Recent heavy flavor measurements (summary for the QM22)

Xiaozhi Bai

University of Science and Technology of China

Outlines

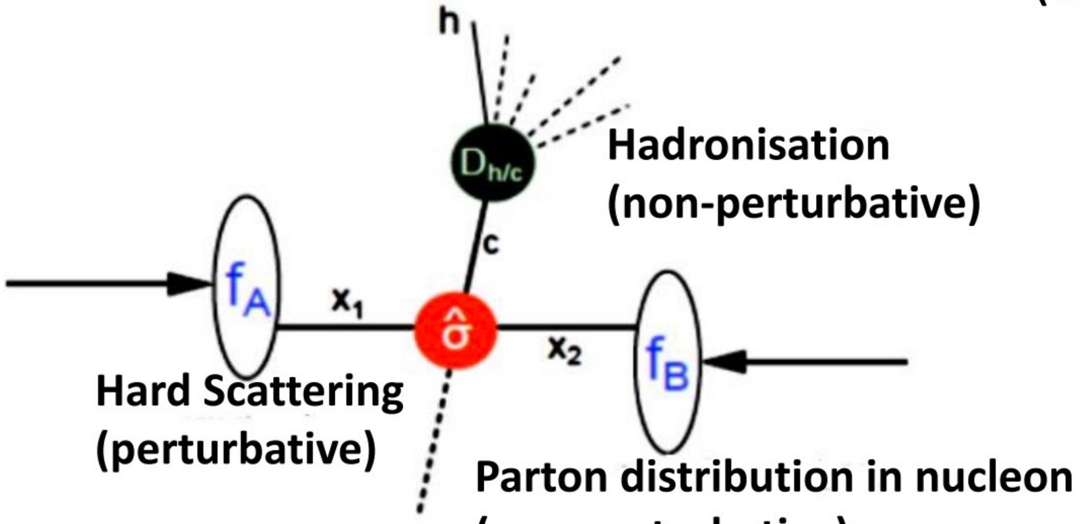
- **Open heavy flavor and quarkonium production in pp**
  - Reference in vacuum, for both CNM and A+A
  - Production mechanism
- **Open heavy flavor and quarkonium production in pA**
  - nPDF
  - Coherent energy loss
  - Nuclear absorption
  - Breakup by co-movers…
- **Open heavy flavor and quarkonium production in AA**

Quarkonium ($c\bar{c}$ and $b\bar{b}$) productions in pp collisions

Production in initial hard-scattering process (Perturbative)

Two Steps

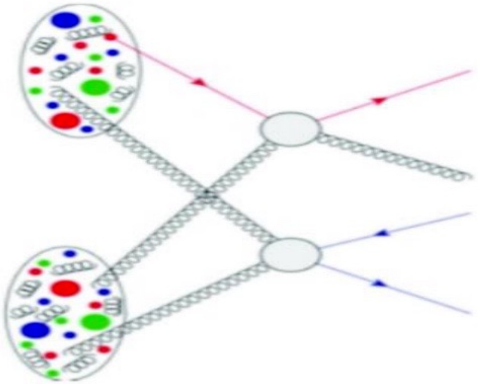
Evolution into colorless bound state (Non-perturbative)



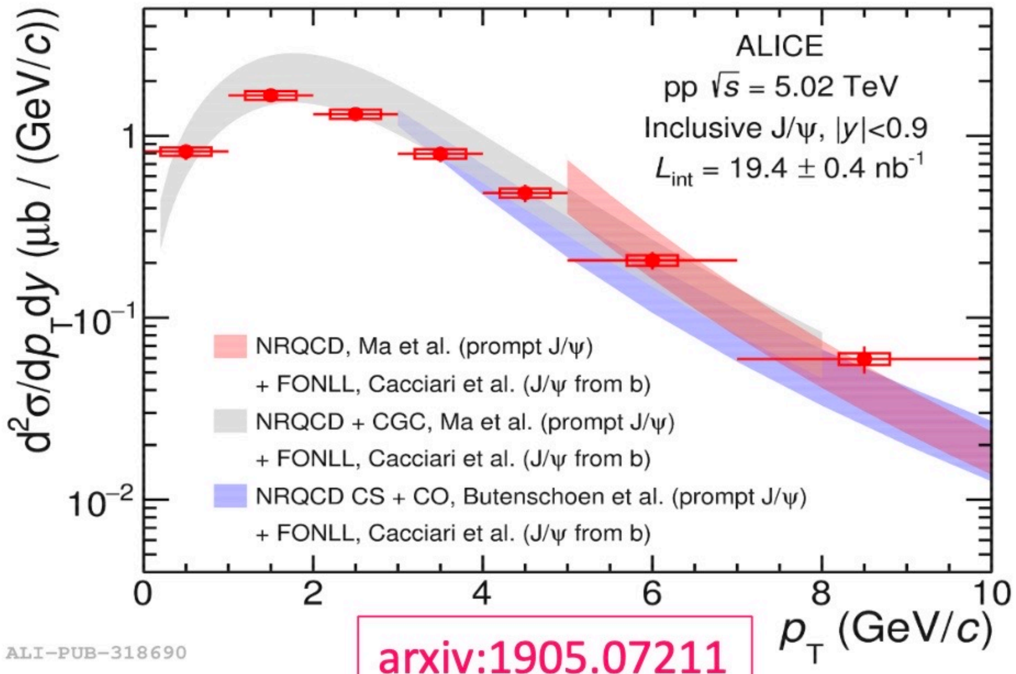
Production cross section provides test ground for several theoretical models

Multiplicity dependent measurements

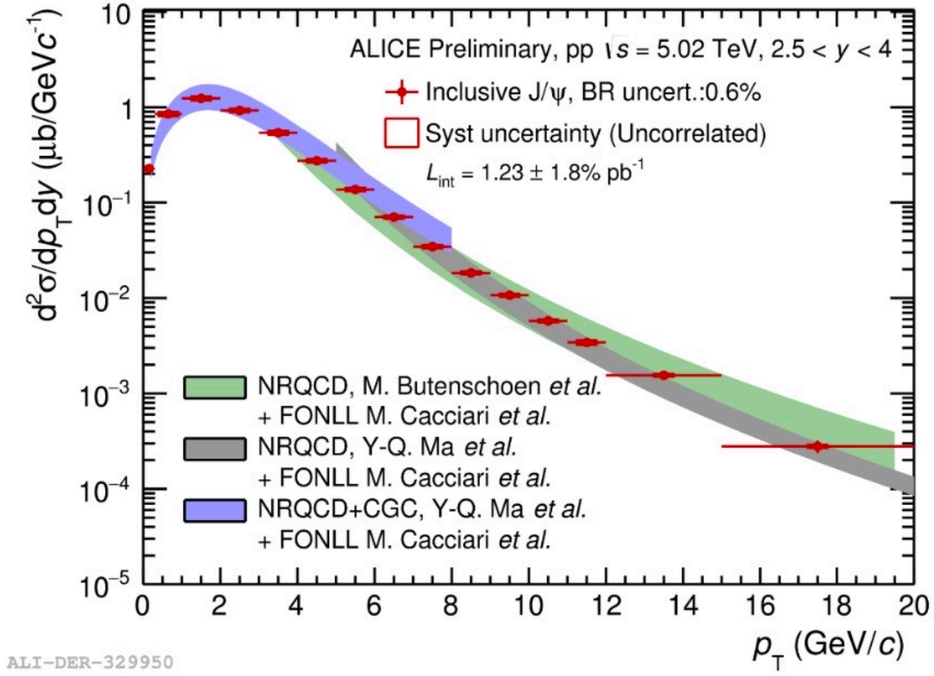
- ❑ Interplay between soft and hard mechanisms of particle production
- ❑ Study the role on Multiple Parton Interactions (MPI)



J/Ψ cross section in pp $\sqrt{s}$ = 5.02 TeV at mid and forward-y

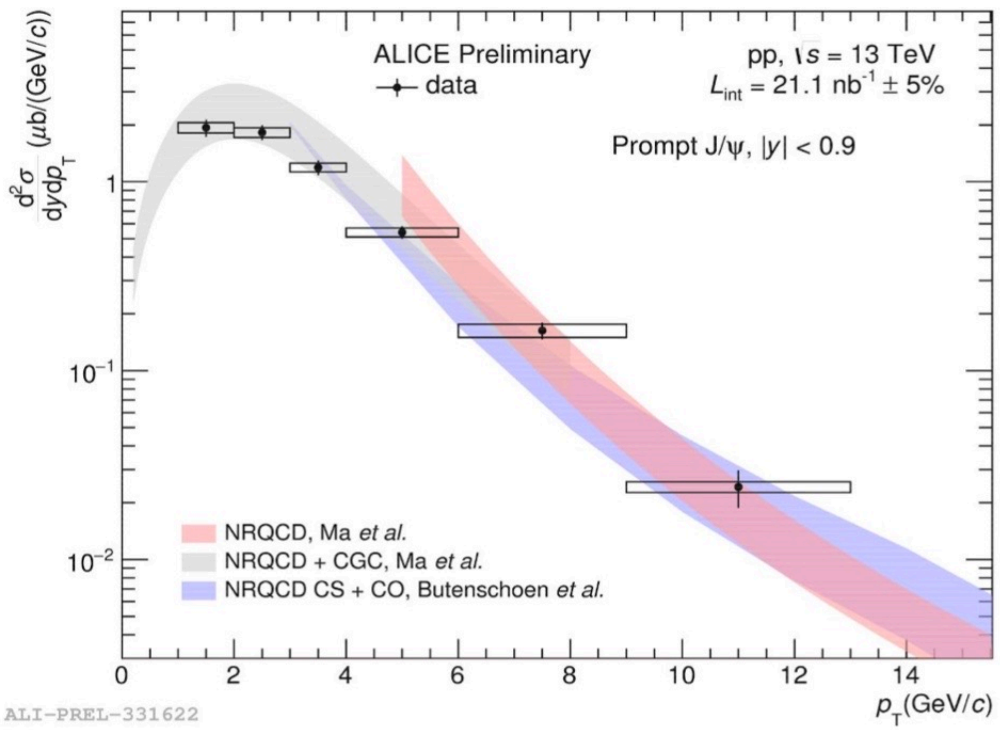


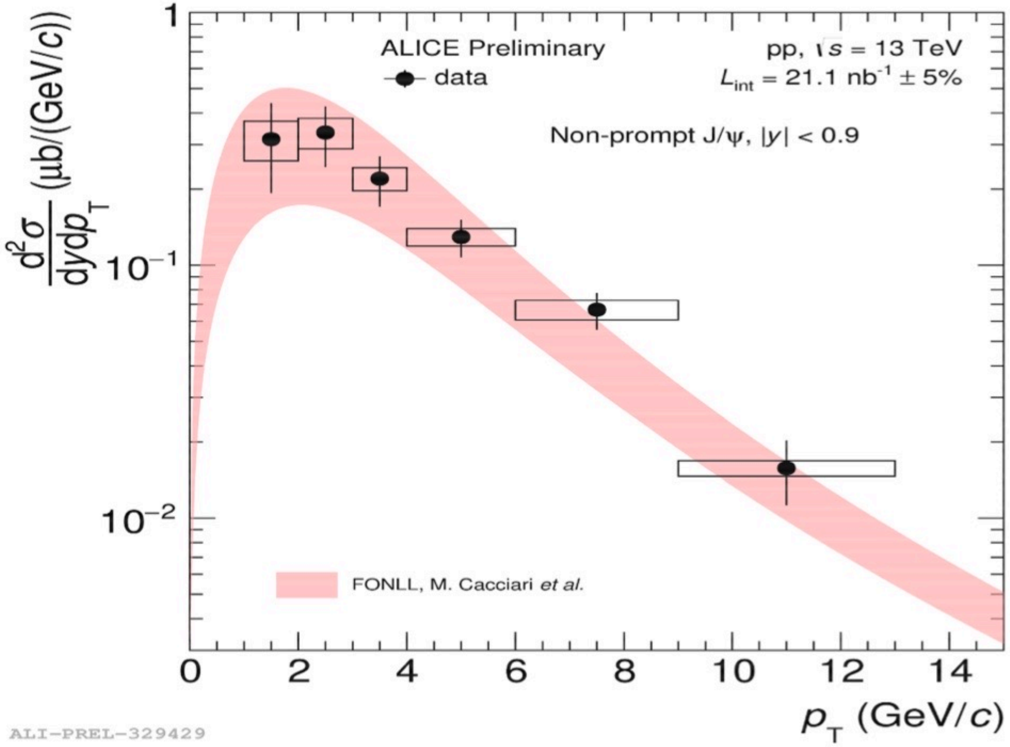
arxiv:1905.07211



- Inclusive (=prompt and non-prompt) measurement
- p_T reach up to 20 GeV/c at forward rapidity, to be used as pp reference for R_{AA} analysis in Pb-Pb collisions
- J/Ψ cross section for p_T < 8 GeV/c is well described by NRQCD+CGC model
- NRQCD+FONLL (for non-prompt contribution) describes the data throughout the whole p_T range at forward rapidity.

