U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

HF meson production at RHIC and LHC

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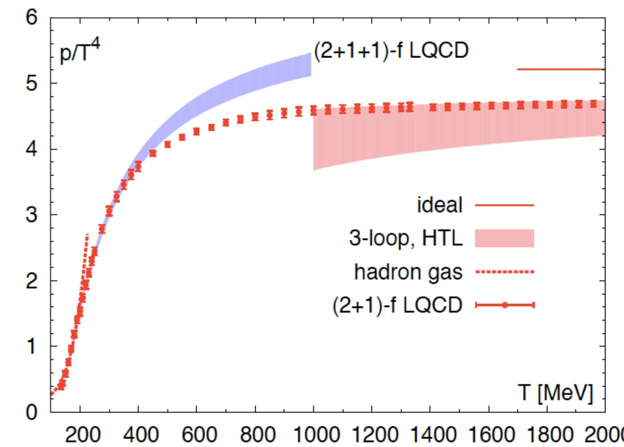
The Spectroscopy Program at EIC and Future Accelerators

Trento, December 19-21, 2018

QGP and Open Heavy Flavor

Bazavov et al, PRD 97 (2018) 014510
Borsányi et al,Nature 539 (2016) 69



- Lattice-QCD predicts a phase transition from confined hadrons to **Quark Gluon Plasma (QGP) where partons are deconfined.**
  - T_c = 156.5±1.5 MeV
  - Behaves like "perfect fluid"
  - Opaque to high energy partons

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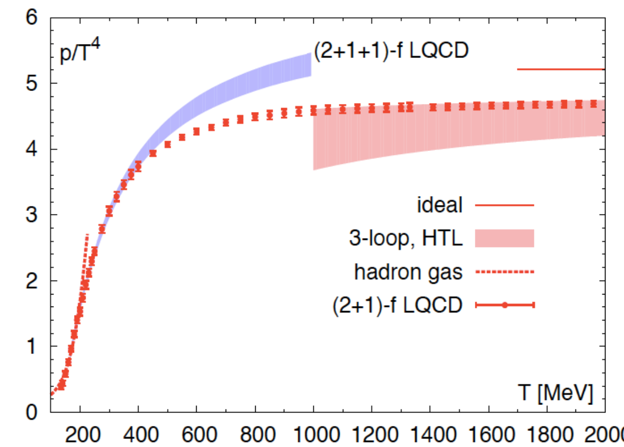
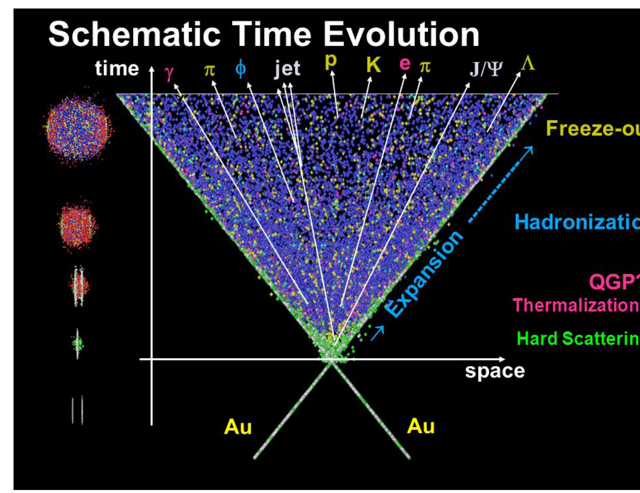


- **Heavy Flavor: $m_{c,b} \gg T_{QGP}, \Lambda_{QCD}$**
  - Produced in high-Q^2 scatterings → calculable in pQCD; numbers conversed
  - Produced at early stage → imprint the entire evolution history of QGP
    - $t_{HF}^{form} < t_{QGP}^{form}$; $t_{HF}^{relax} \sim t_{QGP}^{life\text{-}time}$



Probe QGP with Open HF

What To Measure?

- **Energy loss → transport coefficient**
  - Color charge and parton mass dependence: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  - Variable: $R_{AA} = Y_{AA}/(N_{coll} \times Y_{pp})$
    - Convolution of both energy loss and spectrum shape

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  - Degree of thermalization in the medium
  - Variable: $v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$
    - Energy loss plays a role at high p_T

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  - Is there any change of hadronization process in the medium?

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Where To Measure?

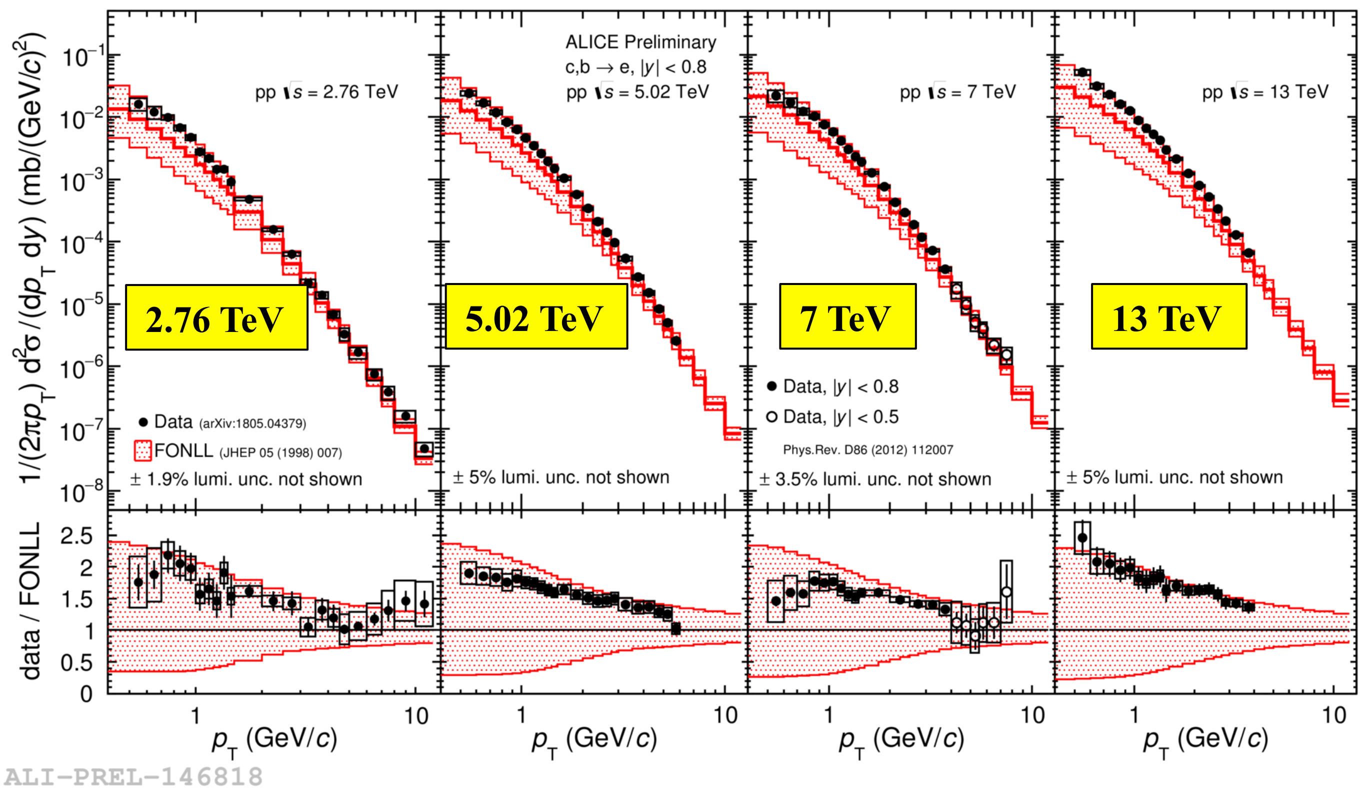
- p+p: baseline; emerging phenomenon
- p+A: CNM (effects due to presence of a nucleus, but not a medium)
- A+A: medium effects

pp Collisions

pA Collisions

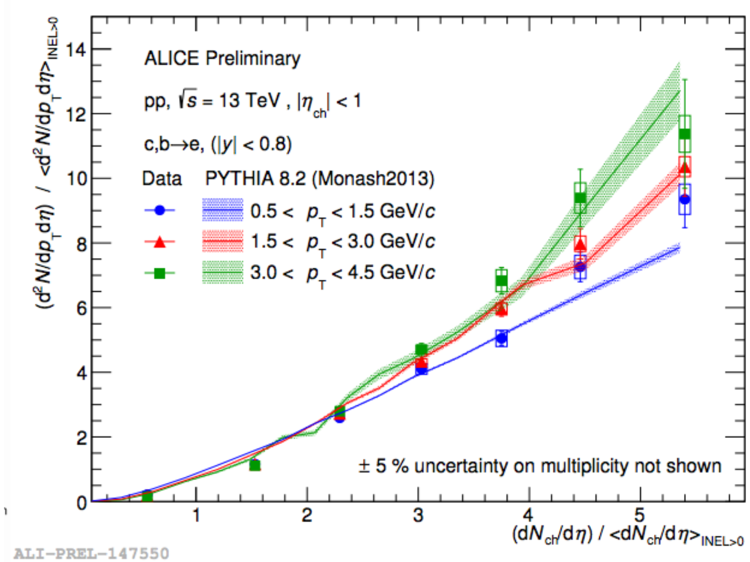
AA Collisions

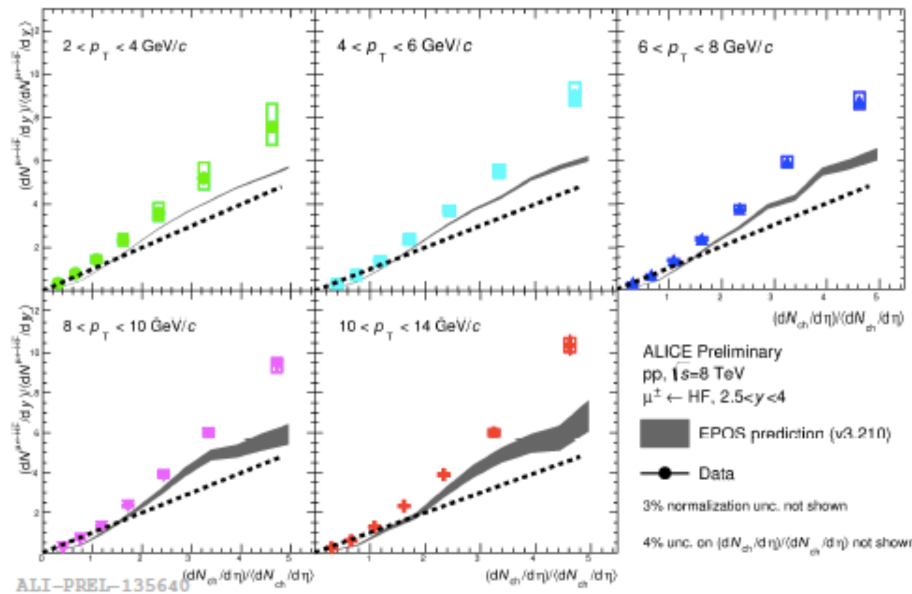
HF Electron Cross-section



- Inclusive cross-section for HF electron from 2.76 – 13 TeV
  - dominated by charm (bottom) decay at p_T<(>) 5 GeV/c
- Data sit at the upper bound of FONLL calculation: good test of pQCD
  - Help to constrain model calculations

