Open heavy-flavor measurements

Ralf Averbeck
ExtreMe Matter Institute EMMI and Research Division
GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany

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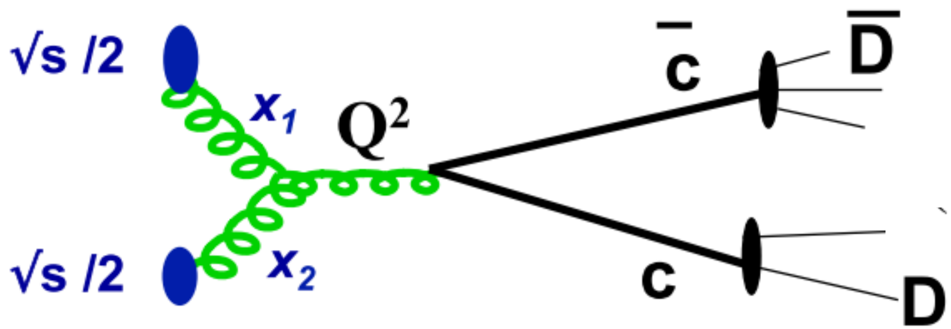
Heavy flavor: a unique probe

- **heavy quarks:** charm (m_c ~ 1.5 GeV), beauty (m_b ~ 5 GeV)
- $m_{c,b} >> \Lambda_{QCD}$
  → heavy quarks = genuine hard probes, even at low p_T
- large mass → short formation time:
  $\tau_{c,b} \sim 1/2m_{c,b} < 0.1$ fm $<< \tau_{QGP} \sim 5\text{-}10$ fm



- heavy quarks are unique
  - interactions with produced QCD medium don‘t change the flavor but can modify the phase-space distribution of heavy quarks
  - thermal production rate in the QGP is “small“ (may be measurable → T)

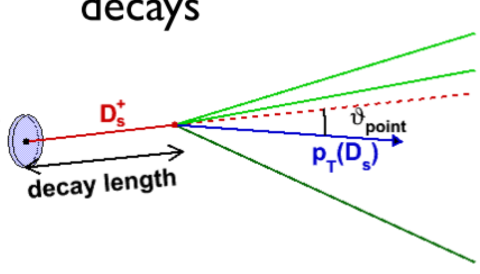
  → destruction or creation in the medium is difficult
  → transported through the whole evolution of the system

Open heavy-flavor measurements

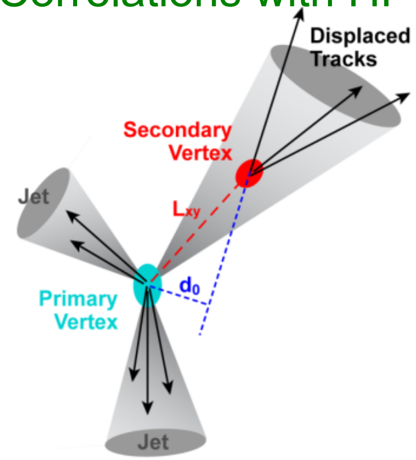
- heavy-flavor hadron decays via weak interaction: decay lengths $c\tau$ ~ few 100 μm → measure decay products

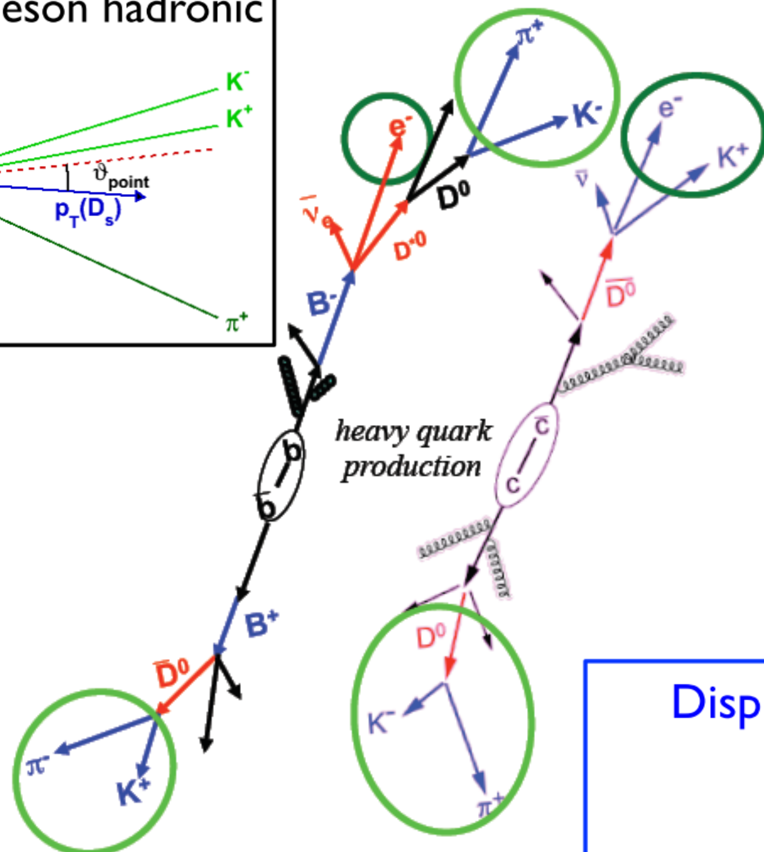
Full reconstruction of D meson hadronic decays

$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
$D^{*+} \rightarrow D^0 \pi^+$
$D_s^+ \rightarrow K^- K^+ \pi^+$

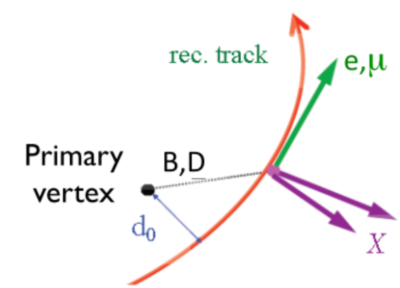


HF jets
Correlations with HF

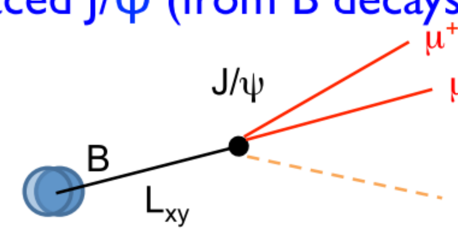




Semi-leptonic decays (c,b)



Displaced J/ψ (from B decays)



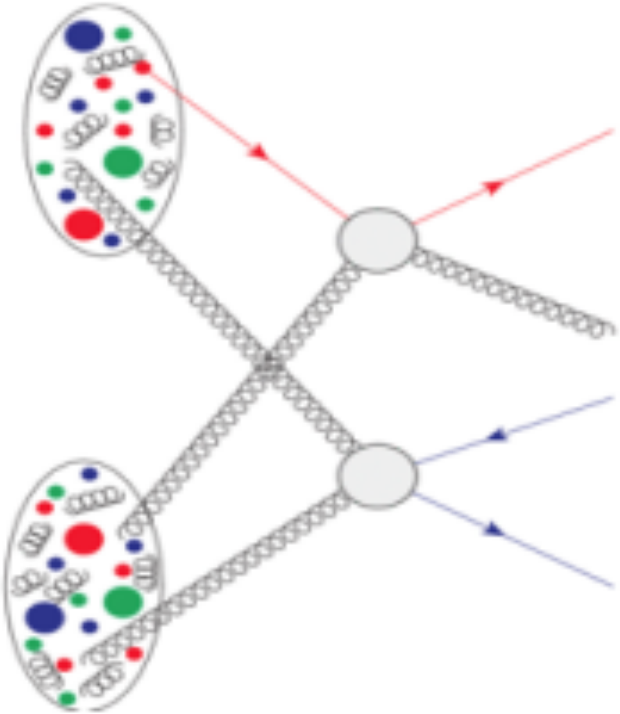
Testing pQCD calculations in pp collisions

RHIC: $\sqrt{s}$ = 200, 500 GeV

LHC: $\sqrt{s}$ = 2.76, 7, 13 TeV

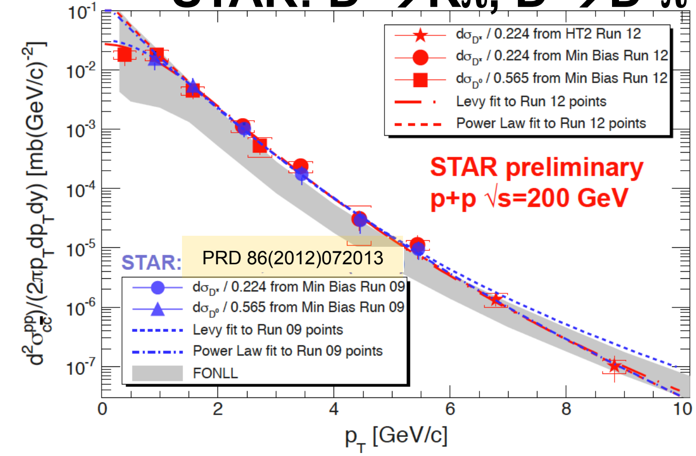
Heavy quarks in pp collisions

- testing ground for perturbative QCD calculations
- relevant production mechanisms
  on the parton level
  - LO: gluon fusion, quark-antiquark annihilation
  - NLO: gluon splitting, flavor excitation
  - or even more complex, e.g.
    Multi Parton Interactions (MPI)
- reference for p(d)-A
  and A-A collisions

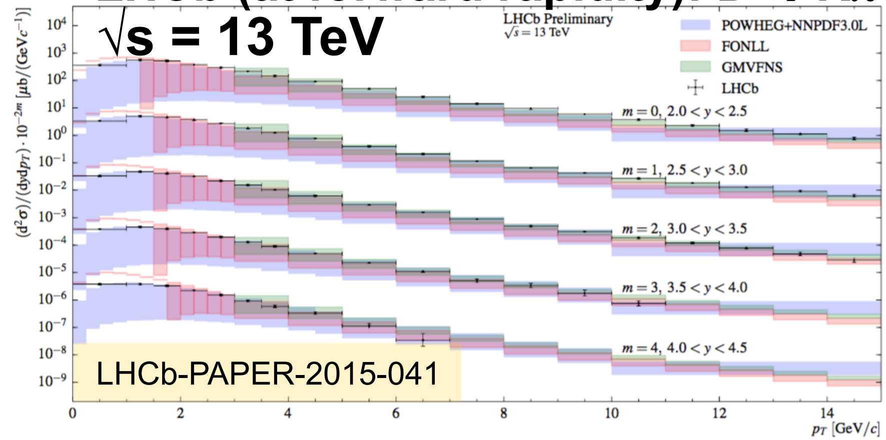


Heavy-flavor hadron production

STAR: $D^0 \to K\pi$, $D^* \to D^0\pi$

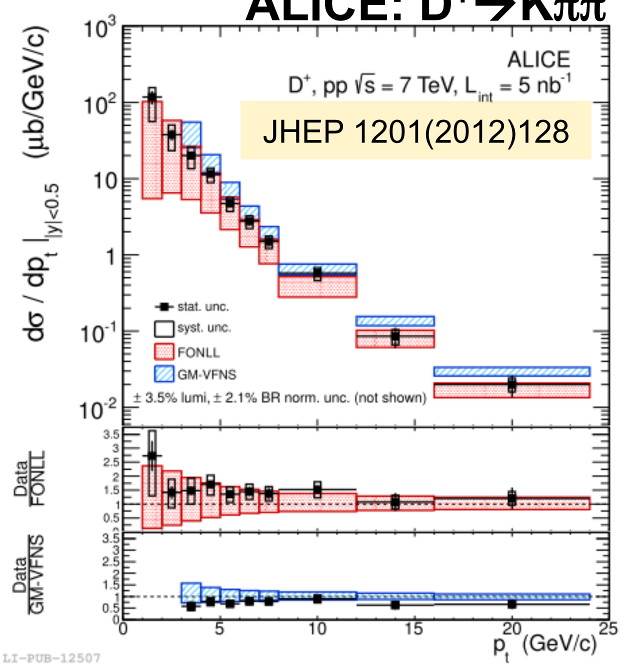


LHCb (at forward rapidity): $D^0 \to K\pi$



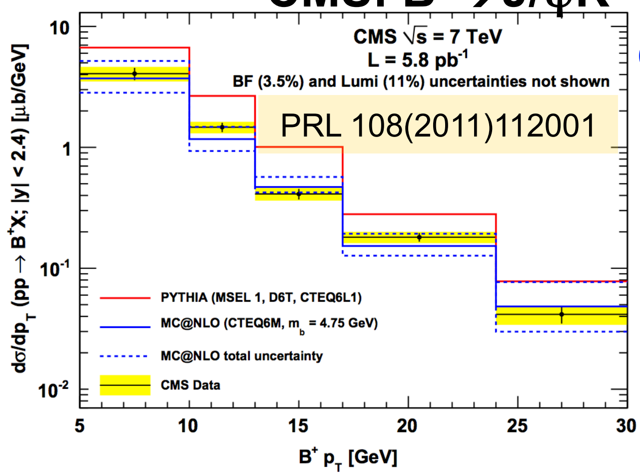
NEW

ALICE: $D^+ \to K\pi\pi$



LI-PUB-12507

CMS: $B^+ \to J/\psi K^+$

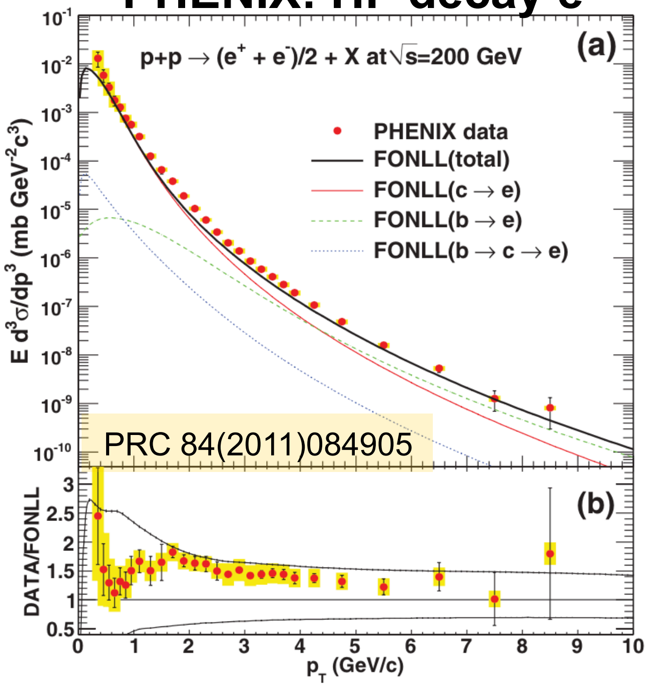


- **pQCD calculations**
  - **FONLL: JHEP 1210(2012)37**
  - **GM-VFNS: EPJ C72(2012)2082**
  - **k_T factorization: PRD 87(2013)094022**

