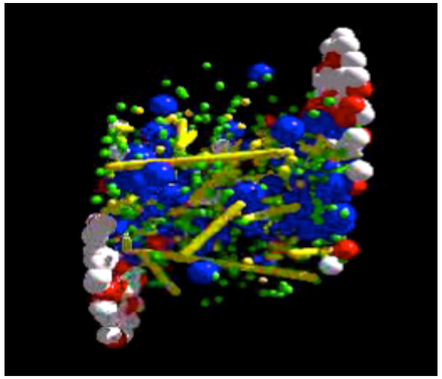
D meson nuclear modification factor and v_2 in Pb-Pb collisions

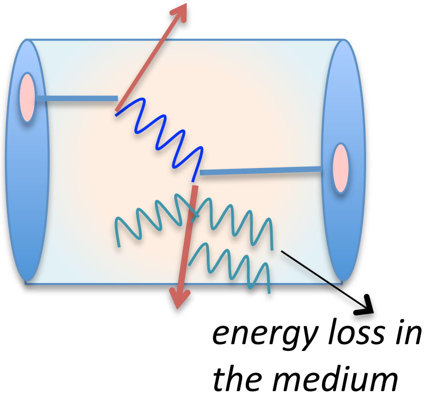
Elena Bruna (INFN Torino)
for the ALICE Collaboration

Strangeness in Quark Matter – SQM July 2013 Birmingham, UK

Why Charm and Beauty?

Heavy quarks are produced in high-Q^2 processes in the initial stage of the collision
→ pp: test perturbative QCD [see R. Bala's talk this session and F. Colamaria's talk pA session]
→ p-Pb: reference for cold nuclear matter effects [see G. Luparello's talk pA session]
→ Pb-Pb: *initially-produced probes* exposed to the medium evolution





How do partons interact with the medium?

- Radiative gluon emission
- Elastic collisions with the constituents

What does the radiative energy loss depend on?

- Medium density, path-length → $\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$
- Colour-charge, Mass ("dead-cone") → $\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$

Dokshitzer and Kharzeev, PLB 519 (2001) 199.

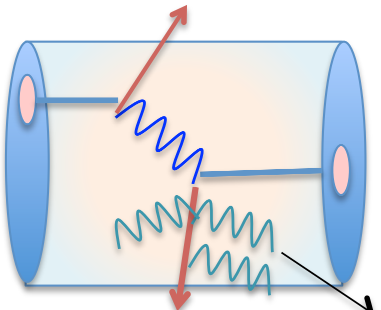
Why Charm and Beauty?

Heavy quarks are produced in high-Q^2 processes in the initial stage of the collision

→ pp: test perturbative QCD [see R. Bala's talk this session and F. Colamaria's talk pA session]

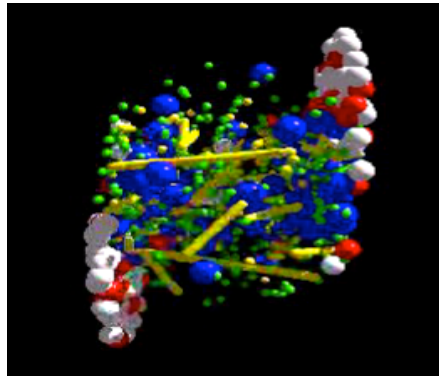
→ p-Pb: reference for cold nuclear matter effects [see G. Luparello's talk pA session]

→ Pb-Pb: *initially-produced probes* exposed to the medium evolution



How do partons interact with the medium?

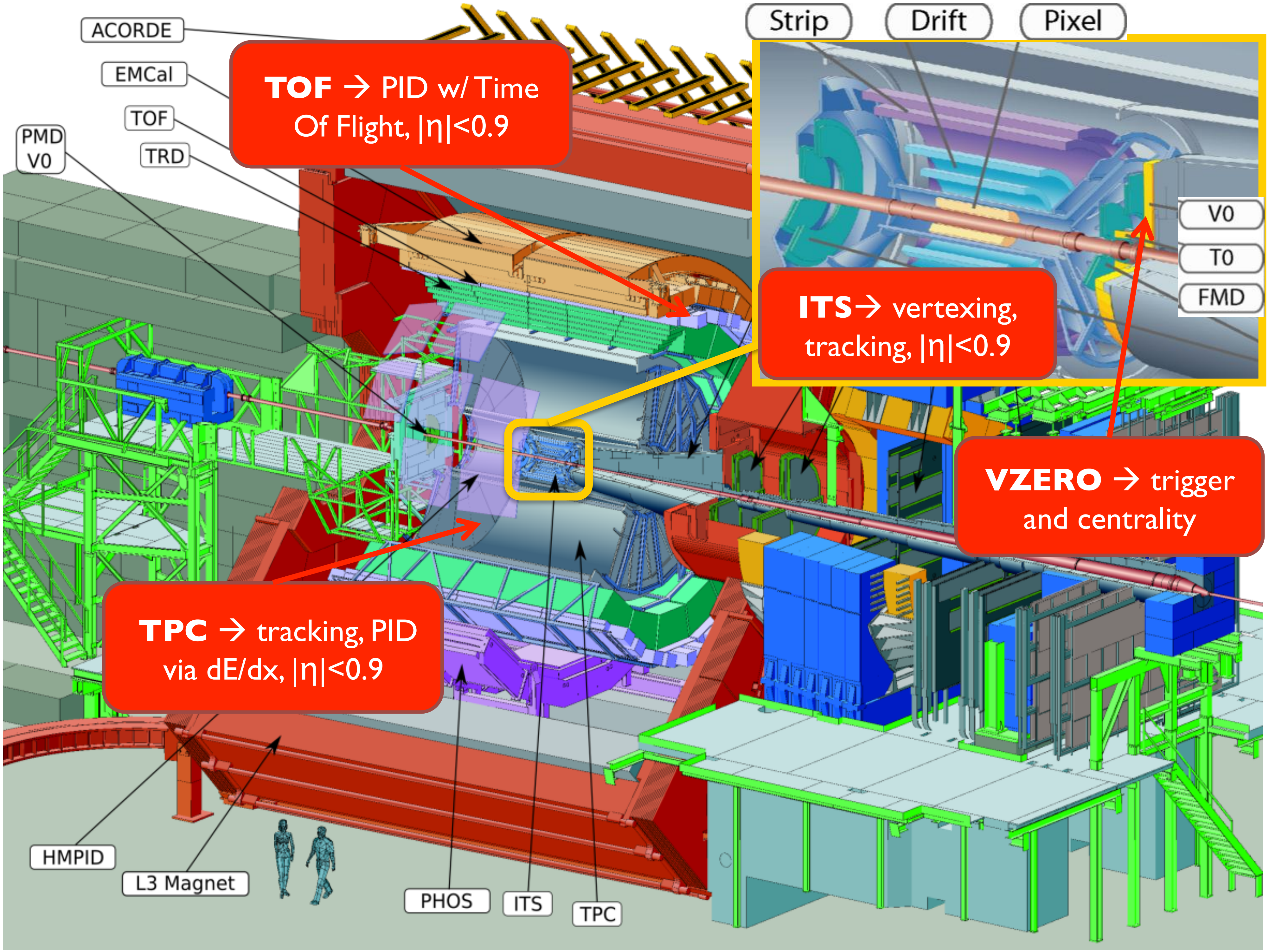
- Radiative gluon emission
- Elastic collisions with the constituents



Comparing nuclear effects on heavy quarks (c and b) vs light quarks and gluons gives insight into medium properties:

- path-length/flavour/colour-charge dependence of energy loss → information on medium density

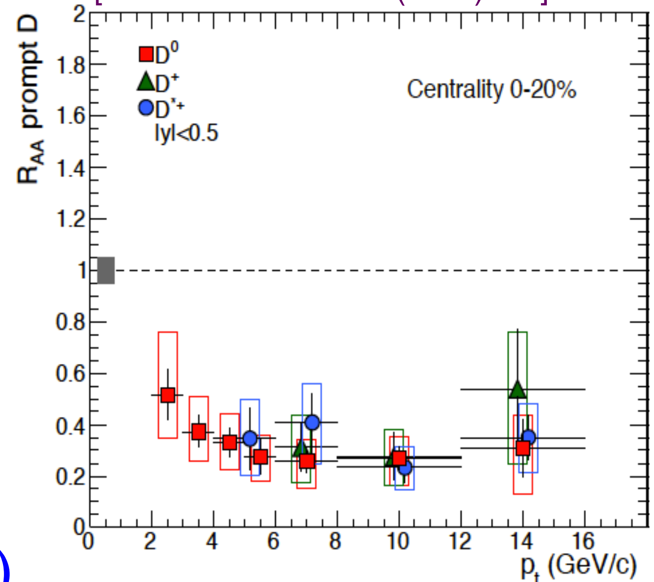
- collective motion at low p_T → information on medium temperature



ACORDE
EMCal
TOF
TRD
PMD
V0
TOF → PID w/ Time Of Flight, |η|<0.9
Strip
Drift
Pixel
V0
T0
FMD
ITS→ vertexing, tracking, |η|<0.9
VZERO → trigger and centrality
TPC → tracking, PID via dE/dx, |η|<0.9
HMPID
L3 Magnet
PHOS
ITS
TPC

New results

Results from 2010 Pb-Pb run
[ALICE Coll. JHEP 09 (2012) 112]



Large statistics with 2011 Pb-Pb run

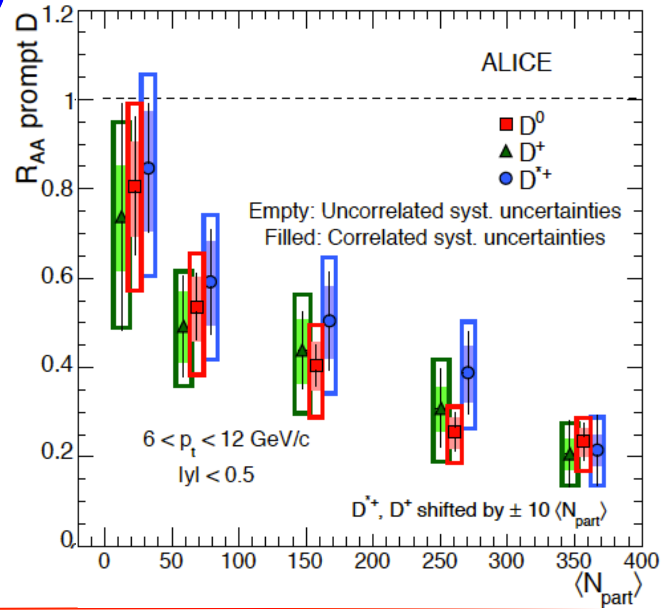
- larger p_T reach in D meson R_{AA} vs p_T
- different p_T ranges for D meson R_{AA} vs centrality

- **Prompt D meson R_{AA} in 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-80% centrality classes**

in **[2-3],[3-5]** GeV/c p_T ranges for D^0 (NEW)
[5,8],[8,16] GeV/c p_T ranges for D^0,D^+,D^* (NEW)

  – R_{AA} in 50-80% from 2010 run

- **Prompt D meson v_2 vs p_T in 30-50%** (NEW, arXiv:1305.2707)



