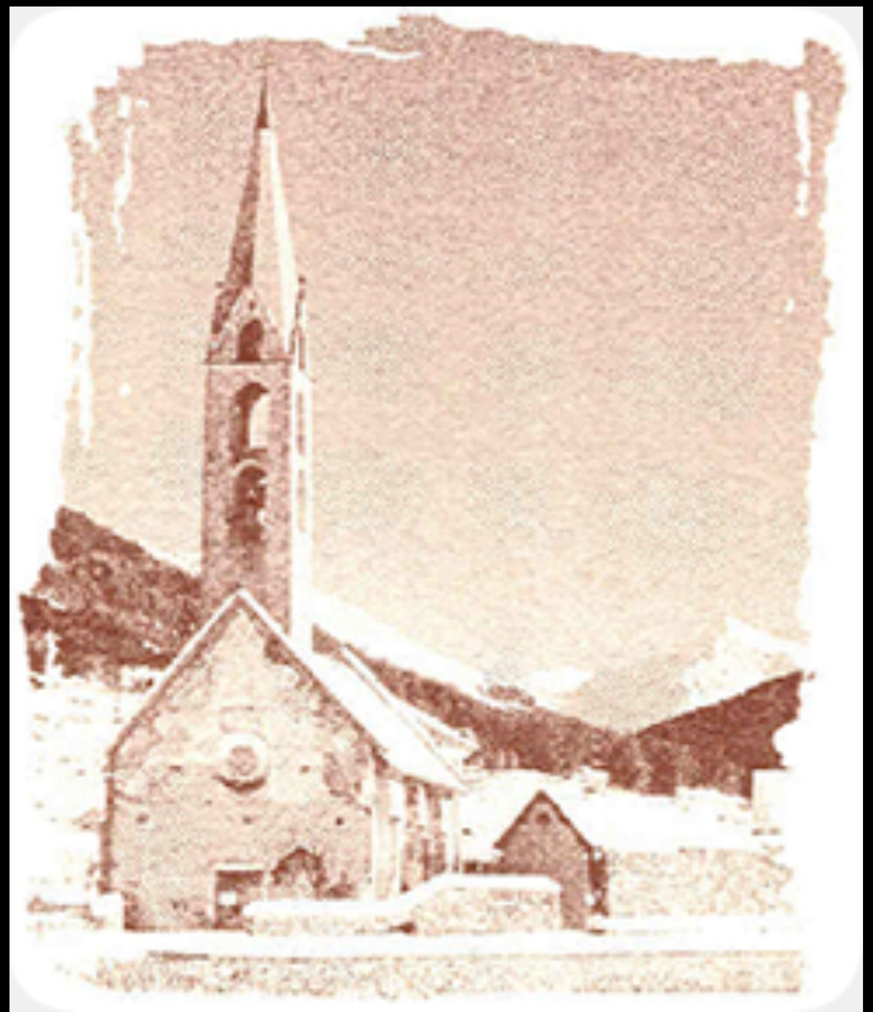


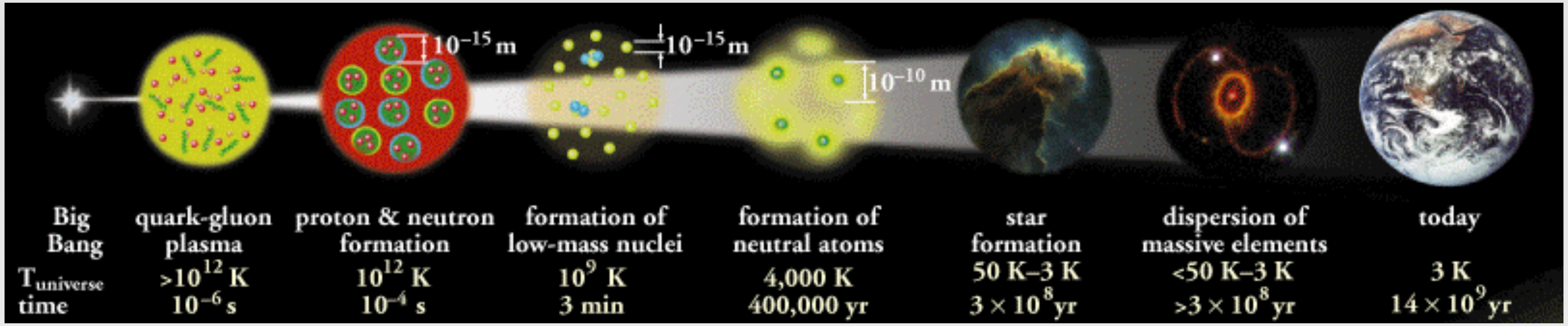
Heavy-ion physics
- selected topics -

Dr. Andrea Dubla

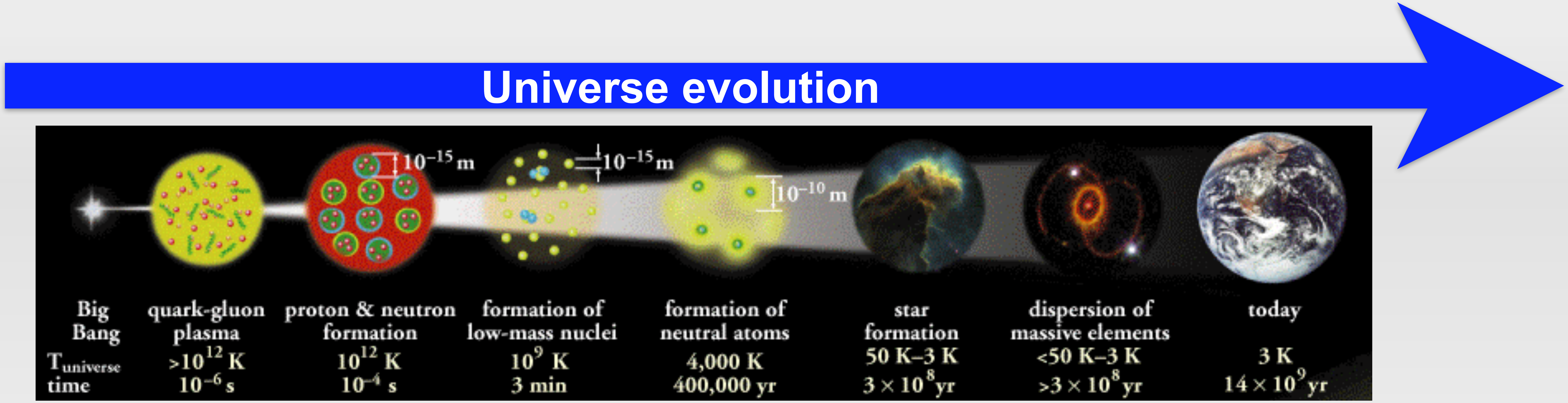
19/01/2020

Introduction

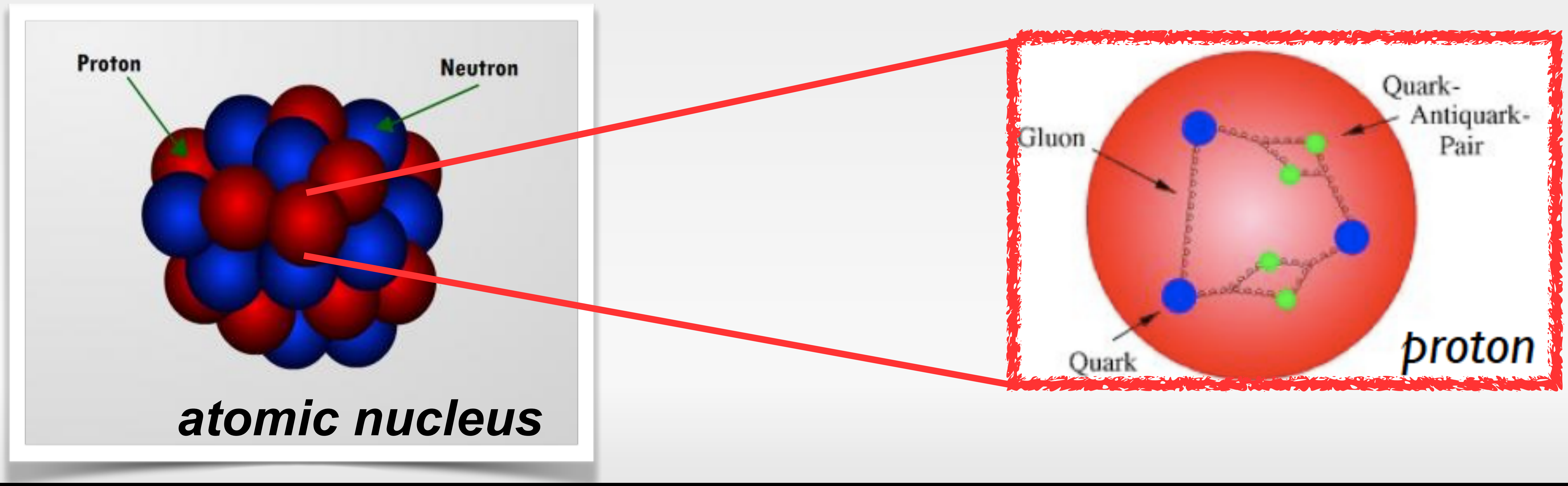
Universe evolution



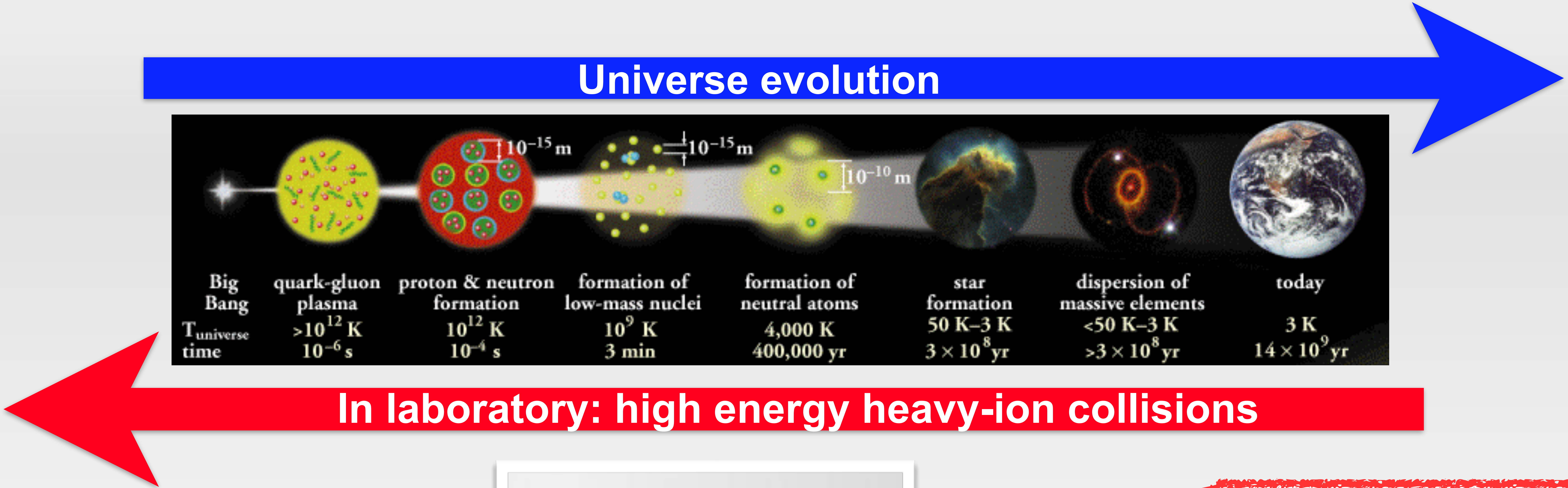
Introduction



➪ In ordinary matter quarks and gluons are confined inside protons and neutrons



Introduction



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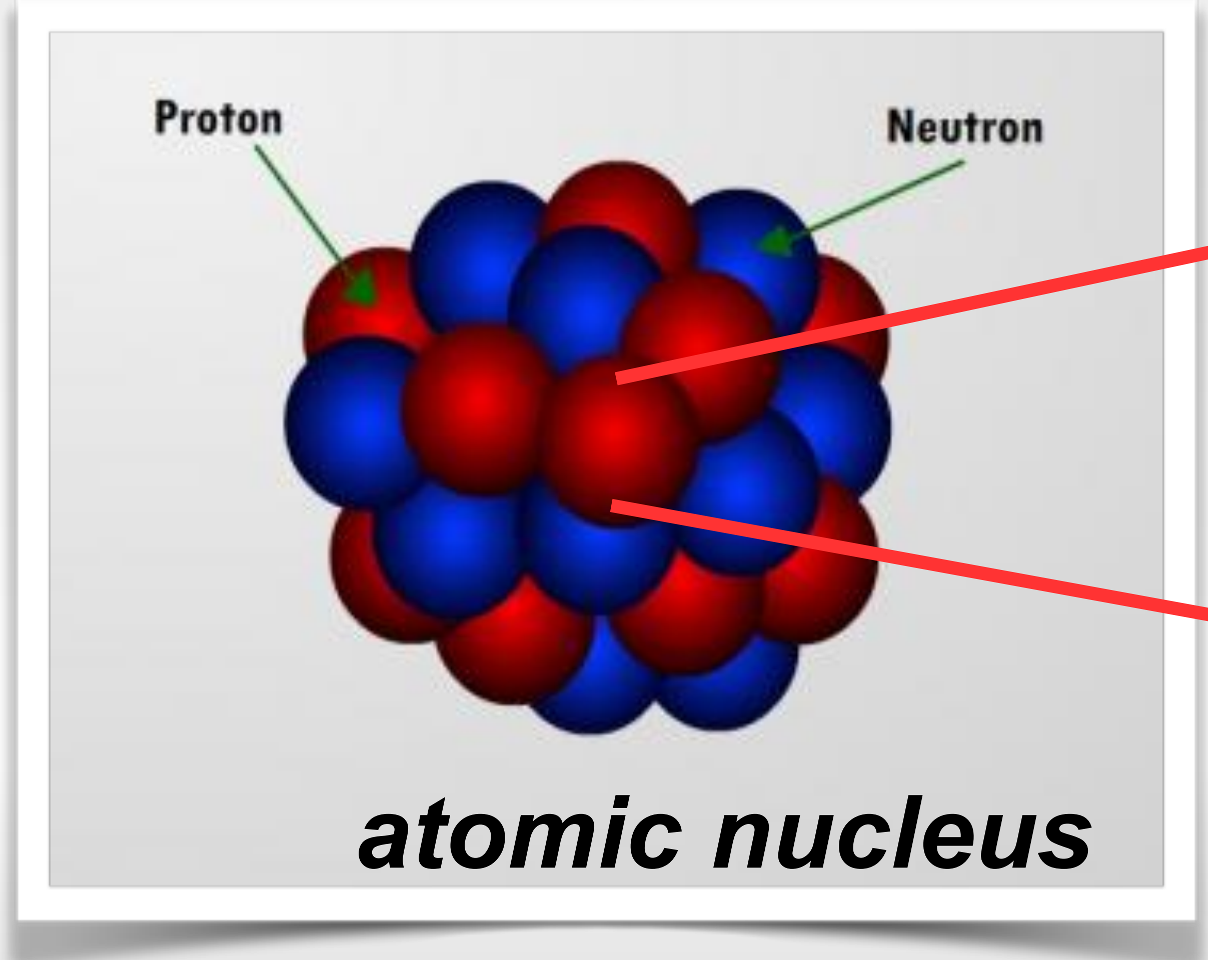
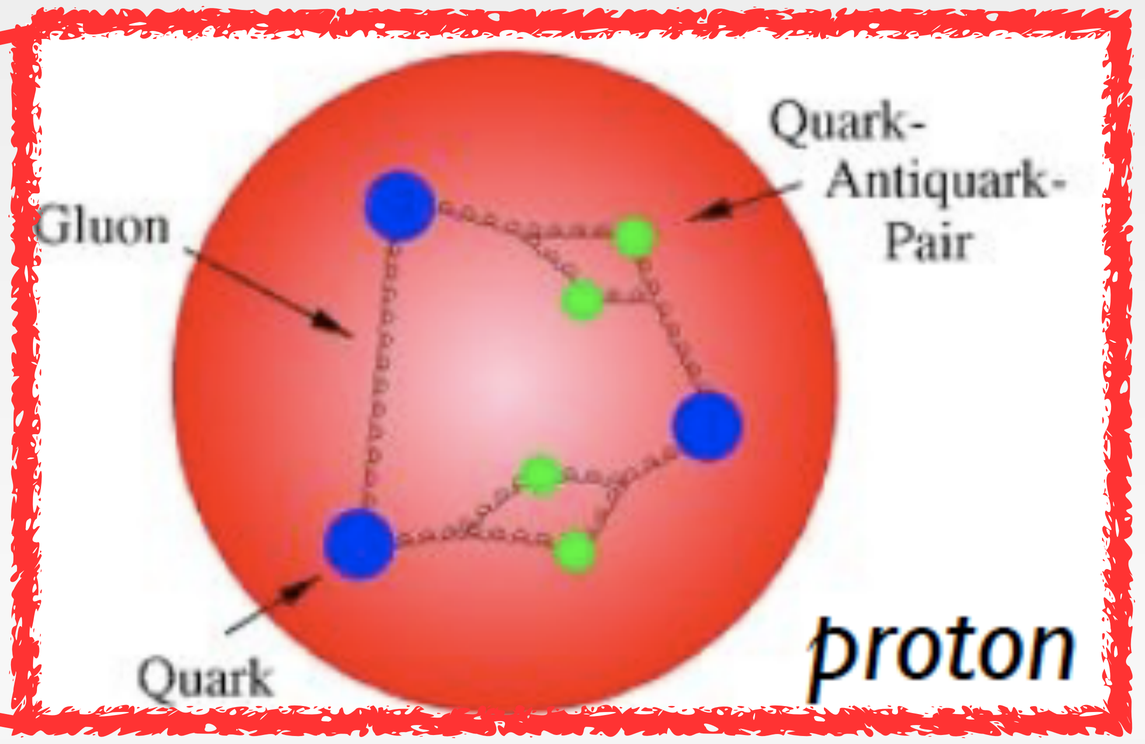
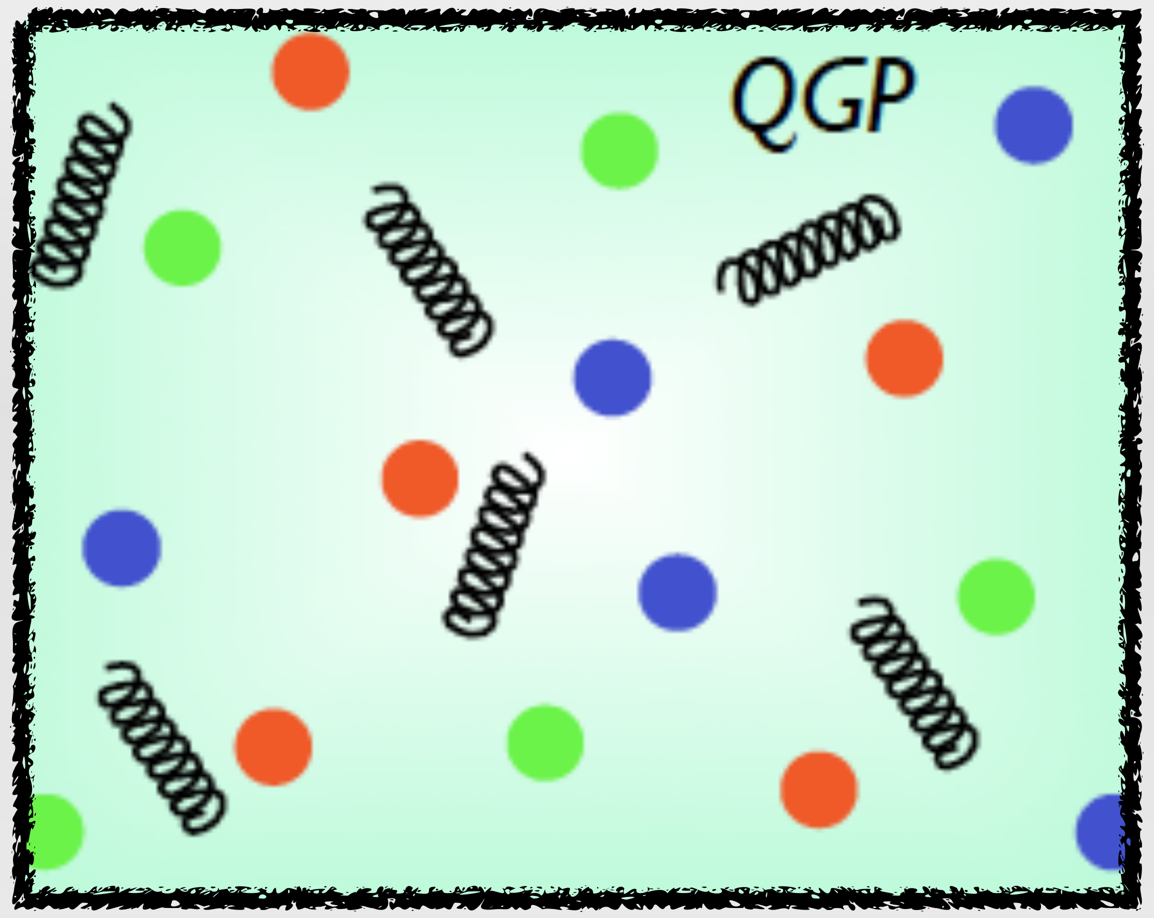


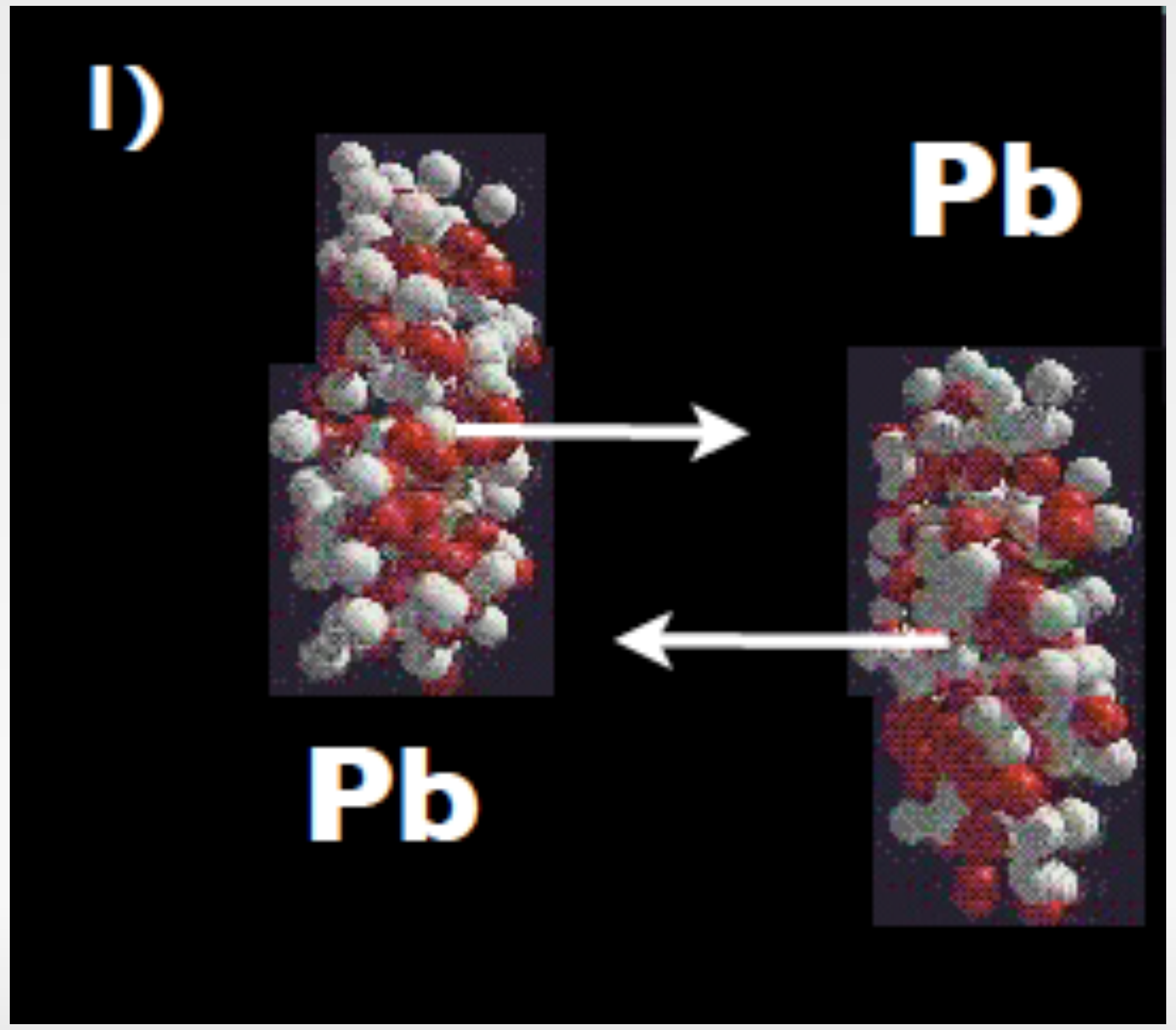


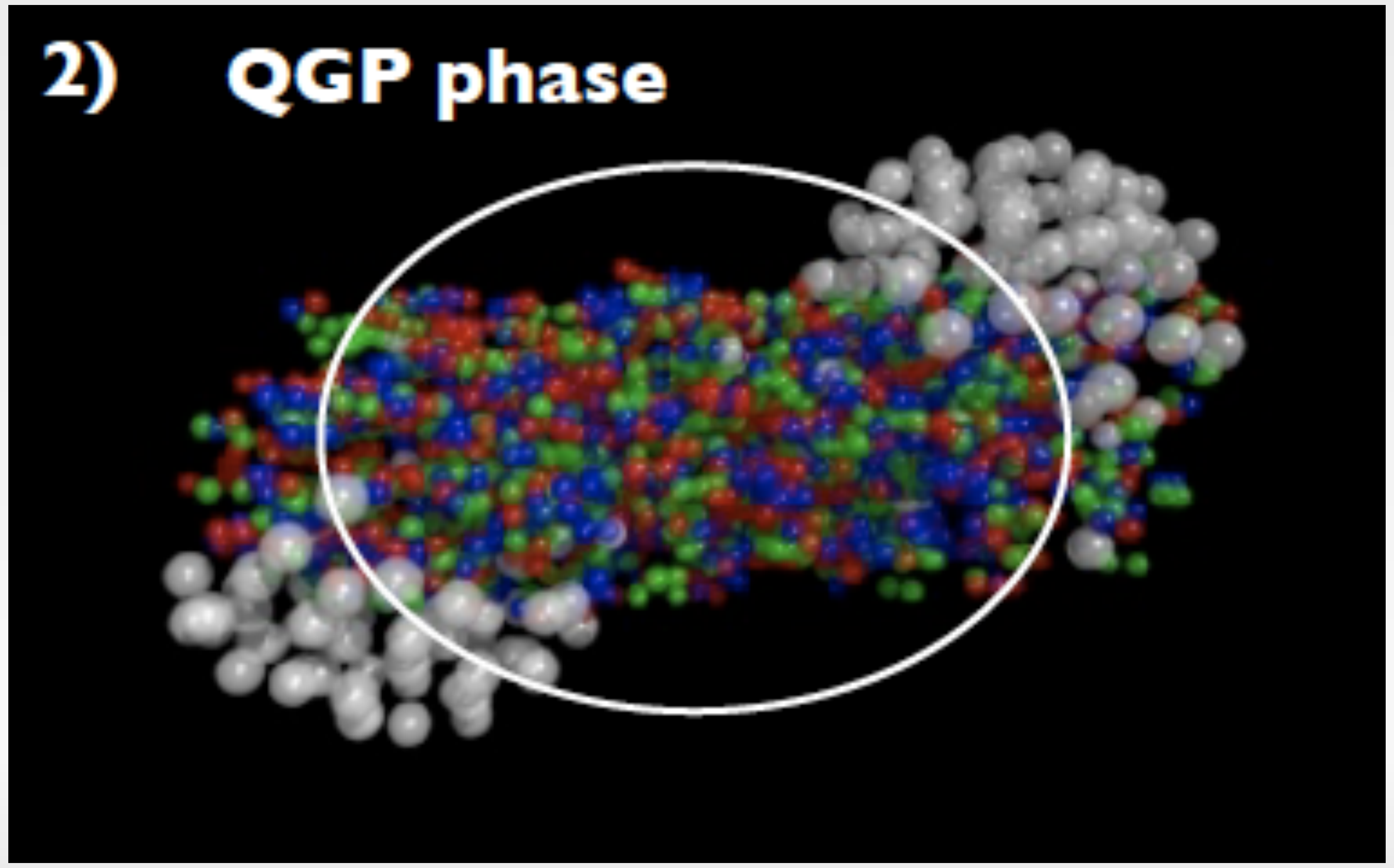
Introduction

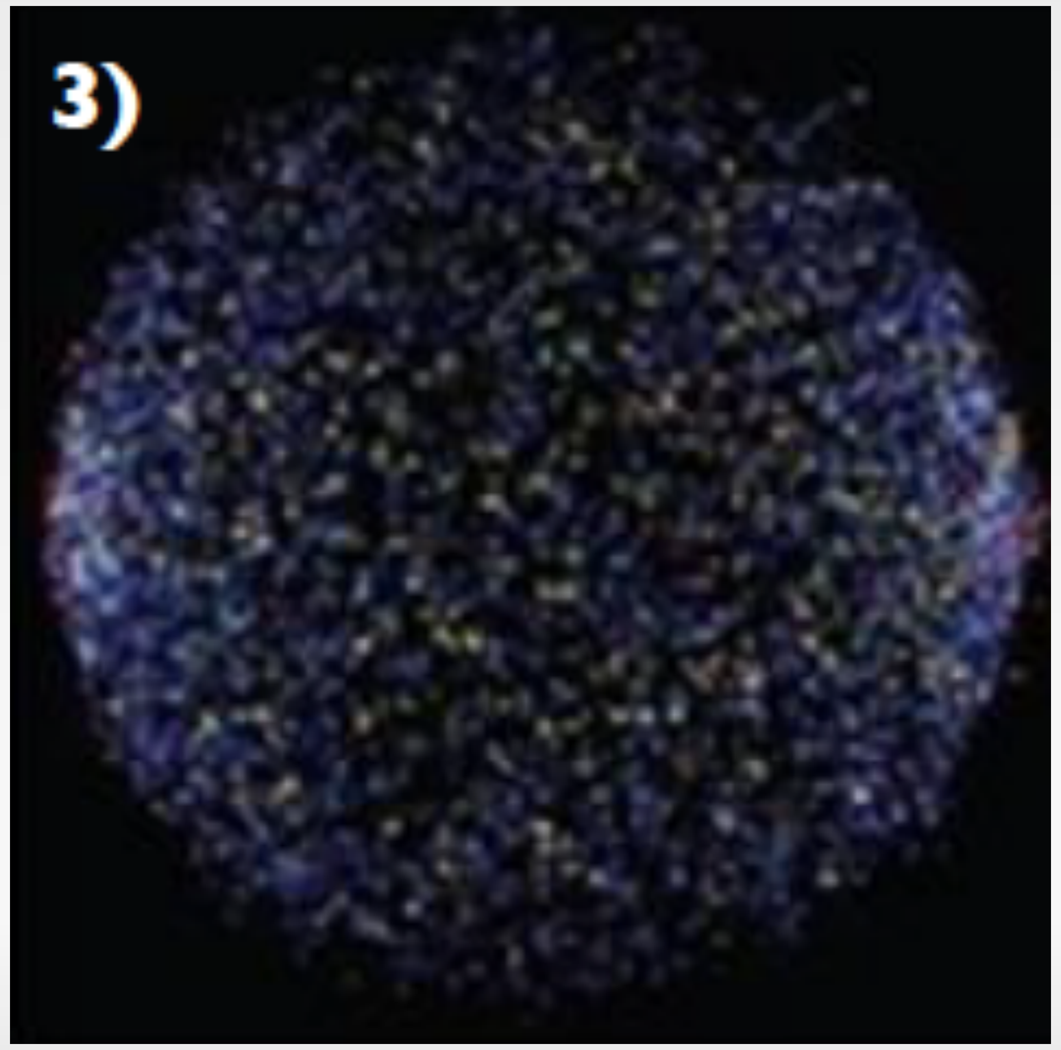
- At **high temperature and/or pressure**, QCD predicts that quarks and gluons are deconfined and form a **new state of matter**, the so-called **Quark-Gluon Plasma (QGP)**



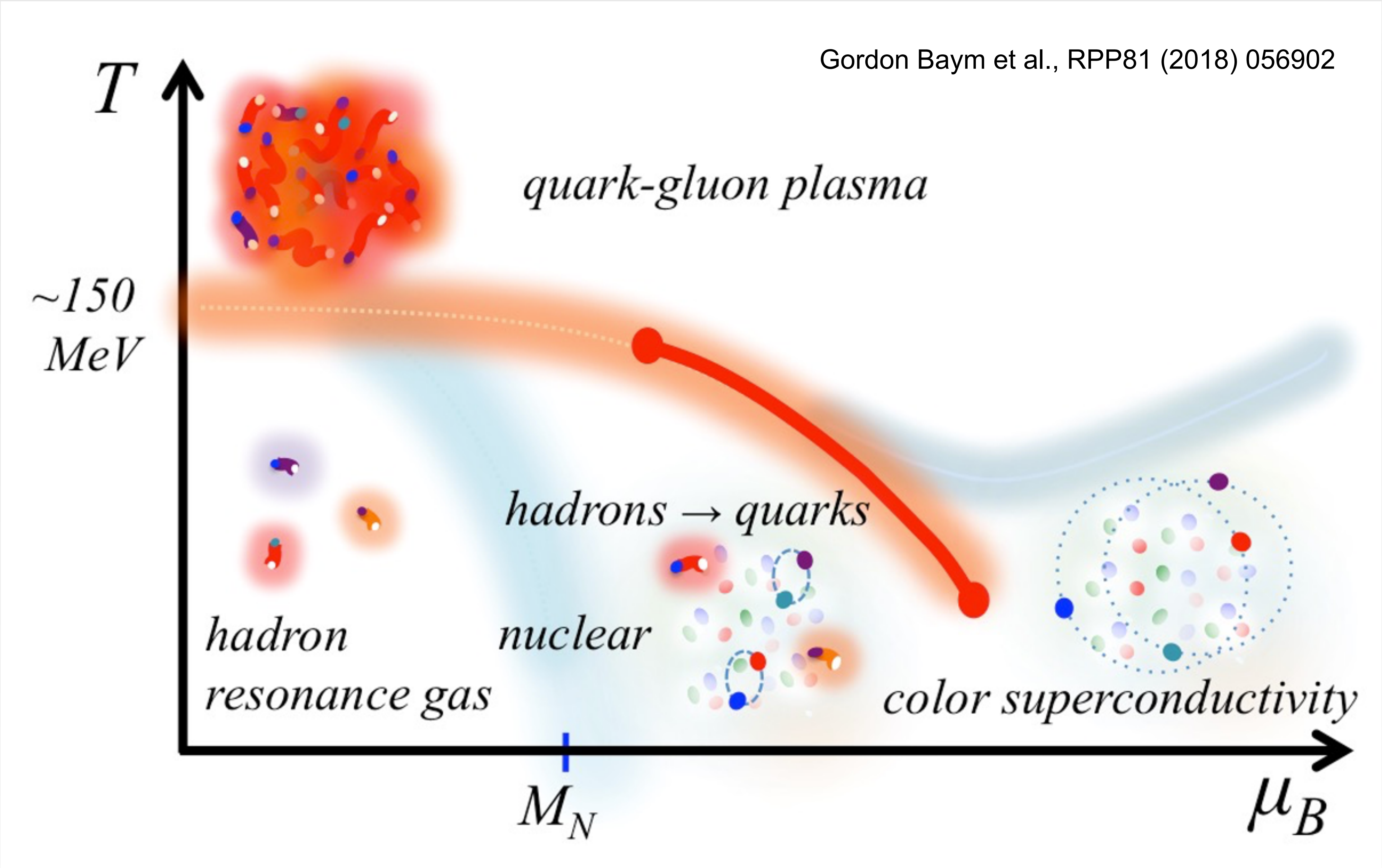
- Heavy-ion collisions can be used to reproduce the **QGP in the laboratory**







Phase diagram



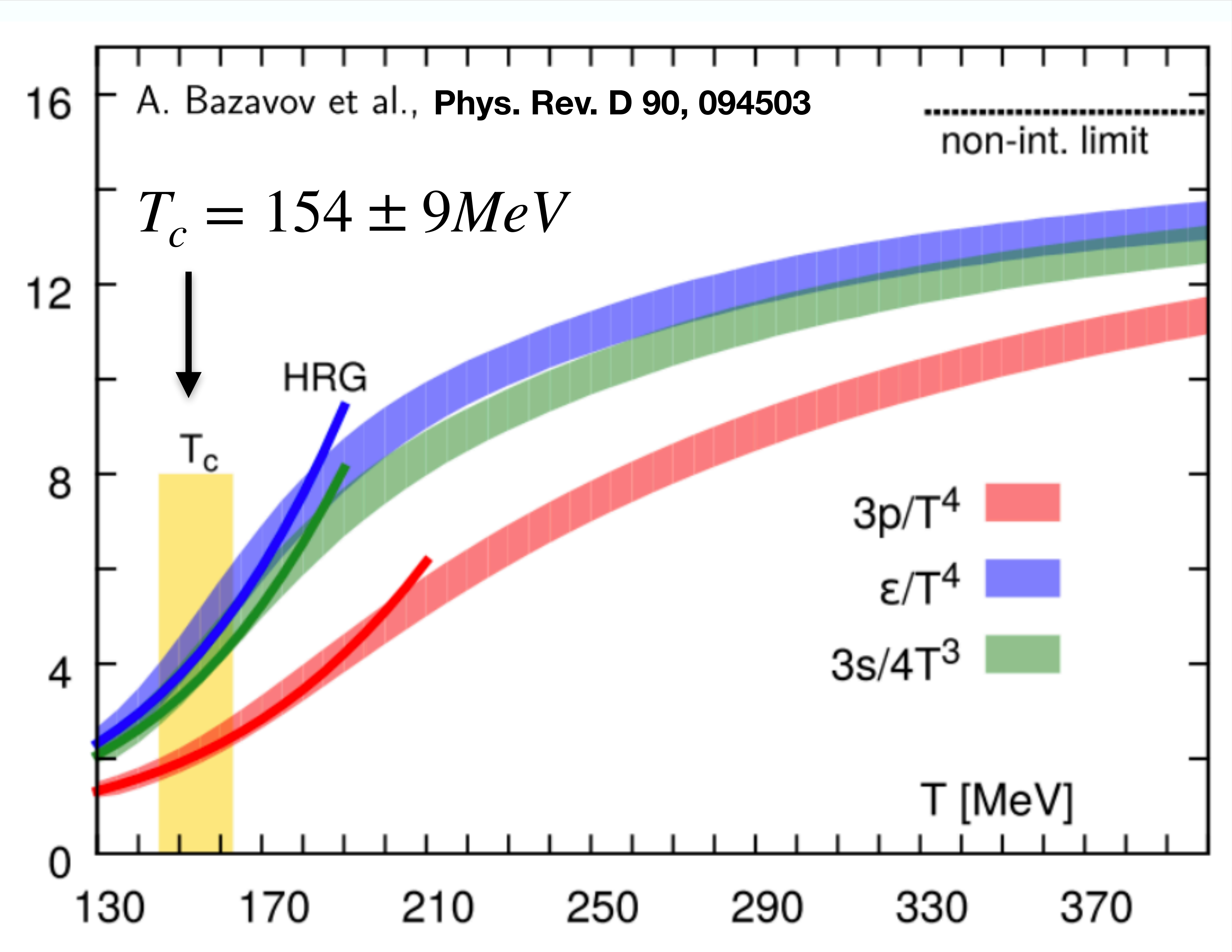
➪ **Phase transition to a deconfined state of quarks and gluons: QGP**

➪ **Temperature and density increase:**

- Thermal agitation of quarks and gluons increases their average kinetic energy
- Average distance decreases due to increased pressure
- Weaker interactions due to the asymptotic freedom of QCD
- Quarks and gluons are deconfined above the critical temperature

Phase transition

- ➯ Numerical QCD computation on a **discrete space-time lattice** (huge computing farms)
- ➯ lattice QCD predicts a **smooth cross-over** phase transition at $\boldsymbol{\mu_B = 0}$



(ideal gas)

quarks and gluons

$\varepsilon_{qg}/T^4 = (16 + \frac{7}{8}12N_f)\frac{\pi^2}{30}$

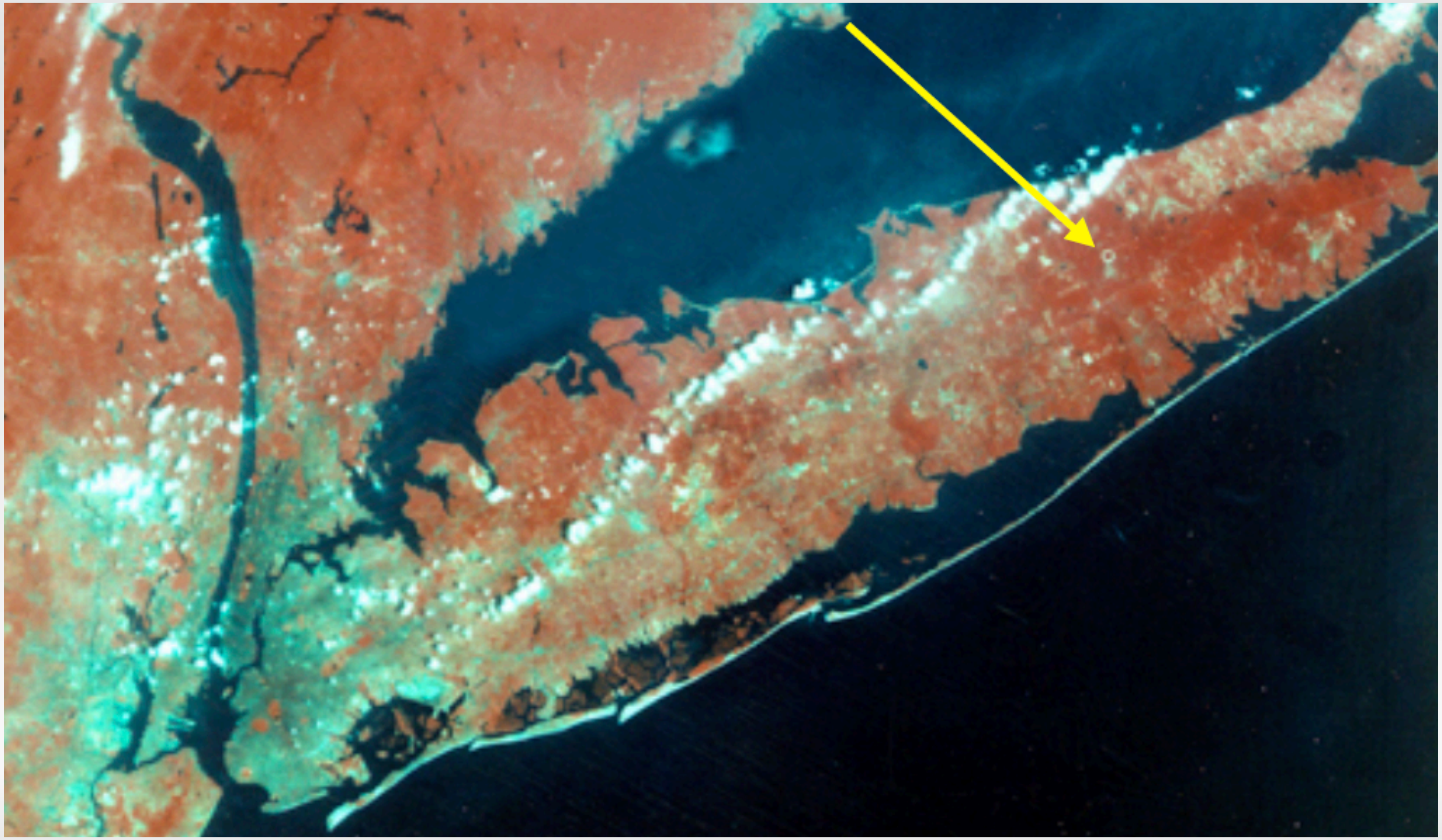
N_f=3 (u,d,s)

hadrons (pions)

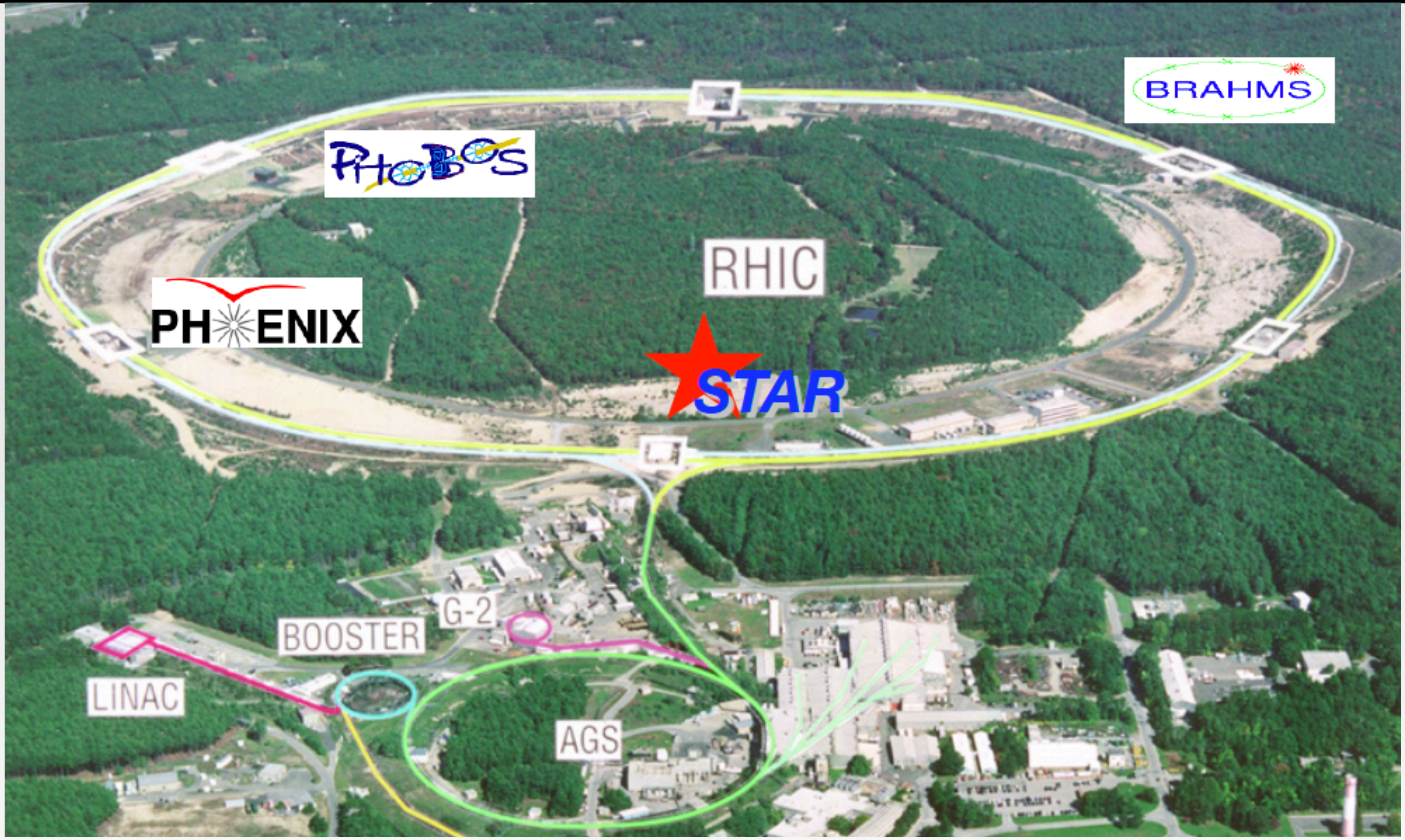
$\varepsilon_{had}/T^4 = 3\frac{\pi^2}{30}$

RHIC at BNL

➯ Relativistic Heavy Ion Collider at Brookhaven National Lab



RHIC at BNL



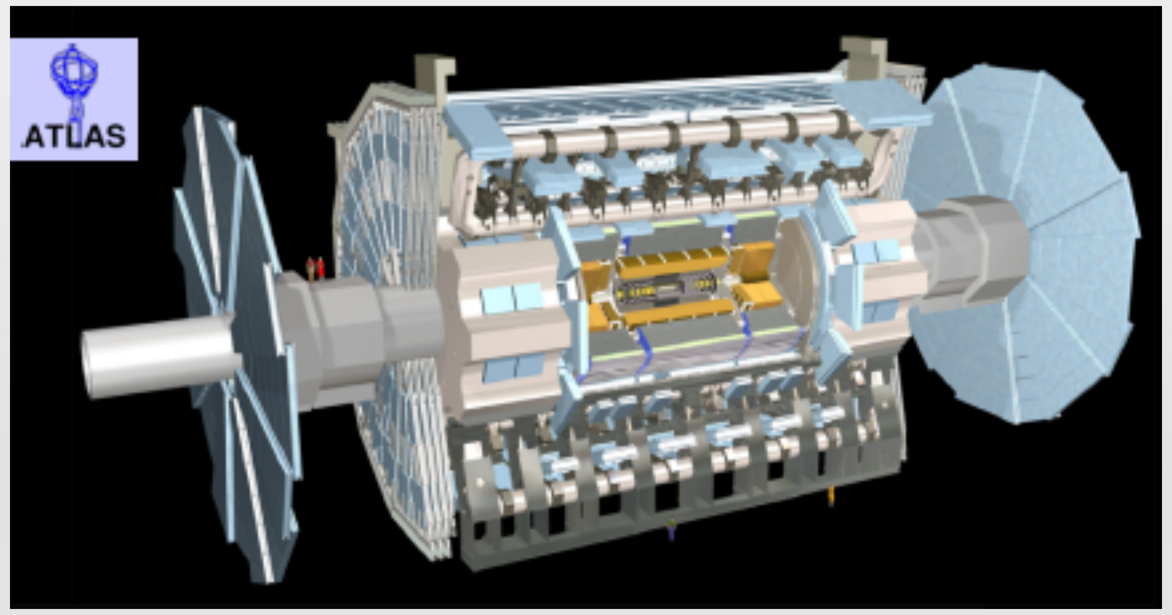
➪ **Relativistic Heavy Ion Collider:**
- 3.83 km circumference, 2 independent rings, superconducting magnets
- pp collisions: $\sqrt{s} \leq$ 500 GeV (polarised beams), A-A collisions: $\sqrt{s_{NN}} \leq$ 200 GeV (A = d, Cu, Au, U, Ru, Zr)

