Ultrarelativistic Heavy-Ion Physics and the Quark-Gluon Plasma

Part3

- Hard Probes (jets, heavy quarks)
- Energy loss
- Quarkonium

How does a quark-gluon plasma affect particles traversing it?

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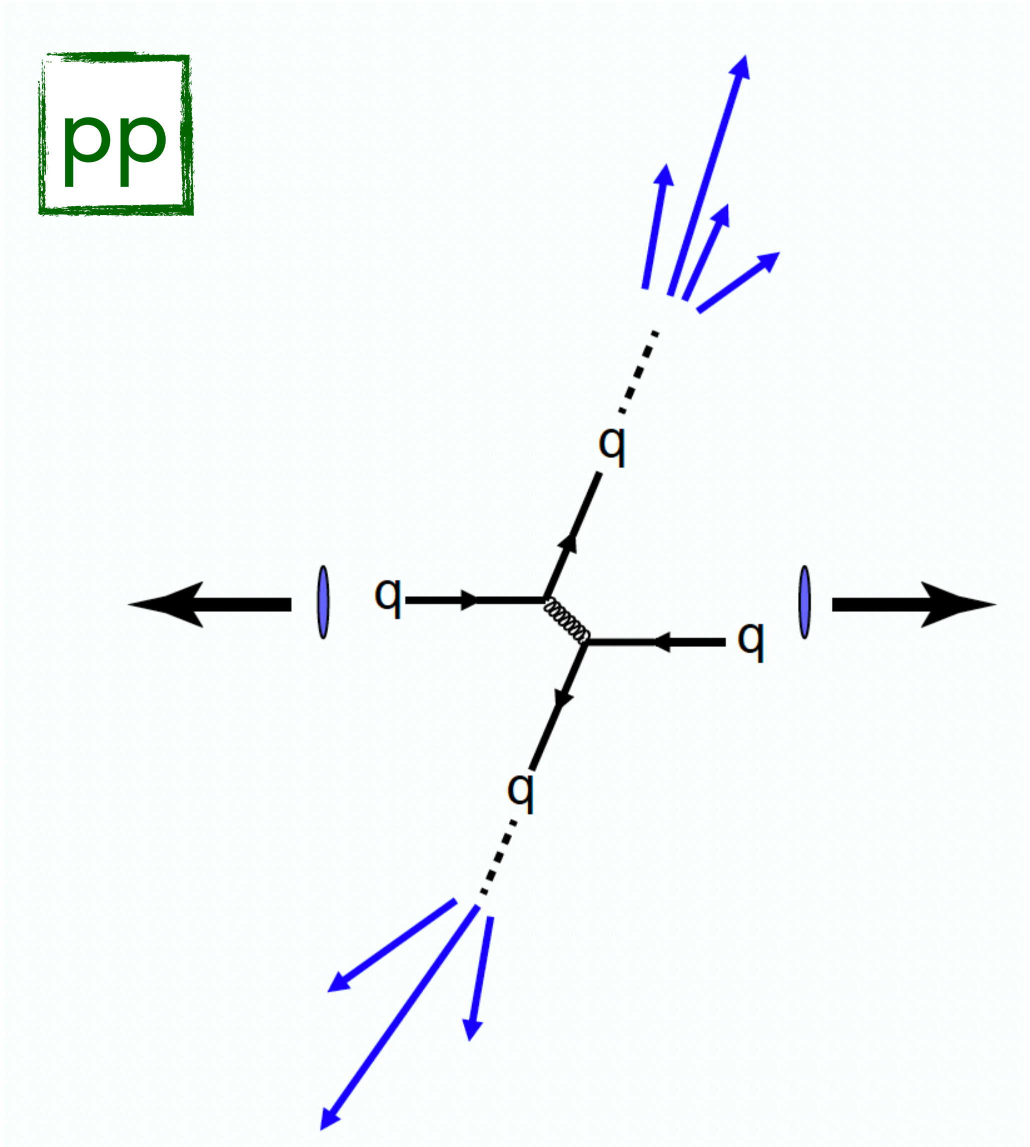
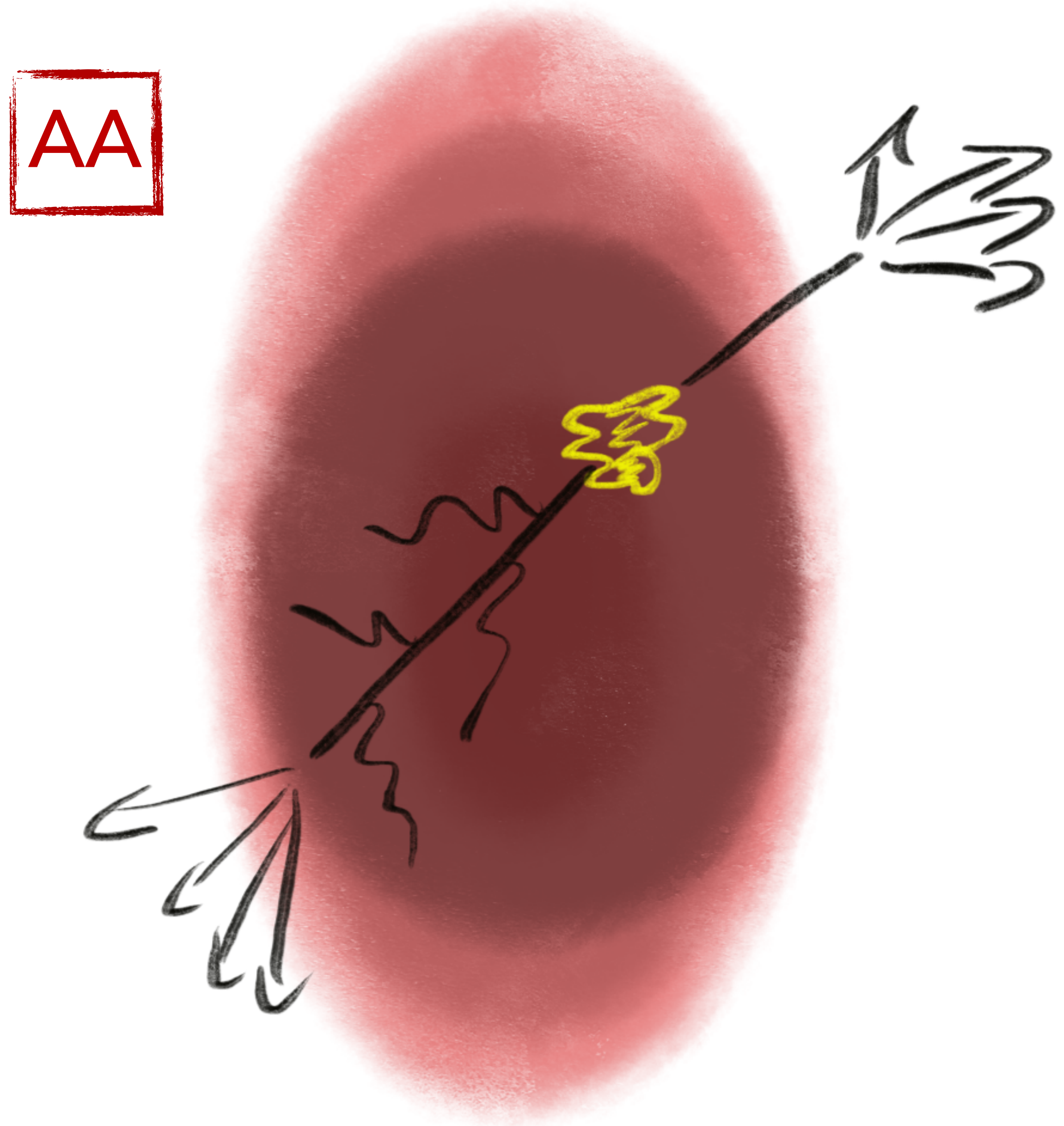
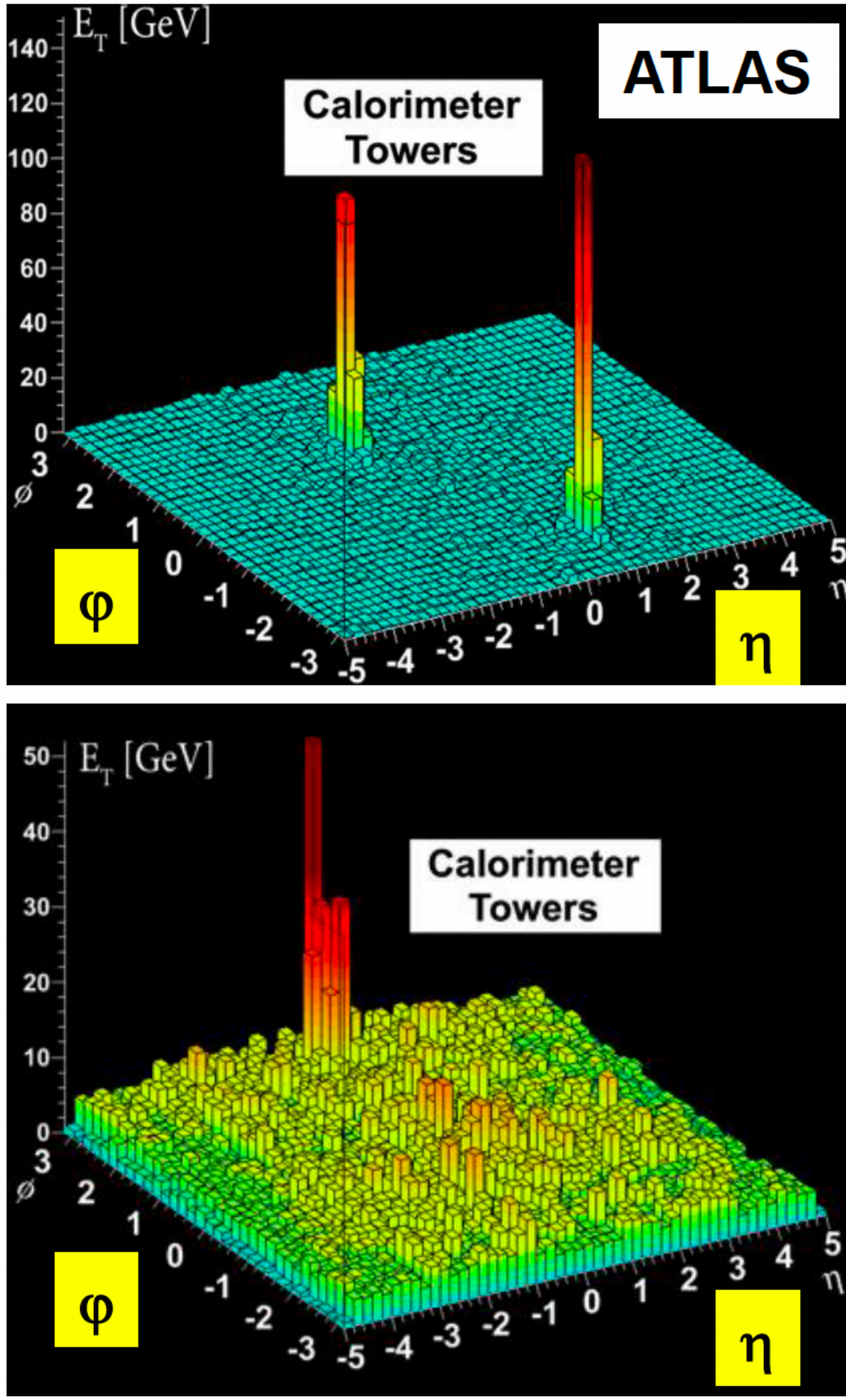
A back-to-back jet







One jet disappears in the QGP → "Jet quenching"

ATLAS, PRL105:252303,2010

Dijet asymmetry

- How often do jets lose lot of energy?
- Quantify by dijet asymmetry
- 2 highest energy jets with $\Delta\phi > \frac{2}{3}\pi$

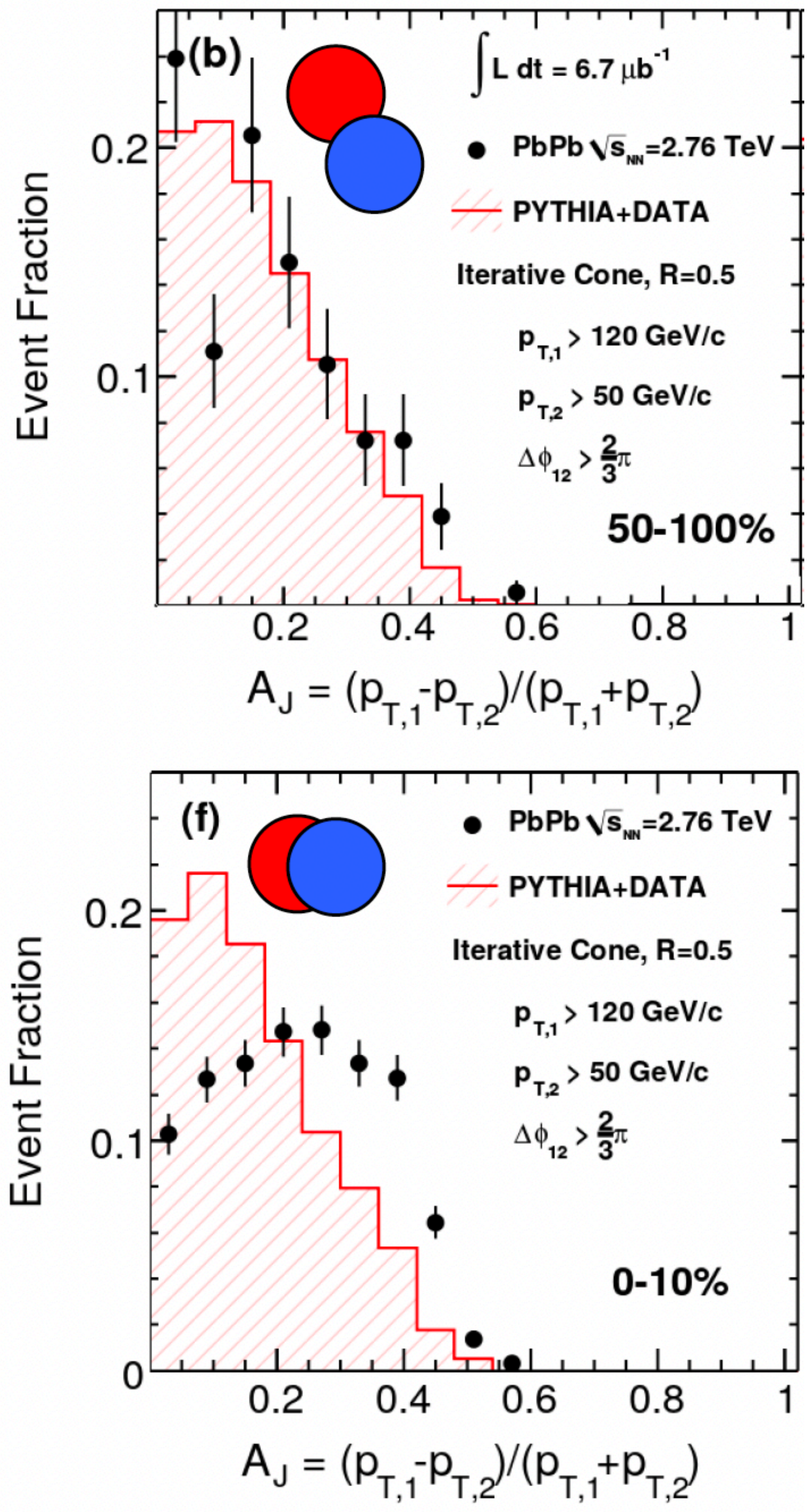
$$A_J = \frac{|p_{T1} - p_{T2}|}{p_{T1} + p_{T2}}$$

$p_{T1} = p_{T2} \rightarrow A_J = 0$

$1/3\ p_{T1} = p_{T2} \rightarrow A_J = 0.5$

- Peripheral collisions: Pb-Pb ~ Pythia
- Central collisions: Significant difference

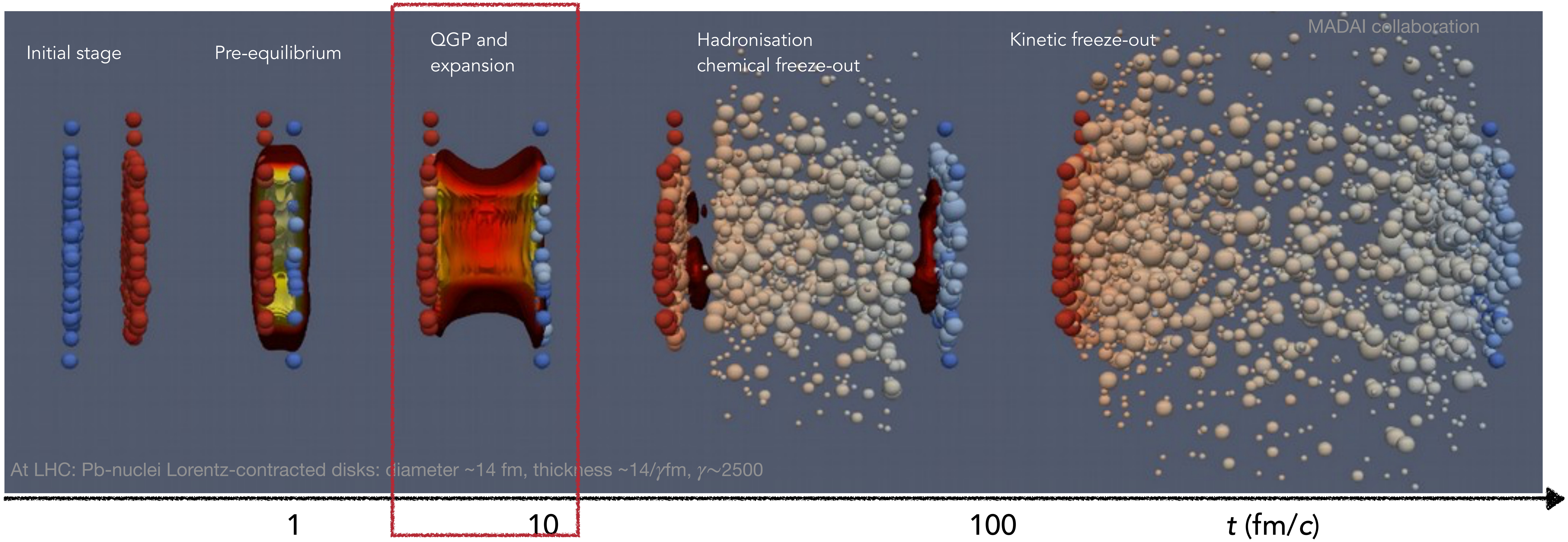
Jets lose up to two thirds of their energy !



PRC 84 (2011) 024906
PRL105:252303,2010

Introduction: Heavy-Ion Physics

Space-Time Evolution of a Heavy-Ion Collision



Characterise medium properties

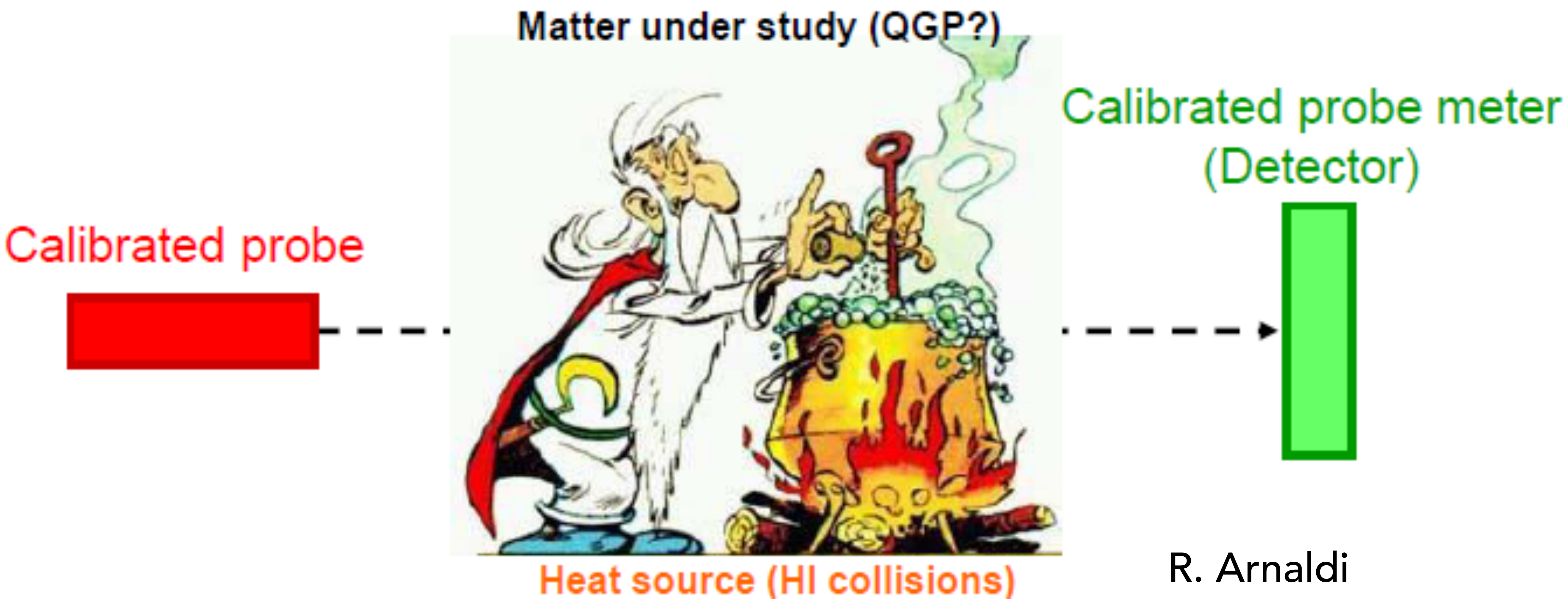
- Colour deconfinement
- Parton energy loss

How can we observe the properties of the created matter?

- External probes cannot be used to study its properties
  - QGP exists in the lab only for ~10^{-23}s
  - No free colour charges as probes

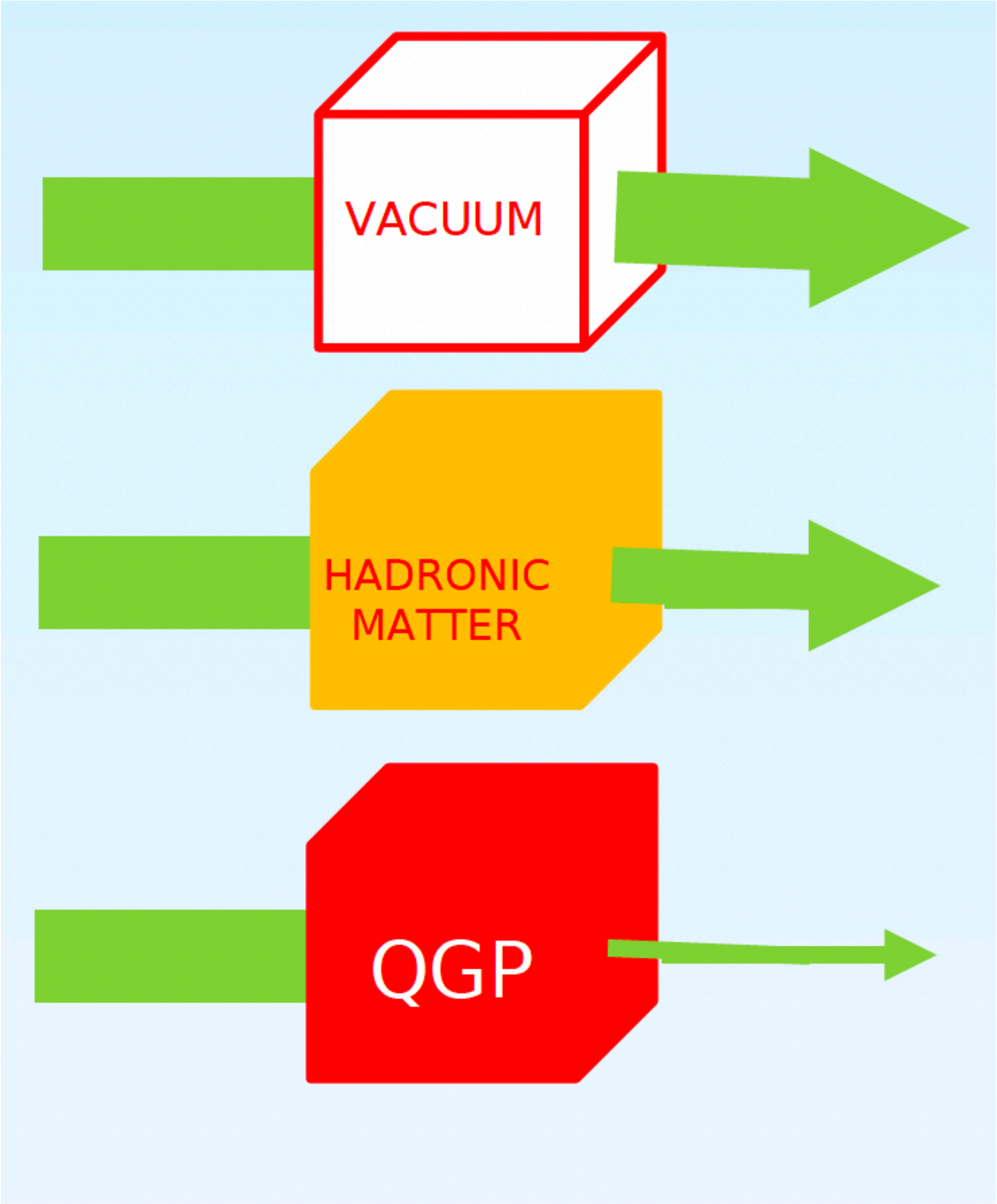
- Instead use energetic particles, produced early in the collision, interact with the medium itself, behaving as penetrating probe

- Study how the matter produced in the collisions affects these probes changing and vice versa



R. Arnaldi

Find a good probe…



- The probe must be produced early in the collision evolution, so that it is there before the matter to be probed
  - $\tau = \frac{\hbar}{Q} \quad Q > 2\mathrm{GeV/c} \rightarrow \tau < 0.1 \ \mathrm{fm}/c$
- The probe must be well calibrated, i.e. its behaviour in "standard" matter should be under control
  - Well understood in pp collisions
  - Calculable perturbatively
- Slightly/not affected by the hadronic matter and in a well understood way (p-A, d-A)
- Strongly affected by the deconfined medium
- Large cross section

… and calibrate it

- Using another probe not affected by the dense QCD matter, to define a baseline reference
  - photons, Drell-Yan di-leptons

- Using “trivial” collision systems, to understand how the probe behaves in absence of “new physics”
  - pp, p-A, light-ion collisions
  - Comparison of peripheral vs. central collisions

Hard probes

- Hard probes are highly penetrating observables (particles, radiation) used to explore properties of matter that cannot be viewed directly
  - High p_T hadrons, jets
  - Open heavy flavours (charm and beauty)
  - Quarkonia $\left(J/\psi, \psi(2S), \Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \ldots\right)$
- Hard probes originate from hard processes, characterised by large momentum transfer Q^2
- High p_T hadrons/open heavy flavours are produced in hard scattering, in the earliest collision time, by fragmentation of high p_T partons
- Cross section can be theoretically predicted using the perturbative QCD framework (pQCD)
- Well understood in vacuum (pp collisions)

Hadron production

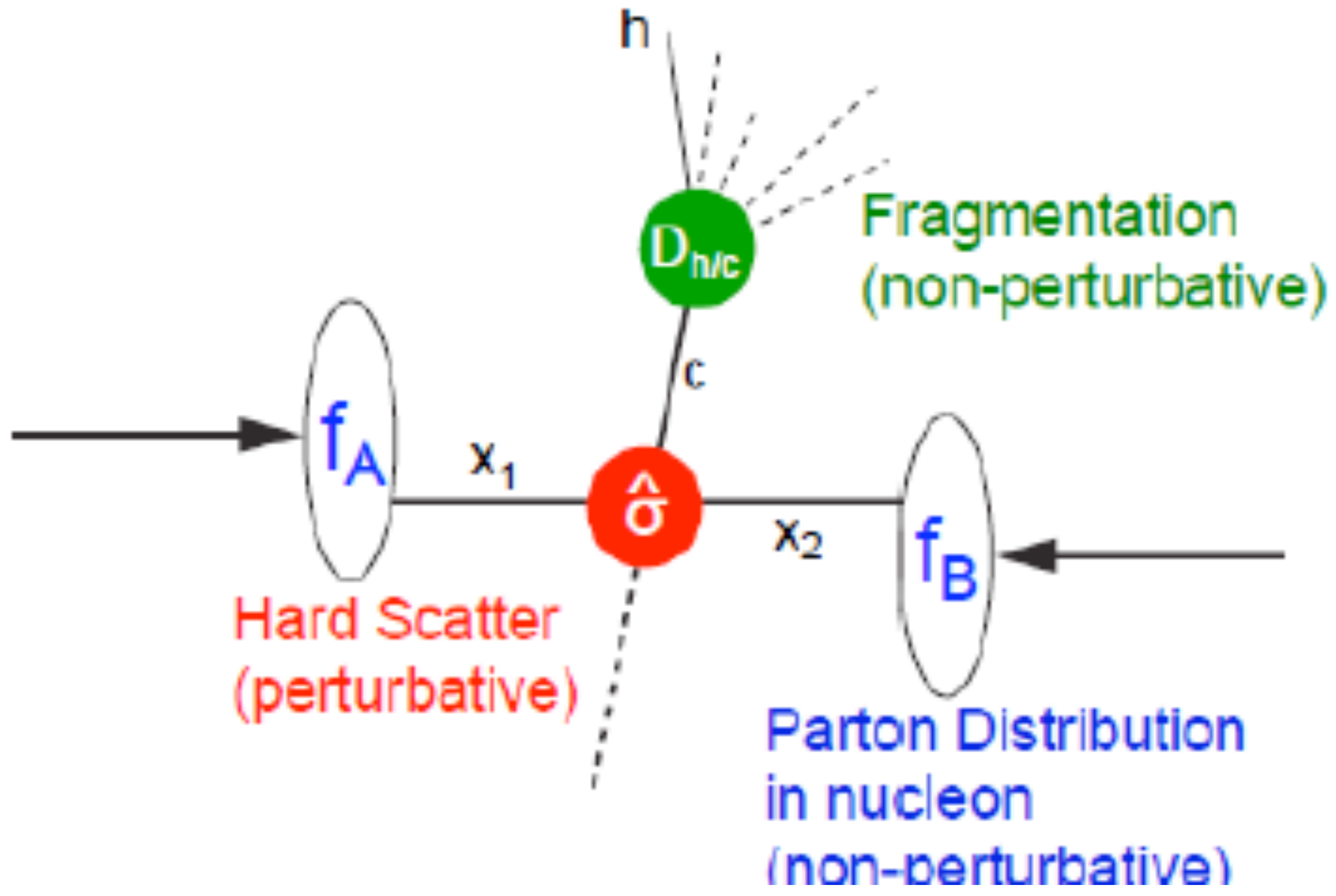
- Hadron production cross section in pp can be calculated in pQCD
- Assumption: factorisation between the hard part and the non-perturbative PDF and fragmentation function
- Assume: universal fragmentation and PDFs

$$\sigma_{hh\rightarrow Hx} = PDF(x_a,Q^2)PDF(x_b,Q^2) \otimes \sigma_{ab\rightarrow q\bar{q}} \otimes D_{q\rightarrow H}(z_q,Q^2)$$

