Open heavy-flavor measurements

-

an overview

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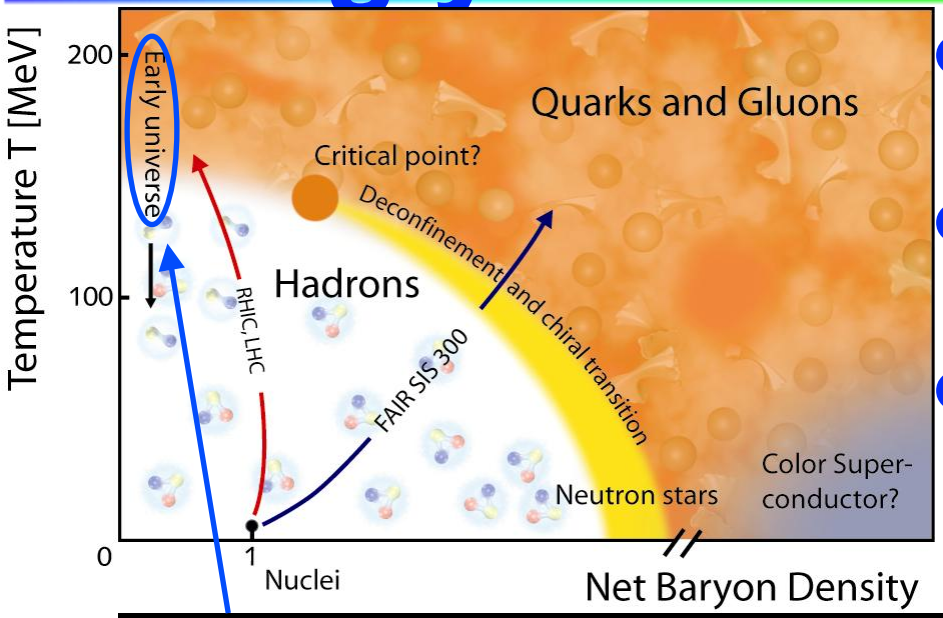
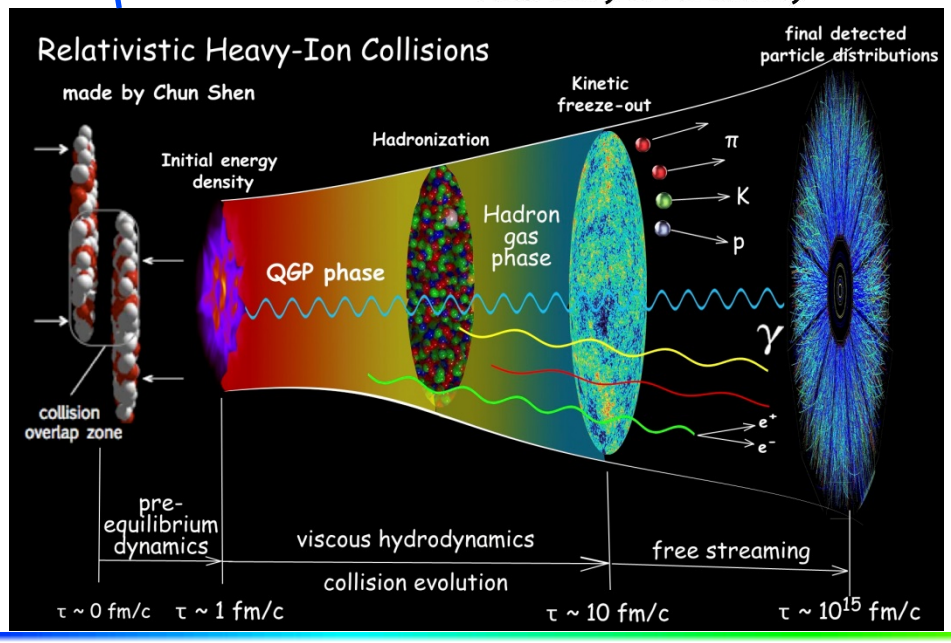
Strongly interacting matter



- QuantumChromoDynamics: theory of strong interactions
- phase diagram of strongly interacting matter
- deconfined QCD matter at high temperature T and/or baryochemical potential μ_B



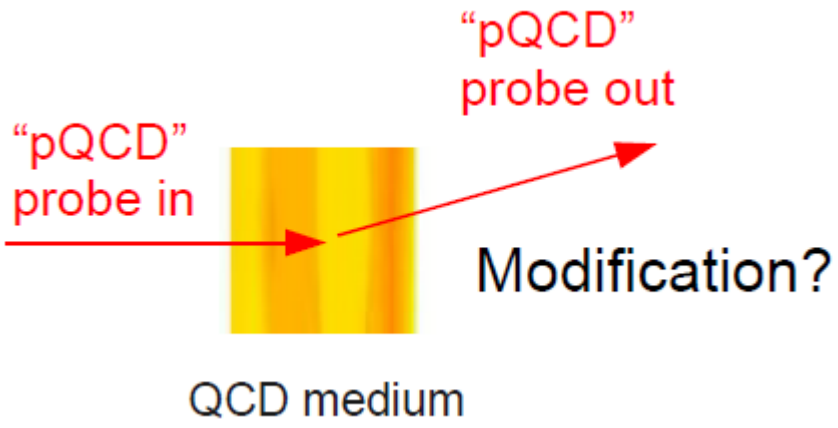
- heavy-ion collisions at ultra-relativistic energy

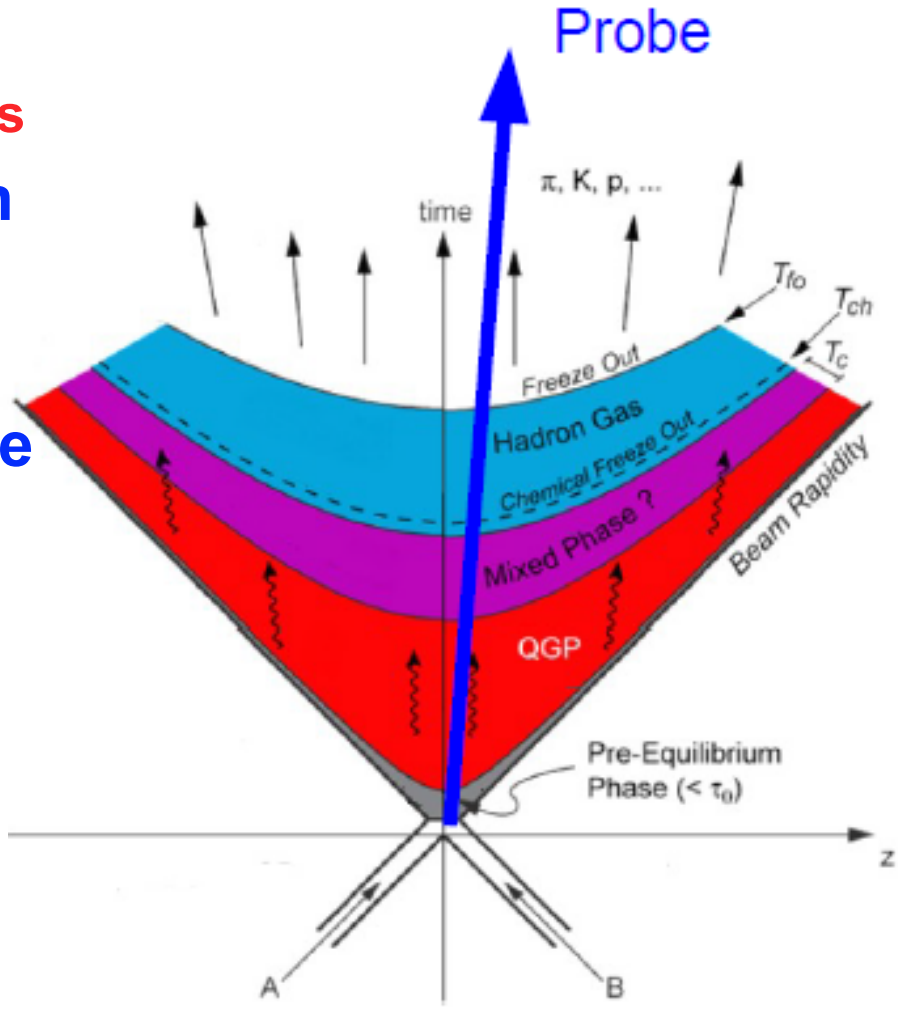
⇩

only experimental tool to study hot and dense QCD matter in the lab!

Hard probes of QCD matter

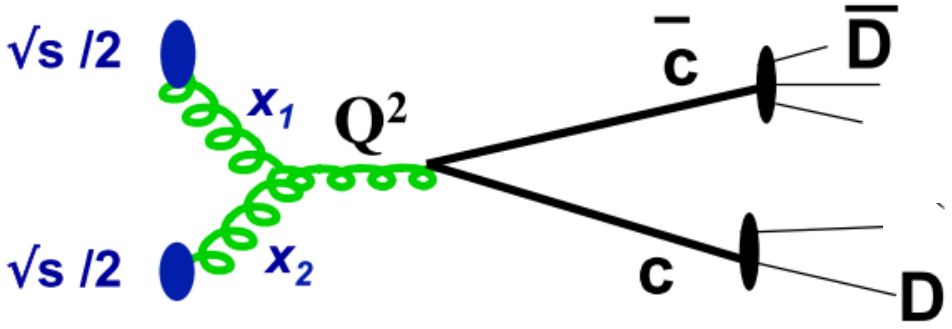
- hard (large Q^2) probes of QCD matter
  - photons, W, Z, jets, heavy quarks
- self generated in the collision at t ~ 1/Q (or t ~ 1/m)
- "tomographic" probes of the hottest and densest phase of the collision





Heavy flavor: a unique probe

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

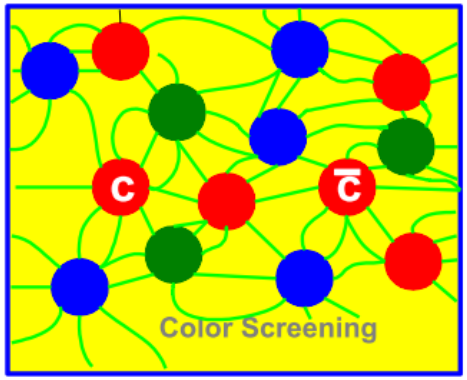


- heavy quarks are unique
  - interactions with produced QCD medium don‘t change the flavor but can modify the phase-space distribution of heavy quarks
  - thermal production rate in the QGP is “small“ (may be measurable → T)

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

Two „historical“ pillars

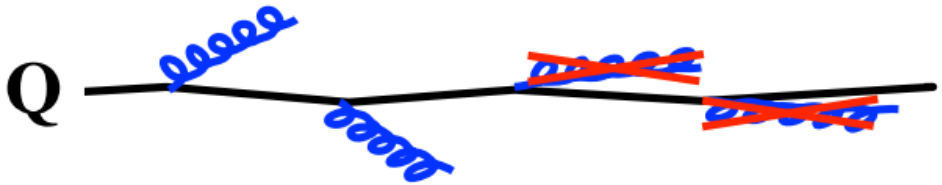
- dissociation of $q\bar{q}$ via color screening
  - Matsui and Satz, 1986



  - probe of deconfinement and medium temperature

Quarkonia

- mass dependence of radiative parton energy loss („dead cone“)
  - Dokshitzer and Kharzeev, 2001
    → energy loss decreases with increasing quark mass m_q



  - probe of QCD interaction dynamics in extended systems

Open heavy flavor

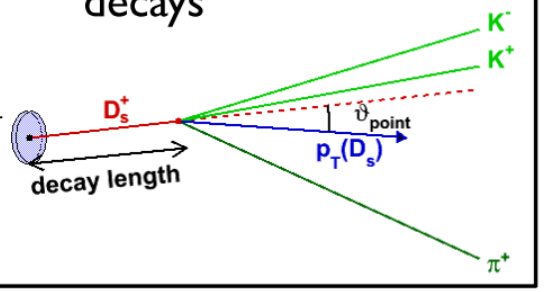
- both pillars: evolved and extended significantly over the years

Open heavy-flavor measurements

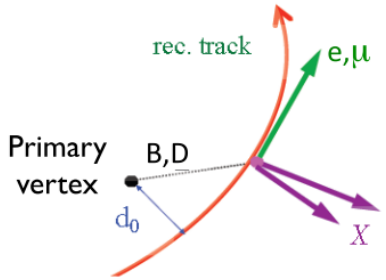
- **heavy-flavor hadron decays via weak interaction: decay lengths cτ ~ few 100 μm → measure decay products**

Full reconstruction of D meson hadronic decays

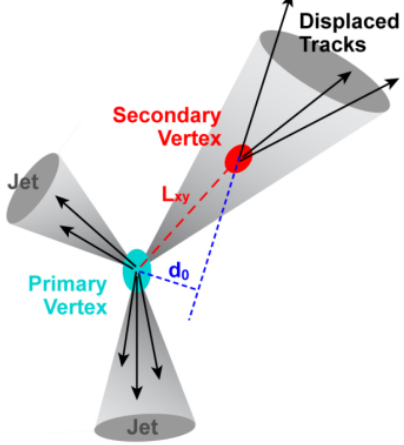
$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
$D^{*+} \rightarrow D^0 \pi^+$
$D_s^+ \rightarrow K^- K^+ \pi^+$



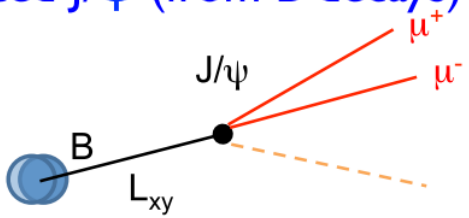
Semi-leptonic decays (c,b)



HF jets
Correlations with HF

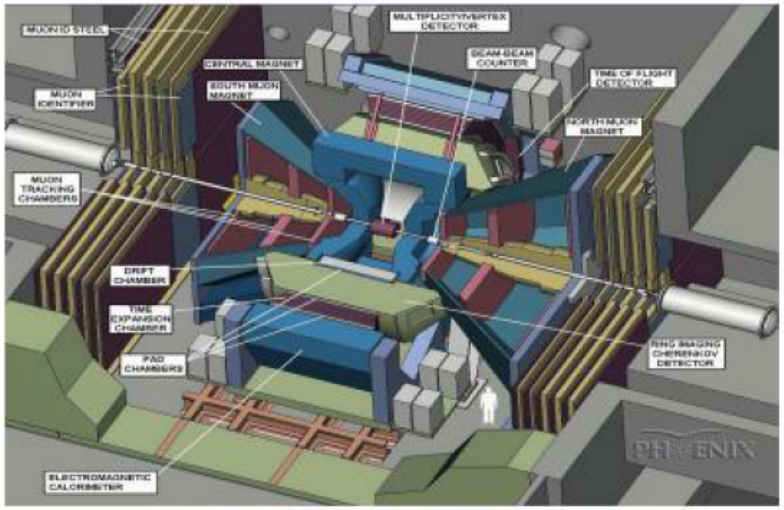


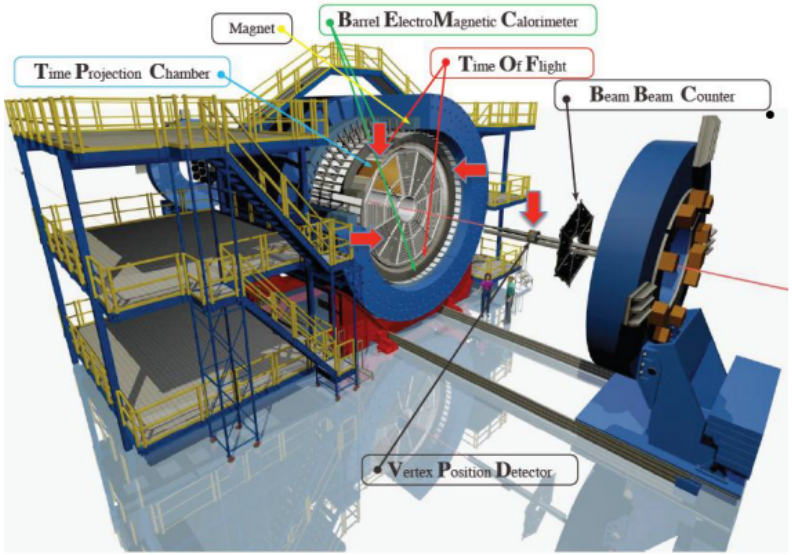
Displaced J/ψ (from B decays)



Experiments at RHIC …

- pp, d-Au, Cu-Cu, Au-Au, U-U collisions at $\sqrt{s_{NN}} \leq 0.2$ TeV
  - since 2000: first systematic open heavy-flavor studies in heavy-ion collisions





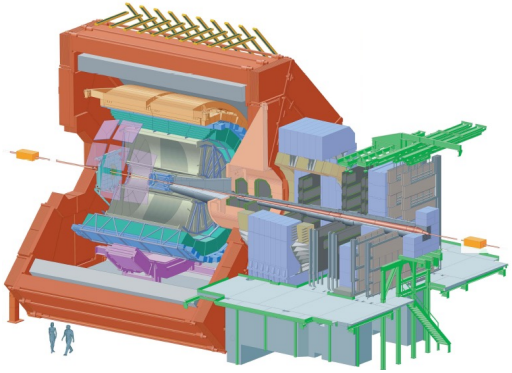
- **PHENIX**
  - heavy flavor via $e^{\pm}$ at mid rapidity and $\mu^{\pm}$ at forward rapidity
- **STAR**
  - heavy flavor via D-meson reconstruction and $e^{\pm}$ at mid rapidity

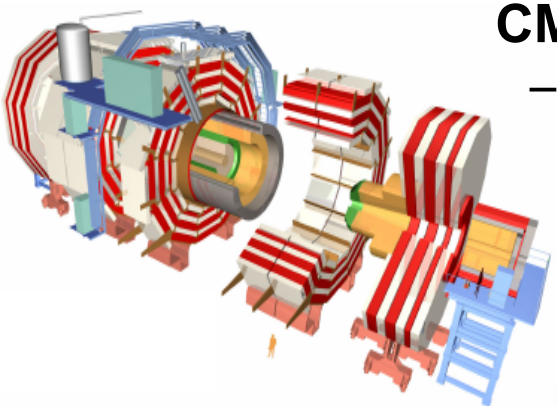
- high resolution silicon vertex trackers only after upgrades (first comprehensive results presented in 2015)

… and at the LHC

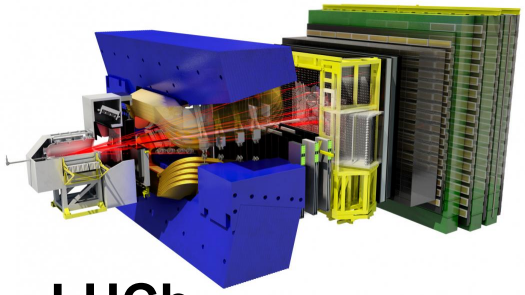
- LHC: pp ($\sqrt{s} \leq 13$ TeV), p-Pb ($\sqrt{s_{NN}} = 5.02$ TeV), and Pb-Pb ($\sqrt{s_{NN}} = 2.76$ and 5.02 TeV) collisions
  - all experiments: precision vertex tracking from Day-1