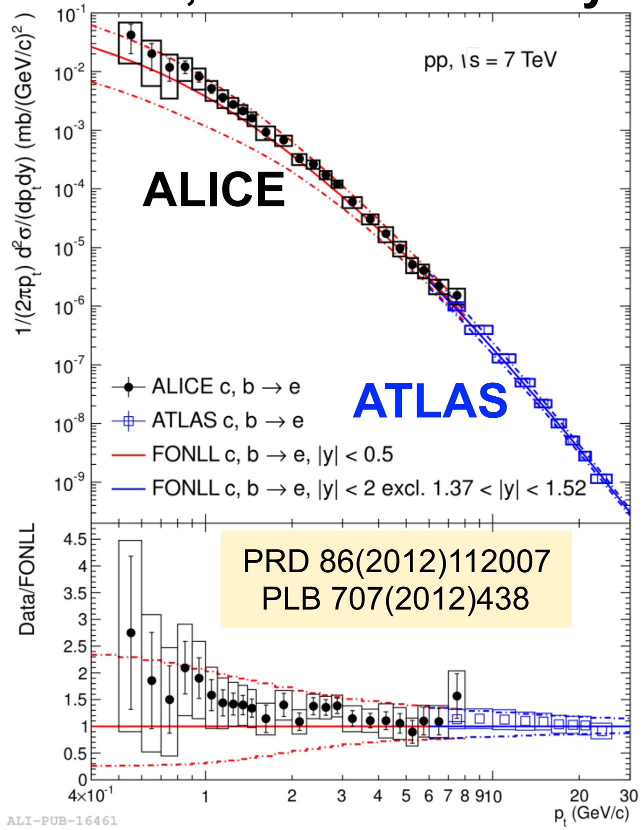
- **pQCD calculations in agreement with measurements within substantial exp. and theor. uncertainties**

Leptons from heavy-flavor decays

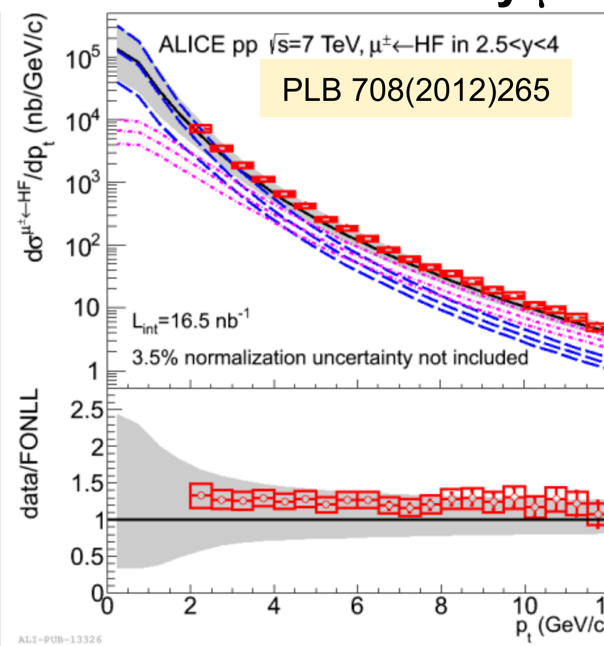
PHENIX: HF decay e±



ALICE, ATLAS: HF decay e±

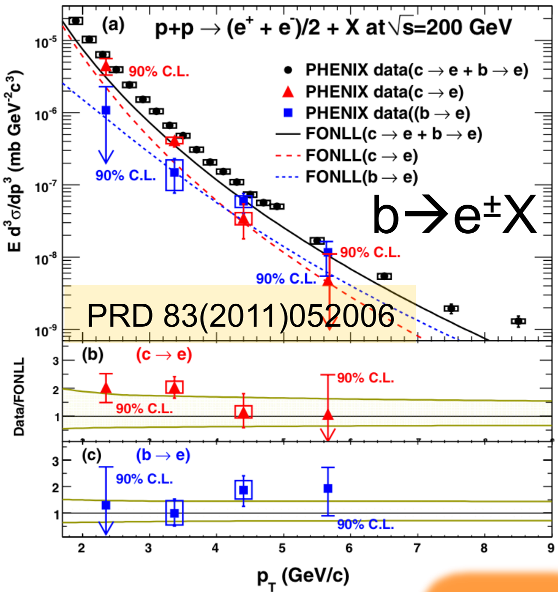


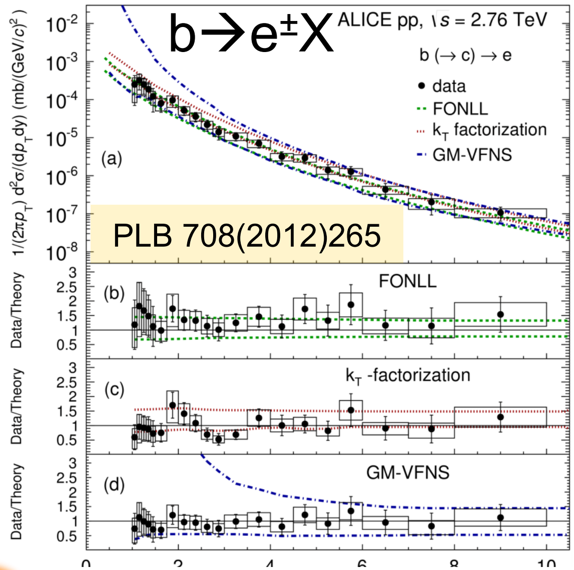
ALICE: HF decay μ±

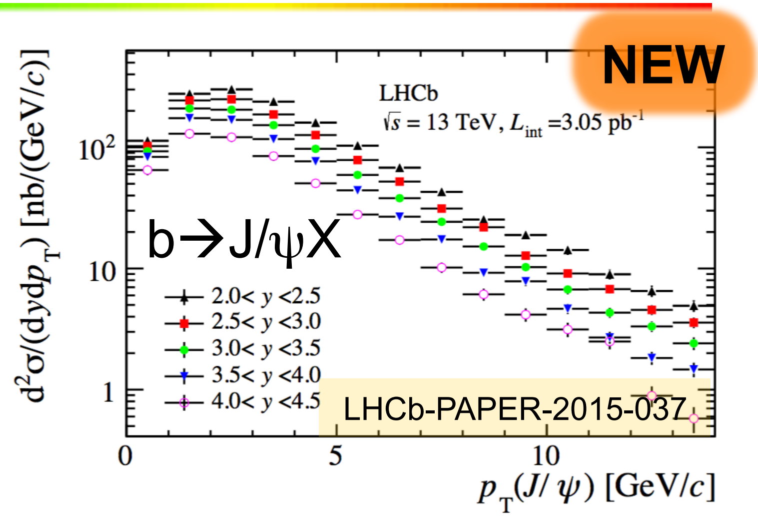


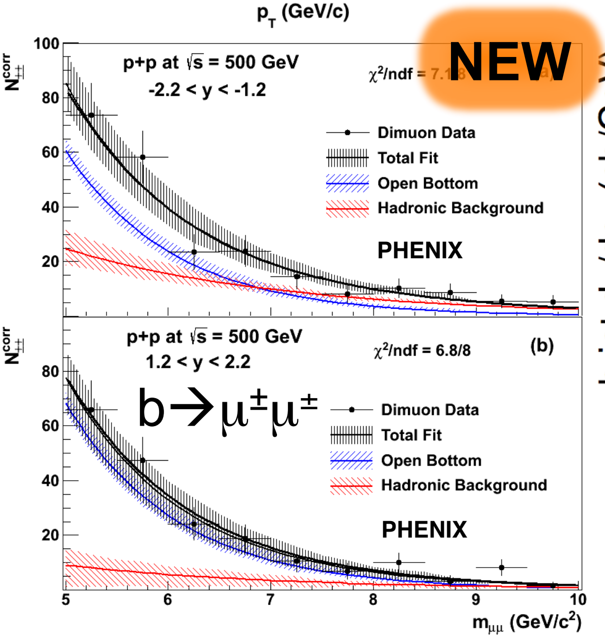
- $e^{\pm}$ ($\mu^{\pm}$) from HF decays at mid (forward) rapidity
- pQCD calculations in reasonable agreement with data within uncertainties

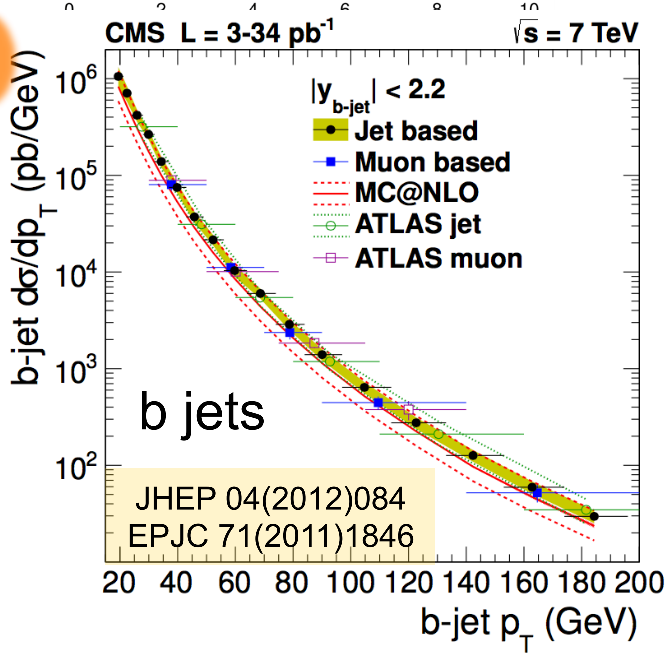
Beauty production





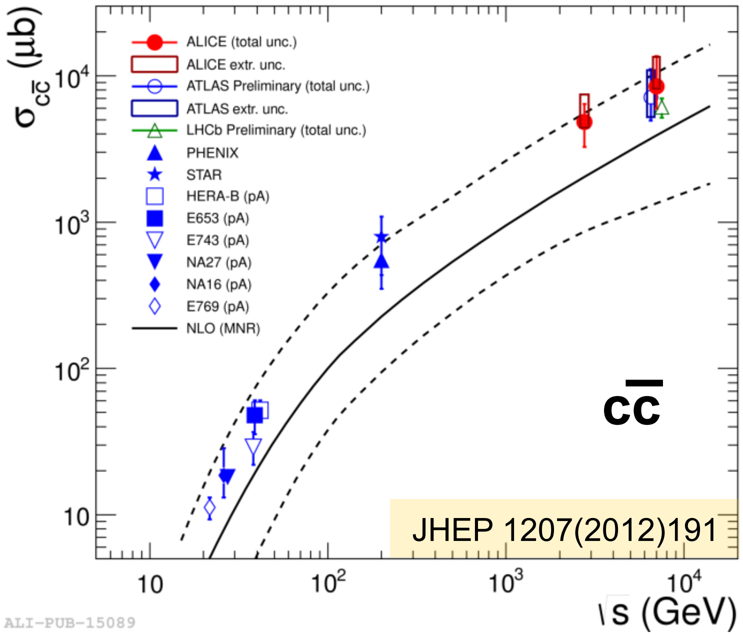


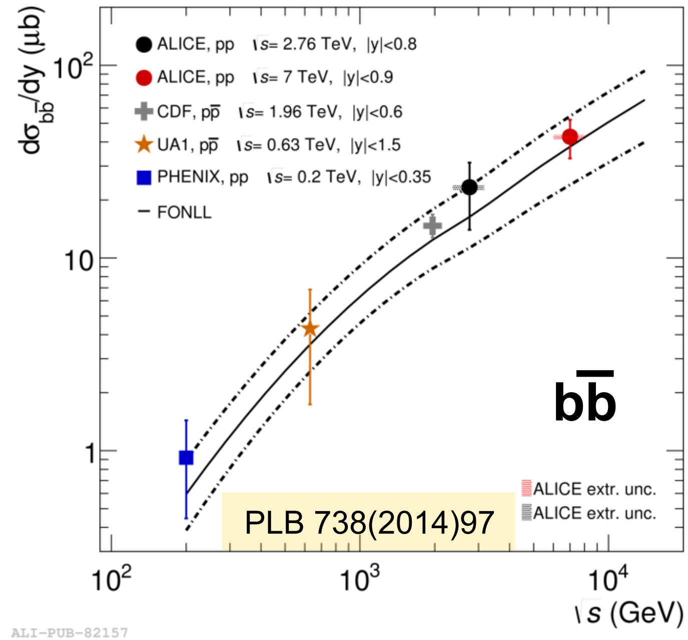




- also beauty production described by pQCD calculations

Total charm & beauty cross sections

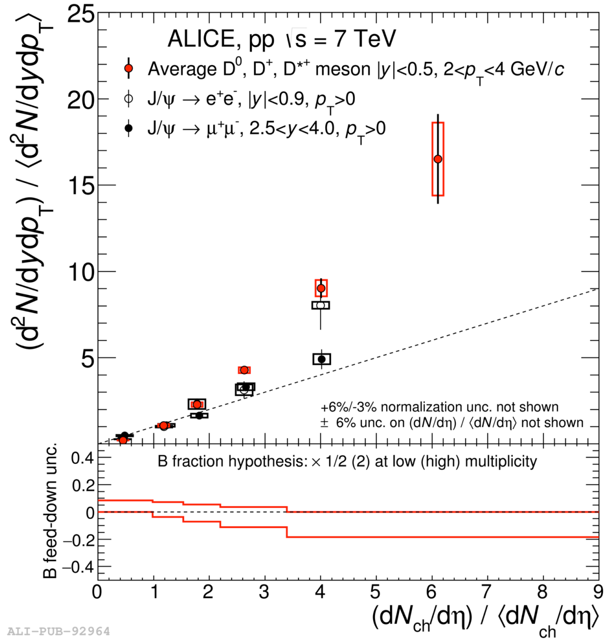


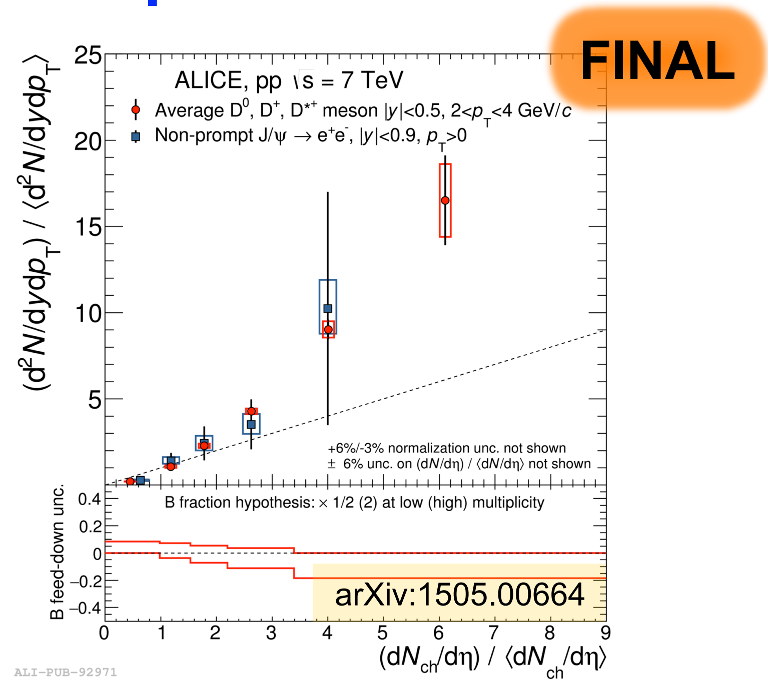


- **experimental precision not yet satisfactory (e.g. for quarkonia reference!)**
  - **extend kinematic coverage (low p_T!)**
  - **larger data samples**
  - **improved control of systematic uncertainties**
- **can data constrain pQCD parameters?**
- **further constraints: more differential measurements**

D-meson yields vs. multiplicity

- do Multi-Parton Interactions (MPI) play a role on the hard scale relevant for heavy-flavor production?





