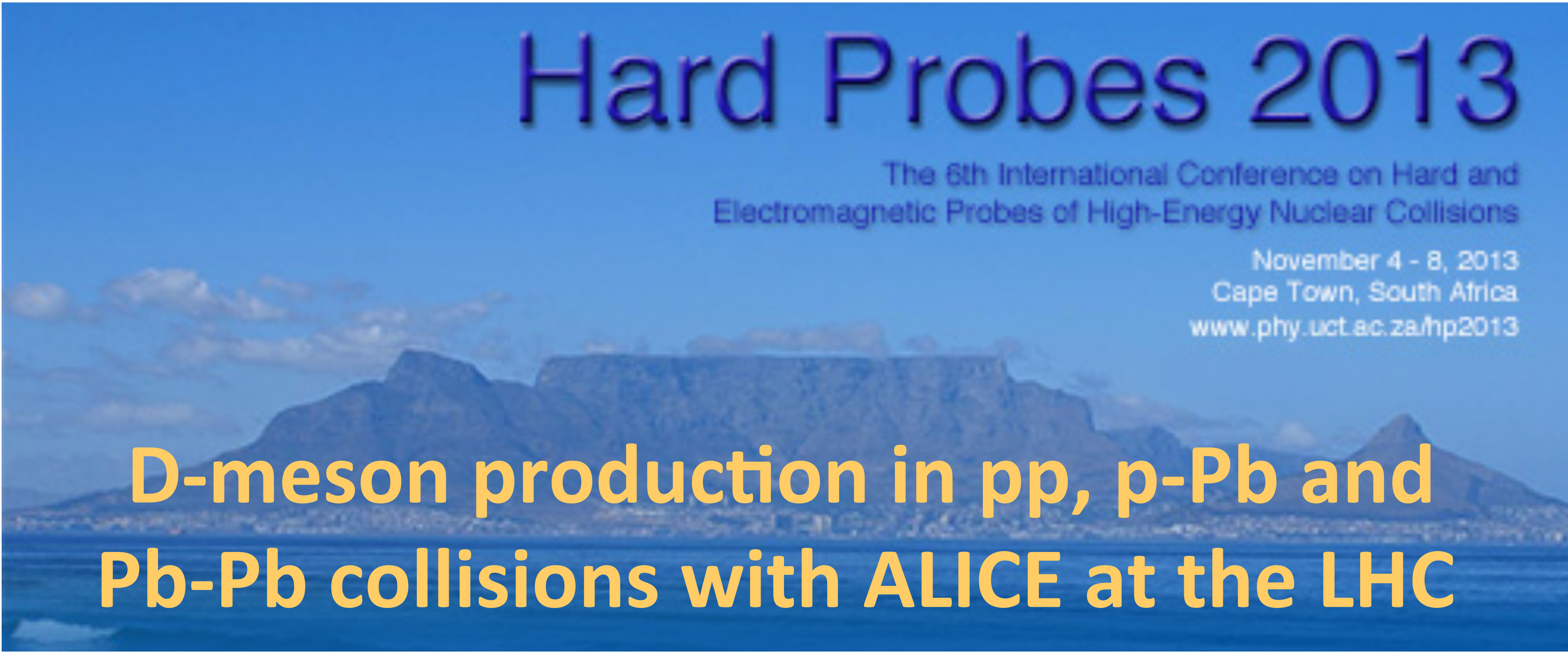


Hard Probes 2013

The 6th International Conference on Hard and
Electromagnetic Probes of High-Energy Nuclear Collisions

November 4 - 8, 2013
Cape Town, South Africa
www.phy.uct.ac.za/hp2013

D-meson production in pp, p-Pb and Pb-Pb collisions with ALICE at the LHC

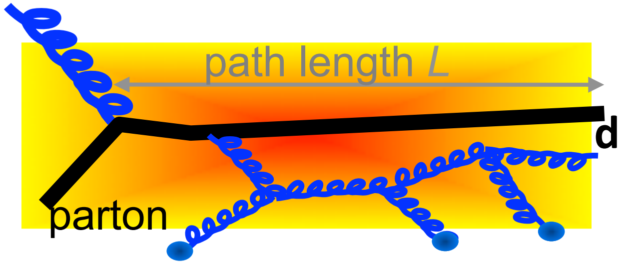
A. Rossi, CERN

on behalf of the ALICE Collaboration

Why heavy quarks in heavy-ion collisions?

- Early production in hard-scattering processes with high Q^2 (large masses)
- Production cross sections calculable with pQCD
- Harder fragmentation ➜ measured meson properties closer to parton ones
- Strongly interacting with the medium they preserve their identity

⇨ **"Calibrated probes" of the medium**



Study their interaction with the medium

- **energy loss via radiative ("gluon Bremsstrahlung") and collisional processes**
    - color charge (Casimir factor)
    - quark mass (← dead cone effect)
    - path length and medium density

$$\left.\right\} \Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

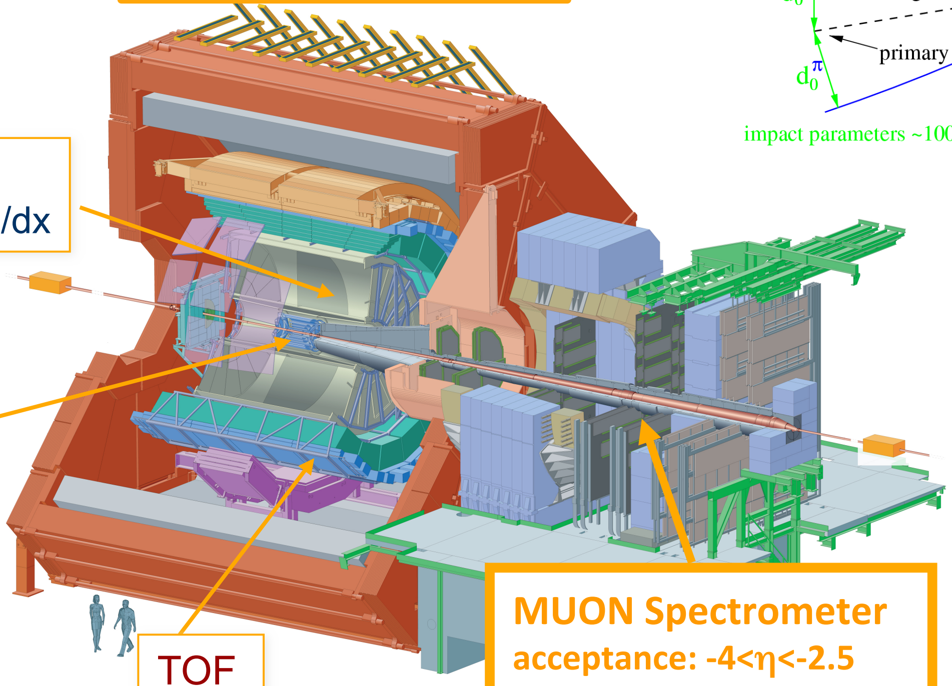
$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

- medium **modification to HF hadron formation**
    - hadronization via quark coalescence
- **participation in collective motion ➜** elliptic flow (v_2)

Disentangle "hot" final state from initial state effects (e.g. shadowing) ➜ p-Pb collisions

ALICE detector and analysis technique

Plenary talk by F. Prino



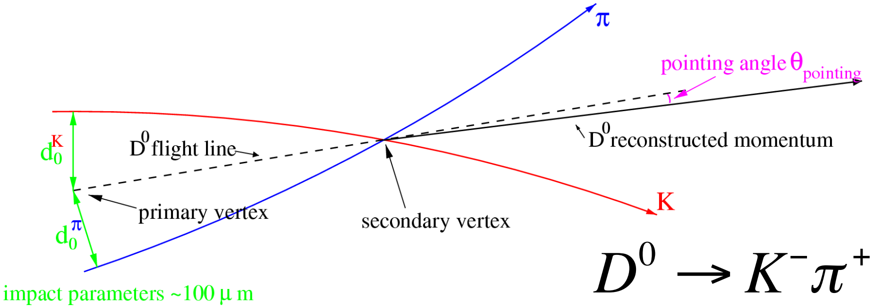
CENTRAL BARREL
acceptance: |η|<0.9

TPC
Tracking, dE/dx

ITS
Vertexing,
Tracking
(dE/dx)

TOF
PID

MUON Spectrometer
acceptance: -4<η<-2.5



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

Decay channels:

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

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

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

$D_s \rightarrow \phi\pi^+$, $\phi \rightarrow K^-K^+$

Analysis strategy:

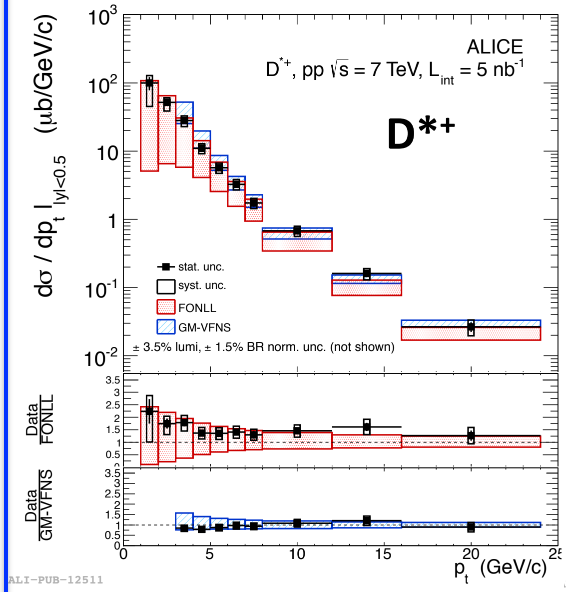
- Invariant mass analysis
- Displaced secondary vertices topology (➔ ITS)
- PID selection (mainly Kaon identification in TOF+TPC) to reduce background

Results from pp collisions: reference for Pb-Pb and test of pQCD- based calculation

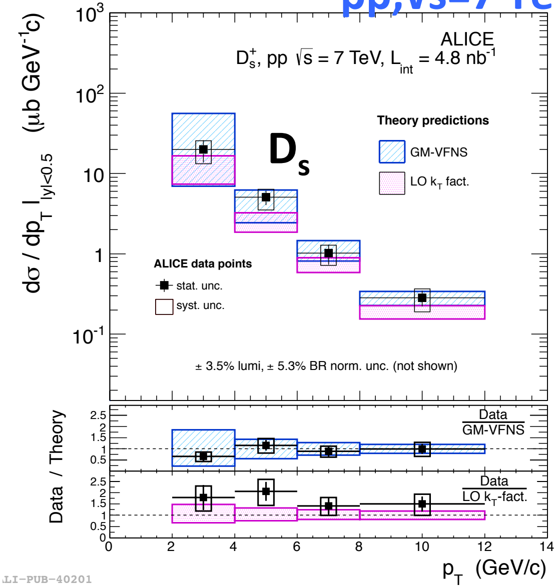
System	$\sqrt{s_{NN}}$ (TeV)	Run	Statistics (min. bias)
pp	7	2010	5 nb^{-1}
pp	2.76	2011	1.1 nb^{-1}
Pb-Pb	2.76	2010	2.12 μb^{-1}
Pb-Pb	2.76	2011	28 μb^{-1}, central trigger
			6 μb^{-1}, semi-peripheral trigger
p-Pb	5.02	2013	48.6 μb^{-1}

D-meson production cross sections

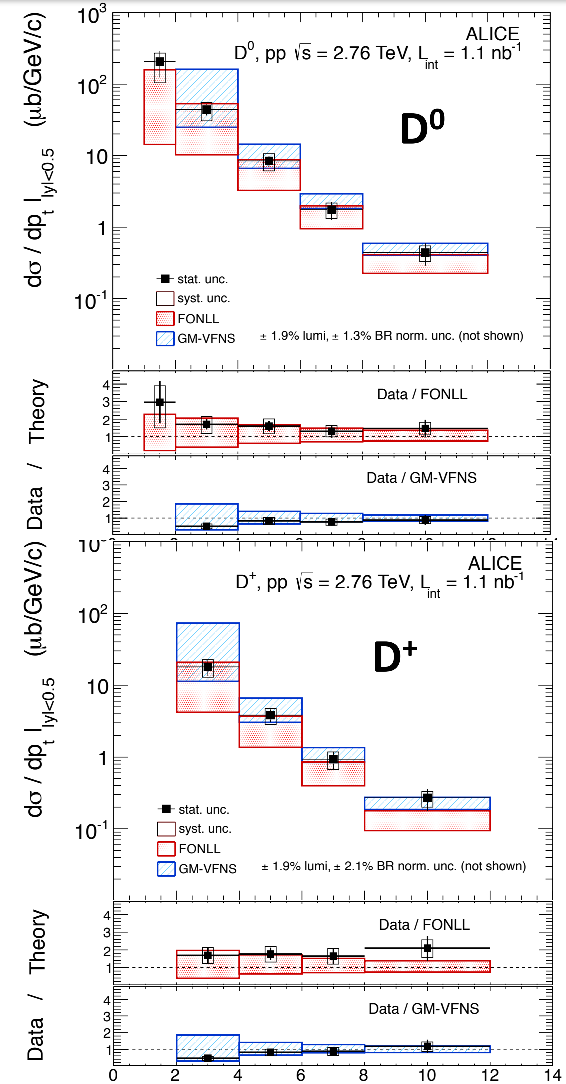
pp,√s=7 TeV



JHEP 1201 (2012) 128



Phys.Lett. B718 (2012) 279-294



pp, √s=2.76 TeV

JHEP 1207 (2012) 191

- D^0,D^+,D^{*+},D_s p_T-differential production cross sections measured between 1 and 24 GeV/c at **√s=7 TeV** and between 1 and 12 GeV/c at **√s=2.76 TeV**
- **In agreement with pQCD-based calculation**

