LPC Workshop on Physics Connections between the LHC and EIC

13-15 November 2019 Fermilab, Wilson Hall

Measurements of leptons from heavy-flavor decays

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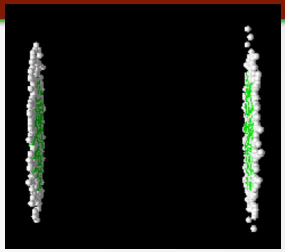
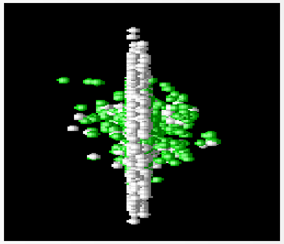
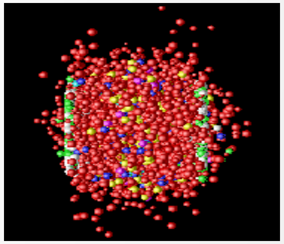
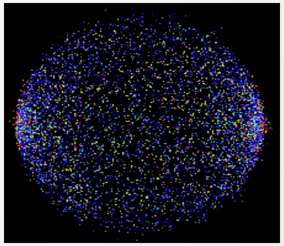
Heavy Quarks



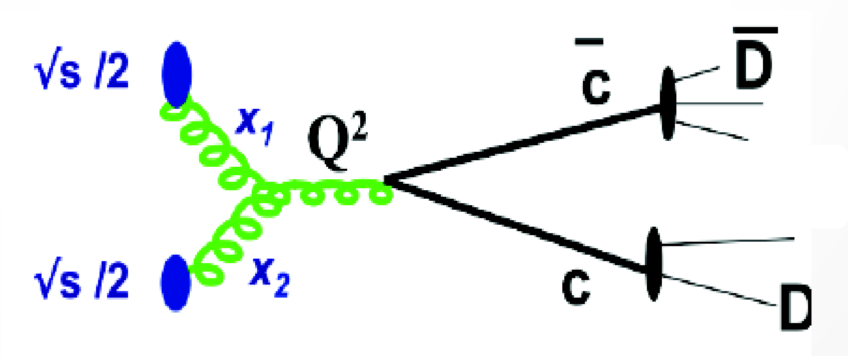






Heavy quarks carry information about early stage of collisions:

- **Charm(c) and bottom(b) quarks are massive**
- **Formation takes place only early in the collision.**
- **Sensitivity to initial gluon density and gluon distribution**



Selected results on HF in next slides
Correlations: jets/flow and Quarkonia (in brief)

R.Rapp,D.Blaschke,P.Crochet, Prog. in Nuclear and Particle Physics 65, 209, 2010
L.Kisslinger, D.Das, Int.J.Mod.Phys.A Vol31(2016) 1630010

Why they are good probes?

Heavy Quarks : Why good probes?

Large Mass : $m_{c,b} >> \Lambda_{QCD}$

Are hard probes, even at low p_T

Do not change flavor while interacting with the QCD medium, although the phase-space distribution does change

$\tau_{prod} \sim 1/2m \sim 0.1$ fm << $\tau_{QGP} \sim 5\text{-}10$ fm

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{Yield\,(A + A)}{Yield\,(p + p) \times \langle N_{coll} \rangle}$$

- **Knowing system properties in a simple way**
  - **calibrated probe**
  - **calibrated interaction**
  - **suppression pattern tells about density profile of the medium**
- **Heavy-ion (AA) collisions**
  - **hard processes : calibrated probe**
  - **transported through the whole**
  - **evolution of the system**
  - **suppression provides density measurements**

Heavy quarks in pp and pA collisions

pp : test understanding of heavy-quark production

- parton level production processes

– LO contributions:
gluon fusion, quark-antiquark annihilation

– NLO contributions:
gluon splitting, flavor excitation

– also complex mechanisms, like,
Multi Parton Interactions (MPI)

- understand perturbative QCD calculations where theoretical uncertainties are due to

– renormalization and factorization scales

– quark masses

- production mechanisms using differential measurements

– multiplicity dependence of heavy-flavor production cross sections

– angular correlation measurements

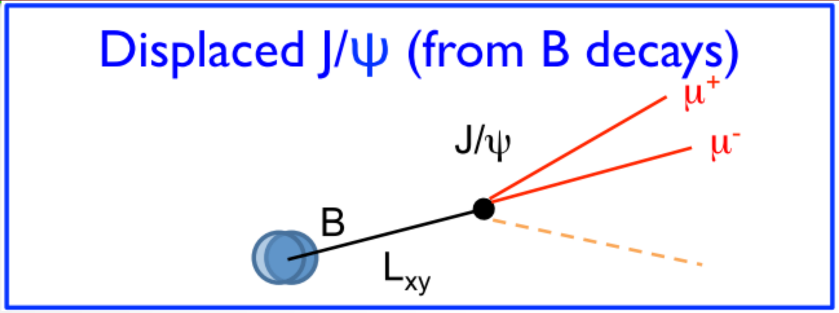
- pp collisions act as a reference for pA and AA collisions

pA collisions : Useful as there is no QGP expected while there are some high density effects

- Nuclear modification of Parton Density Functions
- Saturation and shadowing effects
- Energy loss in Cold Nuclear Matter (CNM)
- Multiple binary collisions and k_T broadening
- Help to compare AA collisions

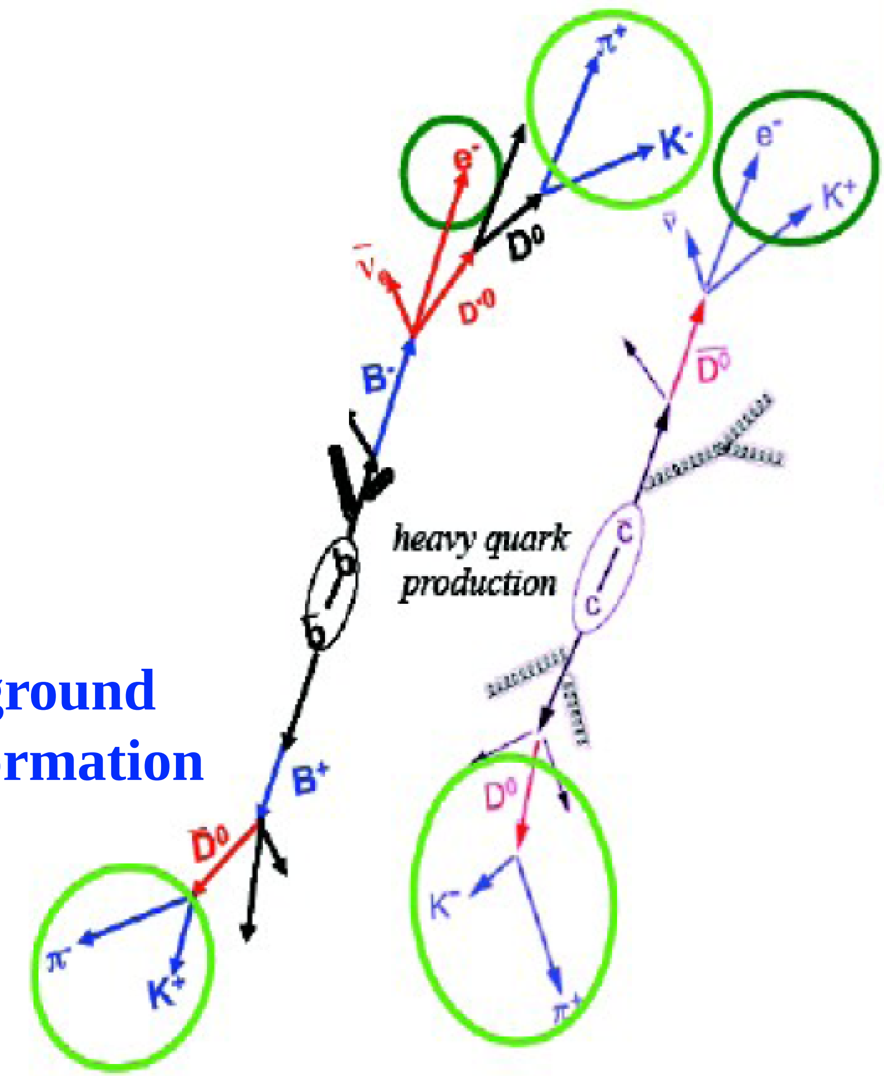
EIC Physics Connections!

Measuring heavy-flavor particles



Heavy-Flavor(HF) hadrons decay via weak interaction:

- **decay length cτ ~ few 100 μm**
- **measure decay products**
- **signal on invariant mass distribution**
- **difficulty is in understanding the background**
- **need good event mixing and vertex information**



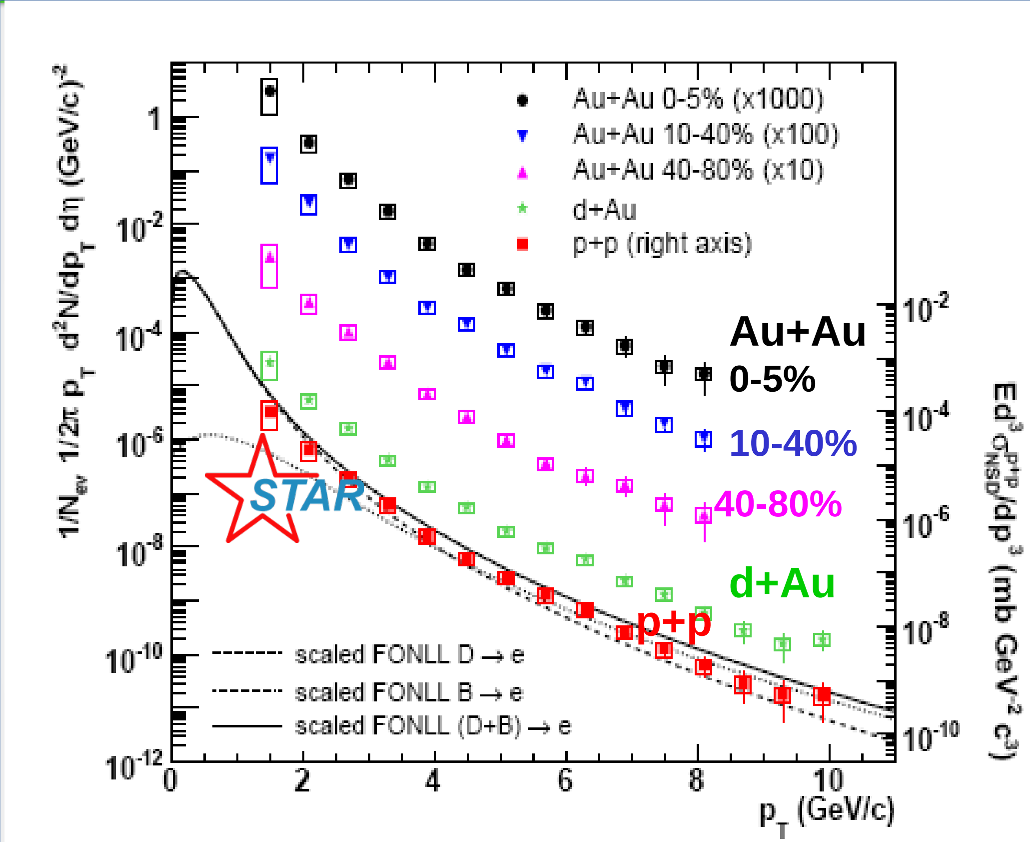
Measurements of electrons and muons from heavy flavor decays

D --> e/μ+X, BR ~ 10%

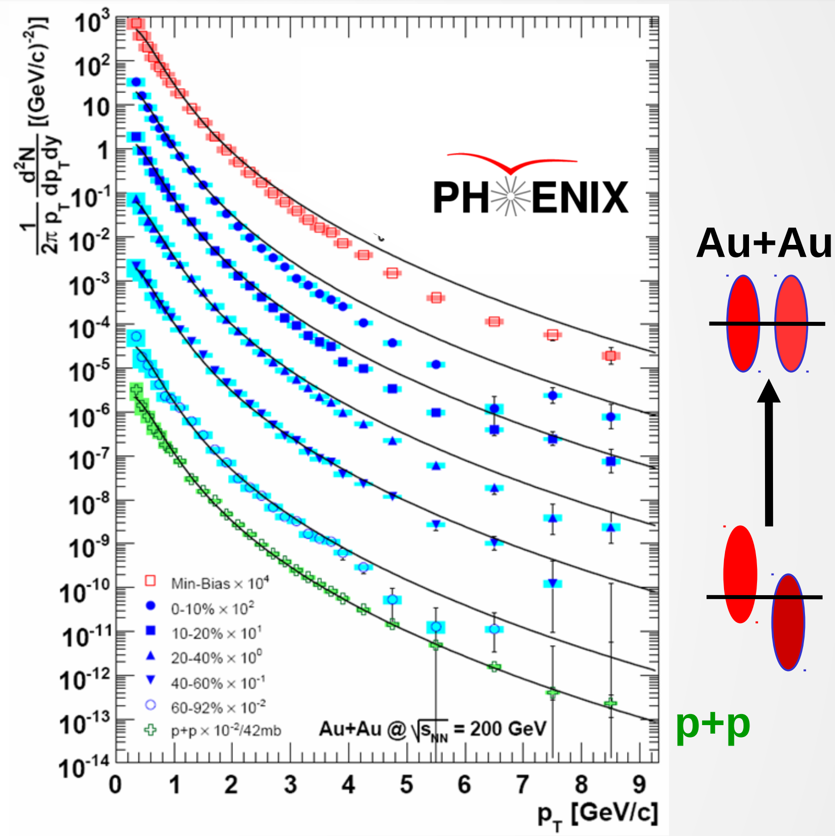
B --> e/μ+X, BR ~ 11%

Single electron spectra (RHIC)

Phys. Rev. Lett. 98 (2007) 192301



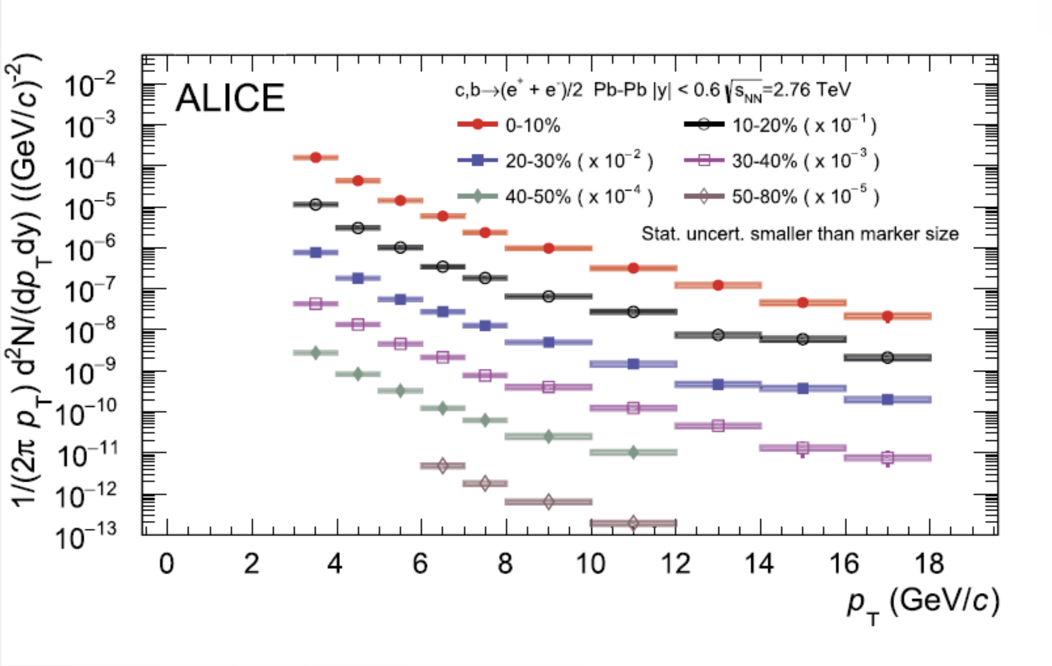
Phys. Rev. Lett. 98, 172301 (2007)