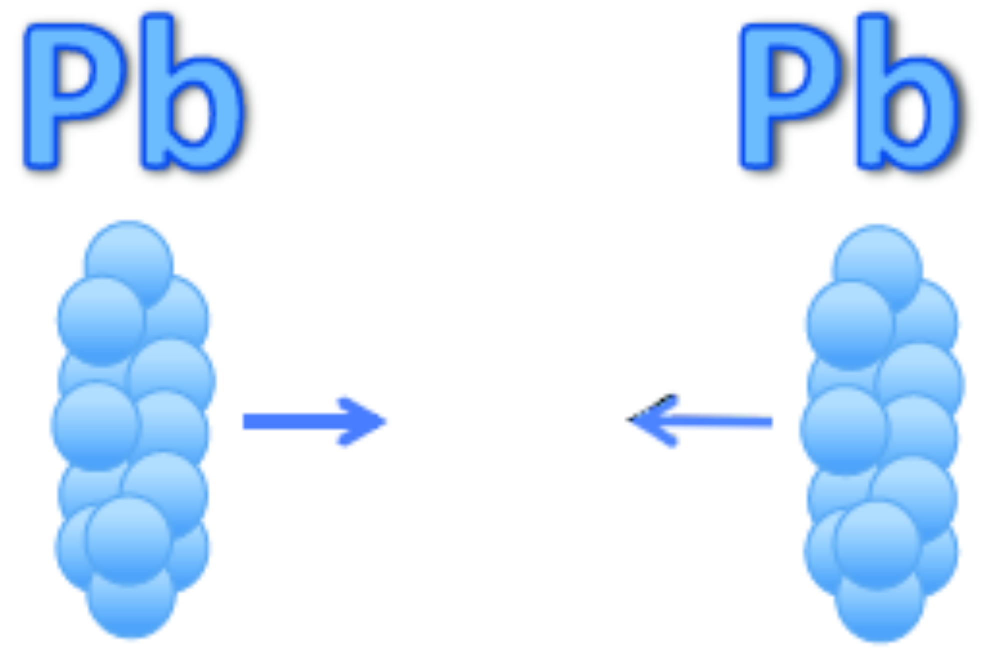
Parton Distribution Functions
x_a, x_b → fraction of the momentum carried by the a,b partons in the hadron

Partonic σ computed in pQCD

Fragmentation of quark q into the hadron H



The Nuclear Modification Factor



Cold nuclear matter effects
+ hot nuclear matter effects
(related to the Quark-Gluon Plasma)

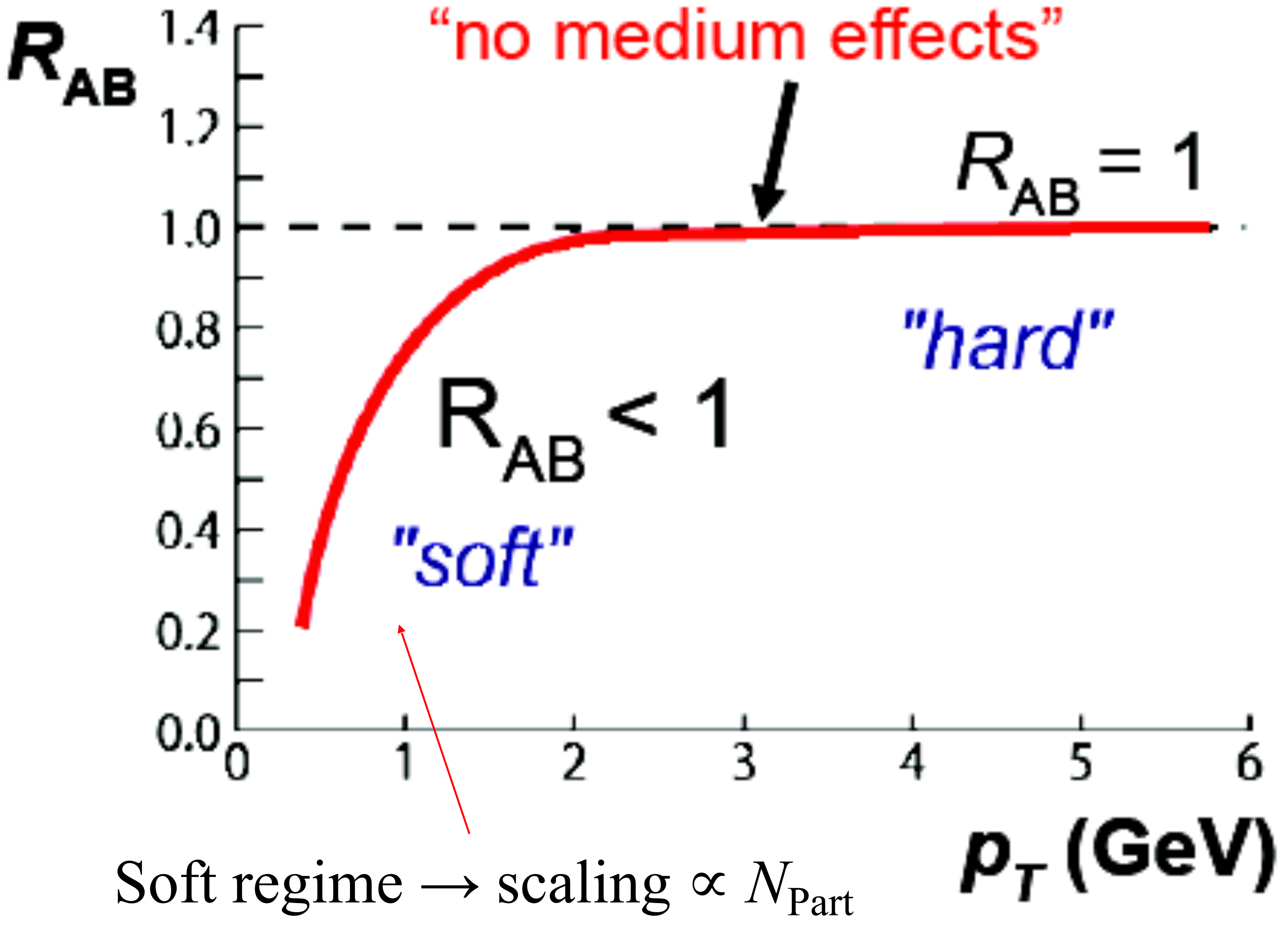
Elementary collision
No nuclear matter effects

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\mathrm{d}N^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

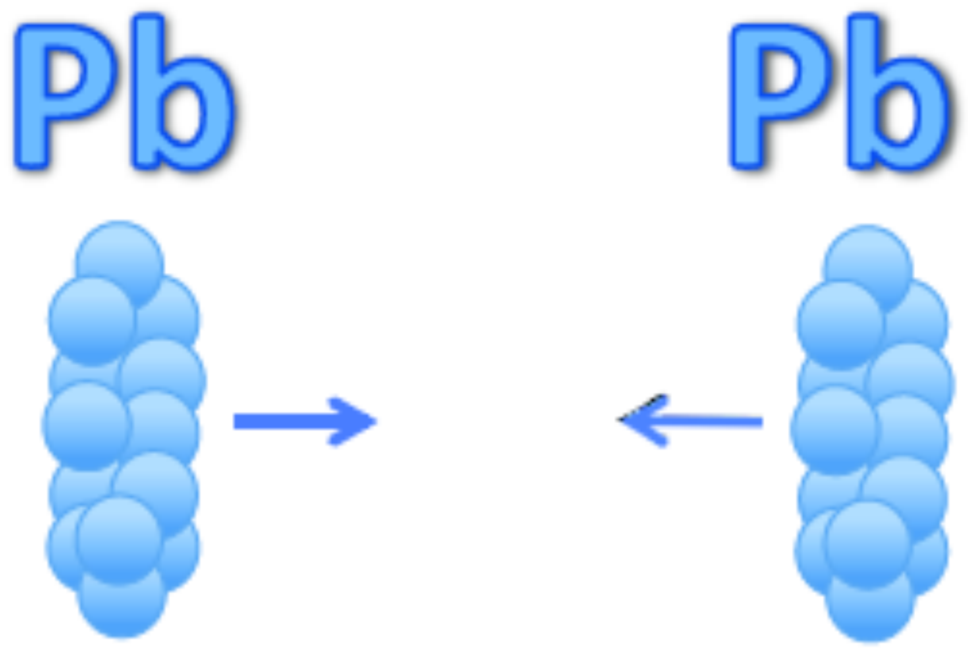
$\langle N_{coll} \rangle$ from Glauber Monte Carlo

Compare particle spectra in p+p and A+A collisions, taking into account increase of scattering centres

In the absence of nuclear effects:
R_{AB} = 1 at high p_T, where hard processes dominate (p_T > 2 GeV)



Can the binary scaling be broken?



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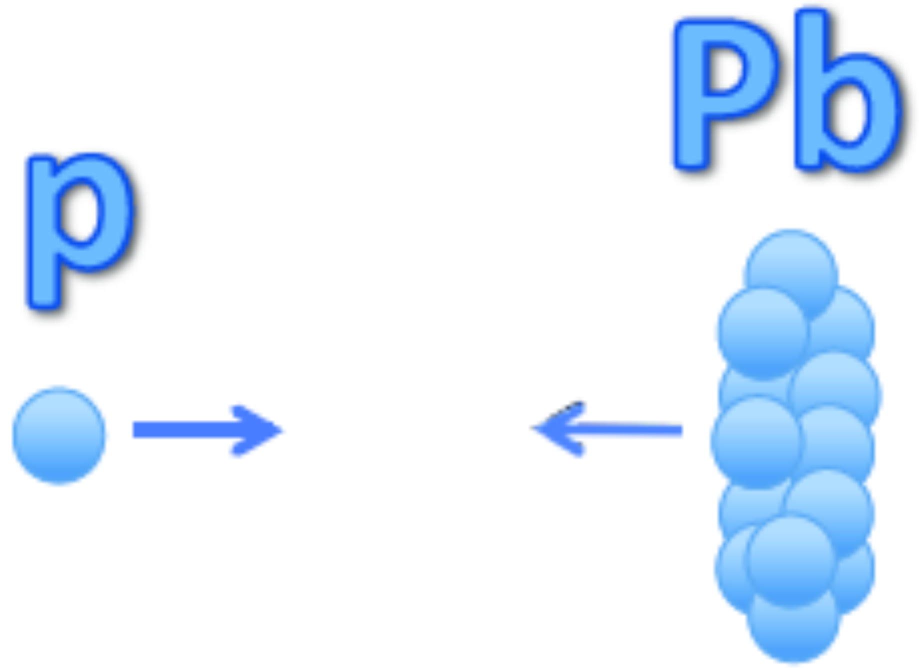
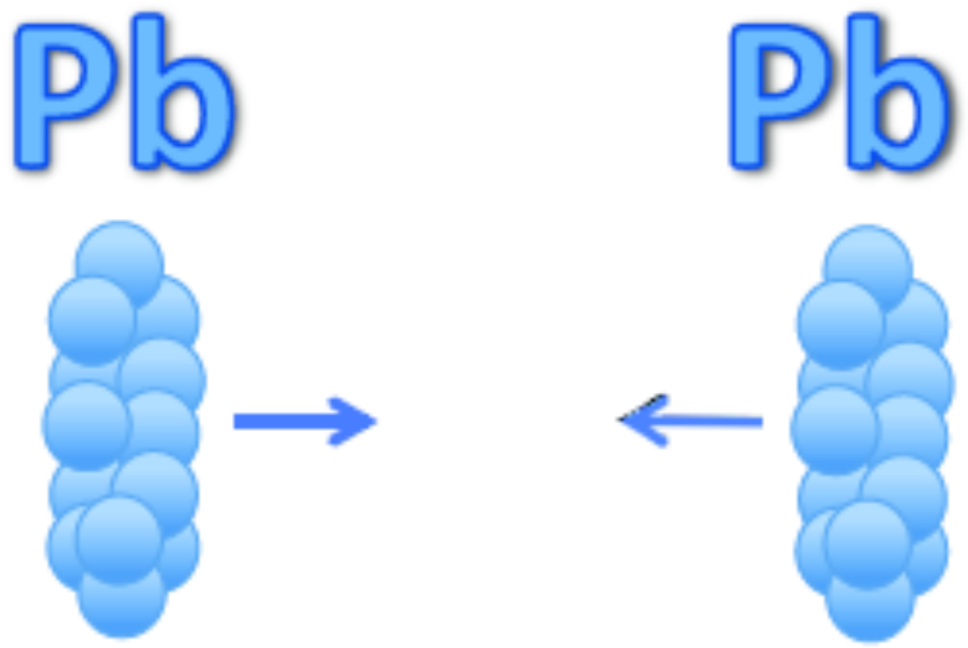


Cold nuclear matter effects - without Quark-Gluon Plasma

- Initial state effects - present in p-A and A-A collisions
  - Cronin effect → inducing changes in the parton momenta
  - Nuclear PDF → changes to the PDF in nuclei wrt to the parton ones
  - Color Glass Condensate → gluon saturation at low *x*
  - …
- Final state effects - present only in A-A collisions
  - Energy loss/jet quenching
  - Modification of the fragmentation function
  - Quarkonium suppression in the hot medium

Can the binary scaling be broken?



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Elementary collision
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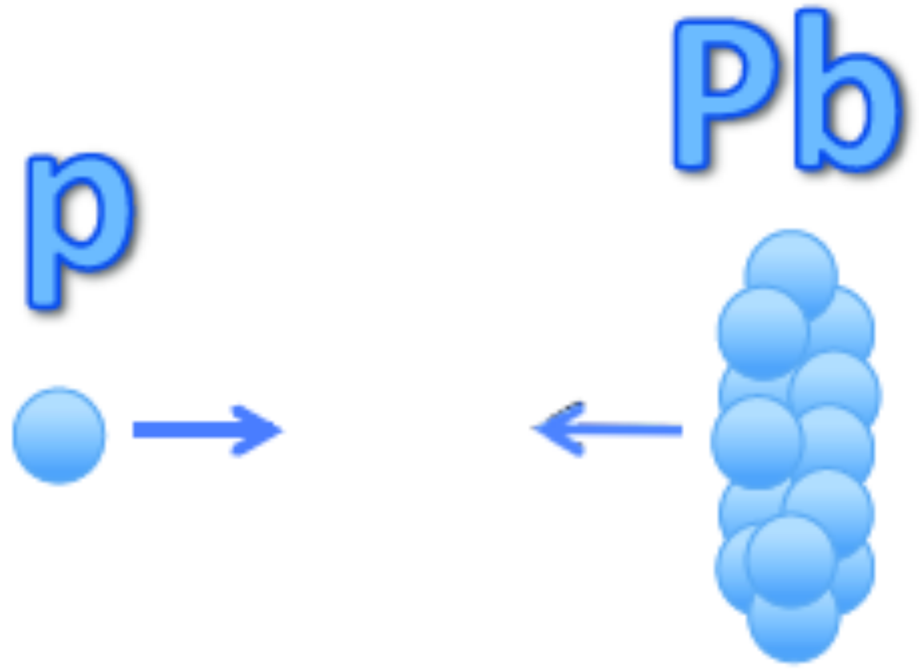
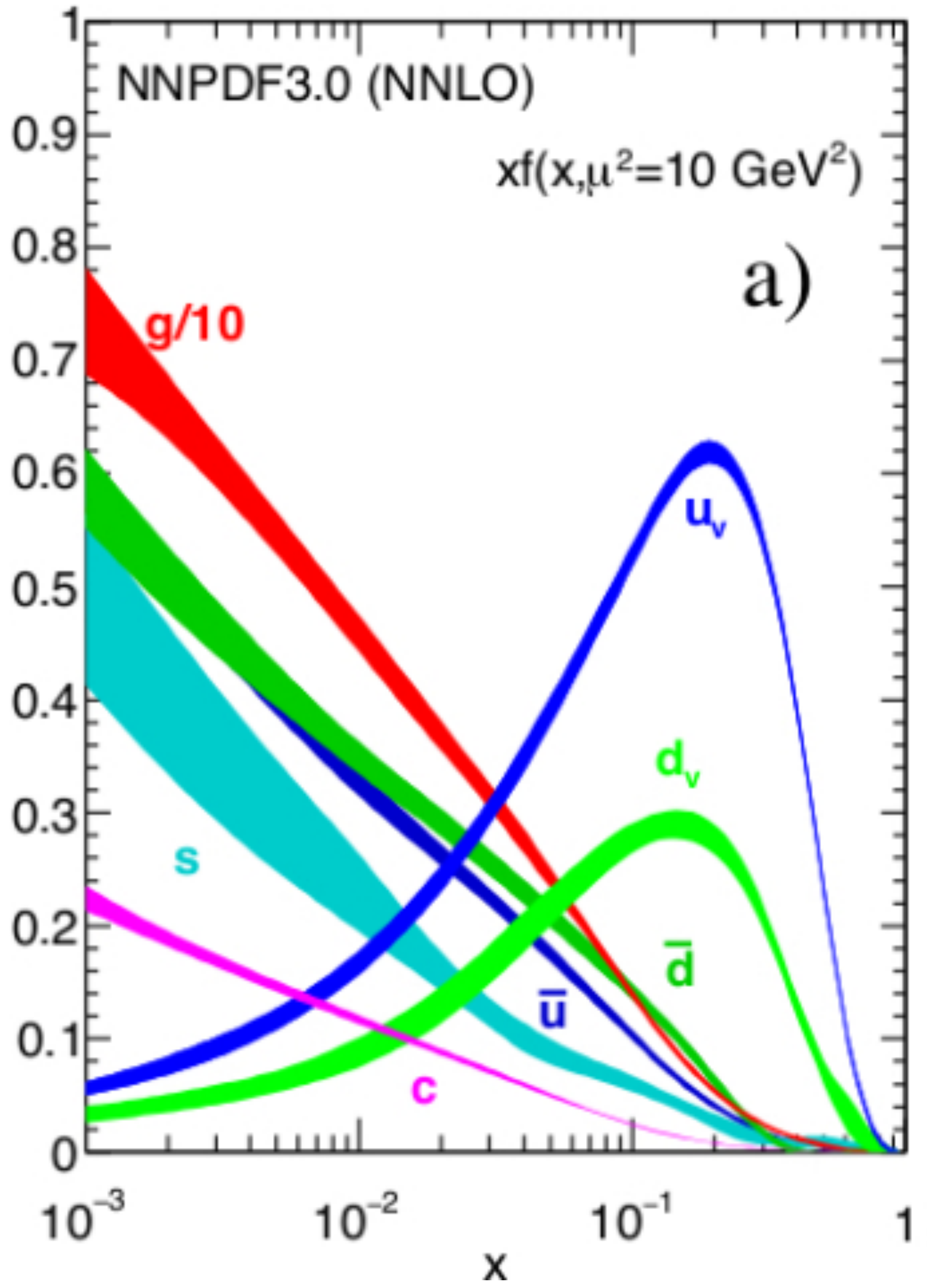
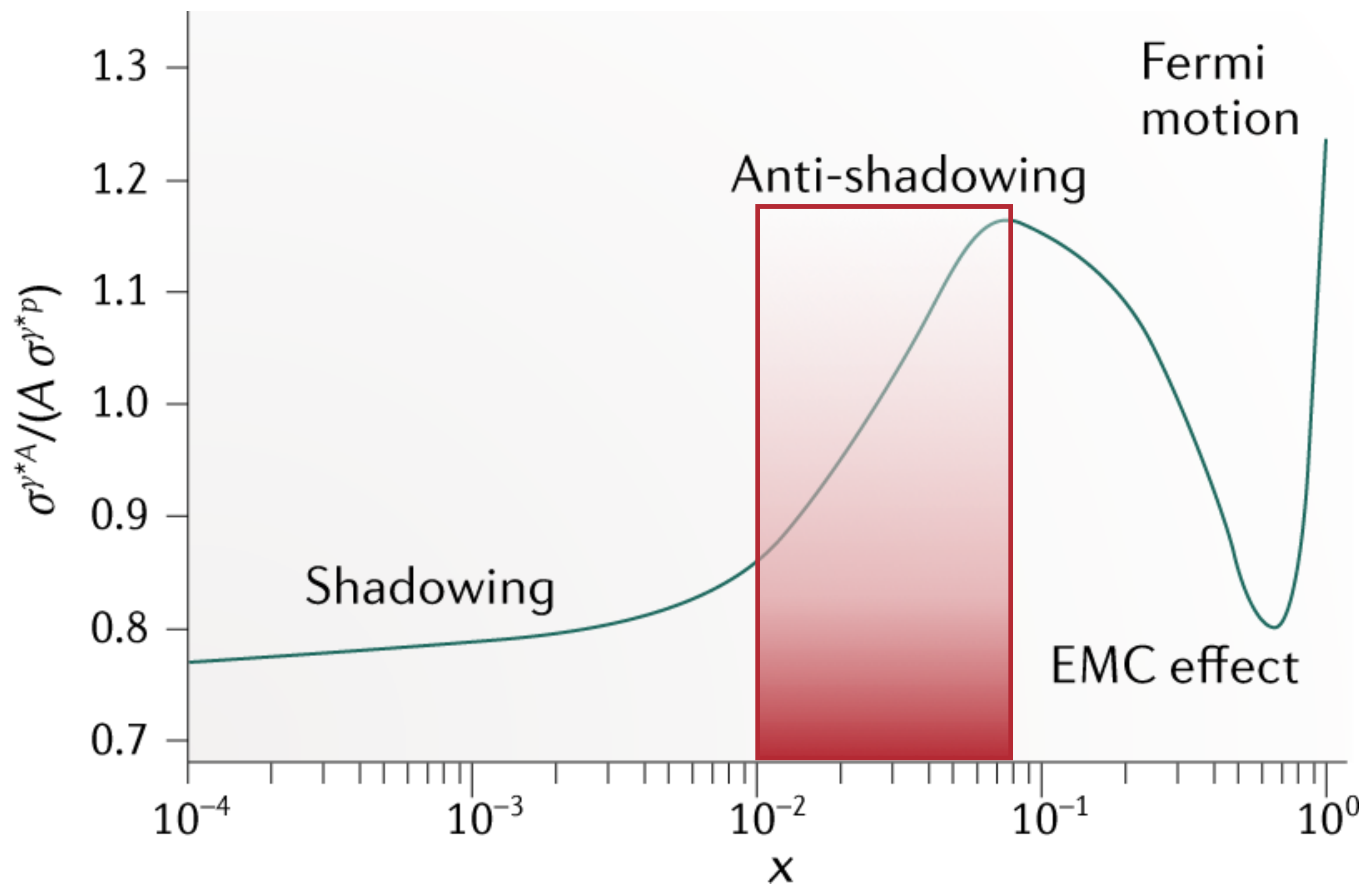


Cold nuclear matter effects -
without Quark-Gluon Plasma

PDFs vs nuclear PDFs

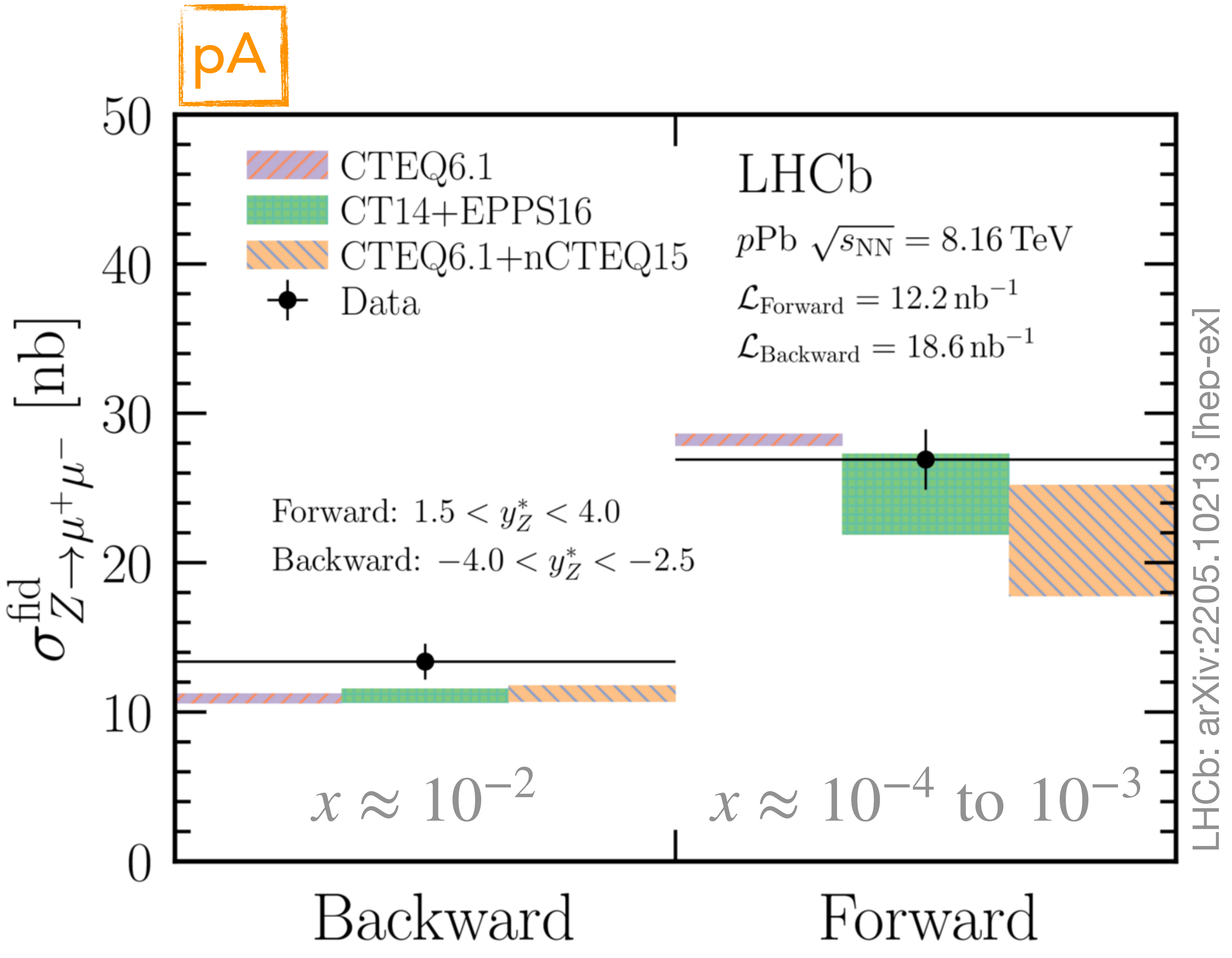


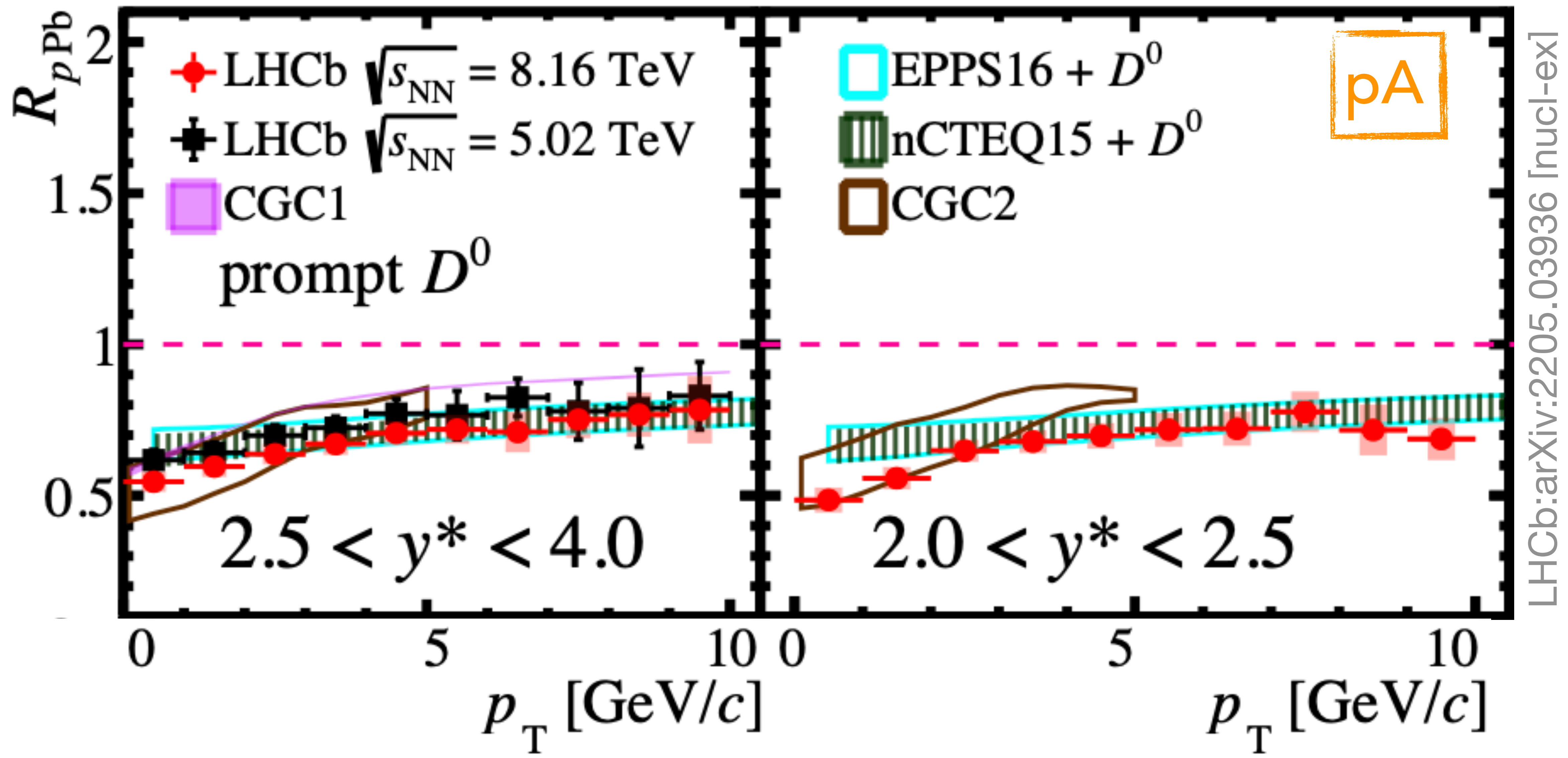


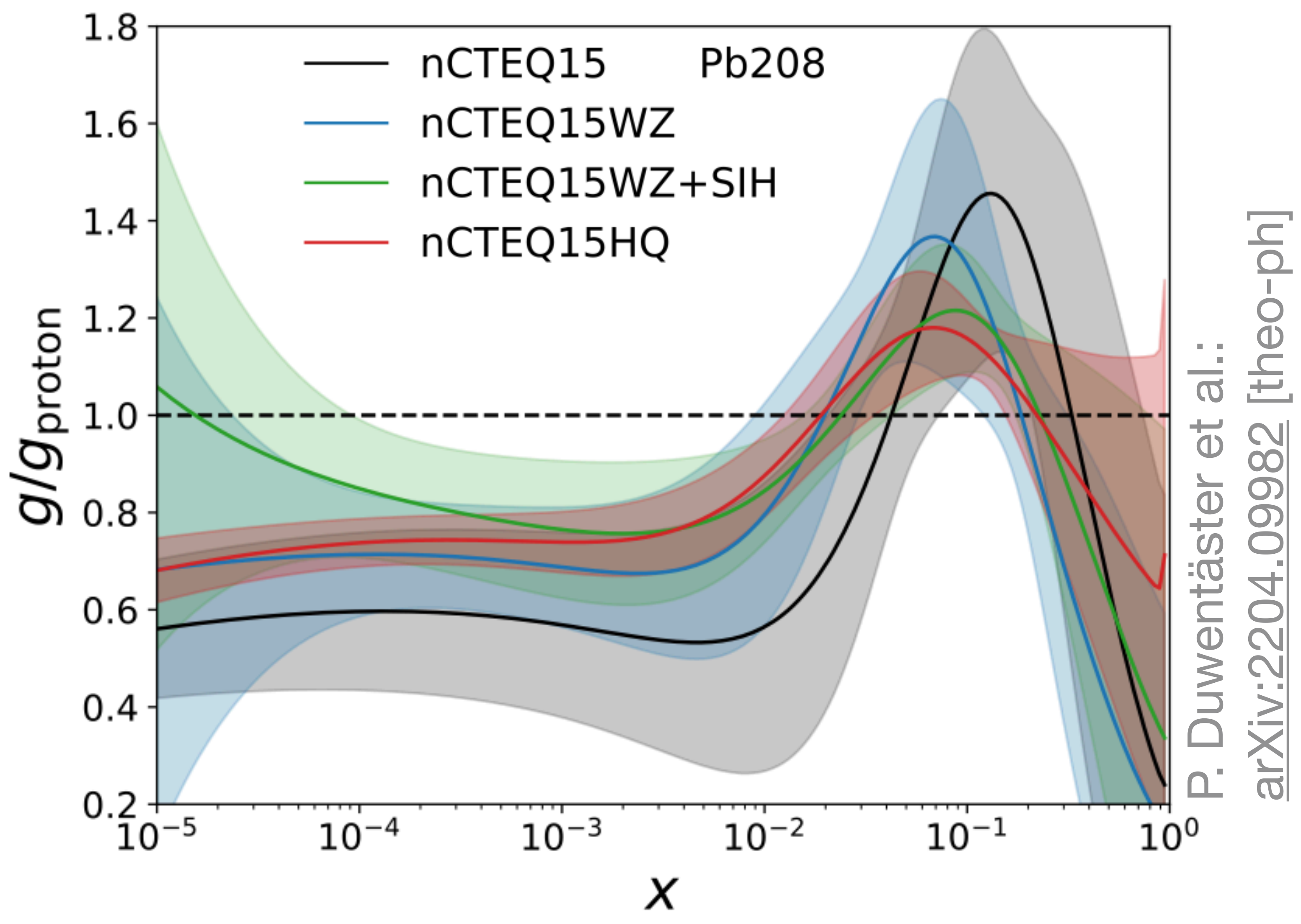
S.R. Klein, H. Mäntysaari
Nat. Rev. Phys. 1 (2019) 662

