"Open heavy-flavour and quarkonium production with ALICE at the LHC"

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on behalf of the ALICE Collaboration

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Outline

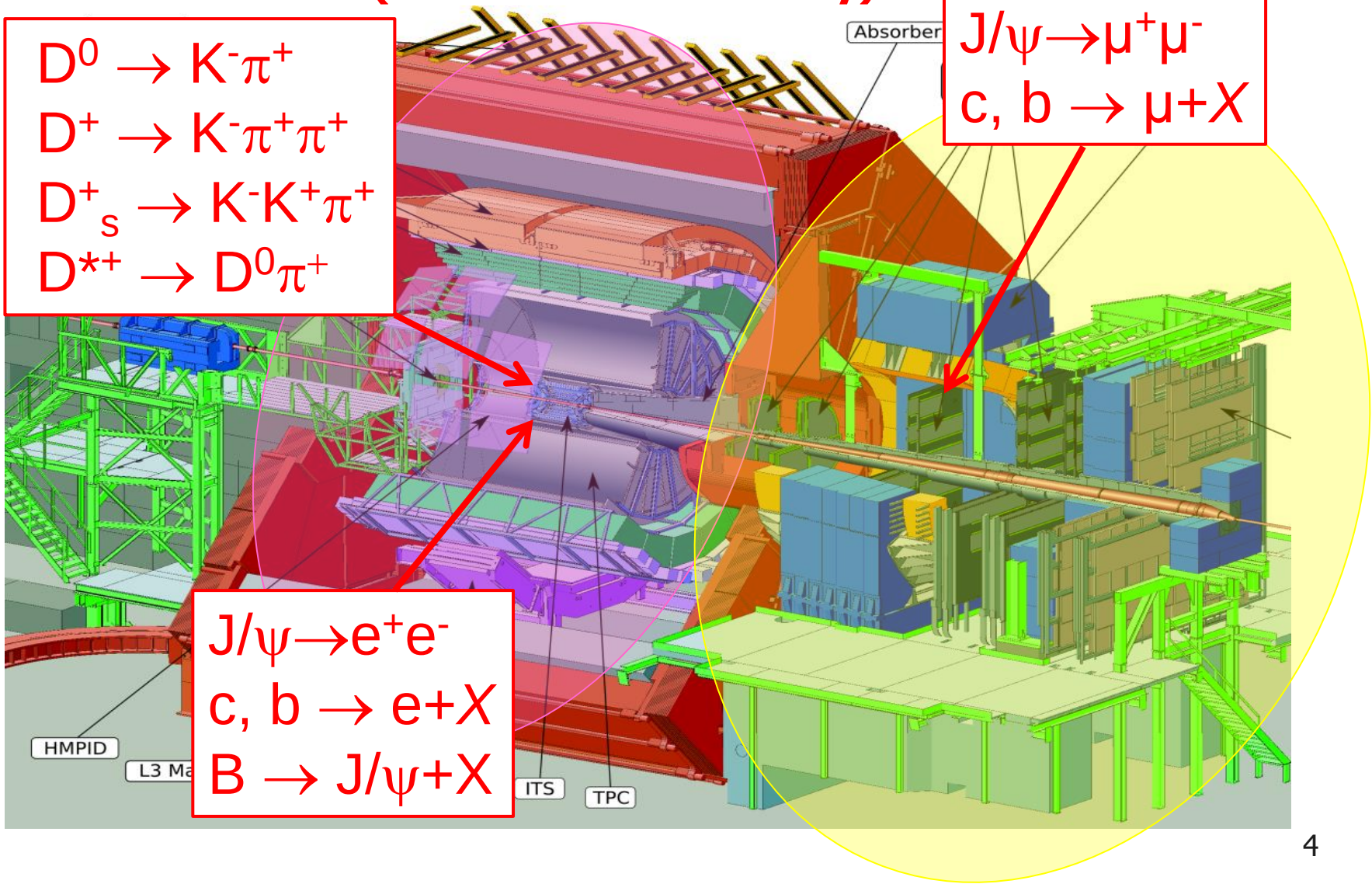
- Introduction:
  - motivations for study of heavy flavours
  - overview of the ALICE experiment
- Selected proton-proton results:
  - cross sections in pp @ $\sqrt{s}$ = 7 TeV
  - reference for PbPb data → pp @ $\sqrt{s}$ = 2.76 TeV
- Focus on Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  - Nuclear suppression factor R_{AA}
  - Elliptic flow v_2
- Prospects for p-Pb collisions
- Conclusions

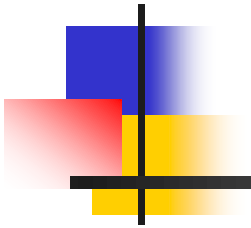
Motivations for studing heavy flavours

- Proton-proton collisions:
  - Test of pQCD and QCD-based models in a new energy domain
  - Reference for Pb-Pb collisions
- Nucleus-nucleus collisions:
  - $c\bar{c}$ and $b\bar{b}$ pairs are special probes of deconfined matter
    - produced at the early stage of collisions → sensitive to full QGP history
  - R_{AA} and v_2 of open and hidden heavy flavours are key measurements:
    - Open HF: parton energy loss and thermalization
    - Hidden HF: regeneration vs suppression
- Proton-nucleus collisions:
  - Cold nuclear matter effects

HF measurements in ALICE

(To be addressed today)

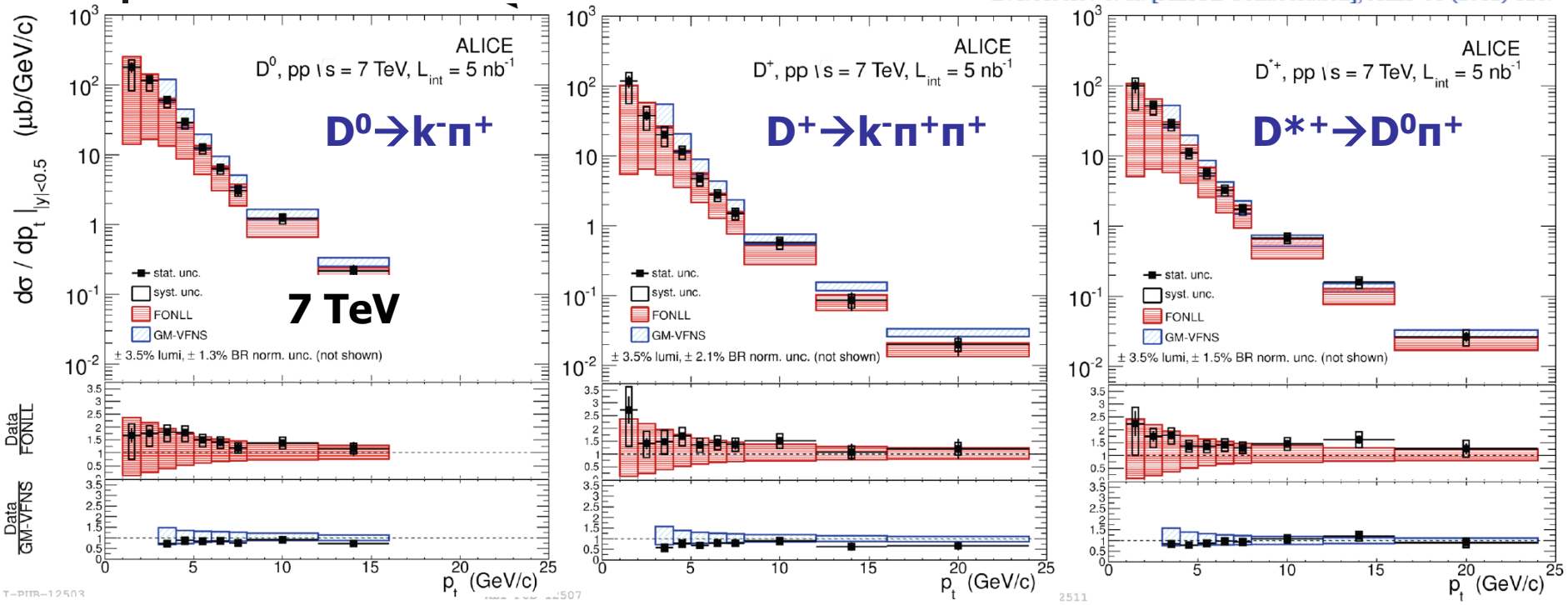




Selected proton-proton results

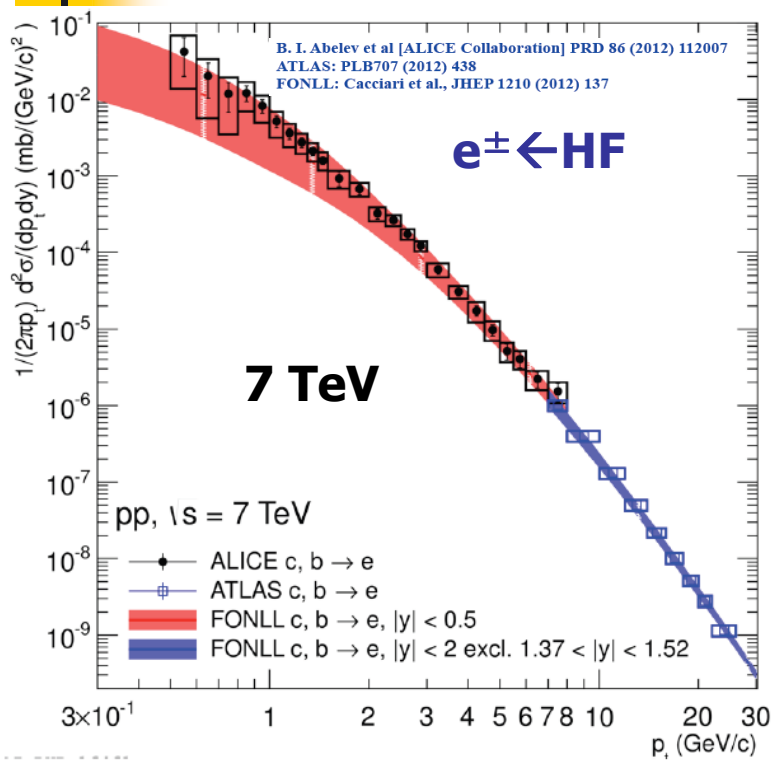
Open HF results @ 7 TeV

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

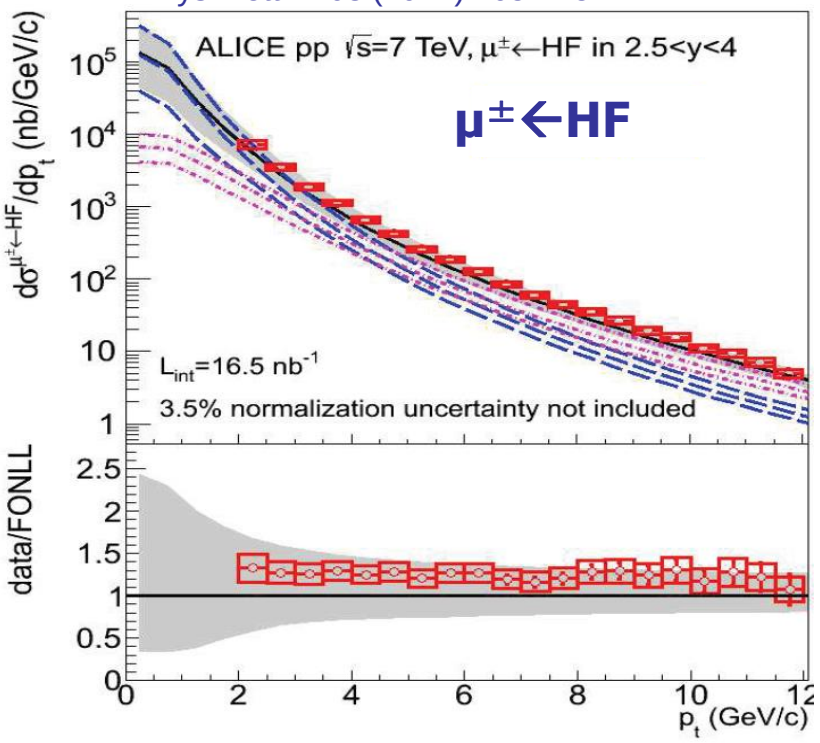


- Good overall agreement with pQCD predictions for p_T-differential cross-sections of D mesons in |y| < 0.5 (FONLL, GM-VFNS)

