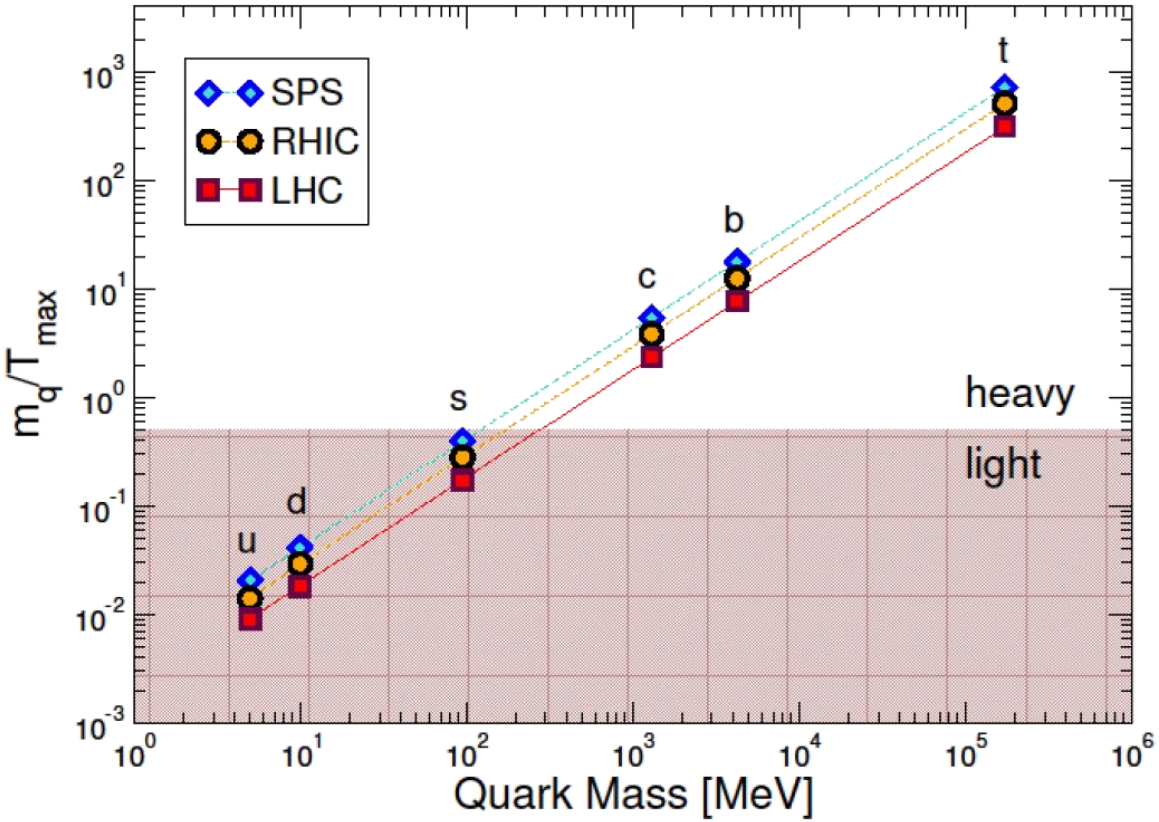
RECENT OPEN HEAVY FLAVOR RESULTS

M. Csanád (Eötvös U) for
ALICE, ATLAS, CMS, LHCb

HEAVY FLAVOR PROBES TIME EVOLUTION

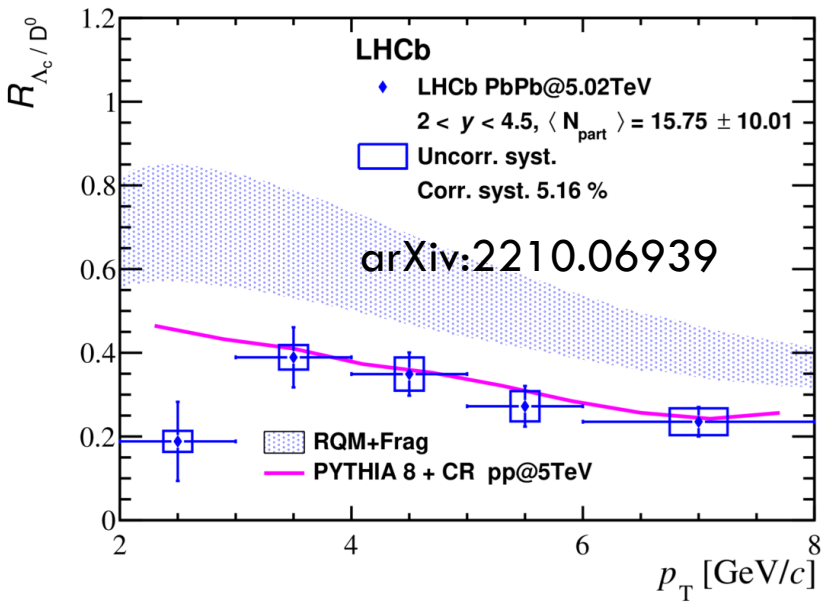
- Special role of heavy flavor: negligible thermal production (mass > temperature), Brownian motion
- From production at less than 0.1 fm/c until QGP lifetime: experience whole evolution
- Initial production:
  - pQCD, shadowing, pre-equilibrium effects, glasma, electromagnetic field, vorticity
- Dynamics in QGP
  - Heavy quark interaction, transport, thermalization
- Hadronization
  - Coalescence, fragmentation, rescattering
- Main heavy flavor observables:
  - Baryon/meson ratios: hadronization
  - R_{AA}: interaction, energy loss
  - v_2: coupling, thermalization

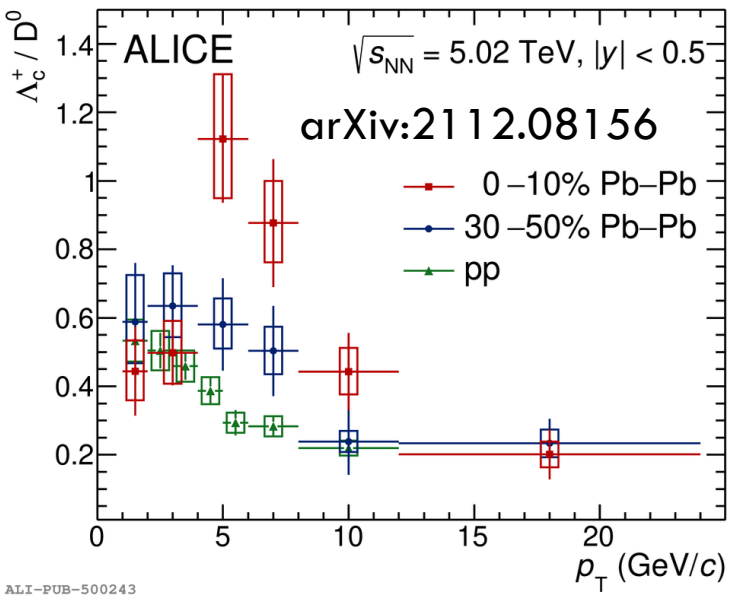
from Santosh Kumar Das, HP 2023

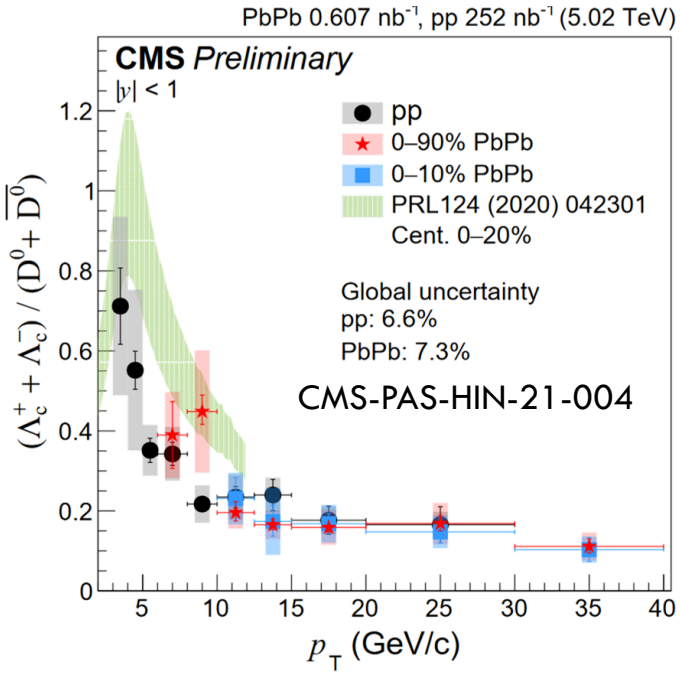


PROMPT Λ_C^+/D^0 RATIO AT 5.02 TEV

- First measurement of prompt Λ_C^+/D^0 at forward rapidities in PbPb [LHCb, arXiv:2210.06939]
  - Enhancement at intermediate p_T, PYTHIA8+CR compatible, Statistical hadronization (RQM+Frag) above data
- Enhanced ratio in PbPb compared to pp at intermediate p_T [ALICE, arXiv:2112.08156]
  - Possibly due to interplay of coalescence and radial flow, or hadronic rescattering for PbPb
- $(\Lambda_c^+ + \Lambda_c^-)/(D^0 + \overline{D^0})$ consistent in pp and PbPb [CMS-PAS-HIN-21-004]
  - No significant contribution from coalescence?



