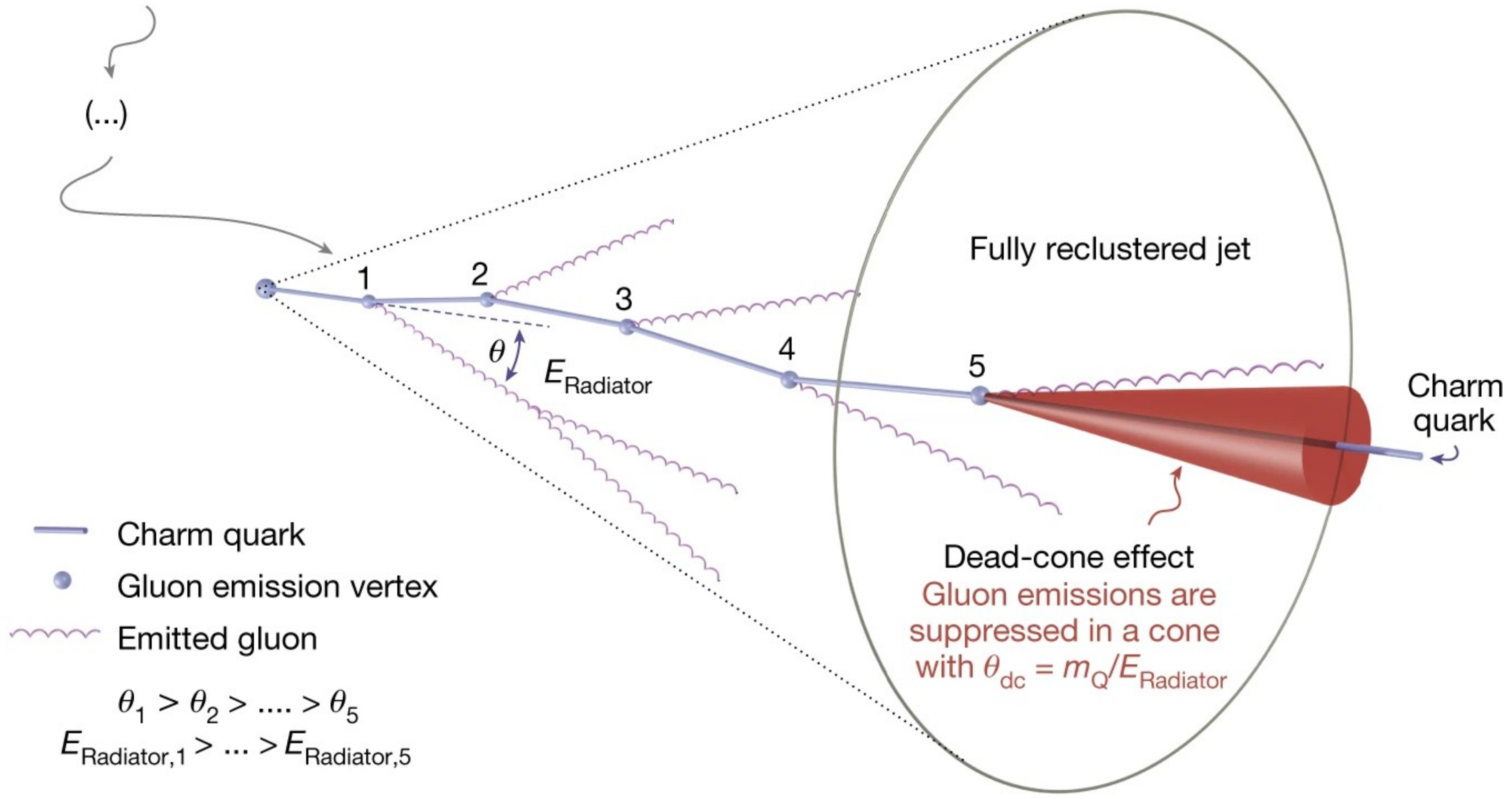
One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

- Direct observation for charm quarks in pp — QCD vacuum



ALICE *Nature* 605 (2022) 440

Dead-cone of charm radiation



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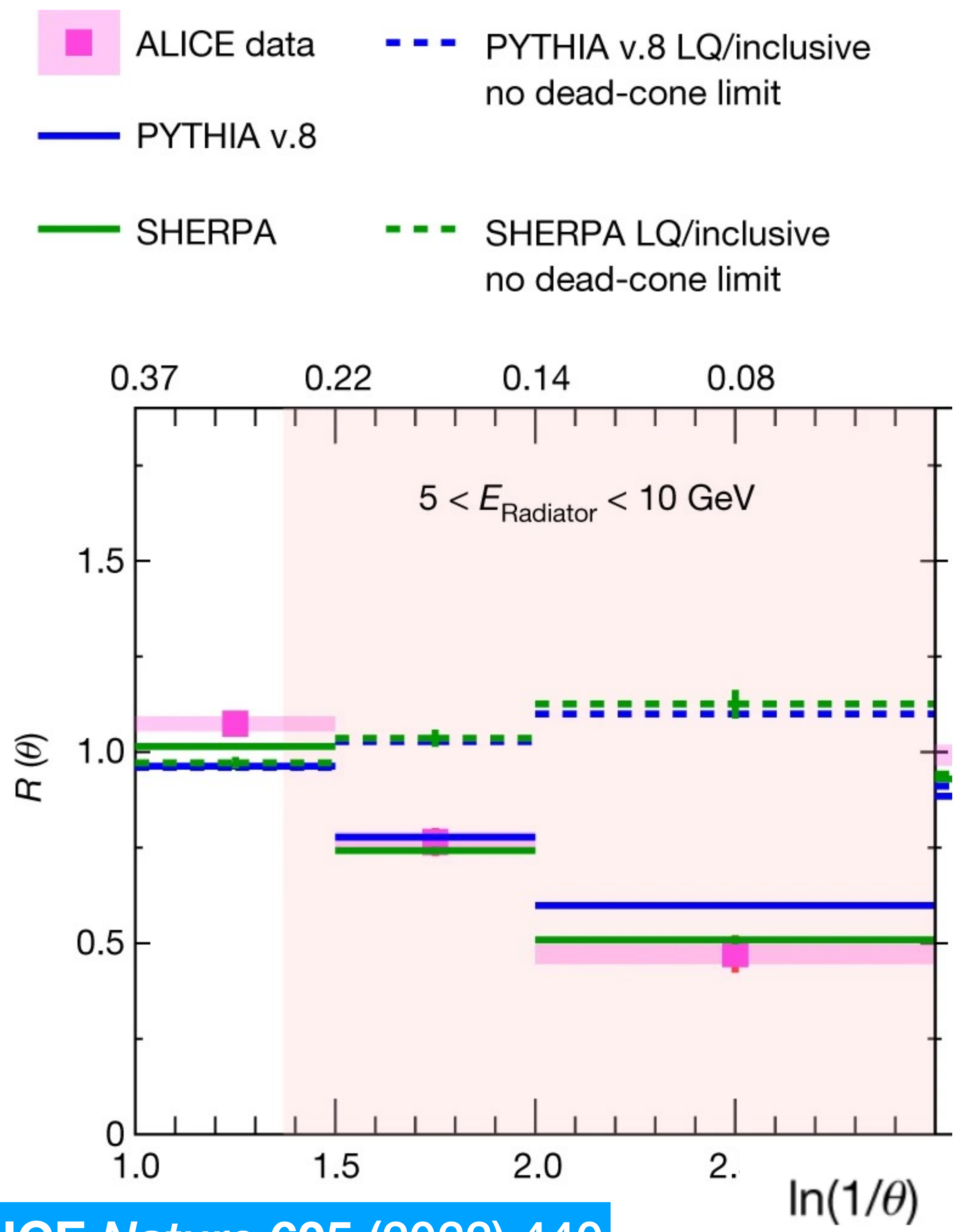


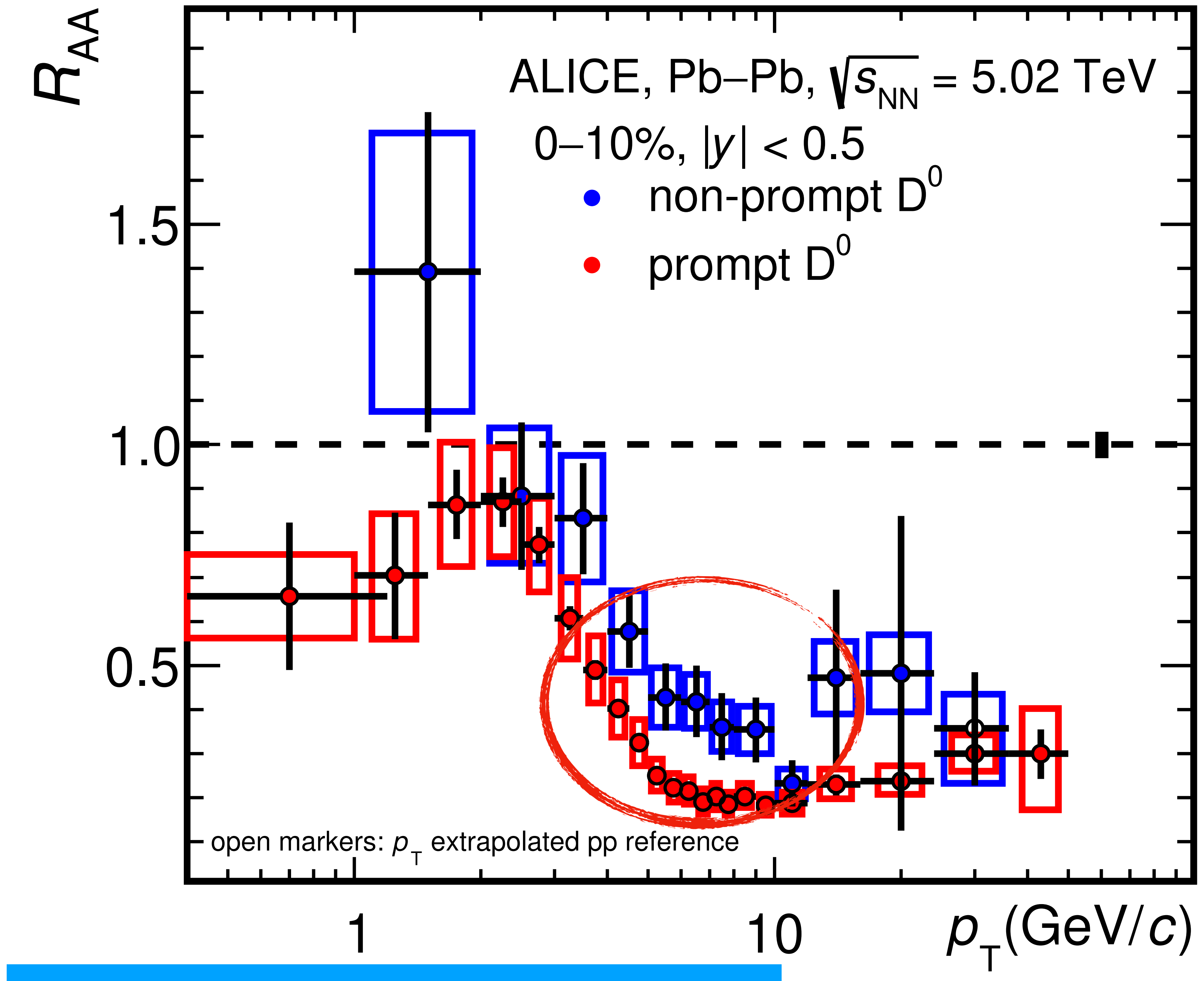
ALICE *Nature* 605 (2022) 440

- Whether is it still validated in QCD medium?

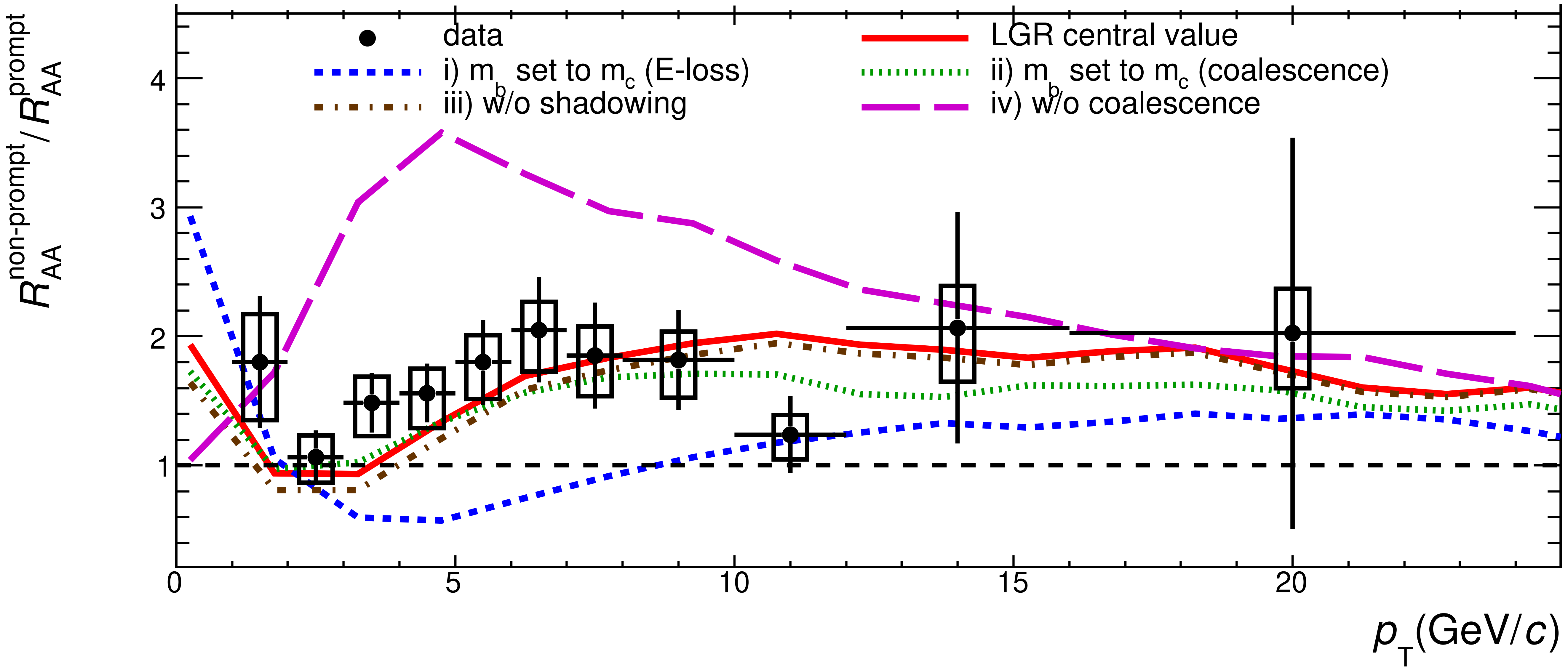
➡ Mass dependent heavy quark radiative energy loss

$\Delta E_{\text{beauty}} < \Delta E_{\text{charm}} \Rightarrow R_{AA}(\text{beauty}) > R_{AA}(\text{charm})$

Beauty quark energy loss



ALICE *JHEP* 2212 (2022) 126

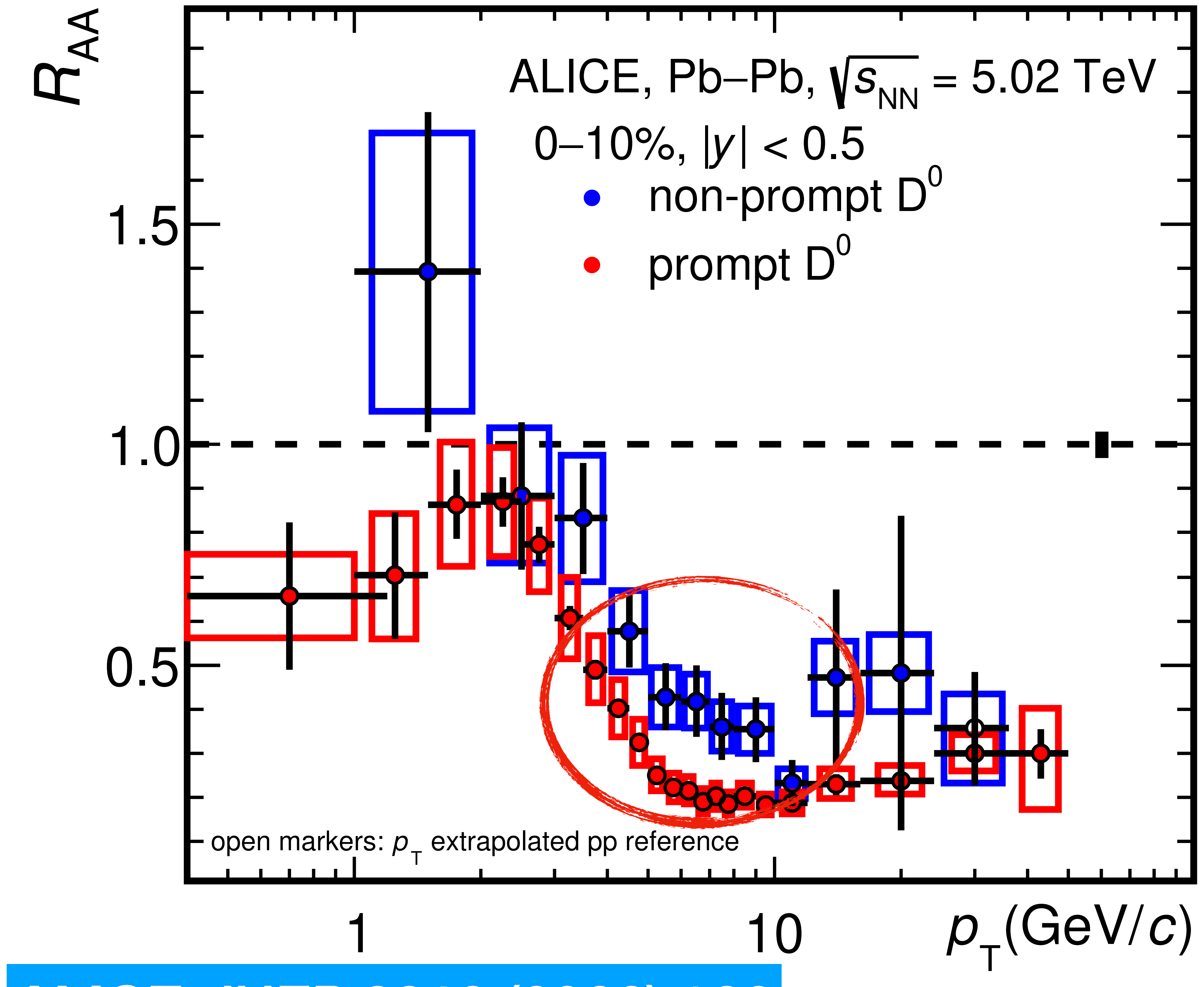


- Mass effect is important to describe data
- However, coalescence is more critical

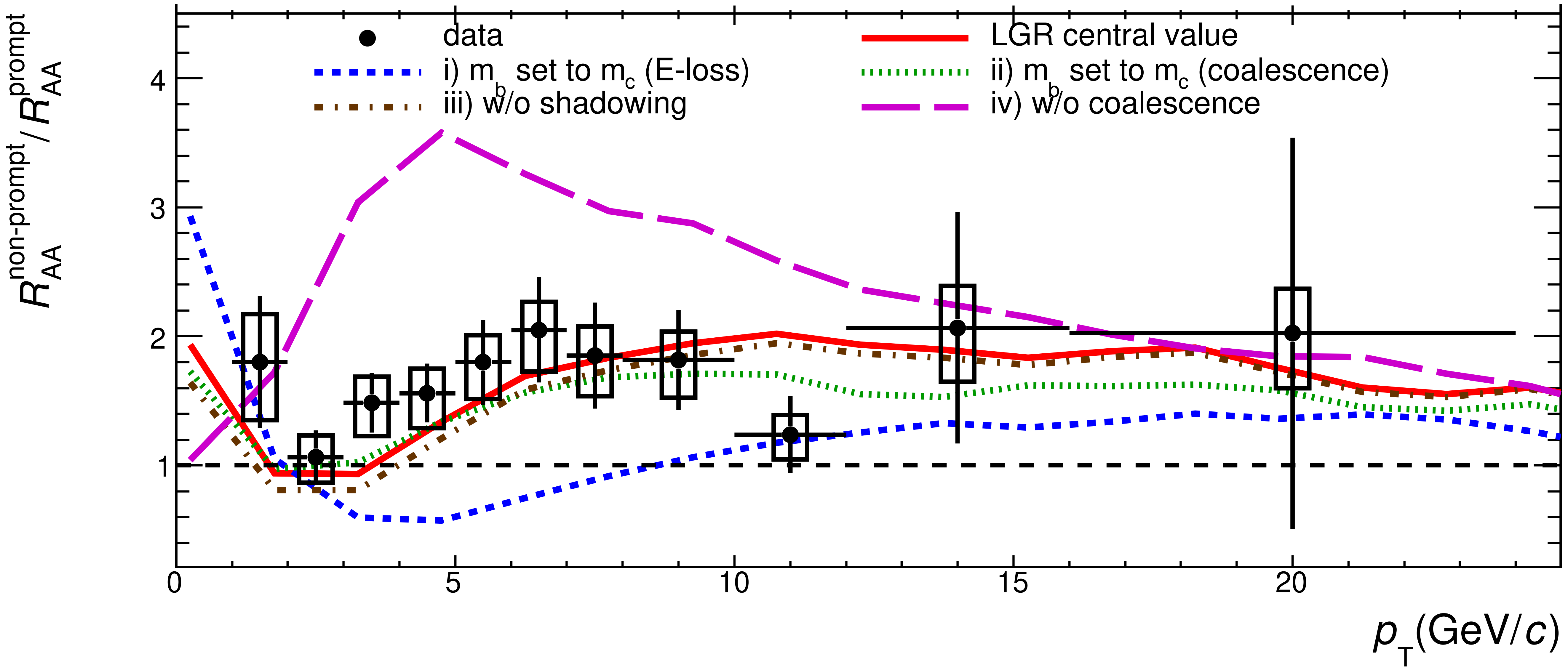
Non-prompt D mesons are less suppressed than prompt D mesons

R_{AA}(beauty) > R_{AA} (charm) ⇒ $\Delta E_{beauty} < \Delta E_{charm}$ (?)