Open HF results @ 7 TeV



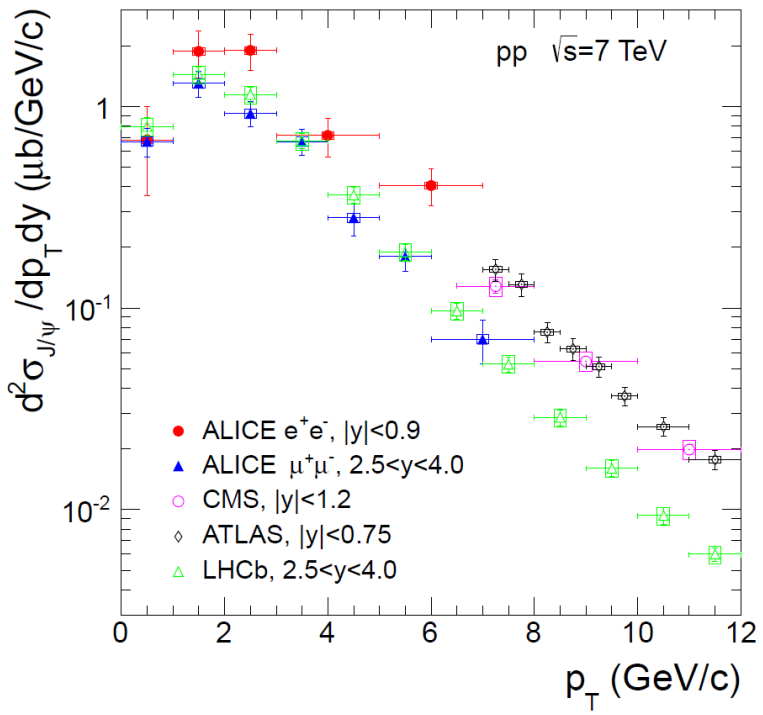
Phys. Lett B708 (2012) 265-275

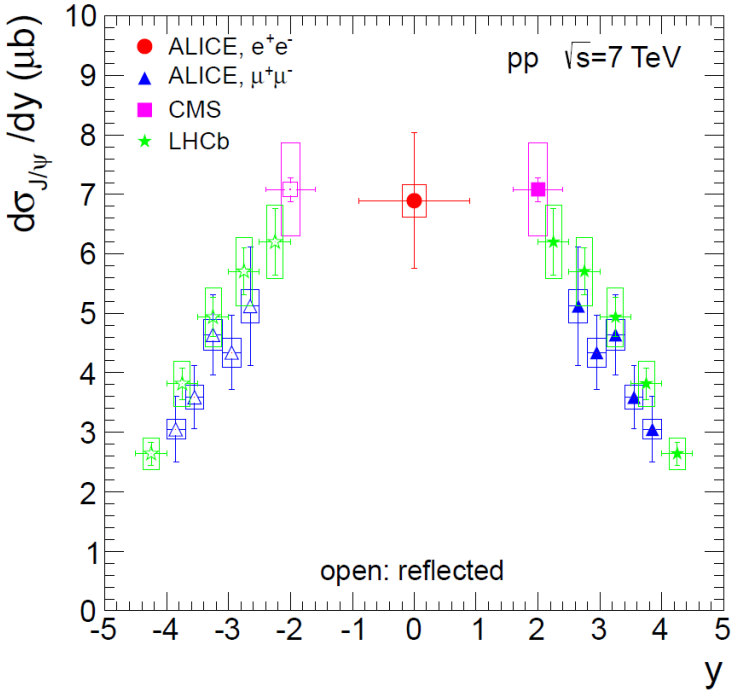


- Good overall agreement with pQCD predictions for p_T-differential cross-sections of D mesons in |y| < 0.5 (FONLL, GM-VFNS), heavy flavour electrons (|y| < 0.9) and muons (2.5 < y < 4)

Quarkonium production in pp @ 7 TeV

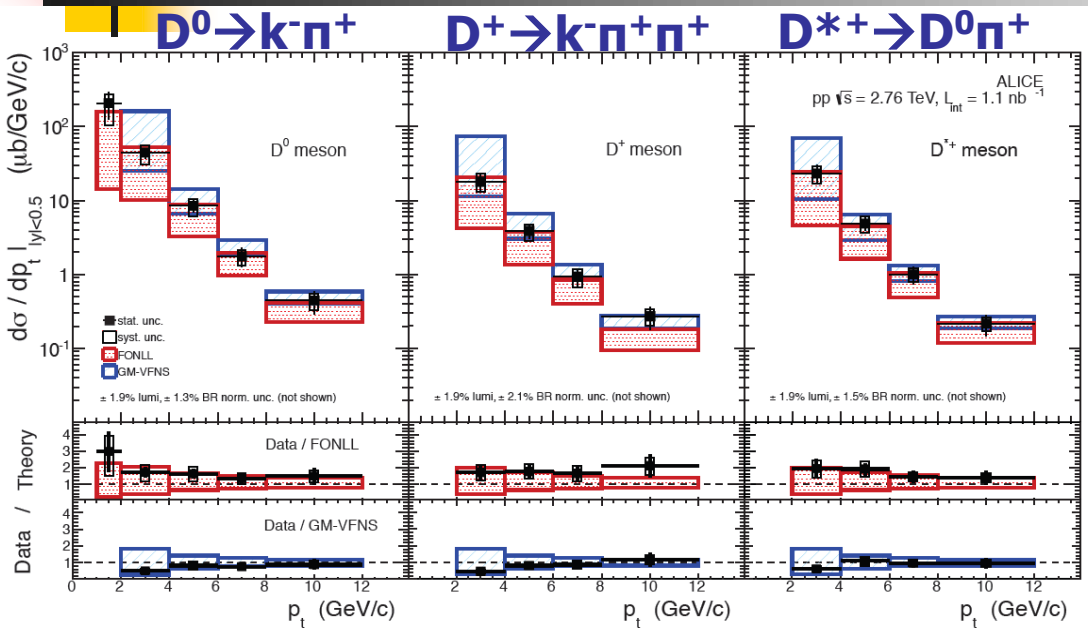
ALICE Coll., Phys. Lett. B704:442 (2011)
Erratum, ibid. B718:692-698 (2012)





- J/ψ production cross sections have been measured down to $p_T = 0$ at both central and forward rapidity

Results in pp @ 2.76 TeV

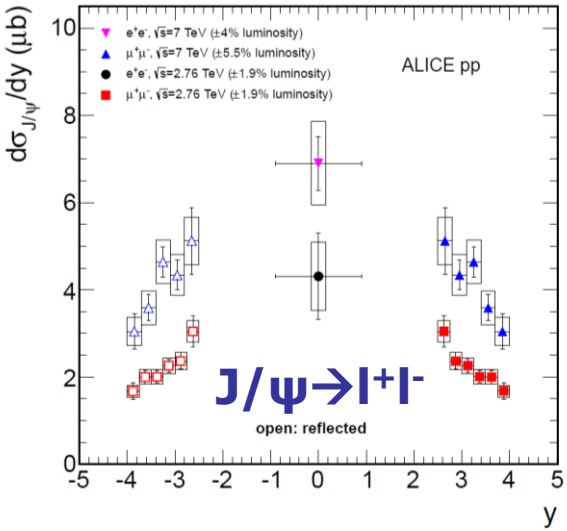


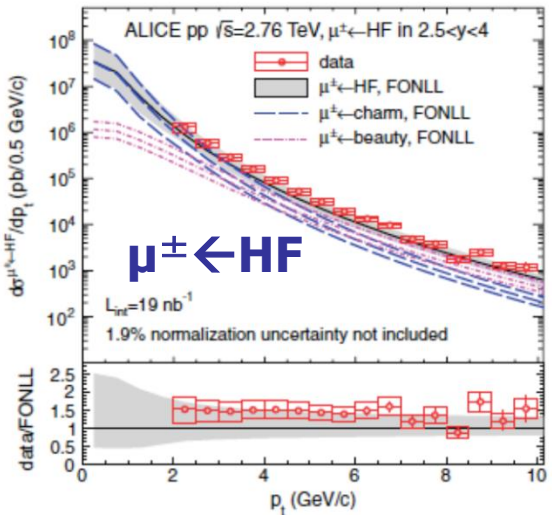
ALICE Coll, Phys.Lett. B718 (2012) 295

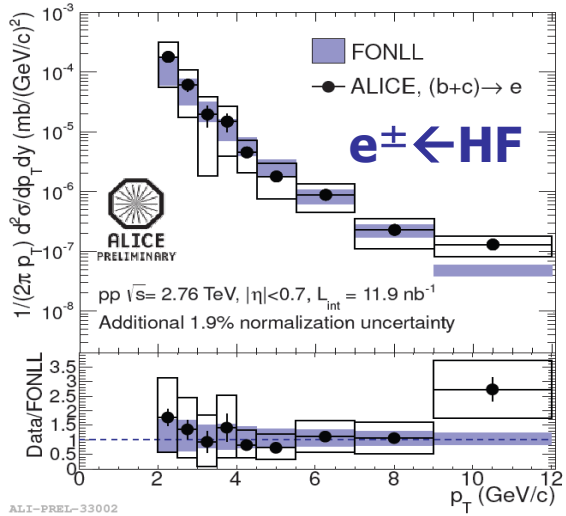
Larger uncertanties w.r.t. 7 TeV data → for D mesons and heavy-flavour decay electron the reference for Pb-Pb is obtained by applying a √s scaling to the cross section measured at √s = 7 TeV using FONLL pQCD calculations

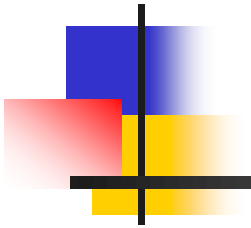
[M. Cacciari et al., JHEP **1210** (2012) 137]

- pp data at √s = 2.76 TeV were used as reference for heavy flavour decay muons and for quarkonia measurements at both central and forward rapidity









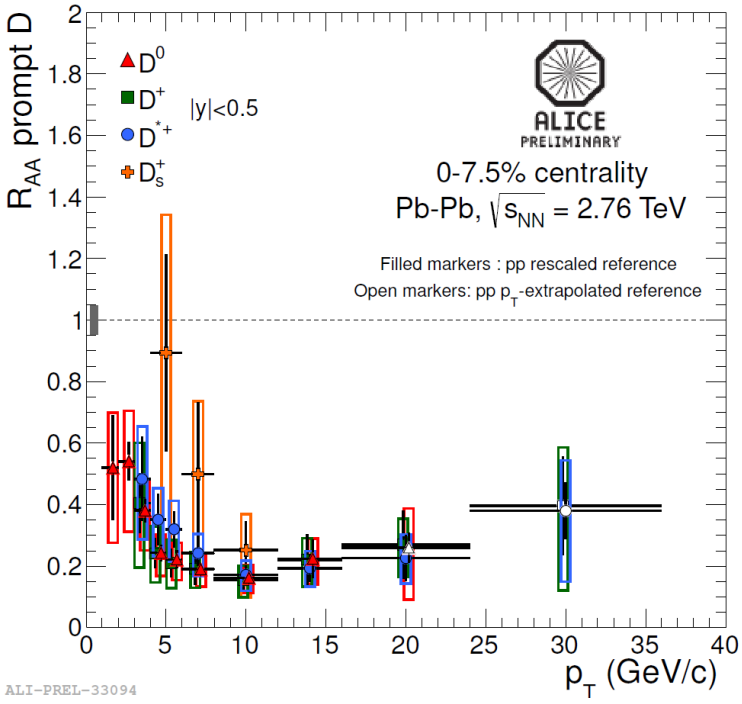
Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

Nuclear modification factor for D mesons (1)

R_{AA} measured for D^0, D^+, D^{*+}

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

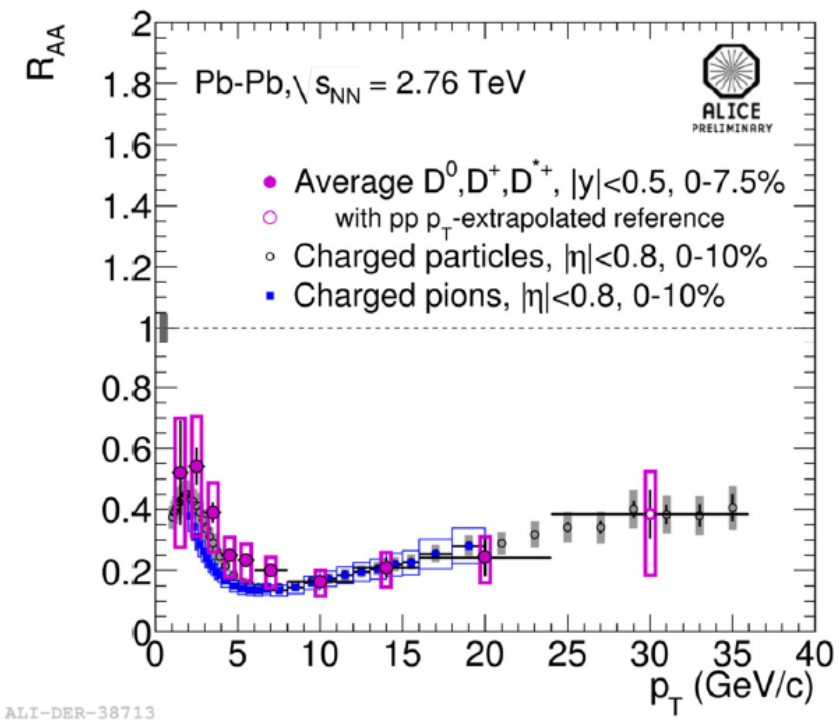
- R_{AA} = 1 indicates no nuclear modification
- R_{AA} < 1 indicates energy loss
- $R_{AA}(B) > R_{AA}(D) > R_{AA}(light)$ due to color charge and quark mass effects in parton energy loss

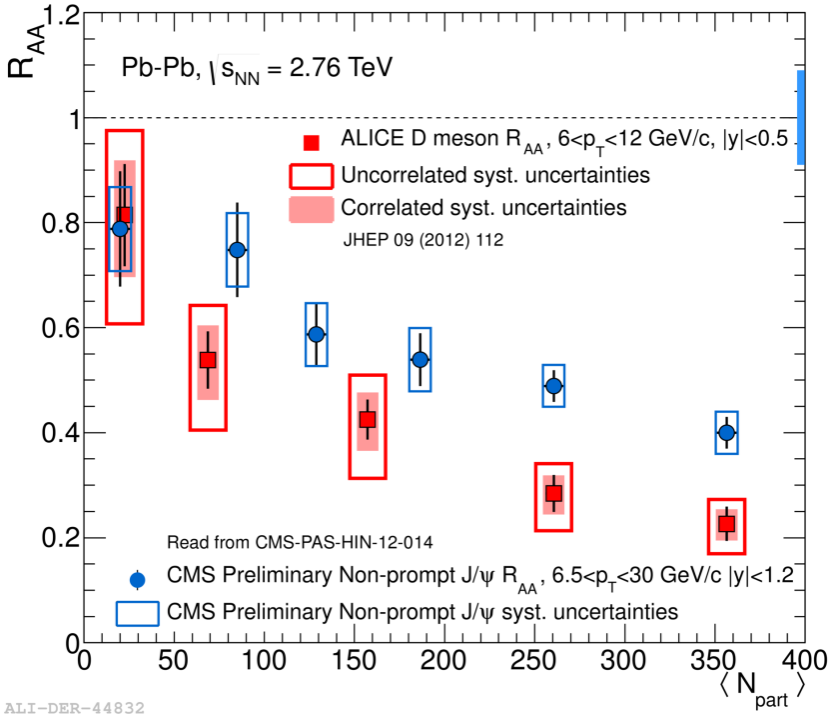


- D^0, D^+ and D^{*+} R_{AA} are consistent within uncertainties
- Strong suppression of prompt D mesons in central collisions → up to a factor of 5 for $p_T \approx 10$ GeV/c
- First measurement of D_s^+ in AA collisions:
  - strong D_s^+ suppression (similar to D^0, D^+ and D^{*+}) for $8 < p_T < 12$ GeV/c
  - with current statistical and systematic uncertainties no conclusion can be drawn on the expected enhancement of D_s mesons with respect to non-strange D mesons at low p_T, due to c-quark coalescence with the abundant strange quarks

