Experimental review of open charm in heavy-ion collisions

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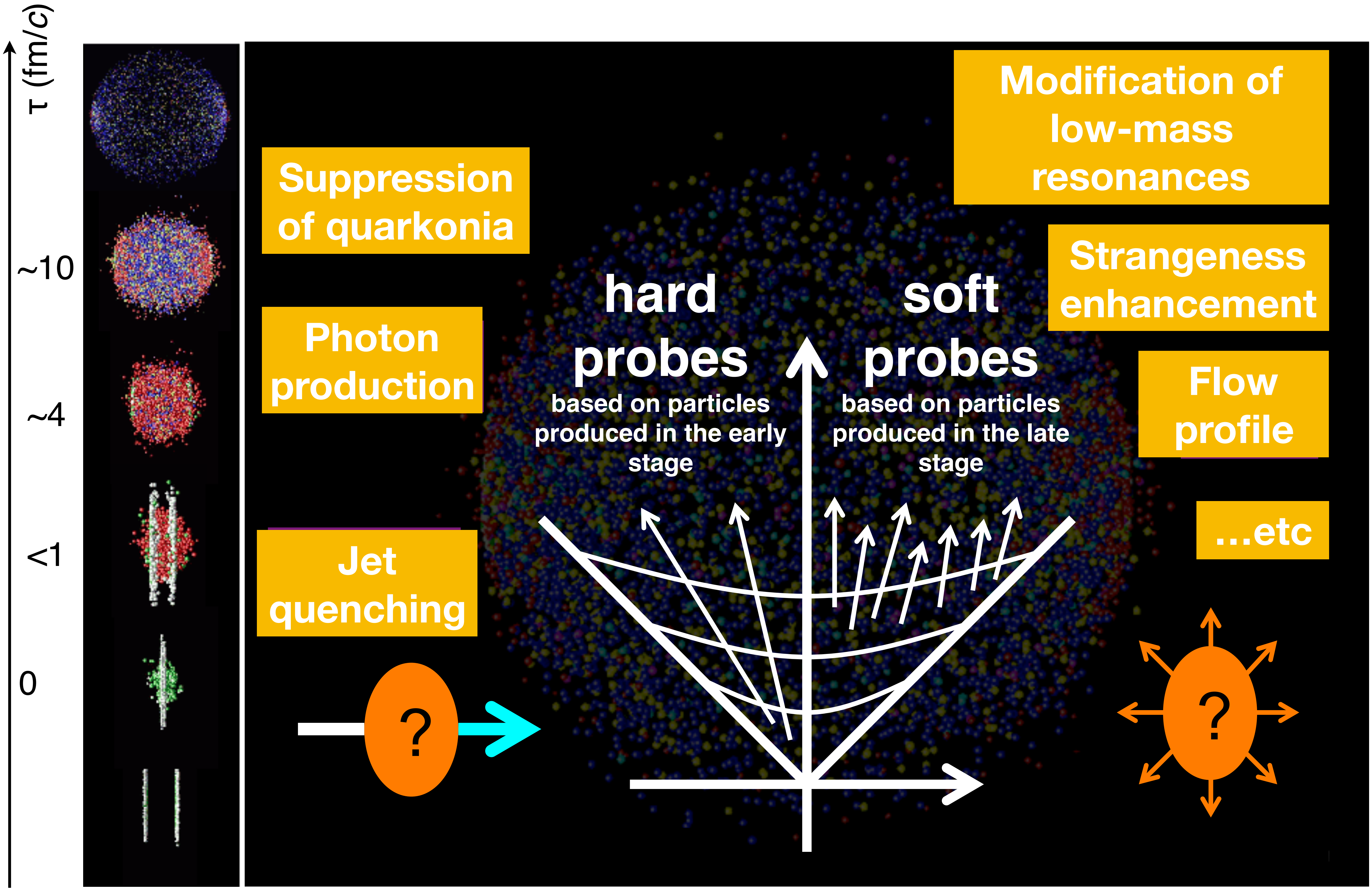
Personal biased collection

ALICE CMS ATLAS EXPERIMENT STAR PHENIX

- Introduction
- Charm energy loss
- Collectivity
- Charmed-hadron production
- Charmed jets
- Conclusion and outlook

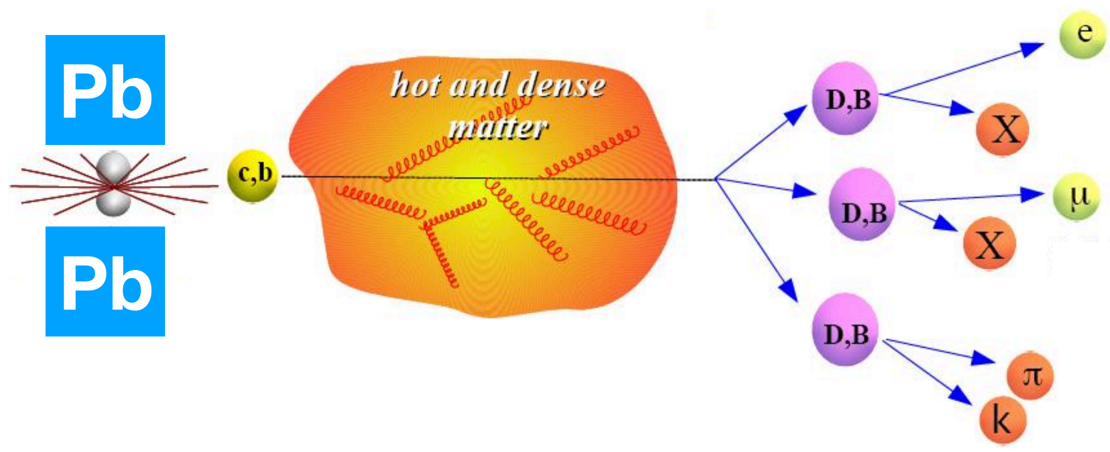
9th International Workshop on Charm Physics
Budker Institute of Nuclear Physics, Novosibirsk, Russia
May 21-25, 2018.
http://charm18.inp.nsk.su/
Novosibirsk State University *THE REAL SCIENCE

Introduction



Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)



Total charm cross section in A–A collisions is expected to scale w. r. t. the number of binary collisions in pp-like collisions

S. Radhakrishnan at QM'18

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+/D^0 ratio in 10-80%** **STAR Preliminary**

- Produced in initial hard scatterings (high Q^2) at the early stage of heavy-ion collisions: $\tau_{c/b}$ ~0.01 — 0.1 fm/c < τ_{QGP} (~0.3 fm/c)
- Production cross section calculable with pQCD (m_c, m_b ≫ Λ_{QCD})
- Experience the entire evolution of the QCD medium — probe transport properties of the deconfined medium

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)

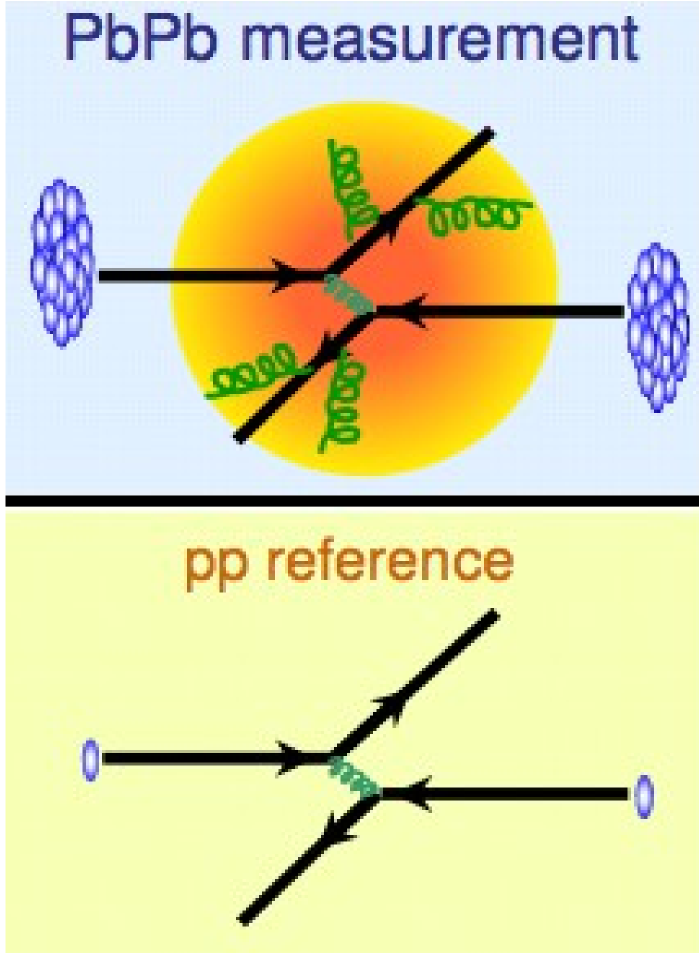
Nuclear modification factor (R_{AA}): heavy quark in-medium energy loss

- Elastic (radiative) vs. inelastic (collisional) processes
- Color charge (Casimir factor) and mass (eg dead-cone effect) dependence

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

QCD medium

QCD vacuum



$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

➡ R_{AA}(light hadron) < R_{AA}(D) < R_{AA}(B) ?

Medium modification of heavy-flavour hadron production

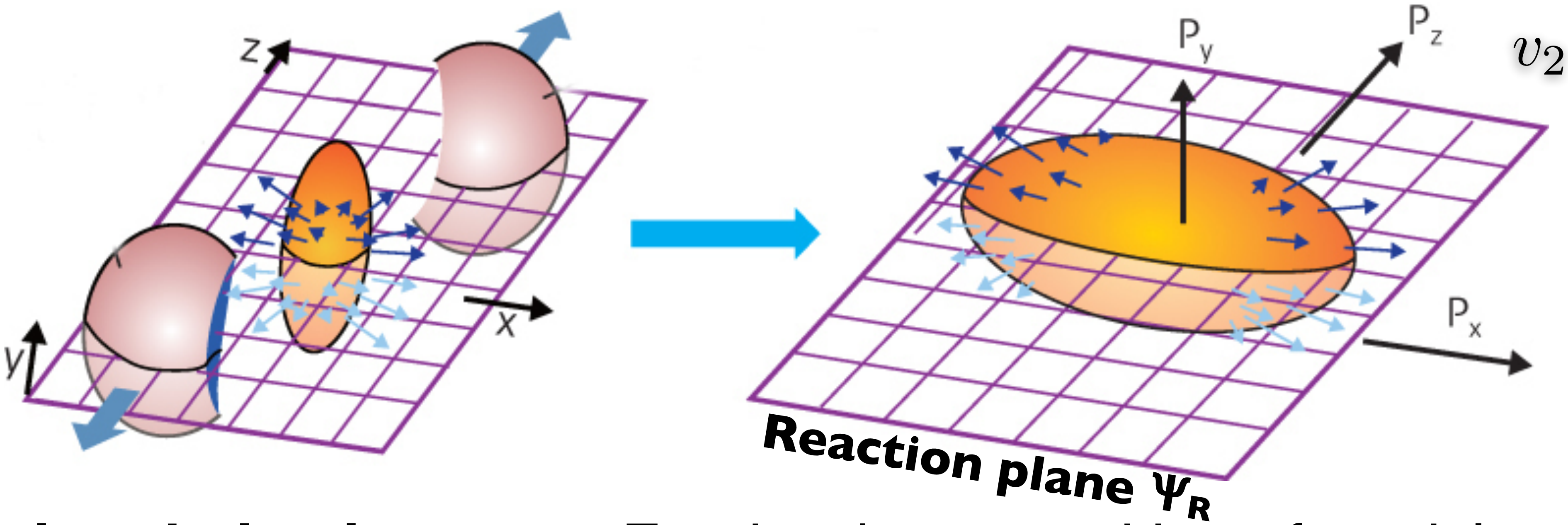
- Hadronization via quark coalescence may modify the D_s^+ / non-strange D and Λ_c / D ratios

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)

$$E\frac{\mathrm{d}^3\sigma}{\mathrm{d}^3\vec{p}} = \frac{\mathrm{d}^2\sigma}{2\pi p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}[1+\sum_{n=1}^{\infty}2v_n\cos n(\varphi-\Psi_\mathrm{R})]$$

$$v_2 = <\cos 2(\varphi-\Psi_\mathrm{R})>$$



Azimuthal anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP})

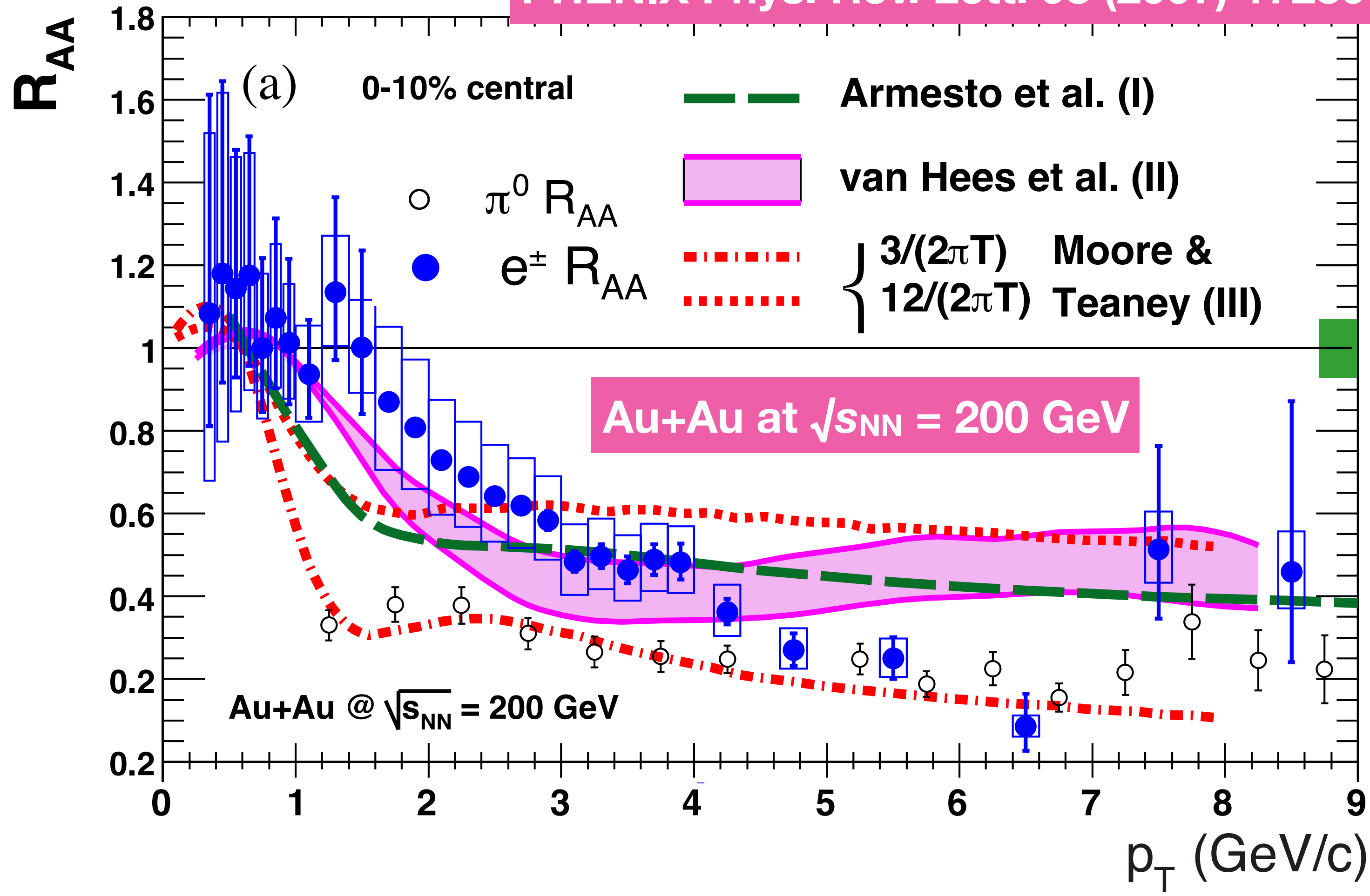
- Elliptic flow (v_2): second order Fourier coefficient

➡ Low and intermediate p_T: collective motion and possible heavy-quark thermalization in the QCD medium