Beauty quark energy loss



ALICE *JHEP* 2212 (2022) 126



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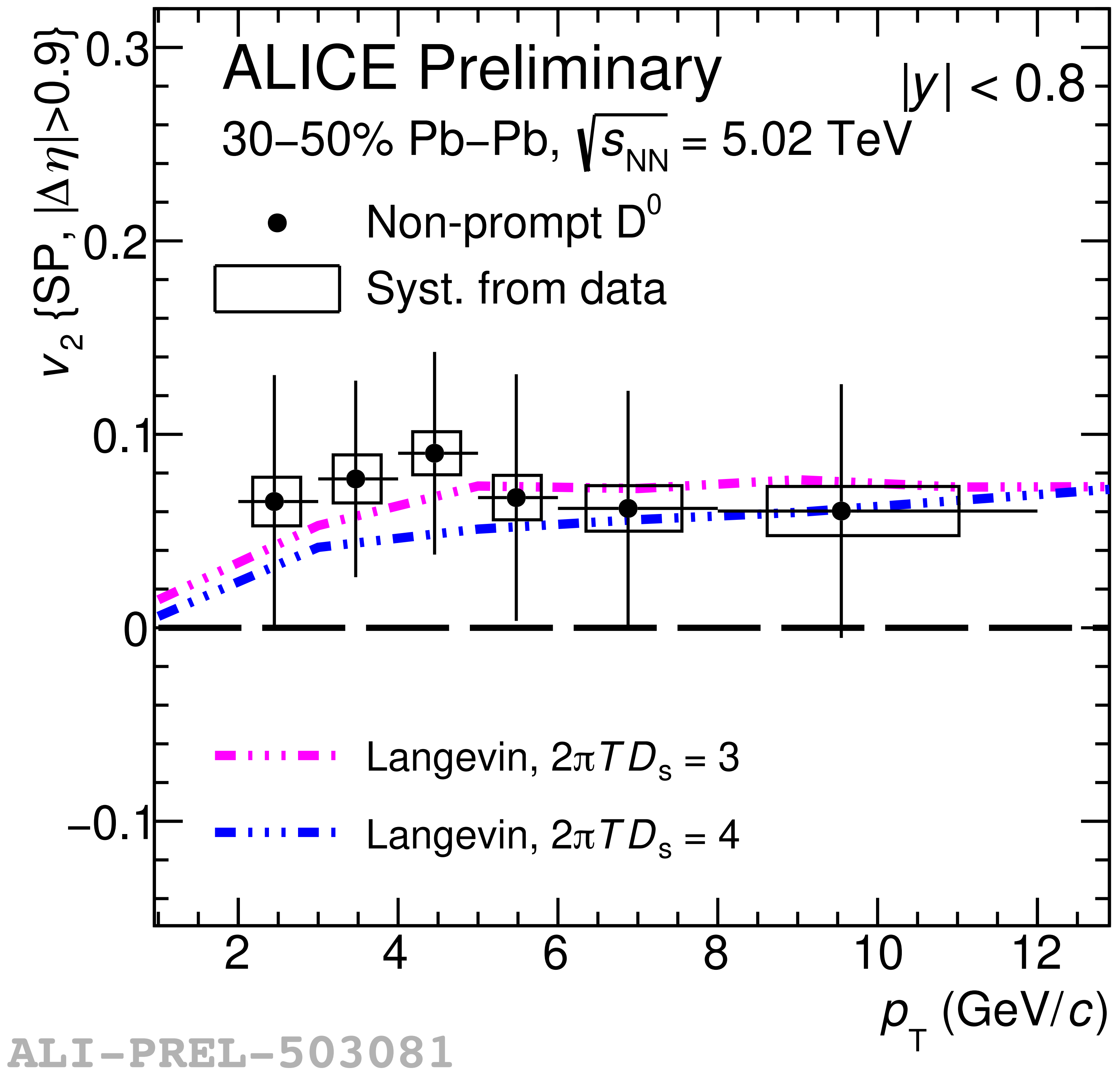
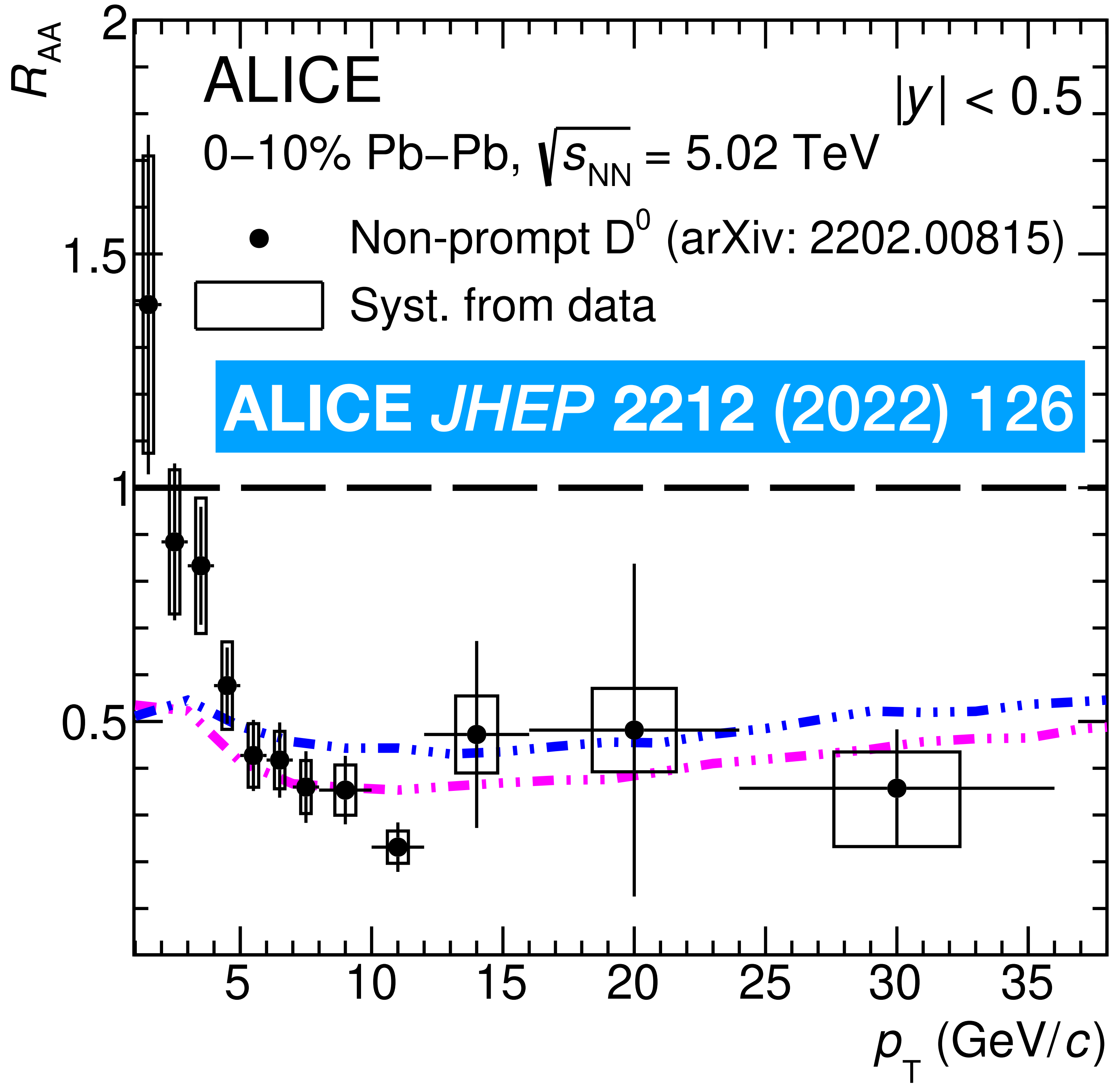
R_{AA}(beauty) > R_{AA} (charm) ⇒ $\Delta E_{beauty} < \Delta E_{charm}$ (?)

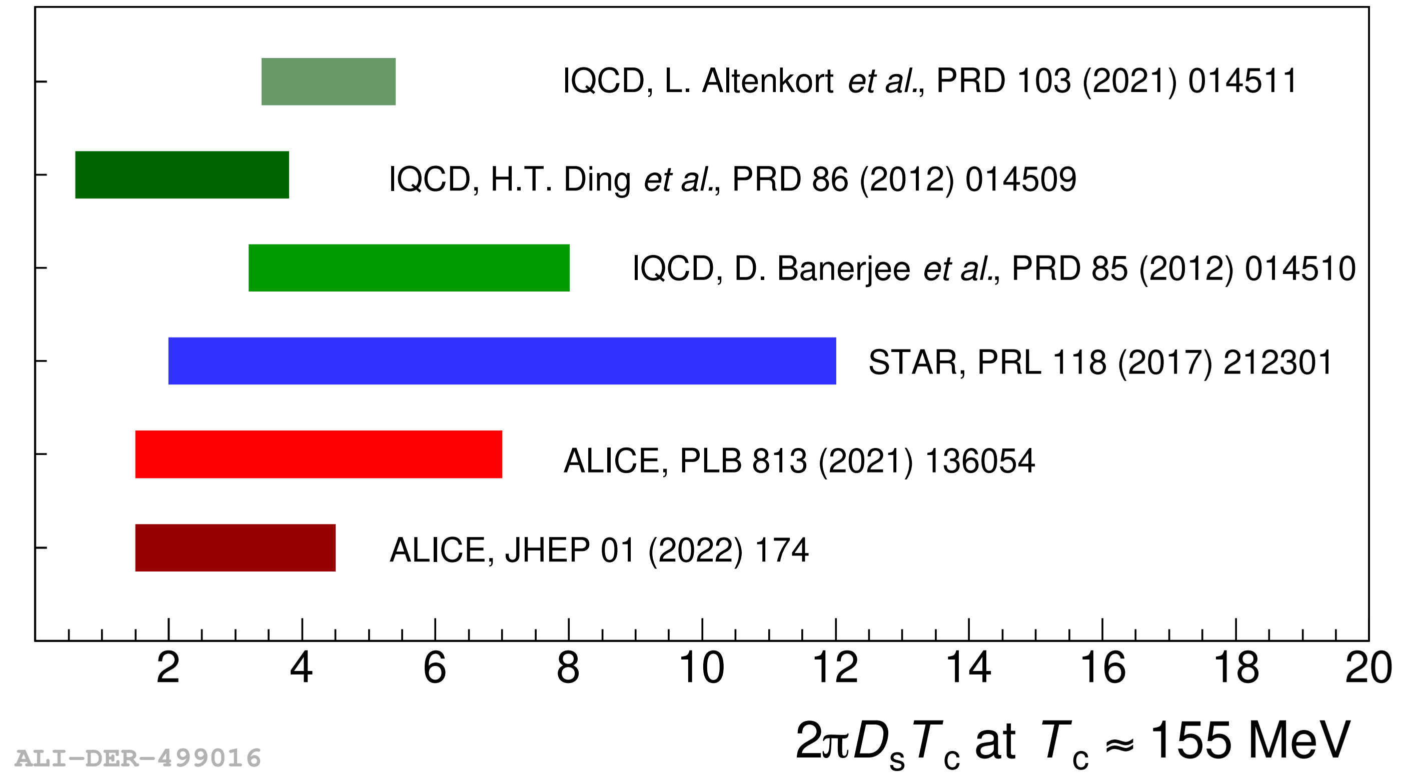
Open question: Can the dead-cone effect be explored directly in the QCD medium?

Beauty quark transport





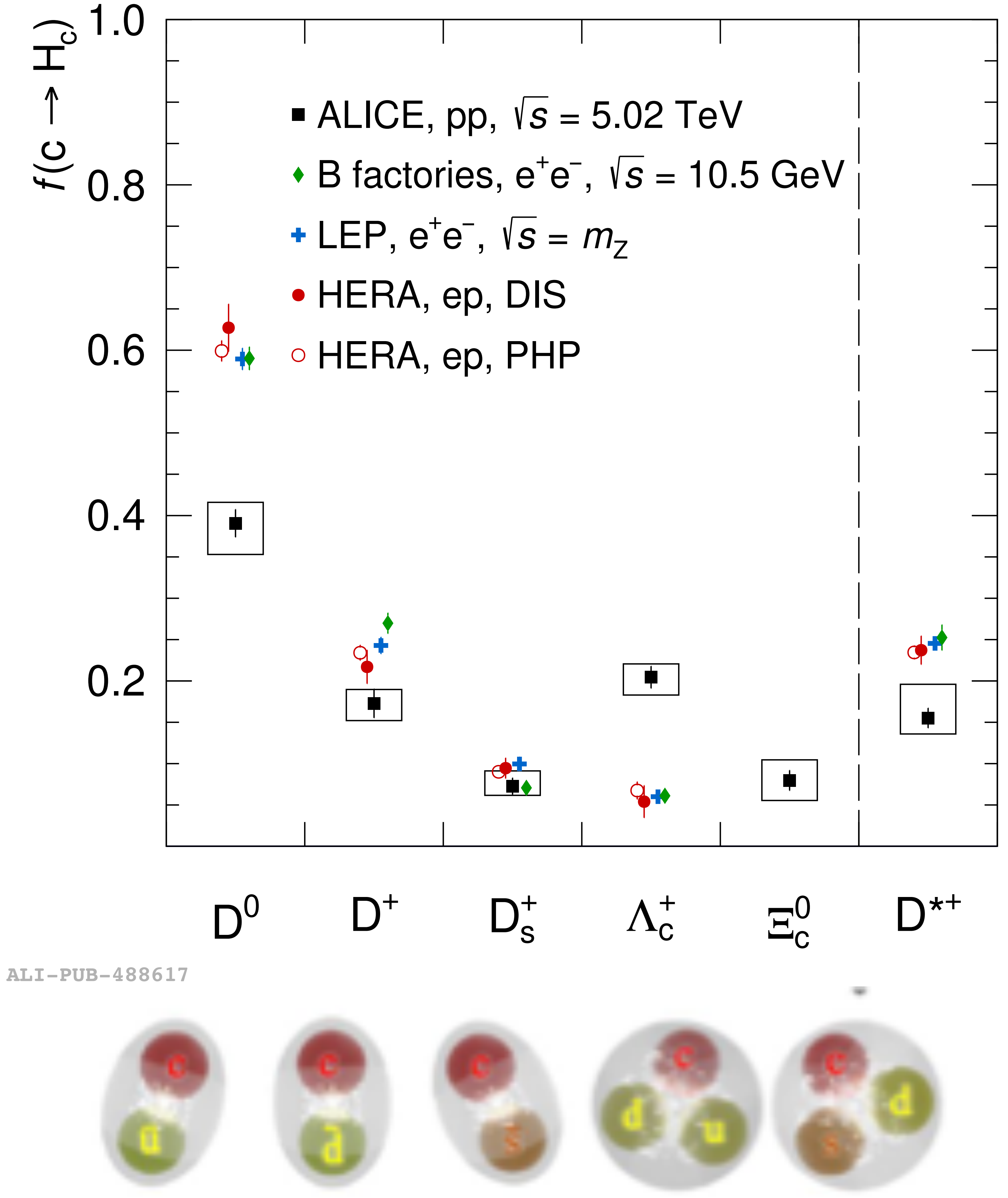
- Beauty particle R_{AA} and v_2 measured via non-prompt D^0 by ALICE
- Conclusion is similar to the measurements of B mesons, non-prompt J/Ψ and B meson semileptonic decays by ATLAS and CMS



- D_s obtained in beauty sector is similar to that in charm sector ($2\pi D_s \approx$ 1.5–4.5 for charm)
- Indicate $\tau_{beauty} \propto m_{beauty} D_s \gtrsim \tau_{medium}$ ($m_{beauty} \approx 3\, m_{charm}$)

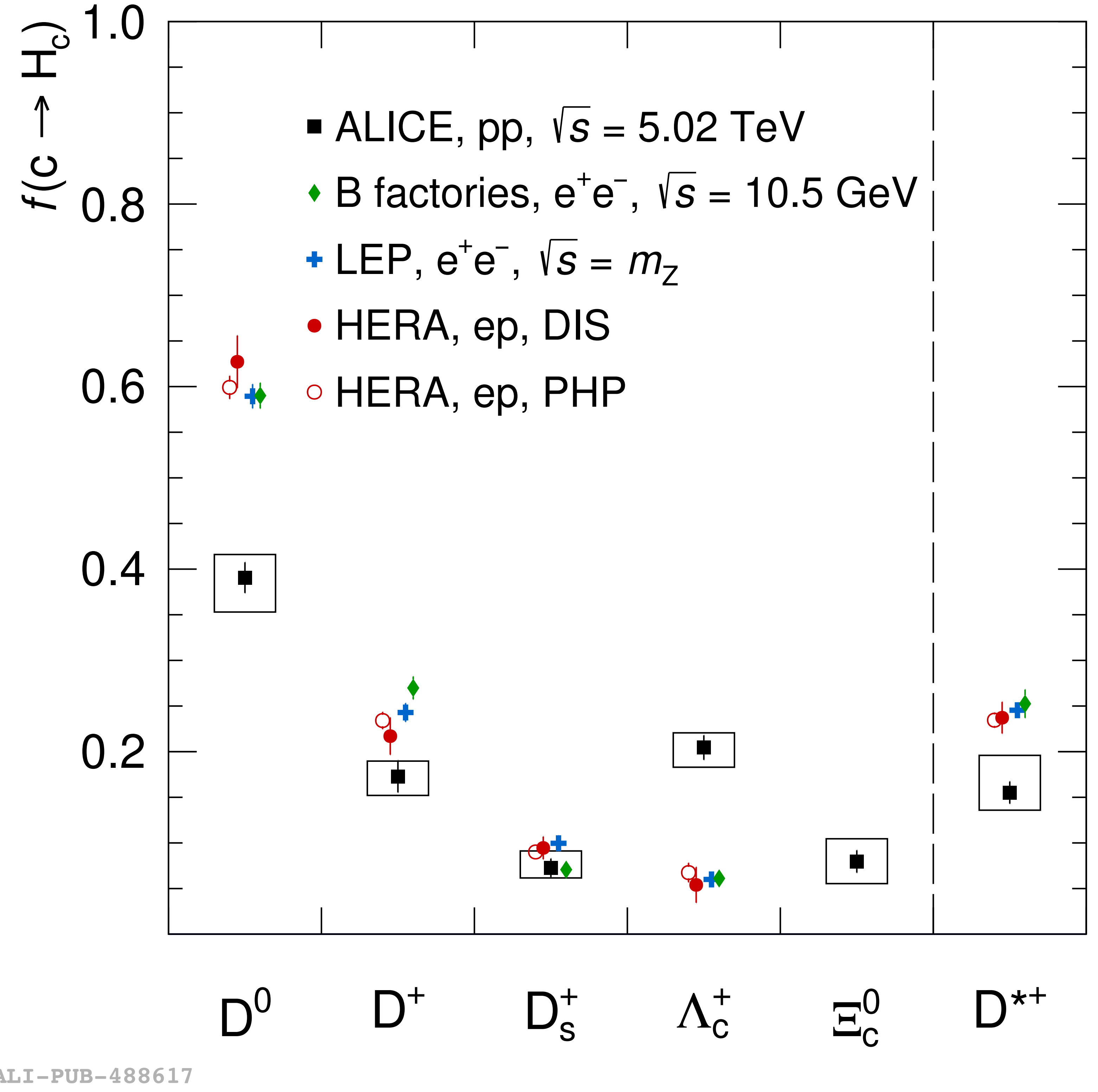
➡ What is thermalization DOF of beauty in the QGP medium?

Charm quark hadronizaton



- Hadronization non-universal between e-e+/ ep and pp collisions
- Additional constraint to hadronization — heavy quarks created in hard scatterings
- Important to calibrate heavy-quark observables for QCD matter studies

Charm quark hadronizaton



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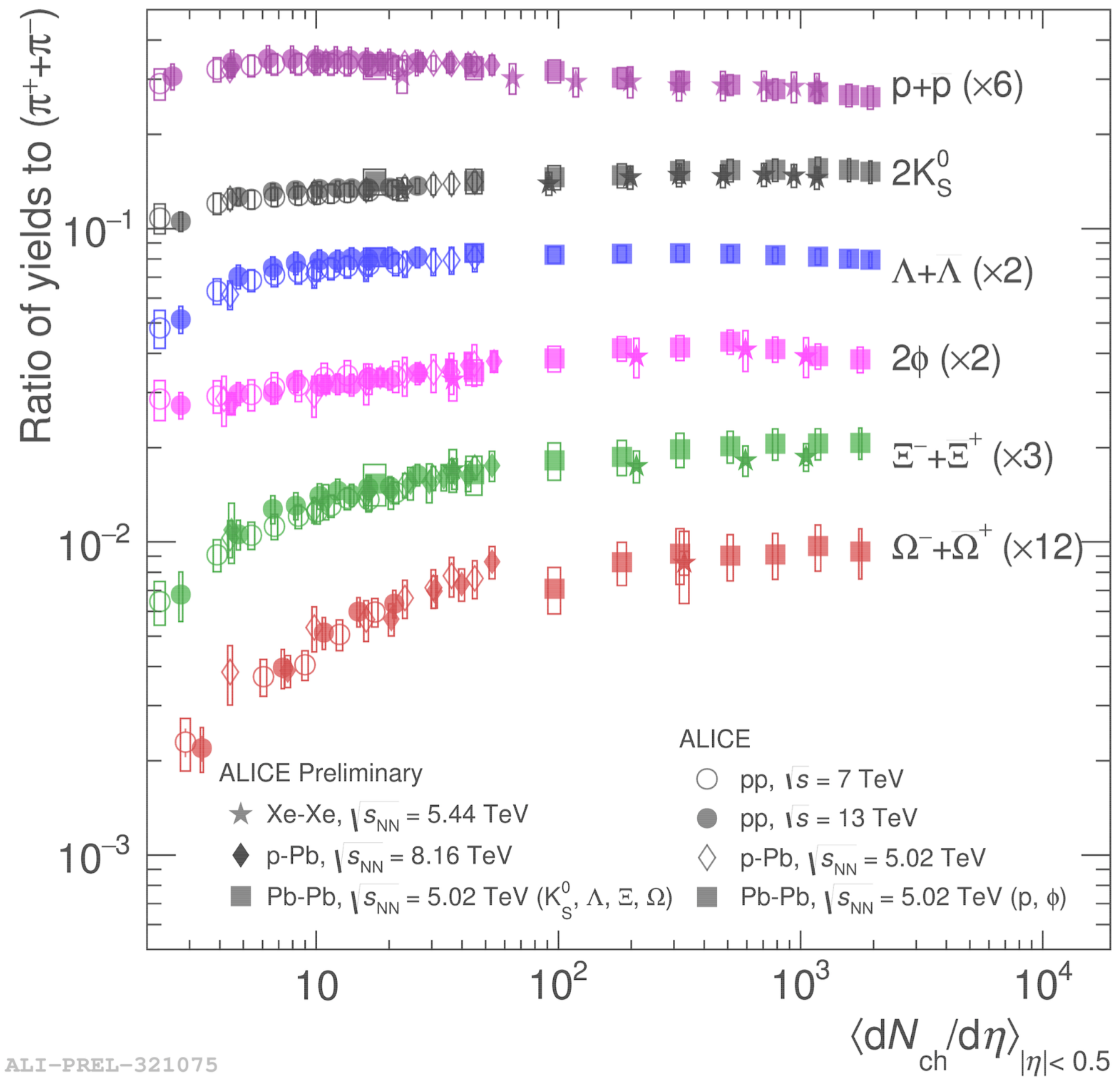
- Additional constraint to hadronization — heavy quarks created in hard scatterings
- Important to calibrate heavy-quark observables for QCD matter studies

$$\frac{\mathrm{d}\sigma^{\mathrm{pp}\to\mathrm{H_Q}}}{\mathrm{d}p_{\mathrm{T}}} = \sum_{ij} f_i(x_1,\mu_{\mathrm{F}}) f_j(x_2,\mu_{\mathrm{F}}) \otimes \frac{\mathrm{d}\sigma^{ij\to\mathrm{Q}}}{\mathrm{d}p_{\mathrm{T}}}(x_1 x_2,\mu_{\mathrm{F}},\mu_{\mathrm{R}}) \otimes D_{\mathrm{Q}\to\mathrm{H_Q}}\left(z_{\mathrm{Q}} = \frac{p_{\mathrm{H_Q}}}{p_{\mathrm{Q}}},\mu_{\mathrm{F}}\right)$$