ALICE
– general purpose: all HF channels down to low p_T

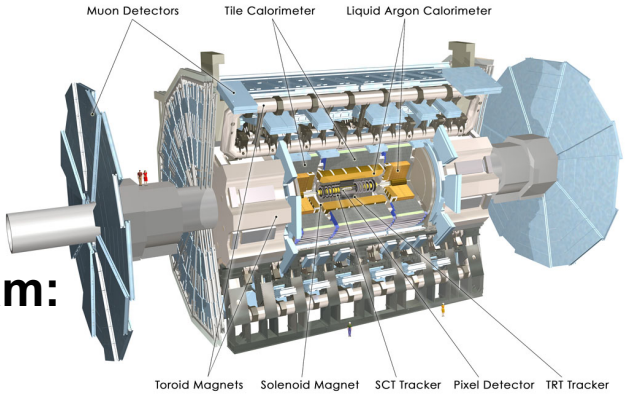




CMS
– targeted AA program: HF jets, non-prompt J/ψ, D mesons (w/o PID)



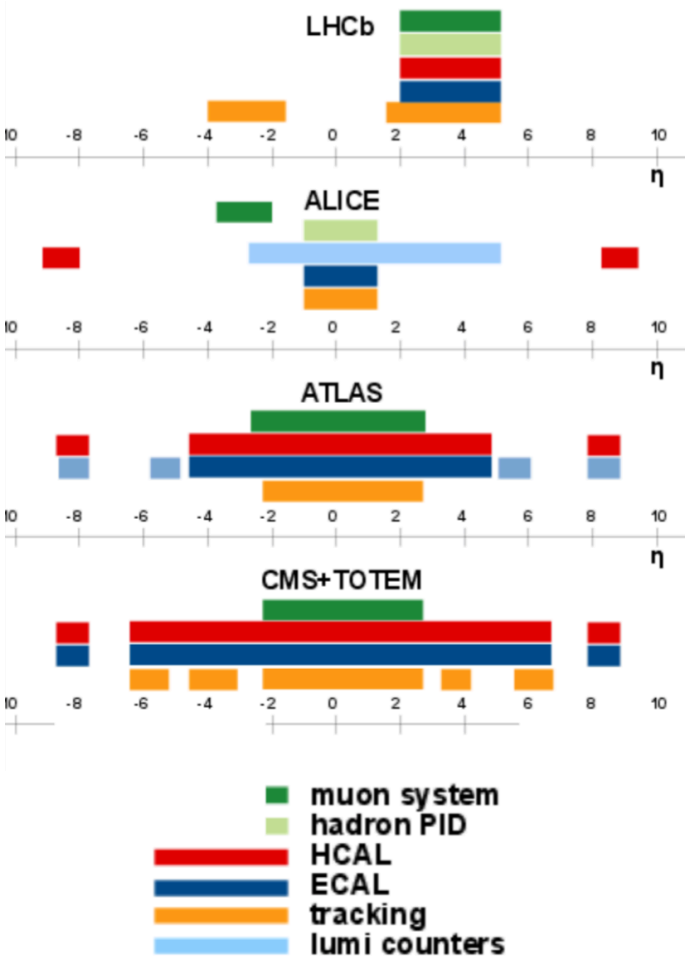
LHCb
– B physics in pp & p-Pb collisions
– Pb-Pb program started
– fixed target AA programm



ATLAS
– targeted AA program: HF → leptons

… and at the LHC

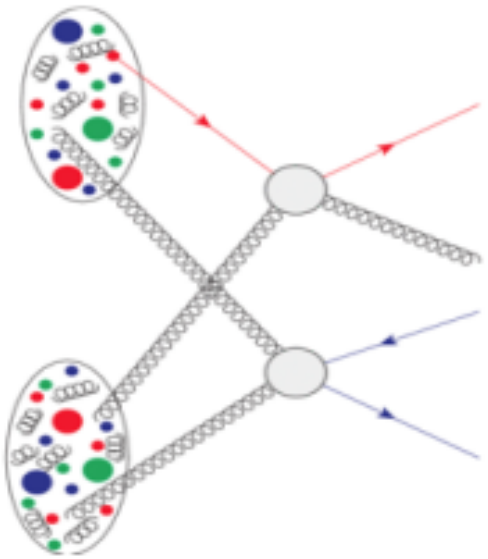
- LHC: pp ($\sqrt{s} \leq 13$ TeV), p-Pb ($\sqrt{s_{NN}} = 5.02$ TeV), and Pb-Pb ($\sqrt{s_{NN}} = 2.76$ and 5.02 TeV) collisions
  - all experiments: precision vertex tracking from Day-1
  - complementary in terms of phase-space coverage
  - hadron PID only with ALICE (mid rapidity) and LHCb (forward rapidity)
  - muons and jets (with HCAL ECAL) at mid rapidity only with ATLAS and CMS



Testing pQCD calculations in pp collisions

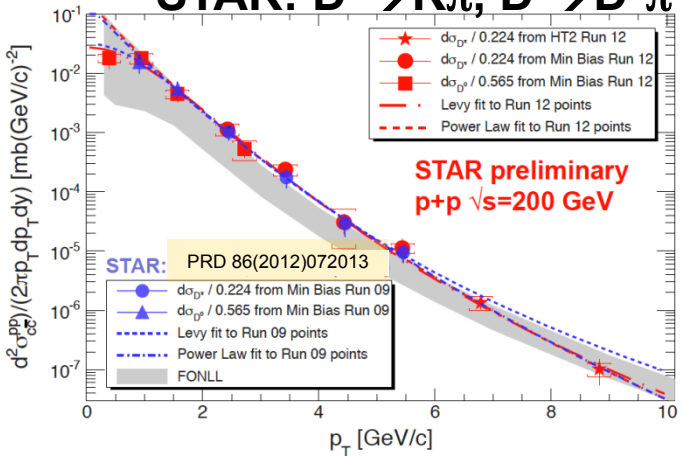
Heavy quarks in pp collisions

- test understanding of heavy-quark production
  - which are the relevant production mechanisms on the parton level
    - LO contributions:
      gluon fusion, quark-antiquark annihilation
    - NLO contributions:
      gluon splitting, flavor excitation
    - or even more complex,
      e.g. Multi Parton Interactions (MPI)
  - testing ground for perturbative QCD calculations
    - theoretical uncertainties are driven by
      - renormalization and factorization scales
      - quark masses
  - investigate production mechanisms via more differential measurements
    - multiplicity dependence of heavy-flavor production cross sections
    - D meson – hadron correlation measurements
  - reference for p-Pb and Pb-Pb collisions

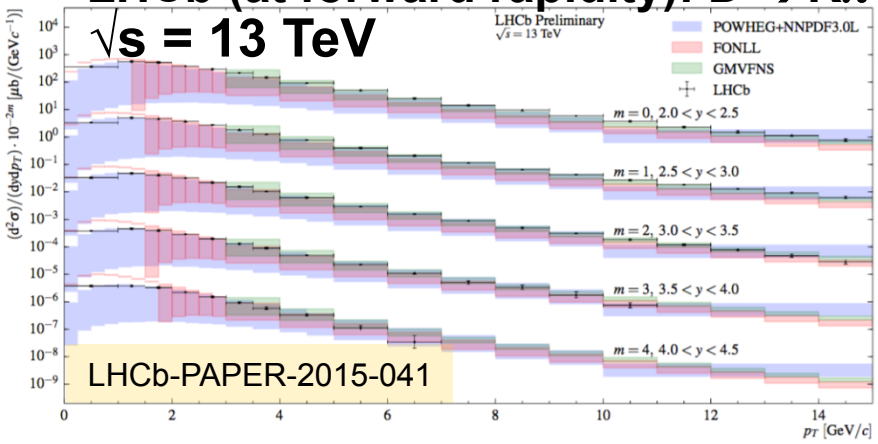


Heavy-flavor hadron production

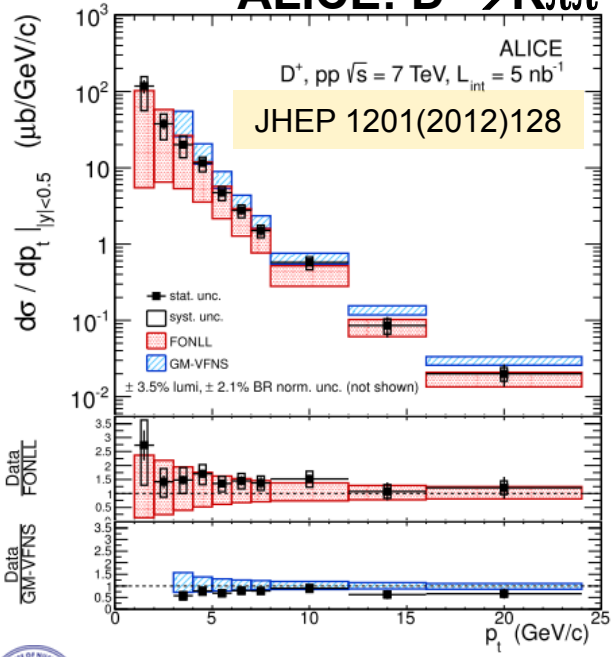
STAR: $D^0 \rightarrow K\pi$, $D^* \rightarrow D^0\pi$



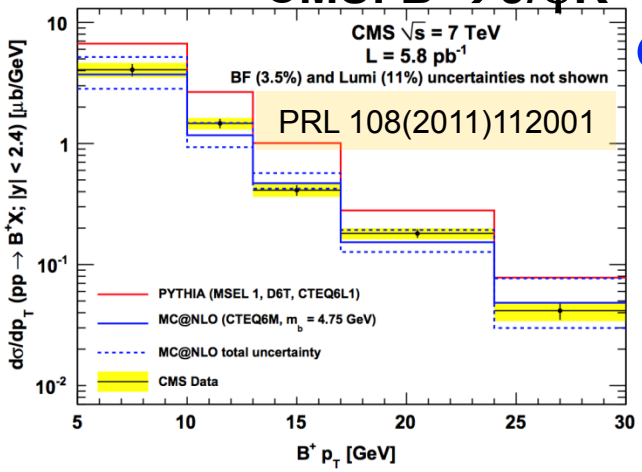
LHCb (at forward rapidity): $D^0 \rightarrow K\pi$



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



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

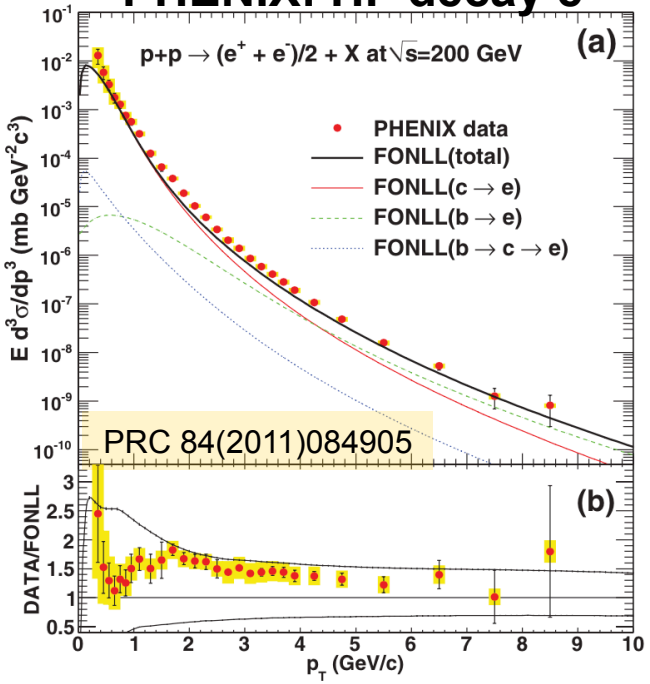


- **pQCD calculations**
  - **FONLL: JHEP 1210(2012)37**
  - **GM-VFNS: EPJ C72(2012)2082**
  - **k_T factorization: PRD 87(2013)094022**

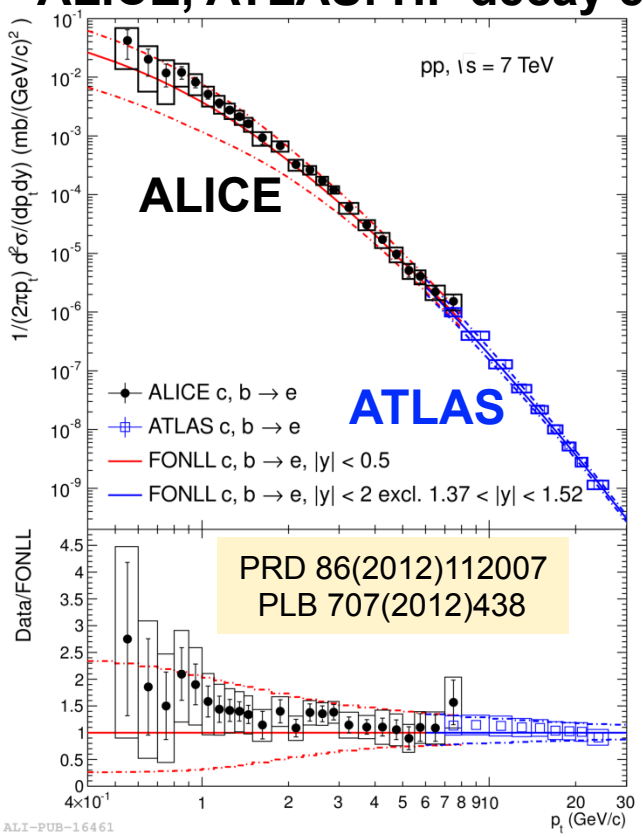
- **pQCD calculations in agreement with measurements within substantial exp. and theor. uncertainties**

Leptons from heavy-flavor decays

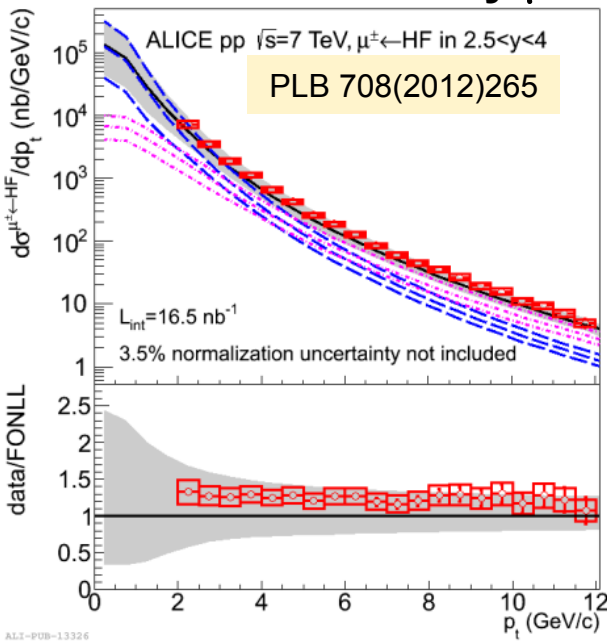
PHENIX: HF decay e±



ALICE, ATLAS: HF decay e±



ALICE: HF decay μ±

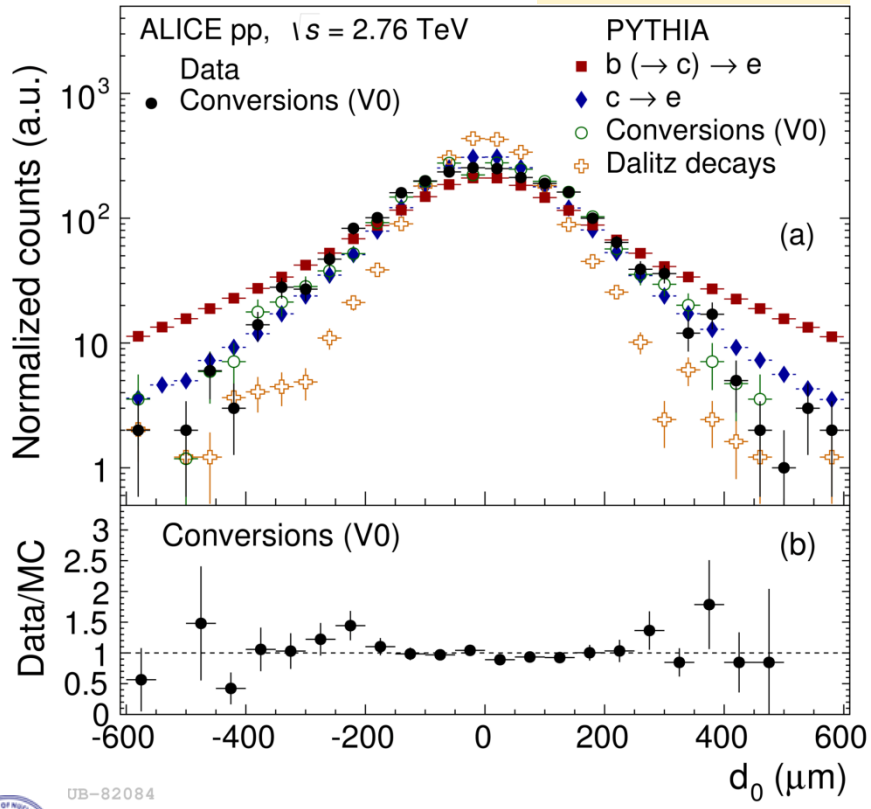


- e± (μ±) from HF decays at mid (forward) rapidity
- pQCD calculations in reasonable agreement with data within uncertainties

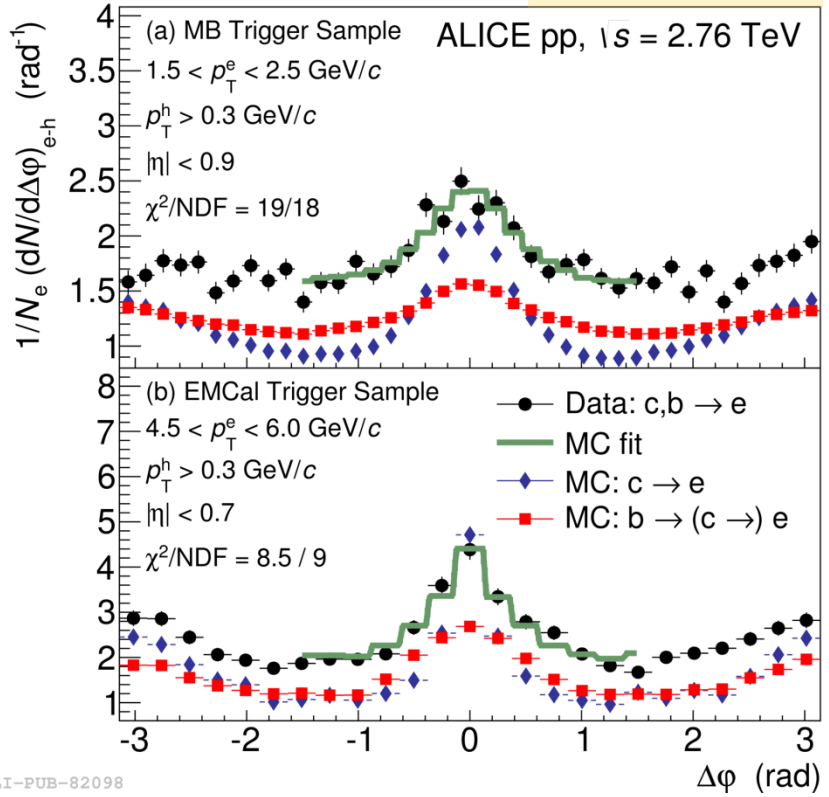
Electrons from beauty decays

- statistical separation of $e^{\pm}$ from charm and beauty decays
  - beauty hadrons: $c\tau \sim 500\ \mu m \rightarrow$ displaced secondary vertex
  - near-side peak in electron-hadron angular correlation wider for electrons from beauty decays than for those from charm decays