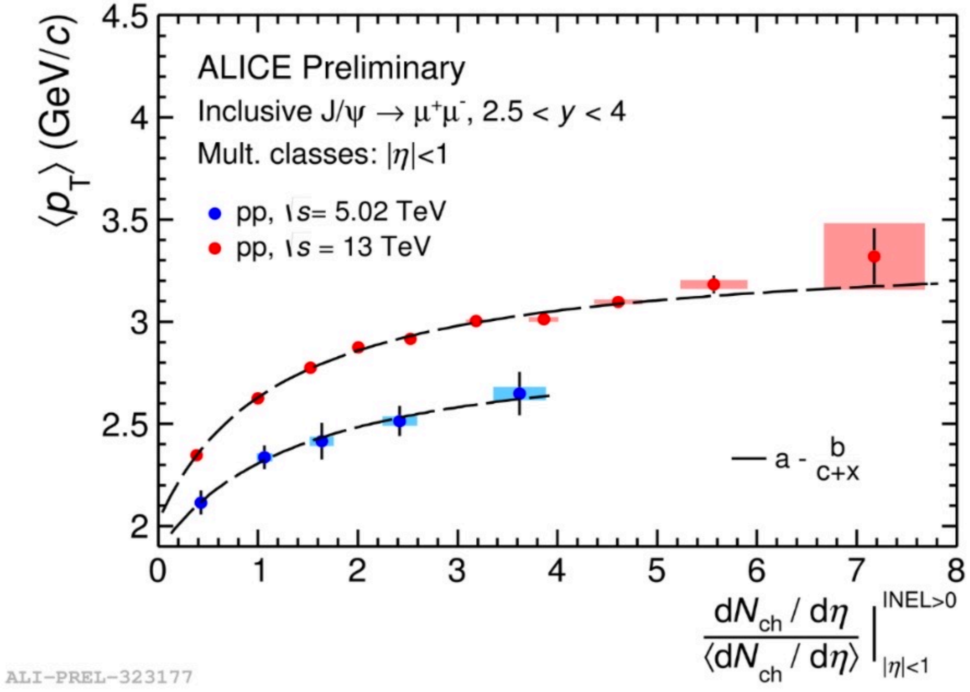
Prompt/non-prompt J/Ψ cross section in pp $\sqrt{s}$ = 13 TeV at mid-*y*

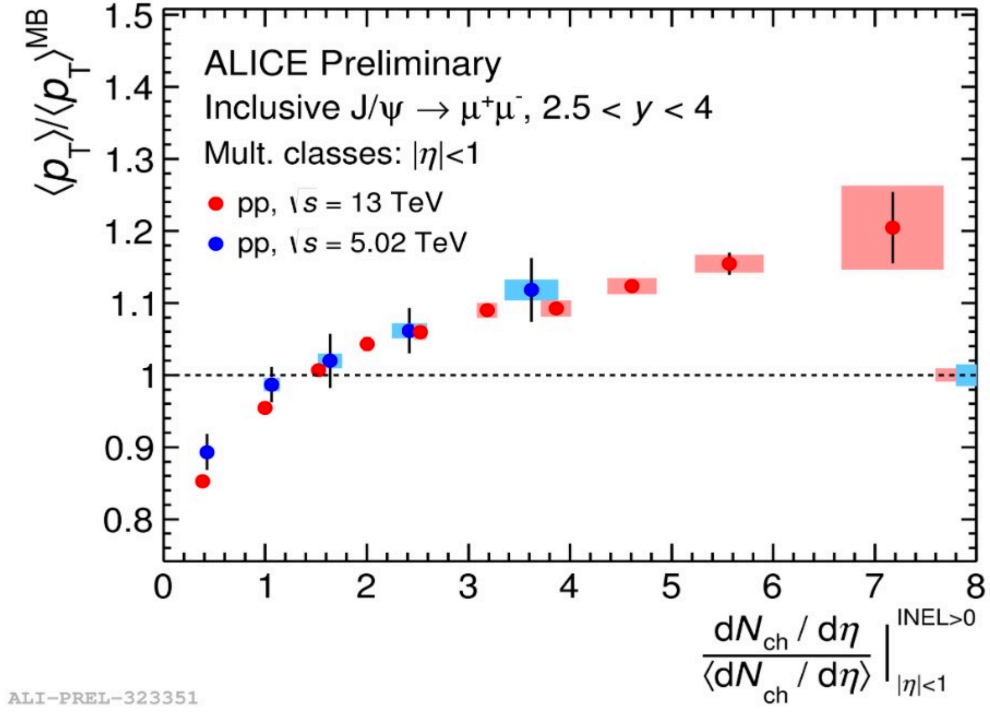




- Theoretical models compared to the data
- NRQCD (+CGC at low p_T describe well the prompt J/Ψ measurements
- FONLL describe well the non-prompt J/Ψ cross section

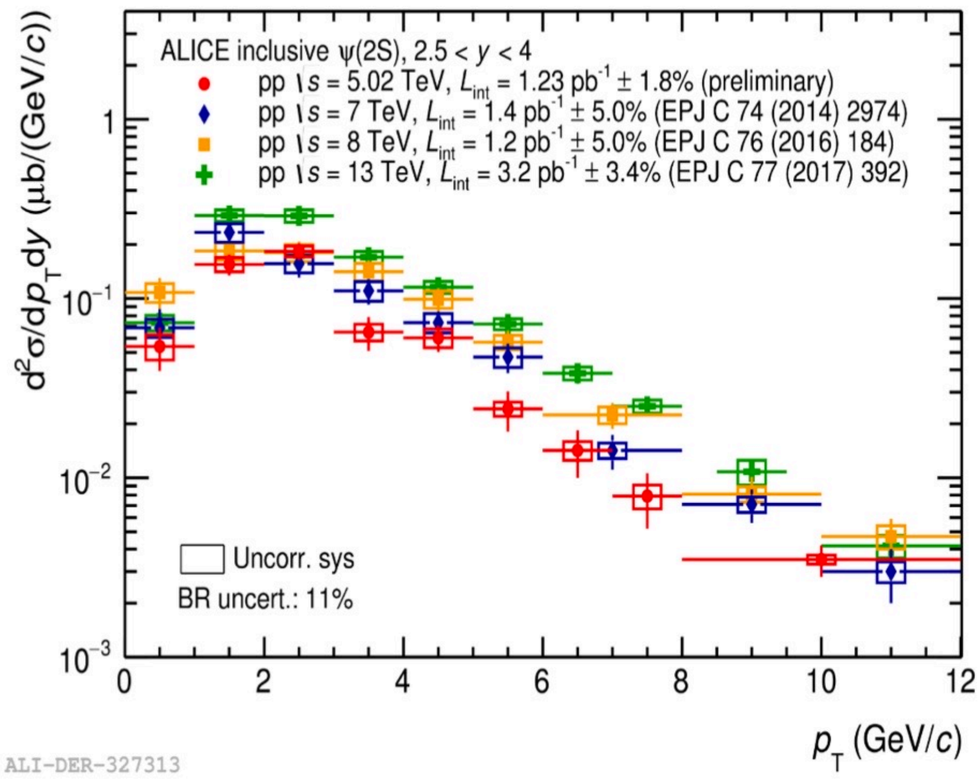
J/Ψ production vs multiplicity in pp $\sqrt{s}$ = 5.02 and 13 TeV

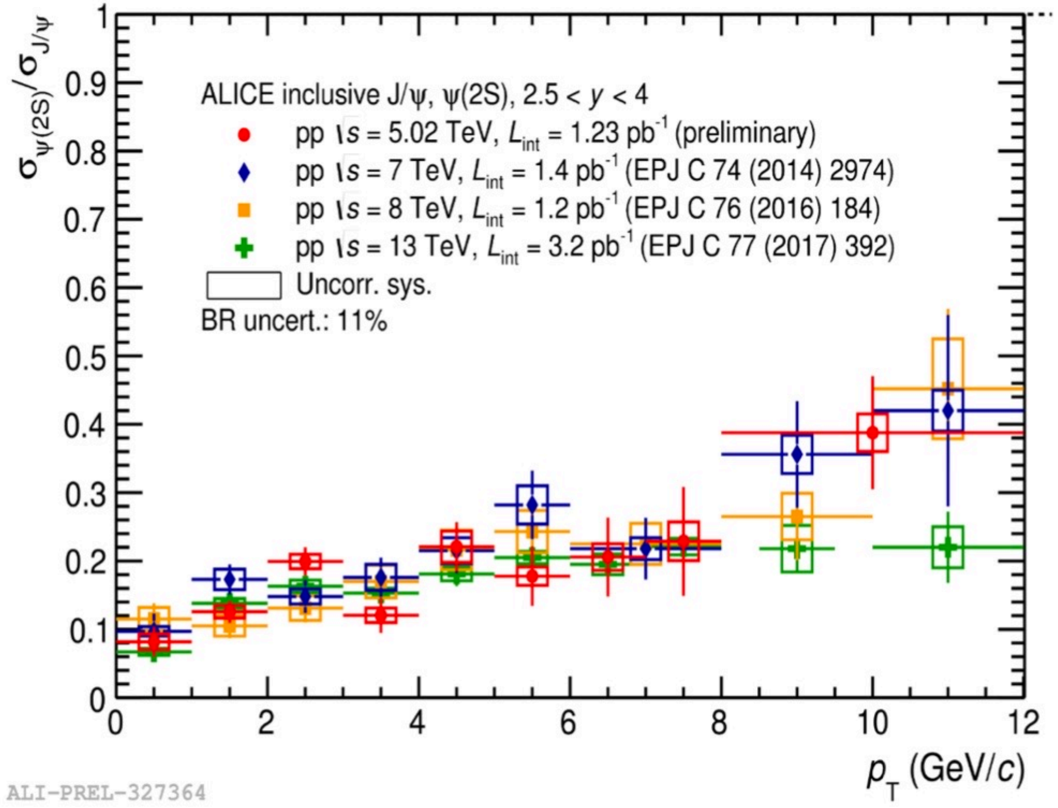




- An increase of $\langle p_T \rangle$ of J/ψ is observed in low multiplicity region, and a saturation towards high multiplicity for both collision energies.
- Relative $\langle p_T \rangle$ is independent of centre-of-mass energy

$\Psi(2S)$ cross section in pp $\sqrt{s}$ = 5.02 TeV at forward rapidity

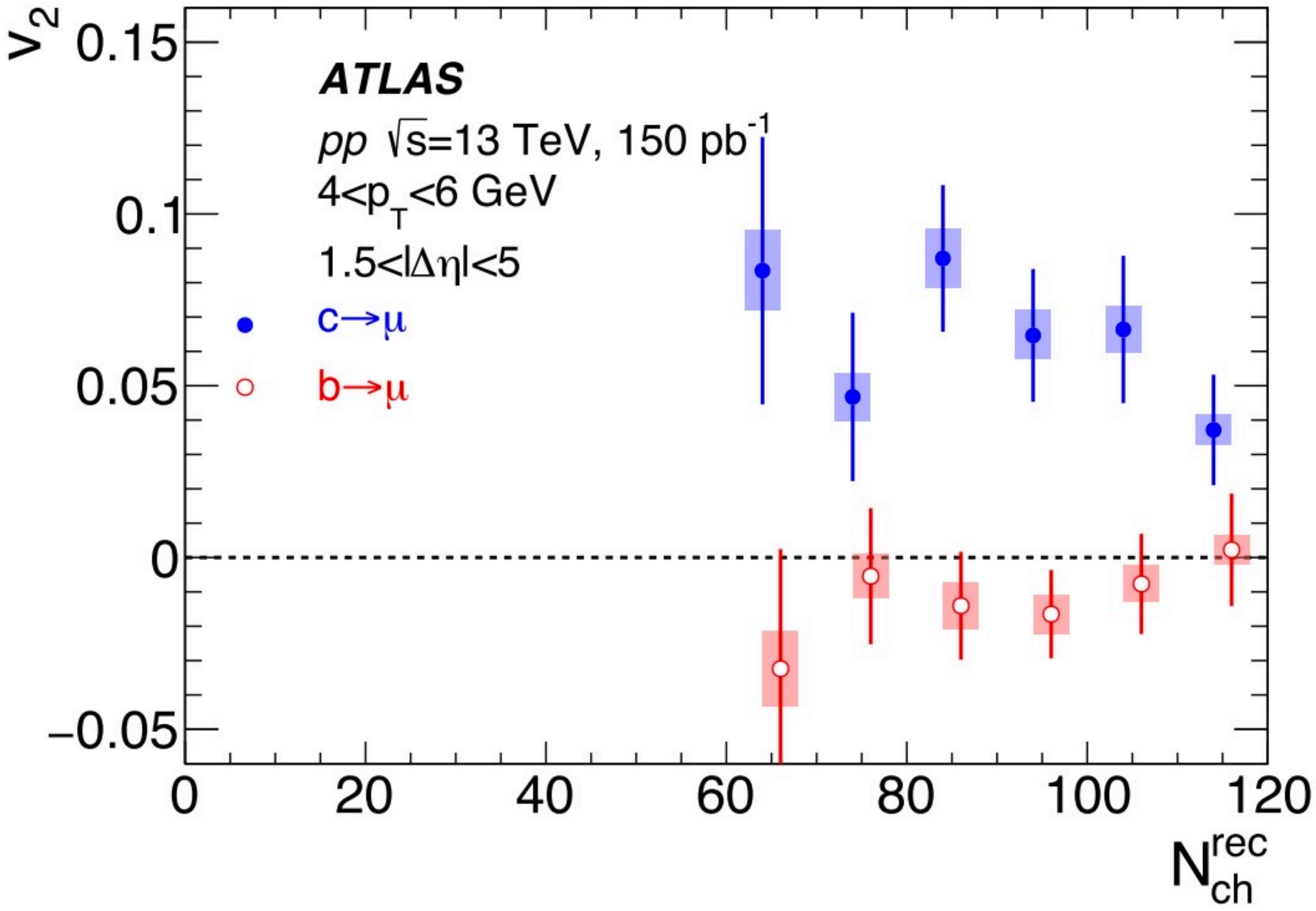




No change in shape or magnitude of the $\Psi(2S)$ to J/Ψ ratio as a function of p_T with collision energies