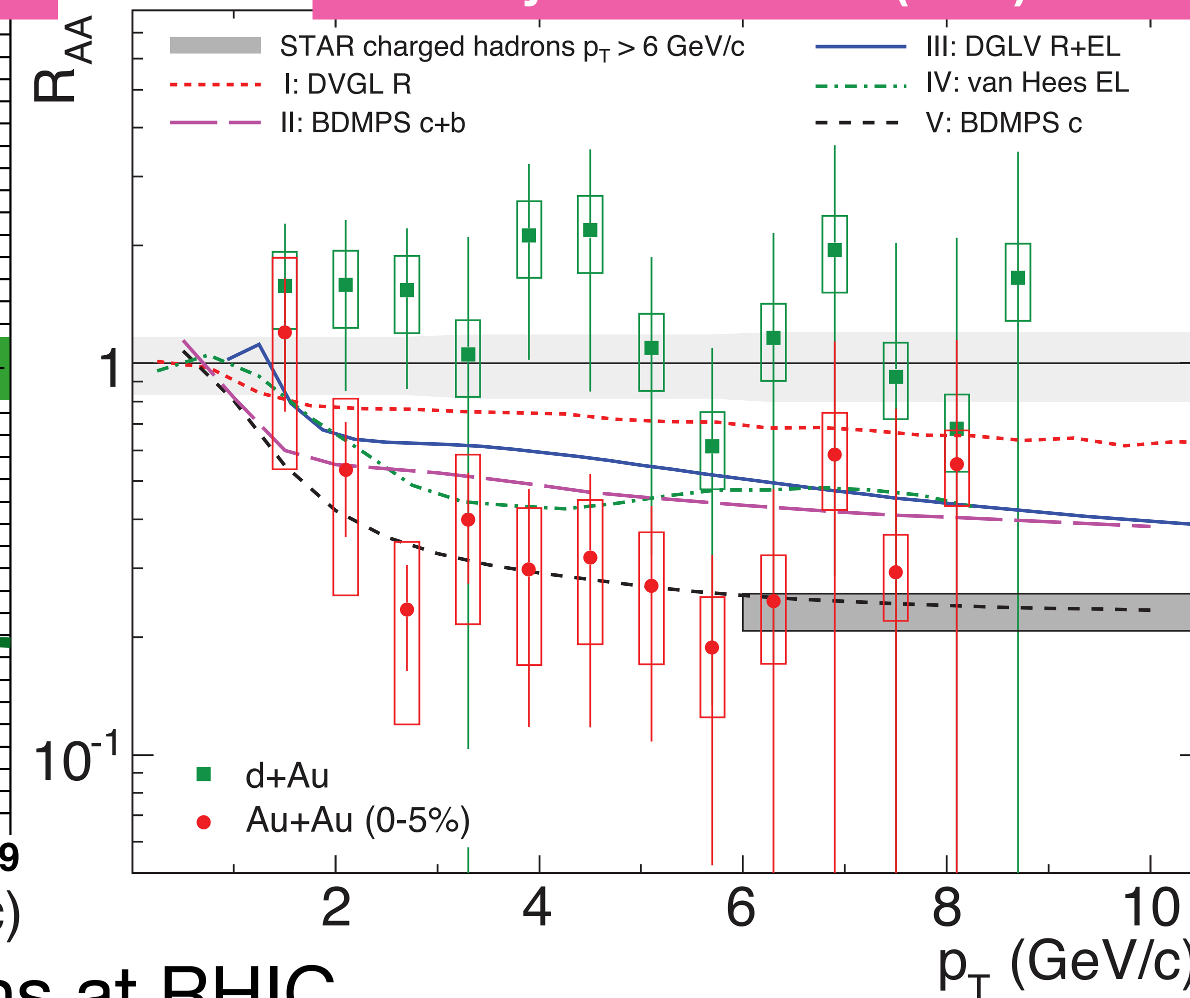
➡ High p_T: path-length dependence of heavy-quark in-medium energy loss

Charm energy loss in the QCD medium

PHENIX Phys. Rev. Lett. 98 (2007) 172301



STAR Phys. Rev. Lett. 98 (2007) 192301



- R_{AA} of open heavy-flavour decay electrons at RHIC
  - ➡ R_{AA}(e←HF) ≈ R_{AA}(light hadrons) at high p_T

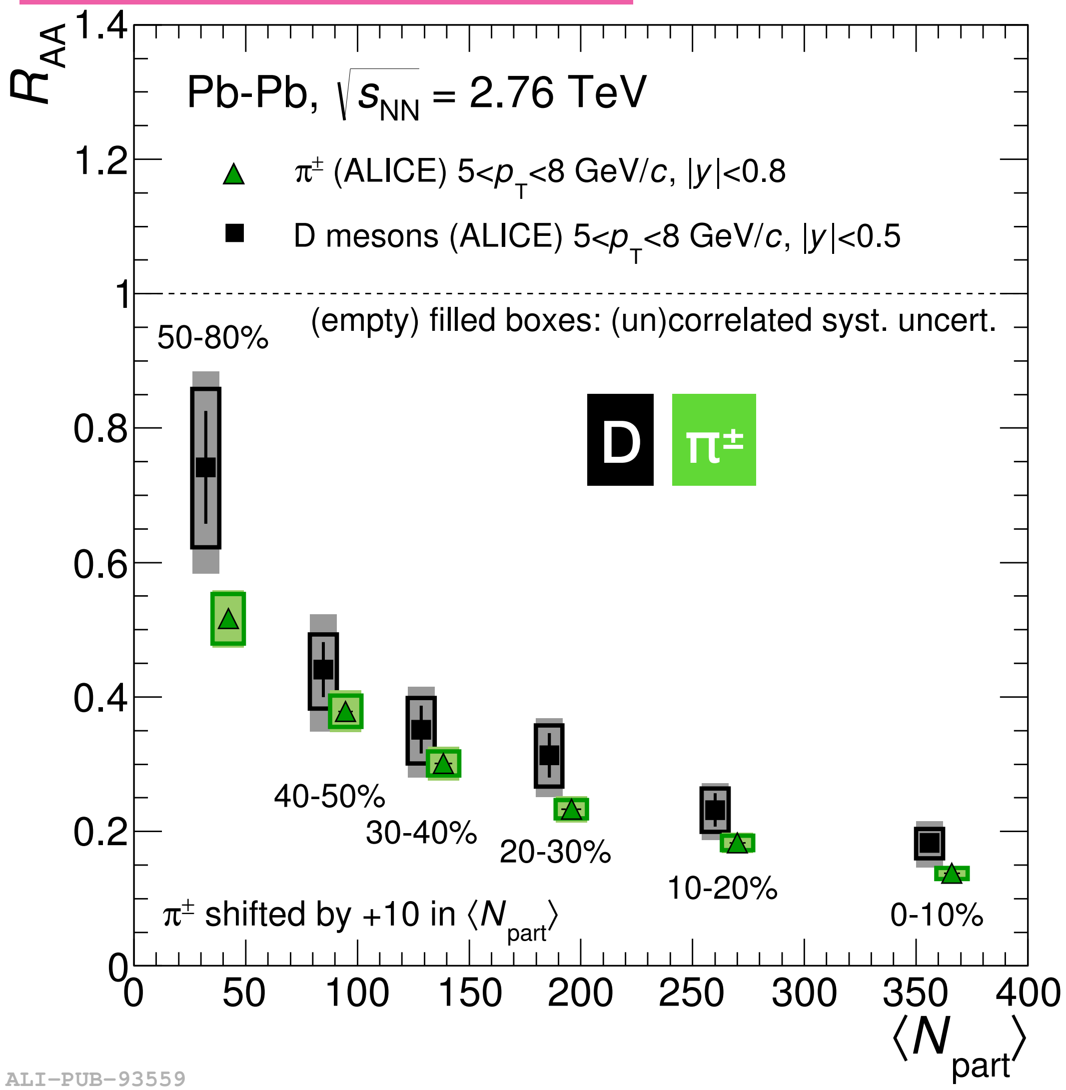
Observed > 10 years ago

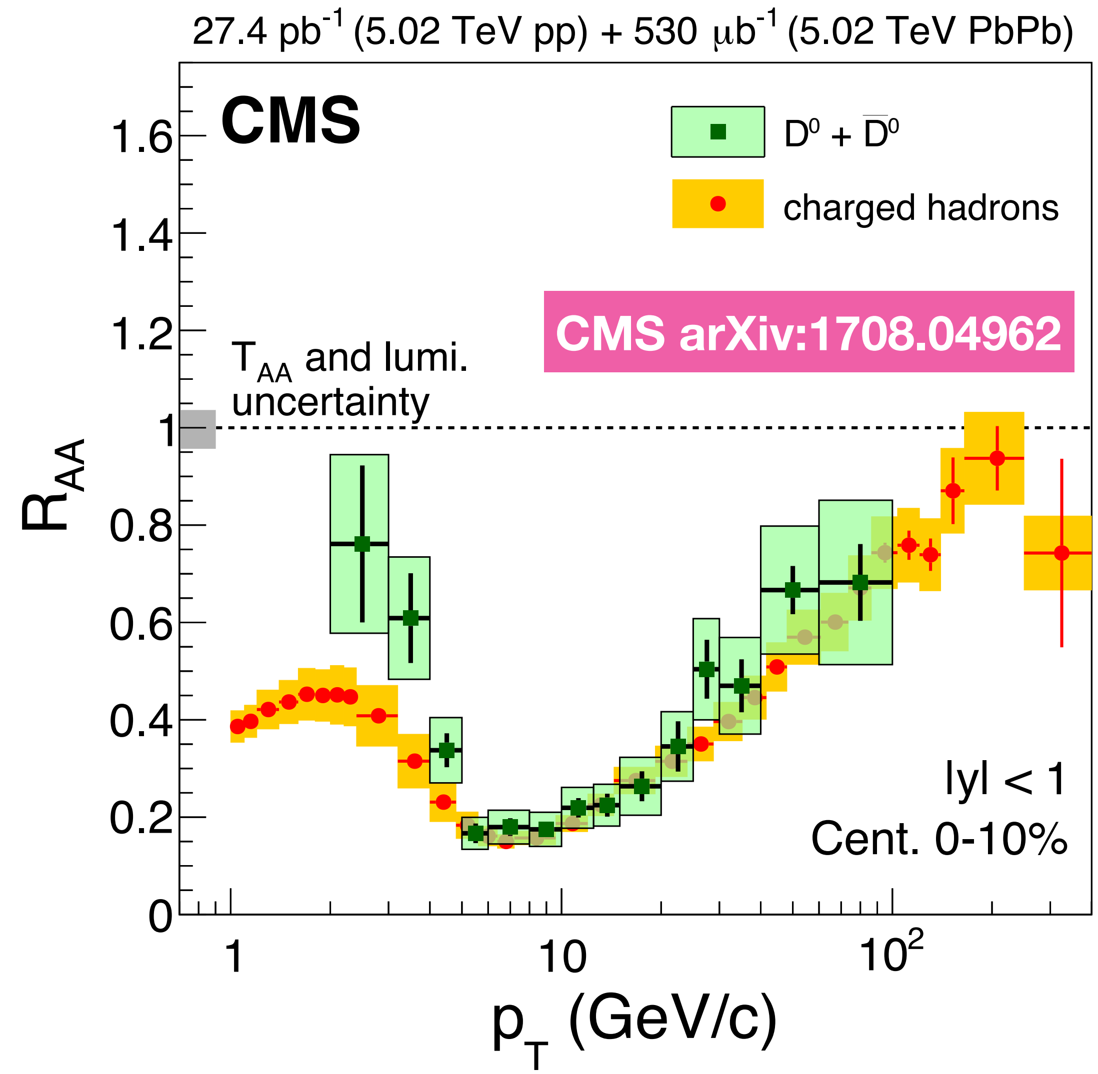
- Color-charge dependent parton in medium energy loss ?
  - ➡ $\Delta E_g > \Delta E_c$? — different parton p_T distribution and fragmentation
  - ➡ Collisional energy loss is important at RHIC energies

Caveat: charm and beauty components are not separated

Charm energy loss in the QCD medium

ALICE JHEP 11 (2015) 205





- R_{AA} of D mesons at the LHC

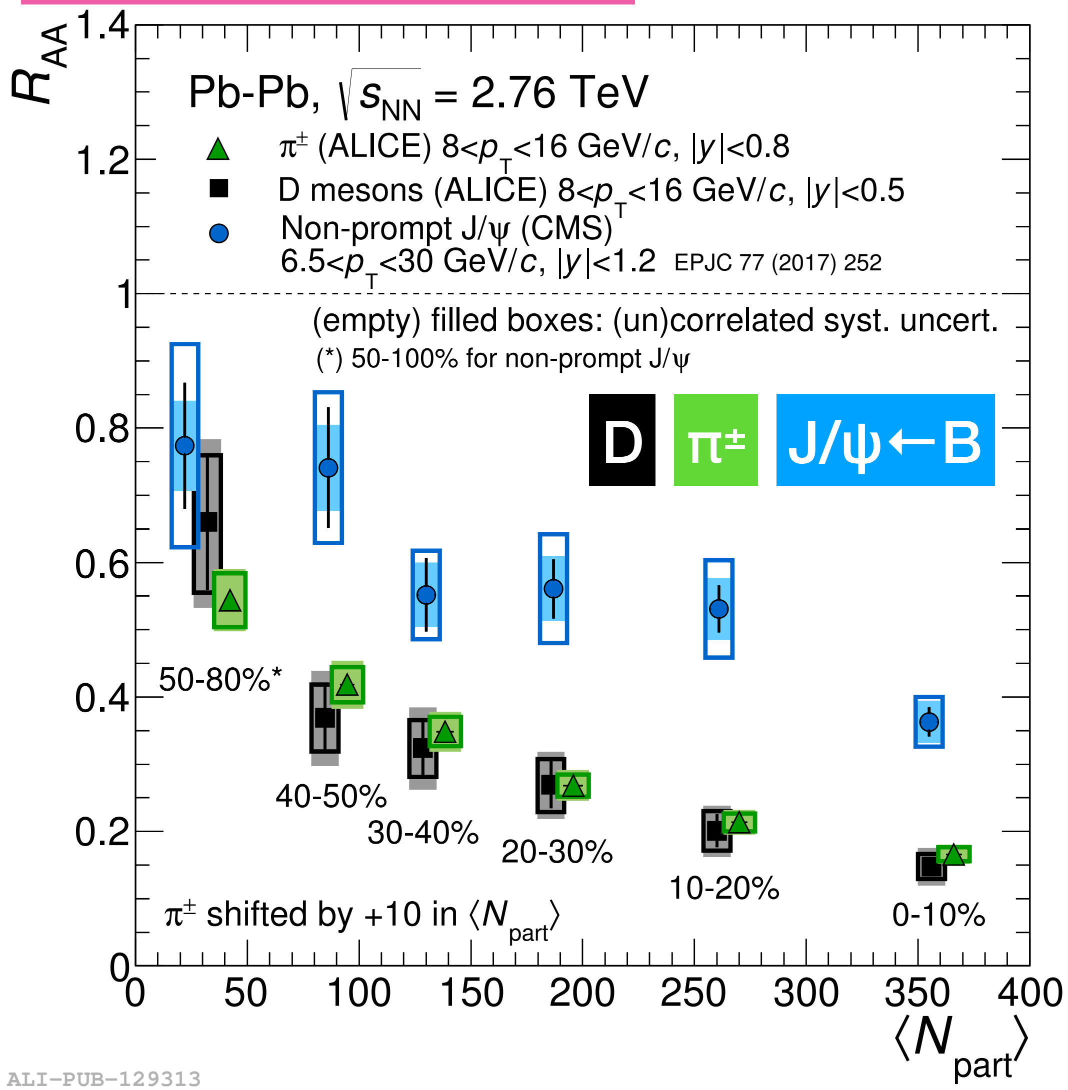
➡ Similar as charged hadrons in (semi-)central collisions for p_T > 5 GeV/c