Initial state: Constraining nuclear PDFs

Quarkonium and open heavy-flavour production at LHC
→ Reducing nPDF uncertainties down to $x \geq 10^{-5}$



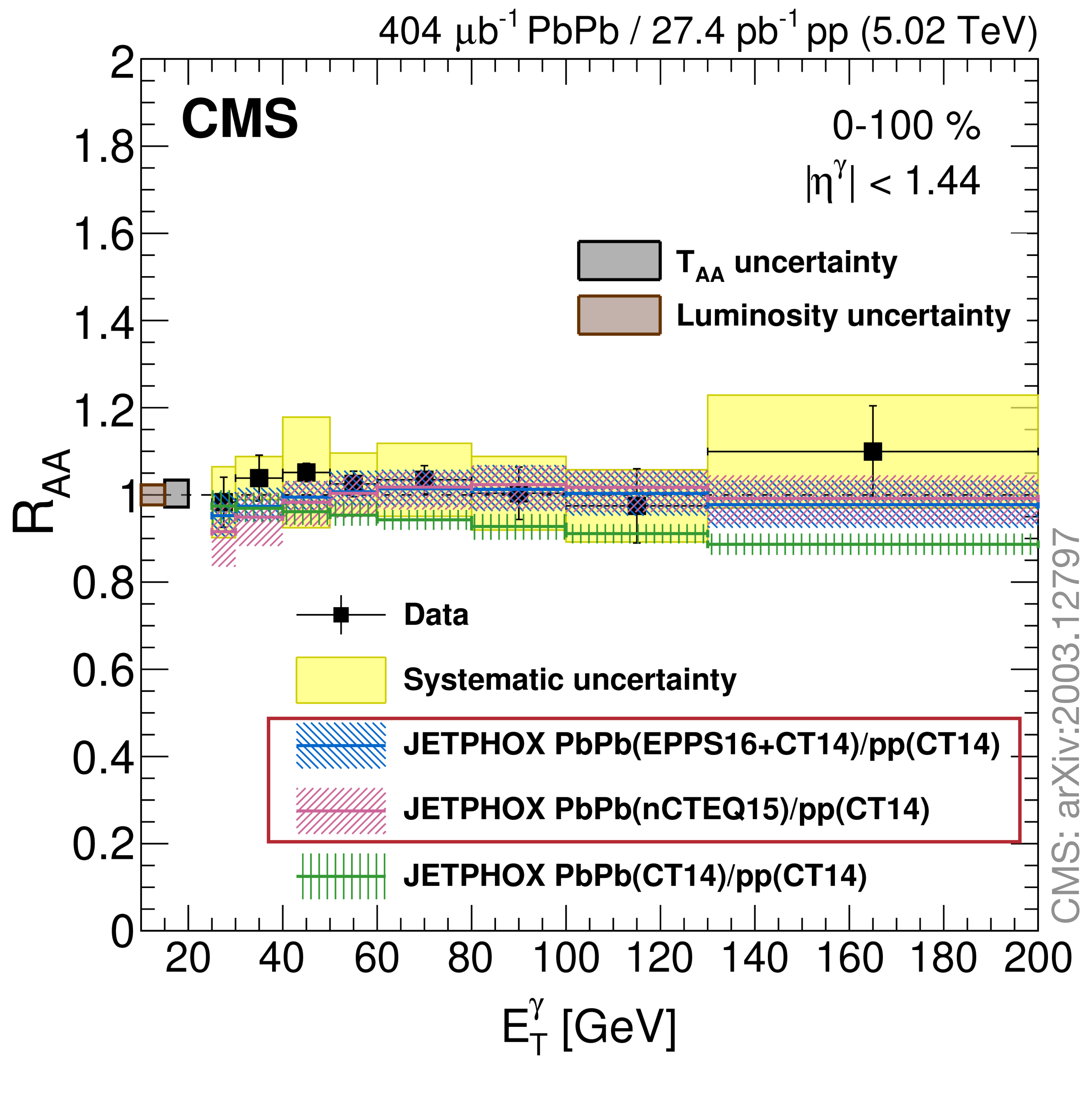




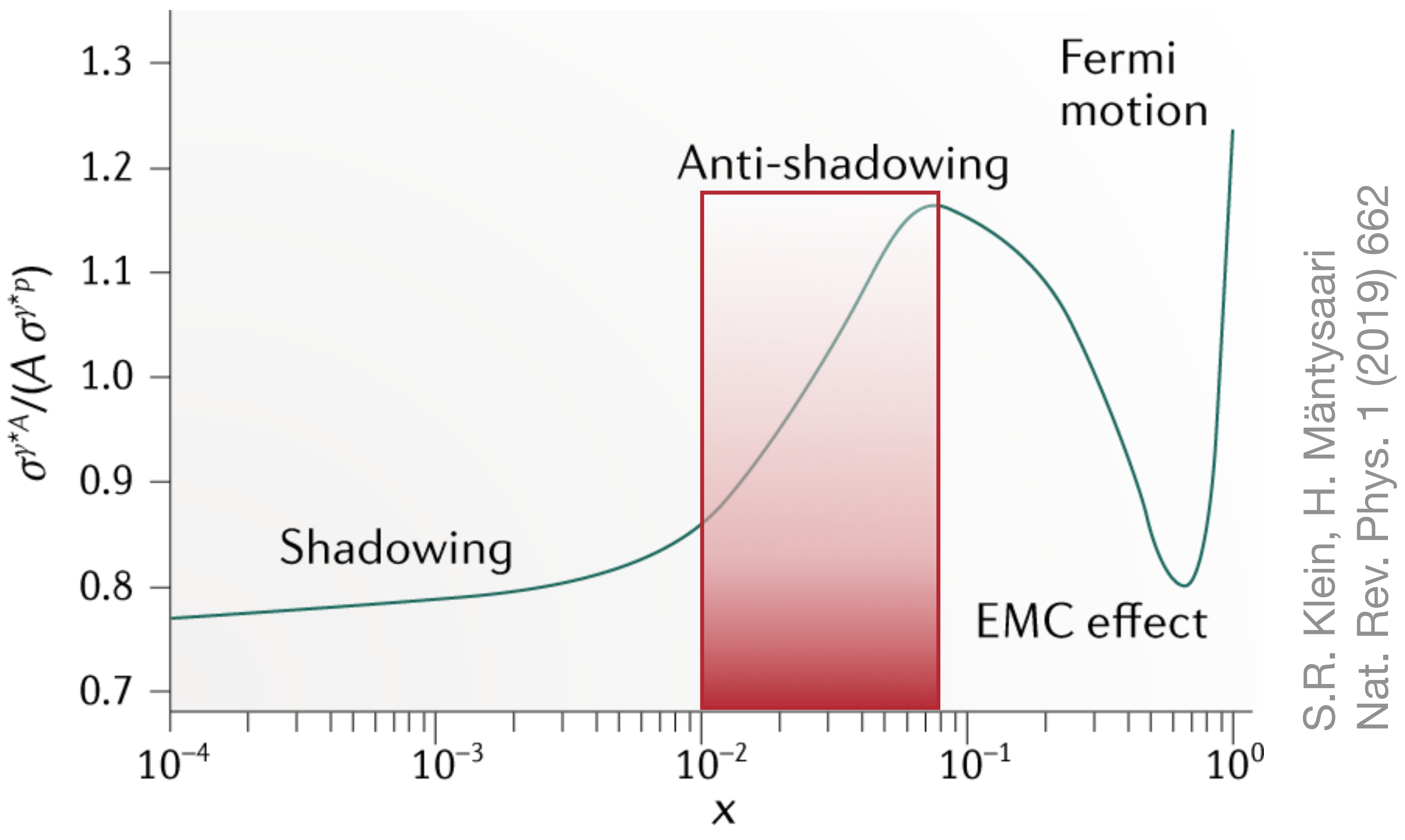
Control probes

- Photons interact only electromagnetically
  → Are not affected by the QGP
  → Scale with N_{coll}

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$



→ Access to initial state
→ constrain the nPDF global fits



Energy loss - jet quenching
A bit of History

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

FERMILAB-Pub-82/59-THY
August, 1982

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

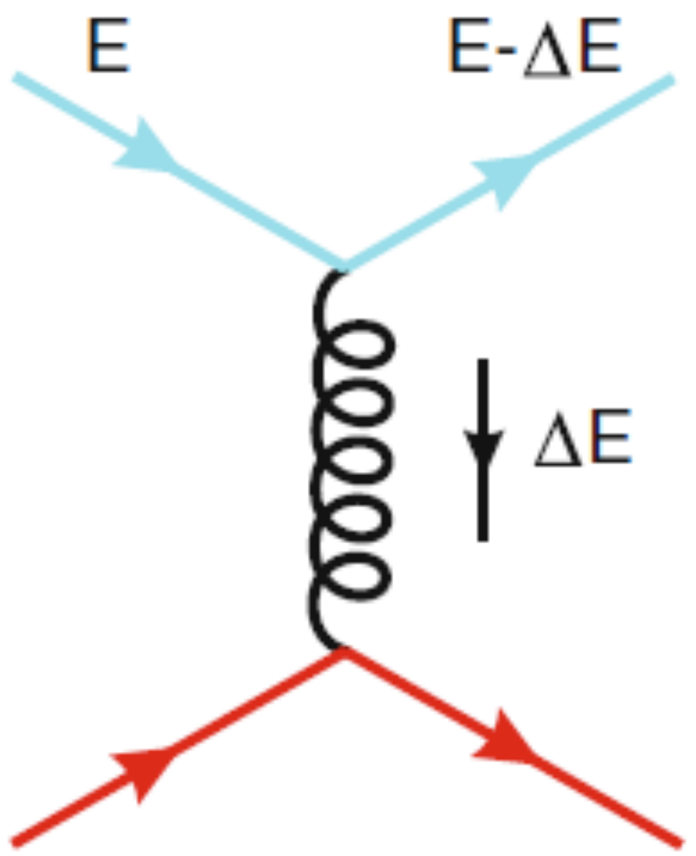
It is now believed that radiative energy loss (gluon bremsstrahlung) is more important than elastic scattering

Mechanisms of energy loss

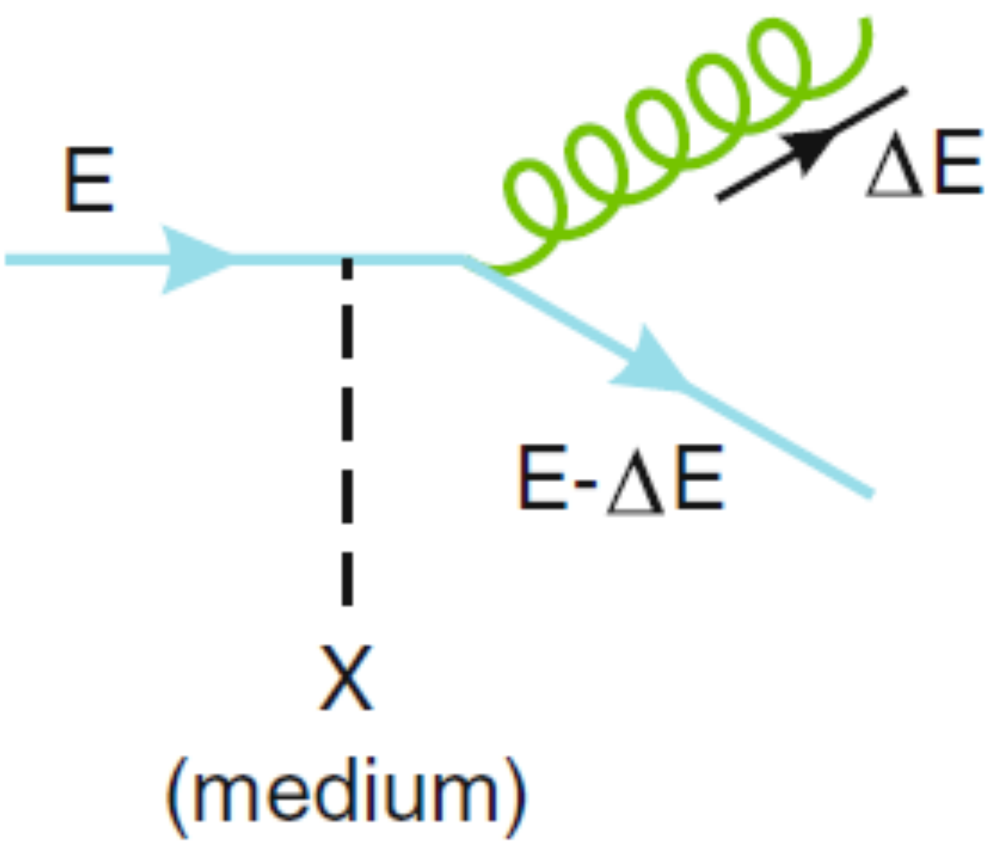
- QGP: high density of quarks and gluons / colour sources
- Traversing quark / gluon feels colour fields
- Collisional energy loss
  - Elastic scatterings
  - Dominates at low momentum
- Radiative energy loss
  - Inelastic scatterings
  - Dominates at high momentum
  - Gluon bremsstrahlung

$$\Delta E = \Delta E_{\mathrm{coll}} + \Delta E_{\mathrm{rad}}$$

Collisional energy loss
(elastic scattering)

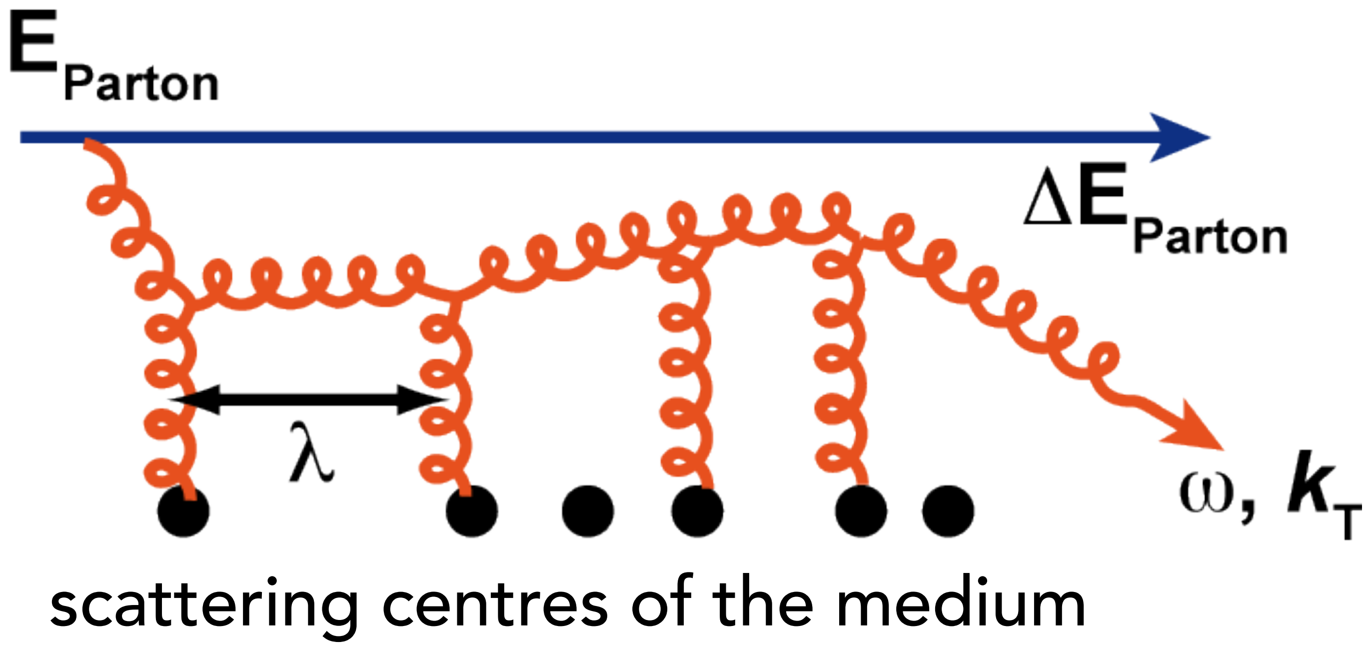


Radiative energy loss
(inelastic scattering)



Radiative energy loss

- BDMPS formalism (Baier, Dokshitzer, Mueller, Peigné, Schiff)
- Energy loss E in a static medium of length L for a parton energy $E \rightarrow \infty$:



$$\langle \Delta E \rangle \approx \alpha_s C_R \hat{q} L^2$$

Casimir Factor (colour charge)
C_R=3 for gg interaction (gluons)
C_R=4/3 for gq interaction (quarks)

En. loss is proportional to L^2, taking into account the prob. to emit a bremsstrahlung gluon and the fact that radiated coloured gluons can interact themselves with the medium (destructive interference, LPM)

transport coefficient, related to the medium characteristics and to the gluon density dN_g/dy
→ allows an indirect measurement of the medium energy density

$$\hat{q} = \frac{\mu^2}{\lambda}$$

μ : typical momentum transfer from medium to parton per collision

λ : mean free path length in the medium

BDMPS result, Nucl. Phys. B 483, 291, 1997

Collisional Energy Loss

- For light quarks and gluons

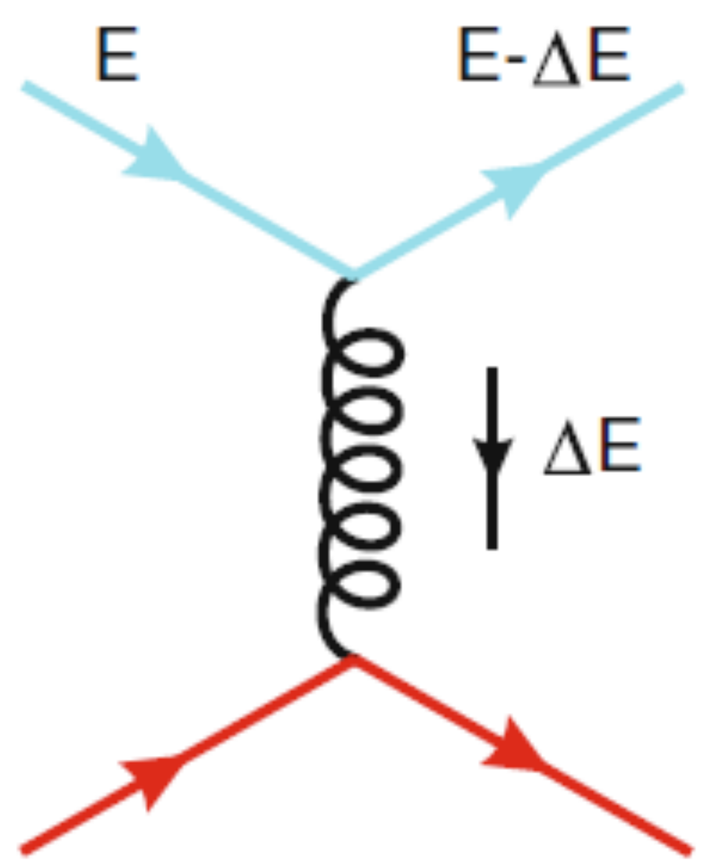
$$\Delta E_{q,g} \sim \alpha_S\, C_R\, \mu^2 L \ln\frac{ET}{\mu^2}$$

- For heavy quarks additional term

$$\alpha_s^2 T^2\, C_R\, \mu^2 L \ln\frac{ET}{M^2}$$

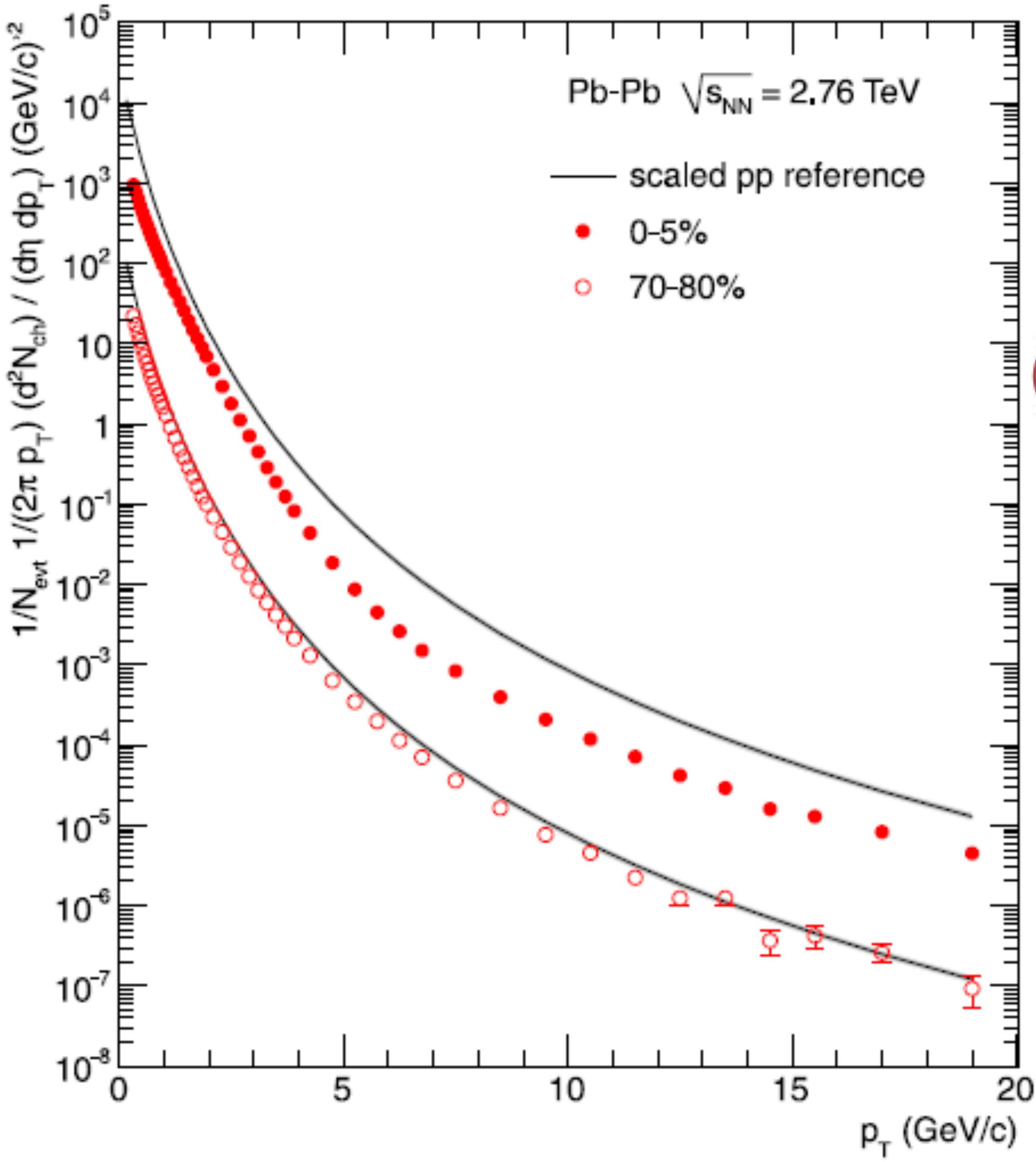
- Energy loss depends on
  - Path length through medium (linear)
  - Parton type (light or heavy)
  - Temperature *T*
  - Mass of heavy quark *M*
  - Medium parameter μ (average transverse momentum transfer)

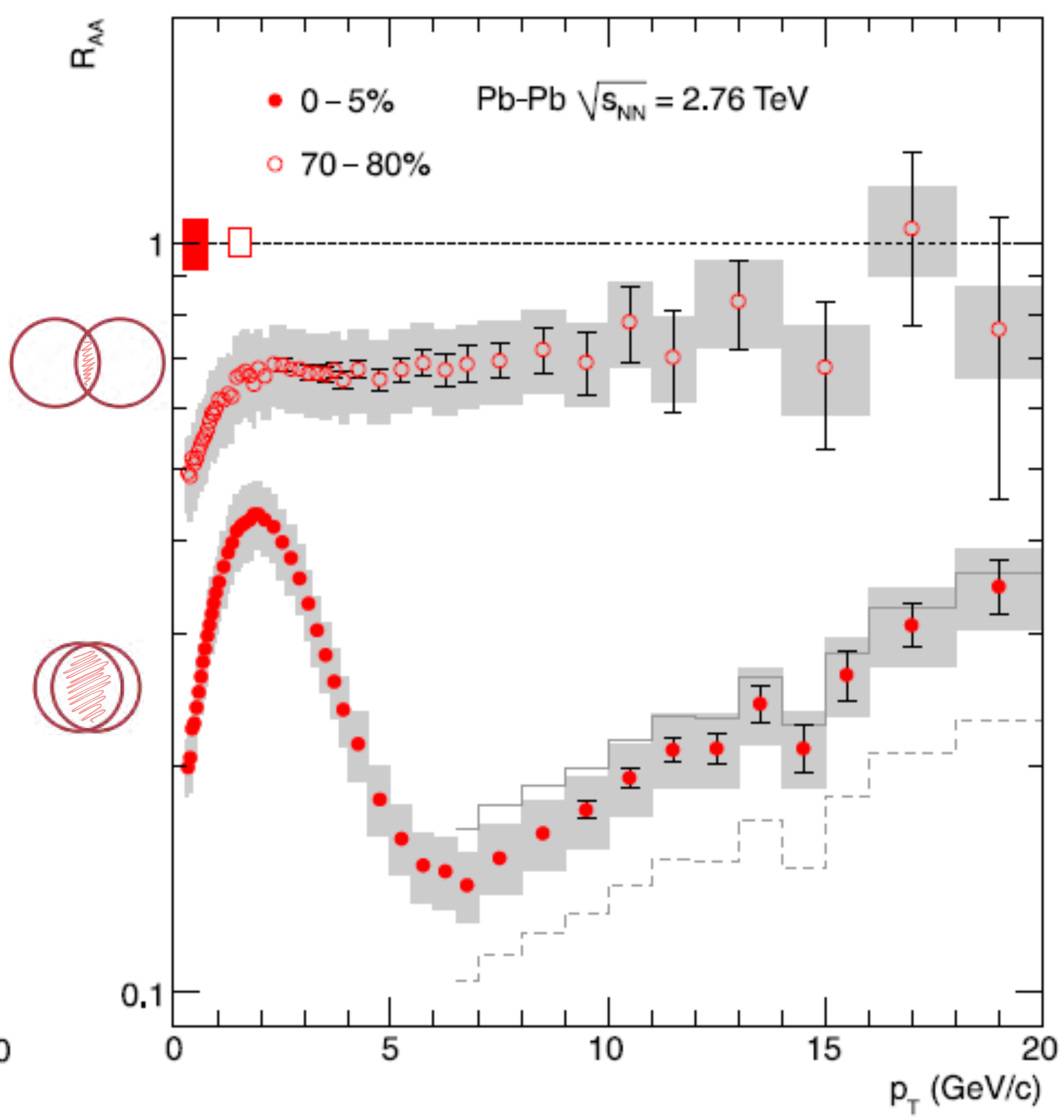
Collisional energy loss
(elastic scattering)



Suppression

ALICE, Physics Letters B 696 (2011) 30





$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

- Max. suppression at p_T ~ 7 GeV/c
- Rise at p_T ~ 10-20 GeV/c

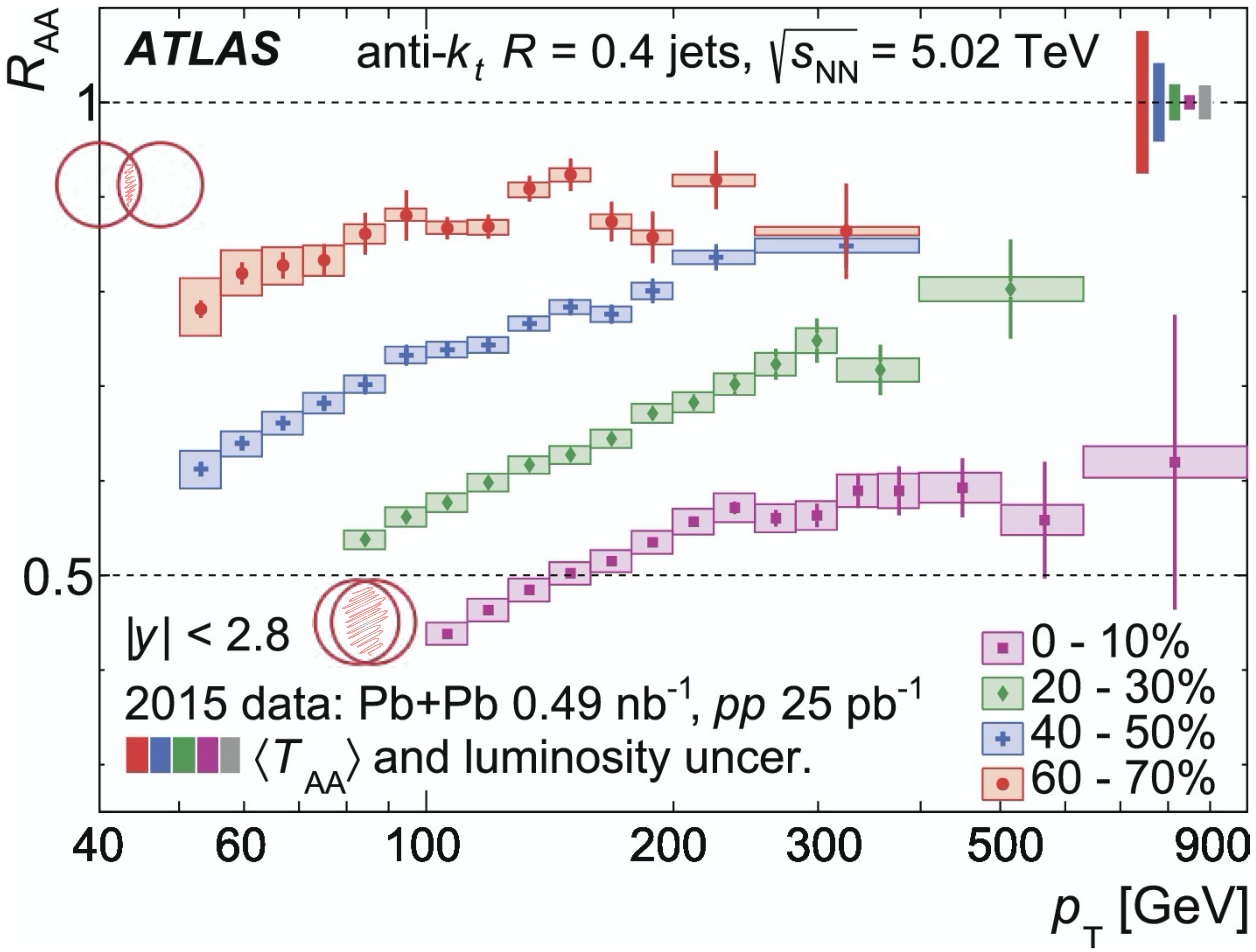
- Shape of p_T distribution changes with collision centrality → different suppression pattern depending on collision centrality

