Open heavy-flavour measurements in pp and Pb-Pb collisions with ALICE at the CERN-LHC

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NWO

Outline

- Physics motivations
- Detector
- D mesons
- Electrons from heavy-flavour hadron decays
- Muons from heavy-flavour hadron decays
- Conclusions

Physics motivations

- Heavy-flavour production provides an excellent QCD test tool.

  - **pp** : test perturbative QCD predictions, baseline for p-Pb and Pb-Pb collisions. Investigate multi-parton interactions
  - **p-A** : assess cold nuclear matter effects
  - **A-A** : probe the high density medium (Quark-Gluon Plasma (QGP))

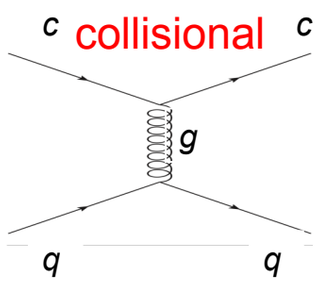
☑ Heavy quarks produced at the early stage of the collision $\tau_{charm} \sim 1/2m_c \sim 0.1$ fm/c
(*large mass requires high* Q^2)

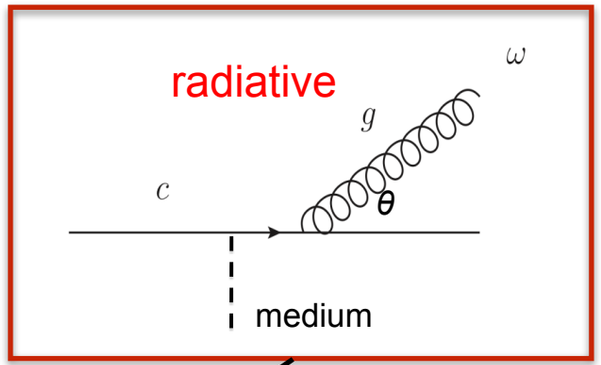
☑ In Pb-Pb collisions, produced before Quark-Gluon Plasma formation (0.1-1 fm/c)
→ experience the full collision history (QGP lifetime ~ 10 fm/c)

→ Good probes of the QCD medium.

In-medium effects

- Heavy quarks are expected to lose less energy than light quarks and gluons due to color-charge and dead cone effect (radiative energy loss) → higher penetrating power into QCD medium.

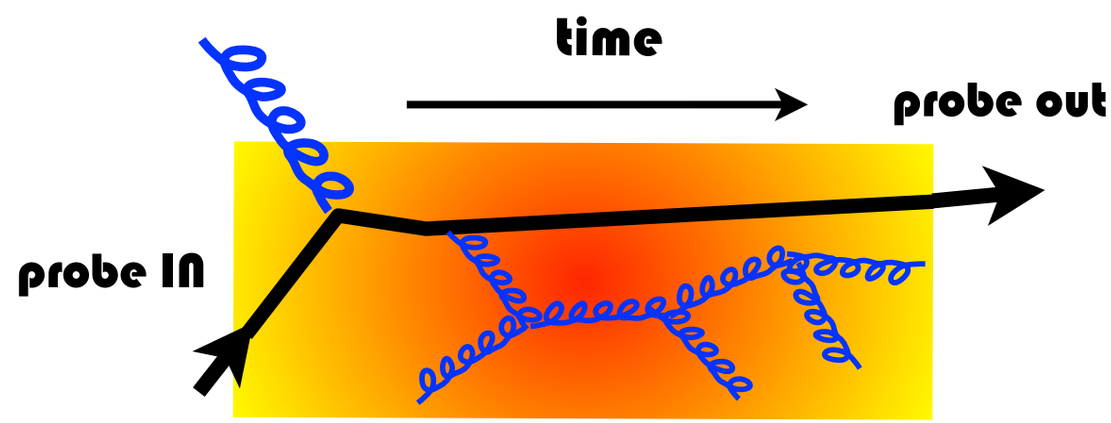




$$\omega \frac{dI}{d\omega}\Big|_{Heavy} = \omega \frac{dI}{d\omega}\Big|_{Light} \times \left(1 + \left(\frac{m_Q}{E_Q}\right)^2\right)\frac{1}{\theta^2}\Big)^{-2}$$

Dead Cone Effect→ larger is the mass smaller the gluon radiation

Dokshitzer, Khoze, Troyan, JPG17(91)1481



N. Armesto, C. A. Salgado and U. A. Wiedemann. PRD 69 (2004) 114003

M. Djordjevic, M. Gyulassy, Nucl. Phys. A733 (2004) 265.

ΔE(g) > ΔE(light) > ΔE(charm) > ΔE(beauty)

- If in-medium quark re-combination is the dominant mechanism of charm hadron formation at low p_T→ strange charm hadron yield (D_s) expected to be enhanced relatively to non-strange D mesons.

I. Kuznetsova and J. Rafelski, Eur.Phys.J. C51 (2007) 113-133.

M. He, R. J. Fries and R. Rapp, Phys.Rev.Lett. 110 (2013) 112301, arXiv:1204.4442 [nucl-th].

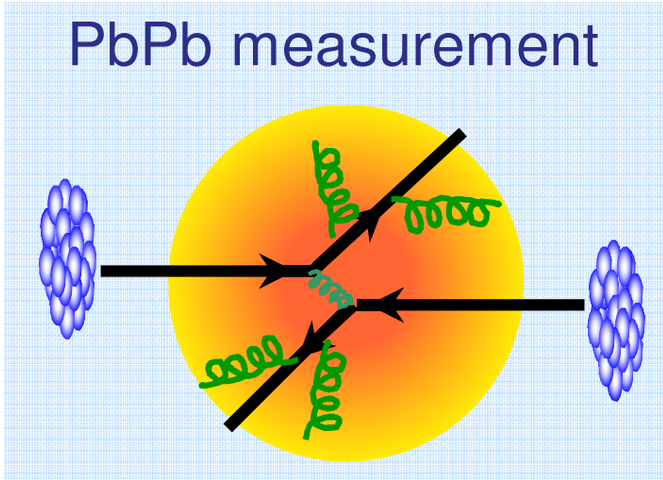
In-medium effects

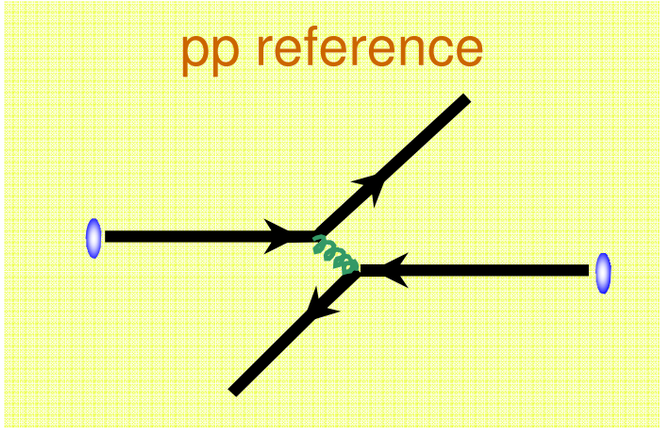
- Study the modificaton of heavy-quark production in a system where QGP is produced (*i.e Pb-Pb collisions)* with respect a system where QGP is not produced (*i.e pp collisions*).

- Observable: Nuclear Modification Factor:

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

Few caveats going from the hierarchy in E_{loss} to the one in R_{AA} (i.e: Steepness of the parton spectra, fragmentation functions, soft particles production at low p_T)

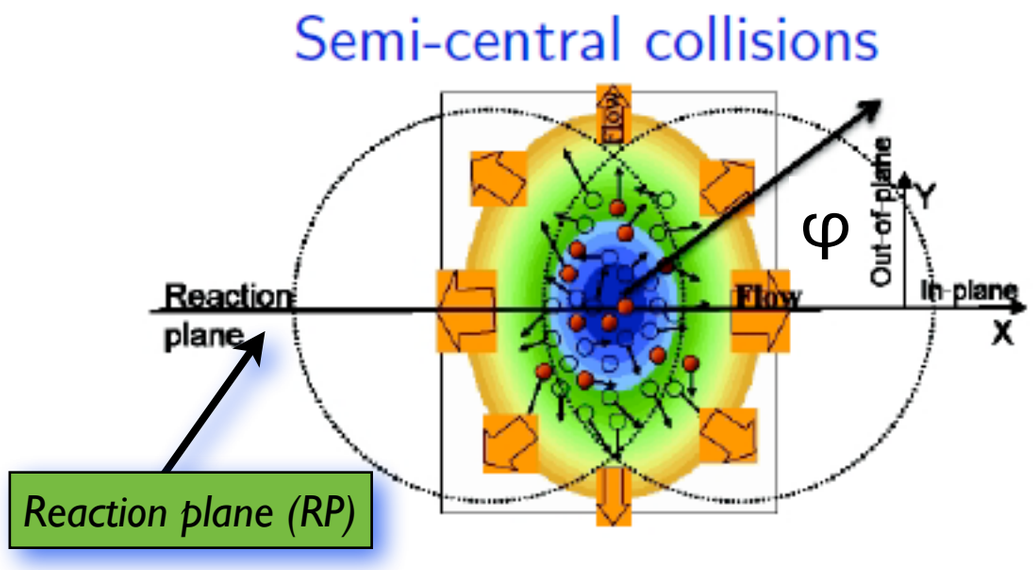




- What are the possibilities?
  - If no nuclear effects present: R_{AA} =1
  - Effects of the hot and dense medium produced in the collision breakup binary scaling: $R_{AA} \neq 1$

R_{AA}(light) < R_{AA}(D) < R_{AA}(B) ?

Thermalization and path-length dependence



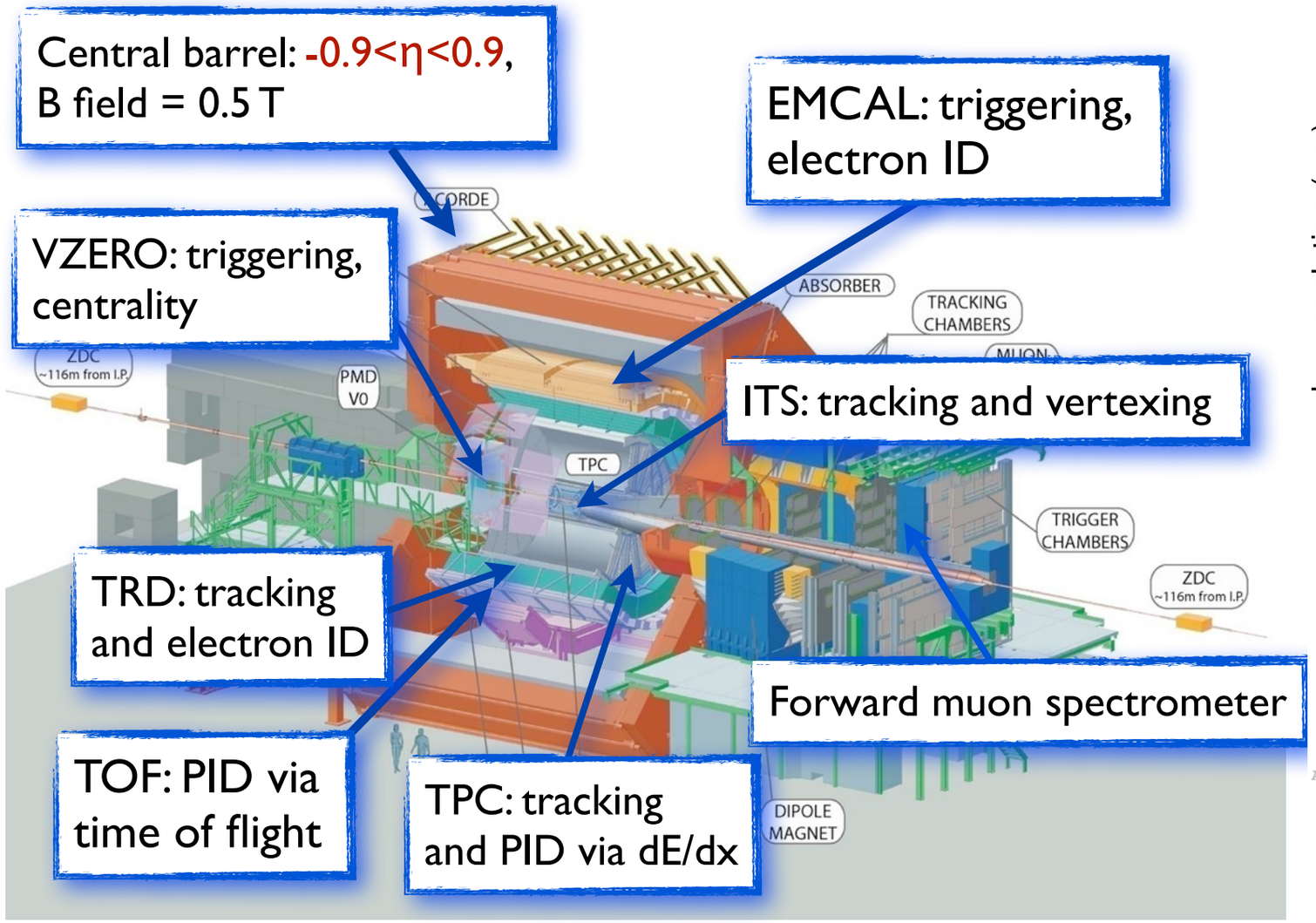
- Interaction among medium constituents convert the initial geometrical anisotropy into momentum anisotropy of final-state particles

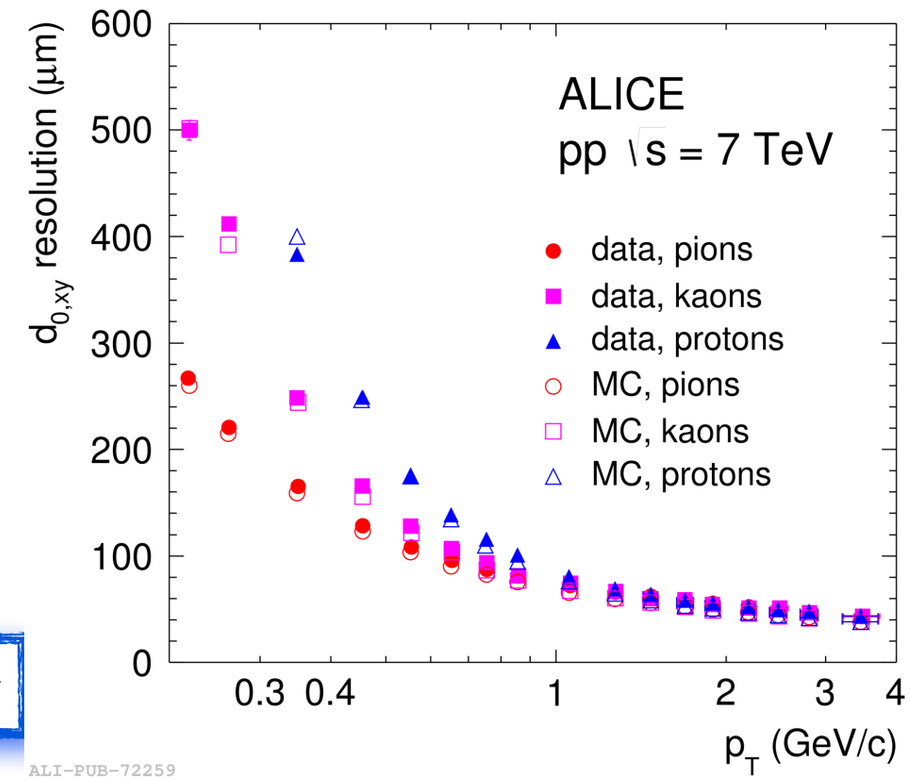
- Quantified via the 2nd order Fourier coefficient **v_2 (Elliptic flow)**

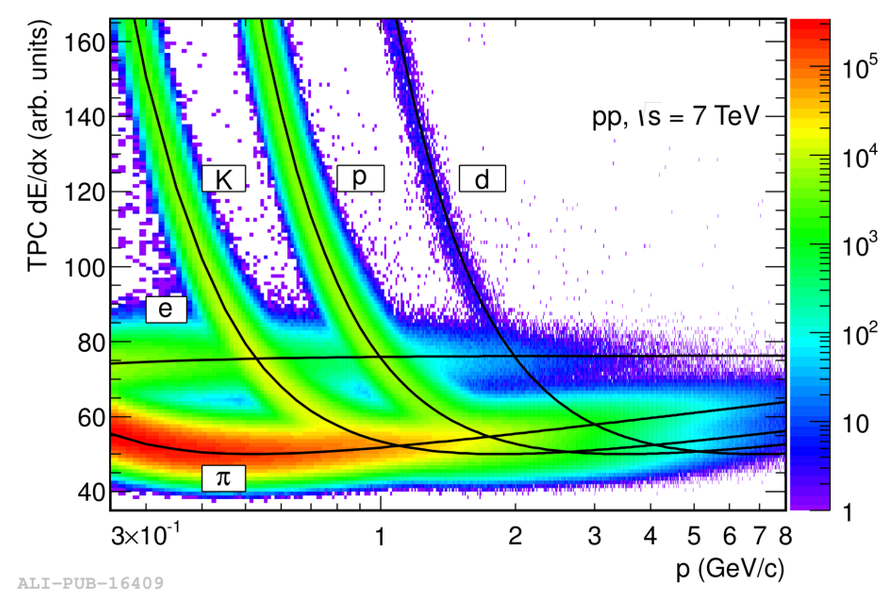
$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}(1+2v_1\cos(\varphi-\Psi_{RP})+2v_2\cos 2(\varphi-\Psi_{RP})+.....)$$

