Heavy-flavour productions in the relativistic heavy ion collisions

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Heavy Flavour (HF) in pp, p-Pb & Pb-Pb

- Heavy-flavour (charm & beauty) production
  - Initial hard scatterings ($M_{HF} >> \Lambda_{QCD}$)
    - Flavour creation, flavour excitation, gluon splitting
- pp collisions
  - Test for perturbative QCD (pQCD)
  - Reference for heavy ion collisions (both experiment & theory)
- Heavy ion collisions
  - Created in initial parton-parton scatterings
  - Traverse and interact with the hot & dense QCD matter
    - A good probe to study properties of the QCD matter
    - Energy loss (R_{AA}), collectivity (v_2), hadronization
- pA collisions
  - Control measurement for heavy ion collisions to disentangle initial from final state effects
    - Cold nuclear matter effect on heavy-flavour production

Energy Loss of heavy flavours

- In-medium parton energy loss
  - Radiative energy loss (PLB 632, 81)
    - gluon bremsstrahlung
    - smaller energy loss for heavy than for light quarks due to “dead cone” effect (PLB 519 (2001) 199.)
    - energy loss depends on the colour charge and is larger for gluons than for quarks
  - Collisional energy loss (PLB 649, 139)
    - energy loss via elastic scattering
- Theoretical predictions:
  - mass & colour charge dependence of energy loss
  - $E_{loss}(g) > E_{loss}(u,d,s) > E_{loss}(c) > E_{loss}(b)$

$$\boxed{R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B} \quad ?}$$

Nuclear modification factor

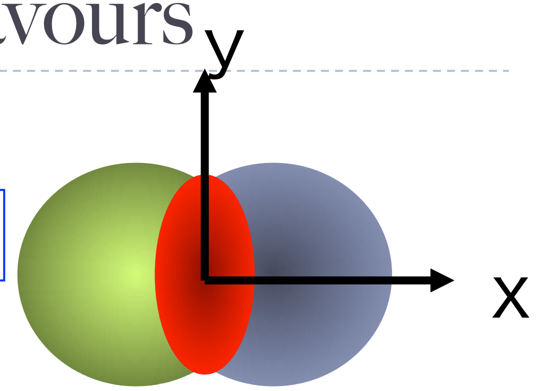
$$R_{AA}(p_T) = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

Azimuthal anisotropy of Heavy flavours

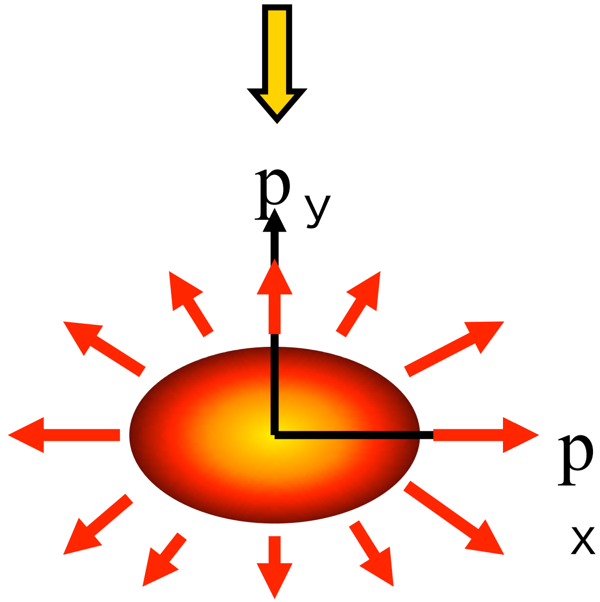
- **Elliptic flow**

$$dN/d(\varphi-\psi_{RP}) = \ldots + N_0(1+2v_2\cos(2(\varphi-\psi_{RP}))) + \ldots$$

- Transfer initial spatial anisotropy to momentum anisotropy
  - macroscopic: hydro model
    => pressure gradient
  - microscopic
    => scattering in the medium
- Low p_T
  - coupling of heavy quarks with the medium and their thermalization
- Intermediate p_T
  - Hadronization mechanism (recombination)
- High p_T
  - Path-length dependence of energy loss



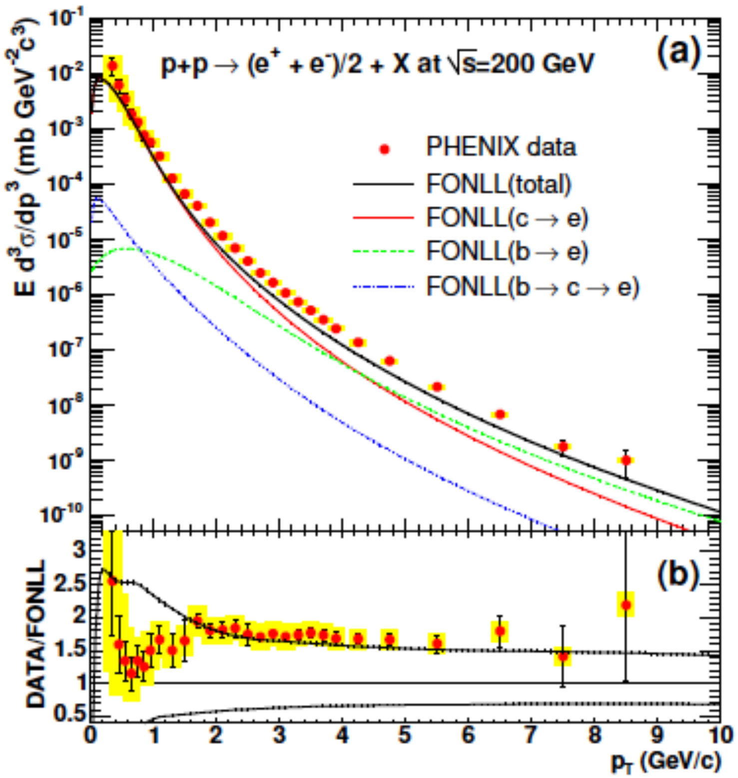
Initial spatial anisotropy

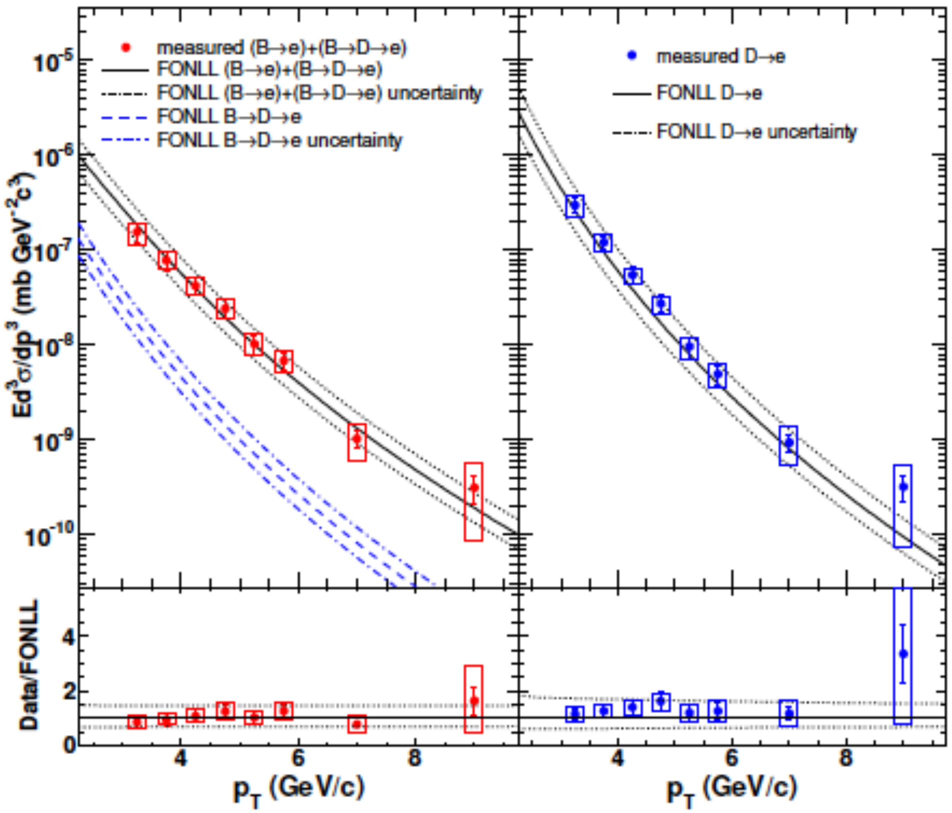


Momentum space anisotropy of particle emission

Heavy-flavour results in pp collisions

HF production in pp collisions at RHIC

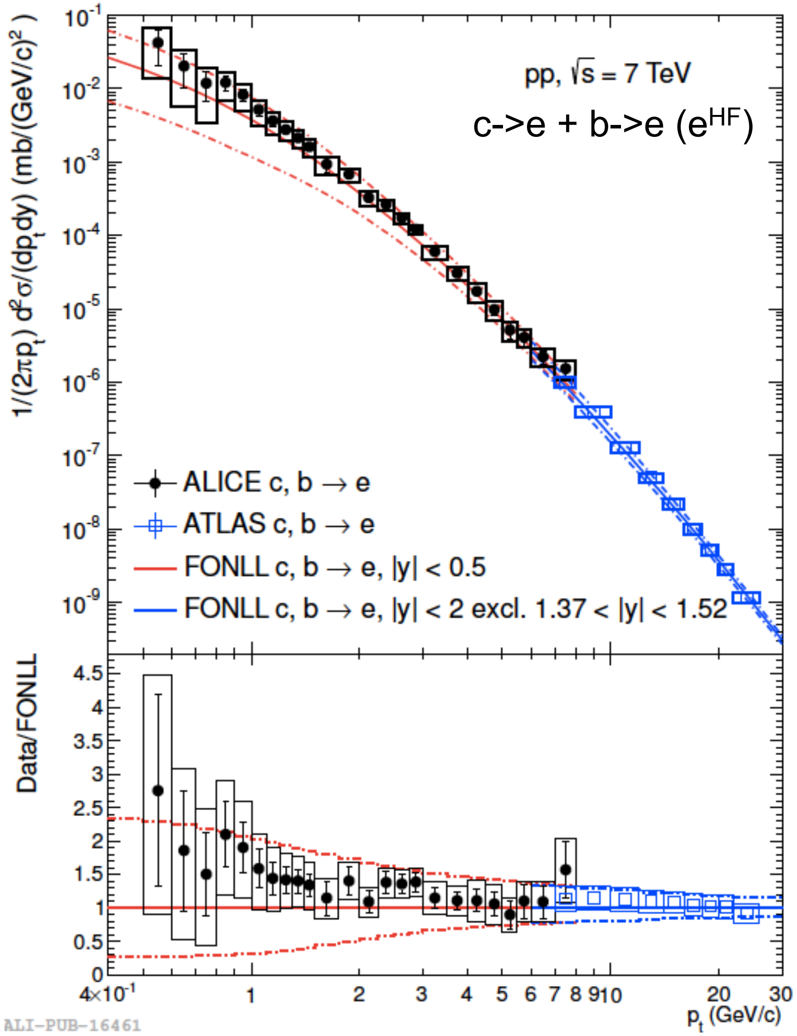




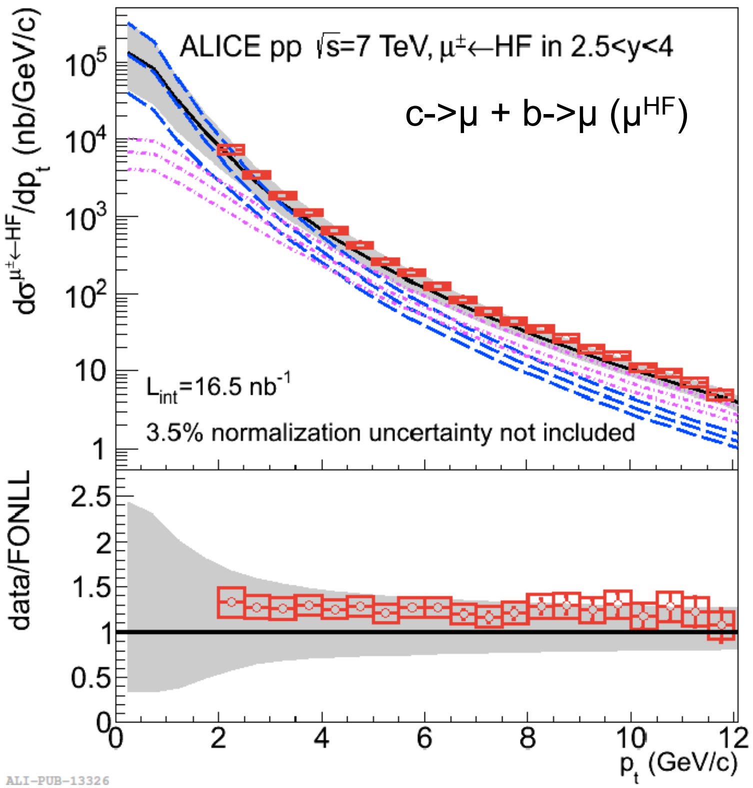
- Charm and beauty production via electrons are in good agreement with FONLL calculation

HF production in pp collisions at LHC

Phys. Rev. D 86, 112007



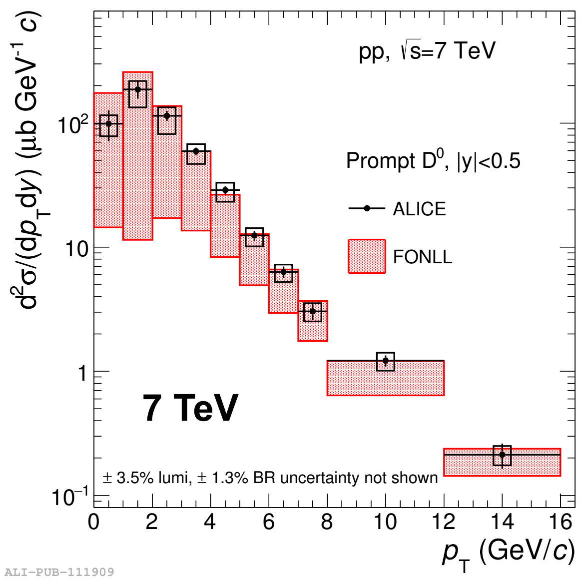
Phys. Lett. B 708(2012) 265



- Productions of leptons (e,μ) from charm + beauty decays in different rapidity ranges are well described by pQCD calculations

