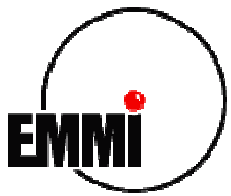
# Heavy-flavor measurements in pp and Pb-Pb collisions with the ALICE experiment at the CERN LHC

**Ralf Averbeck**
**ExtreMe Matter Institute EMMI and Research Division**
**GSI Helmholtzzentrum für Schwerionenforschung**
**Darmstadt, Germany**







**on behalf of the ALICE Collaboration**

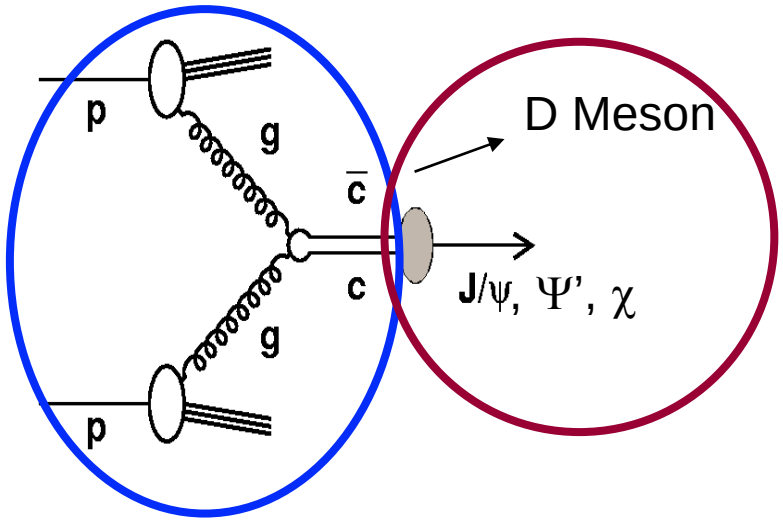

**LHC on the March**
**November 16-18, 2011**
**IHEP, Protvino, Russia**

# Outline

- introduction: heavy flavor in pp and AA collisions
- ALICE: setup and data sets
- heavy-flavor measurements with ALICE
  - D mesons at mid-rapidity
  - $e^{\pm}$ from semileptonic decays at mid-rapidity
  - $\mu^{\pm}$ from semileptonic decays at forward rapidity
- heavy flavor in pp collisions at $\sqrt{s}$ = 7 TeV (and 2.76 TeV)
  - does perturbative QCD work?
  - pp reference for $\sqrt{s}$ = 2.76 TeV from pQCD scaling
- heavy flavor in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
  - how does the medium modify heavy-flavor observables?
- summary

# Introduction

- heavy quark (charm, beauty) production in pp collisions
  - $m_c$~1.3 GeV, $m_b$~4.5 GeV
  - produced early via hard scattering processes
  - open heavy flavor
  - quarkonia (J/ψ, ϒ) → F. Bossu
  - crucial test for perturbative QCD calculations (new LHC energy regime)
  - baseline for studies in pA and AA collisions



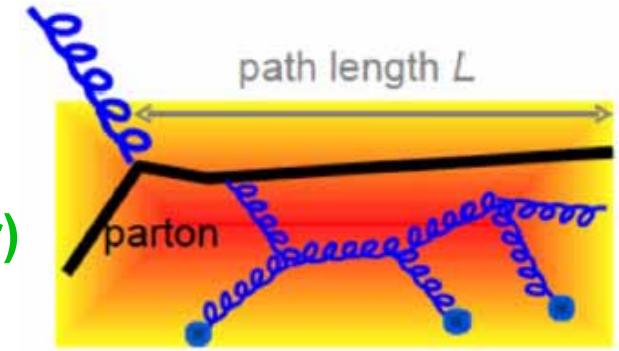

- heavy flavor in pA collisions
  - cold nuclear matter effects
    - shadowing
    - Cronin effect, $k_t$ broadening
    - gluon saturation

# Introduction

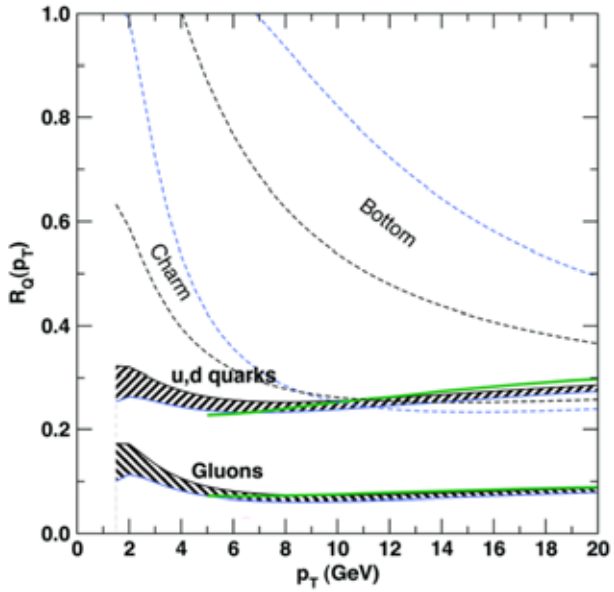
- heavy flavor in AA collisions
  - early production of heavy quarks
    → probes of the produced hot & dense QCD medium
  - energy loss ΔE of partons via induced gluon radiation while traversing the medium
    - color charge dependent (Casimir factor)
      → $\Delta E_{gluon} > \Delta E_{quark}$
    - mass dependent (dead cone effect, Dokshitzer & Kharzeev, PLB 519(2001)199)
      → $\Delta E_{gluon} > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
    - experimentally accessible via nuclear modification factor

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

    - expectation: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
    → not observed at RHIC

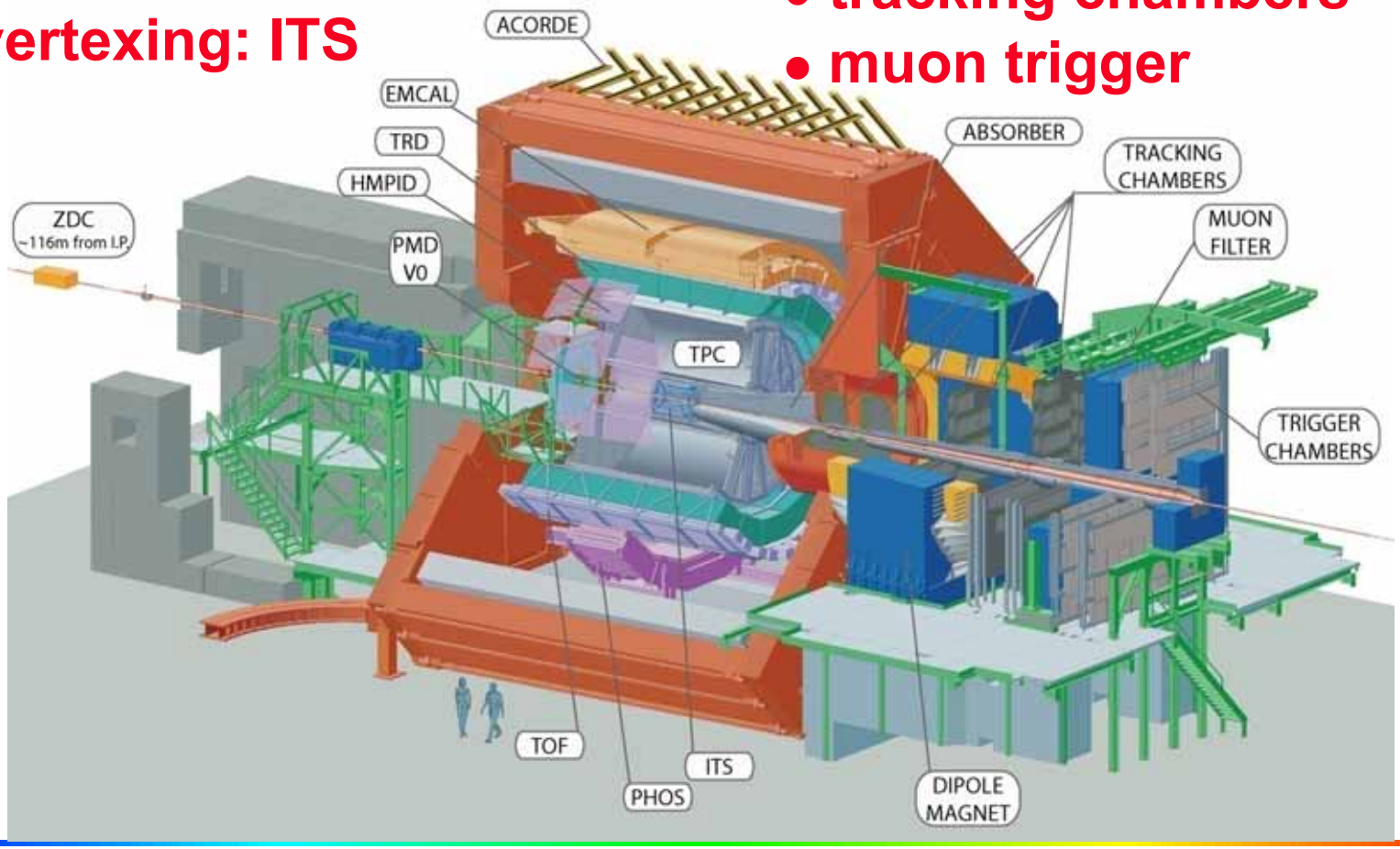



Wicks et al, Nucl. Phys. A784 (2007) 426



# ALICE apparatus

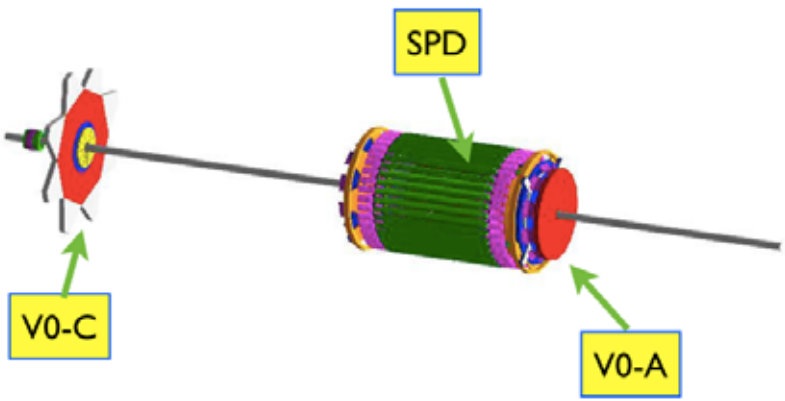
- central barrel ($|\eta|<0.9$)
  - tracking: ITS+TPC+TRD
  - PID: TPC+TOF+TRD+EMCal
  - vertexing: ITS
- muon spectrometer ($-4.0 < \eta < -2.5$)
  - absorber
  - tracking chambers
  - muon trigger



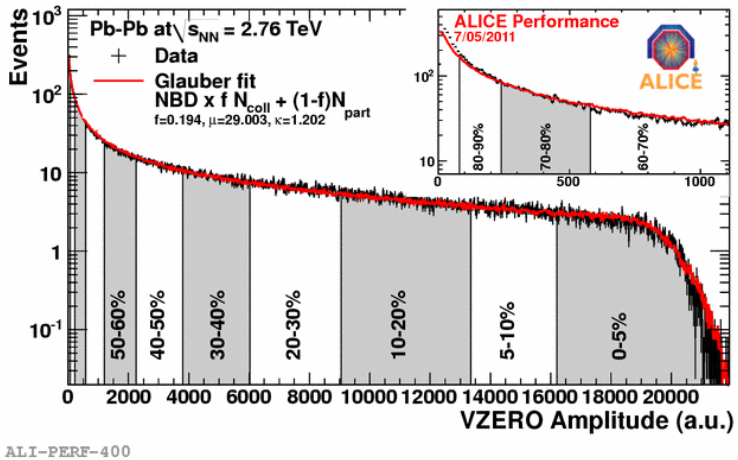
# Data sets and MB trigger (2010)

| system | pp | pp | Pb-Pb |
|---|---|---|---|
| $\sqrt{s_{NN}}$ (TeV) | 7 | 2.76 | 2.76 |
| $N_{MB}$ | $\leq 3 \times 10^8$ | $6.5 \times 10^7$ | $1.7 \times 10^7$ |

- **pp collisions**
  - **minimum bias (MB) trigger**
    - V0-A or V0-C or SPD (V0: scintillator arrays, SPD: silicon pixel det.)