- Carries information on medium transport properties
  - Degree of thermalization of heavy quarks in QGP (low p_T)
  - Path-length dependence of parton energy loss (high p_T)

The ALICE detector







- ☑ Excellent tracking performance with ITS+TPC
- ☑ PID using ITS+TPC+TOF+TRD+EMCAL
- ☑ Single muon studies using the forward muon spectrometer (-4<η<-2.5)

D mesons
at mid-rapidity

D-meson measurement via hadronic decay channels

In this talk:

$D^0 \rightarrow K^- \pi^+$

$D^+ \rightarrow K^- \pi^+ \pi^+$

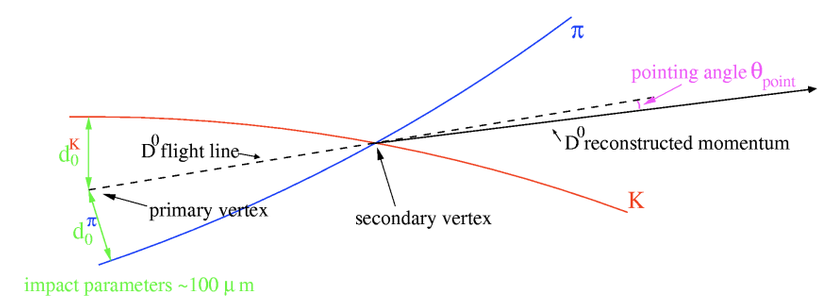
$D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+$

$D^+_s \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$

Except for D^{*+}, the $c\tau$ of the D mesons ranges from ~123 to 312 μm

→ *Decay vertices displaced by a few hundred μm from the primary vertex.*

- Invariant mass analysis (similar strategy for pp, p-Pb and Pb-Pb collisions)

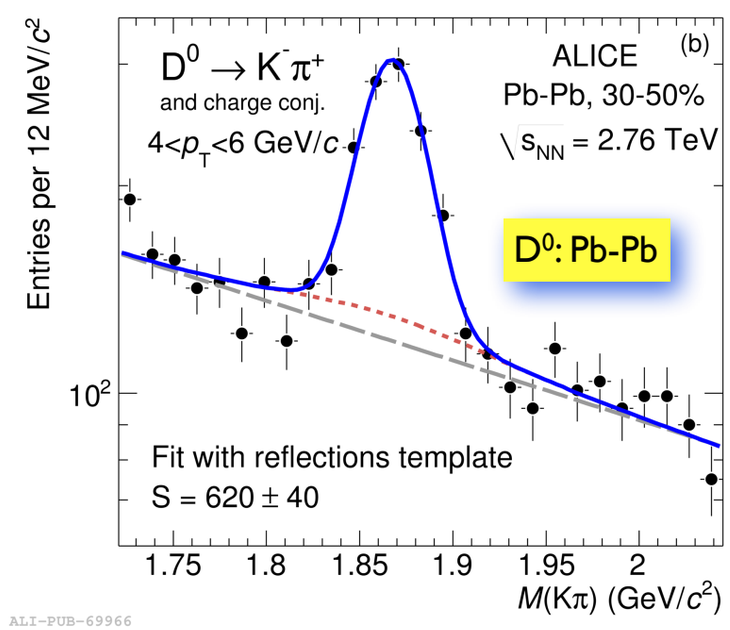


Reconstruction method I: topology

- Topology of the decay resolved via the reconstruction of the secondary vertex. PID to further reduce the combinatorial background.

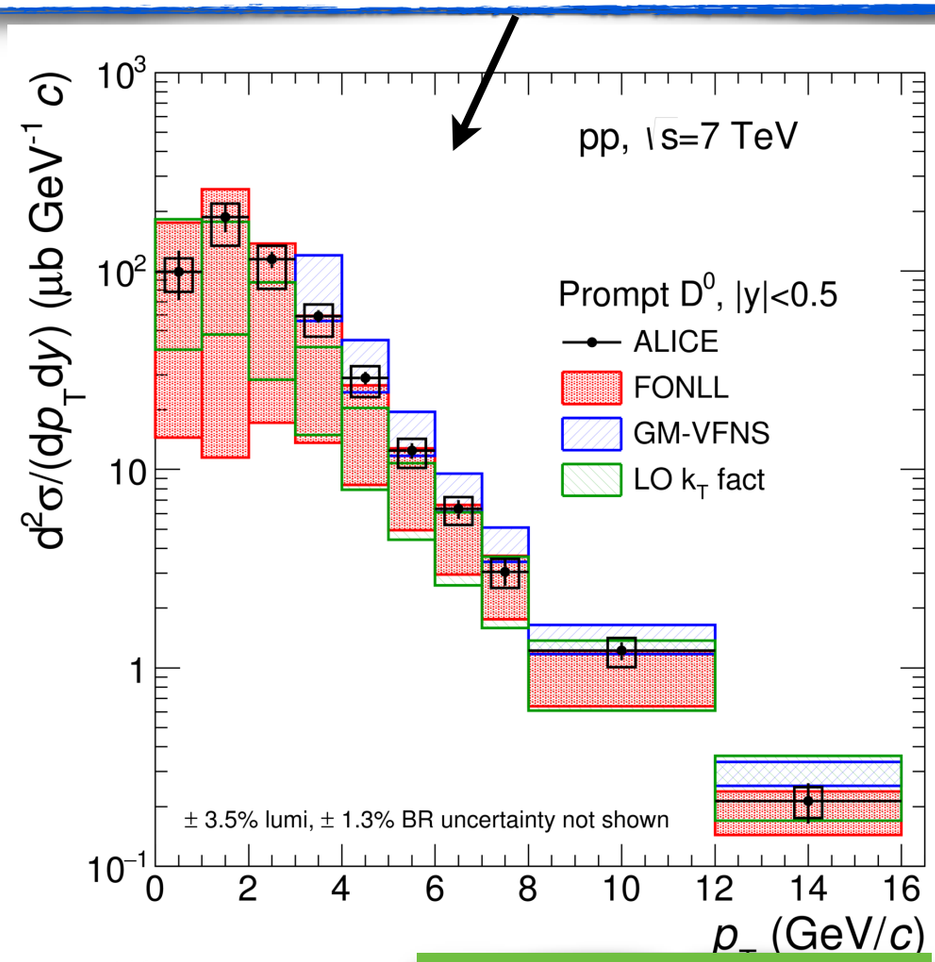
Reconstruction method II: background simulation

- Topological method is limited at low p_T due to the very low efficiencies. Different background subtraction techniques explored for D^0 analysis in order to go down to p_T=0: mixing events, rotational and like sign.

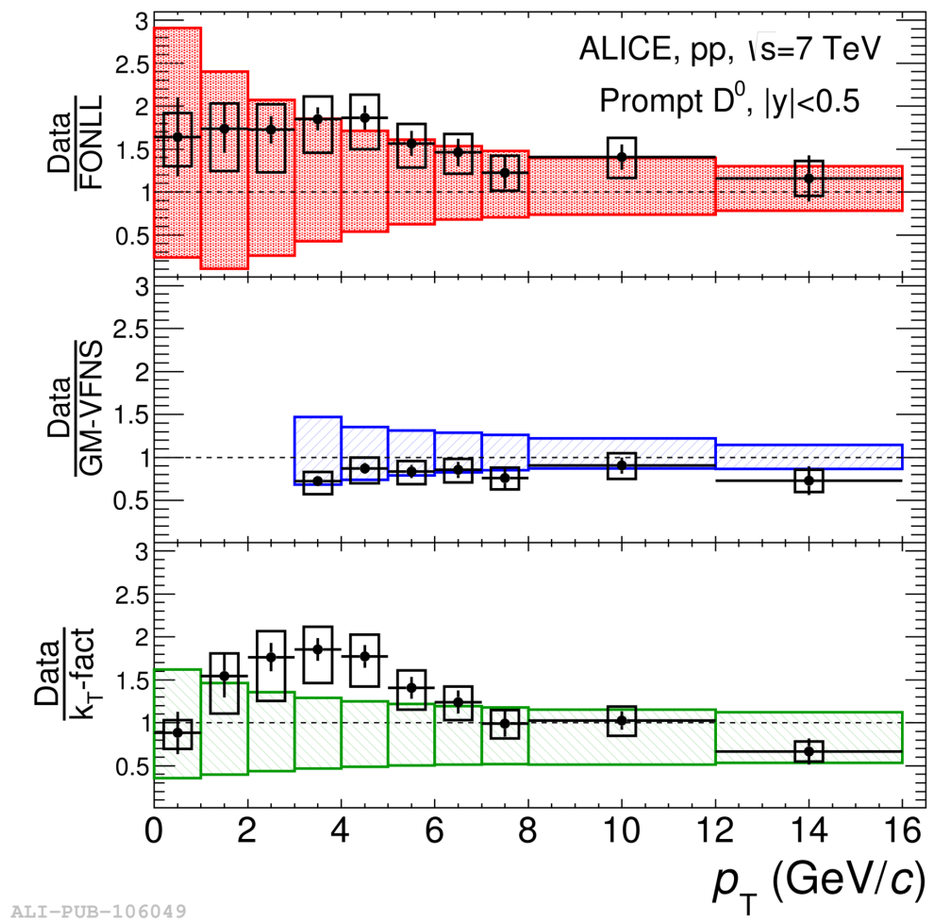


D-meson production cross sections in pp collisions

D^0 cross section at $\sqrt{s} = 7$ TeV, |y|<0.5



down to 0 GeV/c!



- Large p_T coverage D^0 (D^{*+},D^+) [0(1),16(24)] GeV/c, D_s [2,12] GeV/c. Well described by pQCD predictions.

Maciula, Szczurek, Phys.Rev. D87 (2013) 9, 094022

arXiv:1605.07569

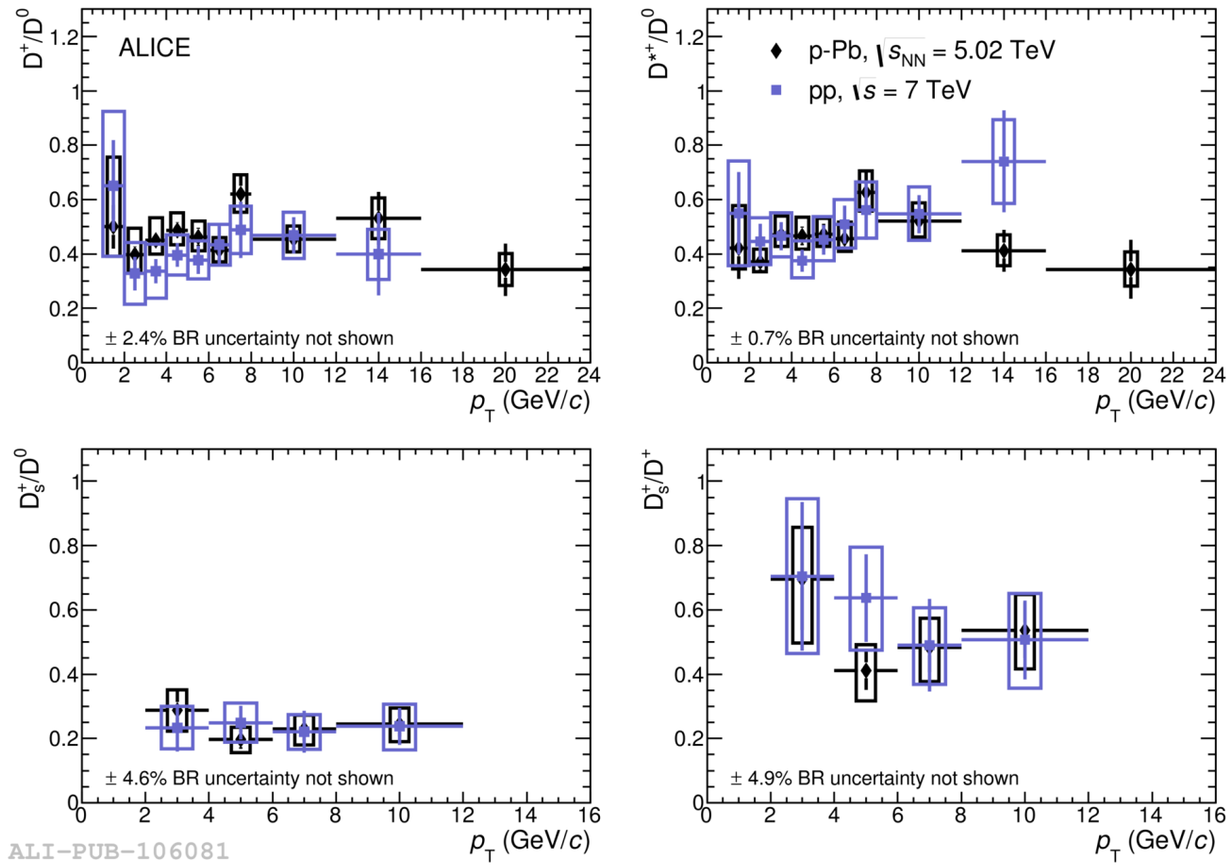
M. Cacciari, M. Greco and P. Nason, JHEP 9805 (1998) 007;
M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, G. Ridolfi, arXiv:1205.6344

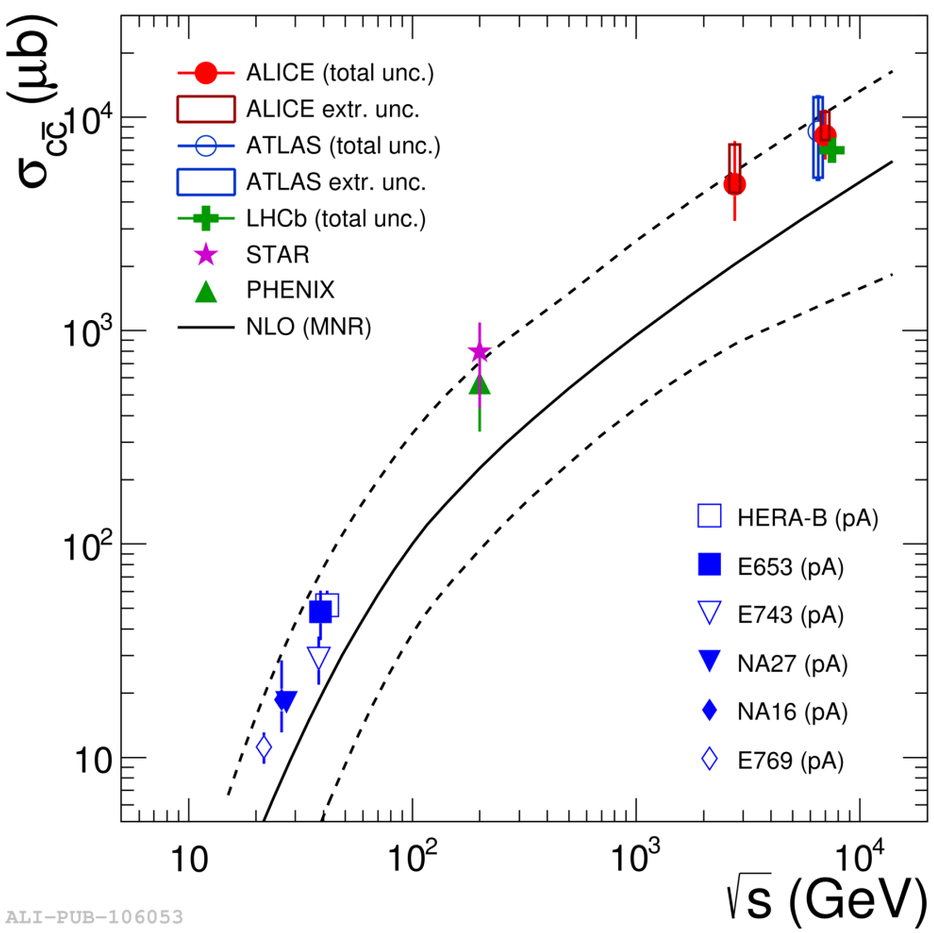
JHEP 1201 (2012) 128

B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, arXiv:1202.0439, DESY-12-013, MZ-TH-12-07, LPSC-12019

D-mesons ratios and charm production cross-section

- Charm production cross-section measured vs $\sqrt{s}$ shows good agreement with models within uncertainty. The central value from NLO calculation tends to be underestimated.