- D-meson yields increase more than linear with $dN_{ch}/d\eta$
- similar increase for open and hidden charm
  → behavior driven by production mechanism, not hadronization
- similar trend for non-prompt J/ψ from open-beauty decays
- models including MPI describe observed trend

Cold nuclear matter effects in p(d)-A collisions

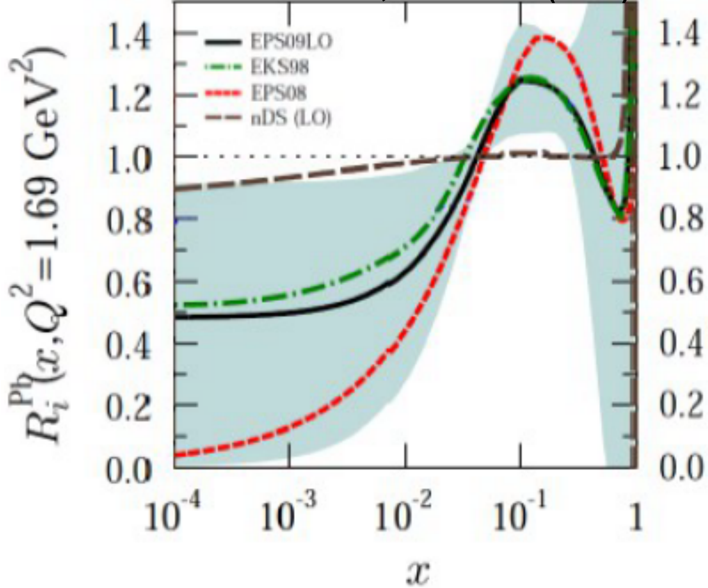
RHIC: d-Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

LHC: p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02TeV

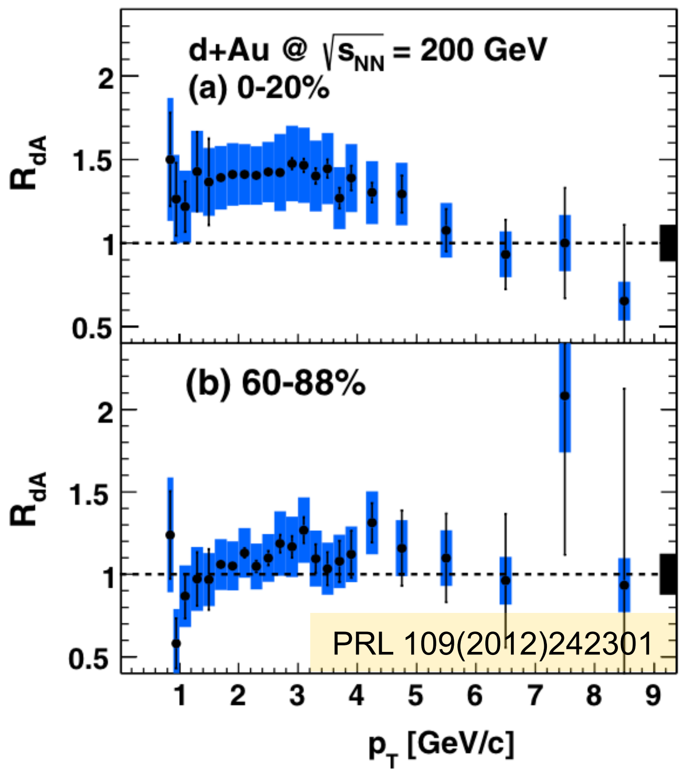
Heavy quarks in p(d)-A collisions

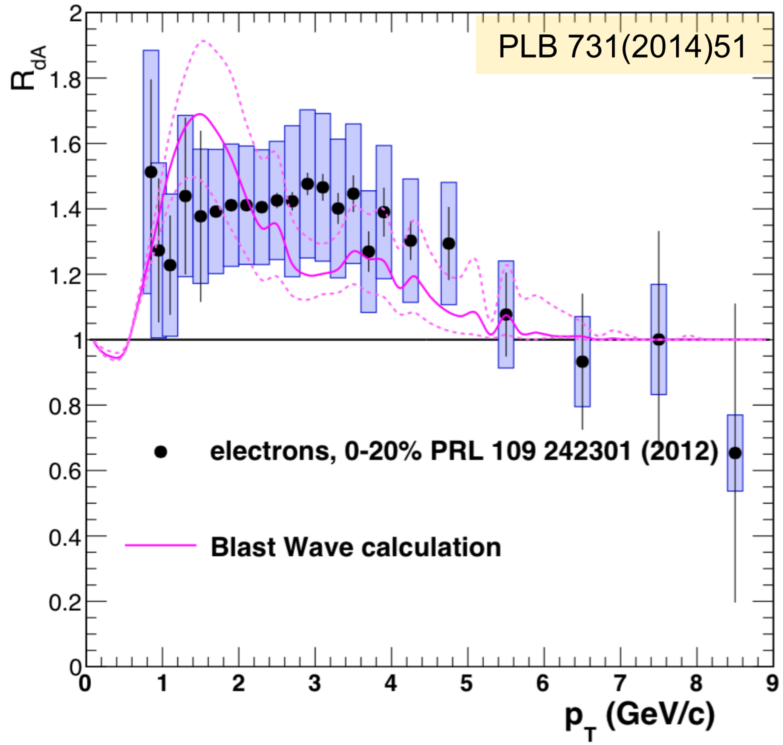
- quantify cold nuclear matter effects
  - nuclear modification of Parton Distribution Functions (shadowing, gluon saturation)
  - k_T broadening
  - energy loss in cold nuclear matter
  - multiple binary collisions
- final state effects?
- reference for A-A collisions

K.J. Eskola et al., JHEP 0904(2009)65



Electrons from HF decays at RHIC





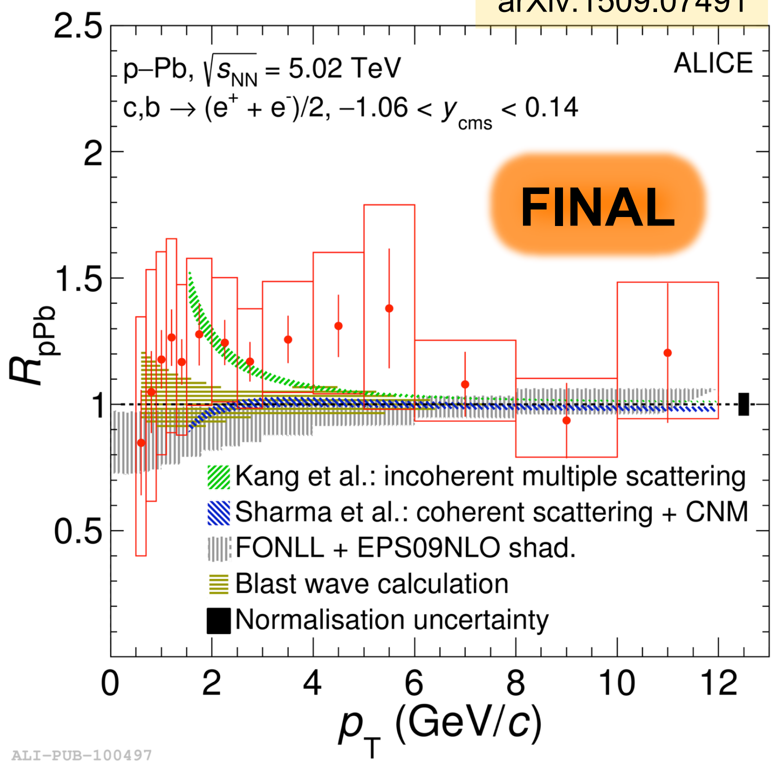
- R_{dA} > 1 for low-p_T electrons at mid rapidity (also for muons at backward rapidity)
- no "large" enhancement via anti-shadowing expected
- consistent with radial flow

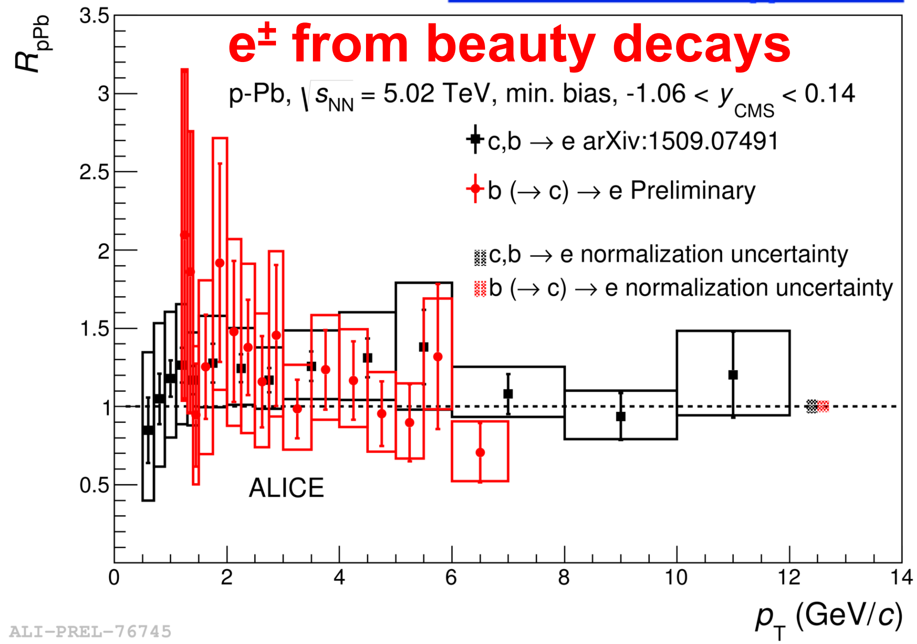
  → D-meson measurement highly desirable

HF decay electron R_{pPb} at the LHC

arXiv:1509.07491

$$R_{pPb} = \frac{d\sigma_{pPb}/dp_T}{A \times d\sigma_{pp}/dp_T}$$

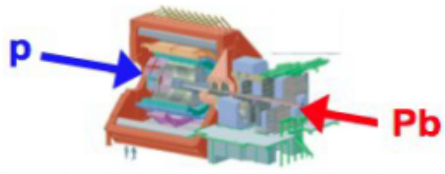




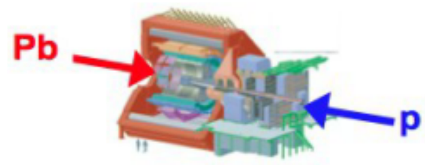
- R_{pPb} consistent with unity and described by models including initial-state effects or radial flow within uncertainties
- R_{pPb} of beauty-hadron decay electrons consistent with inclusive HF decay electron R_{pPb} and with unity
- no indication for suppression at intermediate/high p_T

Kang et al.: PL B740 (2015) 23; Sharma et al.: PR C80 (2009) 054902;
FONLL: M. Cacciari et al., JHEP 9805 (1998) 007; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065