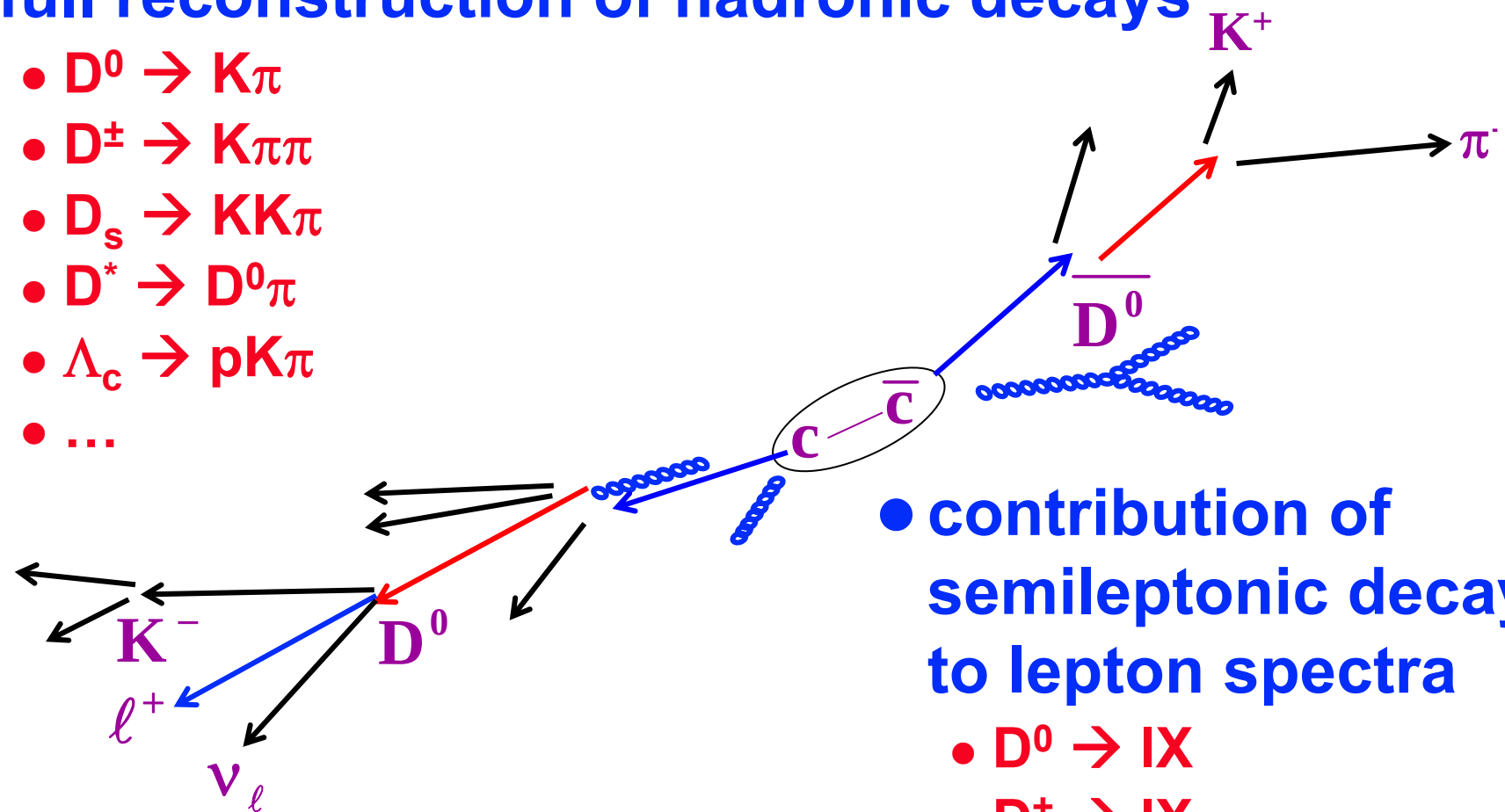



- **Pb-Pb collisions**
  - **MB trigger**
    - V0-A and V0-C and SPD
  - **collision centrality from Glauber fit to V0 signal**



# How to measure heavy flavor

- full reconstruction of hadronic decays
  - $D^0 \rightarrow K\pi$
  - $D^{\pm} \rightarrow K\pi\pi$
  - $D_s \rightarrow KK\pi$
  - $D^* \rightarrow D^0\pi$
  - $\Lambda_c \rightarrow pK\pi$
  - …

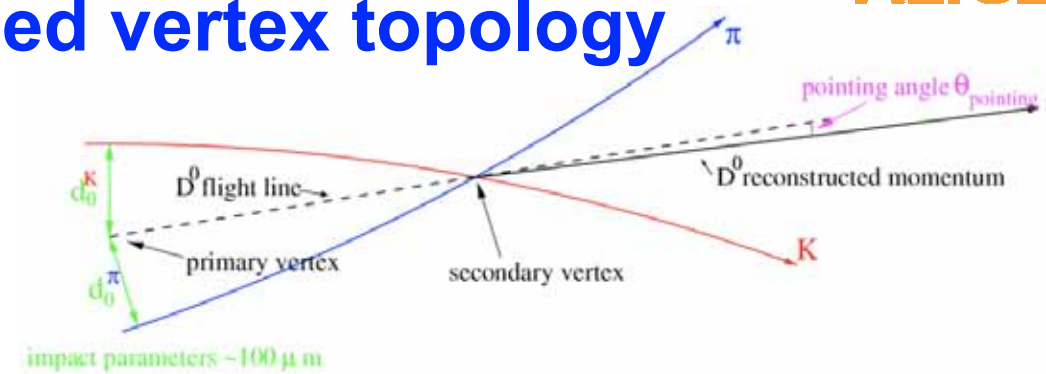



- contribution of semileptonic decays to lepton spectra
  - $D^0 \rightarrow lX$
  - $D^{\pm} \rightarrow lX$
  - $\Lambda_c \rightarrow lX$
  - …

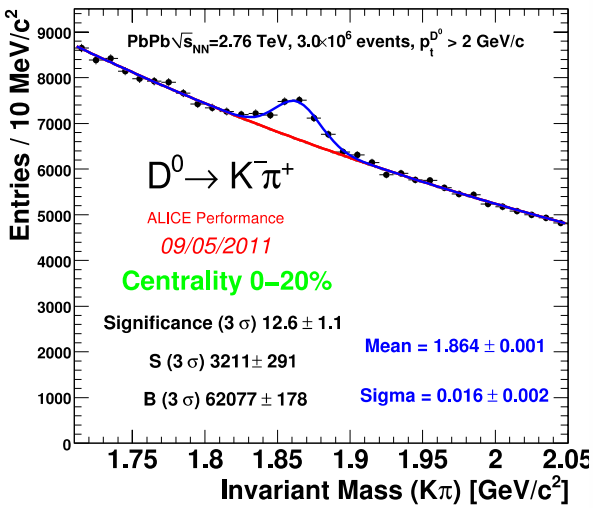
**both approaches are pursued in ALICE**

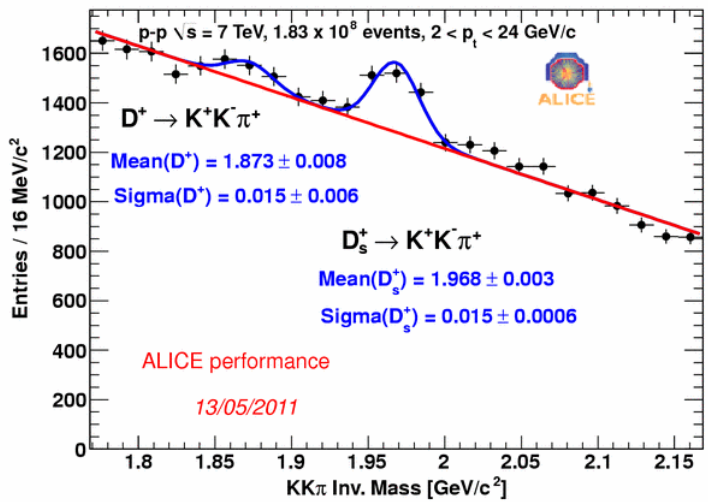
# Hadronic heavy-flavor decays

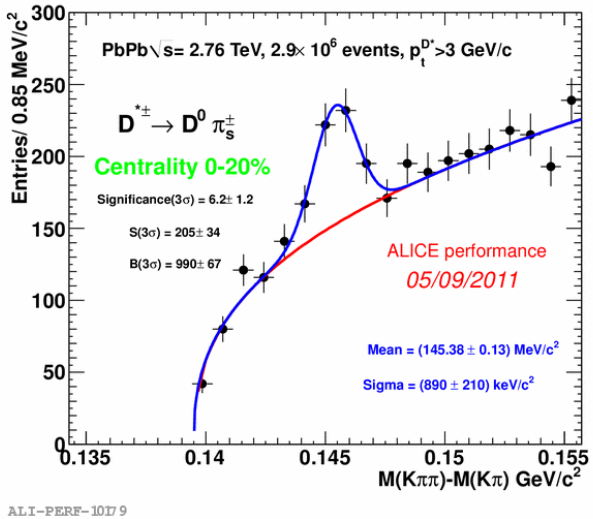
- **key selection: displaced vertex topology**
  - **track reconstruction → TPC + ITS**
  - **particle identification → TPC + TOF**
  - **secondary vertex reconstruction → ITS**




- **performance examples from ALICE central barrel**

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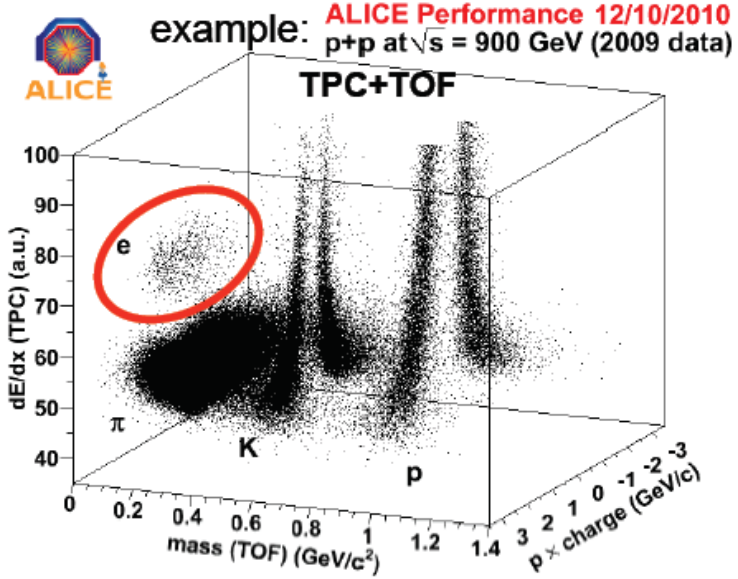
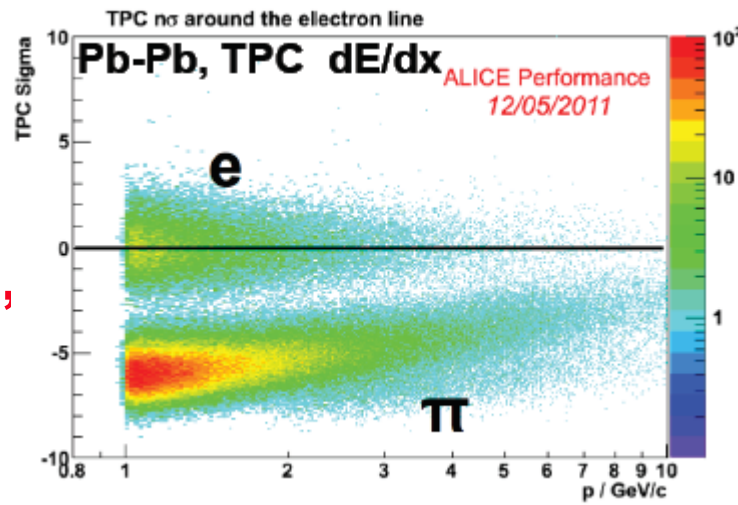
# $e^{\pm}$ from heavy-flavor decays

- step 1: electrons in ALICE central barrel
  - tracks in TPC and ITS (hit in 1st pixel layer ($X/X_0 < 1\%$) → minimize $e^{\pm}$ from $\gamma$ conv.)
  - electron ID
    - TOF → reject K &p (low $p_t$)
    - TPC electron Bethe-Bloch line
    - \+ TRD (currently pp only)
    - \+ EMCal (soon)
  - hadron contamination measured (multi-Gauss fits of TPC dE/dx in slices of p) and subtracted
- step 2: extract HF contribution
  - subtract $e^{\pm}$ background "cocktail"
  - pp only (for now): select $e^{\pm}$ from displaced vertices → beauty