The Large Hadron Collider at CERN

➪ **Large Hadron Collider**

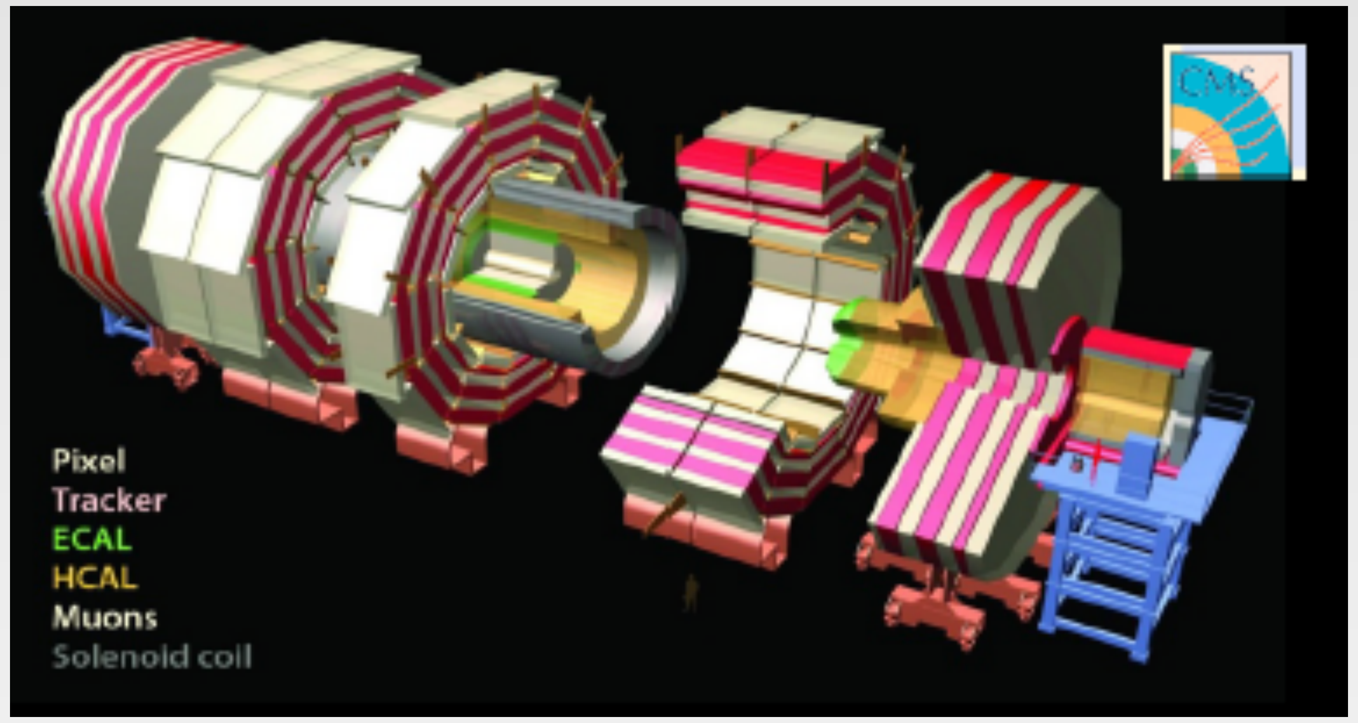
- 27 km circumference
- superconducting magnets (8 T)
- up to 100 m below ground
- pp: $\sqrt{s}$ = 0.9, 2.36, 2.76, 5.02, 7, 8, 13 TeV (top: 14 TeV)
- pPb: $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV (top: 8.8 TeV)
- Pb-Pb: $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV (top: 5.5 TeV)
- Xe-Xe: $\sqrt{s_{NN}}$ = 5.44 TeV

Heavy-ion collision experiments

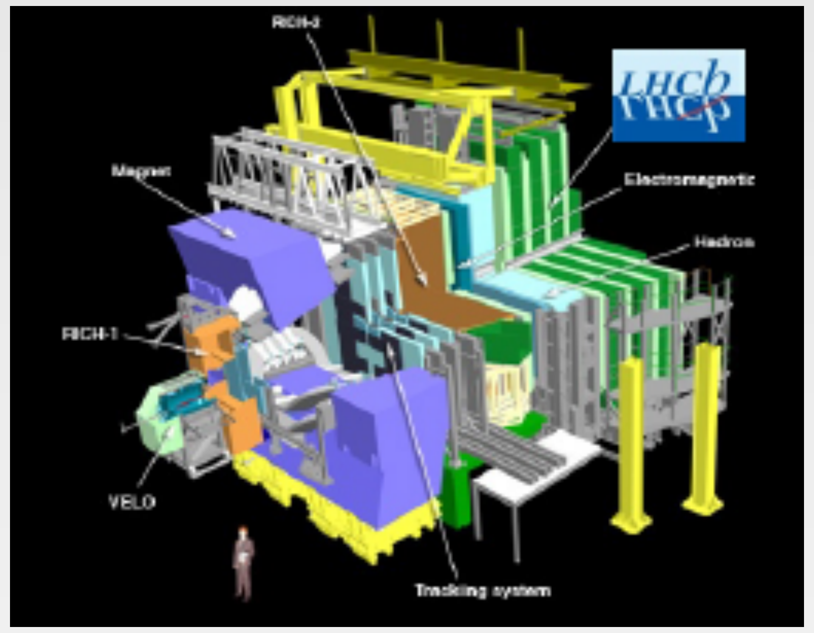


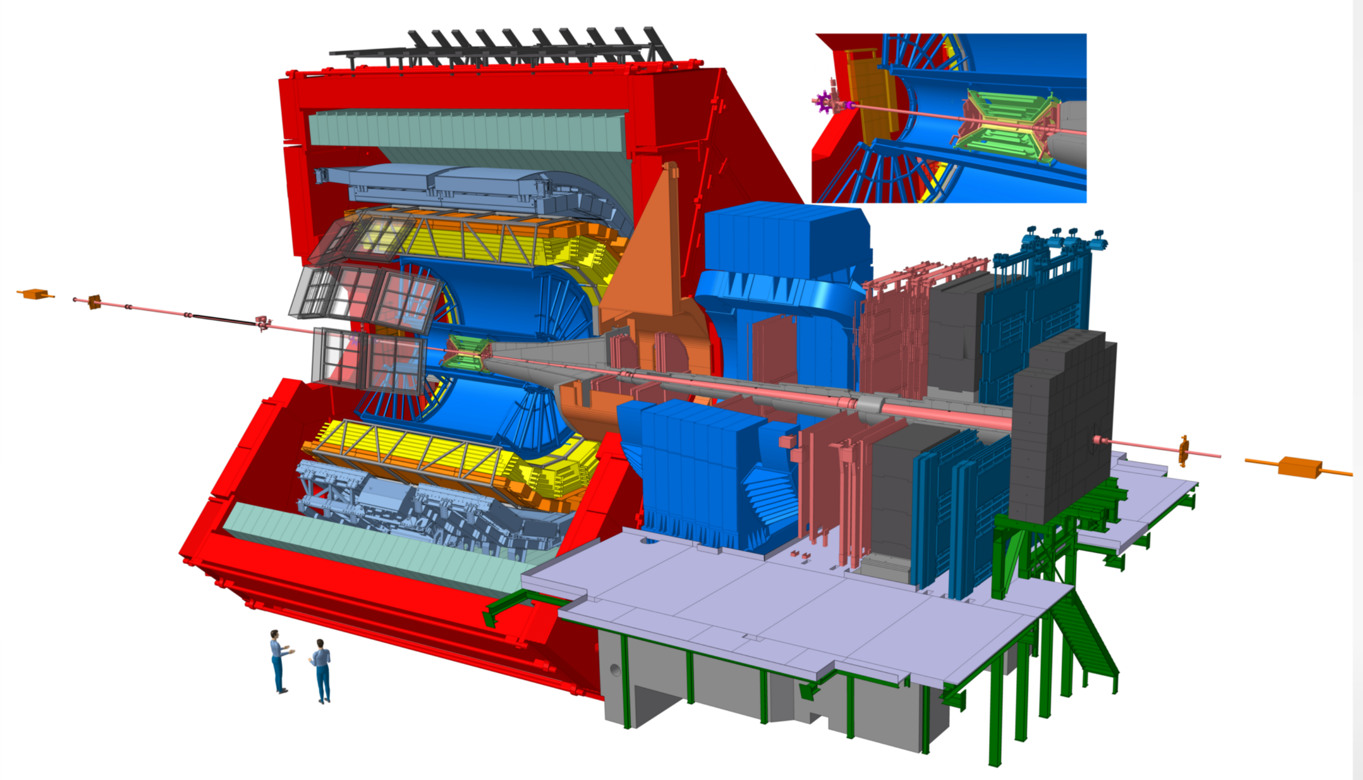
ATLAS

CMS

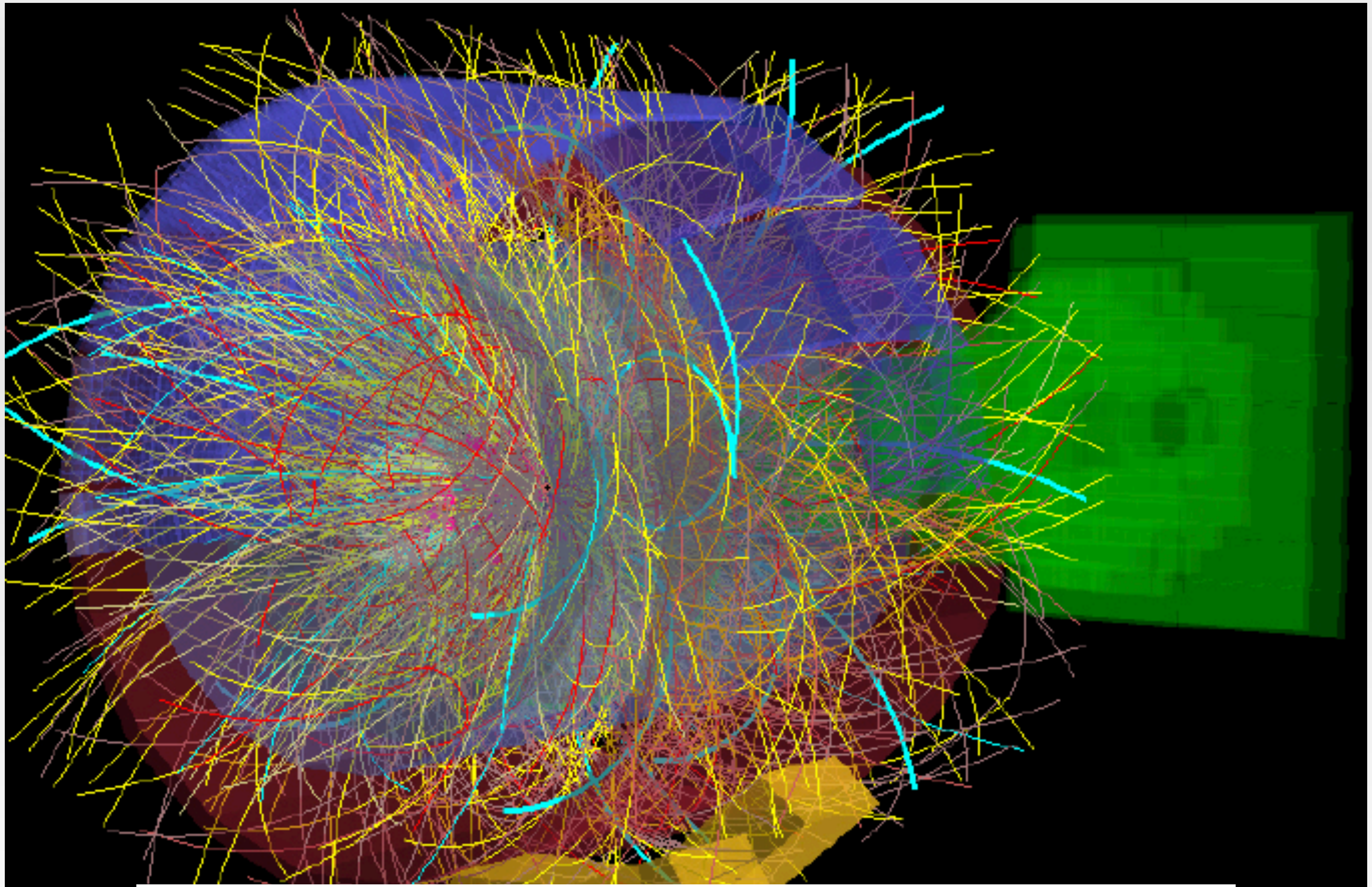


LHCb





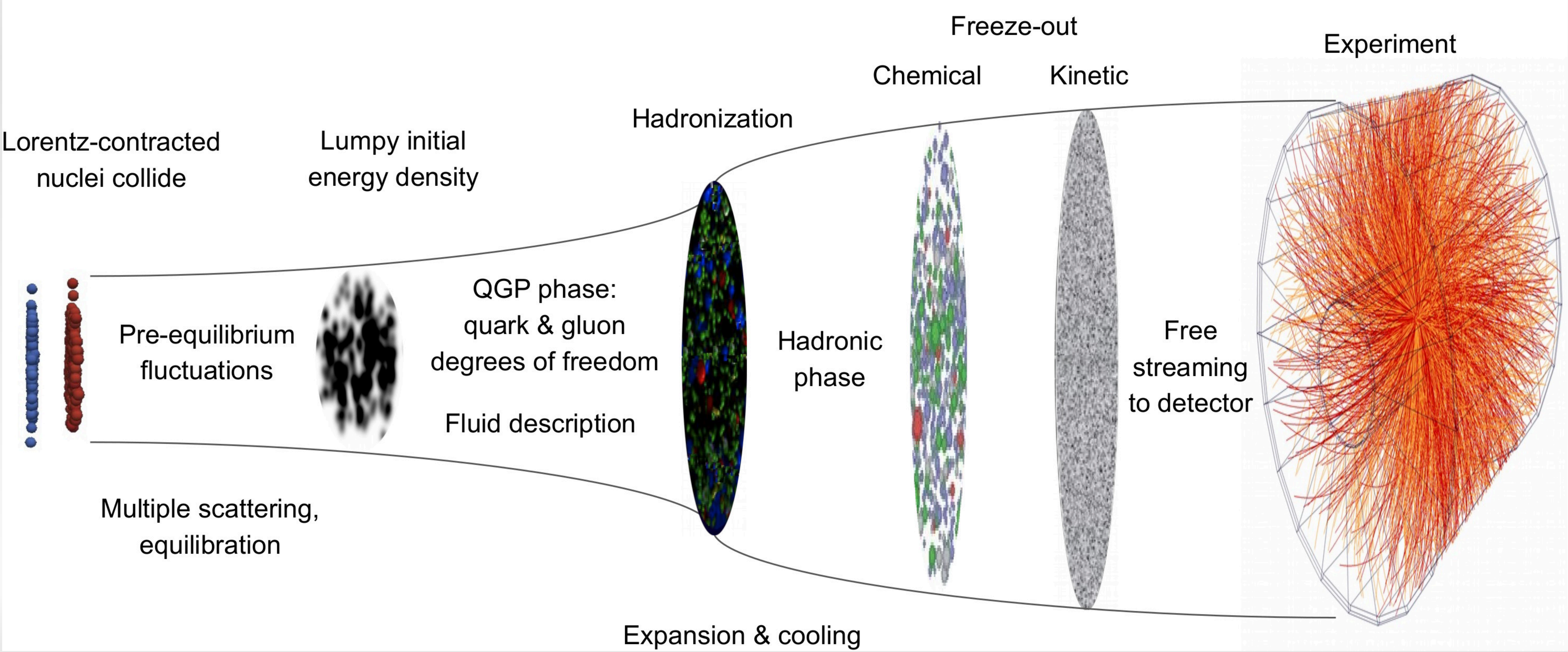
ALICE



- A central Pb–Pb collision produces ~18000 charged particles
  - at midrapidity: 1800 per unit rapidity

Evolution of a heavy-ion collision

$\tau \sim 0$ fm/c | $\tau \sim 1$ fm/c | $\tau \sim 10$ fm/c | $\tau \sim 10^{15}$ fm/c



How to study the QGP

Several different possibilities:

How to study the QGP

Several different possibilities:

⇨ **Production of bulk:**
information about initial densities, constrain the transport coefficients of the QGP and temperature

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⇨ **Calibrated probe:**
travel through the QGP bringing out information on its properties
- Heavy quarks

How to study the QGP

Several different possibilities:

⇨ **Production of bulk:**
information about initial densities, constrain the transport coefficients of the QGP and temperature

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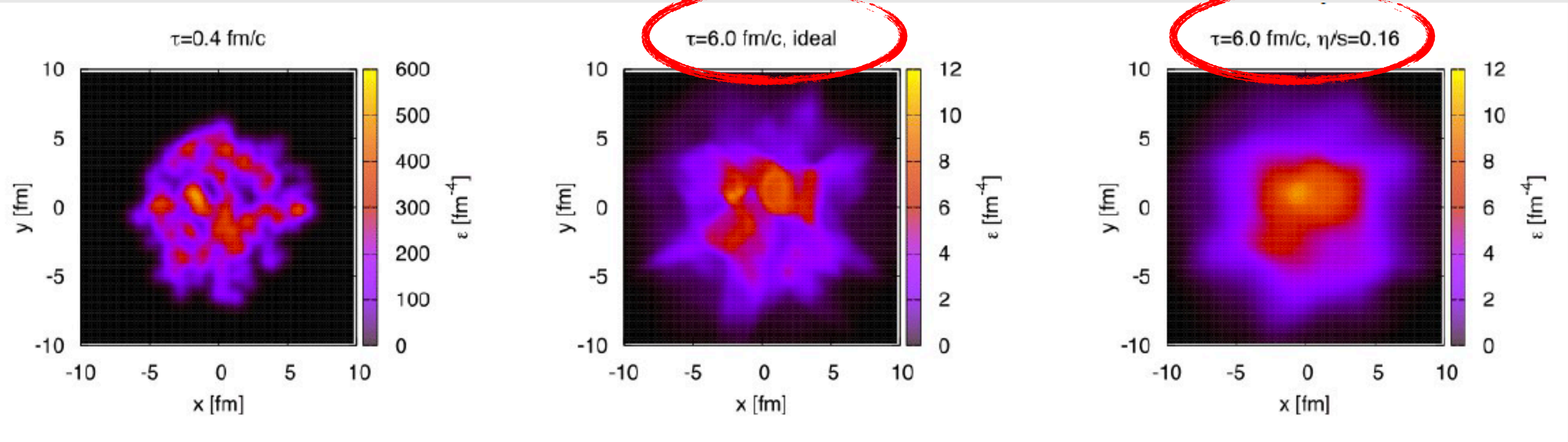
travel through the QGP bringing out information on its properties
- Heavy quarks

Transport coefficients

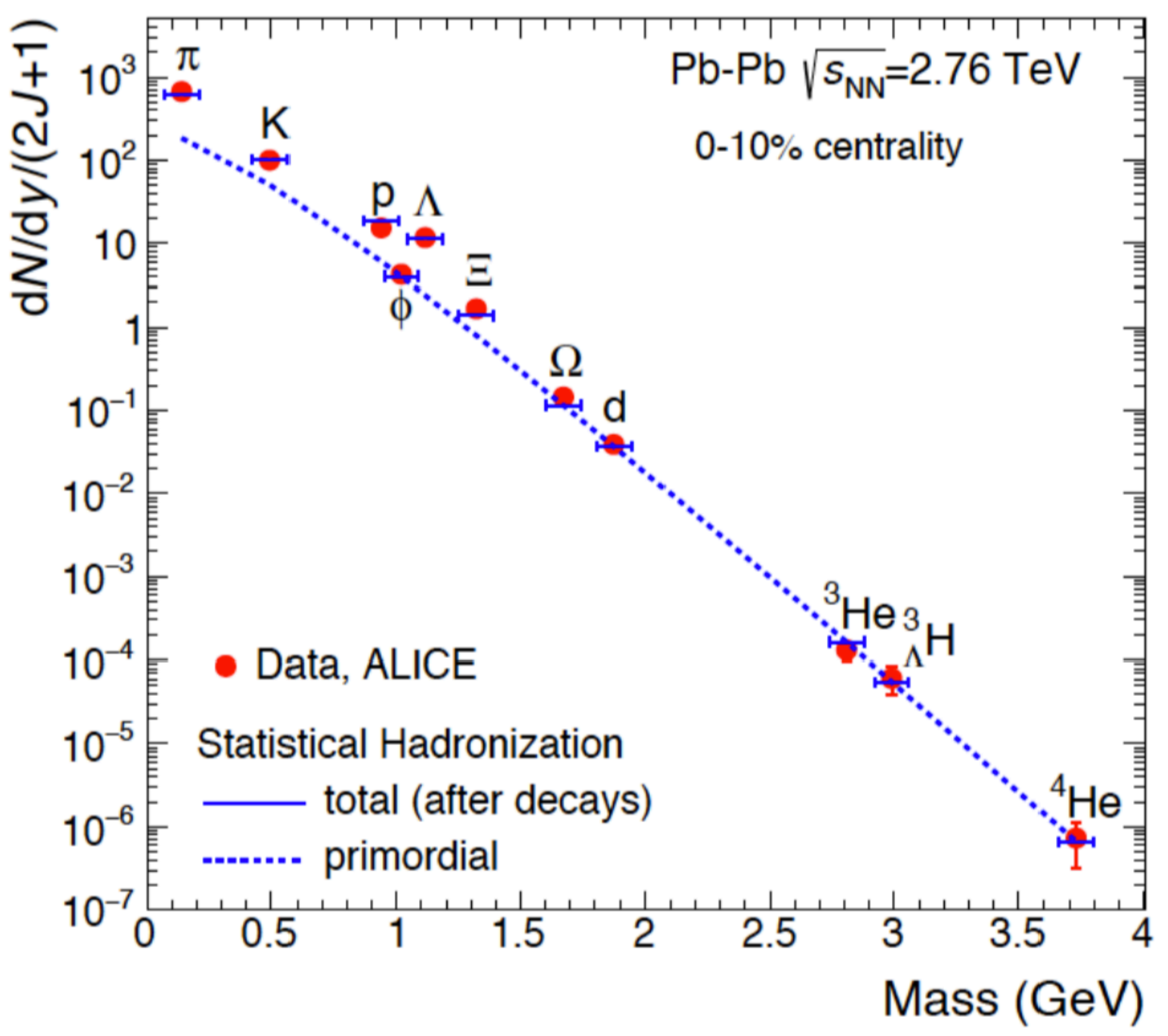
⇨ **Shear viscosity η/s**:
– tries to equalize expansion rates along the different directions
- reduces flow anisotropies

⇨ **Bulk viscosity ζ/s**:
– counteract the expansion: in an expanding fireball it reduces radial acceleration



Particle yields

J.Phys. G28 (2002) 1971-1976



⇨ **Statistical Hadrnization Model (SHM):** thermal emission from equilibrated source

⇨ Particle abundances fixed at the chemical freeze-out

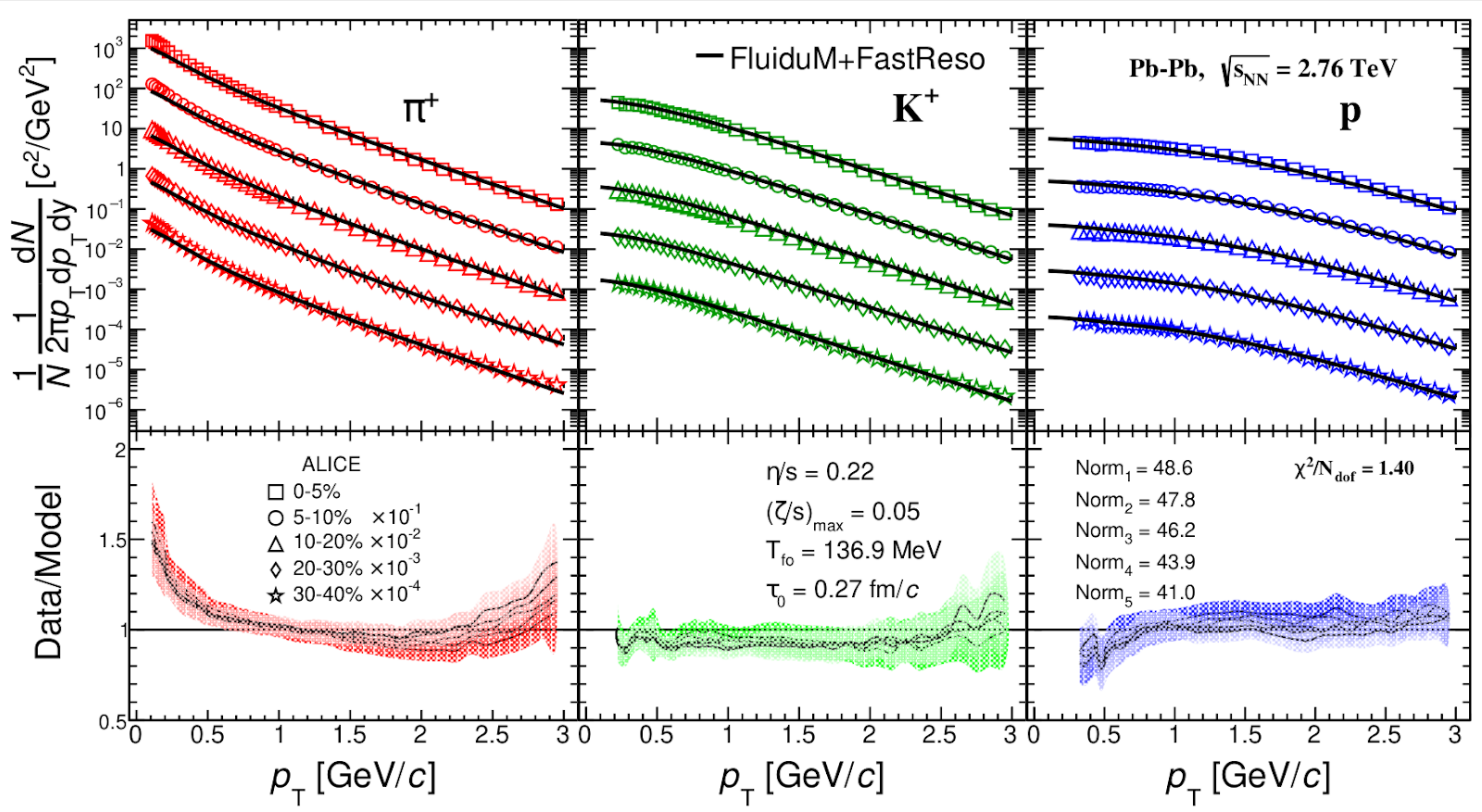
$$N_i = \frac{g_i V}{2\pi^2} \int_0^{+\infty} \frac{p^2 dp}{\exp\left[-\left(\frac{E-\mu_B}{T_{\mathrm{chem}}}\right)\right] \pm 1}$$

⇨ Primordial yields modified by resonance decay

⇨ Excellent agreement with the data using only 3 parameters **T_{chem}, μ_B and V**

⇨ **Universal hadronization?**
- T_{chem} ~ 156 for all species?

p_T-differential particle spectra



$$\frac{d^2N}{m_T dm_T dy} = e^{-\frac{m_T}{T_{slope}}}$$

⇨ ***p_T* spectra of identified hadrons**

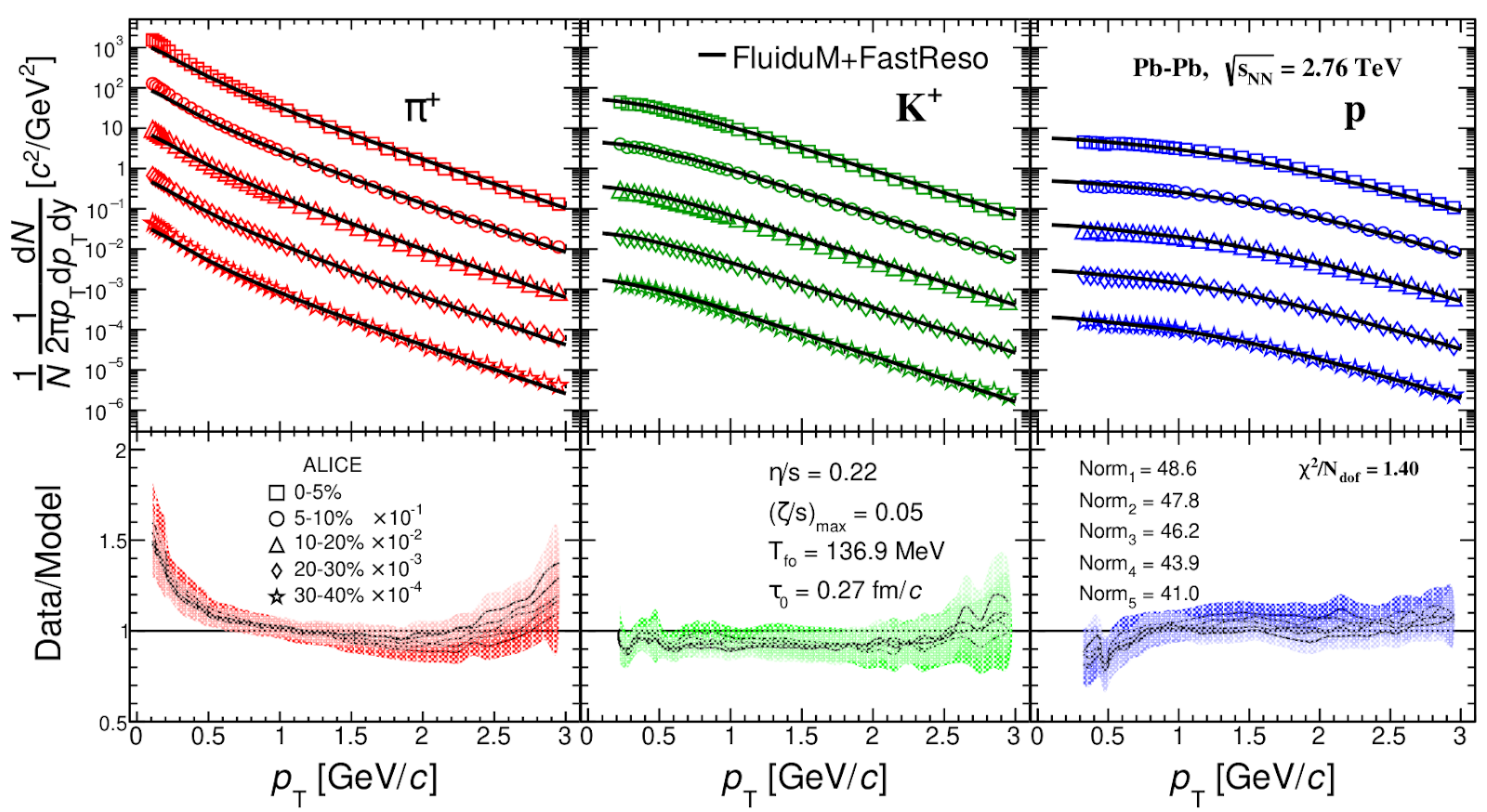
- hardening of the spectra moving from pions to proton

- Radial push (flow) depends on particle mass

$$T_{slope} = T_{kin} + \frac{1}{2} m_i \langle v_\perp \rangle^2$$

D. Devetak et al.
arXiv:1909.10485 [hep-ph]

p_T-differential particle spectra



⇨ **Global fit procedure**

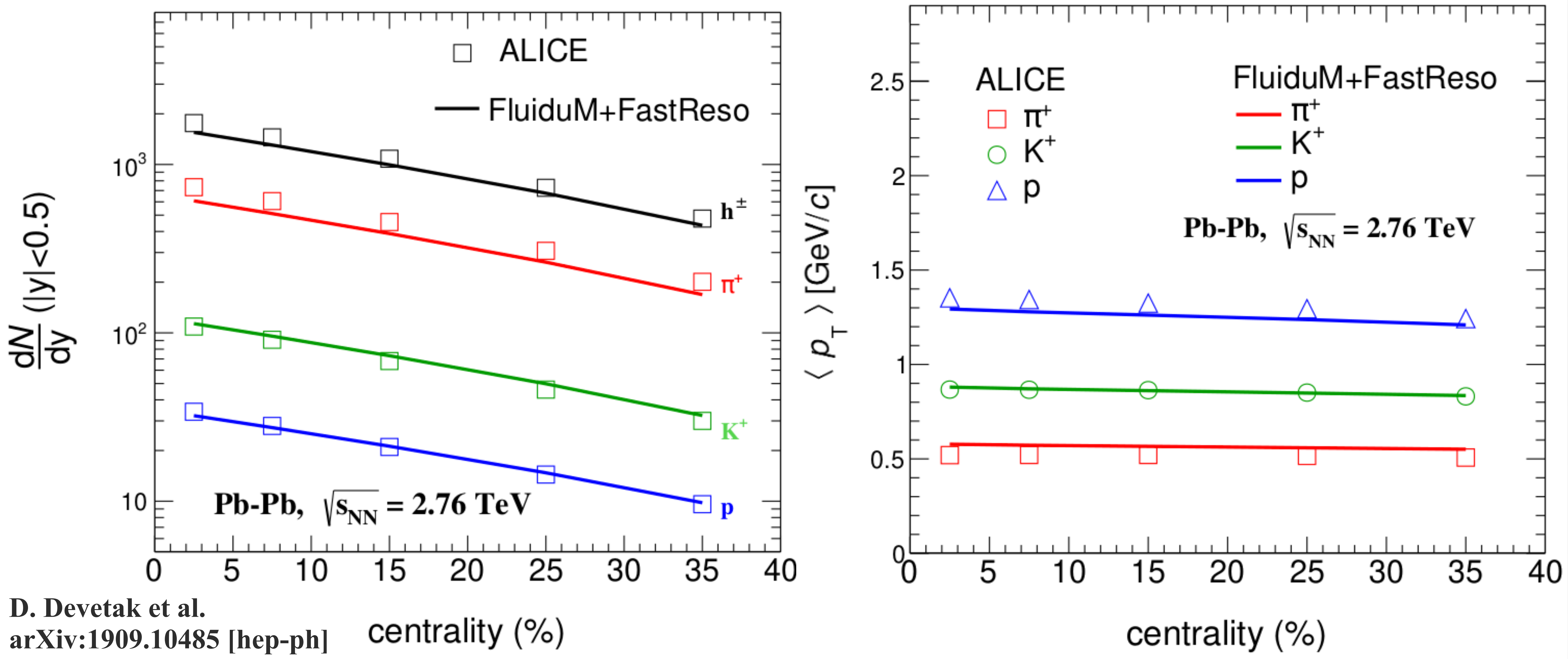
Model	Best fit
τ_0 [fm/c]	0.27
η/s	0.22
$(\zeta/s)_{max}$	0.05
T_{fo} [MeV]	136.9

⇨ Pions at low p_T are significantly underestimated

⇨ Resonances or non-thermal production from evolving coherent fields?

D. Devetak et al.
arXiv:1909.10485 [hep-ph]

Integrated spectra and $<p_{T}>$



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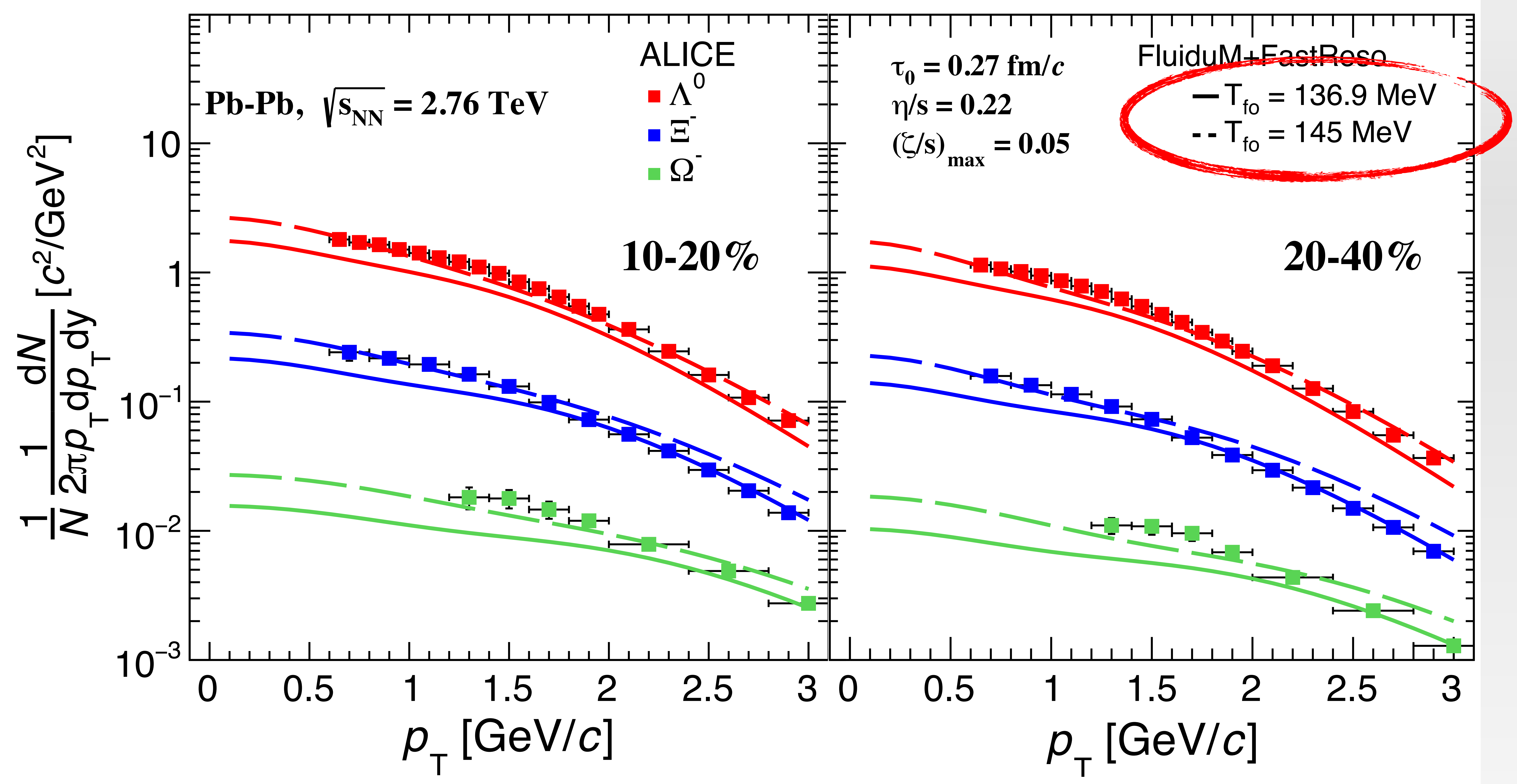
T_{fo} [MeV]	136.9

⇨ Pions are underestimated due to the difference observed at low p_{T}

⇨ $< p_{T} >$ for protons is also not perfectly reproduced - missing hadronic rescattering?

Strange and multi-strange baryons



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⇨ **(multi-)strange** hadrons prefer **higher freeze-out temperature** (T_{fo} = 145 MeV)

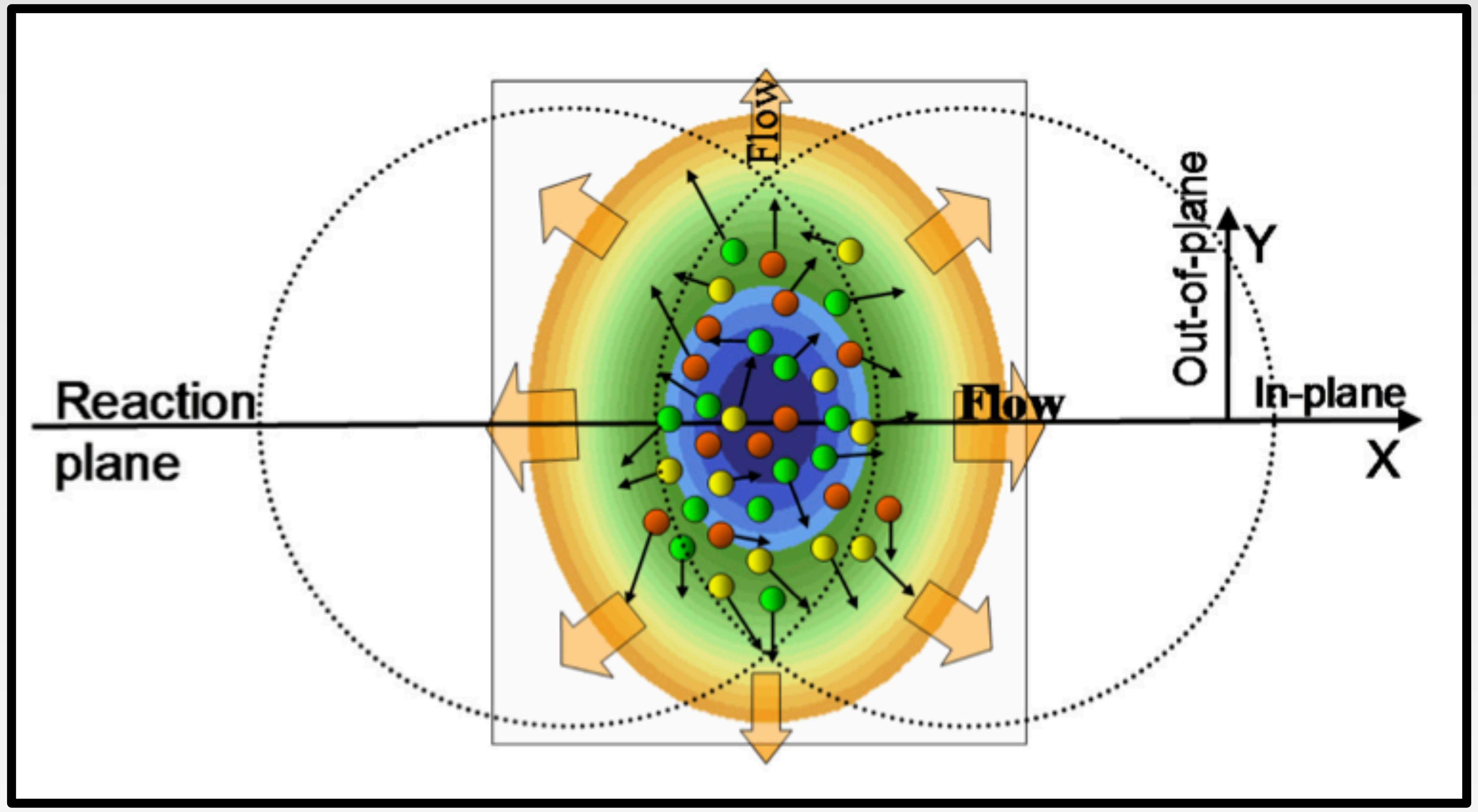
- **sequential hadronization** at different temperatures for different flavours?

  R. Bellwied et.al. PRL 111, 202302 (2013); D. Devetak et al. arXiv:1909.10485 [hep-ph]

- **additional resonance feed-down** might improve the agreement with data

Collectivity: azimuthal anisotropy

⇨ Re-scatterings among produced particles convert the initial **geometrical anisotropy** into an observable **momentum anisotropy**



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

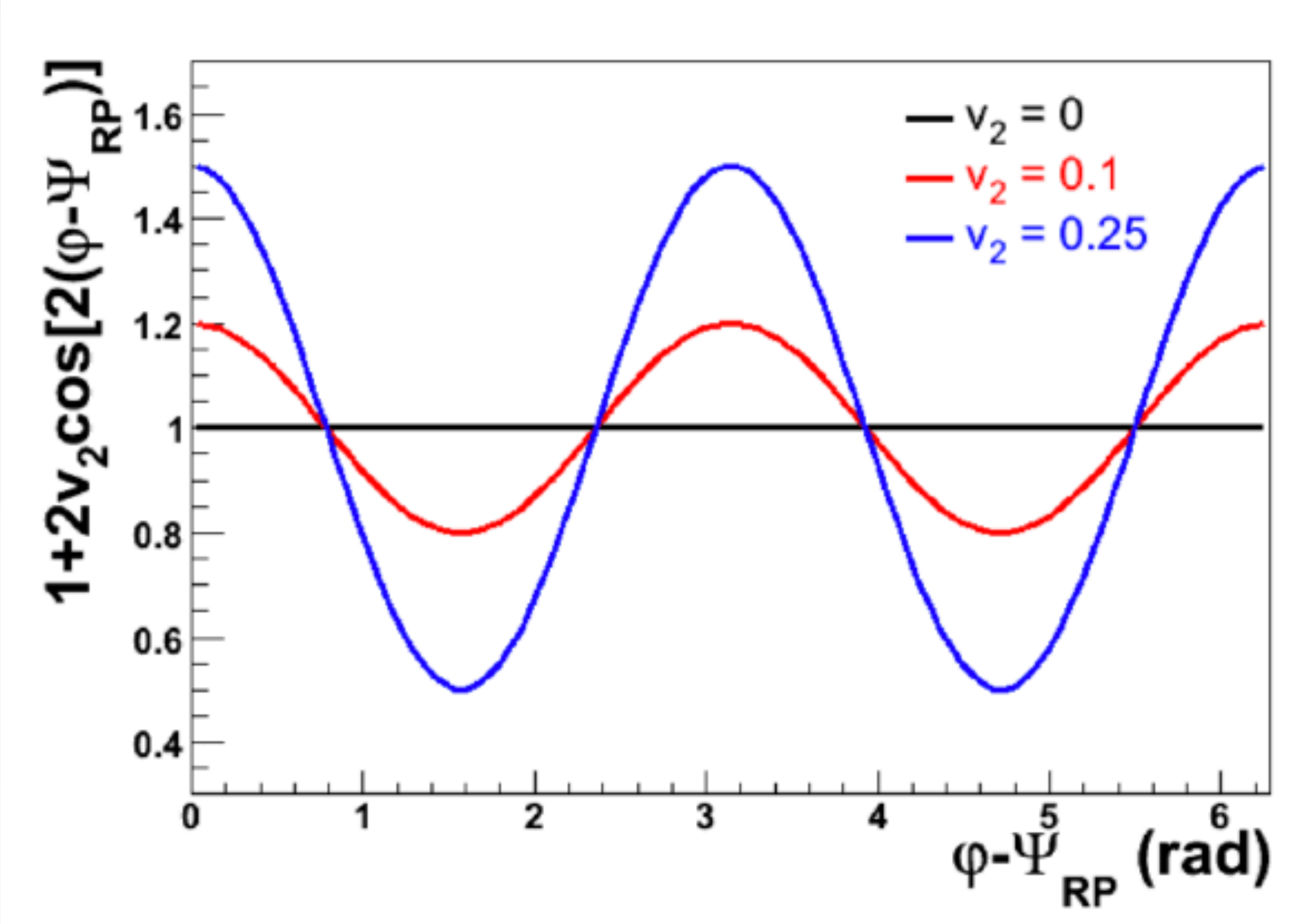
v_n measurements probe:

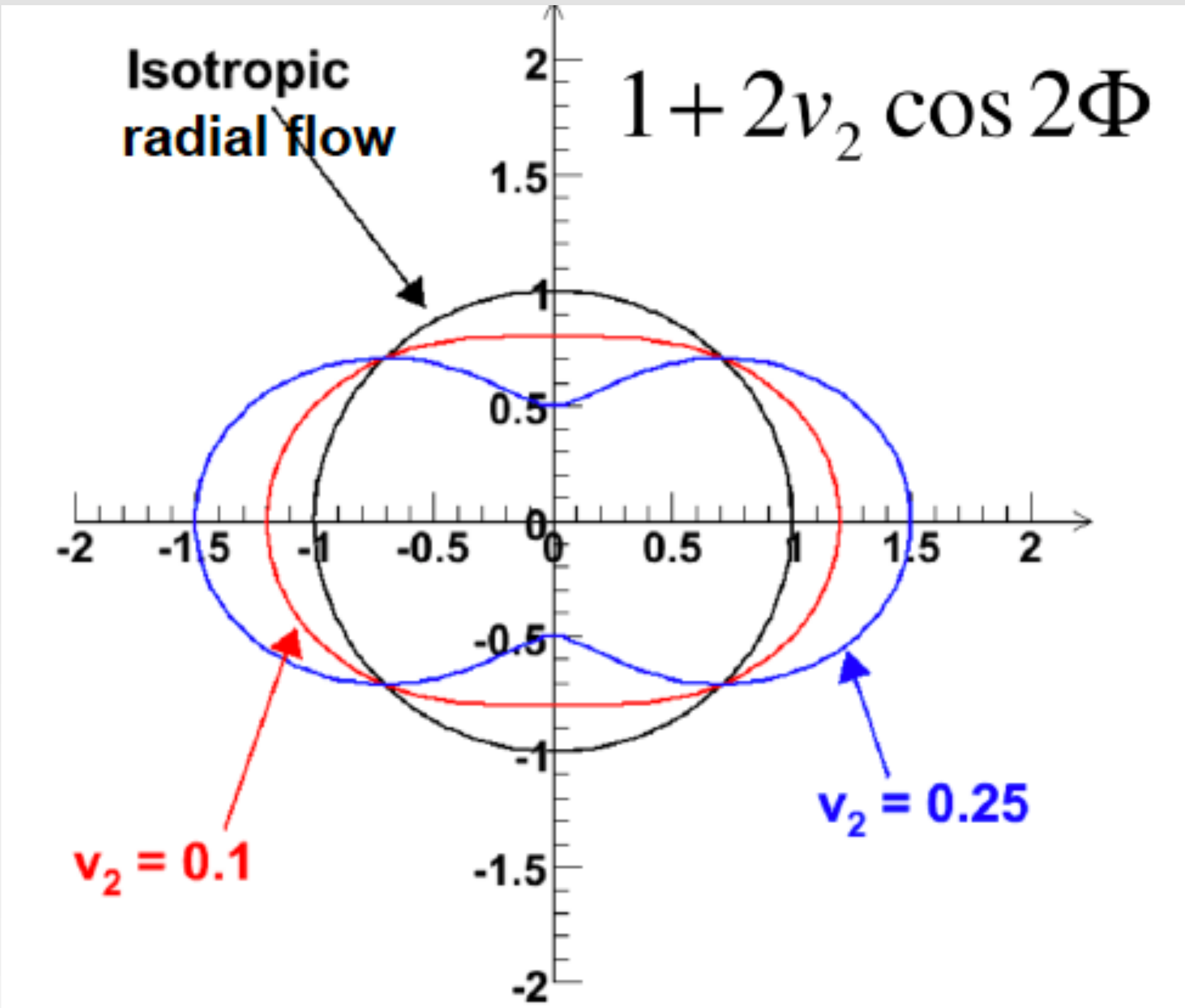
⇨ **Low/intermediate p_T**: collective motion, **degree of thermalization** of produced quarks and **hadronization mechanism** (recombination)

⇨ collective flow is a very powerful observable to learn about the properties (η/s) and the evolution of the system

Collectivity: azimuthal anisotropy

$$\frac{dN}{d(\varphi-\Psi_R)} = \frac{N_0}{2\pi}(1+2\sum_n v_n \cos[n(\varphi-\Psi_R)])$$





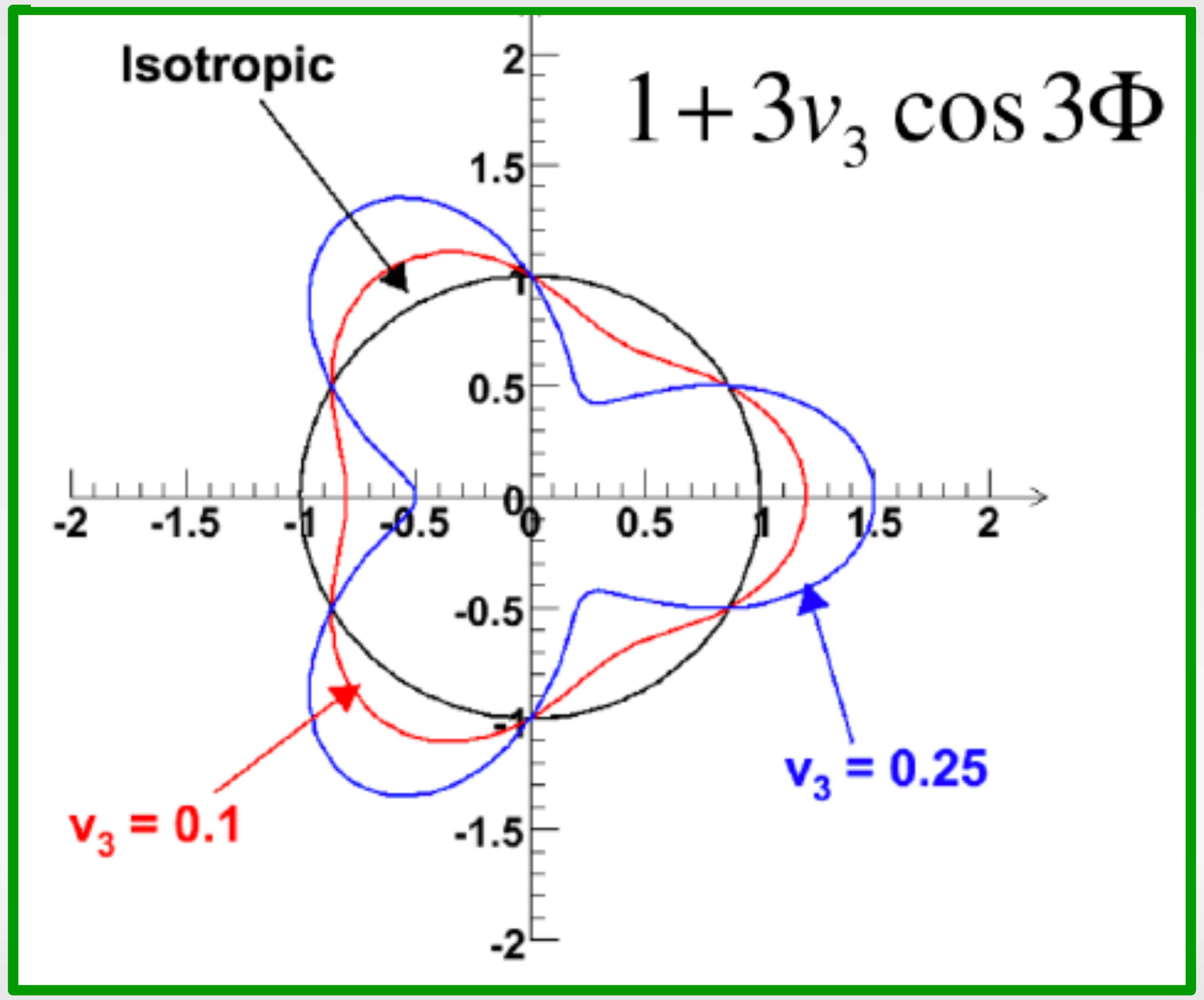
– $v_2 \neq 0$ → difference in the number of particle emitted parallel (0° and 180°) and perpendicular (90° and 270°) to the impact parameter b

→ Elliptic deformation of the source in the transverse plane.