Parton distribution functions (PDF) | Hard scattering cross section (pQCD) | Fragmentation function (Hadronization)

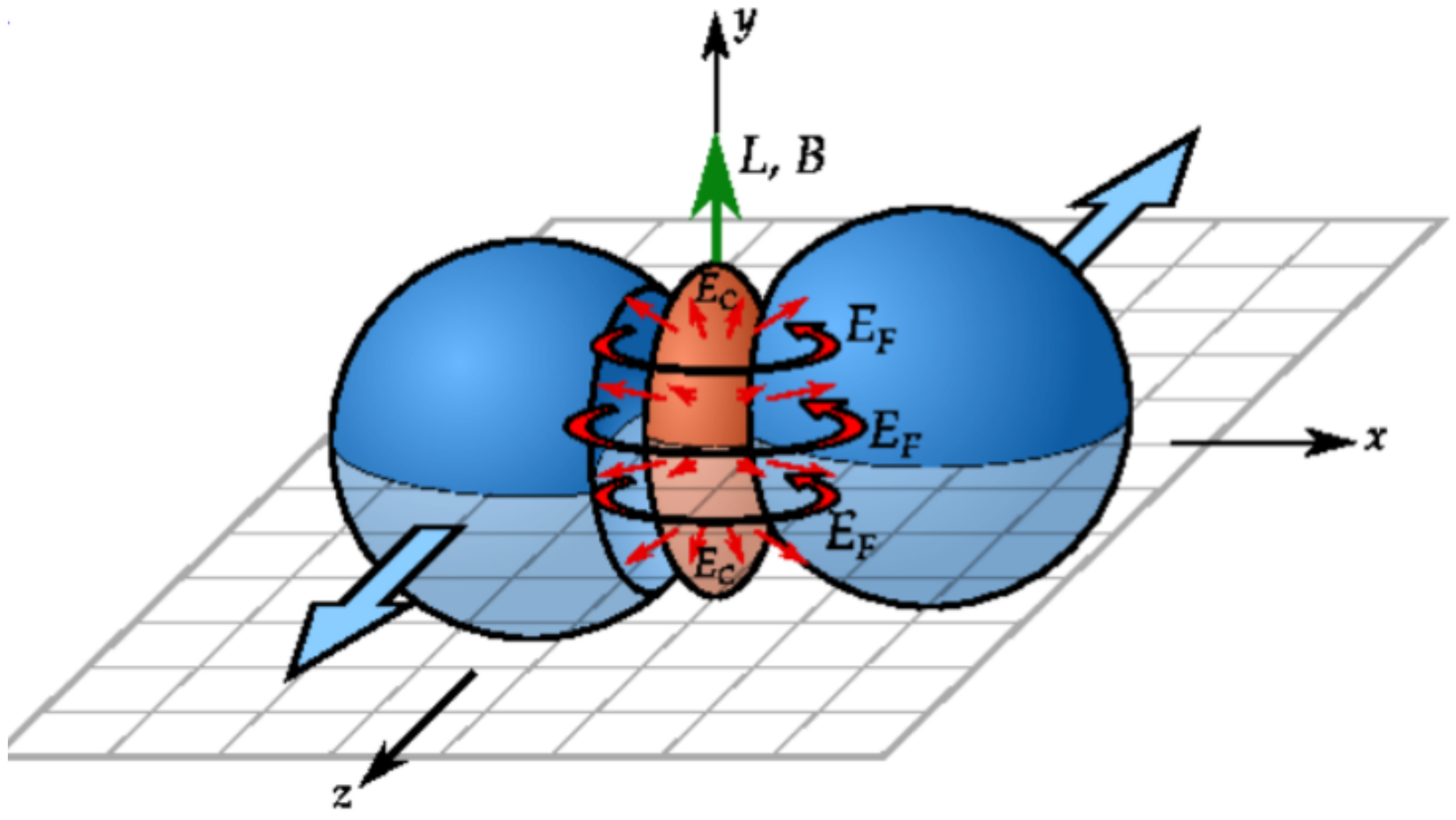
The “pandora box” at the LHC



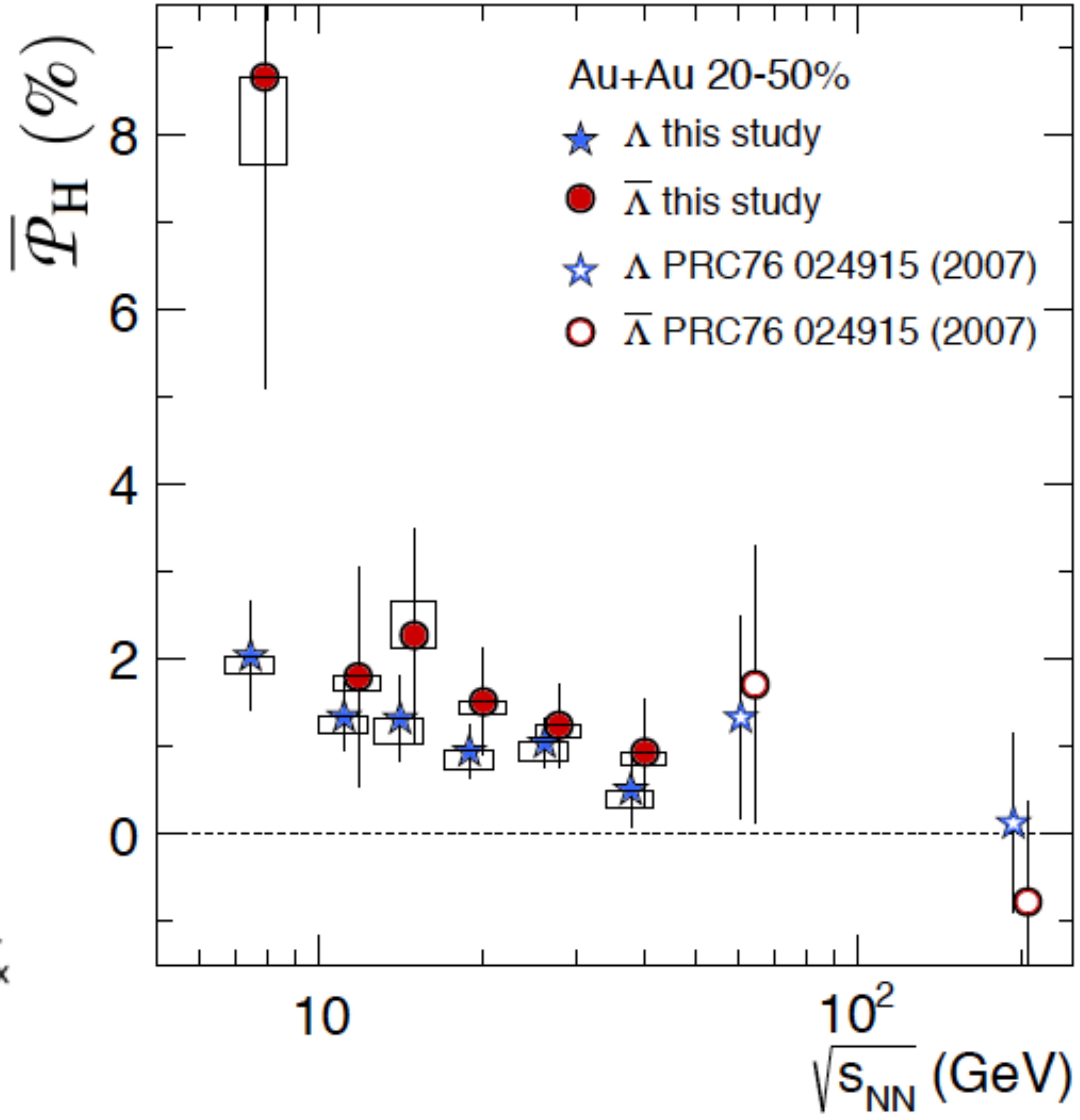
ALICE *Nature Phys* 13 (2017) 535
ALICE *Eur. Phys. J.* C80 (2020) 167

- 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?

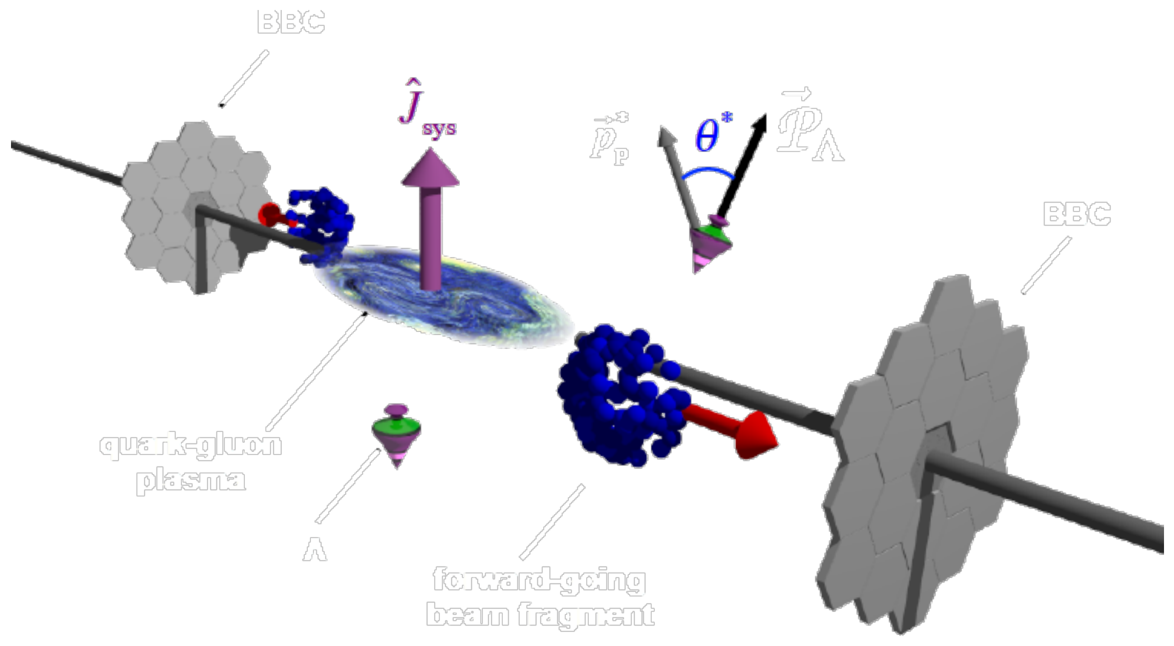
Spin alignment

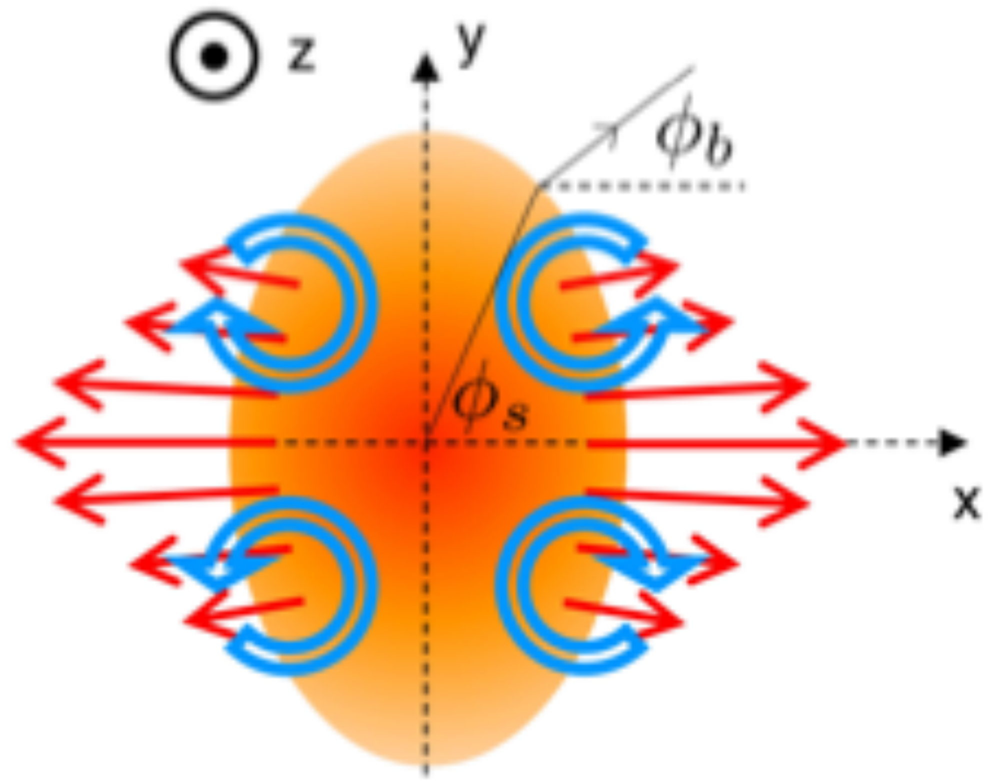


STAR *Nature* **548** (2017) 62

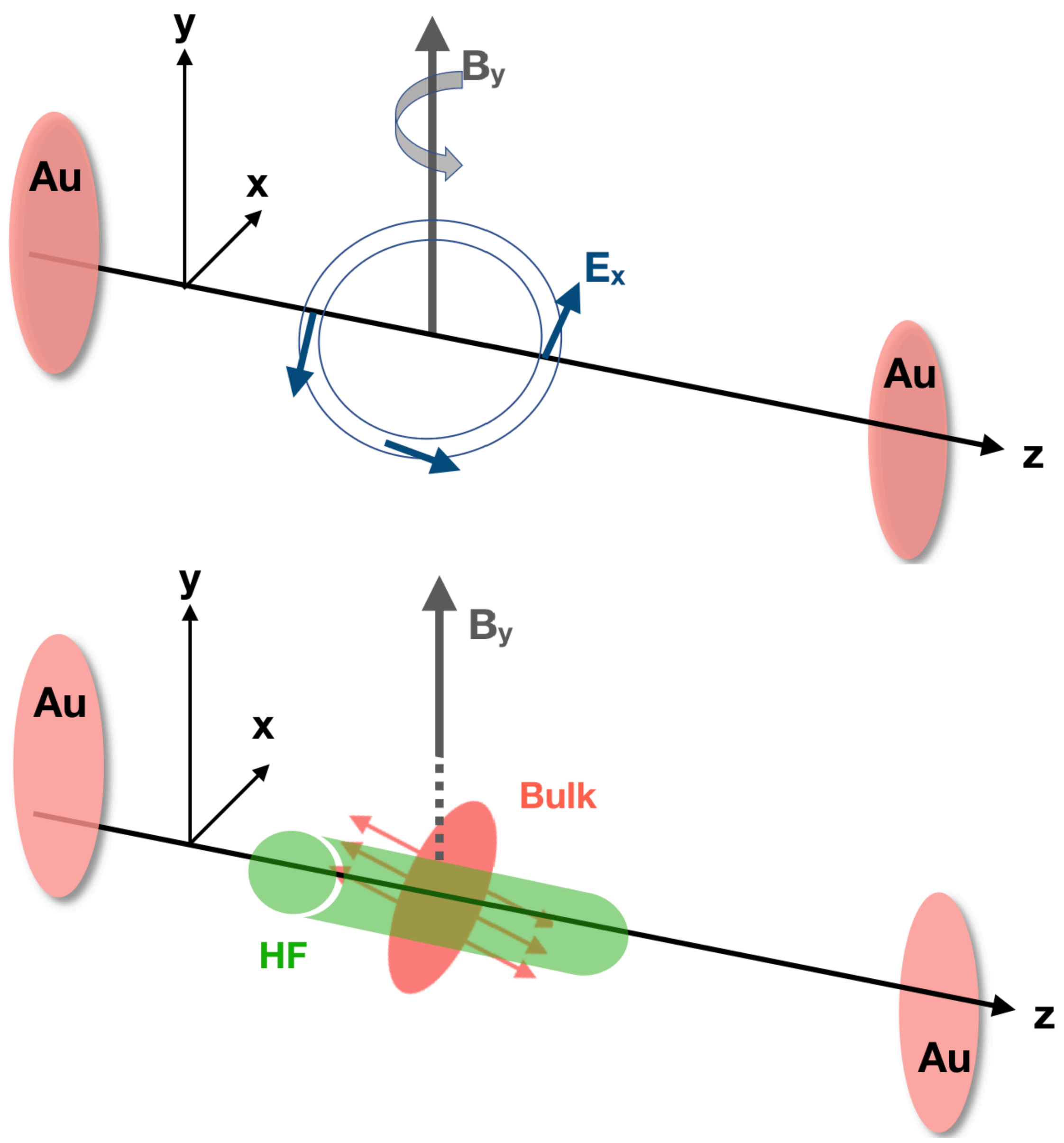


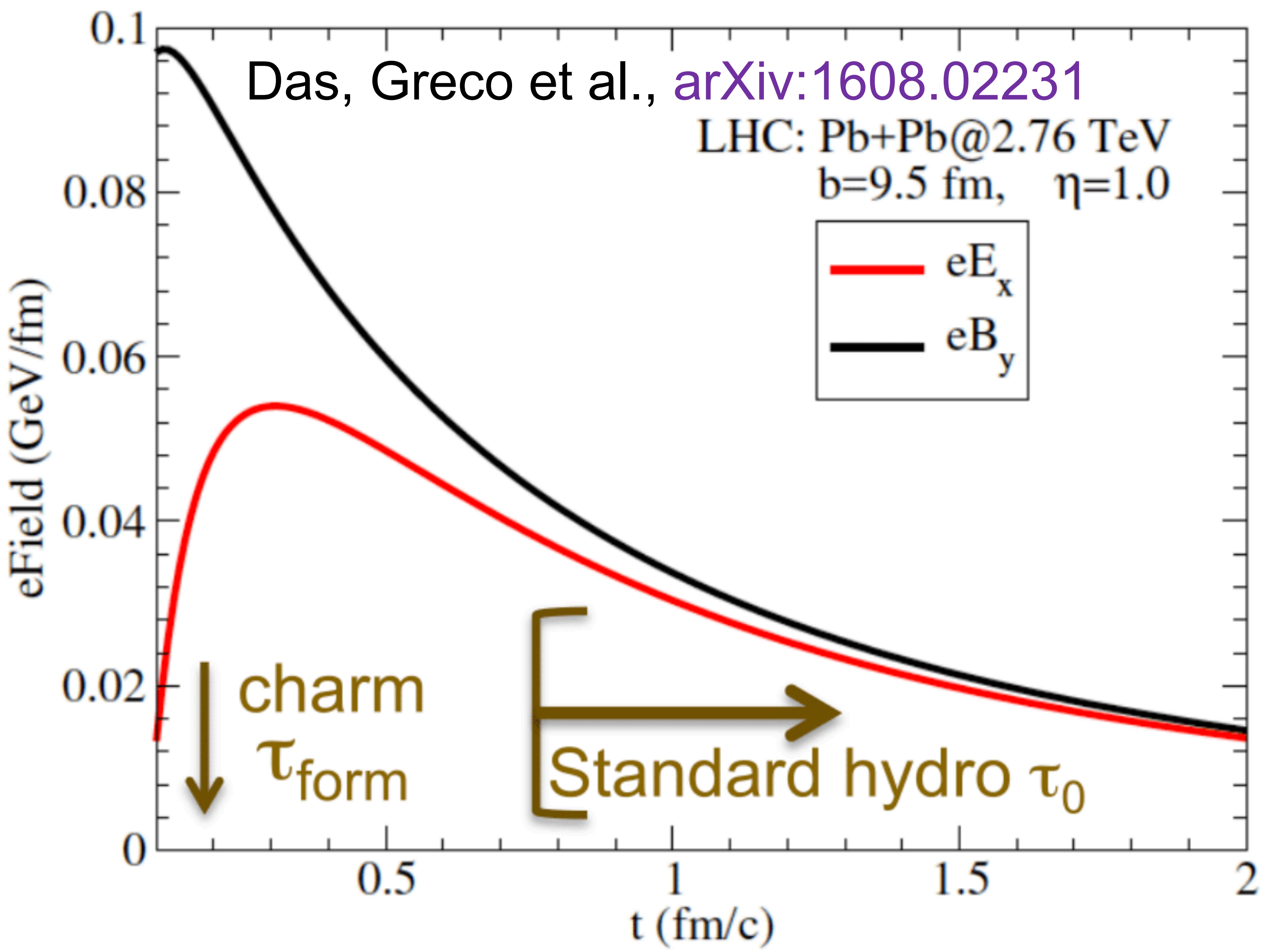
- Large angular momentum in non-central collisions — rotating QGP (~10^{21} r/s)