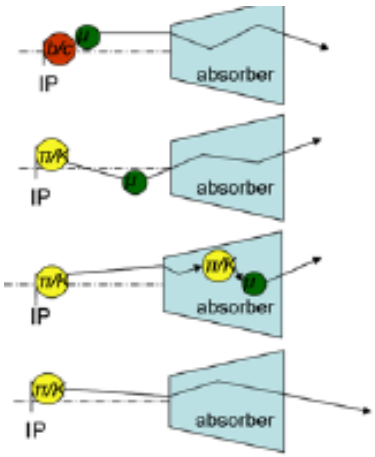



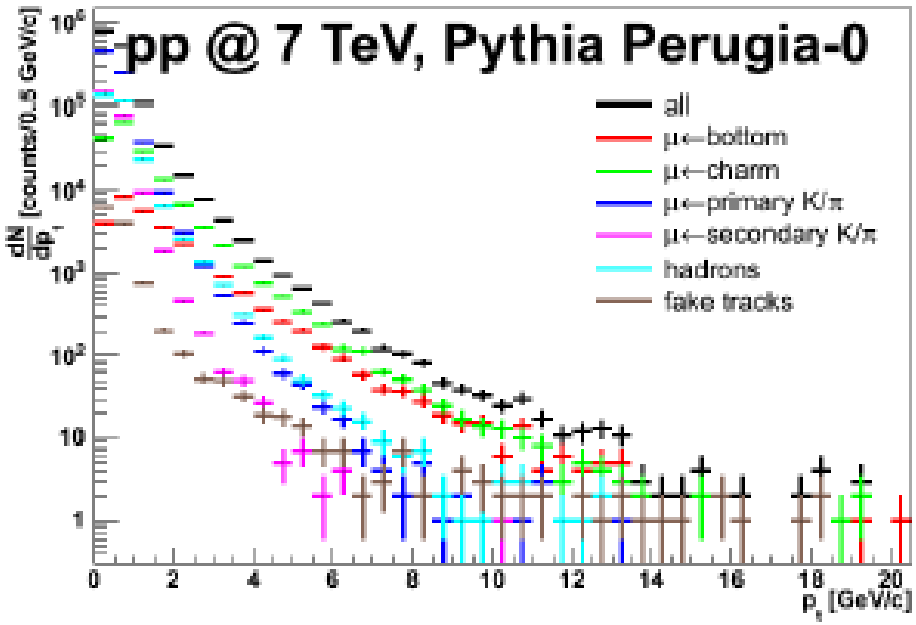
# $\mu^{\pm}$ from heavy-flavor decays

- sources for muons in the ALICE muon spectrometer ($-4 < \eta < -2.5$)
- analysis strategy (pp)
  - remove hadrons and low $p_T$ secondary $\mu^{\pm}$ with muon trigger
  - subtract $\mu^{\pm}$ from $\pi$, K decays using MC (normalized to data at low $p_t$): ~20% @ $p_t > 2$ GeV/c

  → $\mu^{\pm}$ from charm & beauty
- Pb-Pb collisions
  - no subtraction of decay $\mu^{\pm}$ (yet)
  - inclusive $\mu^{\pm}$ at high $p_t$

  → small background contribution only



# HEAVY FLAVOR MEASUREMENTS IN PP COLLISIONS

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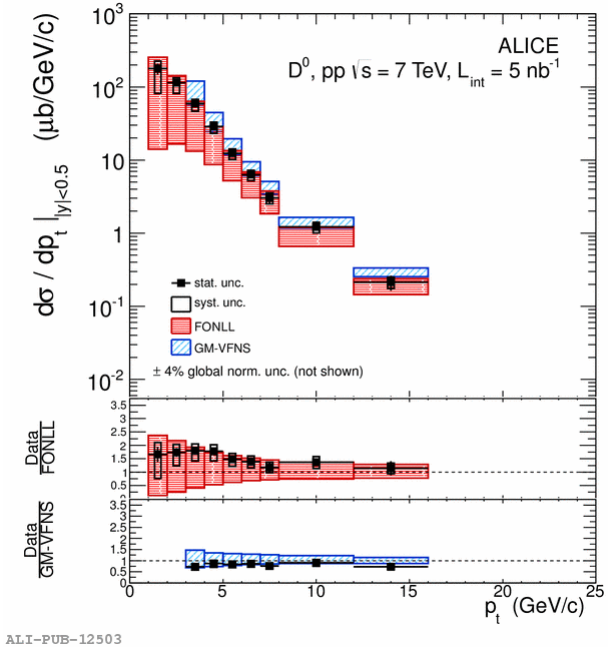
# pQCD at work?

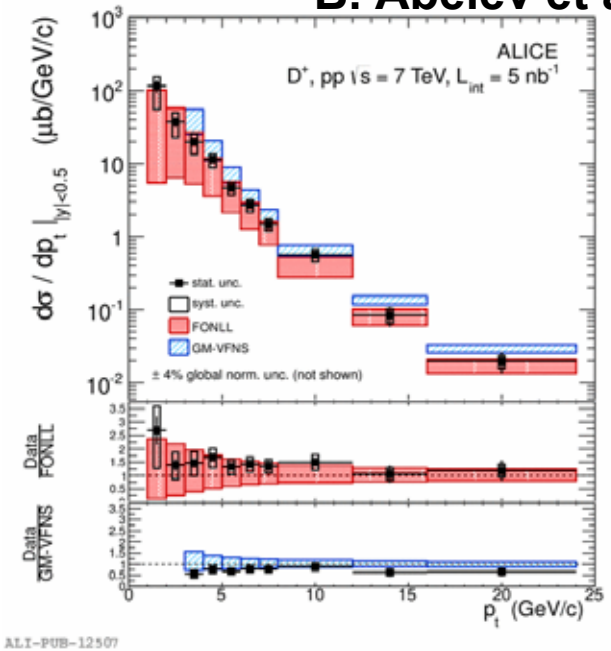
# D mesons at $\sqrt{s}$ = 7 TeV

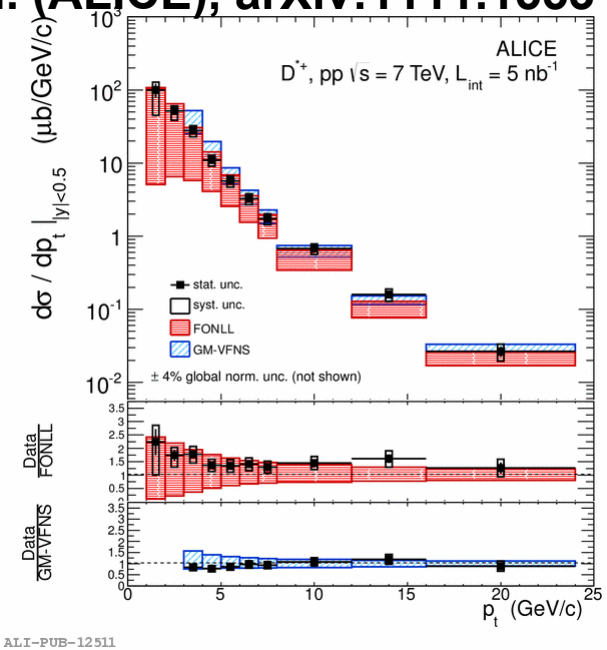
- $p_t$ differential cross section for $D^0$, $D^+$, $D^{*+}$ at mid-rapidity compared with pQCD calculations

$$\left.\frac{d\sigma^{D^0}}{dp_t}\right|_{|y|<0.5} = \frac{1}{2}\frac{1}{2y_{acc}\Delta p_t}\frac{\left. f_{prompt}(p_t)\cdot N^{RawD^0}(p_t)\right|_{|y|<y_{acc}}}{\epsilon_{prompt}(p_t)\cdot BR\cdot L_{int}}$$

B. Abelev et al. (ALICE), arXiv:1111.1553



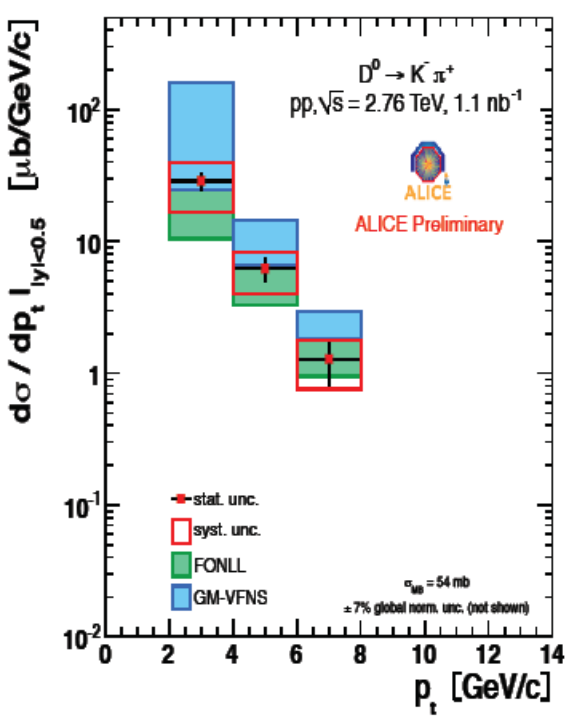



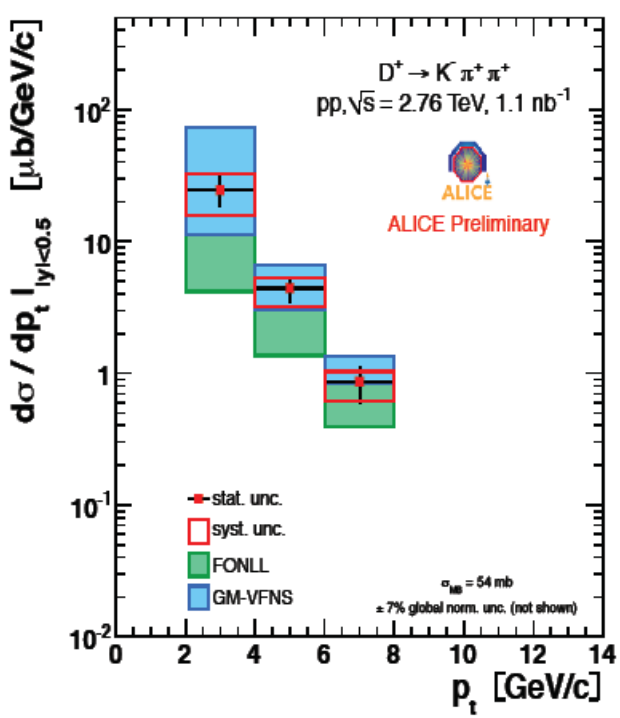



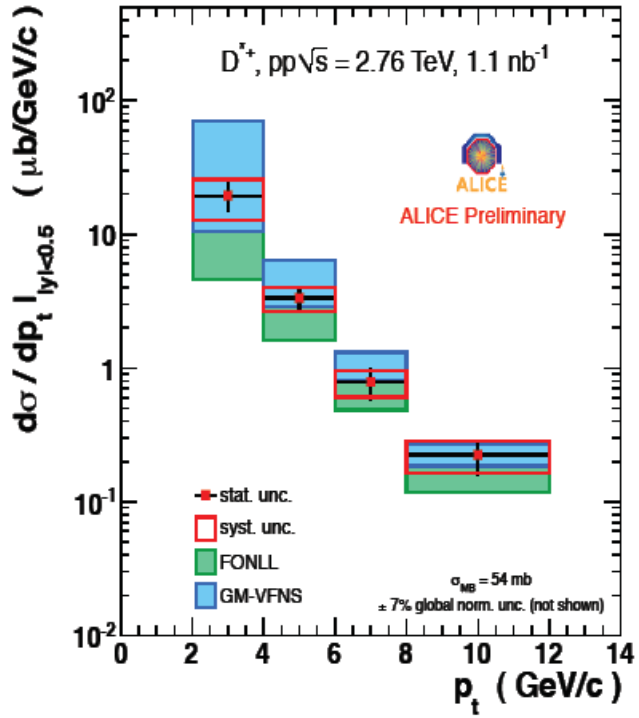

→ FONLL (Cacciari et al., JHEP 9805(1998)007) and GM-VFNS (Kniehl et al., PRL 96(2006)012001) agree with measurement

# D mesons at $\sqrt{s}$ = 2.76 TeV

- $p_t$ differential cross section for $D^0$, $D^+$, $D^{*+}$ at mid-rapidity compared with pQCD calculations
  - 2 days of data taking: integrated luminosity $L_{int}$ = 1.1 nb$^{-1}$