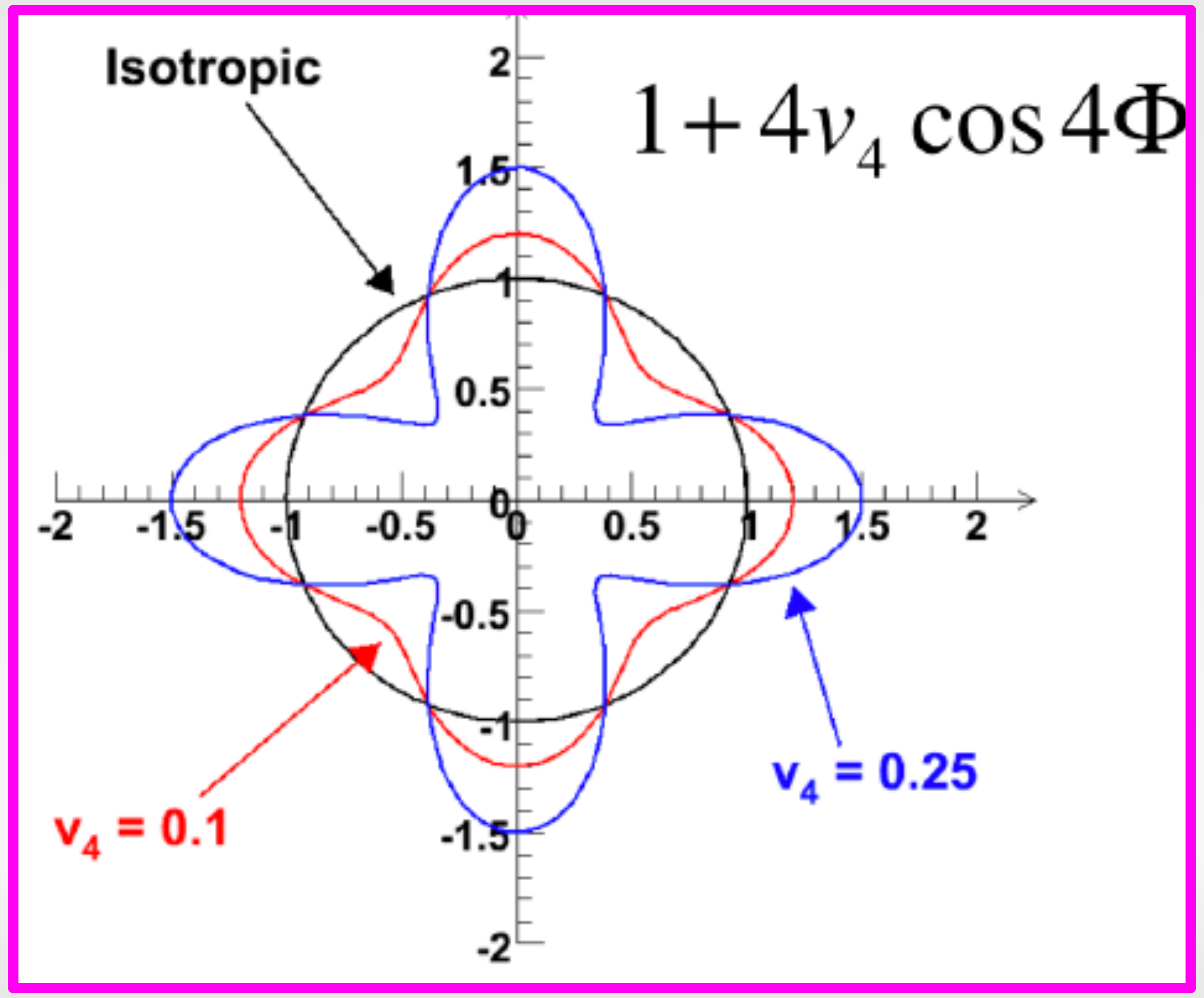
Collectivity: azimuthal anisotropy

$$\frac{dN}{d(\varphi - \Psi_R)} = \frac{N_0}{2\pi}\left(1 + 2\sum_n v_n \cos[n(\varphi - \Psi_R)]\right)$$

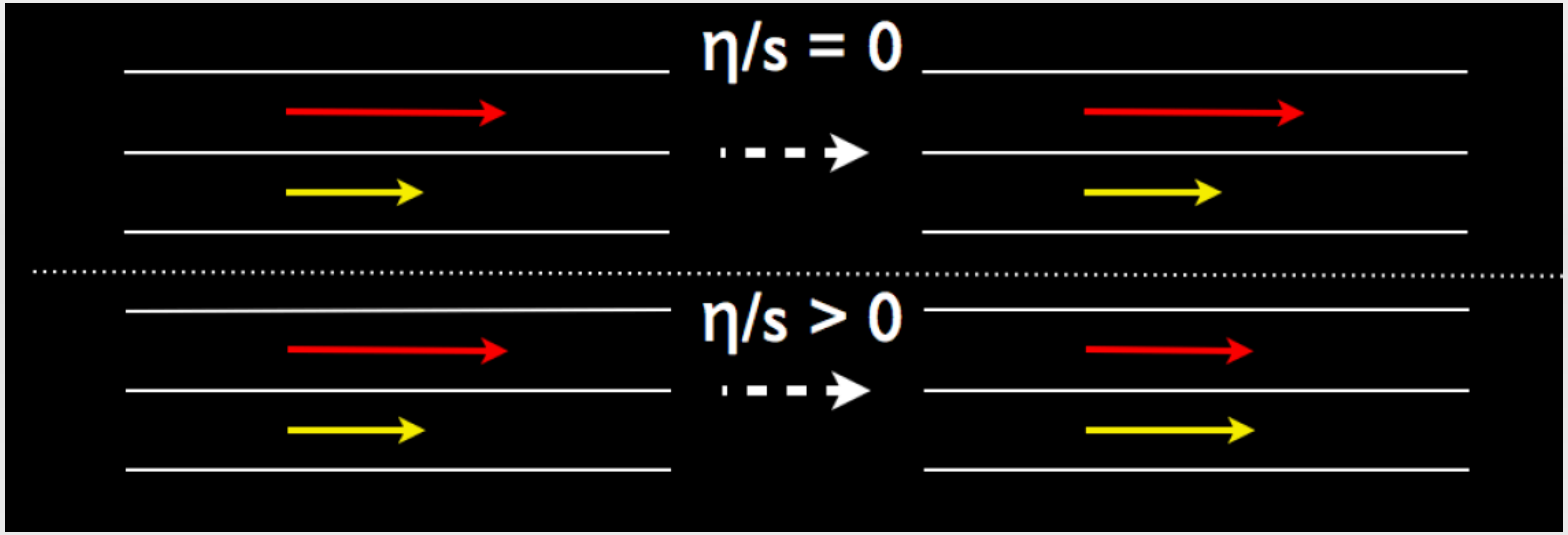
Third harmonic:
in collision of same nuclei v_3 is expected to be = 0, as well as for the other odd coefficients (symmetric system)

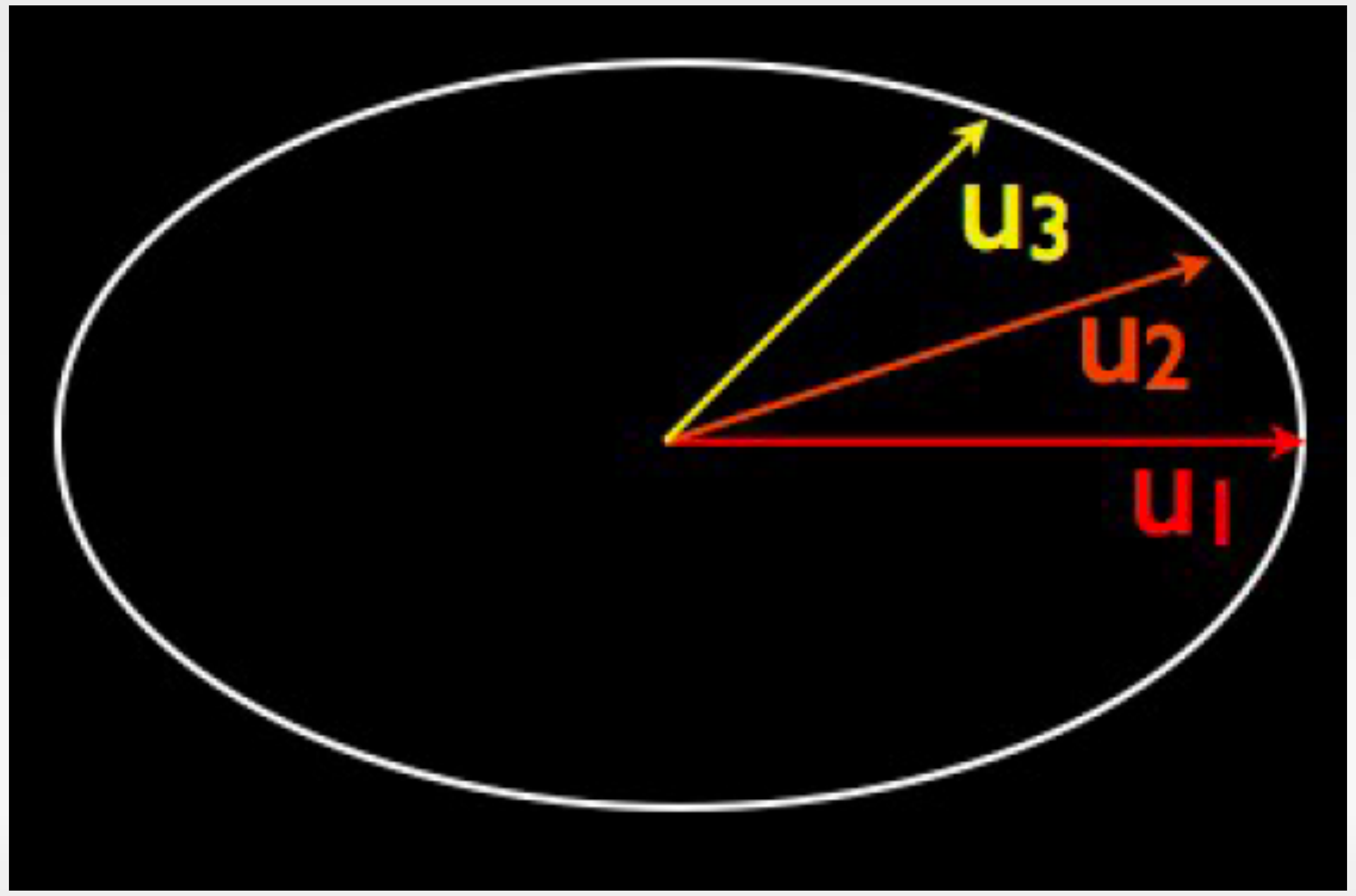


Fourth harmonic:
in case of a perfect fluid it has to be $v_4 = 0.5\, v_2^2$



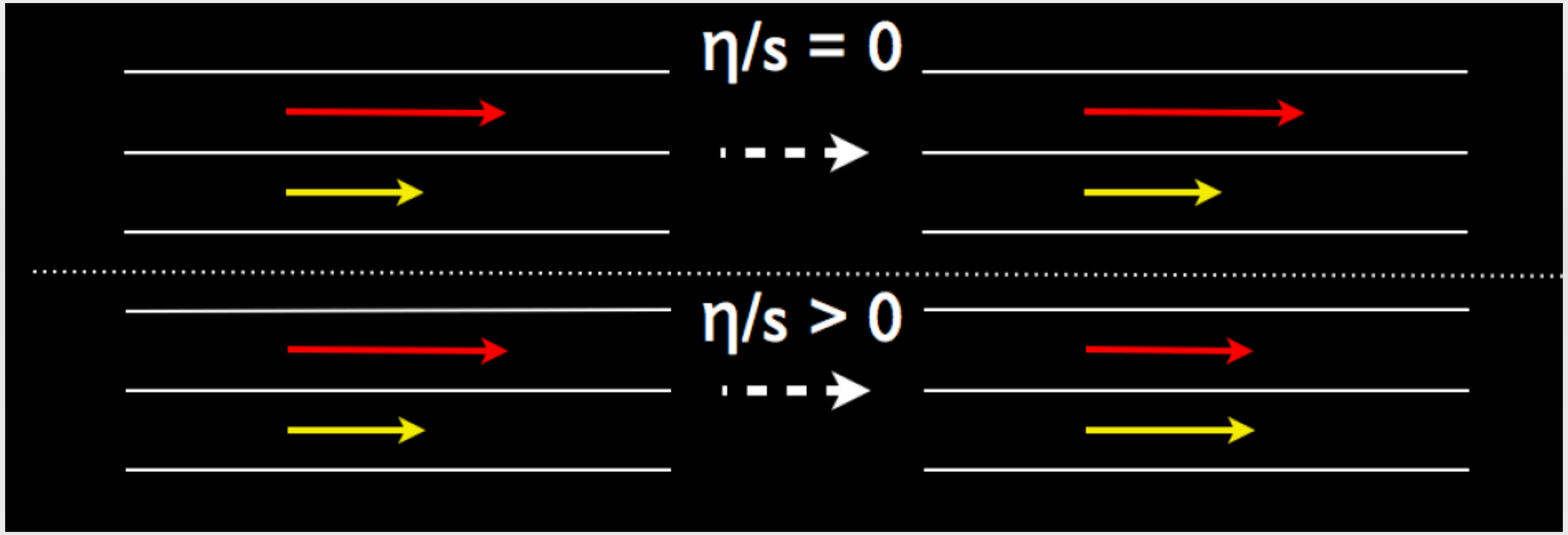
Shear viscosity

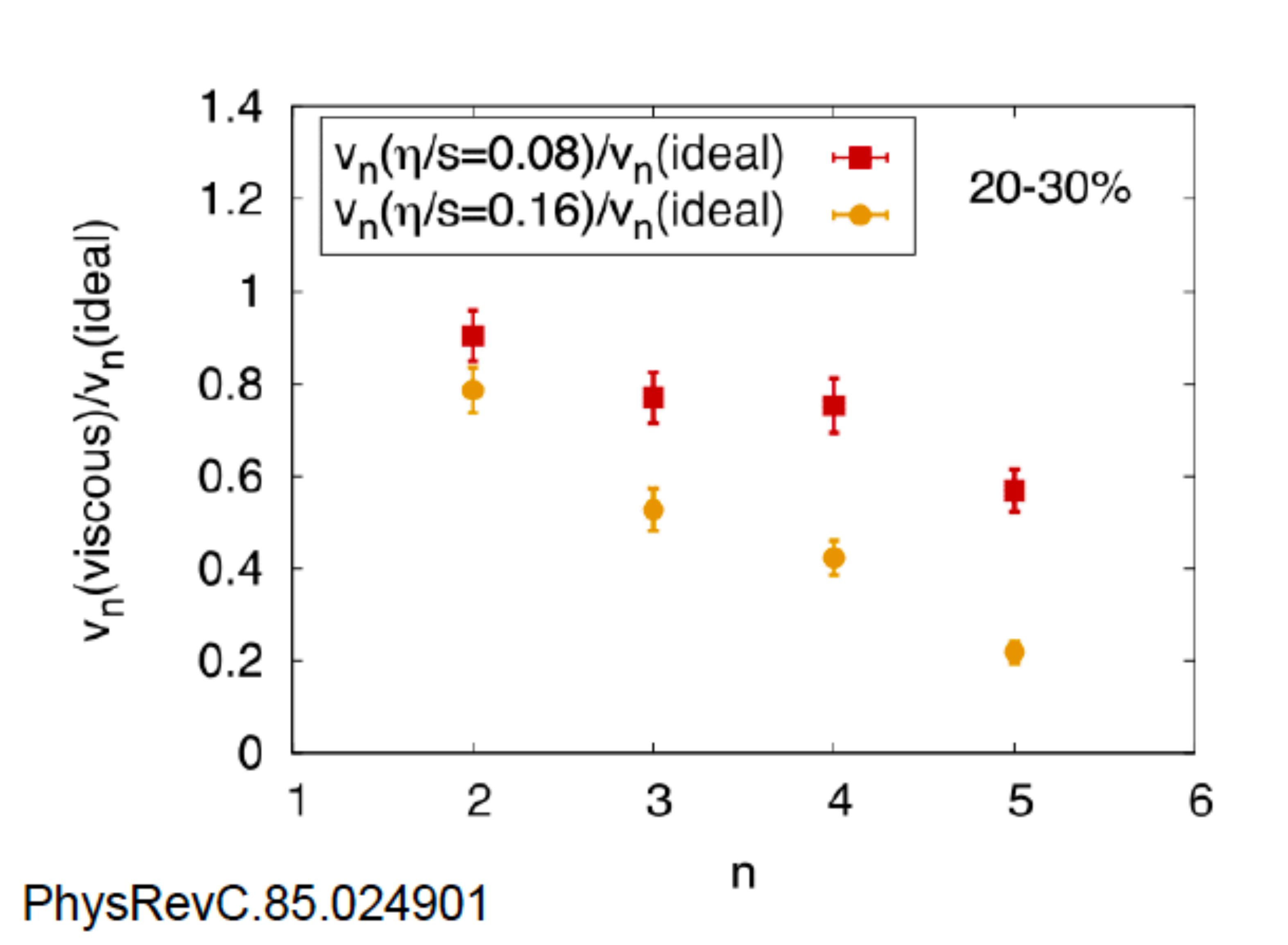




→ u_1 > u_2 > u_3: shear viscosity will make them equal and destroy the elliptic flow v2

Shear viscosity

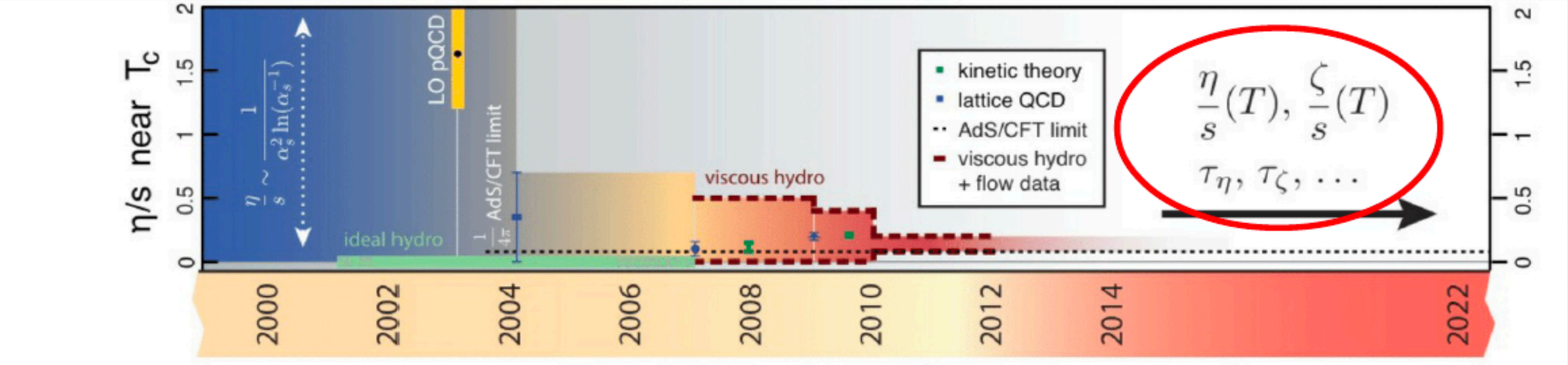




→ $u_1 > u_2 > u_3$: shear viscosity will make them equal and destroy the elliptic flow v2

→ Higher harmonics represent smaller differences which get destroyed more easily, and which, if measurable, makes them more sensitive probes to η/s

Transport coefficients



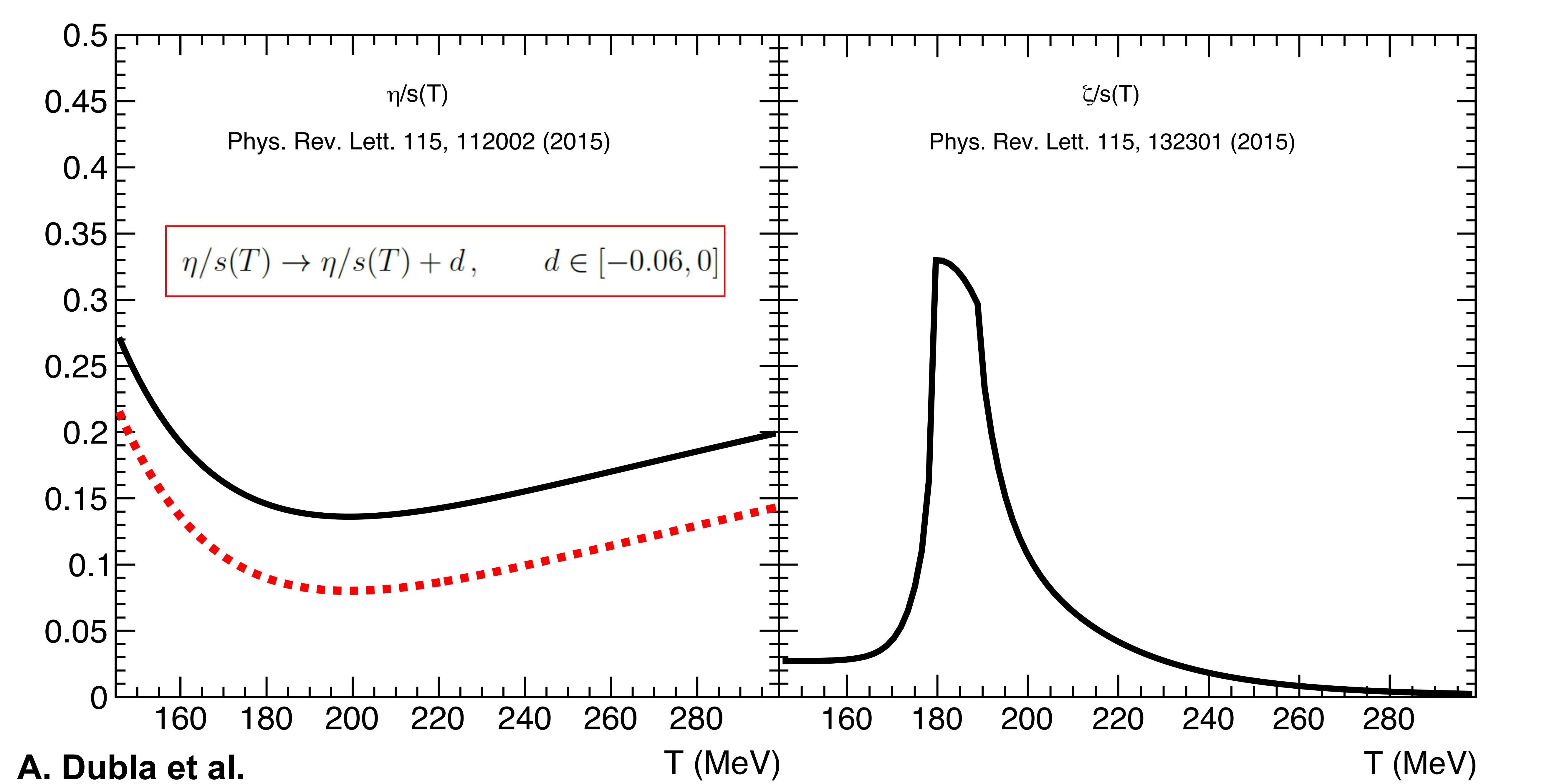
C. Gale et al, Int. J. Mod. Phys. A 28, 1340011 (2013)

Time line of important experimental and theoretical developments leading towards increasingly precise understanding of the transport properties of the QGP and the initial state fluctuations

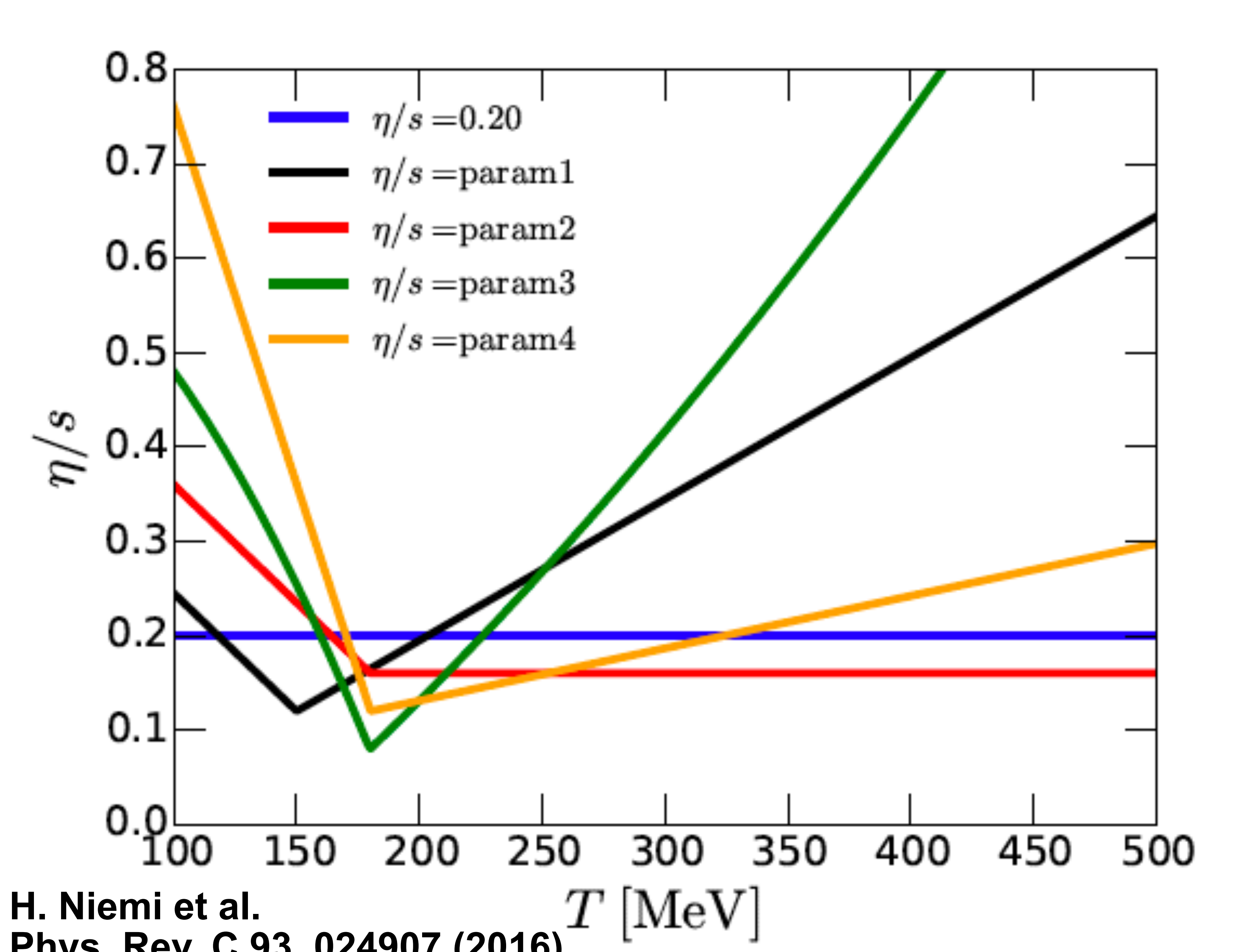
Temperature dependent shear and bulk viscosity!

Transport coefficients

Temperature dependent shear and bulk viscosity



A. Dubla et al.
Nucl.Phys. A979 (2018) 251-264

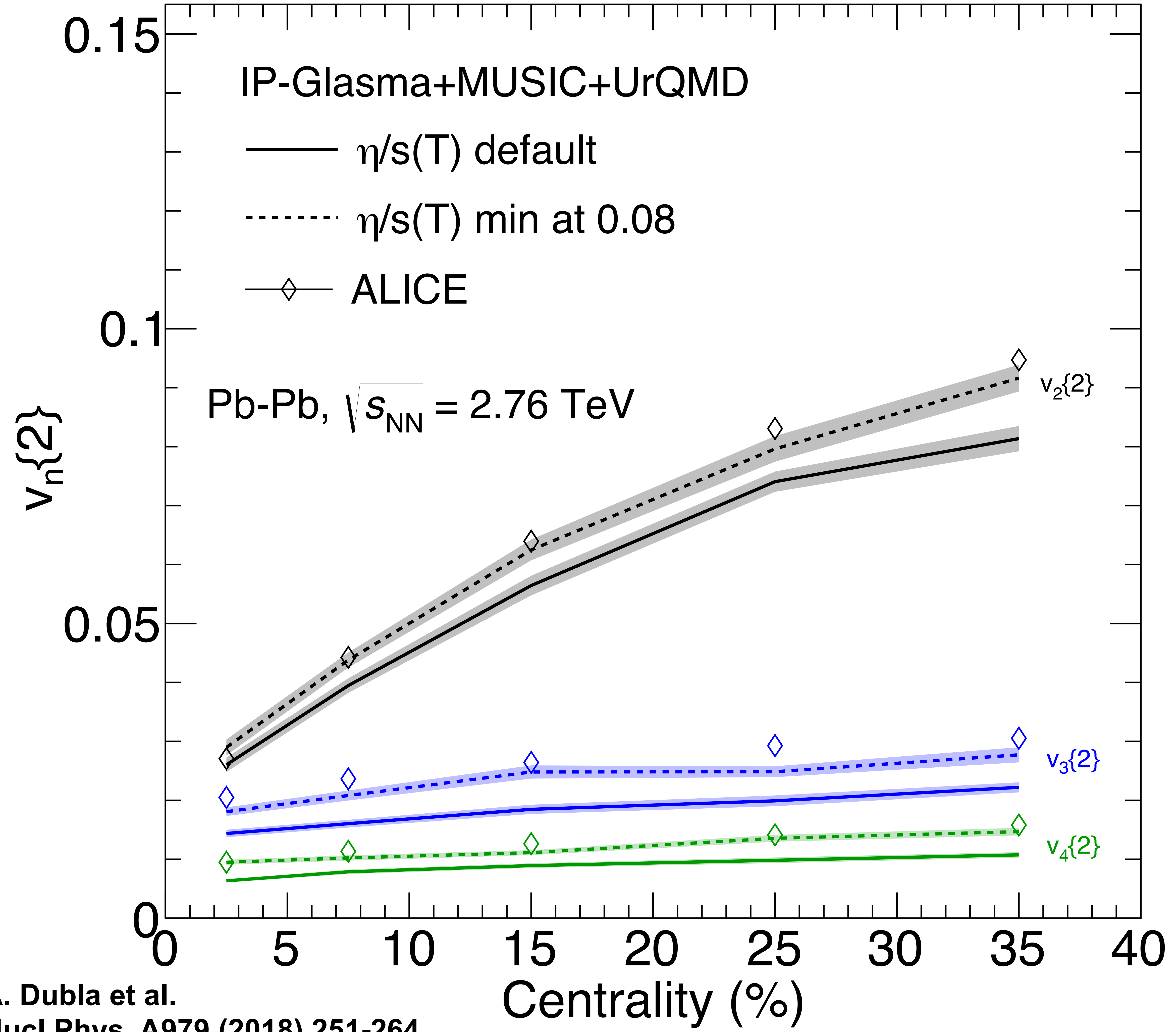


H. Niemi et al.
Phys. Rev. C 93, 024907 (2016)

➪ **η/s(T)** from Yang-Mills theory using a diagrammatic representation based on functional renormalization group in terms of gluon spectral functions (PRL 115, 112002 (2015))

➪ **ζ/s(T)** from phenomenological parameterization (PRL 115, 132301 (2015))

Charged hadron flow

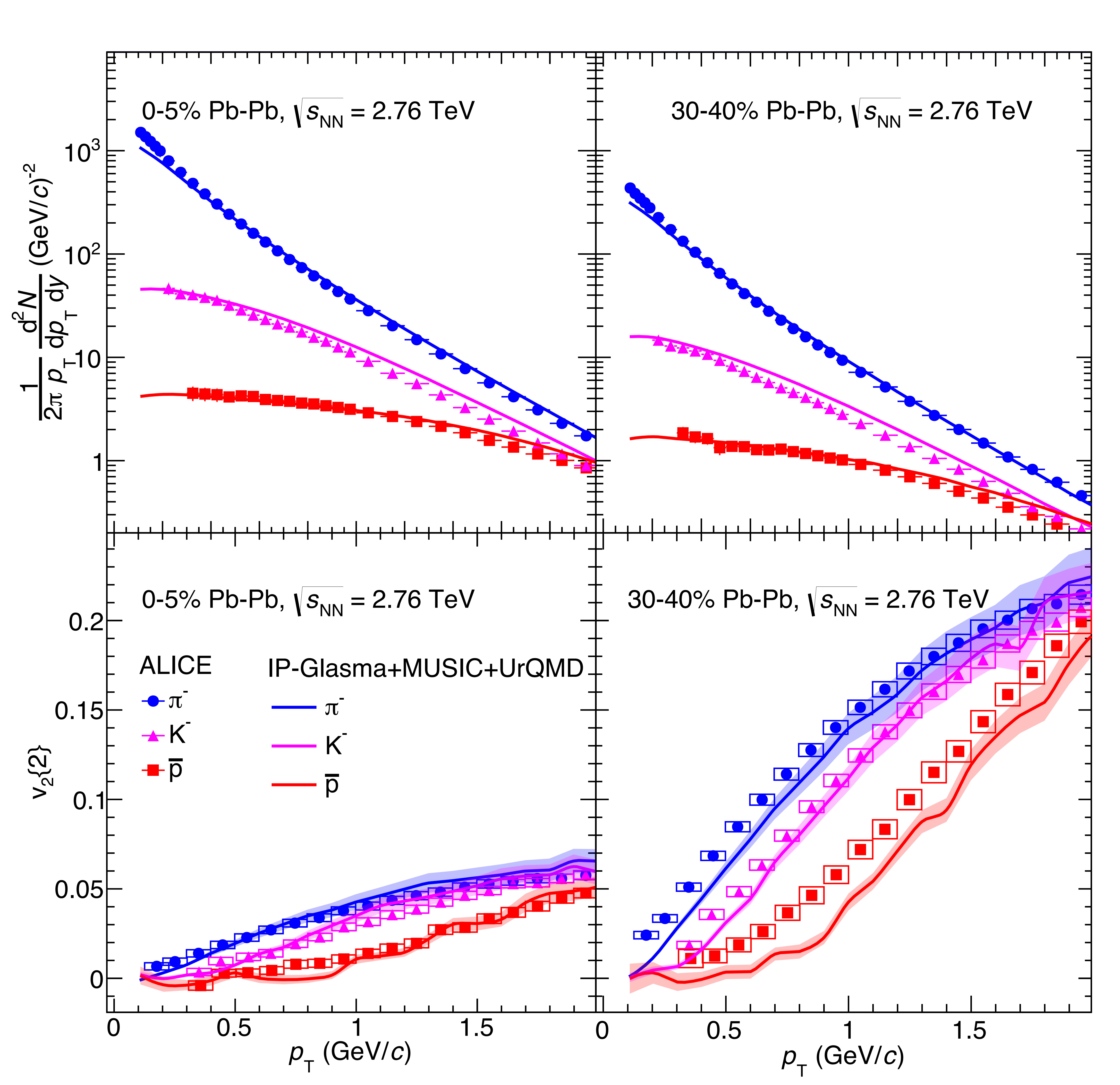


A. Dubla et al.
Nucl.Phys. A979 (2018) 251-264

⇨ **Agreement** within the statistical uncertainties **with the experimental measurements** by ALICE

⇨ Anisotropic flow measurements are sensitive to the shear viscosity over entropy density ratio

Identified particle flow

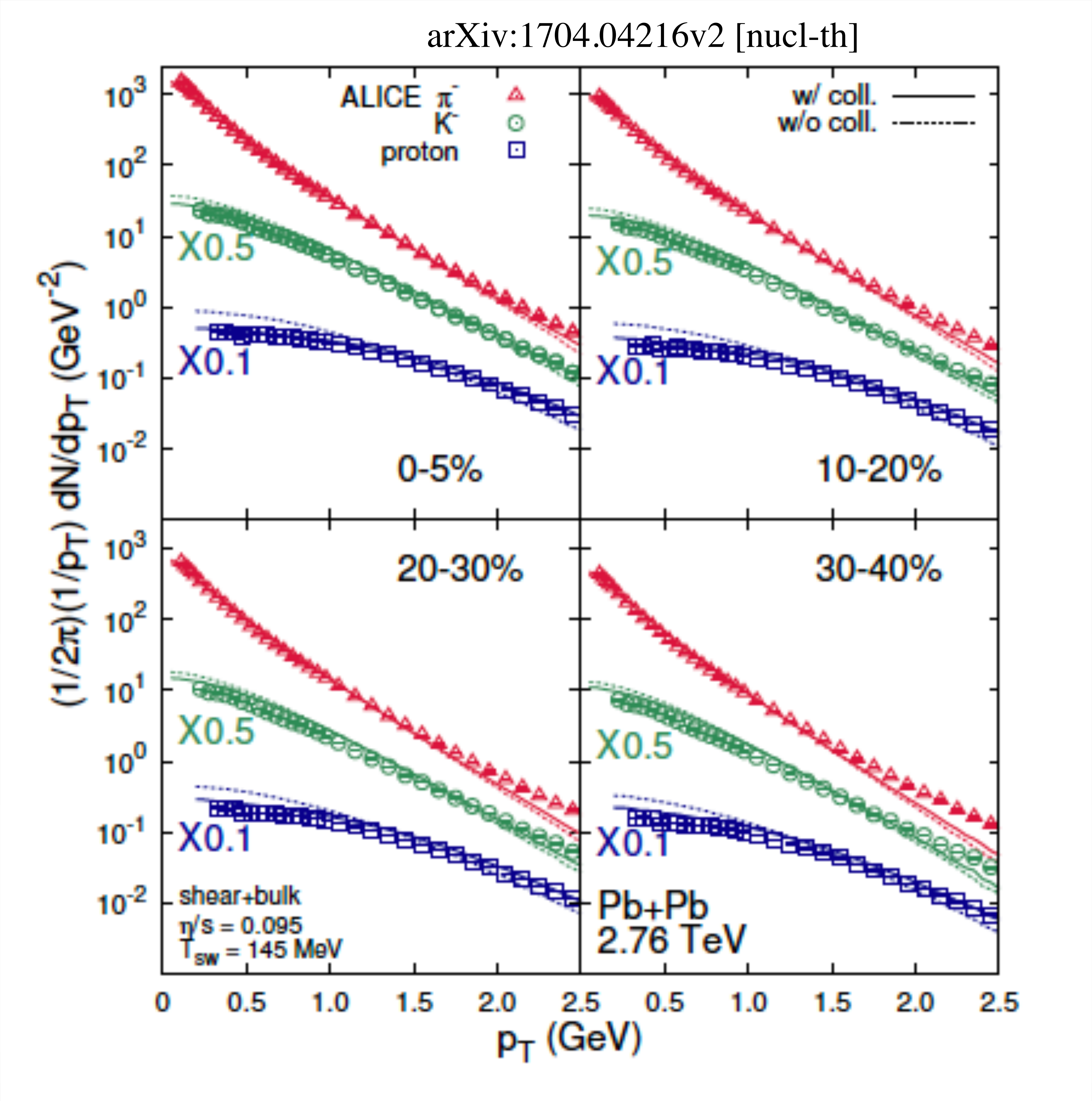


- **Comparison with the p_T spectra of identified hadrons**
  - insight about radial flow of the expanding system

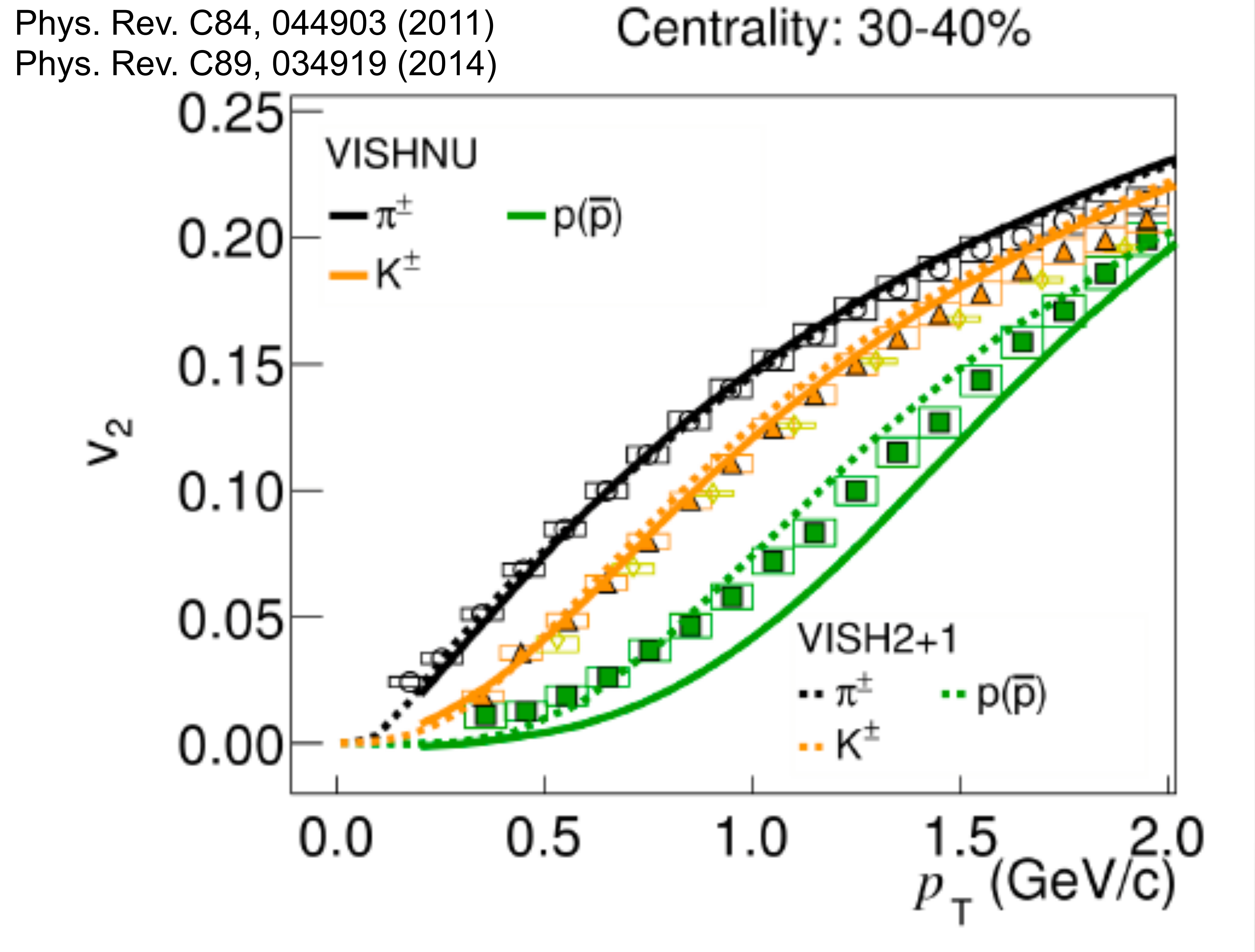
- **Comparison with p_T-differential flow coefficients of identified hadrons**
  - interplay between radial and elliptic flow leads to the mass ordering of the v_n coefficients

A. Dubla et al.
Nucl.Phys. A979 (2018) 251-264

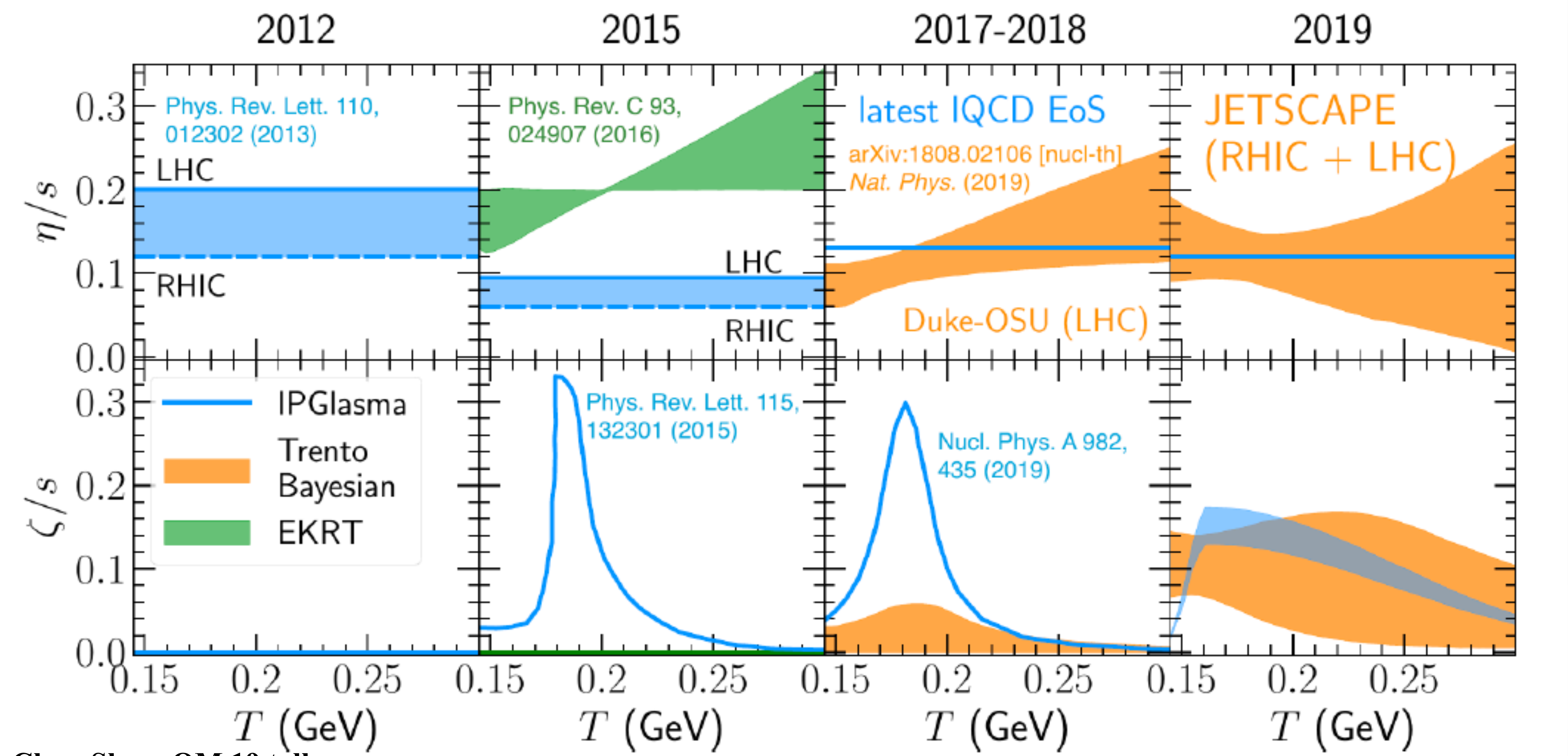
Effect of the hadronic phase



➩ **Comparison with p_T-differential spectra and flow of identified hadrons**
- Heavier particles are pushed to higher momenta
- Larger <p_T>
- Stronger mass scaling