HF azimuthal anisotropy in *pp* collisions

PRL 124 (2020) 082301

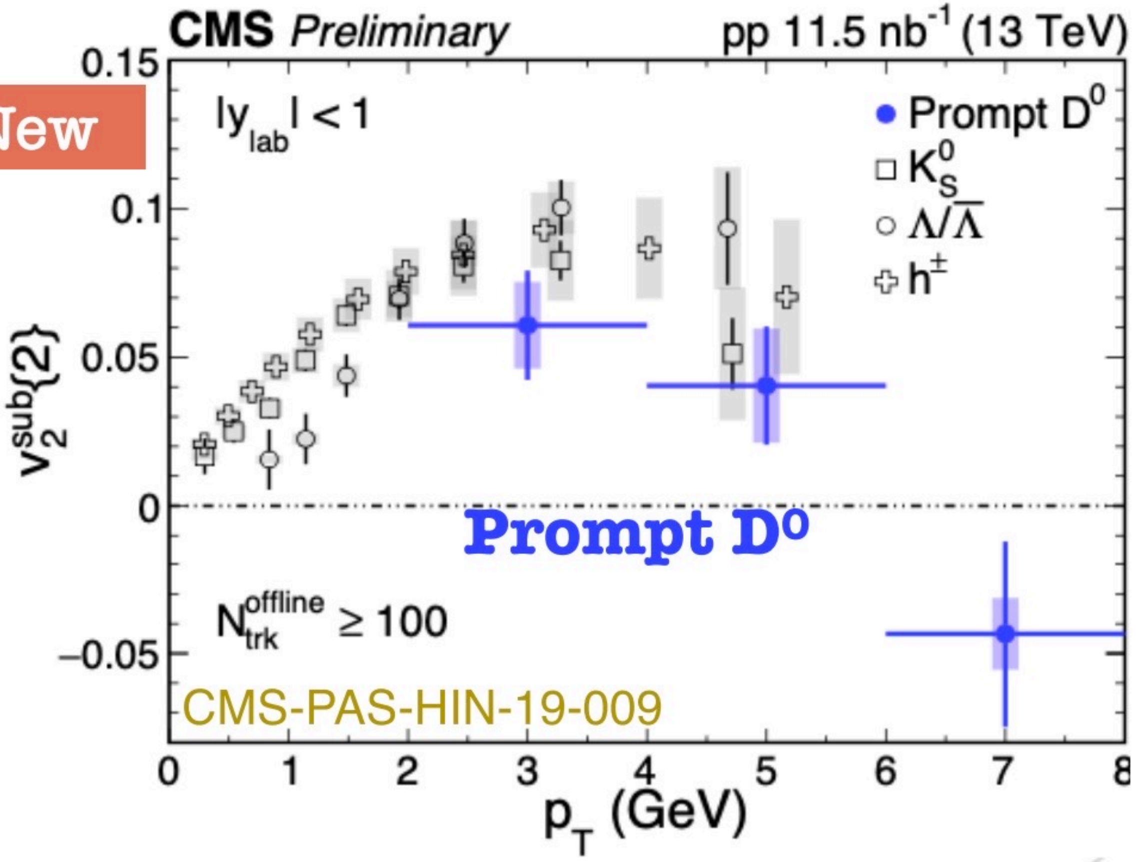


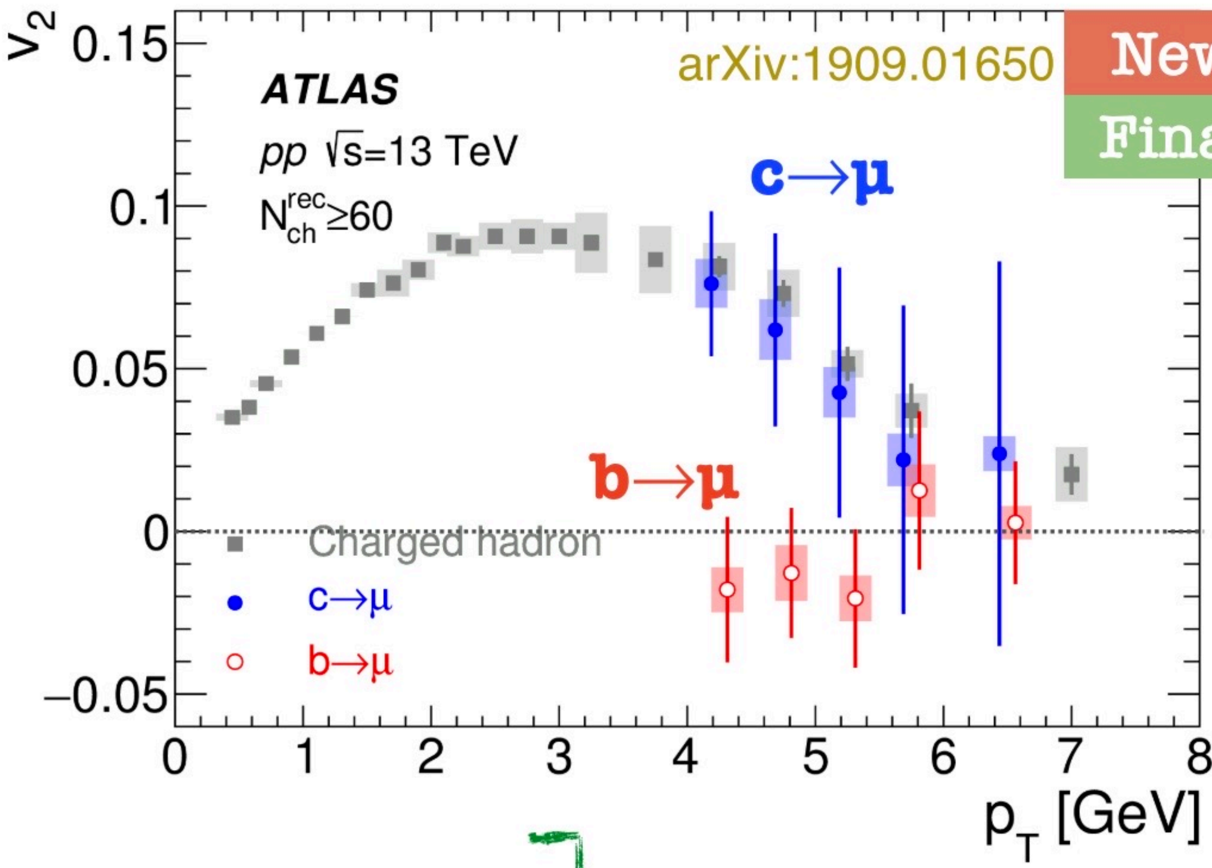
Collective phenomena in small system (*pp*)