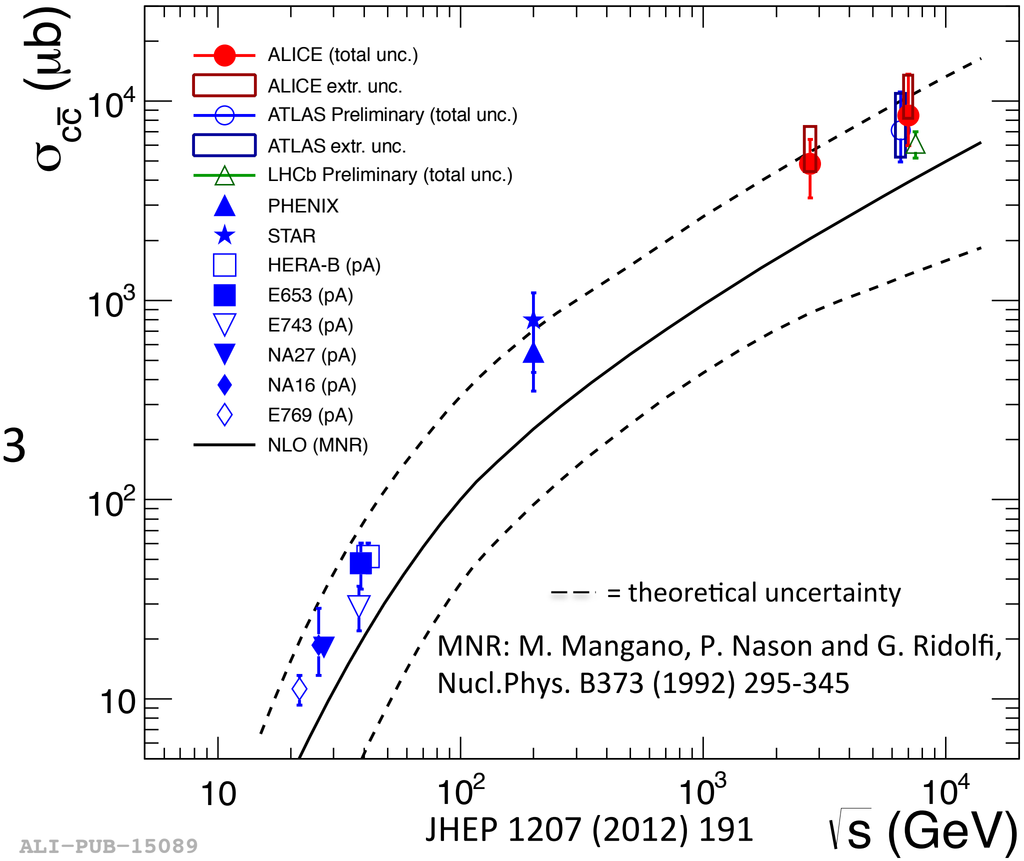
FONLL: Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033

GM-VFNS: B. A. Kniehl, G. Kramer, I. Schienbein and H. Spiesberger, Phys.Rev. D77 (2008) 014011

LO k_T fact: R. Maciula, M. Luszczak and A. Szczurek, arXiv:1208.6126 [hep-ph]

Charm total cross section

Energy dependence of total charm production cross section in pp well reproduced by NLO pQCD-based calculation (MNR) over more than 3 orders of magnitude



ALI−PUB−15089

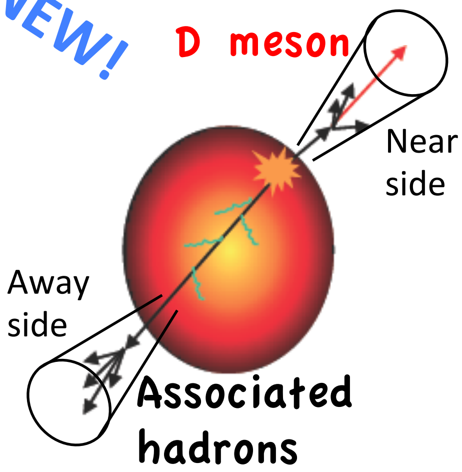
JHEP 1207 (2012) 191

Charm production in pp theoretically under control

D meson-charged hadron azimuthal correlations

See also HF e-hadron correlation
In talk by E. Pereira De Oliveira Filho

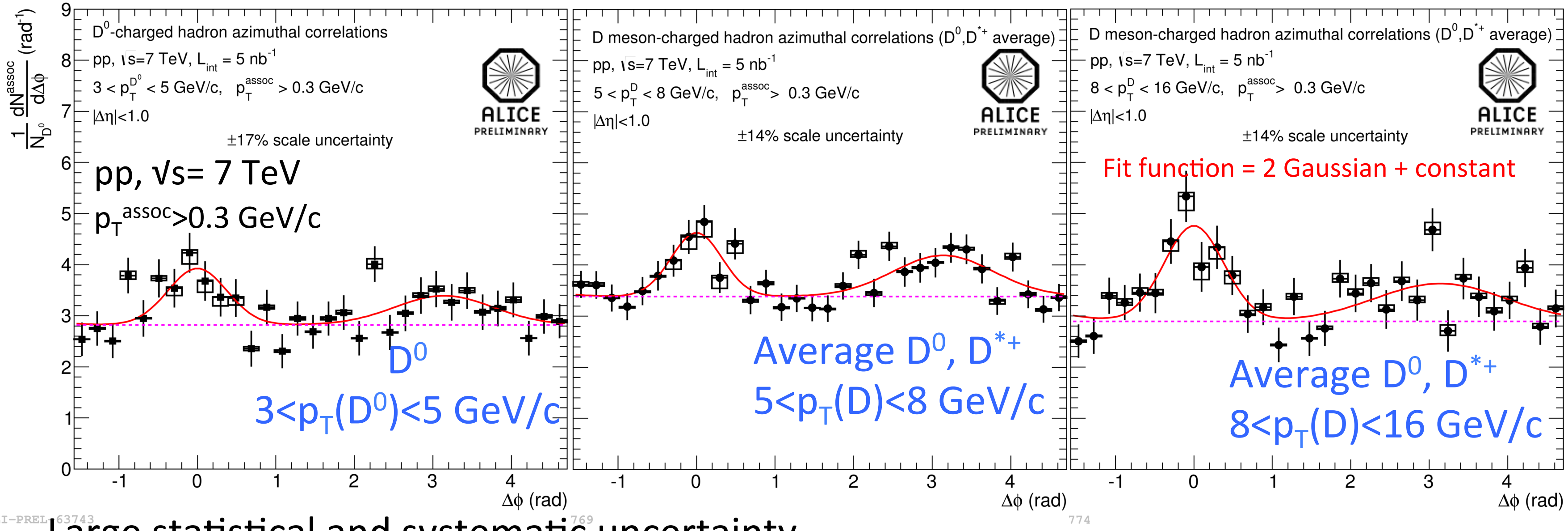
NEW!



Long term physics goal:

- Address medium modification to charm jet properties
- Path length dependence of energy loss

➜ Measure associated yields in near and away side → I_{AA}

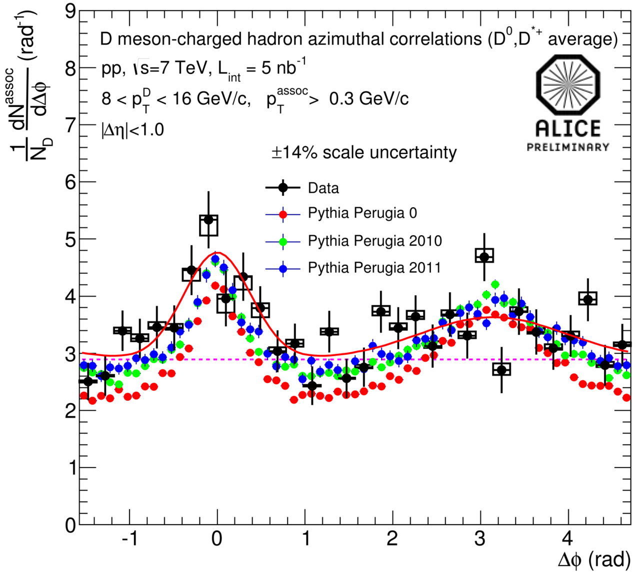


Large statistical and systematic uncertainty

- 14% to 17% scale uncertainty (mainly from uncertainty on D-meson signal extraction from invariant mass fit and D-meson efficiency correction)

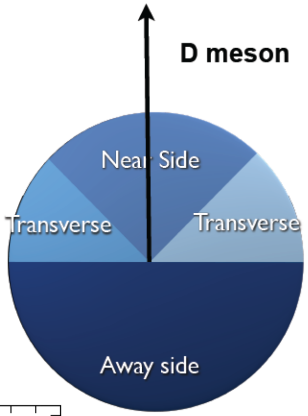
D meson-charged hadron azimuthal correlations

NEW!



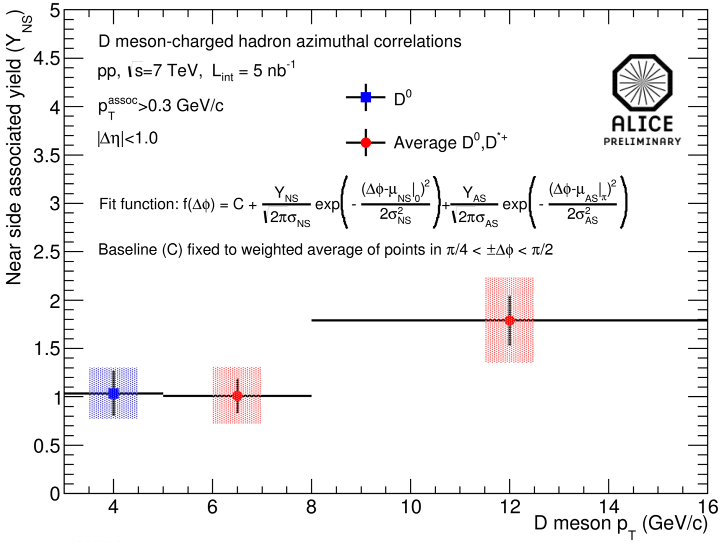
ALI-DER-63803

In agreement with Pythia within large statistical and systematic uncertainties



Fit function: constant baseline + 2 Gaussian
Baseline fixed from weighted average of points in transverse region ($\pi/4<\pm\Delta\varphi<\pi/2$)

Associated yield in near side peak ⟶



ALI-PREL-63789

Large uncertainties prevent quantitative conclusions

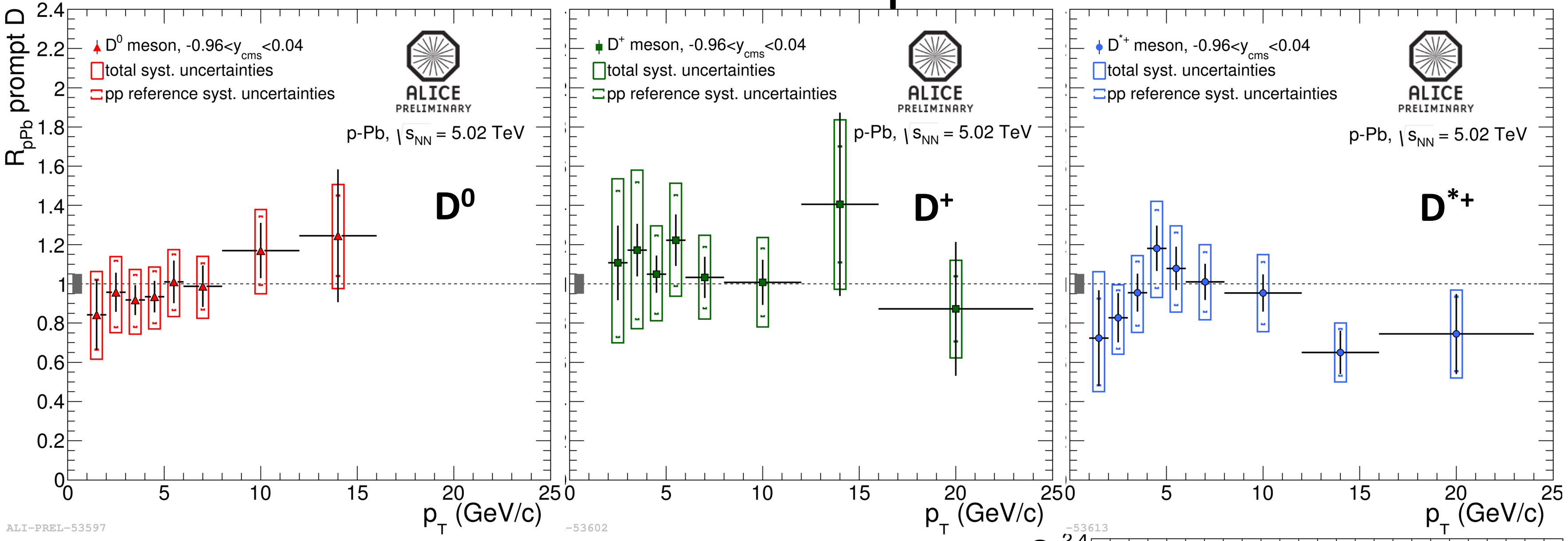
Precise measurement expected from Run 2

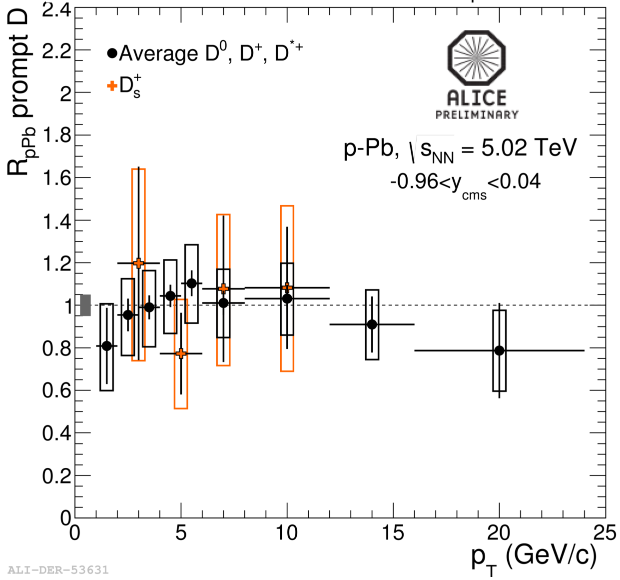
The p-Pb reference: probing initial state effects

System	$\sqrt{s_{NN}}$ (TeV)	Run	Statistics (min. bias)
pp	7	2010	5 nb^{-1}
pp	2.76	2011	1.1 nb^{-1}
Pb-Pb	2.76	2010	2.12 μb^{-1}
Pb-Pb	2.76	2011	28 μb^{-1}, central trigger
			6 μb^{-1}, semi-peripheral trigger
p-Pb	5.02	2013	48.6 μb^{-1}

D-meson R_{pPb} vs. p_T

Poster by R. Russo





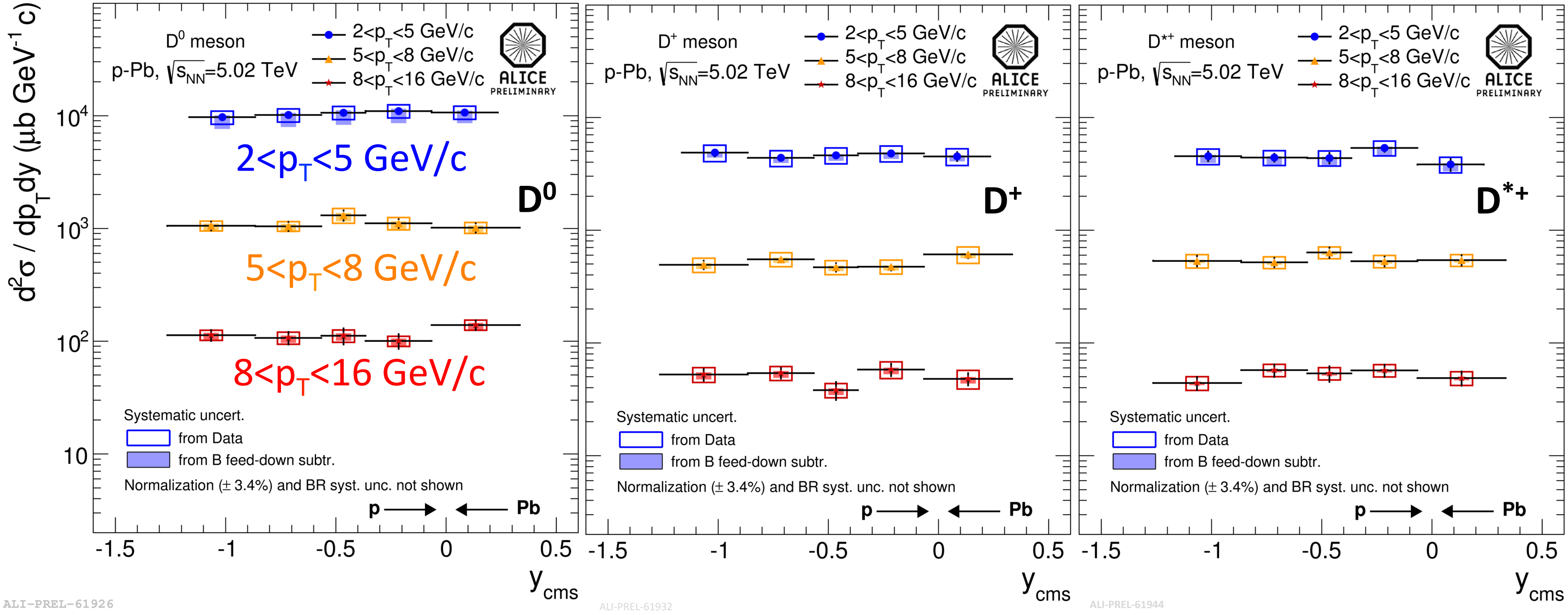
$$R_{pPb}(p_T) = \frac{(d\sigma / dp_T)_{pPb}}{A \times (d\sigma / dp_T)_{pp}}$$