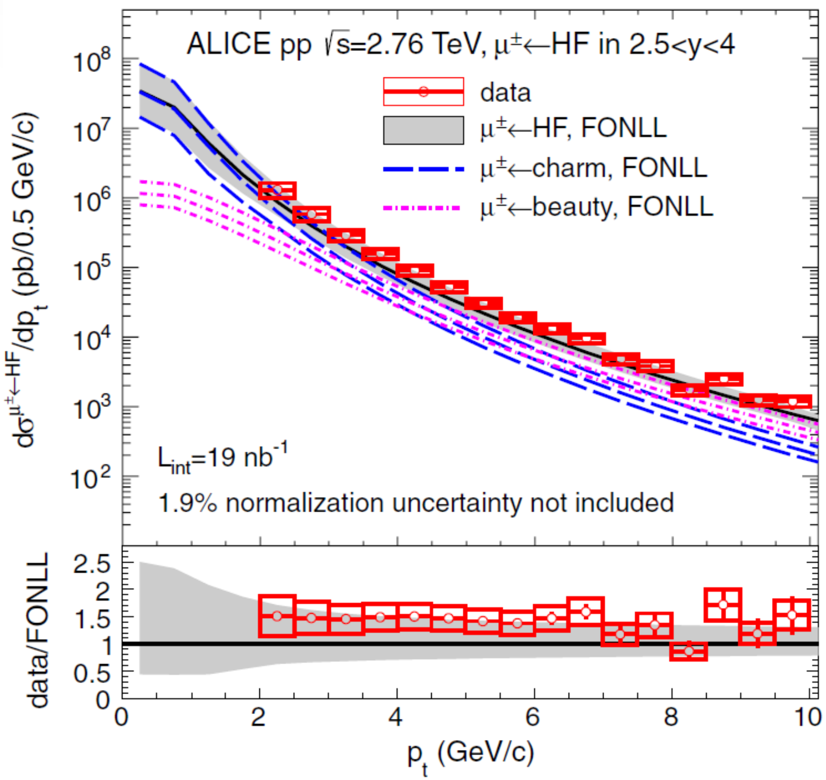


- Single electron spectra (from HF decays) shown till 10 GeV/c
- Integrated yield scale with binary collisions
- Yield strongly suppressed at high p_T in central Au+Au collisions

Electron and Muon spectra at LHC

Pb+Pb Physics Letters B771(2017) 467–481 ALICE PRL 109, 112301 (2012) pp



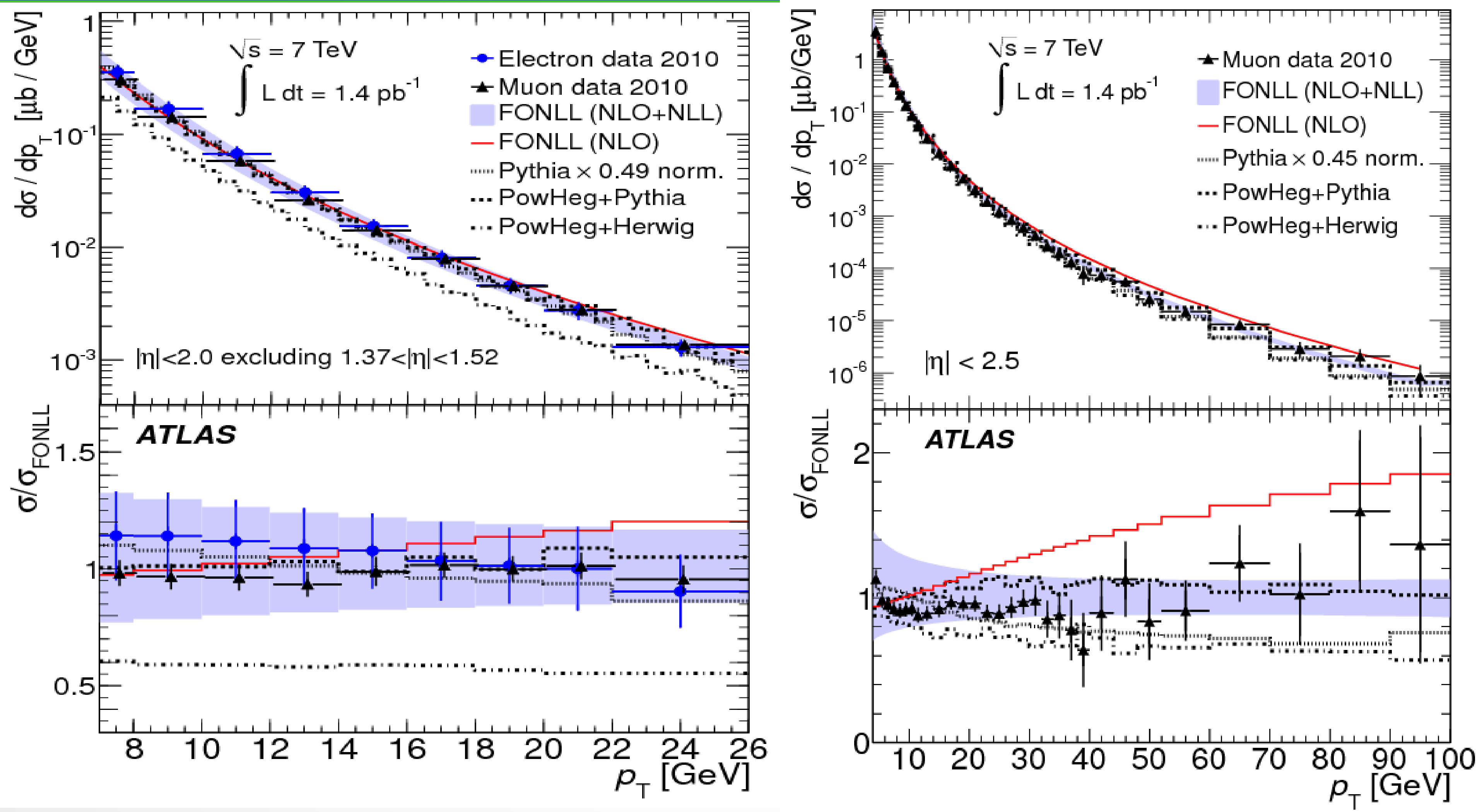


- Left plot : the electrons from semi-leptonic decays of HF hadrons at mid-rapidity in Pb-Pb collisions
- Right plot shows the pQCD calculations in agreement with data at forward rapidity in pp collisions

Electron and Muon spectra at LHC

ATLAS

Phys.Lett. B707 (2012) 438-458



- pQCD calculations agree with e± & μ± (from HF)at high p_T

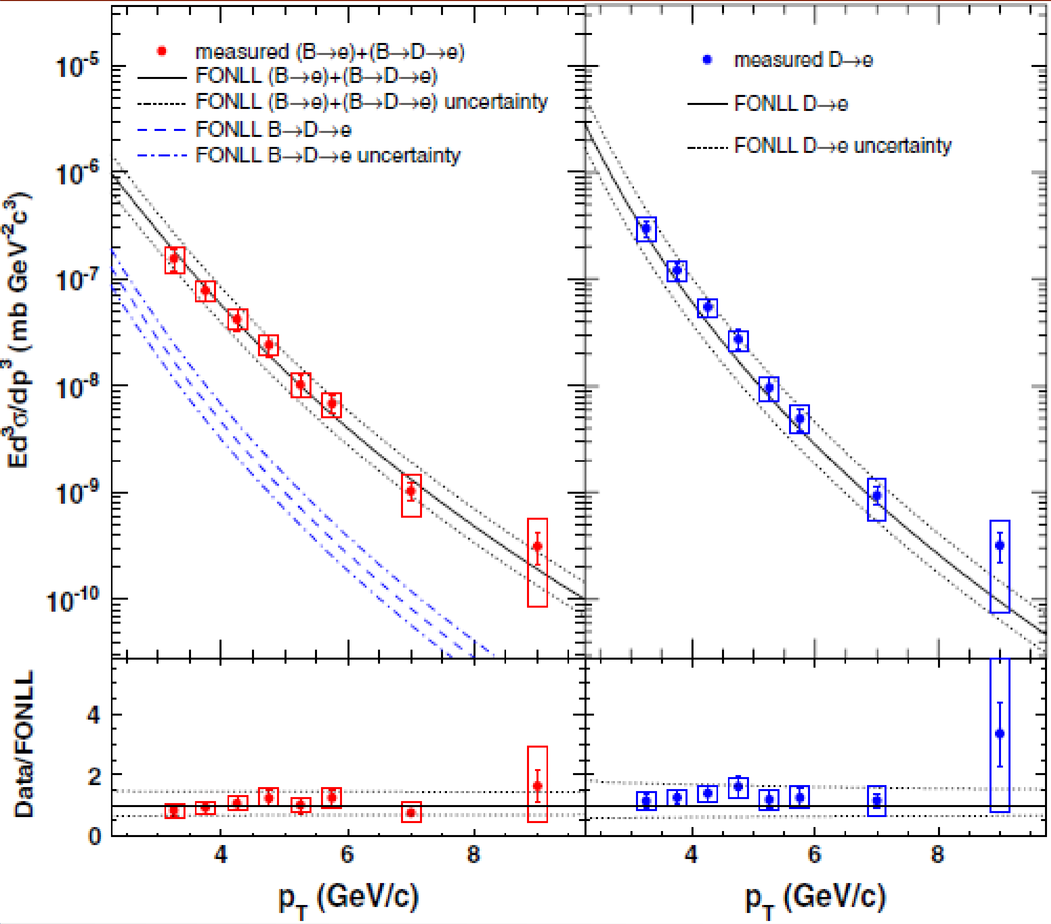
Separate Measurement of B → e and D → e Spectra at RHIC

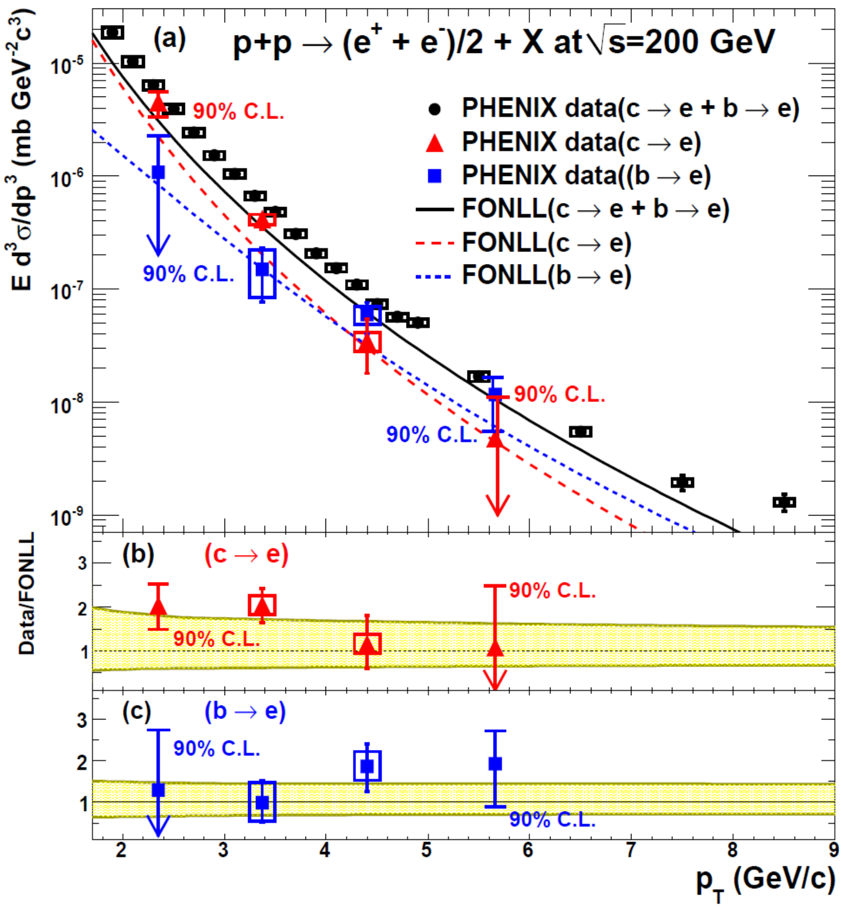
STAR

Phys. Rev. D 83, 052006 (2011)

PHENIX

Phys. Rev. Lett. 103, 082002 (2009)

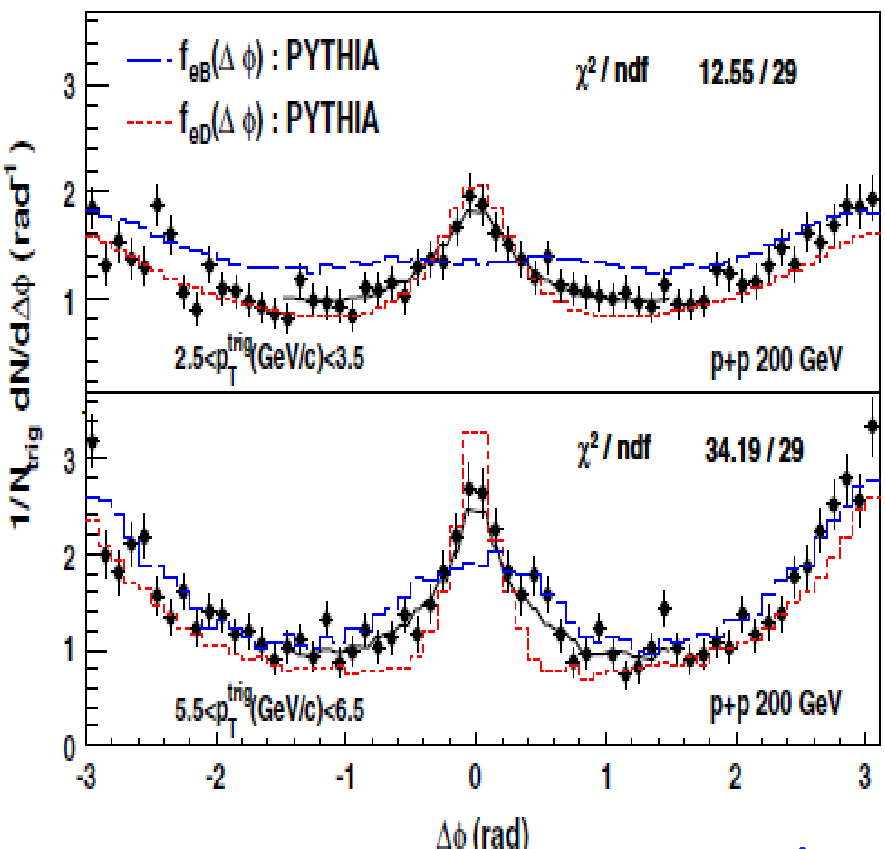




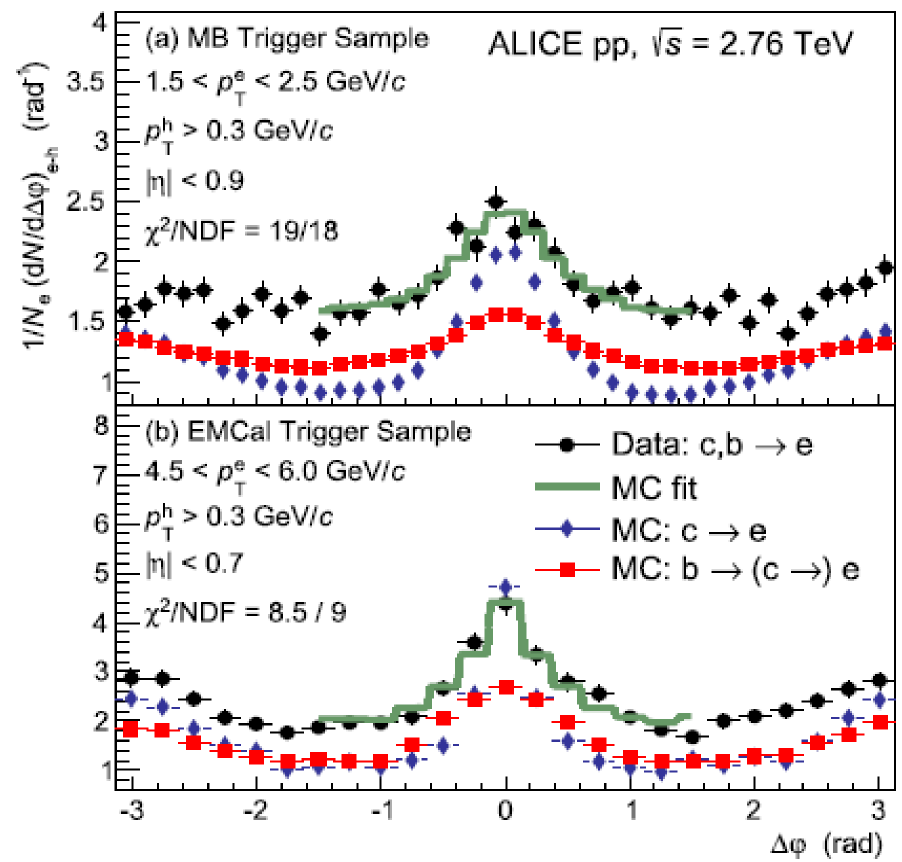
- The results for p+p at 200 GeV
- Such results for Au+Au will be much harder