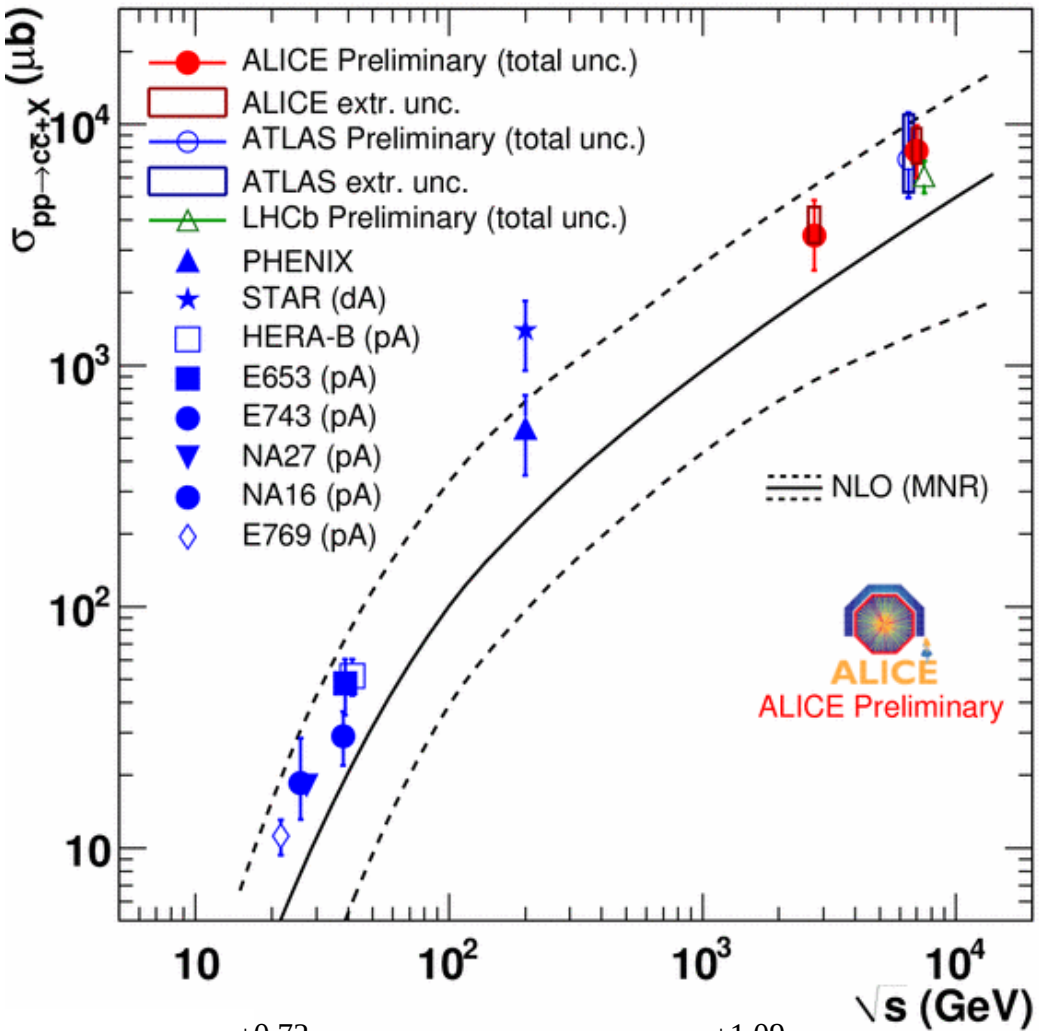




→ FONLL and GM-VFNS compatible with the data

# Energy dependence of $\sigma_{c\bar{c}}$ in pp

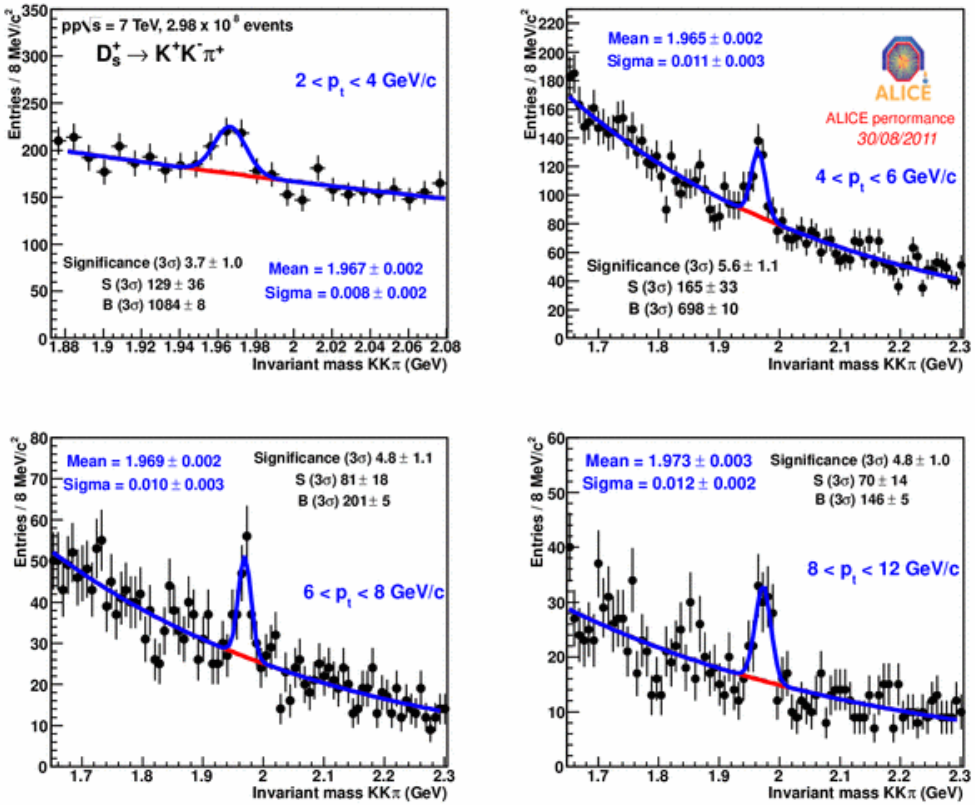
- extrapolation to full phase space using FONLL
  - from $p_t$ = 2 GeV/c to 0 (factor ~2)
  - full rapidity
- measured charm production cross sections in pp are consistent with NLO pQCD for all $\sqrt{s}$




$$\sigma_{c\bar{c}}^{tot}(\mathrm{ALICE}, 2.76\ \mathrm{TeV}) = 3.45 \pm 0.41(\mathrm{stat.})^{+0.72}_{-0.84}(\mathrm{sys.}) \pm 0.17(\mathrm{lum.})^{+1.09}_{-0.24}(\mathrm{extr.})\ \mathrm{mb}$$

$$\sigma_{c\bar{c}}^{tot}(\mathrm{ALICE}, 7\ \mathrm{TeV}) = 7.73 \pm 0.54(\mathrm{stat.})^{+0.74}_{-1.38}(\mathrm{sys.}) \pm 0.44(\mathrm{lum.})^{+1.90}_{-0.87}(\mathrm{extr.})\ \mathrm{mb}$$

# $D_s \rightarrow \phi\pi^+ \rightarrow K^+K^-\pi^+$ at $\sqrt{s}$ = 7 TeV

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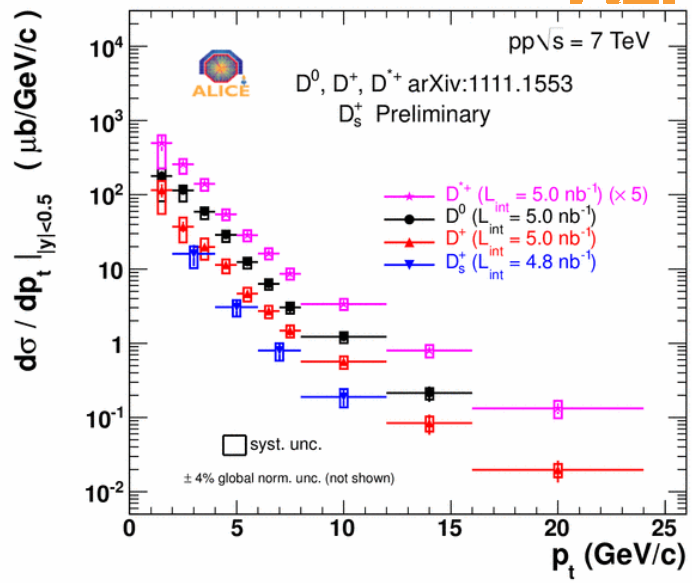


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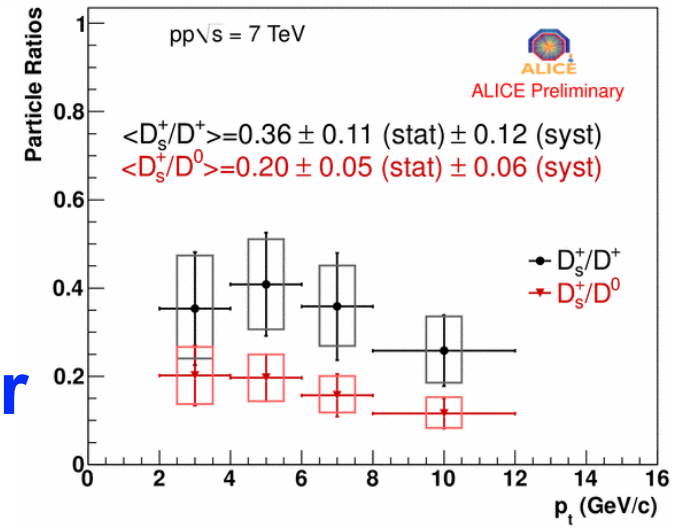


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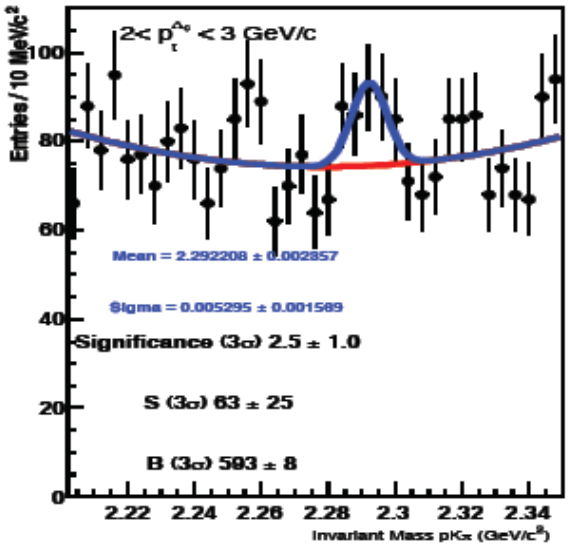
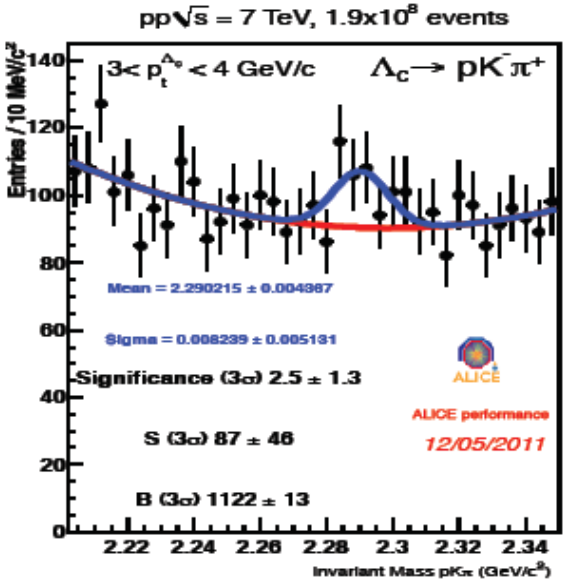
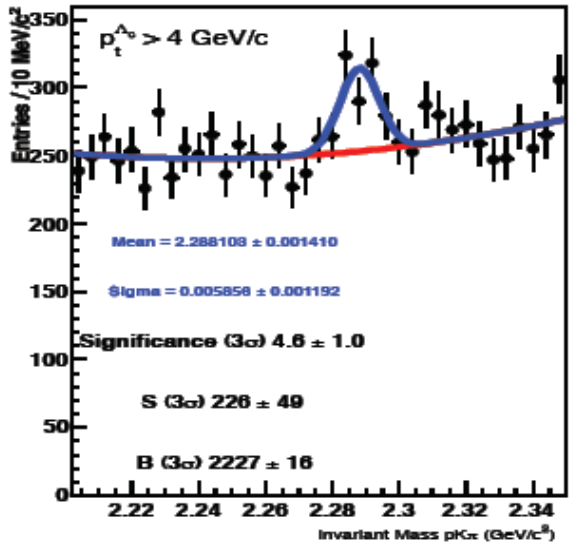
- ratio of $D_s$ to other D mesons consistent with data from other experiments (at different $\sqrt{s}$)

# $\Lambda_c \rightarrow pK^-\pi^+$ at $\sqrt{s}$ = 7 TeV

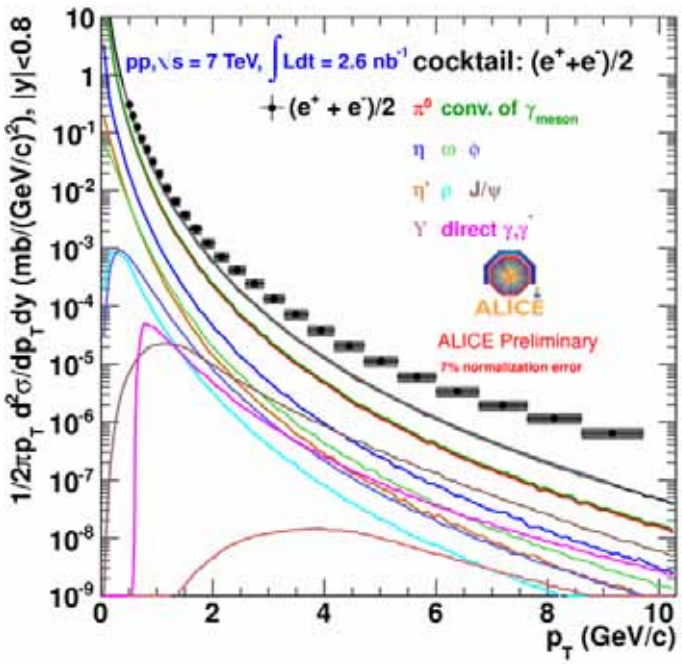
- this is a tough measurement….



