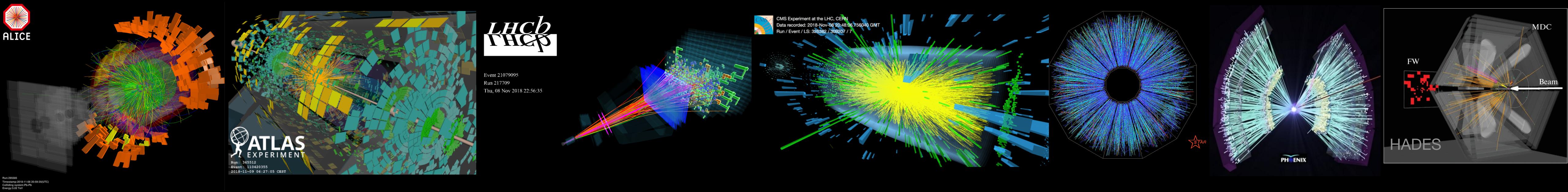


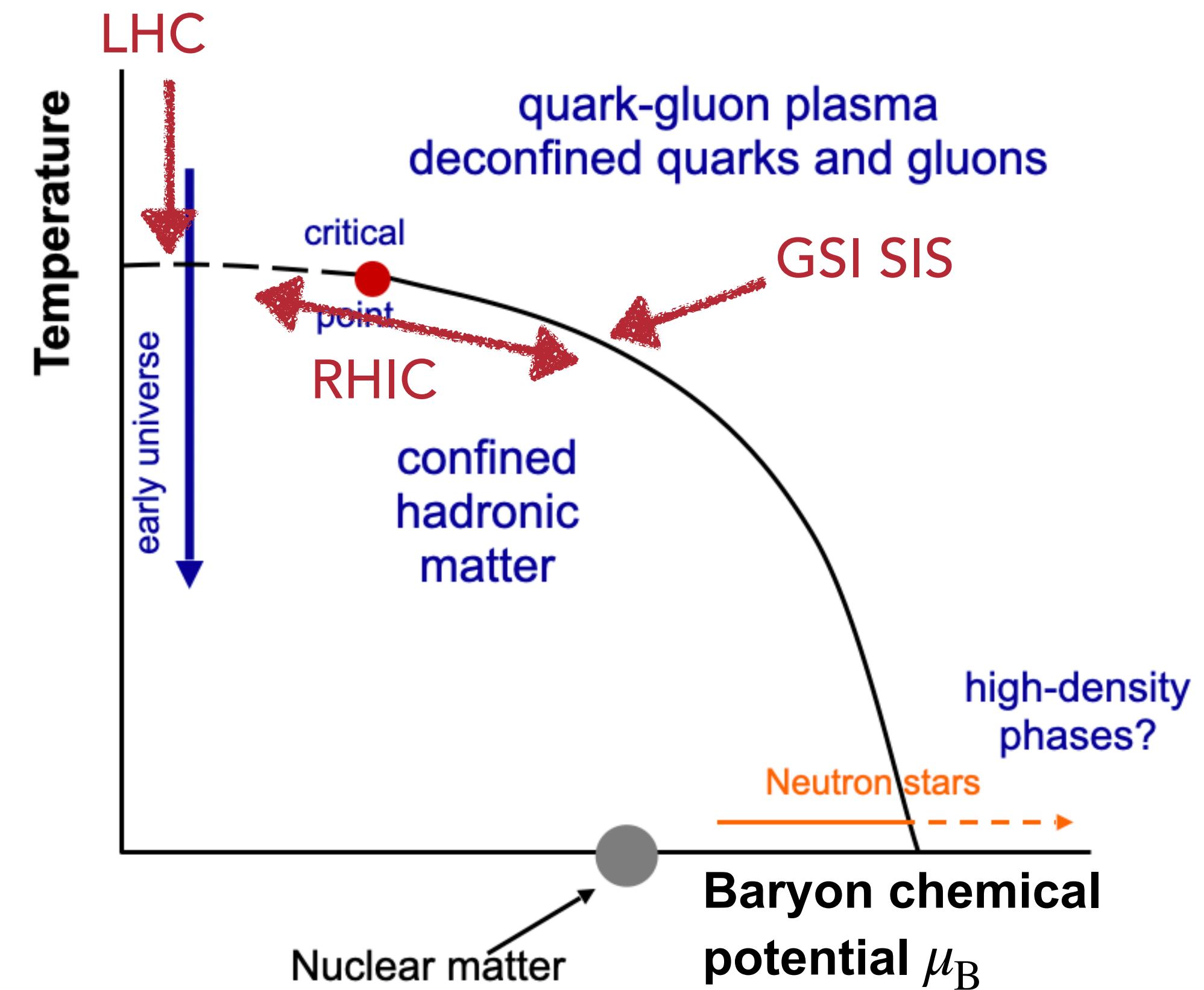
An overview of recent results from heavy-ion experiments

Yvonne Pachmayer
(Physikalisches Institut, Heidelberg University)



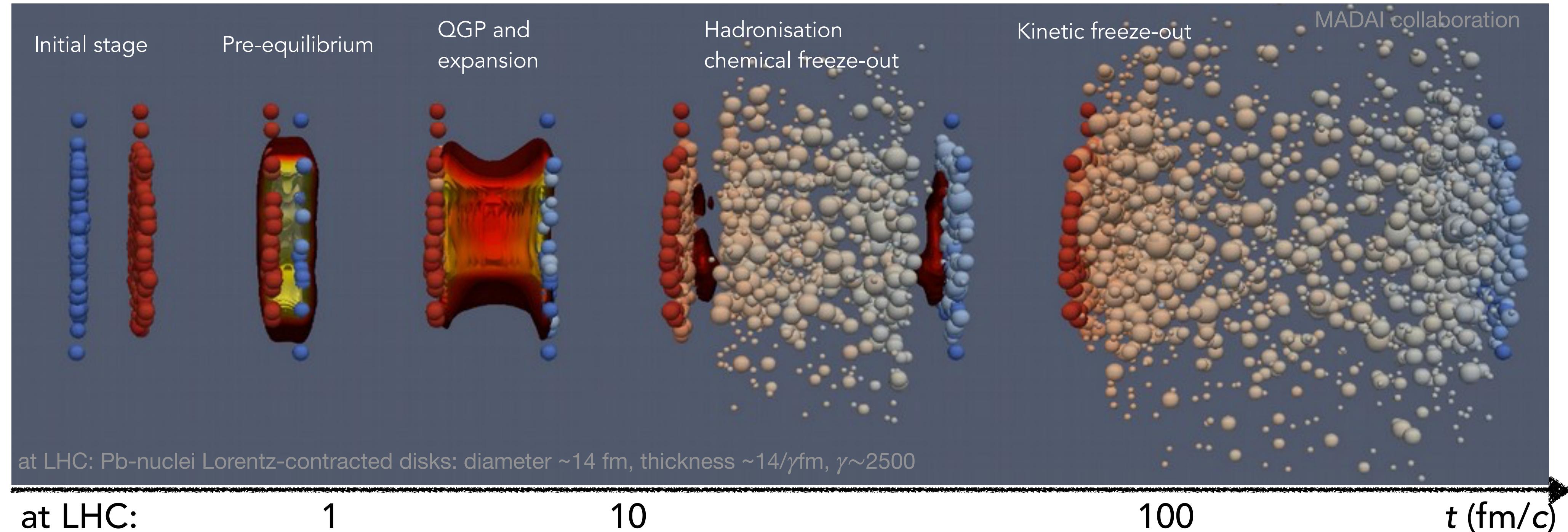
Introduction: Heavy-Ion Physics

- Heavy-ion collisions allow us to study QCD in the laboratory
- Deconfined strongly-coupled matter with color degrees of freedom → **quark-gluon plasma**
 - Restoration of chiral symmetry
- Explore the properties of the deconfined phase at **high temperature** (LHC, RHIC) and/or **high net-baryon number density**
(RHIC Beam Energy Scan + fixed target, CERN SPS, GSI SIS)
- Nature of the phase transition and search for the critical point



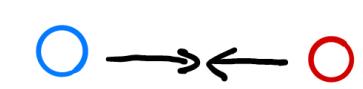
Introduction: Heavy-Ion Physics

Space-Time Evolution of a Heavy-Ion Collision

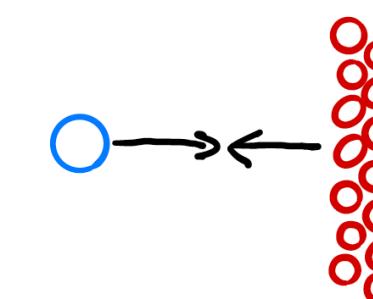


- Original role of reference measurements

- pp collisions as a baseline

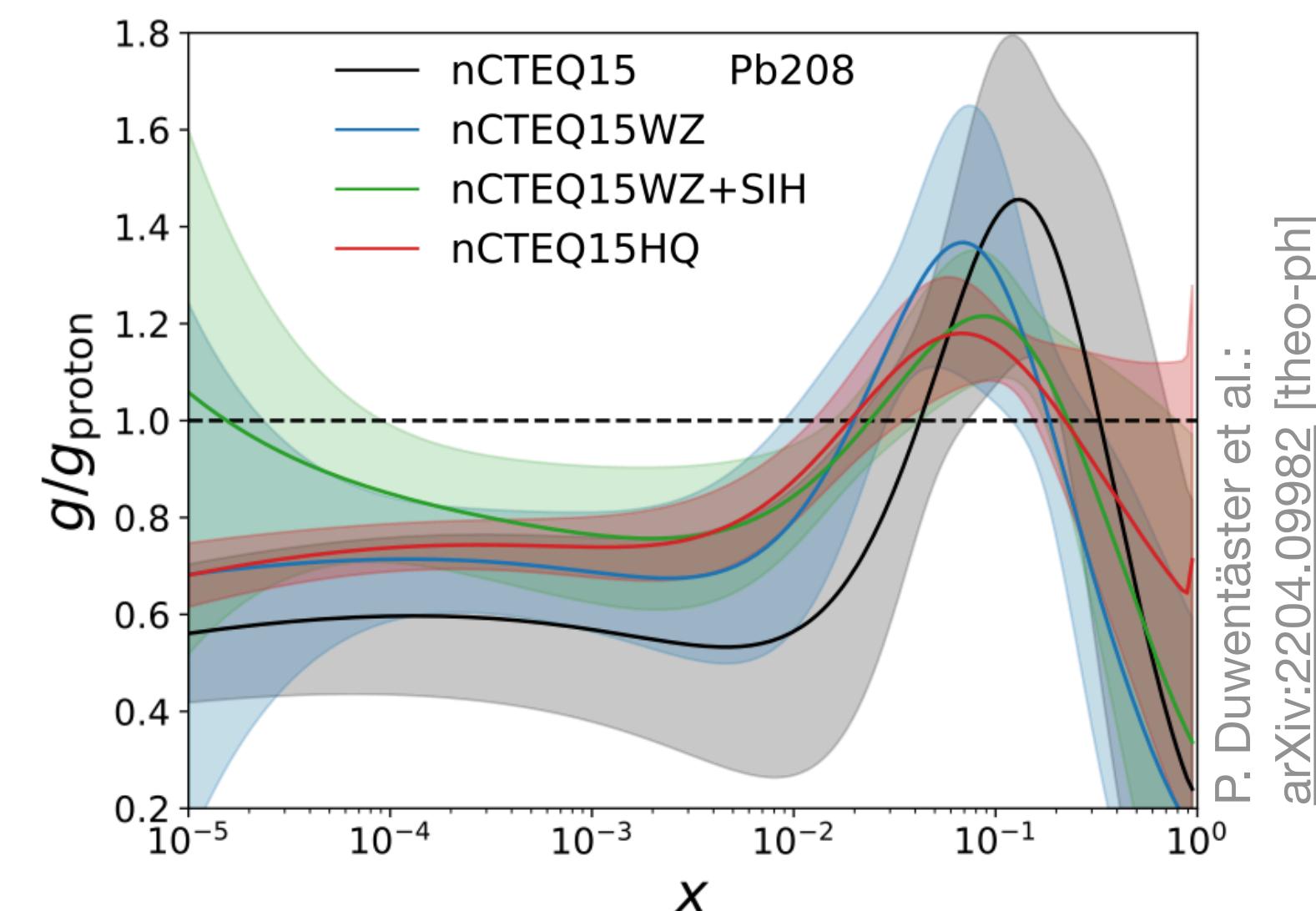
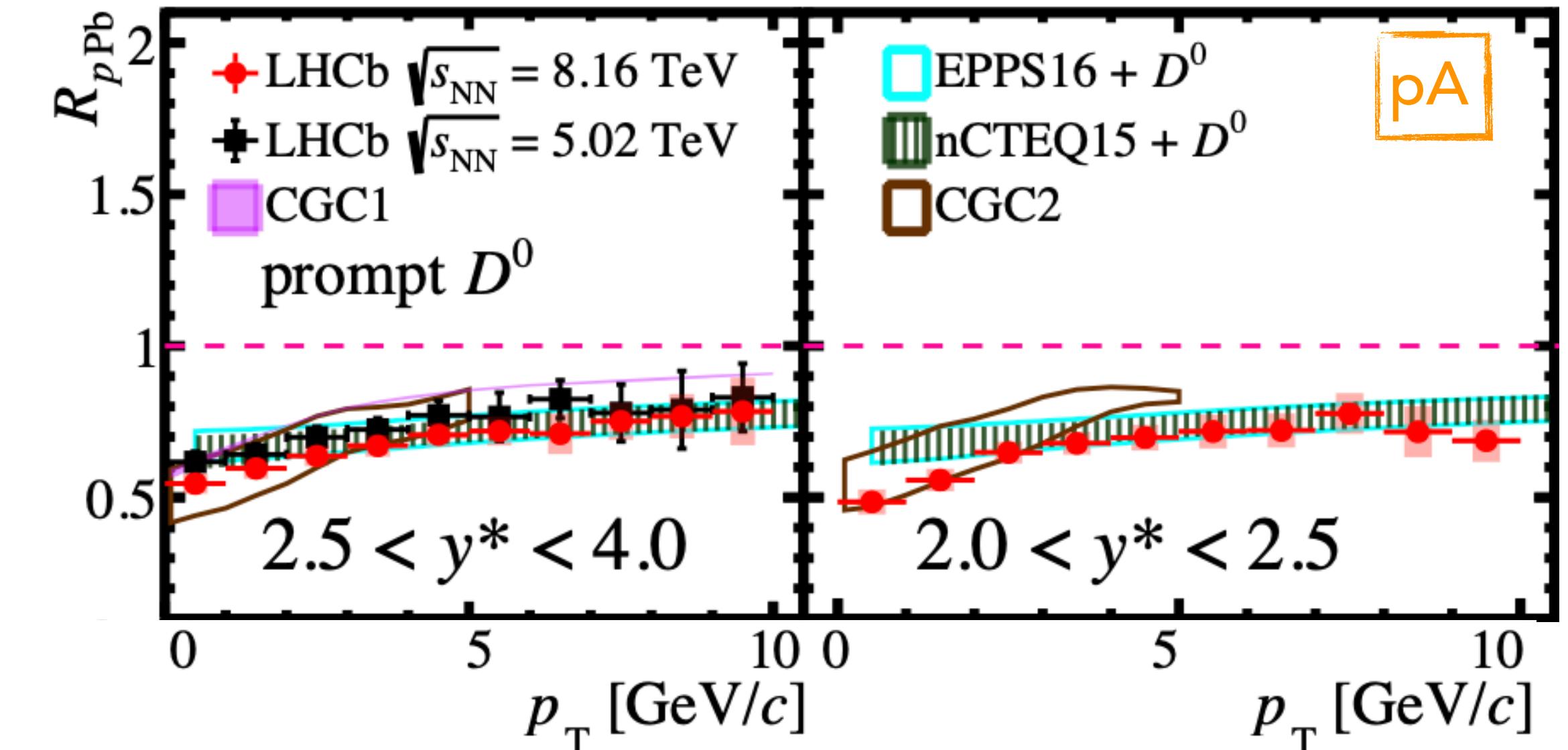
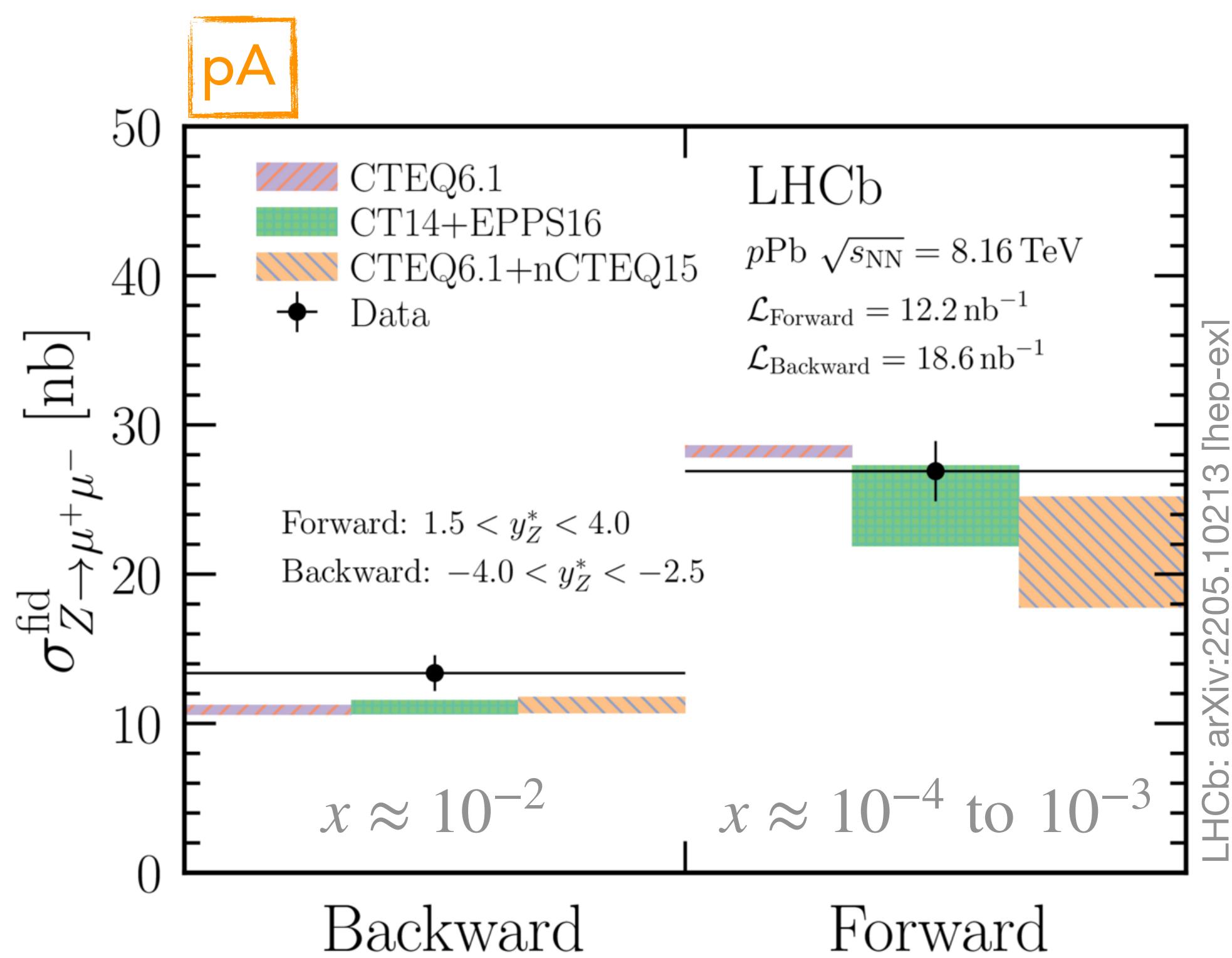


- p-A collisions to study cold nuclear matter effects



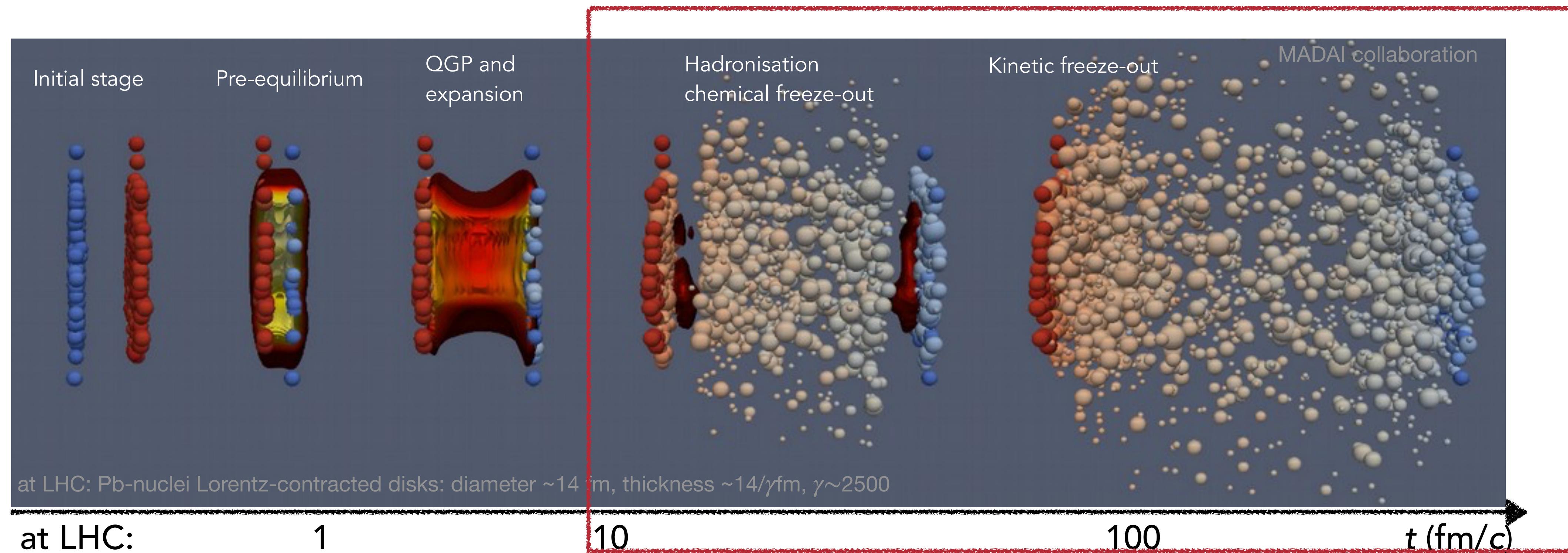
Initial state: Constraining nuclear PDFs

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



Introduction: Heavy-Ion Physics

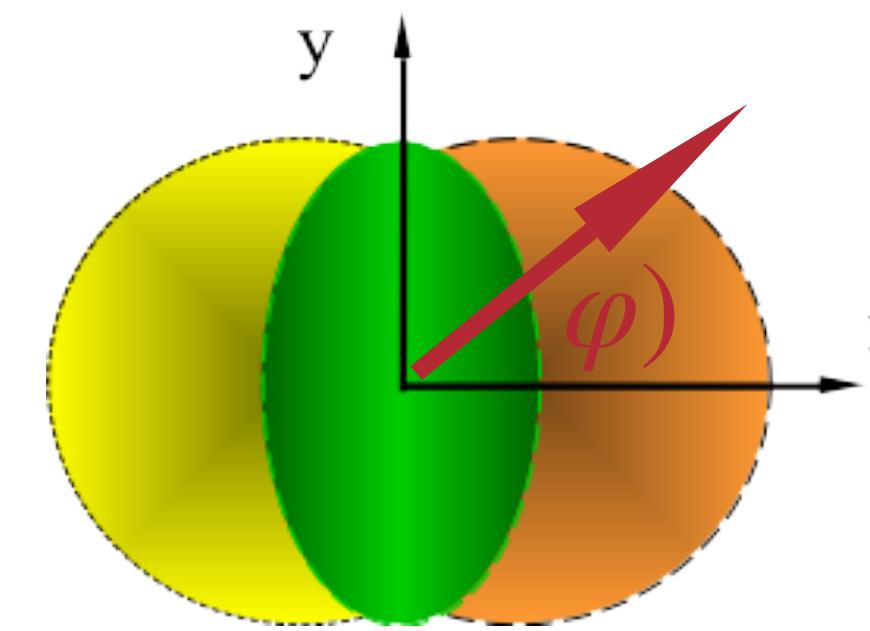
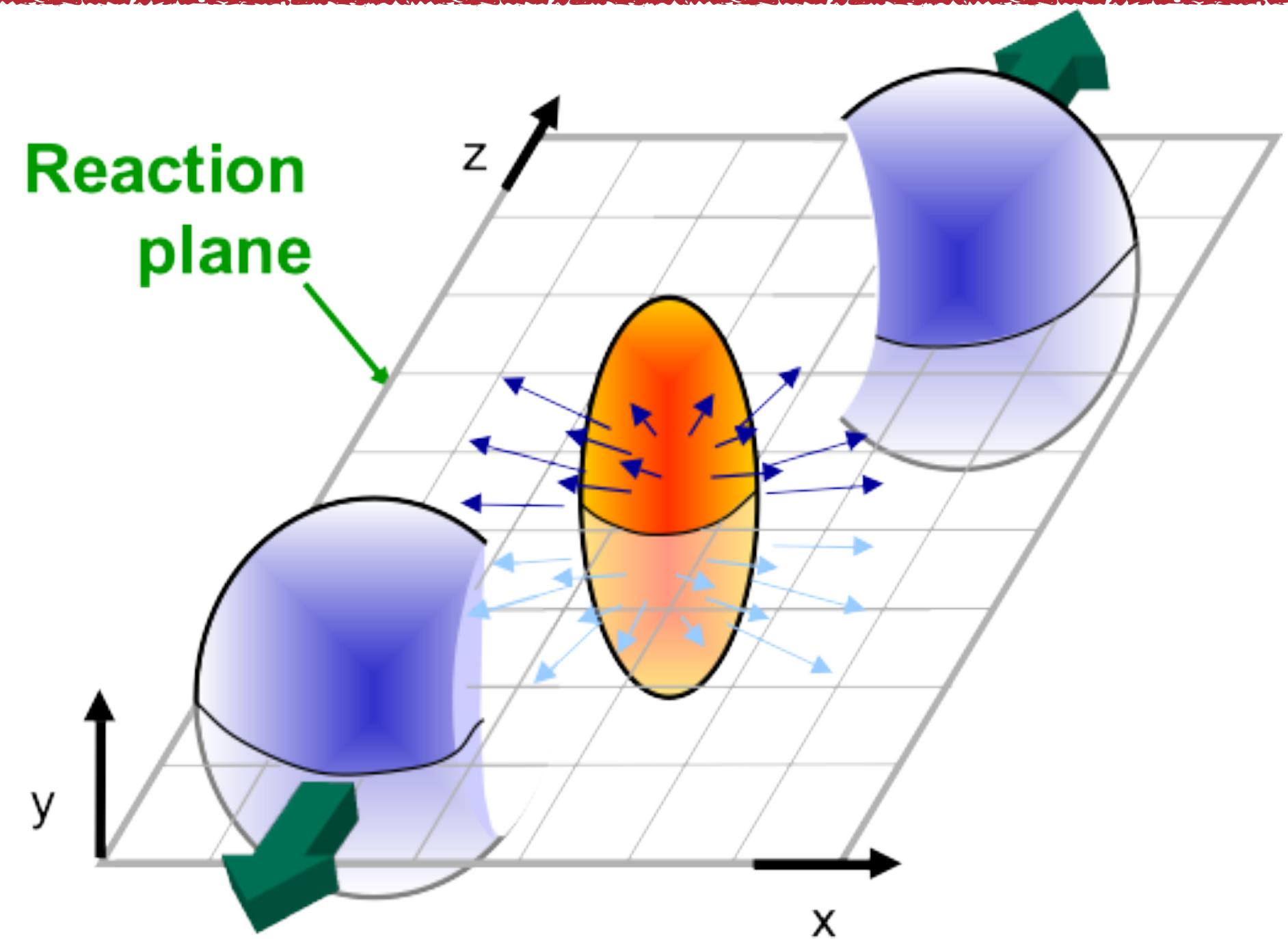
Space-Time Evolution of a Heavy-Ion Collision