Run	System	Collected statistics
2010	Pb-Pb 2.76 TeV	2.12 μb^{-1} (MB) JHEP 9 (2012) 112
2011	Pb-Pb 2.76 TeV	28 μb^{-1} in 0-7.5% 6 μb^{-1} in 15-50%

Analysis overview

(1) Search for secondary vertices displaced by few hundreds μm

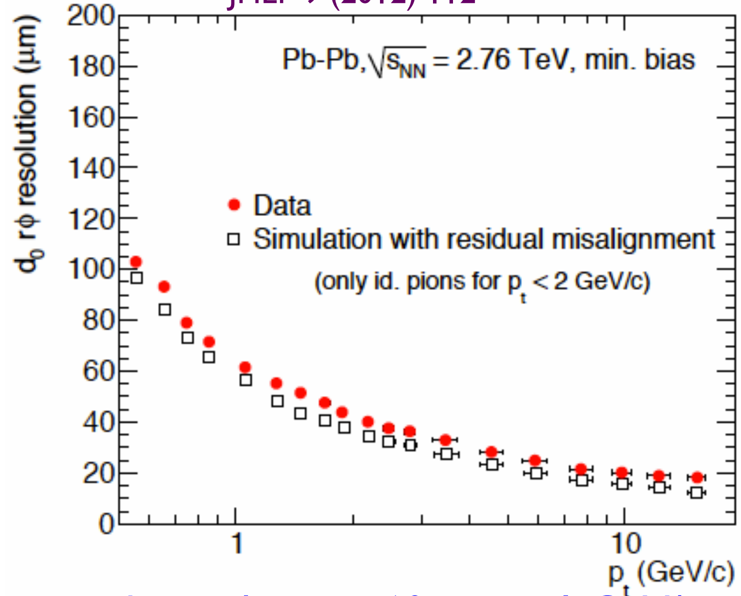
(2) Main selection criteria:

- p_T and impact parameter of the single tracks
- Particle Identification - PID (π, K, p) for background rejection at low p_T (TPC+TOF)
- Pointing angle
- Distance primary-secondary vertices

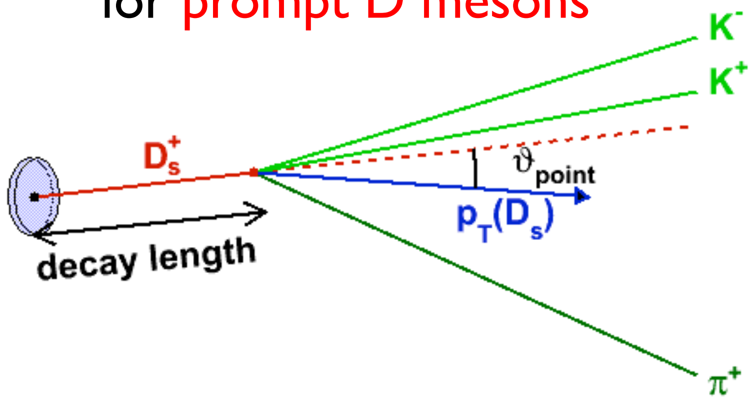
(3) Signal extracted from fits to invariant mass distributions

(4) Correction for beauty feed-down to extract results for prompt D mesons

JHEP 9 (2012) 112



d_0 resolution ~60 μm at 1 GeV/c



$D^0 \to K^-\pi^+$	BR: 3.88%
$D^{*+} \to D^0(\to K\pi)\pi^+$	BR: 2.63%
$D^+ \to K^-\pi^+\pi^+$	BR: 9.13%
$D_s^+ \to \phi(\to K^+K^-)\pi^+$	BR: 2.28%

Analysis overview

(1) Search for secondary vertices displaced by few hundreds μm

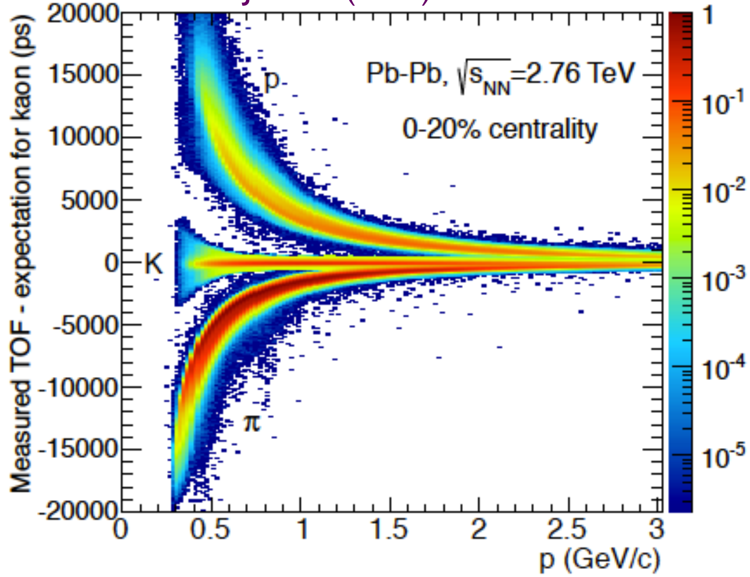
(2) Main selection criteria:

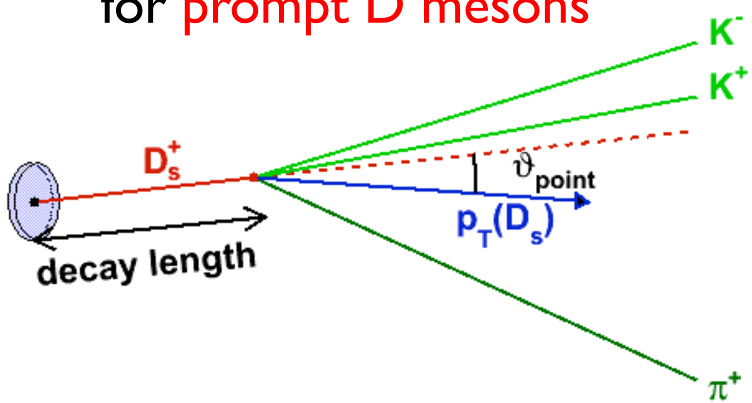
- p_T and impact parameter of the single tracks
- Particle Identification - PID (π, K, p) for background rejection at low p_T (TPC+TOF)
- Pointing angle
- Distance primary-secondary vertices

(3) Signal extracted from fits to invariant mass distributions

(4) Correction for beauty feed-down to extract results for prompt D mesons

JHEP 9 (2012) 112

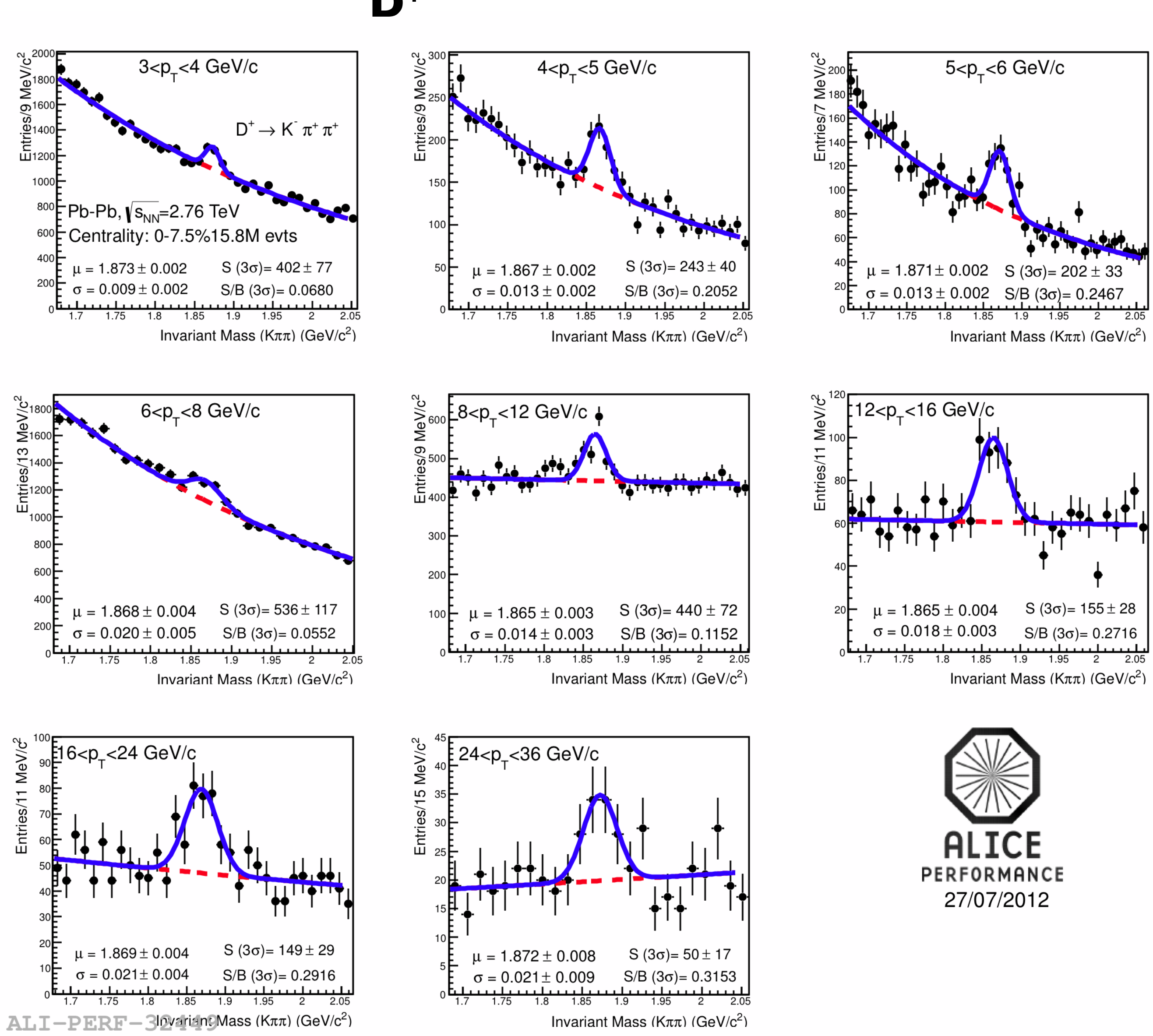




$D^0 \to K^-\pi^+$	BR: 3.88%
$D^{*+} \to D^0(\to K\pi)\pi^+$	BR: 2.63%
$D^+ \to K^-\pi^+\pi^+$	BR: 9.13%
$D_s^+ \to \phi(\to K^+K^-)\pi^+$	BR: 2.28%

D mesons in 0-7.5% centrality

D$^+$



ALICE
PERFORMANCE
27/07/2012

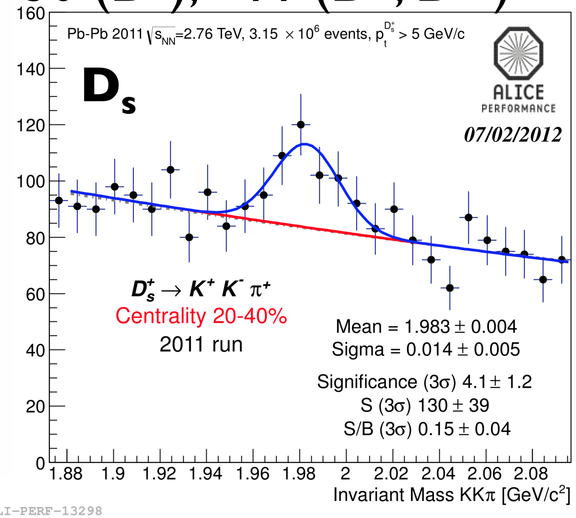
~16x10^6 events w/ 2011 run

Centrality 0-7.5%
(MB + centrality trigger)

