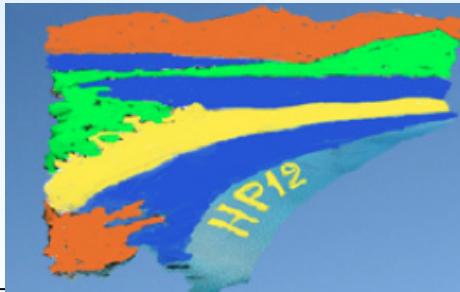




Heavy-flavour production in ALICE at the LHC

Silvia Masciocchi (GSI and EMMI)
for the ALICE Collaboration



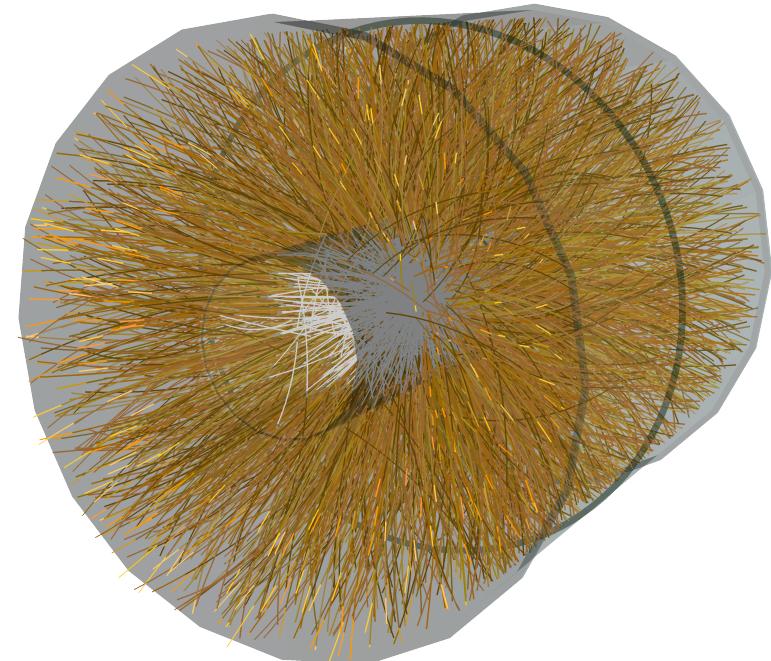
Hard Probes 2012

*5th international Conference on Hard and Electromagnetic Probes of
High-Energy Nuclear Collisions
27 May – 1 June 2012, Cagliari (Sardinia, Italy)*

Outline



- Motivation
- Heavy-flavour program in ALICE
- Results from proton-proton and Pb-Pb collisions
 - Production cross sections
 - Nuclear modification factor
 - Elliptic flow
- Discussion and outlook

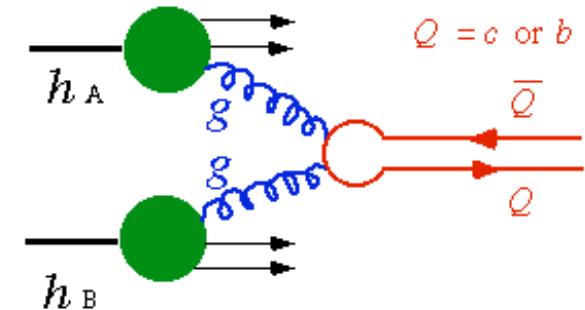


Motivation

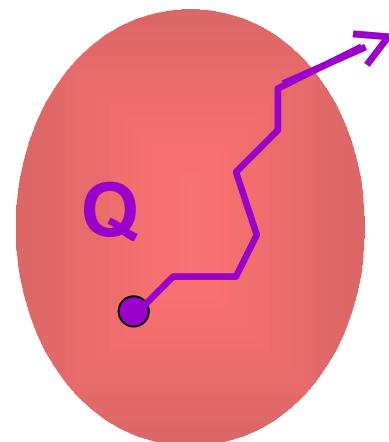


Heavy flavours are produced
in hard scattering processes
in the early phase of the collisions

- Present from the early times
- In the highest density phase
- Travel and interact in the medium, experience the full collision history



**Heavy flavours:
probe of the QGP
produced in AA collisions**





Parton energy loss and collective phenomena

Parton energy loss by:

- Medium-induced gluon radiation
- Collisions with medium partons

Depends on

- Colour charge (Casimir factor, $\Delta E_g > \Delta E_{u,d,s}$)
- Parton mass (dead cone effect, $\Delta E_b < \Delta E_c < \dots$)

$$\Delta E_g > \Delta E_c > \Delta E_b$$

“suppression”: $\pi > D > B$

Elliptic flow of heavy flavours

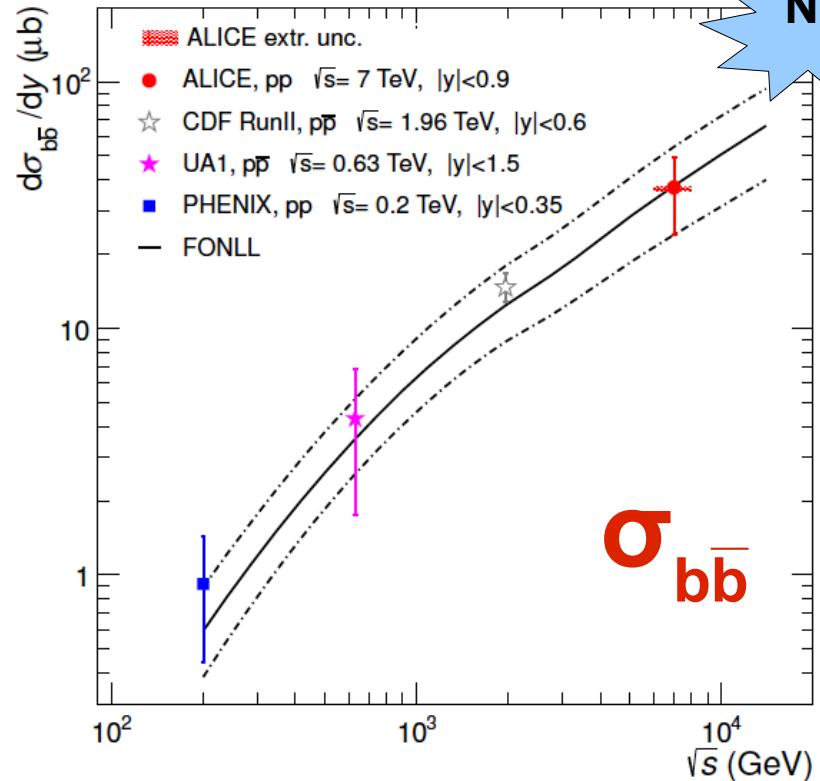
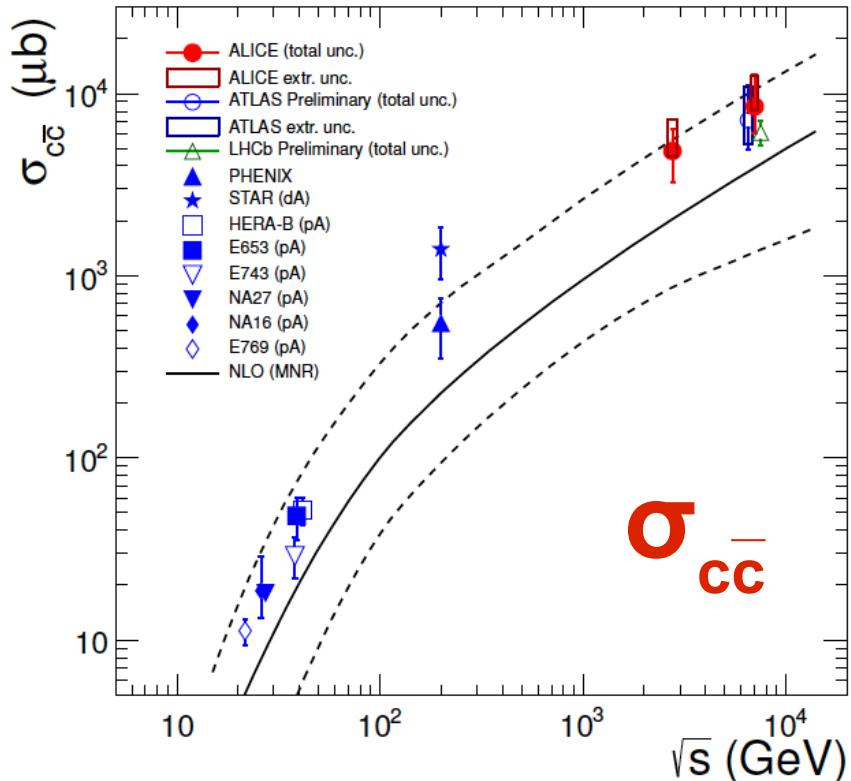
→ information on medium transport properties: thermalization in QGP (low p_t) and path length dependence of the parton energy loss (high p_t)



HF large production cross sections

ALICE

Measured in proton-proton:



Expected in 1 Pb-Pb collision at $\sqrt{s}_{\text{NN}} = 2.76 \text{ TeV}$:

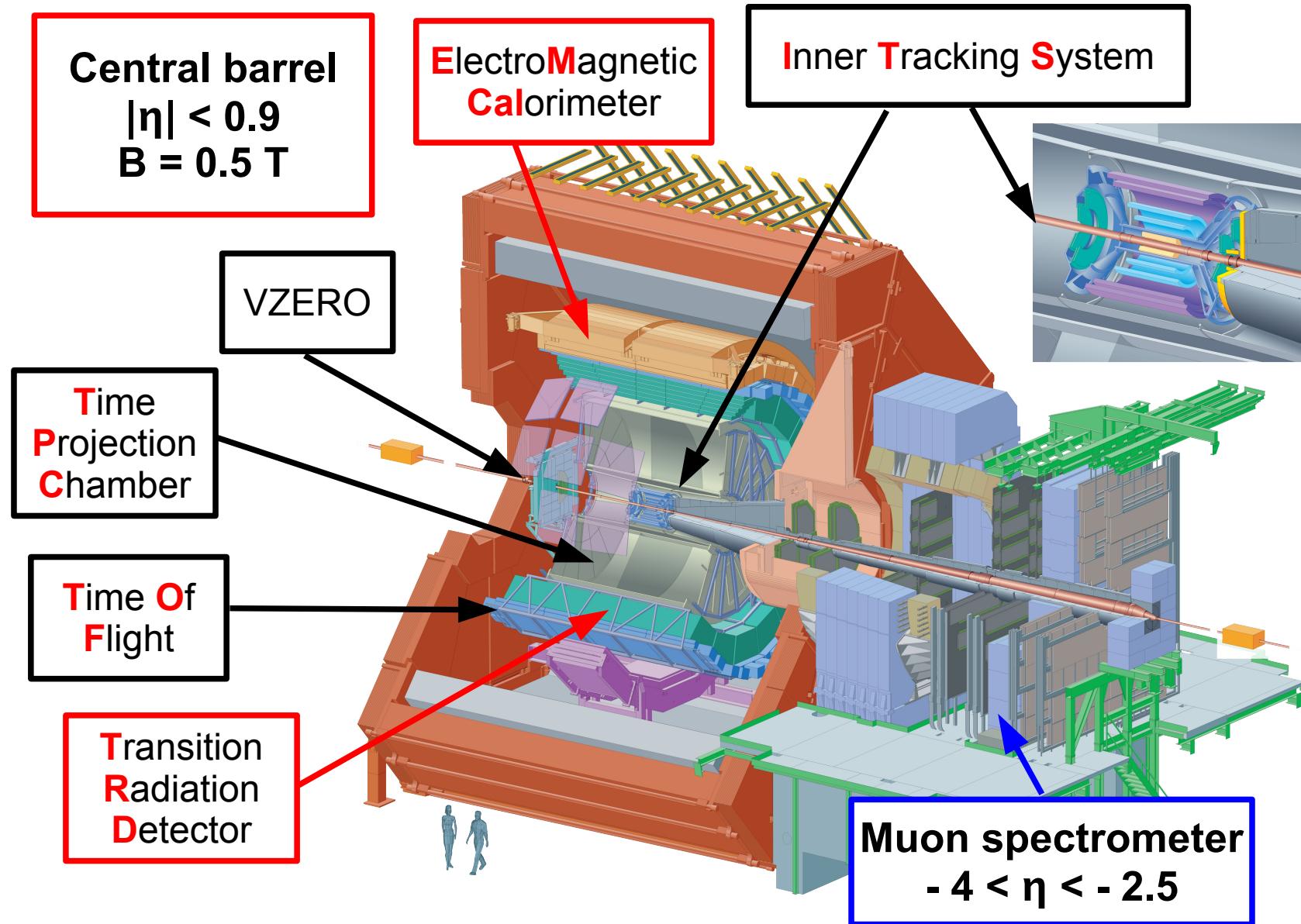
$\approx 60 \text{ } c\bar{c}$ $\approx 2 \text{ } b\bar{b}$

(MNR, shadowing: EKS98, EPS08. Factor 2 uncertainty)

ALICE: A Large Ion Collider Experiment



ALICE



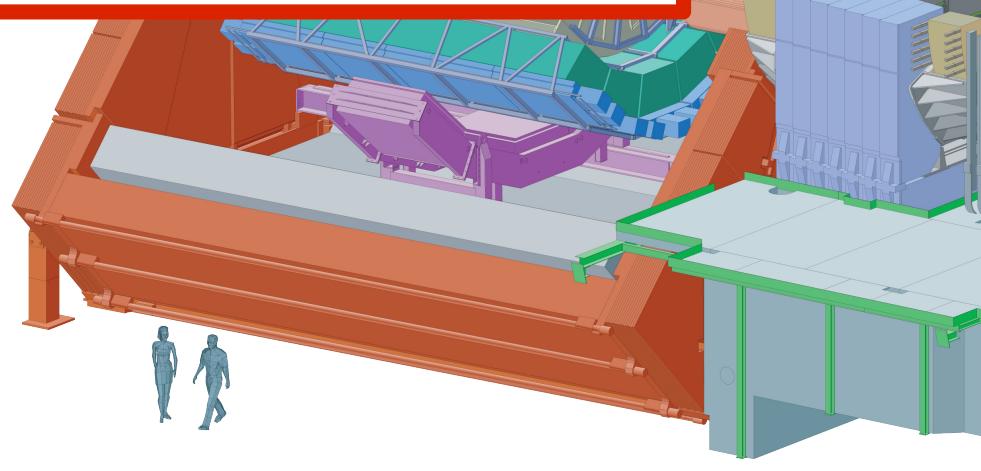
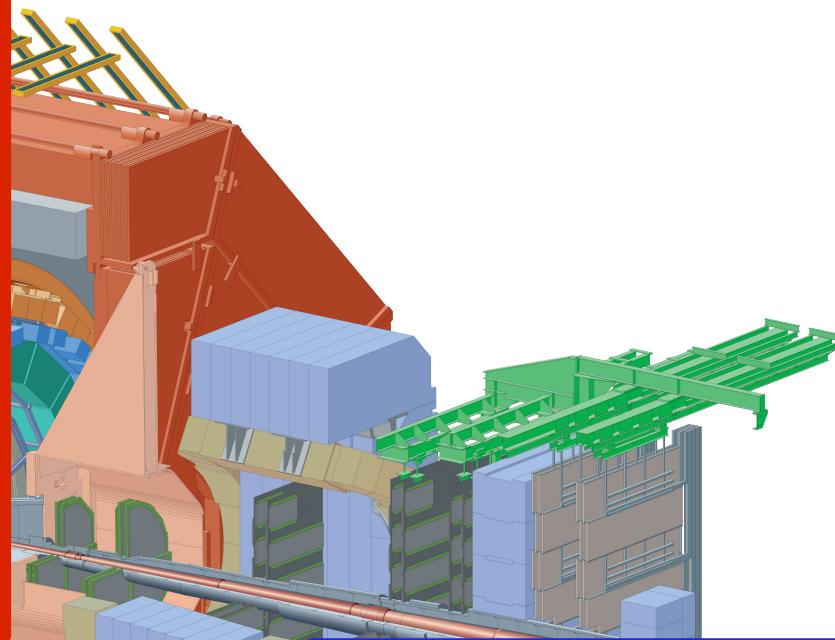
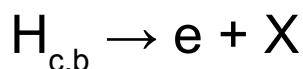
The heavy-flavour program

Mid rapidity:

- Hadronic decays of charm hadrons:

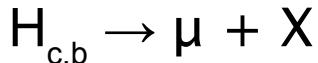


- Semi-electronic decays of charm and beauty hadrons



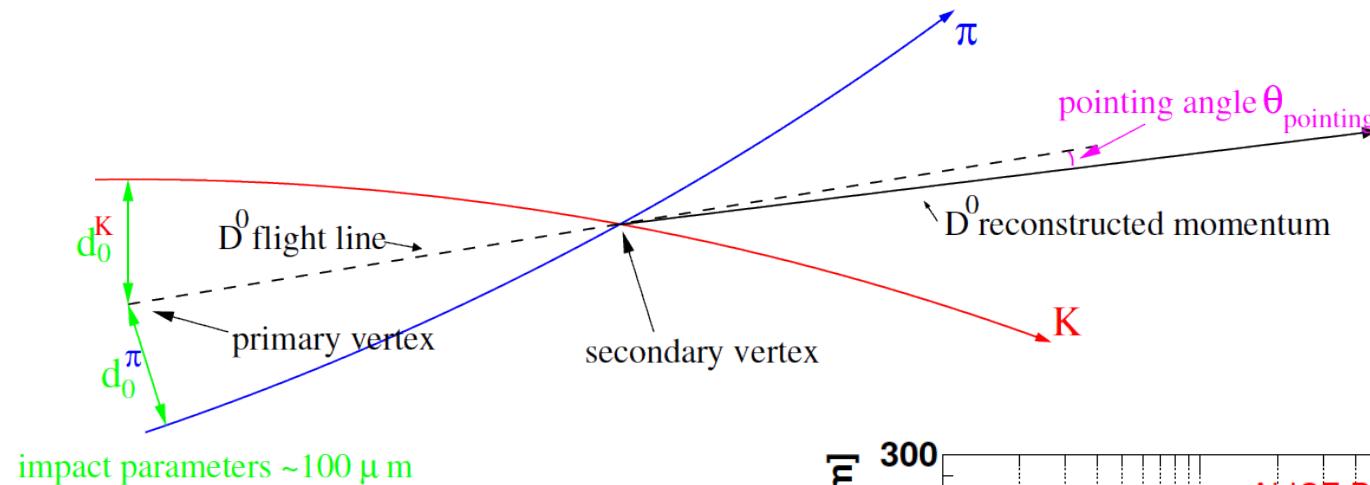
Forward rapidity:

- Semi-muonic decays of charm and beauty hadrons



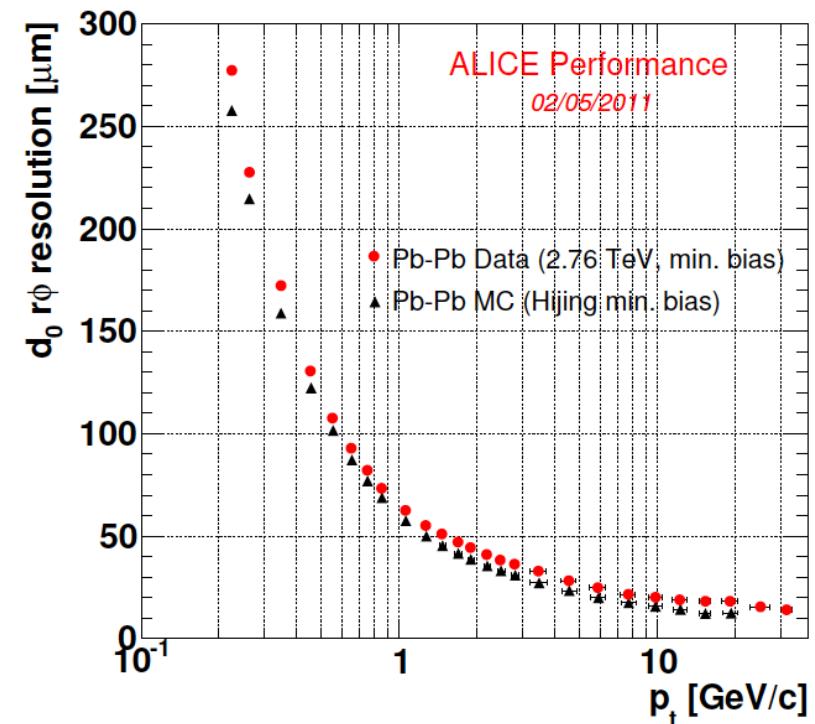


High resolution vertexing



High resolution tracking (ITS, TPC):

- Single track impact parameter to interaction vertex ($D, H_b \rightarrow e$)
- Secondary vertices (D)