Expansion dynamics and hadronisation

Collective effects

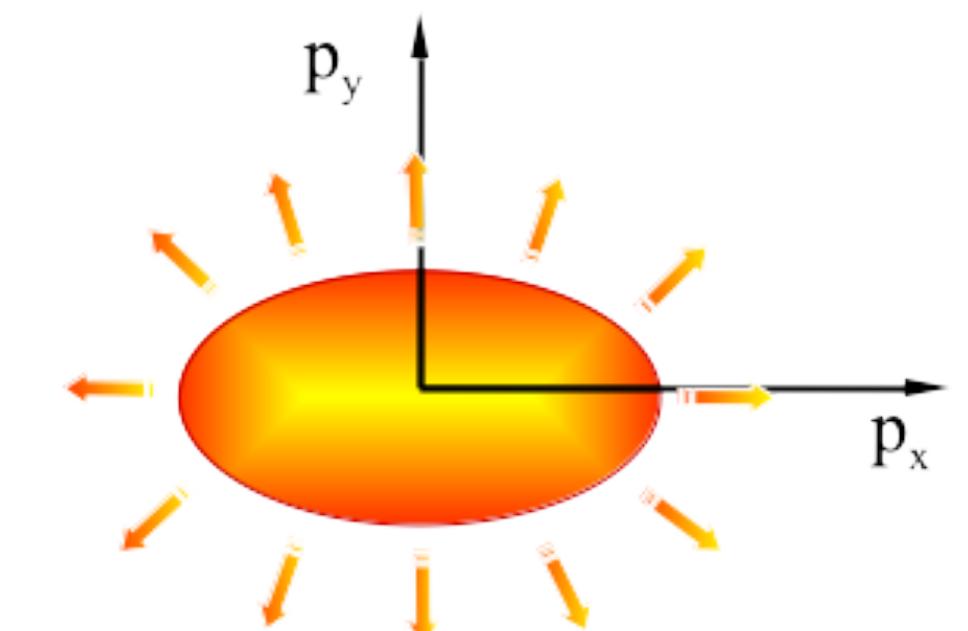
Elliptic flow



Coordinate space:
initial asymmetry



Collective interaction:
pressure gradient larger
in- than out-of-plane



Momentum space:
final asymmetry

Fourier decomposition of momentum distribution relative to reaction plane:

$$\frac{dN}{d\varphi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T) \cos(n(\varphi - \Psi_{RP}))$$

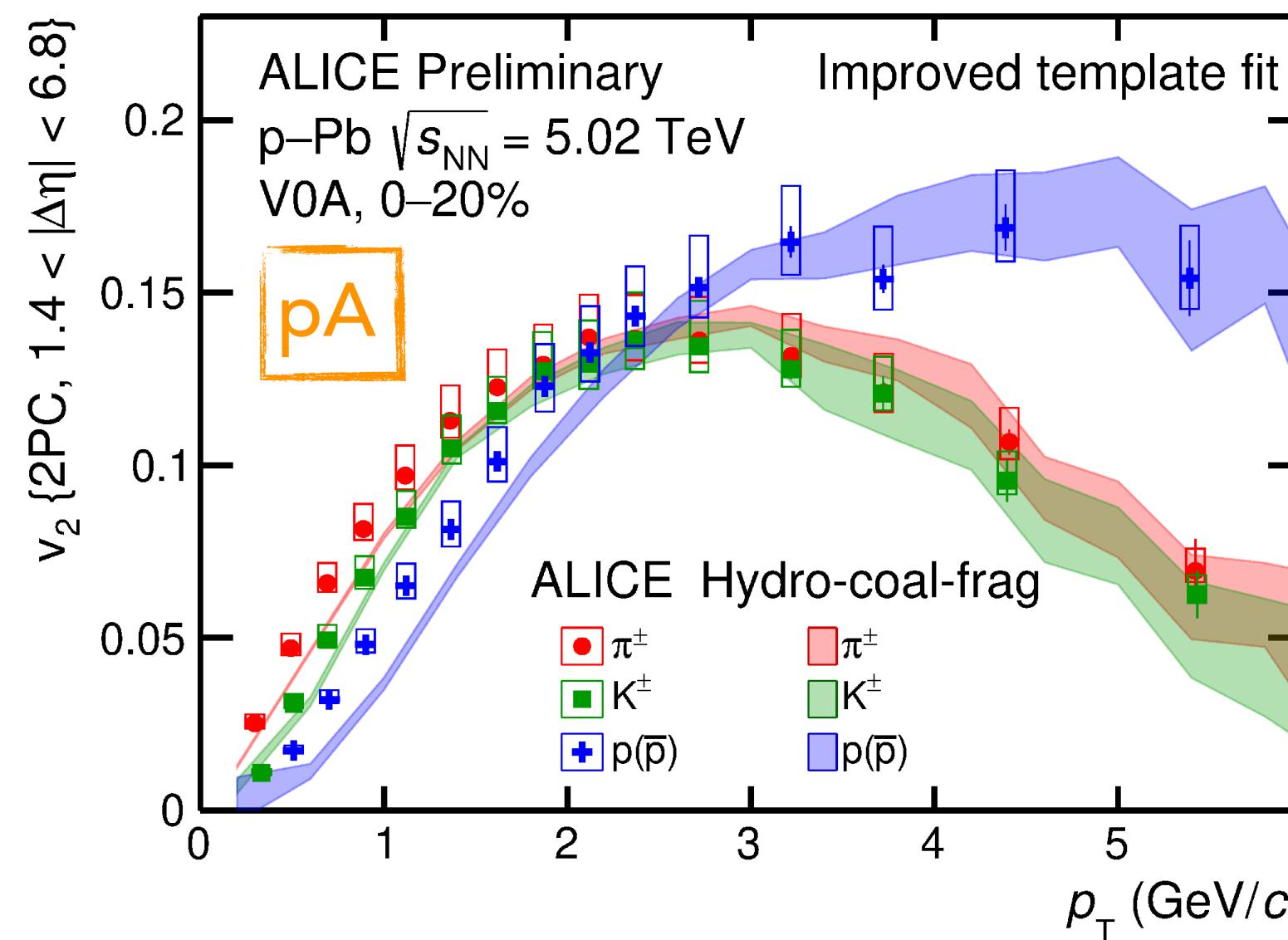
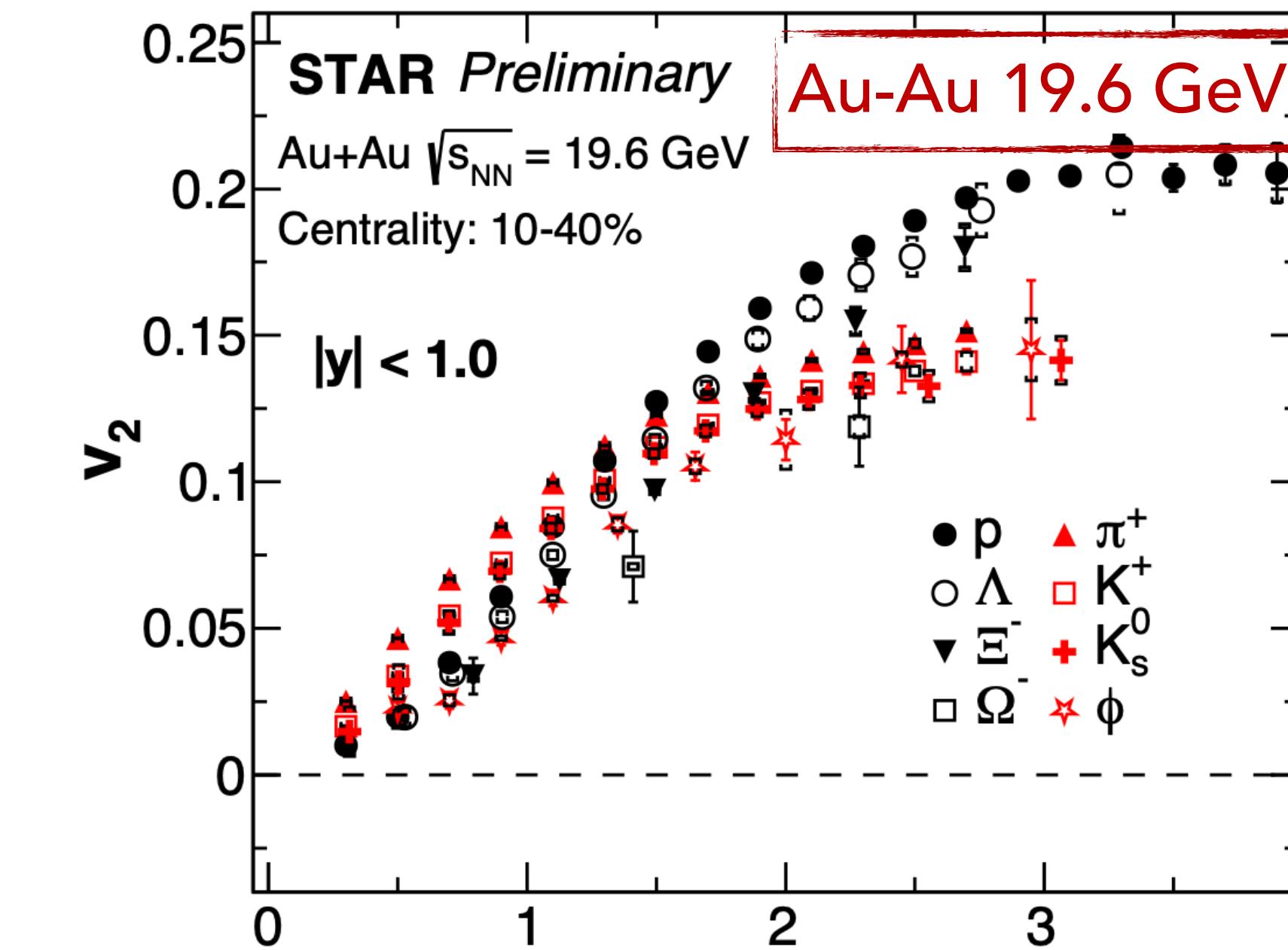
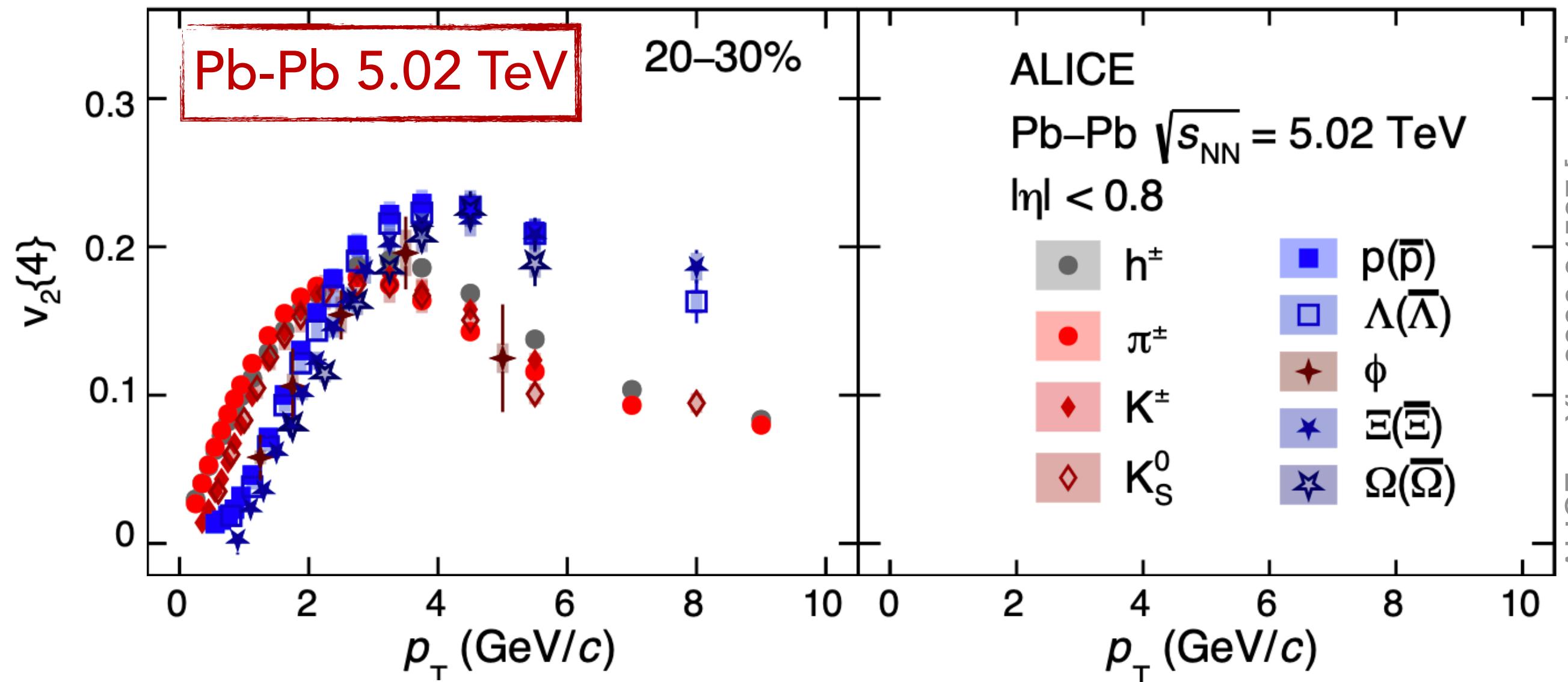
v_1 : directed flow

v_2 : elliptic flow

Sensitive to early expansion of the system

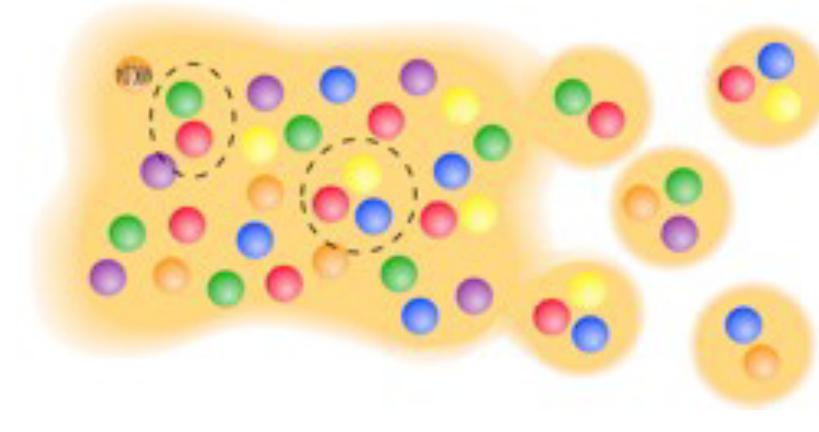
Collective effects

Elliptic flow



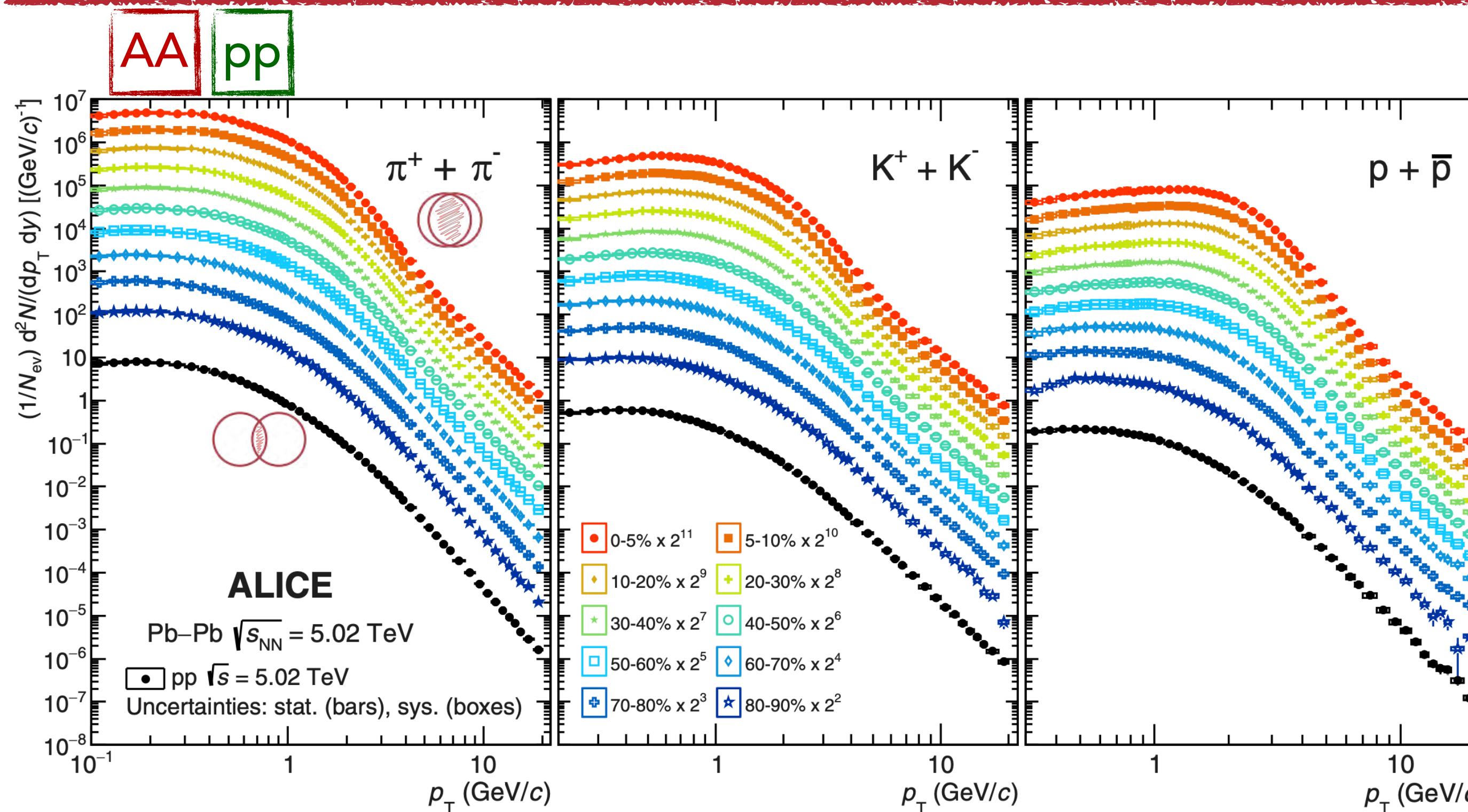
Mass ordering at low $p_T \rightarrow$ hydrodynamic flow
Baryon vs. meson grouping at high p_T
 \rightarrow quark-level flow + recombination ?

**Similar observations at LHC full energy,
RHIC low energy and for p-Pb collisions at LHC**



Soft Probes

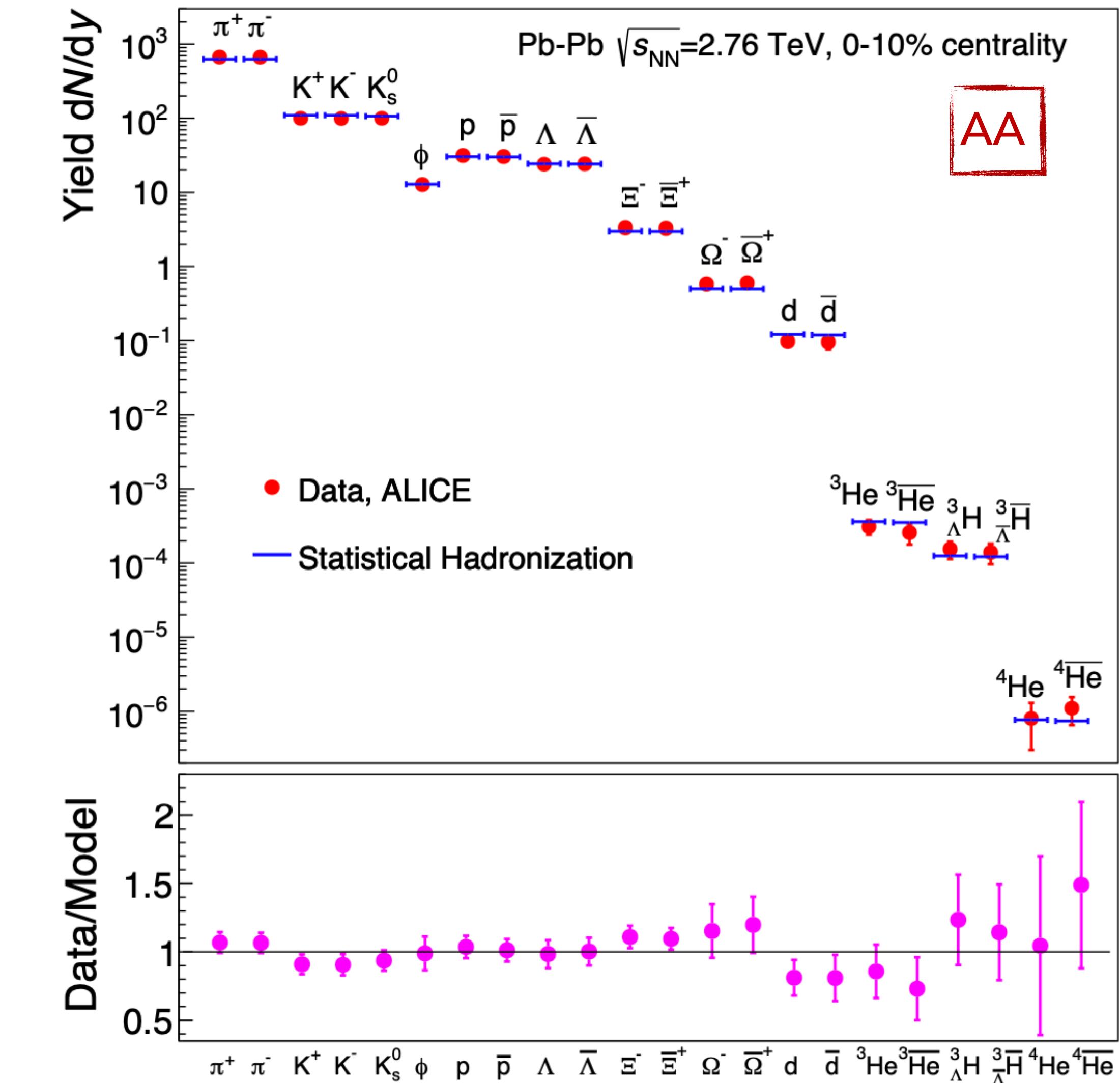
Integrated Yields at the LHC



Grand canonical thermal fit to particle yields

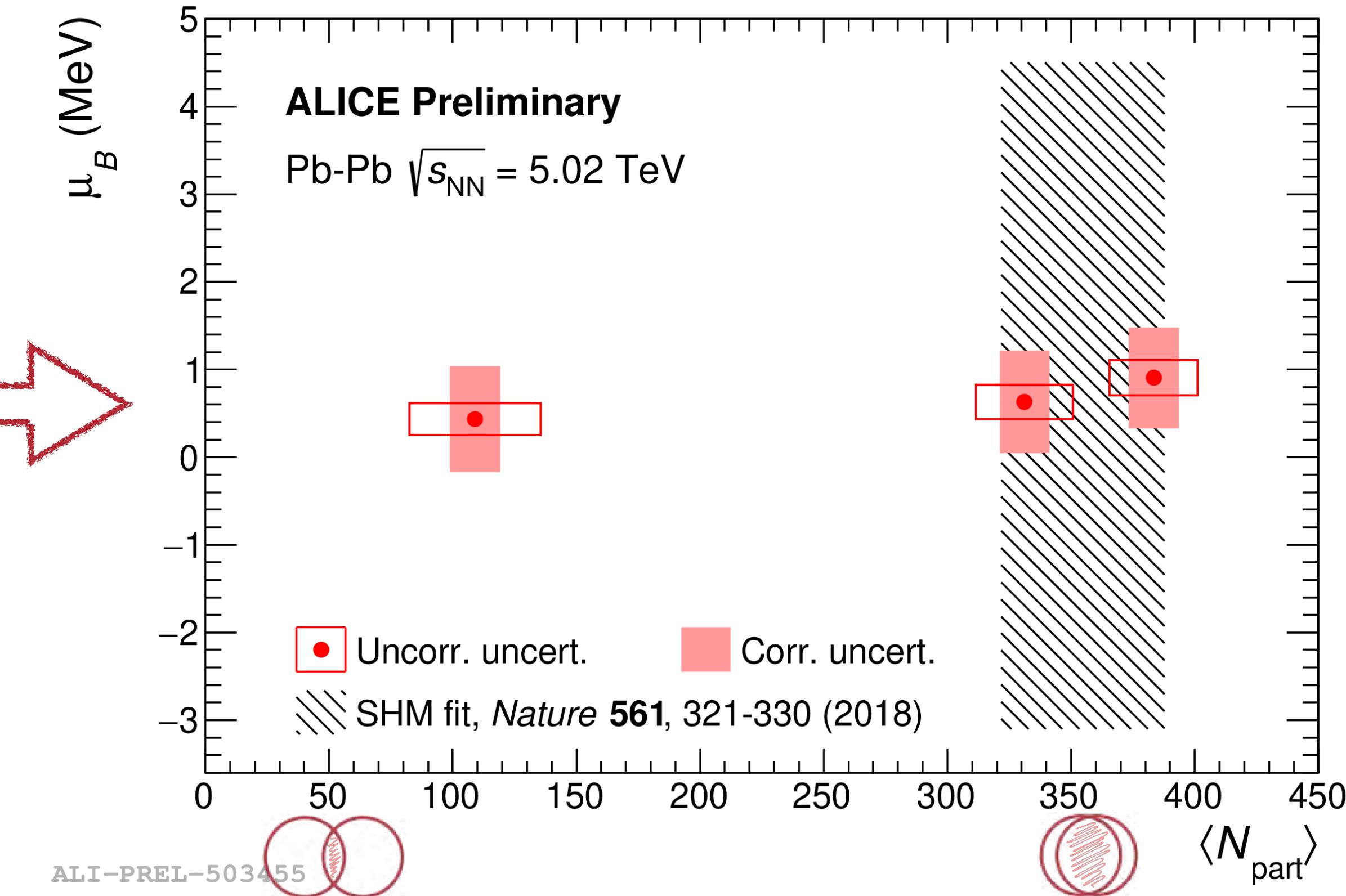
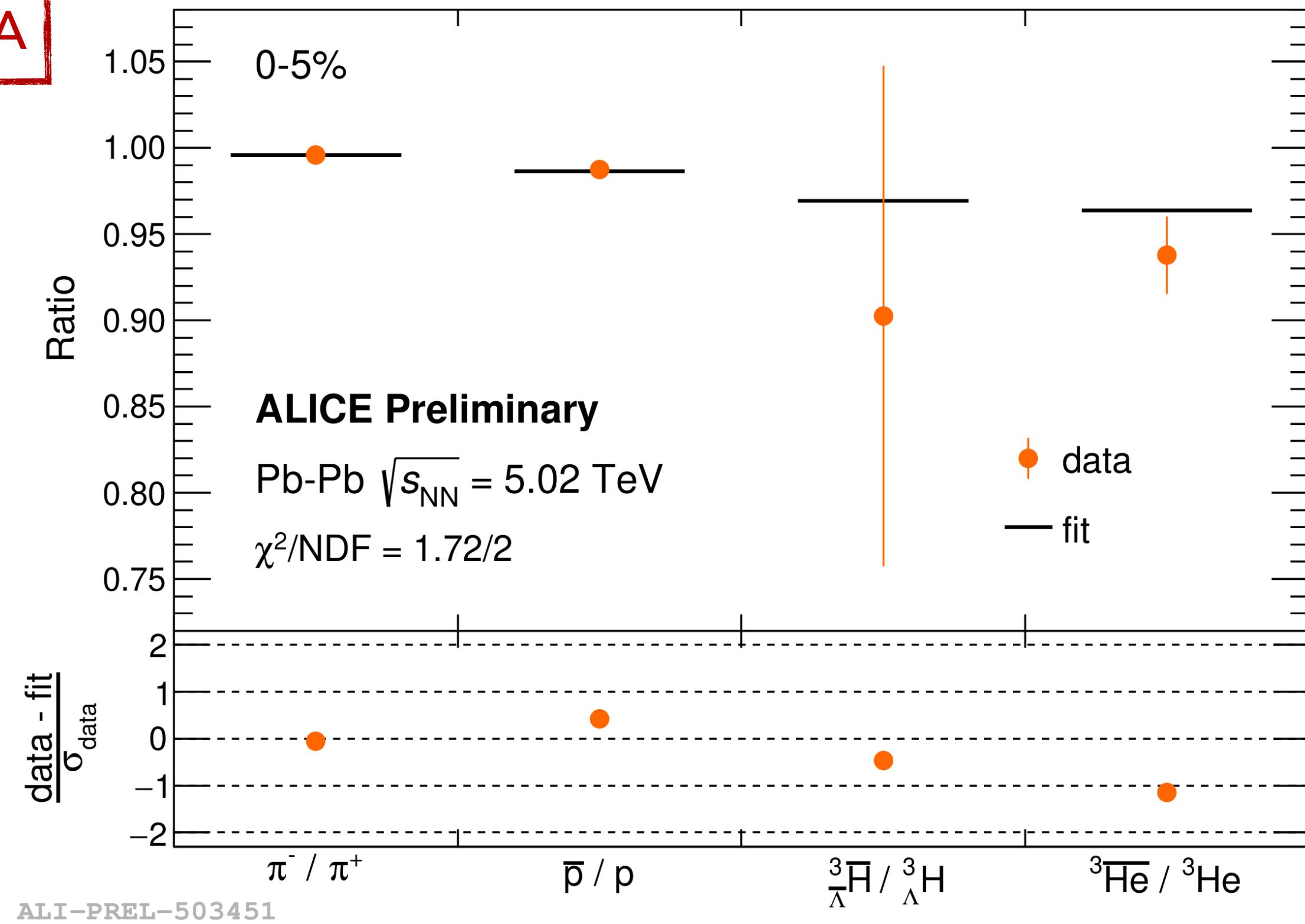
$$\rightarrow T_{\text{cf}} = 156.6 \pm 1.7 \text{ MeV}$$

lattice QCD: $T_c = 156.5 \pm 1.5 \text{ MeV}$



Precision μ_B measurements

AA



- Ratios fitted with statistical model equation

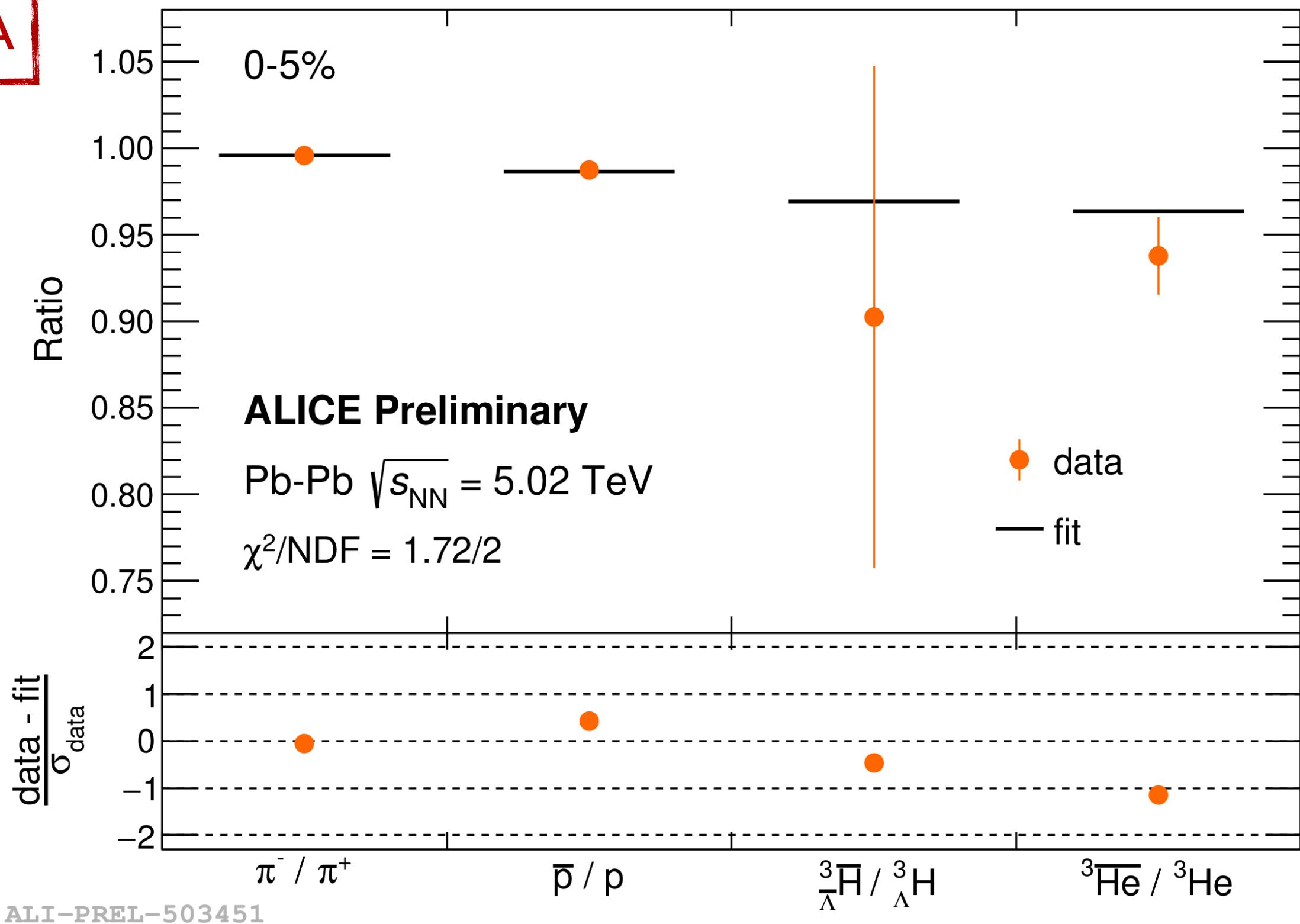
$$\frac{\bar{h}}{h} \propto \left(-2 \left(B + \frac{S}{3} \right) \frac{\mu_B}{T} - 2 I_3 \frac{\mu_{I_3}}{T} \right)$$