Large p_T range explored:

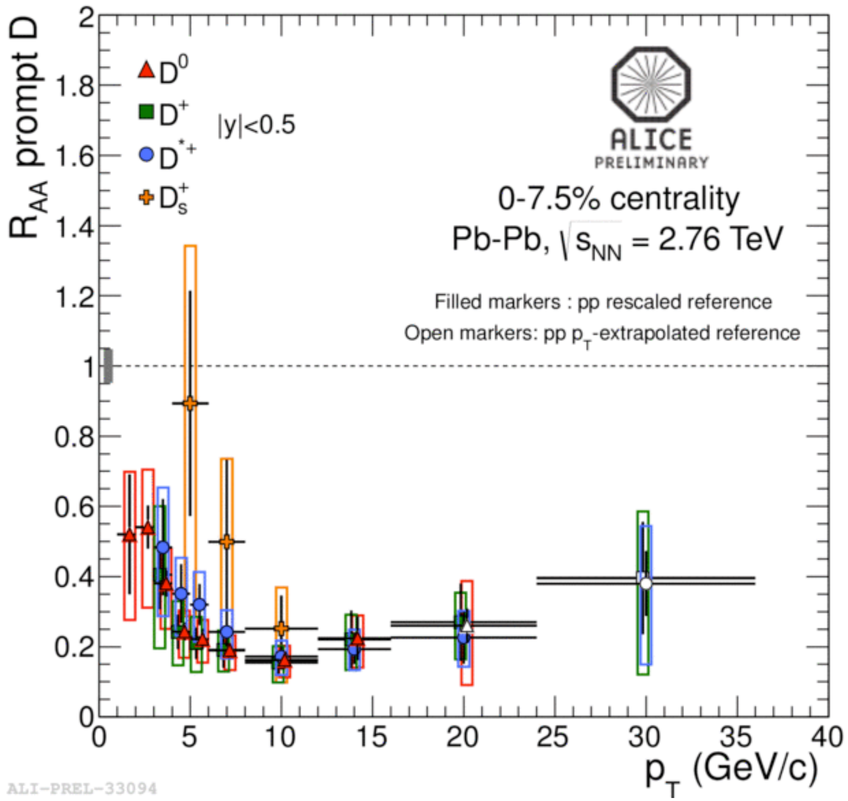
- D^0 $1<p_T<24$ GeV/c
- D$^+$, D^{*+} $3<p_T<36$ GeV/c
- D$_s$ $4<p_T<12$ GeV/c

Significance (p_T integrated) > 30 (D^0), >11 (D$^+$, D^{*+})



D meson R_{AA}

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



pp reference determined by scaling the cross section measured by ALICE at 7 TeV to 2.76 TeV using FONLL predictions - arXiv:1107.3243, JHEP07(2012)191, arXiv:1205.4007

Beauty feed-down subtracted using FONLL prediction with an assumption on the R_{AA} of D mesons from beauty feed-down

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

Larger p_T window explored w/ 2011 Run

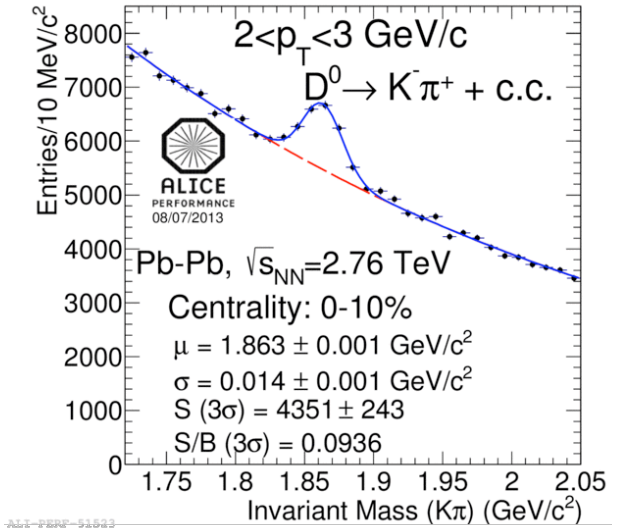
Large suppression in a wide p_T range:
→*factor of 4-5 in $5<p_T<15$ GeV/c*

First measurement of D_s in Pb-Pb collisions with 2011 Run
→*suppression of 3-5 in 8-12 GeV/c*
→more statistics needed to conclude on the expected enhancement of low-p_T D_s

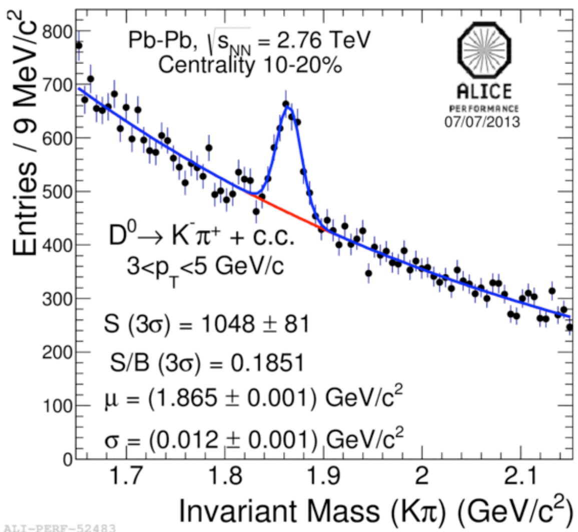
Kuznetsova & Rafelski, EPJ C51(2007)113;
He et al., arXiv:1204.4442;
Andronic et al., arXiv:0708.1488

New Results: D mesons vs centrality

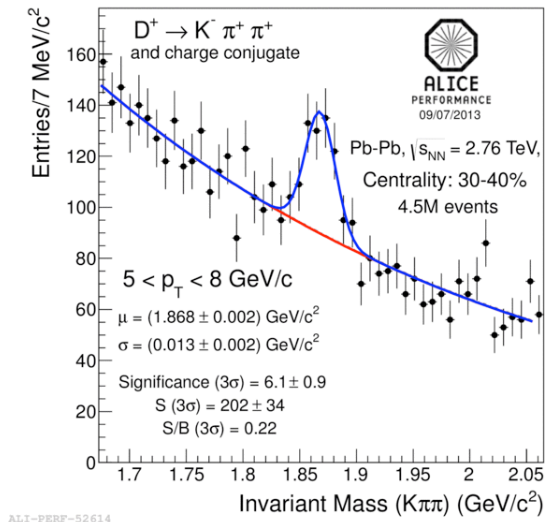
D^0, 0-10%



D^0, 10-20%



D^+, 30-40%



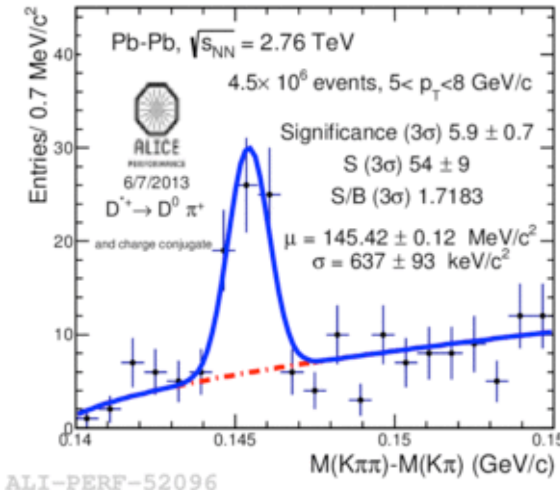
Centrality ranges:

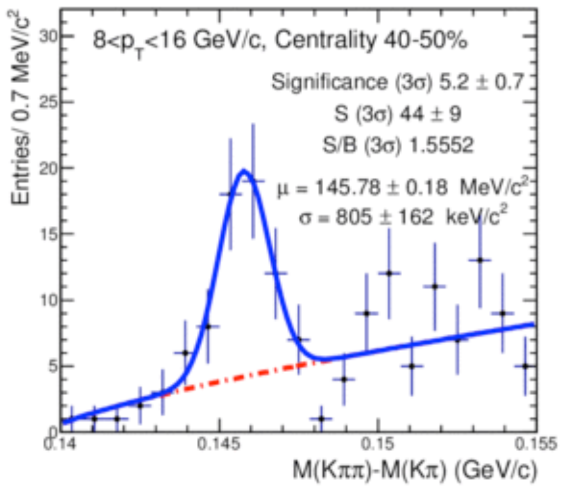
0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-80%

p_T ranges:

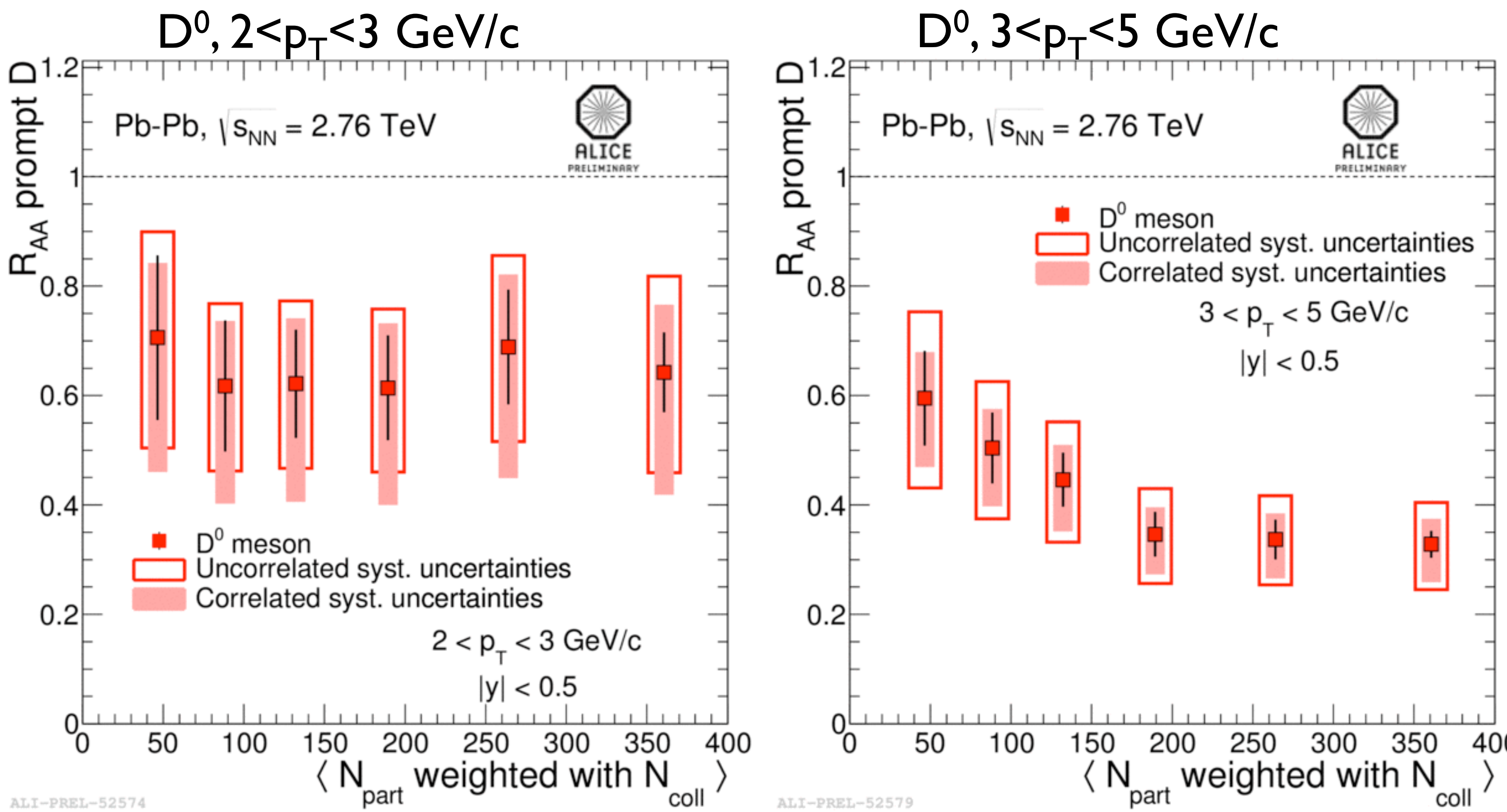
2-3, 3-5 GeV/c (for D^0 only),
5-8, 8-16 GeV/c for D^0, D^+, D^*