Nuclear modification factor for D mesons (2)

R_{AA} measured for D^0, D^+, D^{*+}

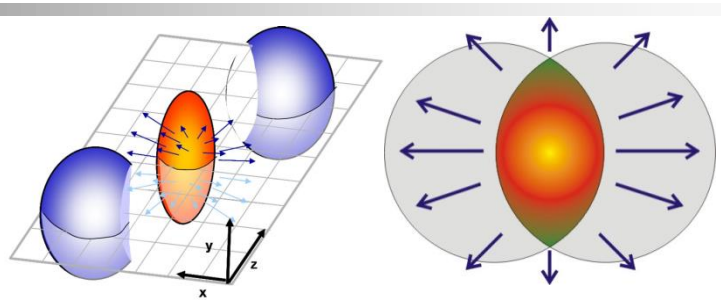


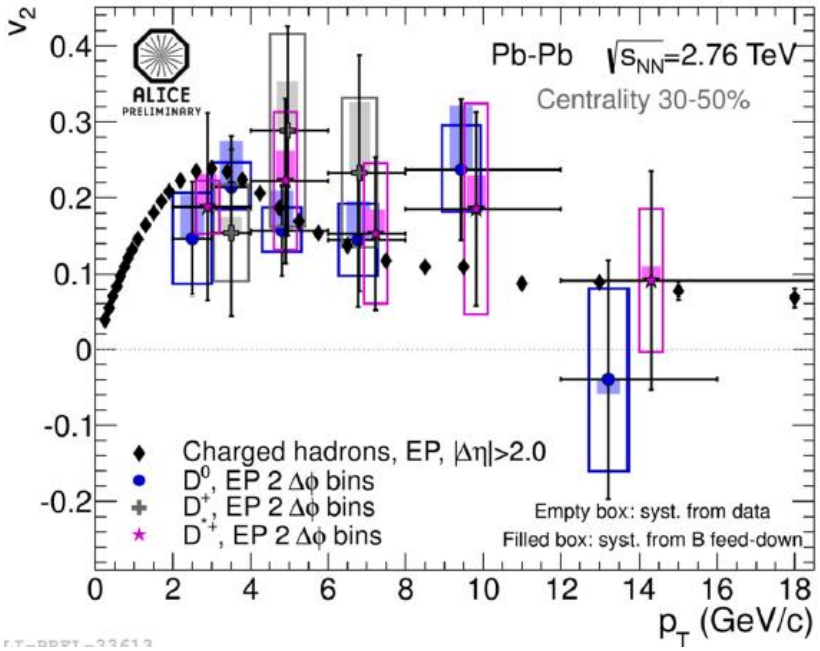


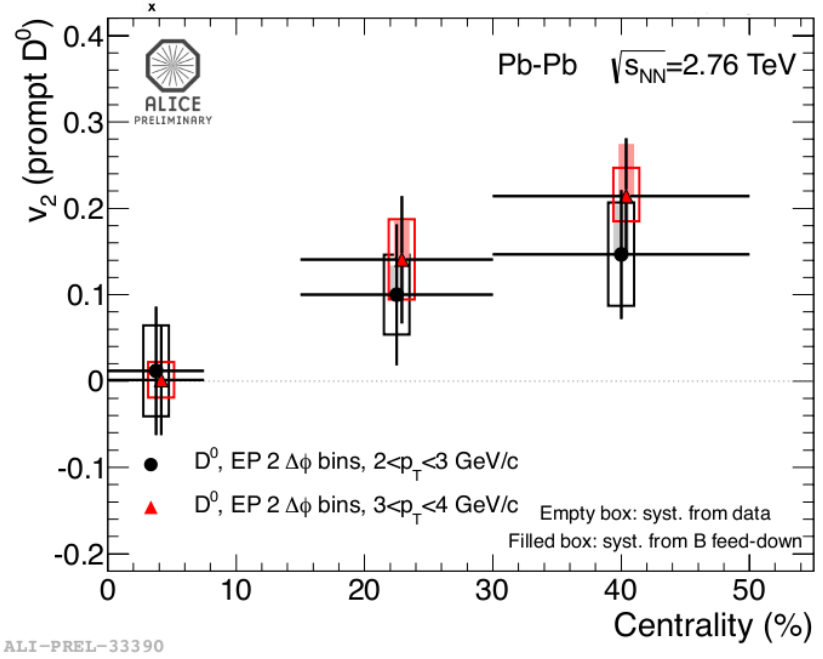
- Maybe a hint for $R_{AA}^{D} \gtrsim R_{AA}^{charged}$ at low p_T, but not conclusive within present uncertainties
- Comparison with the non-prompt J/ψ R_{AA} of CMS [CMS Collaboration arXiv:1201.5069] shows a hint for $R_{AA}^{B} > R_{AA}^{D}$ in the most central collisions (CAVEAT: large p_T range, different y range)

Elliptic flow for D mesons

- Elliptic flow measured using the event plane method:
  $v_2 = \langle\cos(2(\phi-\psi_{RP}))\rangle$





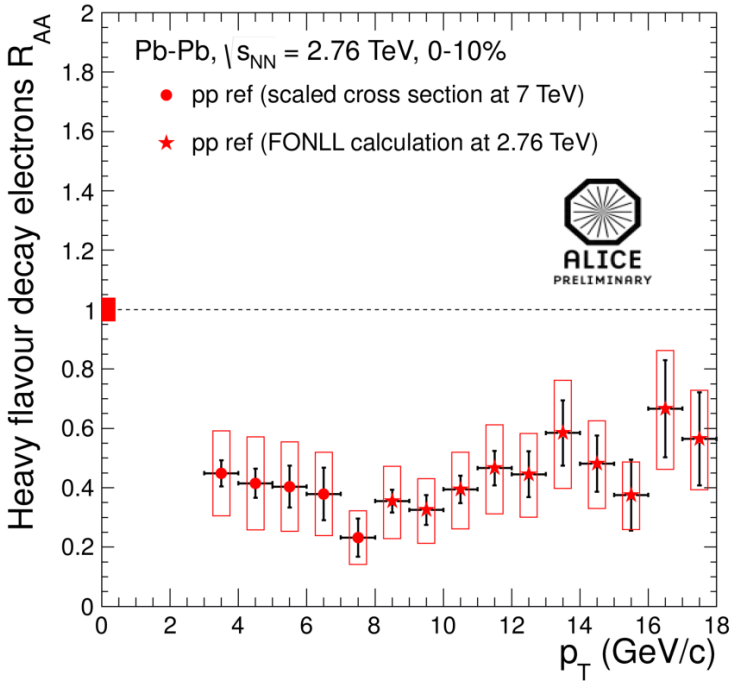


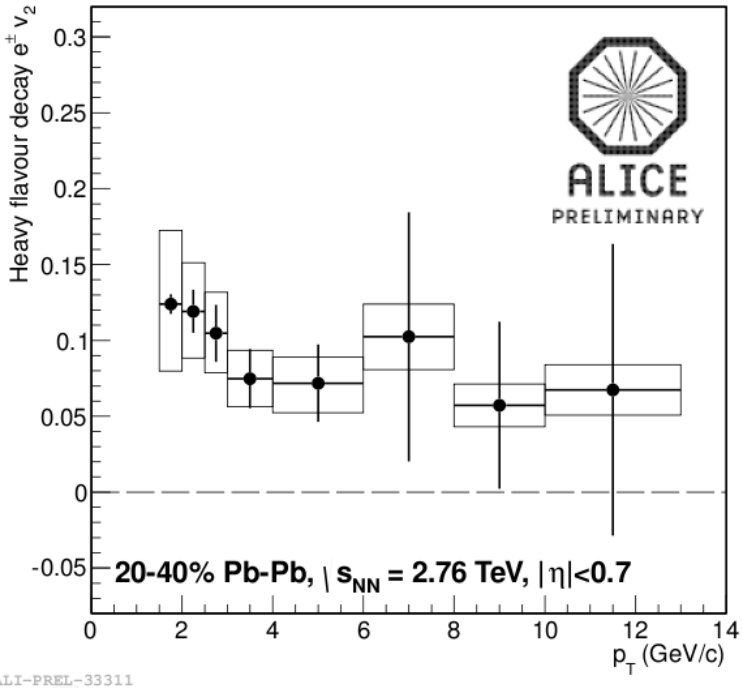
- consistency among different D meson species
- indication of non-zero D meson v_2 in $2 < p_T < 6$ GeV/c (~3σ effect)
- hint of centrality dependence at low p_T

Nuclear modification factor and elliptic flow for HF electrons

- Clear suppression for $3 < p_T < 18$ GeV/c (amounts to a factor 1.5-3 between $3 < p_T < 10$ GeV/c)
  - pp reference is estimated by applying a √s scaling to the cross section measured at √s = 7 TeV using FONLL calculations at low p_T (< 8 GeV/c) and pure FONLL predictions at high p_T (>8 GeV/c)

- Elliptic flow measured with event plane method
  - suggestion of $v_2 > 0$ at low p_T (> 3σ effect in $2 < p_T < 3$ GeV/c)



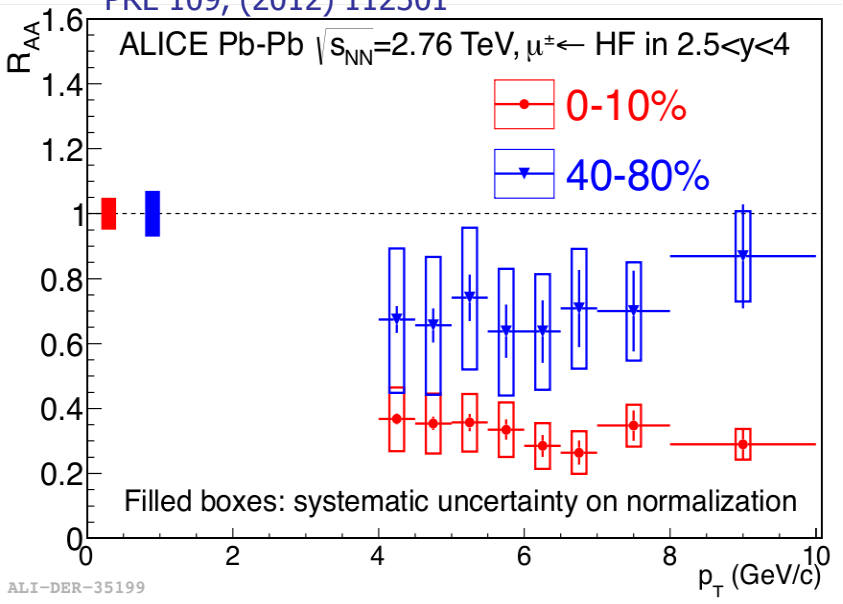


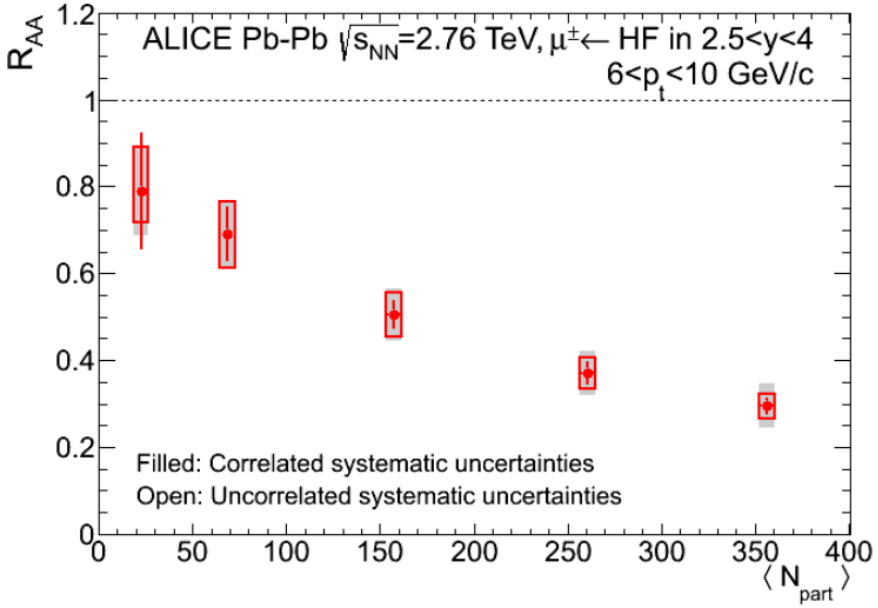
ALI-PREL-33311

Nuclear modification factor for HF muons

- R_{AA} for heavy flavour muons measured at forward rapidity as a function of both p_T and centrality
  - pp reference evaluated from data at √s = 2.76 TeV