HF→ e vs. Event Activity





- Self-normalized HE electron yield increases stronger-than-linearly vs. event multiplicity
  - Similar trend observed at RHIC for J/psi *STAR: PLB 786 (2018) 87*
- Model comparison
  - PYTHIA 8 with MPI: describe data fairly well
  - EPOS including hydrodynamics: under-predicts data

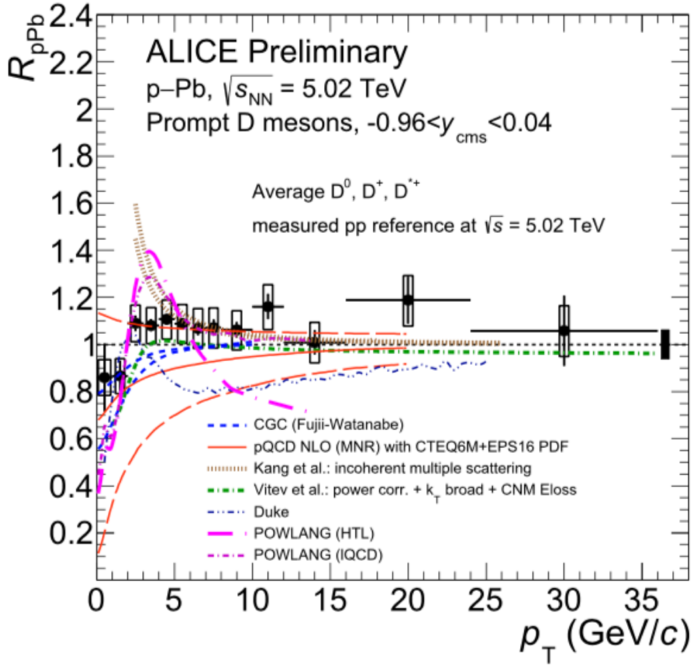
pp Collisions

pA Collisions

AA Collisions

CNM Effects for HF

ALICE: *PRL 113 (2014) 232301*



- **R_{pPb} is consistent with unity**
  - Low p_T: hint of showering?
  - Models of small QGP predicts too much suppression at high p_T

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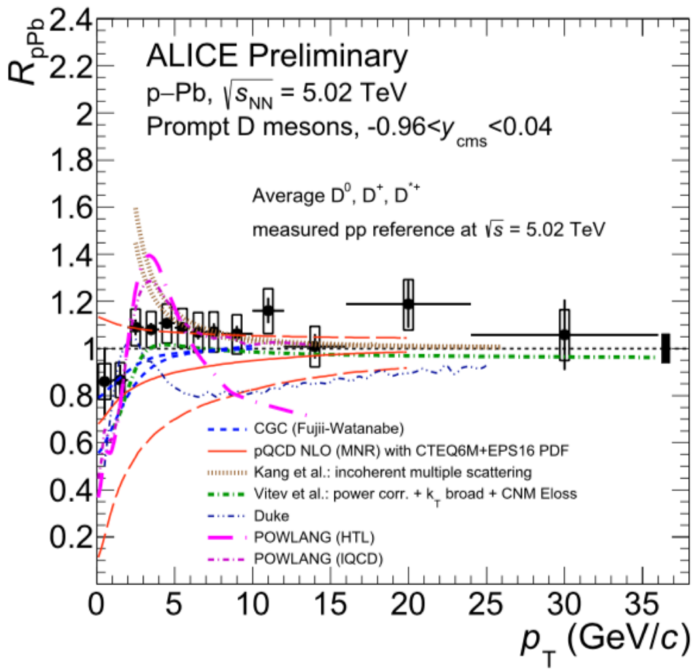
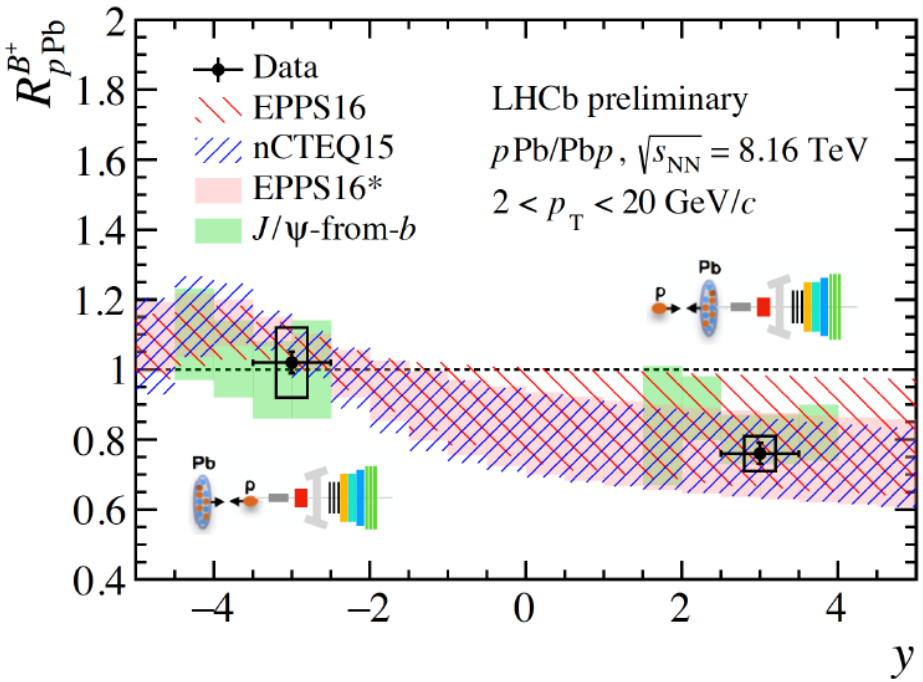
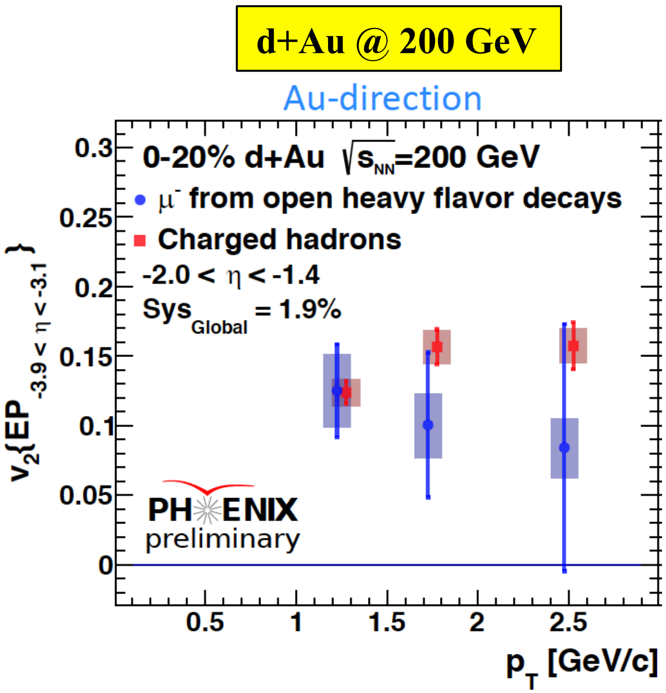
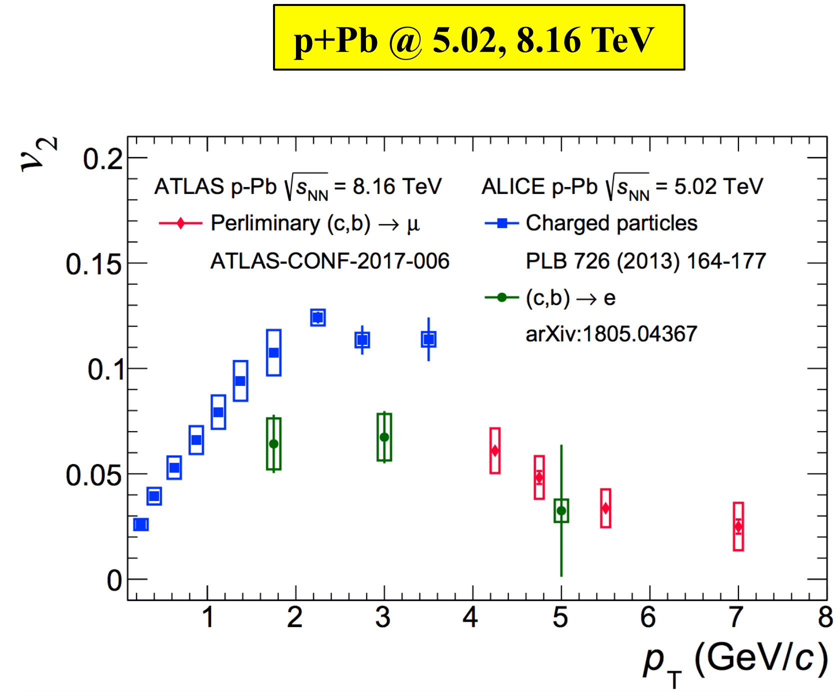




- **R_{pPb} is consistent with unity**
  - Low p_T: hint of showering?
  - Models of small QGP predicts too much suppression at high p_T
- B^+: inline with nPDF expectation
  - Forward rapidity: strong suppression explained by shadowing effect
  - Backward rapidity: consistent with unity