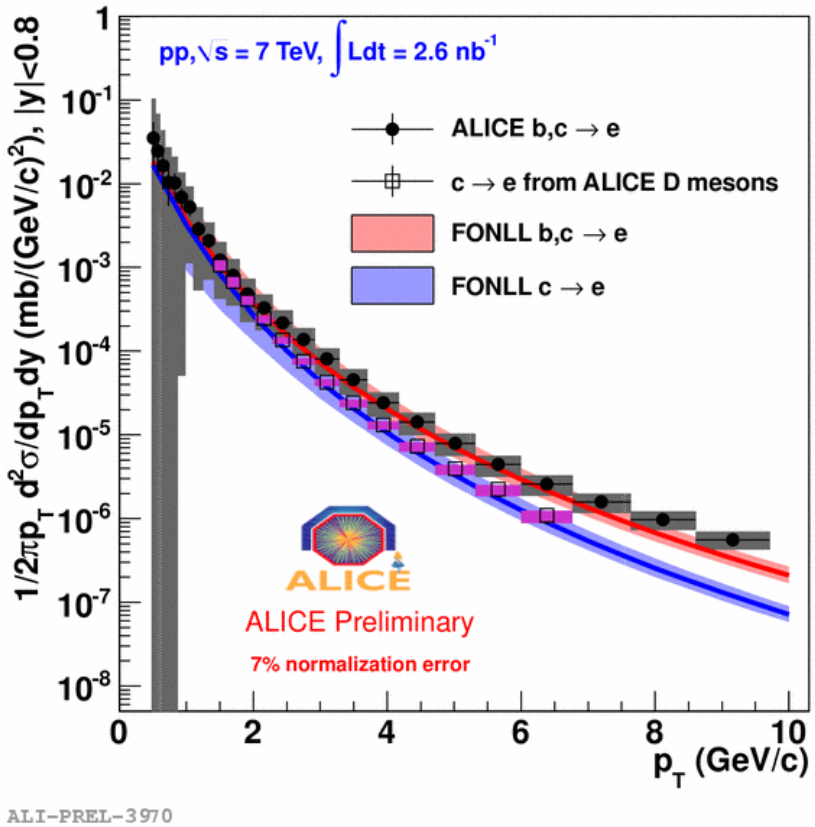



# $e^{\pm}$ from heavy flavor at $\sqrt{s}$ = 7 TeV



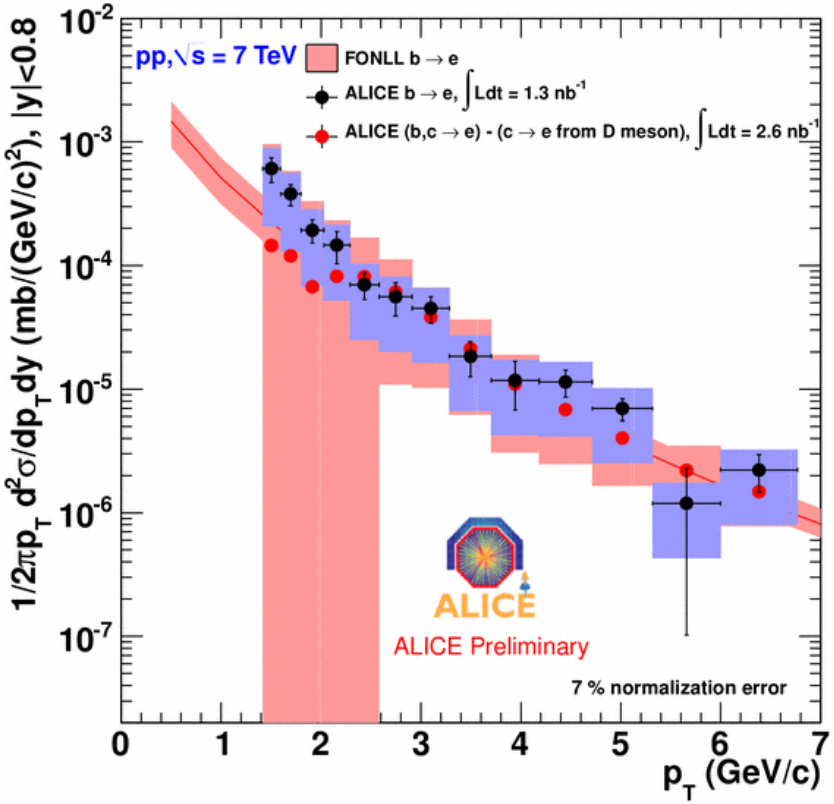

- inclusive $e^{\pm}$ vs. BKG cocktail
  - dominant BKG due to $\pi^0$
  - excess → $e^{\pm}$ from charm/beauty

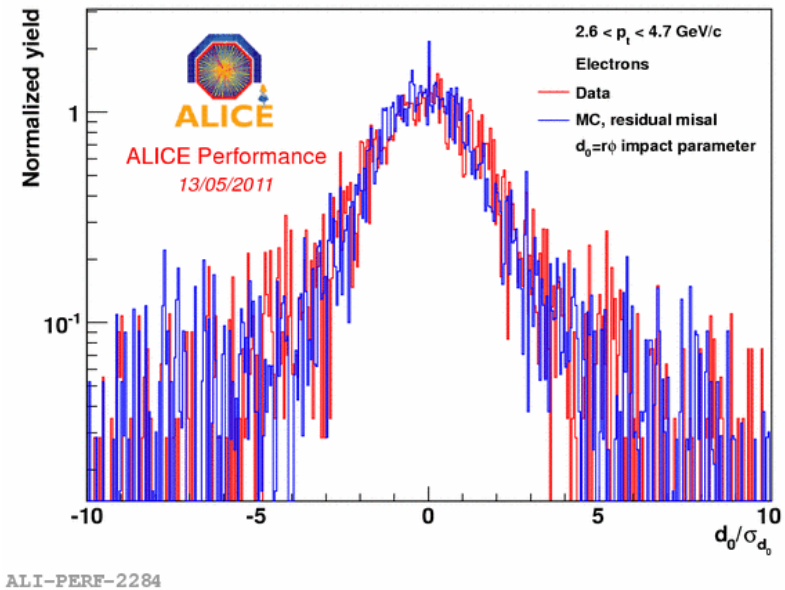



- $e^{\pm}$ from heavy flavor
  - incl. $e^{\pm}$ - cocktail → c+b
  - decay of D mesons → c
  - both $e^{\pm}$ from c+b as well as from c are well described by FONLL

# $e^{\pm}$ from beauty at $\sqrt{s}$ = 7 TeV

- two approaches
  - subtract $e^{\pm}$ from D-meson decays from $e^{\pm}$ from c+b
  - select $e^{\pm}$ from displaced secondary vertex (requires excellent control of vertex measurement)

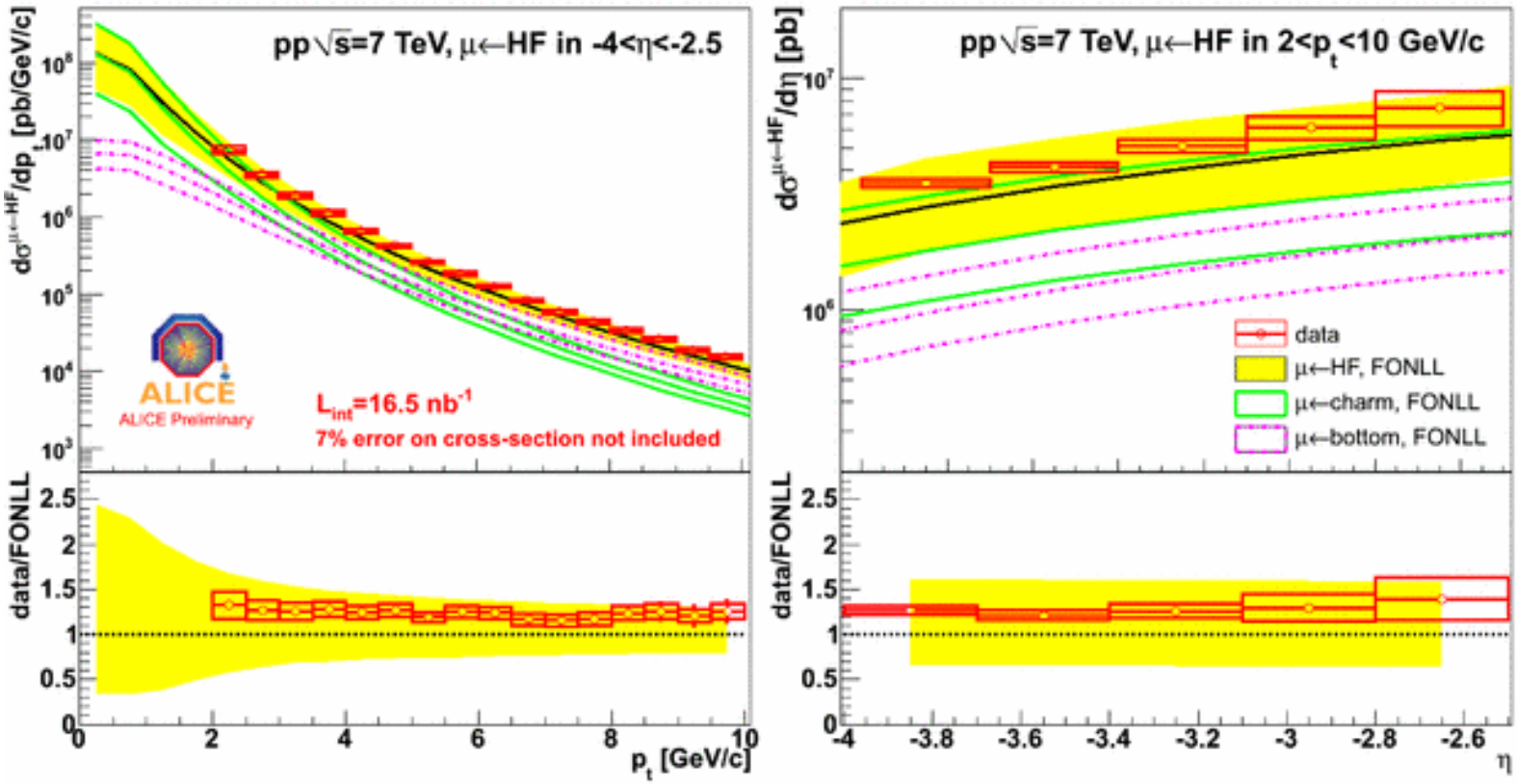



→ results from both methods consistent with each other & FONLL

# $\mu^{\pm}$ from heavy flavor at $\sqrt{s}$ = 7 TeV

- production cross section as function of $p_t$ and $\eta$

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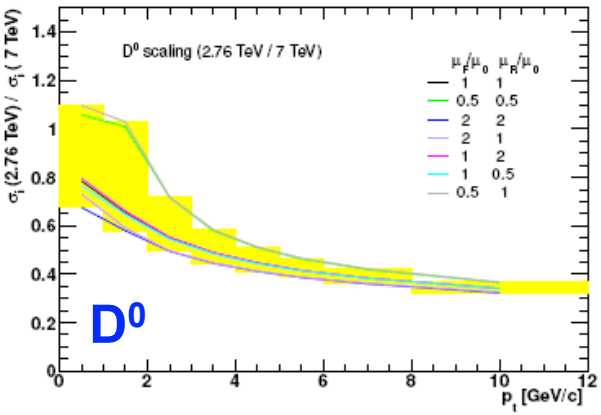
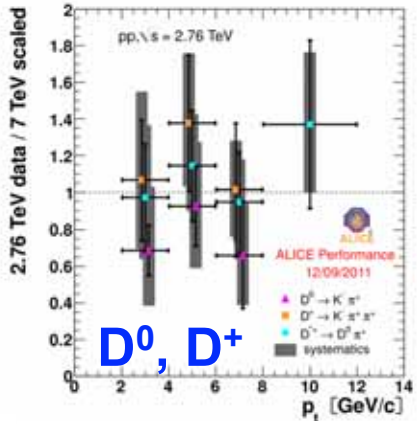
→ FONLL pQCD in good agreement with data

