



# Measurement of heavy - flavour production in pp and Pb-Pb collisions at the LHC with ALICE

**Davide Caffarri**

Università degli studi di Padova – INFN Padova – CERN

[davide.caffarri@pd.infn.it](mailto:davide.caffarri@pd.infn.it)



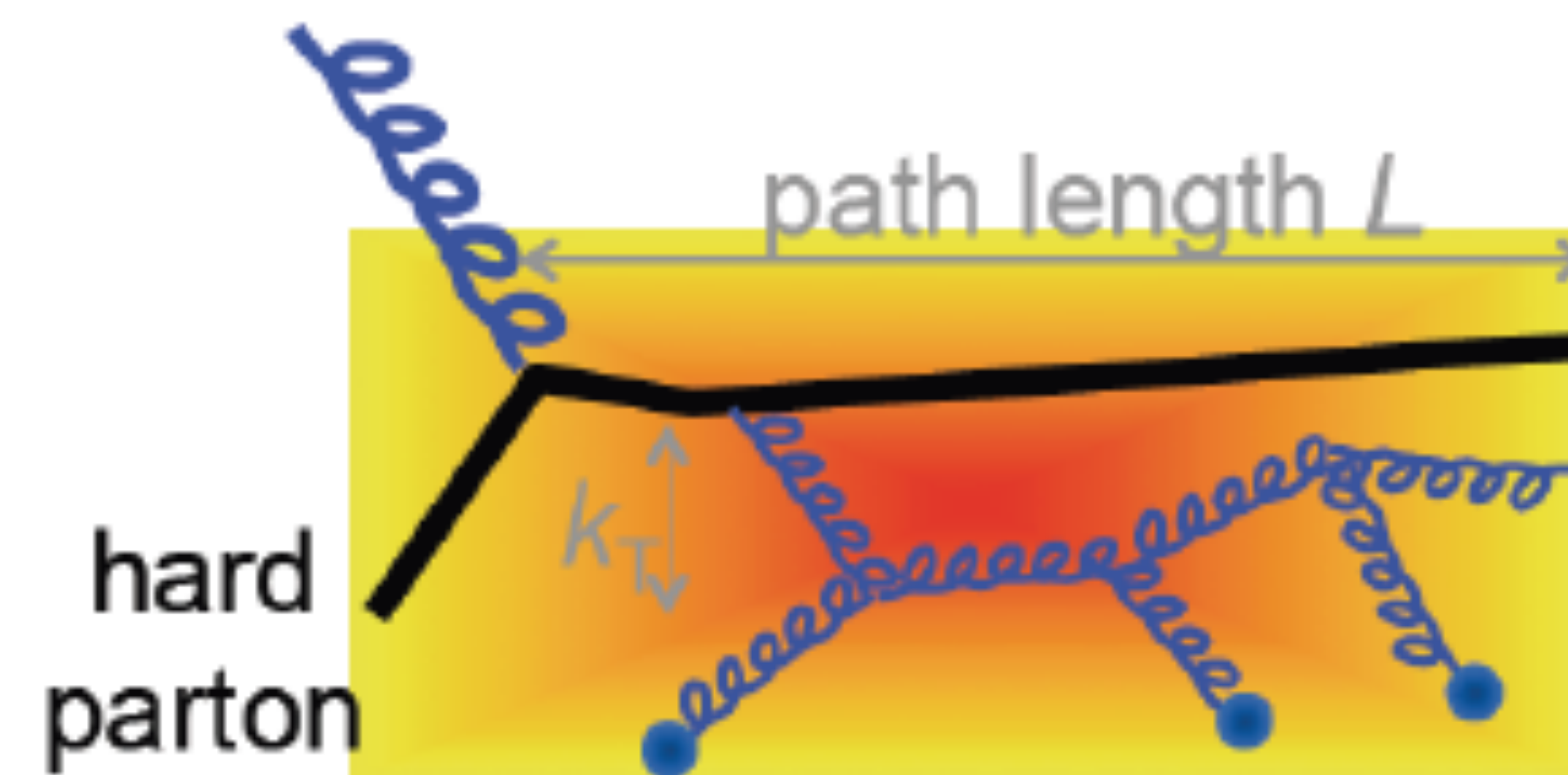
# Outline

- Physics motivation for studying heavy quarks in pp and Pb-Pb collisions
- ALICE apparatus and datasets
- Open heavy flavour measurement in ALICE in pp and Pb-Pb collisions:
  - ✓ muons at forward rapidity
  - ✓ D mesons at central rapidity
  - ✓ electrons at central rapidity
- Summary

# Heavy quarks in ALICE: pp and Pb-Pb

## Pb-Pb

- Heavy quarks are produced in hard scatterings, before medium thermalization and they should experience energy loss in the medium (radiative, collisional energy loss, in-medium fragmentation)



# Heavy quarks in ALICE: pp and Pb-Pb

## Pb-Pb

- Heavy quarks are produced in hard scatterings, before medium thermalization and they should experience energy loss in the medium (radiative, collisional energy loss, in-medium fragmentation)

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

- Energy loss determines a reduction of high  $p_t$  particles and therefore  $R_{AA} < 1$

# Heavy quarks in ALICE: pp and Pb-Pb

## Pb-Pb

- Heavy quarks are produced in hard scatterings, before medium thermalization and they should experience energy loss in the medium (radiative, collisional energy loss, in-medium fragmentation)

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

- Energy loss determines a reduction of high  $p_t$  particles and therefore  $R_{AA} < 1$

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

- Energy loss depends on **medium density, colour charge** ( $C_R$  - Casimir factor 4/3 for quarks, 3 for gluons), **mass**.

Yu.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B519 (2001) 199, arXiv:hep-ph/0106202

# Heavy quarks in ALICE: pp and Pb-Pb

## Pb-Pb

- Heavy quarks are produced in hard scatterings, before medium thermalization and they should experience energy loss in the medium (radiative, collisional energy loss, in-medium fragmentation)

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

- Energy loss determines a reduction of high  $p_t$  particles and therefore  $R_{AA} < 1$

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

- Energy loss depends on **medium density, colour charge** ( $C_R$  - Casimir factor 4/3 for quarks, 3 for gluons), **mass**.

Yu.L. Dokshitzer and D.E. Kharzeev, Phys. Lett. B519 (2001) 199, arXiv:hep-ph/0106202

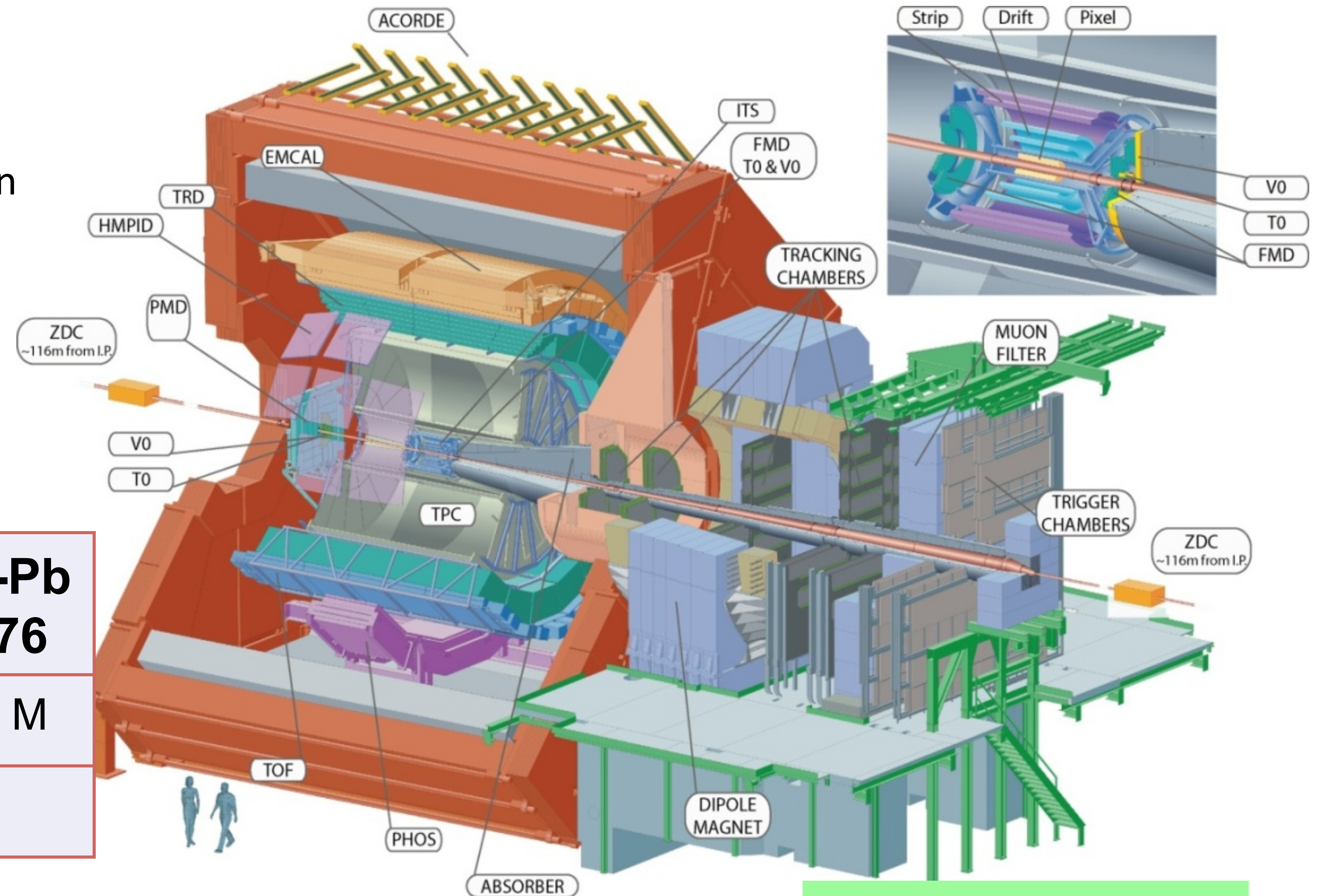
## pp

- Heavy flavour production measurement in pp collisions at the LHC, allows to test pQCD calculations in new energy regime.
  - pp measurements are important as a reference of the Pb-Pb ones.
- In order to build  $R_{AA}$ , the pp 7 TeV  $d\sigma/dp_t$  are scaled to 2.76 TeV using pQCD (FONLL)

# ALICE apparatus and datasets

- **Two main parts:**
  - barrel ( $|\eta| < 0.9$ ),  $B = 0.5$  Tesla
  - forward muon spectrometer,  $-4 < \eta < -2.5$   
 $B = 0.7$  Tesla m perp. to the beam direction
- **Crucial for HF:**
  - vertexing, tracking
  - hadron and lepton ID
- **Datasets used here:**

system, $\sqrt{s_{NN}}$ (TeV)	pp 7	pp 2.76	Pb-Pb 2.76
$N_{MB}$	100-180M	65 M	17 M
$N_{muon}$	130 M	9 M	



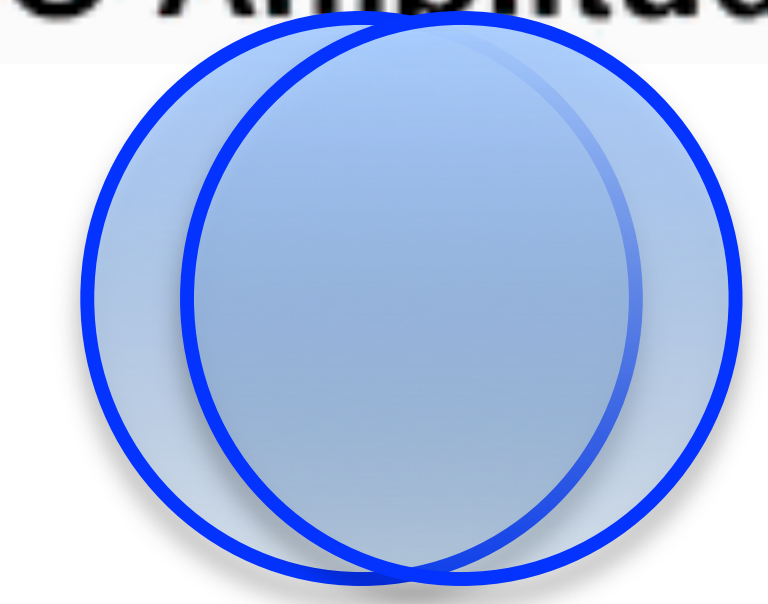
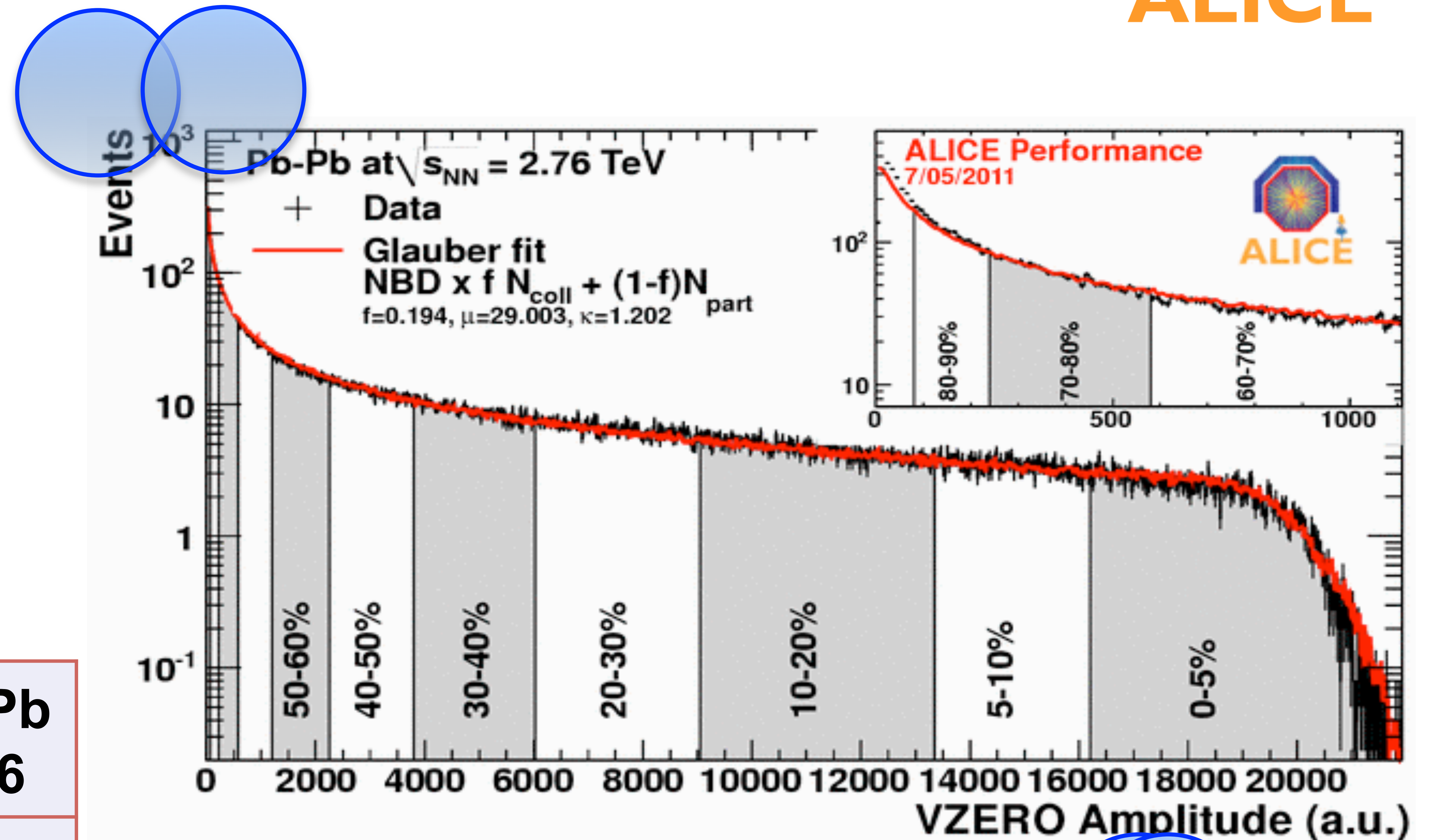
J. Wessels's talk

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

# ALICE apparatus and datasets

- **Two main parts:**
  - barrel ( $|\eta| < 0.9$ ),  $B = 0.5$  Tesla
  - forward muon spectrometer,  $-4 < \eta < -2.5$   
 $B = 0.7$  Tesla perp. to the beam direction
- **Crucial for HF:**
  - vertexing, tracking
  - hadron and lepton ID
- **Datasets used here:**

system, $\sqrt{s_{NN}}$ (TeV)	pp 7	pp 2.76	Pb-Pb 2.76
$N_{MB}$	100-180M	65 M	17 M
$N_{muon}$	130 M	9 M	



J. Wessels's talk

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



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

## Muon Reconstruction:

- muons reconstructed in 5 stations after thick hadron absorber and identified in trigger chambers after a 1m iron wall

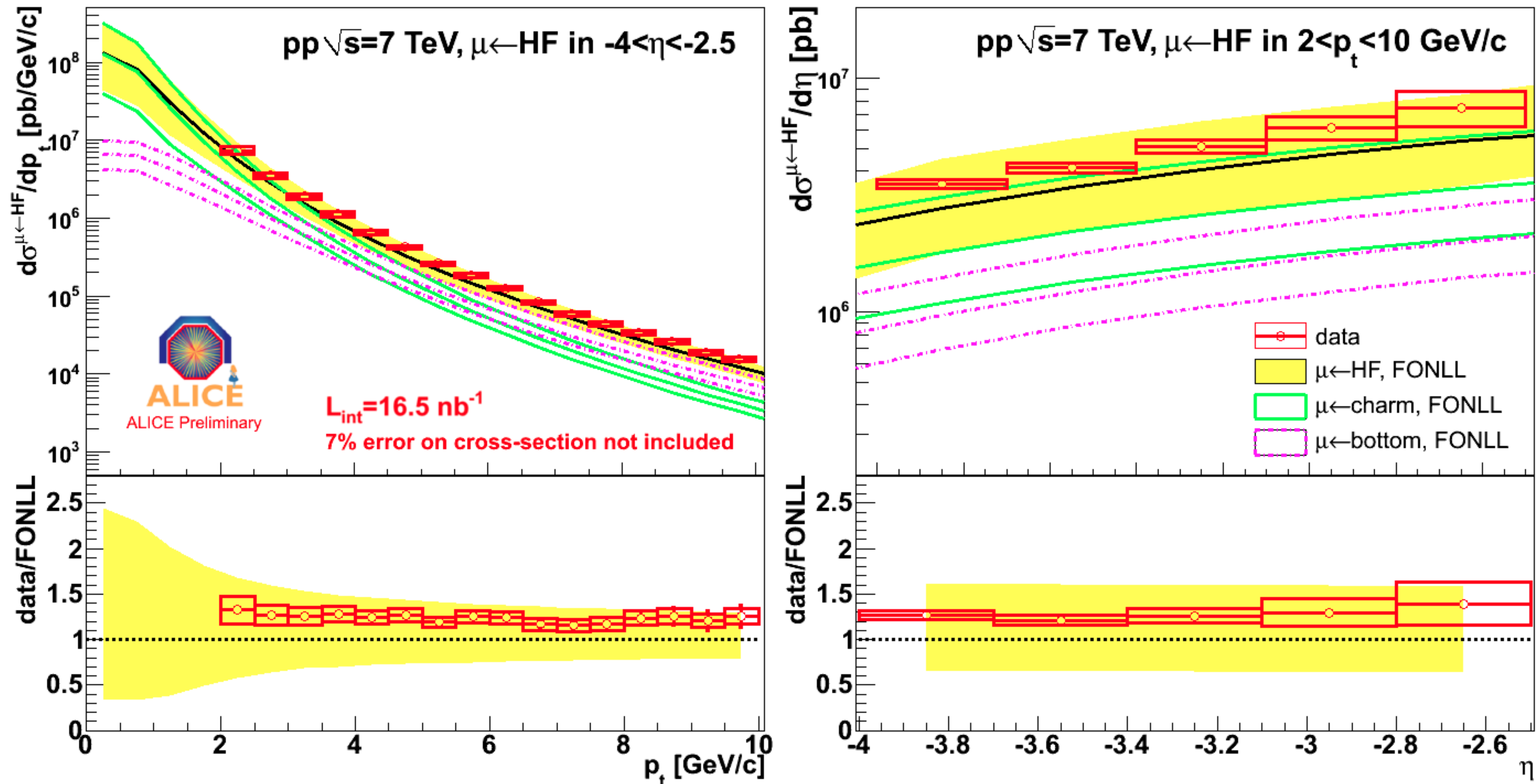
MUON (tracking,  $\mu$  id)

$\mu$

✓  $D, B \rightarrow \mu(\mu) + X$

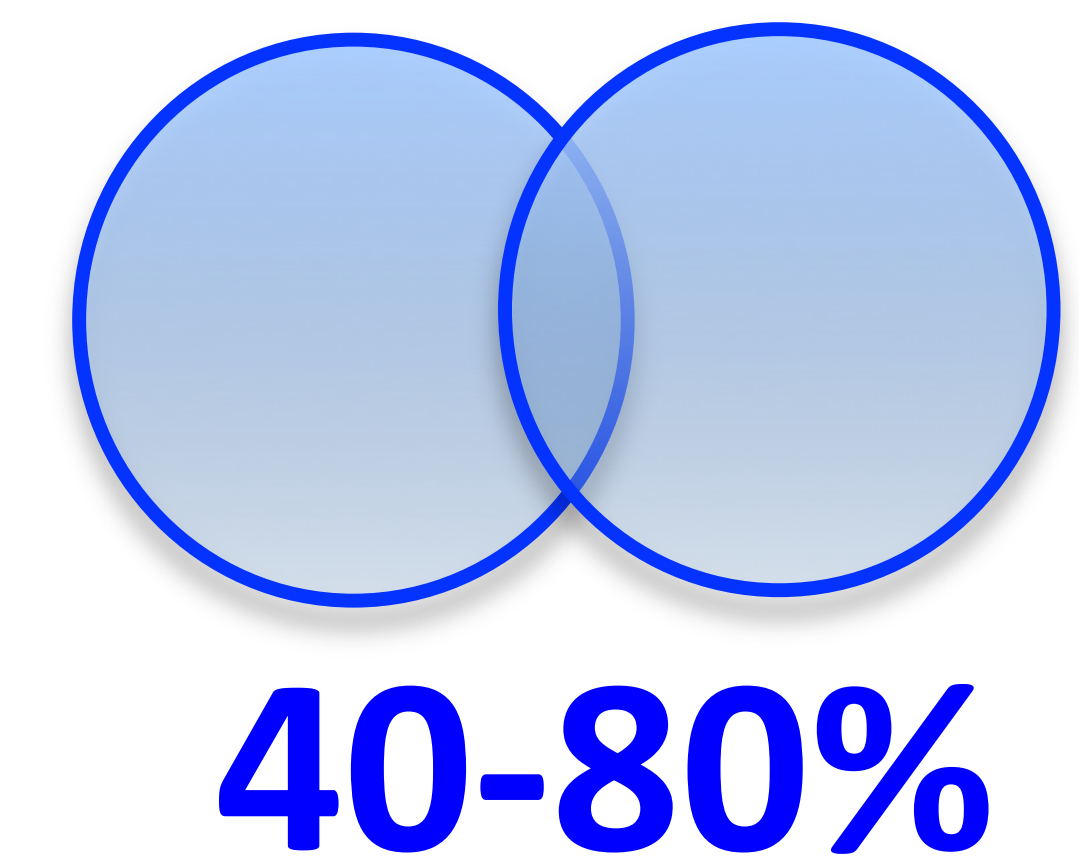
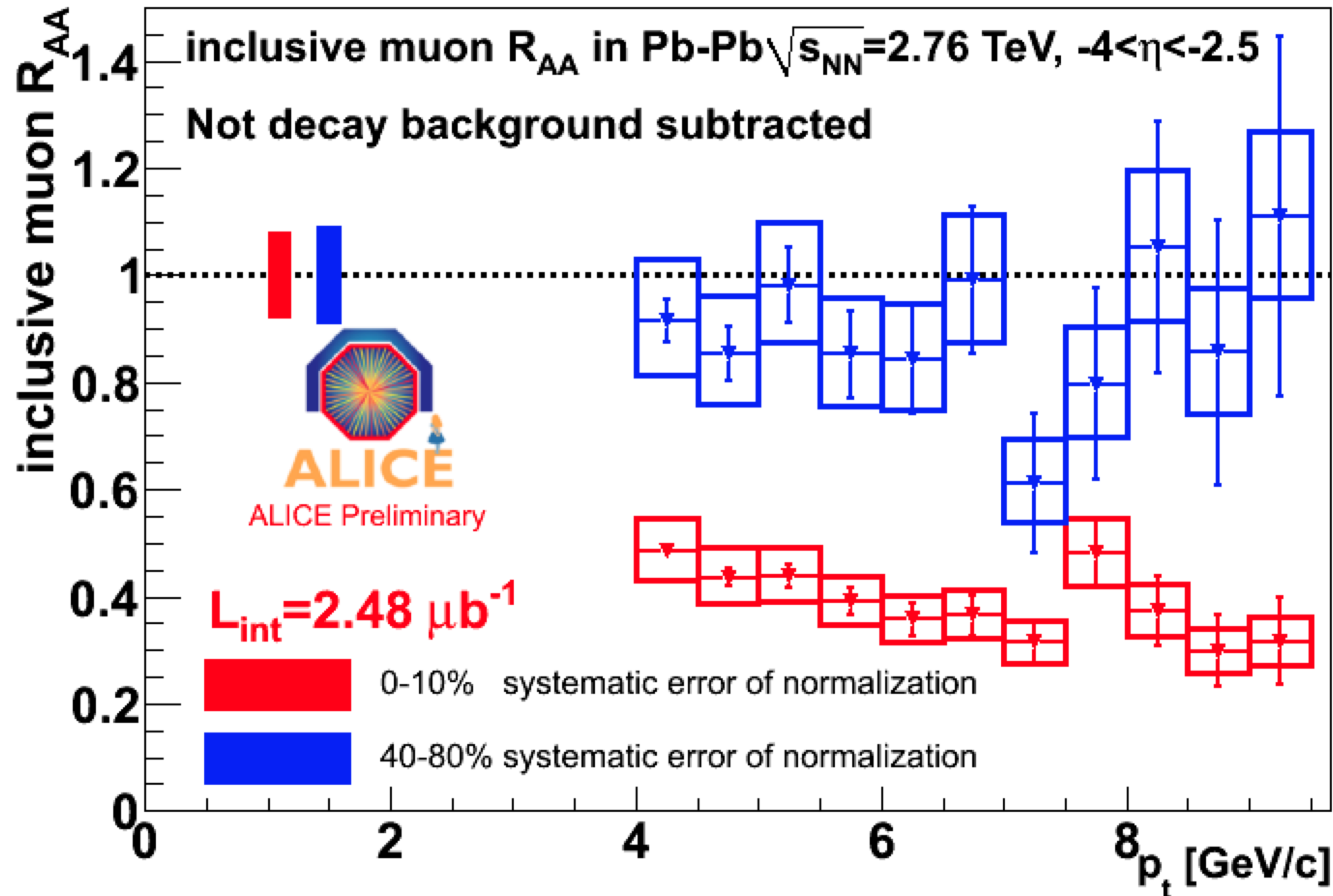
M. Marchisone's poster

# Heavy flavour decay muons cross section in pp collisions at 7 TeV

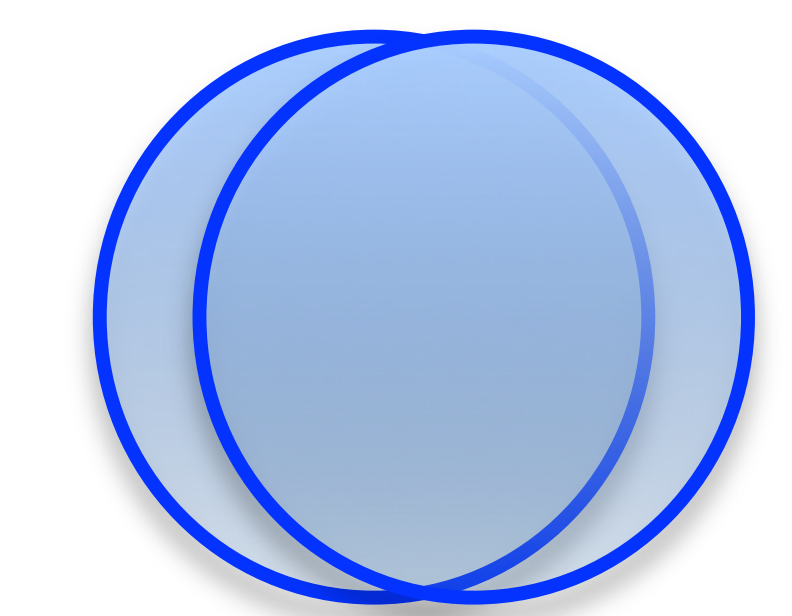


- Measured  $d\sigma/dp_t$  in 2-10 GeV/c and  $d\sigma/d\eta$  in -4 to -2.5
- Well described by FONLL predictions
  - FONLL indicates beauty dominance above 6 GeV/c

# Inclusive muon $R_{AA}$ in Pb-Pb



0-10%

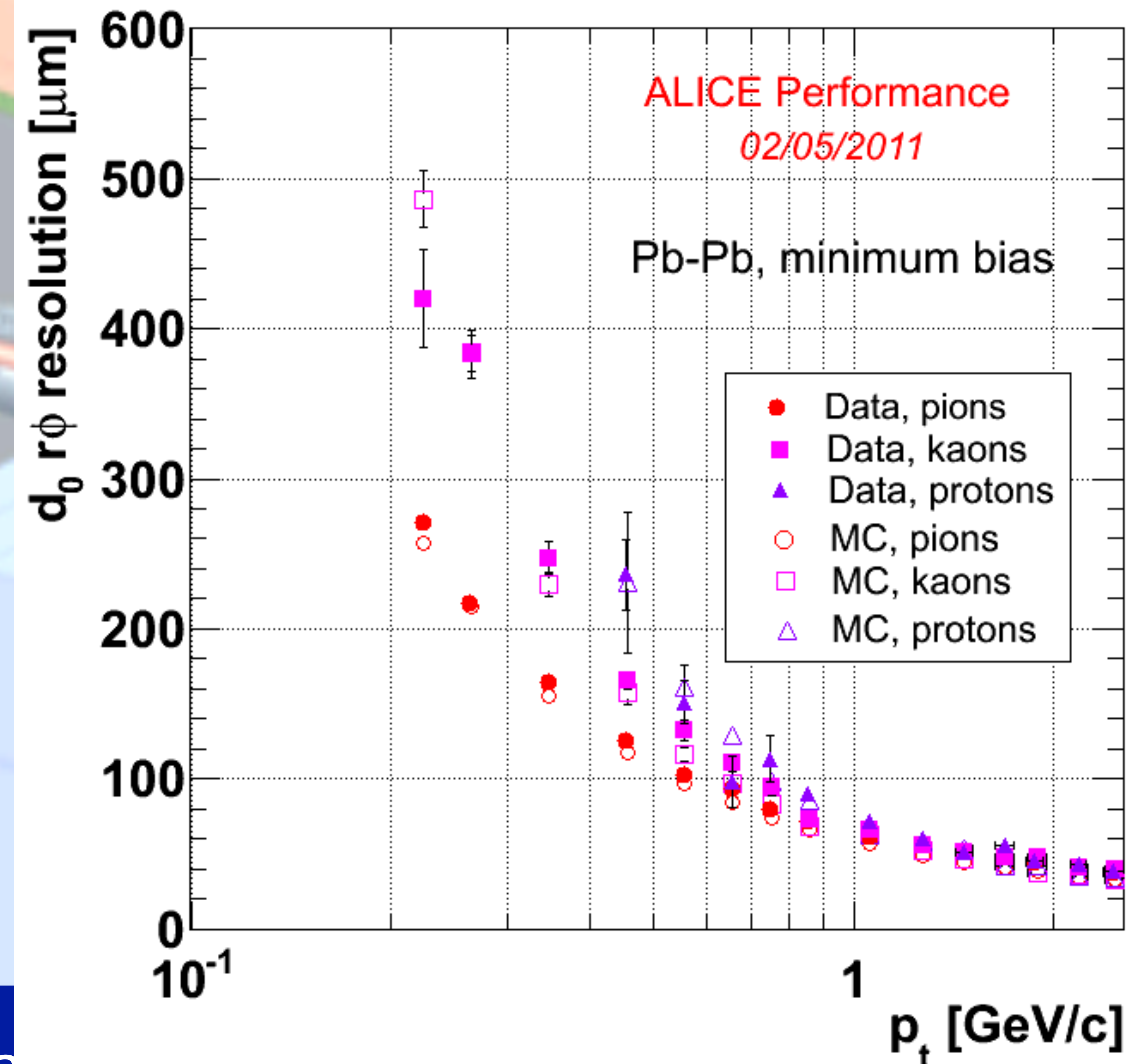
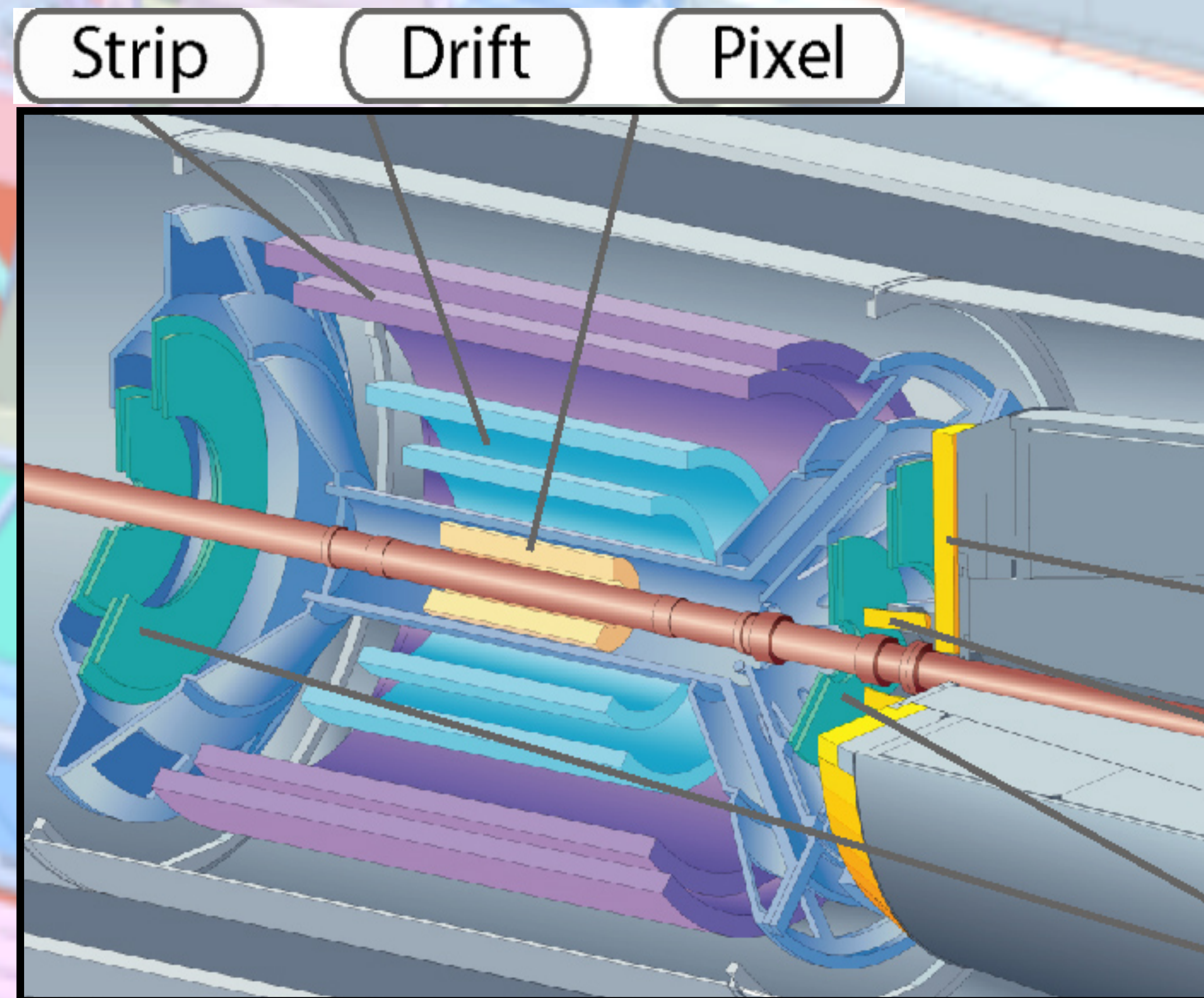


- Suppression is about a factor 3 above 6 GeV/c
- According to FONLL, beauty dominant in this region

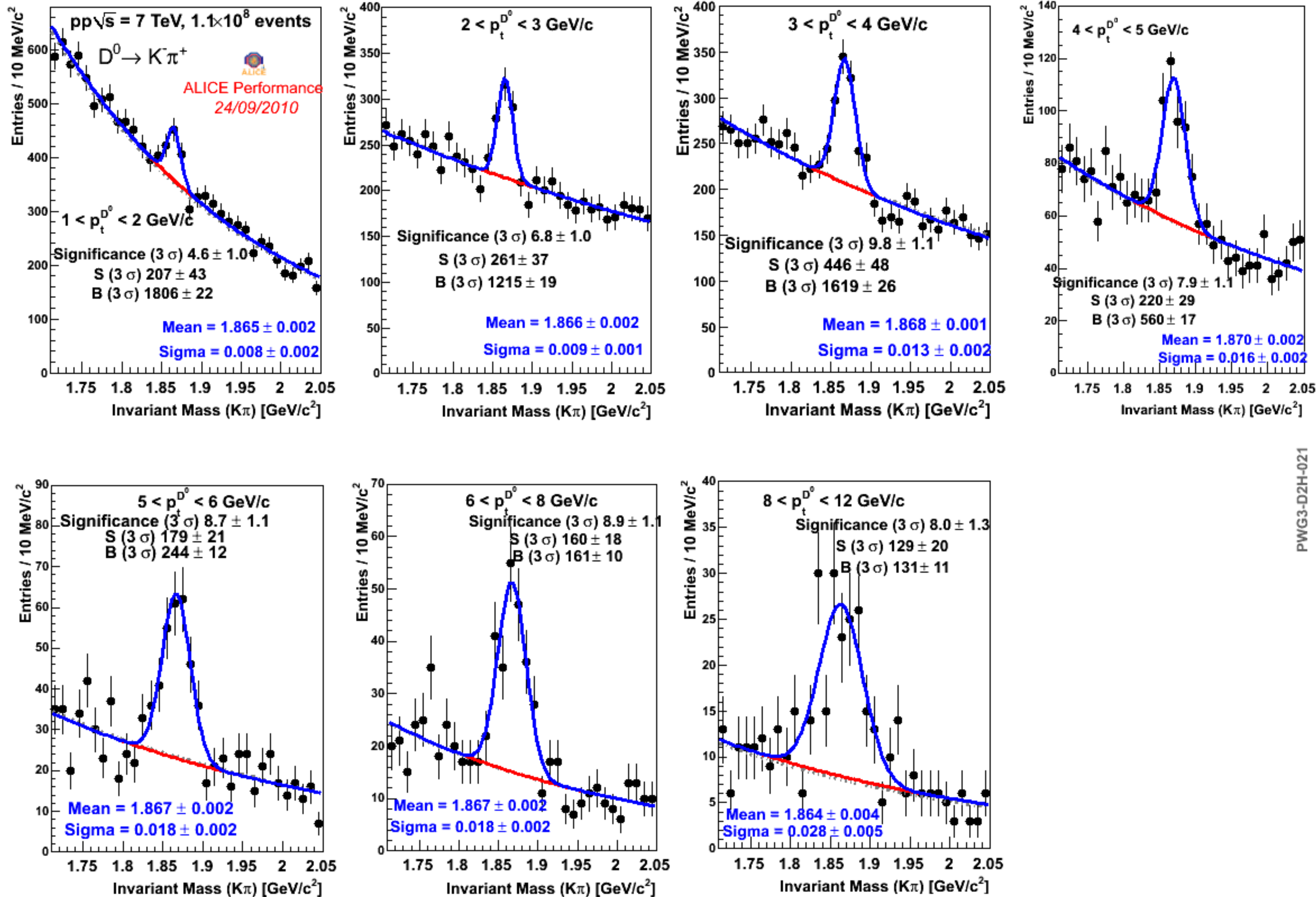
# ALICE Heavy Flavour Program: D mesons, $|\eta| < 0.8$