	π^+	p	${}^3\text{He}$	${}^3\Lambda$
$B+S/3$	0	1	3	8/9
I_3	1	1/2	1/2	0

→ Most precise measurements
of μ_B at the TeV scale

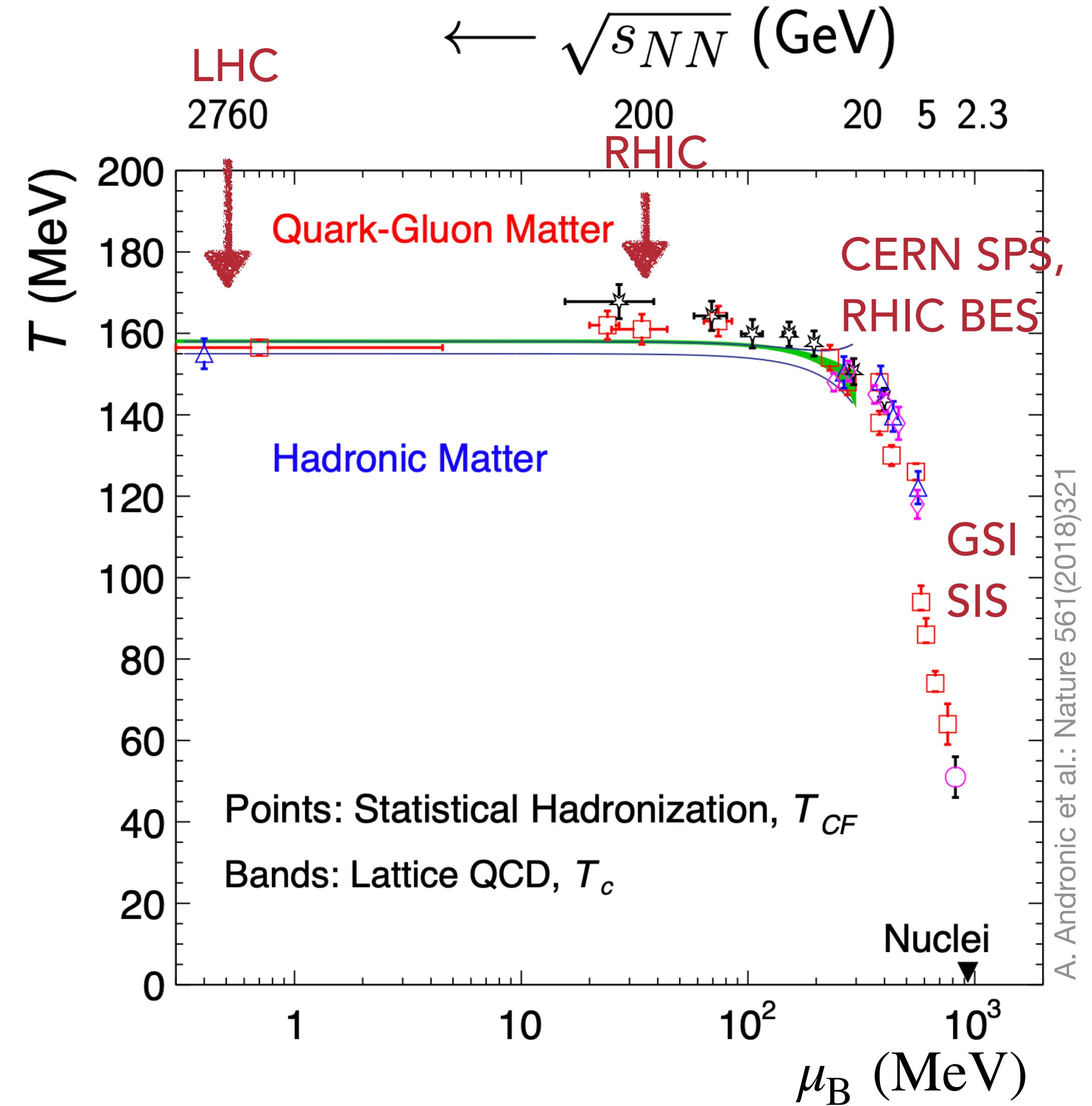
Precision μ_B measurements

AA

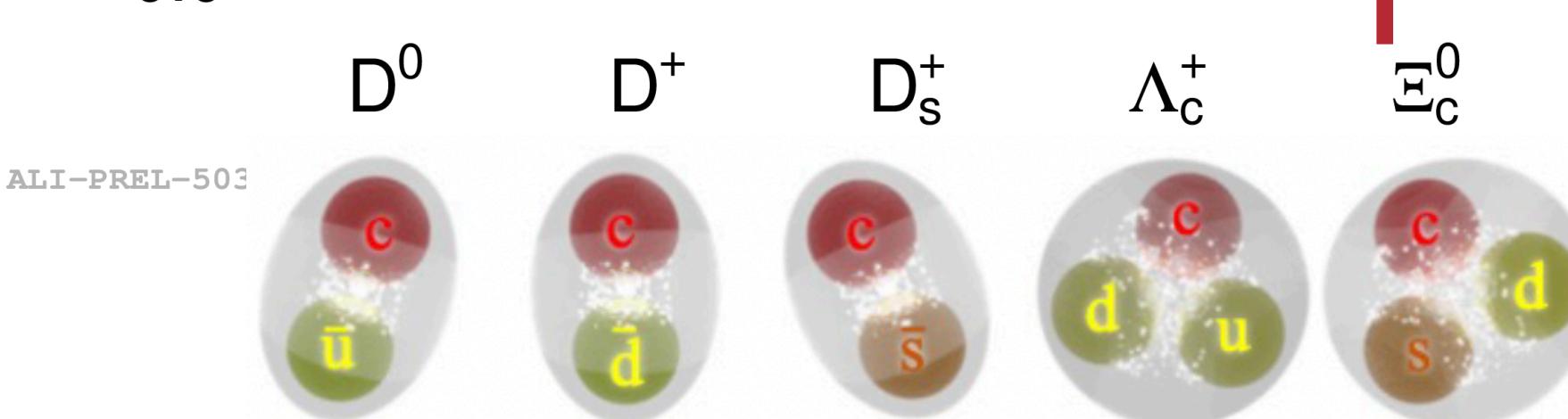
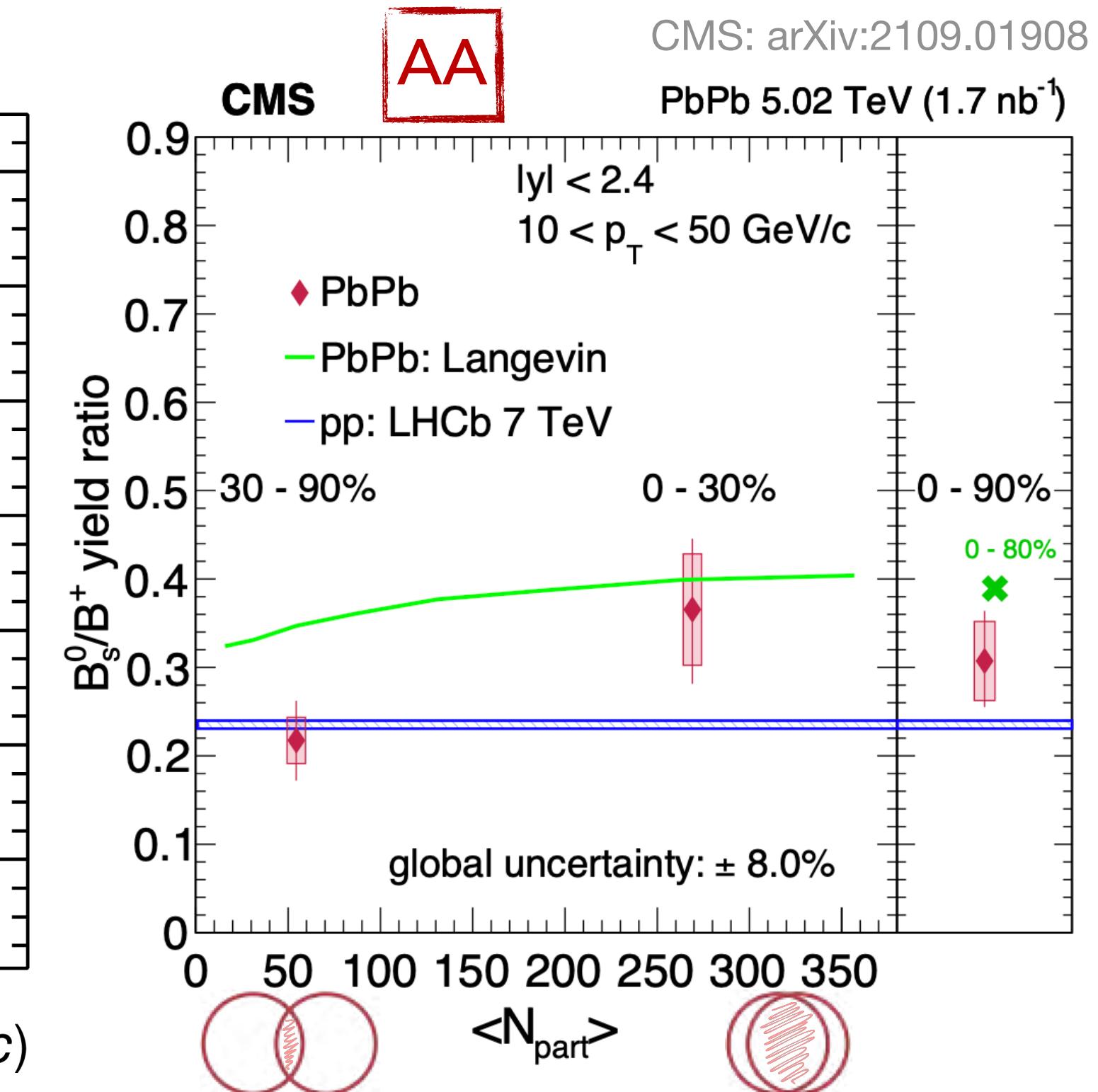
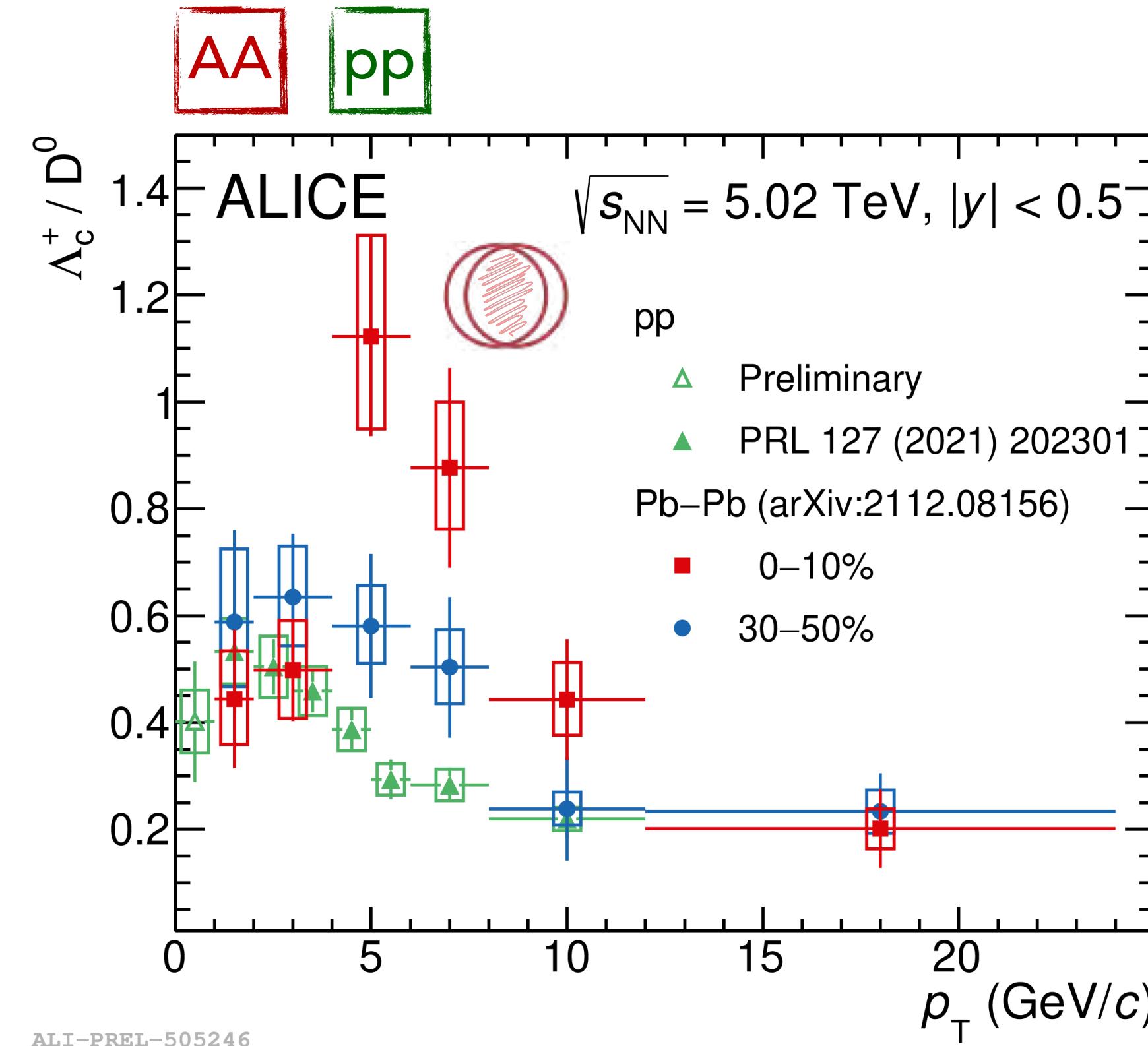
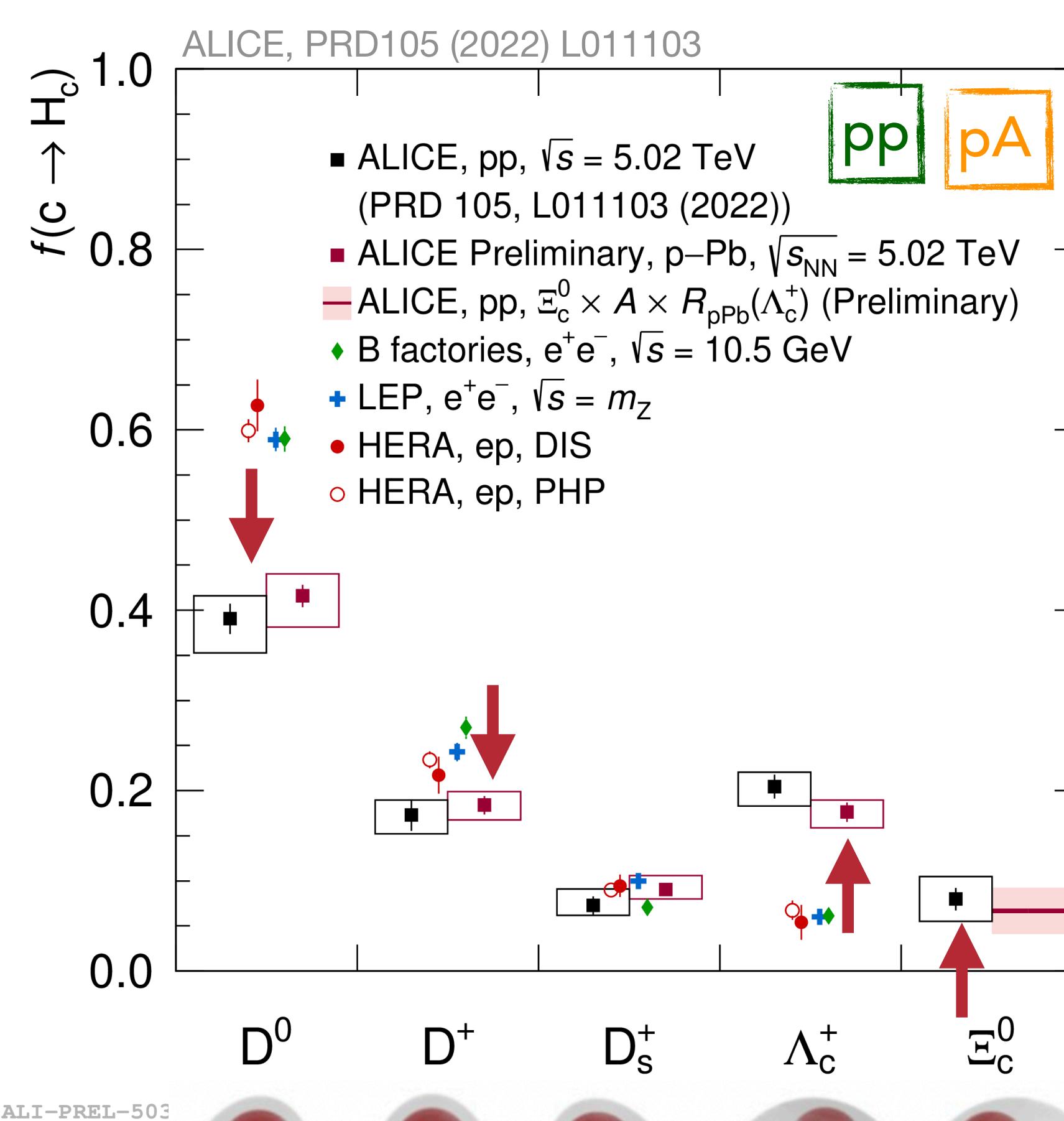


- Ratios fitted with statistical model equation

$$\frac{\bar{h}}{h} \propto \left(-2 \left(B + \frac{S}{3} \right) \frac{\mu_B}{T} - 2 I_3 \frac{\mu_{I_3}}{T} \right)$$



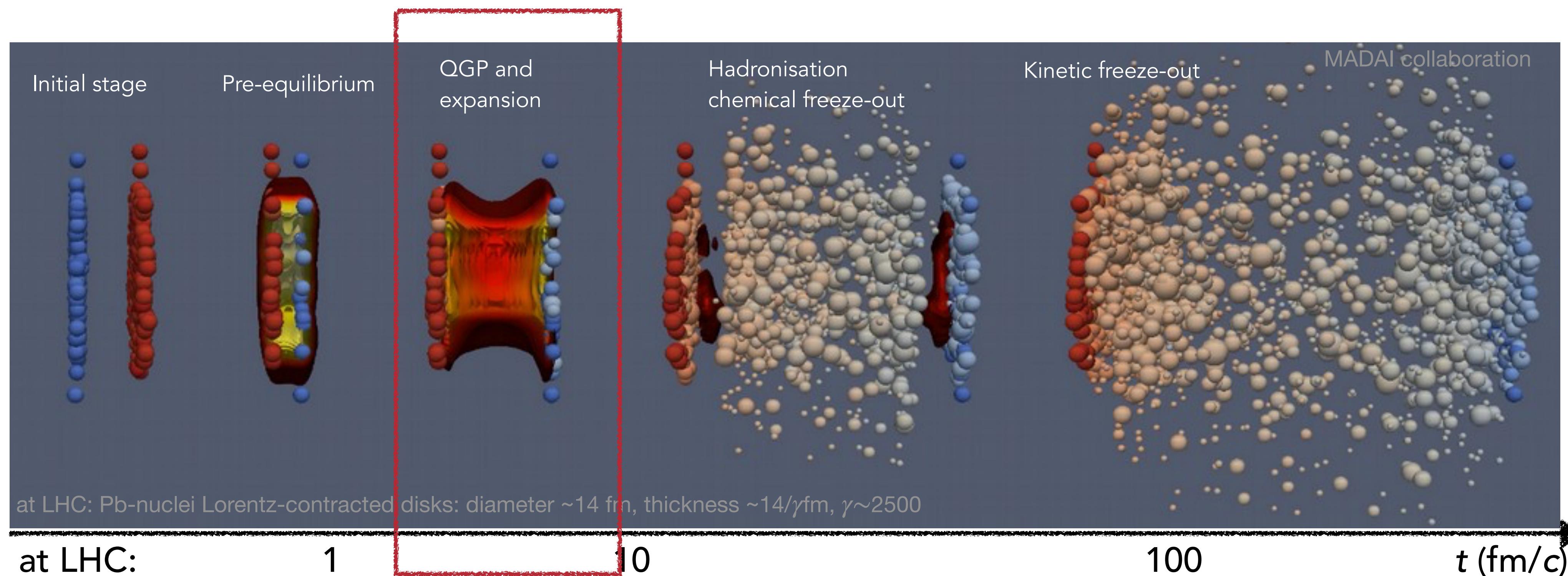
Hadronisation of heavy quarks from pp to Pb-Pb



- Charm-fragmentation fractions not universal in pp and p-Pb
- Hadronisation via recombination + mass-dependent p_T shift by collective expansion in central Pb-Pb
- Strangeness-rich QGP

Introduction: Heavy-Ion Physics

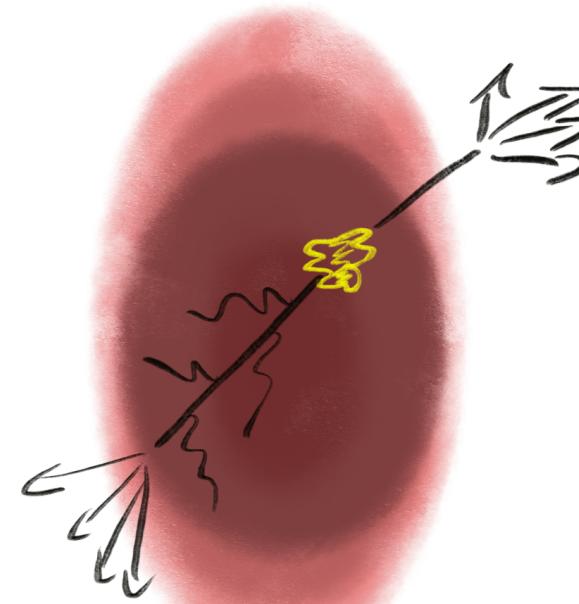
Space-Time Evolution of a Heavy-Ion Collision