D^{*+}, 40-50%





R_{AA} vs centrality in 2-3 and 3-5 GeV/c p_T ranges



Systematic uncertainties:

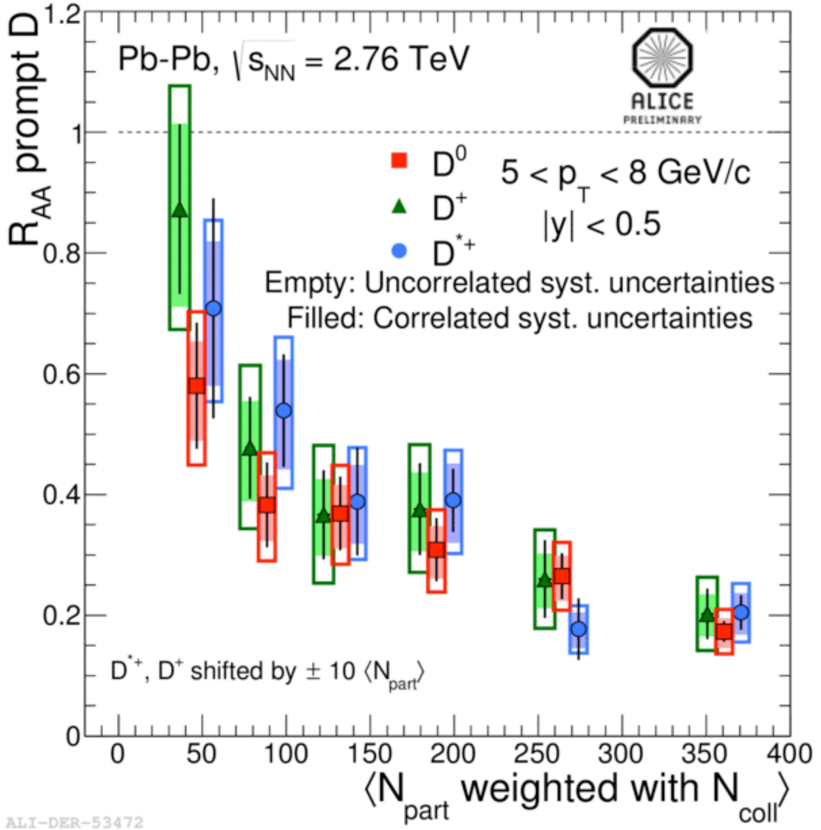
-correlated in centrality classes: normalization, pp reference cross section

-uncorrelated: dominated by data systematics (i.e. cut variation efficiencies) and B feed-down ($R_{AA}^{feed\text{-}down}/R_{AA}^{Prompt}$ might depend on N_{part}).

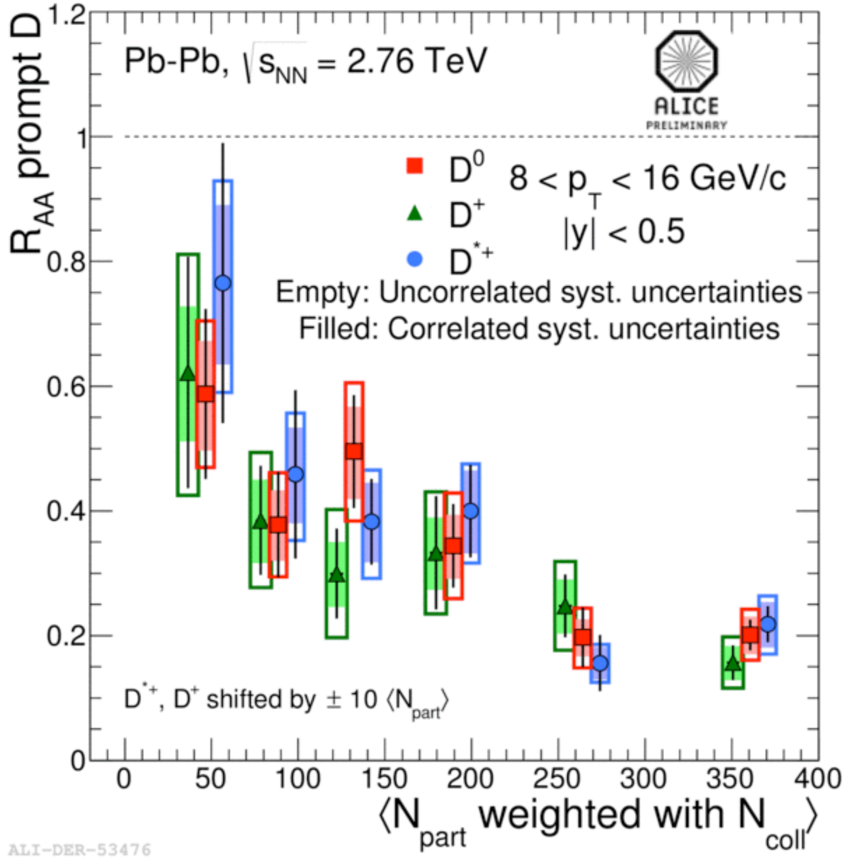
Different suppression trend of D^0 mesons vs N_{part} in 2-3 and 3-5 GeV/c p_T ranges

R_{AA} vs centrality in 5-8 and 8-16 GeV/c p_T ranges

D^0, D^+, D^* $5<p_T<8$ GeV/c



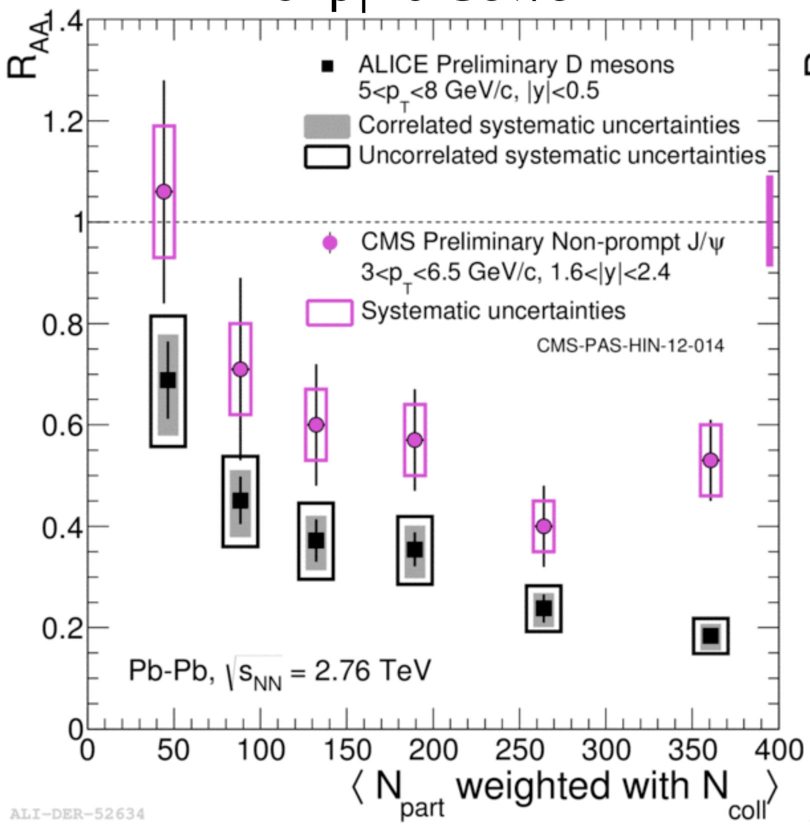
D^0, D^+, D^* $8<p_T<16$ GeV/c



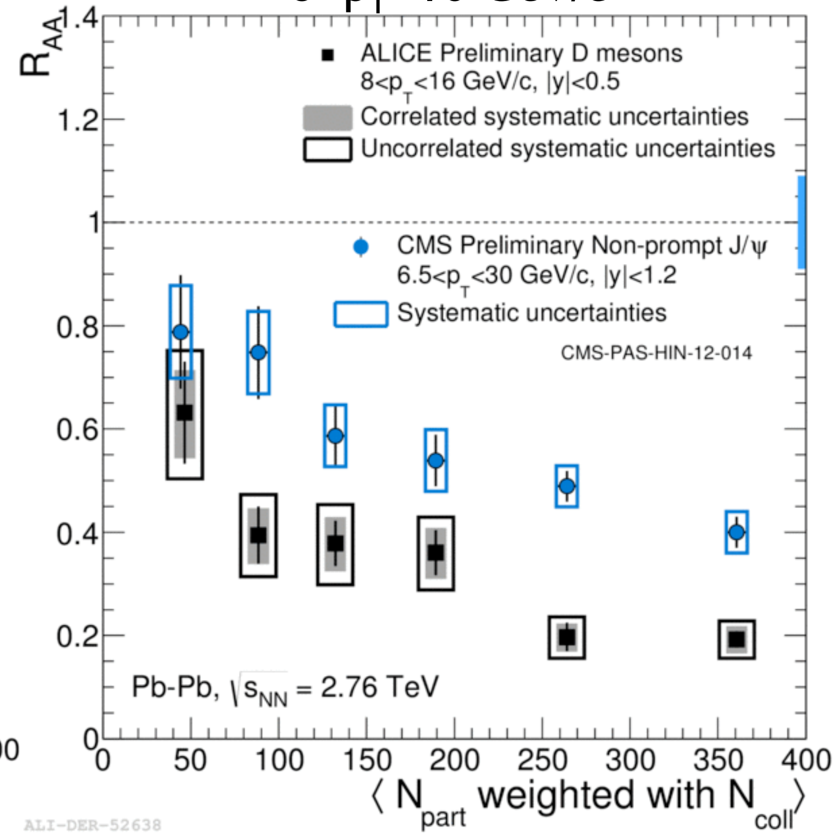
Suppression of D^0, D^+, D^* mesons increases with centrality in 5-8 and 8-16 GeV/c p_T ranges