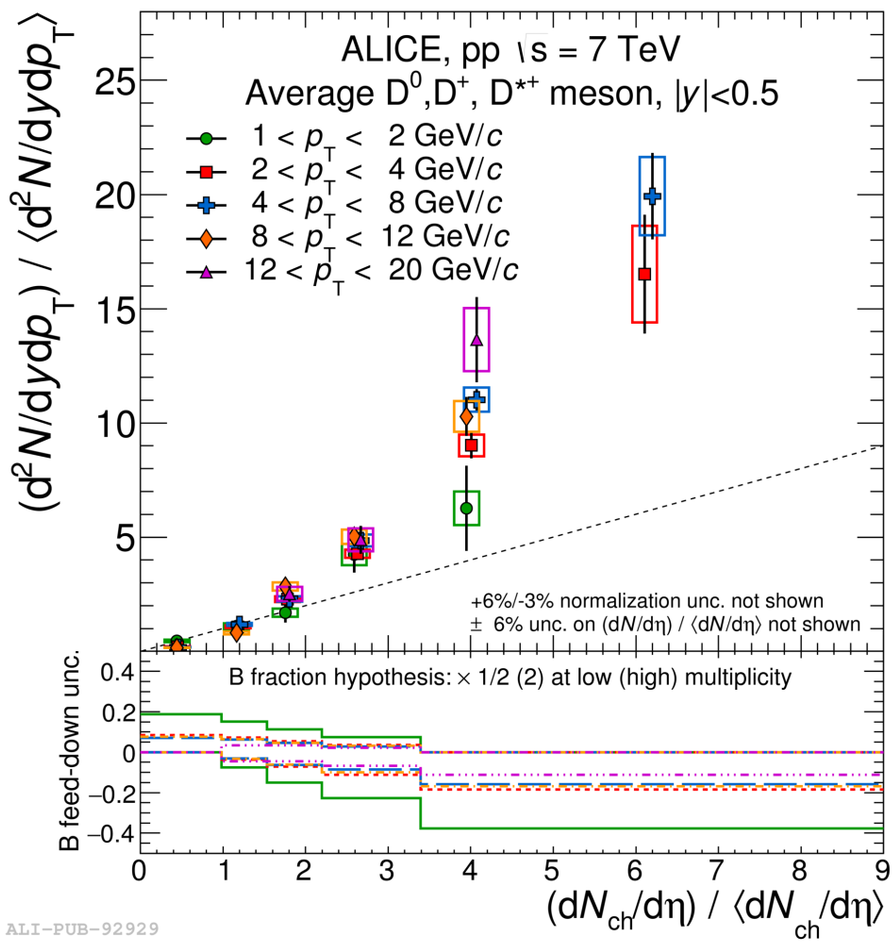


- D-meson ratios measured in pp and p-Pb collisions in a wide p_T range. Similar results among the two systems.

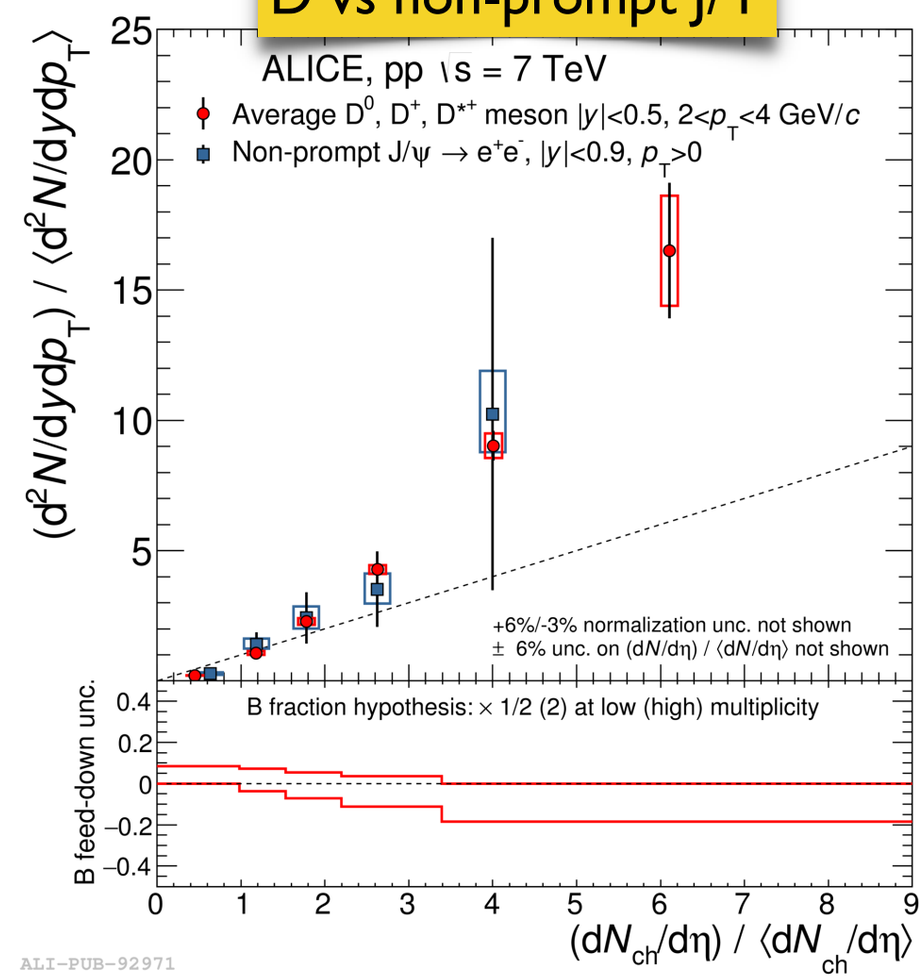
arXiv:1605.07569

Production of D mesons vs multiplicity in pp collisions

JHEP 1509 (2015) 148



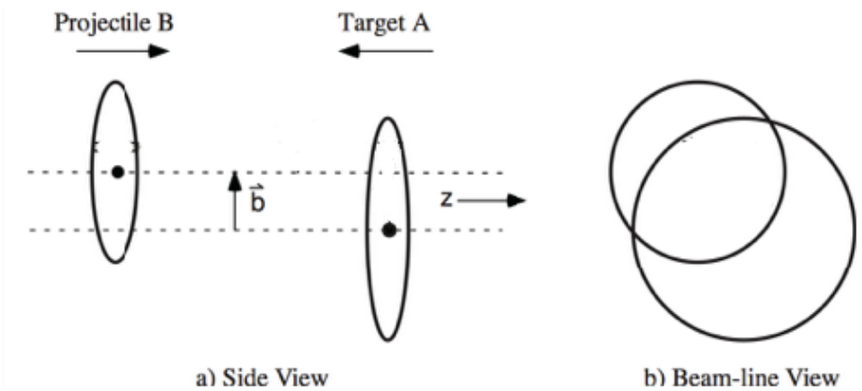
D vs non-prompt J/Ψ

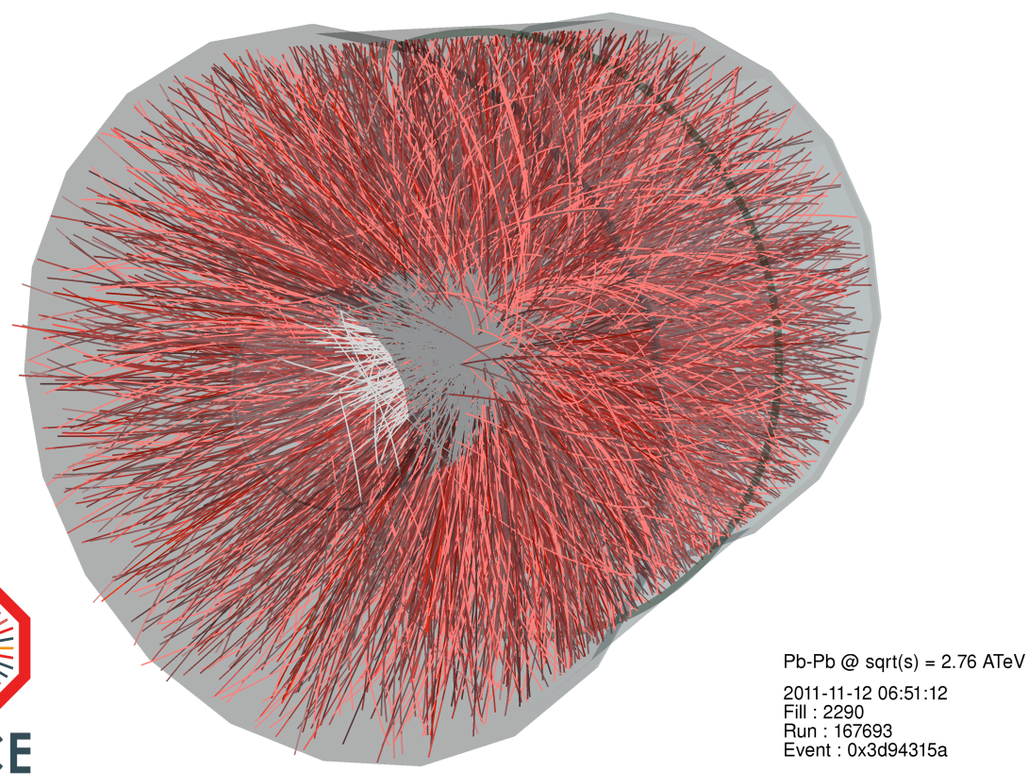


- ☑ Multi-Parton Interactions on an hard scale ⇒ D-meson yield may be correlated to the event charged-particle multiplicity.
- ☑ D mesons and non-prompt J/Ψ behave similairly
- ☑ Similar differential studies done in p-Pb collision system. Furthermore D-h correlations studied in pp and p-Pb collisions: arXiv:1605.06963 JHEP 8 (2016) 1-44

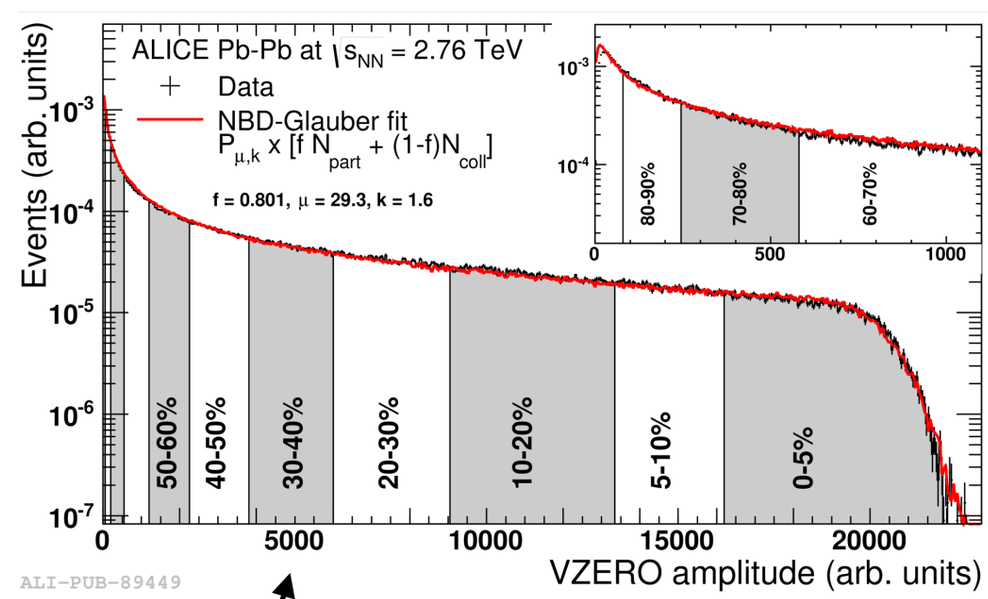
From pp to Pb-Pb events: classification of collisions

- With thousands of tracks in the detector, the environment of a Pb-Pb collision is much more challenging than a pp collision.
- Control the geometry of the collision using the "Centrality"
  - Number of charged particles created in the collision as observable
  - Fit with geometrical model by Glauber to extract the geometry.





Phys. Rev. C 88 (2013) 044909

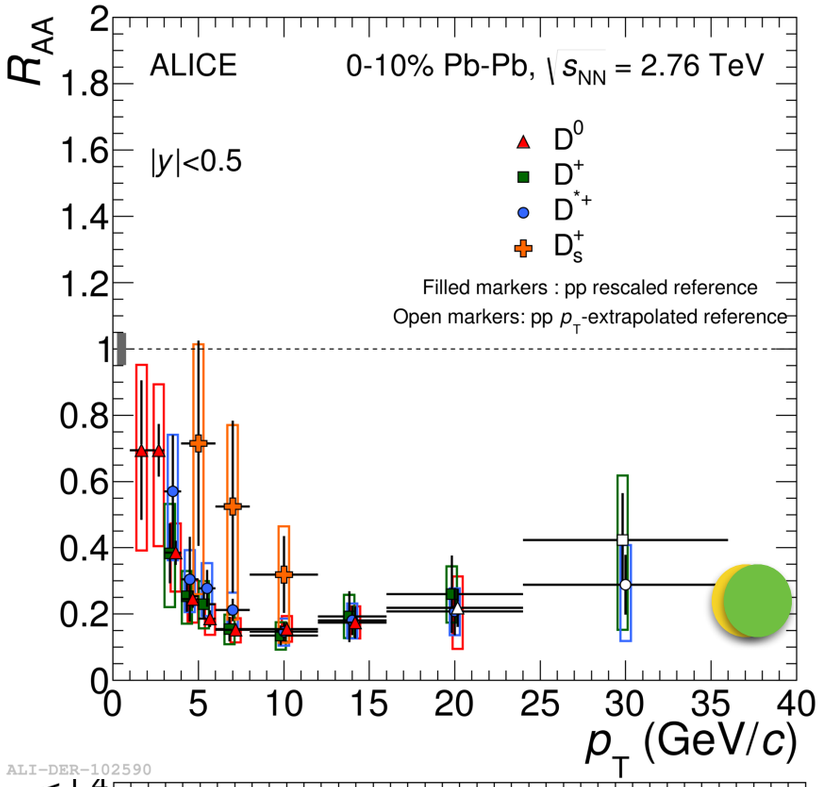


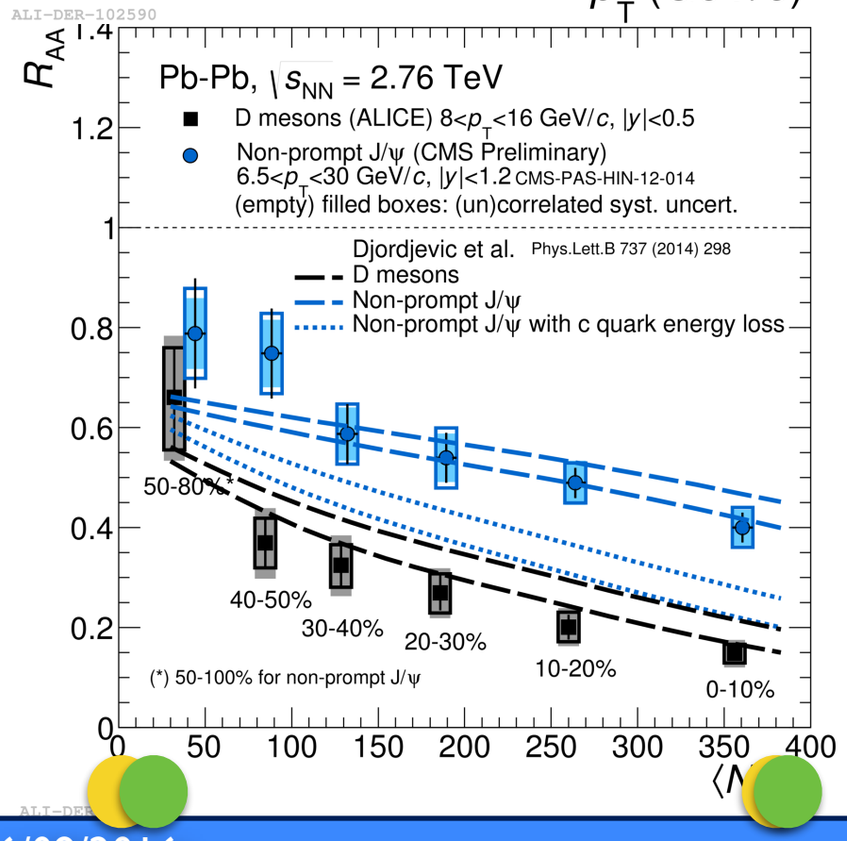
Peripheral: Small overlapping region, low medium densities