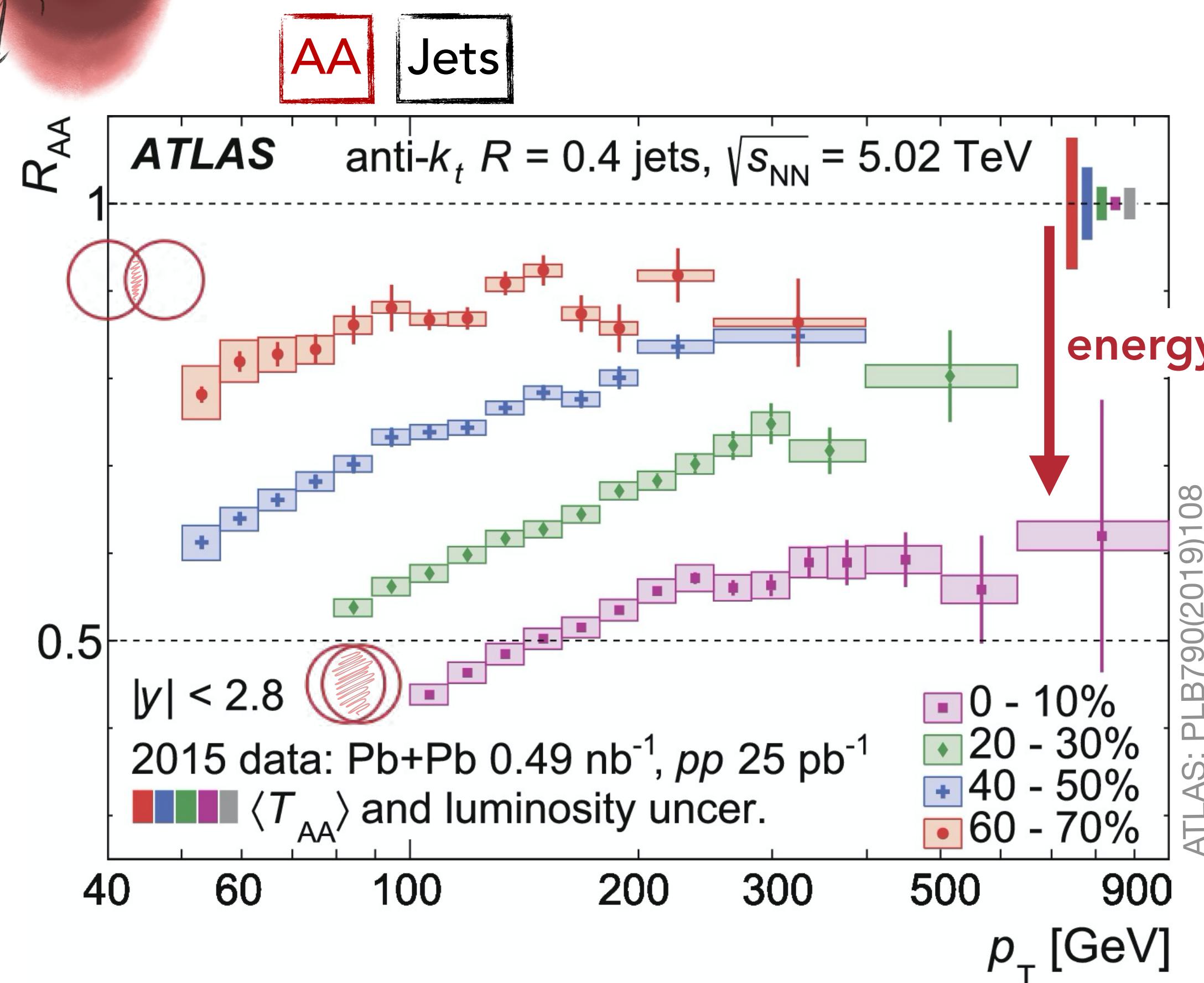
Characterise medium properties

- Colour deconfinement
- Parton energy loss

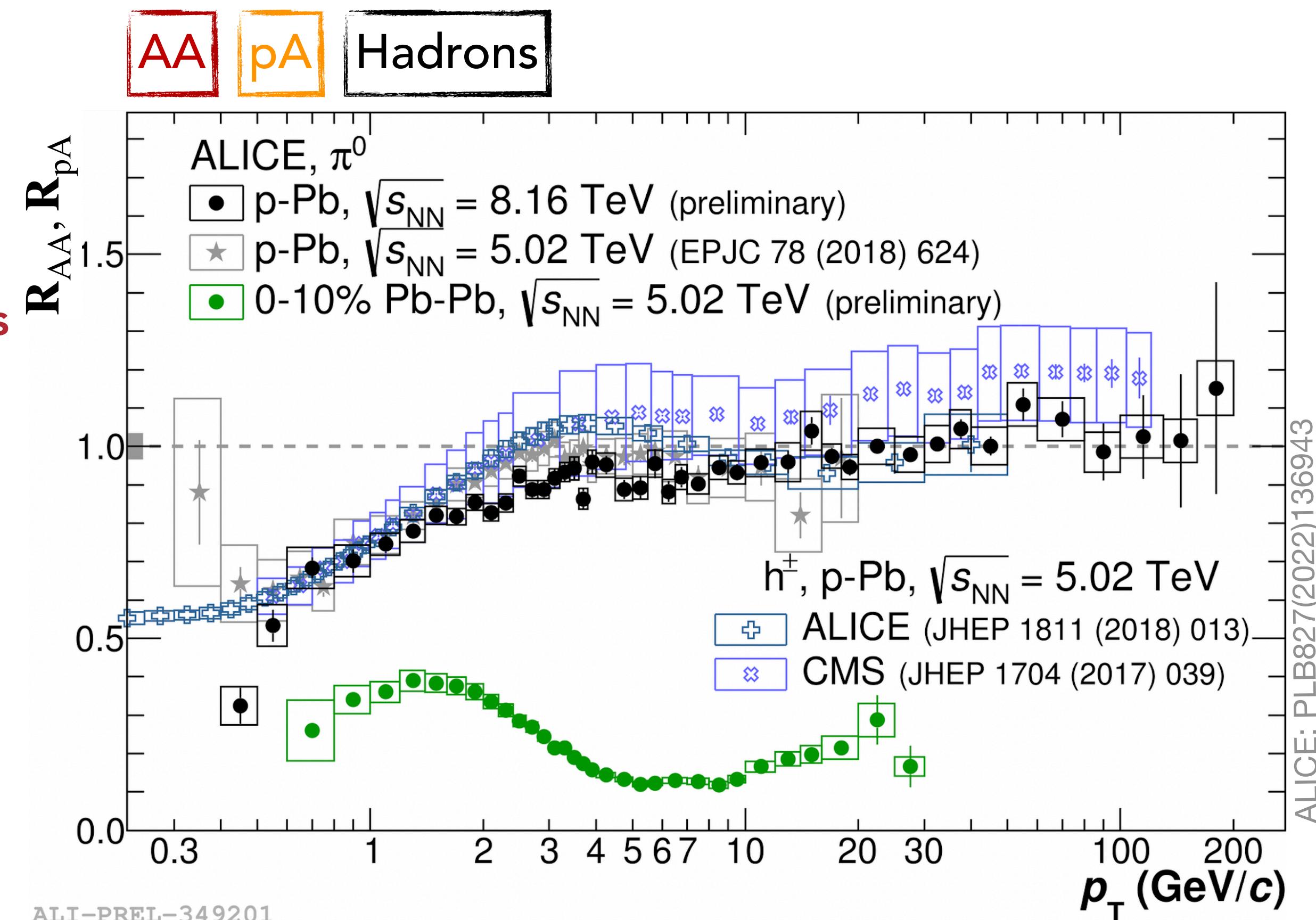
Parton Energy Loss: R_{AA}



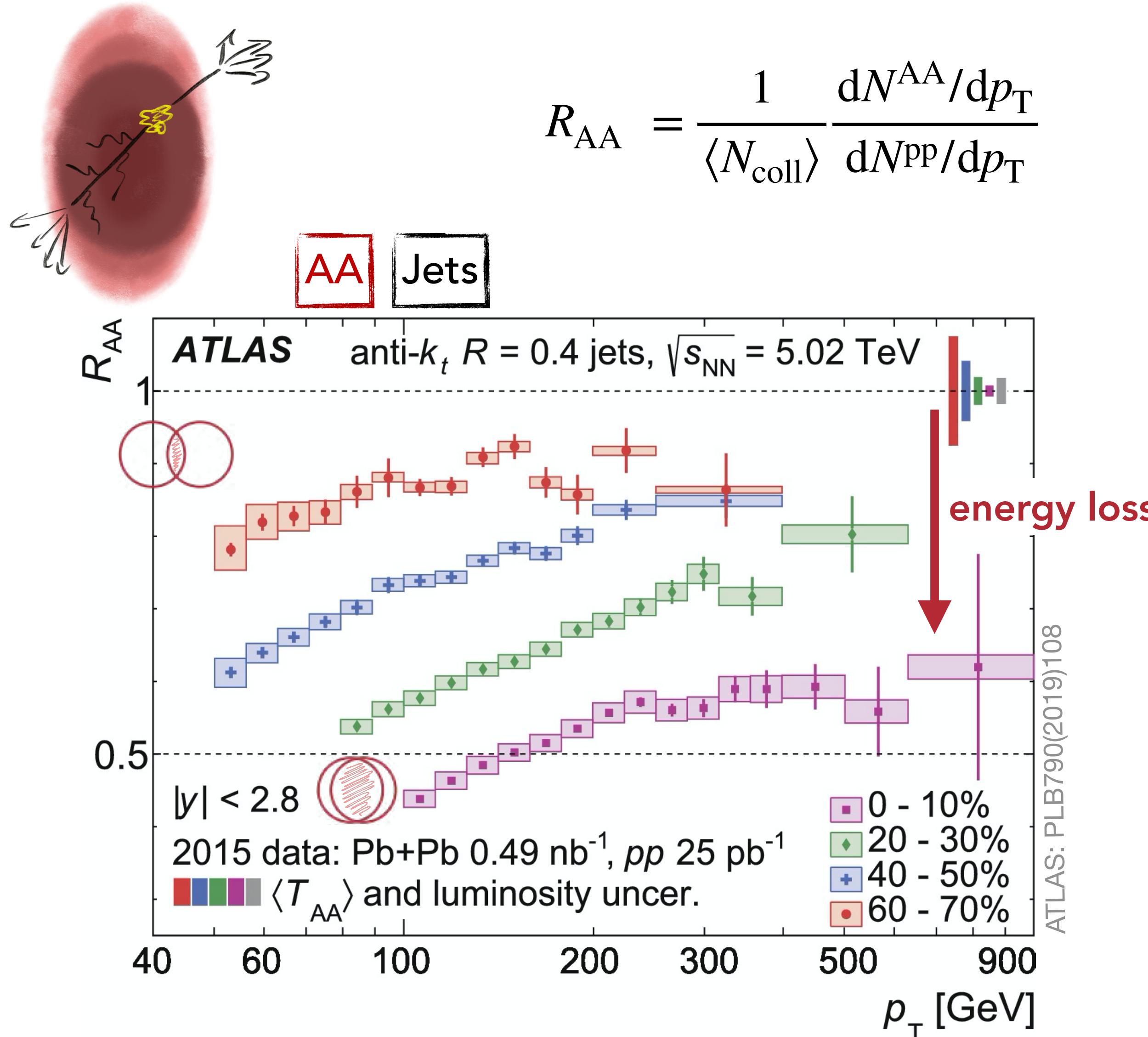
$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{dN^{\text{AA}}/dp_T}{dN^{\text{pp}}/dp_T}$$



→ Energy loss in large systems up to very high p_T



Parton Energy Loss: R_{AA}

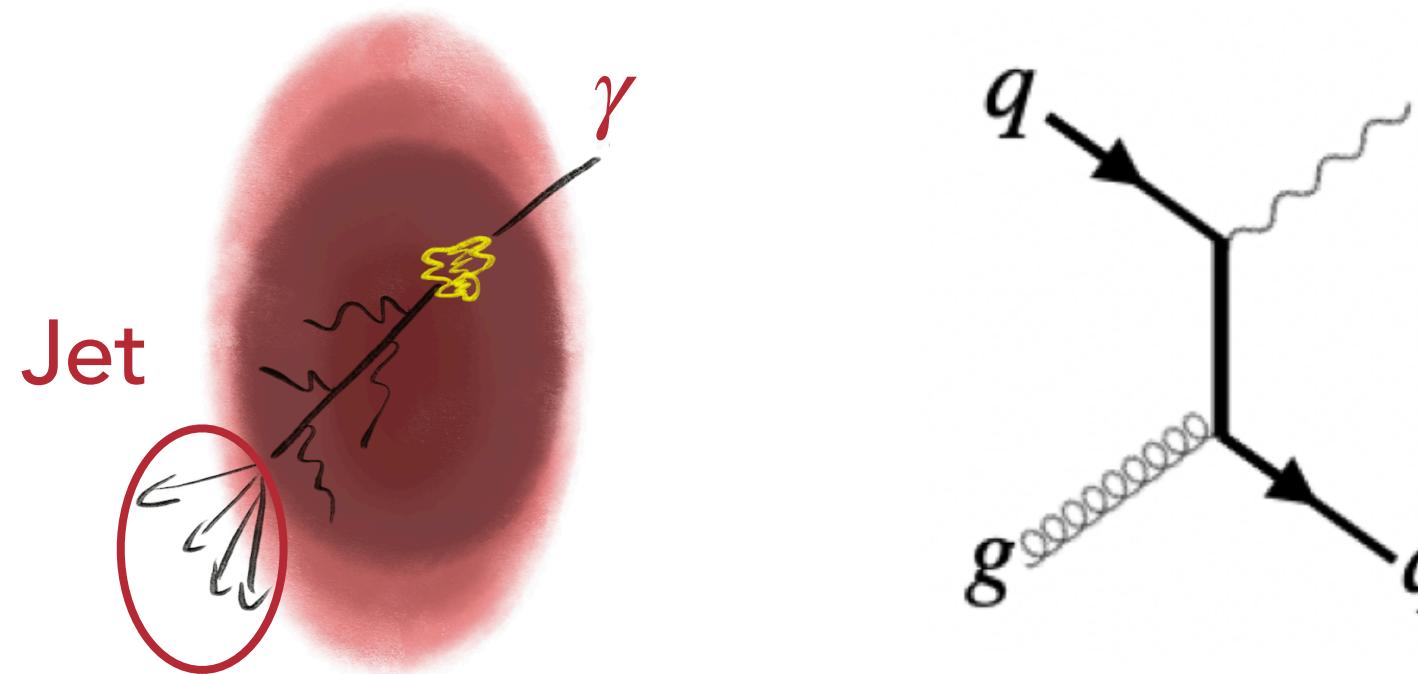


- Parton energy loss
- Colour-charge dependence



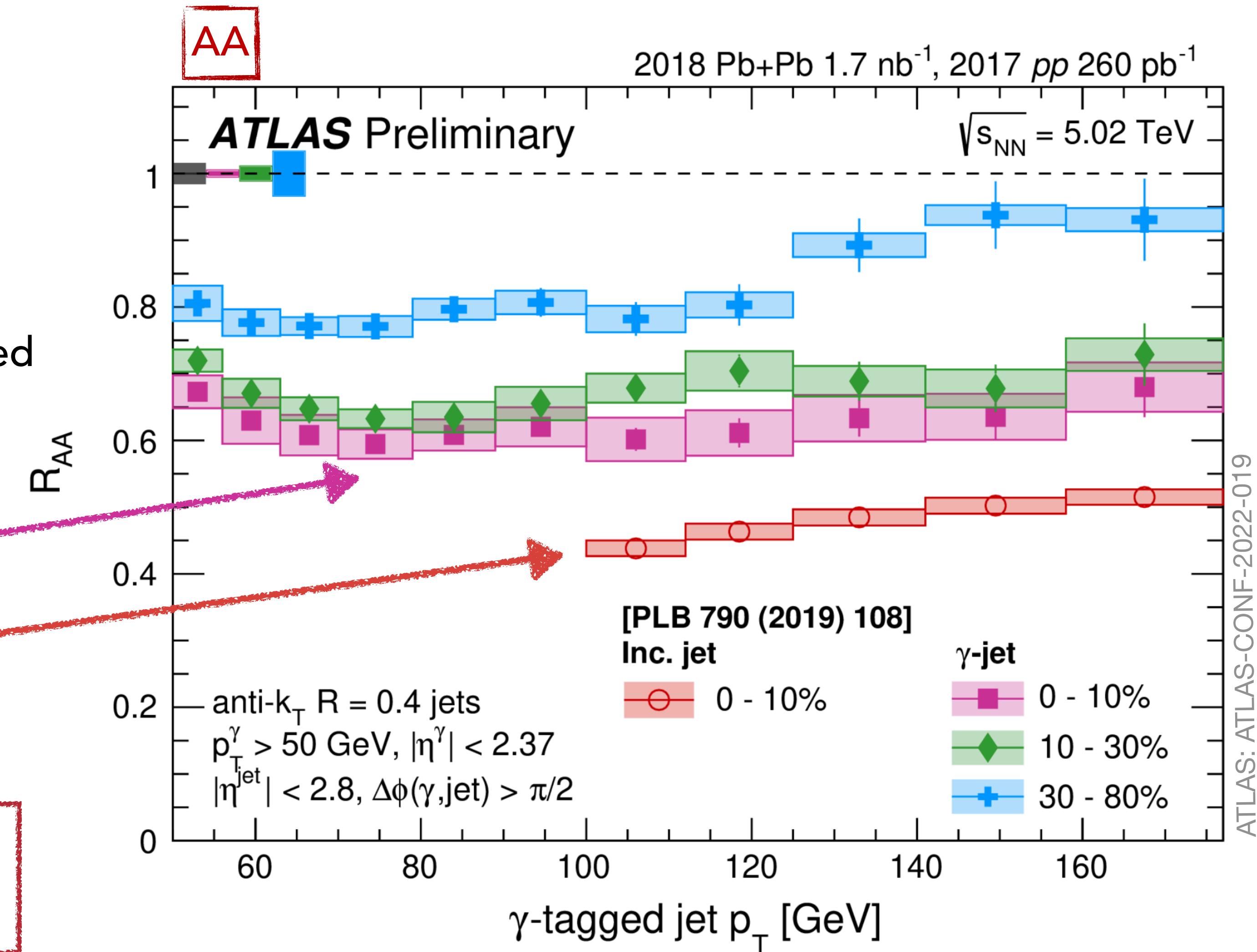
- Mass dependence ("dead-cone effect")
- Large parton mass Small parton mass
- Expected behaviour: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_{\text{charm}} > \Delta E_{\text{beauty}}$
 \rightarrow e.g. R_{AA} (light hadrons) $<$ R_{AA} (D) $<$ R_{AA} (B)

Colour-charge dependence of energy loss



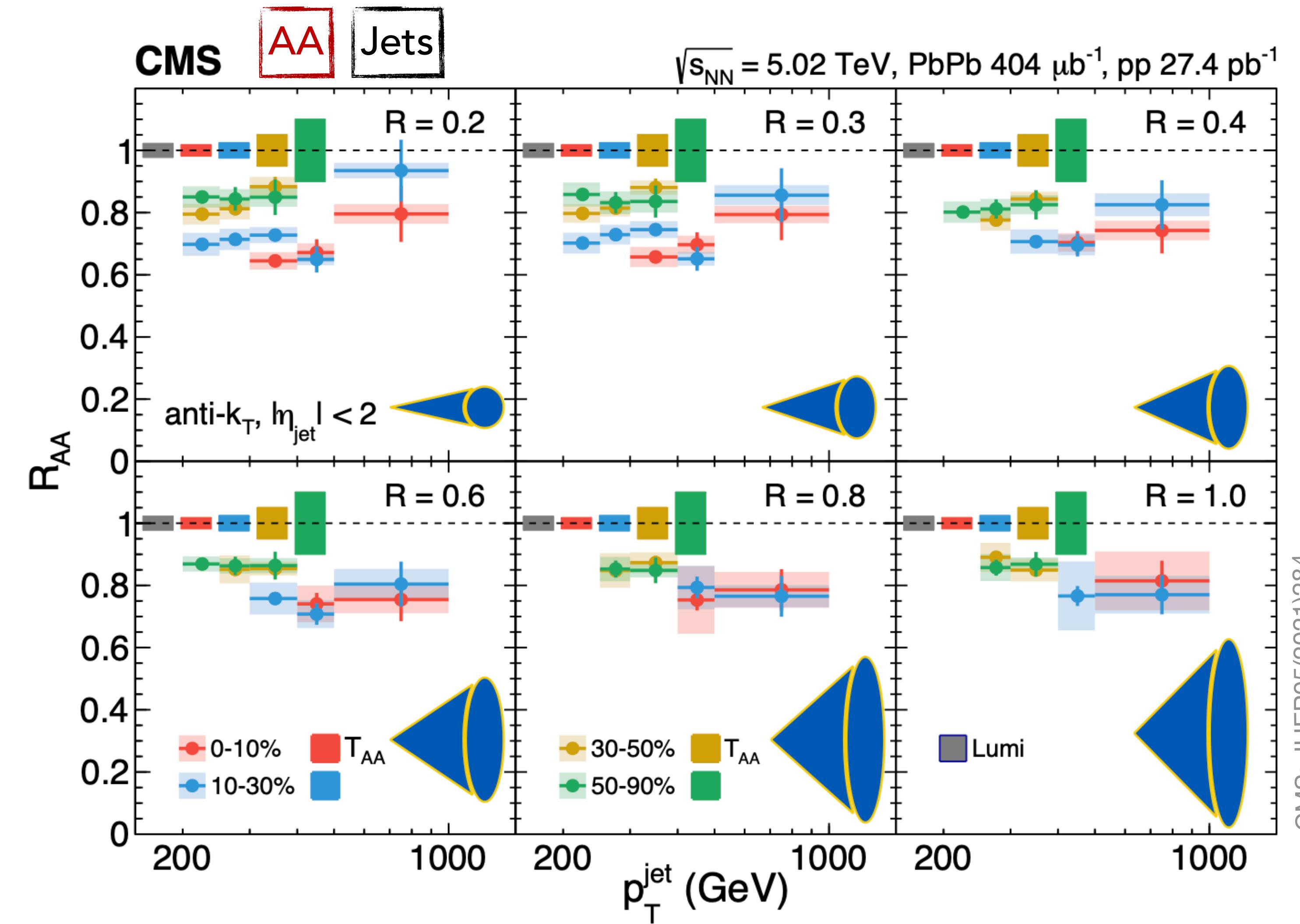
- Photon-tagged jet sample dominated by quark-initiated jets (quark-gluon Compton scattering)
- photon-tagged jet R_{AA} higher than inclusive jet R_{AA}

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



Jets

Differential Studies

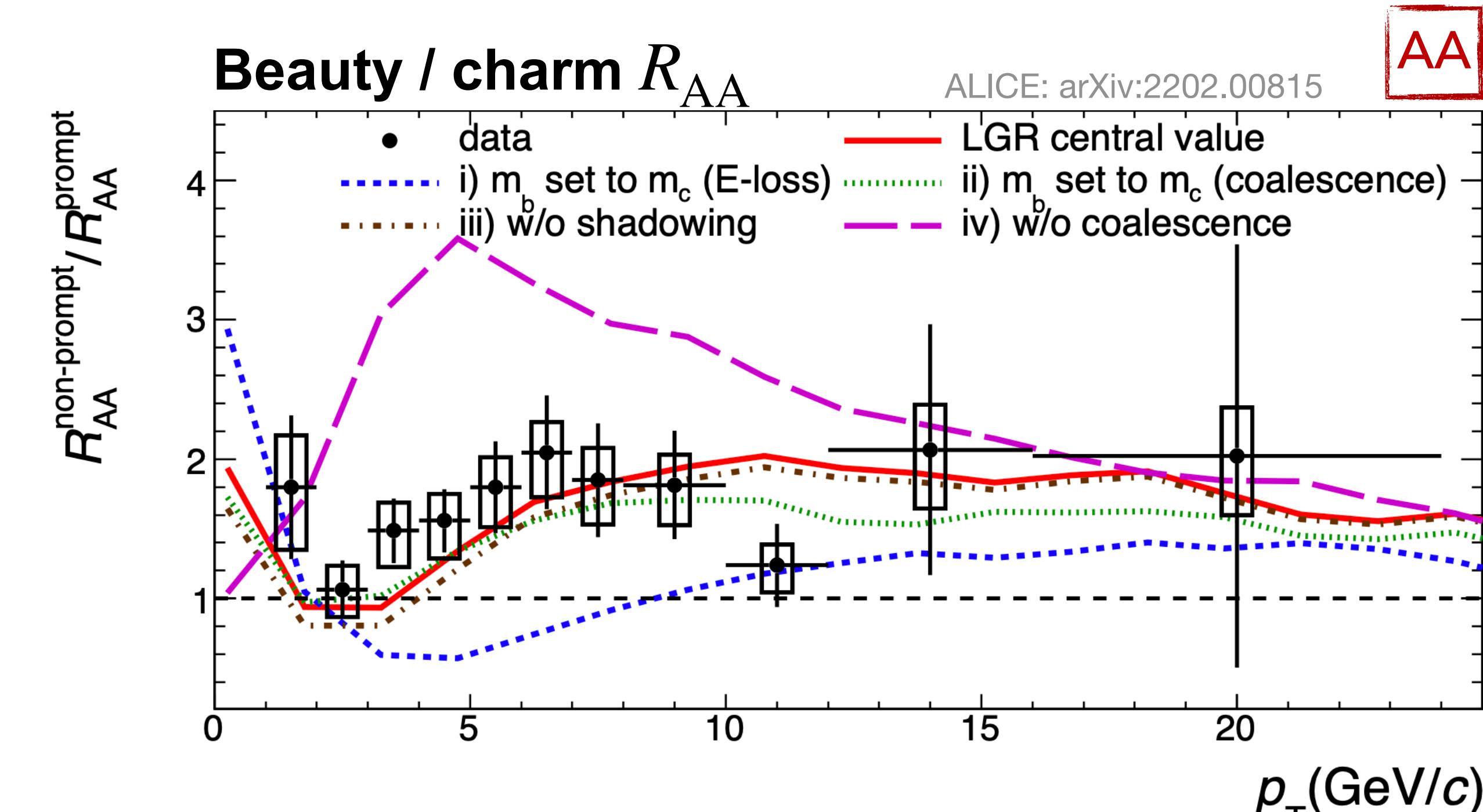
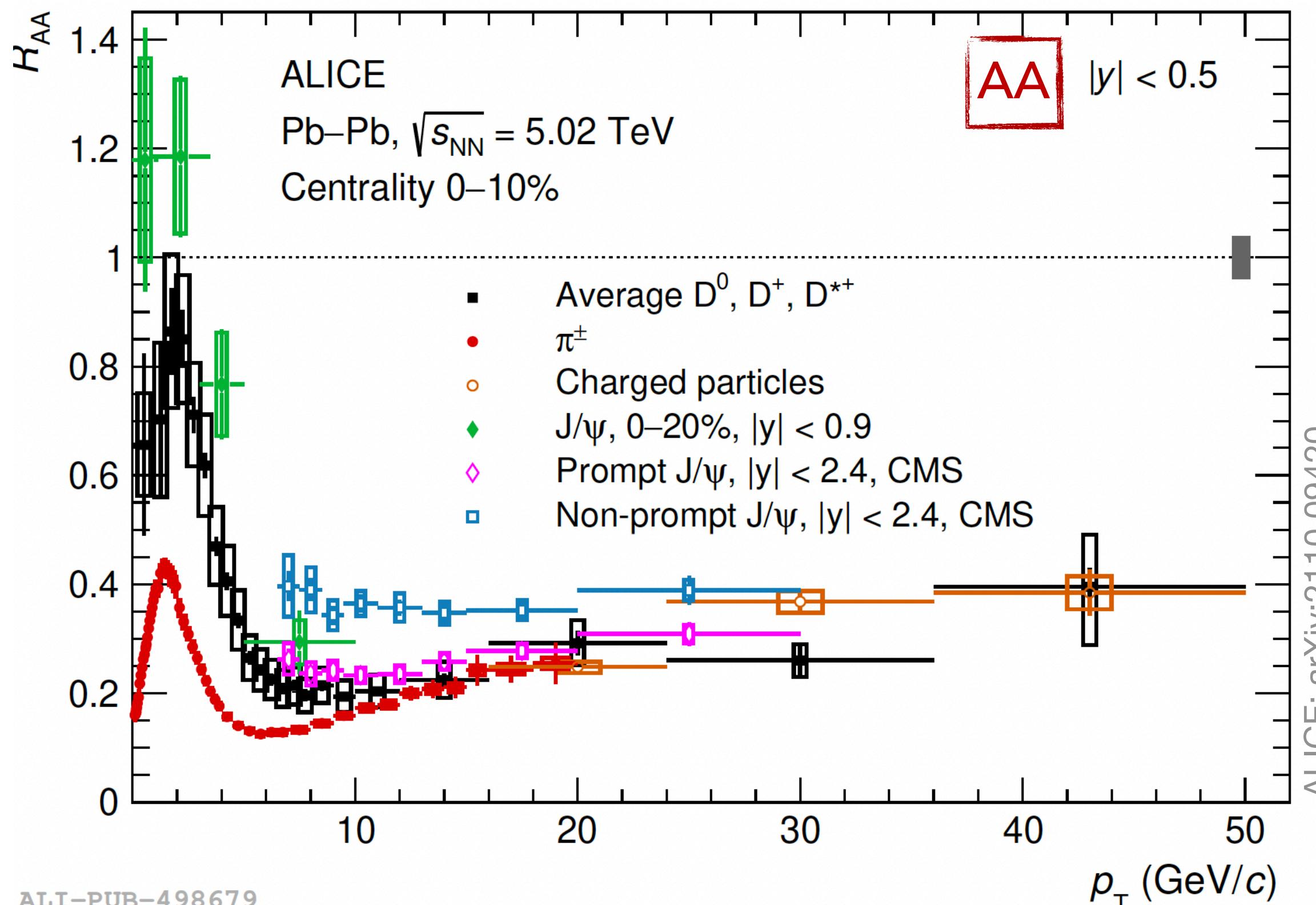


- Recover lost energy? \rightarrow study larger radius R
- Only modest increase, R_{AA} never reaches unity

\rightarrow Significant constraints on models of jet quenching, medium response, large angle radiation

Mass dependence of the energy loss: Heavy quarks

- Expected behaviour: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_{\text{charm}} > \Delta E_{\text{beauty}}$
 → e.g. R_{AA} (light hadrons) $< R_{AA}$ (D) $< R_{AA}$ (B)

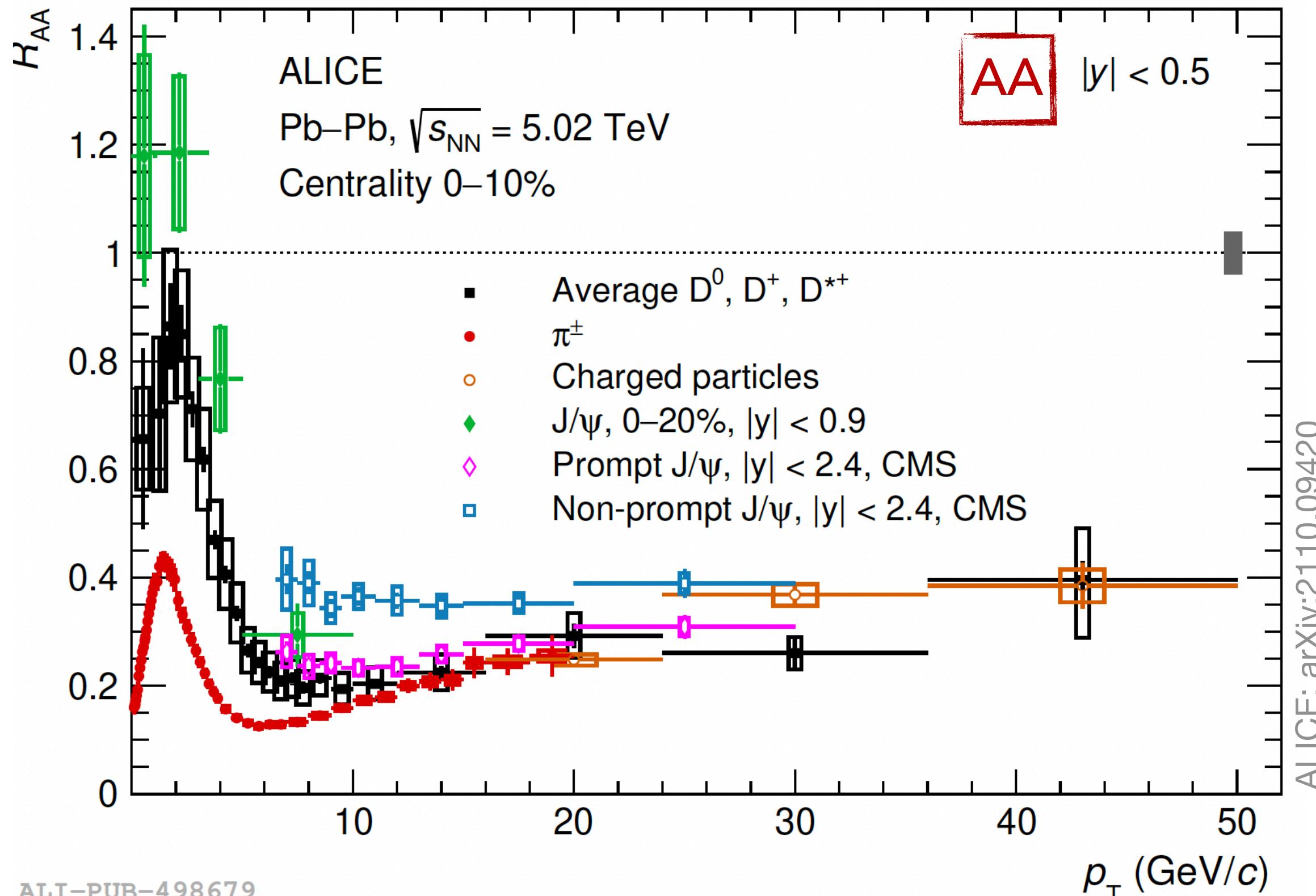


→ D-meson R_{AA} larger than the one for pions for $p_T < 8$ GeV/c
 → Charm and beauty hadrons show quark-mass dependent energy loss at intermediate p_T