Quantitative characterisation of QGP



Chun Shen: QM 19 talk

How to study the QGP

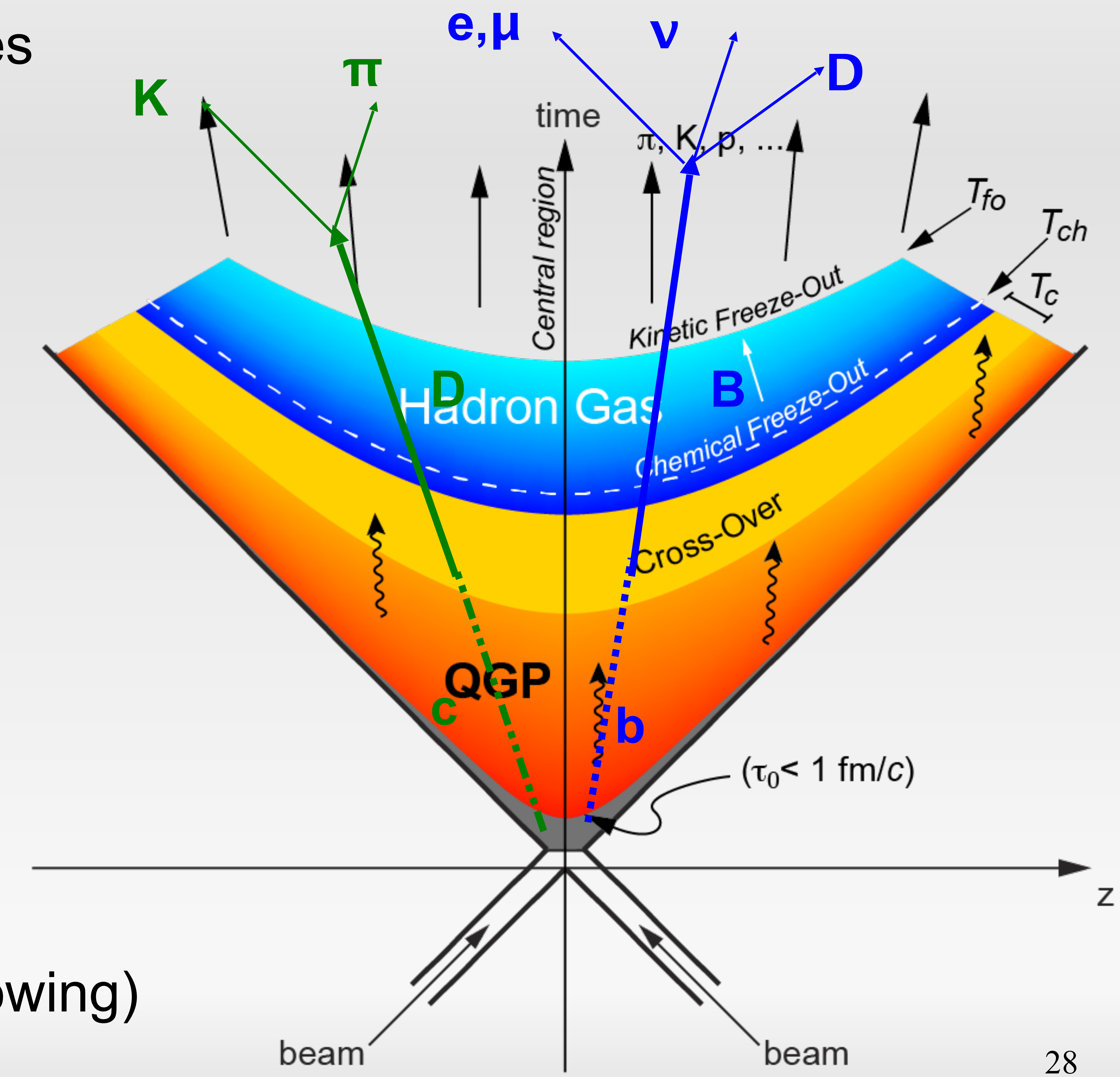
Several different possibilities:

⇨ **Production of bulk:**
information about initial densities, constrain the transport coefficients of the QGP and temperature

⇨ **Calibrated probe:**
travel through the QGP bringing out information on its properties
- Heavy quarks

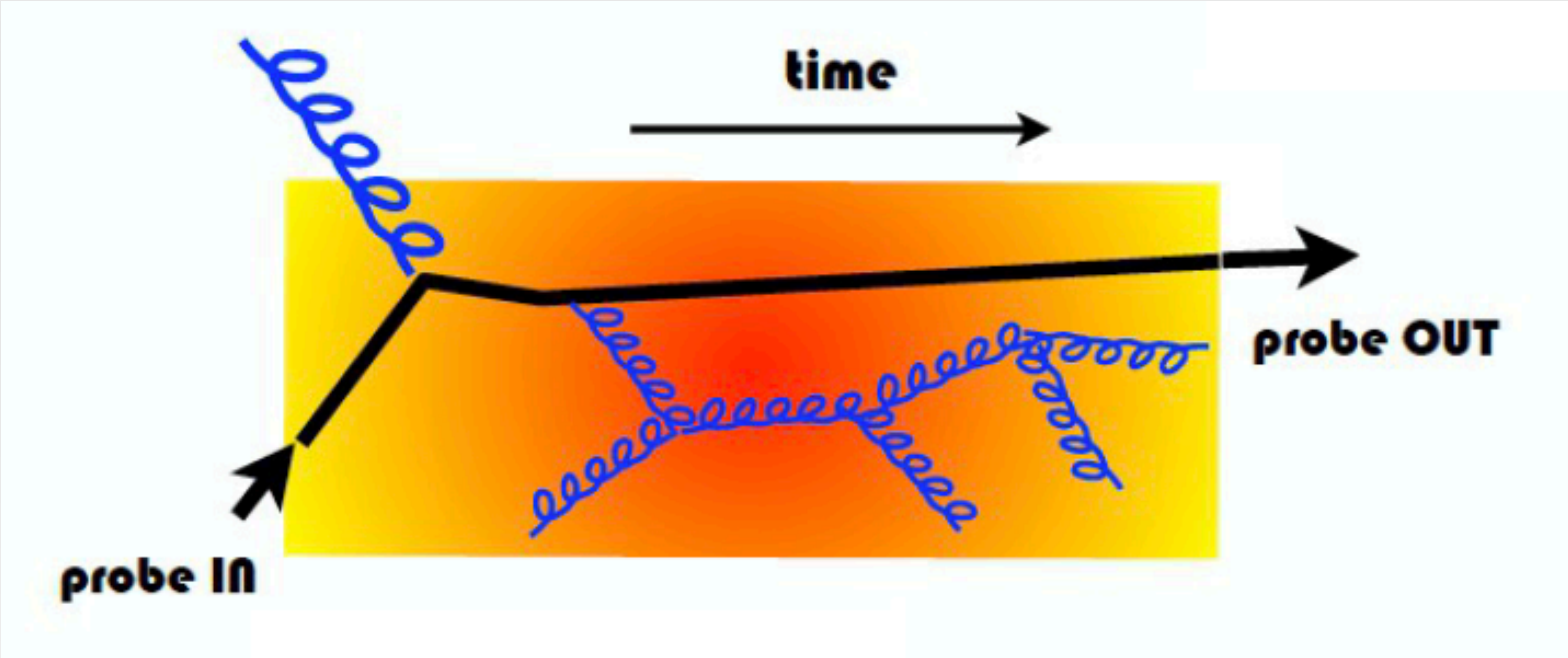
Why heavy quarks?

- ➩ **Charm and beauty** quarks are produced in the initial stages of the collisions via hard scattering processes
- ➩ They experience the full evolution of the system
  → sensitive probes of the properties of the QGP
- ➩ Expected to **lose energy**
- ➩ **Collective expansion**
- ➩ **Hadronization**: fragmentation vs coalescence
- ➩ **Cold Nuclear Matter effect**: modification of nPDF (shadowing)



Quark energy loss in QGP

– Quark can loose energy via collision (collisional) and gluon radiation (radiative)



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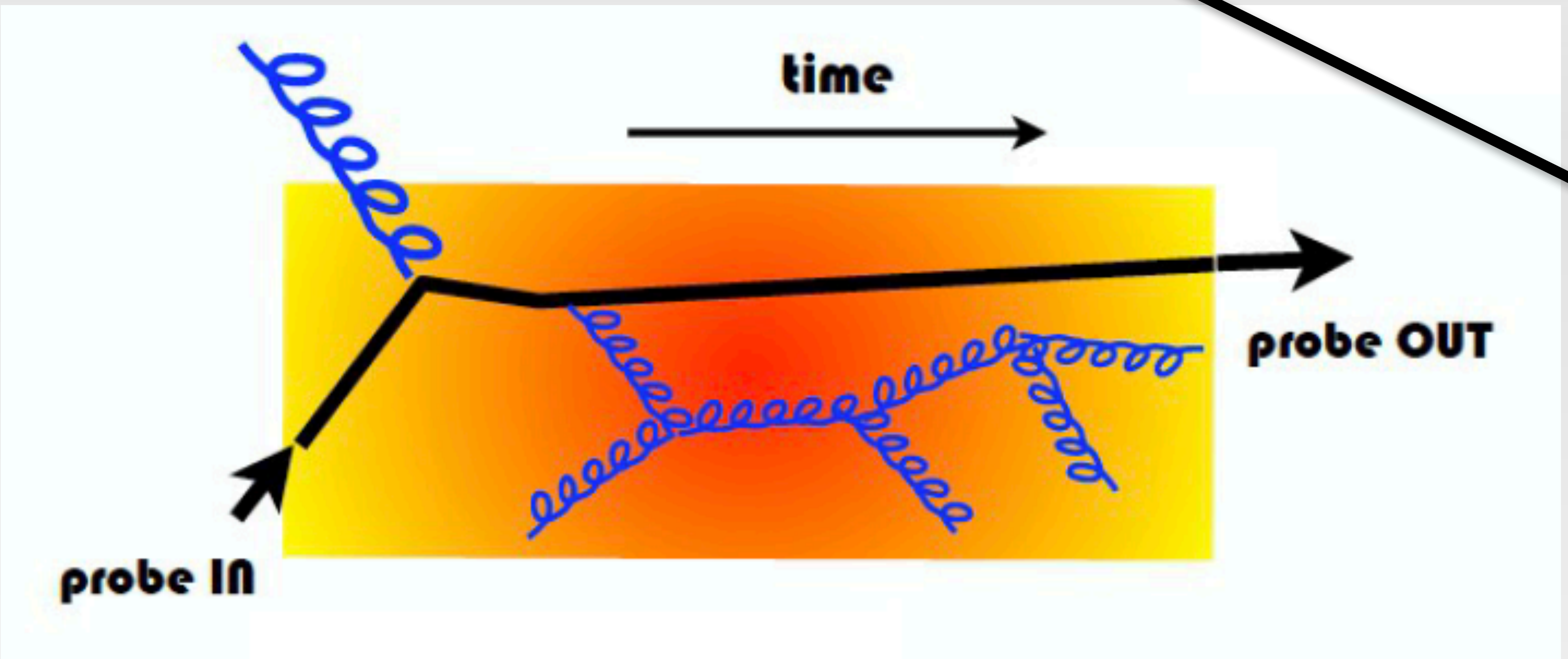
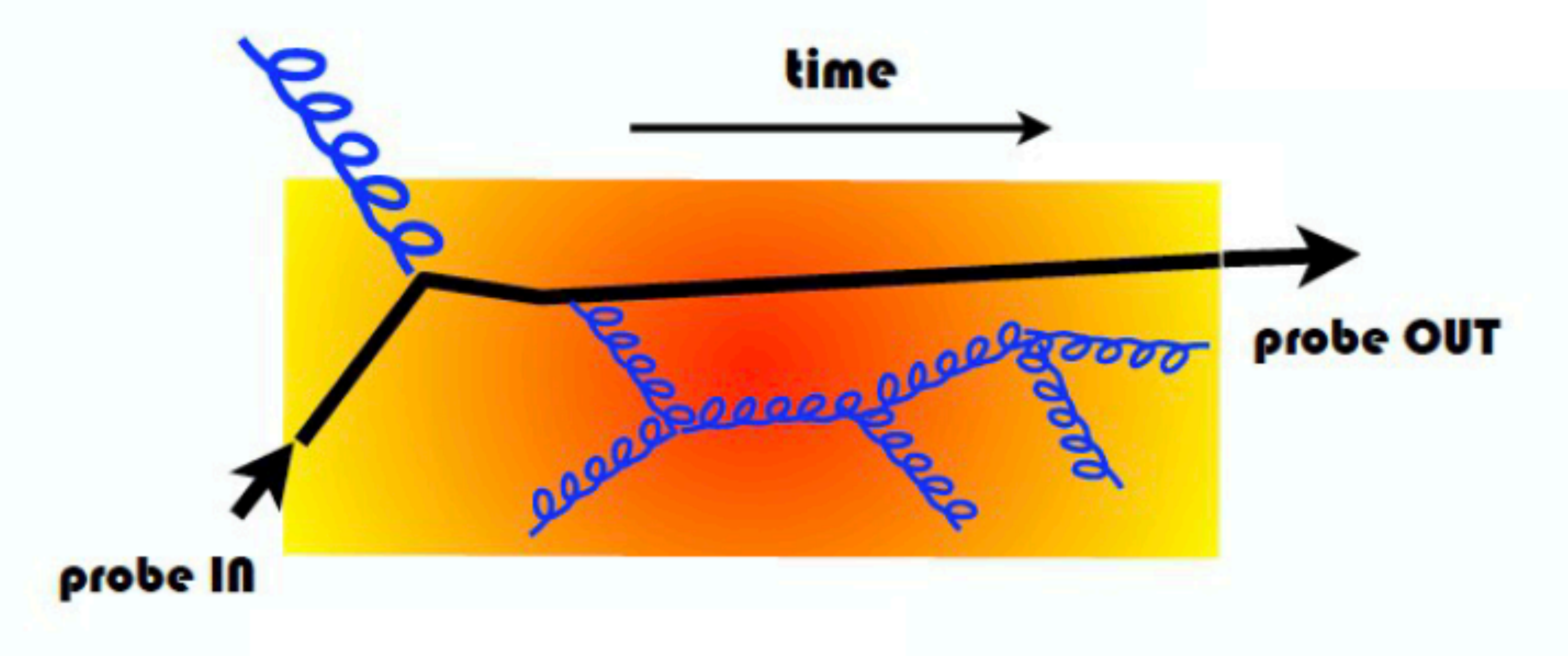


Like a Brownian motion

Quark energy loss in QGP

– Quark can loose energy via collision (collisional) and gluon radiation (radiative)



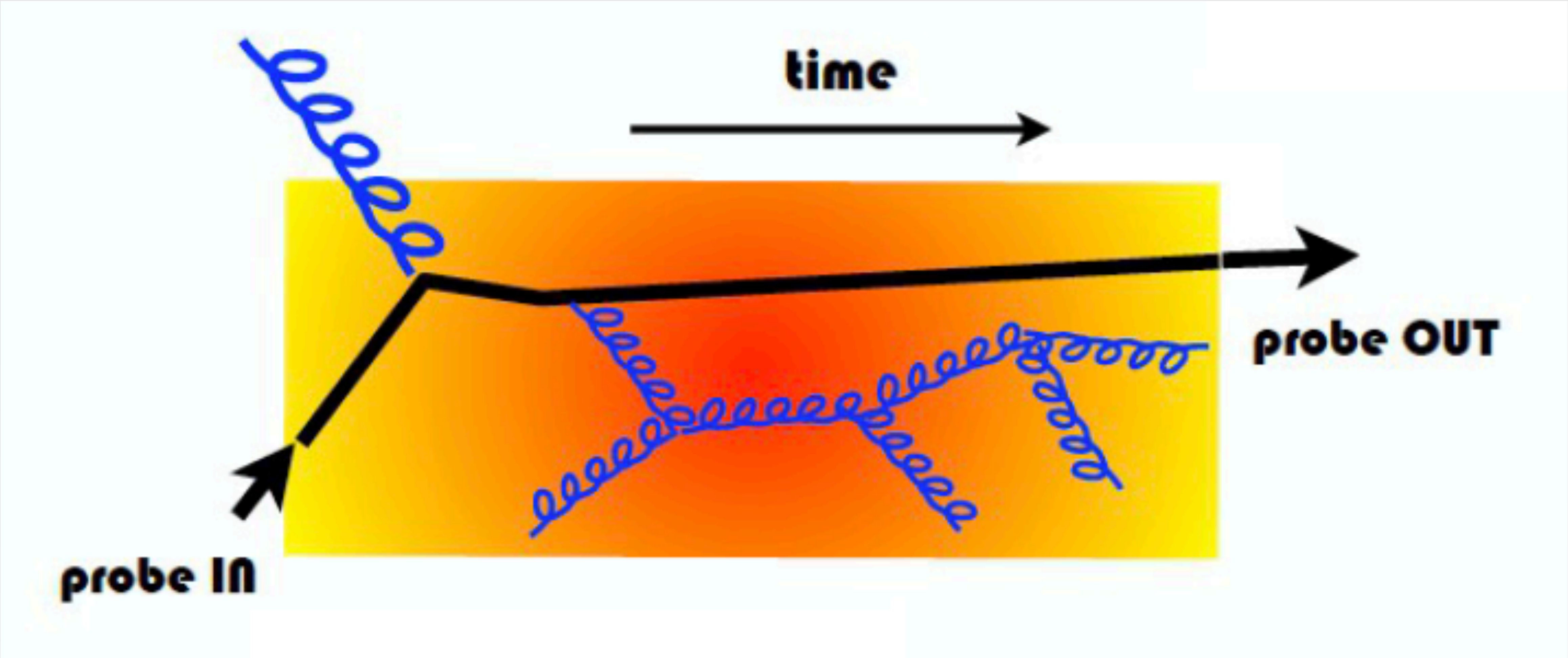
– Radiative energy loss similar to electron bremsstrahlung in electrodynamics

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R$$

Casimir coupling factor:
4/3 for quarks and 3 for gluons

Quark energy loss in QGP

– Quark can loose energy via collision (collisional) and gluon radiation (radiative)



– Radiative energy loss similar to electron bremsstrahlung in electrodynamics

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s C_R$$

Casimir coupling factor:
4/3 for quarks and 3 for gluons

Color-charge effect:
Quarks loose less energy than gluons!

R. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne and D. Schiff:
Nucl. Phys. B 483 (1997) 291
Nucl. Phys. B 484 (1997) 265

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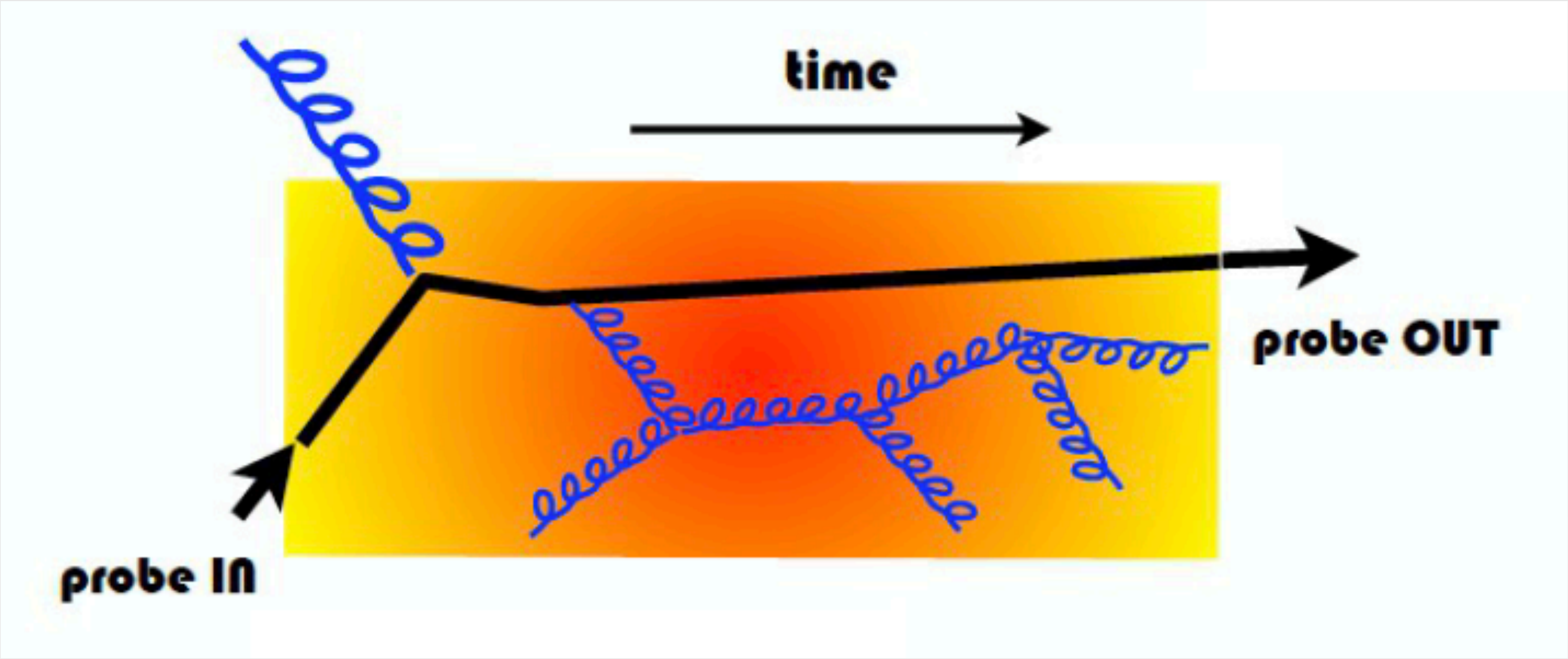

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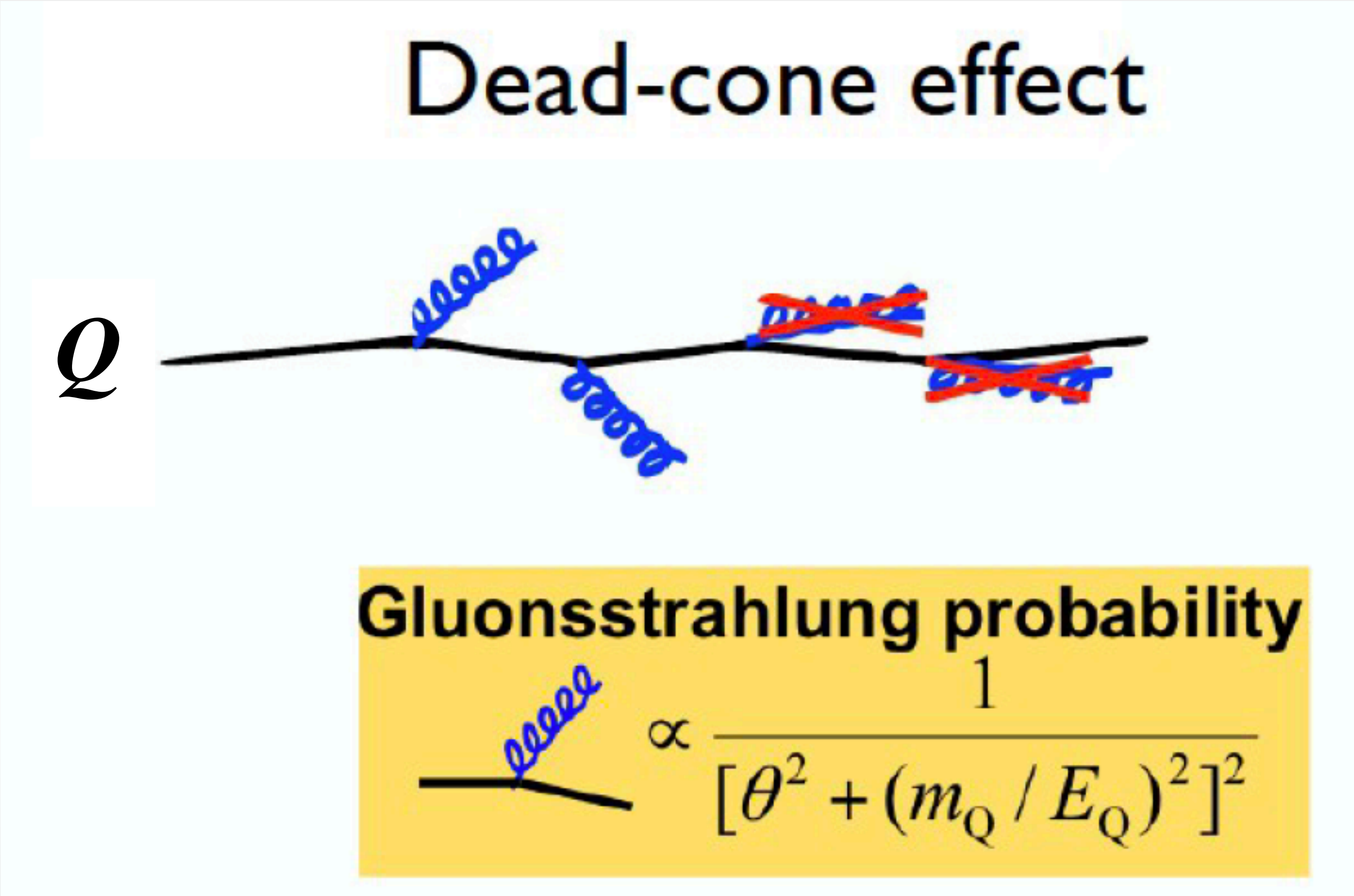

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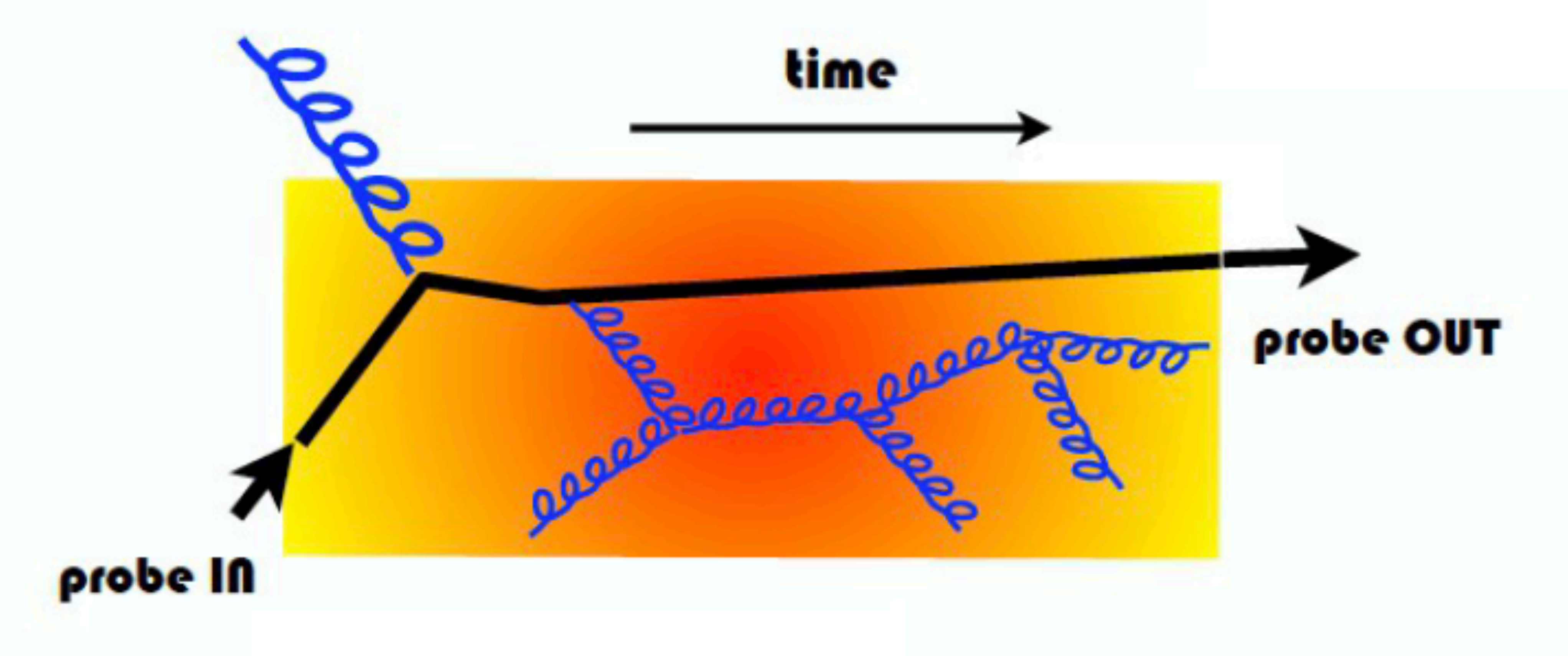

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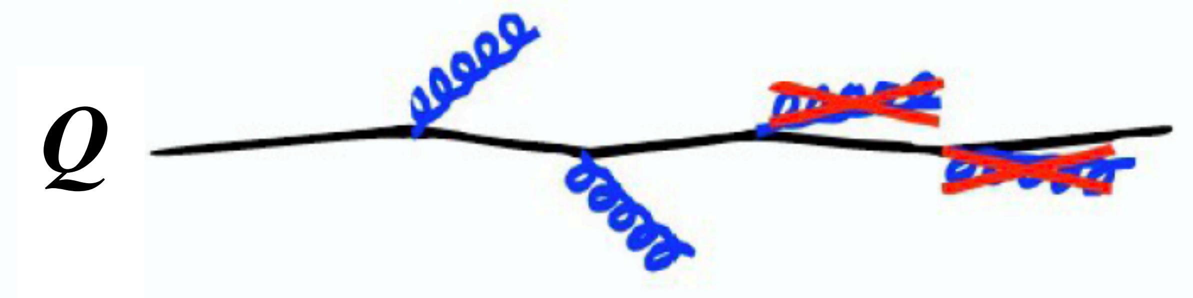


Gluonsstrahlung probability

$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Heavy quarks loose less energy than light quarks!

$\Rightarrow \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

Yu. Dokshitzer and D.E. Kharzeev, Phys.Lett. B 519 199-206 (2001).
M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265. 2

Building an observable: nuclear modification factor

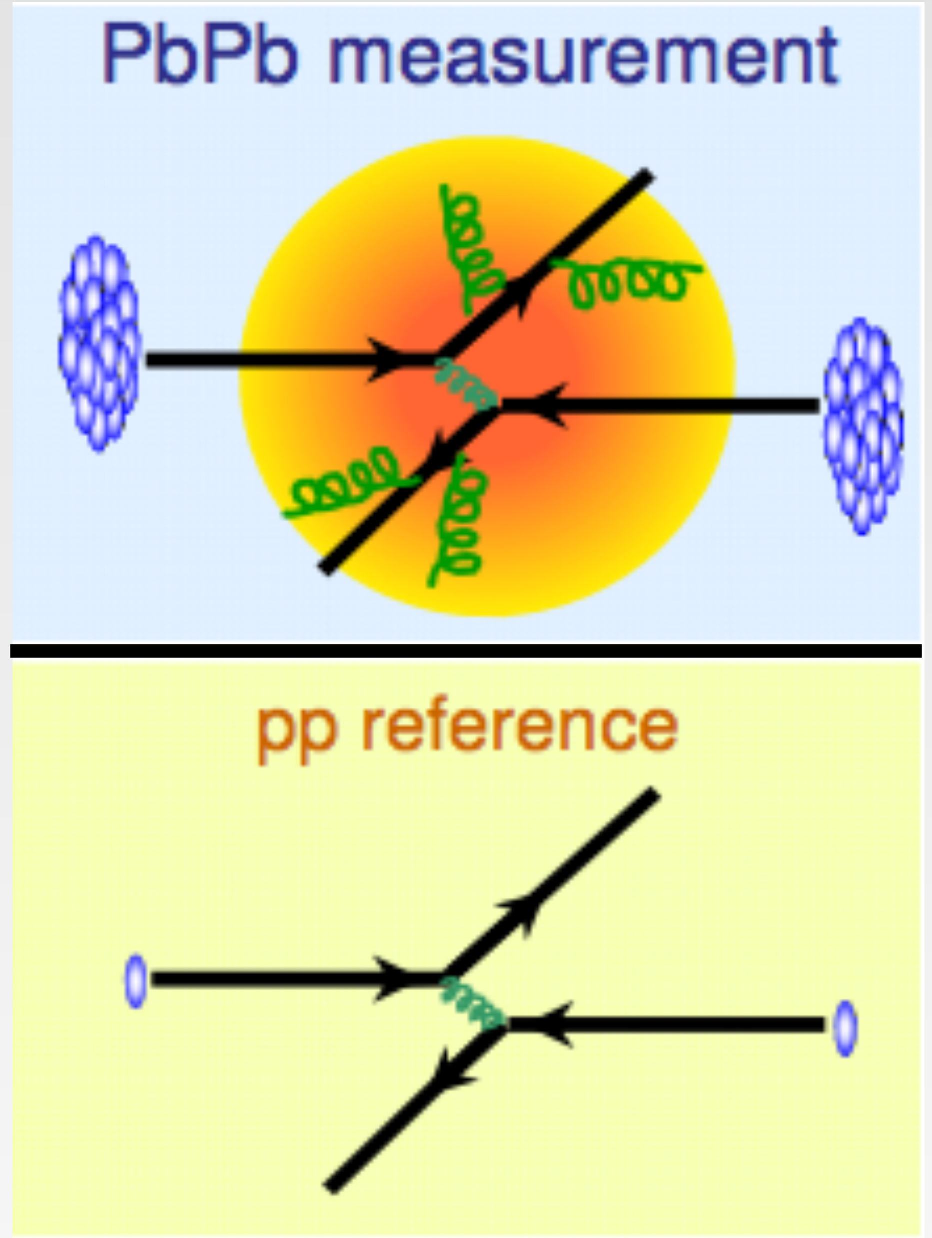
– Production of hard probes (heavy quarks, jets...) in A-A collisions is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)

Production in Pb-Pb

$$R_{\mathrm{AA}}(p_{\mathrm{T}},y) = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}^2 N_{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}{\mathrm{d}^2 \sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \sim \frac{QCD\ \text{medium}}{QCD\ \text{vacuum}}$$

Scaled by the number of binary collisions

Production in pp

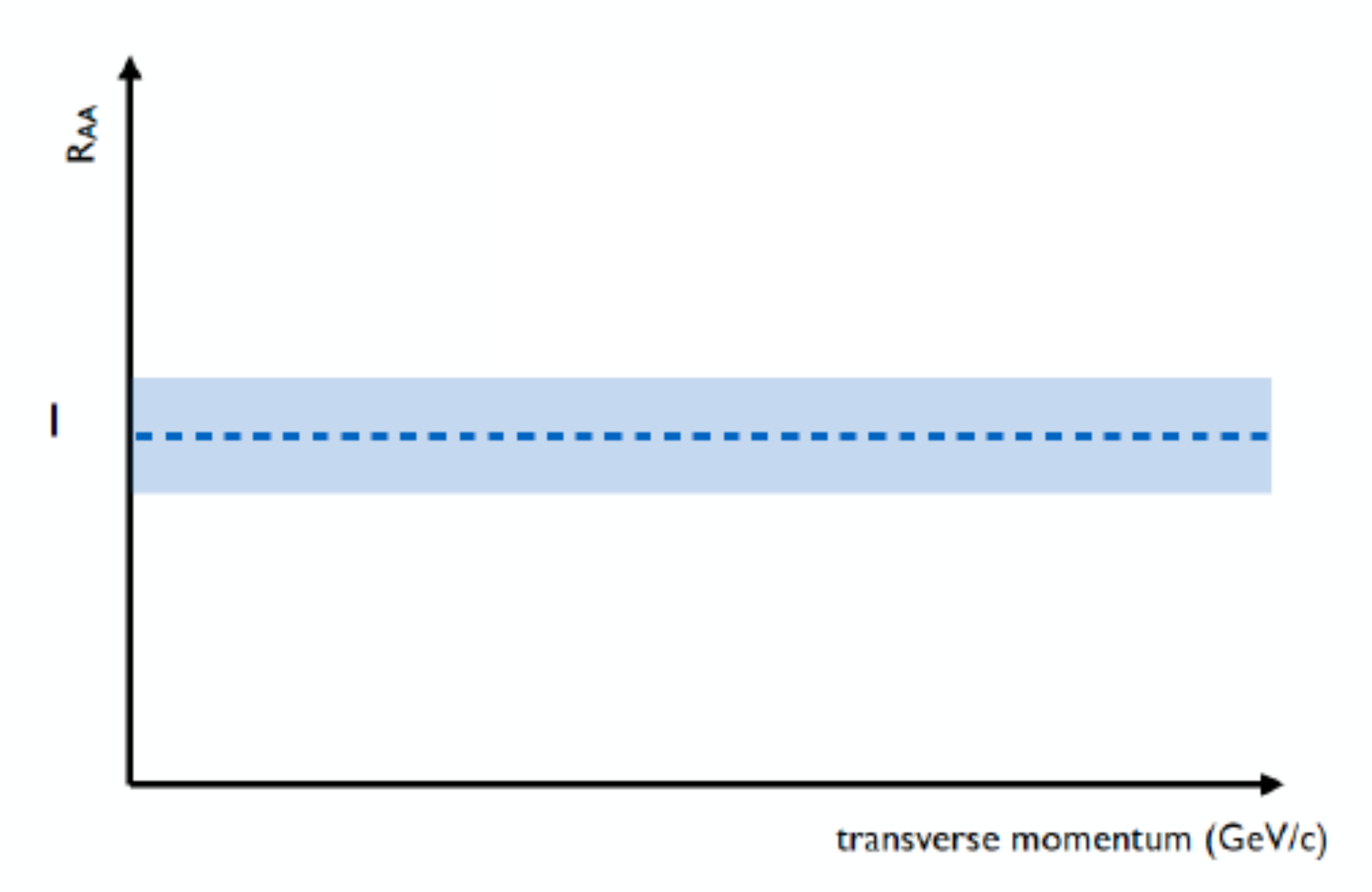


Dokshitzer and Kharzeev, PLB 519 (2001) 199
Wicks, Gyulassy, J.Phys. G35 (2008) 054001

Building an observable: nuclear modification factor

- Production of hard probes (heavy quarks, jets...) in A-A collisions is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)

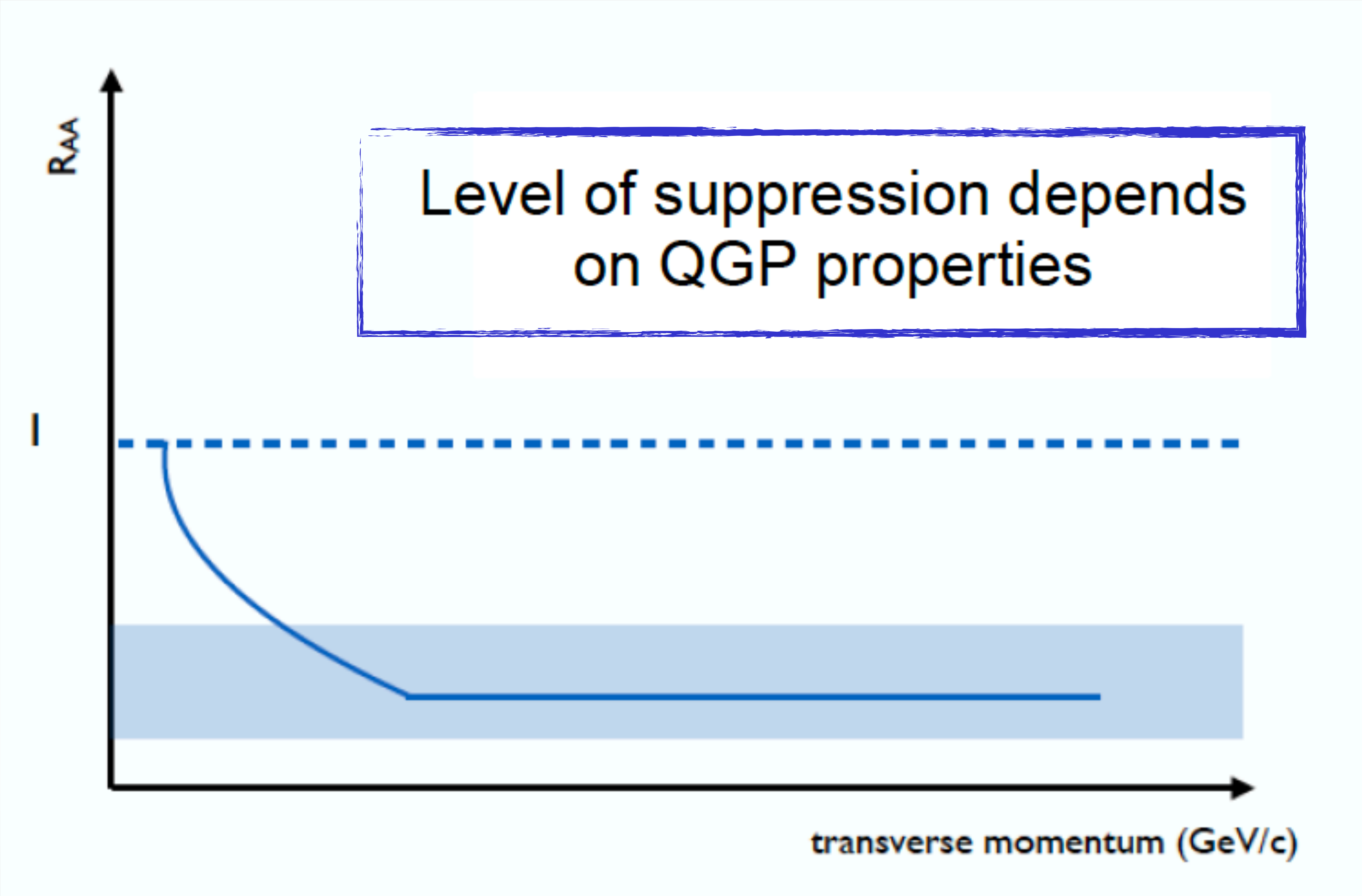
- **If no QGP is formed → R_{AA} = 1 (binary scaling)**



Building an observable: nuclear modification factor

- Production of hard probes (heavy quarks, jets...) in A-A collisions is expected to scale with the number of nucleon-nucleon collisions N_{coll} (**binary scaling**)

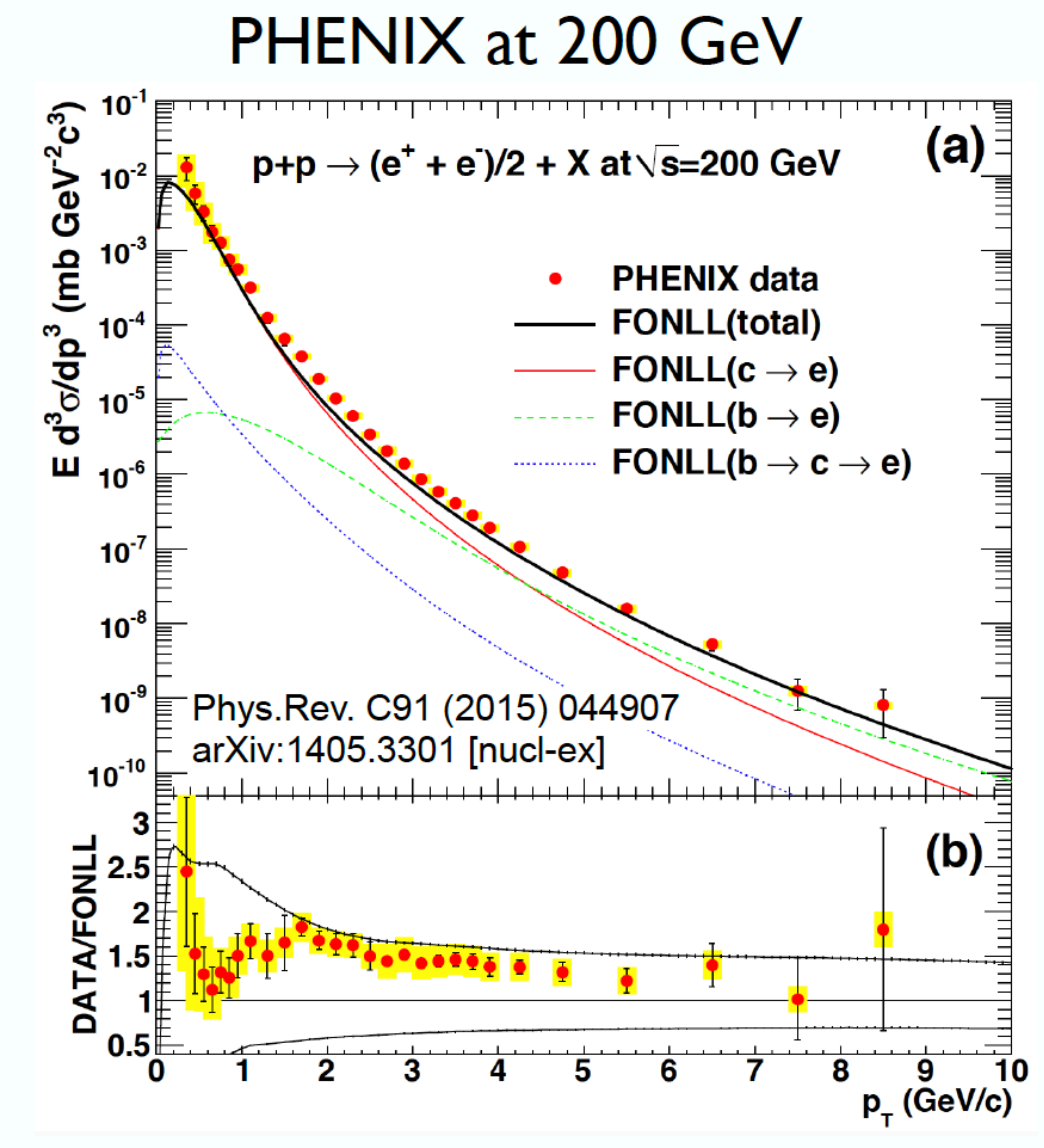
- QGP is formed $\rightarrow R_{AA} < 1$