A.A. Baty, 5 Nov, 08:40
S. Lim, 5 Nov, 09:00

v_2 in high-multiplicity pp

New





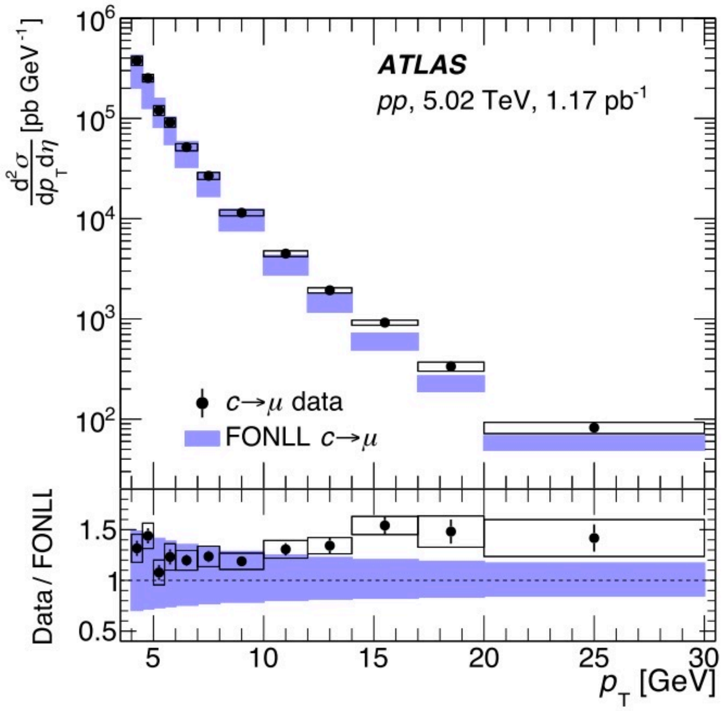
New
Final

- v_2 (open charm) <≈ v_2 (light) at intermediate p_T
- v_2 (open beauty) ≈ 0

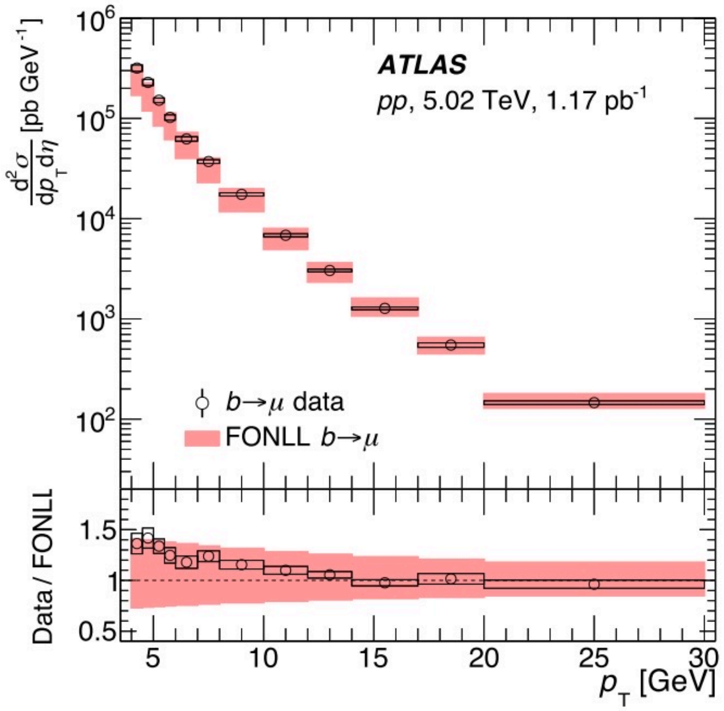
similar w/ pPb

HF production in *pp* collisions

arXiv:2109.00411

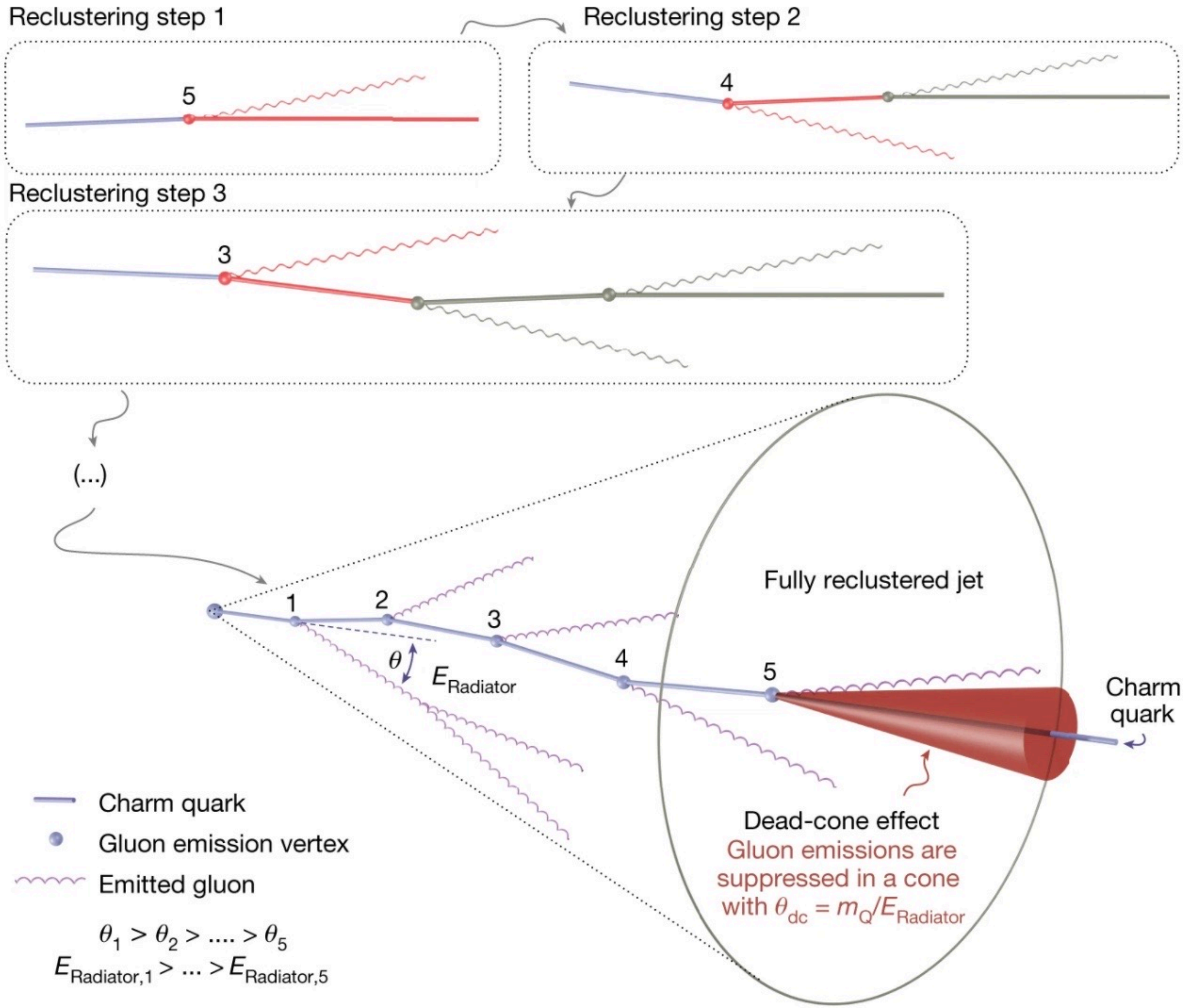


Charm muon

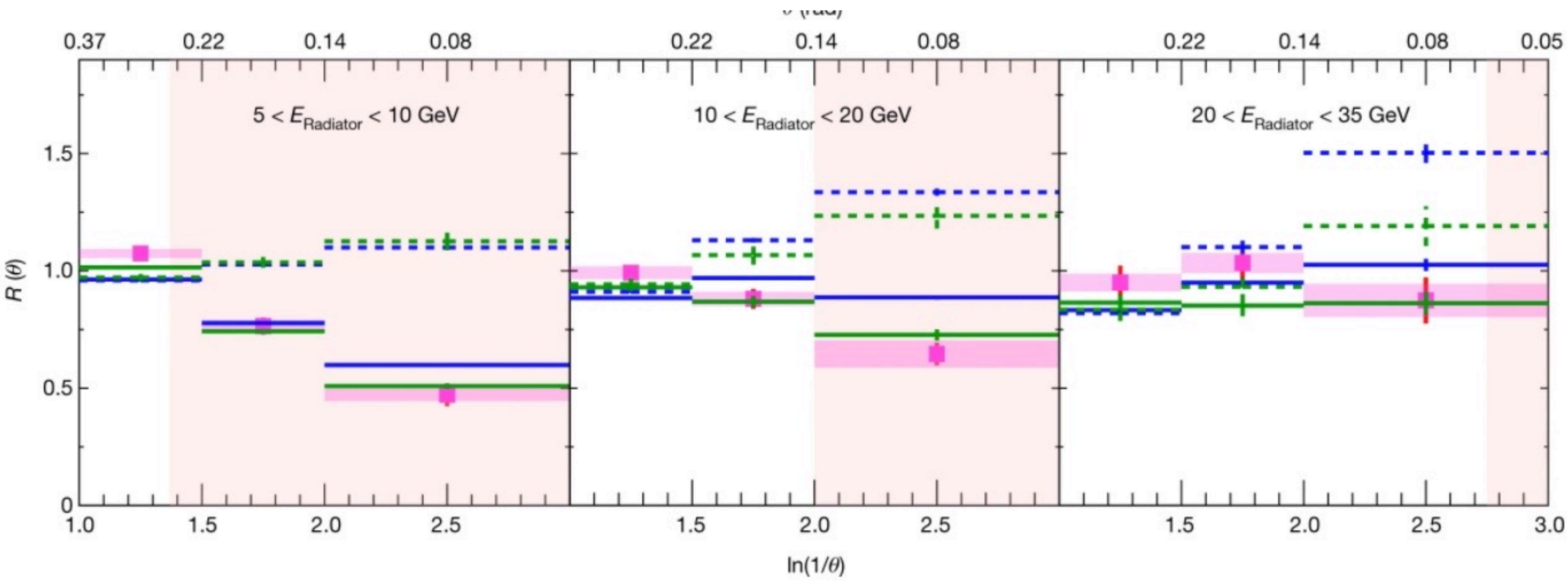


Bottom muon

- **Charm muon** data lay at the upper boundary of **FONLL** uncertainty
- **Bottom muon** data agree with **FONLL**
- Consistent picture with other HF measurements (e.g. ALICE *D*'s: arXiv:2102.13601)



Reclustering step 1
5
Reclustering step 2
4
Reclustering step 3
3
(...)
Fully reclustered jet
1
2
3
4
5
θ
$E_{Radiator}$
Charm quark
Dead-cone effect
Gluon emissions are suppressed in a cone with $\theta_{dc} = m_Q/E_{Radiator}$
Charm quark
Gluon emission vertex
Emitted gluon
$\theta_1 > \theta_2 > .... > \theta_5$
$E_{Radiator,1} > ... > E_{Radiator,5}$

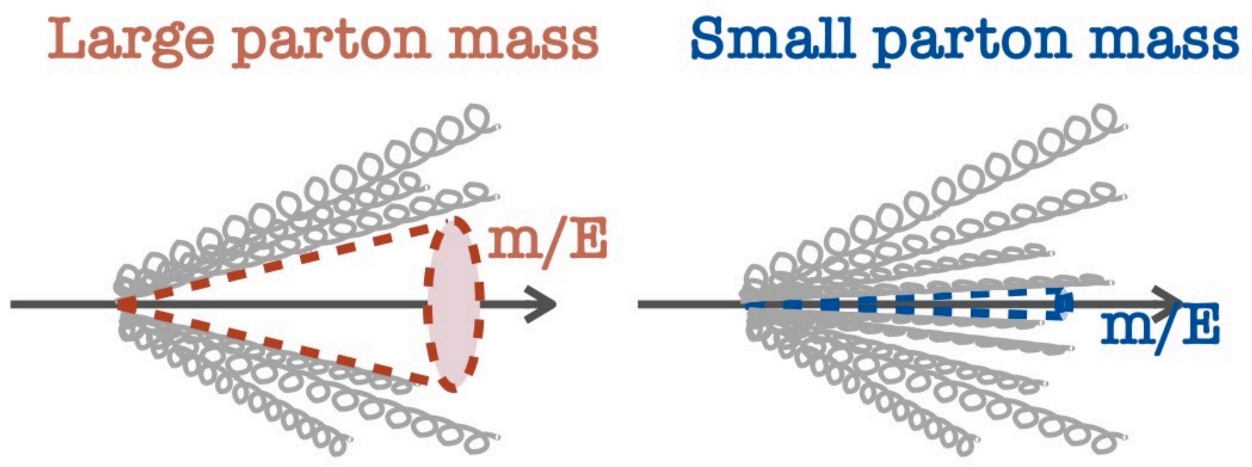


The ratios of the splitting-angle probability distributions for D^0-meson tagged jets to inclusive jets, $R(\theta)$, measured in proton–proton collisions at $\sqrt{s} = 13$ TeV, are shown for $5 < E_{Radiator} < 10$ GeV (left panel), $10 < E_{Radiator} < 20$ GeV (middle panel) and $20 < E_{Radiator} < 35$ GeV (right panel). The data are compared with PYTHIA v.8 and SHERPA simulations, including the no dead-cone limit given by the ratio of the angular distributions for light-quark jets (LQ) to inclusive jets. The pink shaded areas correspond to the angles within which emissions are suppressed by the dead-cone effect, assuming a charm-quark mass of 1.275 GeV/c^2.

https://www.nature.com/articles/s41586-022-04572-w/figures/2

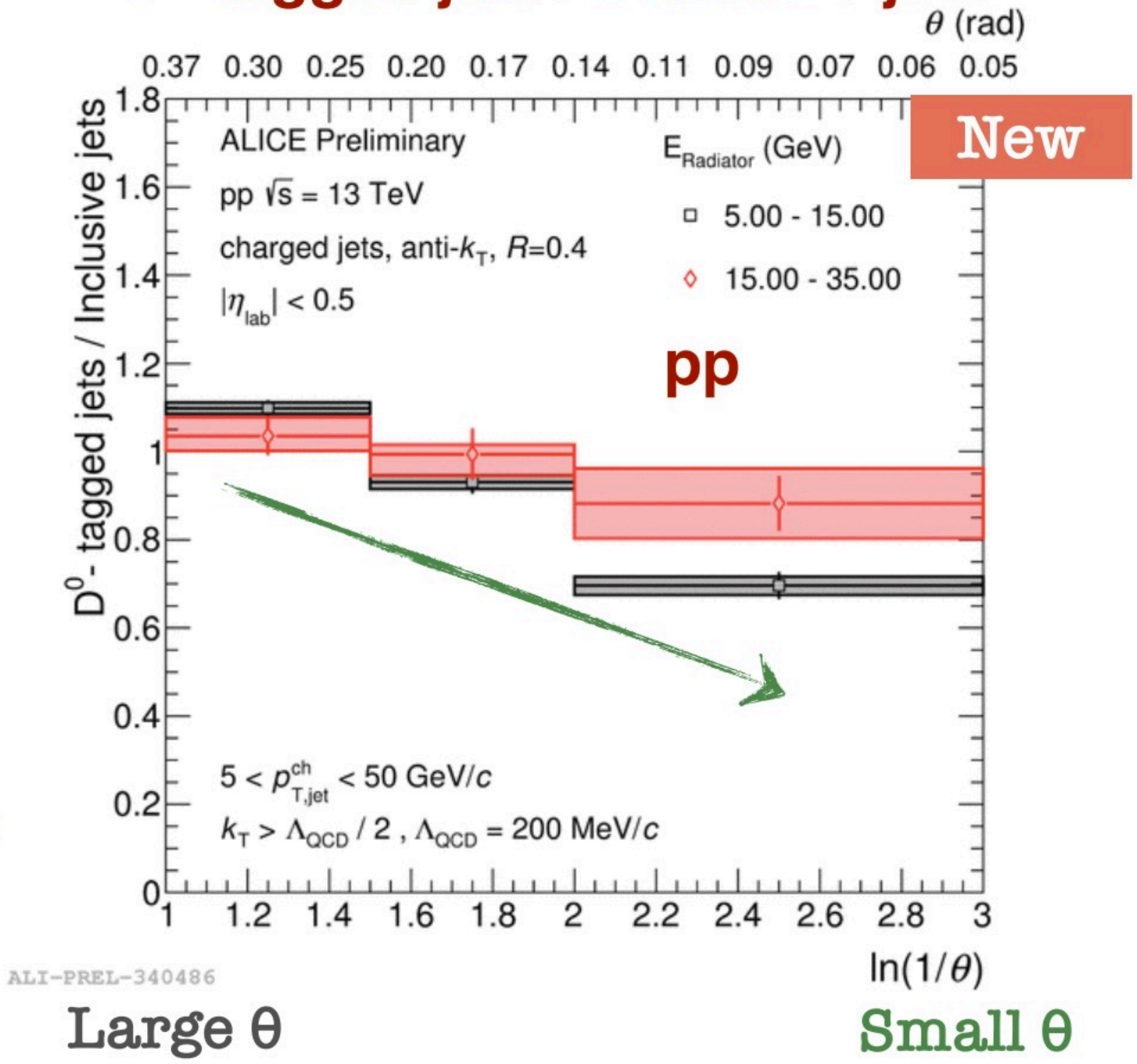
One source of flavor hierarchy: Dead cone effect

- **Dead cone effect**
  ➡ Radiation (for both vacuum and medium induced) is suppressed inside θ < m/E



- **D-tagged jets have lower splitting at small angle**
- First direct observation of dead cone effect!
- Lower-energy radiator has stronger effect

D⁰-tagged jets / Inclusive jets

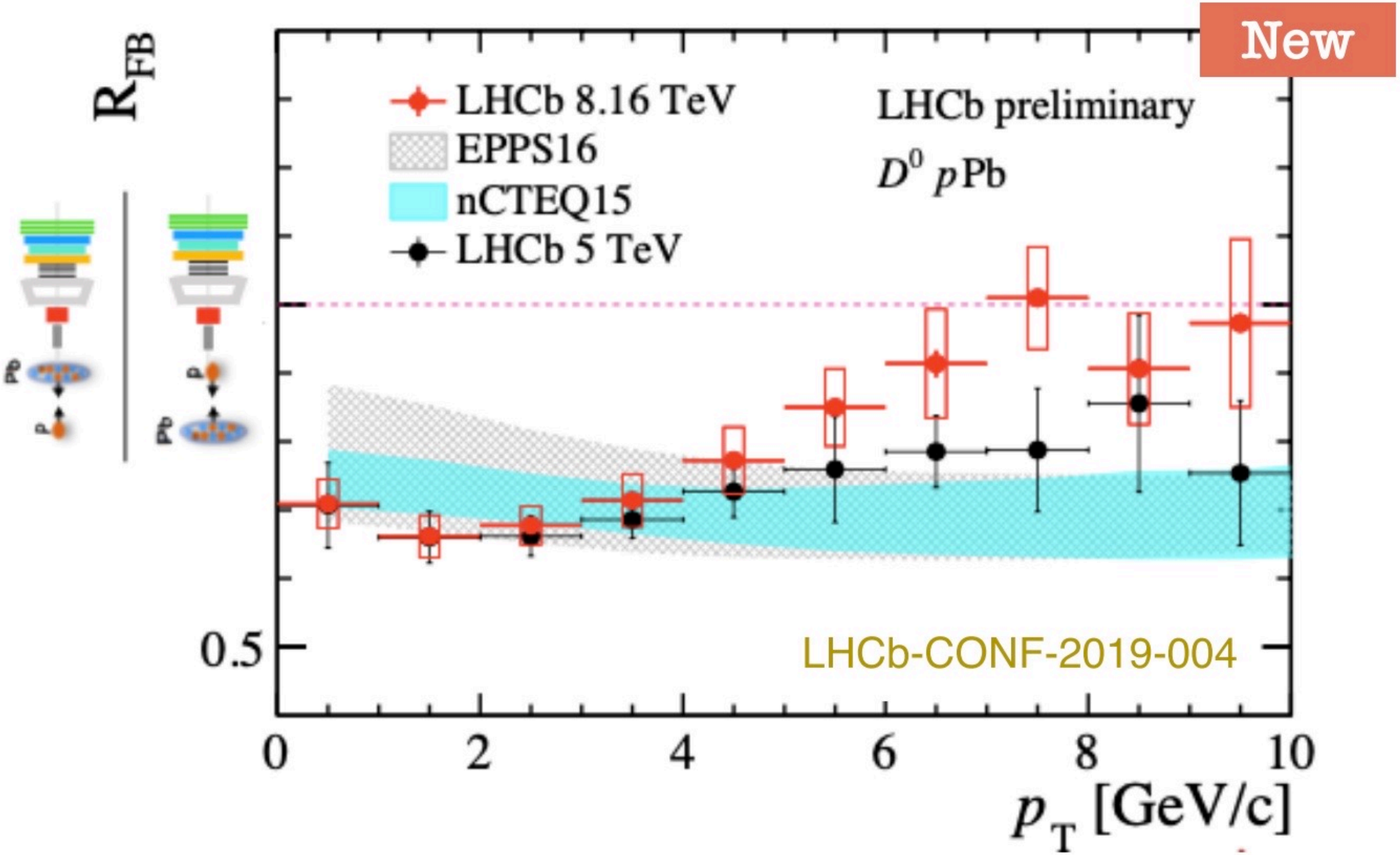


In heavy quark sector, the first estimate of radiative energy loss in the QGP medium was made by Mustafa [192]. For heavy quarks, there is an important effect named "dead cone" effect. It means that, the heavy quark mass suppresses the soft gluon radiation off heavy quarks with energy E in forward-direction within angle smaller than $\theta_D = m_Q/E$. Subsequently, the gluon bremsstrahlung of heavy quark energy loss is suppressed by a factor of $\mathcal{D}_{DK} = (1 + \theta_D^2/\theta^2)^{-2}$ compared to light parton energy loss, and the enhancement of heavy-to-light hadron ratio is predicted in high transverse momentum regime [193]. Based on the GLV opacity expansion, DGLV [194] derived the heavy quark energy loss due to medium-induced gluon radiation to all orders in opacity. To first order in opacity, the heavy quark total radiative energy loss including the plasmon asymptotic mass is