Charm production in pp collisions at LHC

JHEP 1201 (2012) 128



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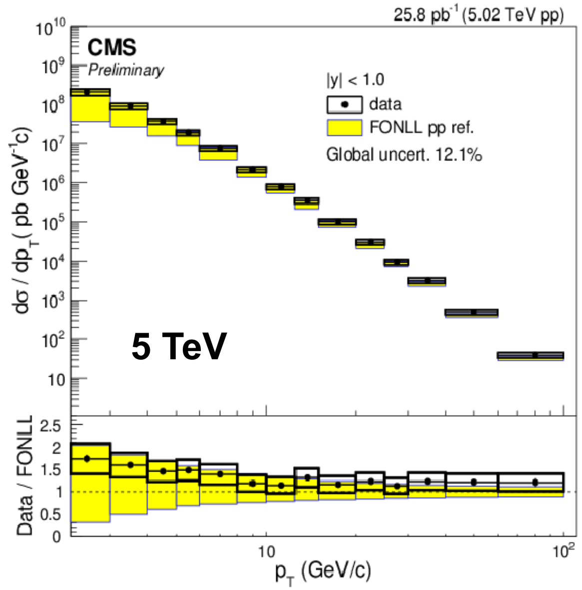
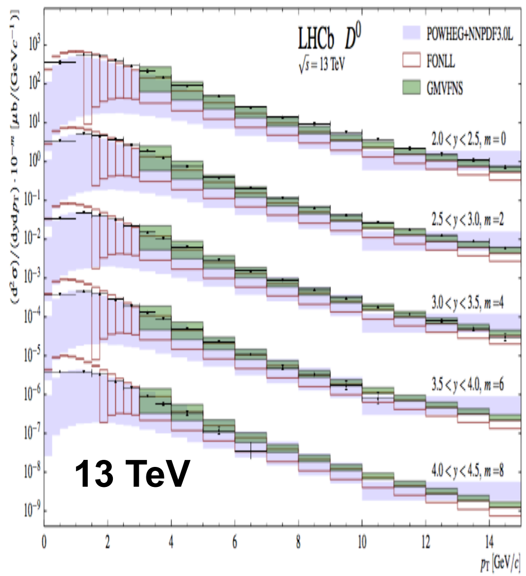
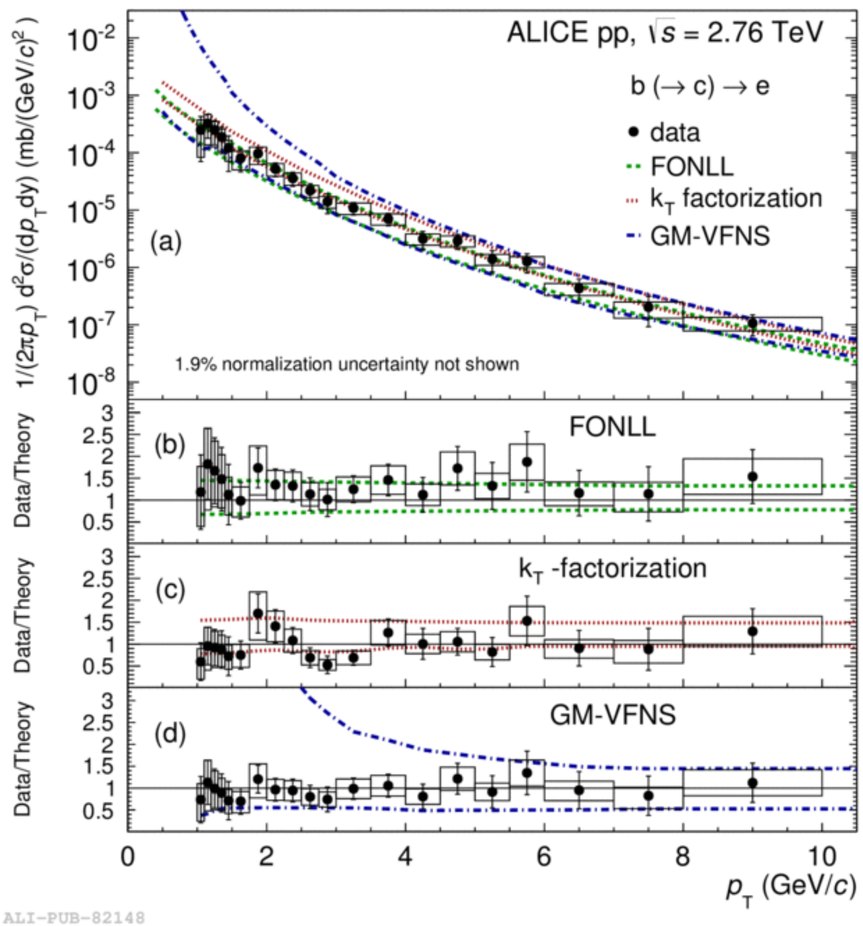


JHEP1603(2016)159

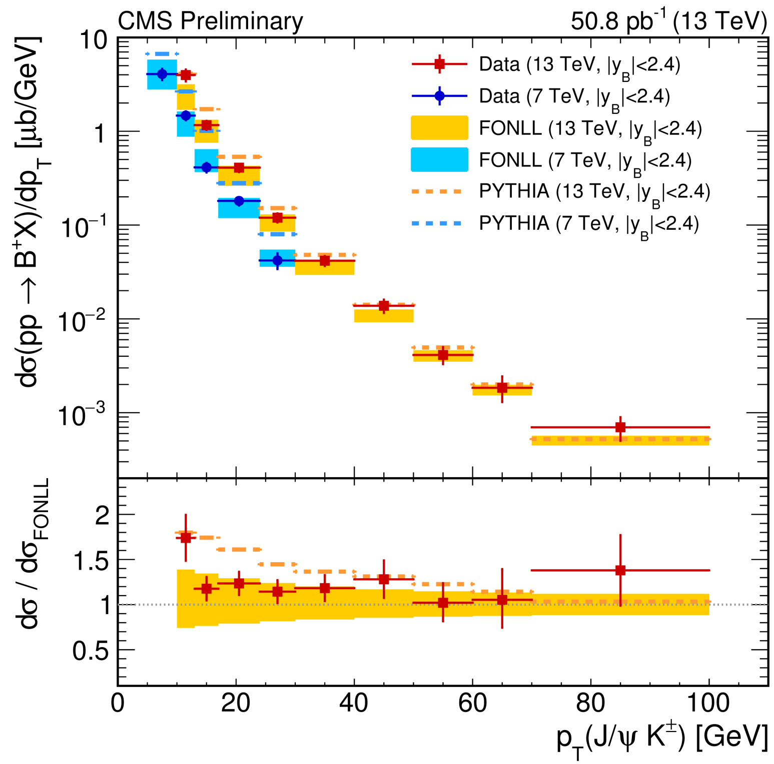


- D meson production mid- and forward-rapidity is in good agreement with pQCD calculations
  - upper side of the FONLL uncertainty band
  - various energies: 5.02, 7 and 13 TeV
  - from p_T = 0 to 100 GeV/c

Beauty production in pp collisions at LHC



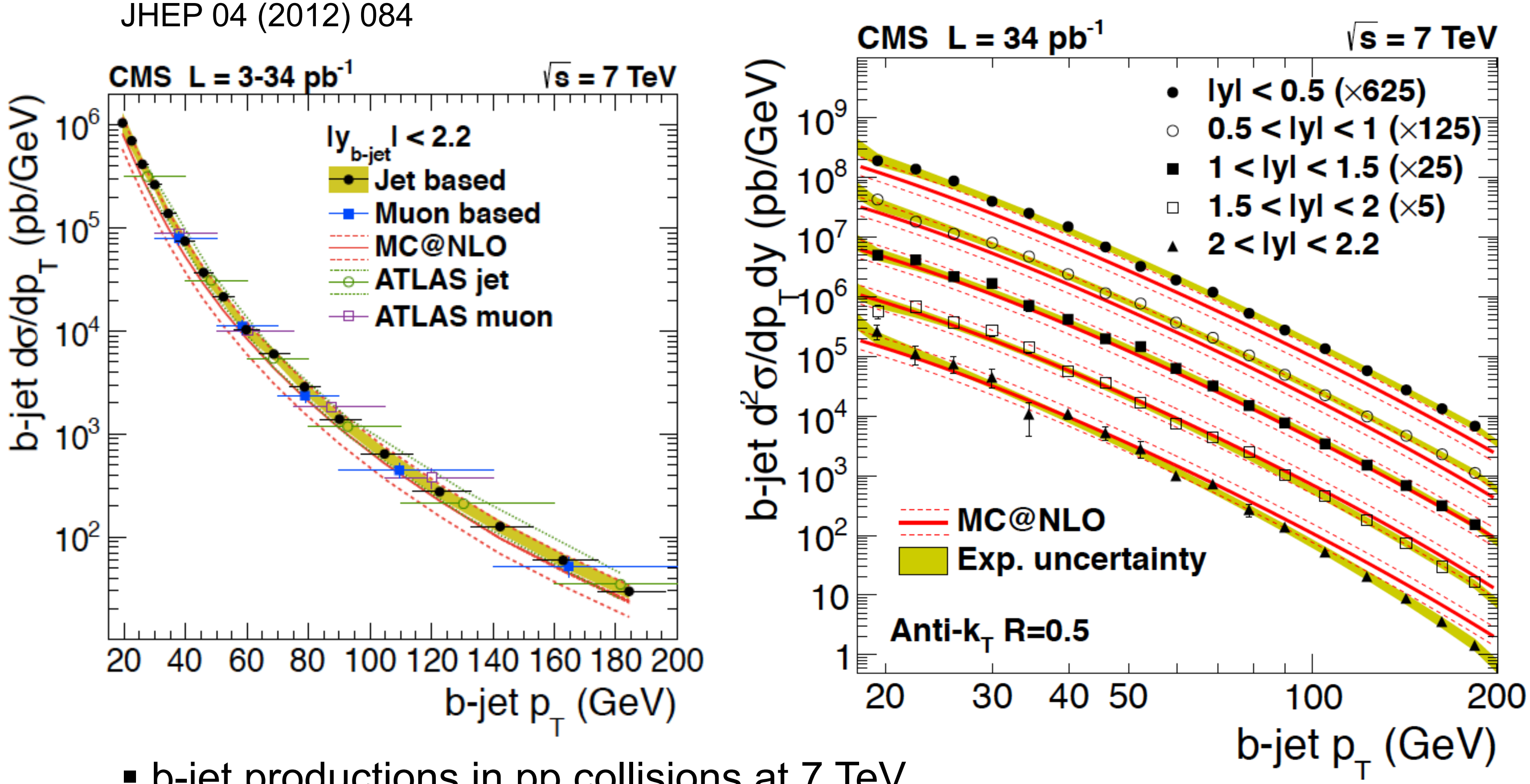
CMS-DP-2016-016



- B meson production is in good agreement with pQCD calculations

Beauty jets production in pp collisions at LHC (2)

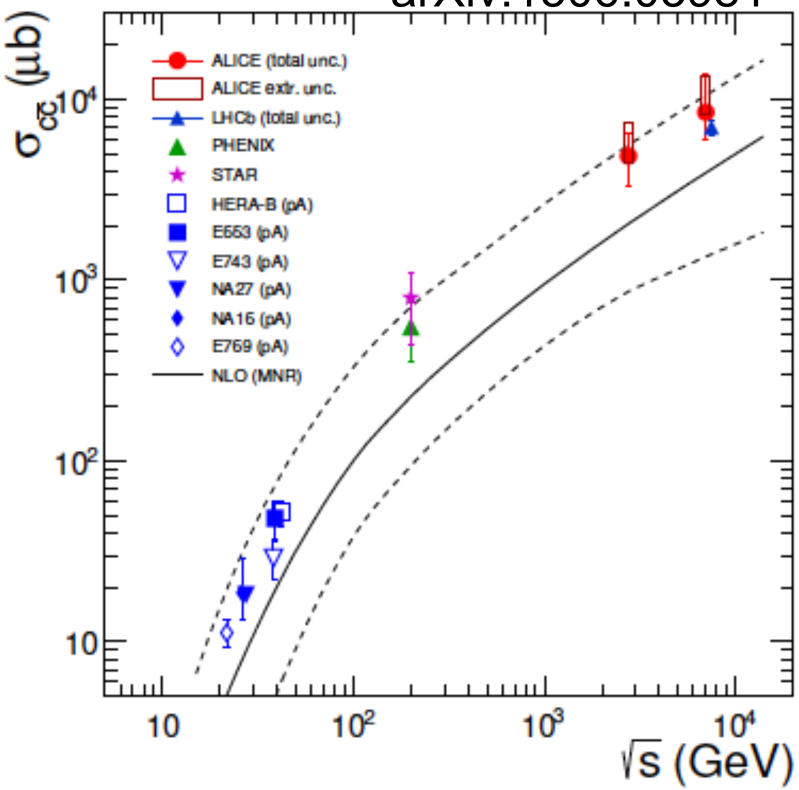
JHEP 04 (2012) 084



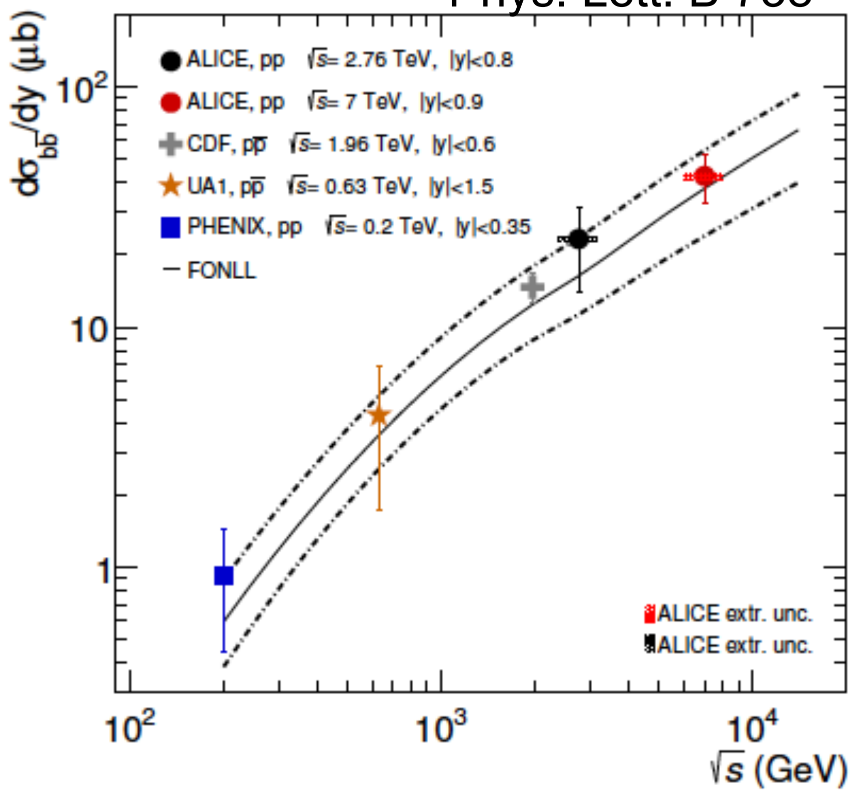
- b-jet productions in pp collisions at 7 TeV
  - production is well described with MC@NLO in large rapidity regions