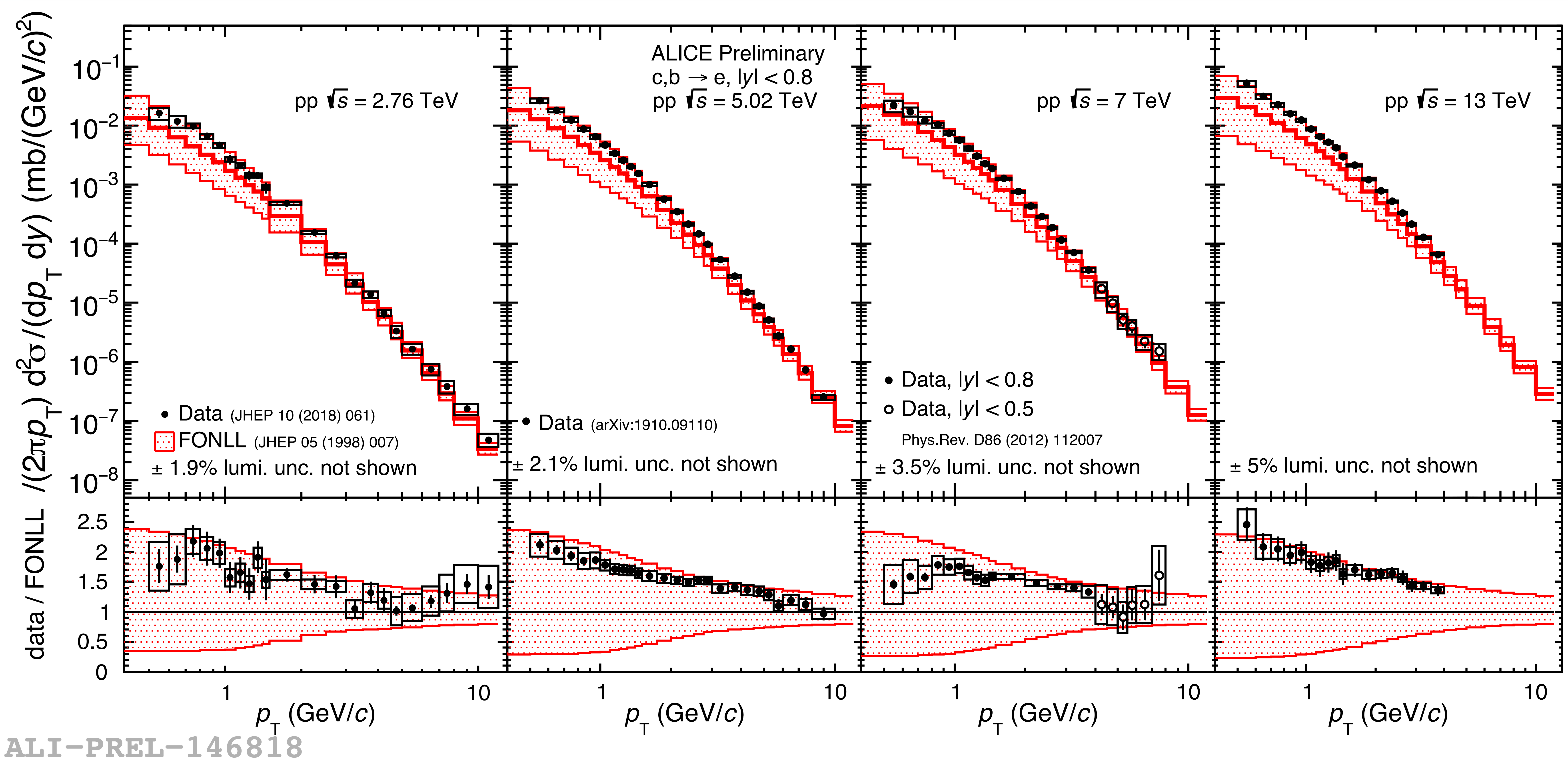


Heavy-flavour production cross section in pp collisions

- JHEP10(2018)061
- ALICE-PUBLIC-2018-005

0.2 TeV → 2.76 TeV → 5.02 TeV → 7 TeV → 13 TeV

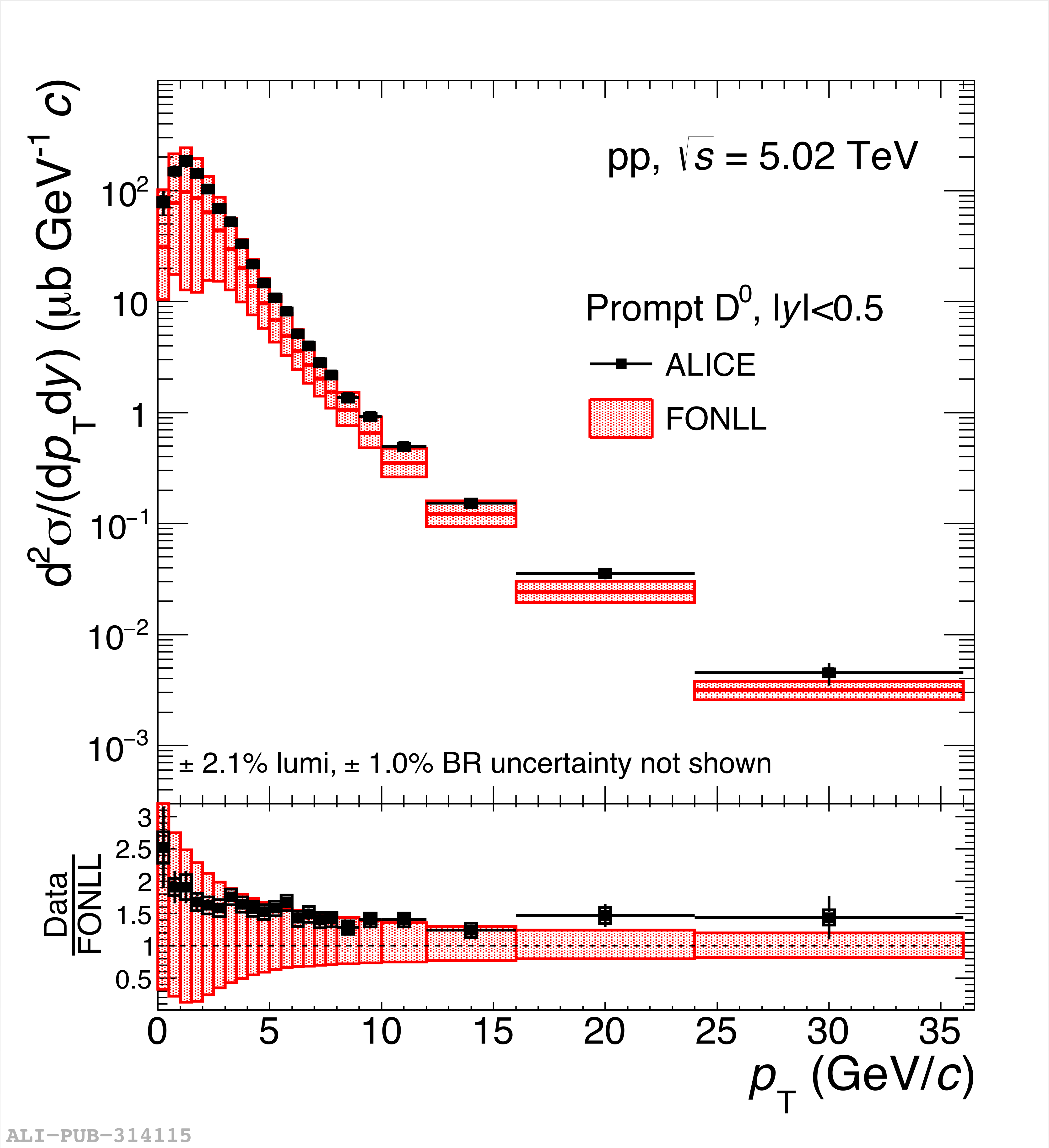


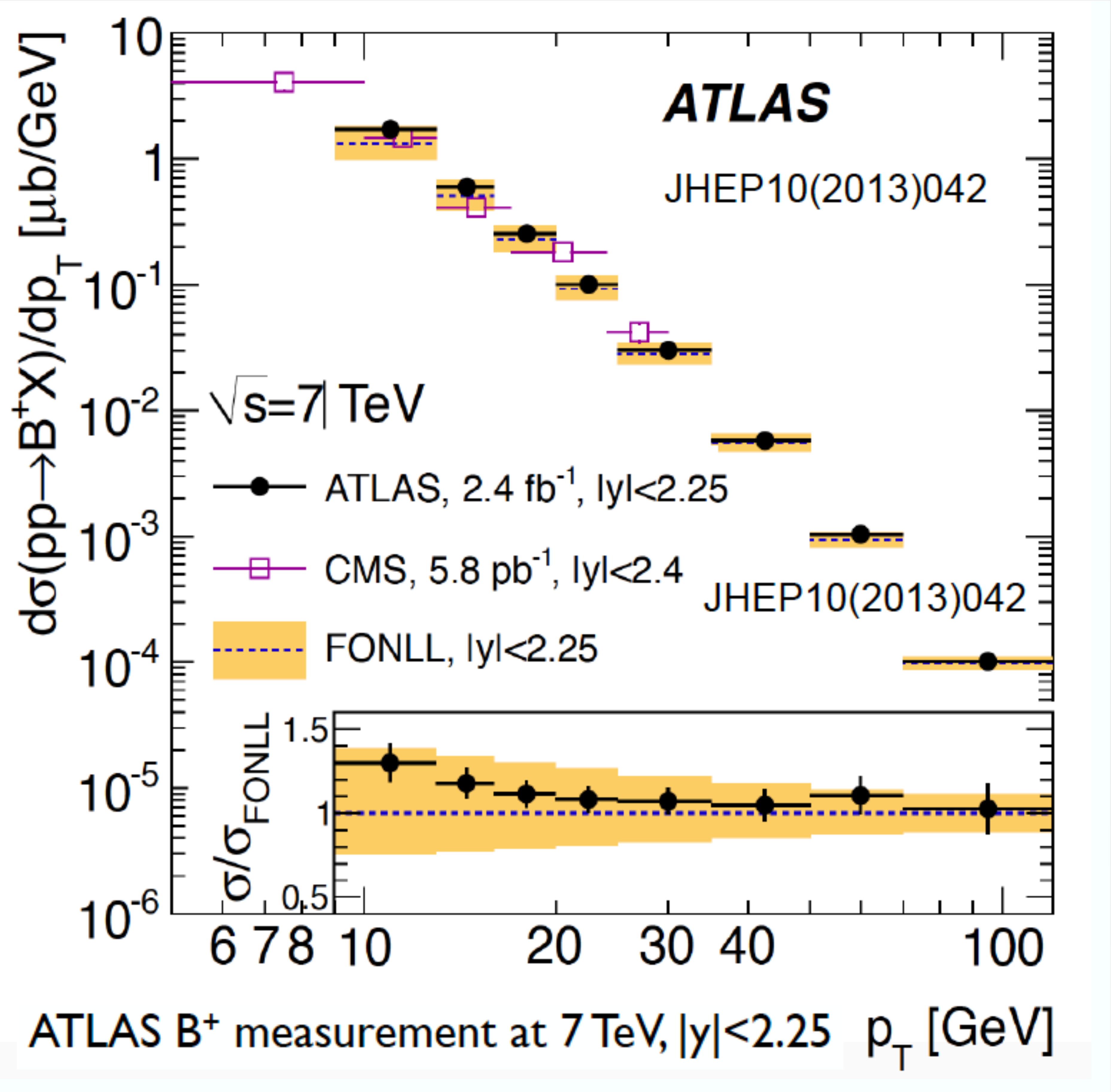


⇨ Testing the **centre-of-mass energy dependence** down to p_T **= 0.5 GeV/*c***

⇨ at the upper edge of FONLL calculation at all energies

D and B meson cross section in pp collisions at LHC

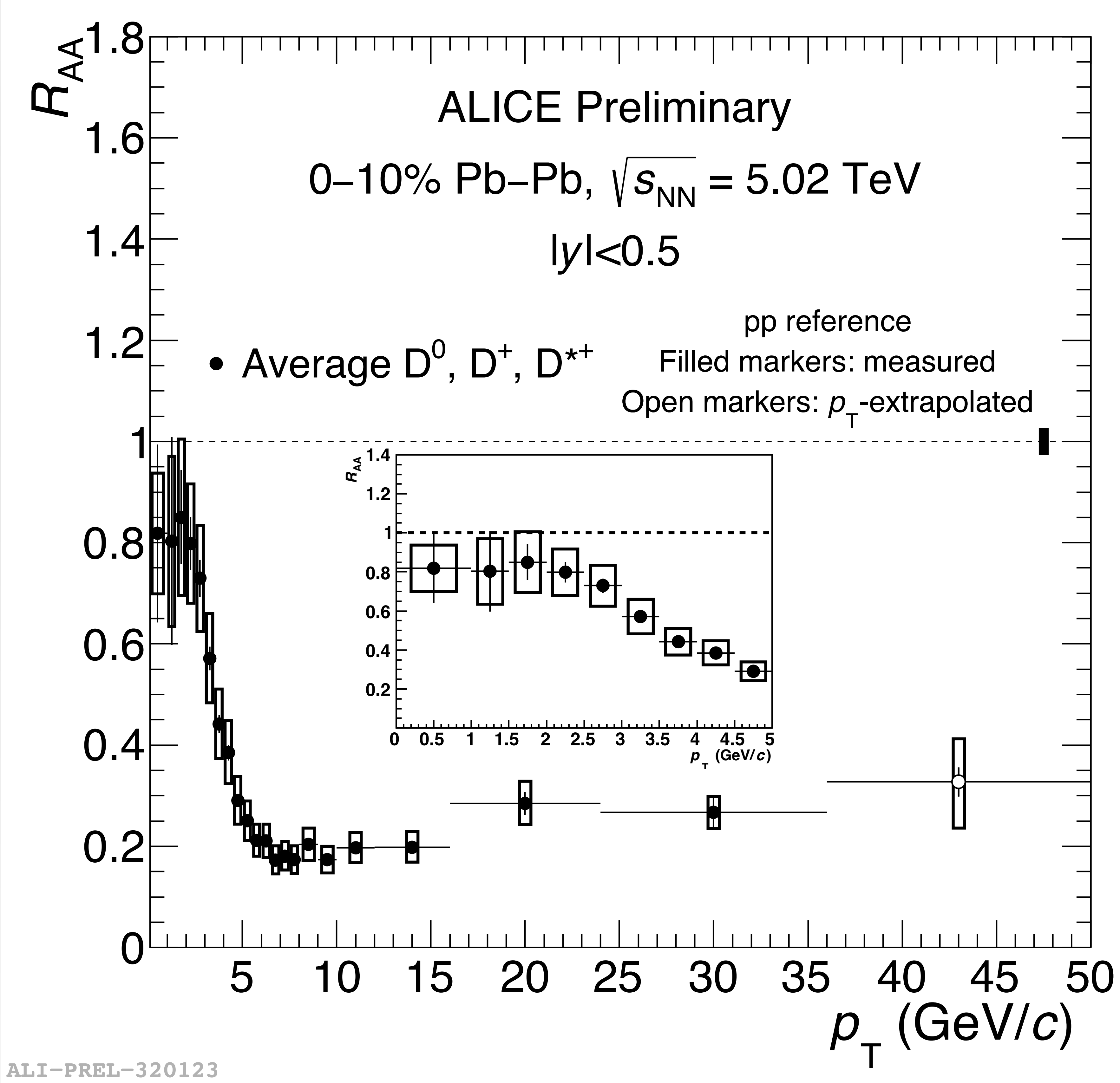




➪ D and B meson production cross sections well described by pQCD calculations:

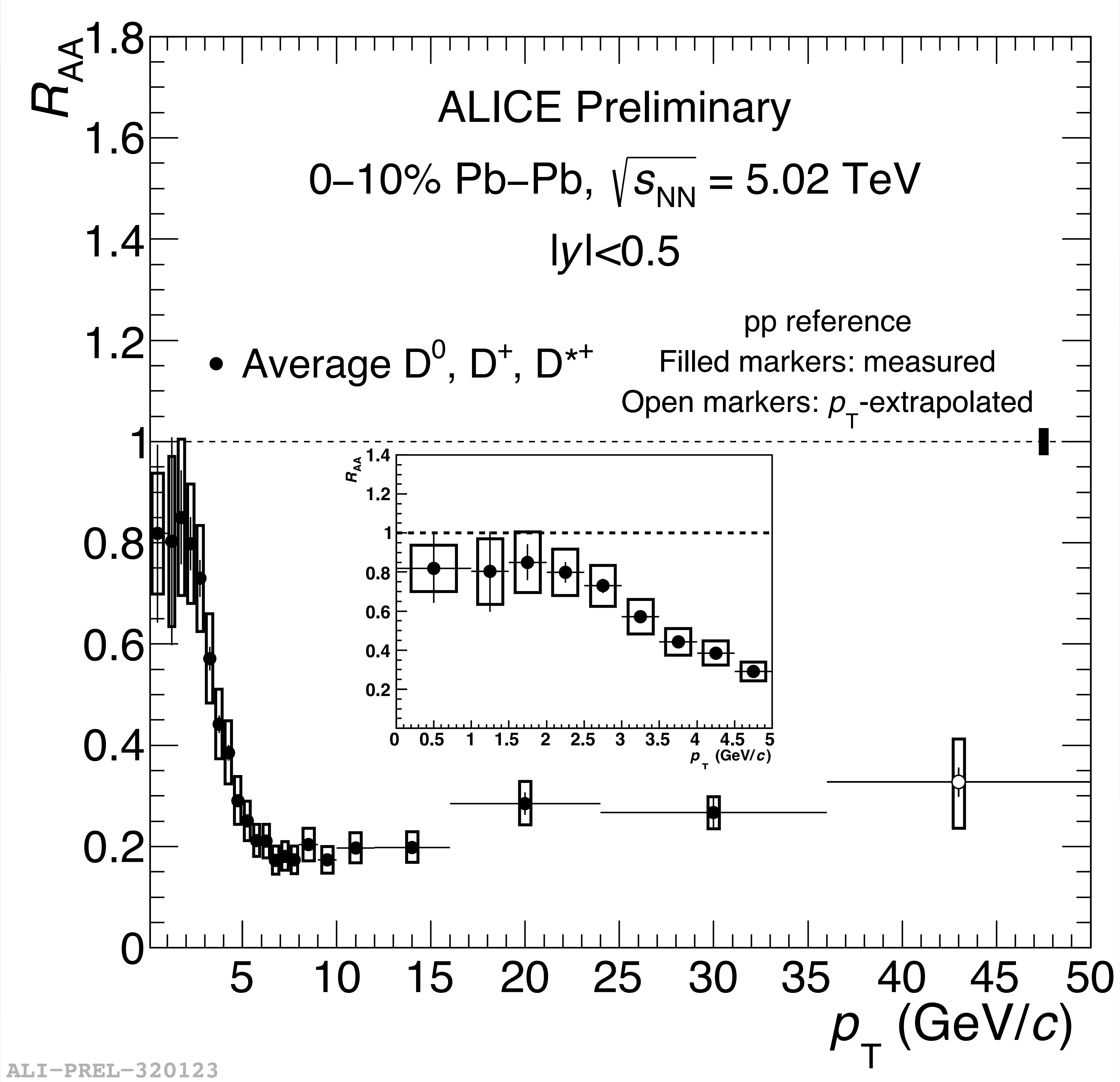
- D meson upper edge of FONLL calculations
- B meson consistent with central values of FONLL at high p_T, on the upper edge at low p_T

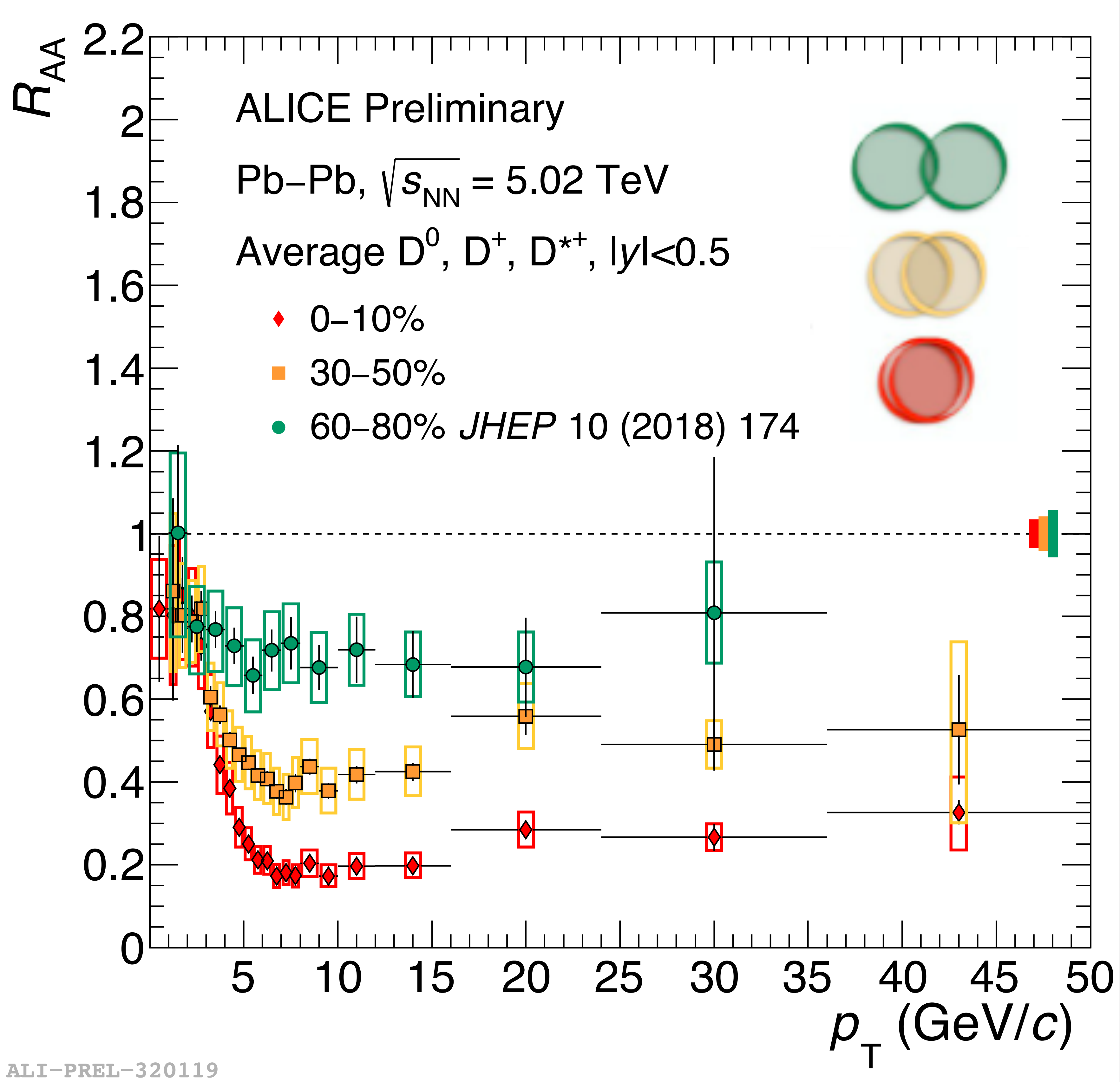
Heavy-flavour nuclear modification factor



➪ R_{AA}(0-10%) → suppression up to a factor 5 observed in the 10% most central Pb-Pb collisions

Heavy-flavour nuclear modification factor

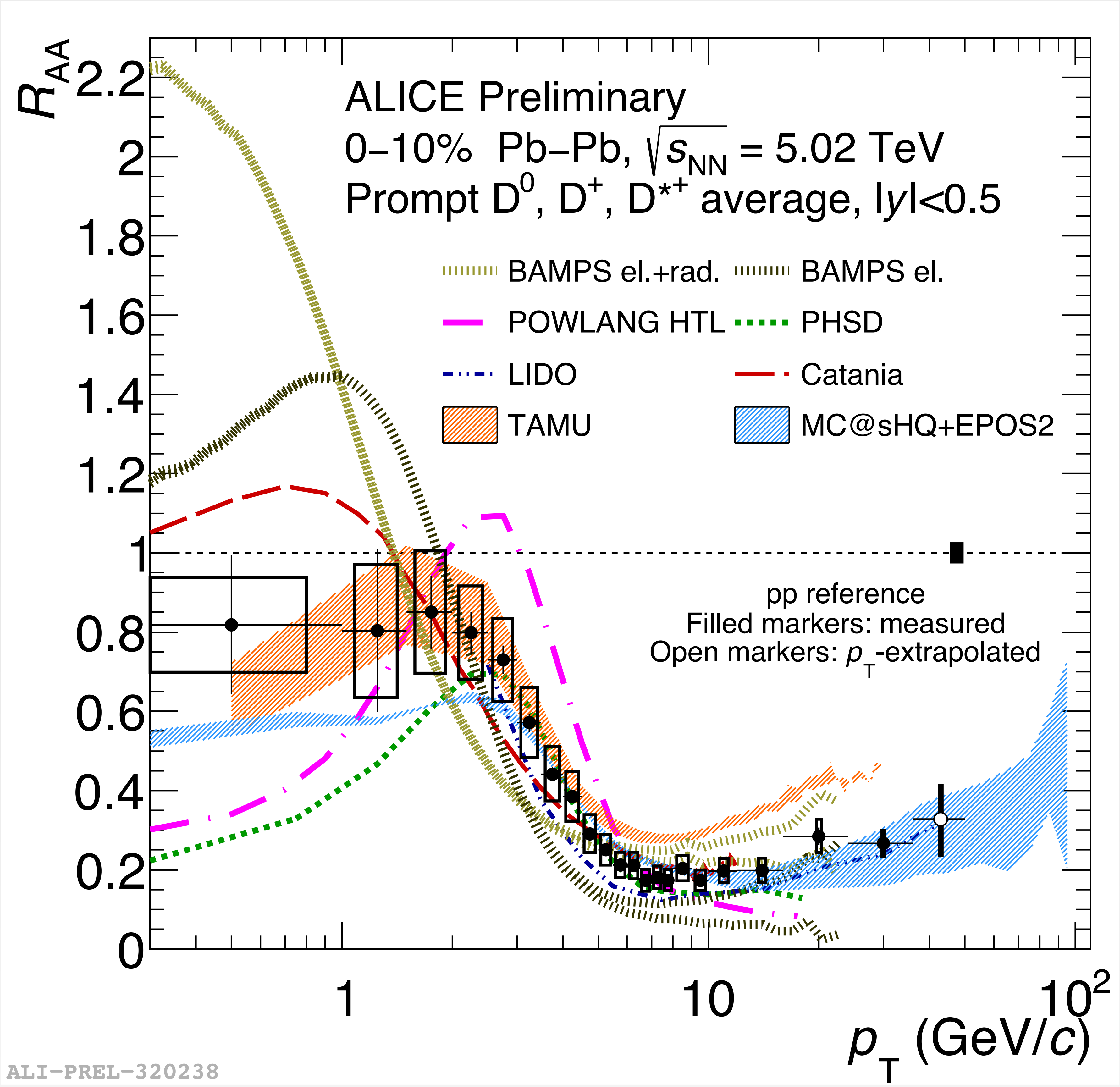




➩ R_{AA}(0-10%) → suppression up to a factor 5 observed in the 10% most central Pb-Pb collisions

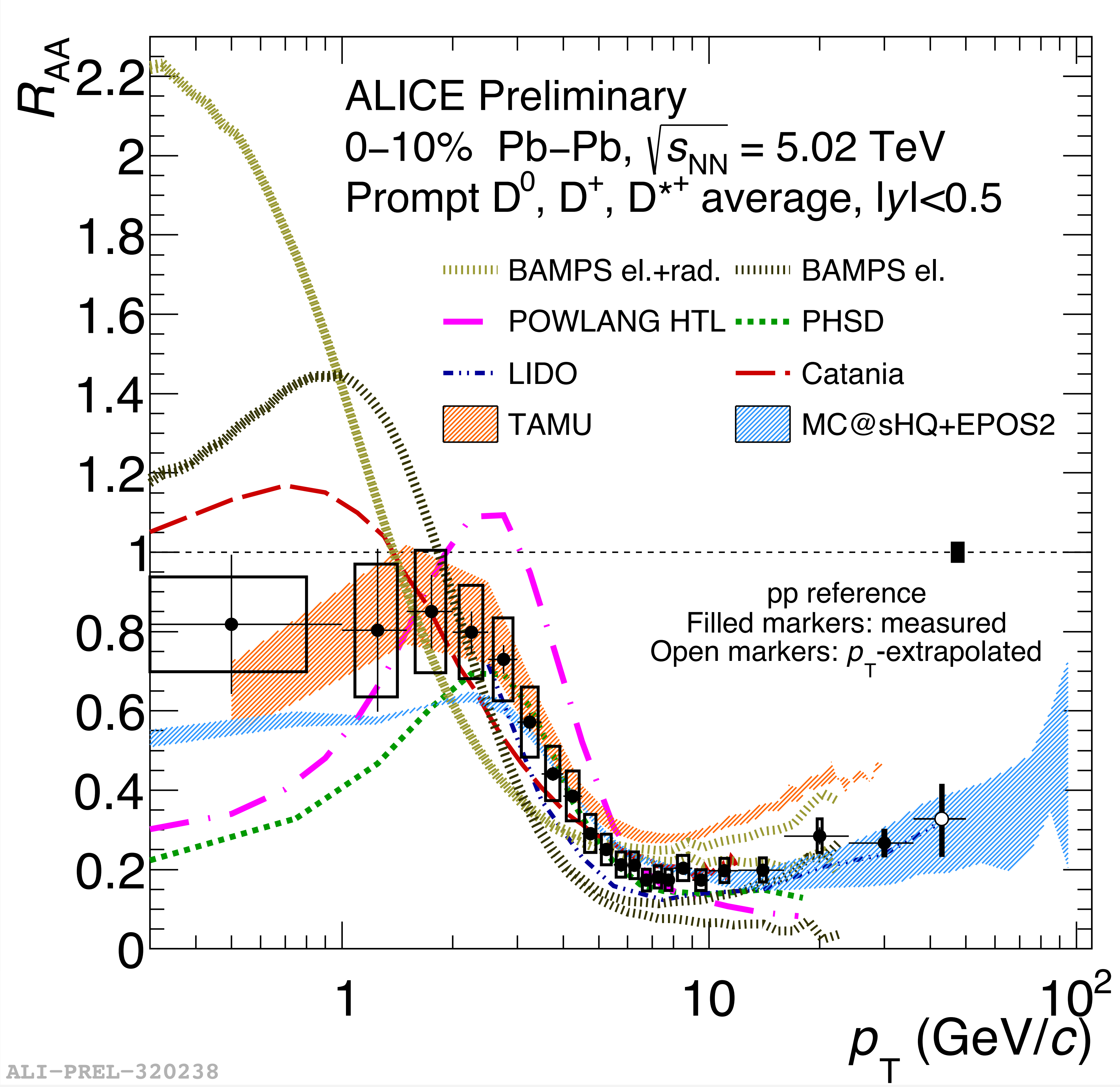
➩ Increasing suppression from peripheral (60-80%) to central (0-10%) Pb-Pb collisions

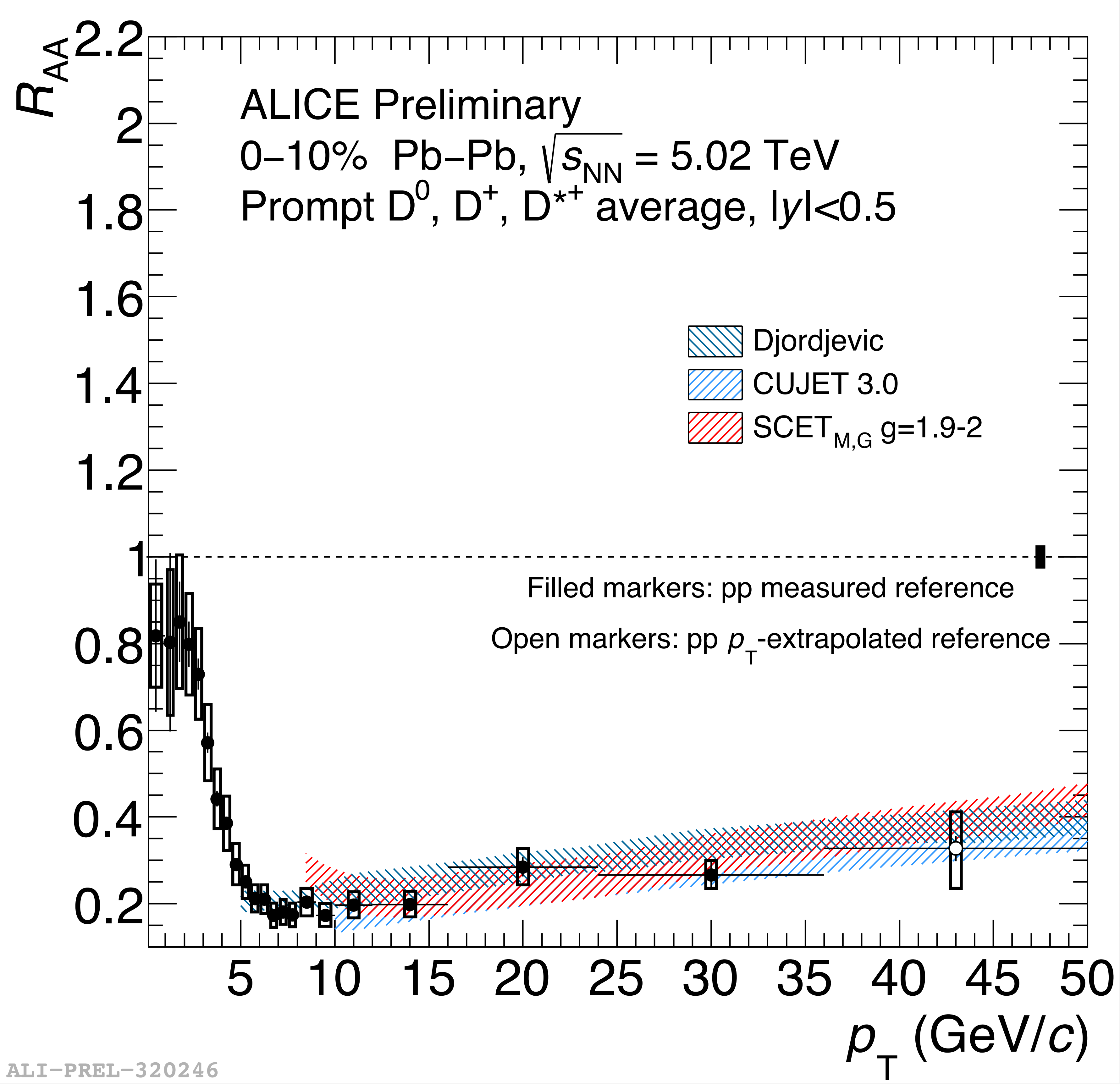
Heavy-flavour nuclear modification factor



➪ Heavy-quark transport in medium with realistic evolution necessary to describe R_{AA} at low/ intermediate p_T — need to include modification of nPDF

Heavy-flavour nuclear modification factor

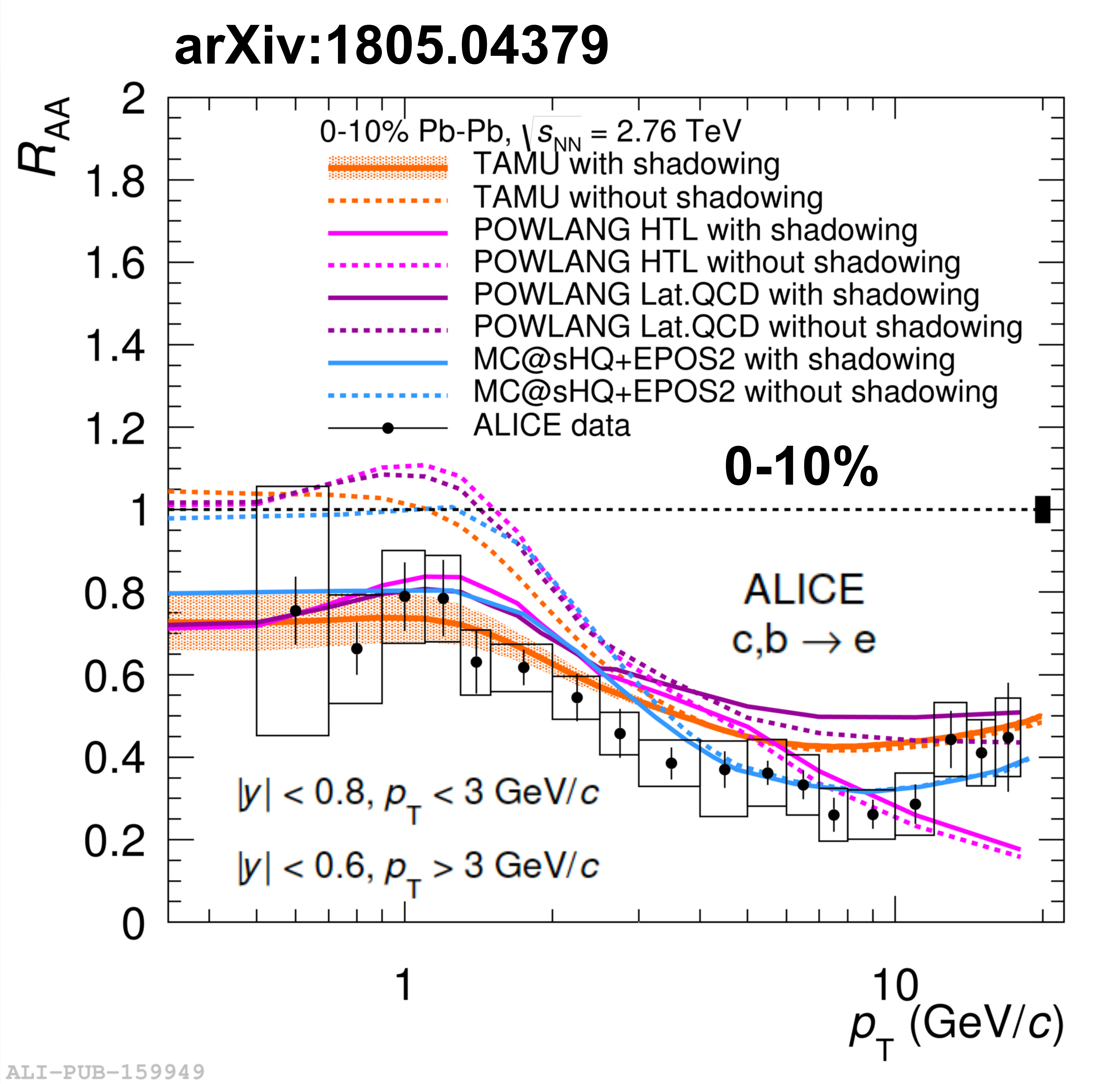


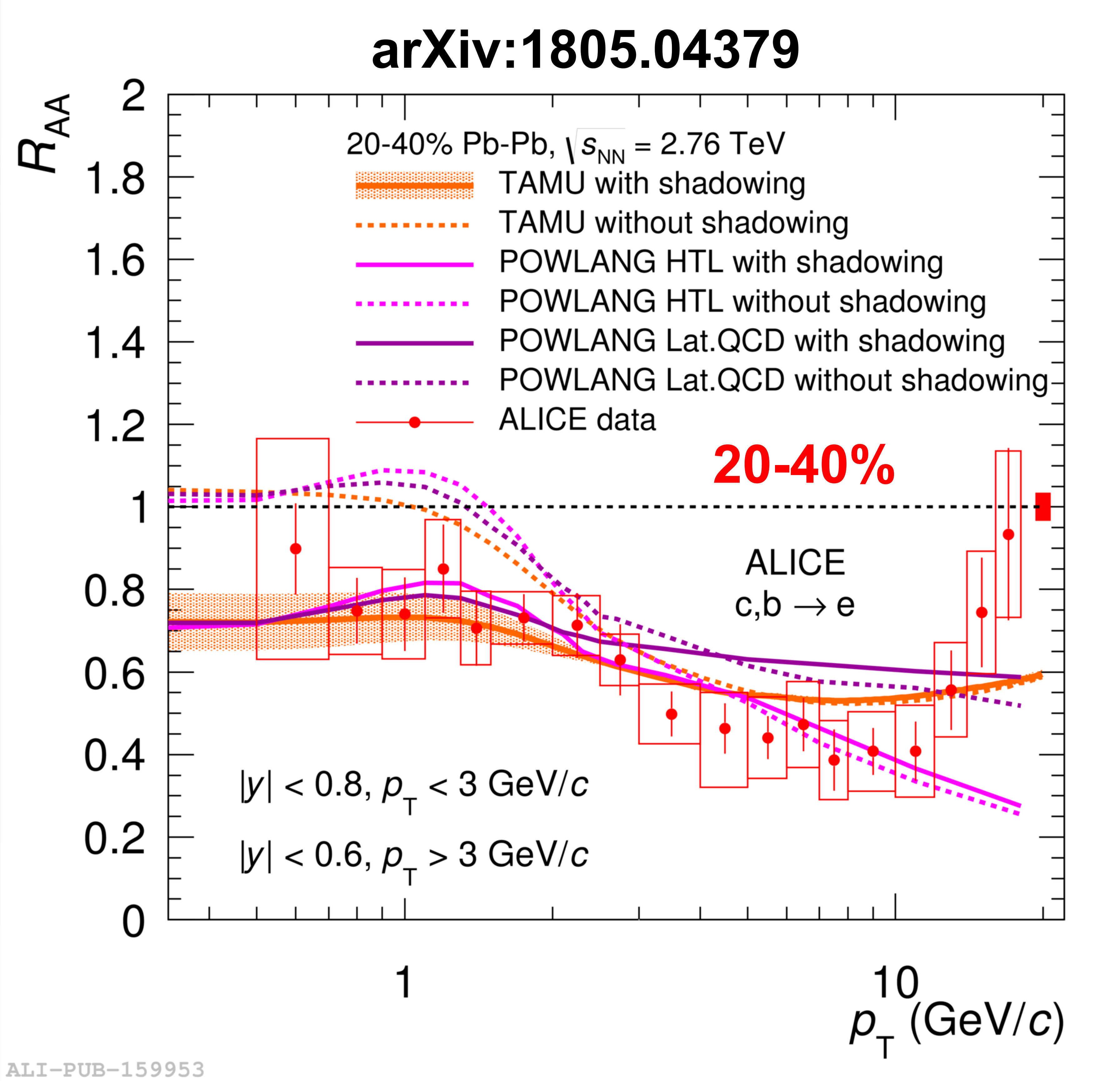


➪ Heavy-quark transport in medium with realistic evolution necessary to describe R_{AA} at low/ intermediate p_T — need to include modification of nPDF

➪ Models based on pQCD energy loss provide a good description of R_{AA} at high p_T

Heavy-flavour hadron decay electron nuclear modification factor



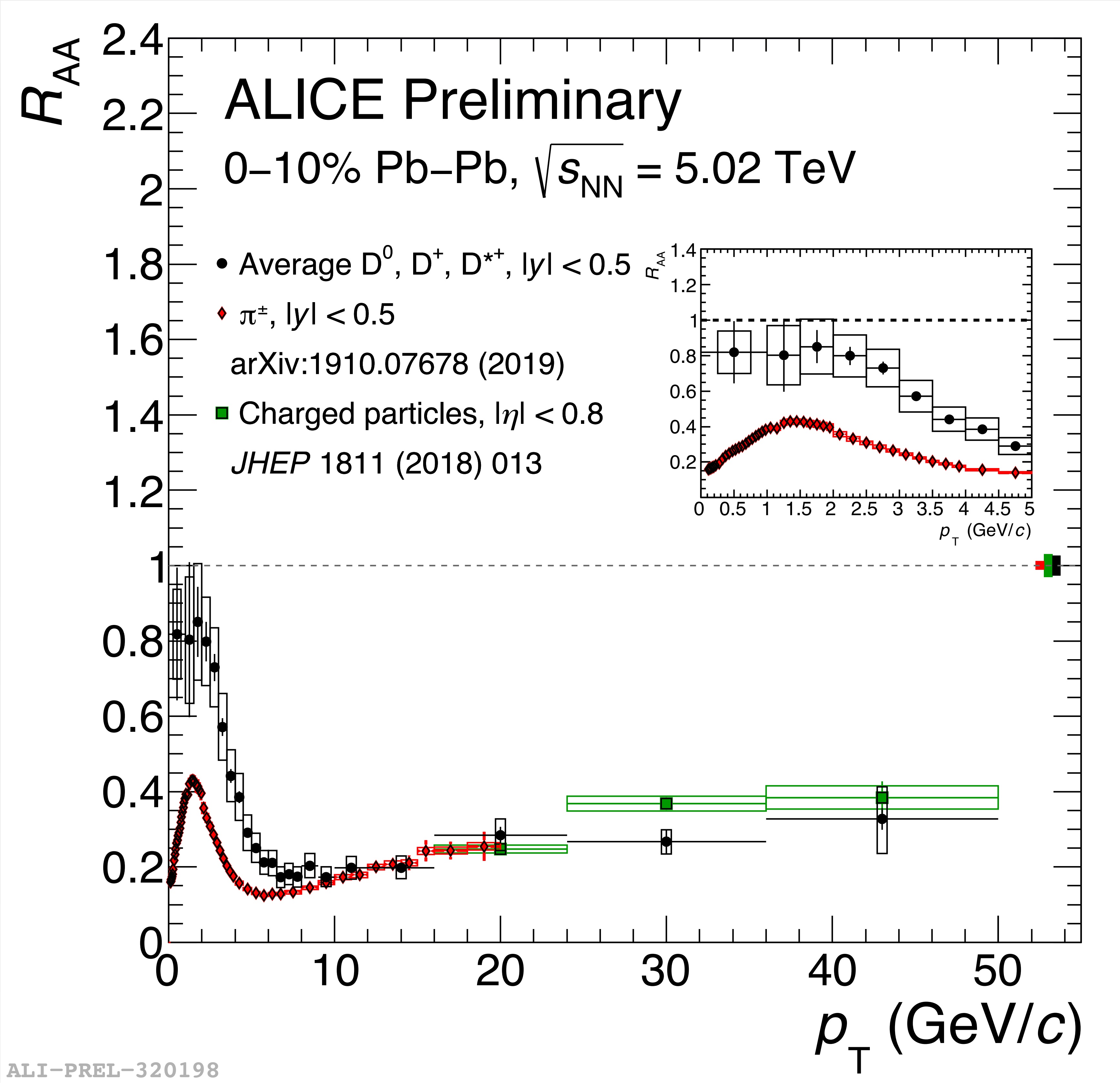


– Data are better described when the nuclear PDFs **(EPS09)** are included in the model calculation (**TAMU**, **POWLANG** and **MC@sHQ+EPOS2**) in both centrality intervals

– POWLANG: Eur.Phys.J. C73 (2013) 2481;
– TAMU: Phys.Lett. B735 (2014) 445–450;
– MC@HQ+EPOS: PRC 89 (2014) 014905;

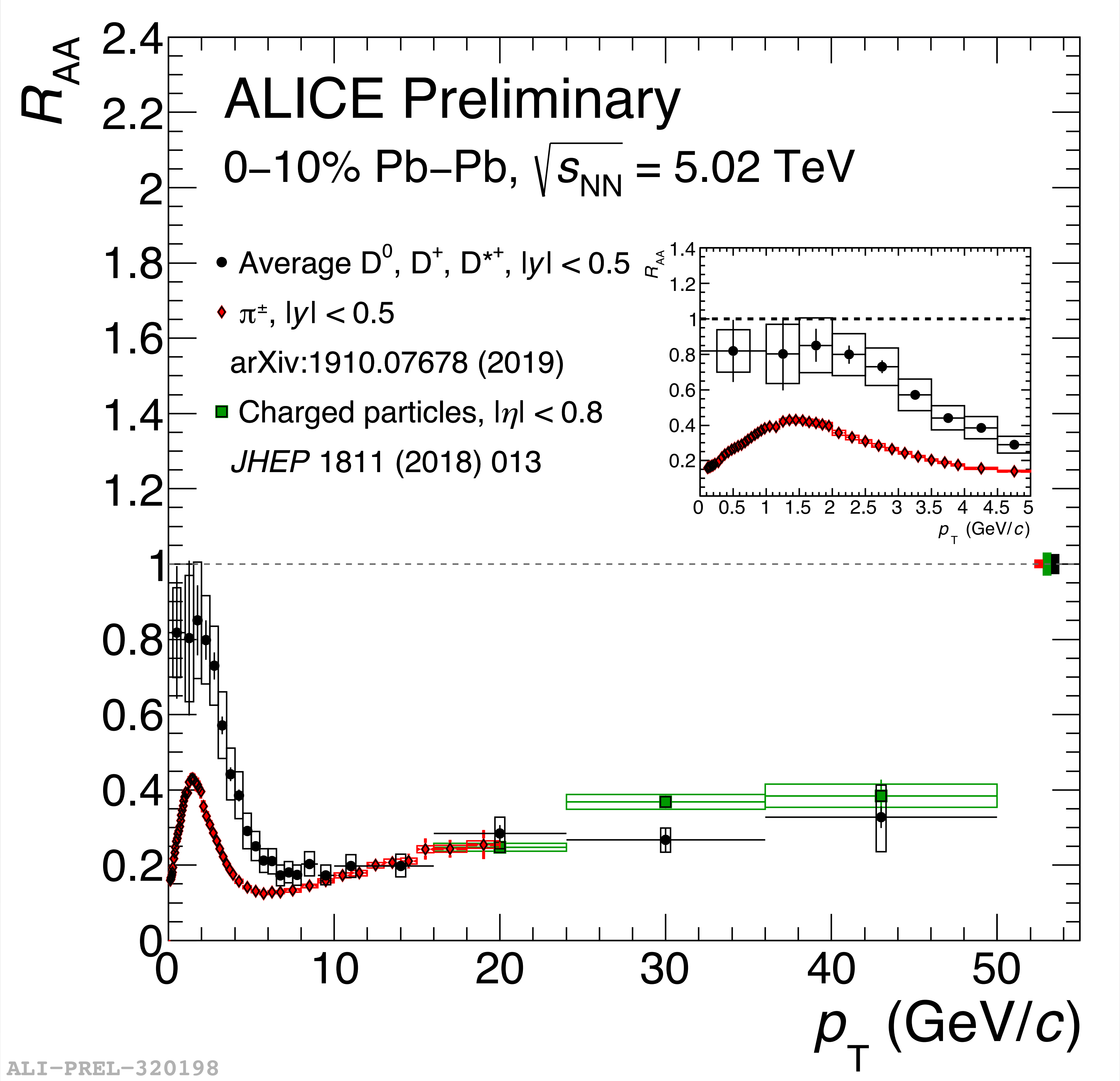
– Suppression at intermediate/high p_T is better described by models that include both **radiative** and **collisional energy loss** processes

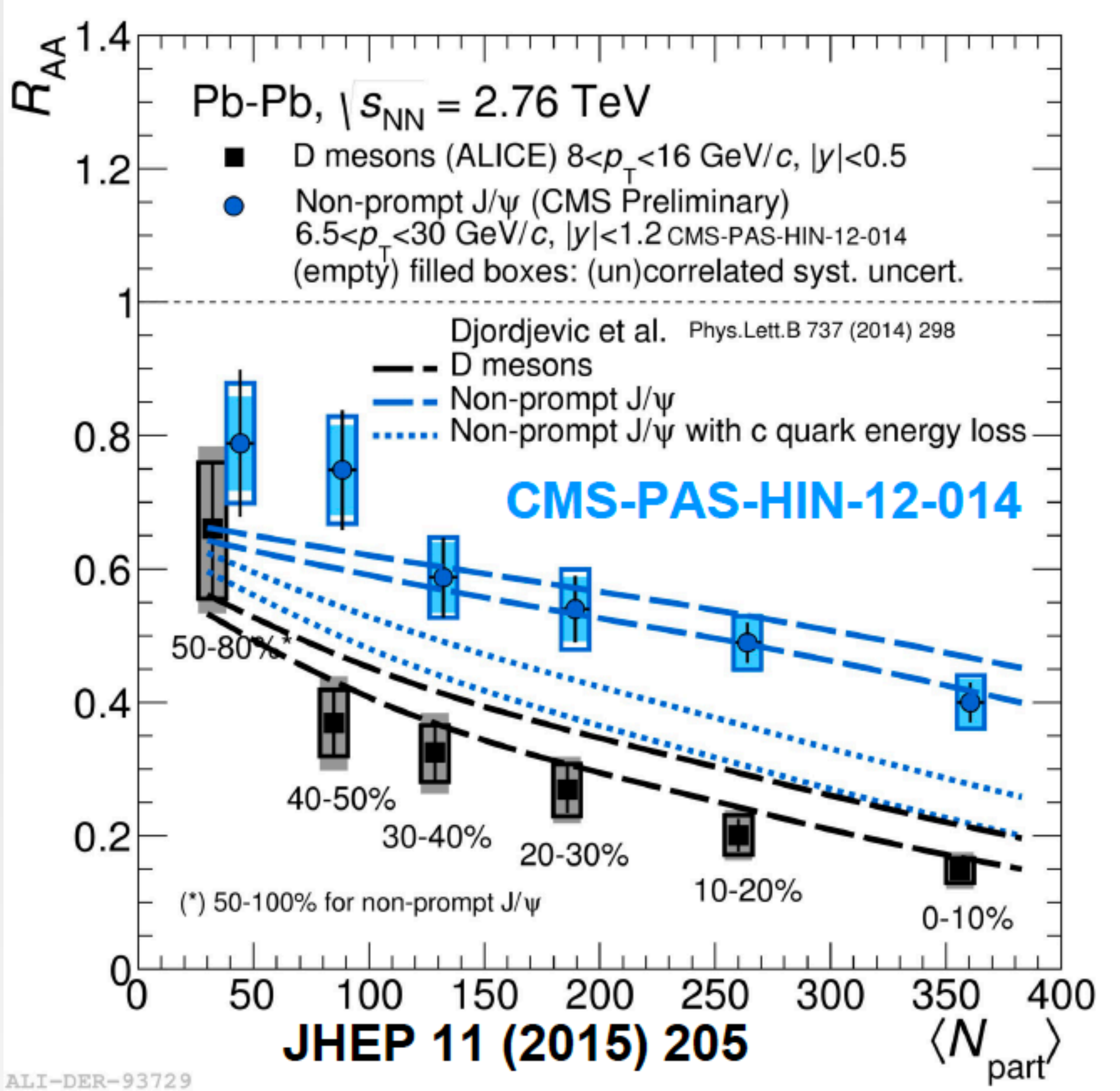
Do we see the different energy loss?