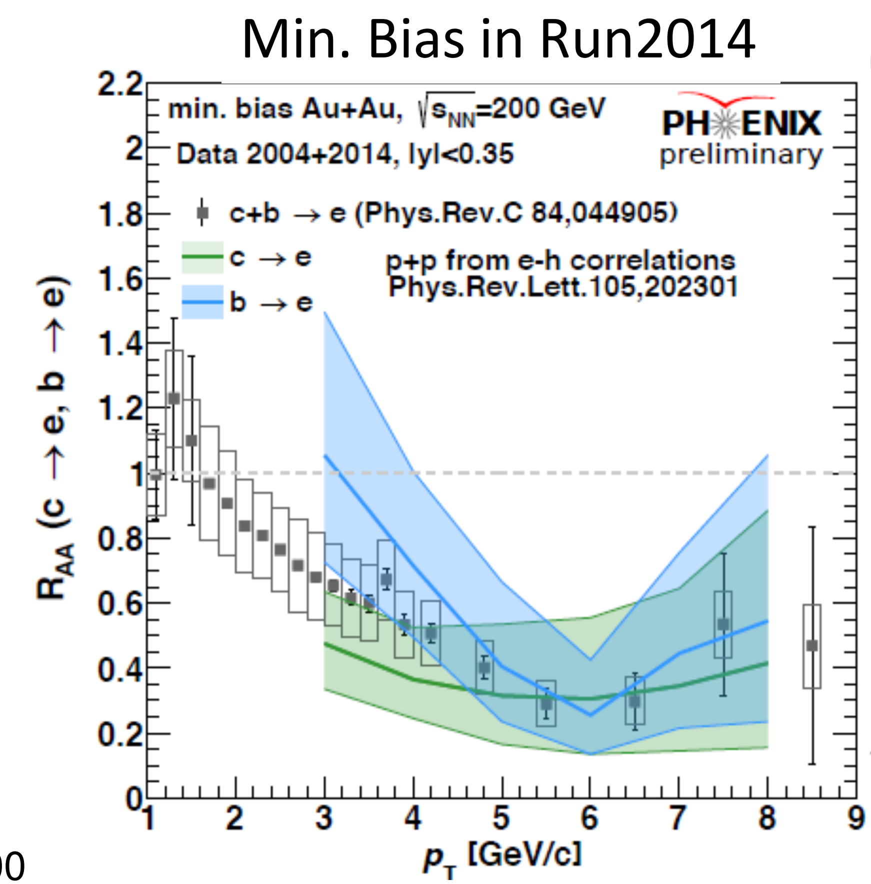
- Suppression exhibits a strong increase towards more central collisions

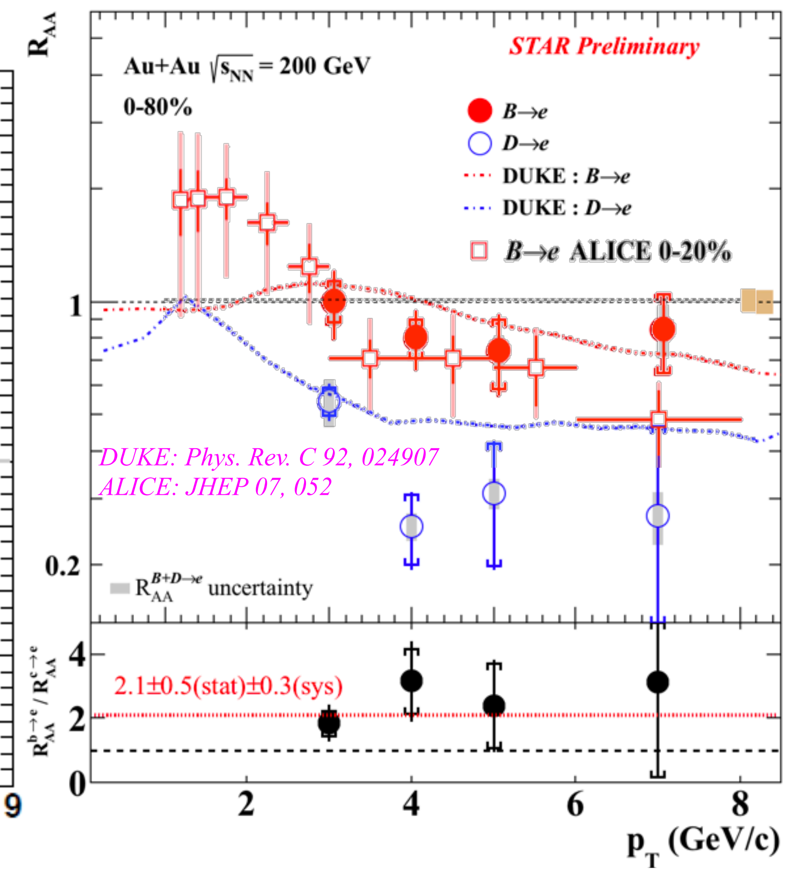
➡ Reaching a factor of ~5 in the most central collisions at p_T ~ 10 GeV/c

Charm energy loss in the QCD medium

ALICE JHEP 11 (2015) 205



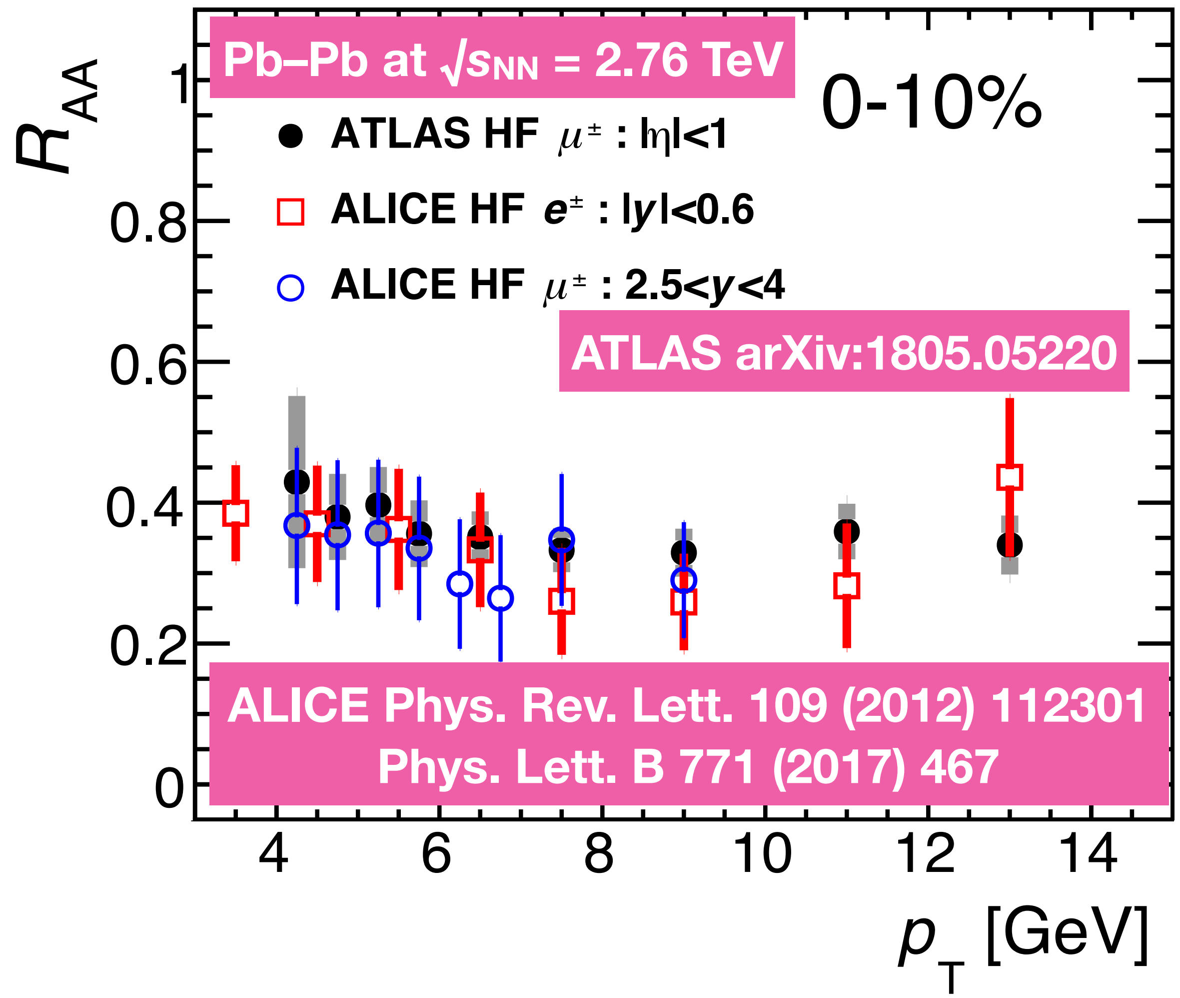


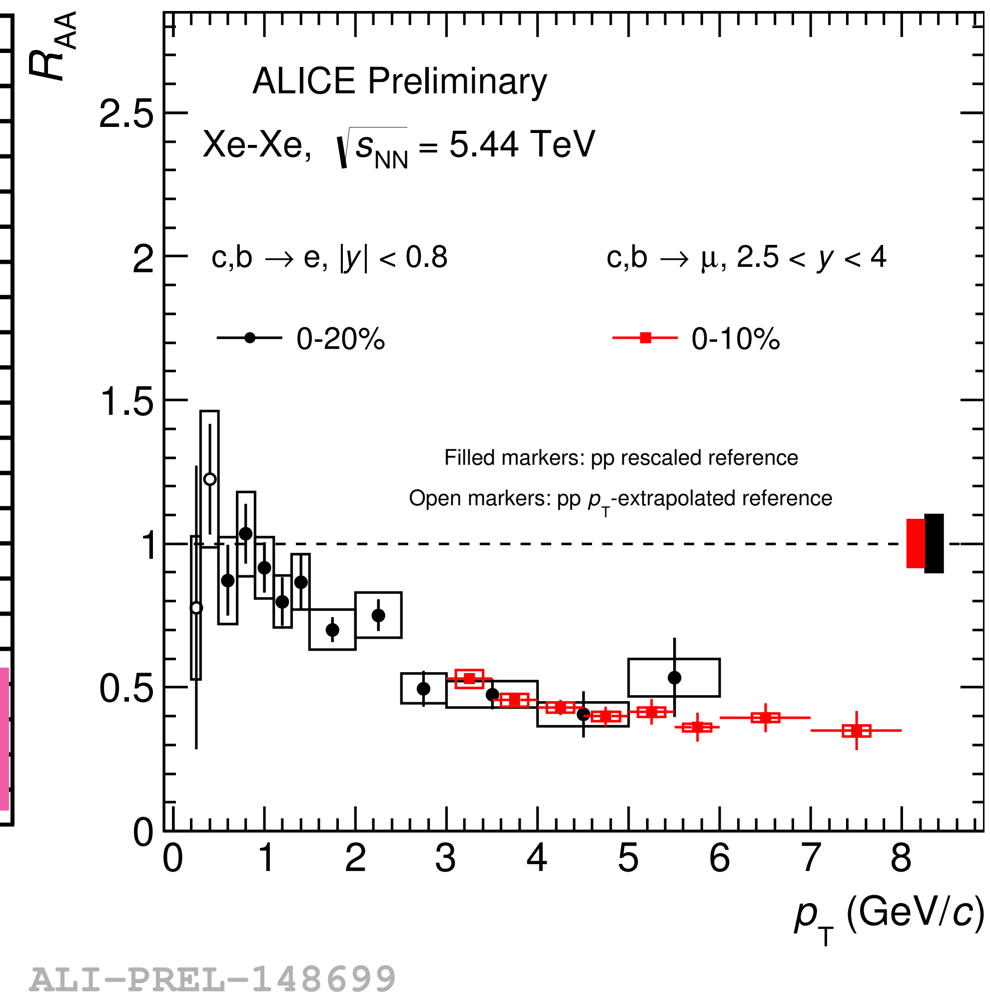


- Indication of R_{AA}(D) < R_{AA}(J/ψ←B) at the LHC
- R_{AA} of open heavy-flavour particles at the RHIC — hint of R_{AA}(D) < R_{AA}(B)

➡ Indication of mass dependence of heavy-quark energy loss: $\Delta E_c > \Delta E_b$