Comparison to non-prompt J/ψ from CMS

5<p_T<8 GeV/c



8<p_T<16 GeV/c



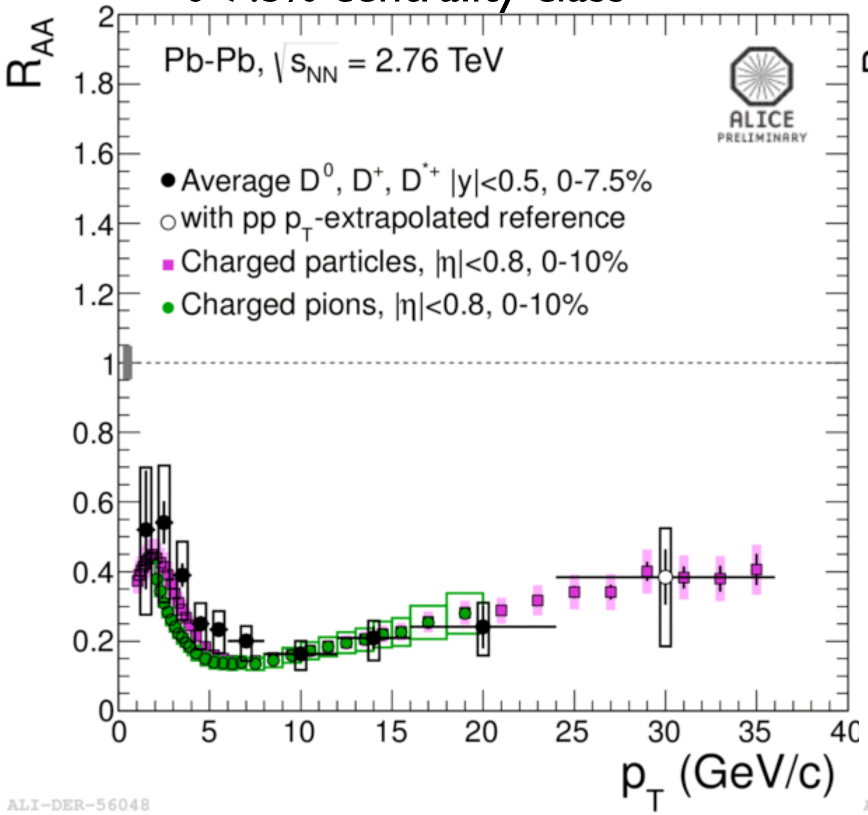
p_T ranges chosen to have similar kinematics for D and B mesons measured via non-prompt J/ψ (based on simulations of decay kinematics, i.e. **$\langle p_T \rangle^D$~10.5 GeV/c** in 8-16 GeV/c, **$\langle p_T \rangle^B$~11.5 GeV/c** in J/ψ p_T range 6.5-30 GeV/c)

CAVEAT: different y ranges for D and non-prompt J/ψ

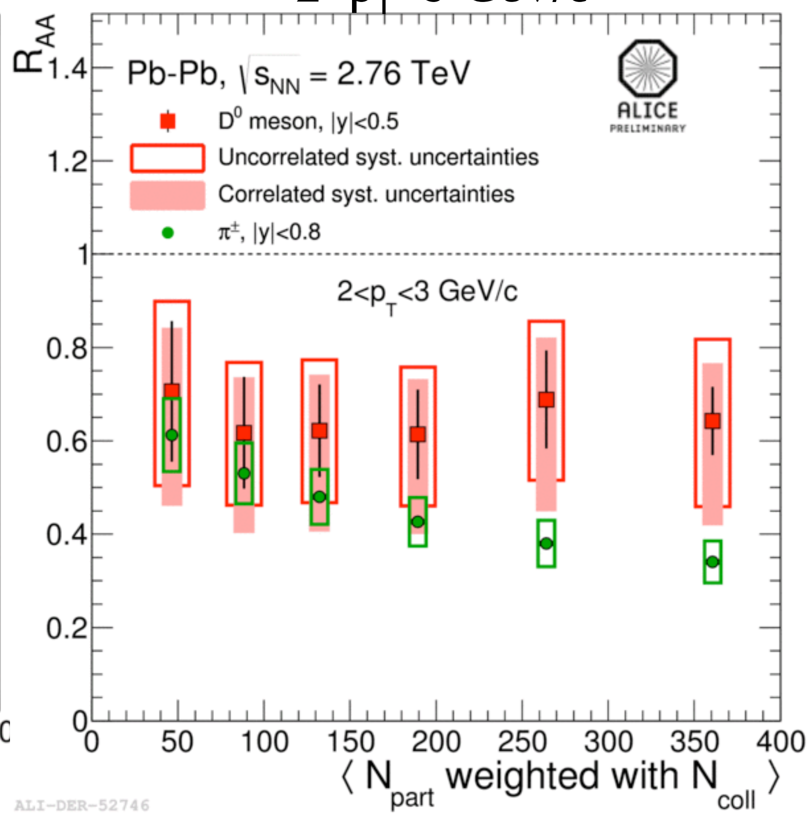
Indication of a difference between charm and beauty suppression in central collisions

Comparison to pions measured by ALICE

0-7.5% centrality class



$2<p_T<3$ GeV/c



Similar suppression of D mesons as light hadrons, suggestion of a difference below 5 GeV/c in central collisions

→more statistics needed to draw conclusion on the expected difference between D and π suppression

[$R_{AA}(D)>R_{AA}(\pi)$ expected from mass hierarchy and colour charge dependence of energy loss]

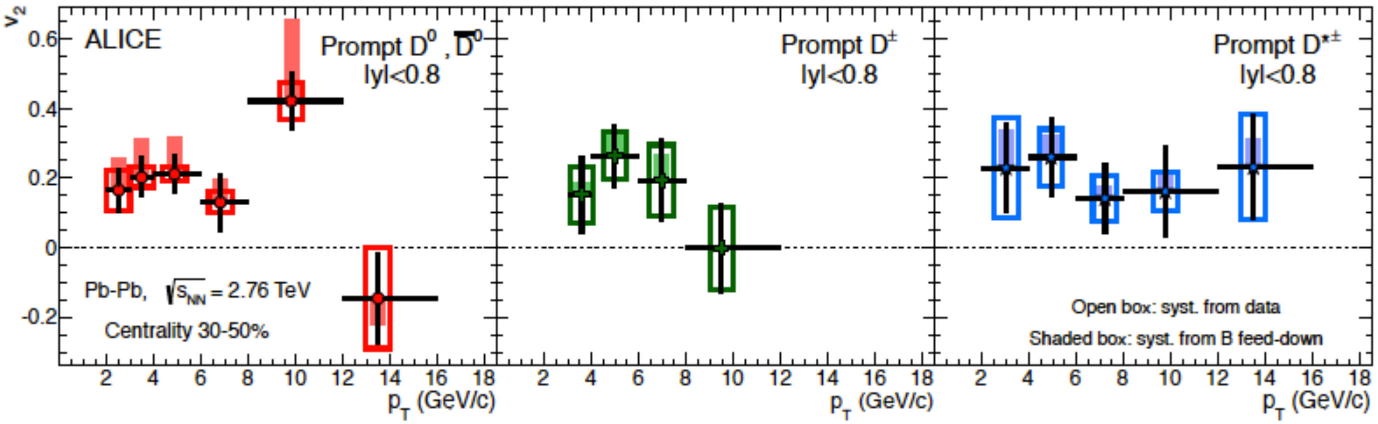
New result: D meson v_2

Event plane method

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

R_2 : event plane resolution

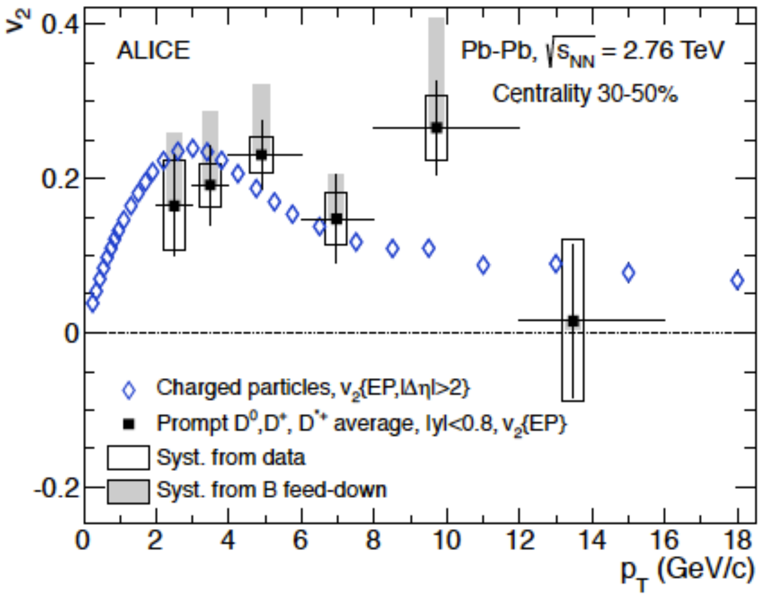
arXiv:1305.2707



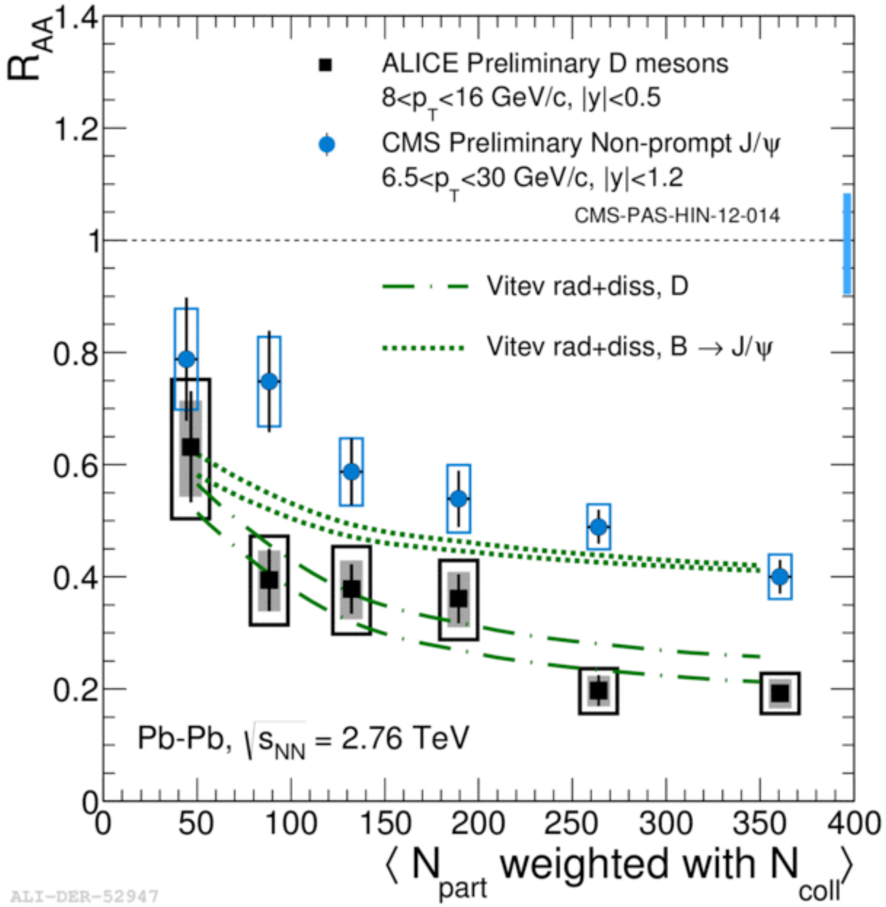
v_2 consistent for D^0, D^+, D^{*+}

D meson v_2>0 at low p_T (~5σ effect for $2<p_T<6$ GeV/c)