➪ R_{AA} of prompt non-strange D mesons compared with those of charged particles and pions

Do we see the different energy loss?



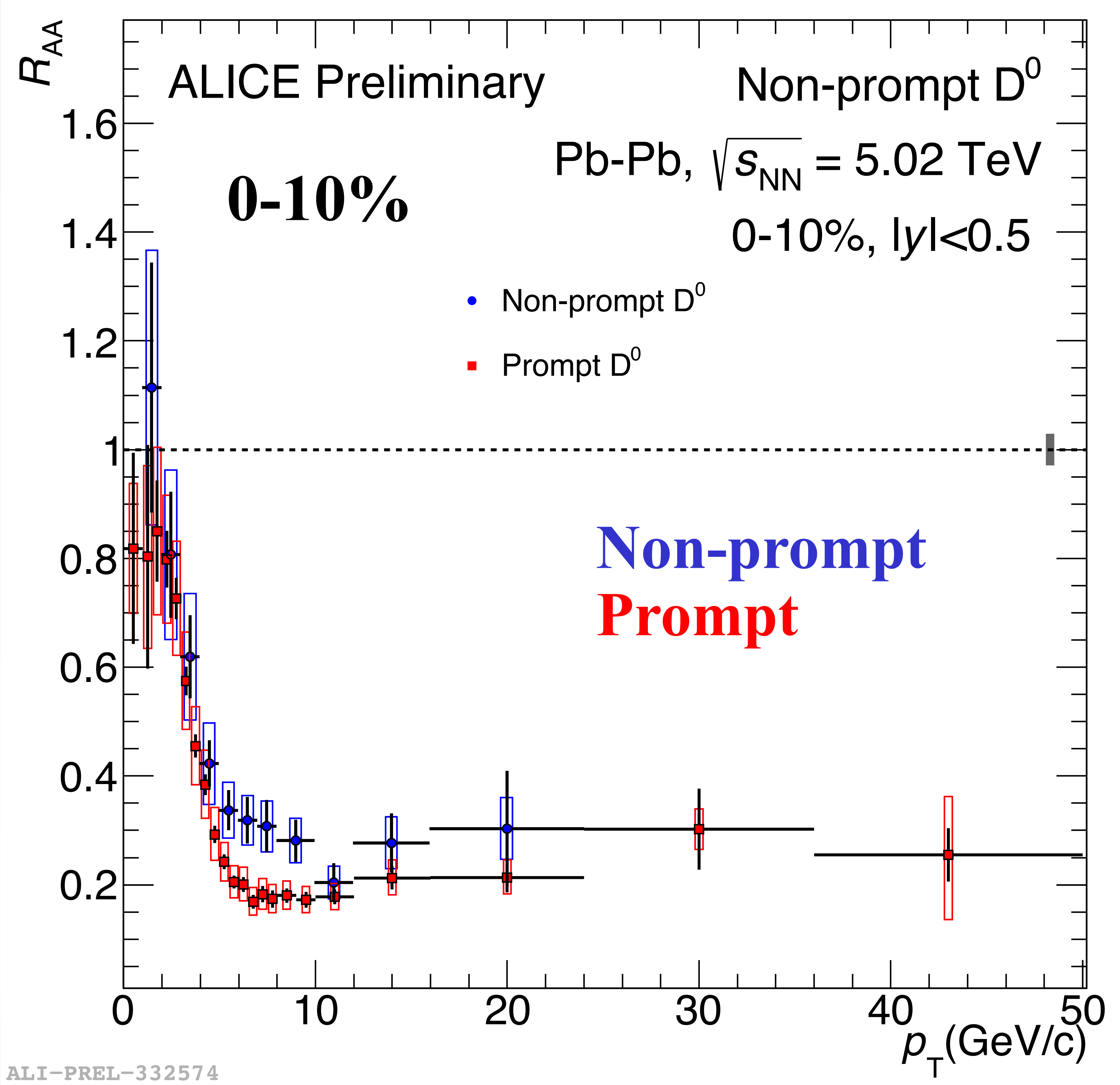


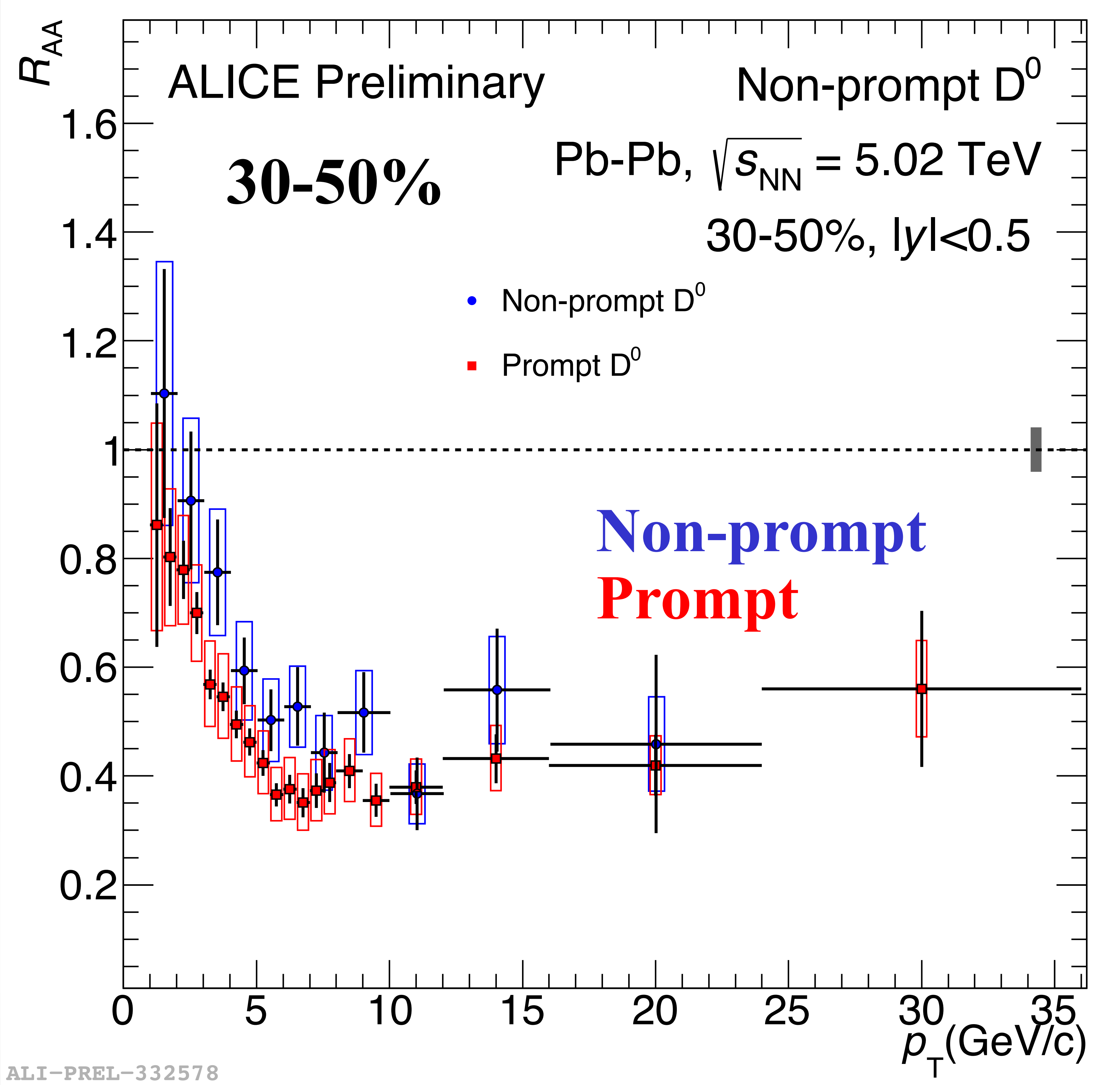
➪ R_{AA} of prompt non-strange D mesons compared with those of charged particles and pions

➪ pQCD models including mass-dependent radiative and collisional energy loss predicts a difference between the D-meson and non-prompt J/ψ R_{AA}

Do we see the different energy loss?

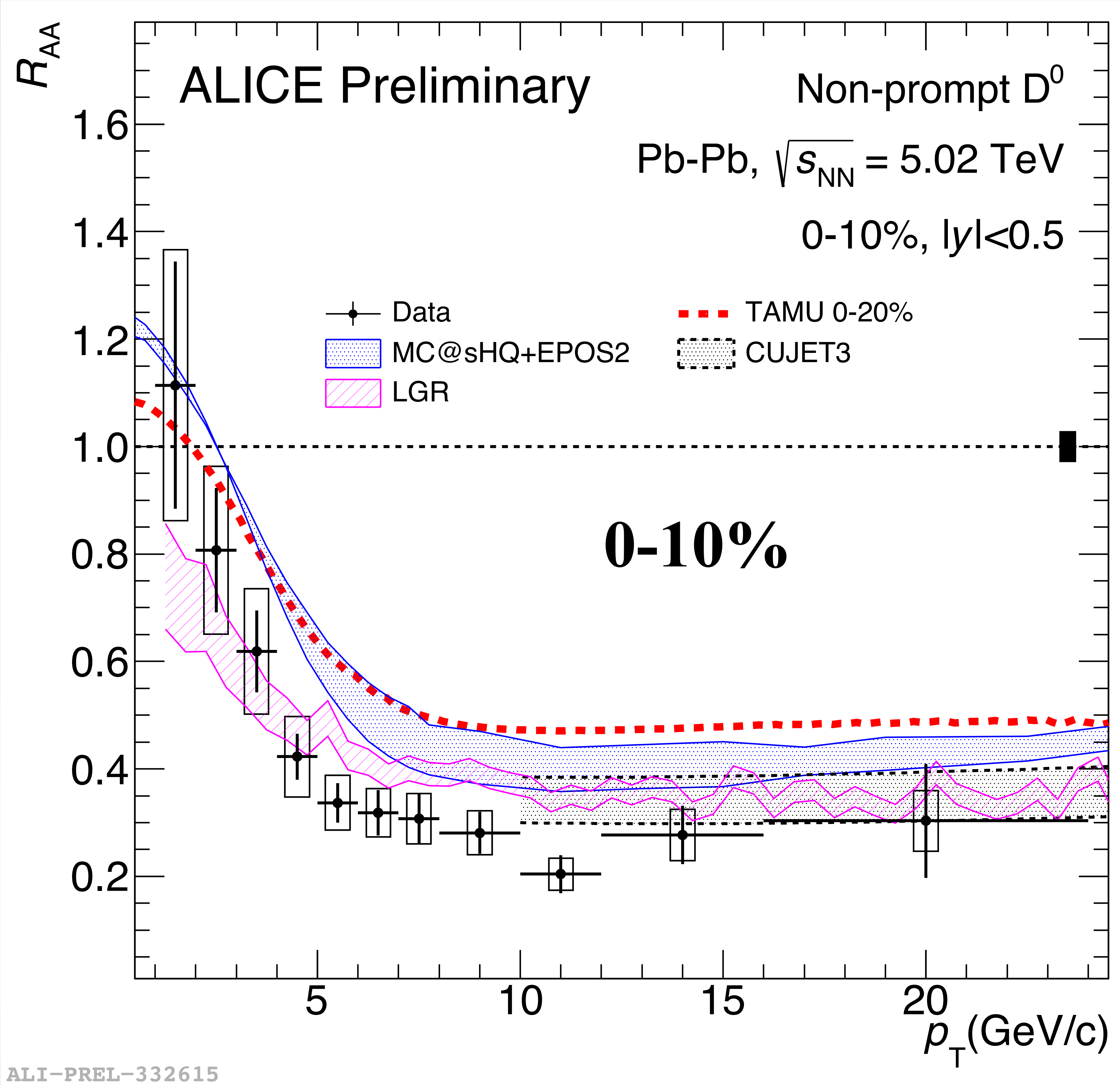
⇨ **New R_{AA}** measurement of **non-prompt D meson**
- hint of a **smaller suppression for** **beauty** **than** **charm**

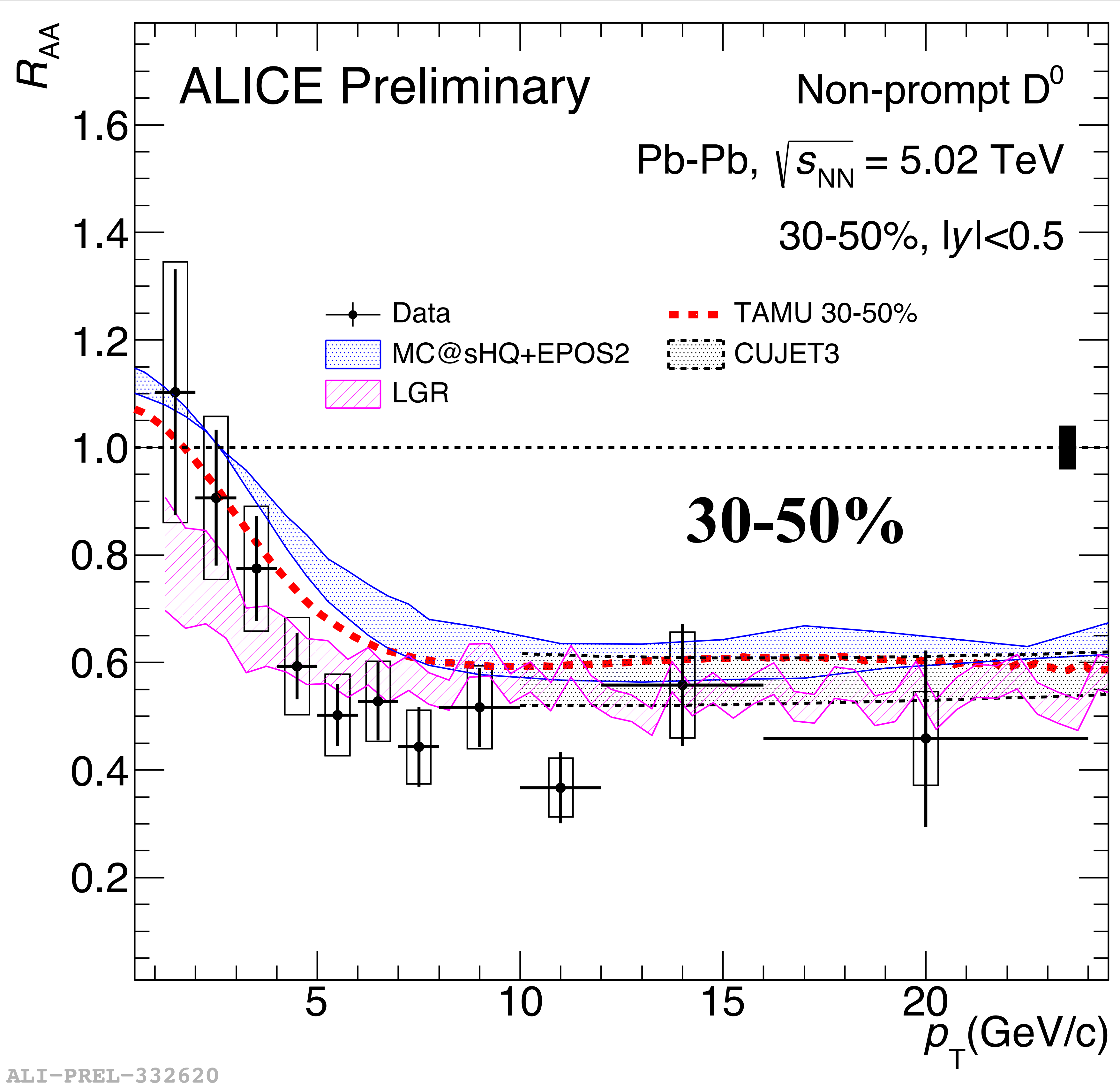




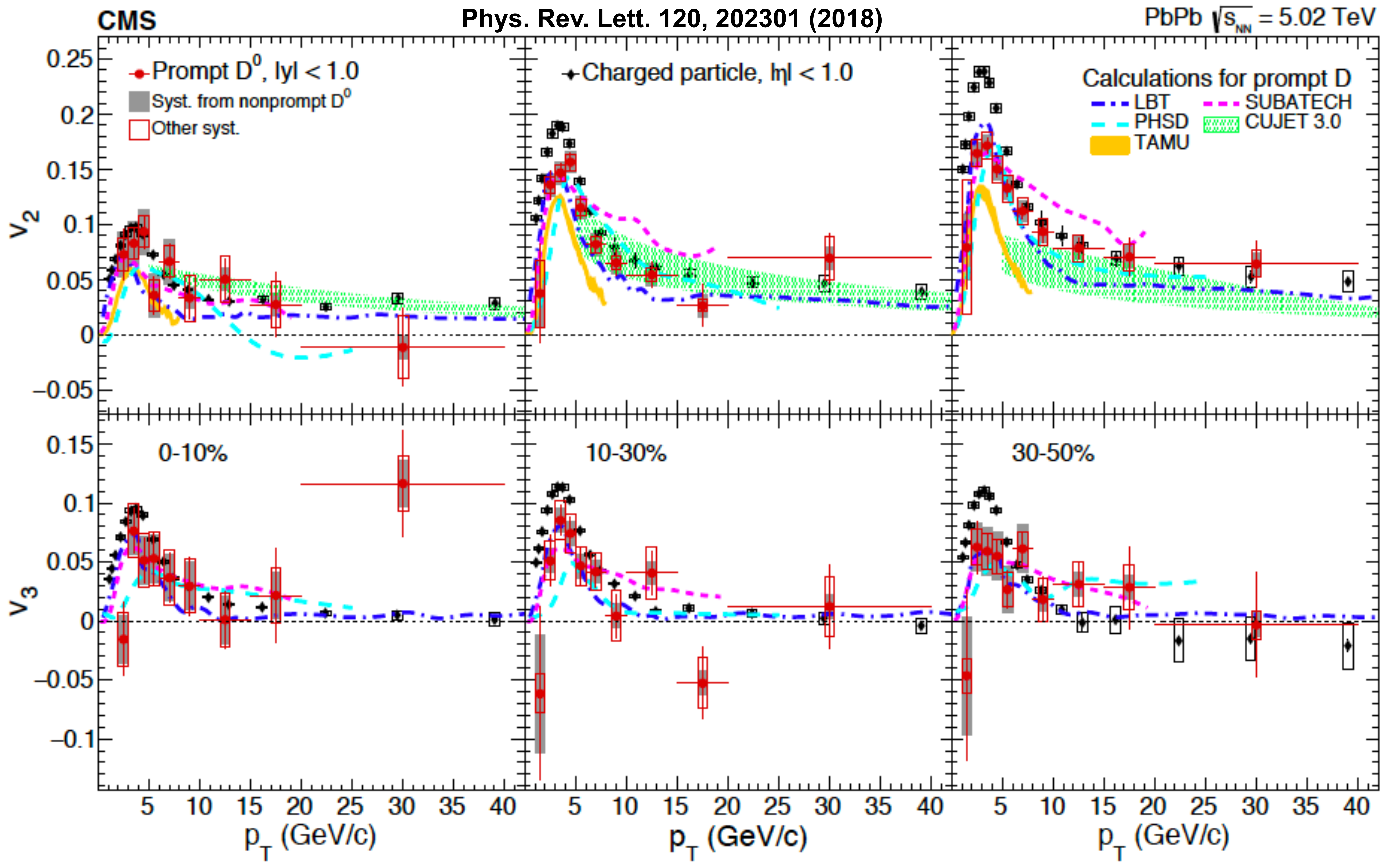
Do we see the different energy loss?

➩ **New R_{AA}** measurement of **non-prompt D meson**
- hint of a **smaller suppression for beauty than charm**
- model can describe the data within uncertainty





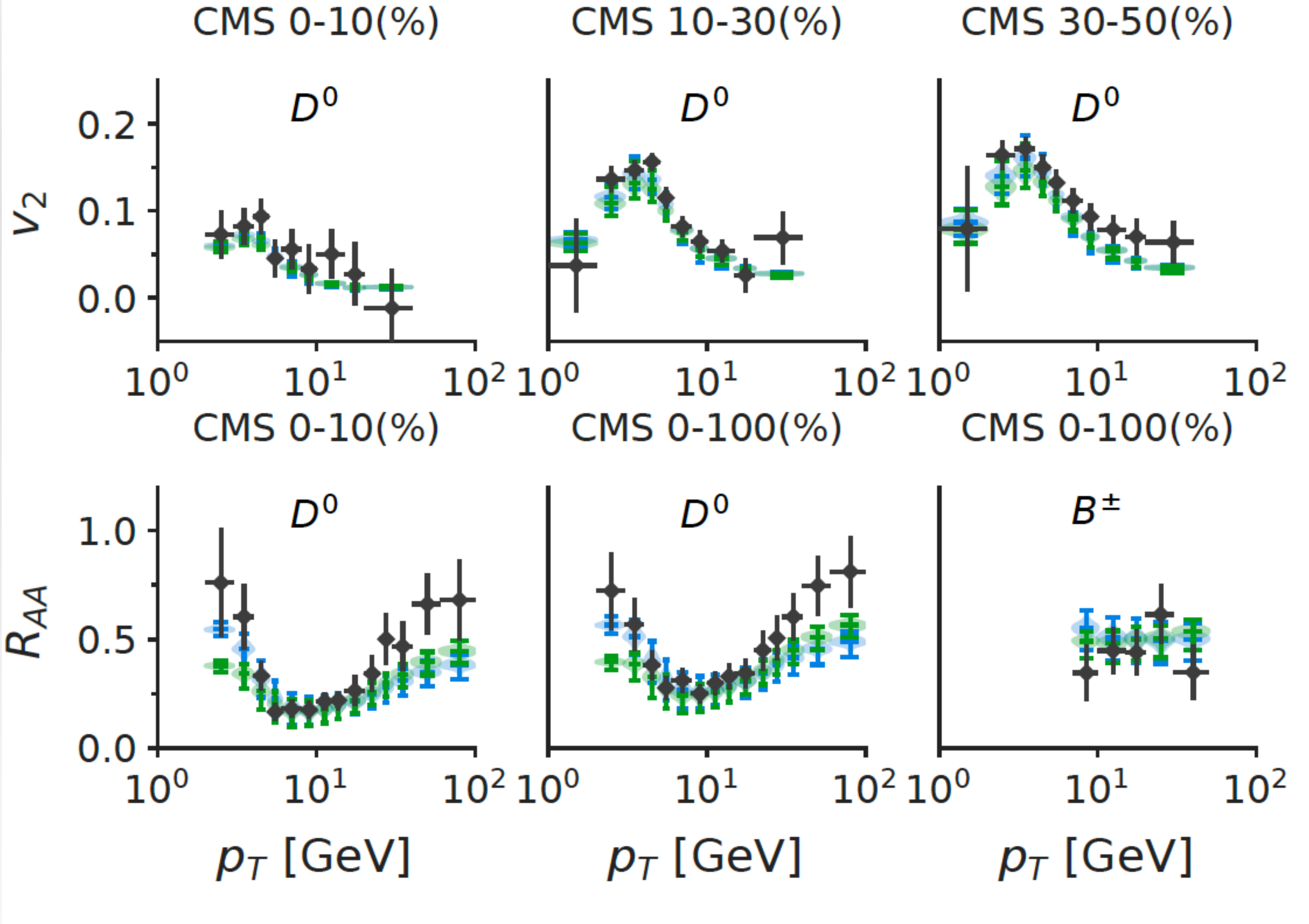
Anisotropic flow of heavy-flavour



- ➪ Strong indication of a non-zero D^0 v_2 and **D^0 v_2 < ch. hadrons v_2**

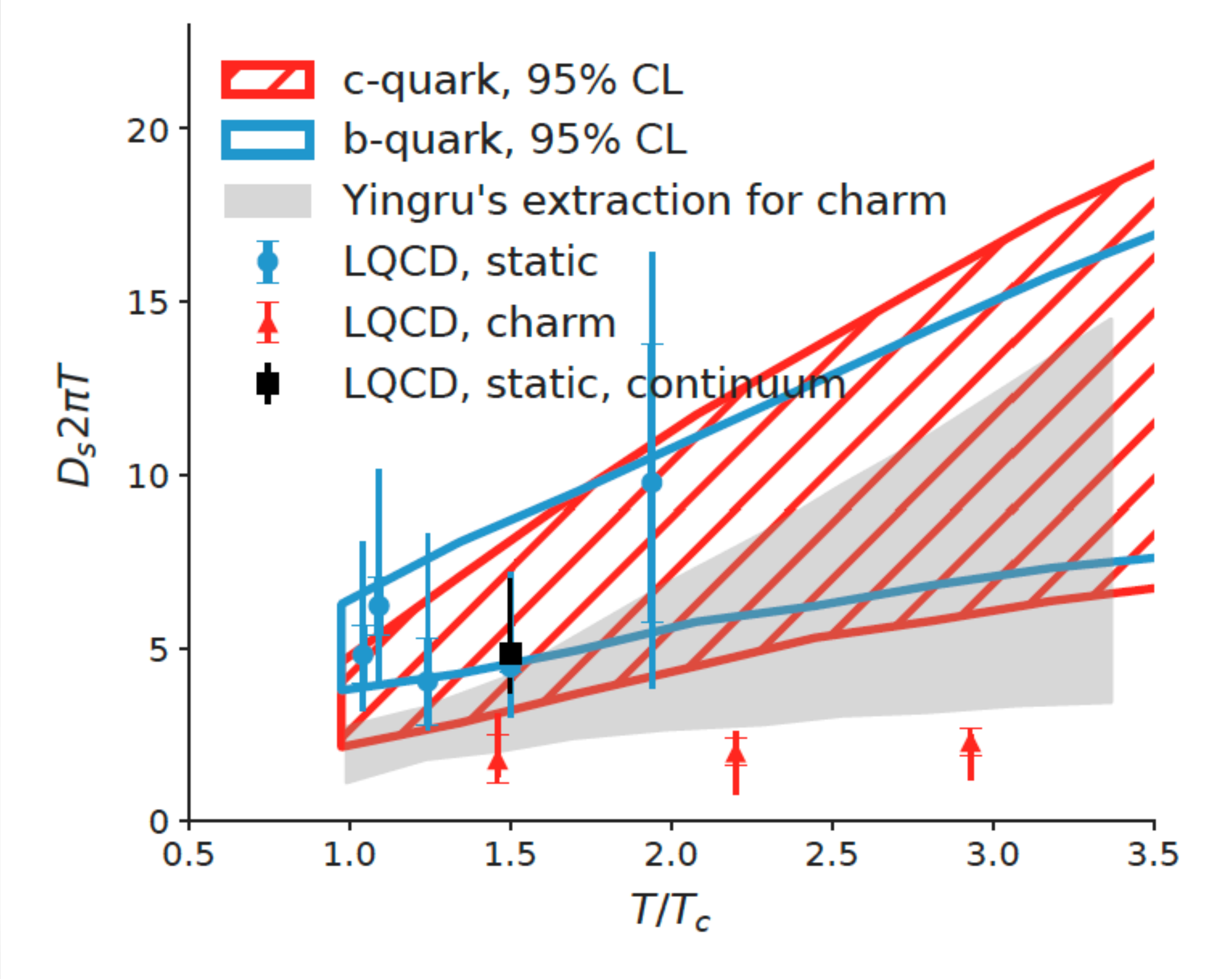
- ➪ **First observations of v_3 > 0 for charm at LHC!**
  - v_3 for charged particle larger that D^0 v_3
    - not fully significative

Extraction of QGP information



Yingru Xu et al.
Nucl.Phys. A967 (2017) 668 - 671
Phys. Rev. C 98, 064901 (2018)

➪ **Models fits** performed to extract info about QGP and heavy-quark energy loss



➪ **Ongoing:** theoretical effort through statistical analysis to constrain model parameter like charm diffusion coefficient

Did we learn already everything?

Did we learn already everything?

Of course NOT!!!

Many questions still need to be addressed….

Some of the missing pieces.....

- **Hadronization** mechanisms: fragmentation vs coalescence

- **Magnetic fields** generated in heavy-ion collisions

- **Future experiments**

Some of the missing pieces…..

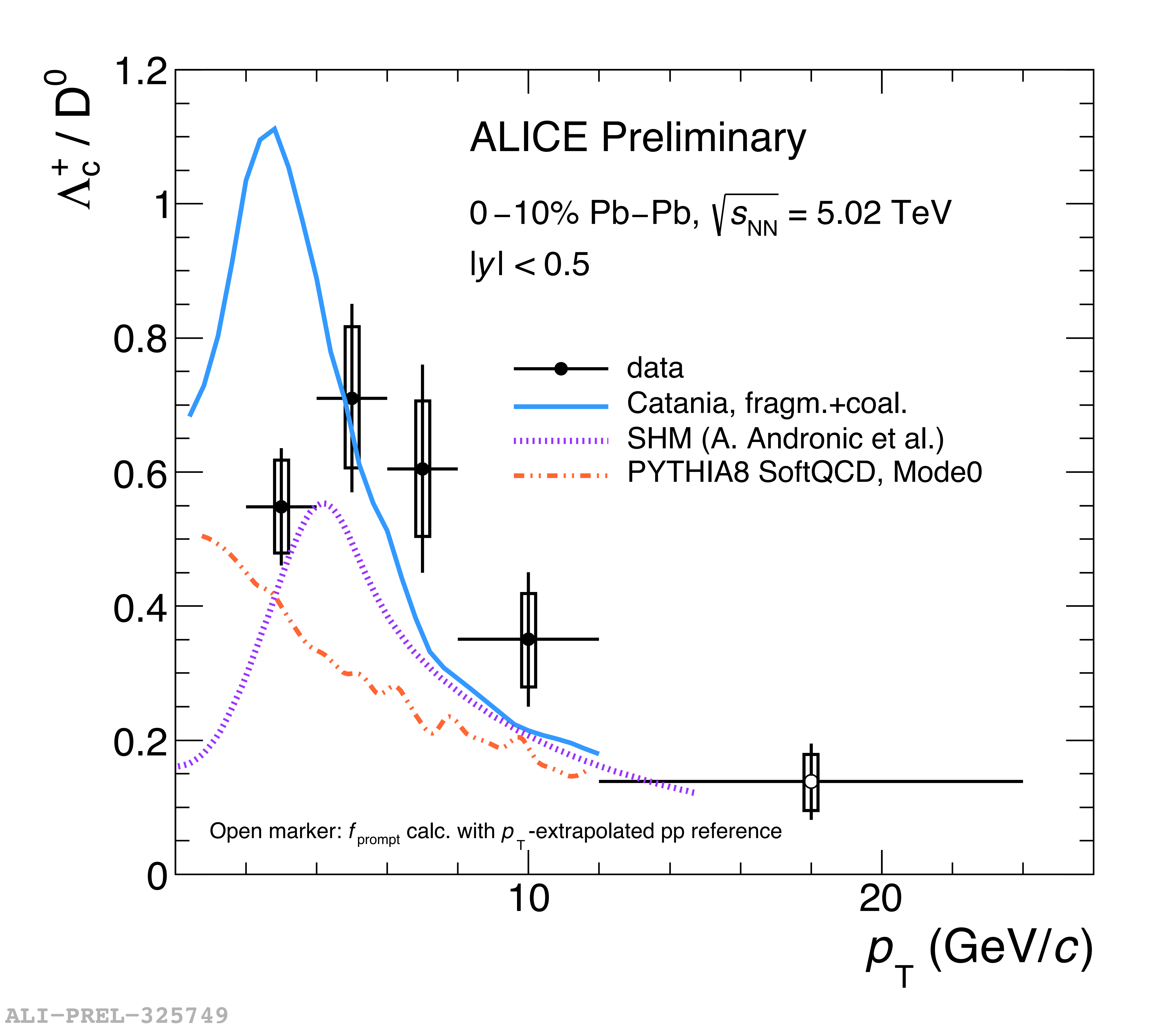
- **Hadronization** mechanisms: fragmentation vs coalescence
- **Magnetic fields** generated in heavy-ion collisions
- **Future experiments**

Charmed baryons

➩ **Λ_c /D0 ratio**

sensitive to hadronisation mechanism

- Recombination → enhancement

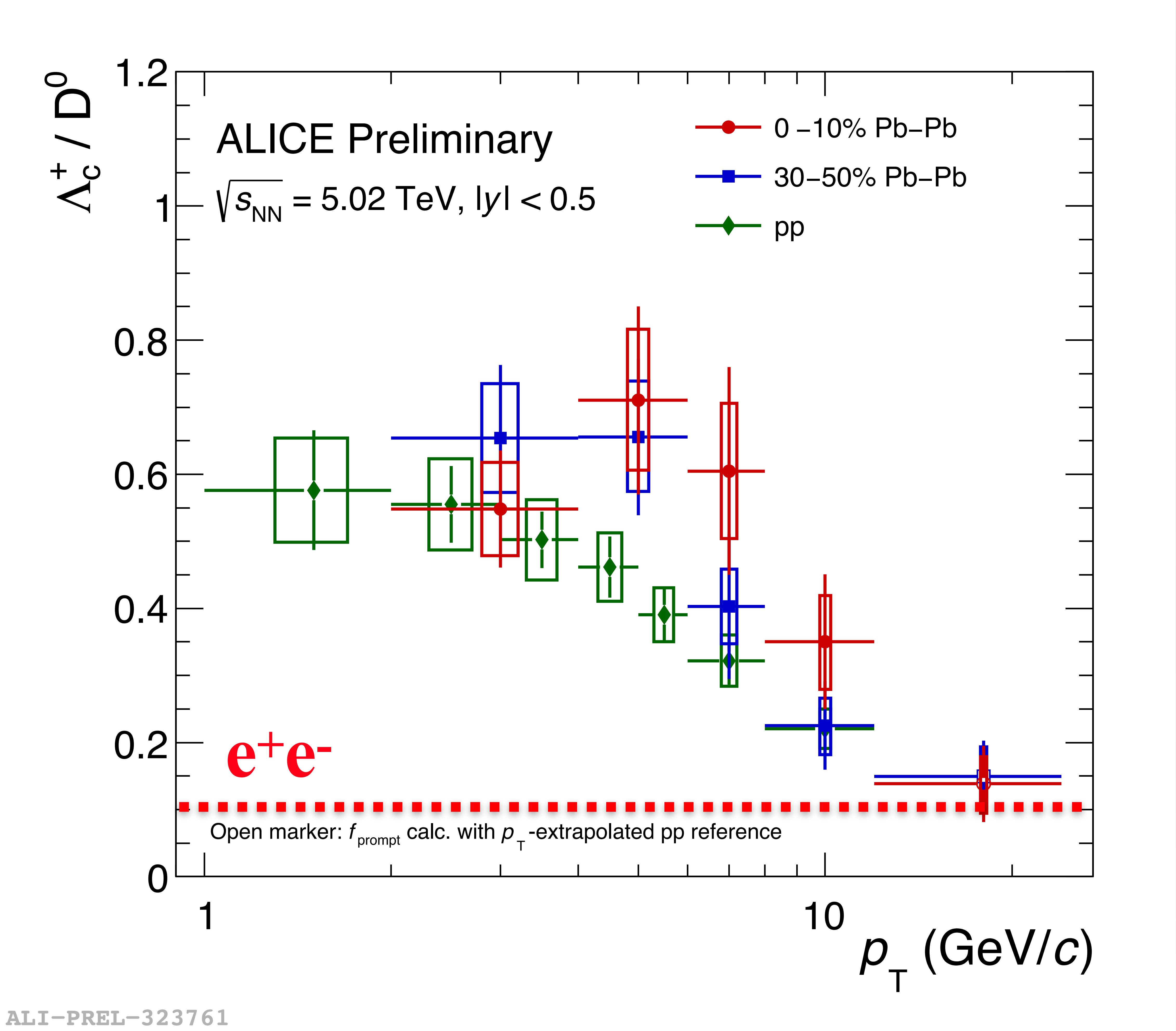


Charmed baryons

➩ **Λ_c /D0 ratio**

sensitive to hadronisation mechanism

- Recombination → enhancement
- **Already an enhancement in small systems**



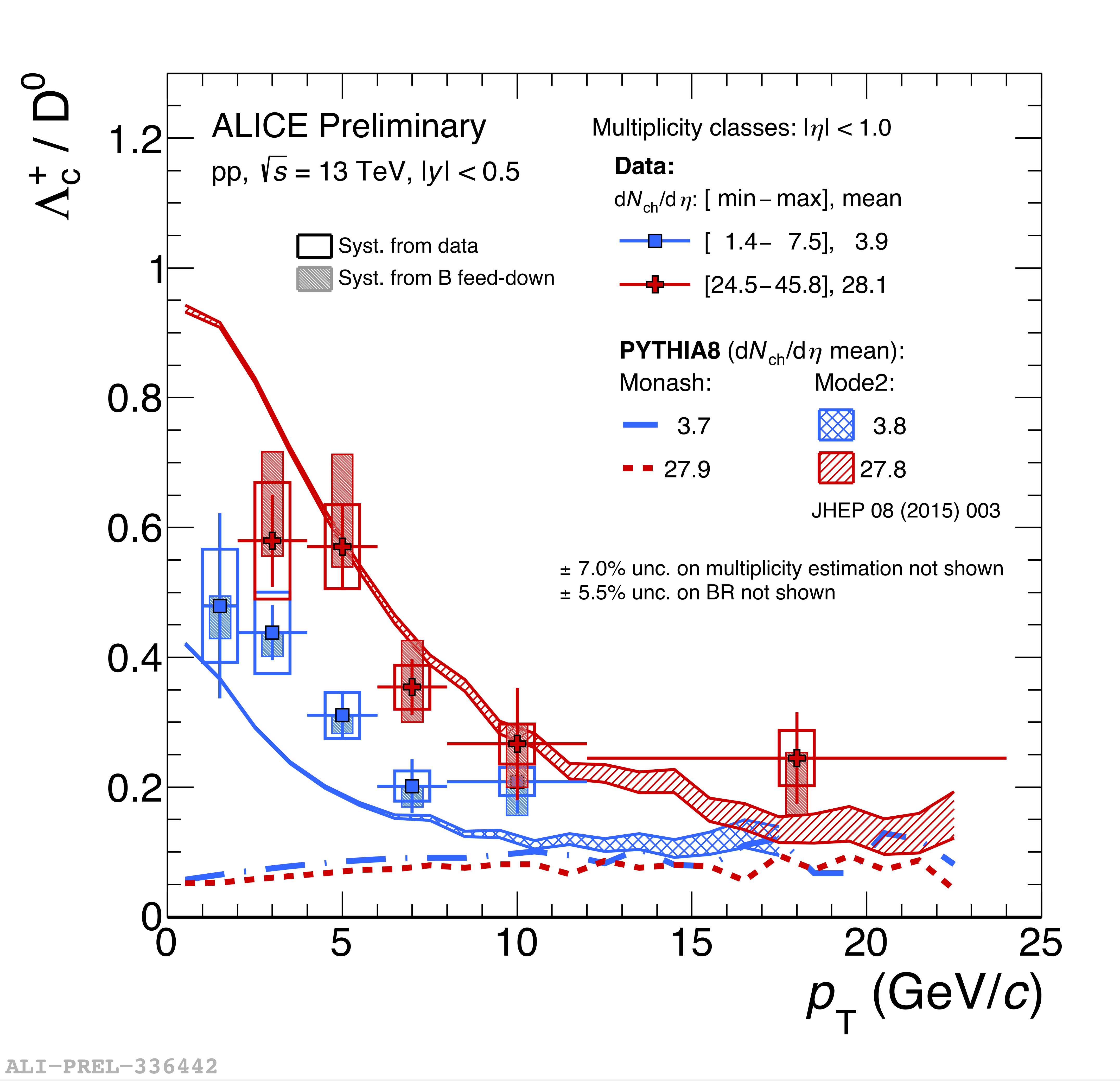
Charmed baryons

- **Λ_c /D0 ratio**
  sensitive to hadronisation mechanism
  - Recombination → enhancement
  - **Already an enhancement in small systems**

- **Multiplicity dependence in pp collisions**
  - Enhancement over default Pythia
  - Color reconnection models describe data

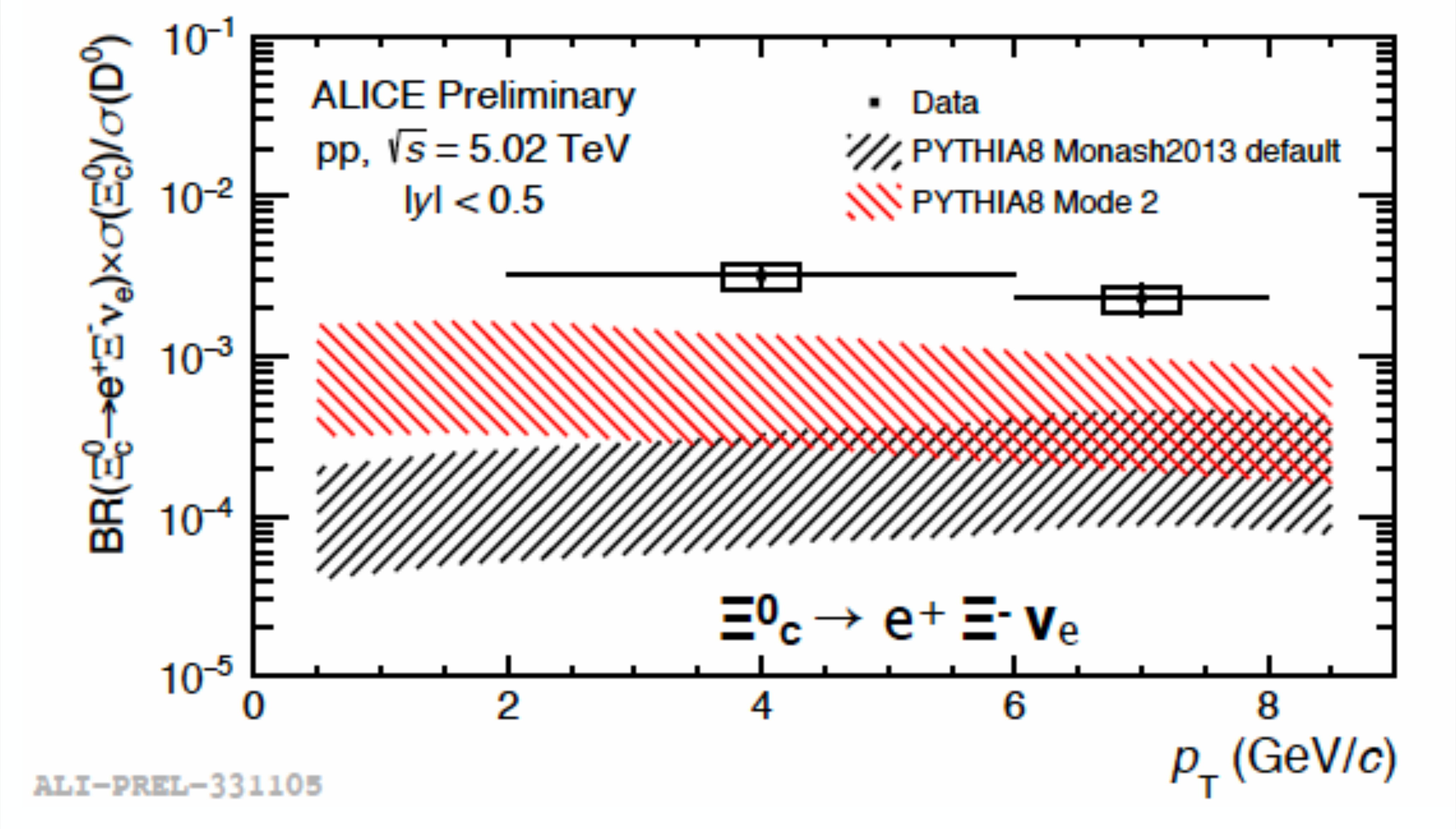
- Severe consequence for **total charm cross section**

- What are the limits of the **factorisation approach** and **fragmentation function universality?**



Charmed baryons

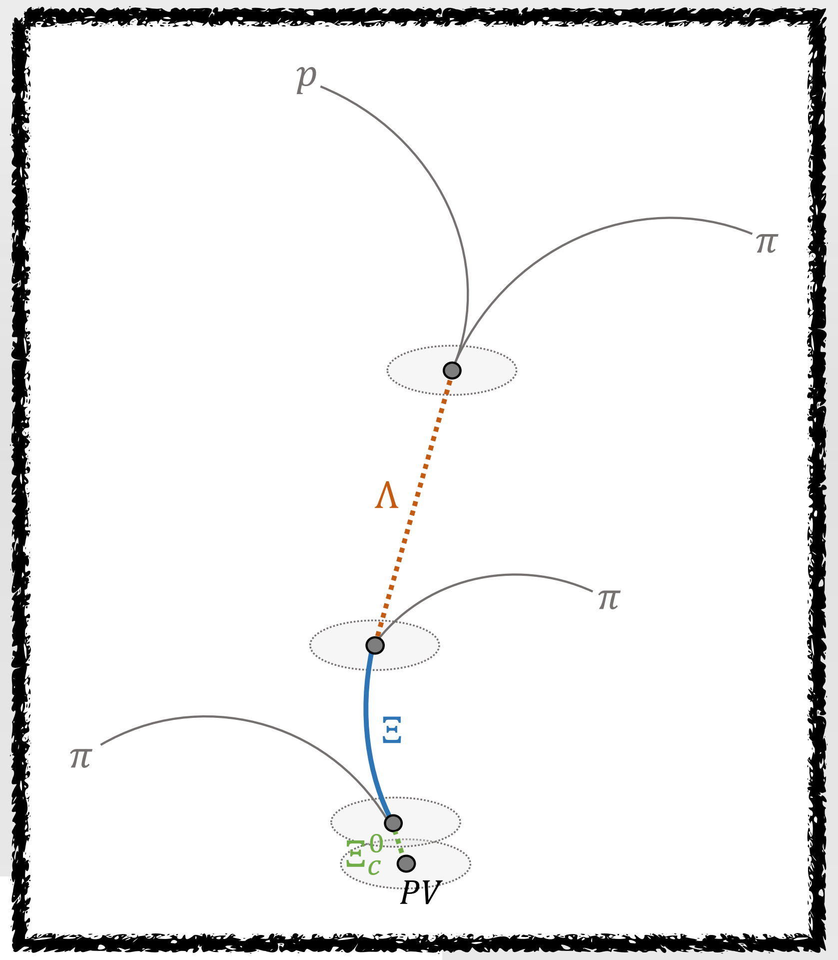
Another player in this game

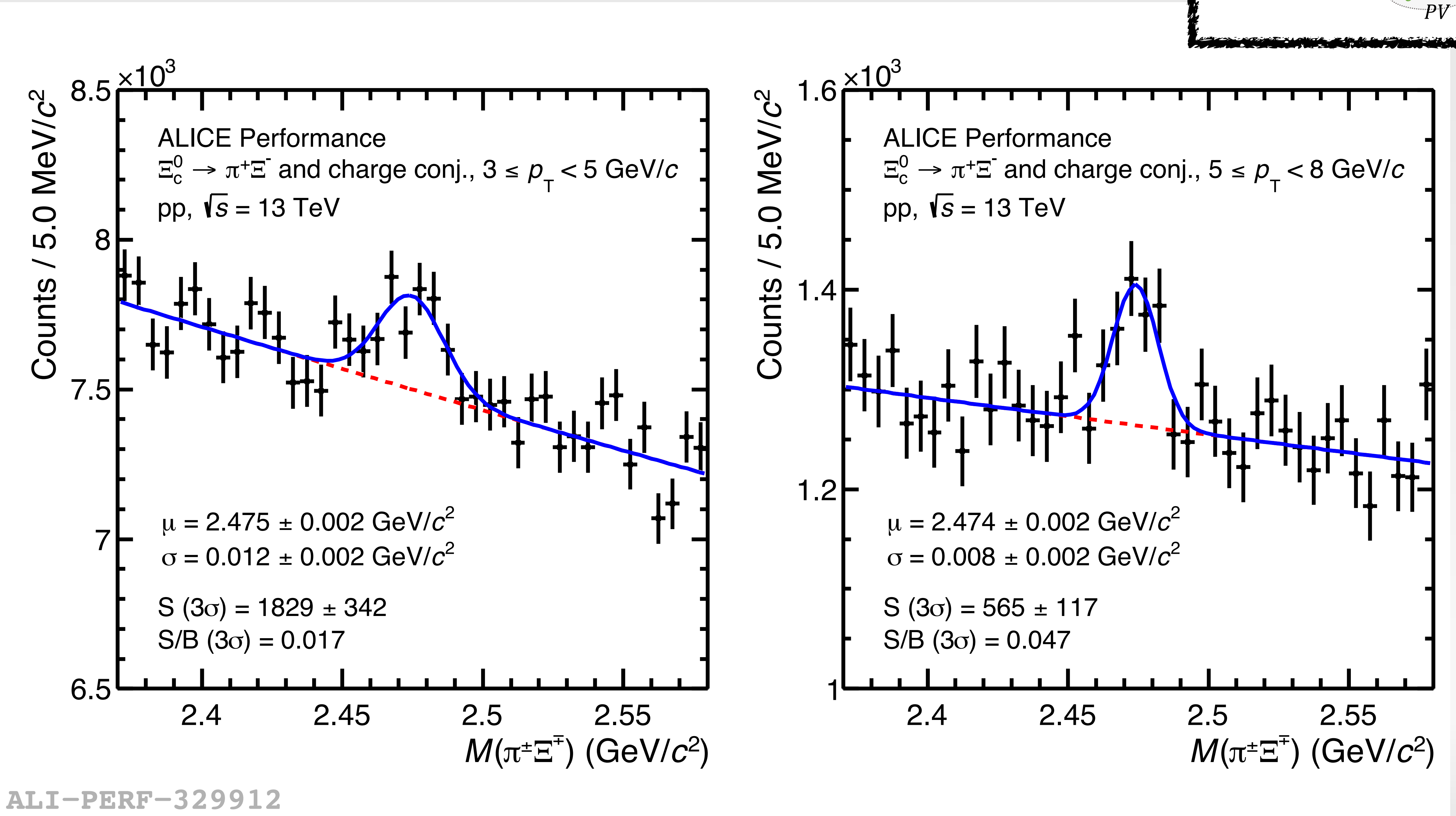


→ Ratio with heavier baryons Ξ^0_c:
- expected larger enhancement

→ First attempt to **fully reconstruct the** $\mathbf{\Xi^0_c}$ in hadronic decay via Ξπ decay

→ Clear and significant peaks in the p_T interval 3-8 GeV/*c*





Some of the missing pieces.....

