Heavy-ion collisions:
a tool for characterizing high-density QCD at colliders

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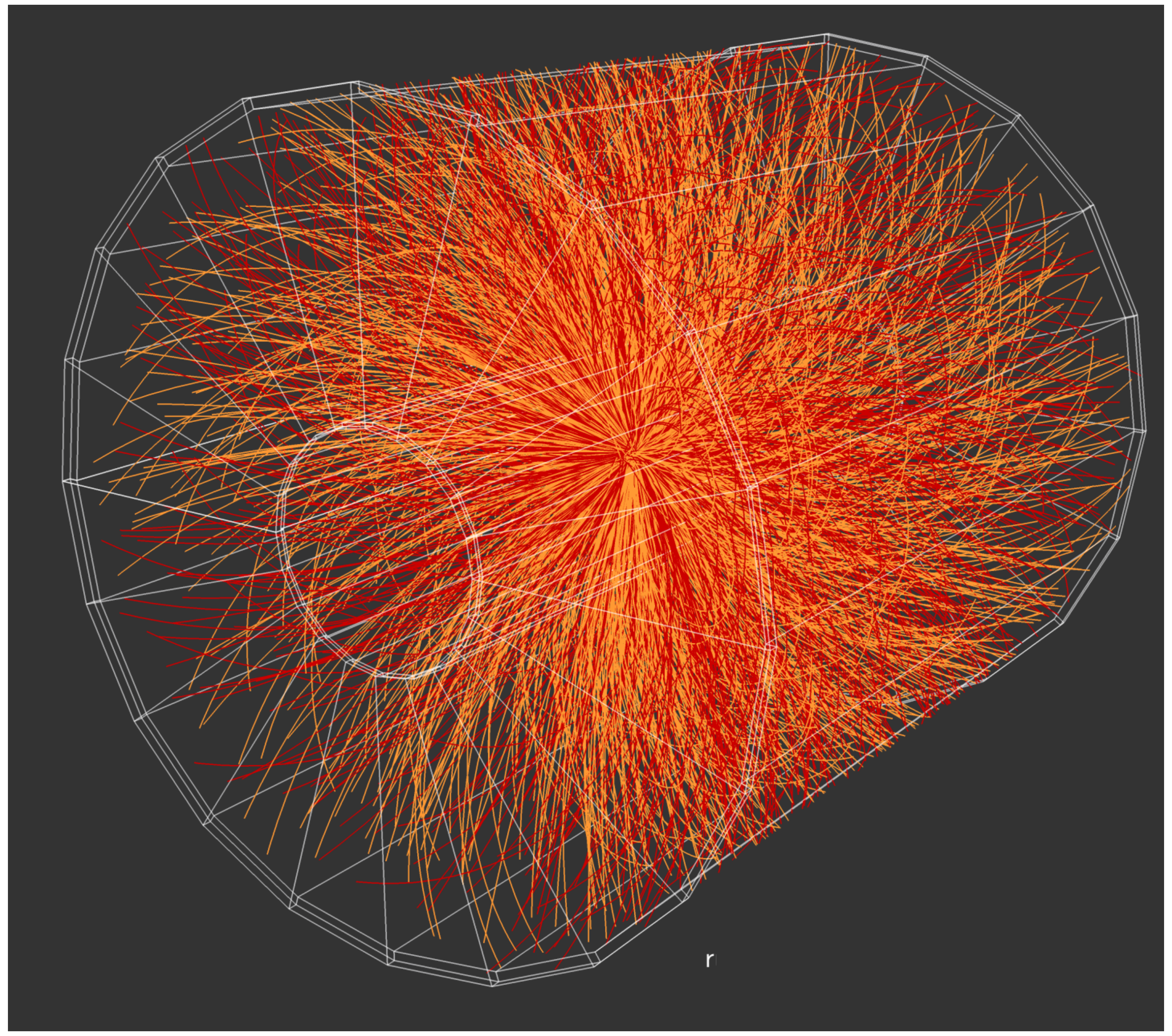
24/08/2023

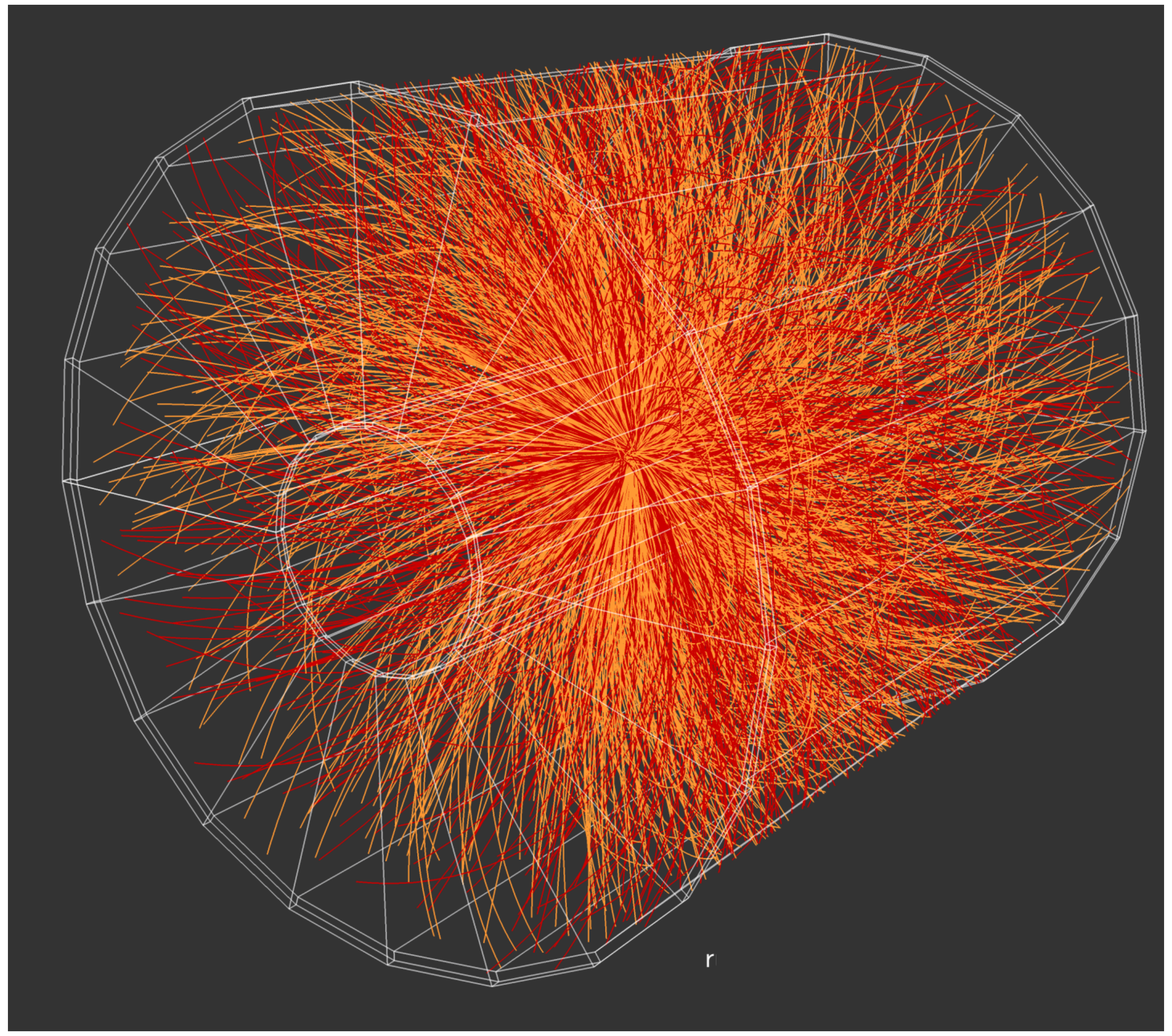
Why heavy-ion experimental physics?



$\longleftrightarrow$

$$\mathcal{L}_{\mathrm{QCD}} = \bar{q}(i\gamma^{\mu}D_{\mu} - m)q - \frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu}_{a}$$

What should you expect from this short course?



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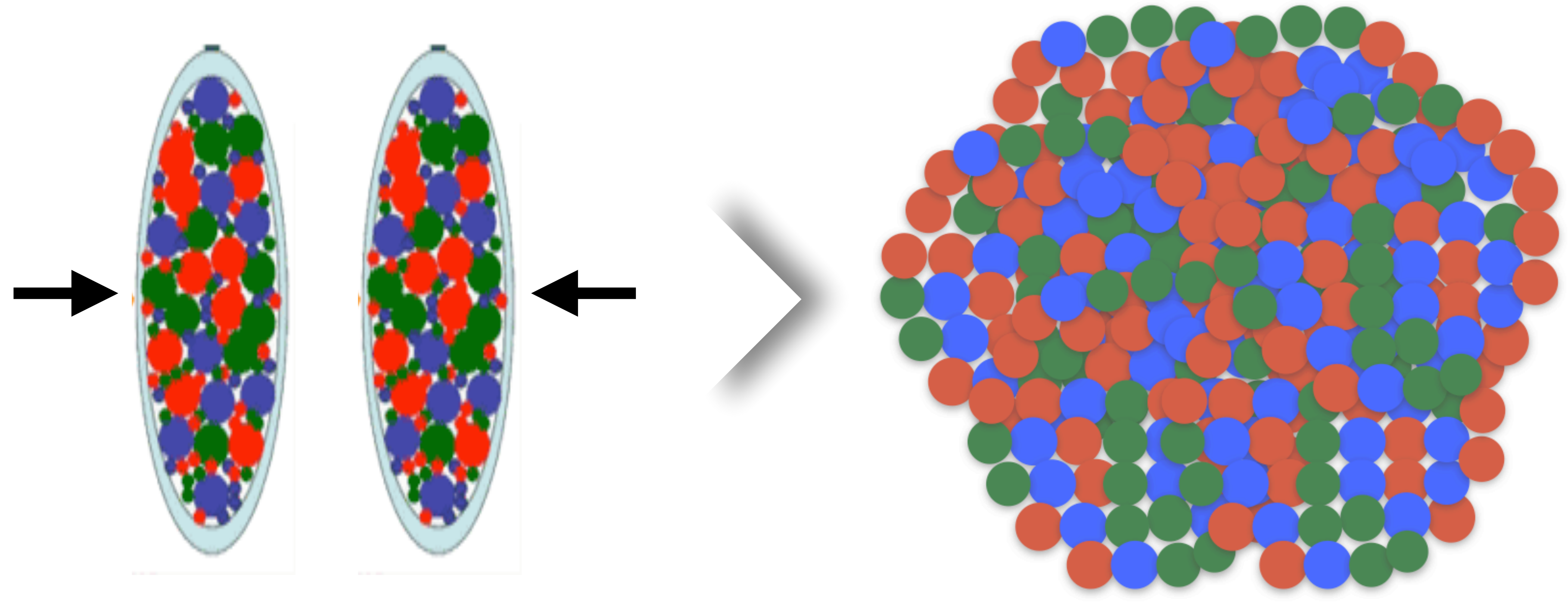
- **Phenomenology of heavy-ion collisions:**
- **Experimental signatures:**
  - Bound-state dissociation
  - Jet quenching
  - Collectivity in hadronic collisions

- **New experimental tools for new (and old) open questions**
- **Prospects for high-density QCD at colliders** over the next two decades

Nuclear matter at high temperature with heavy ions

“Head-on” nucleus-nucleus collisions

→ high-temperature



L ~ 5-10 fm

T~ 200-300 MeV

Colors are no longer “confined” to hadrons

→ partonic properties of QCD

H-.T. Ding et al., arXiv 1504.05274

W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018

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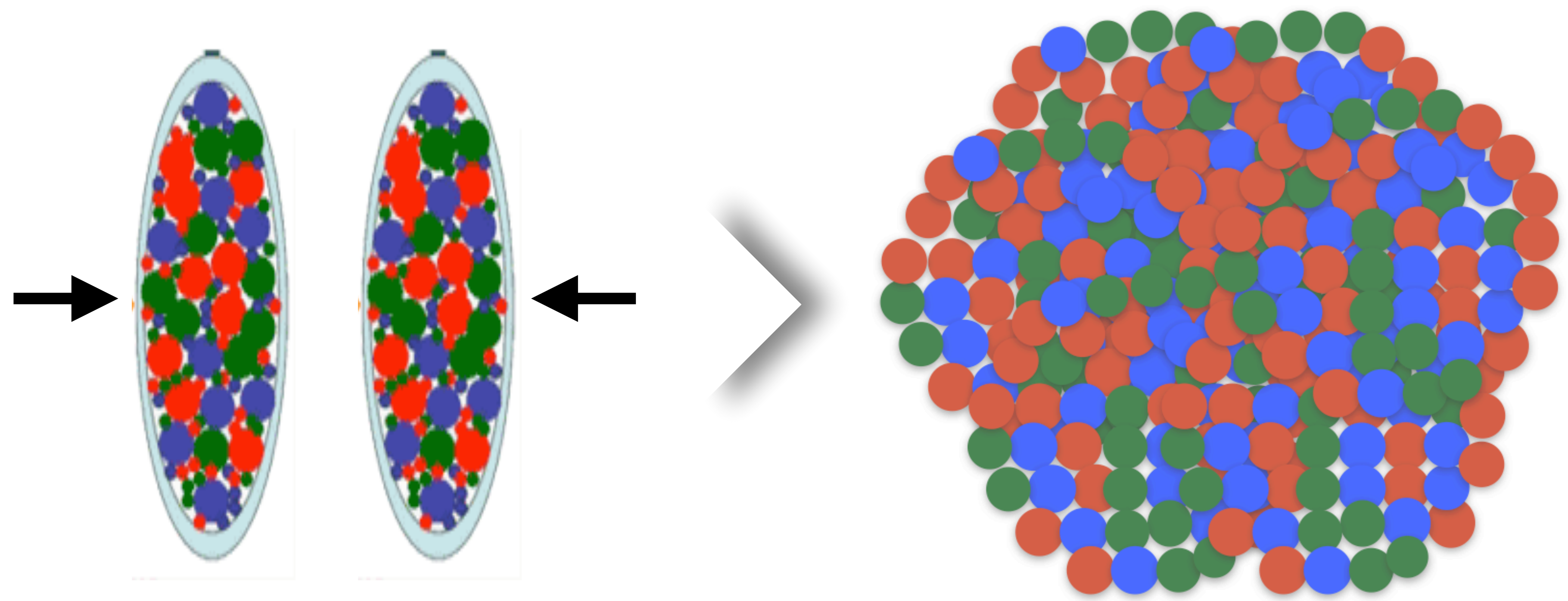

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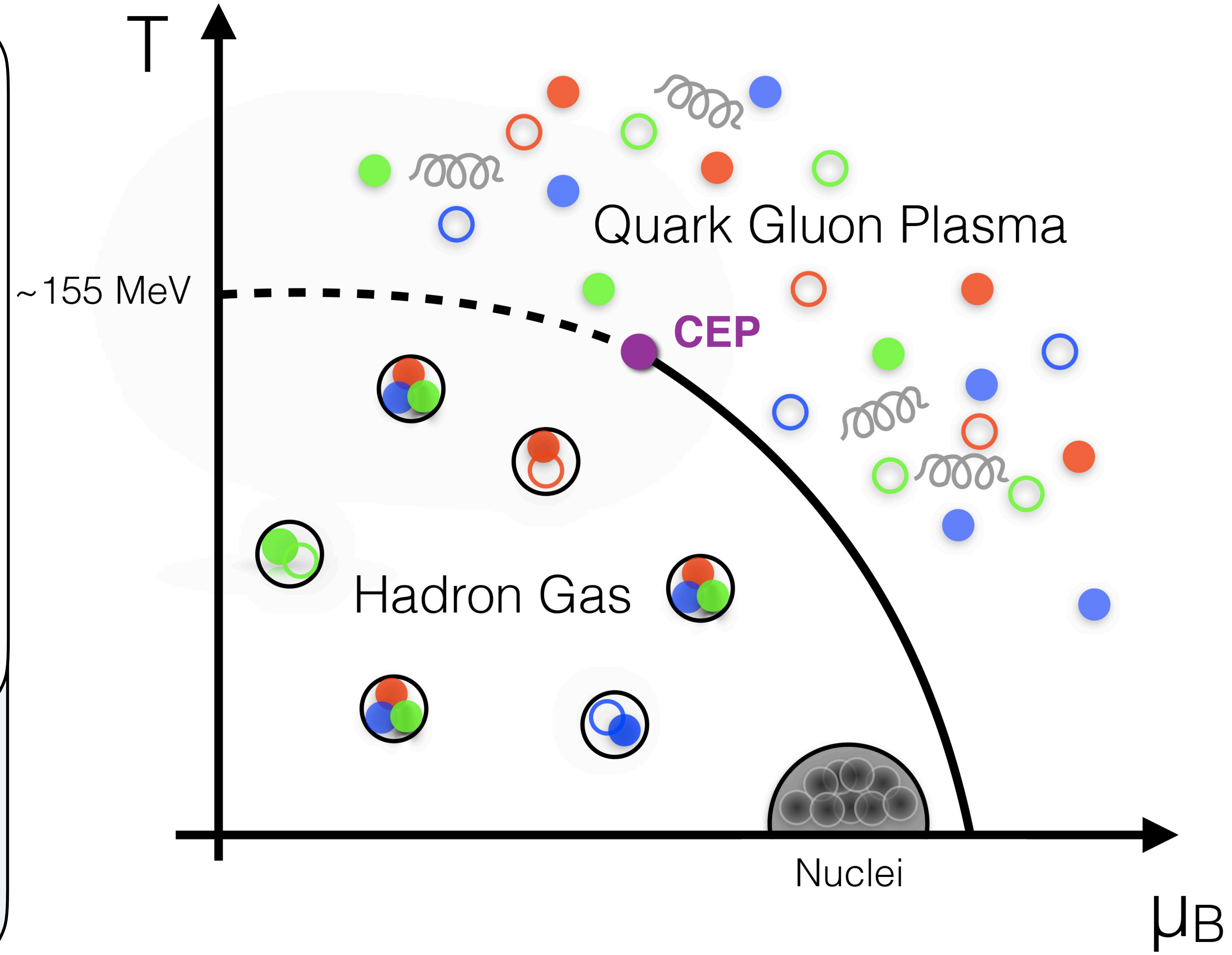
Phase diagram of nuclear matter at equilibrium



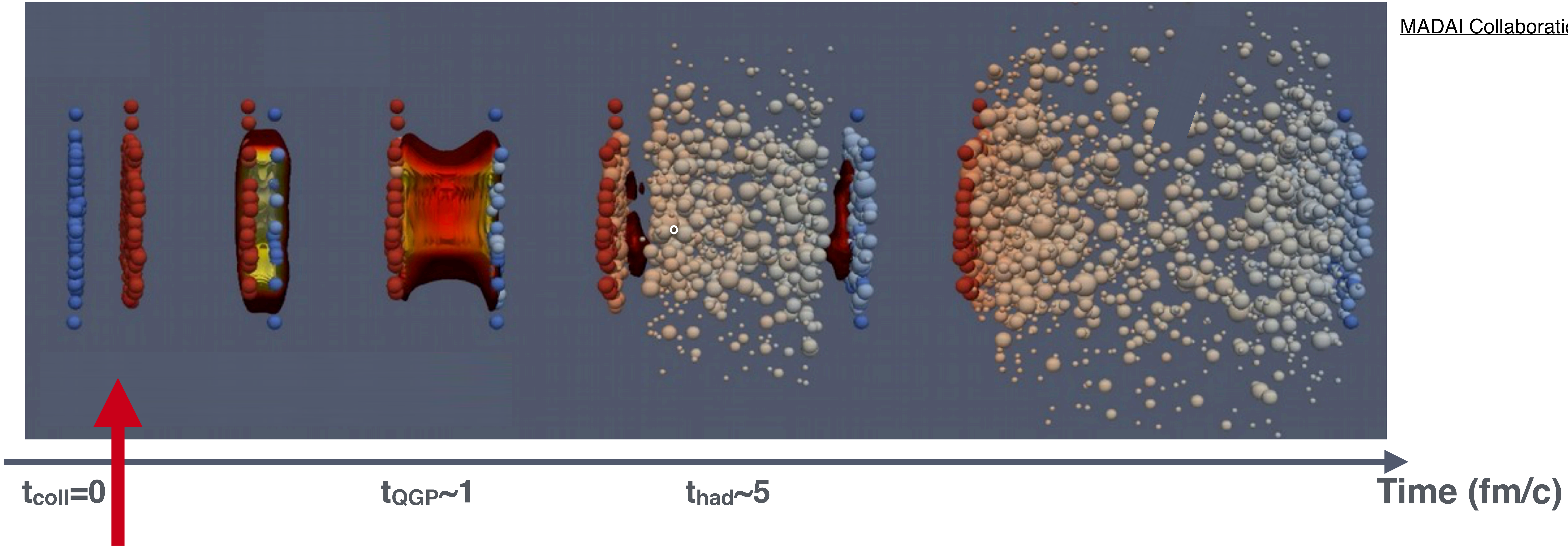
H-.T. Ding et al., arXiv 1504.05274

W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018

The “standard-model” of the evolution of a heavy-ion collision

W. Busza, K. Rajagopal, W. v. d. Schee,
ARNPS, Vol. 68:339-376, 2018

MADAI Collaboration

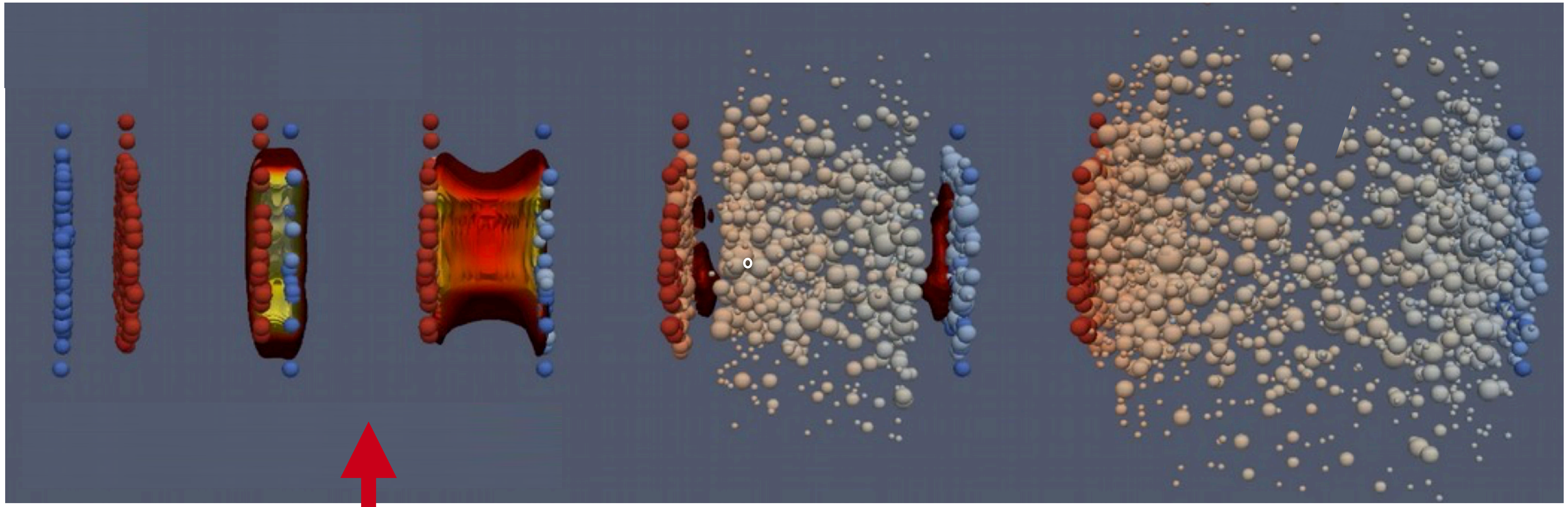


Nuclear matter (“cold”) at high-partonic density
in Lorentz contracted nuclei at v~c
composed of quarks, $q\bar{q}$ pairs from fluctuations, sea gluons

→ quark and gluon nuclear PDFs
→ nuclear matter at extreme gluon densities
(“gluon” saturated matter)

Collision and medium formation

W. Busza, K. Rajagopal, W. v. d. Schee,
ARNPS, Vol. 68:339-376, 2018



MADAI Collaboration

$t_{coll}=0$ $\quad$ $t_{QGP}\sim1$ $\quad$ $t_{had}\sim5$ $\quad$ Time (fm/c)

A few hard perturbative scatterings

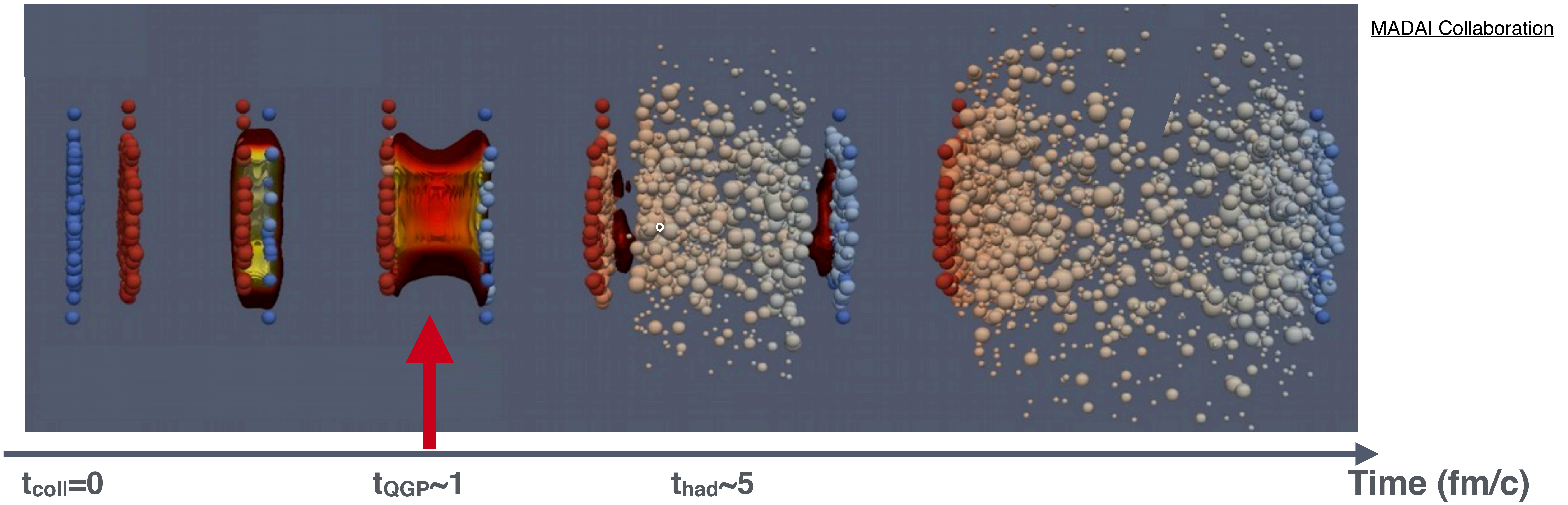
Large amount of "soft" scatterings (small k_T)

→ reduce the energy of the nuclei

→ leads (after τ_{form}) to the formation of a medium

“QGP” phase and expansion

W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018



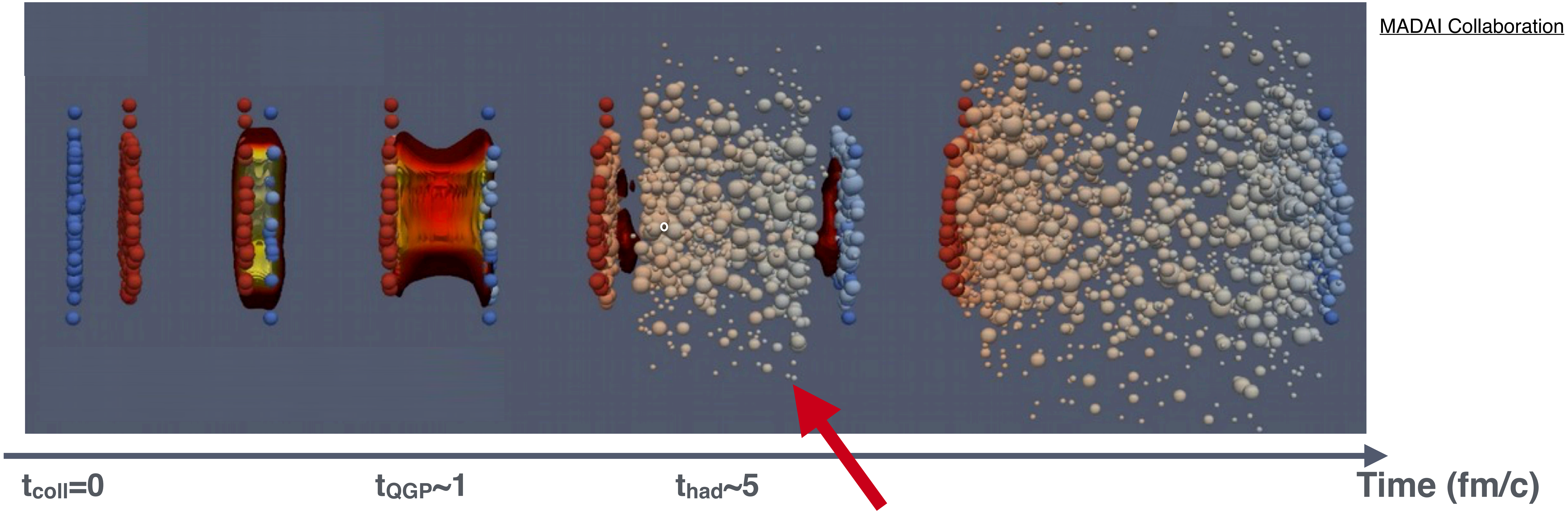
Quark Gluon Plasma phase

→ sensitivity to the partonic properties of the hot nuclear matter

follow by an expansion/cooling phase

Hadron formation and freeze out

W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018



Hadrons are formed when $T<T_{critical}$

Inelastic interactions stop **(chemical freeze out)**

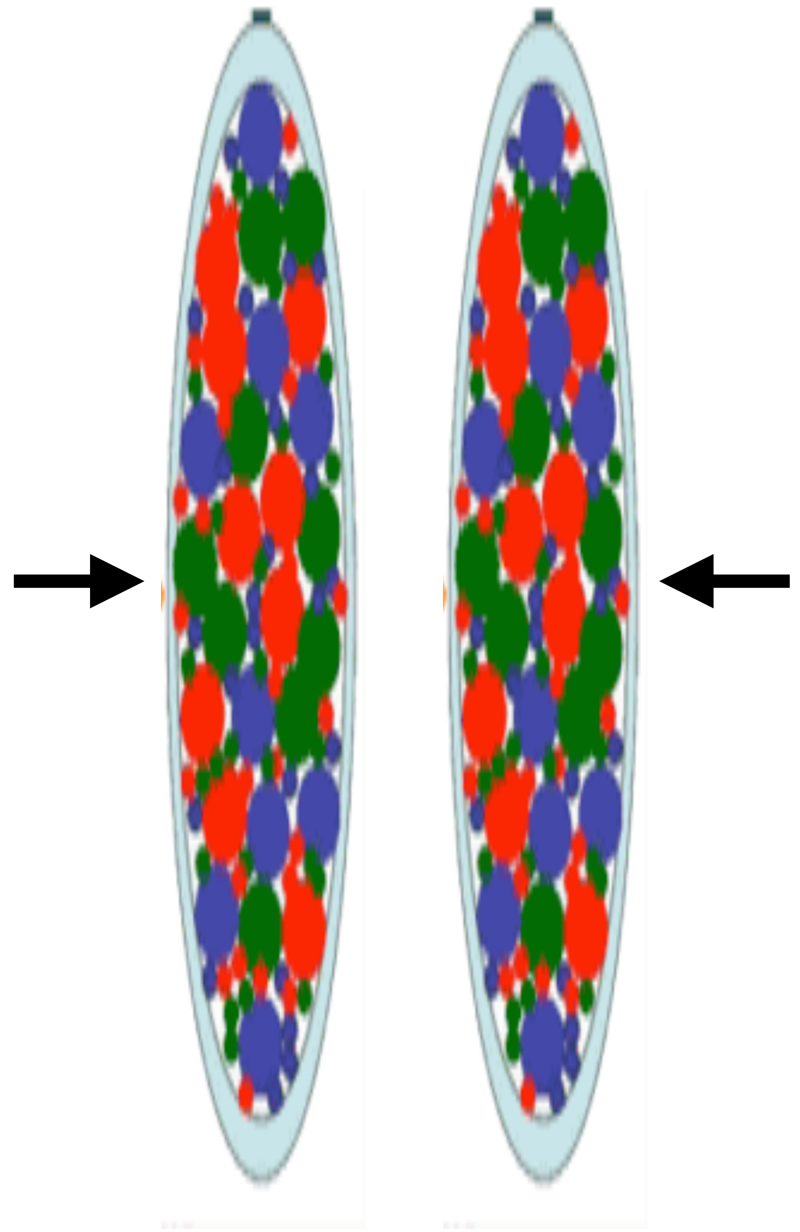
and then elastic interactions stop **(kinetic freeze out)**

How are hadrons are formed at the boundary of a Quark Gluon Plasma phase?