Electrons from beauty decays : RHIC & LHC

STAR, PRL 105, 202301 (2010)



ALICE, PhysicsLetters B738 (2014) 97–108

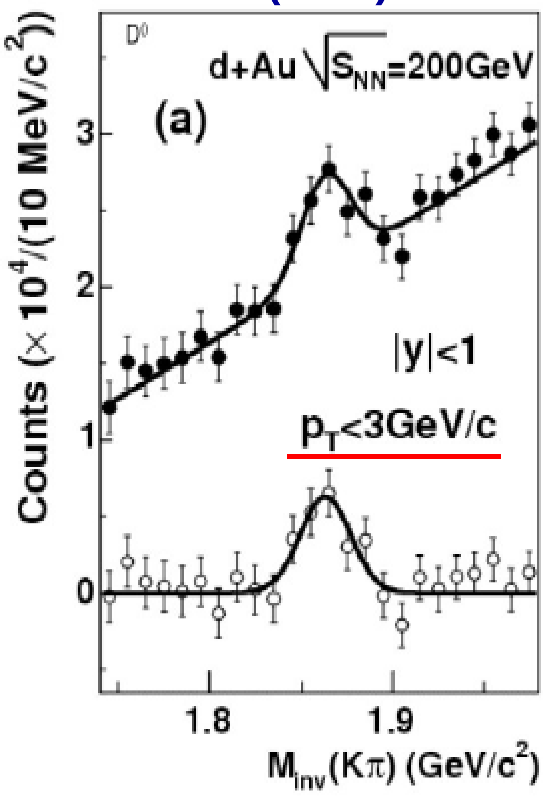


separation of e± from charm and beauty decays

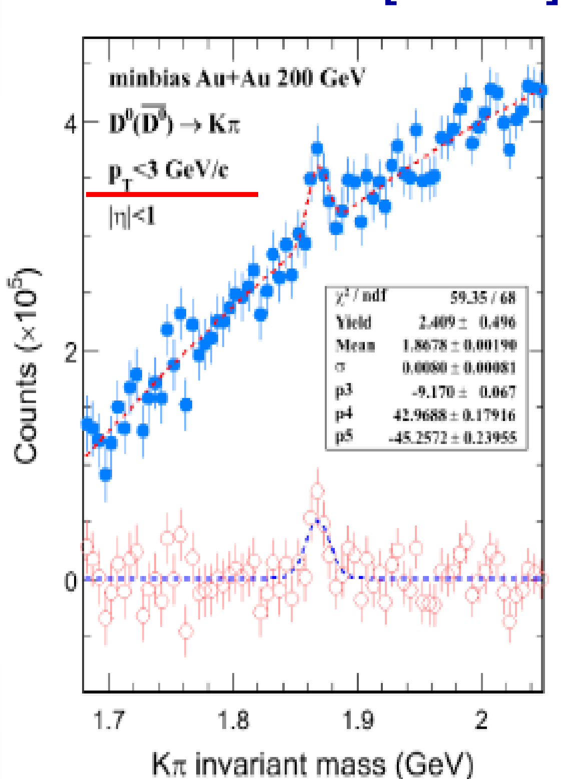
- **near-side peak for electron-hadron angular correlation**
  - **-- wider for electrons from beauty decays than**
  - **-- for those from charm decays**

Next challenge : D^0 reconstruction at RHIC STAR

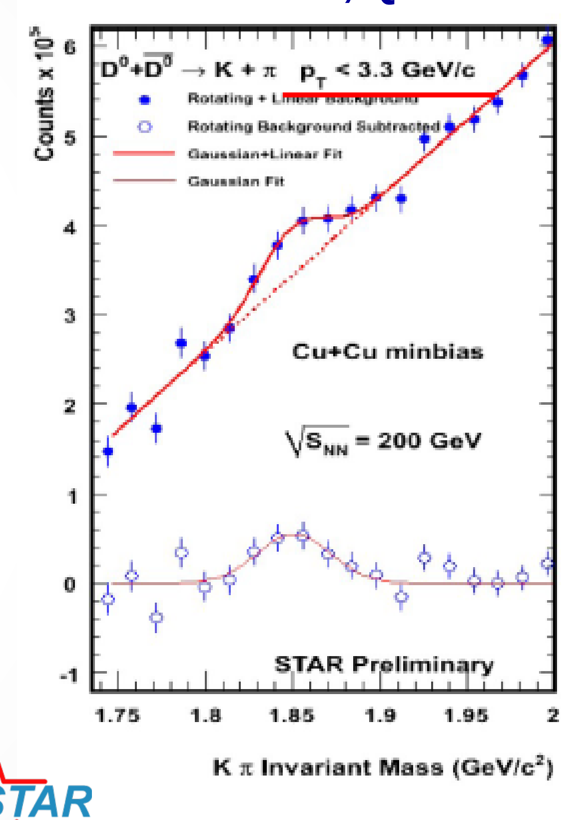
d+Au 200 GeV
PRL 94 (2005) 062301



Au+Au 200 GeV
arXiv:0805.0364 [nucl-ex]



Cu+Cu 200 GeV
A. Shabetai, QM 2008

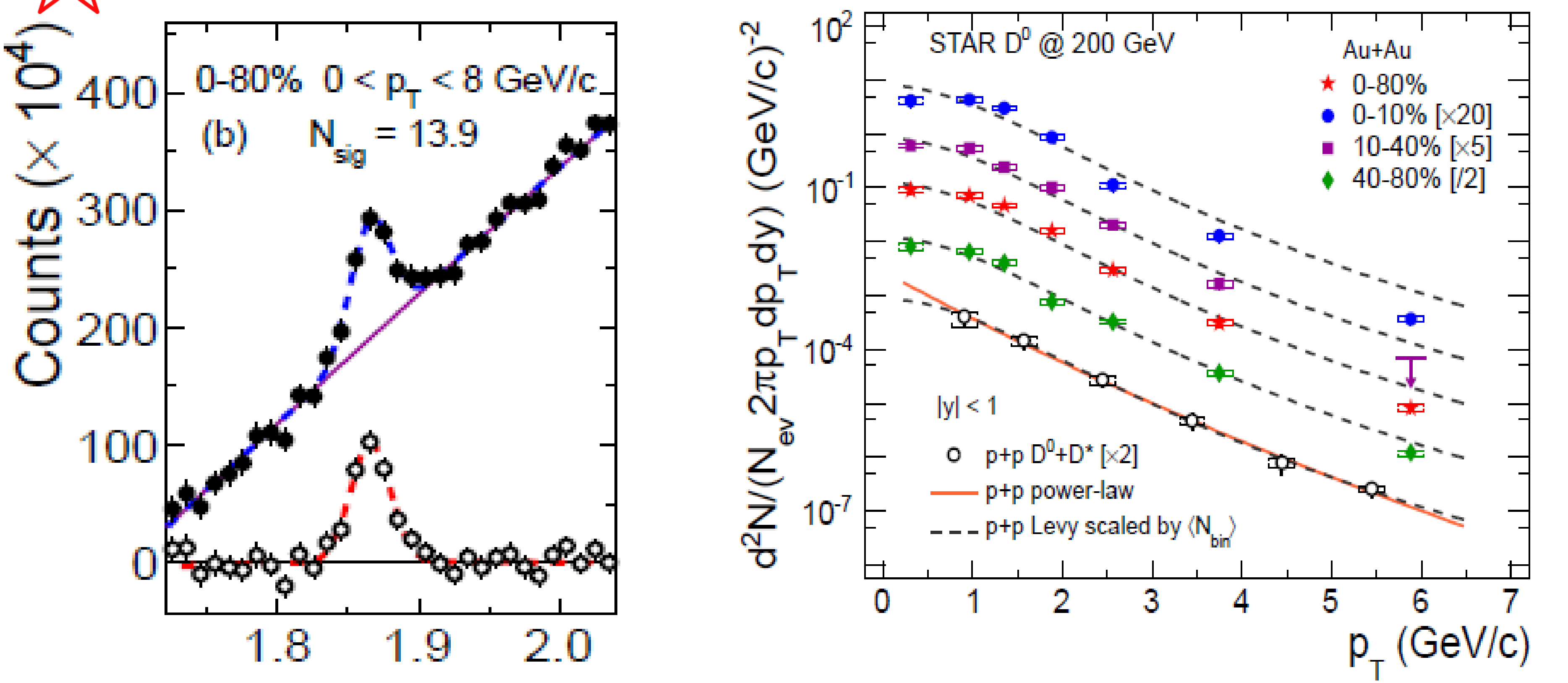


- **Open charmed mesons (first measured) in heavy-ion collisions**

Higher Luminosity : D^0 in Au+Au at RHIC

STAR

STAR Phys.Rev.Lett. 113 (2014) no.14, 142301 (STAR Collaboration)



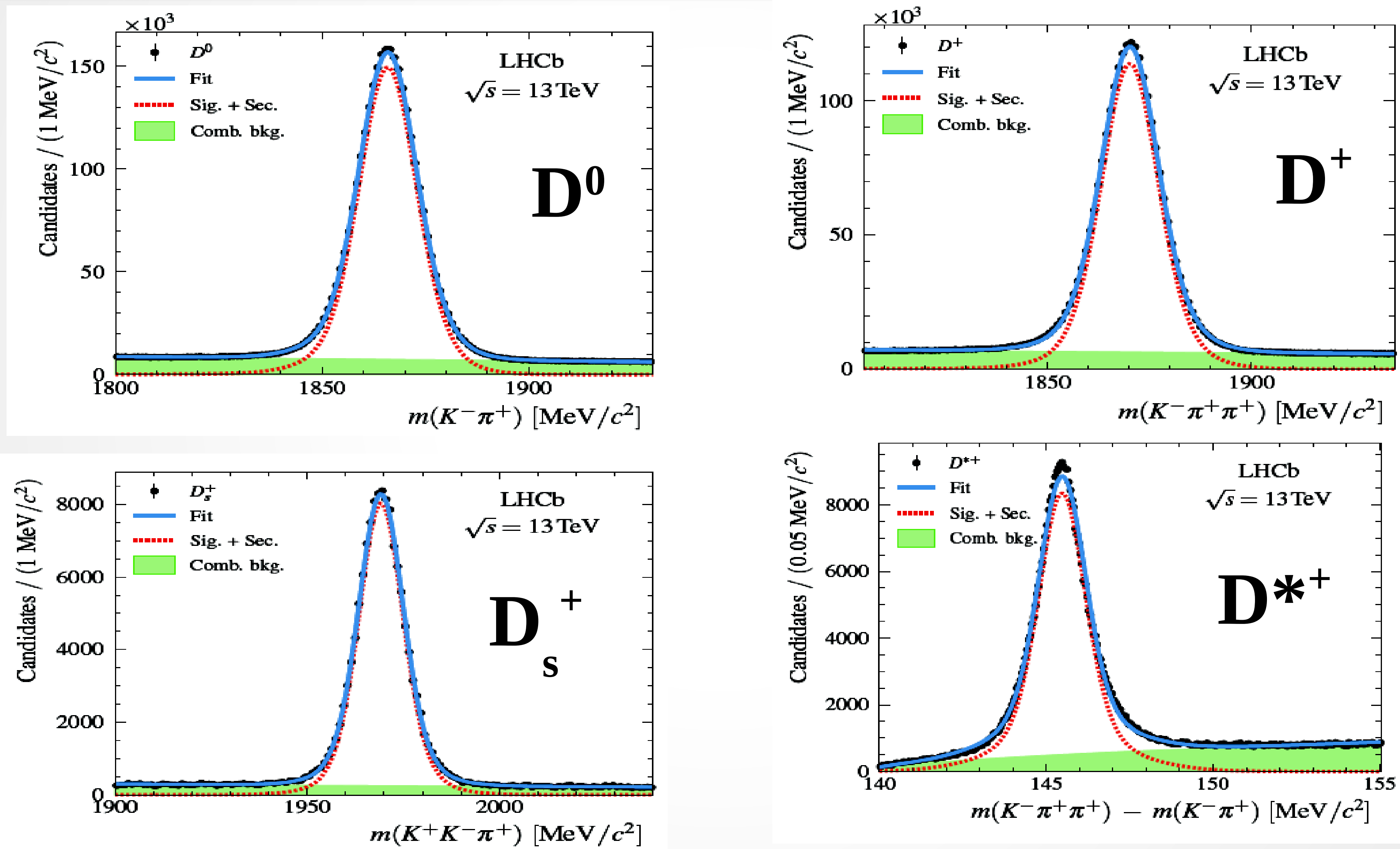
- **Open charmed mesons (first) detail studies in heavy-ion collisions**
- **Also the p_T spectra at different centrality classes are fitted**