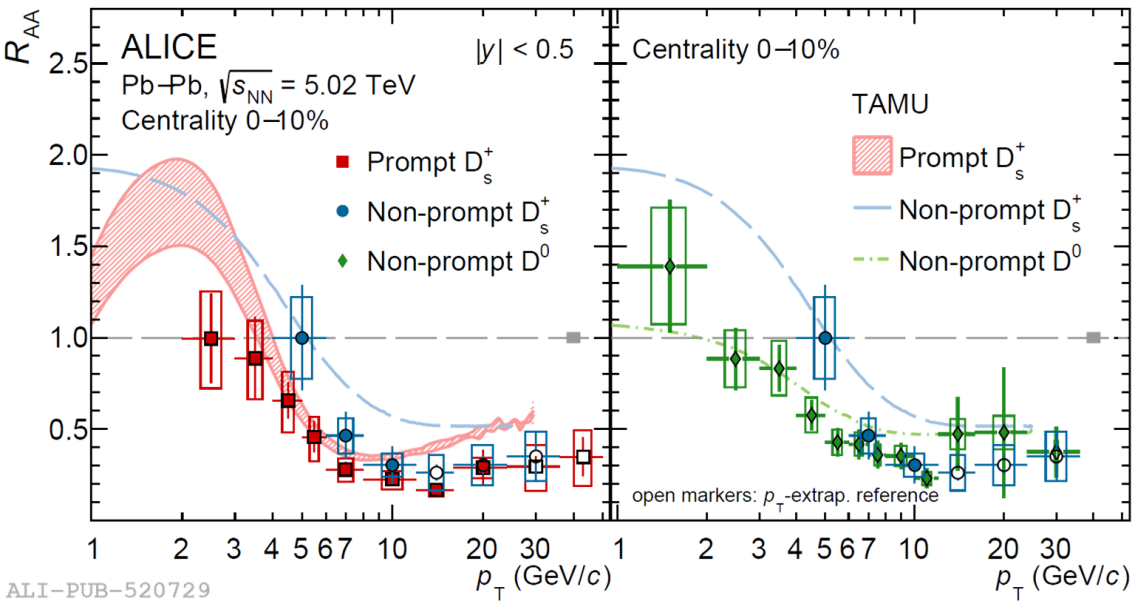


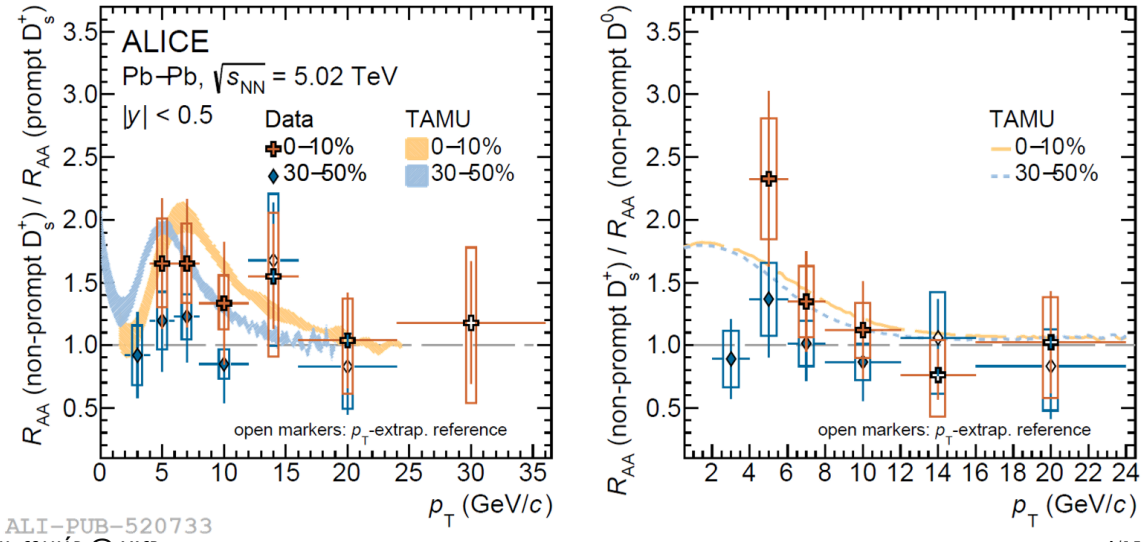


PROMPT AND NON-PROMPT D_S AND D^0 R_{AA} IN PBPB

- Non-prompt D_s and D^0 production measured in PbPb by ALICE
- Compared to prompt results and model calculations
- Larger non-prompt R_{AA} than prompt R_{AA}
  - For both non-prompt D_s and D^0
  - Larger impact of dead-cone effect for beauty
- Hints of larger D_s/D_0 yields in AA than in pp
  - Coalescence production in a strangeness-rich environment
- ALICE paper: arXiv:2204.10386
- Further results in recent ALICE publications
  - JHEP 12 (2022) 126, JHEP 01 (2022) 174, etc.

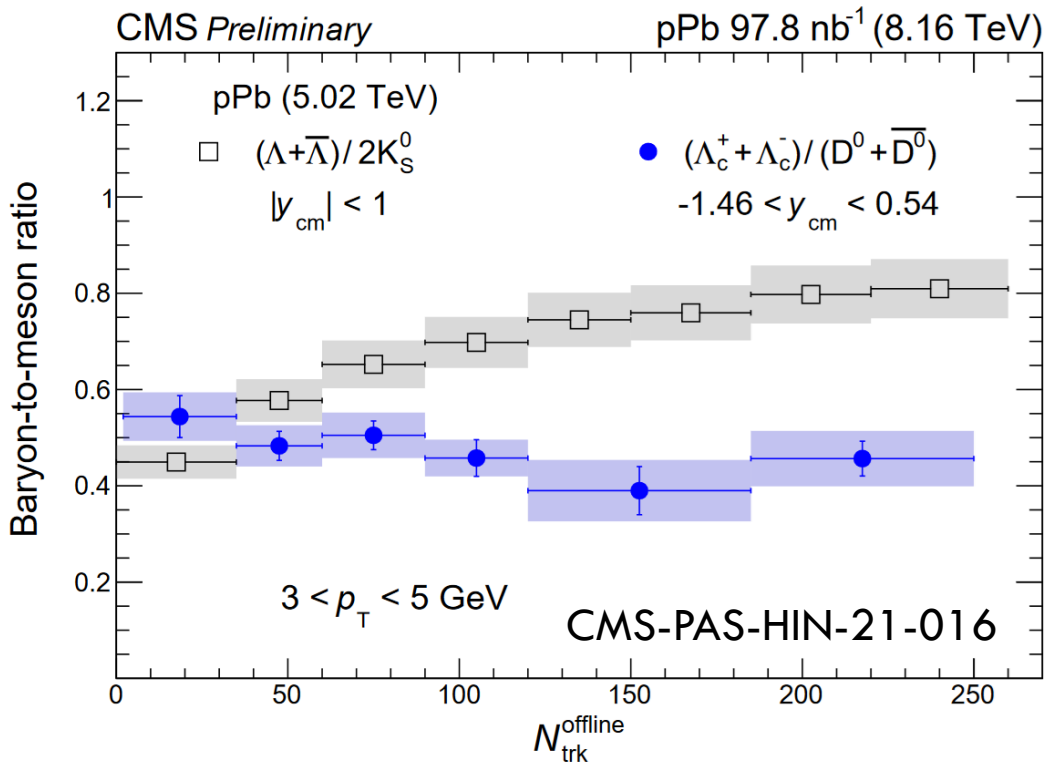
arXiv:2204.10386

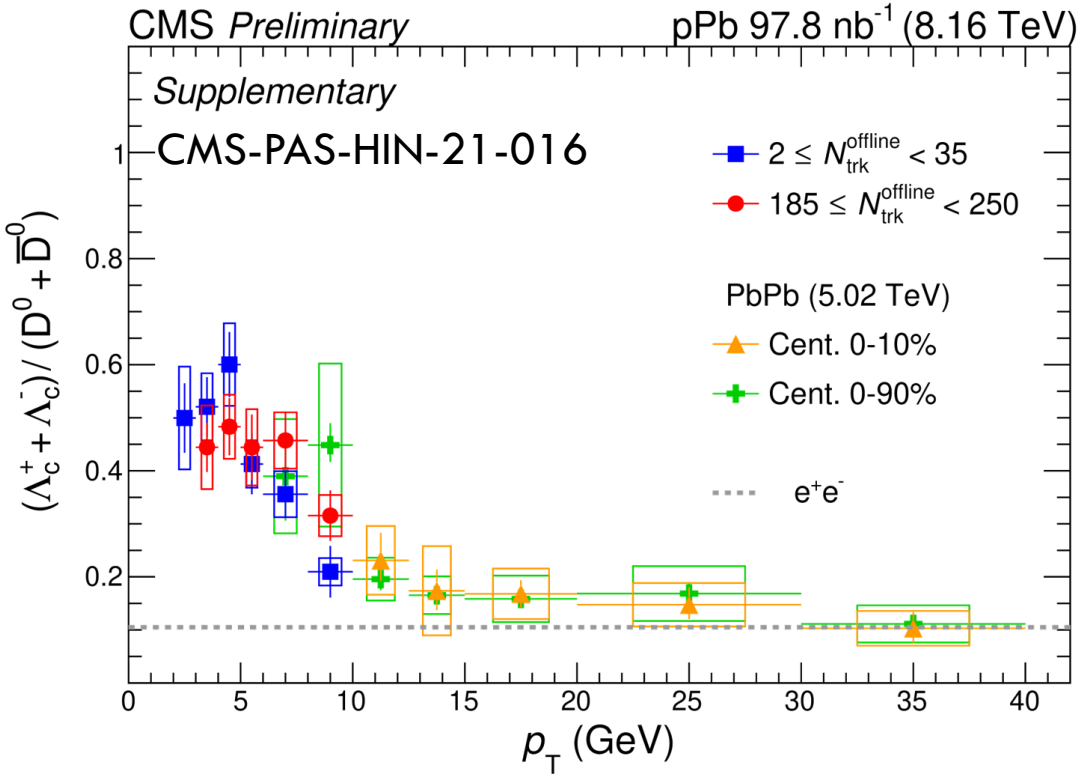




CHARM QUARK HADRONIZATION IN PPB AT 8.16 TEV

- First conclusive measurement of Λ_c/D^0 vs multiplicity in pPb (note similar ALICE preliminary for QM22)
  - Different trend compared to strange sector: smaller dependence
- Extending the system, p_T, and centrality dependence
  - Λ_c/D^0 in pPb and MB PbPb consistent at intermediate momenta
  - High momenta: MB and central PbPb approach the ratio from e^+e^-: no coalescence

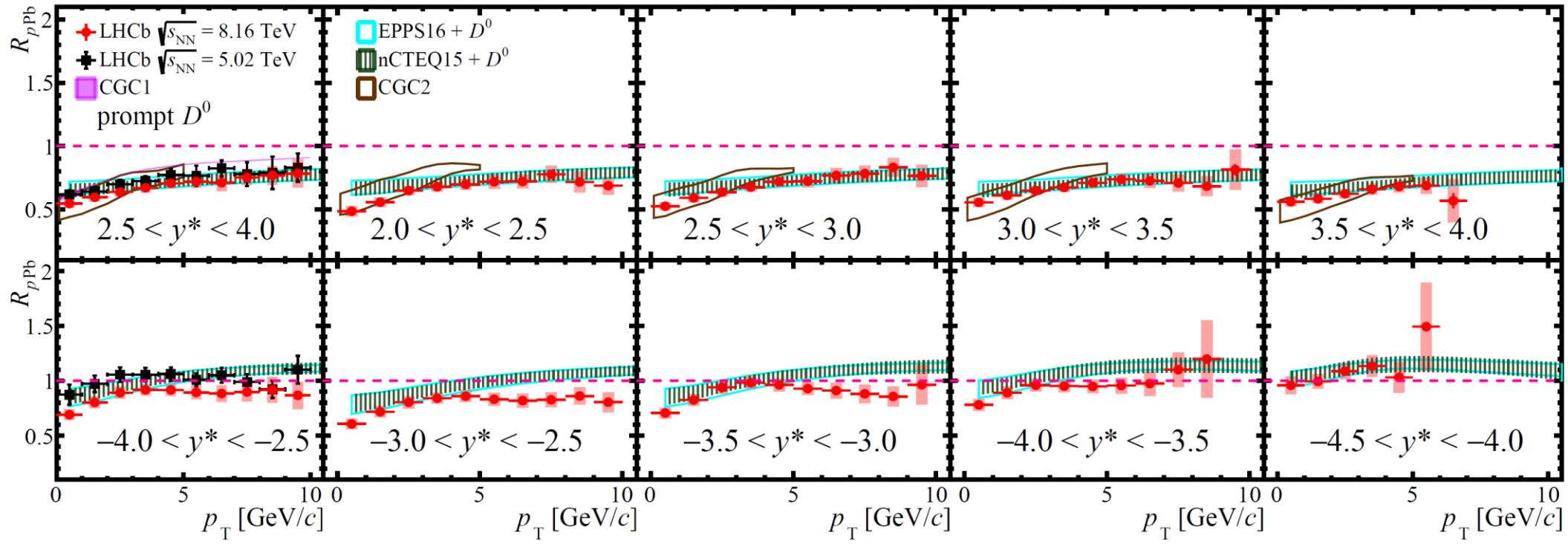




PROMPT D^0 PRODUCTION IN PPB AT 8.16 TEV

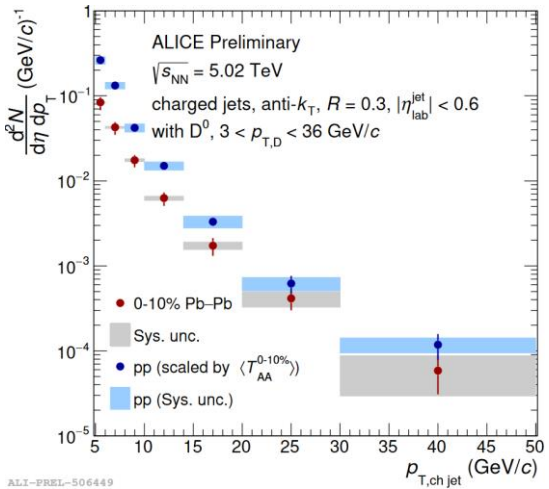
- Forward: suppression consistent with 5.02 TeV result, with nPDF and CGC
- Backward: data partly below nPDF at high p_T
- Room for additional effects at backward rapidity