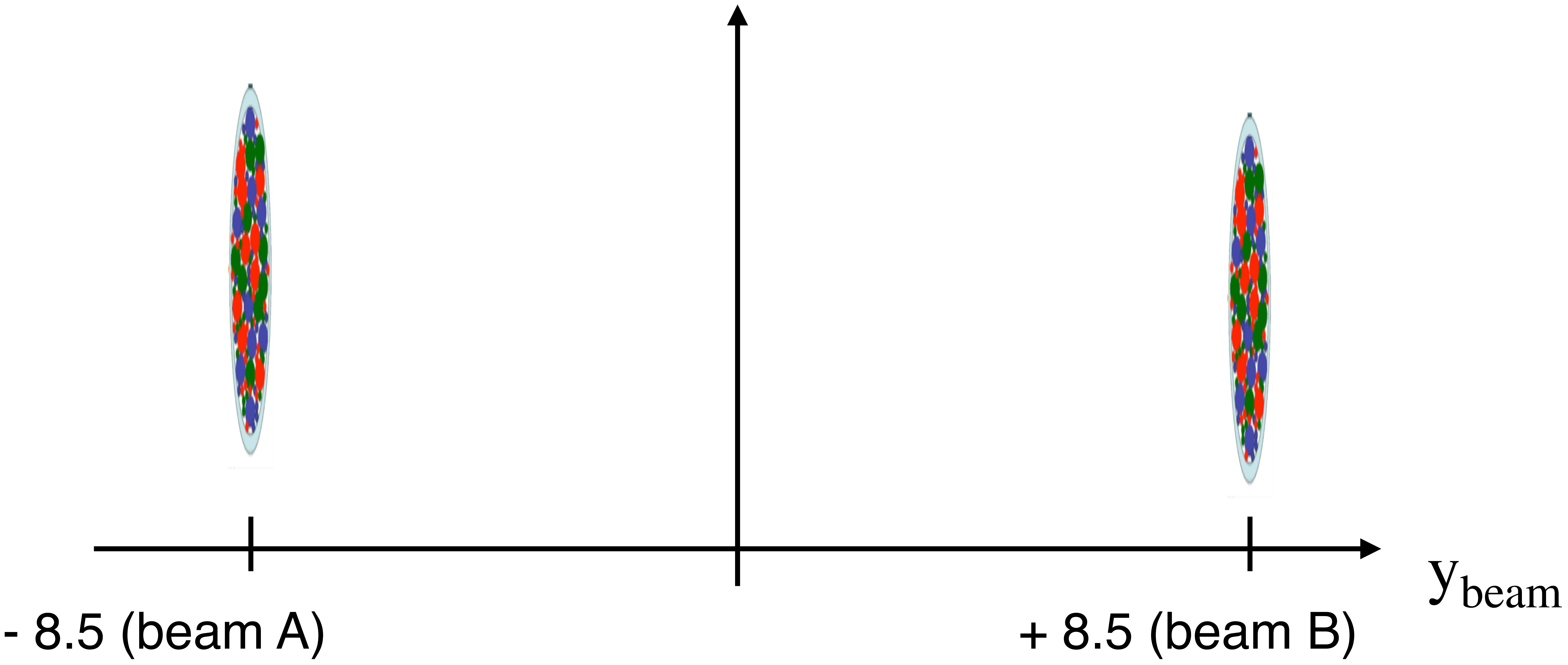
Some quantitative considerations

Run-2 conditions:

- $E_{beam}^{nucleon} = 2510 \text{ GeV}$
- $\sqrt{s_{NN}} = 5020 \text{ GeV}$
- $m_{proton} = 0.938 \text{ GeV}$
- $R_{Pb} = 7 \text{ fm}$

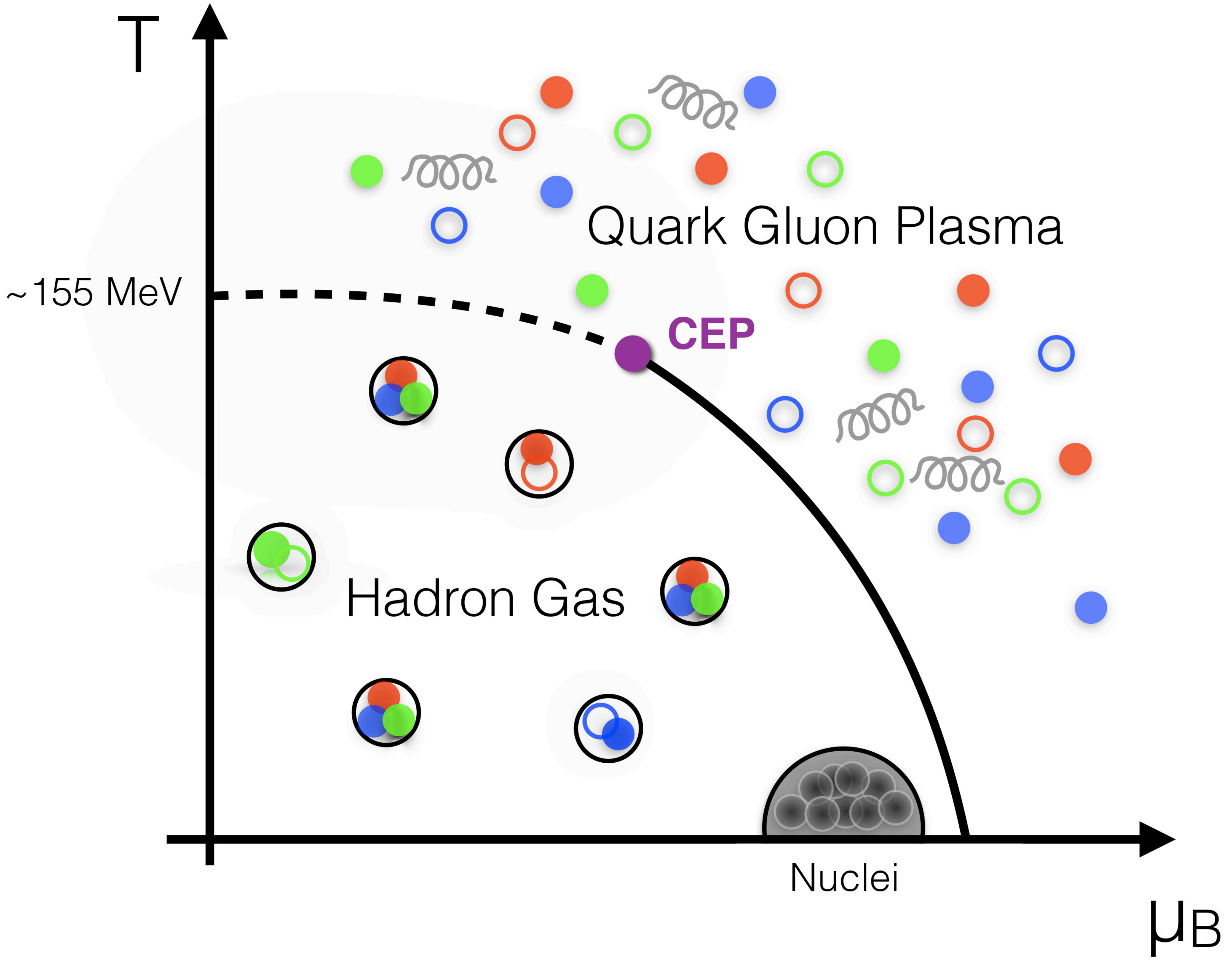


$$\Delta z = 2R_{Pb}/\gamma \approx 0.005 \text{ fm}$$



$$y_{beam} = \frac{1}{2}\ln\frac{E_{beam} + p_z}{E_{beam} - p_z} = (\pm)\ 8.5$$

What is baryonic density of the medium at the LHC?



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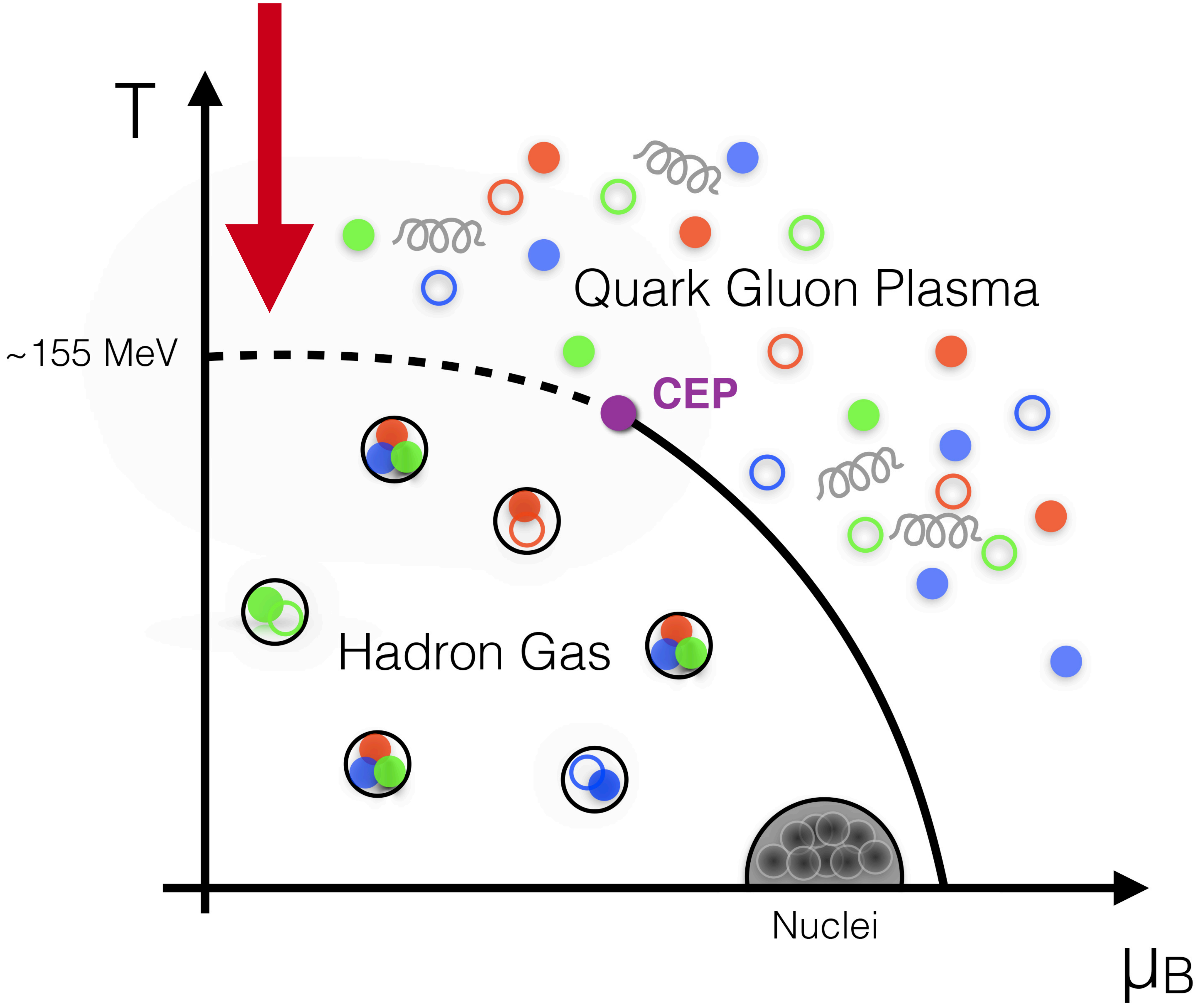
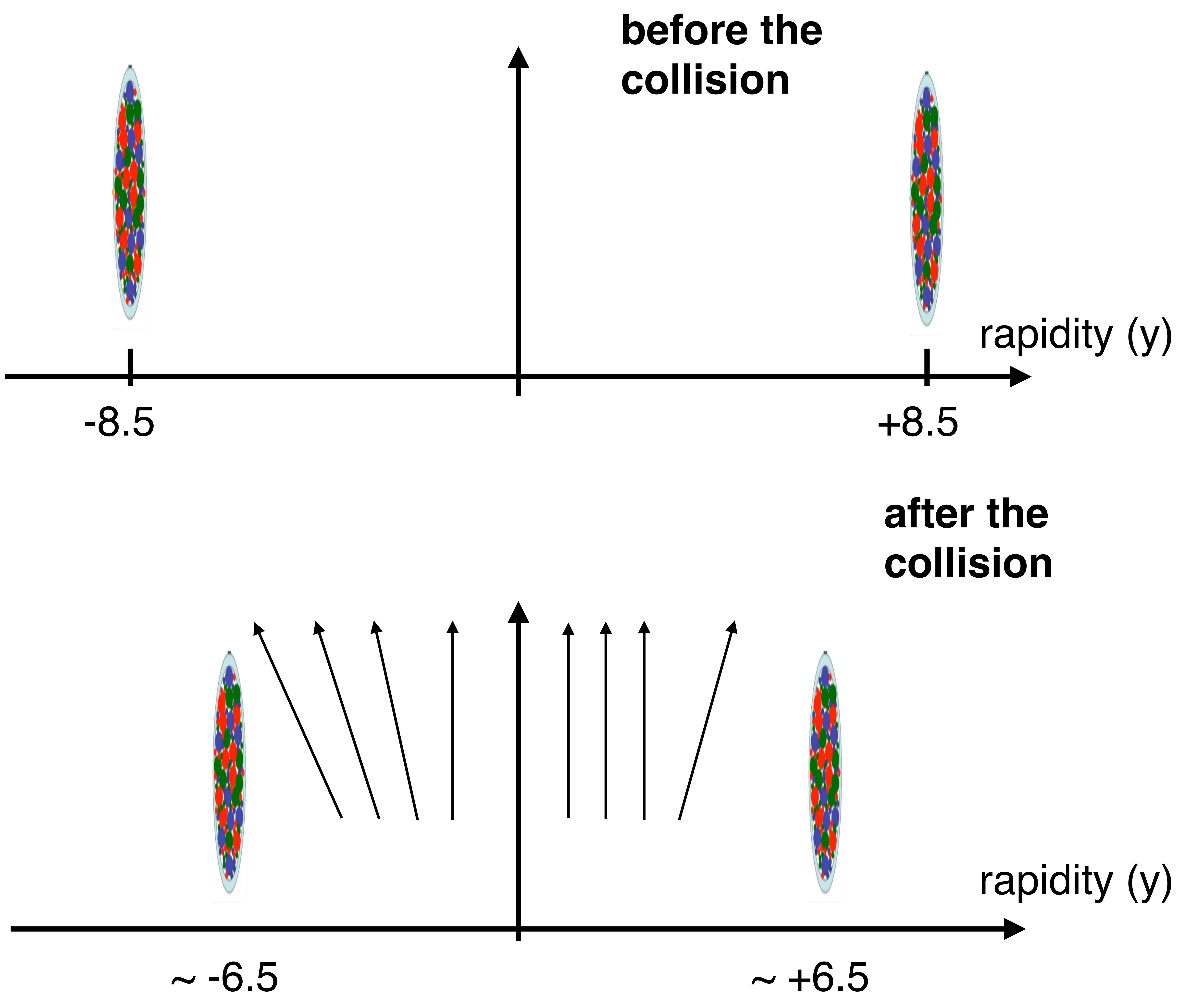




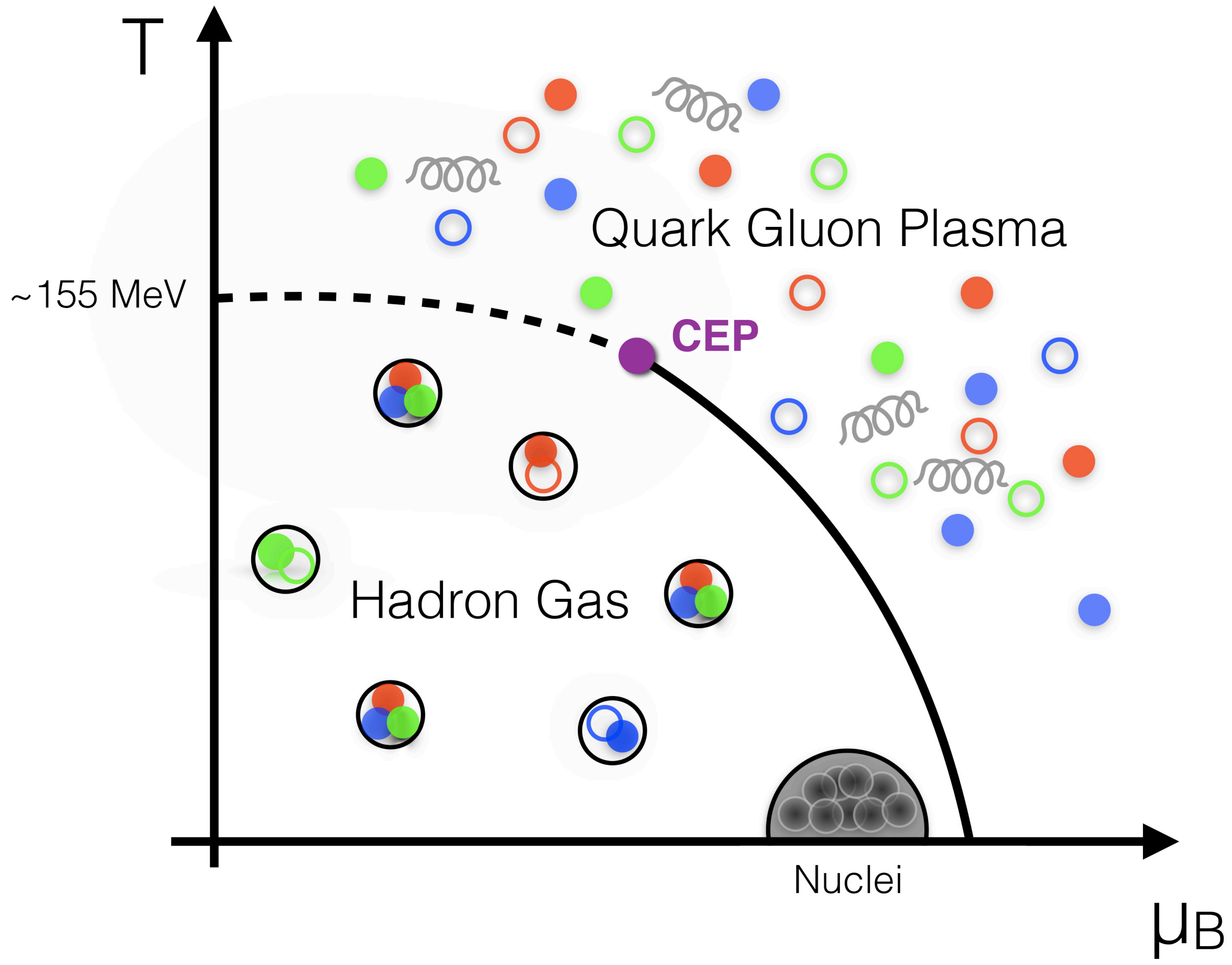
The challenge of experimental heavy-ion physics

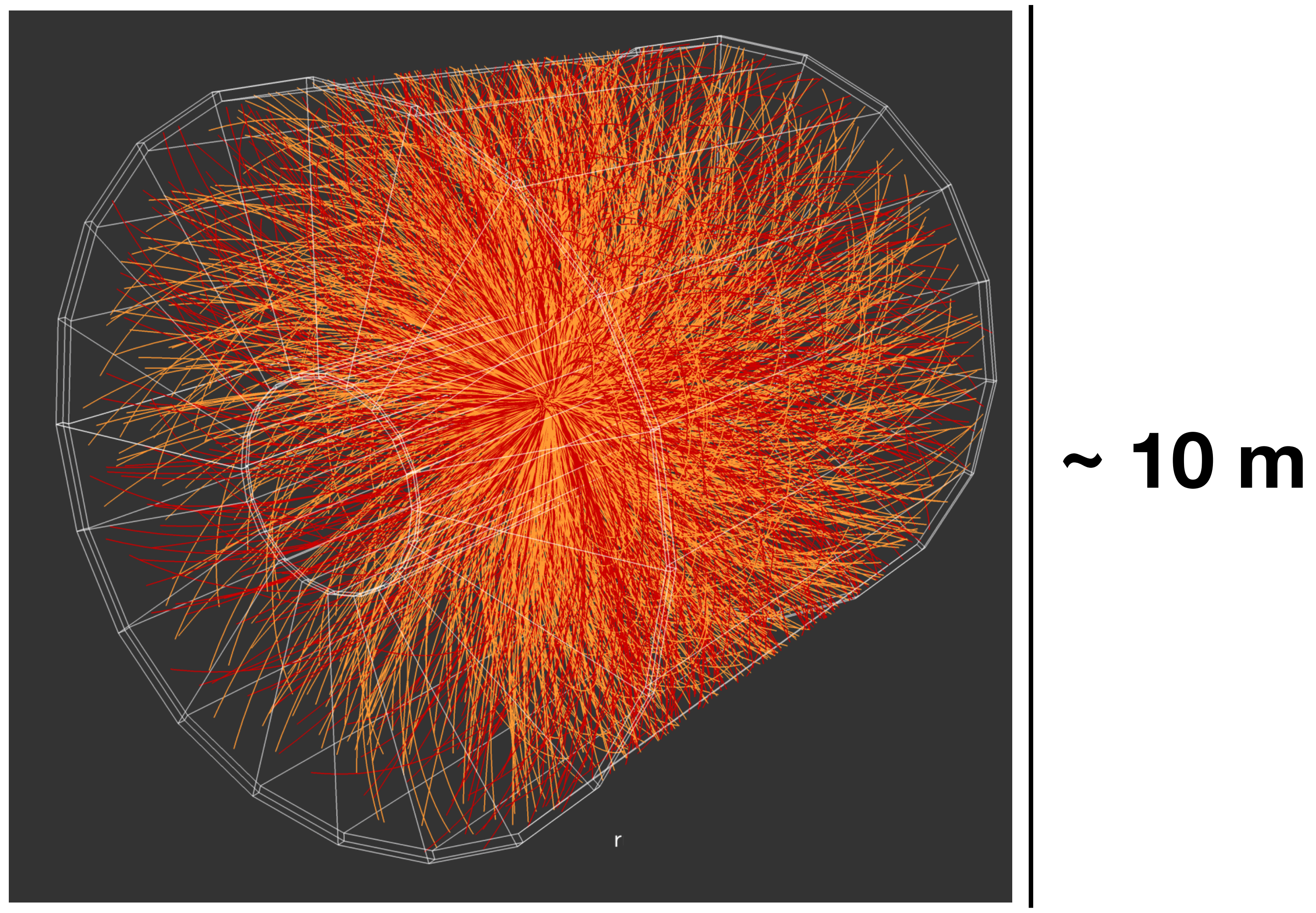
What would we like to know (in brief)?

- **properties of the hot nuclear matter** at different medium temperature, baryonic densities..

What can we access experimentally?

- beam energy and nucleus type
- **kinematic properties of final-state particles**





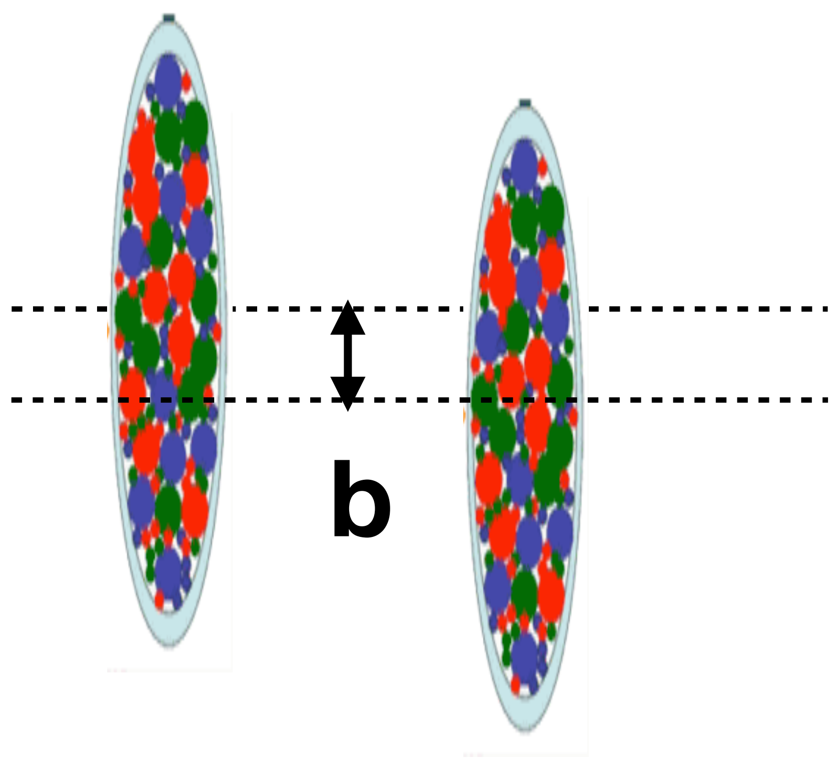
BUT there are no instrumentations that allows us to measure directly T or μ_B of such medium!

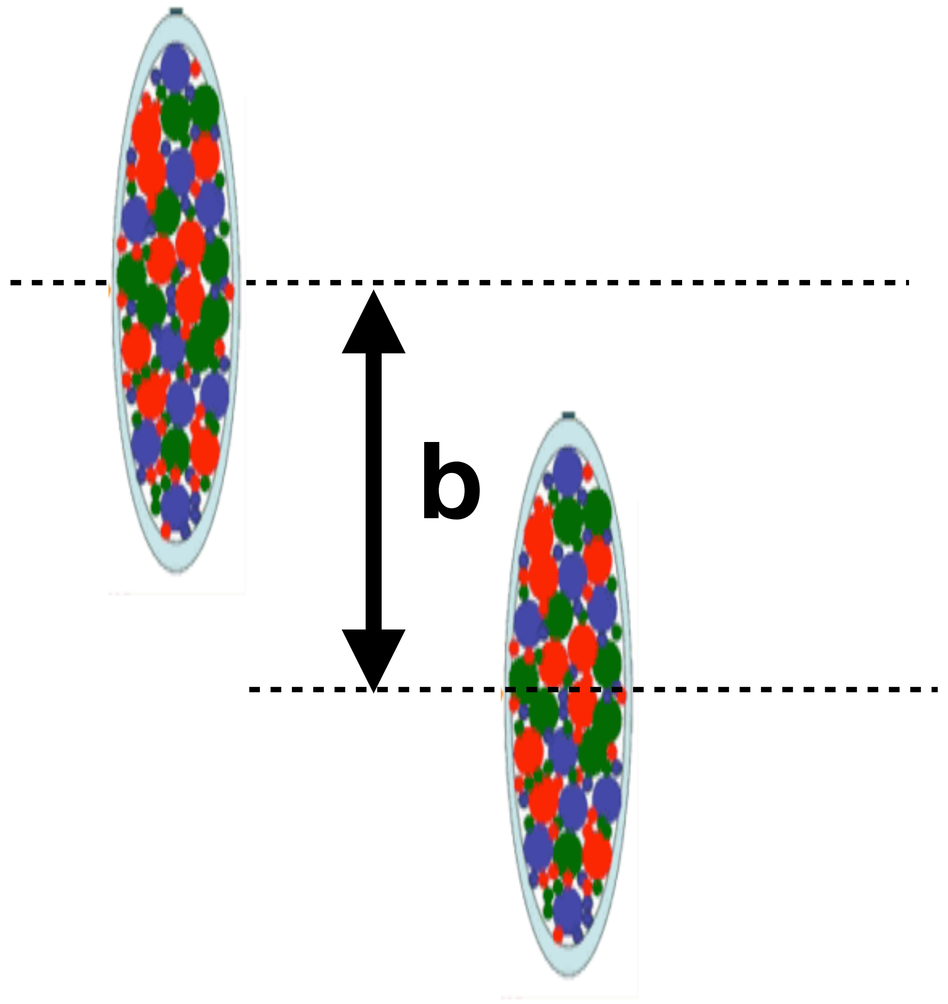
We have to find experimental ways to constrain all these properties through the kinematic properties of final state hadrons.

Phenomenology of heavy-ion collisions

How we model/classify a heavy-ion collision

Geometry of an inelastic heavy-ion collision





Central collisions (b ~ 0)
→ lower medium temperature
→ lower energy density

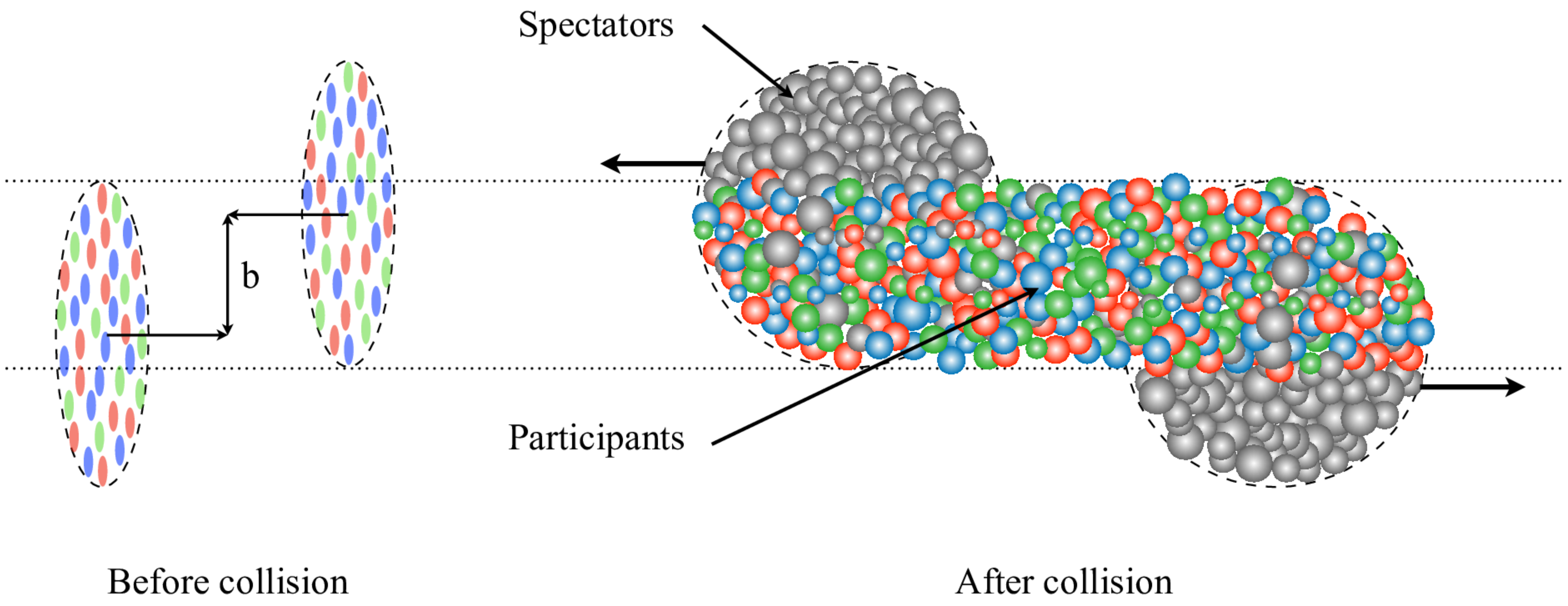
Peripheral collisions (large b)
→ lower medium temperature
→ lower energy density

Can we make use of this accidental property of the collisions to classify events according e.g. to their medium temperature?