Mass dependence of the energy loss: Heavy quarks

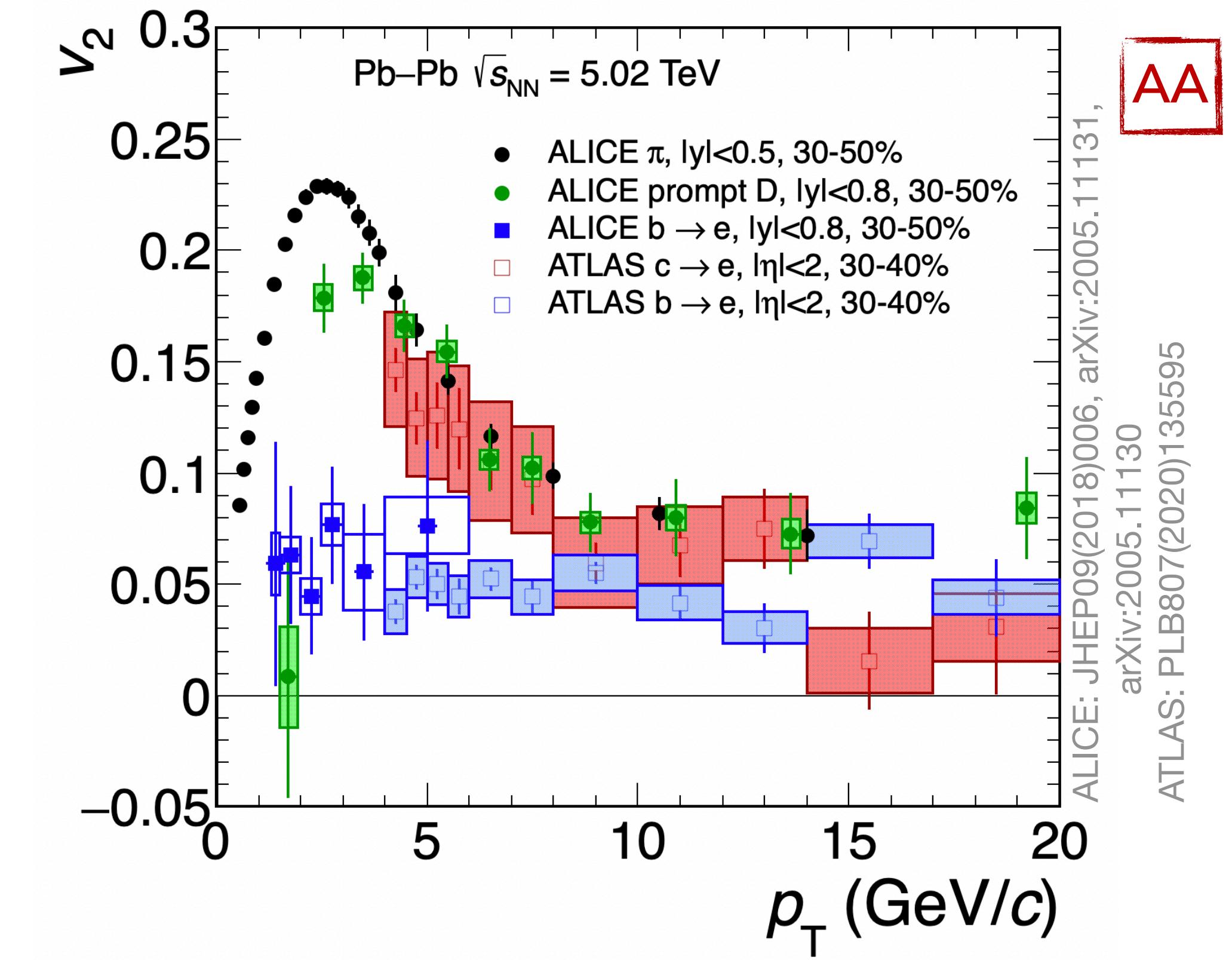
- Expected behaviour: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_{\text{charm}} > \Delta E_{\text{beauty}}$

→ e.g. R_{AA} (light hadrons) $< R_{AA}$ (D) $< R_{AA}$ (B)



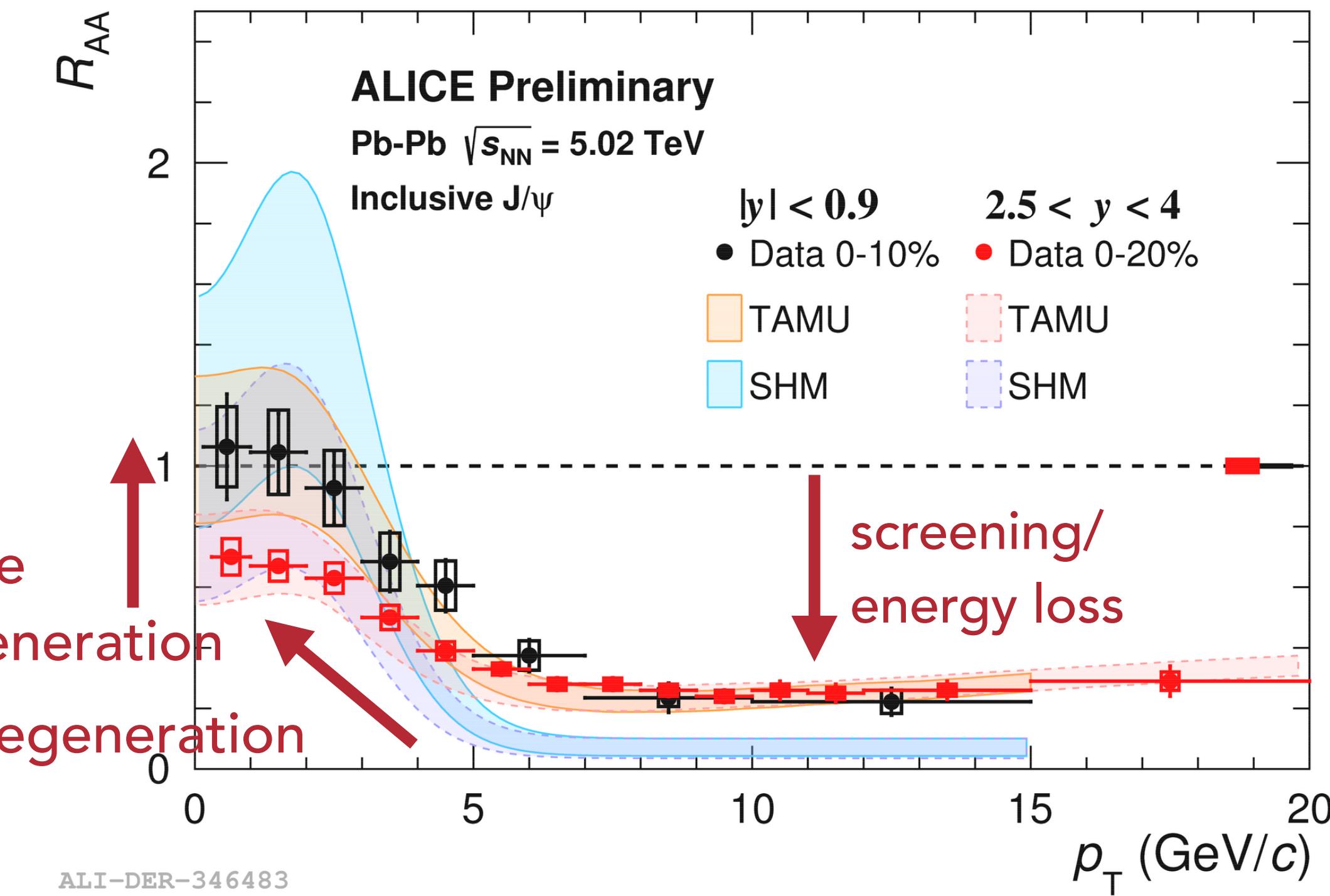
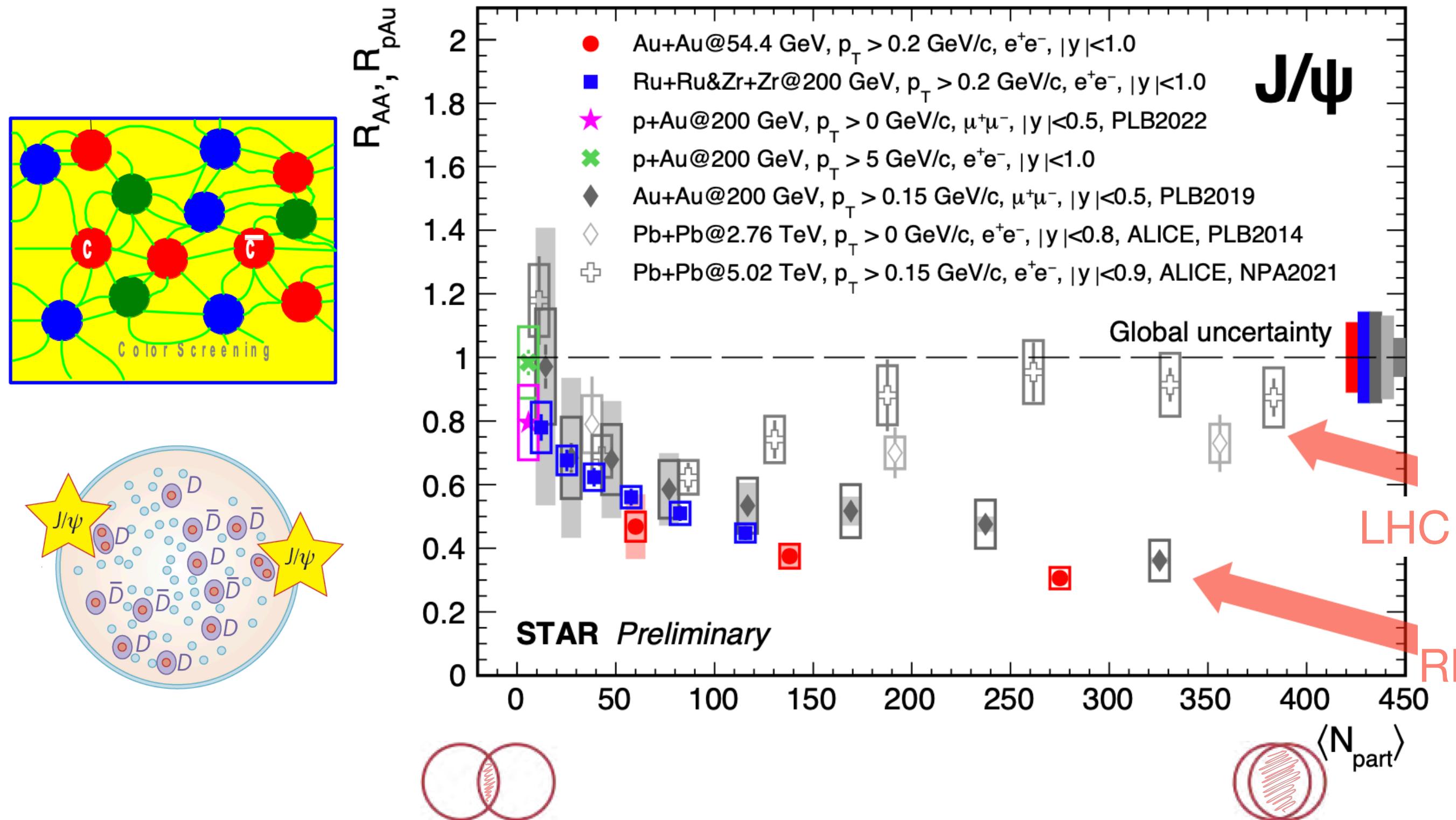
ALI-PUB-498679

ALICE: arXiv:2110.09420



- 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

Quarkonia: J/ψ

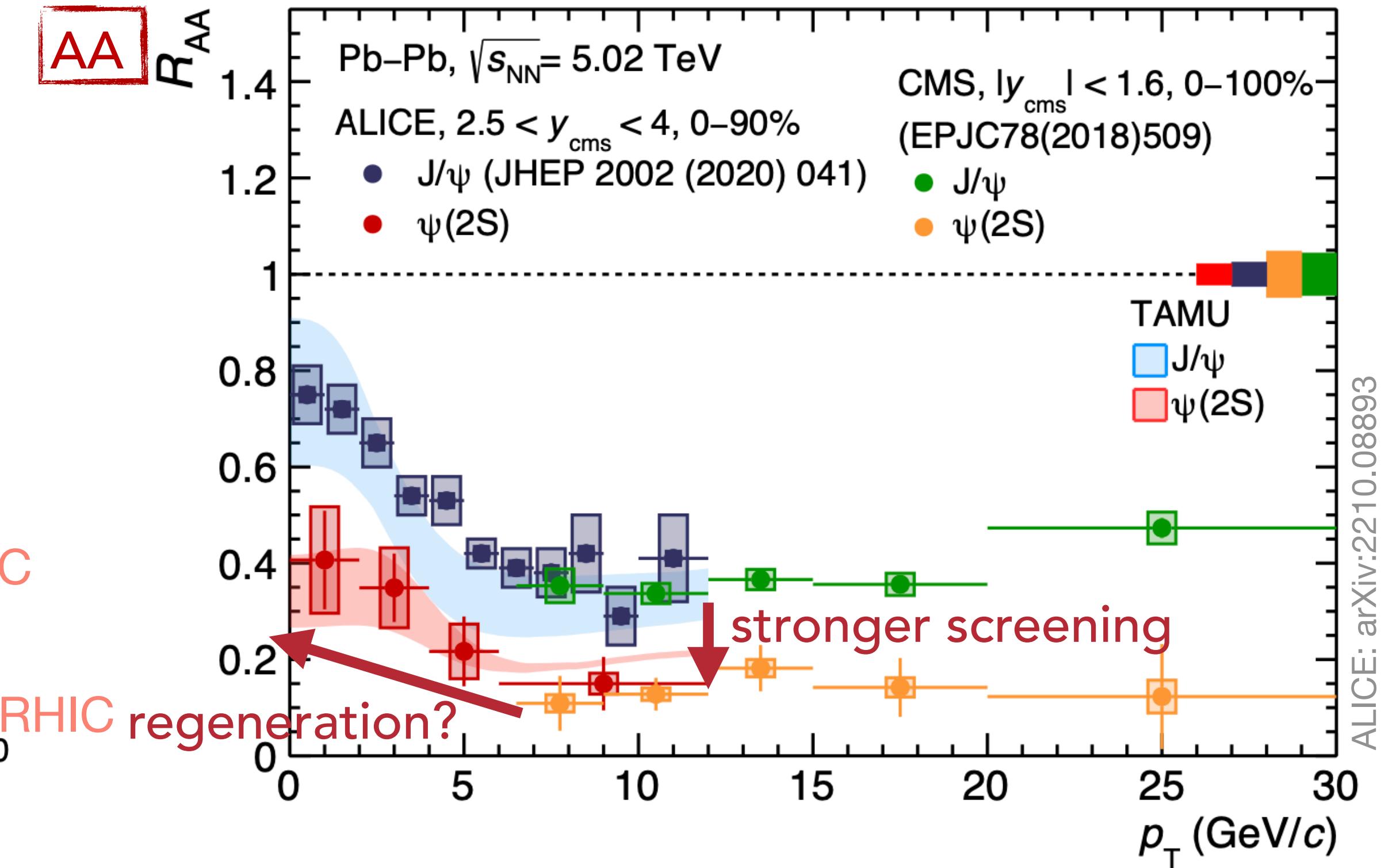
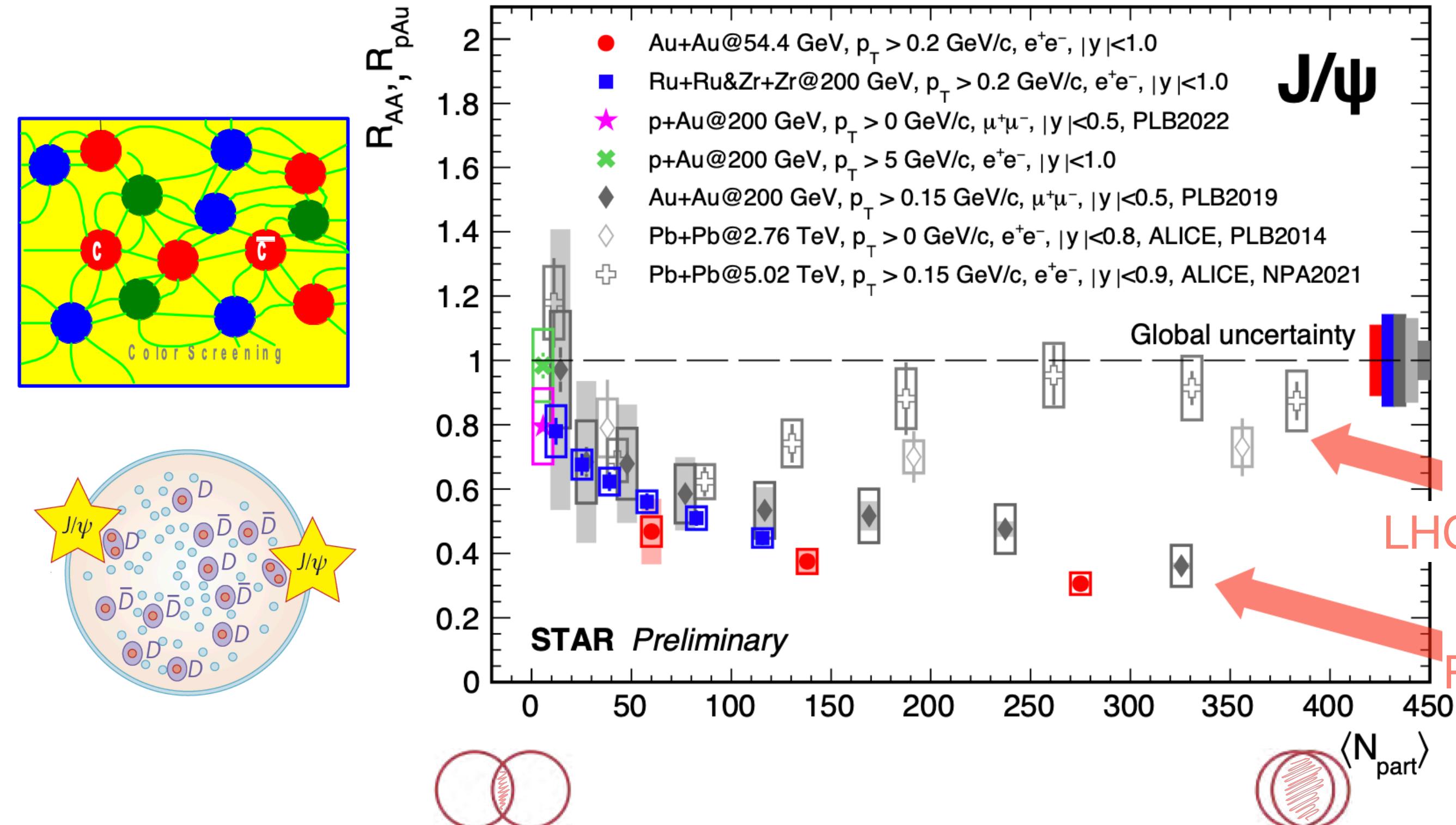


- Quarkonium production mechanism
 - Suppression due to colour screening
 - Production via (re)generation during QGP phase/at hadronisation

→ Suppression at RHIC energies scales with $\langle N_{part} \rangle$
 → No suppression at LHC full energy
 → (Re)generation scenario dominates at low p_T

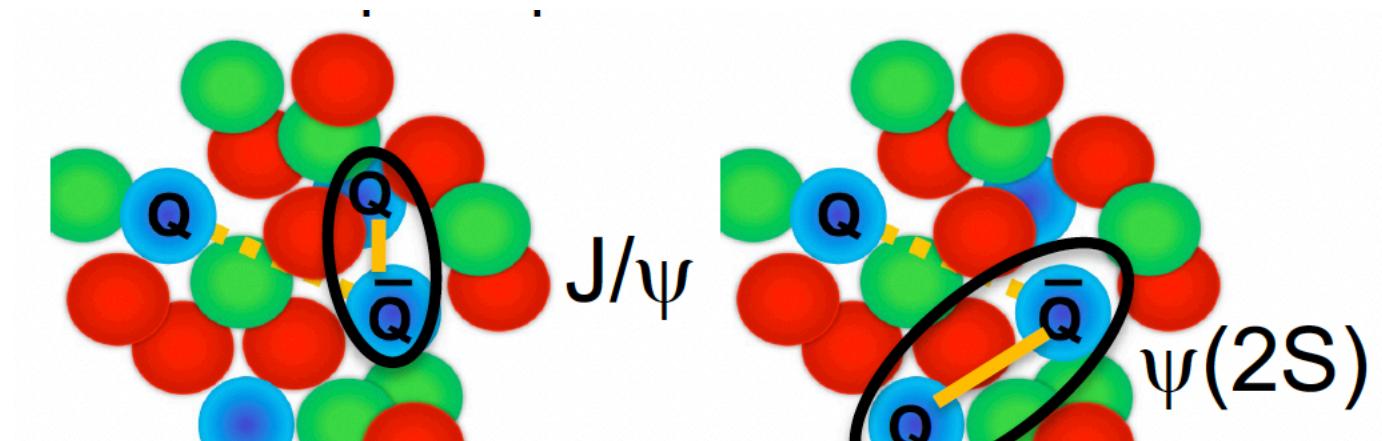
T. Matsui and H. Satz, PLB178(1986)416, P. Braun-Munzinger and J. Stachel, PLB490(2000)196,
 L. Grandchamp and R. Rapp, PLB523(2001)60

Quarkonia: J/ψ and $\psi(2S)$

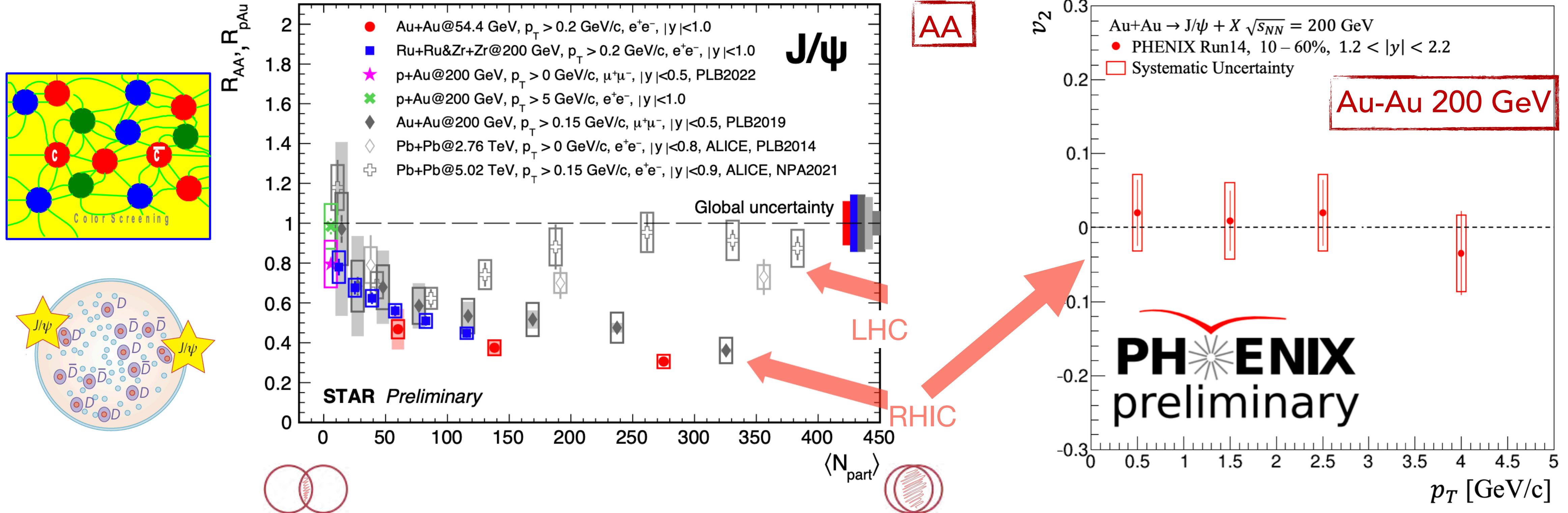


- Quarkonium production mechanism
 - Suppression due to colour screening
 - Production via (re)generation during QGP phase/at hadronisation

T. Matsui and H. Satz, PLB178(1986)416, P. Braun-Munzinger and J. Stachel, PLB490(2000)196,
L. Grandchamp and R. Rapp, PLB523(2001)60



Quarkonia: J/ψ flow

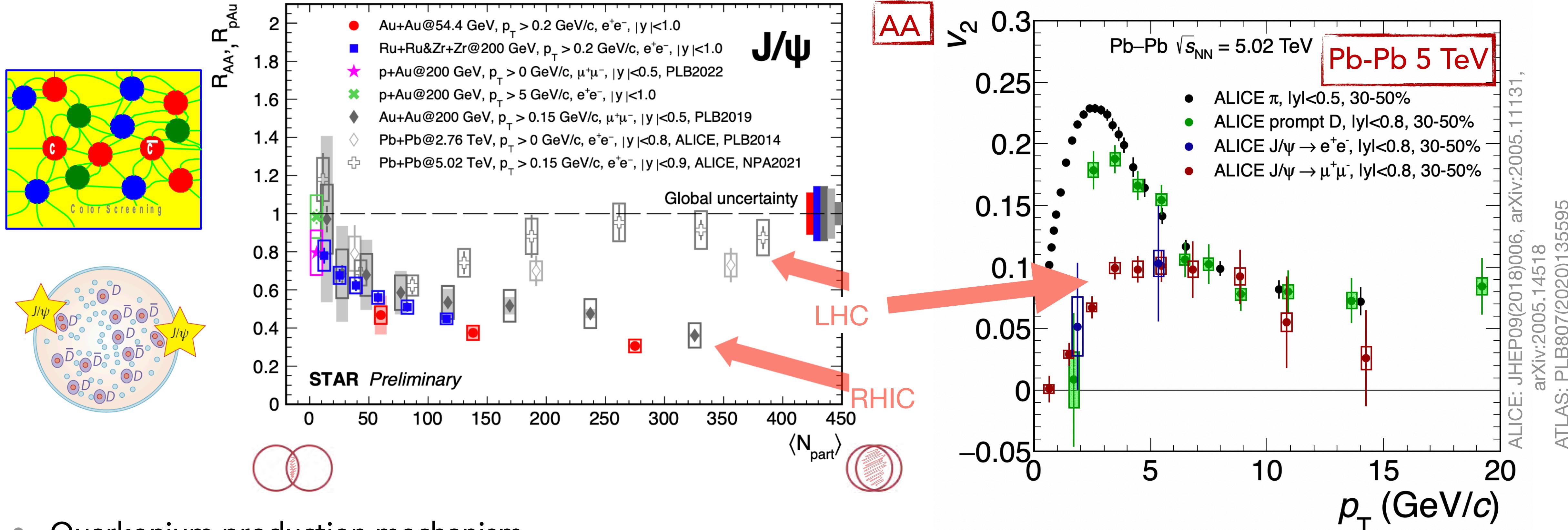


- Quarkonium production mechanism
 - Suppression due to colour screening
 - Production via (re)generation during QGP phase/at hadronisation