LHCb paper: arXiv:2205.03936



D^0-TAGGED JET R_{AA} IN PBPB

- Nuclear modification of D^0-tagged jets in PbPb measured by ALICE
- Compared with single-particle D^0 and inclusive-jets
- Larger R_{AA} for D^0-jets than single-particle D^0
  - in common p_T range
  - hadron-to-parton and jet-to-parton p_T scales differ
- Larger R_{AA} for D^0-jets than inclusive jets
  - Here quark/gluon jet ratio and parton fragmentation differ
- Results: ALI-PREL-506534



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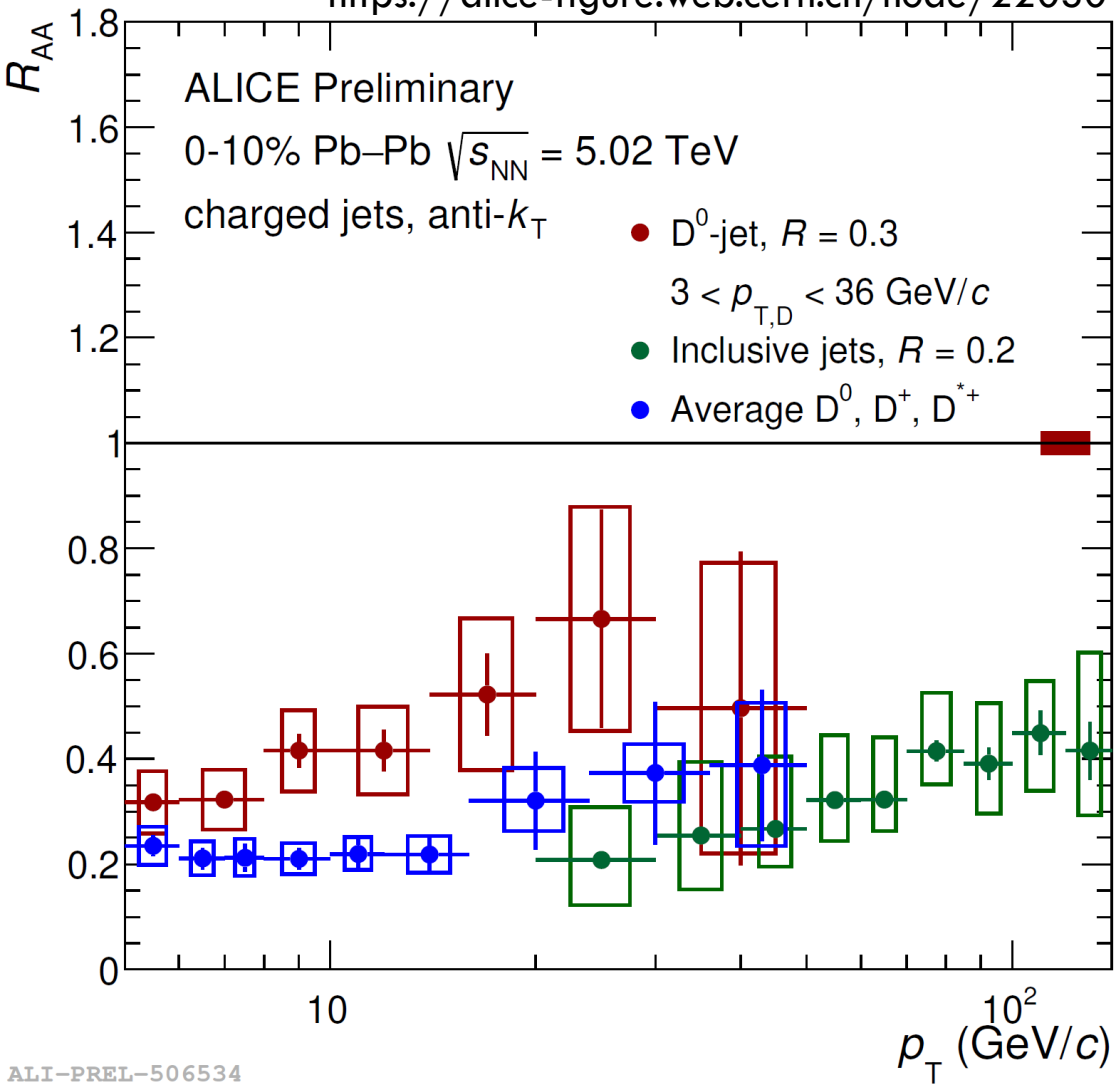
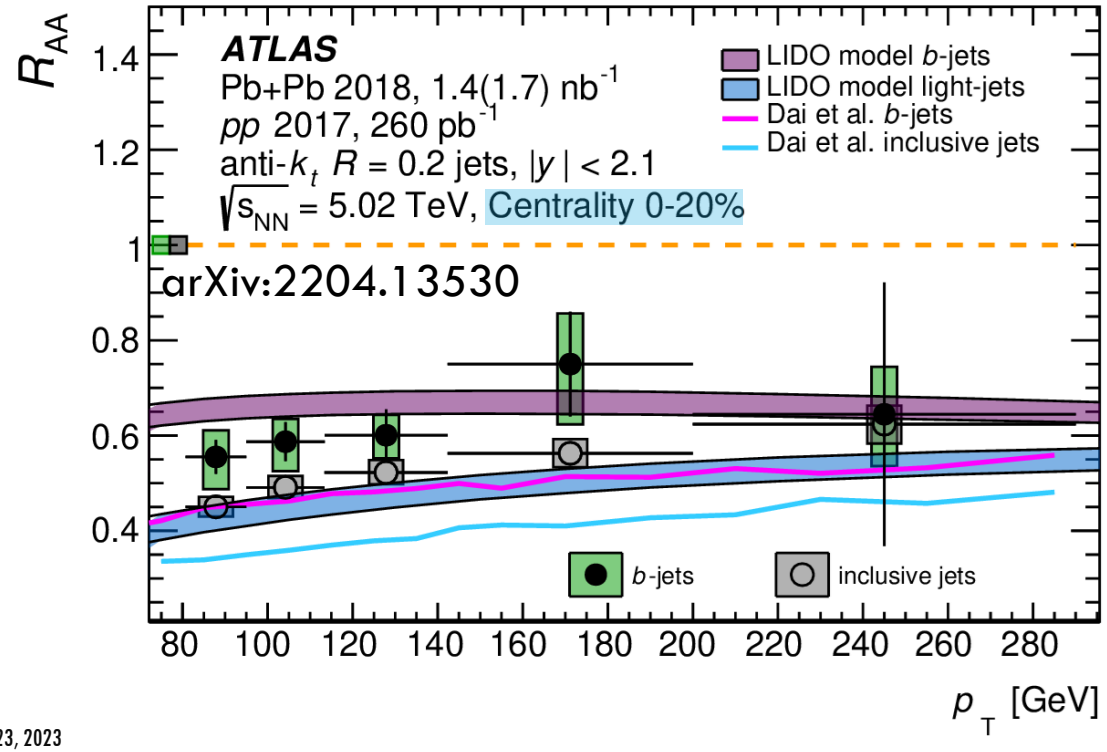
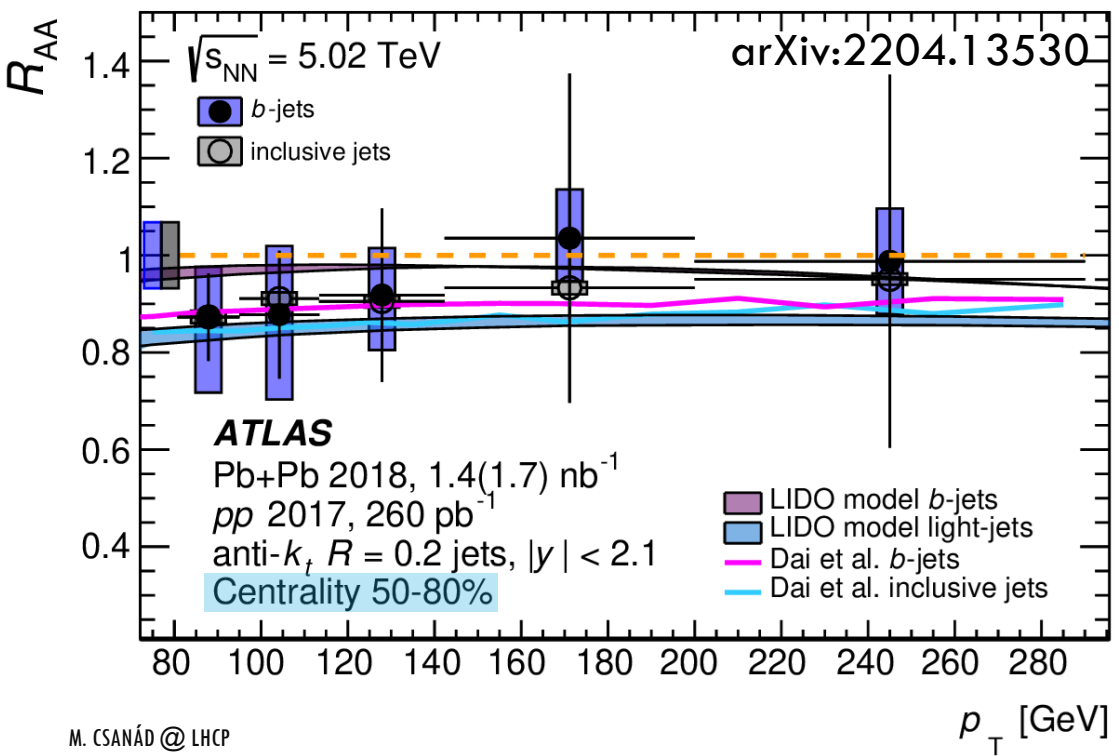


B-JETS IN PBPB COLLISIONS

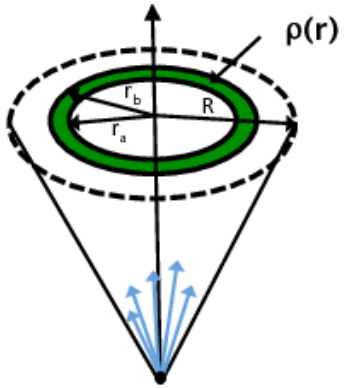
- B-jets: different from inclusive jets due to quark mass
  - Medium-induced gluon radiation suppressed; lose smaller amount energy than gluon jets due to color factor
- B-jet ID: jets with muonic b-decays; template fit of muon momentum relative to jet axis
  - R_{AA} decreased for more central events; larger for b-jets than for light-jets
  - Reason: different gluon fraction – b-mass subdominant at high p_T