The Glauber model of heavy-ion collisions

M.L. Miller, Ann.Rev.Nucl.Part.Sci.57:205-243,2007

→ heavy-ion collision as a superposition of independent **nucleon-nucleon scatterings** ("optical limit")



MODEL ASSUMPTIONS:

- nucleons (protons and neutrons) as point-like objects
- the initial directions of the nuclei are not modified (k_T~0)
- protons and neutrons are indistinguishable

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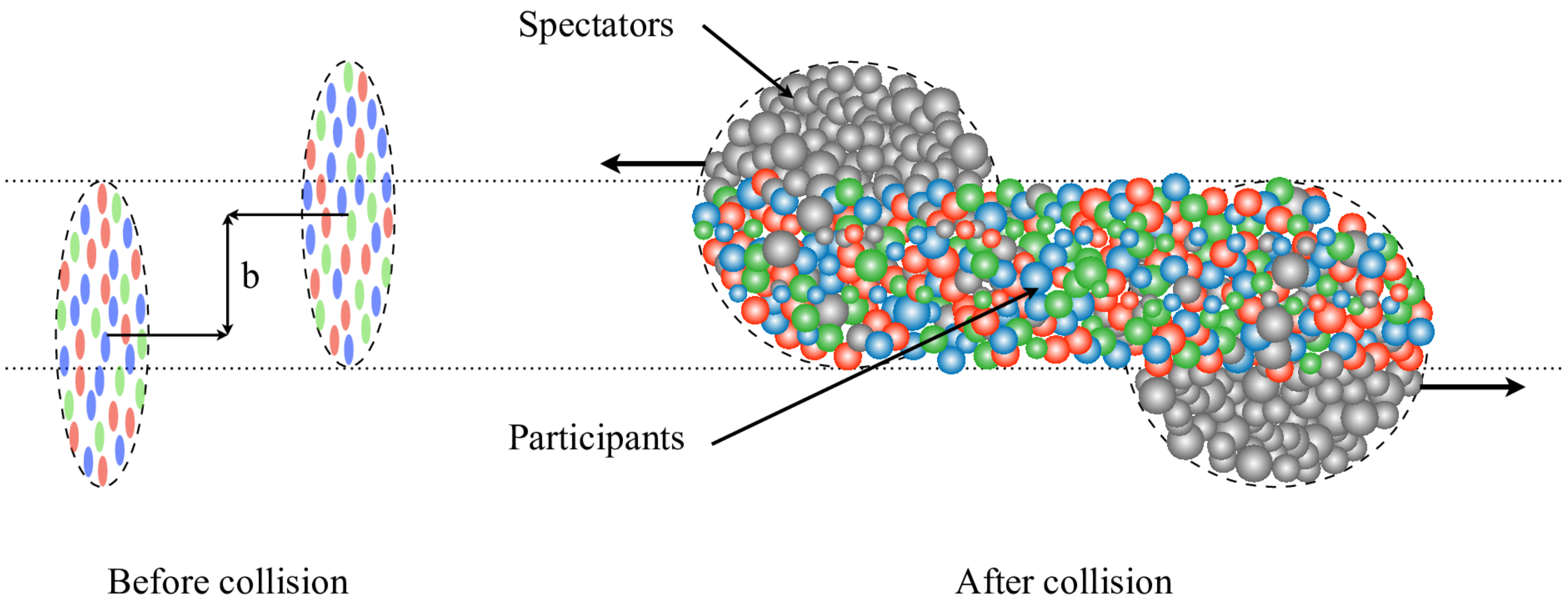


Impact parameter: transverse distance between the center of masses of the two nuclei

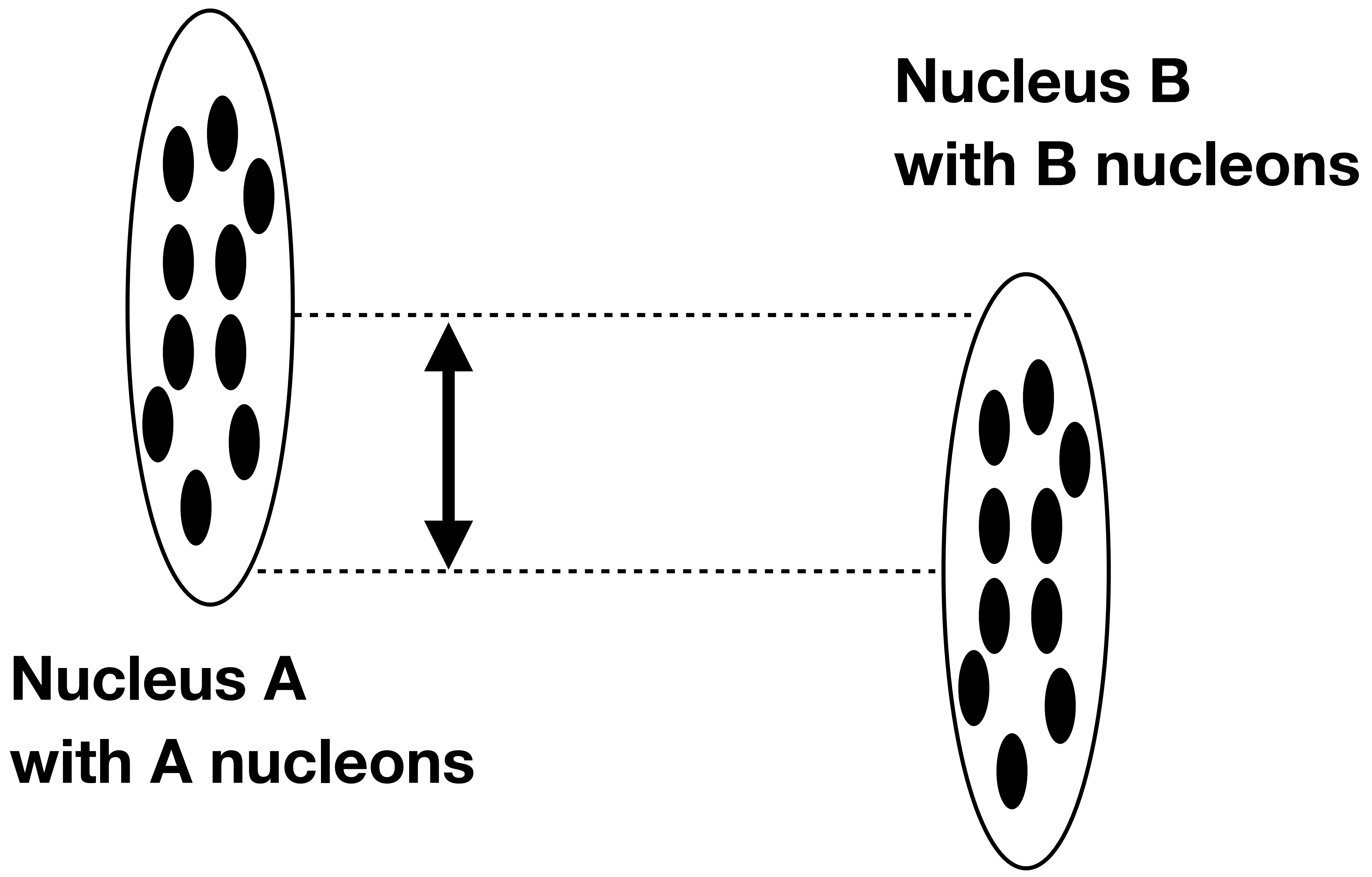
Participants are nucleons that are involved in a nucleon-nucleon scattering
Spectators are nucleons do not collide

A key application of the Glauber model

M.L. Miller, Ann.Rev.Nucl.Part.Sci.57:205-243,2007

→ heavy-ion collision as a superposition of independent **nucleon-nucleon scatterings** (“optical limit”)

→ **Glauber provides a way to describe AA collisions in terms of pp collisions**



Probability of having n nucleon-nucleon collisions:

T_{AB}(b) describes the “geometrical” probability of having two overlapping nucleons in A and B

$$P_n(n) = \binom{AB}{n} \left[\sigma_{inel} T_{AB}(b)\right]^n \left[1 - \sigma_{inel} T_{AB}(b)\right]^{AB-n}$$

Binomial coefficient = n interactions out of AB possibilities

Probability of having n collisions among nucleons

Probability of having AB-n non-interacting nucleon pairs

A key application of the Glauber model

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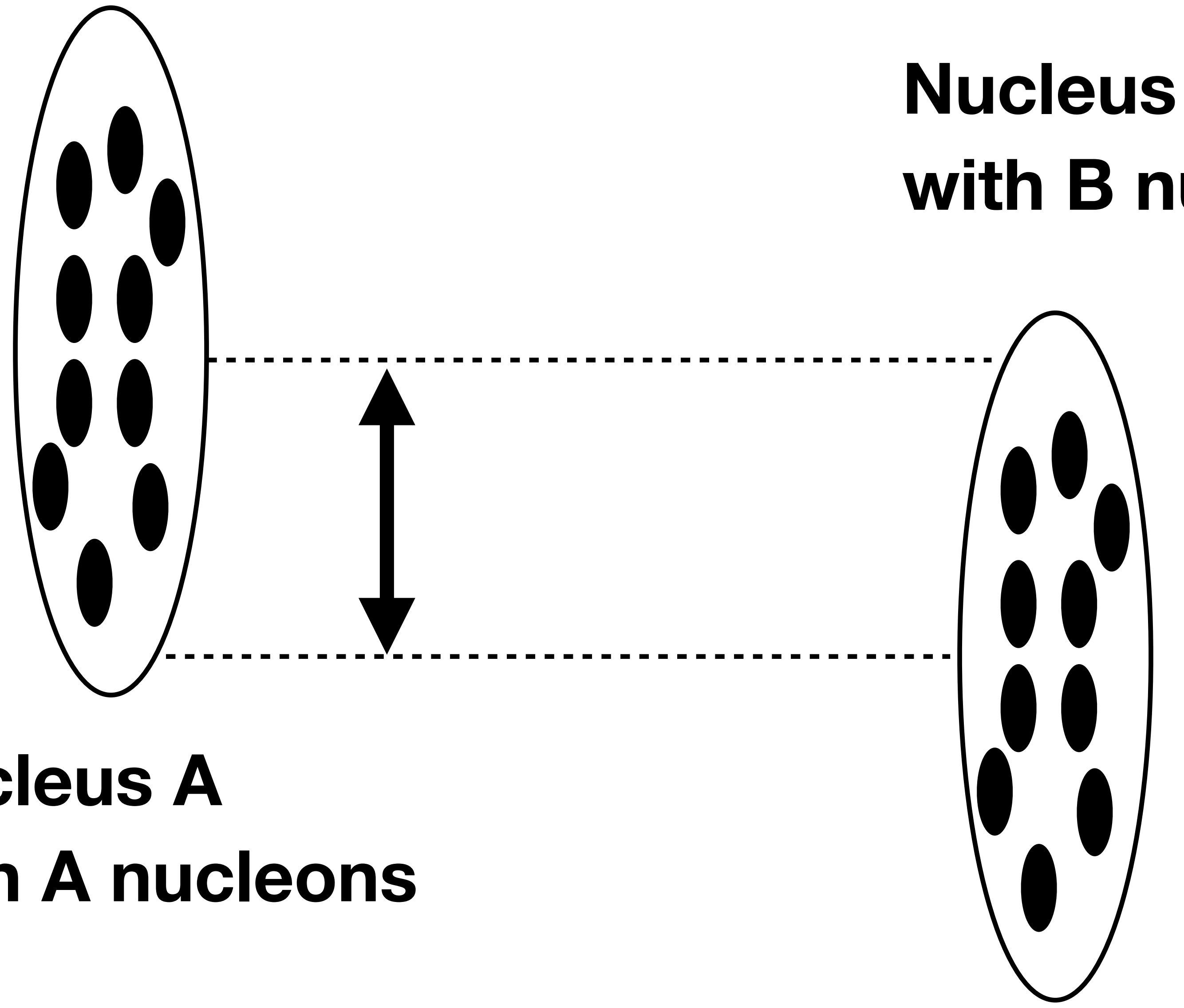

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→ **Estimate the number of nucleon-nucleon "hard" scatterings in a AA collision:**

$$N_{coll}(b) = AB\sigma_{inel}^{pp} T_{AB}(b)$$

→ N_{coll} allows to compare the yields of production measured in AA collisions with pp collisions, **assuming we know b**

M.L. Miller, Ann.Rev.Nucl.Part.Sci.57:205-243,2007

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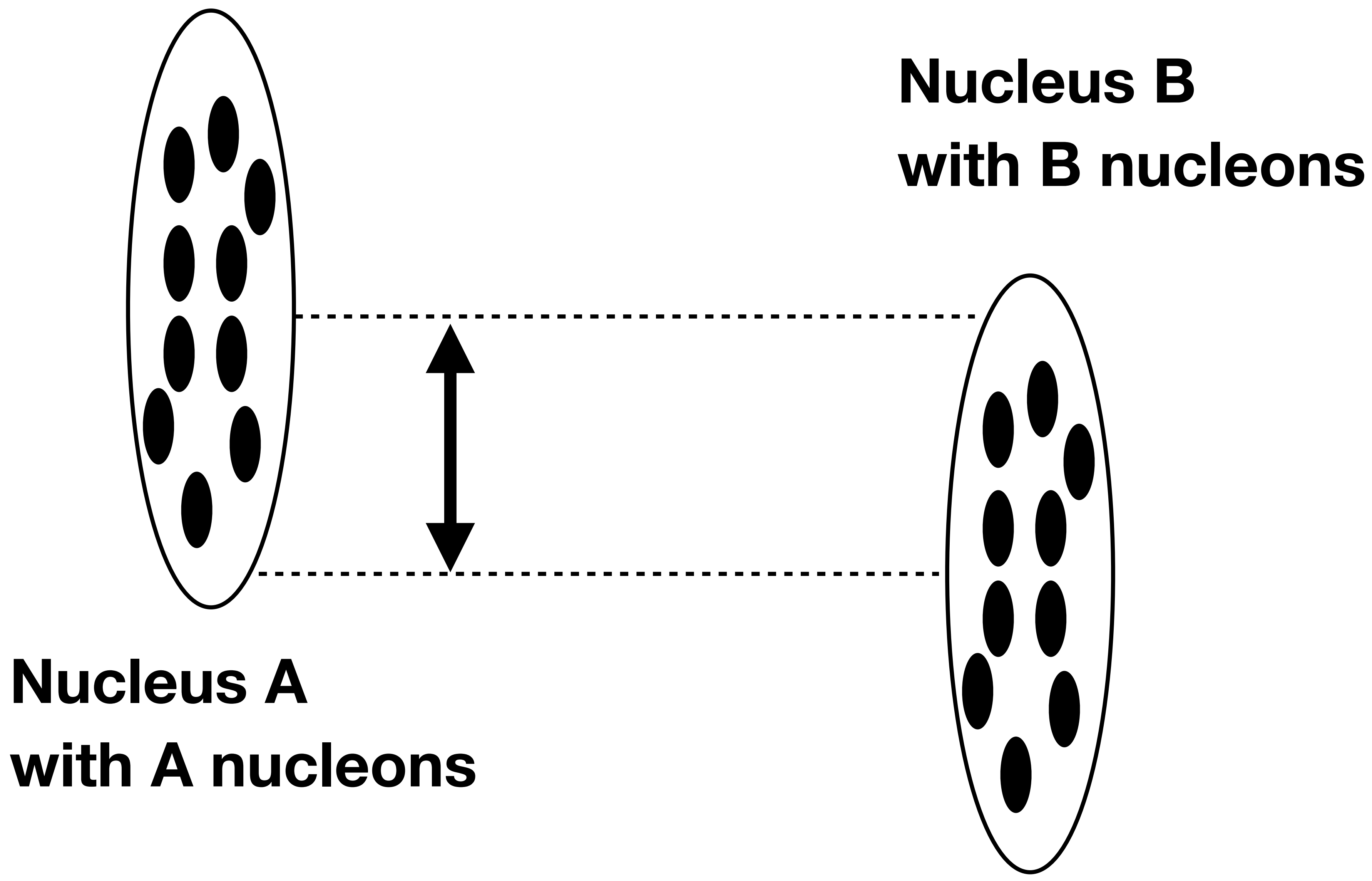
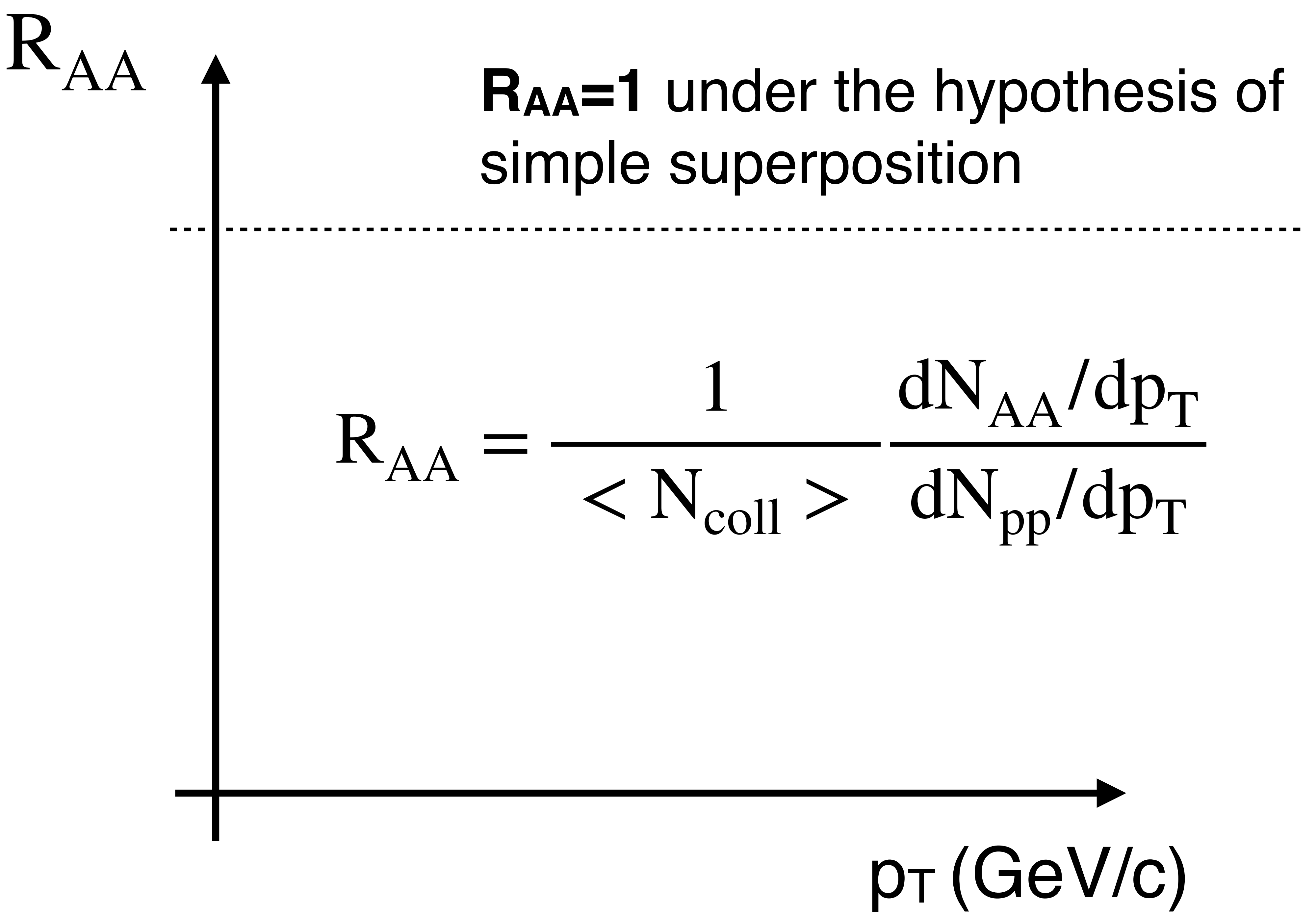




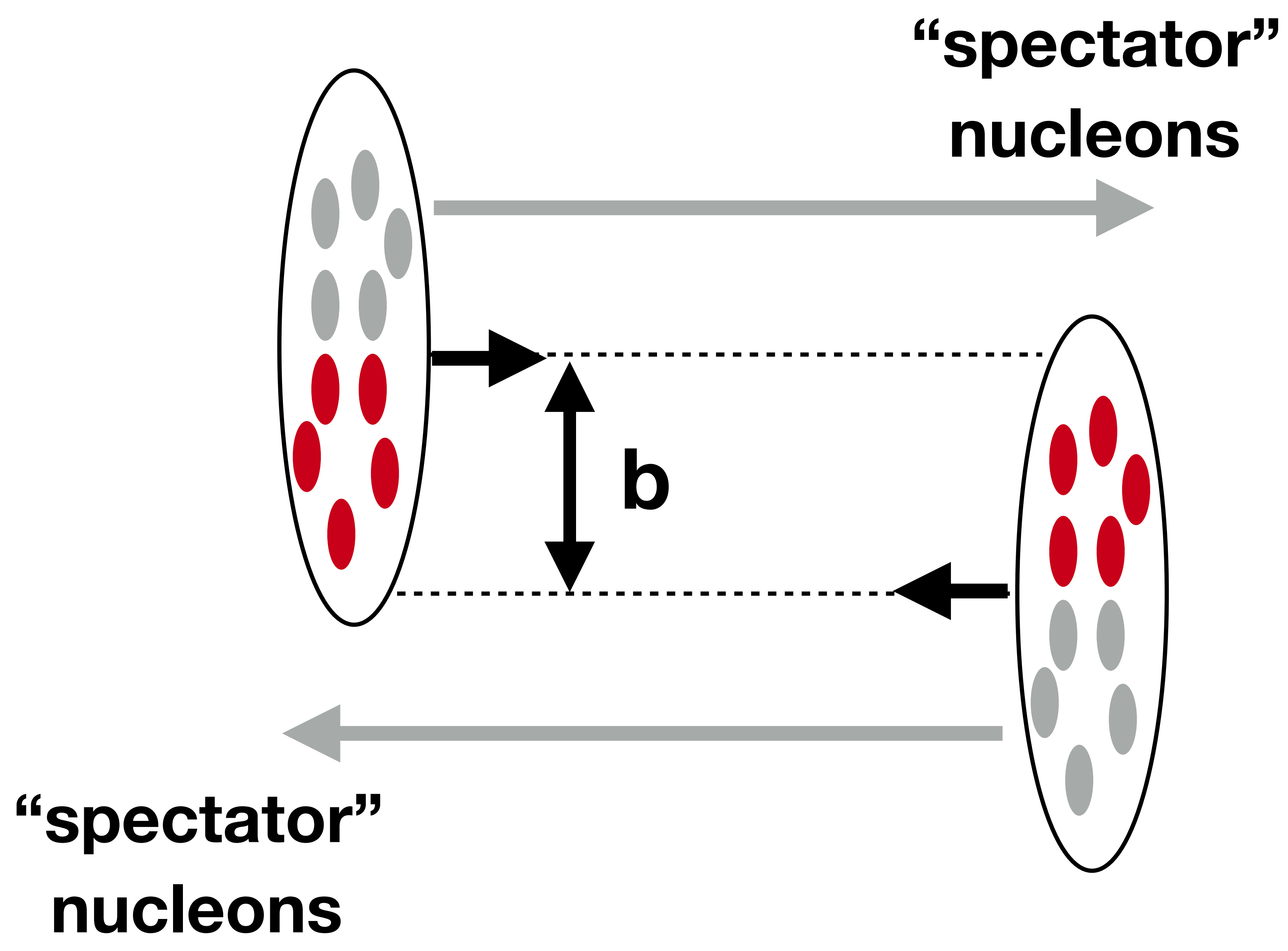
Phenomenology of heavy-ion collisions

characterizing the global properties of the medium

How to measure the impact parameter of a collision?

The Glauber model is a "thought" experiment!

→ b is not a parameter of the collision known a-priori by experimentalist



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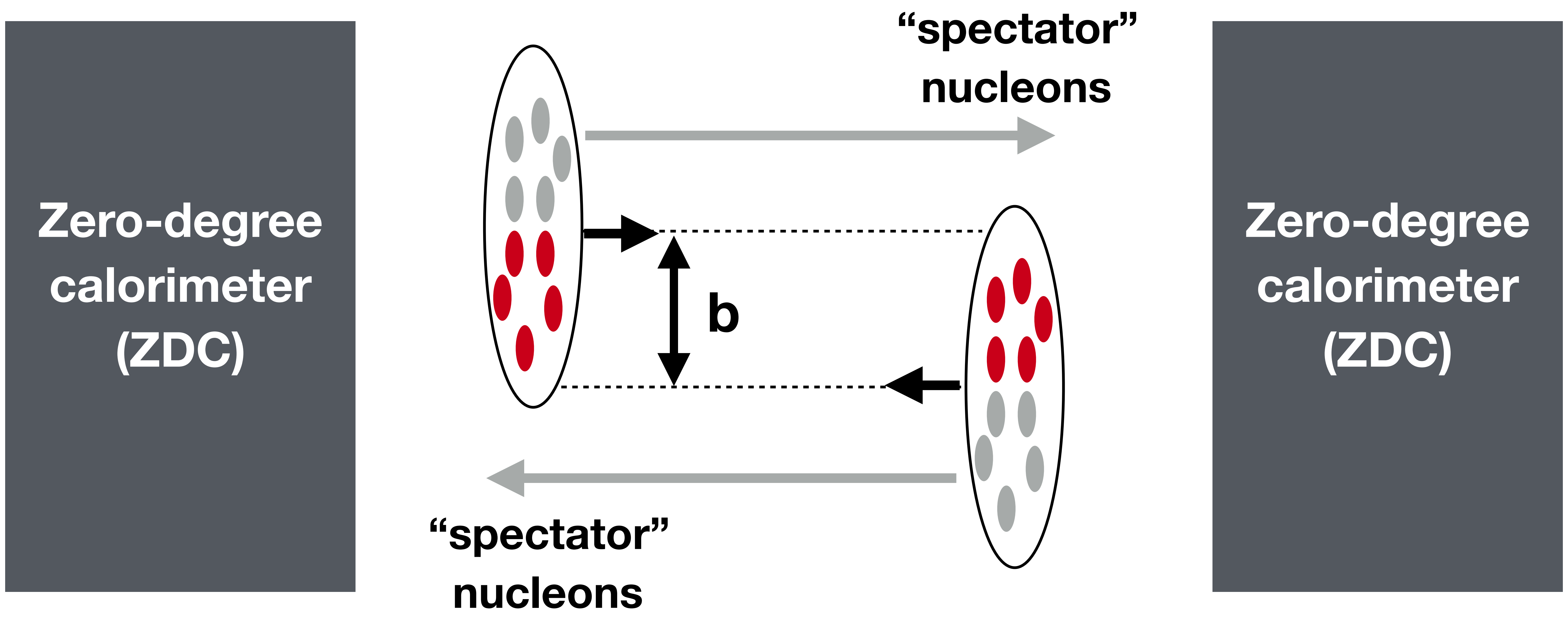


at ~ 0 degree w.r.t. to beam direction

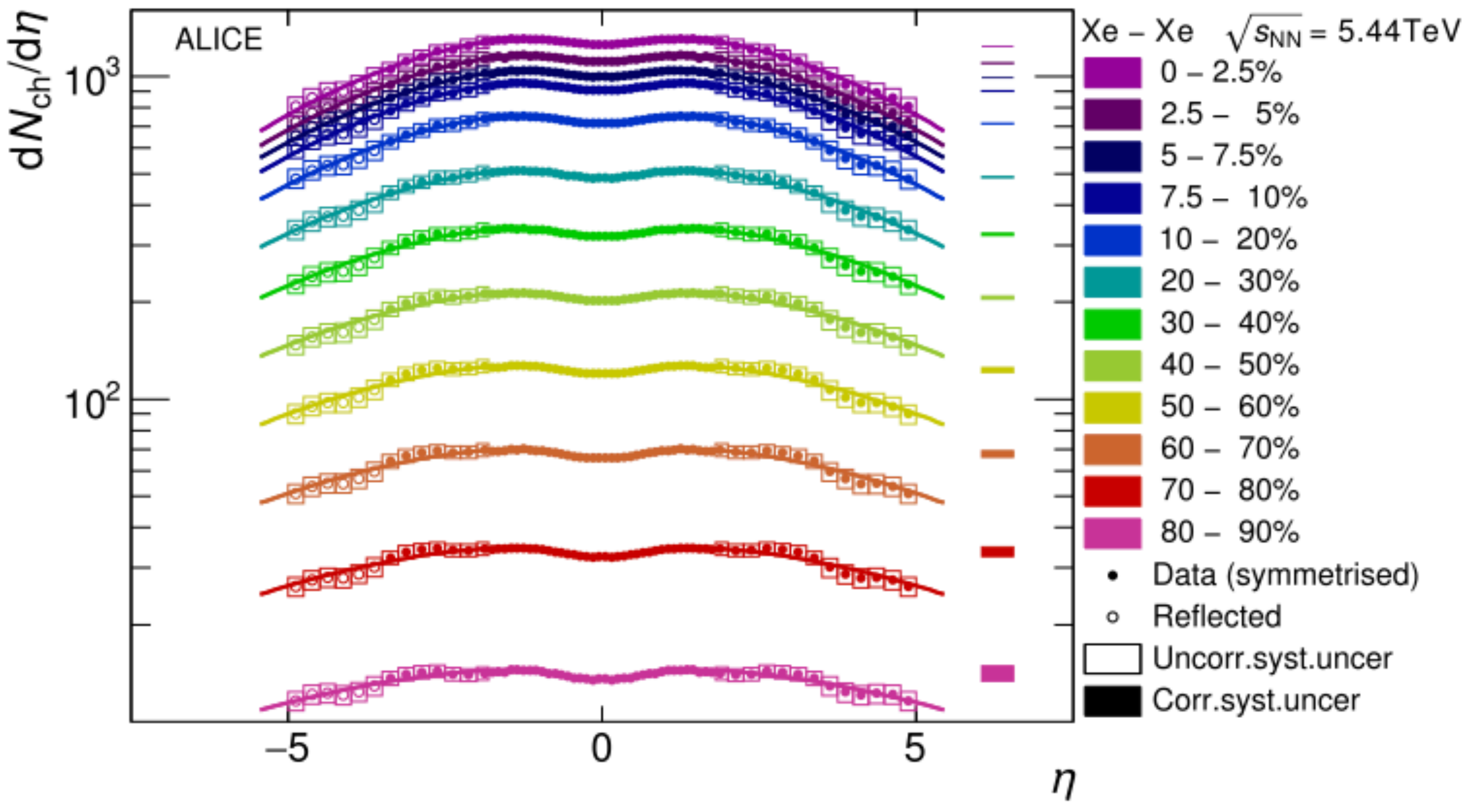
ALICE, Phys. Rev. C 88 (2013) 044909
LHCb, CERN-LHCb-DP-2021-002

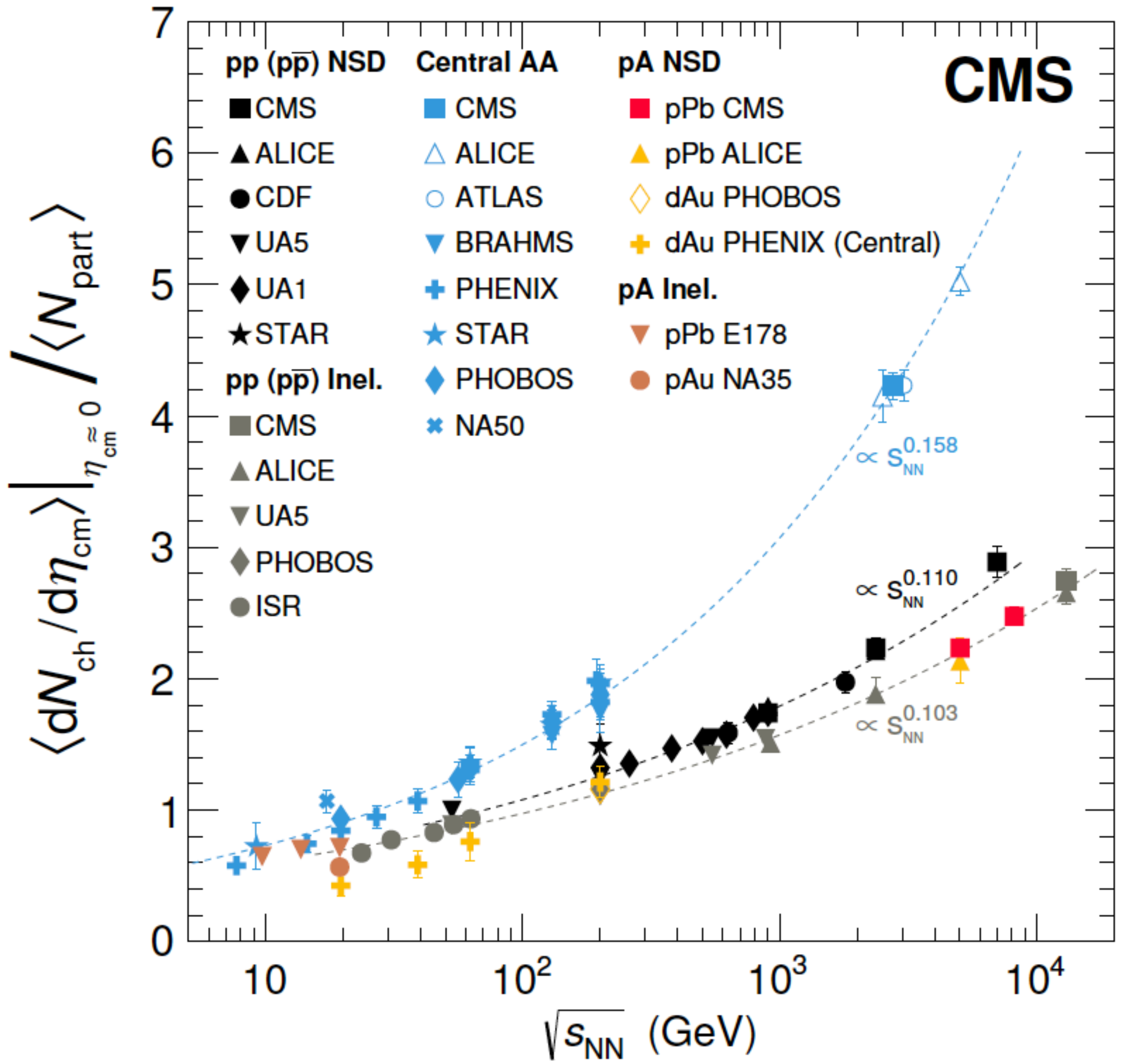
One possibility) **measure the energy deposited in the ZDC by the non-interacting nucleons**

→ Glauber MC simulations allows to estimate the b (or collision centrality) starting from spectator energy

The day-0 measurement: Charged-particle multiplicity

- Hadron production in elementary and nuclear collisions as one of the oldest puzzles in particle physics!