$$\frac{\Delta E}{E} = \int dx d^2 k_\perp x \frac{dn_g}{dx d^2 k_\perp}, \tag{71}$$

PA

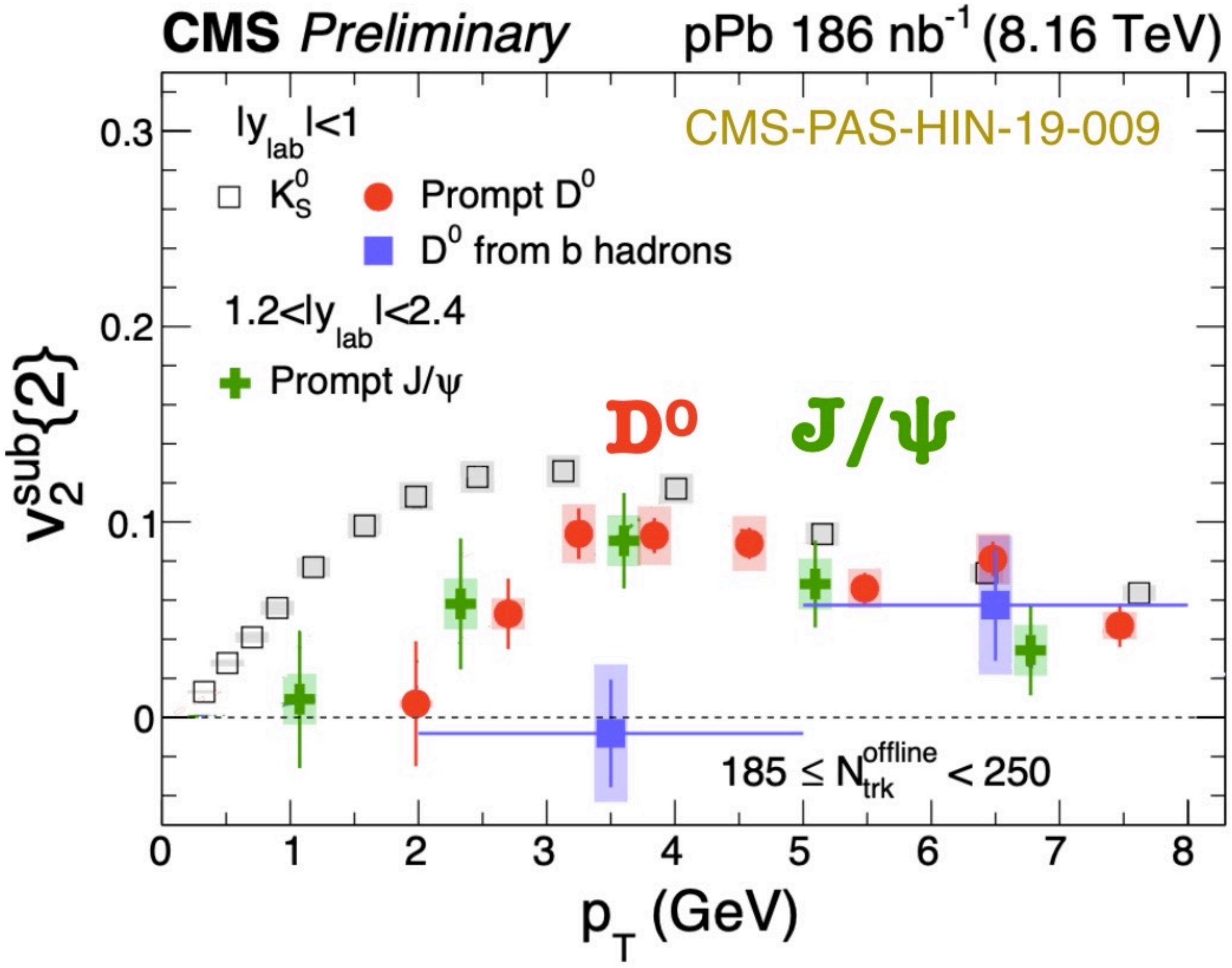
Constrain nPDF

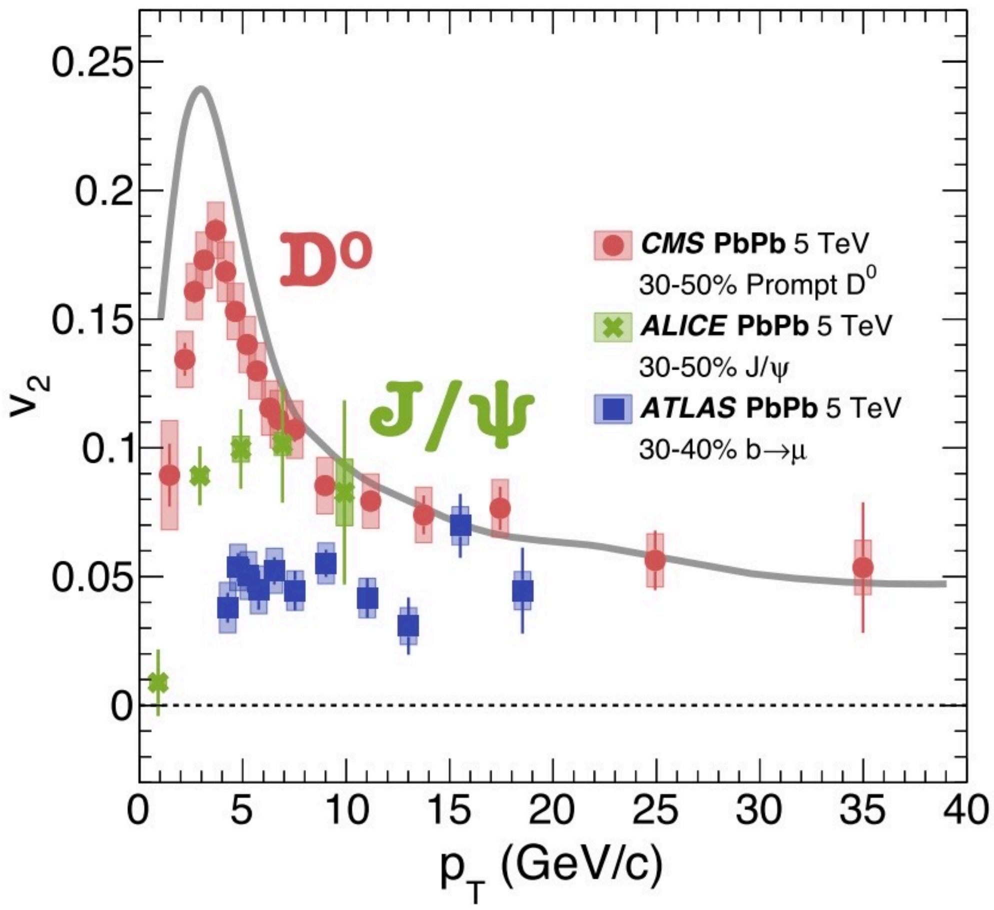


- D meson in pPb contributes to constraining gluon nPDF down to x~10[-5]
- Tension between data and nPDF model predictions?

Collective phenomena in small system (*pA*)