B-JET SHAPES

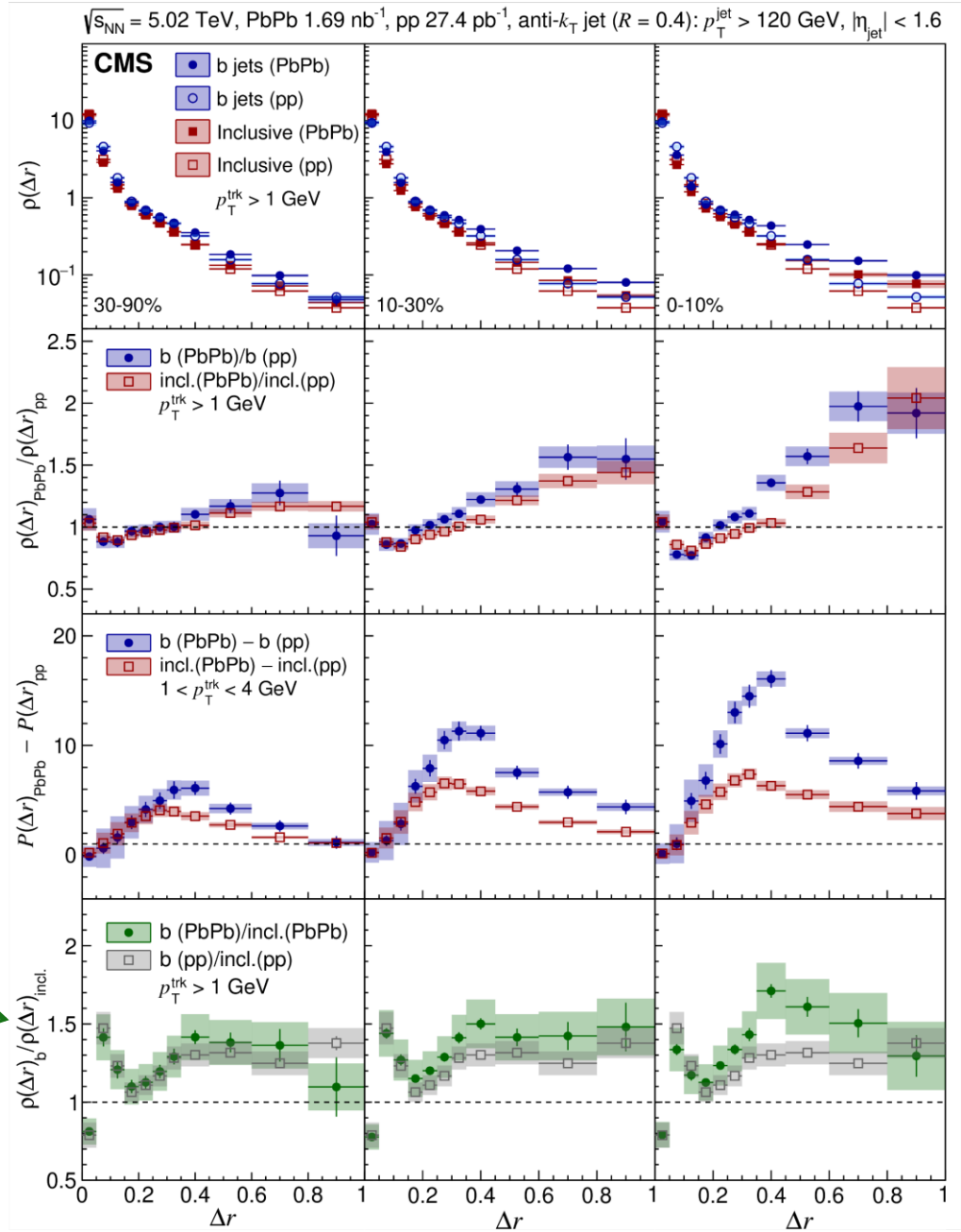
- Jet shape: Measure of charged particle p_T distribution w.r.t. jet axis:



$$P(\Delta r) = \frac{1}{\Delta r_b - \Delta r_a} \frac{1}{N_{jet}} \Sigma_{jets} \Sigma_{trk \in (\Delta r_a, \Delta r_b)} p_T^{trk}$$

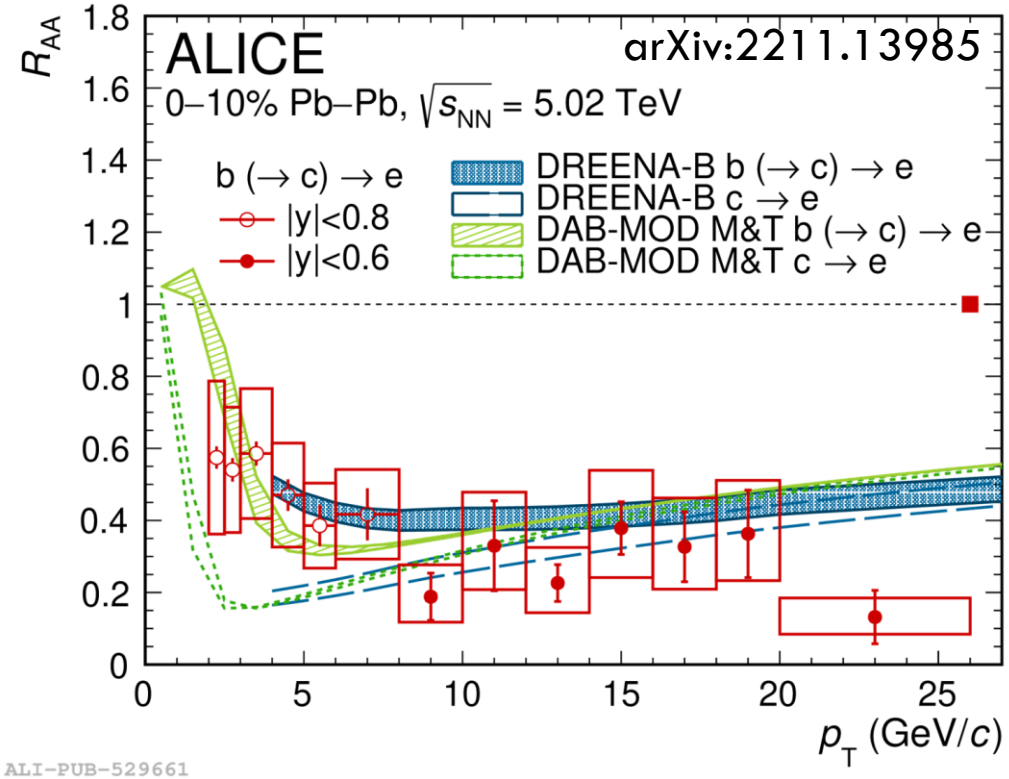
$$\rho(\Delta r) = \frac{P(\Delta r)}{\Sigma_{jets} \Sigma_{trk \in (\Delta r < 1)} p_T^{trk}}$$

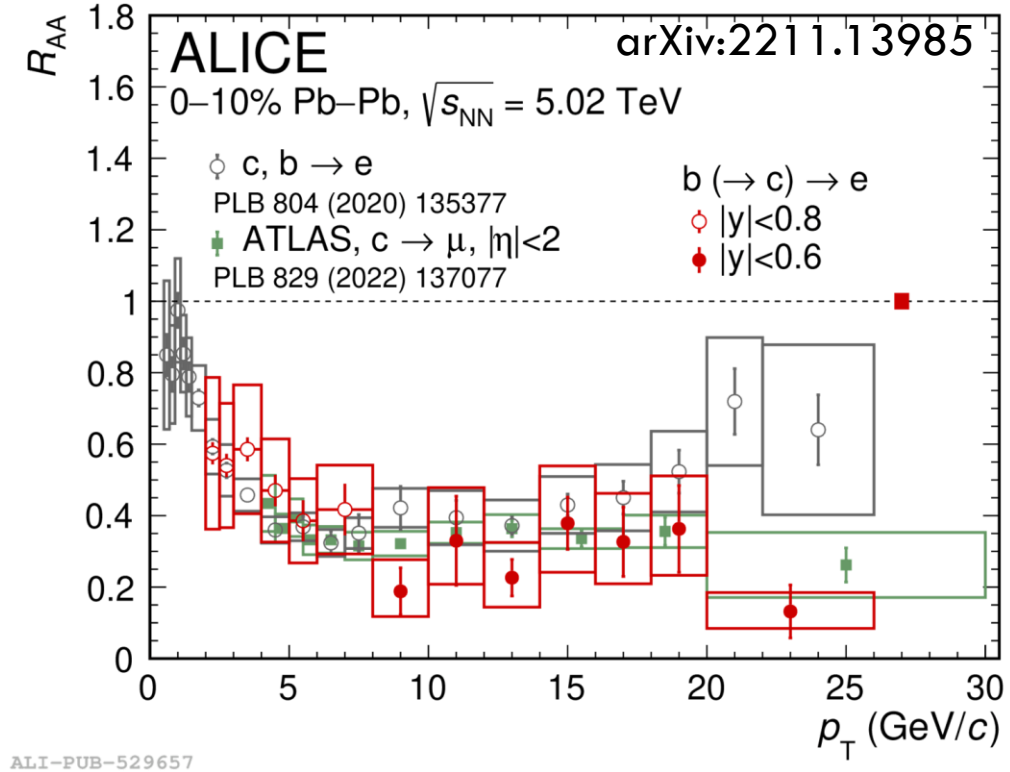
- Depletion of p_T at small Δr from jet axis
  - Already present in pp, consistent with a dead-cone
  - Quantitative measurement of dead-cone effect for b-jets?
- QGP modifies energy flow around b-jets
  - Transfer of p_T from small to large radial distances?
- CMS paper: arXiv:2210.08547



BOTTOM QUARK R_{AA} IN PBPB

- Electrons from b-decays measured by ALICE [arXiv:2211.13985]
- Consistent with models of b-quark energy loss
- Similar R_{AA} of electrons from bottom and charm
  - C.f.: mass ordering or differences seen previously by PHENIX [2203.17058], STAR [2111.14615] and ATLAS [2109.00411]