Open charm at LHC : TeV regime

Spectra

LHCb   Forward rapidity

JHEP 1603 (2016) 159
Erratum: JHEP 1705 (2017) 074



- **Open charmed mesons detail studies in pp collisions at 13 TeV**

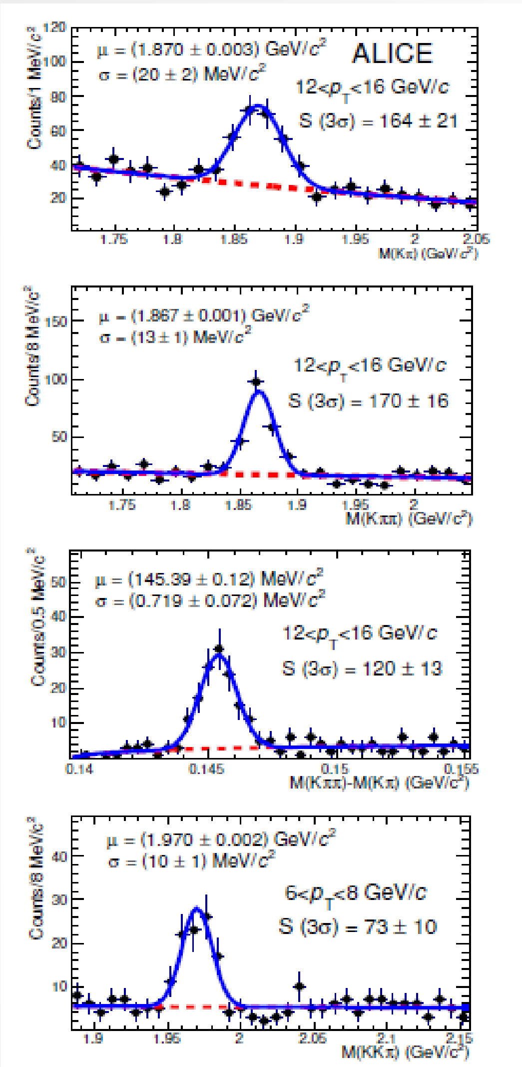
Open charm at LHC : TeV regime

Spectra

pp 7 TeV , Eur. Phys. J. C77 (2017) 550

Mid-rapidity, ALICE

Pb+Pb 2.76 TeV
JHEP 03 (2016) 081

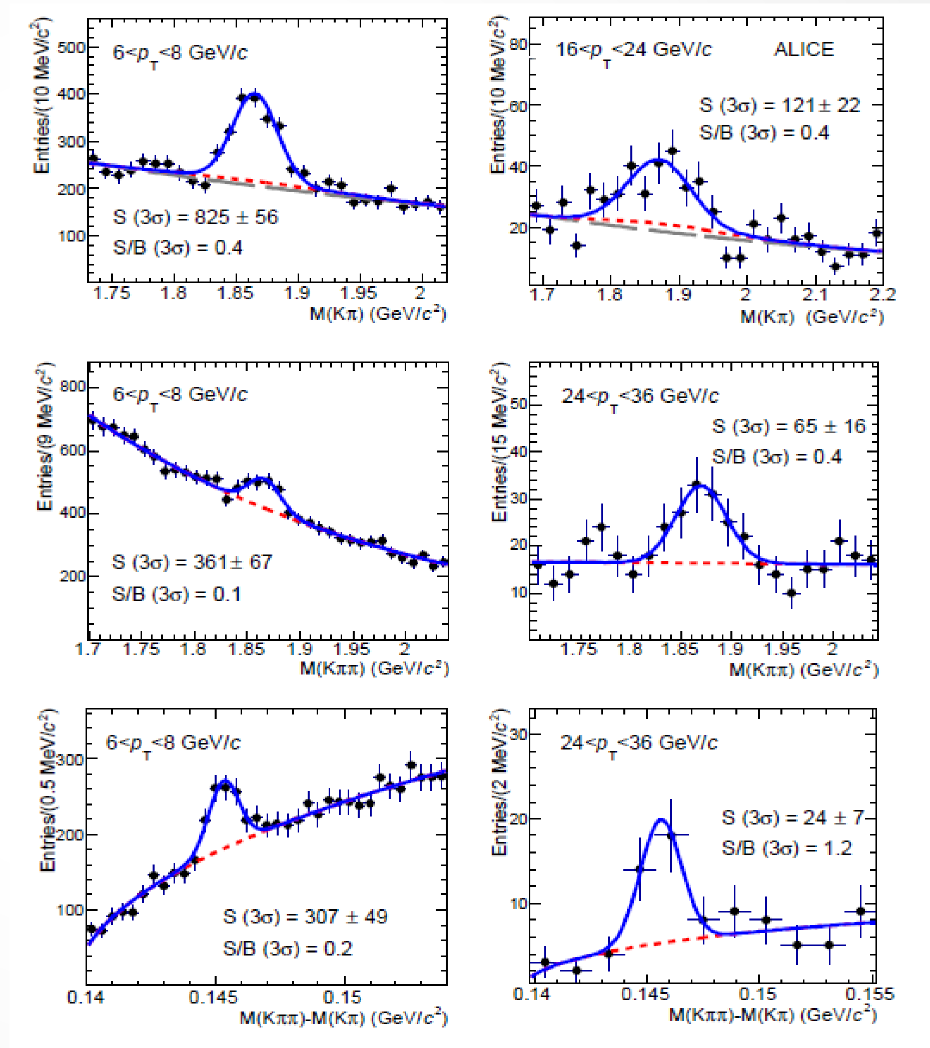


D^0

D^+

D^{*+}

D_s^+



D^0

D^+

D_s^+

- **Open charmed mesons detail studies in pp and also in Pb-Pb**

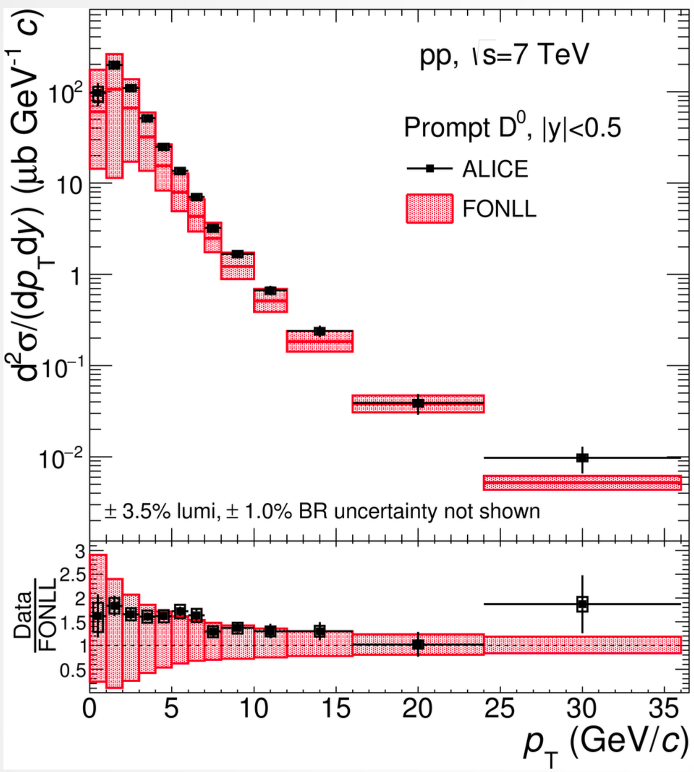
D^0 p_T spectra in pp collisions : LHC

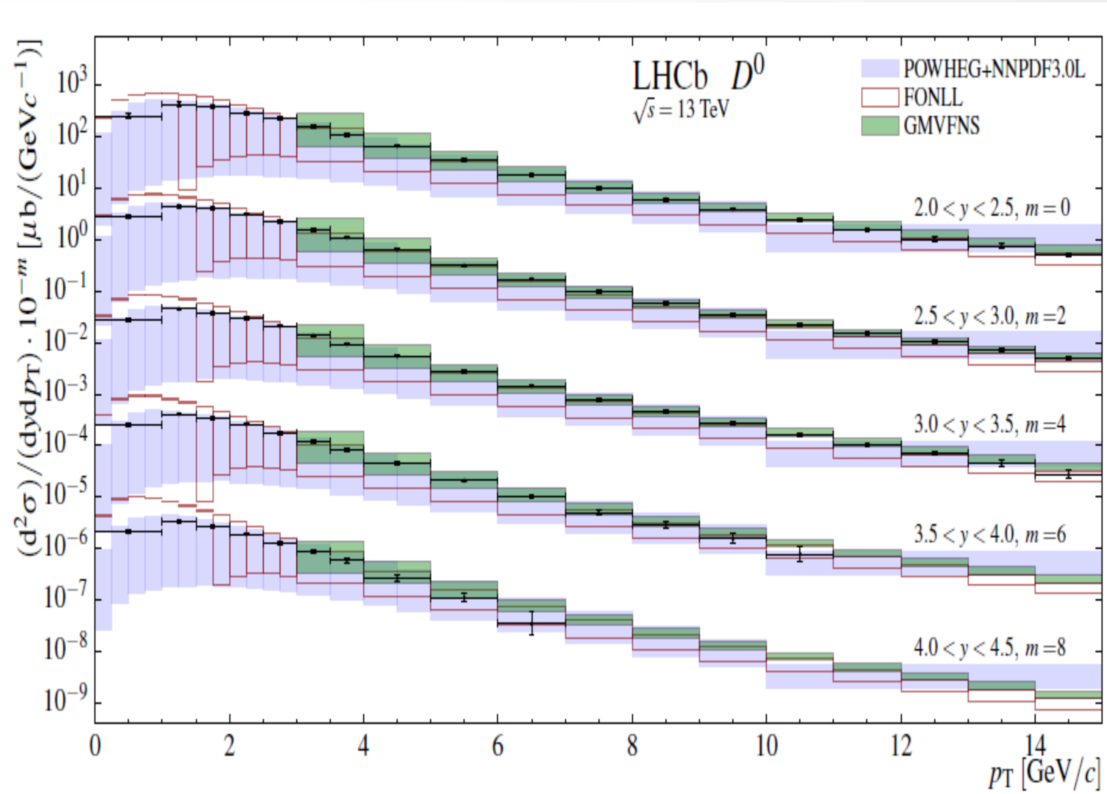
ALICE

LHCb

JHEP 1603 (2016) 159
Erratum: JHEP 1705 (2017) 074

ALICE, Eur. Phys. J. C77 (2017) 550



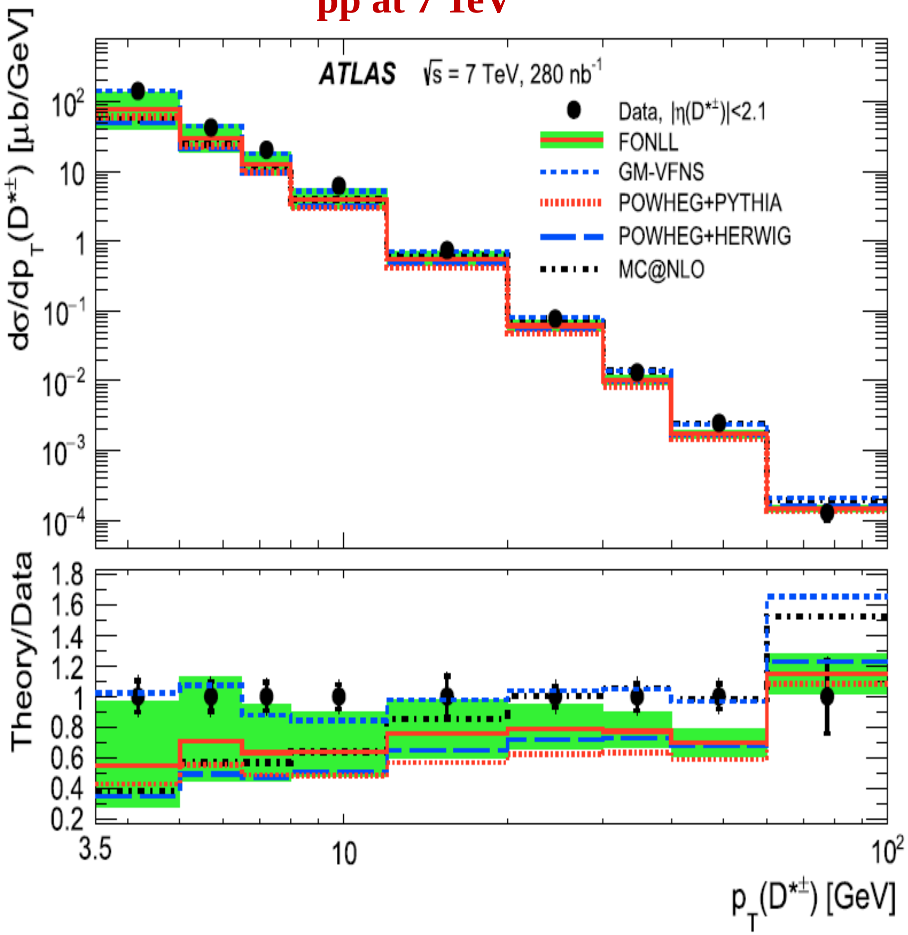


- **ALICE and LHCb D^0 p_T spectra**
- **Both data within FONLL uncertainty band (for $p_T < 3$ GeV/c)**
- **Both data on FONLL band upper edge (for $p_T > 3$ GeV/c)**

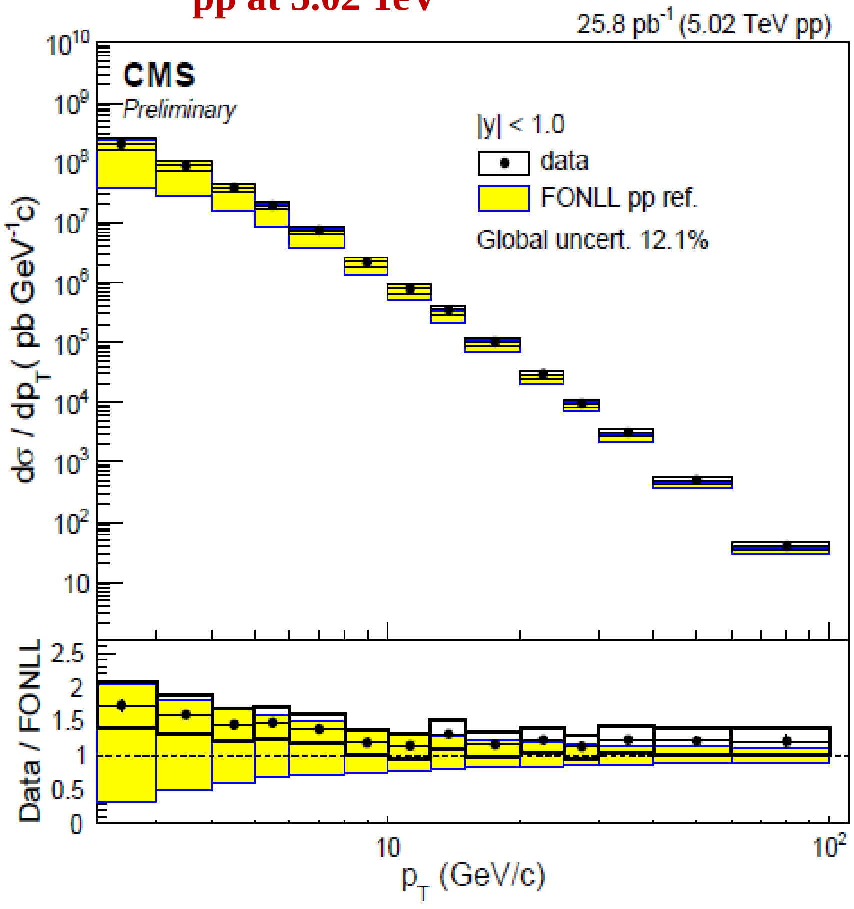
D^* and D^0 spectra at high p_T in pp : LHC

ATLAS NPB 907 (2016) 717 CMS-PAS-HIN-16-001 CMS

pp at 7 TeV



pp at 5.02 TeV



- **ATLAS data in agreement with GM-VFNS**
- **Both data (ATLAS & CMS) at p_T > 20 GeV/c higher than FONLL**