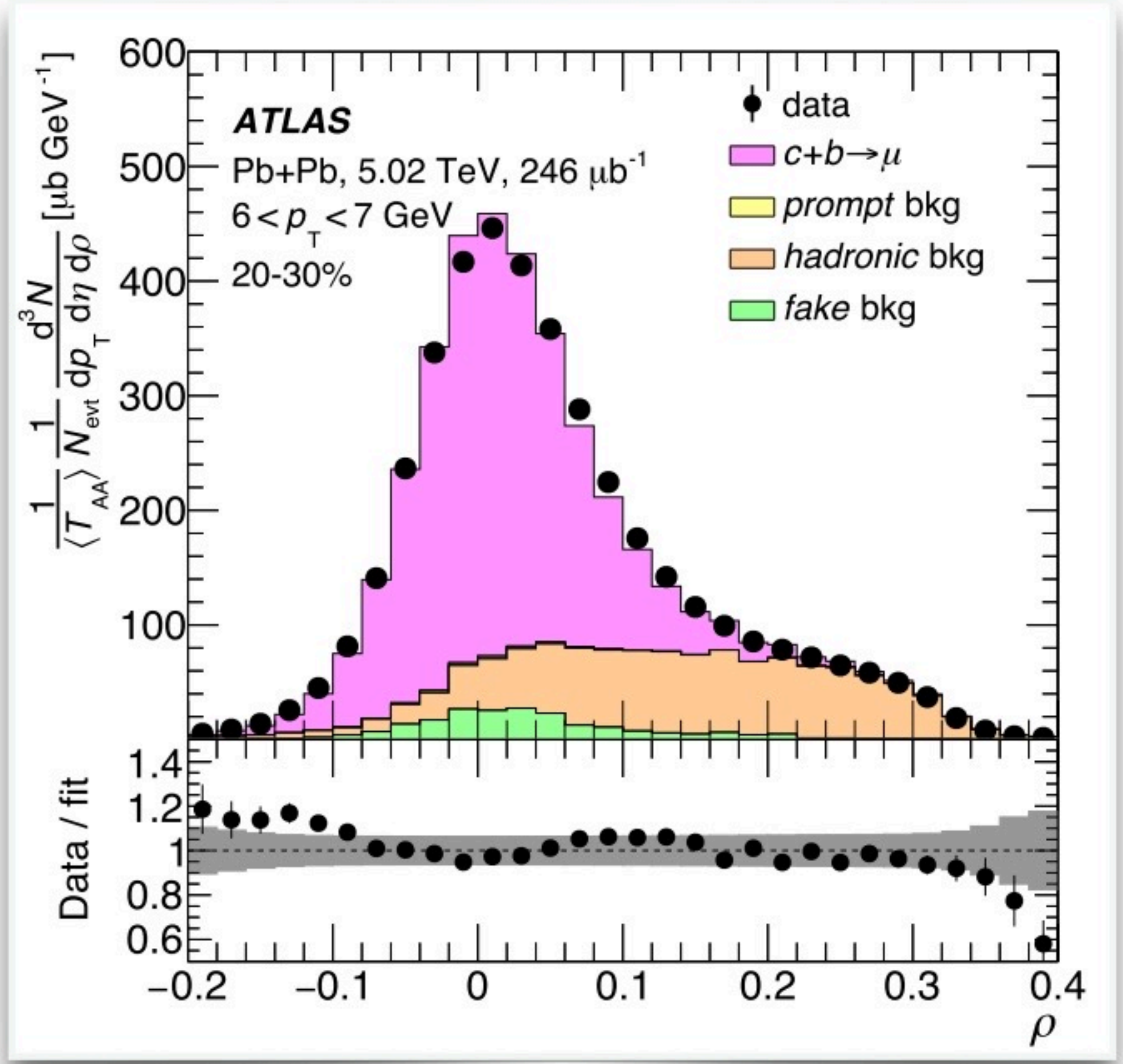
pPb | **PbPb**





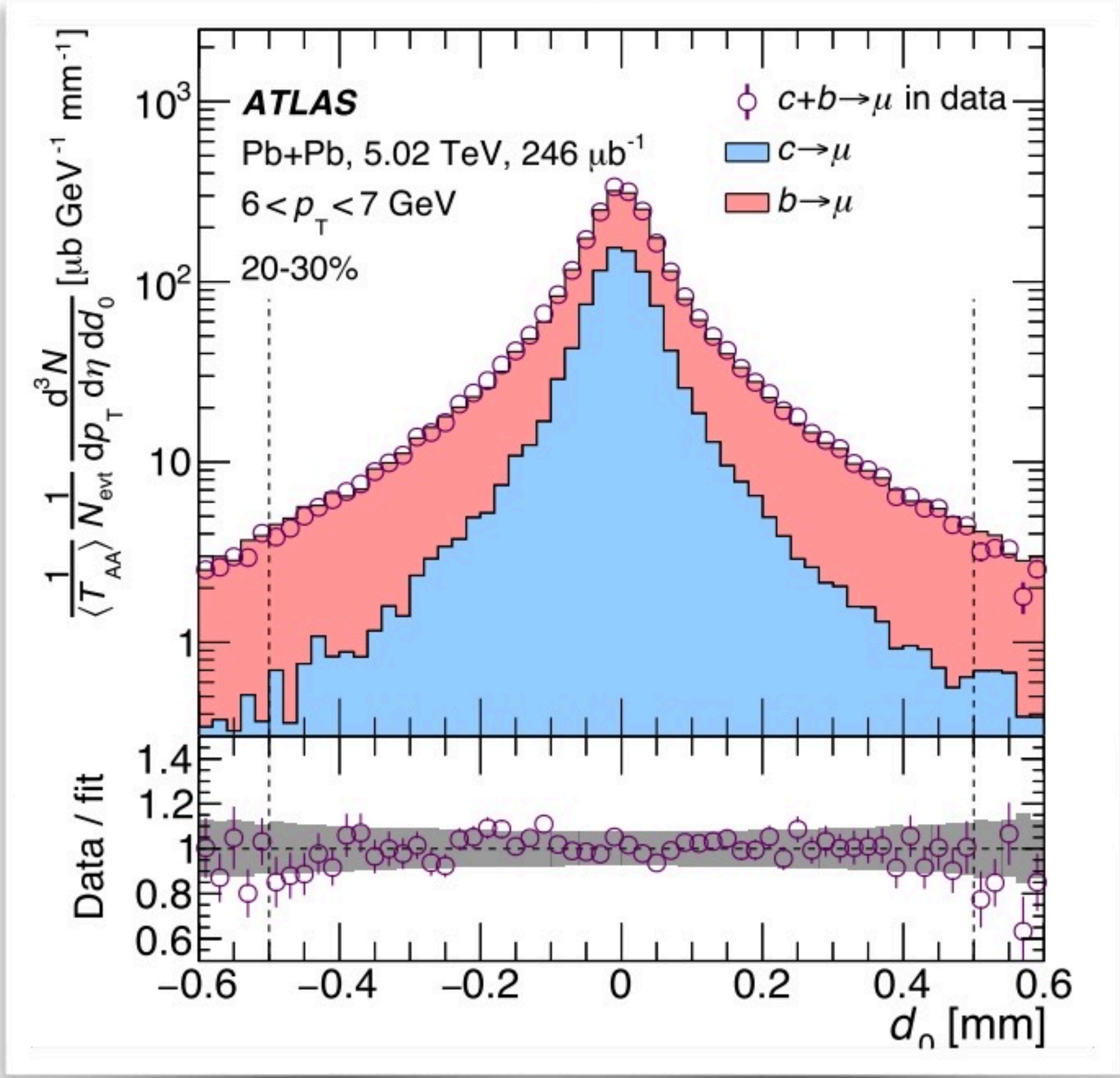
- $v_2(\mathbf{D^0}) \approx v_2(\mathbf{J/\psi})$ in pPb: final state interactions cannot explain

A.A. Baty, 5 Nov, 08:40



Background removed using **ID-MS** momentum difference:

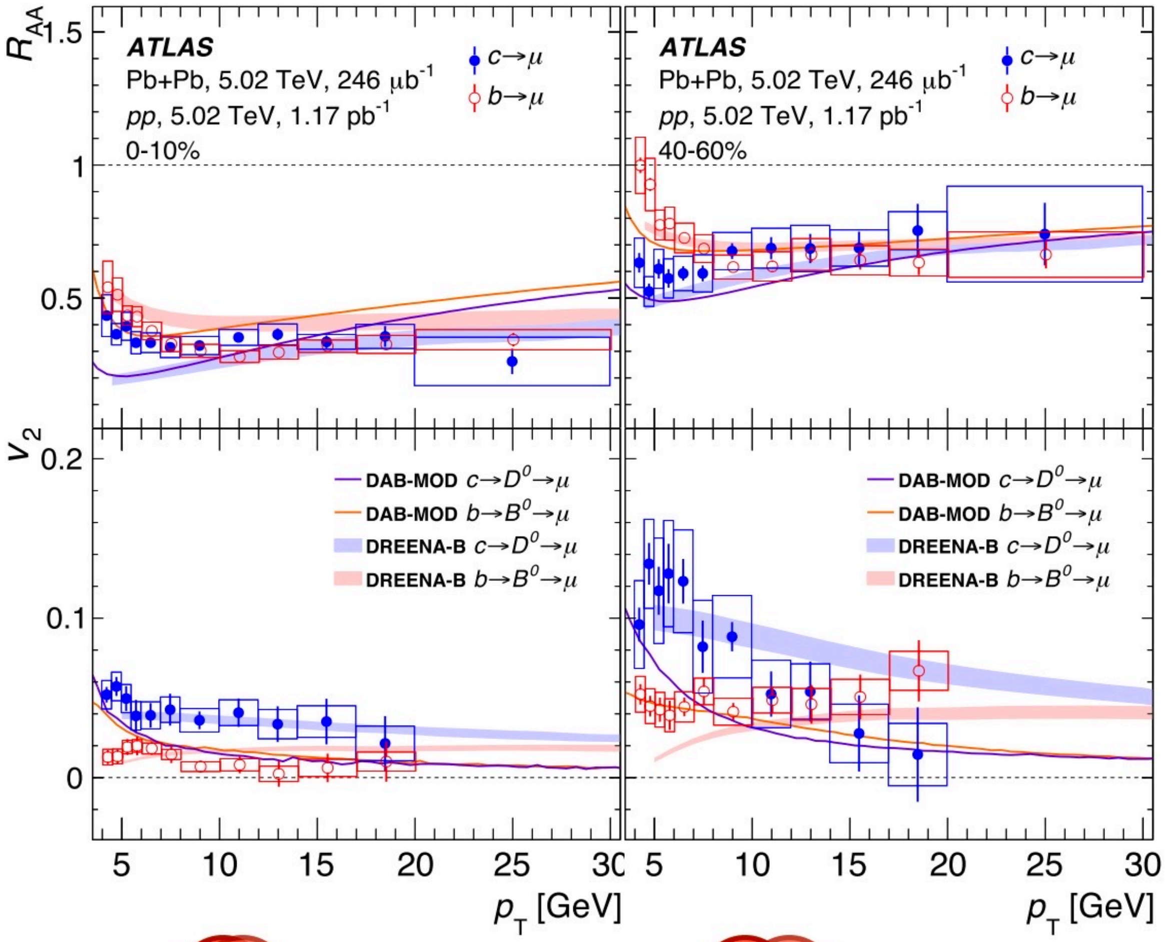
$$\rho = (p_T^{ID} - p_T^{MS})/p_T^{ID}$$



Charm / **bottom** separated via ID impact parameter (DCA): d_0

R_{AA} vs. v_2 — model comparison

R_{AA}: arXiv:2109.00411
v_2: PLB 807 (2020) 135595
DAB-MOD: R. Katz et al. PRC 102 (2020) 024906
DREENA-B: D. Zigic et al. PLB 791 (2019) 236



0-10%

40-60%

- **DAB-MOD** Langevin
- **DREENA-B** dynamical radiative + collisional E_{loss}

Other centrality bins can be found at web

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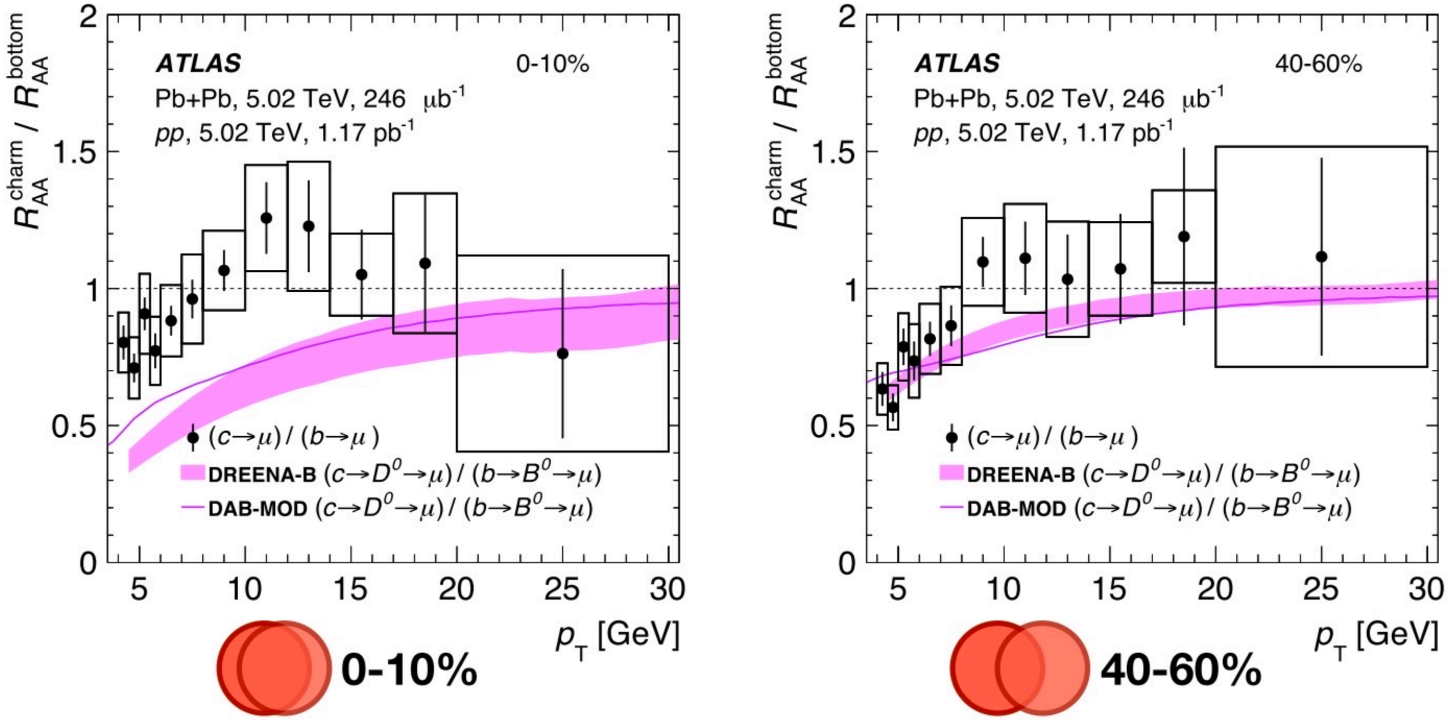
Charm to bottom double ratio

arXiv:2109.00411



- Large uncertainties due to strong anti-correlation between charm and bottom
- **Charm is more suppressed than bottom** at low p_T; comparable at high p_T
- In radiation picture: mass hierarchy inline with “dead-cone” effect

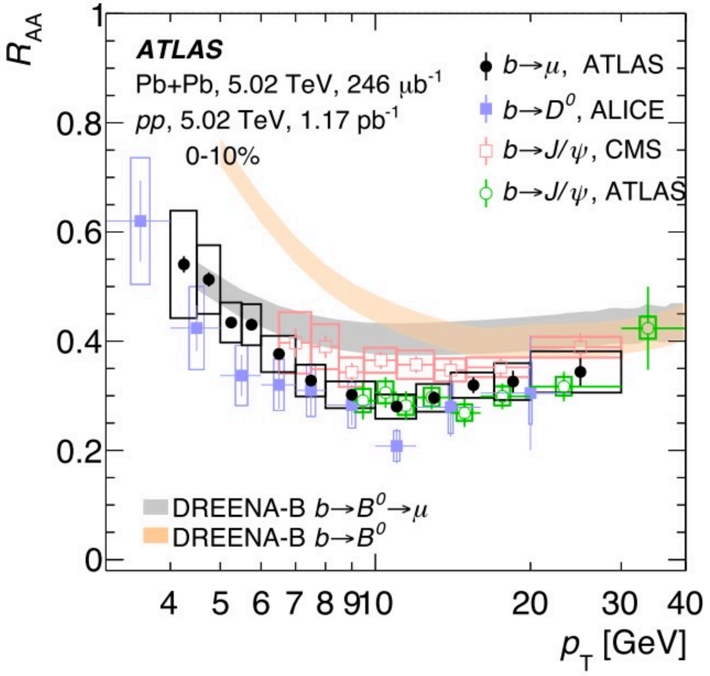
$$dP_{Rad;Q}(\theta) \propto \left(1 + \left(\frac{M_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