Parton Energy Loss: R_{AA}

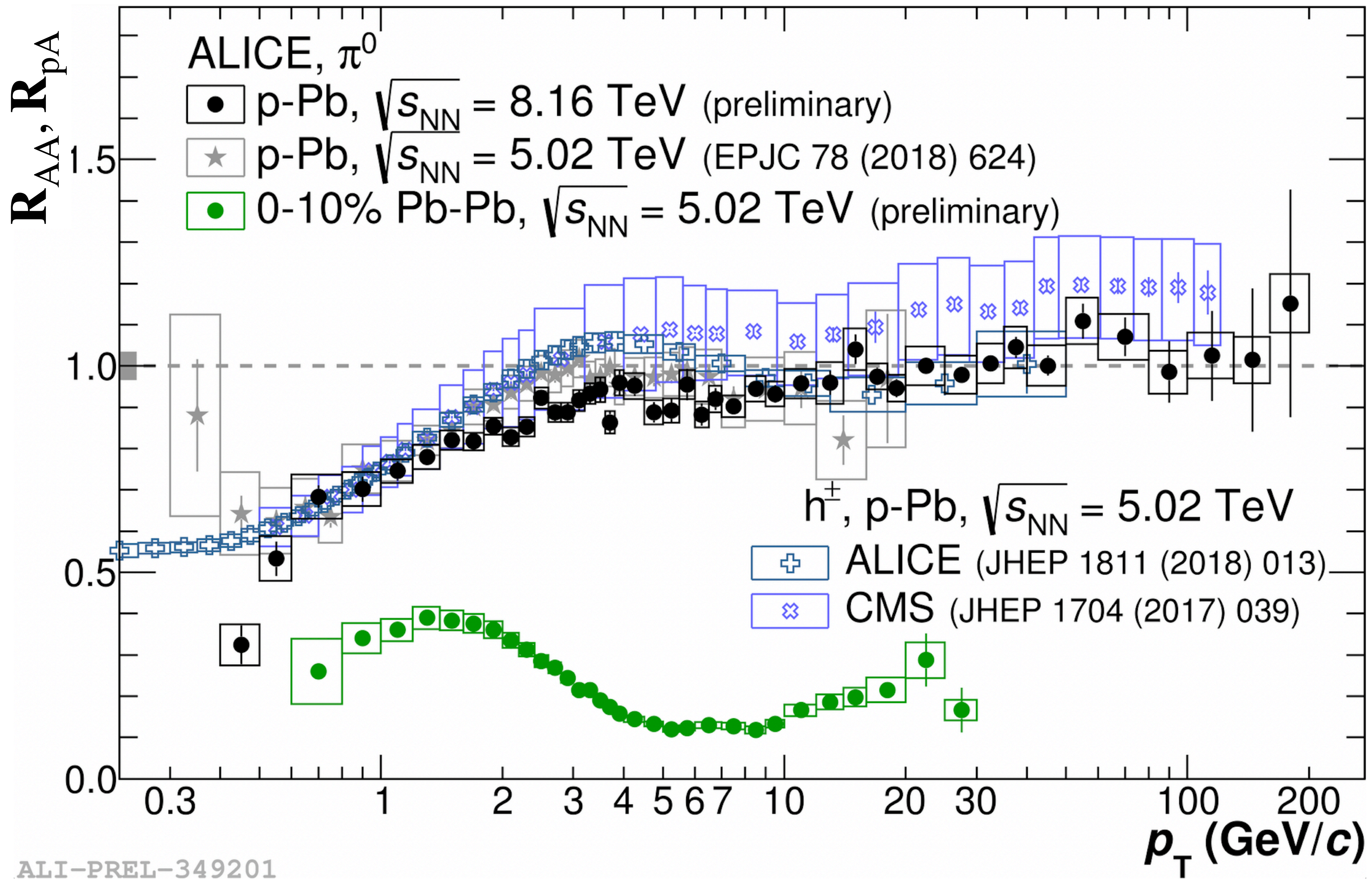
→ Energy loss in large systems up to very high p_T
→ Suppression is a final state effect

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

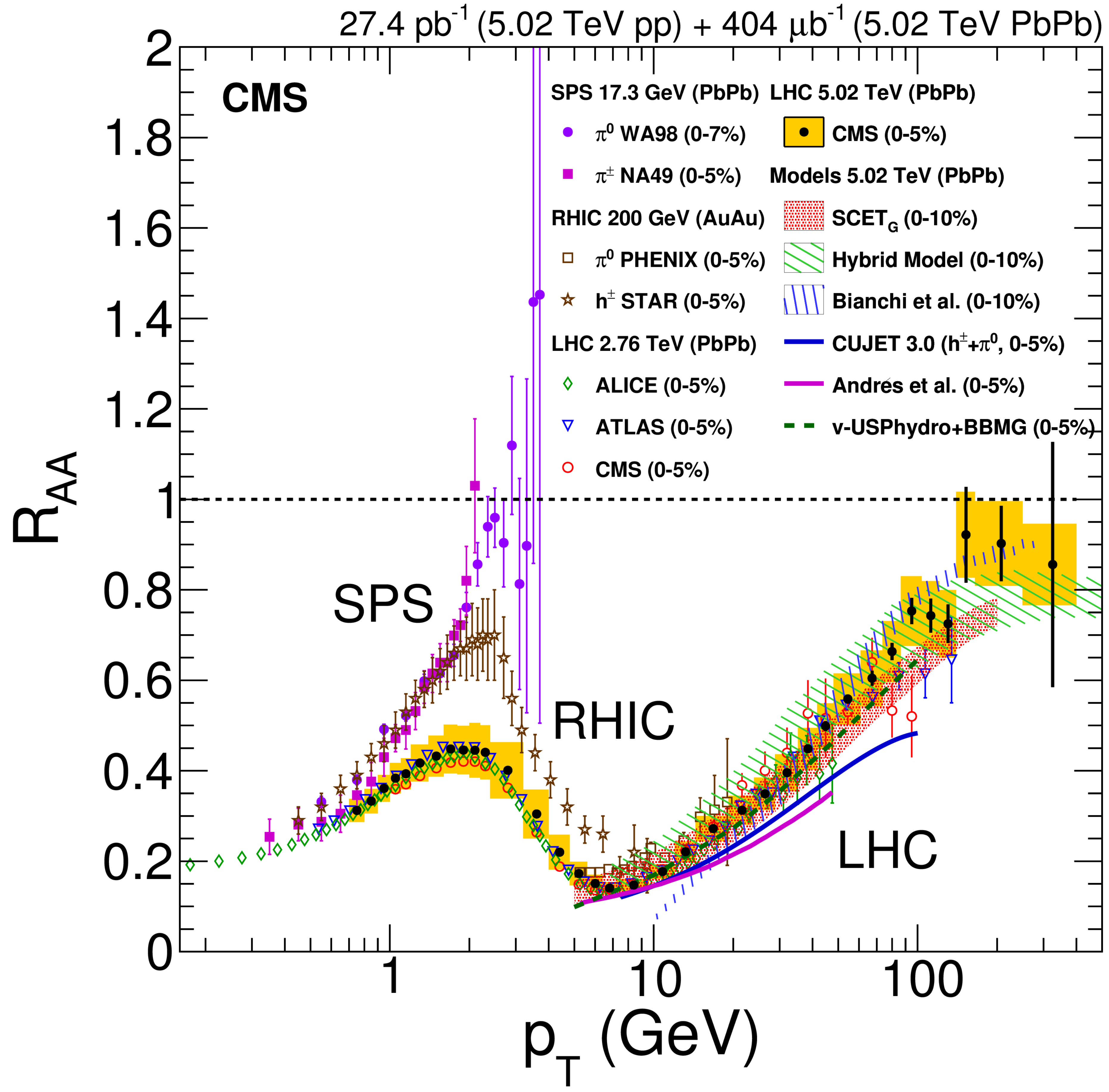
AA



AA pA



LHC vs RHIC



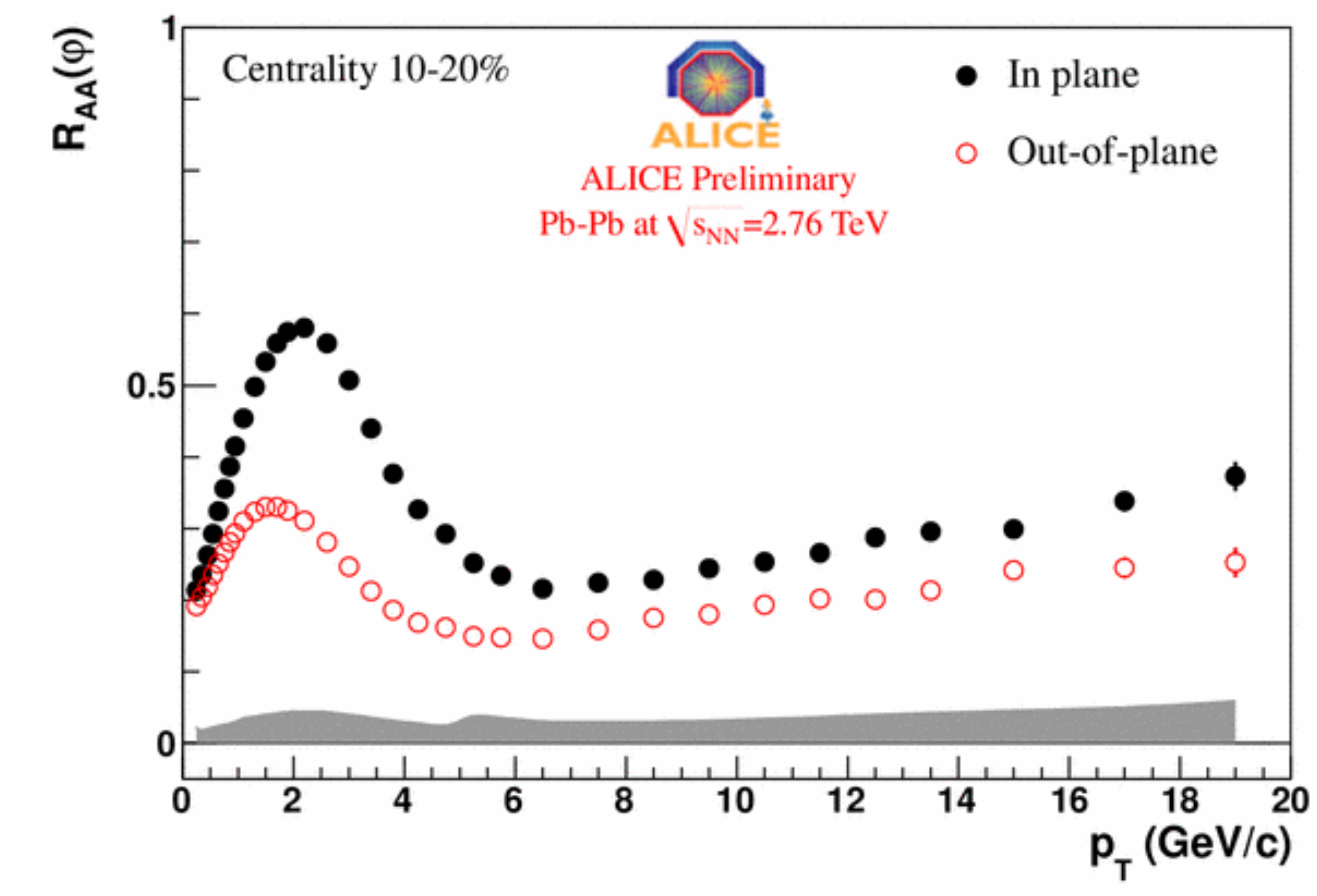
CMS: JHEP 04 (2017) 039

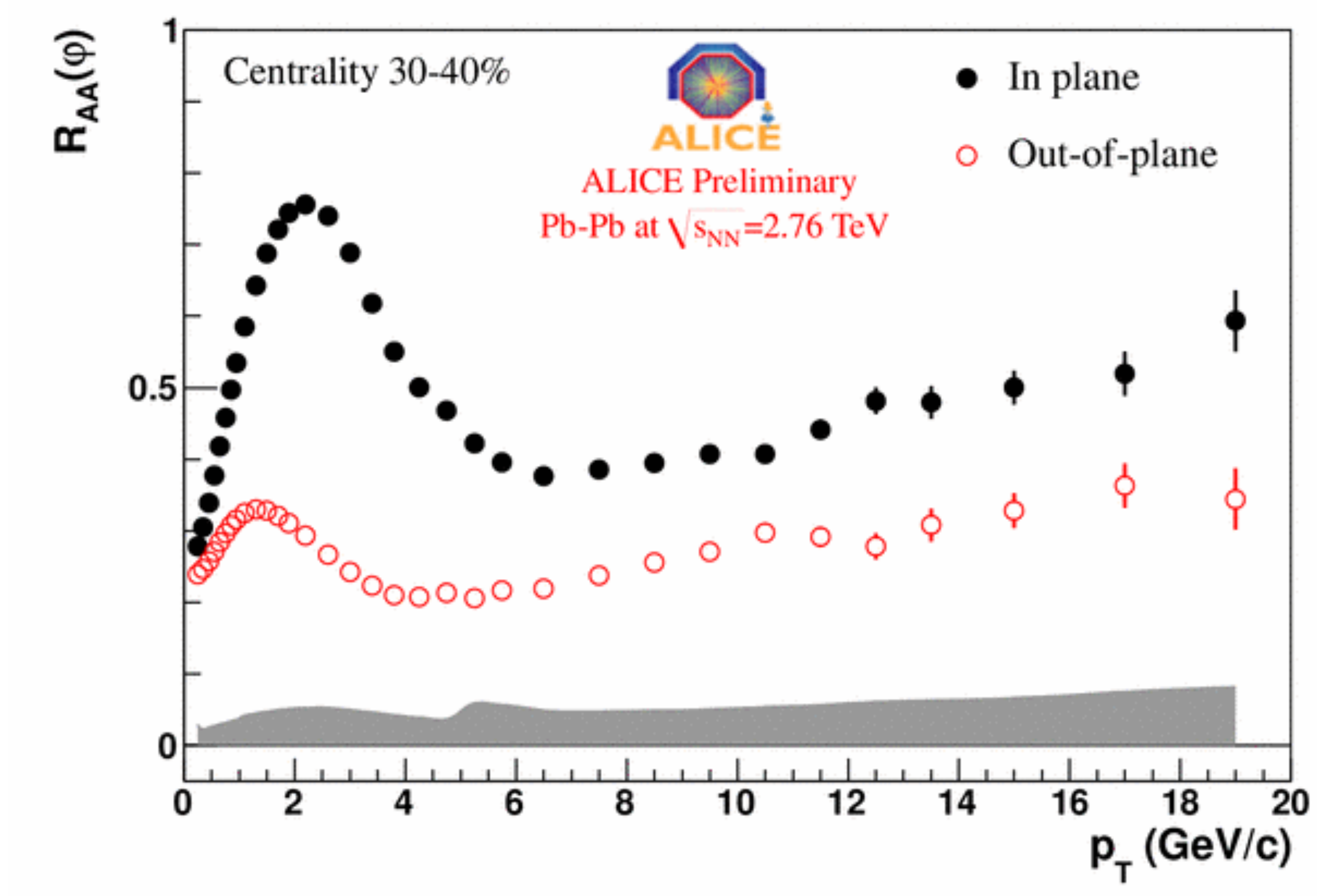
LHC vs RHIC

- R_{AA}(LHC) < R_{AA}(RHIC) for p_T < 10 GeV/c
- Intermediate p_T similar R_{AA} despite harder p_T spectrum at LHC → larger ΔE
- Minimum R_{AA} ~ 0.14 at p_T = 6-7 GeV/c and even at high p_T ~ 200 GeV/c R_{AA} < 1

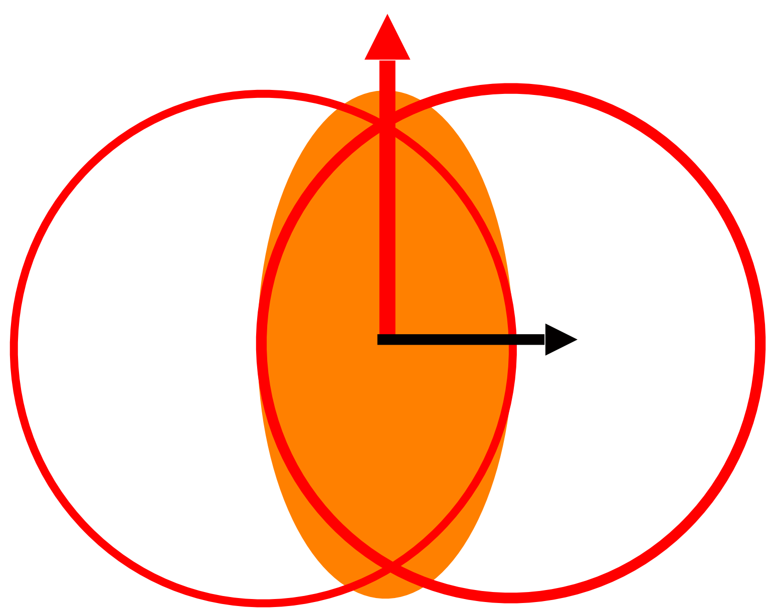
$\hat{q}$ = 1.2 GeV²/fm at T = 370 MeV
$\hat{q}$ = 1.9 GeV²/fm at T = 470 MeV

Path length dependence



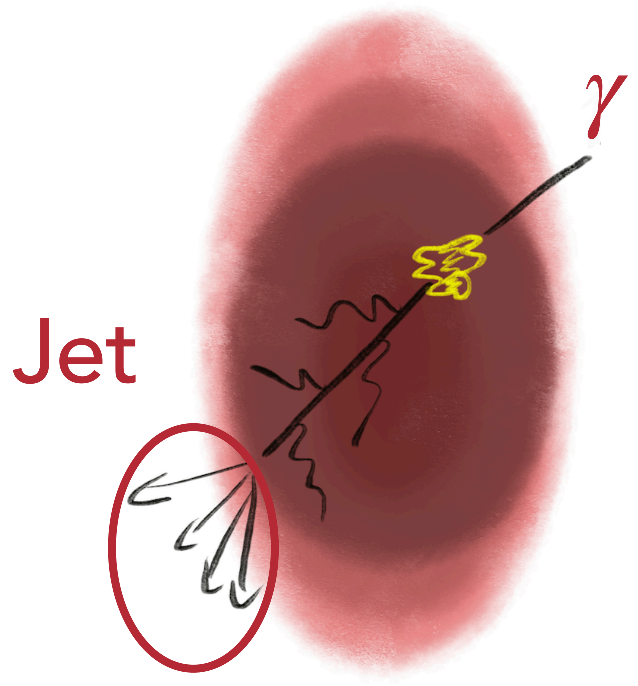


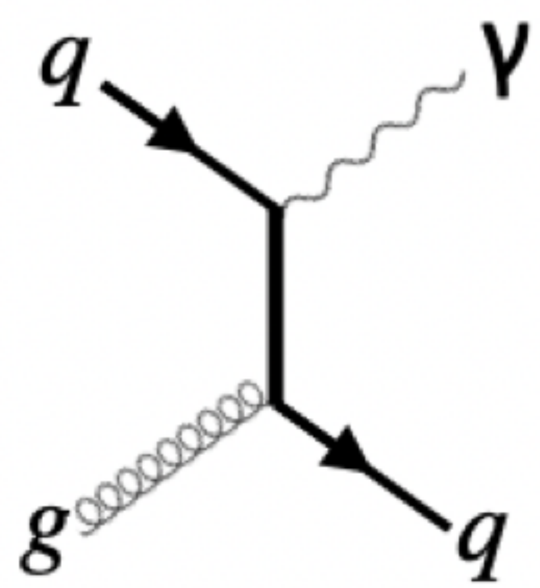
in plane
out-of-plane



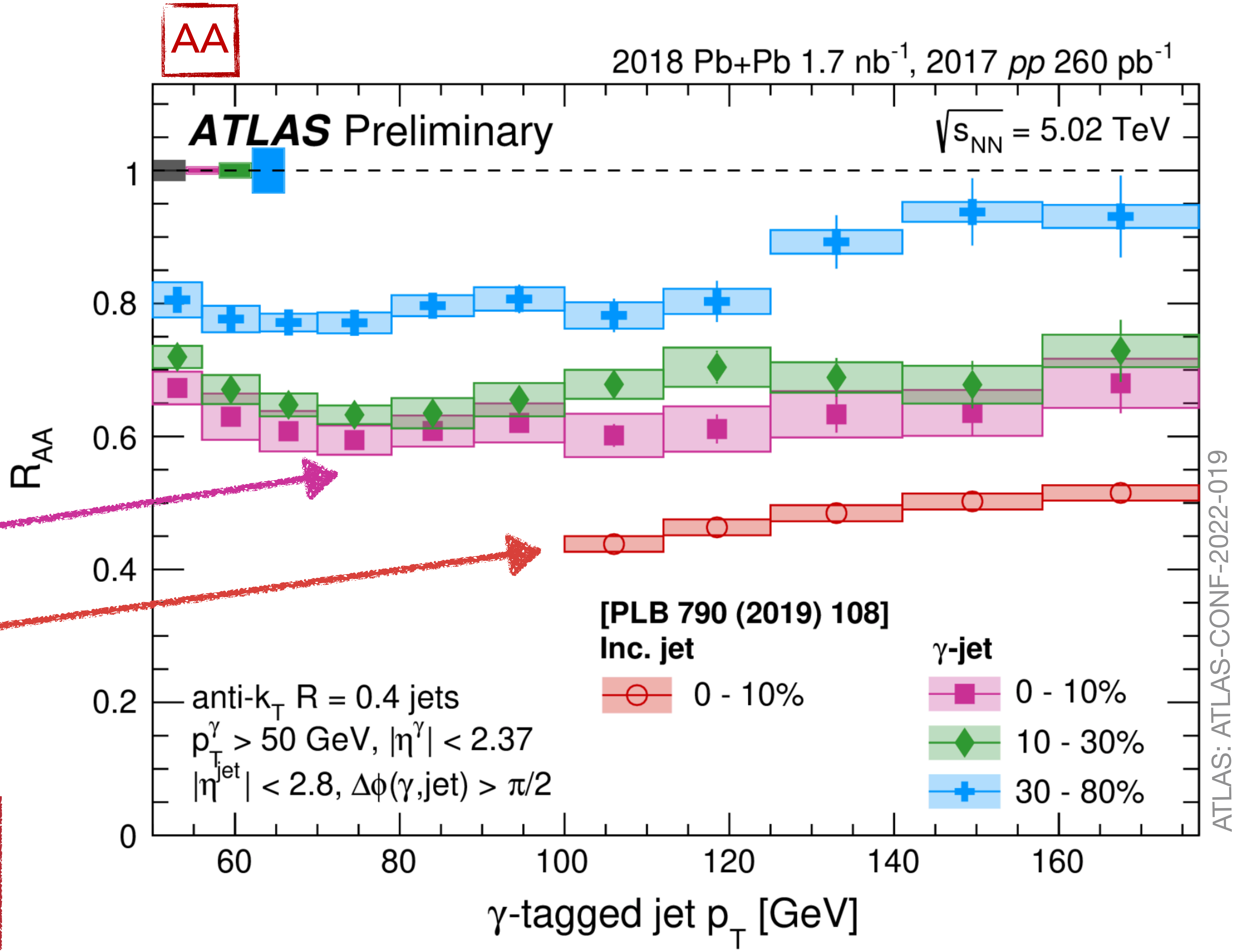
The reaction plane dependence of R_{AA} constrains the path length dependence of parton energy loss

Colour-charge dependence of energy loss



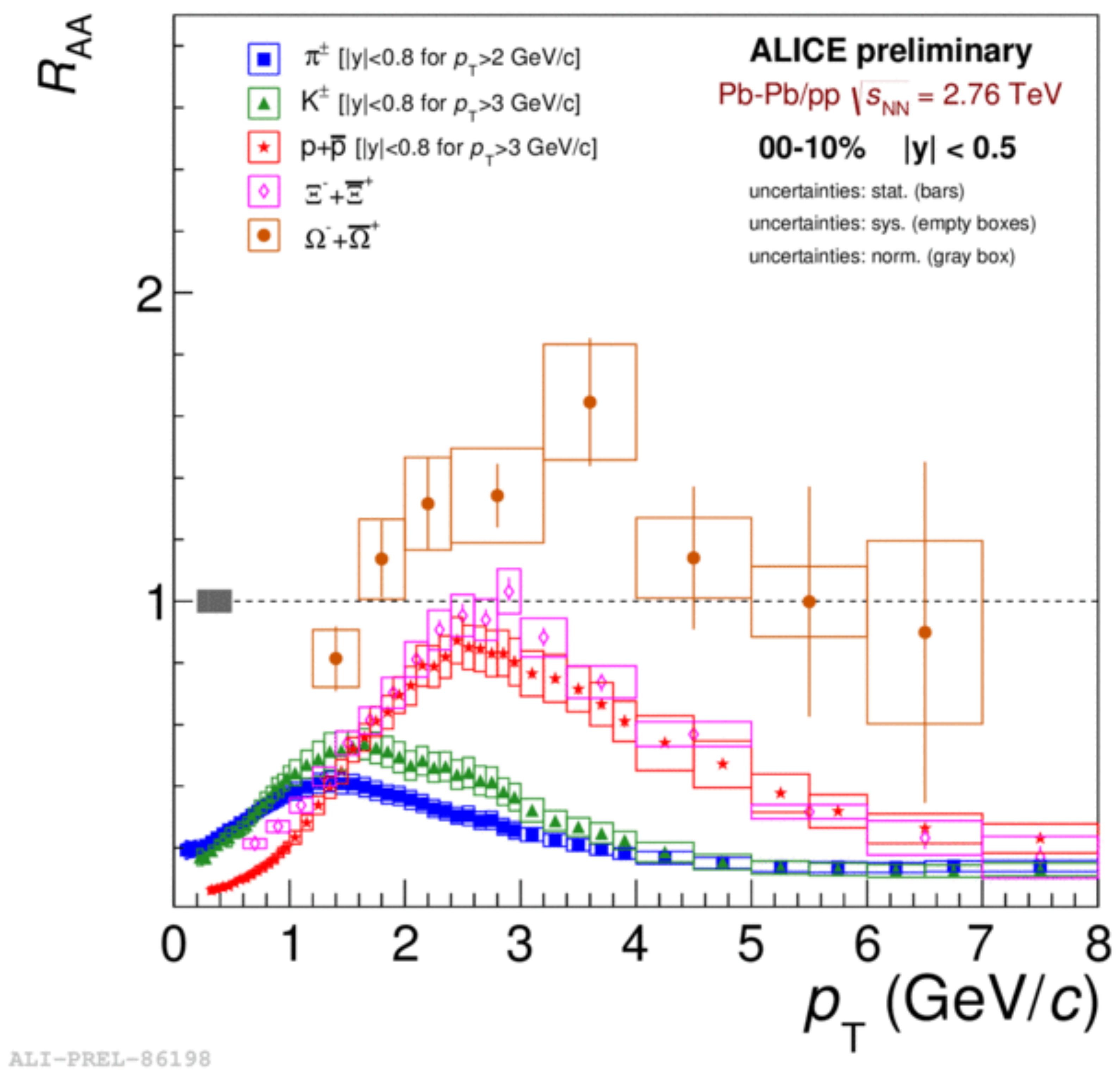


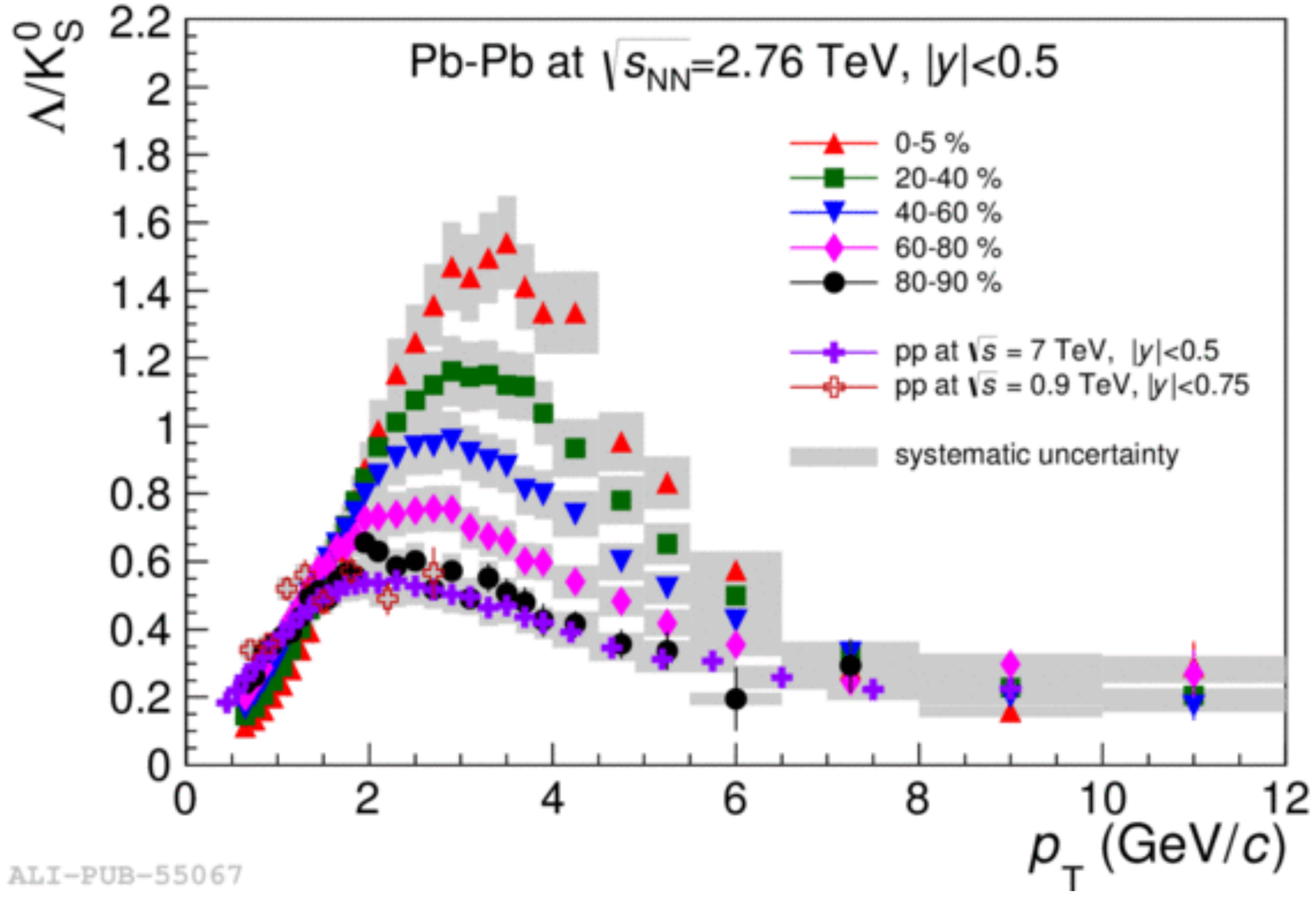
- Photon-tagged jet sample dominated by quark-initiated jets (quark-gluon Compton scattering)
- photon-tagged jet R_{AA} higher than inclusive jet R_{AA}



