Heavy-flavour production in Pb-Pb collisions at the LHC, measured with the ALICE detector

Andrea Dainese

(INFN Padova, Italy)

on behalf of the ALICE Collaboration

Outline of the Talk

- Introduction: probing Quark Matter at LHC with HQs
- ALICE apparatus and datasets
- Open heavy flavour measurements in ALICE
  - D mesons at central rapidity
  - electrons at central rapidity
  - muons at forward rapidity
- Calibrating the probe: pp results at $\sqrt{s}$ = 7 (and 2.76) TeV
- pp reference at 2.76 TeV: $\sqrt{s}$-scaling
- Nuclear modification factors of D mesons and leptons in Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
- Summary

Related Parallel Talks (3) and Posters (15)

- **Andrea Rossi**: D meson R_{AA} → Fri parallel
- **Silvia Masciocchi**: Electrons R_{AA} → Mon parallel
- **Xiaoming Zhang**: Muons R_{AA} → Mon parallel
- Posters:
  - D mesons: **Renu Bala, Chiara Bianchin, Davide Caffarri, Zaida Conesa del Valle, Sadhana Dash, Robert Grajcarek, Alessandro Grelli, Gian Michele Innocenti, Giacomo Ortona, Rosa Romita, Xianbao Yuan**
  - Electrons: **Markus Fasel, MinJung Kweon, Yvonne Pachmayer, Shingo Sakai**
  - Muons: **Matthieu Lenhardt**

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Heavy quarks as medium probes: Energy Loss

A puzzle at RHIC

q: colour triplet

u,d,s: m~0, C_R=4/3
(difficult to tag at LHC)

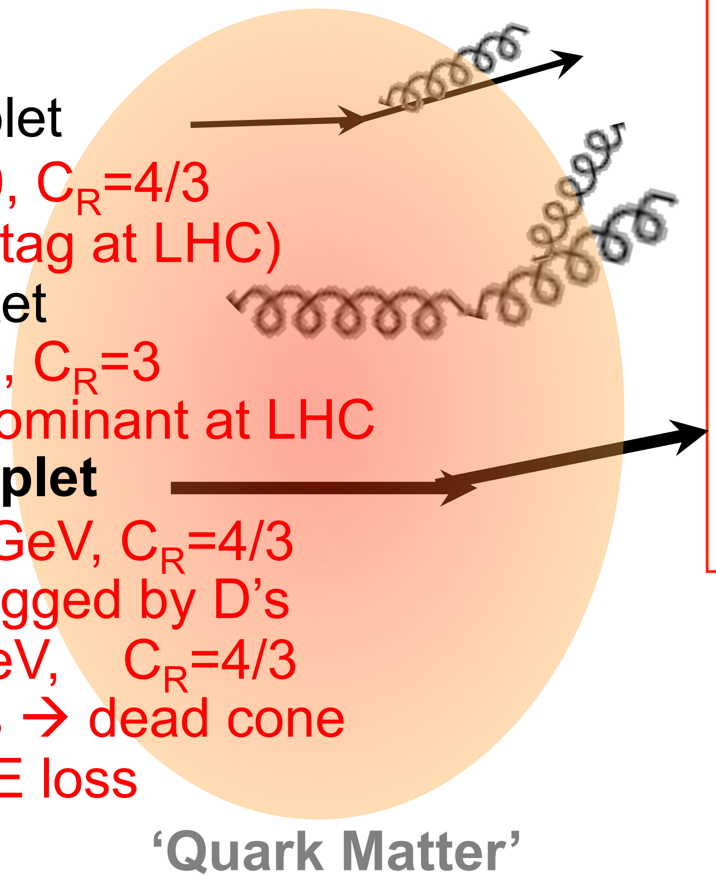
g: colour octet

g: m=0, C_R=3
> E loss, dominant at LHC

Q: colour triplet

c: m~1.5 GeV, C_R=4/3
small m, tagged by D's

b: m~5 GeV, C_R=4/3
large mass → dead cone
→ < E loss



courtesy D.d'Enterria

Parton Energy Loss by

- medium-induced gluon radiation
- collisions with medium gluons

$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

pred: $\Delta E_g > \Delta E_{c \approx q} > \Delta E_b$

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

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

See e.g.:
Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.
Djordjevic, Gyulassy, Horowitz, Wicks, NPA 783 (2007) 493.

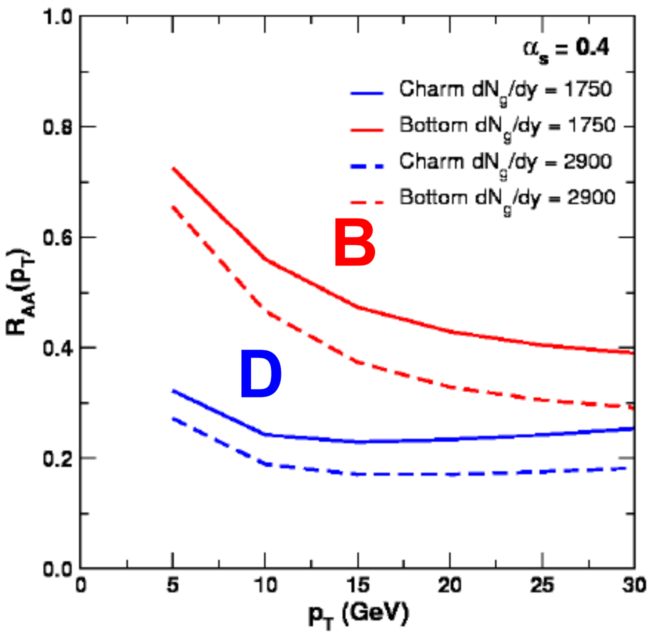
HQs R_{AA}: some expectations …

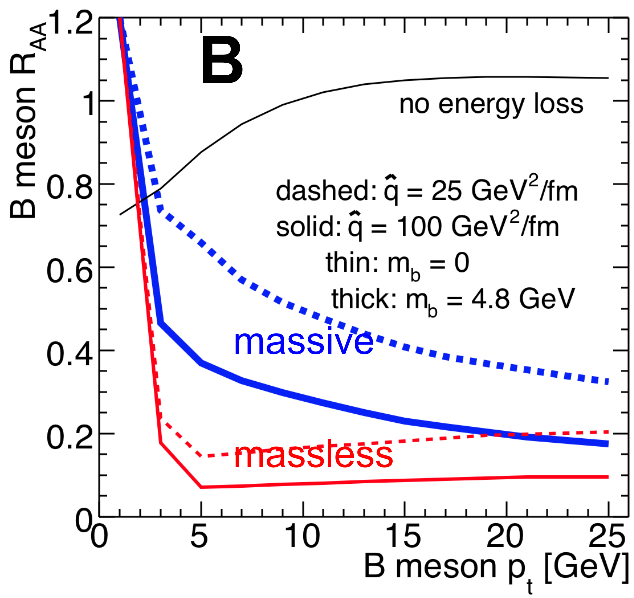
New at LHC

- Energy loss based predictions: factor 3-5 suppression for D mesons
- Significantly smaller suppression for B

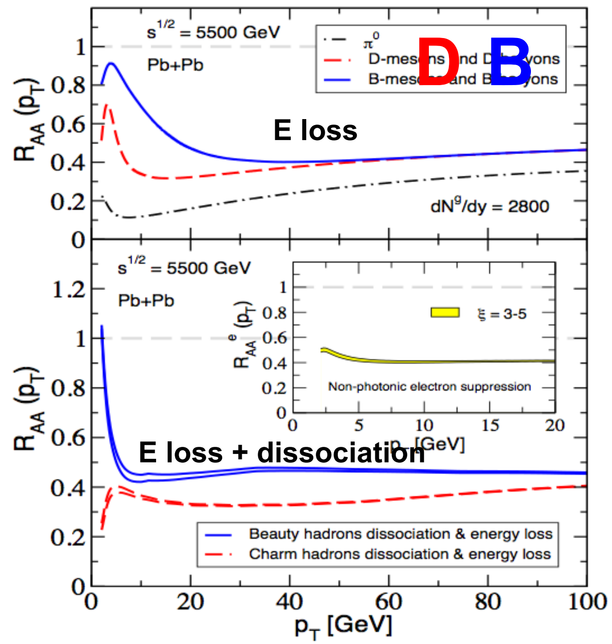
$$R^{D}_{AA}(p_t) \text{ and } R^{B}_{AA}(p_t)$$

Radiative E loss





Light-cone wave function E loss



Wicks, Gyulassy, "Last Call for LHC Predictions" workshop, 2007

Armesto, et al, PRD71 (2005)

Vitev, et al, PRC80 (2009)

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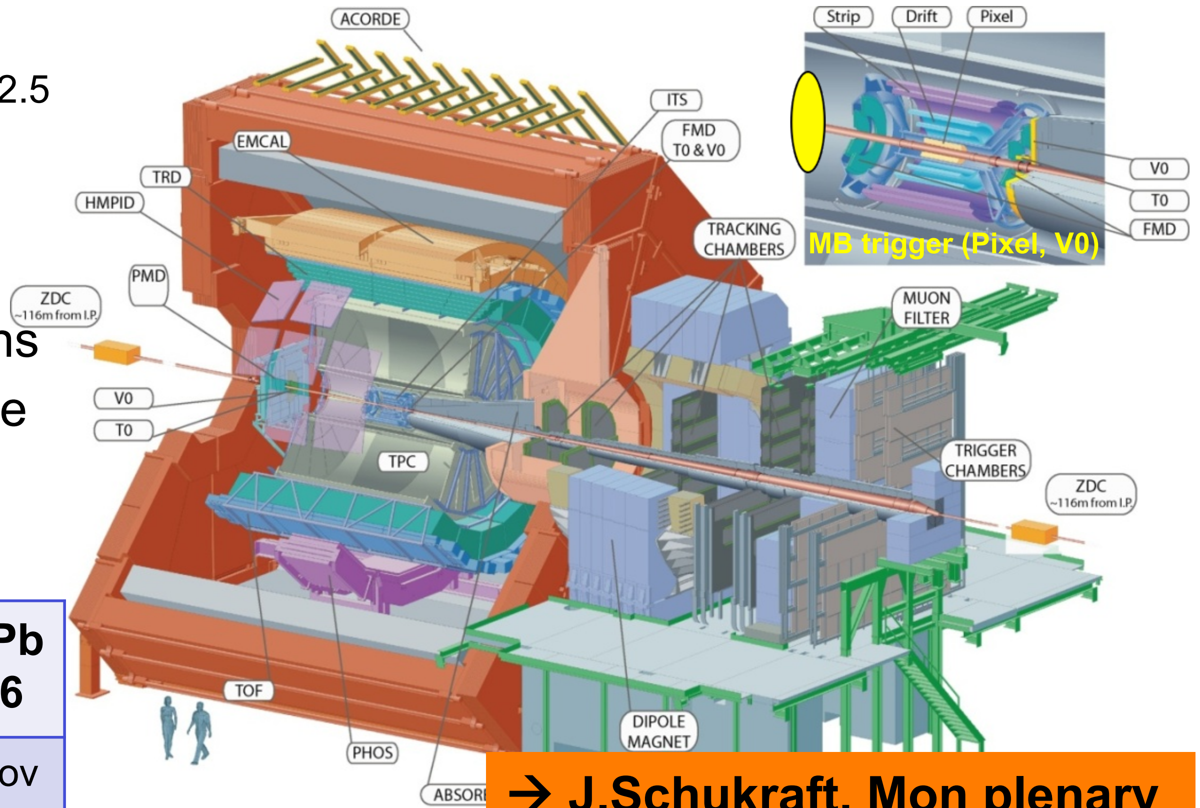
ALICE apparatus and datasets

- Two main parts:
  - barrel (|η|<0.9), B = 0.5 Tesla
  - forward muon spectrometer, -4<η<-2.5
- Crucial for HF:
  - vertexing, tracking
  - hadron and lepton ID
- Collected data for 4 combinations system/energy, fully exploting the superb LHC performance
- Datasets used here:

system, $\sqrt{s_{NN}}$ (TeV)	pp 7	pp 2.76	Pb-Pb 2.76
when	10/apr-aug	11/mar	10/nov
N_{MB}	100-180M	65 M	17 M



→ J.Schukraft, Mon plenary

- Pb-Pb centrality: Glauber model analysis of large-η V0 scintillator amplitudes (centrality from many other detectors as well: ZDC, Pixel, TPC)

→ A.Toia, Tue plenary

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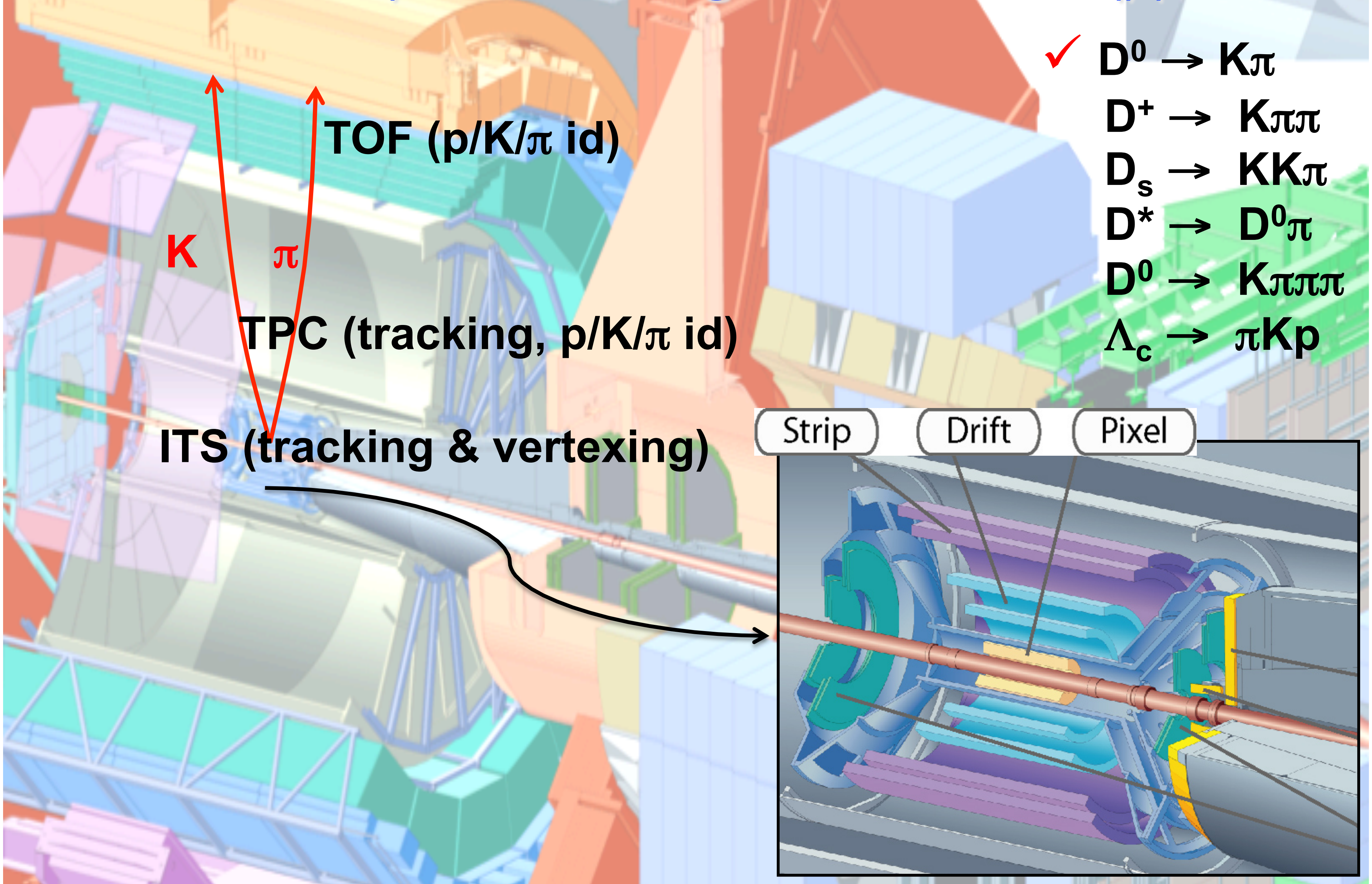
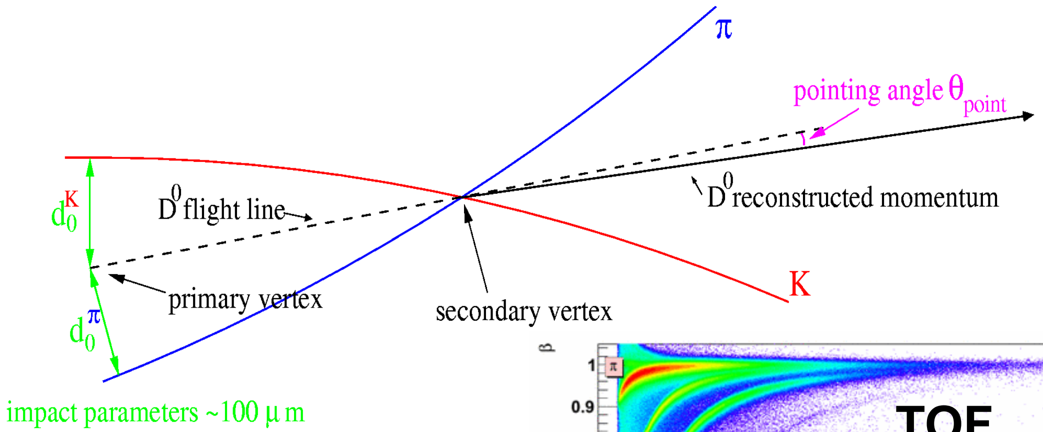
ALICE Heavy Flavour Program: D mesons, |y|<0.8

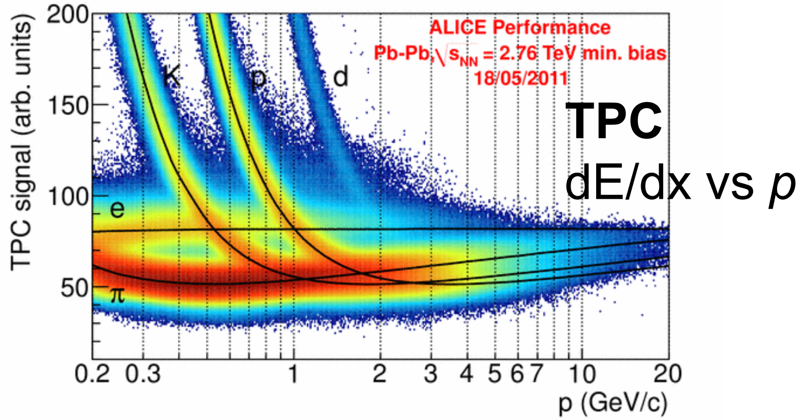
- ✓ $D^0 \rightarrow K\pi$
- $D^+ \rightarrow K\pi\pi$
- $D_s \rightarrow KK\pi$
- $D^* \rightarrow D^0\pi$
- $D^0 \rightarrow K\pi\pi\pi$
- $\Lambda_c \rightarrow \pi K p$

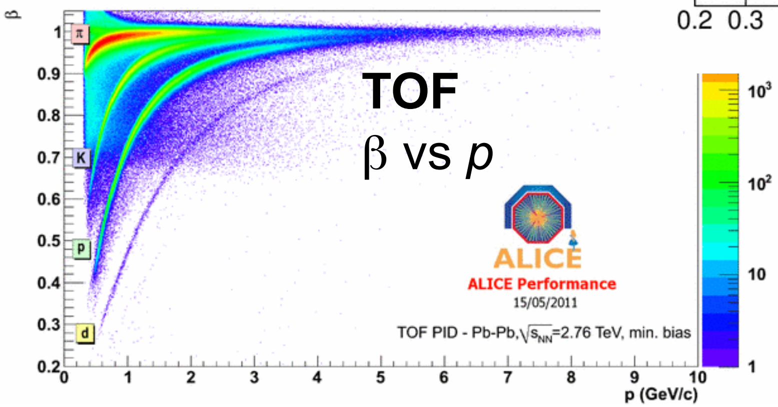


D meson reconstruction in ALICE

- Main selection: displaced-vertex topology
- Example: $D^0 \rightarrow K^- \pi^+$
  - good pointing of reconstructed D momentum to the primary vertex
  - pair of opposite-charge tracks with large impact parameters
- K ID in TPC+TOF helps in rejecting background at low p_t