- D-meson R_{pPb} measured from 1 to 24 GeV/c
- D^0, D^+, D^{*+} ,D_s R_{pPb} compatible within uncertainties

R_{pPb} compatible with 1
w/o appreciable dependence on p_T

D-meson production vs. y_{cms}

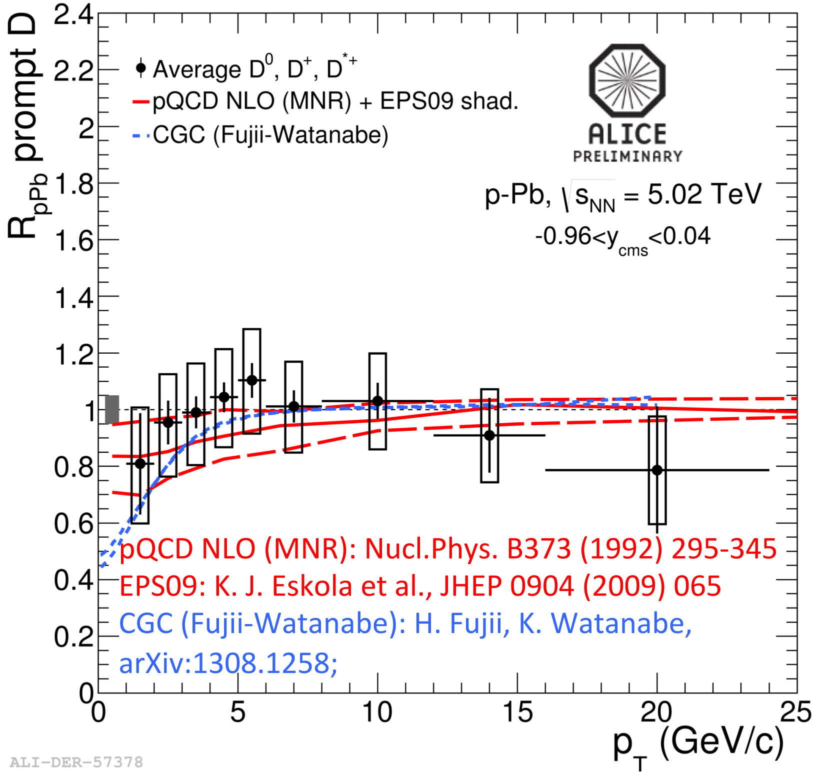
NEW!



No significant dependence on rapidity observed

Comparison to predictions

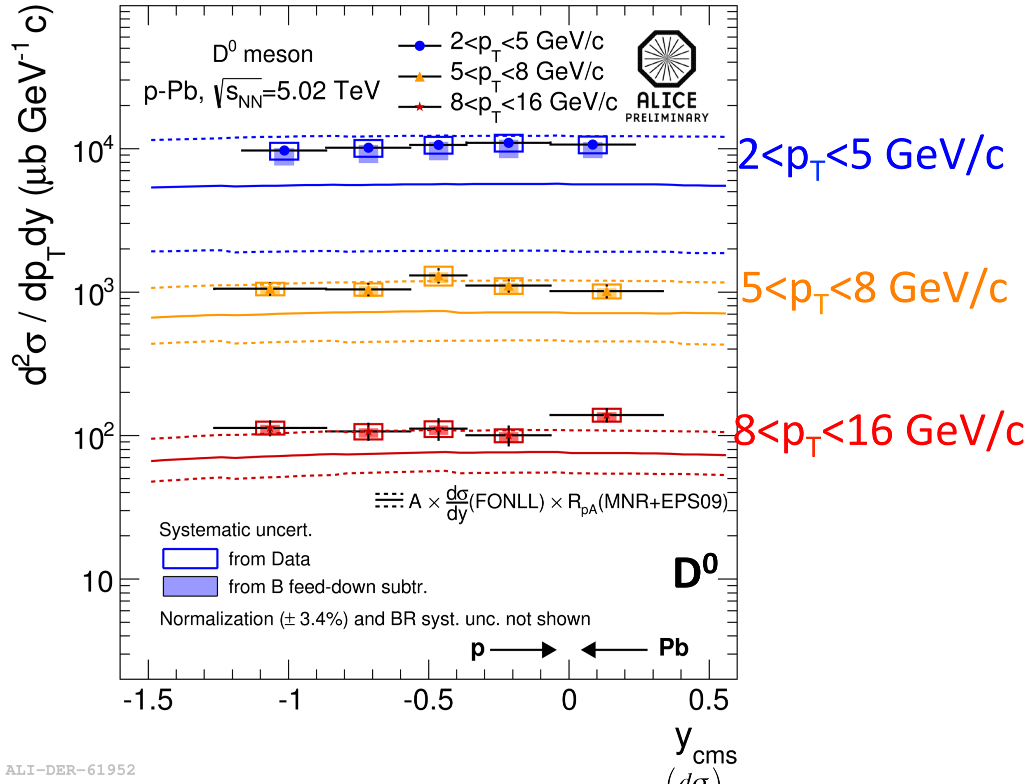
NEW!



pQCD NLO (MNR): Nucl.Phys. B373 (1992) 295-345

EPS09: K. J. Eskola et al., JHEP 0904 (2009) 065

CGC (Fujii-Watanabe): H. Fujii, K. Watanabe, arXiv:1308.1258;



Theoretical predictions (lines): $A \times \left(\frac{d\sigma}{dy}\right)_{FONLL} \times R_{pA}(\text{MNR+EPS09})$

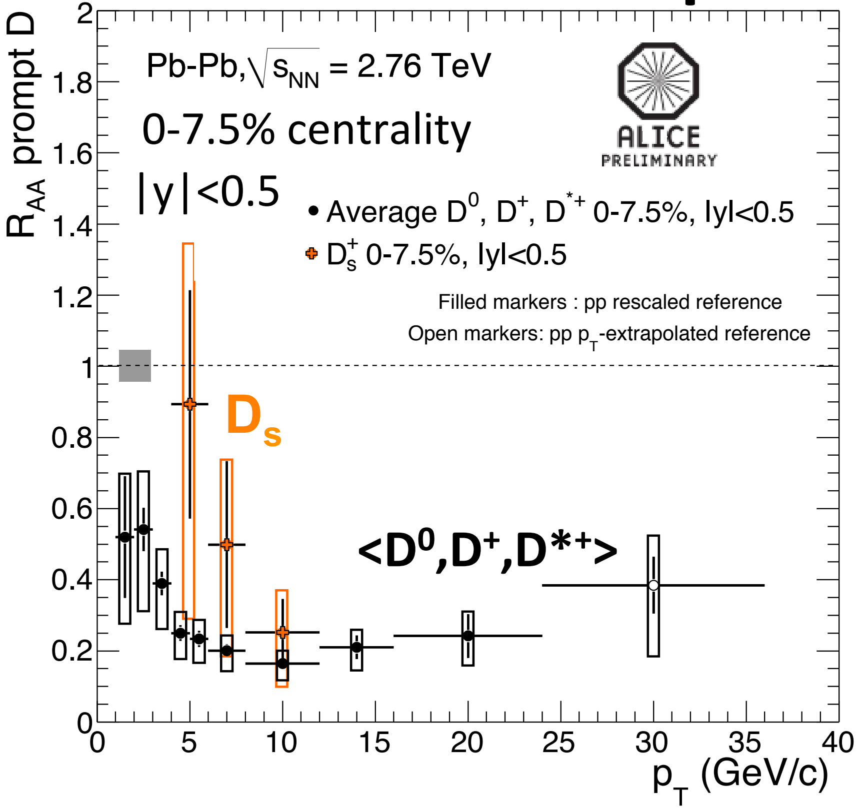
FONLL: JHEP0407 (2004) 033

- p_T and rapidity trends in agreement with pQCD + EPS09 shadowing calculations
- CGC prediction by Fujii-Watanabe also describes well the p_T dependence

Pb-Pb results

System	$\sqrt{s_{NN}}$ (TeV)	Run	Statistics (min. bias)
pp	7	2010	5 nb^{-1}
pp	2.76	2011	1.1 nb^{-1}
Pb-Pb	2.76	2010	2.12 μb^{-1}
Pb-Pb	2.76	2011	28 μb^{-1}, central trigger
			6 μb^{-1}, semi-peripheral trigger
p-Pb	5.02	2013	48.6 μb^{-1}

Prompt D-meson R_{AA}



$$R_{AA}(p_T) = \frac{(dN/dp_T)_{Pb-Pb}}{\langle T_{AA}\rangle \times (d\sigma/dp_T)_{pp}}$$

Strong suppression observed (factor 3-5) for p_T>5 GeV/c

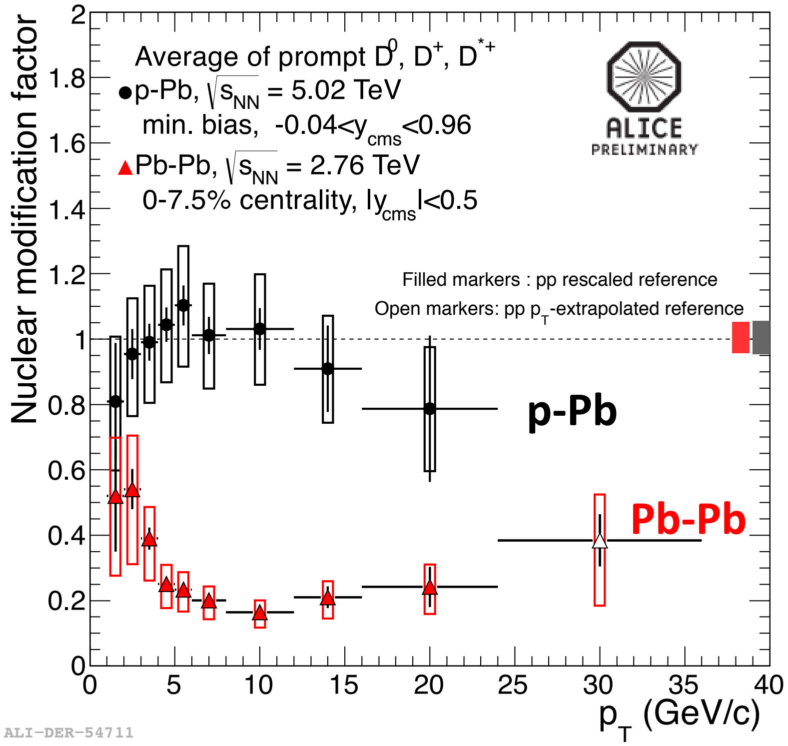
Based on 2011 Pb-Pb data: extends p_T range ($1<p_T<36$ GeV/c) of measurement published in JHEP 09 (2012) 112 ($2<p_T<16$ GeV/c, cent. 0-20%)

First measurement of D_s in Pb-Pb with 2011 run data

- Similar suppression of non strange D mesons in 8-12 GeV/c
- $R_{AA}(D_s) > R_{AA}(D^0,D^+,D^{*+})$ at low p_T? More more statistics needed
  - Important for constraining quark coalescence models

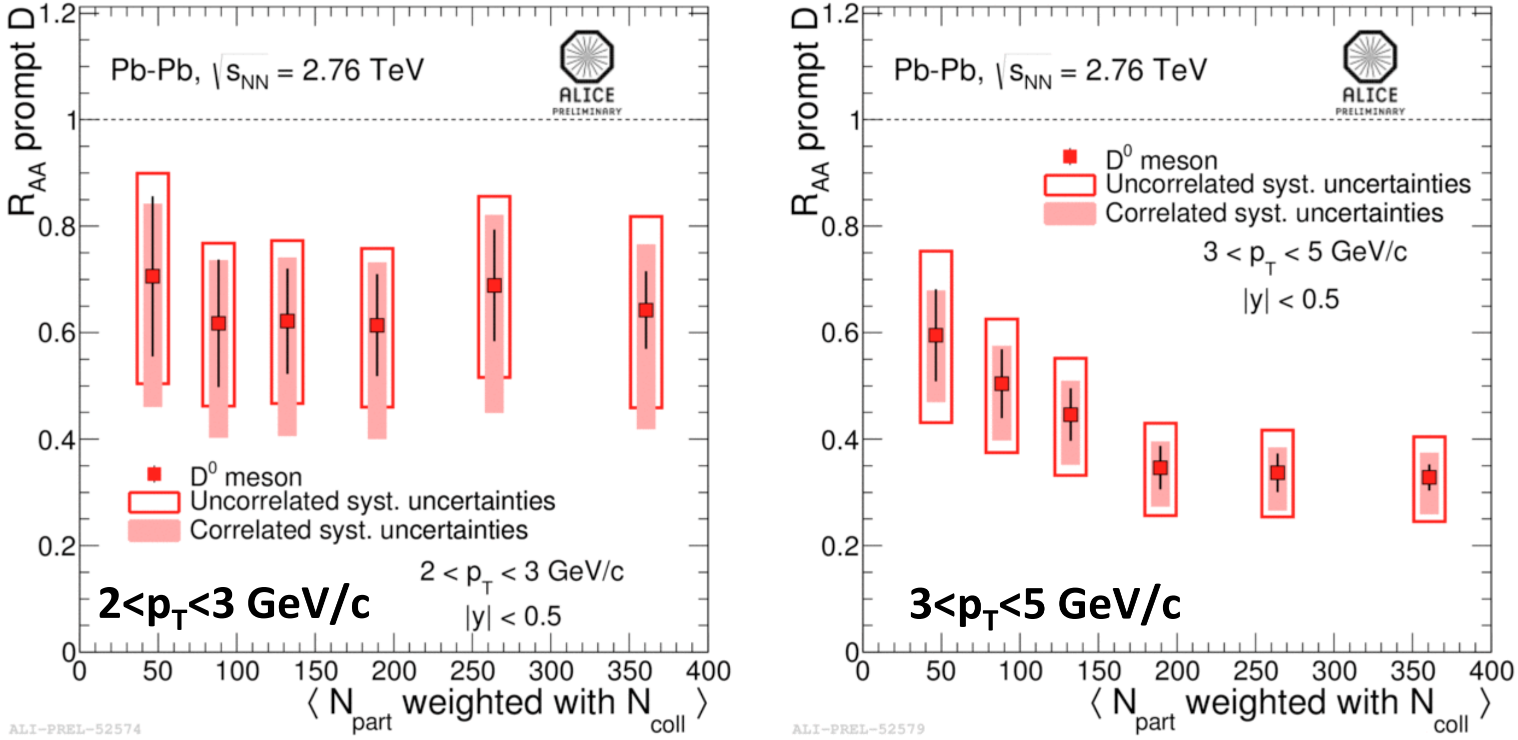
Kuznetsova & Rafelski, EPJ C51(2007)113;
He et al., arXiv:1204.4442;
Andronic et al., arXiv:0708.1488)