$\kappa$   $\pi$   
 TOF (p/K/ $\pi$  id)  
 TPC (tracking, p/K/ $\pi$  id)  
 ITS (tracking & vertexing)

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

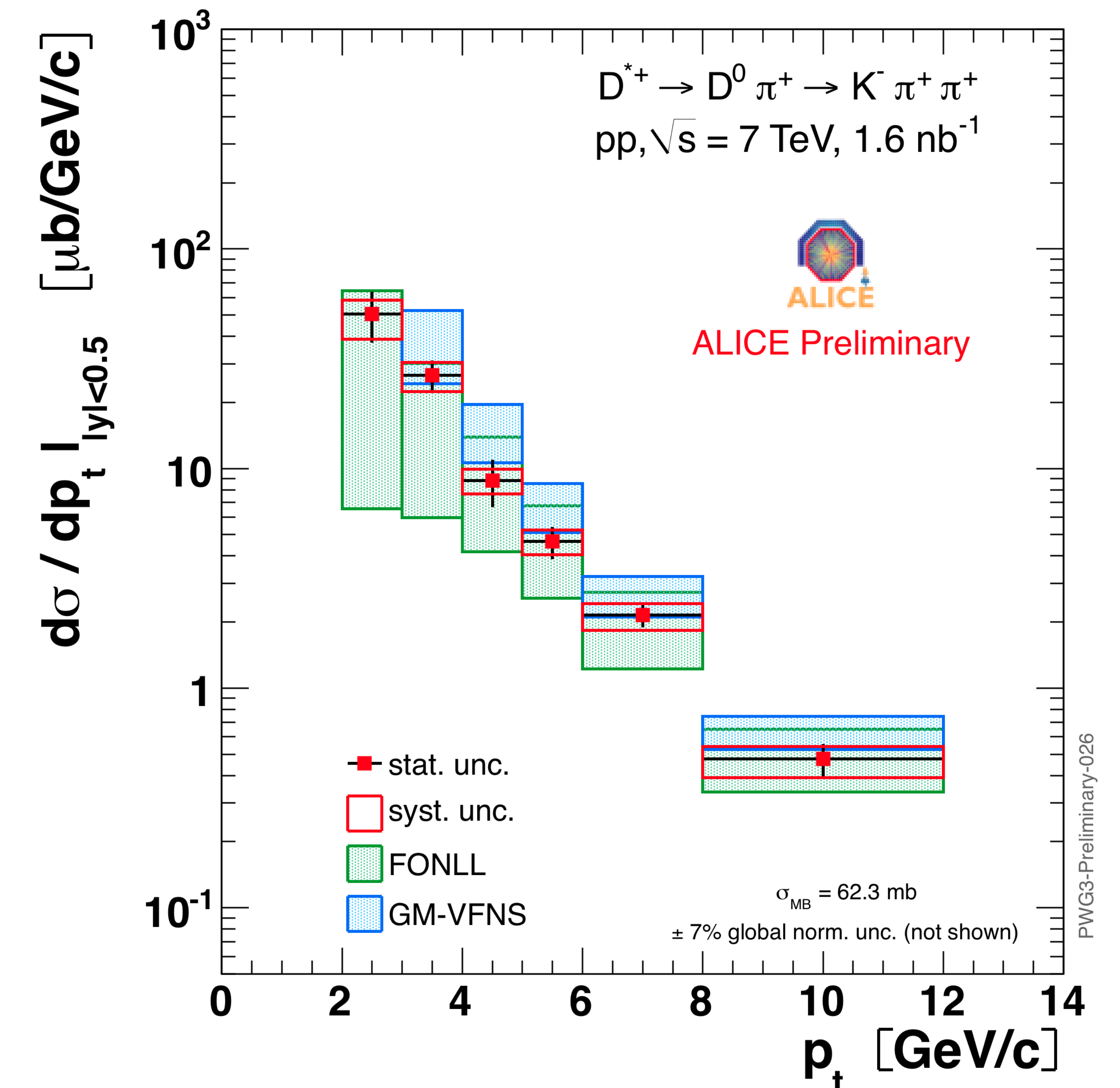
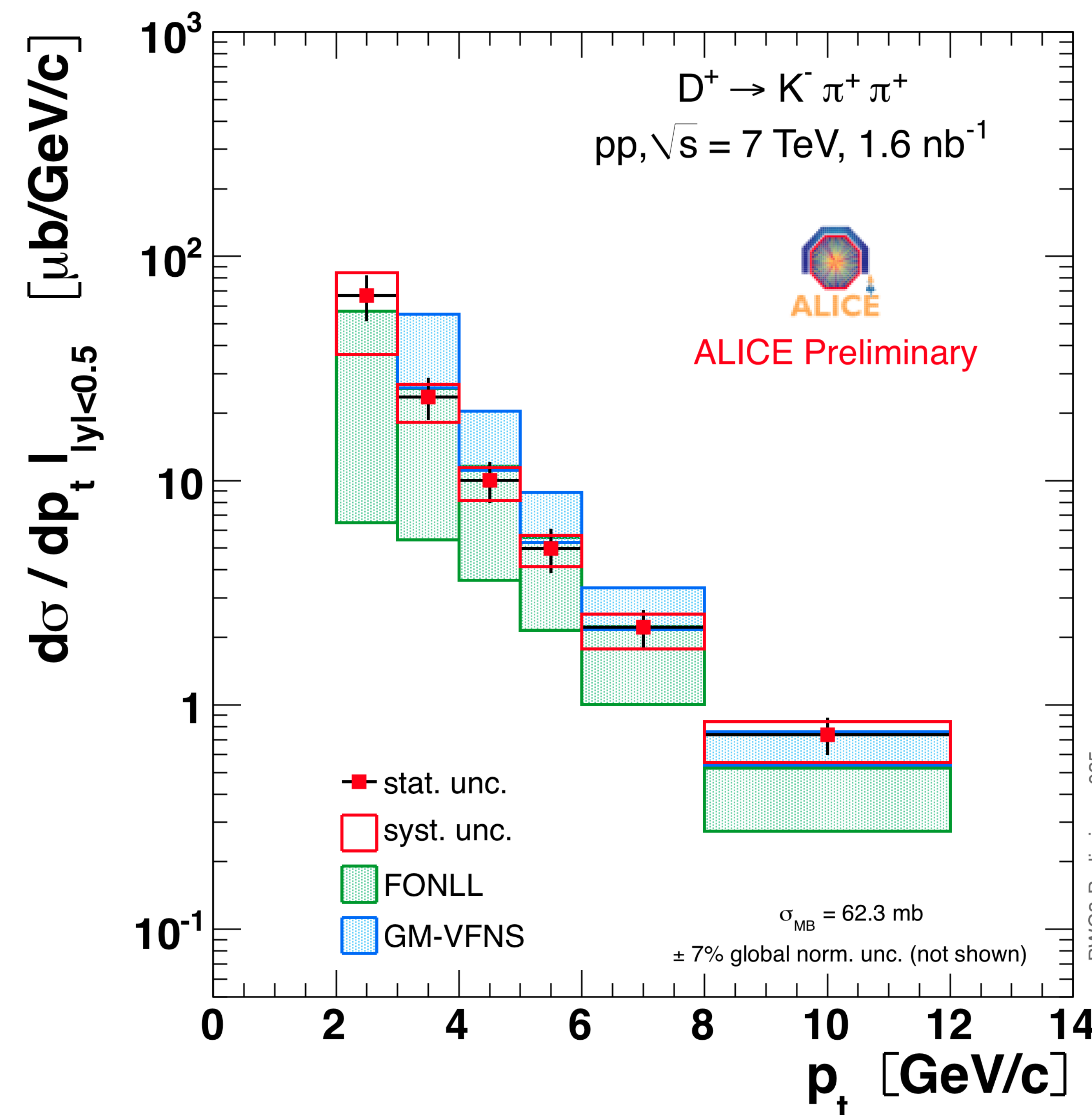
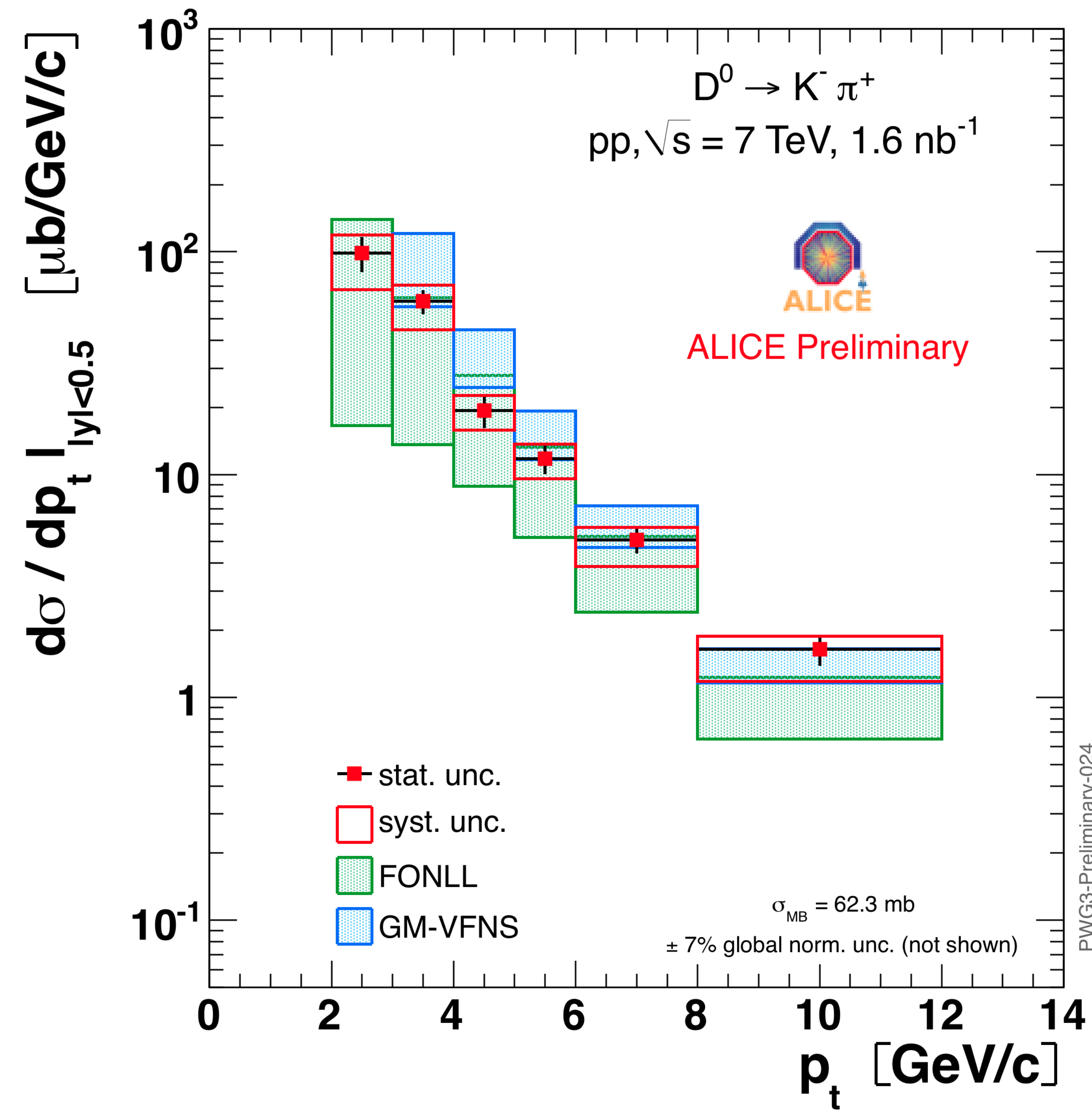


# D mesons cross section in pp @ 7 TeV



PWG3-D2H-021

# D mesons cross section in pp @ 7 TeV



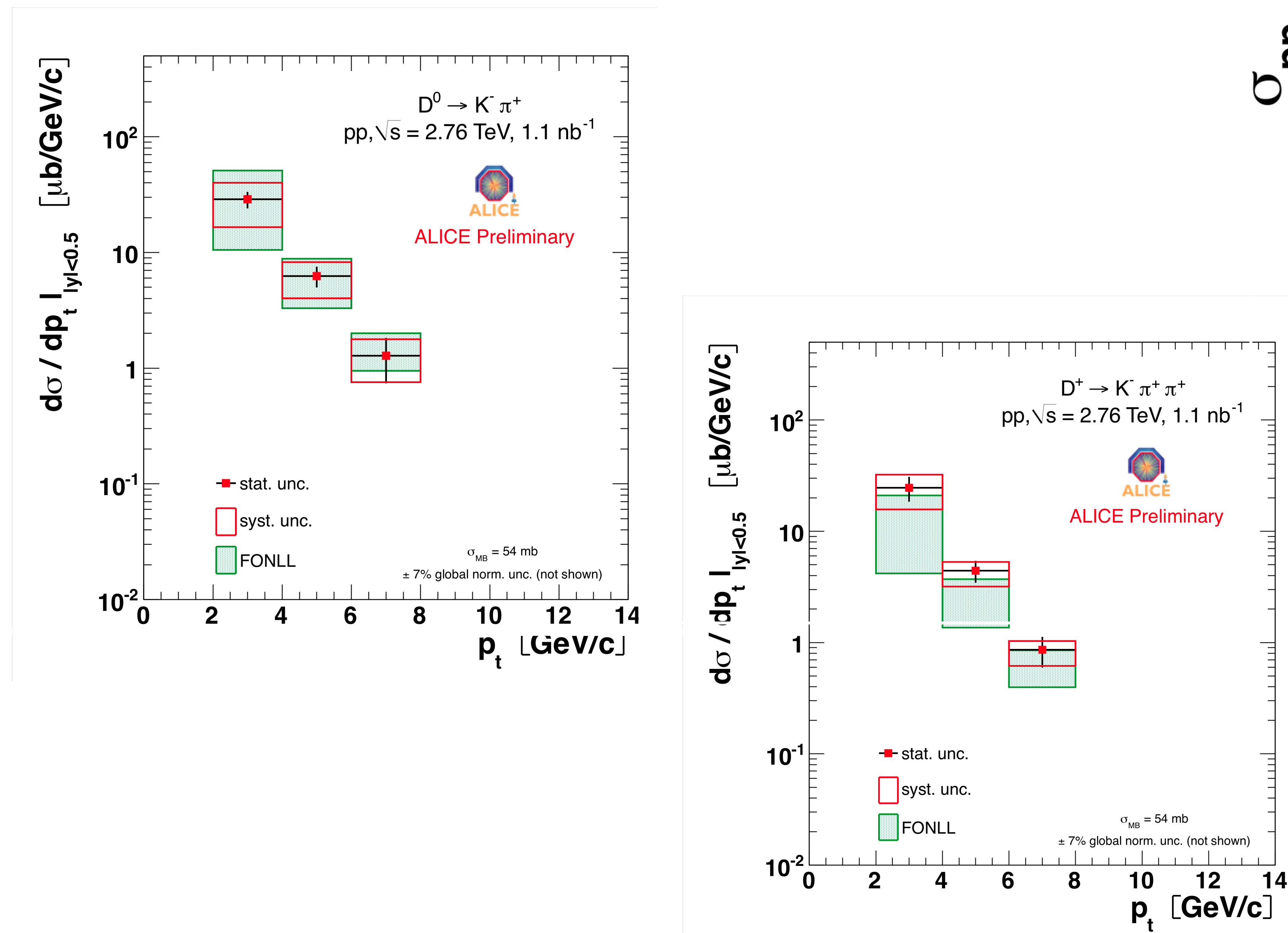
FONLL: Cacciari et al., private comm.  
GM-VFNS: Kniehl et al., private comm.

- $2 < p_t < 12$  GeV/c, with  $1.6 \text{ nb}^{-1}$  ( $\sim 20\%$  of 2010 statistics)
- $y$  acceptance is  $p_t$ -dep ( $\Delta y \sim 1.6$ ): data scaled to  $|y| < 0.5$
- pQCD predictions (FONLL and GM-VFNS) compatible with our data
- Also  $D_s$  and  $\Lambda_c$  signals observed. G. Innocenti's poster

X. Yuan's poster

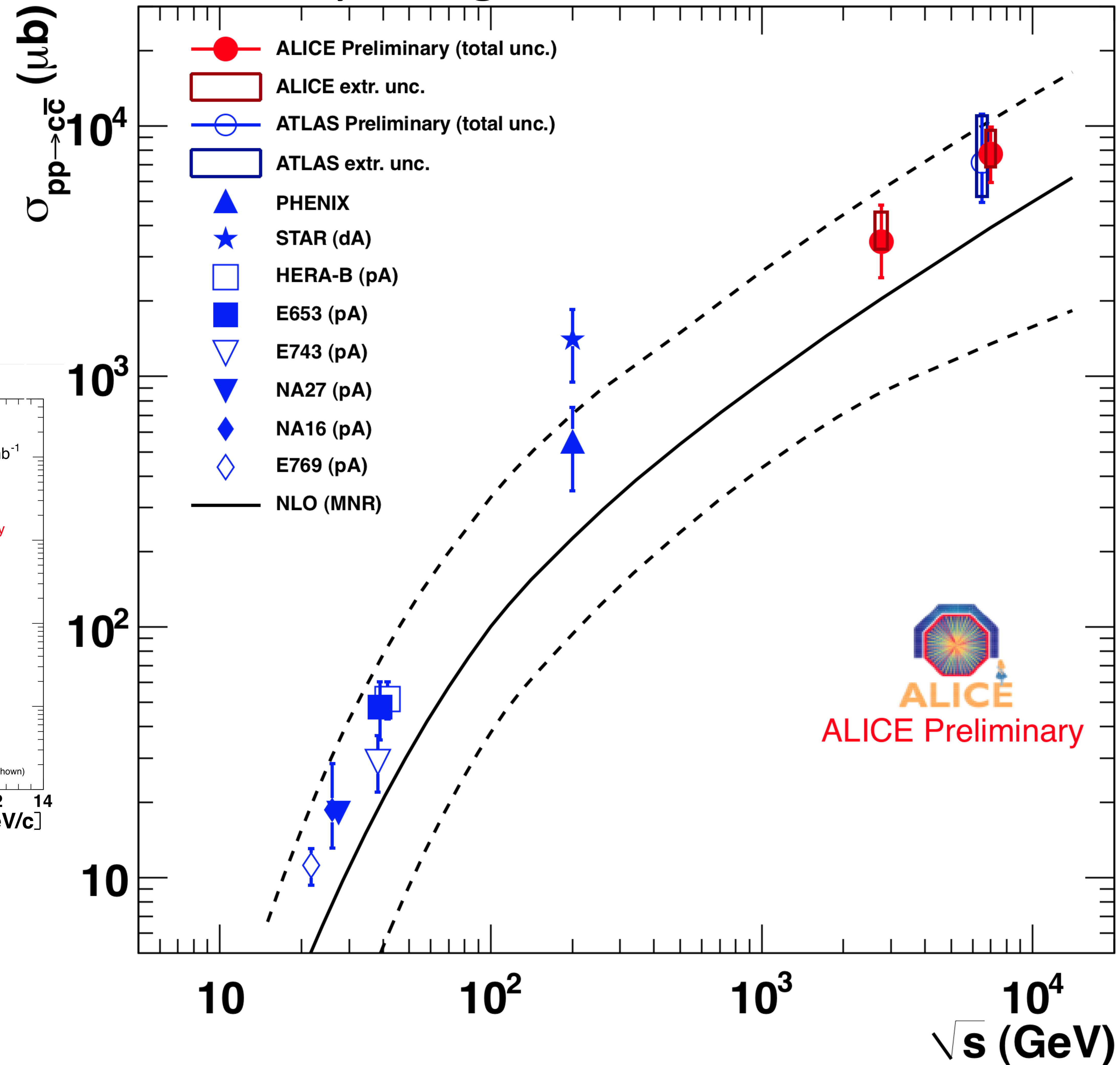
# Total charm cross section in pp

$D^0$  and  $D^+$  cross section at 2.76 TeV  
 $2 < p_t < 8$  GeV/c with  $1.1 \text{ nb}^{-1}$   
 (3 days of data march 2011)



Consistent comparison  
 with NLO over 3 orders of  
 magnitude

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



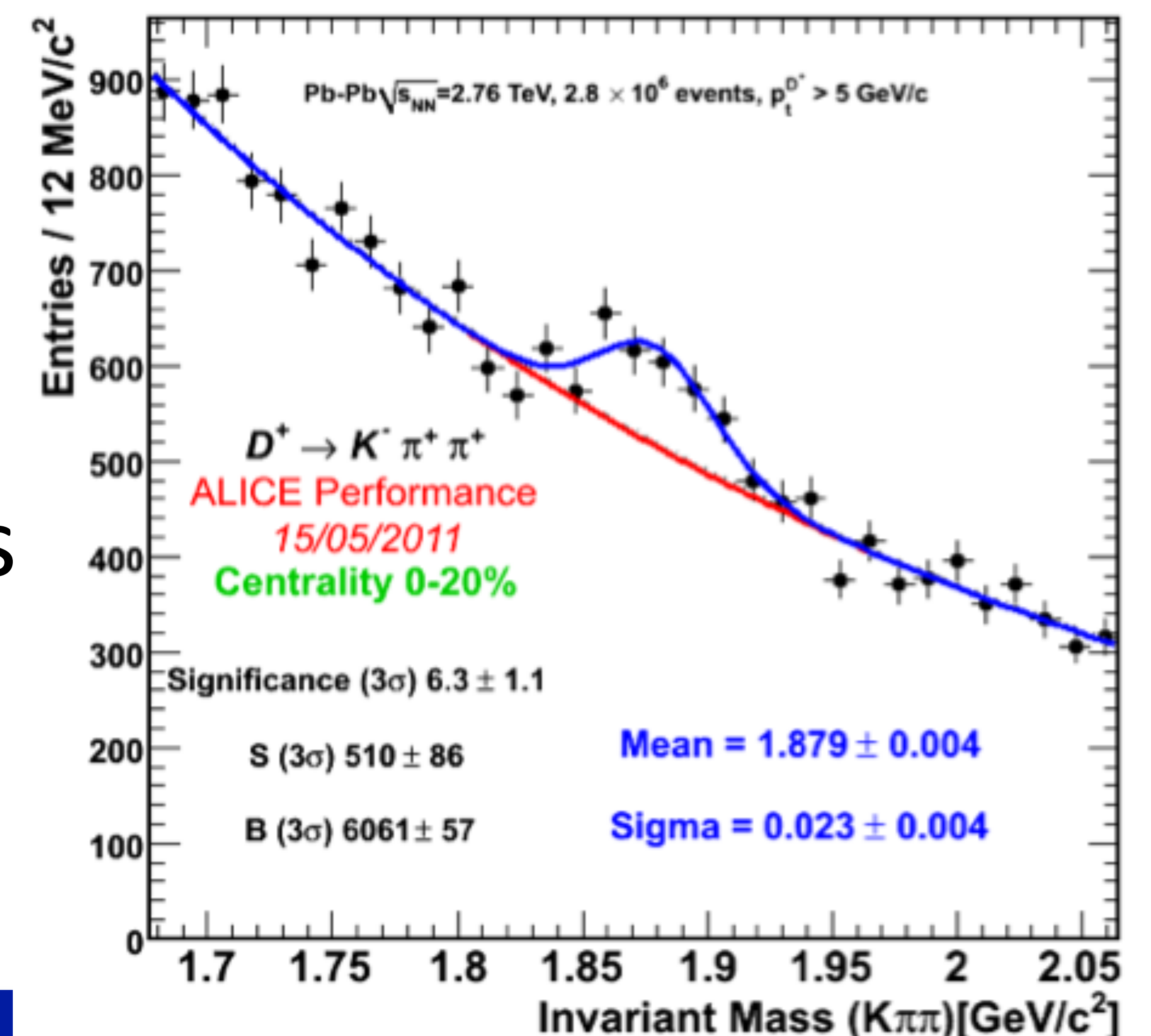
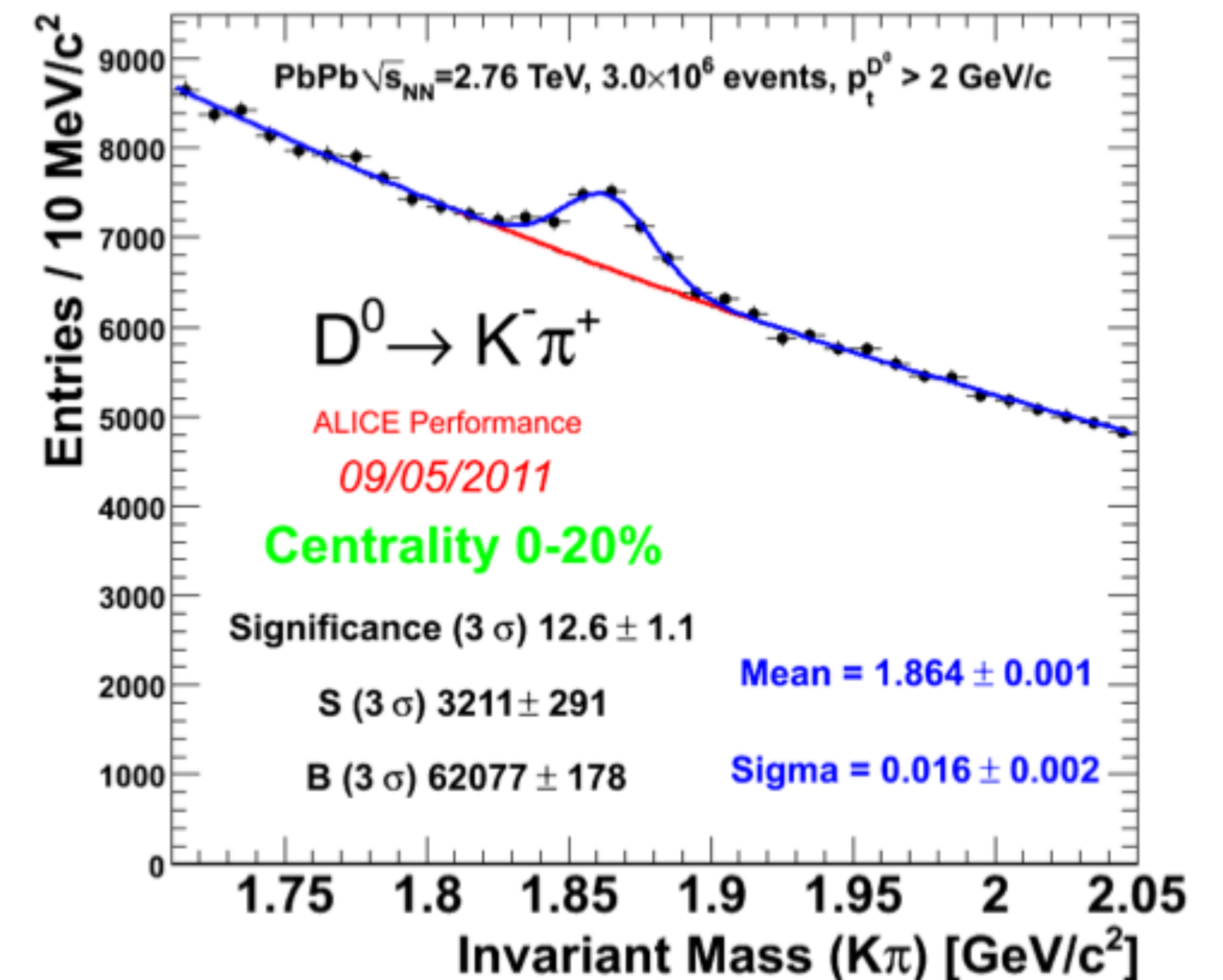
$$\sigma_{c\bar{c}}^{tot}(\text{ALICE}, 2.76\text{TeV}) = 3.45 \pm 0.41(\text{stat.})_{-0.84}^{+0.72}(\text{syst.}) \pm 0.17(\text{lum.})_{-0.24}^{+1.09}(\text{extr.})\text{mb}$$

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

# D<sup>0</sup> and D<sup>+</sup> in Pb-Pb collisions

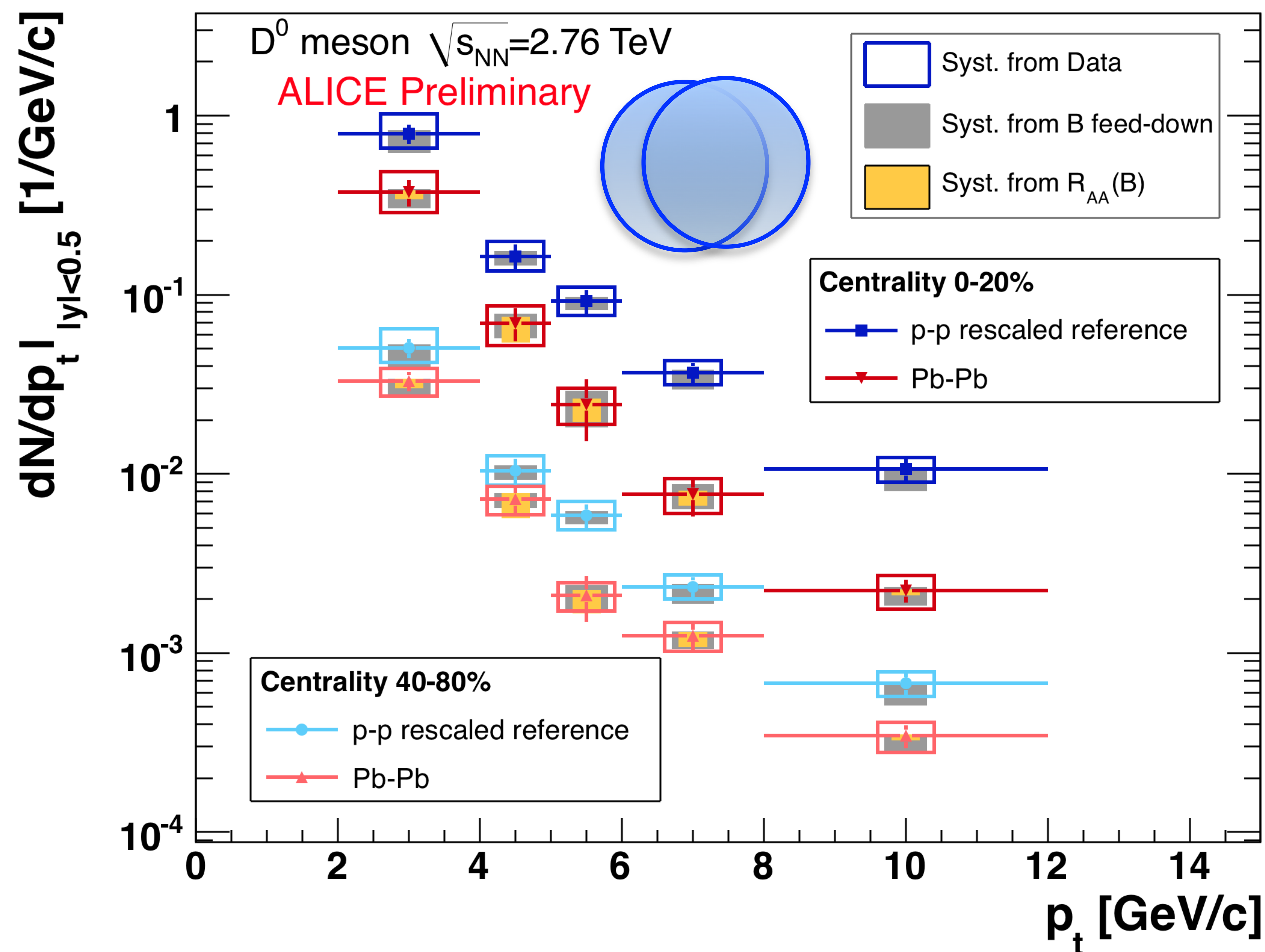


- In ~3M central collisions (0-20%):
  - D<sup>0</sup> : 5  $p_t$  bins in 2-12 GeV/c
  - D<sup>+</sup> : 3  $p_t$  bins in 5-12 GeV/c
- Reconstruction and selection efficiency ~1-10%
  - evaluated from MC simulation
    - detector status and performance described by the MC at the level of few relative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

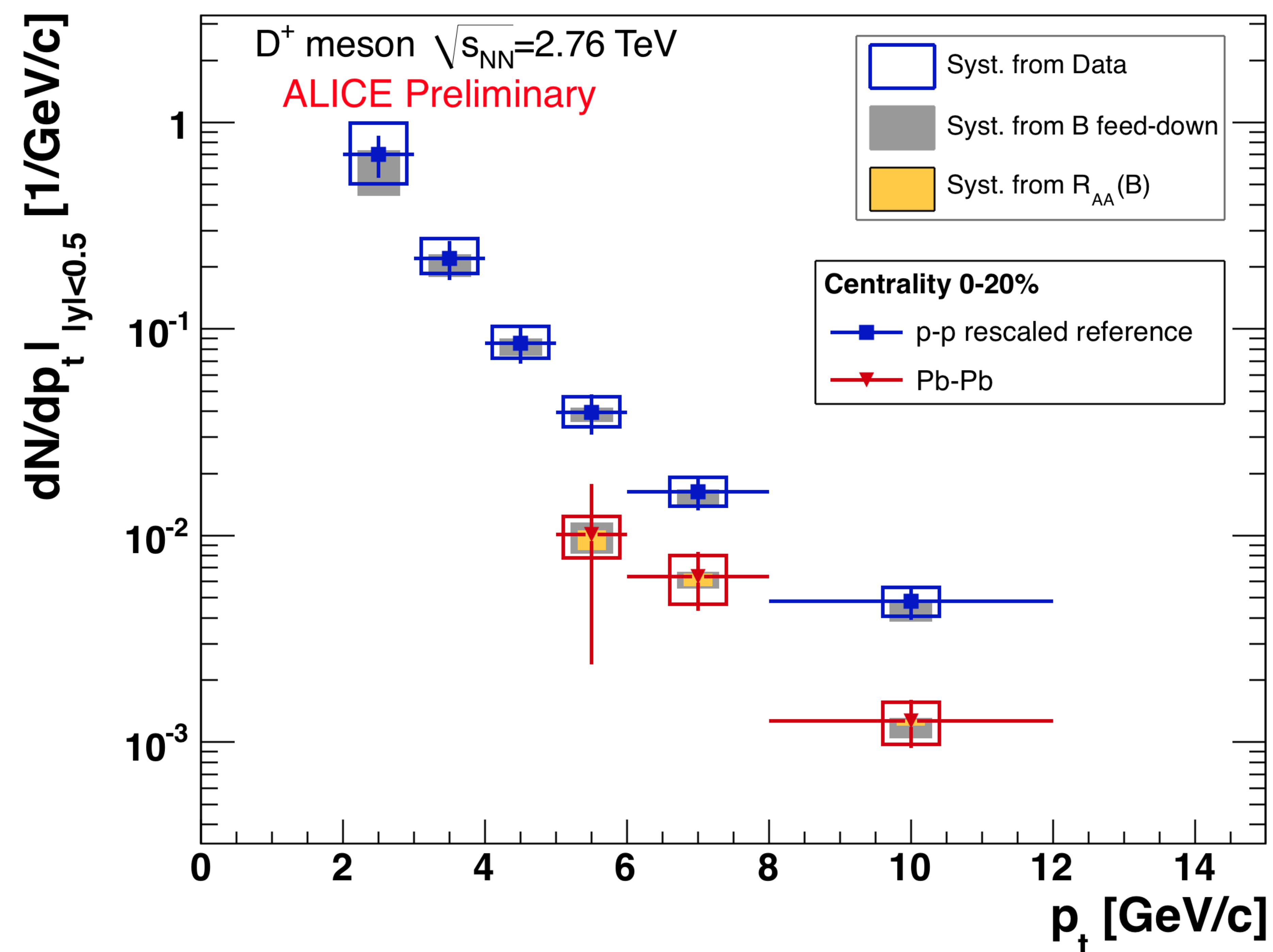




# D<sup>0</sup> and D<sup>+</sup> p<sub>t</sub> distribution in Pb-Pb

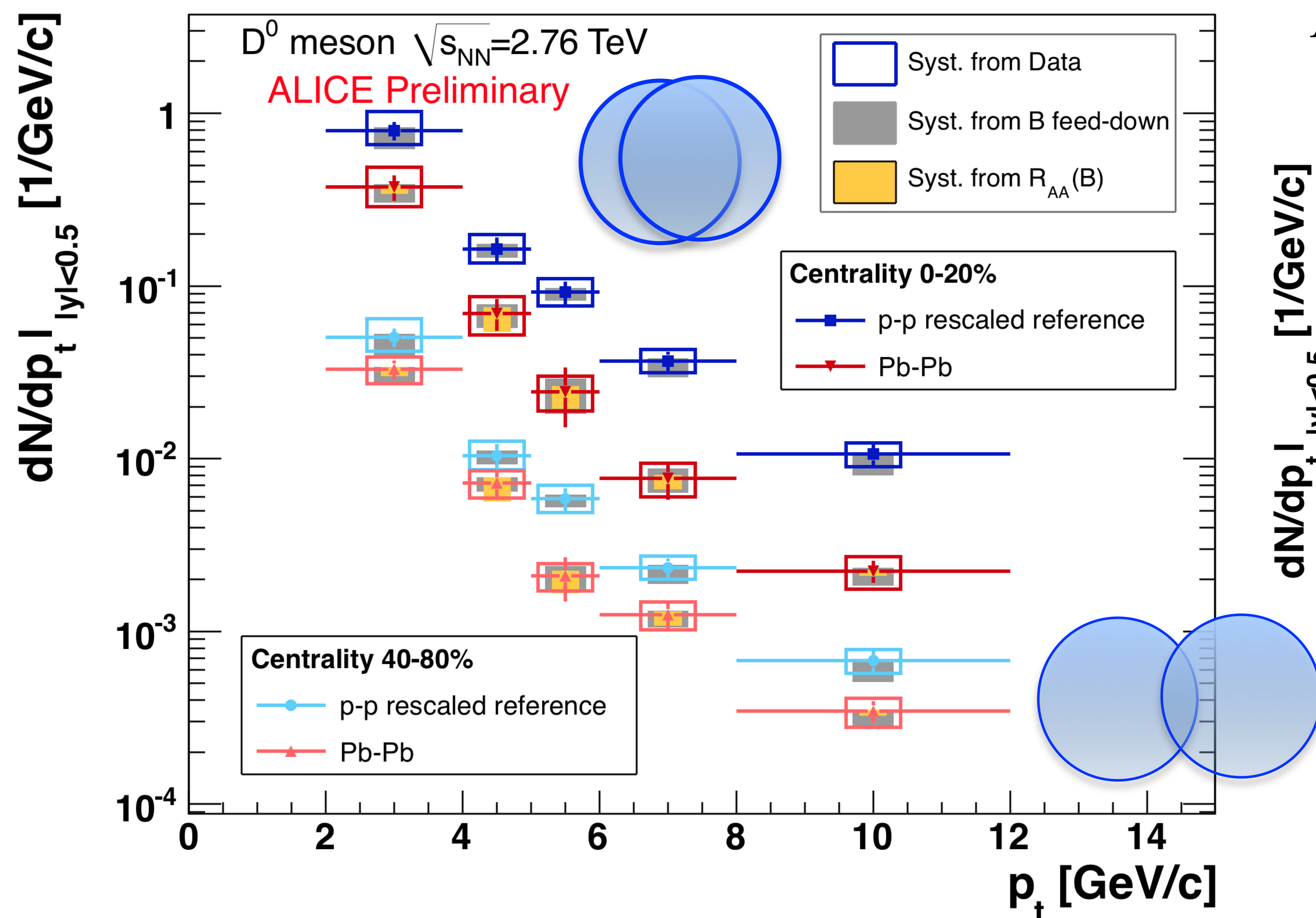


$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA} / dp_t}{d\sigma_{pp} / dp_t}$$