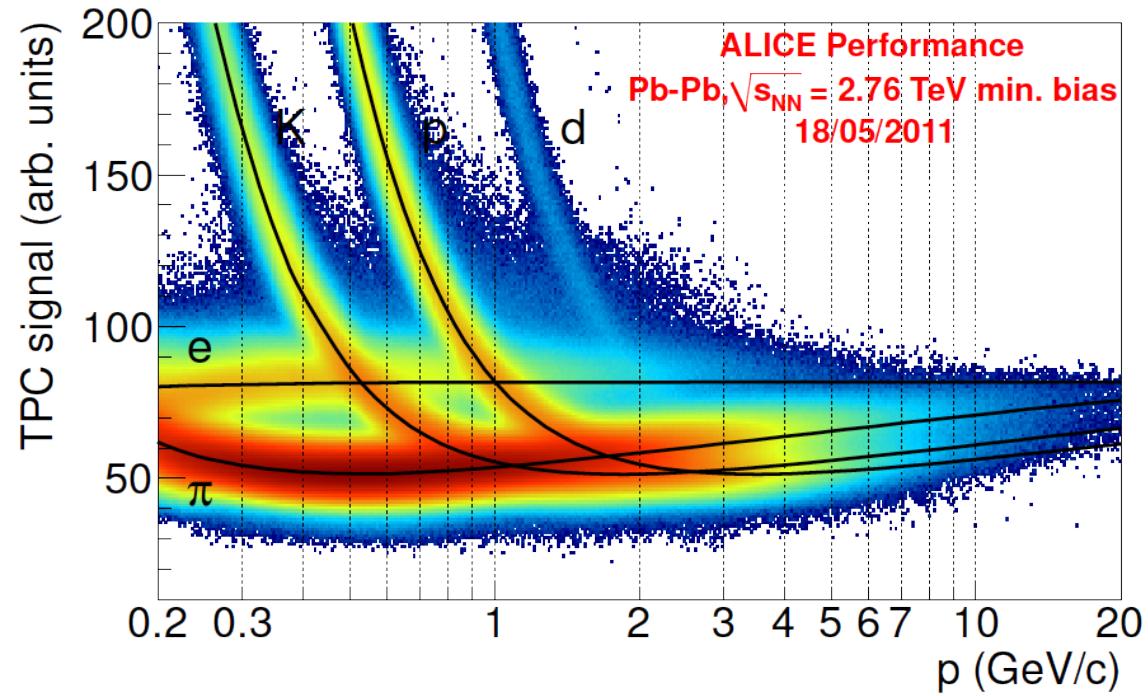




Mid rapidity: particle identification

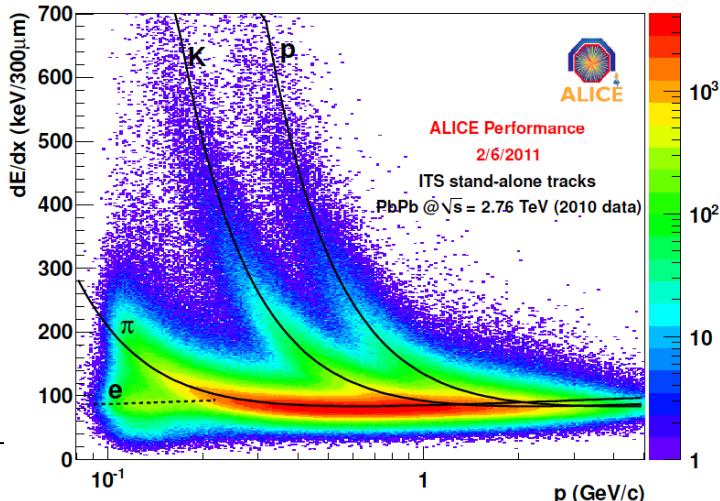
ALICE

Time
Projection
Chamber



TALK (1B)
P. Christiansen

arXiv:1203.2160

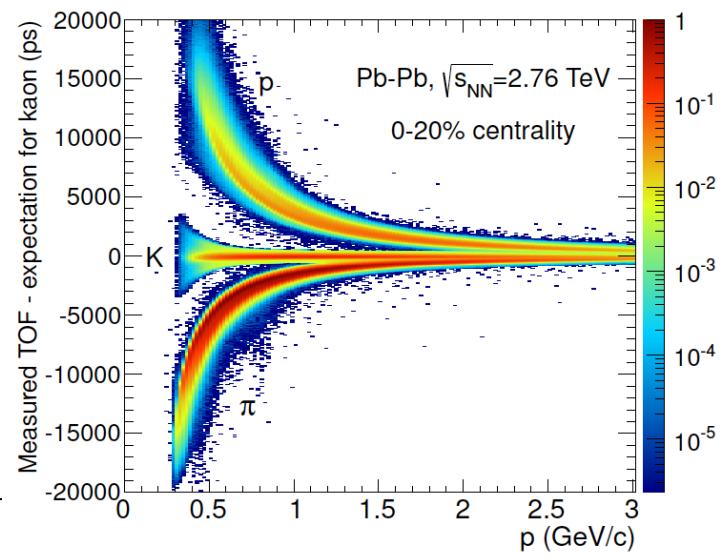


Inner Tracking
System



Time of Flight

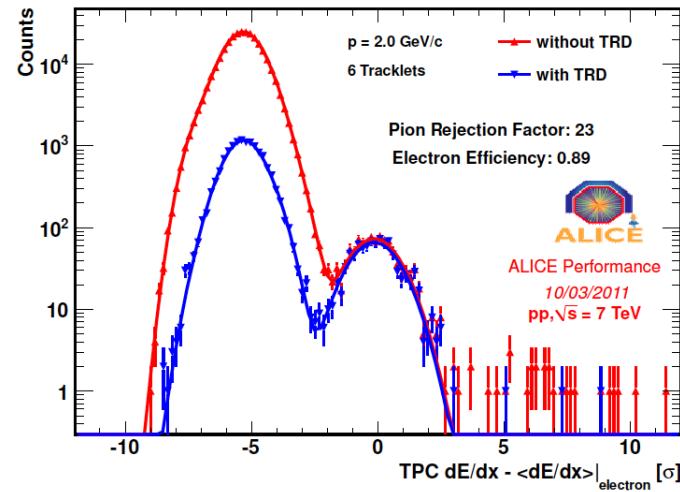
ALICE Heavy flavours, HP2012



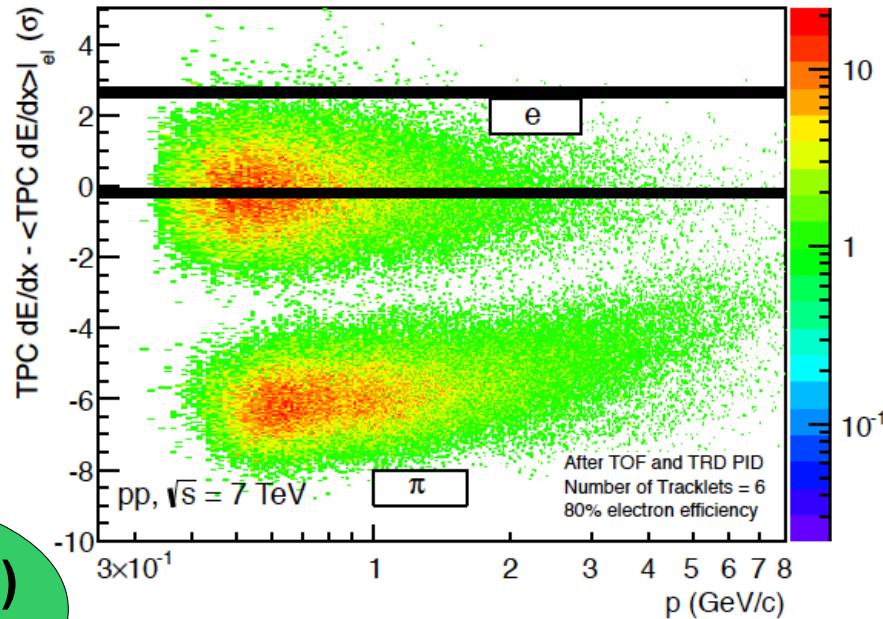


Mid rapidity: electron identification

**Transition
Radiation
Detector**
e/ π sep.



+ TOF
 $(\pm 3\sigma_e)$

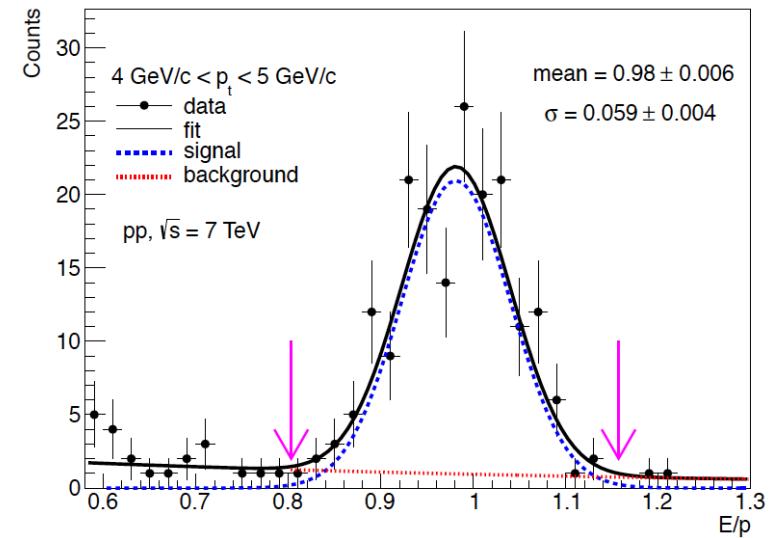


TALK (IVA)
M. Kweon

ccacci@gsi.de

**ElectroMagnetic
Calorimeter**

Combined with TPC dE/dx
E/p



arXiv:1205:5423



Muons at forward rapidity

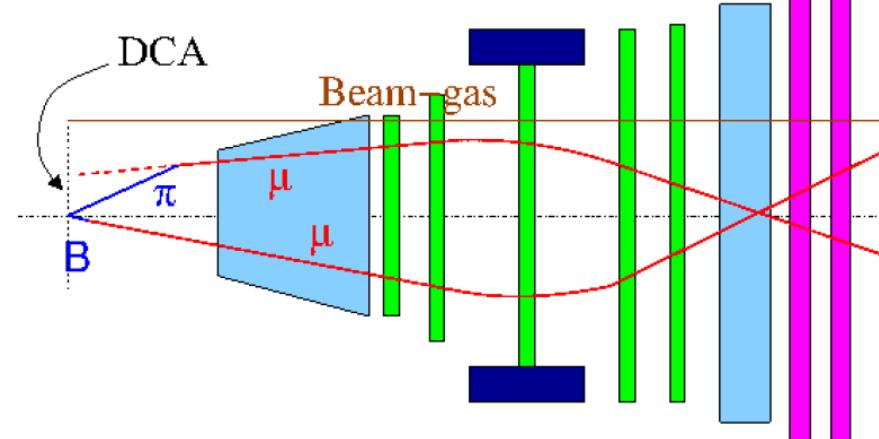
TALK (IIIA)
D. Stocco



ALICE

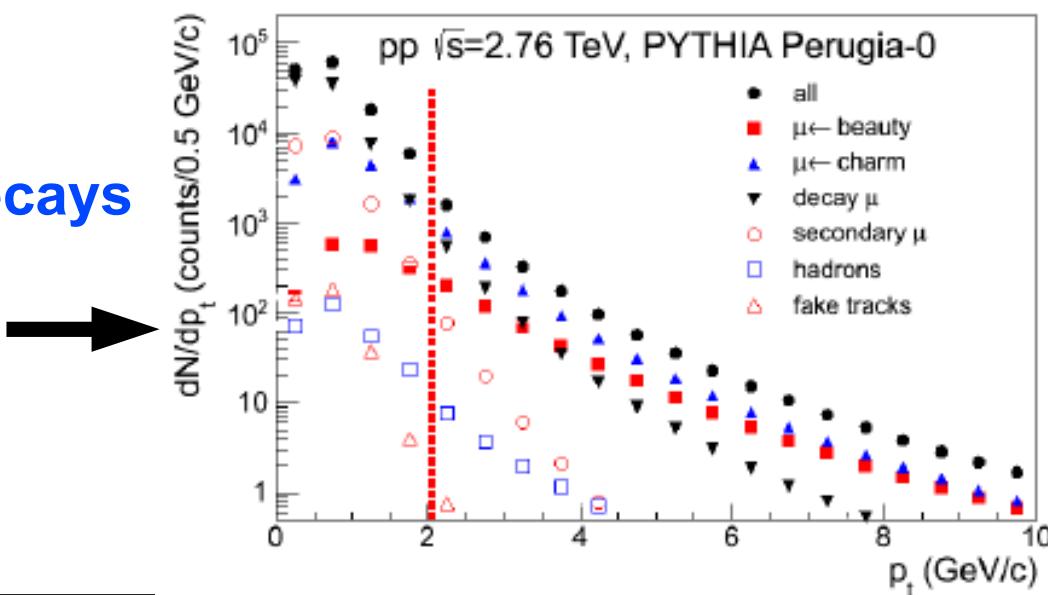
• Track selection

- Match track with segments in the trigger chambers → reject punch-through hadrons
- Distance of Closest Approach to primary cut rejects tracks from beam-gas interactions



• Background subtraction: π , K decays

- Focus on $p_t > 2$ (4) GeV/c (Pb-Pb)
- pp: using as input MC simulations
- PbPb: using ALICE data at mid rapidity



Proton-proton: highlights

- Charm and beauty production cross section (2.76 and 7 TeV) and comparison with FONLL and GM-VFNS
 - D mesons: D^0 , D^+ , D^*
 - Single muons
 - Single electrons
- More charmed hadrons: D_s , Λ_c
- Beauty via electrons:
 - Impact parameter analysis
 - e-h correlations

TALK (IIIA)
C. Geuna

pp data samples:
 $\sqrt{s} = 2.76 \text{ TeV}$ – 2011
 $\sqrt{s} = 7 \text{ TeV}$ – 2010



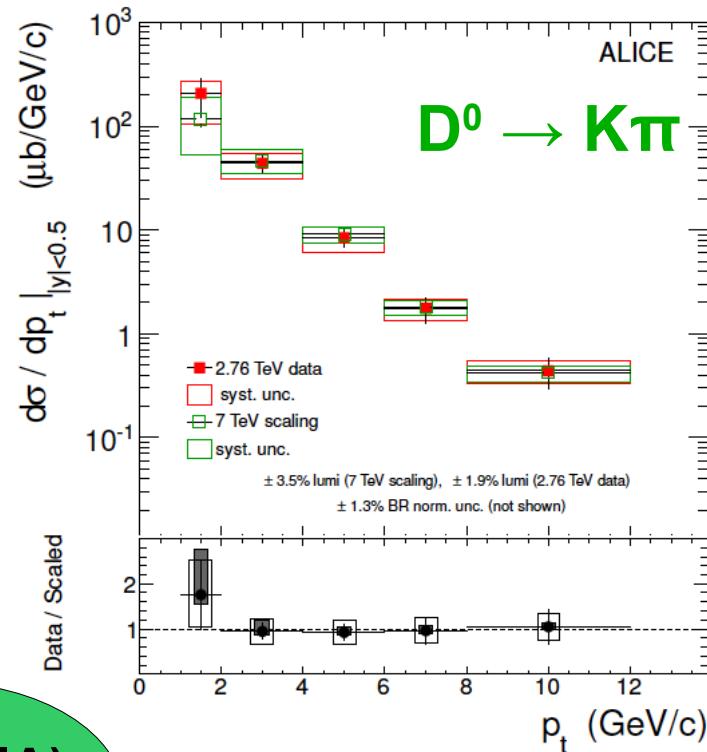
pp at $\sqrt{s} = 2.76$ TeV: D mesons, muons

ALICE

- Reference sample for PbPb collisions ($\sqrt{s}_{NN} = 2.76$ TeV)
- Relatively small data sample 2011 ($L_{int}^D = 1.35 \text{ nb}^{-1}$, $L_{int}^\mu = 19 \text{ nb}^{-1}$)
- Differential cross section measured for D mesons and single muons
 - Cross check of spectra extrapolated with FONLL from pp at $\sqrt{s} = 7$ TeV

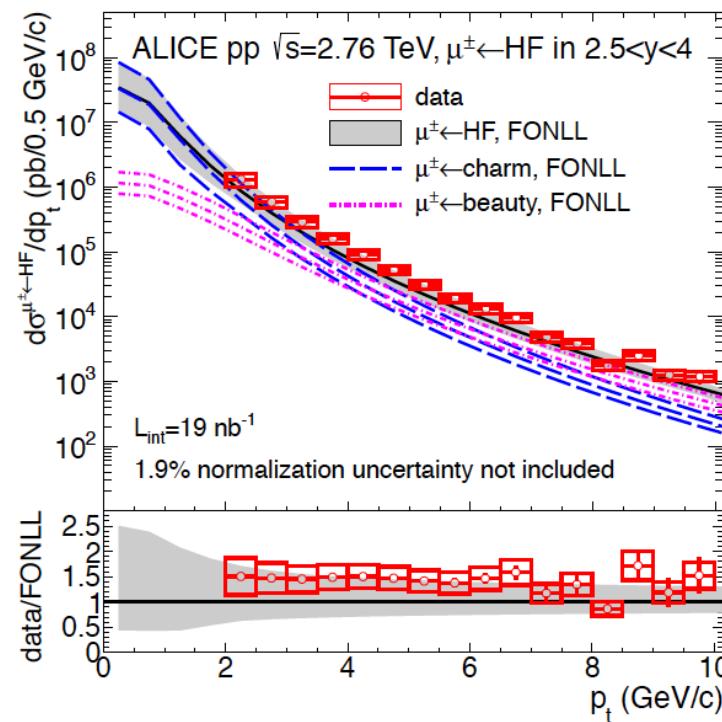
arXiv:1107.3243

Also:
 $D^+ \rightarrow K\pi\pi$
 $D^* \rightarrow D^0\pi$



TALK (IIA)
Z.C.d.Valle

arXiv:1205:4007



TALK (IIIA)
D. Stocco

pp at $\sqrt{s} = 7$ TeV: D mesons, muons, electrons



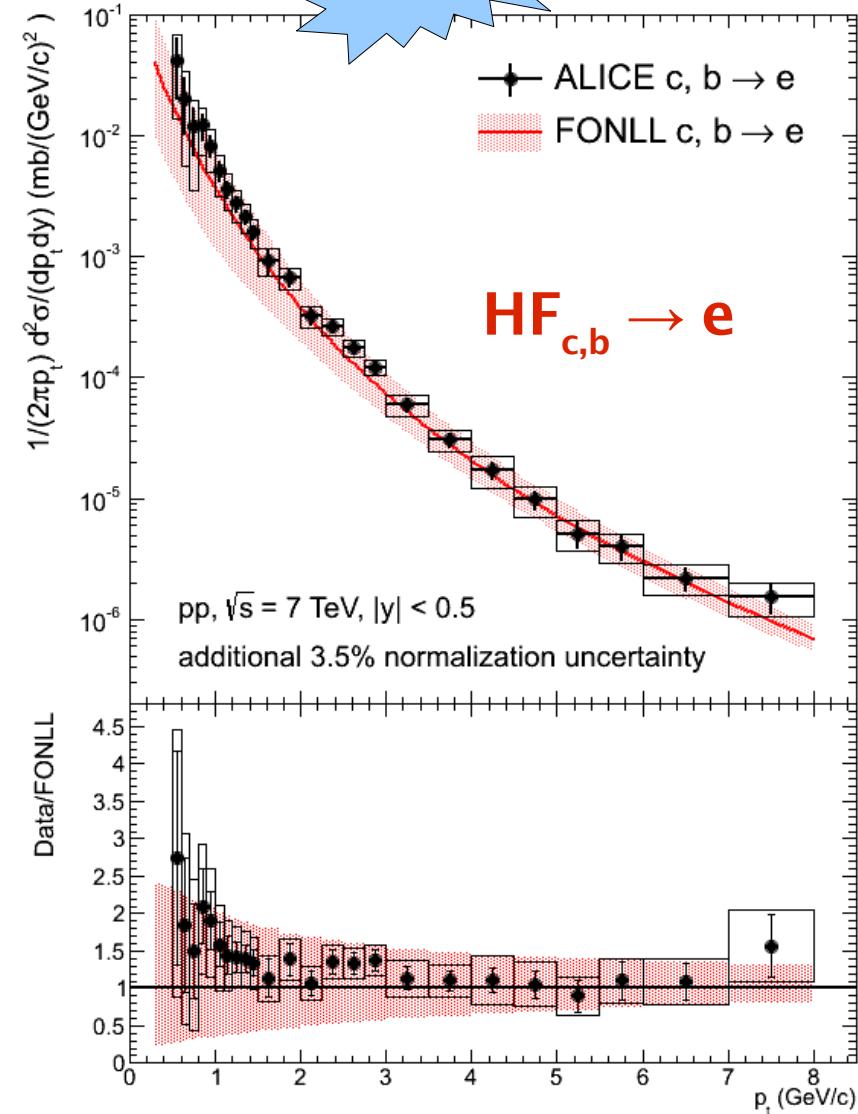
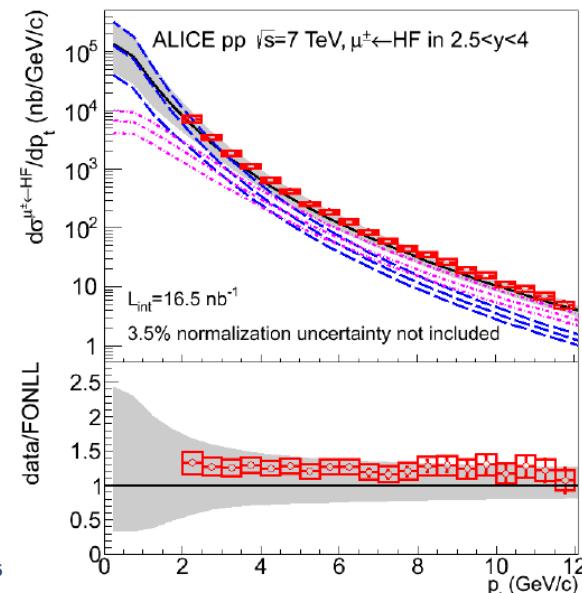
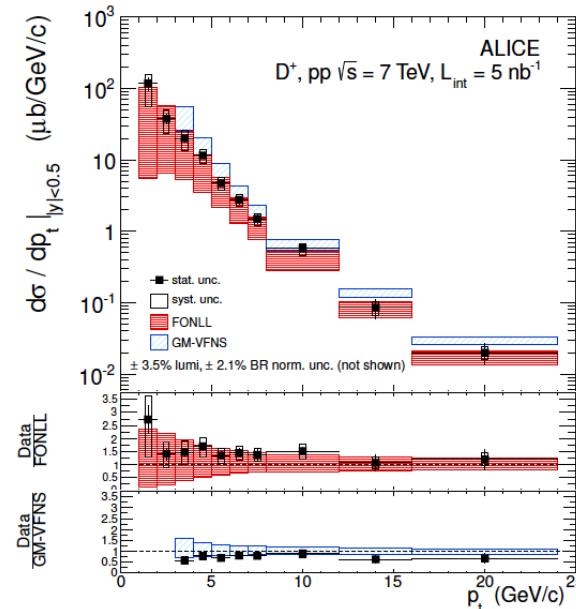
NEW

ALICE

Heavy flavour production cross section:

D mesons
JHEP01 (2012) 128

HF_{c,b} → μ
PLB 708 (2012) 265



Data are well described by pQCD predictions (FONLL, GM-VFNS) within uncertainties