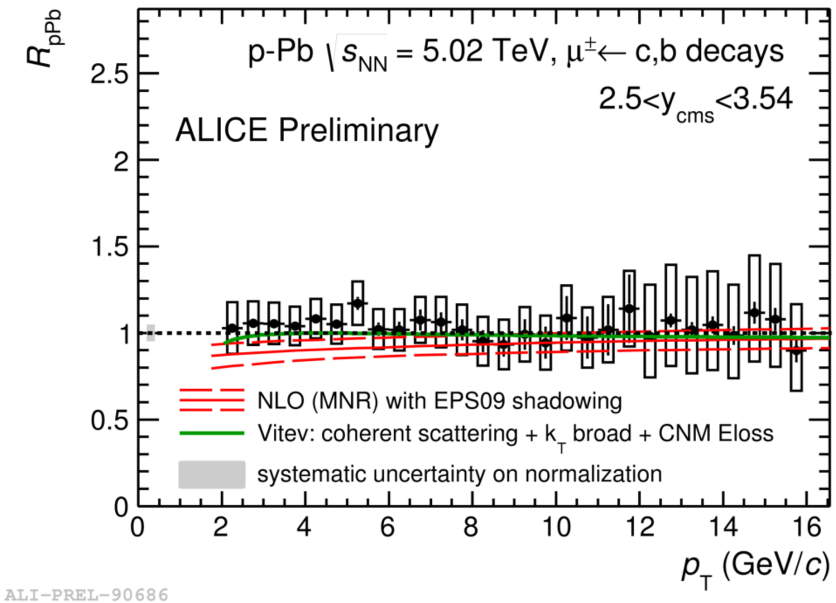
HF decay muon R_{pPb} at the LHC

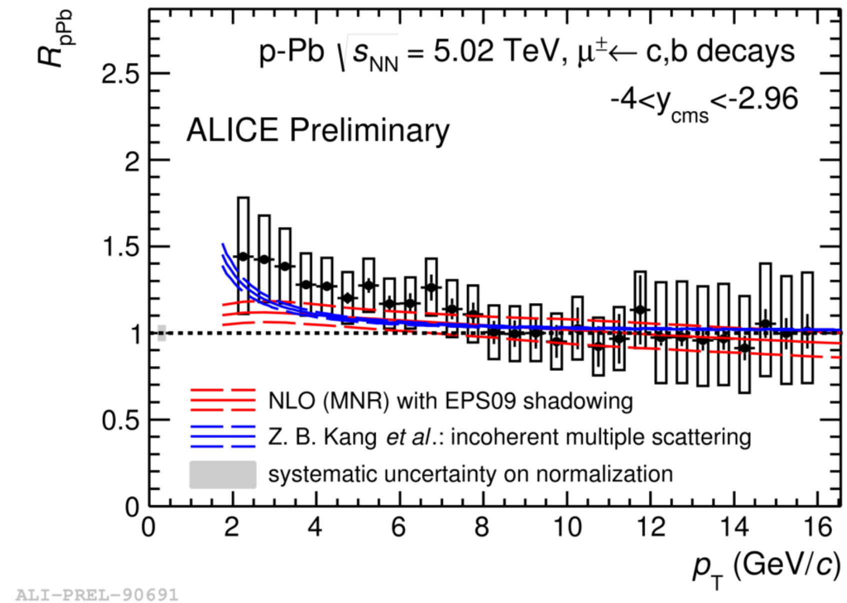


Forward:
p-going



Backward:
Pb-going



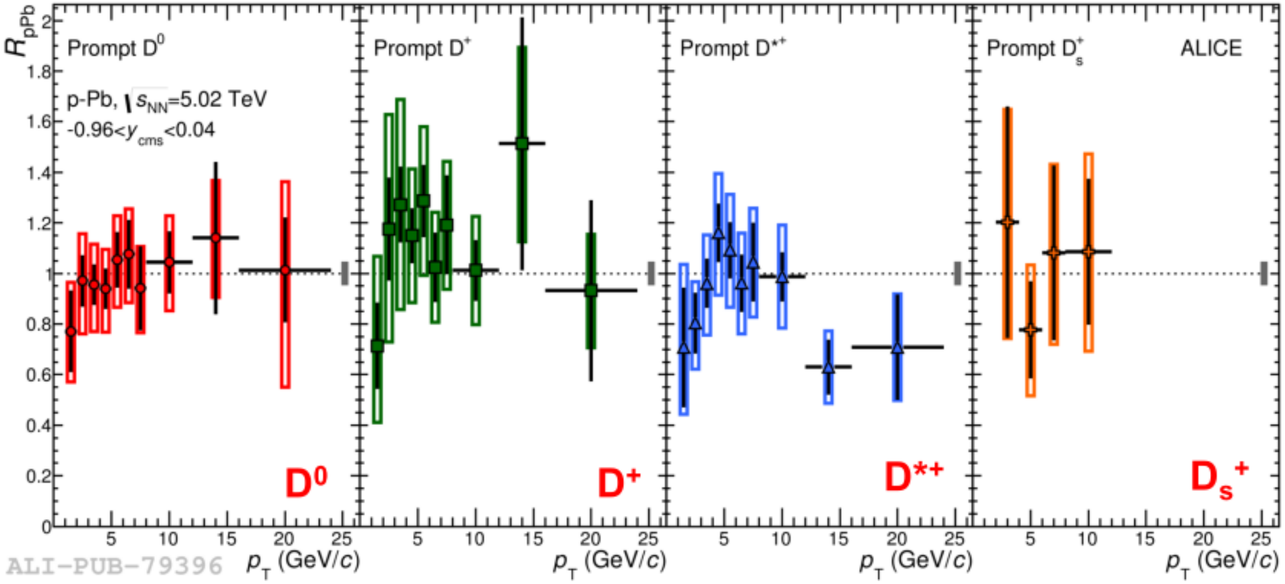


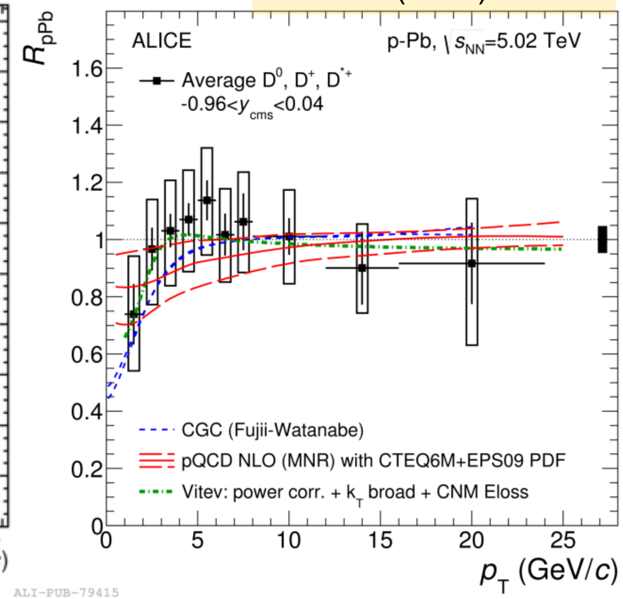
- **R_{pPb} of HF decay muons is consistent with unity at forward rapidity and slightly larger than unity at backward rapidity for 2 < p_T < 4 GeV/c**
- **described within uncertainties by models including cold nuclear matter effects**

NLO (MNR): M. Mangano et al., NP B373 (1992) 295; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065; Z. B. Kang et al.: PL B740 (2015) 23; I. Vitev: PR C75 (2007) 064906

D-meson R_{pPb} at the LHC

PRL 113(2014)232301





- R_{pPb} consistent with unity for all D-meson species
- described within uncertainties by models including initial-state effects
- no indication for suppression at intermediate/high p_T

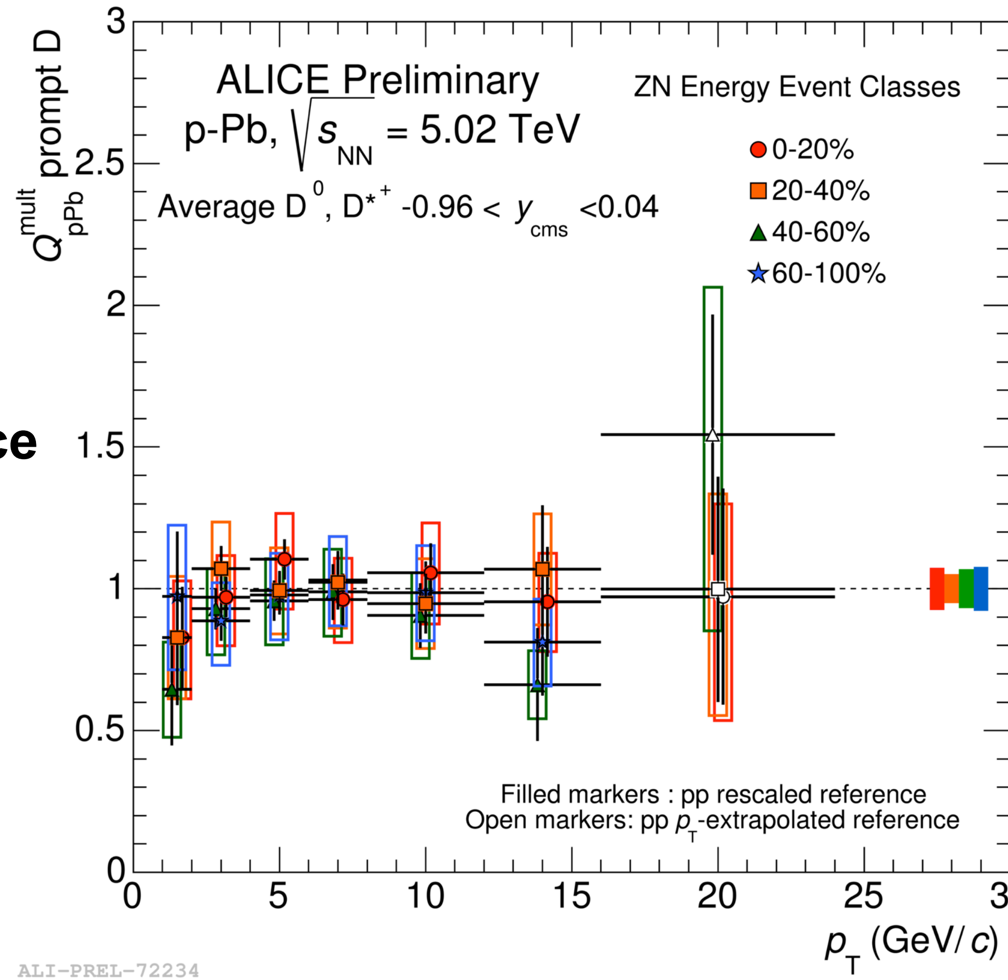
H. Fujii & K. Watanabe, arXiv:1308.1258; pQCD NLO (MNR): M. Mangano et al., NP B373 (1992) 295; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065; Vitev: PR. C75 (2007) 064906

Multiplicity (in)dependence: Q_{pPb}

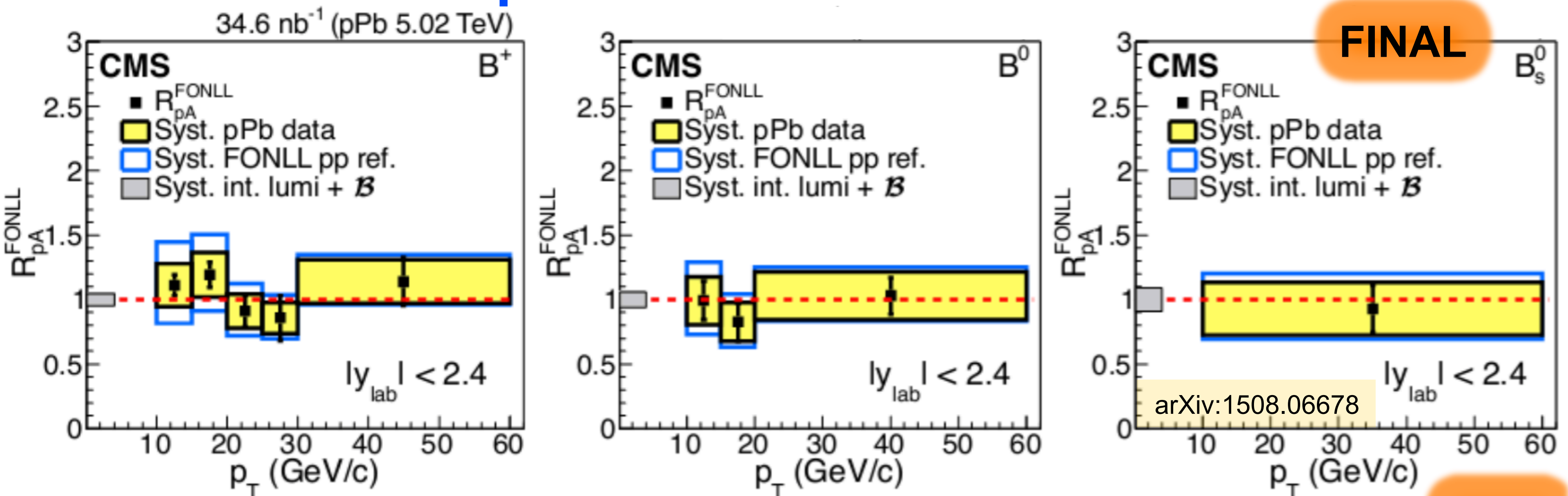
- multiplicity dependent nuclear modification factor Q_{pPb}

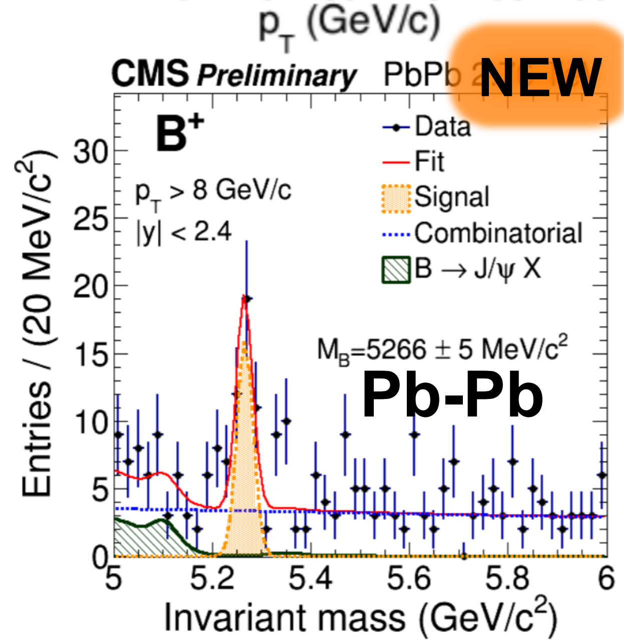
$$Q_{pPb}^{mult} = \frac{dN_{pPb}/dp_T}{\langle T_{pPb}^{mult} \rangle d\sigma_{pp}/dp_T}$$

- nuclear overlap function $\langle T_{pPb} \rangle$ determined based on energy deposited by neutrons in Zero Degree Calorimeters
- prompt D-meson Q_{pPb}
  - no multiplicity dependence
  - no p_T dependence in any multiplicity class



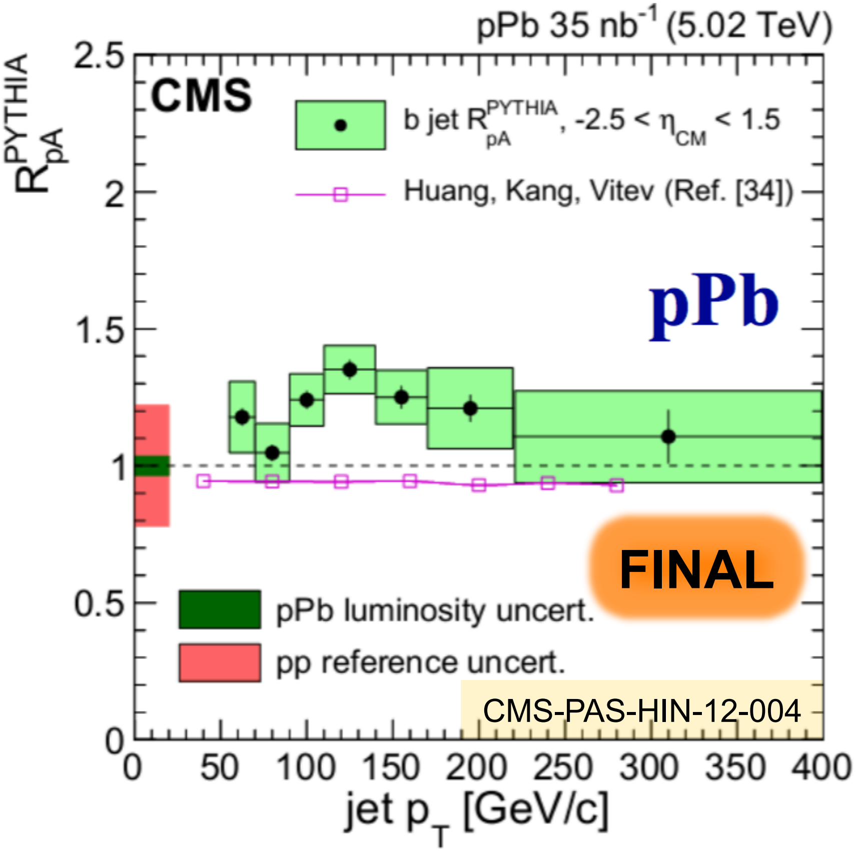
B-meson R_{pPb} at the LHC

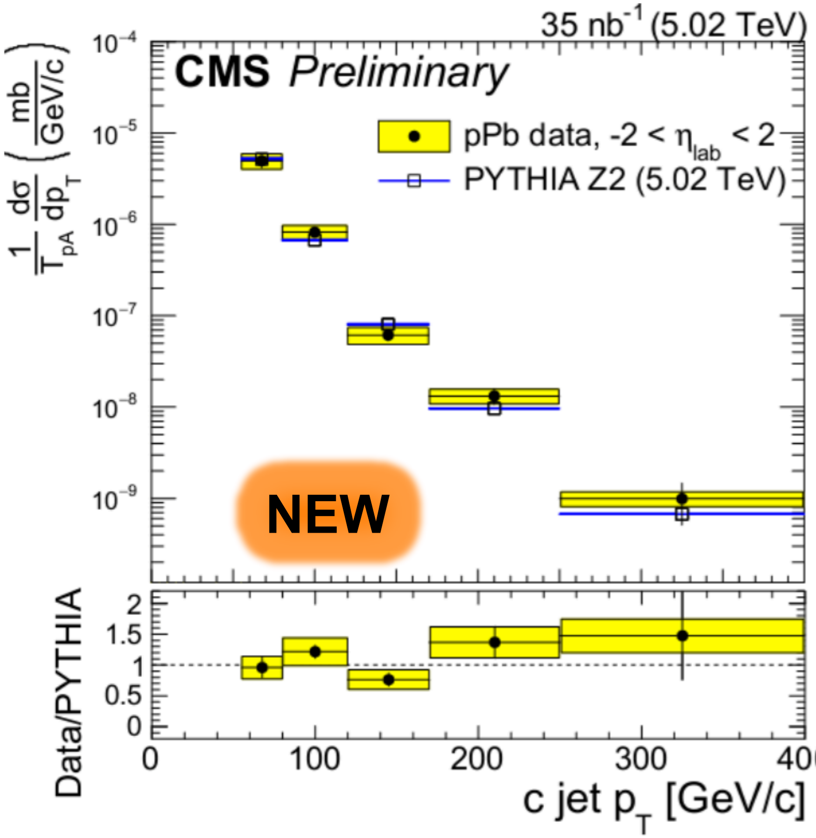




- **B-meson R_{pPb} for various species**
  - **pp reference from FONLL pQCD**
  - **consistent with unity**
    → no indication for significant cold nuclear matter effects
- ***capability to reconstruct B mesons in Pb-Pb collisions as well!***