PLB 708(2012)265



PLB 738(2014)97



Electrons from beauty decays

- differential cross sections in pp collisions at $\sqrt{s}$ = 2.76 TeV

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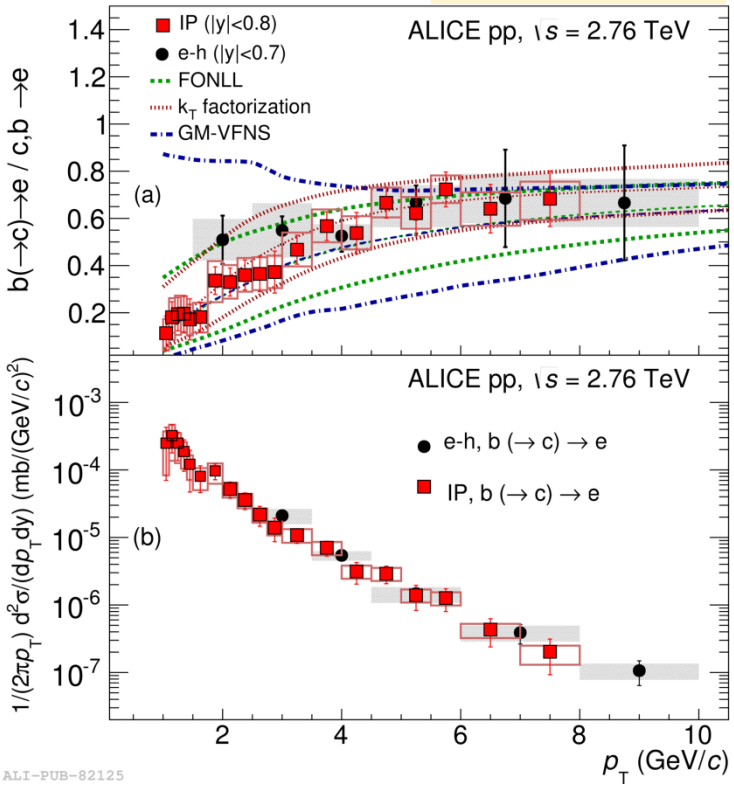

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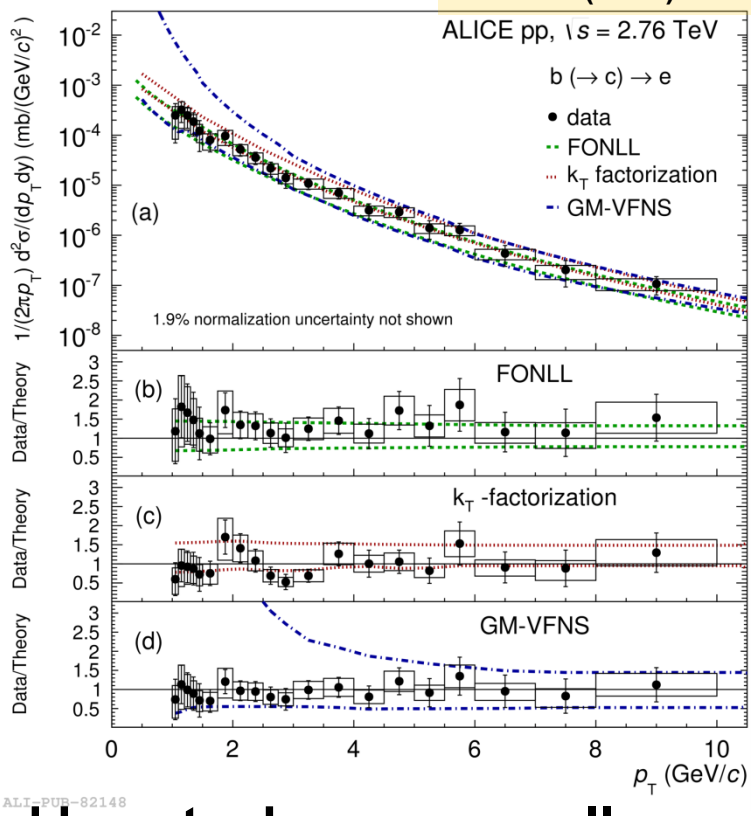
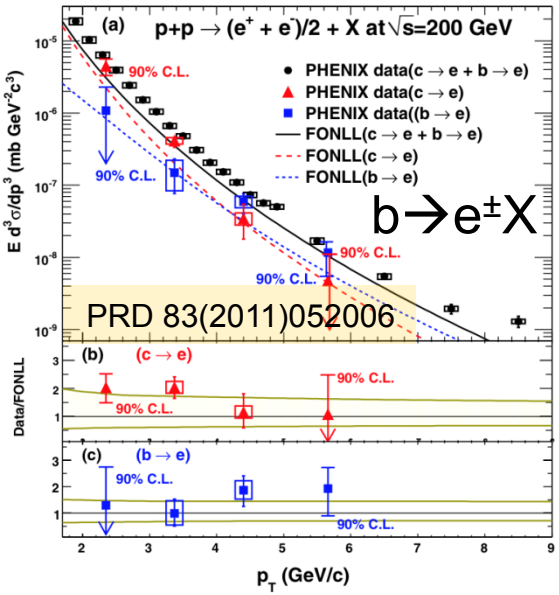
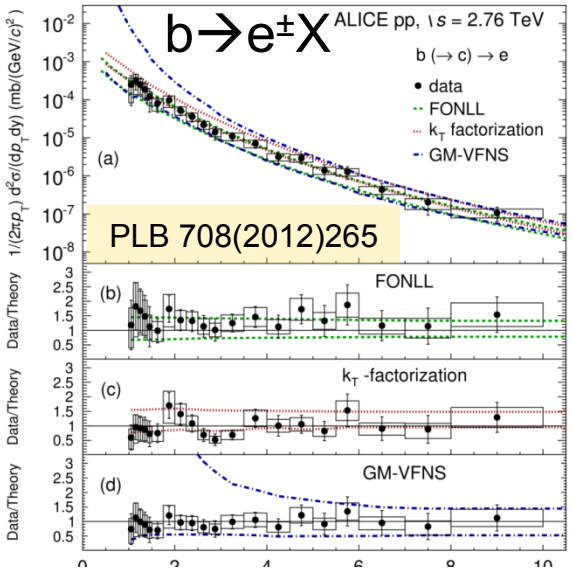
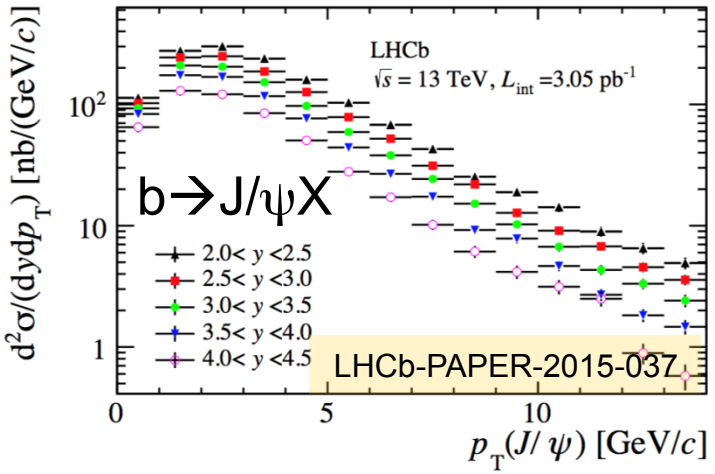


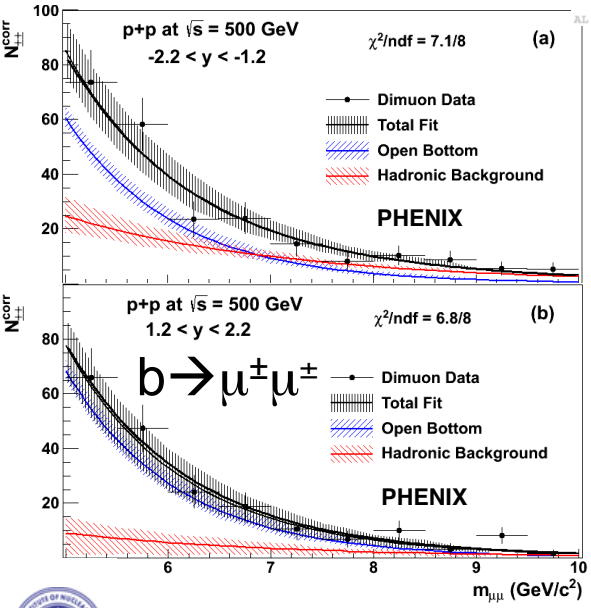
- relative contributions of charm and beauty decays as well as beauty-decay electron cross section reproduced by pQCD calculations (also at $\sqrt{s}$ = 7 TeV)
  - FONLL: JHEP 1210(2012)37
  - GM-VFNS: EPJ C72(2012)2082
  - k_T factorization: PRD 87(2013)094022

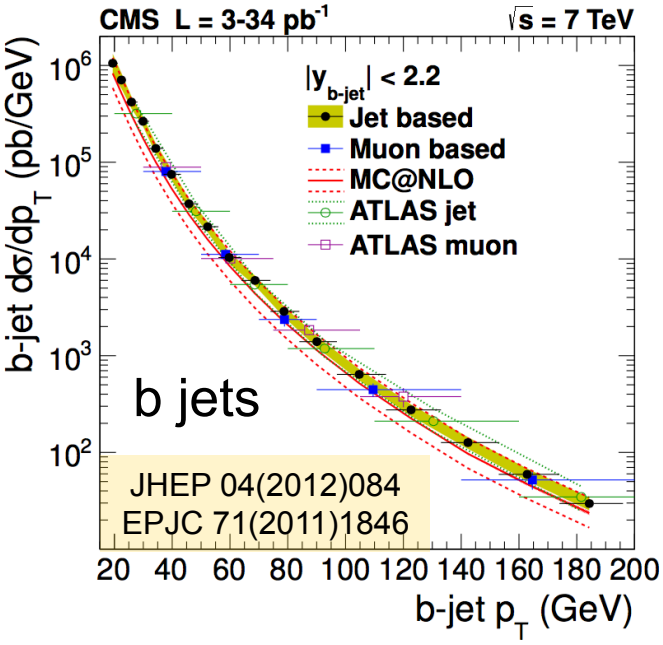
Beauty production





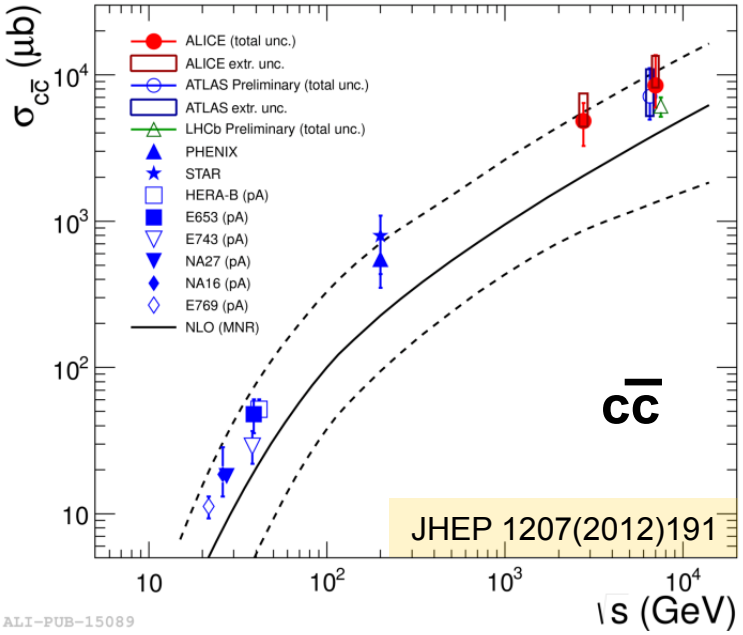


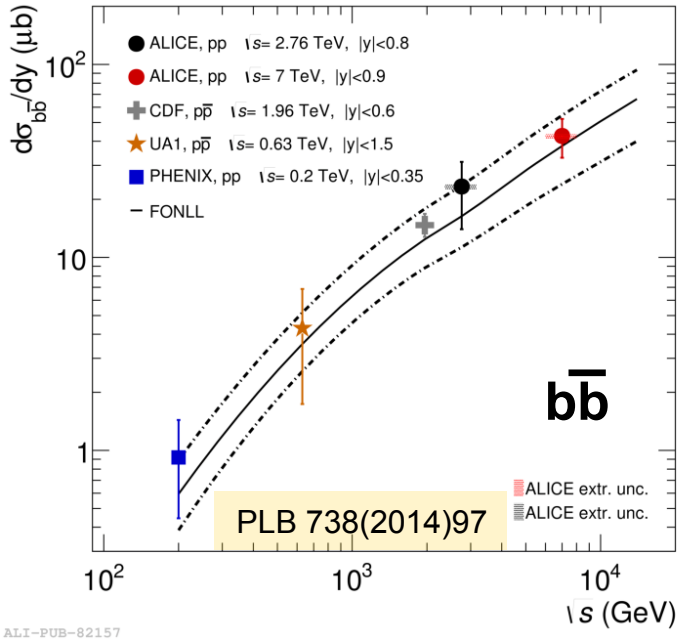




- also beauty production described by pQCD calculations

Total charm & beauty cross sections

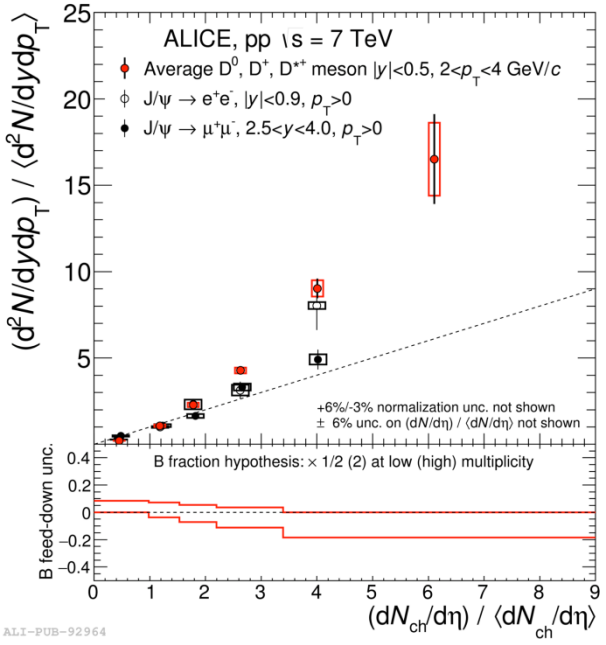


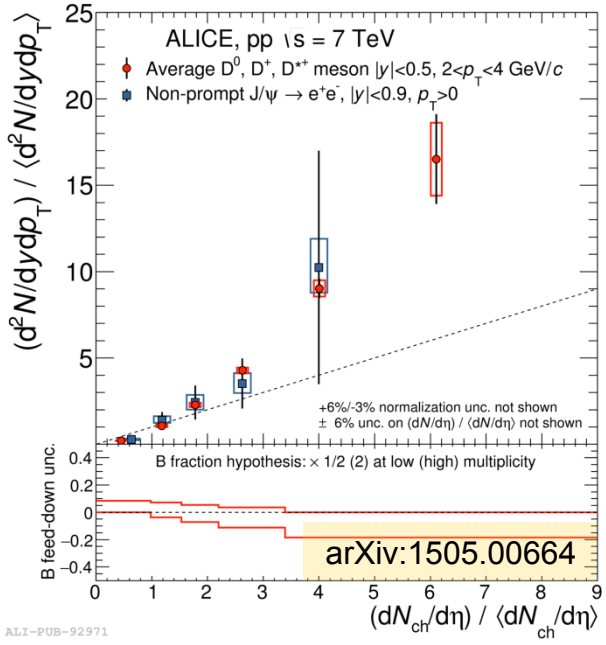


- **experimental precision not yet satisfactory (e.g. for quarkonia reference!)**
  - **extend kinematic coverage (low p_T!)**
  - **larger data samples**
  - **improved control of systematic uncertainties**
- **can data constrain pQCD parameters?**
- **further constraints: more differential measurements**