Important test of pQCD

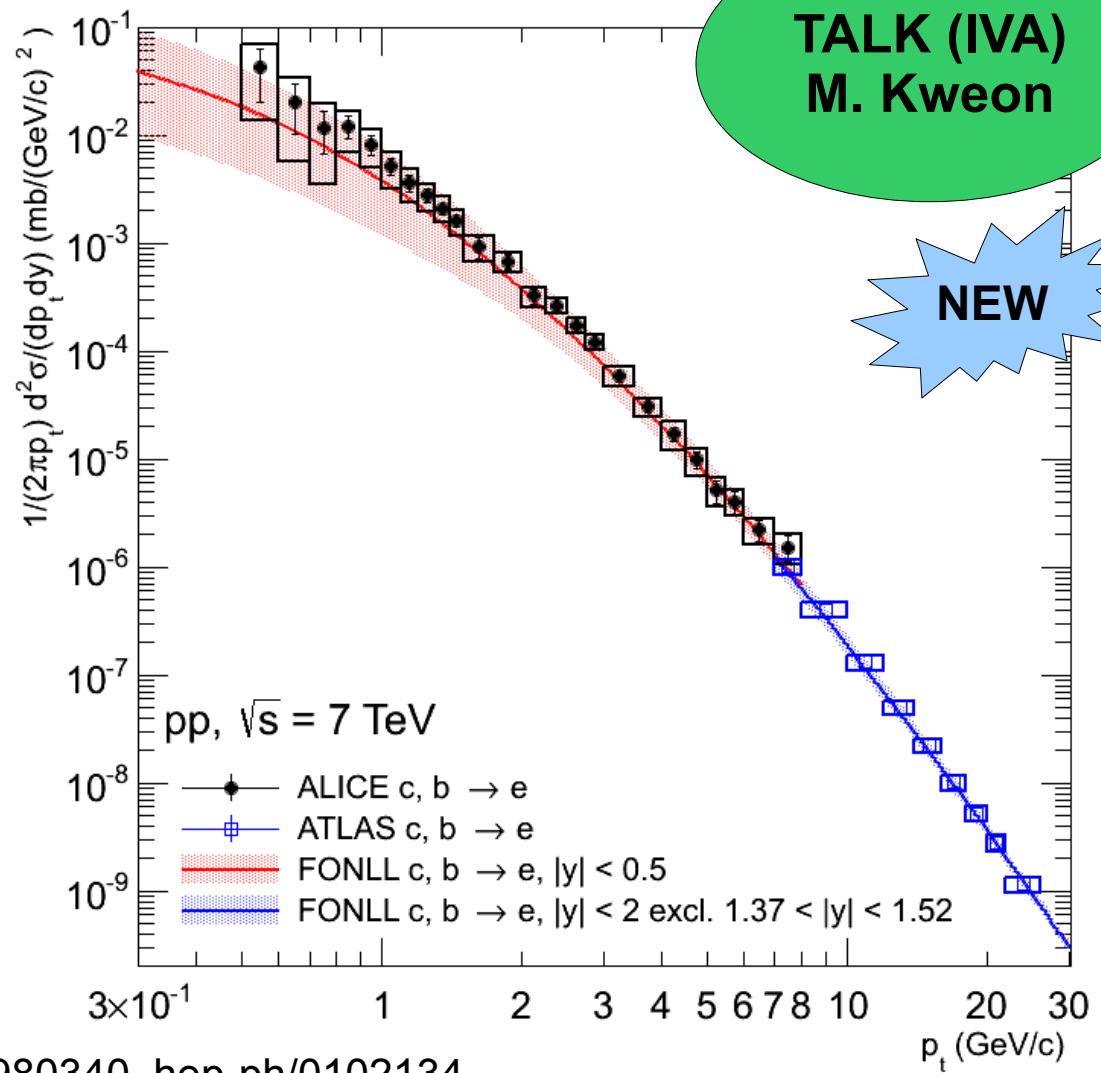
arXiv:1205:5423



ALICE

pp at $\sqrt{s} = 7$ TeV: single electrons

- Cocktail subtraction method (ALICE π^0 and η measured spectra → Y. Kharlov IIC)
- ALICE data: $0.5 < p_t < 8$ GeV/c → cover (FONLL)
 - ~50% electrons from charm
 - ~90% electrons from beauty





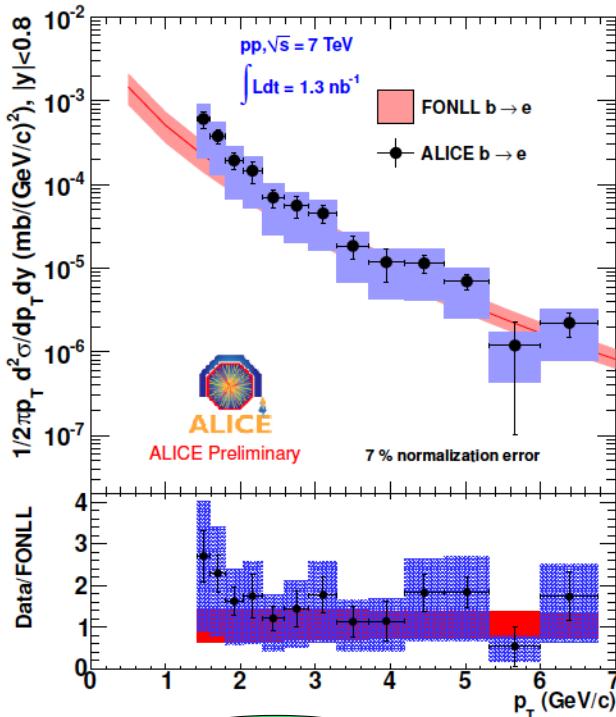
Beauty measurements with electrons

ALICE

Beauty separation based on an impact parameter cut

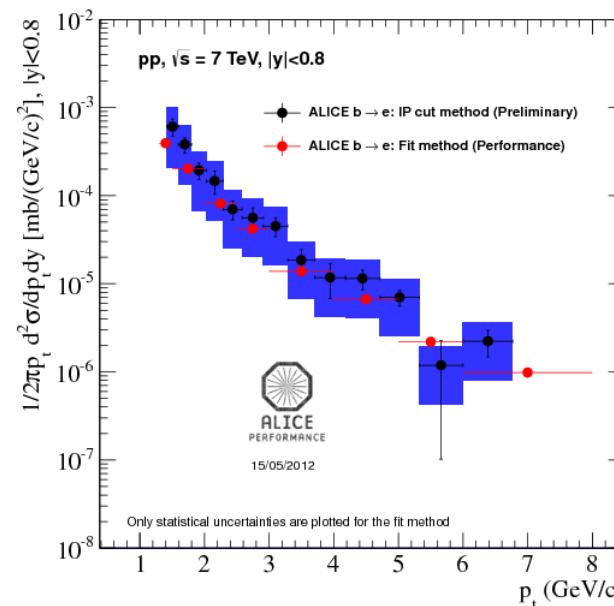
pp at
 $\sqrt{s} = 7 \text{ TeV}$

$\text{CT } (b) \approx 500 \mu\text{m}$



TALK (IVA)
M. Kweon

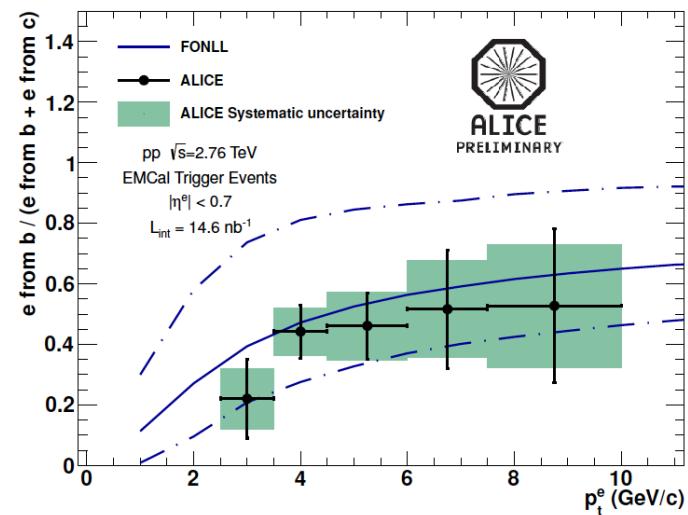
New method with IP template fits



POSTER
M. Heide

Electron-hadron correlations

(pp at $\sqrt{s} = 2.76 \text{ TeV}$)
→ relative beauty contribution
to the HF electron yield

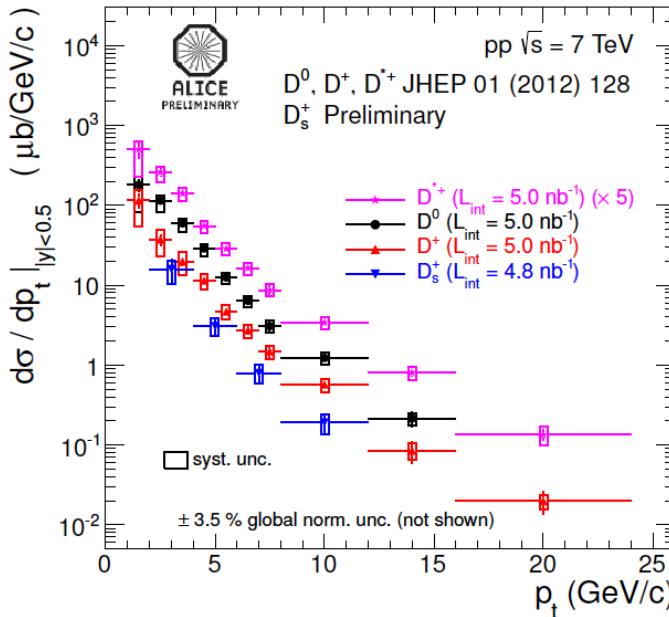


POSTER
D. Thomas

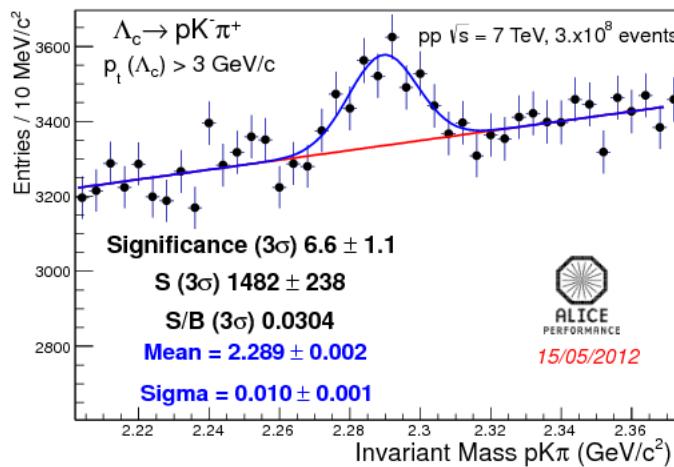


More charmed hadrons

- $D_s \rightarrow K\pi\pi$
production cross section
- $\Lambda_c \rightarrow pK\pi, pK_s$
signals



POSTER
G.M. Innocenti



POSTER
P. Pagano

PbPb: highlights

- Nuclear modification factor:

$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{\text{coll}}} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}$$

- Single muons at forward rapidity
- D mesons at mid rapidity
- Elliptic flow of D mesons

PbPb data samples:
 $\sqrt{s_{NN}} = 2.76 \text{ TeV} - 2010 \& 2011$
**Minimum bias + (centrality,
 EMCal and muon triggers)**

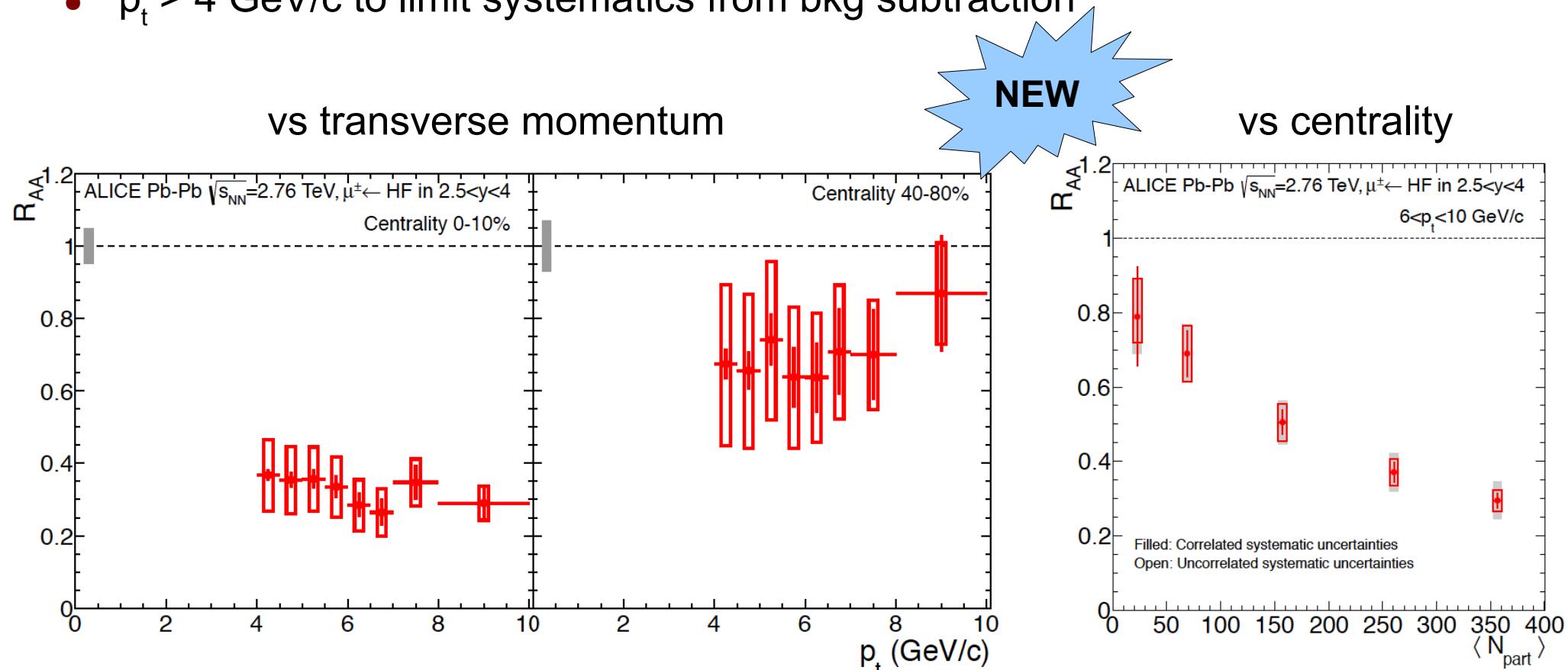
Single muon R_{AA} : $2.5 < y < 4$

TALK (IIIA)
D. Stocco



ALICE

- Subtraction of muons from light hadron decays, based on π and K measurements at mid rapidity
- $p_t > 4$ GeV/c to limit systematics from bkg subtraction



arXiv:1205.6443

Strong suppression in central collisions
No significant p_t dependence

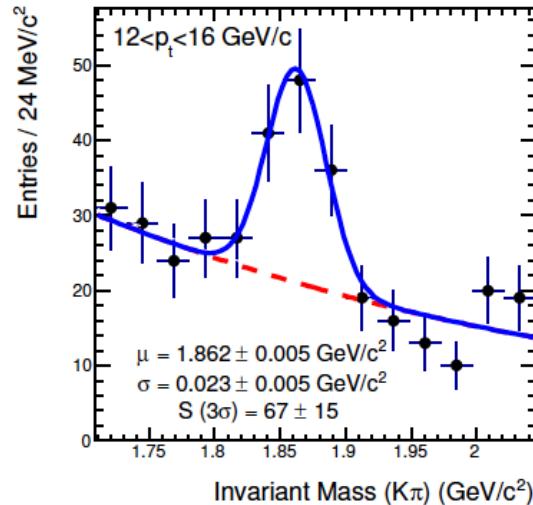
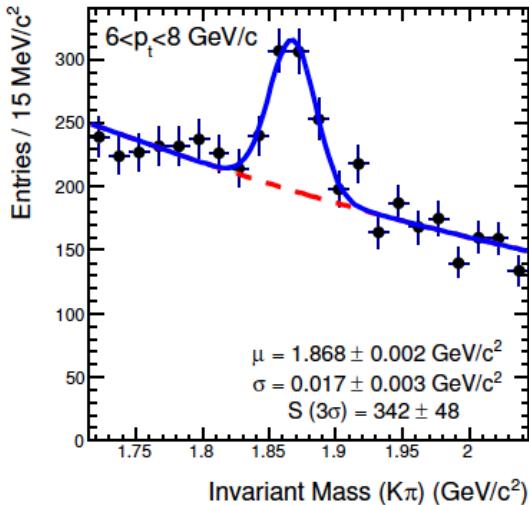
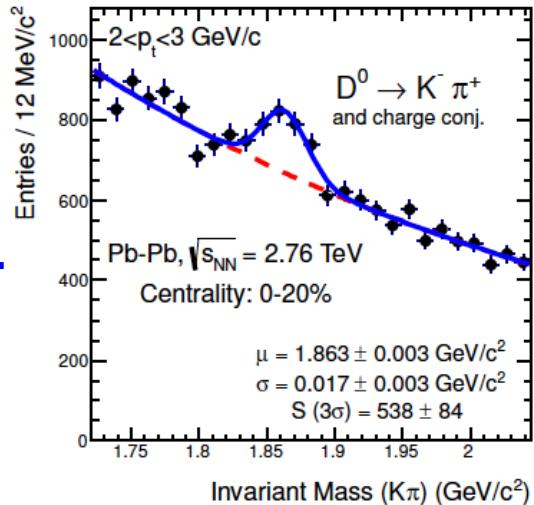
D mesons in PbPb

TALK (IIA)
Z. Conesa d.V.

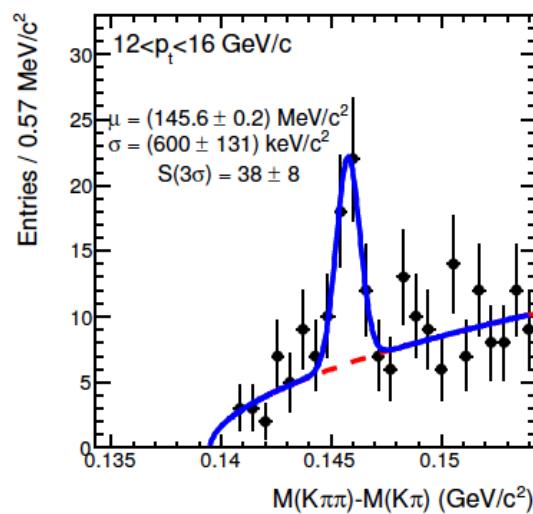
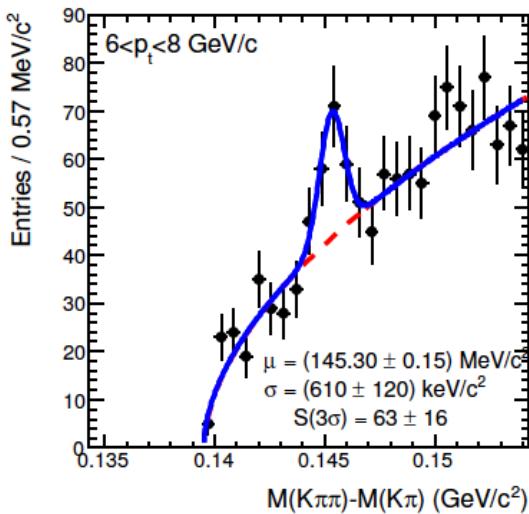
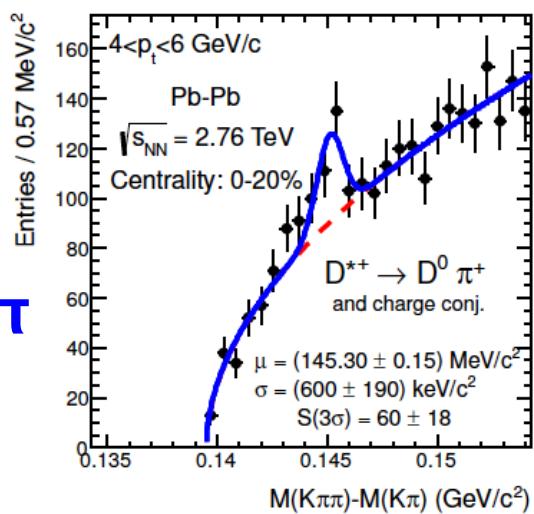


ALICE

$D^0 \rightarrow K\pi$



$D^* \rightarrow D^0\pi$



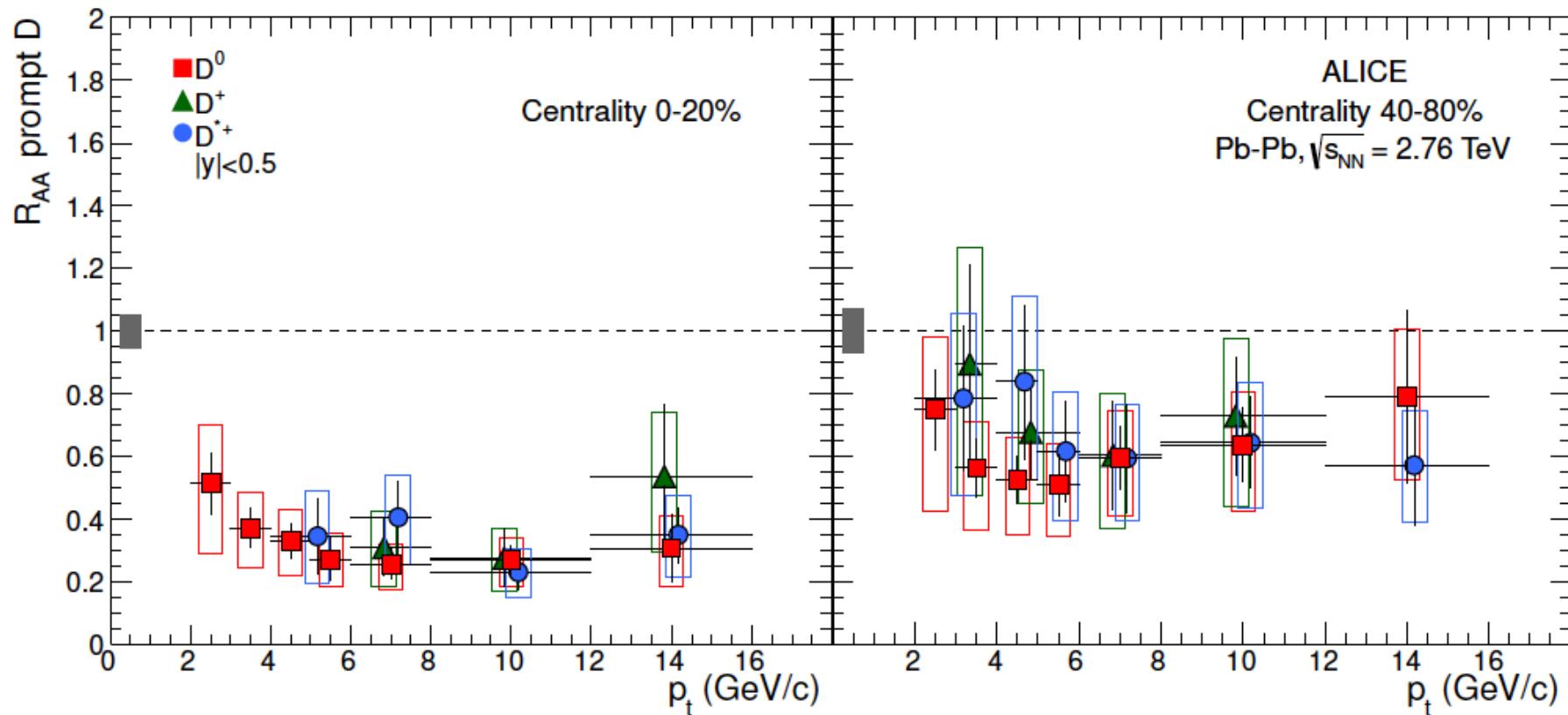
Also $D^+ \rightarrow K\pi\pi\pi$

D meson R_{AA} : $|y|<0.5$

TALK (IIA)
Z. Conesa d.V.