Beauty and charm jets





- b-jet R_{pPb} consistent with unity within uncertainties
  - no significant suppression due to cold nuclear matter effects

- first c-jet measurement in nuclear collisions
  - PYTHIA agrees with measured spectrum

Dense/hot QCD matter effects in A-A collisions

RHIC: Au-Au (U-U) collisions at $\sqrt{s_{NN}}$ = 200 (193) GeV

LHC: Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76TeV

Heavy quarks in A-A collisions

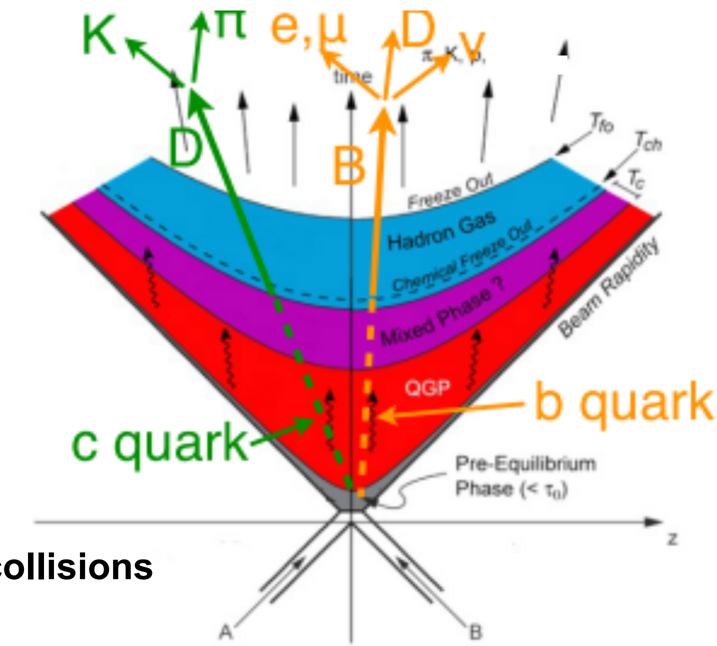
● interaction of heavy quarks with hot/dense medium

- **parton energy loss via radiative and collisional processes**
  - depends on
    - color charge
    - quark mass
    - path length in the medium
    - medium density and temperature

→ **expect:** $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

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

  - caveats:
    - different shapes of parton p_T distributions in pp collisions
    - different fragmentation functions
    - role of soft particle production at low p_T

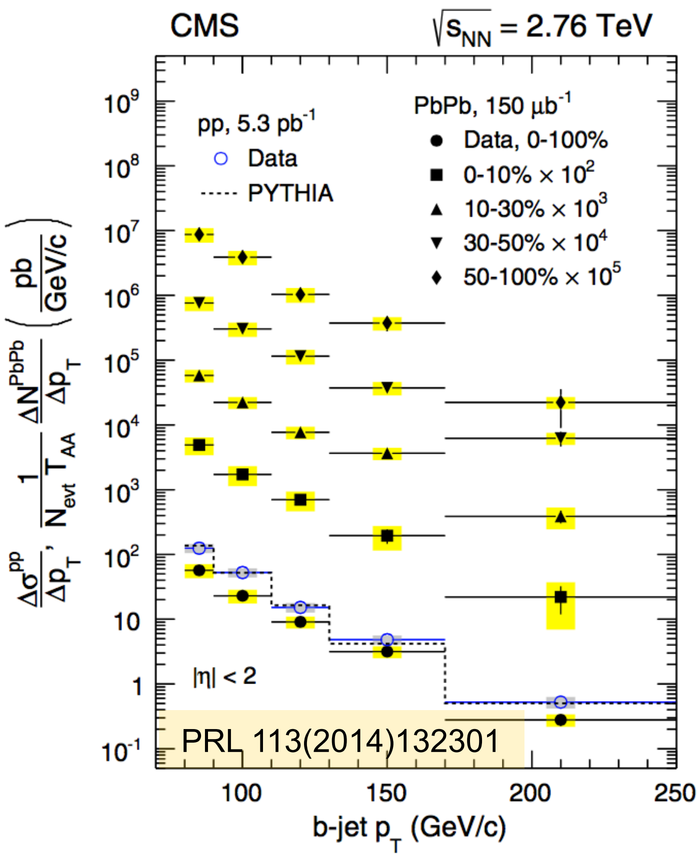


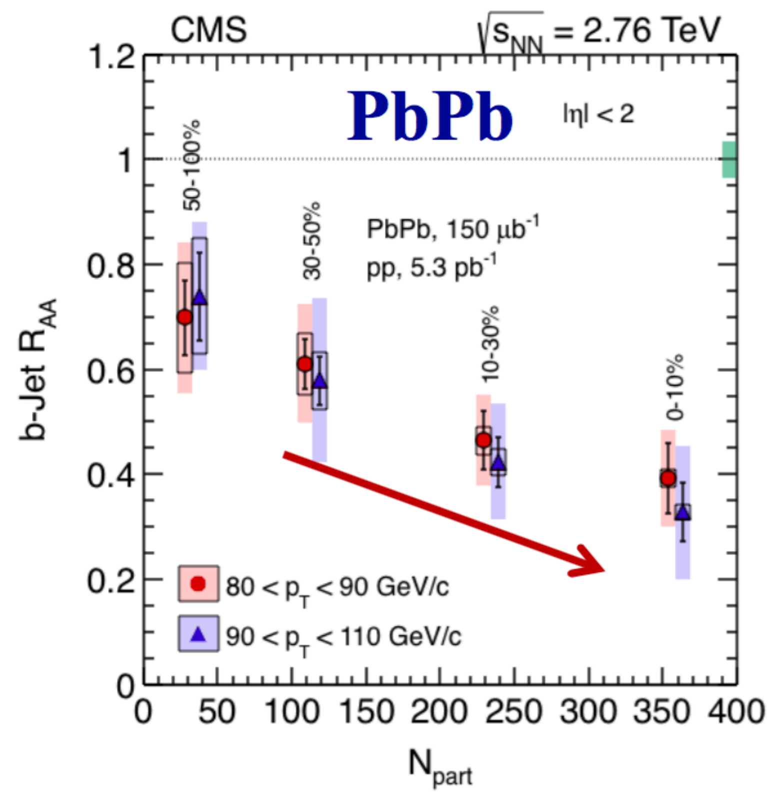
- **collectivity in the QGP**
  - initial spatial asymmetry
    → azimuthal asymmetry of particle emission in momentum space
  - heavy quarks participate in collectivity of the medium in case of sufficient re-scattering → approach to thermalization
  - high p_T: path-length dependence of energy loss → azimuthal asymmetry

$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > \times d\sigma_{pp}/dp_T}$$

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos(\varphi - \Psi_2) + \ \ldots\right)$$

B-jet suppression at the LHC

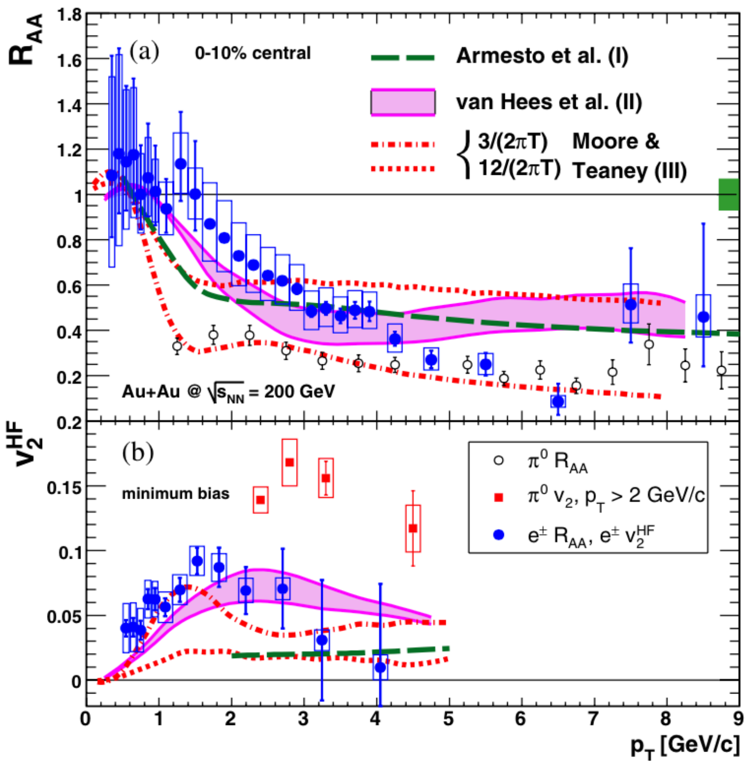


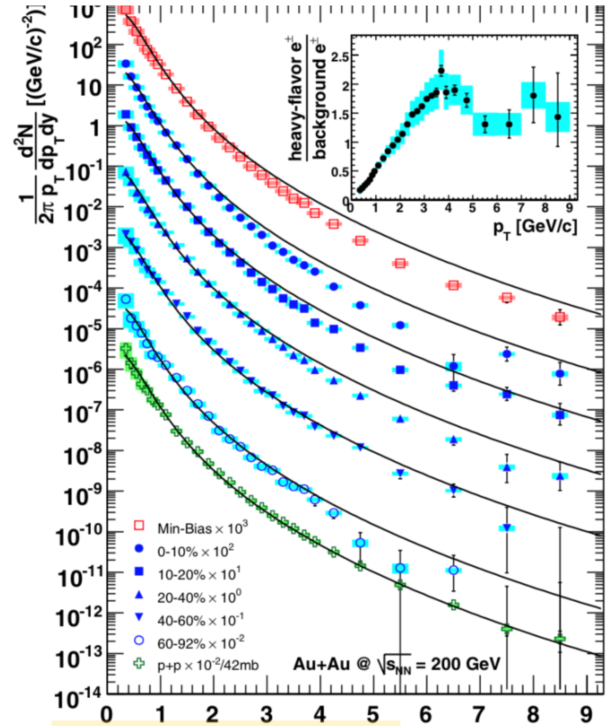


- **fully reconstructed b jets in Pb-Pb collisions at 2.76 TeV**
  - **suppressed compared to measured pp reference**
  - **qualitatively consistent with light-flavor jet suppression**
  - **b-jet suppression shows strong centrality dependence**

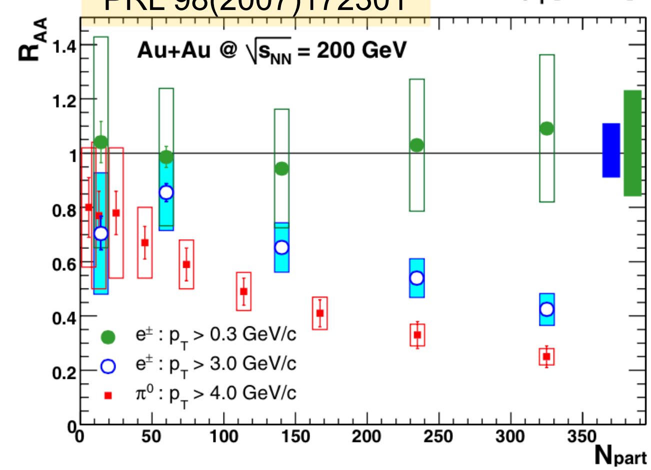
Electrons at RHIC

- electrons from HF decays in Au-Au collisions at 200 GeV
  - suppression of the yield at high p_T
  - binary scaling of the total yield
  - positive v_2
  - model comparison: constrain transport properties of the produced medium



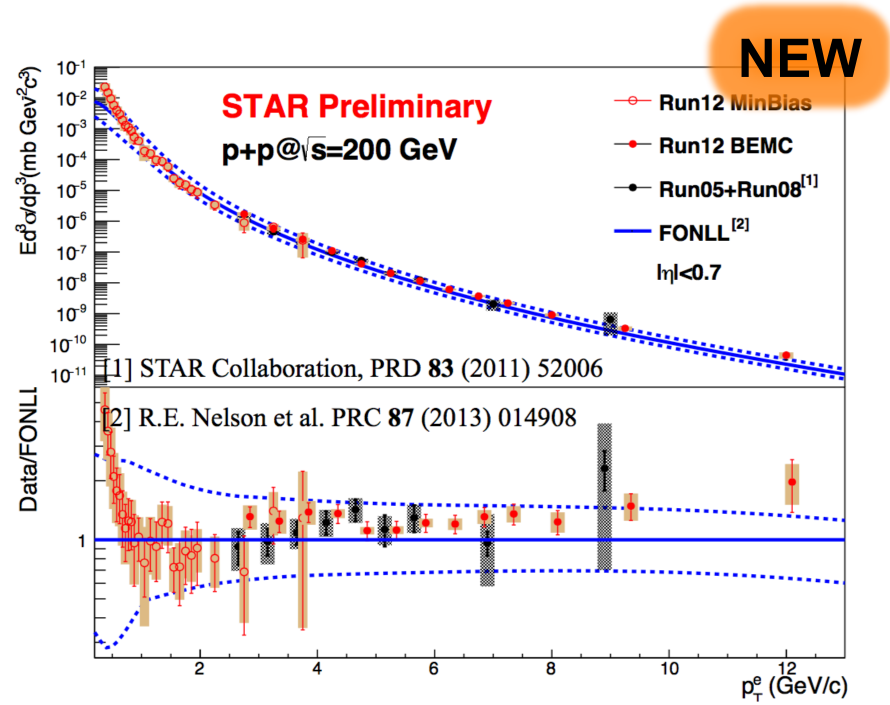


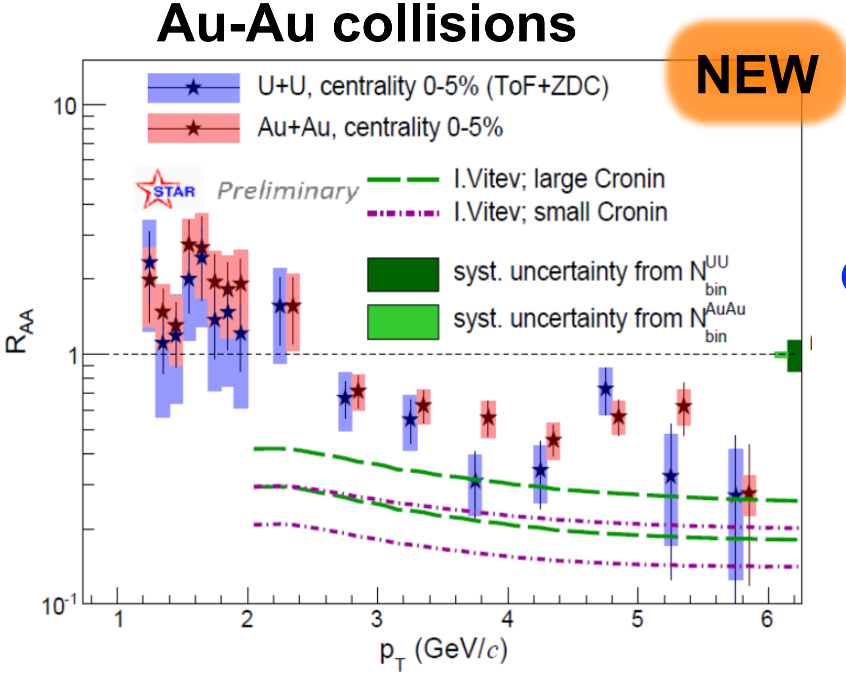
PRL 98(2007)172301



Electrons in U-U collisions at RHIC

- **new pp reference from STAR for electrons from HF decays**
  - p_T reach extended to higher and lower p_T
- **U-U collisions**
  - energy density ~20% larger than in same centrality Au-Au collisions