Heavy Flavor : D* in Jets

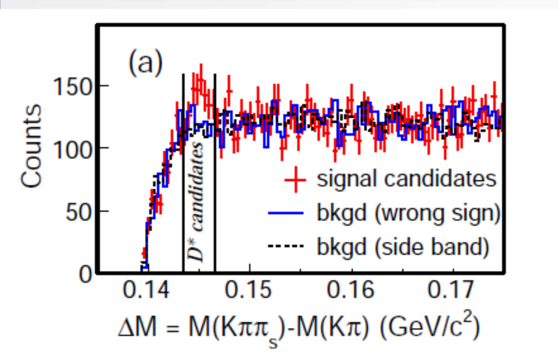
STAR

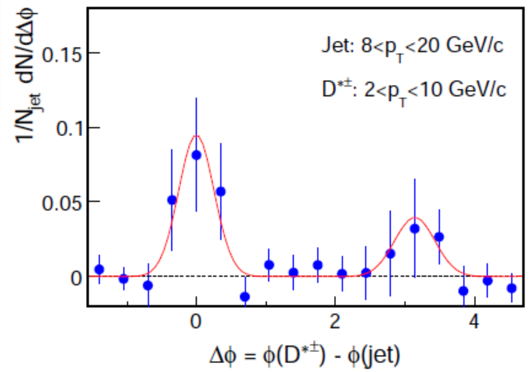
Phys.Rev.D 79, 112006, 2009

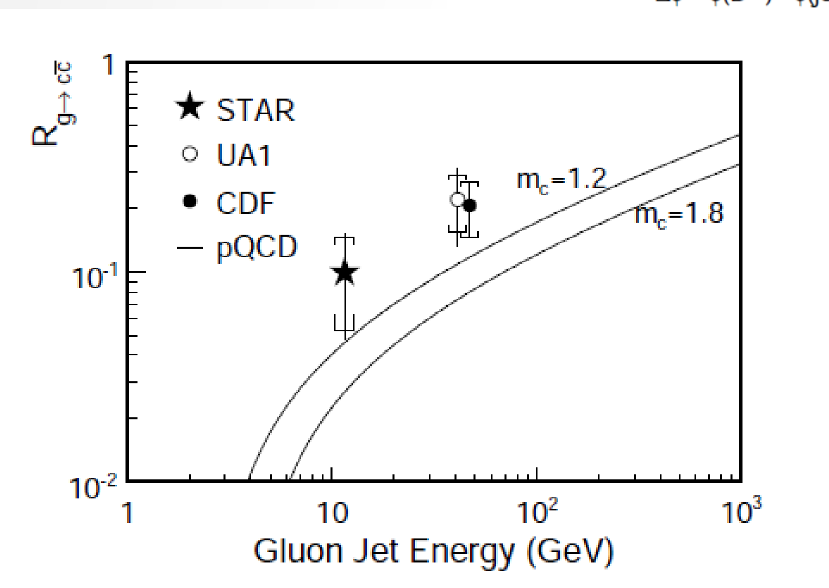
Jets

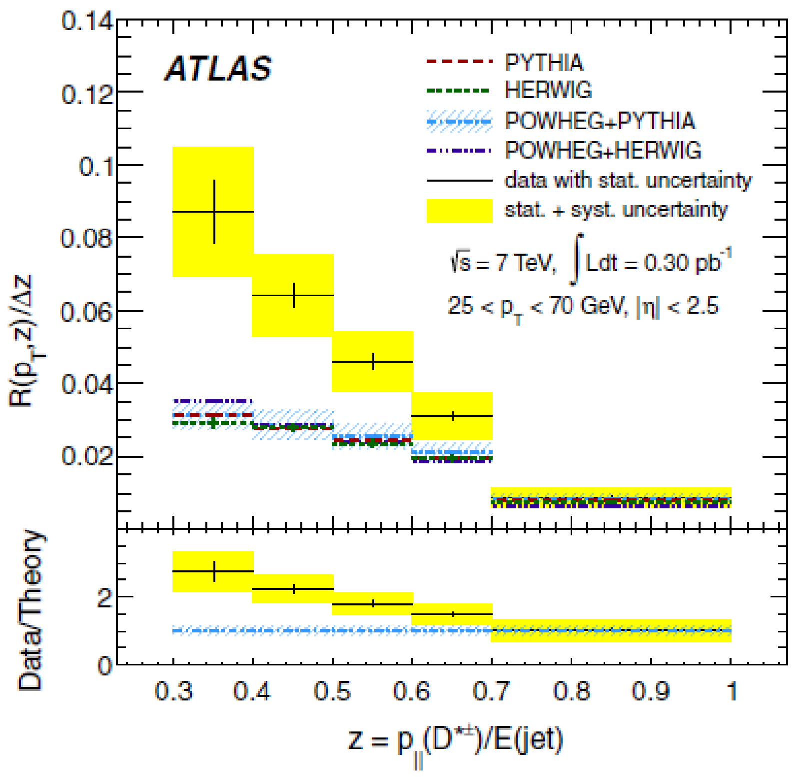
ATLAS

Phys.Rev. D 85, 052005 ,2012









Charm content in Jets : The ratio $N(D^{*+} + D^{*-}) / N$ (jet) is measured to be 0. 015 ± 0. 008(stat) ± 0. 007(sys) for D^* mesons with fractional momenta $0.2 < z < 0.5$ in jets with a mean transverse energy of 11.5 GeV.

Charm content in Jets : $N(D^{*\pm}) / N$ (jet) is 0. 025 ± 0. 001(stat) ± 0. 004(sys) for jets with transverse momentum between 25 and 70 GeV in $|\eta| < 2.5$ and $D^{*\pm}$ mesons with fractional momenta $0.3 < z < 1$.

EIC Physics Connections!

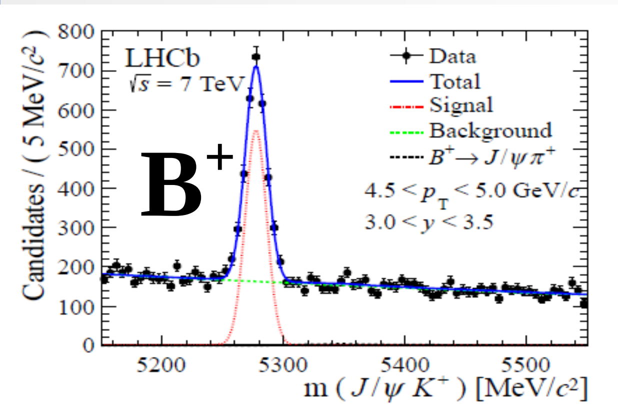
Open bottom at LHC : TeV regime

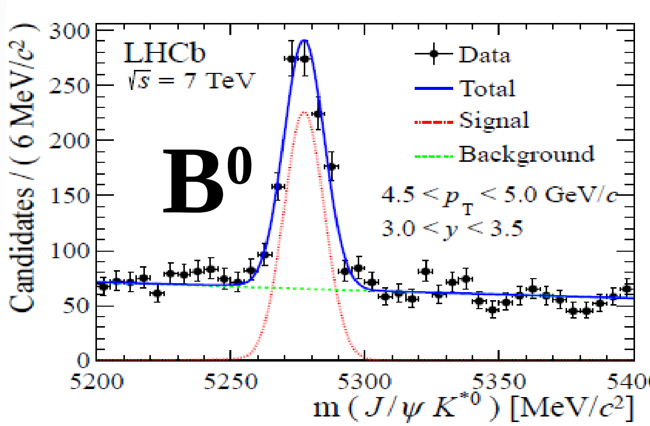
Spectra

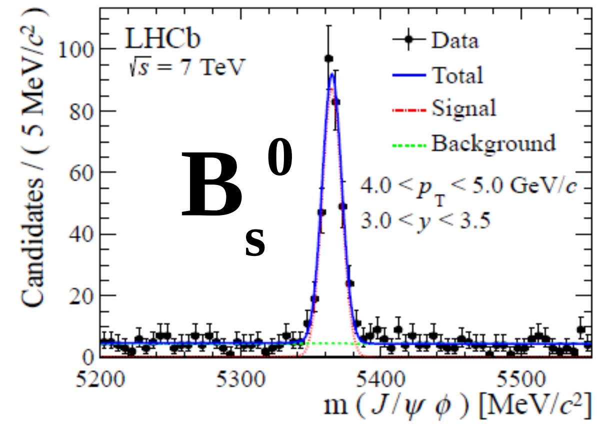
LHCb, Forward rapidity

pp at 7 TeV

JHEP08(2013)117



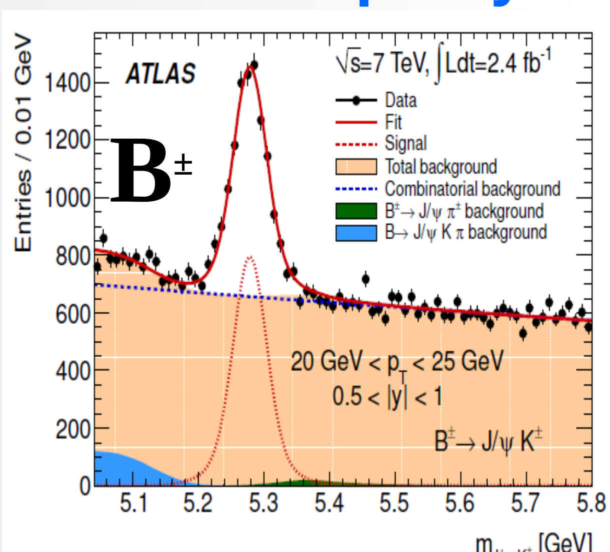




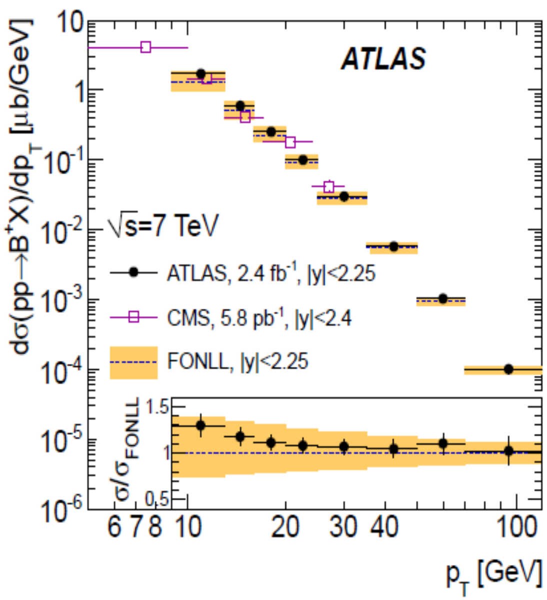
Mid - rapidity

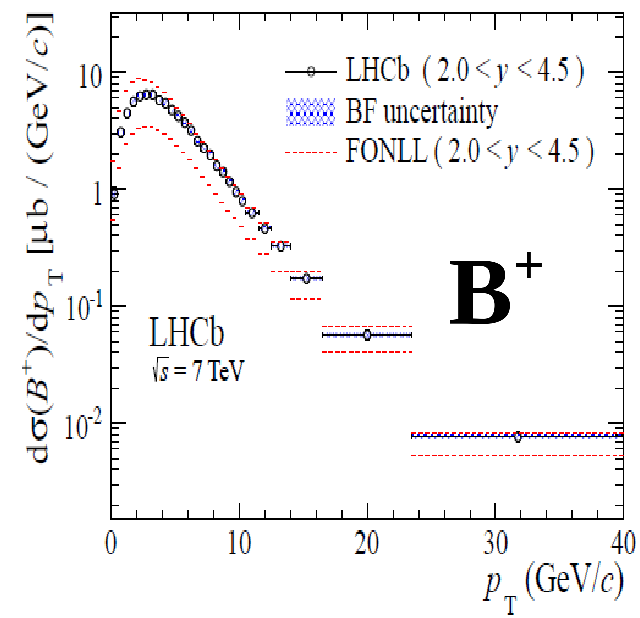
ATLAS

LHCb



ATLAS, JHEP10(2013)042





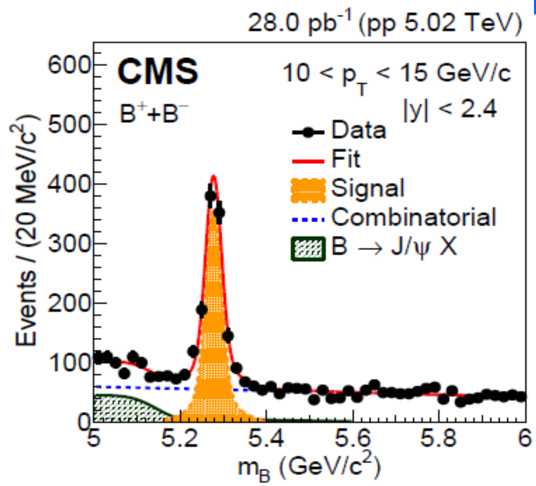
- **Open bottom mesons detail studies in pp collisions at 7 TeV**

B^+ p_T spectra at LHC

CMS

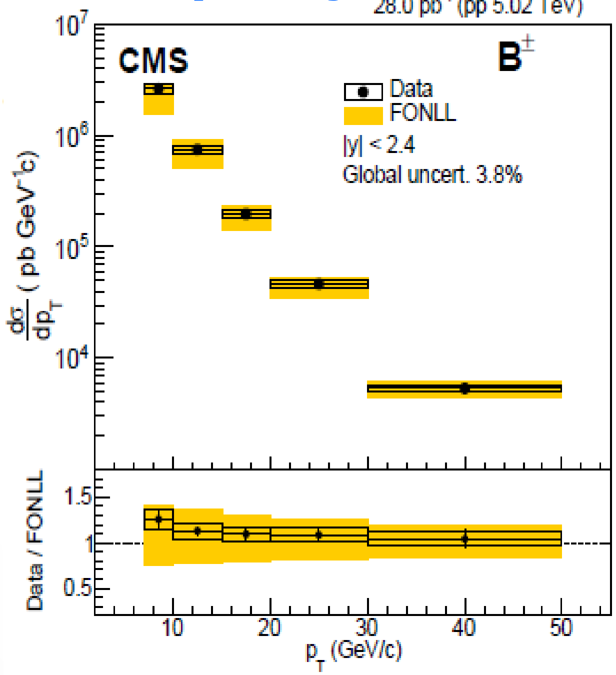
Phys. Rev. Lett. 119, 152301 (2017)

pp at 5.02 TeV

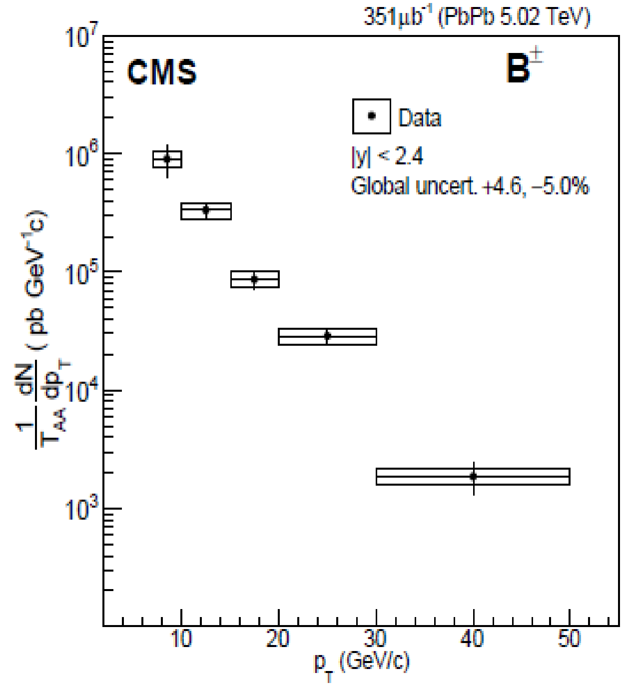


Mid - rapidity

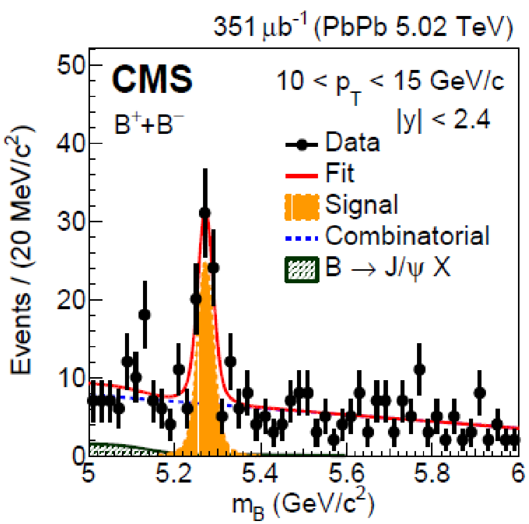
pp at 5.02 TeV



Pb+Pb at 5.02 TeV



Pb+Pb at 5.02 TeV



- **FONLL describes the pp data well for CMS**
- **FONLL agrees with LHCb (forward rapidity)**
- **FONLL explains ATLAS & CMS data at 7 TeV**