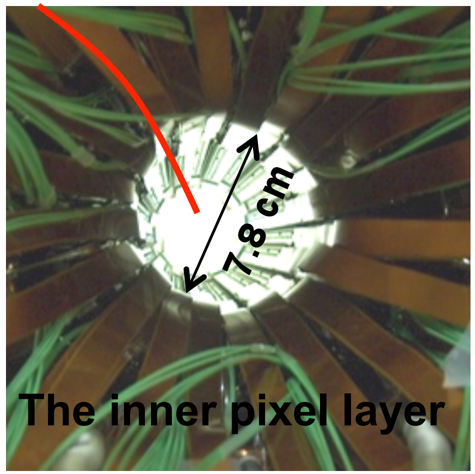


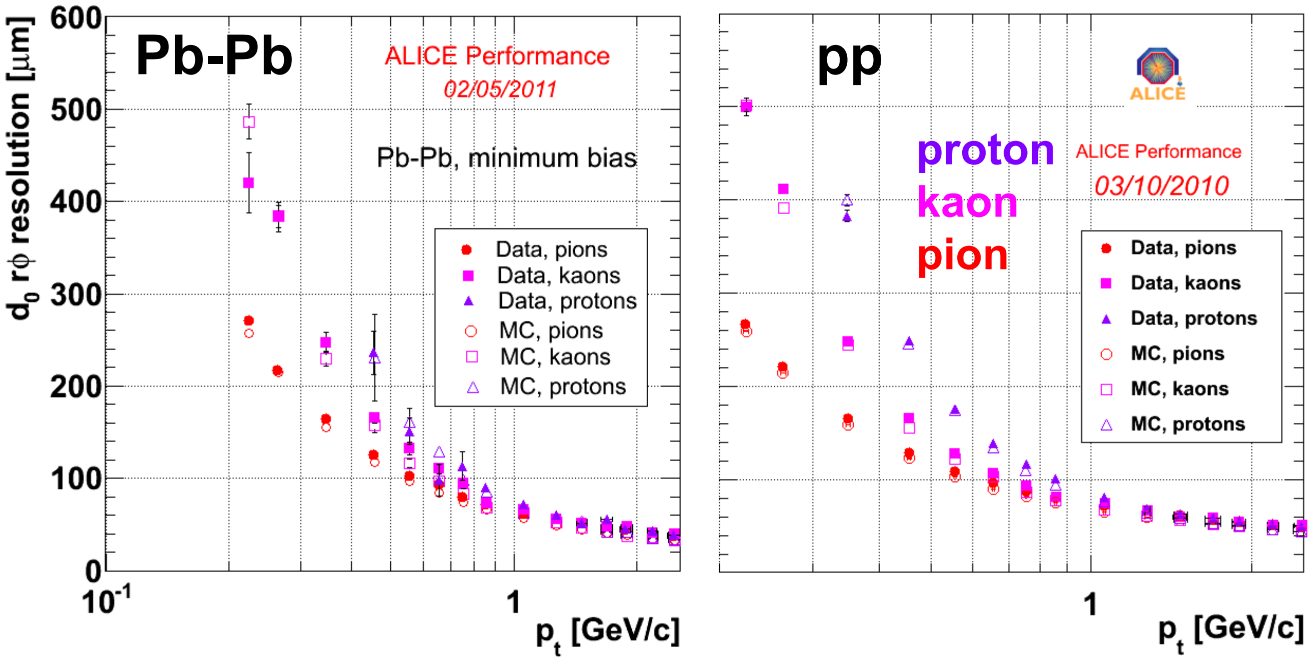




D meson reconstruction in ALICE

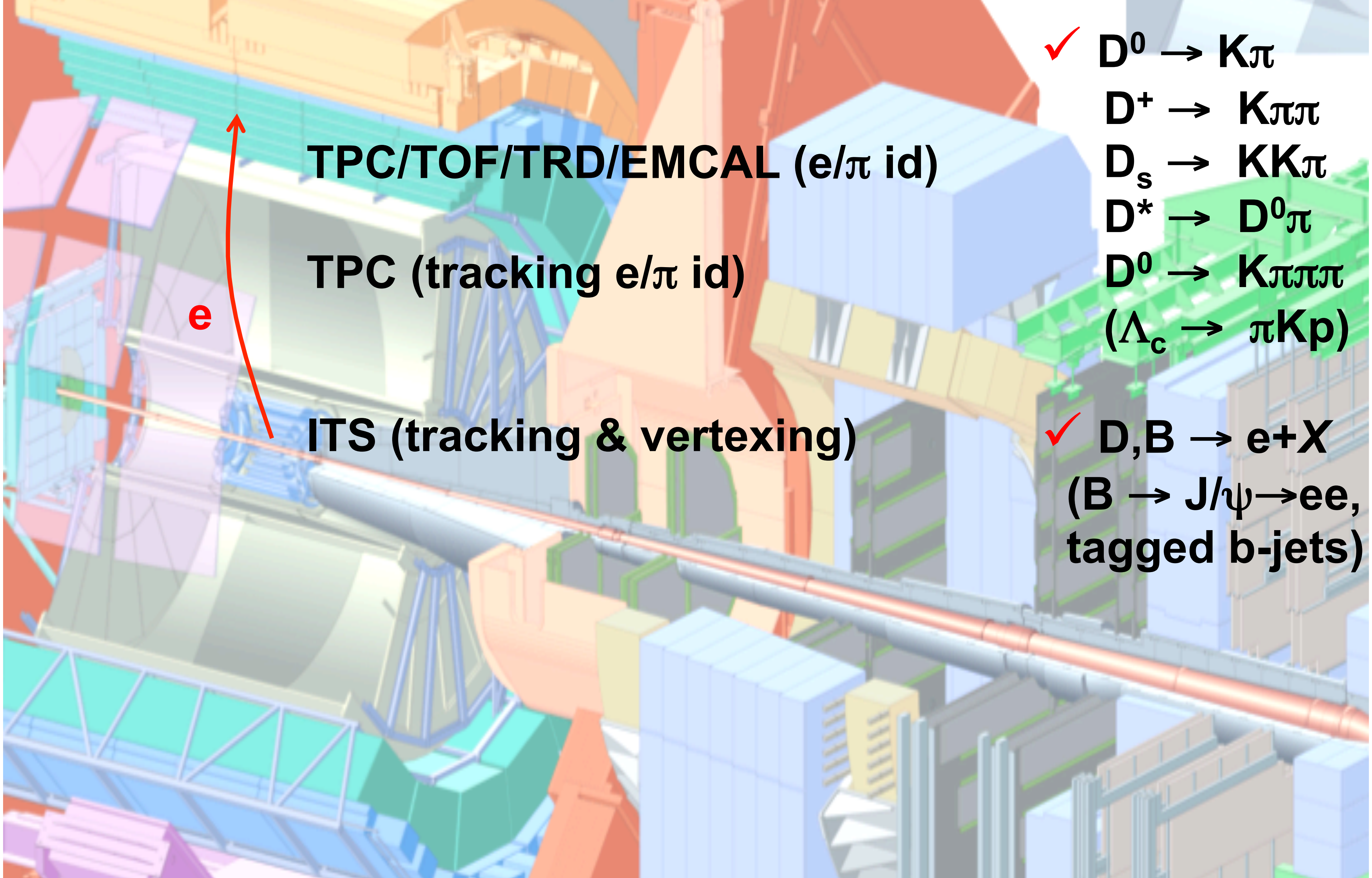
- Main selection: displaced-vertex topology
- Tracking and vertexing precision is crucial here
- Inner Tracking System (ITS) with 6 Si layers
  - two pixel layers at 3.9 cm (closest barrel layer at LHC!) and 7 cm
- The ITS was aligned using cosmics and collisions
  - current resolution for pixels: 14 μm (nominal: ≈11 μm)





Same tracking precision in pp and Pb-Pb, described in MC, incl. mass dep.

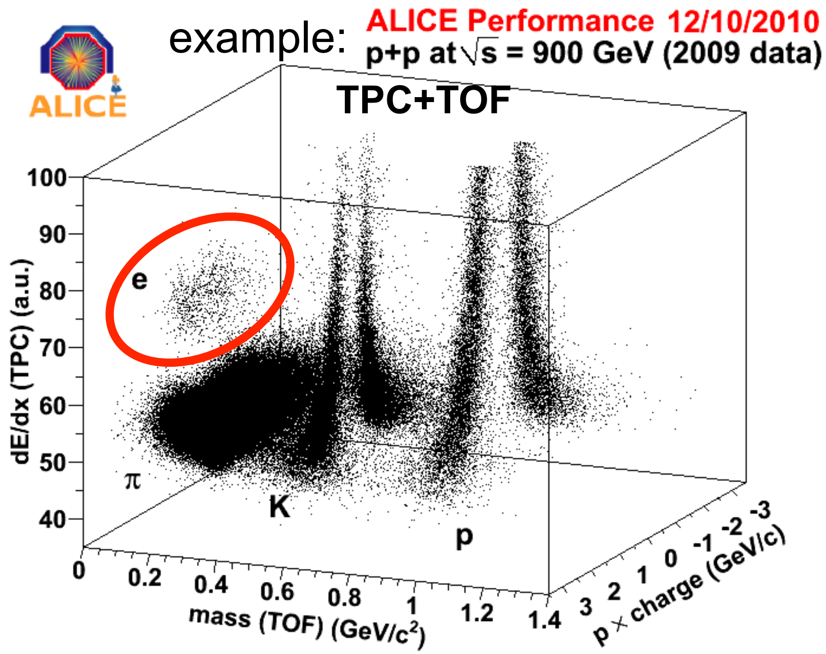
ALICE Heavy Flavour Program: electrons, |y|<0.8

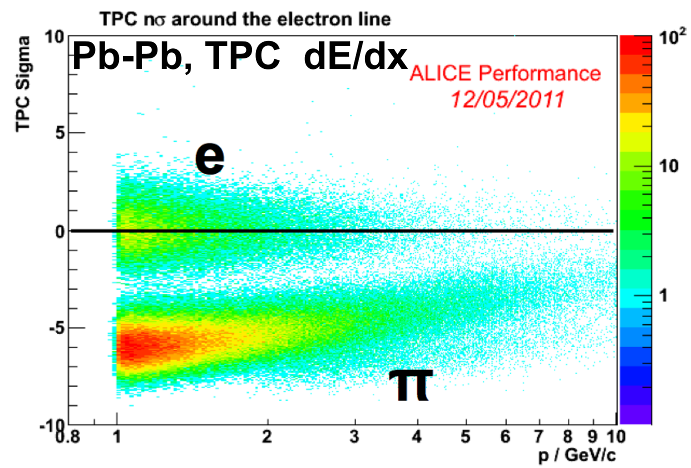


Heavy flavour decay electrons: e-ID

- High quality tracks in TPC and ITS
  - Hit in innermost Si layer to reduce γ−conv. (beam pipe + ~1/3 inner pixel = 0.5% X_0)
- Electron identification:
  - Pb-Pb: TOF + TPC-dE/dx
    - TOF to reject K and p
    - TPC: asymmetric cut around the electron Bethe-Bloch line
  - pp: TOF + TPC-dE/dx + TRD (+EMCAL)
  - hadron contamination measured with a 2-component fit to the TPC dE/dx in *p* slices
- Two procedures to get heavy flavour:
  1. **subtract cocktail of "photonic" electron sources, à la PHENIX**
  2. select electrons with large displacement to interaction vertex → beauty dominance (only in pp for now)

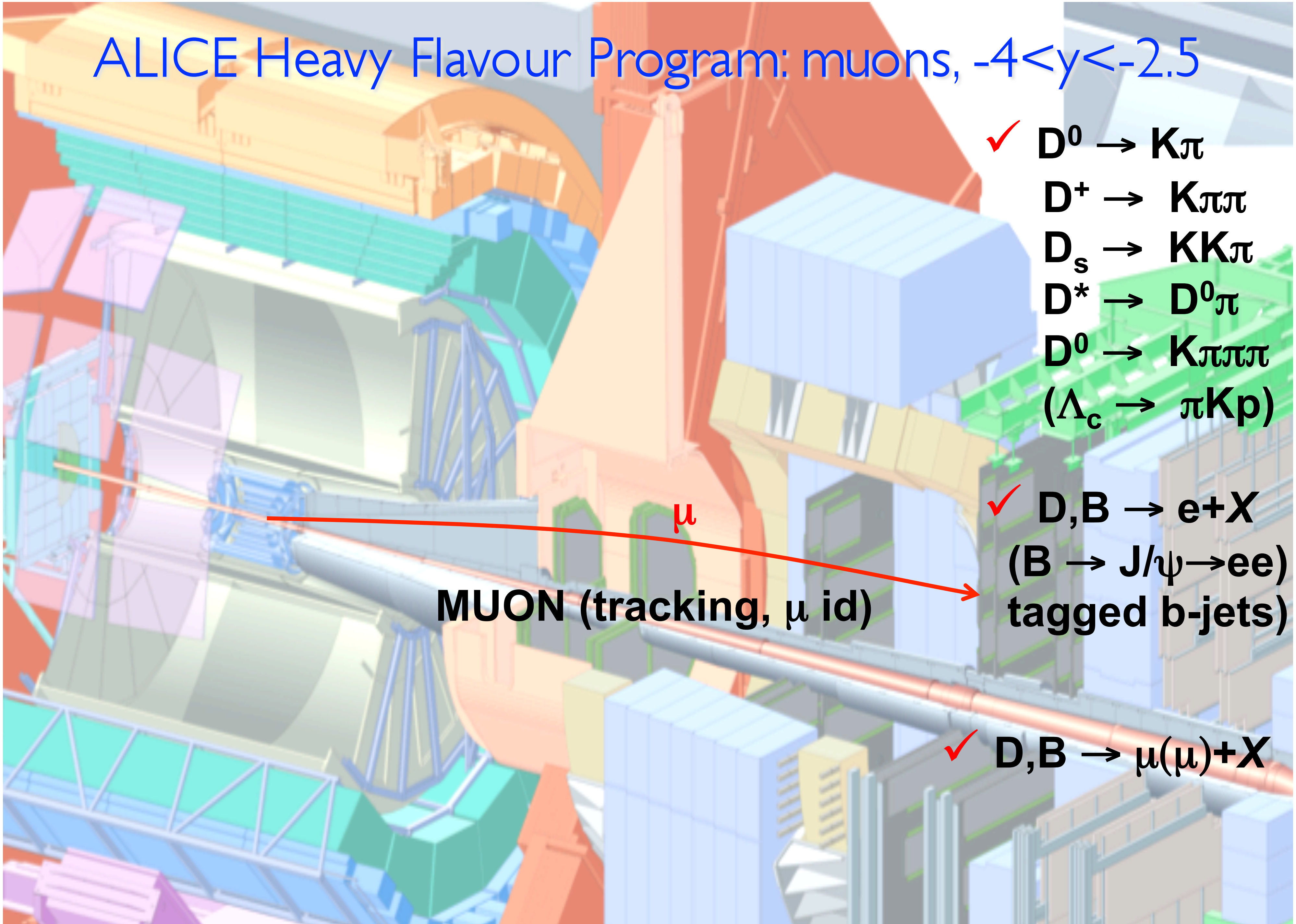
example:





→ S.Masciocchi, Mon parallel

ALICE Heavy Flavour Program: muons, -4<y<-2.5



✓ $D^0 \rightarrow K\pi$

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

$D_s \rightarrow KK\pi$

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

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

$(\Lambda_c \rightarrow \pi Kp)$

✓ D,B $\rightarrow$ e+*X*

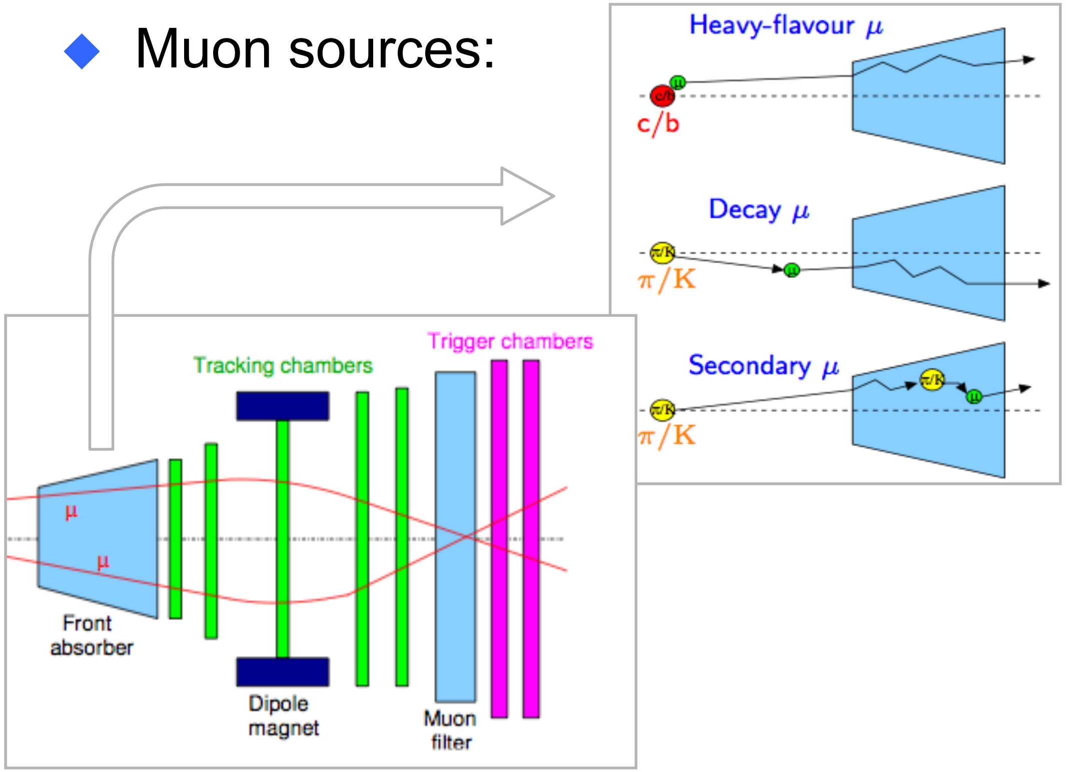
(B $\rightarrow$ J/$\psi \rightarrow$ee)

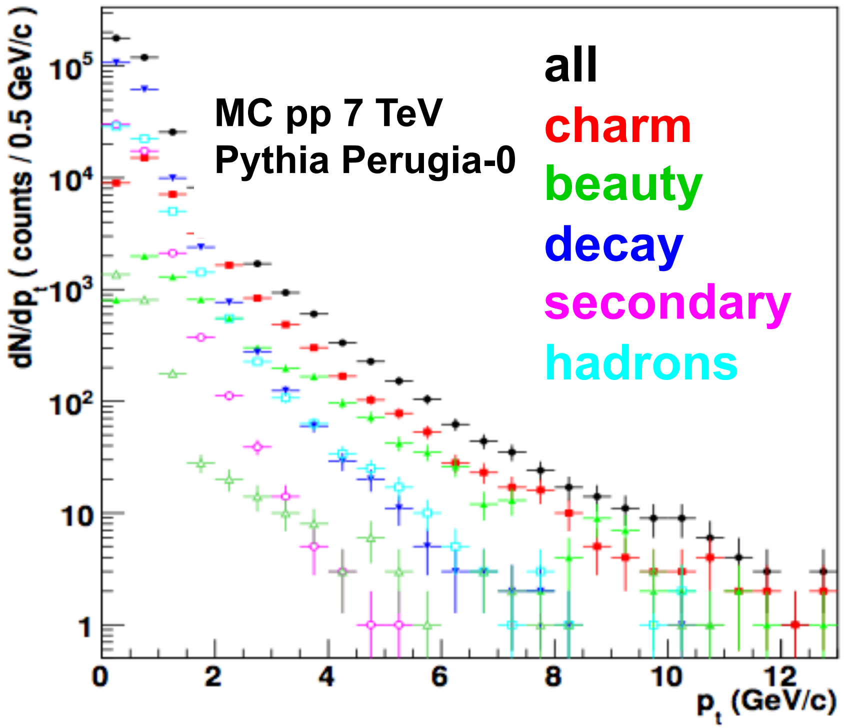
tagged b-jets)

✓ D,B $\rightarrow \mu(\mu)$+X

Heavy flavour from forward single muons

- Muon sources:





- Analysis strategy:
  - remove hadrons and low p_t secondary muons by requiring a muon trigger signal
  - remove decay muons by subtracting MC dN/dp_t normalized to data at low p_t
  - what is left are muons from charm and beauty
- In Pb-Pb, we don't subtract the decay muons for now, but restrict the analysis to a high-p_t region, where this background is small

→ X.Zhang, Mon parallel

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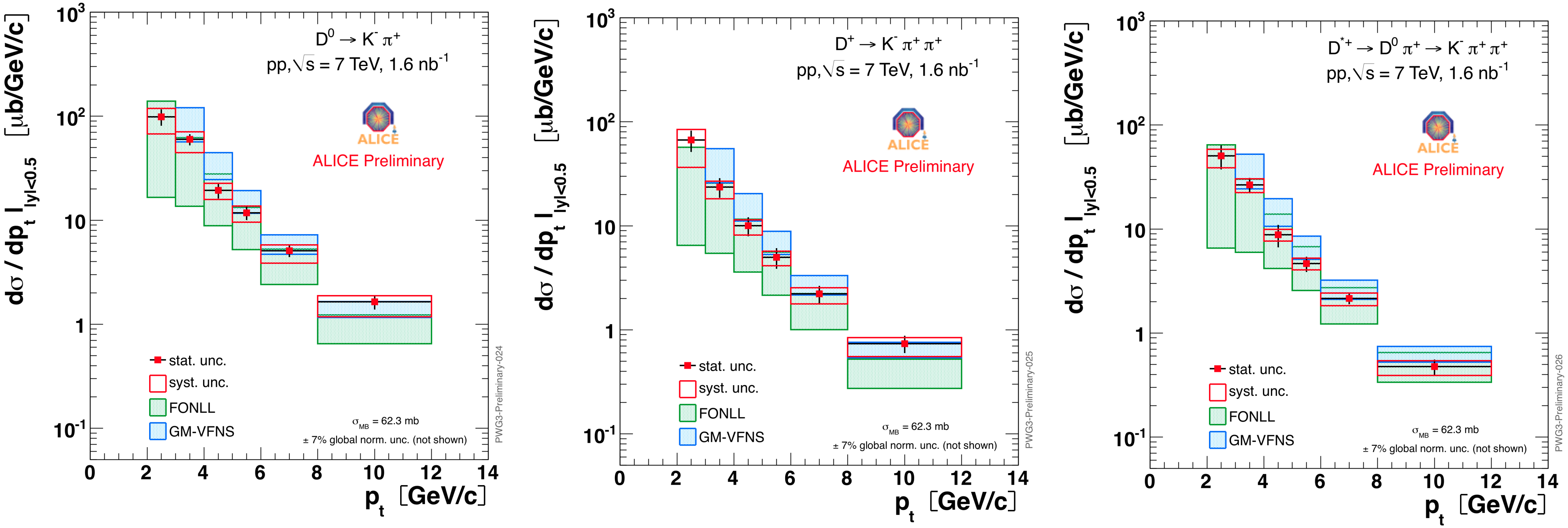
D mesons cross sections: pp 7 TeV, |y|<0.5

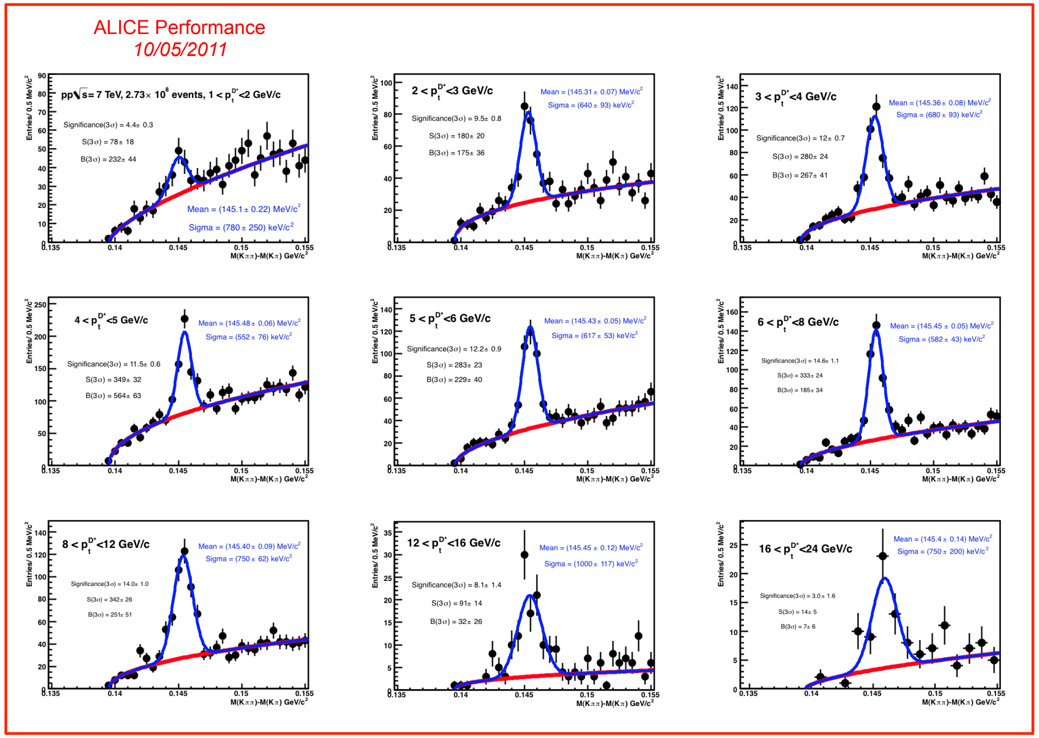


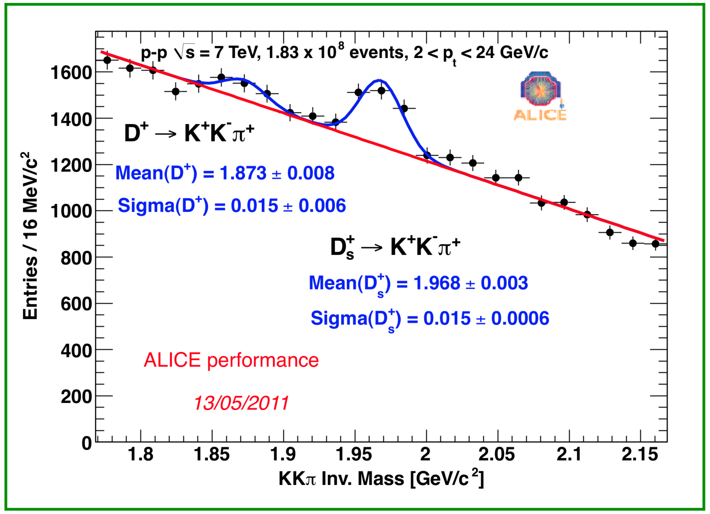
FONLL: Cacciari et al., private comm.
GM-VFNS: Kniehl et al., private comm.