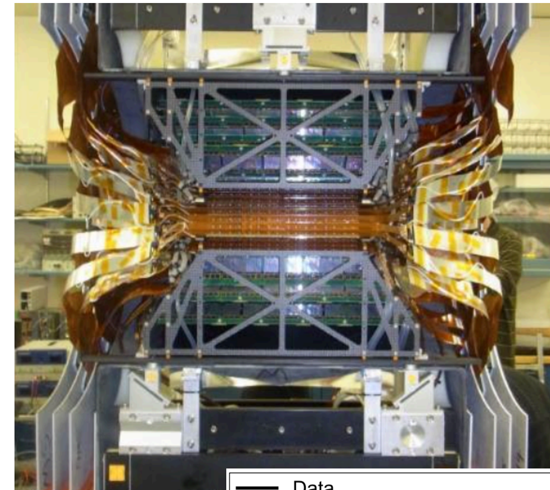


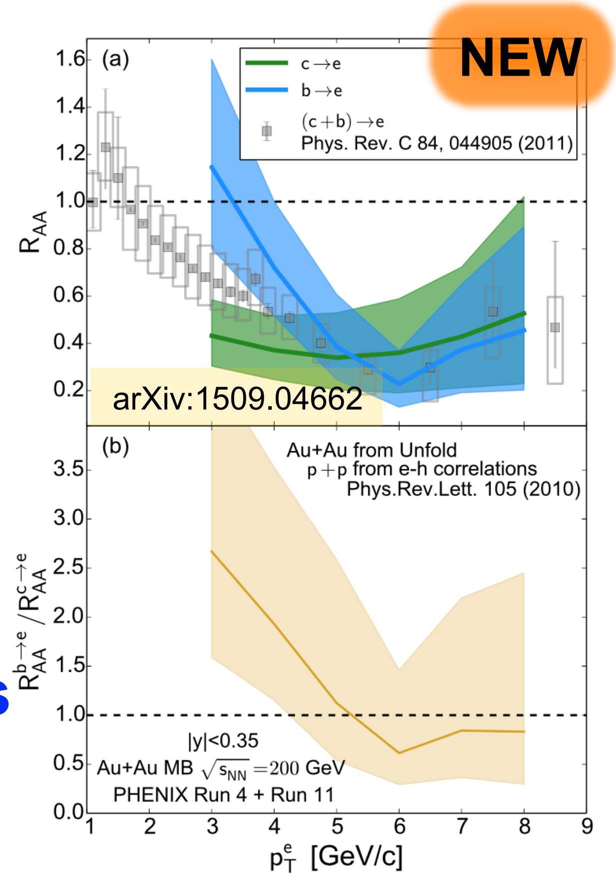


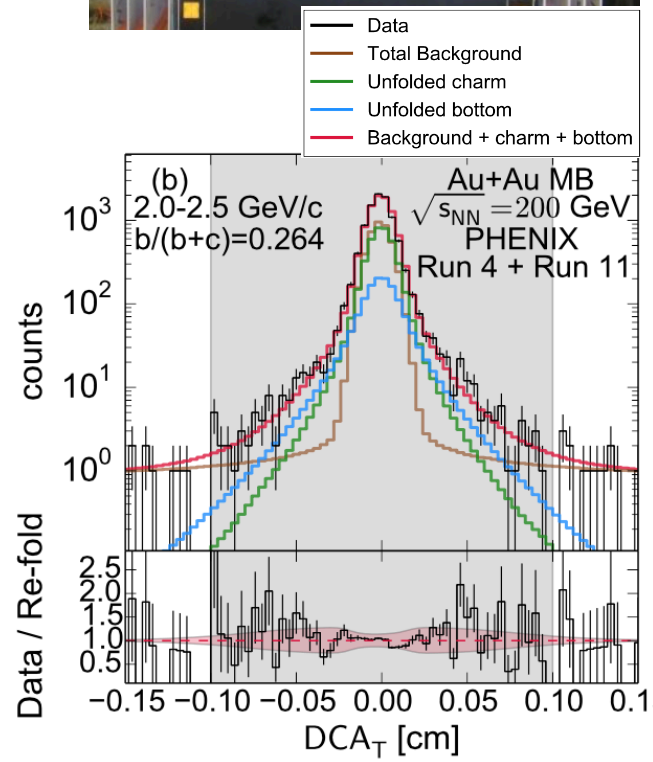
- **R_{AA} for electrons from HF decays in 5% most central collisions systematically lower than for Au-Au collisions, but still within uncertainties**

c→e vs. b→e at RHIC

- **PHENIX Silicon Vertex Detector (VTX)**
  - DCA_T resolution ~ 60 μm
- **unfolding of measured electron dN/dp_T and DCA_T distributions → dN/dp_T of c & b hadrons**
- **p_T^e < 4 GeV/c**
  - electrons from beauty decays suppressed less than those from charm decays
- **new constraints for models**

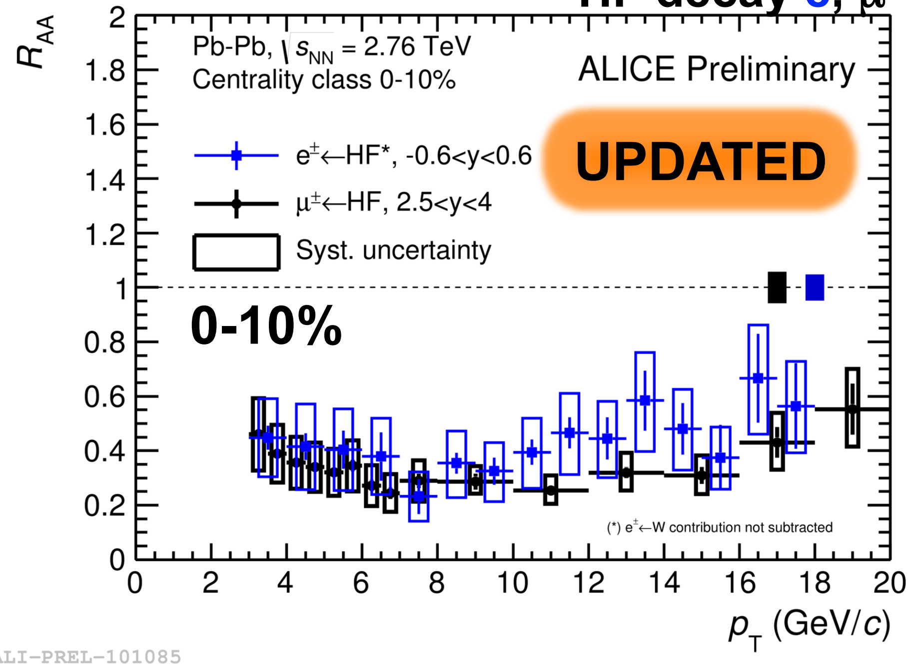




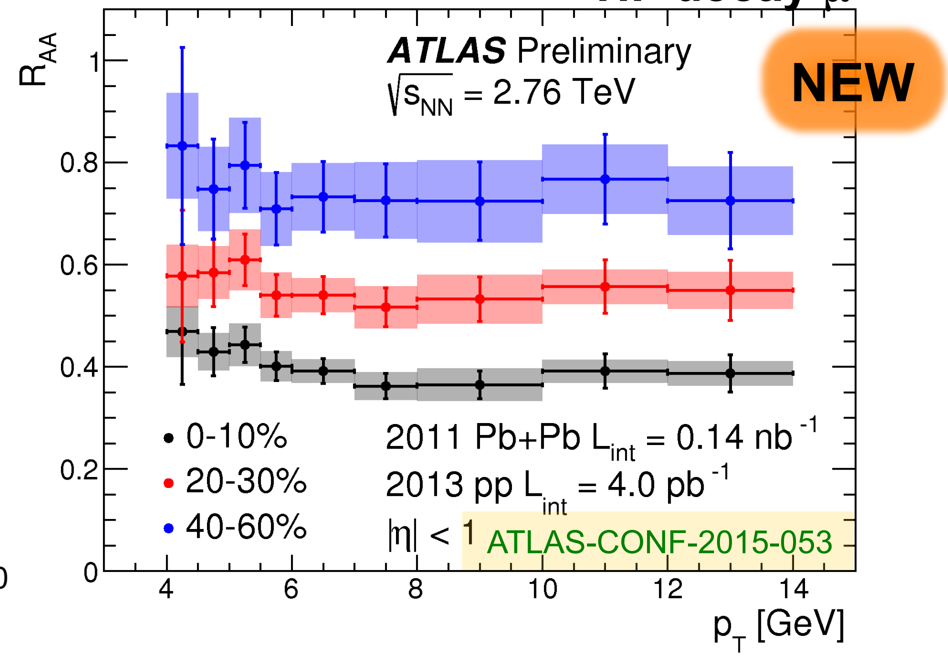


HF decay leptons at the LHC: R_{AA}

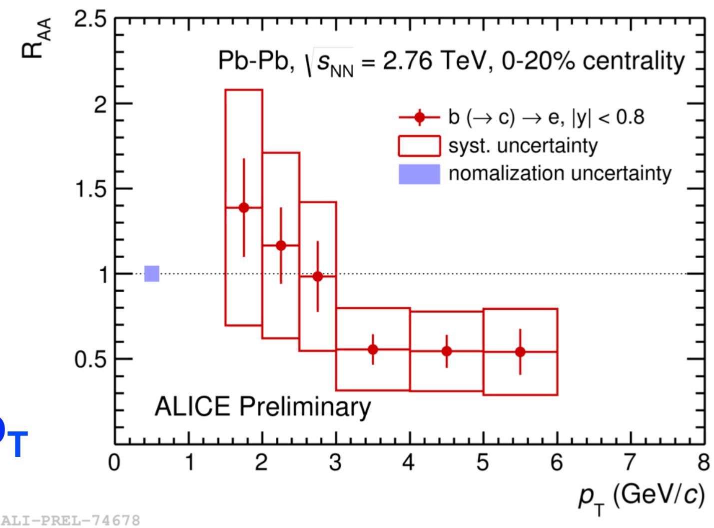
HF decay e, μ



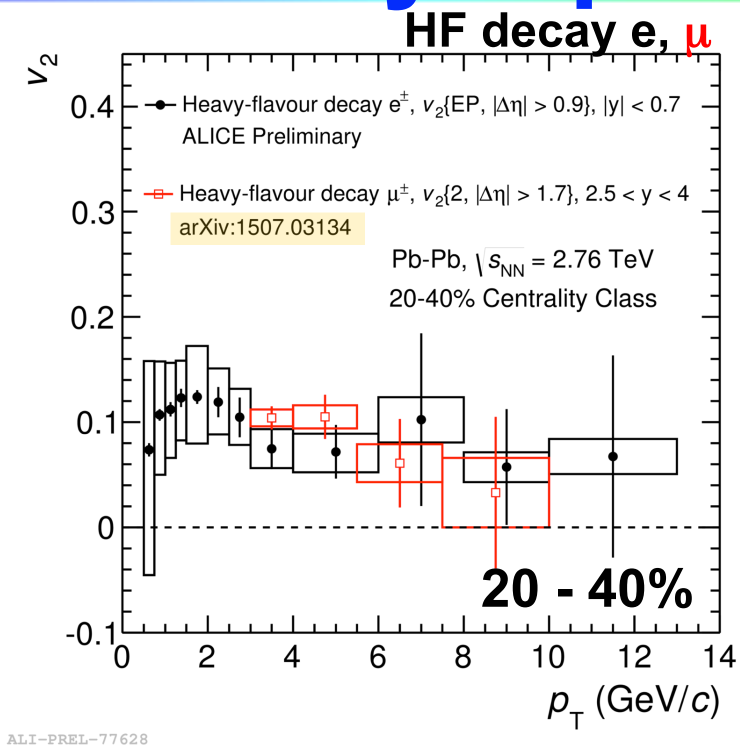
HF decay μ

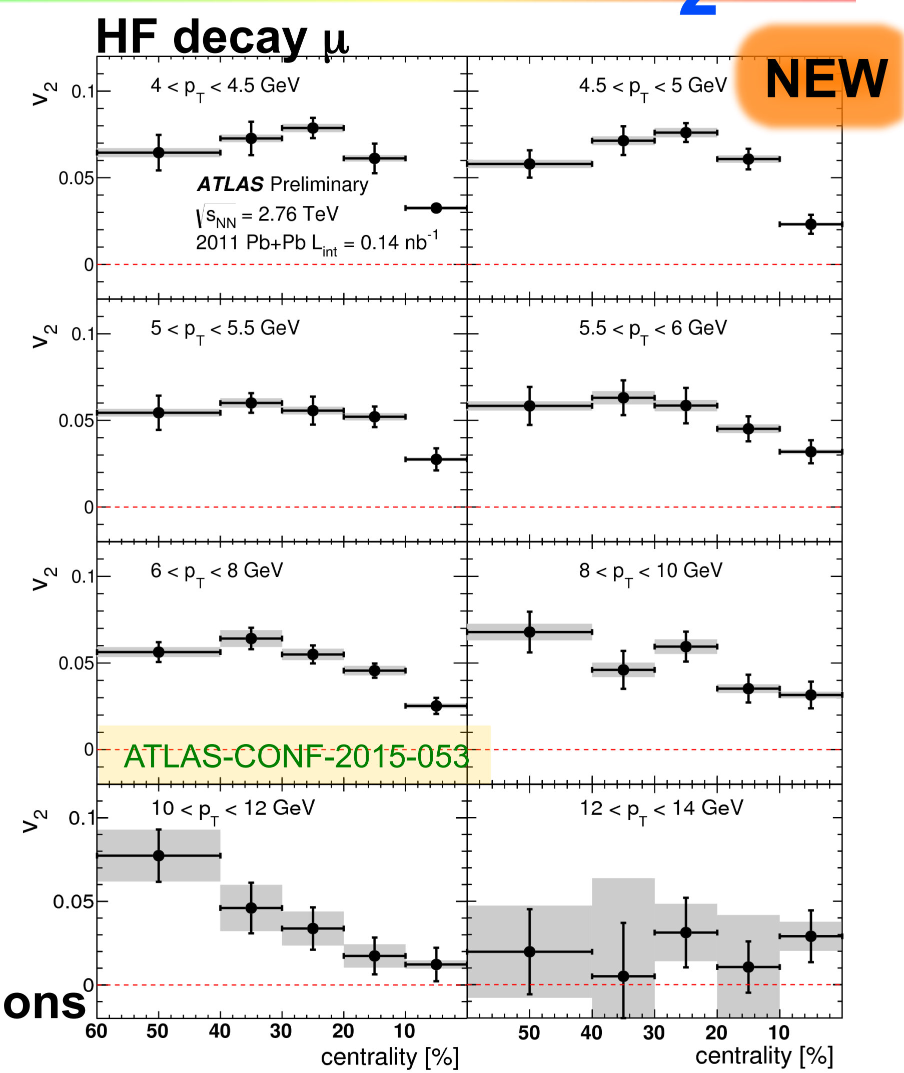


- **high-p_T leptons suppressed**
  - **similar for HF decay electrons ($|y|$ < 0.6) and muons (2.5 < y < 4, |y| < 1)**
  - **pronounced centrality dependence**
  - **also: hint for suppression of electrons from beauty decays**
- **cold nuclear matter effects small at high p_T → hot/dense medium effect**