D-meson yields vs. multiplicity

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

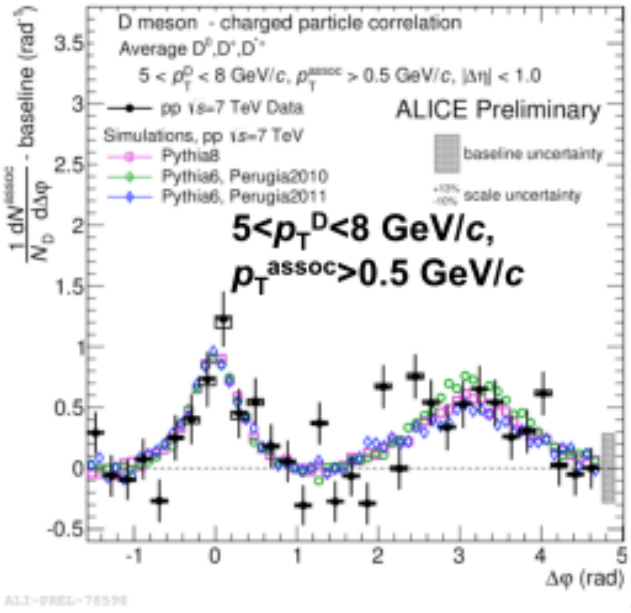


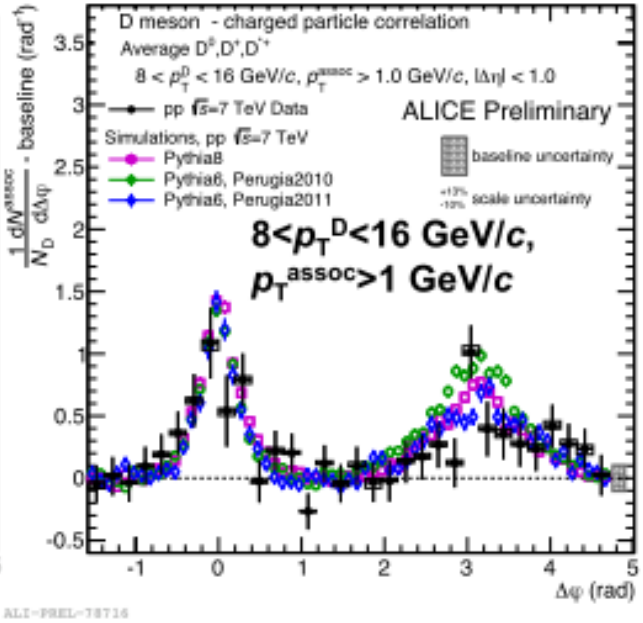


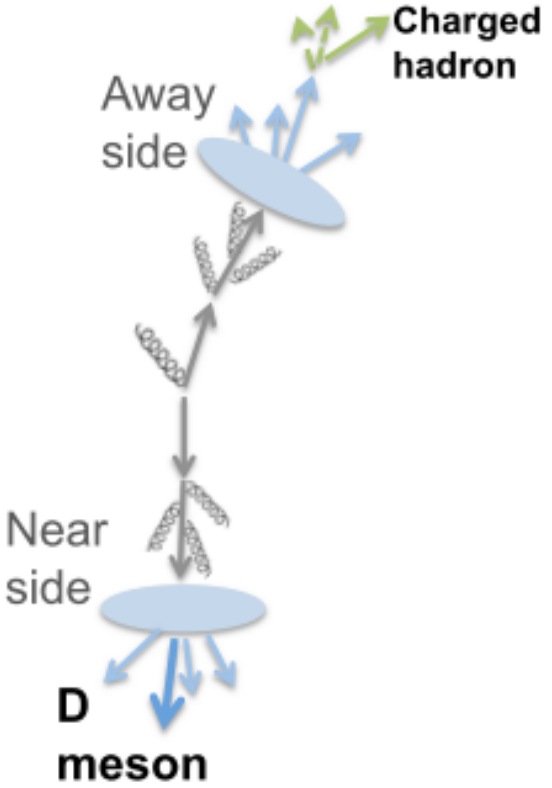
- D-meson yields increase more than linear with $dN_{ch}/d\eta$
- similar increase for open and hidden charm
  → behavior driven by production mechanism, not hadronization
- similar trend for non-prompt J/ψ from open-beauty decays
- models including MPI describe observed trend

D meson – hadron correlations

- measurement of associated hadron yields on the near and away side
- sensitive to charm production mechanism and fragmentation
  - → charm jet properties
  - → constrain models







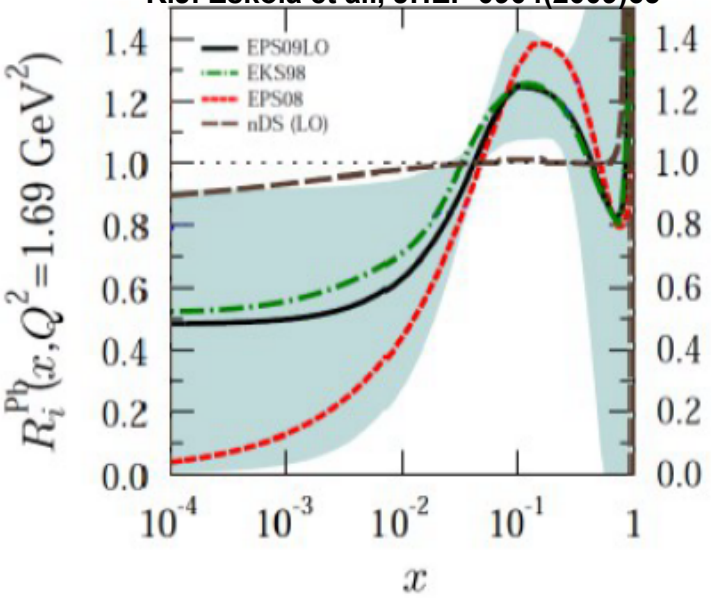
- different PYTHIA tunes are compatible with correlation measurement in pp collisions after baseline subtraction
- better precision requires more data from Run-2 at the LHC

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

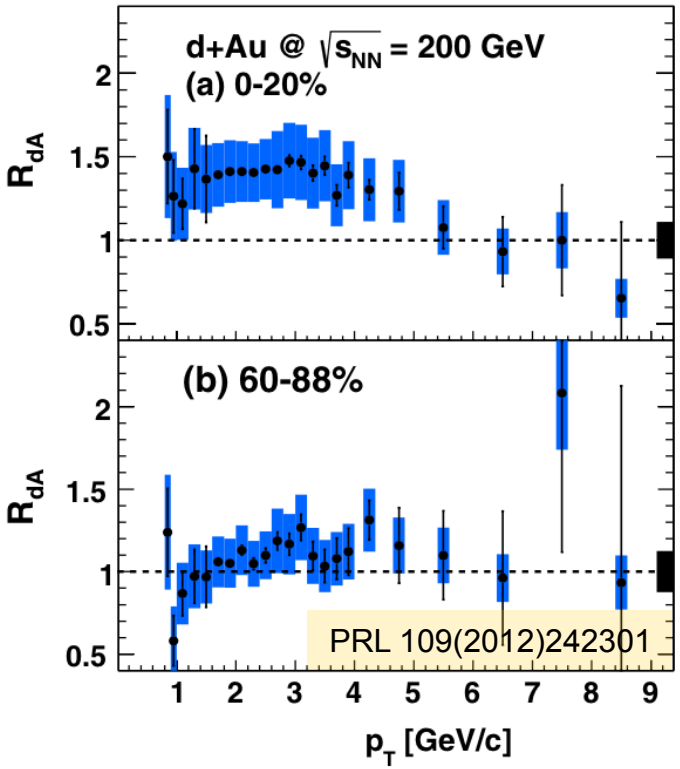
Heavy quarks in p(d)-A collisions

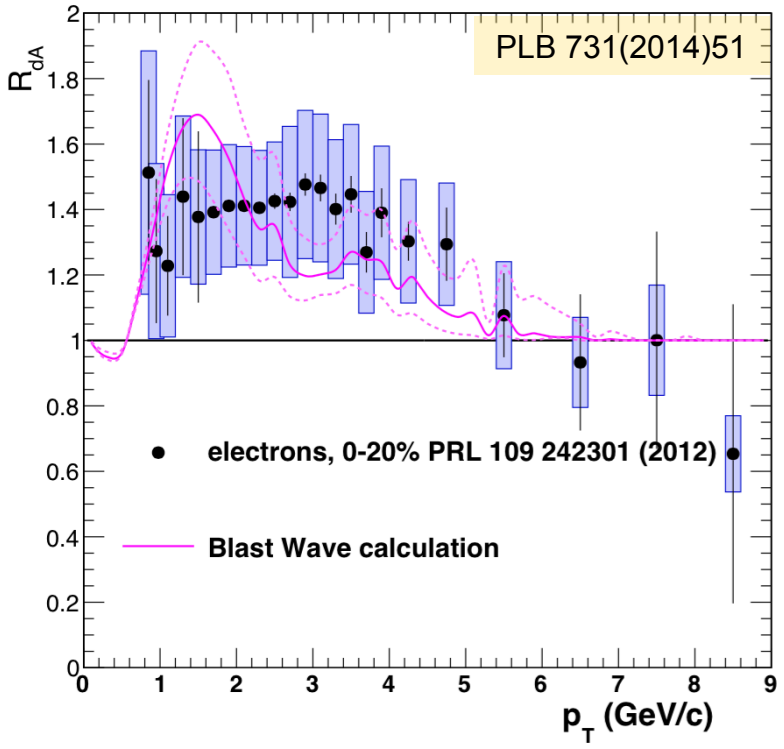
- quantify cold nuclear matter effects
  - nuclear modification of Parton Distribution Functions (shadowing, gluon saturation)
  - k_T broadening
  - energy loss in cold nuclear matter
  - multiple binary collisions
- final state effects?
- reference for A-A collisions

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



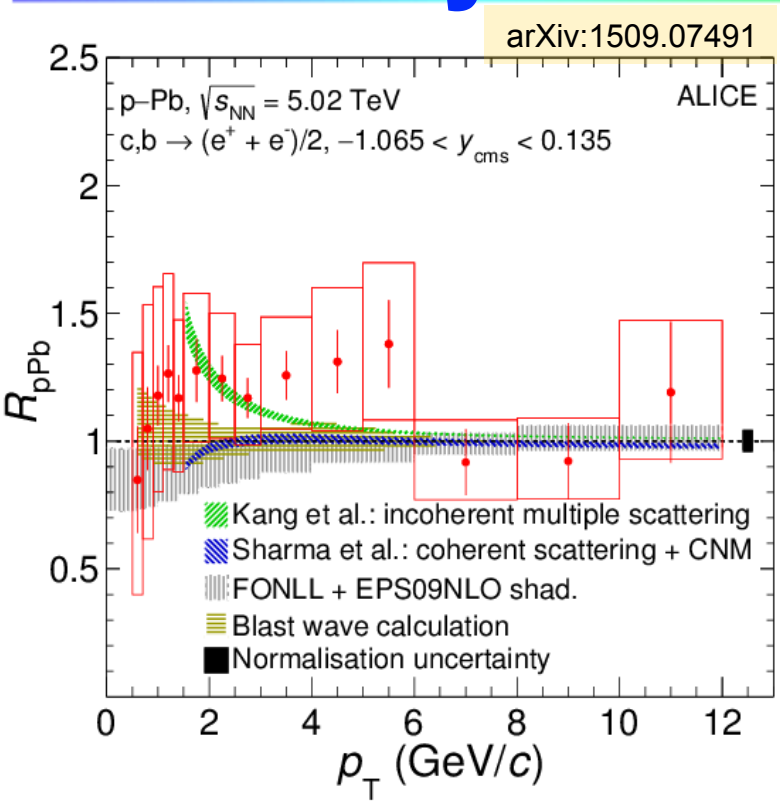
Electrons from HF decays at RHIC



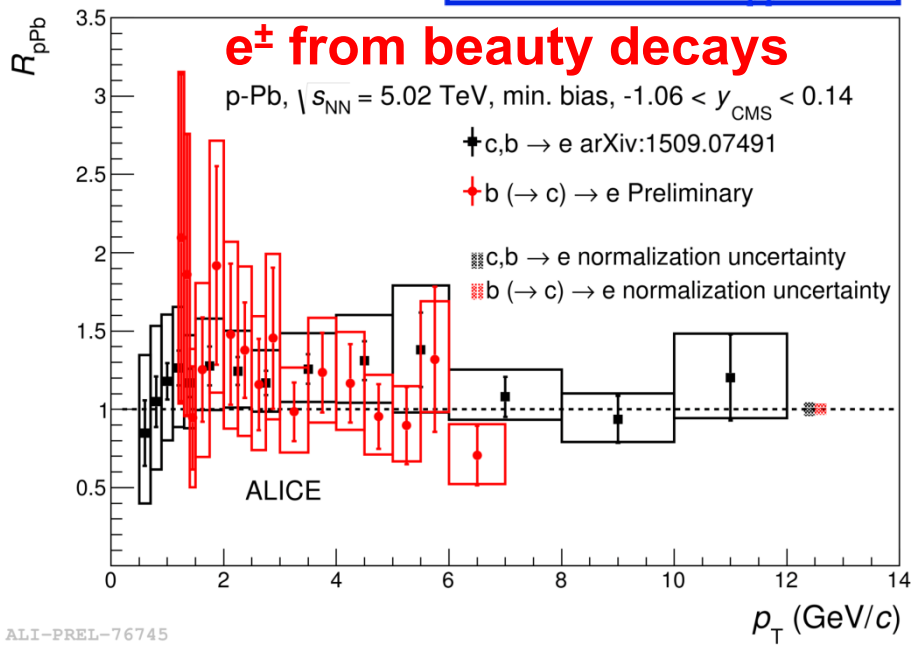


- R_{dA} > 1 for low-p_T electrons at mid rapidity (also for muons at backward rapidity)
- no "large" enhancement via anti-shadowing expected
- consistent with radial flow!?
  → D-meson measurement highly desirable

HF decay electron R_{pPb} at the LHC



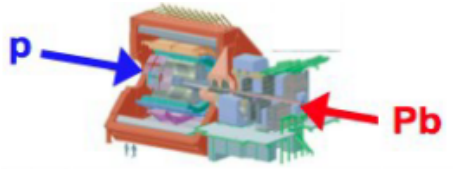
$$R_{pPb} = \frac{d\sigma_{pPb}/dp_T}{A \times d\sigma_{pp}/dp_T}$$



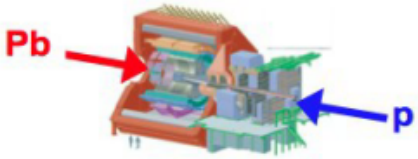
- R_{pPb} consistent with unity and described by models including initial-state effects or radial flow within uncertainties
- R_{pPb} of beauty-hadron decay electrons consistent with inclusive HF decay electron R_{pPb} and with unity
- no indication for suppression at intermediate/high p_T

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

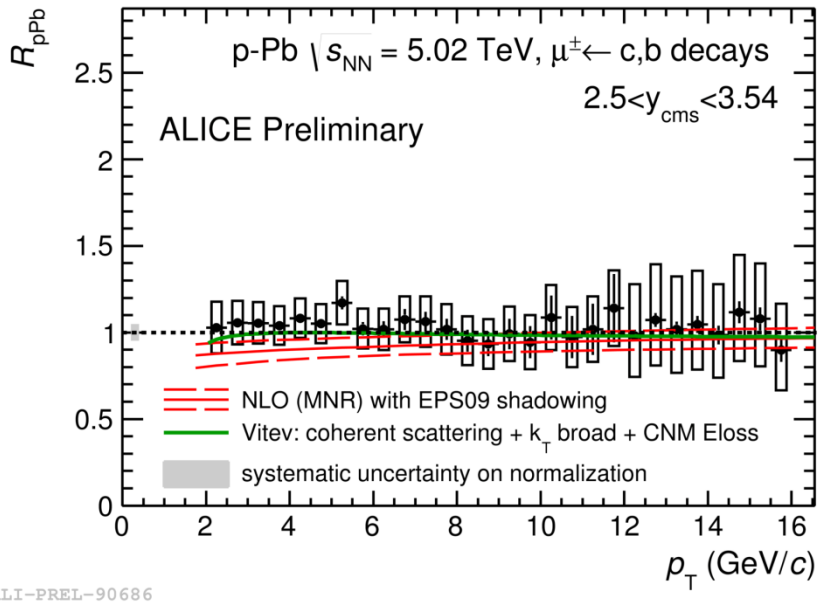
HF decay muon R_{pPb} at the LHC

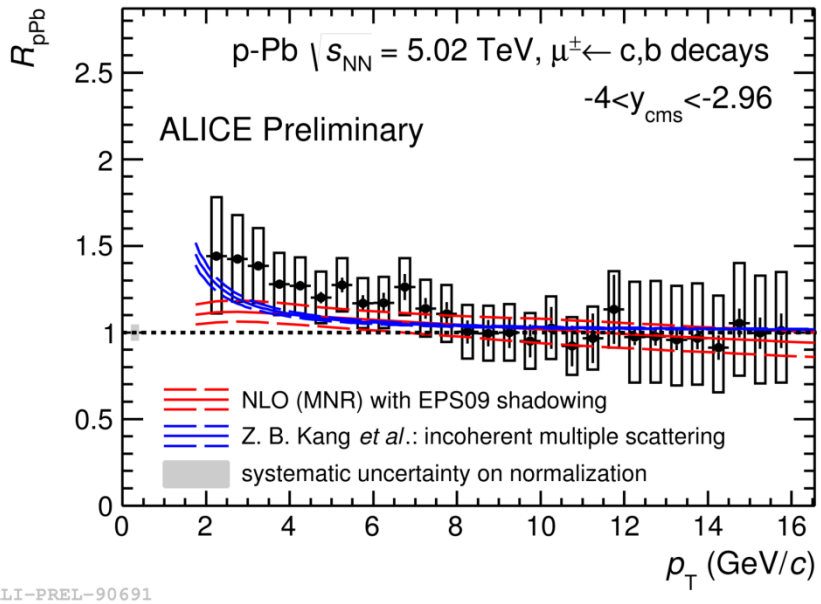


Forward: p-going



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 mesons: p_T-differential R_{pPb}

$$R_{pA} = \frac{1}{< T_{pA} >} \frac{dN_{pA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{A} \frac{d\sigma_{pA}/dp_T}{d\sigma_{pp}/dp_T}$$

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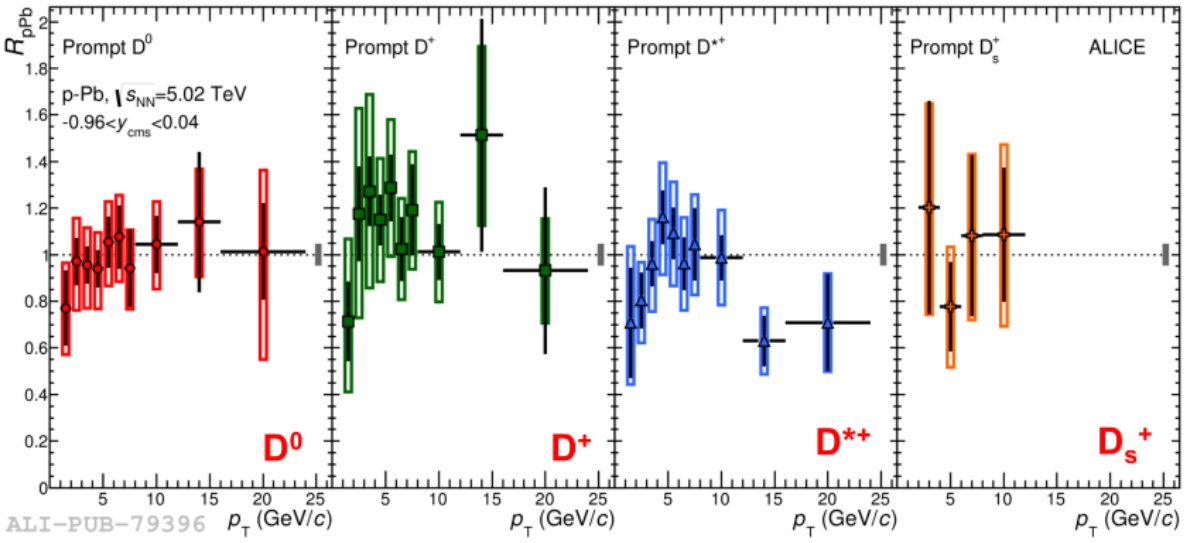
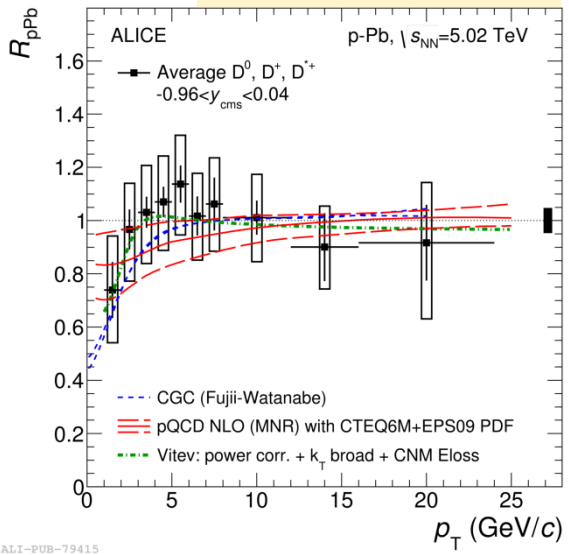