Collective Flow in High-mult Events

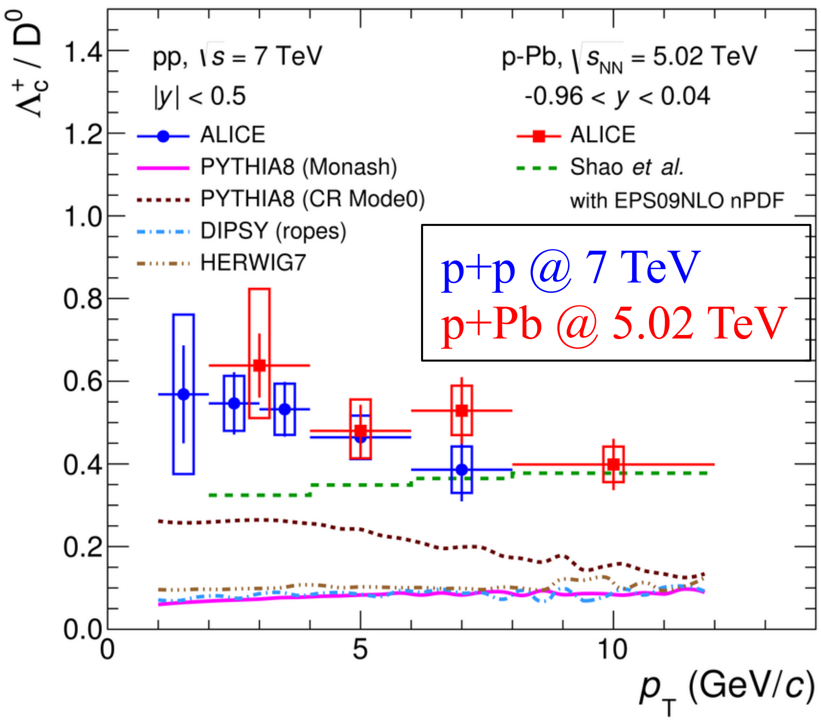


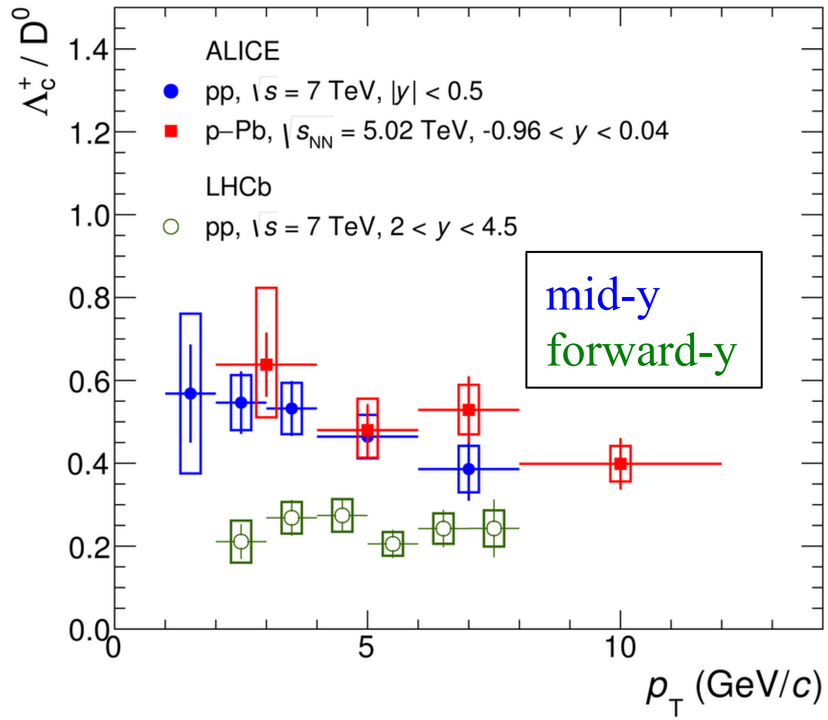


- HF-decayed leptons: non-zero flow observed in high-multiplicity p+A collisions at both RHIC and LHC
  - Smaller values than charged hadrons
- What is the origin?
  - CGC: correlation in the emitted gluons (Can it be observed at EIC? Unlikely)
  - Small drop of QGP?
  - Other mechanisms?

Charm Baryon Production

JHEP 04 (2018) 108





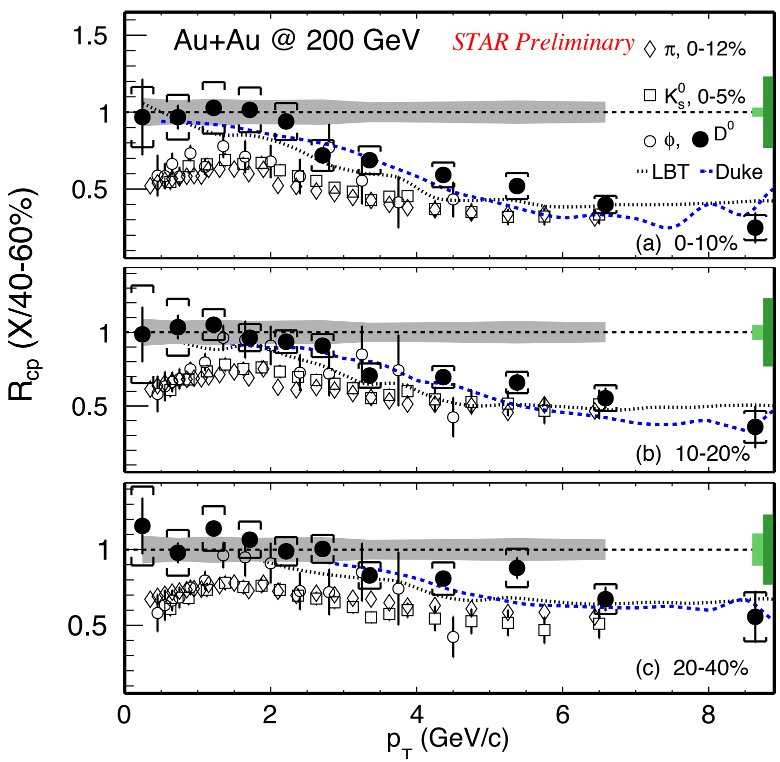
- Mid-y: Λ_c/D^0 ratio in p+p collisions is significantly higher than model calculations
  - PYTHIA with CR is closer to data
- Similar ratios in p+Pb and p+p collisions
- *However, there seems strong rapidity dependence for the ratio. Different mechanism for hadronization?*

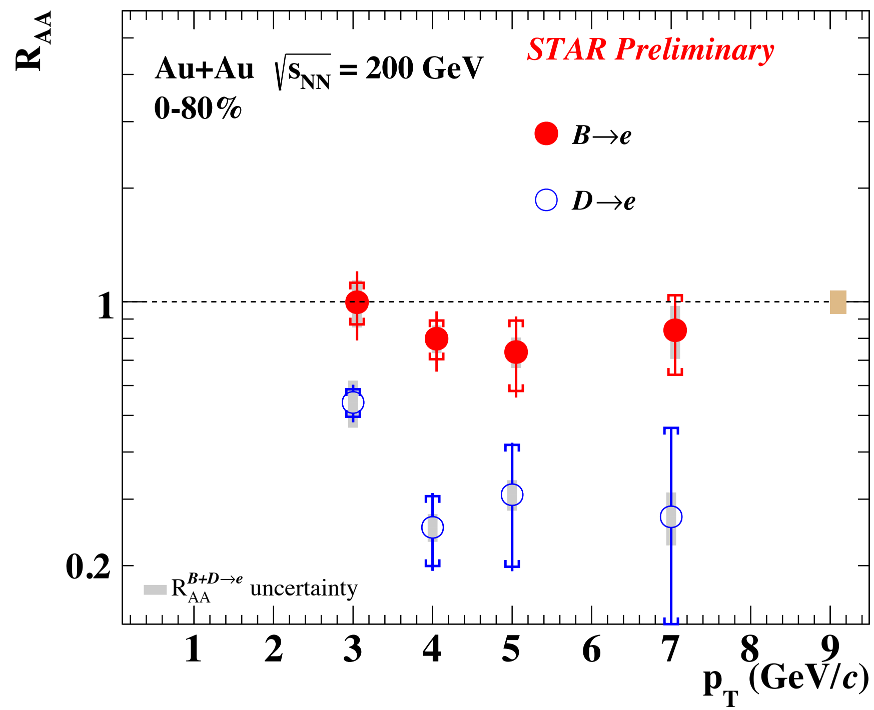
pp Collisions

pA Collisions

AA Collisions

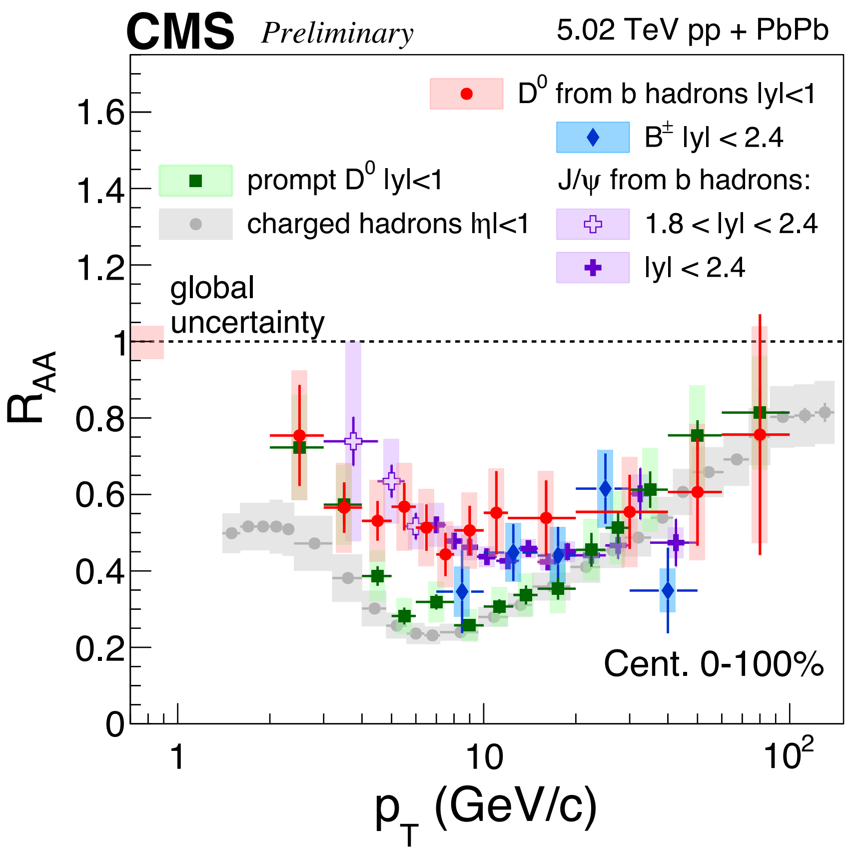
HF Suppression at RHIC





- Strong suppression of D^0 and HF e at high p_T → **strong interactions between charm and medium**
  - Bottom quarks also seem to lose energy
- Indication of energy loss hierarchy: $R_{CP}^{\pi} < R_{CP}^{D}$, $R_{AA}^{c\text{->}e} < R_{AA}^{b\text{->}e}$
- Help to extract transport coefficient of the QGP