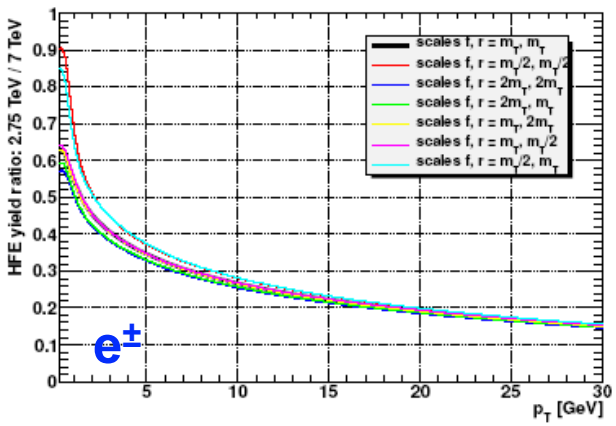
# pp reference at $\sqrt{s}$ = 2.76 TeV

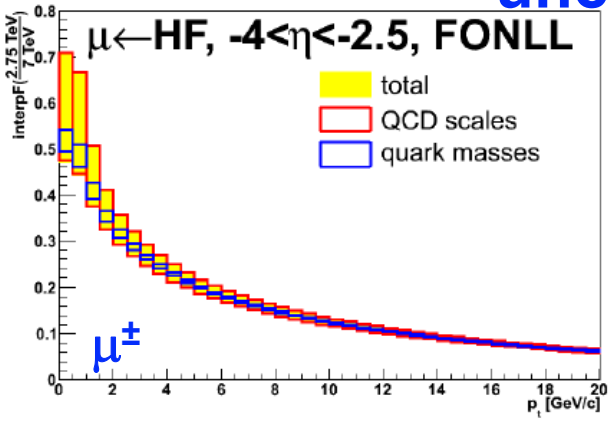
- scale HF cross sections from 7 to 2.76 TeV using a pQCD (FONLL) driven method
  - assumption: no change of pQCD scales ($\mu_r$, $\mu_f$) and quark masses with $\sqrt{s}$
  - rel. scaling uncertainty: 25 (10) % at $p_t$ = 2 (10) GeV/c




- cross sections measured (with low statistics) at 2.76 TeV agree with the scaled reference within uncertainties




R. Averbeck et al., arXiv:1107.3243

# HEAVY FLAVOR MEASUREMENTS IN Pb-Pb COLLISIONS

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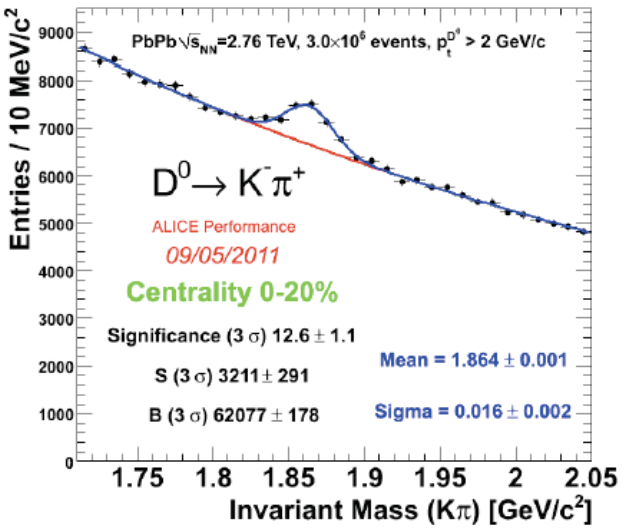
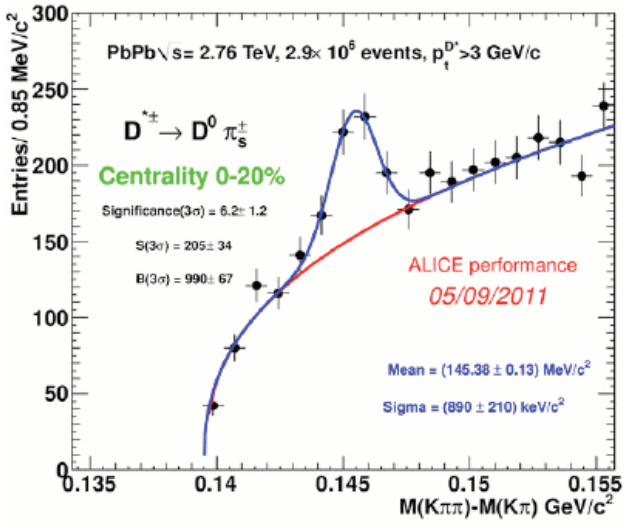
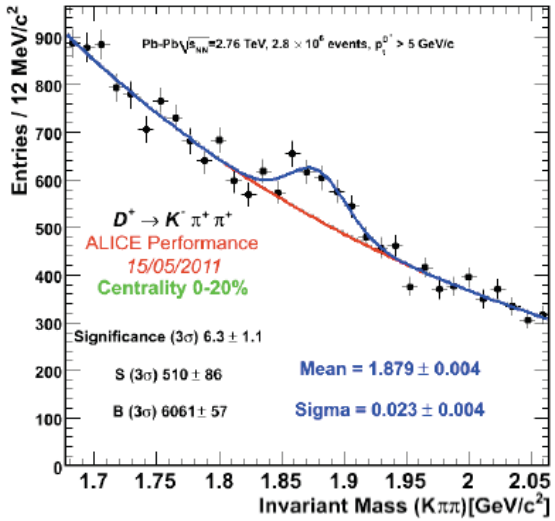
# effects of the hot and dense medium?

# D mesons at $\sqrt{s_{NN}}$ = 2.76 TeV

- ~3x10$^6$ central Pb-Pb collisions (0-20%)
- D mesons measured for 2 < $p_t$ < 16 GeV/c



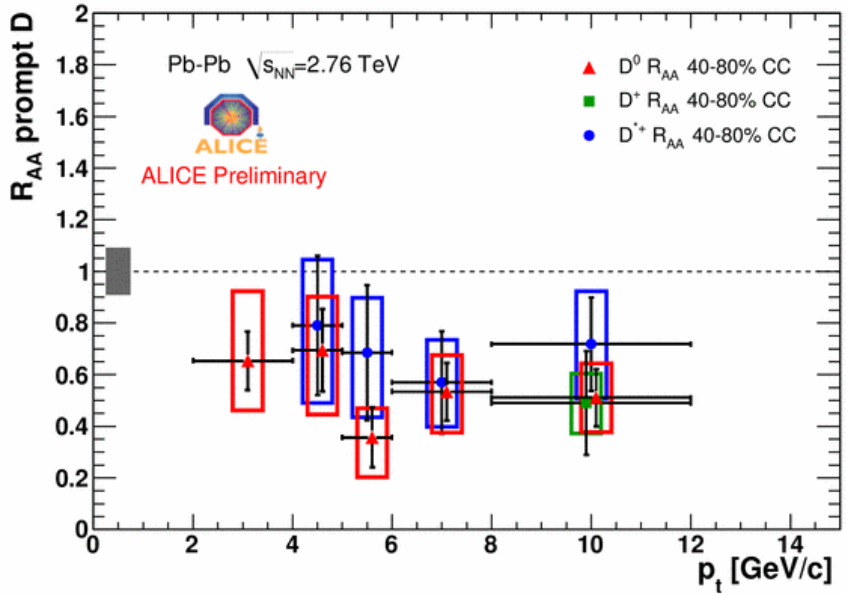



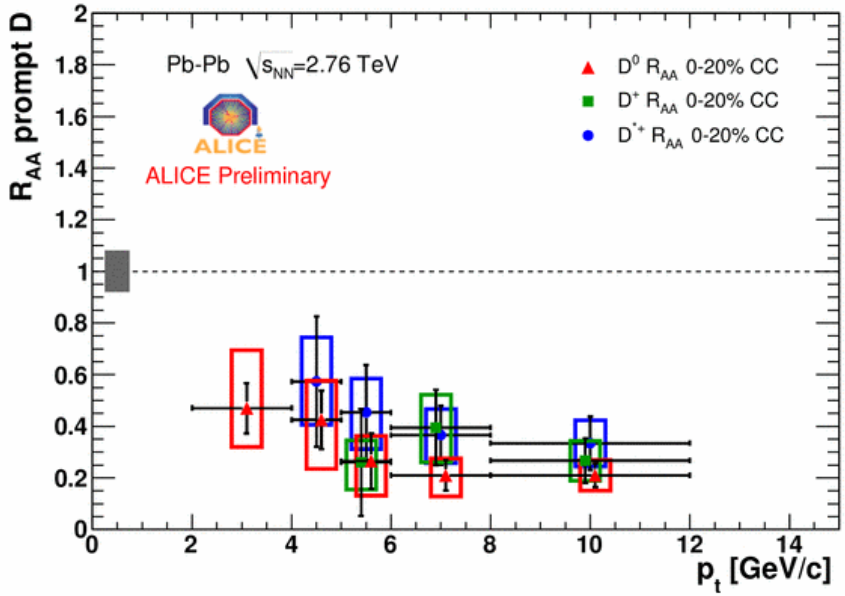

- reconstruction efficiency (~1–10%) evaluated from MC
- feed down from B decays (~10-15% after cuts) evaluated based on FONLL and subtracted
  (requires assumption for B suppression: 1/3 < $R_{AA}^D/R_{AA}^B$ < 3)

# D meson modification factor

- nuclear modification factor $R_{AA}$ of D mesons in central (0-20%) and more peripheral (40-80%) Pb-Pb collisions

$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN^D_{Pb-Pb}/dp_t}{d\sigma^D_{pp}/dp_t}$$



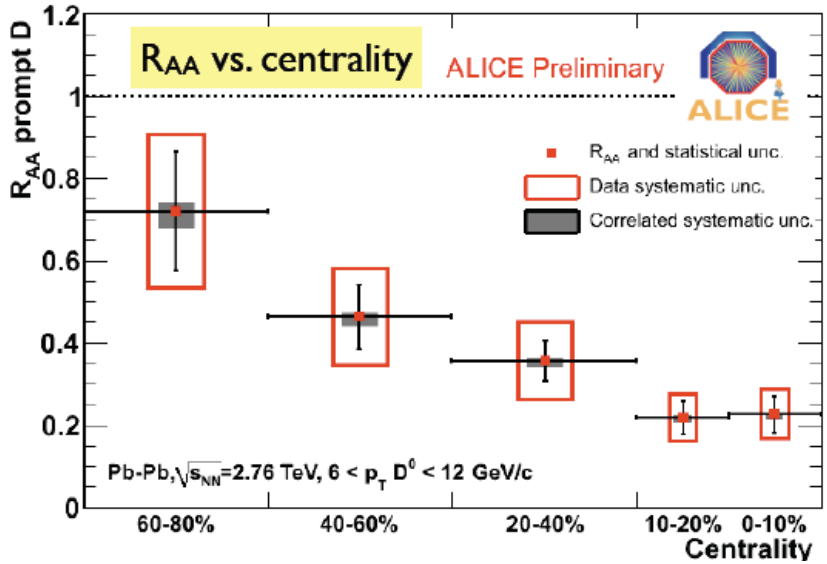

- $R_{AA}$ of different D-meson species agree within stat. errors
- large suppression observed at high $p_t$ in central collisions

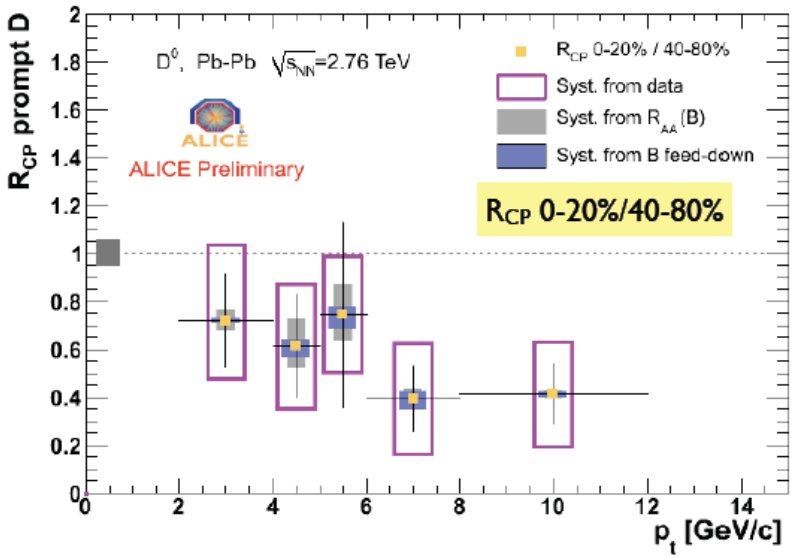
# D meson $R_{AA}$ vs. centrality and $R_{CP}$

- $R_{AA}$ of $D^0$ mesons ($6 < p_t < 12$ GeV/c) versus collision centrality
  - strong centrality dependence
- $R_{CP}$ of $D^0$ mesons

$$R_{CP}(p_t) = \frac{\left\langle 1/T_{AA}^{C} \right\rangle \times dN^{D,C}/dp_t}{\left\langle 1/T_{AA}^{P} \right\rangle \times dN^{D,P}/dp_t}$$