→ clear observation of colour-charge dependence of energy loss: $\Delta E_g > \Delta E_{u,d,s}$

Particles species dependence
Baryon anomaly



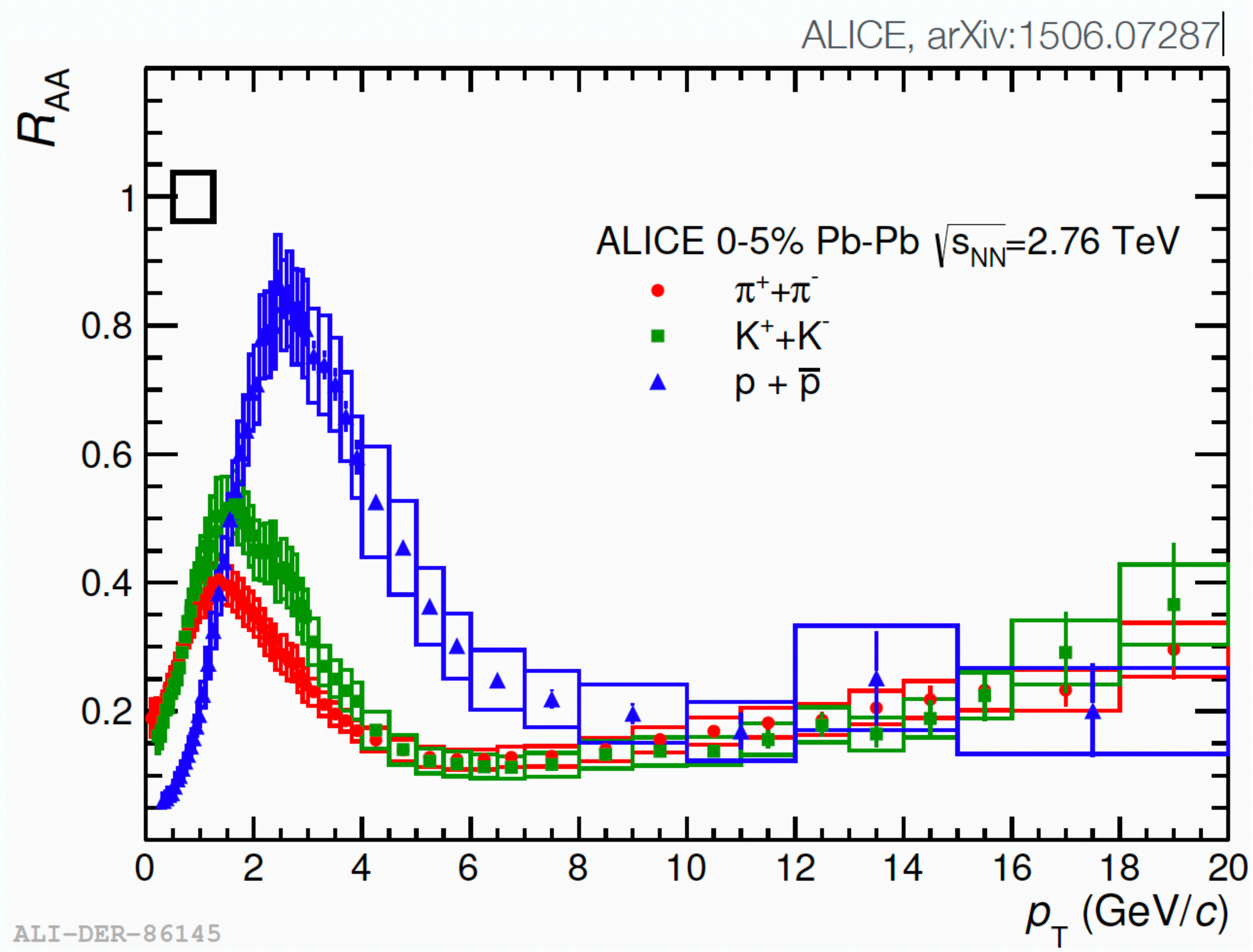


$qq \rightarrow$

$qqq \rightarrow$

- Baryons more abundant at intermediate p_T
- Ratio increases with centrality
  - In most central events x3 compared with pp at 3 GeV/*c*
  - Consistent with recombination
  - Flow – mass dependence

Suppression independent of hadron species for $p_T \gtrsim 8$ GeV/c

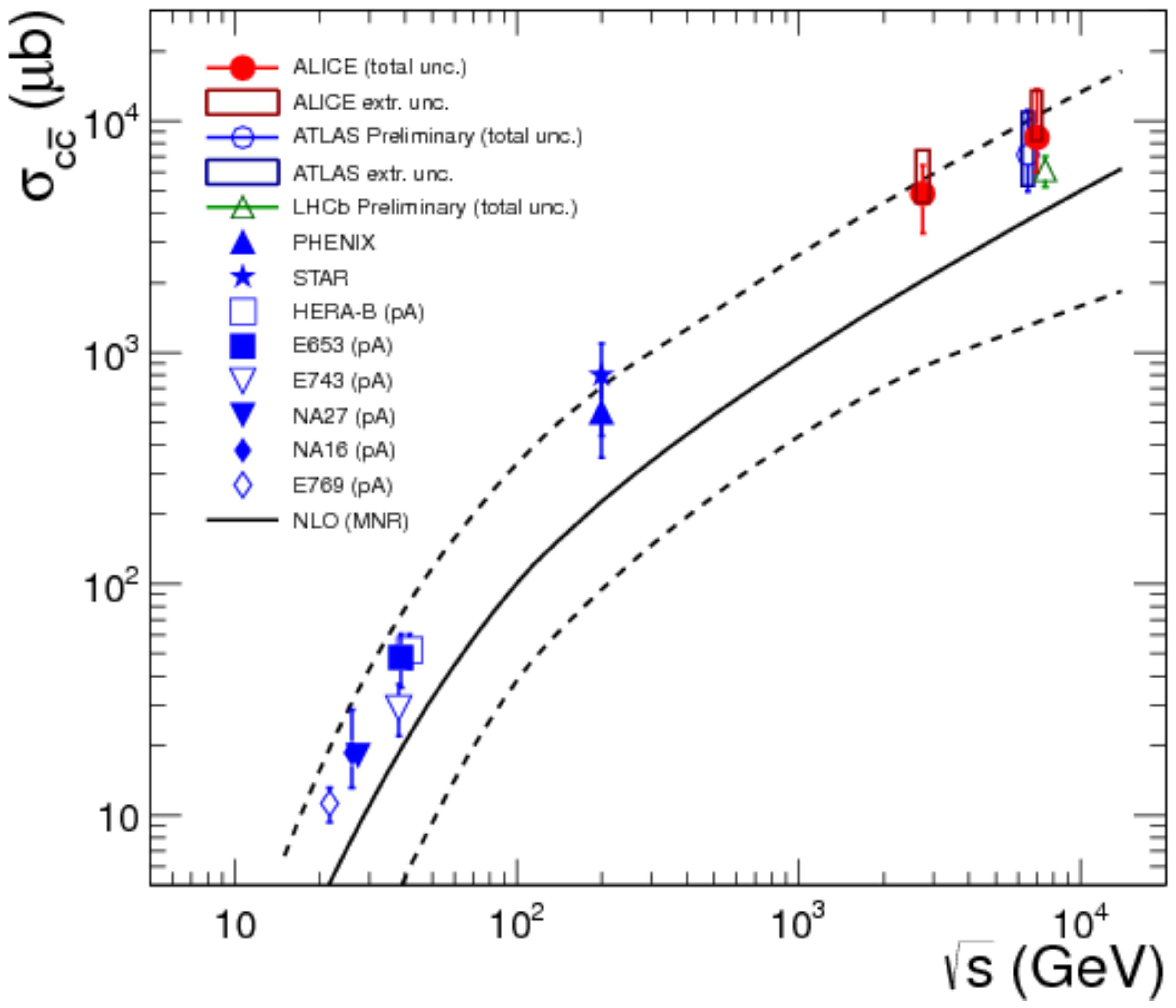


- $R_{AA}(p) > R_{AA}(K) \approx R_{AA}(\pi)$ for $3 < p_T < 8$ GeV/c
- Similar p, K and π R_{AA} for $p_T > 8$ GeV/c
- Leading-parton energy loss followed by fragmentation in QCD vacuum (as in pp) for $p_{T,hadron} > 8$ GeV/c?

Heavy quarks: unique probes

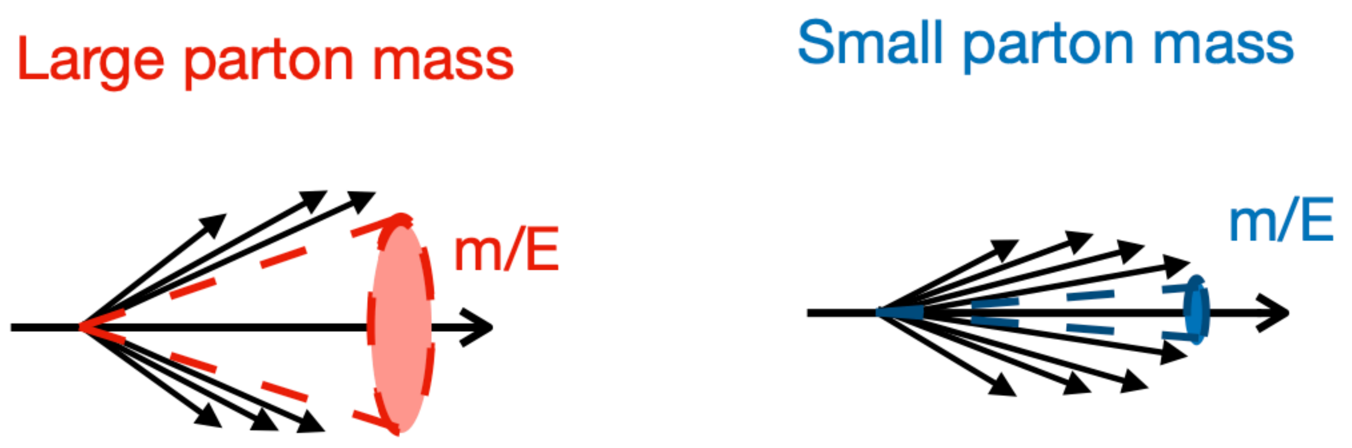
- Heavy quarks: charm (m_c ~1.3 GeV/c²), beauty (m_b ~4.2 GeV/c²)
  - $m_{c,b} >> \Lambda_{QCD}$, T_{pc} → heavy quarks = genuine hard probes, even at low p_T
  - Large mass → short formation time: $\tau \approx 1/(2m_q) \leq 0.1$ fm/c
  - Produced in the very early stage of the collision in partonic processes with large Q^2
  - Perturbative QCD can be used to calculate initial cross sections
  - Large cross sections at LHC energy

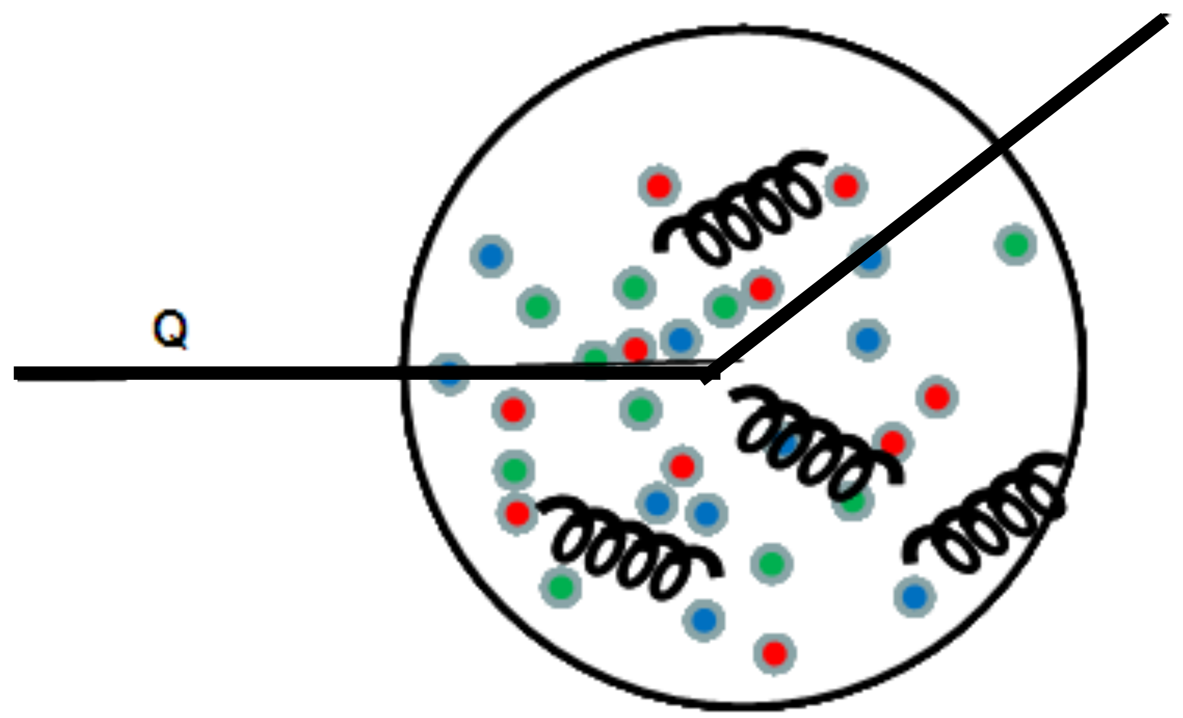
- Heavy quarks are unique
  - Interactions with produced QCD medium don't change the flavour, but can modify the phase-space distribution of heavy quarks
  - Thermal production rate in the QGP is "small"
  - Destruction or creation in the medium is difficult
  - Transported through the whole evolution of the system



Energy loss in the medium - heavy quarks

- Interaction of heavy quarks with hot/dense medium
- Parton energy loss via radiative and collisional processes depends on
  - Properties of the medium (gluon densities, path length)
  - Properties of the probe (colour charge, mass)
- Dead cone effect
  - Gluon radiation is suppressed for angles $\theta < m_q/E_q$





$\rightarrow \Delta E_g > \Delta E_{up,down,strange} > \Delta E_{charm} > \Delta E_{beauty}$

$\rightarrow R_{AA}$ (light hadrons) $< R_{AA}$ (D) $< R_{AA}$ (B)

Possible other mechanisms for interactions with the medium (collisional energy loss, in-medium dissociation, resonance scattering)

Dokshitzer and Kharzeev, PLB 519 (2001) 199.
Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

Open Heavy-Flavour measurements

- Heavy-flavour hadrons decay via weak interaction:
  decay lengths $c\tau$ ~ few 100 μm → measure decay products

Hadronic decays (c):

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

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

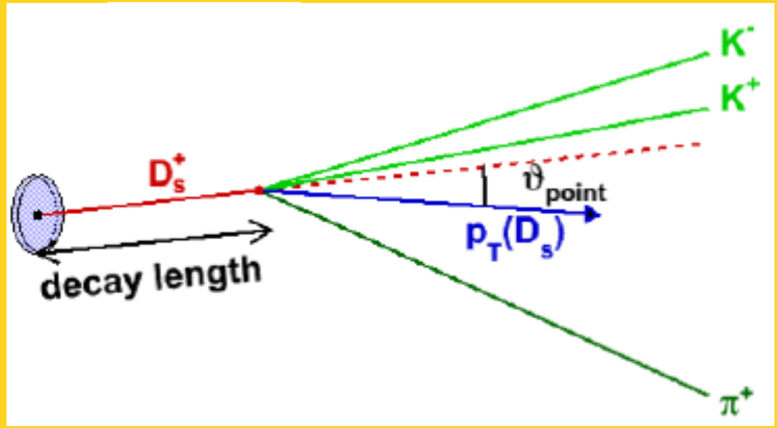
$D^0 \rightarrow K^+\pi^-\pi^+\pi^-$

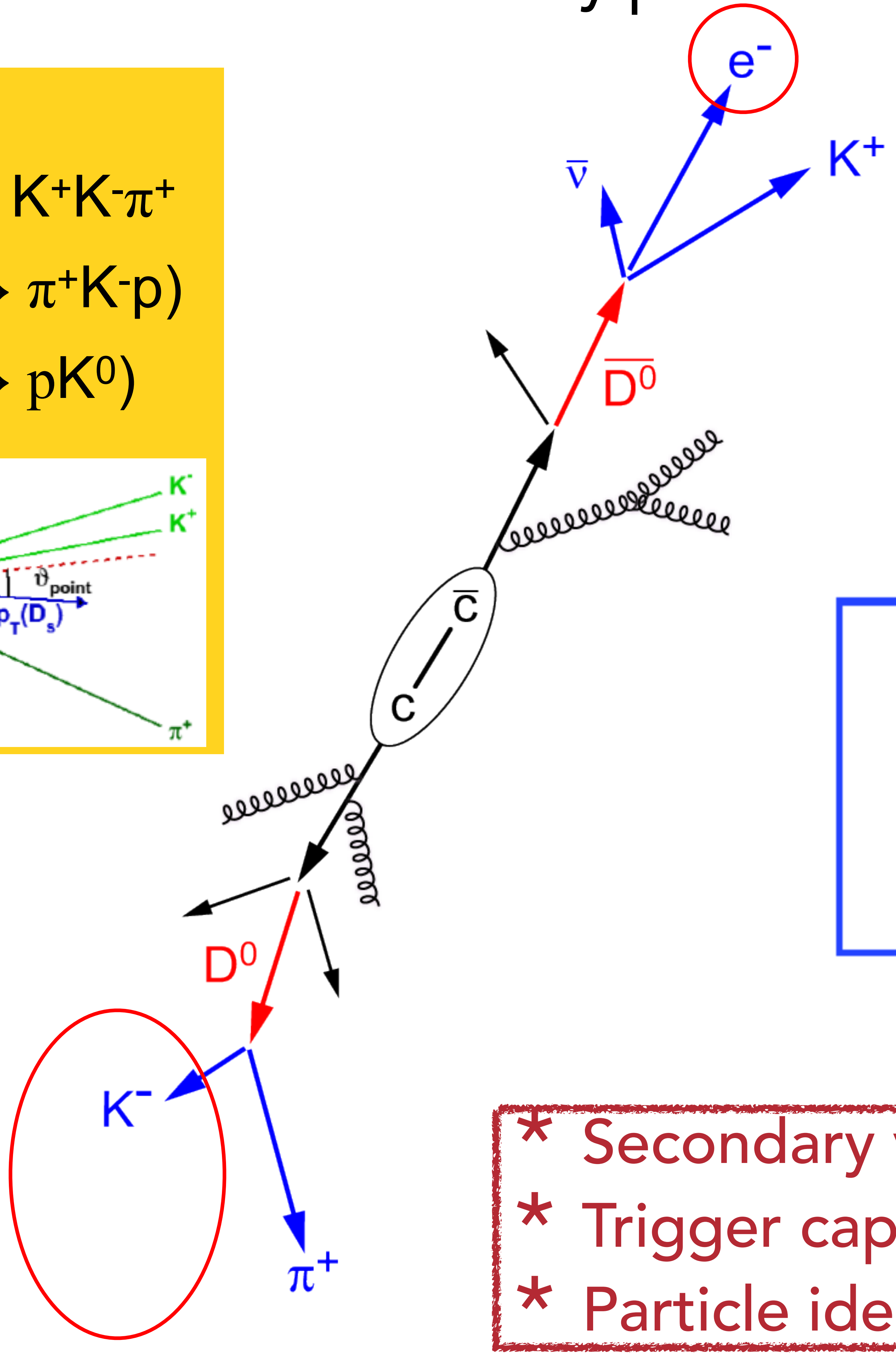
$D^{*+} \rightarrow D^0\pi^+$

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

$(\Lambda^+_c \rightarrow \pi^+K^-p)$

$(\Lambda^+_c \rightarrow pK^0)$

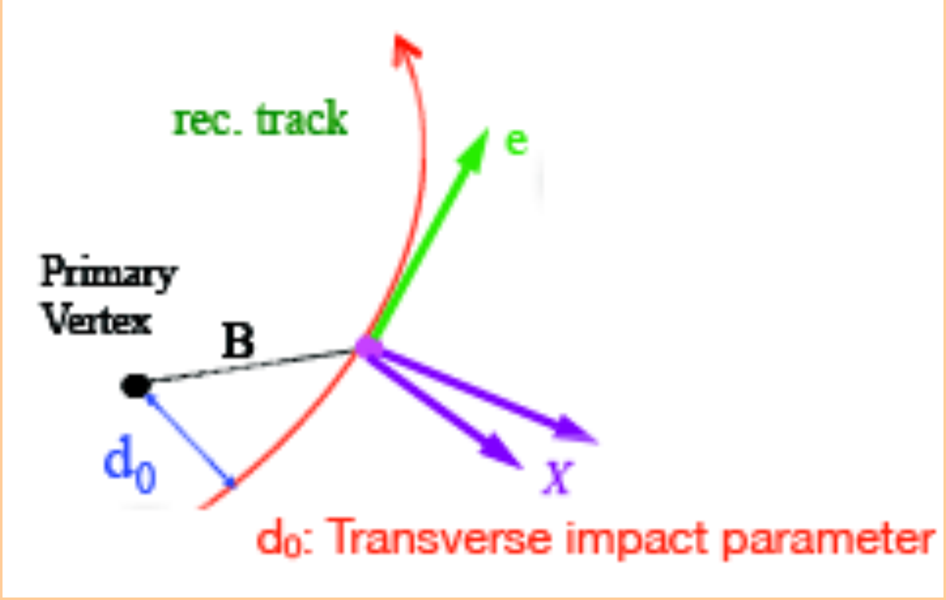




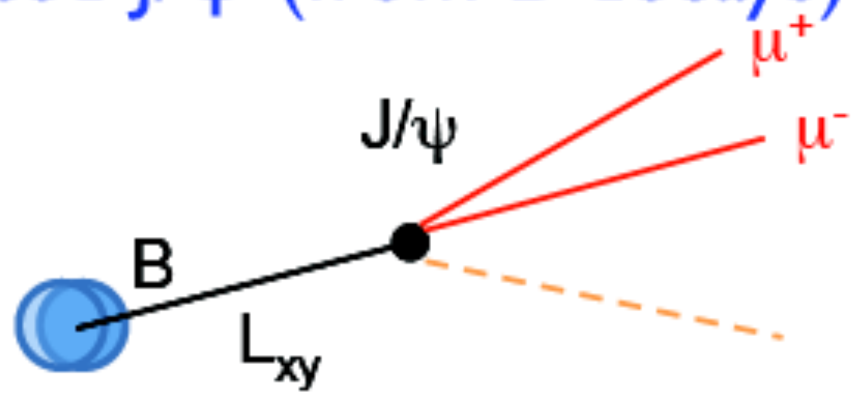
Semi-leptonic decays (c, b):

D, B, Λ_c , ... → e + anything

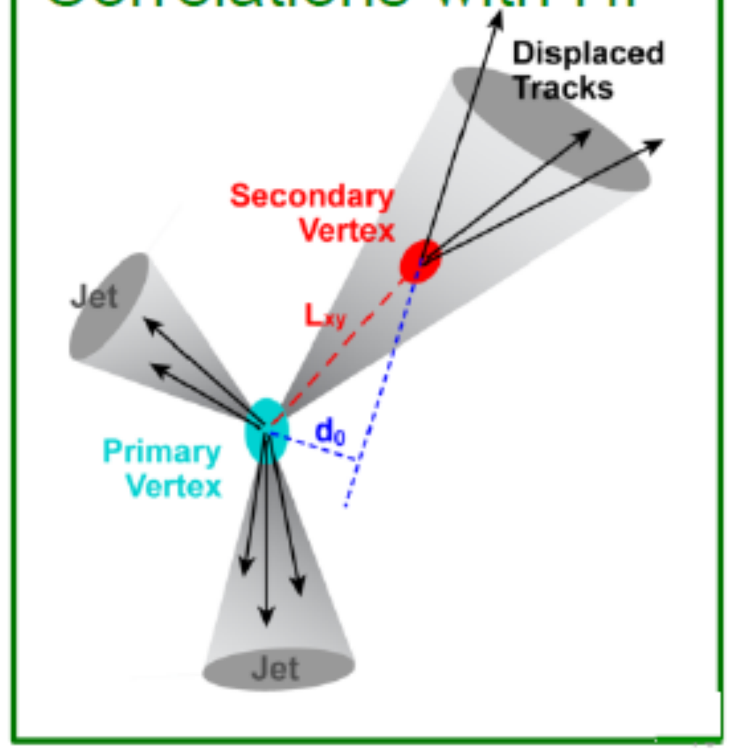
D, B, Λ_c , ... → μ + anything



Displaced J/ψ (from B decays)



HF jets
Correlations with HF



* Secondary vertexing
* Trigger capabilities
* Particle identification

Hadronic decays (b):

$B^+ \rightarrow \pi^+ D^0$

$B^0 \rightarrow J/\psi + K^*(892)^0$

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

D Meson Decay Reconstruction

- D^0 meson: m = 1.87 GeV/c^2; $c\tau$ = 123 μm
  - Rather short lived
  - Many decay modes
- D^0 -> K + π (branching ratio 3.9%)

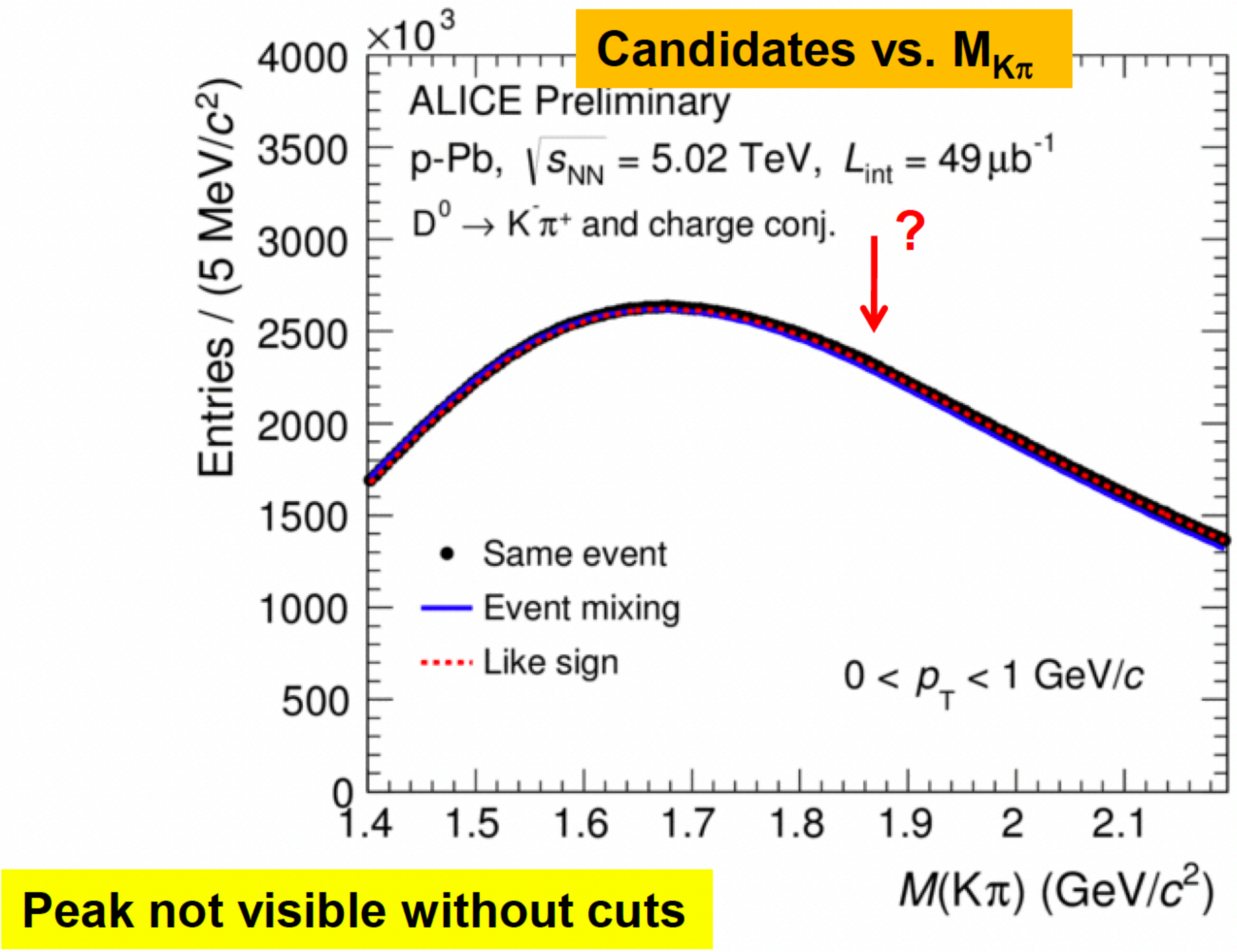
- Standard method: invariant mass of opposite charge pairs
  - **Per central event (D^0 -> K + π with a p_T > 2 GeV/c, incl. efficiencies): 0.001 compared to ~700 K and up to ~2500 π**
  - Signal over background far too small to extract a peak

- Reduce combinatorial background
  - Topological cuts
  - Particle identification (PID) of K and π