PRL 109, (2012) 112301



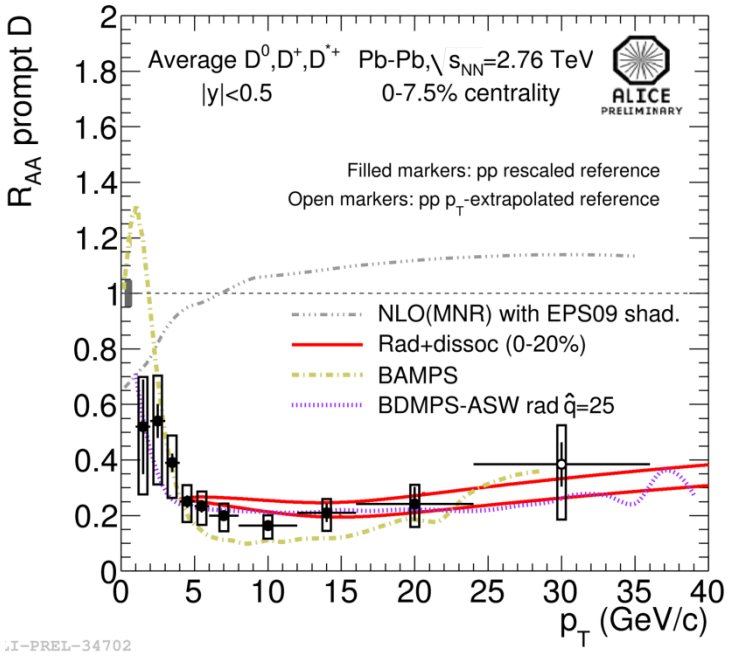


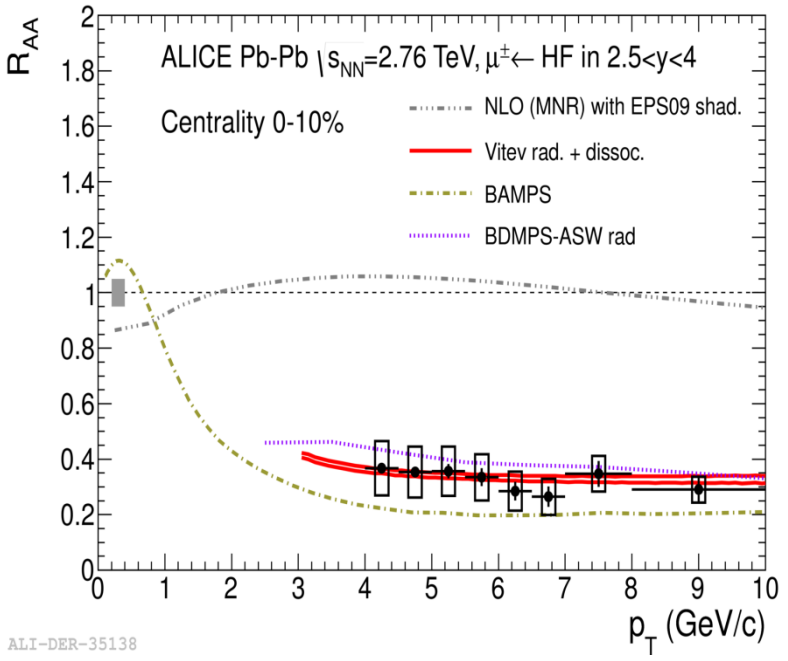
- Higher suppression in central collisions (a factor 2-4 in the 0-10% centrality class) than in peripheral collisions

- Suppression shows a small dependence on p_T

Comparison with models

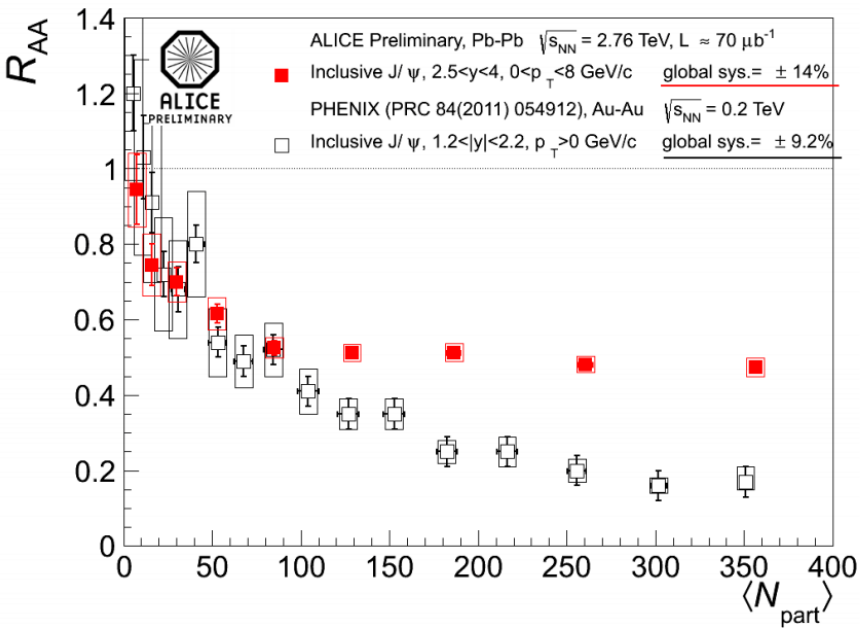
Comparison of D meson and HF muon nuclear modification factor with several theoretical models based on parton energy loss:

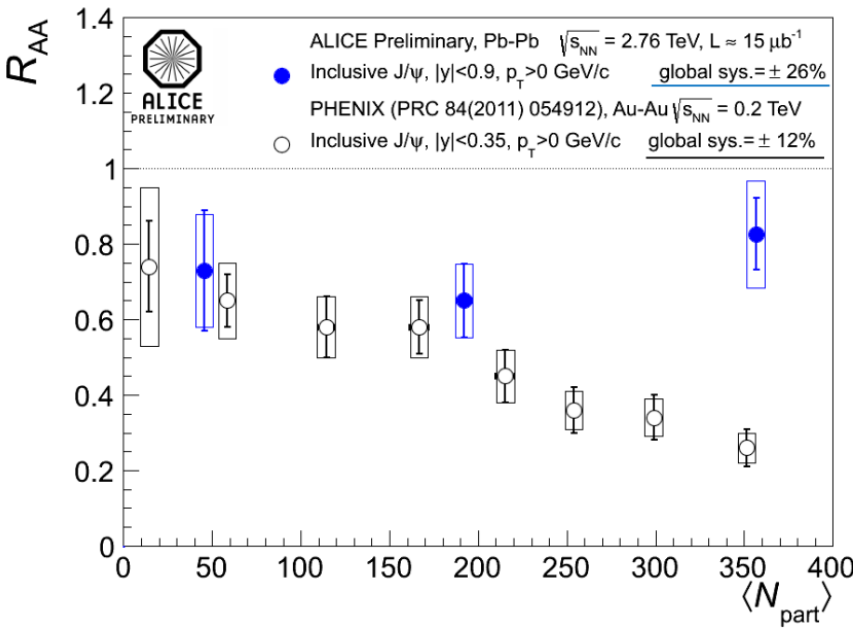




- R_{AA} of heavy-flavour muons and D mesons cannot be explained by shadowing alone for p_T > 4 GeV/c
  - Final state effects are dominant
  - p-Pb data are needed to quantify initial state effects
- Models with final state effects describe the data reasonably well

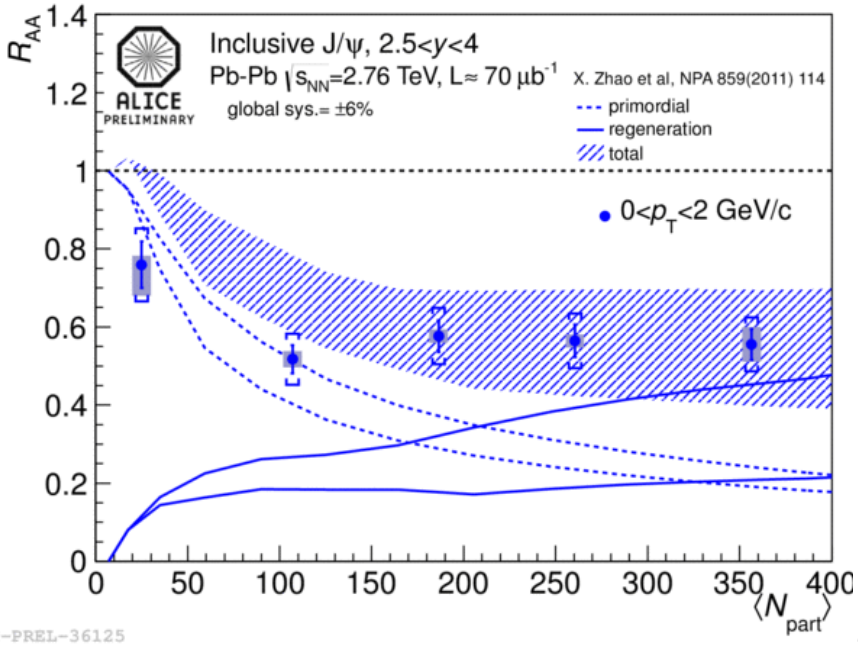
Quarkonia - J/ψ nuclear modification factor

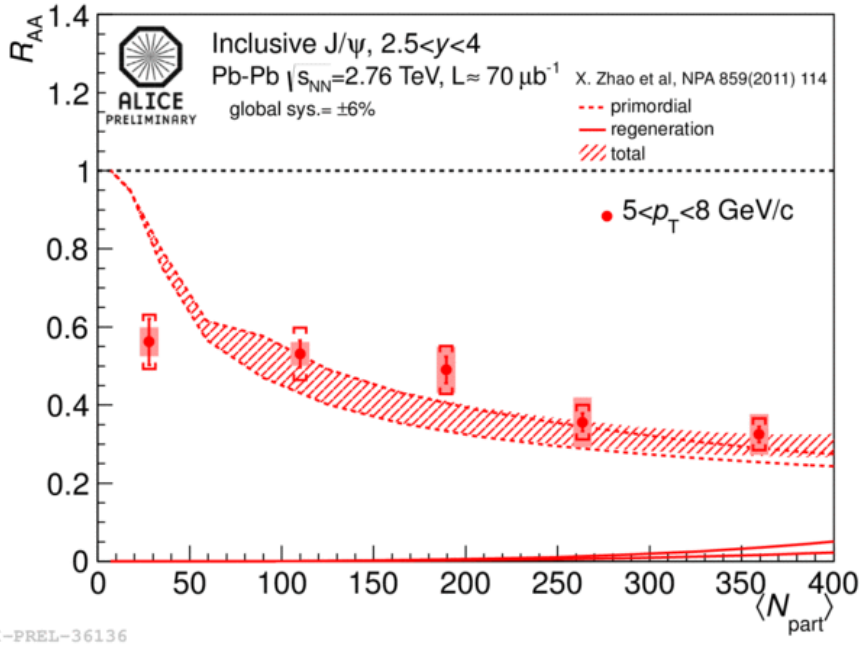




- Centrality dependence of R_{AA} for J/ψ studied at both central and forward rapidity
- At forward rapidity R_{AA} becomes flat for N_{part} > 100
- Large uncertainty on the (midrapidity) pp reference prevents a final conclusion on a different behaviour for central events at mid- and forward rapidity
- Comparison with PHENIX:
  - stronger centrality dependence at lower energy
  - systematically larger R_{AA} values for central events in ALICE → behaviour qualitatively expected in a (re)generation scenario

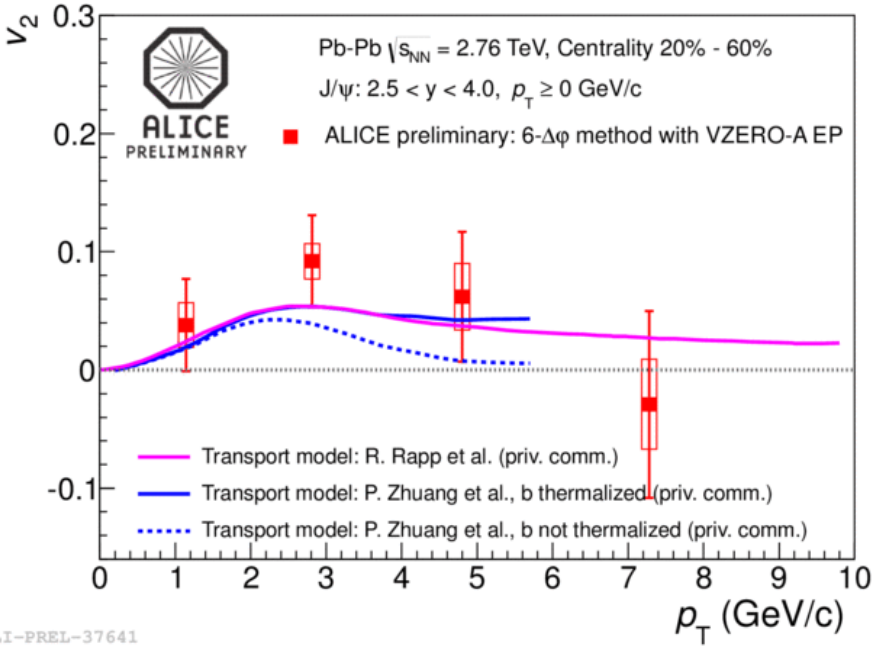
J/ψ nuclear modification factor: comparison with models