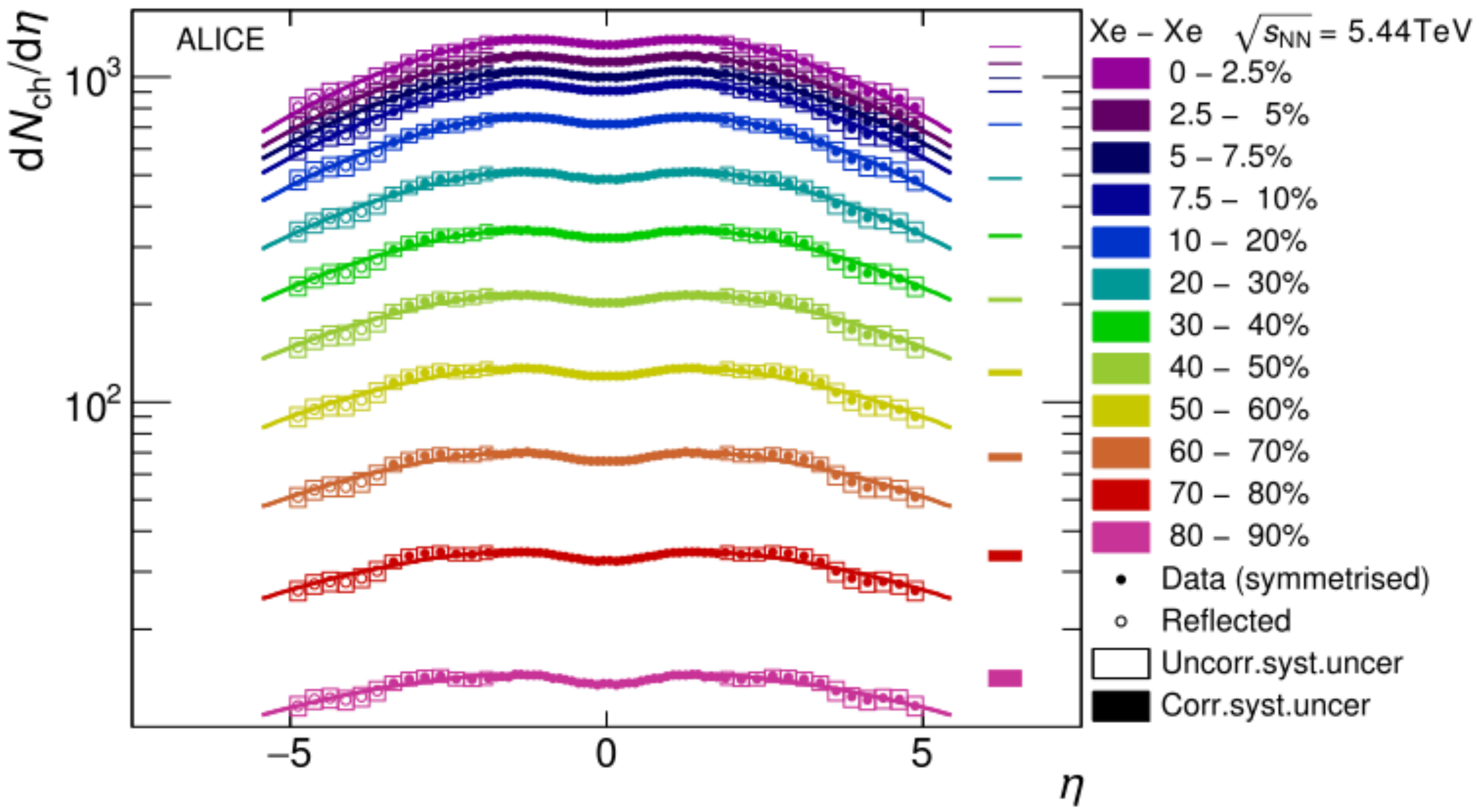




W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018
ALICE, Phys. Lett. B 790 (2019) 35
CMS, JHEP 01 (2018) 045

Charged-particle multiplicity to estimate energy density

- Hadron production in elementary and nuclear collisions as one of the oldest puzzles in particle physics!
- In heavy-ion collisions → **a tool to constrain the initial energy density**



Bjorken's method (valid at $\mu_b = 0$)
→ A tool to constrain the initial energy density

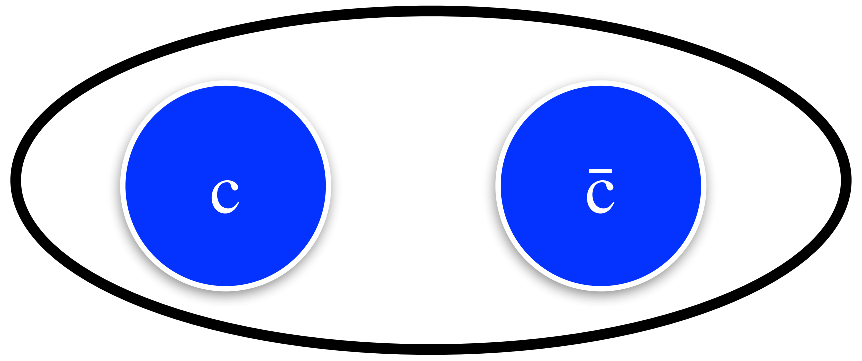
$$\rho^{PbPb}_{energy}\ (\tau = 1\ fm/c) \approx \frac{E_T}{\pi R^2 L_z} \approx 12\ GeV/fm^3$$

$$\rho^{PbPb}_{energy}\ (\tau = 1\ fm/c) >> \ \rho^{regular\ matter}_{energy}$$

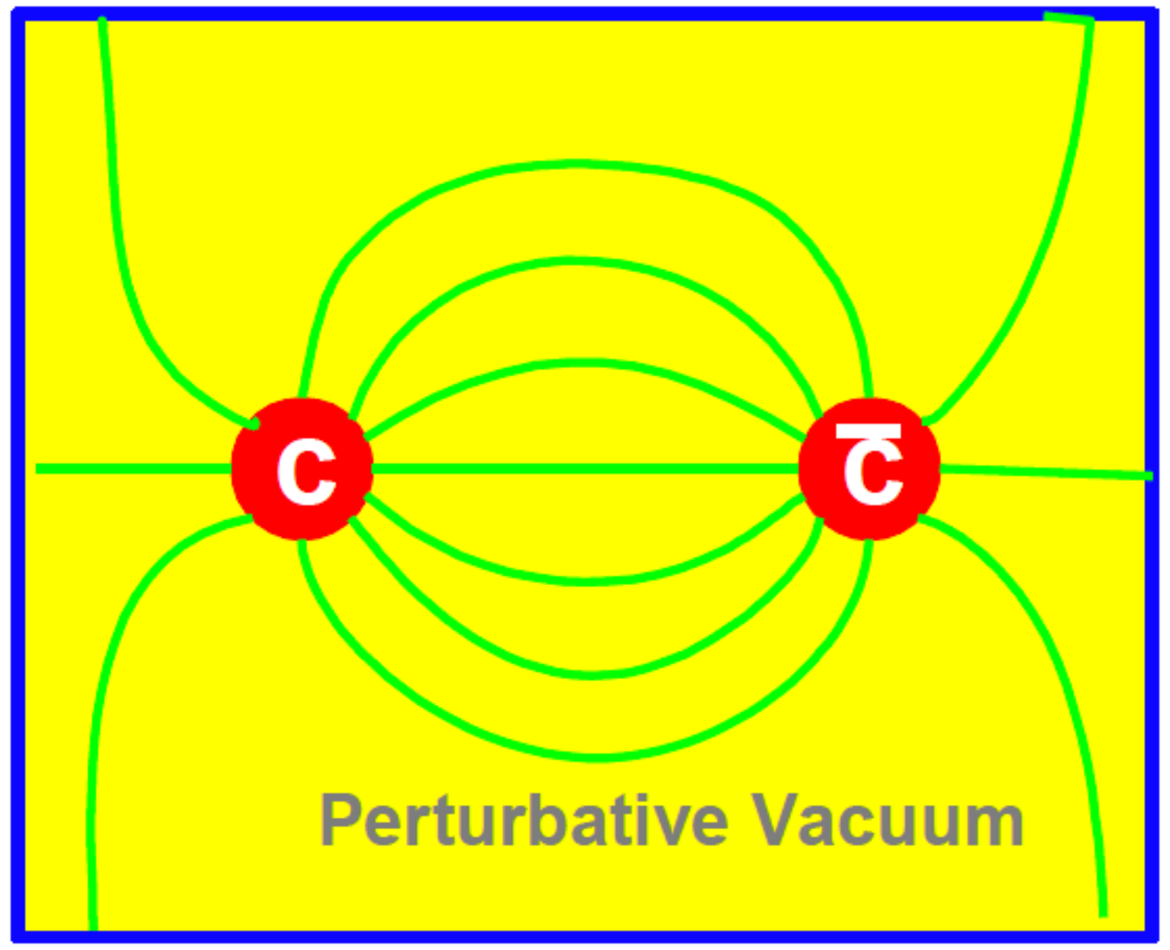
W. Busza, K. Rajagopal, W. v. d. Schee, ARNPS, Vol. 68:339-376, 2018
ALICE, Phys. Rev. Lett. 105 (2010) 252301
ALICE, Phys. Lett. B 790 (2019) 35

“Signatures” for the presence of a new phase of matter

Bound states to test the presence of deconfined colors?



Color screening in the QGP: the historical picture

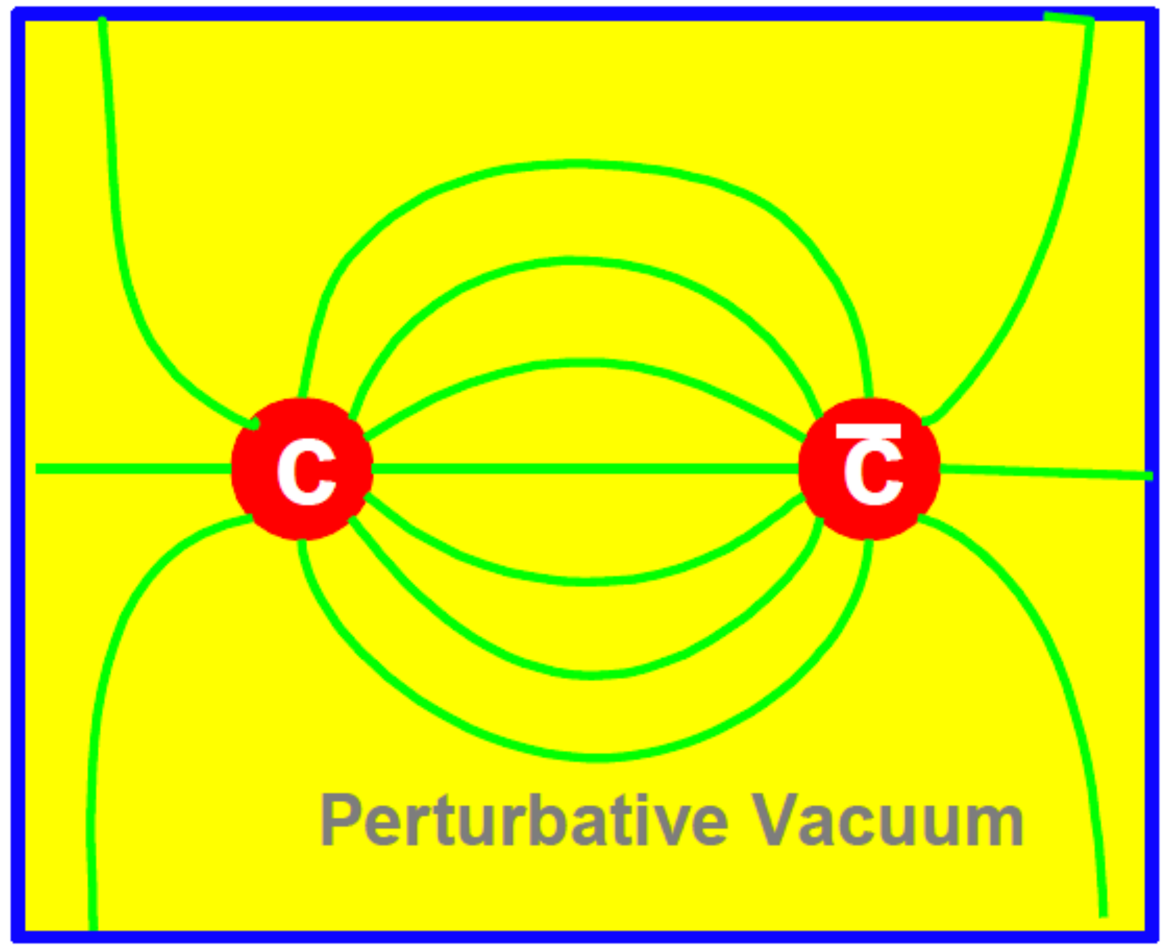


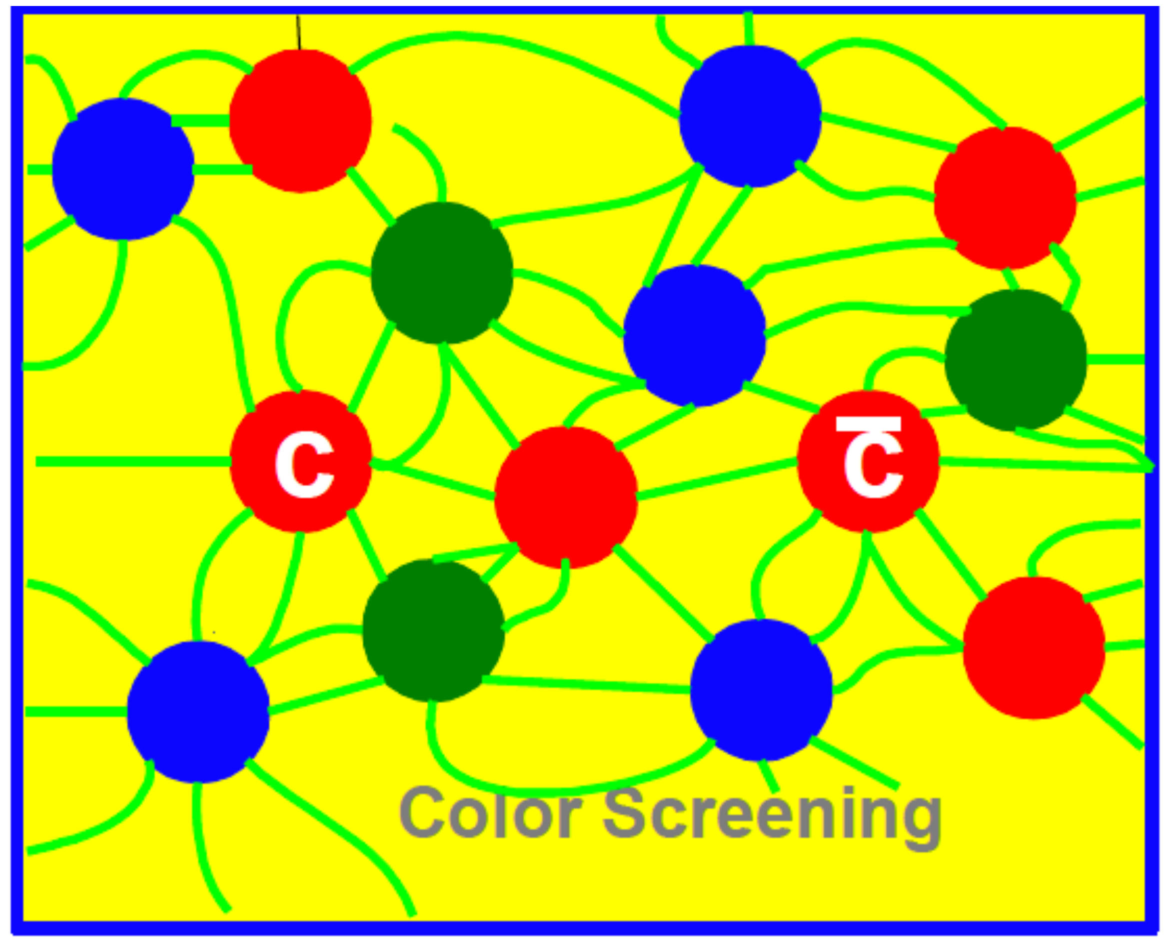
The spectrum of $c\bar{c}$ bound states can be well described in vacuum with a Cornell potential as:

$$H = -\frac{\vec{p}^2}{2\mu} - \frac{\alpha}{r} + kr$$

What happens to this potential when the $c\bar{c}$ state in immersed in the Quark Gluon Plasma?

Color screening in the QGP: the historical picture





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$$H = -\frac{\vec{p}^2}{2\mu} - \frac{\alpha}{r} e^{-r/\lambda_D}$$

$$\lambda_D \sim \frac{1}{gT}$$

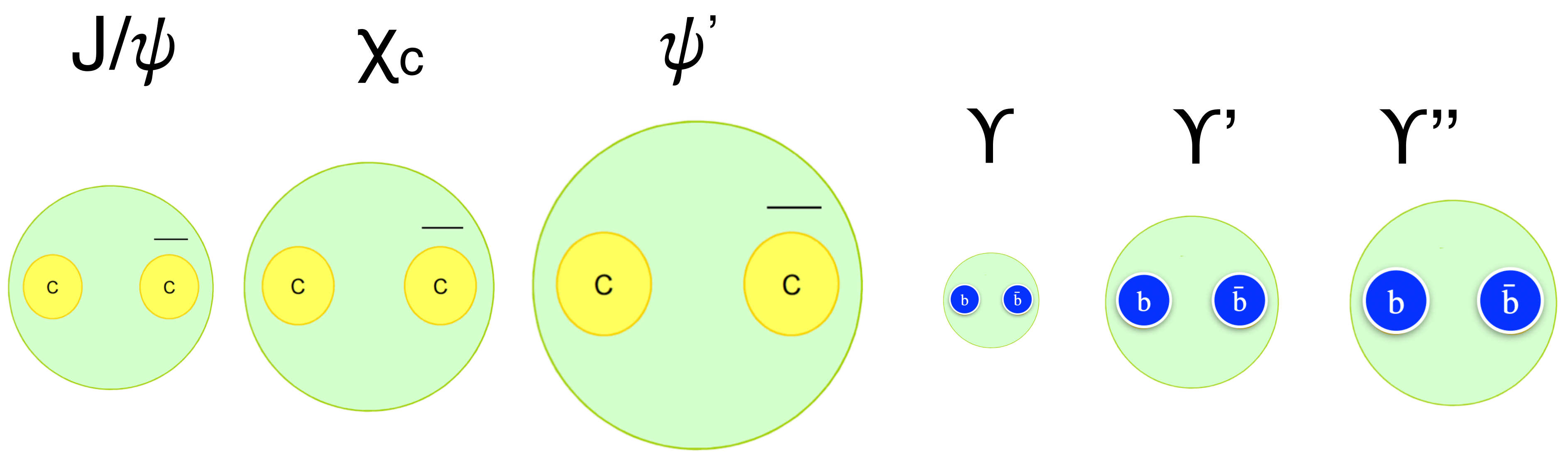
Yukawa potential
which includes a screening factor due to the presence of a high-color "density"

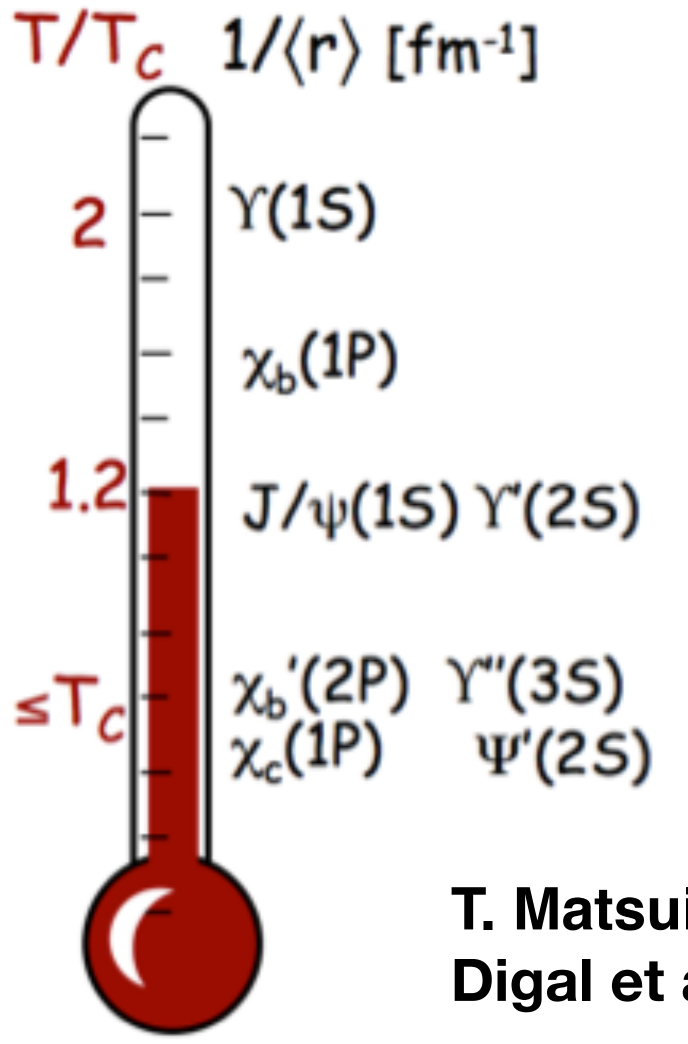
The bound state becomes "weaker for increasing values of temperature and coupling constant!

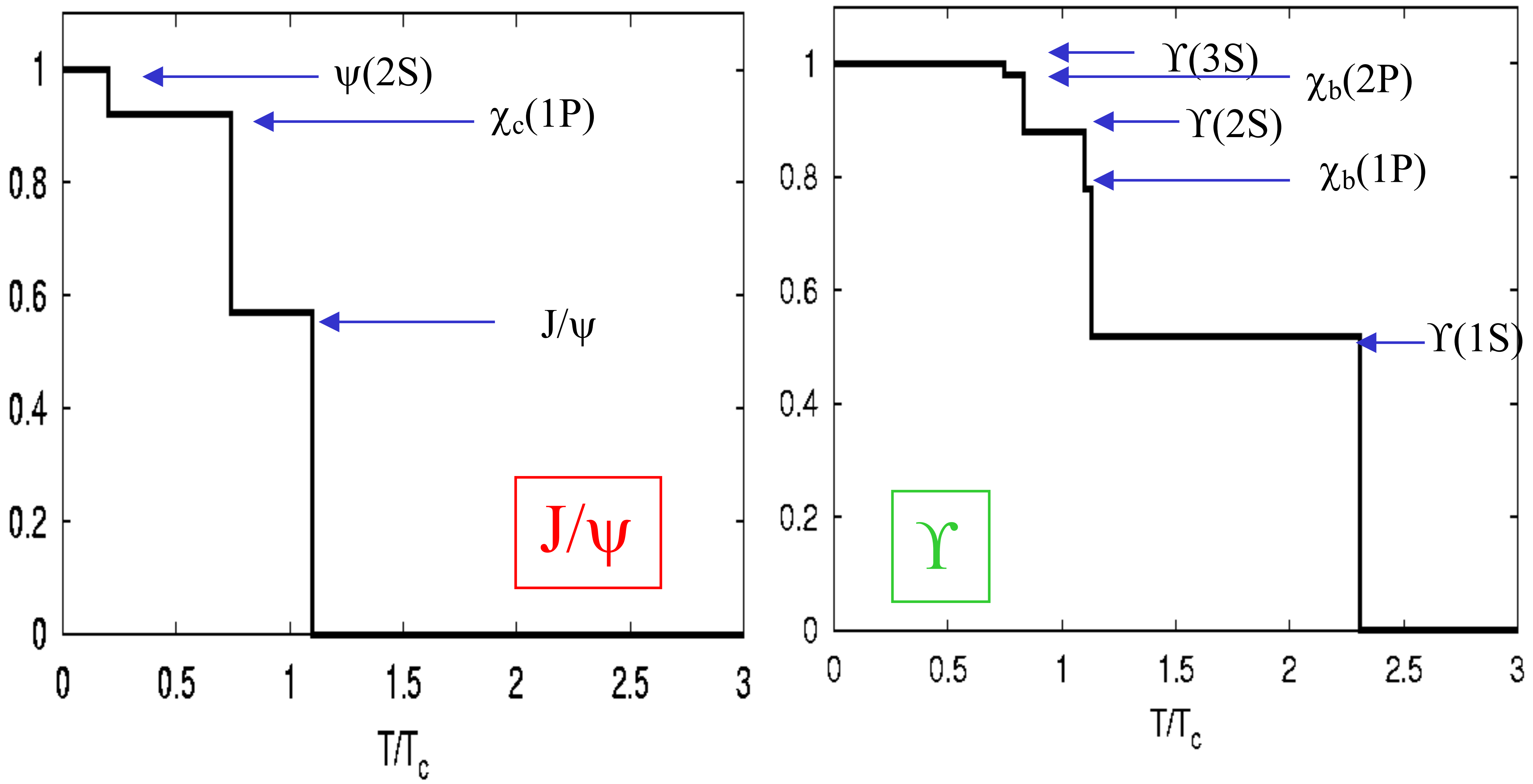
T. Matsui, H. Satz, Phys. Lett. B178 (1986) 416,

The hypothesis of quarkonium sequential suppression

Different bound states have different binding energies and radii → **Different dissociation temperatures in the Quark Gluon Plasma**



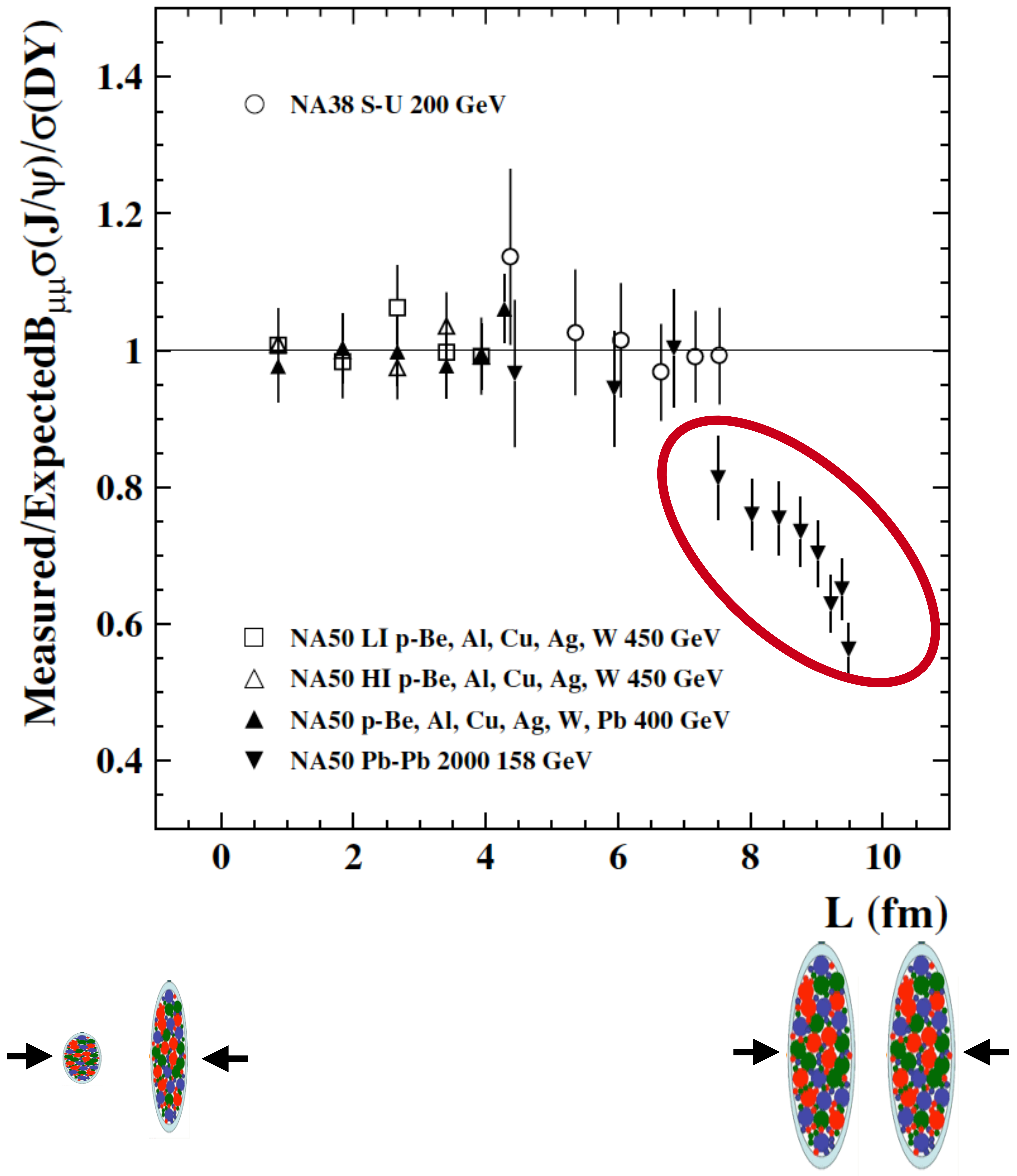




T. Matsui, H. Satz, Phys. Lett. B178 (1986) 416,
Digal et al., Phys.Rev. D64(2001)094015

Can the quarkonium states be used as a medium thermometer?