D meson R_{AA} vs. R_{pPb}



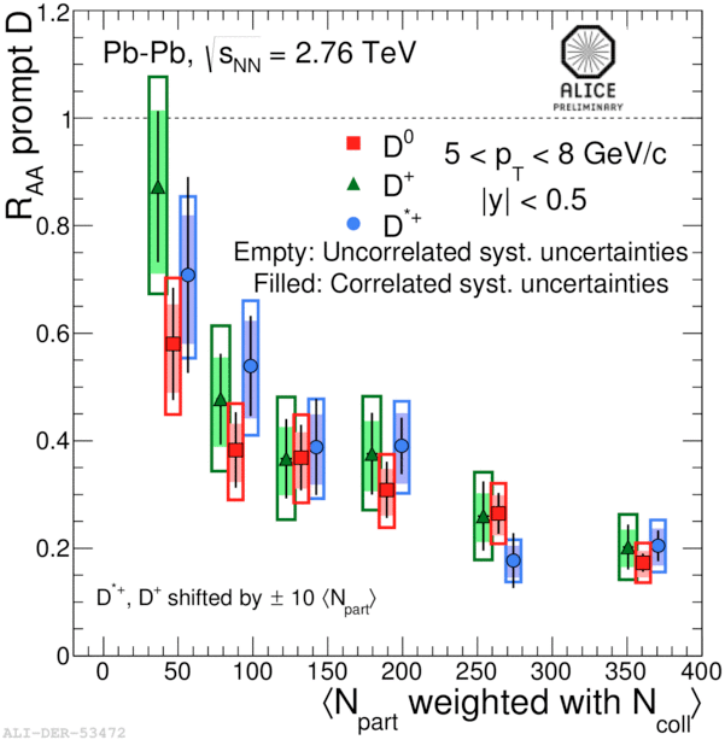
Observed suppression is a final state effect

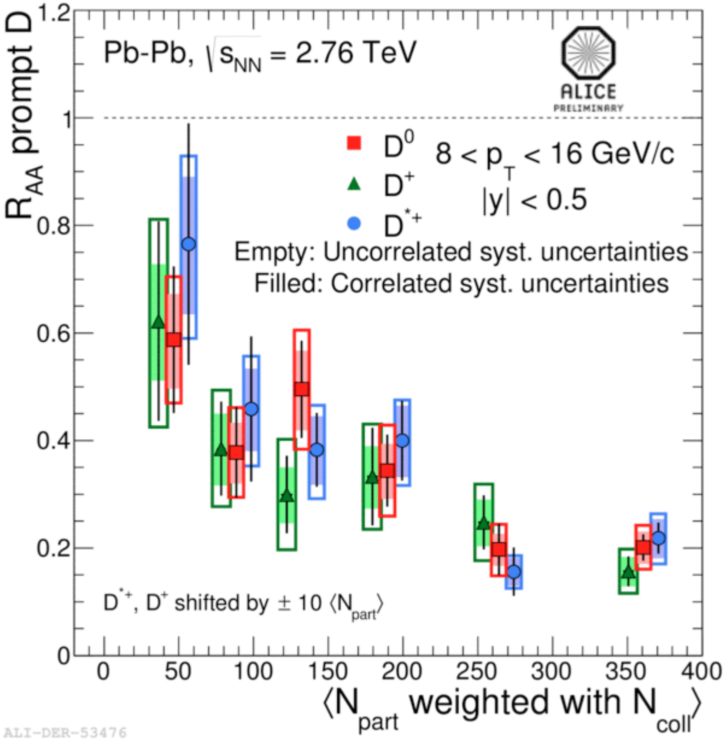
R_{AA}: centrality dependence



Suggest a different D^0-meson suppression trend in 2<p_T<3 GeV/c and 3<p_T<5 GeV/c

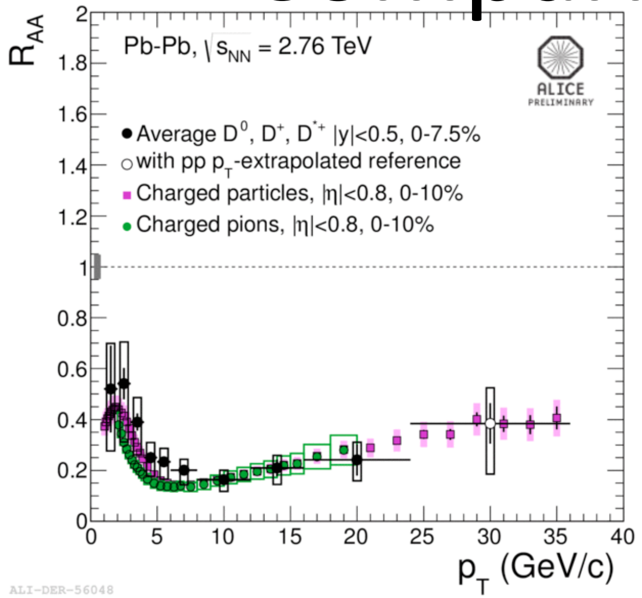
R_{AA}: centrality dependence



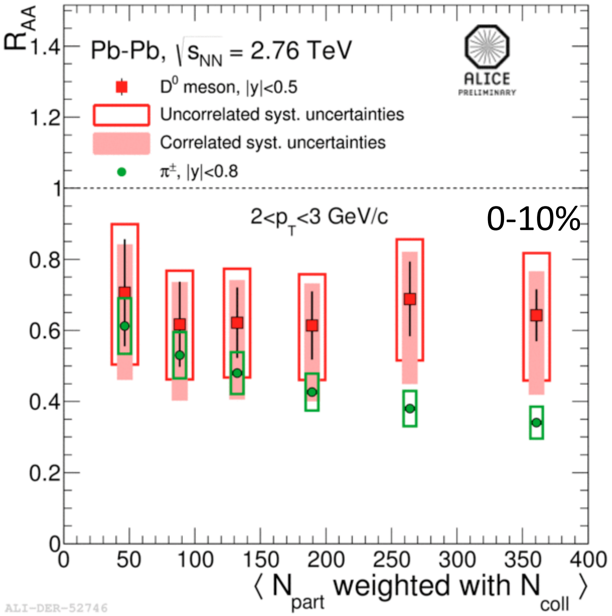


Suppression increasing with centrality for p_T>3 GeV/c

Comparison with pion R_{AA}



ALI-DER-56048



ALI-DER-52746

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

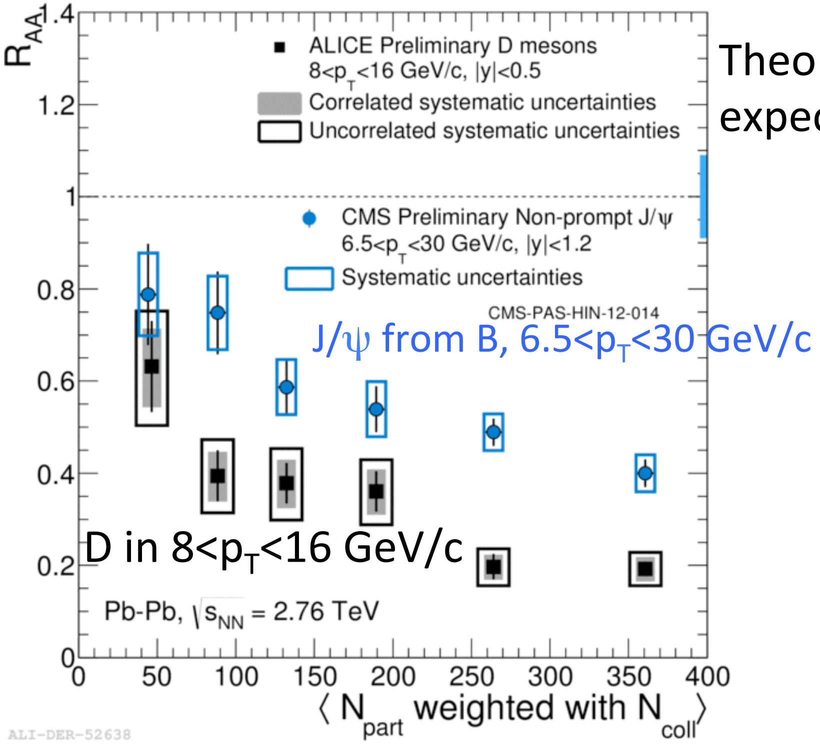
$$\Rightarrow \quad R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

Implication non trivial for D and π R_{AA} comparison, especially at low p_T:

- p_T spectrum shapes
- Different fragmentation
- Not all pions from hard scattering (might not scale with N_{coll})

D-meson and pion R_{AA} compatible within uncertainties

ALICE D vs. CMS J/ψ from B mesons



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

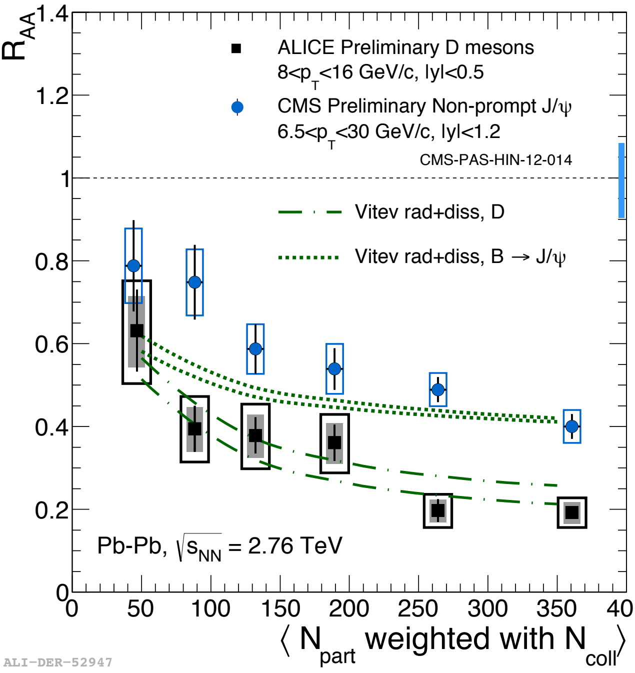
$$\Rightarrow R^{\pi}_{AA} < R^{D}_{AA} < R^{B}_{AA}$$

Indication for a stronger suppression for charm than beauty in central Pb-Pb collisions

D-meson p_T range chosen in order to have similar kinematics with respect to B mesons decaying in a J/ψ in the measured p_T range.
From simulation: $<p_T>^B$ ~11.5 GeV/c , $<p_T>^D$~10.5 GeV/c

Rapidity range slightly different ($|y|^D<0.5$, $|y|^{J/\psi}<1.2$)

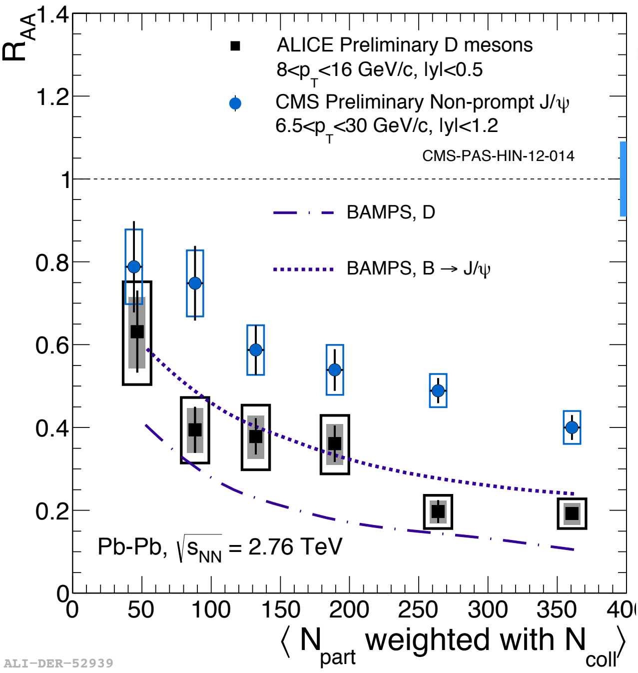
Comparison to theoretical models



Vitev et al.

(Vitev et al.: Phys. Rev. C80 (2009) 054902, Phys. Lett. B 713 (2012) 224); private comm.

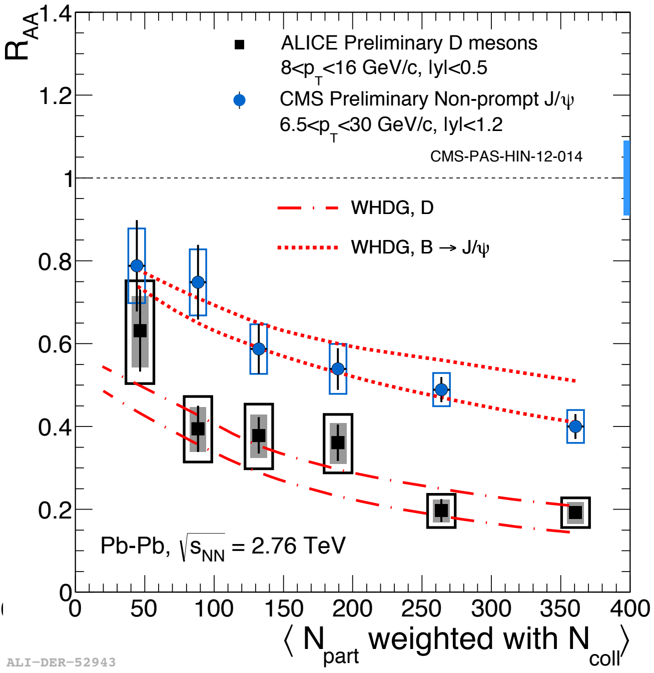
Radiative energy loss + D meson in-medium formation & dissociation



BAMPS

(O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. **G38** (2011) 124152); private comm.