Central: Large overlapping region, high medium densities

p_T-differential nuclear modification factor in Pb-Pb collisions

JHEP 1511 (2015) 205 JHEP 1603 (2016) 082





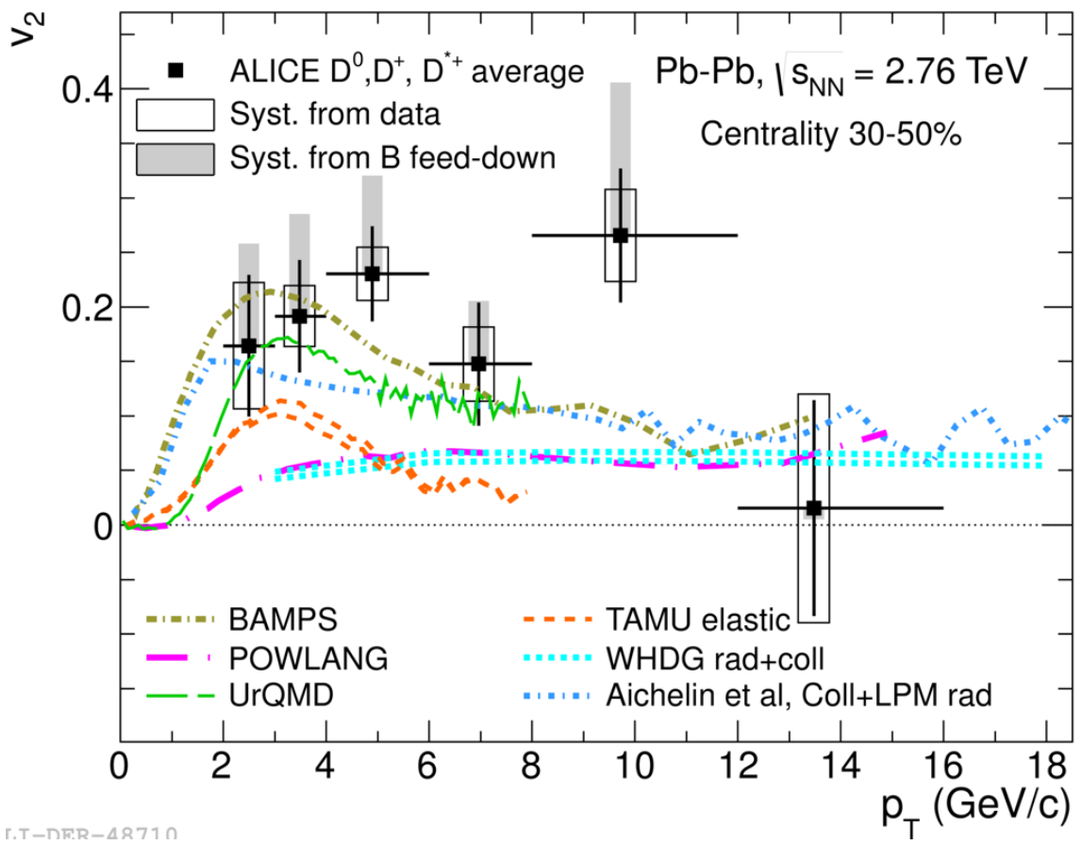
Nuclear modification factor (R_{AA})

- ☑ D^0, D^+ and D^{*+} R_{AA} measured in the range [1,36] GeV/c with 2011 data. Compatible within uncertainties
- ☑ Suppression up to a factor 5 for D^0, D^+ and D^{*+} at p_T~10 GeV/c
- ☑ Enhancement of D^+_s relative to the other D mesons due to strangness content? Data not conclusive yet.
- ☑ Comparison of non prompt J/Ψ (from beauty decays) shows a clear indication of a different suppression. In the most central collisions (0-10% and 10-20%) the separation exceeds the 3 sigma.
  - the data are compared to models where the mass is switched between charm and beauty and one sees clearly a difference. Based on this, we conclude that this could suggest a mass effect

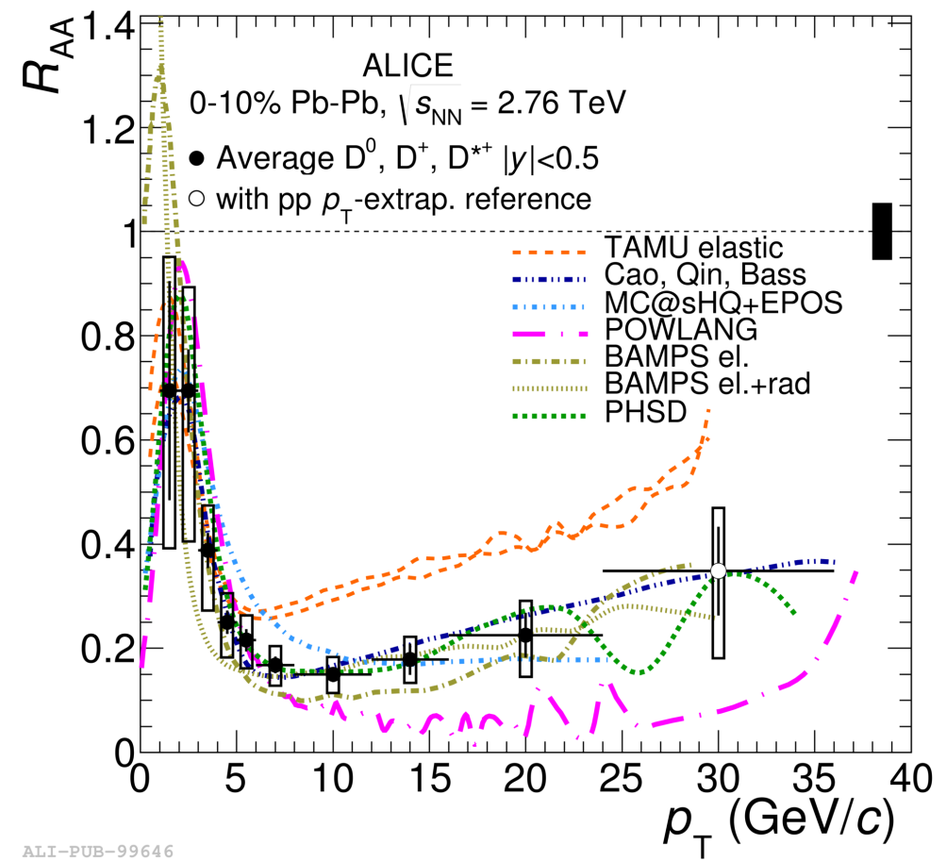
JHEP 1603 (2016) 081 CMS-PAS-HIN-12-014 Rhys. Lett. B 737 (2014), 298

R_{AA} and elliptic flow: comparison with models

Phys.Rev. C90 (2014) no.3, 034904



JHEP 1603 (2016) 081



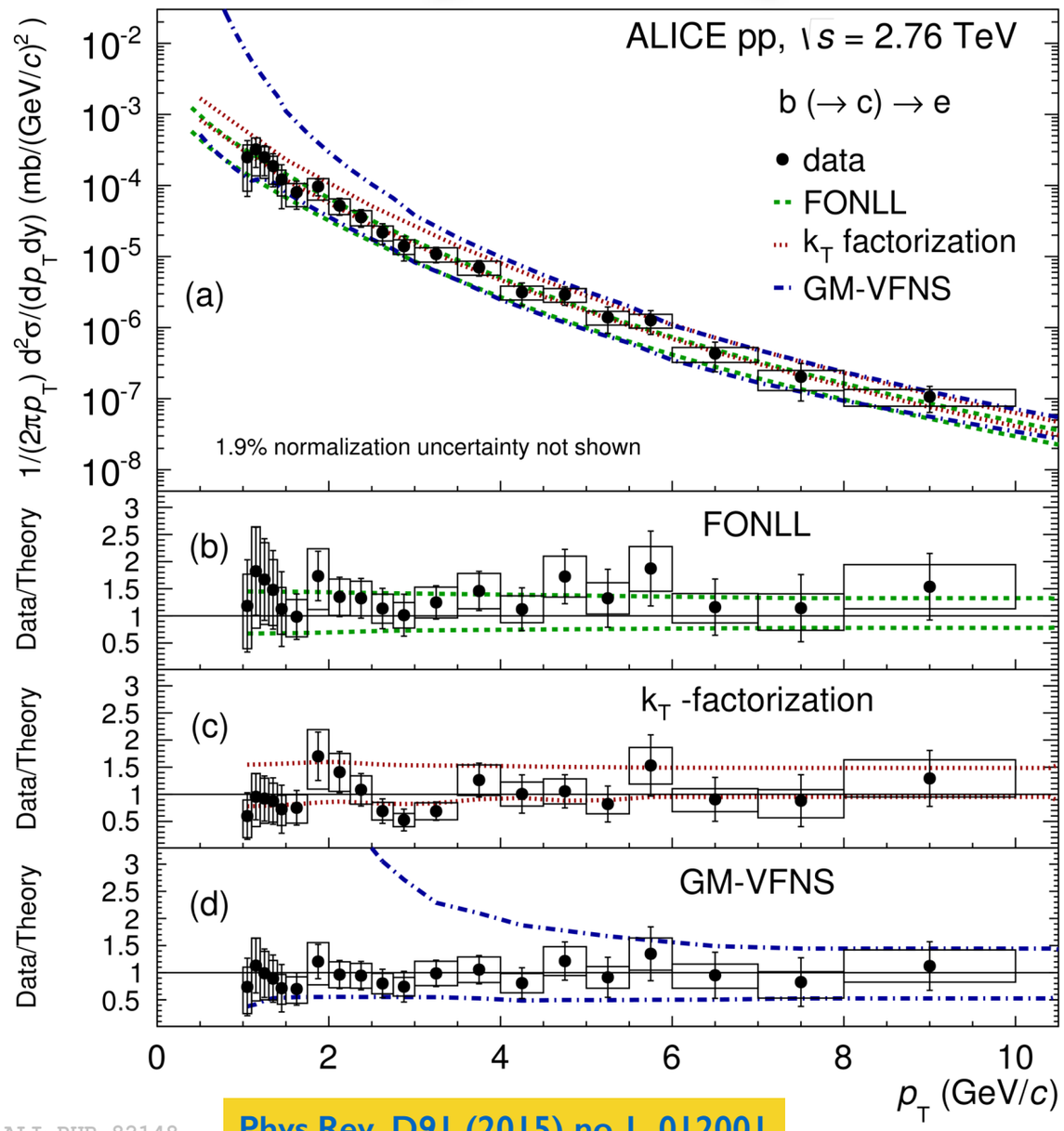
☑ Simultaneous description of D-meson R_{AA} and v_2 → understanding of heavy-quark transport coefficients of the medium (challenging for models)

BAMPS: Uphoff et al. arXiv:1112.1559., O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. G38 (2011) 124152.
Aichelin et al. Phys. rev. C 79 (2009) 044906,
W.A. Horowitz et al. J. Phys. G38, 124064 (2011).,W. A. Horowitz and M. Gyulassy, J. Phys. G38 (2011) 124114.
W. M. Alberico et al. Eur. Phys. J. C 71, 1666 (2011). M. He, R.J Fries and R. Rapp, arXiv:1204.4442 [nucl-th]

Heavy-flavour (HF) decay electrons in pp collisions at mid-rapidity

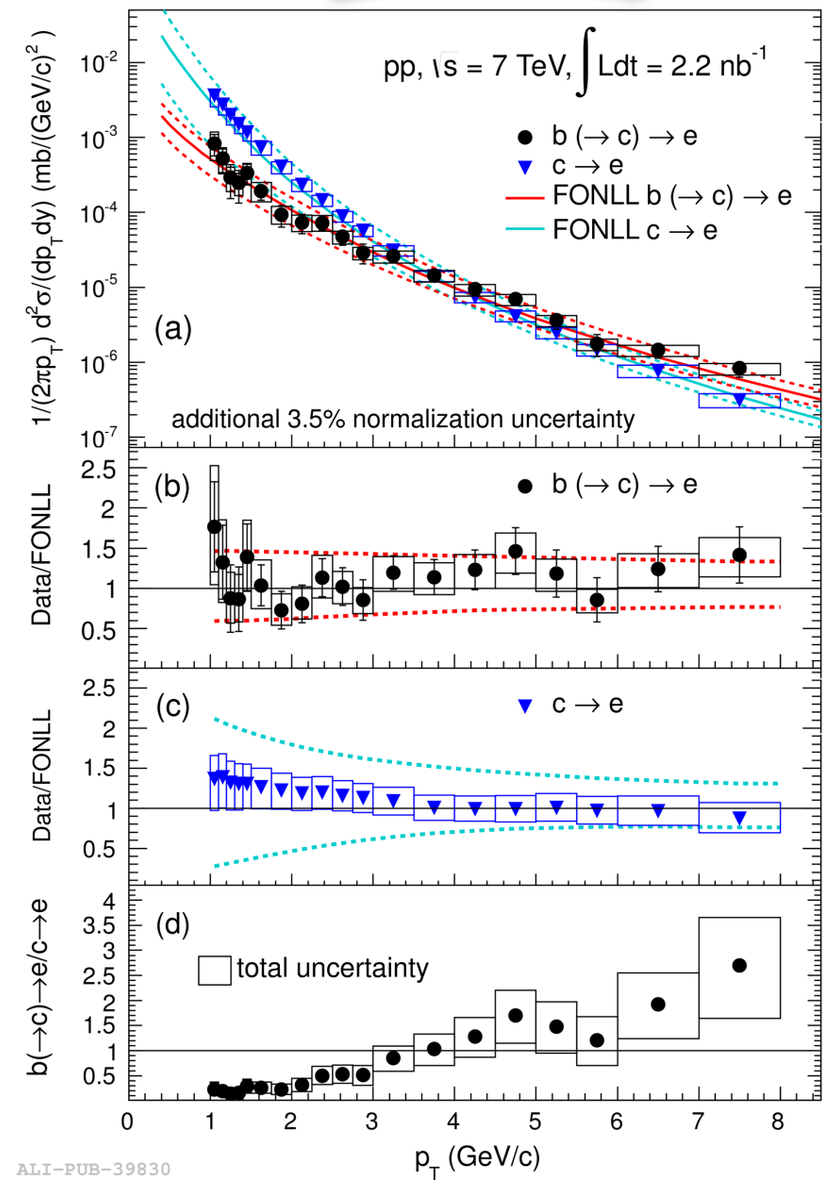
Beauty decay electrons in pp collisions

pp @2.76 TeV



Phys.Rev. D91 (2015) no.1, 012001

pp @ 7 TeV



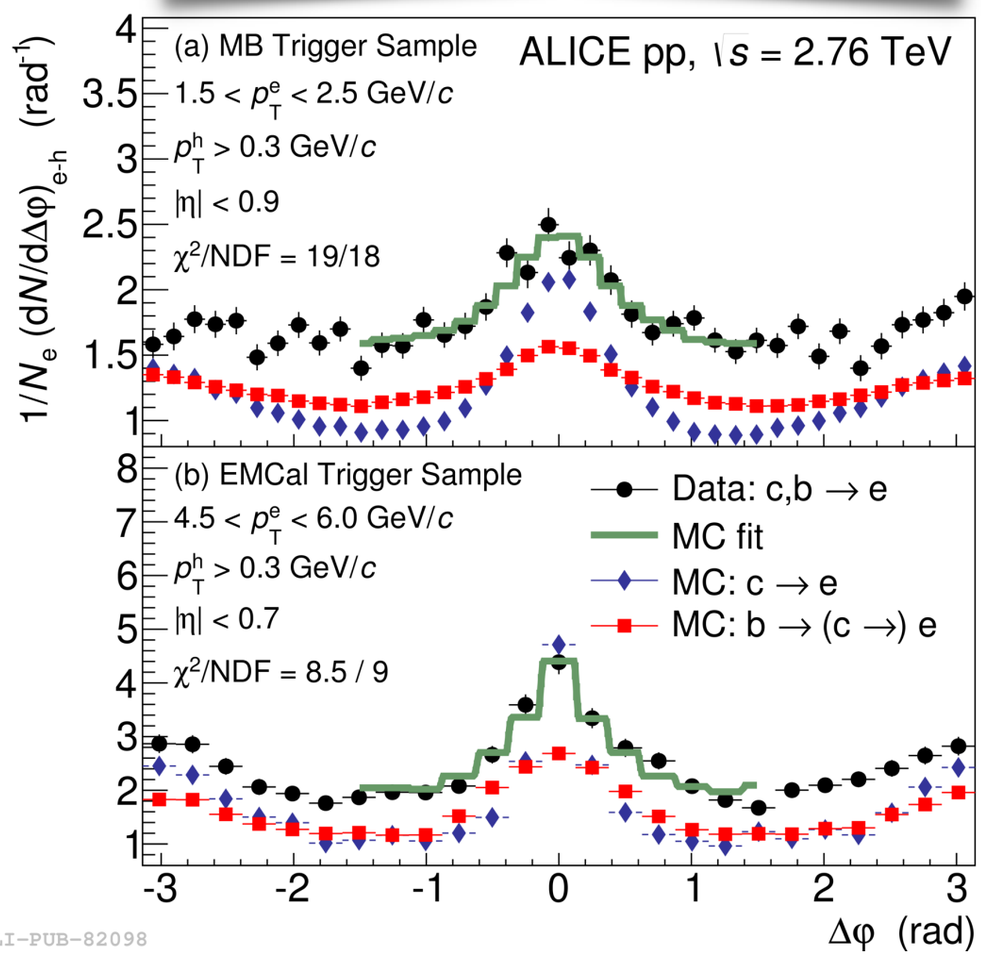
Phys.Lett. B721 (2013) 13-23

☑ Exploit the large displacement of beauty decay electrons. Cut on impact parameter.