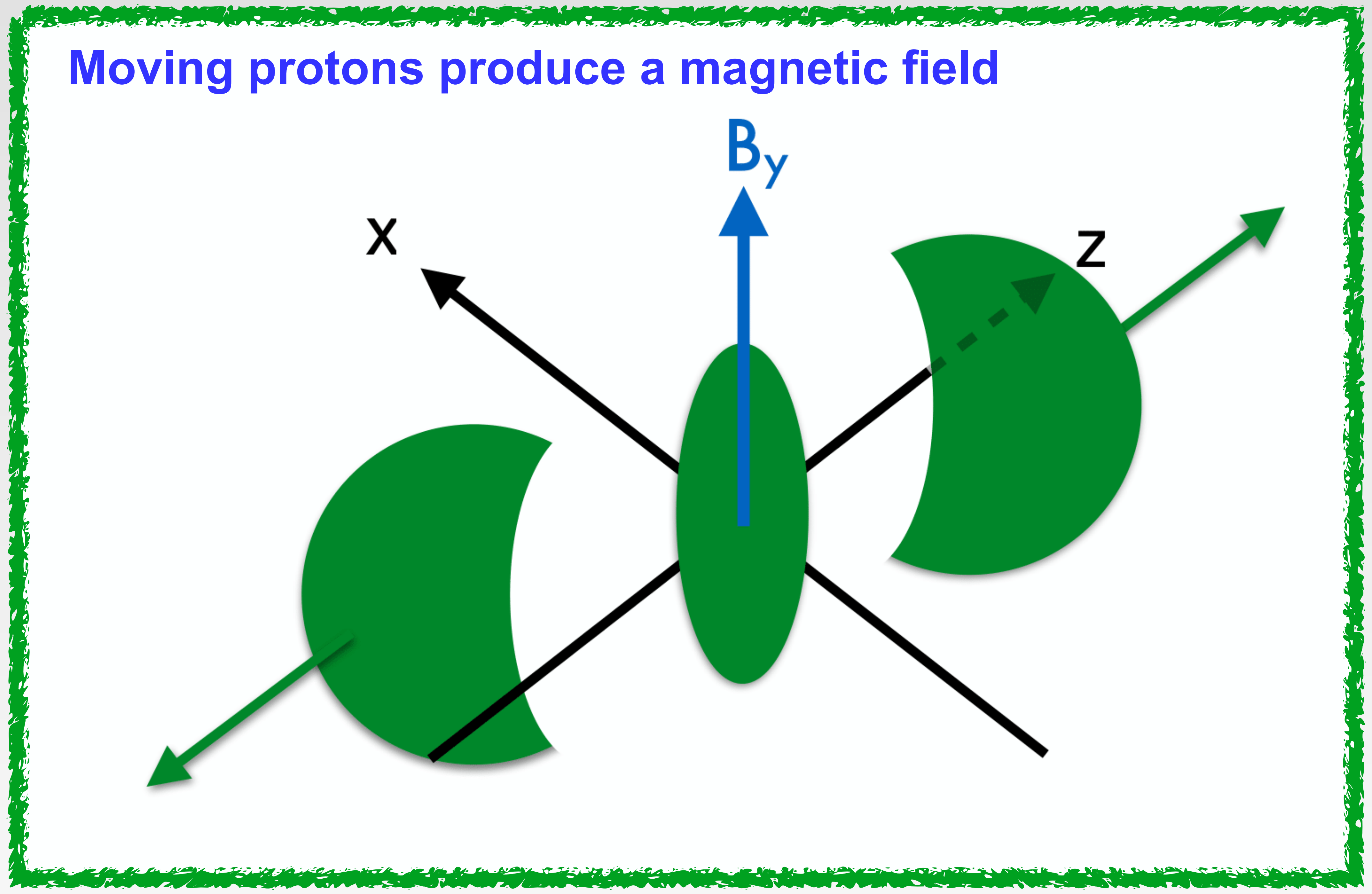
- **Hadronization** mechanisms: fragmentation vs coalescence

- **Magnetic fields** generated in heavy-ion collisions

- **Future experiments**

Magnetic field in QGP

➩ In non-central heavy-ion collisions an **enormous magnetic field (10^{18} G)** is generated by the movement of the **non-colliding protons** **(Biot-Savart law)**



Biggest magnetic field in the universe

→ order of magnitude larger than the one of the magnetars

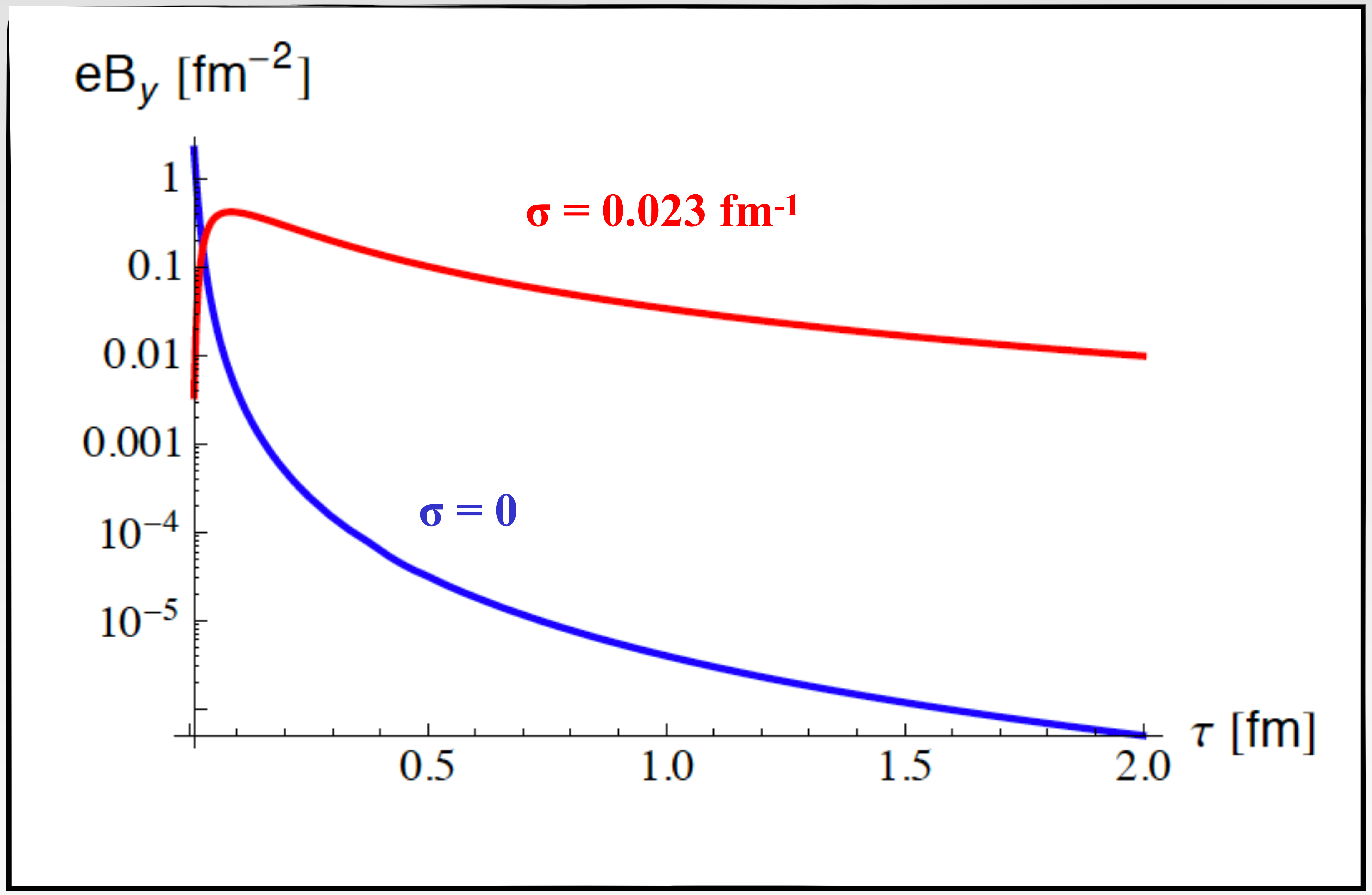
→ it will have a **lot of implications**: astrophysics, cosmology

➩ Quickly decreases (~1 fm/*c*) as the non-colliding protons fly away

The idea*

➪ **varying magnetic field will influence moving charges (quarks)**

➪ very few ingredients needed: **charged and conductive QGP**



➪ presence of a conducting QGP substantially delays the decay of the magnetic field

- **assumption**: constant conductivity as a function of temperature
$\sigma = 0.023\ \mathrm{fm}^{-1}$

H.-T. Ding, et al, Phys. Rev. D 83, 034504
B. B. Brandt et al, JHEP 1303, 100 (2013)
A. Amato, et al, Phys. Rev. Lett. 111, 172001 (2013)

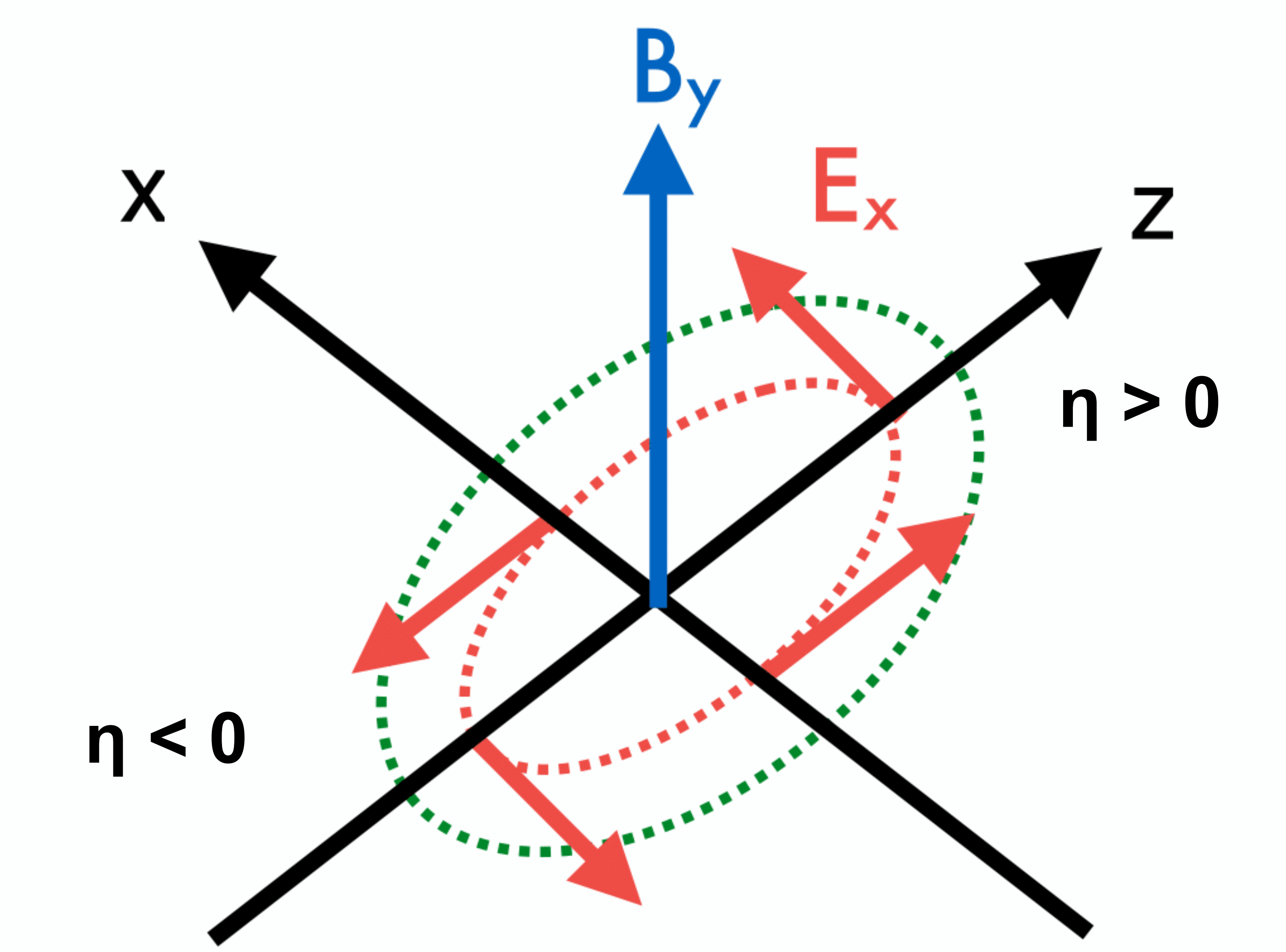
*first proposed by Gursoy *et al:* Phys. Rev. C 89, 054905 (2014)

The idea*

- ➪ **varying magnetic field will influence moving charges (quarks)**
- ➪ very few ingredients needed: **charged and conductive QGP**
- ➪ the result: charge-dependent **directed flow**, asymmetric in rapidity

– where does it come from?

→ electric field induced by decreasing B
(Faraday effect)



$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

*first proposed by Gursoy *et al:* Phys. Rev. C 89, 054905 (2014)

The idea*

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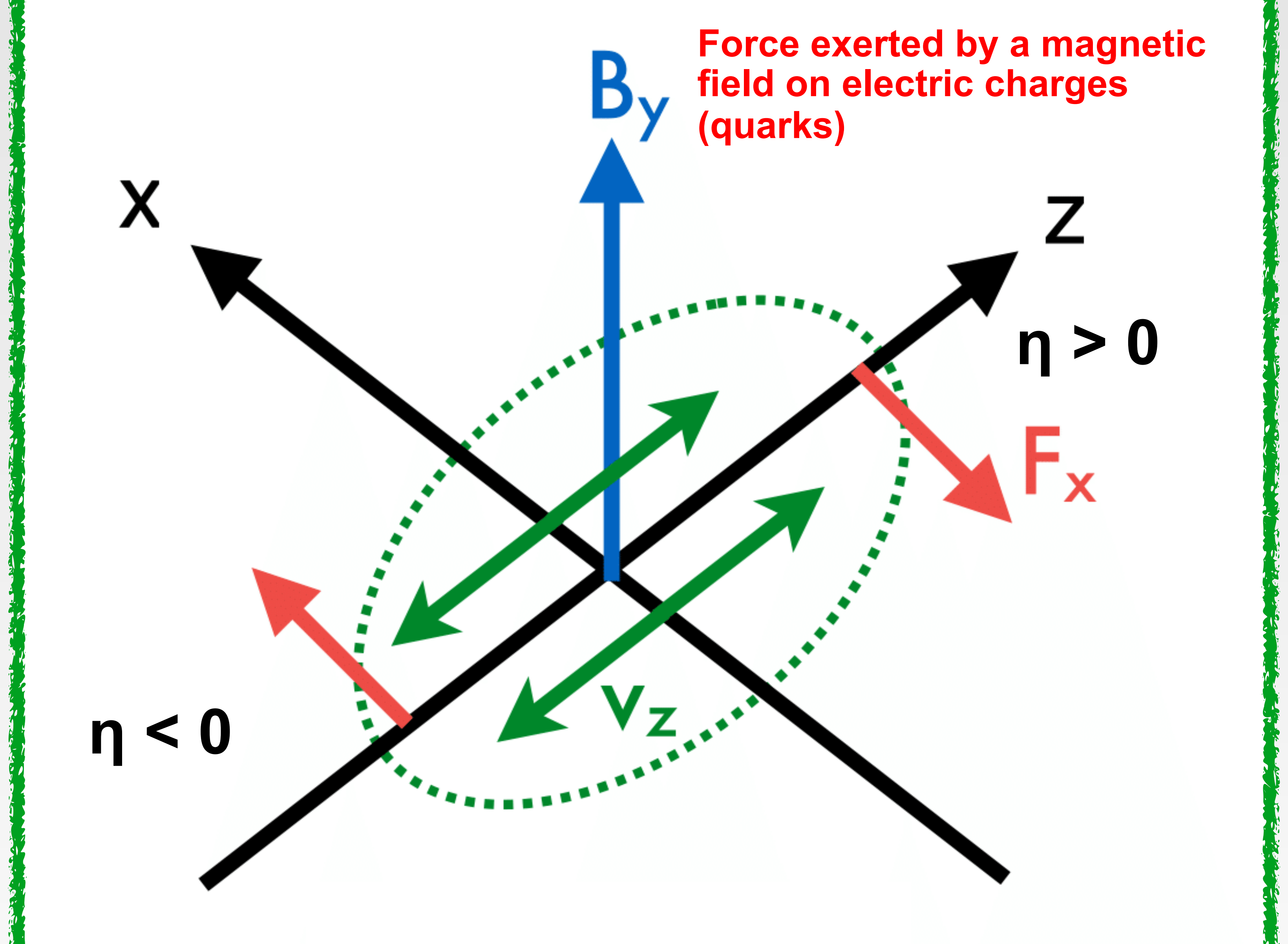
– where does it come from?

→ electric field induced by decreasing B
(Faraday effect)

→ Lorentz force on moving charges
(Hall effect)

Competing effects



$$\mathbf{F} = q\mathbf{v} \times \mathbf{B} + q \cdot \mathbf{E}$$

*first proposed by Gursoy *et al:* Phys. Rev. C 89, 054905 (2014)

The idea*

- **varying magnetic field will influence moving charges (quarks)**
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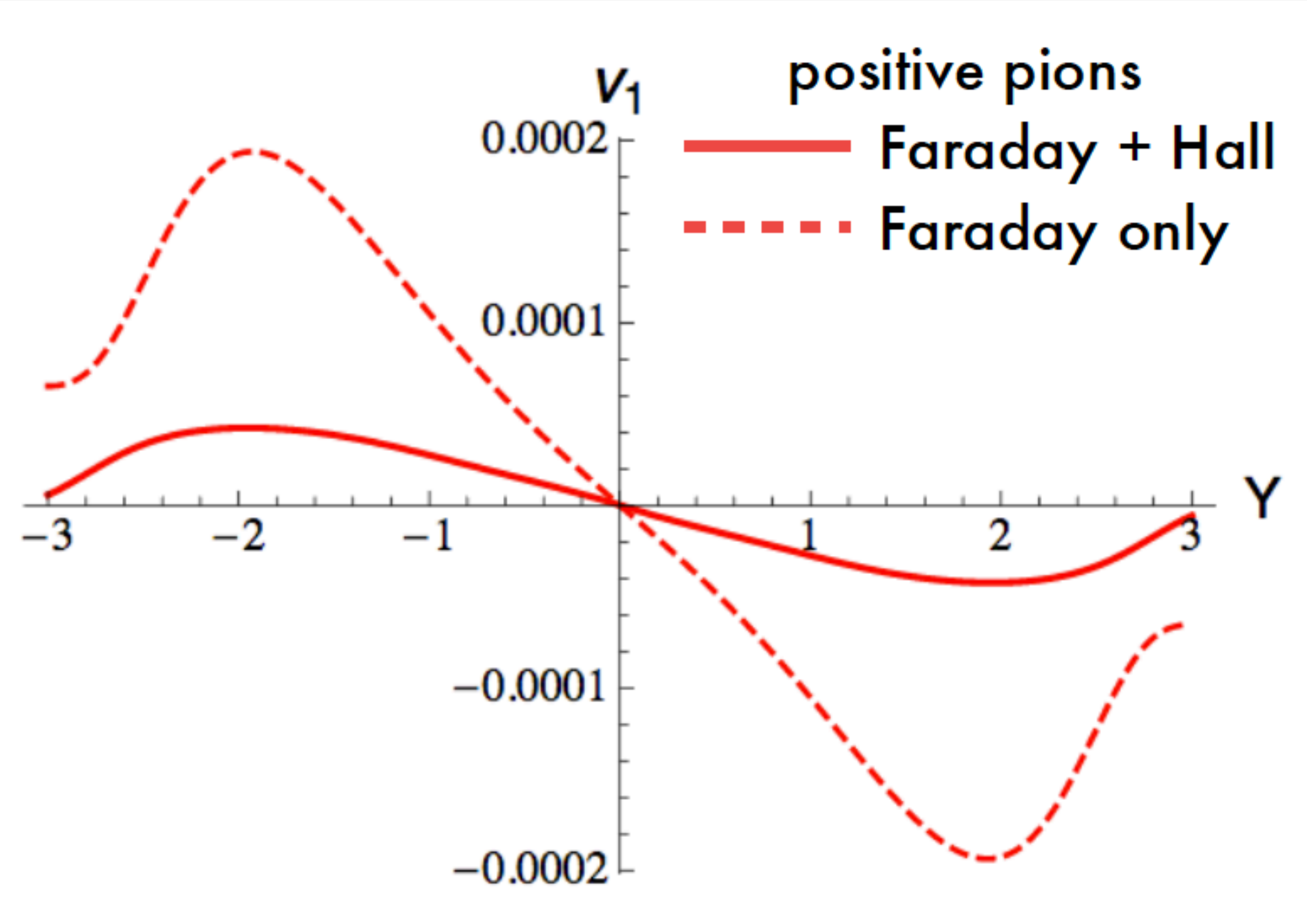
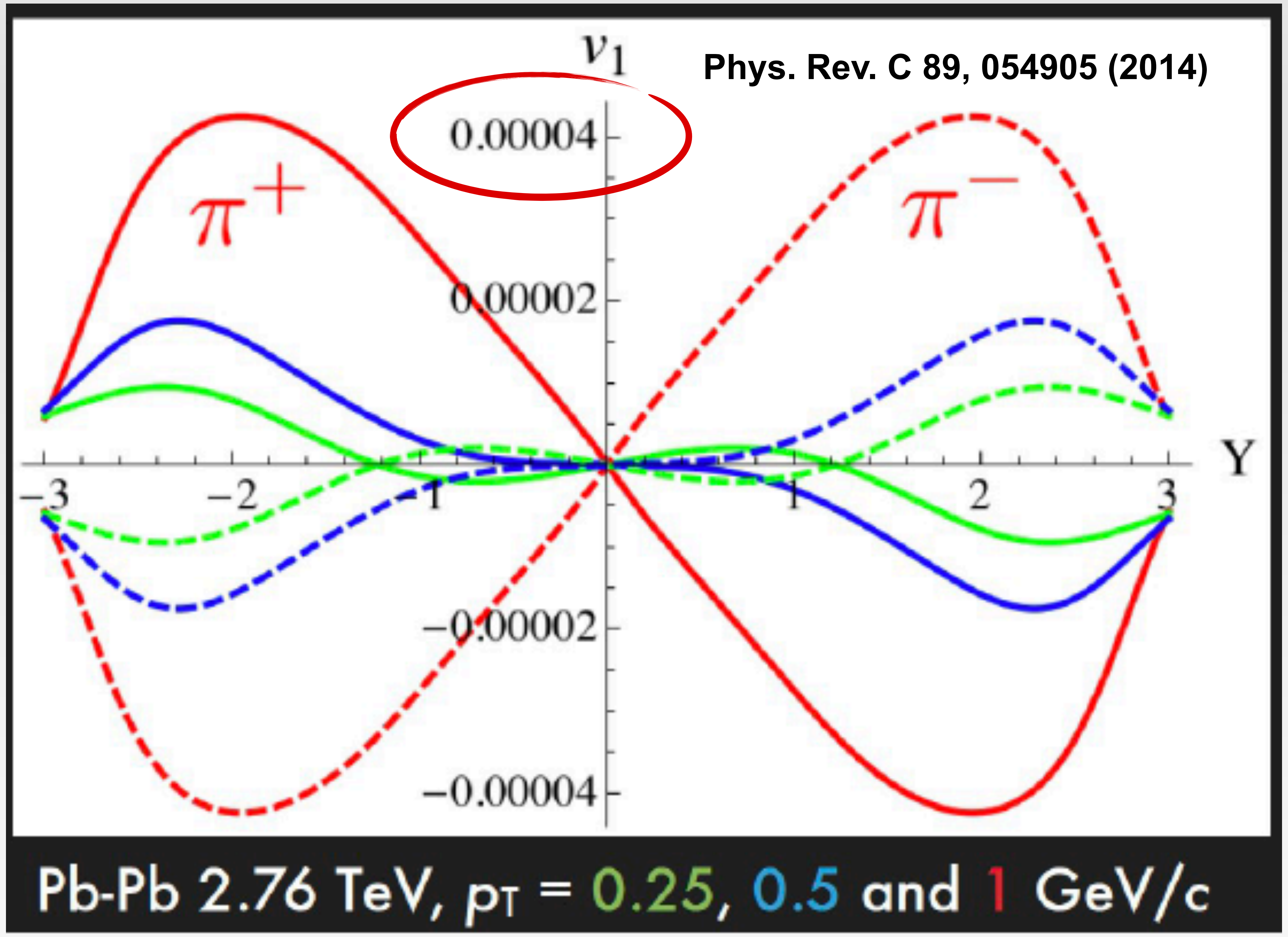


*first proposed by Gursoy *et al:* Phys. Rev. C 89, 054905 (2014)

Charge-dependent v_1

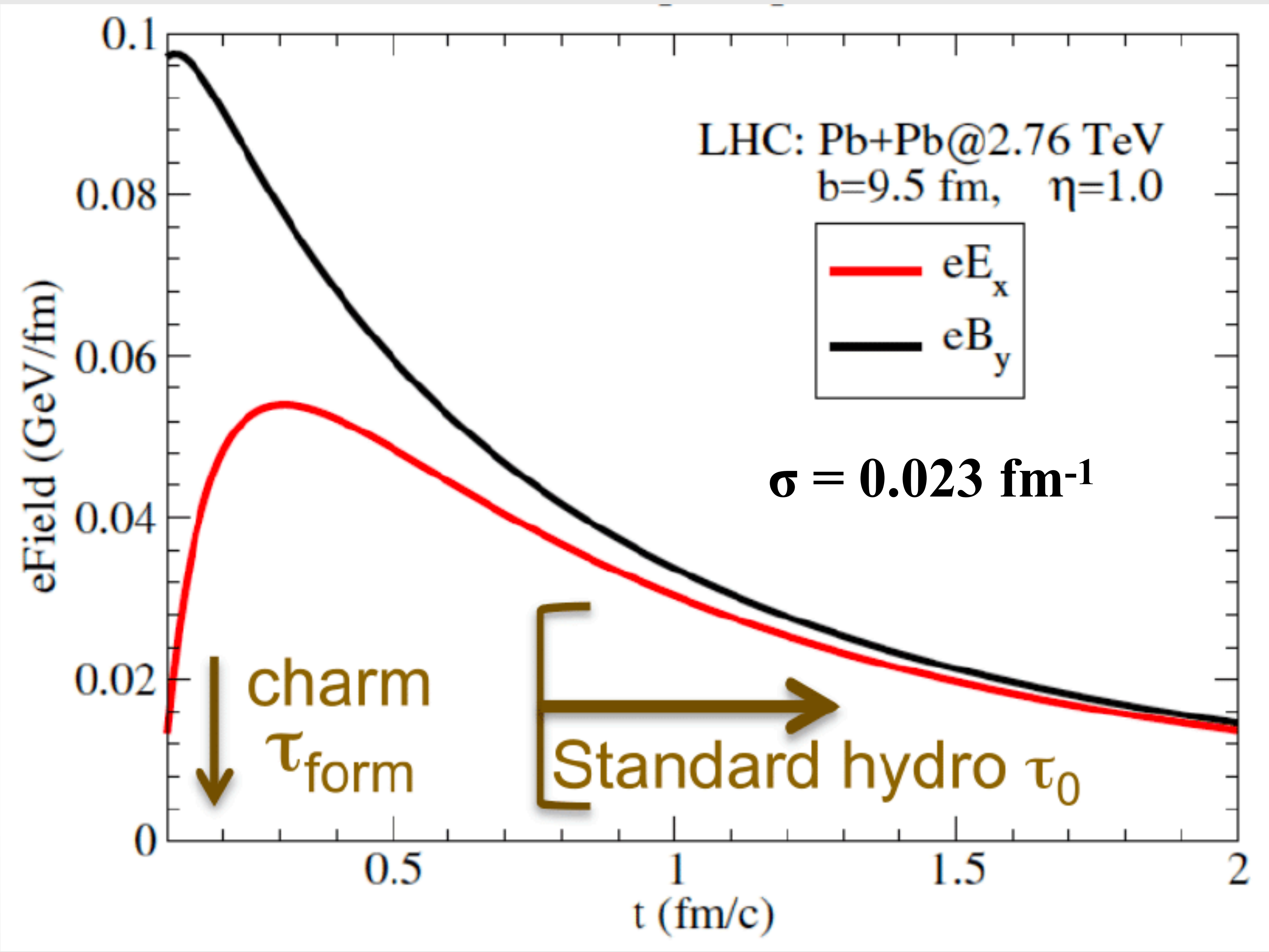
➩ prediction for Pb-Pb collisions at 2.76 TeV: **~10^{-5}**



- the rapidity slope varies with p_T, different contribution of Faraday and Lorentz

What about heavy-flavour?

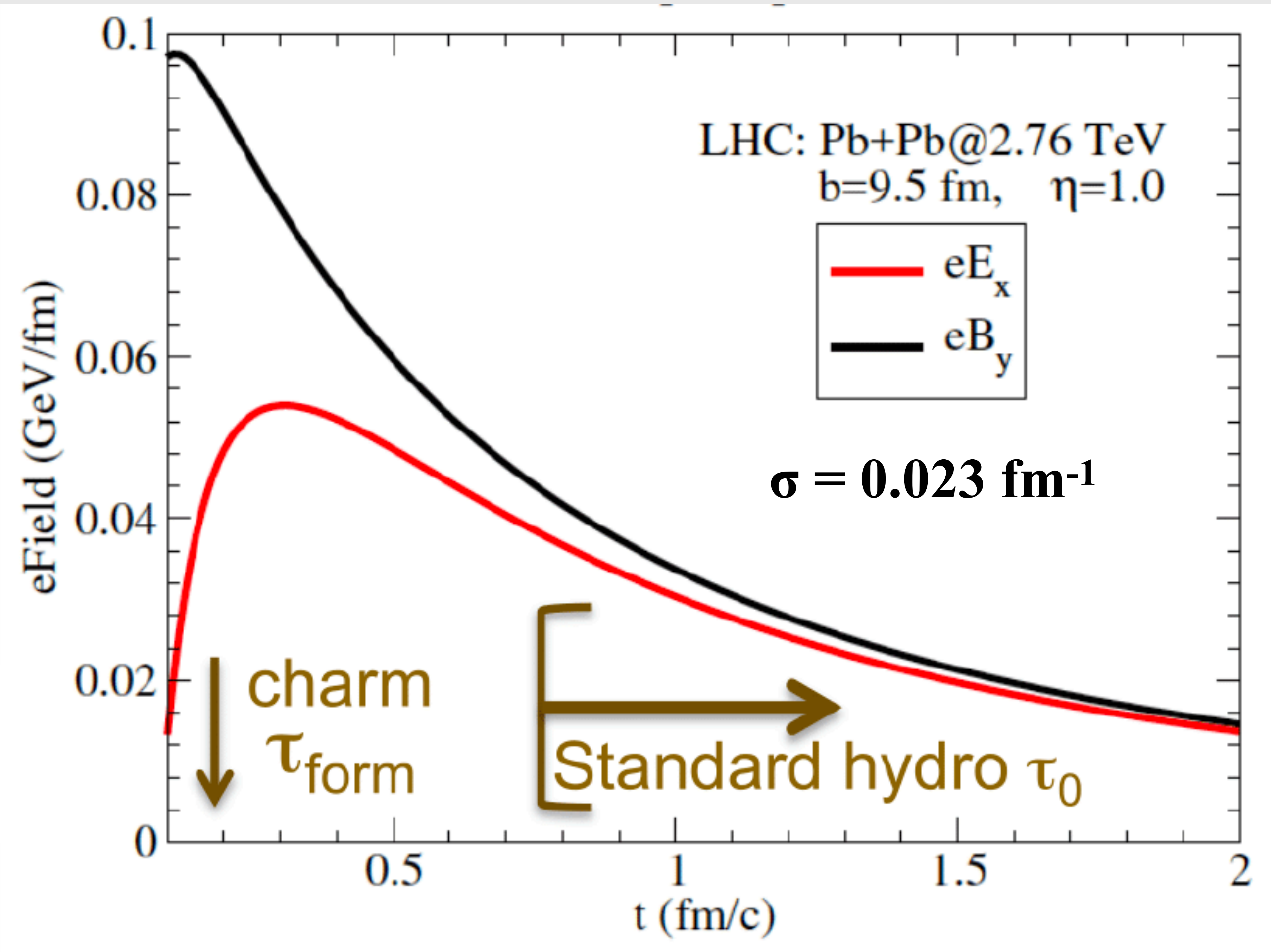
➩ **formation time** ~ 0.1 fm/c → comparable to the time scale **when B is maximum**

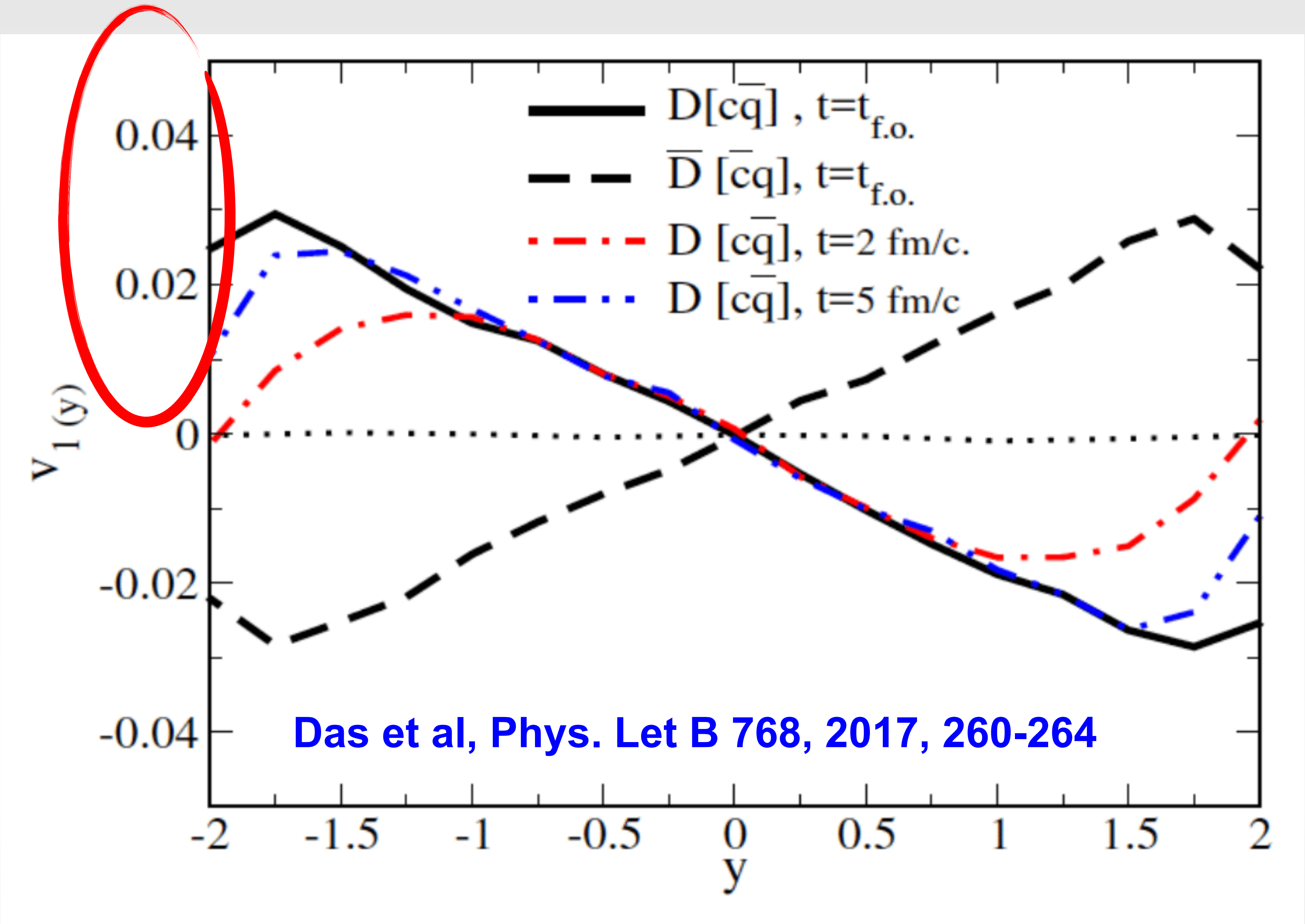


What about heavy-flavour?

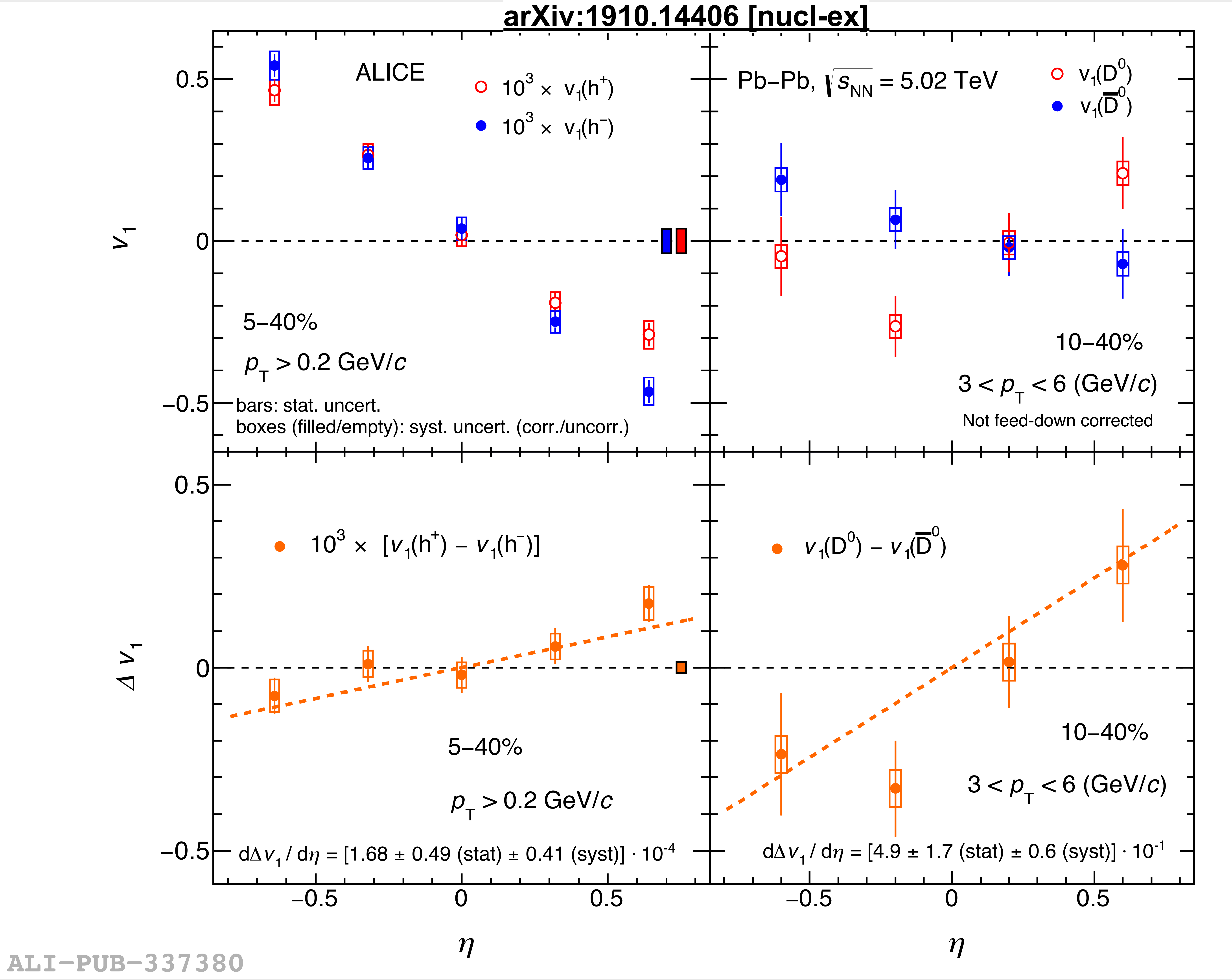
➪ **formation time** ~ 0.1 fm/c → comparable to the time scale **when B is maximum**

➪ resultant effects entail a **significantly larger directed flow** v_1 of charm quarks compared to light quarks





Charged partivle vs heavy-flavour

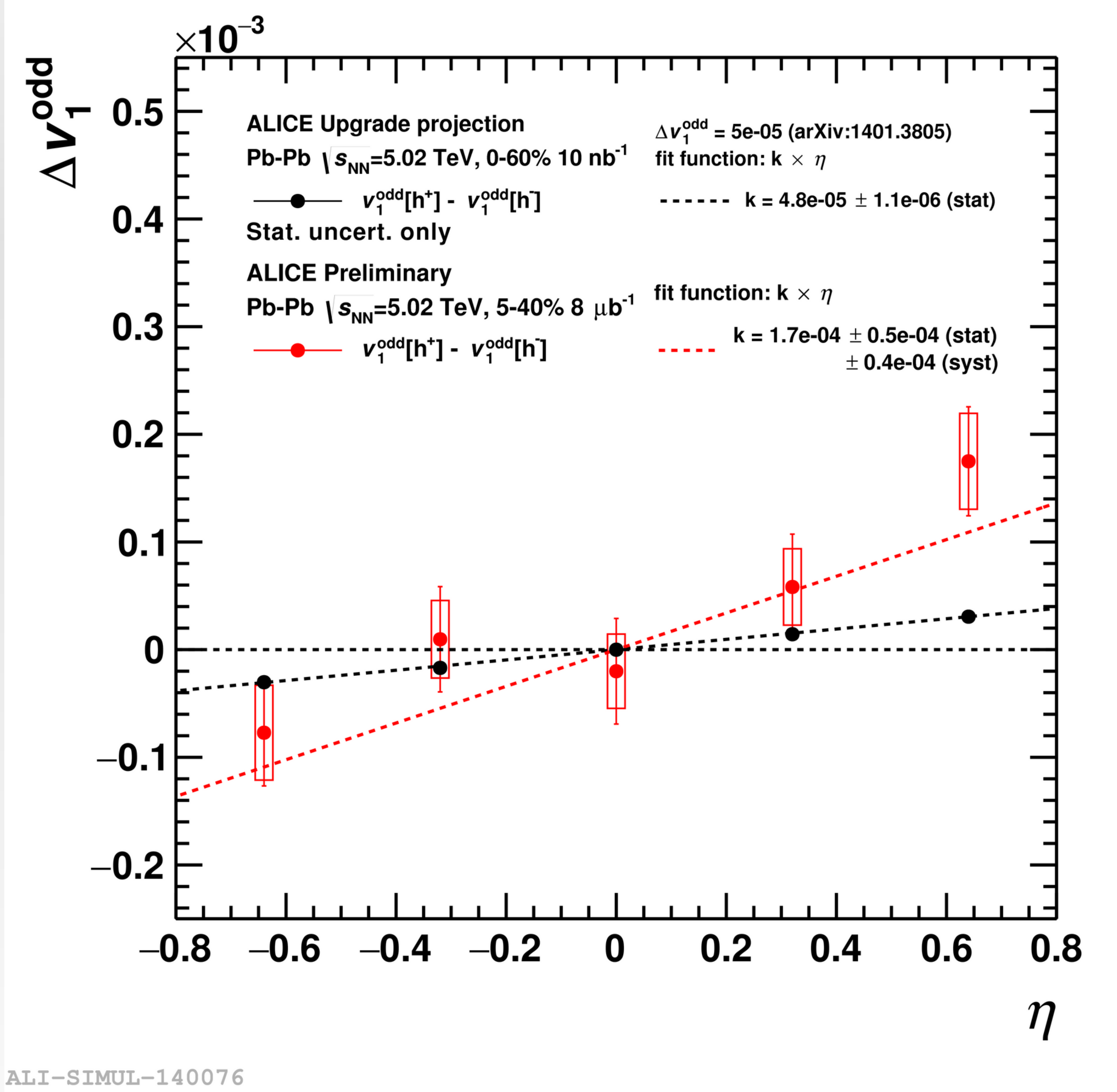


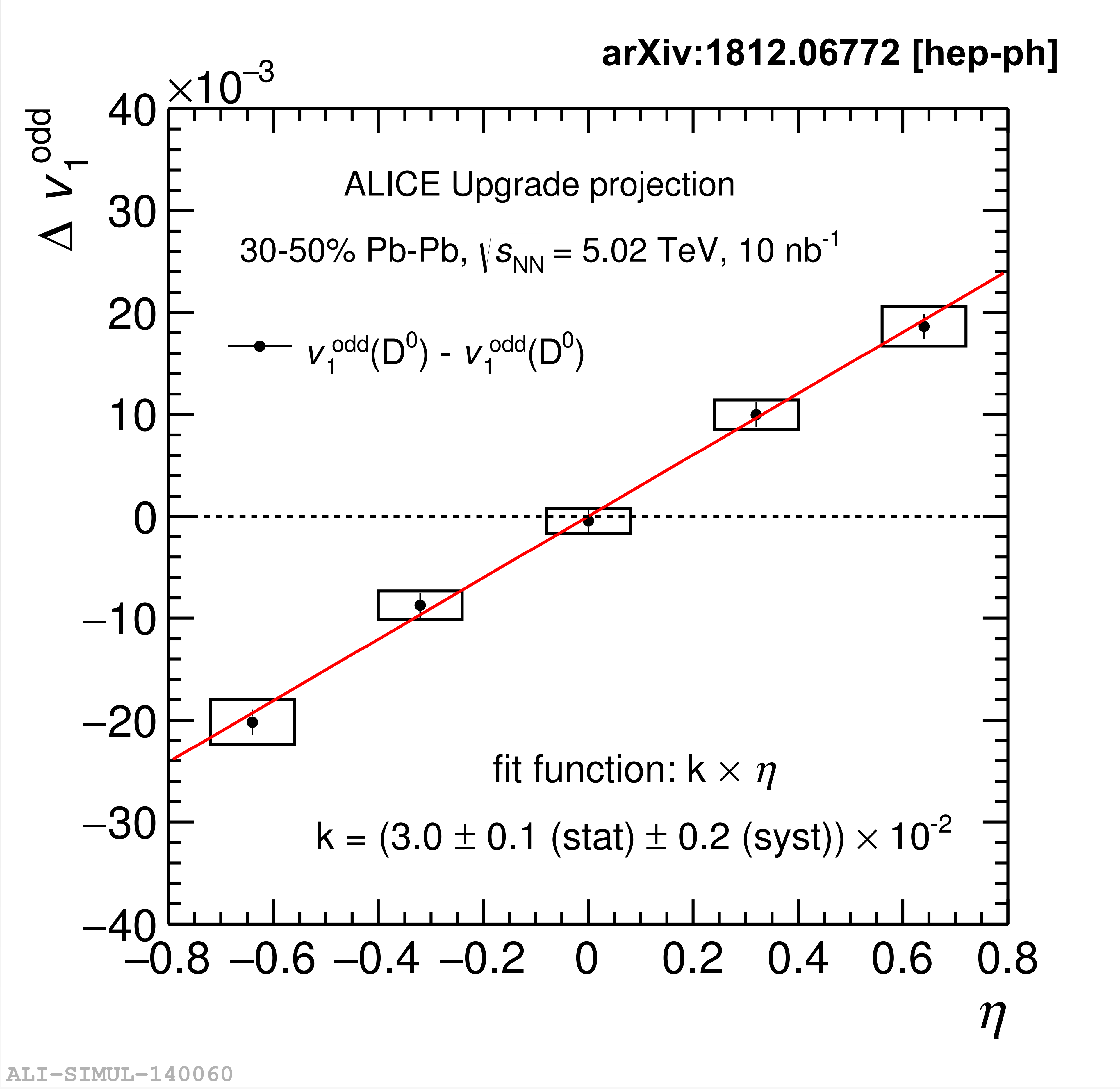
➪ First measurements at the LHC of charge dependent directed flow of light and heavy flavour particles

➪ The **3 orders of magnitude difference** between charged-particle and heavy-flavour predicted by theory will be **experimentally accessible**

➪ it will **constrain fundamental and unexplored properties of the QGP** like the **conductivity**

Projections for Run3/4





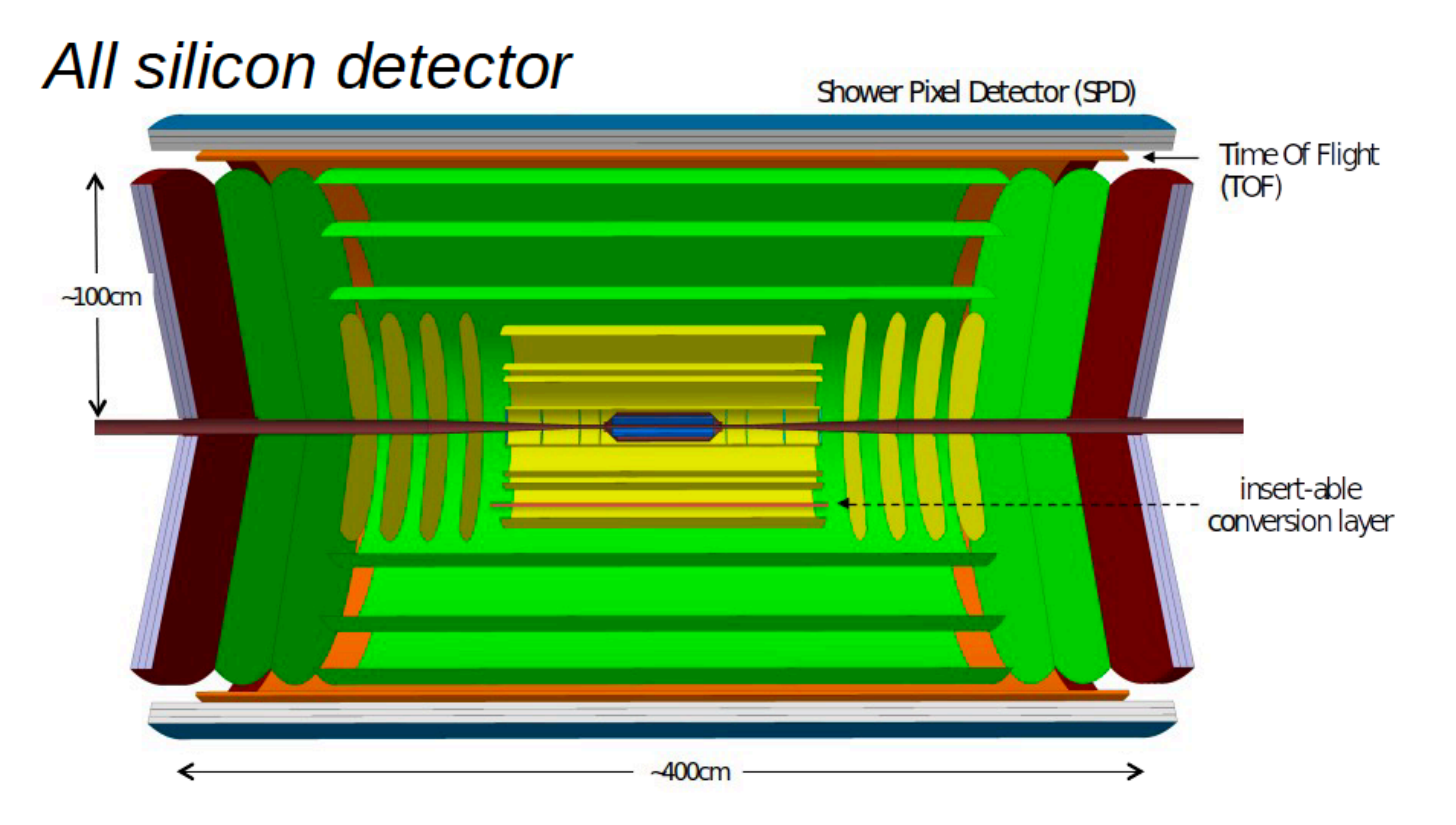
Extremely good significance is expected in Run3/4

Simulations performed according to the signal expected by theory calculations

Some of the missing pieces…..