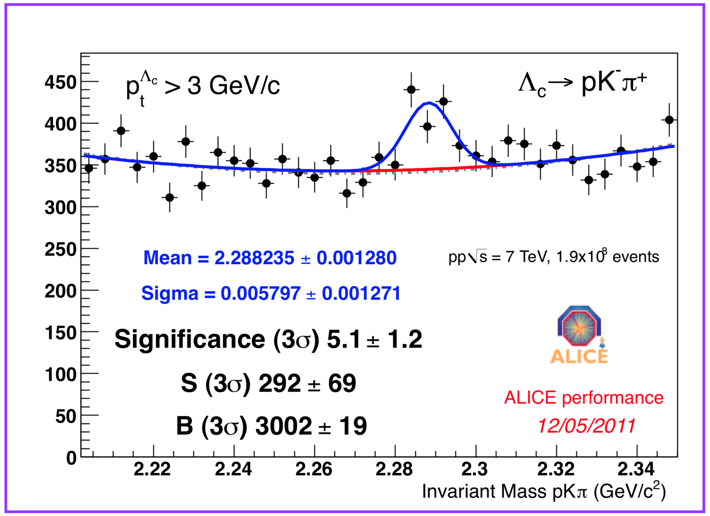
- 2 < p_t < 12 GeV/c, with 1.6 nb^{-1} (~20% of 2010 statistics)
- y acceptance is p_t-dep (Δy~1.0→1.6): data scaled to |y|<0.5
- pQCD predictions (FONLL and GM-VFNS) compatible with our data

Charm in pp 7 TeV: Outlook

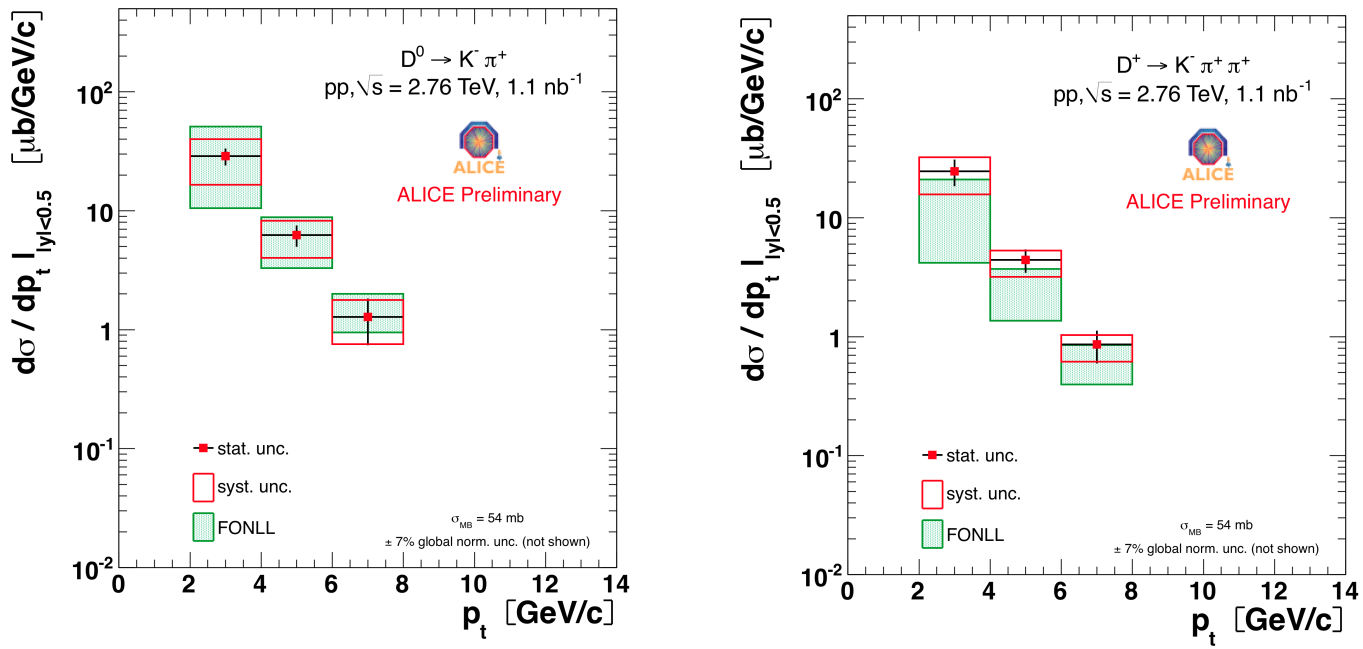
- Extend p_t range with full 2010 statistics: 1—20 GeV/c (e.g. D* shown)
- The shy charming: D_s and Λ_c







D mesons cross sections: pp 2.76 TeV, |y|<0.5

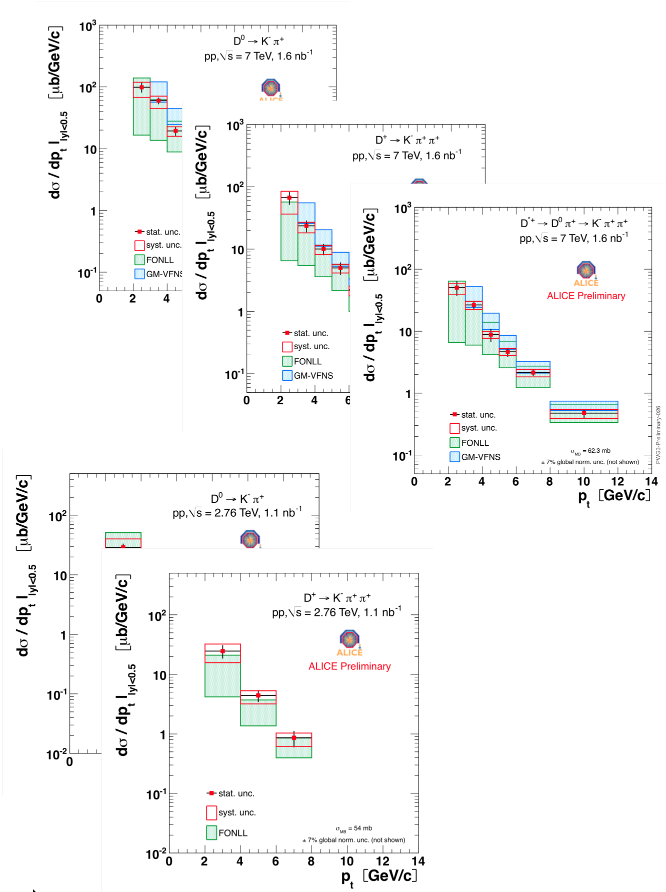


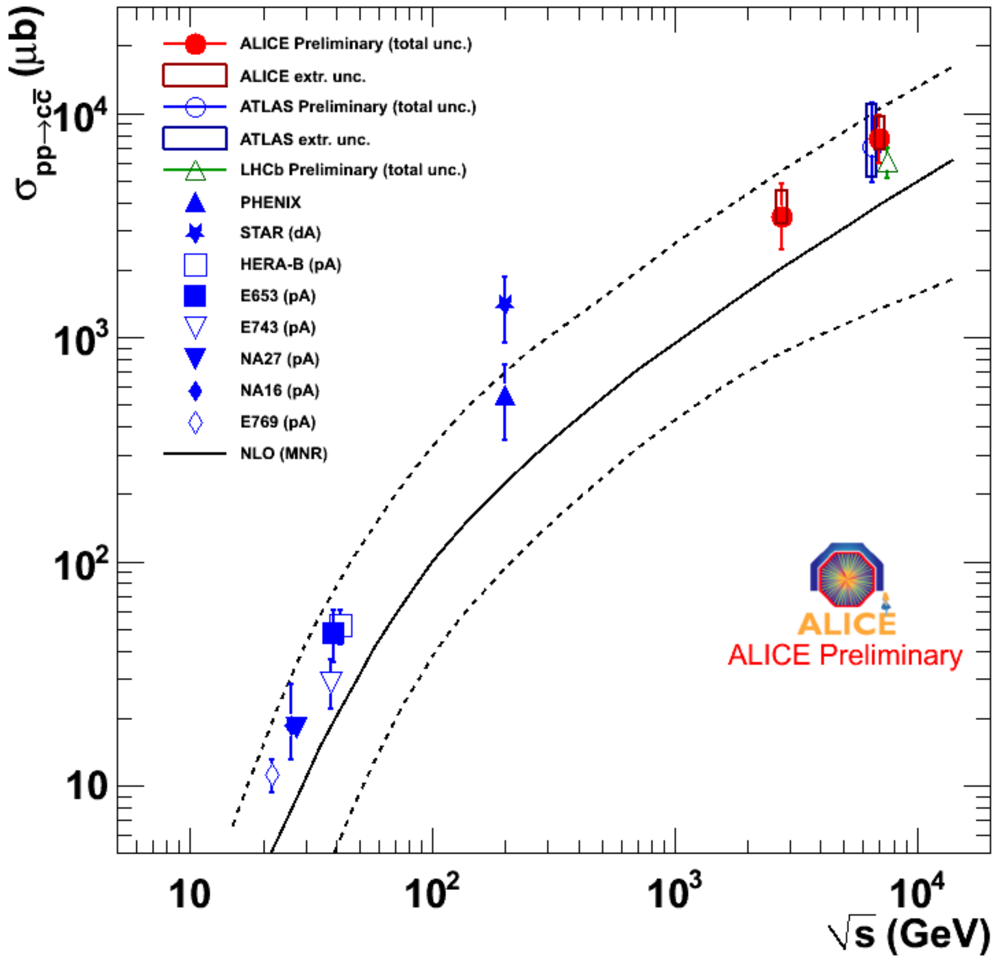
FONLL: Cacciari et al., private comm.

- $2 < p_t < 8$ GeV/c, with 1.1 nb^{-1} (3 days of data 3 months ago!)
- y acceptance is p_t-dep (Δy~1.0→1.6): data scaled to $|y|<0.5$
- pQCD predictions (FONLL) compatible with our data

The Total Charm Cross Section in pp

Extrapolation from $p_t = 2$ GeV/c to 0 (about ×2) and full y using FONLL



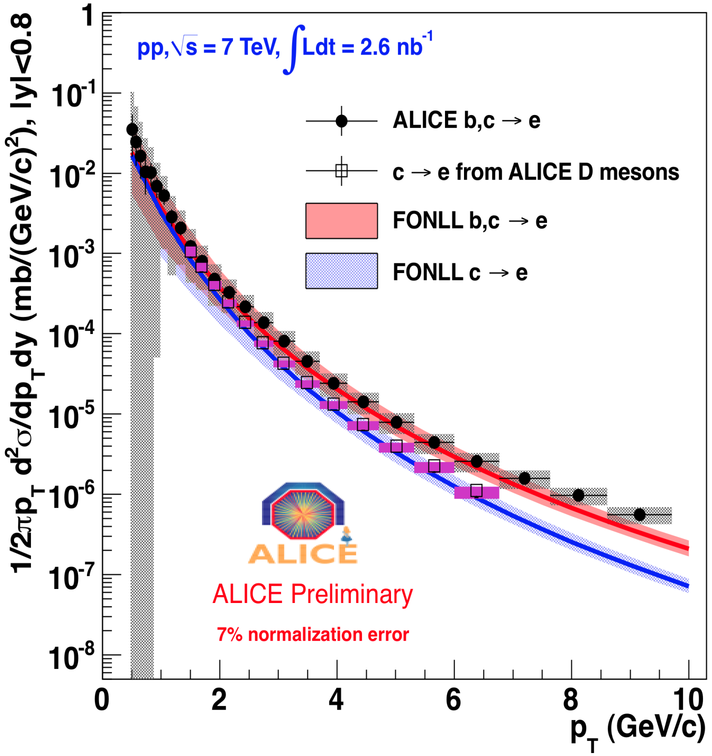


Consistent comparison with NLO over 3 orders of magnitude

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

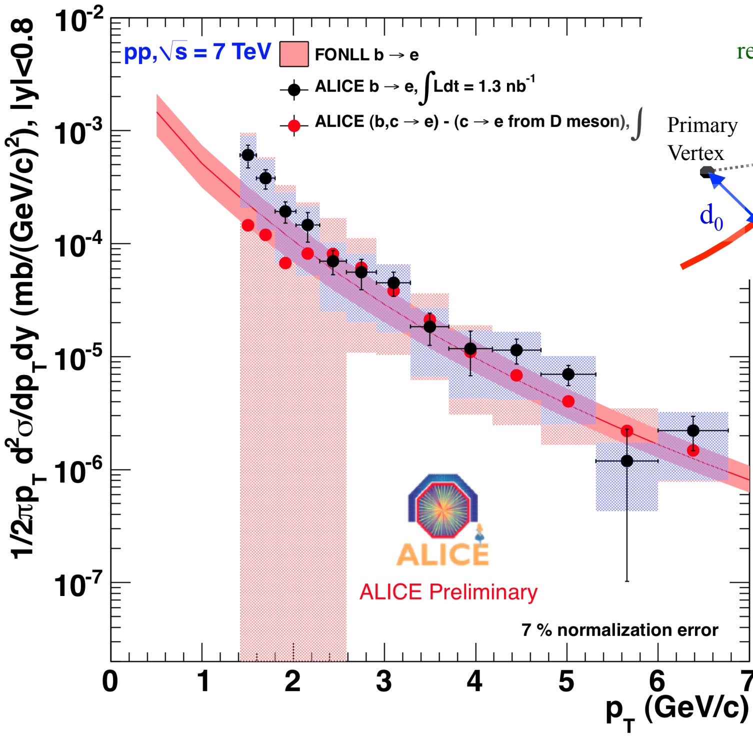
$$\sigma^{tot}_{c\bar{c}}(\text{ALICE}, 7\text{TeV}) = 7.73 \pm 0.54(\text{stat.})^{+0.74}_{-1.38}(\text{syst.}) \pm 0.44(\text{lum.})^{+1.90}_{-0.87}(\text{extr.})\text{mb}$$

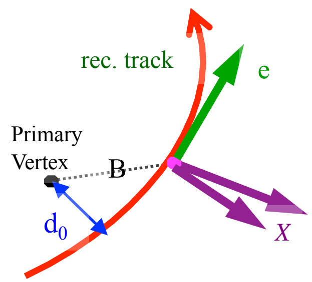
Heavy flavour decay electrons: pp 7 TeV, |y|<0.8



- Cocktail of "photonic" backgrounds based on measured π^0 cross section
- Inclusive – Cocktail: electrons from c and b decays
- Agrees with measured-D decay electron spectrum at low p_t
- Well described by FONLL

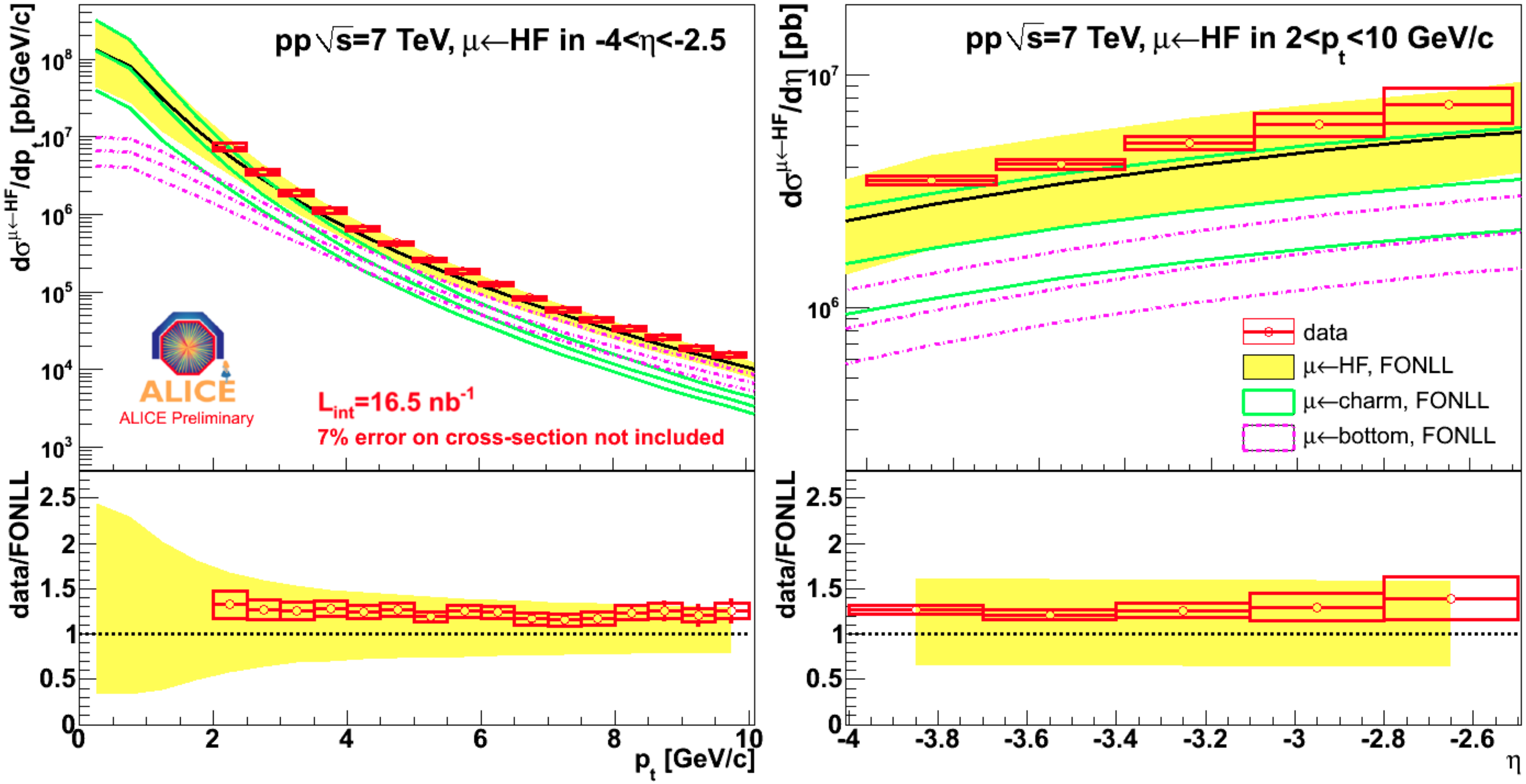
- + Select electrons displaced from interaction vertex
- Electrons from beauty decays!
- Agrees with difference: = -
- Well described by FONLL





→ S.Masciocchi, Mon parallel

Heavy flavour decay muons: pp 7 TeV, -4<η<-2.5



- Measured $d\sigma/dp_t$ in 2-10 GeV/*c* and $d\sigma/d\eta$ in -4 to -2.5
- Well described by FONLL predictions
  - FONLL indicates beauty dominance above 6 GeV/*c*

→ X.Zhang, Mon parallel

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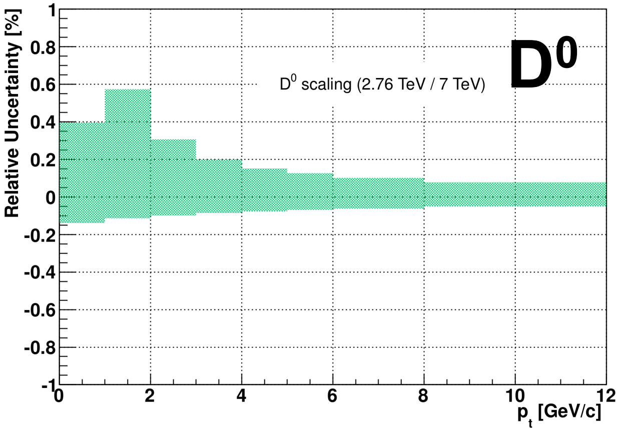
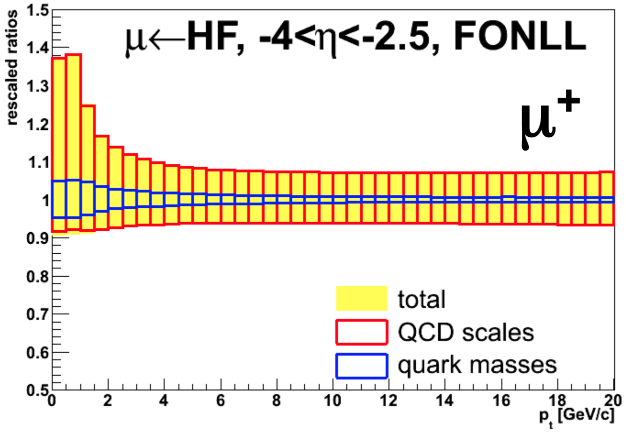
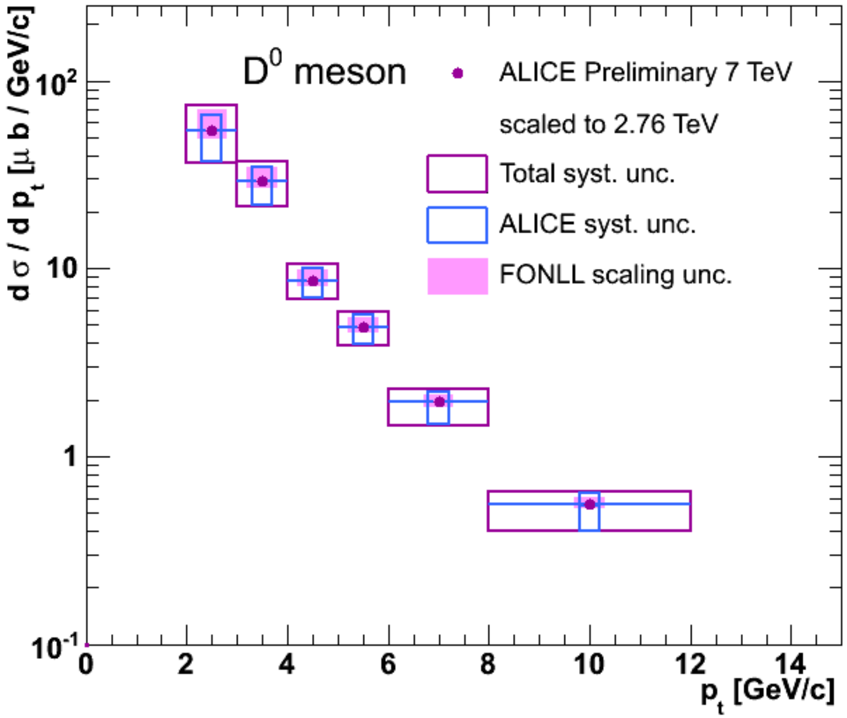
pp reference at 2.76 TeV via pQCD-driven √s-scaling

- Scale the 7 TeV cross sections by the 2.76/7 factor from FONLL, with full theoretical uncertainty
  - assume that pQCD scales and quark masses don't change with √s
  - relative scaling uncertainty: 25% → 10% in p_t = 2 → 10 GeV/c





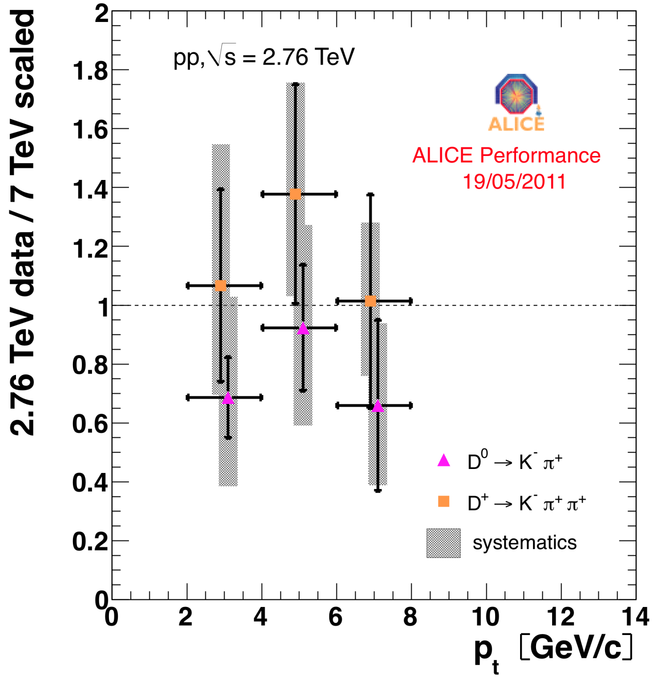


→ Z.Conesa del Valle, poster

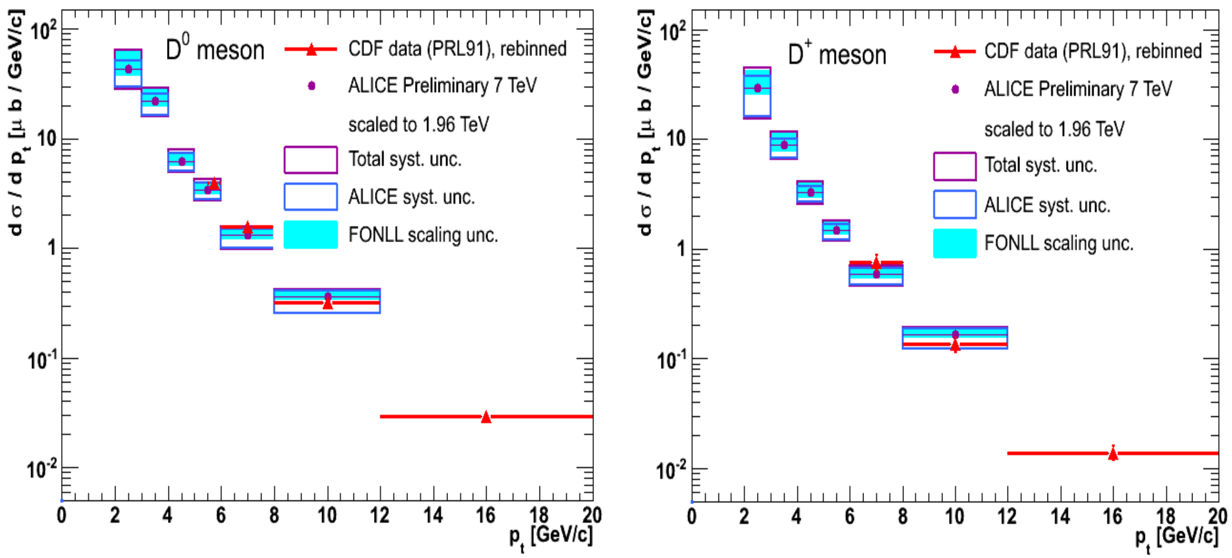
pp reference at 2.76 TeV via pQCD-driven √s-scaling