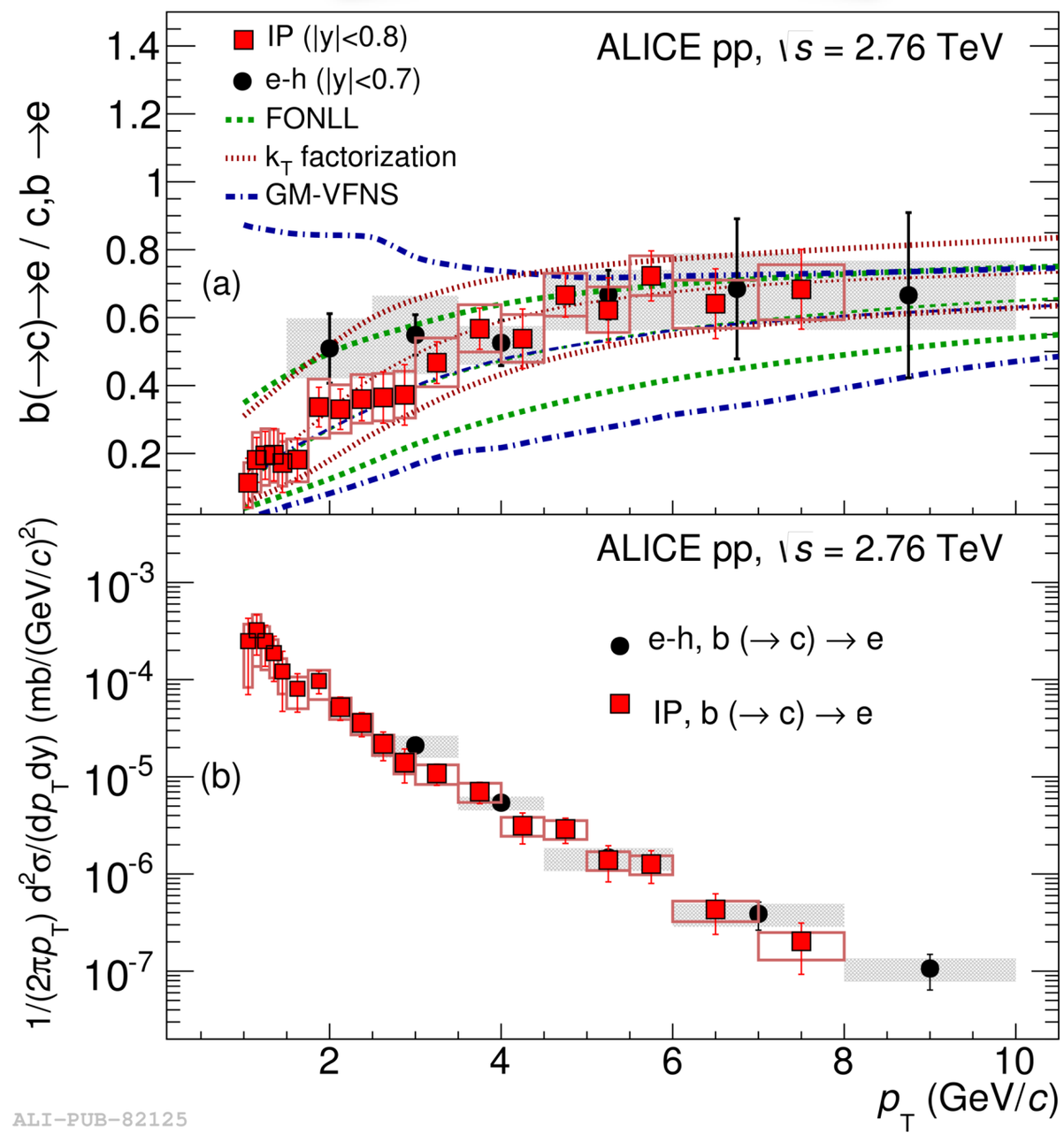
Heavy-flavour decay electron-hadron correlation in pp collisions

- Complementary method based on e-hadron near-side azimuthal correlations.
  - Exploit different correlation width
  - Monte Carlo template
  - Extract $R_b = e_b/(e_b+e_c)$

e-h correlations in pp @2.76 TeV



pp@2.76 TeV as example

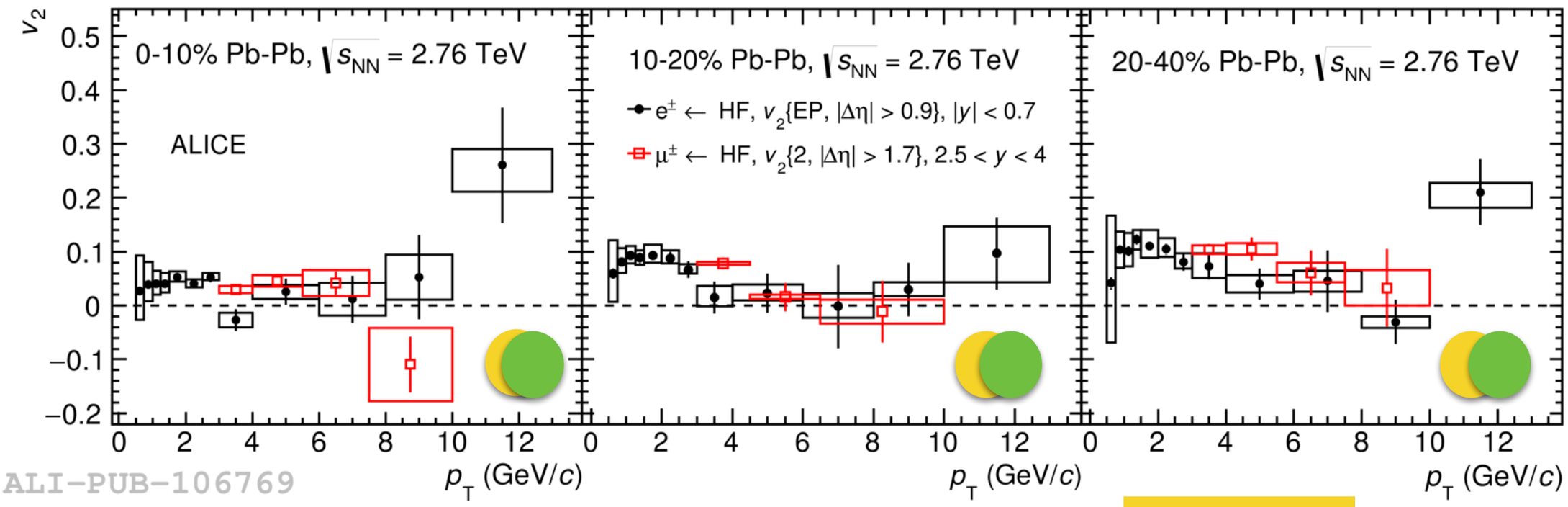


- Electrons from beauty decays are dominant at high p_T

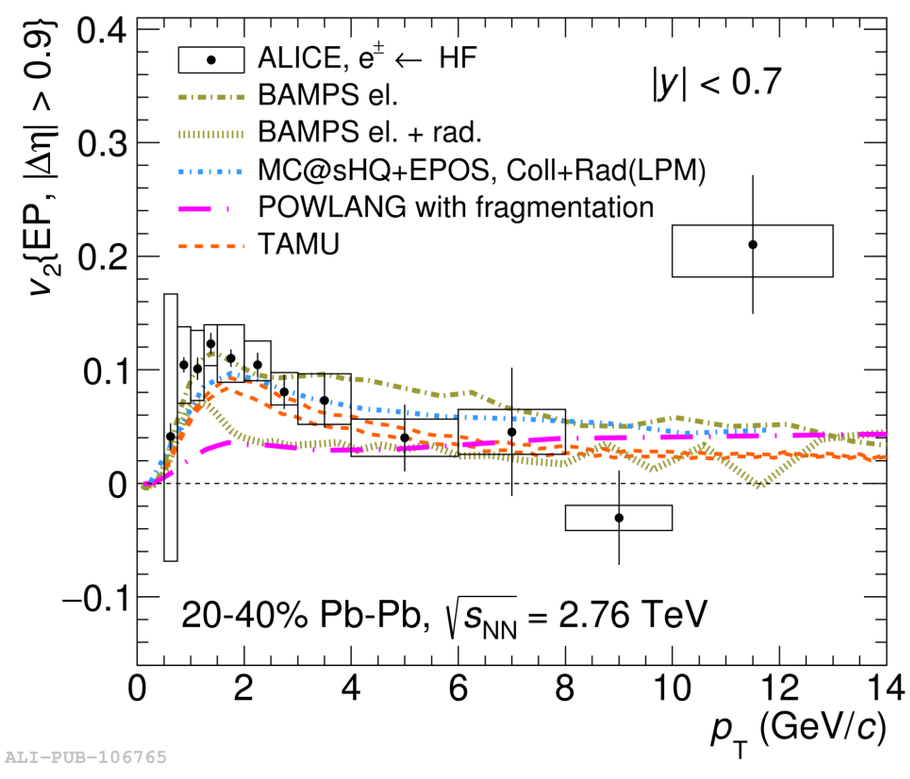
Phys.Lett. B738 (2014) 97-108

Flow of
Heavy-flavour (HF) decay electrons in Pb-Pb at mid-rapidity
and
Heavy-flavour (HF) decay muons at forward rapidity ($-4<\eta<-2.5$)

v_2 of HF-decay muons and HF-decay electrons



arXiv:1606.00321

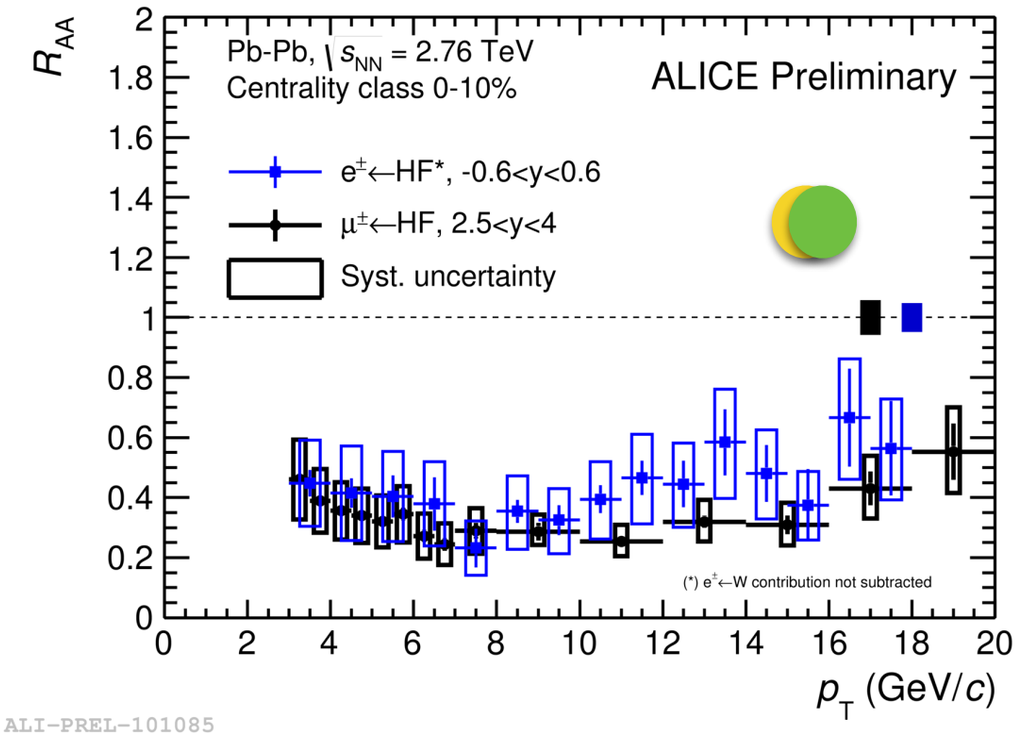


- Clear centrality dependence of the HF-decay electron (|y|<0.7) and HF-decay muon (2.5<y<4) v_2. Good agreement, within uncertanties, of the two measurements.
- HF-decay electron v_2 measured down to 0.5 GeV/c. Good agreement with models that include radiative energy loss

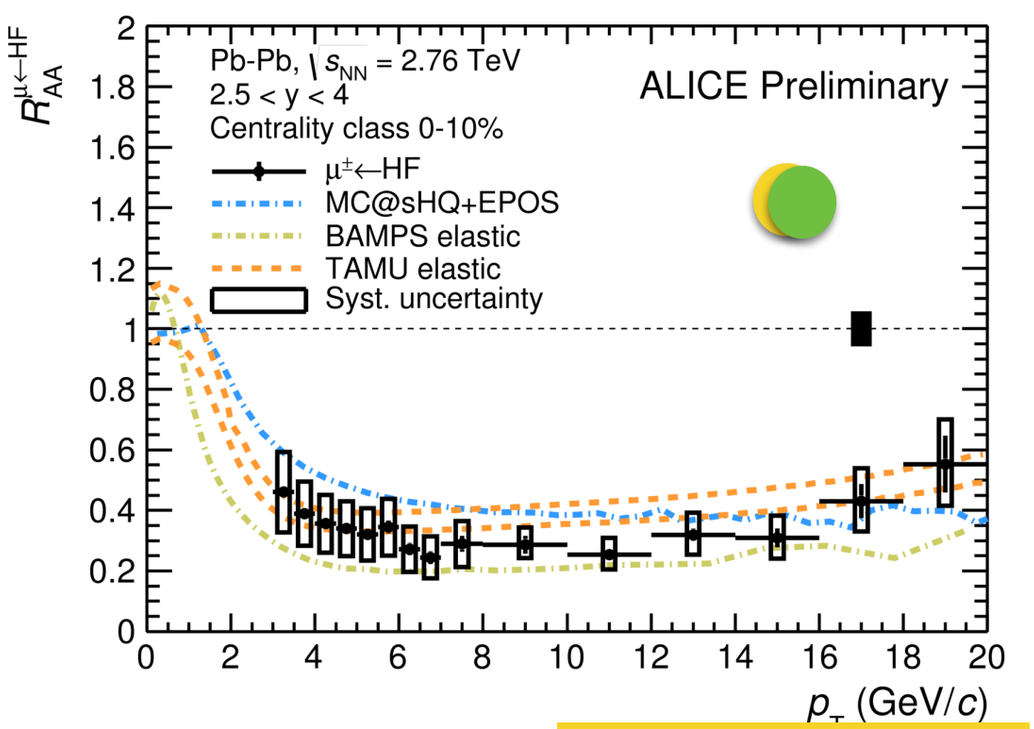
BAMPS: Uphoff et al. arXiv:1112.1559., O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. G38 (2011) 124152.
Aichelin et al. Phys. rev. C 79 (2009) 044906,
W. M. Alberico et al. Eur. Phys. J. C 71, 1666 (2011).
M. He, R.J Fries and R. Rapp, arXiv:1204.4442 [nucl-th]

R_{AA} of
Heavy-flavour decay electrons
at mid-rapidity
and
Heavy-flavour decay muons
at forward rapidity ($-4<\eta<-2.5$)

R_{AA} of HF-decay muons and HF-decay electrons

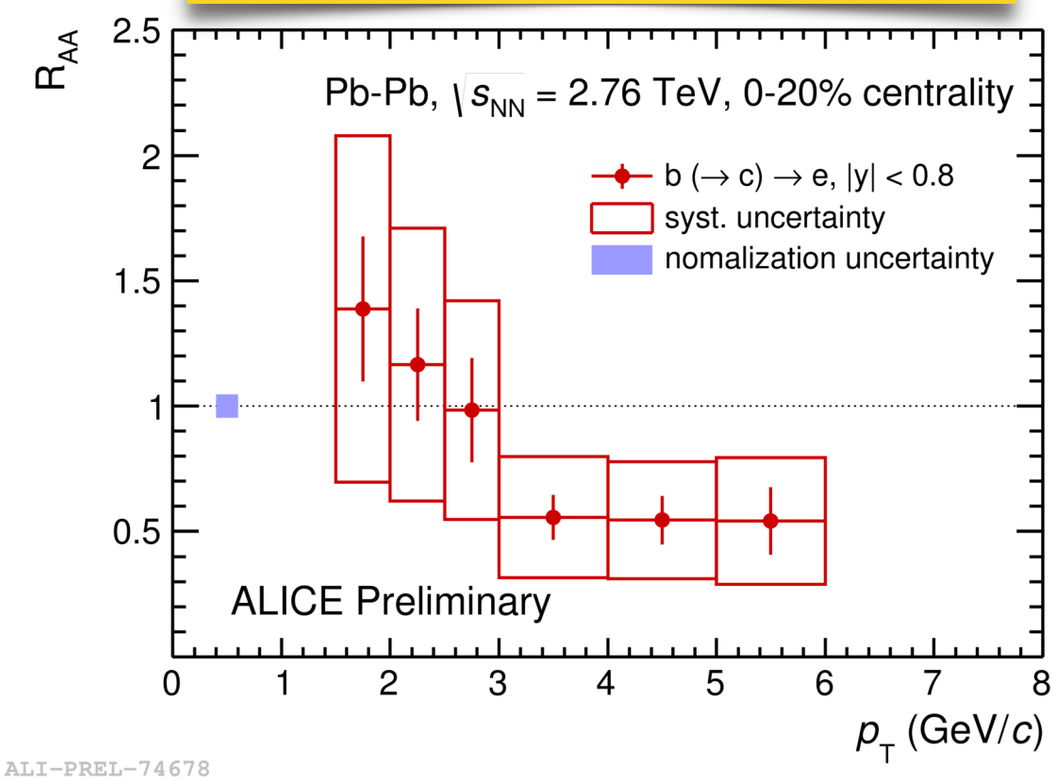


- p_T-differential R_{AA} of HF-decay muons and HF decay electrons in good agreement.
- p_T-differential R_{AA} in qualitative agreement with models.
- Beauty decay electron R_{AA} measured.