- **Hadronization** mechanisms: fragmentation vs coalescence
- **Magnetic fields** generated in heavy-ion collisions
- **Future experiments**

Future heavy-ion detector



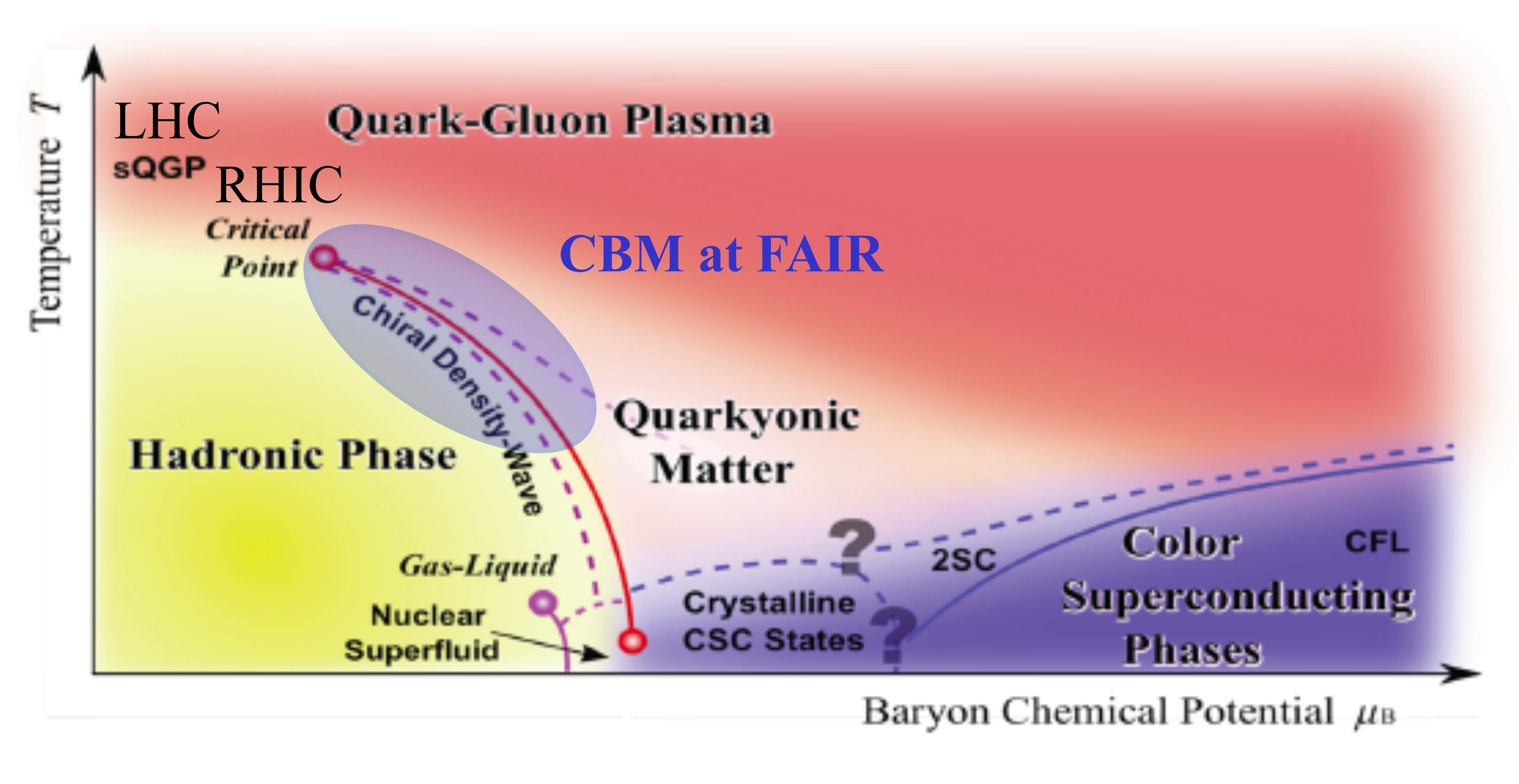
⇨ **Physics potential (just few examples)**

- **heavy-flavour and quarkonia**
  - multi-charm hadrons (Ξ_{cc}, Ω_{cc}, Ω_{ccc})
  - X, Y, Z states
- **Soft hadronic and electromagnetic radiation**
  - hadrons down to few 10's of MeV/c
- **BSM**
  - dark photons searches

EoI document signed by ~400 physicists (Dec 2018) submitted to European Strategy for Particle Physics Preparatory Group arXiv:1902.01211

CBM at FAIR, Darmstadt

➩ **CBM** aims to investigate the strongly interacting matter in the region of **high baryonic densities**

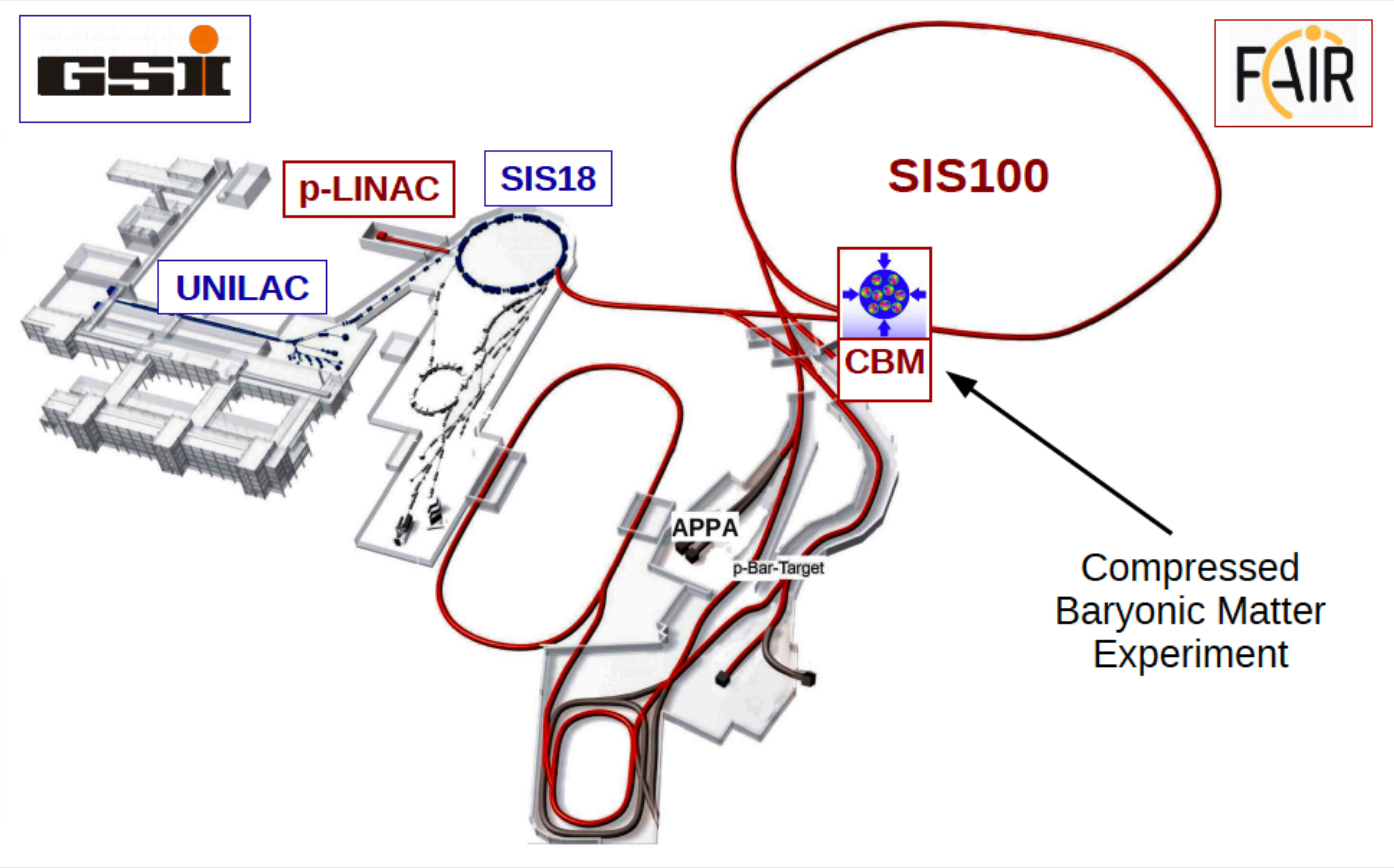


- partonic-hadronic **phase transition** (critical point)
- **equation of state** at high densities (neutron stars)
- **hypernuclei** and multi-strange hadrons
- **charm production** at threshold beam energies
- spectra and **collective flow studies**

K. Fukushima and T. Hatsuda,
Rept. Prog. Phys. 74 (2011) 014001

Thank you for your attention

CBM at FAIR, Darmstadt



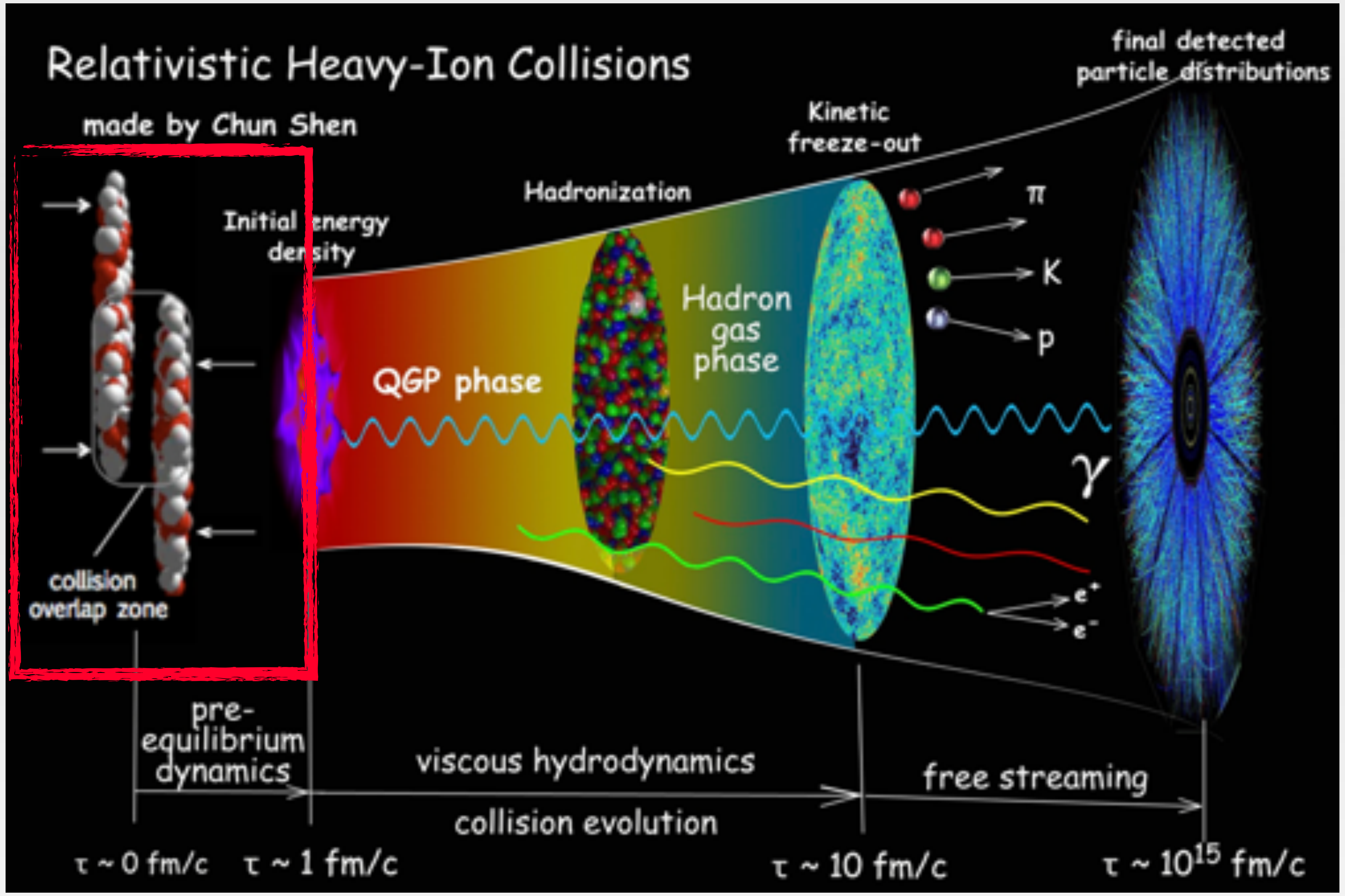
Recap....

⇨ **magnetic field** in heavy-ion collision is expected to
lead to several novel phenomena
e.g. Chiral Magnetic Effect (CME)

⇨ **we face different problems:**
→ **hard to decouple signal** (charge separation across reaction plane)
from background (local charge conservation + flow)

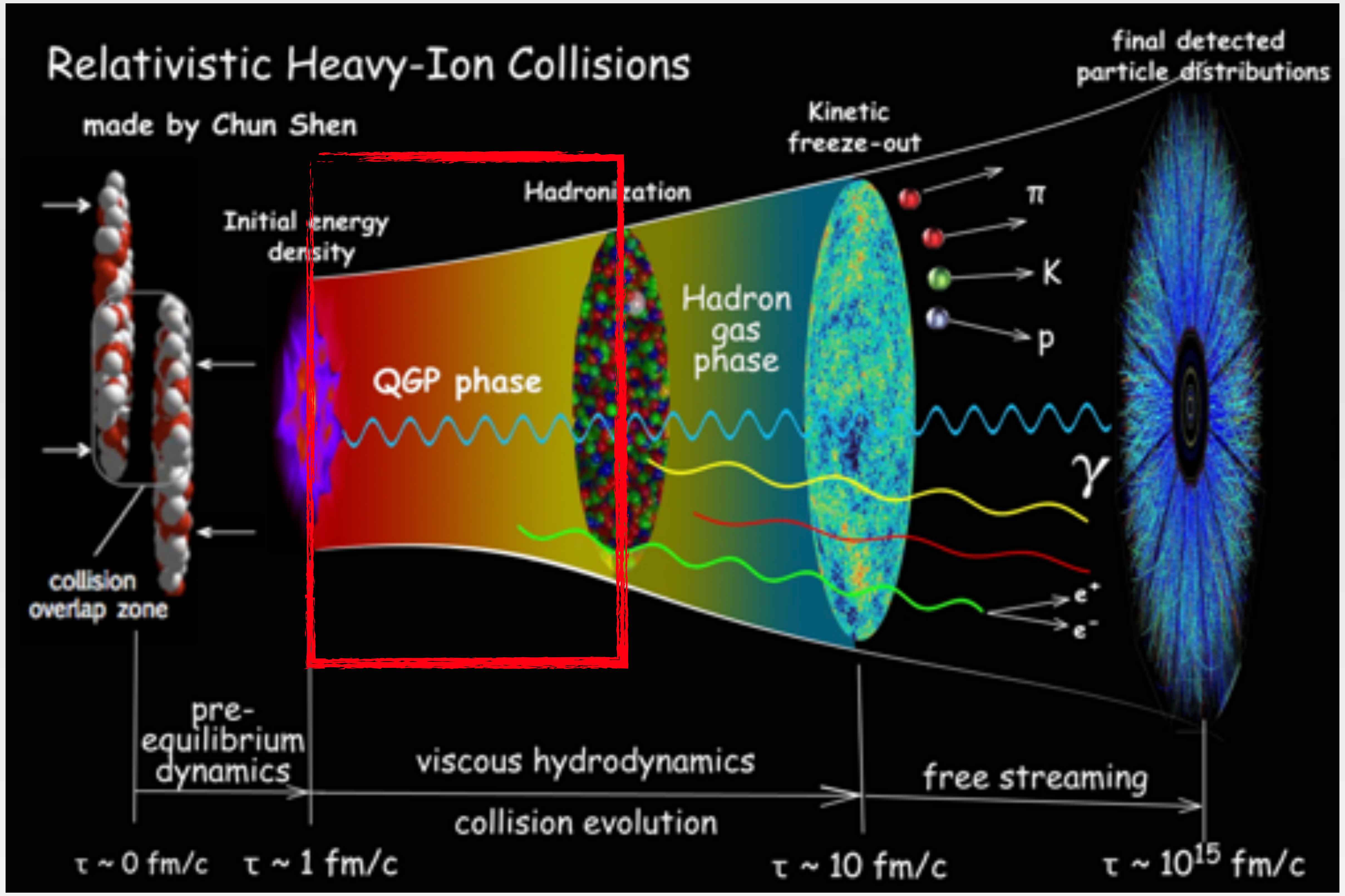
⇨ **proposal: charge-dependent directed flow**
measure a **simpler and cleaner observable**
(not related to the chiral imbalance),
use it to calibrate the strength and lifetime of the electromagnetic field

Phases of the collision



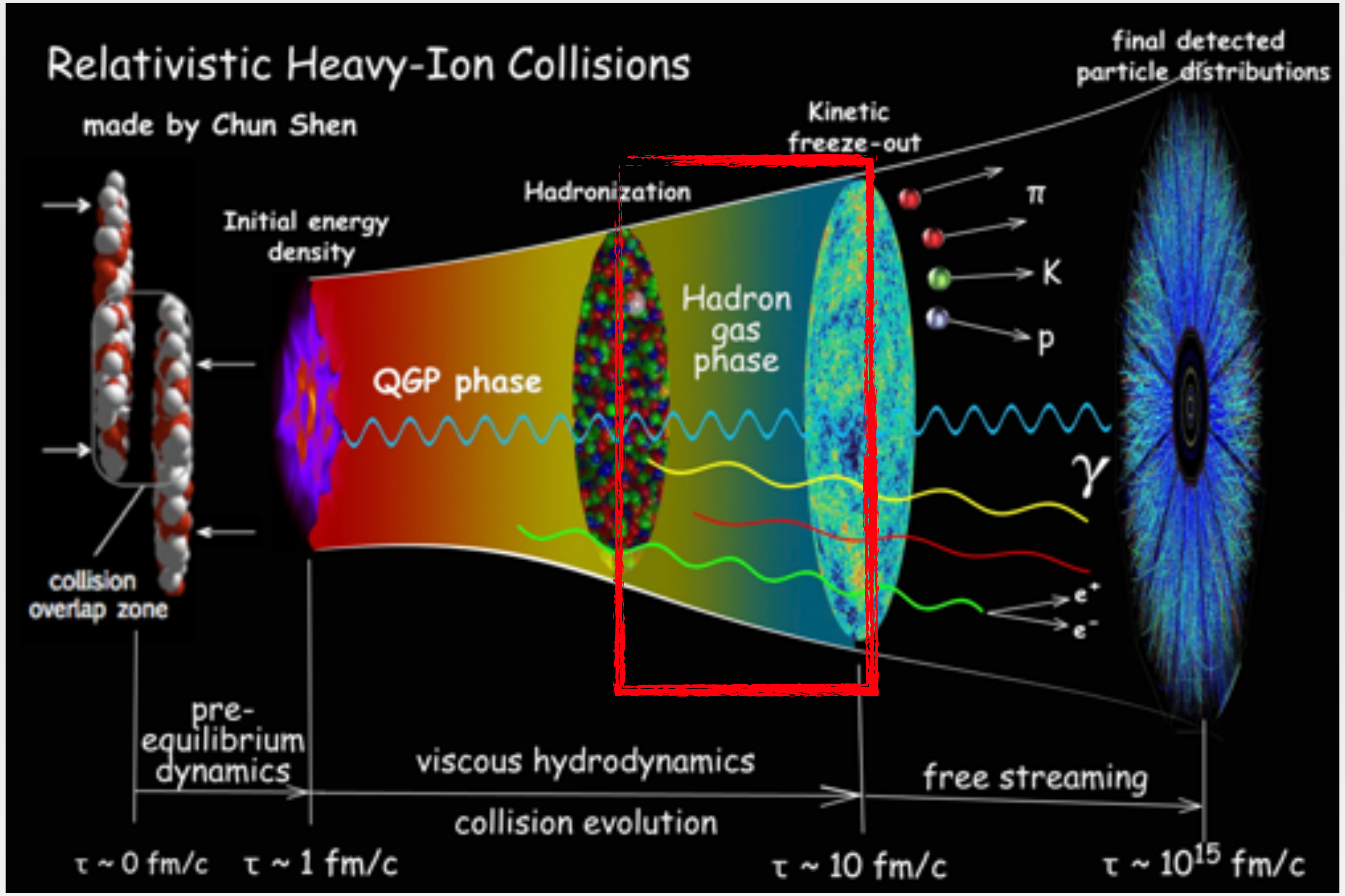
- ➩ hard parton scattering processes
- ➩ high energy in a small volume
- ➩ **initial energy density fluctuations** → geometrical eccentricities
- ➩ **strong interacting gluon field** → non-zero radial and anisotropic flow

Phases of the collision



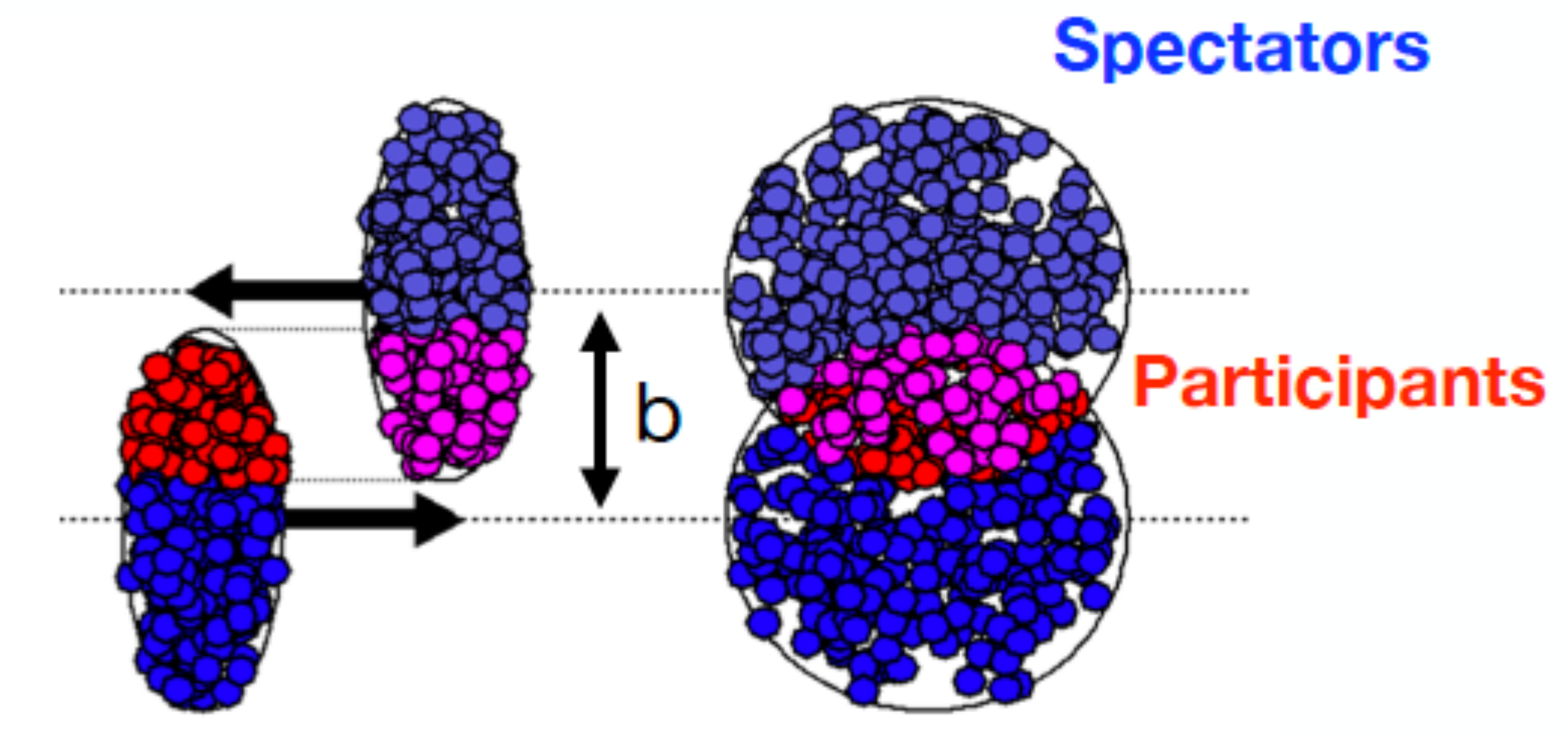
⇨ Quark-Gluon Plasma: **Viscous hydro → EoS, η/s and ζ/s**
⇨ geometrical eccentricities → converted in momentum anisotropies
⇨ main stage in which the flow is built

Phases of the collision

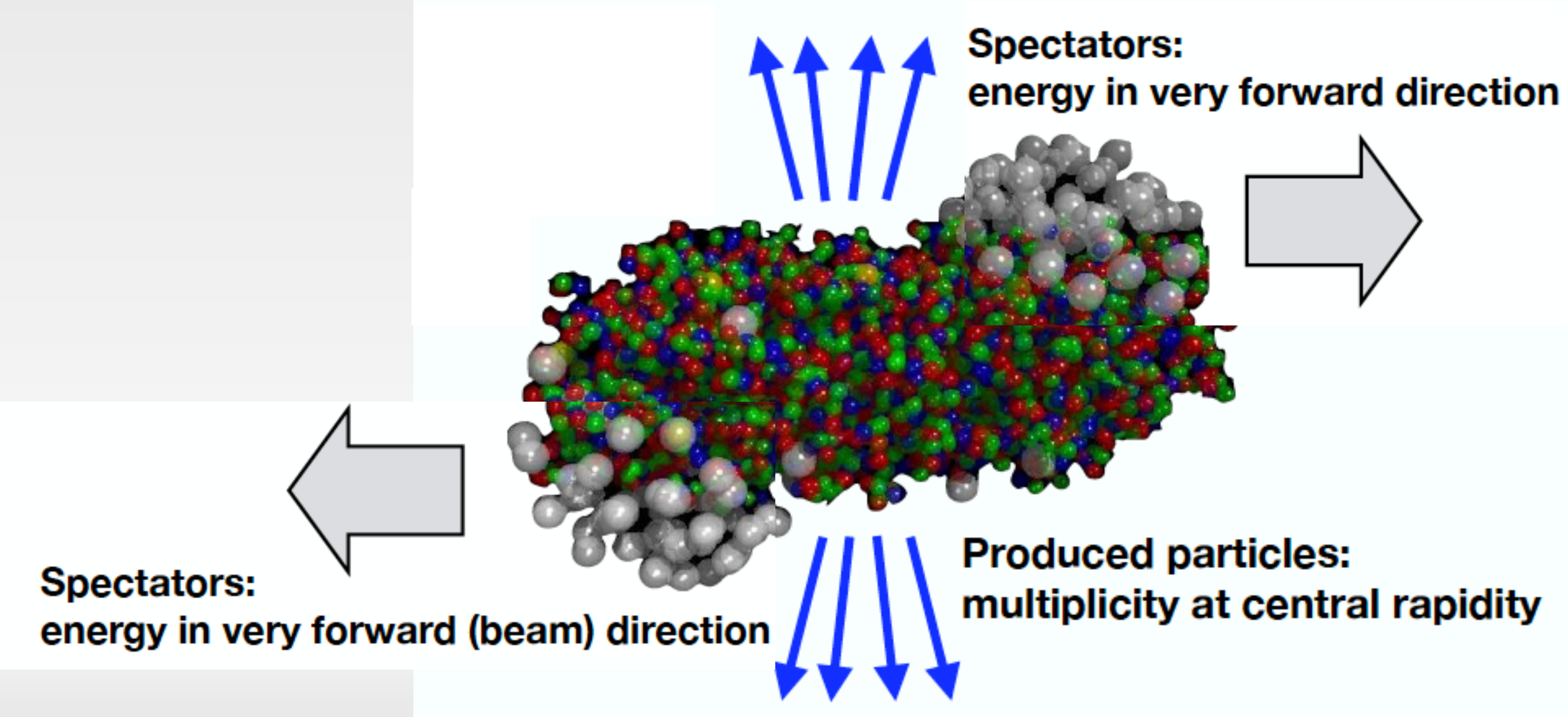


- ➪ phase transition (decrease degrees of freedom)
  - chemical freeze-out: inelastic collisions ceases
  - kinetic freeze-out: elastic collisions ceases
- ➪ **hybrid** = IP-Glasma(IS) + MUSIC(QGP) + UrQMD(hadron cascade)

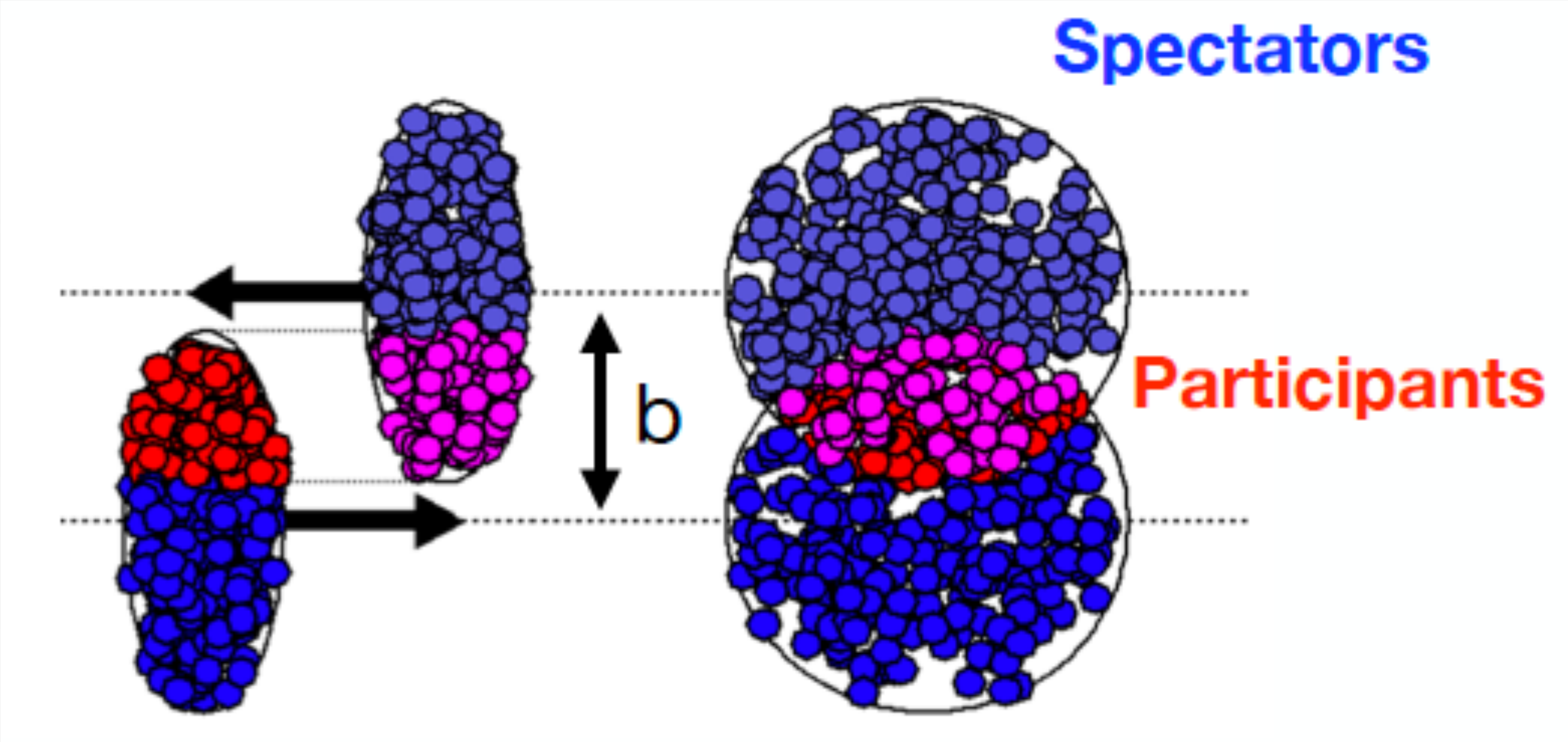
Interlude: Centrality

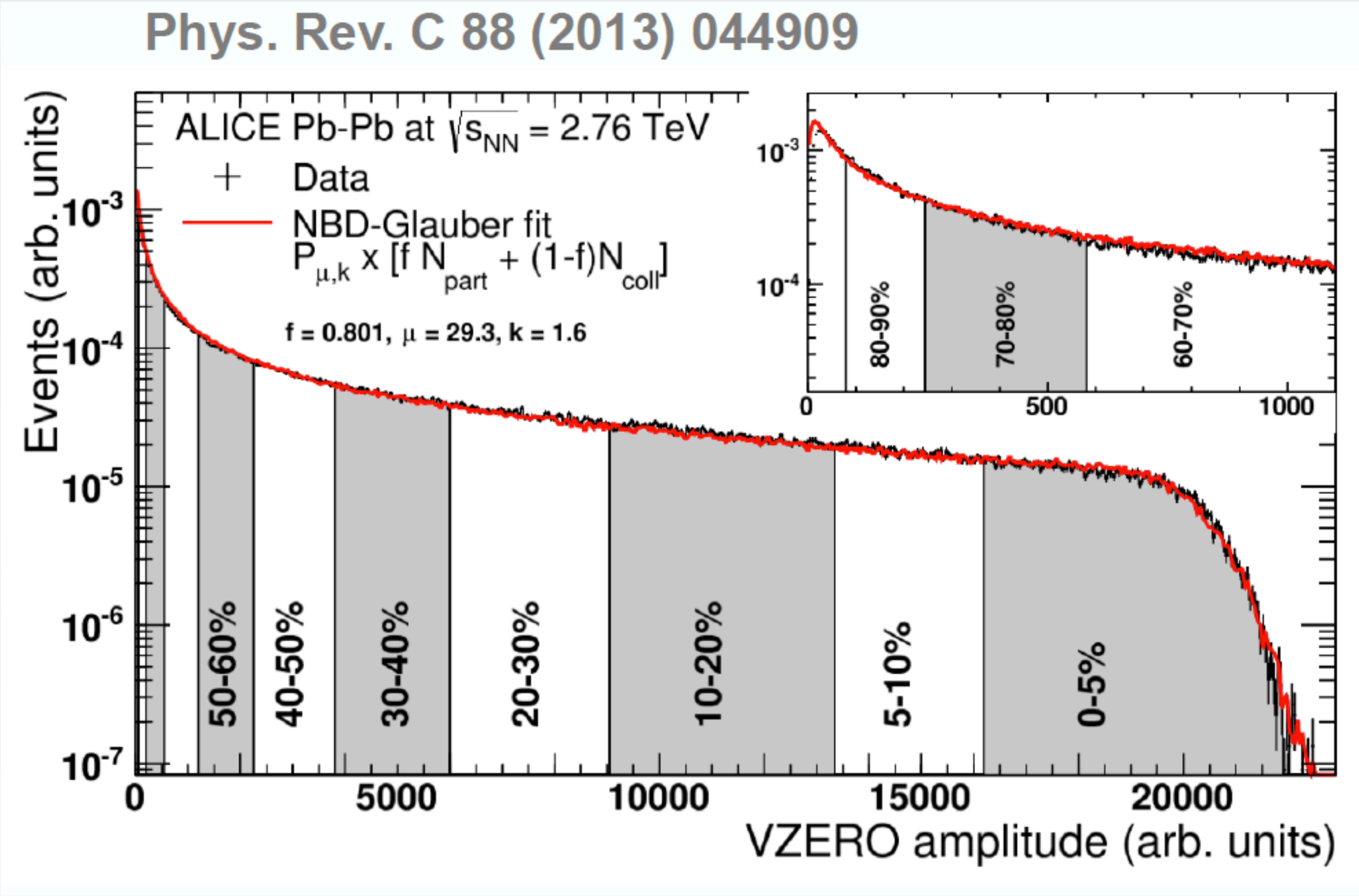


- Centrality of a collision:
  - "impact parameter" b
  - N_{coll}: number of inelastic nucleon-nucleon collisions
  - N_{part}: number of nucleons undergoing at least one inelastic nucleon-nucleon collision



Interlude: Centrality

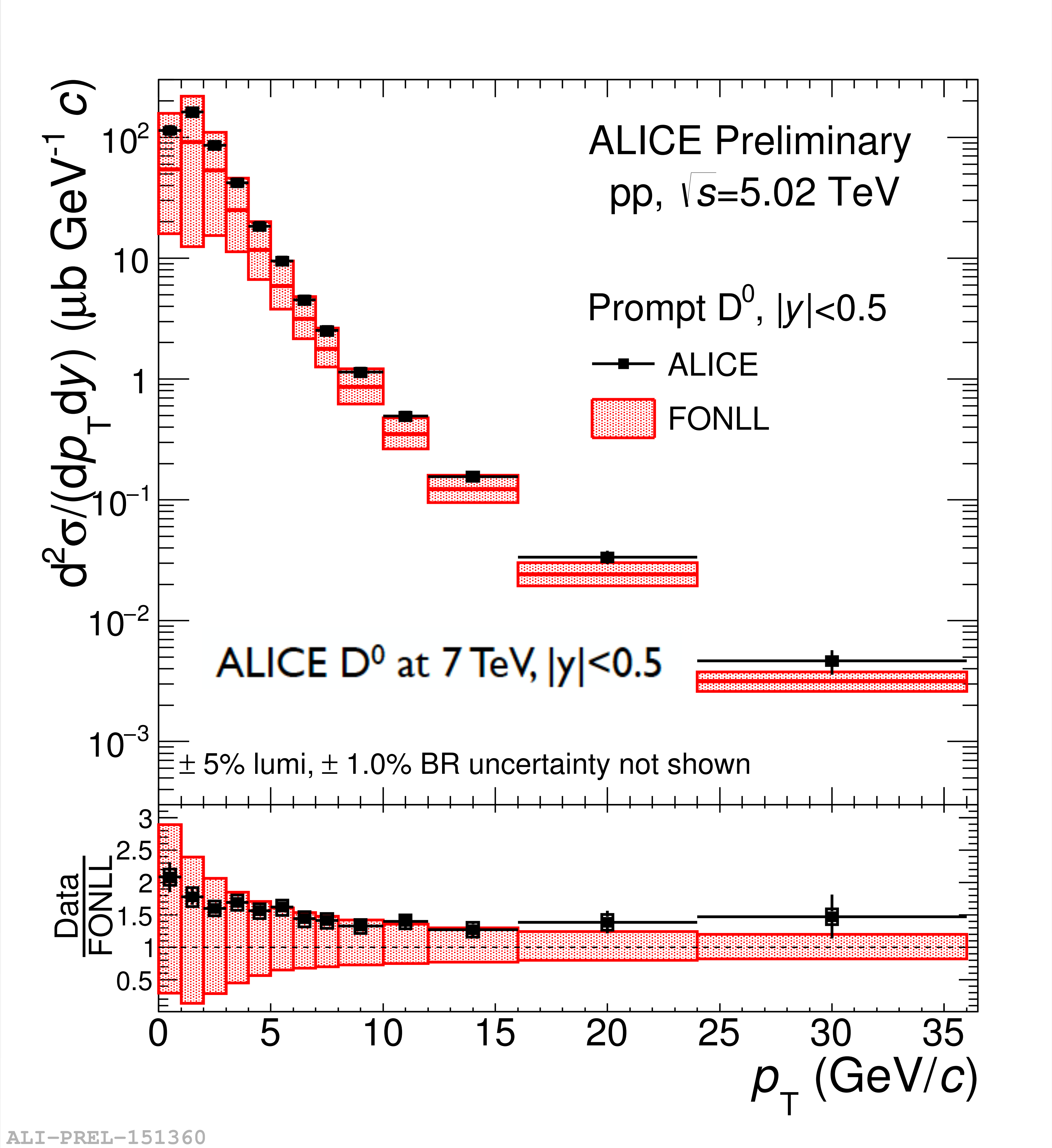




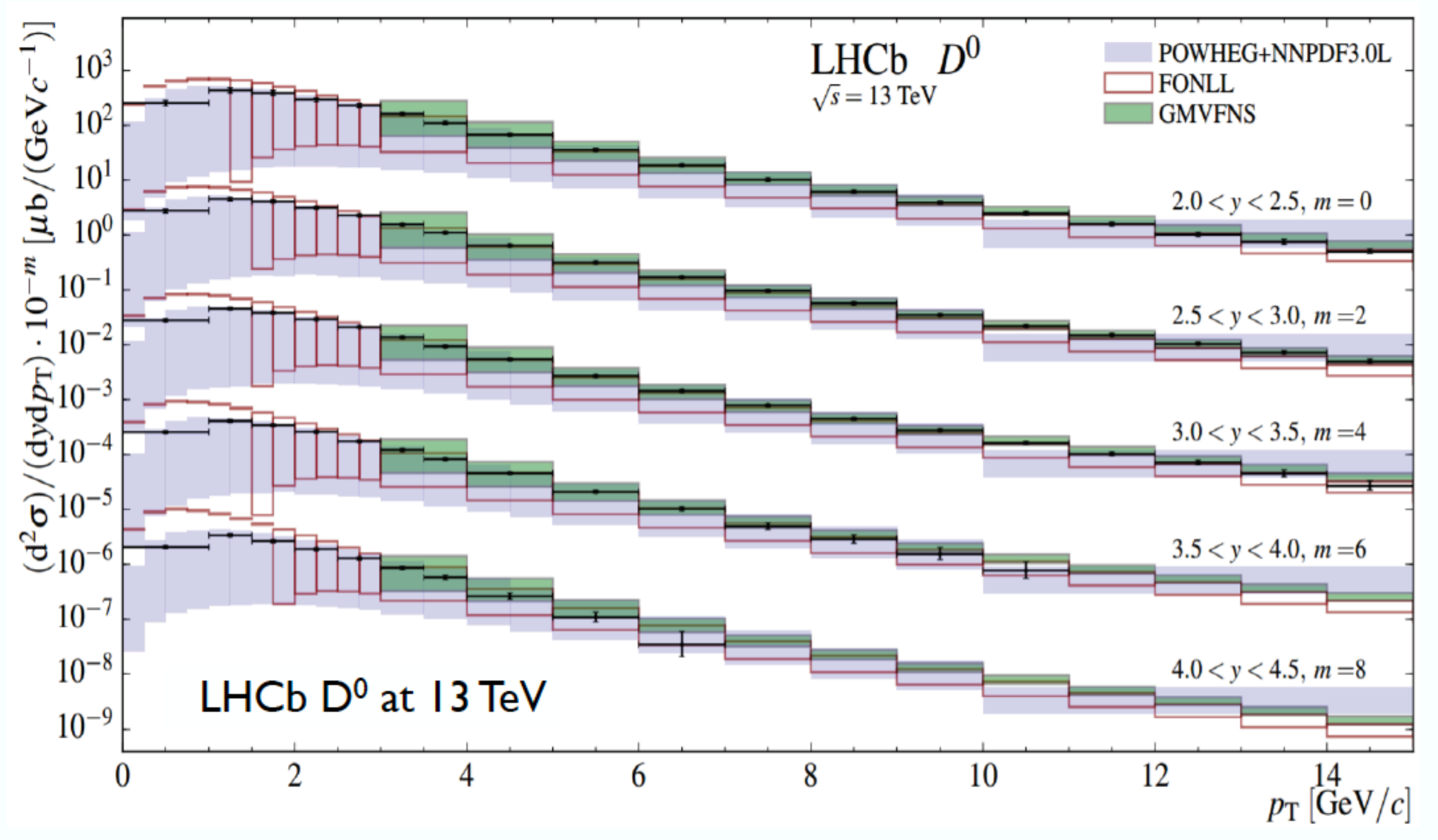
- Geometrical quantities simplify comparison btw. data and theory
- Usually not directly measured but derived from Glauber calculations

Centrality classes defined in terms of multiplicity percentile

D meson production at low p_T



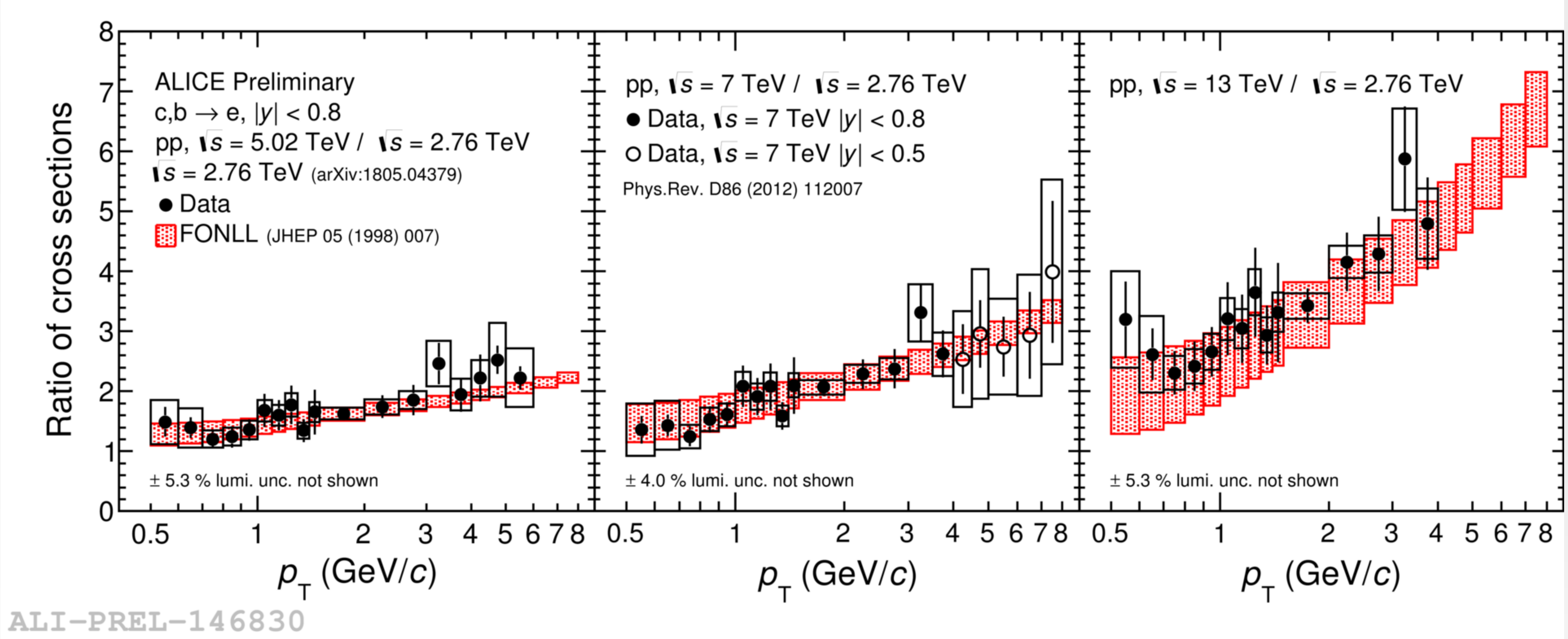
JHEP 1603 (2016) 159
Erratum: JHEP 1705 (2017) 074



⇨ With D0 mesons HF measurements performed down to 0 GeV/*c*!

- Upper band of FONLL both at central rapidity (ALICE) and forward (LHCb).
- LHCb data can be used to constrain gluon parton density functions for x < 10^{-4}

Heavy-flavour decay electrons in pp collisions



– Ratios of cross sections at different energies can be used in order to further test the pQCD FONLL calculation. In the ratios, part of the uncertainties cancel out

– at low p_T may help to set constraints to the gluon PDF → small values of Bjorken-x

Eur.Phys.J. C75 (2015) no.12, 610

Charmed baryons

➪ provide further **insights into the hadronisation processes** in pp collisions

➪ charm-baryon production in pp collisions also serve as a reference for heavy-ion collisions

➪ Ξ_c could also provide **additional input** to better understand the hadronisation mechanism of **strange quarks** in pp and Pb-Pb collisions