  - pp reference not needed
  - high $p_t$ suppression clearly seen as well

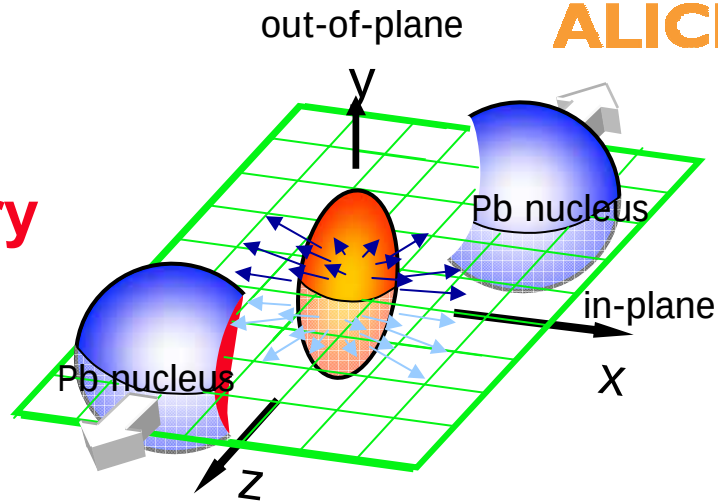


# $D^0$-meson elliptic flow

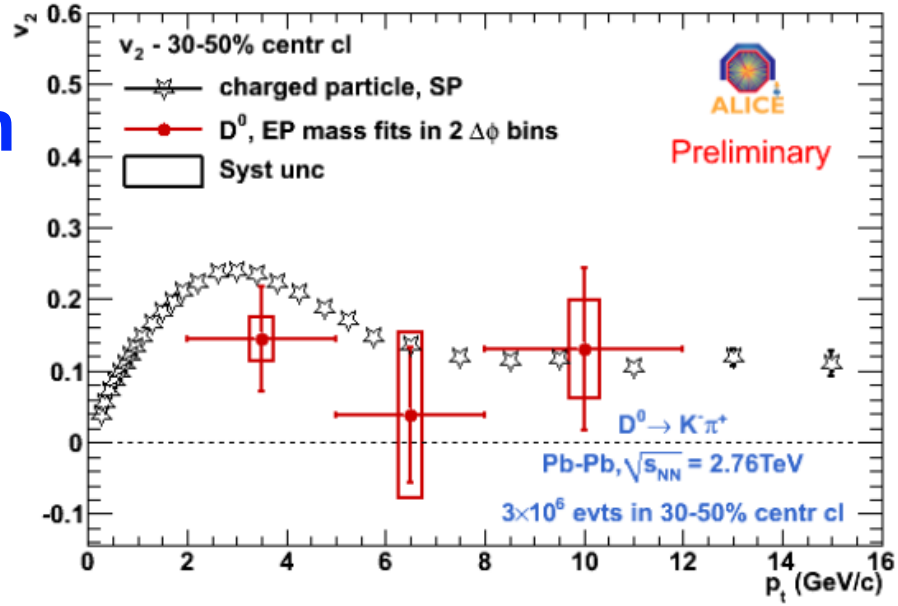
- dynamical medium evolution
  - initial state spatial asymmetry
  - final state momentum asymmetry
  - Fourier expansion

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T dp_T dy d\varphi}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$



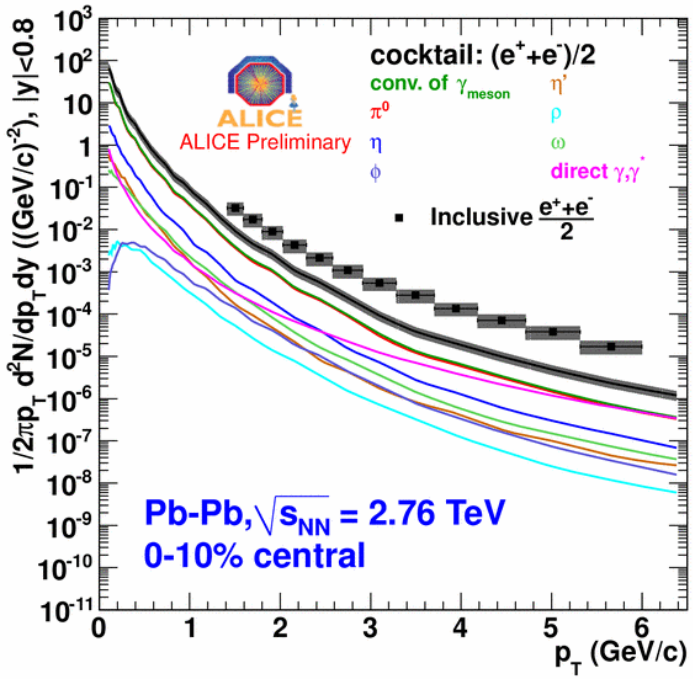

  - elliptic flow $v_2$ sensitive to early thermalization

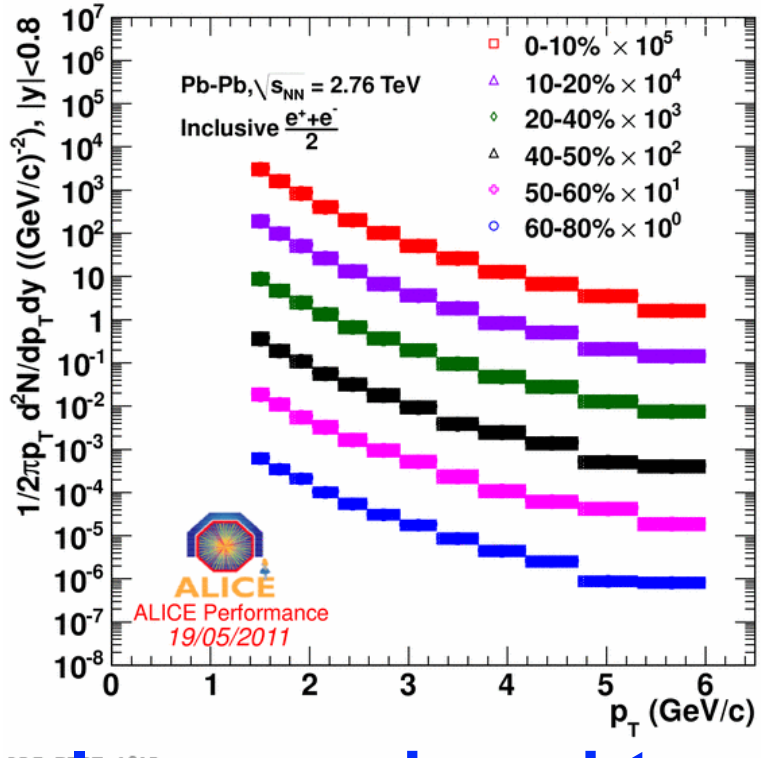
- measurement of $D^0$ with respect to the orientation of the reaction plane
  - → hint for non-zero $D^0$ elliptic flow
  - → participation of charm in collective dynamics?



# $e^{\pm}$ spectra in Pb-Pb

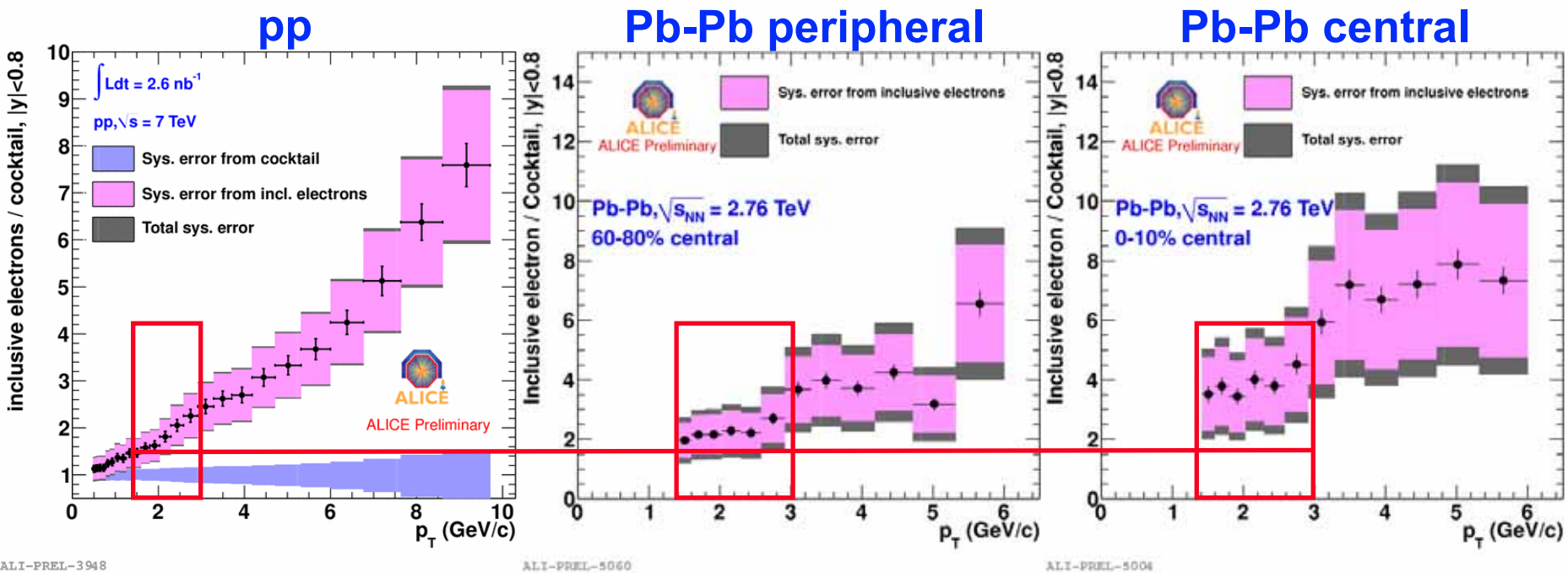
- inclusive $e^{\pm}$ $p_t$ spectra in six centrality bins
  - PID with TPC+TOF
  - hadron contamination (<10%) subtracted




- usual approach: subtract cocktails of background electrons → $e^{\pm}$ from heavy-flavor decays

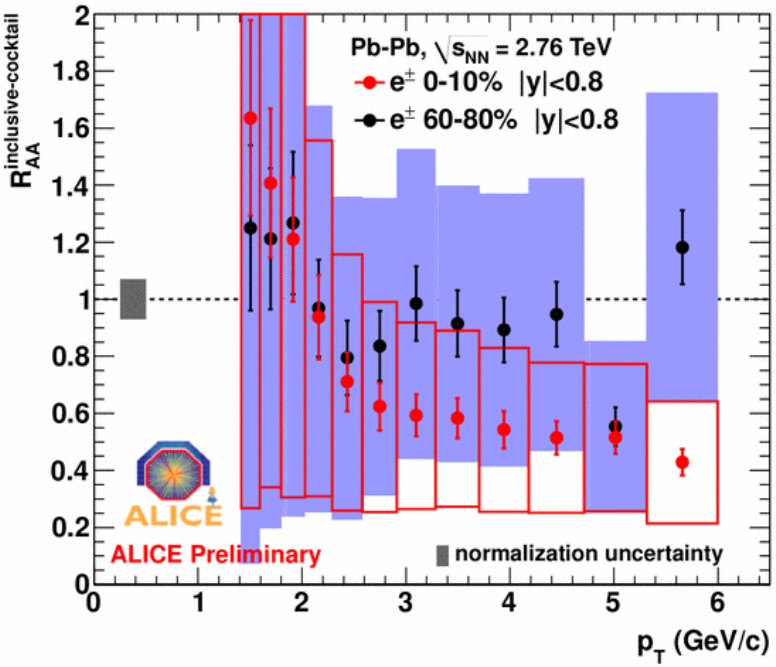
# Ratio of inclusive $e^{\pm}$ to cocktail

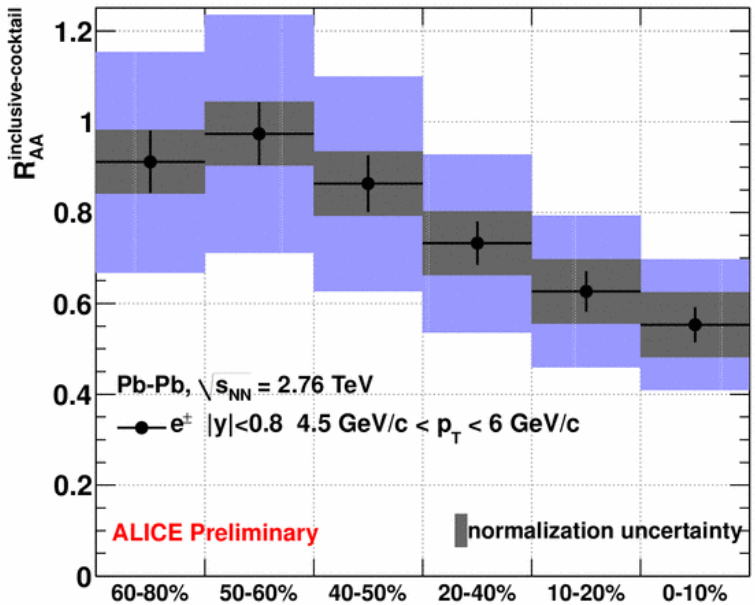



- hint for an electron excess at low $p_t$ in Pb-Pb
  - excess increases with centrality
  - thermal charm production?
  - thermal radiation?
    (observed by PHENIX at RHIC, Adare et al., PRL 104(2010)132301)