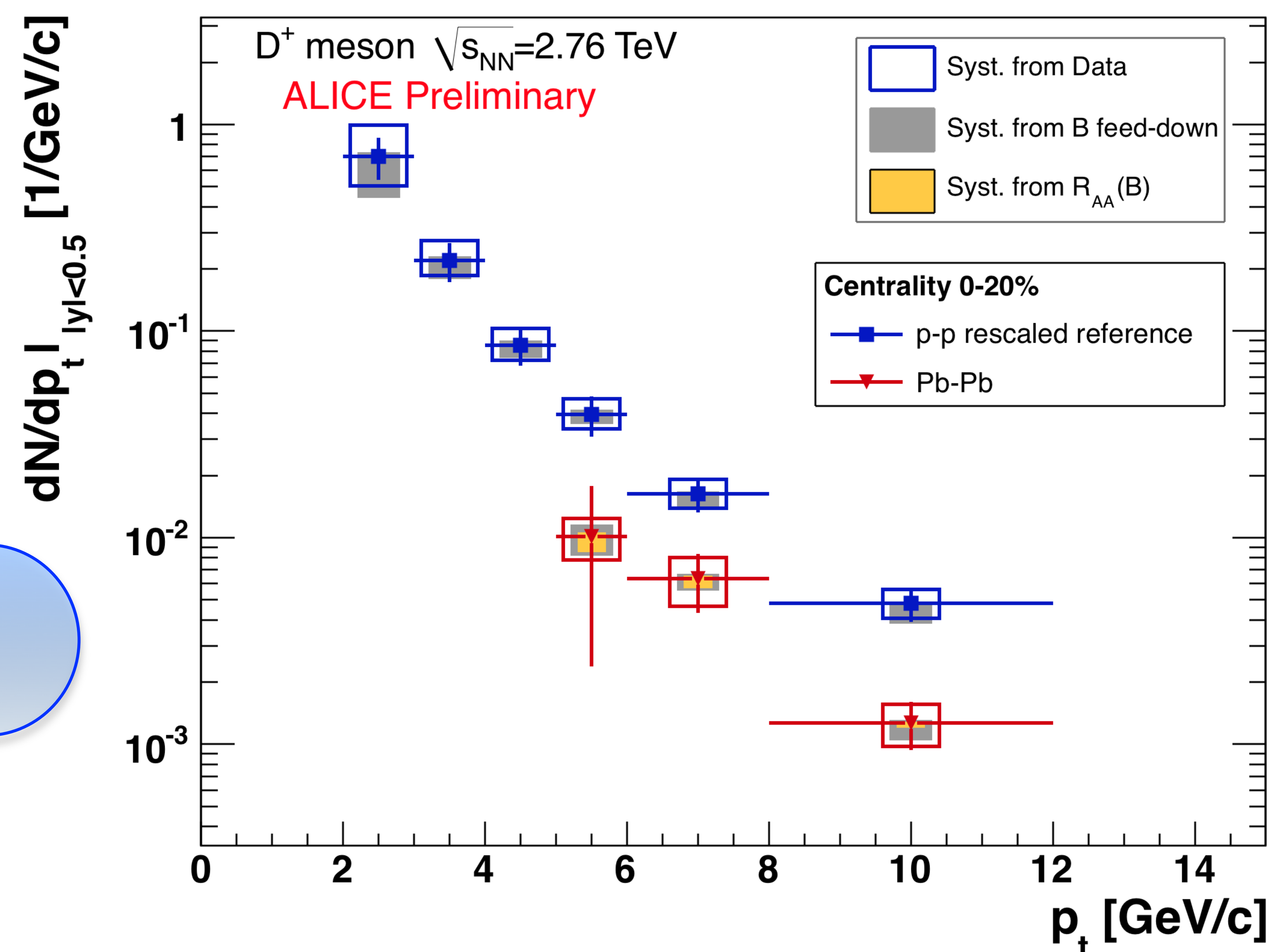


- Strong suppression observed in **central collisions (0-20%)** wrt  $T_{AA}$ -scaled pp reference
- Significant suppression also in **semiperipheral (40-80%)** wrt  $T_{AA}$ -scaled pp reference

# D<sup>0</sup> and D<sup>+</sup> p<sub>t</sub> distribution in Pb-Pb

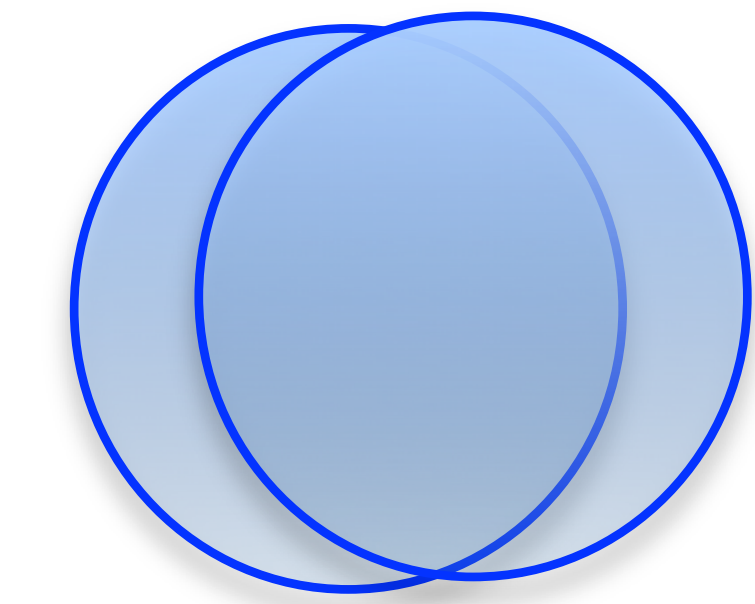
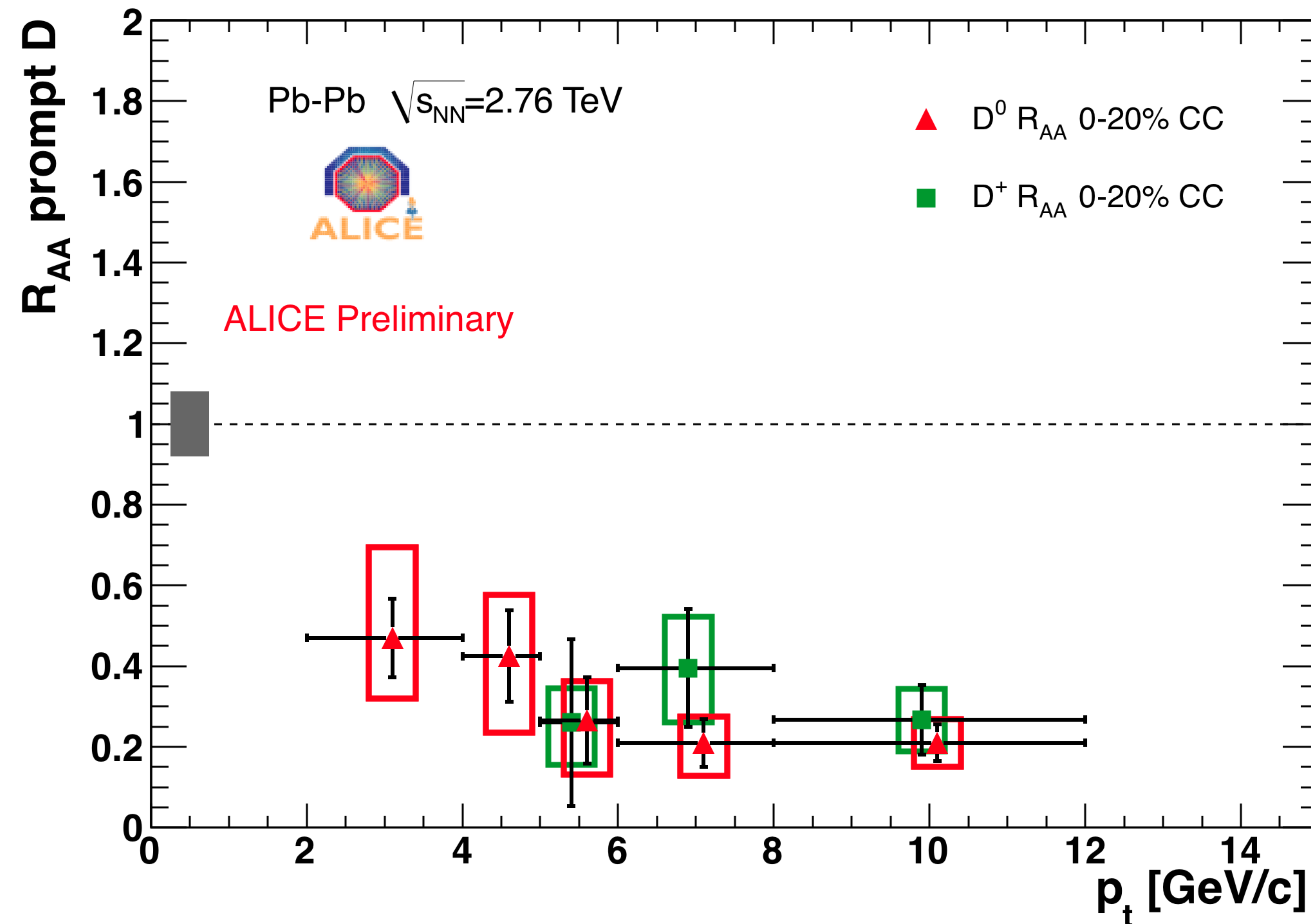


$$R_{AA}(p_t) = \frac{1}{\langle T_{AA} \rangle} \frac{dN_{AA} / dp_t}{d\sigma_{pp} / dp_t}$$



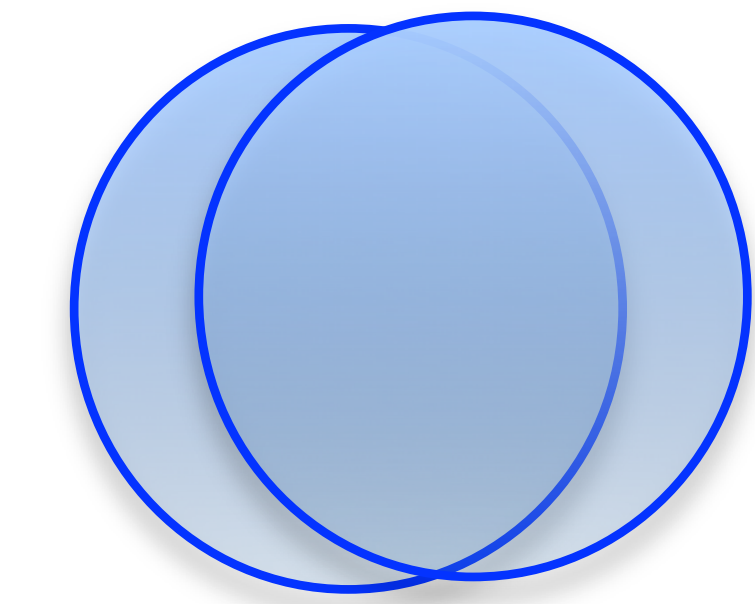
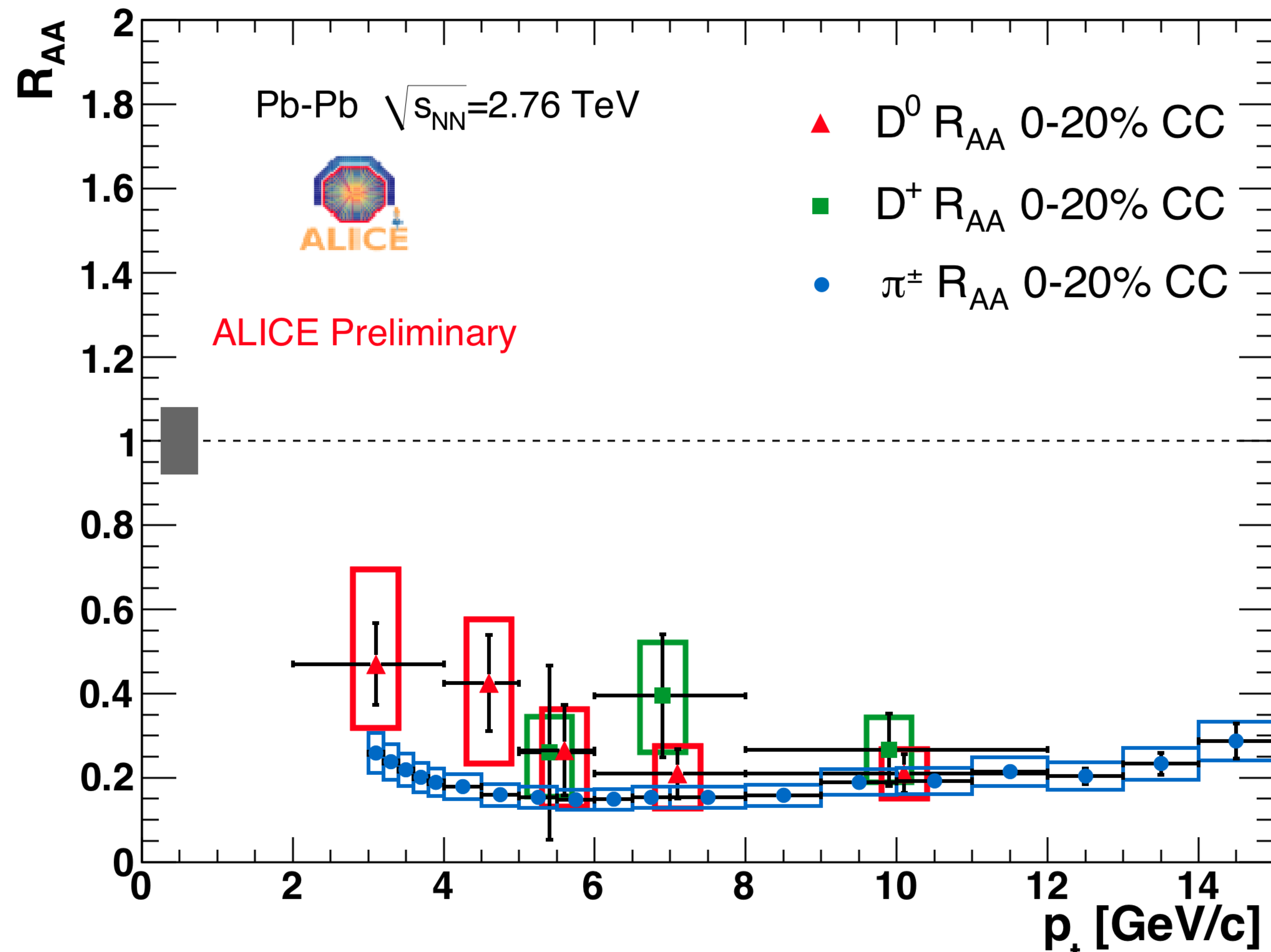
- Strong suppression observed in **central collisions (0-20%)** wrt  $T_{AA}$ -scaled pp reference
- Significant suppression also in **semiperipheral (40-80%)** wrt  $T_{AA}$ -scaled pp reference

# D mesons $R_{AA}$ : first measurement in central heavy ion collisions



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

# D mesons $R_{AA}$ : first measurement in central heavy ion collisions



- Suppression for charm is a factor 4-5 above 5 GeV/c
- $R_{AA}$  for charged pions seems small at low  $p_t$  but systematic uncertainties don't allow to conclude for the moment.

# ALICE Heavy Flavour Program: electrons, $|\eta| < 0.8$

TPC/TOF/TRD/EMCAL (e/ $\pi$  id)

TPC (tracking e/ $\pi$  id)

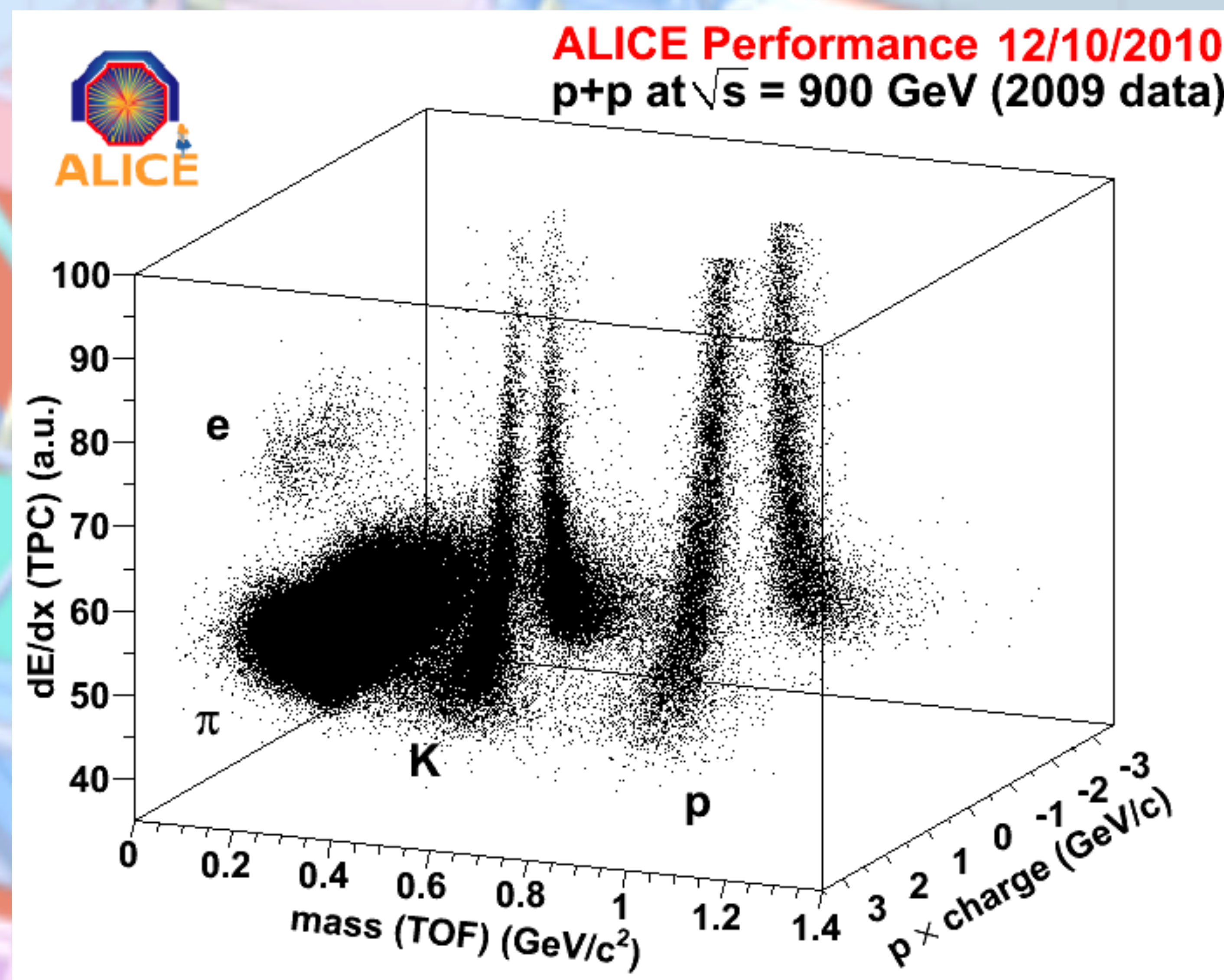
ITS (tracking & vertexing)

e

- ✓  $D^0 \rightarrow K\pi$
- $D^+ \rightarrow K\pi\pi$
- $D_s \rightarrow KK\pi$
- $D^* \rightarrow D^0\pi$
- $D^0 \rightarrow K\pi\pi\pi$
- $(\Lambda_c \rightarrow \pi Kp)$

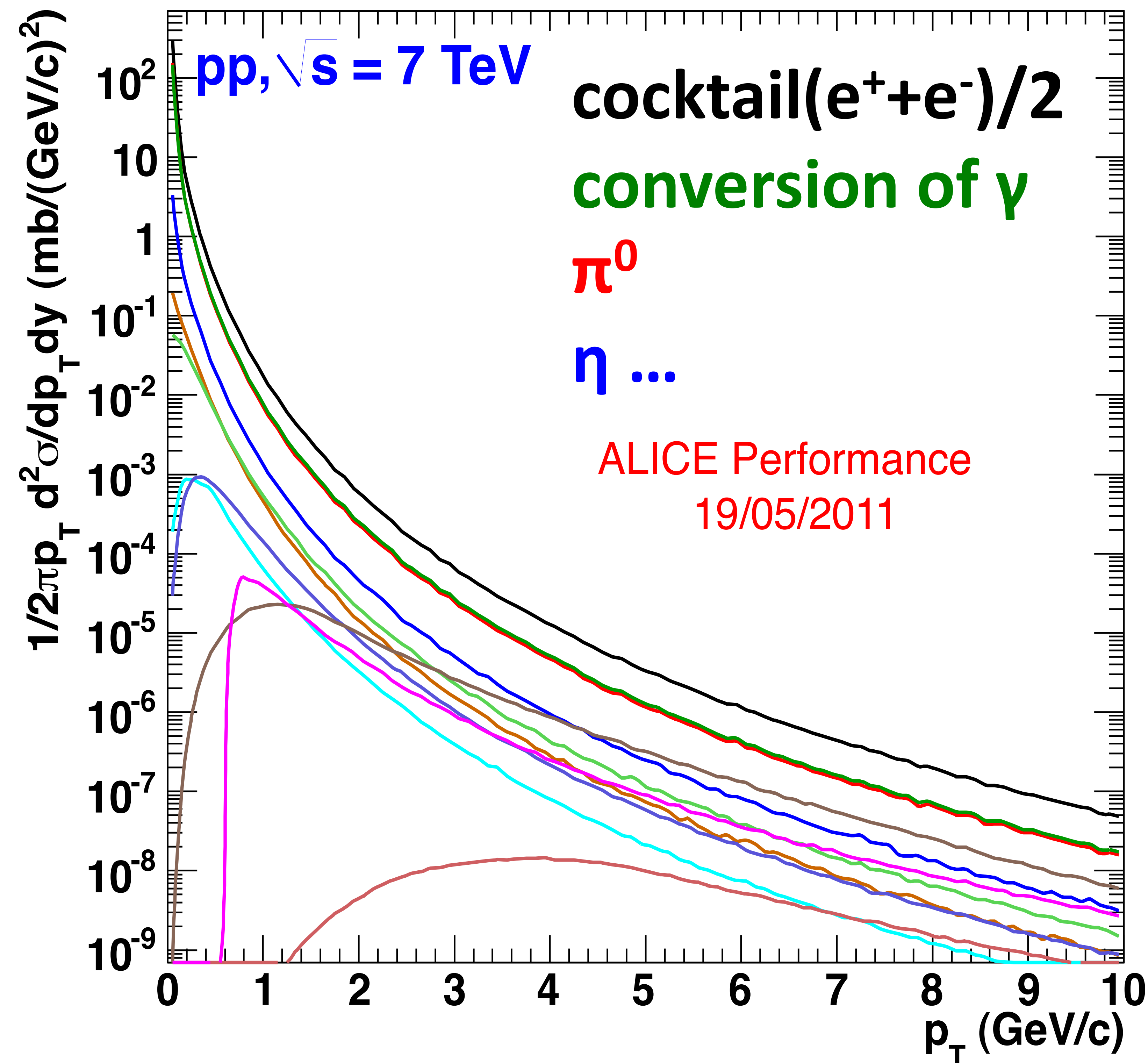
- ✓  $D, B \rightarrow e+X$   
( $B \rightarrow J/\psi \rightarrow ee$ ,  
tagged b-jets)

- ✓  $D, B \rightarrow \mu(\mu)+X$



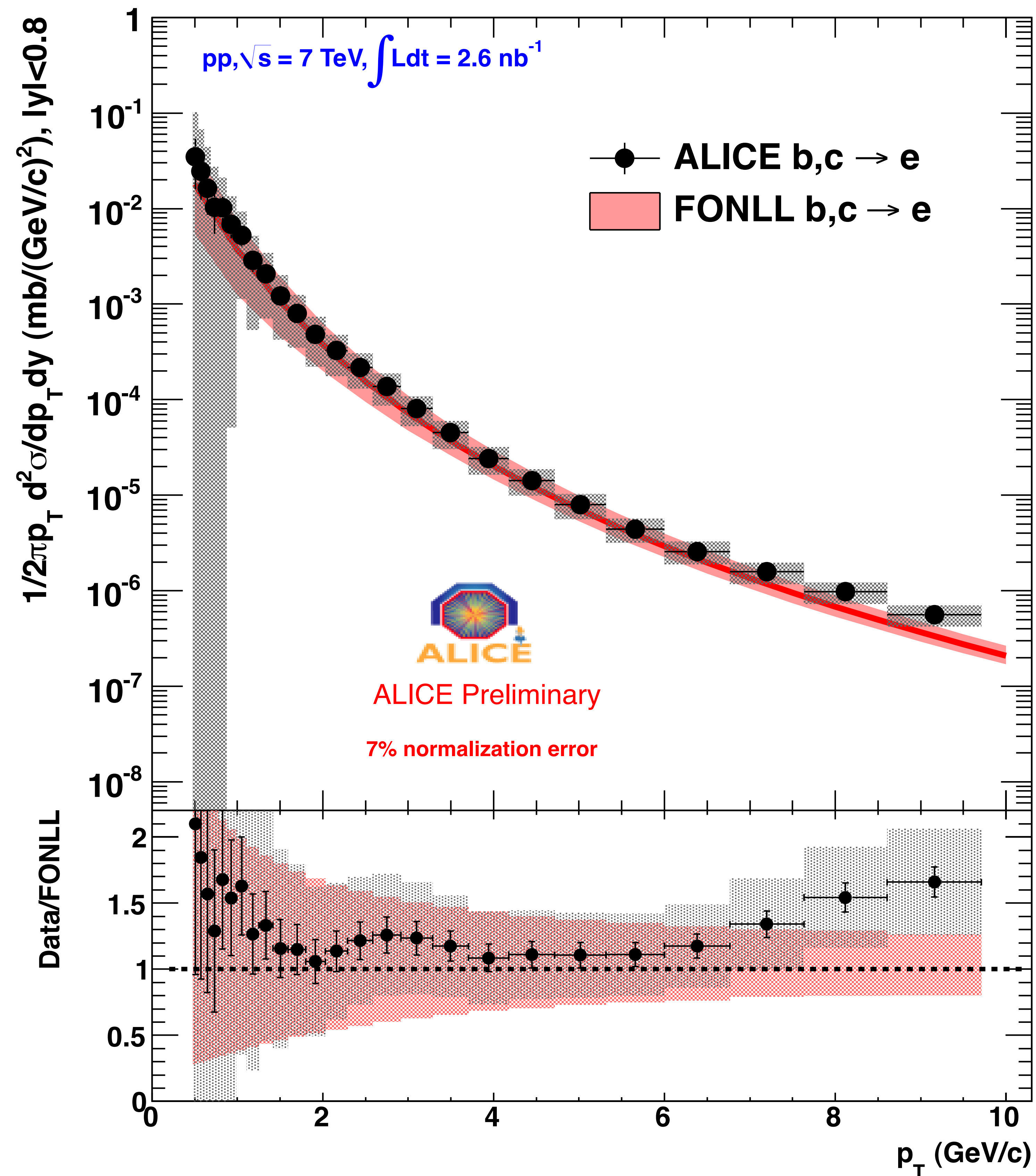
F. Bellini's poster

# Heavy Flavour electron spectra @ 7 TeV



- Cocktail of “photonic” electrons backgrounds based on measured  $\pi^0$  cross section
- Inclusive – Cocktail: electrons from c and b decays
- Well described by FONLL

# Heavy Flavour electron spectra @ 7 TeV

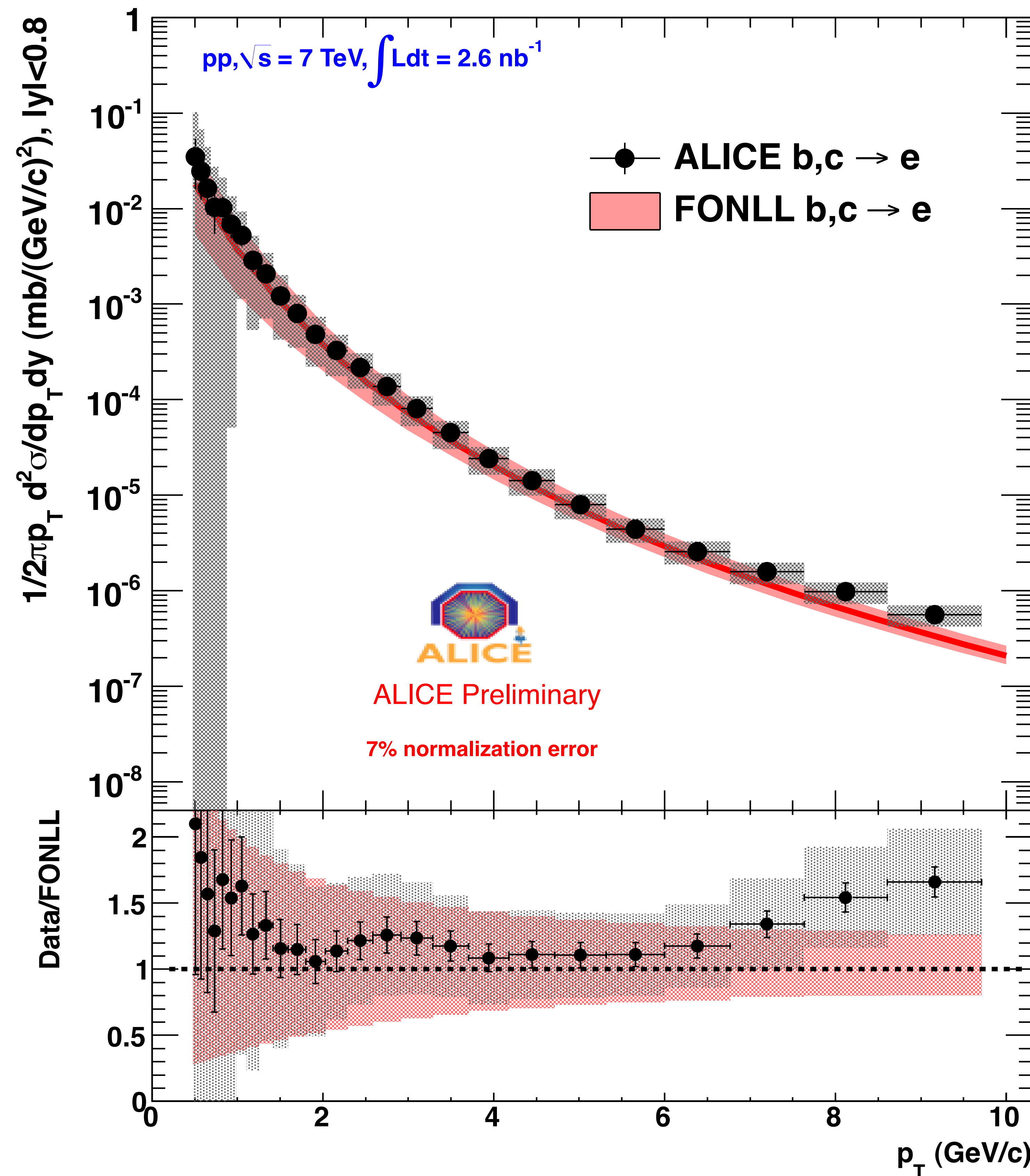


Cocktail of “photonic” electrons  
backgrounds based on measured  $\pi^0$   
cross section

Inclusive – Cocktail: electrons from c  
and b decays

Well described by FONLL

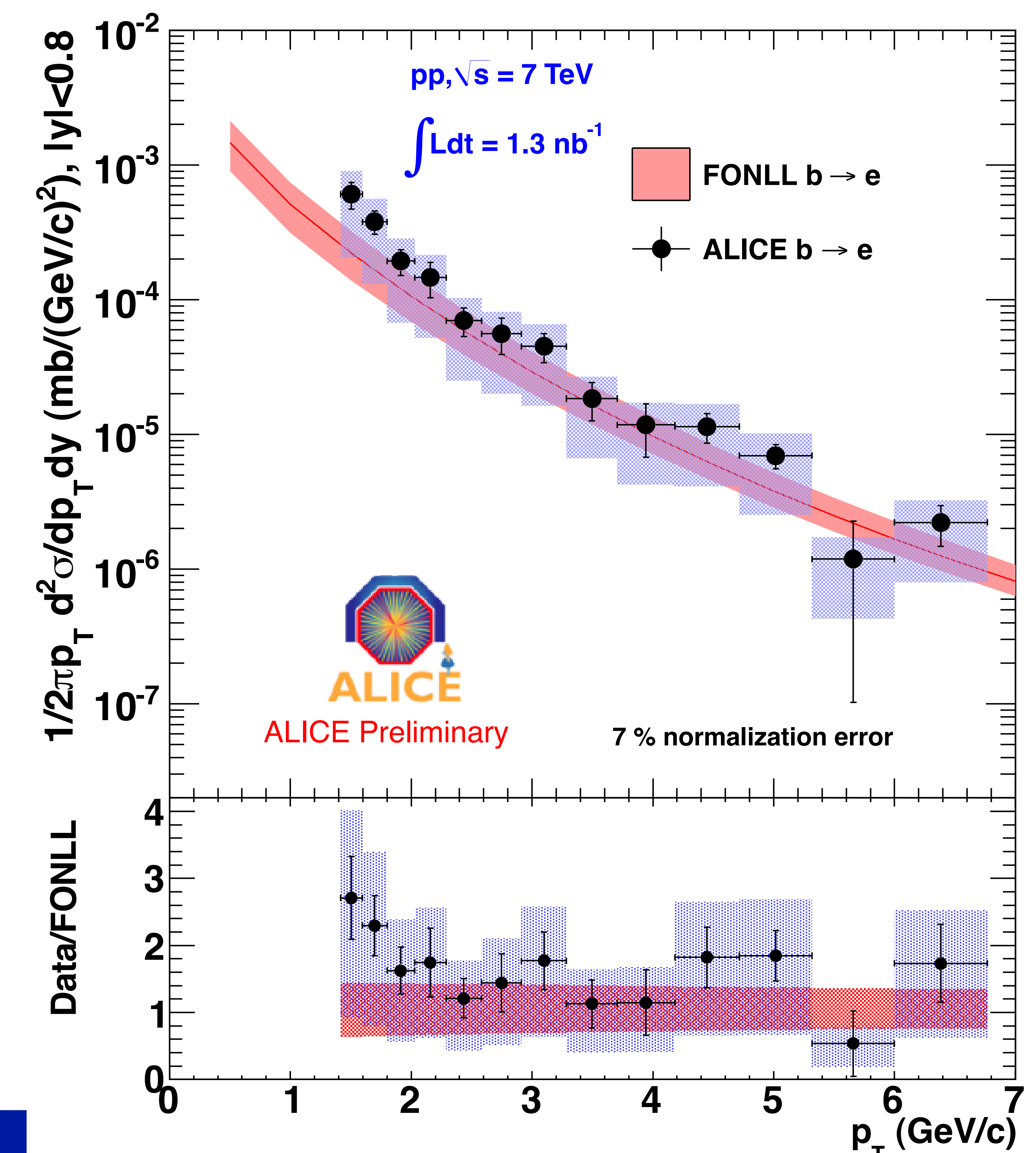
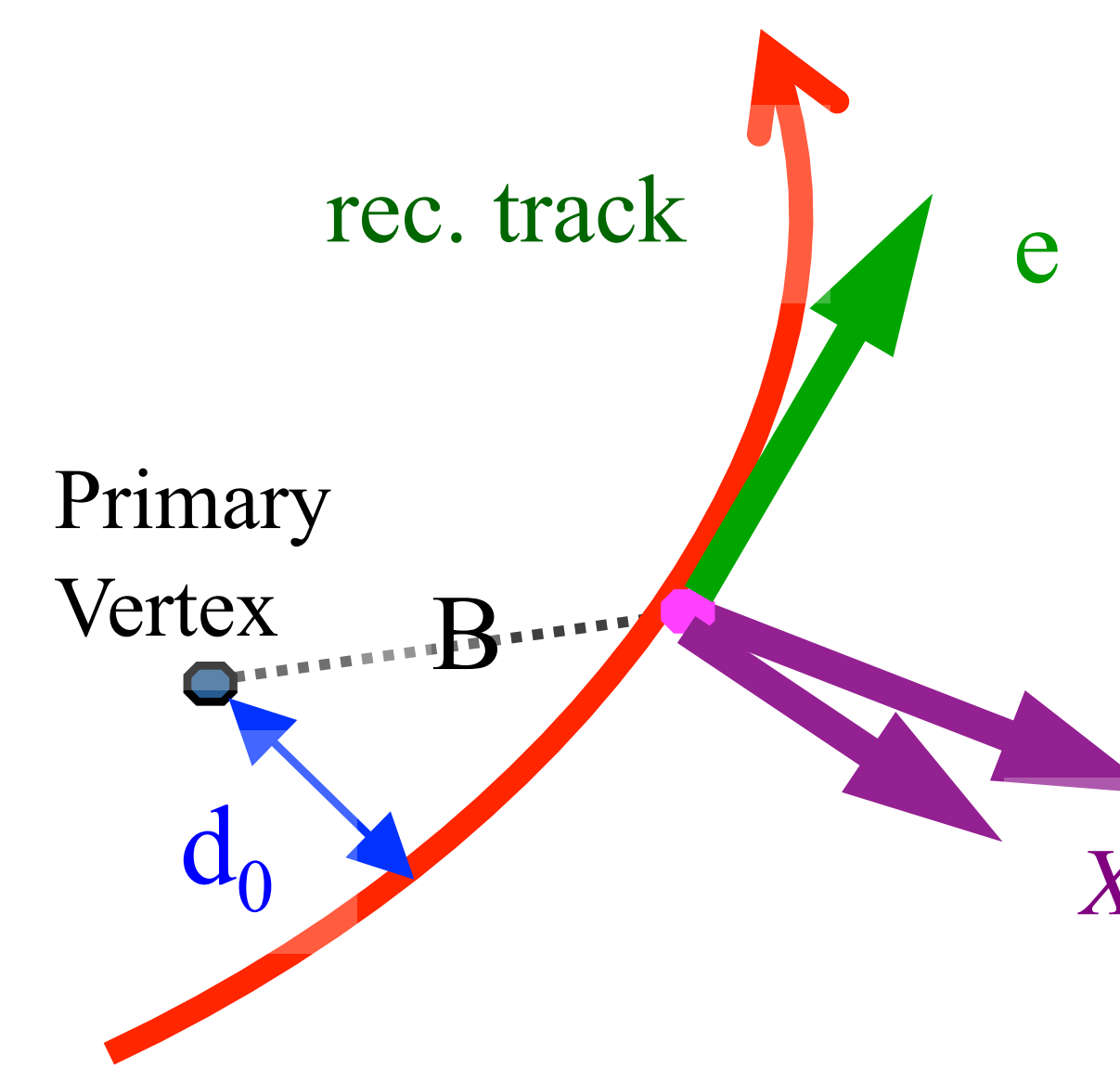
# Heavy Flavour electron spectra @ 7 TeV



Cocktail of “photonic” electrons  
backgrounds based on measured  $\pi^0$   
cross section