The last two bullets from previous slide 7 TeV pp data-sets

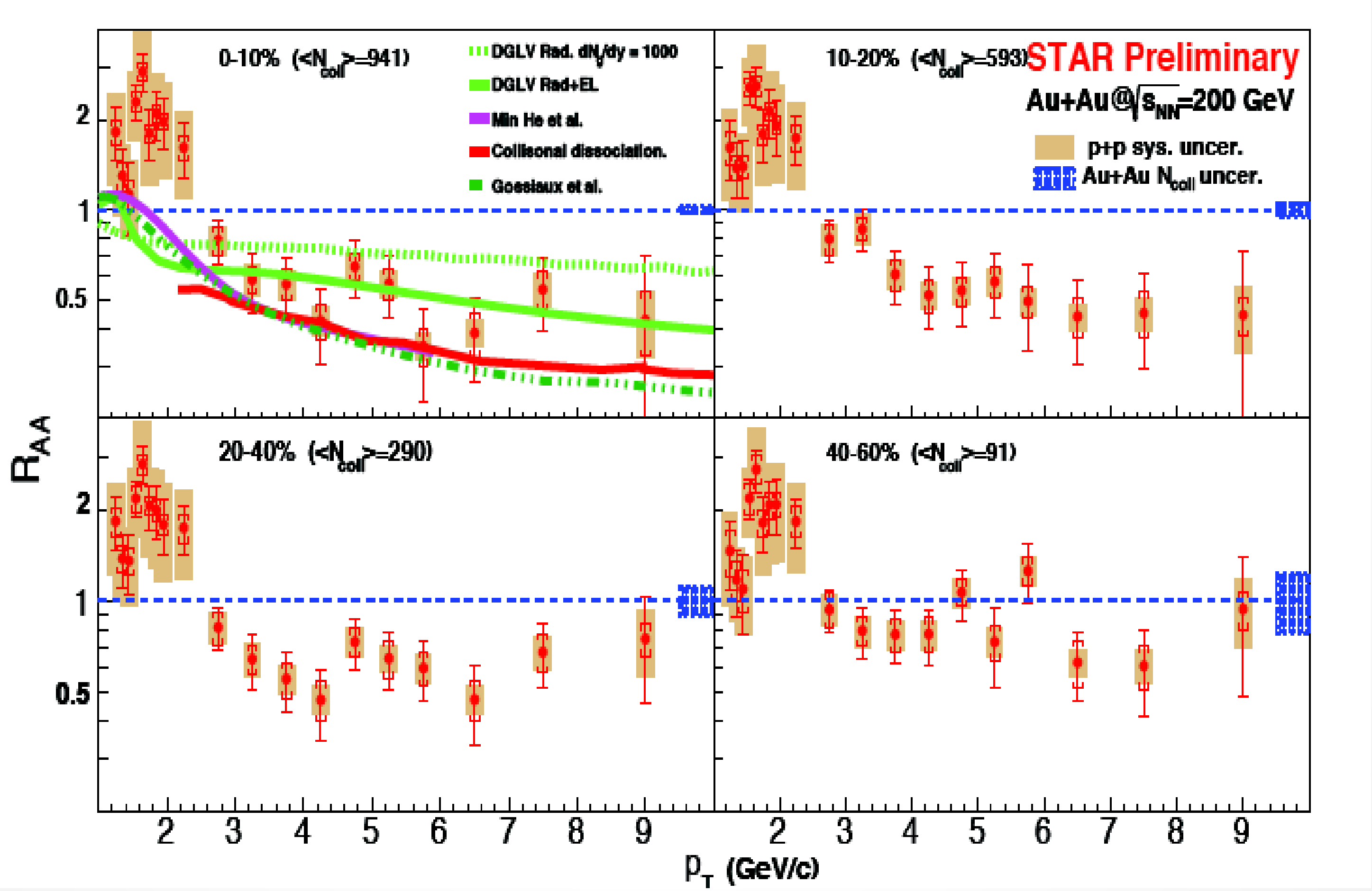
Nuclear modification factor

Single electron R_{AA} : RHIC

Medium studies

STAR

QM 2015, Nuclear Physics A 956 (2016) 513–516



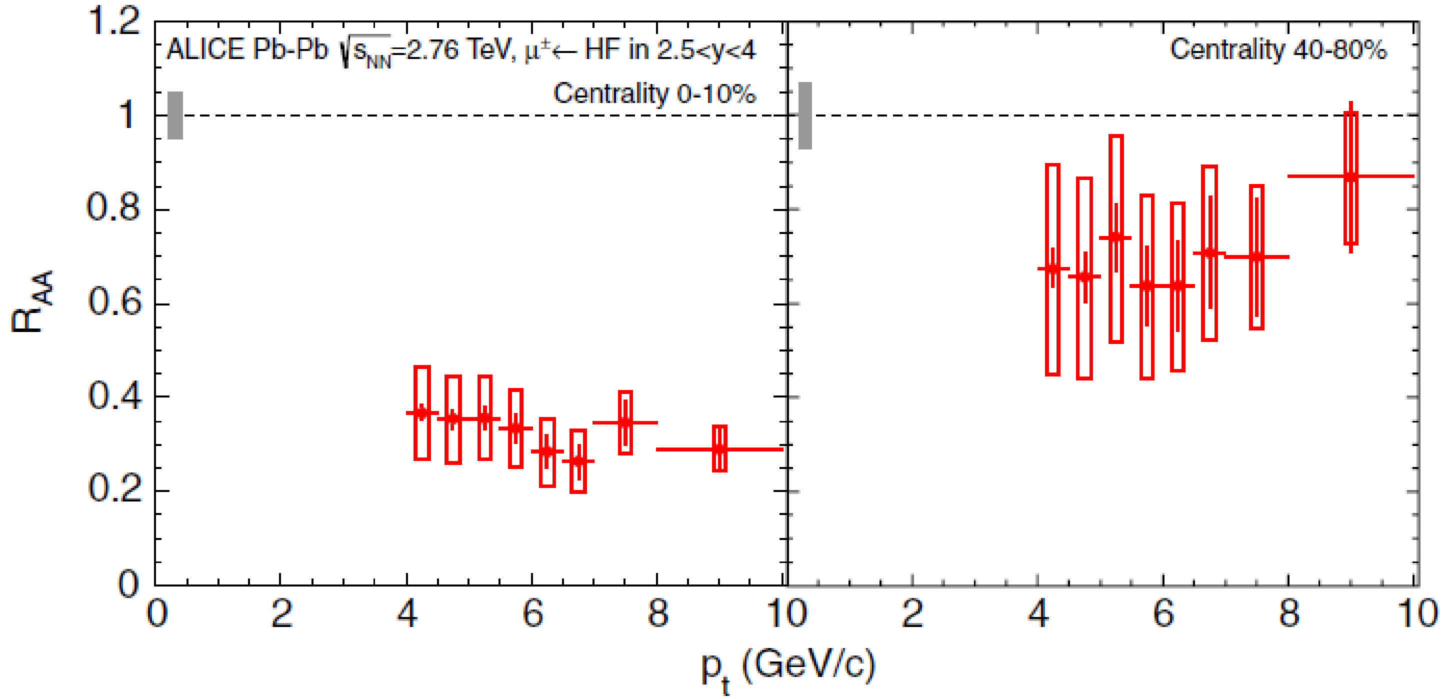
- Strong suppression for p_T> 4 GeV/c in central collisions but less towards more peripheral collisions
- Likely enhancement at low p_T in both central and peripheral collisions

HF decay lepton R_{AA} : LHC

PRL 109, 112301 (2012)

Pb+Pb 2.76 TeV

ALICE

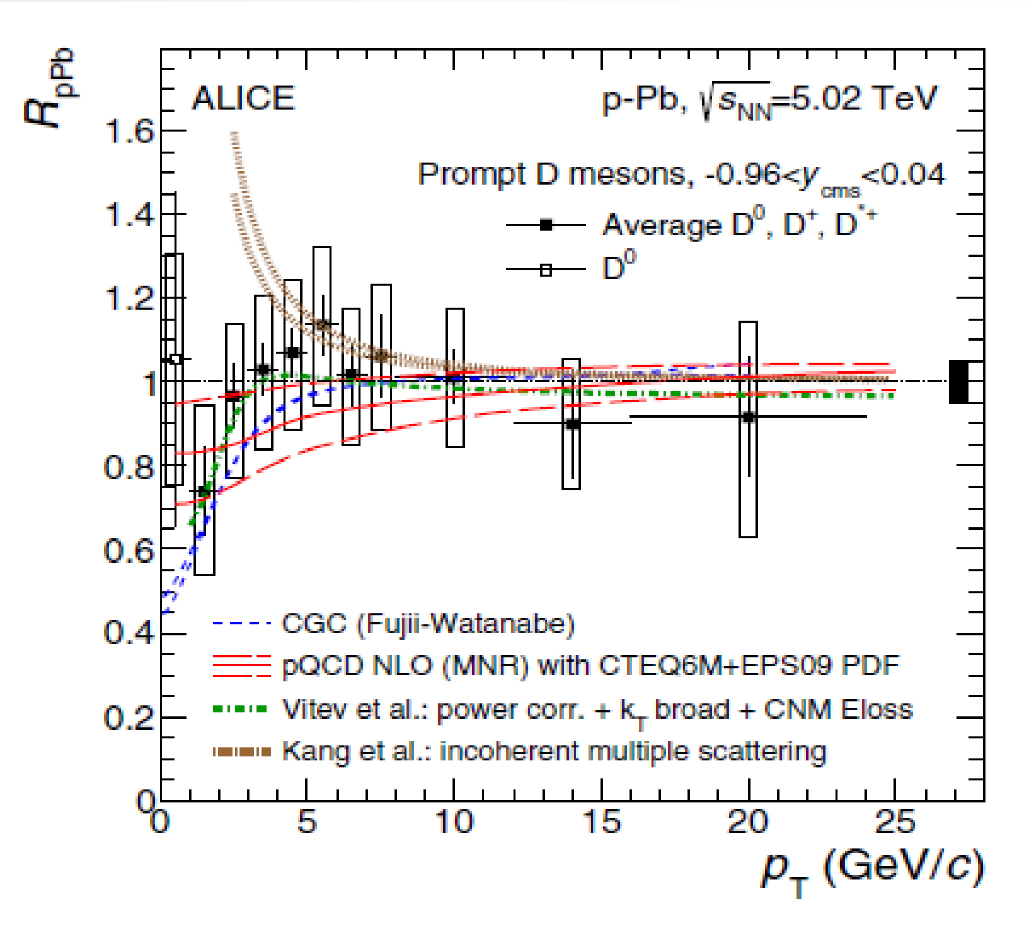


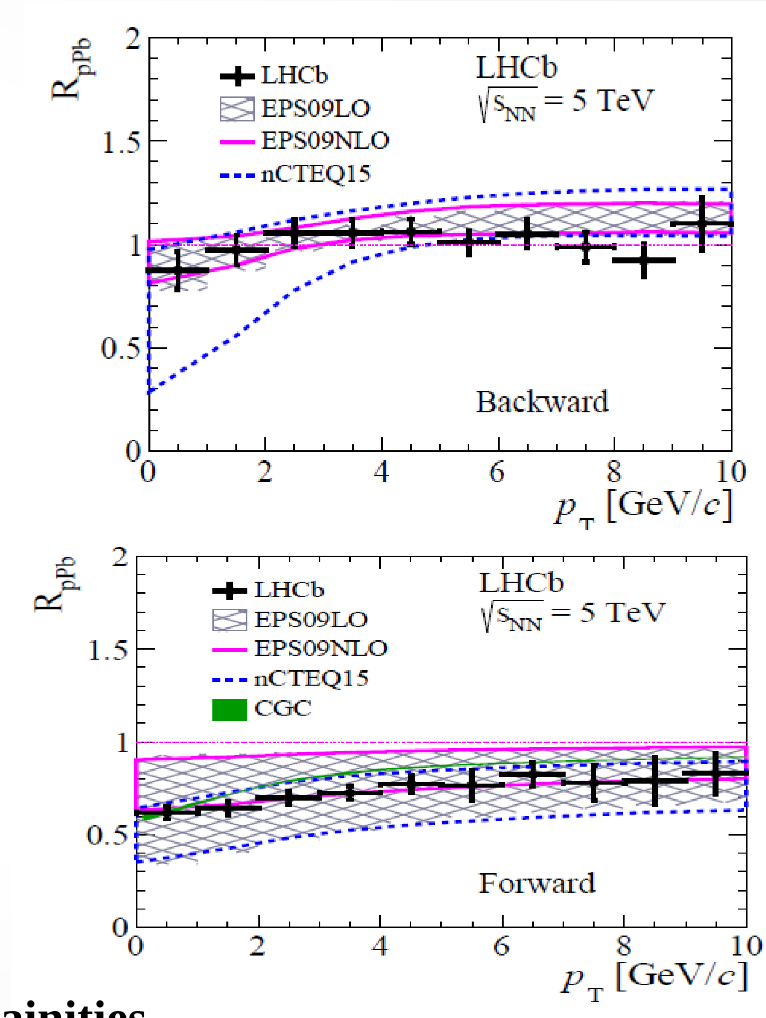
- yields of leptons from heavy-flavor decays show suppression at high p_T in central Pb-Pb collisions, compared with binary scaled pp collisions
- less suppression in more peripheral collisions

D^0 mesons in pA collisions : LHC

ALICE, PHYSICAL REVIEW C 94, 054908 (2016)