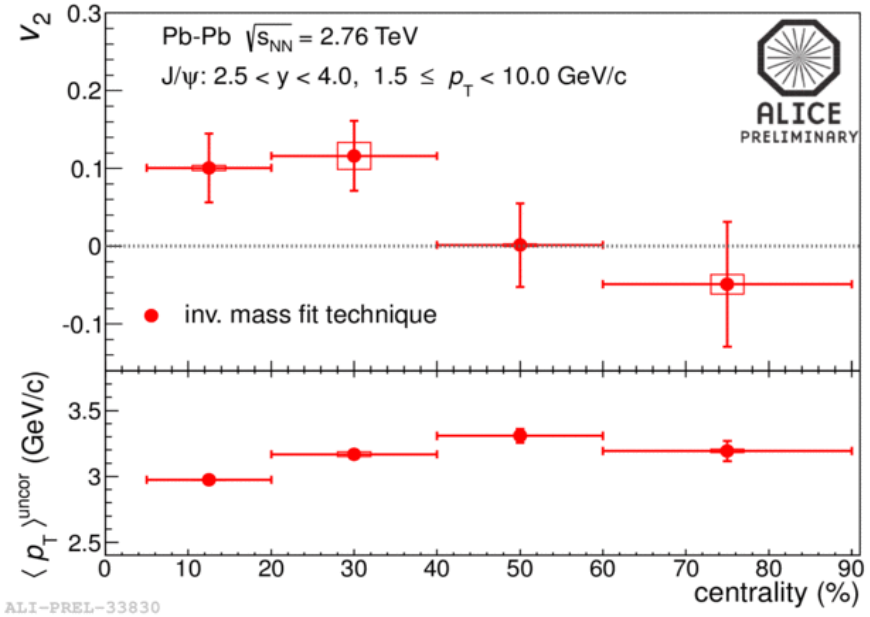




- Different suppression pattern for low- and high-p_T J/ψ
- In the models, ~50% of low-p_T J/ψ in central events are produced via (re)combination, while at high p_T the contribution is negligible → fair agreement for N_{part} > 100

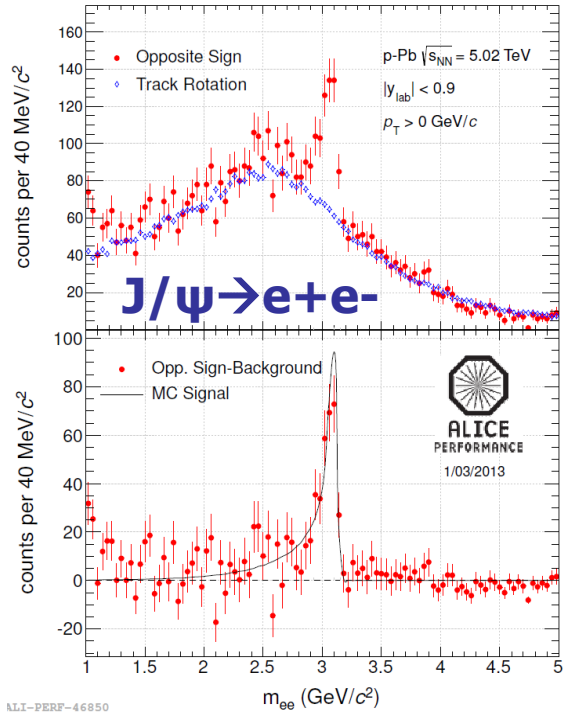
J/ψ elliptic flow at forward rapidity

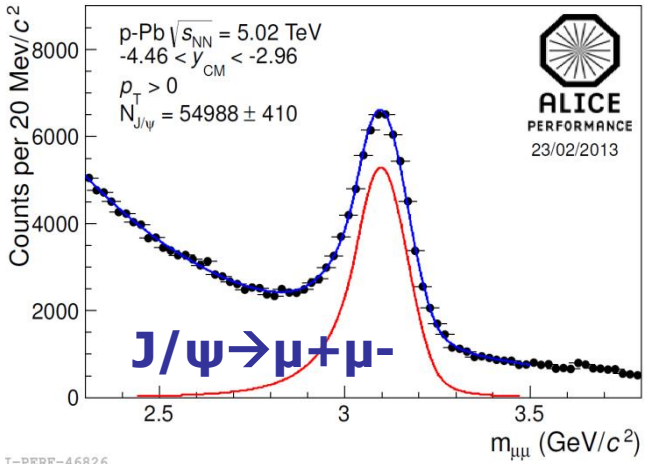


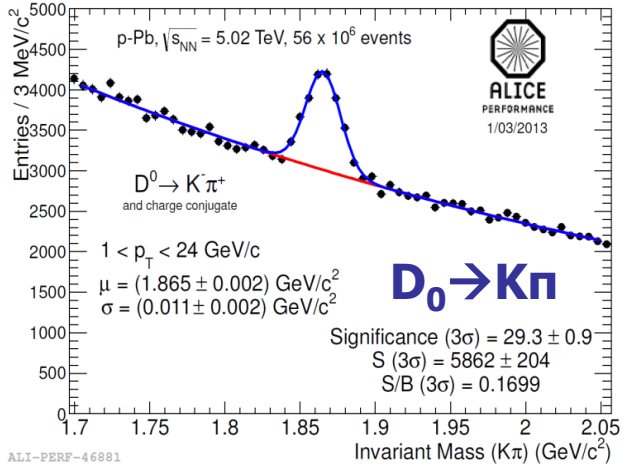


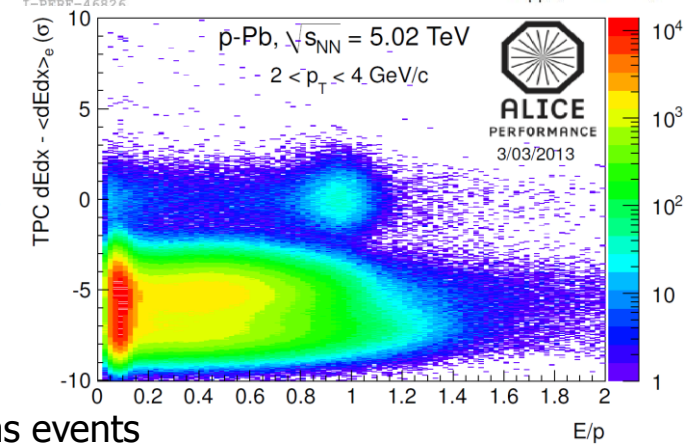
- Elliptic flow measured using the 'event' plane method
- STAR: v_2 compatible with zero for all p_T range → ALICE: hint for non-zero v_2 in both
  - 20-60% central events in $2 < p_T < 4$ GeV/c
  - 5-20% and 20-40% central events for $1.5 < p_T < 10$ GeV/c
- Qualitative agreement with transport models including regeneration
- Complements indications obtained from R_{AA} studies

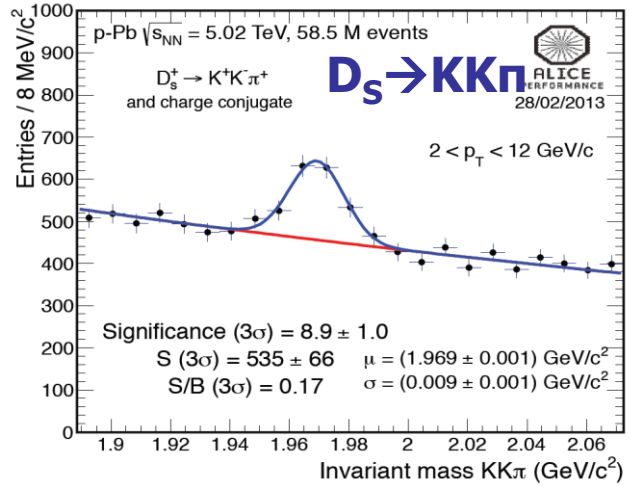
Prospect for p-Pb collisions











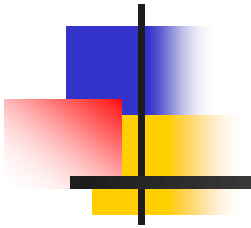
- Collected statistics:
  - ~133 M minimum bias events
  - 5.4nb^{-1} p-Pb + 6.0nb^{-1} Pb-p triggered dimuons events

- The quality checks show good performance for tracking and PID at central rapidity
- D^{*+}, D^0, D^+ and D_S signals are clearly visible with large significances and S/B in a large p_T range
- J/ψ signal clearly visible in both central and forward rapidity regions
- Good quality measurements expected soon

Conclusions

- pp: good agreement for all HF cross sections with theoretical models based on QCD

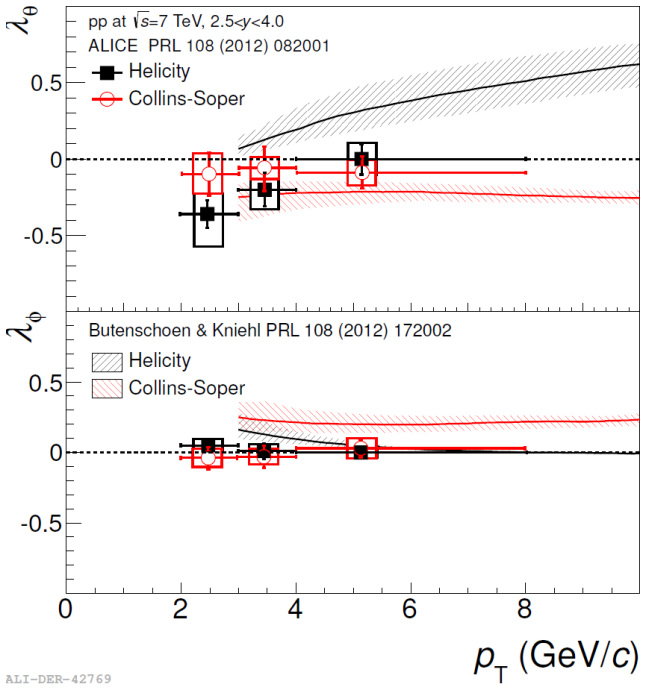
- PbPb collisions:
  - Open charm:
    - Nuclear Modification Factor (R_{AA}) and elliptic flow (v_2) have been studied as a function of p_T and centrality
    - Strong suppression (a factor 2-4) in the most central collisions
    - Hint of the expected hierarchy in the nuclear modification factors: $R_{AA}(B)>R_{AA}(D)>R_{AA}(light)$
  - Hidden charm, i.e. J/ψ:
    - R_{AA} for the J/ψ systematically higher than at RHIC (by a factor ~3 for central events)
    - Smaller J/ψ suppression at low p_T, contrary to RHIC/SPS data, and consistent with a significant contribution of (re)generated J/ψ
    - Hints for non-zero v_2 of the J/ψ at intermediate p_T, as expected in a (re)combination scenario