Inclusive – Cocktail: electrons from c  
and b decays

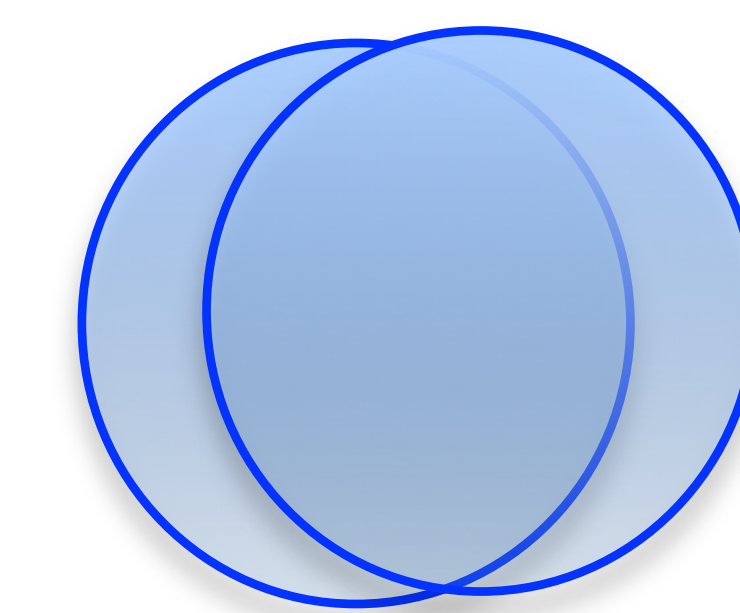
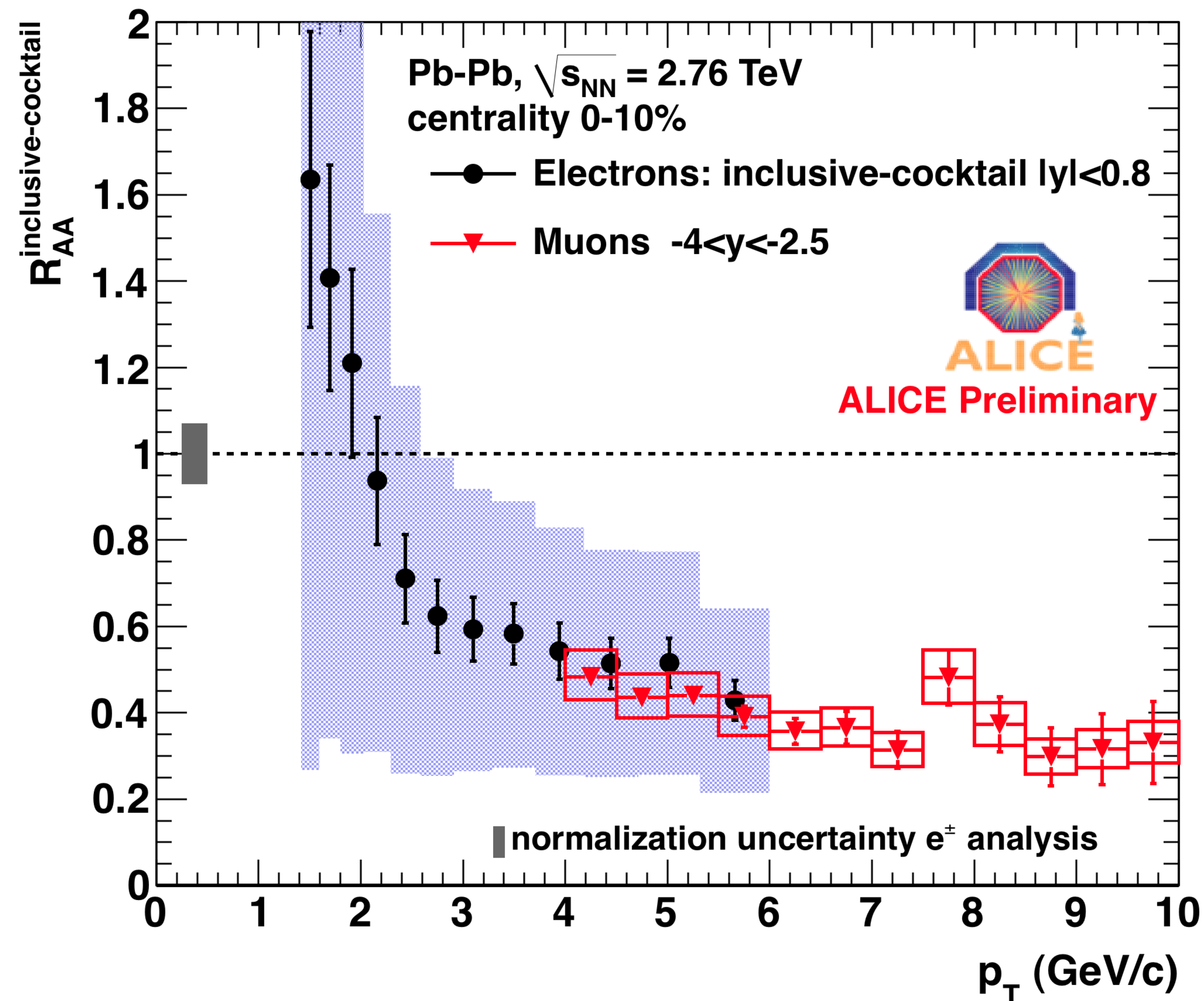
Well described by FONLL



- Select electrons displaced from interaction vertex
- Electrons from beauty decays
- Well described by FONLL



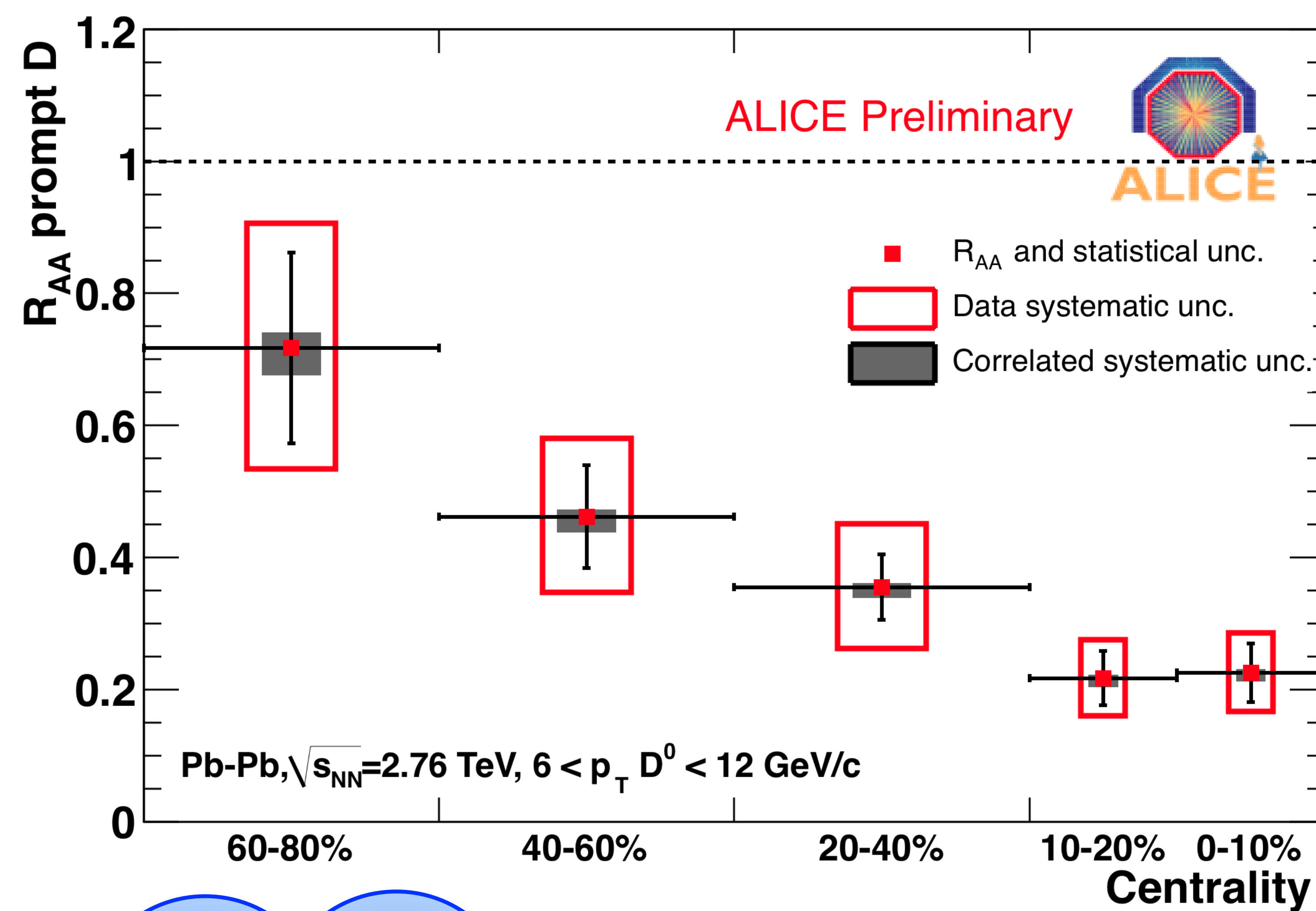
# Lepton $R_{AA}$ comparison at different rapidities



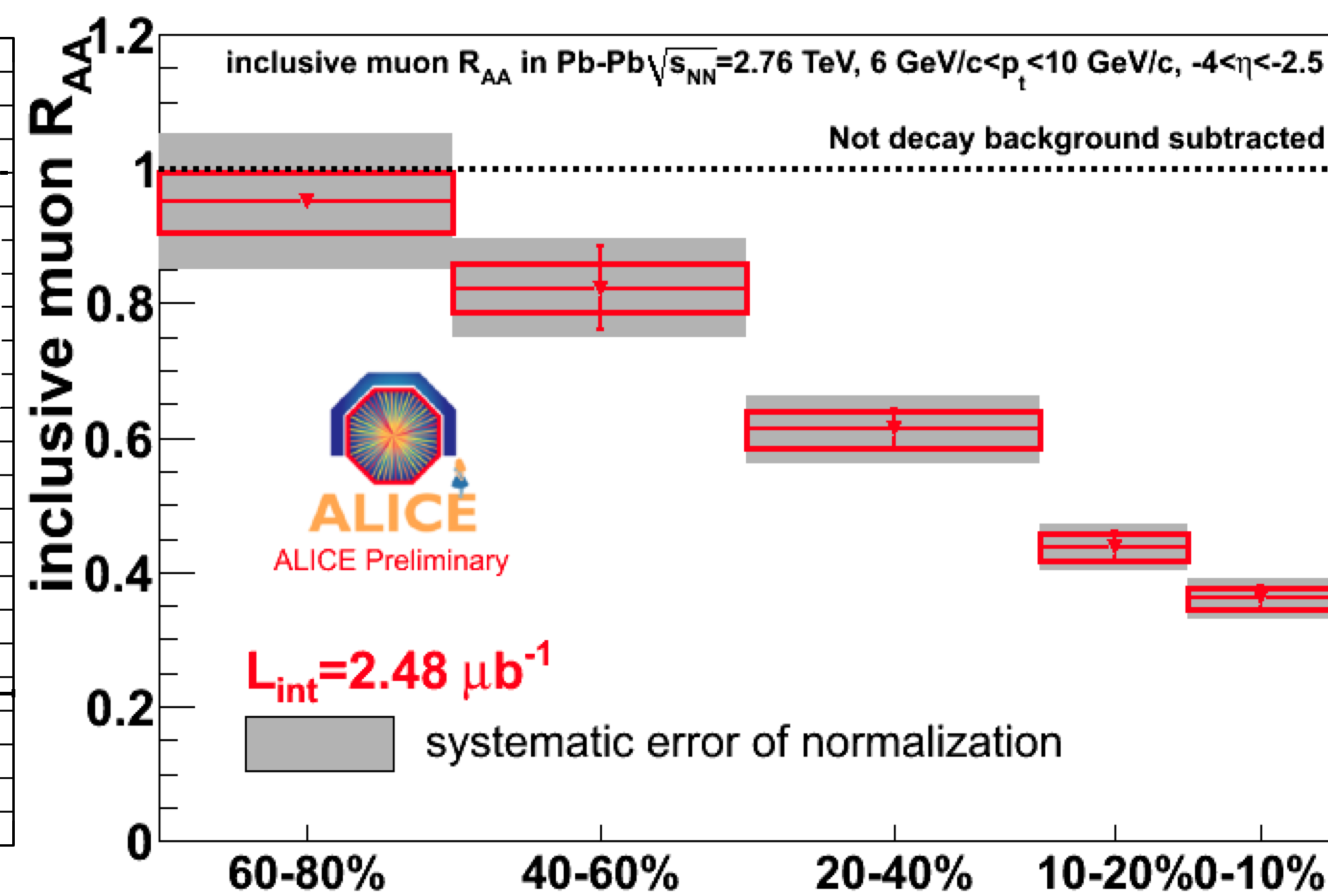
- Electron  $R_{AA}$  in the centrality class 0-10% measured at central rapidity ( $y \sim 0$ )
- Muon  $R_{AA}$  in the centrality class 0-10% measured at forward rapidity ( $y \sim 3$ )
- The two measurements are compatible within errors.

# Heavy Flavour $R_{AA}$ vs centrality

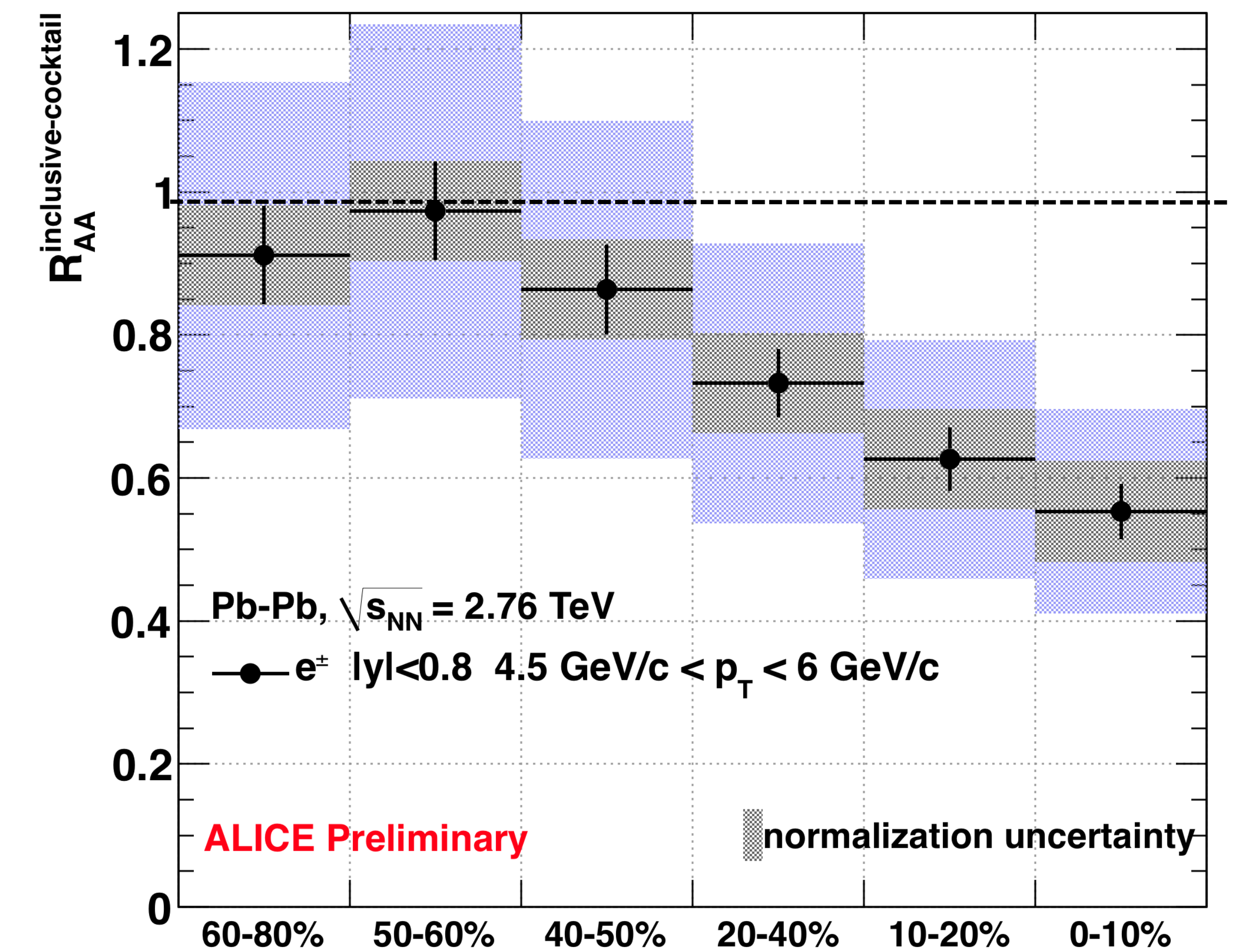
$D^0 p_t > 6 \text{ GeV}/c$



$\mu p_t > 6 \text{ GeV}/c$



$e p_t > 4.5 \text{ GeV}/c$



- Consistent centrality dependence
- Muons  $\sim$  Electrons
- D mesons clearly lower
- In peripheral collisions the suppression tends to disappear ( $N_{coll}$  scaling)



# Summary and outlook

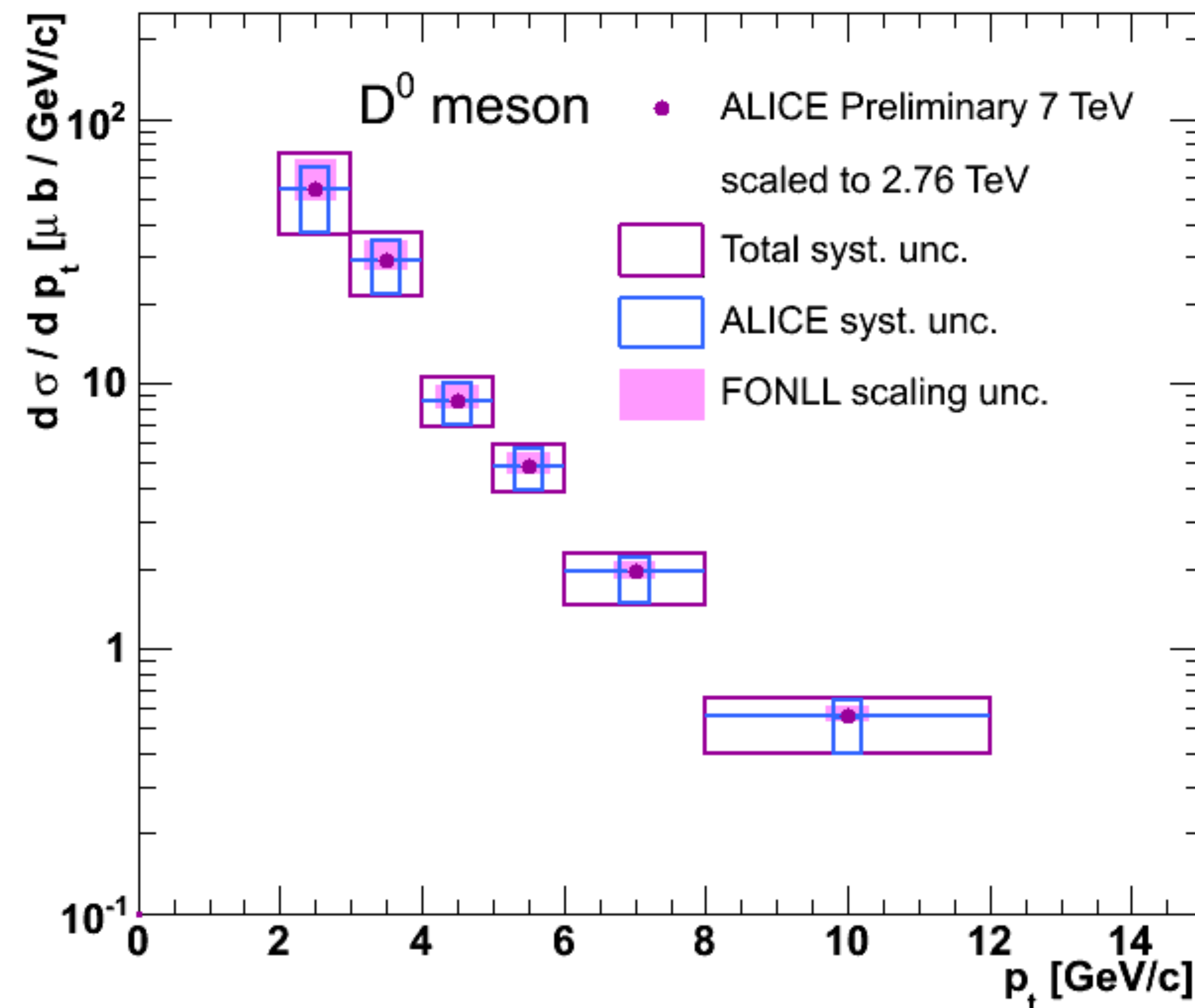
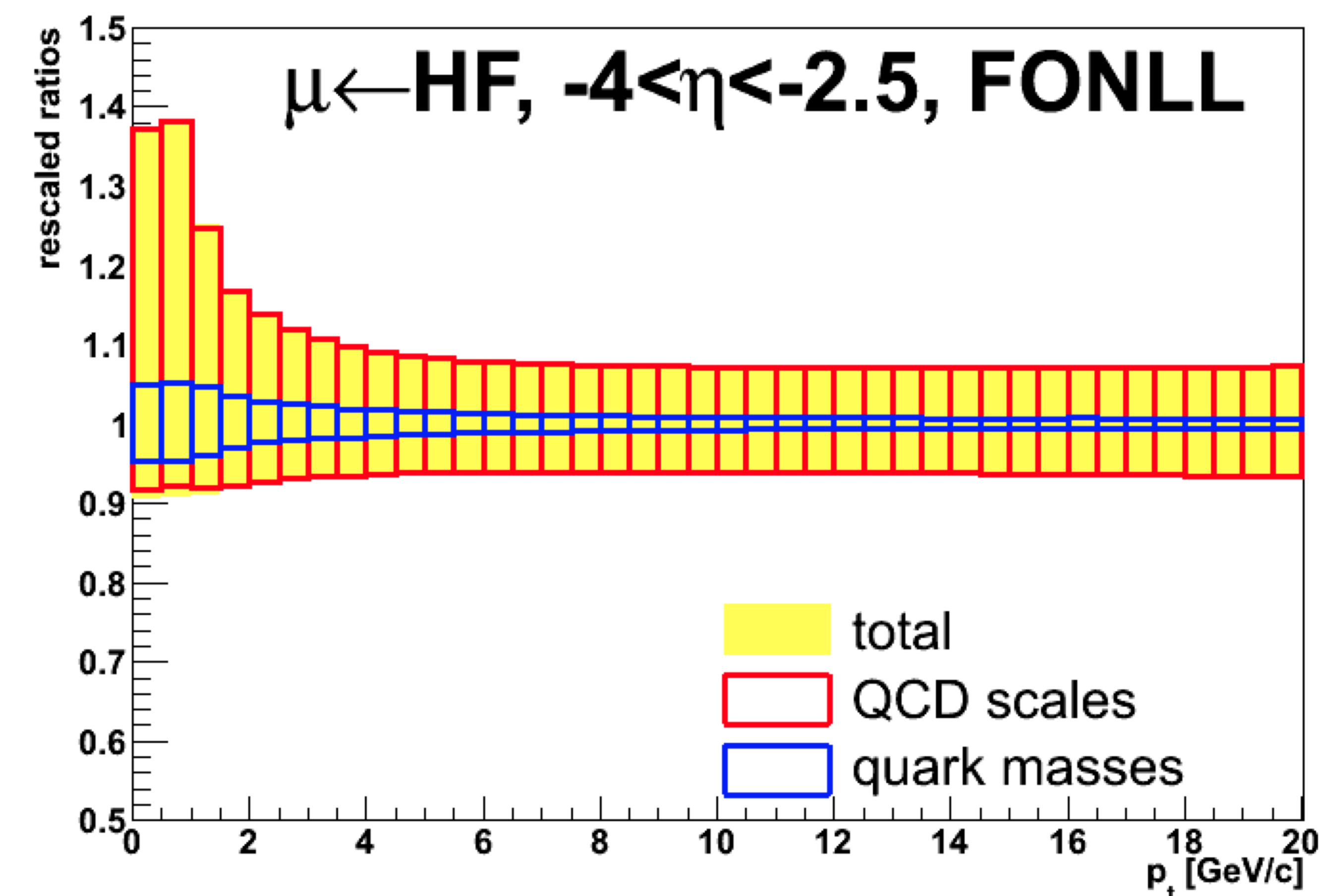
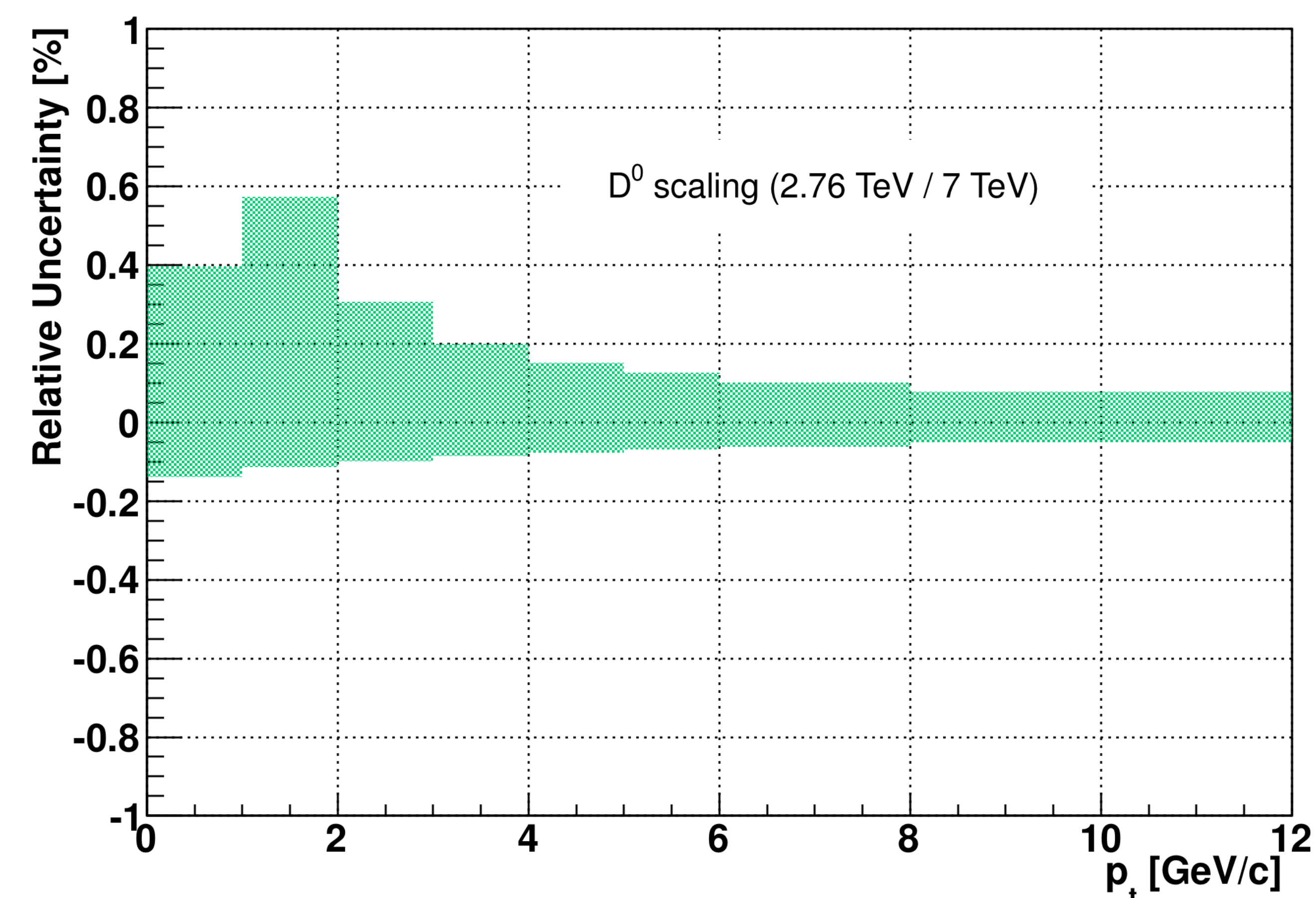
- The nuclear modification factors in Pb-Pb for heavy flavour have been measured by ALICE
- The D meson and high- $p_t$  lepton  $R_{AA}$  exhibit a strong suppression in central collisions (down to  $\sim 0.2$  for D's)
  - The suppression tends to vanish towards peripheral collisions
- Cross sections for D mesons, electrons and muons in pp have been measured at 7 TeV and are used as a reference for Pb-Pb studies.
- In pp analyses,  $p_t$  range extension is expected using the full 2010 statistics.
- A Pb-Pb higher statistics run is expected in November 2011, and between other topics, a finer  $p_t$  binning for D mesons  $R_{AA}$  measurement is foreseen and to access beauty  $R_{AA}$ .



# BACK UP SLIDES

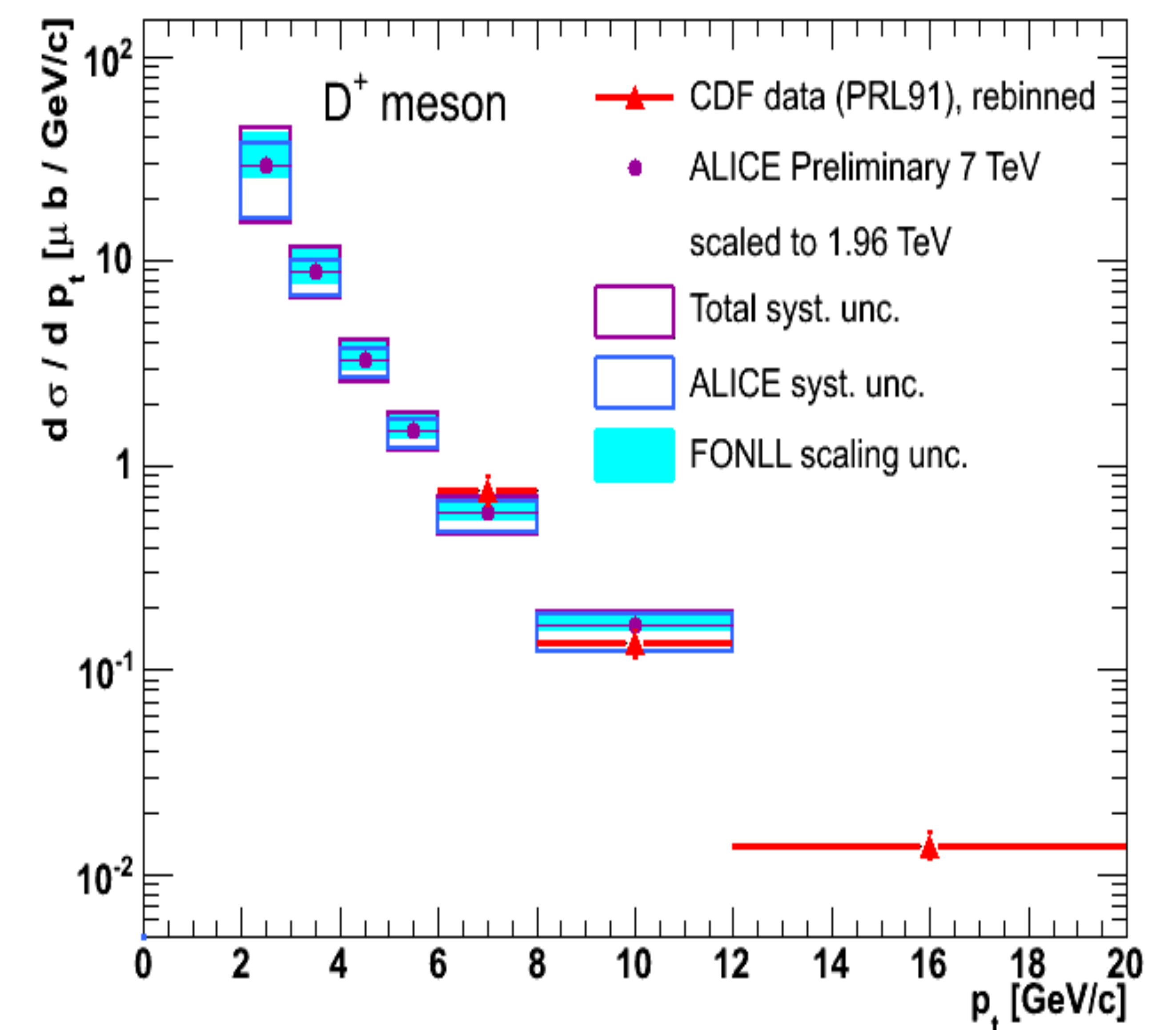
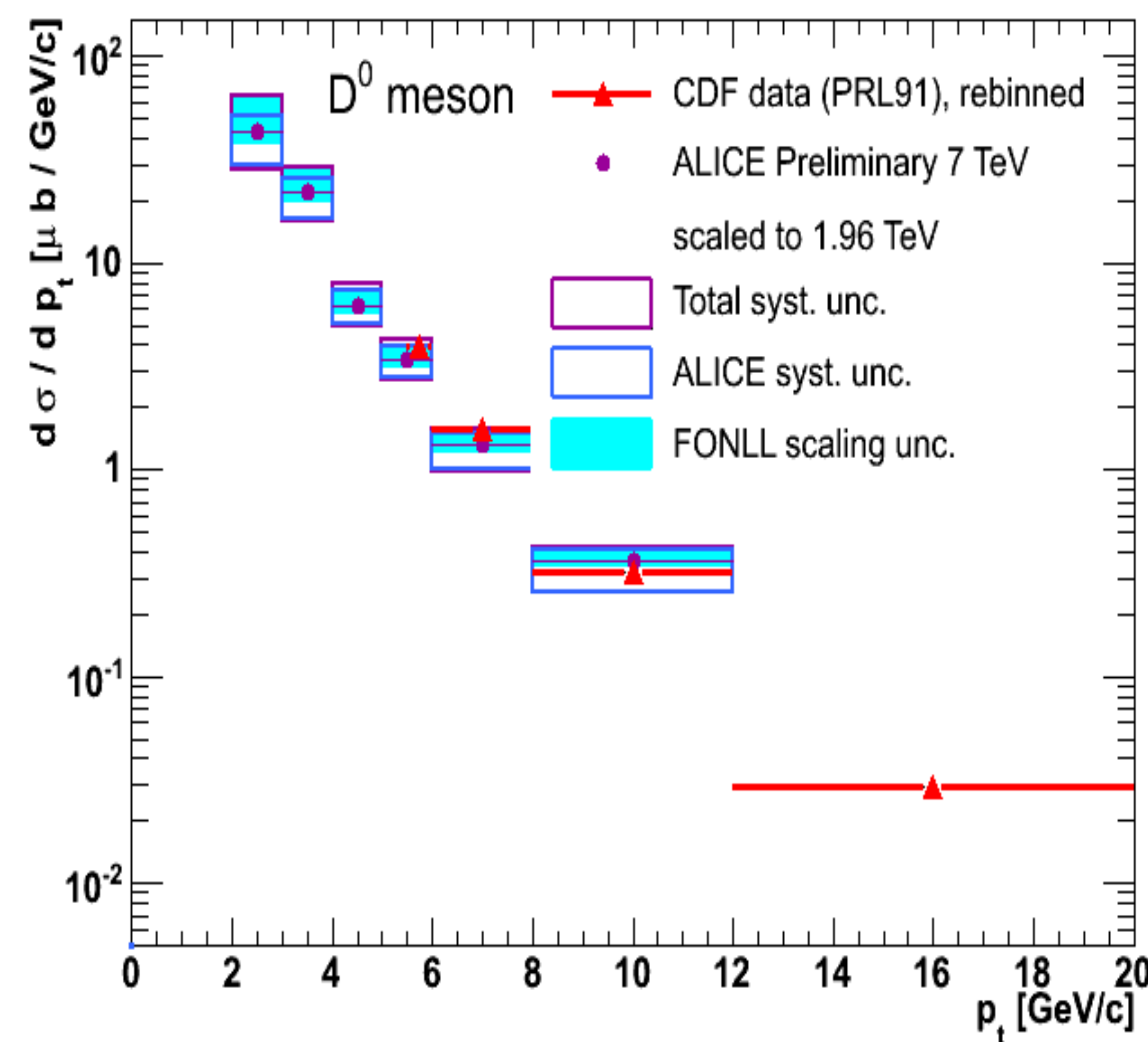
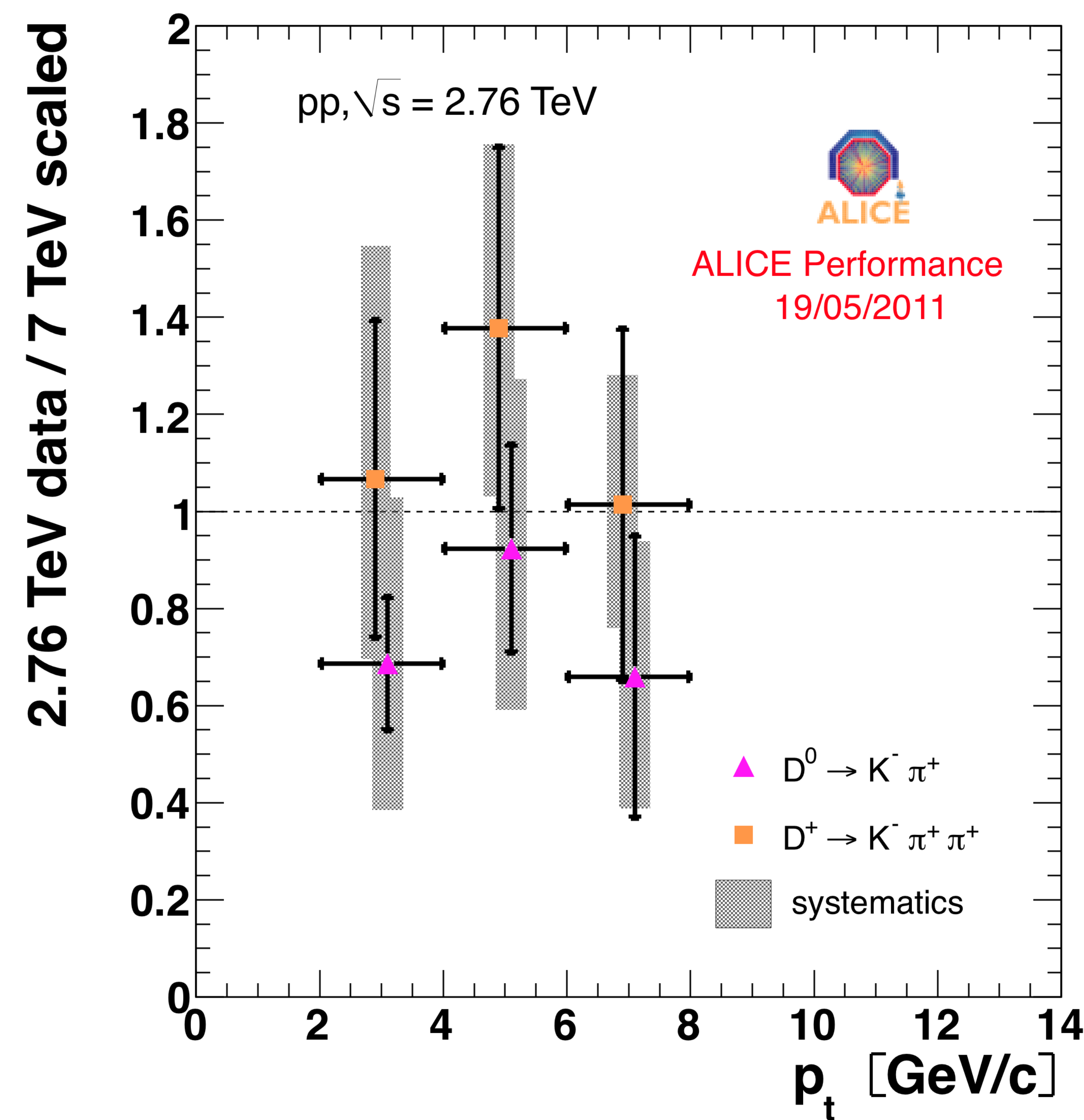
# pp reference at 2.76 TeV scaled with pQCD

- 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  $\sqrt{s}$
  - relative scaling uncertainty: 25%  $\rightarrow$  10% in  $p_t = 2 \rightarrow 10$  GeV/c