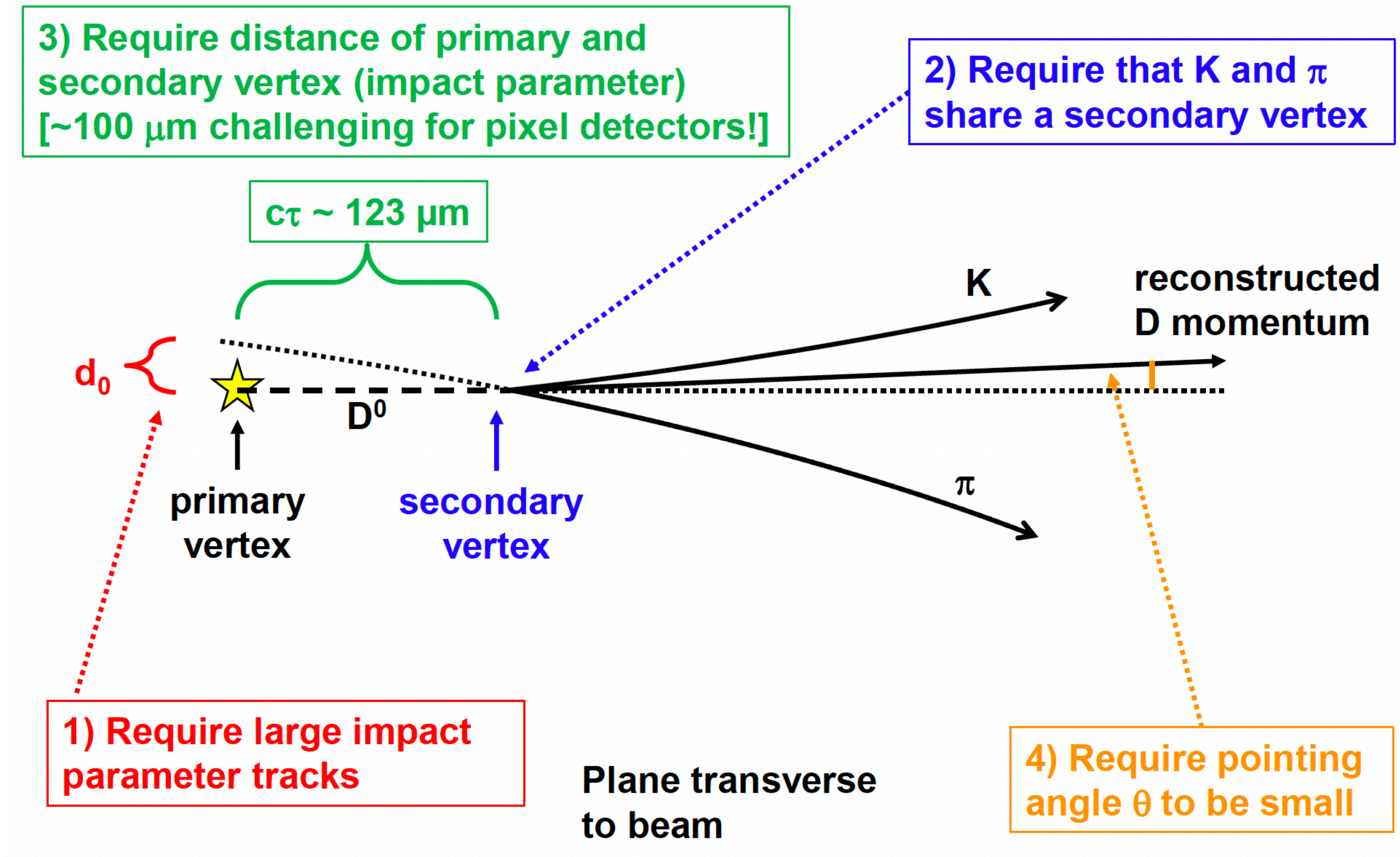
- Feed-down from B meson decays corrected with FONLL or template fit methods

Invariant mass

- $D^0 \rightarrow K\,\pi$ without PID and without topological cuts



Topological selection criteria

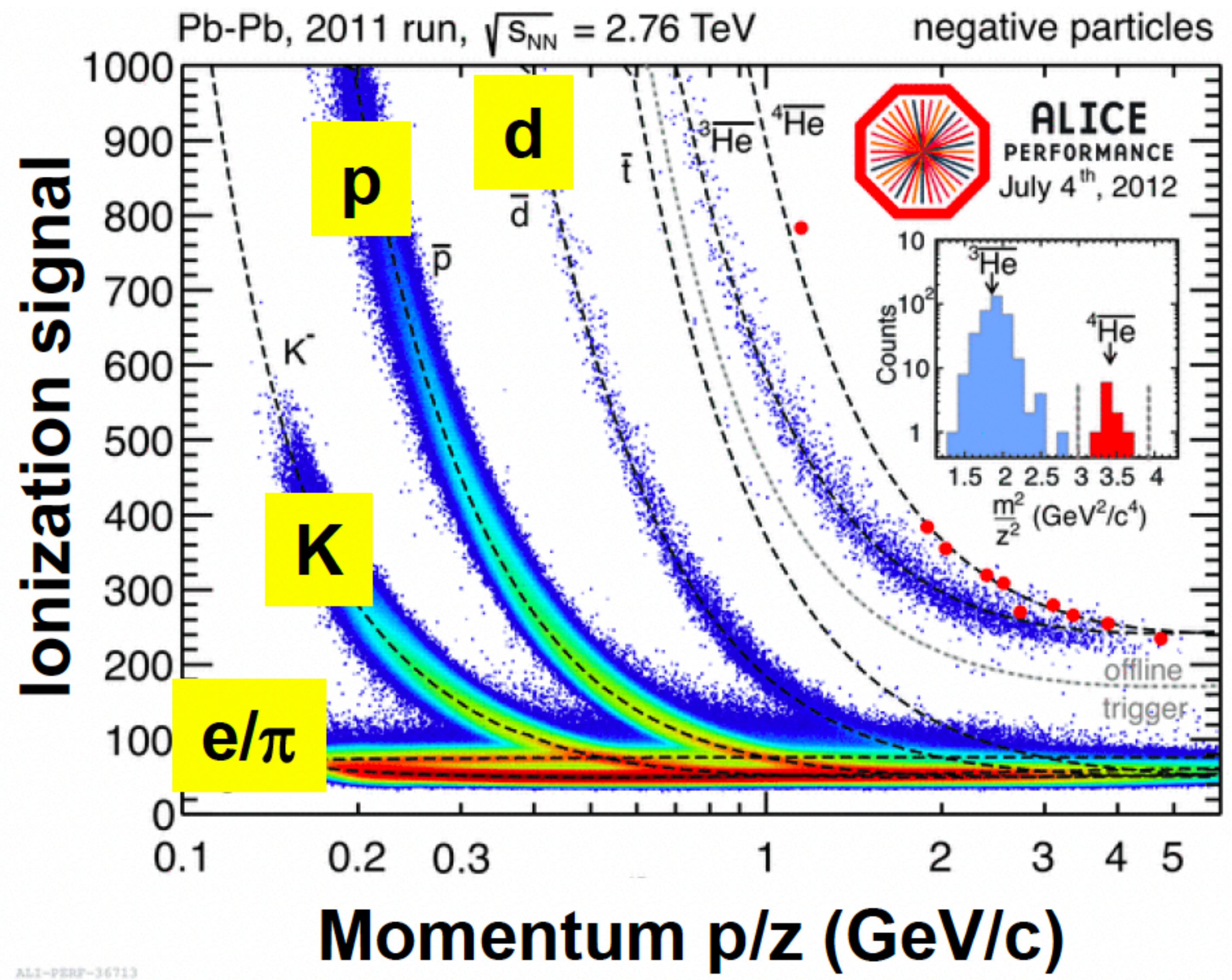


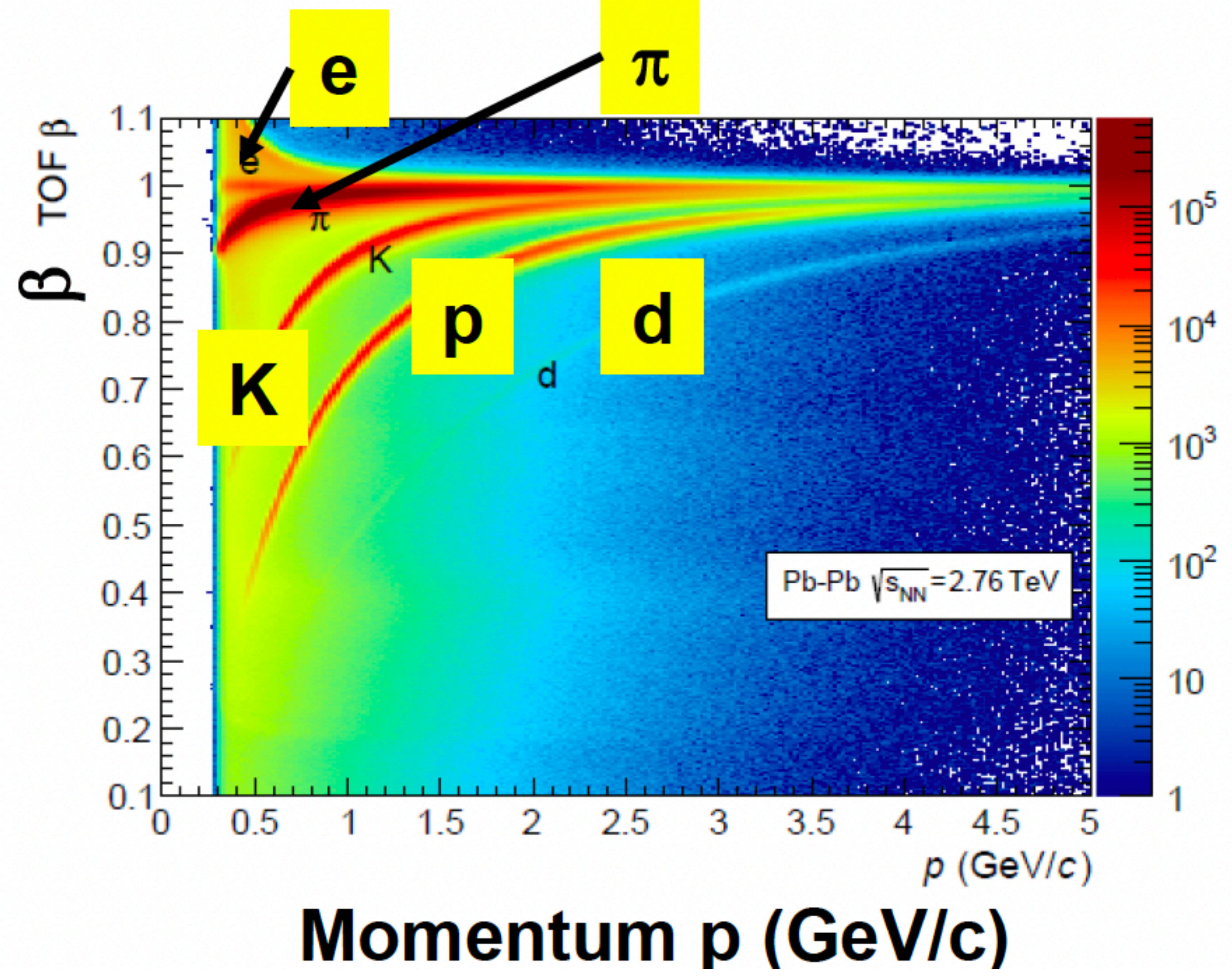
Particle identification

- TPC
  - Specific ionisation energy loss

- Time Of Flight
  - Particles with the same momentum have slightly different speed due to their different mass
  - Needed flight time precision, e.g. for a particle with *p* = 3 GeV/*c*, flying length 3.5 m
  - t(π) ~ 12 ns and t(K) – t(π) ~ 140 ps

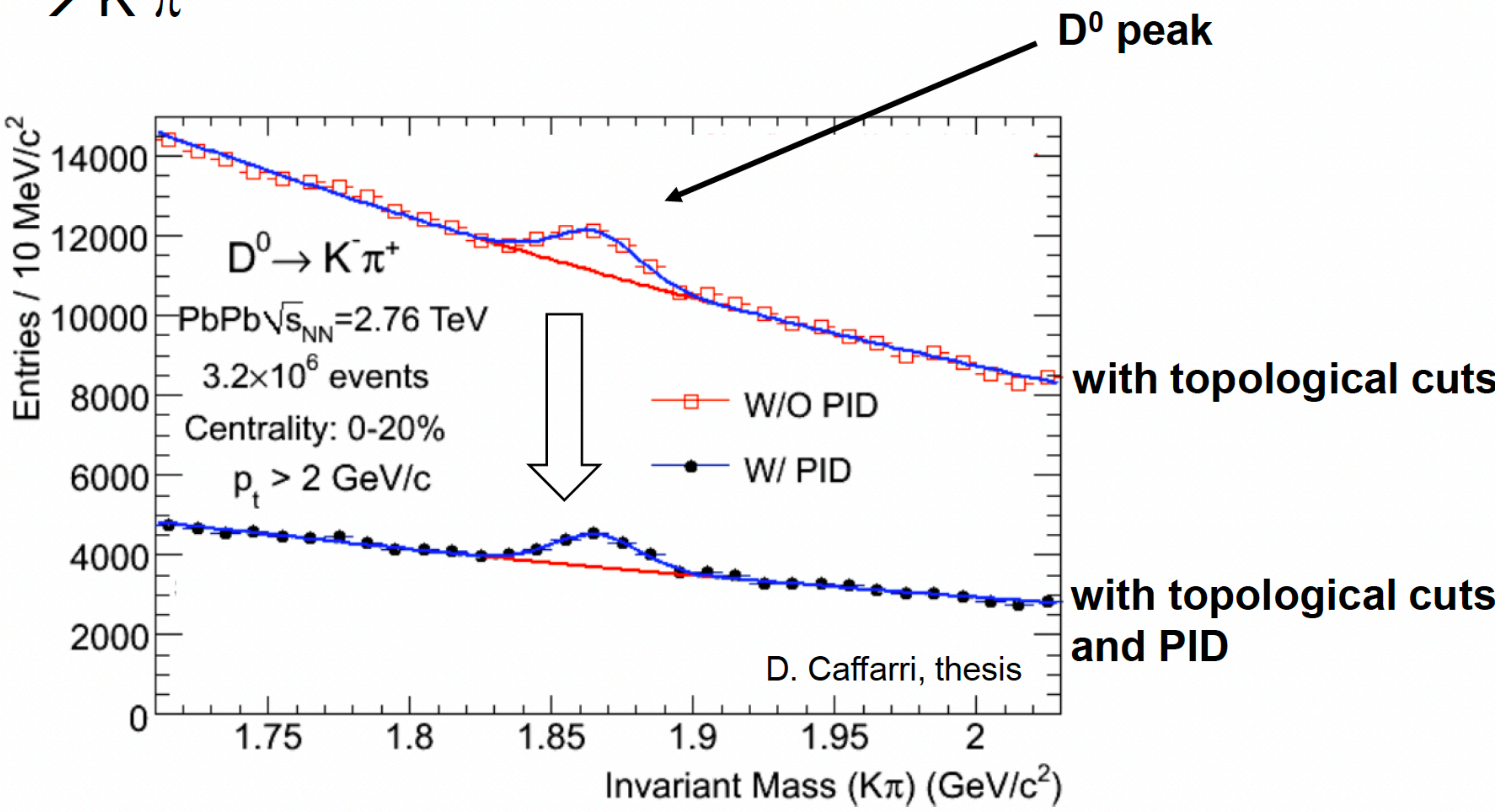
- Methods can be combined





Invariant mass with selection criteria

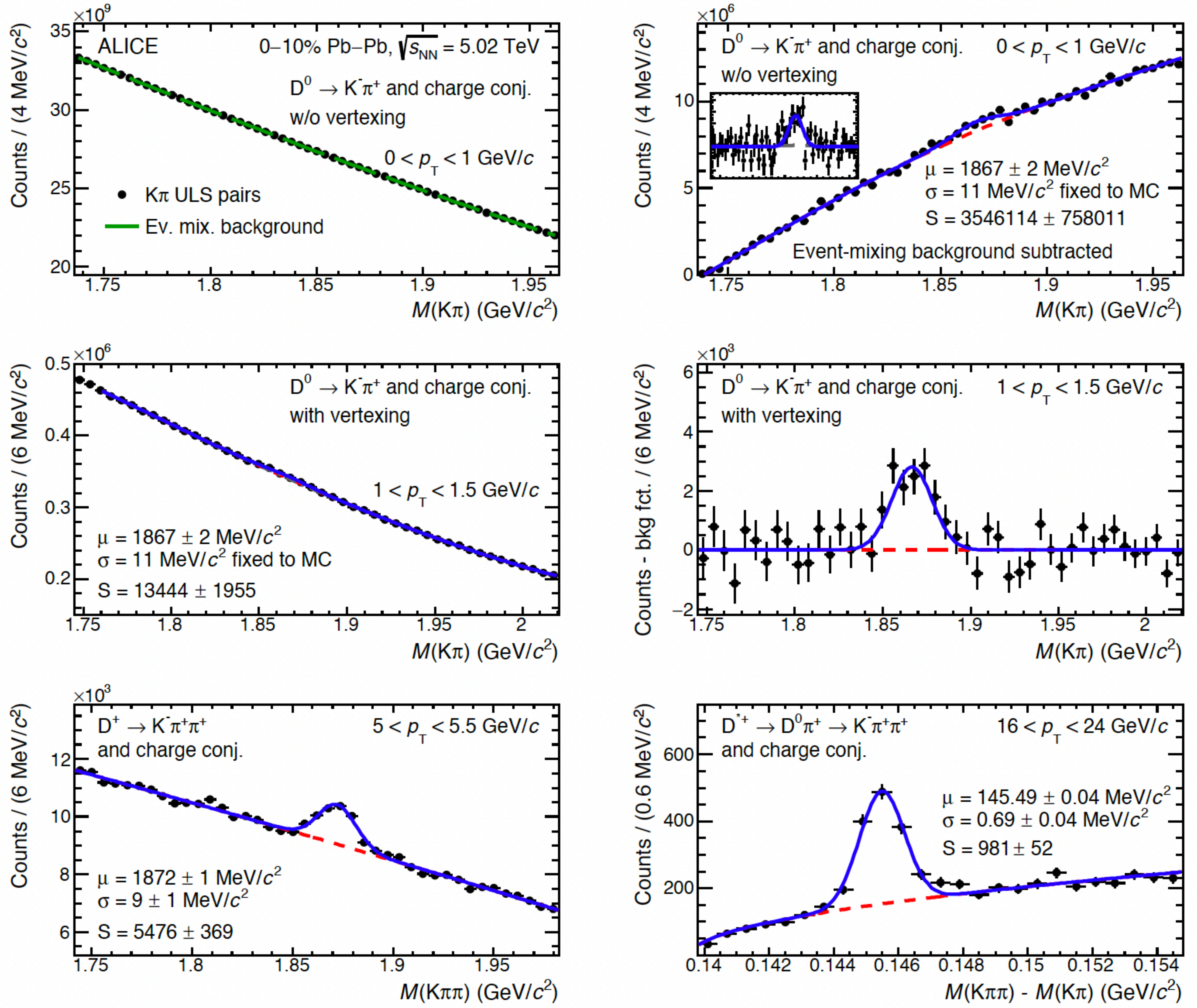
- $D^0 \rightarrow K\,\pi$



PID reduces background, but signal peak stays of same magnitude

D meson invariant mass in momentum intervals

- Rare signal
- Combinatorial background reduced with particle identification and topological cuts
- Invariant mass distribution
- Background with mixed event technique and/or fit function
- Apply fit to extract yield



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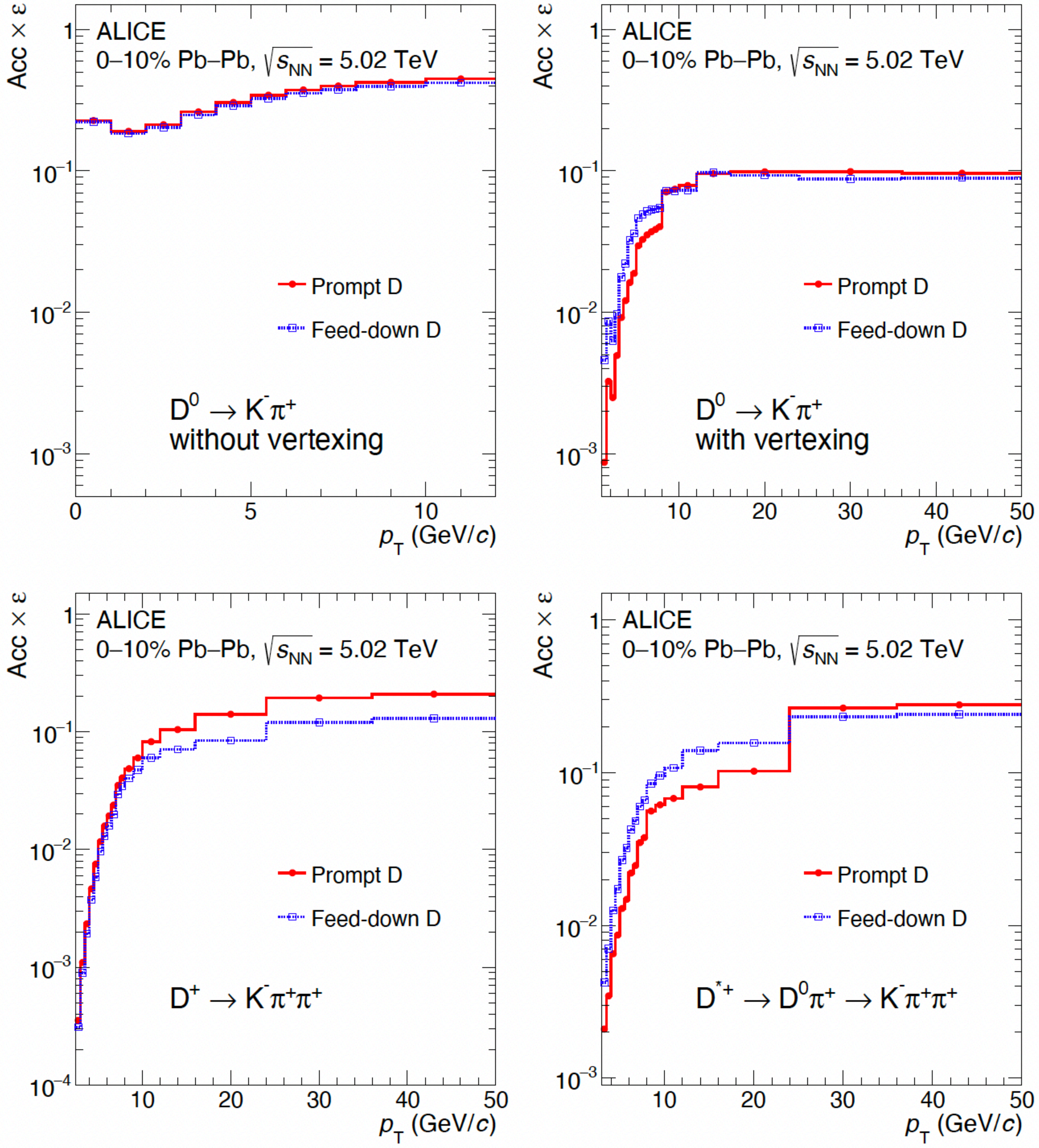
Acceptance and efficiency

- Prompt vs feed-down D



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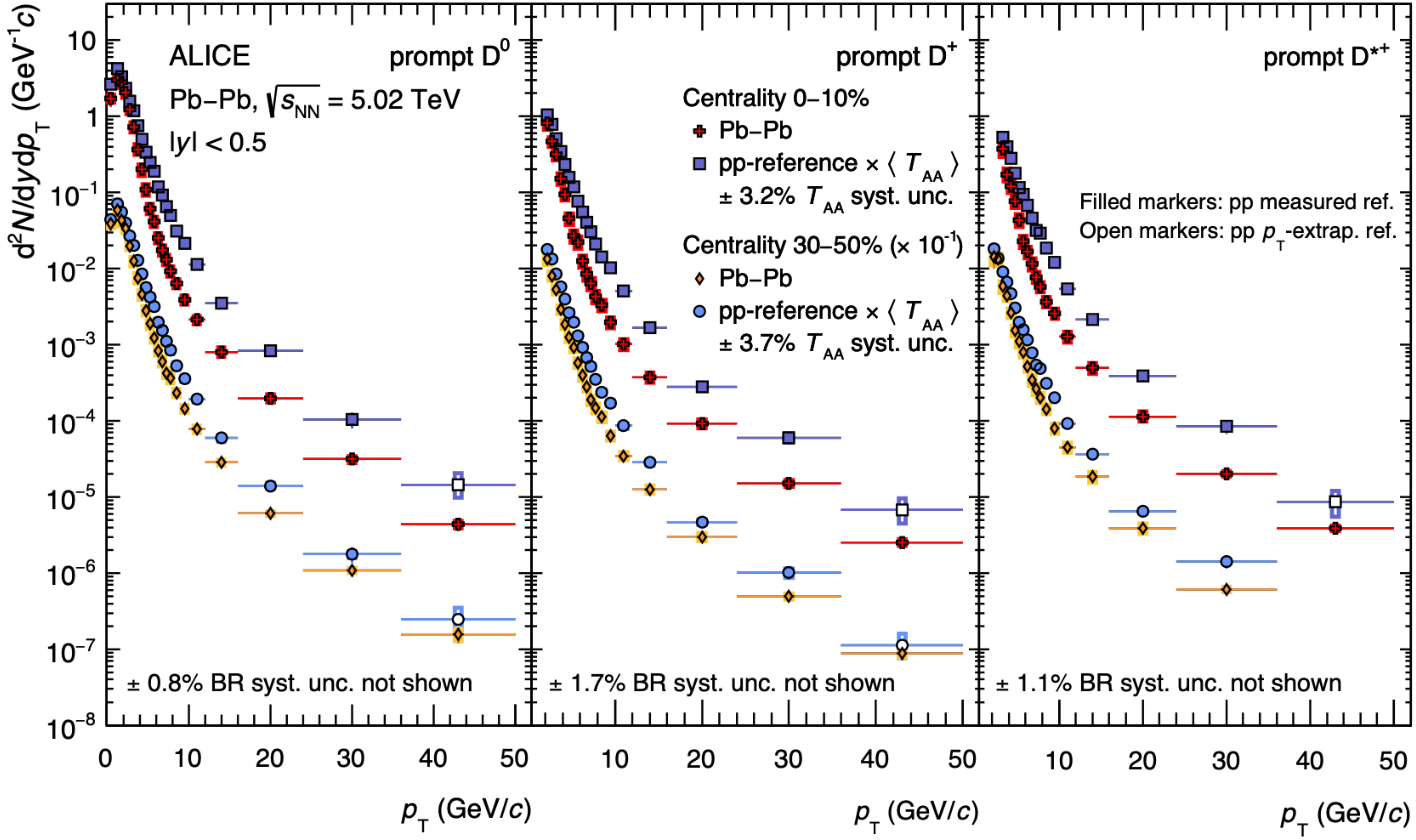
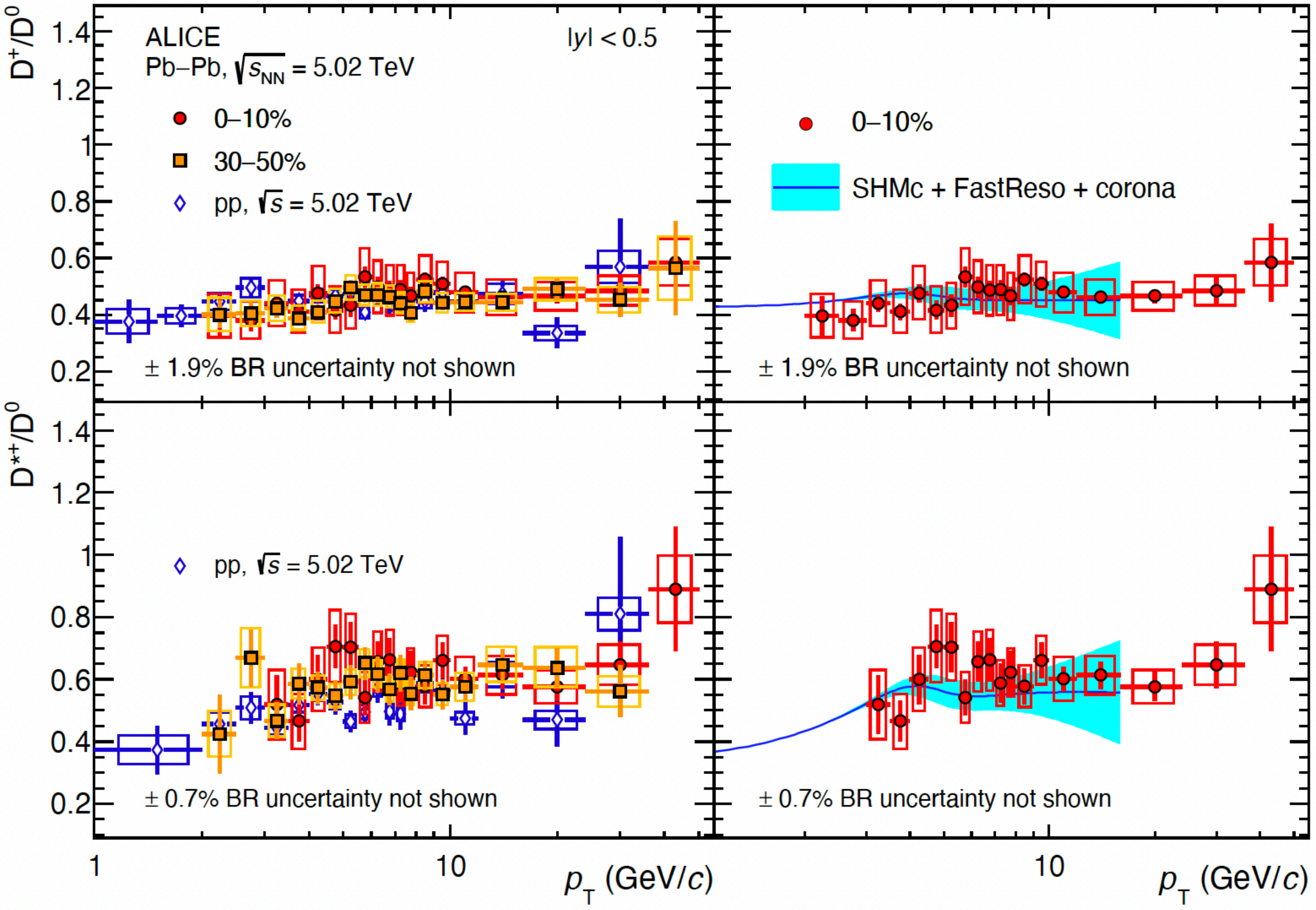
D meson spectra



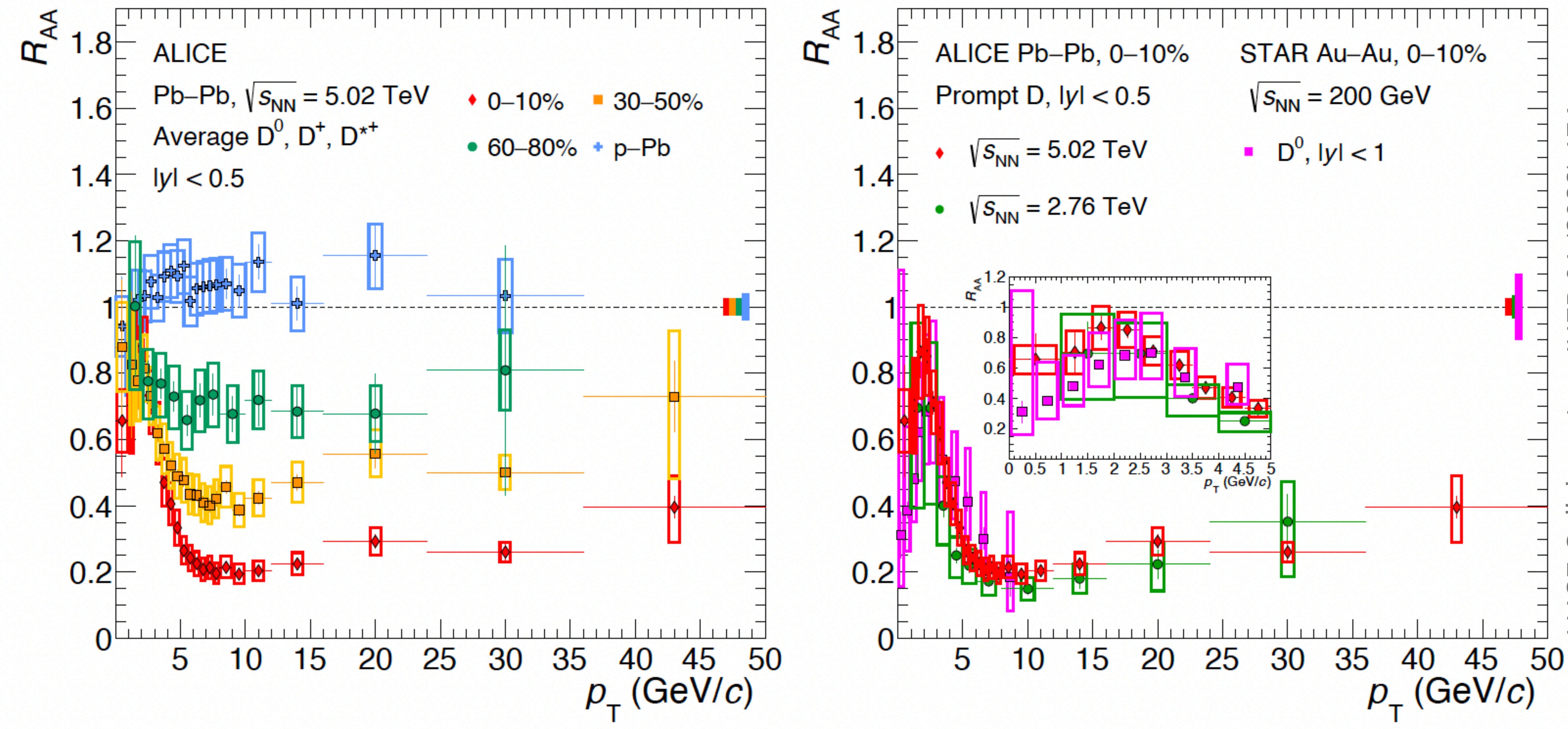
Ratios of particle yields

- Ratios compatible within uncertainties vs p_T and in the different centrality intervals
- Described by GSI-Heidelberg statistical hadronisation model (SHMc)