Collisional energy loss in an expanding medium



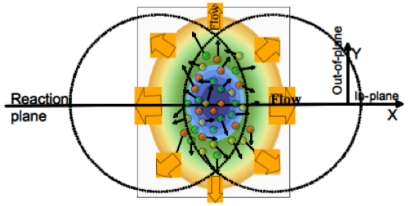
WHDG

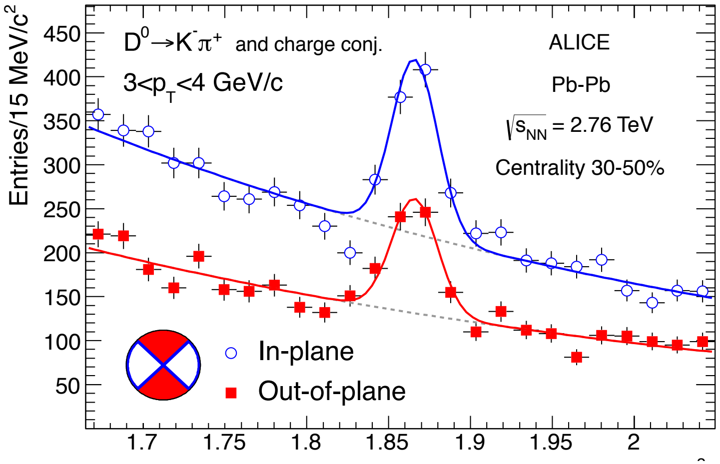
(W. A. Horowitz and M. Gyulassy, J. Phys. **G38** (2011) 124114); private comm.

Collisional and radiative energy loss in an anisotropic medium

Models including a mass dependence of energy loss predict a difference between the D-meson and non-prompt J/ψ R_{AA} similar to that observed

D meson azimuthal anisotropy

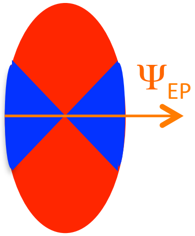




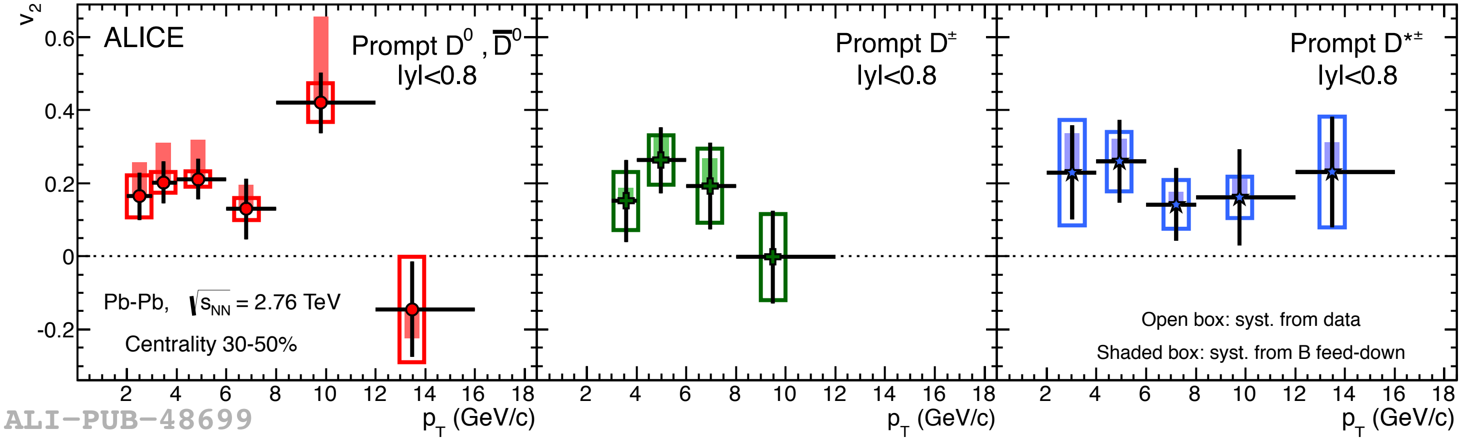
ALI−PUB−48695

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N^{\mathrm{In-Plane}} - N^{\mathrm{Out-Ot-Plane}}}{N^{\mathrm{In-Plane}} + N^{\mathrm{Out-Ot-Plane}}}$$

R_2 : event plane resolution



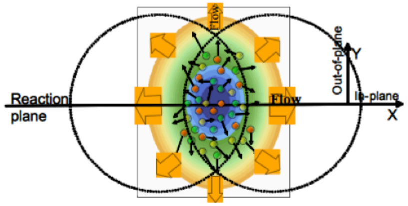
Phys.Rev.Lett. 111 (2013) 102301

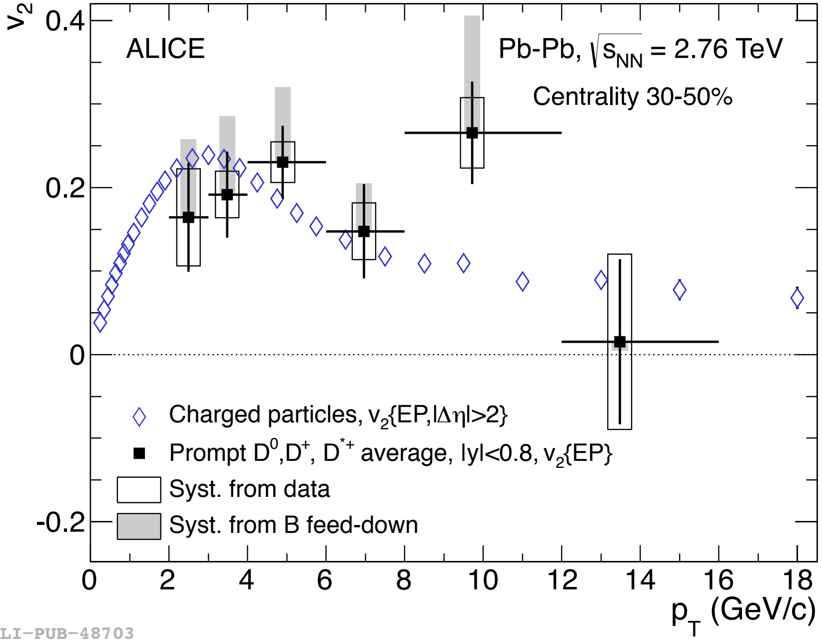


ALI−PUB−48699

- D^0,D^+,D^{*+} v_2 compatible within uncertainties

D meson azimuthal anisotropy

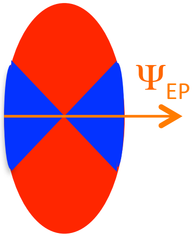




Phys.Rev.Lett. 111 (2013) 102301

$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N^{\mathrm{In-Plane}} - N^{\mathrm{Out-Ot-Plane}}}{N^{\mathrm{In-Plane}} + N^{\mathrm{Out-Ot-Plane}}}$$

R_2 : event plane resolution



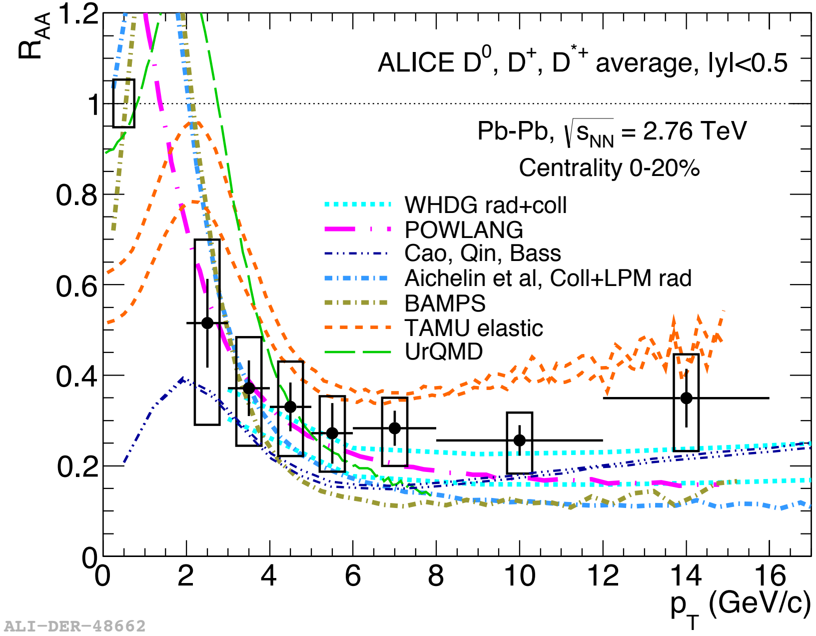
- D meson v_2>0 (5σ effect) in 2<p_T<6 GeV/c in 30-50% class
- Comparable to v_2 of charged hadrons

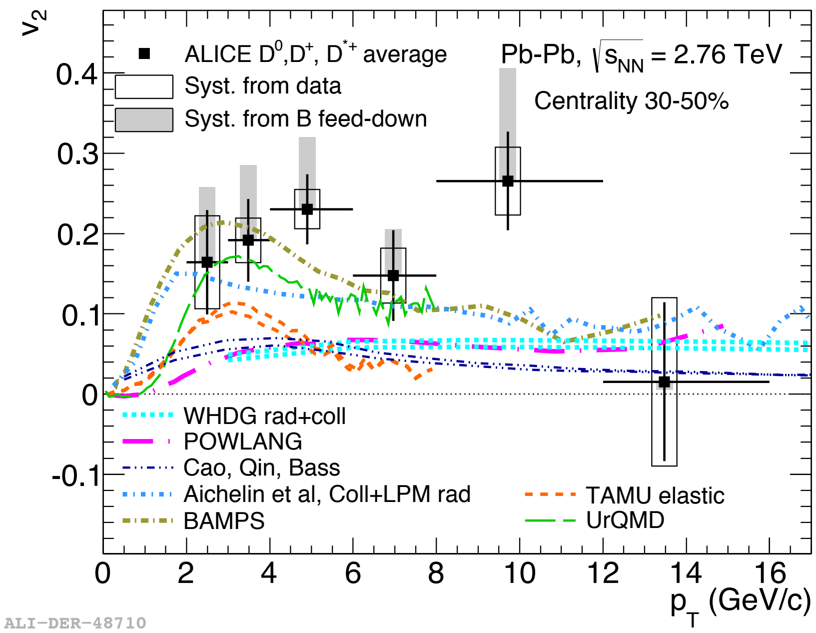
Initial spatial anisotropy of the collision affects D meson production:

- low p_T: **charm quarks sensitive to the system collective motion?**
- a finite v_2 at high p_T could arise from the path-length dependence of energy loss

Comparison to theoretical models

- only models that have predictions for both v_2 and R_{AA} are displayed-





Many models can reproduce R_{AA} reasonably well but they are challenged by simultaneous description of R_{AA} and v_2

BAMPS, O. Fochler, J. Uphoff, Z. Xu and C. Greiner, J. Phys. **G38** (2011) 124152.

WHDG, W. A. Horowitz and M. Gyulassy, J. Phys. **G38** (2011) 124114.

POWLANG, W. M. Alberico, *et al.*, Eur. Phys. J. **C71** (2011) 1666; J. Phys. **G38** (2011) 124144.

Coll+LPM P. B. Gossiaux, R. Bierkandt and J. Aichelin, Phys. Rev. **C79** (2009) 044906;
P. B. Gossiaux, J. Aichelin, T. Gousset and V. Guiho, J. Phys. **G37** (2010) 094019.

TAMU: M. He, R. J. Fries and R. Rapp, Phys. Rev. **C86** (2012) 014903.

UrQMD: T. Lang, H. van Hees, J. Steinheimer and M. Bleicher, arXiv:1211.6912;
T. Lang, H. van Hees, J. Steinheimer, Y. -P. Yan and M. Bleicher, arXiv:1212.0696.

Cao, Qin, Bass: S. Cao, G. Qin, S. A. Bass, arXiv:1308.0617

See also HF μ results in talk by S. Li and HF summary by D. Caffarri (Wednesday)

Conclusions

D-meson production in pp collisions

- Well described by pQCD-based calculation
- More differential measurements ongoing (e.g. D-hadron correlations)

In p-Pb collisions

- R_{pPb} compatible with 1 from 1 to 24 GeV/c
- No significant dependence on rapidity
- **In agreement with pQCD-based predictions incorporating nuclear modification of PDF and with CGC predictions as well**

In Pb-Pb collisions

- **Strong suppression** in central collisions for p_T>5 GeV/c ➜ **medium effect**
- R_{AA} centrality dependence of D meson and J/ψ from B (CMS) ➜ indication for a **larger suppression for charm than beauty**
- **Non zero D-meson v_2 in $2<p_T<6$ GeV/c in semi-peripheral collisions**
- Compatible with light-hadrons v_2 ➜ **charm taking part to the collective motion of the system?**

More data from Run 2 and after detector upgrade (LS2) will allow to reduce both statistical and systematic uncertainties and further constrain theoretical models

Thanks!

Related talks:

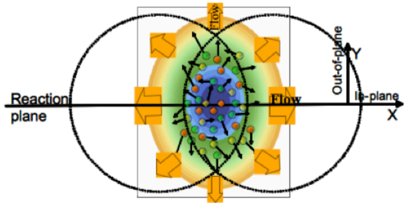
F. Prino (plenary, Monday morning)

D. Caffarri (plenary, Wednesday morning)

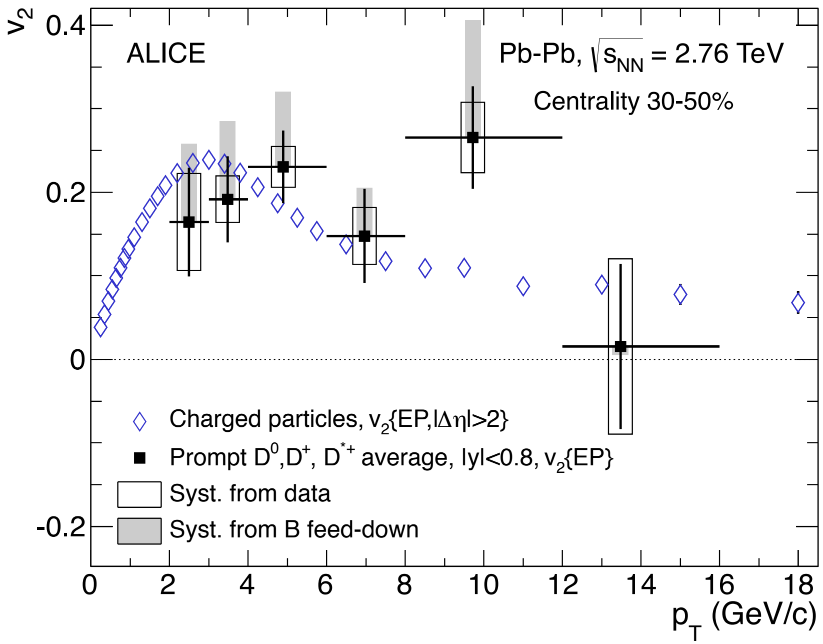
S. Li (this session)

E. Pereira De Oliveira Filho (HF session, Tuesday afternoon)

D meson azimuthal anisotropy

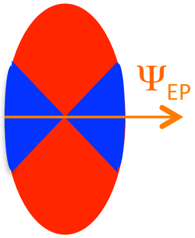


Today on arXiv: 1305.2707



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N^{\mathrm{In-Plane}} - N^{\mathrm{Out-Ot-Plane}}}{N^{\mathrm{In-Plane}} + N^{\mathrm{Out-Ot-Plane}}}$$