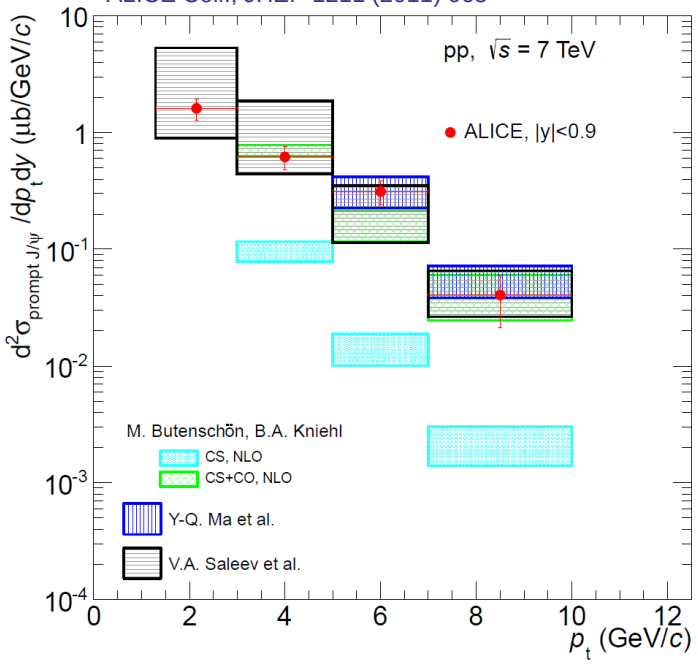
Back-up

Quarkonium production in pp @ 7 TeV

ALICE Coll. PRL 108 (2012) 082011

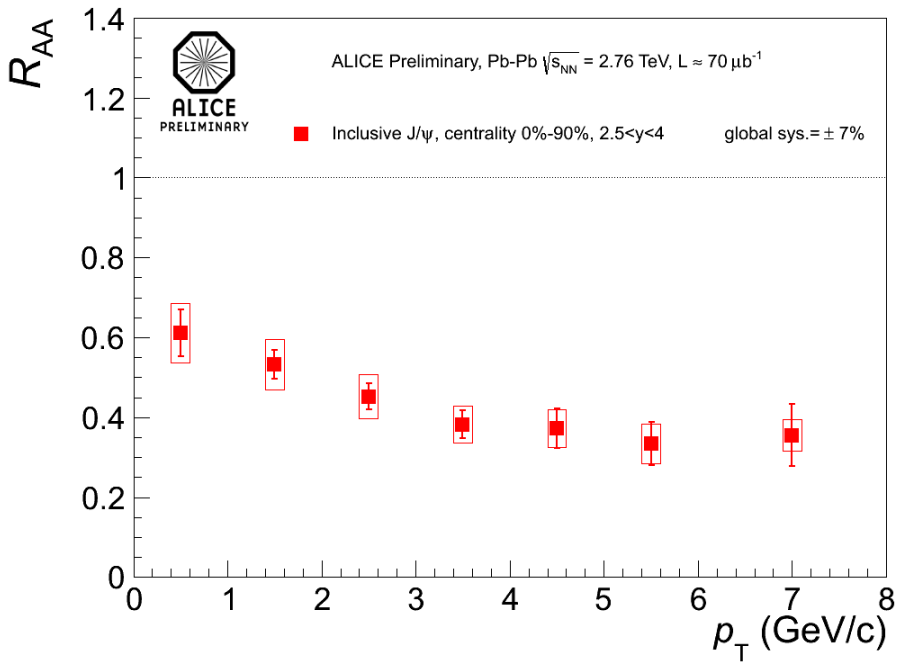


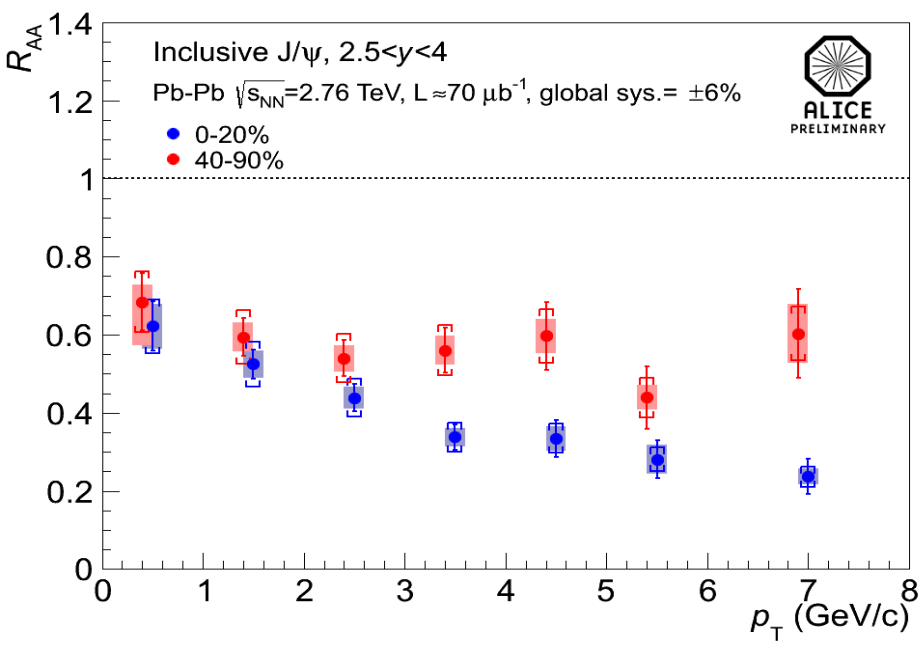
ALICE Coll., JHEP 1211 (2011) 065



- Polarization and prompt J/ψ cross section measured at forward and central rapidity respectively
  - good agreement with NRQCD calculations at central rapidity
  - polarization NLO NRQCD calculations [Butenschoen and Kniehl, Phys. Rev. Lett. **108**, 172002] are in fair agreement with our data

J/ψ nuclear modification factor at forward rapidity

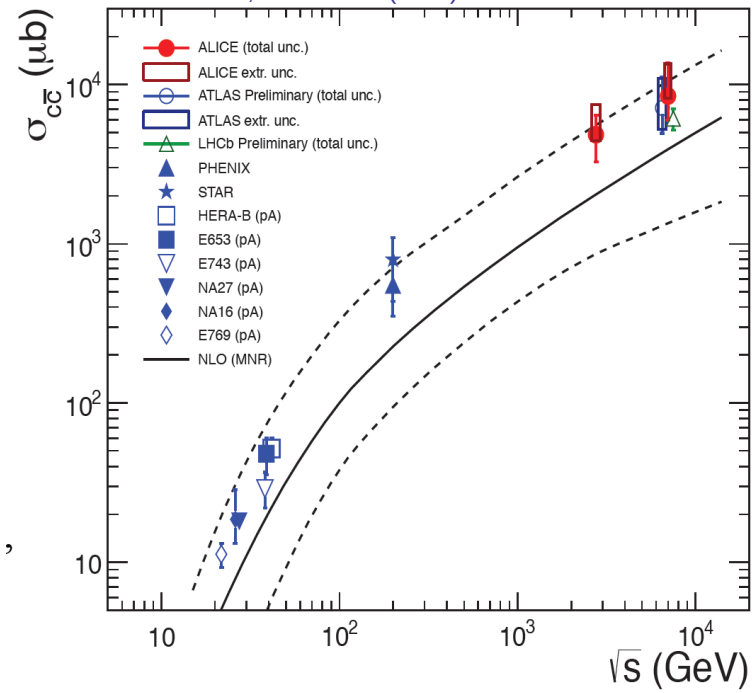




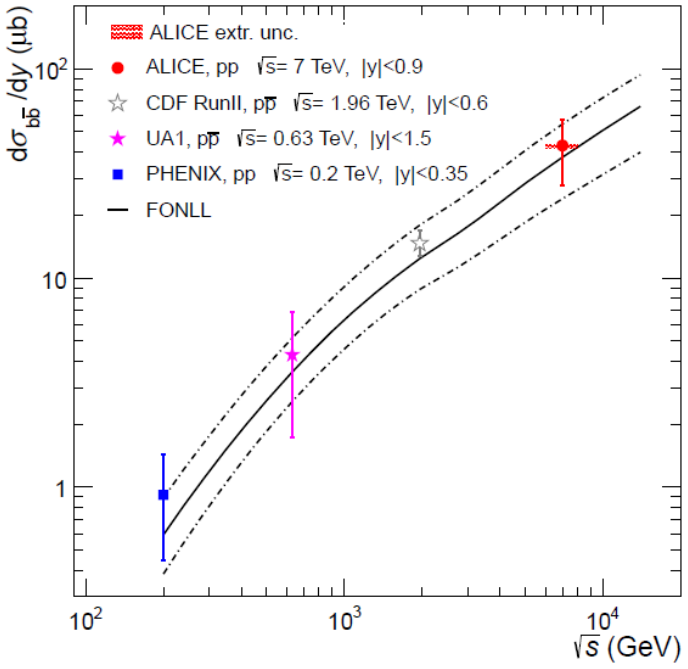
- R_{AA} is measured at forward rapidity (2.5 < y < 4) as a function of p_T and in different centrality ranges
- Stronger suppression observed for high p_T J/ψ (R_{AA} ~ 0.6 at low p_T and becomes ~0.35 at high p_T)
- Splitting in centrality bins we observe that the difference low vs high p_T suppression is more important for central collisions

Open HF results @ 7TeV

ALICE Coll., JHEP 1207 (2012) 191



ALICE Coll., JHEP 1211 (2011) 065



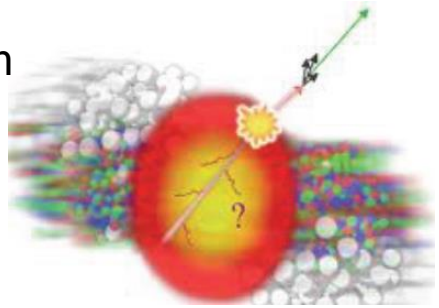
- total charm and beauty production cross sections at mid rapidity confirm the expected trend vs √s

Motivations for studing heavy flavour (2)

- Parton energy loss:
  - medium-induced gluon radiation: $\Delta E \propto \alpha_s C_r \hat{q} L^2$ → gluon radiation of heavy quarks is suppressed (Casimir factor, "dead cone" effect)

$$\Delta E_{u,d,s} > \Delta E_c > \Delta E_b \longrightarrow R_{AA}(\pi) > R_{AA}(D) > R_{AA}(\mathrm{B})$$

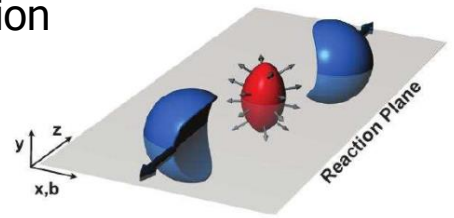
where $R_{AA} = \frac{1}{<N_{coll}>} \frac{\frac{dN_{AA}}{dp_t}}{\frac{dNpp}{dp_t}}$ is the **nuclear modification factor**

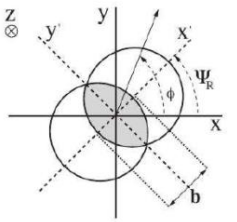


- Initial space asimmetry → elliptic flow
  - quantified by the second term of the fourier expansion

$$\frac{\mathrm{d}N}{\mathrm{d}\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \dots\right)$$

  - $v_2 > 0$ → heavy quarks are thermalized in the QGP





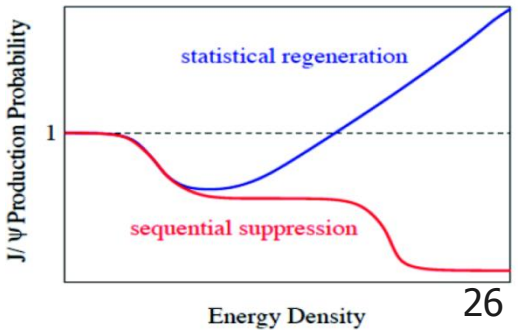
- Quarkonia suppression in the QGP:
  - J/ψ suppression via color screening → QGP signature

T. Matsui and H. Satz, Phys. Lett. B178, 416 (1986).

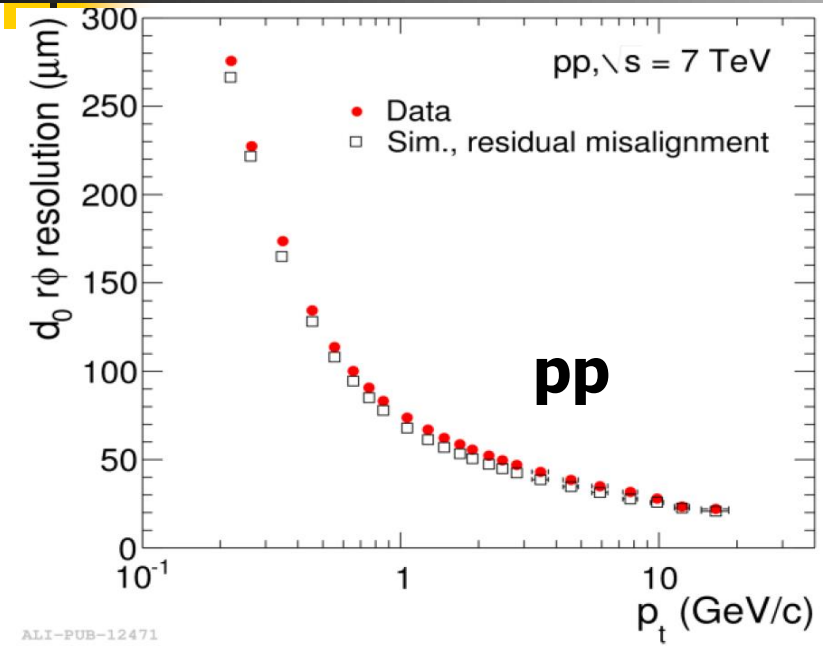
  - Regeneration mechanisms can counteract suppression at LHC energies

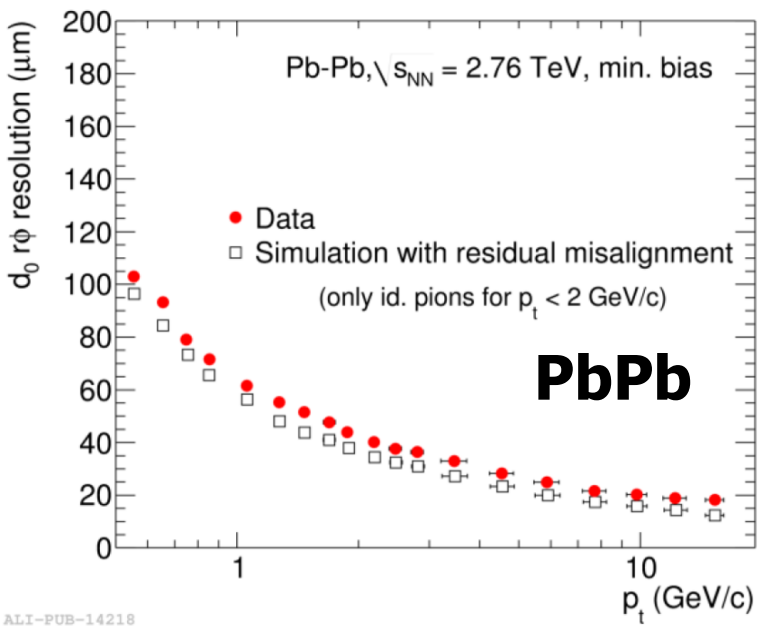
P. Braun-Munzinger and J. Stachel, Phys. Lett. B490, 196 (2000)

R.L. Thews, M. Schroedter, and J. Rafelski, Phys. Rev. C63, 054905 (2001).