Charm energy loss in the QCD medium



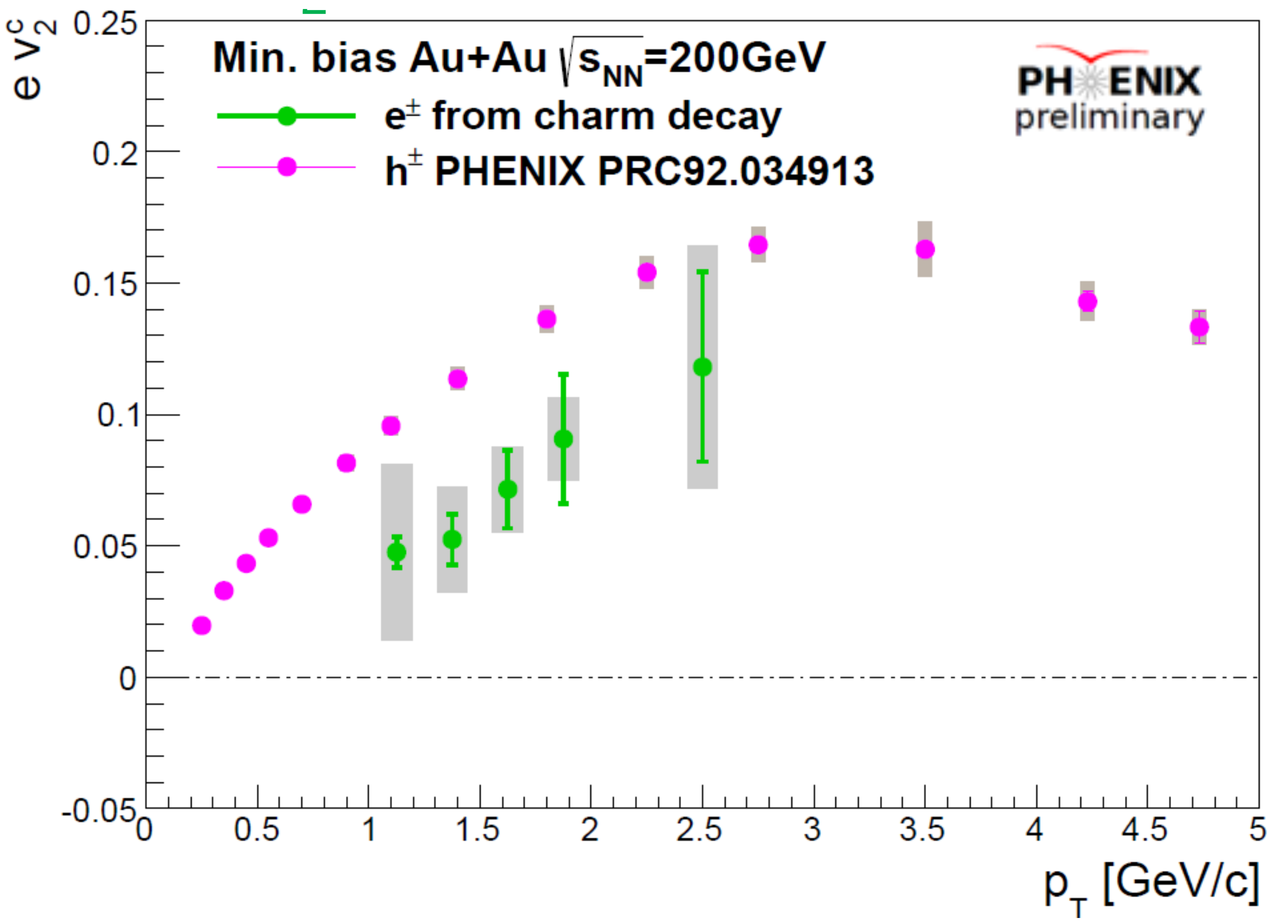


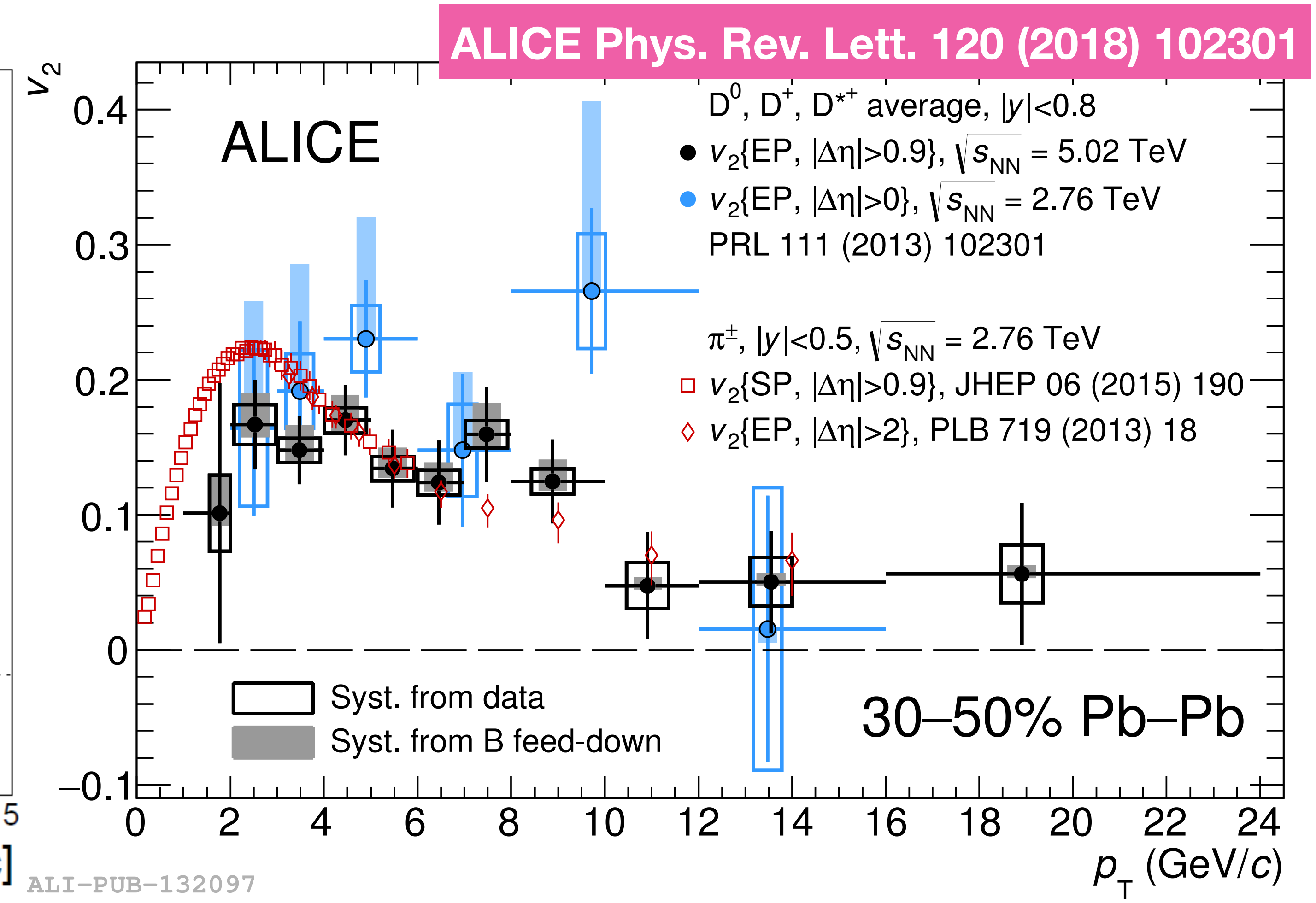
- R_{AA}(e/μ←HF) at mid-rapidity is consistent with R_{AA}(μ←HF) at forward rapidity within uncertainties

➡ Heavy quarks undergo strong interactions in the QCD medium in a wide rapidity window

➡ Xe–Xe vs. Pb–Pb collisions: may add sensitivity to probe the path-length dependence of energy loss

Elliptic flow of open charm





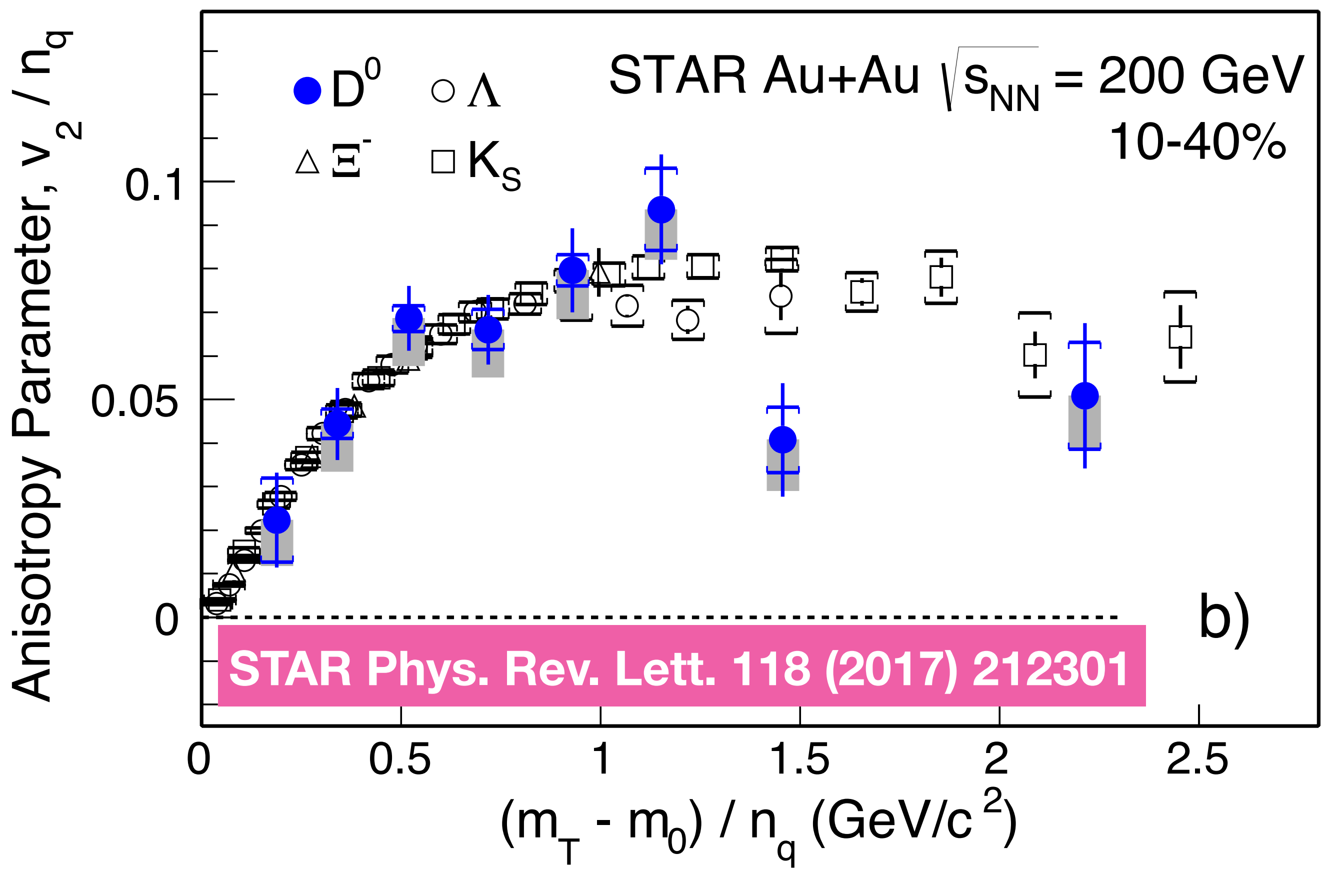
- Positive v_2 of open charm hadron decay electrons and D mesons at low / intermediate p_T observed at the RHIC and LHC, respectively

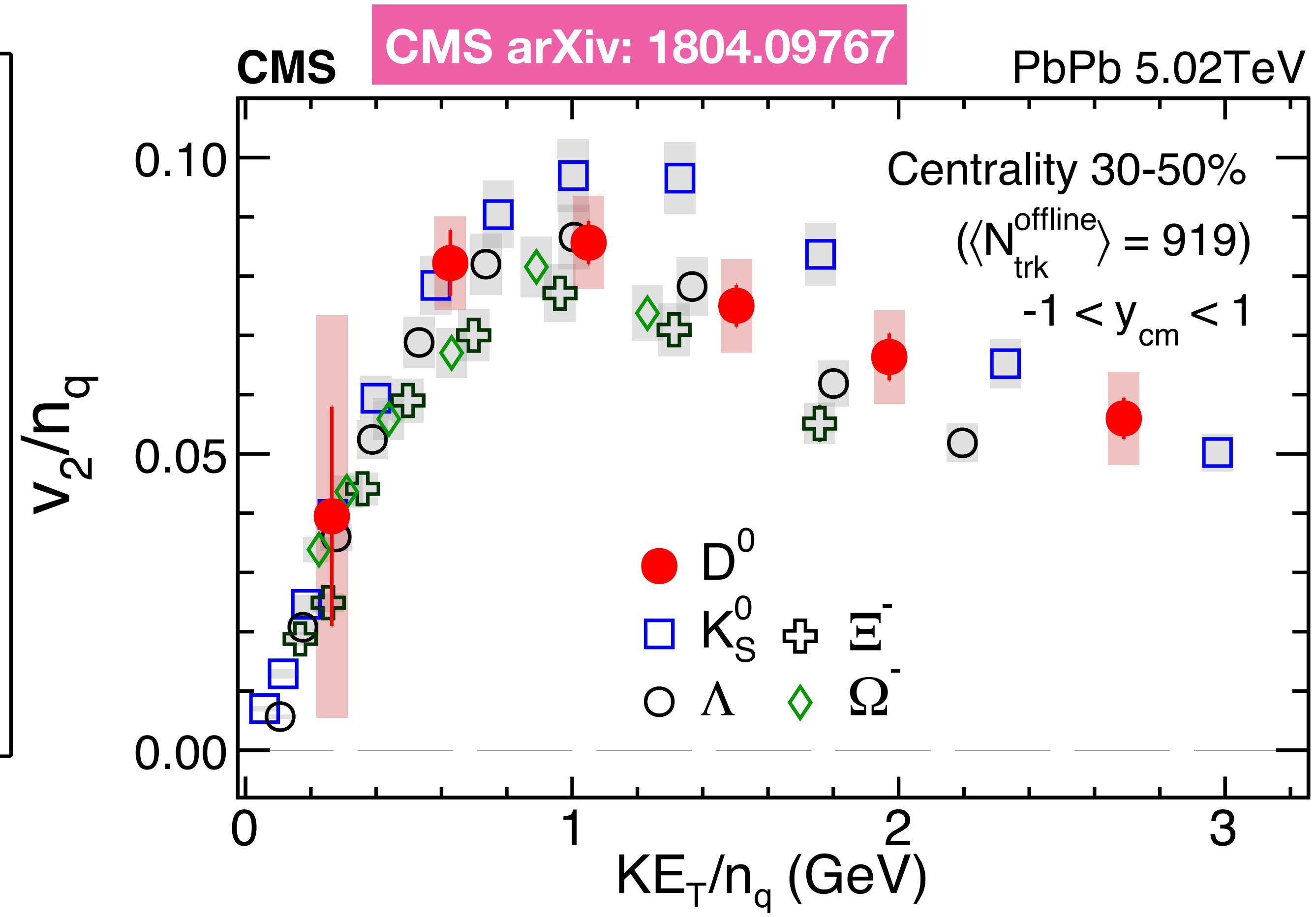
➡ Participation of charm quarks in the collective motion of the medium

- At the LHC: $v_2(D) \approx v_2(\pi^\pm)$ at high p_T

➡ Suggests a similar path-length dependent in-medium energy loss

Elliptic flow of open charm





- D mesons seem to follow the same number of constituent quarks (NCQ) and kE_T scaling as light hadrons — observed at both RHIC and LHC

➡ Similar collective motion of charm quarks and light quarks (?) — charm thermalization (?)

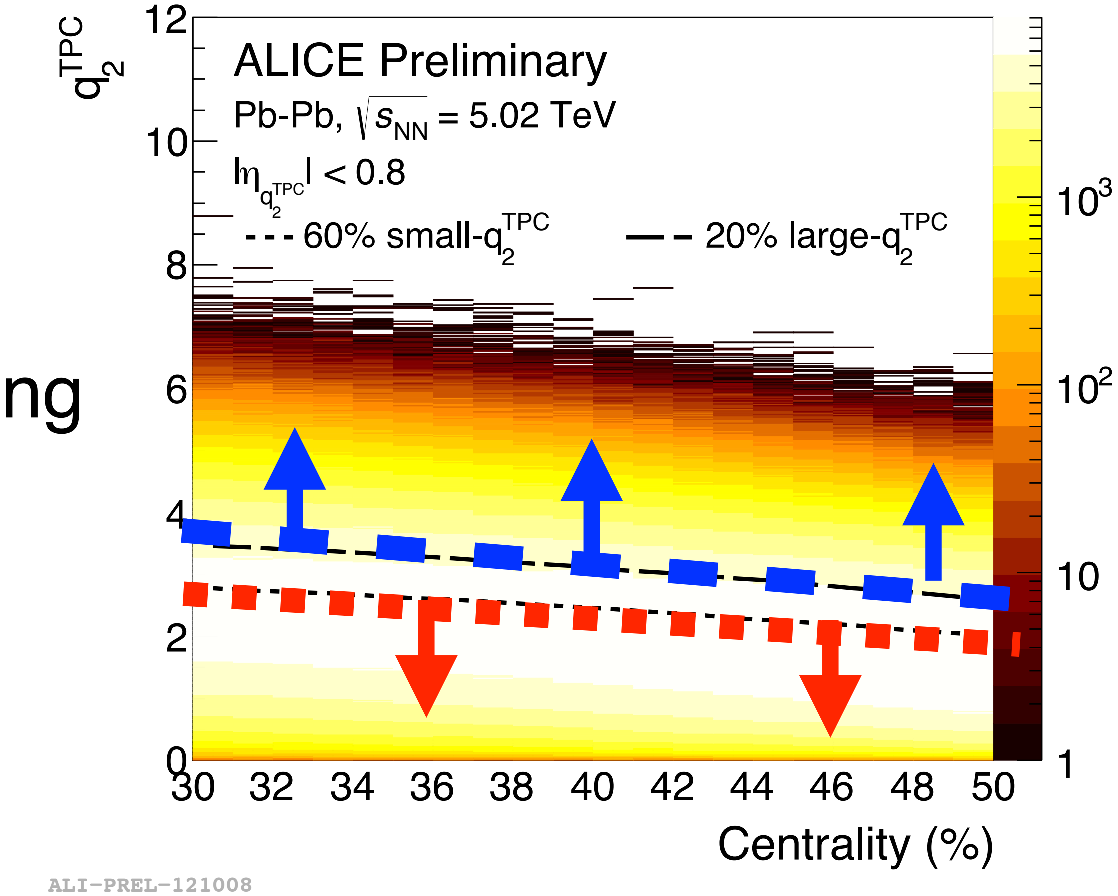
➡ Strong interaction of charm quarks with the medium — consistent with the R_{AA} measurement