- The D meson reference was checked against
  - ALICE data at 2.76 TeV, p_t<8 GeV/c (only 3 days… limited p_t cov., large uncertainties)
  - CDF data, p_t>6 GeV/c (using a scaling to 1.96 TeV)

ALICE 2.76 TeV: data/reference



Comparison with CDF at 1.96 TeV



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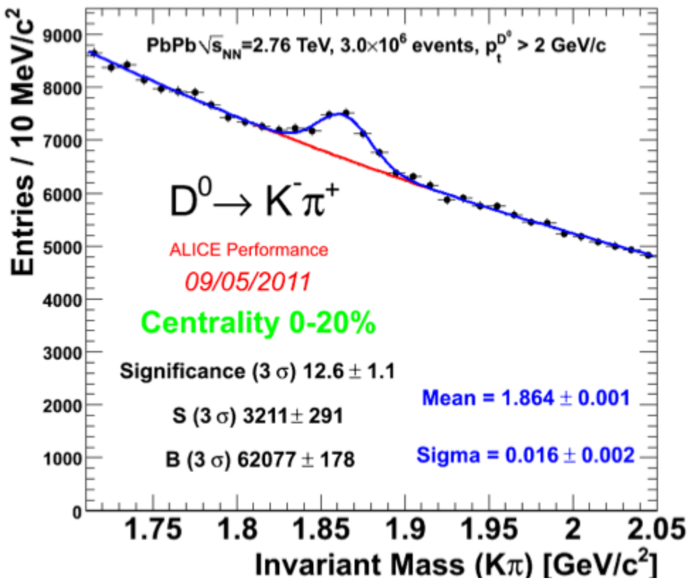
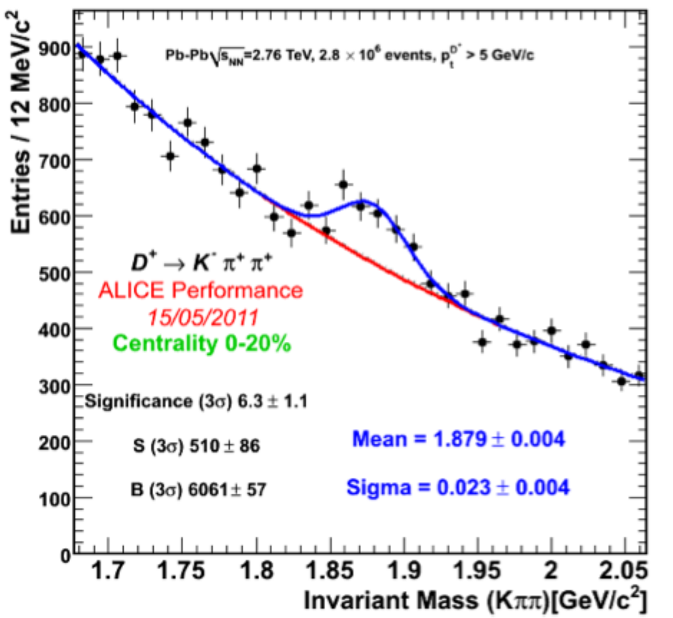
D^0 and D^+ reconstruction in Pb-Pb

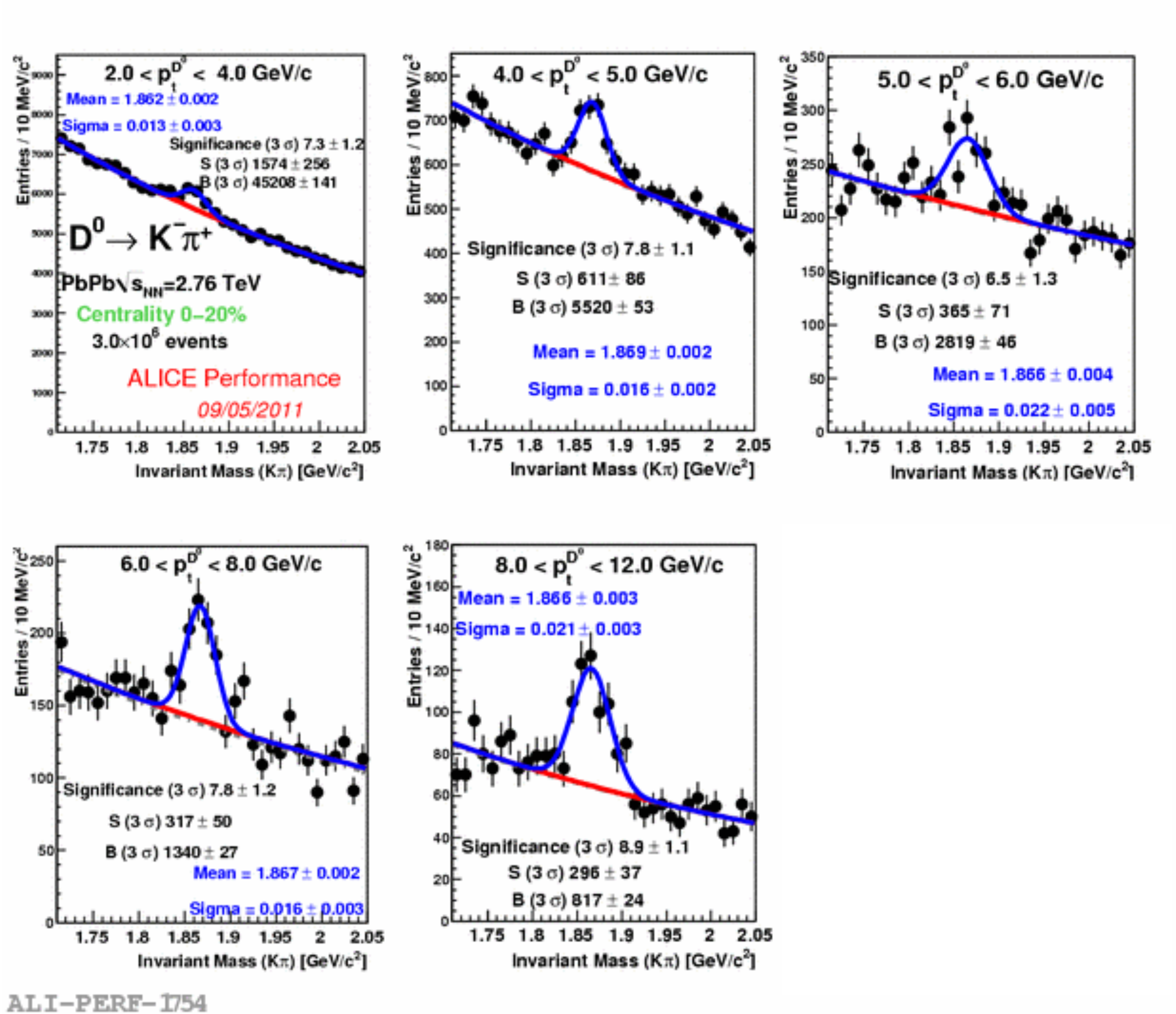




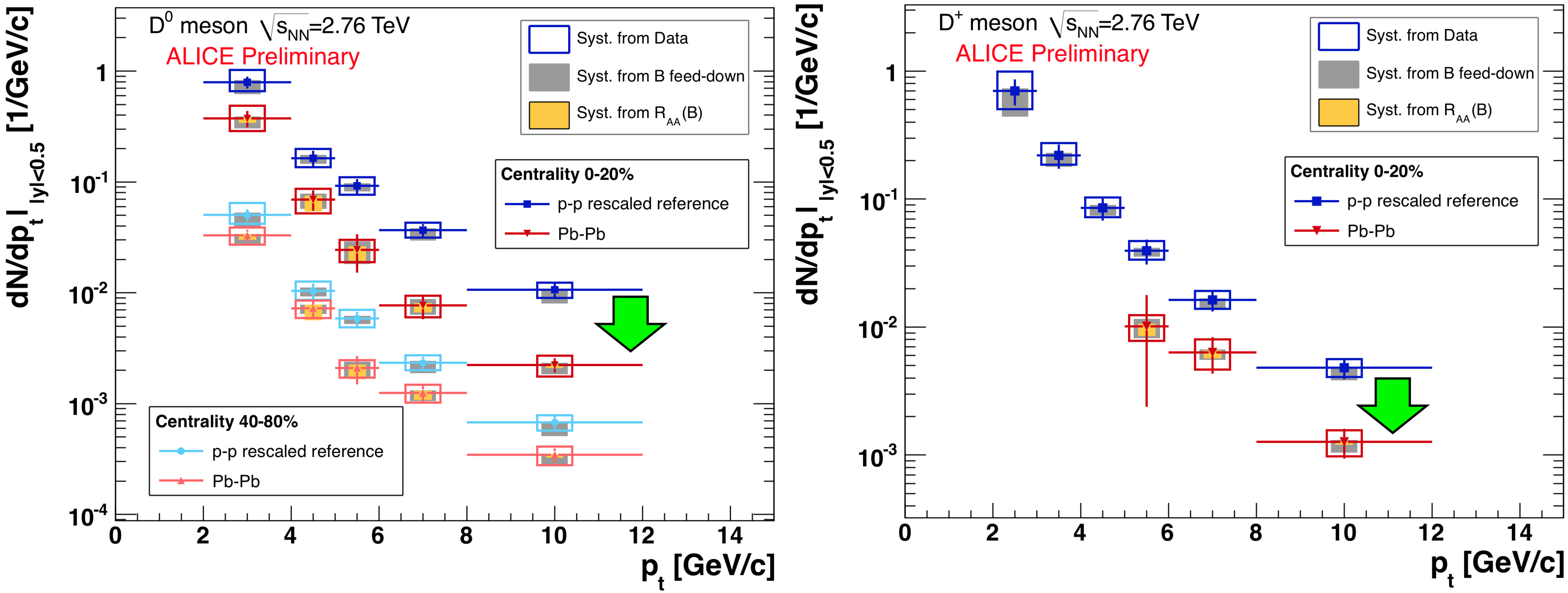
- In ~3M central collisions (0-20%):
  - D^0 : 5 p_t bins in 2-12 GeV/c
  - D^+ : 3 p_t bins in 5-12 GeV/c
- Reconstruction efficiency ~1-10%
  - evaluated from MC simulation
    - detector status and performance described by the MC to few % level
    - no centrality dependence found
- Feed-down from B decays ~10-15% after cuts
  - subtracted based on FONLL with hypothesis on R_{AA}^{B} (→ more later)

→ A.Rossi, Fri parallel

$D^0 \rightarrow K\pi$ in central Pb-Pb (0-20%)

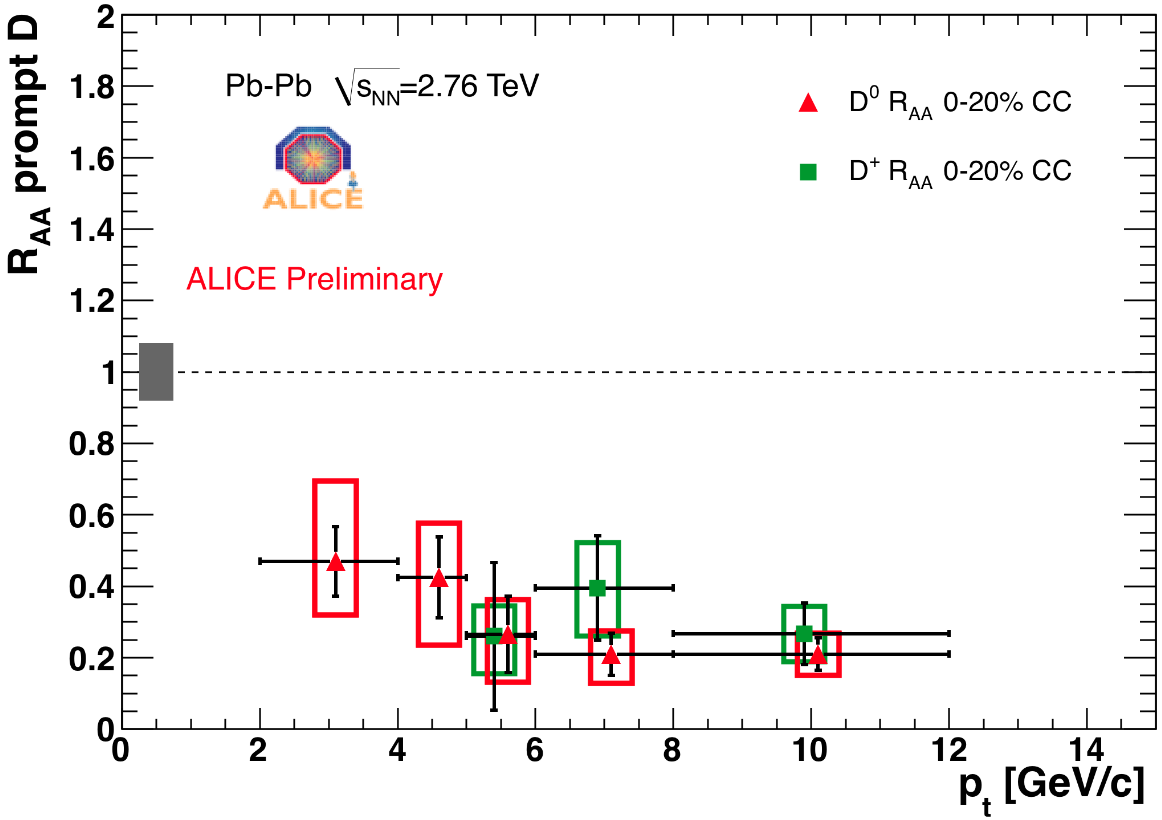


D^0 and D^+ p_t distributions in Pb-Pb



- Strong suppression observed in central collisions (0-20%) wrt T_{AA}-scaled pp reference
- Significant suppression also in semiperipheral (40-80%) wrt T_{AA}-scaled pp reference

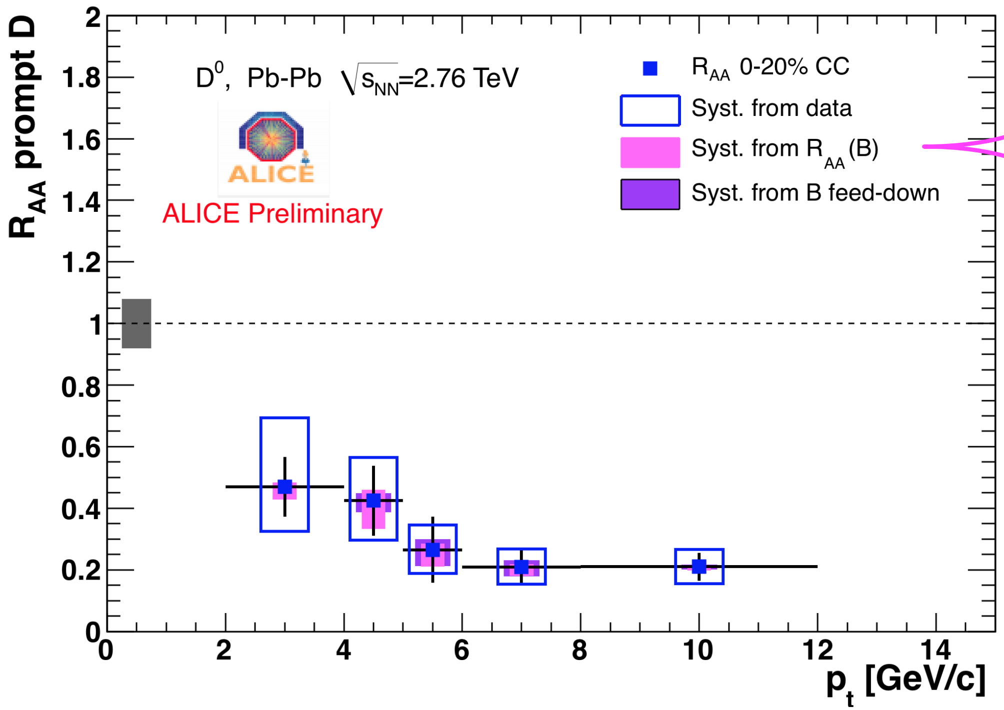
The D meson R_{AA} (0-20%)

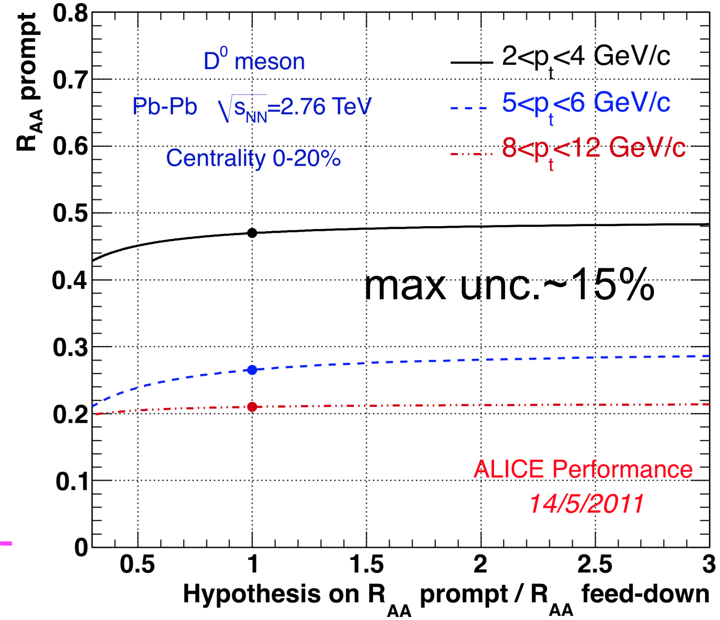


- Suppression for charm is a factor 4-5 above 5 GeV/*c*

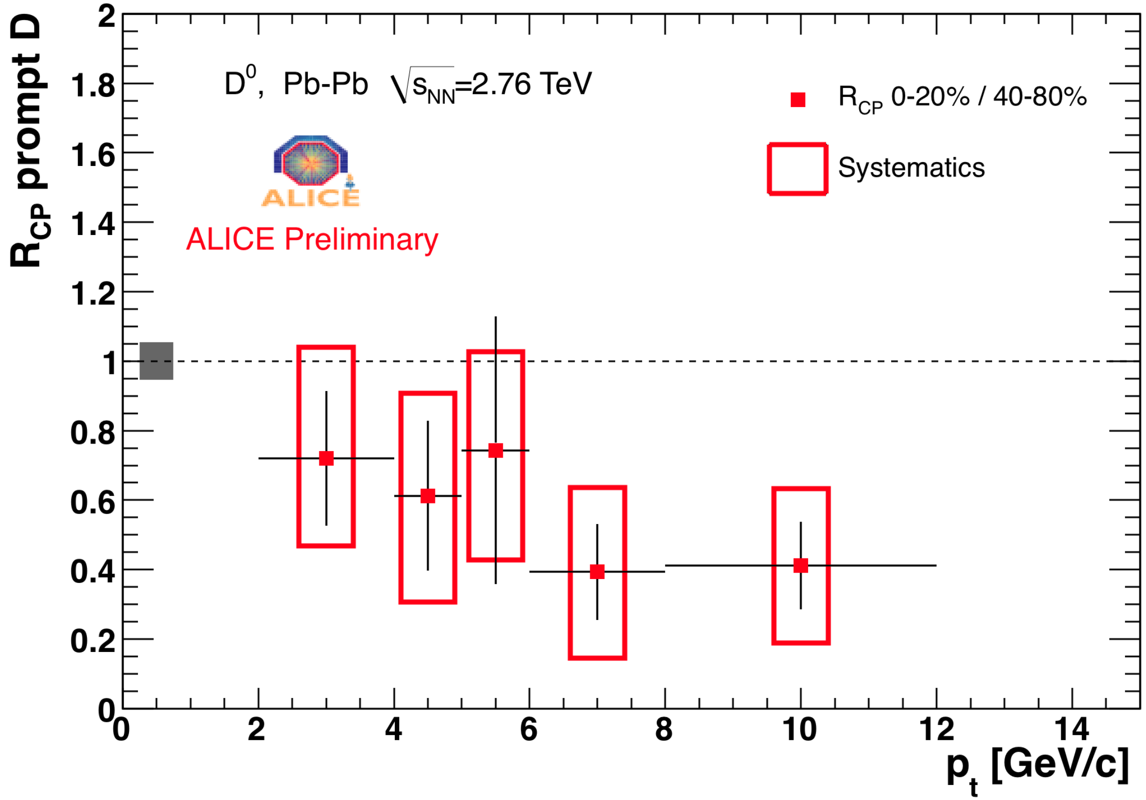
B feed-down: effect on R_{AA}^{D}

- Correction for B→D: $-\langle T_{AA}\rangle \times \varepsilon^{MC}_{DfromB} \times \frac{d\sigma^{FONLL}_{DfromB}}{dp_t} \times R^{B}_{AA}$
  - from FONLL, using ALICE efficiencies for these D's: ~10-15%
    - systematic uncertainty from FONLL, partly cancels in R_{AA}^{D}
  - + need to make hypothesis on R_{AA}^{B}
    - conservative: $1/3 < R_{AA}^{D}/R_{AA}^{B} < 3$ → systematic uncert. on R_{AA}^{D}





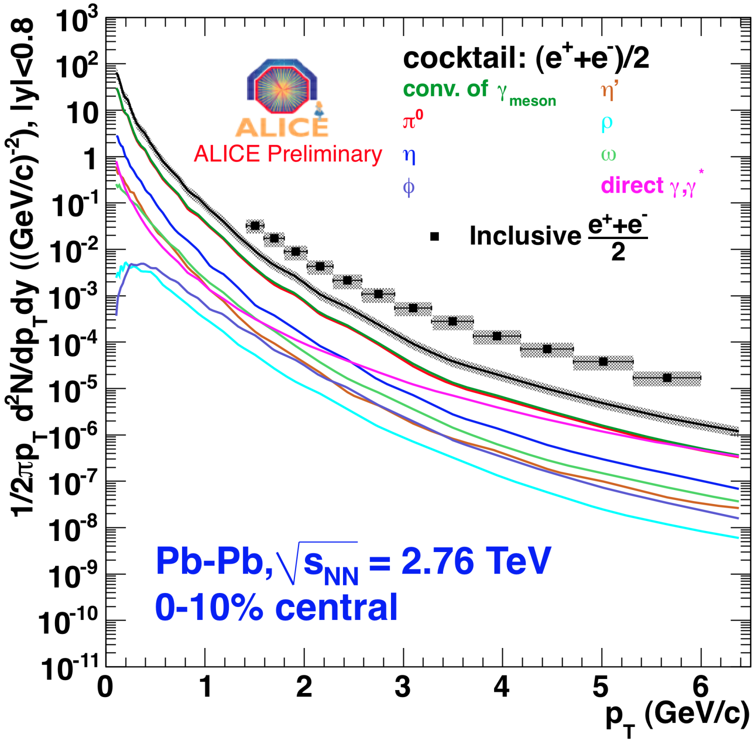
The D^0 meson R_{CP} (0-20%/40-80%)