Total c-cbar & b-bbar cross section in pp

arXiv:1506.03981



Phys. Lett. B 738



- Cross section of charm and beauty are in good agreement with pQCD
- Beam energy dependence is consistent with pQCD (NLO, FONLL)

Heavy-flavour results in pA collisions

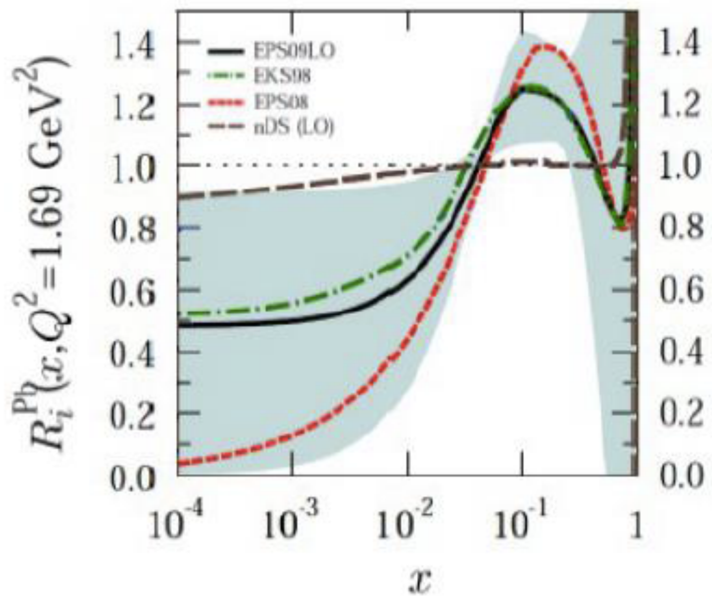
p-A collisions

- Heavy-flavour in p-A collisions
  - control measurement for heavy-ion collisions to disentangle initial (cold nuclear matter effects) from final state effects
- Cold nuclear matter effects
  - nuclear modification of Parton distribution Functions (PDF): shadowing or gluon saturation

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

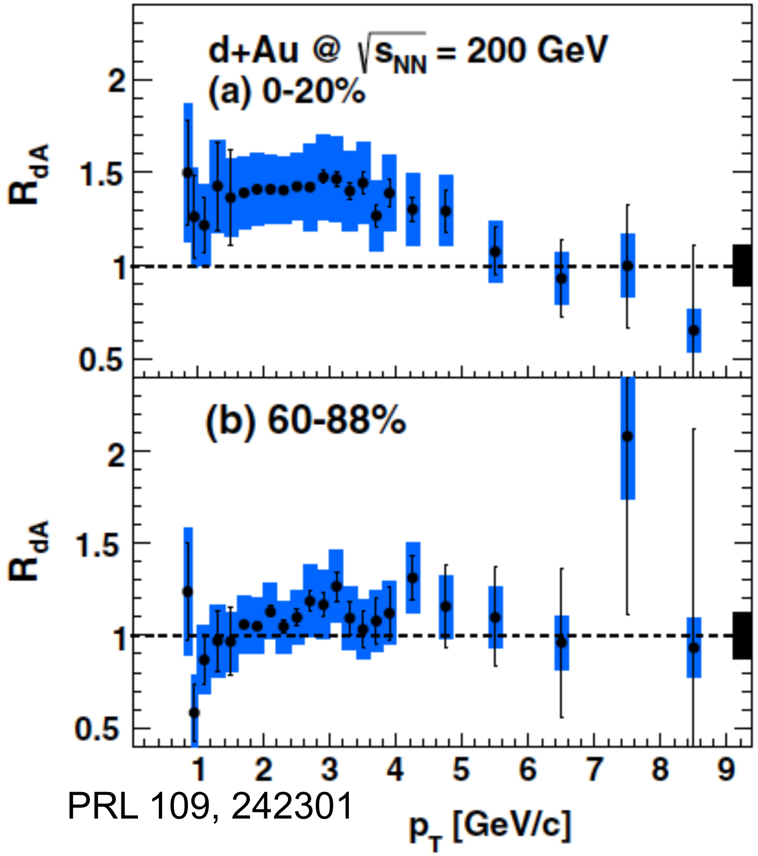
    H. Fuji & K. Watanabe, NPA 915 (2013) 1
  - energy loss I. Vitev et al., PRC 75(2007) 064906
  - k_T broadening (Cronin enhancement)
  - multiple collisions

    A.M. Glenn et al., PLB 644(2007)119

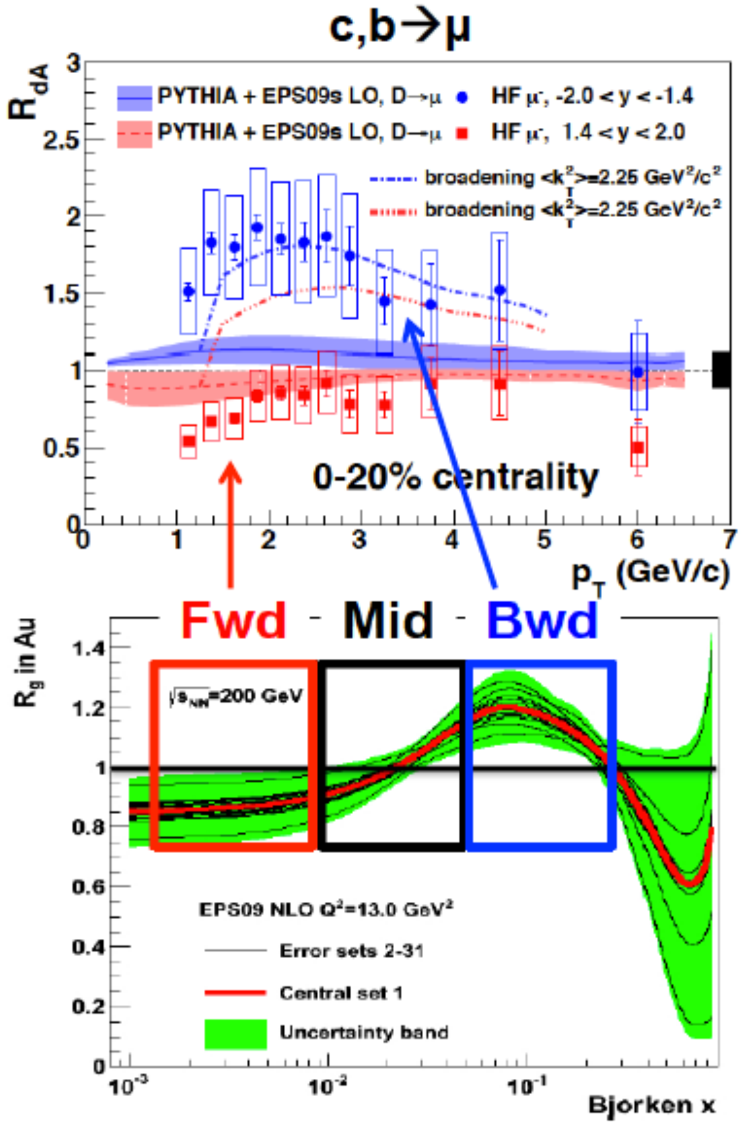


$$R_{pPb}(p_T) = \frac{dN_{pPb}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

R_{dA} of e^{HF} & μ^{HF} at RHIC



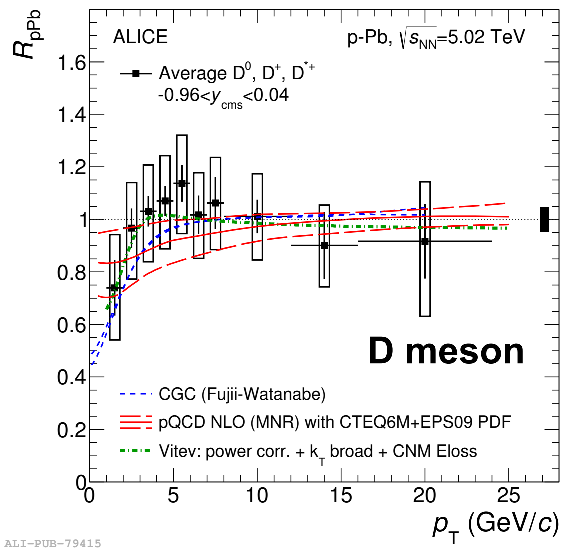
PRL 109, 242301



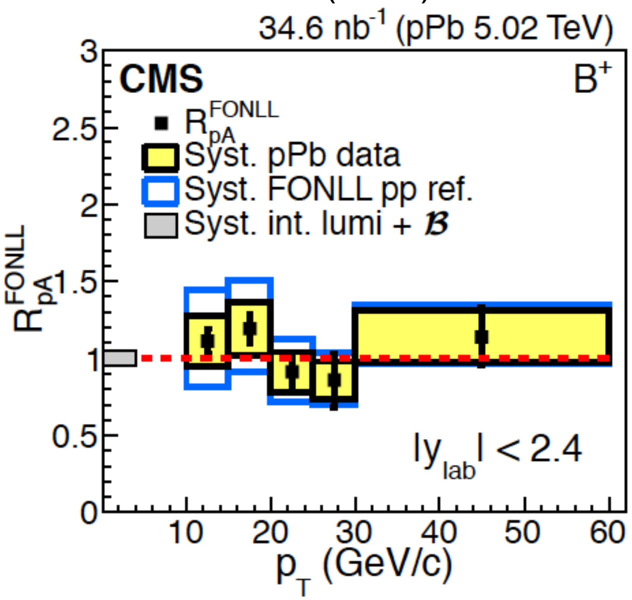
- HF production in d+Au at 200 GeV
  - mid-, forward & backward

R_{pPb} of D, B and e^{HF} at mid-rapidity at LHC

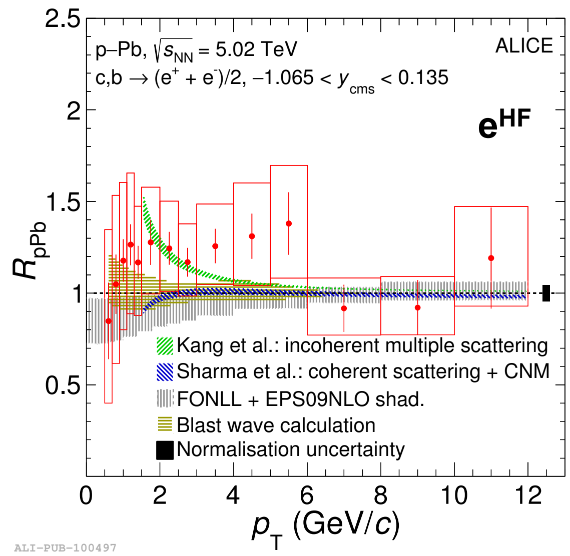
PRL 113 (2014) 232301



PRL 115 (2016) 032301

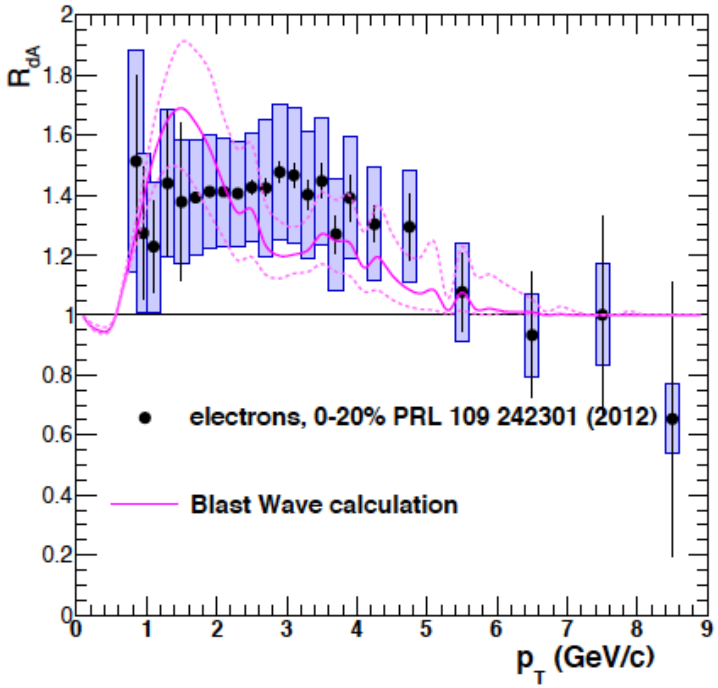


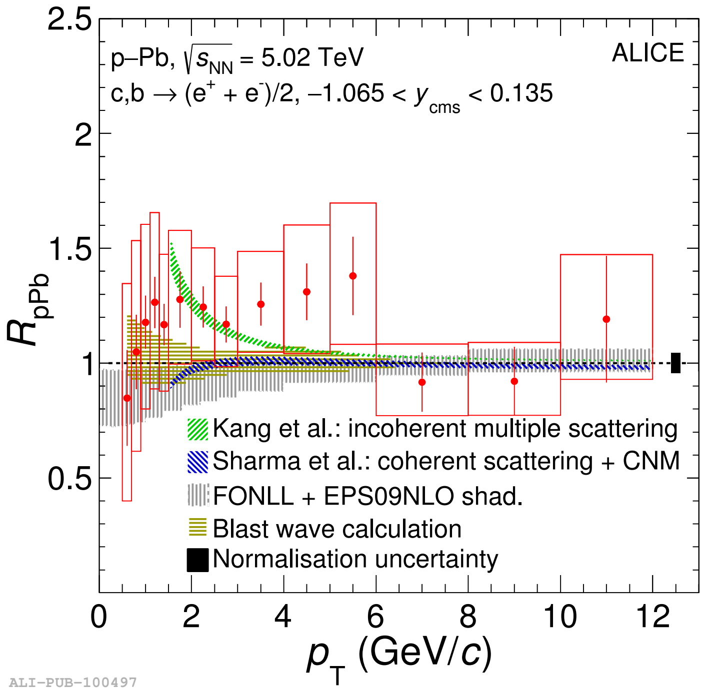
Phys. Lett. B 754 (2016) 81-93



- R_{pPb} of D mesons, B mesons and e^{HF} is consistent with unity
  - No significant cold nuclear matter effects on heavy-flavour production
- Theoretical calculations with CNM effects are consistent with data
  - predict a small suppression at low p_T due to gluon saturation at low x