LHCb , JHEP 1710 (2017) 090



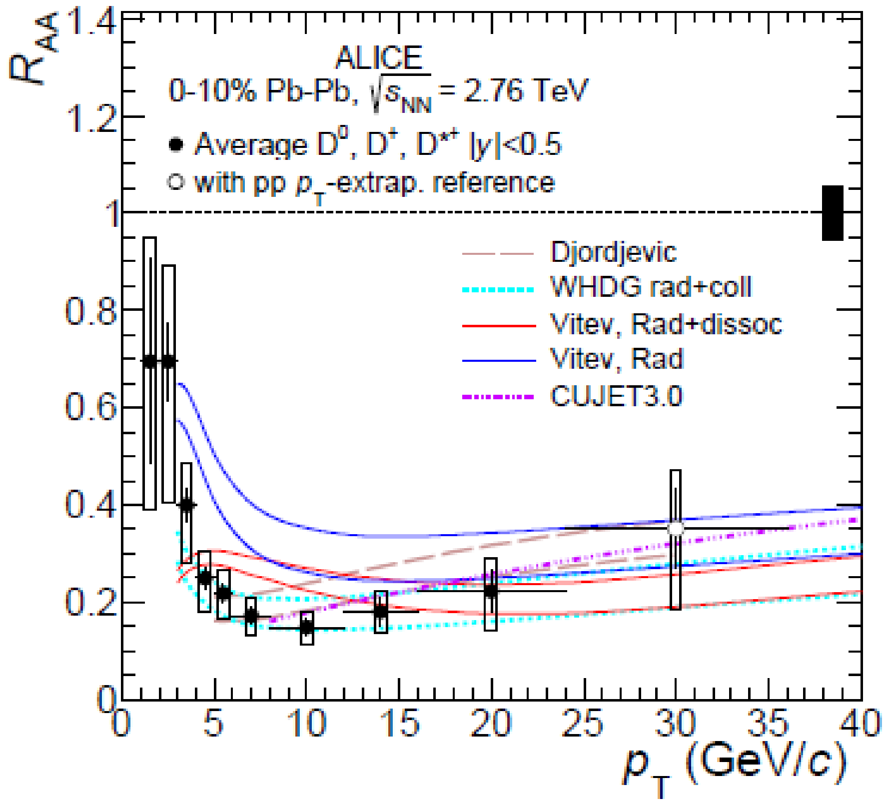


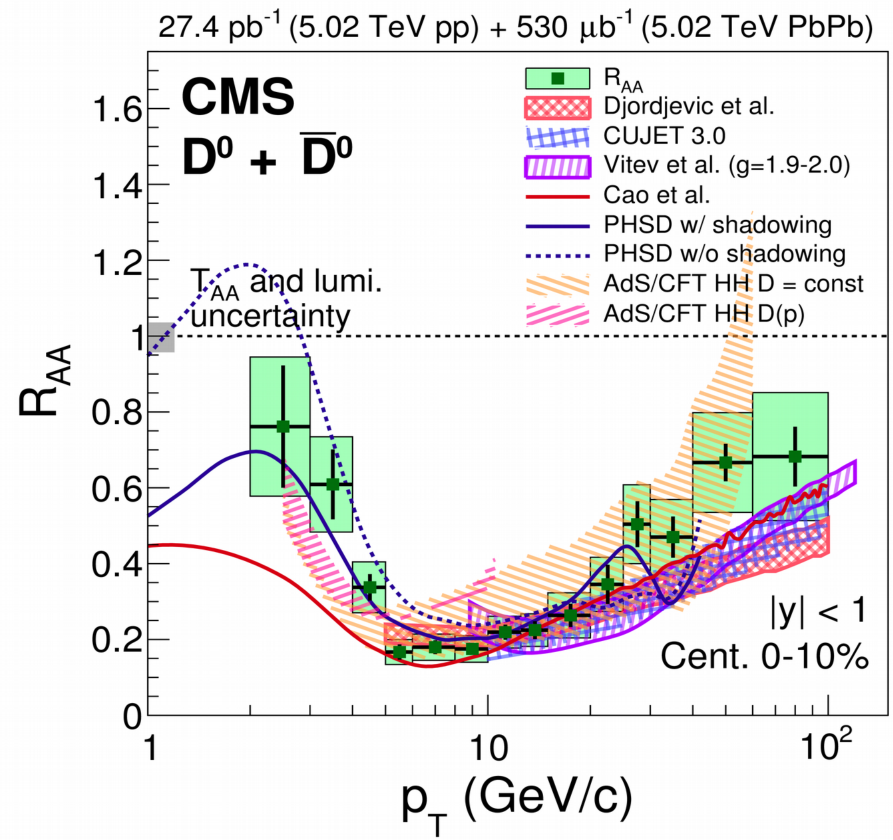
- **ALICE R_{pA} data are consistent with 1 within uncertainities**
  - **We see no major modification in pPb and also similar with LHCb**
- **We need more precise data to be able to separate between the models**

D mesons in AA collisions : LHC

ALICE , Pb+Pb 2.76 TeV
JHEP 03 (2016) 081

CMS , Pb+Pb 5.02 TeV , CMS-PAS-HIN-16-001 ,
arXiv:1708.04962



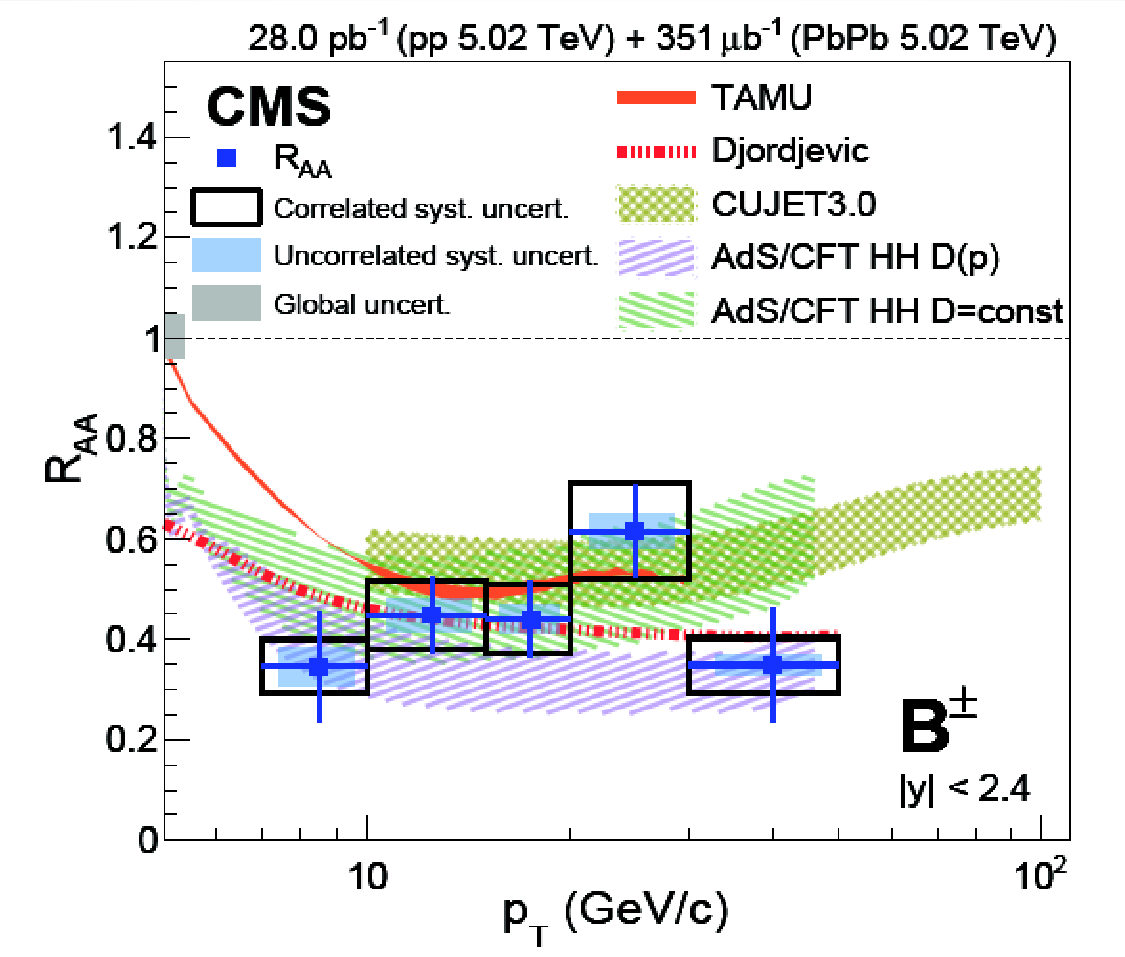


- **Similar suppression in Pb+Pb at 2.76 TeV and 5.02 TeV**

Beauty Suppression : LHC

CMS

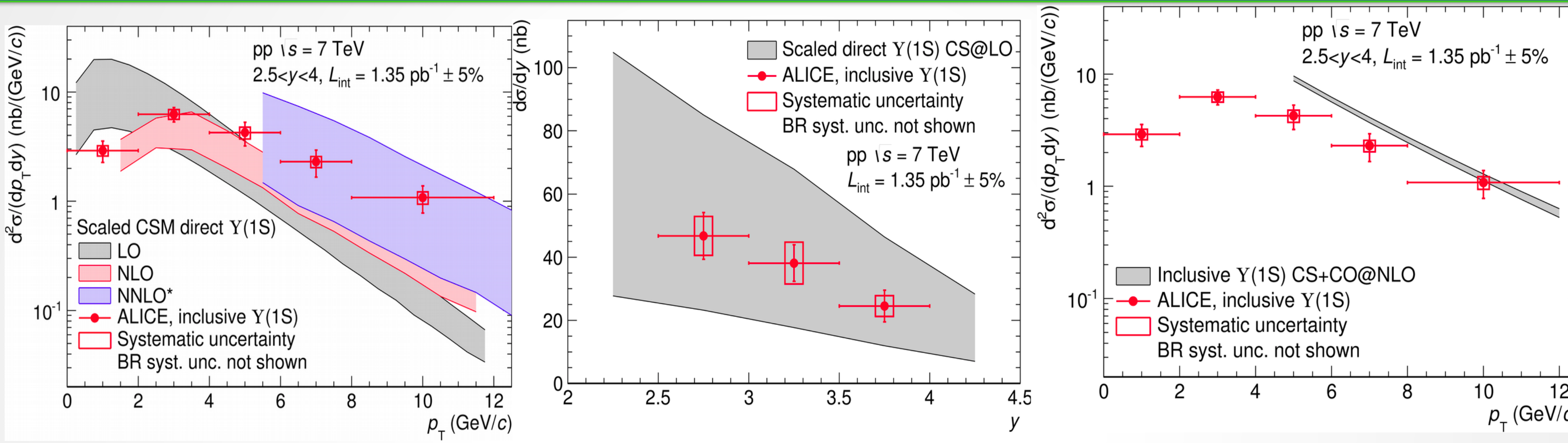
Pb+Pb 5.02 TeV, Phys. Rev. Lett. 119, 152301 (2017)



- Consistent with various models
- But we need more precise data to extract detailed underlying mechanism from the various models

Forward Rapidity : with Onia and Models

EPJC 74 (2014) 2974
p-p @ 7 TeV



Color Singlet Model [NPA470 (2013) 910]

– Calculations for LO and NLO
- Qualitative features like data for low p_T and rapidity dependence
- Underestimates the data at high p_T

– Also the leading-p_T NNLO contributions
- Better agreement at high p_T, but with large uncertainties

Non-Relativistic QCD (NRQCD)
[PRD84 (2011) 114001, PRD85 (2012) 114003]
-- Theory overestimates the data
-- Smaller disagreement at high p_T

ϒ(2S) -to-ϒ(1S) ratio in good agreement with CSM & NRQCD & Hybrid [Mod. Phys. Lett. A 28, 1350120 (2013)]
(L.S.Kisslinger and DD)

More on Forward rapidity

Onia

JHEP 1511, 103, (2015)

LHCb, pp

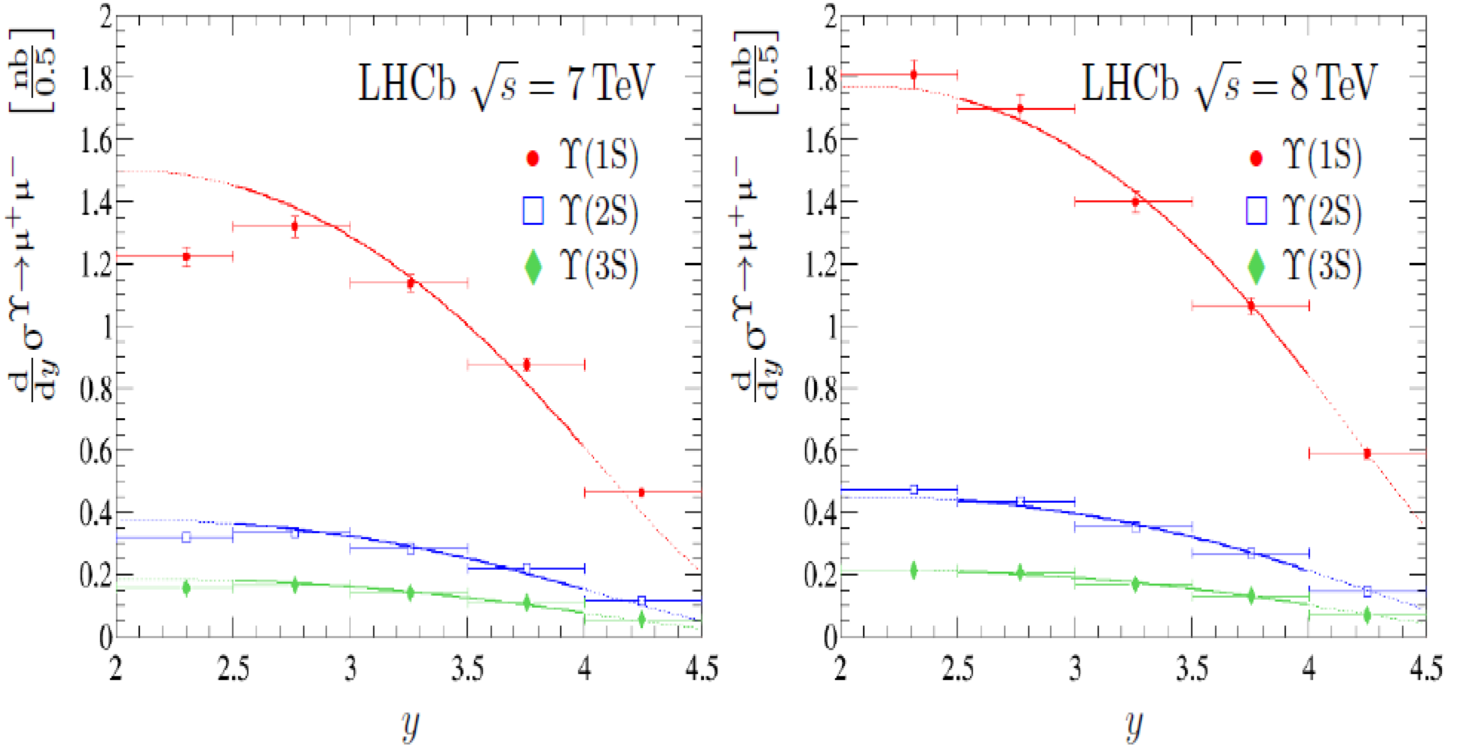


Figure 4. Differential cross-sections $\frac{d}{dy}\sigma^{\Upsilon\to\mu^+\mu^-}$ in the range $p_T < 30$ GeV/c for (red solid circles) $\Upsilon(1S)$, (blue open squares) $\Upsilon(2S)$ and (green solid diamonds) $\Upsilon(3S)$ mesons for (left) $\sqrt{s} = 7$ TeV and (right) $\sqrt{s} = 8$ TeV data. Thick lines show fit results with the CO model predictions from refs. [63, 64] in the region $2.5 < y < 4.0$, and dashed lines show the extrapolation to the full region $2.0 < y < 4.5$. The data points are positioned in the bins according to eq. (6) in ref. [62].

(L.S.Kisslinger and DD)
Mod.Phys.Lett. A28 (2013) 1350067 (forward rapidity)
Mod.Phys.Lett. A28 (2013) 1350120. (7.0 TeV)
Mod.Phys.Lett. A29 (2014) 1450082. (8.0 TeV)

Onia

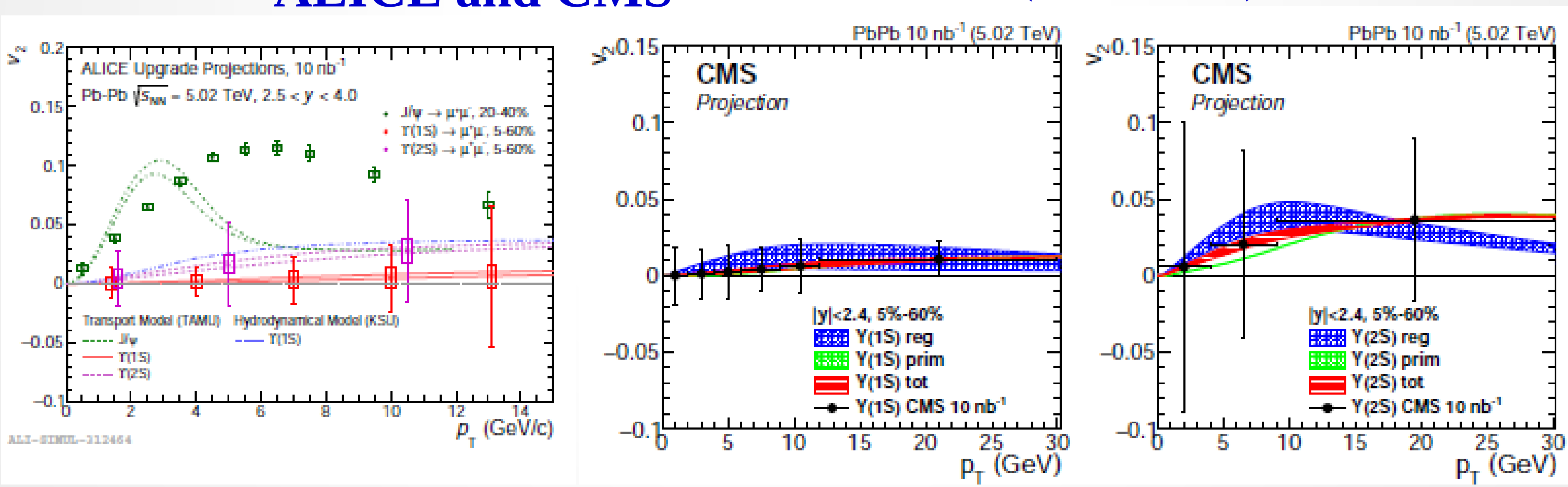
Bottomonia flow?