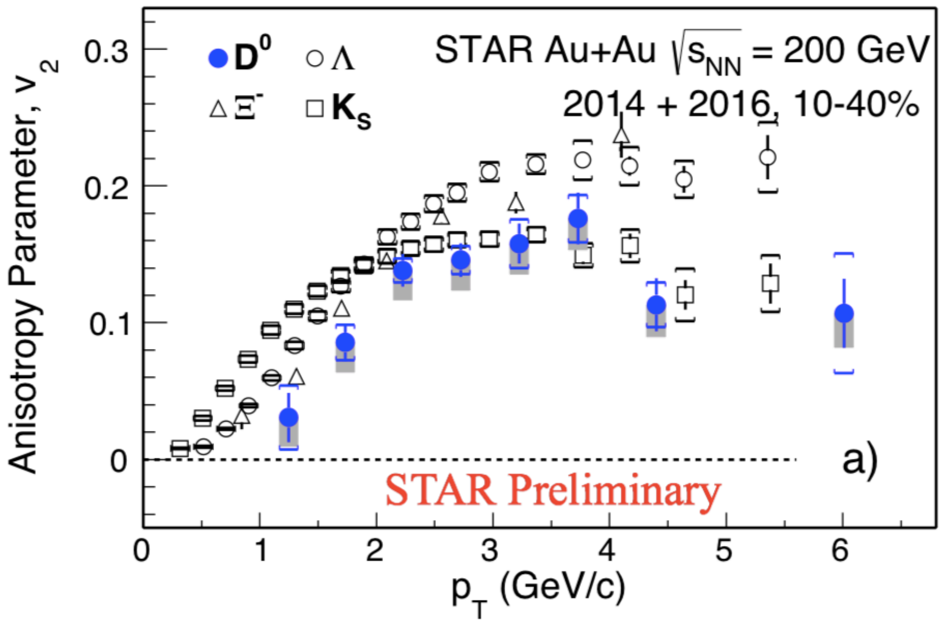
A Similar Picture at the LHC



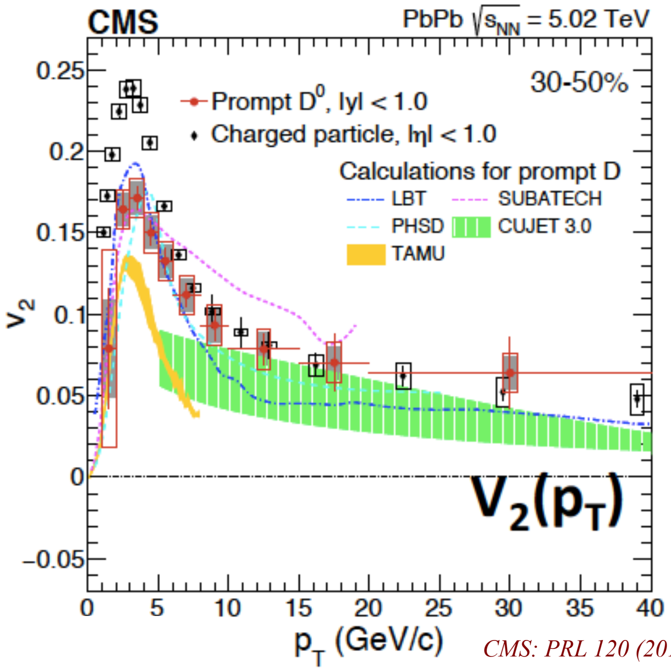
- p_T < 10 GeV/c or so: mass hierarchy of energy loss
- p_T > 20 GeV/c: all R_{AA} start to converge as the parton mass becomes less important compared to momentum
  - Spectrum shape needs to be taken into account
- Precision will be improved with more data to come

Charm Quark Flows in the Medium

RHIC: Au+Au @ 200 GeV



LHC: Pb+Pb @ 5.02 TeV

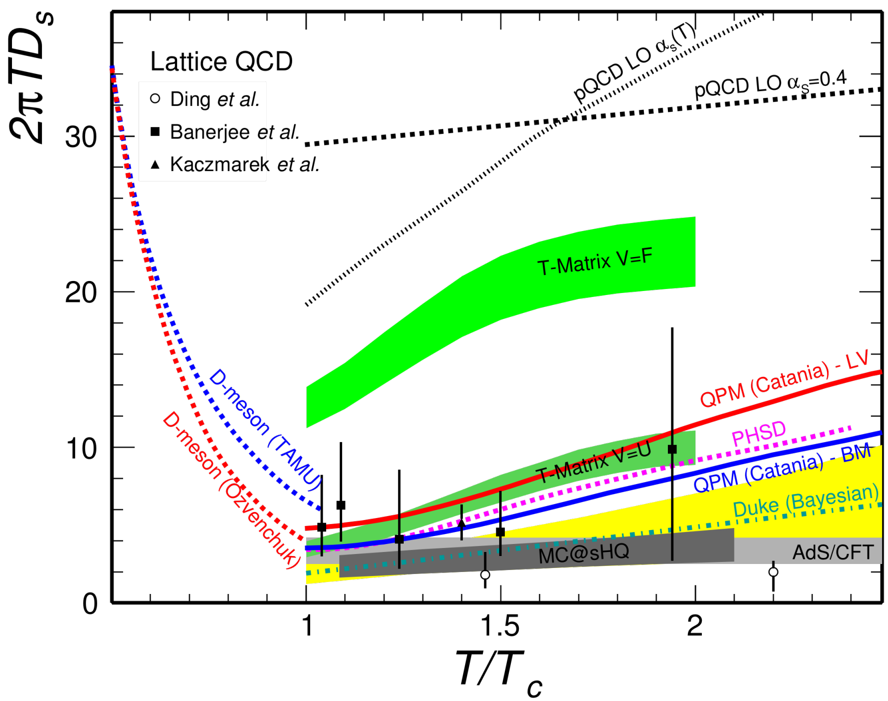


CMS: PRL 120 (2018) 202301

- Significant v_2 → strong collective behavior of charm quarks in the medium
- Smaller value compared to LF hadron at low p_T
  - Mass dependence?
  - Charm quarks do not flow as strong as light quarks?
- LHC: models with strong charm-medium interaction (low p_T), and collisional and radiative energy losses (high p_T) can qualitatively describe data

Diffusion Coefficient vs. T

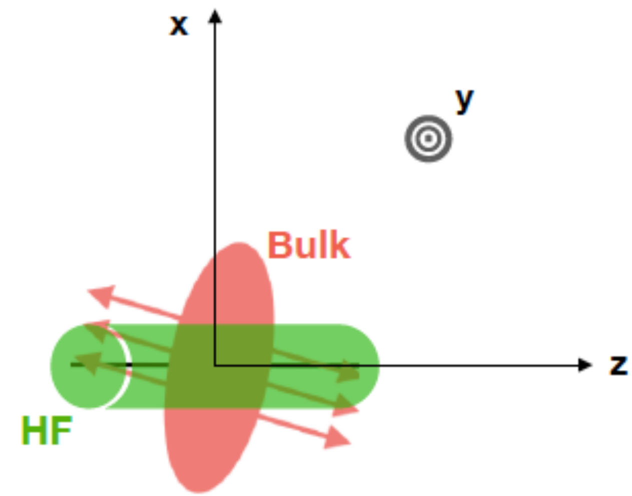
X. Dong and V. Greco, Progr. Part. Nucl. Phys. (2018)



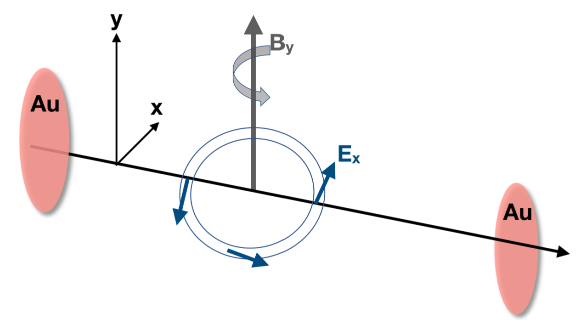
- $2\pi TD_s$: fundamental properties of the medium. Large discrepancy among different models.
- D^0 v_2 can help to constrain:
  - RHIC: 2 ~ 12 within T_c to $2T_c$ *STAR: PRL 118 (2017) 212301*
  - LHC: 1.5 ~ 7 at T_c *ALICE: PRL 120 (2018) 102301*

D^0 v_1: A Different Perspective

1. HF drag: mis-match between symmetric production profile for HF and titled bulk medium
   - $v_1^{HF} > v_1^{LF}$
   - Same effect for HF and anti-HF

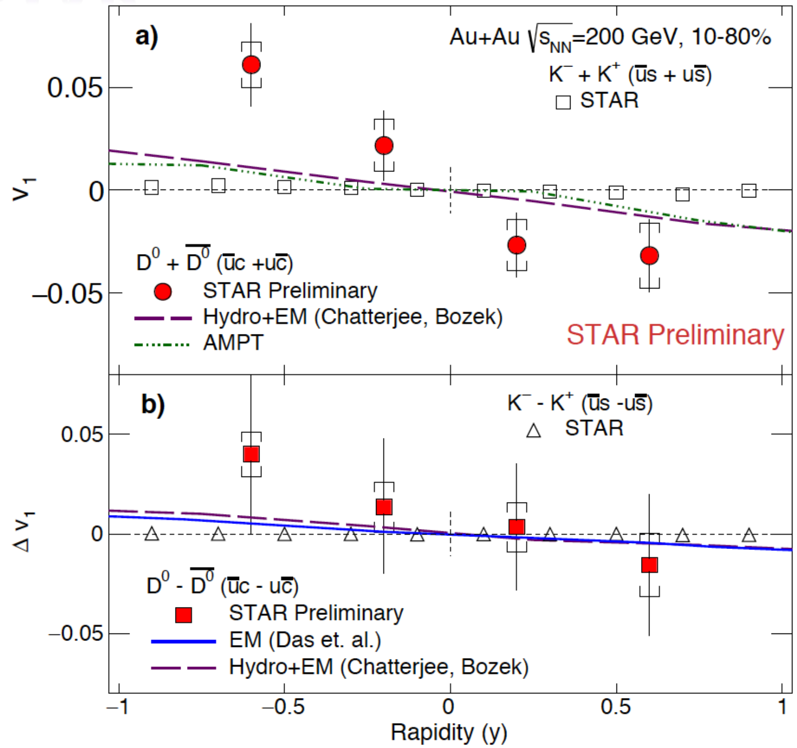


2. Initial EM field: strong impact for HF as they are produced early
   - $v_1^{HF} >> v_1^{LF}$ (EM field decays rapidly)
   - Opposite effect for HF and anti-HF