D meson v_2 comparable to that of charged particles → hint for collective motion of charm quarks at low p_T



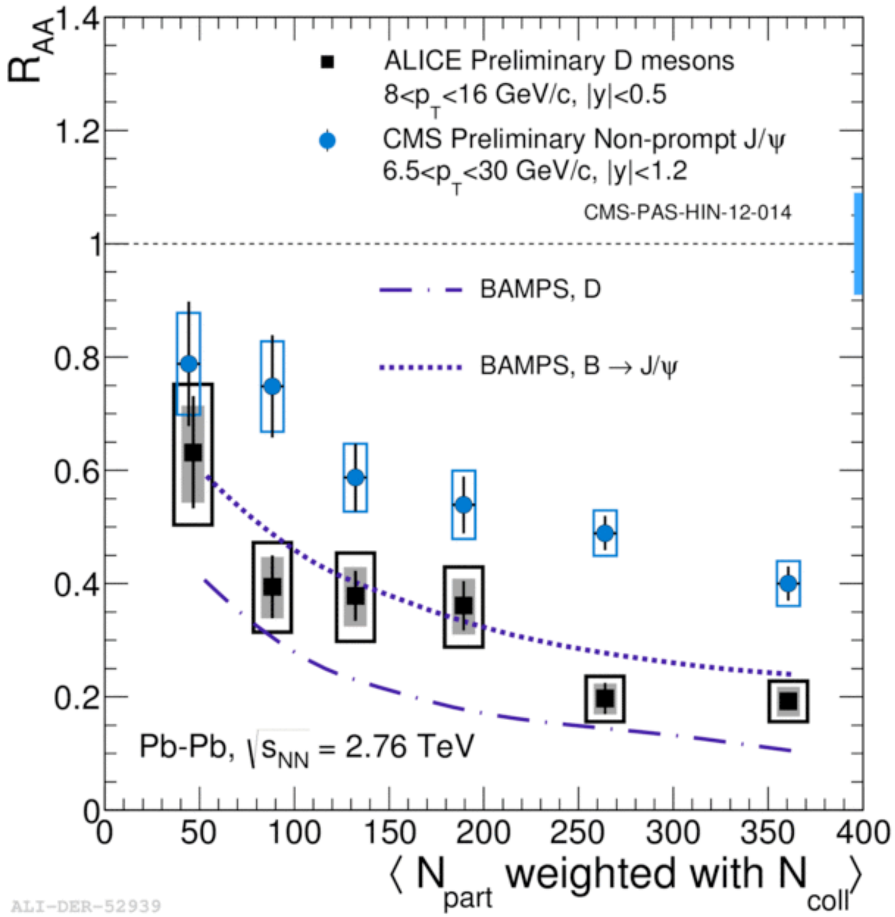
Comparison to models (1/3)



Vitev et al.: agreement with D meson R_{AA} vs N_{part} ; underestimate the non-prompt J/ψ suppression

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

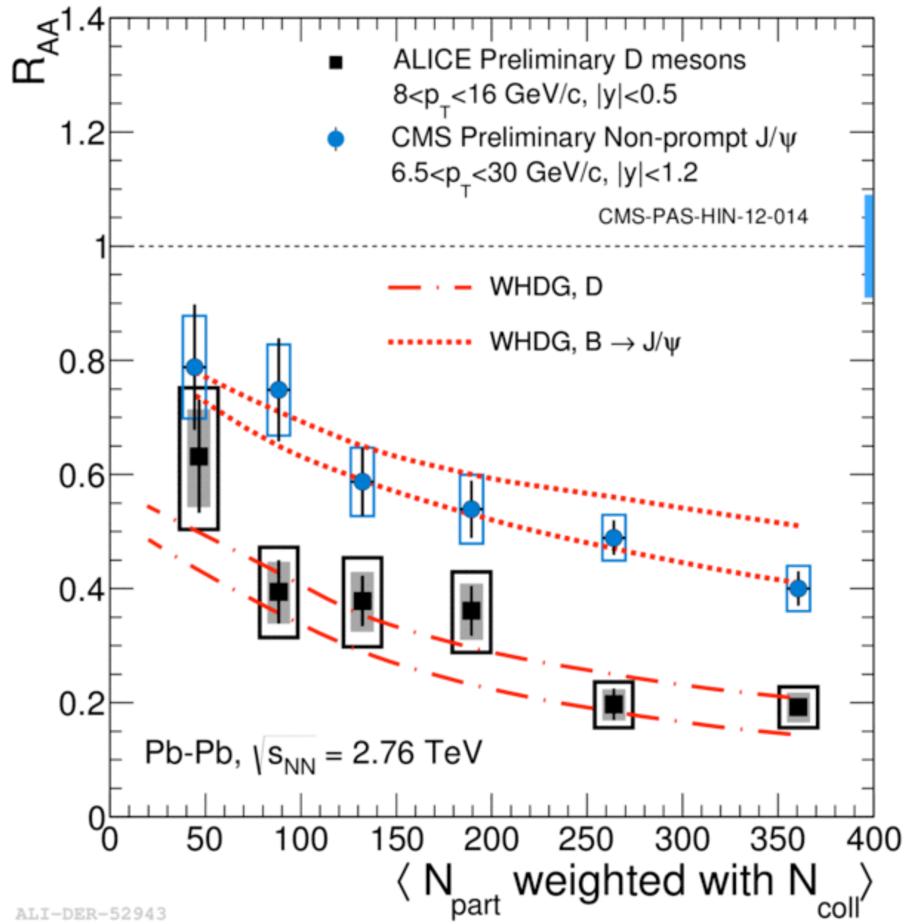
Comparison to models (1/3)



BAMPS: seems to underestimate both D meson and non-prompt J/ψ R_{AA} vs N_{part}

BAMPS: Fochler et al., J. Phys. G38 (2011) 124152

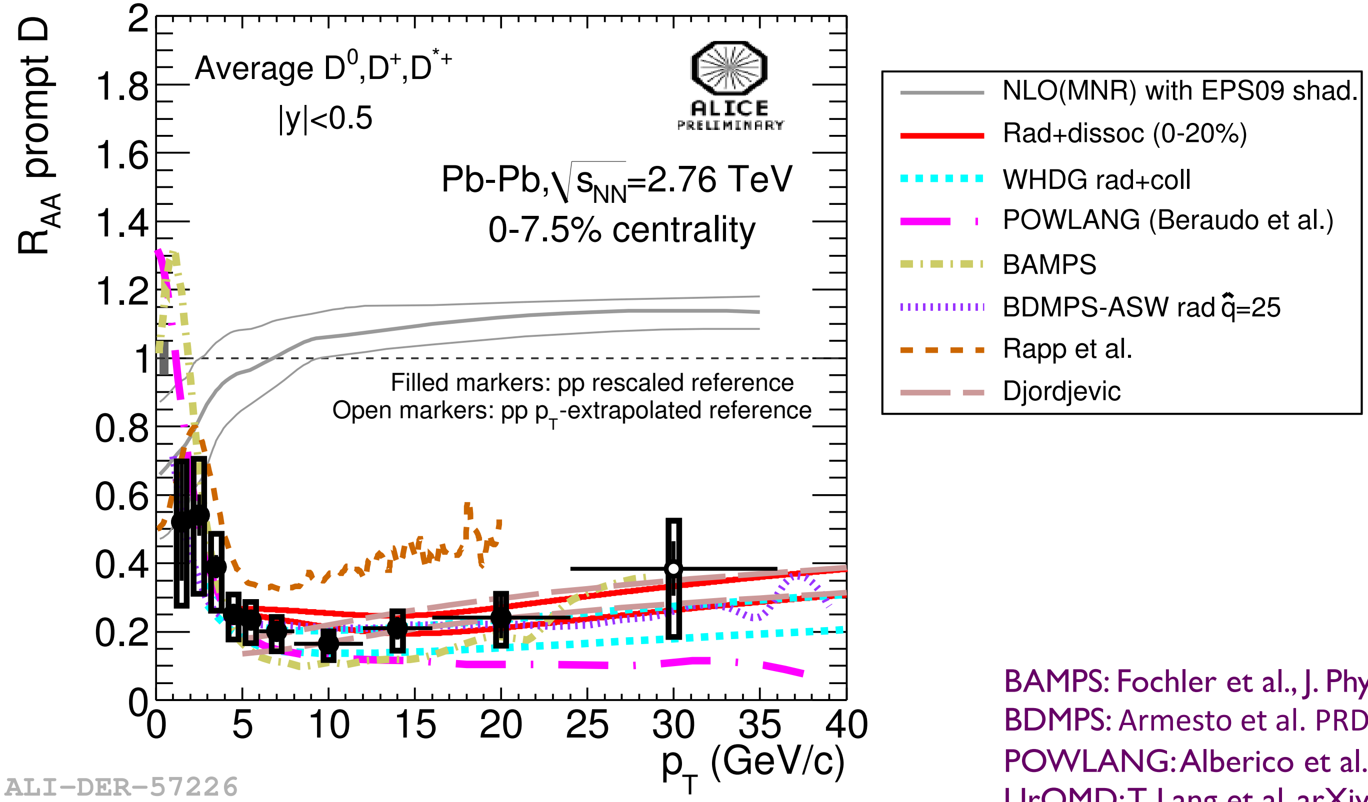
Comparison to models (1/3)



WHDG: agreement with D meson R_{AA} and with non-prompt J/ψ R_{AA} vs N_{part}

WHDG: Horowitz et al., JPhys G38 (2011) 124114

Comparison to models (2/3)