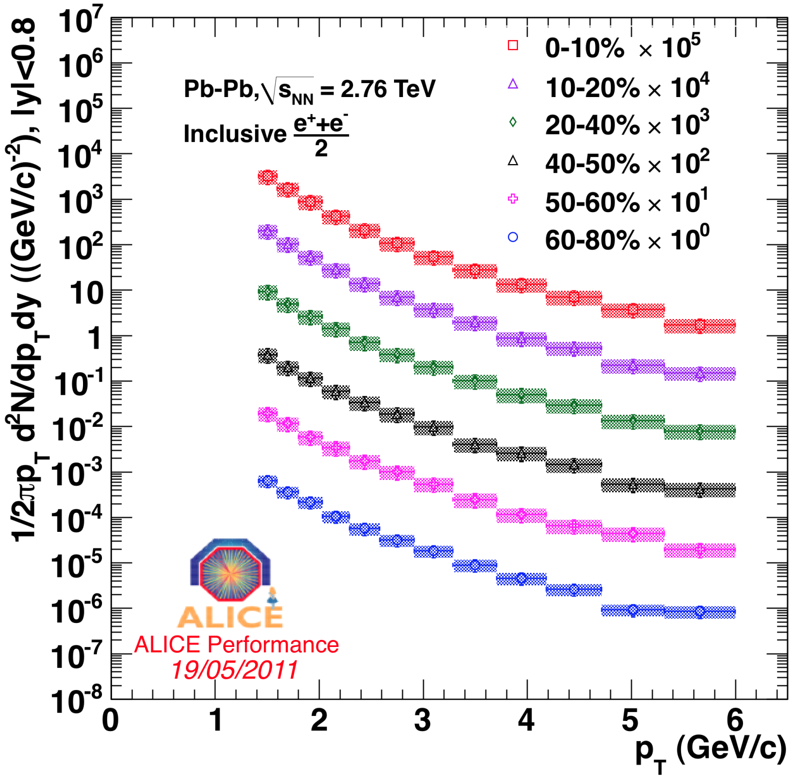


- Suppression clearly seen also in R_{CP} (no pp reference)
- Factor 2-3 above 5 GeV/*c*

Electron p_t spectrum in Pb-Pb

- Inclusive electron p_t spectra in six centrality bins
  - hadron cont. <10% up to 6 GeV/c, measured from TPC dE/dx fits

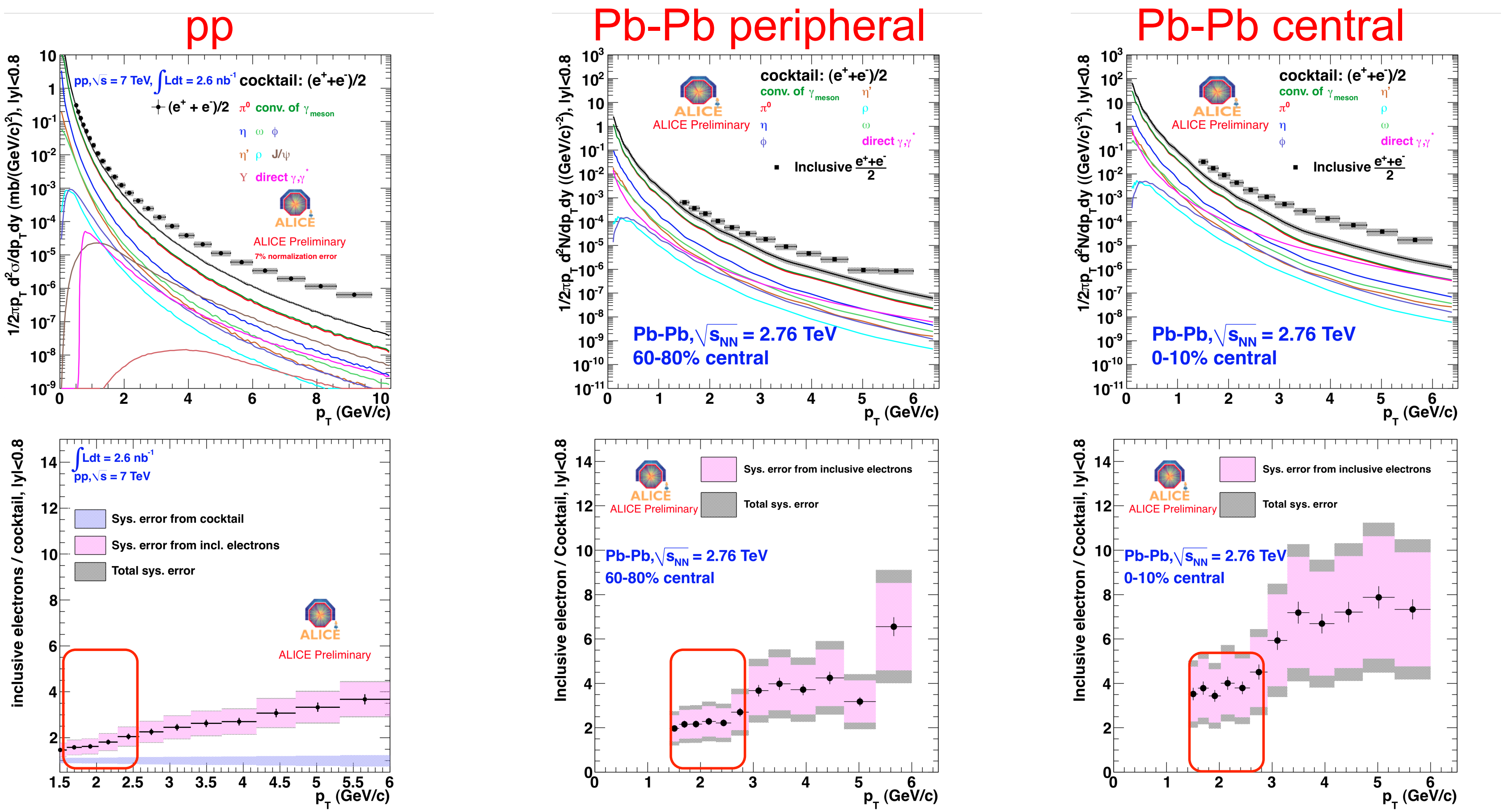




- Background electron cocktail, based on $\pi^{\pm}$ spectra + m_t-scaling + pQCD direct photons
- Compare inclusive spectra to cocktail …

→ S.Masciocchi, Mon parallel

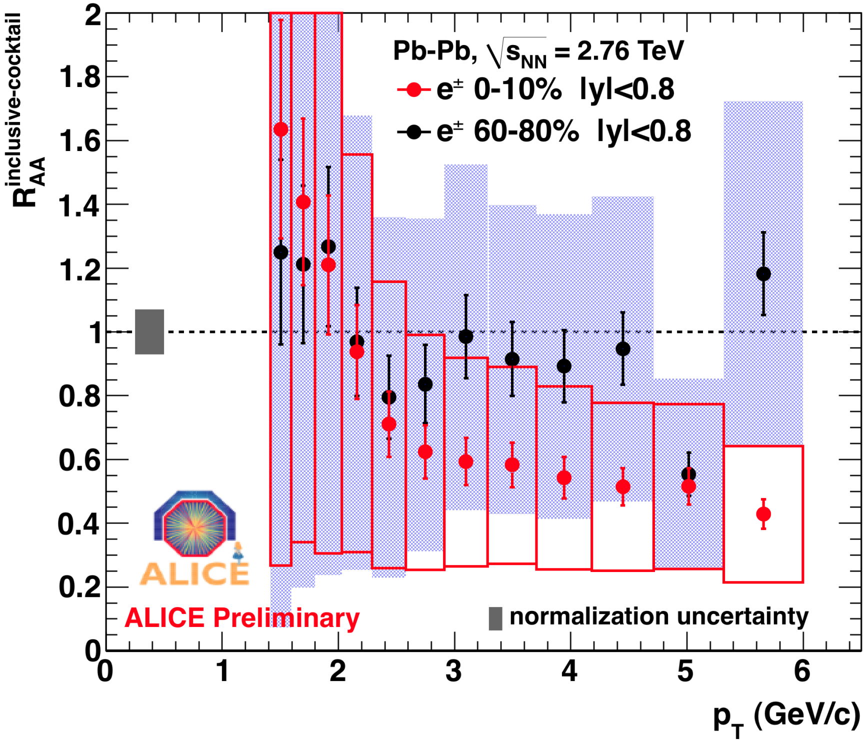
Electron spectrum in Pb-Pb vs. cocktail



- Hint of an electron excess at low p_t (beyond our systematic errors, mainly from e ID)
- Increases with centrality
- Might be explained by thermal photons (cfr. PHENIX, PRL104 and QM2011)

Cocktail-subtracted Electron R_{AA}

- Consider (inclusive electrons – cocktail) spectrum
  - low p_t: large systematic uncertainties (also from pp reference)
  - above 3-4 GeV/c: *dominated by charm and beauty decays*

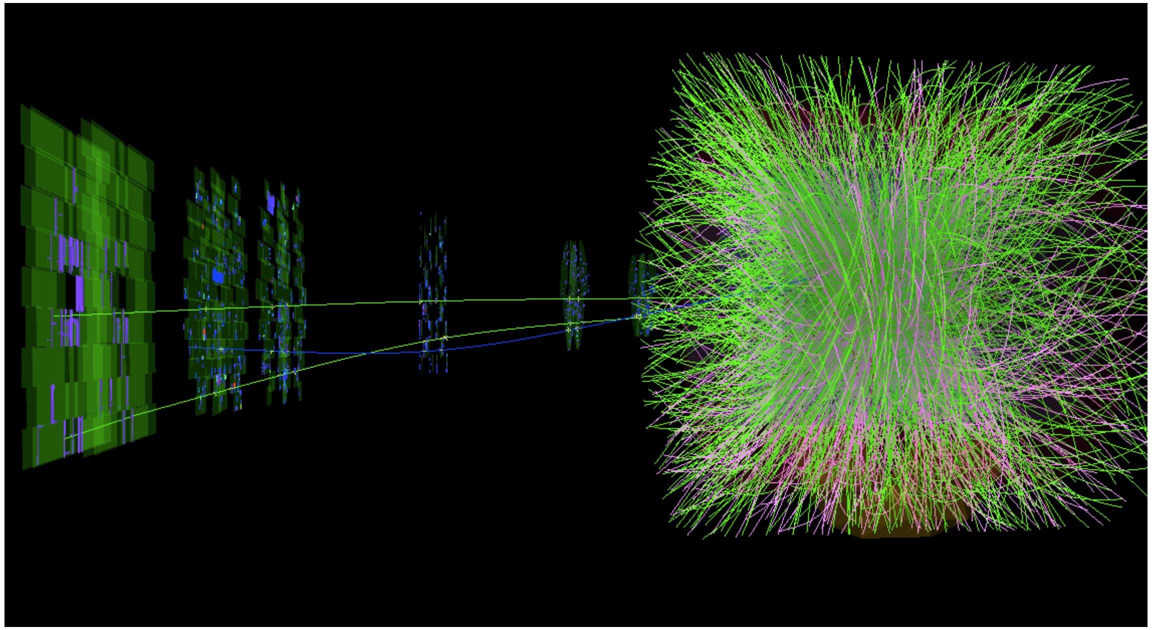


60-80%

0-10%

- Suppression in central collisions: factor 1.5-4

Muons at forward rapidity in Pb-Pb



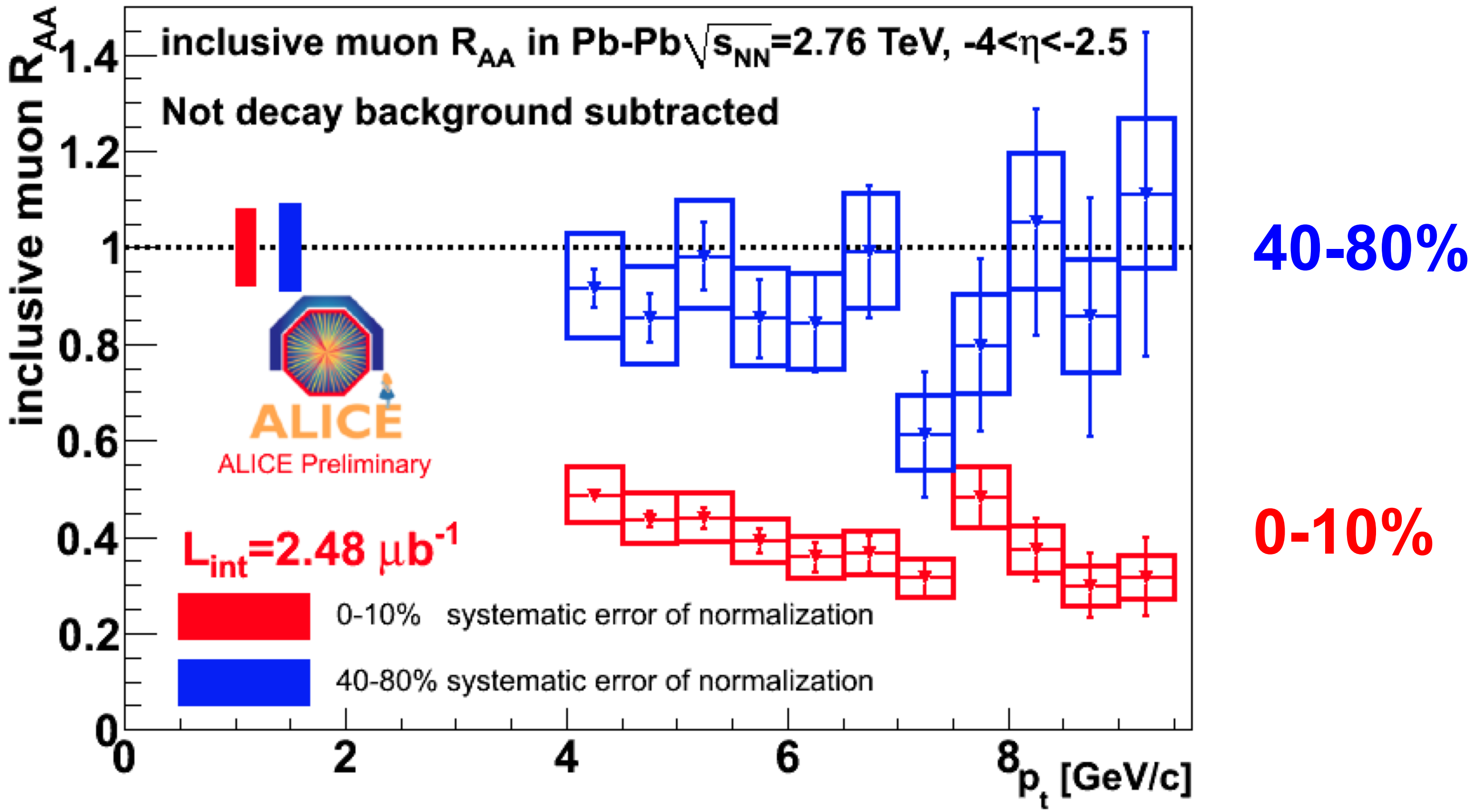
- $-4<\eta<-2.5$, p >4 GeV/c
- Pointing to interaction vertex to remove fake tracks (don't point)
- Efficiency from MC simulation, validated by J/ψ embedding

- The low-p_t background of muons from π/K decays is not subtracted (will be done based on ALICE data)
- We provide the inclusive muon R_{AA}
- We estimate from Hijing simulations that this background is about 15% (10%) at p_t = 4 (6) GeV/c

  → heavy flavour decay dominance

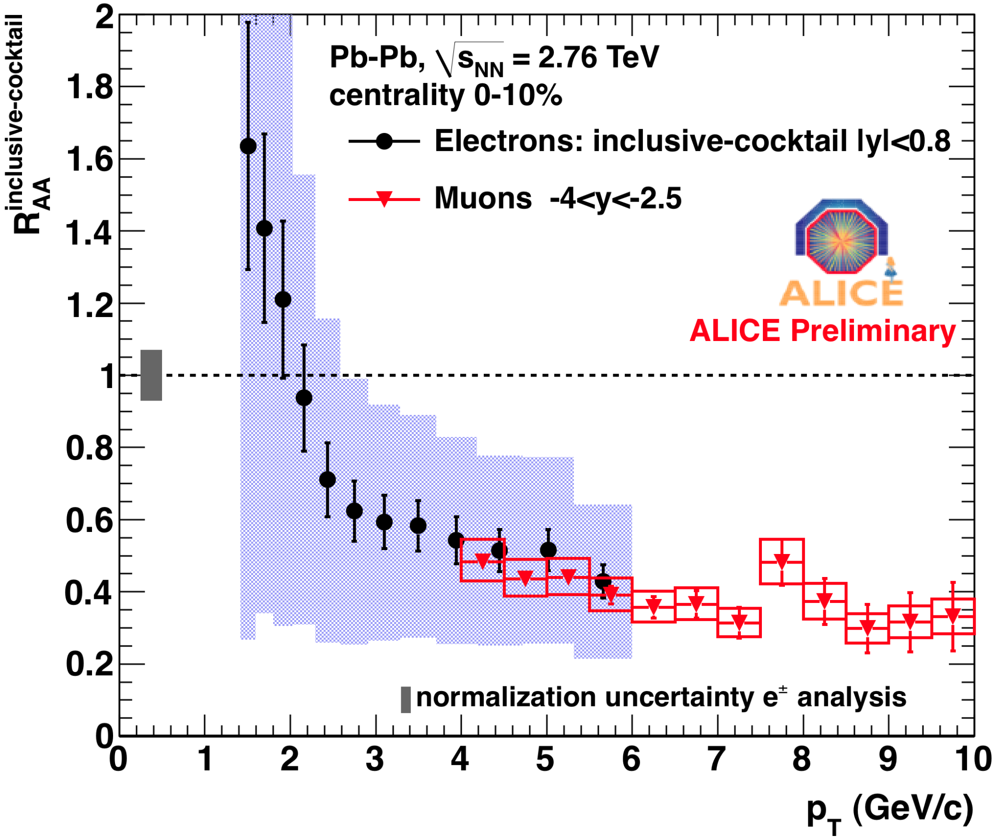
→ X.Zhang, Mon parallel

Muon R_{AA} at forward rapidity



- Suppression is of about a factor 3 above 6 GeV/*c*
- According to FONLL, beauty dominant in this region

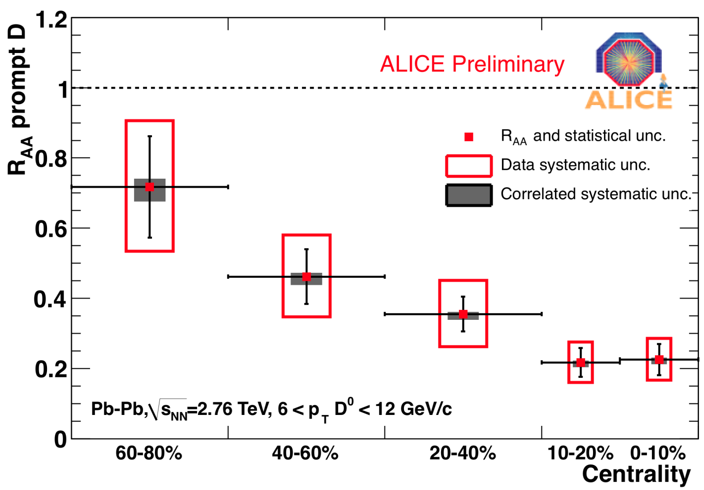
Data Comparison: Leptons y~0, y~3

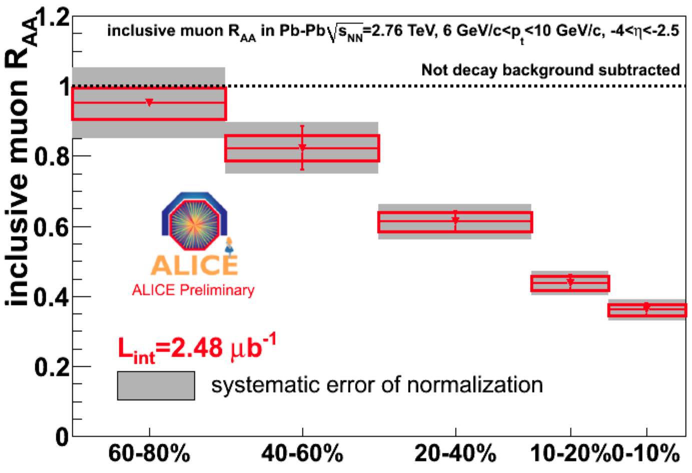


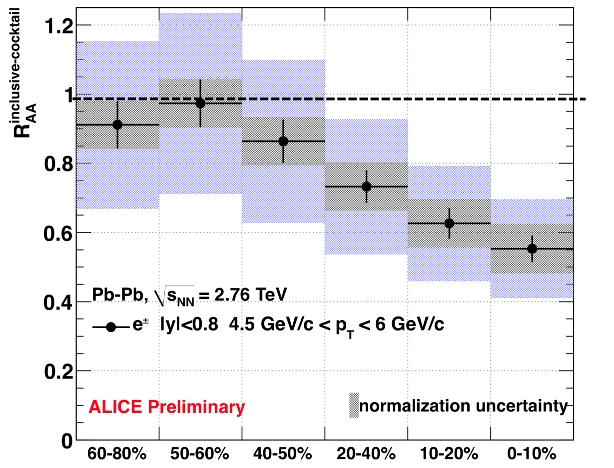
- Consistent with the large uncertainties of electron PID

Data Comparison: Centrality Dependence

D^0 p_t > 6 GeV/c | μ p_t > 6 GeV/c | e p_t > 4.5 GeV/c





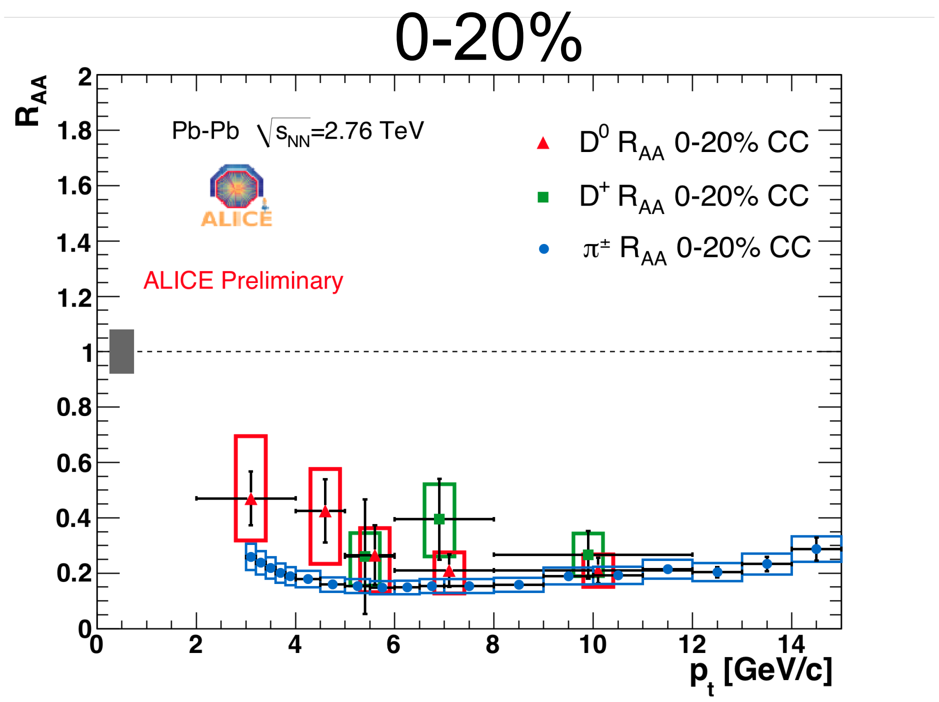


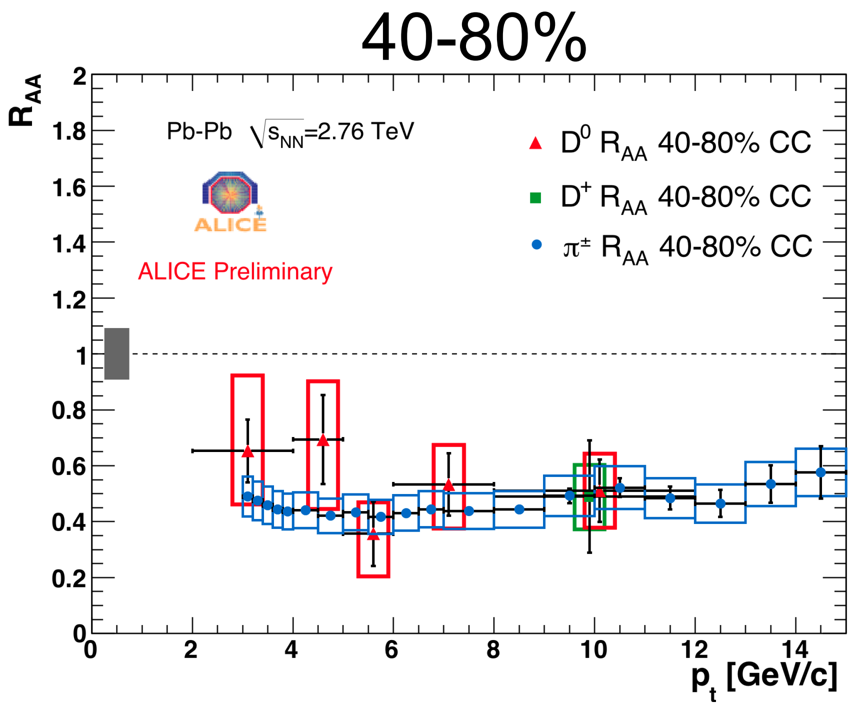
→ Consistent centrality dependence

→ Muons ~ Electrons ~ CMS J/ψ from B (QM2011)

→ D mesons clearly lower (charm vs beauty?)