R_{pA}: RHIC vs. LHC

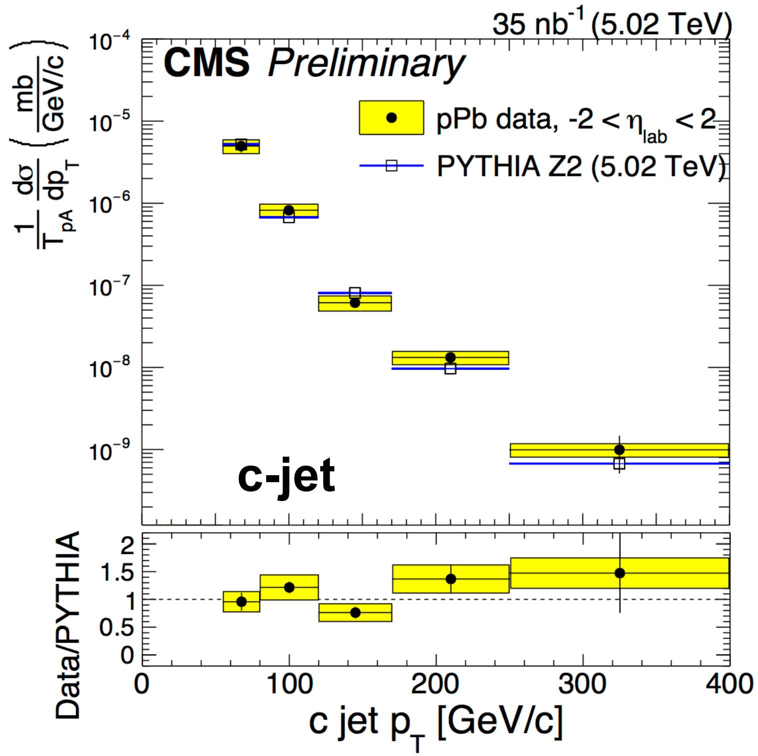




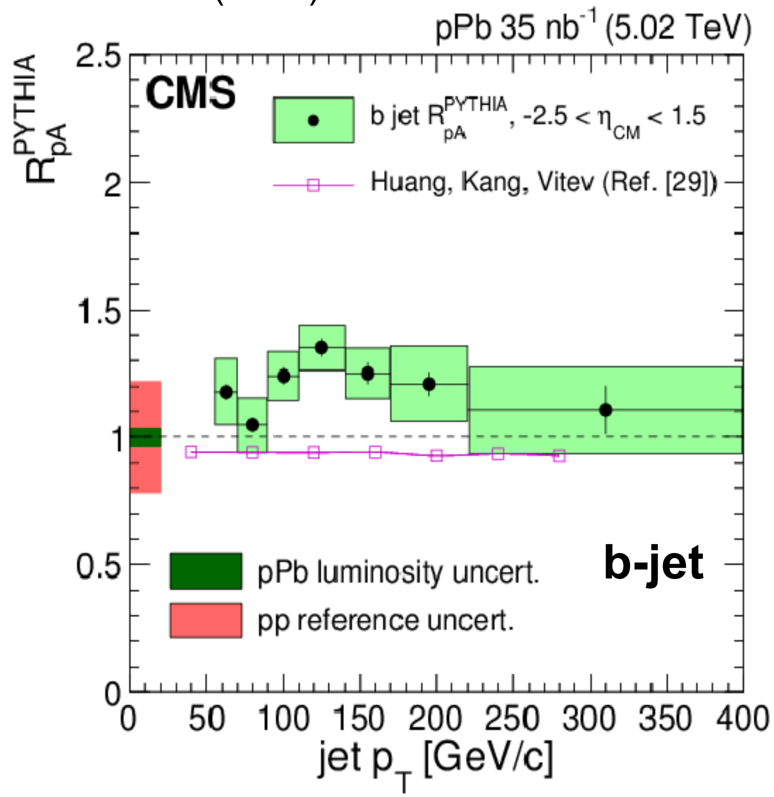
- Enhancement of e^{HF} production in 0-20% in d+Au is well reproduced by Blast-wave model [PLB 731 (2014) 51]
- Possible enhancement due to radial flow is predicted smaller at LHC
    - consistent with data
    - due to harder D and B meson p_T at higher collision energy

R_{pPb} of c-jets and b-jets at mid-rapidity

CMS-HIN-15-012



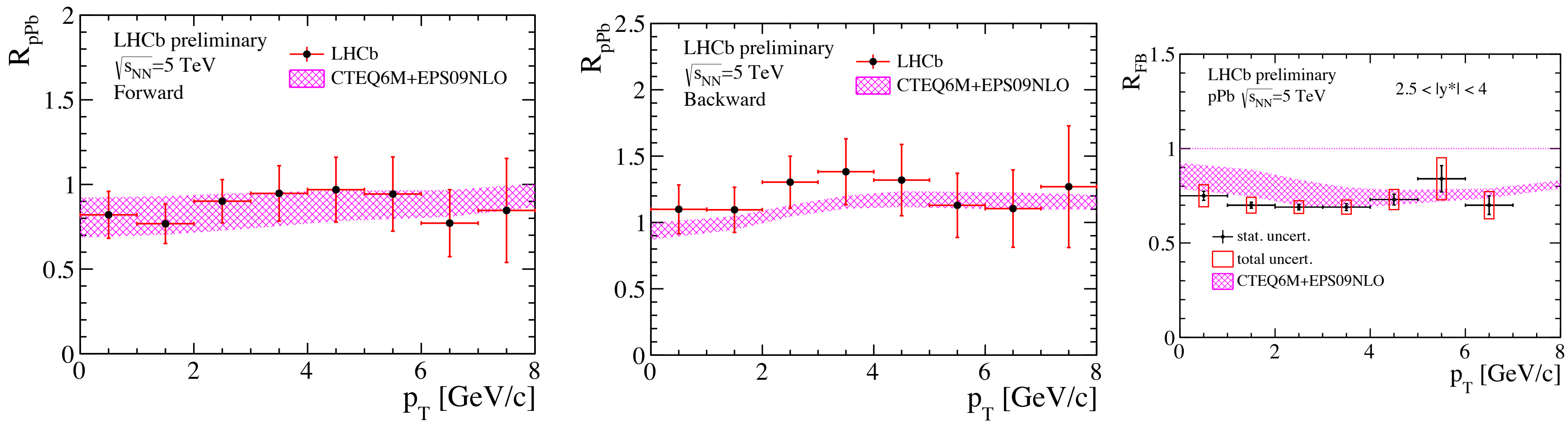
PLB 754 (2016) 59



- Measured c-jet cross section in p-Pb is consistent with PYTHIA simulation
- R_{pPb} of b-jet with PYTHIA-based estimation is consistent with unity
  - considering the uncertainty on the PYTHIA reference

D production at forward-backward rapidity

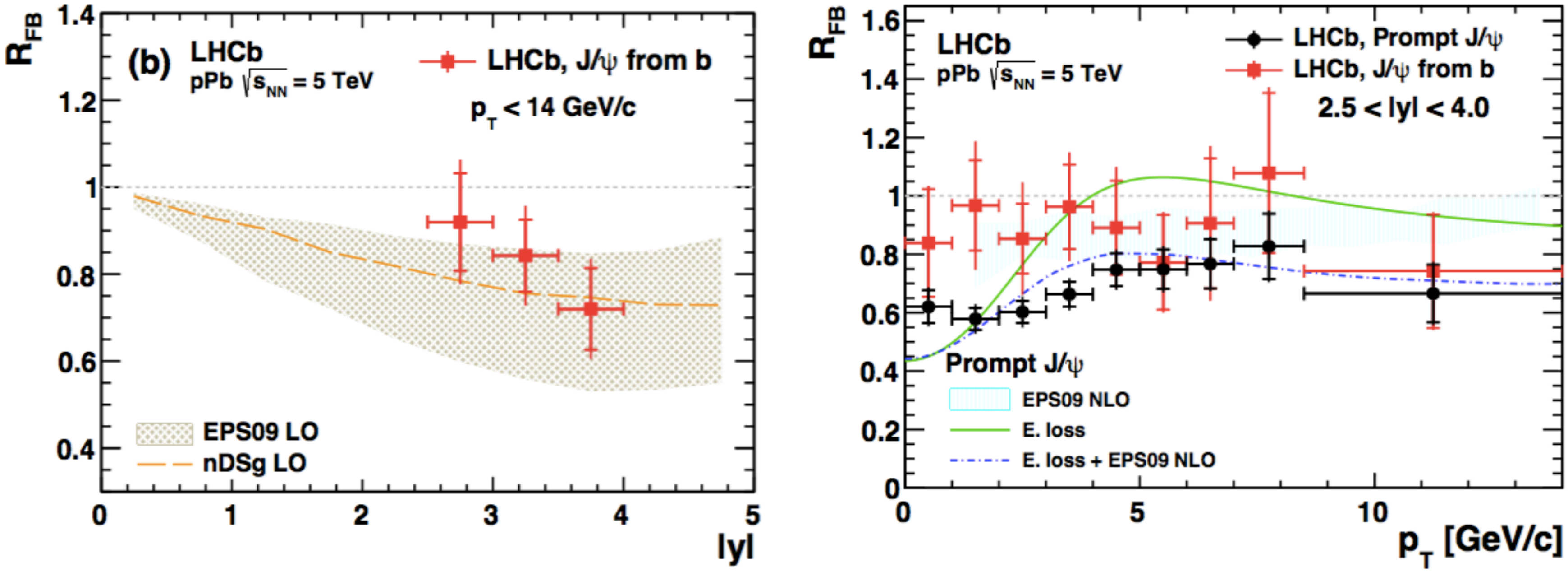
LHCB-CONF-2016-003



- D^0 production at forward and backward rapidity
  - forward: p-going, 1.5 < y < -4
  - backward: Pb-going, -5 < y < -2.5
- Significant D^0 production asymmetry in forward – backward rapidity regions
- Measurements are consistent with a theoretical calculation
  - NLO with CTEQM and EPS09NLO

B->J/Ψ production at forward-backward rapidity

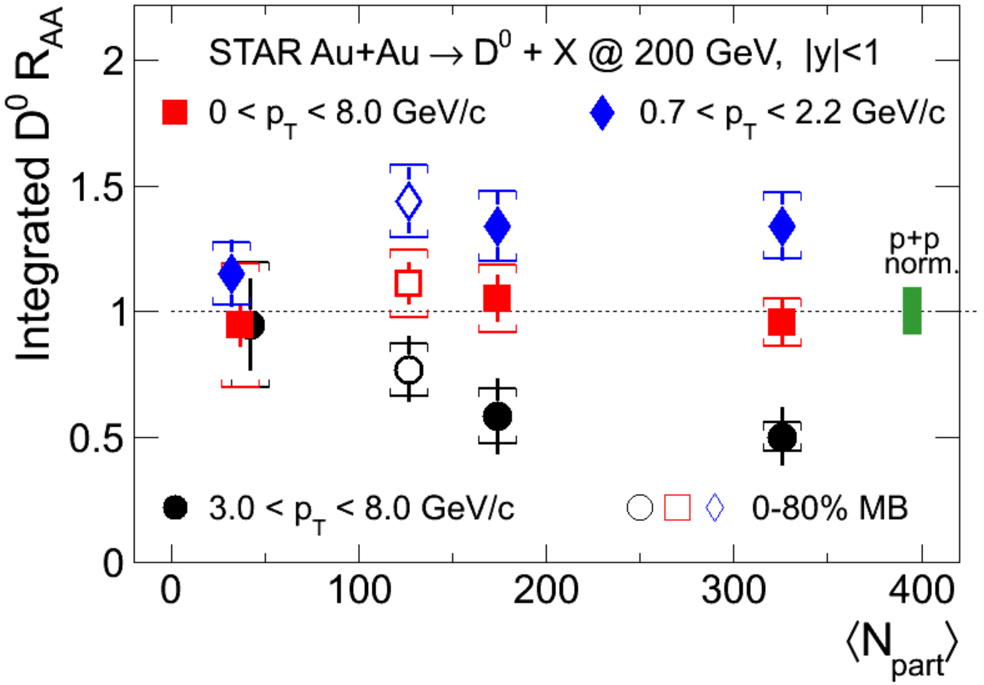
JHEP 02 (2014) 072

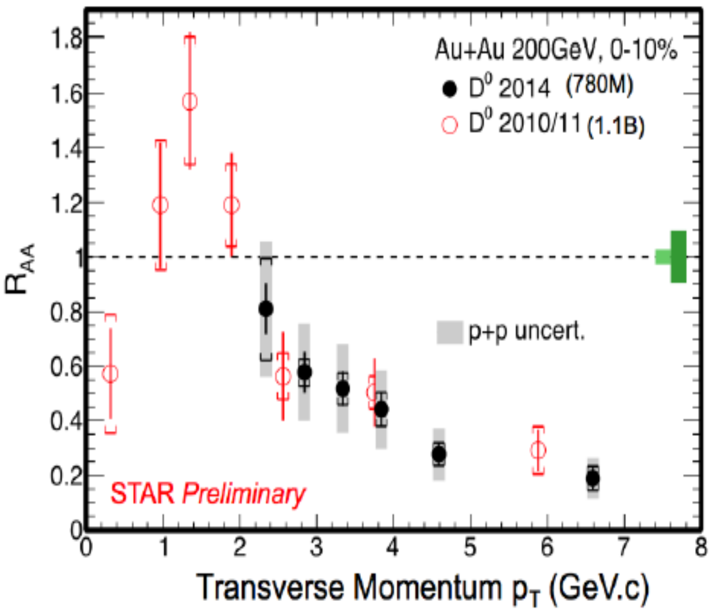


- B->J/Ψ production at 1.5 < η < 4.0 (forward) and -5 < η < -2.5 (backward)
- R_{FB} of B->J/Ψ is asymmetry
  - backward yield is suppressed w.r.t. forward yield
- R_{FB} of B->J/Ψ is larger than R_{FB} of prompt J/Ψ
  - indicate cold nuclear matter effect is less pronounced for b hadrons