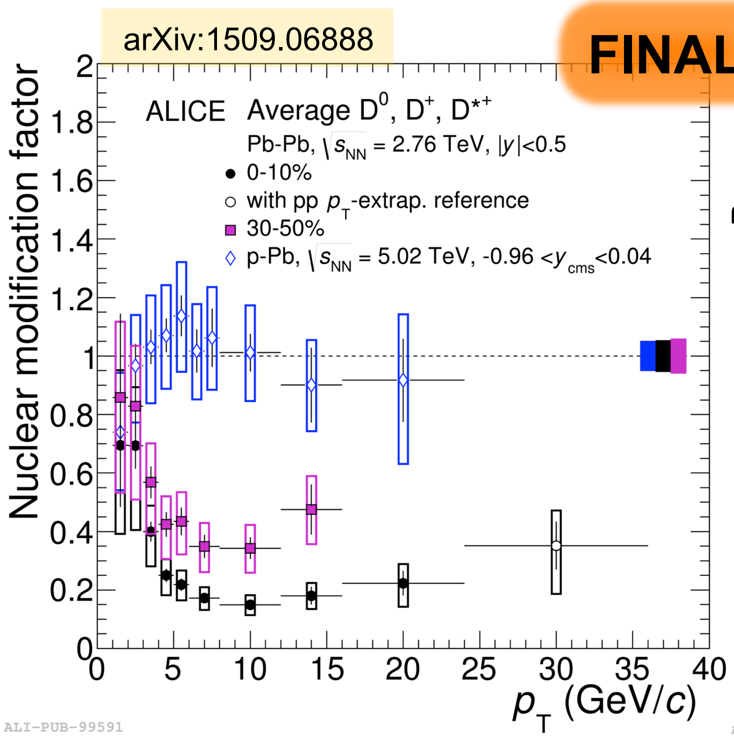
HF decay leptons at the LHC: v_2

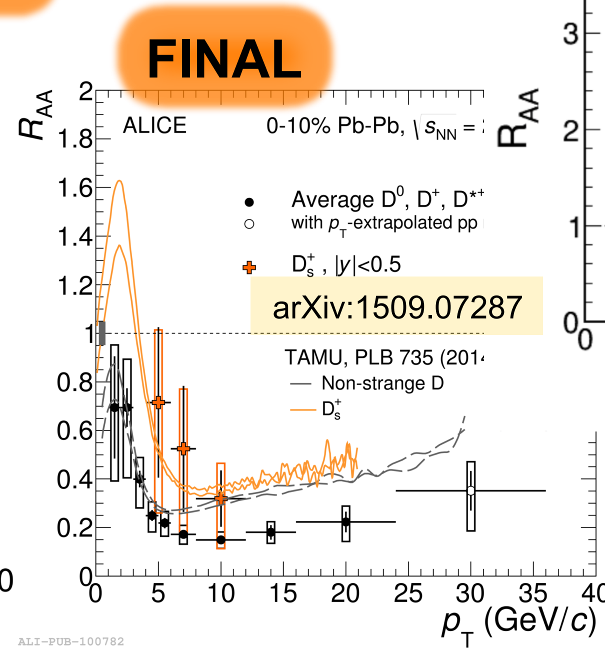


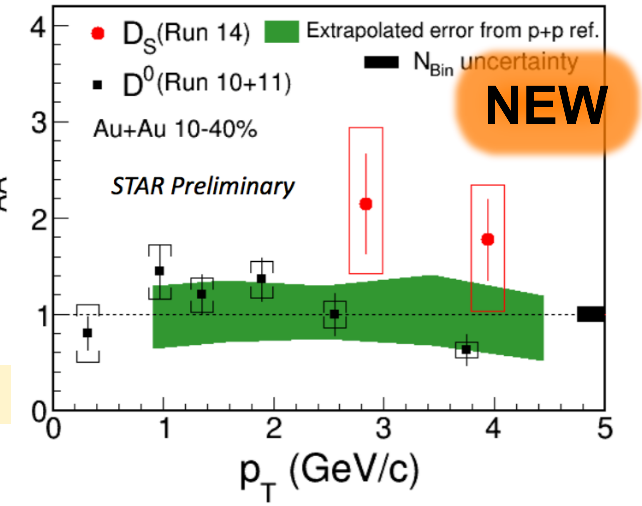


- **$v_2 > 0$ at intermediate/high p_T**
  - **similar for $e^{\pm}$ and $\mu^{\pm}$ at mid rapidity and muons at forward rapidity**
  - **v_2 decreases towards central collisions**
  - **confirms strong interaction of heavy quarks with the medium**
  - **charm (even beauty?) quarks participate in the collectivity of the QGP**

D-meson suppression







Kuznetsova, Rafelski EPJ C 51 (2007) 113
He et al. PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149

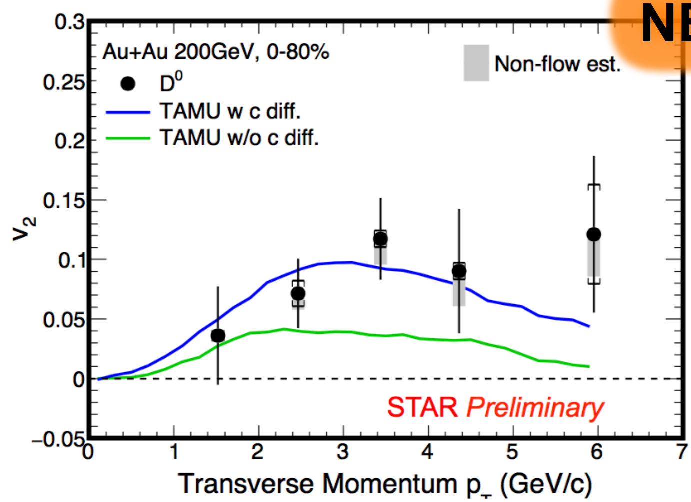
- **observed suppression in central Pb-Pb collisions at the LHC is due to the strong interaction of charm quarks with the dense/hot partonic medium**
- **hint for less suppression of D_s^+ compared to non-strange D mesons at LHC/RHIC**
  - **expected if recombination plays a role in charm hadronization**

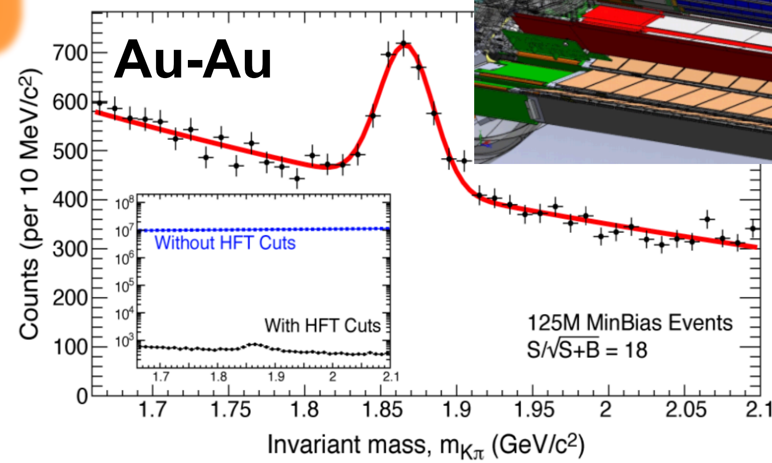
TAMU: He et al.: PRL 110(2013)112301; Kuznetsova, Rafelski: EPJ C51(2007)113; Andronic et al.: PL B659(2008)149

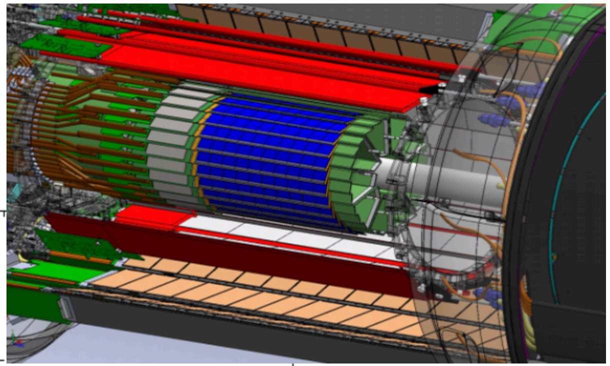
D-meson R_{AA} and v_2 at RHIC

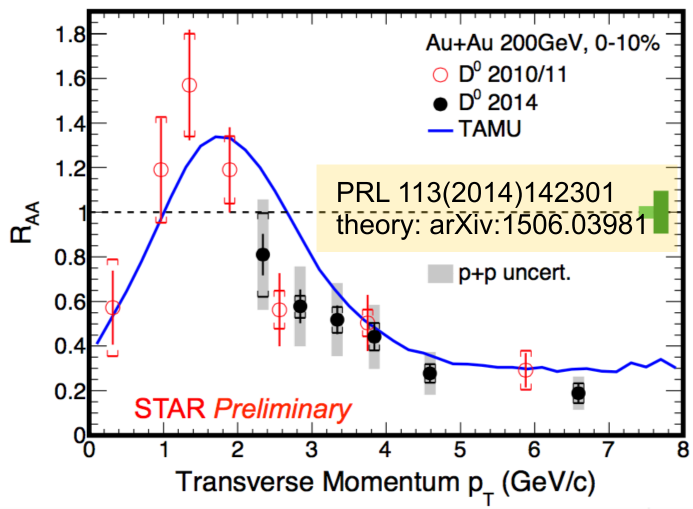
- **STAR Heavy Flavor Tracker (HFT)**
  - **DCA_T resolution ~ 30 μm**

NEW



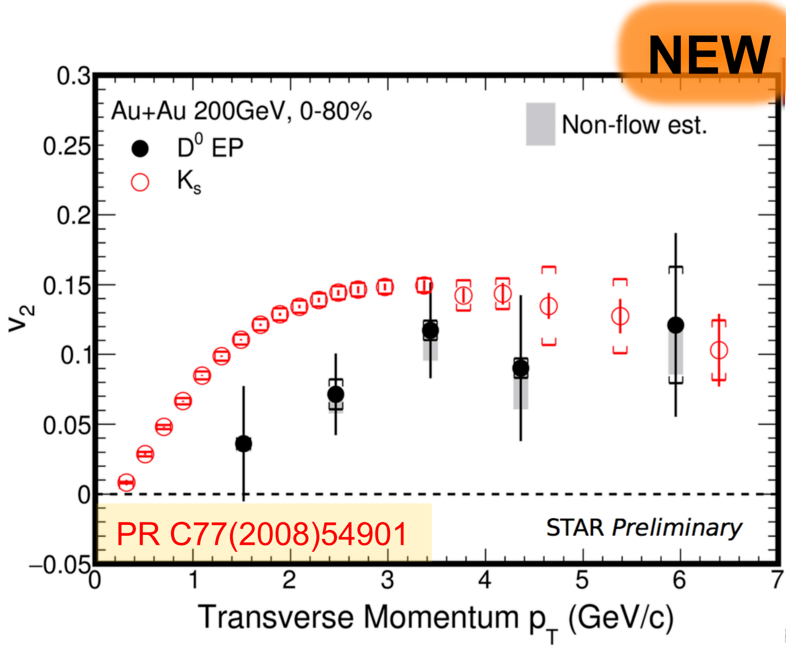




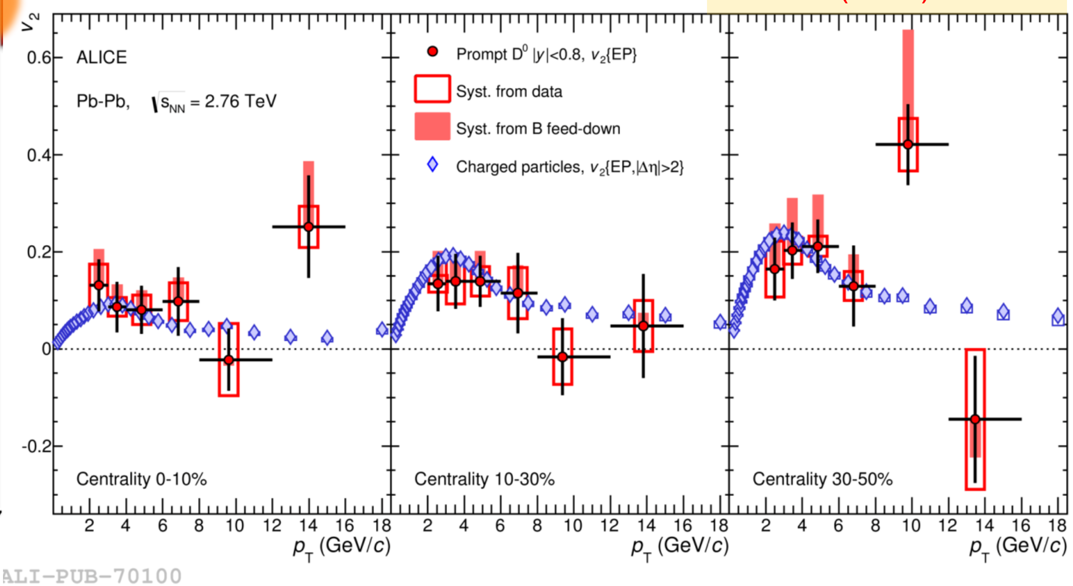


- **D^0 mesons in Au-Au at 200 GeV**
  - **v_2 > 0 for p_T > 2 GeV/c**
  - **yield suppressed at high p_T**
  - **enhancement at 1< p_T < 2 GeV/c (charm coalescence with flowing medium)**
  - **R_{AA} and v_2 model comparisons constrain charm diffusion coefficient**