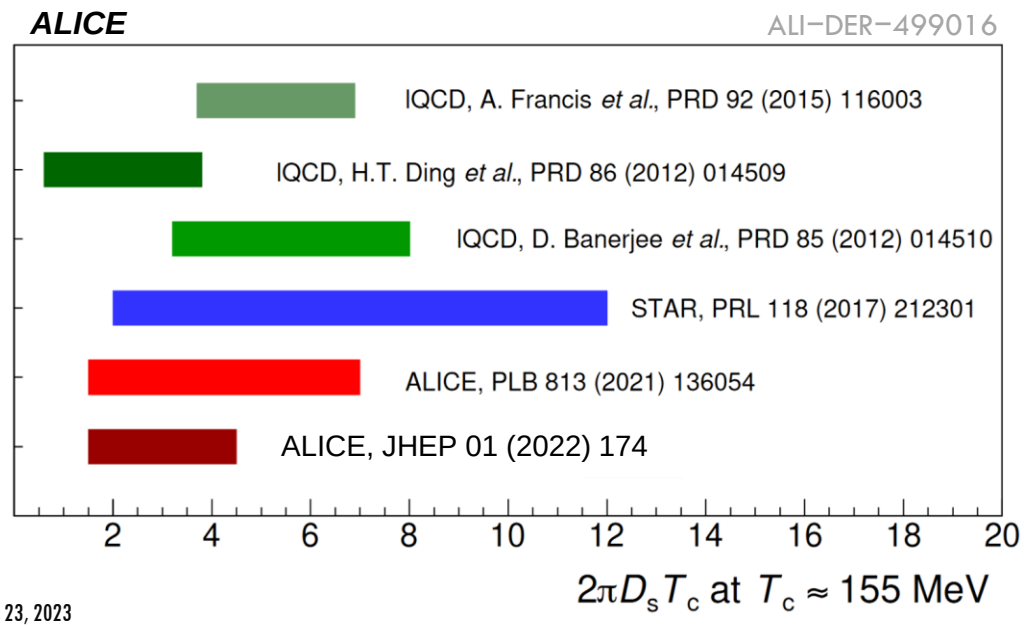


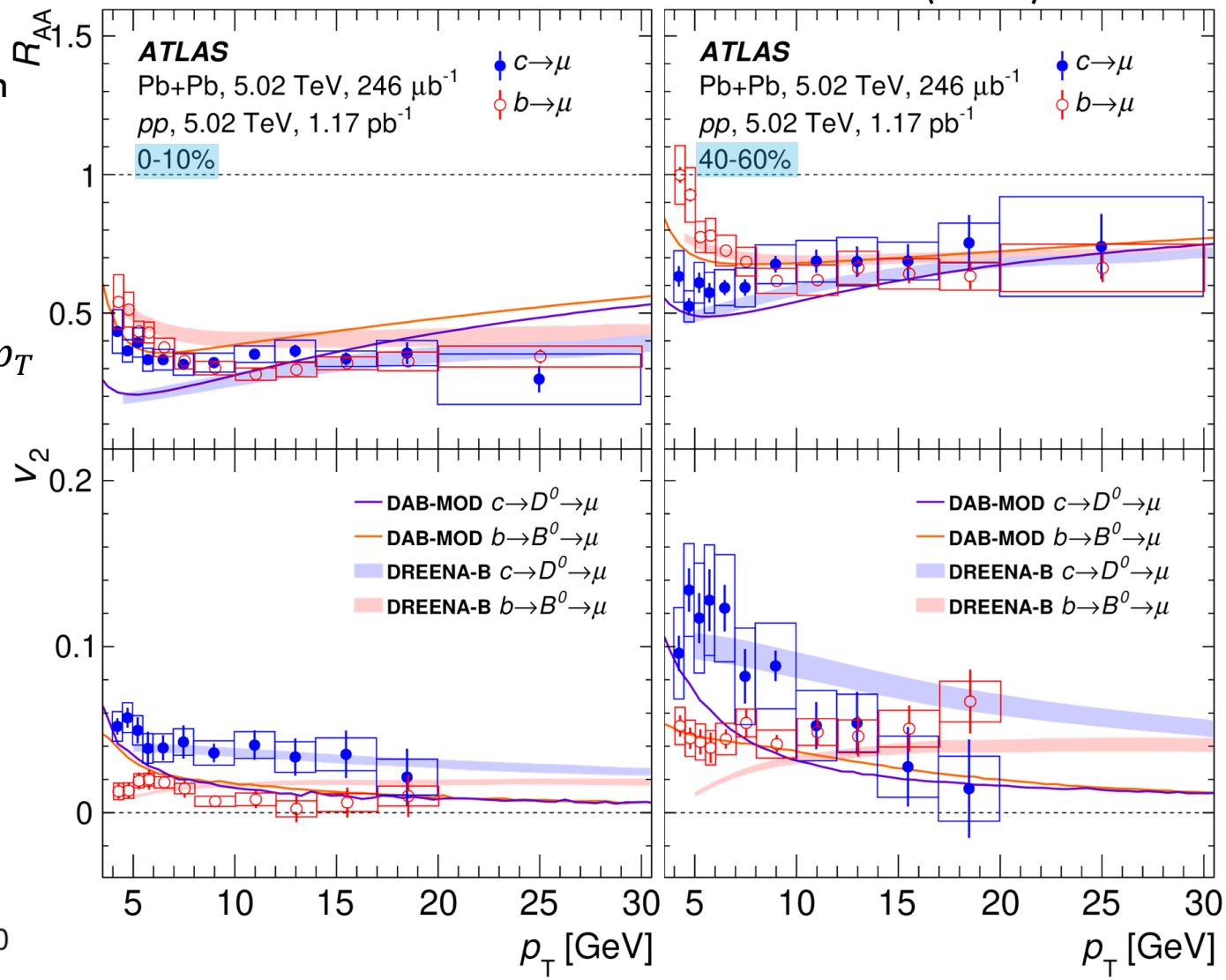


EXPLORE ENERGY LOSS AND QGP EXPANSION: R_{AA} AND V_2

PLB 829 (2022) 137077

- Constraining spatial diffusion coefficient
  - Different transport models for E-loss & hadronization
  - Simultaneous description: $1.5 < 2\pi D_s T_c < 4.5$
  - HF probes becoming powerful tomography tools
- Measurement of R_{AA} and v_2 for c and b
  - Mass splitting of v_2 at low p_T, convergence at high p_T
  - Charm D_s: 2.23 (bottom: 2.79); in line with ALICE

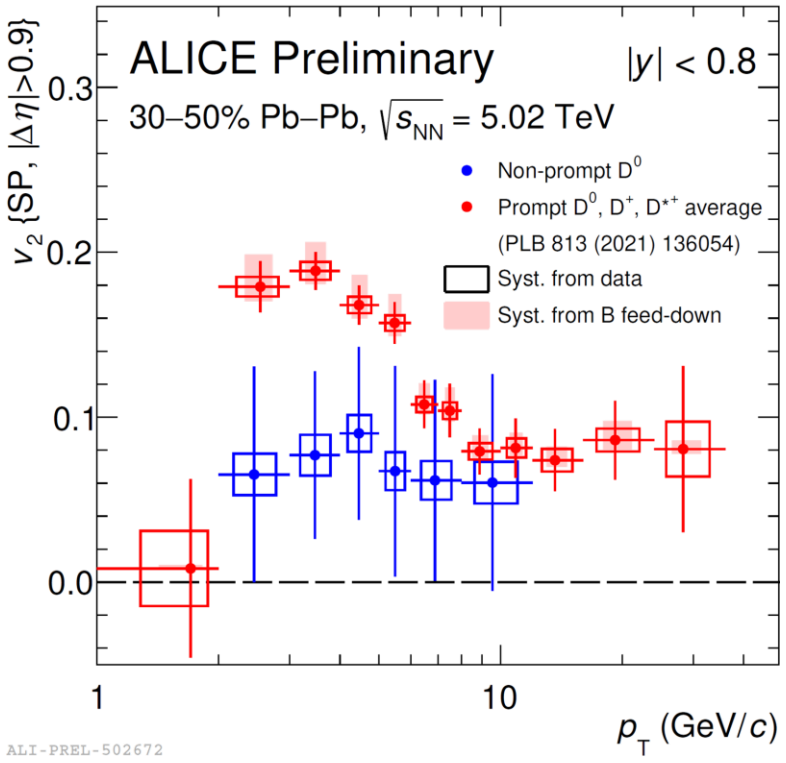


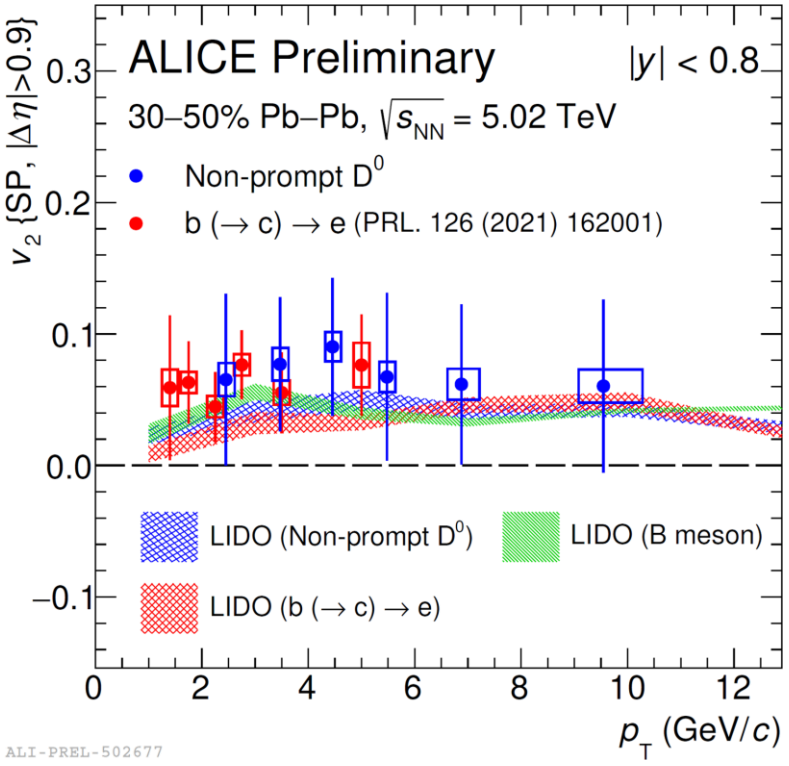


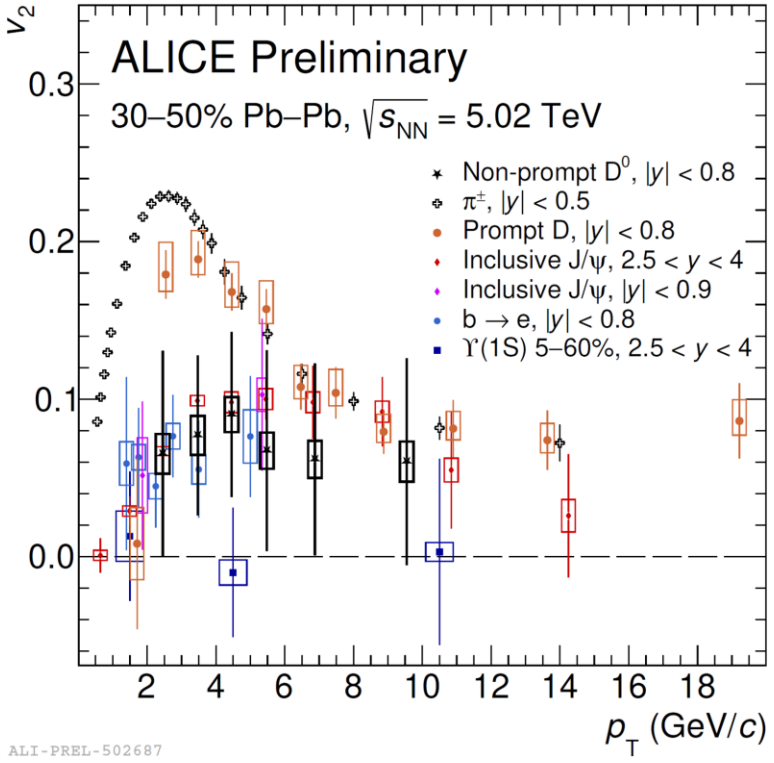
NON-PROMPT D^0 ELLIPTIC FLOW IN PBPB

- Non-prompt D^0 v_2 measured in 30-50% PbPb by ALICE, compared with prompt D^0
- Non-zero non-prompt flow observed, although smaller than prompt and larger uncertainties
- LIDO model compatible with current and earlier data on $b(\rightarrow c) \rightarrow e$