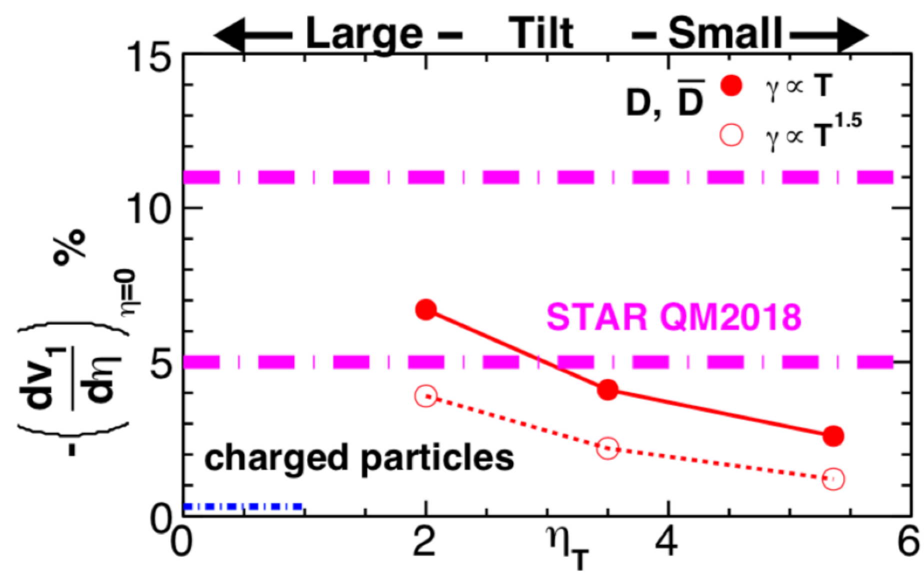


D^0 v_1 at RHIC

STAR



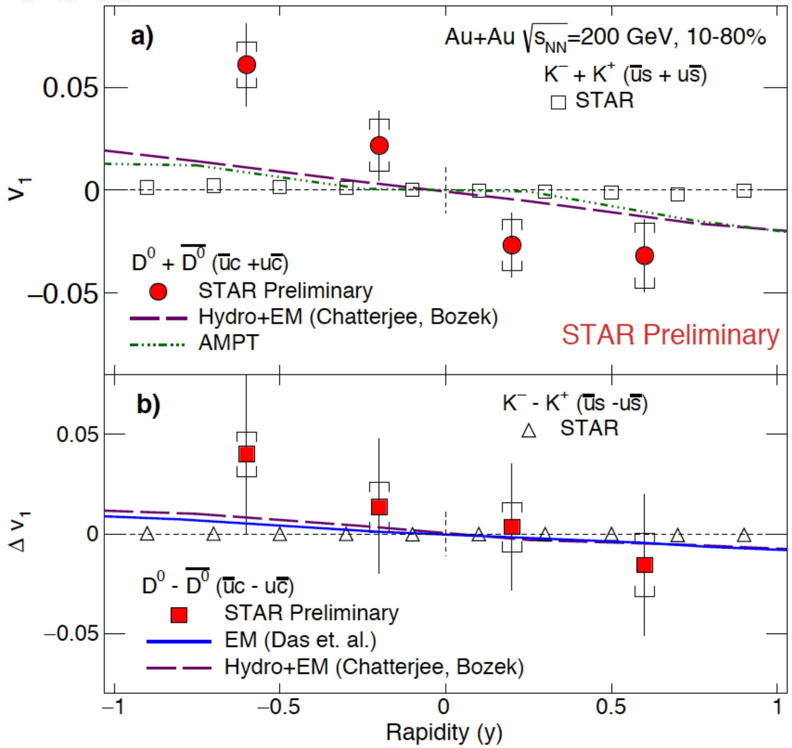
Chatterjee, Bozek, arXiv: 1804.04893



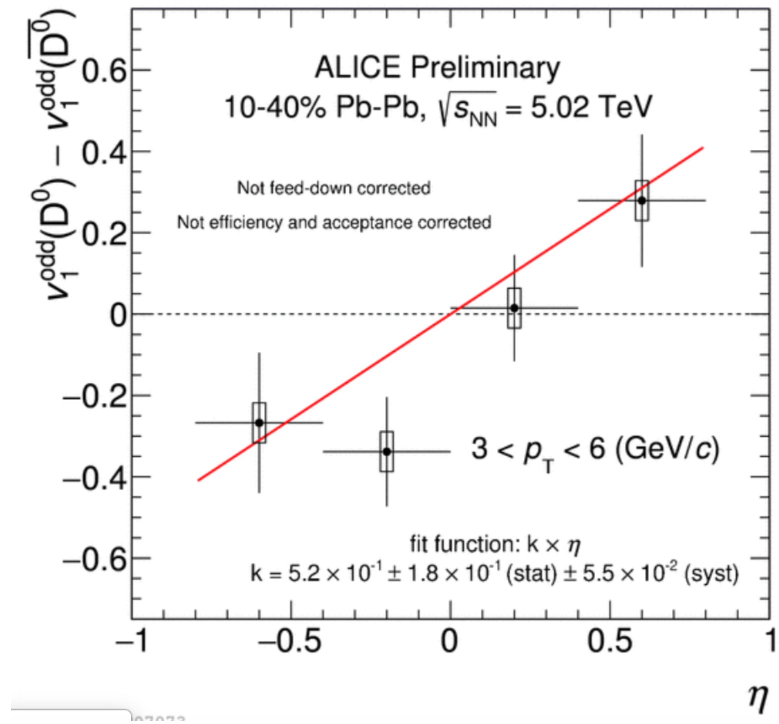
- v_1(D^0+anti-D^0): much larger than Kaon v_1
  - Model predicts correct sign but lower magnitude
- $v_1(D^0)$-v_1(anti-D^0): hint of splitting, but not precise enough
- Data seem to favor larger drag coefficient.

D^0 v_1: RHIC vs. LHC

STAR



ALICE

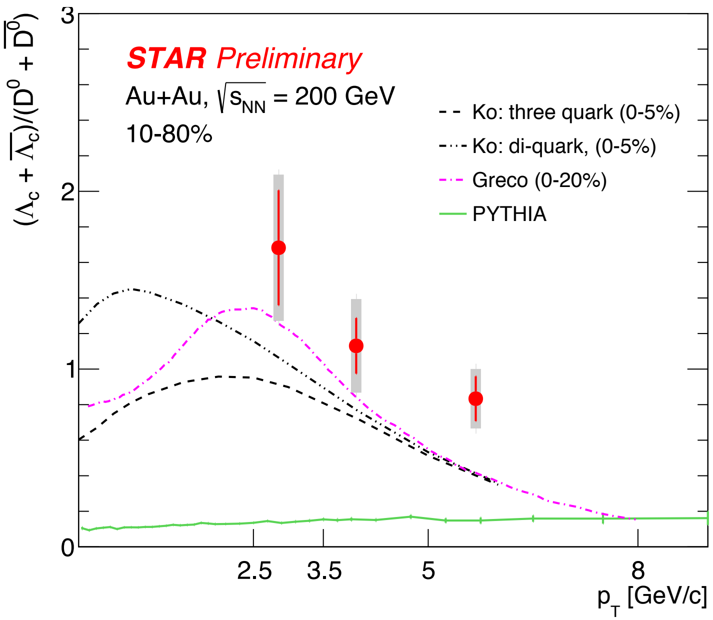


- $v_1(D^0)$-v_1(anti-D^0): opposite splitting between RHIC and LHC
- Model calculation and better experimental precision are needed to understand the apparent difference

HF Hadronization: Λ_c

- Baryon-to-meson ratio enhanced for LF, and explained by coalescence hadronization

RHIC: Au+Au @ 200 GeV



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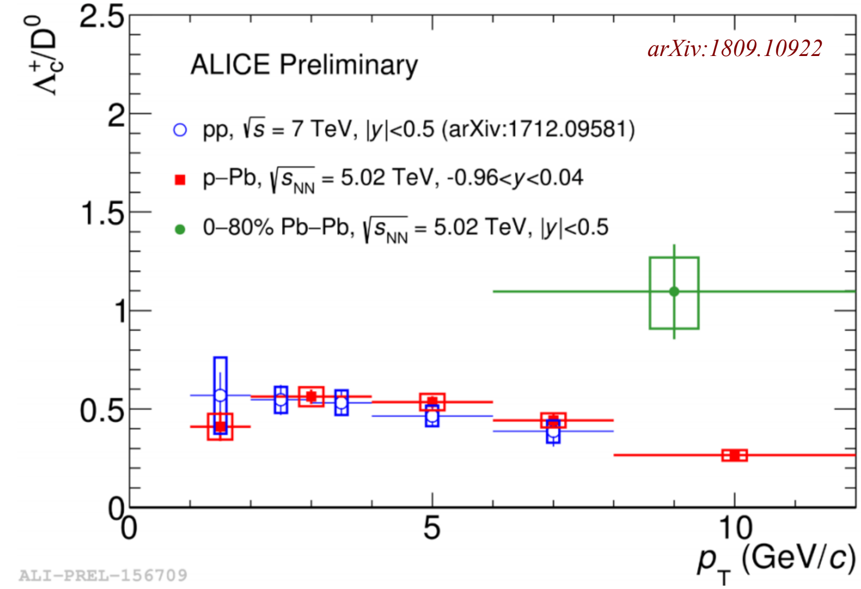


- Strongly enhanced Λ_c/D^0 ratio in A+A collisions compared to baseline
  - Decrease with increasing p_T
  - Level of enhancement is similar to LF
- RHIC: model calculations with coalescence hadronization are closer to data, but still not sufficient

Summary

- *Open HF has served as an important probe in understanding the properties of the QGP*
- **p+p**: charm cross section agrees with pQCD
  - Yield increases rapidly with event multiplicity → MPI
- **p+A**: consistent with nPDF expectation
  - Origin of the collective motion
  - Rapidity dependence of fragmentation
- **A+A**: strong interactions between charm quarks and medium → transport/diffusion/drag coefficients
  - Expected mass/flavor hierarchy of energy loss
  - Charm quark coalescence in the medium