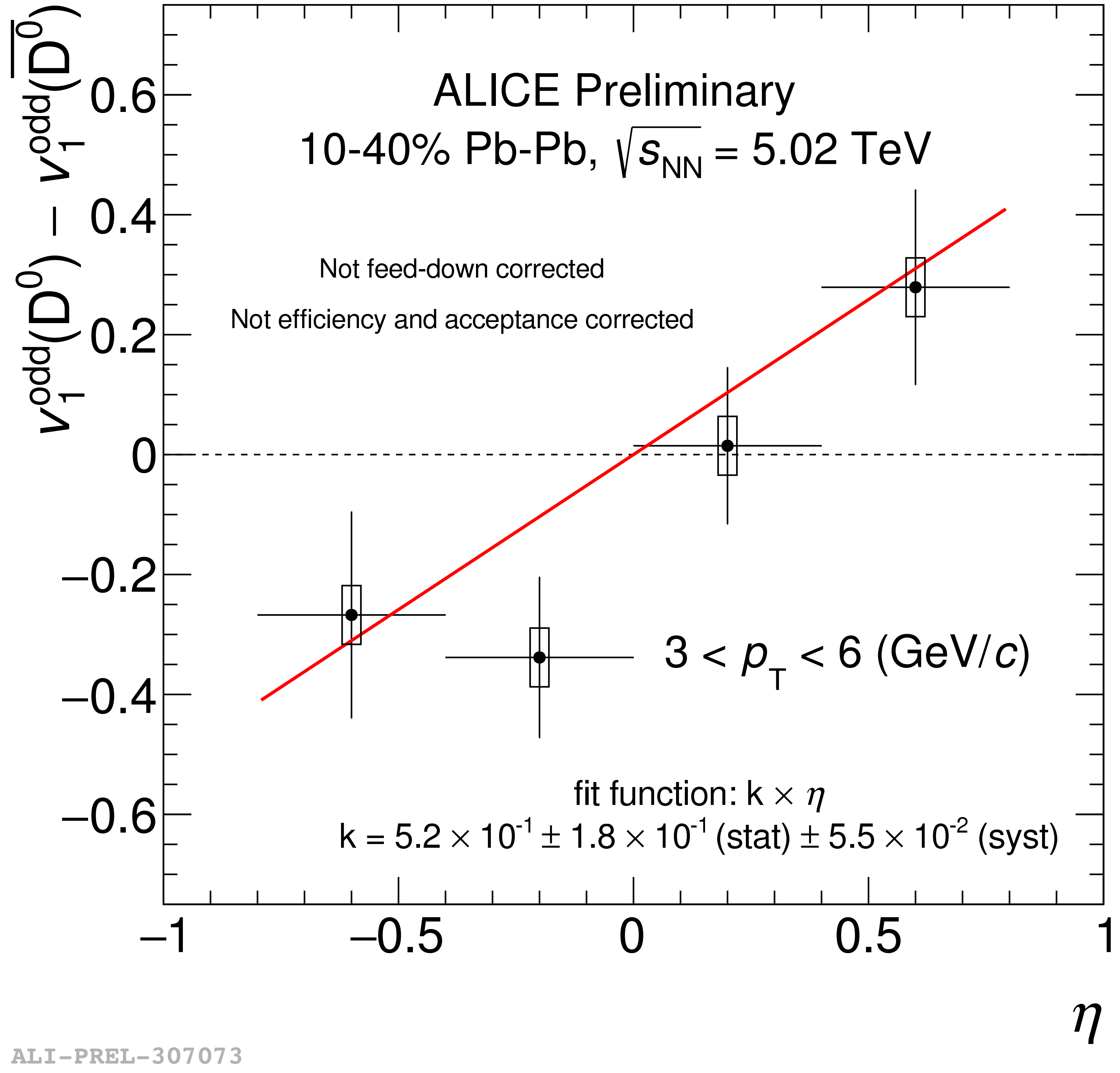


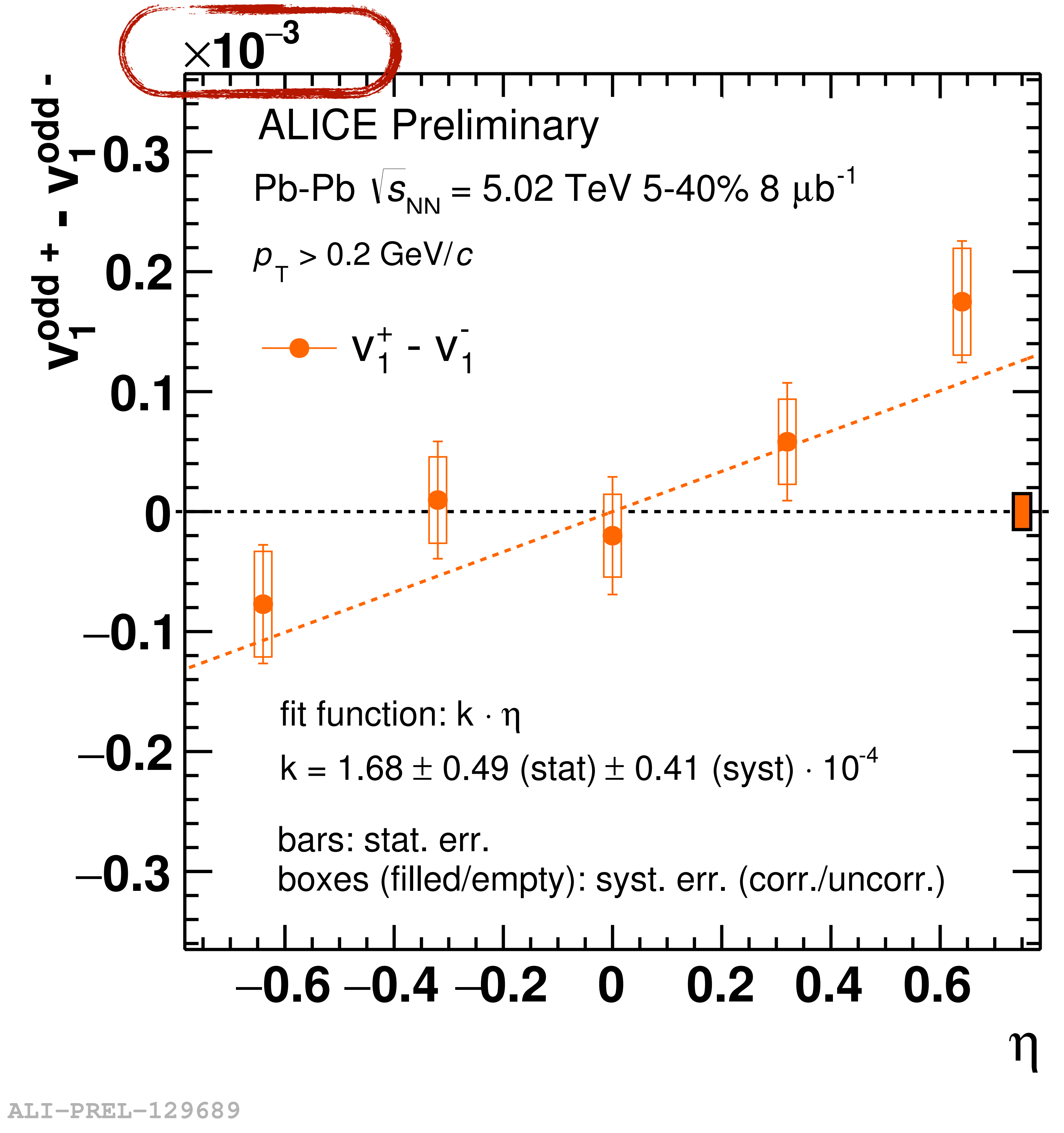


Magnetic field effects







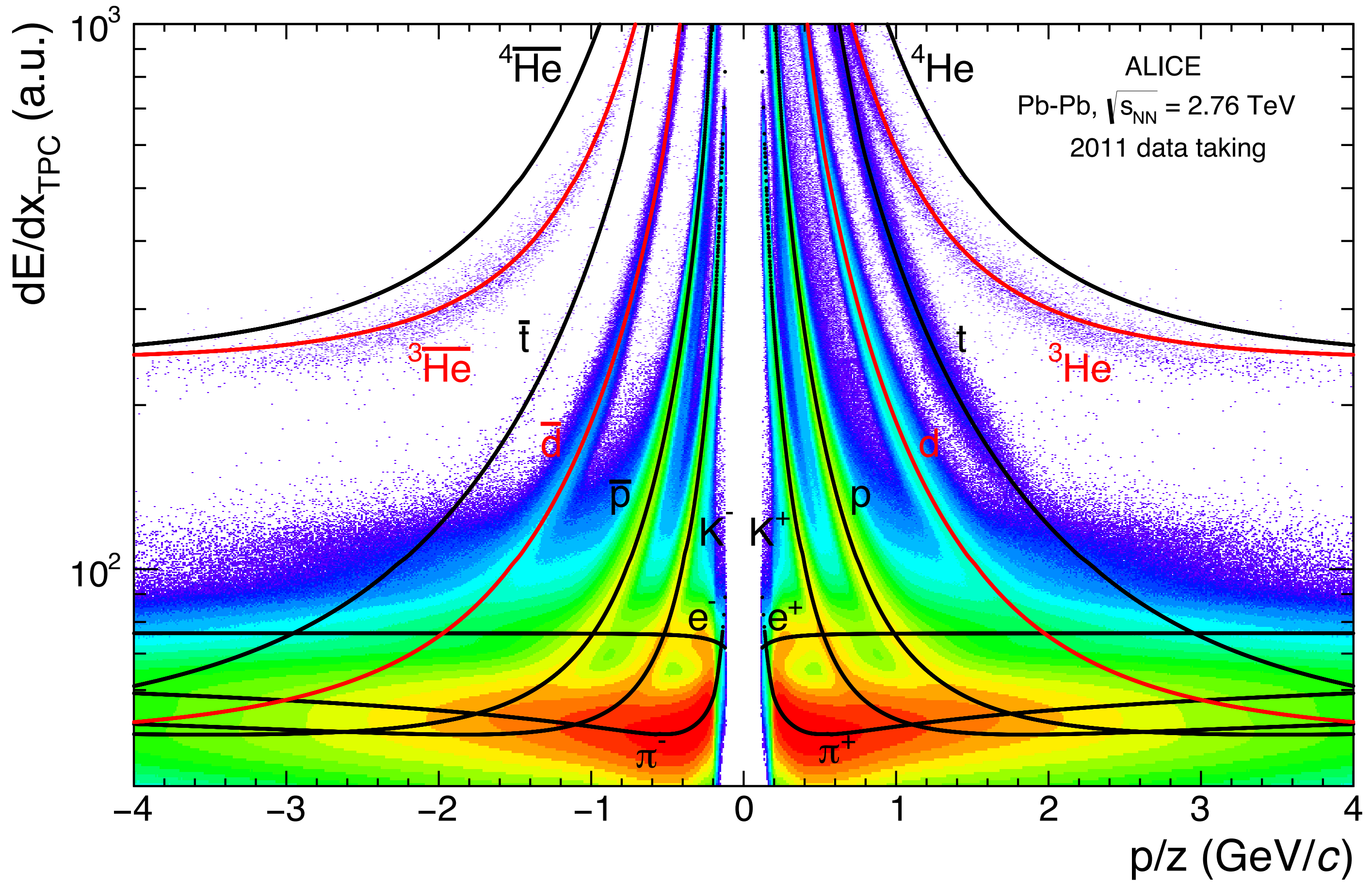


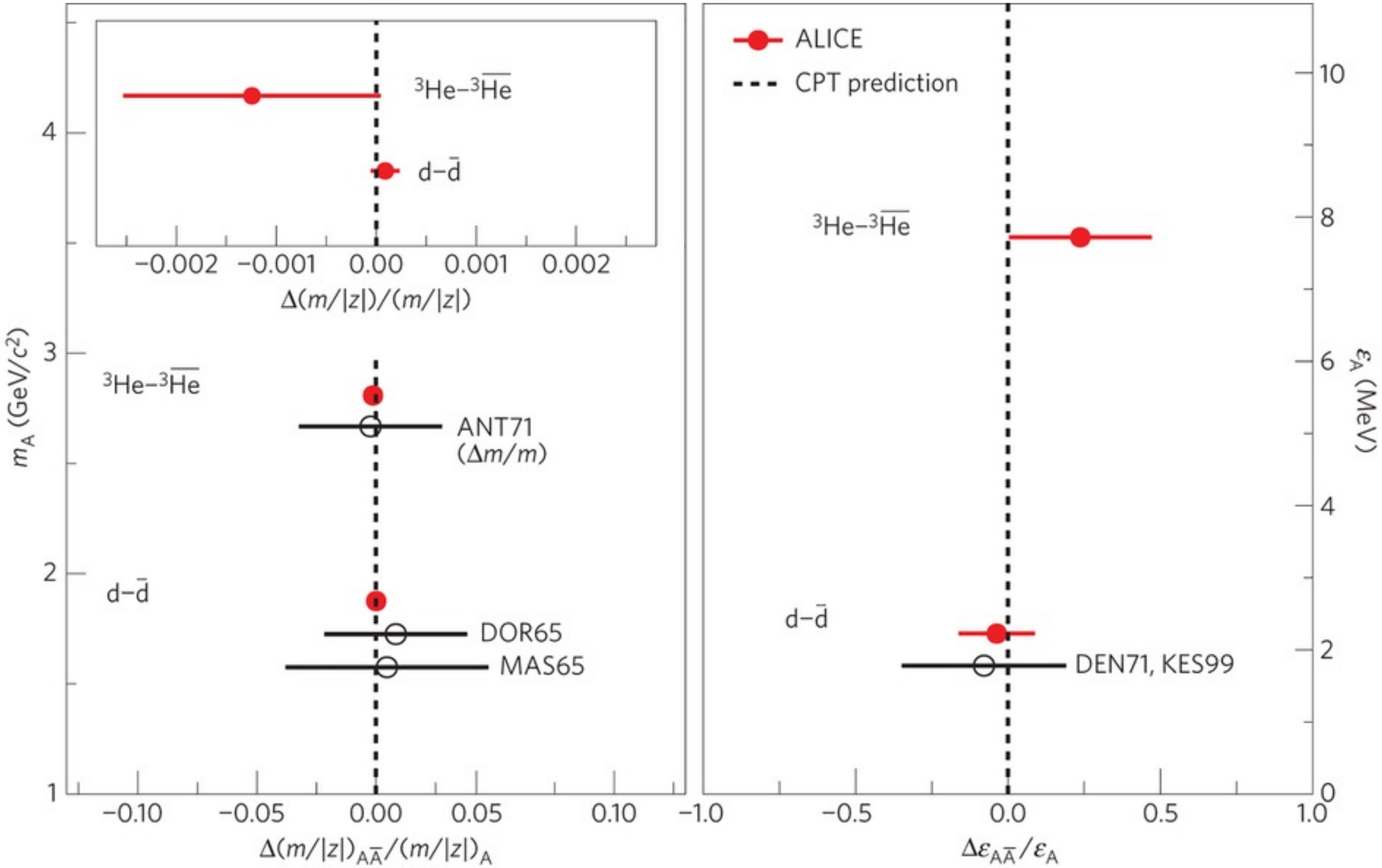
Hint of positive slope with a significance of 2.7σ

Similar trend observed for charged particles, but different magnitude

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)

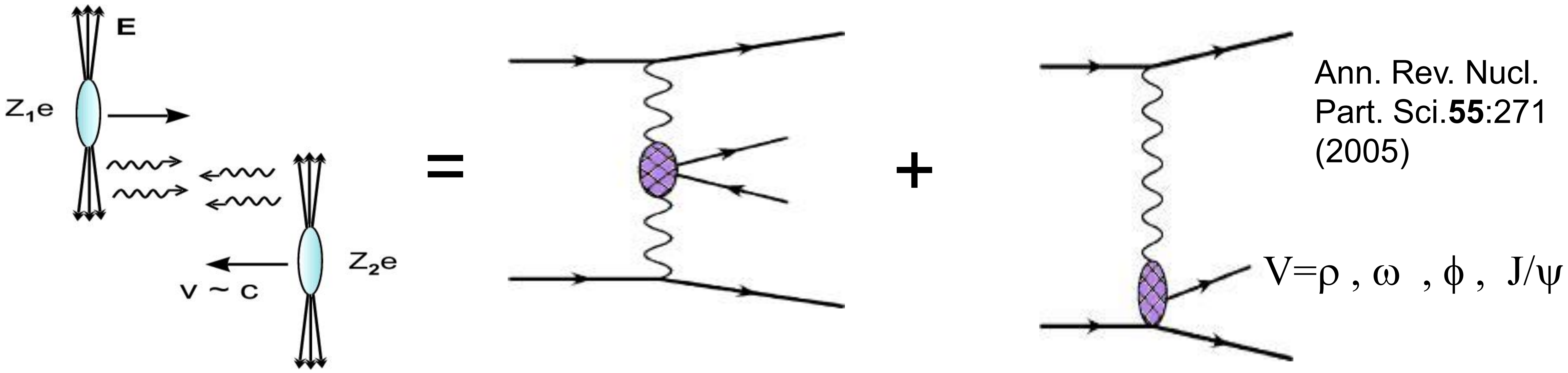




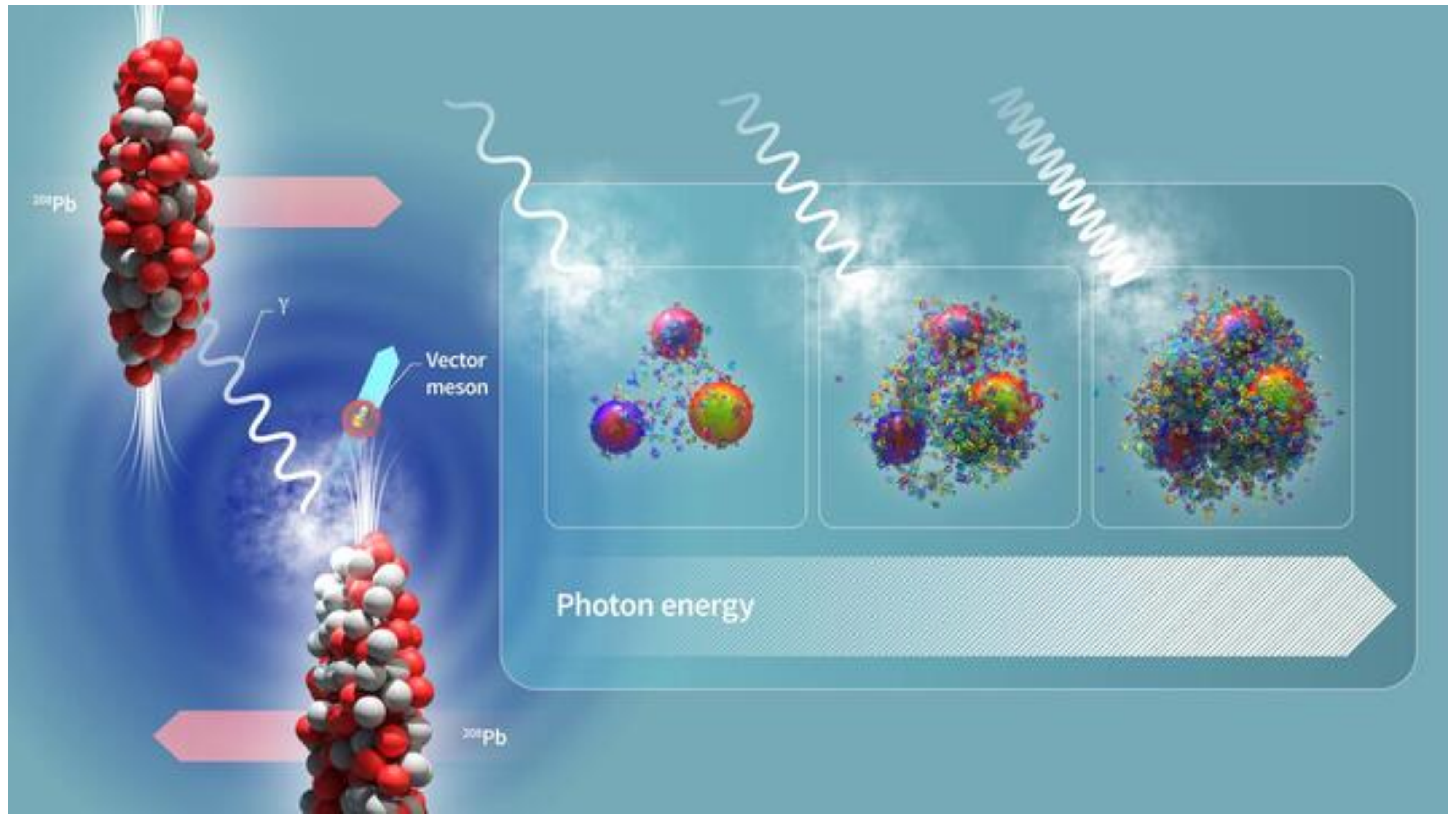
- Improved by one to two orders of magnitude compared to earlier measurements
- First measurement of binding-energy for (anti-)^{3}He
- Confirms CPT invariance for light nuclei