→ J/ψ flow consistent with zero at RHIC

T. Matsui and H. Satz, PLB178(1986)416, P. Braun-Munzinger and J. Stachel, PLB490(2000)196,
L. Grandchamp and R. Rapp, PLB523(2001)60

Quarkonia: J/ψ flow

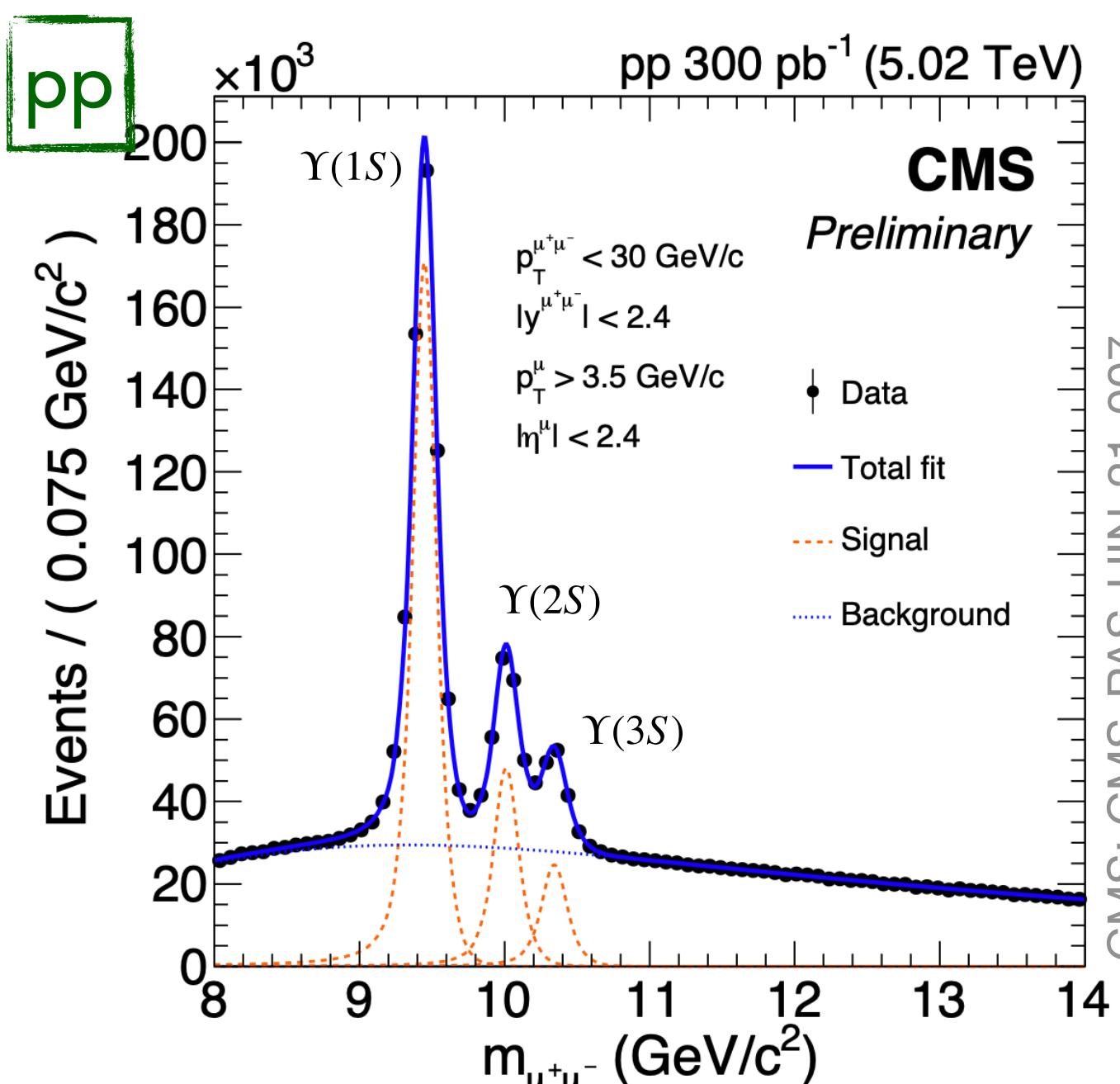


- Quarkonium production mechanism
 - Suppression due to colour screening
 - Production via (re)generation during QGP phase/at hadronisation

T. Matsui and H. Satz, PLB178(1986)416, P. Braun-Munzinger and J. Stachel, PLB490(2000)196,
L. Grandchamp and R. Rapp, PLB523(2001)60

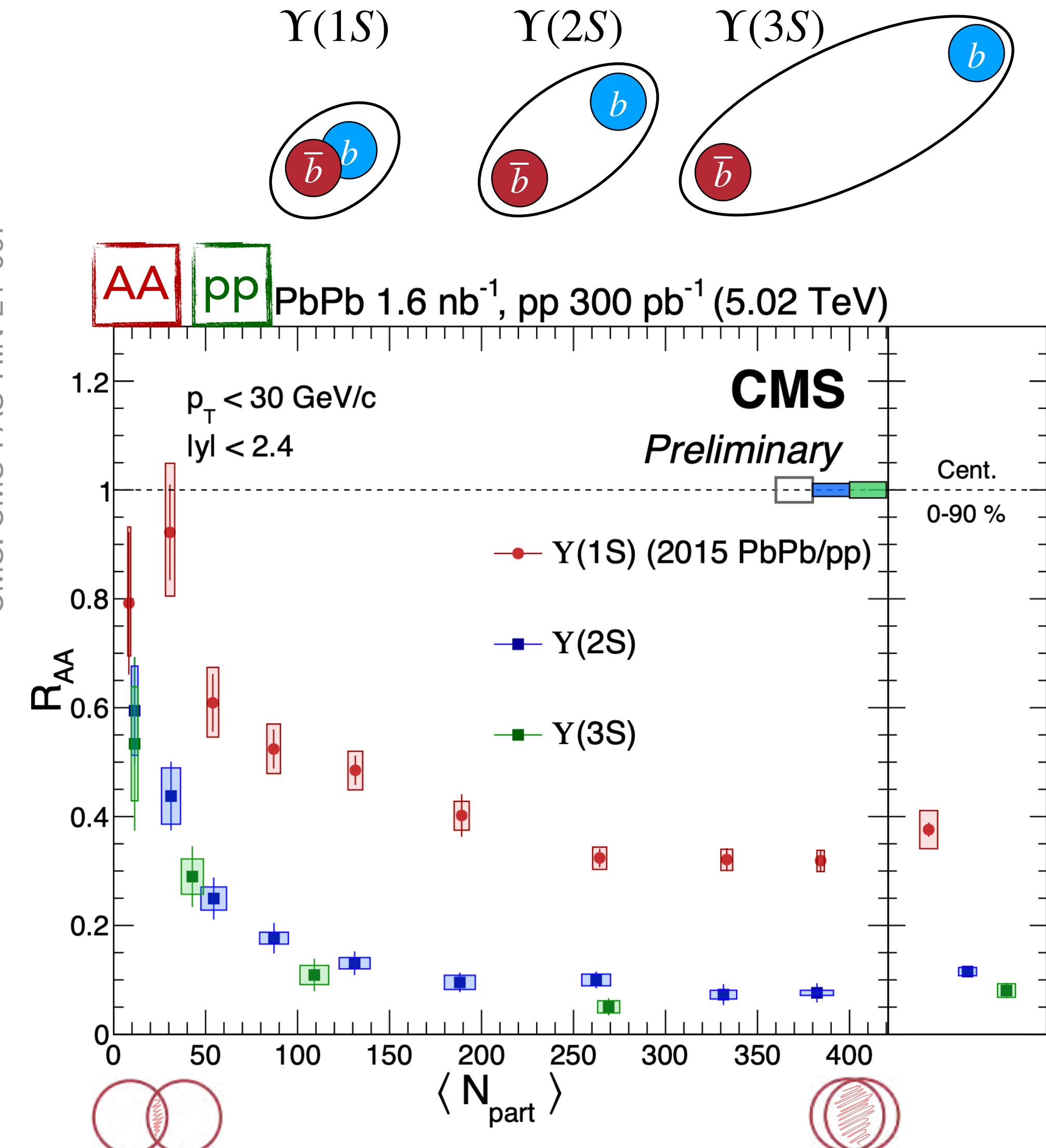
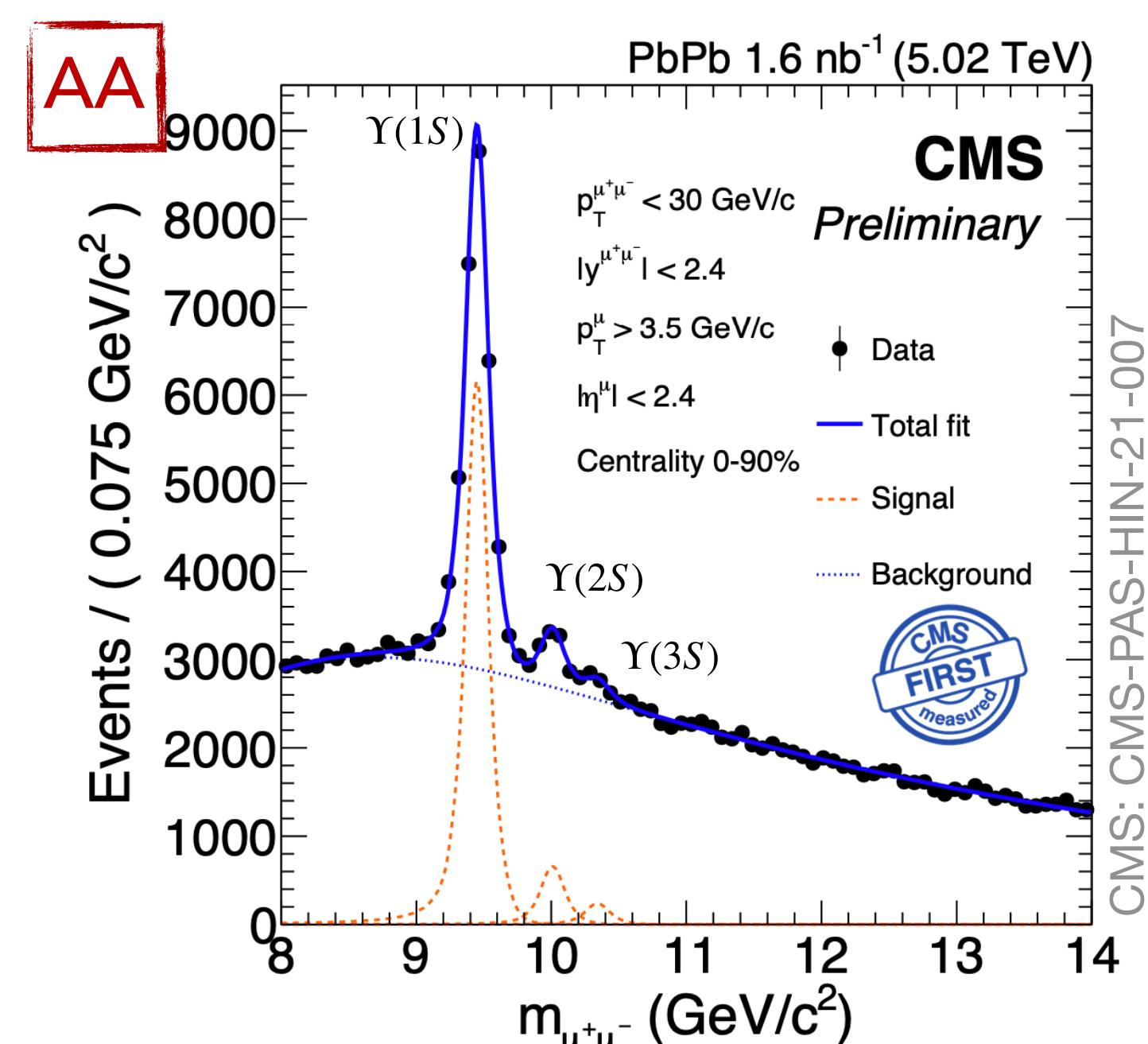
→ J/ψ flow consistent with zero at RHIC
→ J/ψ flows at LHC
→ Signature of deconfinement

Quarkonia: Bottomonium Family



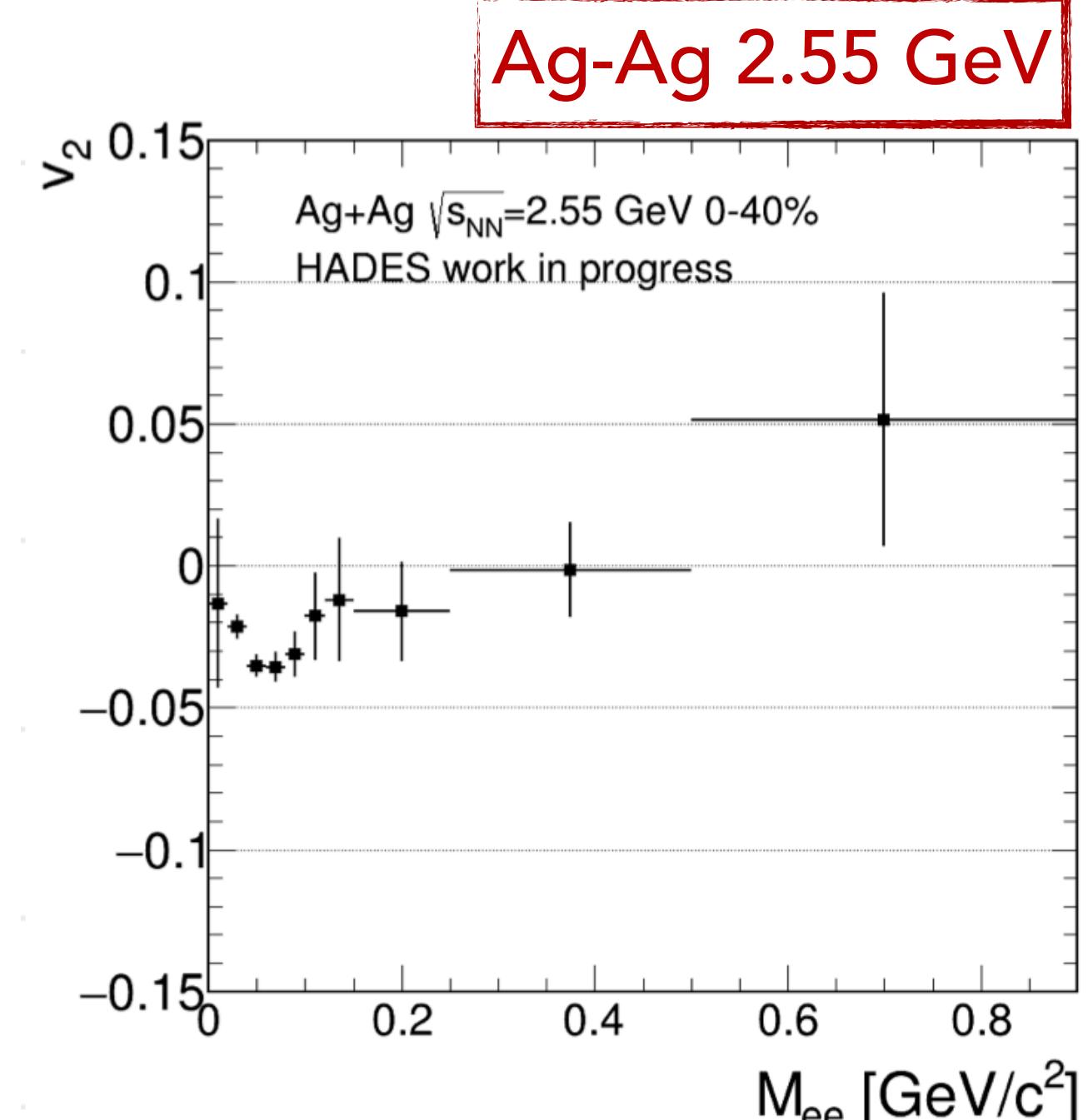
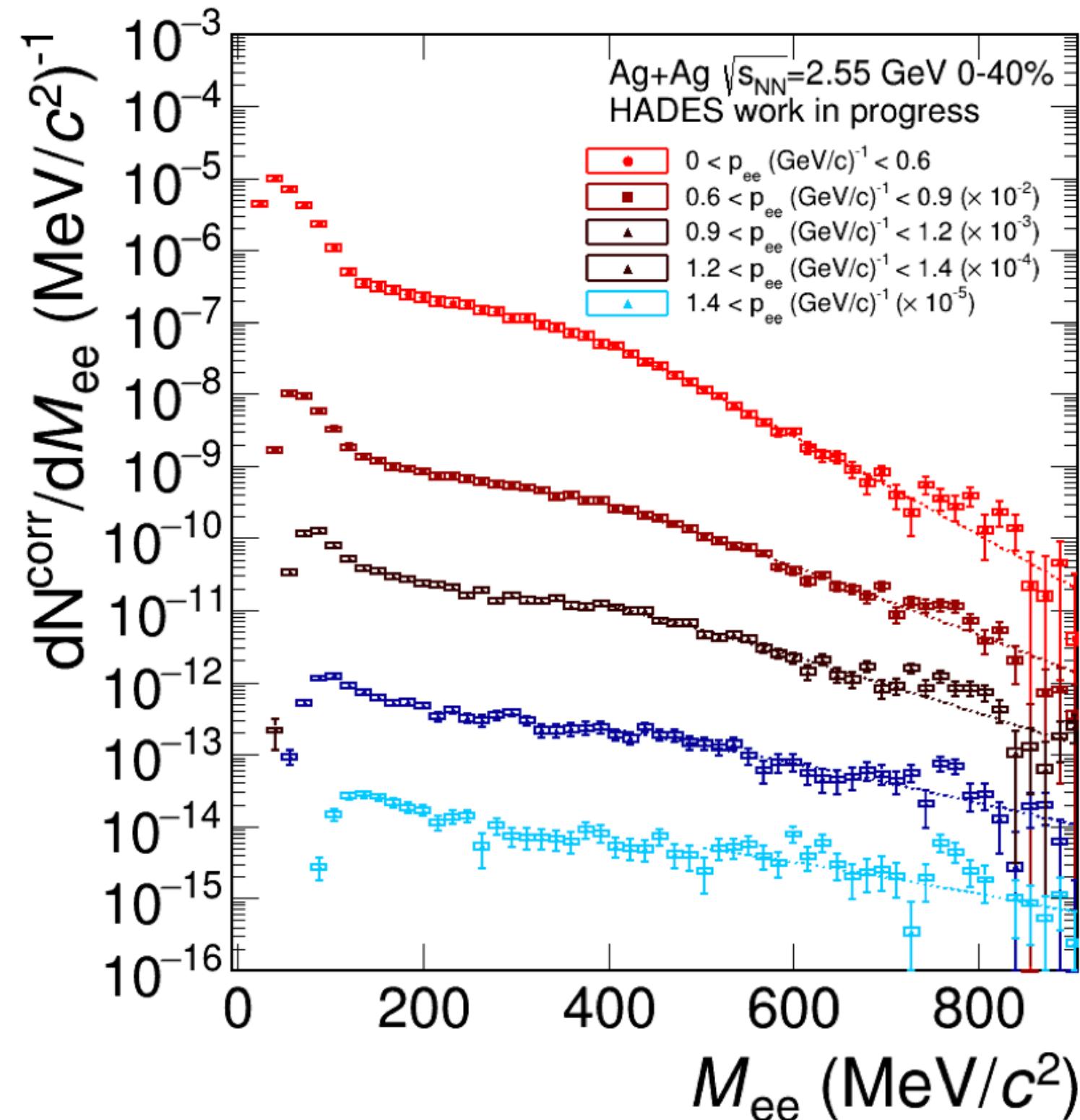
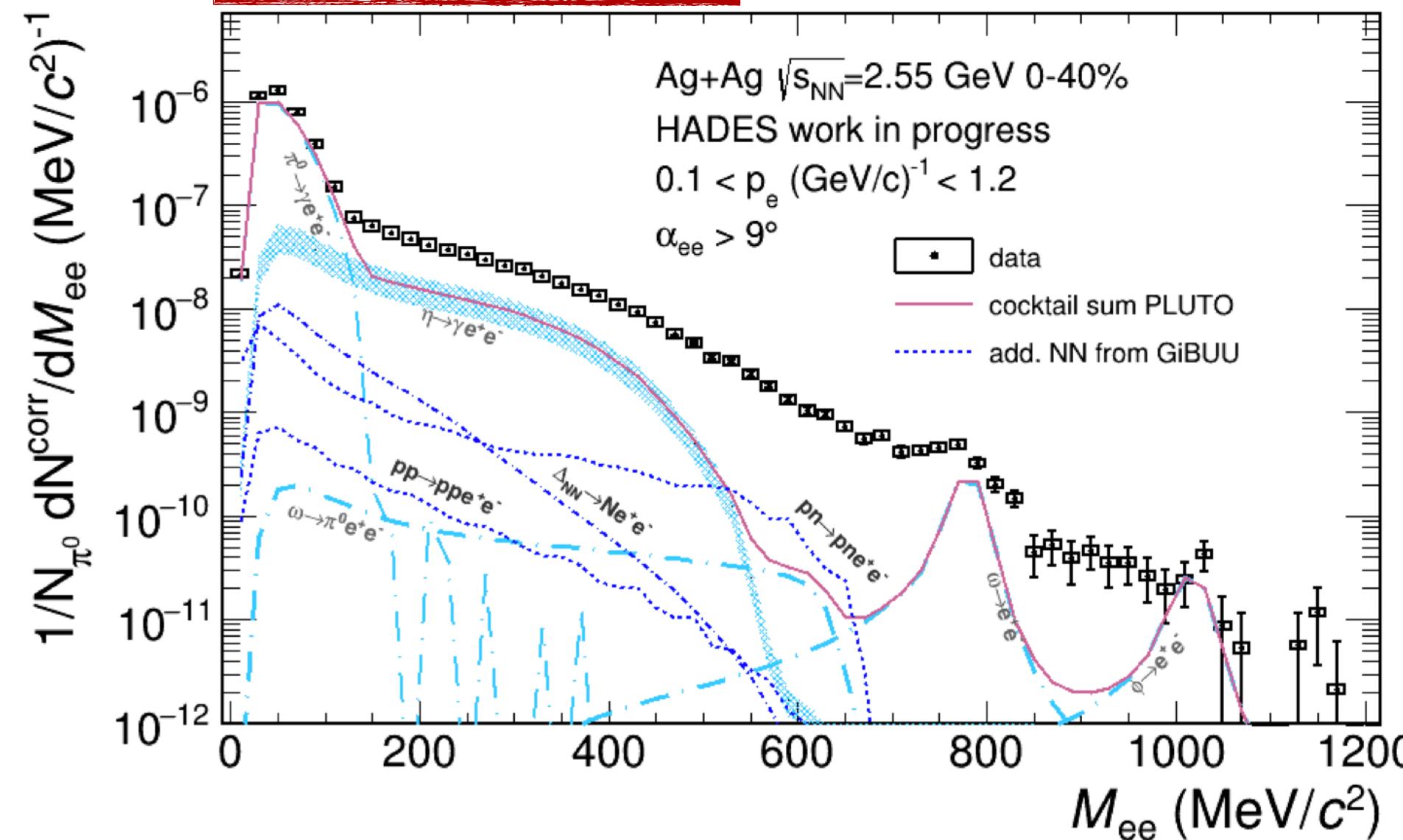
$$R_{AA}(1S) > R_{AA}(2S) > R_{AA}(3S)$$