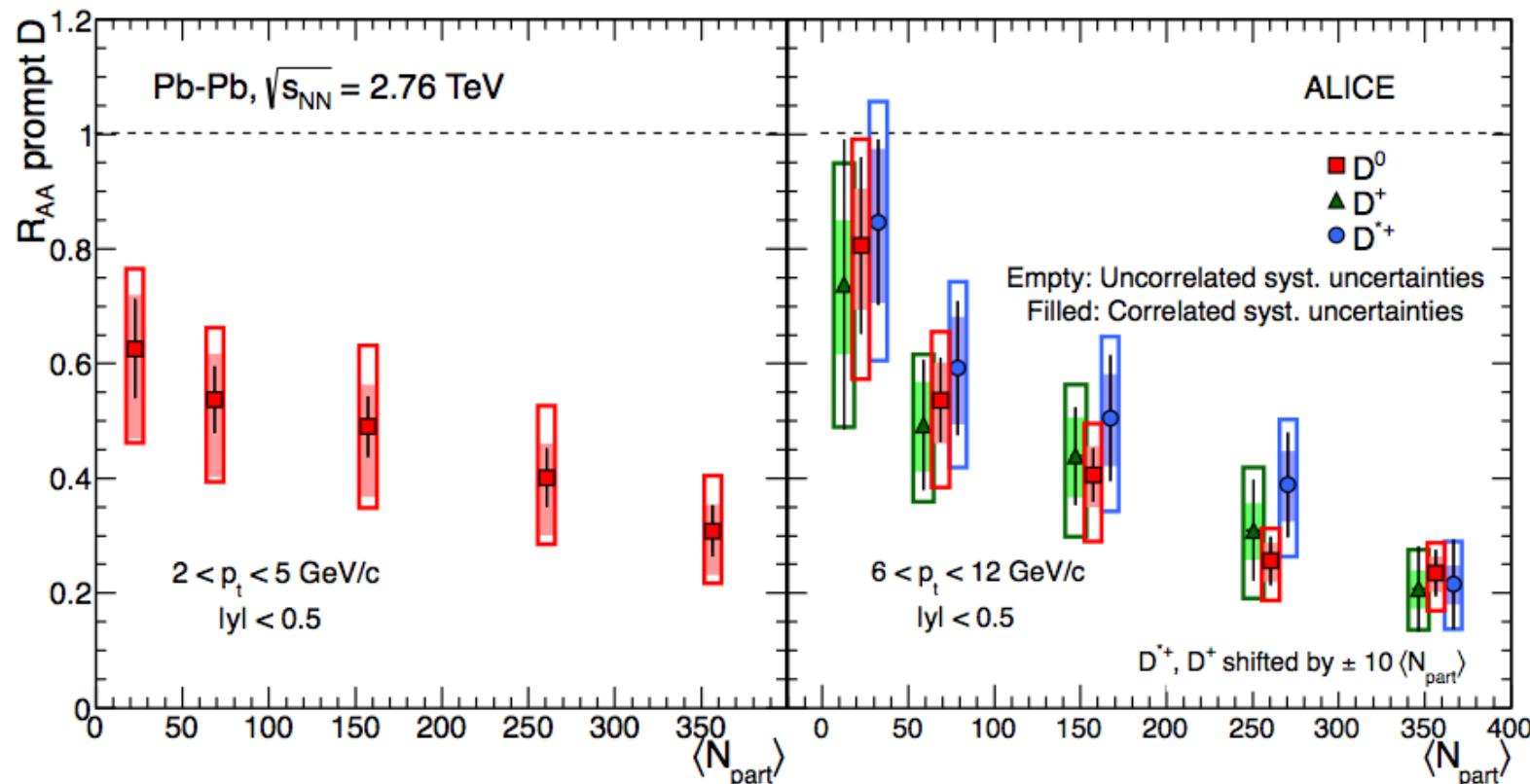
NEW



- D^0, D^+, D^* compatible
- Strong suppression in central collisions

arXiv:1203.2160

Centrality dependence



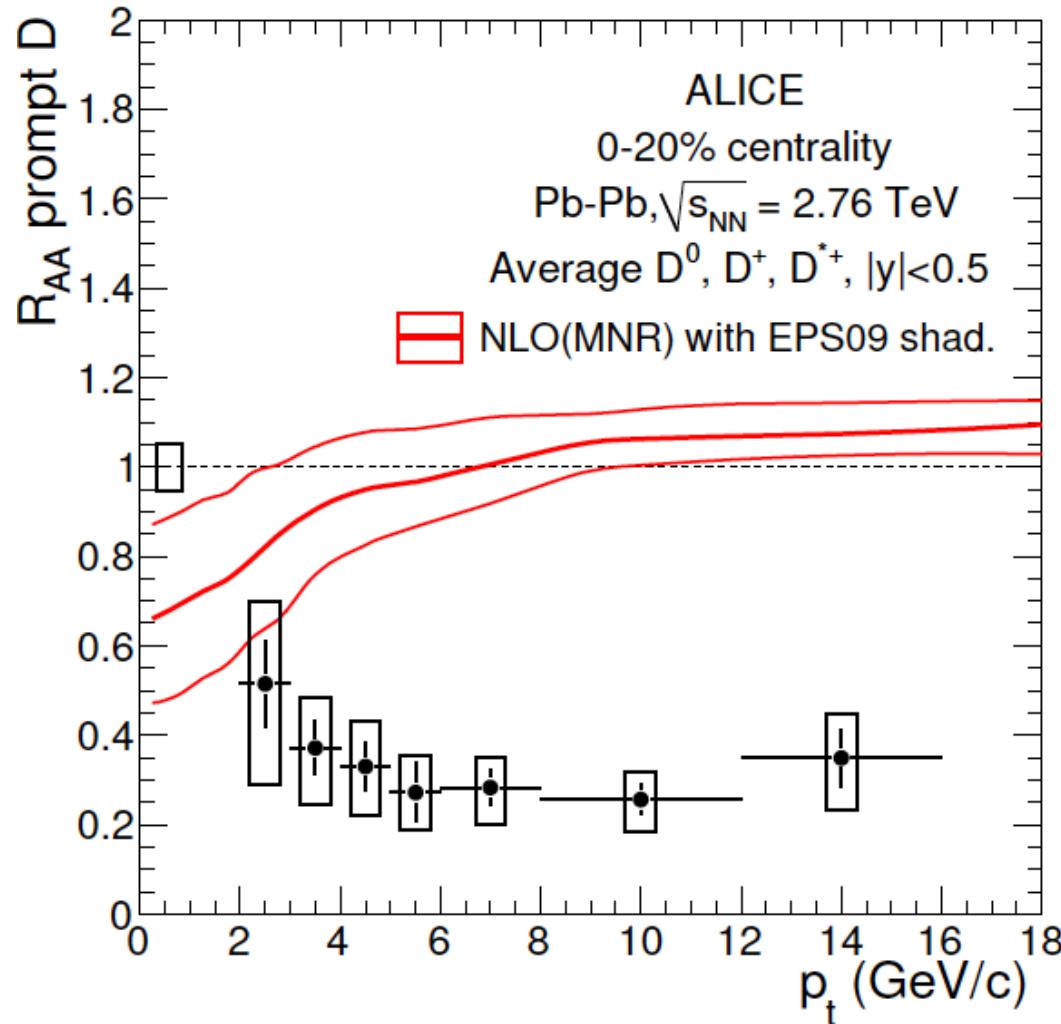
$2 < p_t < 5$ GeV/c

$6 < p_t < 12$ GeV/c

Nuclear shadowing



NEW



arXiv:1203.2160

Current estimates of the nuclear shadowing effects on R_{AA} at $p_t > 6 \text{ GeV}/c$ is limited to $\pm 15\%$

**Importance of the p-Pb run in 2012!
Crucial to verify current expectations!**

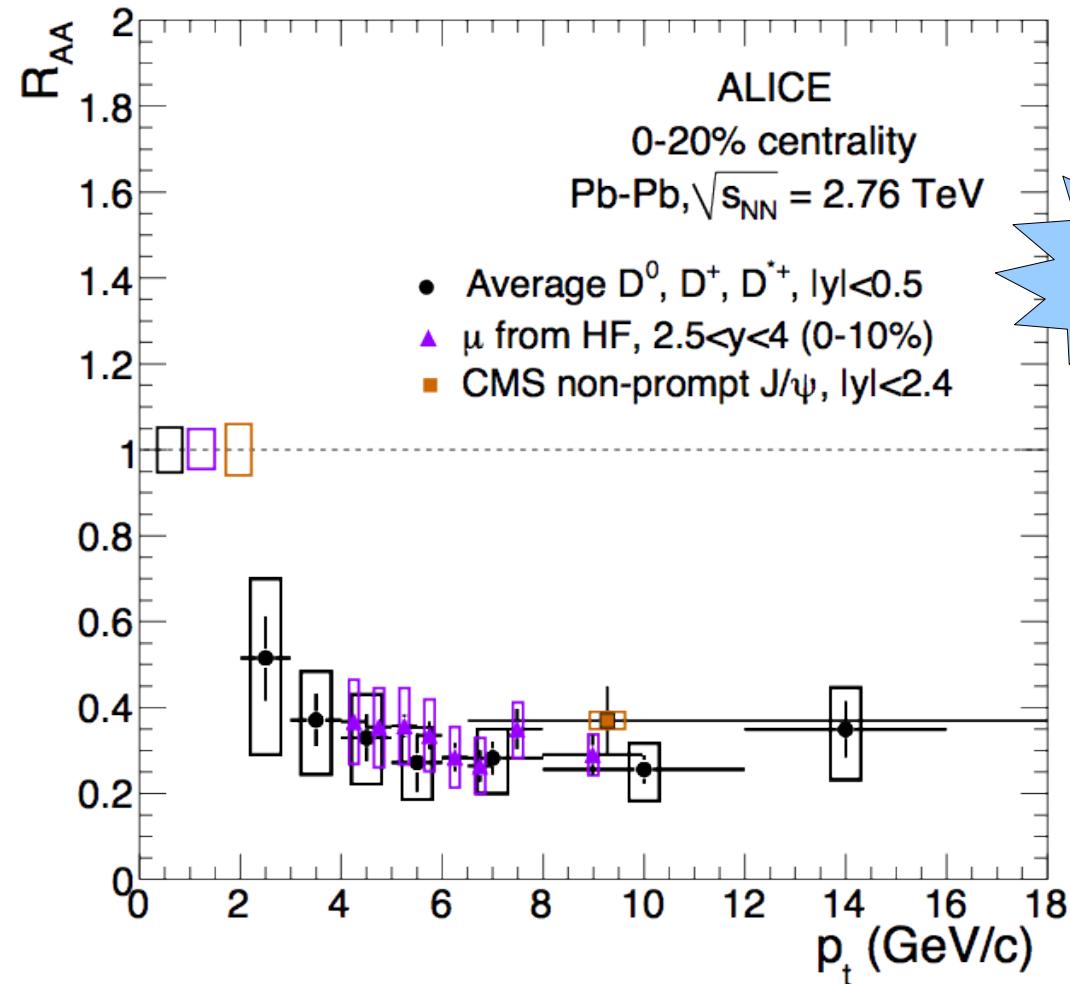
NLO: Nucl Phys B373 (1992) 295
EPS09: JHEP 0904 (2009) 065

R_{AA} compilation: charm and beauty



ALICE

- $H_{c,b} \rightarrow \text{muons}$
- D mesons (charm)
- $B \rightarrow J/\psi$ (beauty) CMS
arXiv:1201.5069



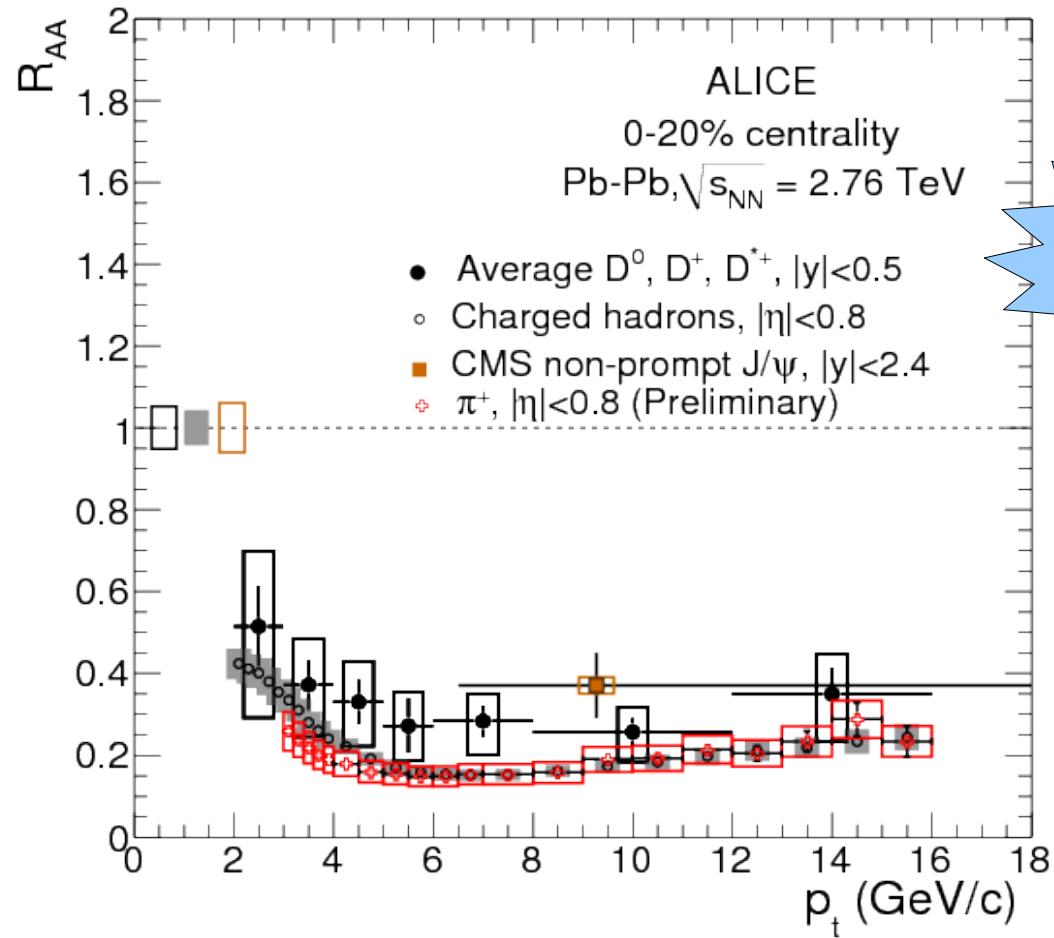
- Charm and beauty: no evidence of mass effects yet (dead cone,)

R_{AA} compilation: and light mesons



ALICE

- Charged hadrons
- Identified pions
- D mesons (charm)
- $B \rightarrow J/\psi$ (beauty) CMS
arXiv:1201.5069

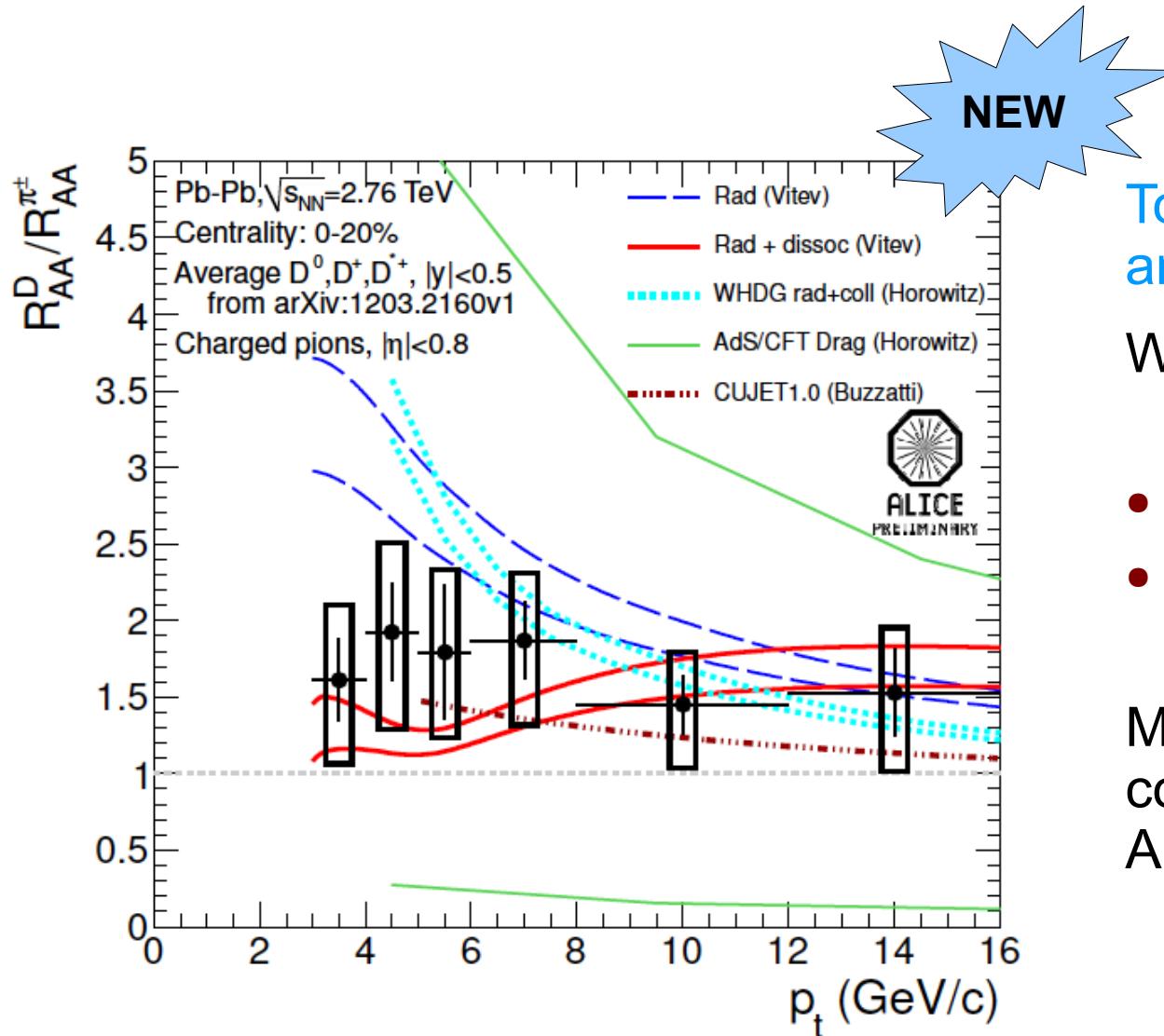


- Charm and beauty: no evidence of mass effects yet (dead cone,)
- Pions, charm and beauty R_{AA} : similar. Hint of a hierarchy? → Look !

R_{AA} ratio and models



ALICE



To compare charm mesons
and pions \rightarrow ratio of R_{AA} 's

With the current uncertainties:

- Hint of $R > 1$
- Color charge effect?

Measurements are not yet
conclusive \rightarrow in reach for
ALICE ! More precision !

Elliptic flow of D mesons

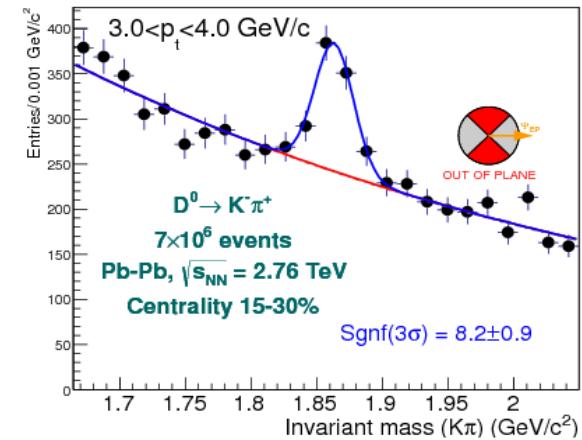
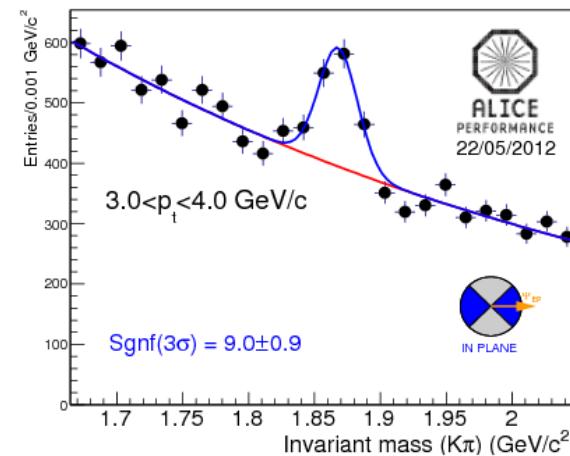
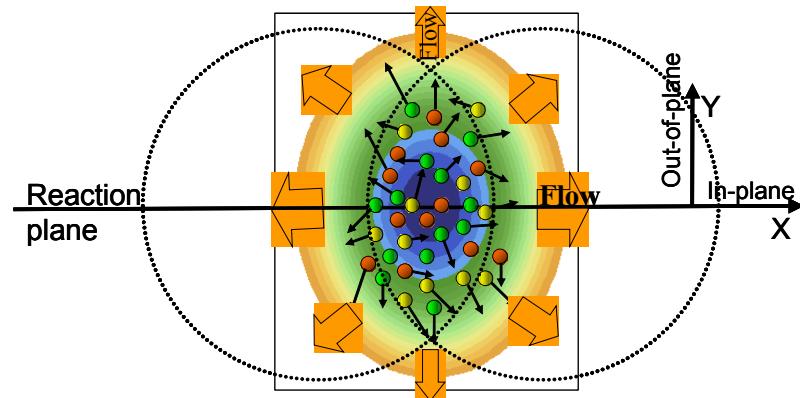


TALK (IIA)
G. Ortona

POSTER
D. Caffarri

- Invariant mass analysis (D^0 , D^+)
- Two centrality classes considered: 30-50% and 15-30% (2011 data, 9.5 and 7.1×10^6 ev. respec.)
- Event plane determined with TPC tracks ($\eta > 0$)
- Signal extraction in plane and out of plane
- Correction for B feed-down (FONLL)

$$v_2 = \frac{\pi}{4} \frac{N_{\text{IN}} - N_{\text{OUT}}}{N_{\text{IN}} + N_{\text{OUT}}}$$

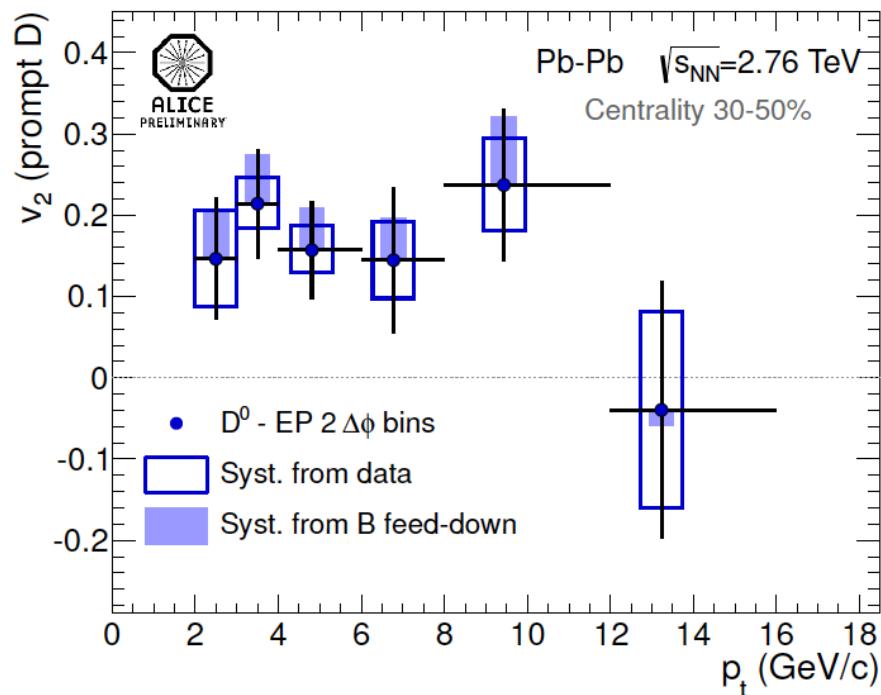


Elliptic flow of D: results

NEW



- $D^0 v_2$ in 30-50% centrality
(confirmed by Q-cumulants and scalar product methods)