ALICE *Nature Physics* 11 (2017) 811

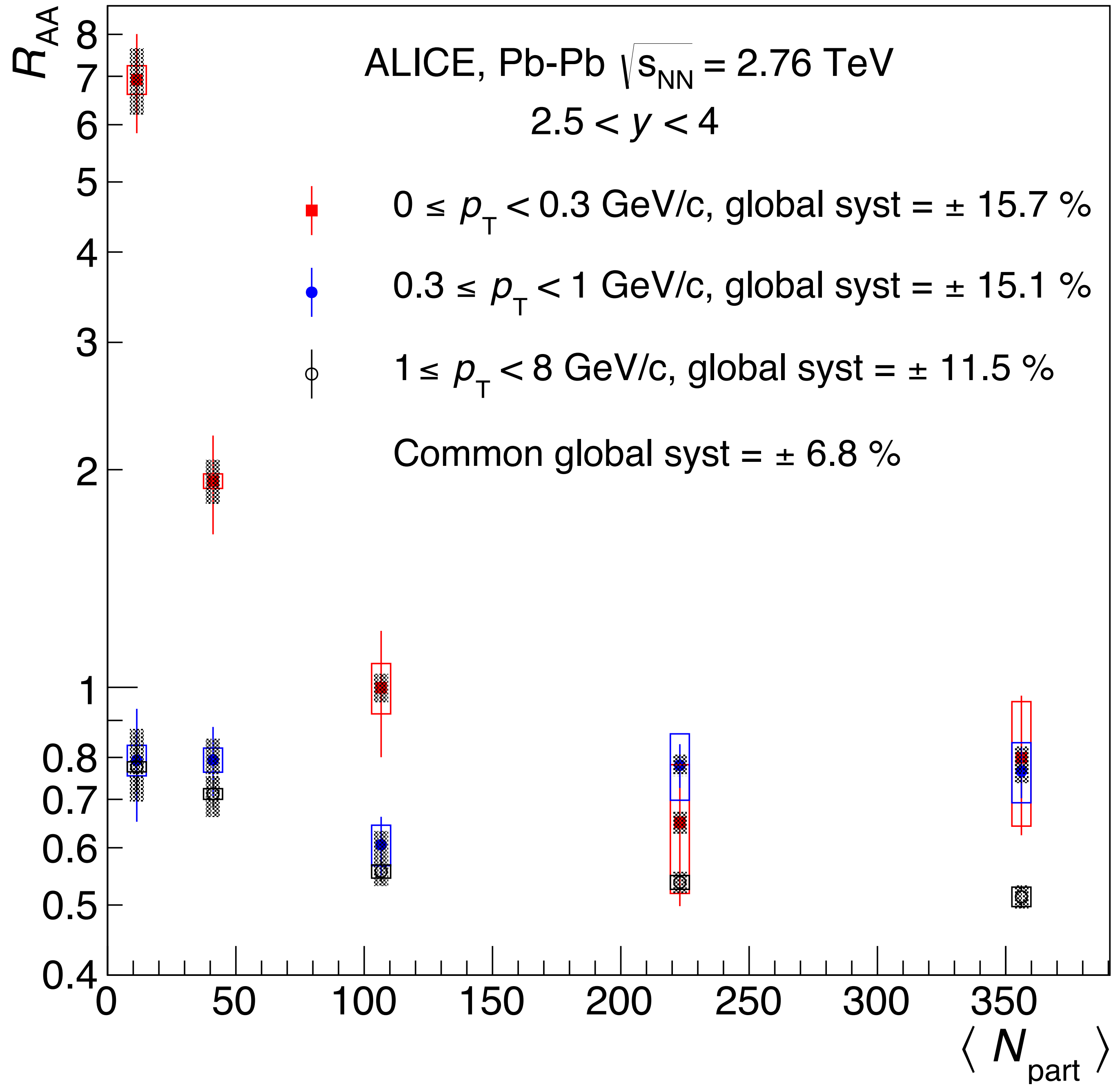
Photon interactions



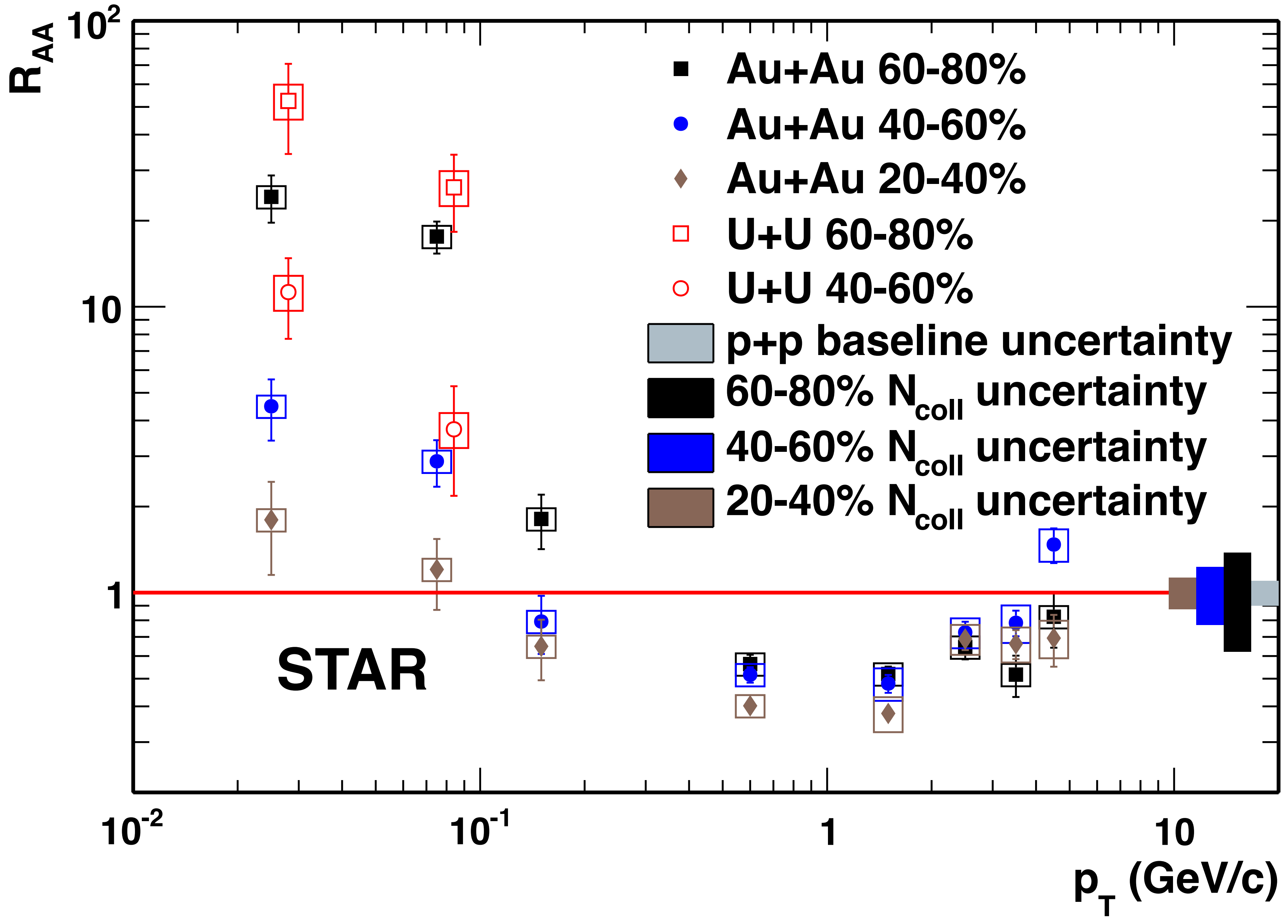
Ann. Rev. Nucl. Part. Sci. **55**:271 (2005)



ALICE *Phys. Rev. Lett.* **116** (2016) 222301

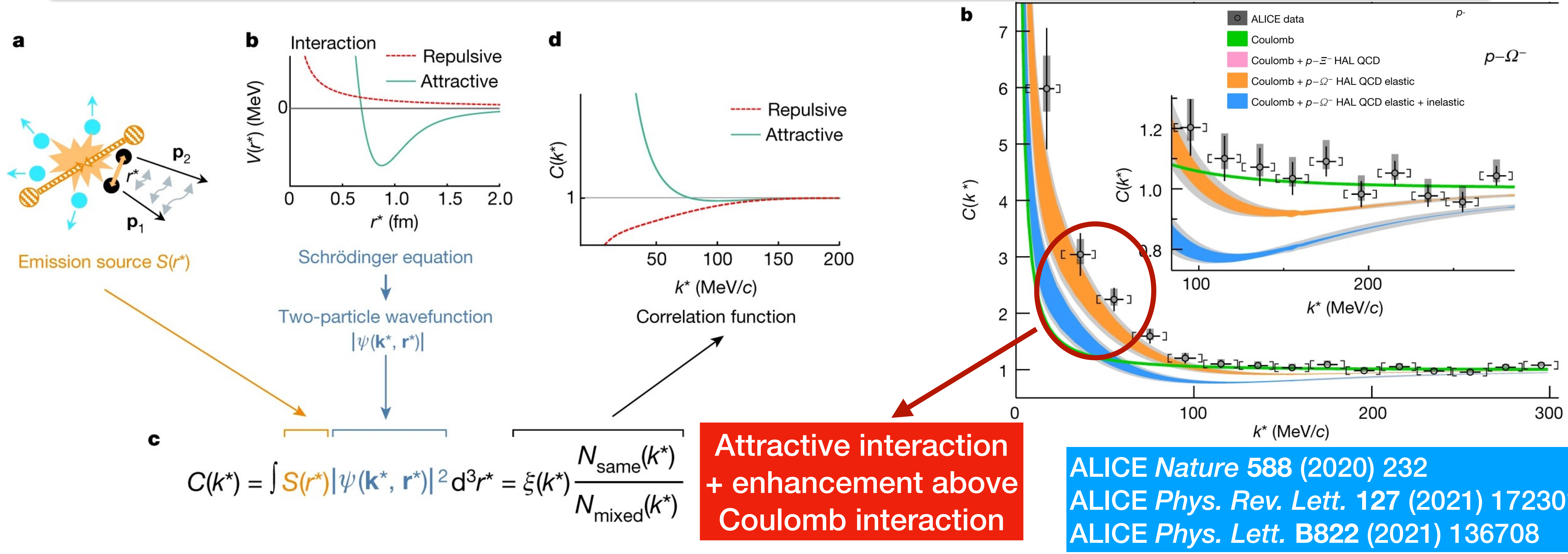


STAR *Phys. Rev. Lett.* **123** (2019) 132302



- Exceed J/ψ at low-p_T: coherent photo-production
- Sensitive to gluon distribution function at very low Bjorken-*x*

Unveiling strong interaction

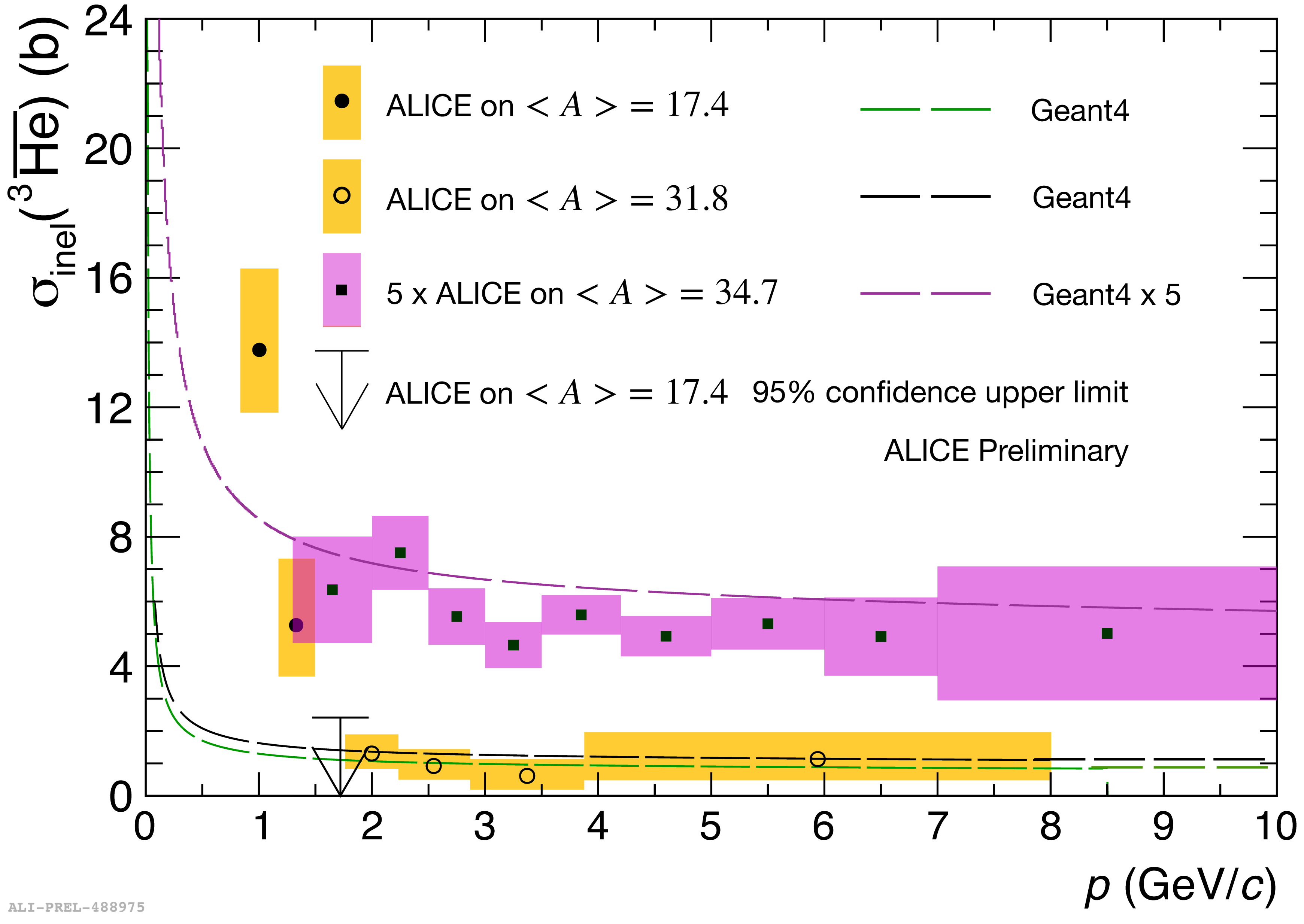


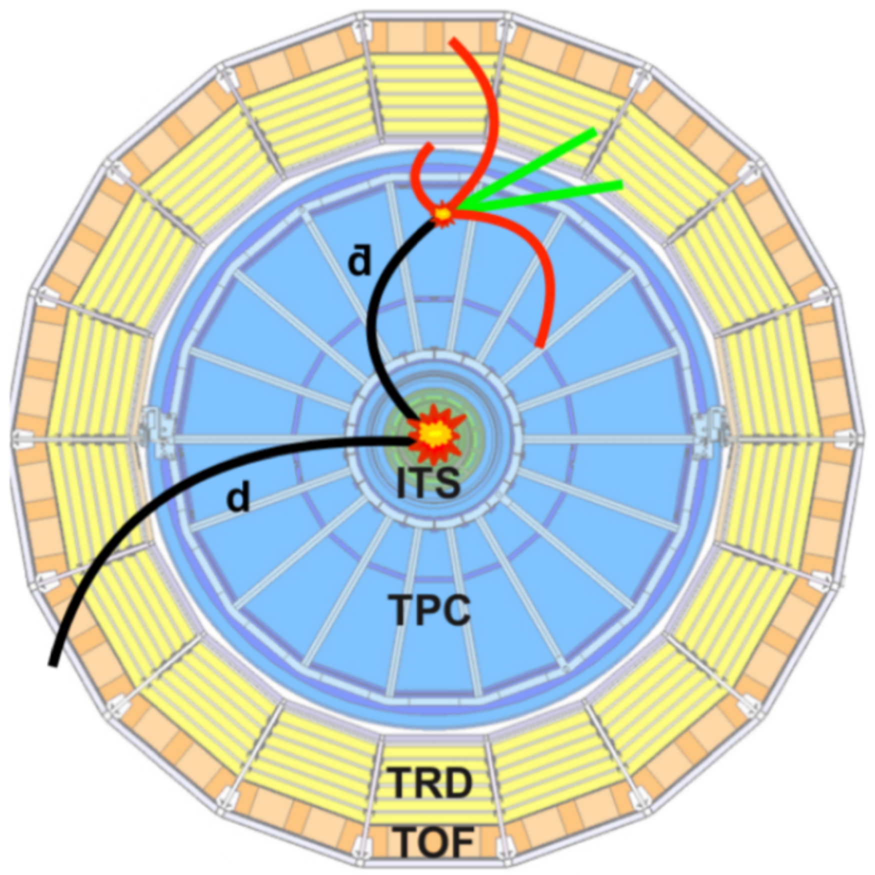
Attractive interaction + enhancement above Coulomb interaction

ALICE *Nature* **588** (2020) 232
ALICE *Phys. Rev. Lett.* **127** (2021) 172301
ALICE *Phys. Lett.* **B822** (2021) 136708

- Unveiling strong-interaction potentials among hadrons via femtoscopy
- Important test for lattice QCD, input for EOS of neutron stars

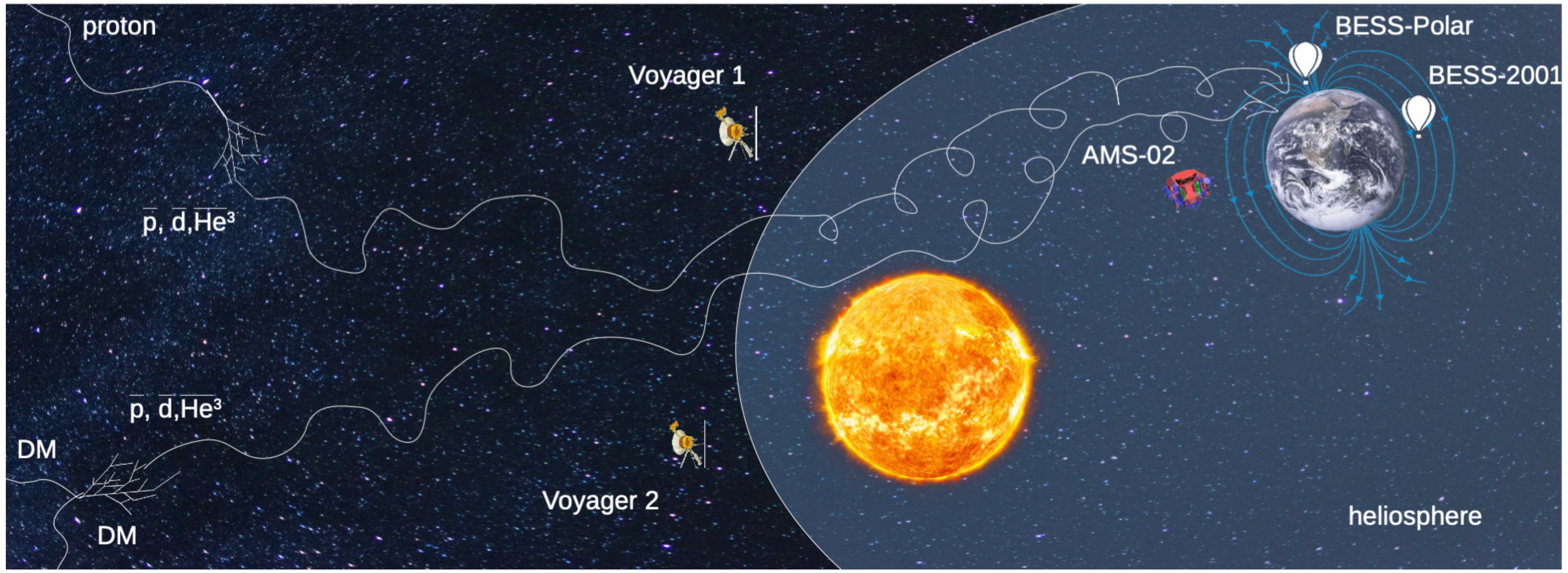
(Anti-)nuclei factory





- Production not yet fully understood
- Nucleon coalescence, statistical hadronizaton…
- New tool to study QGP hadronizaton

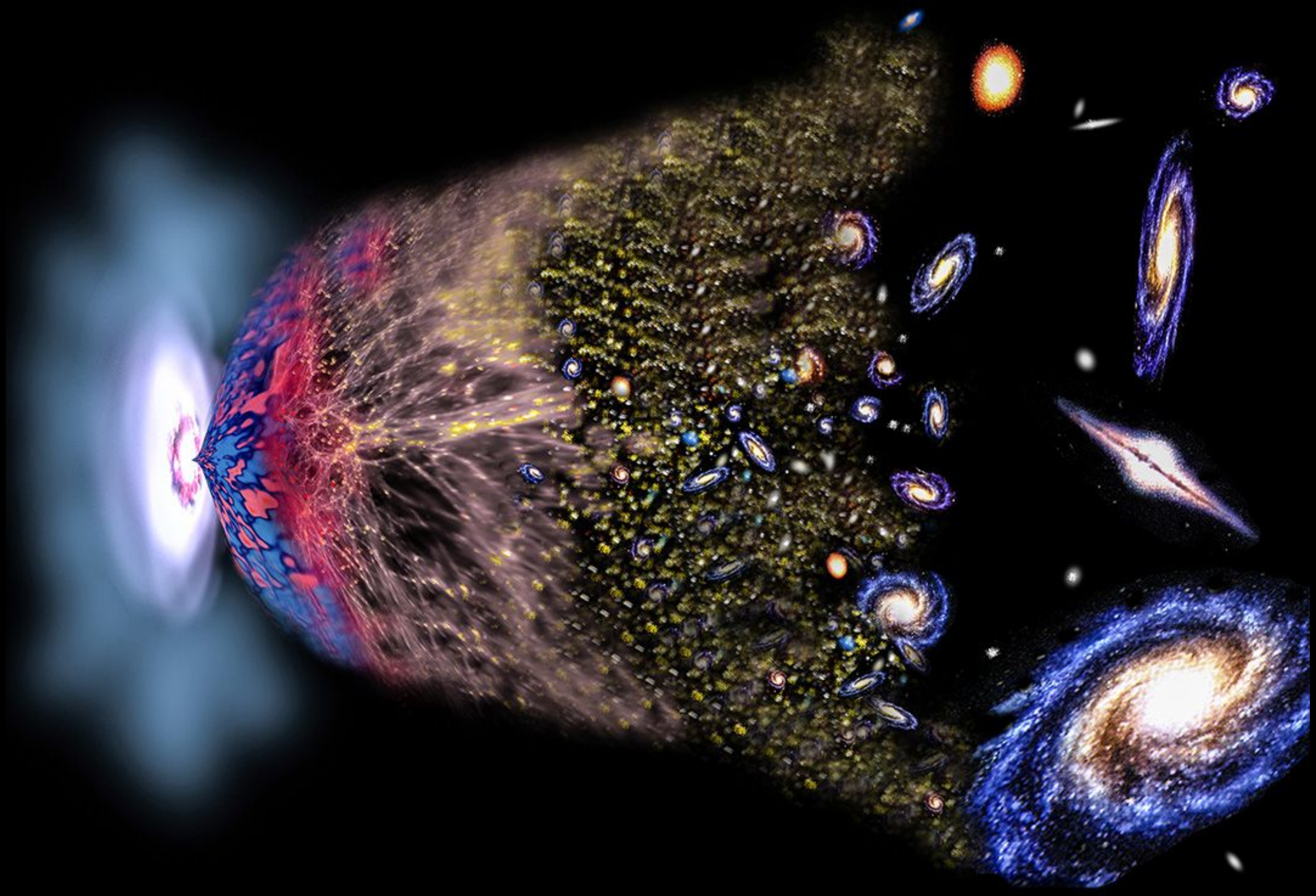
ALICE *Phys. Rev. Lett.* **127** (2021) 172301
Nature Phys. **19** (2023) 61



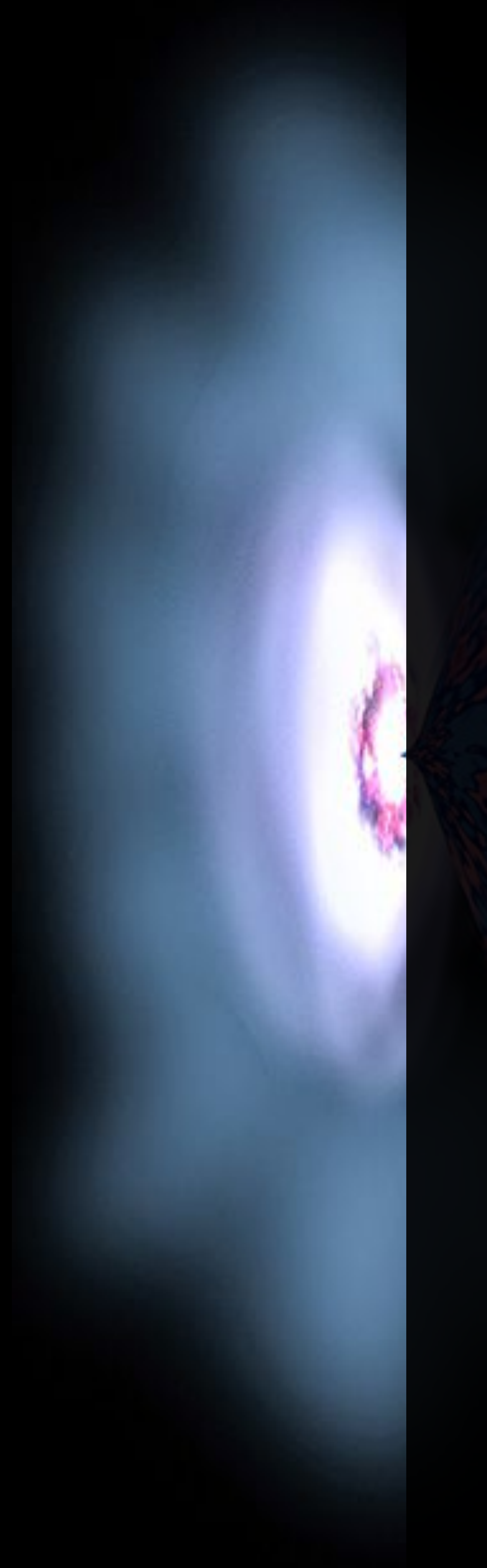
- Strong impact on Dark Matter searches, e.g.