→ Suppression mechanism dominates for bottomonium family



Dielectron measurements at high baryochemical potential

Ag-Ag 2.55 GeV

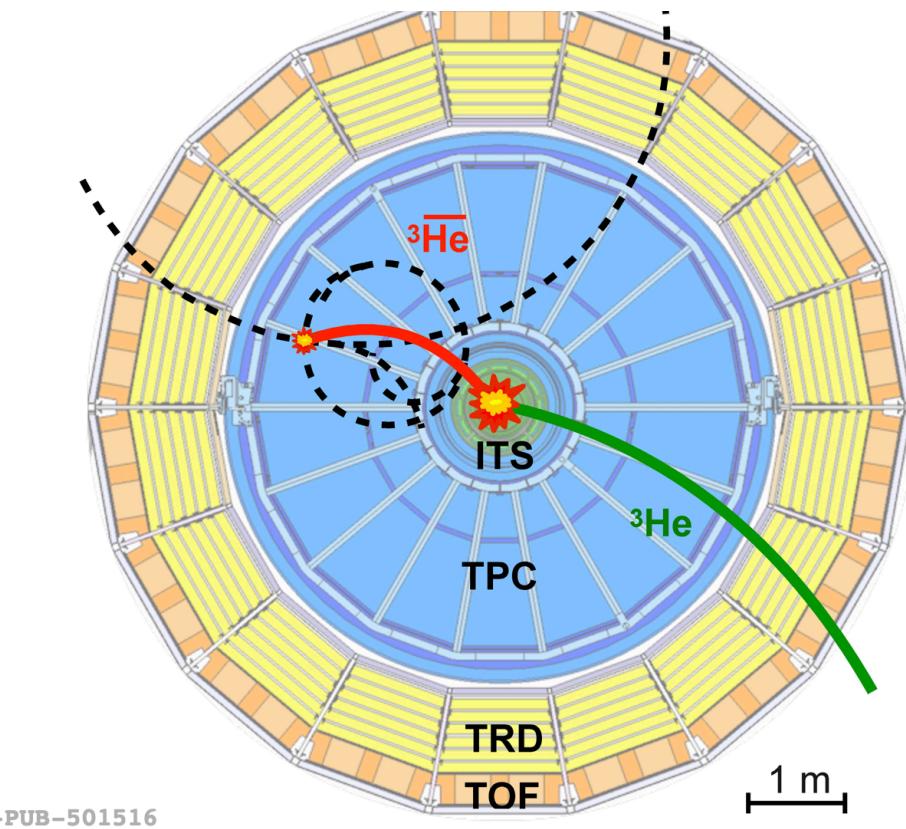
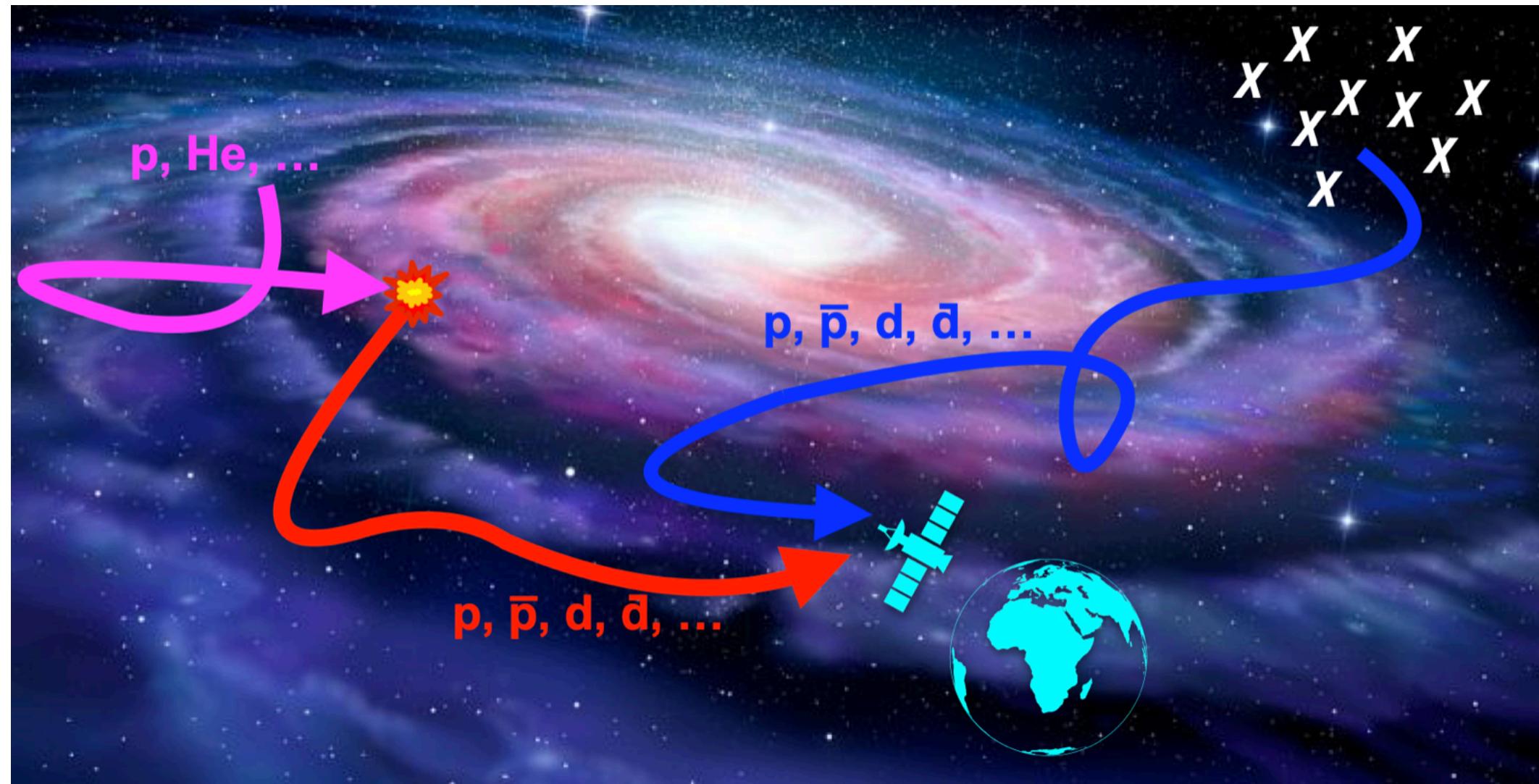
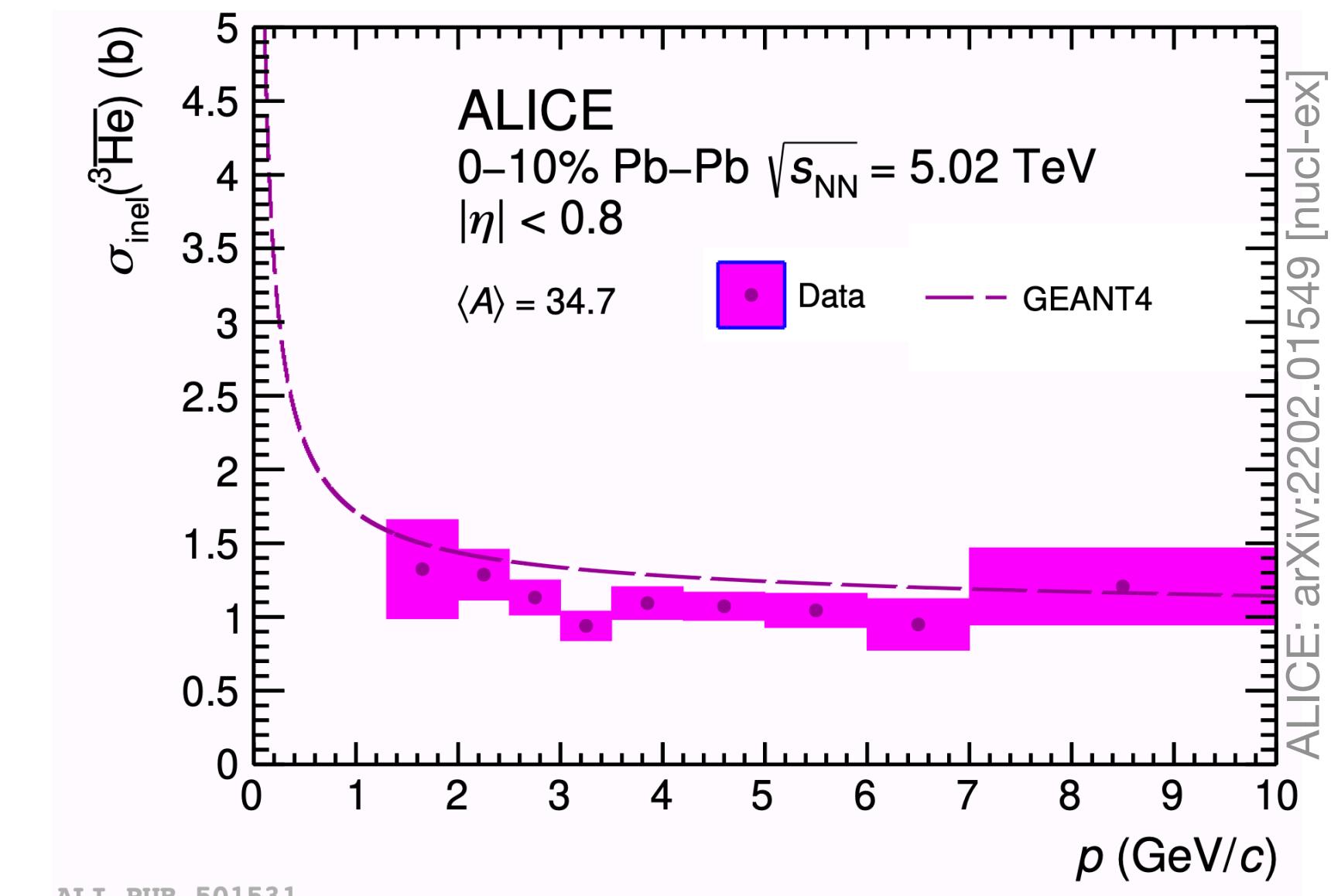
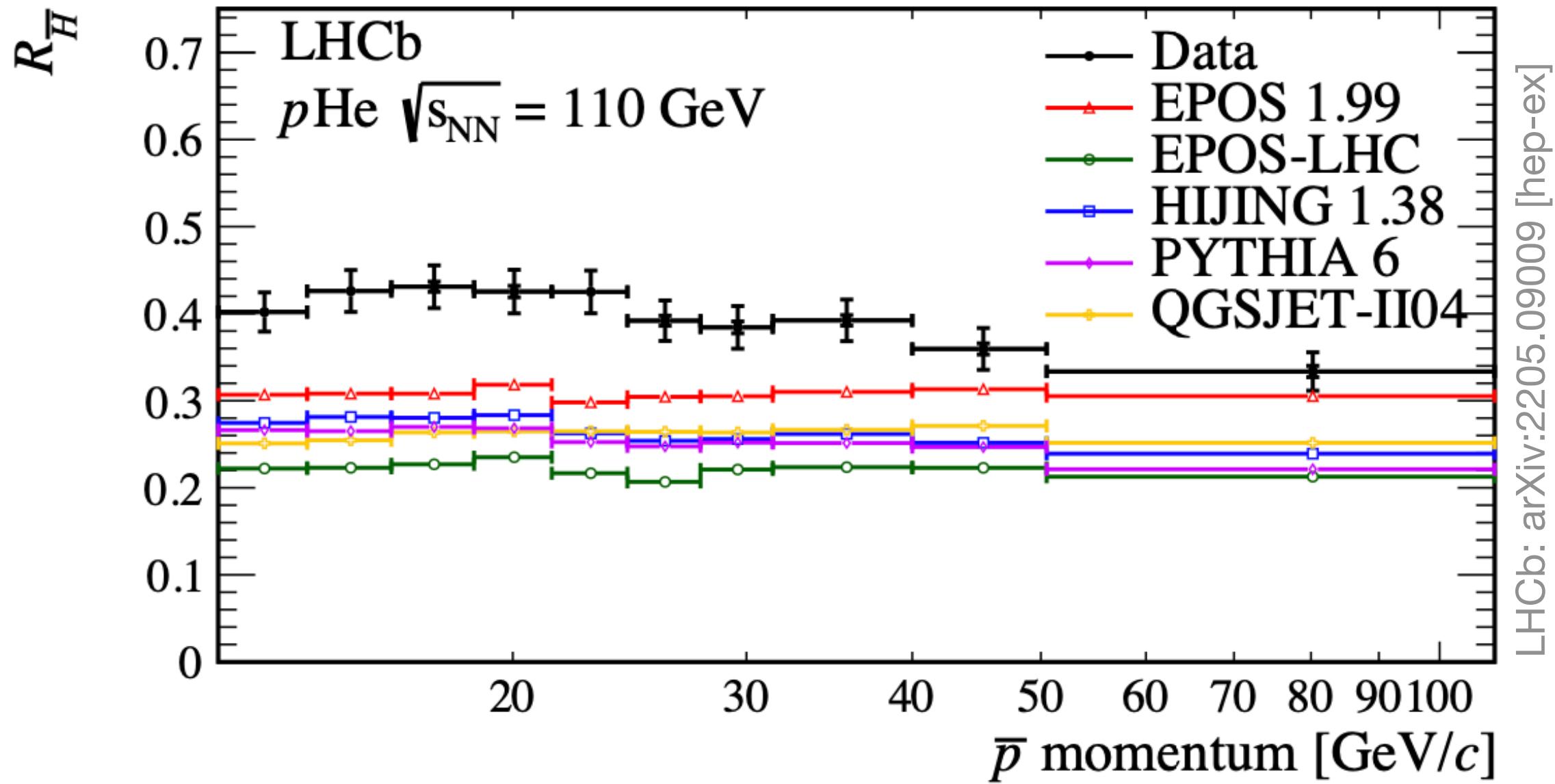


- Excess of virtual photons above η meson $\langle R_{AA}^{\text{AgAg}} \rangle \approx 3.05$ observed above the π^0 mass region
- “Disappearance” of ω mesons at low p_T^{ee}
- At high masses, v_2 consistent with 0 → dileptons are penetrating probes of the hot and dense medium

Impact beyond Heavy-Ion Physics

- Input for searches for dark matter signals; understand antinuclei production and tune event generators ...
- LHCb fixed target measurements
- ALICE detector as absorber to study the antinuclei inelastic cross section

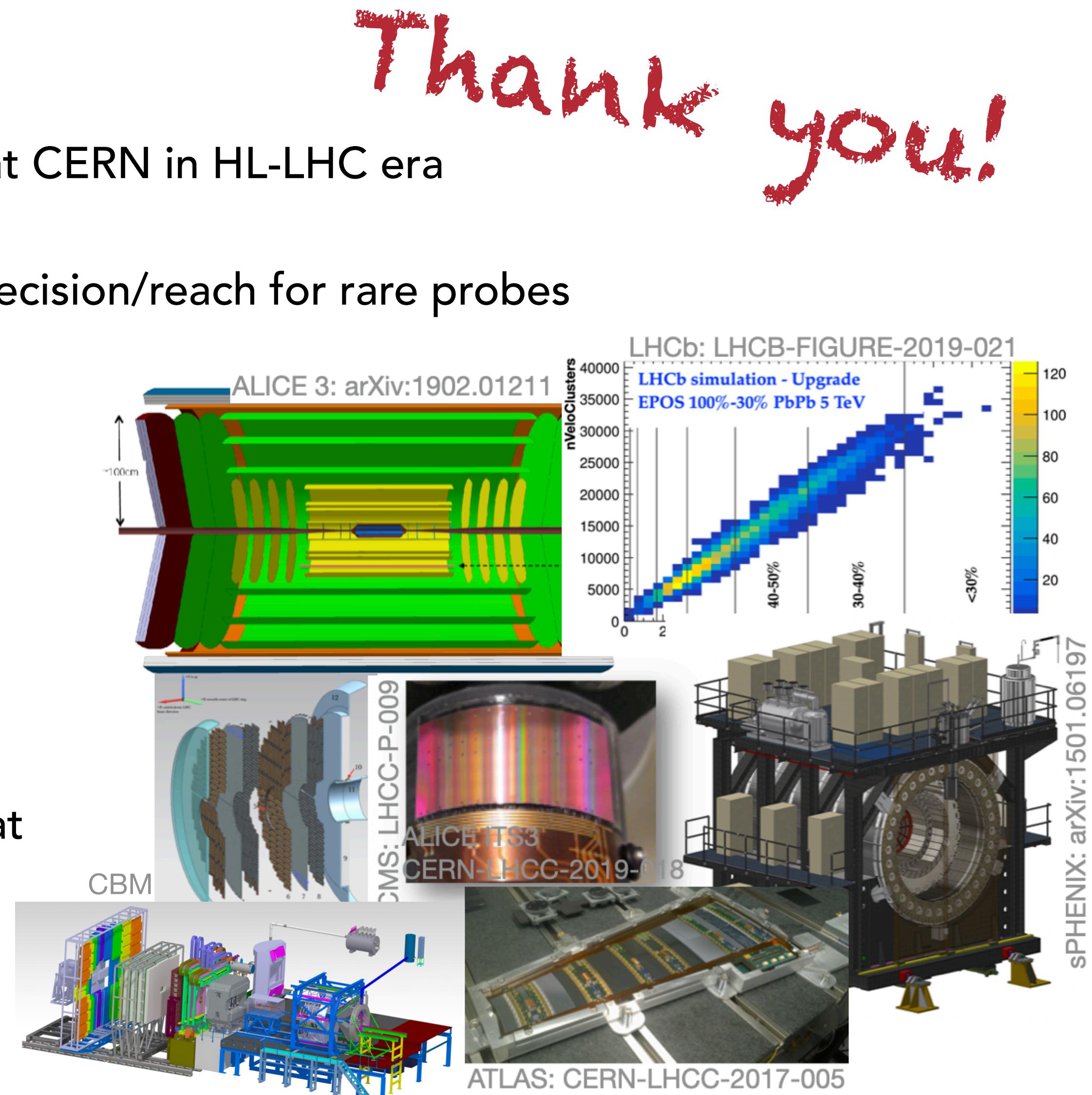
Inclusive $\bar{H} = \bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}, \bar{\Omega}, \dots$



Future of Heavy-Ion Physics

- Wealth of beautiful new results from heavy-ion experiments
- European strategy → encouraging the heavy-ion programme at CERN in HL-LHC era
- New era for ultra-relativistic heavy-ion physics → improving precision/reach for rare probes
 - LHC Run 3 and 4
 - LHC upgrades (ALICE, ATLAS, CMS, LHCb)
 - Collider and fixed-target program at CERN
 - sPHENIX and STAR at RHIC (incl. Beam Energy Scan, fixed target)
- LHC Run 5 and beyond
 - A next-generation LHC heavy-ion experiment: ALICE 3
 - LHCb Upgrade II
- High net-baryon number density frontier - facilities coming up at lower center-of-mass energies: NICA, FAIR, ...
- Electron-ion collisions at the EIC
 - nPDF, diffraction, saturation, ...

→ see talk by
Jochen Klein



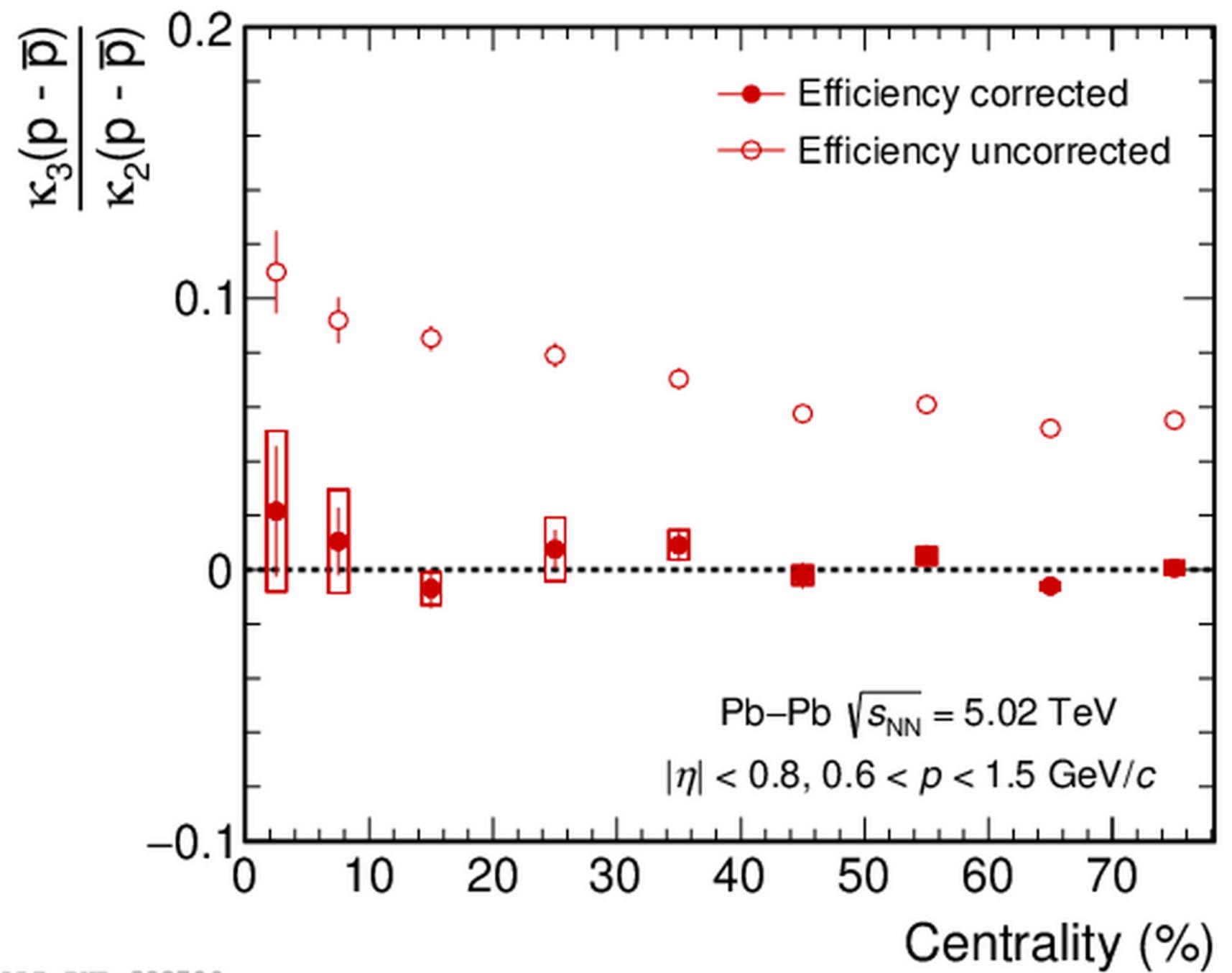
Back-Up

Event-by-Event Fluctuations

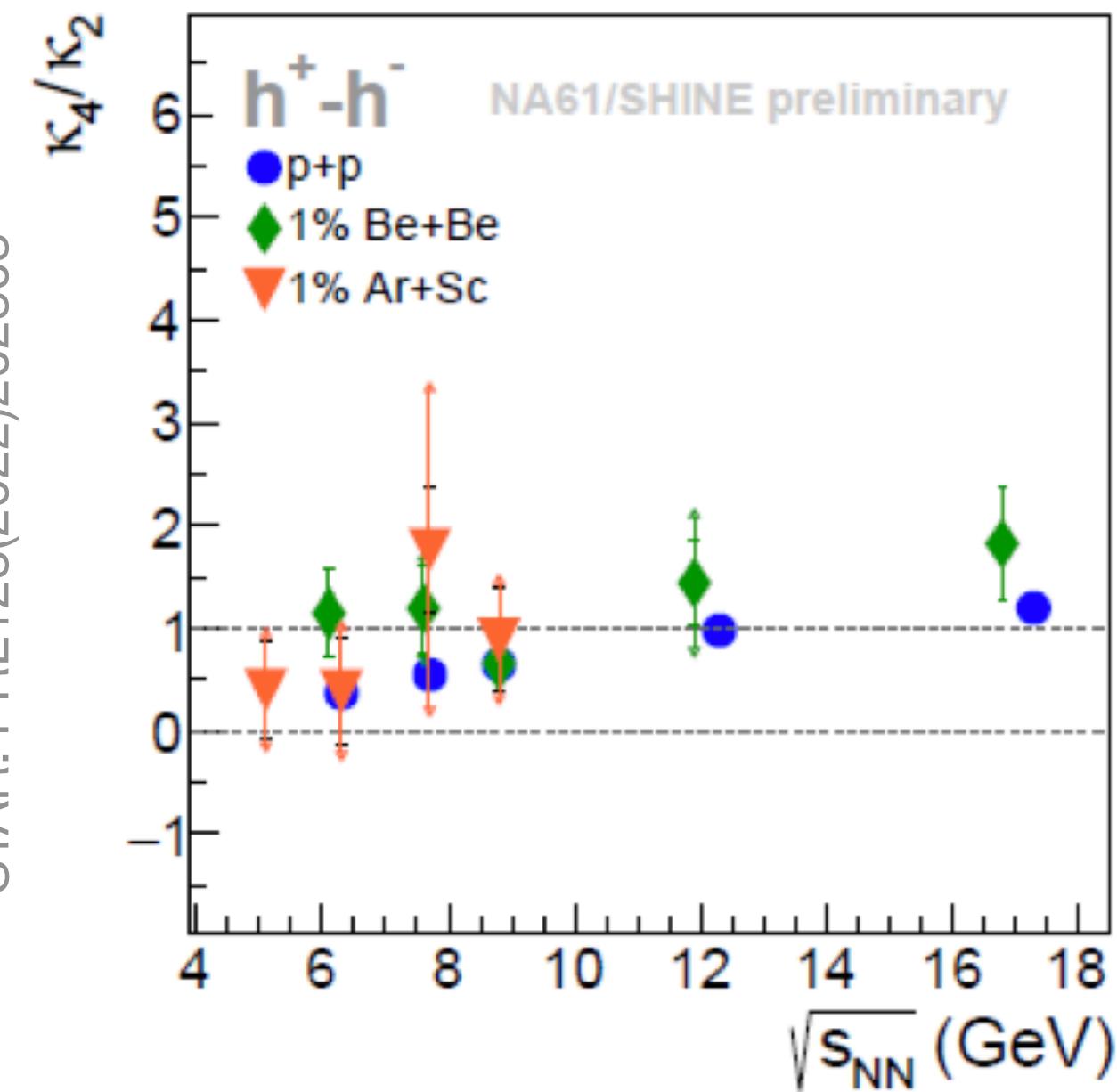
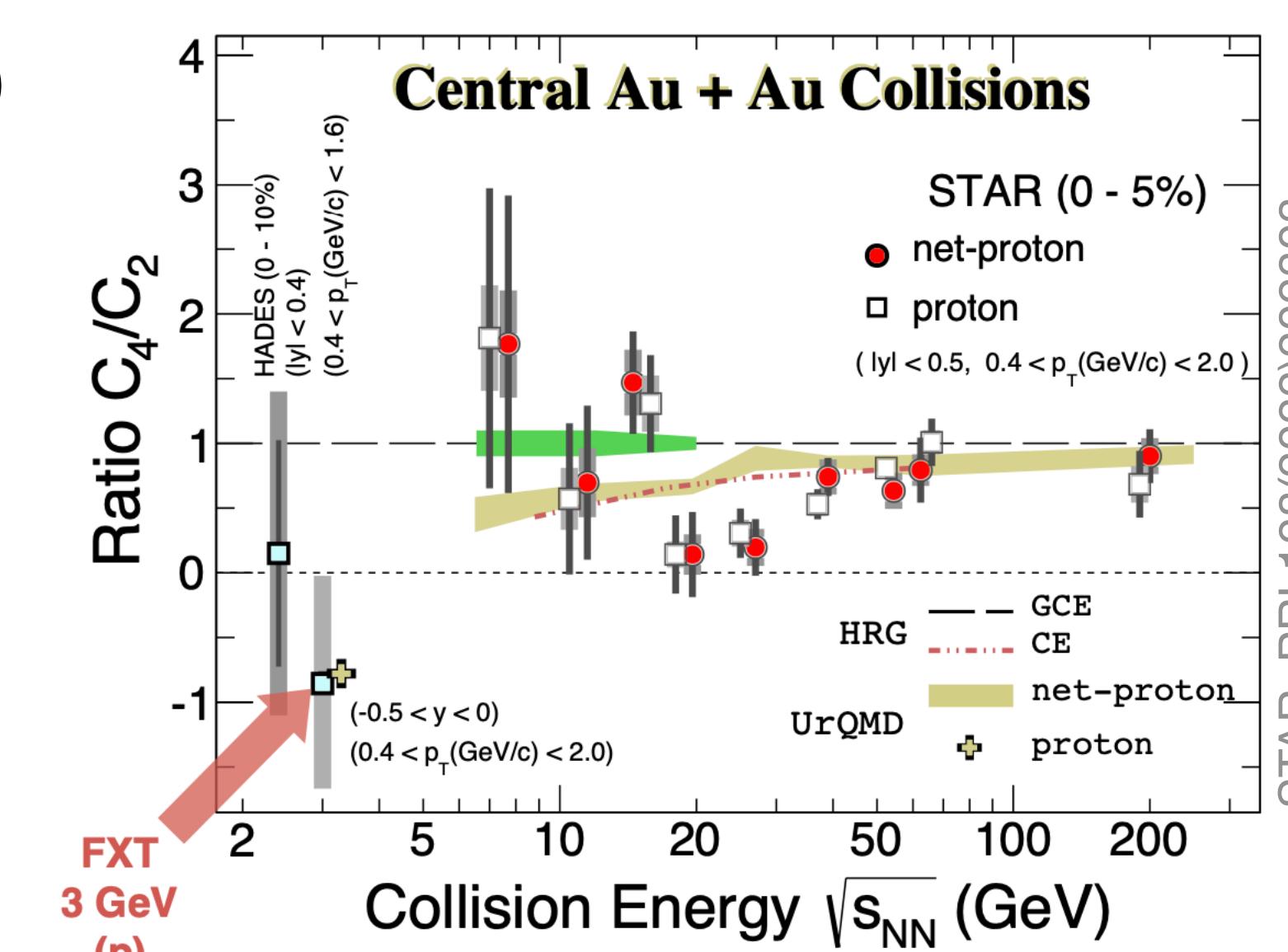
Net-Proton Number

- Grand canonical description: susceptibilities ($\hat{\chi}_n^B$) from IQCD correspond to cumulants (κ_n):

$$\frac{\kappa_n(N_B - N_{\bar{B}})}{VT^3} = \frac{1}{VT^3} \frac{\partial^n \ln Z(V, T, \mu_b)}{\partial(\mu_b/T)^n} \equiv \hat{\chi}_n^B$$



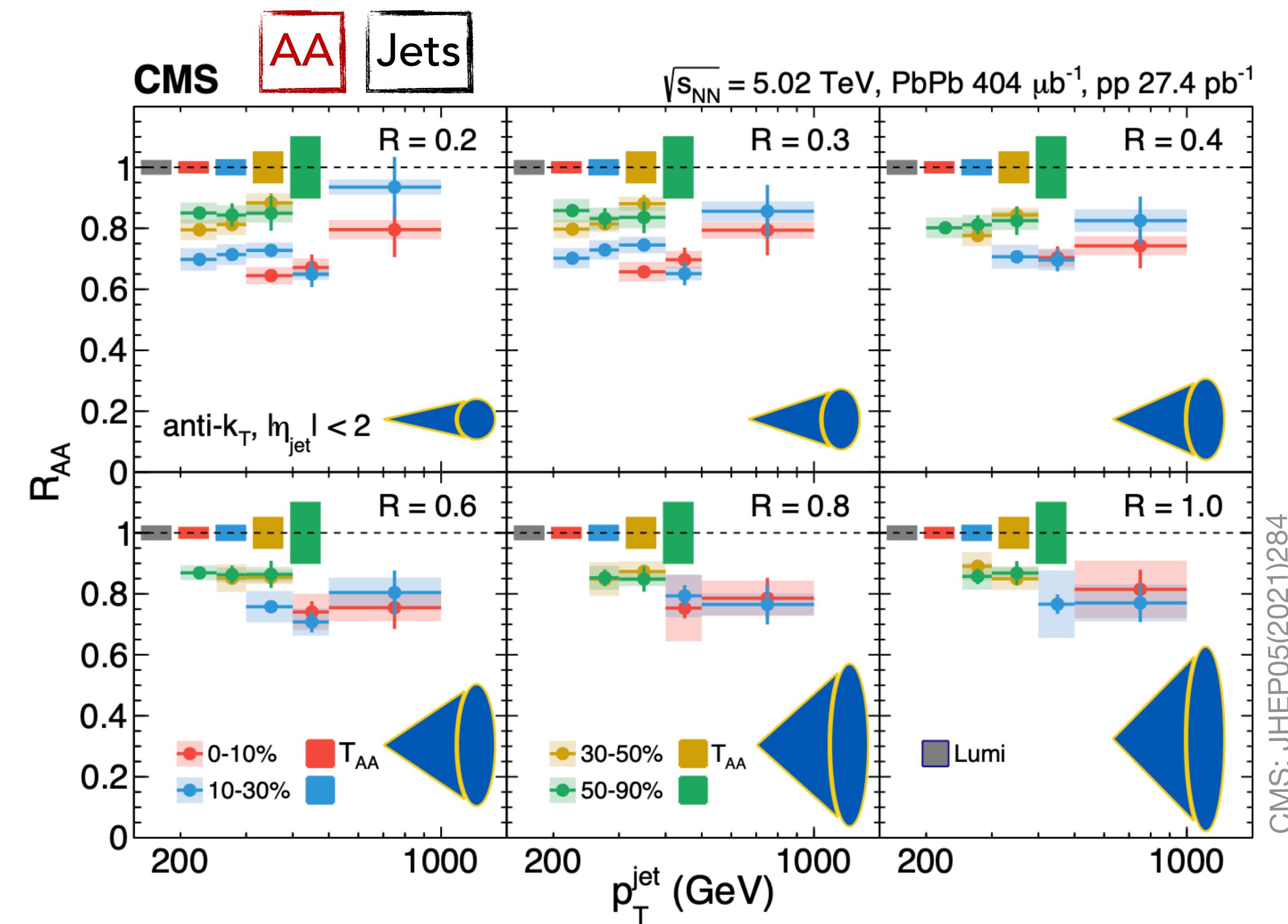
ALI-PUB-523790



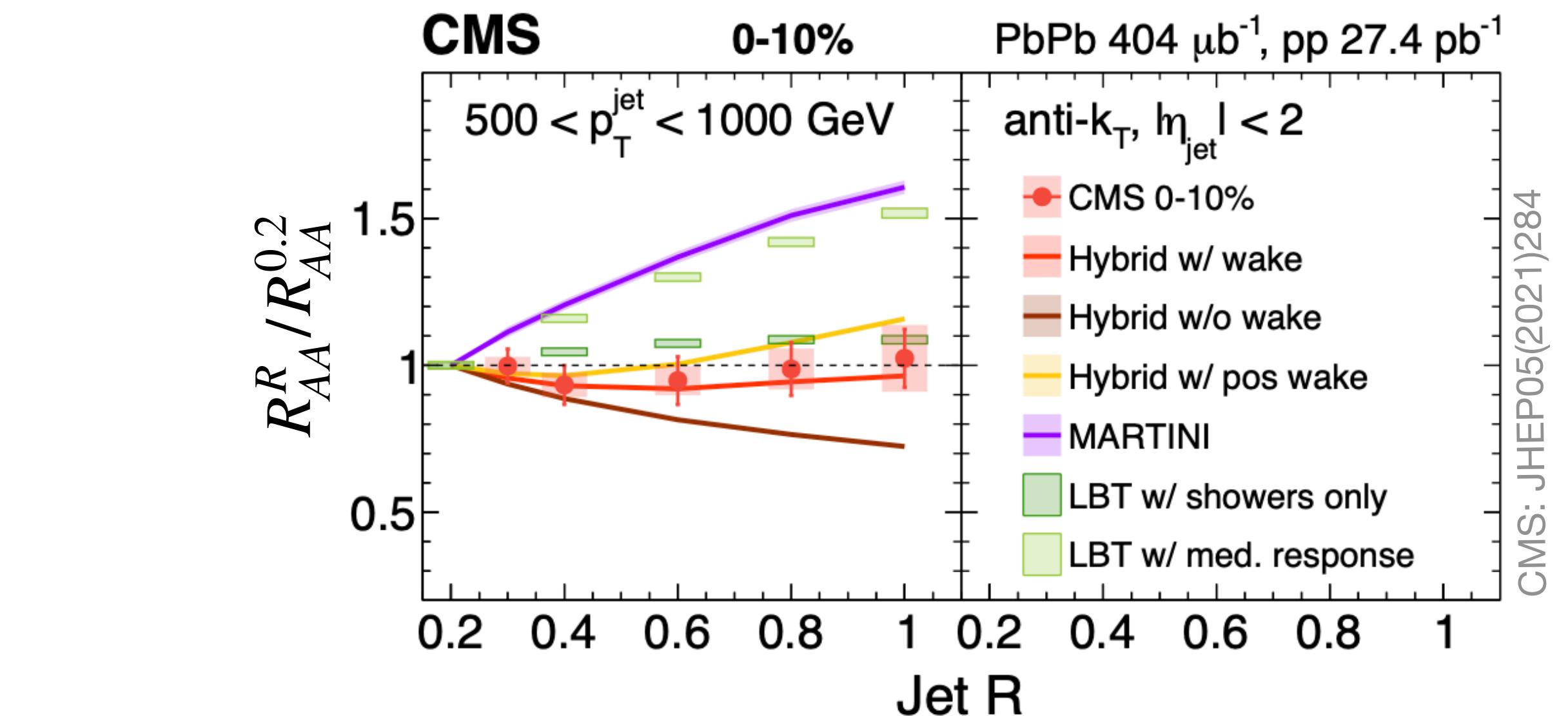
- μ_B very close to 0 at LHC energies
 - No evidence for critical behaviour
 - Larger data samples + better understanding of biases needed