# Cocktail-subtracted $e^{\pm}$ $R_{AA}$

- subtract cocktail from inclusive $e^{\pm}$ spectrum
  - low $p_t$: excess $e^{\pm}$ and huge sys. uncertainties
  - above 3-4 GeV/c: dominated by heavy-flavor decays



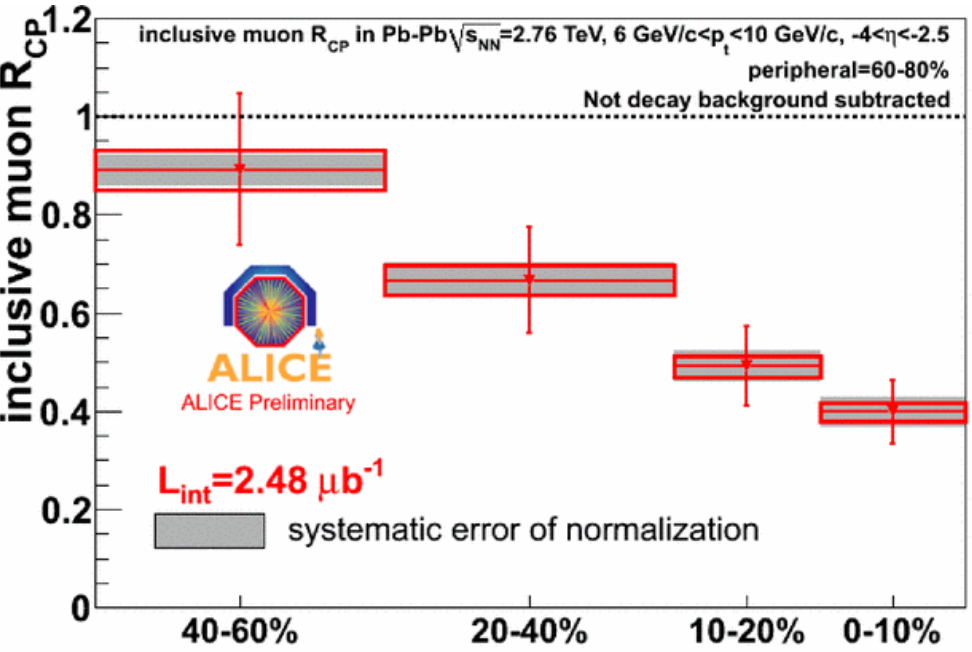



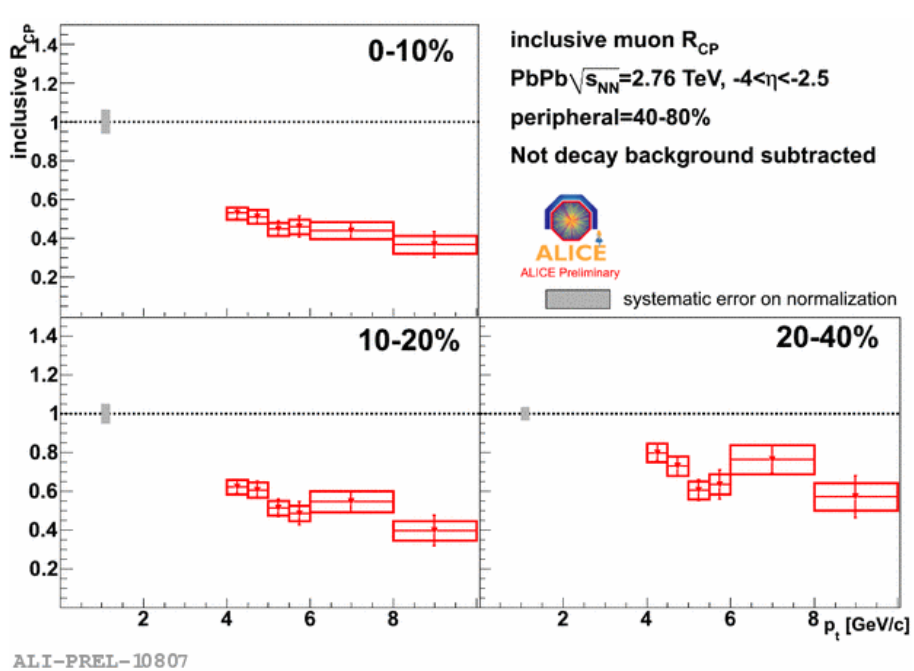

- suppression of $e^{\pm}$ from heavy-flavor decays in Pb-Pb collisions increasing with centrality

# $R_{CP}$ for inclusive $\mu^{\pm}$

- NO subtraction of BKG from $\pi$, K decay

  → focus on $R_{CP}$ of inclusive $\mu^{\pm}$ with $p_t$ > 4-6 GeV/c (≤15% BG estimated from HIJING w/o quenching)

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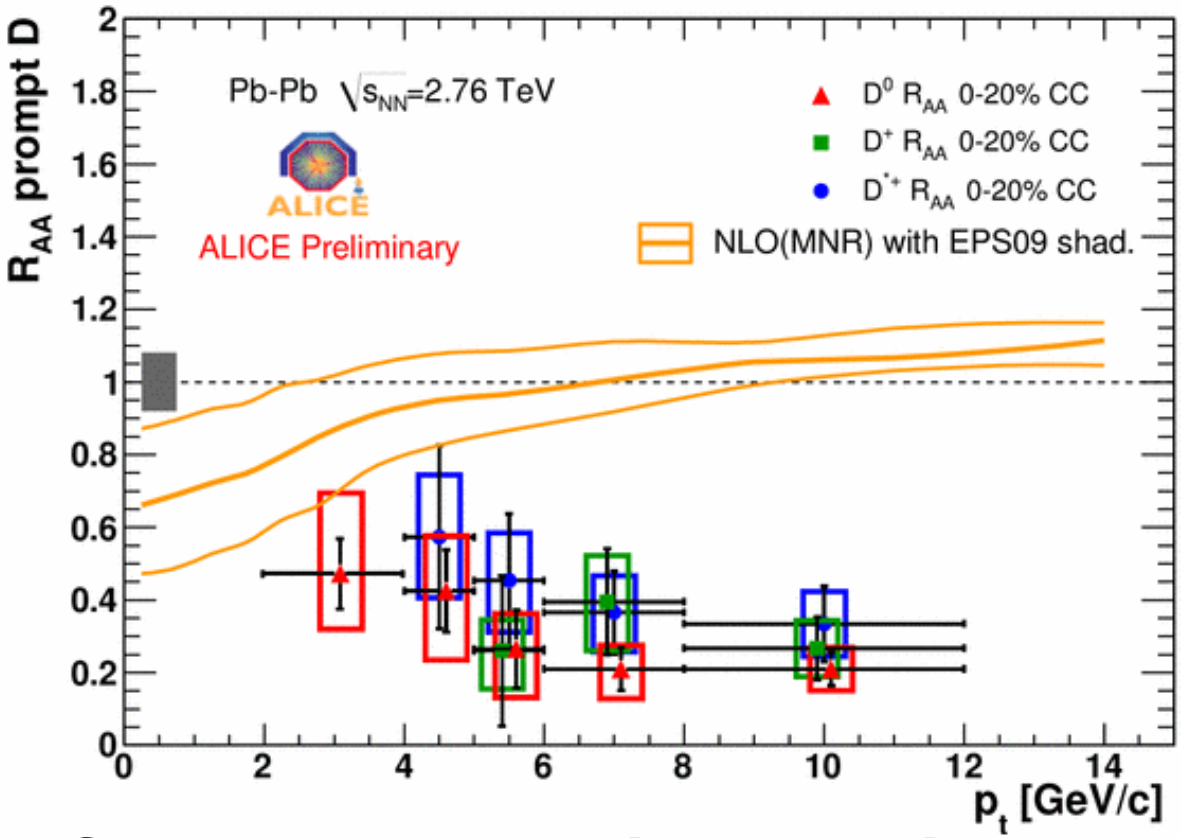
$$R_{CP}(p_t) = \frac{\langle 1/T_{AA}^{C} \rangle \times dN^{\mu,C}/dp_t}{\langle 1/T_{AA}^{P} \rangle \times dN^{\mu,P}/dp_t}$$

→ suppression increasing with centrality without significant $p_t$ dependence

# Effect of shadowing

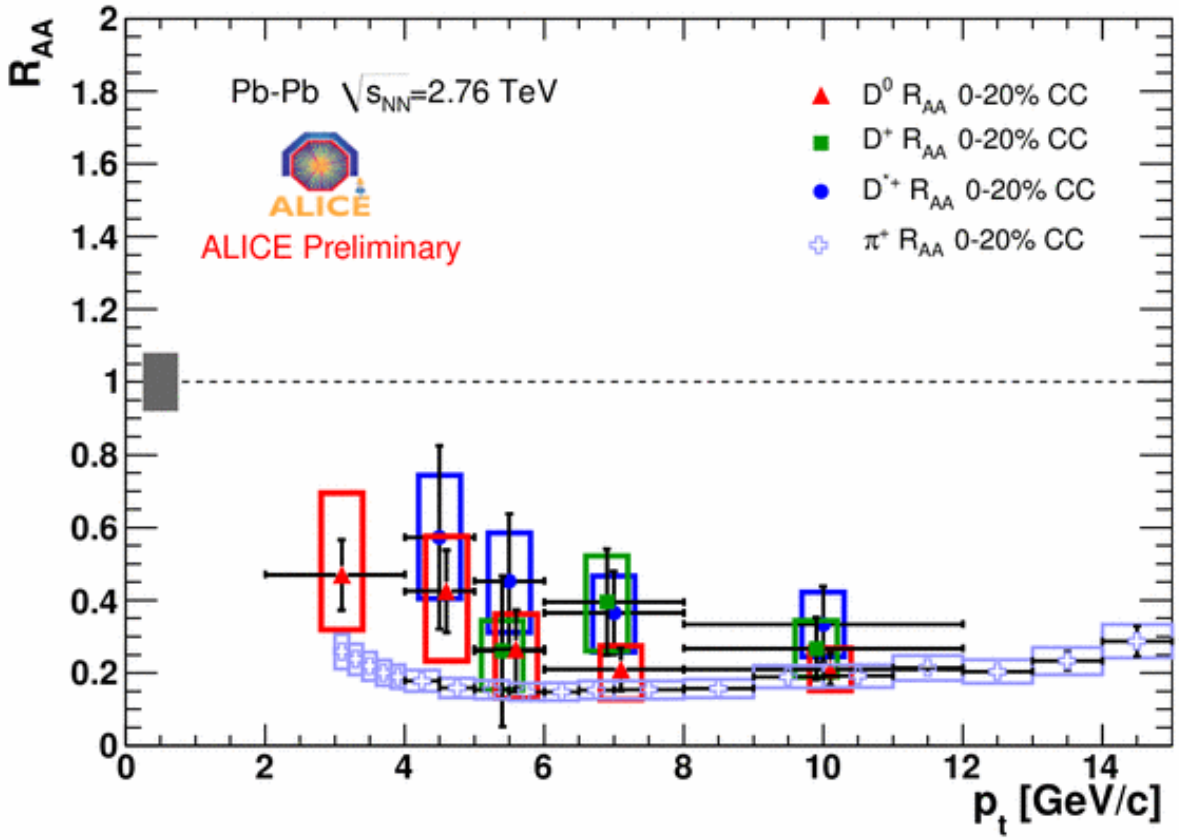
- comparison of D-meson $R_{AA}$ with model expectation indicating the effect of shadowing




→ heavy-flavor suppression not due to shadowing but due to interaction with the produced medium

# $R_{AA}$: D mesons versus pions

- central Pb-Pb collisions
  - D-meson $R_{AA}$ compatible with $\pi$ $R_{AA}$ within uncertainties
  - hint for less suppression of D's w.r.t. pions at low $p_t$
    → more statistics required for conclusive statement



# Summary

- ALICE has measured prompt D meson as well as $e^{\pm}$ and $\mu^{\pm}$ from heavy-flavor decays at the LHC
  - in pp collisions
    - → pQCD calculations are in reasonable agreement with all data
  - in Pb-Pb collisions
    - → substantial suppression of heavy flavor in central collisions
    - → heavy flavor $R_{AA}$ data exhibit clear centrality dependence
    - → first measurement of $D^0$ elliptic flow
- heavy-flavor measurements hungry for statistics
  → look forward to data from the ongoing Pb-Pb run