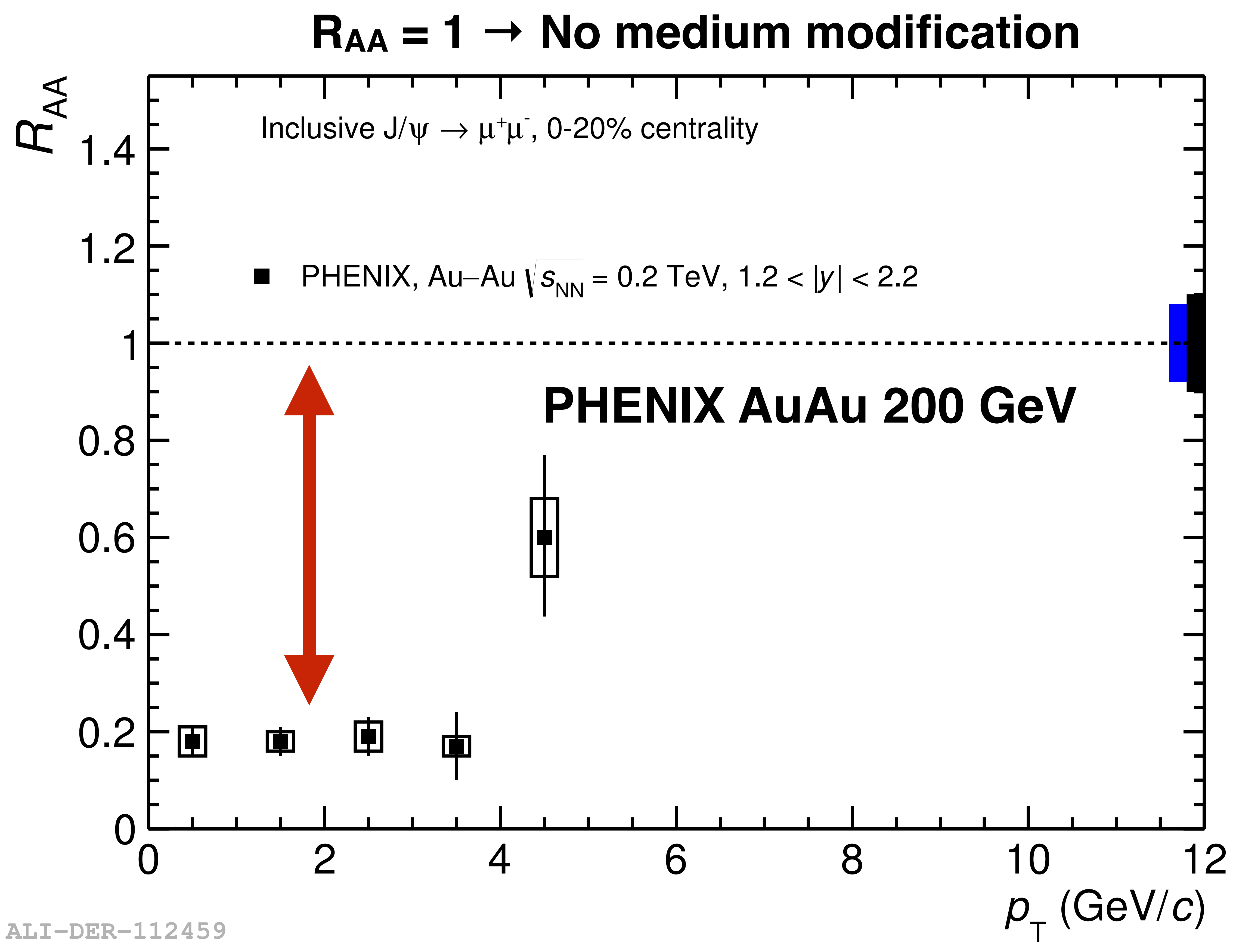
J/ψ suppression at the SPS in PbPb collisions



Anomalous suppression observed in PbPb collisions at 158 GeV
if compared to expectation based on HP of superposition of pp collisions

→ **considered the first concrete evidence for the creation of a deconfined phase of matter**

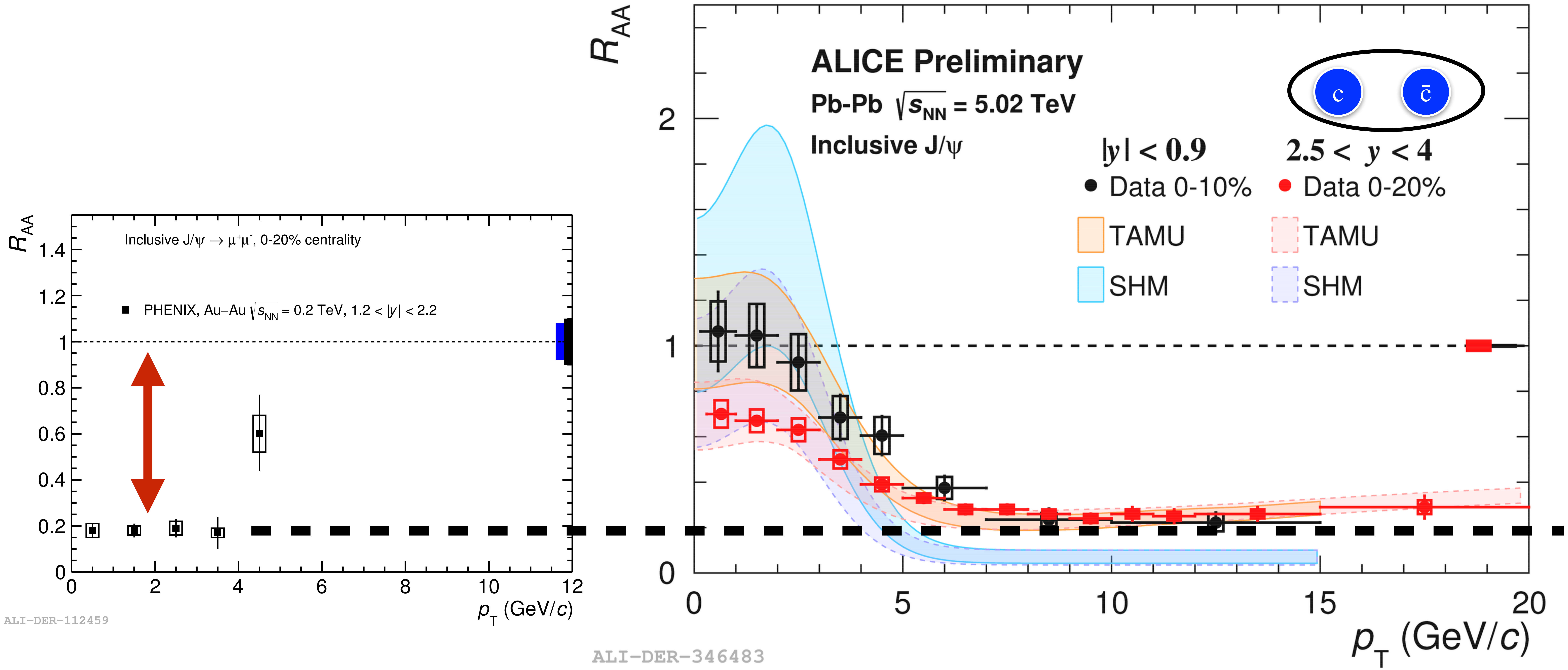
J/ψ nuclear modification factor at RHIC (AuAu 200 GeV)



More differential study study confirmed the evidence for a strong suppression of J/ψ in Au-Au collision

What would you expect for LHC energies?
Naively more J/ψ dissociating due to the higher temperature of the medium

J/ψ nuclear modification factor at the LHC!



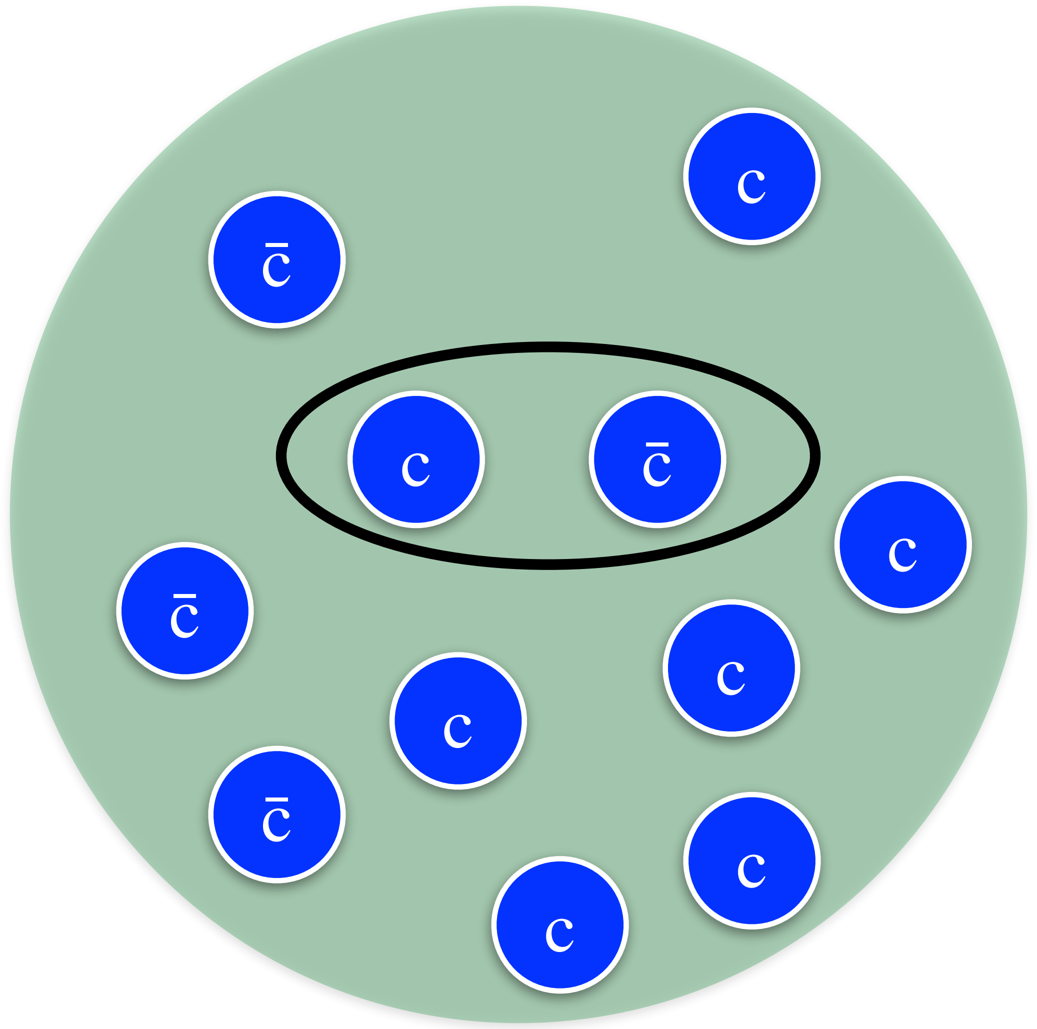
More **J/ψ survives even in the presence of a hotter medium???**

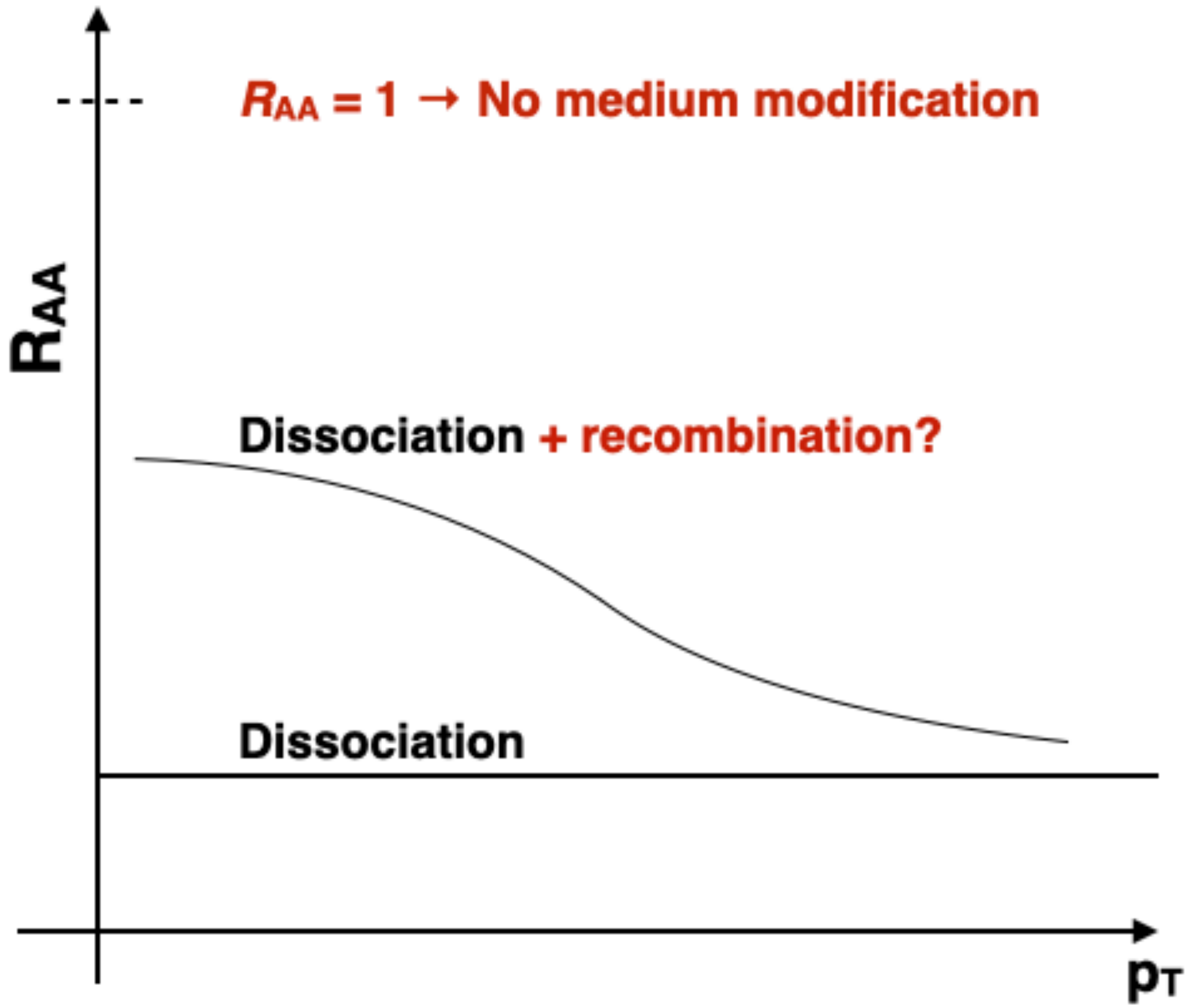
Any competing mechanism?

J/ψ "regeneration" in the Quark Gluon Plasma

New mechanisms of hadron formation in the presence of a hot medium:

- J/ψ created in the QGP by combination of uncorrelated charm-anti-charm pairs





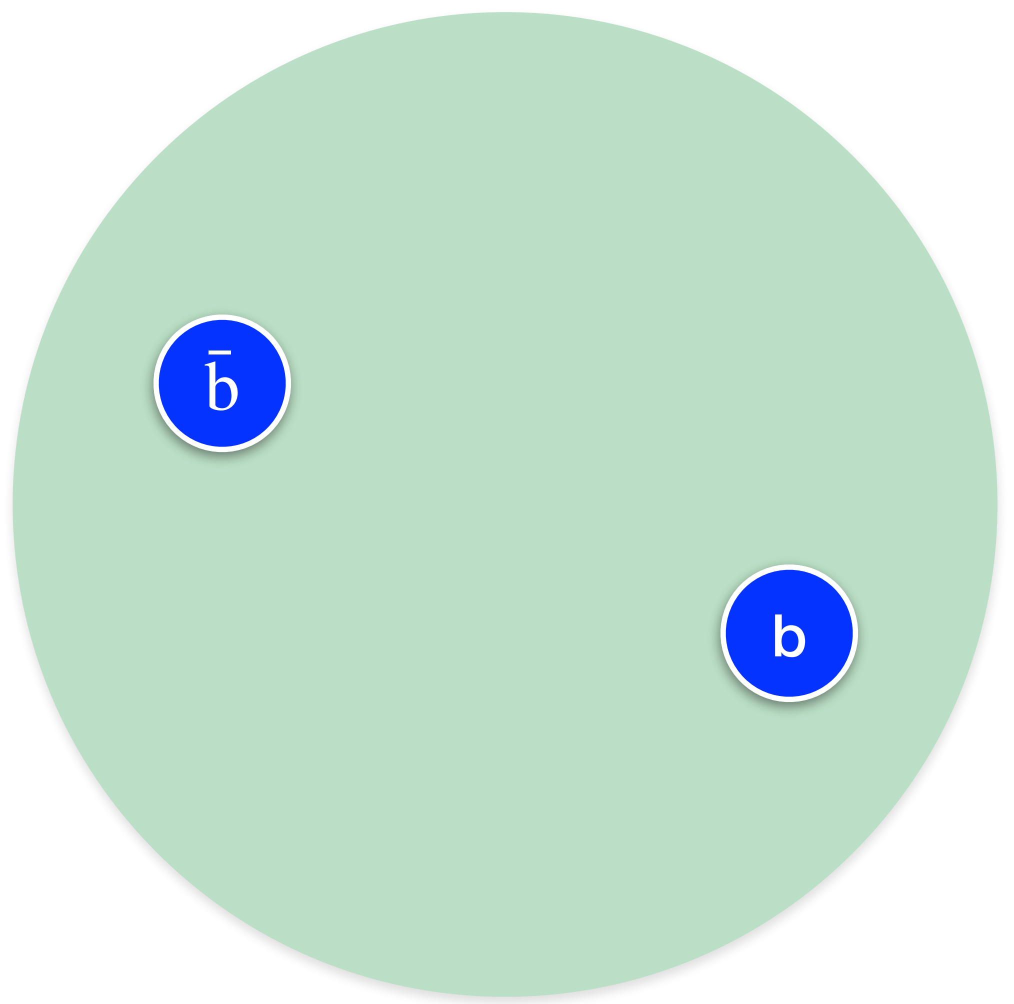
→ **One of the highlight of the heavy-ion program at the LHC**
predicted well before within the framework of Statistical Hadronization Models

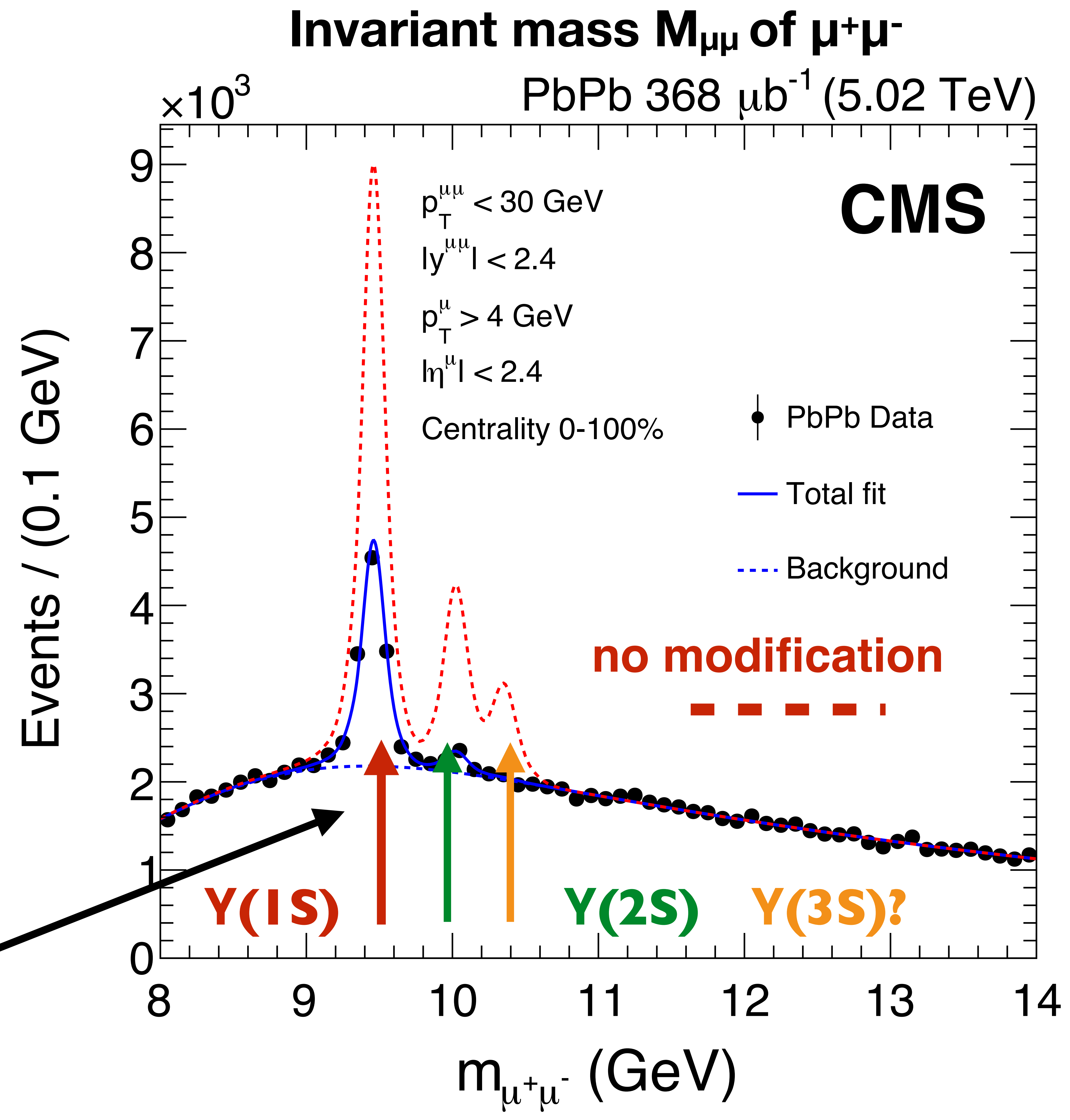
A.P. Kostyuk, J. Phys. G28:2047-2050, 2002
A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel, Phys. Lett. B652:259-261,2007

Bottomonium suppression in PbPb collisions

CMS, Phys. Lett. B. 770, 357(2017)

Bottomonia less affected by recombination due to lower $b\bar{b}$ cross section!



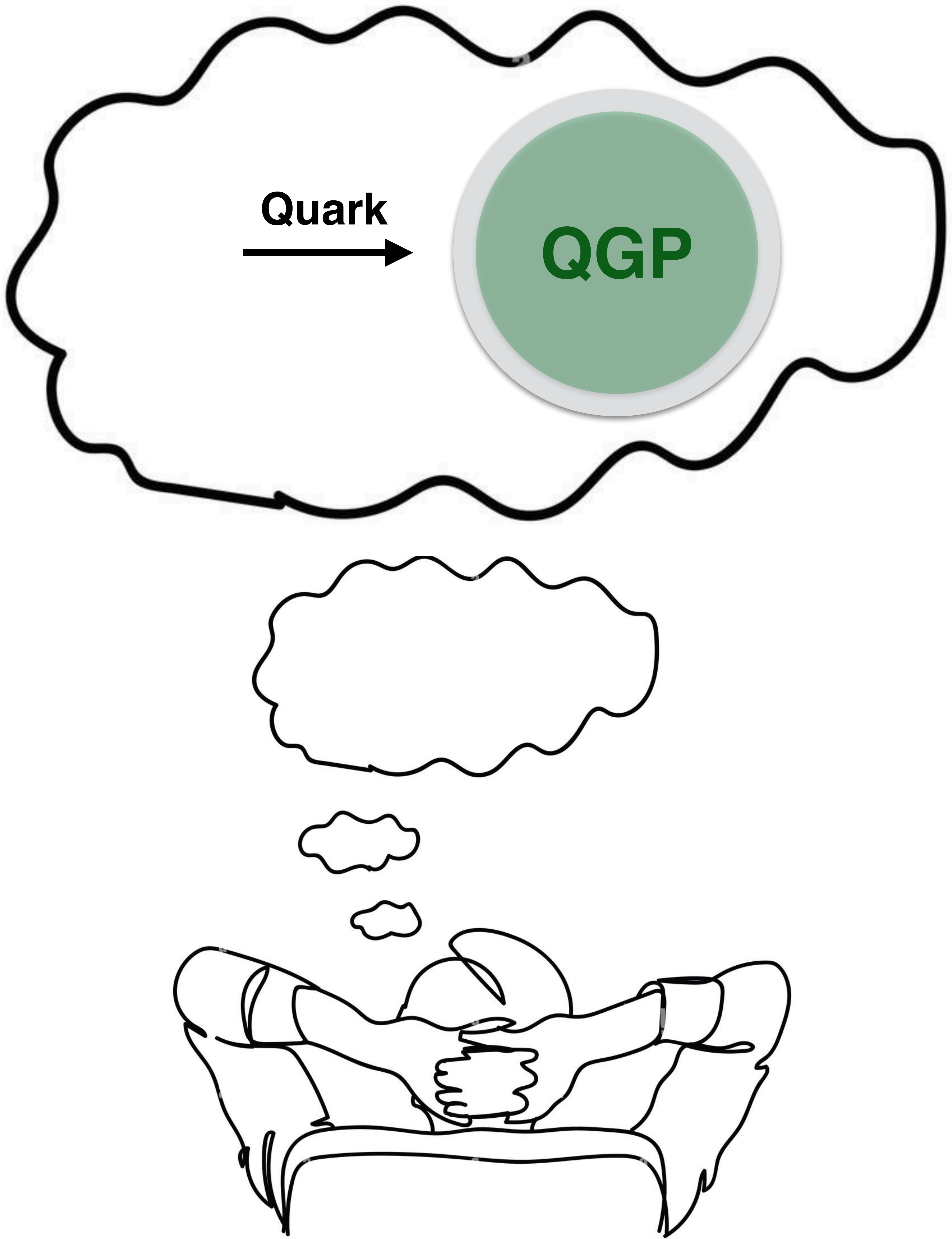


When we "switch" off regeneration using b quarks:

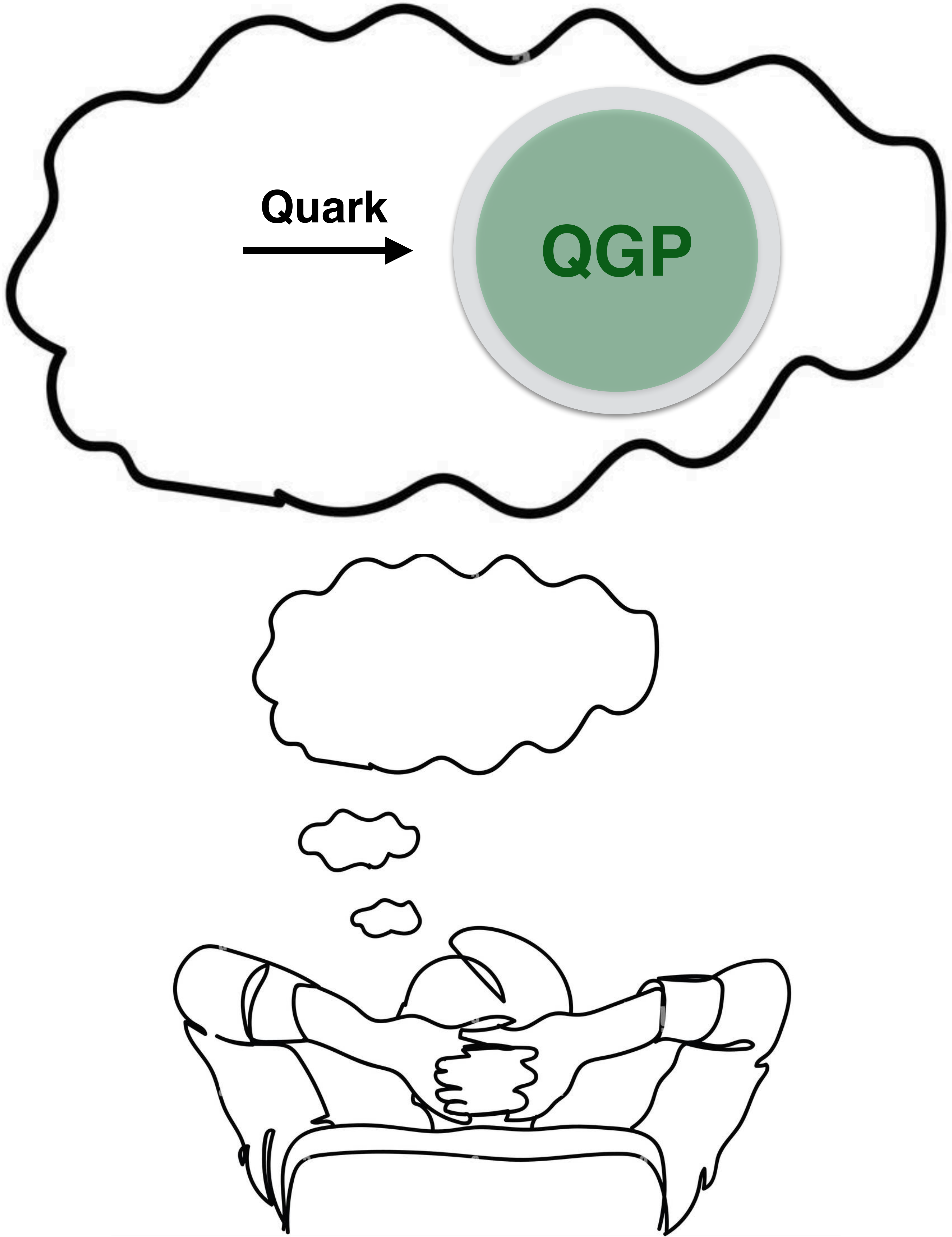
→ Loosely bound states (2S,3S) more suppressed than (1S) as predicted by sequential suppression

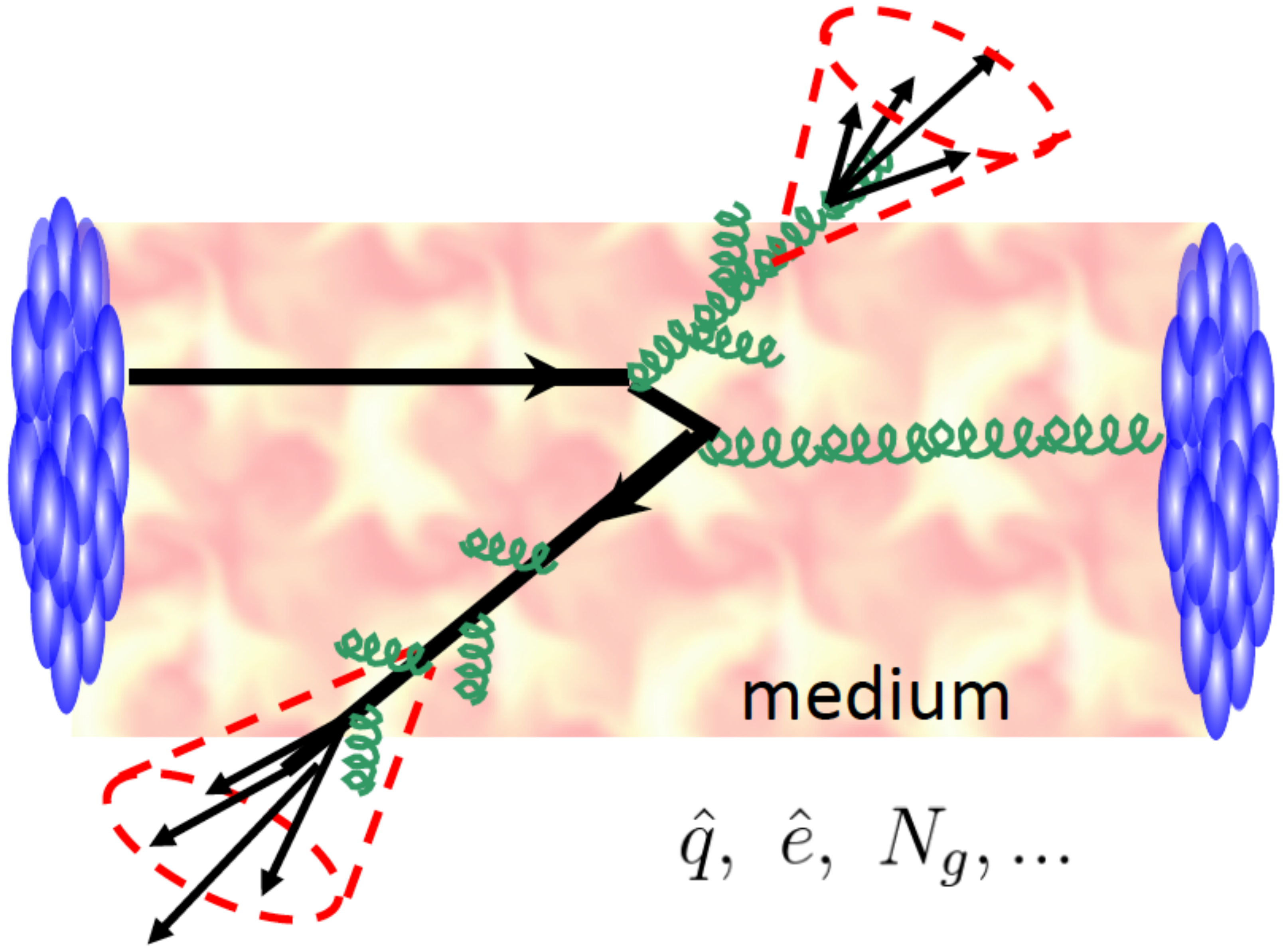
→To this date, one of the strongest signatures for the formation of a system with deconfined colors

can we measure the stopping power of the medium with high-energy probes?



can we measure the stopping power of the medium with high-energy probes?