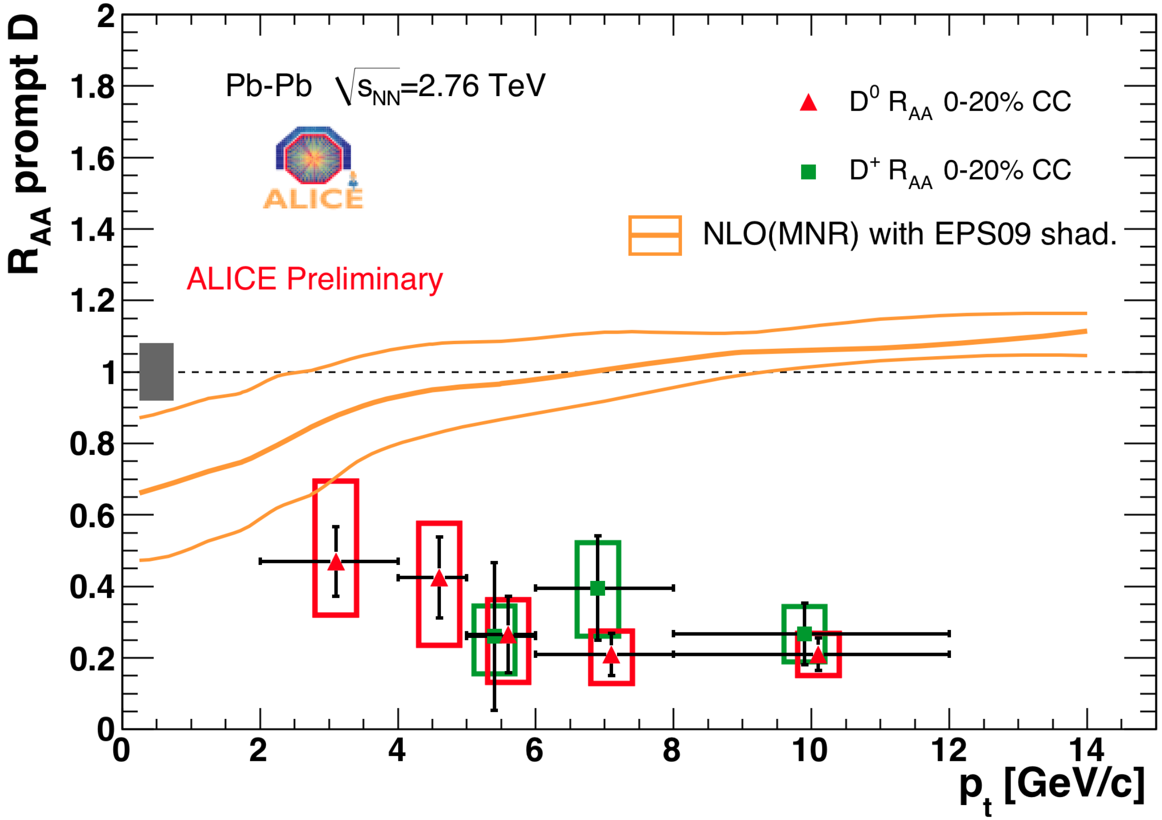
Data Comparisons: D and $\pi^{\pm}$





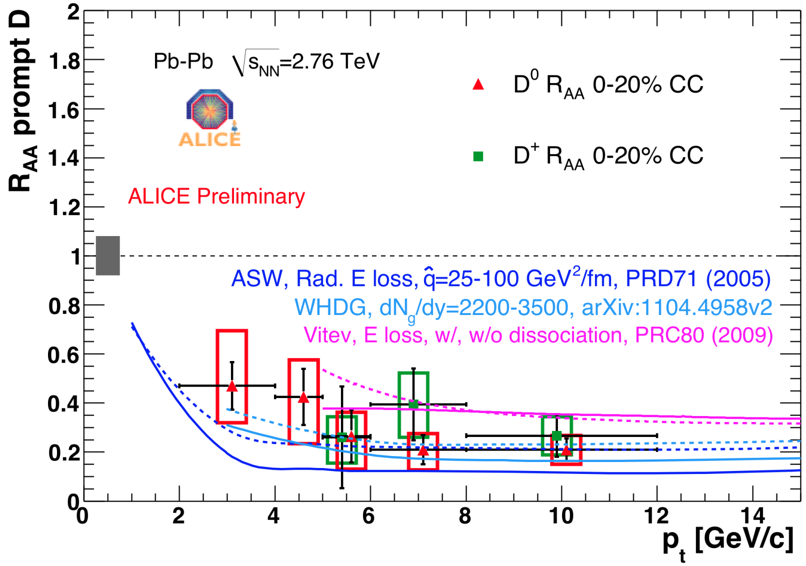
- Suppression for charm is a factor 4-5 above 5 GeV/*c*
- Compatible with pions R_{AA} (slightly larger below 5 GeV/*c*)
  - maybe hint for $R_{AA}^{D} > R_{AA}^{\pi}$? stay tuned for 2011 Pb-Pb run results

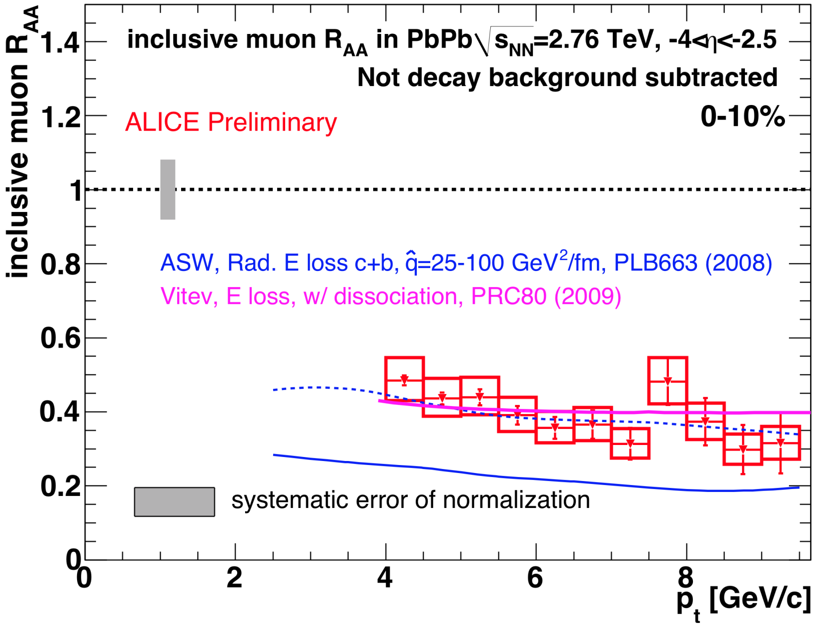
Model Comparisons: Shadowing



- Suppression for charm is a factor 4-5 above 5 GeV/*c*
- This is a hot medium effect (little shadowing at these p_t's)
- p-Pb run at LHC crucial to understand the low-p_t rise

Model Comparisons: Energy Loss





- Published calculations are mostly for 5.5 TeV
- Radiative E loss (BDMPS—ASW)
  - data lie on same curve, both D and muons
- Radiative+collisional E loss (WHDG, 2.76 TeV)
  - fair description
- Light-cone wave function approach with dissociation (Vitev)
  - a bit high for D mesons, OK for muons (~beauty)

Summary and Outlook

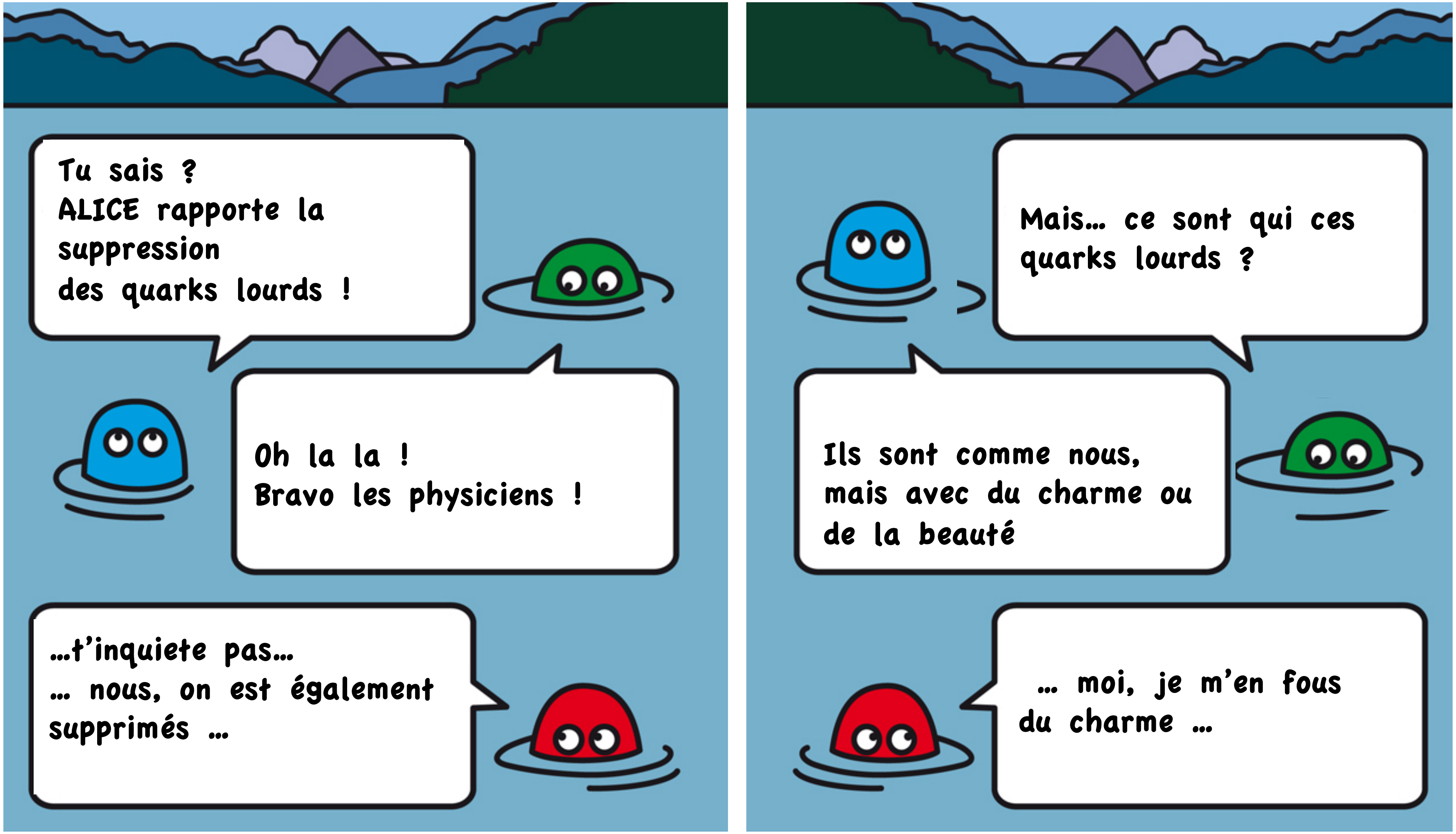
- The nuclear modification factors in Pb-Pb for heavy flavour have been measured by ALICE

- The D meson and high-p_t lepton R_{AA} exhibit a strong suppression in central collisions (down to ~0.2 for D's)
  - The suppression tends to vanish towards peripheral collisions
  - It persists in a momentum range where very small initial state effects are expected

- *These analyses can be performed vs. event plane → Flow*
- *The cross section of electrons from B decays can be measured, as done in pp*

EXTRA SLIDES

…et les Quarkoissons du Lac d'Annecy…



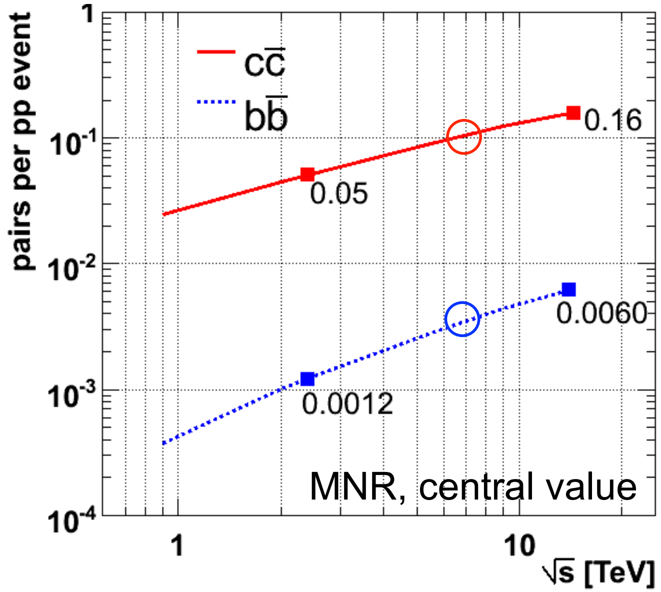
(not on behalf of the ALICE Collaboration)

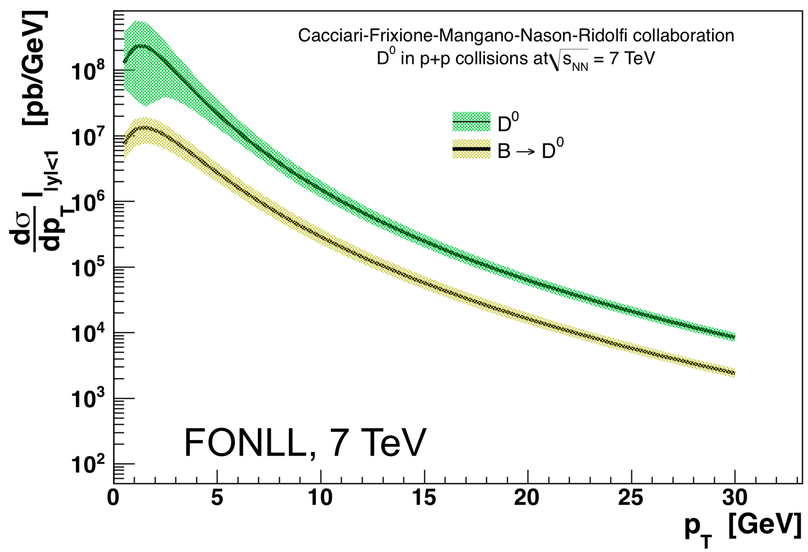
LHC: heavy quarks factory!

- NLO predictions (**charm** & **beauty**)
  - ~ factor 2 uncertainty from NLO and shadowing (Pb-Pb)

system : $\sqrt{s_{NN}}$:	Pb-Pb (0-5%) 5.5 TeV	**Pb-Pb (0-5%) 2.76 TeV**	pp 14 TeV	**pp 7 TeV**
$\sigma_{NN}^{Q\overline{Q}}$ [mb]	3.4 / 0.14	**2.1 / 0.075**	11.2 / 0.5	**6.9 / 0.23**
$N_{tot}^{Q\overline{Q}}$	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



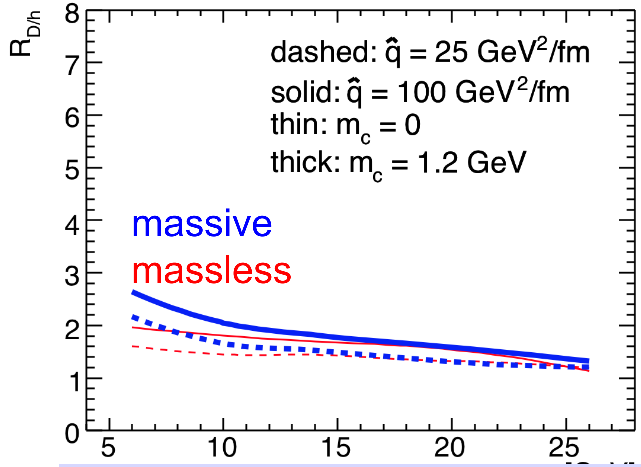


HQs R_{AA}: some expectactions …

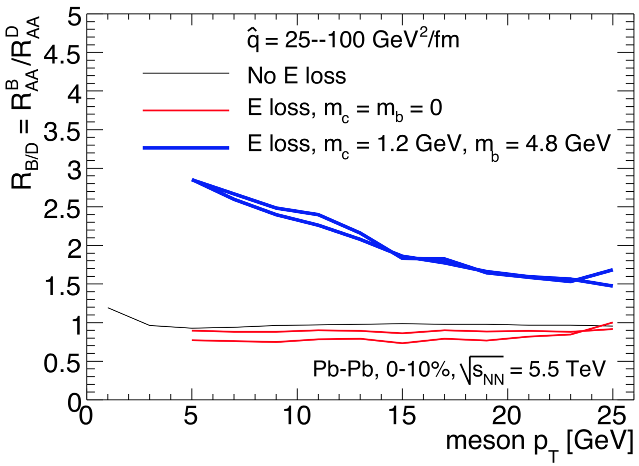
New at LHC

◆ **Heavy-to-light ratios**: parton colour charge and mass dependence

$$R_{D/h}(p_t) = R^D_{AA}(p_t) / R^h_{AA}(p_t)$$

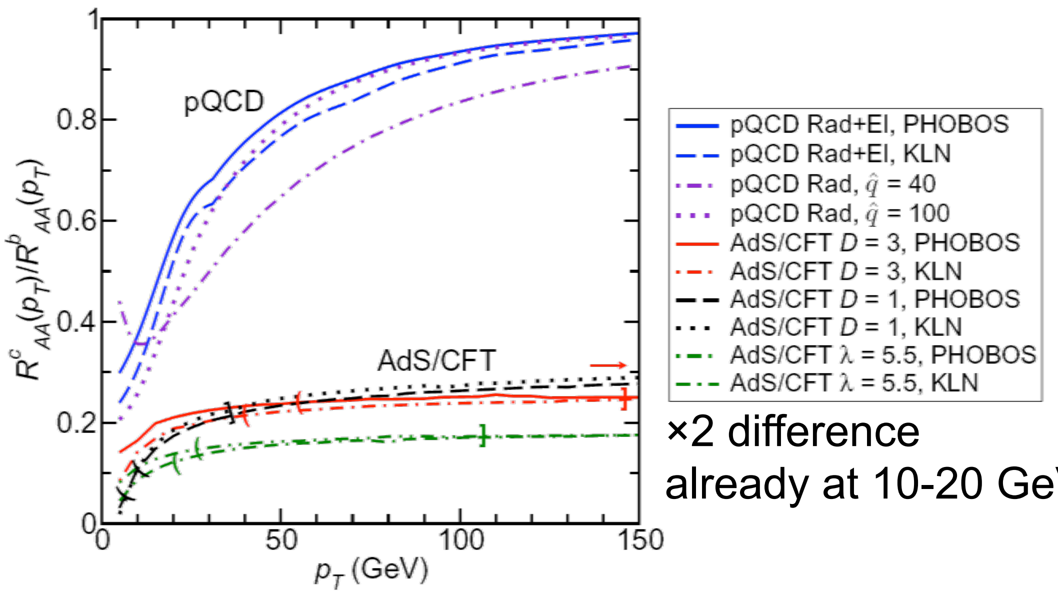


$$R_{B/D}(p_t) = R^B_{AA}(p_t) / R^D_{AA}(p_t)$$



… and, quite a different picture from AdS/CFT

$$1/R_{B/D}(p_t) = R^D_{AA}(p_t) / R^B_{AA}(p_t)$$



×2 difference already at 10-20 GeV

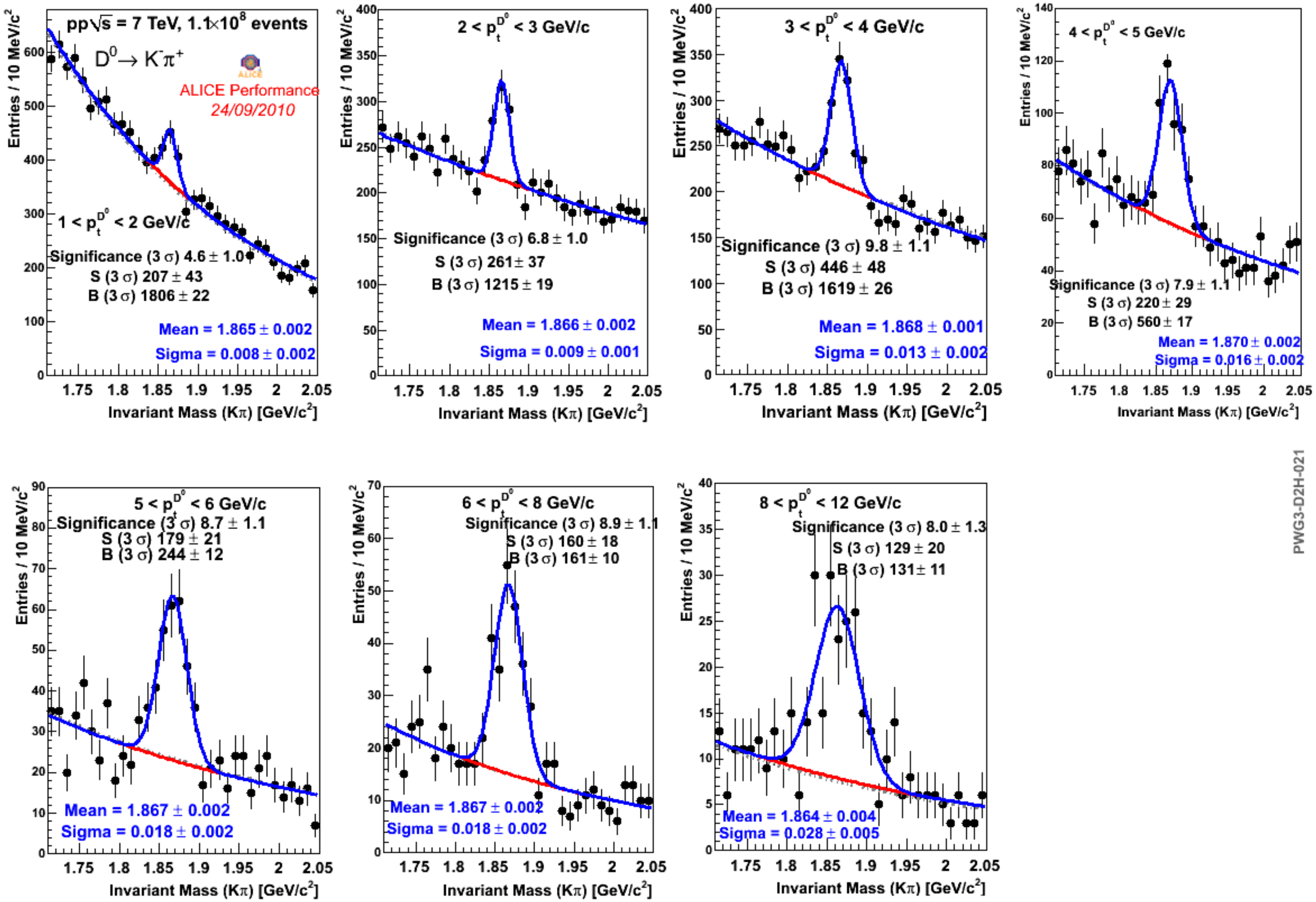
AdS/CFT → D.Mateos, Fri plenary

Armesto, et al, PRD71 (2005)