https://alice-figure.web.cern.ch/node/21498

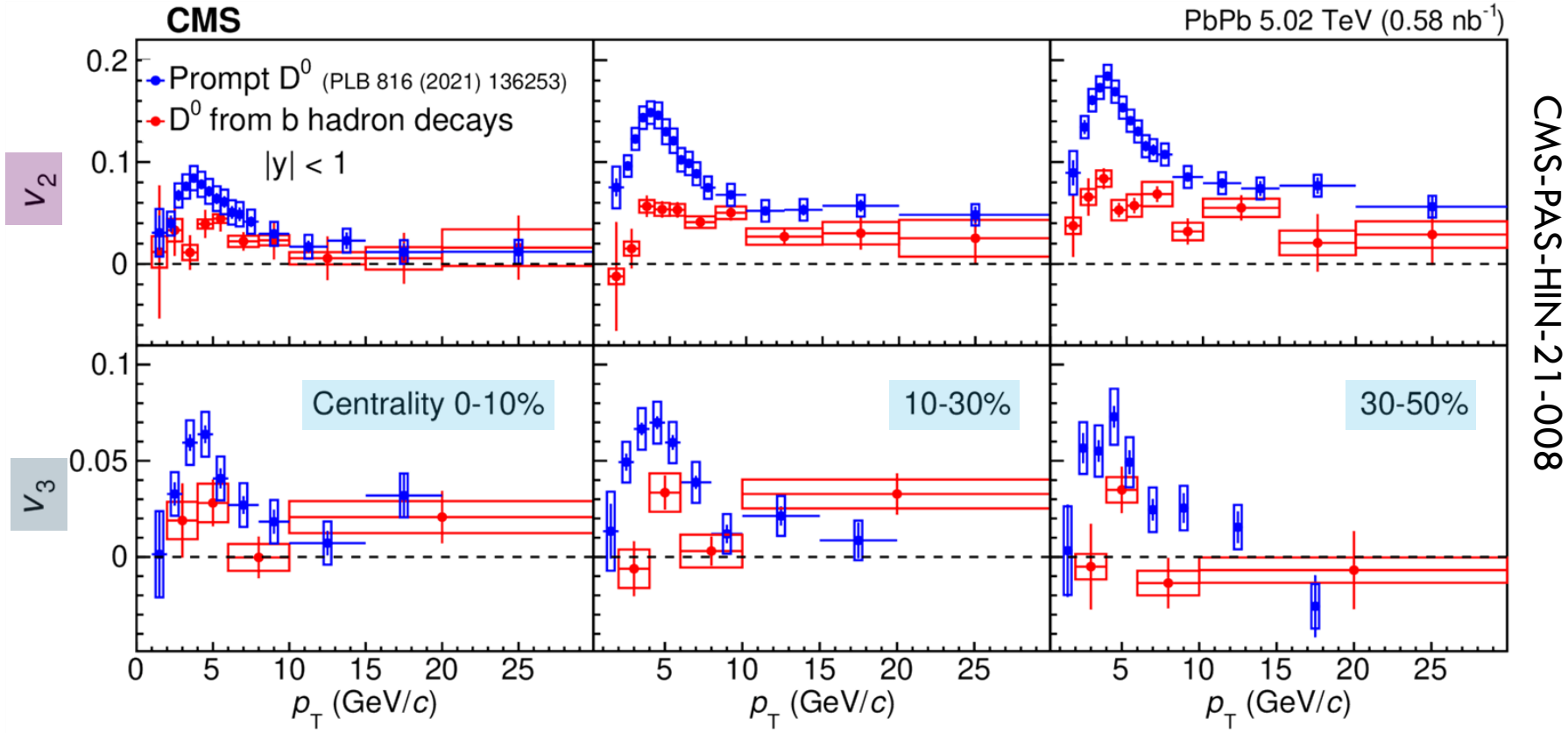






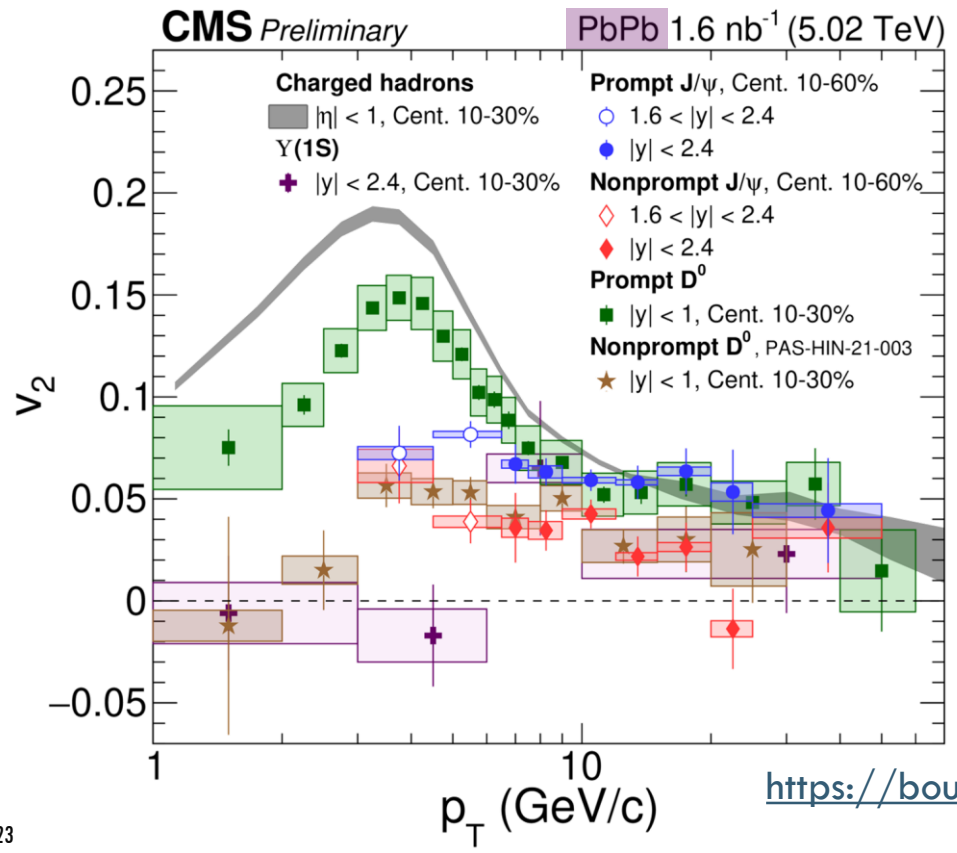
PROMPT AND NON-PROMPT HEAVY FLAVOR V_2 AND V_3

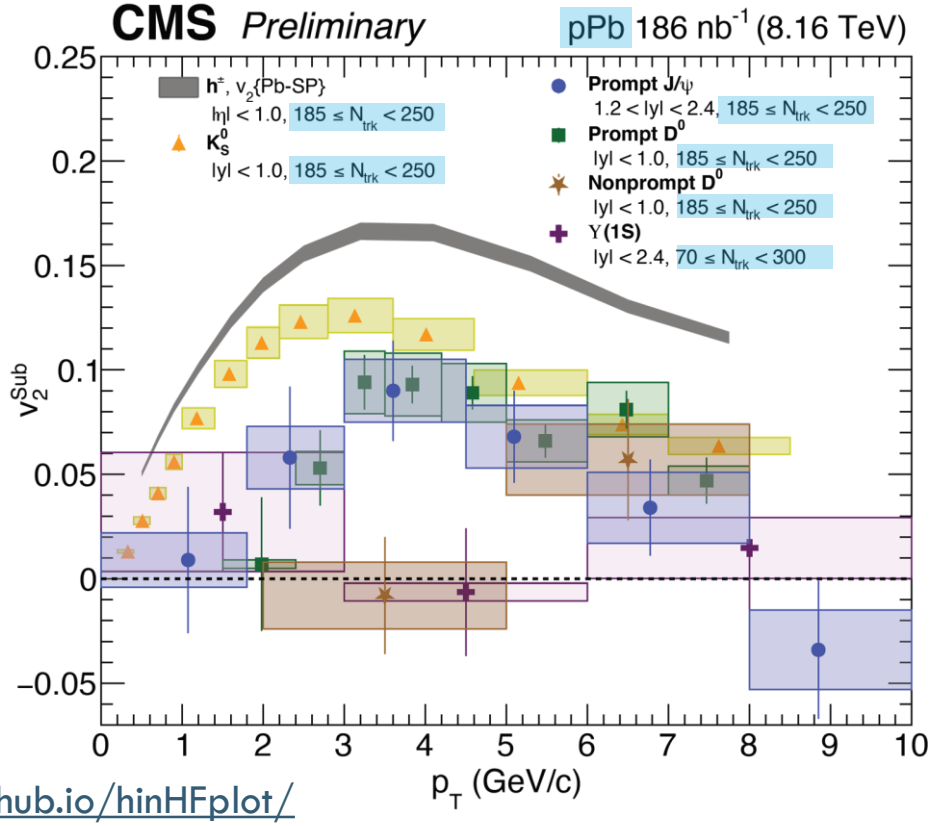
- Prompt and non-prompt D^0: DCA separation
- Charm v_2 and v_3: affected by flow and energy loss characteristics
- Bottom: less flow, more resistant to collective effects, but still path-length dependent energy loss



HEAVY FLAVOR FLOW HIERARCHY

- Bridging heavy flavor flow measurements in small and large systems
- Clear mass hierarchy: heavier particles exhibit less flow in PbPb and in high-multiplicity pPb as well
  - $h^{\pm}$, D^0, J/ψ, $b \to D^0$, $b \to J/\psi$, $\Upsilon(1S)$
- Question: open/closed b flow as well?