Jets

Differential Studies



- Recover lost energy? → study larger radius R
- Only modest increase, R_{AA} never reaches unity



- Competing effects: lost energy recovered, but larger R more sensitive to energy loss

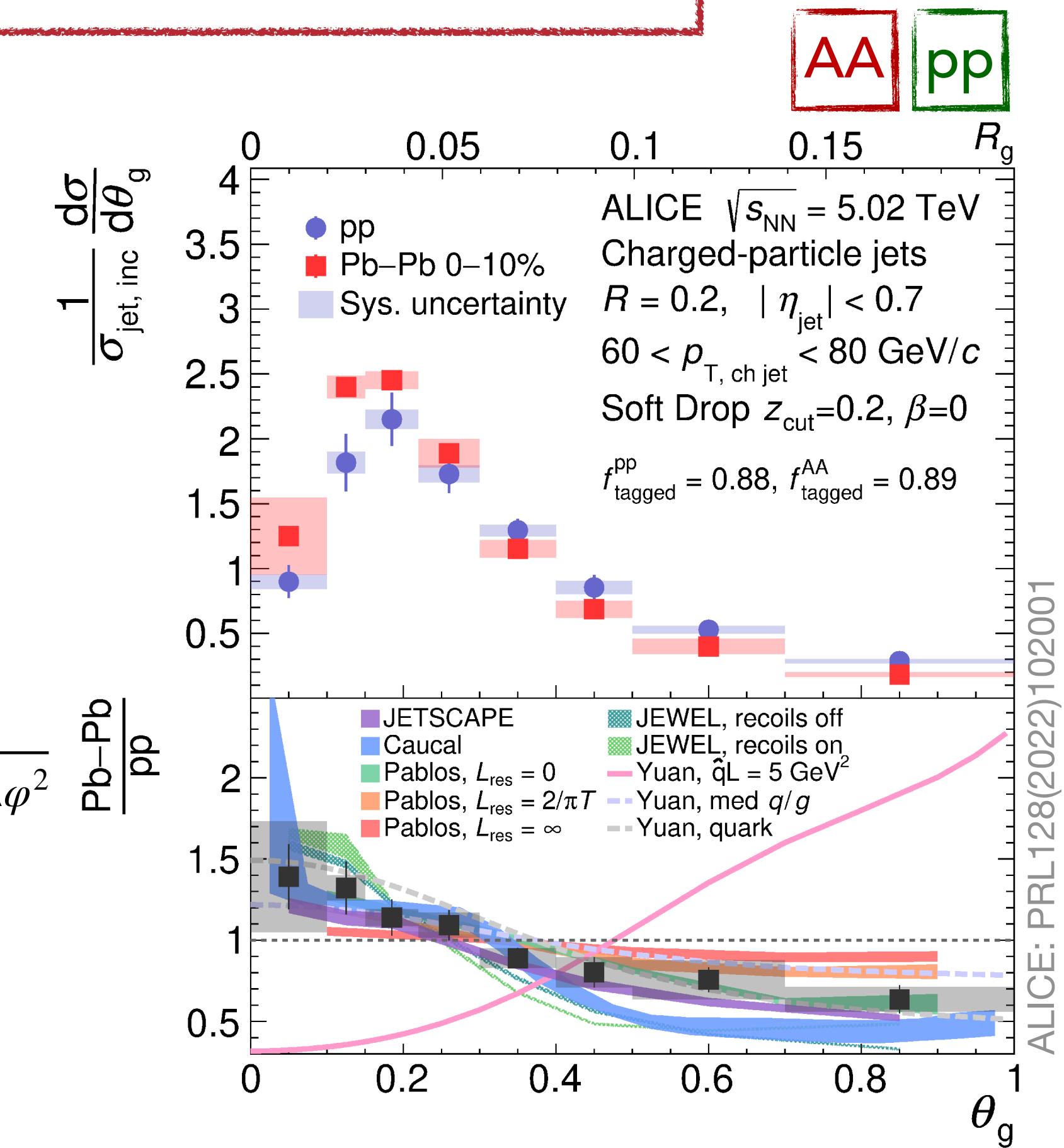
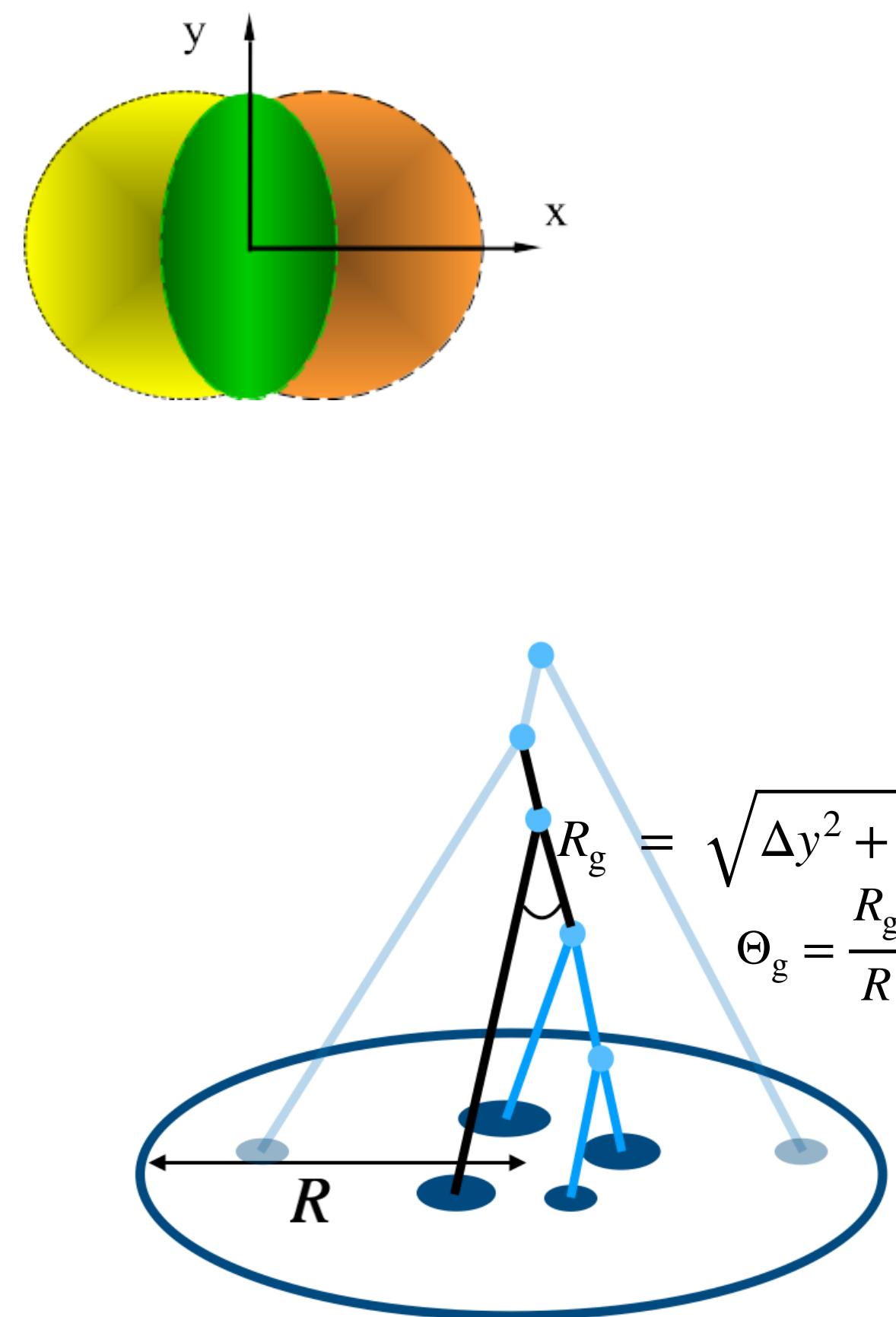
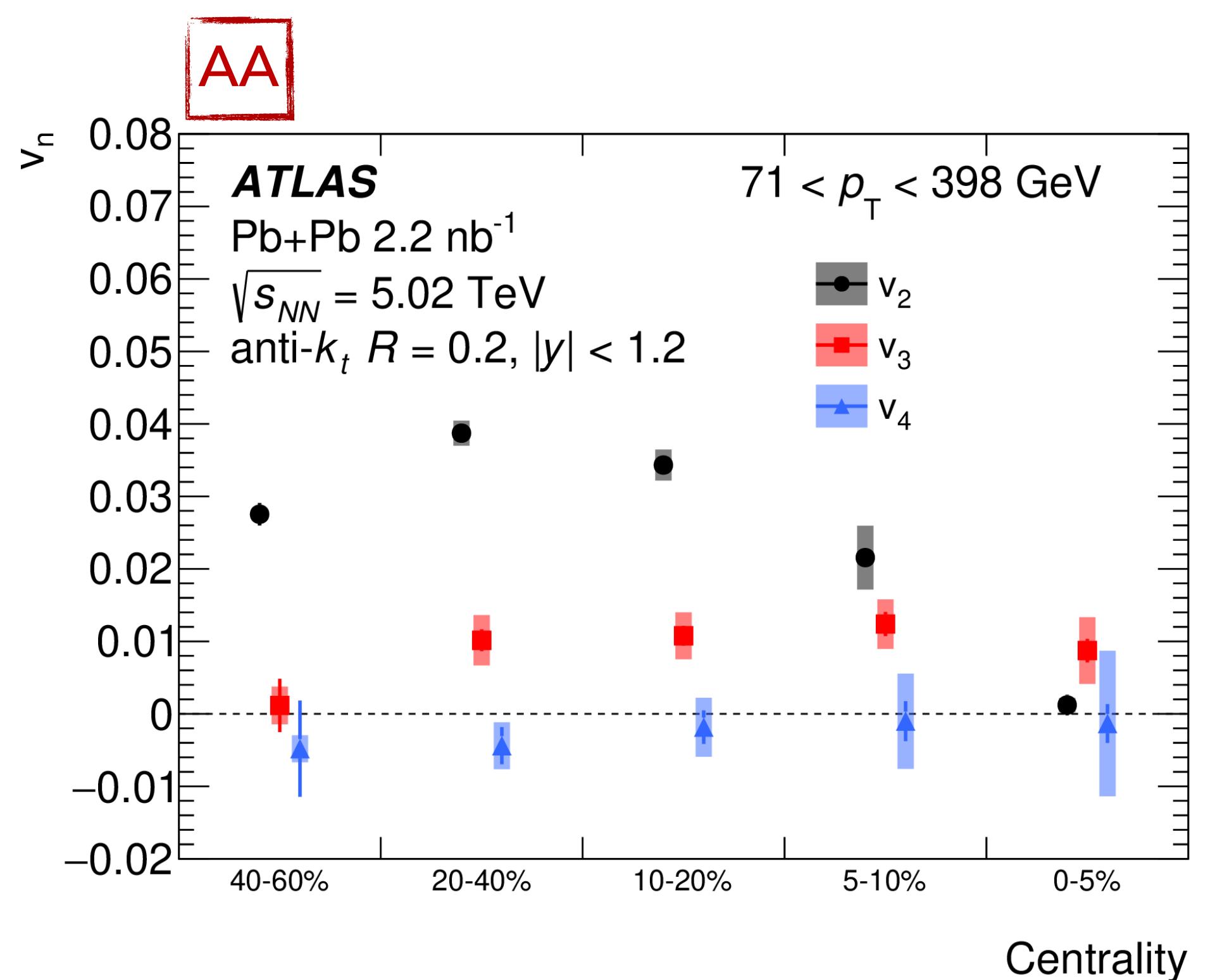
→ Significant constraints on models of jet quenching, medium response, large angle radiation

Jets

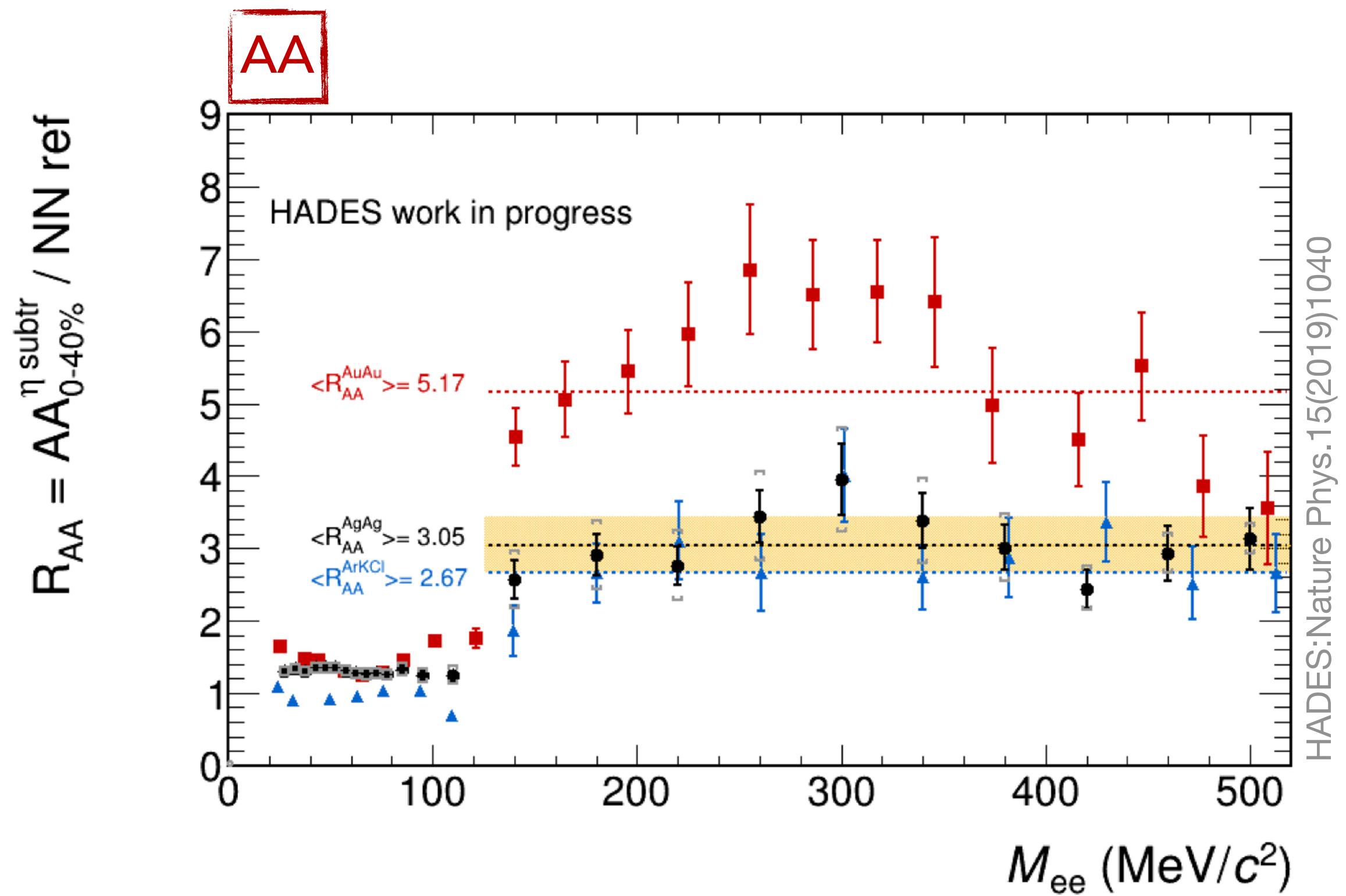
Differential Studies

→ Energy loss depends on path length
 → v_3, v_4 set limits on initial-state fluctuations

→ Jet substructure
 modified by hot medium



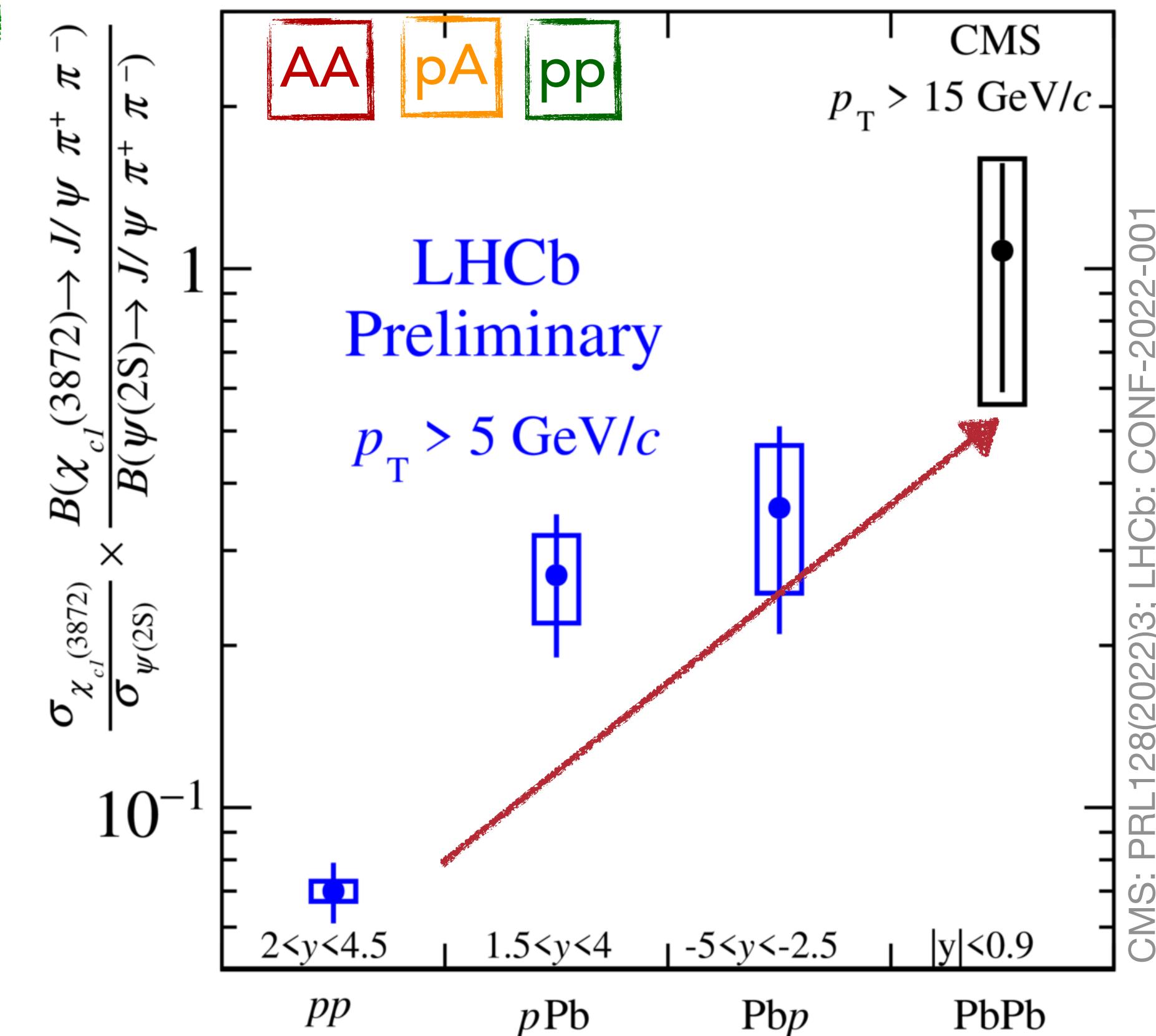
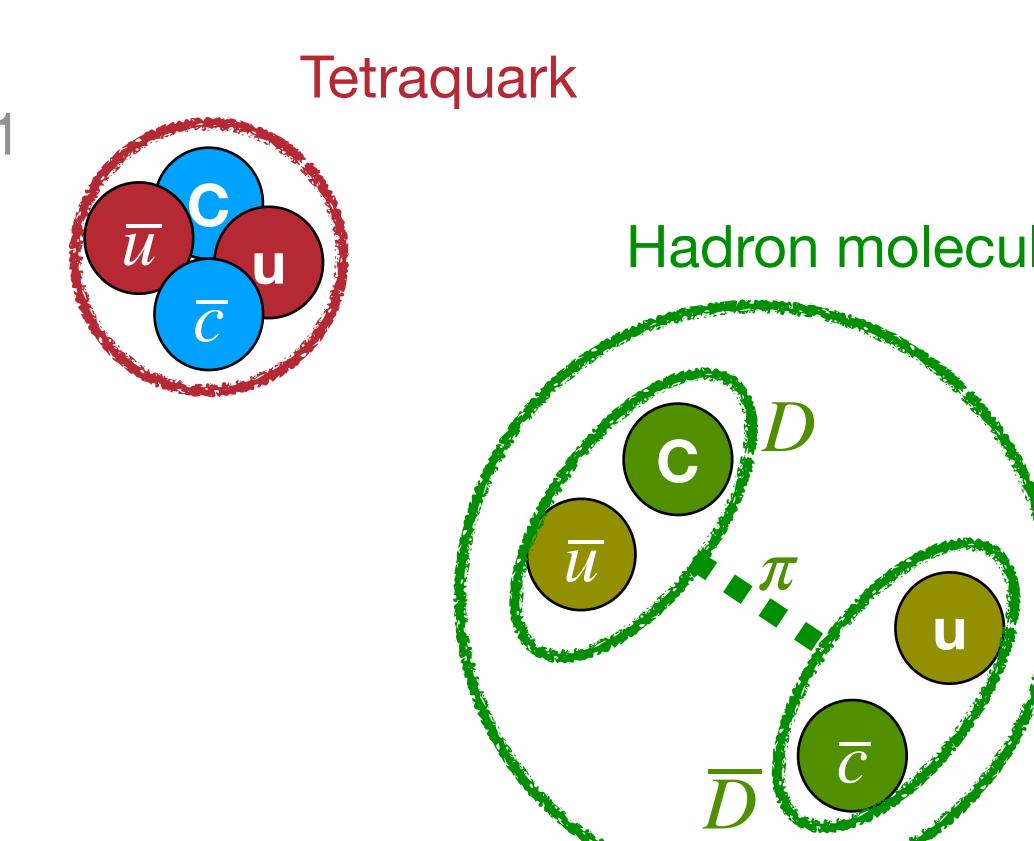
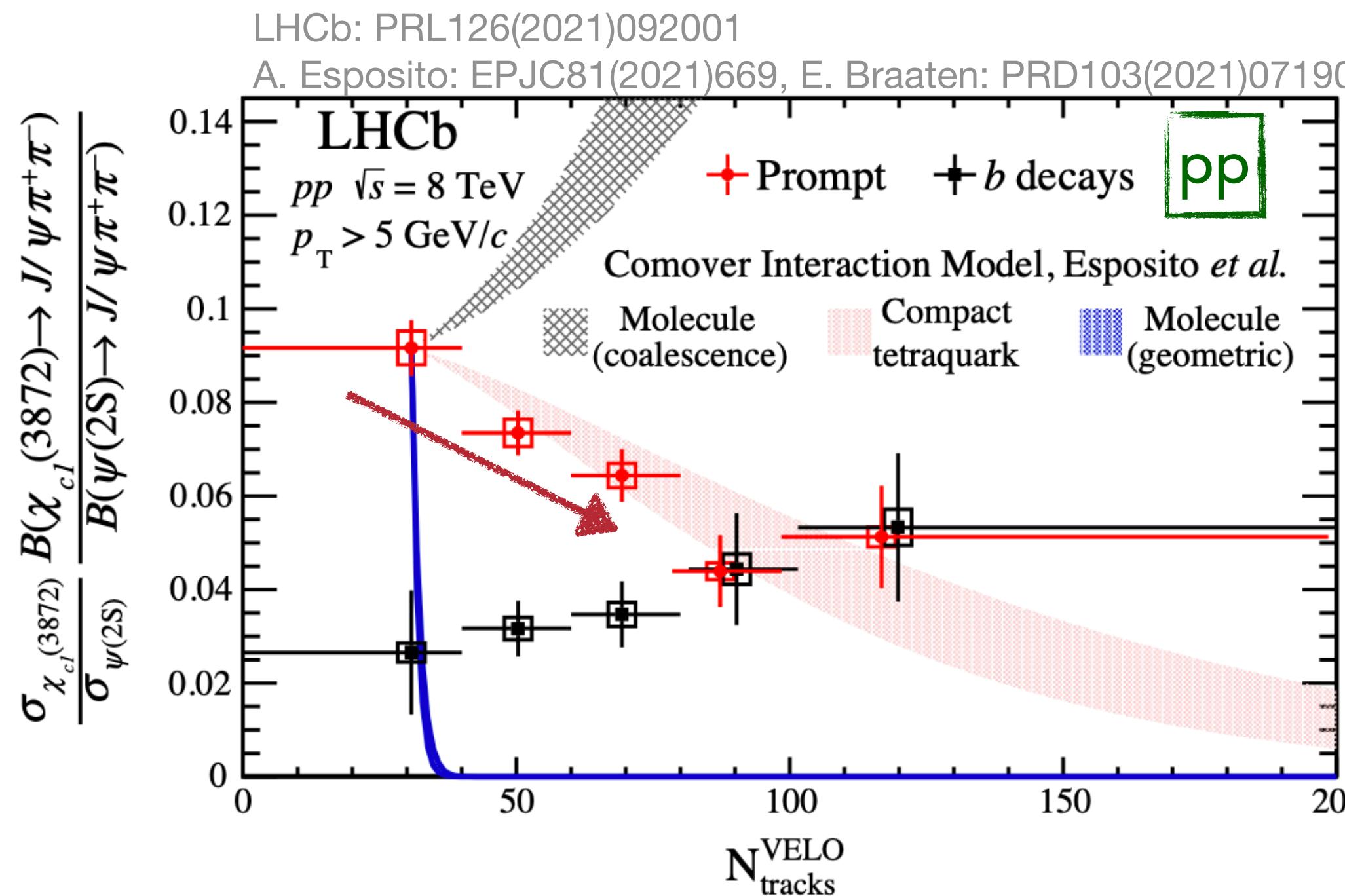
Dielectron excess ratio



System	$\langle N_{\text{part}} \rangle$
ArKCl	38.5
AgAg	102
AuAu	173

Rare Probes

X(3872)



- pp collisions: ratio of prompt X(3872)/ψ(2S)
decreases with number of tracks in detector
- What is it's nature? → HI collisions could help
- Pb-Pb collisions: (re)generation of X(3872) at $p_T > 15 \text{ GeV}$?
- Future: larger data samples → extend to lower p_T region