Heavy-flavour results in AA collisions

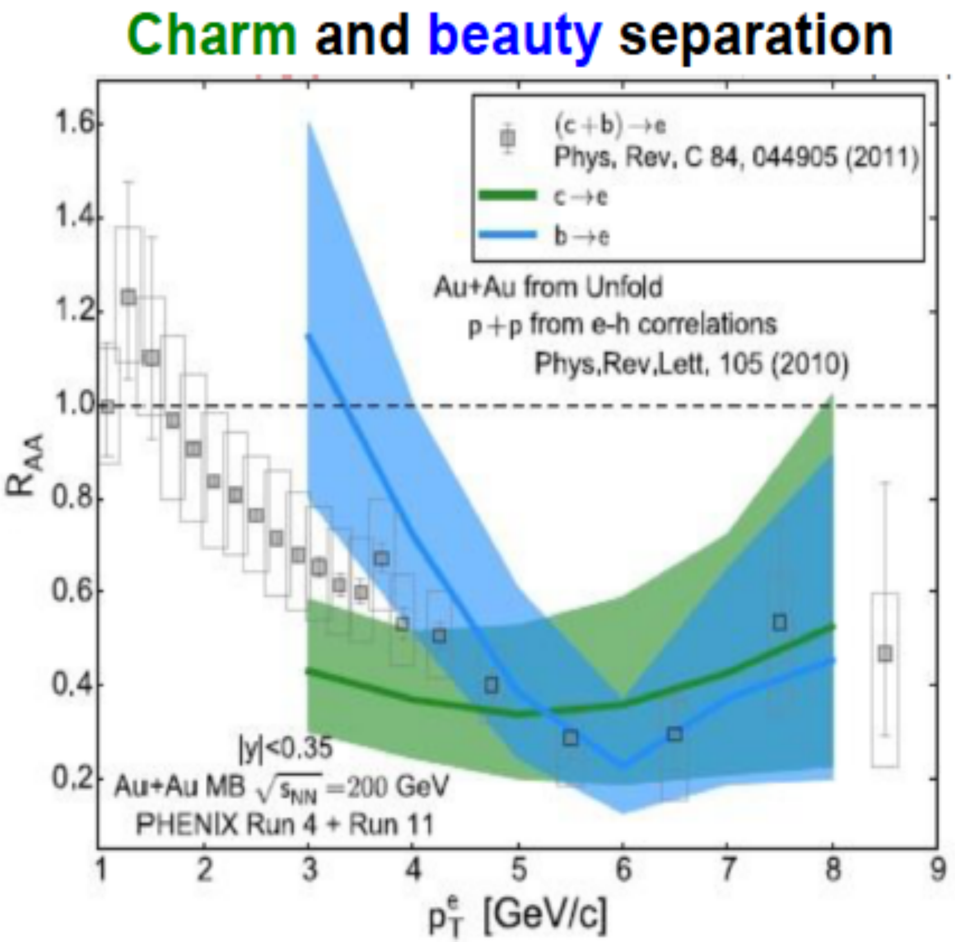
D mesons in Au-Au (200 GeV)





- D meson production at 200 GeV in Au-Au collisions
- Total production follow binary scale
- low p_T (< 2 GeV/c): tend larger than unity
  - recombination, radial flow ?
- high p_T (>2 GeV/c): strongly suppressed
  - indicate charm energy loss in the matter

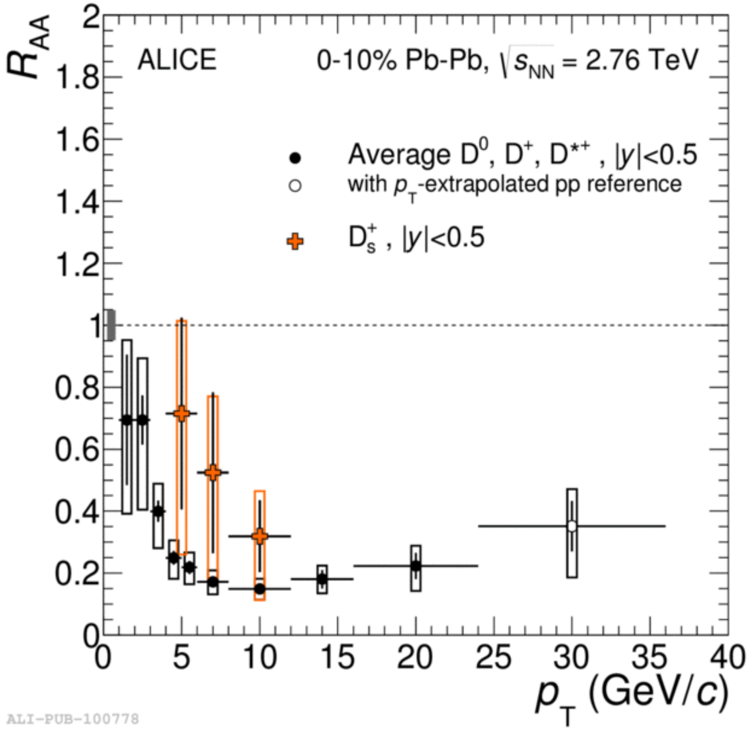
R_{AA} of e^{HF} (c->e and b->e) in Au-Au (200 GeV)



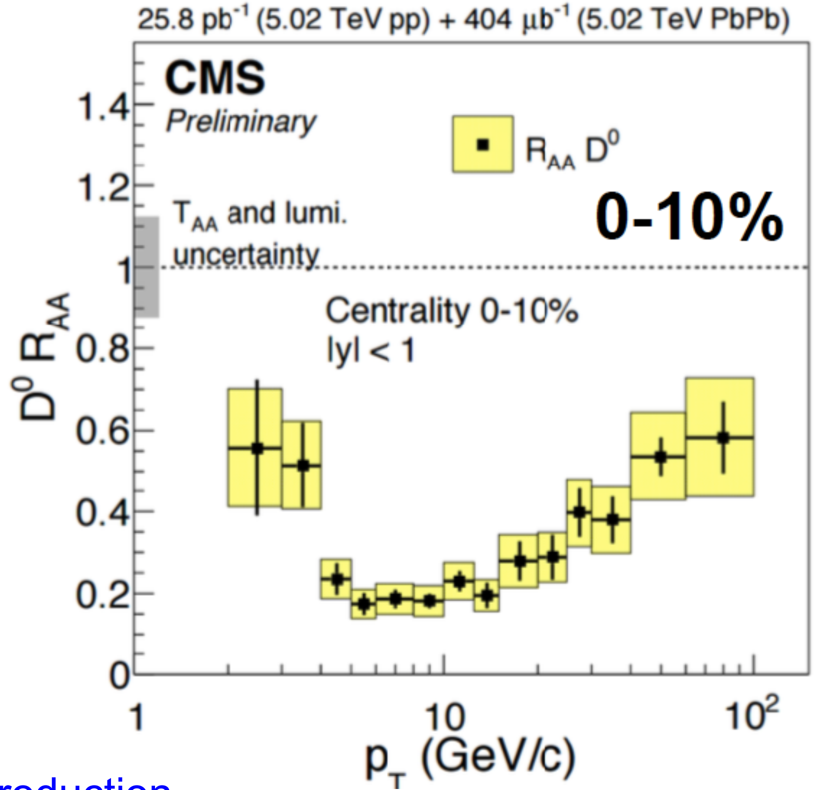
- R_{AA} of D->e and B->e
- Strong suppression both electrons original from charm and beauty indicate charm and beauty energy loss in the matter
- R_{AA} of B->e and D->e are consistent within current uncertainty
  - not conclude mass dependence of energy loss

D mesons in central Pb-Pb collisions (2.76 TeV)

JHEP 03 (2016) 081, JHEP 03 (2016) 082



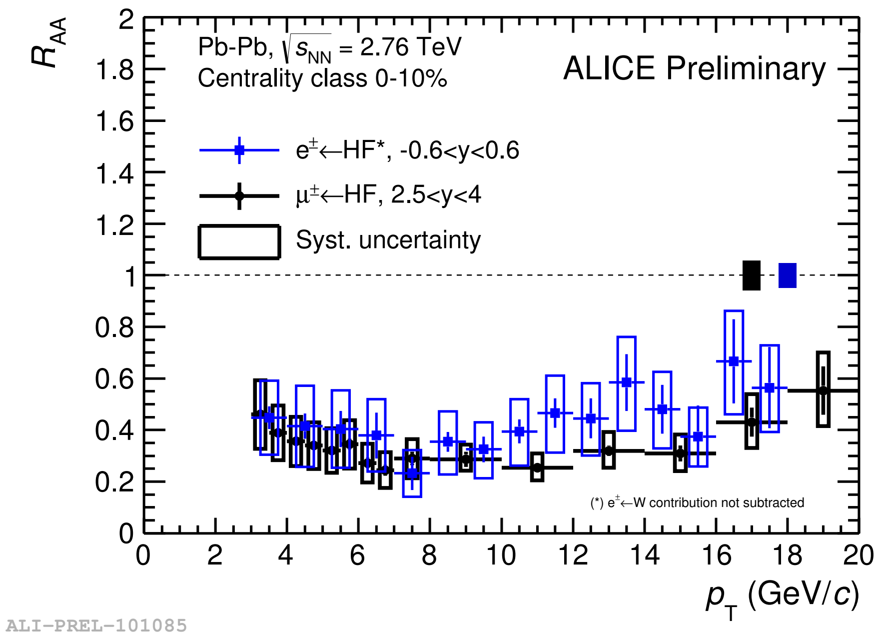
CMS-HIN-16-001



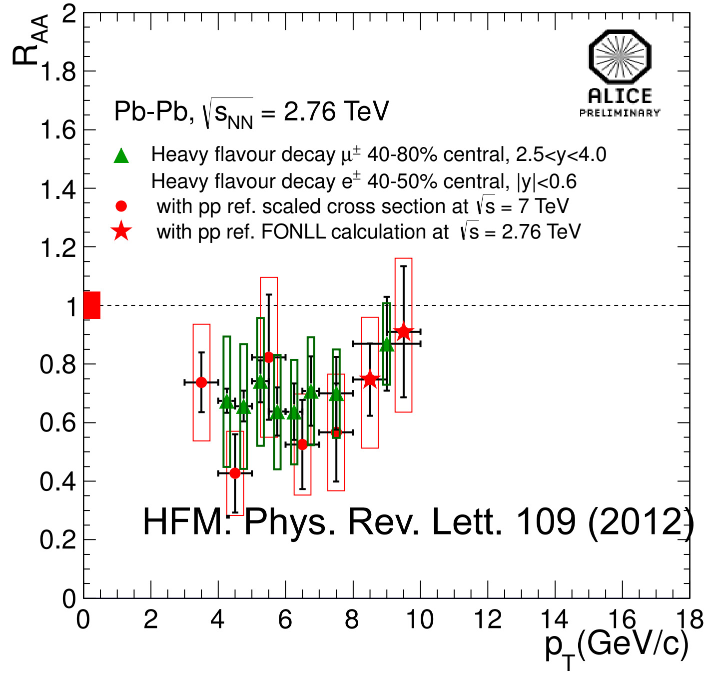
- Strong suppression of D mesons production
  - similar magnitude of suppression in 2.76 and 5.02 TeV
  - suppression observed up to 100 GeV/*c* at 5.02 TeV
  - D_S tends to larger : a hint of recombination process
- Suggest significant energy loss of charm in the medium

e^{HF} & μ^{HF} production in Pb-Pb collisions (2.76 TeV)

0-10%

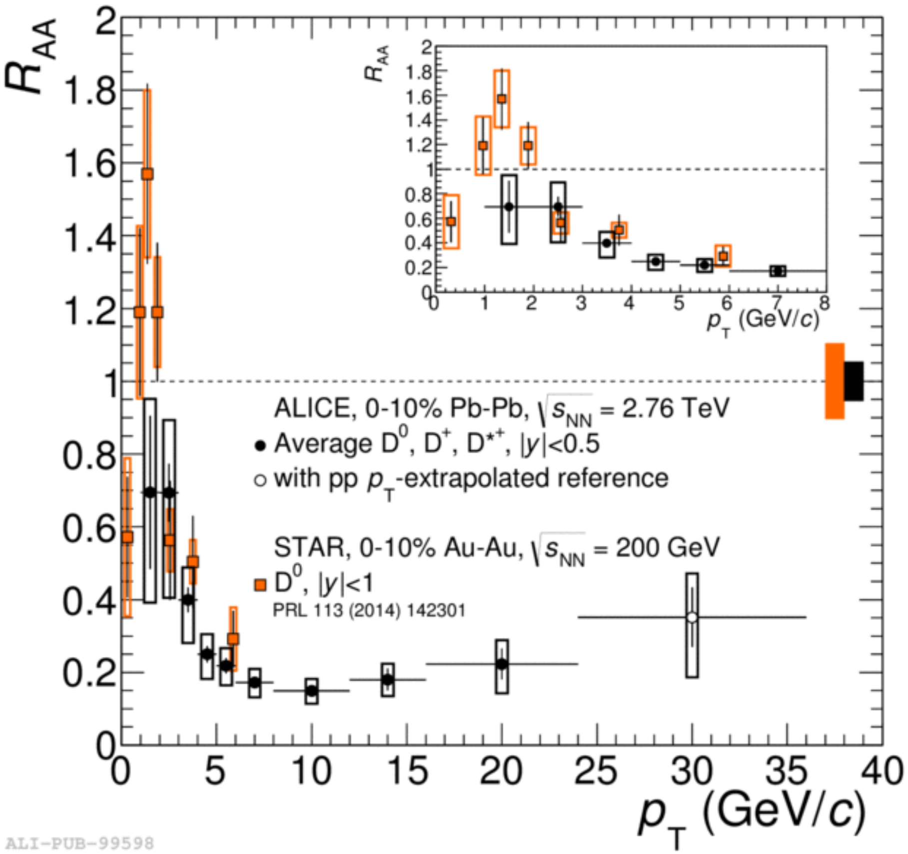


40-50% (e^{HF}), 40-80%(μ^{HF})



- Strong suppression of e^{HF} (|y|<0.6) & μ^{HF} (2.5<y<4) in central collisions
  - similar suppression of e^{HF} & μ^{HF} in different rapidity regions
  - less suppression in mid-central collisions in both rapidity regions
  - high p_T: large contribution from beauty
- Suggest significant energy loss of charm and beauty in the medium