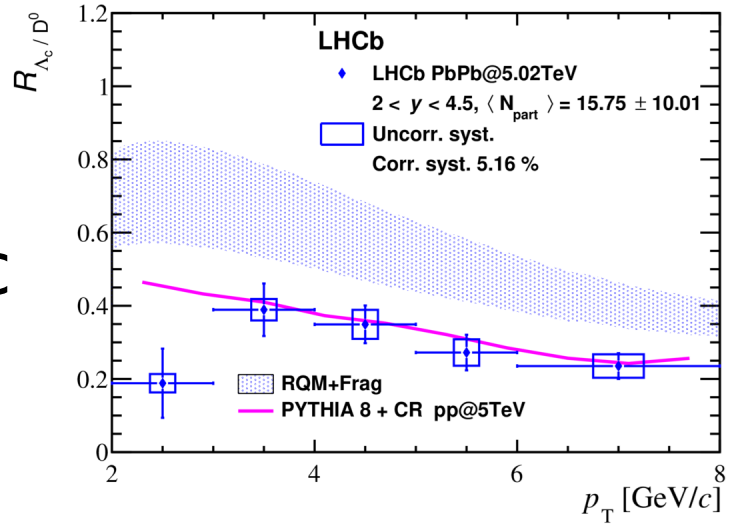


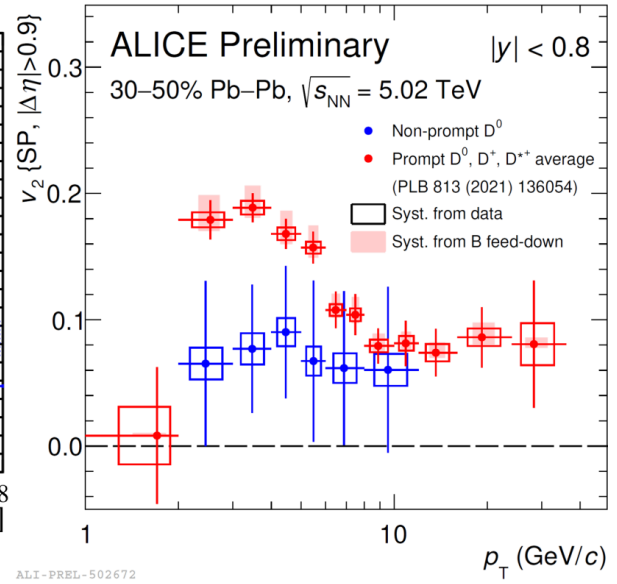


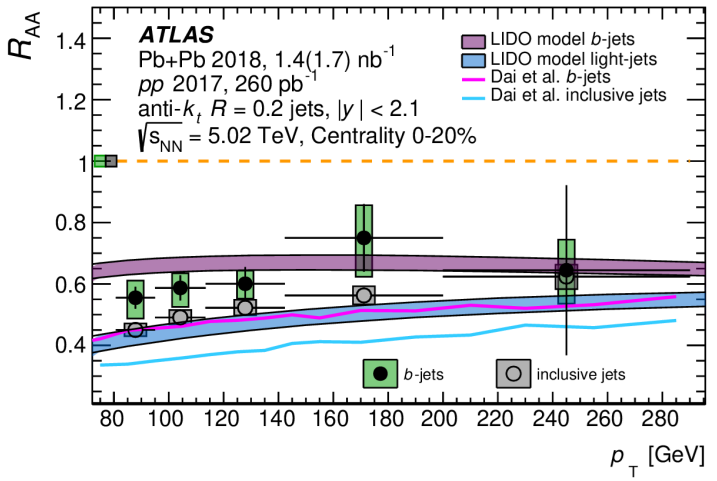
https://boundino.github.io/hinHFplot/

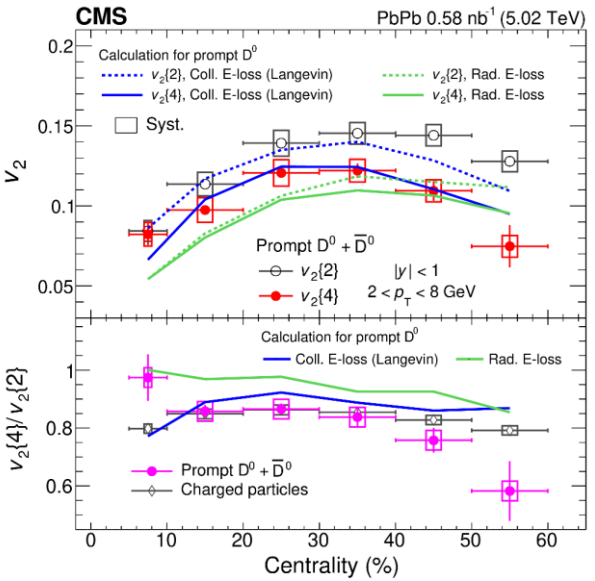
SUMMARY

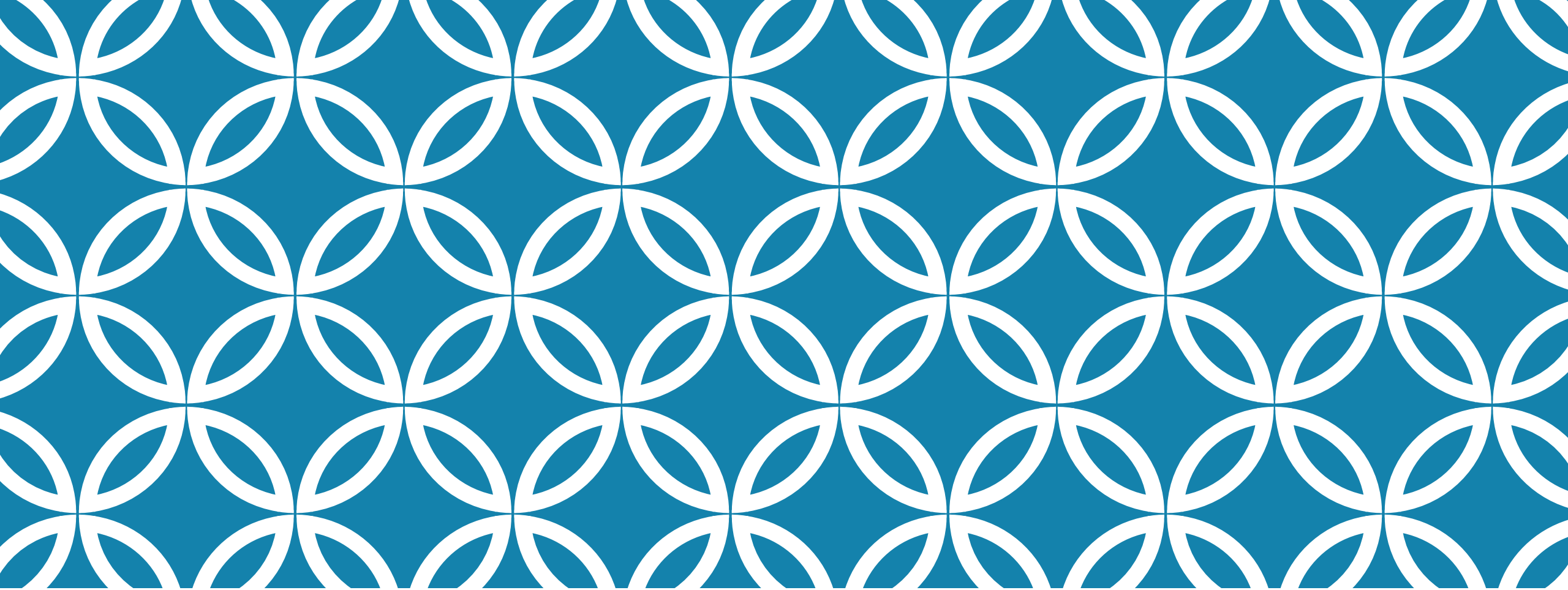
- Many HF observables measured at LHC
- Baryon/meson ratios (Λ_c/D^0)
  - Role of coalescence
- Suppression (R_{AA})
  - D- and b-tagged jets measured
  - Understanding energy loss and fragmentation
- Azimuthal anisotropy
  - Non-prompt D^0 v_2 observed
  - Heavy flavor v_2 and v_3: even for bottom
  - Clear heavy flavor flow hierarchy established
- THANK YOU FOR YOUR ATTENTION!









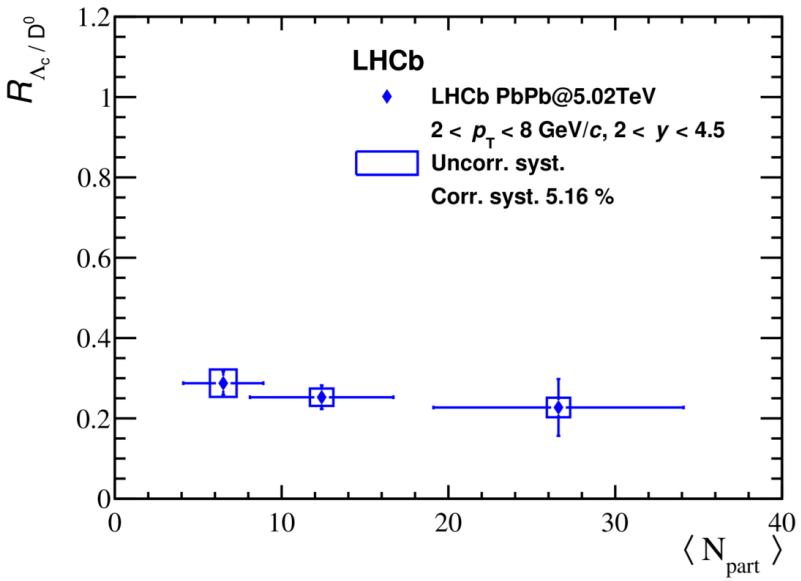


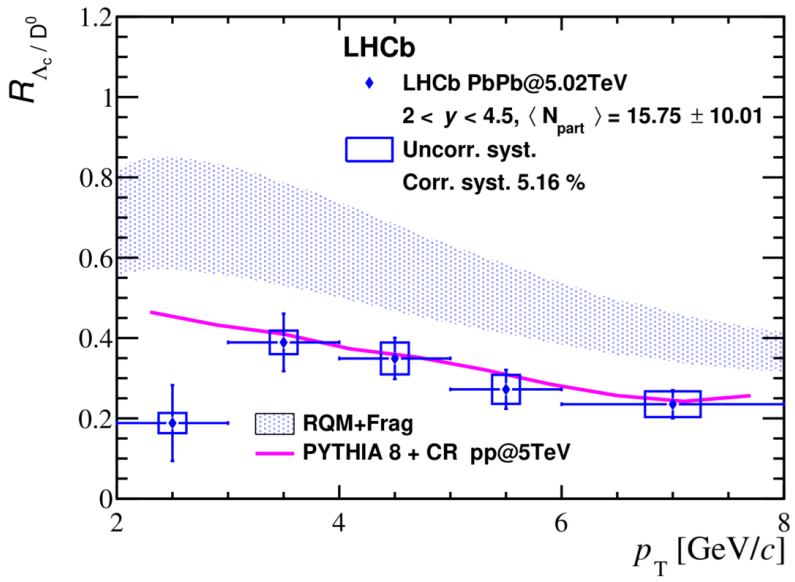
BACKUP SLIDES

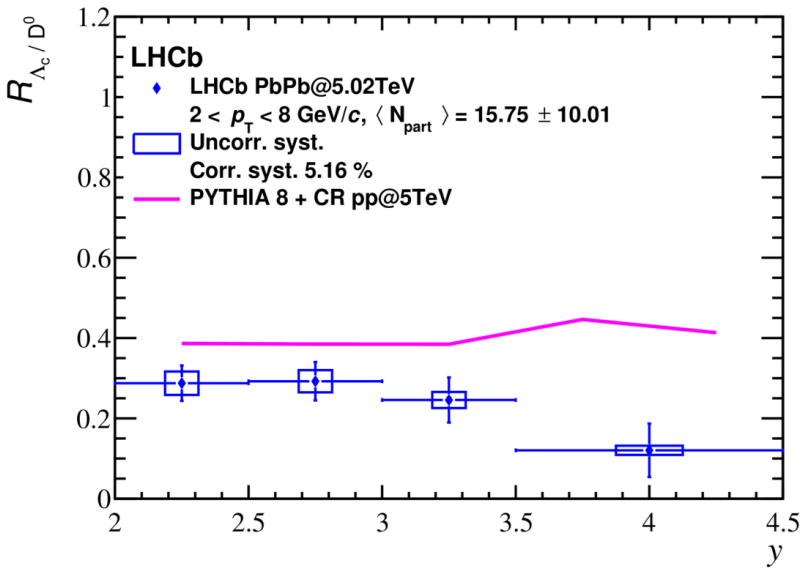
PROMPT Λ_C^+/D^0 RATIO AT 5.02 TEV WITH LHCB

- First measurement of prompt Λ_C^+/D^0 at forward rapidities in PbPb [arXiv:2210.06939]
  - Flat ratio versus multiplicity and rapidity, enhancement at intermediate pT
- Pythia8 + color reconnection: compatible with the data within 3σ
- Statistical Hadronization Model (RQM+Frag): above the data
- Need better understanding of charm hadronization