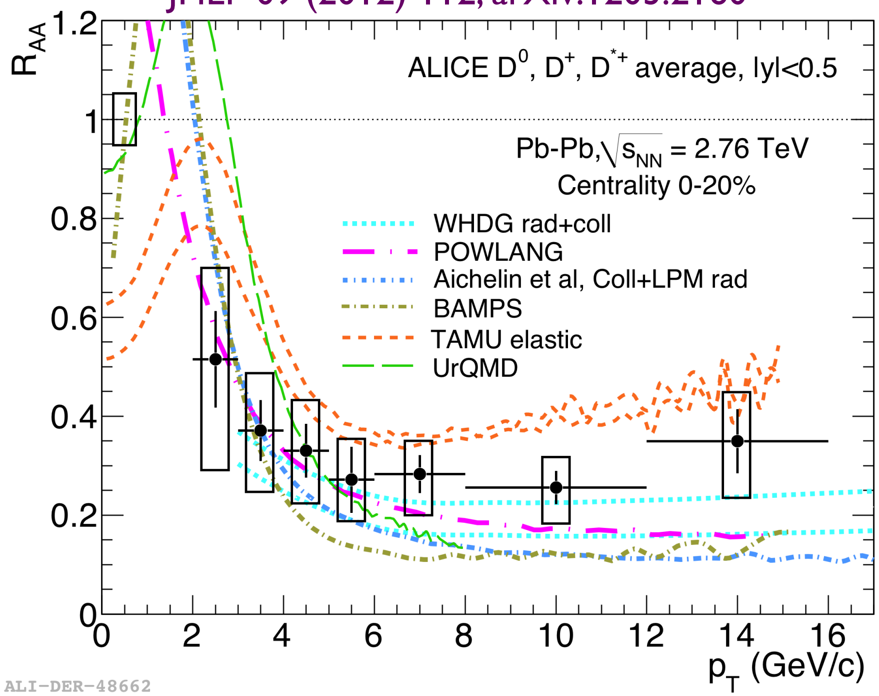


Several theoretical models based on in-medium parton energy loss reproduce R_{AA} of prompt D mesons reasonably well

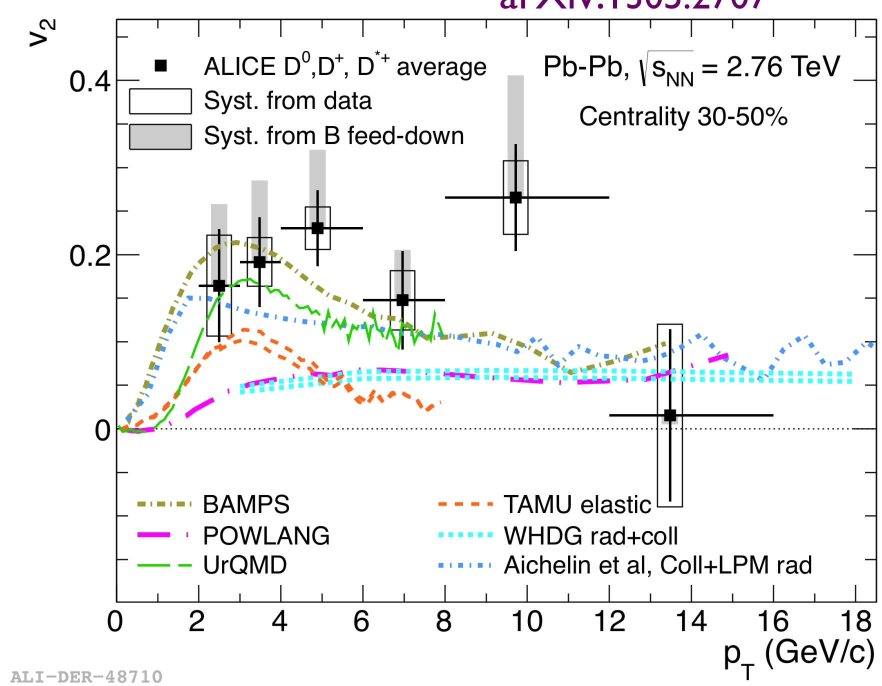
BAMPS: Fochler et al., J. Phys. G38 (2011) 124152
BDMPS: Armesto et al. PRD71 (2005) 054027
POWLANG: Alberico et al., Eur.Phys.J C71 (2011) 1666
UrQMD: T. Lang et al, arXiv:1211.6912 [hep-ph];
T. Lang et al., arXiv:1212.0696 [hep-ph].
TAMU: Rapp, He et al., Phys. Rev. C 86 (2012) 014903
WHDG: Horowitz et al., JPhys G38 (2011) 124114
Aichelin et al.: Phys. Rev. C79 (2009) 044906
J. Phys. G37 (2010) 094019
Djordjevic et al.: arXiv:1307.4098
Vitev et al.: Phys. Rev. C80 (2009) 054902,
Phys. Lett. B 713 (2012) 224

Comparison to models (3/3)

JHEP 09 (2012) 112, arXiv:1203.2160



arXiv:1305.2707



Theoretical models reproduce reasonably well R_{AA} but are challenged by simultaneously reproducing results from heavy-flavour R_{AA} and v_2

BAMPS: Fochler et al., J. Phys. G38 (2011) 124152
POWLANG: Alberico et al., Eur.Phys.J C71 (2011) 1666
UrQMD: T. Lang et al, arXiv:1211.6912 [hep-ph];
T. Lang et al., arXiv:1212.0696 [hep-ph].
TAMU: Rapp, He et al., Phys. Rev. C 86 (2012) 014903
WHDG: Horowitz et al., JPhys G38 (2011) 124114
Aichelin et al.:Phys. Rev. C79 (2009) 044906
J. Phys. G37 (2010) 094019

Conclusions

D meson R_{AA} vs p_T in central (0-7.5%) Pb-Pb:

- strong suppression by a factor of 4-5 in $5<p_T<15$ GeV/c
- D_s: suppression by a factor of 3-5 in 8-12 GeV/c

D meson R_{AA} vs N_{part}:

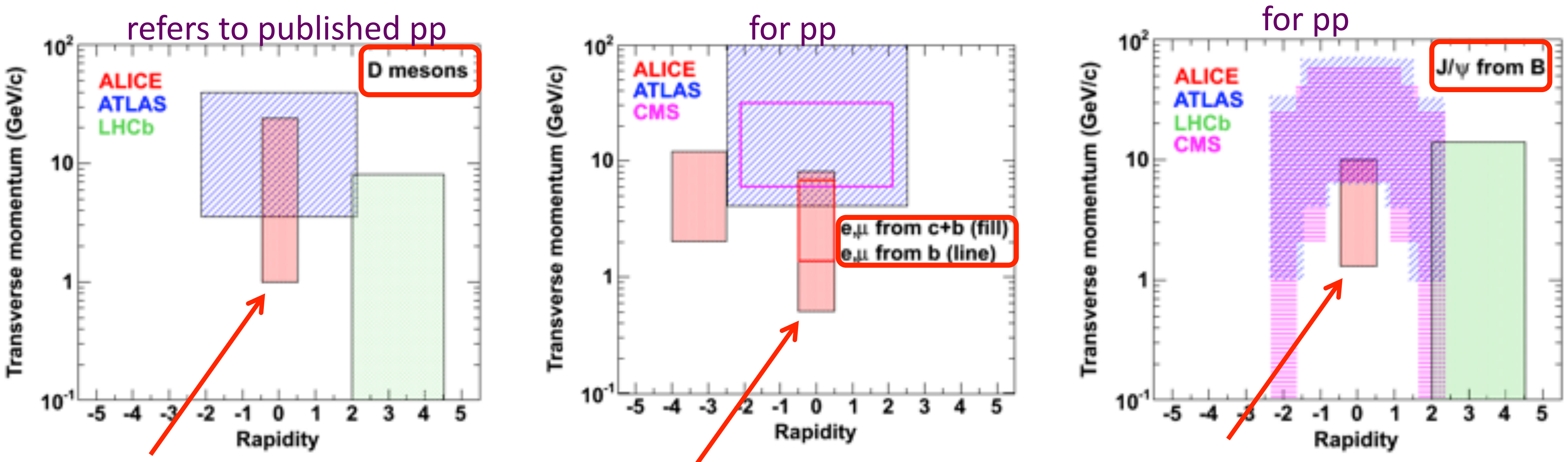
- suppression increases with increasing centrality for 3-5, 5-8, 8-16 GeV/c
- suppression tends to be constant with centrality in the lowest p_T range, 2-3 GeV/c
- observed difference in suppression of D mesons (ALICE) and non-prompt J/ψ from B meson decays (CMS) at high p_T in central collisions

Non-zero v_2 for D mesons (2-6 GeV/c) in semi-peripheral Pb-Pb collisions.

Models predict reasonably well D meson R_{AA}. Challenge for theory to simultaneously reproduce R_{AA} and v_2. With future data, smaller statistical and systematic uncertainties will help to further constrain theory. [see C. Terrevoli's talk Future session]

Backup

ALICE vs the other LHC experiments



ALICE uniqueness: low p_T (thanks to tracking+PID) especially at y=0

Why crucial to go to low p_T?

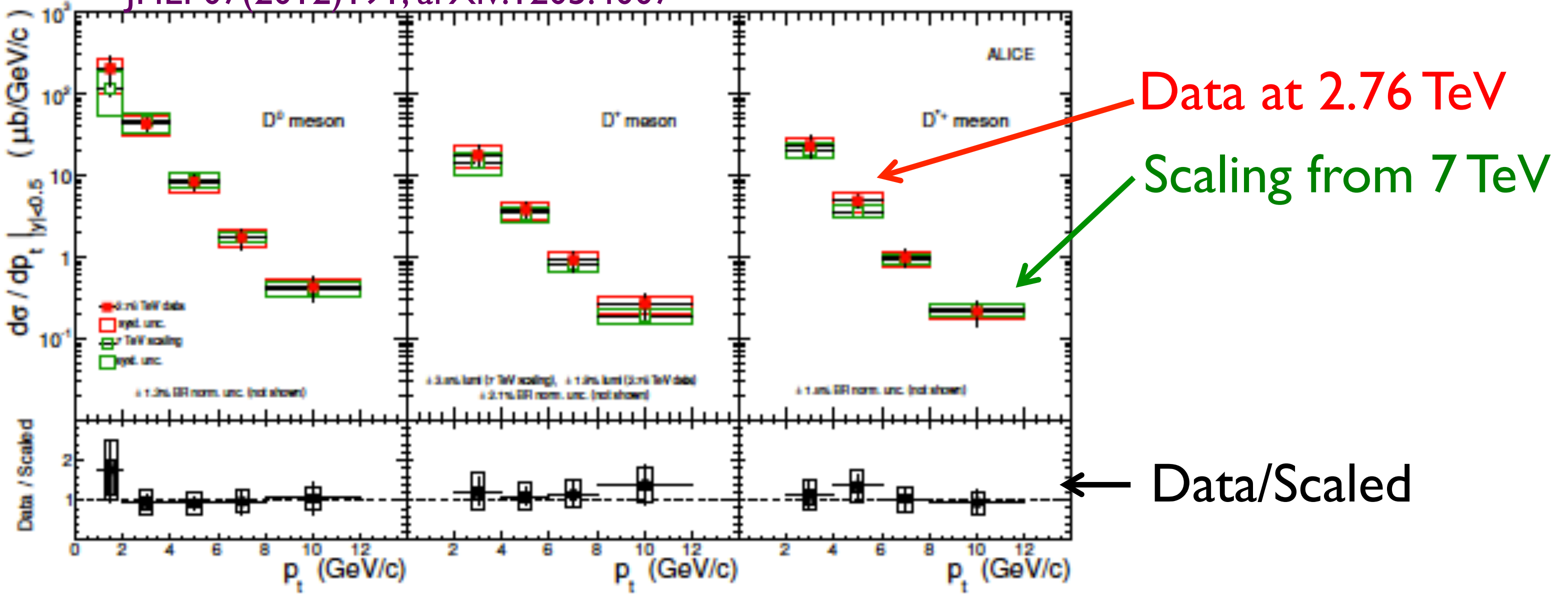
- *better constraint on* the measured *cross-section*
- *mass dependence of energy loss* (the mass effect vanishes when mass of the quark is neglible wrt its energy)
- *test models of thermal production* of charm at LHC (if so, it occurs at low p_T)
- *test the expected enhancement of charmed-strange hadrons* at low p_T (consequence of the strangeness enhancement)

pp reference at 2.76 TeV for R_{AA}

Determined by scaling the cross section measured by ALICE at 7 TeV to 2.76 TeV.
arXiv:1107.3243