Phys.Lett. B753 (2016) 41-56

RAA of Beauty hadron decay electrons



Conclusions

Results from pp collisions:

- D^0 cross-section at $\sqrt{s}$ = 7 TeV measured down to p_T = 0. Described by pQCD calculations within uncertainties
- Measurement of D-mesons production versus multiplicity shows a faster then linear increase.
- Measurement of beauty contribution to heavy-flavour decay electrons down to 1 GeV/c at both $\sqrt{s}$ = 2.76 and 7 TeV
- Measurement of inclusive heavy-flavour decay leptons at central and forward rapidity.

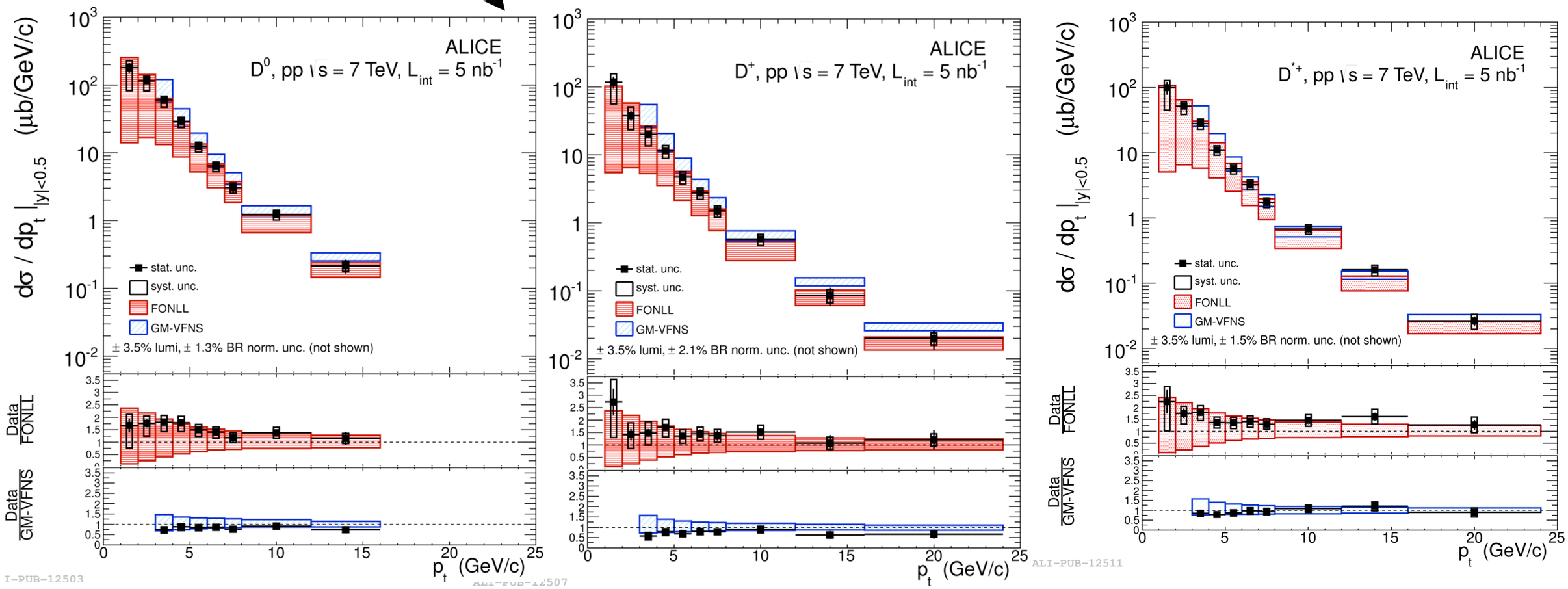
Results from Pb-Pb collisions:

- R_{AA} of D mesons, heavy-flavour decay electrons and muons show strong suppression at high p_T; factor 5 at p_T = 10 GeV/c in the case of D mesons. Clear indication of a hot and dense QCD medium produced. R_{AA} of D mesons shows stronger suppression than R_{AA} of non-prompt J/ψ (mainly from B mesons). Suggest mass ordering in the energy loss.
- D-meson flow measured. It is positive at 5σ confidence level. HF-decay electron elliptic flow measured down to 0.5 GeV/c. Good agreement with single muon elliptic flow in the overlapping p_T region. The positive v_2 suggests collettive motion of charm quark at low-p_T

Backup

pp as baseline for Pb-Pb: D^0, D^+ and D^{*+}

D^0, D^+, D^{*+} cross section at $\sqrt{s} = 7$ TeV, $|y|<0.5$



B. I. Abelev et al. [ALICE Collaboration], JHEP 01 (2012) 128.

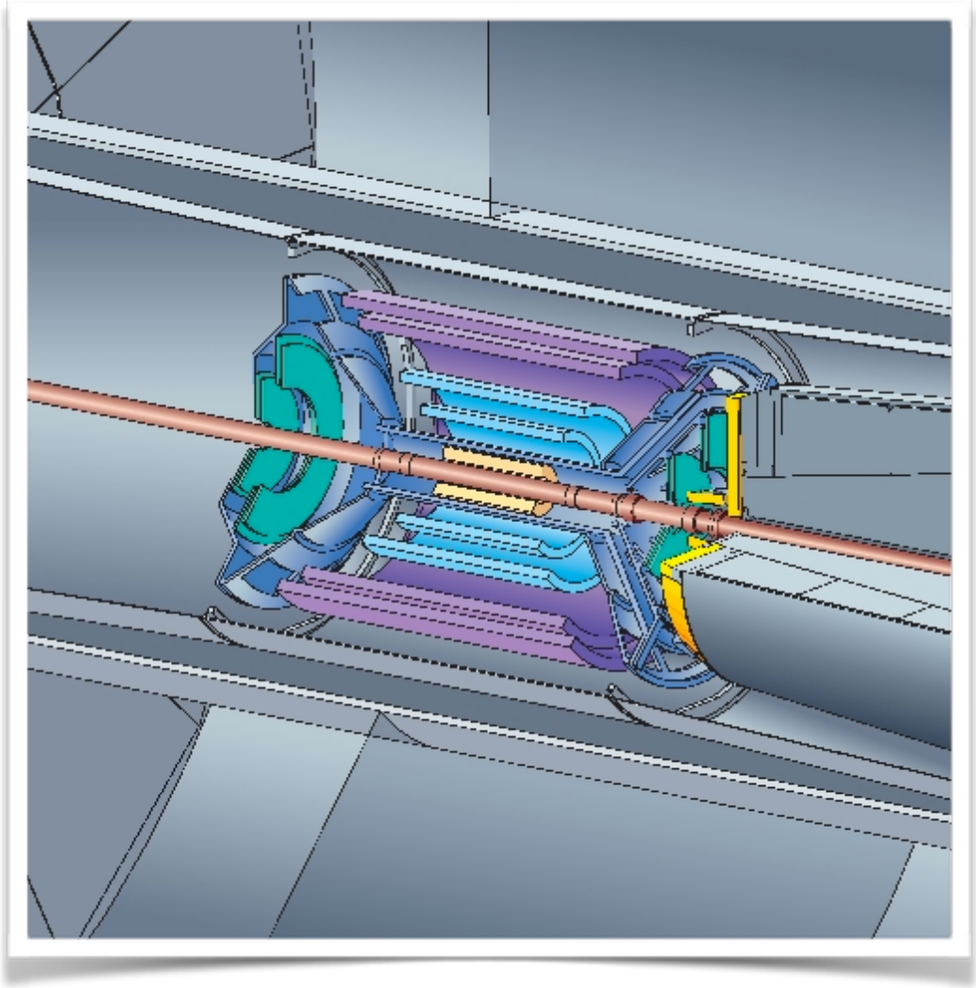
☑ Large p_T coverage [1,24] GeV/c and well described by pQCD predictions.

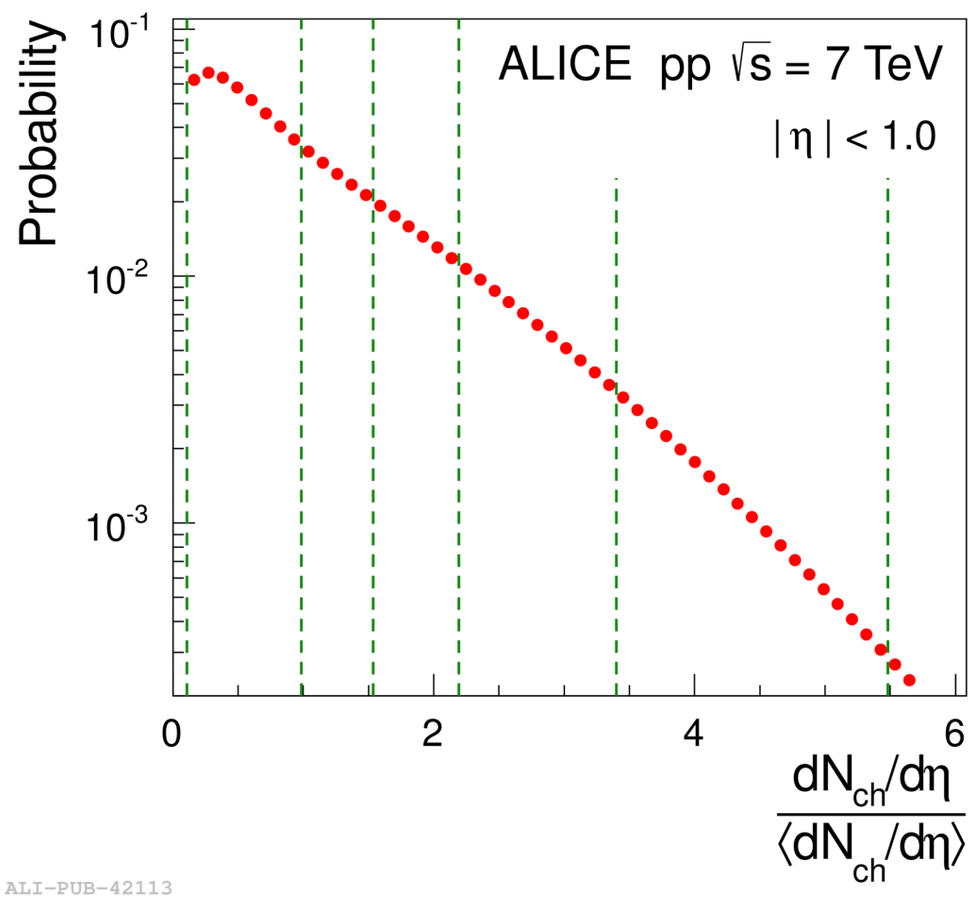
M. Cacciari, M. Greco and P. Nason, JHEP 9805 (1998) 007;
M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, G. Ridolfi, arXiv:1205.6344

B.A. Kniehl, G. Kramer, I. Schienbein, H. Spiesberger, arXiv:1202.0439, DESY-12-013, MZ-TH-12-07, LPSC-12019

Production of D mesons vs multiplicity

- Multiplicity estimator: number of track segmenta (or tracklets) of the Silicon Pixel Detector.
- The analysis required corrections to account for the detector performance variation vs time.





Ntracklets $\propto$ dNch/dη

$\langle dNch/d\eta \rangle = 6.01 \pm 0.01(stat.)\ ^{+0.20}_{-0.12}(syst.)$
for $|\eta|<1.0$

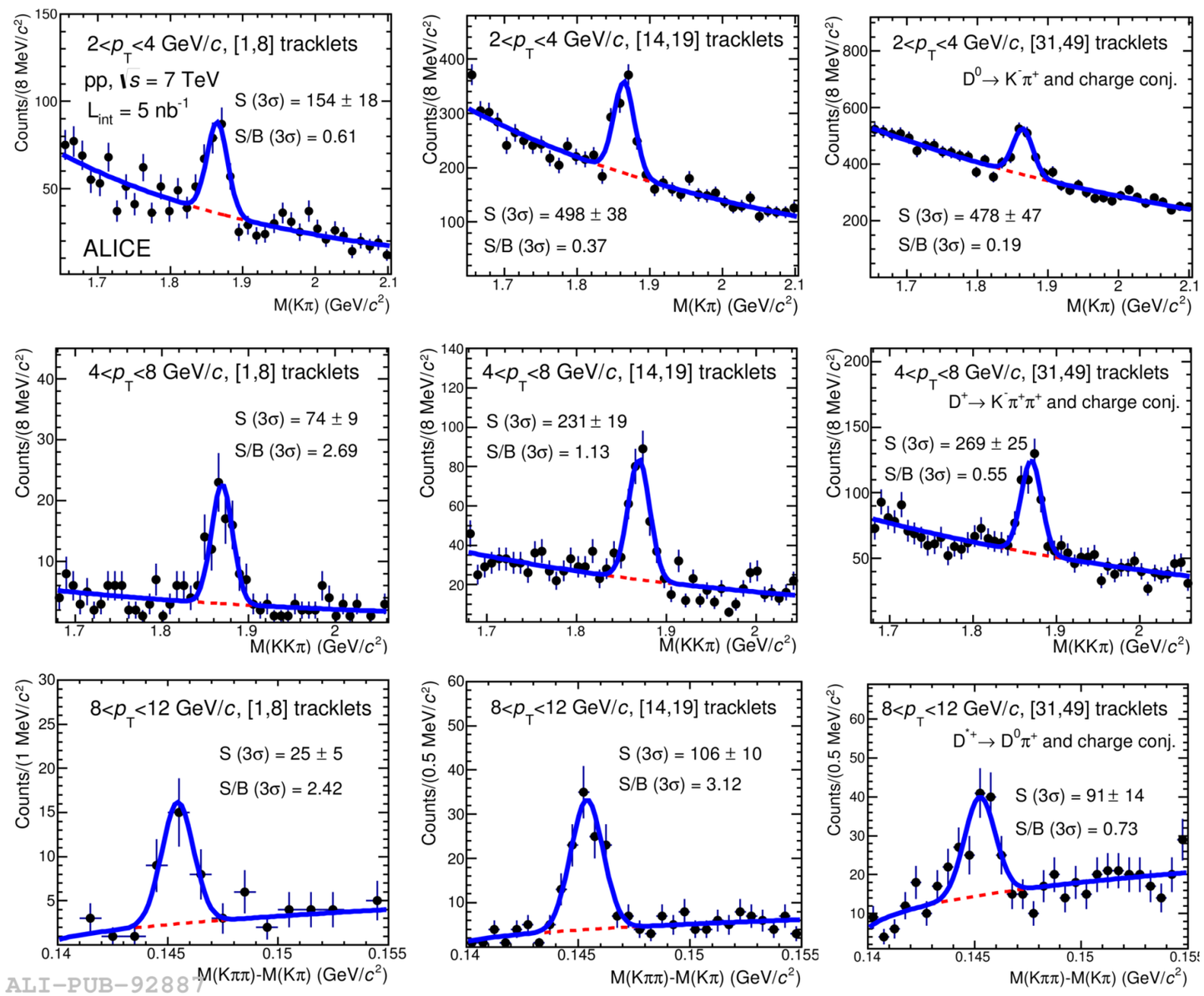
ALICE Coll., Eur. Phys. J. C 68 (2010) 345.
ALICE Coll., Phys. Lett. B 712 (2012) 3, 165–175

Production of D mesons vs multiplicity in pp collisions

- D^0, D^+ and D^{*+} signal studied:
  - in 5 multiplicity bins with number of tracklets (1, 9, 14, 23, 31, 50)
  - and 5 p_T bins (1, 2, 4, 8, 12, 20)