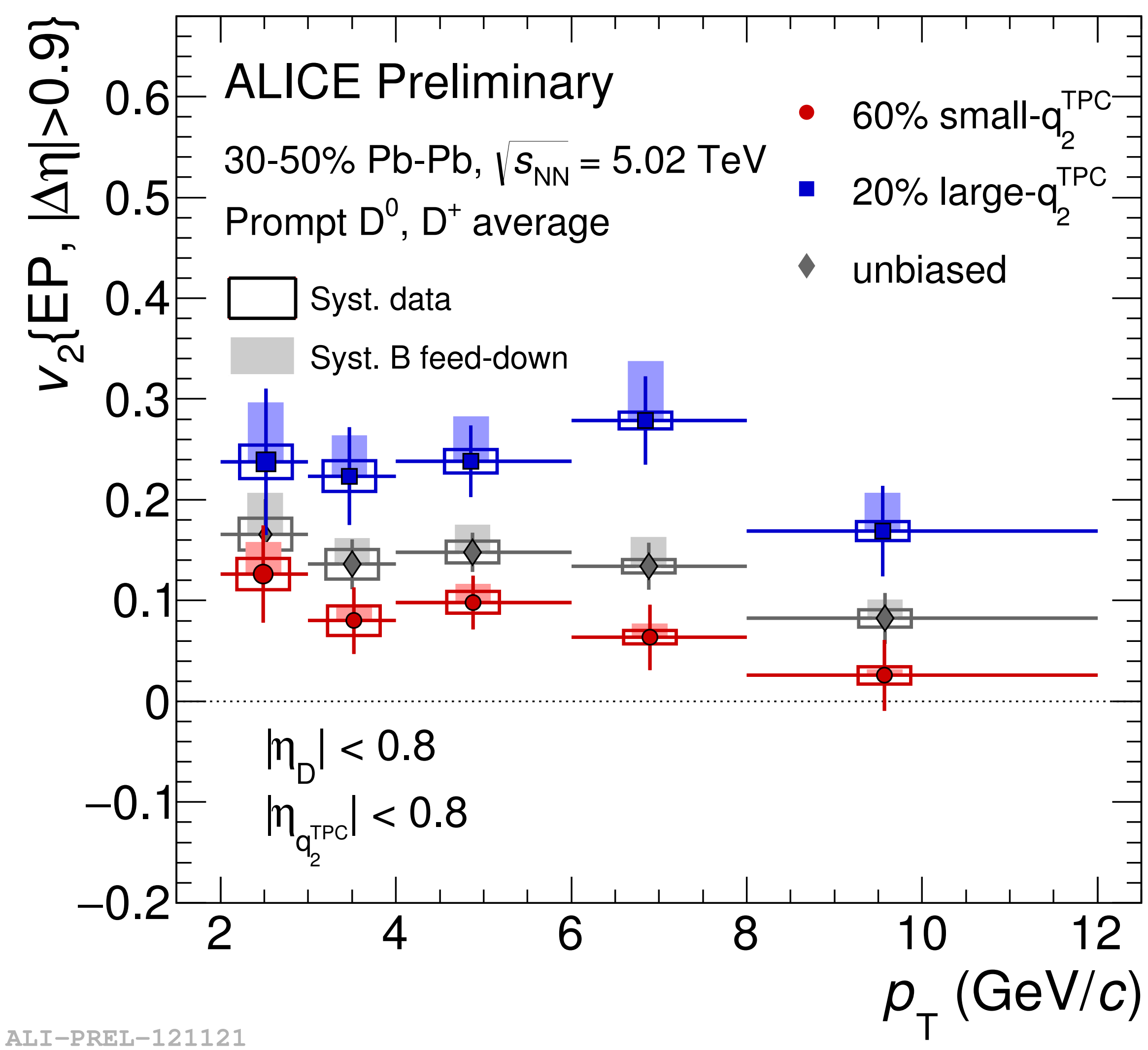
Event-shape engineering

- Event eccentricity quantified by q_2:

➡ $<(q_2)^2> \approx 1 + <M-1> <(v_2)^2>$

- Opportunity to study the charm-quark coupling to the light-hadron bulk by measuring v_2 at different q_2 values



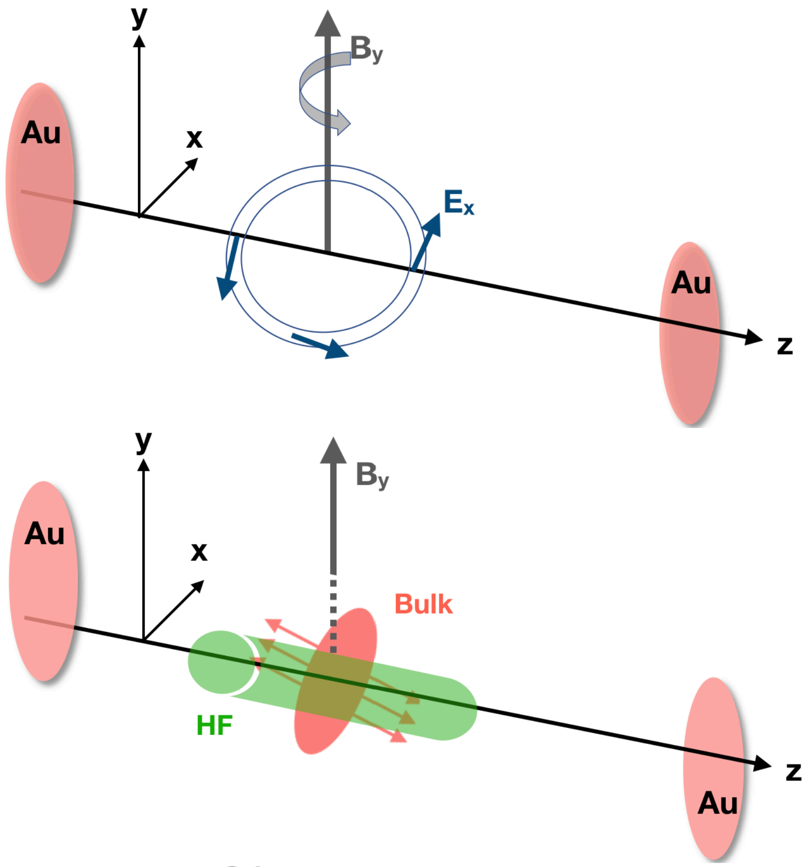


- Significant separation of D-meson v_2 in events with large and small q_2

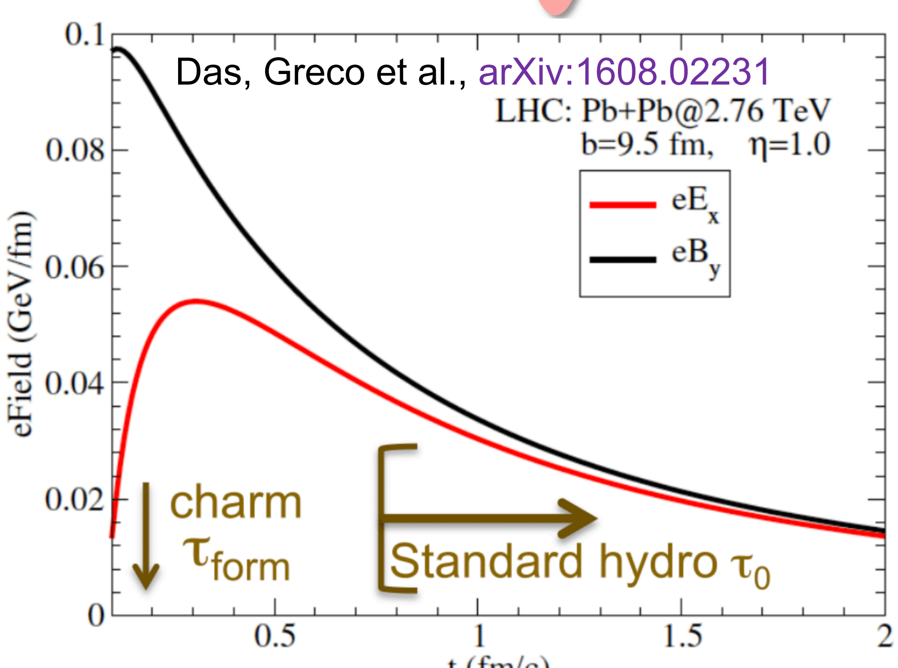
➡ Charm quarks sensitive to the light-hadron bulk collectivity and event-by-event initial condition fluctuations

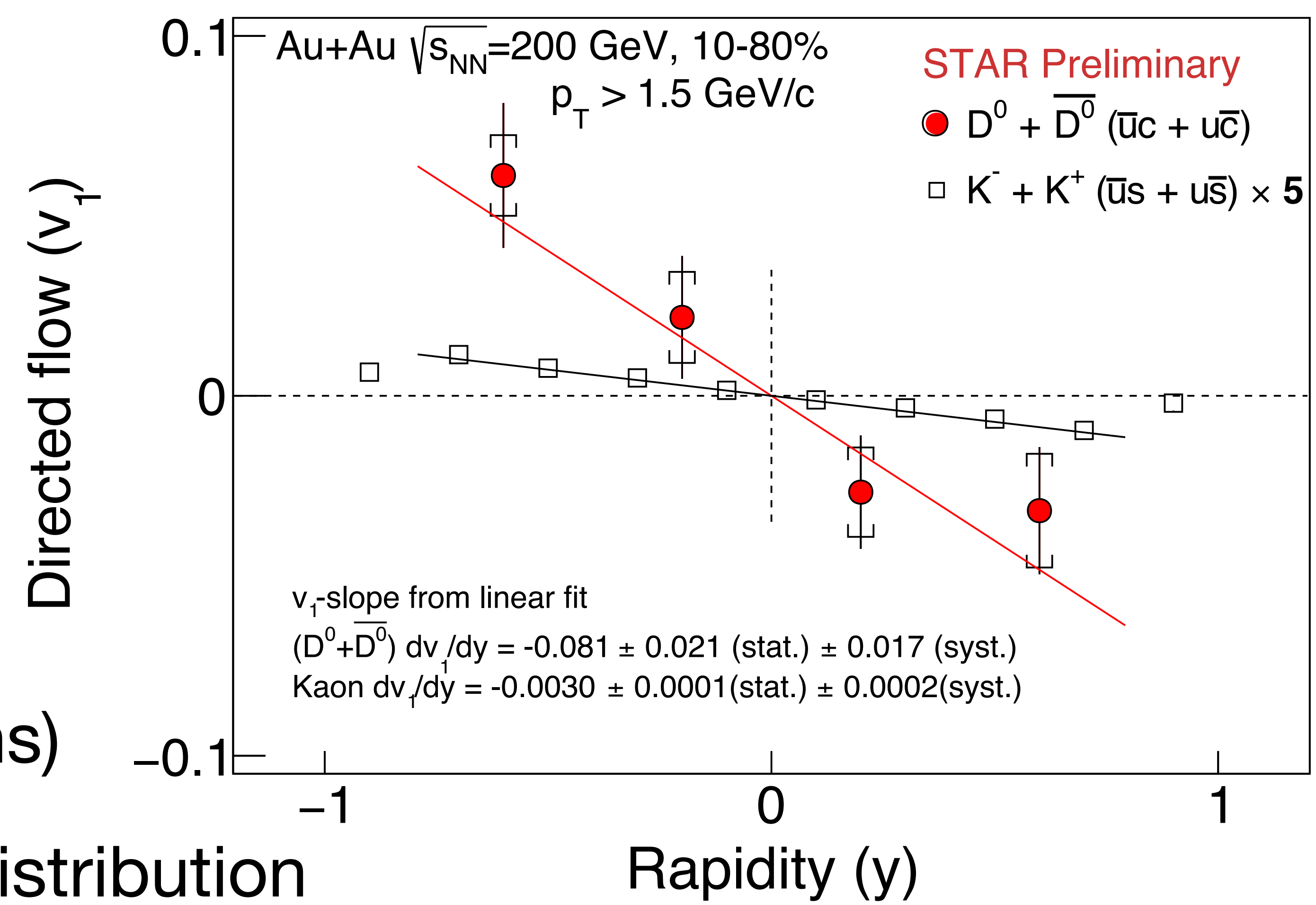
Autocorrelation and non-flow effects between q_2 determination and D-meson reconstruction are present

Directed flow of open charm



- Sensitive to the early time EM fields in the collisions
  - ➡ Provide constraint for CME related physics
- Charm dragged by tilted bulk: production points are shifted from the bulk at $y \neq 0$ — larger v_1 for D mesons than for light flavours
  - ➡ Probe the longitudinal profile of the initial matter

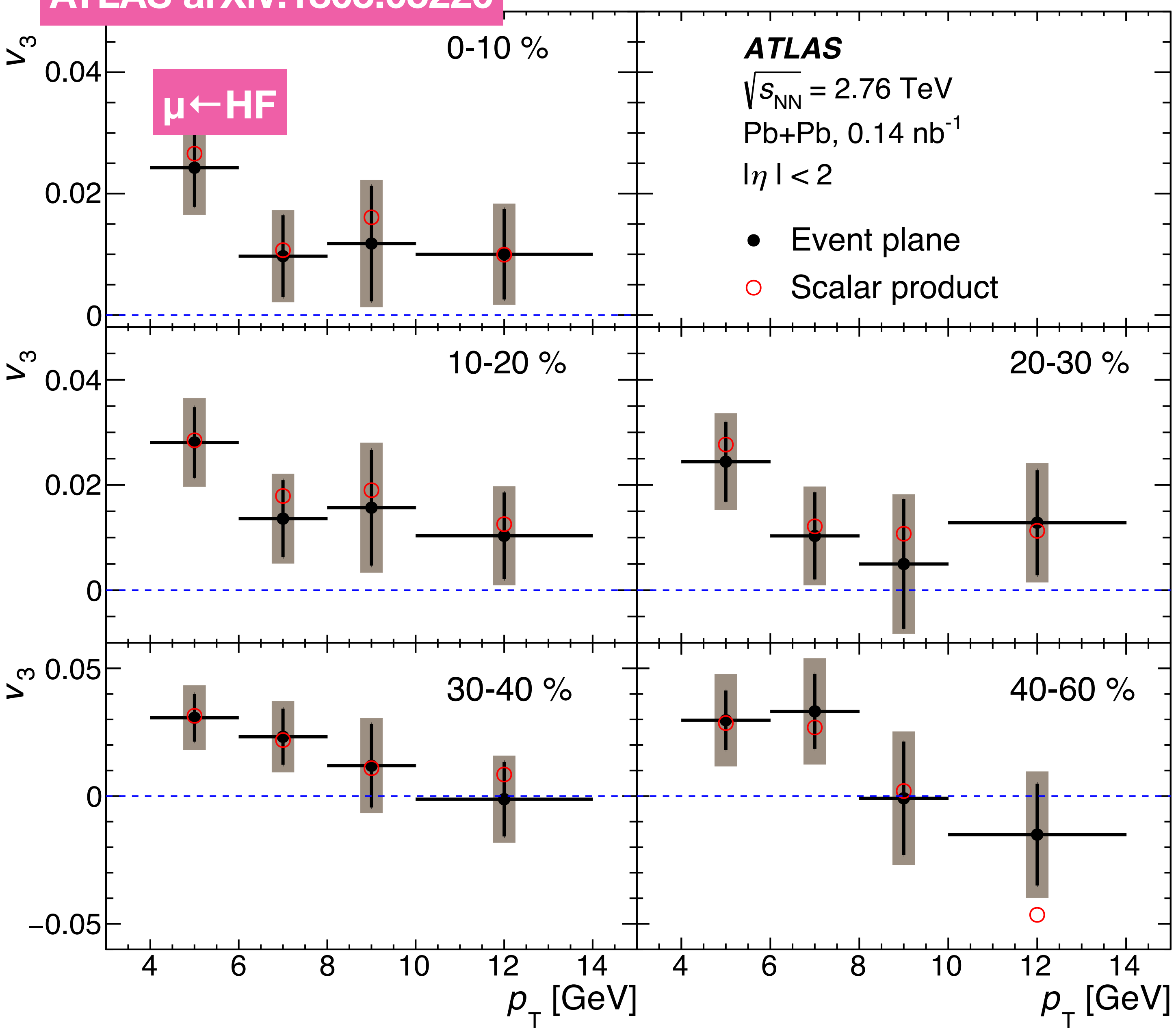




- Non-zero $v_1(D^0) > v_1$(light hadrons)
- Help to study the initial matter distribution