DD and N.Dutta, Int.J.Mod.Phys. A33 **(June 2018)** no.16, 1850092

Studies of J/ψ v_2 at RHIC and LHC energies have provided important elements toward the understanding on the production mechanisms and thermalization of charm quarks. Bottomonia has an advantage since it is a cleaner probe. A brief discussion has been provided for $\Upsilon(1S)$ v_2, which can become the new probe for QGP, including the necessity of studies for small systems.

ALICE and CMS

ArXiv: 1812.06772 **(December 2018)** YELLOW REPORT

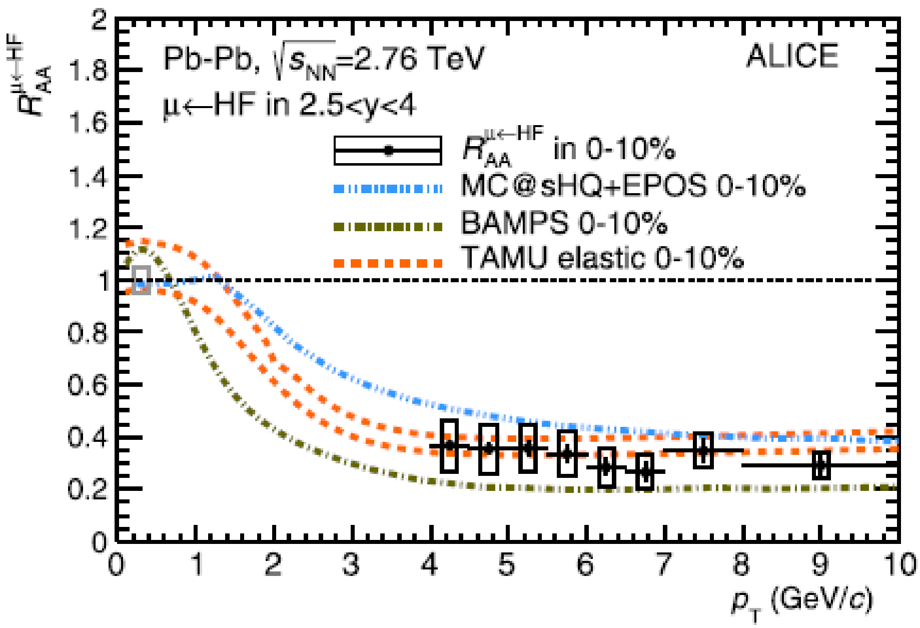


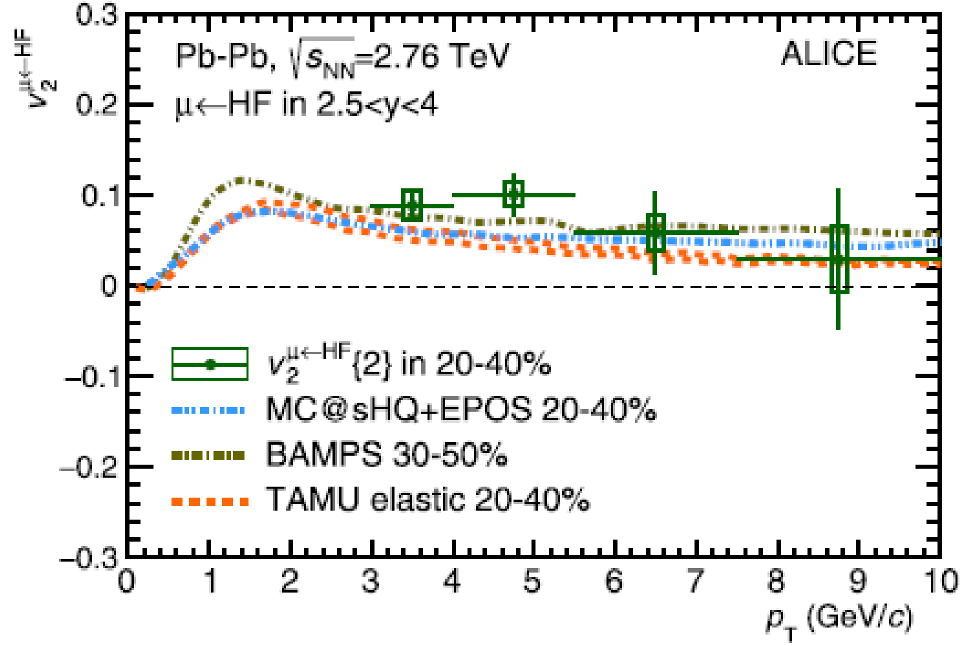
(CERN) Yellow Report on Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

What's new (2019) : **ALICE** : arXiv:1907.03169 & **CMS** : http://cds.cern.ch/record/2698580 comparable at 5.02 TeV Pb+Pb

Where lies the challenge?

ALICE, PLB 753 (2016) 41





simultaneous description of HF decay R_{AA} and v_2 is a challenge

-- can constrain energy loss models

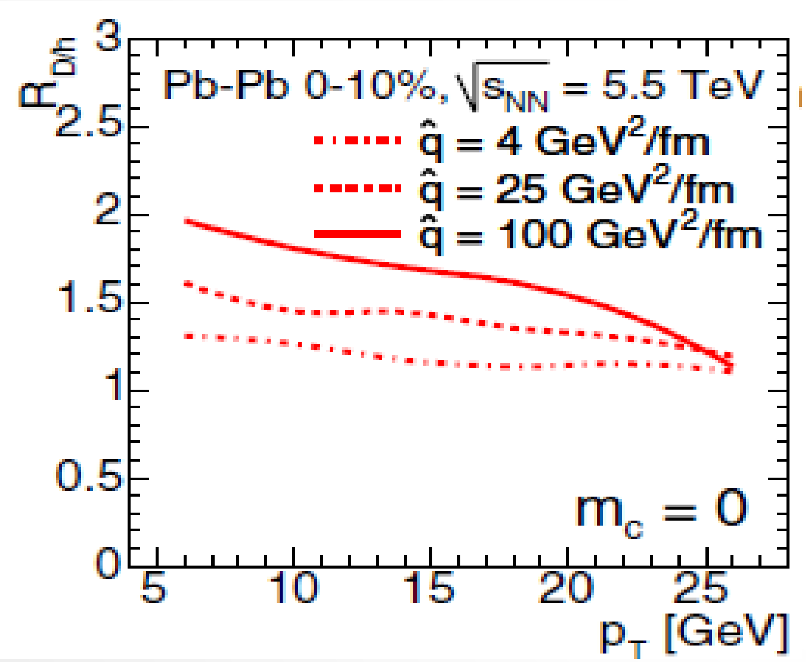
Heavy-flavor energy loss at LHC : ADS/CFT

Armesto,Dainese,Salgado,Wiedemann
PHYSICAL REVIEW D 71, 054027 (2005)

Horowitz, Gyulassy
Physics Letters B 666 (2008) 320–323

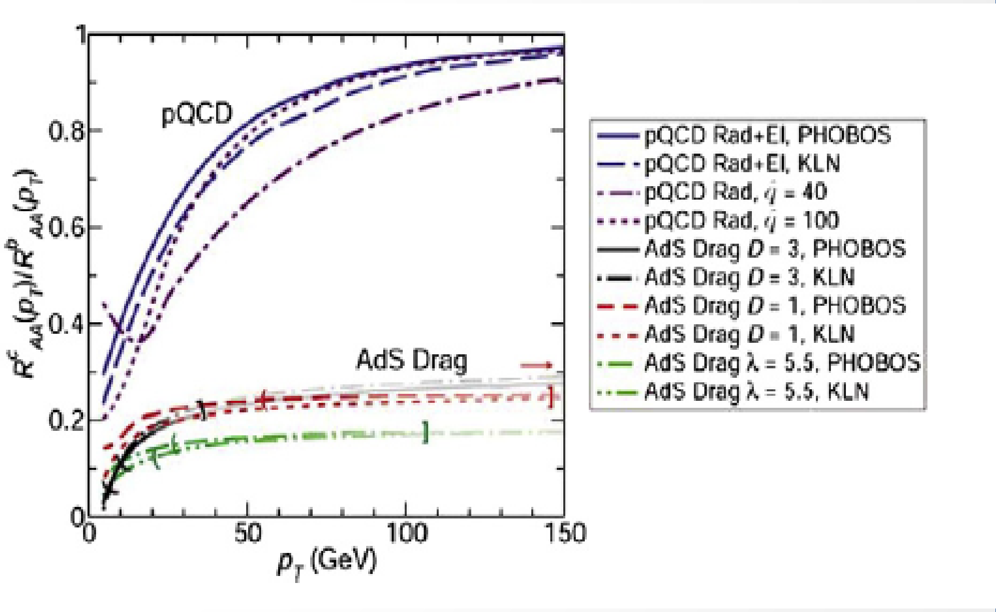
Colour charge dependence

$$R_{D/h}(p_t) = R^D_{AA}(p_t) / R^h_{AA}(p_t)$$



Mass hierarchy

$$R_{B/D}(p_t) = R^{e\ \mathrm{from\ B}}_{AA}(p_t) / R^{\mathrm{e\ from\ D}}_{AA}(p_t)$$



- More intricacies on heavy-flavor quenching mechanisms
- R^c_{AA}/R^b_{AA} ratio differ as we see for pQCD and AdS/CFT

Unanswered Questions and next steps

- **Heavy quarks are particularly good probes to study the properties of hot QCD matter**
- **pp data are important baseline measurements**
  - **examine interplay of soft and hard processes**
- **pA which is more than just a control**
  - **needed to study the CNM effects in various x ranges**
- **AA collisions : for understanding dense/hot QCD matter**
  - **strong interaction of heavy quarks with the QCD medium**
- **But do we understand fully the suppression at high p_T at RHIC ?**
- **In this perspective what is the role of collisional energy loss?**
- **Difference between Pb+Pb at 2.76 TeV and 5.02 TeV ?**
- **The role of shadowing effect ?** **EIC Physics Connections!**
- **Next steps :**

- Need more statistics, better precision and extended coverage (in terms of p_T)

- Need new differential measurements to constrain models and address open questions

- New probes like top quarks ?

Liliana Apolinário, José Guilherme Milhano, Gavin P. Salam, Carlos A. Salgado, PRL. 120, 232301(2018)
L.Kisslinger, D.Das, Mod.Phys.Lett.A Vol. 34 (2019) 1950353; http://cds.cern.ch/record/2699428 (CMS)

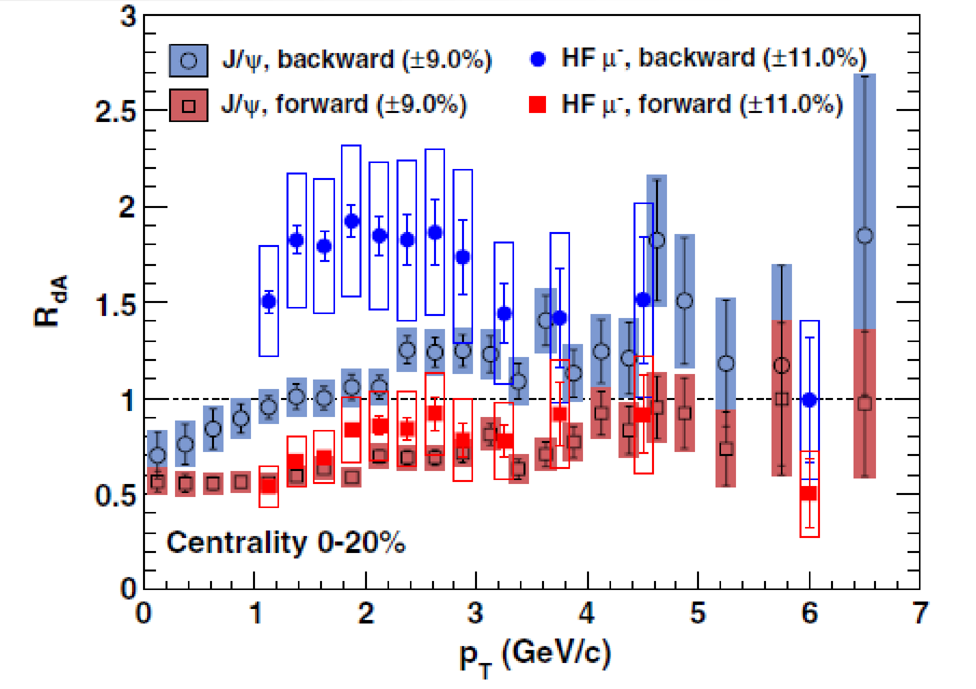
MORE

Different particle species

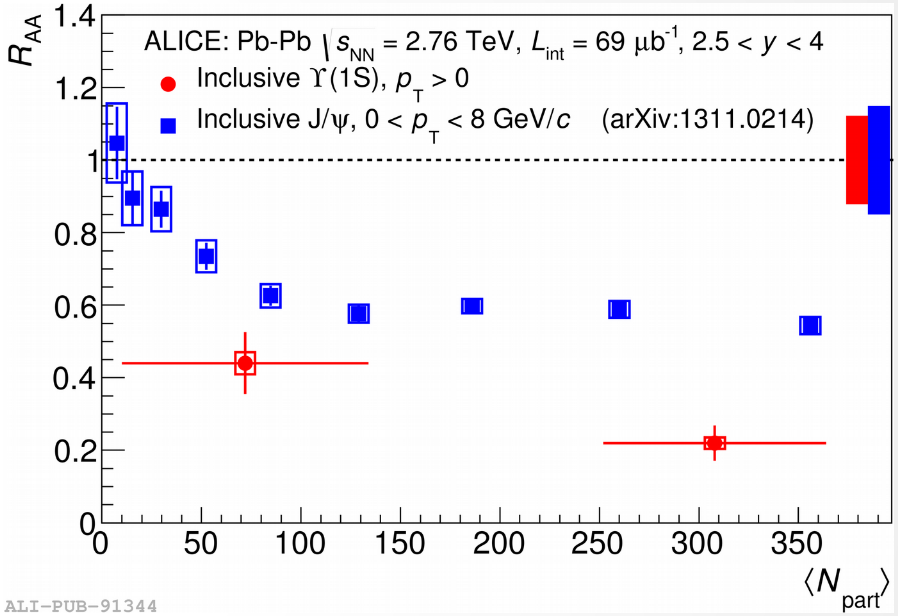
Phenix, d-Au PRL 112, 252301 (2014)

ALICE, Pb-Pb Phys. Lett. B 738 (2014) 361

200 GeV , R_{dA}



2.76 TeV, R_{AA}



Backward rapidity (−2.0 < y < −1.4, Au-going direction)

Forward rapidity (1.4 < y < 2.0, d-going direction)

Comparisons at LHC

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