R_{AA}

- Suppression in Pb-Pb is a final state effect
- Results in Pb-Pb at 2.76 and 5.02 TeV compatible within uncertainties
  - Higher medium temperature and density at 5.02 TeV -> larger energy loss and thus lower R_{AA}, but harder p_T distribution of charms quarks at 5.02 TeV



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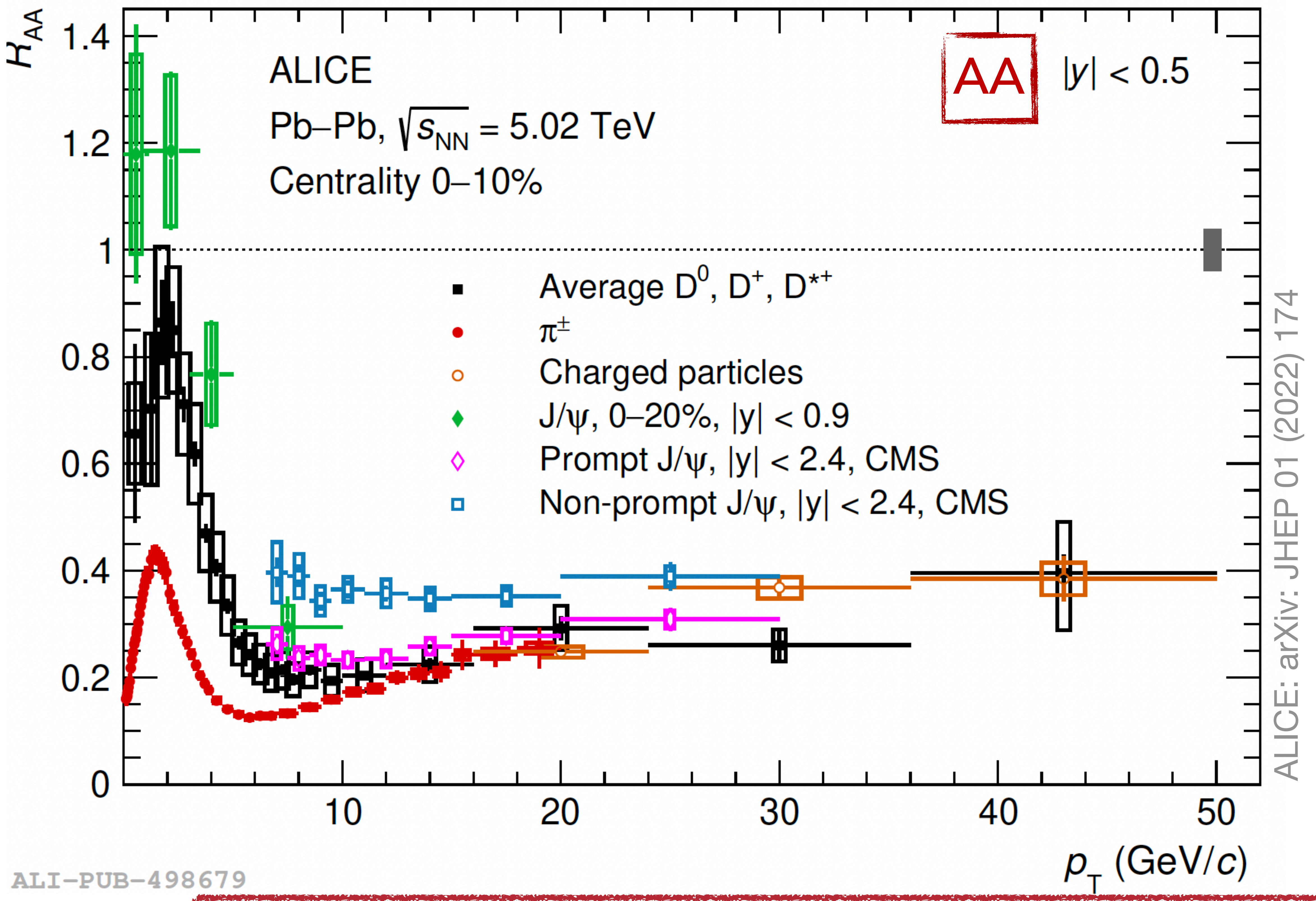
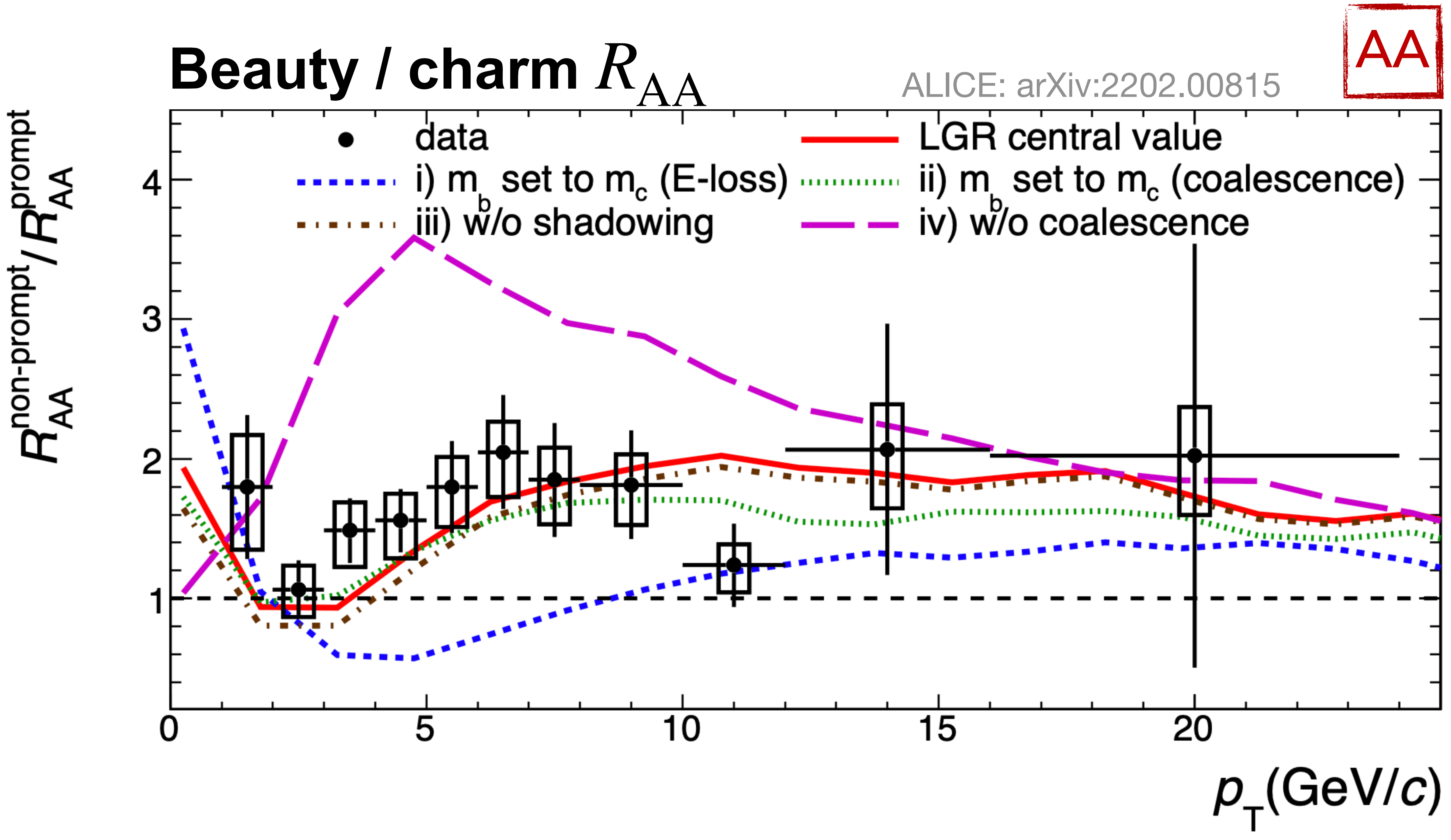
Mass dependence of the energy loss: Heavy quarks

- Expected behaviour: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_{charm} > \Delta E_{beauty}$

  → R_{AA} (light hadrons) < R_{AA} (D) < R_{AA} (B)





→ D-meson R_{AA} larger than the one for pions for p_T < 8 GeV/c

→ Charm and beauty hadrons show quark-mass dependent energy loss at intermediate p_T

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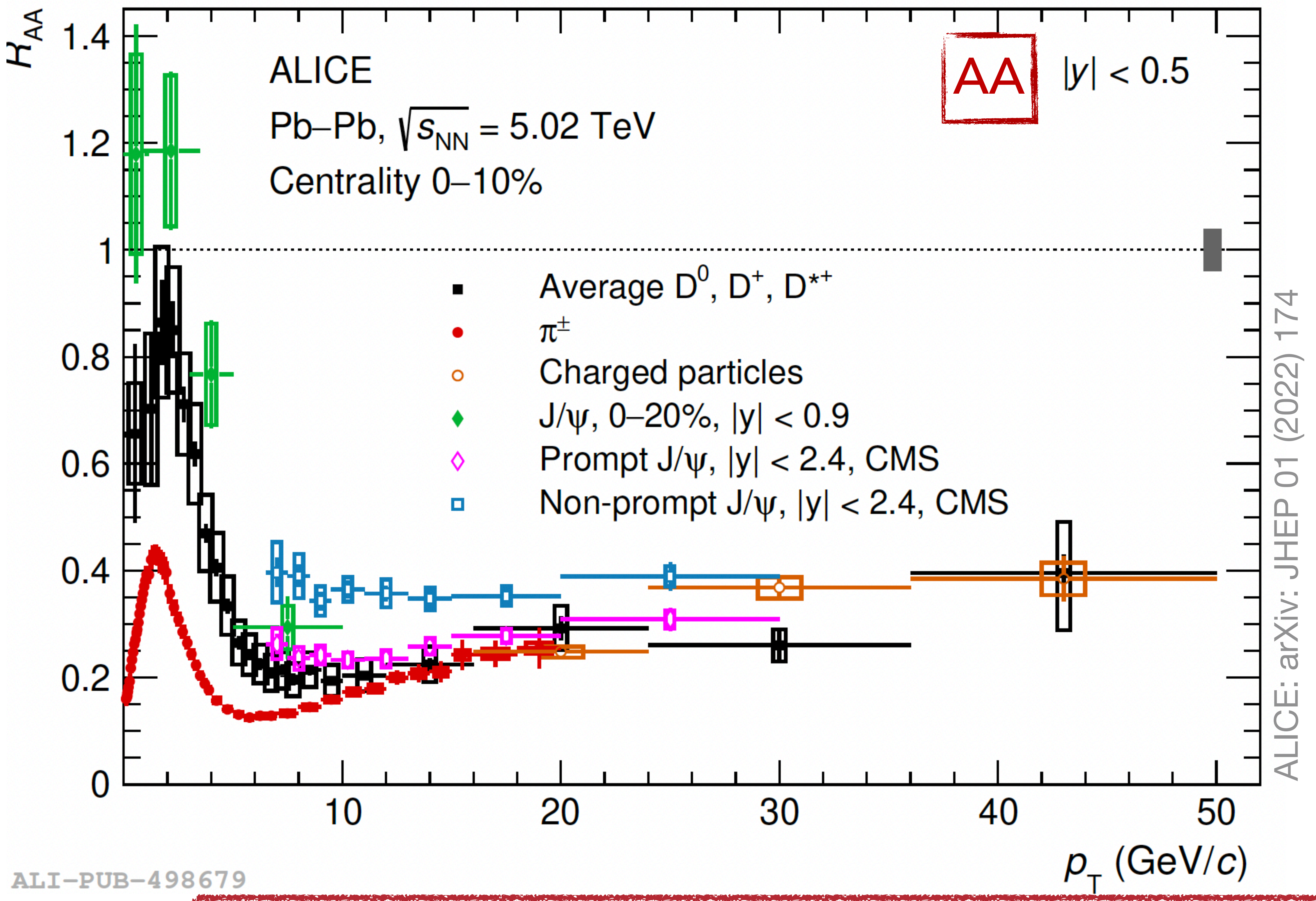
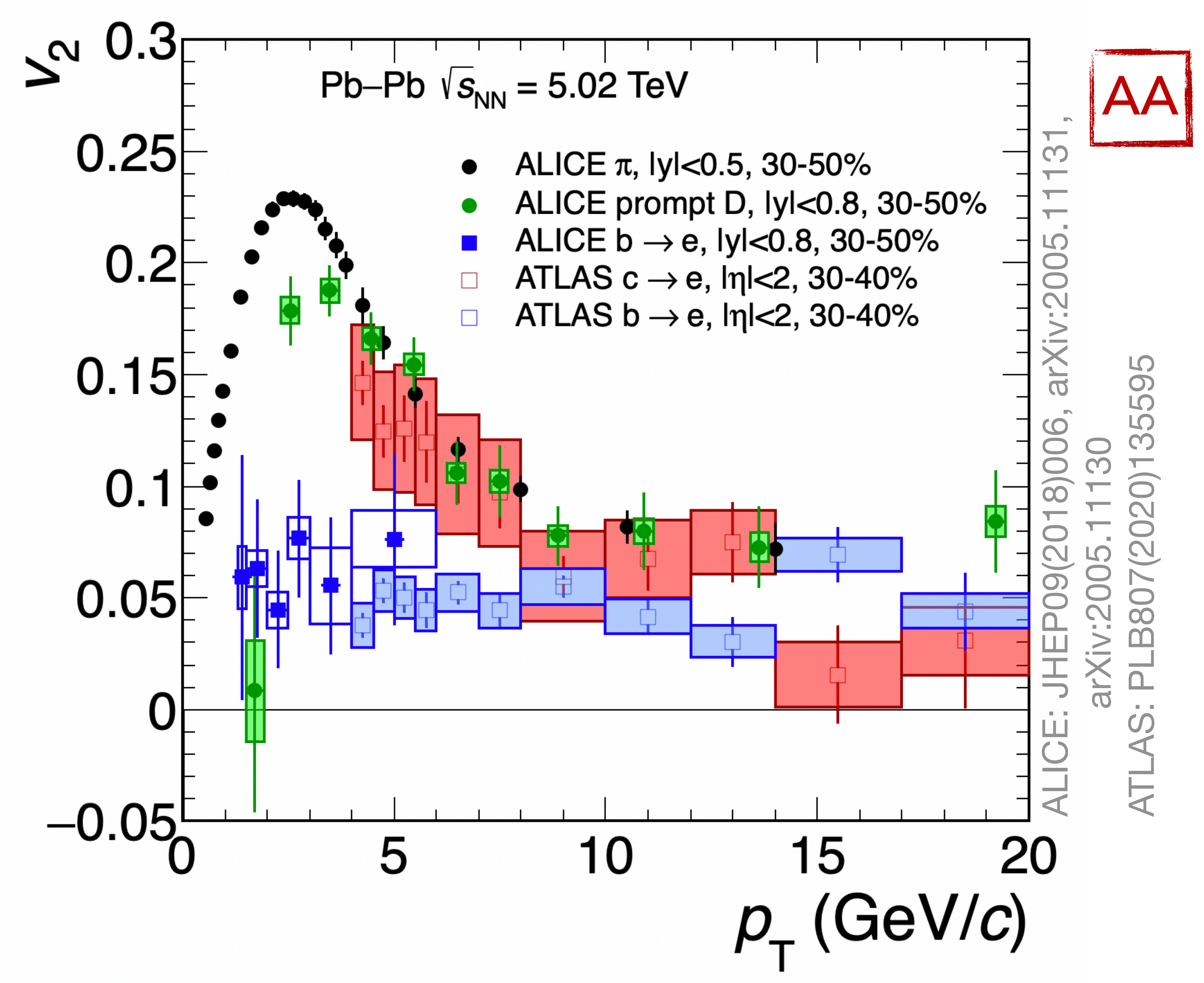




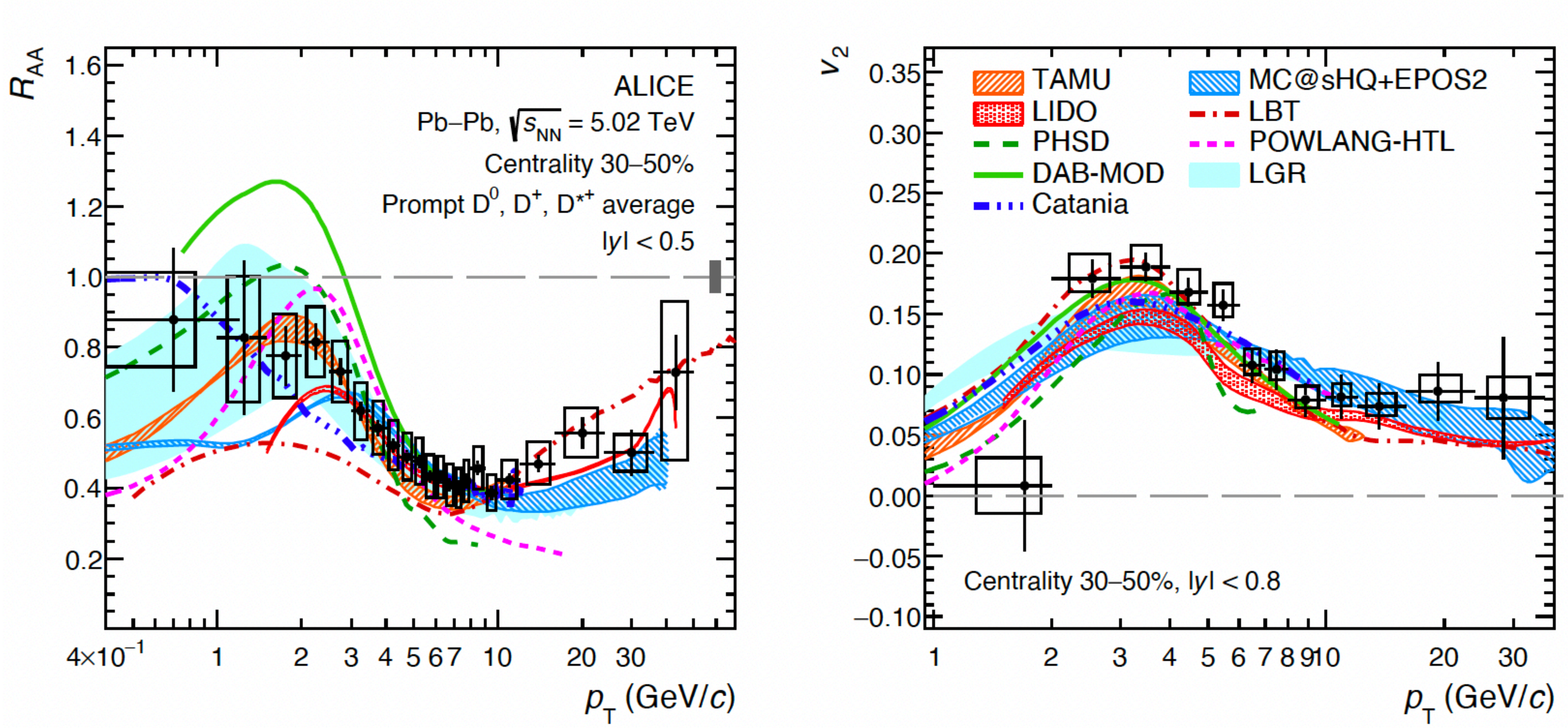
→ D-meson R_{AA} larger than the one for pions for p_T < 8 GeV/c

→ Charm and beauty hadrons show quark-mass dependent energy loss at intermediate p_T

→ Charm and beauty quarks participate in the collective motion

Comparison with models

- Simultaneous description difficult



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Diffusion coefficient

- Robert Brown - paper from 1828
  - Pollen in water
- Transport models
  - Pollen = D meson
  - Water = pions
  - Then increase the temperature …
- In a naive way, a small (large) spatial diffusion corresponds to a short (long) mean-free path and thus strong (weak) HQ-medium coupling strength

THE
PHILOSOPHICAL MAGAZINE
AND
ANNALS OF PHILOSOPHY.
[NEW SERIES.]
SEPTEMBER 1828.

XXVII. *A brief Account of Microscopical Observations made in the Months of June, July, and August,* 1827, *on the Particles contained in the Pollen of Plants; and on the general Existence of active Molecules in Organic and Inorganic Bodies. By* Robert Brown, *F.R.S., Hon. M.R.S.E. & R.I. Acad., V.P.L.S., Corresponding Member of the Royal Institutes of France and of the Netherlands, &c. &c.*

[We have been favoured by the Author with permission to insert the following paper, which has just been printed for private distribution.—Ed.]

THE observations, of which it is my object to give a summary in the following pages, have all been made with a simple microscope, and indeed with one and the same lens, the focal length of which is about $\frac{1}{32}$nd of an inch*.

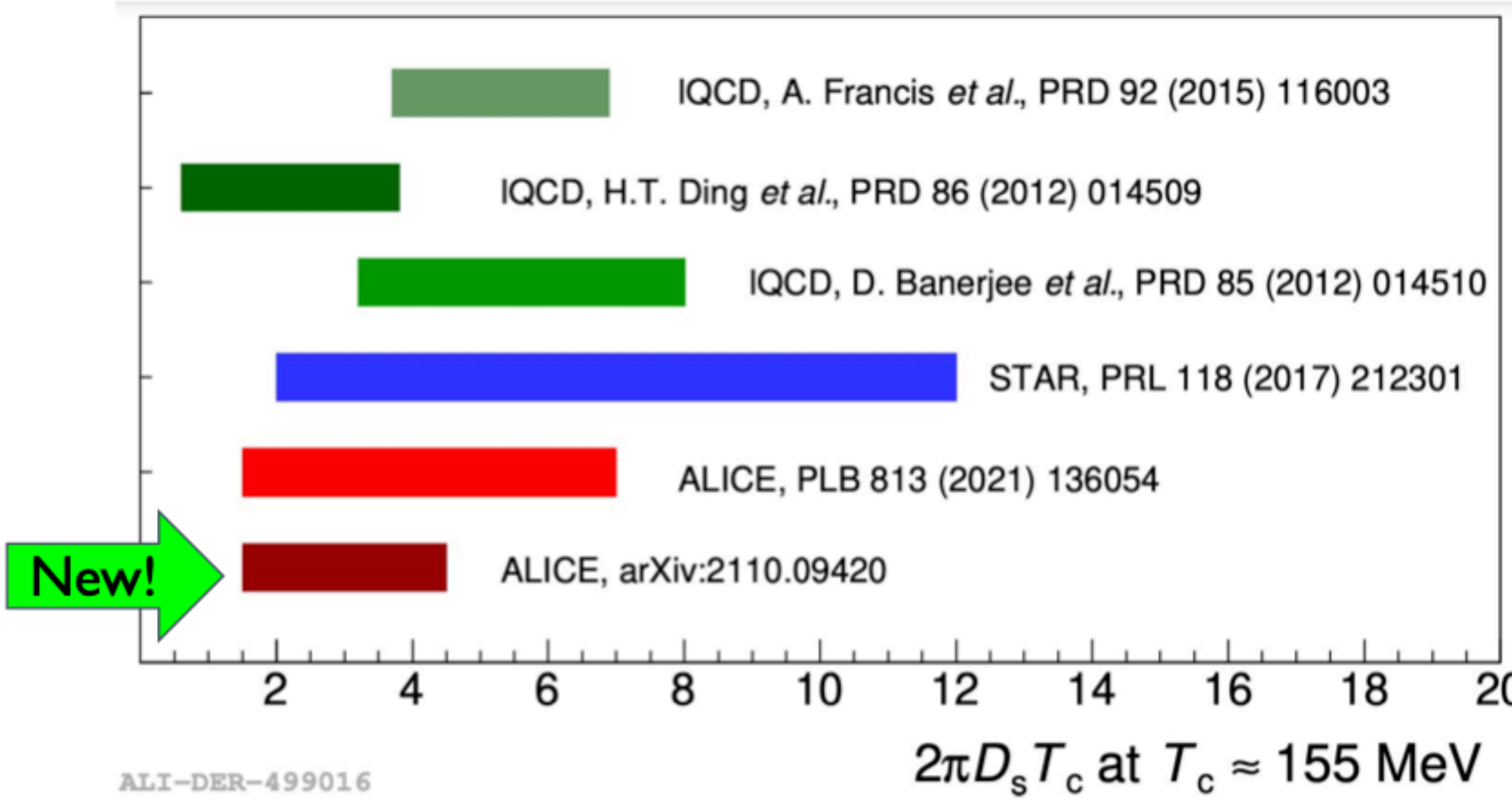
The examination of the unimpregnated vegetable Ovulum, an account of which was published early in 1826†, led me to attend more minutely than I had before done to the structure of the Pollen, and to inquire into its mode of action on the Pistillum in Phænogamous plants.

In the Essay referred-to, it was shown that the apex of the

* This double convex Lens, which has been several years in my possession, I obtained from Mr. Bancks, optician, in the Strand. After I had made considerable progress in the inquiry, I explained the nature of my subject to Mr. Dollond, who obligingly made for me a simple pocket microscope, having very delicate adjustment, and furnished with ex-

Diffusion coefficient

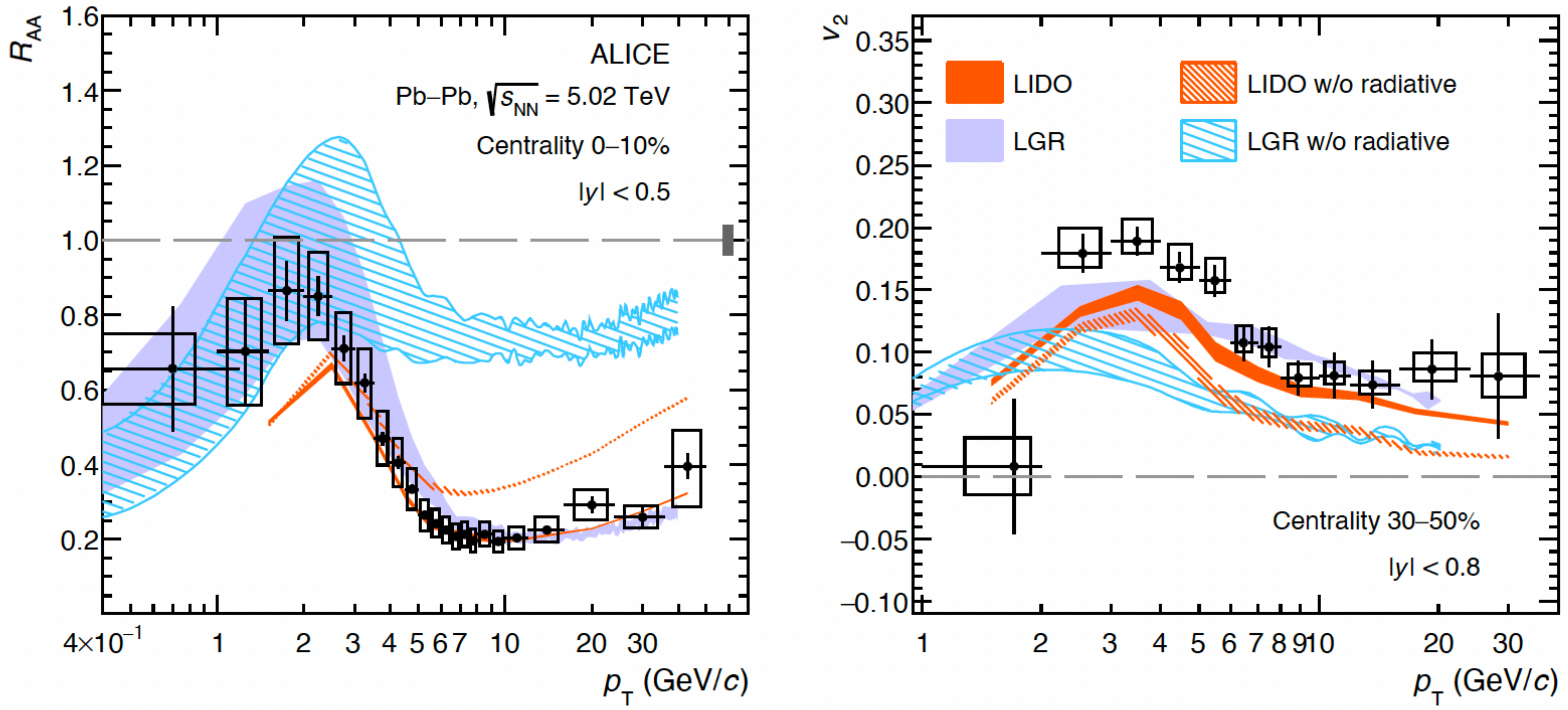
- Low p_T is dominated by charm diffusion in the medium (multiple elastic scatterings in QGP "Brownian motion")
- Improved determination of diffusion coefficient of the QGP



ALICE Collaboration, JHEP 01 (2022) 174

Models w/o radiative energy loss

- Transport model w/o radiative energy loss



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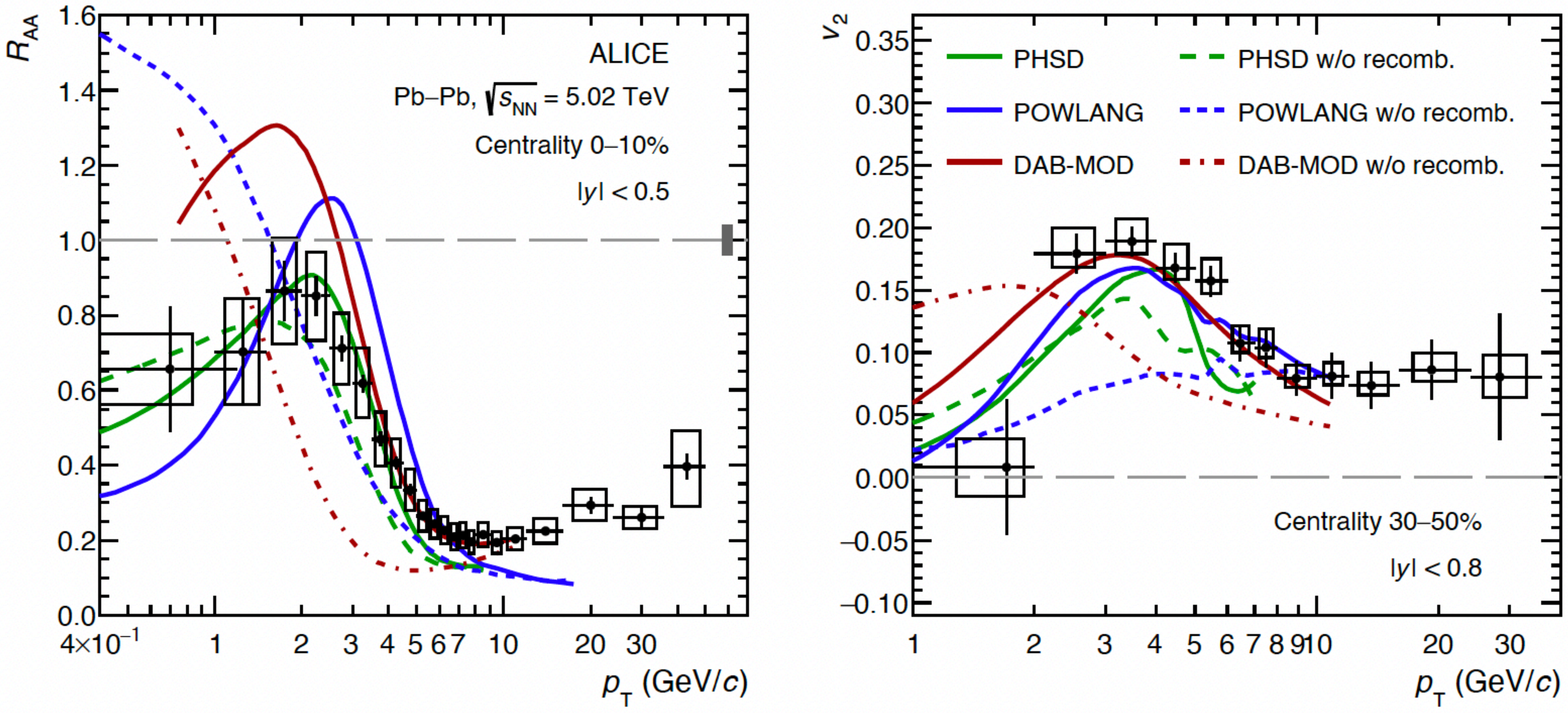
Models w/o recombination