$N_{tracklets}$ = track segments in the silicon pixel layers

$N_{tracklets} \propto dN_{ch}/d\eta$

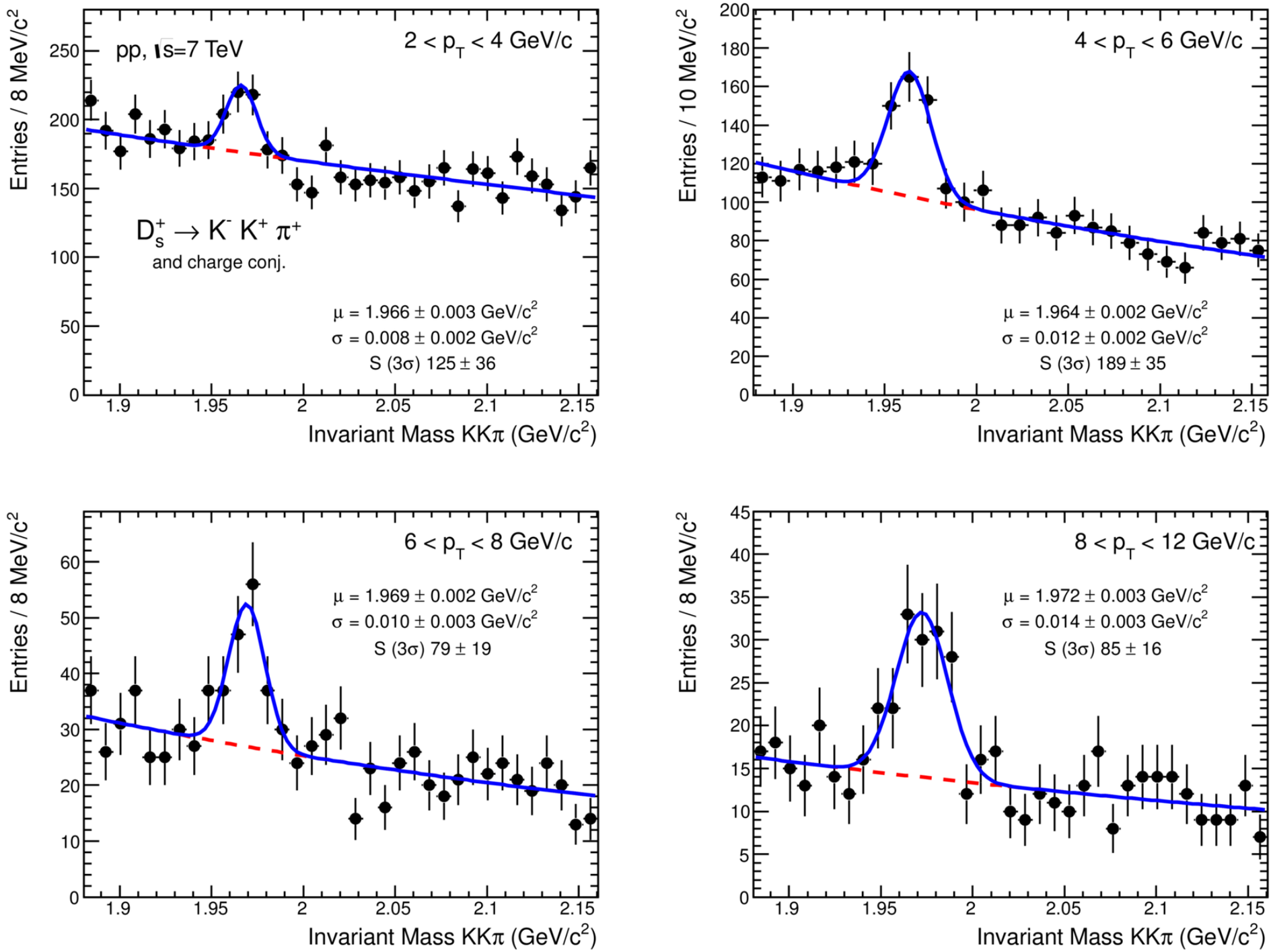


D^0 spectra

D^+ spectra

D^{*+} spectra

D^+_s invariant mass analysis

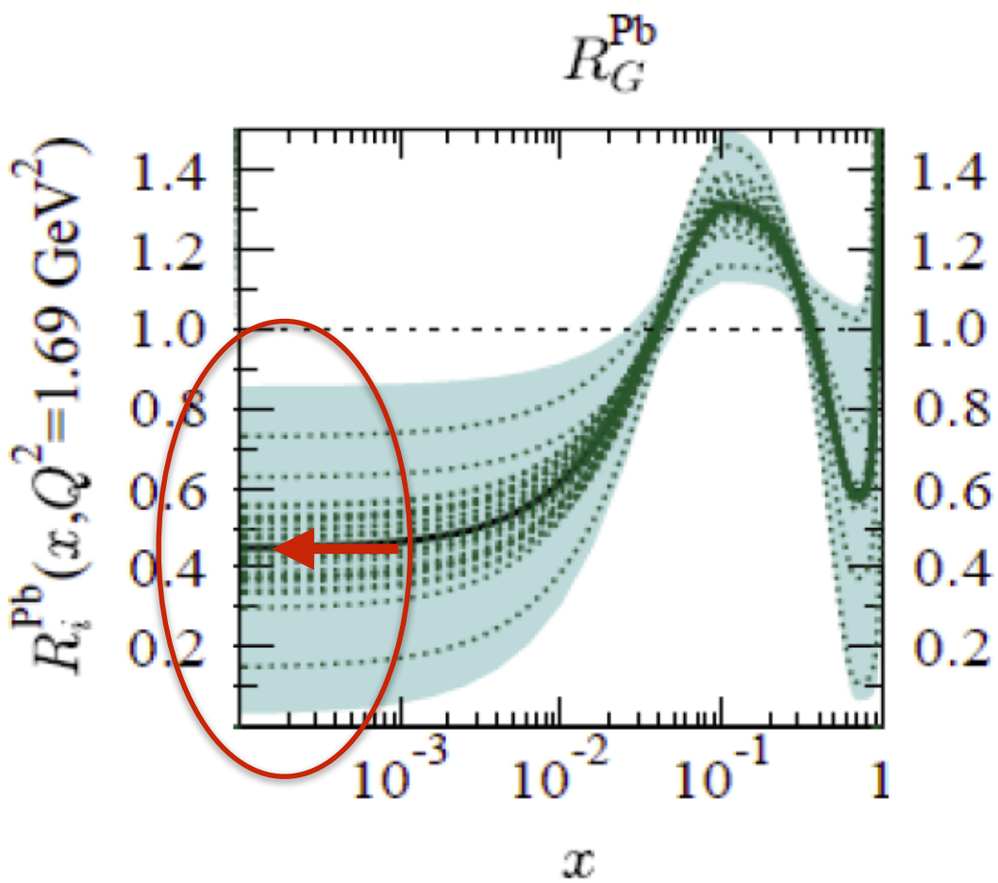


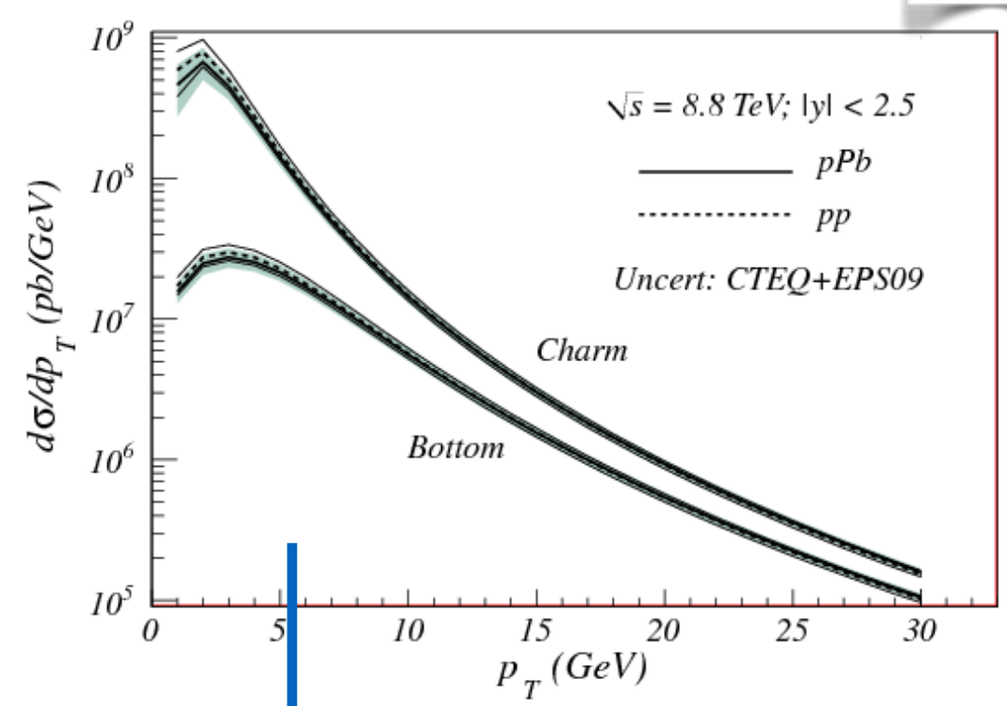
ALI-PUB-40180

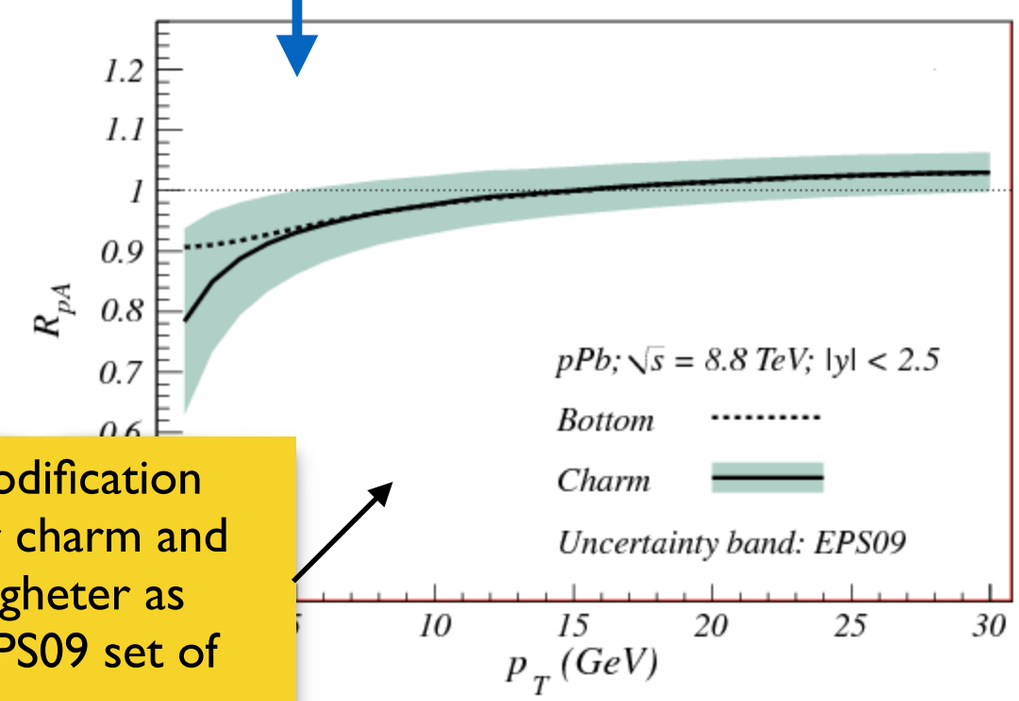
Phys.Lett. B718 (2012) 279-294

Motivations for the p-Pb run

- ☑ Study cold-nuclear matter effects, reference for Pb-Pb
- ☑ Low-x region accessed at the LHC
- ☑ Shadowing/saturation at low-x (Color Glass Condensate, CGC?)







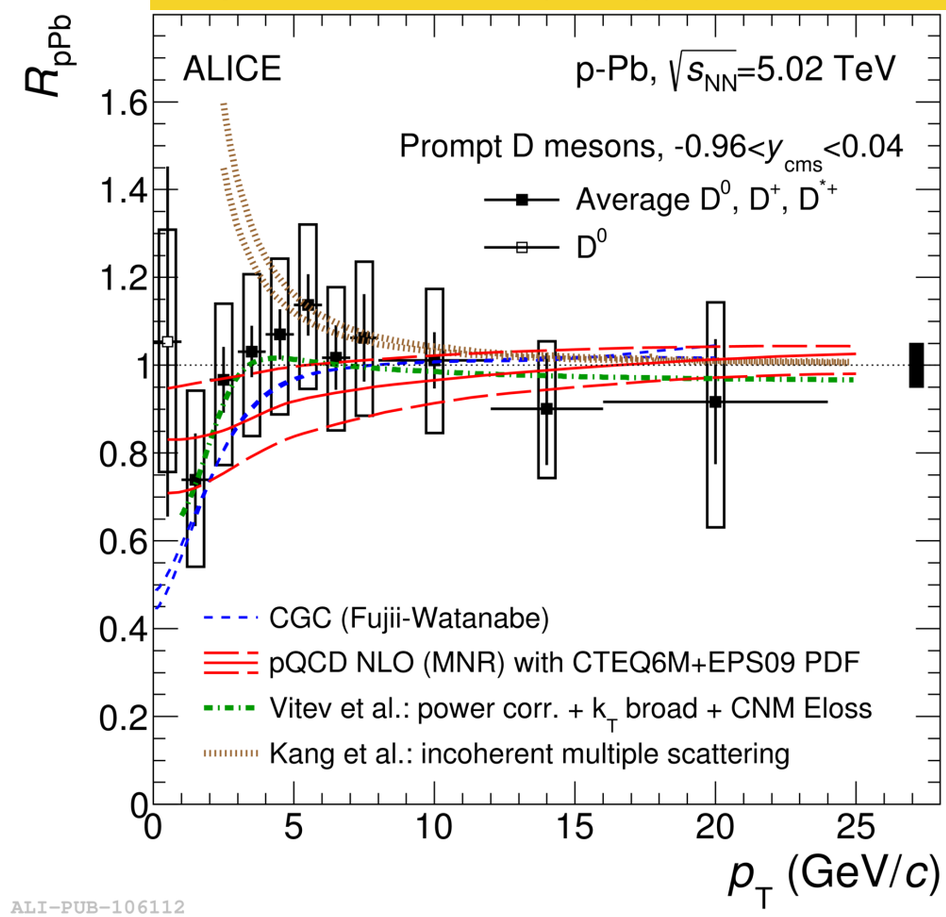
nuclear modification factors for charm and bottom togheter as given by EPS09 set of nPDFs

J.Phys. G39 (2012) 015010

Prog.Part.Nucl.Phys. 76 (2014)

D-meson in p-Pb collisions: R_{pPb}

Phys.Rev.Lett. 113 (2014) no.23, 232301



- First measurement of the D-meson R_{pPb}.

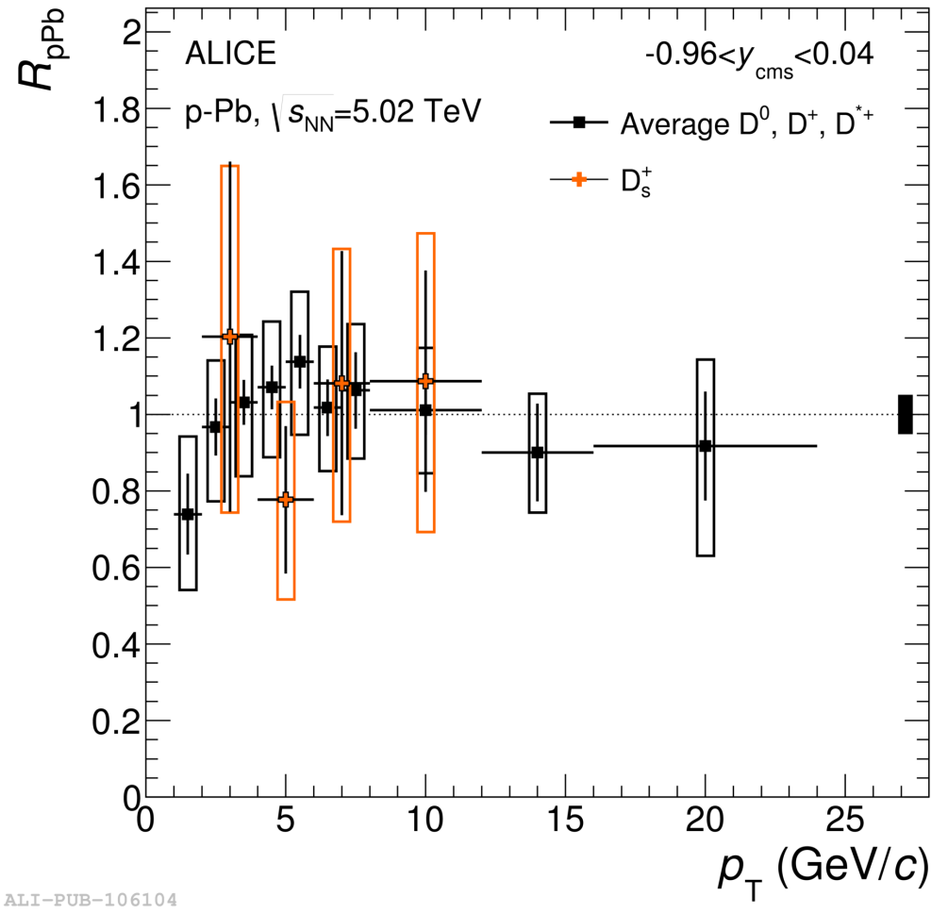
$$R_{pPb} = \frac{\left(\frac{d\sigma}{dp_T}\right)_{pPb}}{A \times \left(\frac{d\sigma}{dp_T}\right)_{pp}}$$