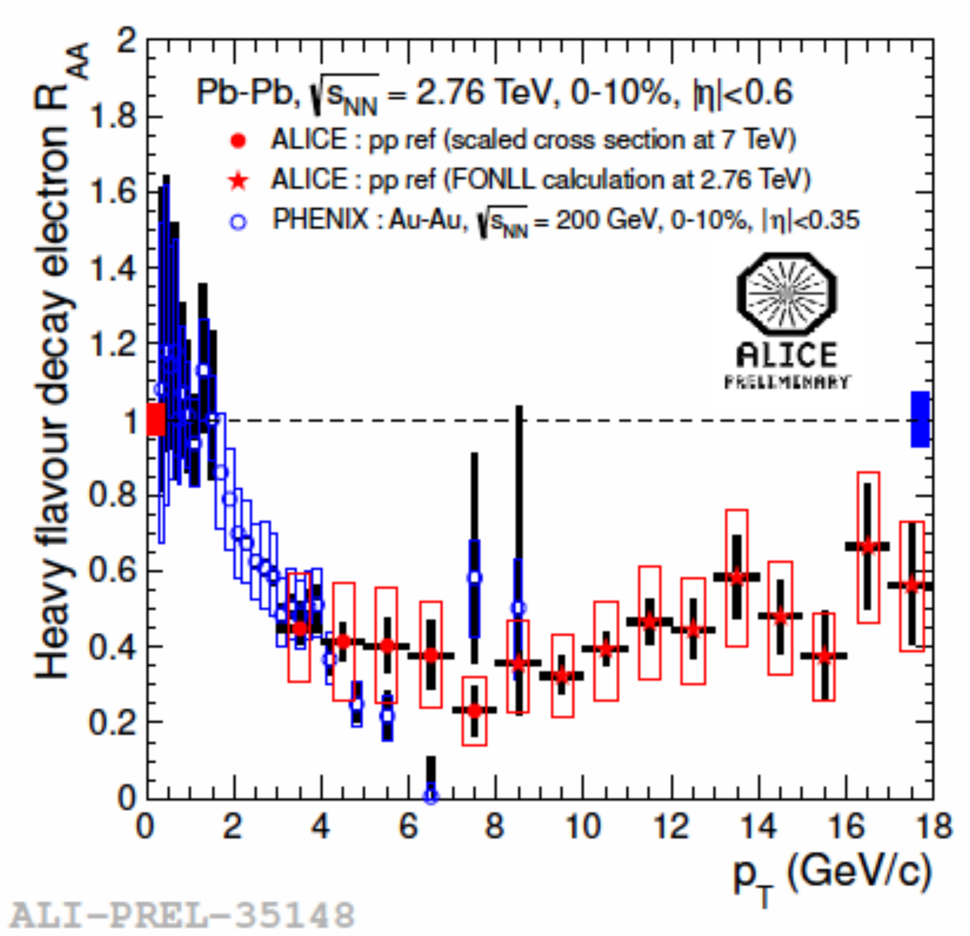
RHIC vs. LHC: D meson production



STAR, PRL113(2014)142301
ALICE, JHEP1603(2016)081

- Similar order of suppression of D meson production in 0.2 TeV (Au-Au) and 2.76 TeV (Pb-Pb) in most-central collisions at $2<p_T<6$ GeV/c
- Looks there is difference at low p_T
  - recombination, radial flow @ RHIC ?
  - shadowing @ LHC ?

RHIC vs. LHC: HF->e production

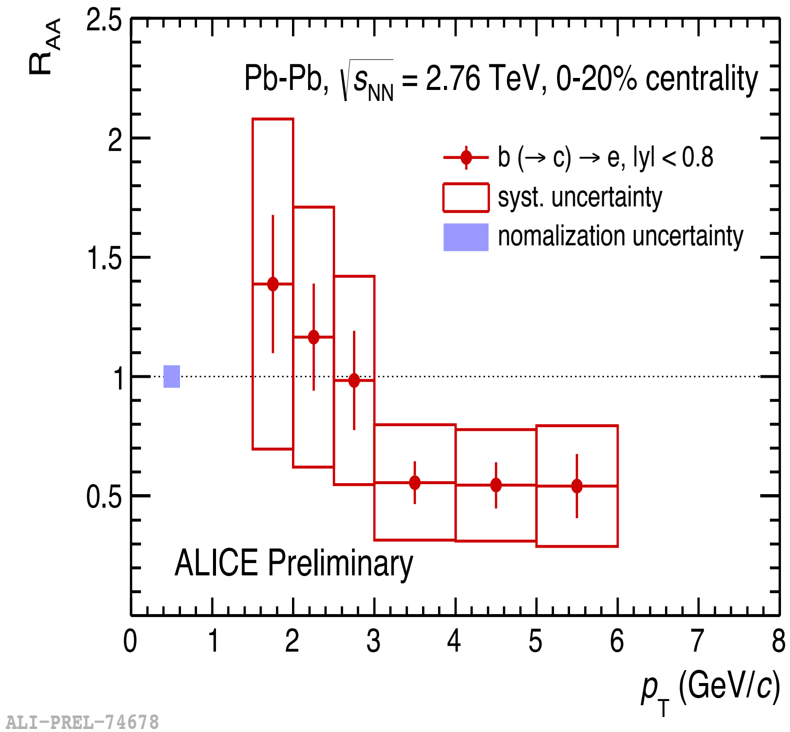


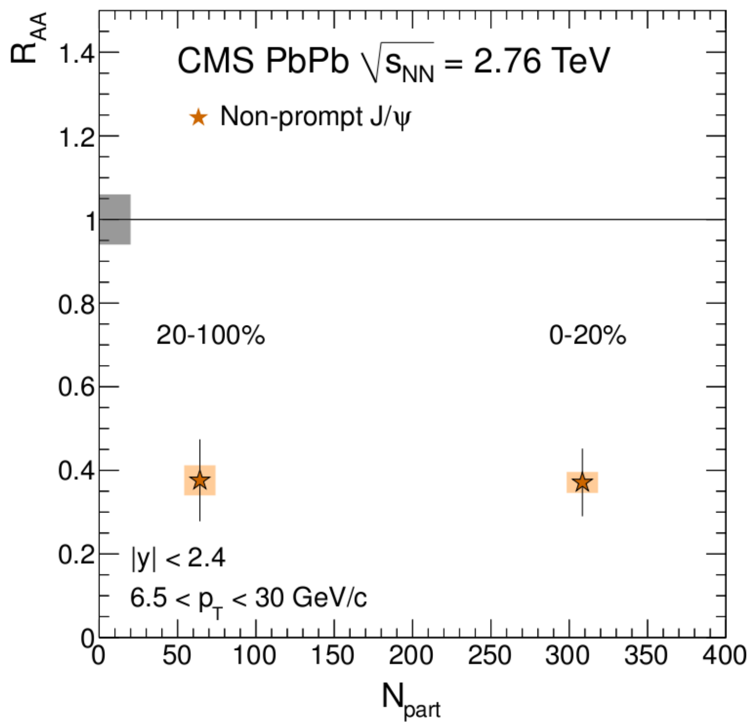
- Similar order of suppression of c->e + b->e production in 0.2 TeV (Au-Au) and 2.76 TeV (Pb-Pb) in most-central collisions at $3<p_T<9$ GeV/c
- Not imply similar HF energy loss between RHIC and LHC
  - combined effect of a denser medium and harder initial p_T spectrum at LHC

    arXiv:1509.06888

R_{AA} of B meson decays (B->e & B->J/Ψ) in LHC

JHEP 1205 (2012) 063

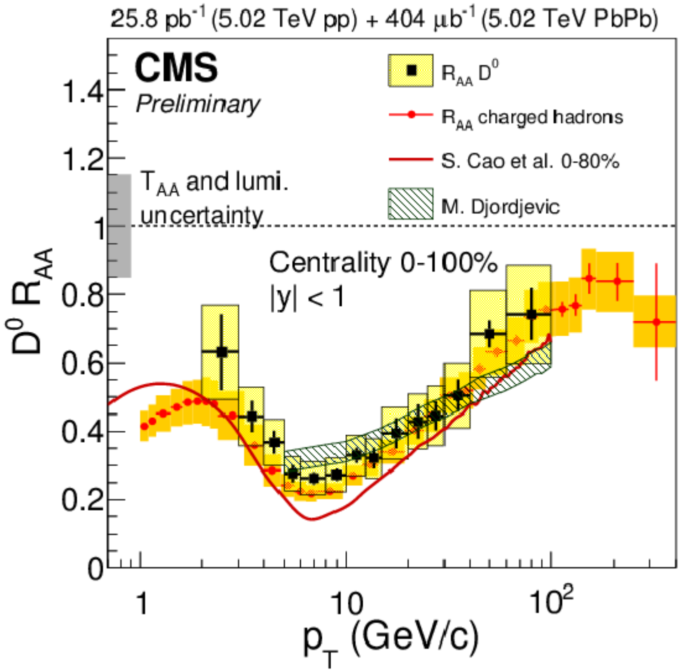




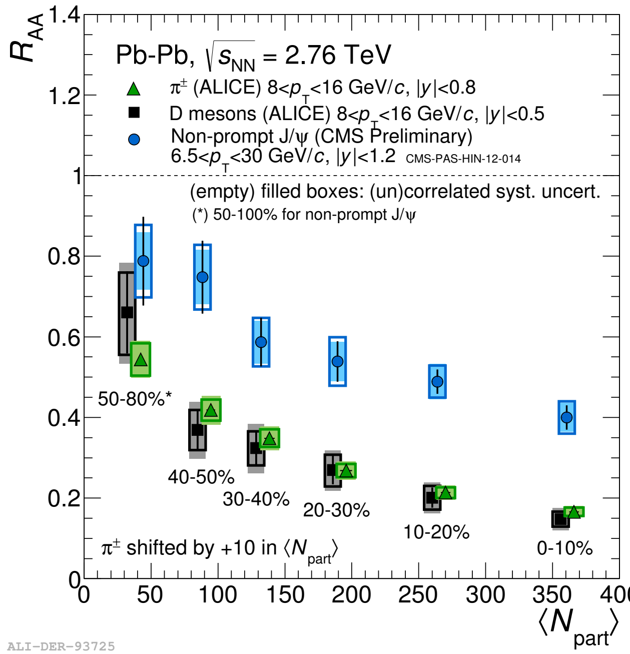
- Suppression of B->e and B->J/Ψ at high p_T
  - lower p_T : tends to follow binary scaling (consistent with unity)
  - high p_T (> 3 GeV/c): R_{AA} ~ 0.4-0.5
- Suggestions of beauty energy loss in the dense QCD matter

R_{AA} of charged particles, D and B->J/Ψ in LHC

CMS-PAS-HIN-16-001



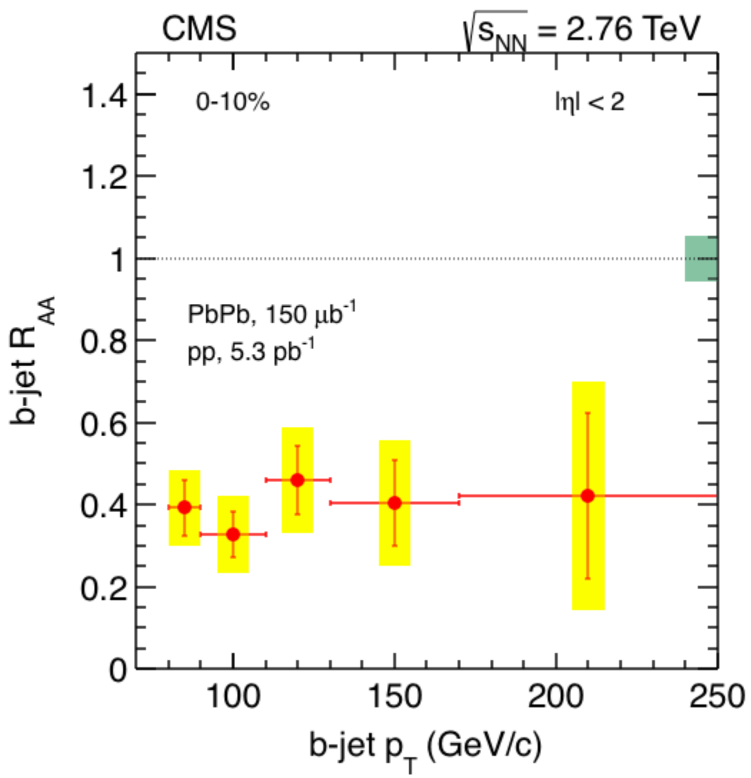
JHEP 1511 (2015) 205, CMS-PAS-HN-12-014

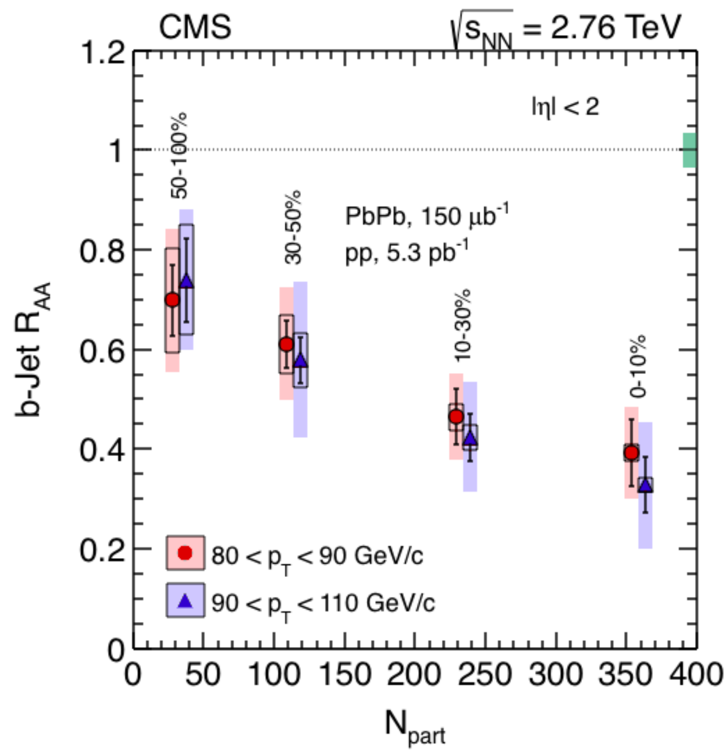


- The magnitude of D meson suppression is similar to charged particles (π) within uncertainties at p_T > 8 GeV/c
  - can't conclude on the expectation : R_{AA} (D) > R_{AA} (π)
- R_{AA} of D meson is smaller than R_{AA} of B->J/Ψ
  - indication of smaller energy loss of beauty than charm