- FONLL predictions at 7 and 2.76 TeV used to determine the ratio of cross sections
- Scaling validated with short pp run at 2.76 TeV.
  - scaling uncertainty from +25% -10% at low p_T (2-4 GeV/c) to ~5% at high p_T

JHEP07(2012)191, arXiv:1205.4007



- At high-p_T (~16 GeV/c for D^0, >24 GeV/c for D^+,D^*) no pp measurement is available. Reference extrapolated with data/theory relying on the FONLL p_T shape

Beauty feed-down subtraction

$$f_{\rm prompt} = 1 - \left(N^{\rm D\ feed-down\ raw} / N^{\rm D\ raw}\right) =$$

$$= 1 - \langle T_{\rm AA} \rangle \cdot \left(\frac{{\rm d}^2\sigma}{{\rm d}y\,{\rm d}p_{\rm t}} \right)^{\rm FONLL}_{\rm feed-down} \cdot R_{\rm AA}^{\rm feed-down} \cdot \frac{({\rm Acc} \times \varepsilon)_{\rm feed-down} \cdot \Delta y \Delta p_{\rm t} \cdot {\rm BR} \cdot N_{\rm evt}}{N^{\rm D\ raw}/2}$$

Secondary D from B decays estimated from FONLL predictions

Assumptions on B suppression:

- analysis on R_{AA} vs p_T in 0-7.5%

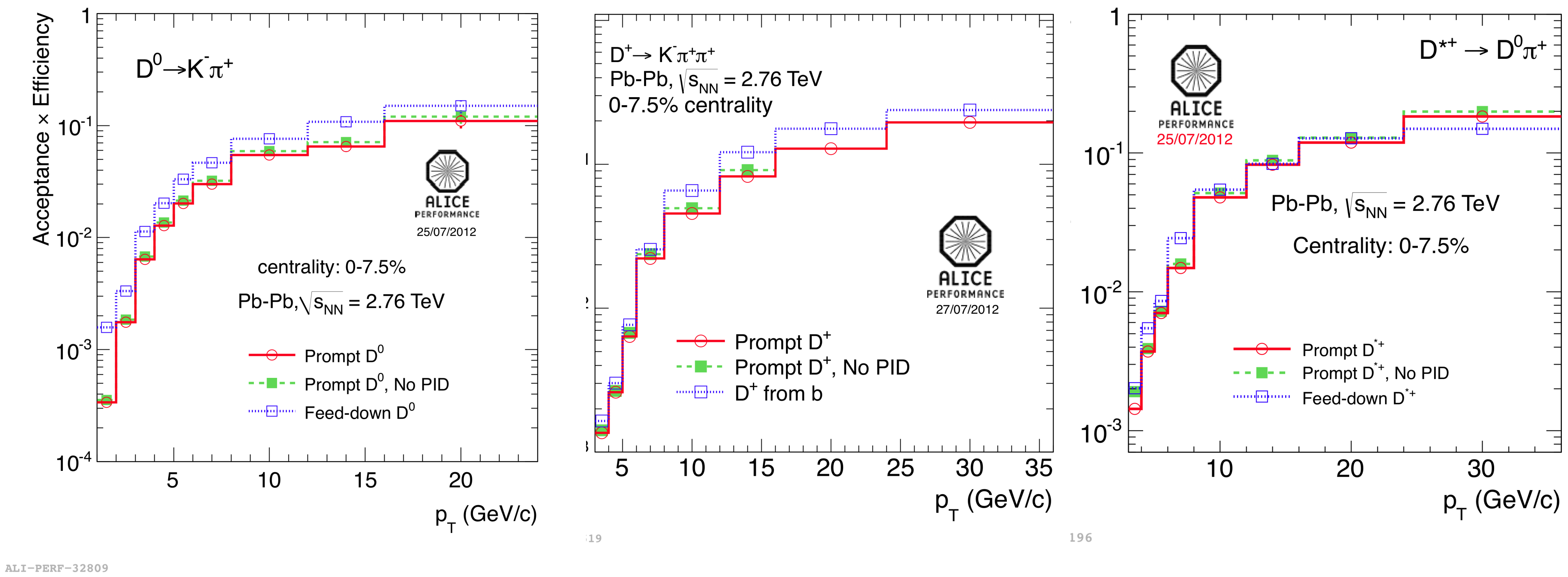
  $R_{AA}^{\text{feed-down}} = R_{AA}^{\text{Prompt D}}$ and $R_{AA}^{\text{feed-down}}$ ranging from 0.3 to 3x $R_{AA}^{\text{Prompt D}}$

- new analysis on R_{AA} vs centrality:

  $R_{AA}^{\text{feed-down}} = 2 \times R_{AA}^{\text{Prompt D}}$ and $R_{AA}^{\text{feed-down}}$ ranging from 1 to 3x $R_{AA}^{\text{Prompt D}}$

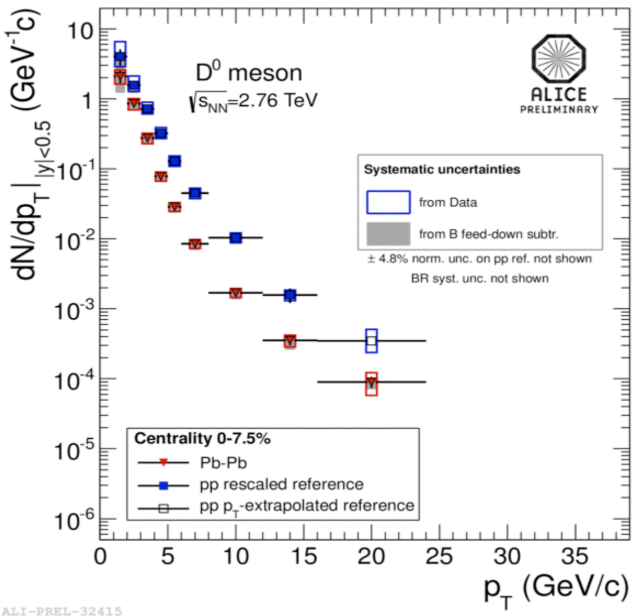
Note: new choice of $R_{AA}^{\text{feed-down}}$ driven from comparison to R_{AA} from non-prompt J/ψ (CMS) in central collisions. Effect of the two $R_{AA}^{\text{feed-down}}$ hypothesis (~2-8%) within statistical errors
Systematic uncertainties from B energy loss ~6-10%

D meson efficiencies

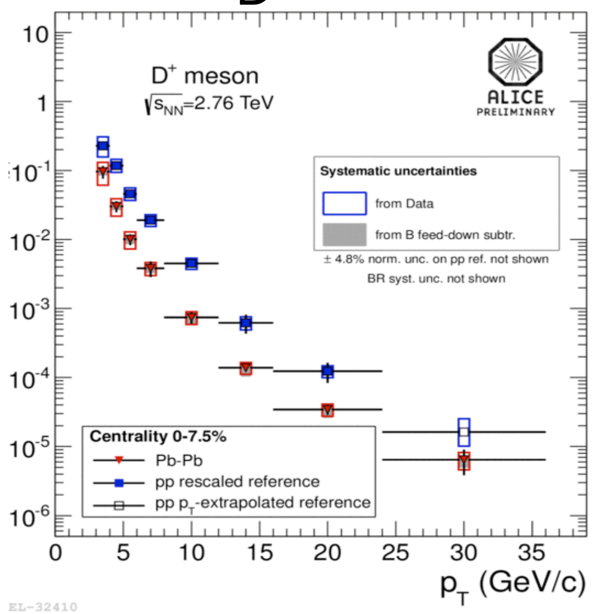


D meson dN/dp_T

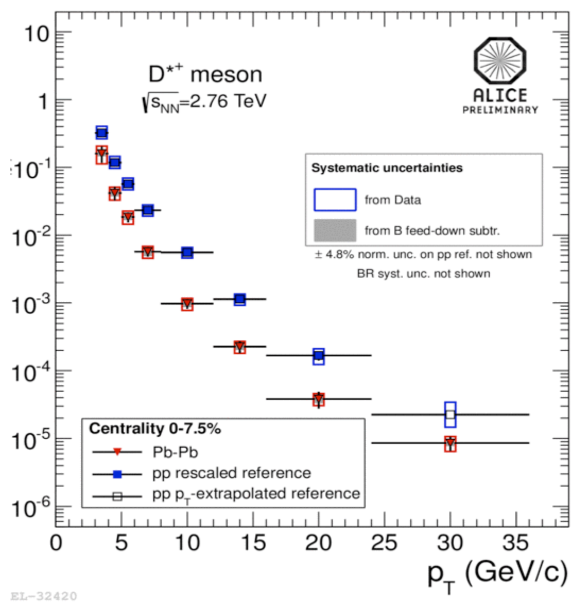
D^0

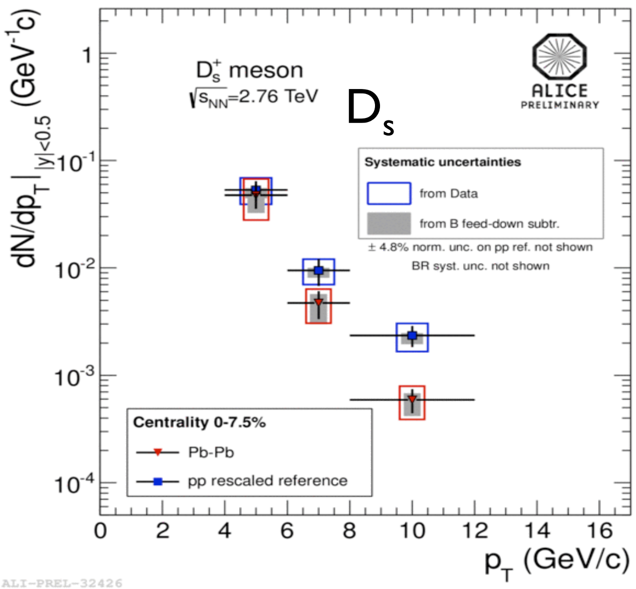


D^+



D^{*+}





prompt D mesons = (inclusive D) – (D from B decays)

- pp: "D from B" yield estimated from pQCD
- Pb-Pb: as for pp, but *uncertainty on unknown B R_{AA}*:
  → R_{AA}(D from B) between 1/3 and 3 x R_{AA}(D)

pp reference from 7 TeV scaled to 2.76 TeV (+ high-p_T FONLL extrapolation) and multiplied by $\langle T_{AA} \rangle$

Large suppression in Pb-Pb relative to pp

Systematic uncertainties