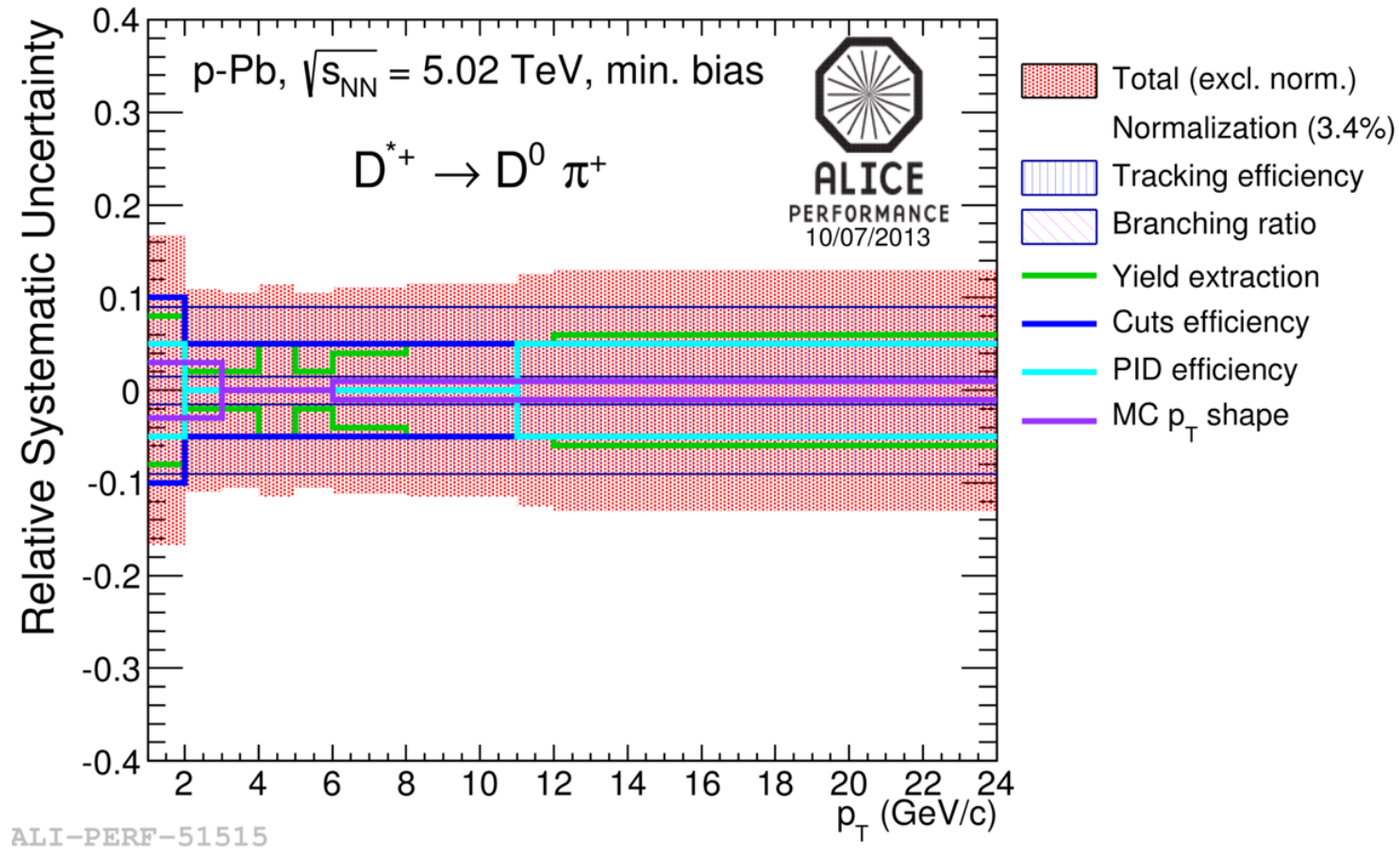
- D^0, D^+, D^{*+} and D_s^+ show a compatible trend within uncertanties
- pp reference measurement based on a theoretical scaling of the 7 TeV D^0, D^{*+} ,D^+ and D_s^+ cross section down to 5.02 TeV by using FONLL calculations
- Comparison with EPS09 nPDF calculations shows a good agreement over the whole p_T region covered by the measurement
- Data in agreement with the expectation of small cold nuclear matter effects at LHC

D-mesons R_{pPb}

arXiv:1605.07569

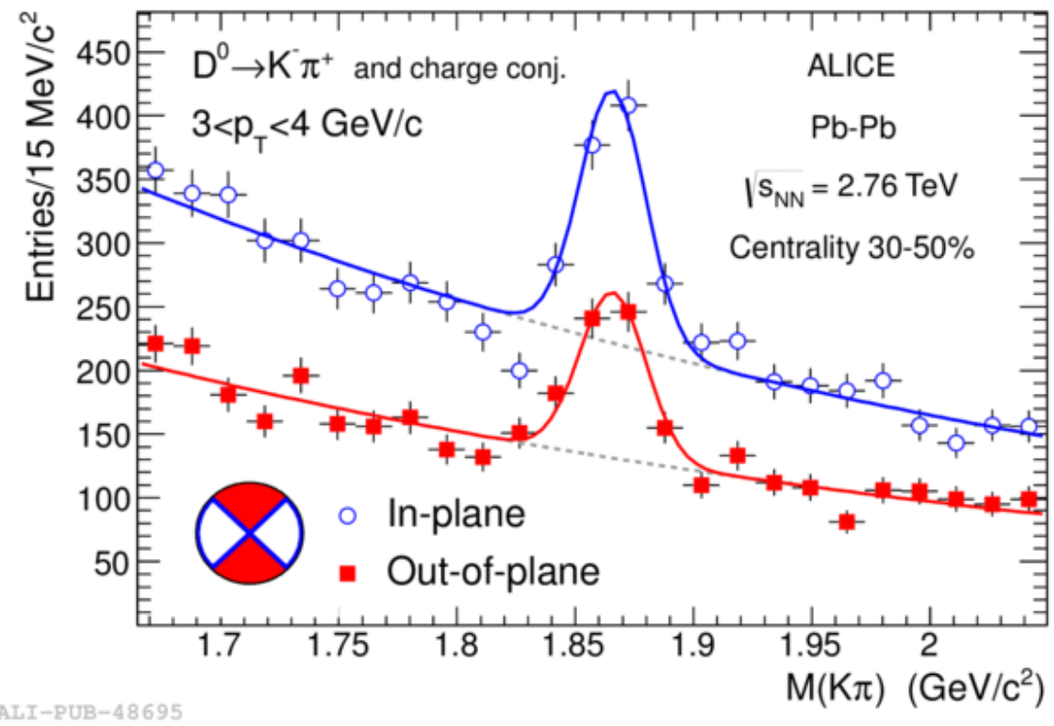
Phys. Rev. Lett. 113 no. 23, (2014) 232301



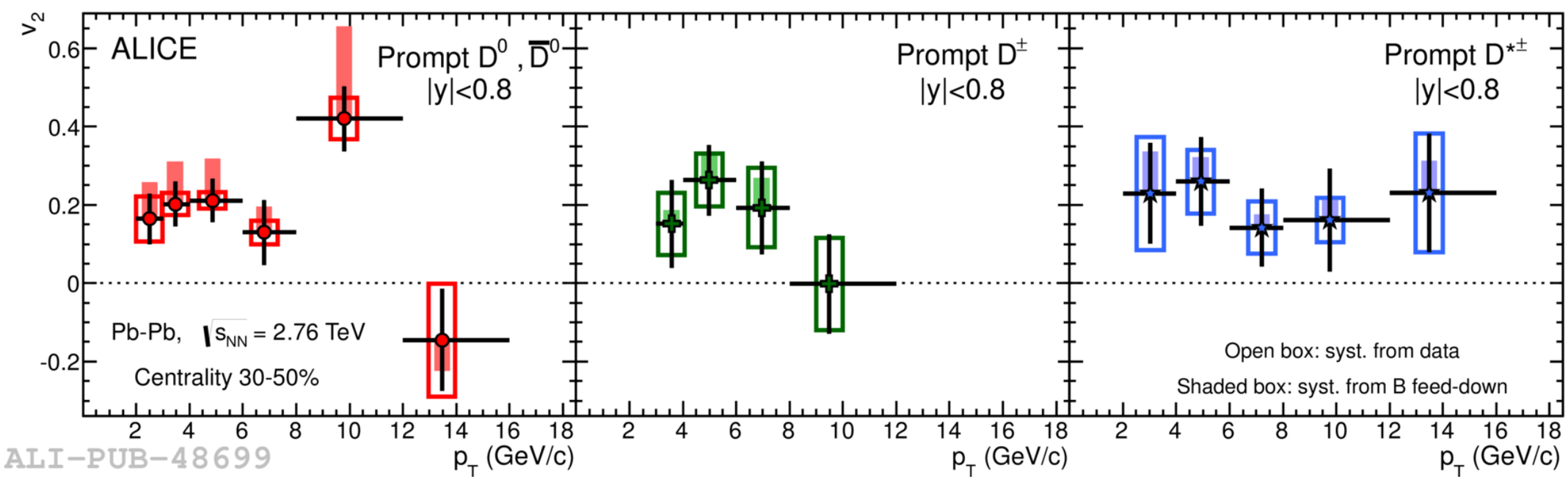


- D mesons R_{pPb} measured for D^0, D^+ and D^{*+} in the range $1<p_T<24$ GeV/c. The average is shown here
- D_s R_{pPb} measured in the range $2<p_T<12$ GeV/c
- Several sources of systematics investigated. D^{*+} as example

D mesons v_2

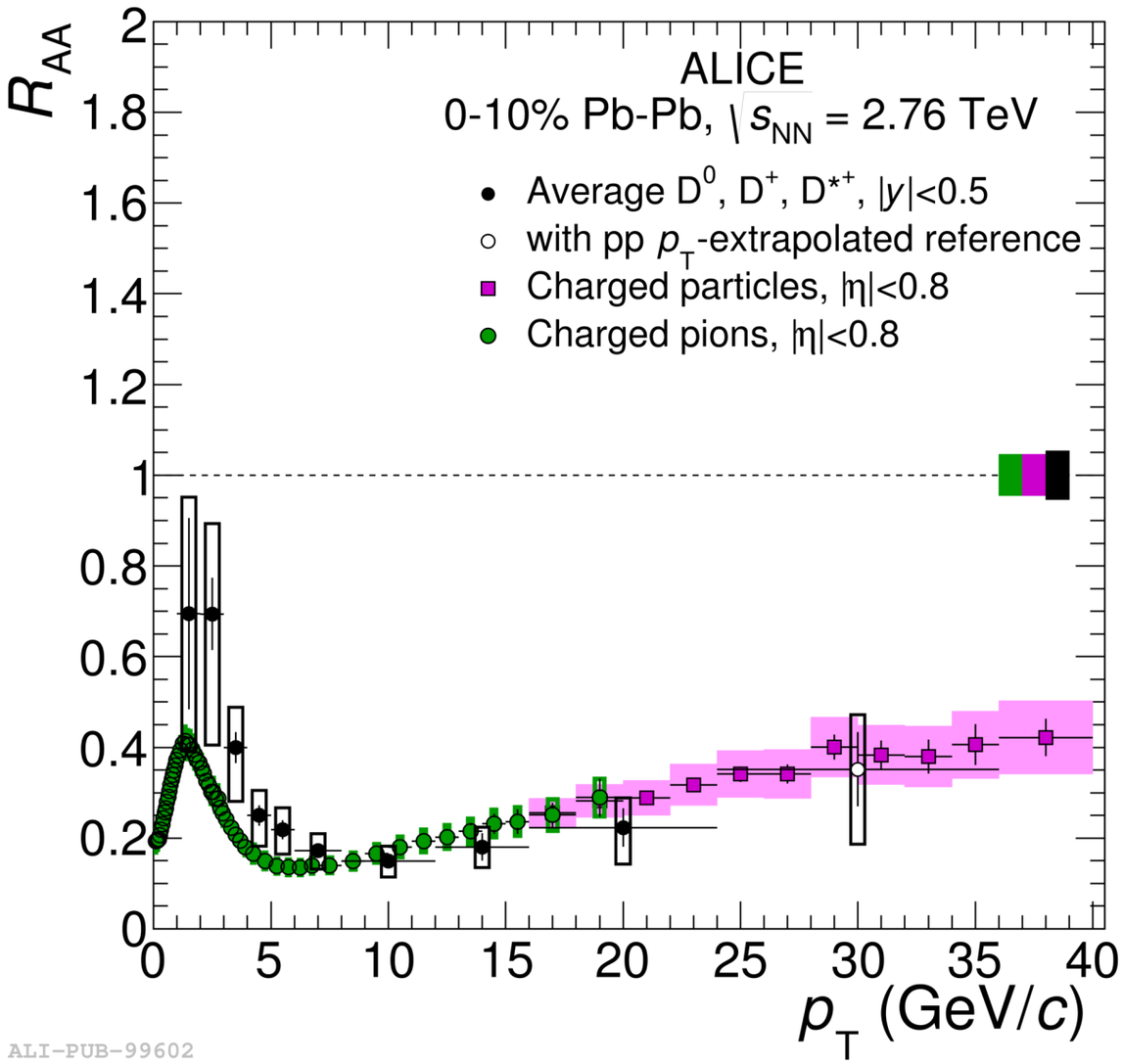


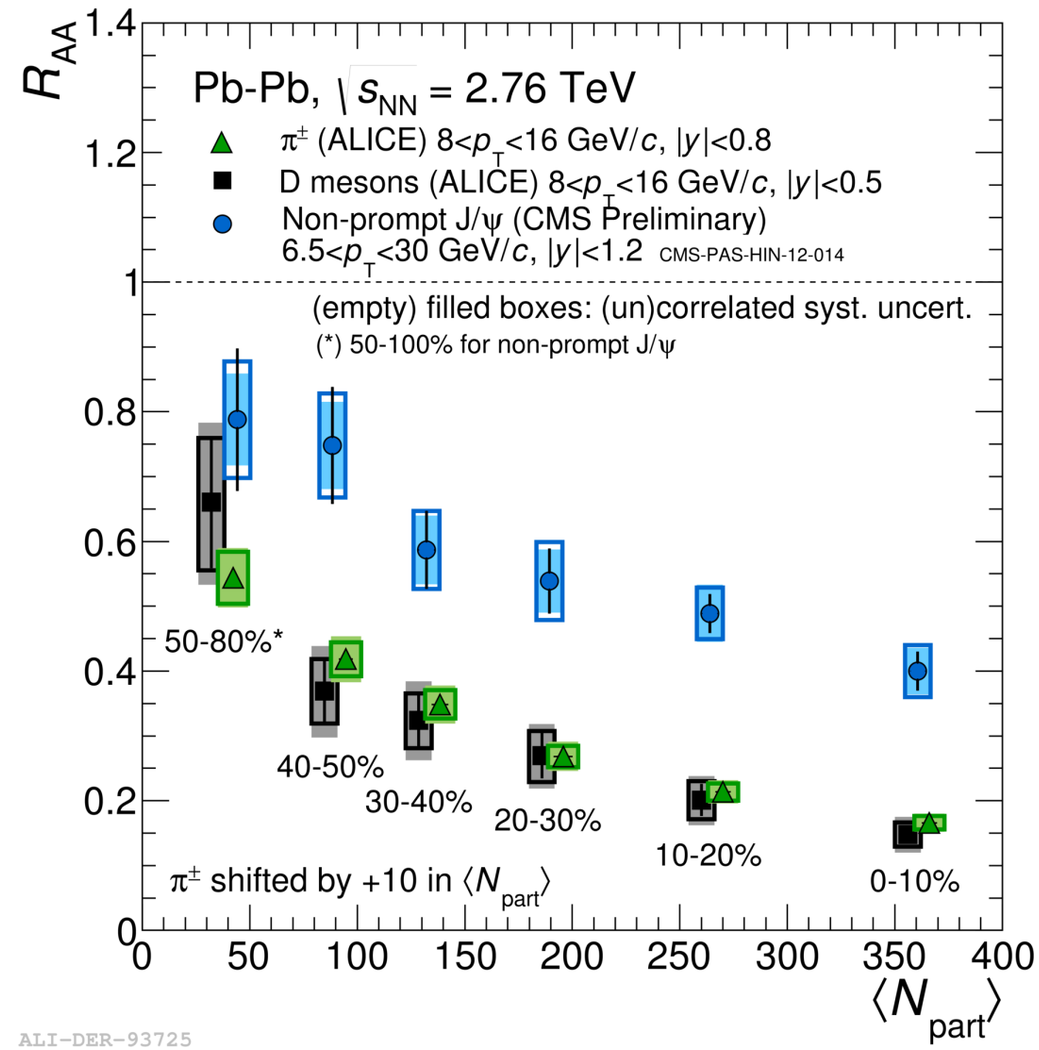
Phys.Rev.Lett. 111 (2013) 102301



Centrality dependent R_{AA}: Mass hierarchy

JHEP 1603 (2016) 081





☑ In the transverse momentum range $2<p_T<3$ GeV/c the R_{AA} vs N_{part} of the D^0 shows a hint of $R_{AA}(\pi)<R_{AA}(D)$ in the 2 most central bins