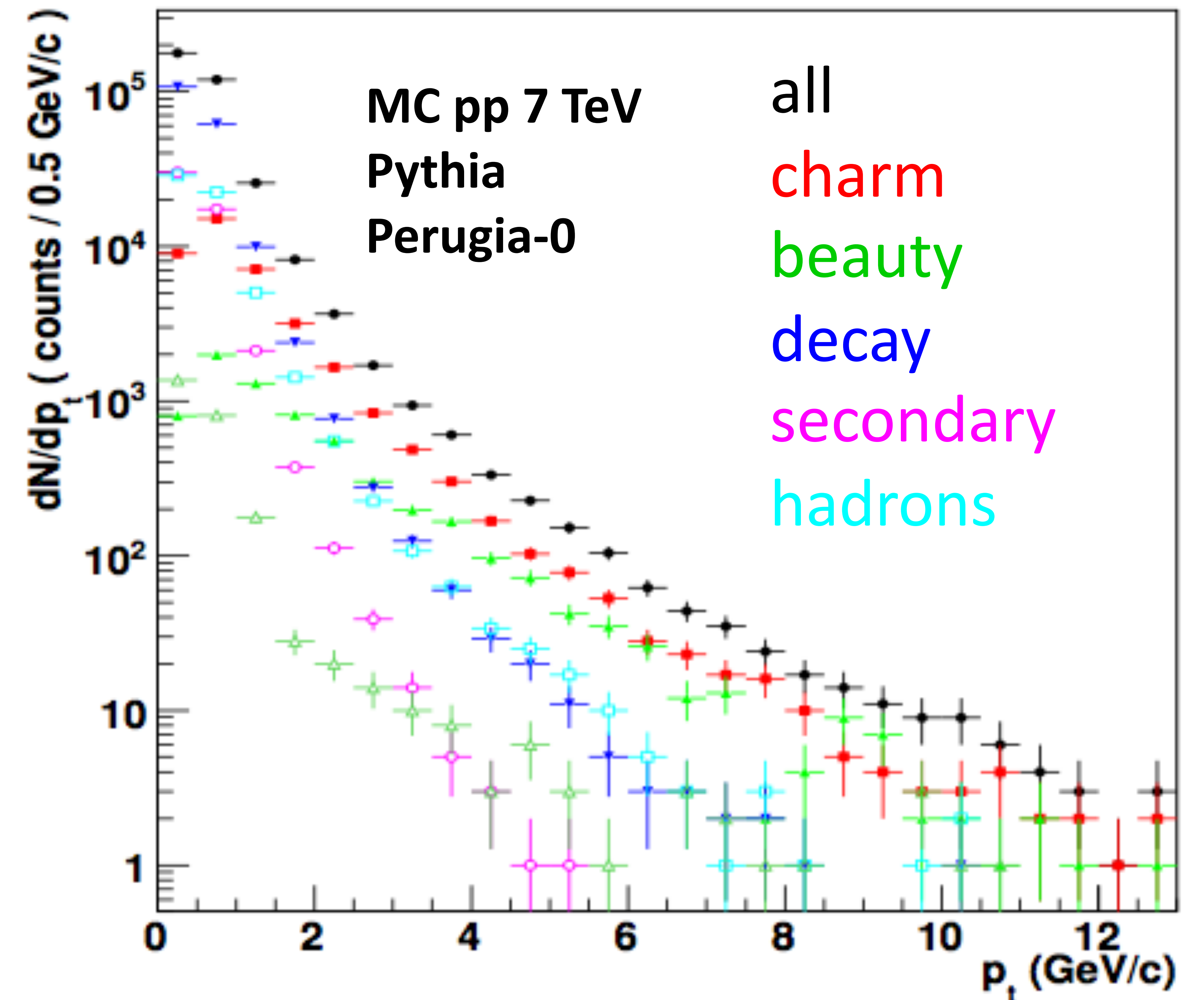
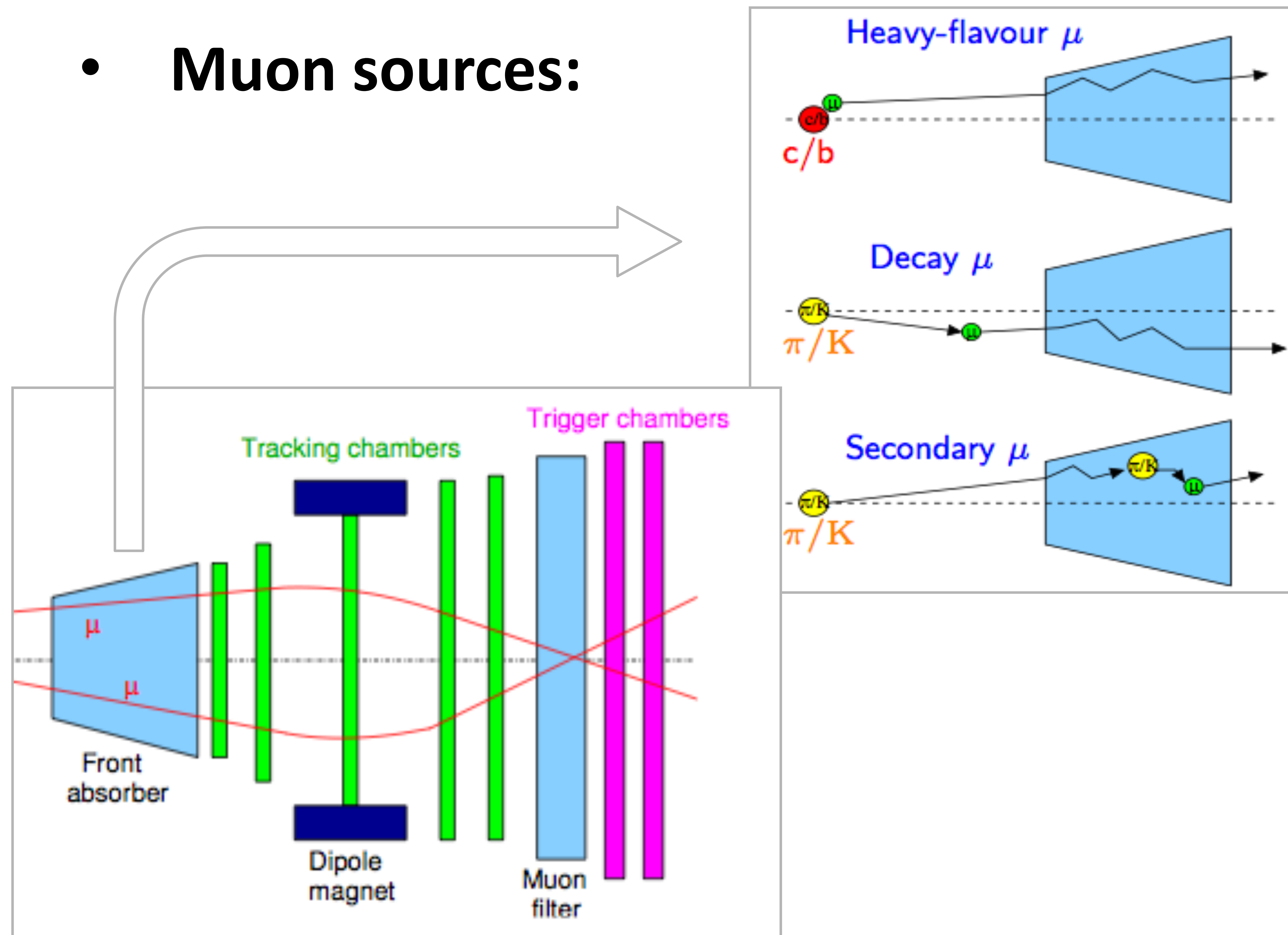
# pp reference at 2.76 TeV: comparisons

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



# Muon reconstruction strategy

- **Muon sources:**

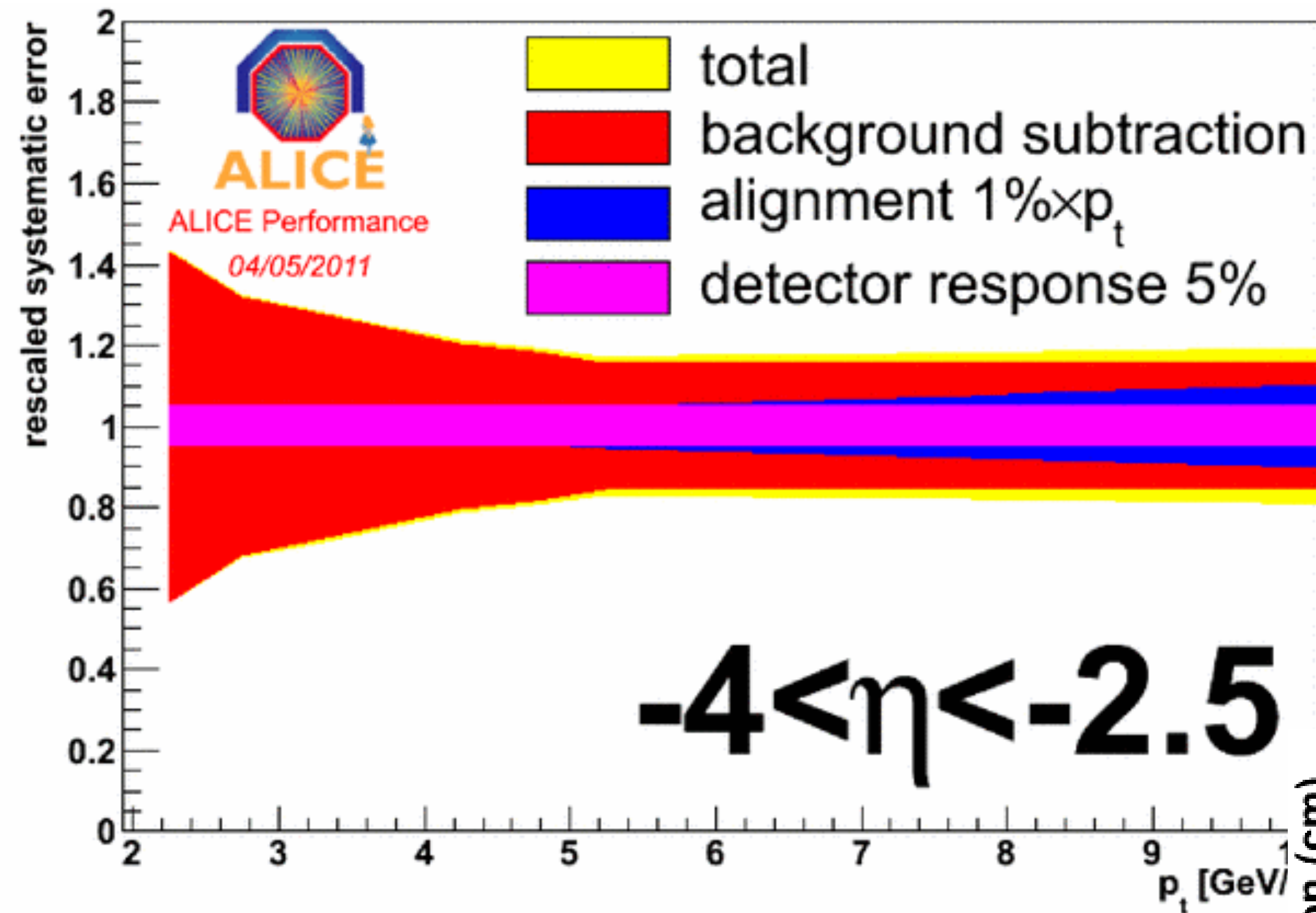


- **Analysis strategy:**

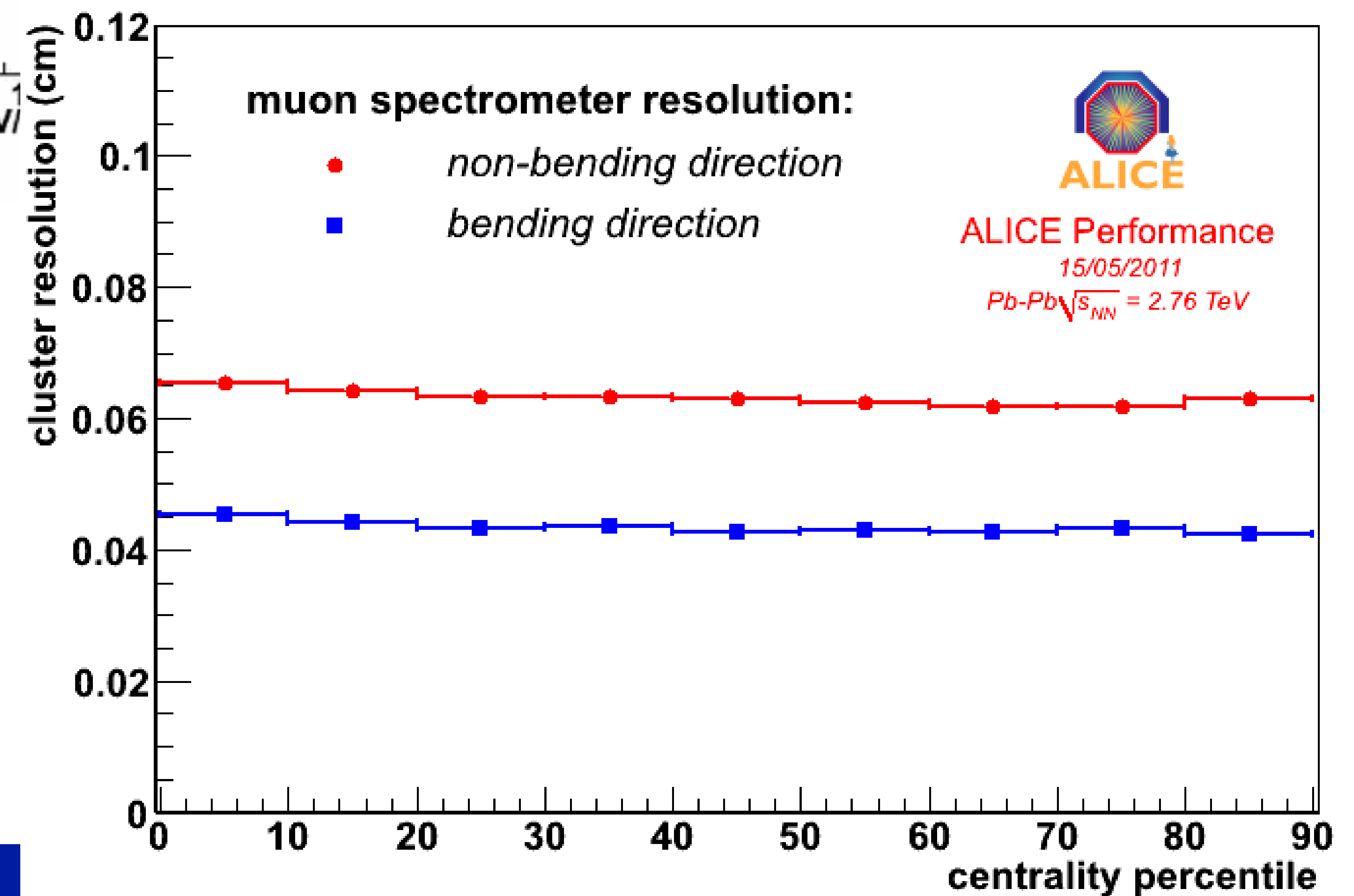
- remove **hadrons** and **low  $p_t$  secondary** muons by requiring a muon trigger signal
- remove **decay** muons by subtracting MC  $dN/dp_t$  normalized to data at low  $p_t$
- what is left are muons from **charm** and **beauty**

- **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**

# Systematic uncertainties muon PbPb



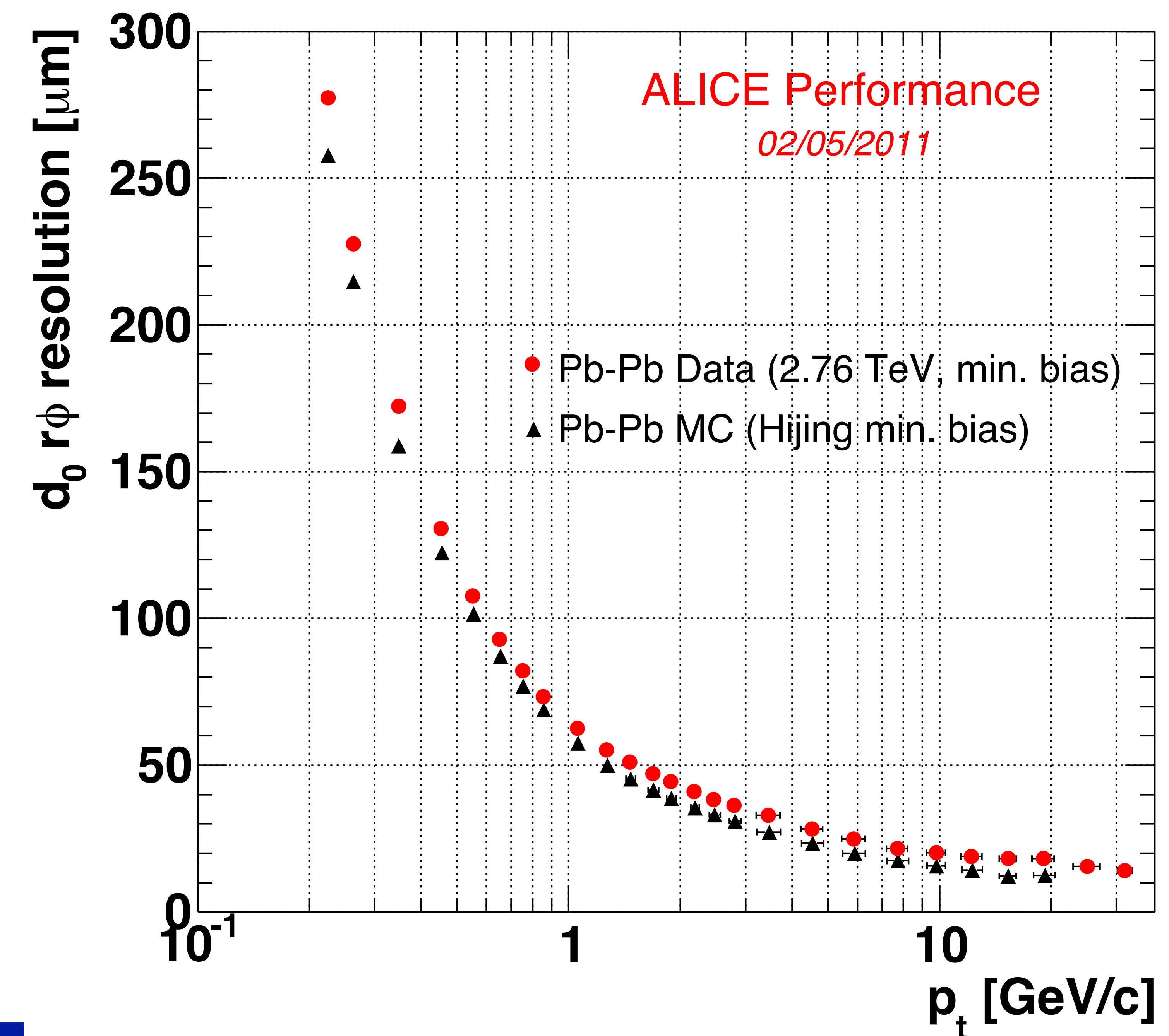
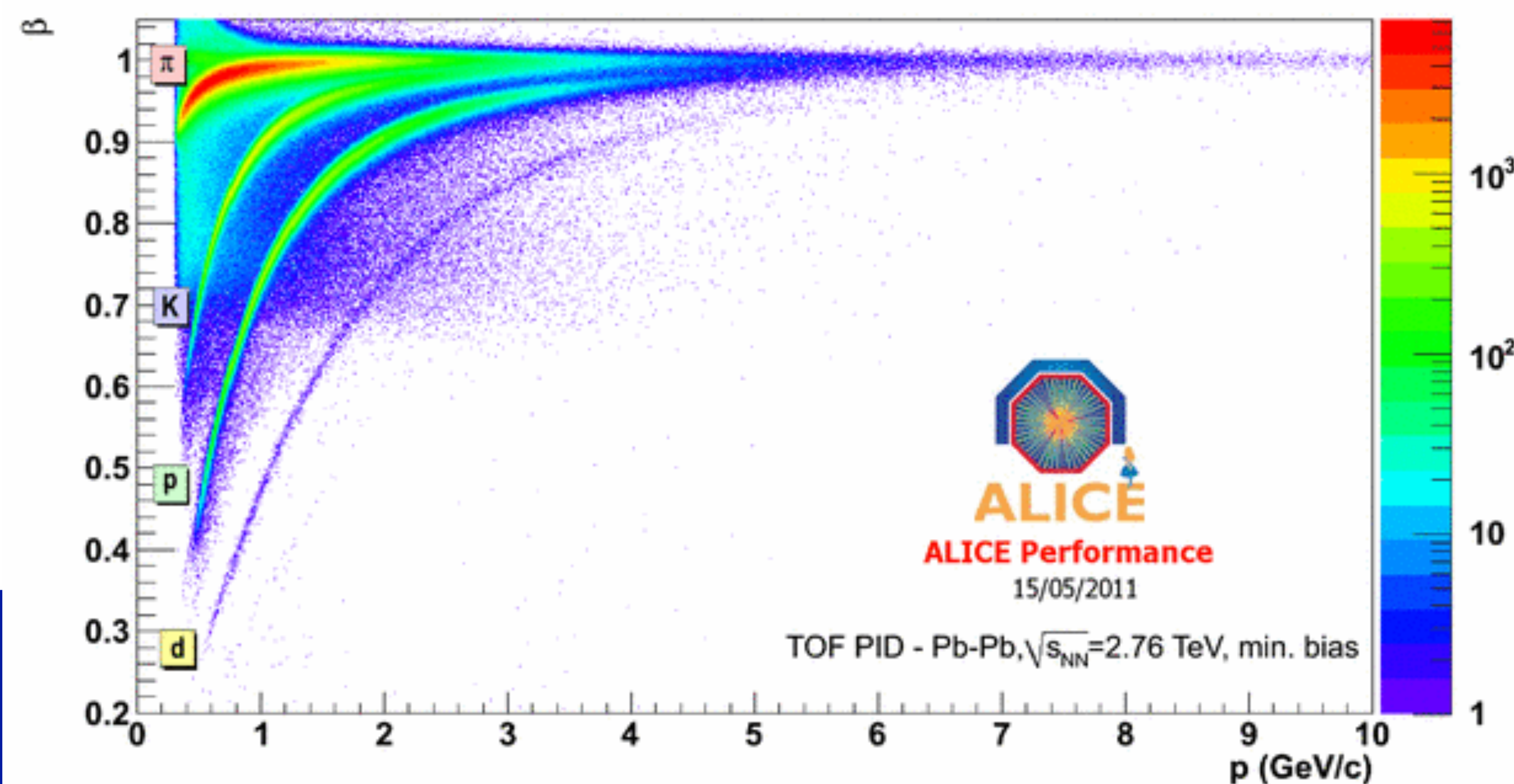
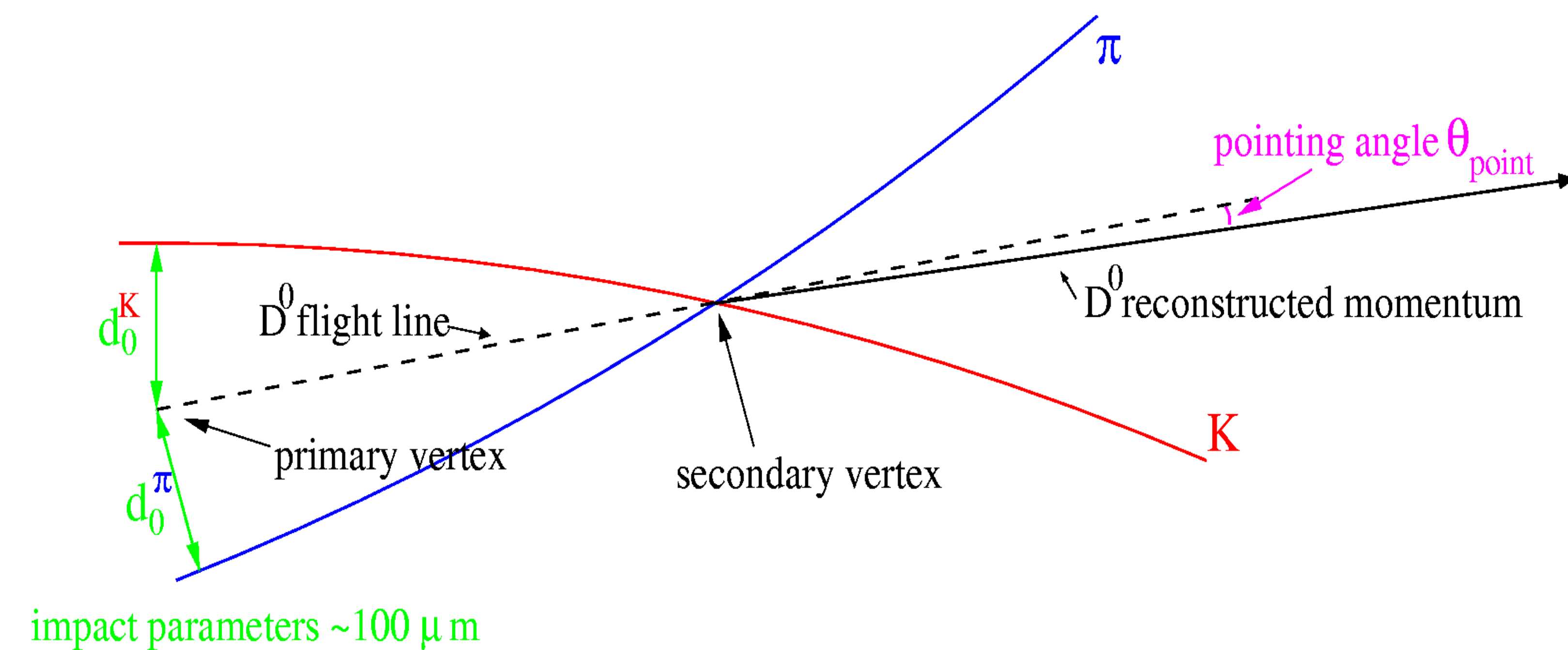
ALI-PERF-2843





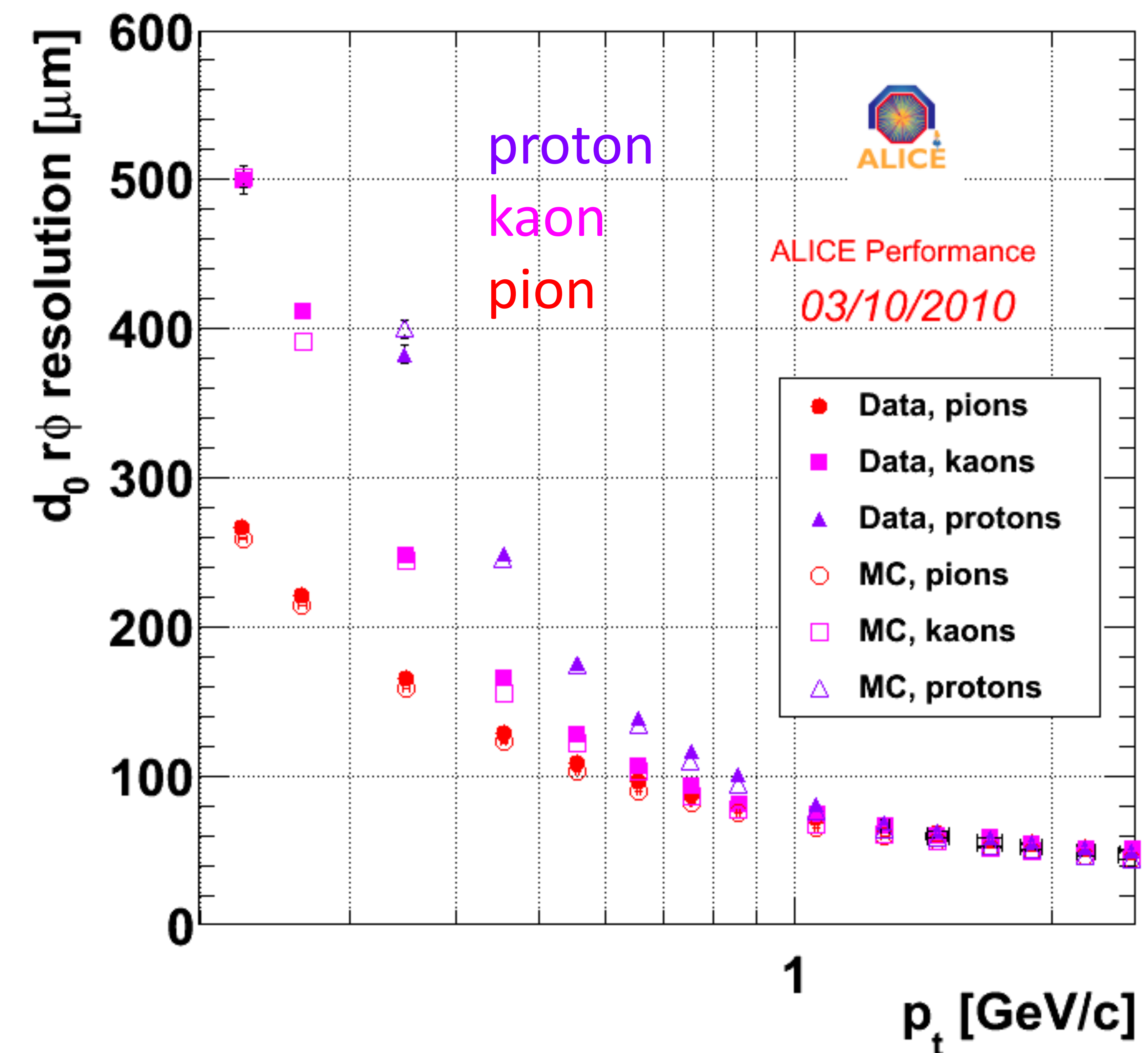
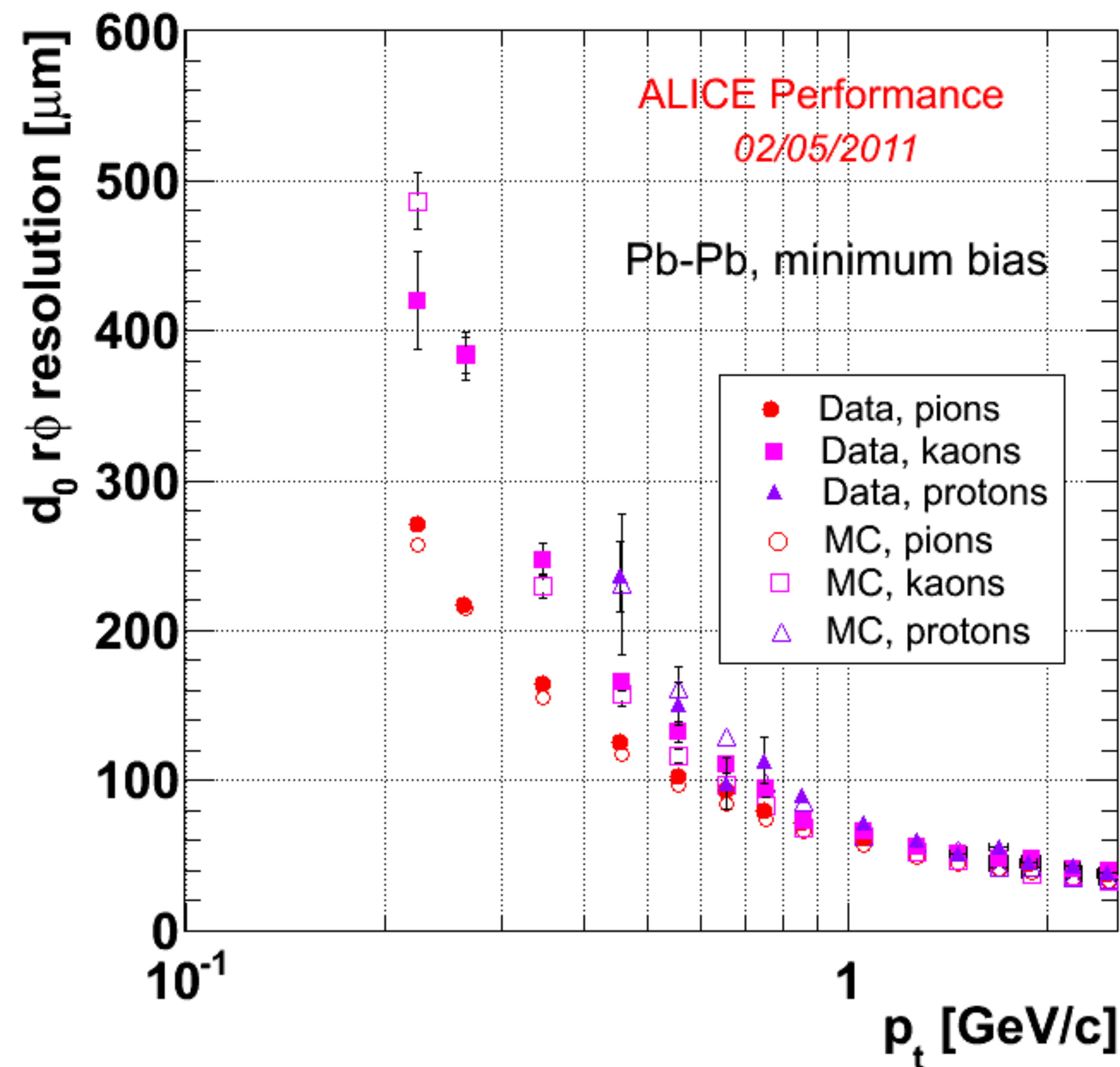
# D meson reconstruction strategy

- Main selection: displaced secondary 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 allows to reject background at low  $p_t$



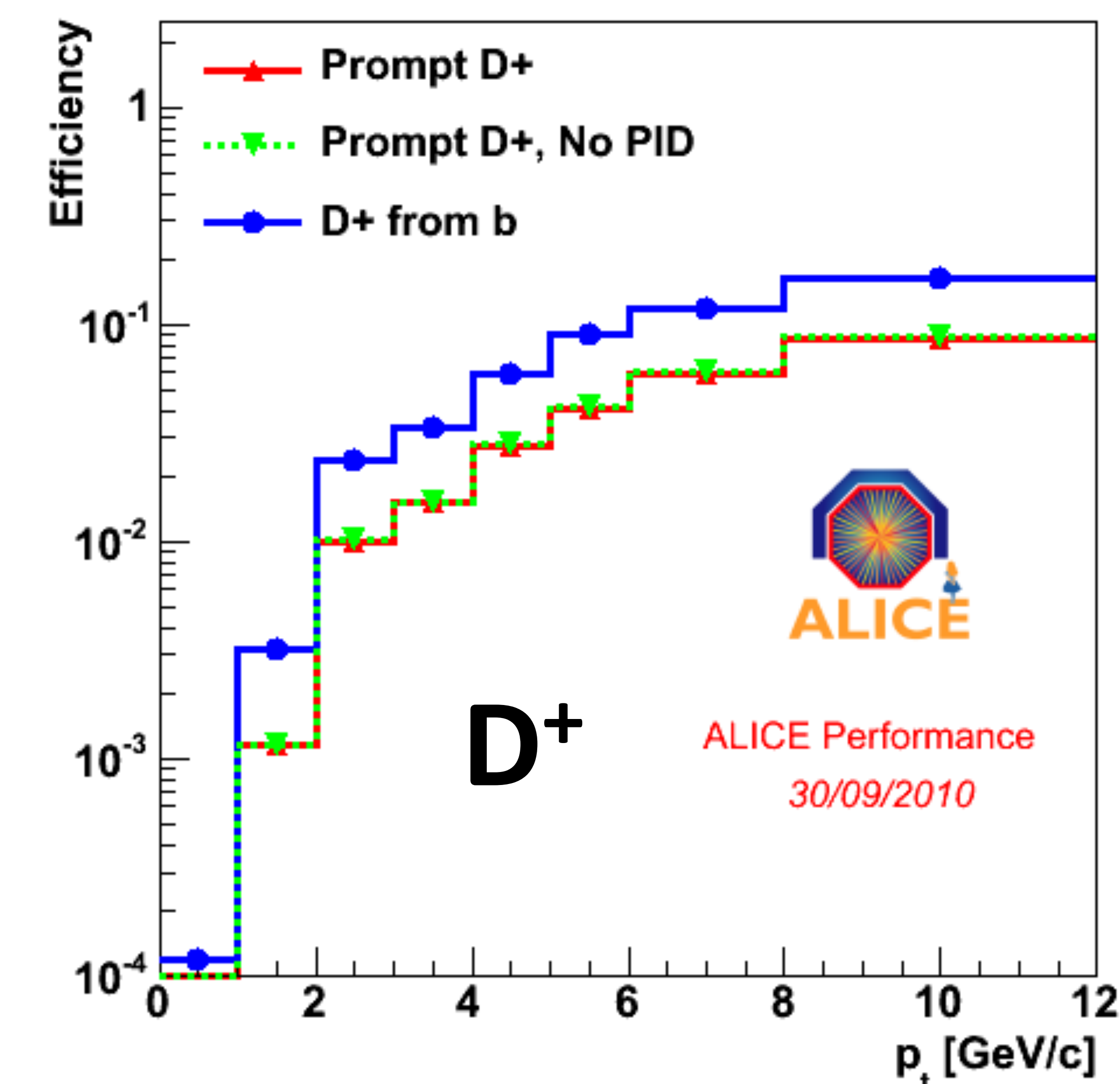
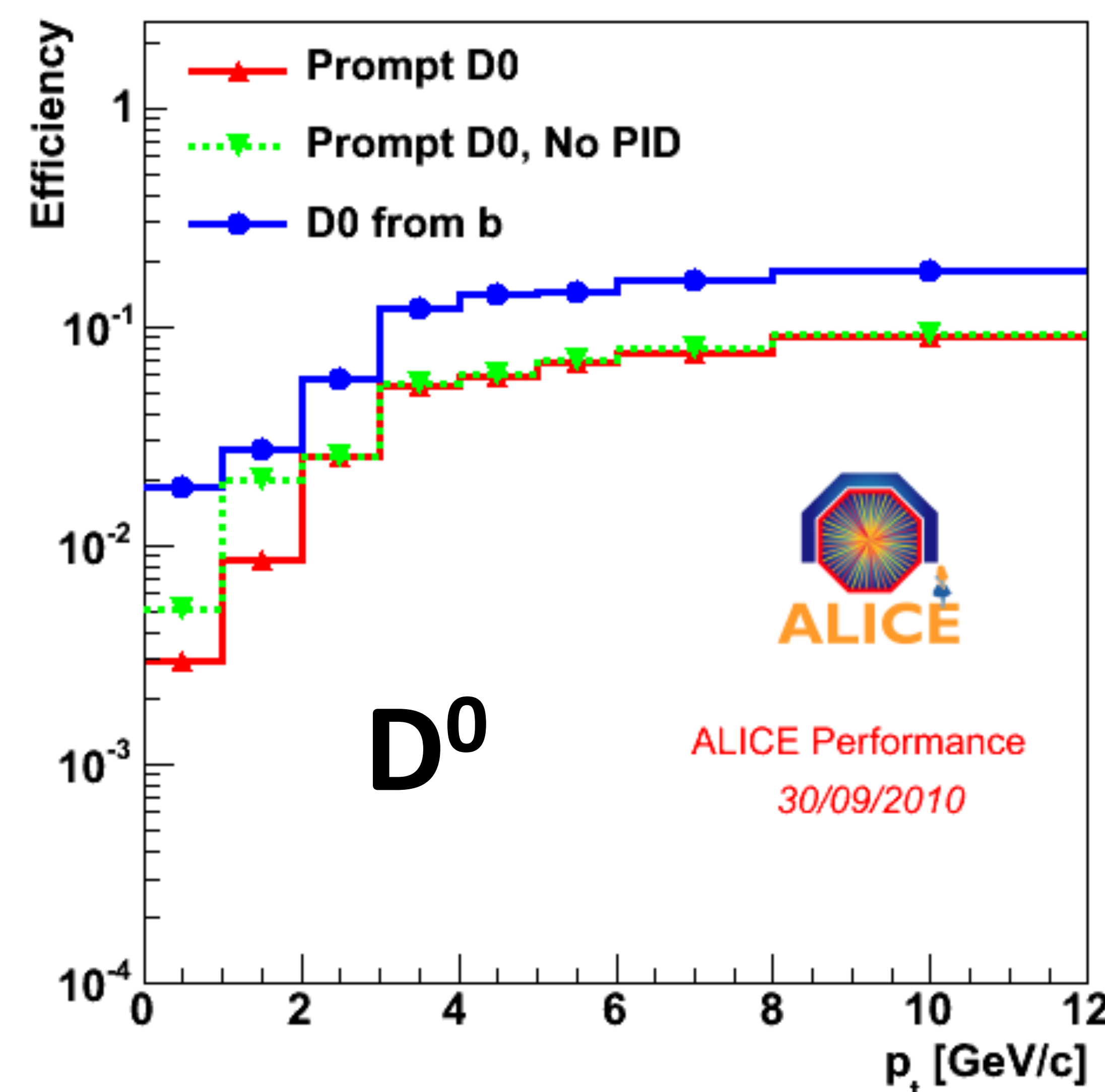
# Impact parameter identified particles