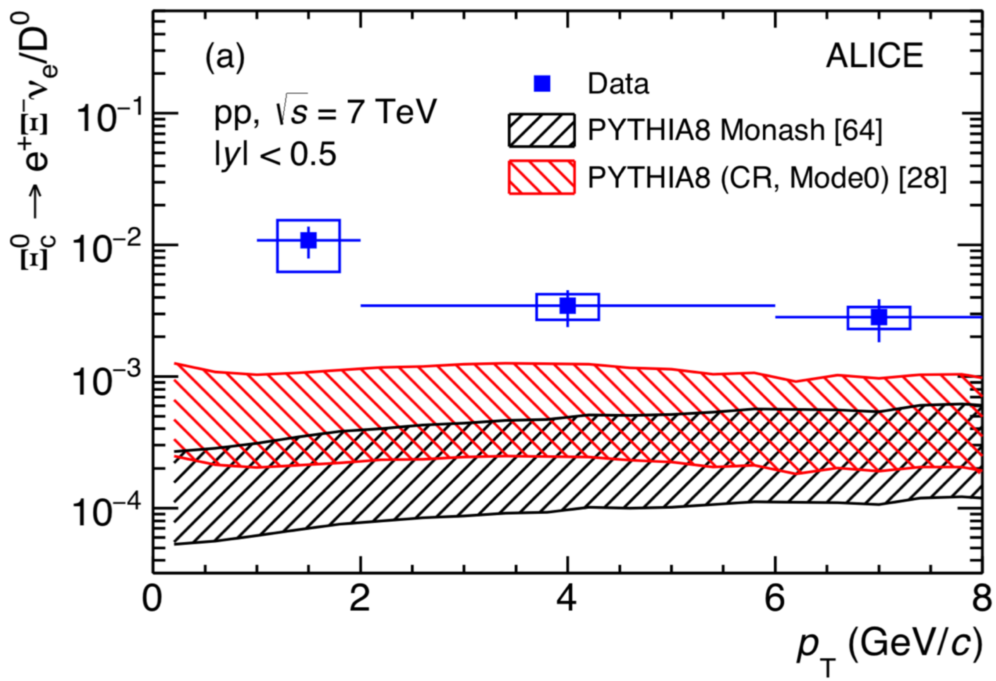
What Can EIC Bring?

- Precise determination of 3D spatial and momentum distributions of partons as well as their fluctuations in the nucleus
  - Initial condition for hydrodynamic modeling for extracting fundamental properties of the QGP
  - Baseline for interpreting energy loss measurement
  - Shed lights on emerging phenomena in pA collisions

Backup

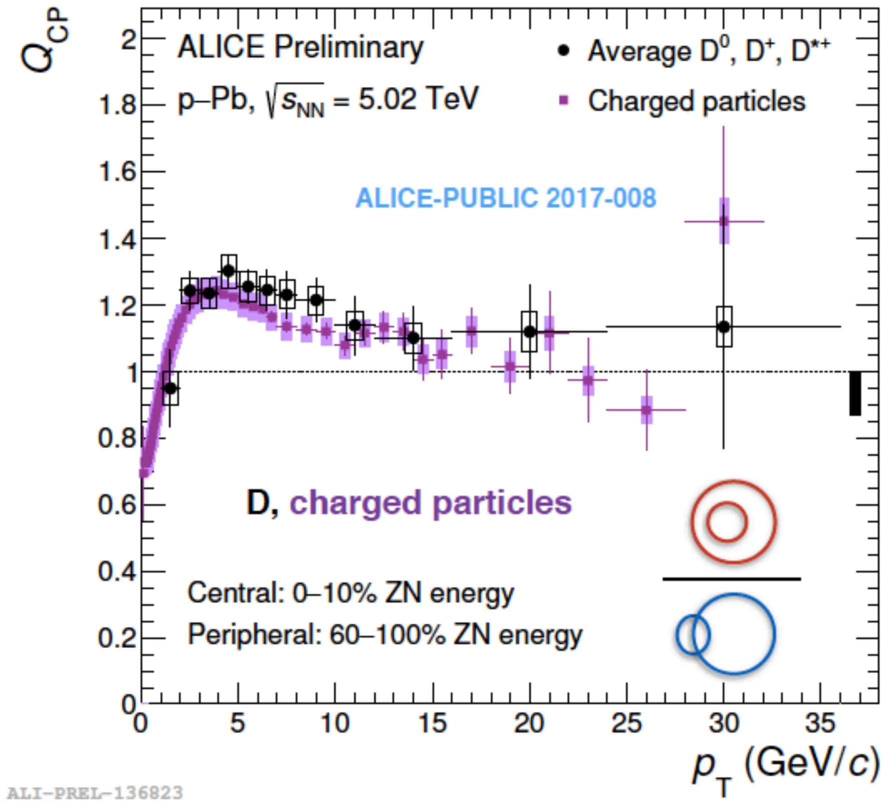
HF Hadronization in p+p Collisions

ALICE: PLB 781 (2018) 8



- First measurement of Ξ_c^0 at the LHC
- Measured Ξ_c^0/D^0 in 7 TeV p+p collisions is significantly larger than PYTHIA prediction

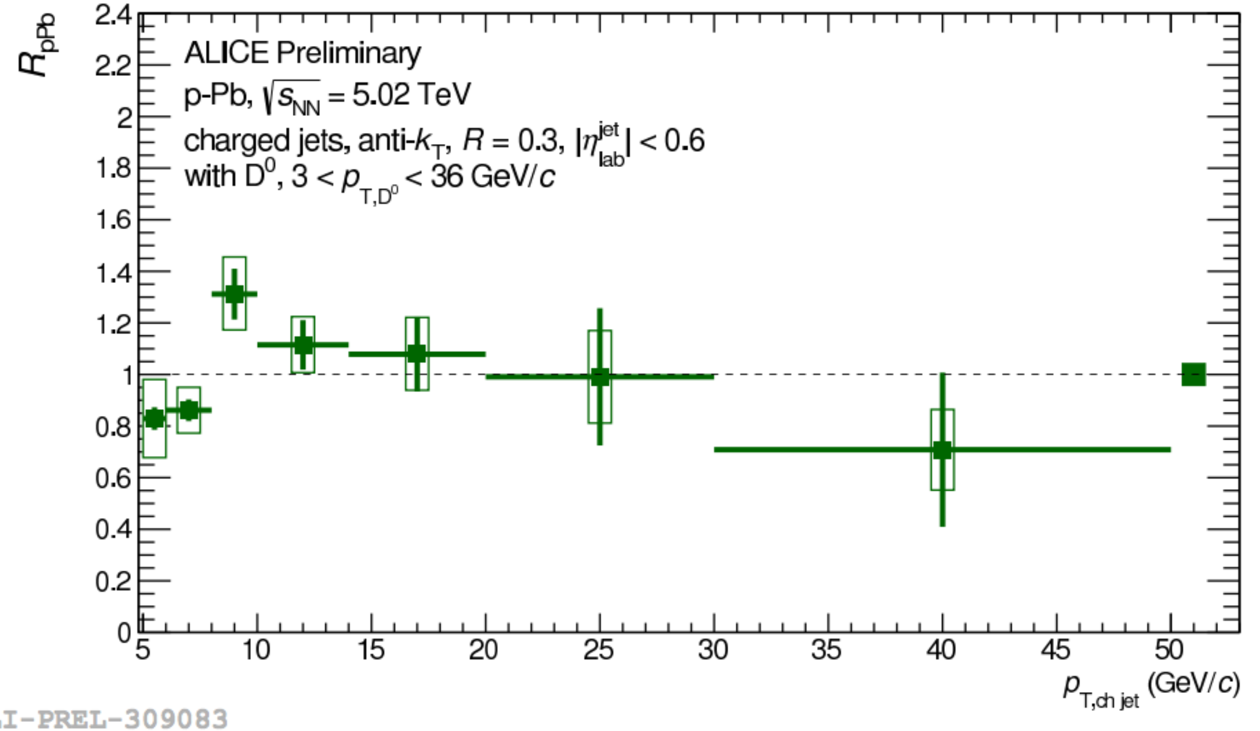
D Meson in High-mult Events



PRC 91 (2015) 064905

- D^0: enhancement in high-mult p+Pb events compared to low-mult events
  – *Magnitude similar to charged hadrons*
  – *Effects of radial flow?*
- Not inline with the existence of QGP