Horowitz, Gyulassy, PLB666 (2008)

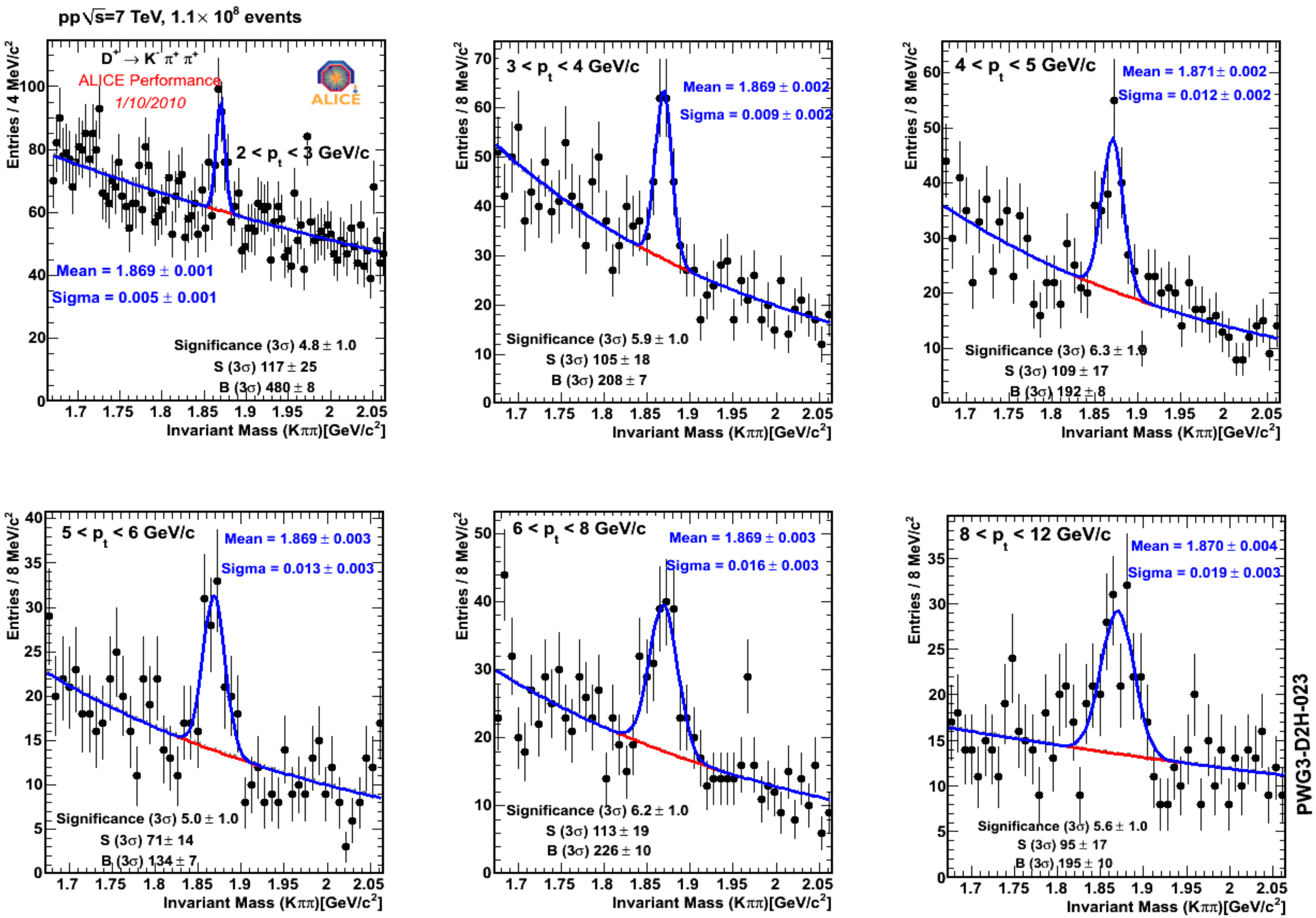
Signals: $D^0 \rightarrow K^- \pi^+$

10^8 events; 1-12 GeV in 7 bins



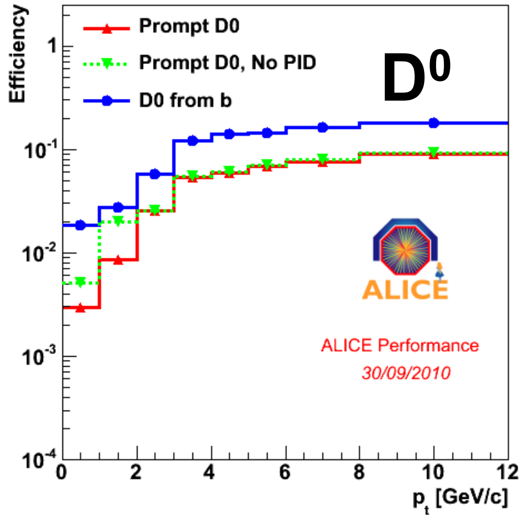
Signals: $D^+ \rightarrow K^-\pi^+\pi^+$

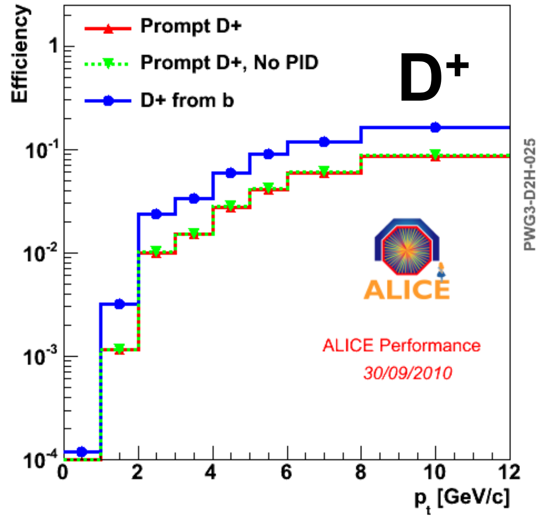
10^8 events; 2-12 GeV in 6 bins



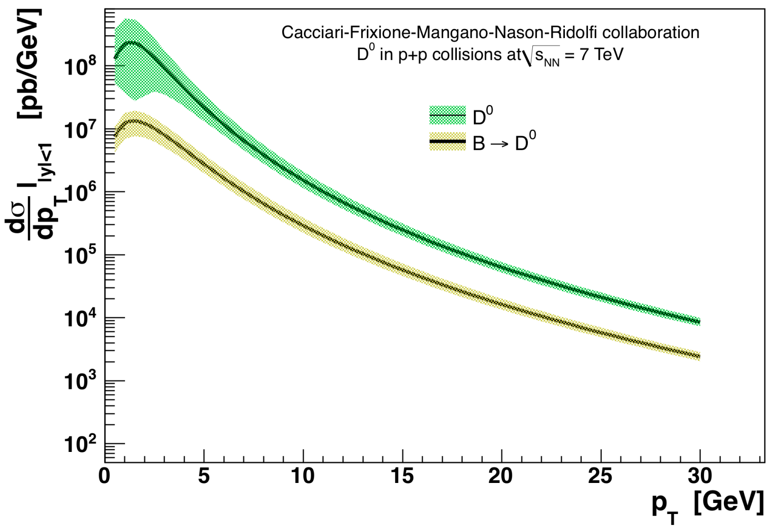
D mesons pp 7 TeV: from signals to cross sections

- Corrections: 1) efficiency
  - 1% → 10% from low to high p_t
  - factor 2 larger for B feed-down D mesons





- Corrections: 2) feed-down B→D
  - ~20-25%
  - will be corrected based on data (D displacement to vertex, à la CDF)
  - for now, subtract using FONLL predictions



D mesons: from signals to cross sections

$$\left.\frac{d\sigma}{dp_t}\right|_{|y|<0.5} = \frac{1}{2}\cdot\frac{1}{\Delta y(p_t)}\cdot\frac{1}{B.R.}\cdot\frac{1}{\varepsilon_c}\cdot \boxed{f_c(p_t)}\cdot\frac{\left.N^D_{raw}(p_t)\right|_{|y|<\Delta y(p_t)}}{\Delta p_t}\,\frac{(\sigma^{CINT1B}/\sigma^{V0AND})}{N_{CINT1B}}\,\sigma^{V0AND}$$

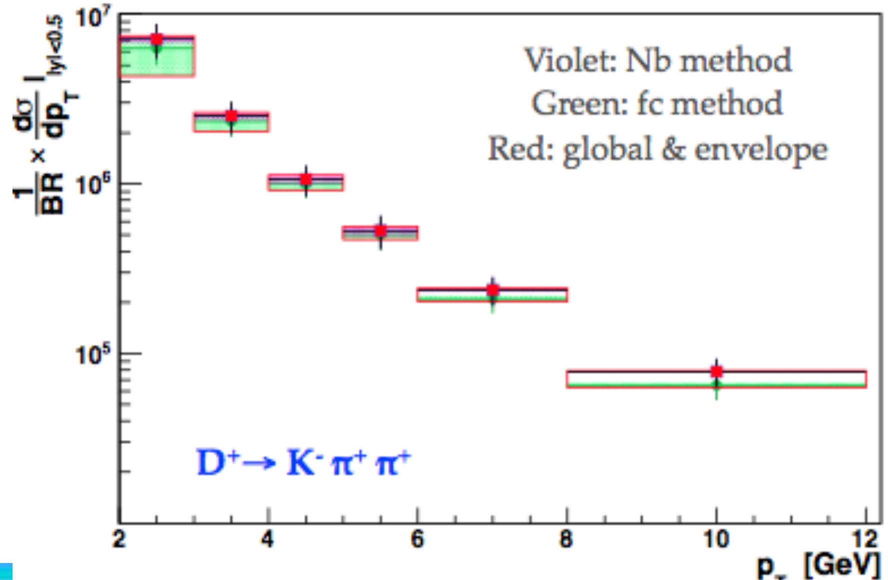
- Corrections: feed-down B→D: ~10-15%
  - main method (“Nb-subtraction”): FONLL input is only the DfromB cross section

$$f_c(p_t)\cdot \left.N^D_{raw}(p_t)\right|_{|y|<\Delta y(p_t)} = \left.N^D_{raw}(p_t)\right|_{|y|<\Delta y(p_t)} - \left.N^{DfromB}_{FONLL}(p_t)\right|_{|y|<\Delta y(p_t)}$$

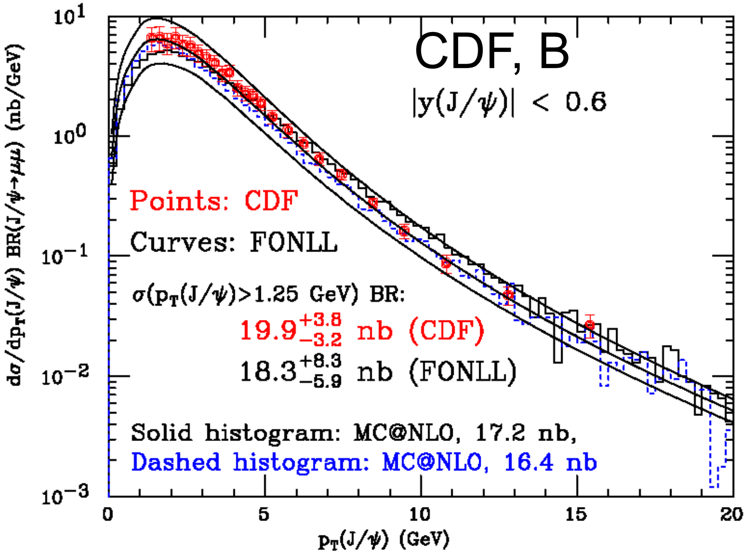
where:

$$\left.N^{DfromB}_{FONLL}(p_t)\right|_{|y|<\Delta y(p_t)} = \sigma^{DfromB}_{FONLL}(pt)\cdot \varepsilon_{DfromB}\cdot \Delta y\Delta p_t\cdot 2\cdot BR\cdot L_{\text{int}}$$

  - second method (“prompt fraction fc”): FONLL input is the ratio of prompt to total D meson cross sections
  - use the total envelope of the error bands (from FONLL) of two methods as a systematic error

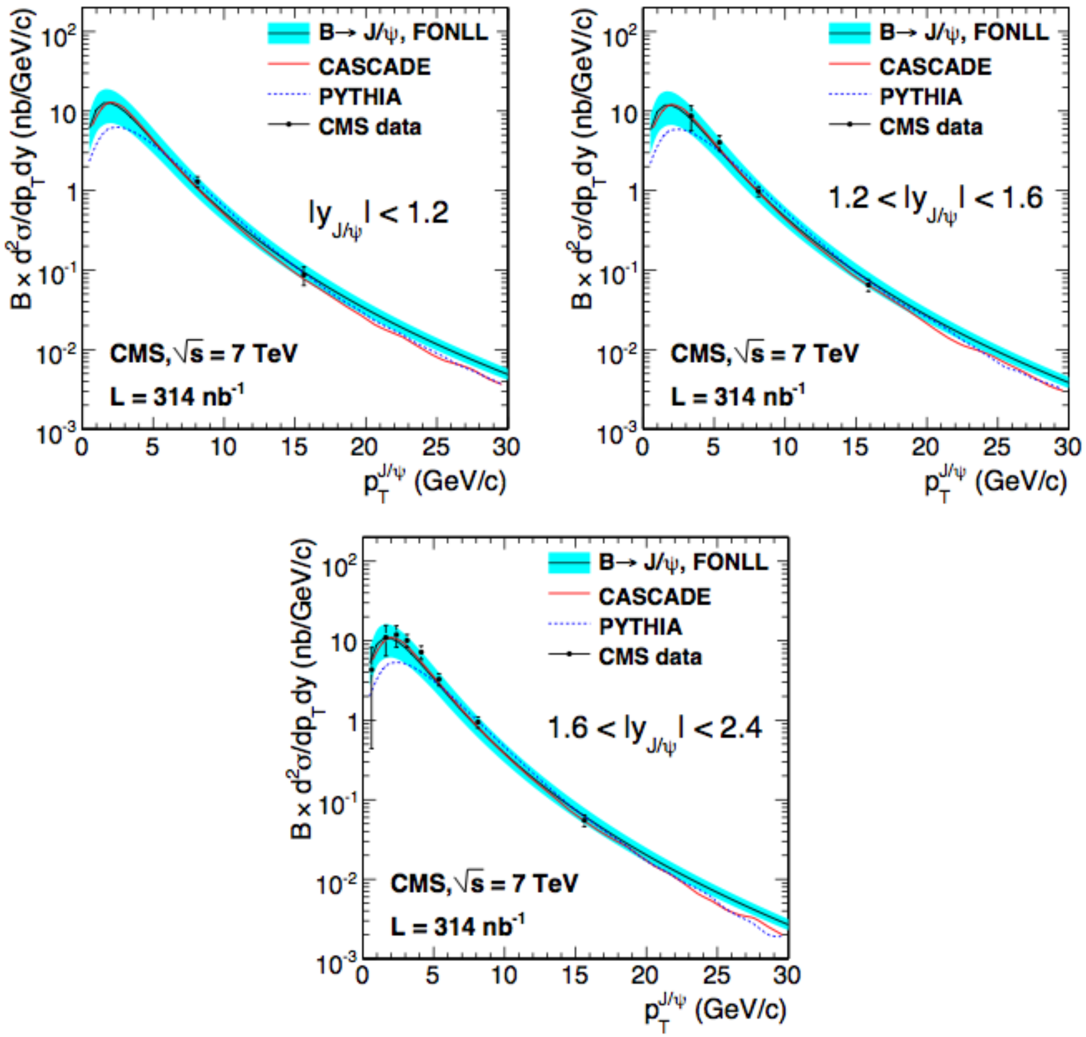


FONLL vs. data, beauty production 2-7 TeV



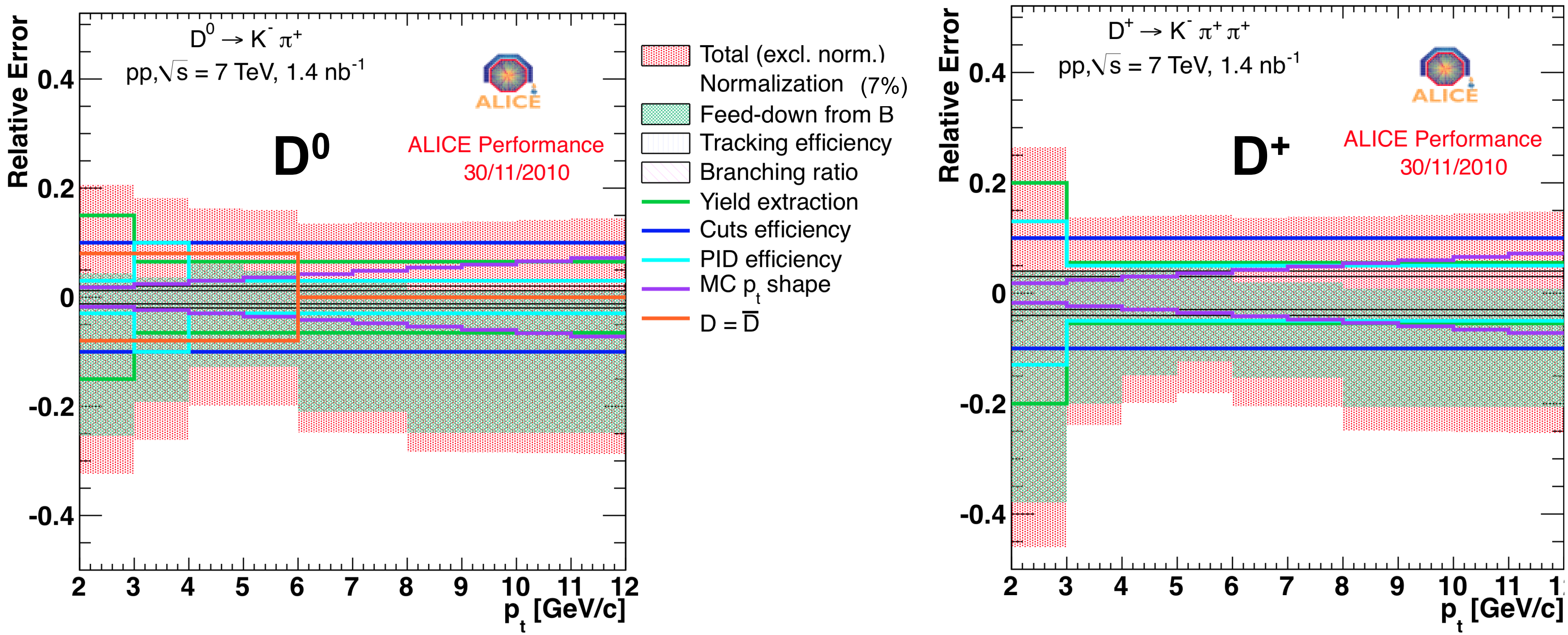
FONLL, MC@NLO:
Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033

CMS, arXiv:1011.4193

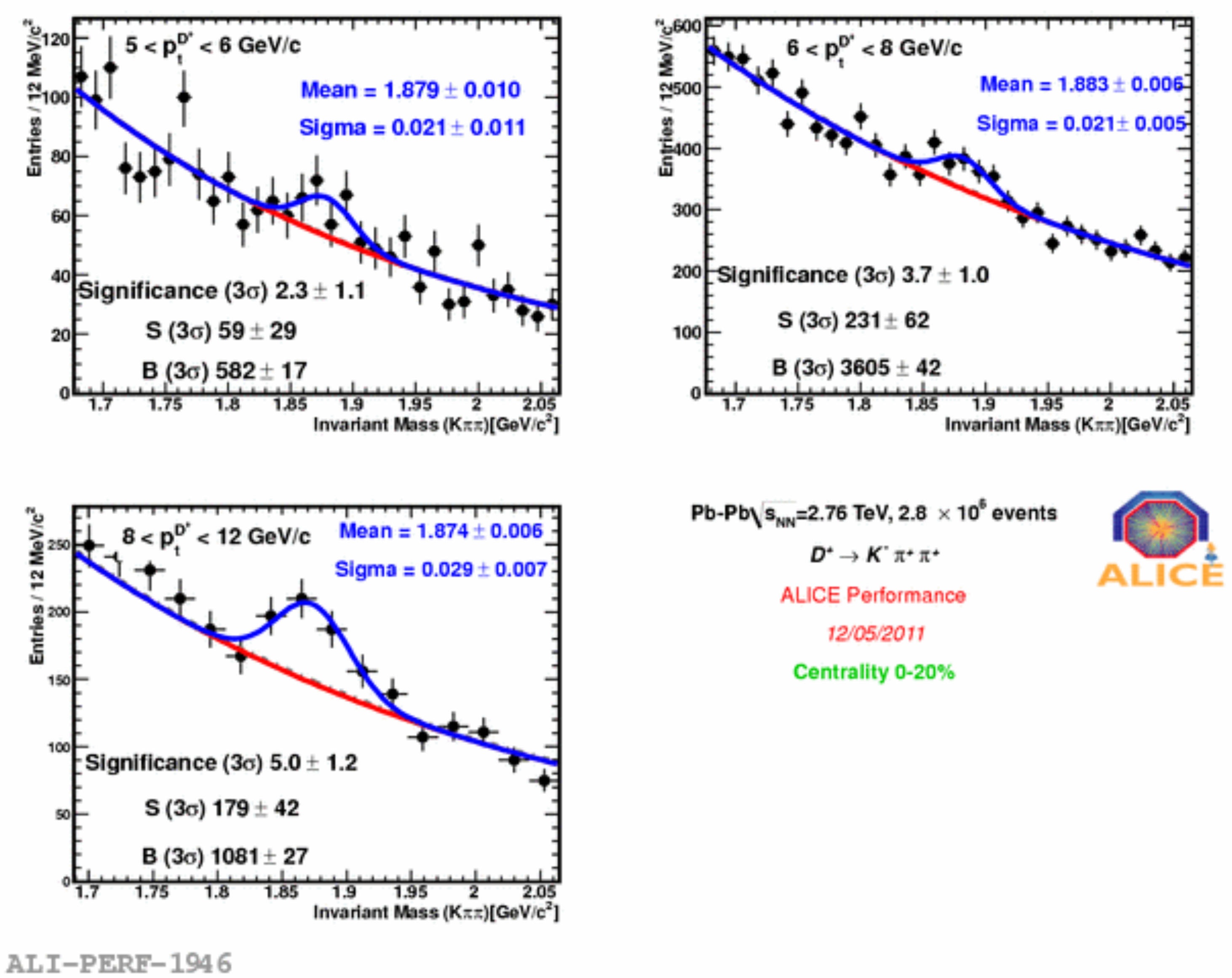


Systematic Uncertainties: D pp 7

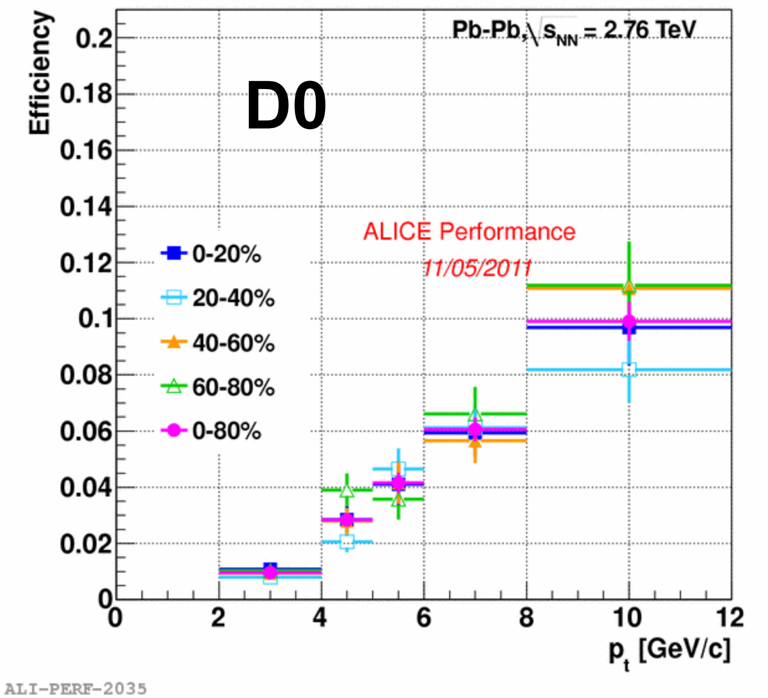
- Total systematic 20-40% p_t-dep. + 7% on σ_{MB} (VdM scan)
- Main systematic error: B feed-down from FONLL + ALICE-MC
  - conservative estimate of error
    - FONLL uncertainty (small for B) +
    - two methods considered (subtr. of D from B, fraction of prompt D)
  - to be reduced using data-driven method with full 2010 statistics