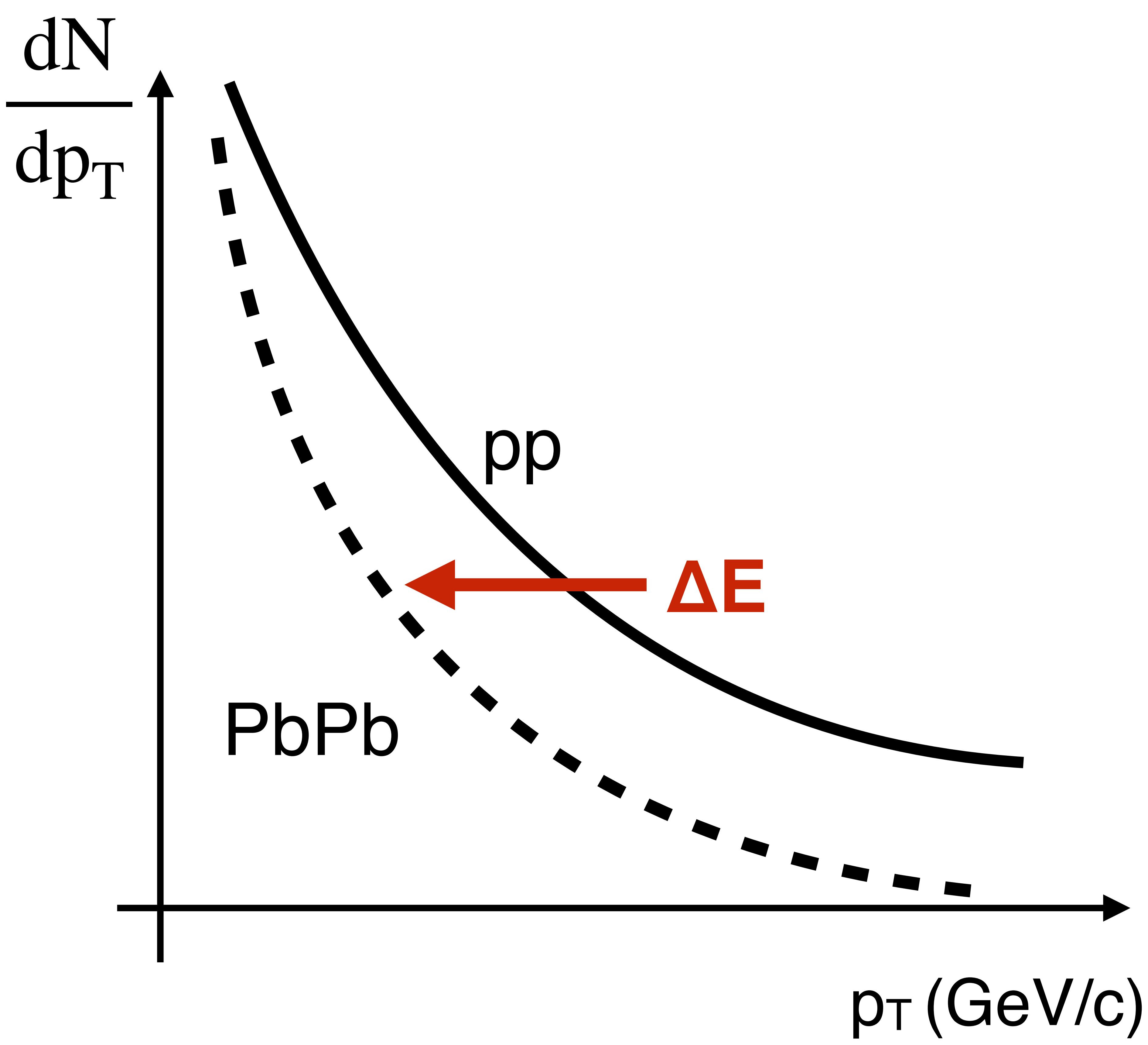


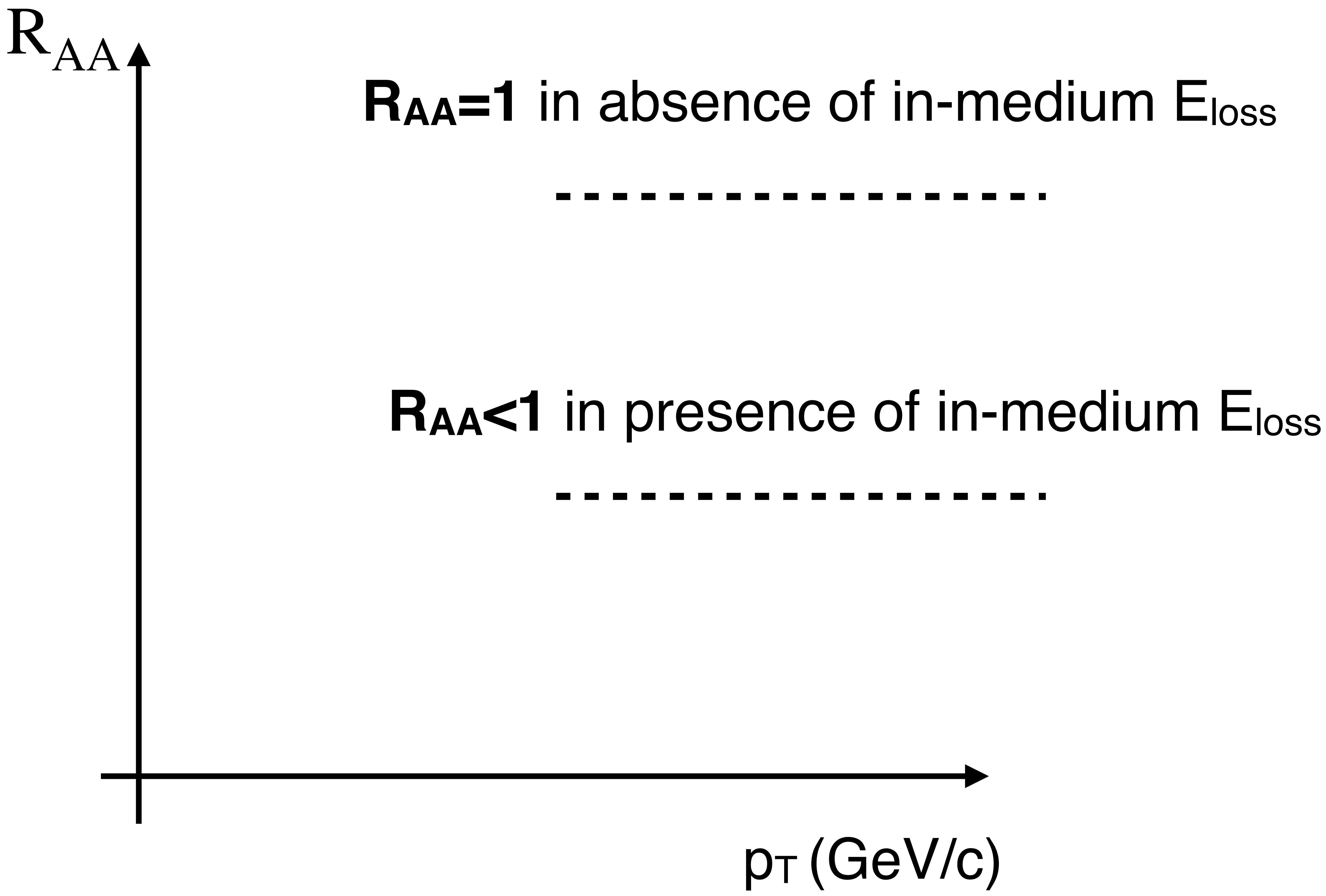
→**Use high-p_T partons as "self-generated" probes for the medium properties**

Bjorken (1982), FERMILAB-PUB-82-059-THY

The nuclear modification factor R_{AA}

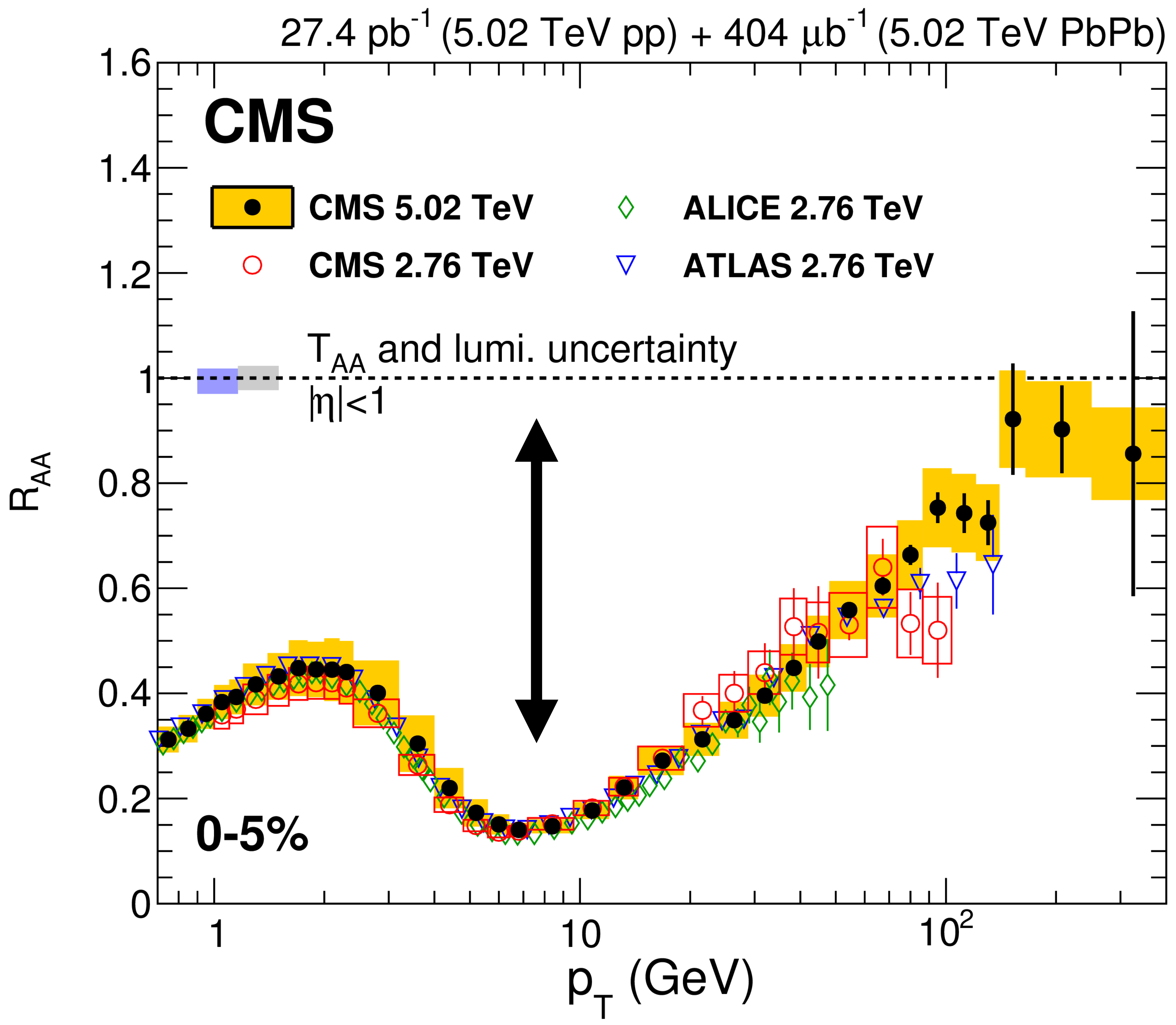
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$

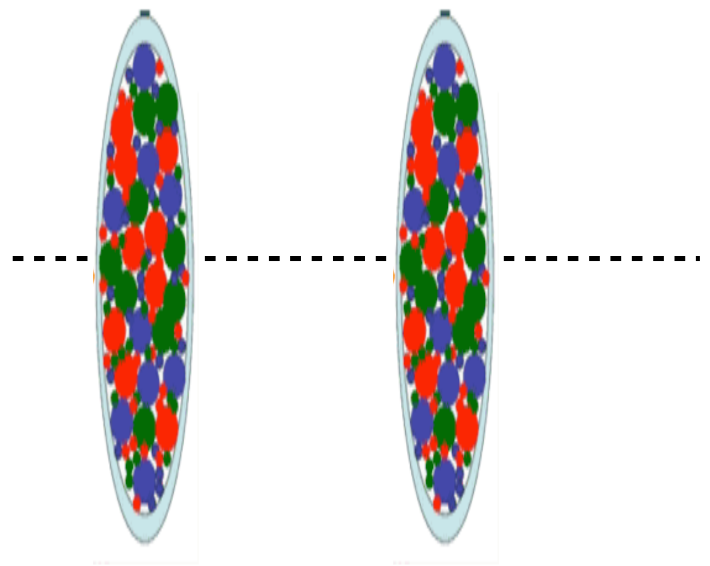


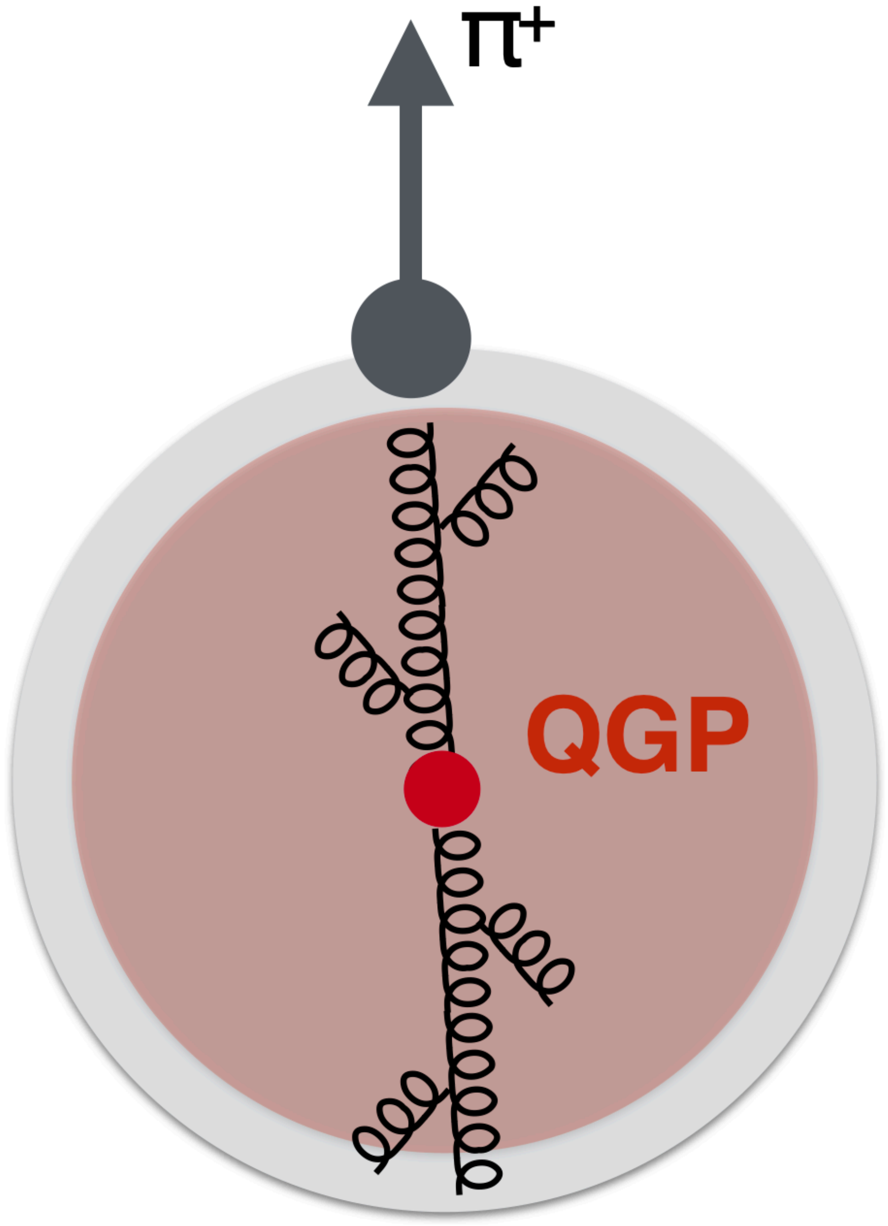


Charged hadron R_{AA} in central PbPb collisions

CMS, JHEP 04 (2017) 039



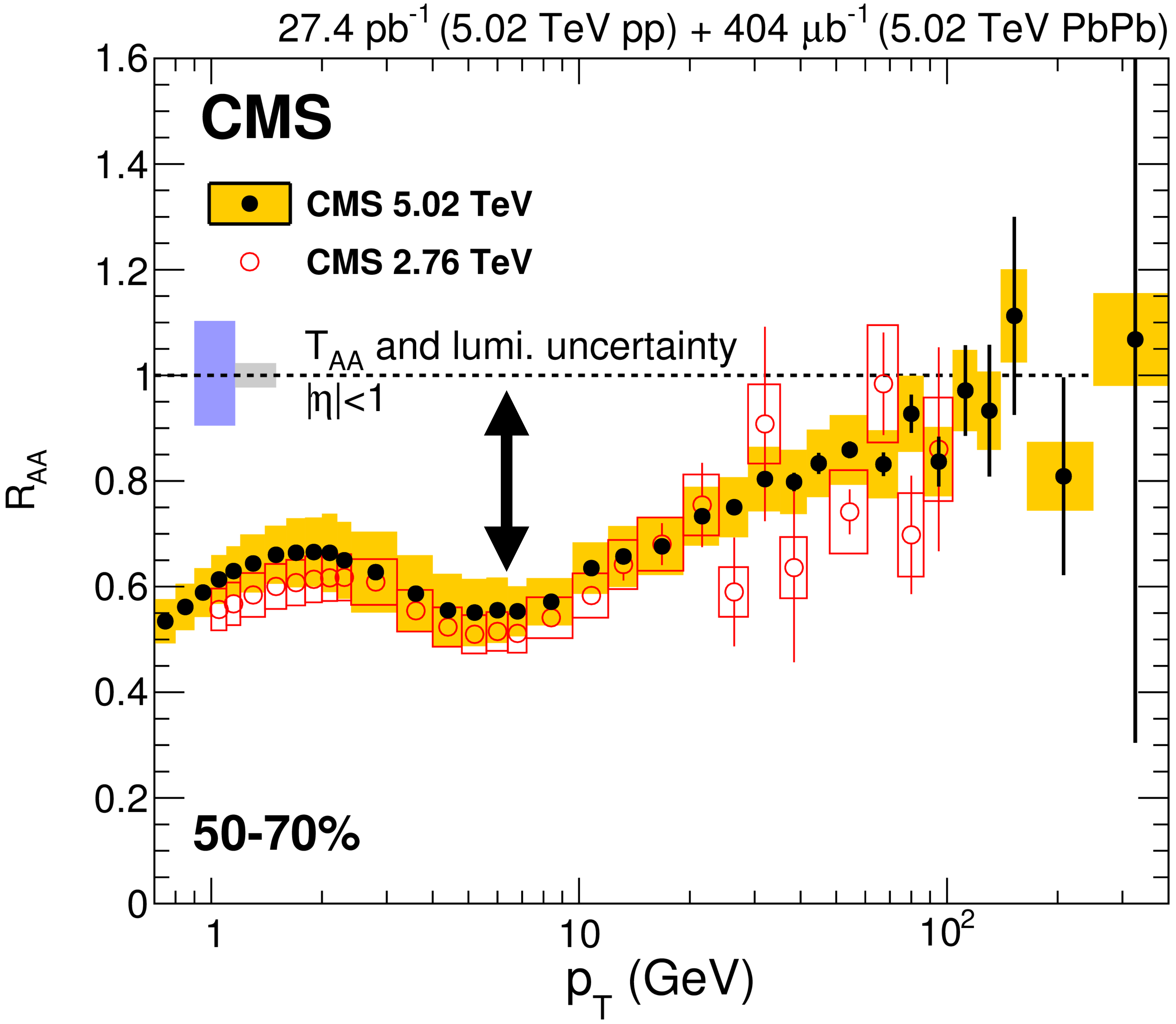


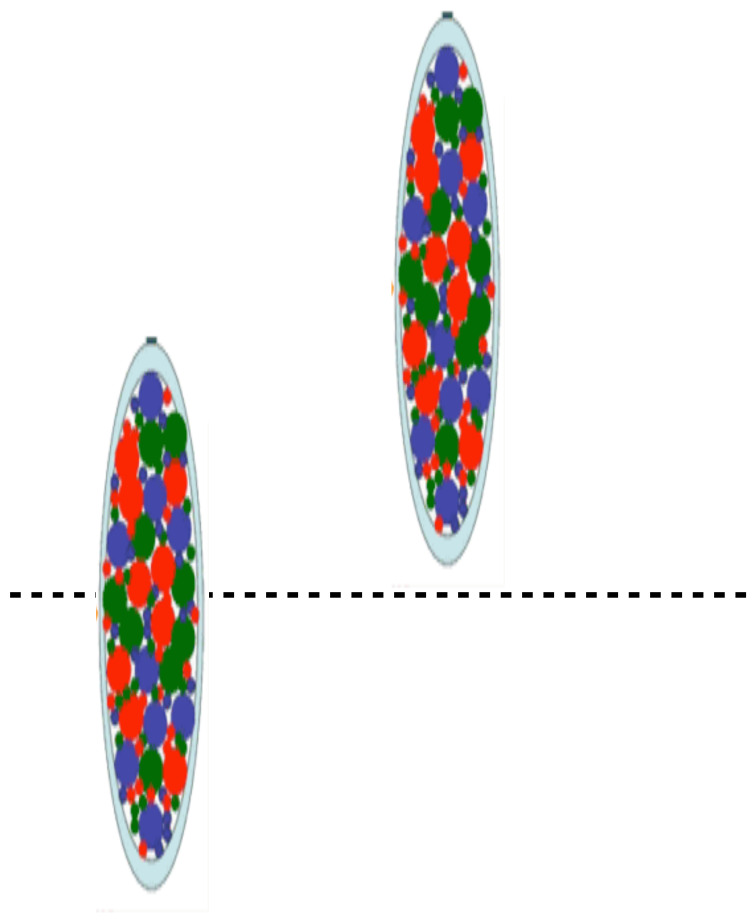


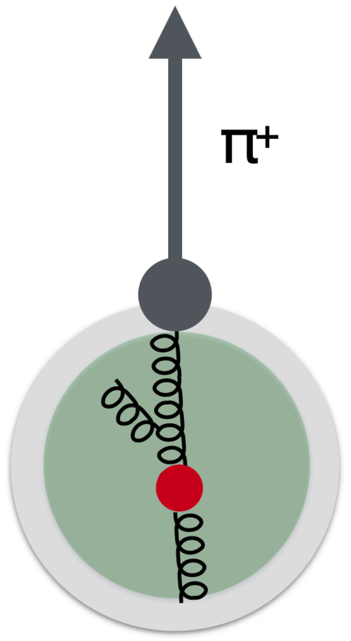
→**Strong suppression observed in central (head-on) collision** where the hottest and largest QGP is created

Charged hadron R_{AA} in "peripheral" PbPb collisions

CMS, JHEP 04 (2017) 039



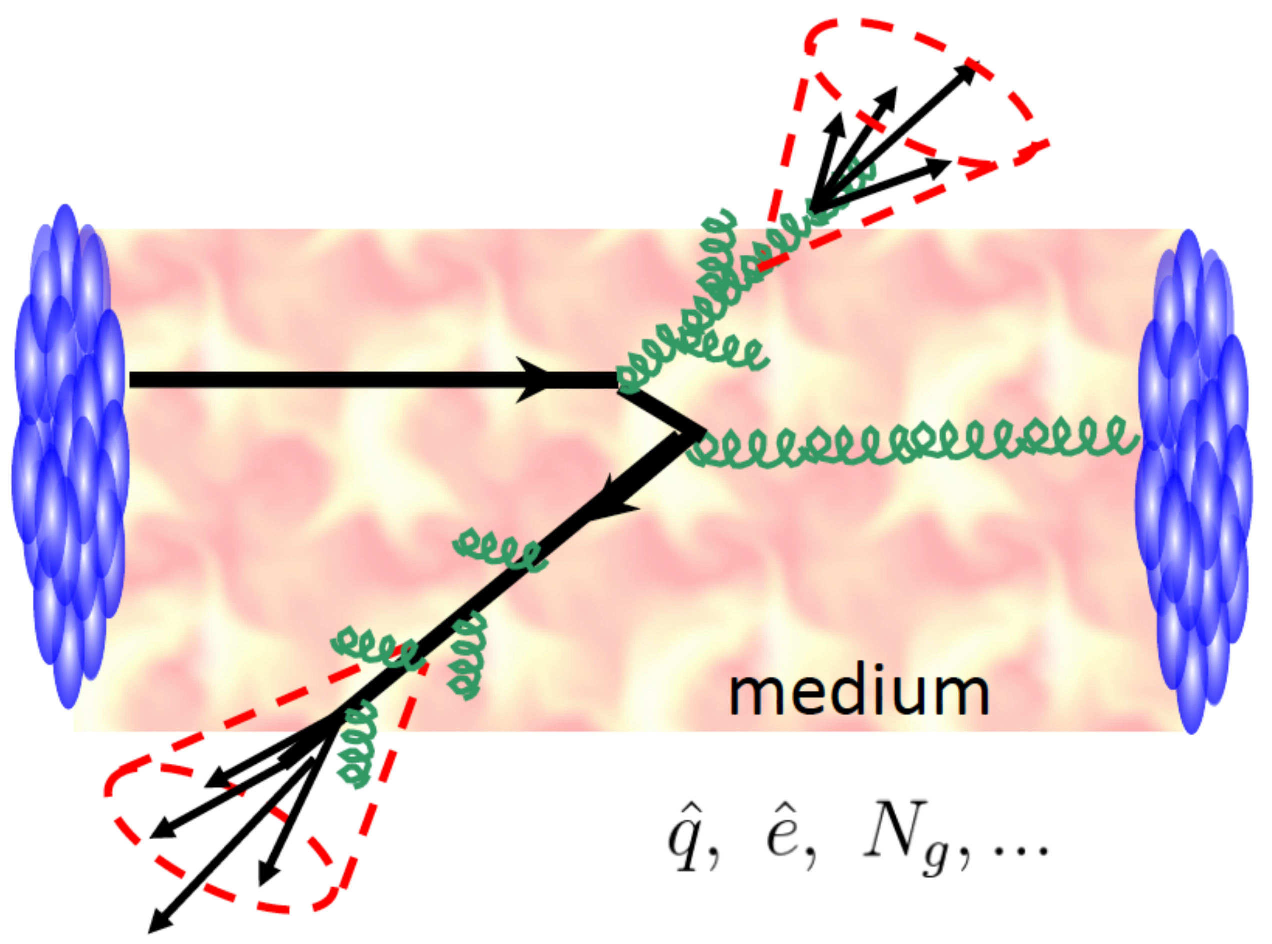




→Suppression is reduced in peripheral collision as naively expected in presence of a colder medium

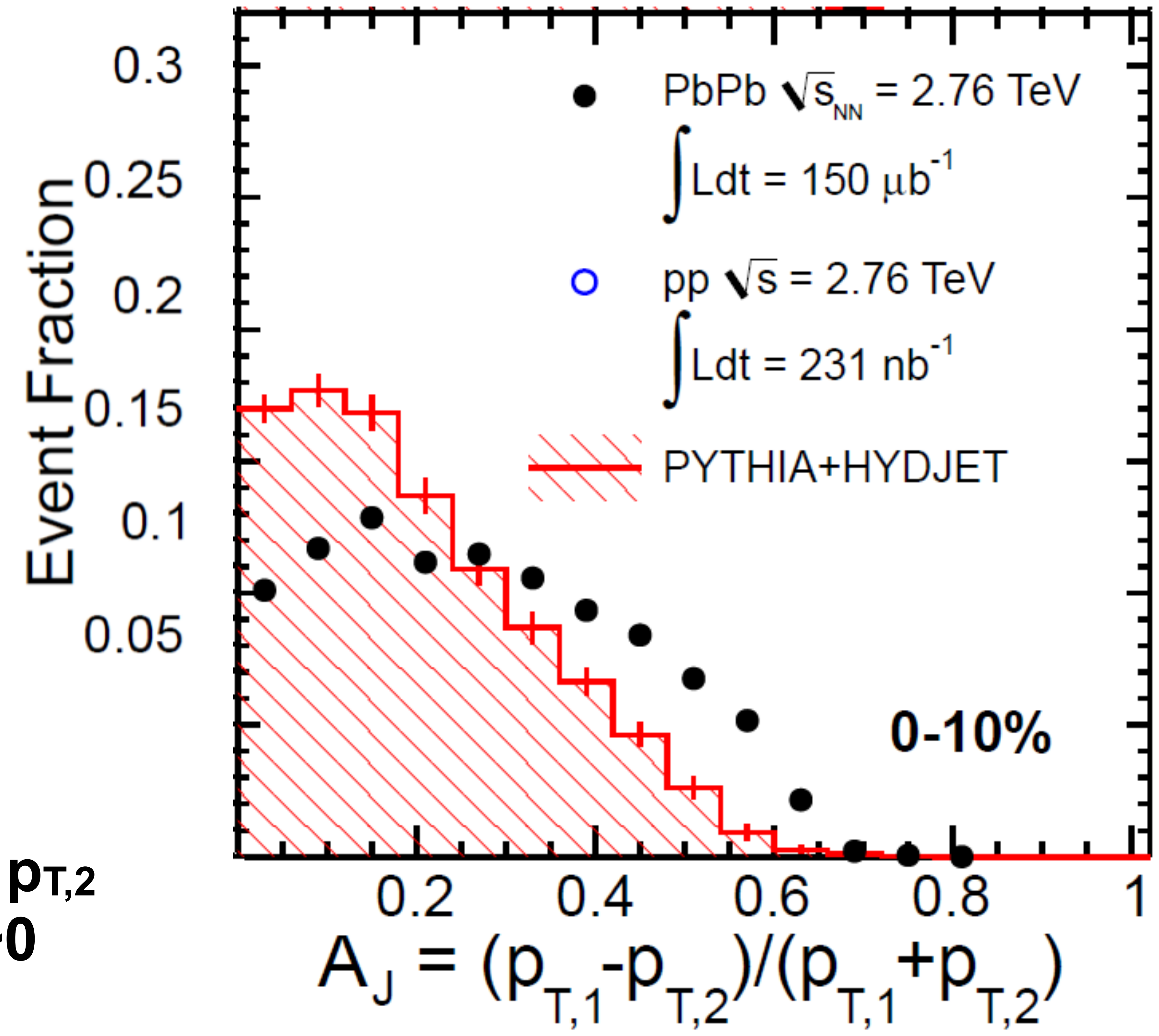
Jet-p_T asymmetry to probe quenching

$$A_j = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$



The two partons typically traverse a different path length inside the medium

$p_{T,1} \sim p_{T,2}$
$A_j \sim 0$



$p_{T,1} \gg p_{T,2}$
$A_j \sim 1$

→ **increase of the number of jets with large p_T asymmetry in PbPb compared to pp**