Triangular flow of open heavy flavours

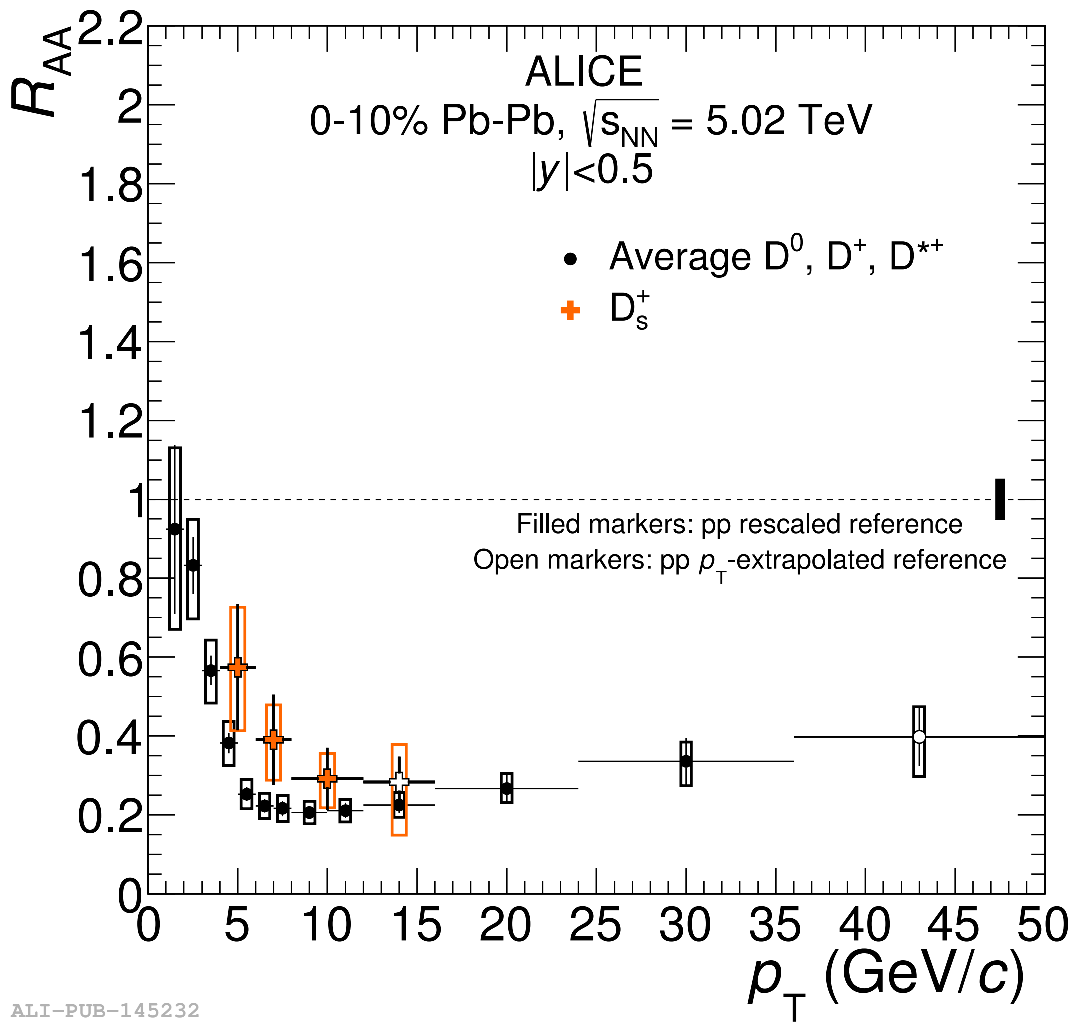
ATLAS arXiv:1805.05220

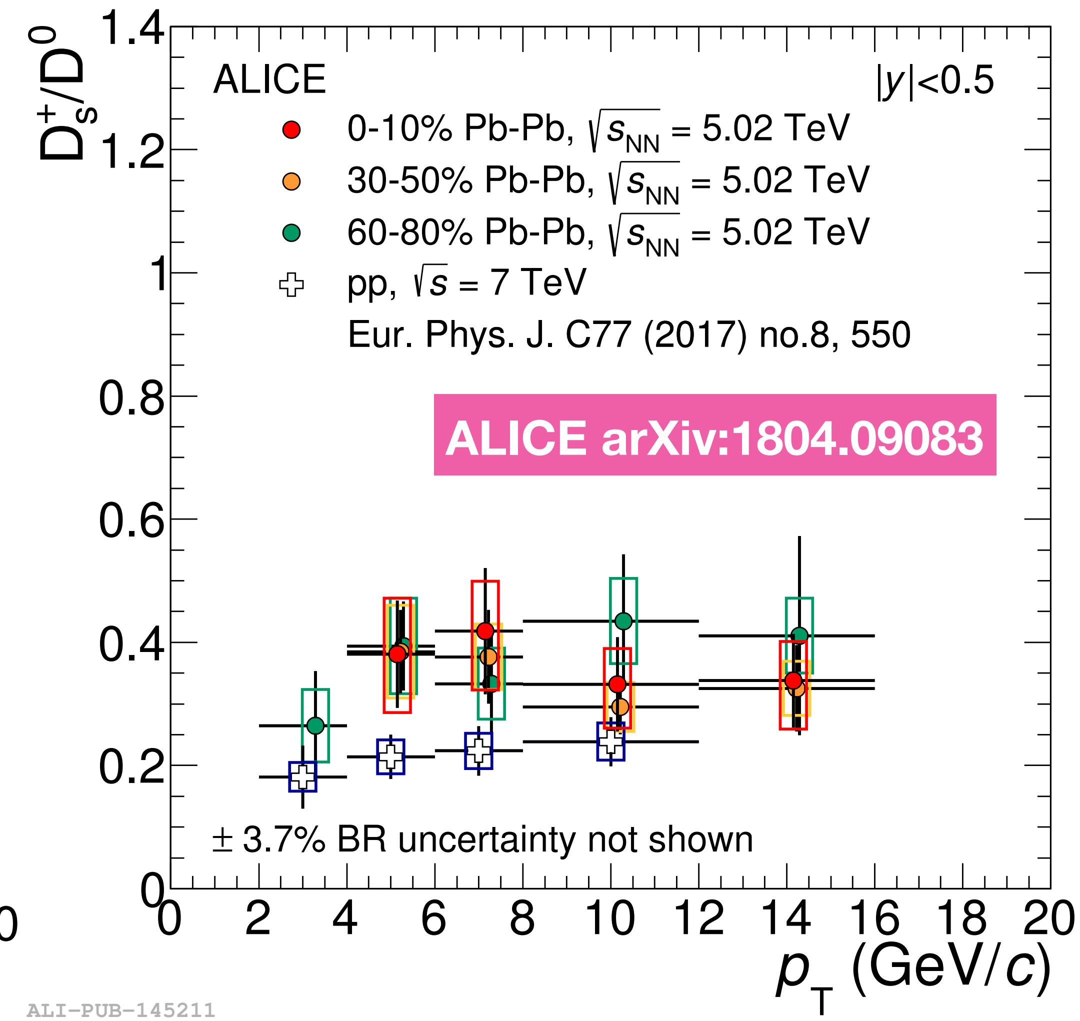


- Higher order flow coefficients (v_3, v_4…)
  - ➡ Bring additional constraints on the initial conditions, η/s, EoS, freeze-out conditions…

- v_3 of open heavy-flavour hadron decay muons
  - ➡ Generally decreases with increasing p_T, weak variation with centrality
  - ➡ Limited by statistics at high p_T

D_s production in heavy-ion collisions

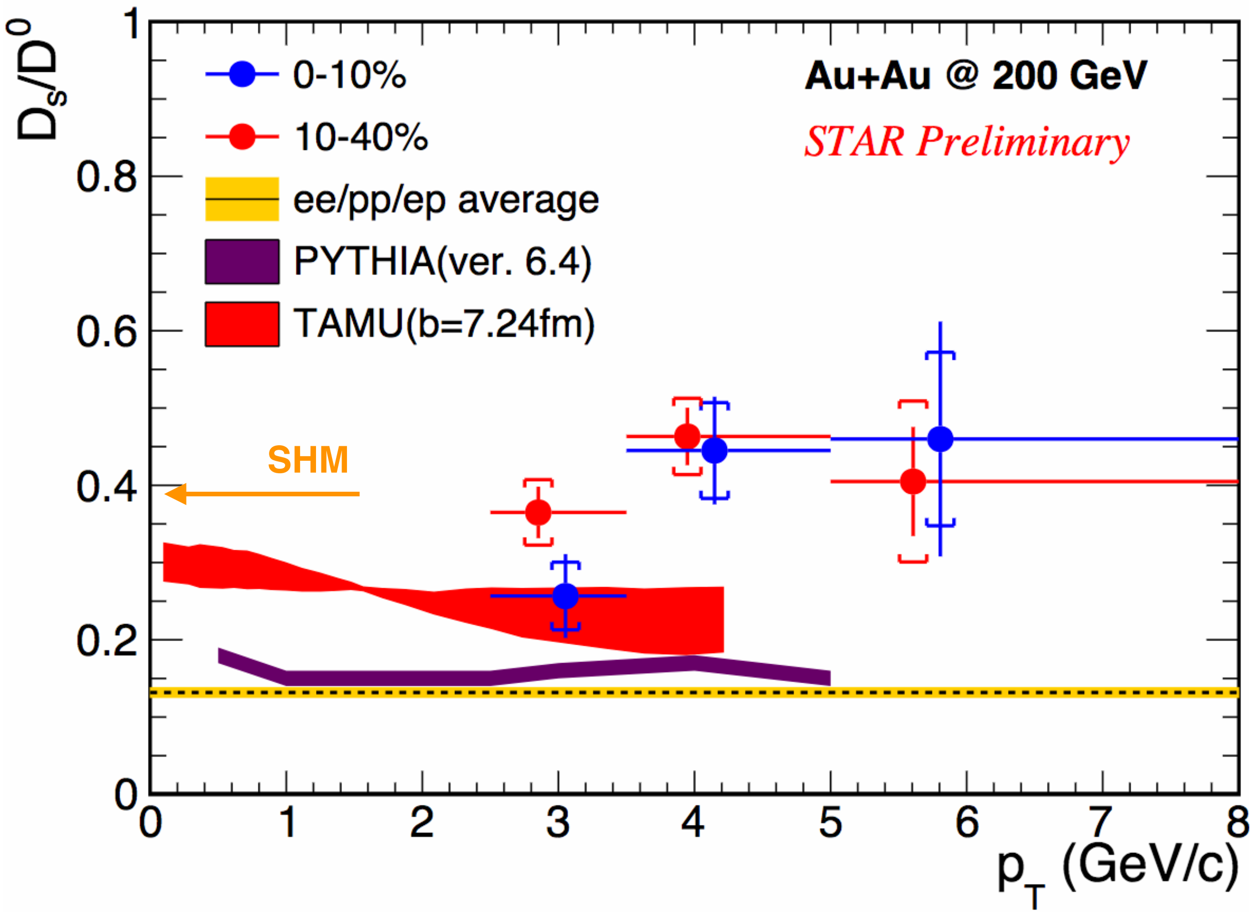


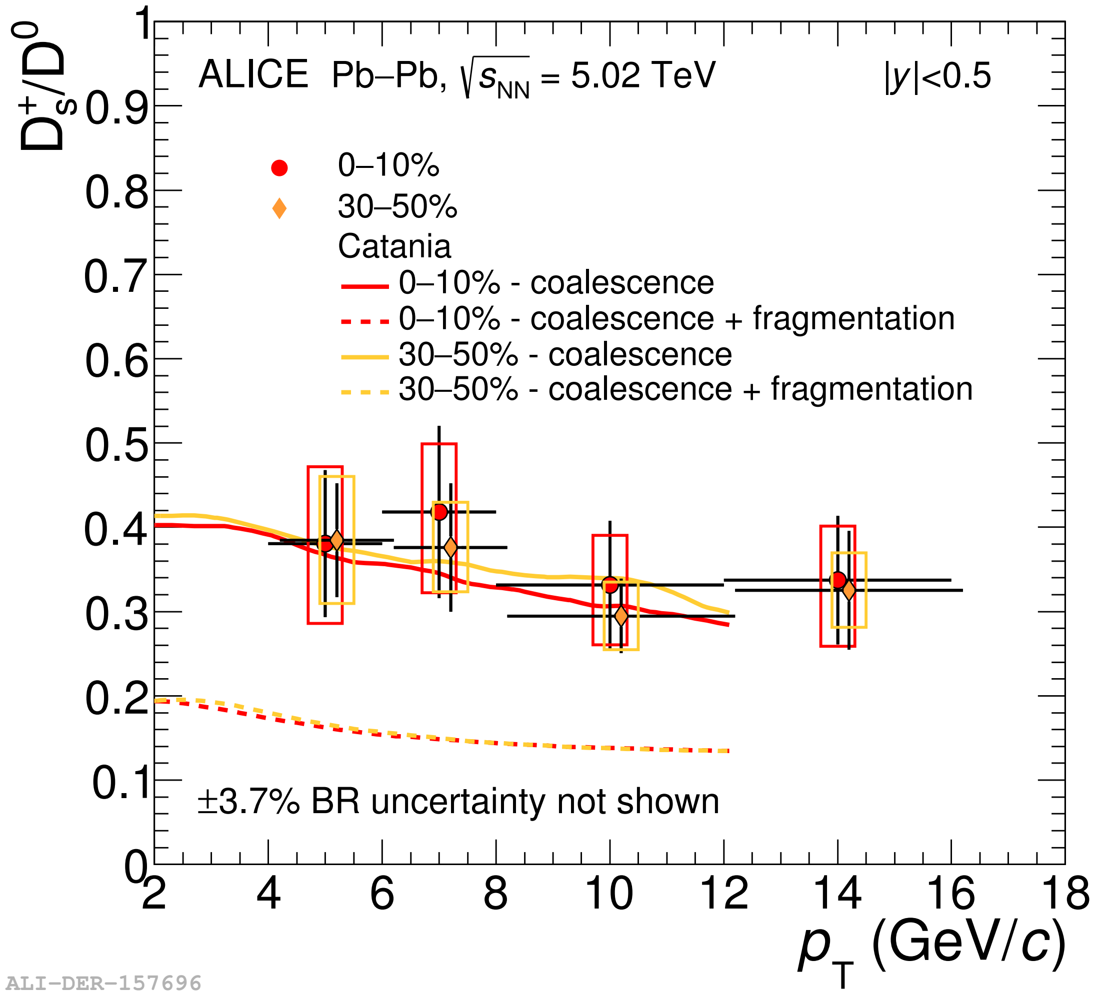


- Hint of $R_{AA}(D_s) > R_{AA}(D)$ in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (still large uncertainty to draw conclusion)
- Hint for a higher D_s / D^0 ratio in Pb–Pb collisions compared to pp collisions, no centrality dependence with current uncertainties

More statistics needed to draw conclusions on the contribution from coalescence mechanism on D_s hadronization

D_s production in heavy-ion collisions





- RHIC: D_s / D^0 ratio in Au+Au collisions is enhanced w. r. t. PYTHIA

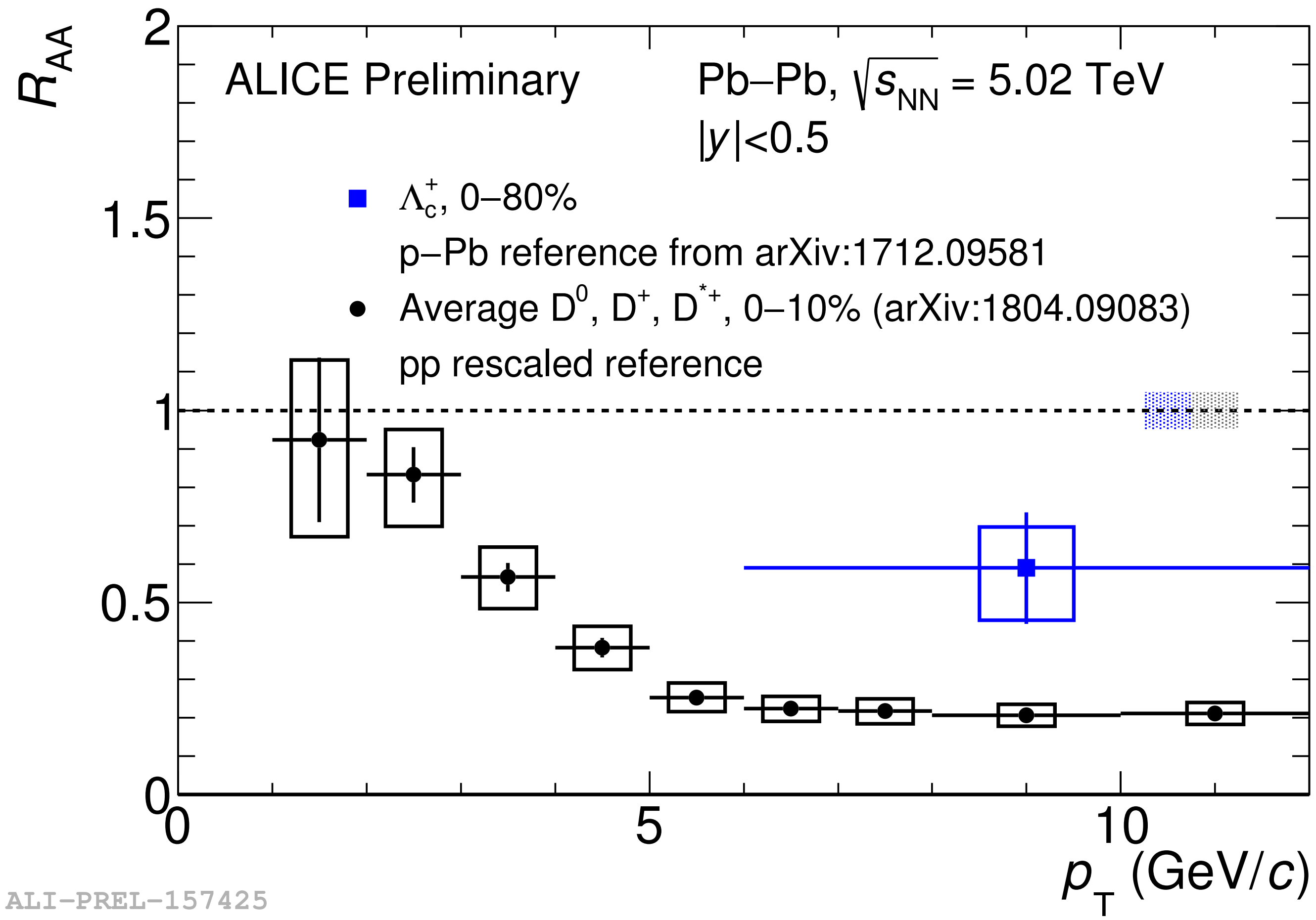
➡ Larger than model predictions, particularly at higher p_T