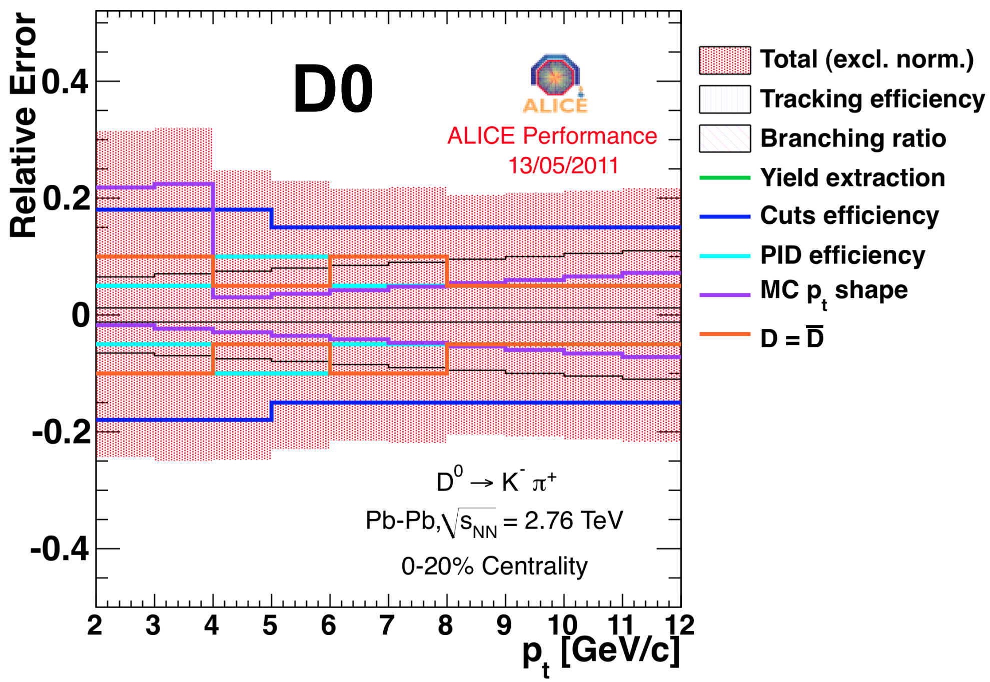


Mass Plots D^+ Pb-Pb 0-20%

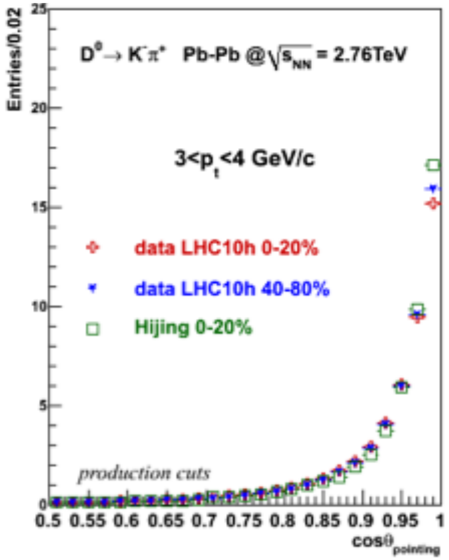


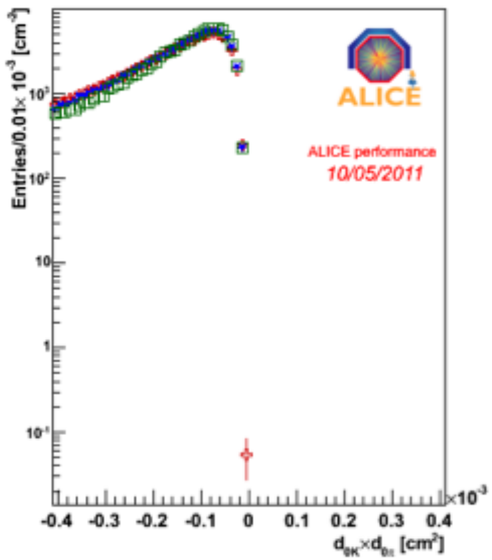
Systematic uncertainties D Pb-Pb

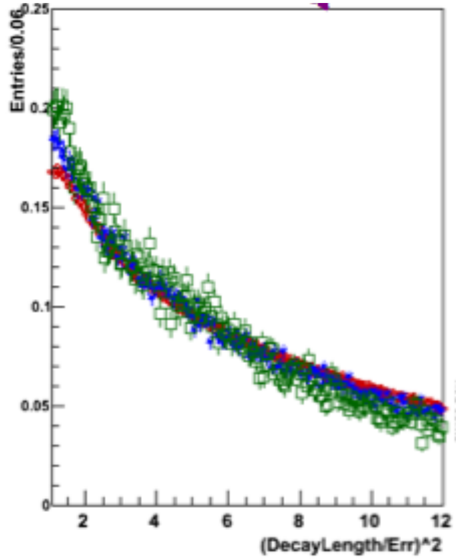


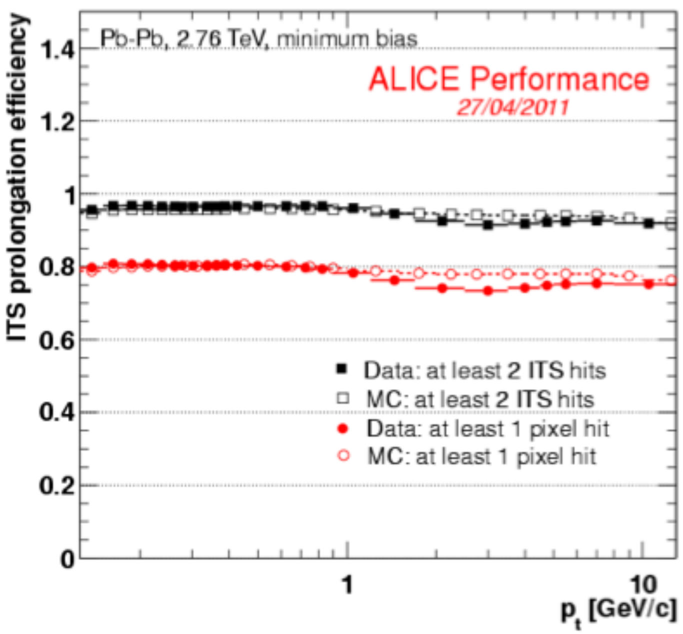


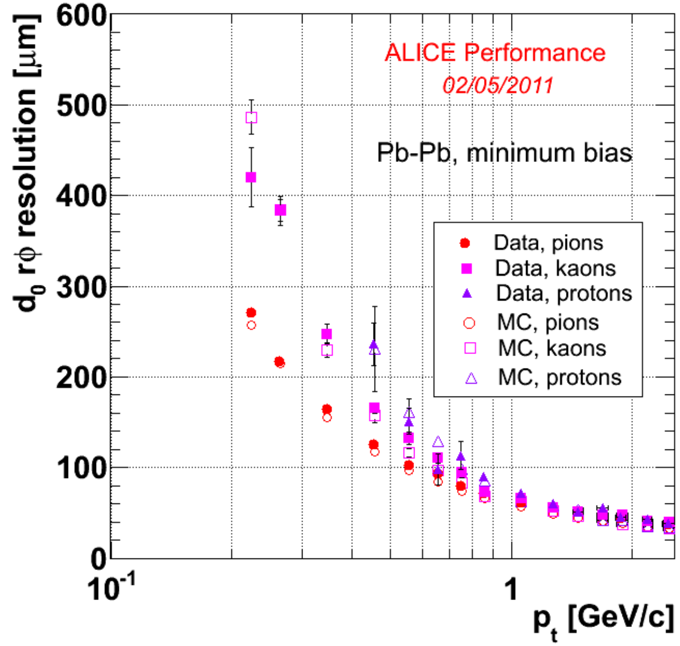
D mesons Pb-Pb: data vs MC





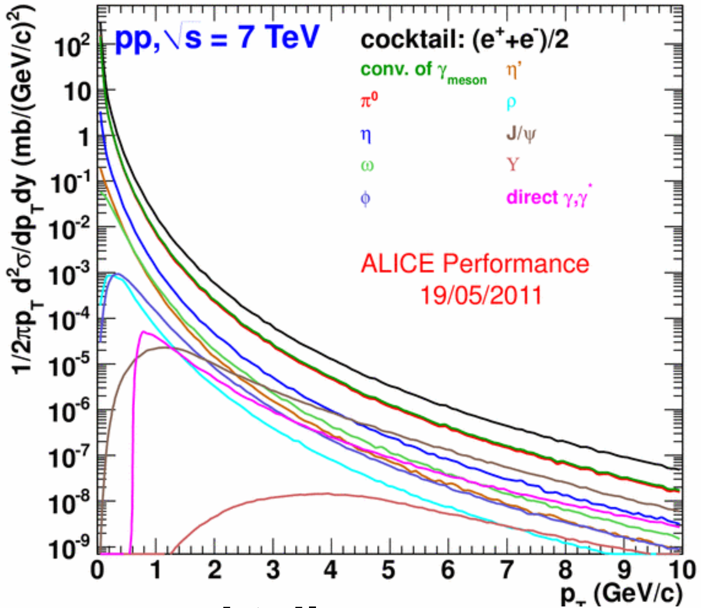


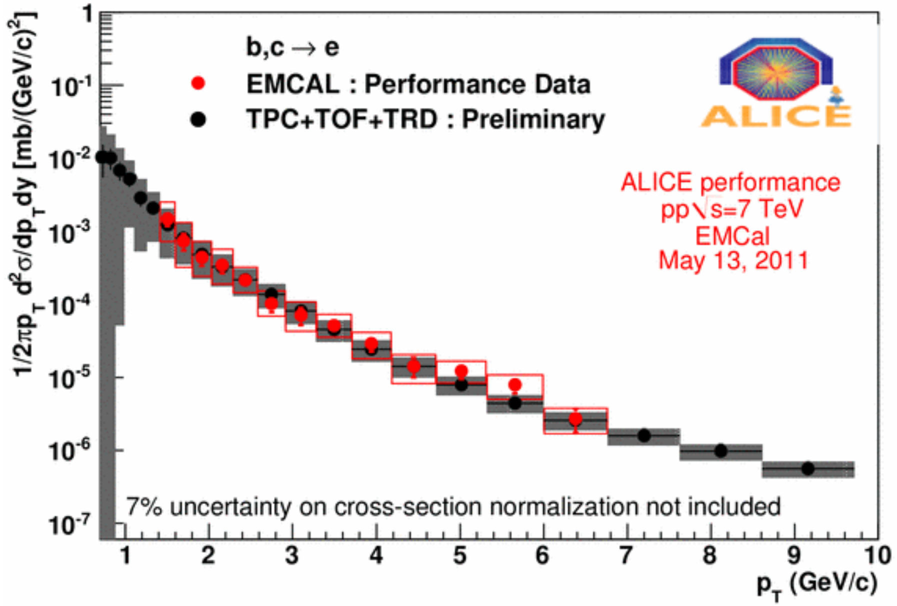




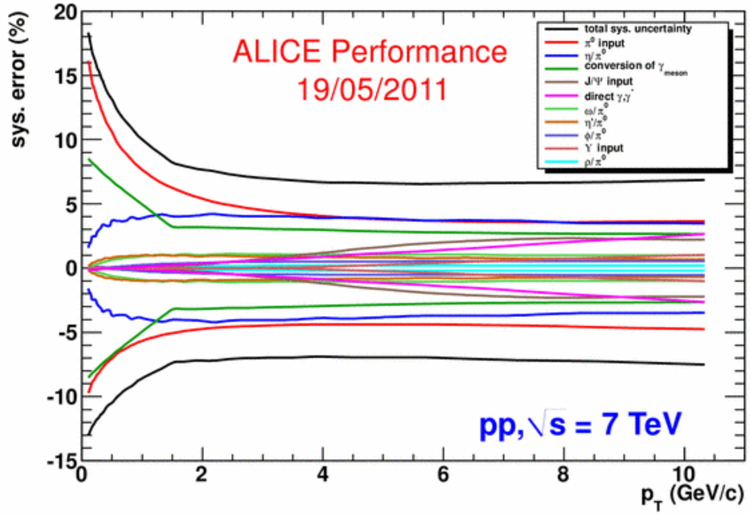
Electrons pp 7 TeV

cocktail

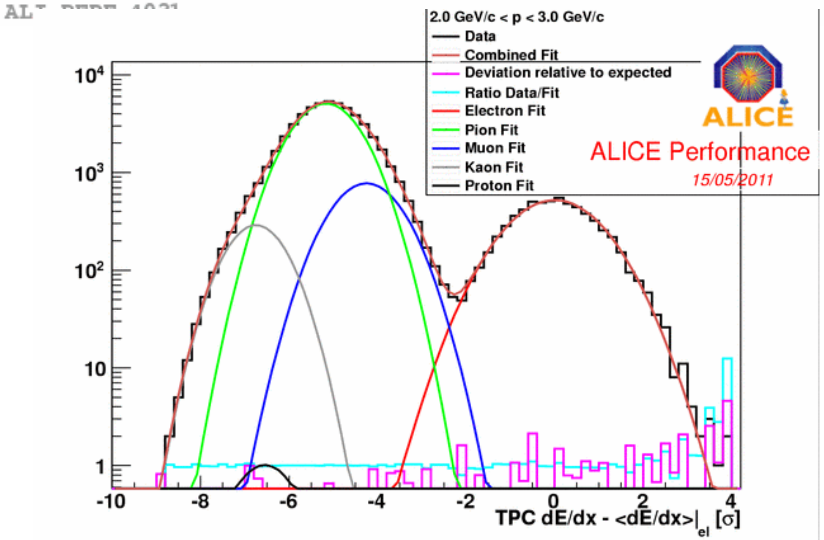




cocktail unc.

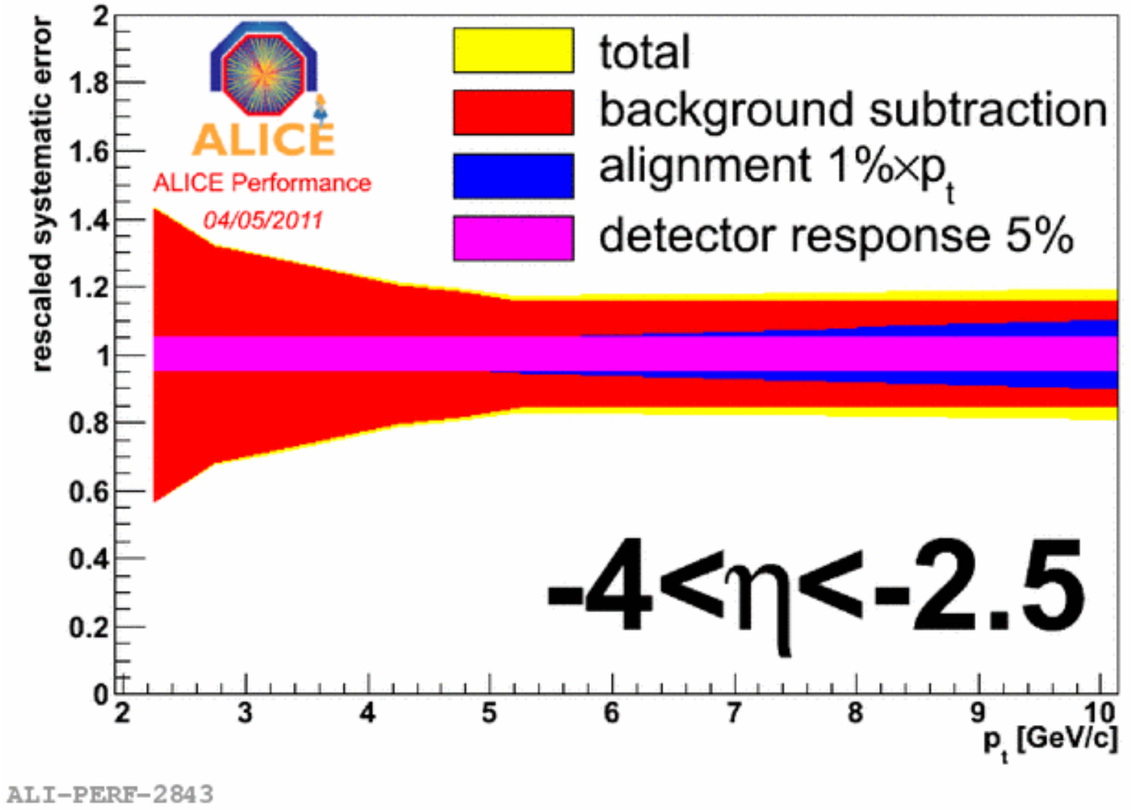


ALI-PERF-6379



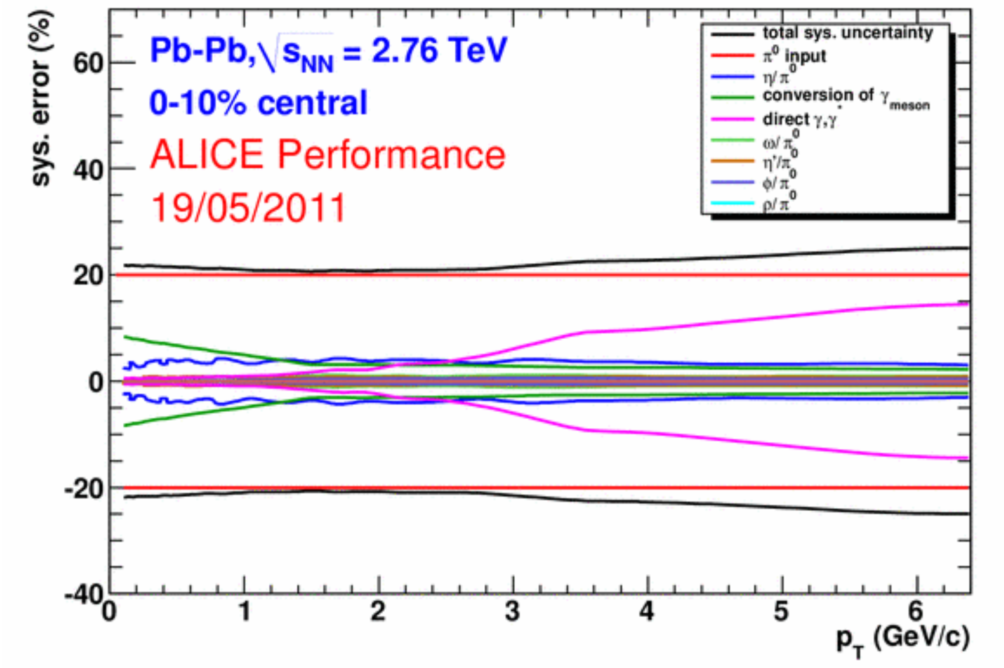
ALI-PERF-2329

Systematic unc. Muons Pb-Pb



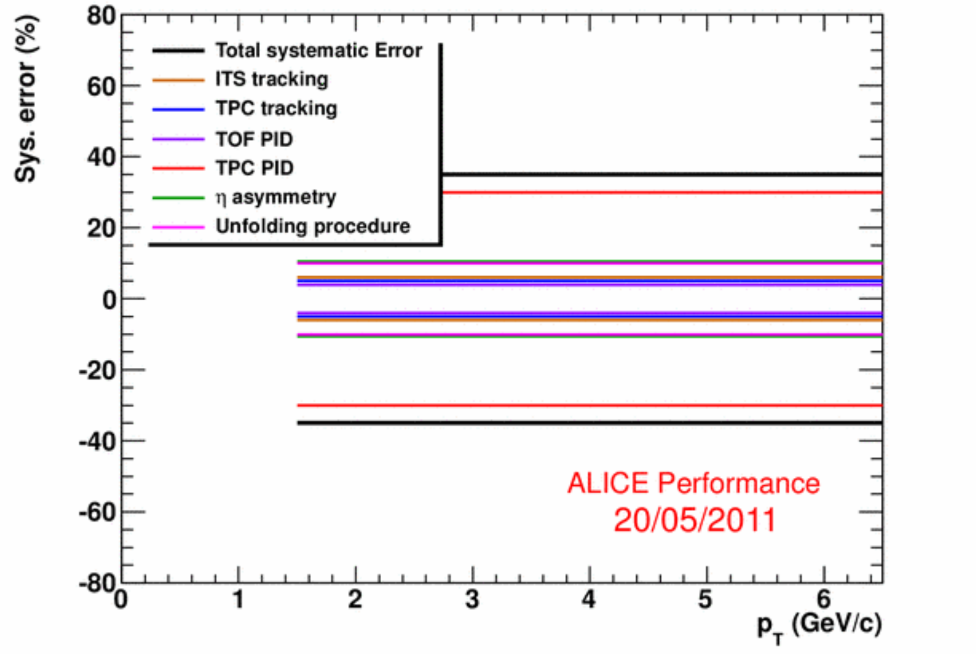
Systematic unc. Electrons Pb-Pb

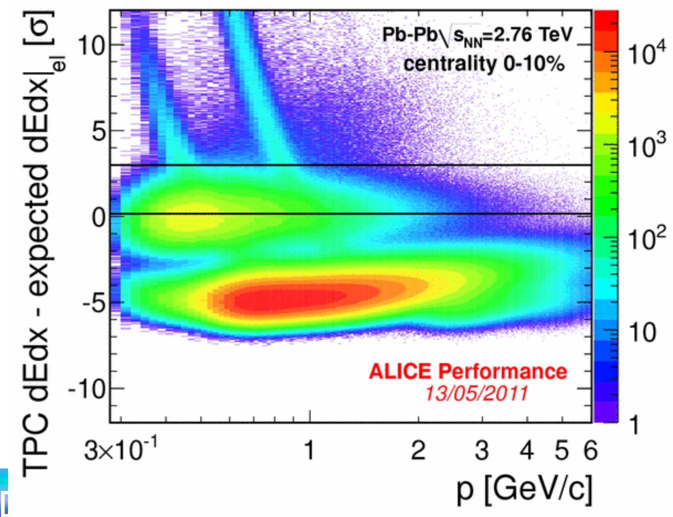
from cocktail : 25%



ALI-PERF-3466

from electron reco/ID: 35%





ALI-PERF-2722

B-decay muon R_{AA}, ASW

- Z. Conesa del Valle et al, PLB663 (2008)