→ **All these measurements (both with single hadrons and jets) can be described by calculations ONLY in the presence of parton energy loss inside a colored medium!**

Jet quenching measurements with heavy flavor hadrons

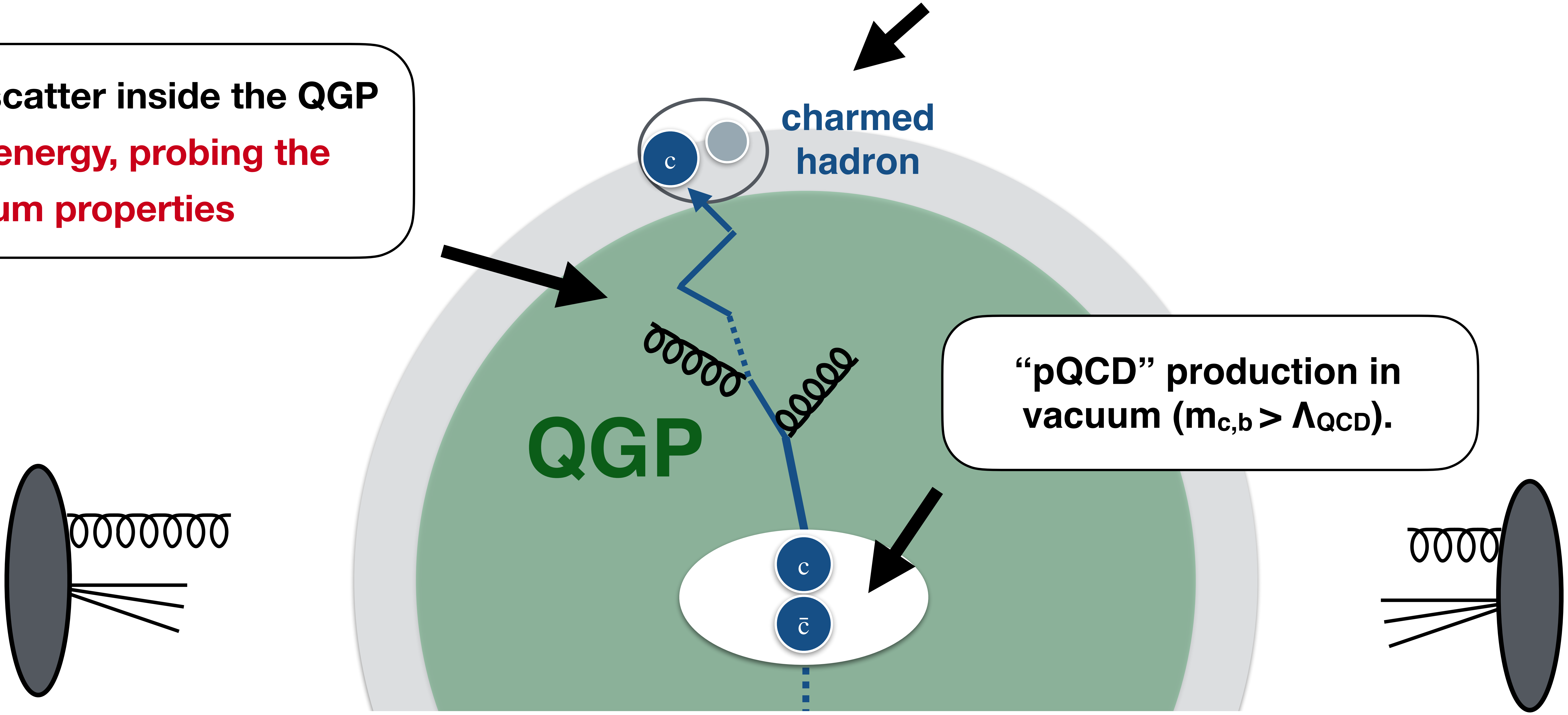
H-.T. Ding et al., arXiv 1504.05274
W. Busza, et al., ARNPS, Vol. 68:339-376, 2018

$m_c \sim$ 1.5 GeV
$\Lambda_{QCD} \sim$ 200 MeV
$T_{QGP} \sim$ 300 MeV
$m_{u,d,s} \lesssim T_{QGP}$

Hadronizes at the boundary of the QGP phase:
→probing the mechanisms of hadronization

HQs rescatter inside the QGP
→ lose energy, probing the medium properties

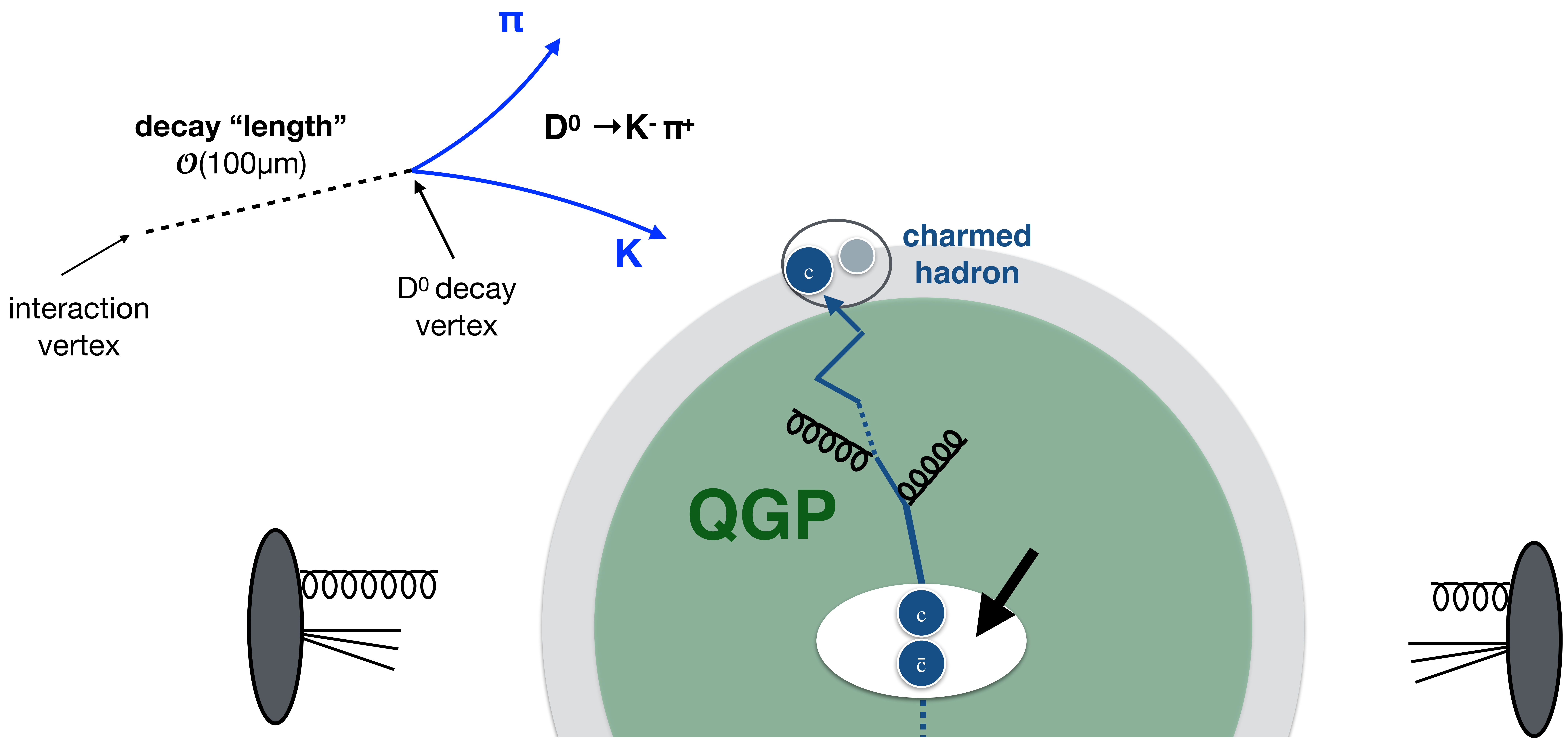
"pQCD" production in vacuum ($m_{c,b} > \Lambda_{QCD}$).



Jet quenching measurements with heavy flavor hadrons

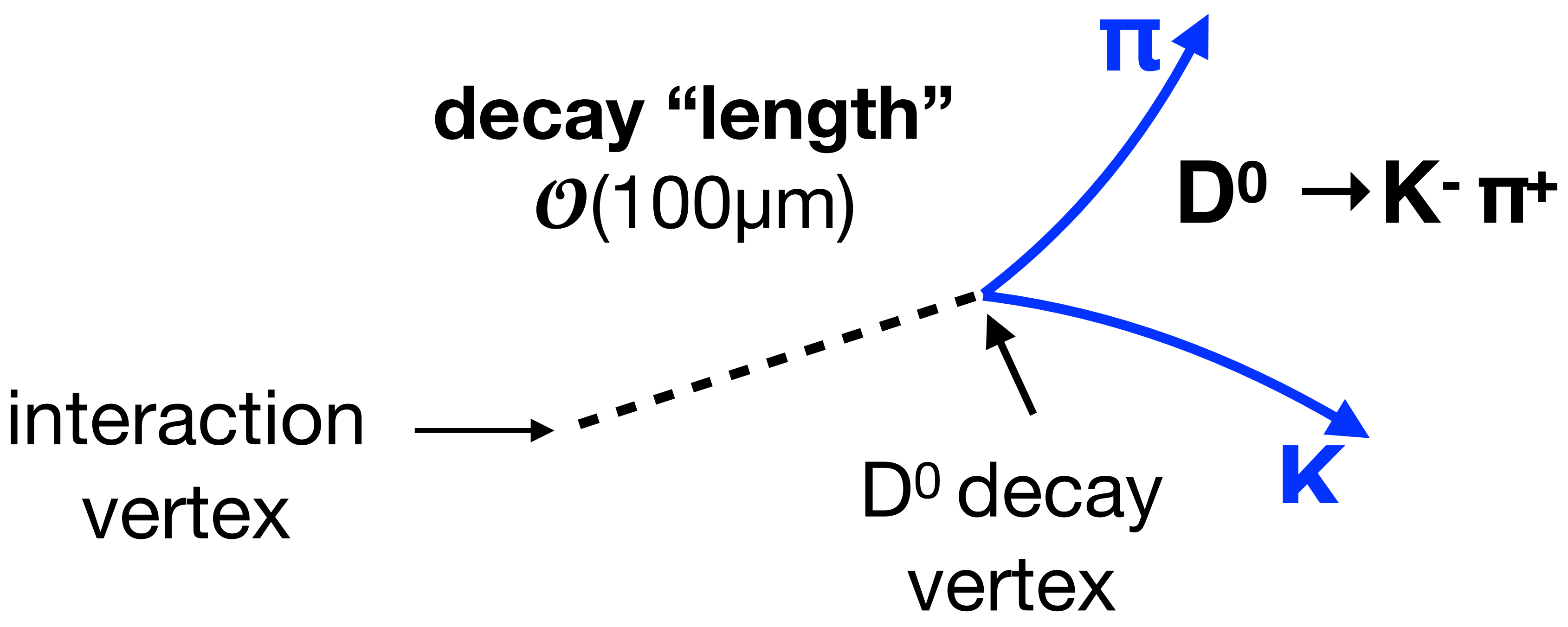
H-.T. Ding et al., arXiv 1504.05274
W. Busza, et al., ARNPS, Vol. 68:339-376, 2018

→ **Conserved and traceable witness of the QGP evolution** (no “thermal production)
→ **Experimentally accessible at any p_T via fully-reconstructed decays**

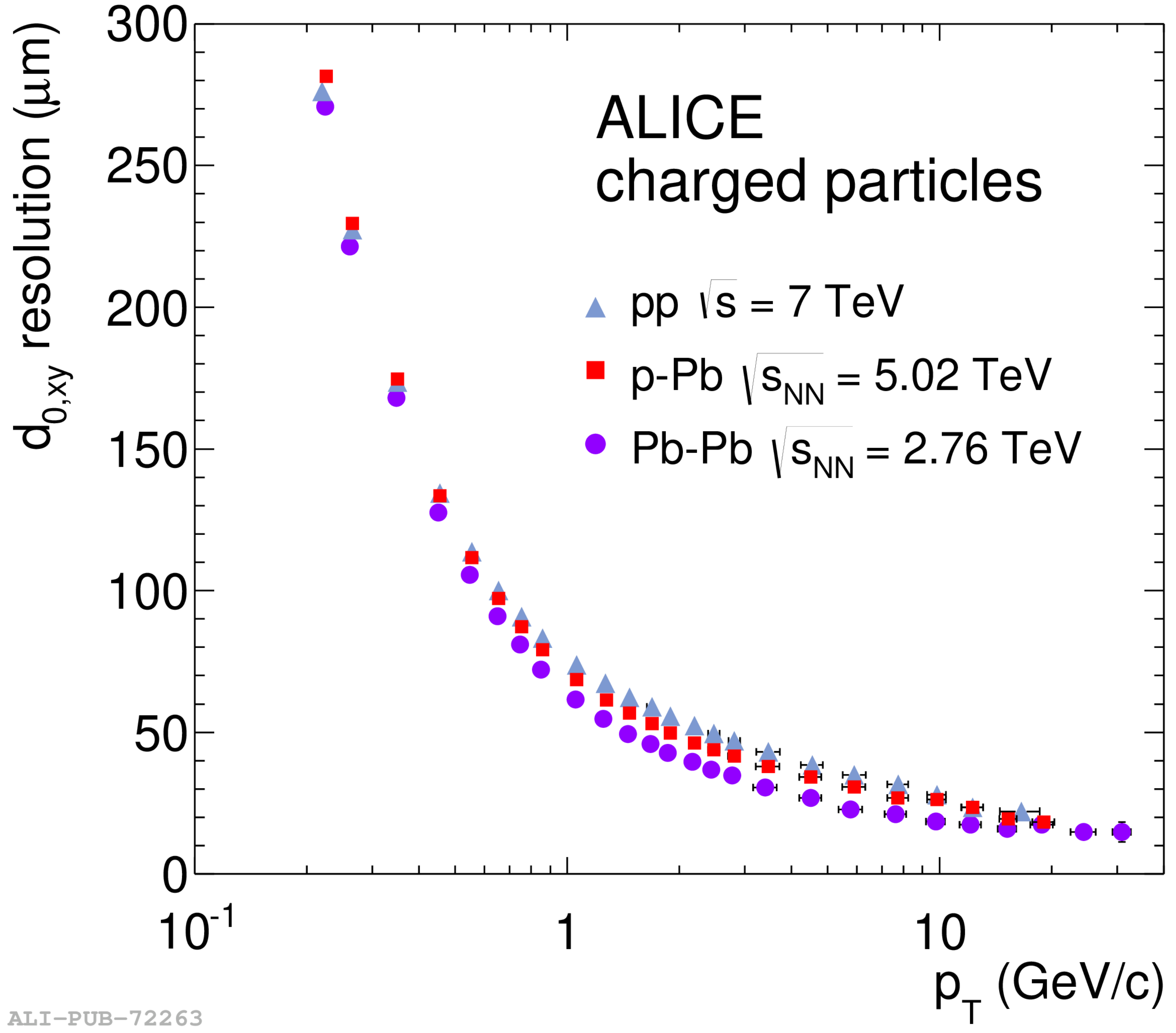


Fully-reconstructed heavy-flavor measurements in ALICE

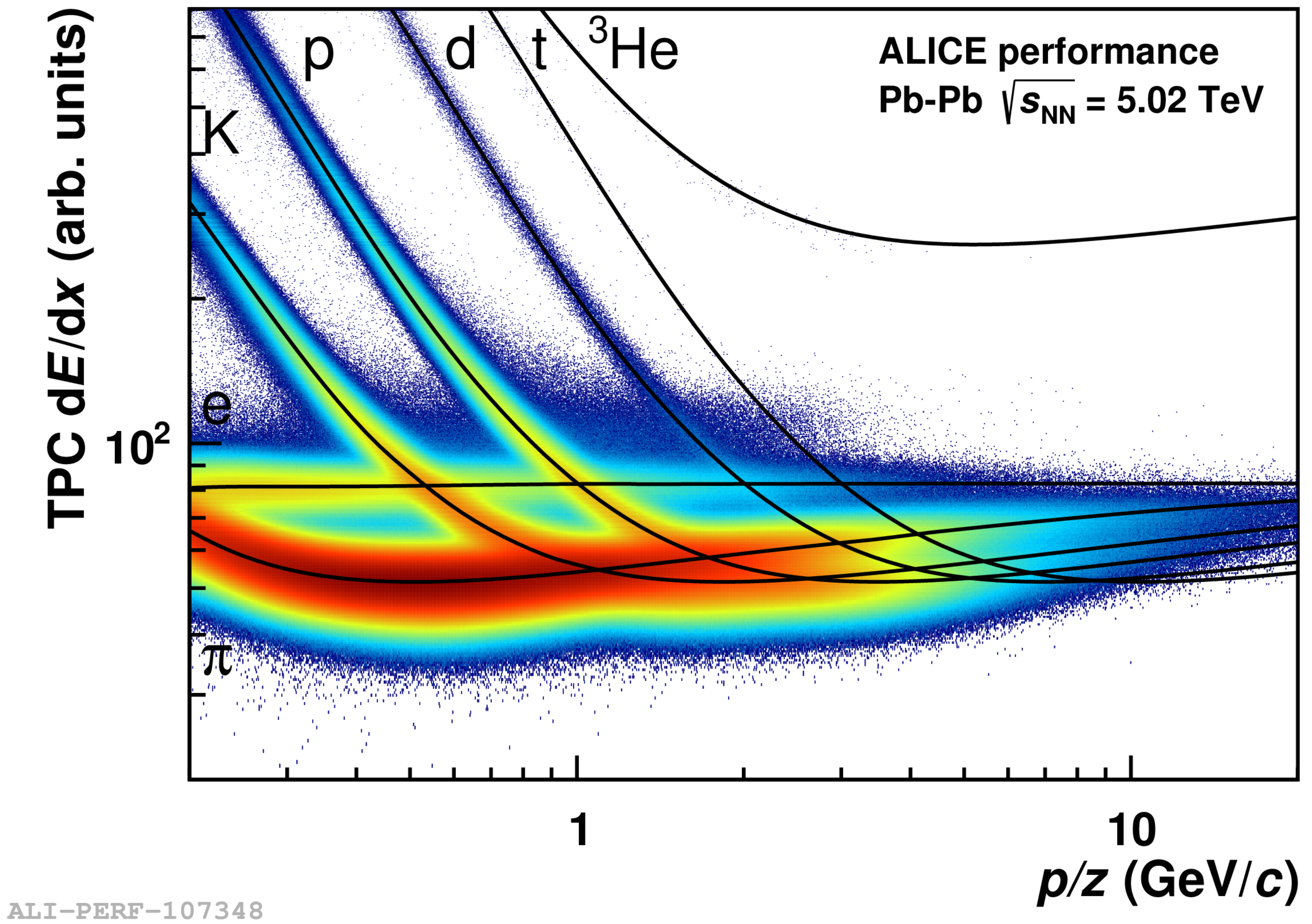
ALICE pioneered in Run 1 the **first measurements of fully reconstructed charm meson and baryons** down to low p_T with large minimum bias samples



Reconstruction of the secondary decay vertex



Particle identification of final state decays
with Time Projection Chamber dE/dx and Time of Flight



D and B meson reconstruction with CMS

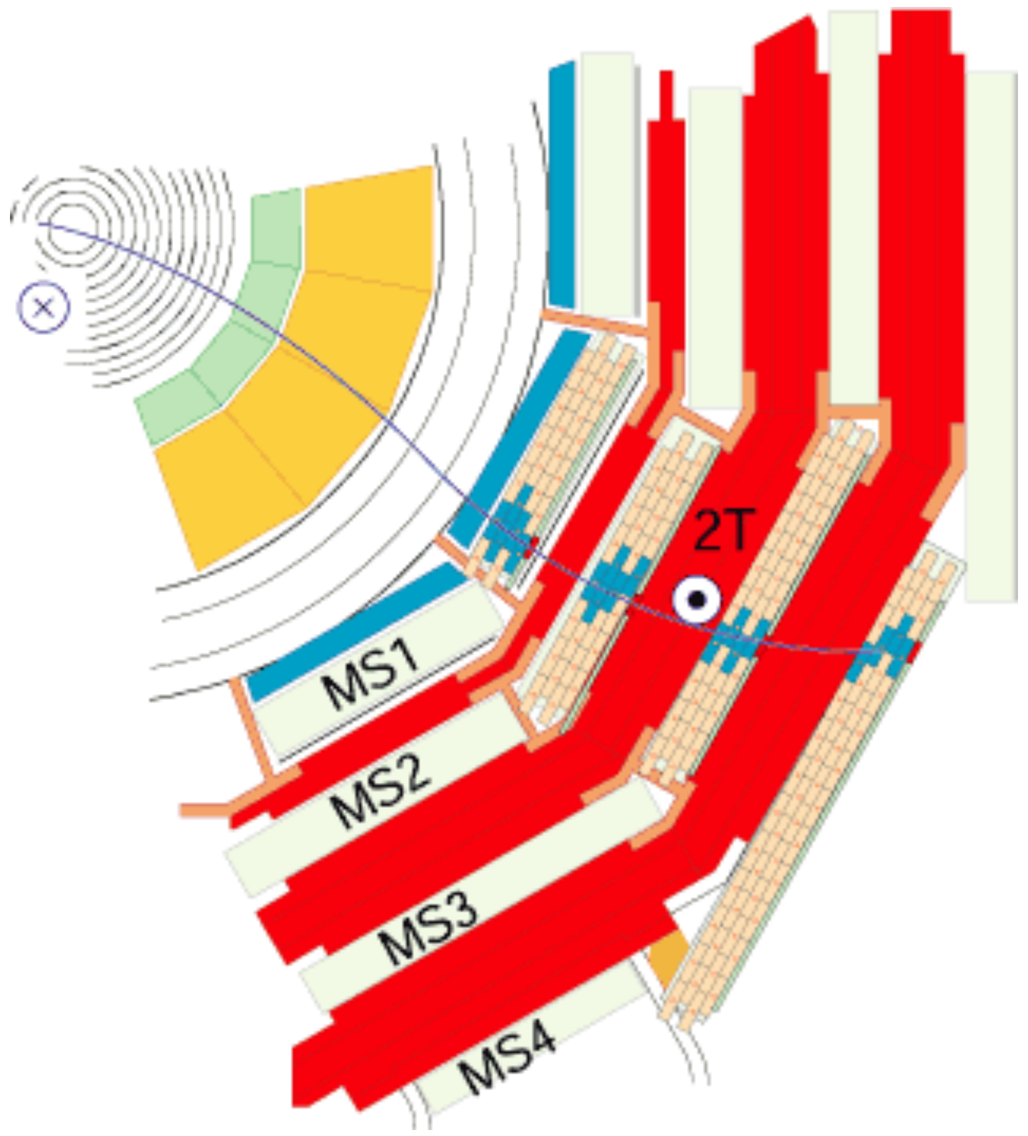
→ test the mechanisms of heavy-quark interaction with the hot medium at higher p_T

→ characterize the relevance of mass in the process of enhanced gluon radiation

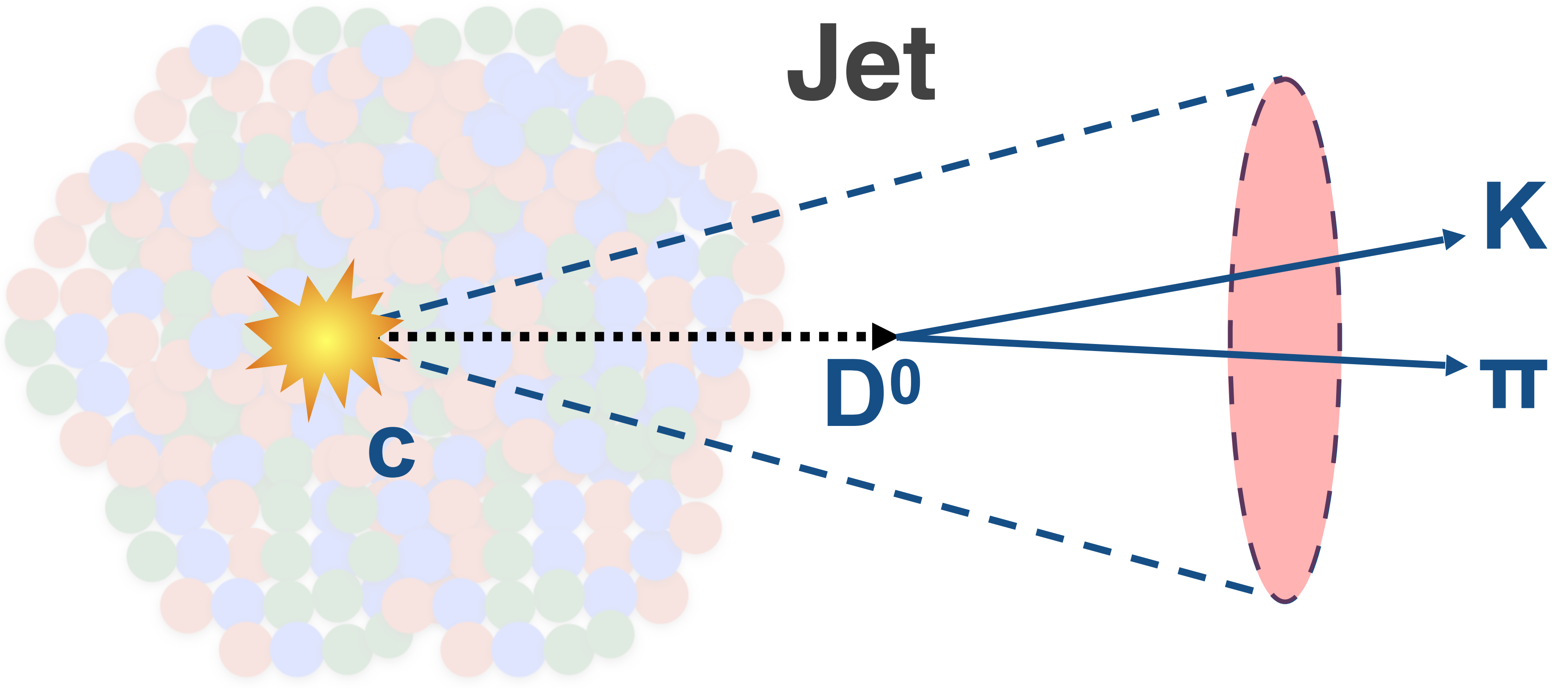
First B-hadron analyses in heavy-ion collisions:

→ **direct** access to the energy loss of b quarks

$B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+ \mu^- K^+$



D^0 measurement up to high-p_T



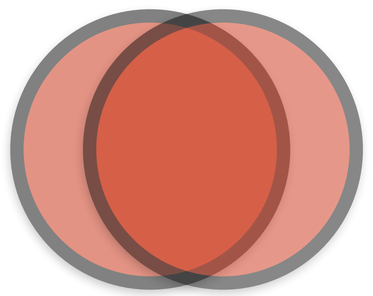
First D^0 jet-based trigger in heavy-ion collisions

- **hardware triggers with jet-background subtraction**
  - → upgrade of the Level-1 trigger system
- **"Online" D^0 tagging using software (High-Level) triggers**

CMS Collaboration, Phys. Lett. B 782 (2018) 474
B. Kreis, GMI et al., 2016 JINST 11 C01051

Evidence for in-medium energy loss of charm quarks

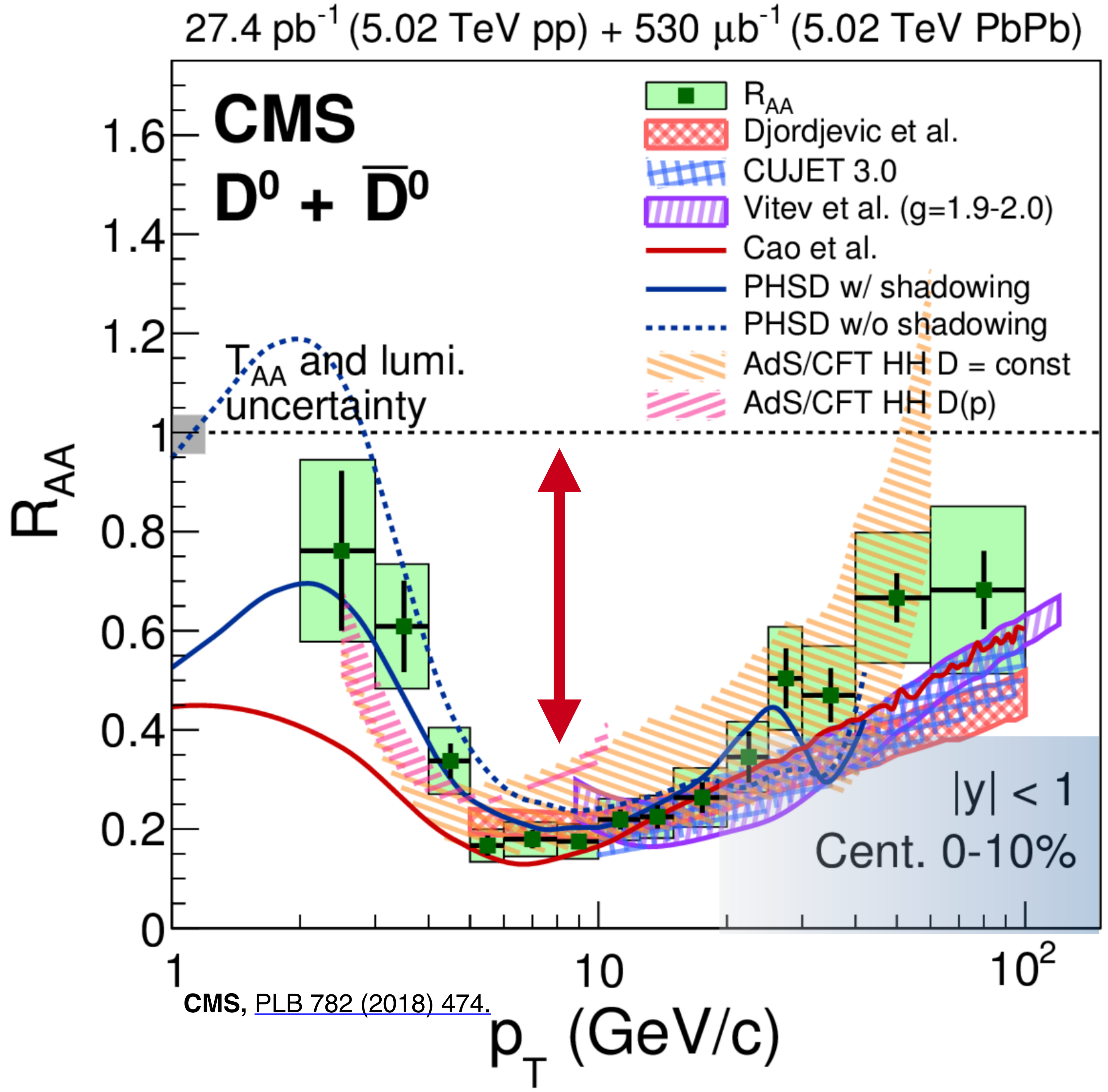
D^0 mesons



Central 0-10%

→ head-on collision!

→ larger energy density



CMS, PLB 782 (2018) 474.