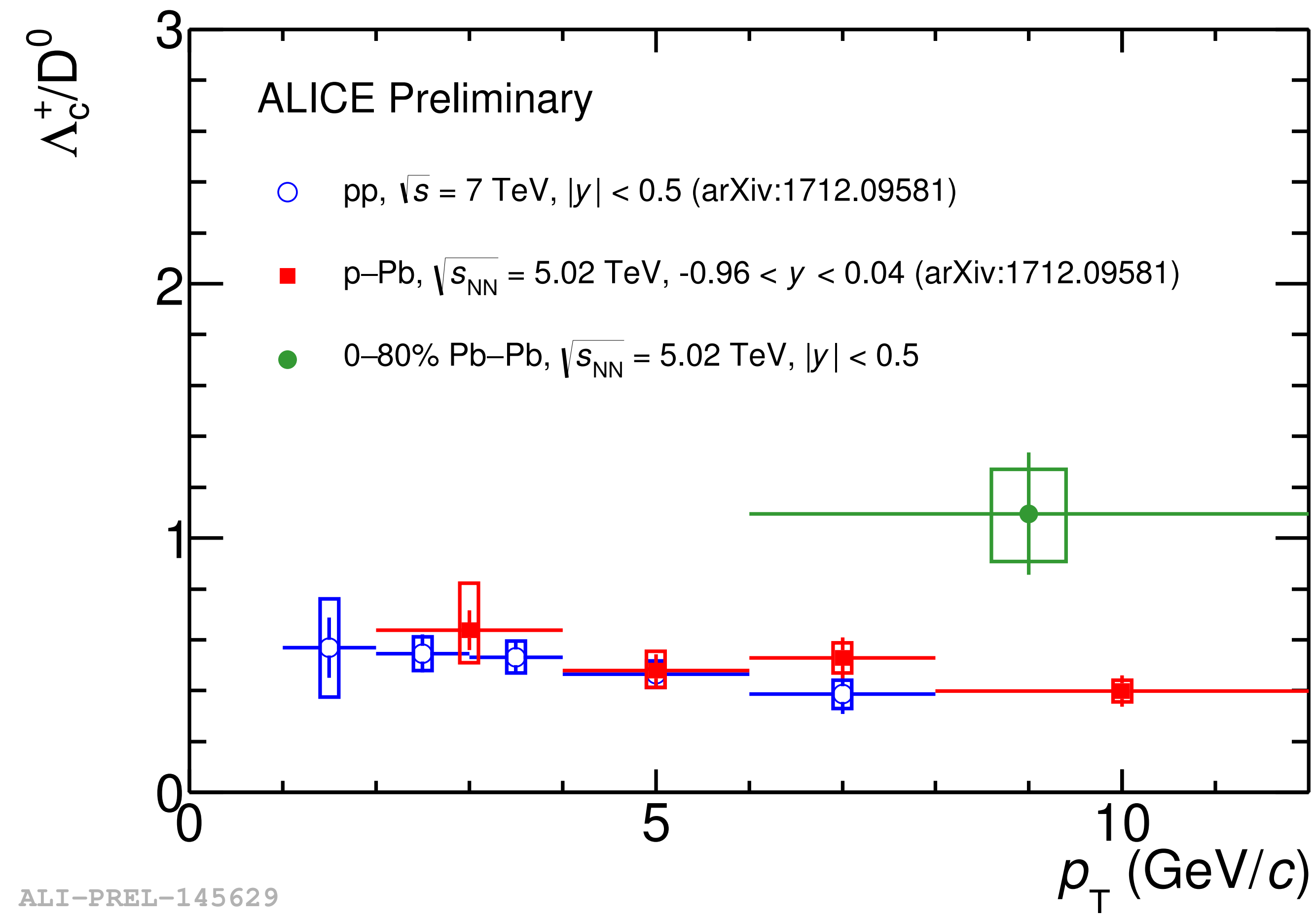
- LHC: D_s / D^0 ratio expected from models

➡ coalescence + strangeness enhancement (?)

More statistics needed to draw conclusions on the contribution from coalescence mechanism on D_s hadronization

Λ_c production in heavy-ion collisions



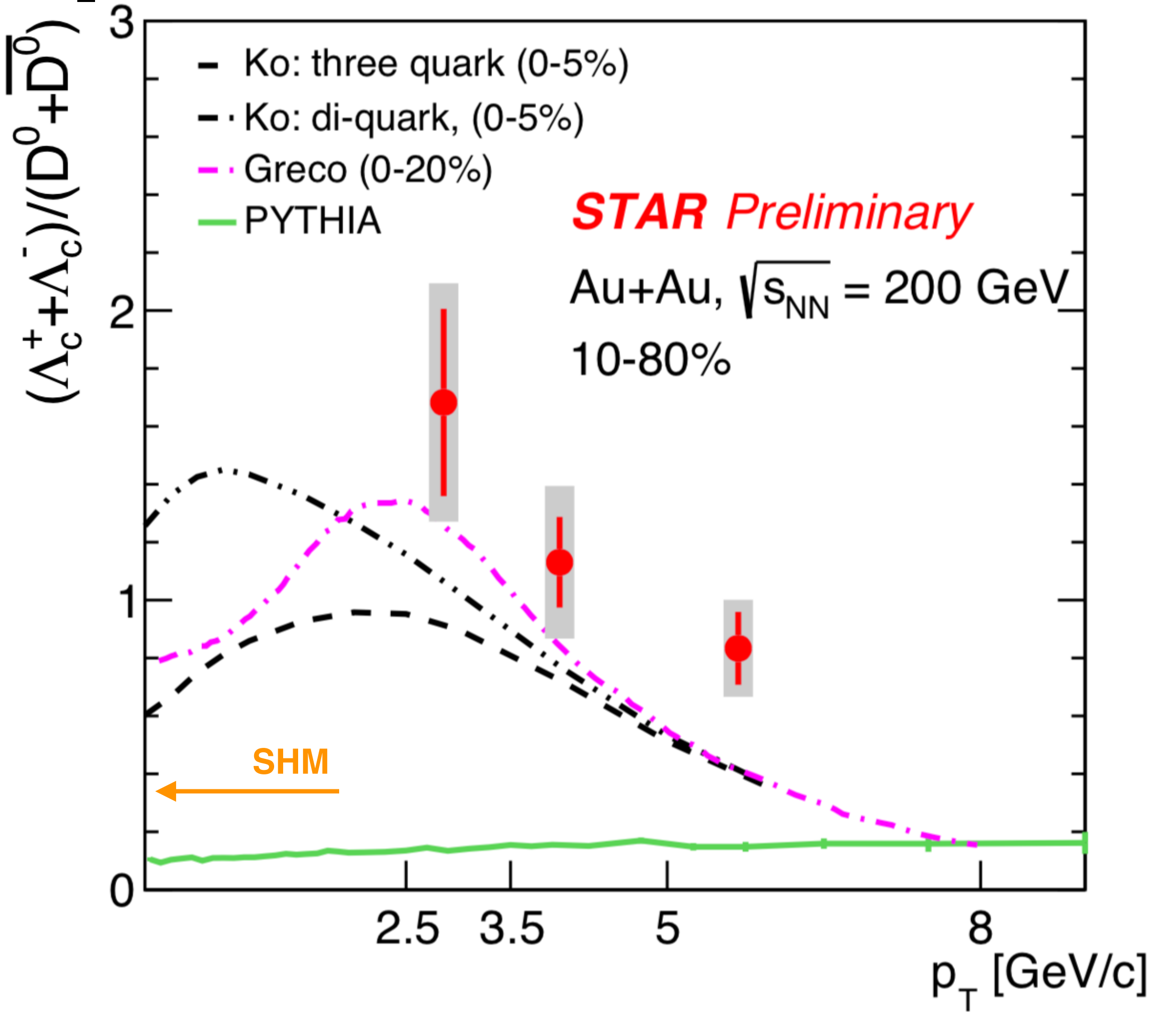


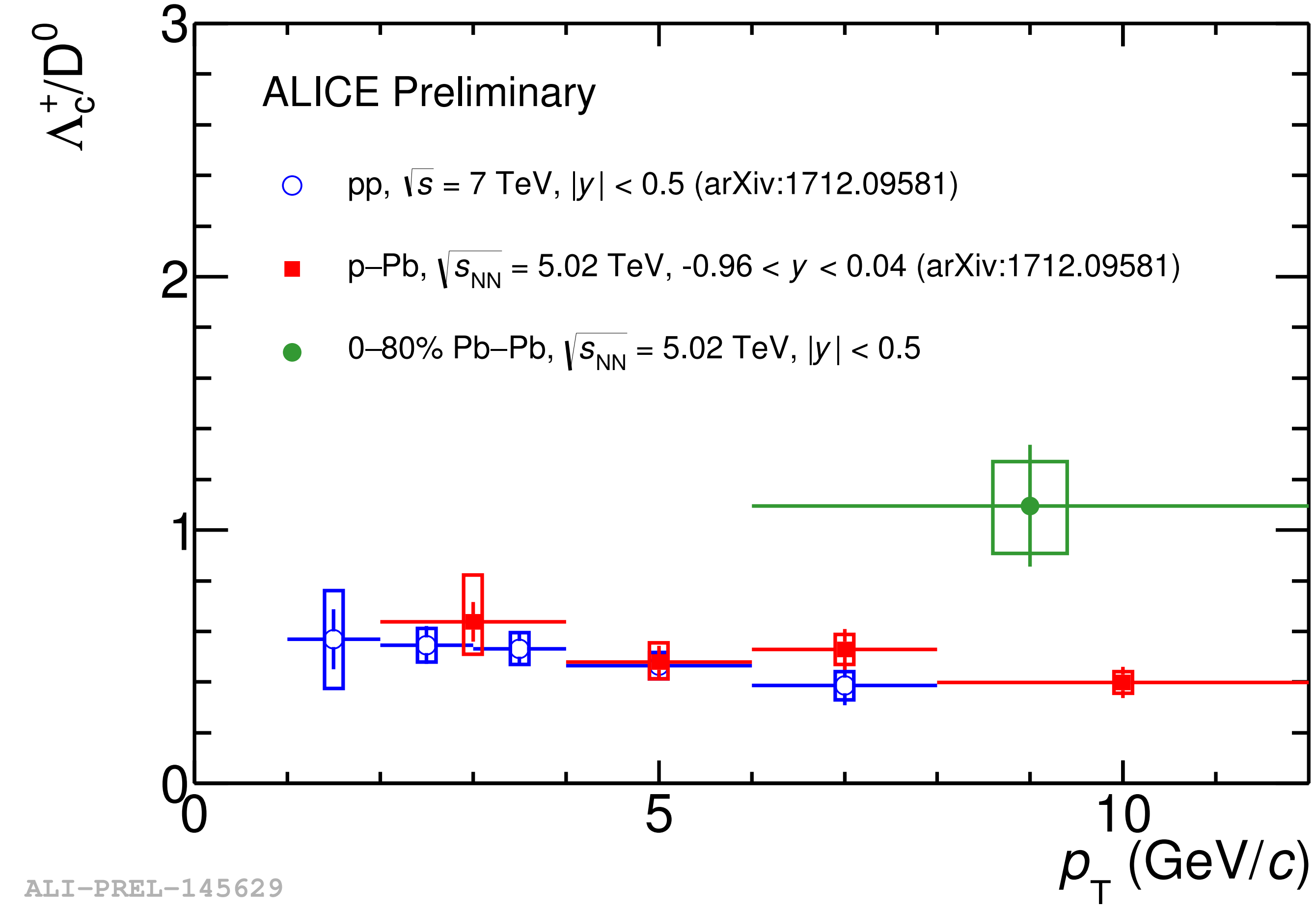
- Λ_c measured in Pb–Pb collisions at 5.02 TeV for 0–80% centrality class

➡ Hint of larger R_{AA} than D mesons in 0–10% centrality class

➡ Hint of Λ_c / D^0 ratio enhanced in Pb–Pb collisions w. r. t. pp and p–Pb collisions