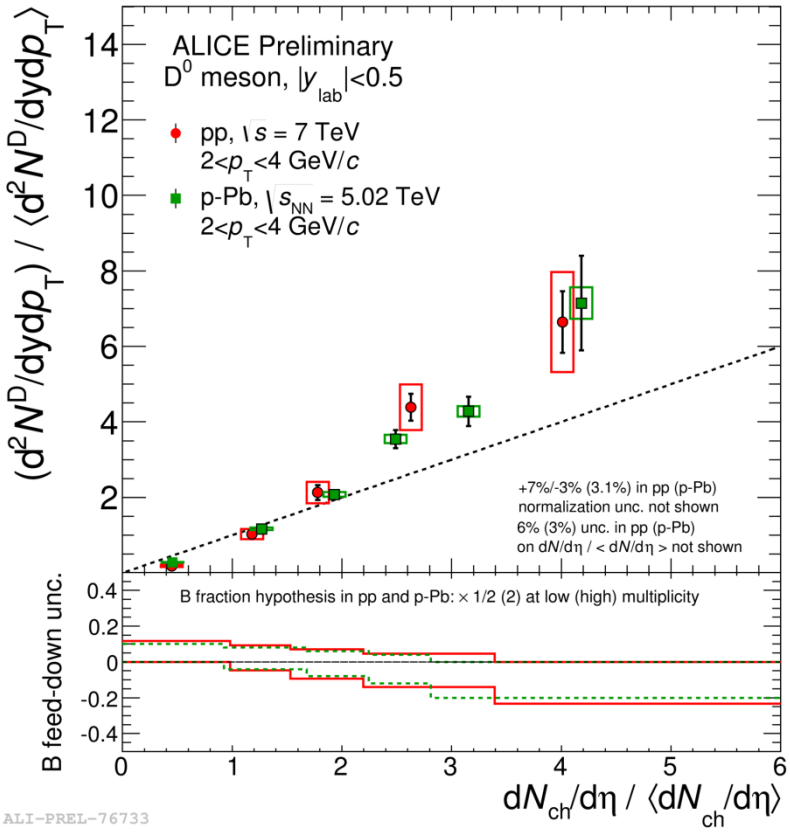


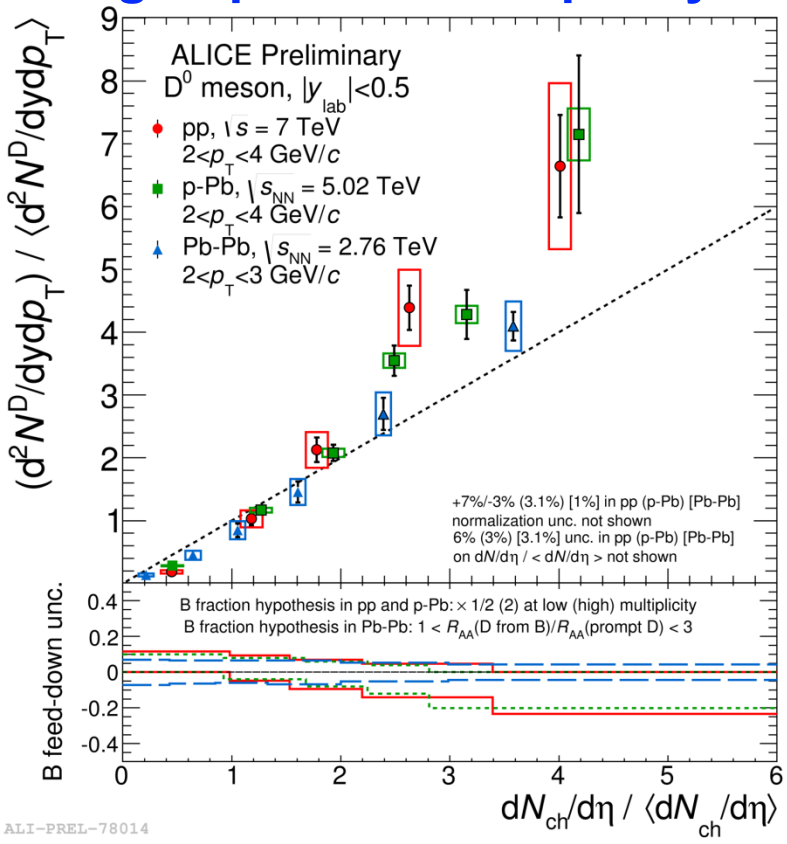
- R_{pPb} consistent with unity for all D-meson species
- D-meson R_{pPb} can be described by
  - Color Glass Condensate (CGC) calculations (arXiv:1308.1258)
  - MNR pQCD calculations (NPB 373(1992)295) with EPS09 nuclear PDF (JHEP 04(2009)065)
  - model including energy loss in cold nuclear matter, nuclear shadowing, and k_T broadening (PRC 75(2007)064906)

→ cold nuclear matter effects are small at high p_T!

D-meson yields vs. multiplicity

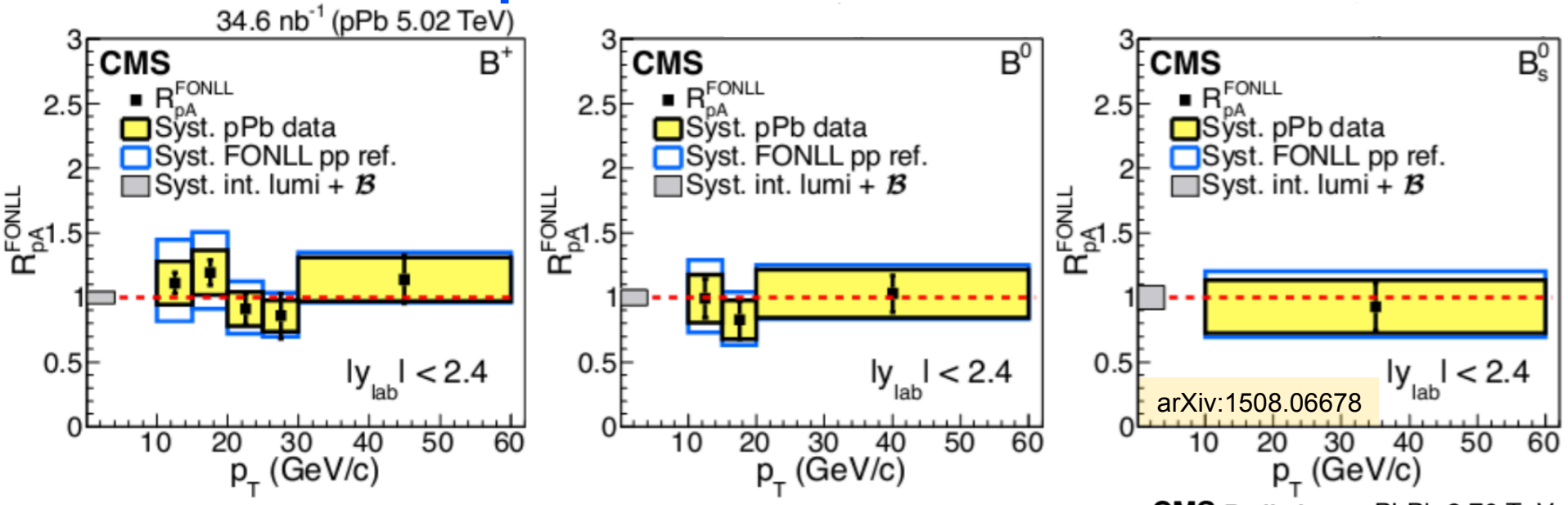
- self-normalized D-meson yields vs. charged-particle multiplicity



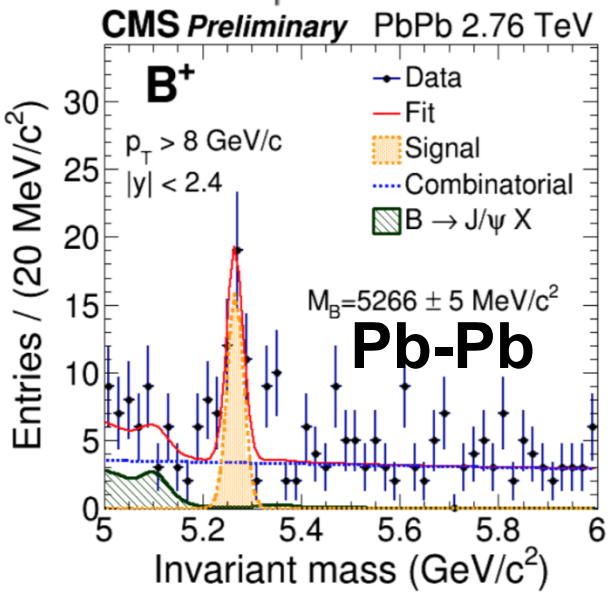


- similar trend of D-meson yields vs. multiplicity in pp and p-Pb collisions
  - pp collisions: high-multiplicity events mainly from MPI
  - p-Pb collisions: high multiplicity events also due to $N_{coll} > 1$
- similar trend also in Pb-Pb collisions
  - highest multiplicity bin in Pb-Pb (pp) collisions: 10% (1%) of the total cross section

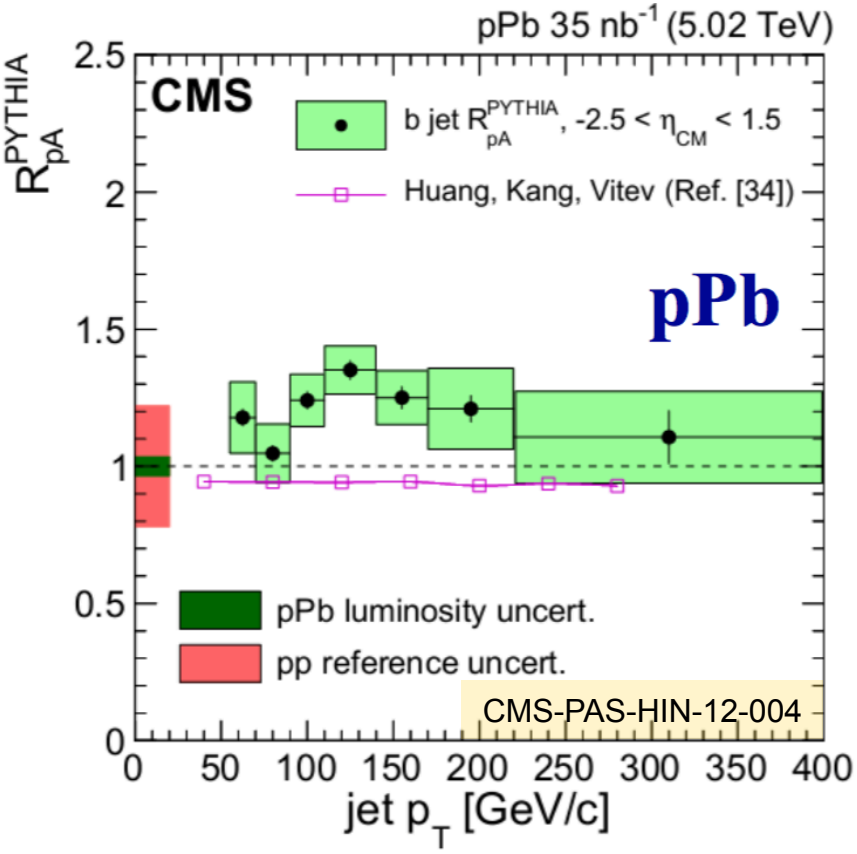
B-meson R_{pPb} at the LHC

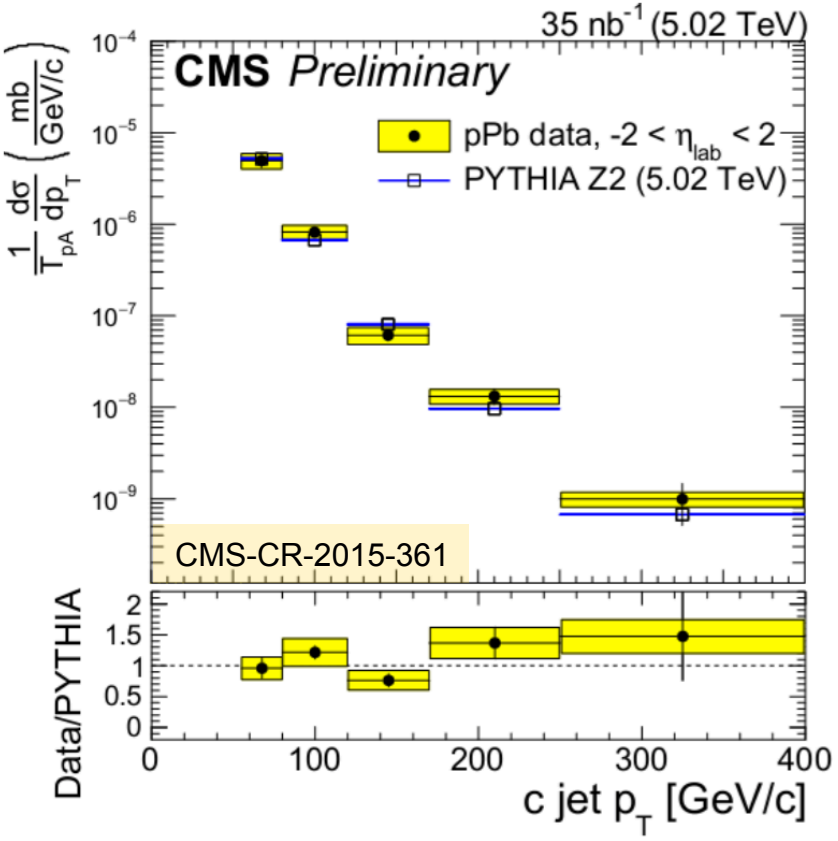


- **B-meson R_{pPb} for various species**
  - **pp reference from FONLL pQCD**
  - **consistent with unity**
    → no indication for significant cold nuclear matter effects
- **capability to reconstruct B mesons in Pb-Pb collisions as well!**



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

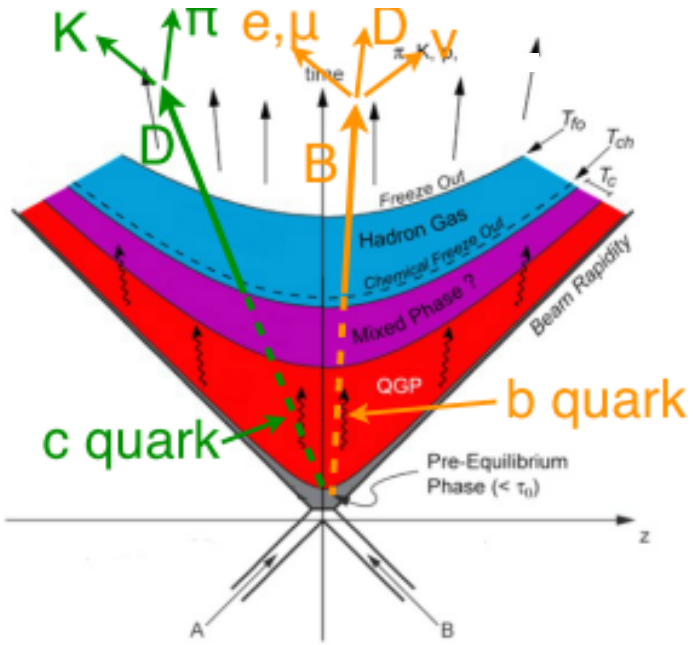
Dense/hot QCD matter effects in A-A collisions

Energy loss

- 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: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$

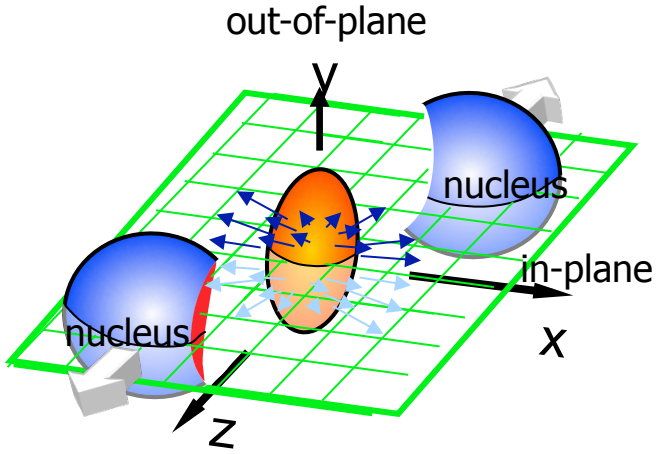
$$R_{AA} = \frac{dN_{AA}/dp_T}{< T_{AA} > \times d\sigma_{pp}/dp_T}$$



→ 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

Azimuthal asymmetry

- collectivity in the hot/dense medium
  - initial spatial anisotropy
    → anisotropy of particle emission in momentum space
  - quantified via a Fourier expansion in azimuthal angle with respect to the reaction/symmetry planes



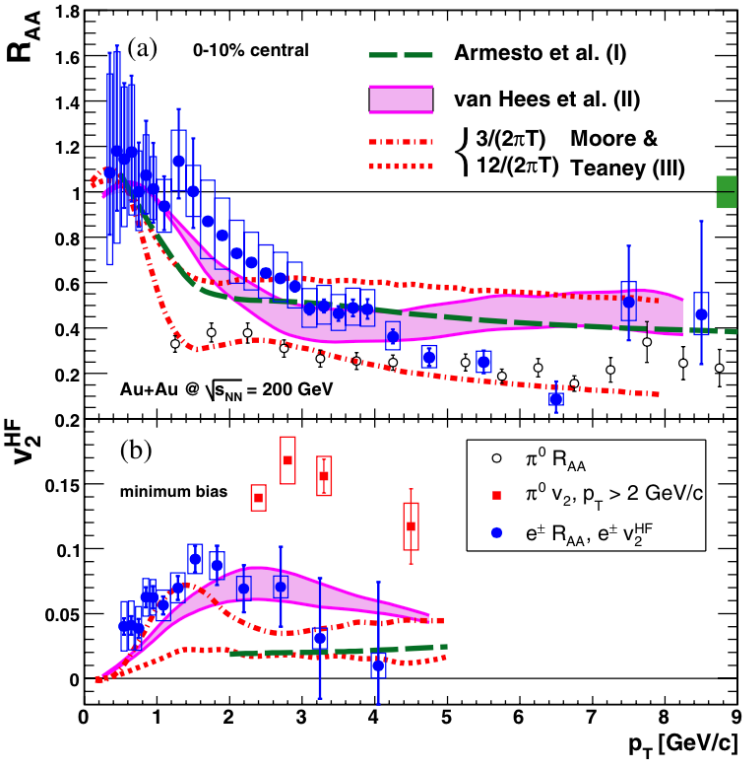
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos(\varphi - \Psi_2) + \ ...)$$