- Indication for non zero D meson v_2 (3σ in $2 < p_t < 6$ GeV/c)

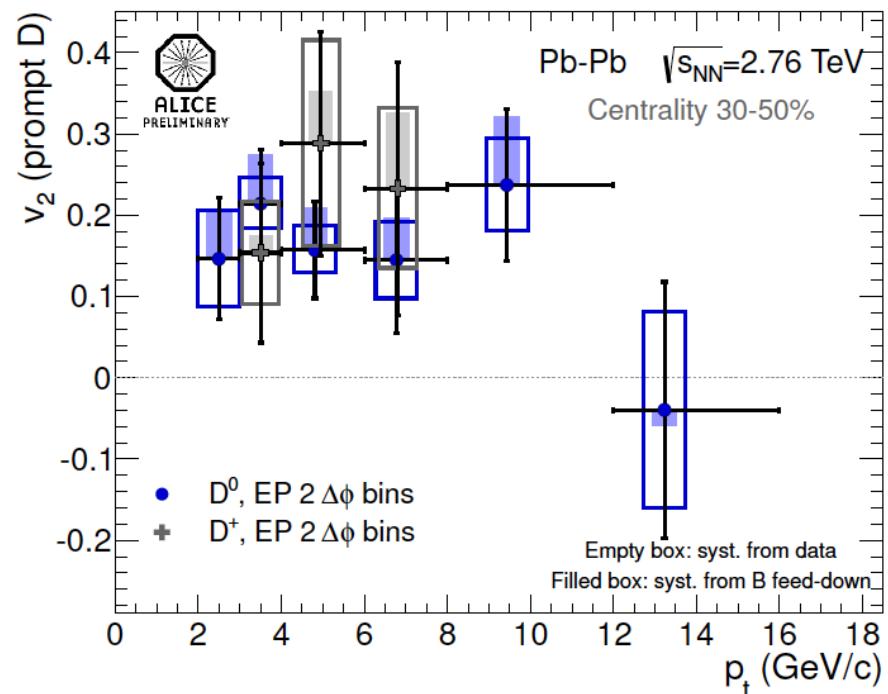
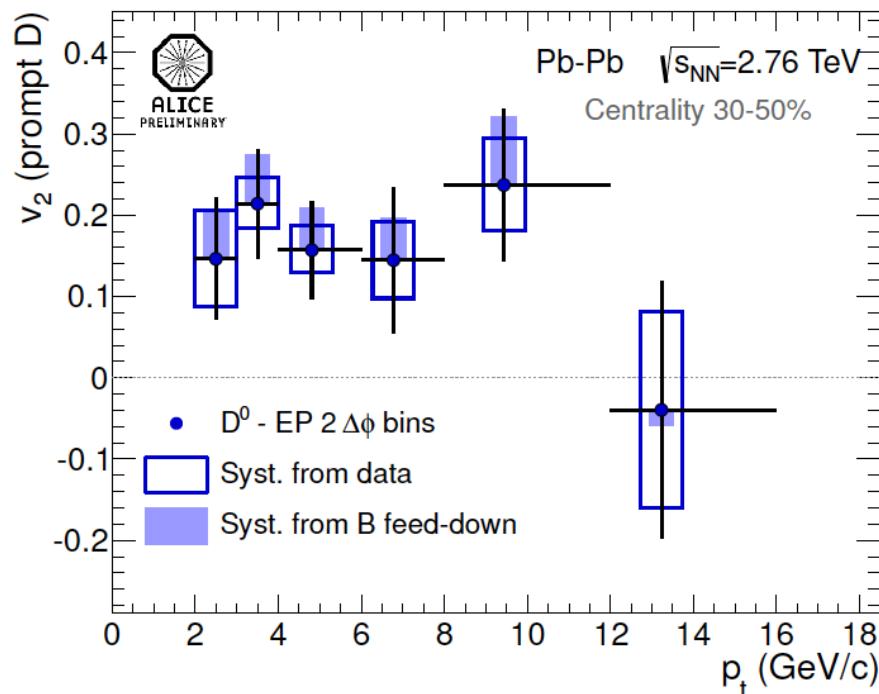
Elliptic flow of D: results

NEW



ALICE

- $D^0 v_2$ in 30-50% centrality
- $D^+ v_2$ in 30-50% centrality
Comparable within uncertainties



- Indication for non zero D meson v_2 (3σ in $2 < p_t < 6$ GeV/c)

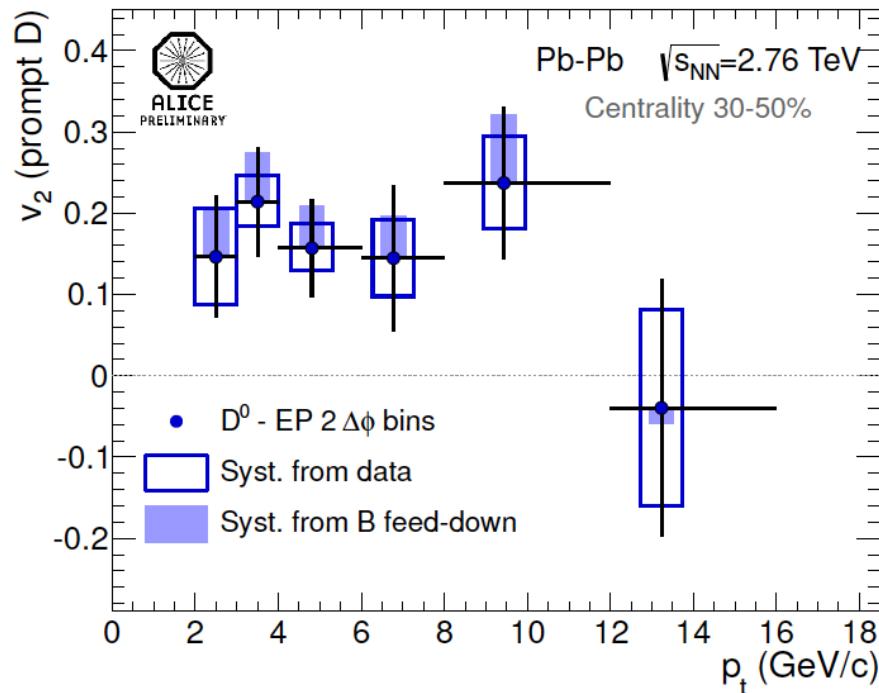
Elliptic flow of D: results

NEW

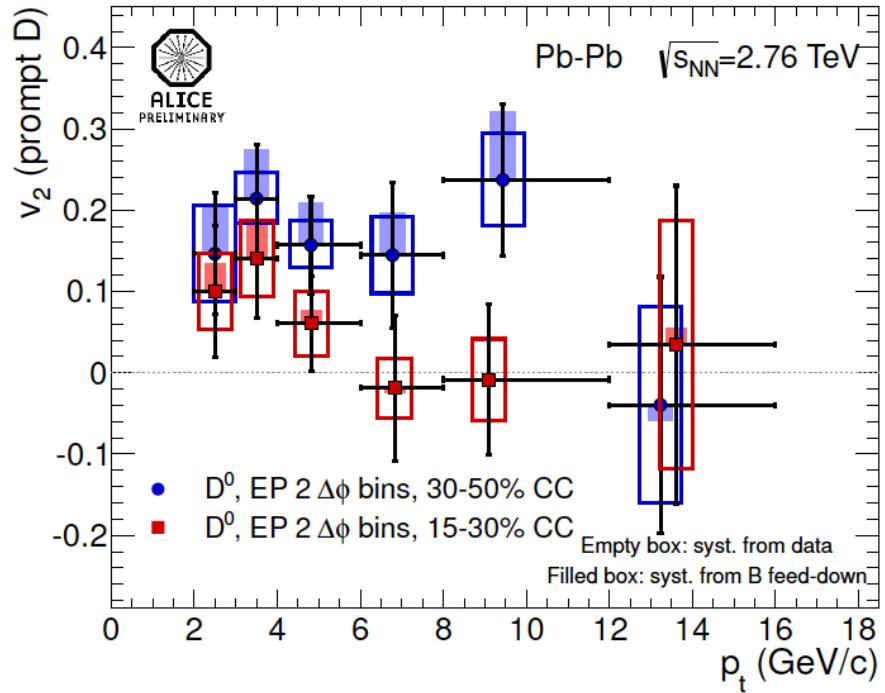


ALICE

- $D^0 v_2$ in 30-50% centrality



- $D^0 v_2$ in 15-30% centrality



- Indication for non zero D meson v_2 (3σ in $2 < p_t < 6$ GeV/c)
- Hint of centrality dependence: $D^0 v_2$ flow larger in less central collisions

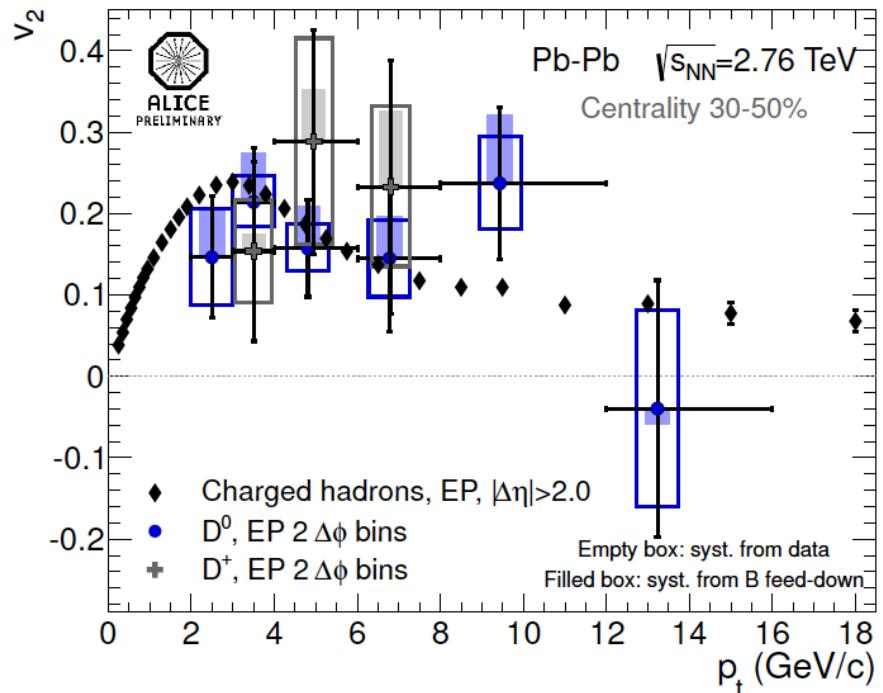
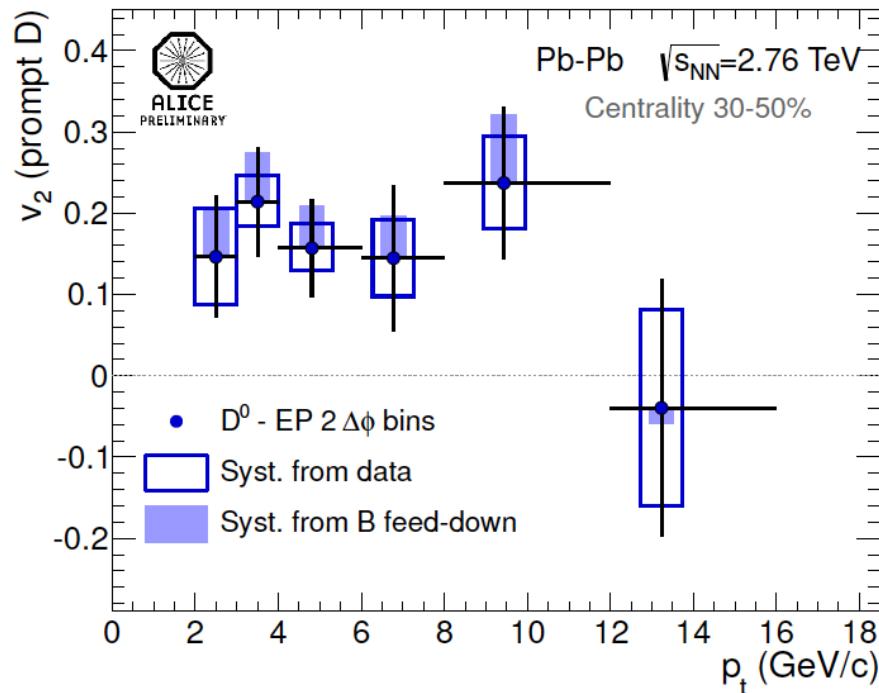
Elliptic flow of D: results

NEW



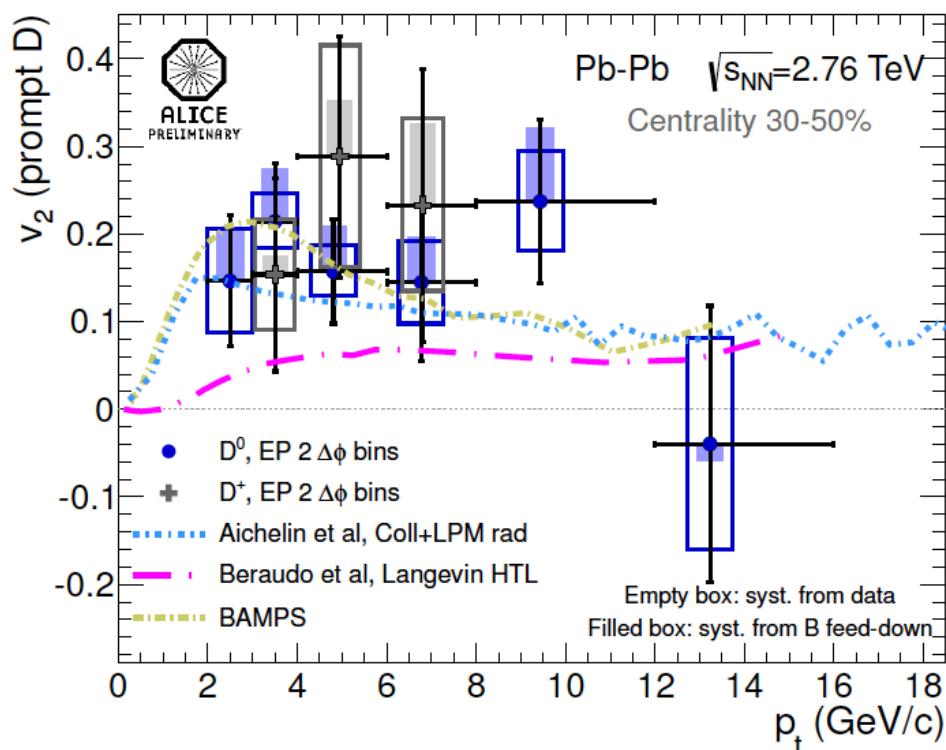
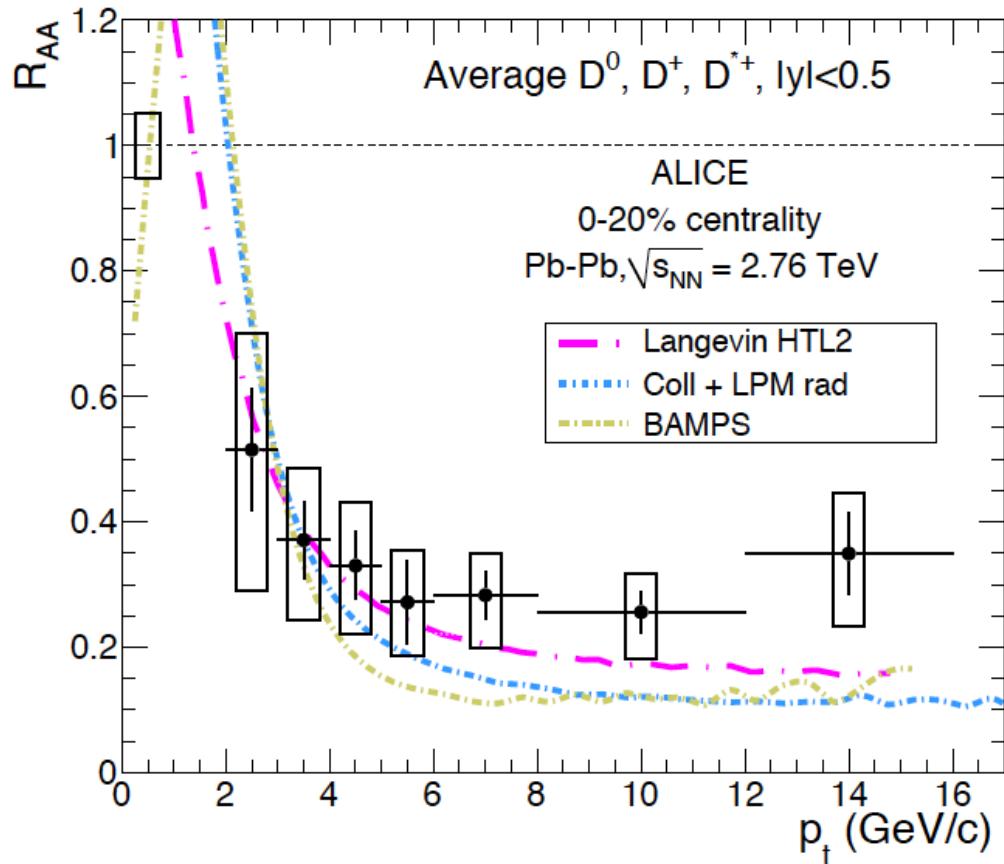
ALICE

- $D^0 v_2$ in 30-50% centrality
- D meson compared to charged hadrons



- Indication for non zero D meson v_2 (3σ in $2 < p_t < 6$ GeV/c>)
- Hint of centrality dependence: $D^0 v_2$ flow larger in less central collisions
- Comparable with charged hadrons elliptic flow

ALICE results and models

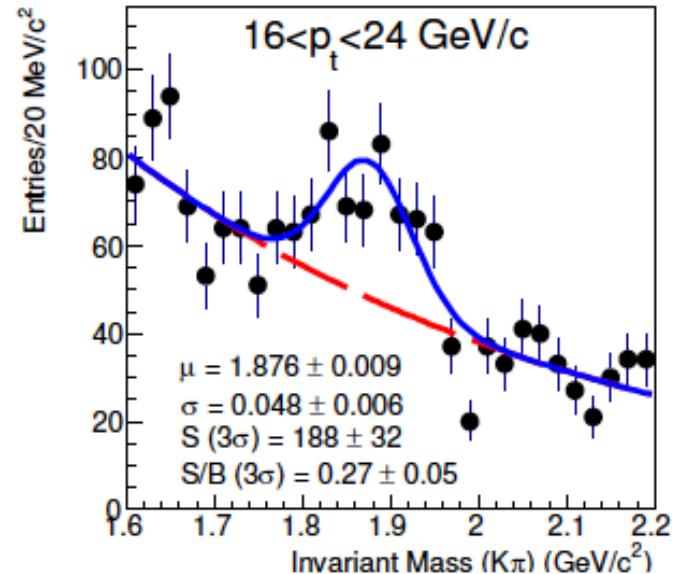
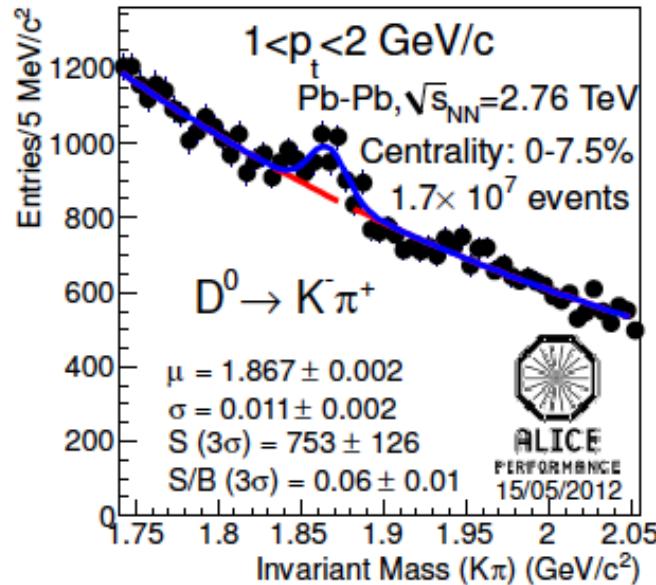


**Challenge for the models:
describe both R_{AA} and v_2**

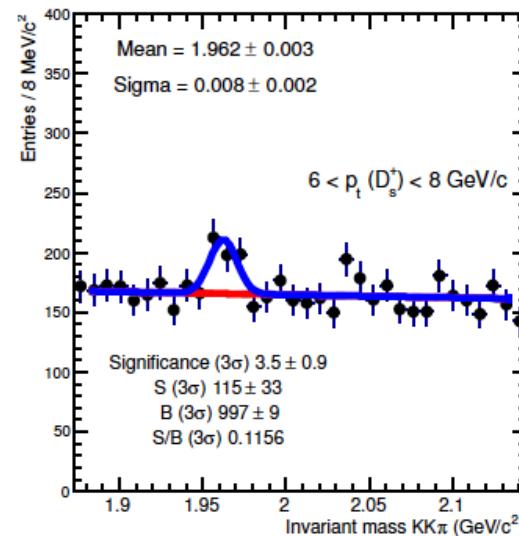
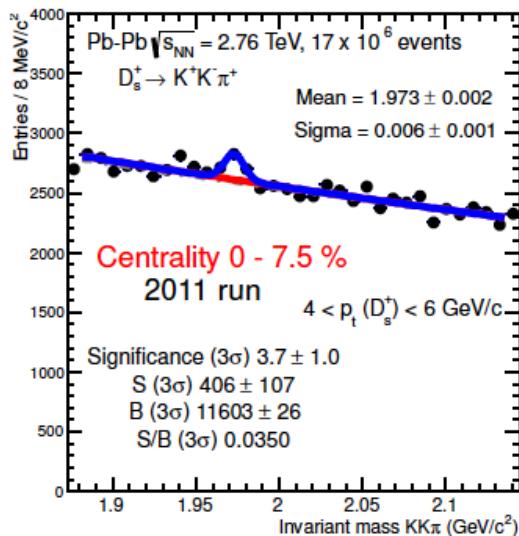