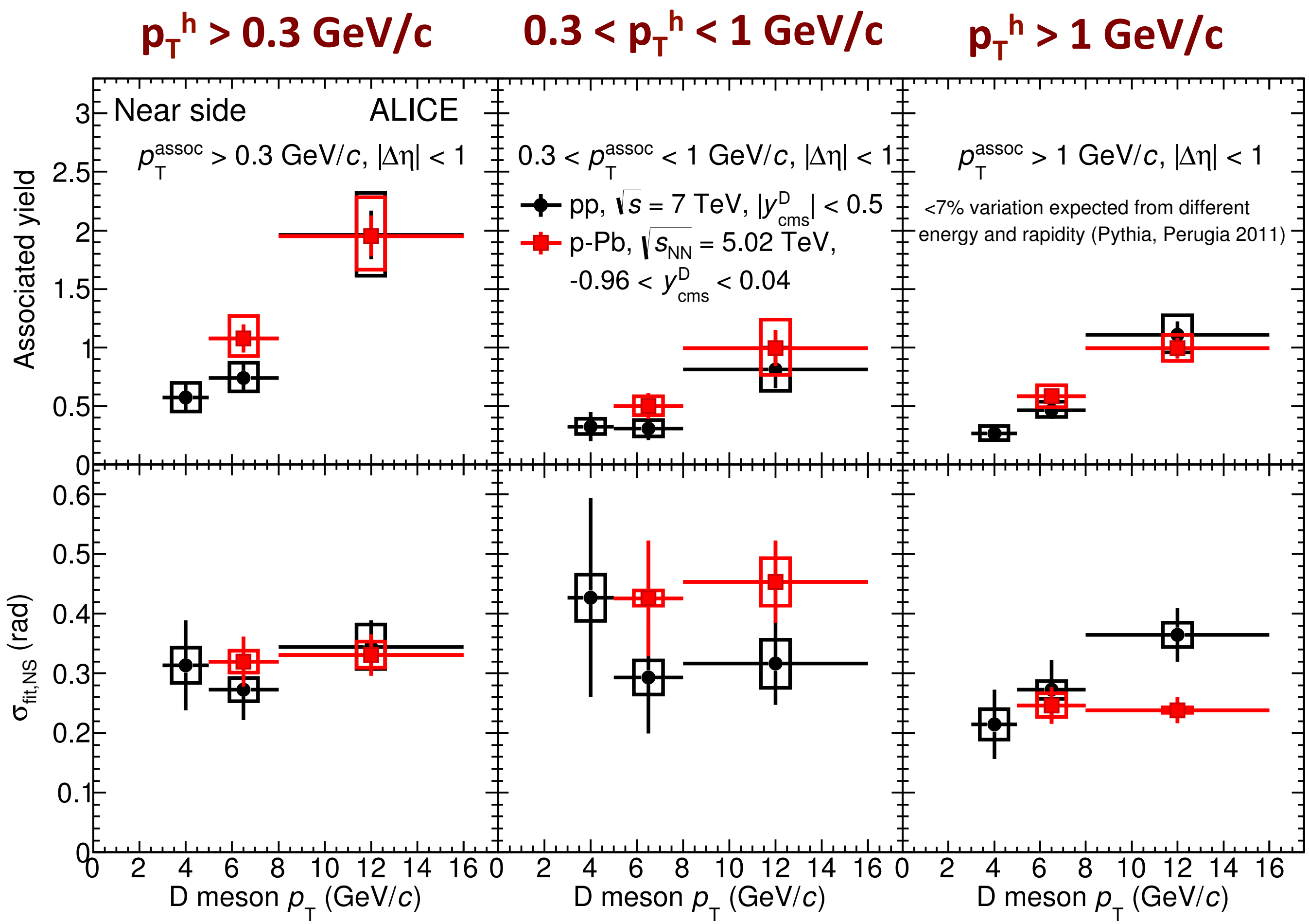
Jets with D-meson



- R_{pPb} ~ 1 for jets with D^0, 3 < p_T^D < 6 GeV/c
- **No strong CNM effects for charm quarks**

D-h Correlation

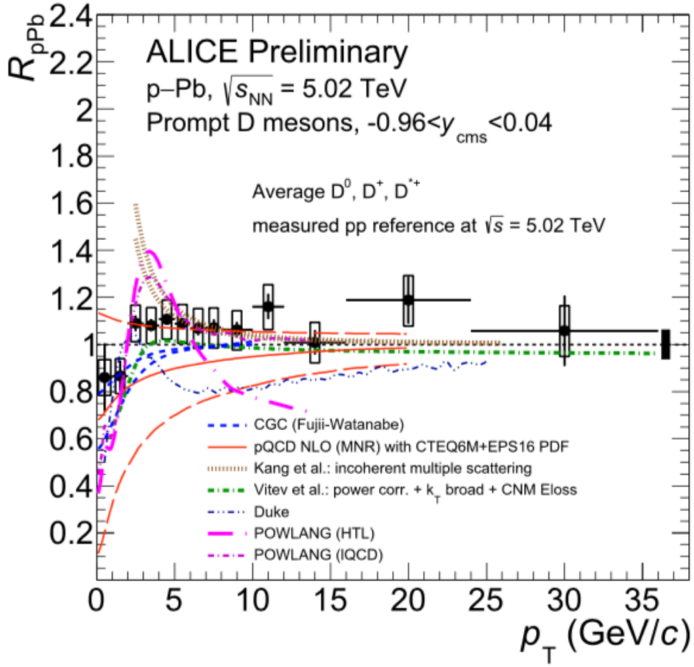
EPJC 77 (2017) 245

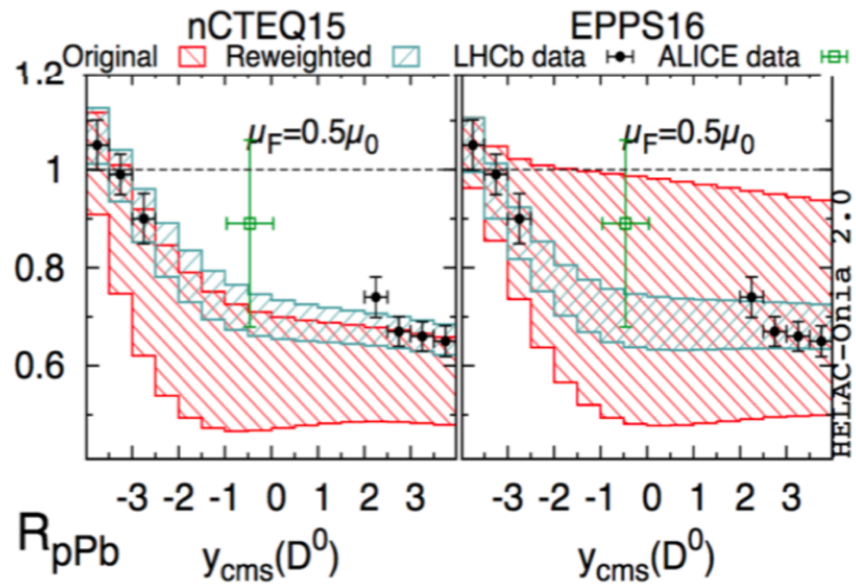


- Near-side peak is compatible between pp and pPb
- Fragmentation to D meson seems largely unaltered in pPb

CNM Effects for Charm

ALICE: ***PRL 113 (2014) 232301***

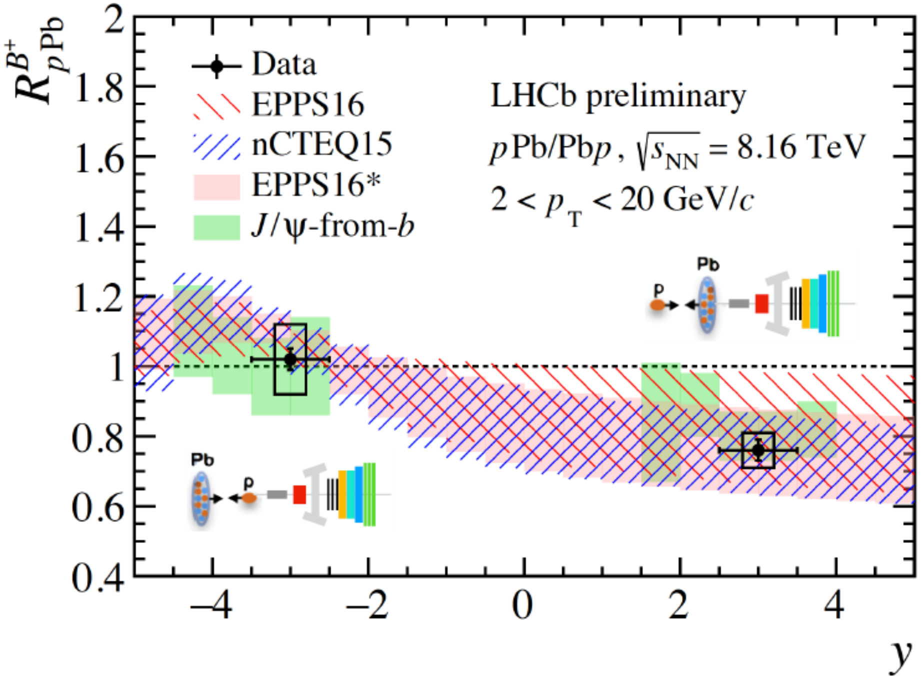


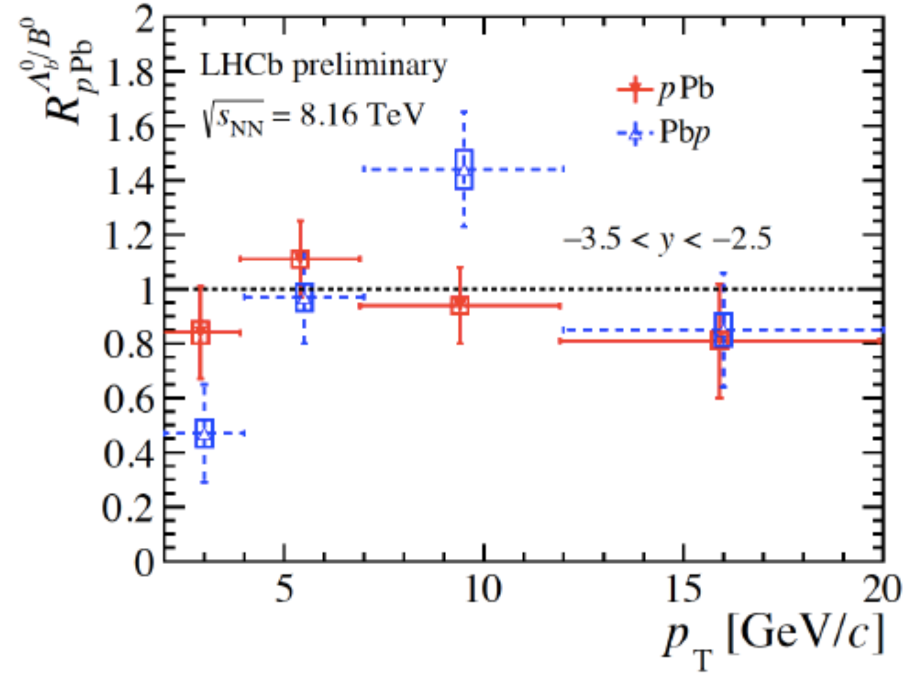


A. Kusina, et al.
PRL 121 (2018) 052004

- **R_{pPb} is consistent with unity**
  - Low p_T: hint of showering?
  - High p_T: not much room for >20% suppression
- Models of small QGP predicts too much suppression at high p_T
- **Provide valuable constraints to nPDF**

CNM Effects for Bottom

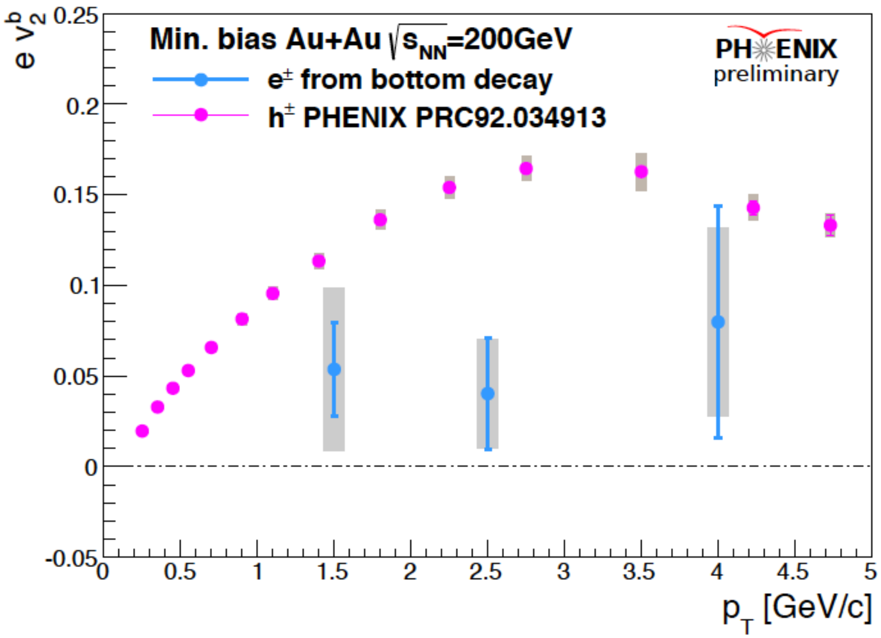




- **B^+**
  - **Forward rapidity: strong suppression explained by shadowing effect**
  - **Backward rapidity: consistent with unity**
- Λ_b: similar level of CNM effects as B^0 at forward/backward rapidities

Does Bottom Quark Flow?