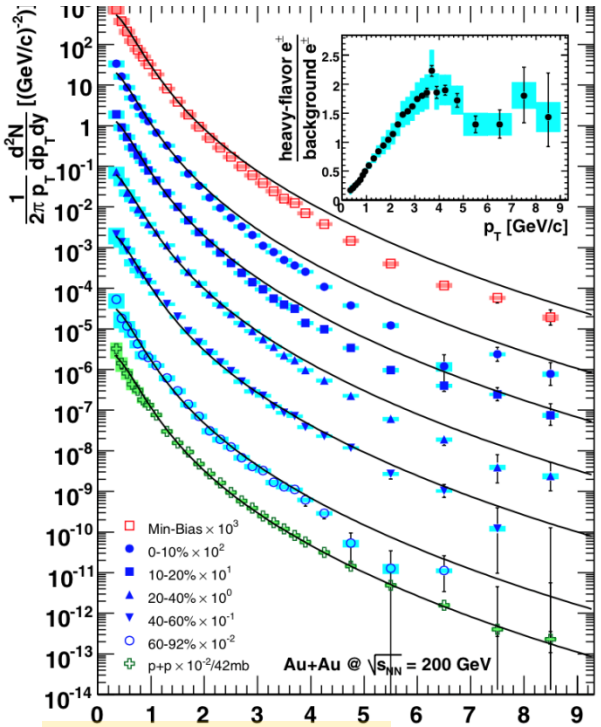
  - heavy quarks participate in collectivity of the medium in case of sufficient re-scattering → approach to thermalization
  - high p_T: path-length dependence of energy loss → azimuthal asymmetry

- various methods are available to evaluate v_2
  - event plane
  - 2-particle cumulants (QC, SP methods), 4-particle cumulants …
  - Lee-Yang zeros

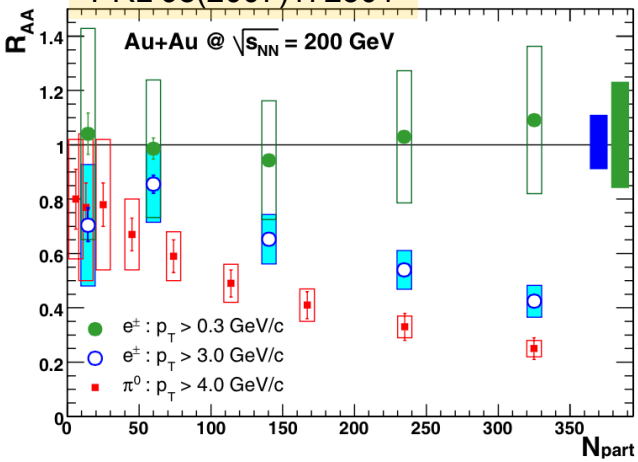
Electrons at RHIC

- 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



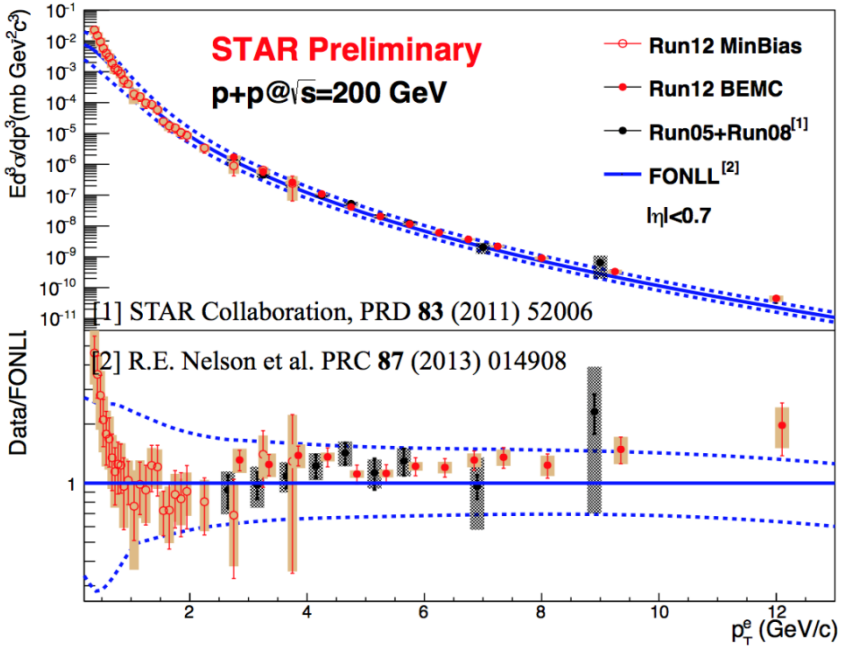


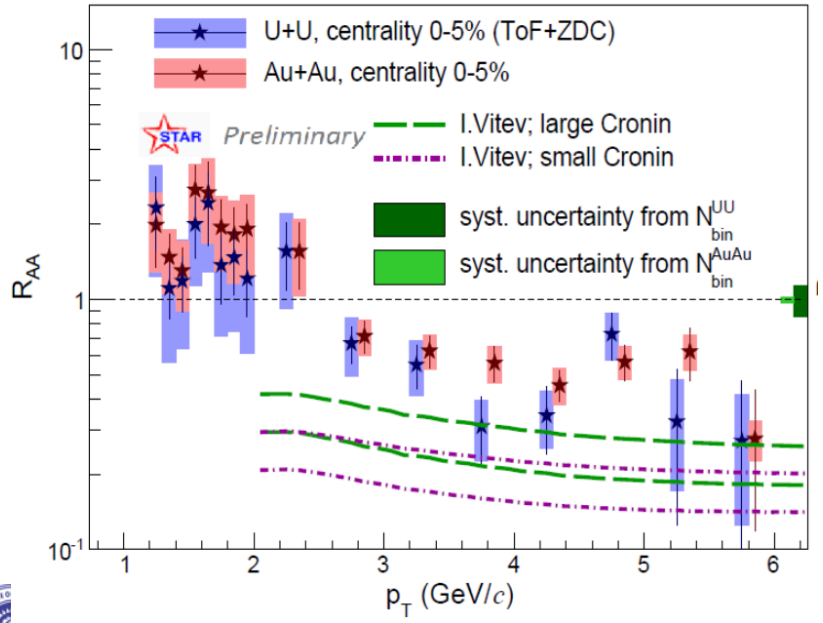
PRL 98(2007)172301



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

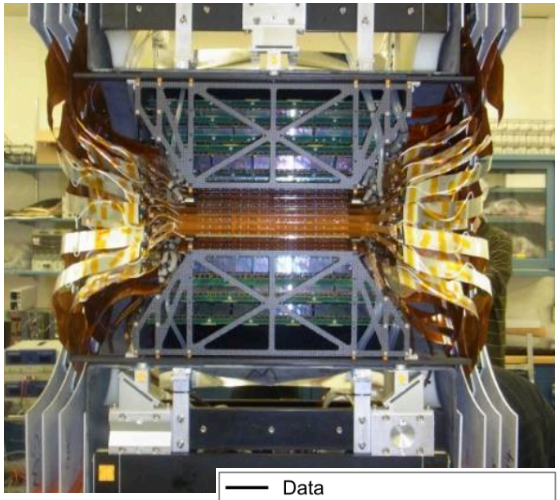


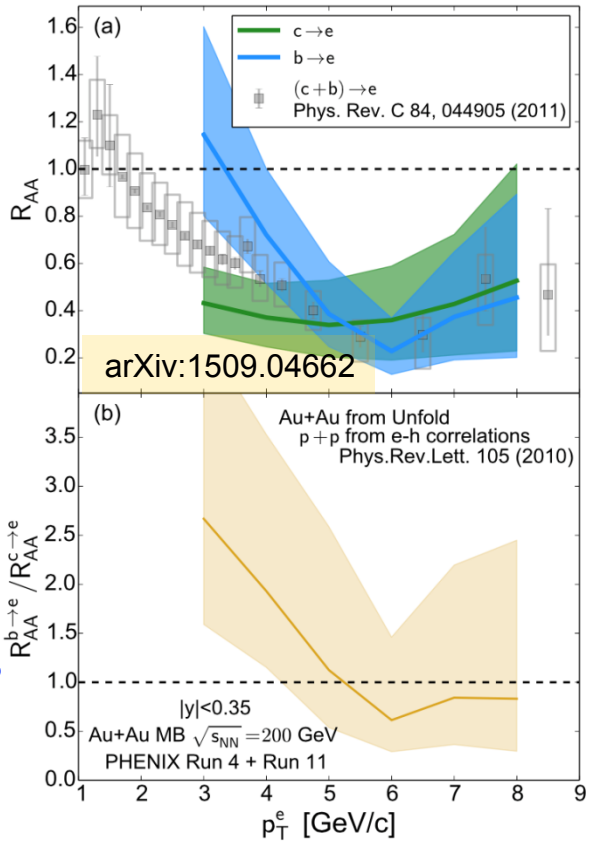


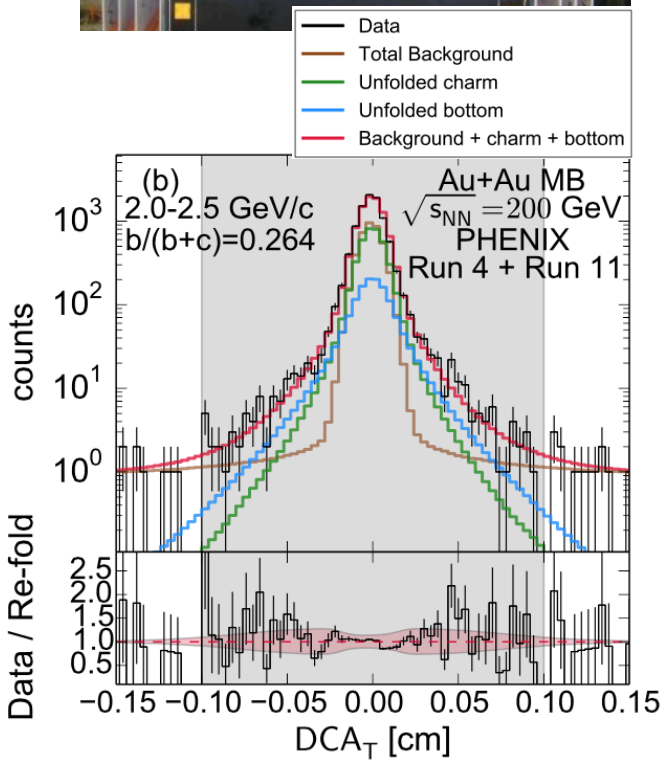
- R_{AA} for electrons from HF decays in 5% most central collisions systematically lower than for Au-Au collisions, but still within uncertainties

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

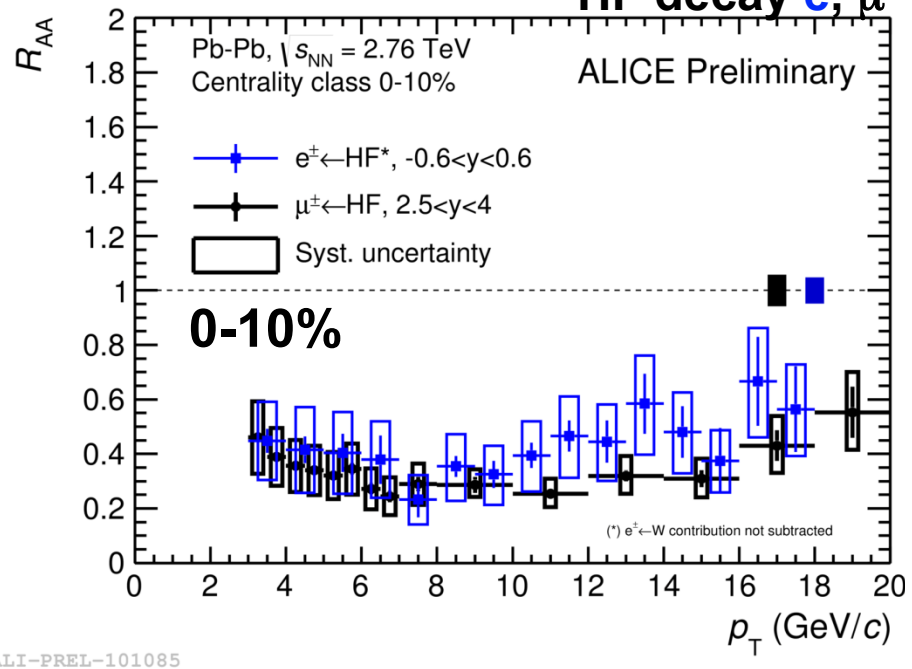




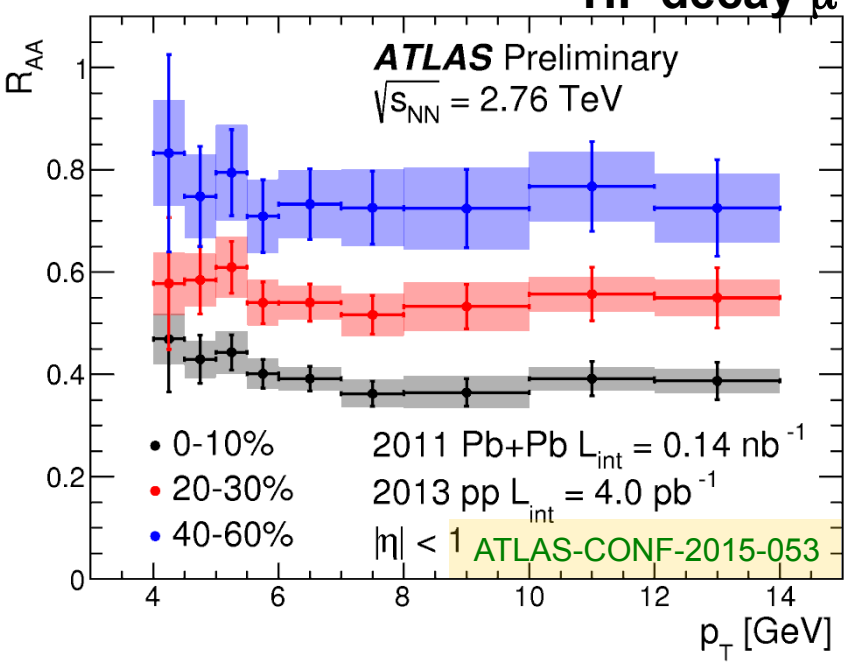


HF decay leptons at the LHC: R_{AA}

HF decay e, μ

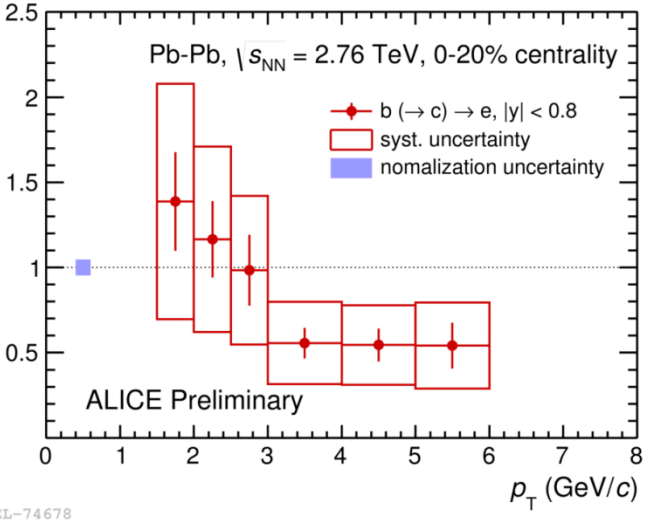


HF decay μ



ALI-PREL-101085

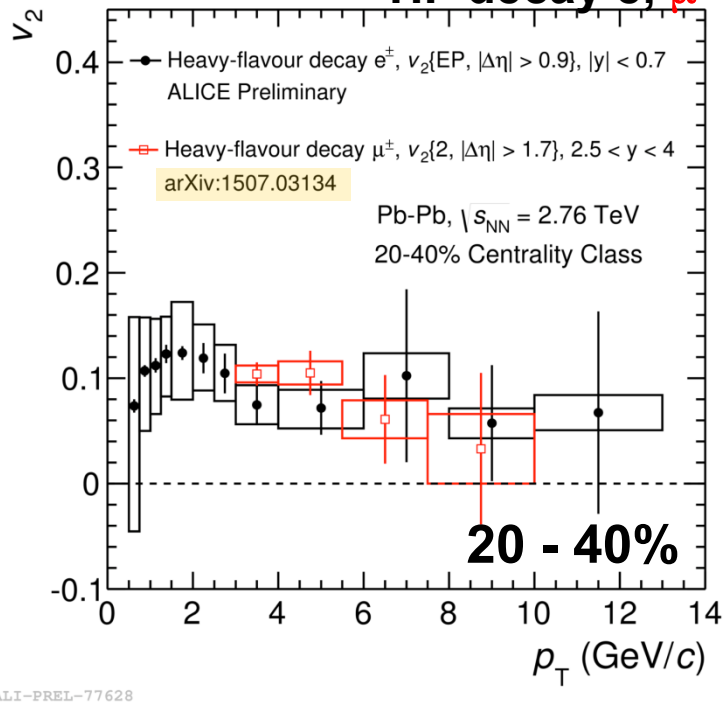
- high-p_T leptons from HF decays suppressed
  - similar for HF decay electrons ($|y| < 0.6$) and muons ($2.5 < y < 4$, $|y| < 1$)
  - pronounced centrality dependence
  - also: hint for suppression of electrons from beauty decays
- cold nuclear matter effects small at high p_T
  → hot/dense medium effect