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

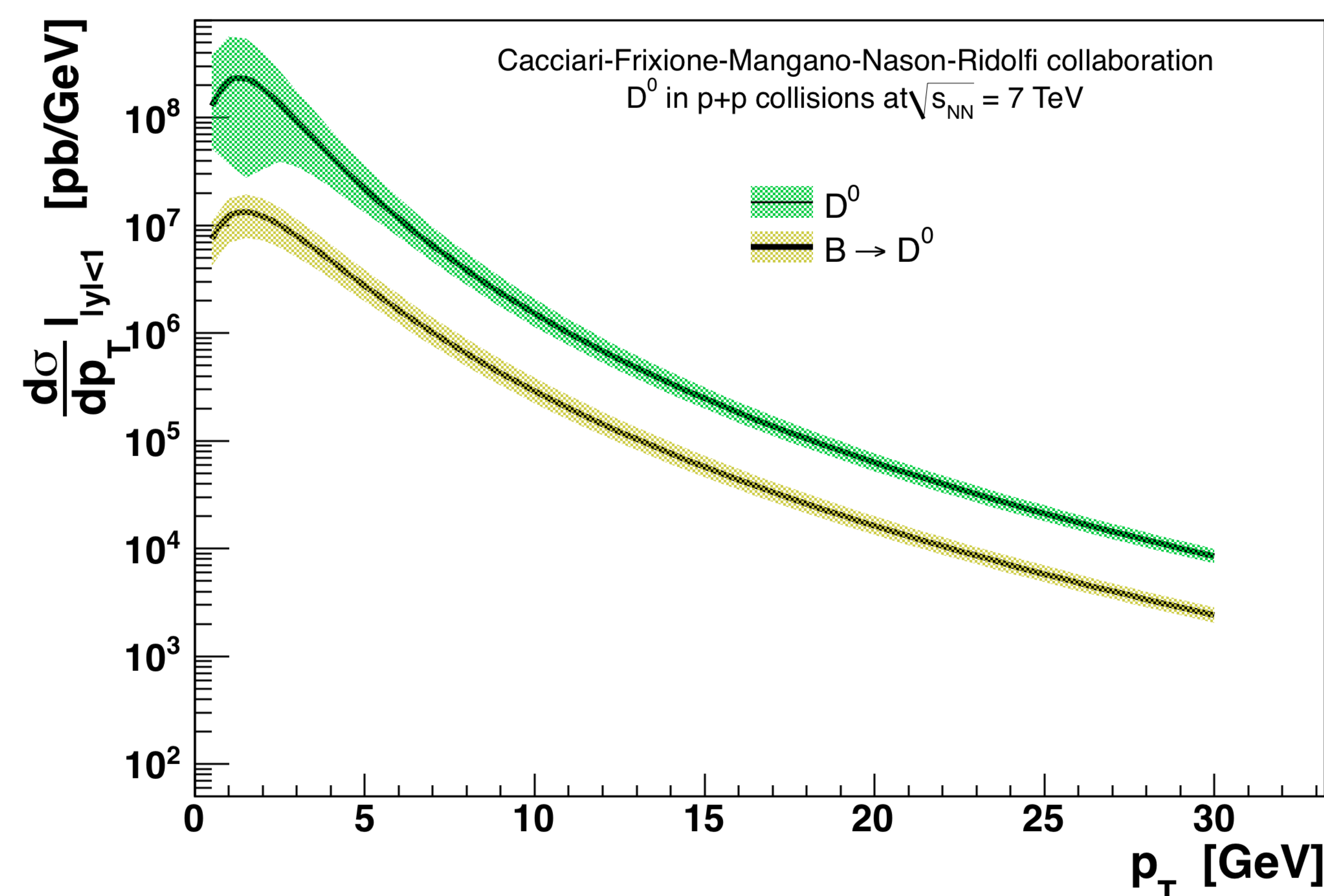


# D mesons: corrections

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



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



# D systematic uncertainties in pp

Total systematic 20-40%  $p_t$ -dep. + 7% on  $\sigma_{MB}$  (VdM scan)

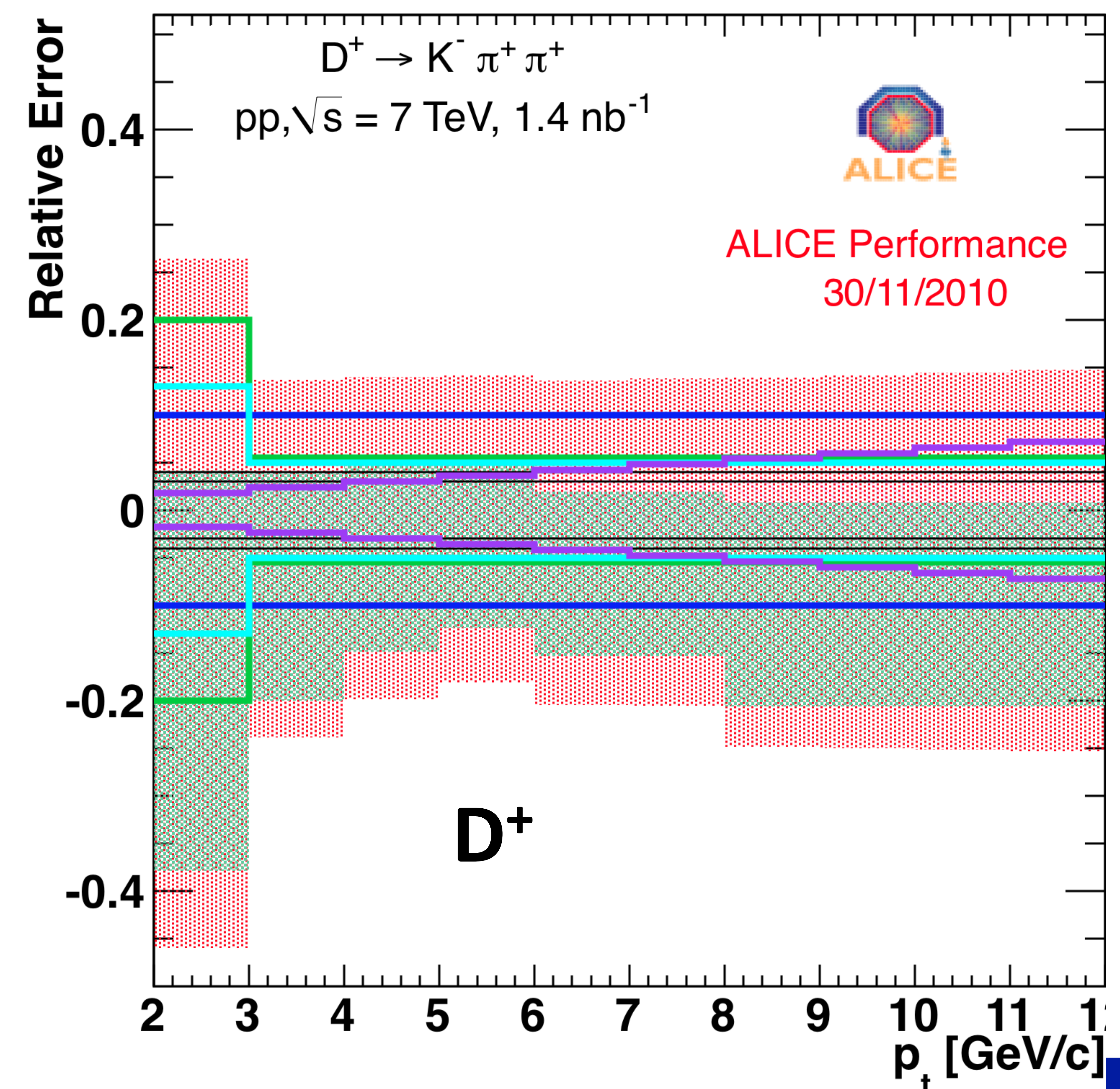
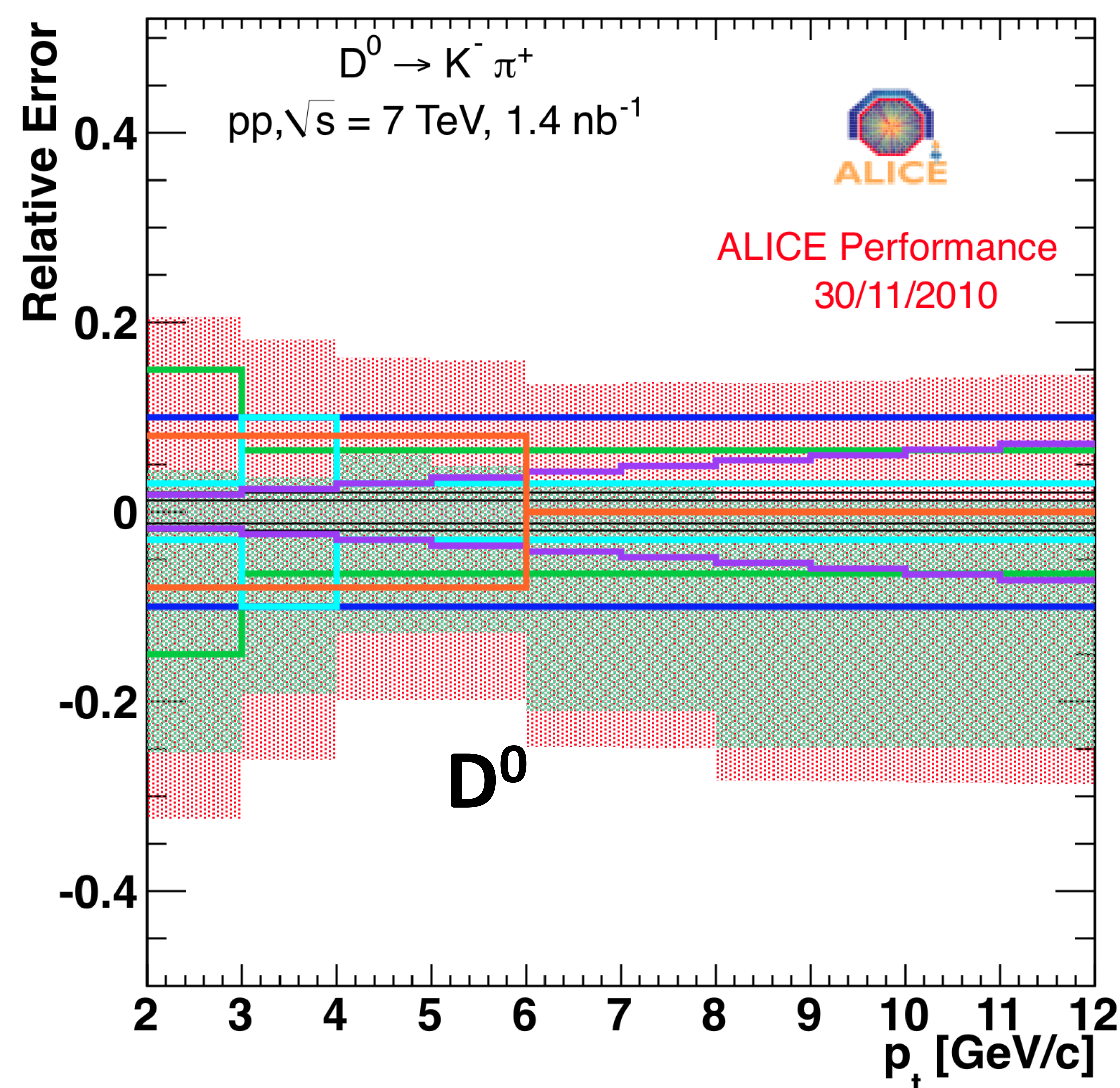
Main systematic error: B feed-down from FONLL + ALICE-MC

- 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

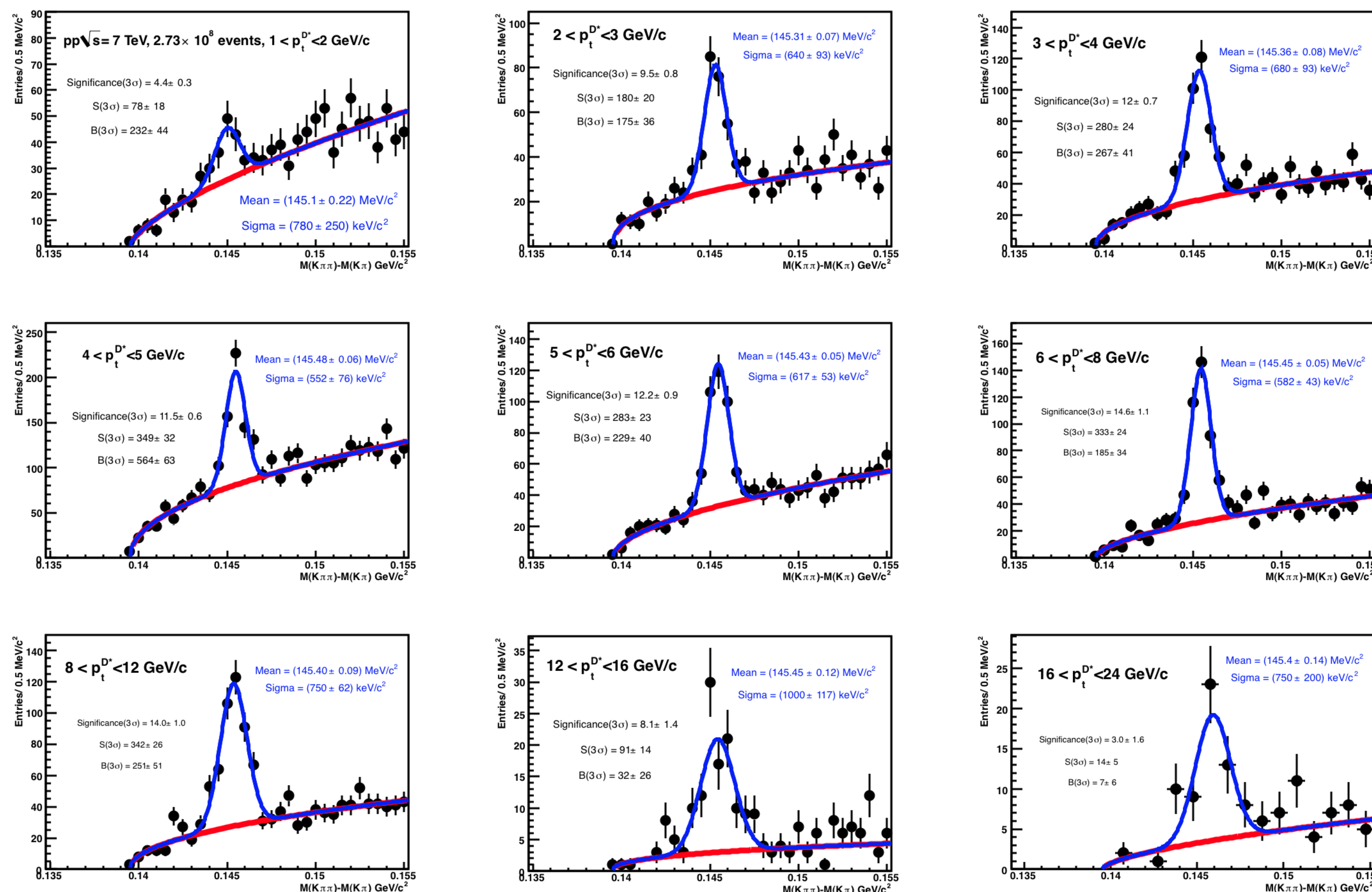
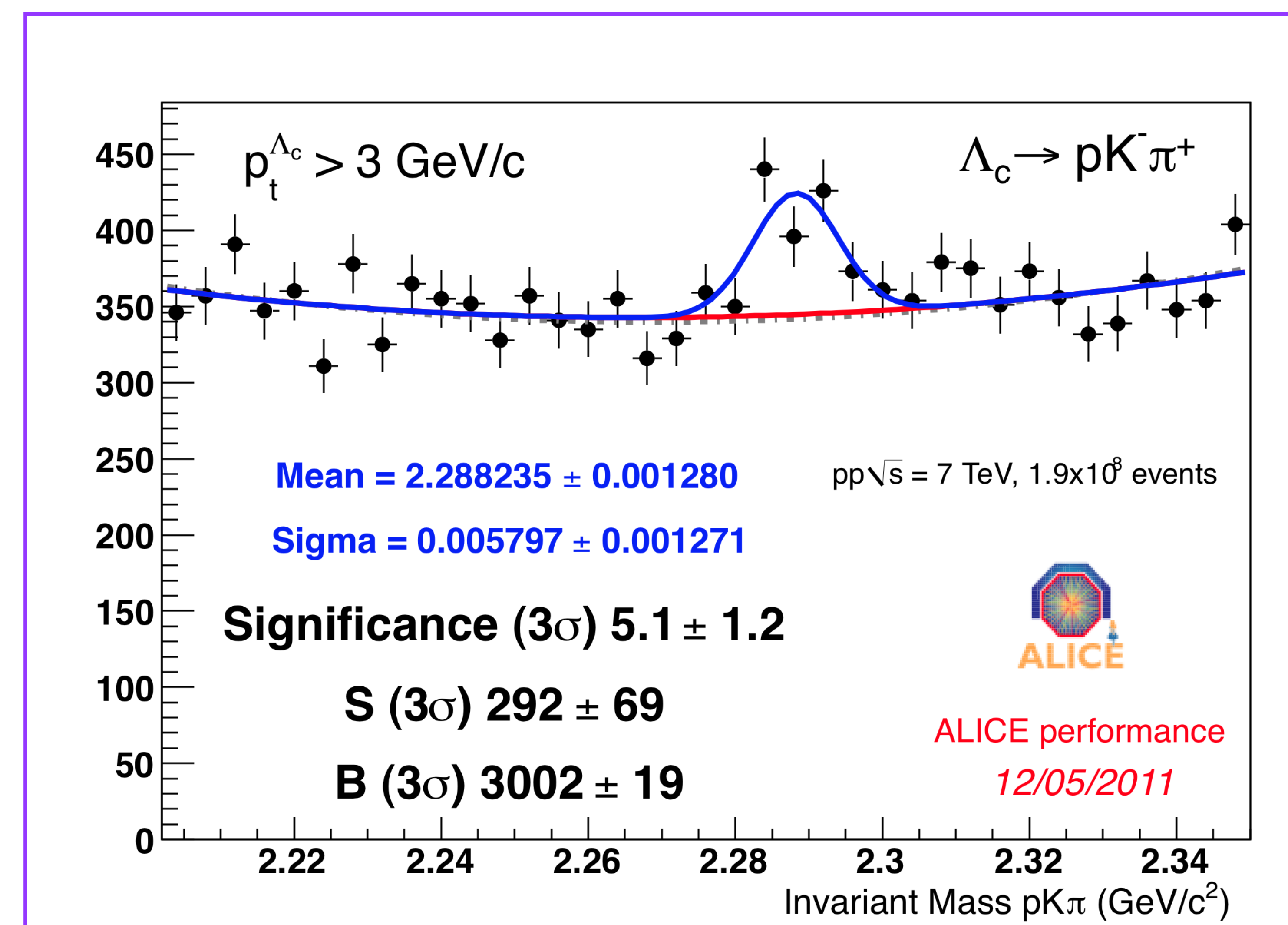
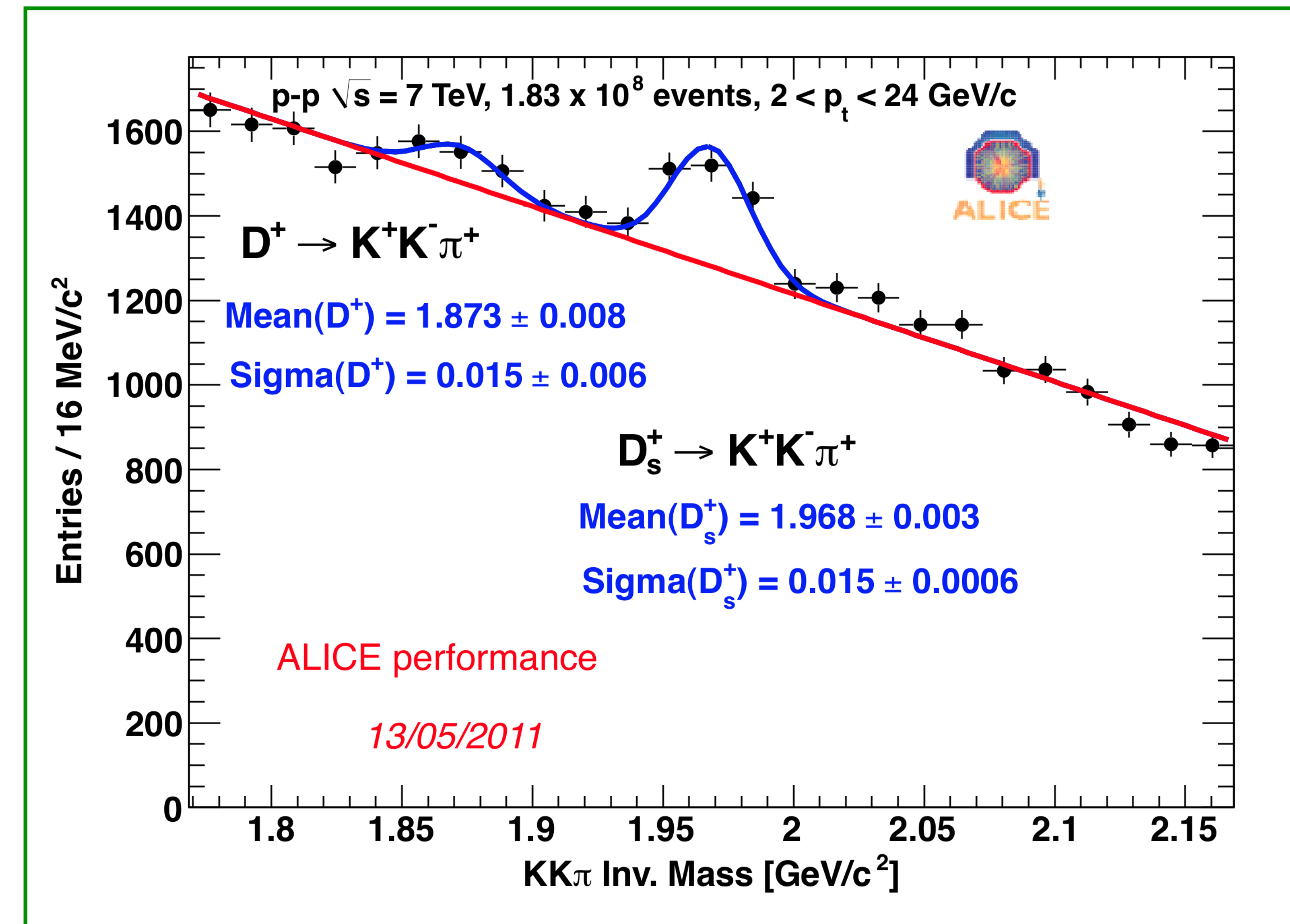


# Other “charming” particles @ 7 TeV...

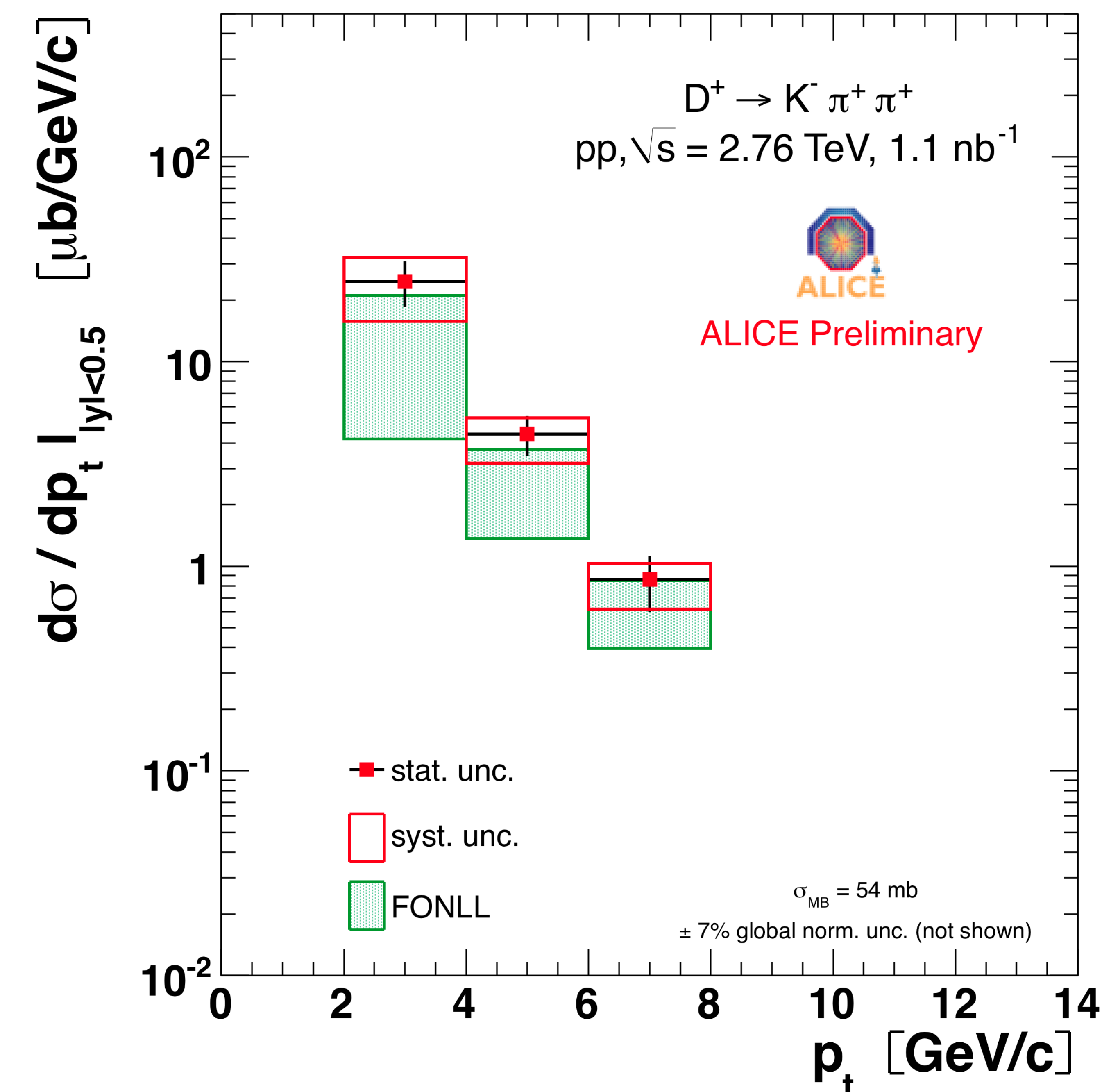
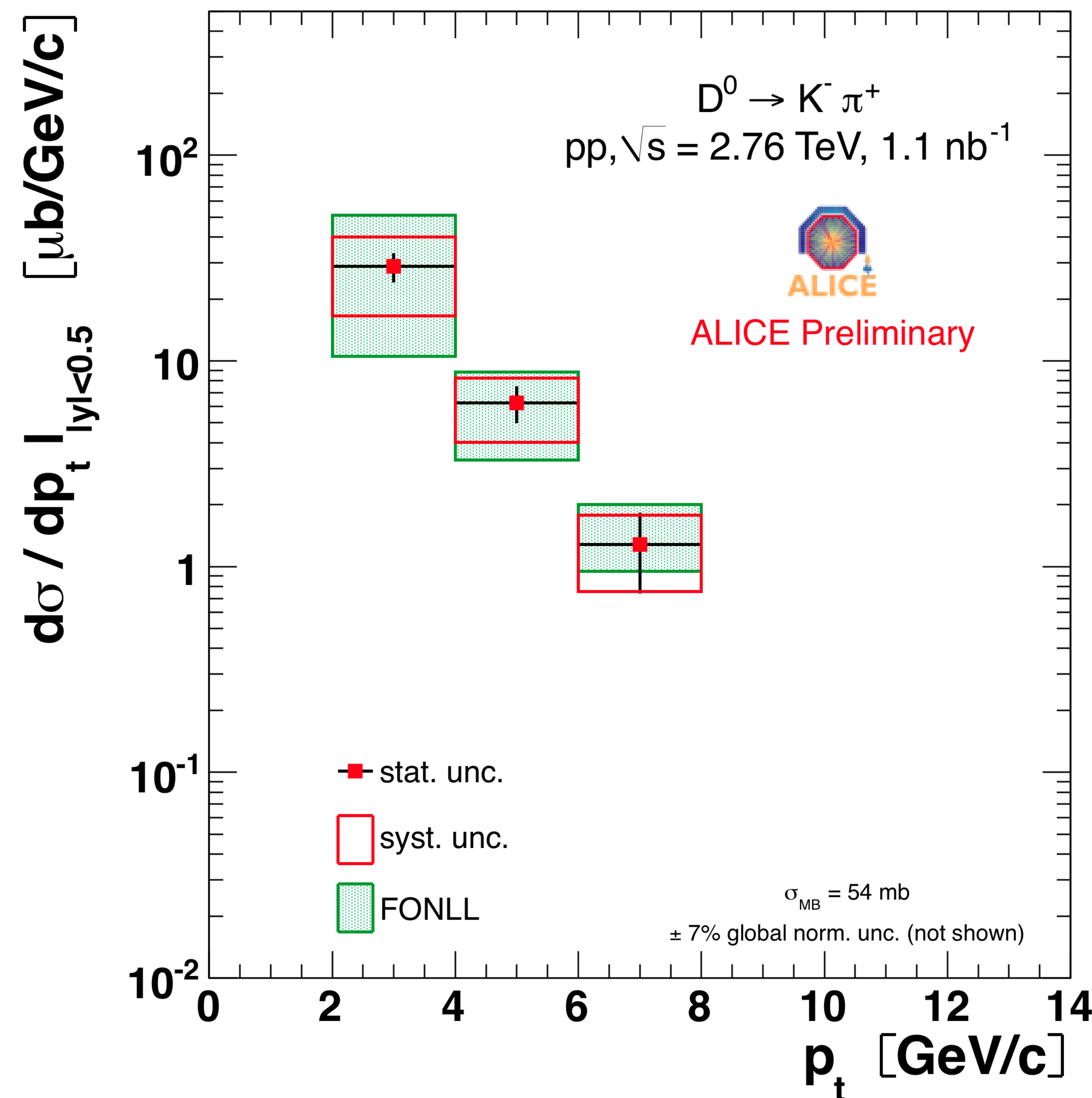


- The full 2010 statistic would allow to extend the pt range of the cross section measurement ( $D^*$  from 1 to 20 GeV/c).
- Already some hint of  $D_s$  and  $\Lambda_c$

ALICE Performance  
10/05/2011



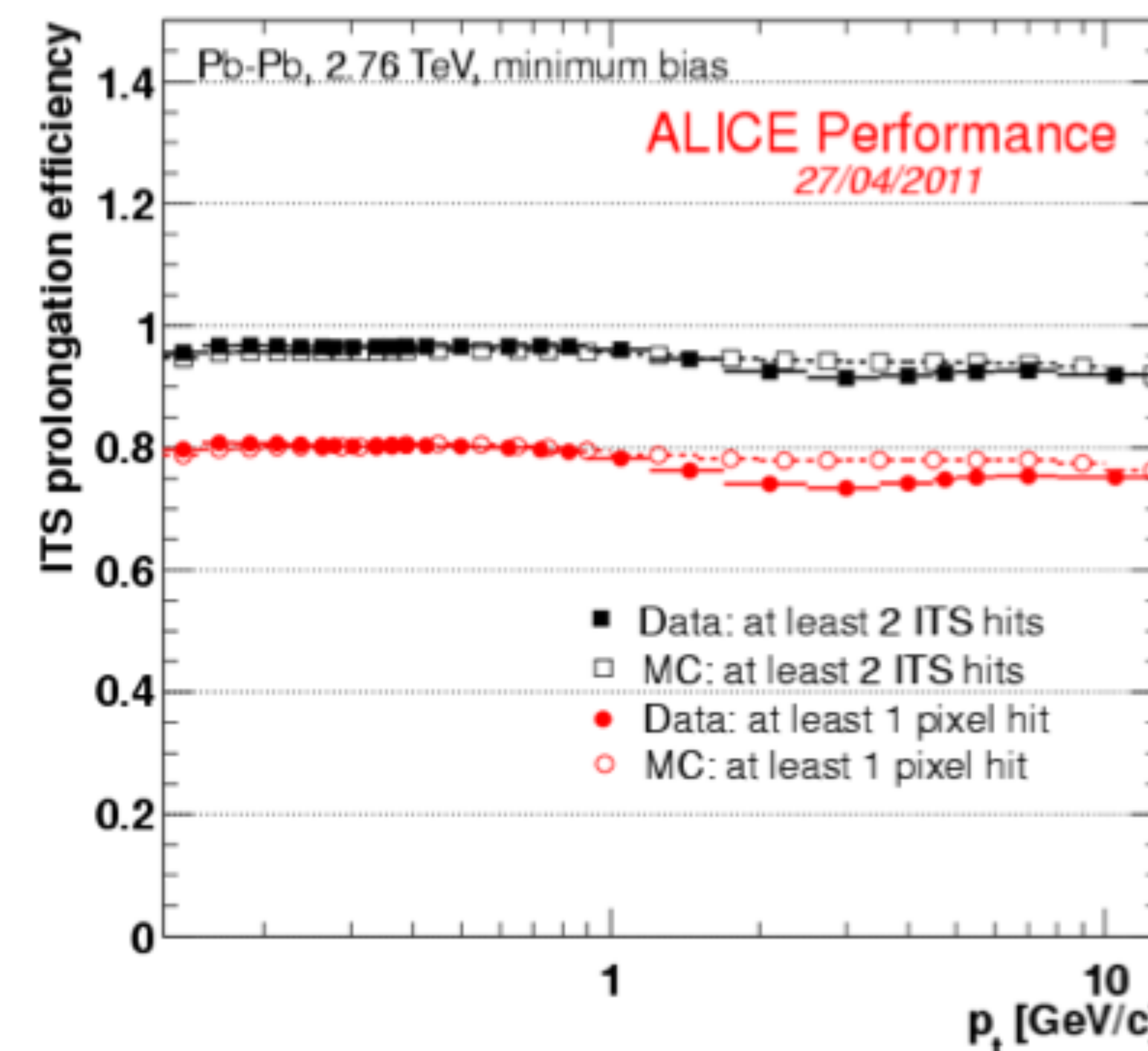
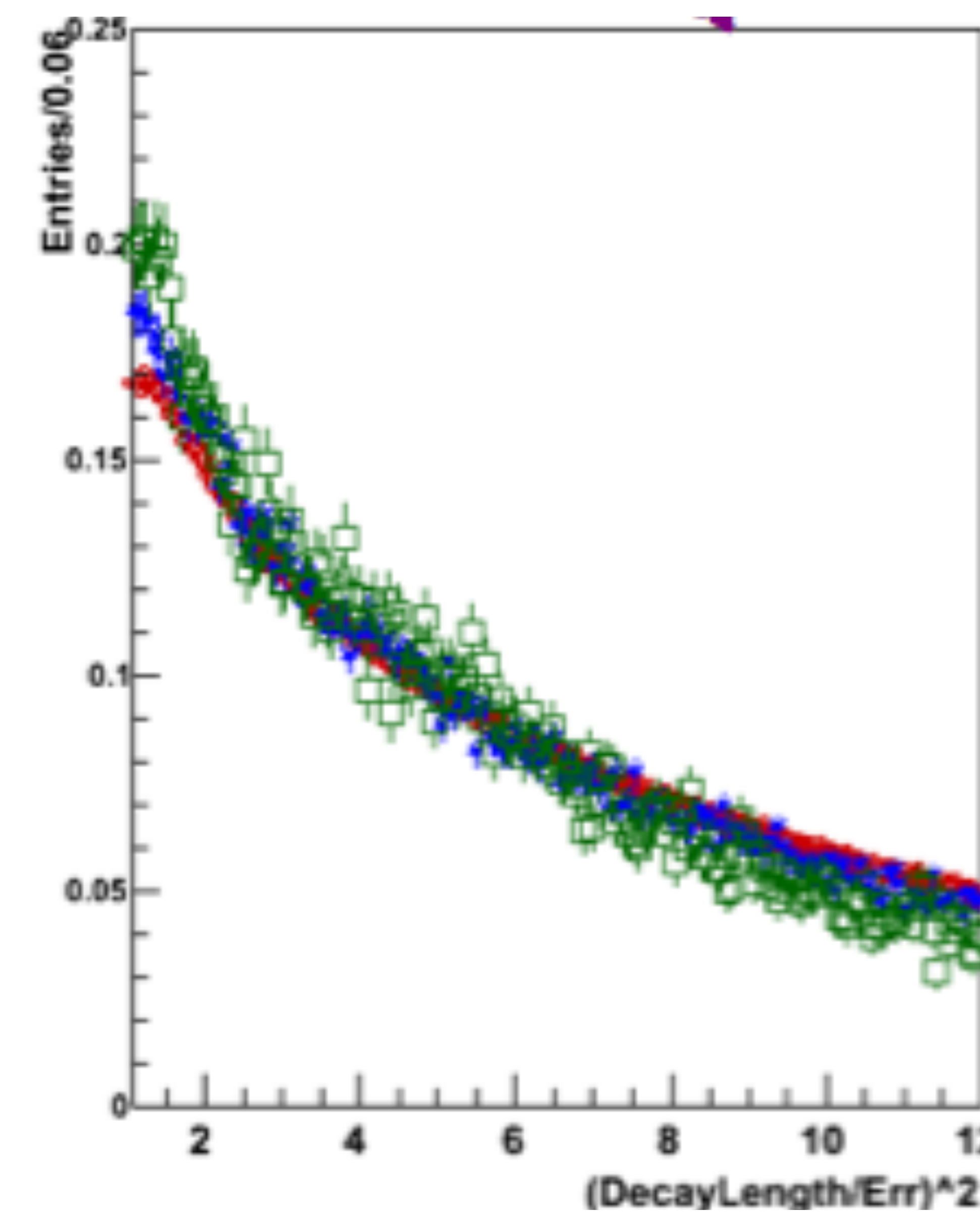
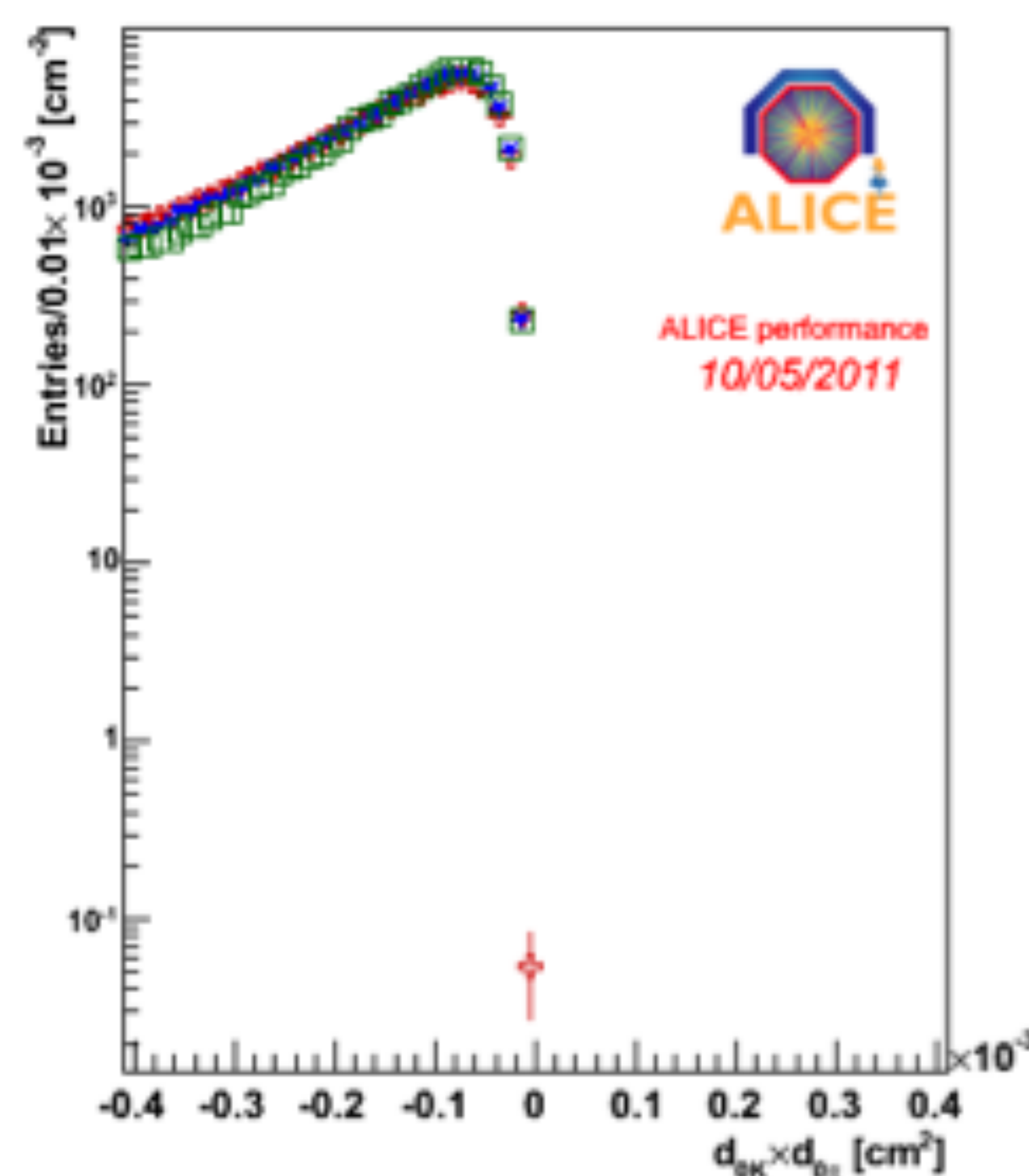
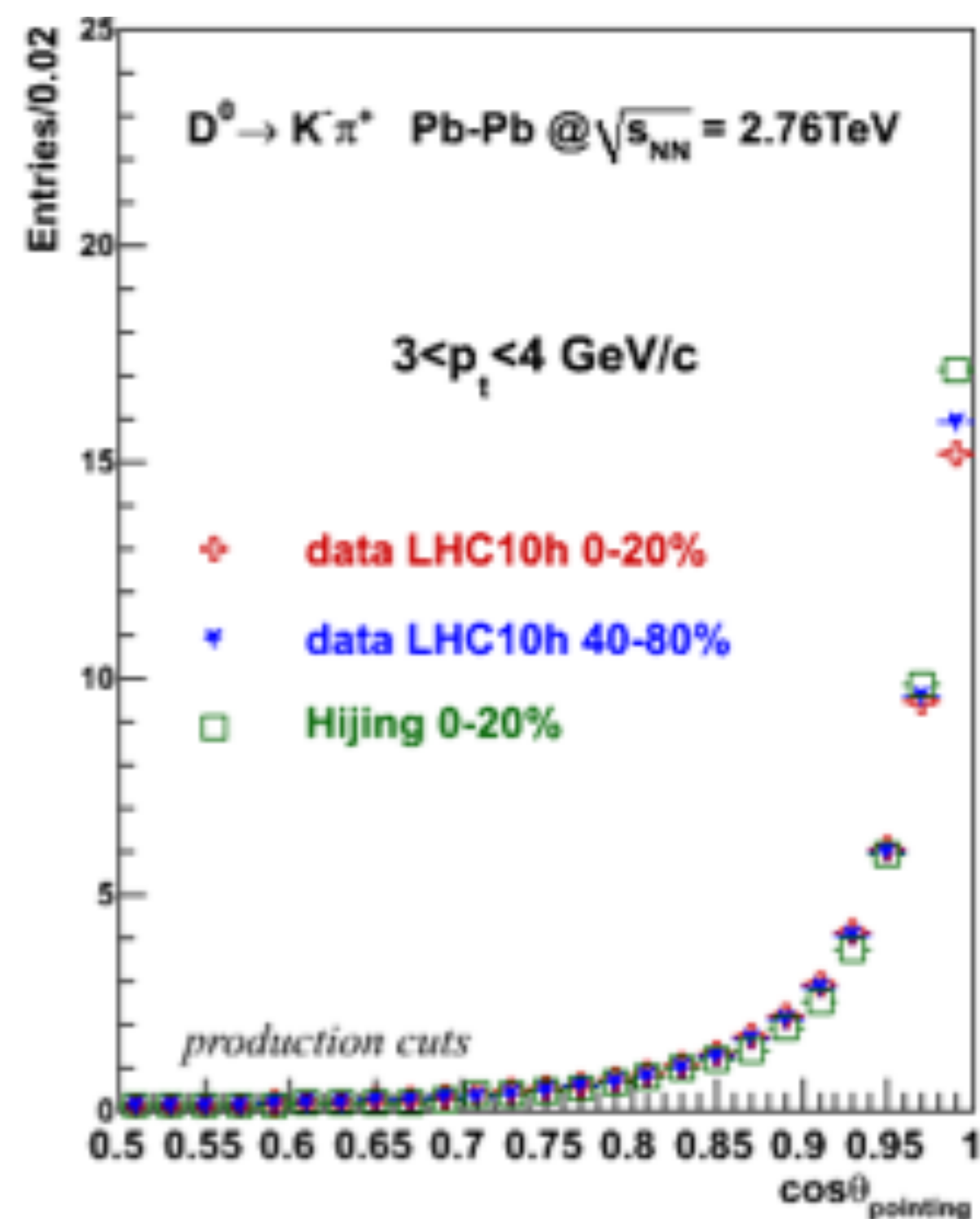
# D0, D+ cross section @ 2.76 TeV