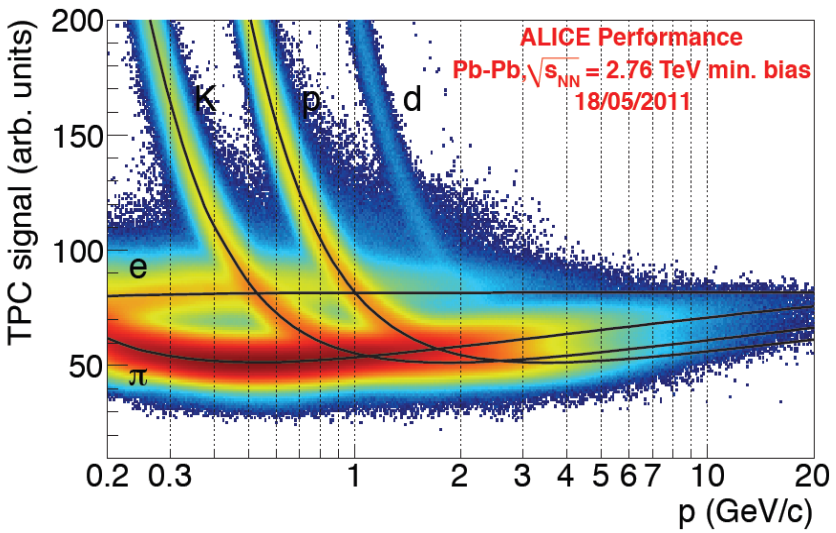
The ALICE detector – performances (1)

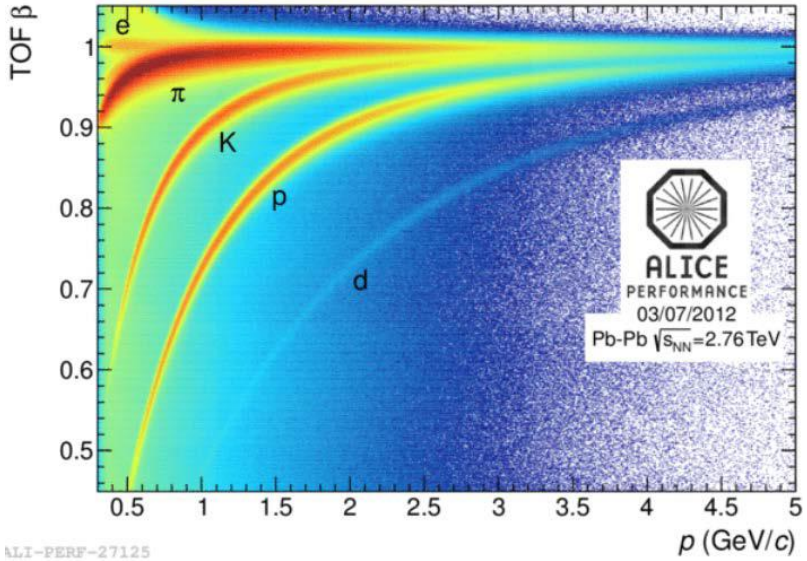




- Excellent impact parameter resolution at low p_t (~ 60-70μm for p_t = 1 GeV/c, better for PbPb) thanks to the two layers of silicon pixel detectors (SPD)
  - Open heavy flavour: tracking and vertexing precision crucial → analysis based on secondary vertex detection ($c\tau$~123μm for D^0, $c\tau$~312μm for D^+, $c\tau$~59μm for Λ_c)
  - Quarkonia: measurement of non-prompt J/Ψ coming from beauty hadron decays (at central rapidity)

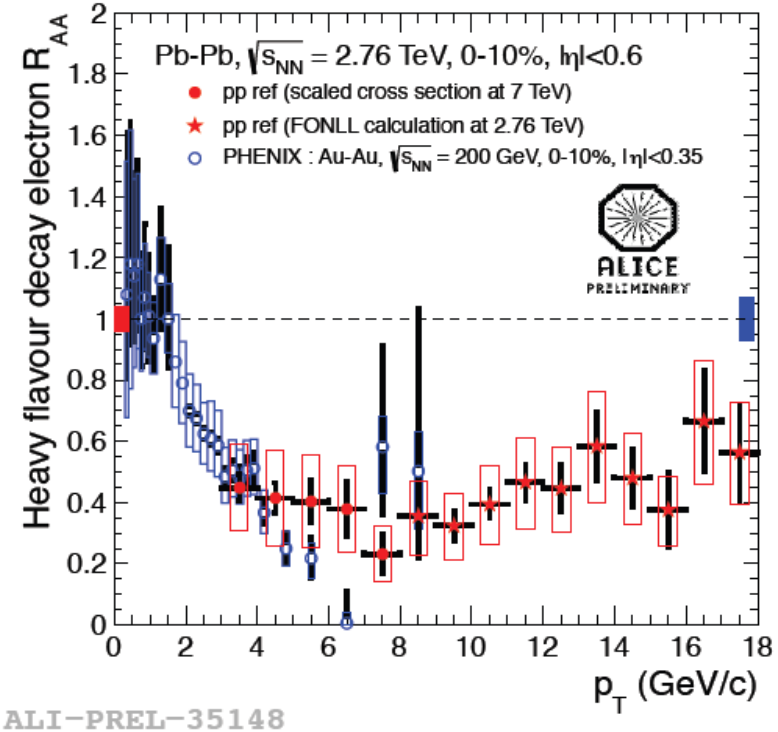
The ALICE detector – performances

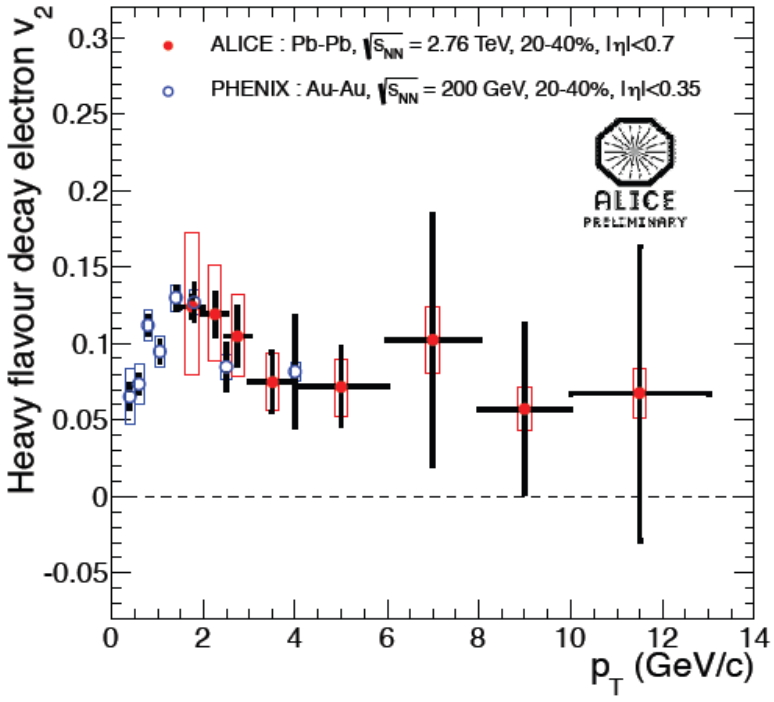




- Particle identification at central rapidity (|y|<0.9):
  - crucial for electron identification for quarkonia and single heavy flavour electron measurements
  - combined PID with TOF and TPC helps to reject background at low p_t
- Muon identification at forward rapidity (2.5<y<4):
  - Hadron contamination and low p_t muons removed by a single track p_t trigger in the muon spectrometer

HFE R_{AA} and v2 at RHIC and LHC

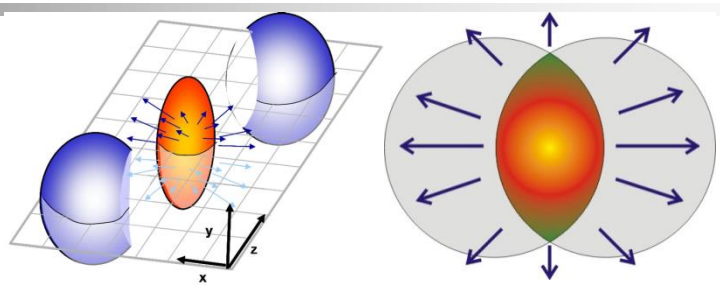




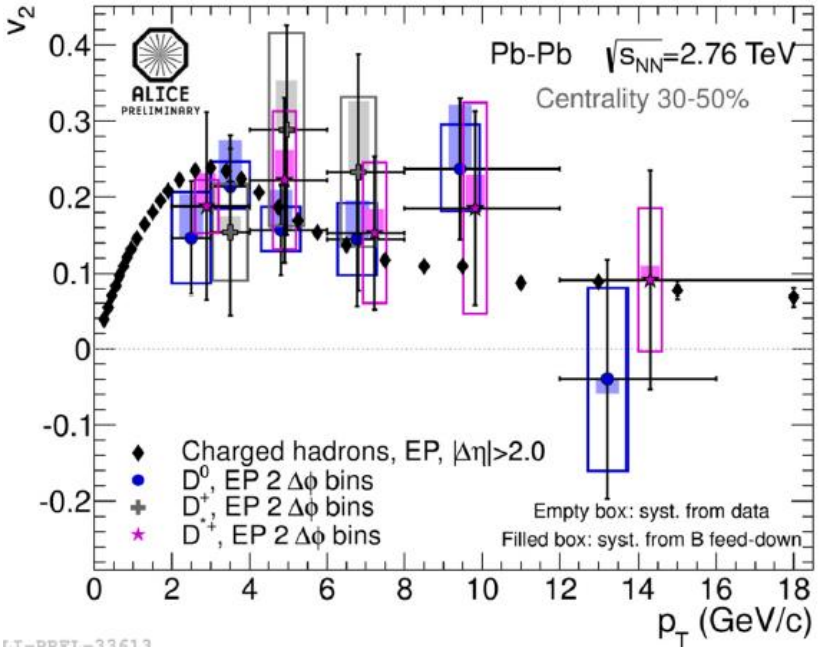
→Similar magnitude of heavy flavor electron R_{AA} ($3<p_T<9$ GeV/c) and v_2 ($1.5<p_T<4$ GeV/c) at $\sqrt{S_{NN}}$=200 GeV (PHENIX) and $\sqrt{s_{NN}}$=2.76 TeV (ALICE)

Elliptic flow for D mesons

- Elliptic flow measured using the event plane method:
  $v_2 = \langle \cos(2(\phi - \psi_{RP})) \rangle$



$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$



B feed-down subtraction:

- the measured elliptic flow v^{obs}_2 is a combination of the elliptic flows of prompt D and D from B feed-down1

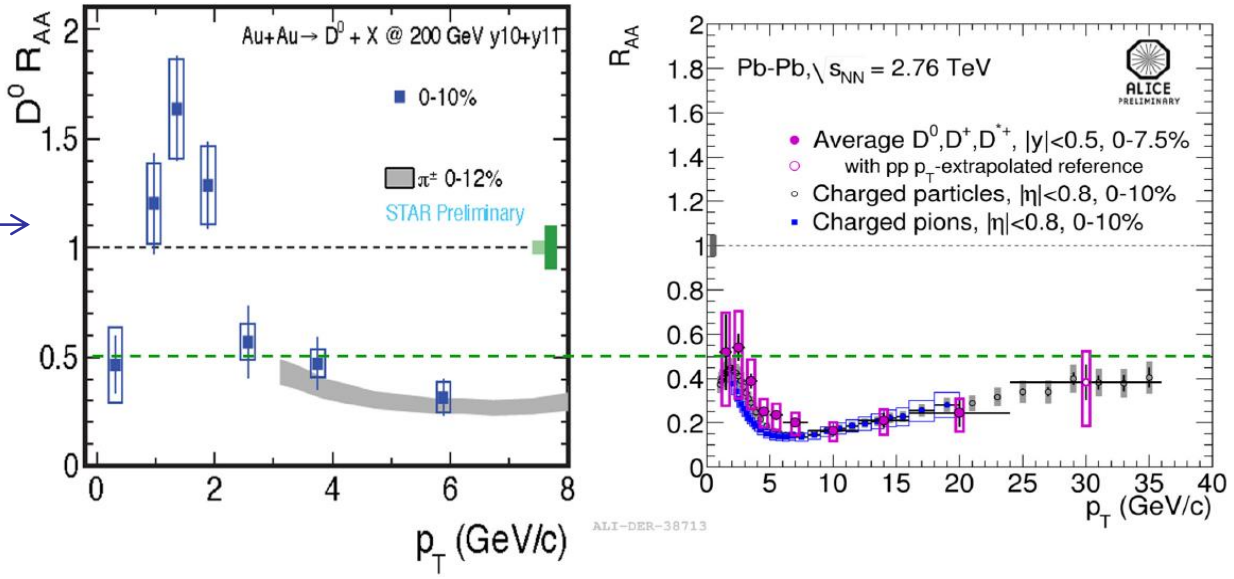
$$v^{obs}_2 = f_{prompt} v_{2\text{-prompt}} + (1 - f_{prompt}) v_{2\text{-feed-down}}$$

- f_{prompt} is estimated from MonteCarlo simulations and FONLL predictions

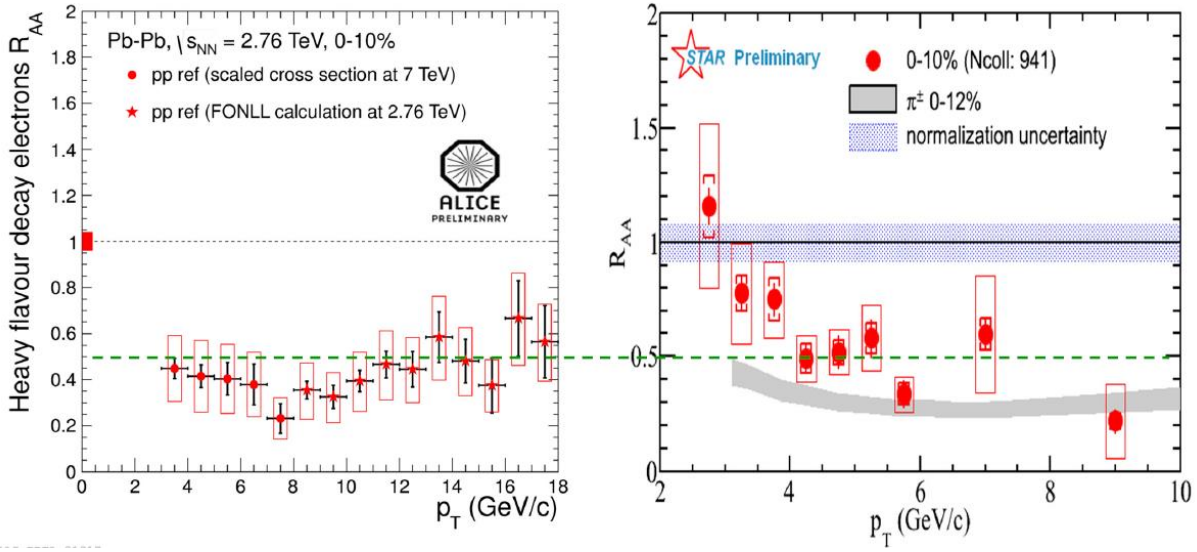
- assumption: $v_{2\text{-feed-down}} = v_{2\text{-prompt}}$
(systematics: $0 \le v_{2\text{-feed-down}} \le v_{2\text{-prompt}}$)