Coming up

$D^0 \rightarrow K\pi$
Extension of
the p_t range



$D_s \rightarrow K\pi\pi$
in Pb-Pb



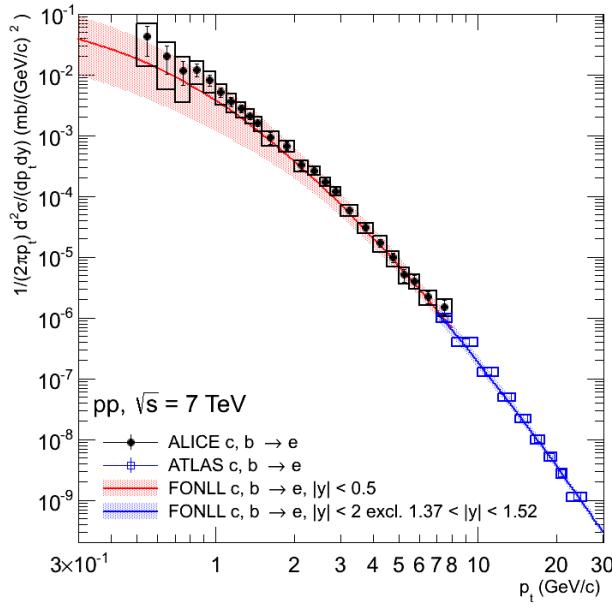
POSTER
G.M. Innocenti

Summary

Rich collection of heavy flavour results from ALICE
 New measurements, with improved precision:

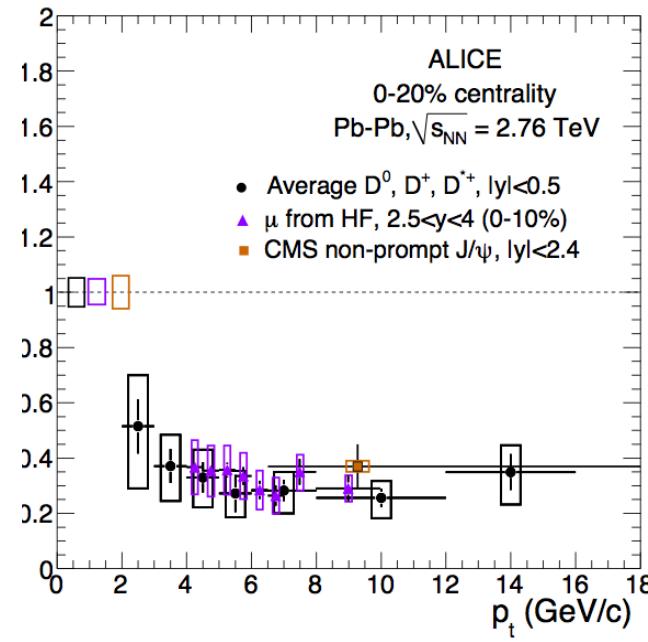
pp: $H_{c,b} \rightarrow e + X$

Important low p_t reach,
 precision measurements



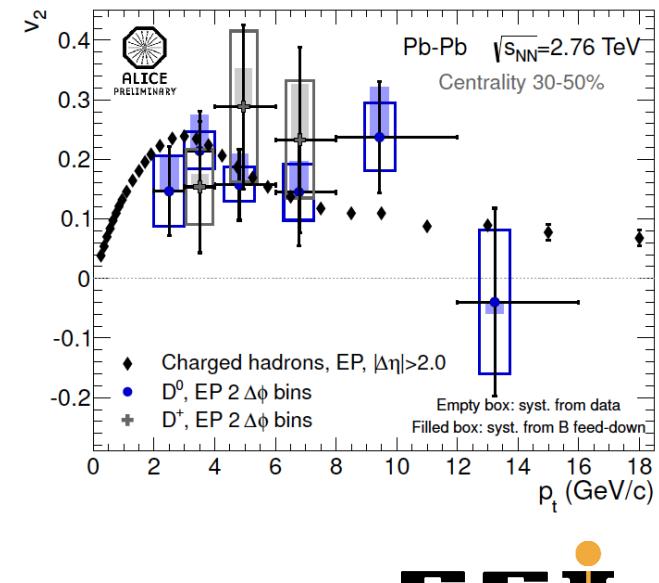
PbPb: R_{AA}

No evidence for mass effects
 yet, hint of color charge effects?



PbPb: v_2

Indication for non zero
 D meson elliptic flow

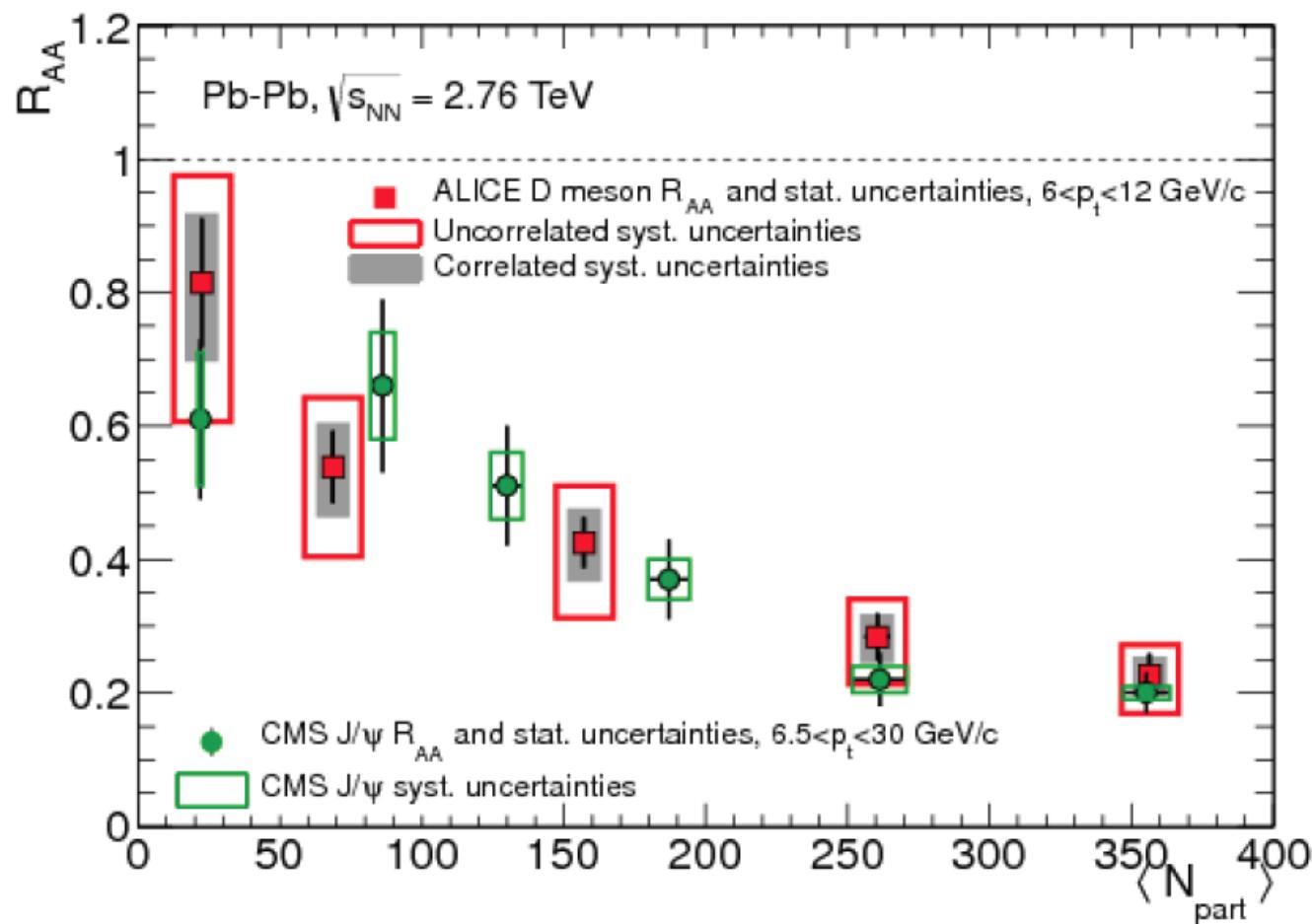




ALICE

Something interesting

- ALICE D mesons: $|y| < 0.5$, $6 < p_t < 12 \text{ GeV}/c$
- CMS J/ ψ : $|y| < 2.4$, $6.5 < p_t < 30 \text{ GeV}/c$



ALICE HF contributions to HP2012

- Parallel talks
 - Z. C. d. Valle, “D mesons suppression in Pb--Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured by ALICE” (IIA)
 - G. Ortona, “Open-charm meson elliptic flow measurement in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the LHC with ALICE” (IIA)
 - D. Stocco, “Measurement of heavy-flavour decay muon production at forward rapidity in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE experiment” (IIIA)
 - C. Geuna, “Open Heavy-Flavour and J/ ψ production in proton-proton collisions measured with the ALICE experiment at LHC” (IIIA)
 - M. Kweon, “Measurement of the nuclear modification factor of electrons from heavy-flavour decays in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with ALICE” (IVA)

ALICE HF contributions to HP2012

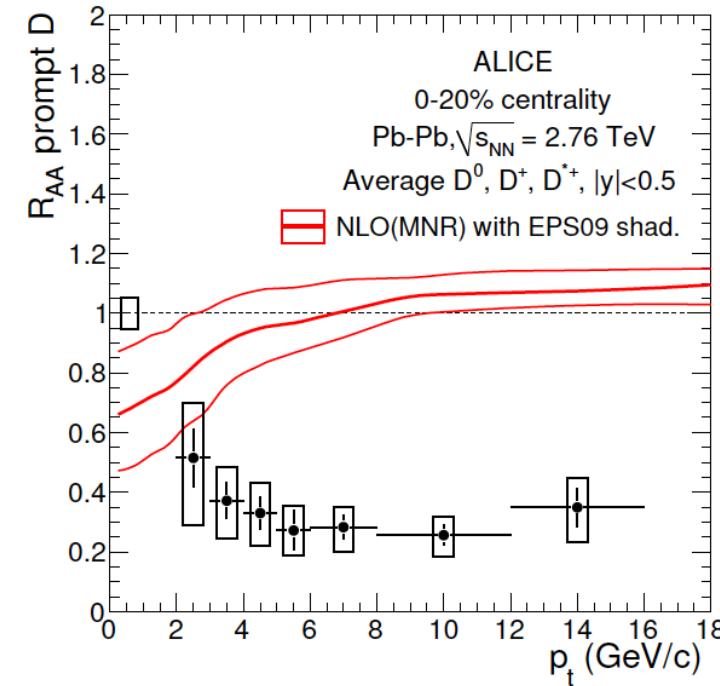
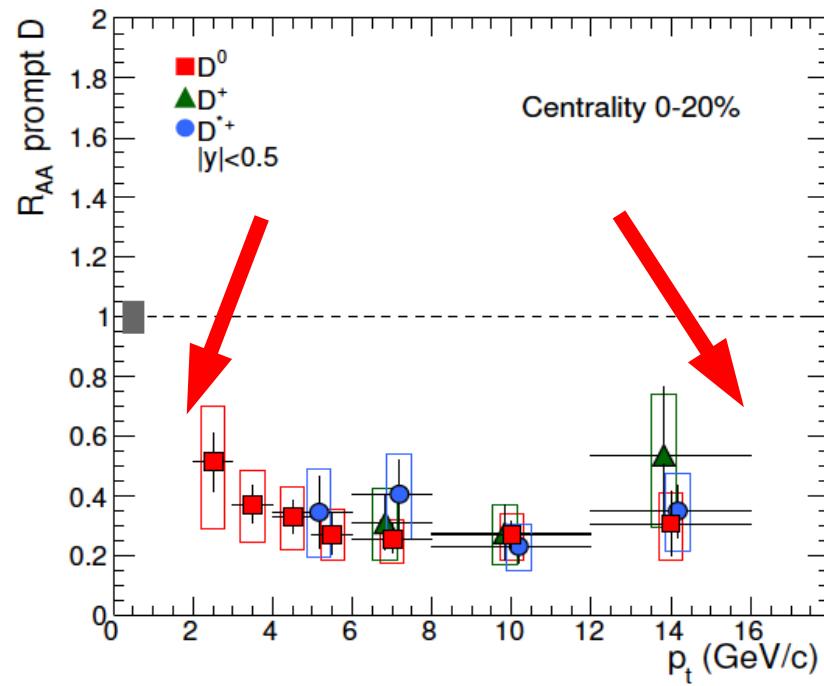
- Posters

- M. Heide, “Measurement of B meson production in pp collisions at $\sqrt{s} = 7$ TeV via displaced electrons in ALICE”
- M. Völkl, “Study of the nuclear modification factor of electrons from B meson decays at mid-rapidity in Pb-Pb collisions at $\sqrt{s}_{NN} = 2.76$ TeV with ALICE”
- P. Pagano, “Reconstruction of the charmed baryon Λ_c in pp collisions at $\sqrt{s} = 7$ TeV with ALICE”
- D. Thomas, “Azimuthal angular correlations between heavy flavor decay electrons and charged hadrons in pp collisions at 2.76 TeV in ALICE”
- S. Bjelogrlic, “Azimuthal angular correlations between D^* mesons and charged hadrons (kaons) in 7 TeV proton-proton collisions in ALICE”
- D. Caffarri, “Measurement of charm suppression and charm flow in Pb-Pb collisions at $\sqrt{s}_{NN} = 2.76$ TeV via $D^0 \rightarrow K\pi$ reconstruction in ALICE”
- G.M. Innocenti, “ D_s production in pp collisions at $\sqrt{s} = 7$ TeV and prospects for the Pb-Pb analysis with the ALICE detector”

SPARES

Outlook

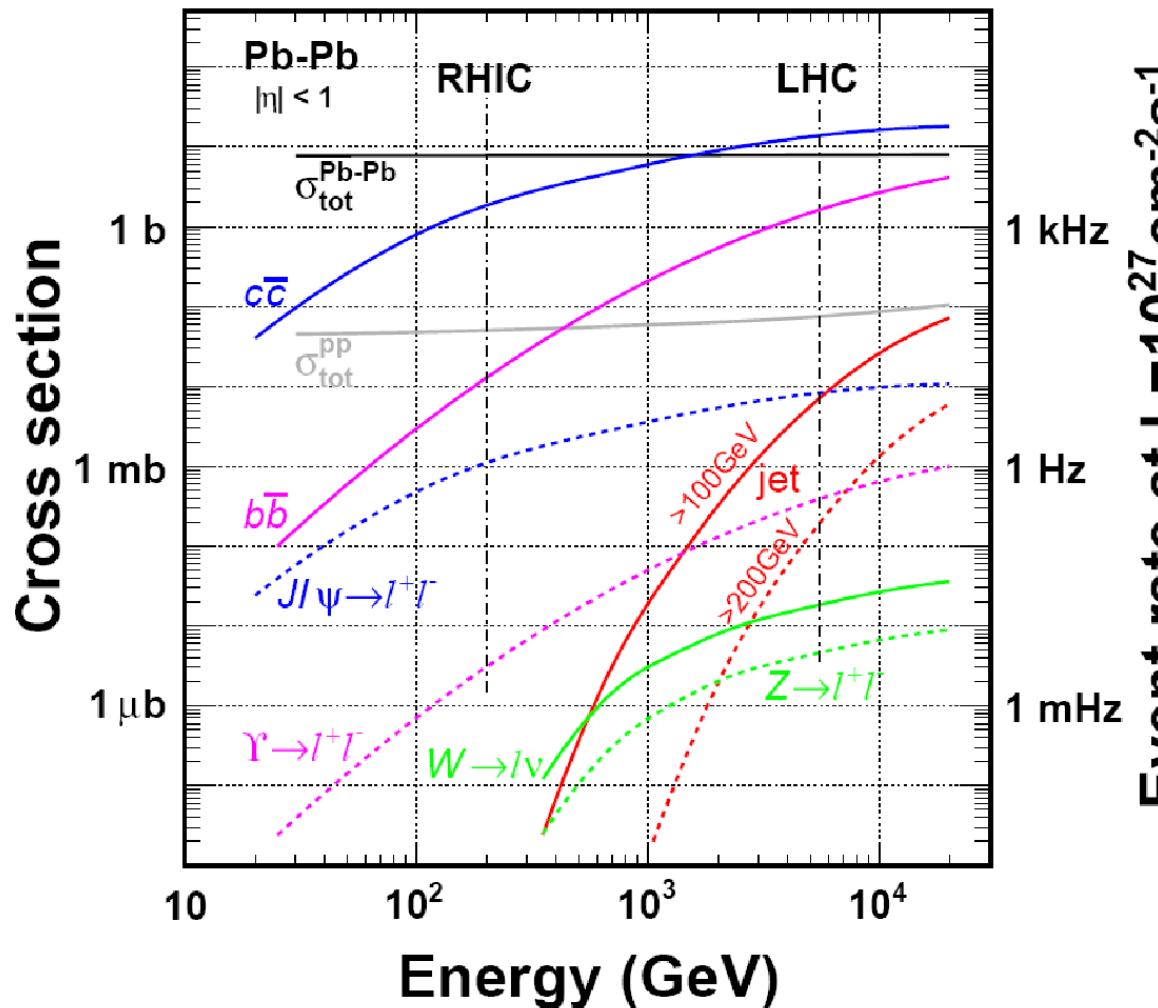
- Further improve precision and extend p_t range
- Separation of **beauty**
- More about D_s and Λ_c
- More on **elliptic flow**, also with electrons and muons
- p-Pb run in 2012, to investigate cold nuclear matter effects





HF large production cross sections - 1

Expected: *reference?*



In 1 Pb-Pb collision
at $\sqrt{s}_{\text{NN}} = 2.76 \text{ TeV}:$
 $\approx 56\text{-}60 \text{ } c\bar{c}$
 $\approx 2 \text{ } b\bar{b}$

(MNR, shadowing: EKS98,
EPS08. Factor 2 uncertainty)

references?

HF pair production rates

➤ ~ factor 2 uncertainty from NLO and shadowing (Pb-Pb)

system :	Pb-Pb (0-5%)	Pb-Pb (0-5%)	pp	pp
$\sqrt{s_{NN}}$:	5.5 TeV	2.76 TeV	14 TeV	7 TeV
$\sigma_{NN}^{Q\bar{Q}} [\text{mb}]$	3.4 / 0.14	2.1 / 0.075	11.2 / 0.5	6.9 / 0.23
$N_{tot}^{Q\bar{Q}}$	90 / 3.7	56 / 2	0.16 / 0.007	0.10 / 0.003
$C_{shadowing}^{EKS98/EPS08}$	0.58 / 0.77	0.60 / 0.85	--	--

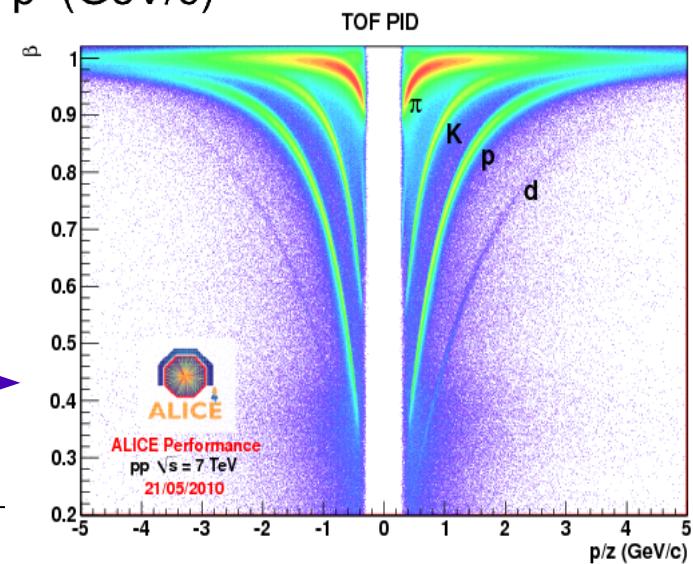
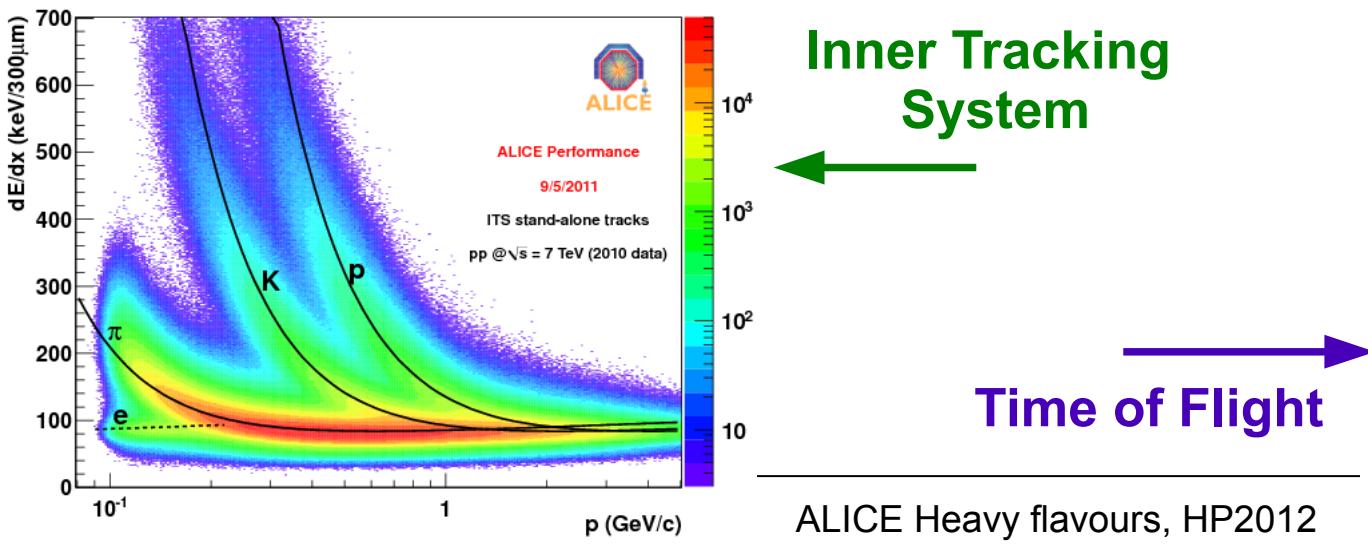
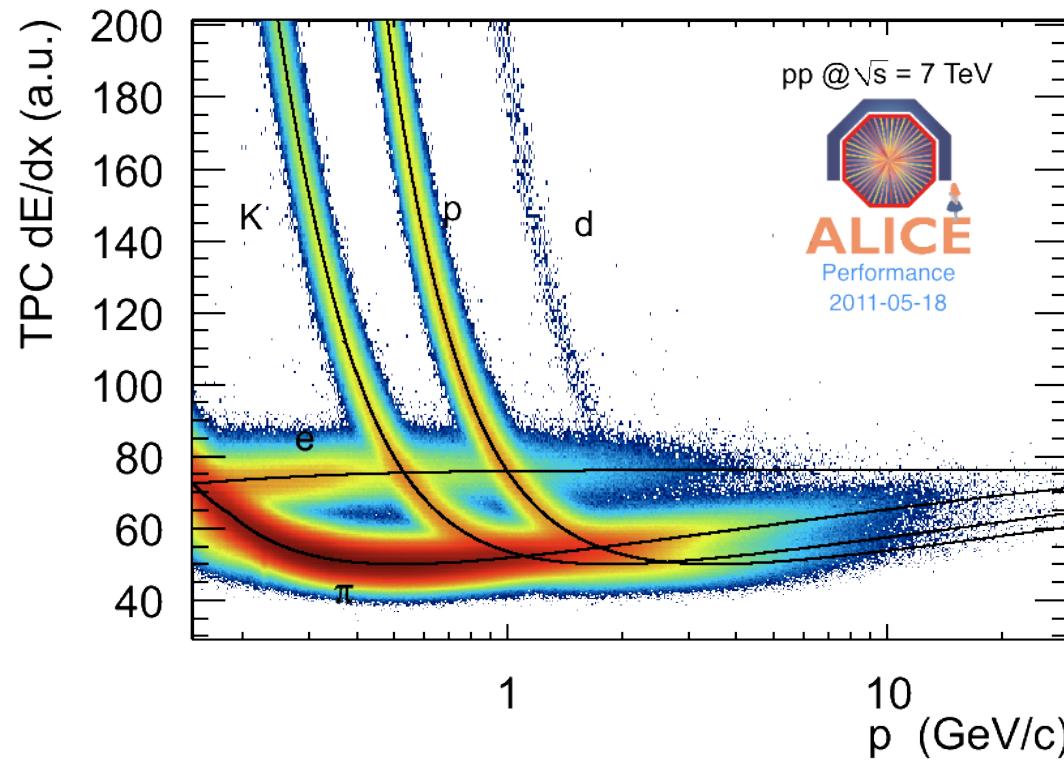
MNR code: Mangano, Nason, Ridolfi, NPB373 (1992) 295. EKS98, EPS08: Eskola et al., EPJC9 (1999) 61; JHEP07 (2008) 102