Beauty jet in LHC

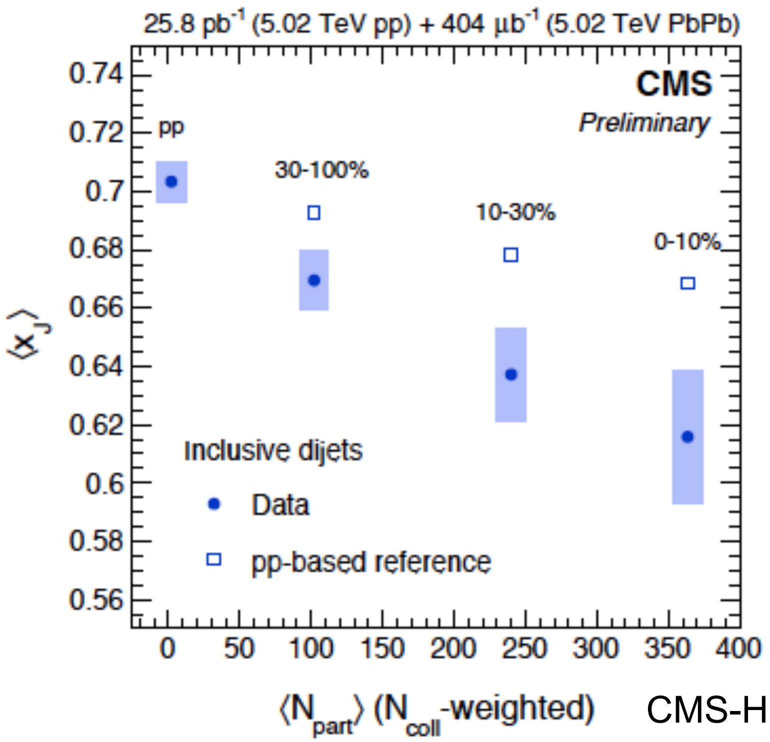
PRL 113 (2014) 132301



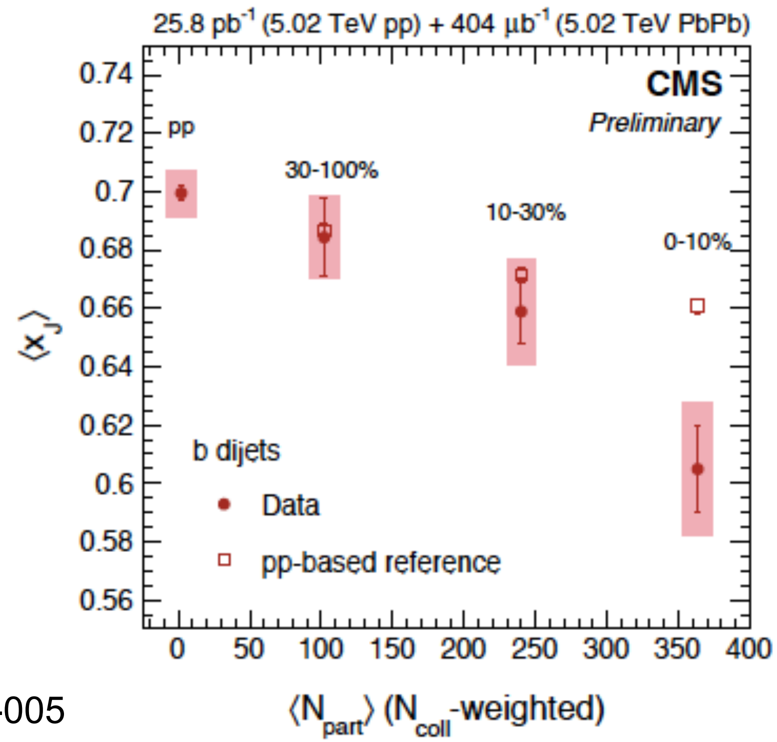


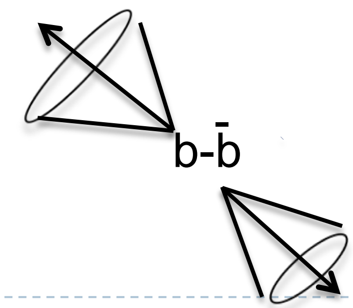
- Heavy-flavour jets: allow to address energy loss at parton level
- Observed strong suppression of b-jets in most-central collisions
  - similar magnitude of suppression to inclusive jet
  - high p_T b-jets: largely comes from gluon splitting

Imbalance of pairs of b jets in LHC



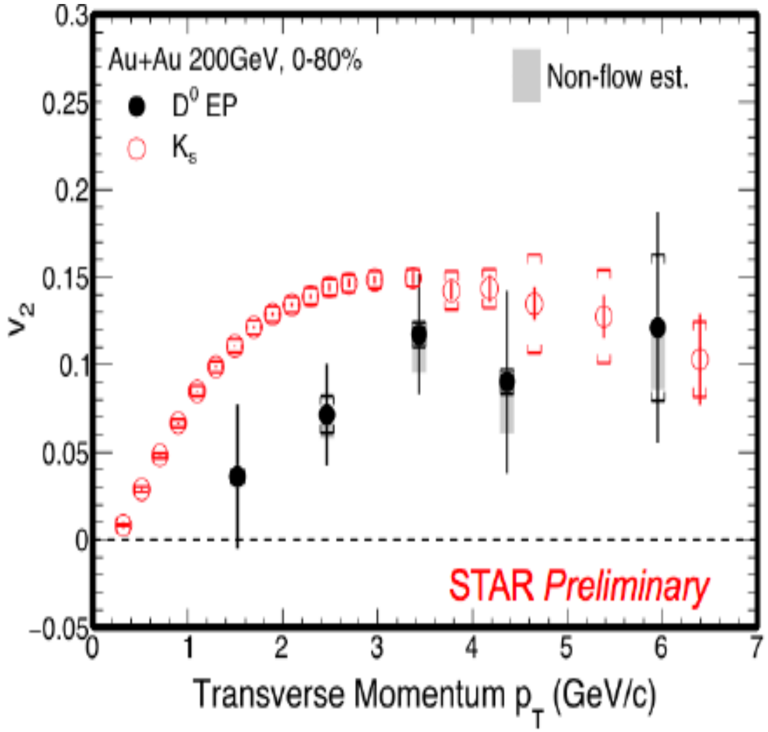
CMS-HIN-16-005



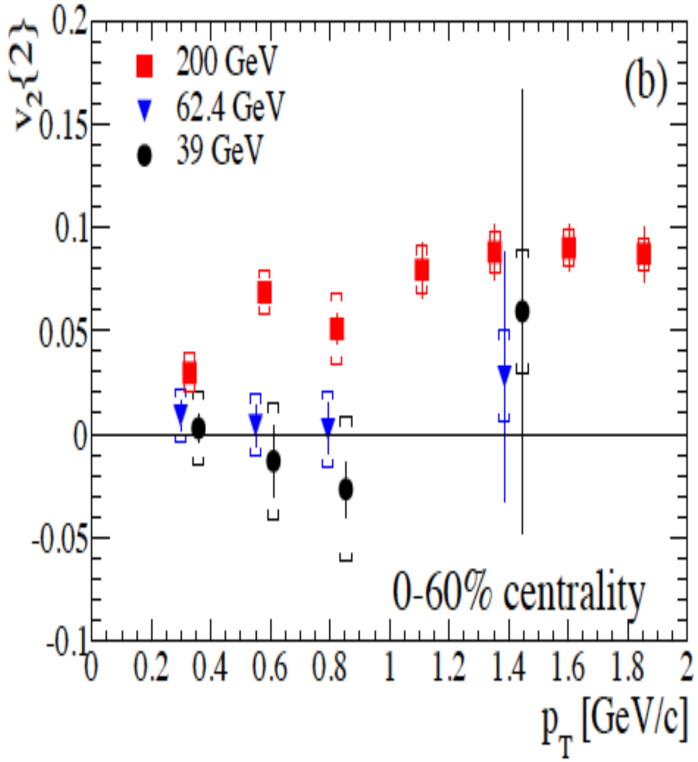


- Sub-leading recoil jets
  - larger path-length, primary b-jets from flavour creation
- Toward increasing imbalance with increasing centrality
  - similar imbalance as inclusive dijet

Azimuthal anisotropy of HF (D and e) at RHIC



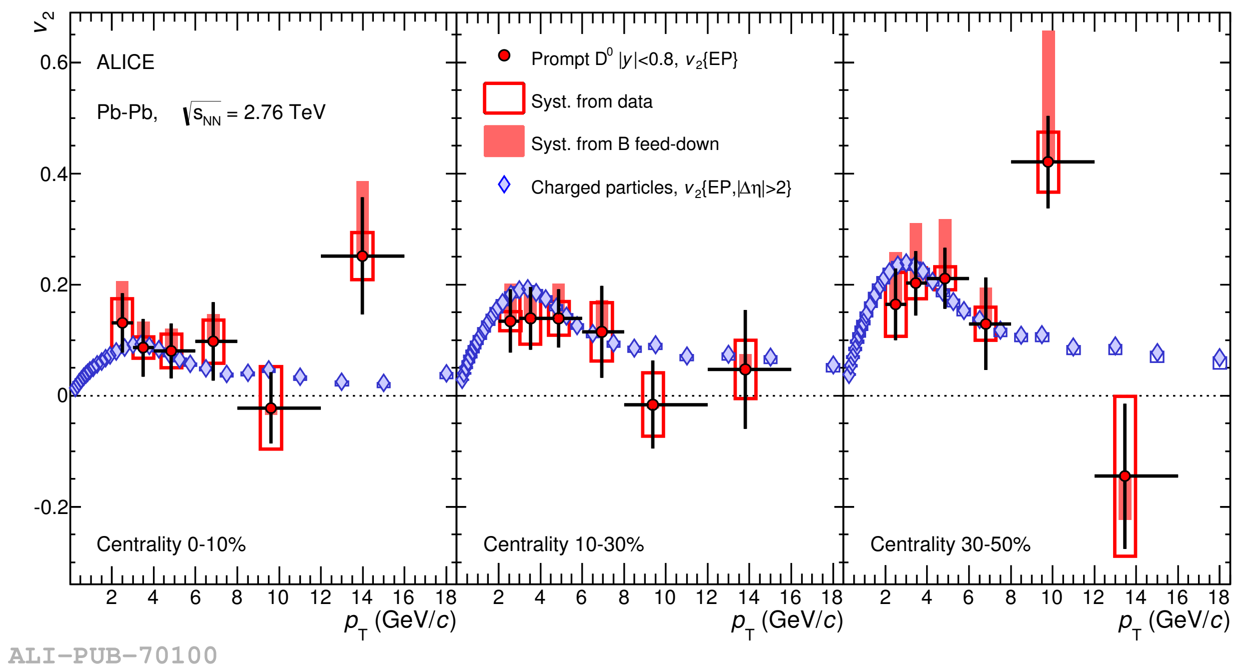
arXiv: 1405.6348



- Non-zero HF v_2 (D & e^{HF}) in Au-Au collisions at 200 GeV
- v_2 at lower energies (62.4 & 39 GeV) is consistent with zero at p_T < 2 GeV/c
  - non-zero light-flavour (π,k & p) v_2 in the energy regions (arXiv:1601.07052)

Azimuthal anisotropy of D mesons in LHC

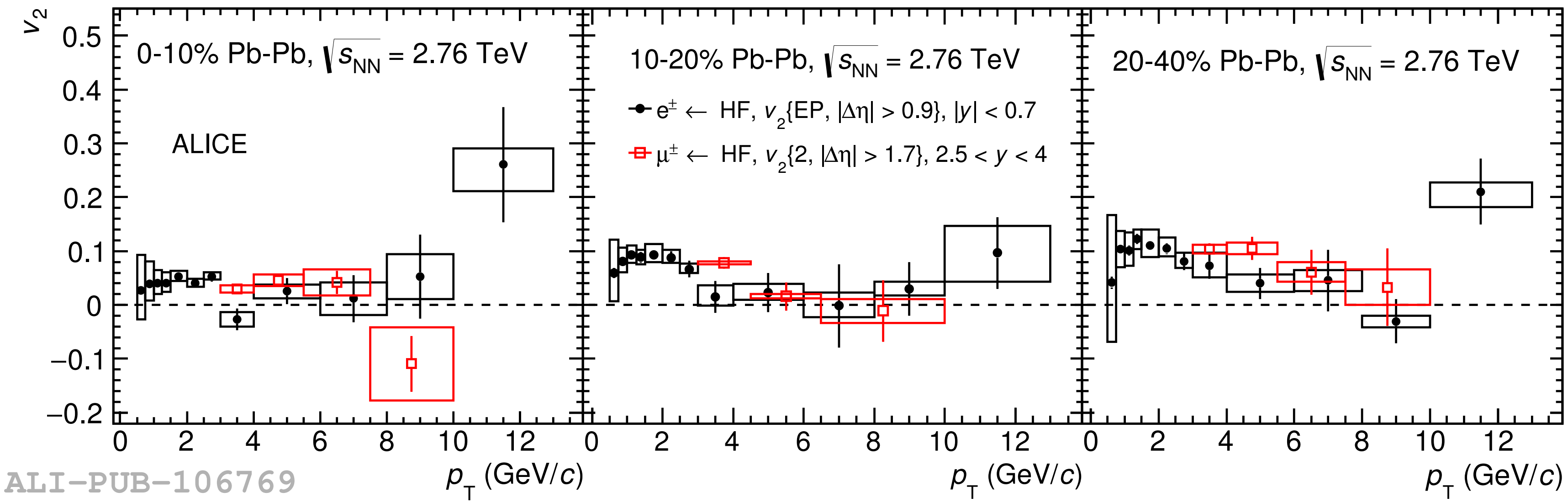
PRC 90 (2014) 034904



- Non zero D v_2 at low p_T
- Tends to get large from central (0-10%) to mid-central (30-50%)
  - Hydrodinamical behavior
- Consistent with charged particle v_2
- Charm quarks participate to the collective motion of the system

Azimuthal anisotropy of e^{HF} and μ^{HF} in LHC

e^{HF} : arXiv: 1606.00321, μHF: PLB 753 (2016) 41-56



- Non-zero v_2 of e^{HF} at |y|<0.7 and μ^{HF} at 2.5<y<4
  - the magnitude is compatible in mid- and forward-rapidities
- v_2 of e^{HF} measured from p_T > 0.5 GeV/*c*
  - similar p_T dependence to other light hadron v_2
- v_2 at high p_T e^{HF} and μ^{HF} reflects beauty
- Charm quarks participate to the collective motion of the system

Comparison with models (1)