➡ $\chi_0\chi_0 \rightarrow \bar{\mathrm{d}}, \overline{^3\mathrm{He}} + X$

Backup



Plank epoch



- God created the Universe at

$$t = 0$$

- Physics started at

$$t \approx t_P \approx 10^{-43}\ \text{s}$$

- Temperature

$$T(t_P) \approx m_P \approx 10^{19}\ \text{GeV}$$

- Gravitational interaction is strong, classical concept of space-time breaks down

Conjectural epochs

$$T(t) = \sqrt{\frac{\hbar m_P}{g^{1/2} t}}$$

- **Grand unified epoch**

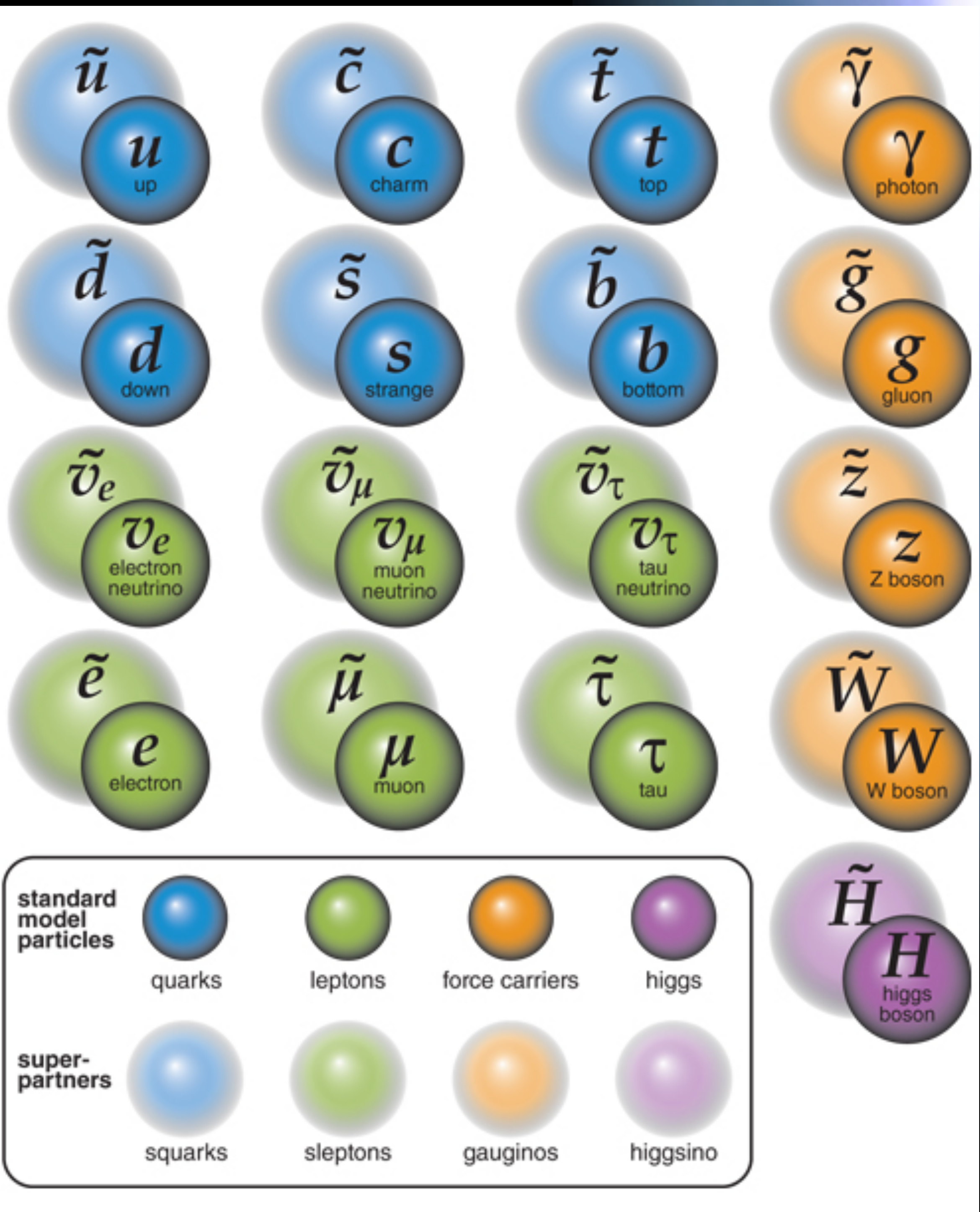
  $t < 10^{-36}$ s, $T > 10^{16}$ GeV

  Currently no hard evidence that nature is described by a Grand Unified Theory

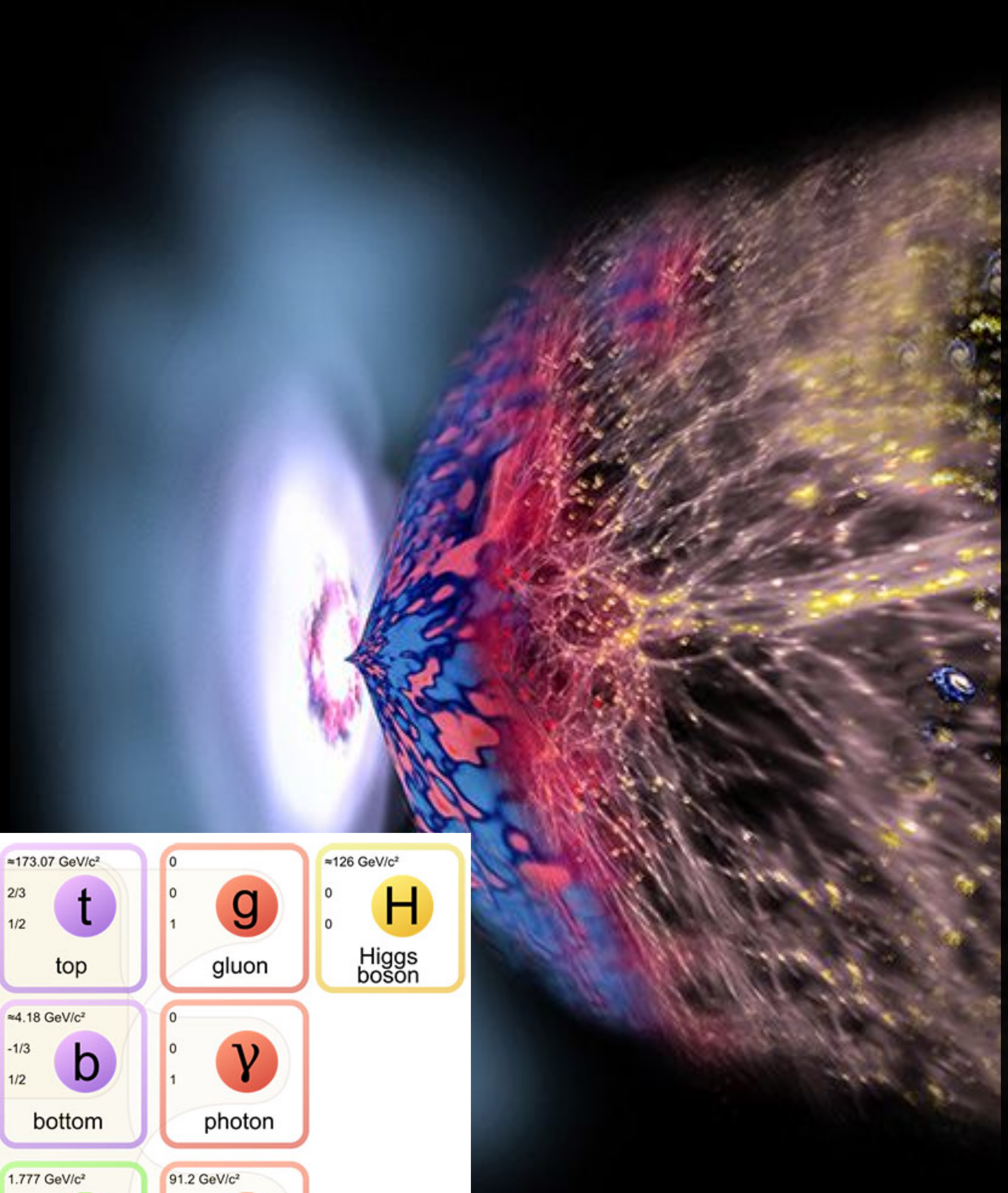
- **Inflection epoch**

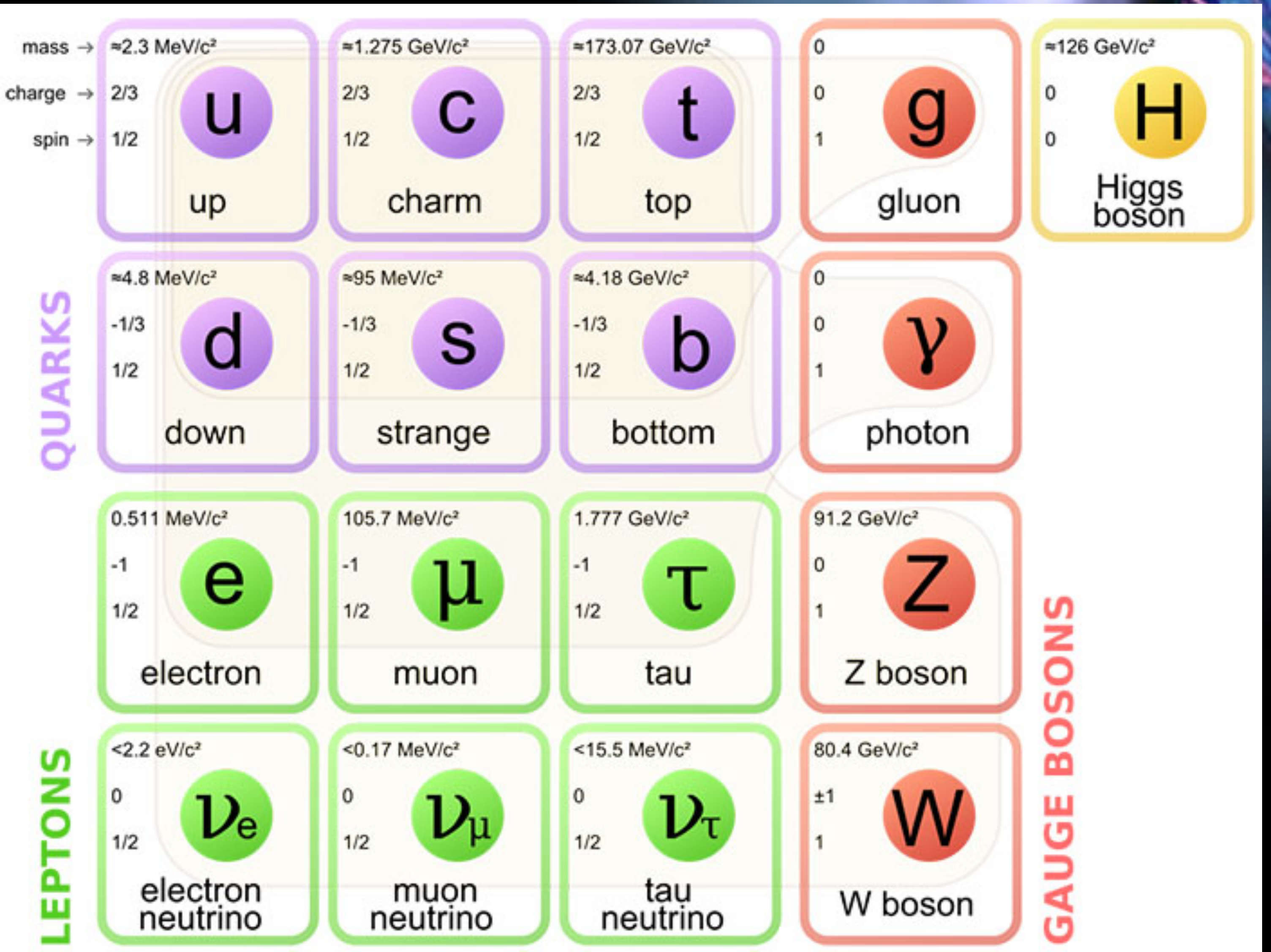
  $10^{-36} < t < 10^{-32}$ s

  The detailed particle physics mechanism responsible for inflation is unknown



Standard model epochs





$$T(t) = \sqrt{\frac{\hbar m_{\mathrm{P}}}{g^{1/2} t}}$$

- **Electroweak epoch ends at**

  $t \approx 10^{-12}$ s, $T \approx 150$ GeV

- **Quark epoch**

  $10^{-12} < t < 10^{-5}$ s

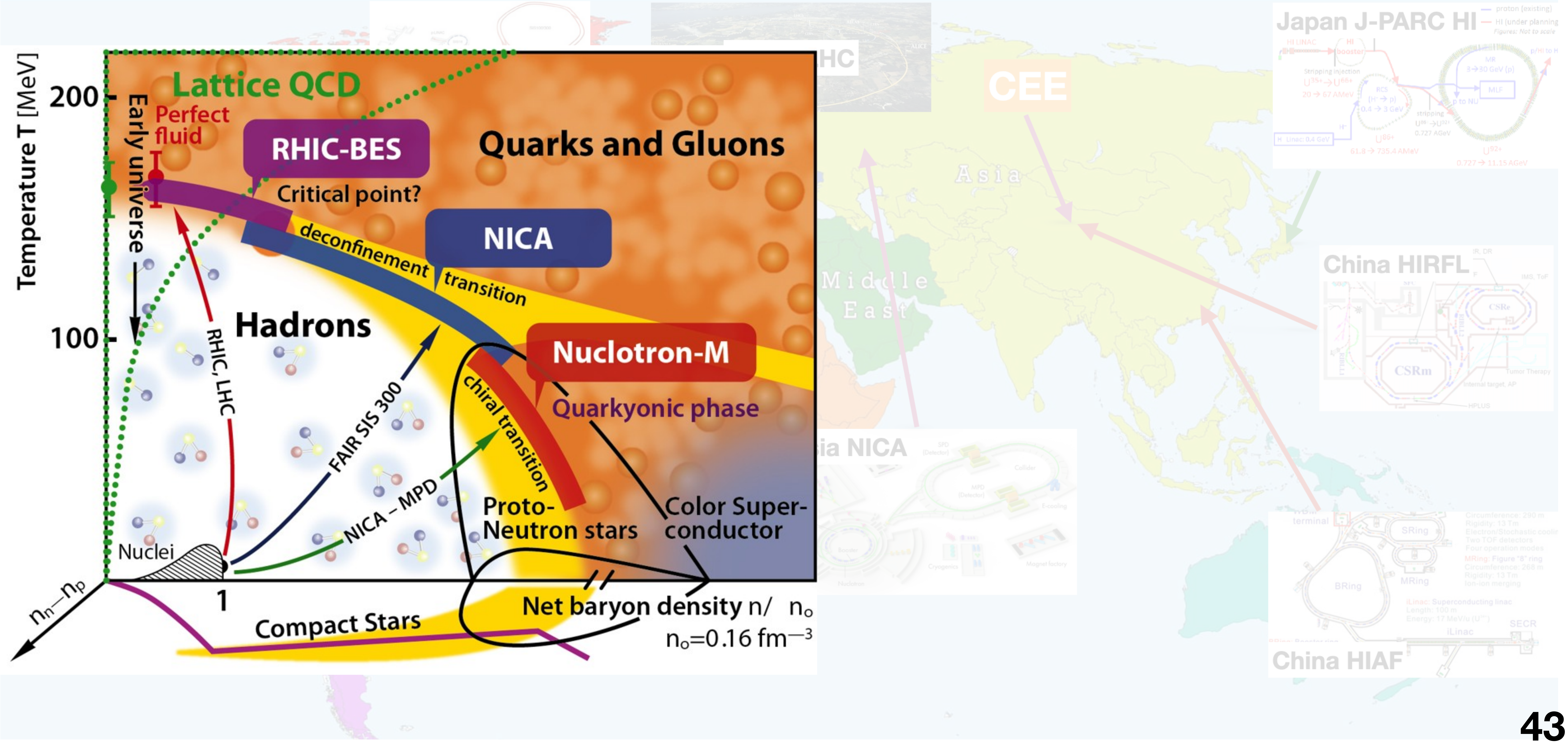
  150 MeV $< T <$ 150 GeV

- **Hadron epoch starts at**

  t $\approx 10^{-5}$ s, $T <$ 150 MeV

Heavy-ion program

Heavy-ion program



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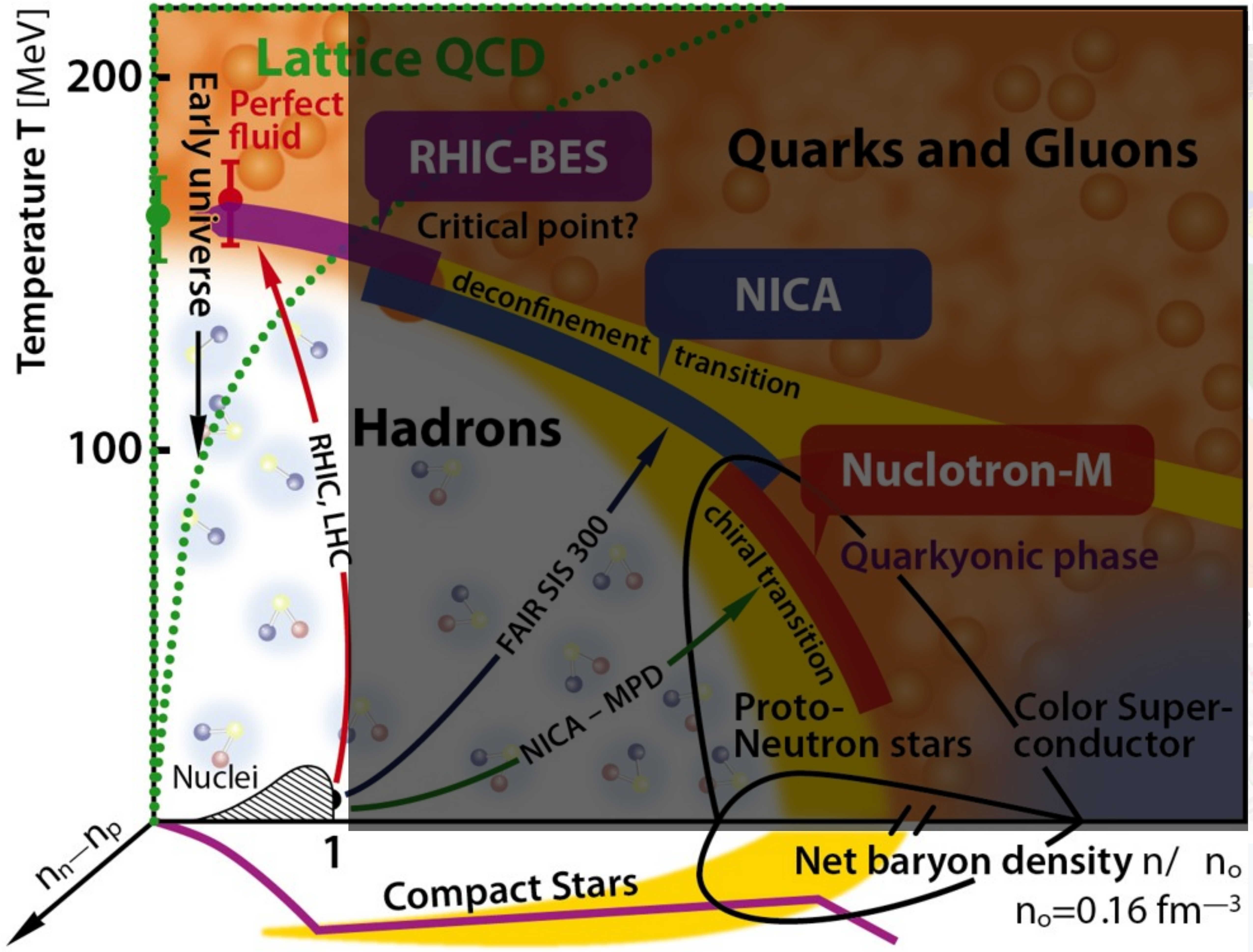


High temperature and low μ_B: LHC, RHIC

- Global properties (T, η/s…) and collectivity
- Hard probes (jets, heavy quarks…)

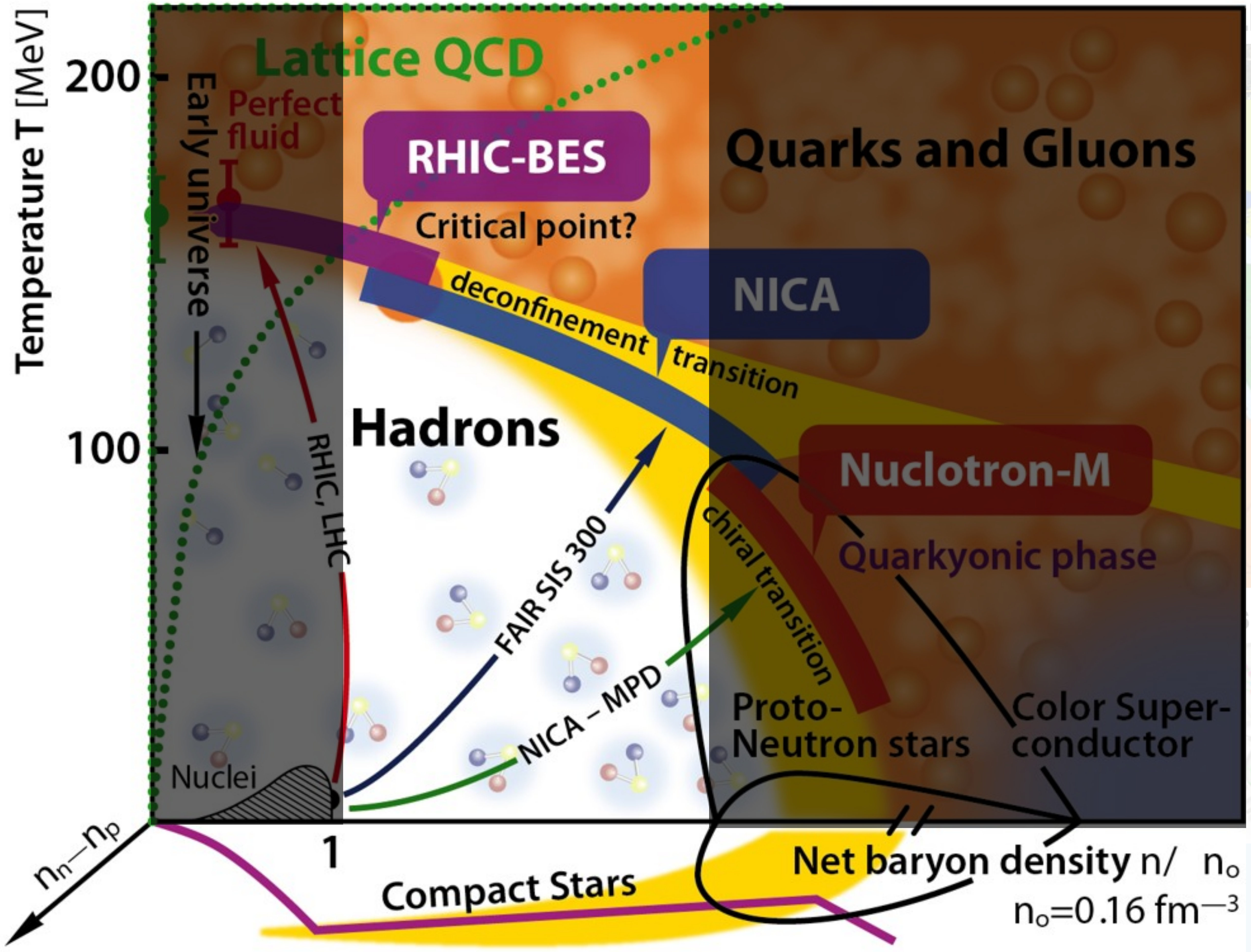
Finite temperature and μ_B: RHIC-BES, NICA