Mid rapidity: particle identification

ALICE

Time
Projection
Chamber



TALK (1B)
P. Christiansen

Charmed baryon: Λ_c

POSTER
P. Pagano



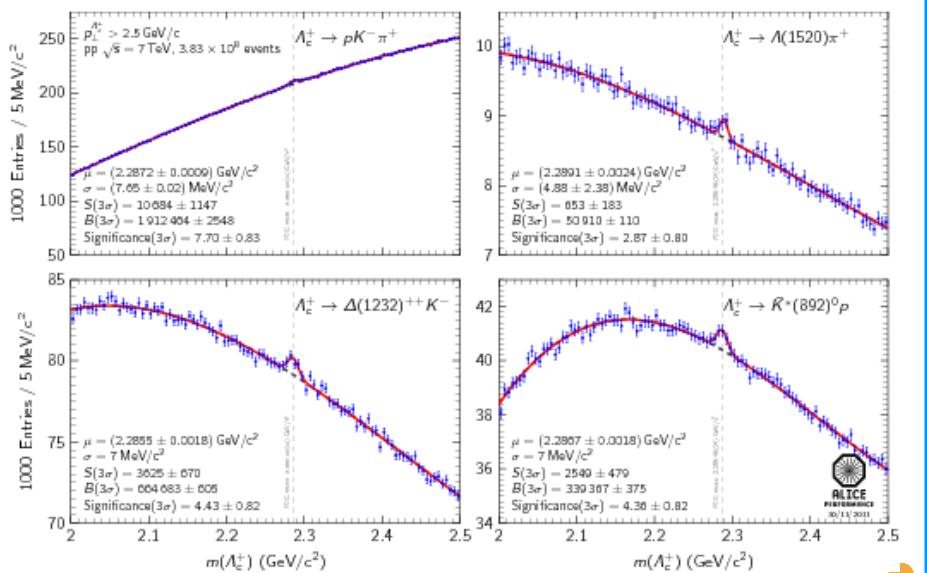
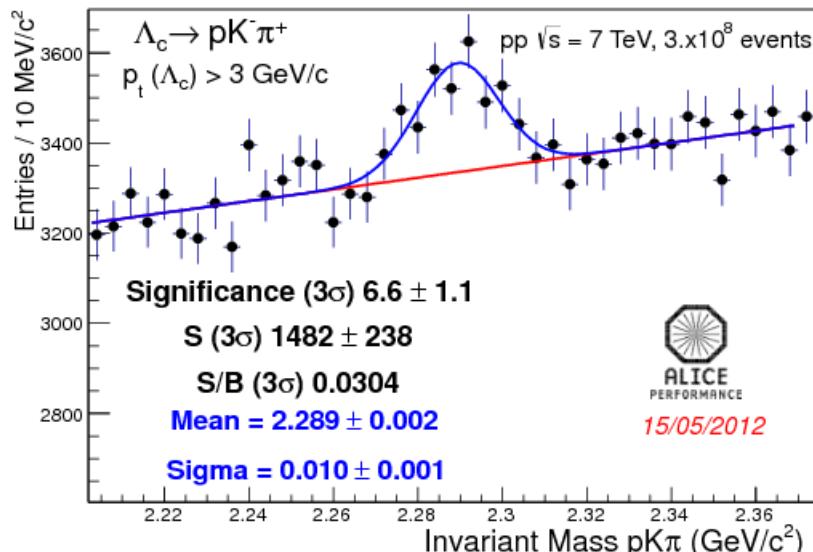
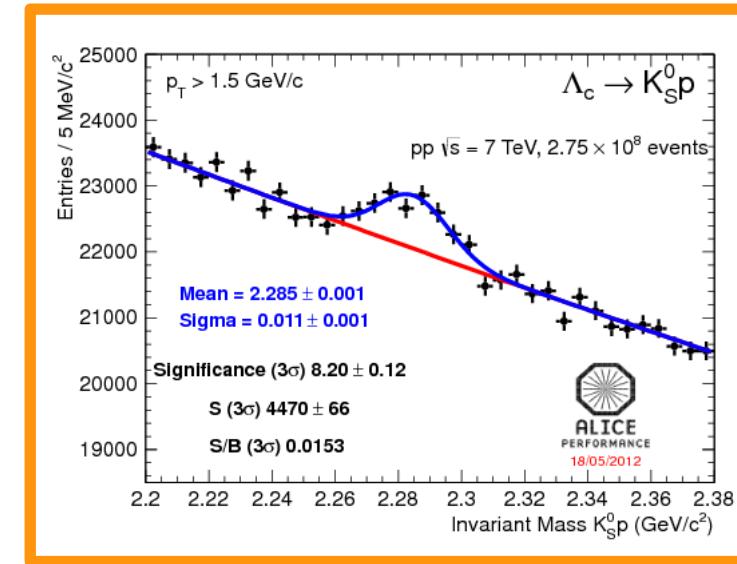
ALICE

- **Baryon / meson ratio in the charm sector**
- **Production cross section: new in pp and Pb-Pb**
- Vertexing ($c\tau = 60 \mu\text{m}!$) and particle identif.
- Several channels:

$\Lambda_c \rightarrow p K \pi$

with resonant decays

$\Lambda_c \rightarrow K^0_s p$

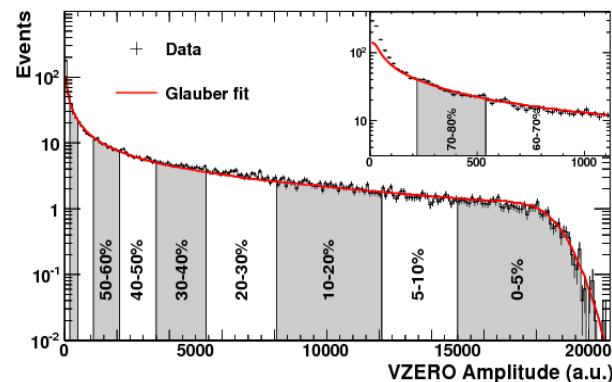


PbPb collisions

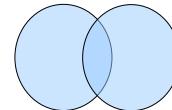
The nuclear modification factor

$$R_{AA} = \frac{\text{Yield in AA}}{\text{Yield in pp}} \cdot \frac{1}{N_{\text{coll}}} = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_t}{d\sigma_{pp}/dp_t}$$

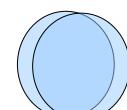
Collision centrality measured with VZERO scintillator hodoscope



peripheral



central



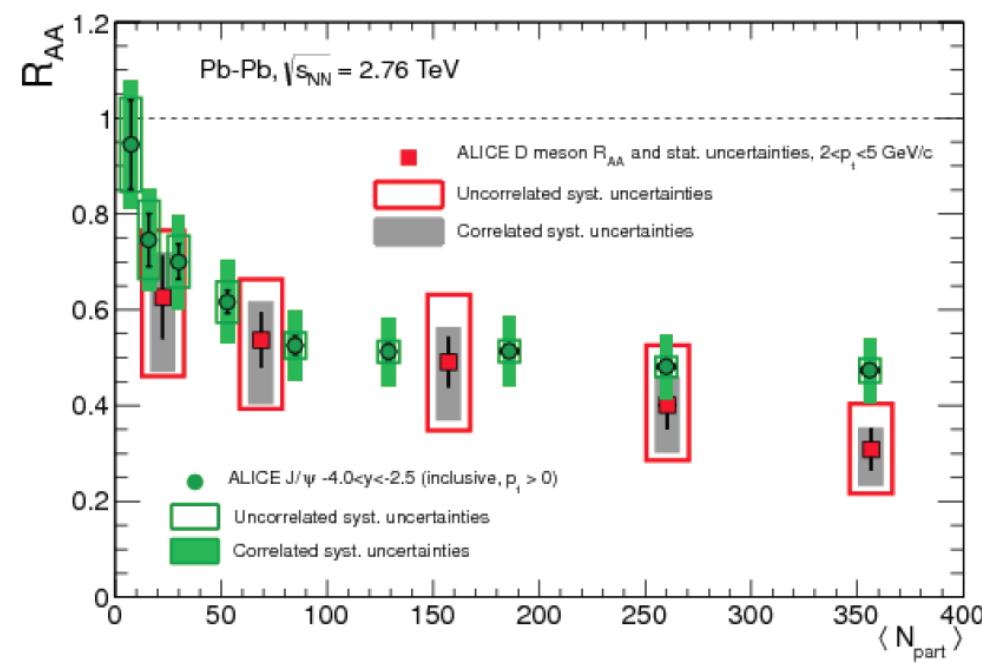
PRL 106, 032301 (2011)

**Centrality: percentile
of total hadronic
cross section**

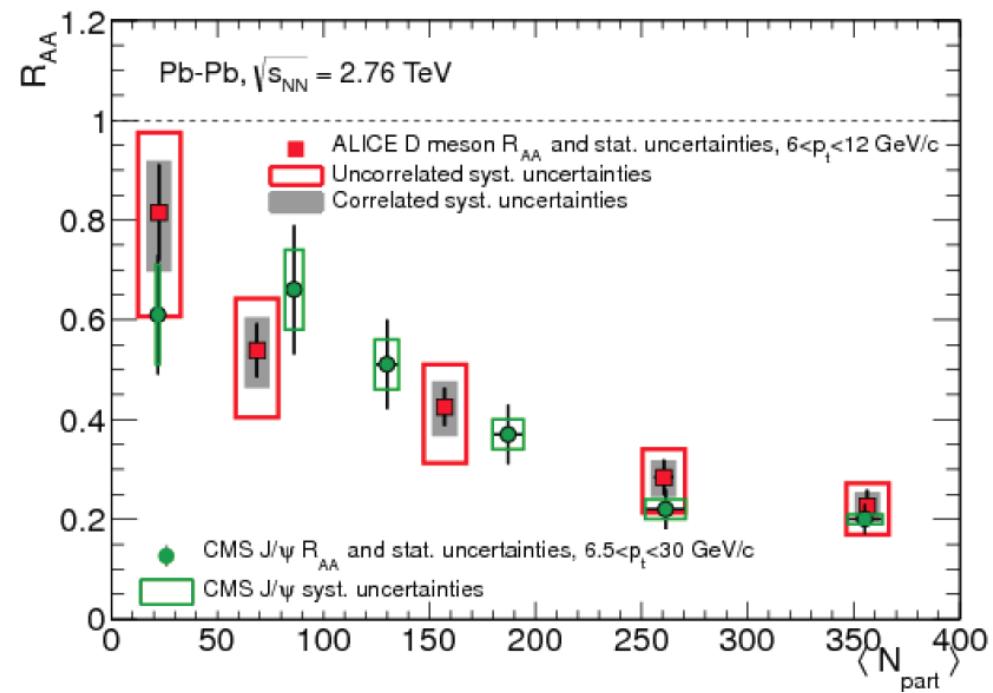


Something interesting

- ALICE D mesons: $|y|<0.5$, $2 < p_t < 5 \text{ GeV}/c$
- ALICE J/ ψ : $2.5 < y < 4$ (*) , $p_t > 0 \text{ GeV}/c$ (*)
- ALICE D mesons: $|y|<0.5$, $6 < p_t < 12 \text{ GeV}/c$
- CMS J/ ψ : $|y|<2.4$, To be discussed $p_t > 6.5 \text{ GeV}/c$

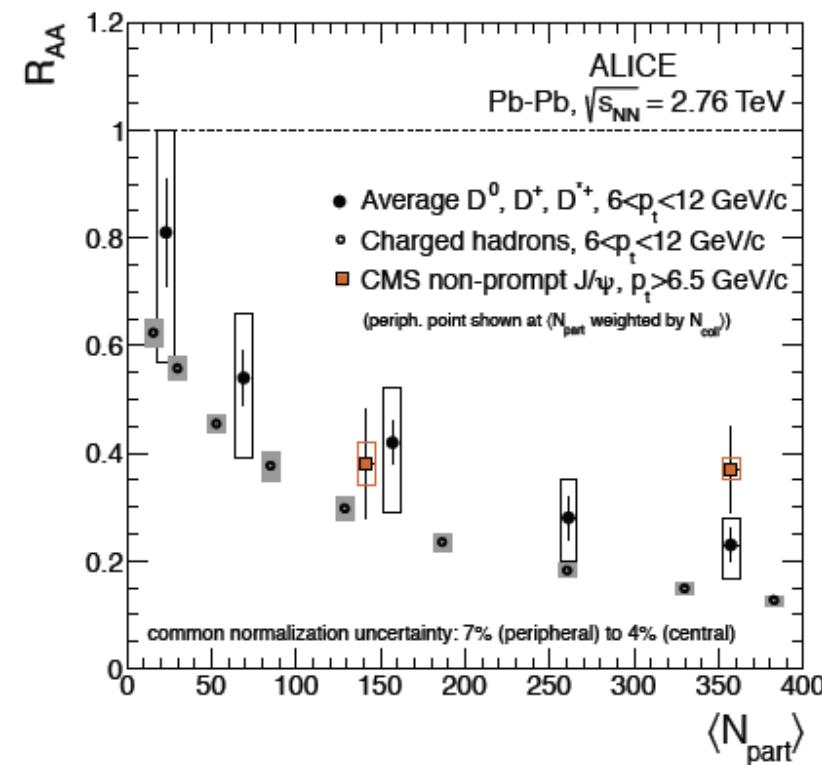
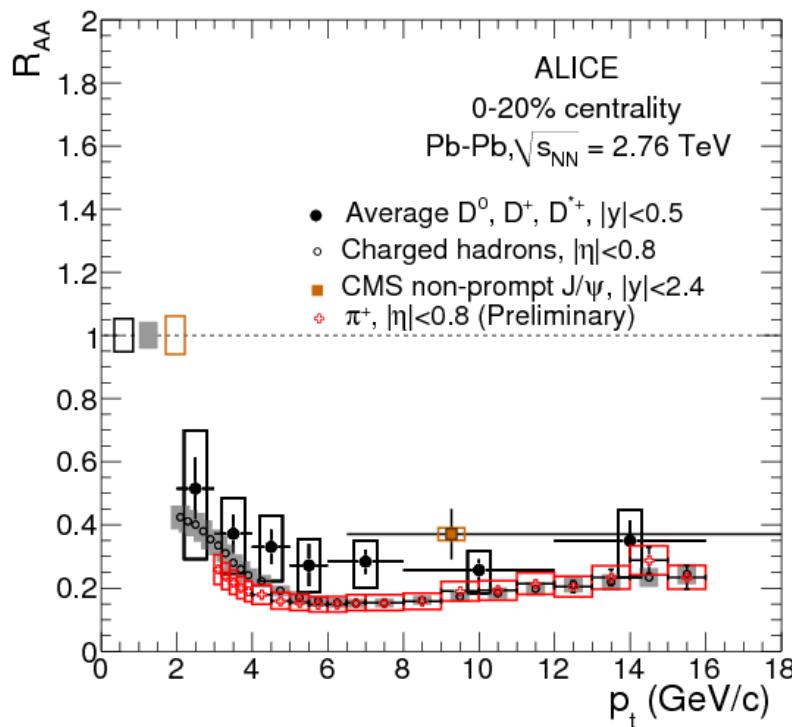


(*) careful, different !!



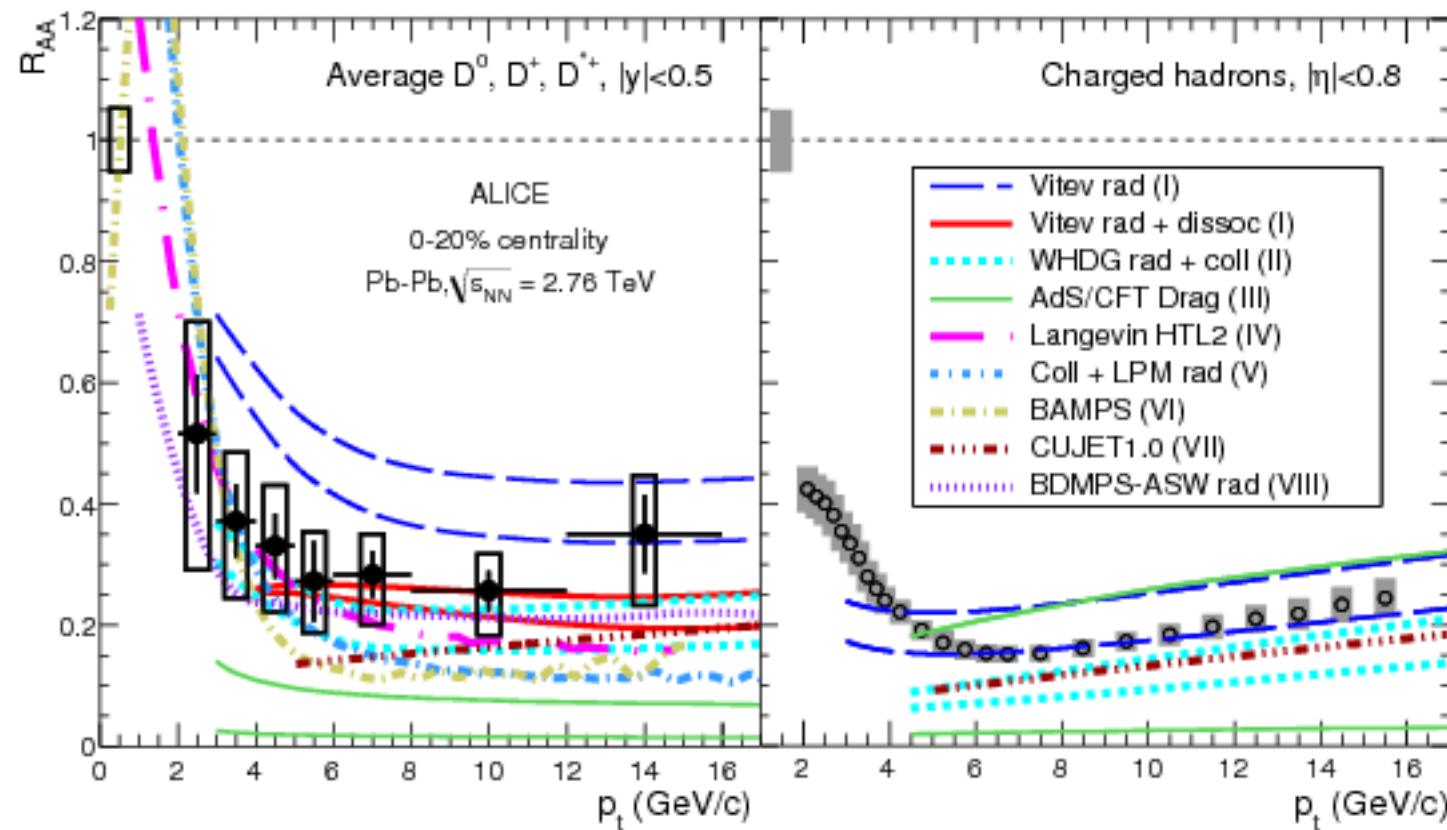
R_{AA} compilation: more hadrons

- Charged hadrons
- Identified pions
- Average D mesons (charm)
- CMS: $B \rightarrow J/\psi$ (beauty) arXiv:1201.5069

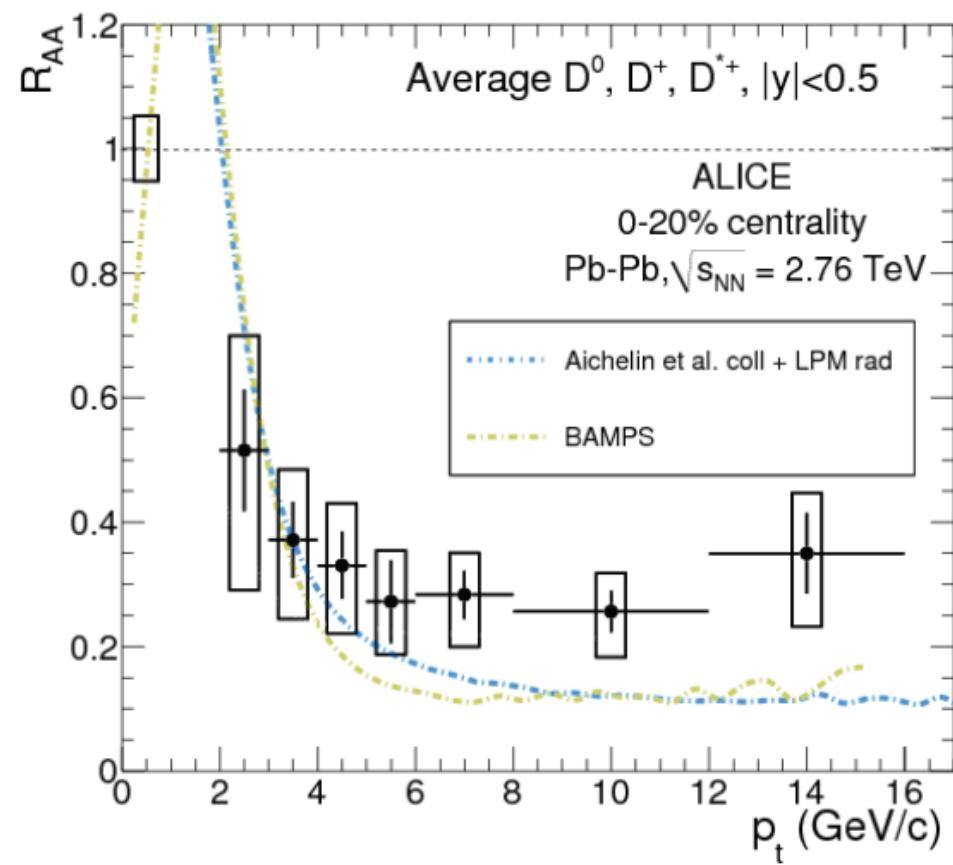
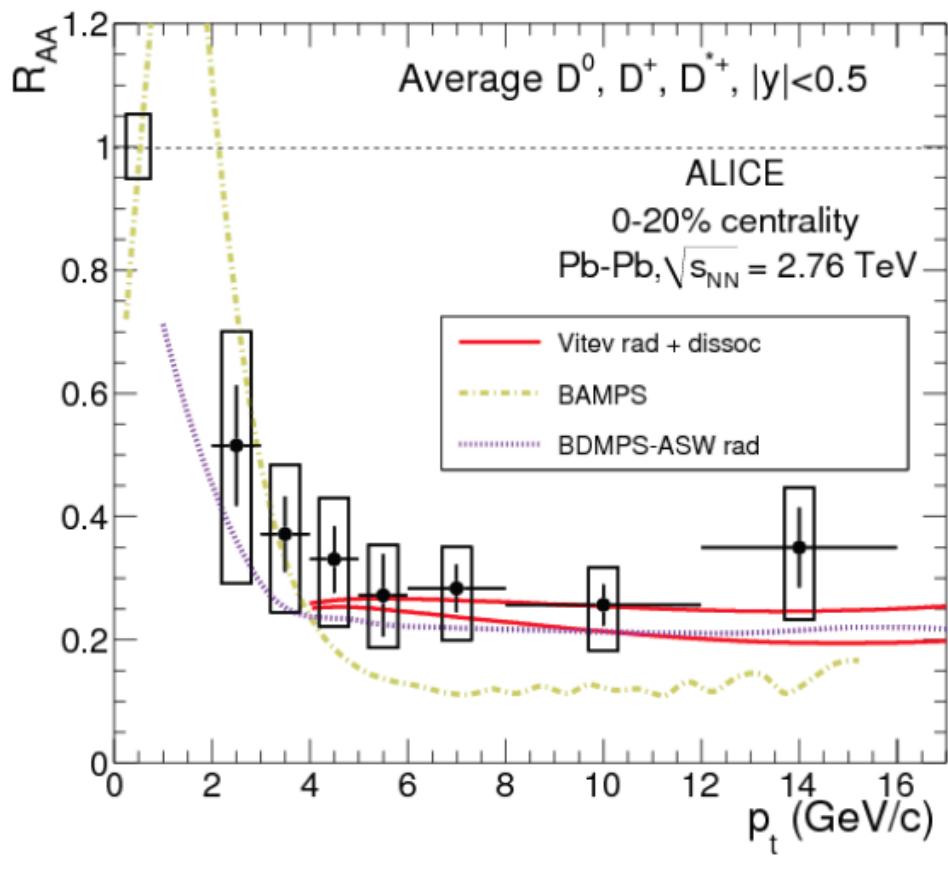


- Charged, pions, charm and beauty R_{AA} : similar. Hint of a hierarchy?
- Color charge dependence? Dead cone effect?
- Further improve the precision of the results and add p-Pb data !