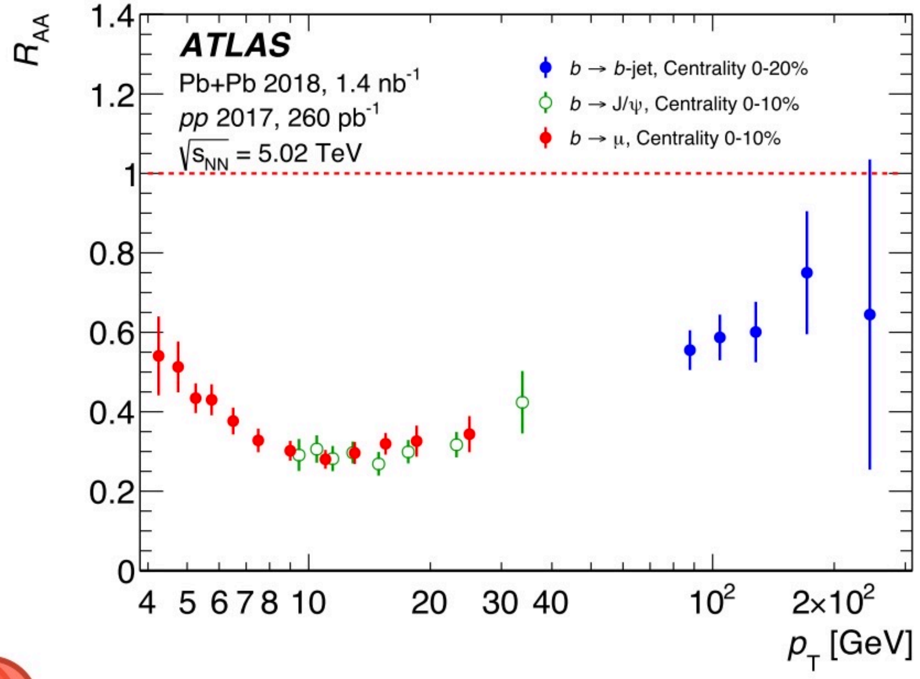
Other centrality bins can be found at web

8

ATLAS muon: arXiv:2109.00411
ATLAS J/ψ: EPJC 78 (2018) 762
ATLAS b-jet: HION-2018-24
ALICE D^0: arXiv:2202.00815
CMS J/ψ: EPJC 78 (2018) 509

Comparison — bottom R_{AA}



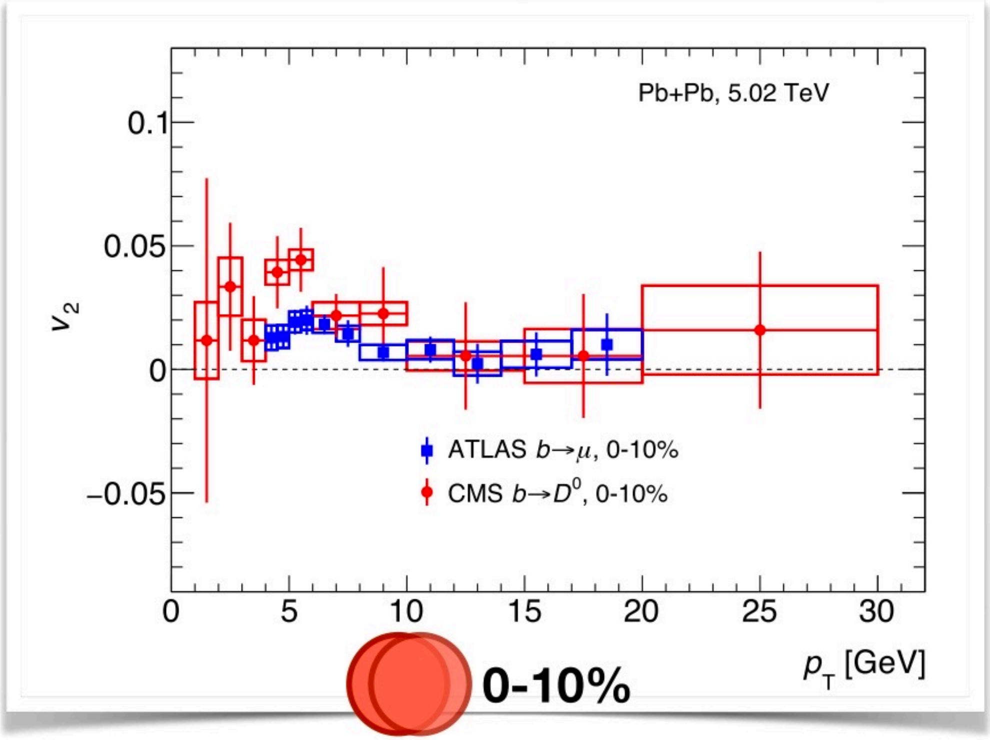


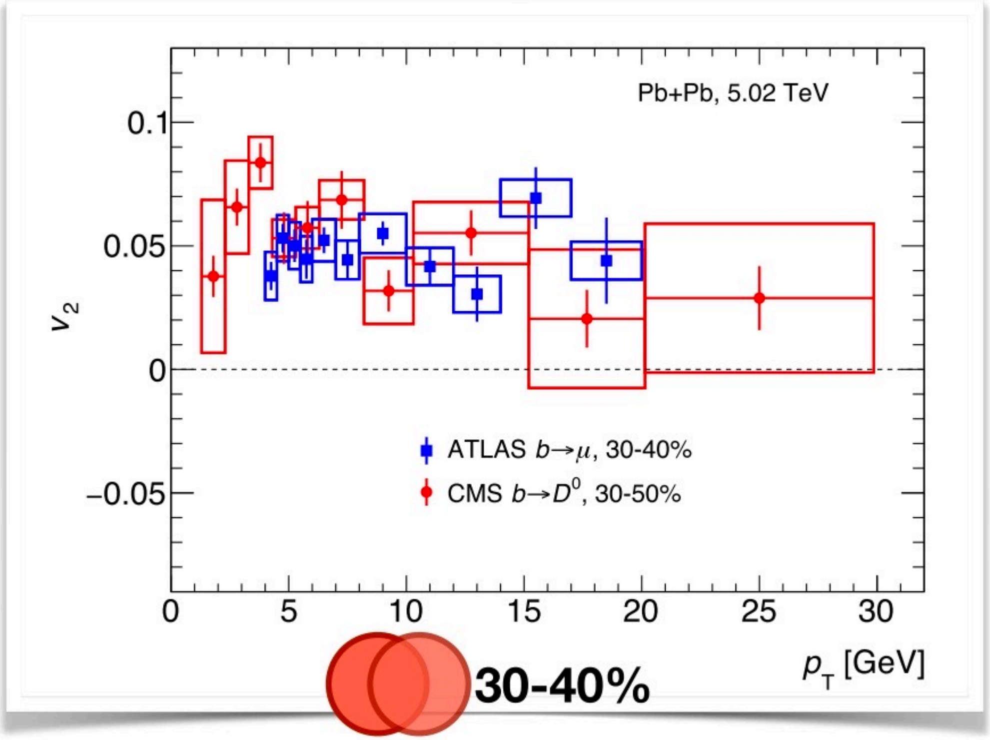
0-10%

- B-decay (muon, D^0, J/ψ) in 0-10% in comparison to **DREENA-B**
- B-decay and (muon-tagged) b-jet show smooth trend in wide p_T range

Comparison — bottom v_2

ATLAS muon: PLB 807 (2020) 135595
CMS D^0: HIN-21-003

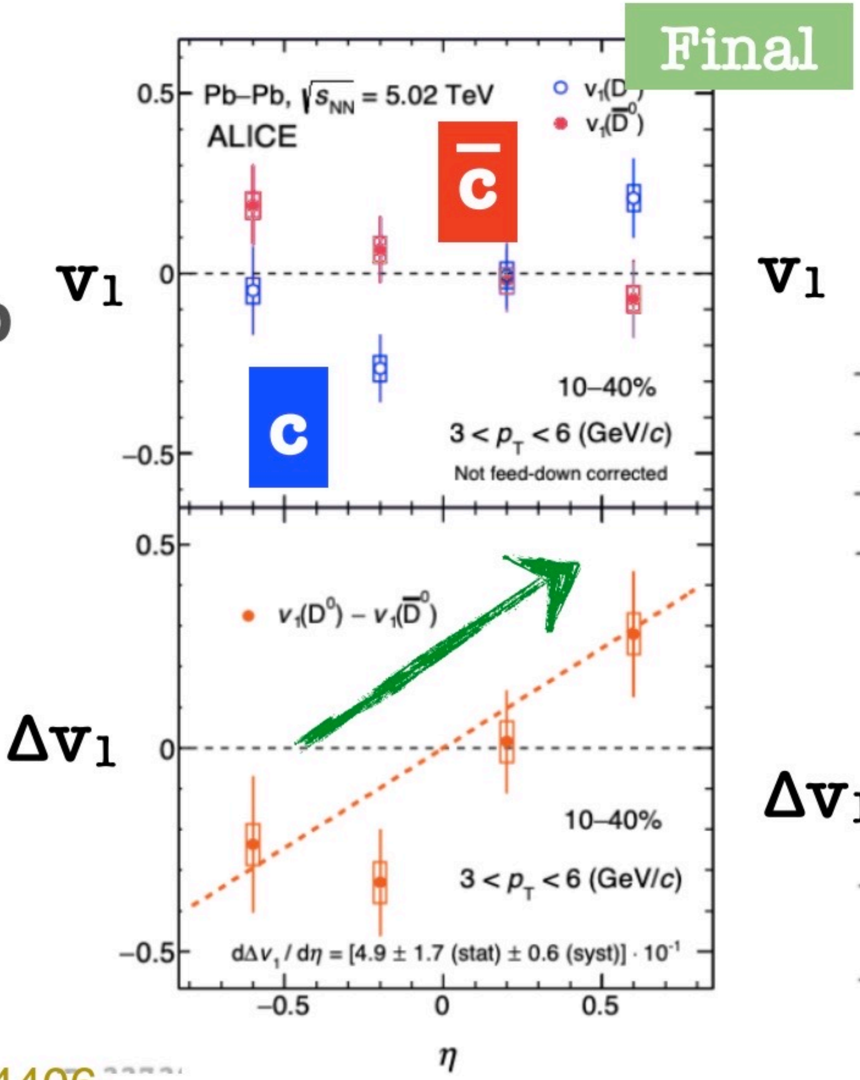


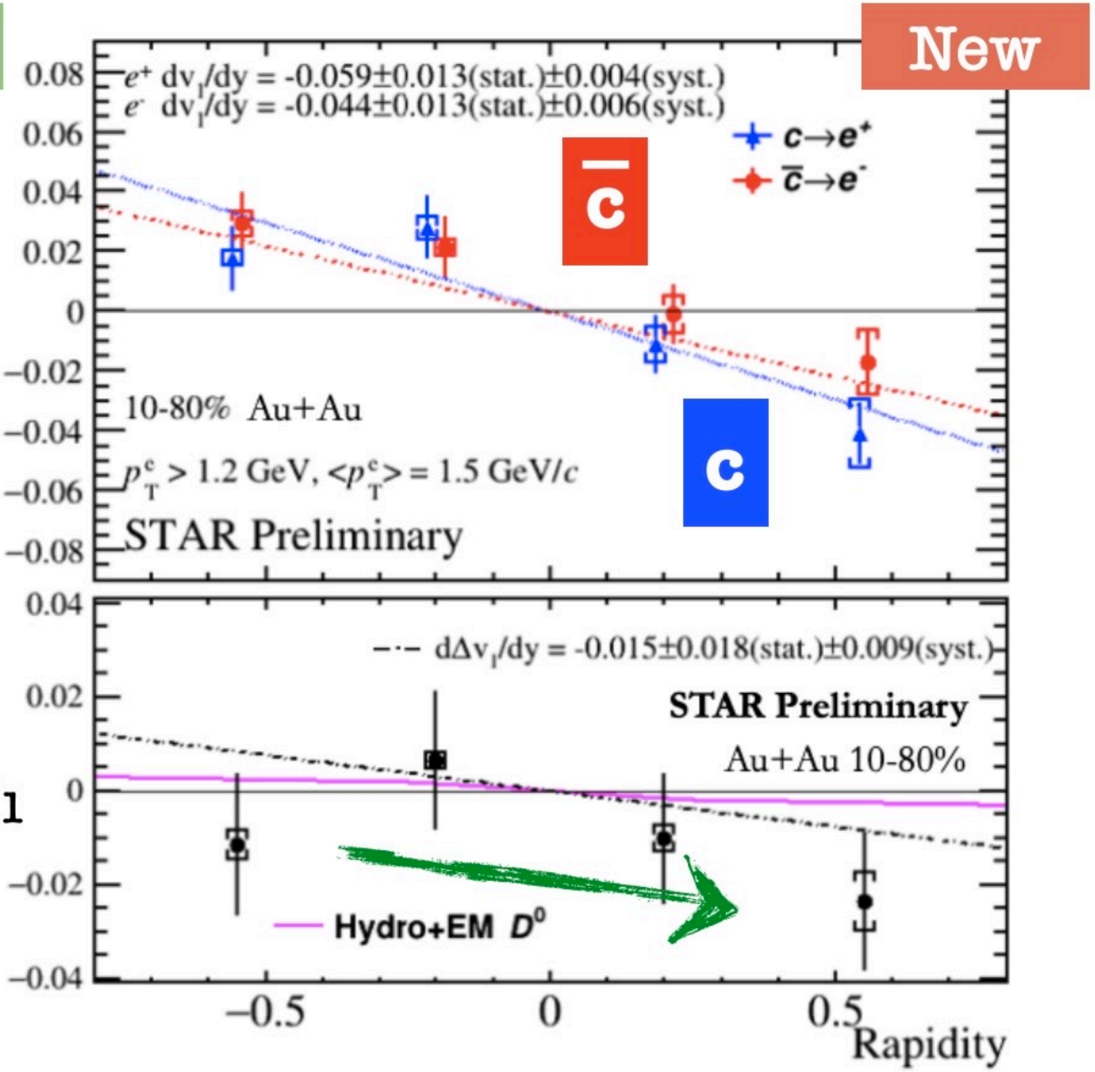


- Similar v_2 for muon and D^0 from b
- Different channels have different advantages