arXiv:2210.06939

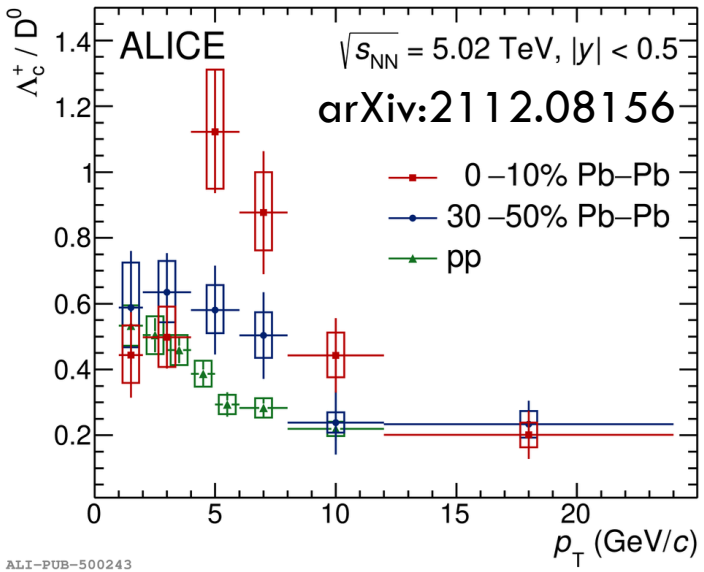


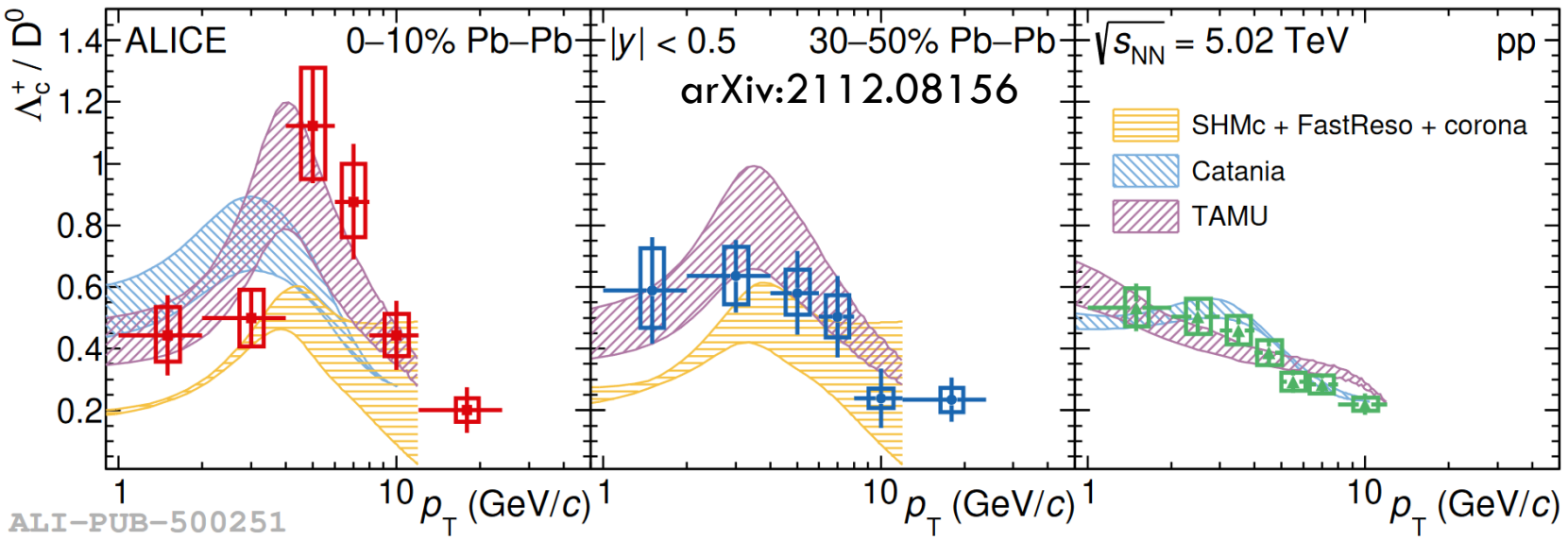




Λ_c^+/D^0 RATIO MEASURED BY ALICE

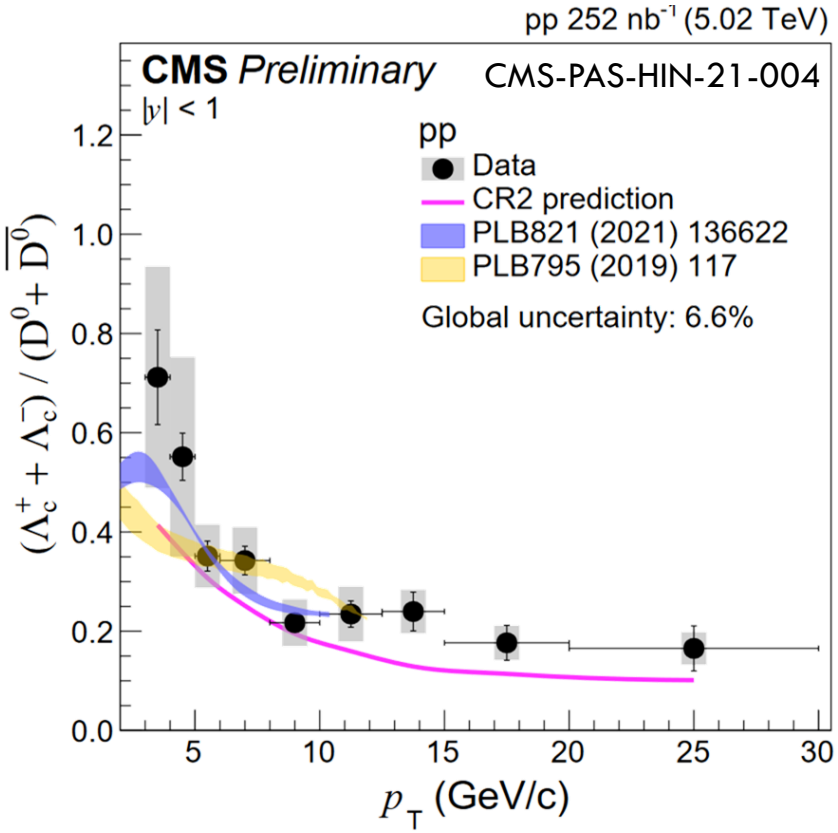
- Λ_c^+/D^0 ratio (and individual yields) measured in PbPb [ALICE, arXiv:2112.08156]
- Enhanced ratio in PbPb compared to pp at intermediate p_T
  - Although integrated ratios compatible in PbPb and pp
  - Possibly due to interplay of coalescence and radial flow, or hadronic rescattering for PbPb
- Models capture the trend of the data
  - Statistical hadronization models extended to charm hadron production
  - Models including hadronization via coalescence

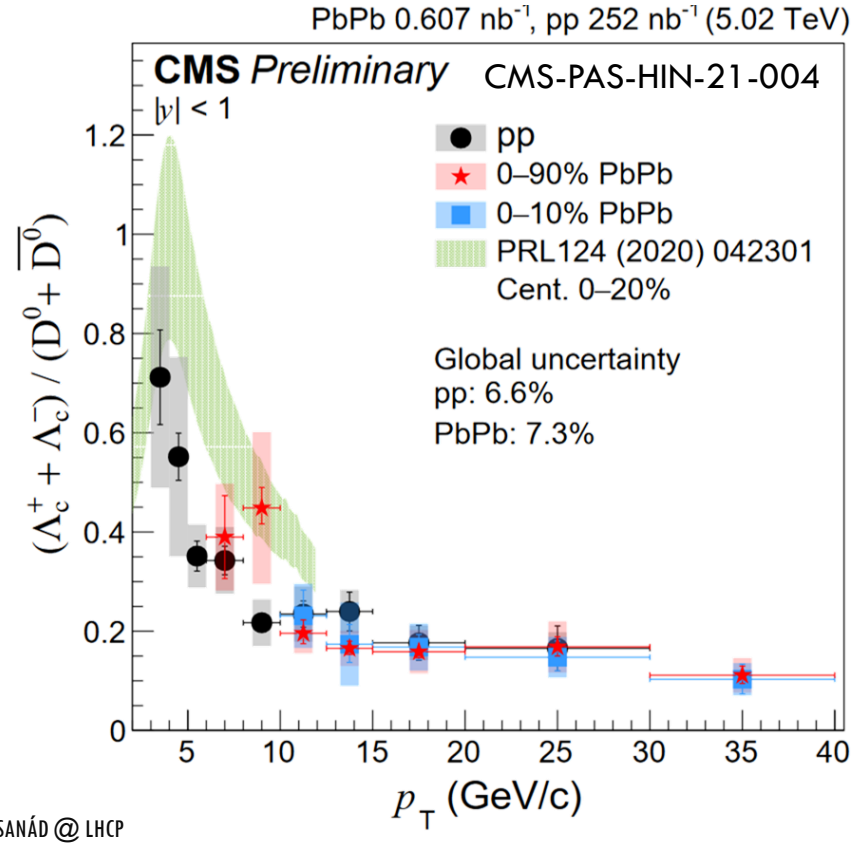




CHARM QUARK HADRONIZATION IN PP AND AA WITH CMS

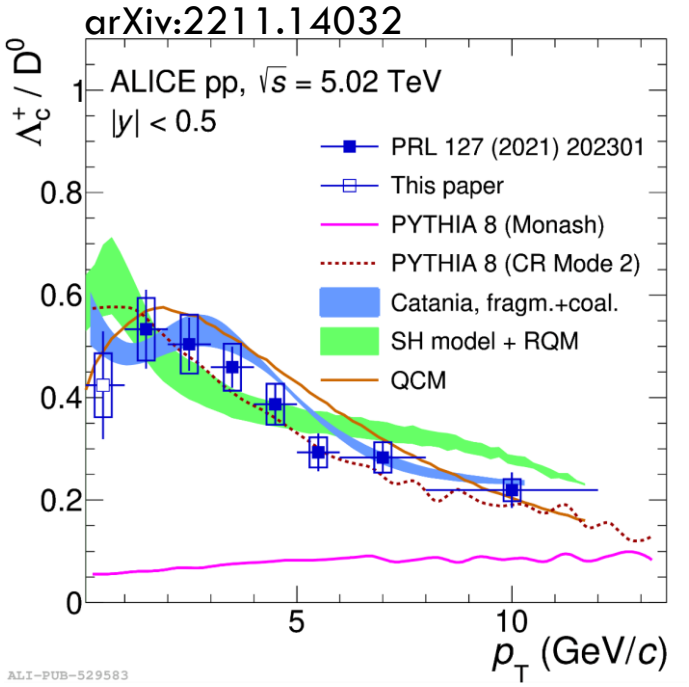
- PYTHIA+CR describes $(\Lambda_c^+ + \Lambda_c^-)/(D^0 + \overline{D^0})$ at $p_T < 10$ GeV in pp, similar to models
  - Containing decays of excited charm baryons; involving coalescence and fragmentation
- New results extend the p_T and centrality reach in PbPb
  - Ratio in pp and PbPb consistent: no significant contribution from coalescence

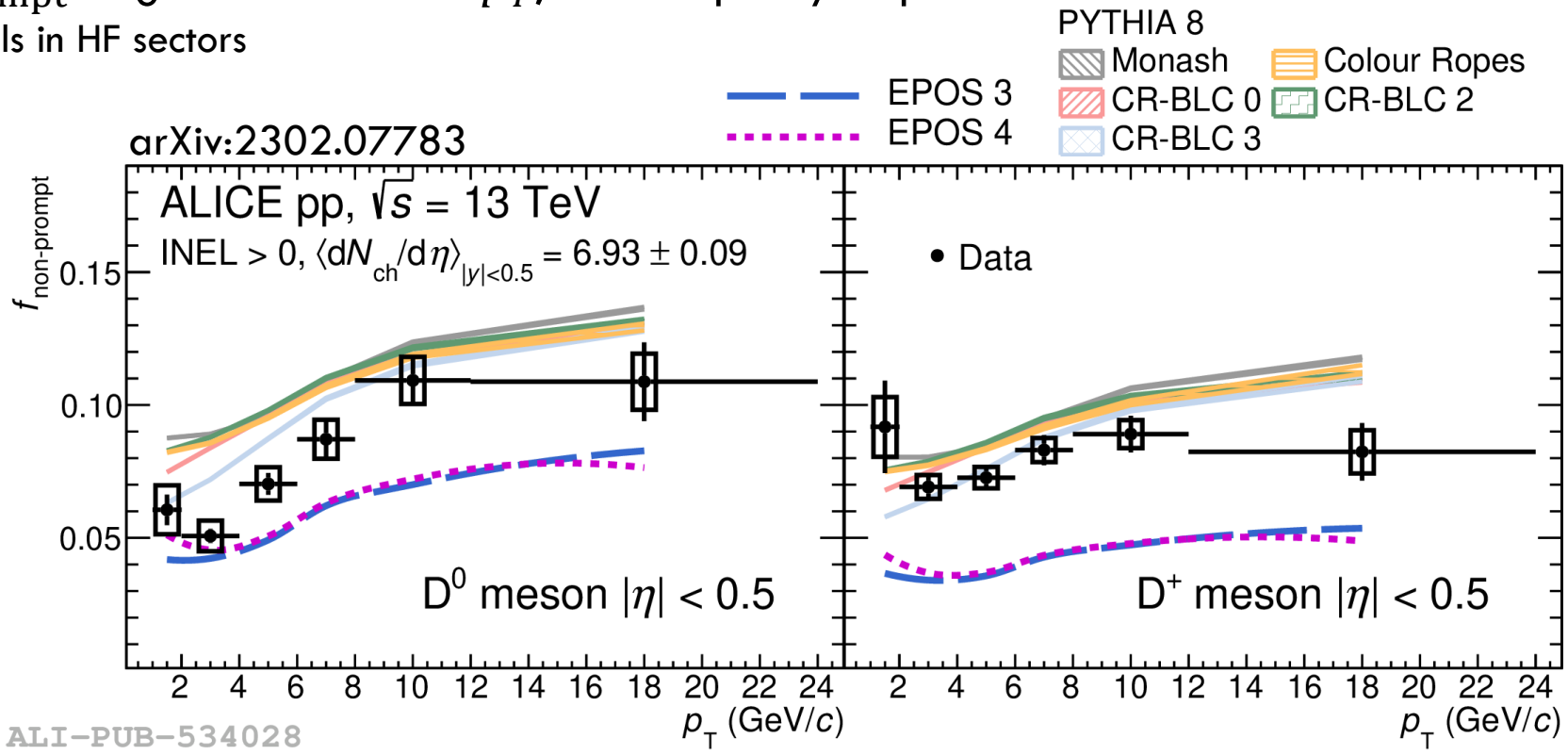




HEAVY FLAVOR HADRONIZATION IN PP WITH ALICE

- Charm baryon/meson ratios partially explained by models with modified hadronization mechanism
- Λ_c^+/D^0: Pythia Monash underestimates results, models with baryon enhancement work qualitatively
  - Ingredients: color reconnection, feed-down from unobserved charm baryons or coalescence (recombination)
- D^0 non-prompt fraction $f_{\mathrm{non-prompt}}$: slight increase with p_T, no multiplicity dependence
  - Important test for hadronization models in HF sectors





CHARM ELLIPTIC FLOW IN AA WITH CUMULANTS

- Prompt D^0 elliptic flow measured with 2- and 4-particle cumulants: $v_2\{2\}$ and $v_2\{4\}$
  - Two-step fit process: mass spectrum and cumulant fit in p_T intervals and centrality ranges
- Similar cumulant ratio as charged particles, pointing to similar origin: event-by-event fluctuations
- CMS paper: Phys. Rev. Lett. 129 (2022) 022001