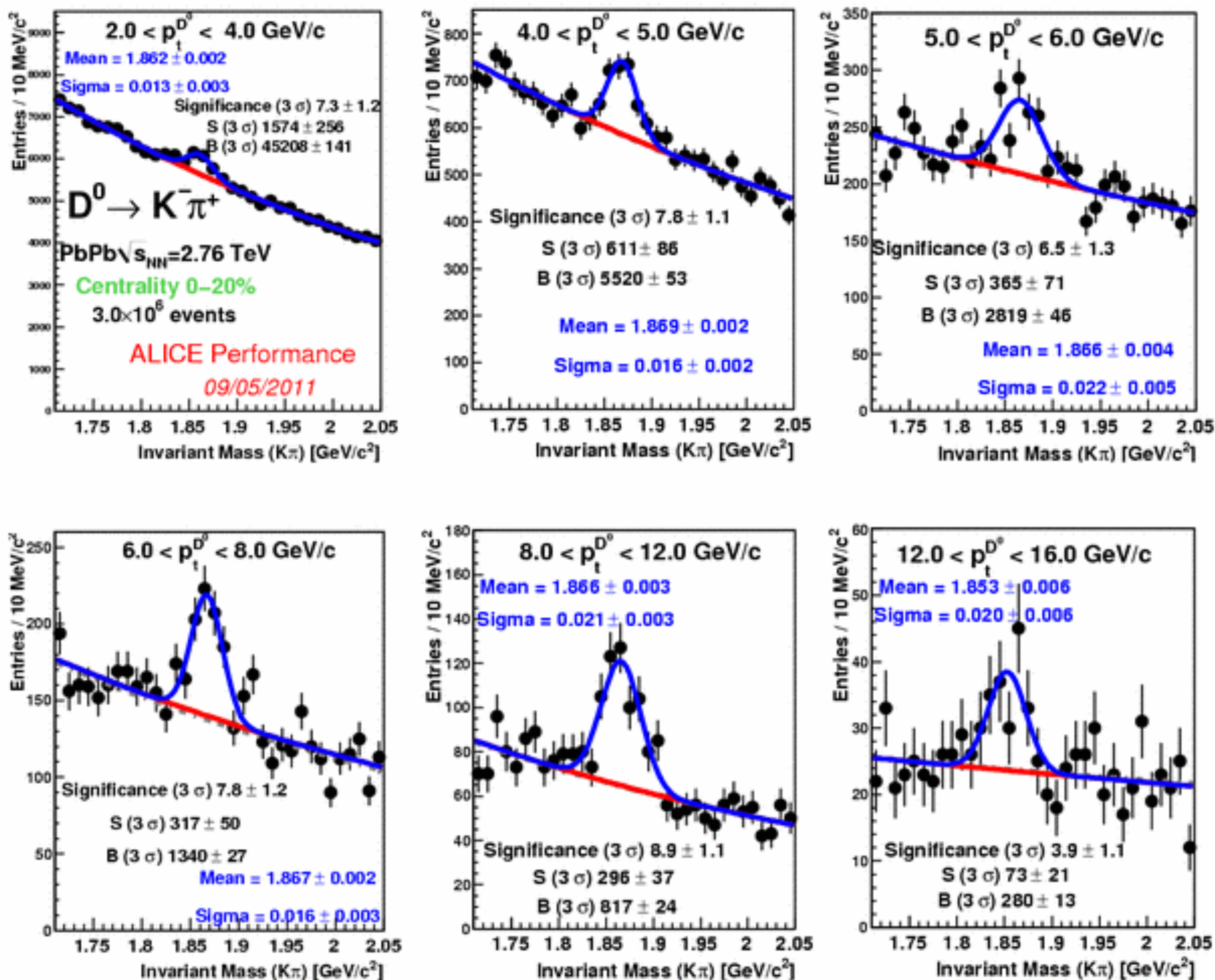
FONLL: Cacciari et al., private comm.

- $2 < p_t < 8 \text{ GeV/c}$ , with  $1.1 \text{ nb}^{-1}$  (3 days of data march 2011)
- $y$  acceptance is  $p_t$ -dep ( $\Delta y \sim 1.0 \rightarrow 1.6$ ): data scaled to  $|y| < 0.5$
- pQCD predictions (FONLL) compatible with our data

# D<sup>0</sup> mesons: data VS MC



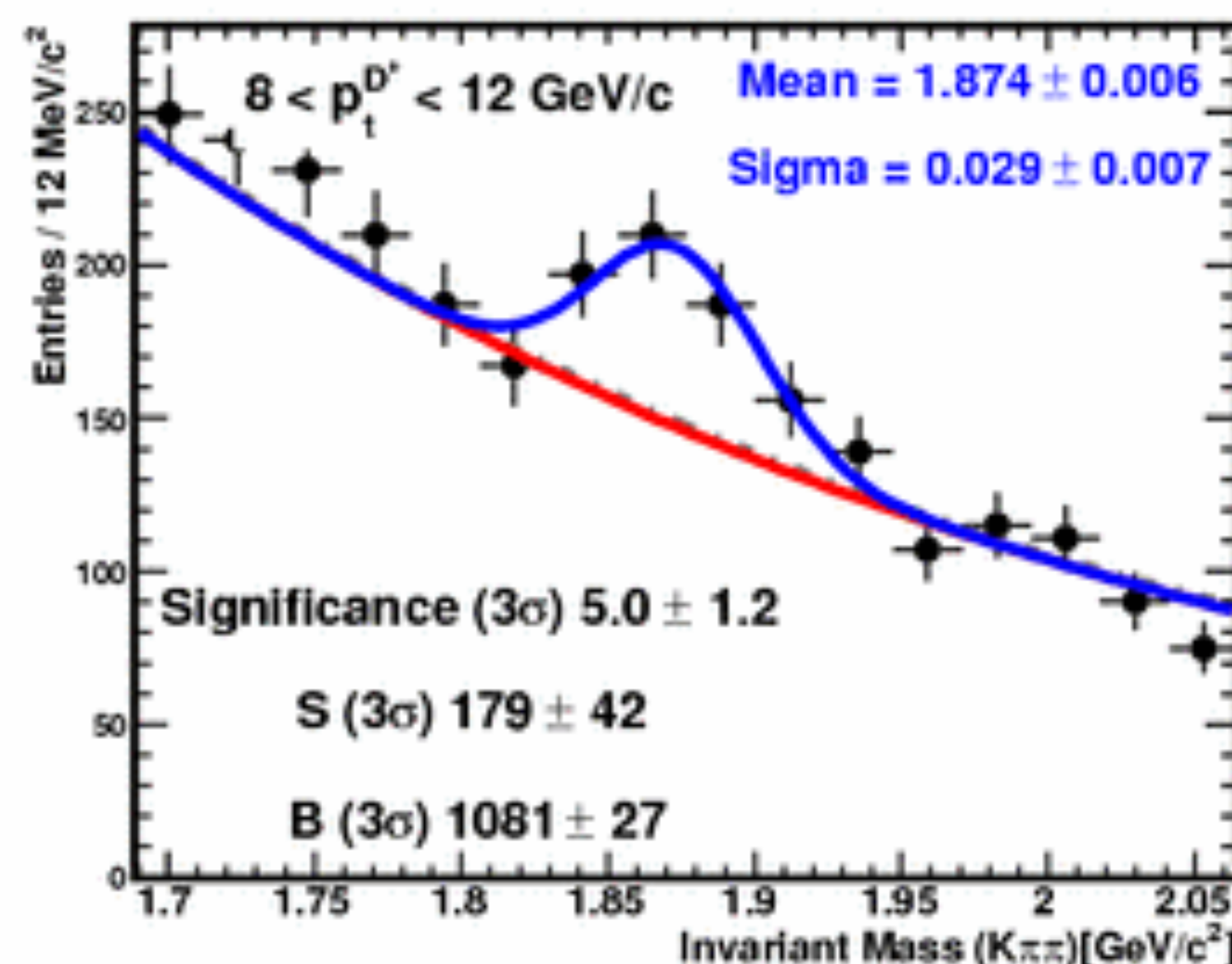
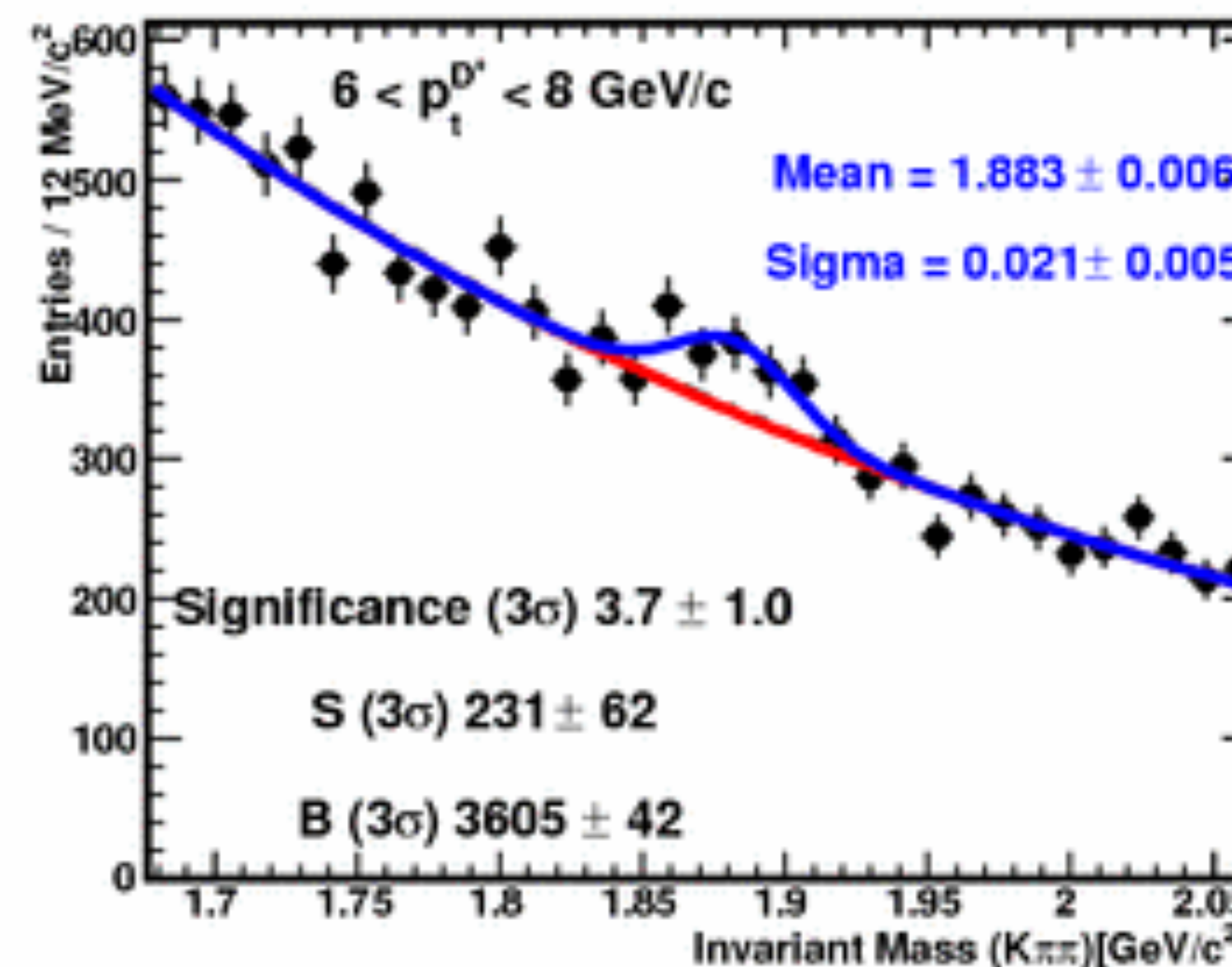
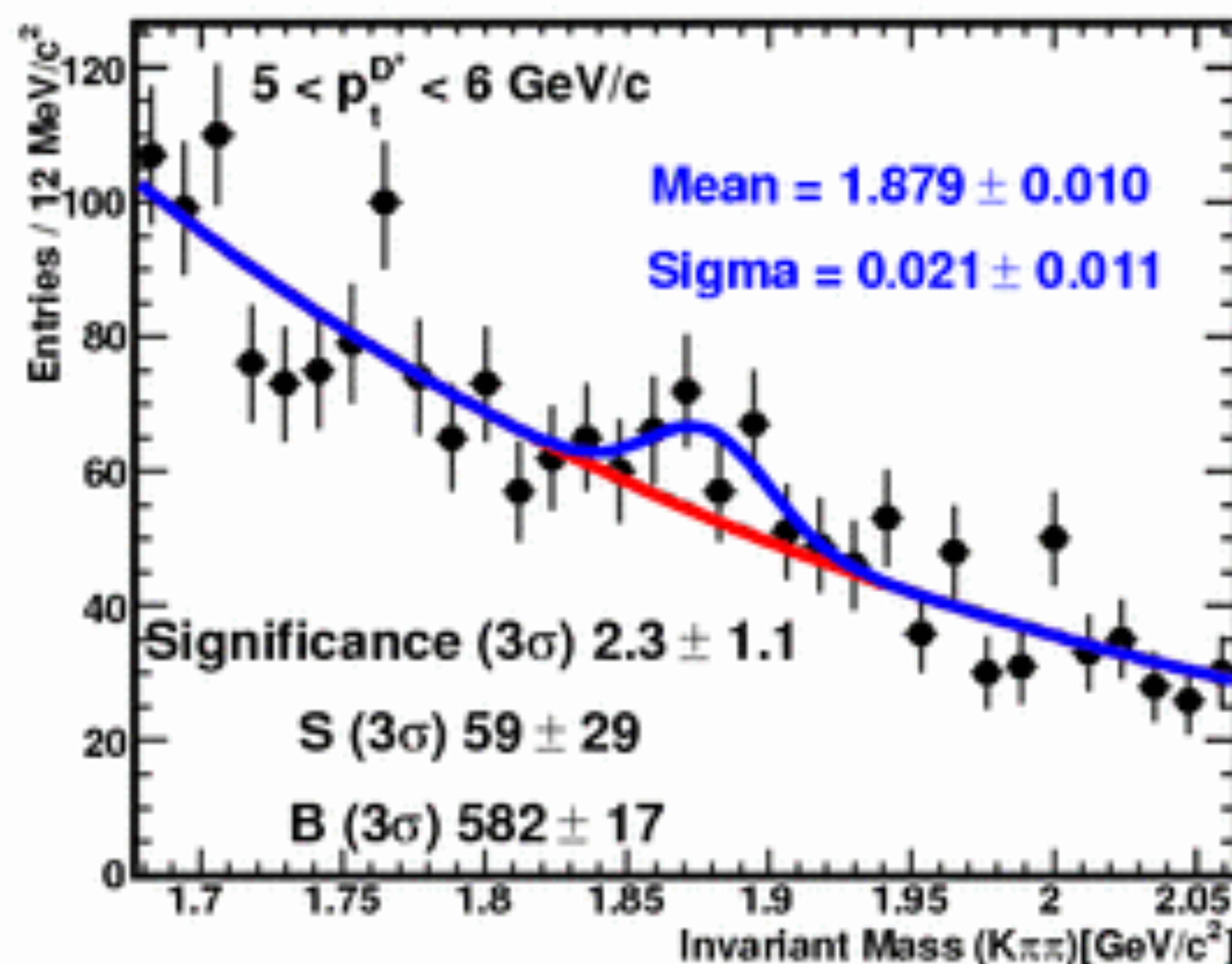
# D0 → Kπ signals in PbPb (0-20%)



ALI-PERF-I754



# D+ → Kππ signals in PbPb (0-20%)



Pb-Pb  $\sqrt{s_{NN}}=2.76$  TeV,  $2.8 \times 10^6$  events

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

ALICE Performance

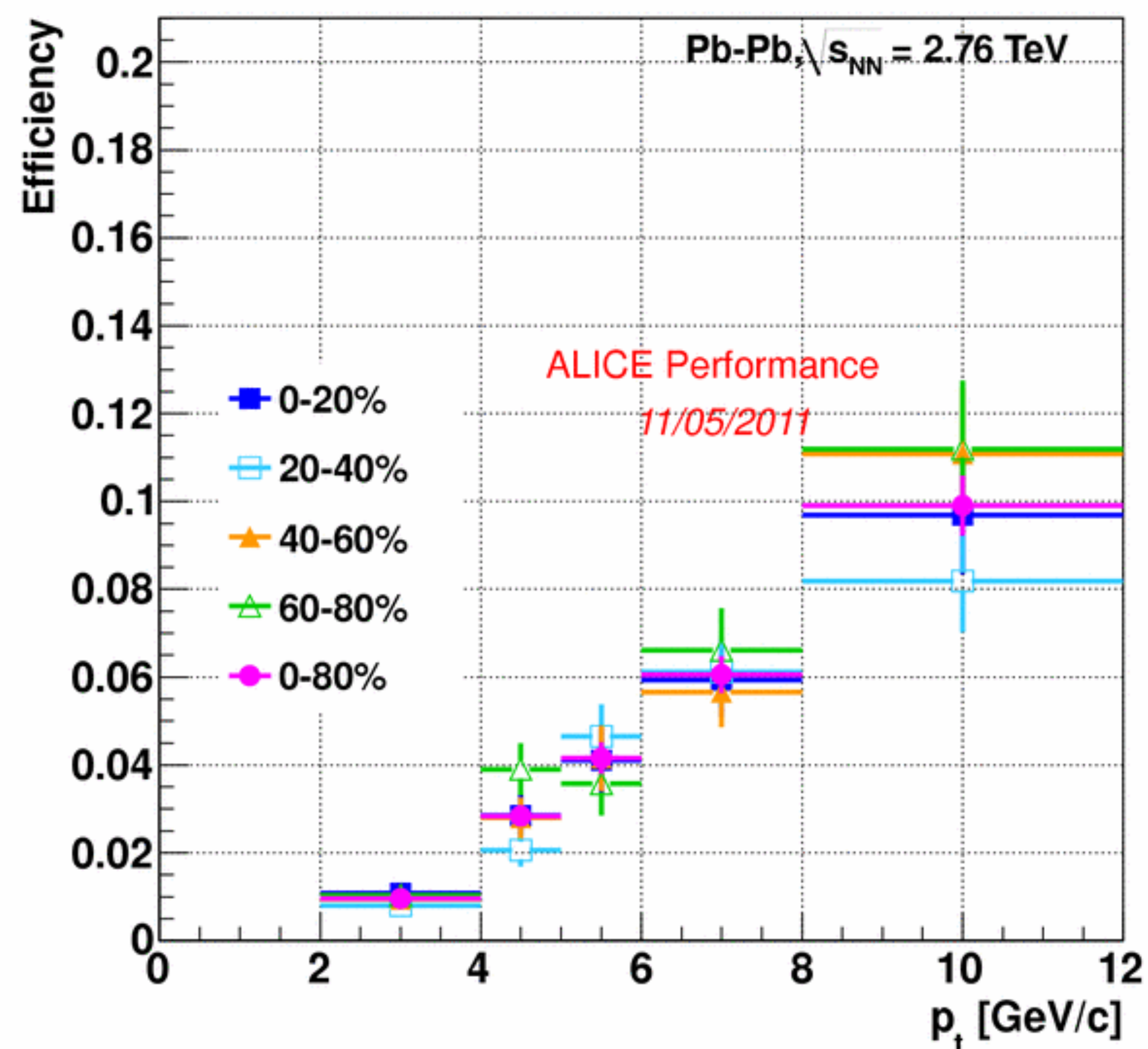
12/05/2011

Centrality 0-20%

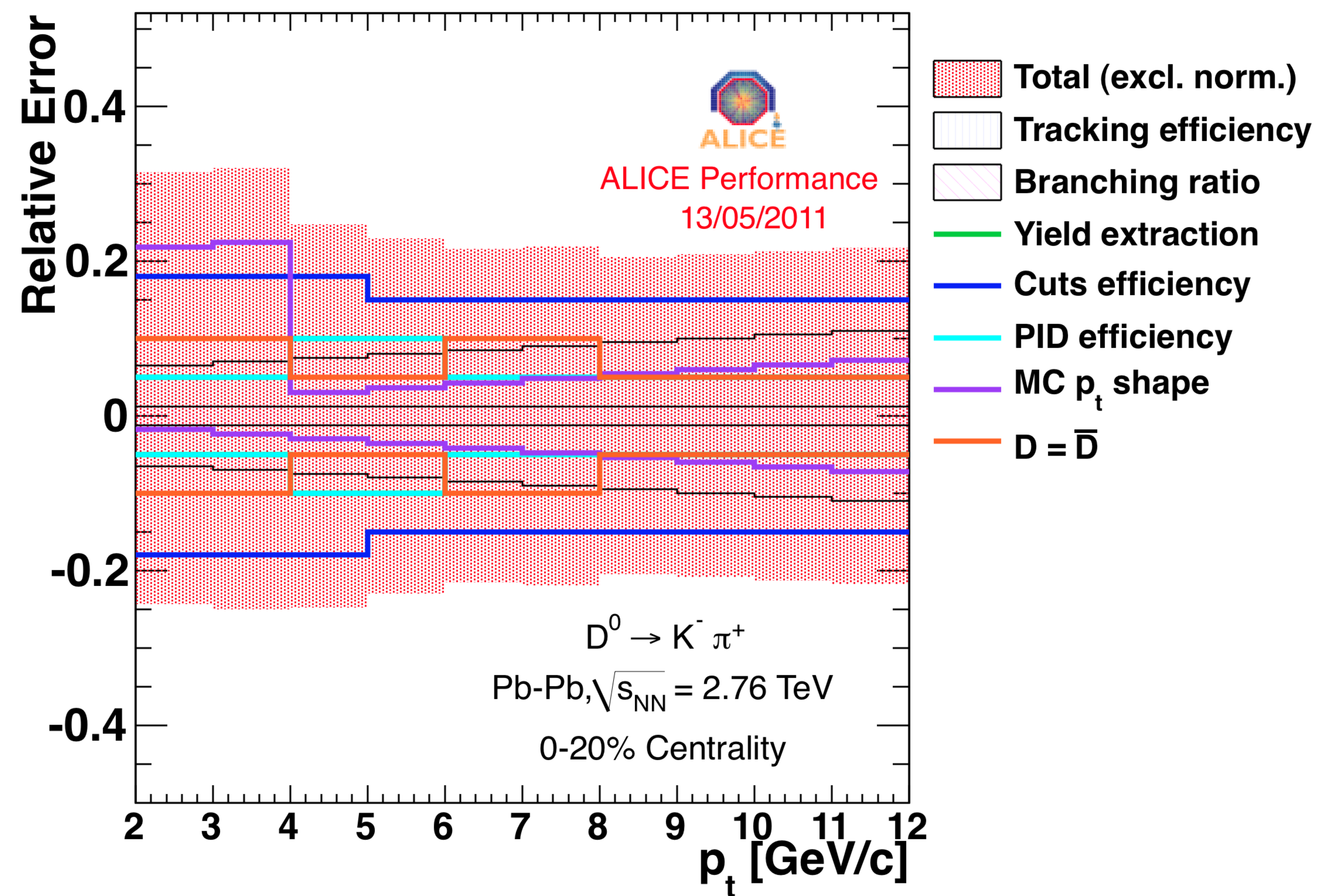


ALI-PERF-1946

# D<sup>0</sup> systematic uncertainties in Pb-Pb



## D<sup>0</sup> 0-20% CC

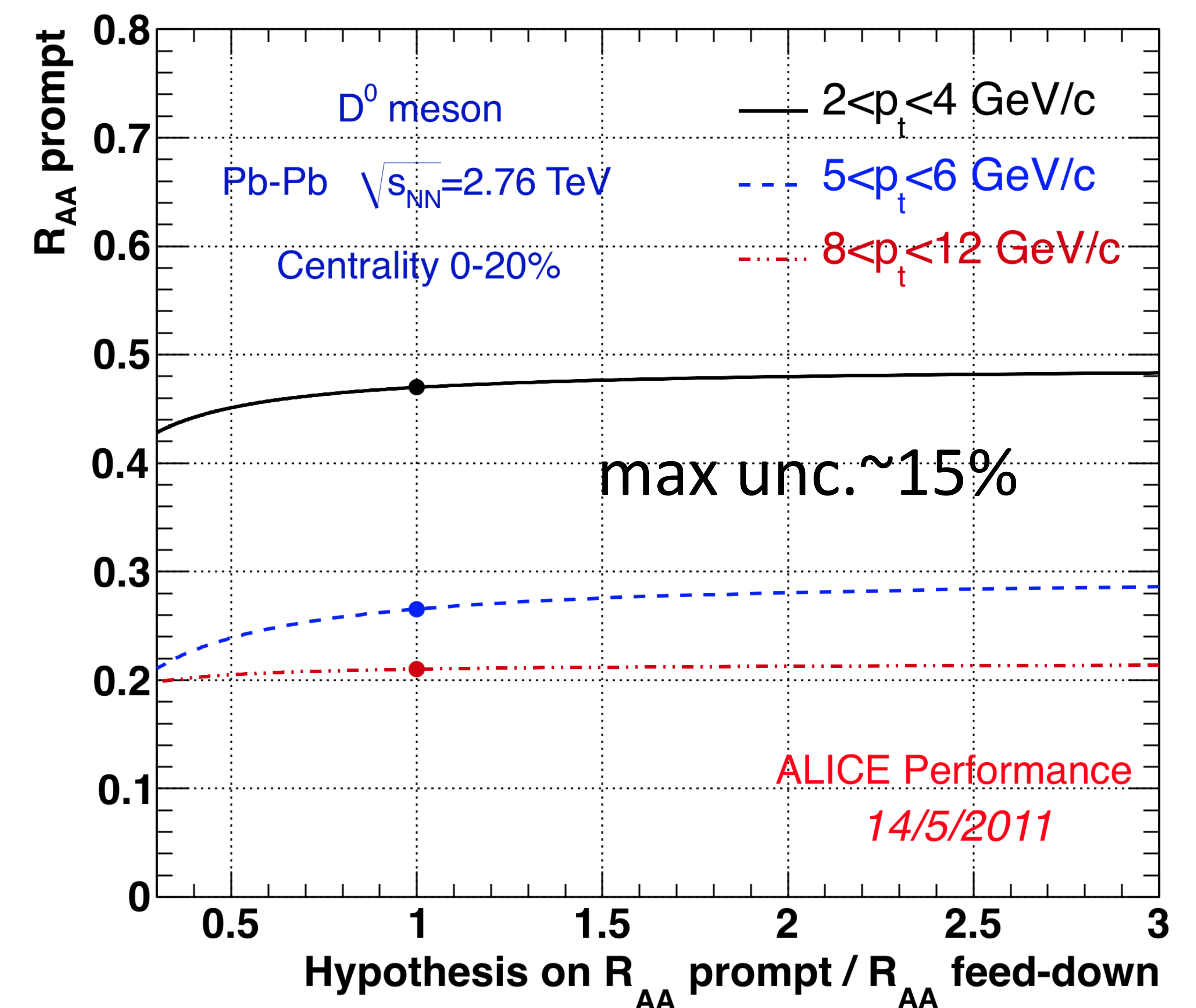
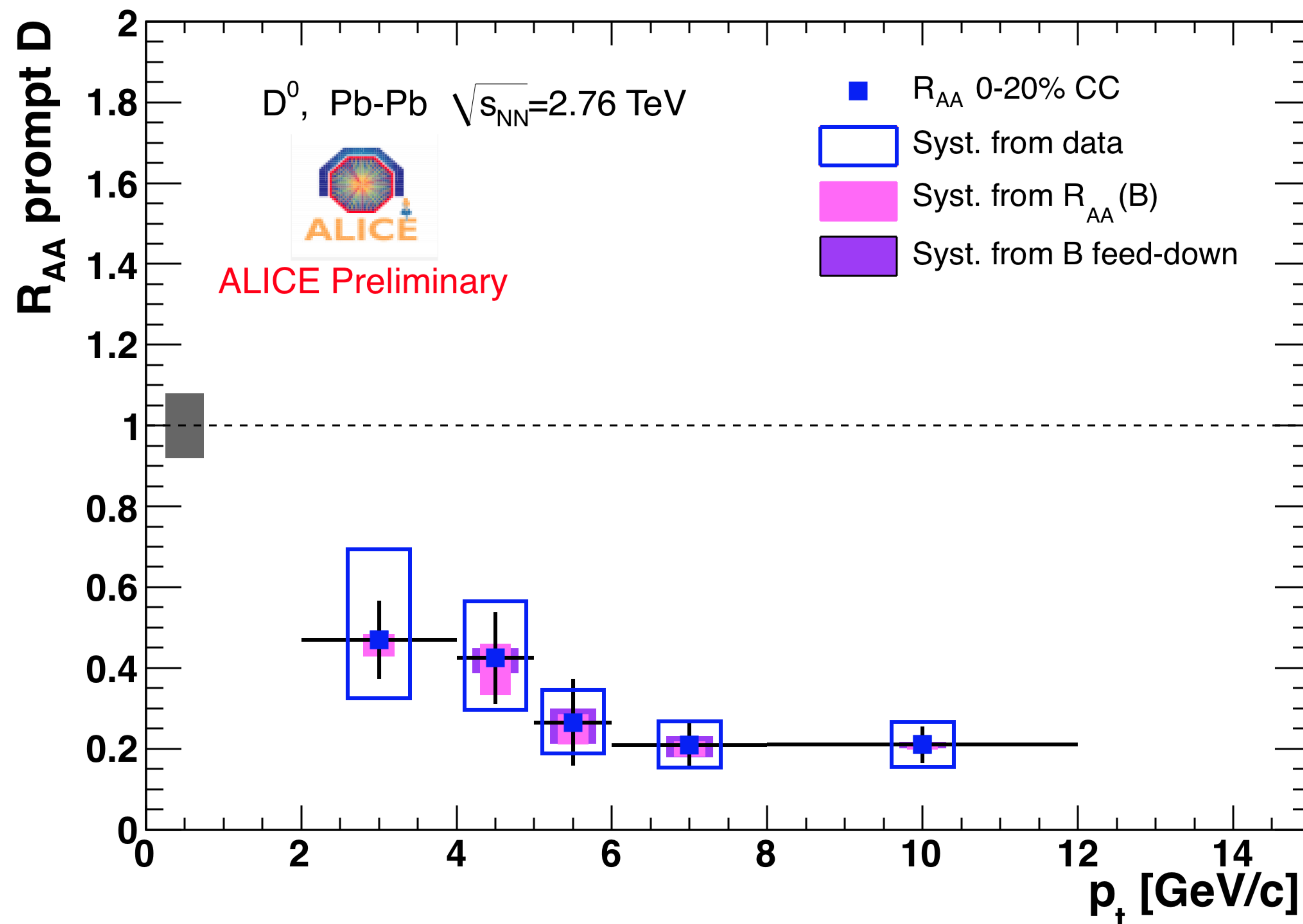