Probing the strong initial EM-field

ALICE
D^0 v_1
in PbPb





STAR
$c \rightarrow e$ v_1
in AuAu

arXiv:1910.14406
S. Tang 5 Nov, 16:40
M. Kelsey, 5 Nov, 17:40

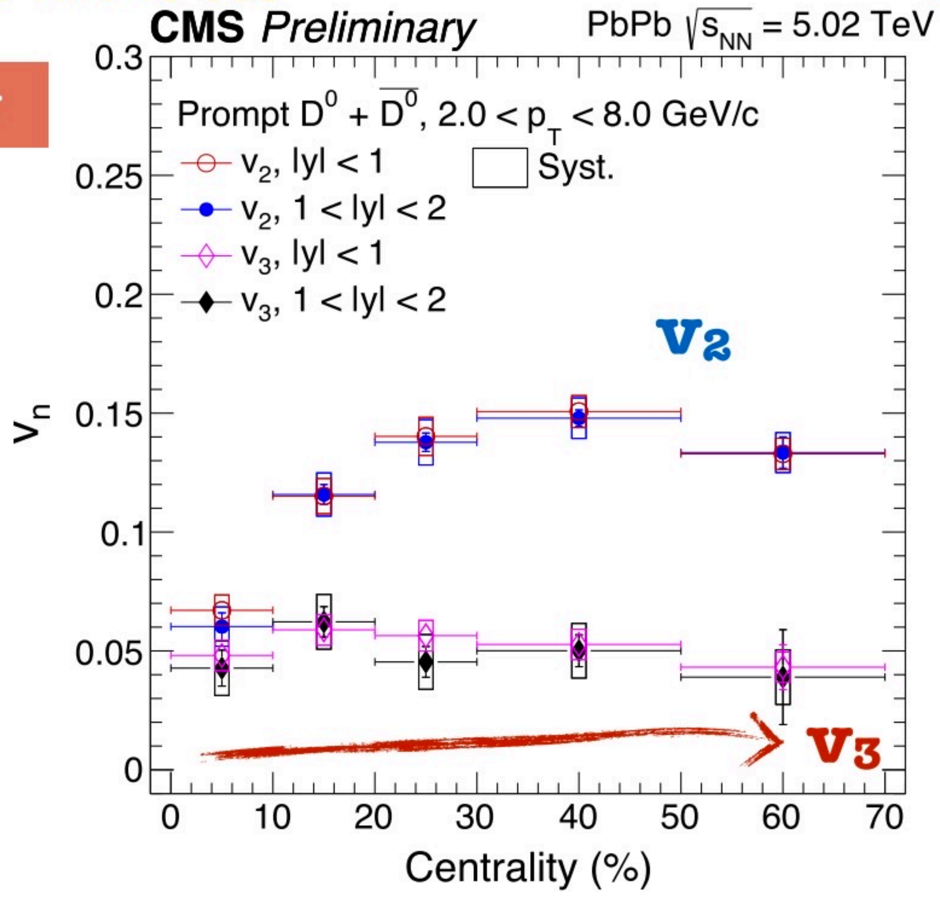
- $d\Delta v_1/d\eta$ slope: negative (RHIC) vs. positive(LHC)?

Probing initial fluctuations: heavy flavor v_3

v_3 in PbPb

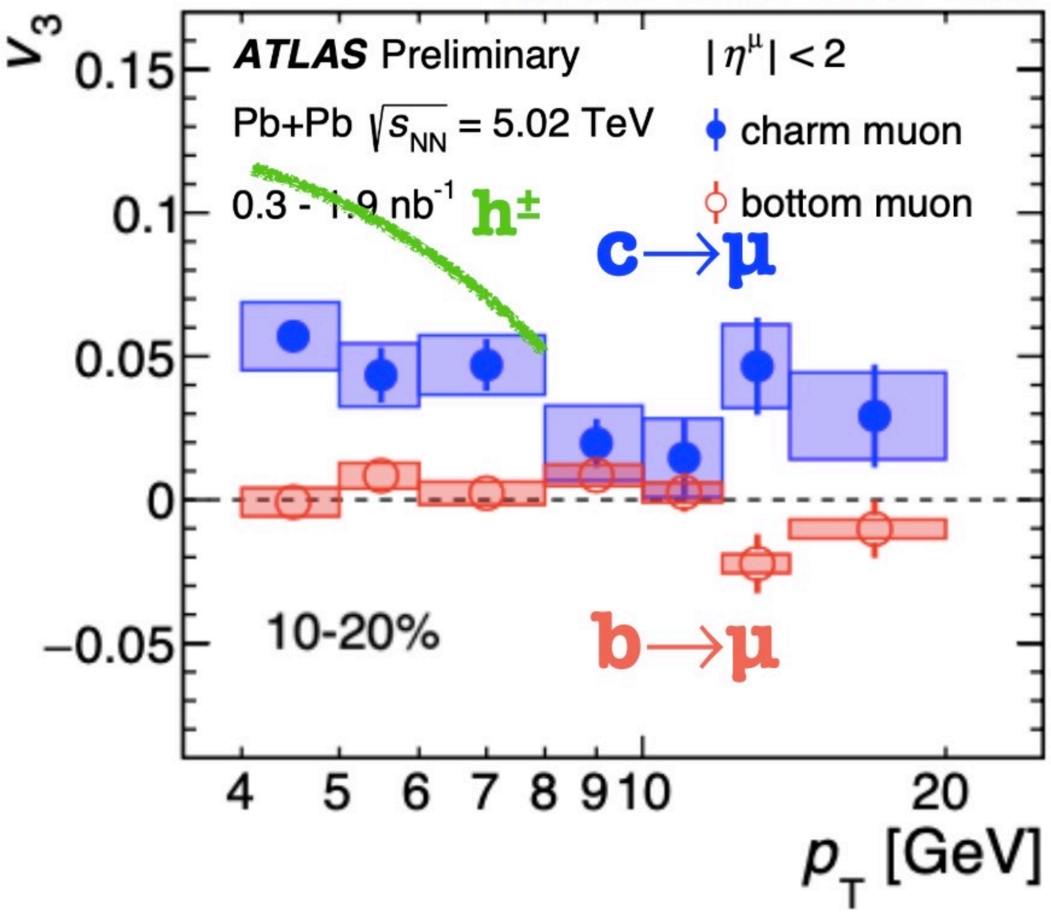
CMS-PAS-HIN-19-008

New



ATLAS-CONF-2019-053

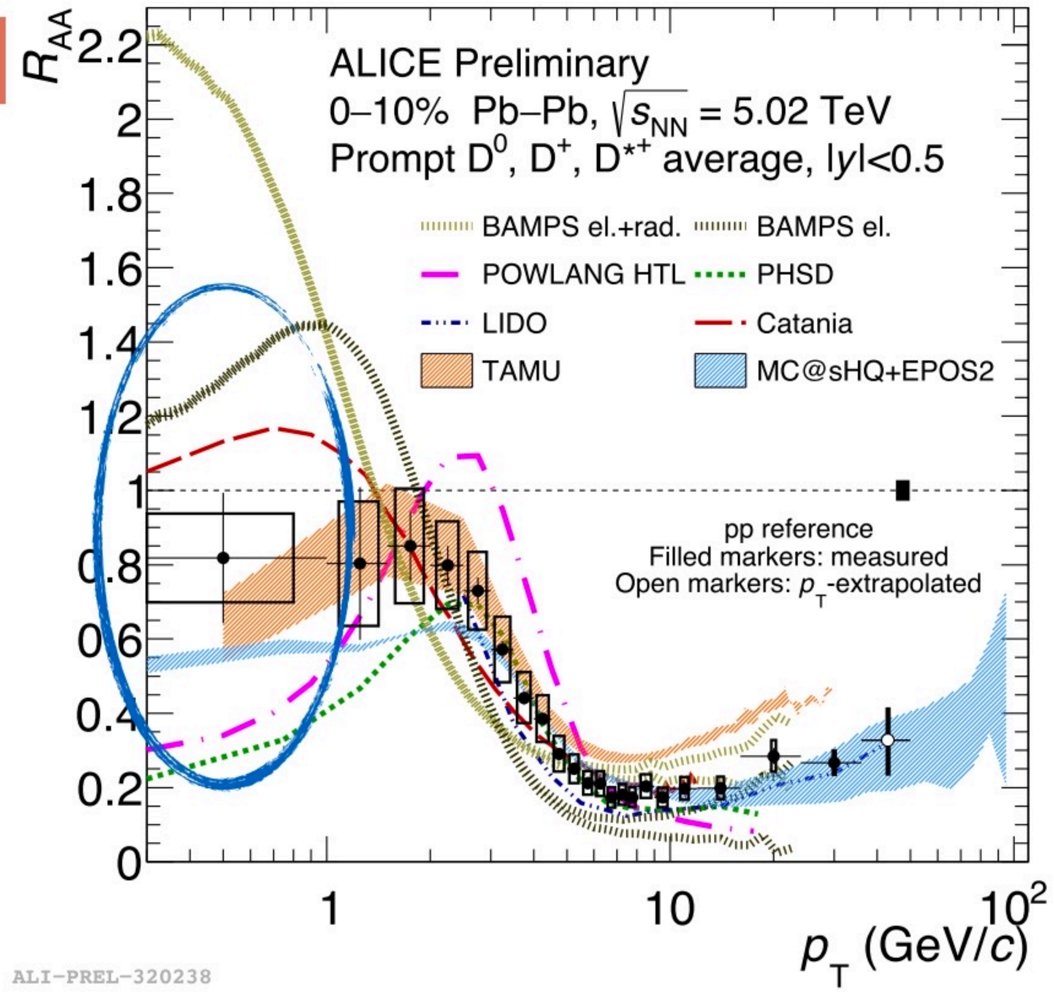
New



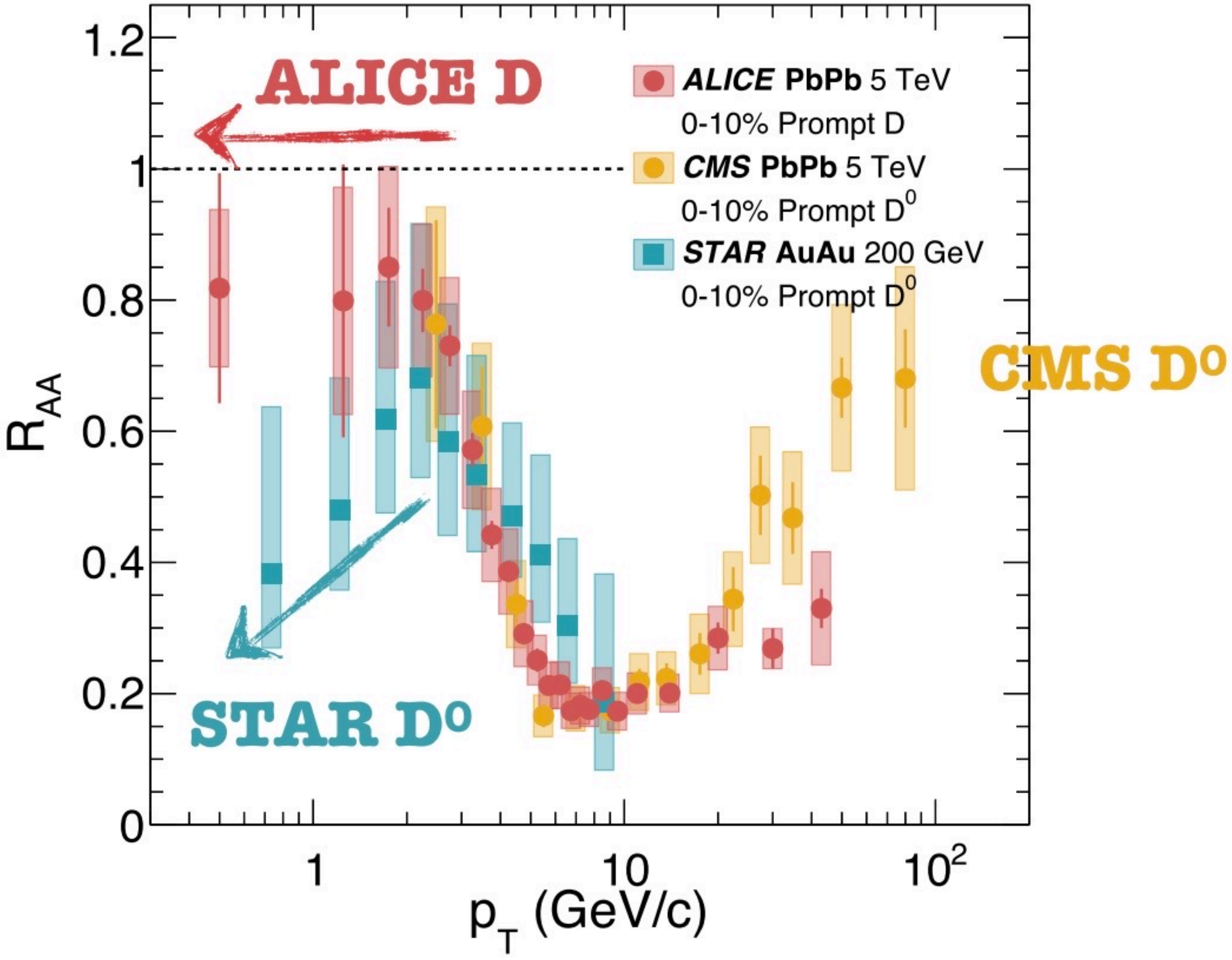
- No centrality dependence
- $v_3(h^{\pm}) > v_3(\text{charm}) > v_3(\text{beauty}) \approx 0$

Energy loss in medium: Open *charm* R_{AA}

New



World open charm R_{AA} (0-10%)



- Difference trend between LHC and RHIC?