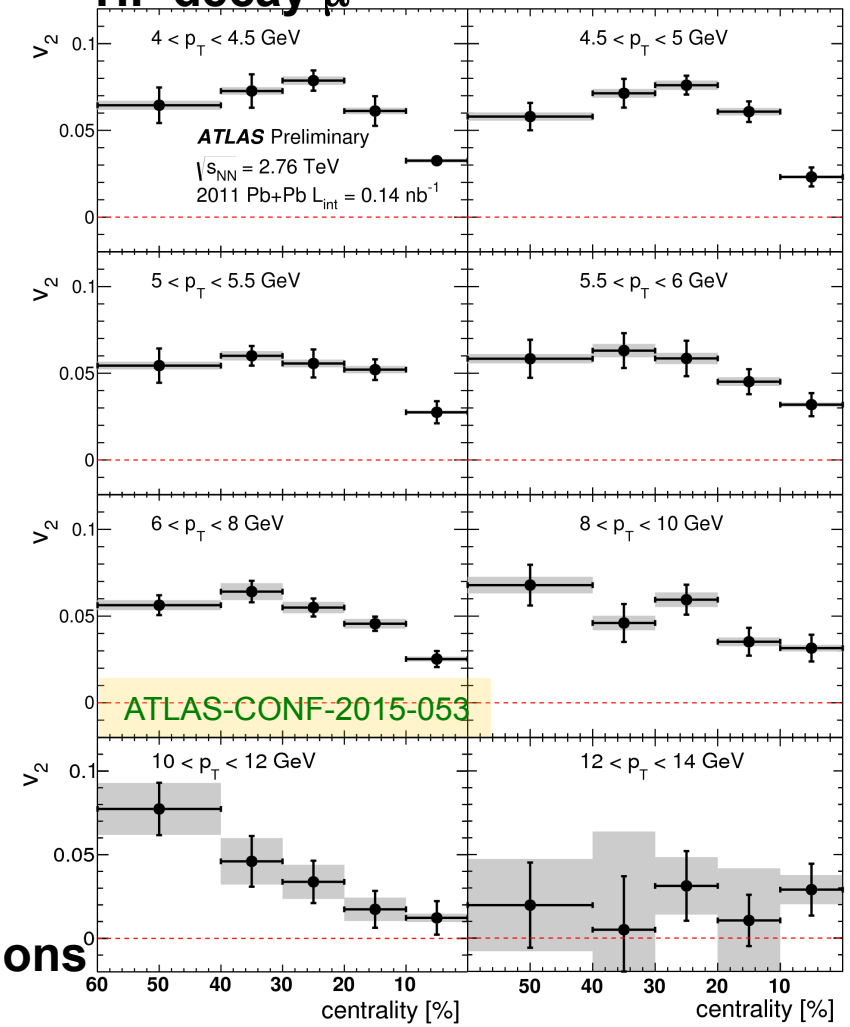
ALI-PREL-74678

HF decay leptons at the LHC: v_2

HF decay e, μ



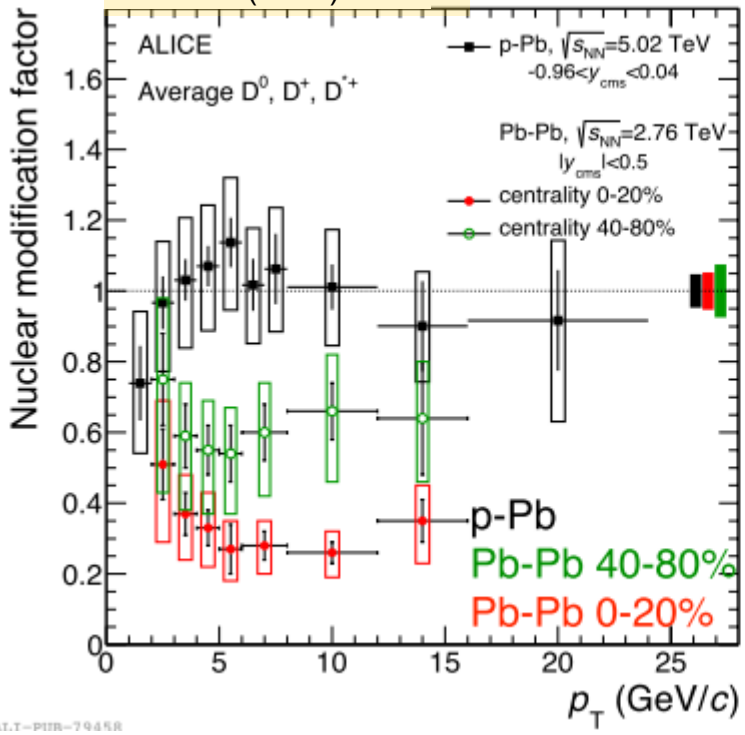
HF decay μ

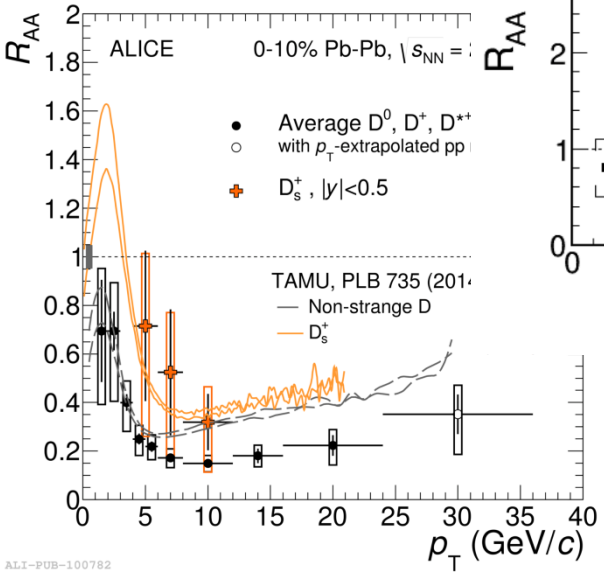


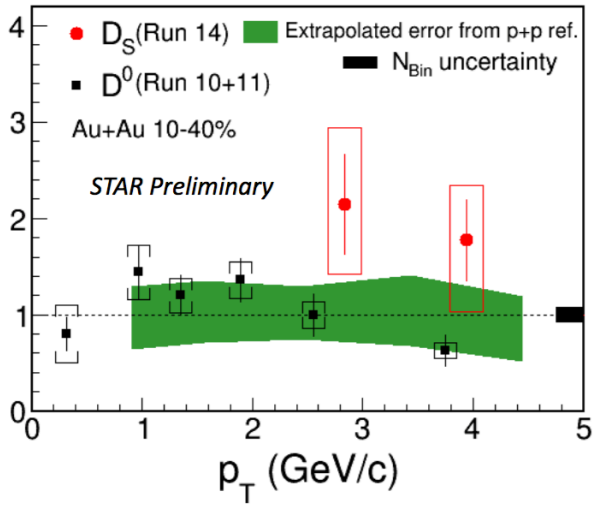
- $v_2 > 0$ at intermediate/high p_T
  - similar for e± and μ± at mid rapidity and muons at forward rapidity
  - v_2 decreases towards central collisions
  - confirms strong interaction of heavy quarks with the medium
  - low-p_T charm quarks participate in the collectivity of the QGP

D-meson suppression

PRL 113(2014)232301







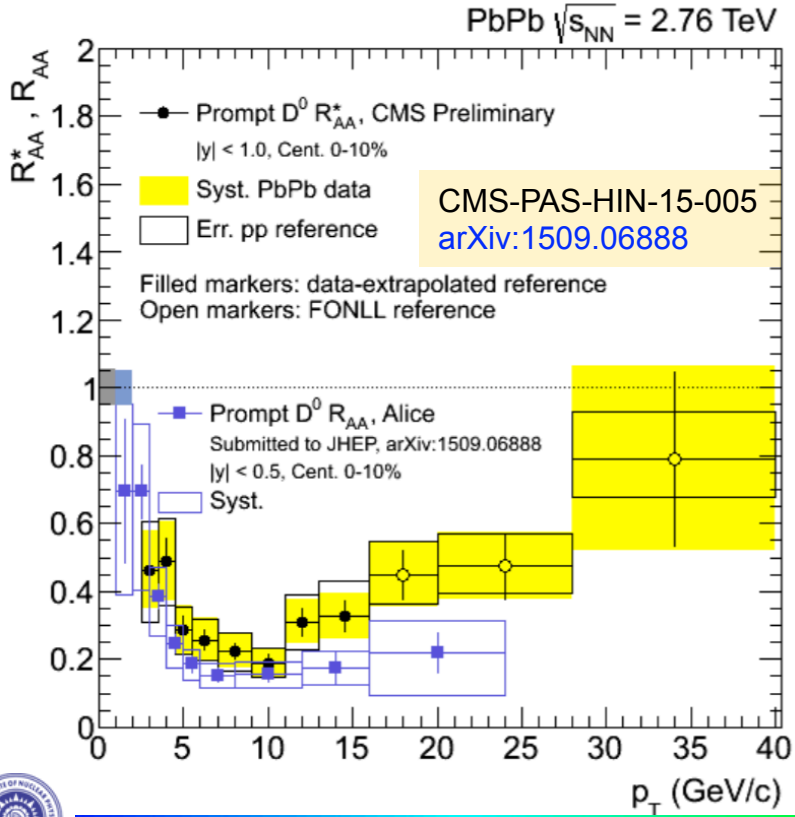
Kuznetsova, Rafelski EPJ C 51 (2007) 113
He et al. PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149

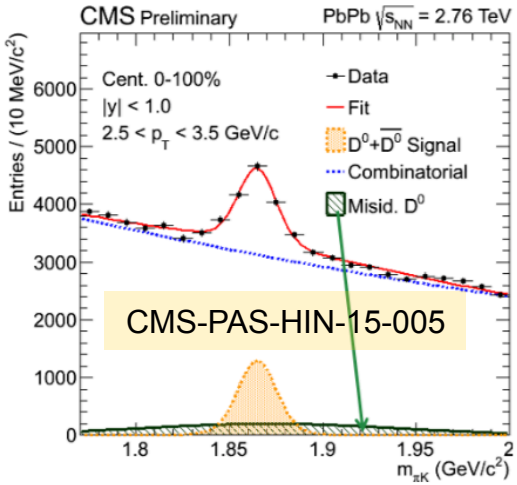
- observed suppression in central Pb-Pb collisions at the LHC is due to the strong interaction of charm quarks with the dense/hot partonic medium
- hint for less suppression of D_s^+ compared to non-strange D mesons at LHC/RHIC
  - expected if recombination plays a role in charm hadronization

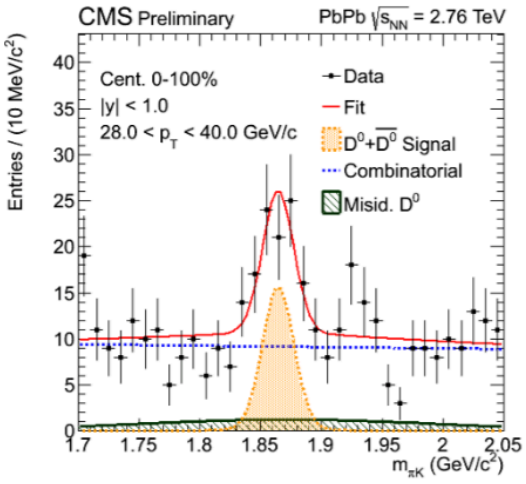
TAMU: He et al.: PRL 110(2013)112301; Kuznetsova, Rafelski: EPJ C51(2007)113; Andronic et al.: PL B659(2008)149

D^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



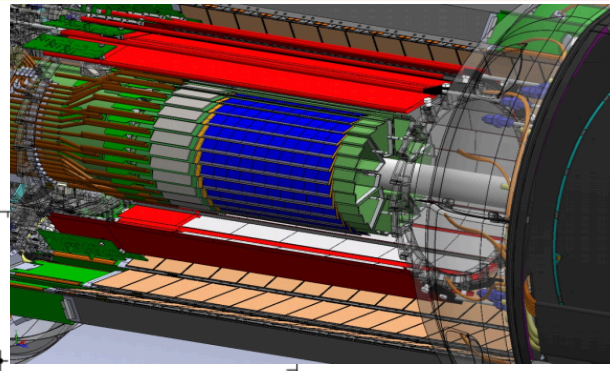


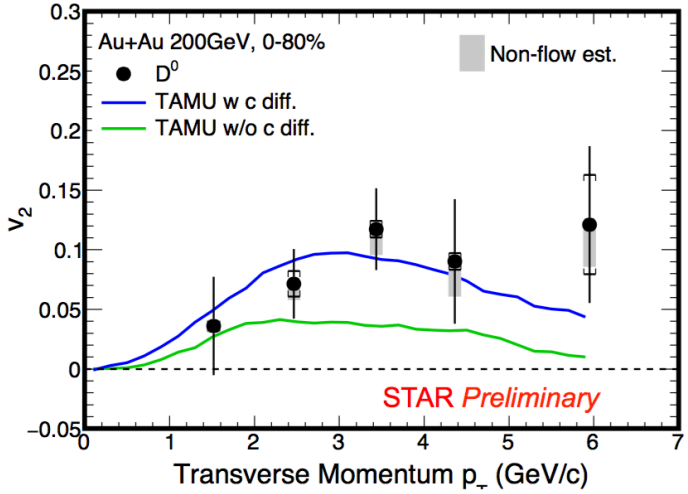


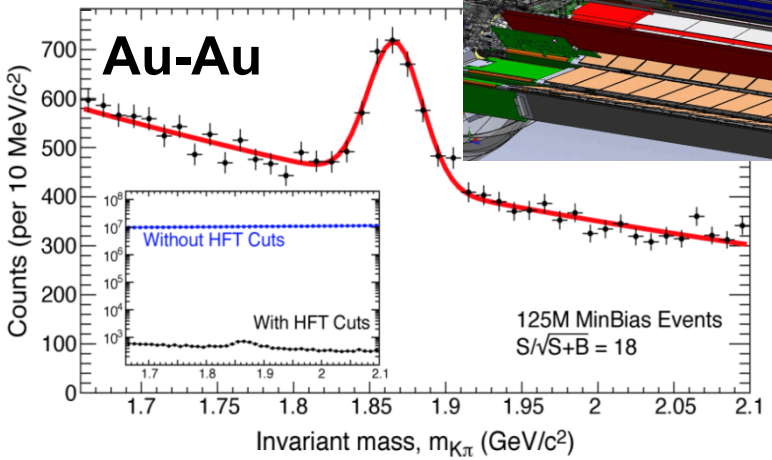
- R_{AA} shows suppression in central Pb-Pb collisions relative to data/FONLL based reference
  - significant interaction of charm quarks with the medium
  - pronounced centrality dependence
  - tension with ALICE D-meson R_{AA} for $p_T > 16$ GeV/c
    → different reference

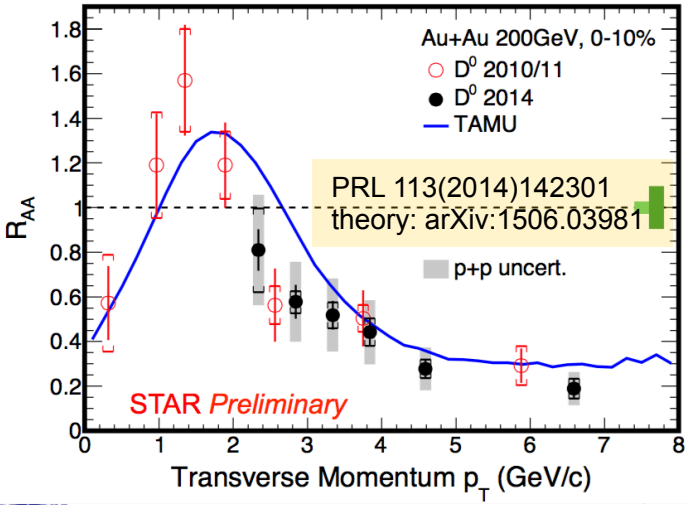
D-meson R_{AA} and v_2 at RHIC

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







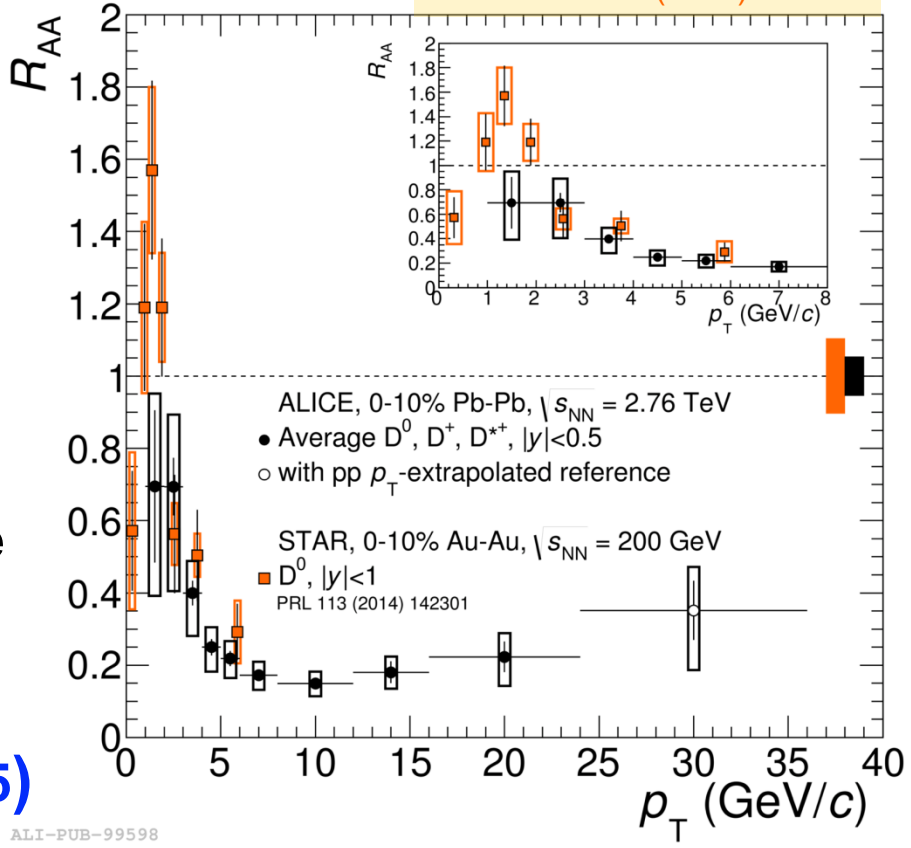


- D^0 mesons in Au-Au at 200 GeV
  - $v_2 > 0$ for $p_T > 2$ GeV/c
  - yield suppressed at high p_T
  - enhancement at $1 < p_T < 2$ GeV/c (charm coalescence with flowing medium)
  - R_{AA} and v_2 model comparisons constrain charm diffusion coefficient

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

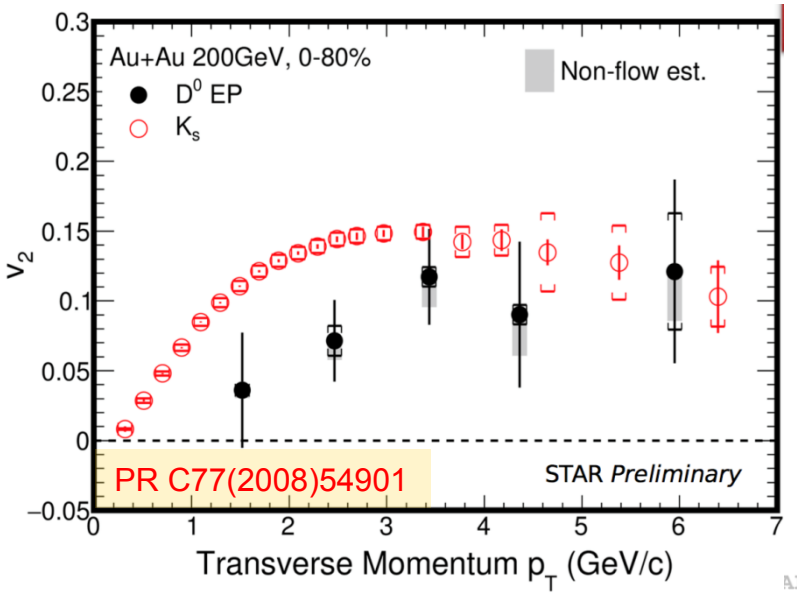
- D mesons at the LHC and at RHIC
  - different trend for D-meson R_{AA} at low p_T?
- differences between
  Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  and
  Au-Au collisions at $\sqrt{s_{NN}}$ = 0.2 TeV
  - different shape of pp reference
  - different modification of nPDFs
  - different radial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