- Critical point search
- Correlations, di-lepton production…

Low temperature and large μ_B: NICA, FAiR

- Search rich structure of phase diagram
- EOS at large μ_B, chiral symmetry…

Heavy-ion program



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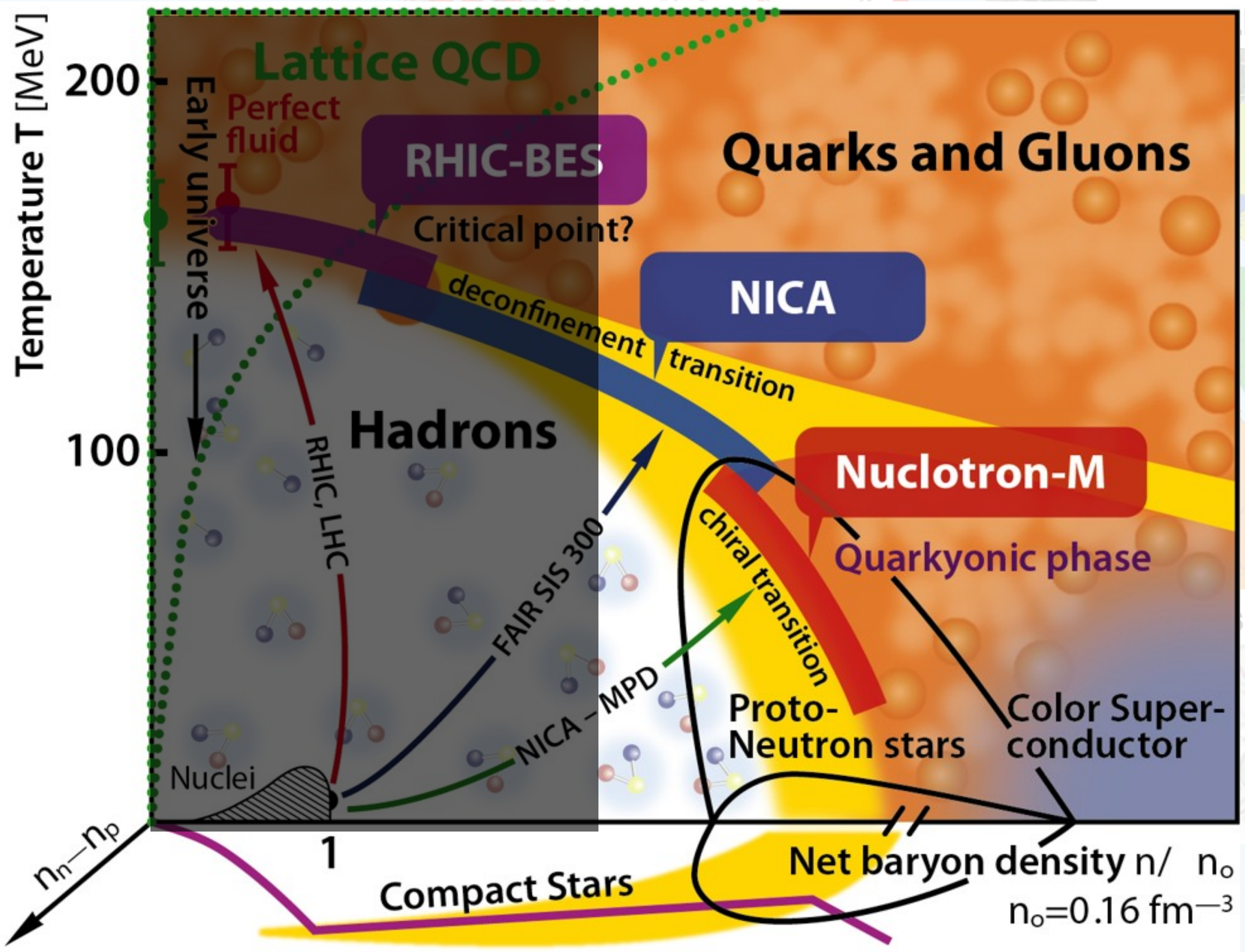

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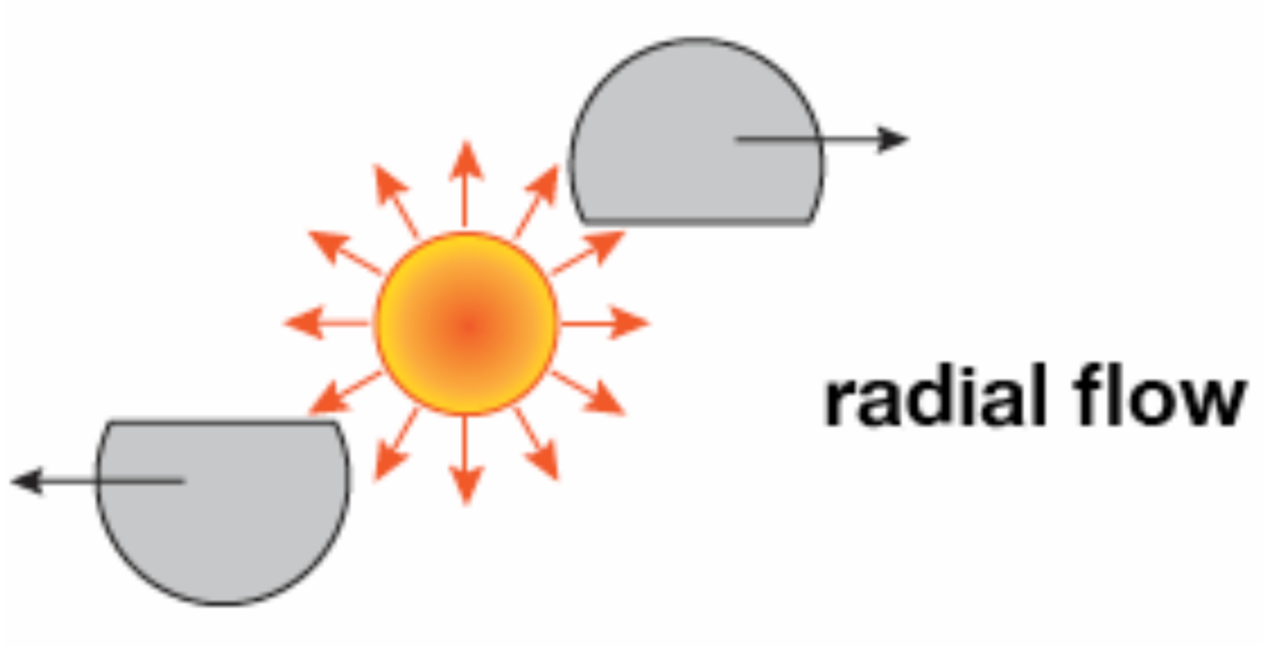
Radial flow

Collective expansion

➡ "Zero order" — radial flow

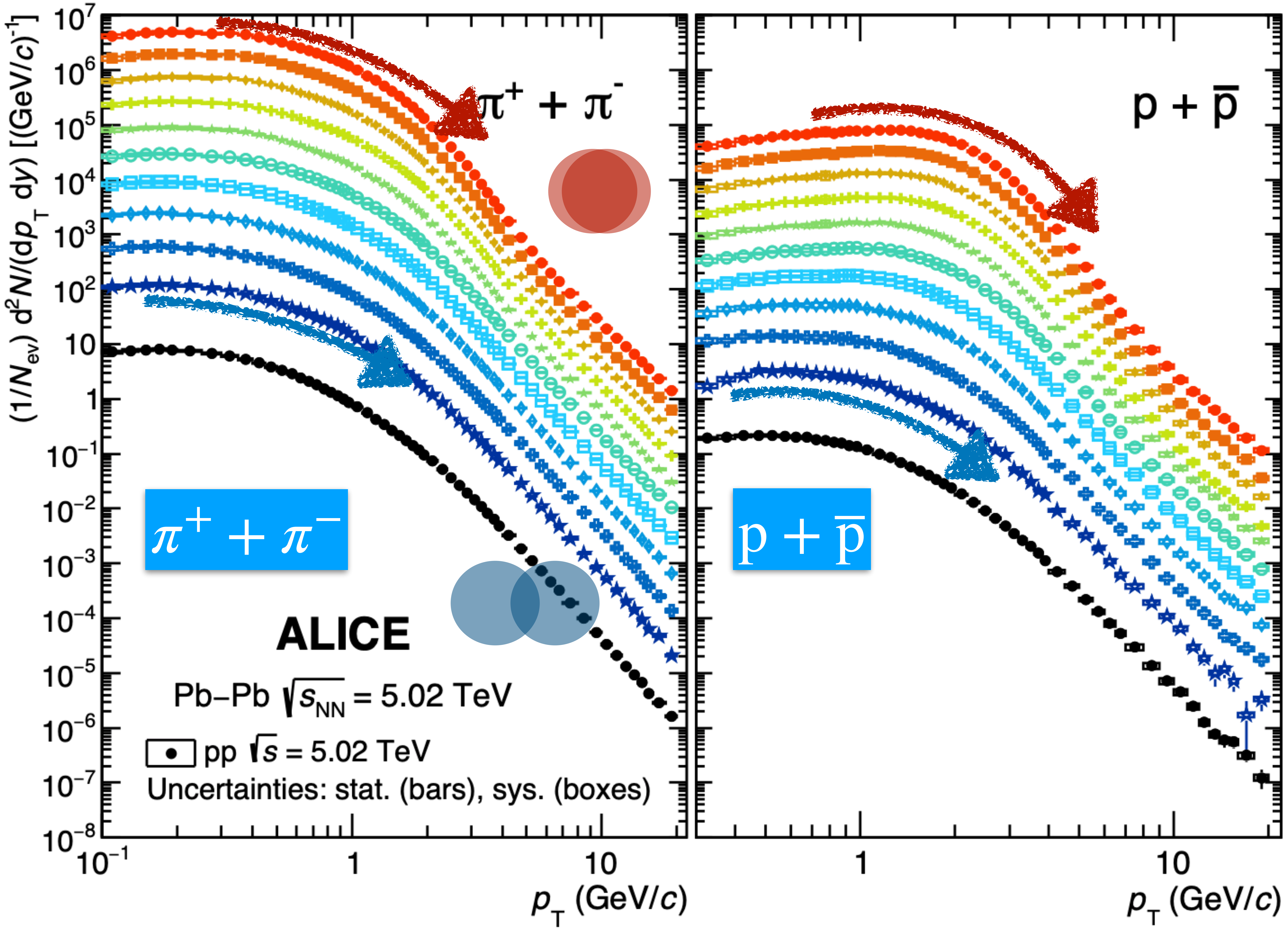


➡ Push low p_T particles toward intermediate p_T

$$p = p_0 + \beta m$$

***p_0*: initial momentum**
***β*: flow velocity**
***m*: particle mass**

➡ More pronounced in central collisions



ALICE *Phys. Rev.* C101 (2020) 044907

Radial flow

Collective expansion

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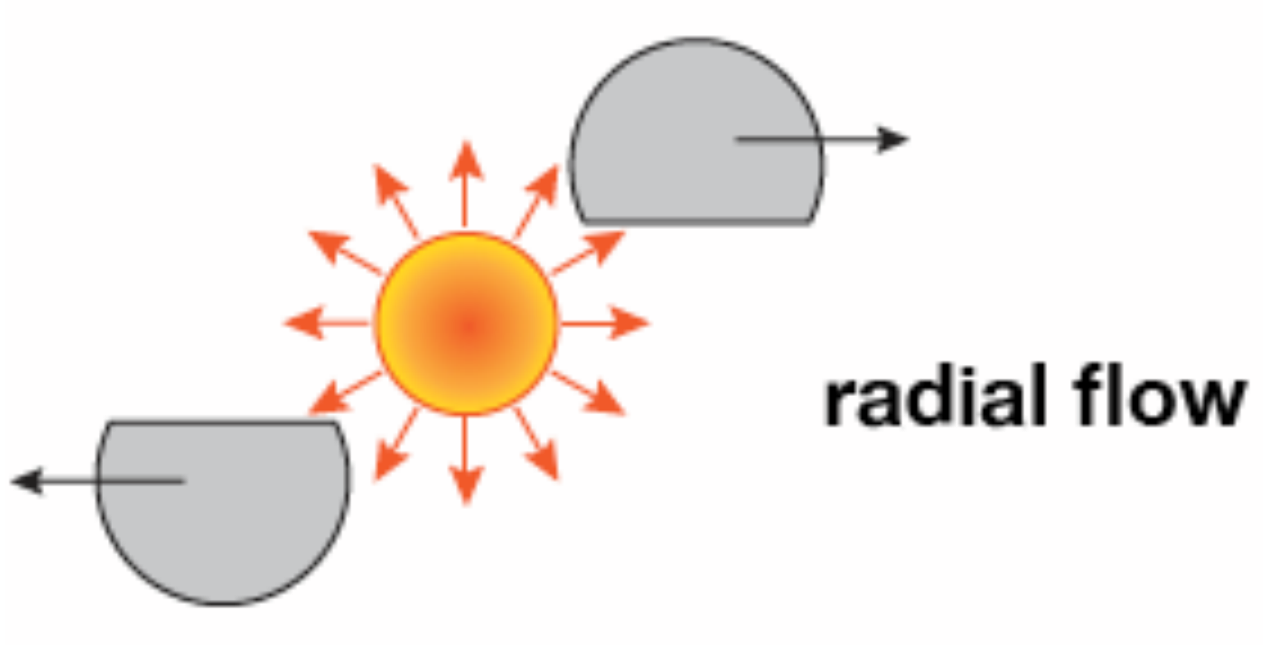

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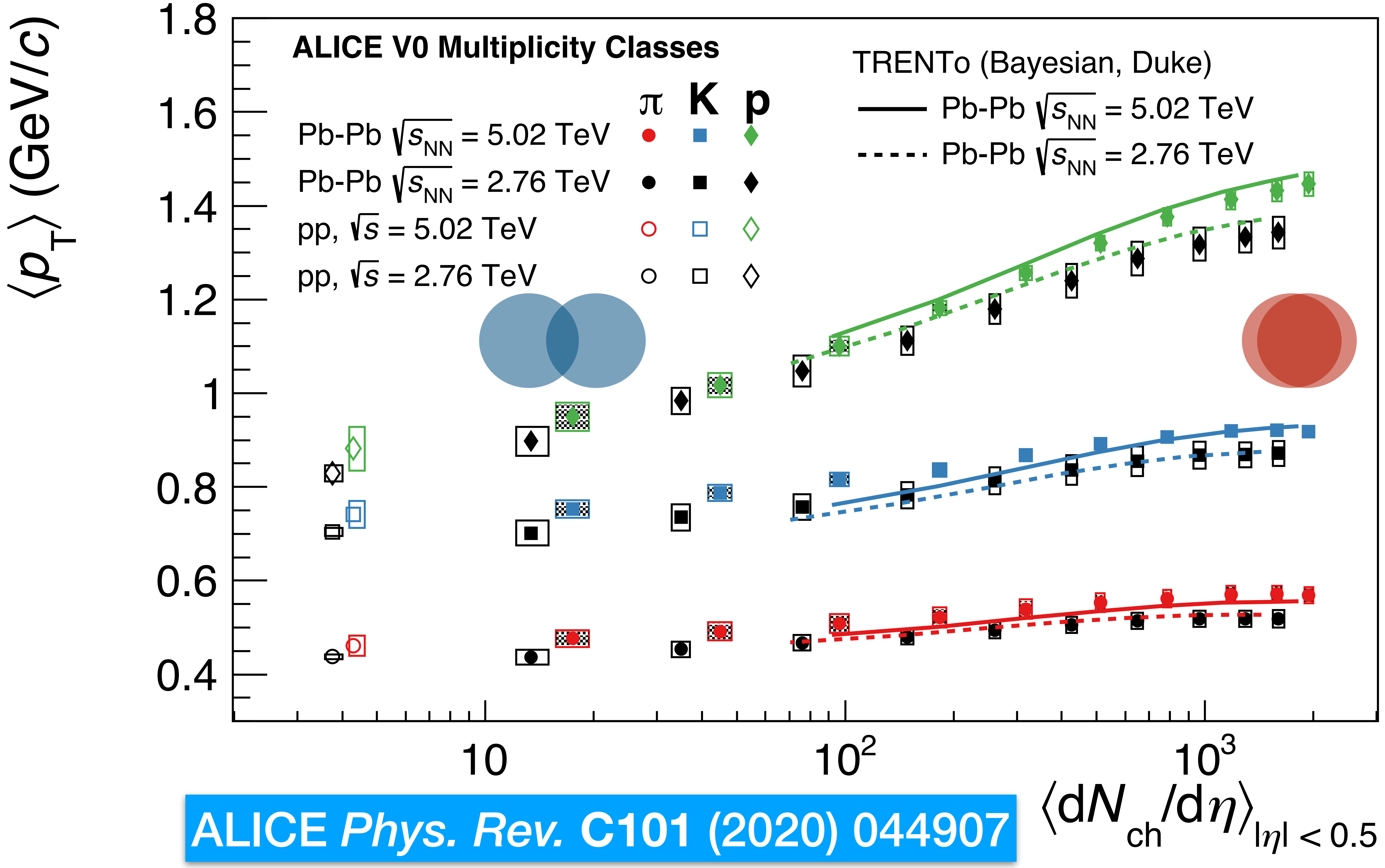
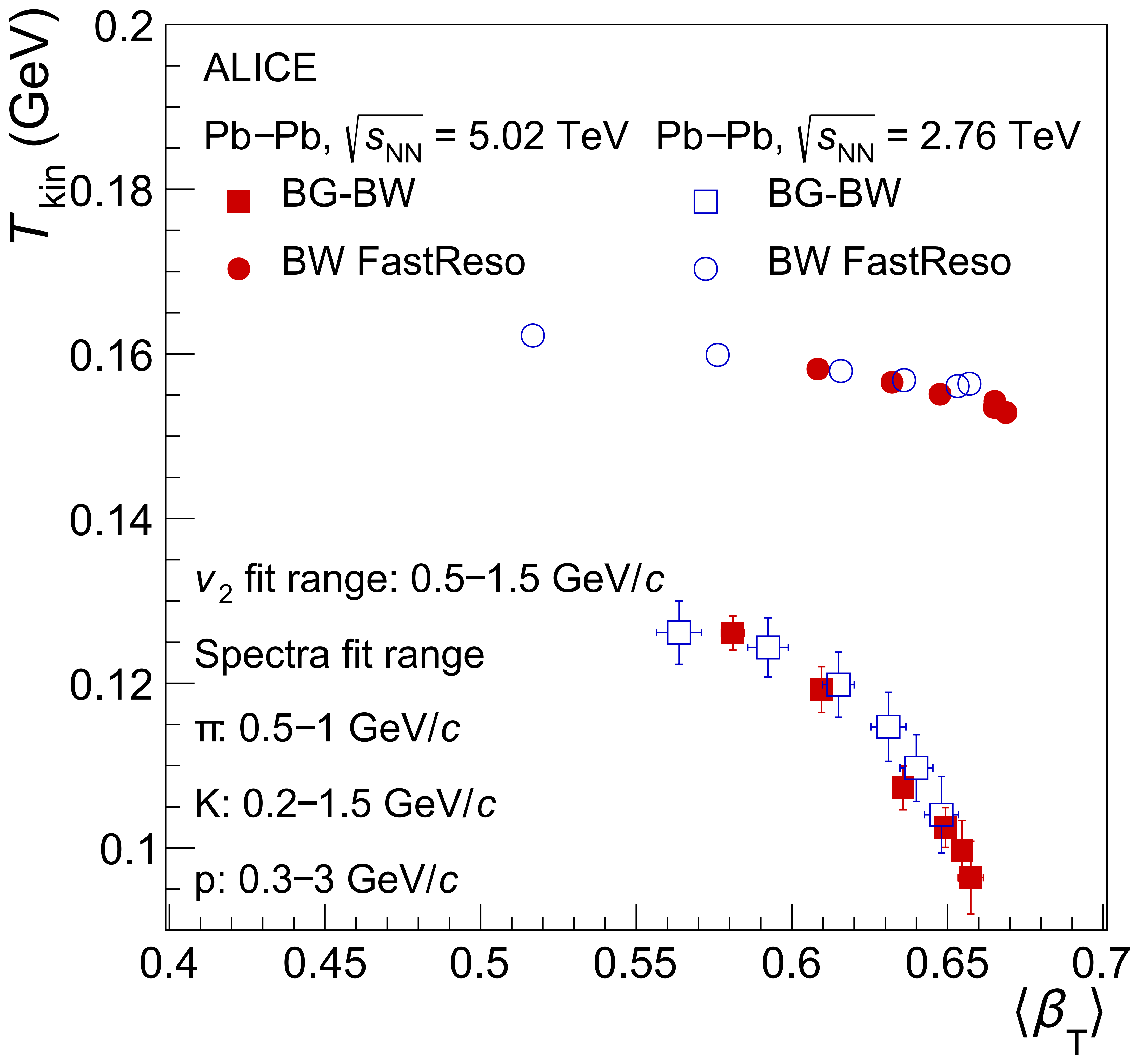
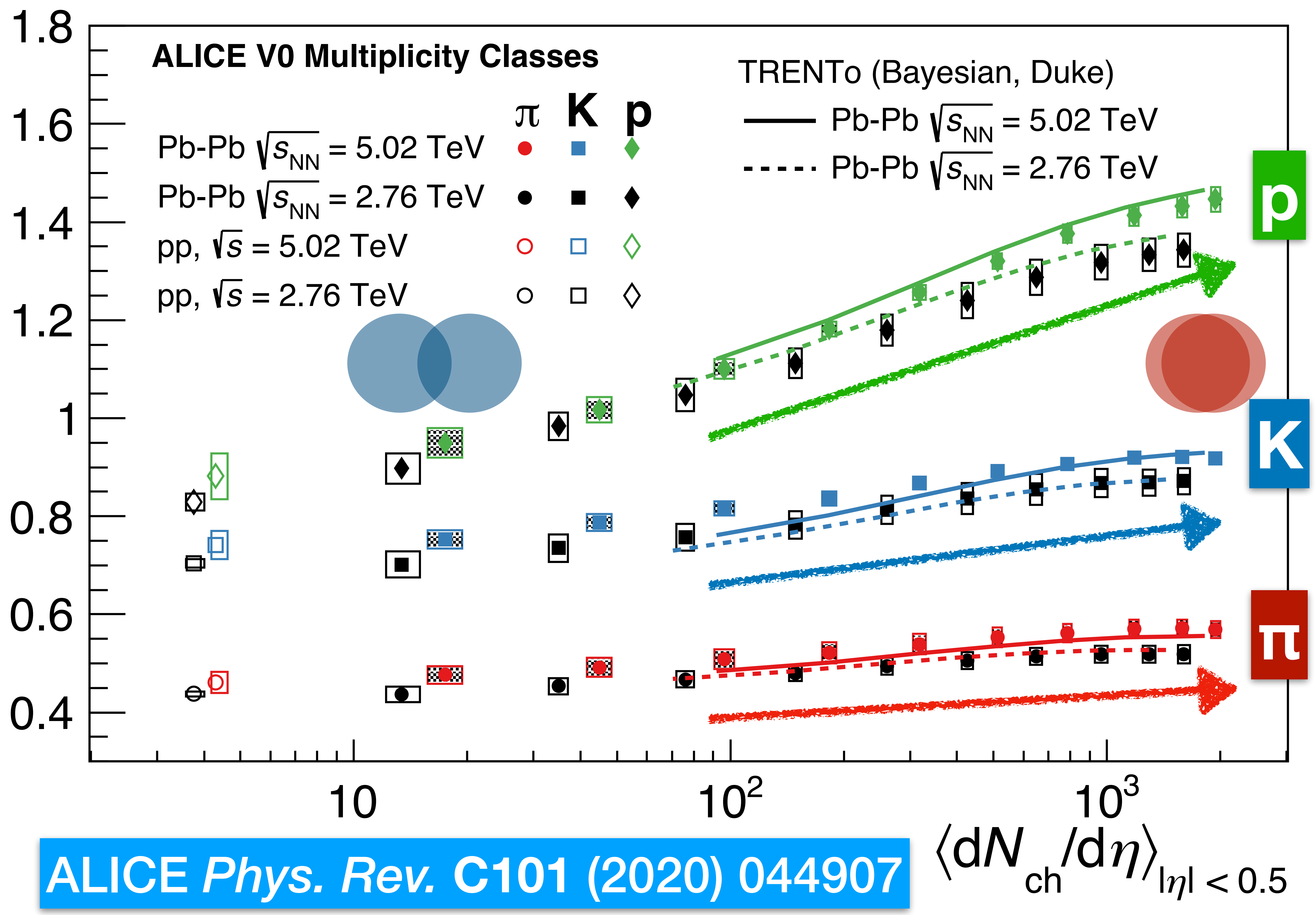