D-meson v_2: RHIC vs. LHC



PRL 111(2013)102301
PRC 90(2014)034904



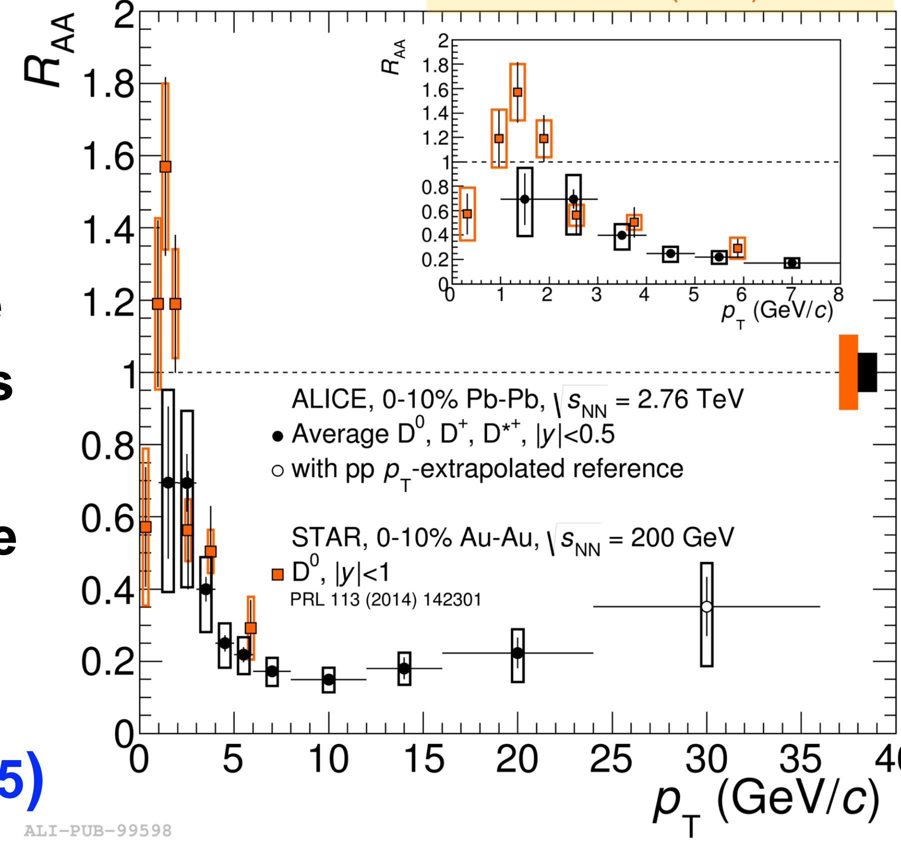
- RHIC: D^0 v_2 < light-hadron v_2 for p_T < 3 GeV/c
- D-meson v_2 measured by ALICE at the LHC
  - D-meson v2 > 0 and similar to charged-particle v_2
  - hint for increasing v_2 with decreasing centrality
- significant interaction of charm quarks with the medium

→ collective motion of low-p_T charm quarks with the medium

D-meson R_{AA}: RHIC vs. LHC

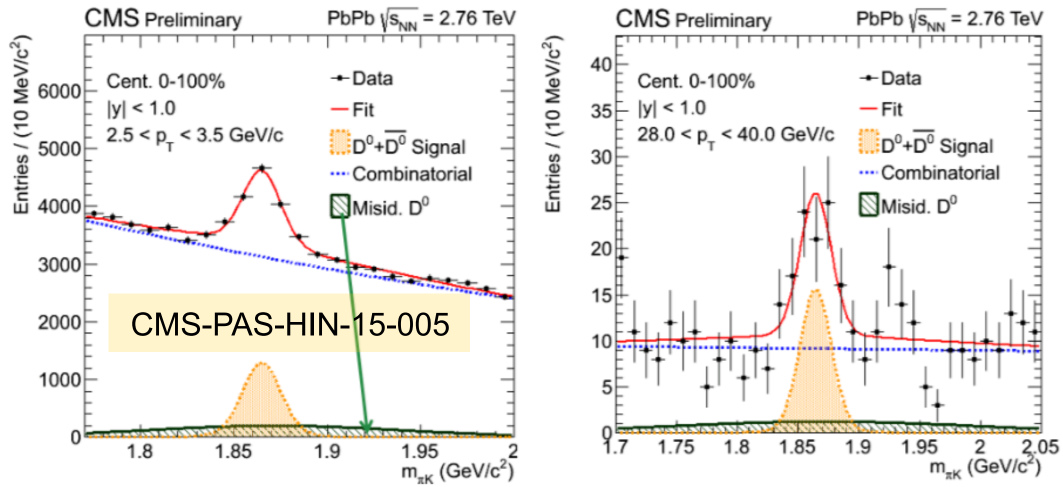
- D mesons at the LHC and at RHIC
  - different trend for D-meson R_{AA} at low p_T?
- differences between
  Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  and
  Au-Au collisions at $\sqrt{s_{NN}}$ = 0.2 TeV
  - different shape of pp reference
  - different modification of nPDFs
  - different radial flow
  - different impact of coalescence
- some models describe both measurements reasonably well (e.g. TAMU, PLB 735(2014)445)

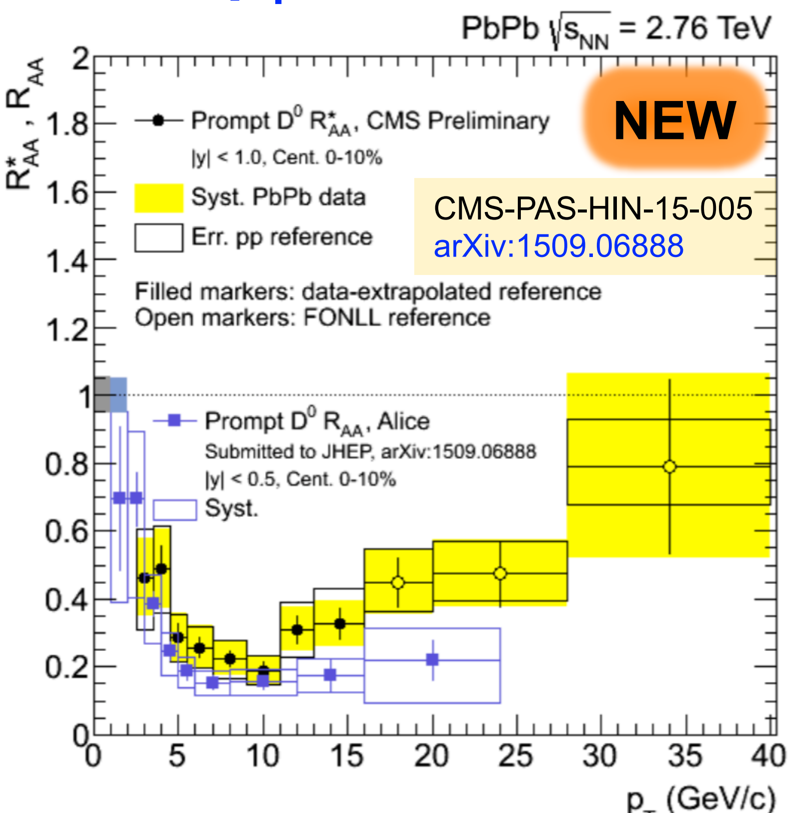
ALICE: arXiv:1509.06888
STAR: PRL 113(2014)142301



D^0 mesons at the LHC

- D^0, D^+, D^{*+}, D_s^+ mesons measured by ALICE
- prompt D^0 measured by CMS in the range $2.5 < p_T < 40$ GeV/c

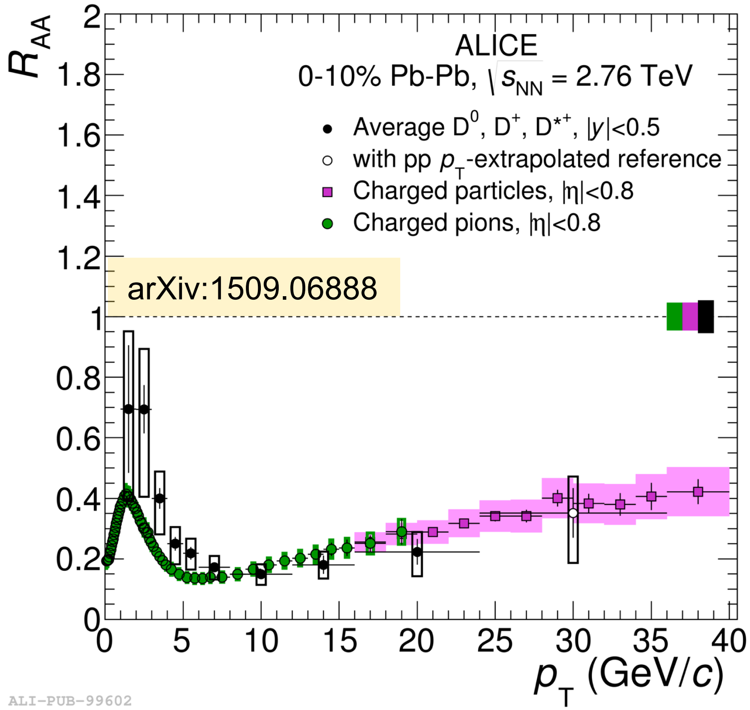


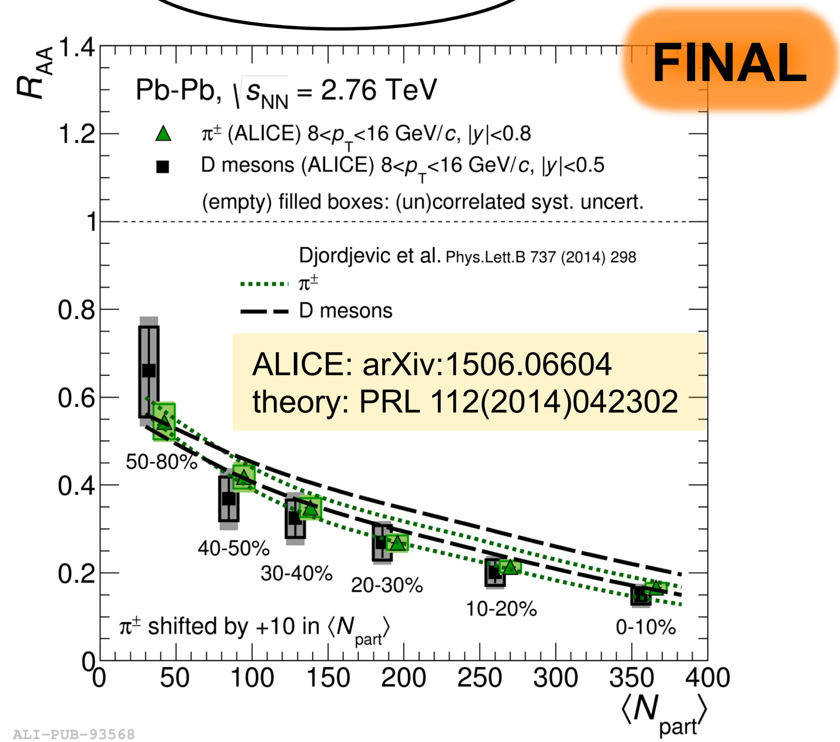


- R_{AA} shows suppression in central Pb-Pb collisions relative to data/FONLL based reference
  - significant interaction of charm quarks with the medium
  - pronounced centrality dependence
  - tension with ALICE D-meson R_{AA} for $p_T > 16$ GeV/c
    → difference in pp reference

R_{AA}: D-mesons vs. pions

naively: ΔE(g) > ΔE(u,d,s) > ΔE(c) > ΔE(b) → $R_{AA}(\pi)$ < $R_{AA}(D)$ < $R_{AA}(B)$

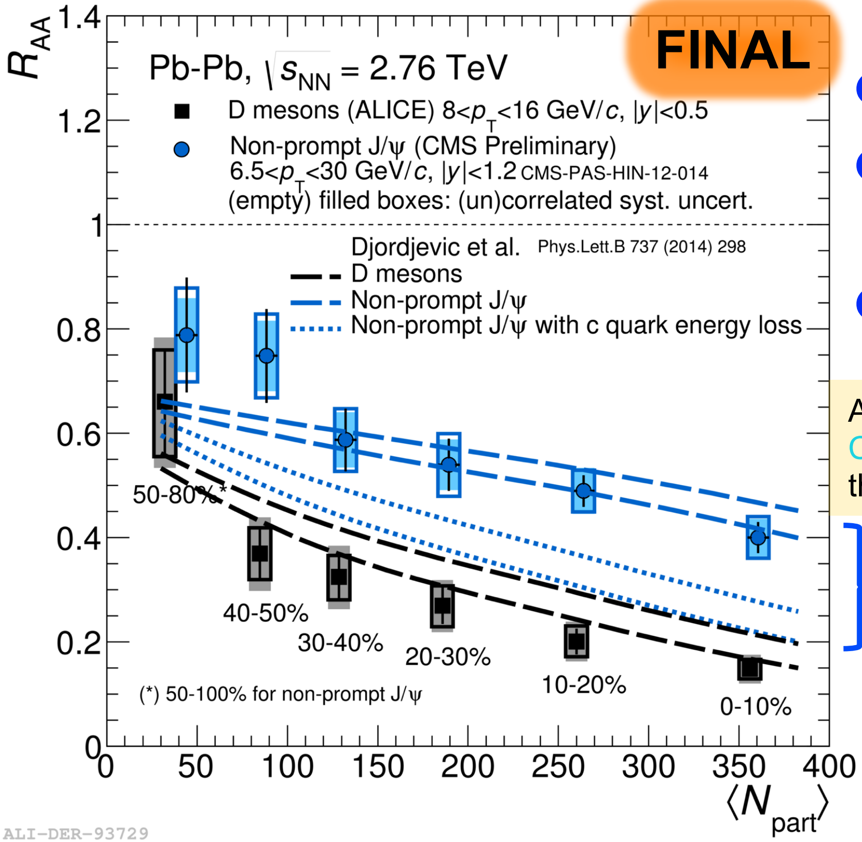




- **D-meson and pion R_{AA} are compatible within uncertainties**
- **agreement consistent with models including**
  - **energy loss hierarchy: ΔE(g) > ΔE(u,d,s) > ΔE(c)**
  - **different shapes of the parton p_T distributions**
  - **different fragmentation functions**

R_{AA}: D mesons vs. non-prompt J/ψ

naively: ΔE(g) > ΔE(u,d,s) > ΔE(c) > ΔE(b) → $R_{AA}(\pi)$ < R_{AA}(D) < R_{AA}(B)



- **similar <p_T> for D and B mesons**
- **indication for R_{AA}(D) < R_{AA}(J/ψ ← B) in central Pb-Pb collisions**
- **confirmed by CMS D^0 measurement**

ALICE: arXiv:1506.06604
CMS: CMS-PAS-HIN-12-014
theory: PL B734(2014)286

consequence of mass difference of c and b quarks in pQCD based model calculation (Djordjevic, PL B734(2014)286)

- **pQCD model including mass-dependent energy loss predicts a difference between the R_{AA} of D mesons and non-prompt J/ψ similar to the observation**
- **similar for other calculations (BAMPS, WHDG, Vitev et al.)**

Summary

- pp collisions
  - pQCD calculations describe heavy-flavor cross sections
  - interplay of soft and hard processes under investigation
  - what about correlations?
- p(d)-A collisions
  - no indication for substantial cold nuclear matter effects
  - what about collectivity in small systems?
- A-A collisions
  - strong interaction of heavy quarks with the medium
    → suppression of yields at high p_T consistent with partonic energy loss
    → indication for charm (maybe beauty?) participating in the medium's collective expansion
- what is missing?
  - better precision, more statistics, extended p_T coverage (high and low (!) p_T)
  - smaller uncertainties and new differential measurements will help to
    - constrain model calculations quantitatively
    - address open questions concerning the energy-loss mechanisms, their path-length dependence, thermalization, coalescence involving heavy quarks ….