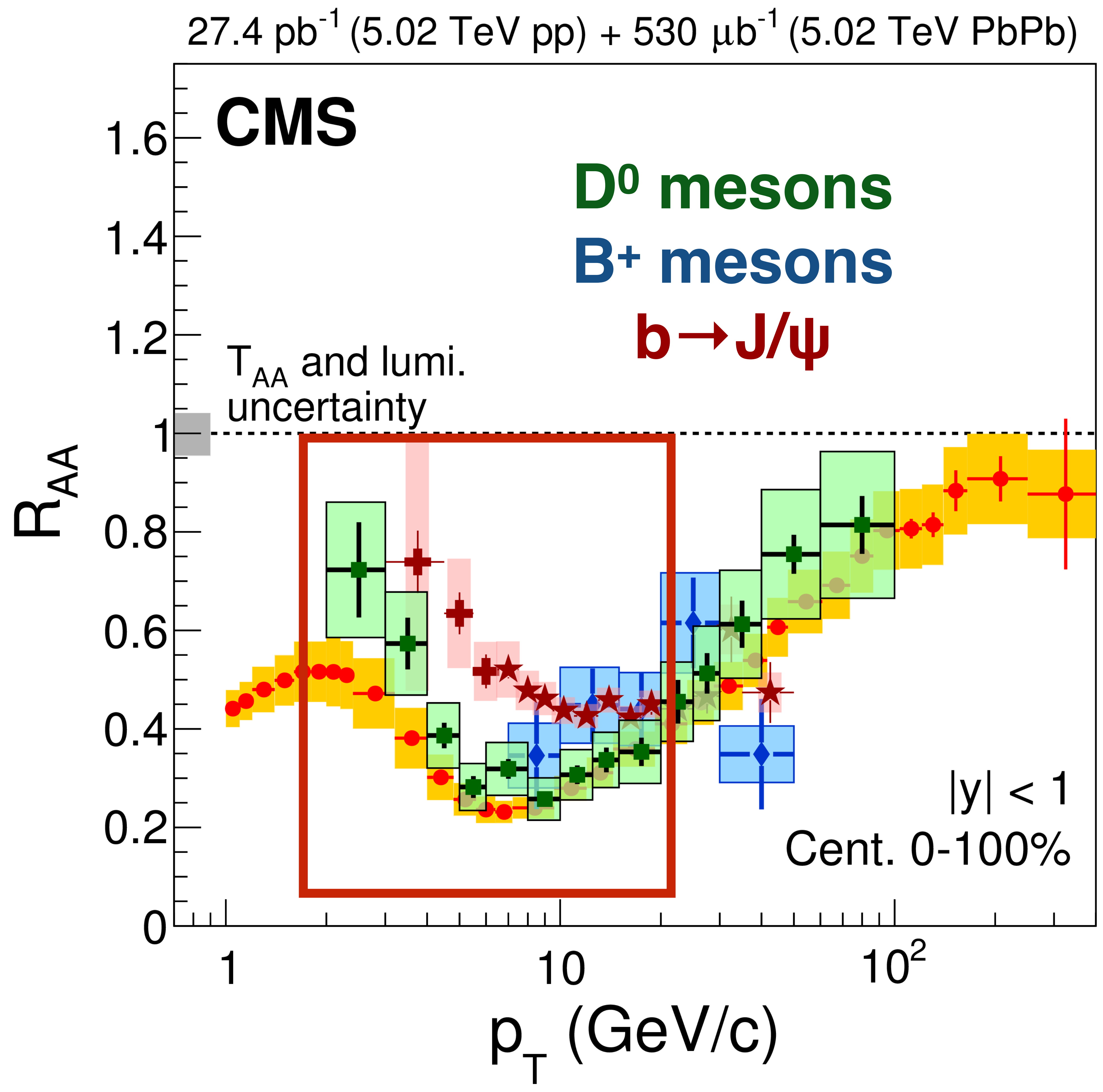
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(AA)}{dN/dp_T(pp)}$$

← R_{AA}=1: **no modification**

R_{AA} << 1 → charm quarks strongly interact with the hot medium, and lose a sizeable amount of energy!

Mapping the role of mass in heavy-quark E_{loss}

CMS, PRL (2016), 032301.
CMS, PLB 782 (2018) 474.
CMS, PRL 119, 152301 (2017).
CMS, PRL 125, 102001 (2020).



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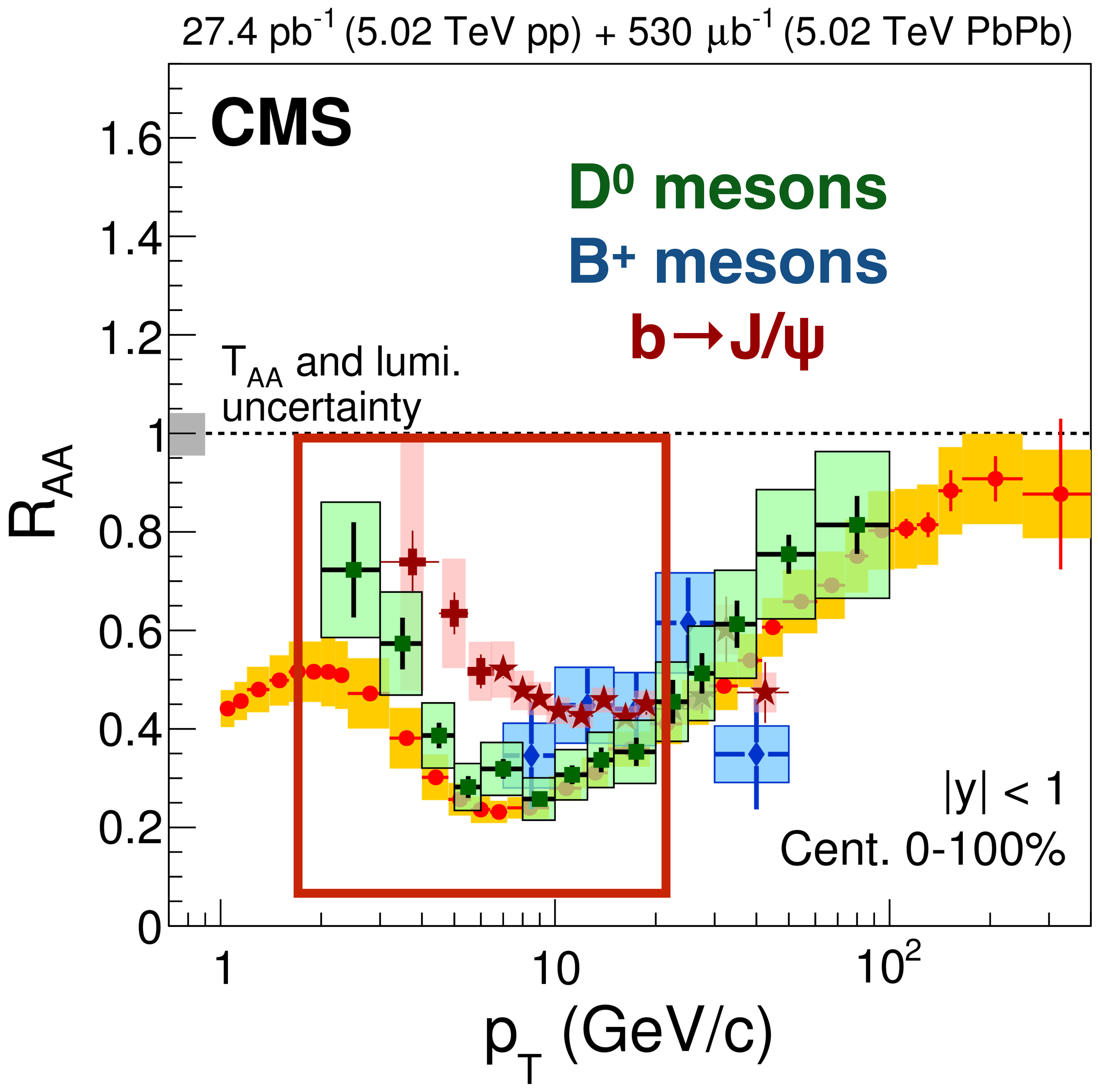
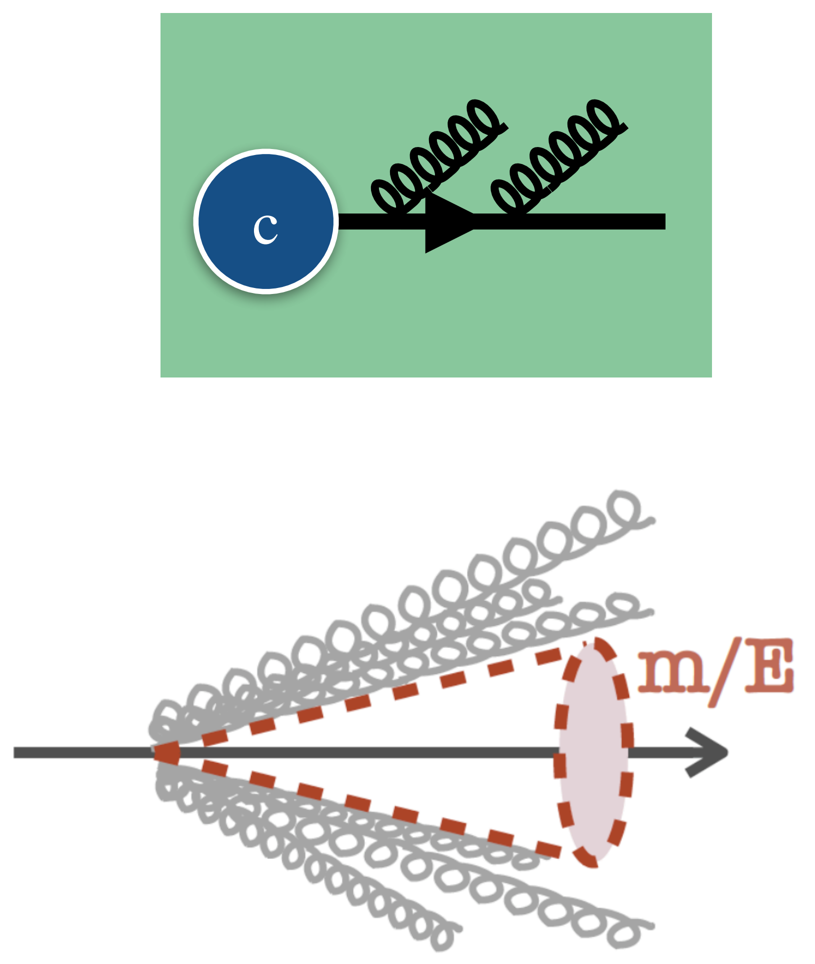


→ **First constraints on the different magnitude of charm and beauty E_{loss}**

Physics interpretation (perturbative QCD)



→ increased gluon radiation

→ **modified spitting functions $P_{c\to cg}$**

Suppression of small angle radiation for heavy quarks

→ **E_{loss} (c) > E_{loss} (b)**

BDMPS, Nucl.Phys., B484:265–282, 199
B.G. Zakharov, JETP Lett., 63:952–957, 1996.

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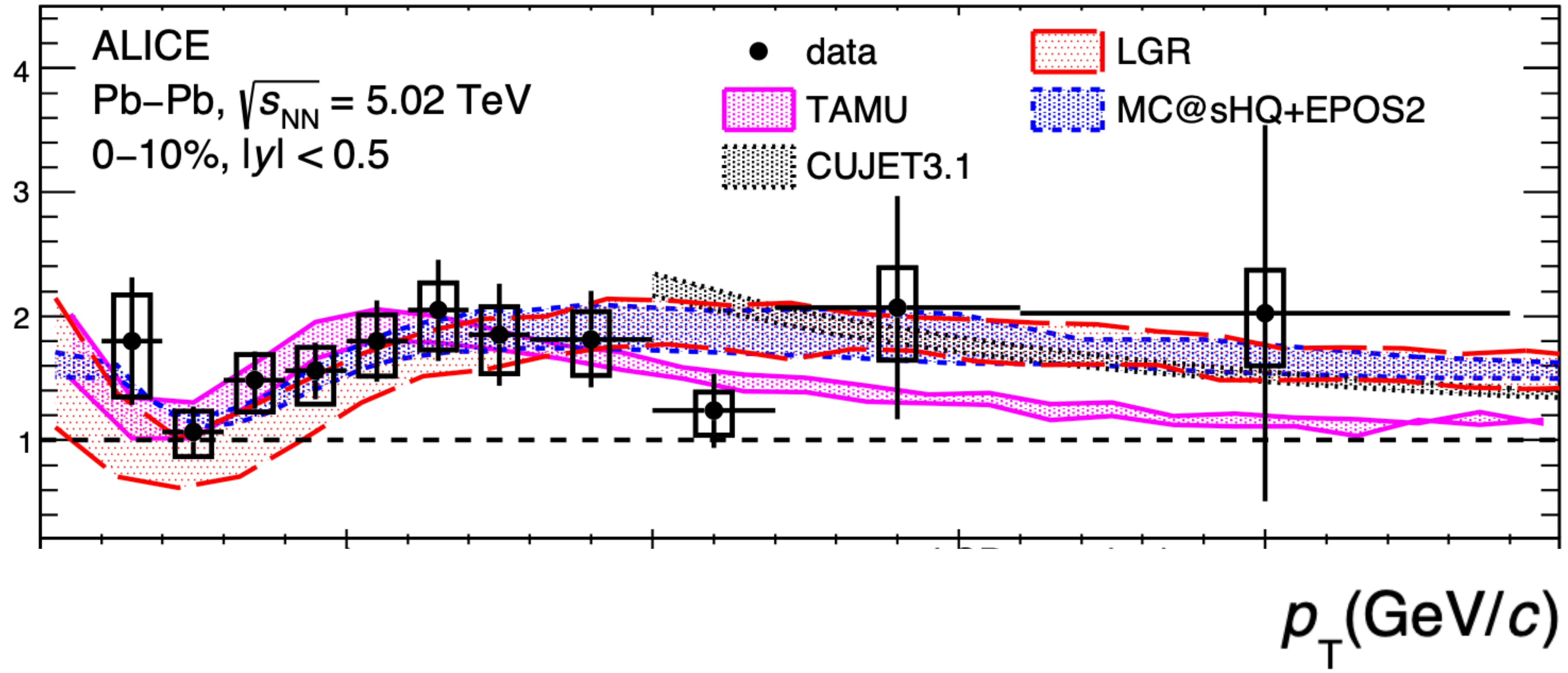
CMS, PRL 119, 152301 (2017).
CMS, PRL 125, 102001 (2020).

ALICE, JHEP 12 (2022) 126

$$\frac{R_{AA}(b \rightarrow D^0)}{R_{AA}(D^0)}$$



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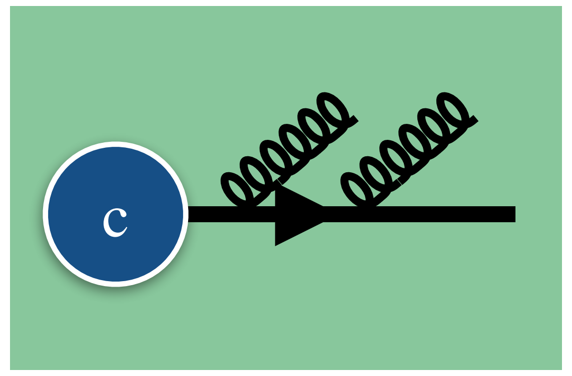

→ increased gluon radiation
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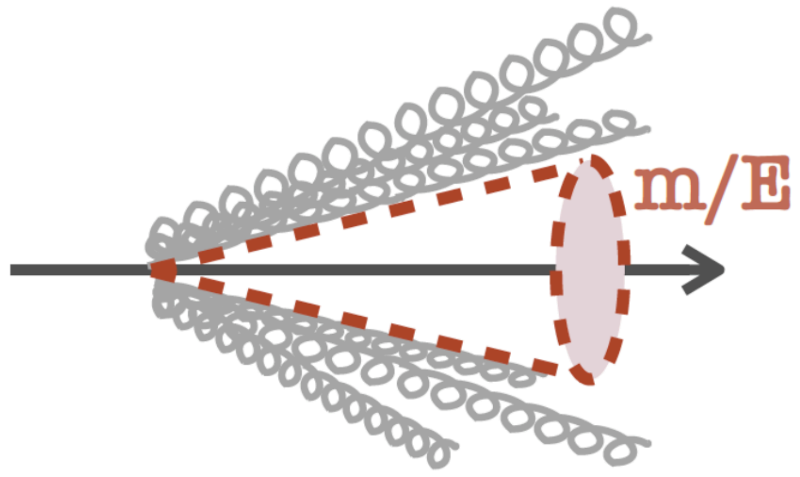

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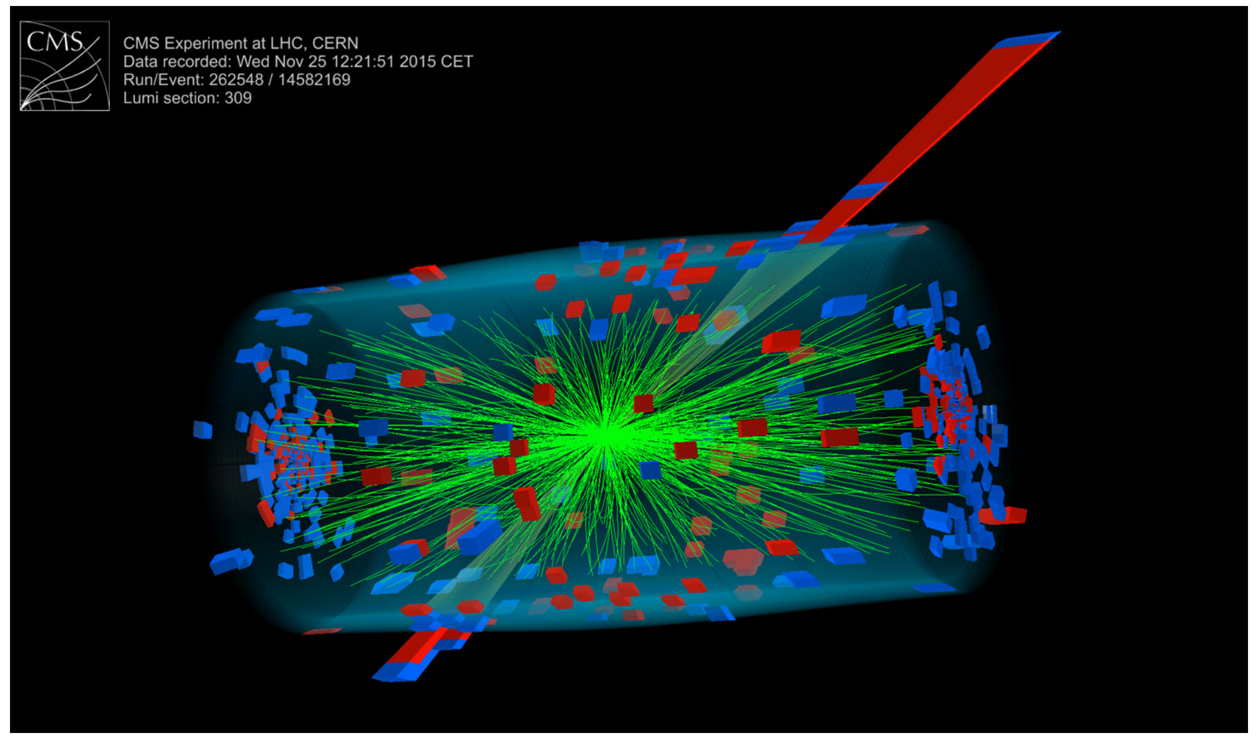
→ **Flavor-dependence of in-medium energy loss** as a “clean” predictions of pQCD in the presence of a “colored” medium (although it might be not as simple as we thought …)

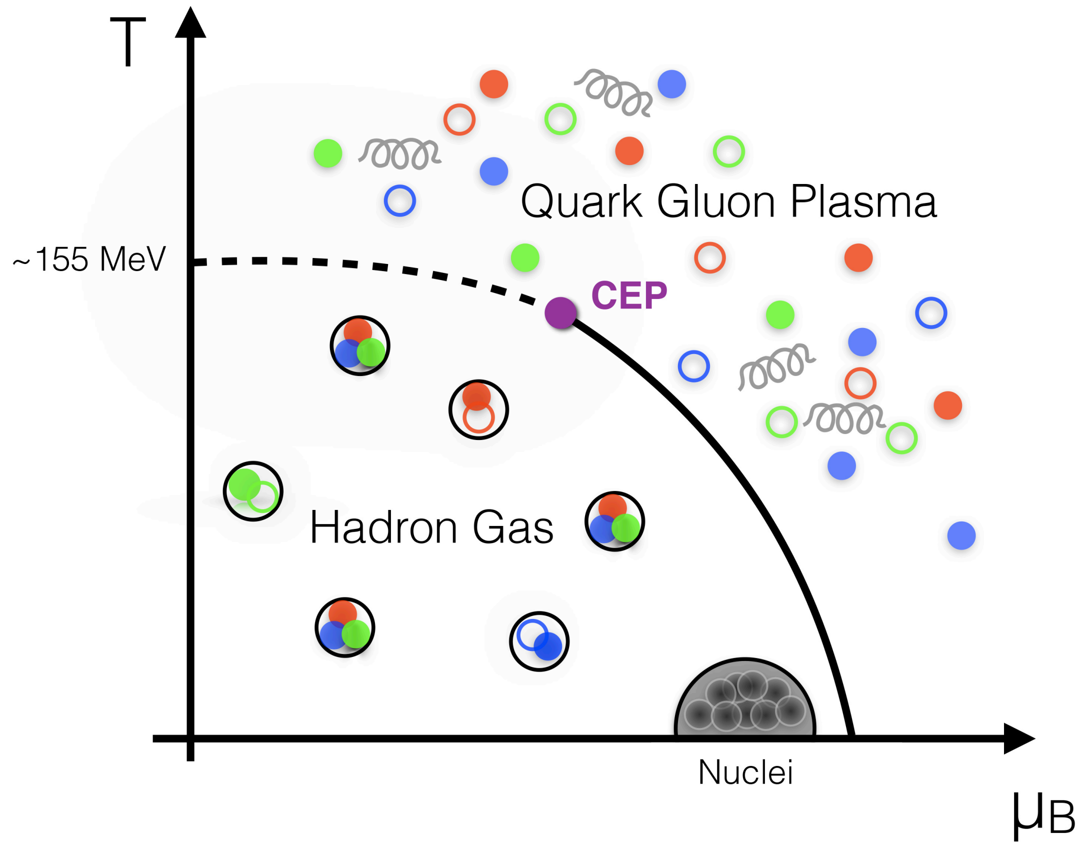
Summary

What have we learnt about heavy-ion physics?

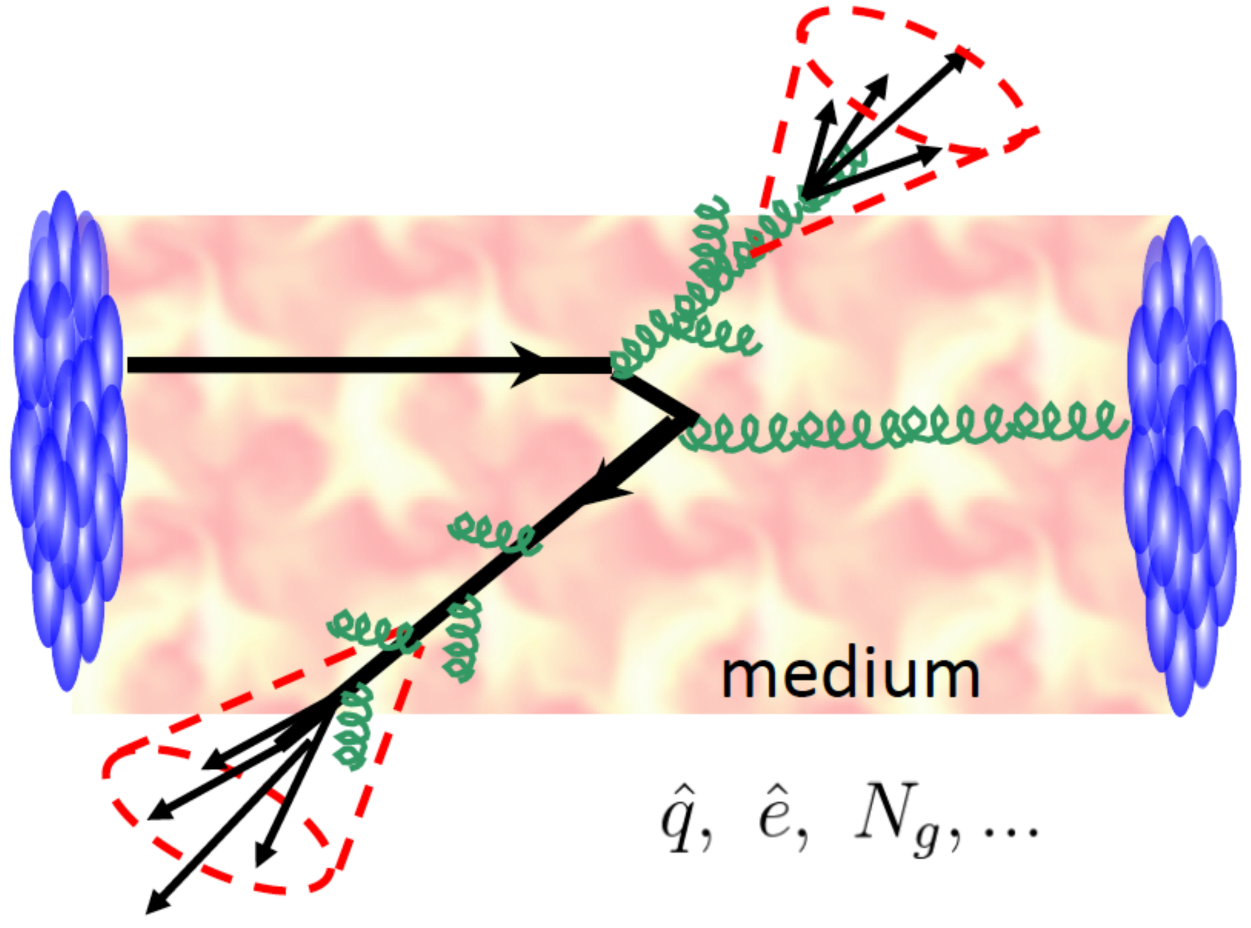
The challenge

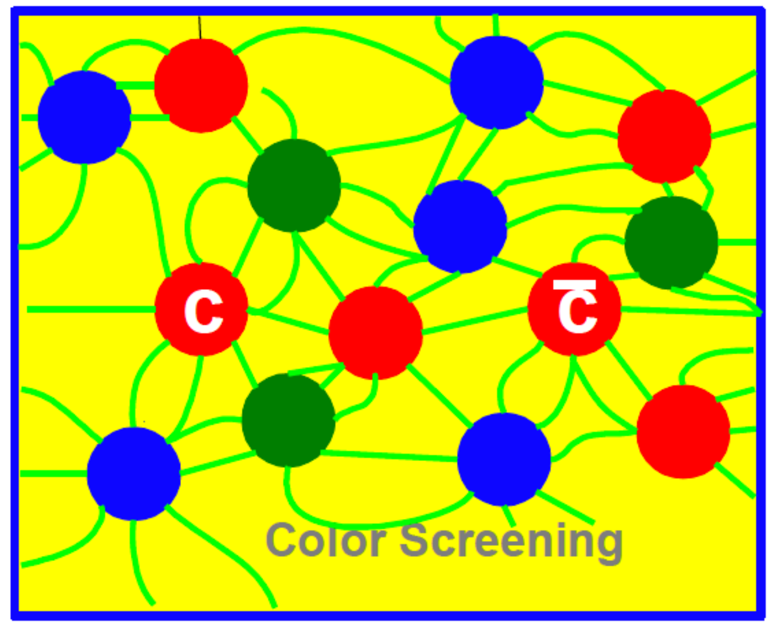


$$\mathcal{L}_{\rm QCD} = \bar{q}(i\gamma^\mu D_\mu - m)q - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu}_a$$

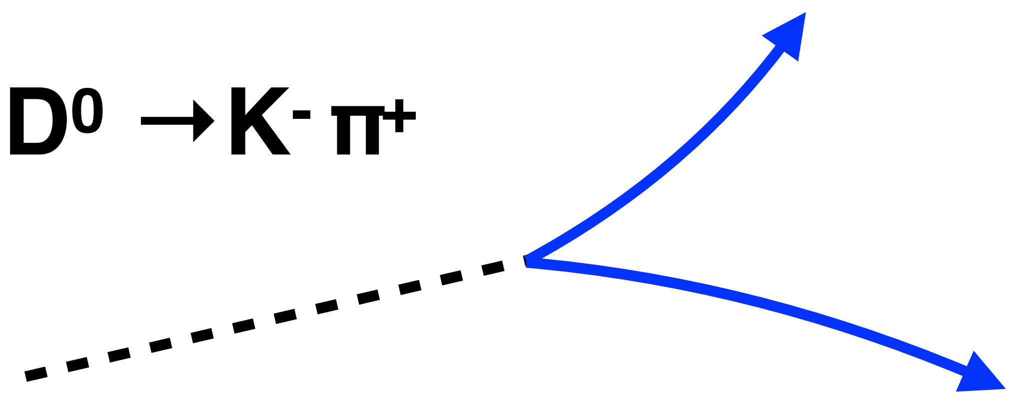


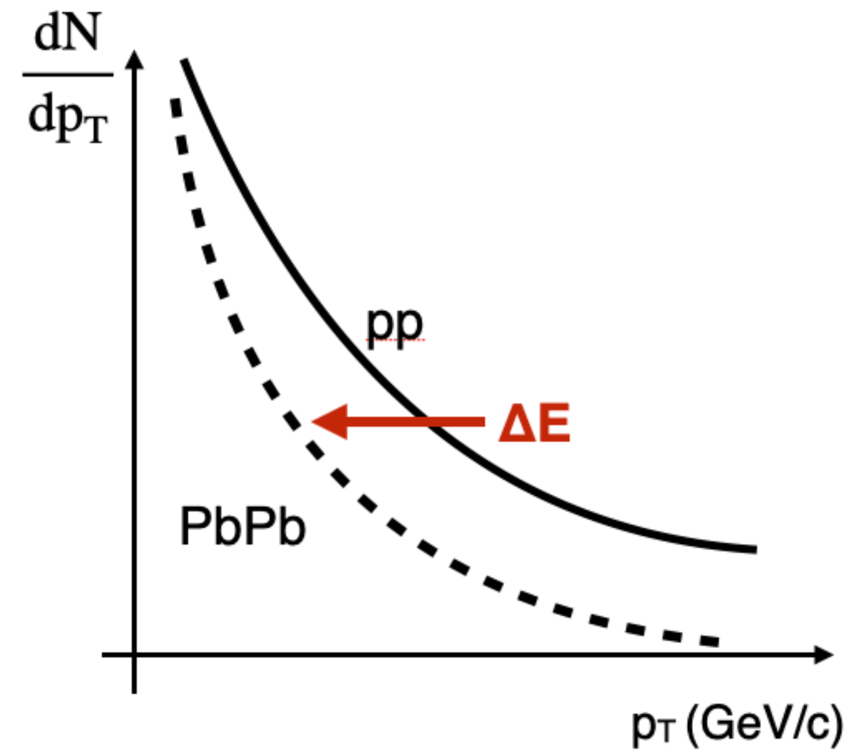
Theoretical and experimental “toolbox”





$D^0 \rightarrow K^- \pi^+$





What have we learnt about the hot nuclear matter we create?

- **In heavy-ion collisions,** we create the conditions for forming a new phase of nuclear matter
- Several experimental evidences confirm the creation of **a hot nuclear medium with deconfined color charges**

- **What kind of deconfined medium have we created?**
- **Does it behave like a weakly-interacting gas of quark and gluons?**

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- **Does it behave like a weakly-interacting gas of quark and gluons?**

  → **More detail tomorrow 🙂!**

↓

- **Experimental signatures (II):**
  - Collectivity in hadronic collisions
- **From phenomenology to first principle QCD:**
  - a new era for quenching measurements
- **High-density QCD in the 20's, 30's and beyond**

thank you for your attention!

ginnocen@cern.ch

BACKUP SLIDES