LHC vs RHIC: D mesons and HFE R_{AA}

D mesons →



HFE →

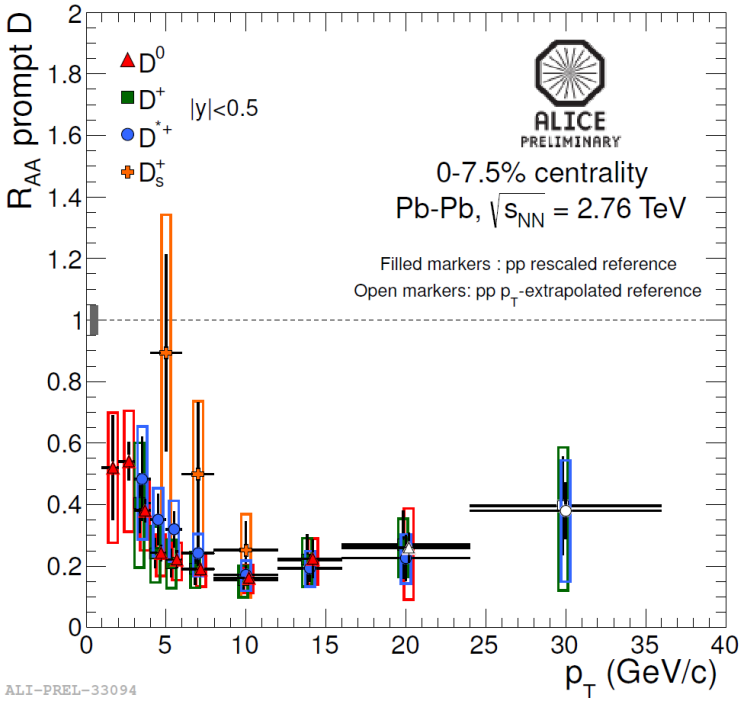


Nuclear modification factor for D mesons

R_{AA} measured for D^0, D^+, D^{*+}

$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

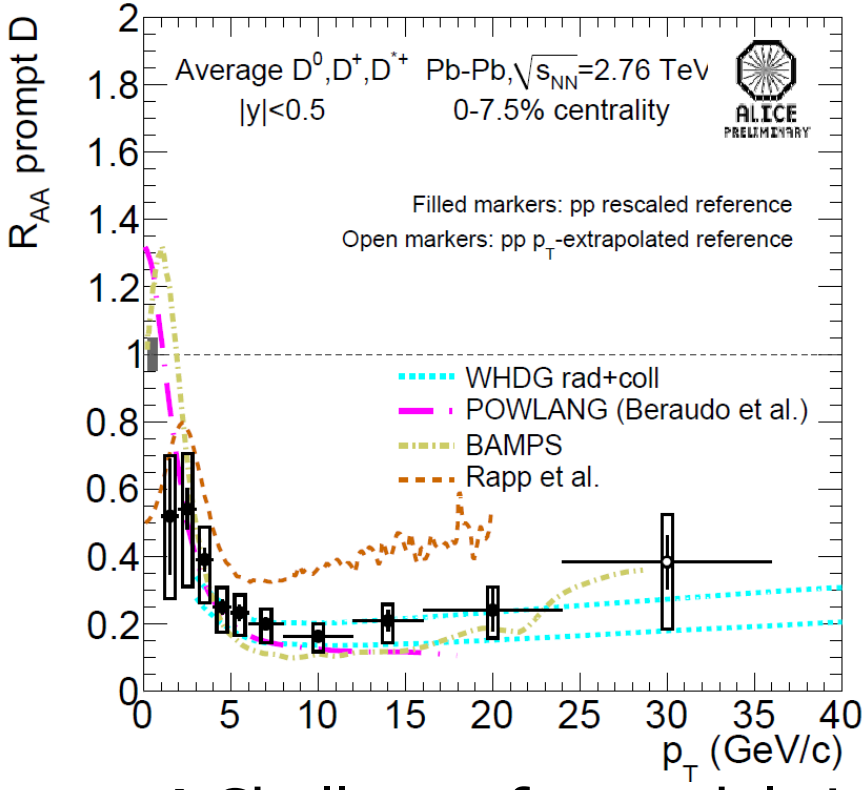
- R_{AA} = 1 indicates no nuclear modification
- R_{AA} < 1 indicates energy loss
- $R_{AA}(B) > R_{AA}(D) > R_{AA}(light)$ due to color charge and quark mass effects in parton energy loss

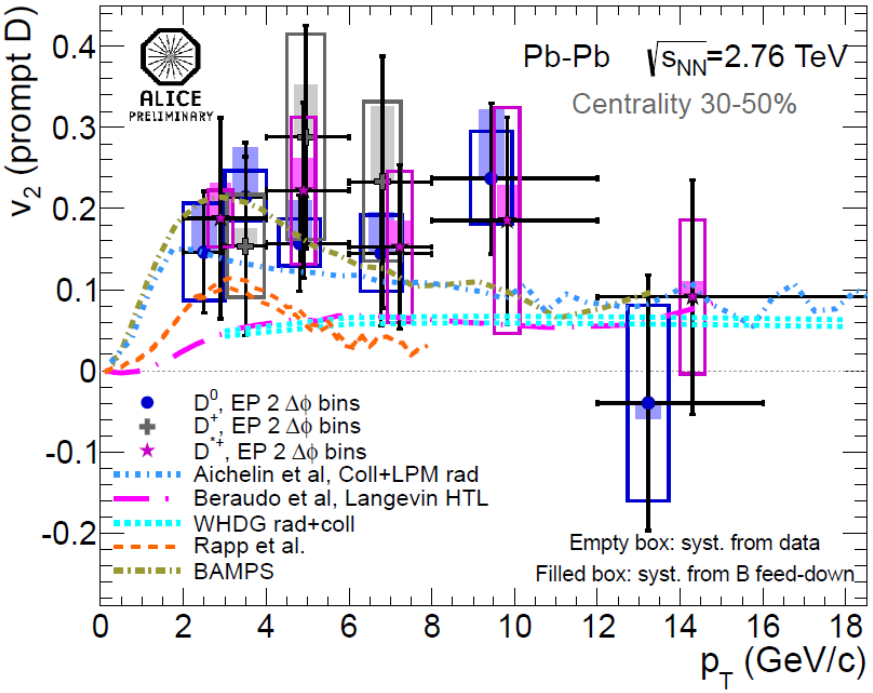


- Feed down from B (10-15% after cuts) subtracted using pQCD (FONLL) predictions
  - Plus in PbPb hypothesis on R_{AA} of D from B ($1.3 < R_{AA\text{-feed-down}}/R_{AA} < 3$)

Comparison with models (2)

R_{AA} and v_2 for D mesons

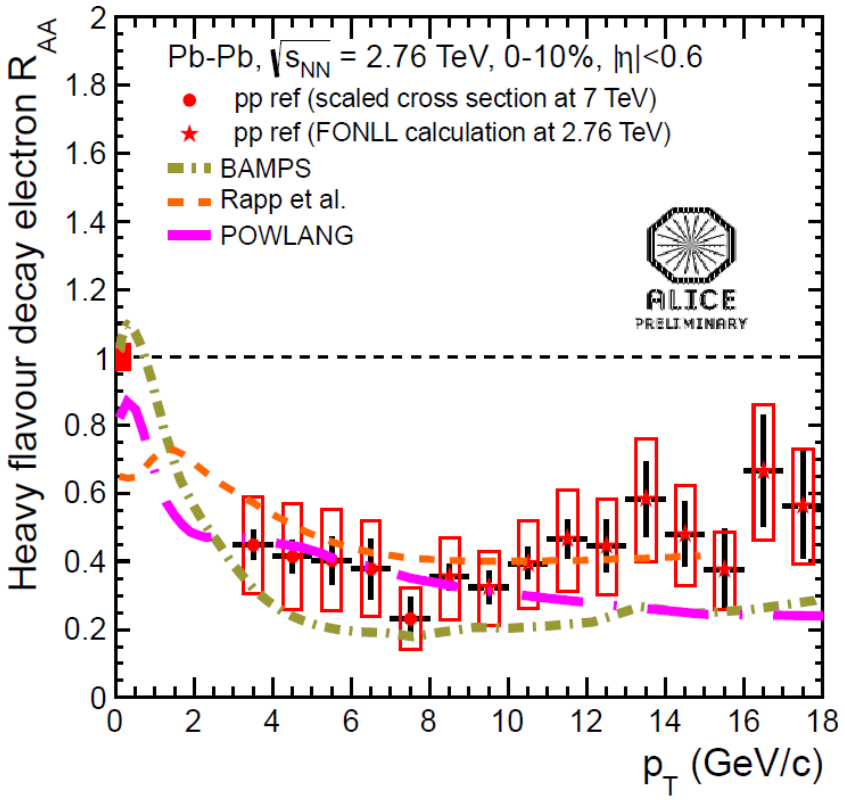


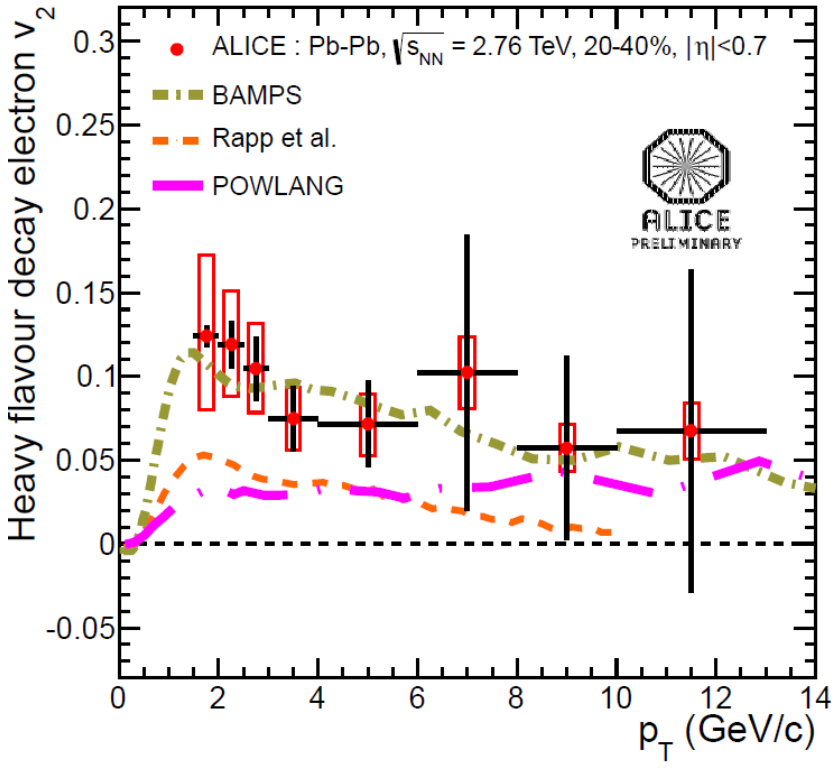


→Challenge for models implementing parton propagation in a deconfined medium to reproduce suppression and elliptic flow simultaneously

Comparison with models (2)

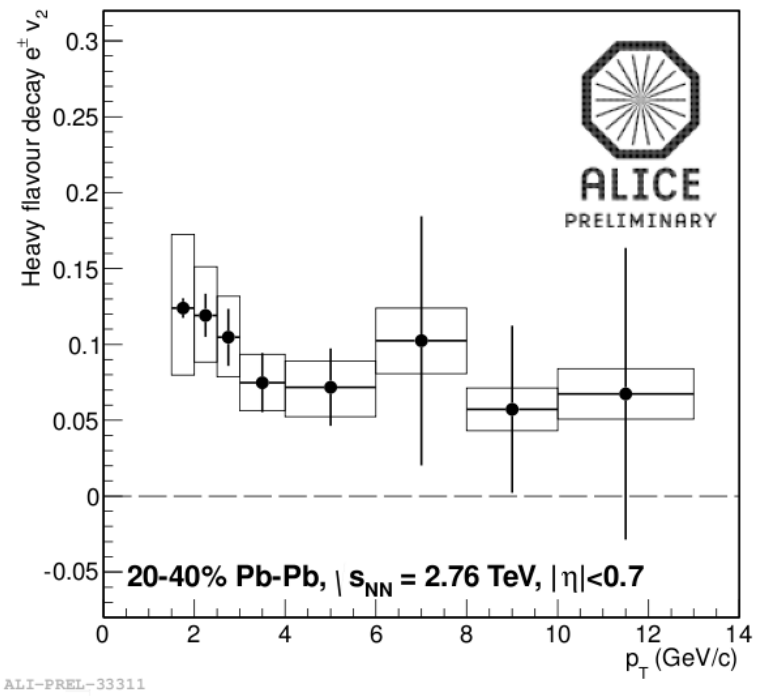
R_{AA} and v_2 for HF electrons





→Challenge for models of parton propagation in a deconfined medium to reproduce suppression and elliptic flow simultaneously

HFE elliptic flow



- 20-40% central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (2010 and 2011 data)
- Electron identification with TPC+TOF and TPC+EMCal
- TPC+TOF - Minimum bias and centrality trigger
- TPC+EMCal - EMCal and centrality triggers
- Background electron v2:
  - Calculated via cocktail using measured v2 of main electron background sources

Event plane method:

$$v_2^{HF\,e} = \frac{(1+R)\,v_2^{incl.\,e} - v_2^{backg.e}}{R} \qquad \text{where} \quad R = N^{HFe} / N^{backg.e}$$