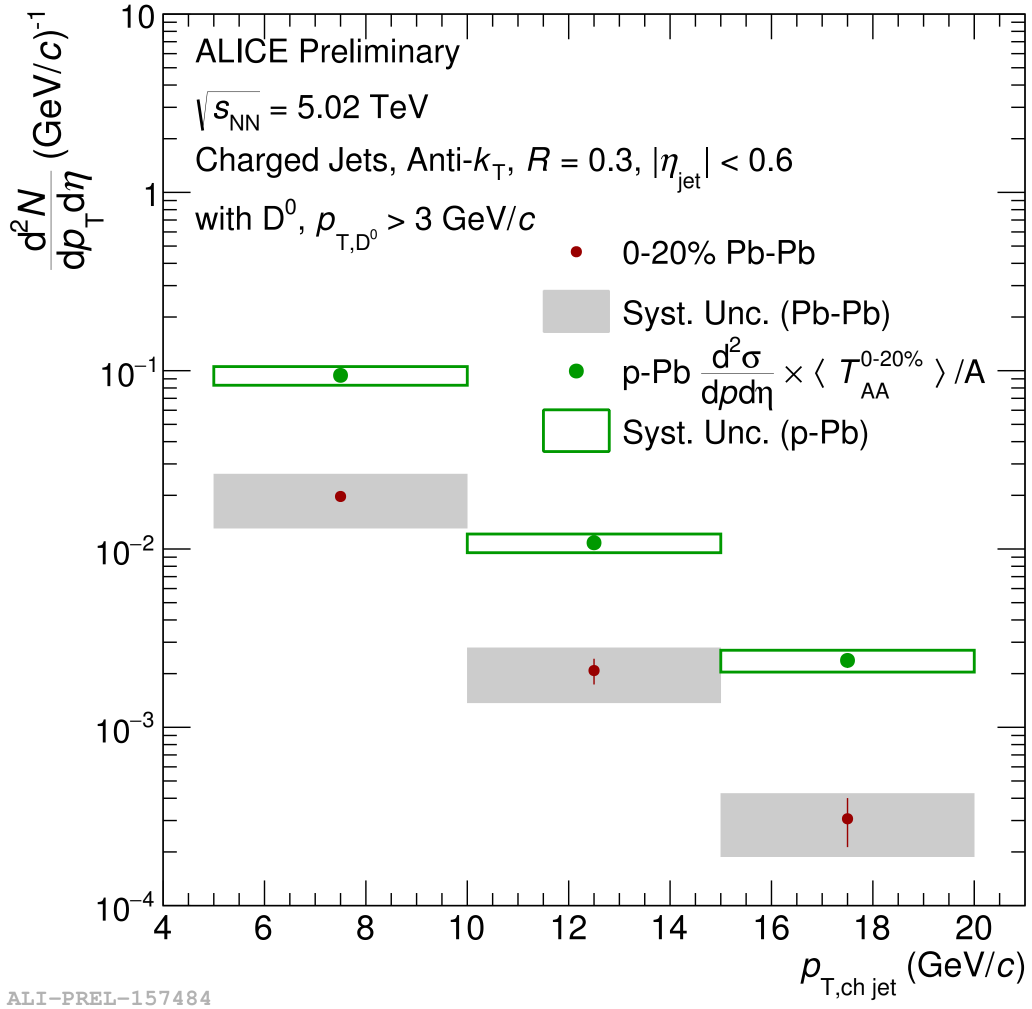
Λ_c production in heavy-ion collisions

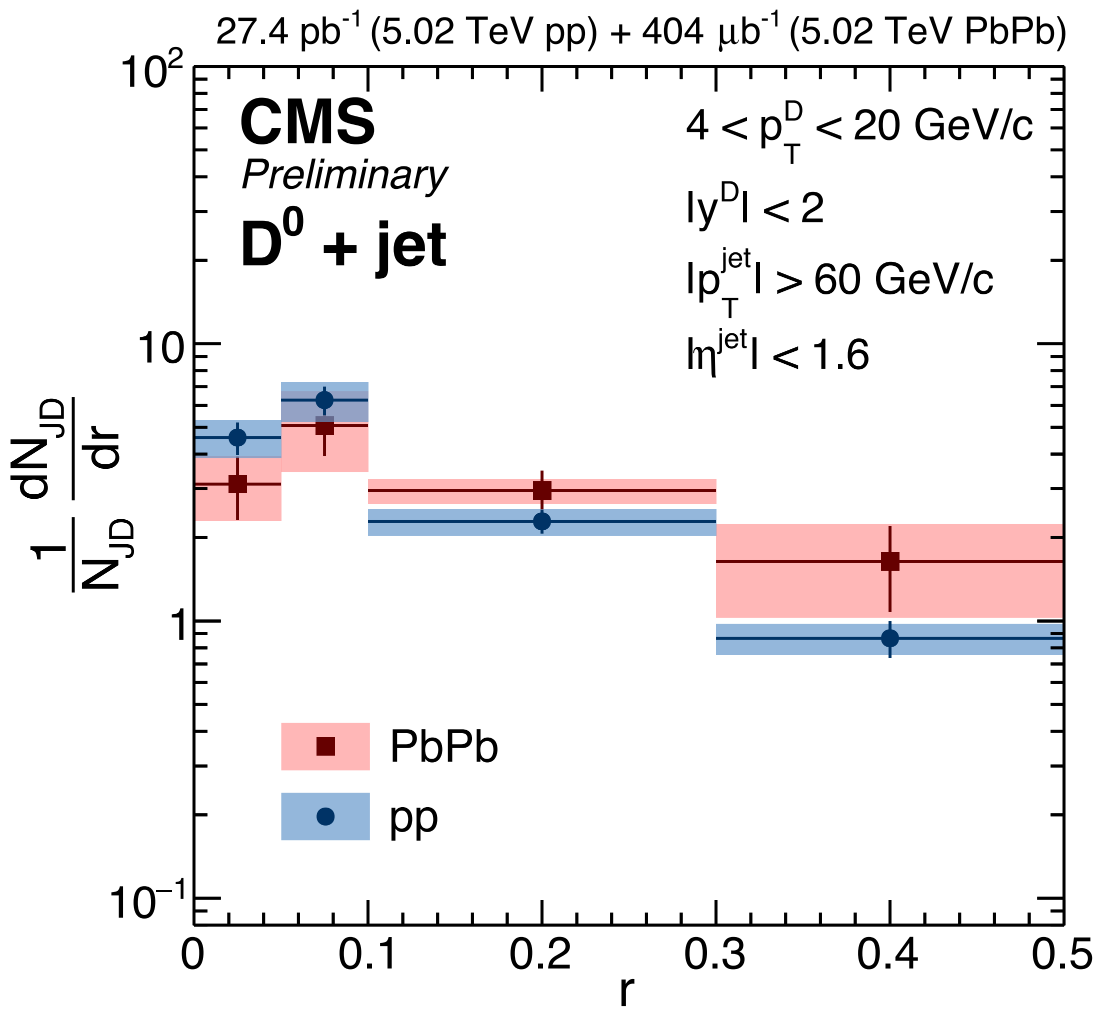


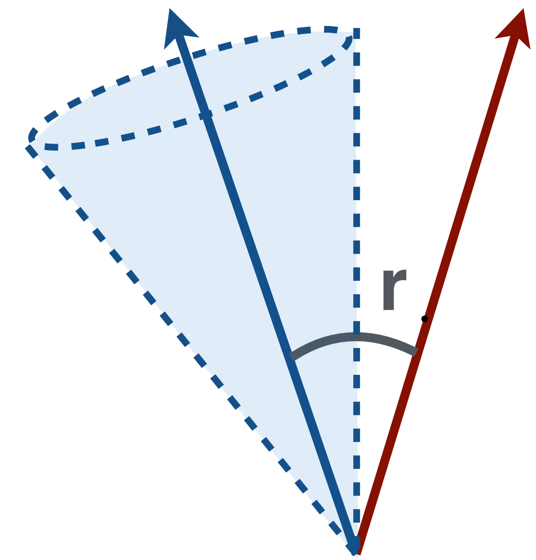


- Λ_c measured in Pb–Pb collisions at 5.02 TeV for 0–80% centrality class
  - ➡ Hint of larger R_{AA} than D mesons in 0–10% centrality class
  - ➡ Hint of Λ_c / D^0 ratio enhanced in Pb–Pb collisions w. r. t. pp and p–Pb collisions
- RHIC data: Λ_c / D^0 ratio is strongly enhanced compared to PYTHIA — enhancement increases towards low p_T

D-meson tagged jets





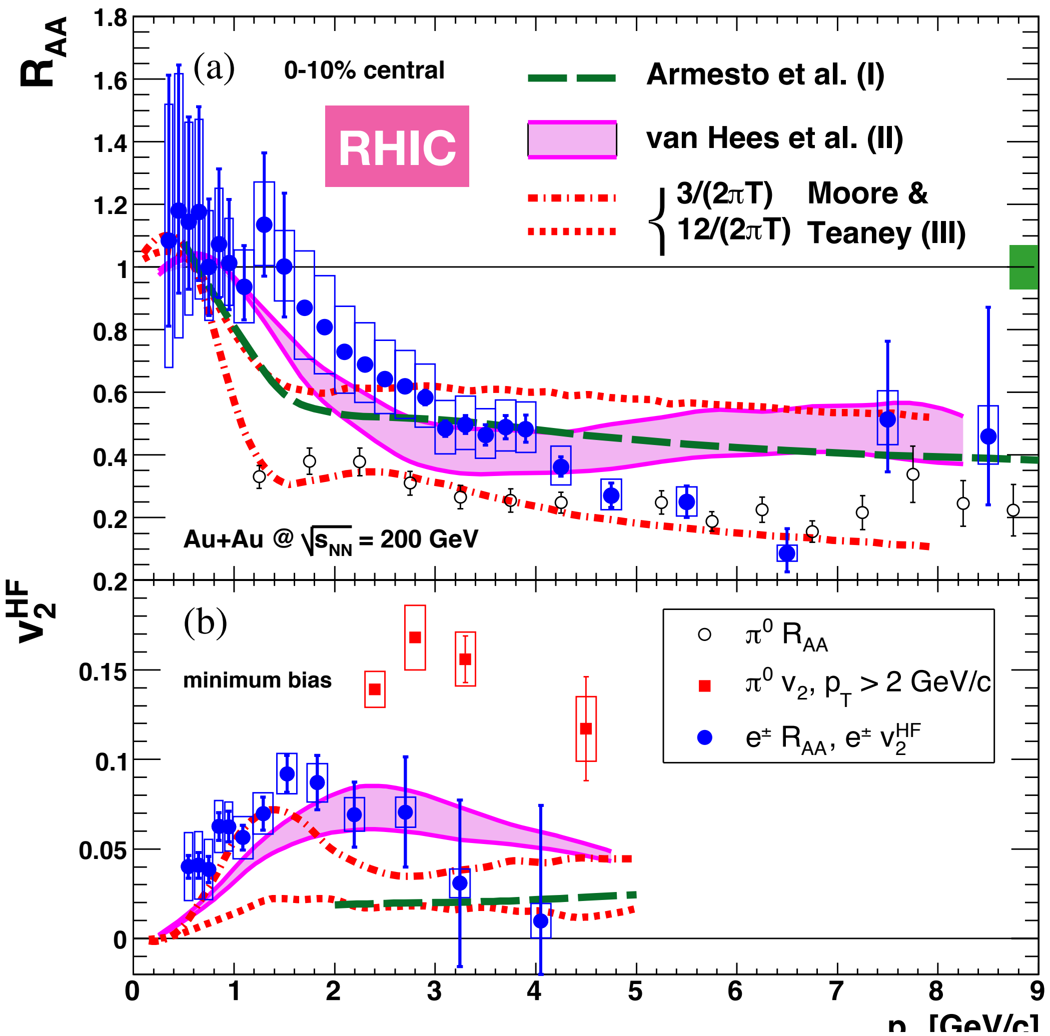


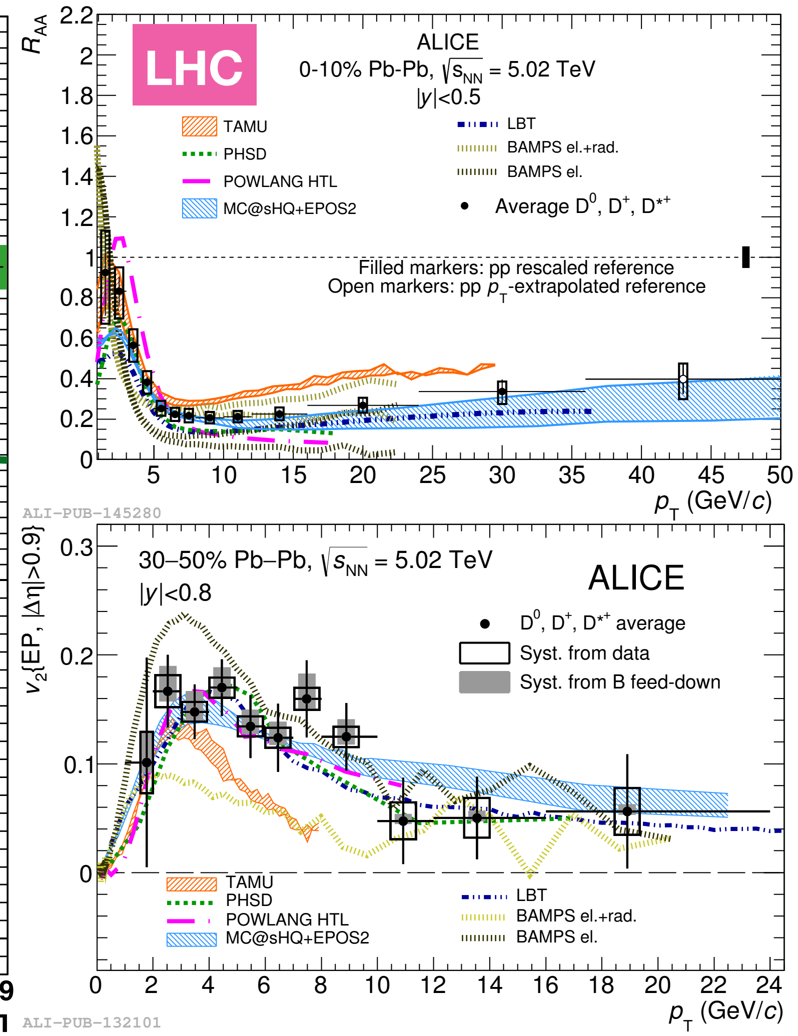
$$r = \sqrt{\Delta\phi_{JD}^2 + \Delta\eta_{JD}^2}$$

- Observed strong suppression of D^0-tagged jets in Pb–Pb collisions compared to p–Pb collisions
- Data suggest a wider D^0-meson radial profile in Pb–Pb collisions than in pp collisions for D^0 mesons in $4 < p_T < 20$ GeV/c

First seminal measurements! Will provide new constraints on charm quark energy loss and diffusion

Conclusion





Heavy quark diffusion coefficient

- RHIC: $(4 - 6) / 2\pi T$ for $0.2 < T < 0.4$ GeV
- LHC: $(1.5 - 7) / 2\pi T$ for $T = T_c$

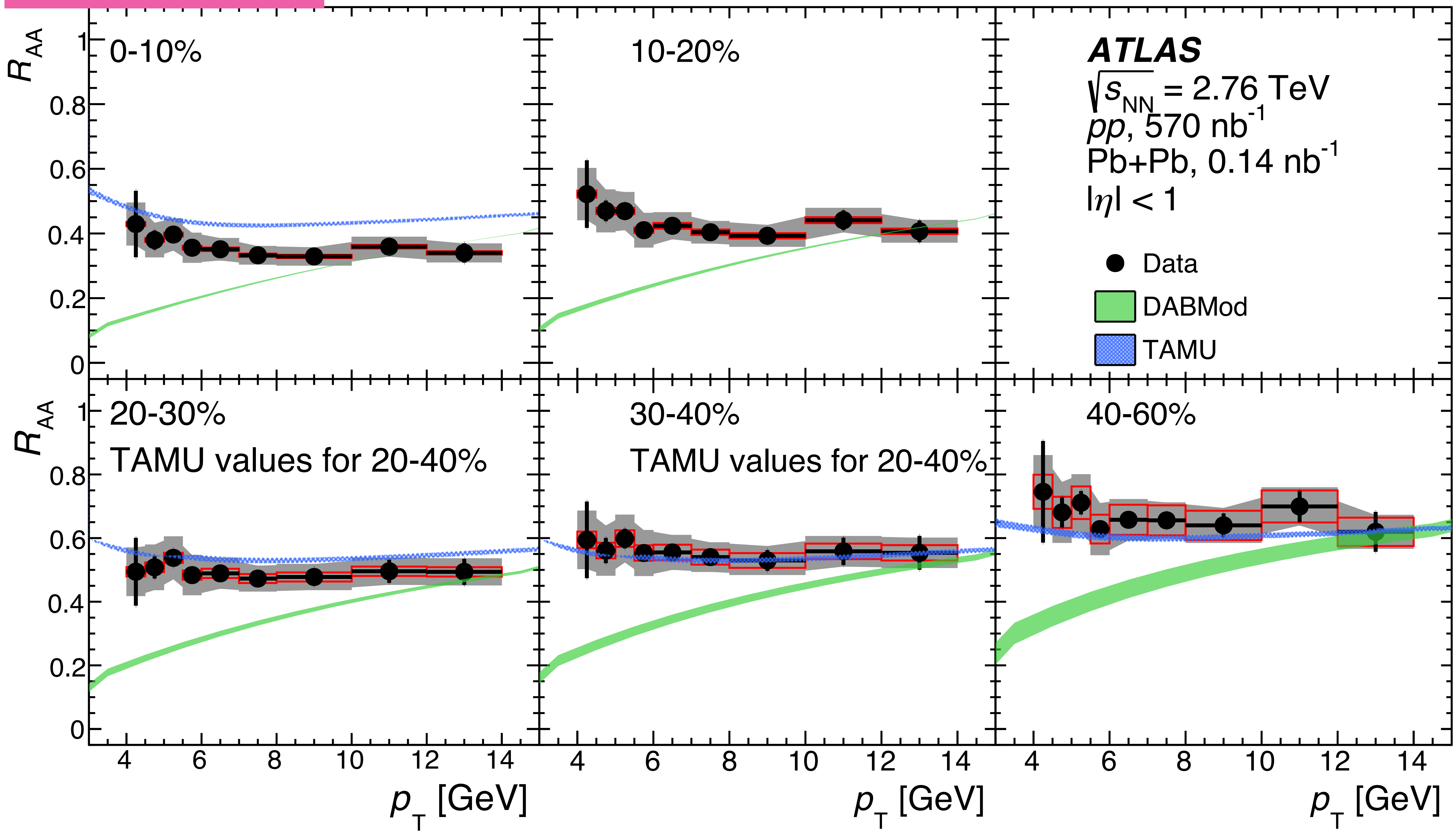
- New channels: charmed meson and baryon production, charmed jets

➡ Further constraints on transport properties and degree of thermalization of charm quarks in the QCD medium

Backup

R_{AA} of HFm: model comparison

ATLAS arXiv:1805.05220



v_2 and v_3 of HFm: model comparison

ATLAS arXiv:1805.05220