RHIC: Au+Au @ 200 GeV



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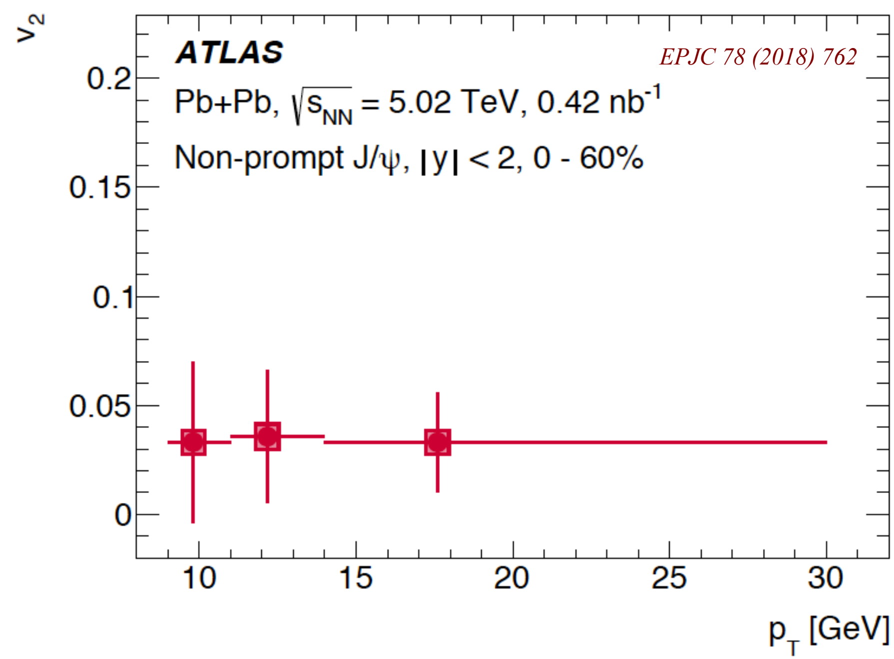
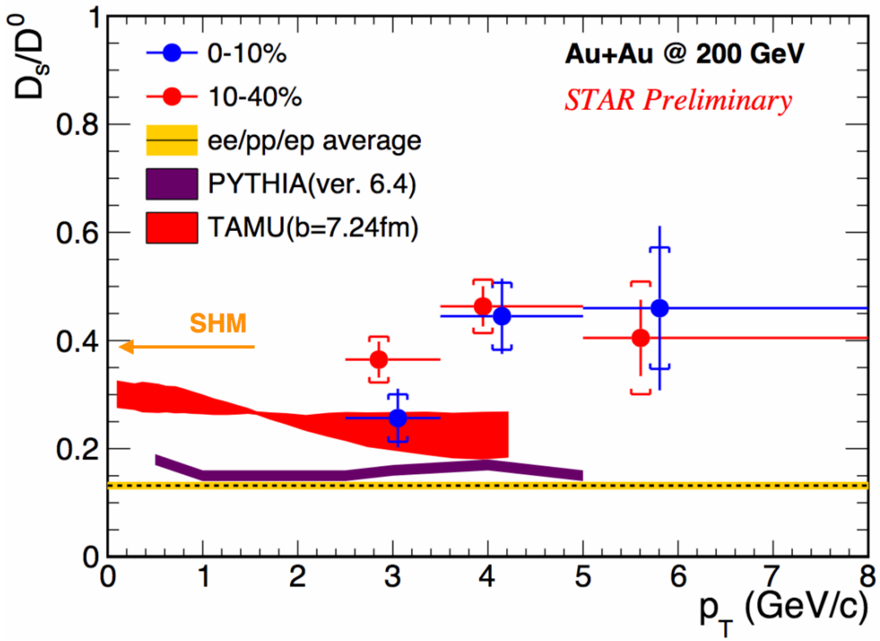


- Hint of non-zero v_2 for bottom quarks at both RHIC and LHC.
- Improved precision on measurement is needed.

HF Hadronization: D_s

- Expect enhanced D_s production in the medium: i) strangeness enhancement; ii) coalescence

RHIC: Au+Au @ 200 GeV



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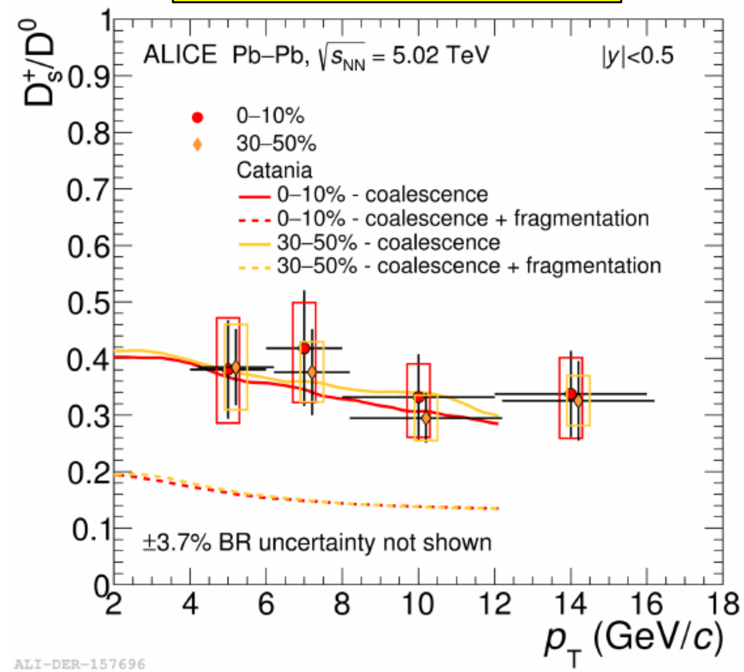
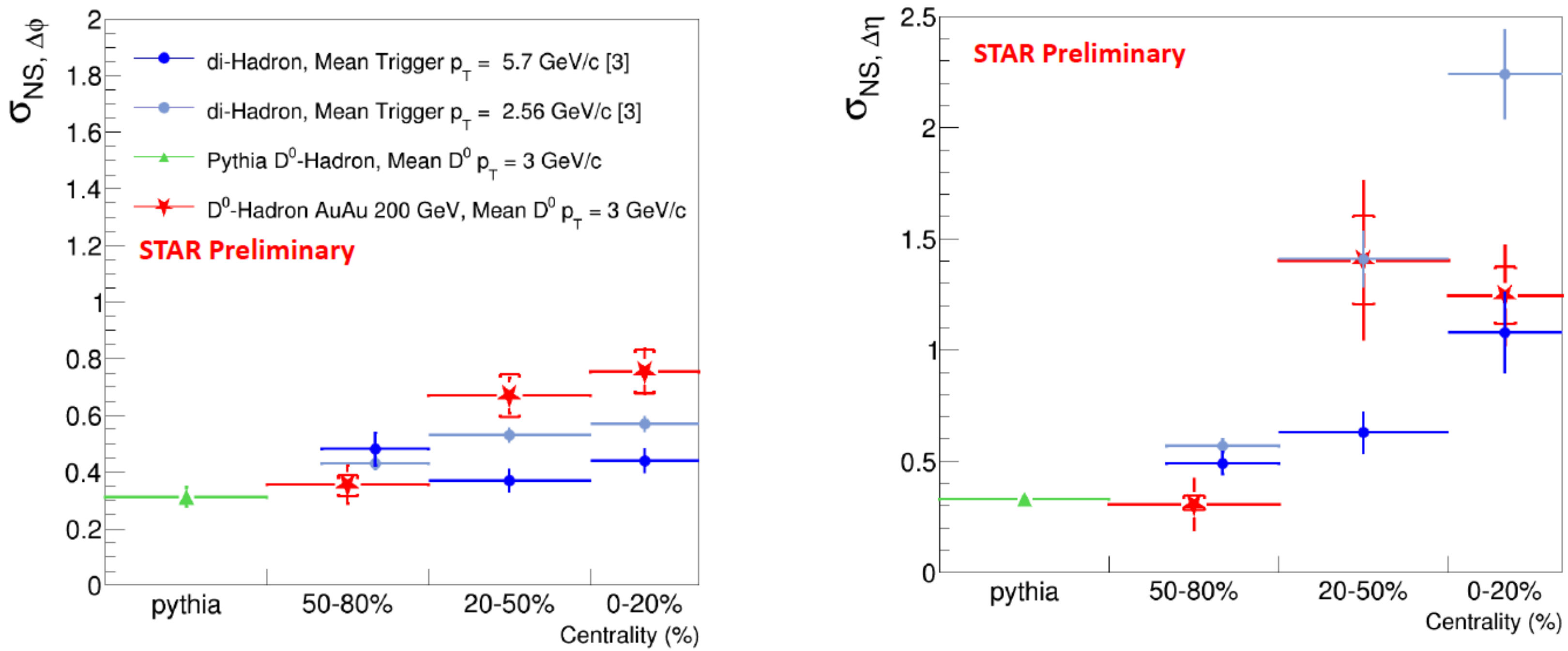


- Enhanced D_s/D^0 ratio compared to fragmentation baseline
- No strong centrality dependence, and persists to high p_T
- Model calculation with coalescence hadronization is closer to data, but not able to do so at high p_T

How Do HF Jets Modified?

- RHIC: extract near-size widths from D^0-h correlation



- Widths in peripheral events are similar to those in PYTHIA
- **In central and semi-central collisions, substantial broadening of near-side jets along both η and φ directions**
- Levels of broadening is similar to those for charged hadrons at similar mean p_T