R_{AA} and models



R_{AA} and models

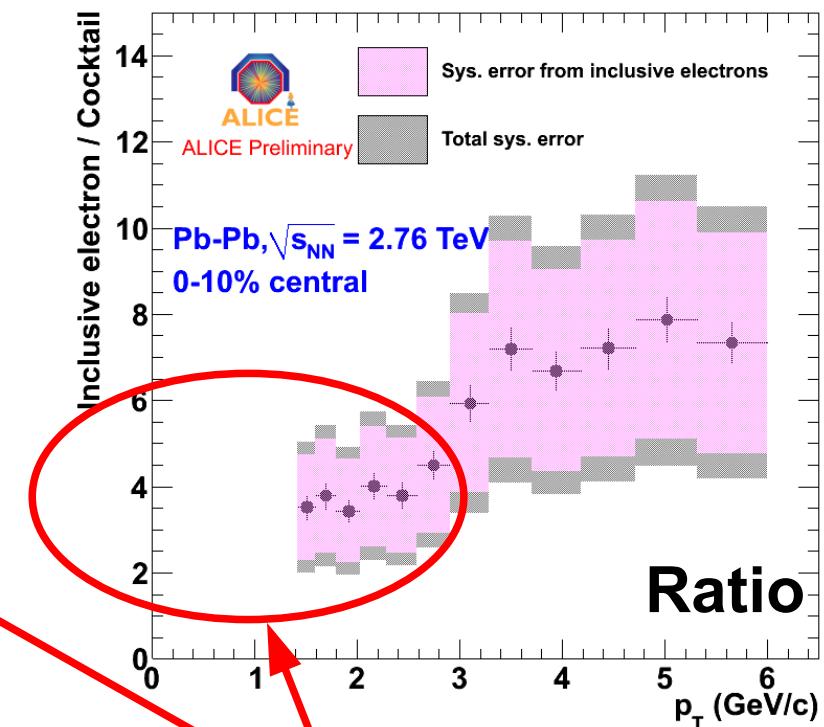
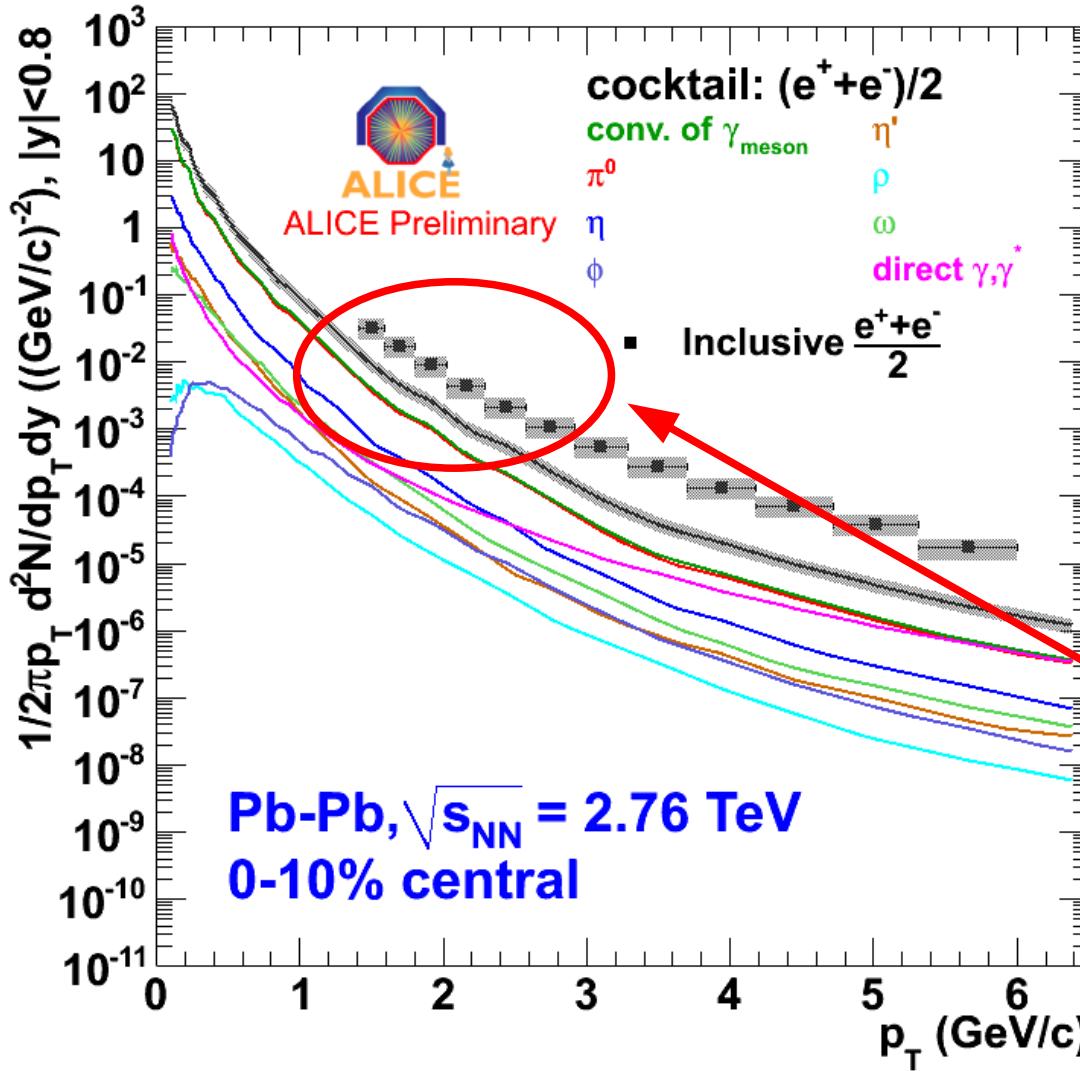


PbPb: Inclusive and cocktail - 0-10%



ALICE

Inclusive – cocktail = electrons from heavy flavour decays
... Only??



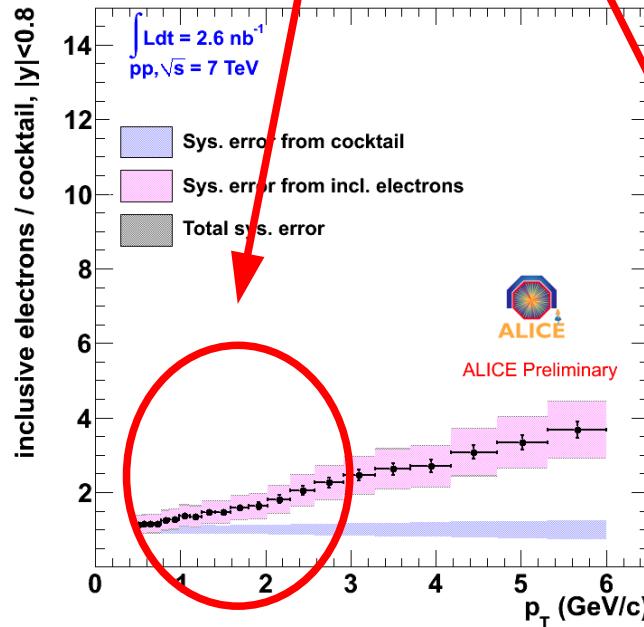
Low p_T region:
Excess ?

pp, PbPb peripheral and PbPb central

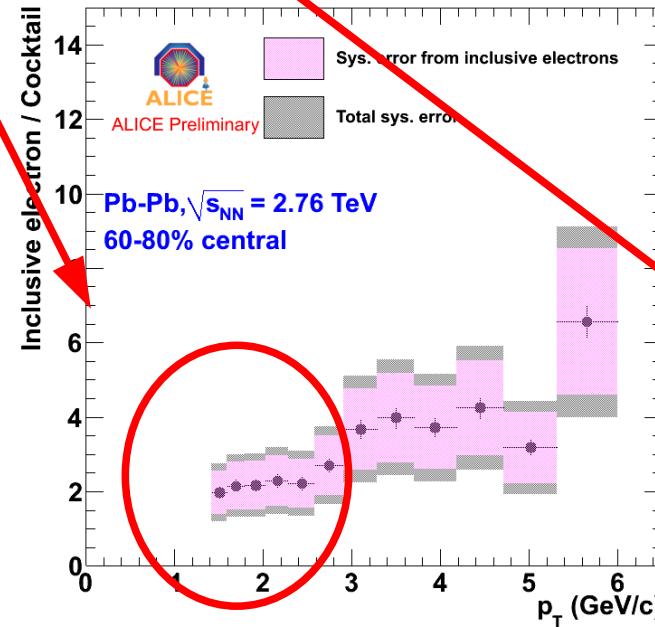


**At low p_T : hint for an excess
Increases towards more central collisions**

pp

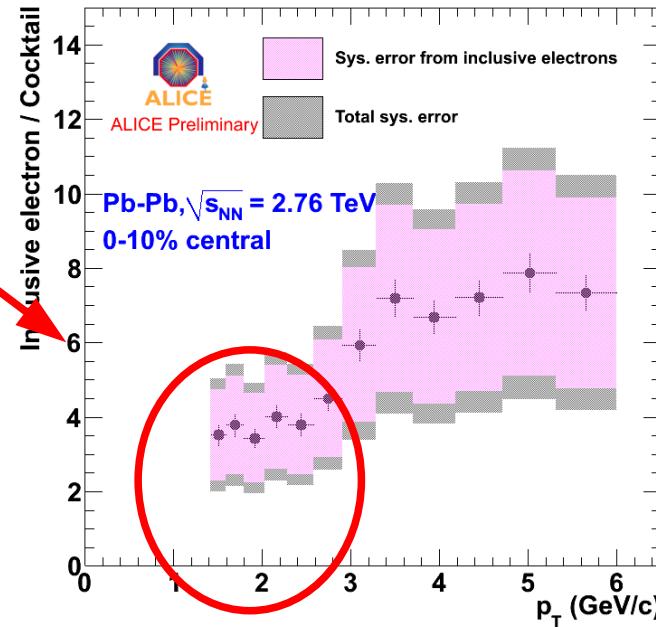


60-80%

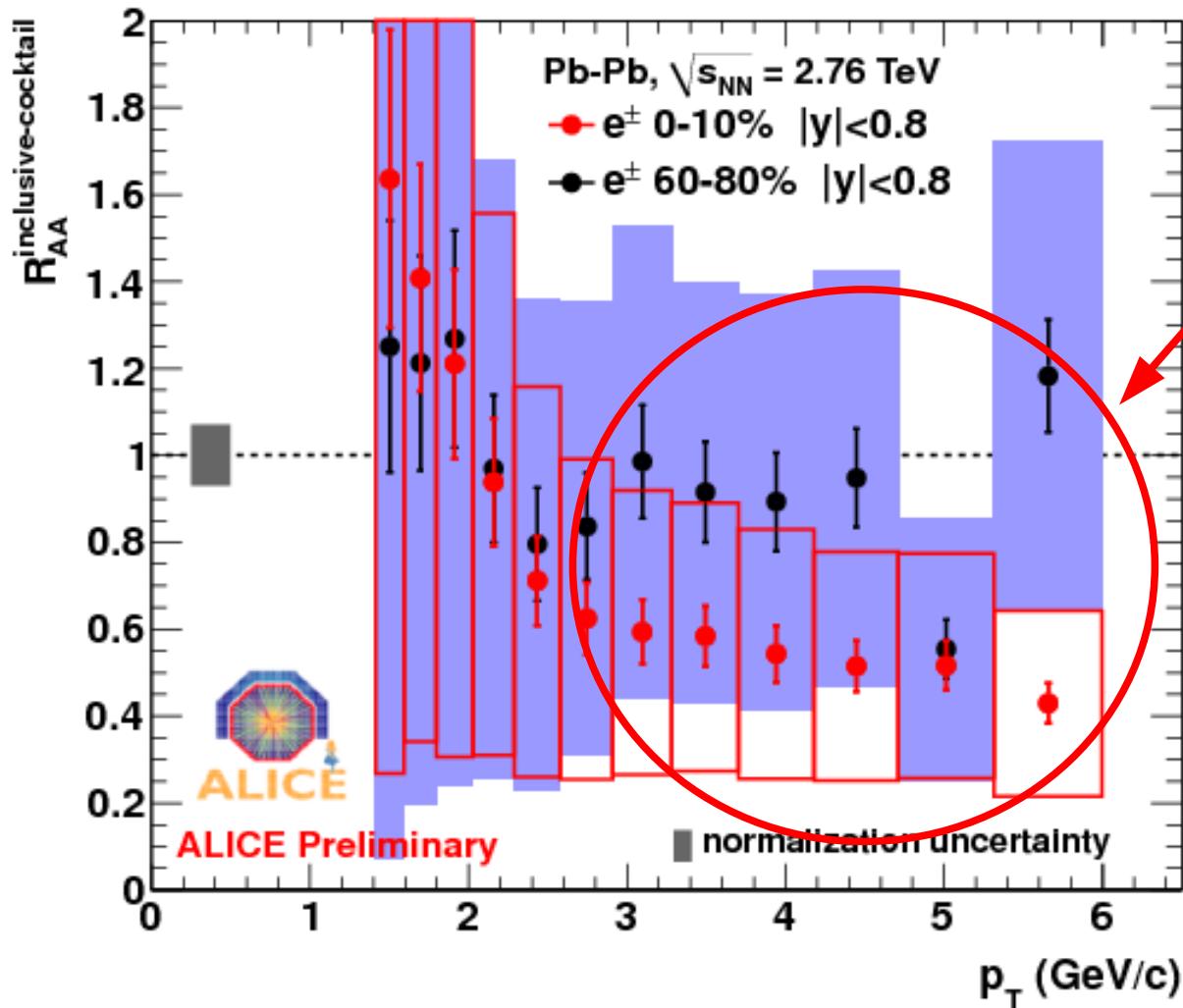


Consistent with thermal radiation?
Thermal photons observed at RHIC

0-10%



Electron R_{AA} : central vs peripheral



Electrons from heavy
flavour hadron decays

→ CHARM + BEAUTY

Suppression in
central collisions

Large uncertainties

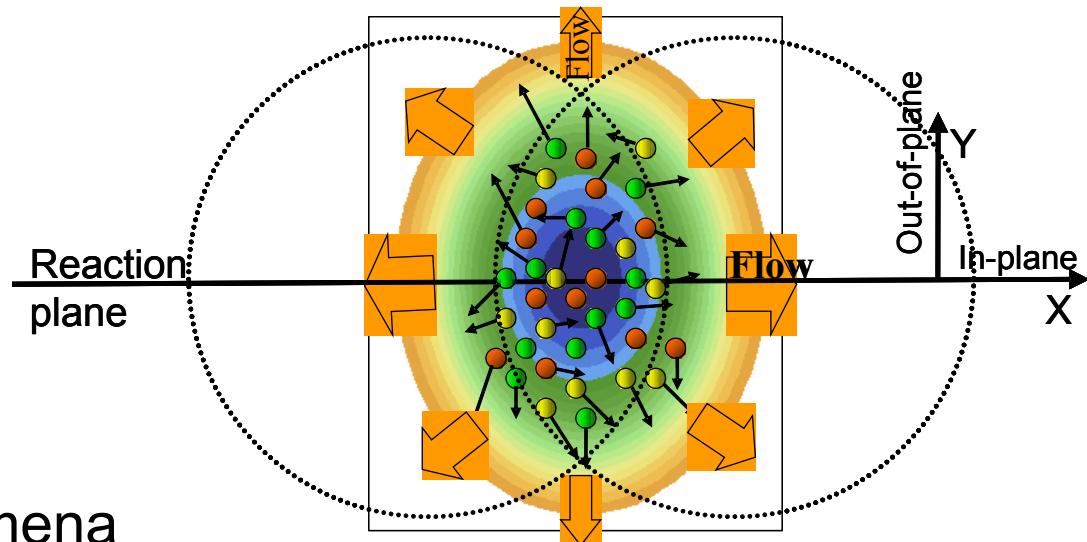


Charm elliptic flow

Non-central collisions:

- Initial spatial anisotropy
- Asymmetric pressure gradient
- Momentum anisotropy

Elliptic flow v_2 provides a measure
of the strength of collective phenomena



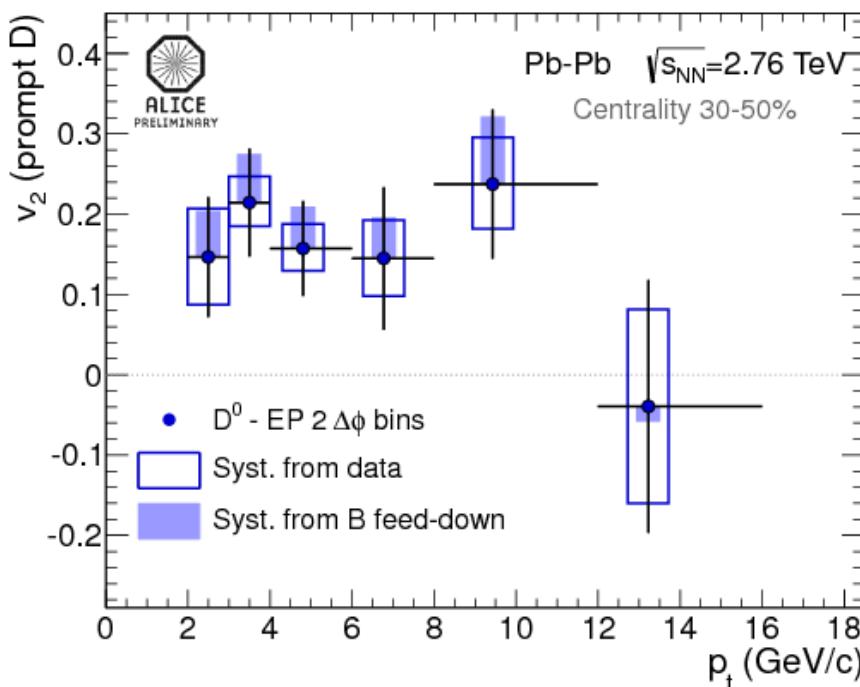
Elliptic flow of **charm** particles is sensitive to

- thermalization of the medium (low p_t)
- path length dependence of energy loss (high p_t)

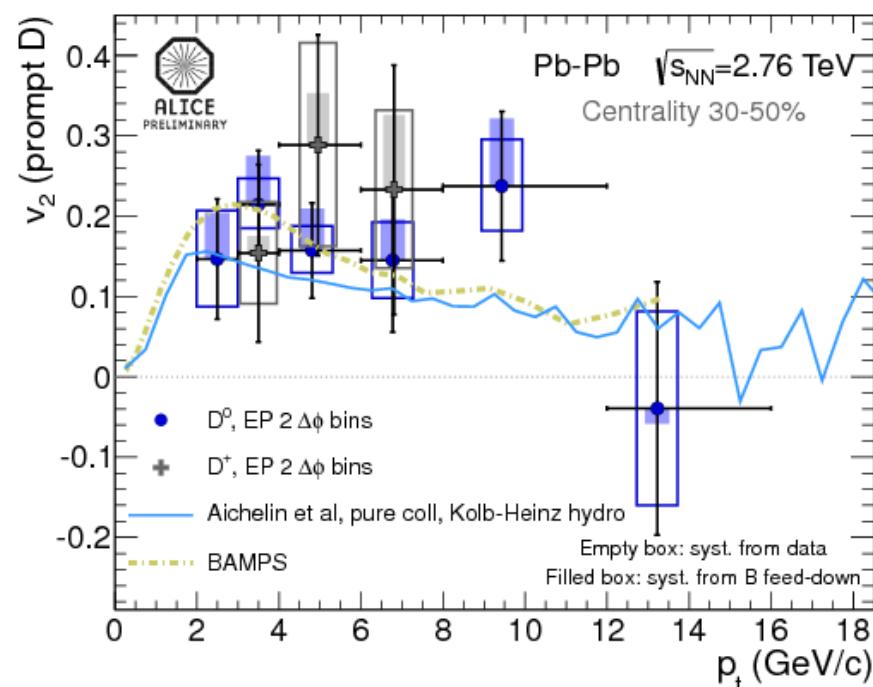
R_{AA} and v_2 are both sensitive to medium transport properties

Elliptic flow of D: results

- $D^0 v_2$ in 30-50% centrality



- D meson compared to models
 - BAMPS arXiv: 1112.1559
 - Aichelin et al. Phys.Rev. C78 (2008) 014904



- Non zero D meson v_2 for $2 < p_t < 12 \text{ GeV}/c$
- Hint of centrality dependence: $D^0 v_2$ flow larger in less central collisions
- Compatible with charged hadrons elliptic flow
- Comparison to models $\rightarrow R_{AA}$