- Transport model w/o recombination



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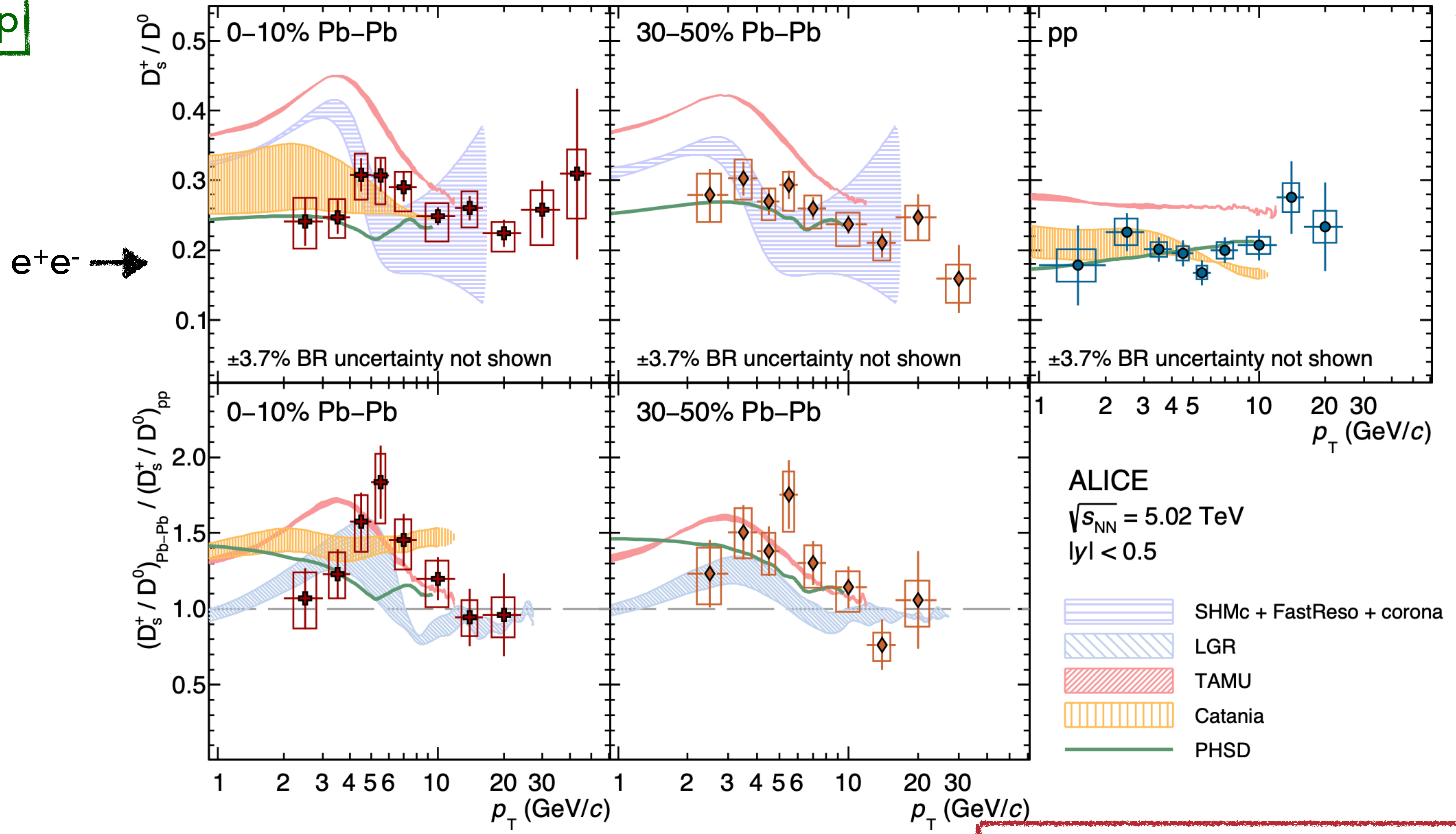
Charm and beauty: hadronisation

Strange to non-strange D and B meson ratios

AA pp



ALICE Collaboration, JHEP 01 (2022) 174

- Strange to non-strange D and B meson ratios
- Double-ratio Pb-Pb/pp larger than unity predicted by models with hadronisation by coalescence of charm and strangeness quarks
- Run 3 data will allow us to make a firm conclusion and constrain mechanisms

→ Hints of enhanced production of strange hadrons due to strangeness-rich QGP (recombination)

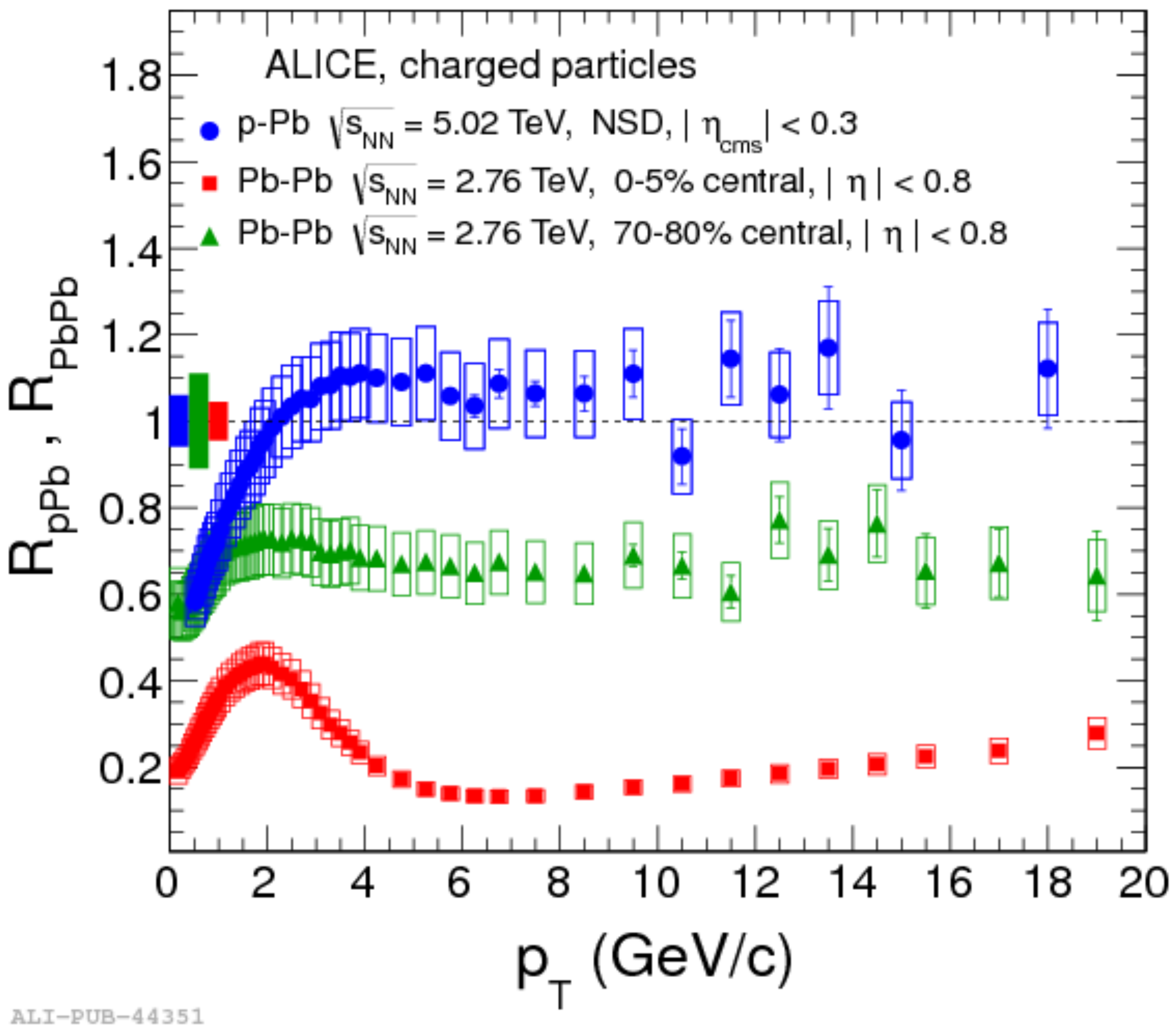
Summary: hard probes

- Suppression in heavy-ion collisions is a final state effect
- Evidence for colour factor and quark mass dependent energy loss
- QCD inspired models are capable of reproducing many features seen in the data
  - Medium properties can be constrained
- What’s next?
  - First generation of models focussed on leading-particle energy loss
  - (“medium-modified fragmentation function”)
  - Need to describe full parton shower evolution in the medium
  - Can one eventually describe parton energy loss based on first principles?
  - Can one connect heavy-quark energy loss to string theory via the gauge/gravity duality?

Backup slides

Suppression

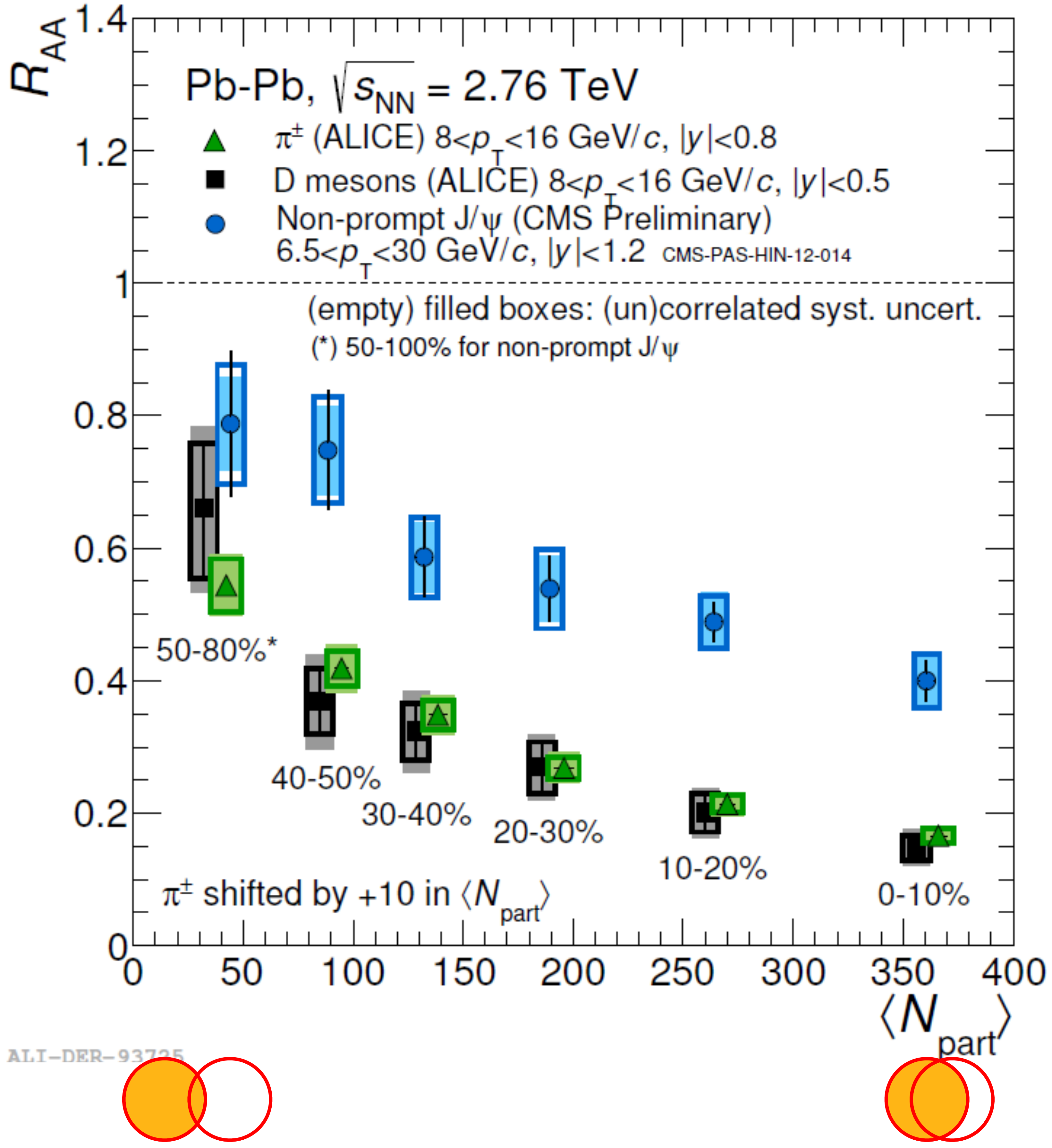
ALICE, Physics Letters B 696 (2011) 30

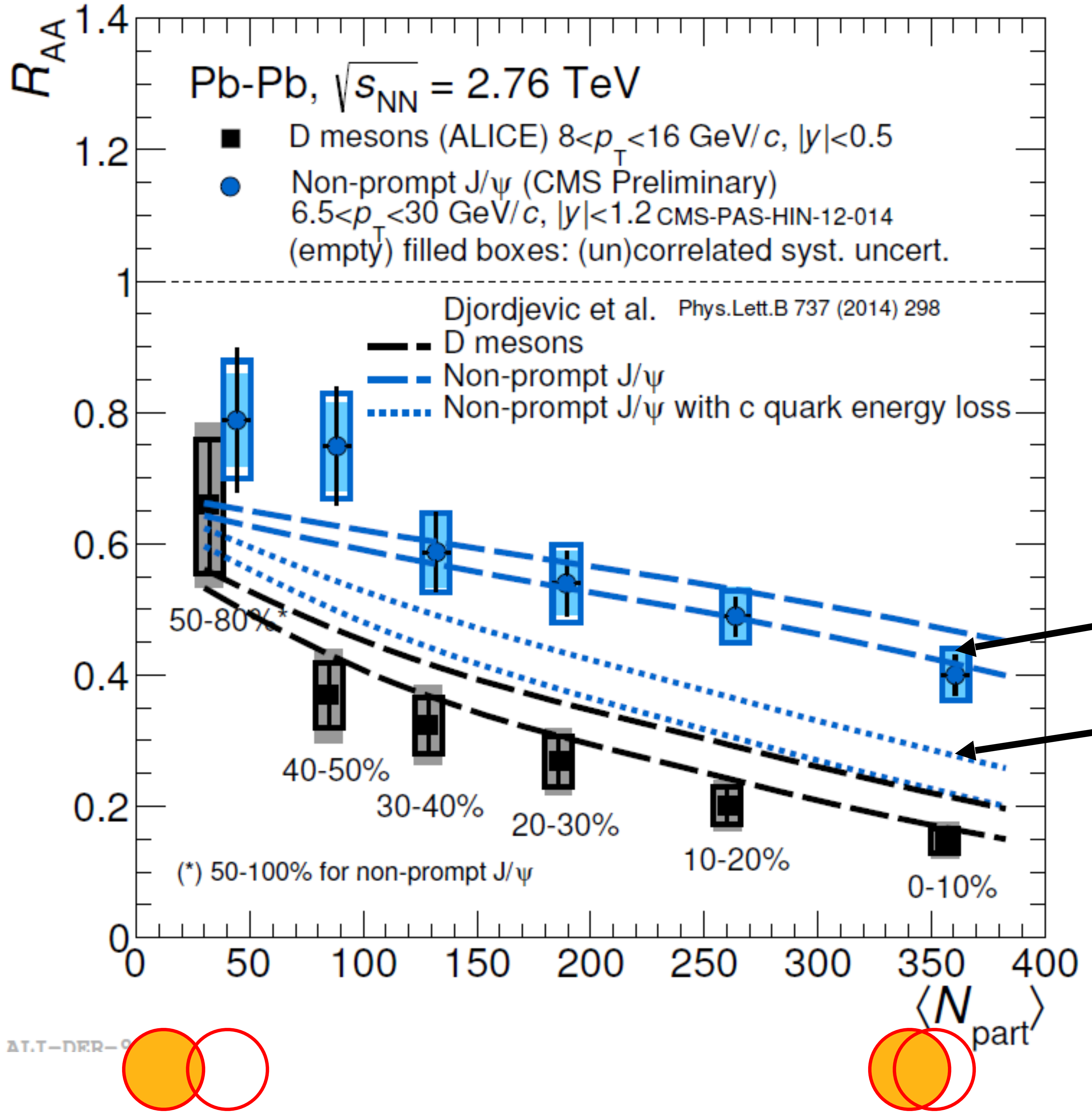


$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

→ Suppression is a final state effect

R_{AA}: D mesons vs J/ψ from B





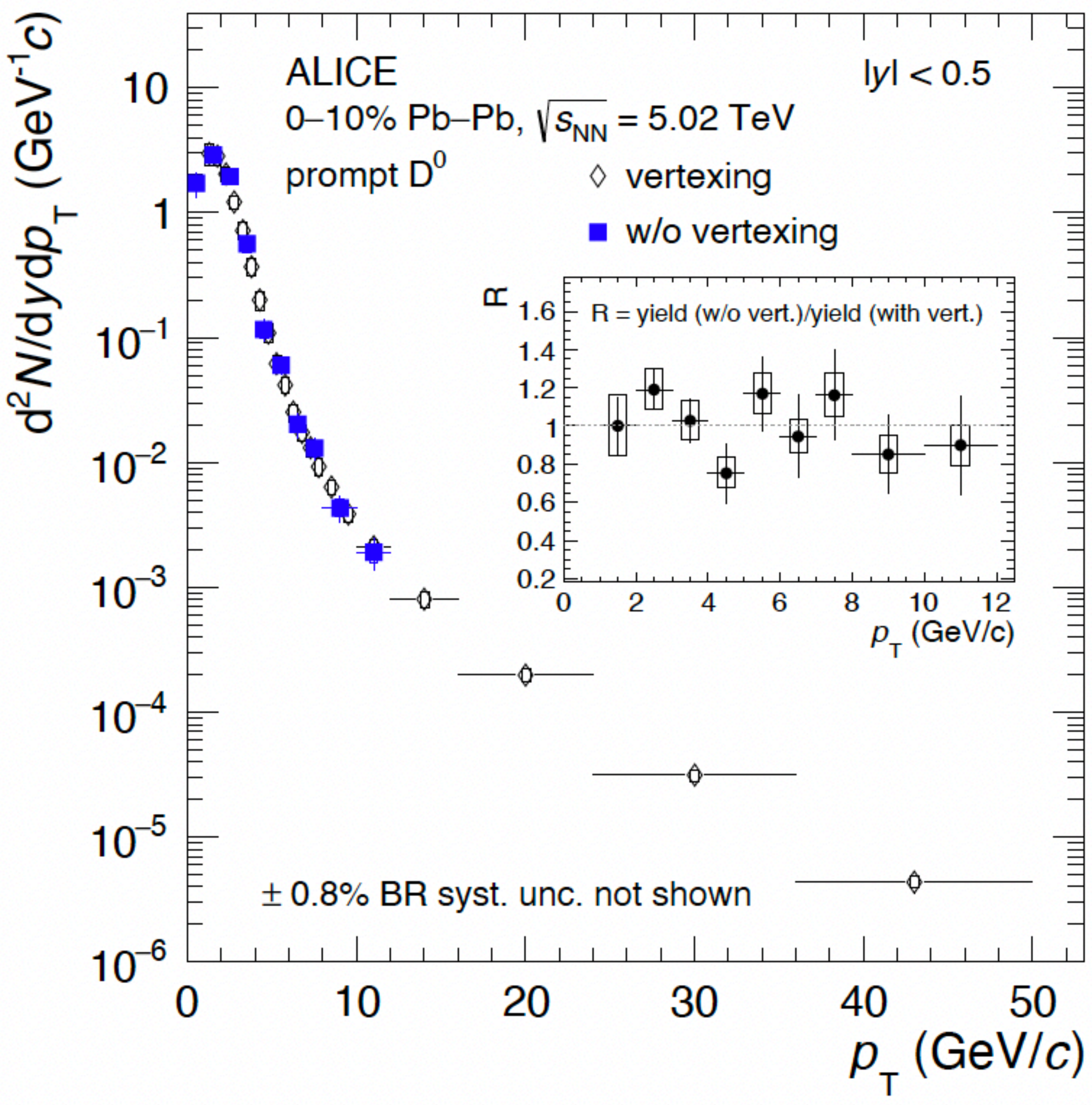
ALICE: JHEP1511 (2015) 205
CMS: CMS-PAS-HIN-12-014, CMS-PAS-HIN-15-005

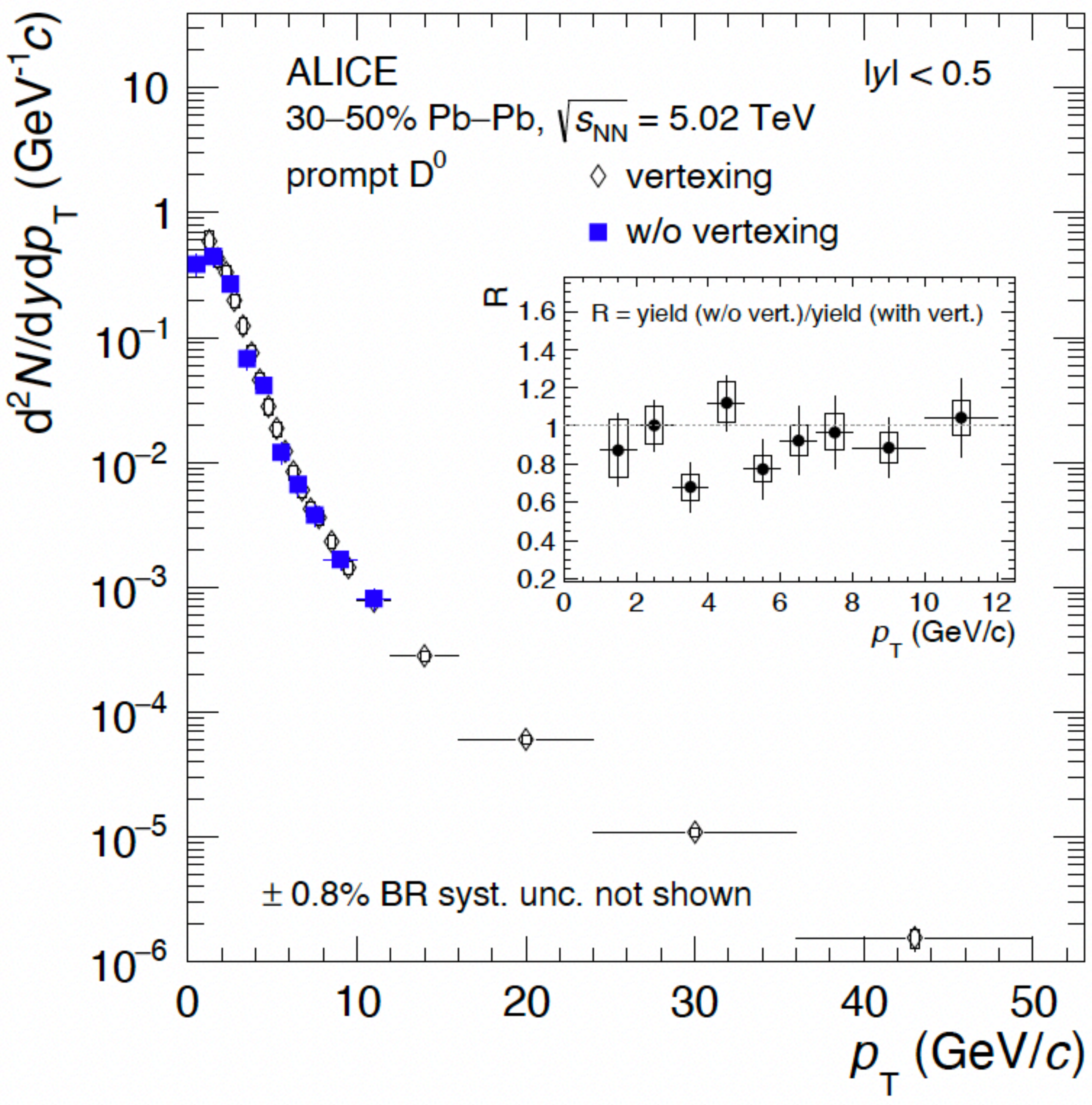
Djordjevic, PLB737 (2014) 298

Two mass assumptions for non-prompt J/ψ RAA

- Clear indication for R_{AA} (B) > R_{AA} (D)
- Consistent with the expectation $\Delta E_{charm} > \Delta E_{beauty}$
- Described by models including quark-mass dependent energy loss

w/o vertexing





D meson yield and statistical hadronisation model

	Measured dN/dy	SHMc dN/dy
0–10% centrality		
D^0	6.819 ± 0.457 (stat.) $^{+0.912}_{-0.936}$ (syst.) ± 0.054 (BR)	6.42 ± 1.07
D^+	3.041 ± 0.073 (stat.) $^{+0.154}_{-0.155}$ (syst.) ± 0.052 (BR) $^{+0.352}_{-0.618}$ (extrap.)	2.84 ± 0.47
D^{*+}	3.803 ± 0.037 (stat.) $^{+0.084}_{-0.085}$ (syst.) ± 0.041 (BR) $^{+0.854}_{-1.175}$ (extrap.)	2.52 ± 0.42
30–50% centrality		
D^0	1.275 ± 0.099 (stat.) $^{+0.167}_{-0.173}$ (syst.) ± 0.010 (BR)	1.06 ± 0.15
D^+	0.552 ± 0.008 (stat.) $^{+0.024}_{-0.024}$ (syst.) ± 0.009 (BR) $^{+0.068}_{-0.114}$ (extrap.)	0.471 ± 0.069
D^{*+}	0.663 ± 0.023 (stat.) $^{+0.038}_{-0.039}$ (syst.) ± 0.007 (BR) $^{+0.149}_{-0.165}$ (extrap.)	$0.419\ ^{+0.065}_{-0.061}$

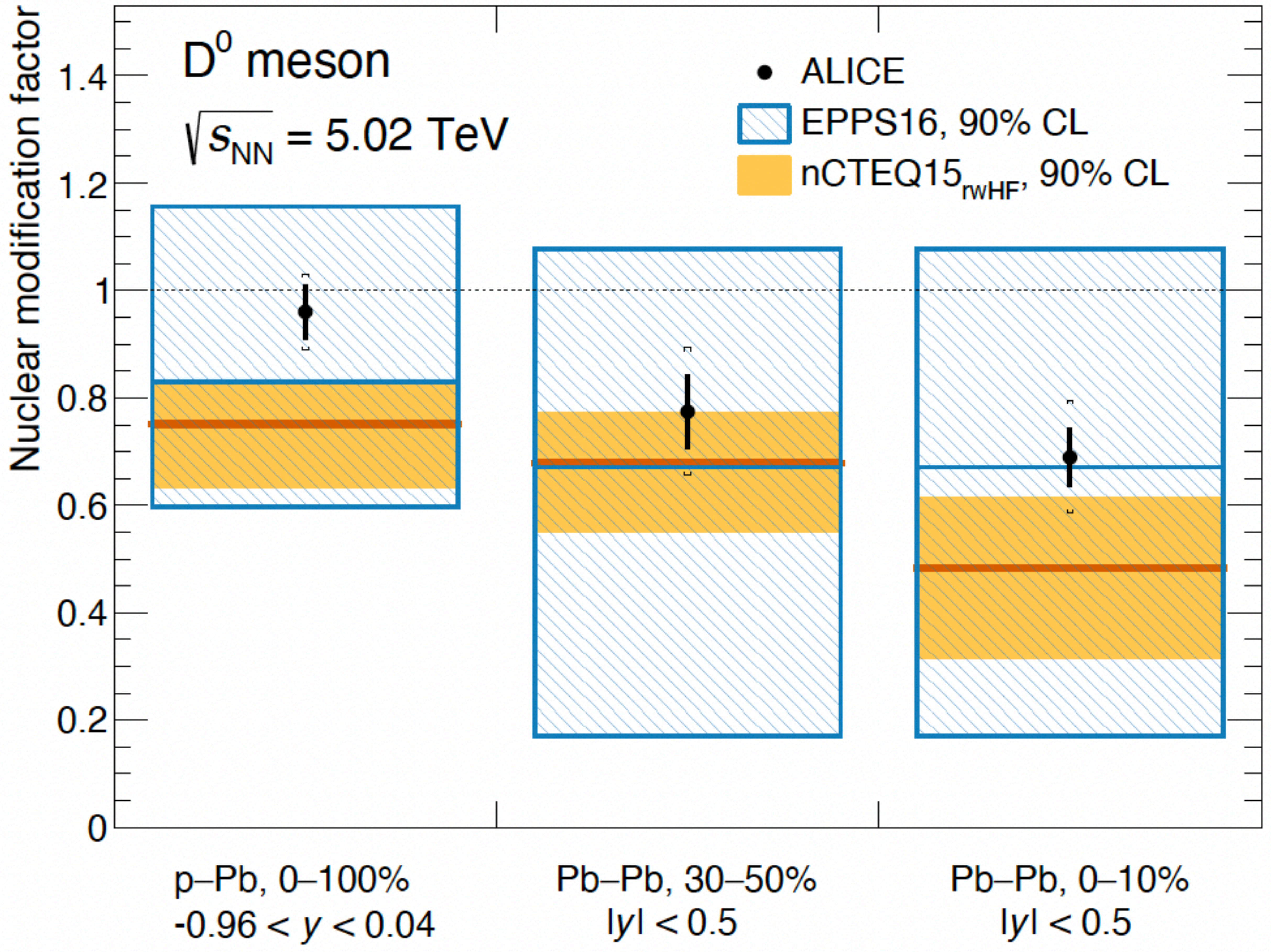
D mesons

- EPPS: no centrality dependent shadowing

- nCTEQ15:
  - Bayesian reweighting of nuclear PDFs constrained by measurements of heavy-flavour production in p-Pb at LHC
  - Centrality dependent nuclear PDFs
  - 90% confidence level uncertainty
  - Factorisation scale uncertainties

- Both models relative abundance of different charm hadron species due to hadronisation via recombination

- Measured value on upper edge of theoretical calculation -> smaller shadowing in data



pQCD models with energy loss

- Energy loss models
  - Radiative
  - Collisional