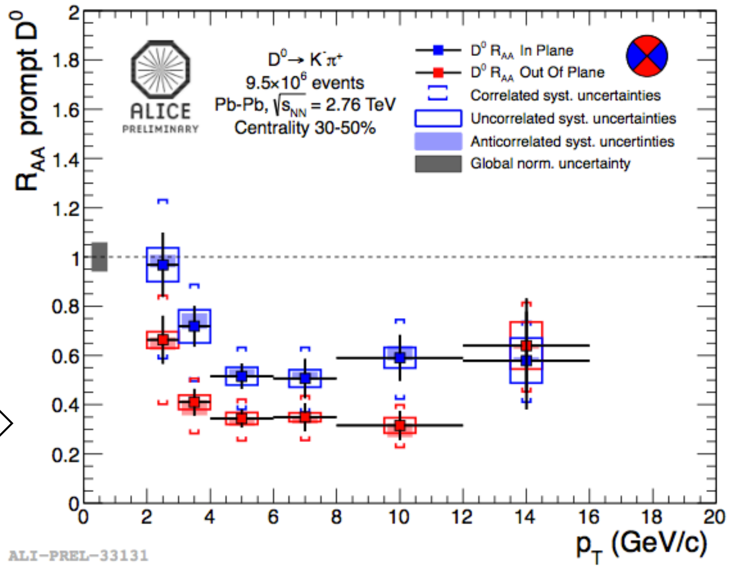
R_2 : event plane resolution



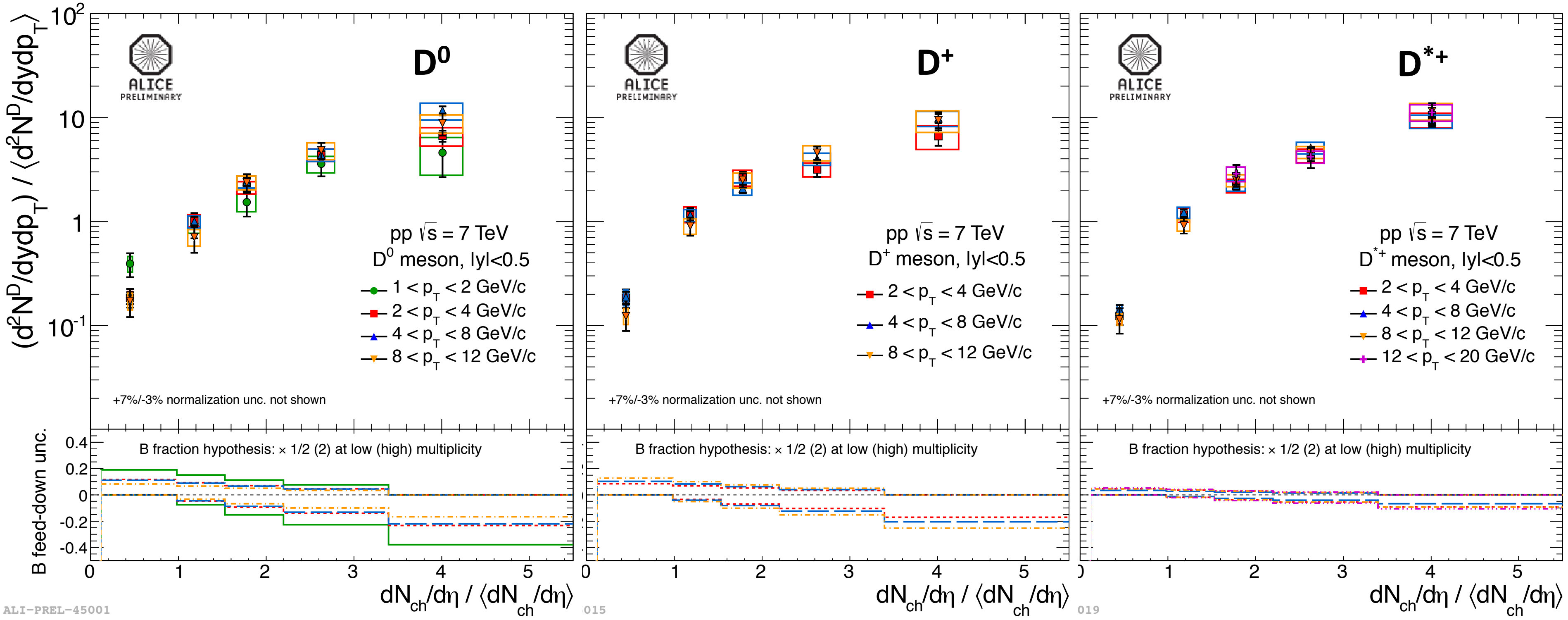
- D meson v_2>0 in 30-50% class
- Comparable to v_2 of charged hadrons

- at intermediate-high p_T: path-length dependence of energy loss

R_{AA} "in-plane" (shorter path in the medium)
vs. R_{AA} "out-of-plane" (longer path)



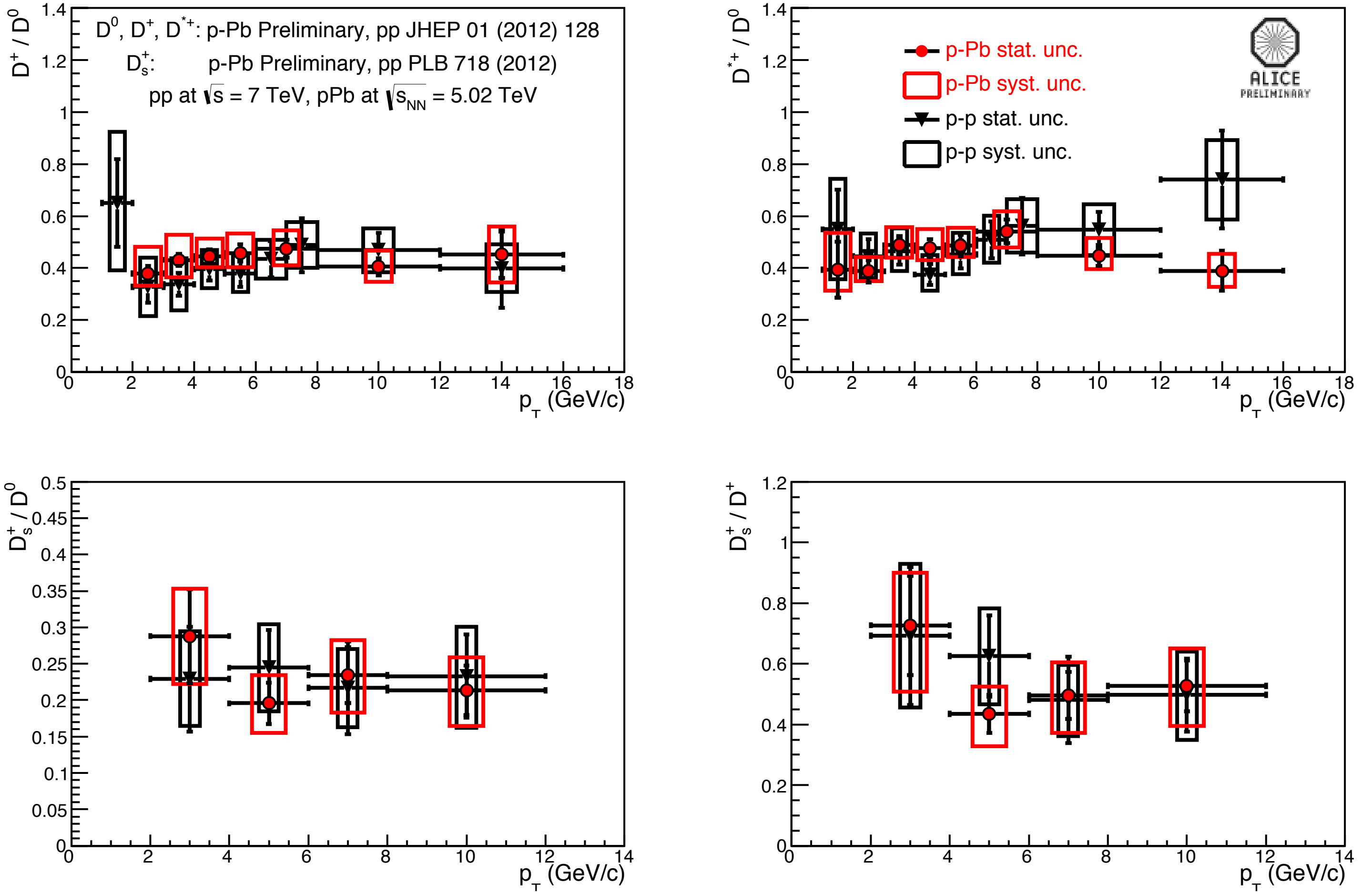
Towards more differential measurements: D-meson yields vs. charged-particle multiplicity



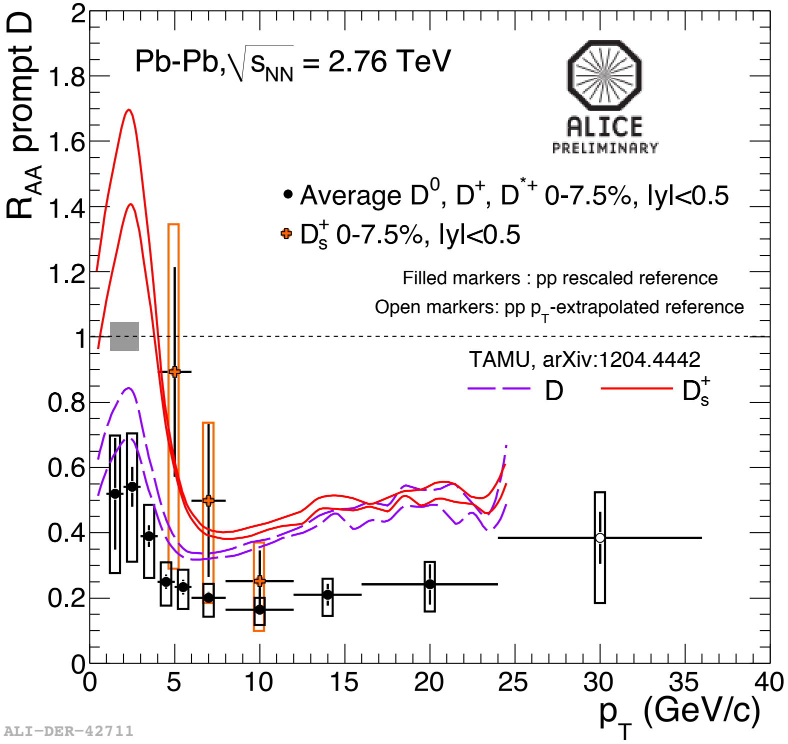
- D-meson yields increase with event multiplicity (similar trend observed for prompt J/ψ, see Phys.Lett. B712 (2012) 165-175)
  - no appreciable p_T dependence
- May suggest a connection of D-meson production to a strong hadronic activity or to multiple parton interactions

D meson relative abundances

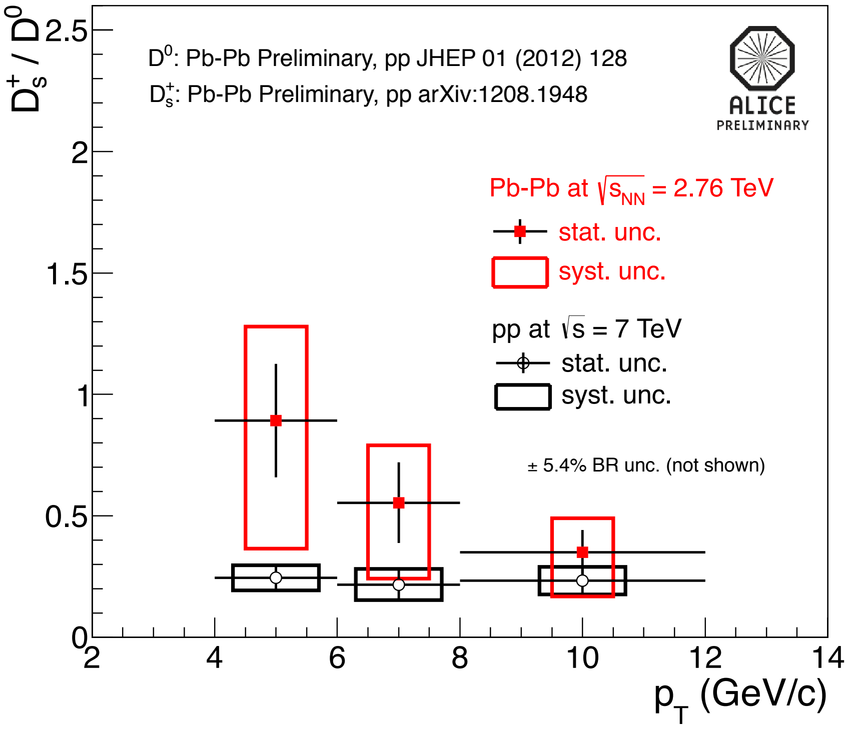
NEW!