ALICE *Phys. Rev.* C101 (2020) 044907

QGP hydrodynamics



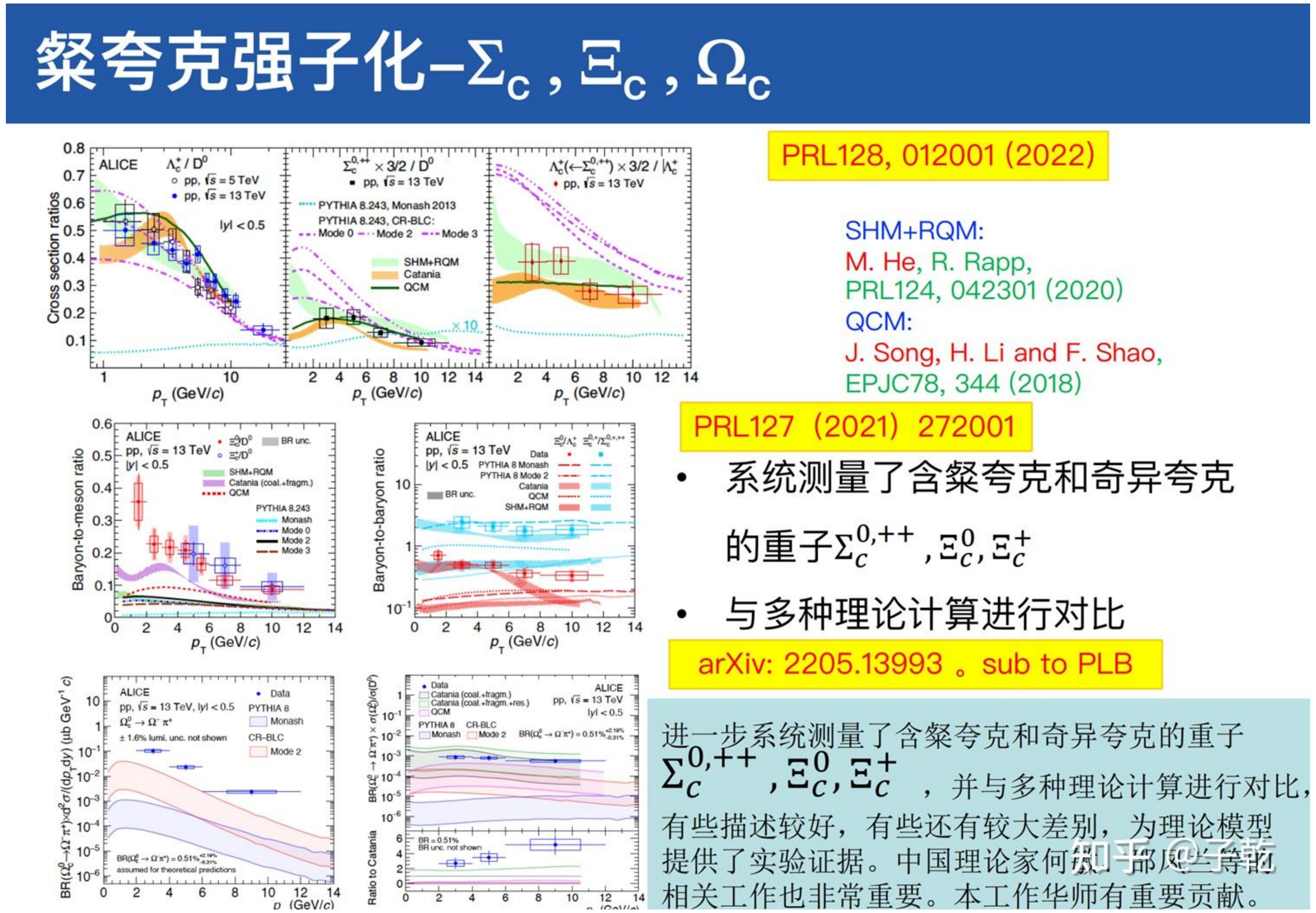


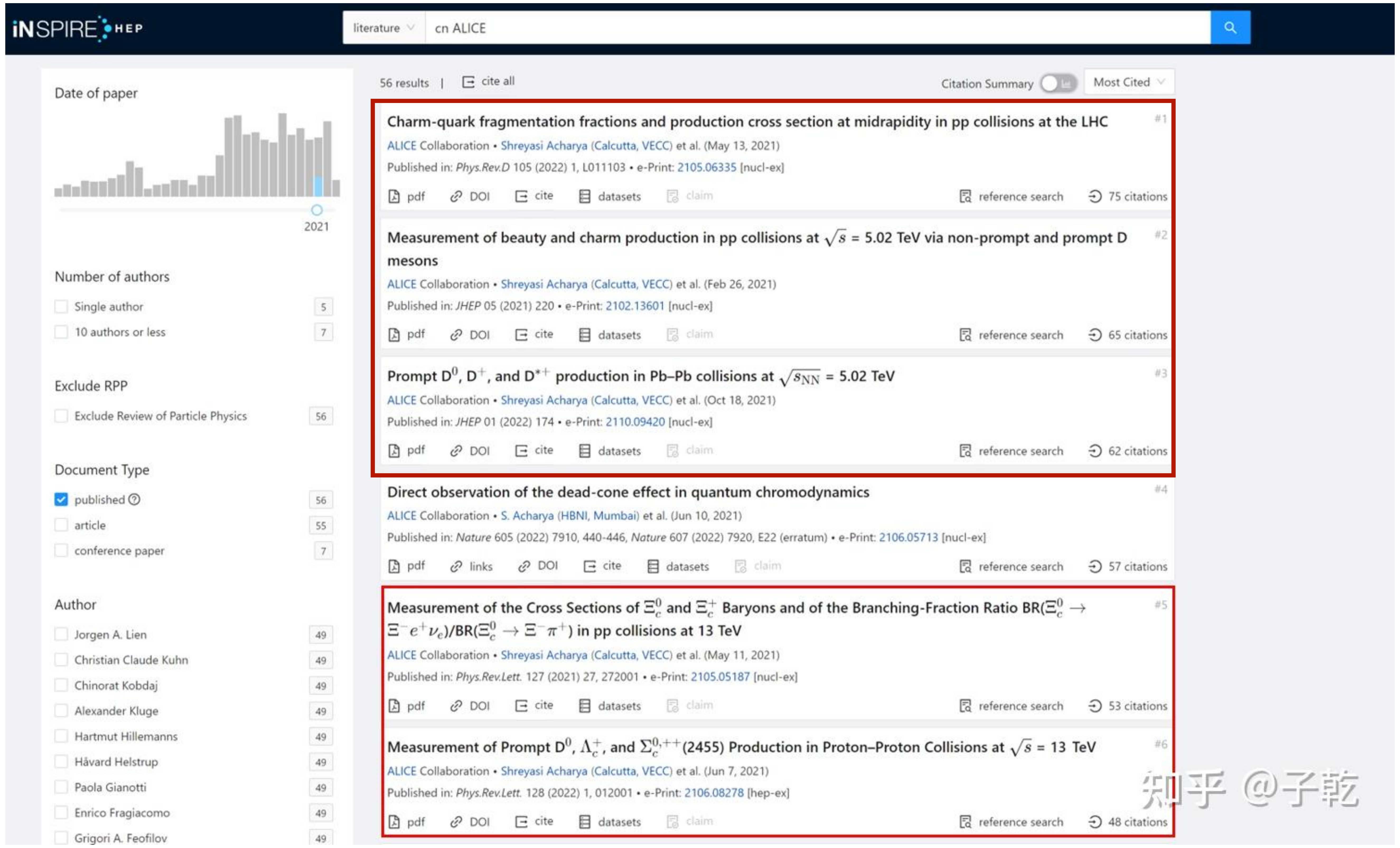
ALICE *Phys. Rev.* C101 (2020) 044907

自然科学 科学家 科学 科学学 基础科学

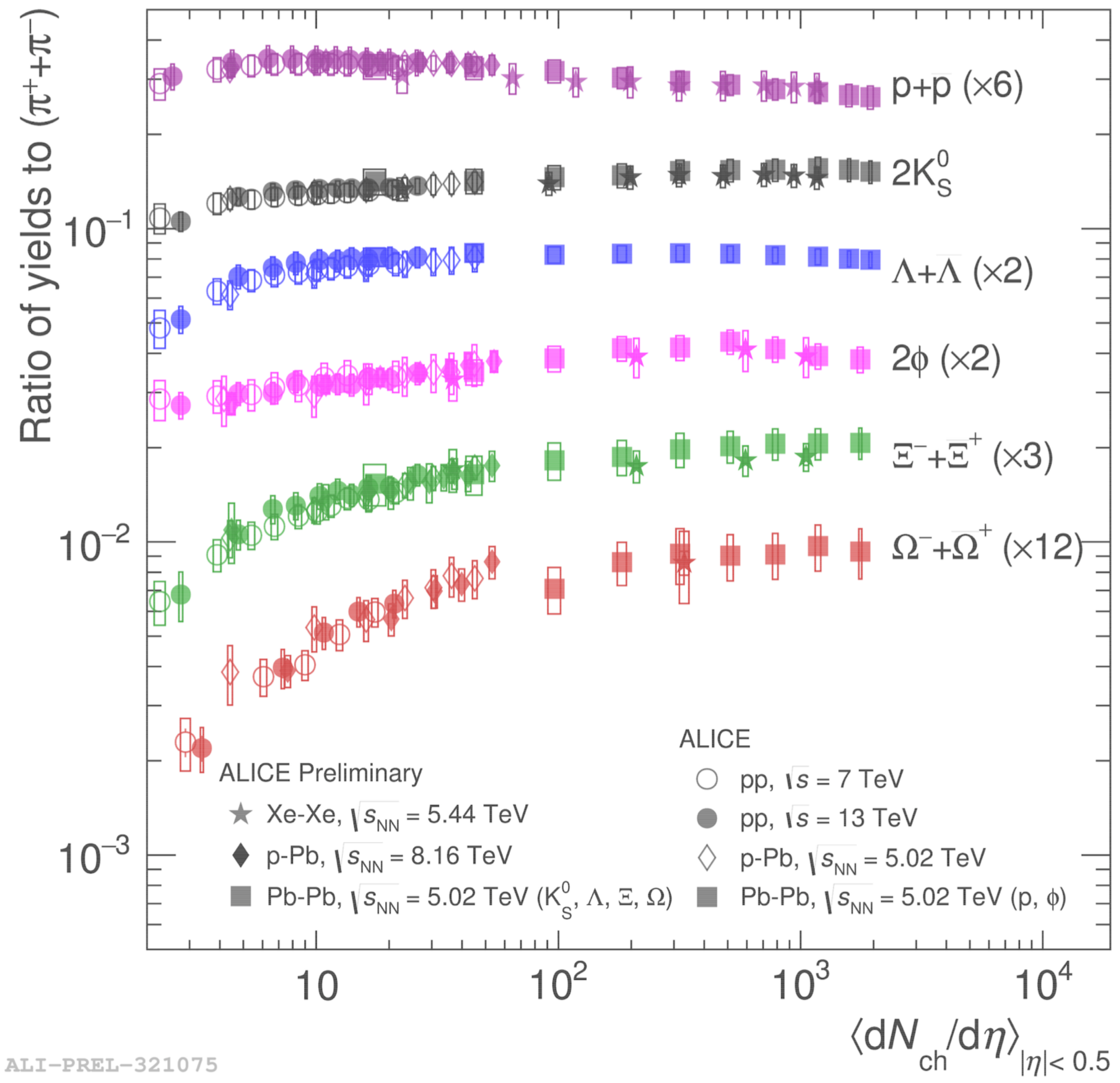
最近五十年内，中国科学家在基础科学领域都有哪些世界级的贡献？任何应用技术不在此讨论之内？

在PRL（稍微科普一下，在粒子物理研究中，PRL是顶级的期刊，一定程度上比NatureScience受到的认可还高）上发表论文，算得上世界级的贡献了吧？





The “pandora box” at the LHC



ALICE *Nature Phys* 13 (2017) 535
ALICE *Eur. Phys. J.* C80 (2020) 167

(Multi-)strange hadron to pion yield ratio

➡ Smooth evolution with charged-particle multiplicity across different collision systems (Pb–Pb, p–Pb and pp)

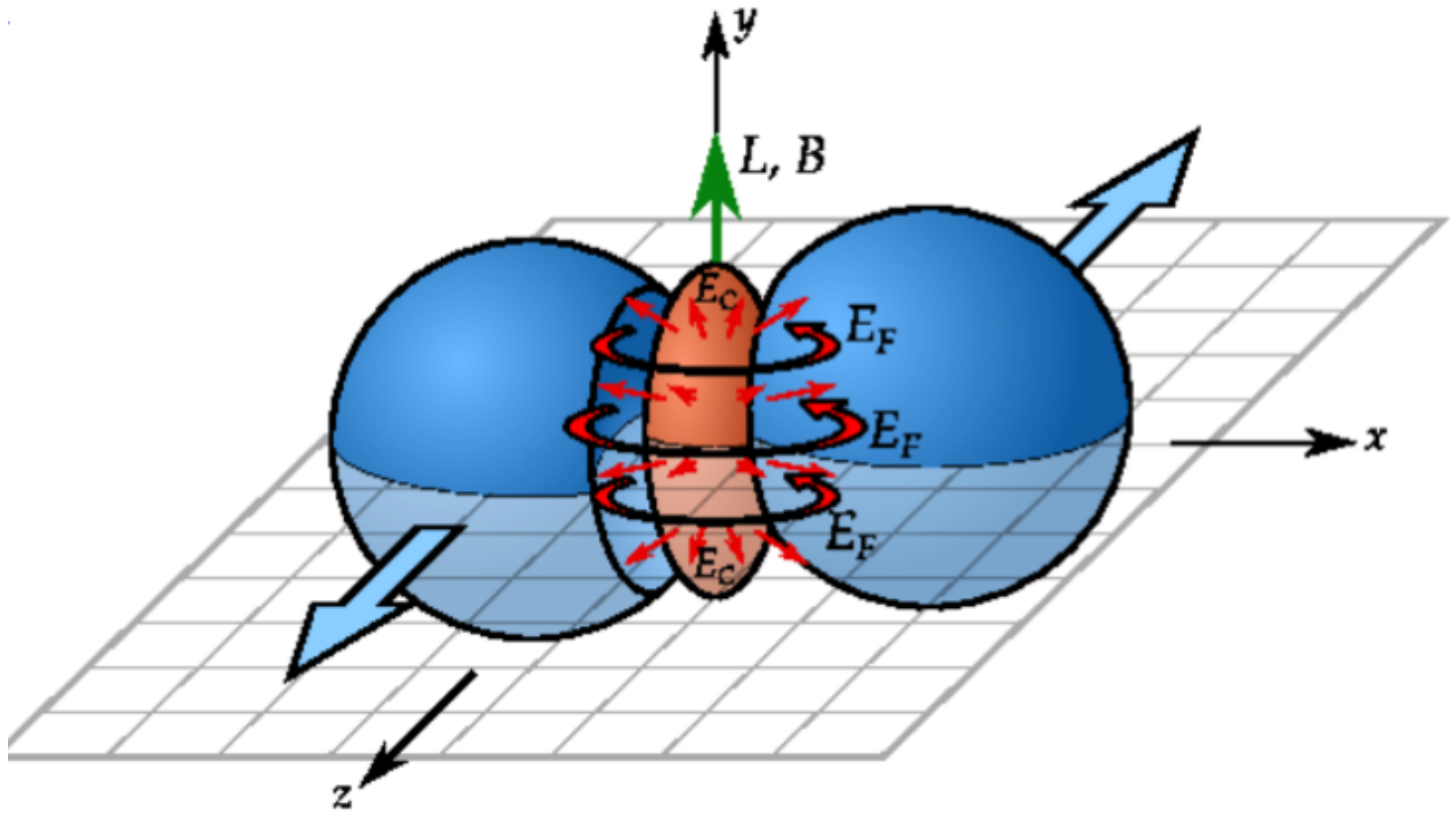
➡ No collision energy dependence at the LHC

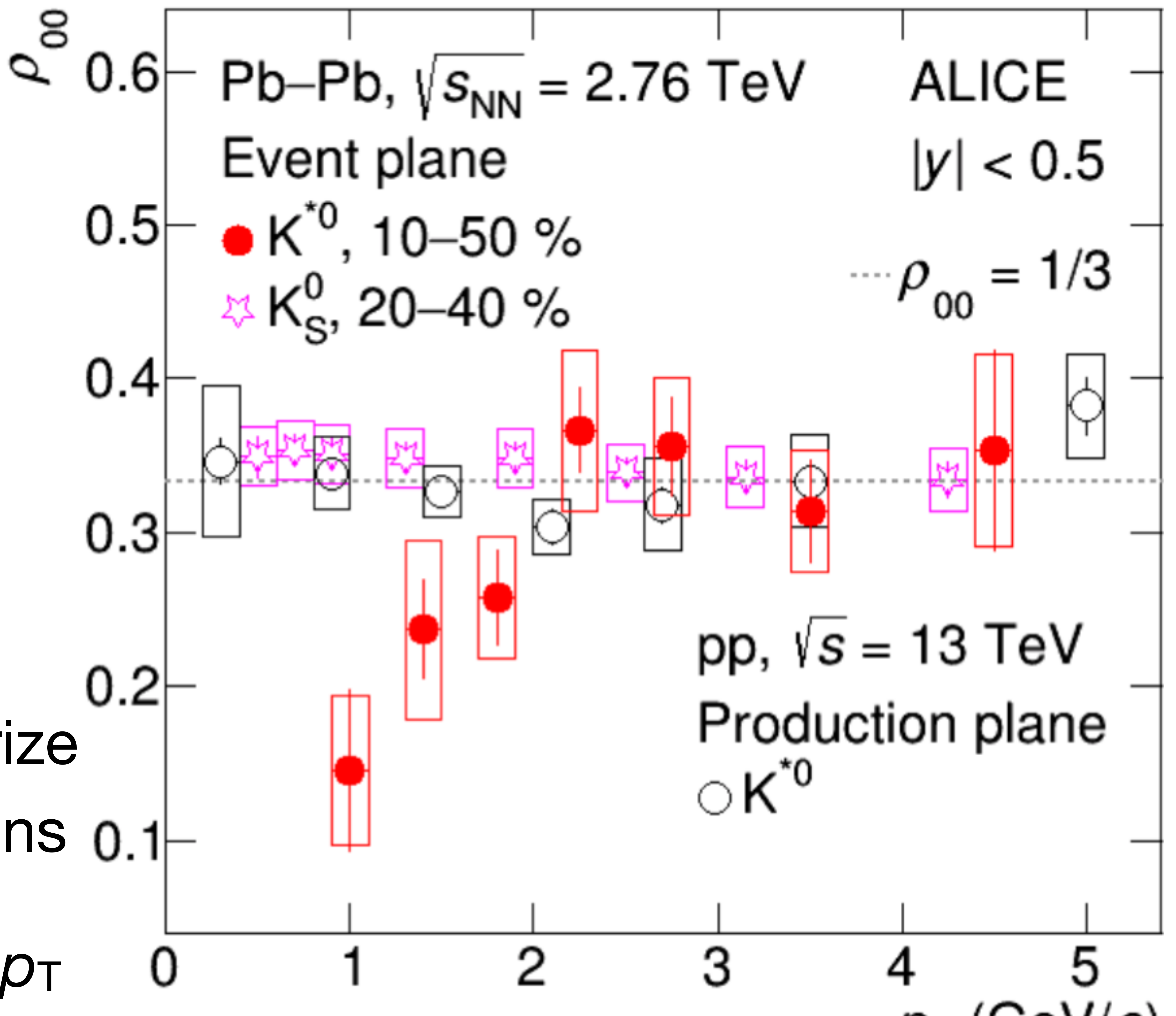
➡ Enhancement is stronger with larger strangeness content ($\Omega^{\pm} > \Xi^{\pm} > \Lambda$)

Possible explanation

- Canonical Statistical Model (CSM) [Vovchenko *et al. Phys. Rev.* **C100** (2019) 054906]
  - ➡ Exact conservation of charges in correlation volume
- Core–Corona two-component model [Kanakubo *et al. Phys. Rev.* **C101** (2020) 024912]
  - ➡ Evolution from thermal QGP to string fragmentation
- Ropes hadronization [Nayak *et al. Phys. Rev.* **D100** (2019) 074023]
  - ➡ Overlapping strings at high energies

Spin alignment





ALICE *Phys. Rev. Lett.* 125 (2020) 012301

- Large angular momentum in non-central collisions — rotating QGP (~10^{21} r/s)
- Spin-orbit interactions expected to polarize quarks — spin alignment of vector mesons
- $K^{*0} \rightarrow K\pi$ decays show a 3σ effect at low p_T

Magnetic field effects