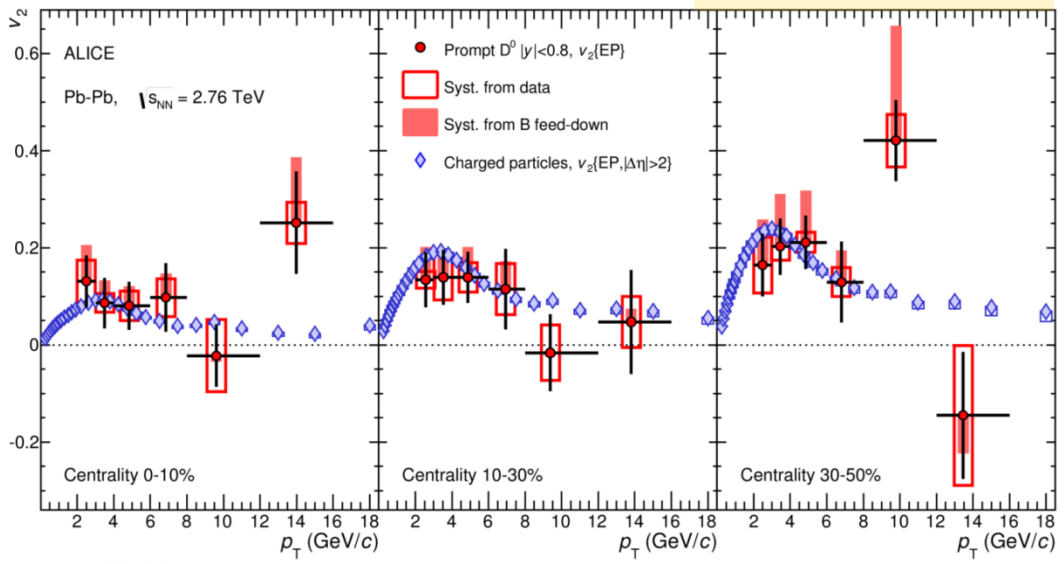
ALICE: arXiv:1509.06888
STAR: PRL 113(2014)142301



D-meson v_2: RHIC vs. LHC

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



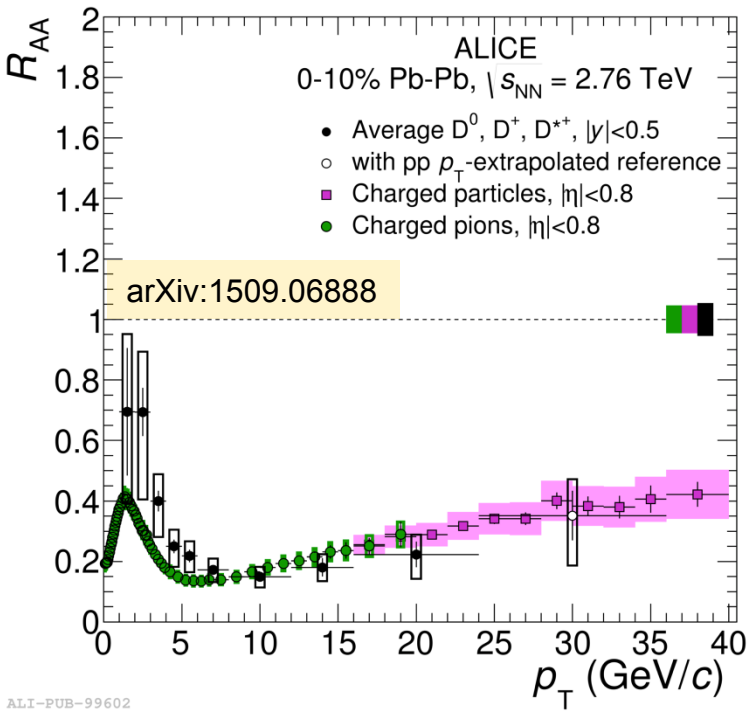


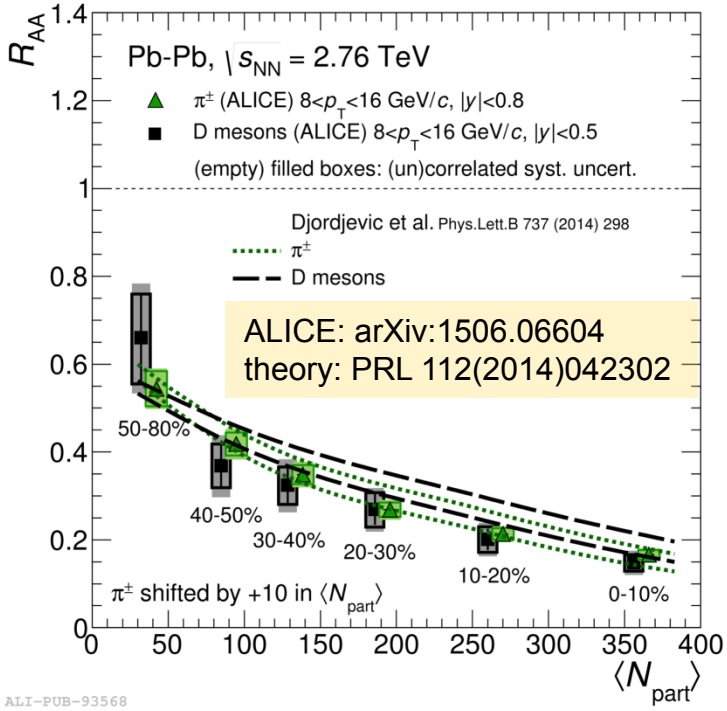
- RHIC: D^0 v_2 < light-hadron v_2 for p_T < 3 GeV/c
- D-meson v_2 measured by ALICE at the LHC
  - D-meson v2 > 0 and similar to charged-particle v_2
  - hint for increasing v_2 with decreasing centrality
- significant interaction of charm quarks with the medium

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

R_{AA}: D-mesons vs. π

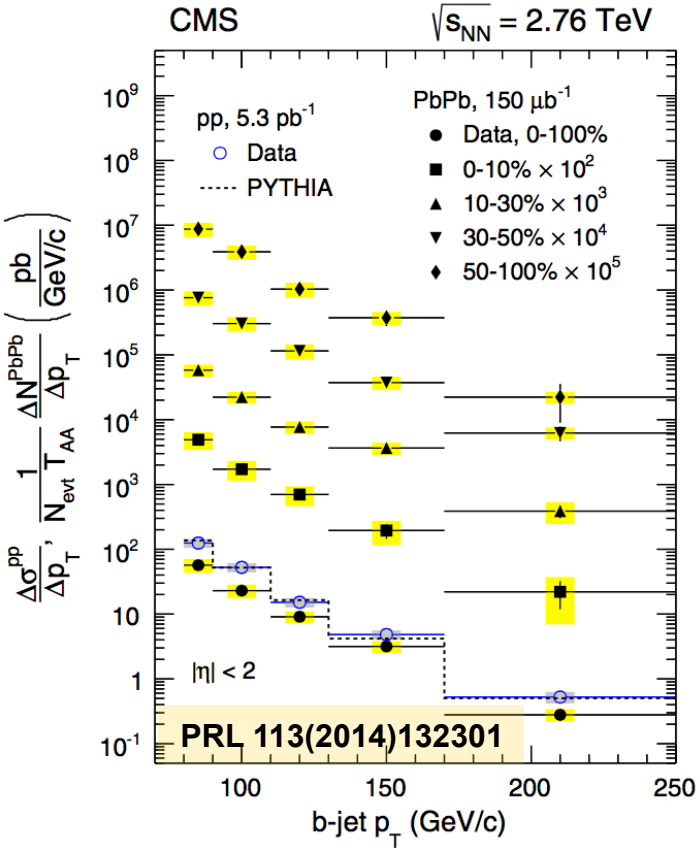
naively: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b) \rightarrow R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$

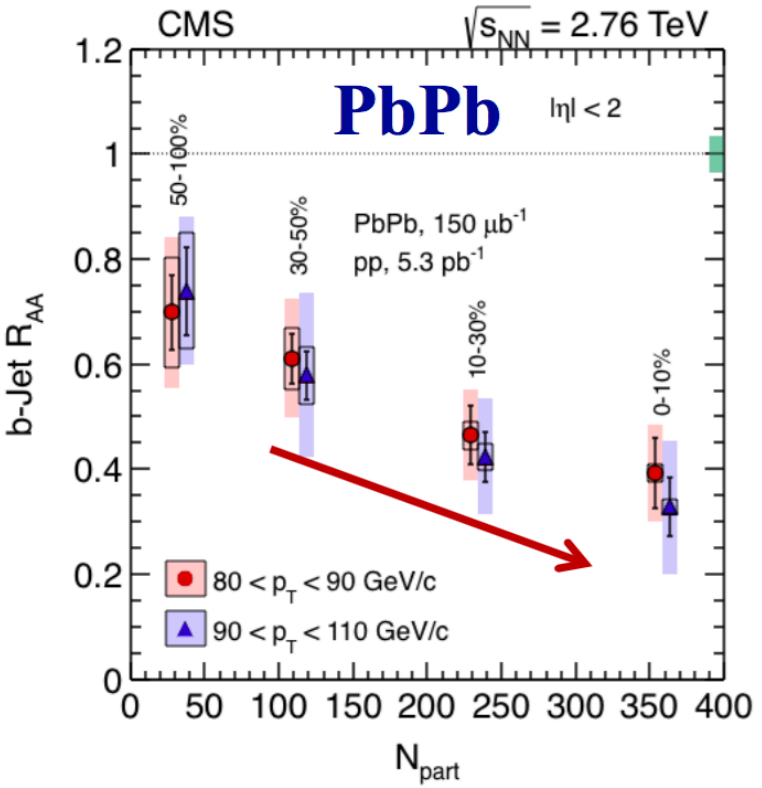




- D-meson and π R_{AA} are compatible within uncertainties
- agreement consistent with models including
  - energy loss hierarchy: $\Delta E(g) > \Delta E(u,d,s) > \Delta E(c)$
  - different shapes of the parton p_T distributions
  - different fragmentation functions

B-jet suppression at the LHC

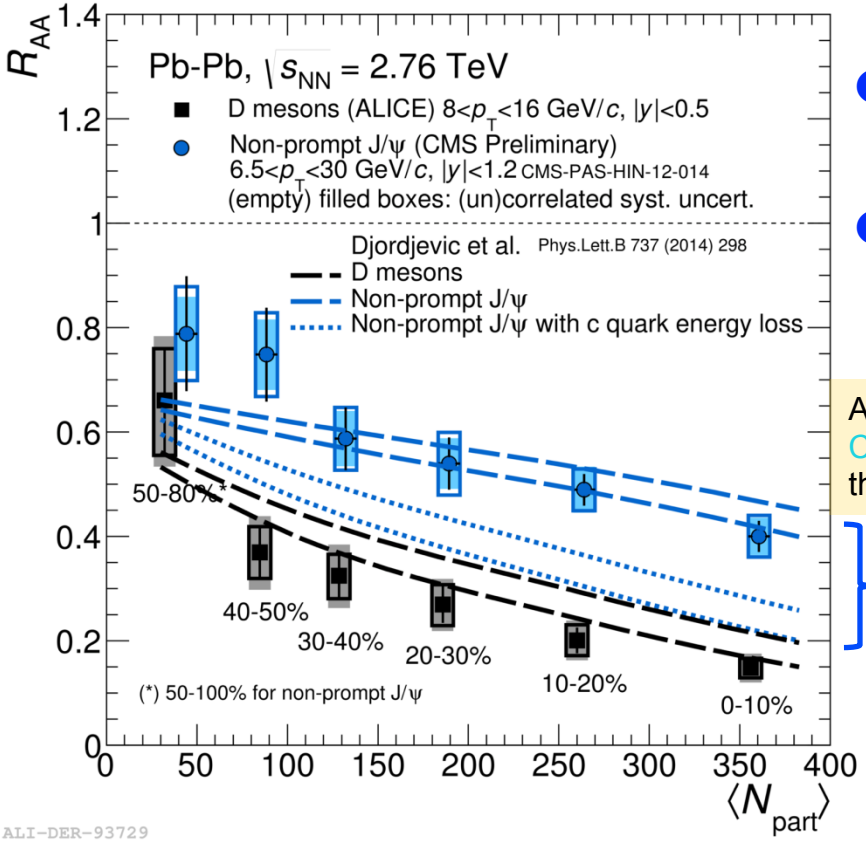




- fully reconstructed b jets in Pb-Pb collisions at 2.76 TeV
  - suppressed compared to measured pp reference
  - qualitatively consistent with light-flavor jet suppression
  - b-jet suppression shows strong centrality dependence

R_{AA}: D mesons vs. non-prompt J/ψ

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



- indication for $R_{AA}(D) < R_{AA}(J/\psi \leftarrow B)$ in central Pb-Pb collisions
- similar $\langle p_T \rangle$ for D and B mesons (~10 GeV/c) but slightly different rapidity range

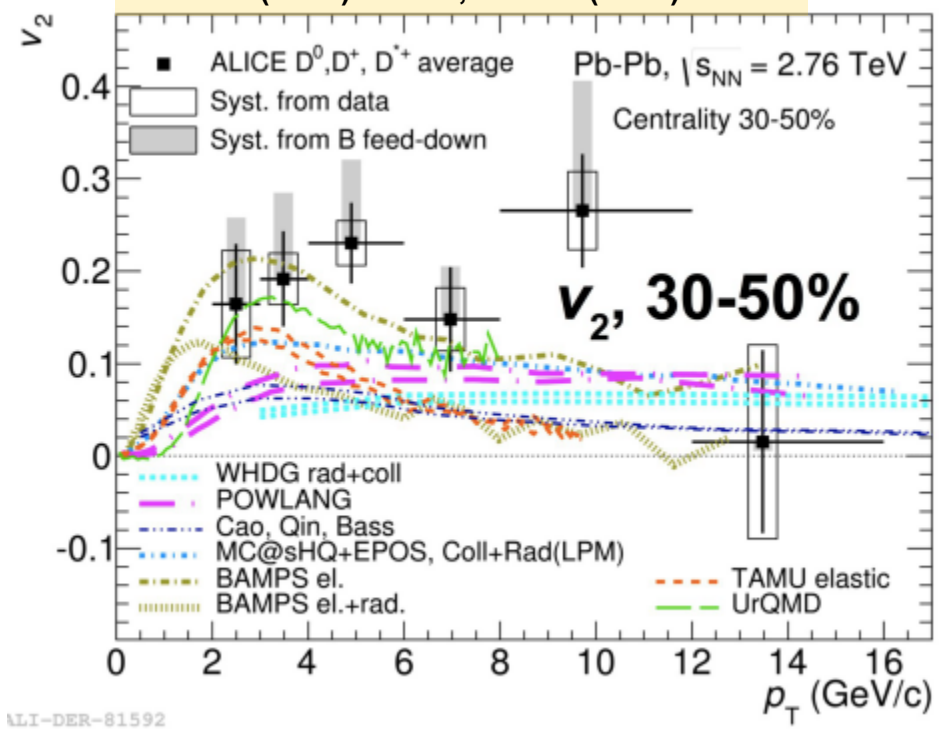
ALICE: arXiv:1506.06604
CMS: CMS-PAS-HIN-12-014
theory: PL B734(2014)286

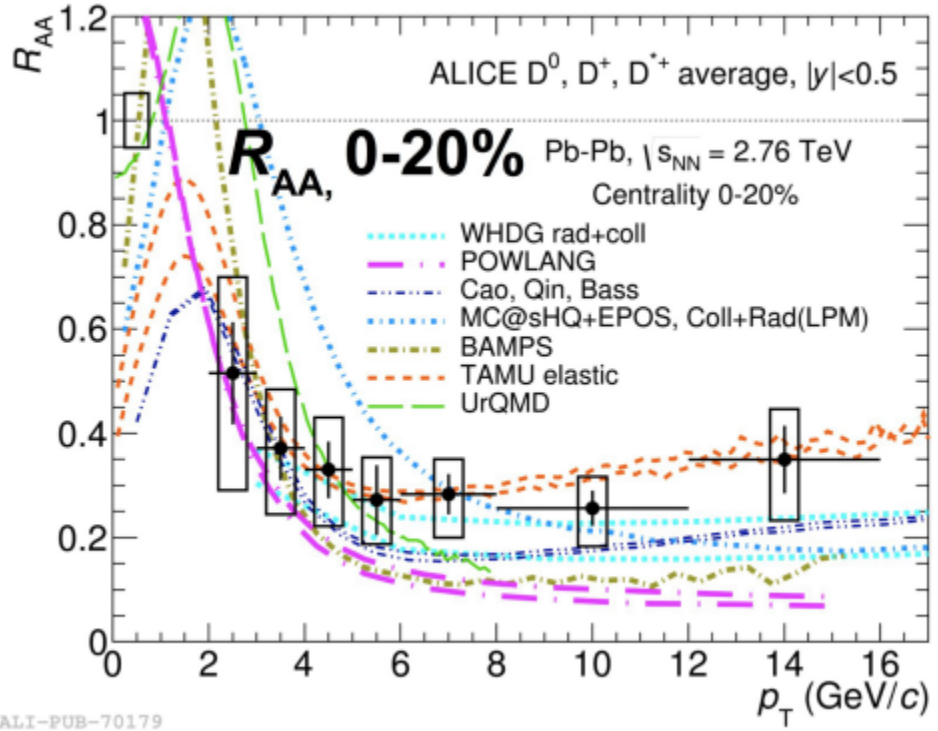
consequence of mass difference of c and b quarks in pQCD based model calculation (Djordjevic, PLB 734(2014)286)

- 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.)

D-meson R_{AA} and v_2 vs. models

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





→ simultaneous reproduction of R_{AA} and v_2 challenging for models

→ task for us: reduction of stat. and sys. uncertainties of data

● $e^{\pm}$ and $\mu^{\pm}$ from heavy-flavor decays: similar situation

WHDG: Nucl. Phys. A 872 (2011) 265; MC@sHQ+EPOS, Coll+Rad(LPM): Phys. Rec. C89 (2004) 014905; TAMU elastic: arXiv:1401.3817 [nucl-th]; POWLANG: Eur. Phys. J. C71 (201) 1666, J.Phys. G 38 (2011) 124144; BAMPS: Phys. Rev. C 84 (2011) 024908; J. Phys. G38 (2011) 124152 Phys. Lett. B 717 (2012) 430;arXiv:1310.3597v1[hep-ph] ; UrQMD: arXiv:1211.6912[hep-ph]; J. Phys.Conf. Ser. 426 (2013) 012032; Cao, Qin, Bass: Phys. Rev. C 88 (2013) 044907

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 ….