D_s vs. non-strange D mesons



ALI-DER-42711

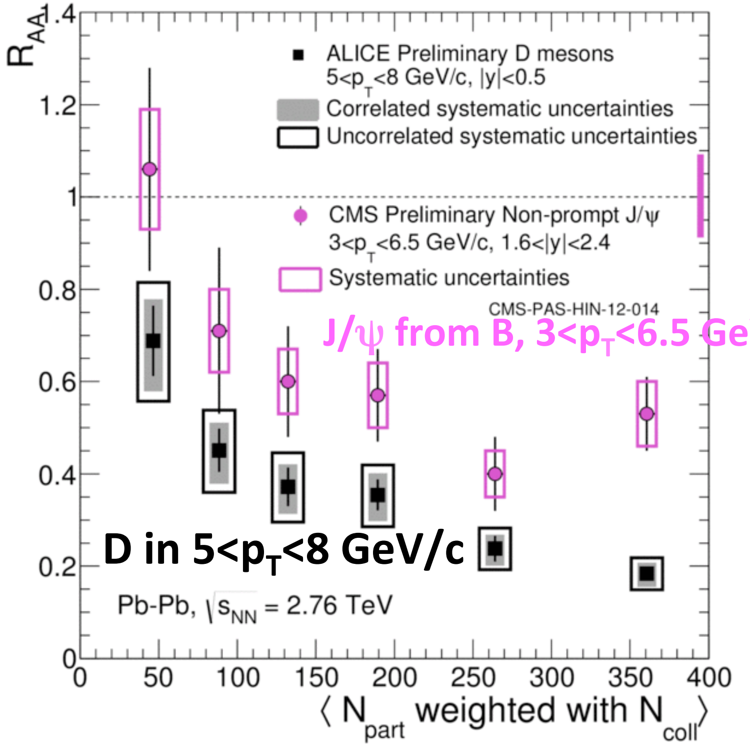


ALI-DER-44038

First measurement of D_s in Pb-Pb with 2011 run data

- Similar suppression of non strange D mesons in 8-12 GeV/c
- $R_{AA}(D_s) > R_{AA}(D^0, D^+, D^{*+})$ at low p_T? More more statistics needed
  - Important for constraining quark coalescence models

ALICE D vs. CMS J/ψ from B mesons



J/ψ from B, $3<p_T<6.5$ GeV/c

D in $5<p_T<8$ GeV/c

$1.6<y^{J/\psi}<2.4$

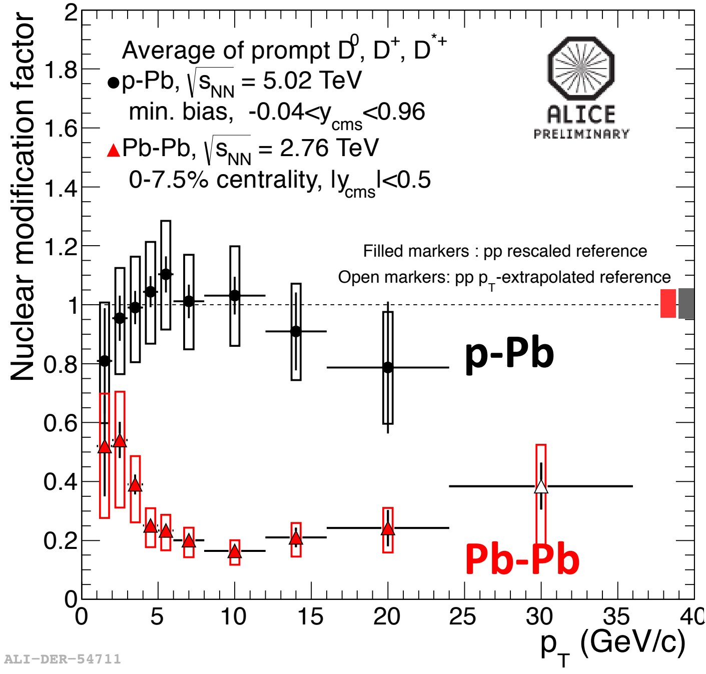
$|y|^D<0.5$

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

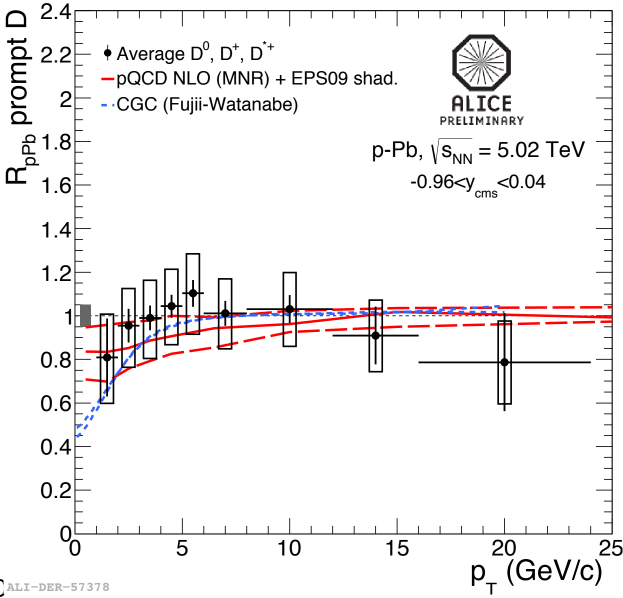
$$\Rightarrow \quad R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}$$

R_{AA} (J/ψ from B) > R_{AA} (D)
also at lower p_T
(but different kinematic range)

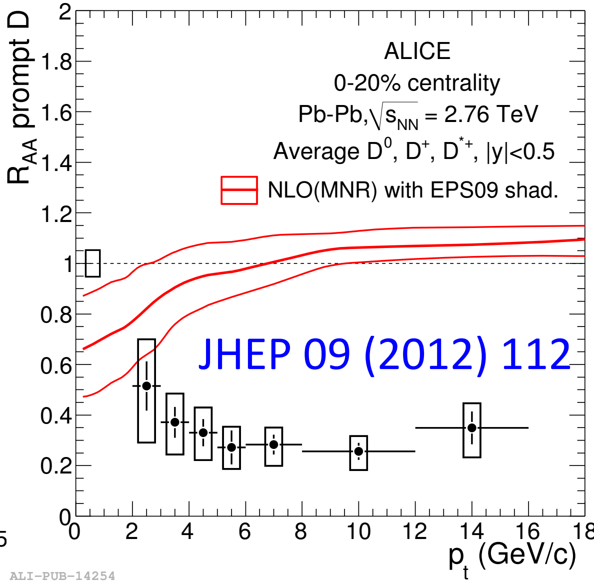
D meson R_{AA} vs $R_{p\text{-}Pb}$



ALI-DER-54711



ALI-DER-57378

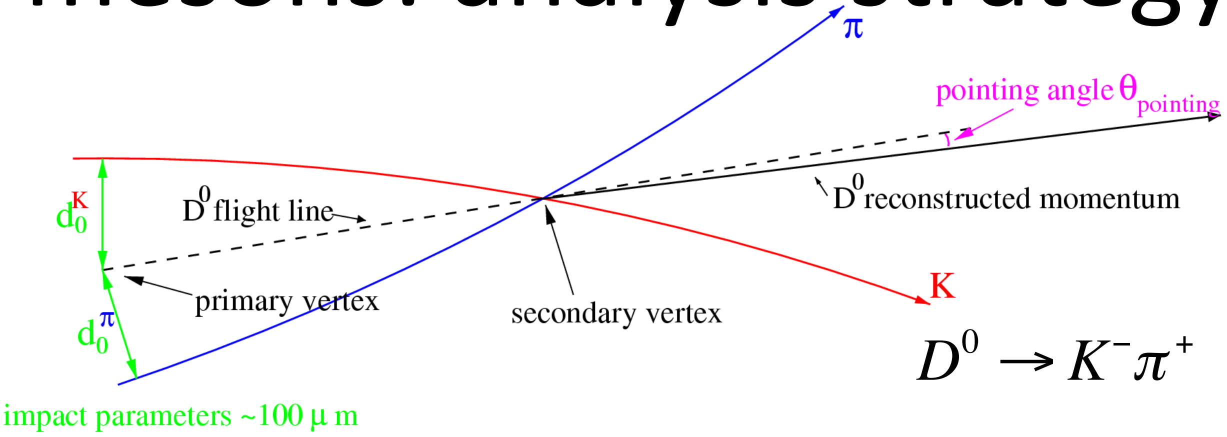


ALI-PUB-14254

pQCD NLO (MNR): Nucl.Phys. B373 (1992) 295-345
EPS09: K. J. Eskola et al., JHEP 0904 (2009) 065
CGC (Fujii-Watanabe): H. Fujii, K. Watanabe, arXiv:1308.1258; private communication

Observed suppression is a final state effect

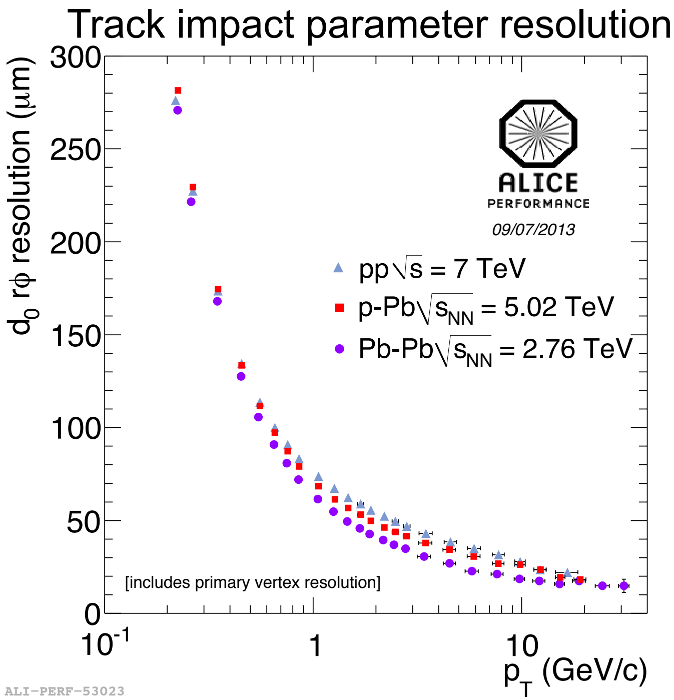
D mesons: analysis strategy



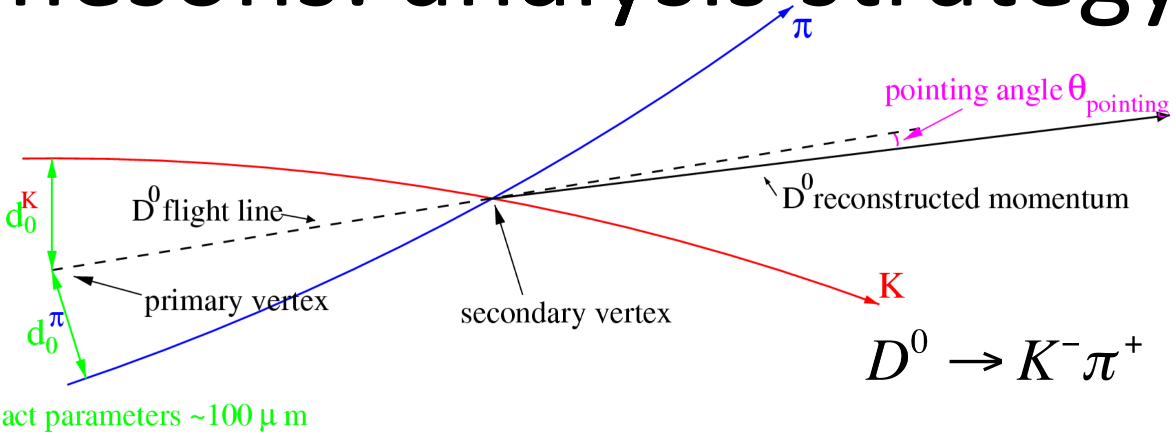
Main selection strategy:

Displaced secondary vertices topology (➜ ITS)

- (e.g. $D^0 \rightarrow K^-\pi^+$) : pair of opposite charge tracks with large impact parameters
- good pointing of reconstructed D momentum to the primary vertex



D mesons: analysis strategy



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

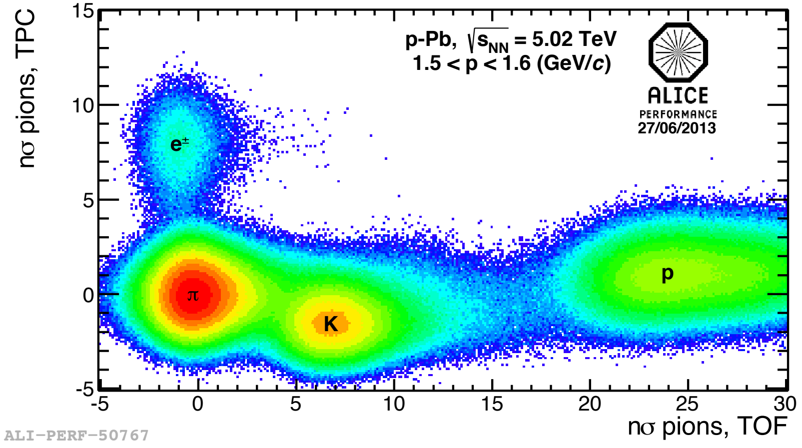
Main selection strategy:

Displaced secondary vertices topology (➔ ITS)

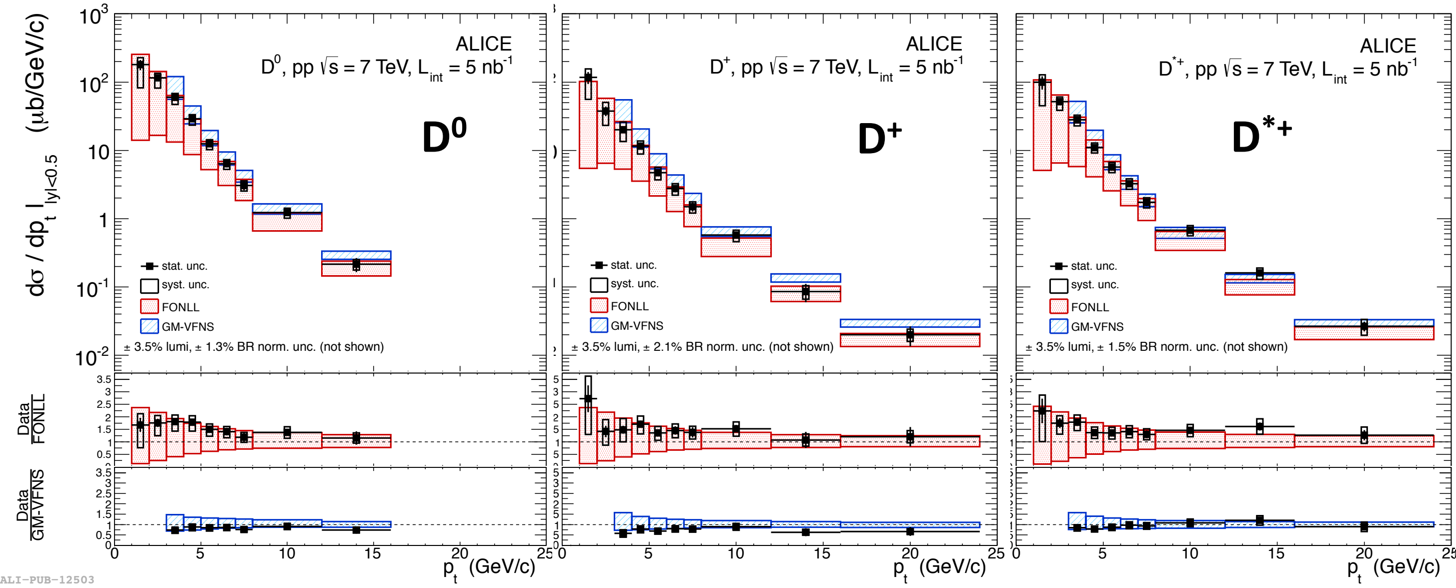
- (e.g. $D^0 \to K^-\pi^+$) : pair of opposite charge tracks with large impact parameters
- good pointing of reconstructed D momentum to the primary vertex

PID selection (TOF+TPC) to reduce background (mainly via K identification)

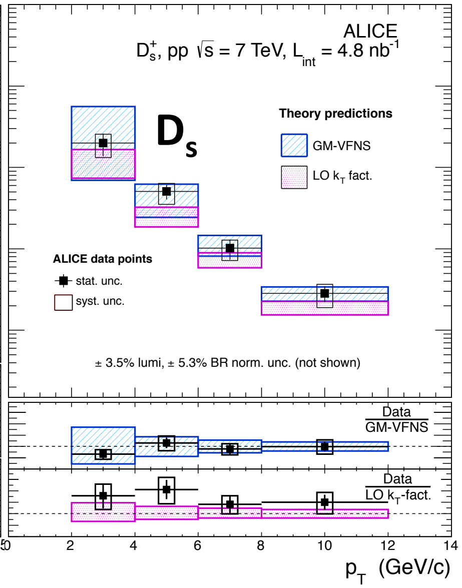
➔ **Invariant mass analysis**



D-meson production cross sections



JHEP 1201 (2012) 128



Phys.Lett. B718 (2012) 279-294

- D^0,D^+,D^{*+},D_s p_T-differential production cross sections **at √s=7 TeV** in agreement between 1 and 24 GeV/c with pQCD

FONLL: Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033

GM-VFNS: B. A. Kniehl, G. Kramer et al., I. Schienbein and H. Spiesberger, Phys.Rev. D77 (2008) 014011

LO k_T fact: R. Maciula, M. Luszczak and A. Szczurek, arXiv:1208.6126 [hep-ph]

How can we measure medium effects?

1) Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a “geometrical” factor (from Glauber model)

PbPb

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

Nuclear overlap function

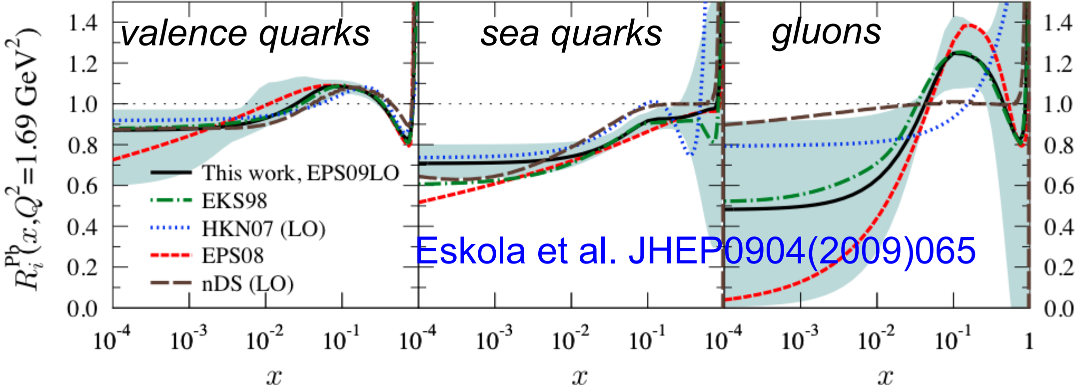
pp

If **$R_{AA}=1$** → no nuclear effects
if **$R_{AA}\neq 1$** → binary scaling broken

Initial state (“Cold Nuclear Matter”) effects, e.g.

- Parton shadowing
- Cronin effect
- Parton energy loss in CNM

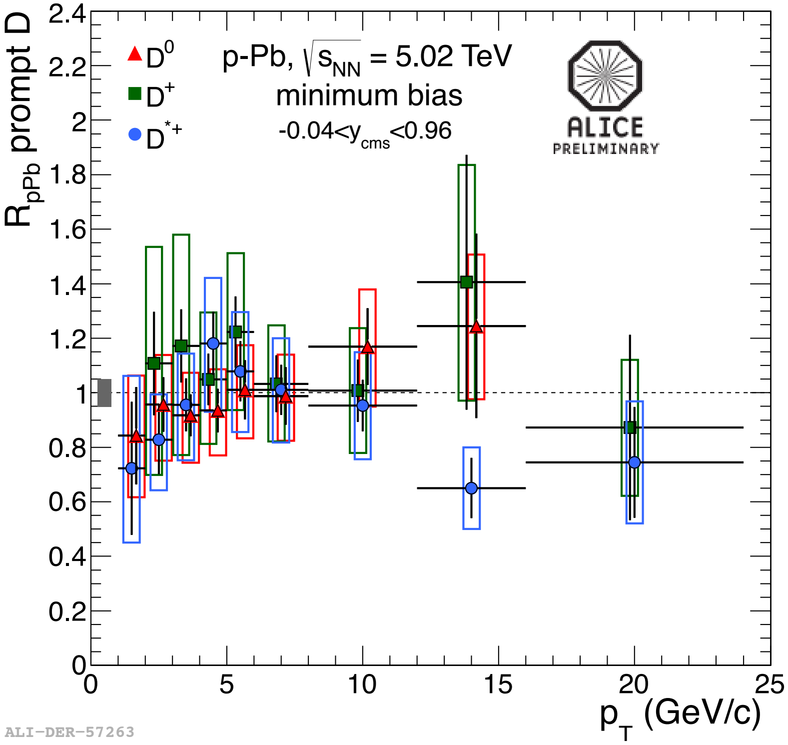
“Hot medium” effects
e.g. production suppression, energy loss → *$R_{AA}<1$*



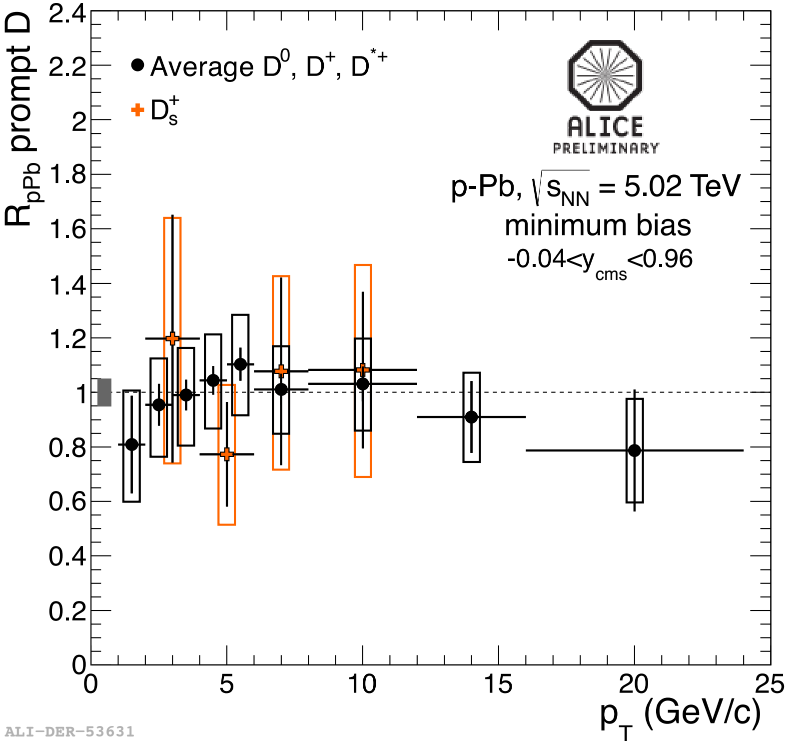
Eskola et al. JHEP0904(2009)065

p-Pb results fundamental for interpretation of Pb-Pb results

D meson R_{pPb} vs. p_T



ALI-DER-57263



ALI-DER-53631

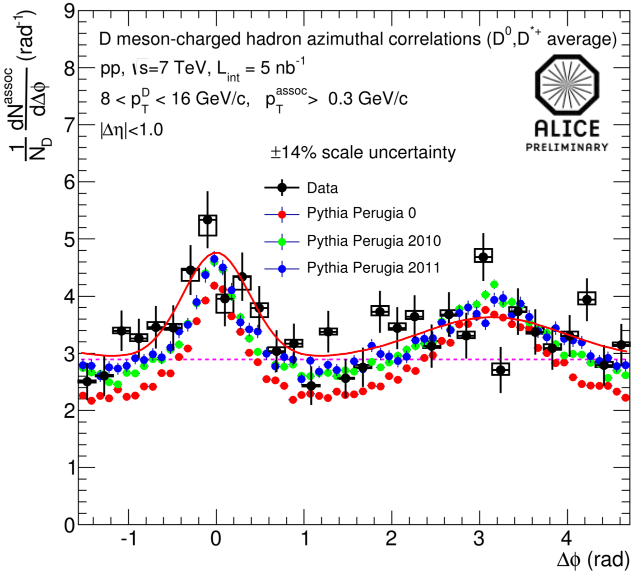
- D meson R_{pPb} measured from 1 to 24 GeV/c
- D^0, D^+, D^{*+} ,D_s R_{pPb} compatible within uncertainties

$$R_{pPb}(p_T) = \frac{\left(d\sigma / dp_T\right)_{p-Pb}}{A \times \left(d\sigma / dp_T\right)_{pp}}$$

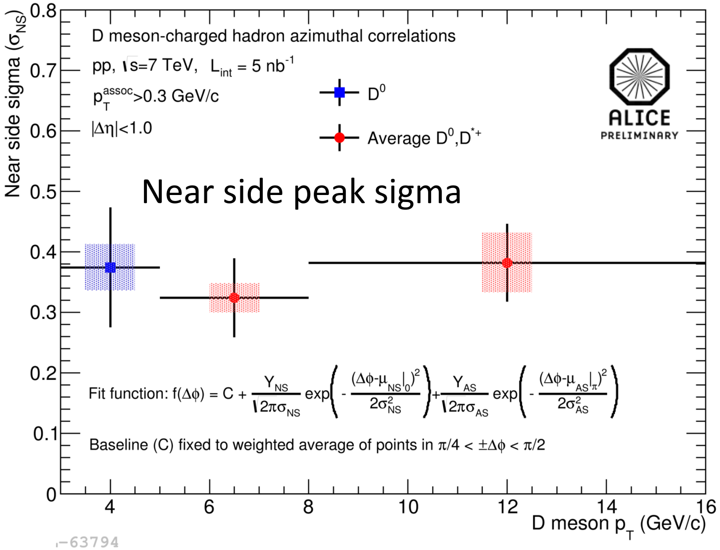
R_{pPb} compatible with 1 w/o appreciable dependence on p_T

D meson-charged hadron azimuthal correlations

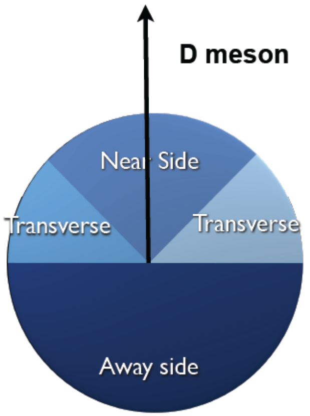
NEW!

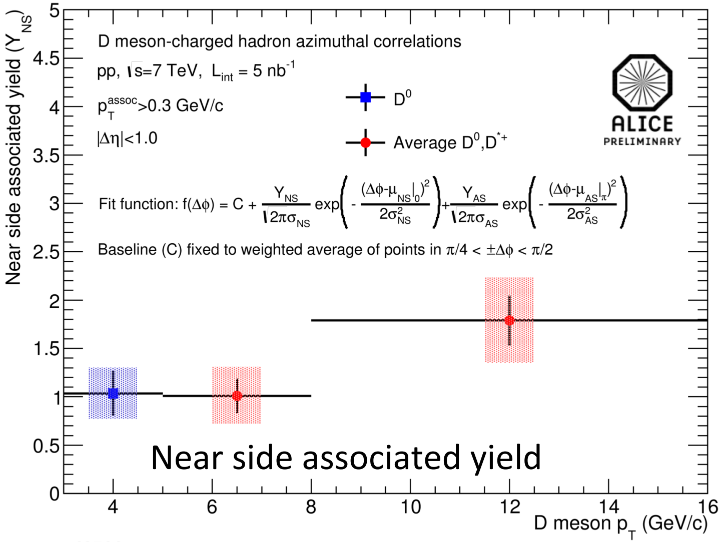


ALI-DER-63803

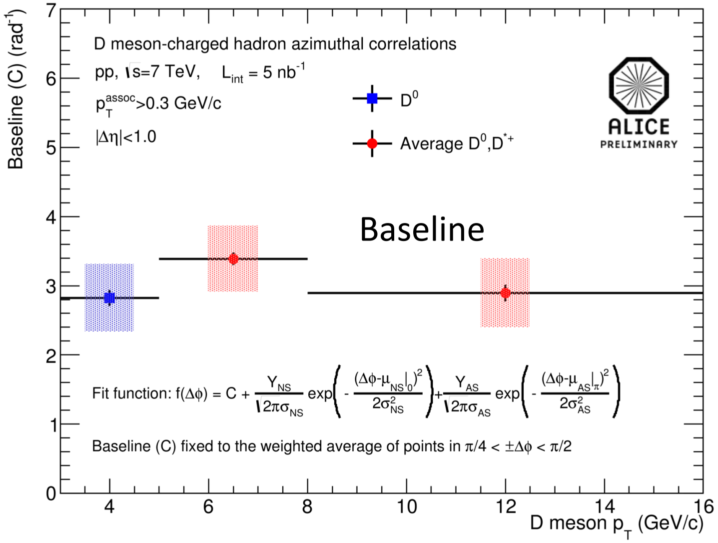


-63794





ALI-PREL-63789

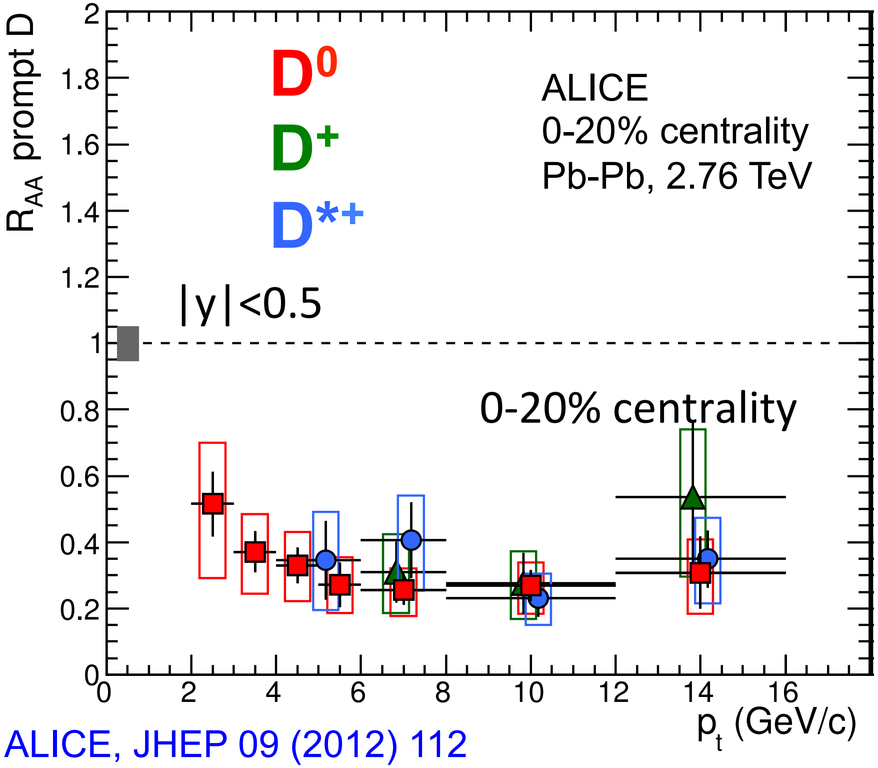


I-PREL-63799

In agreement with Pythia within large statistical and systematic uncertainties

Precise measurement expected from Run II

Prompt D meson R_{AA}



ALICE, JHEP 09 (2012) 112

First measurement of D meson R_{AA} in central heavy-ion collisions (2010 Pb-Pb run)

Strong suppression observed (factor 3-5 for p_T>5 GeV/c)

D^0, D^+, D^{*+} R_{AA} compatible within errors