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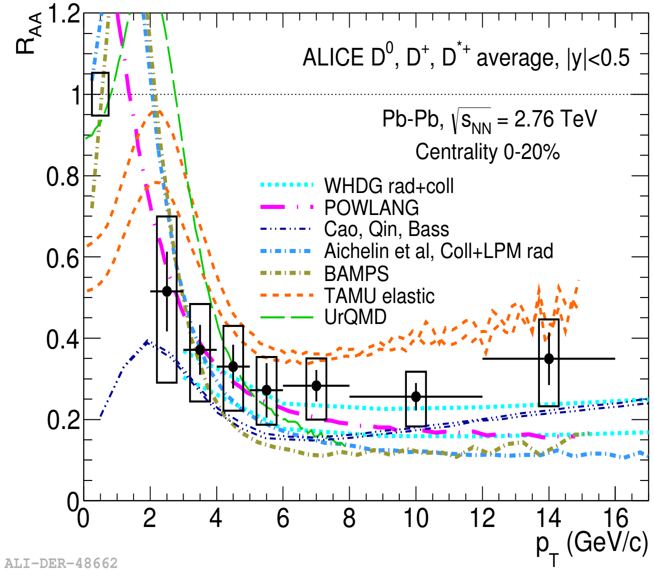
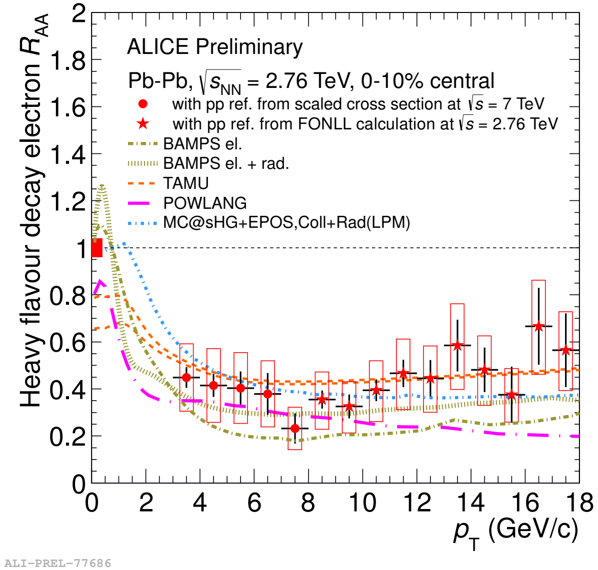
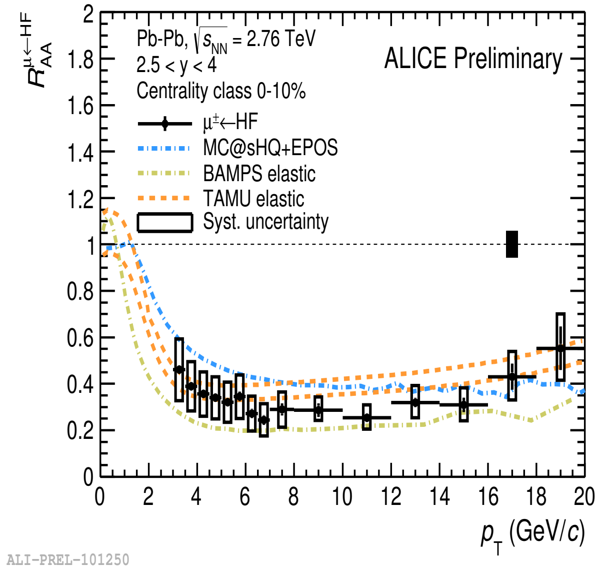




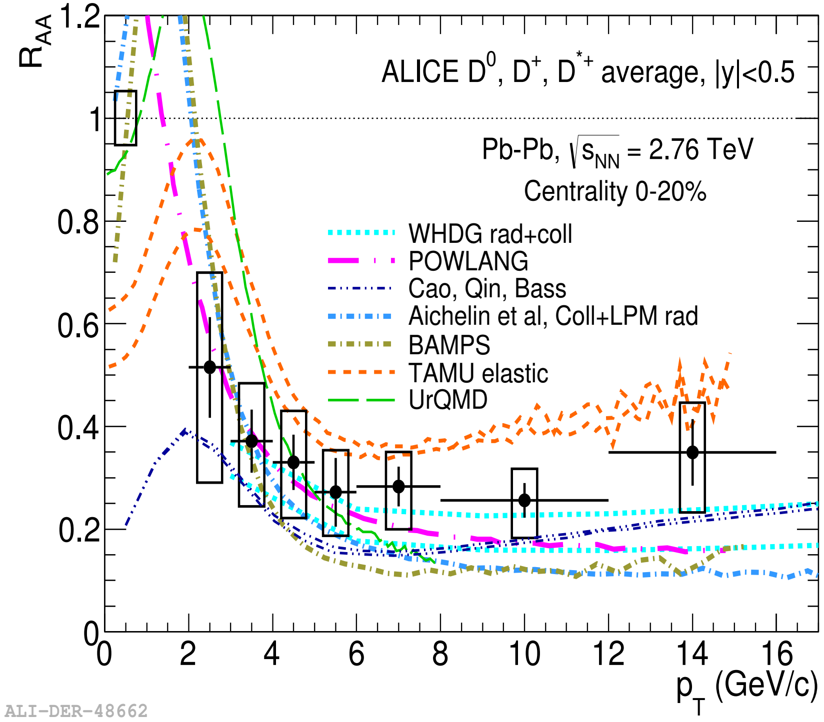


- Theoretical calculations
  - initial: with/without cold nuclear matter from PDF
  - medium modeling: Hydro, Glauber, parton transportation
  - interaction: radiative, collisional, resonant interaction
  - hadronization: fragmentation, coalesence
- Models represent R_{AA} of D mesons, e^{HF} and μ^{HF}
  - mid- and forward-rapidity regions
  - high p_T leptons (e,μ) mainly from beauty decay

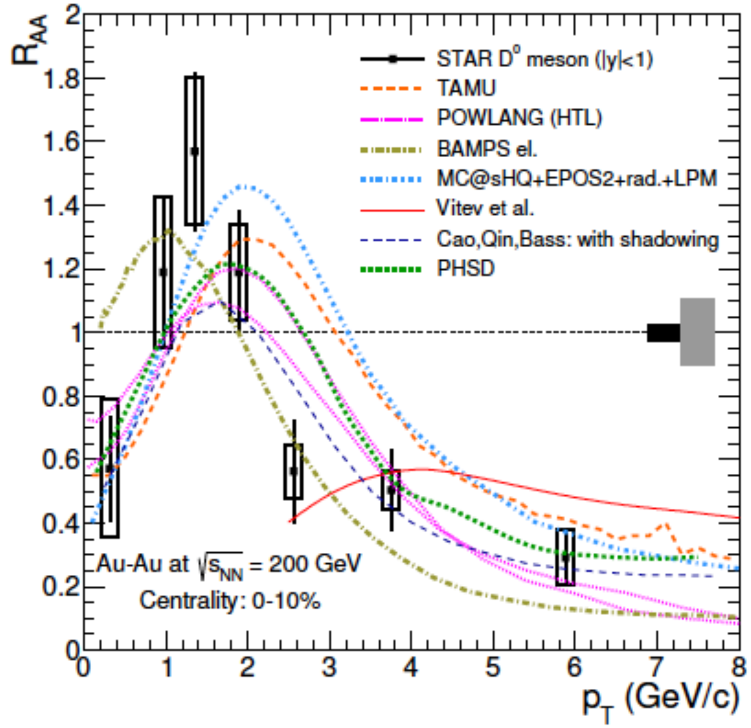
BAMPS: J. Phys. G 38 (2011) 124152,
POWLANG: Eur. Phys. J C 71(2011)1666,
UrQMD: arXiv:1211.6912,J. Phys. Conf. Ser. 426,012032(2013),
TAMU: Phys. Rev. C 86 (2012) 014903,
WHDG: J. Phys. G38(2011)124114,
Aichelin: Phys. Rev. C79(2009)044906, J. Phys. G37(2010)094019
Cao,Qin, Bass: arXiv:1308.0617

Comparison with models (2)

JHEP09(2012)112

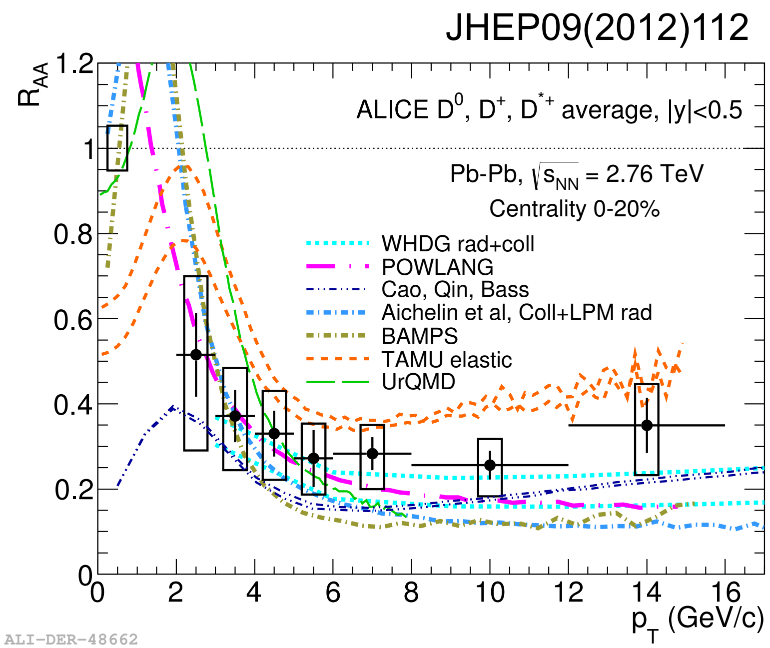


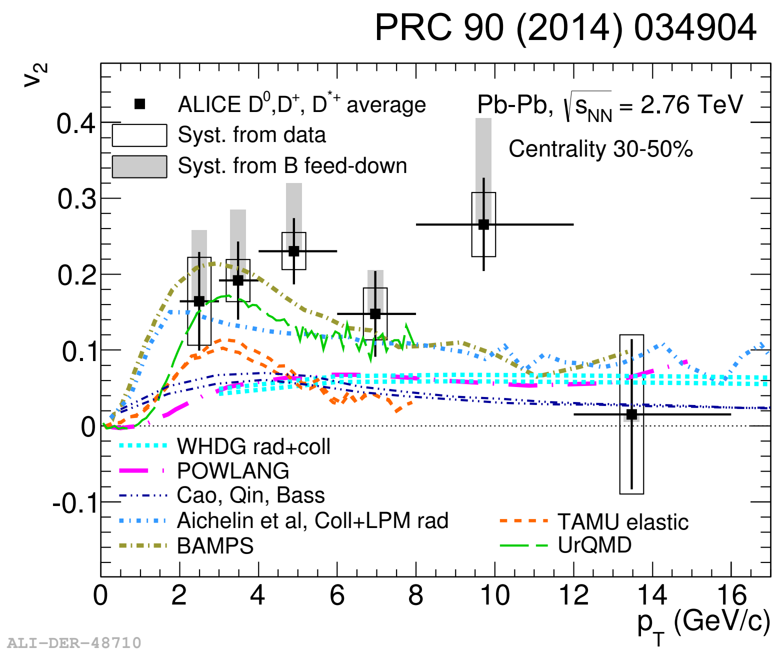
arXiv: 1603.00529



- Model calculations are reasonably reproduced D meson R_{AA} in both RHIC (0.2 TeV Au-Au) and LHC (2.76 TeV Pb-Pb)

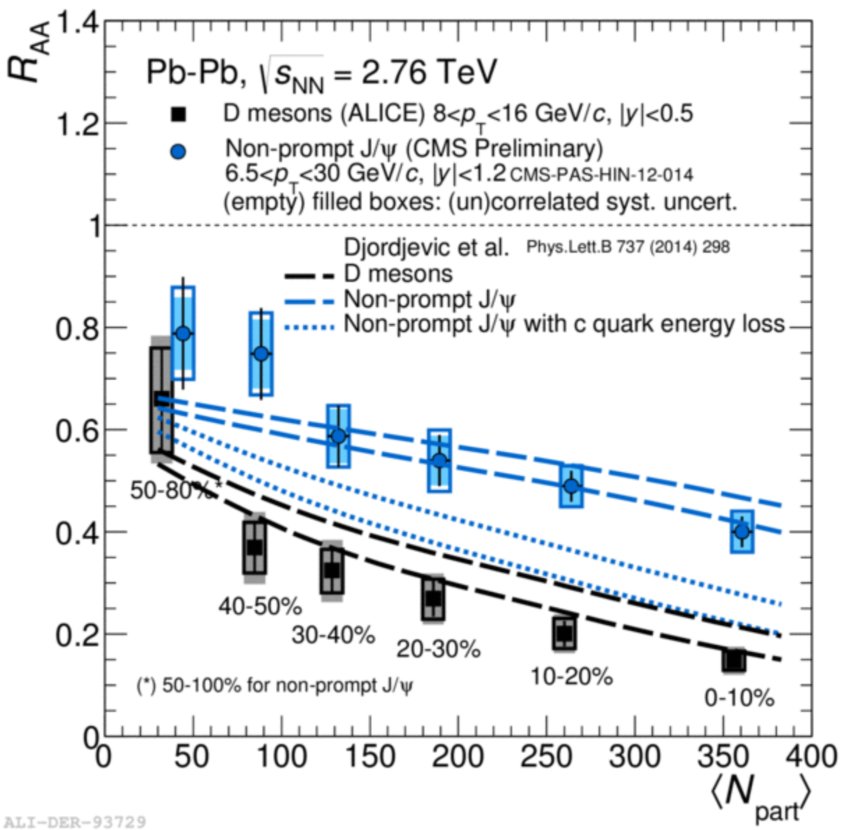
Comparison with models (3)





- Theoretical calculations
  - initial: with/without cold nuclear matter from PDF
  - medium modeling: Hydro, Glauber, parton transportation
  - interaction: radiative, collisional, resonant interaction
  - hadronization: fragmentation, coalesence
- Large suppression and non-zero v_2 (at low p_T) are represented by models, but simultaneous reproduction of the R_{AA} and v_2 is challenging

Comparison with models (3)



- Experimental result
  - R_{AA}(D) < R_{AA}(B->J/Ψ)
- Theoretical model
  - radiative + collisional energy loss
  - used two masses (charm and beauty) for calculating B->J/Ψ R_{AA} to study mass dependence
  - result using beauty mass well represents centrality dependence of R_{AA} (B->J/Ψ)
  - the difference between D meson and B->J/Ψ is mainly from mass in this model

Summary

- Heavy-flavour productions in pp collisions at 200 GeV, 2.76 TeV, 7 TeV and 13 TeV
  - The productions are well described by pQCD calculations
- Heavy-ion collisions (Au-Au 200 GeV, Pb-Pb 2.76 & 5.02 TeV)
  - Strong suppression of heavy-flavour yield
    - Clear indication for substantial energy loss of charm and beauty in the hot and dense matter
  - Non-zero & centrality dependence of v_2
    - Suggest strong re-interaction in the medium
- Heavy flavours observed to be significantly affected by hot and dense QCD medium