ALI-PERF-2035

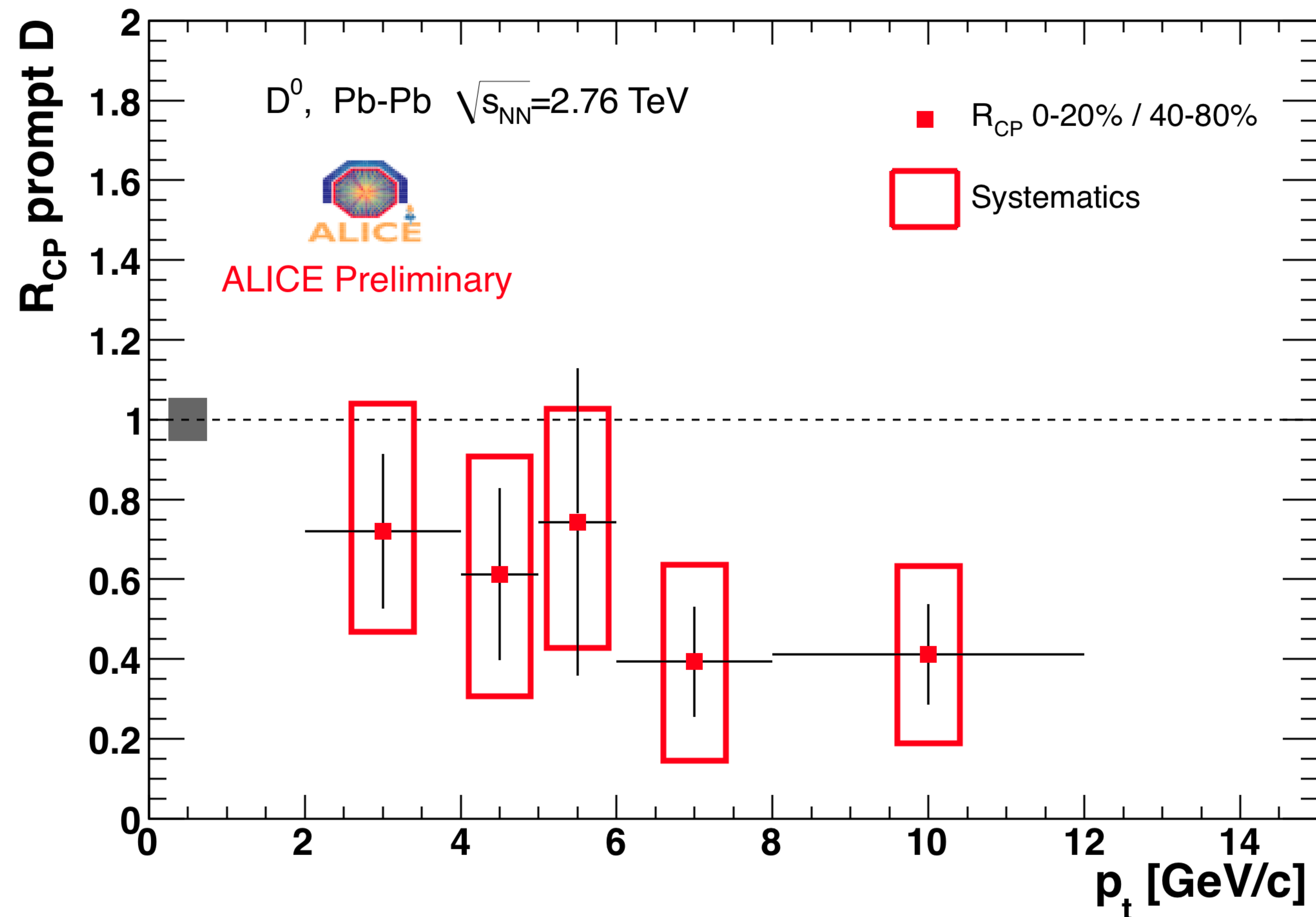
no centrality dependence observed

# Feed down correction and beauty energy loss hypothesis

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

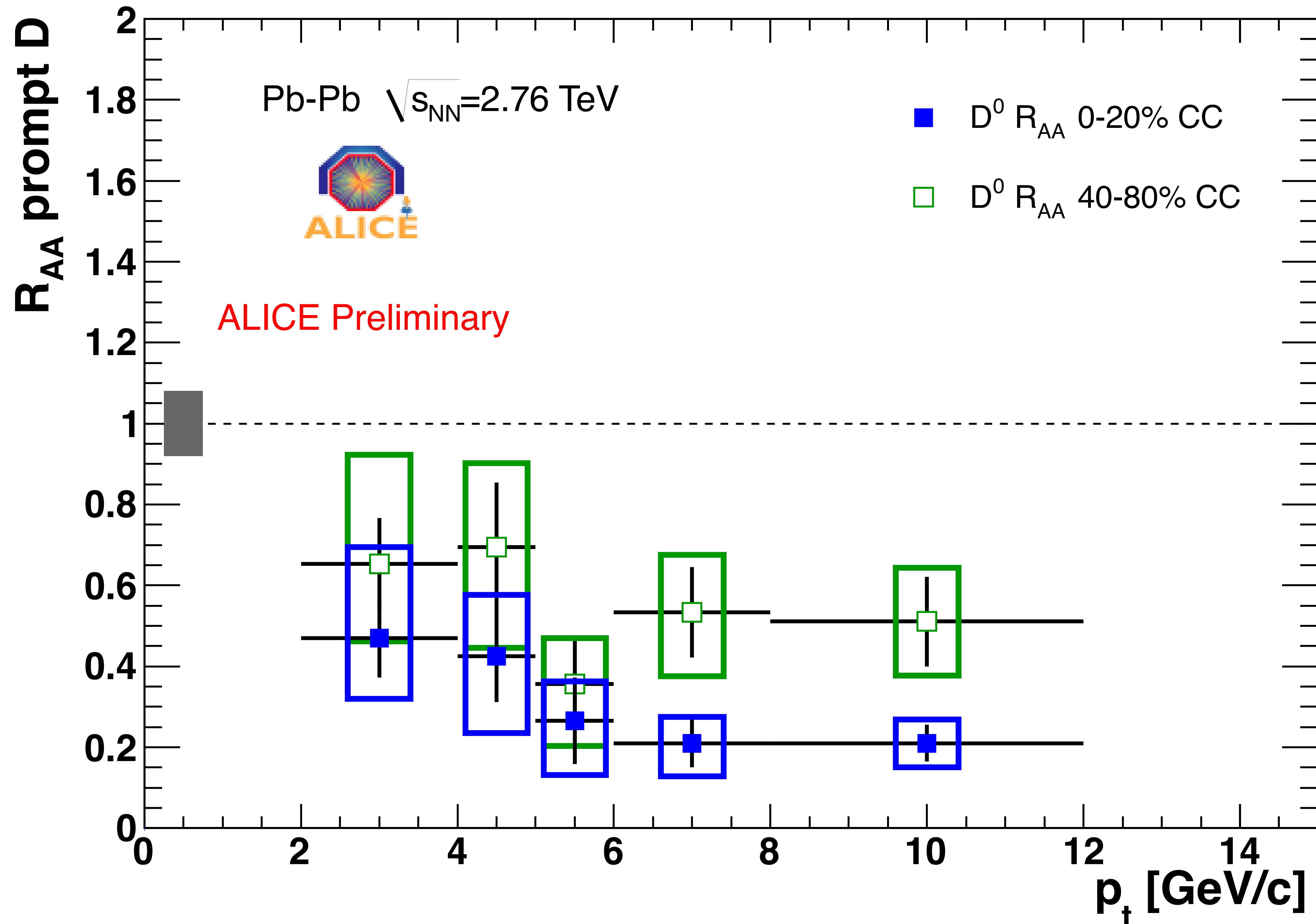


# $R_{CP}$ of D mesons (0-20%/40-80%)



Suppression clearly seen also in  $R_{CP}$  (no pp reference)  
 Suppression of a factor 2-3 above 5 GeV/c

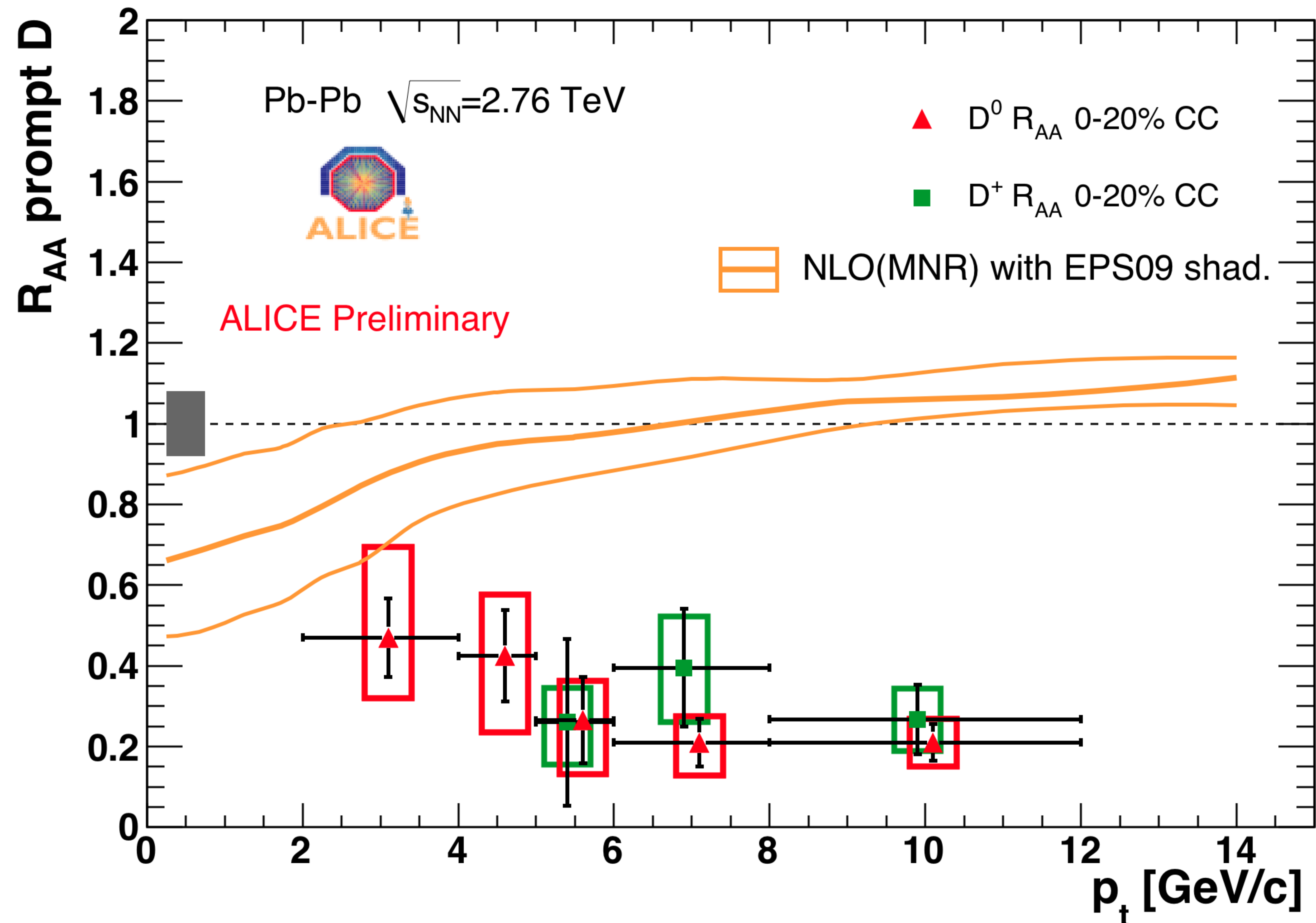
# $R_{AA}$ of D mesons: 0-20% 40-80%



Suppression of a factor 2 above 5 GeV/c for 40-80%, 4-5 for 0-20%

More central events show higher suppression.

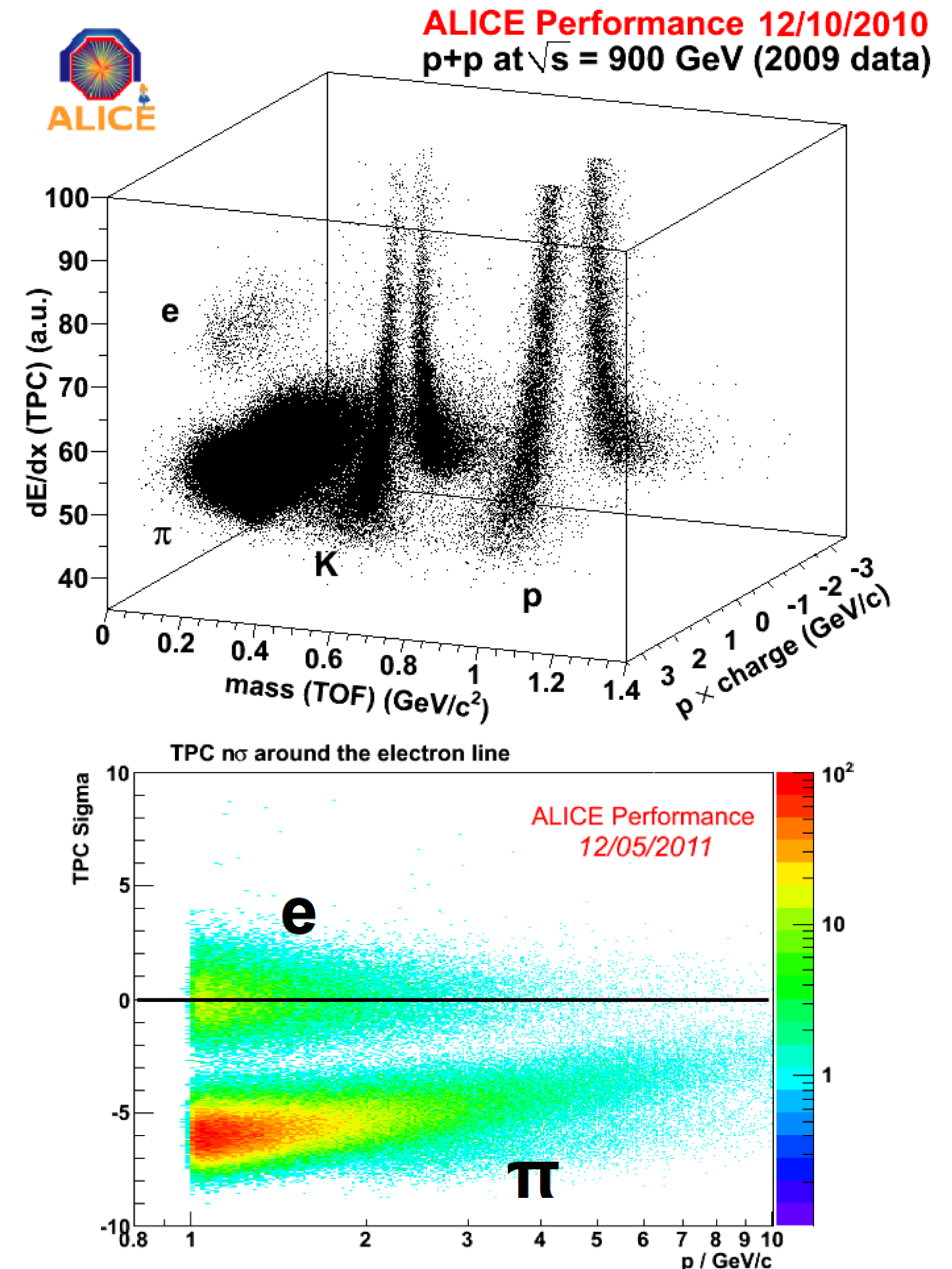
# $R_{AA}$ of D mesons: shadowing



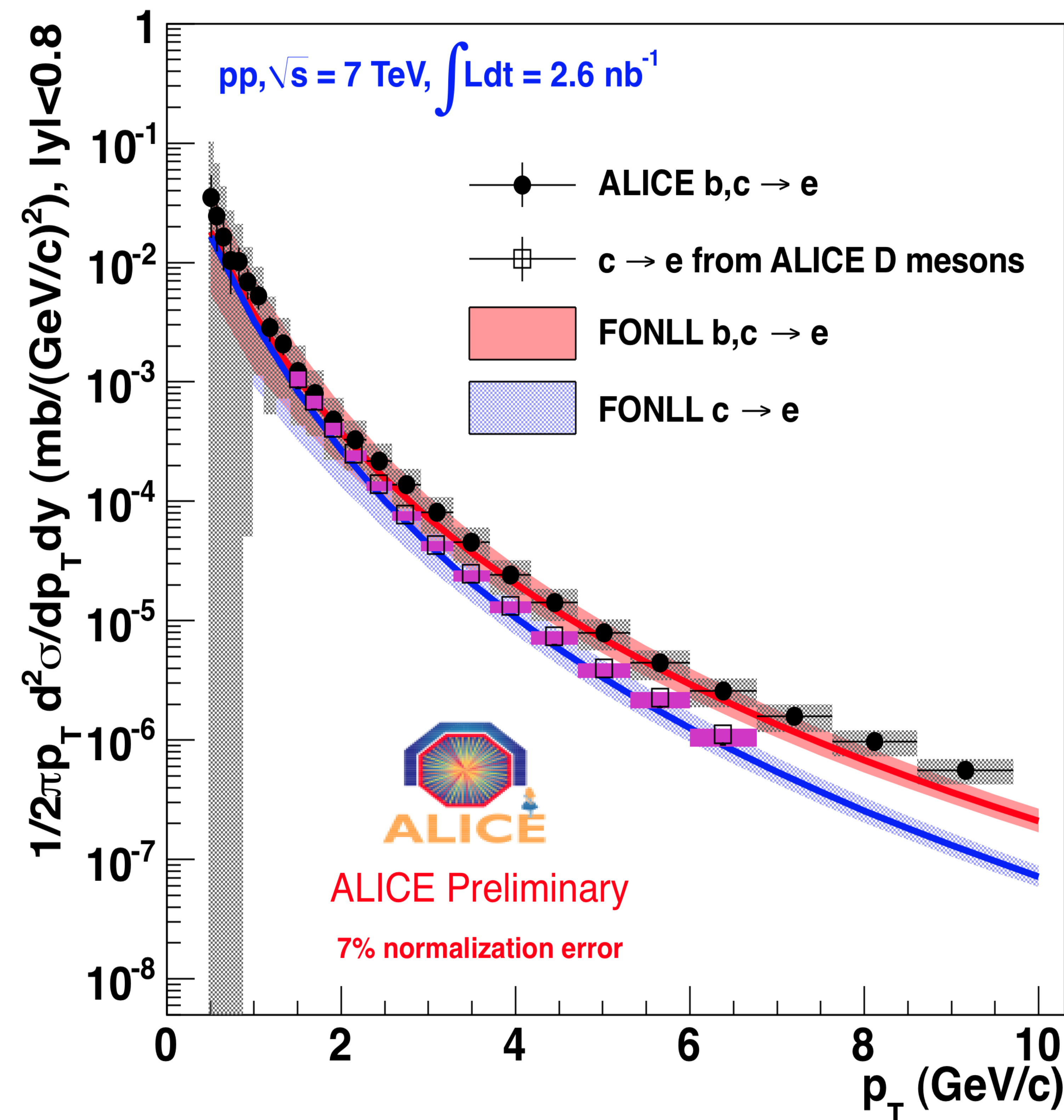
- Suppression for charm is a factor 4-5 above 5 GeV/c
- This is a hot medium effect (little shadowing at these  $p_t$ 's)
- p-Pb run at LHC crucial to understand the low- $p_t$  rise

# Electron reconstruction strategy

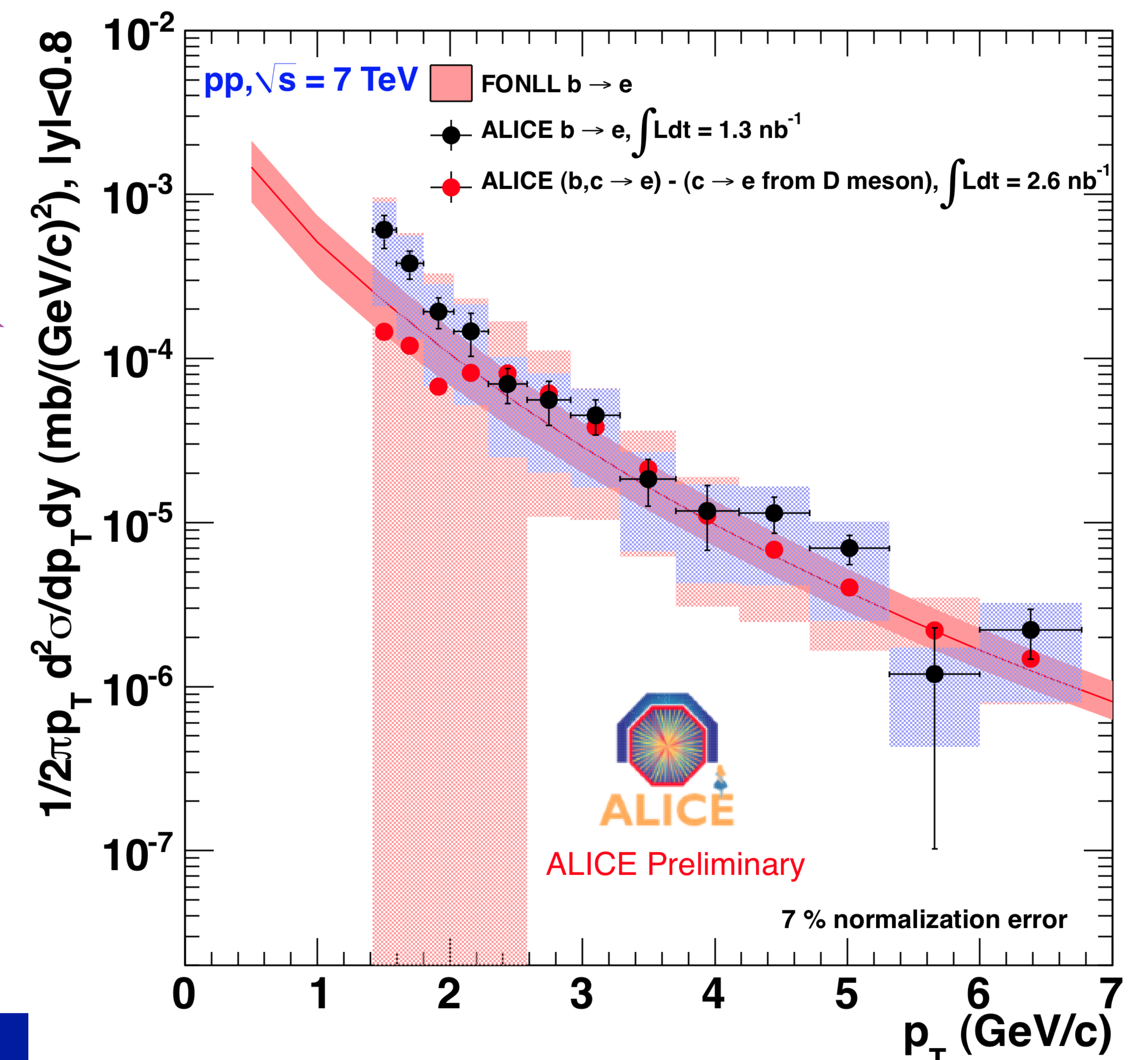
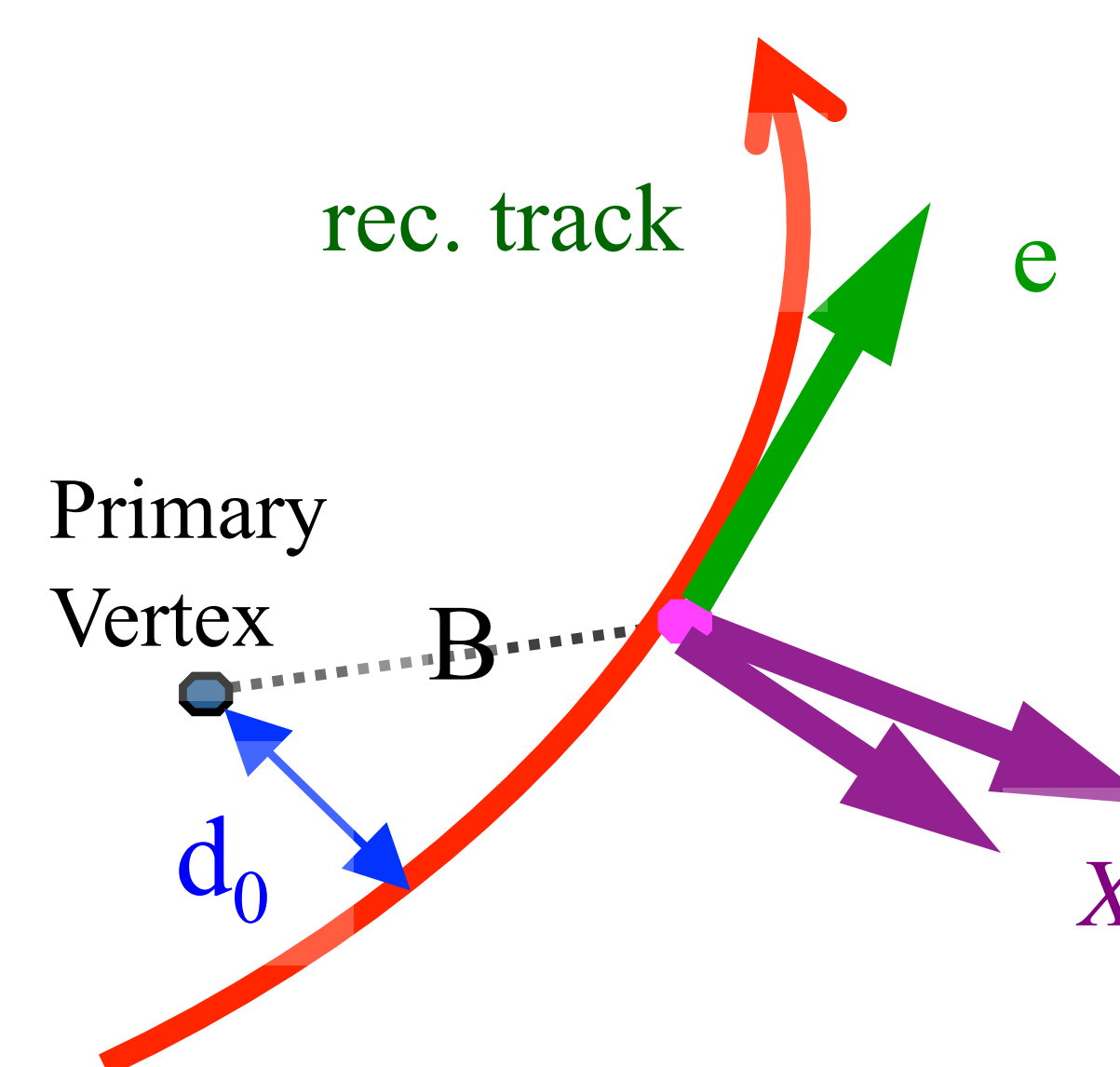
- High quality tracks in TPC and ITS
  - Hit in innermost Si layer to reduce  $\gamma$ -conv. (beam pipe +  $\sim 1/3$  inner pixel =  $0.5\% X_0$ )
- Electron identification:
  - **Pb-Pb: TOF + TPC-dE/dx**
    - TOF to reject K and p
    - TPC: asymmetric cut around the electron Bethe-Bloch line
  - **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  $\rightarrow$  beauty dominance (only in pp for now)



# Heavy Flavour electron spectra @ 7 TeV



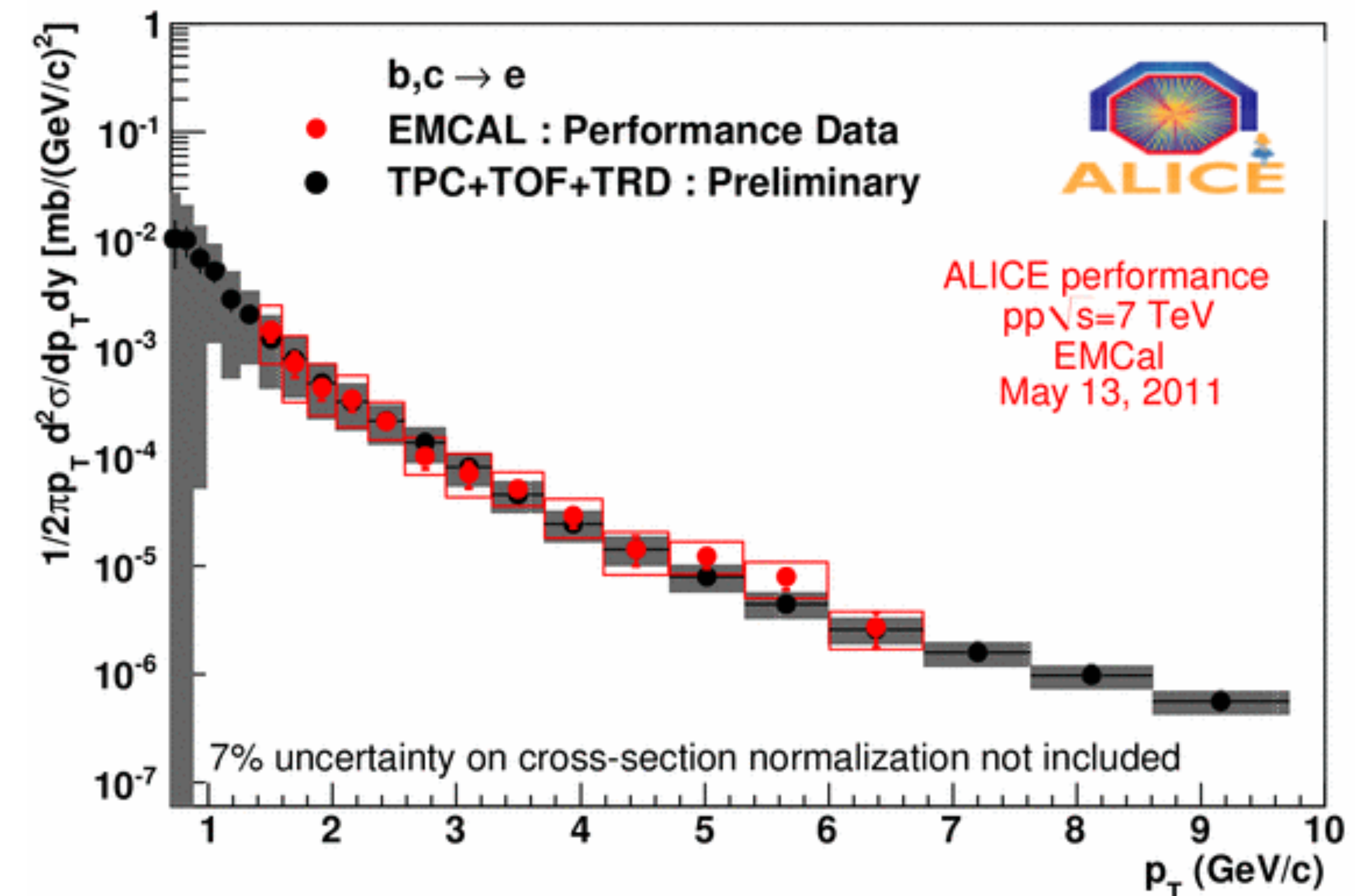
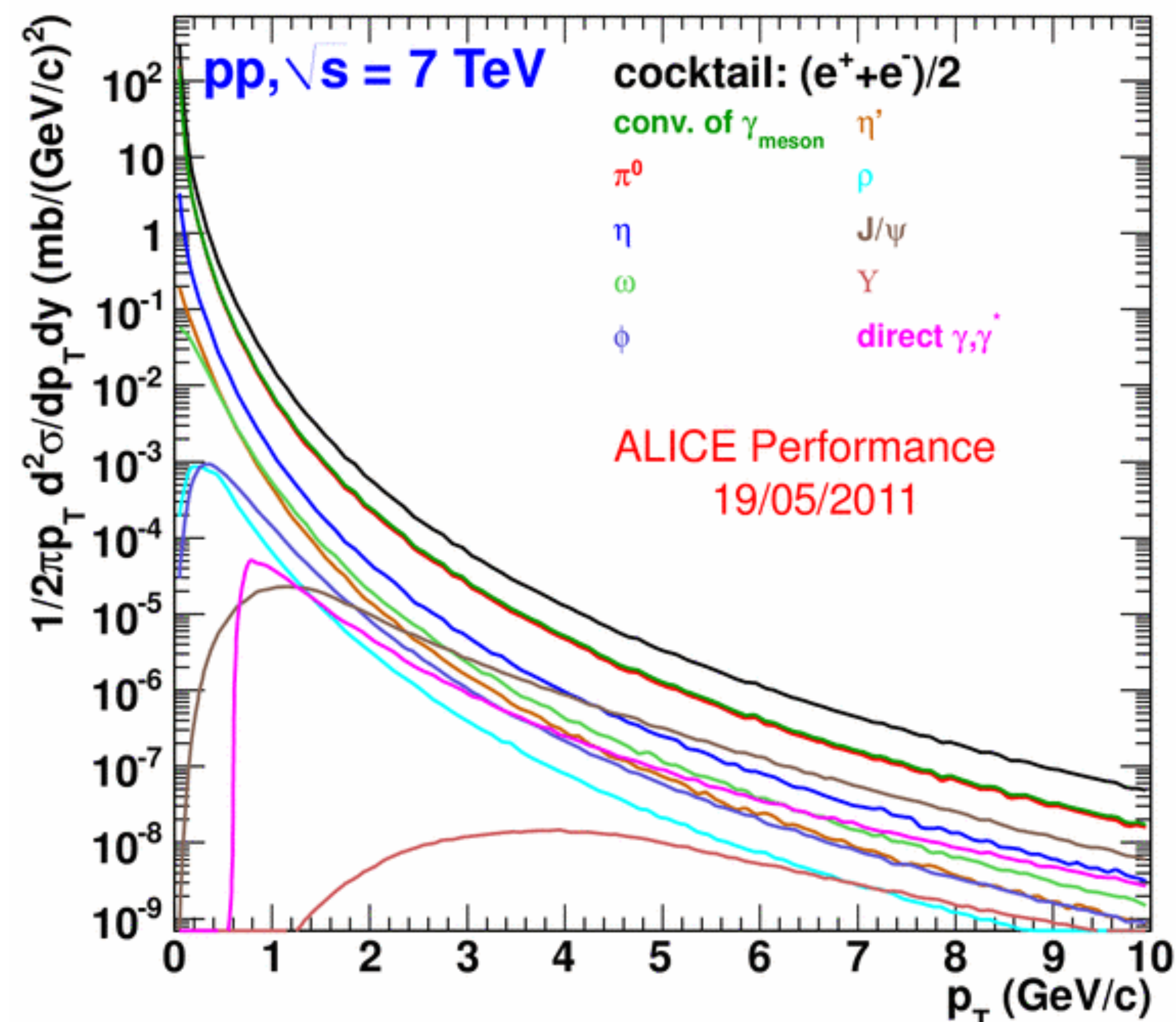
- Cocktail of “photonic” backgrounds based on measured  $\pi^0$  cross section
- Inclusive – Cocktail: electrons from c and b decays
- Well described by FONLL



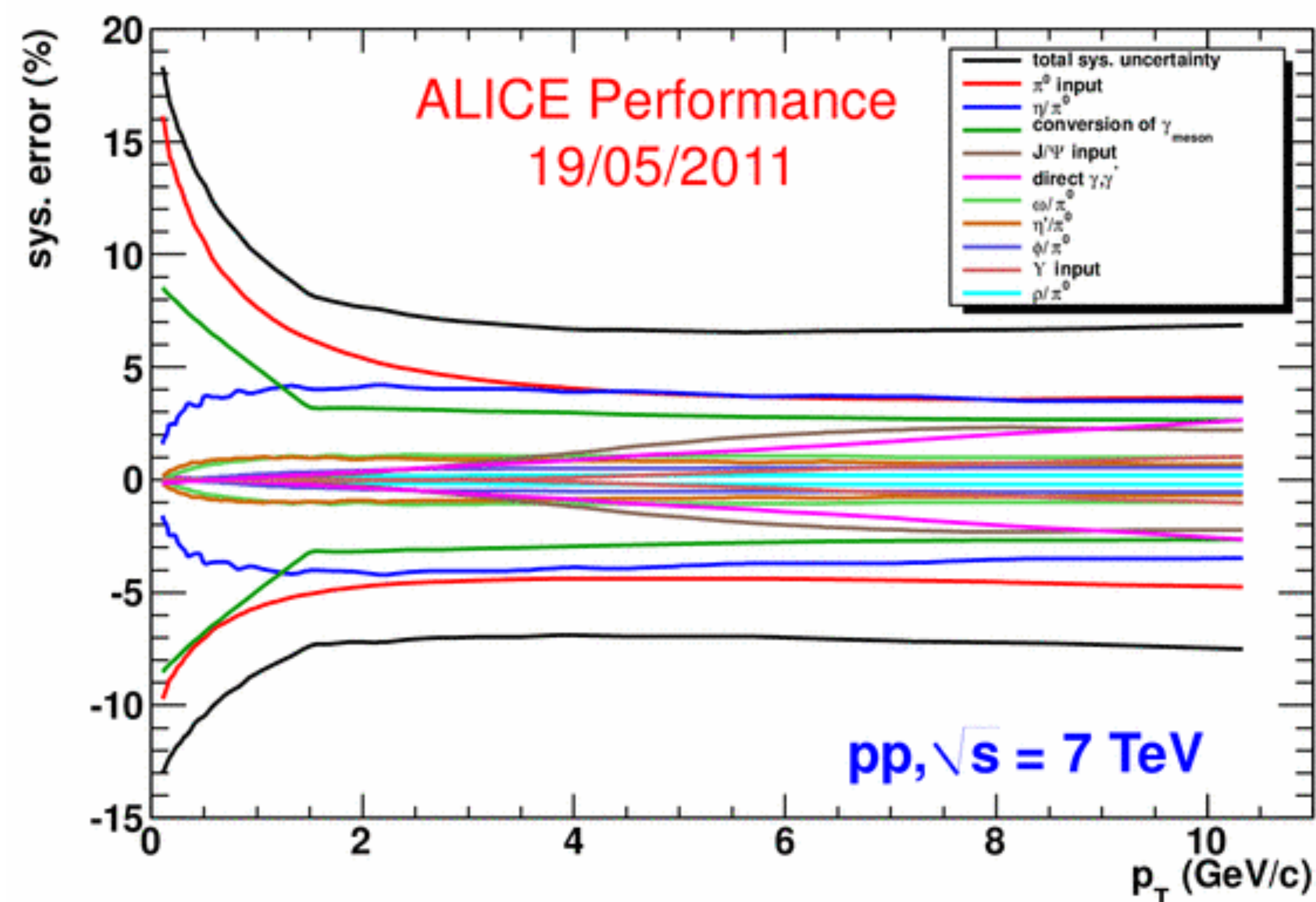
- Select electrons displaced from interaction vertex
- Electrons from beauty decays
- Well described by FONLL



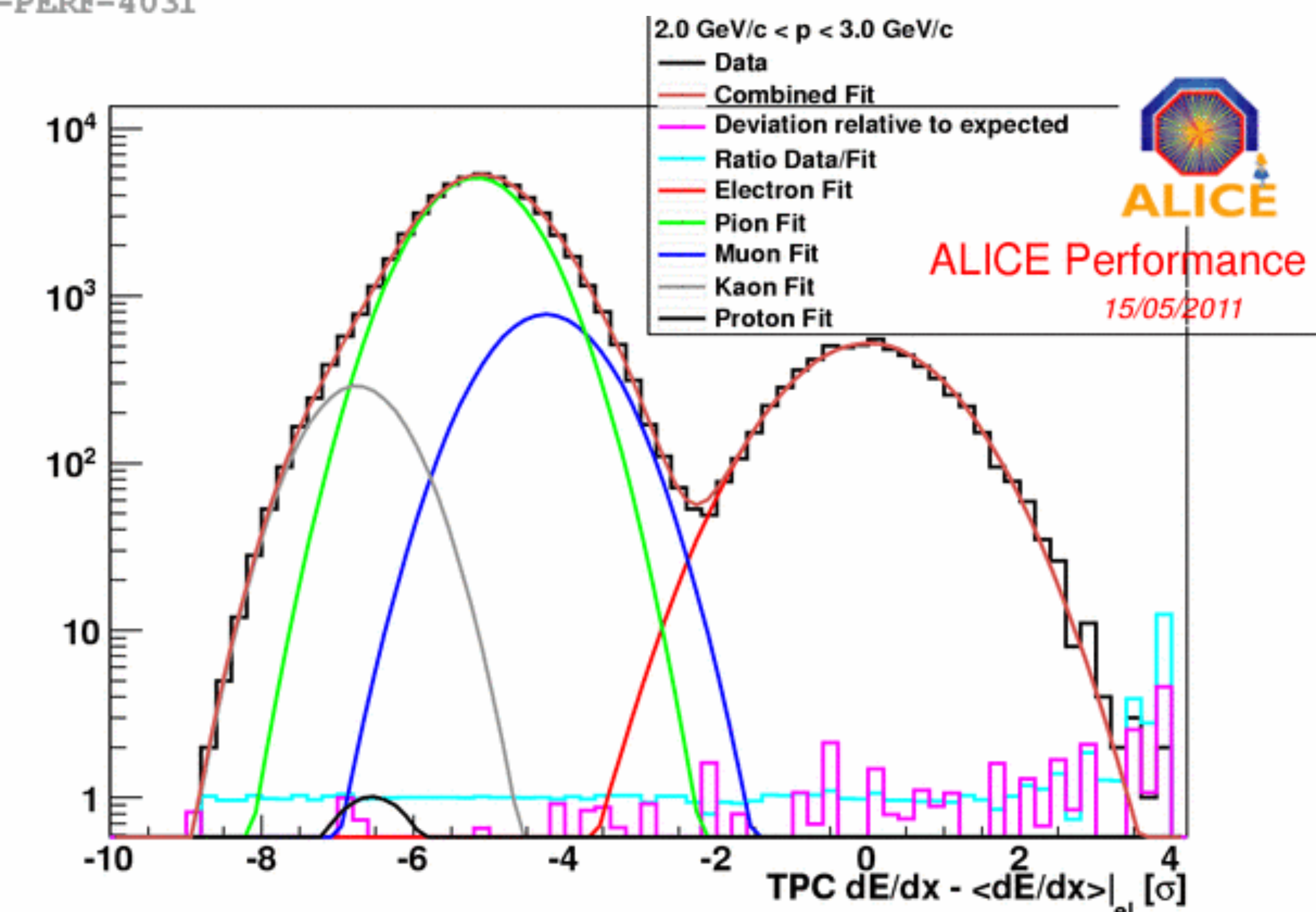
# Electrons at 7 TeV: cocktails, spectra...



ALI-PERF-4031



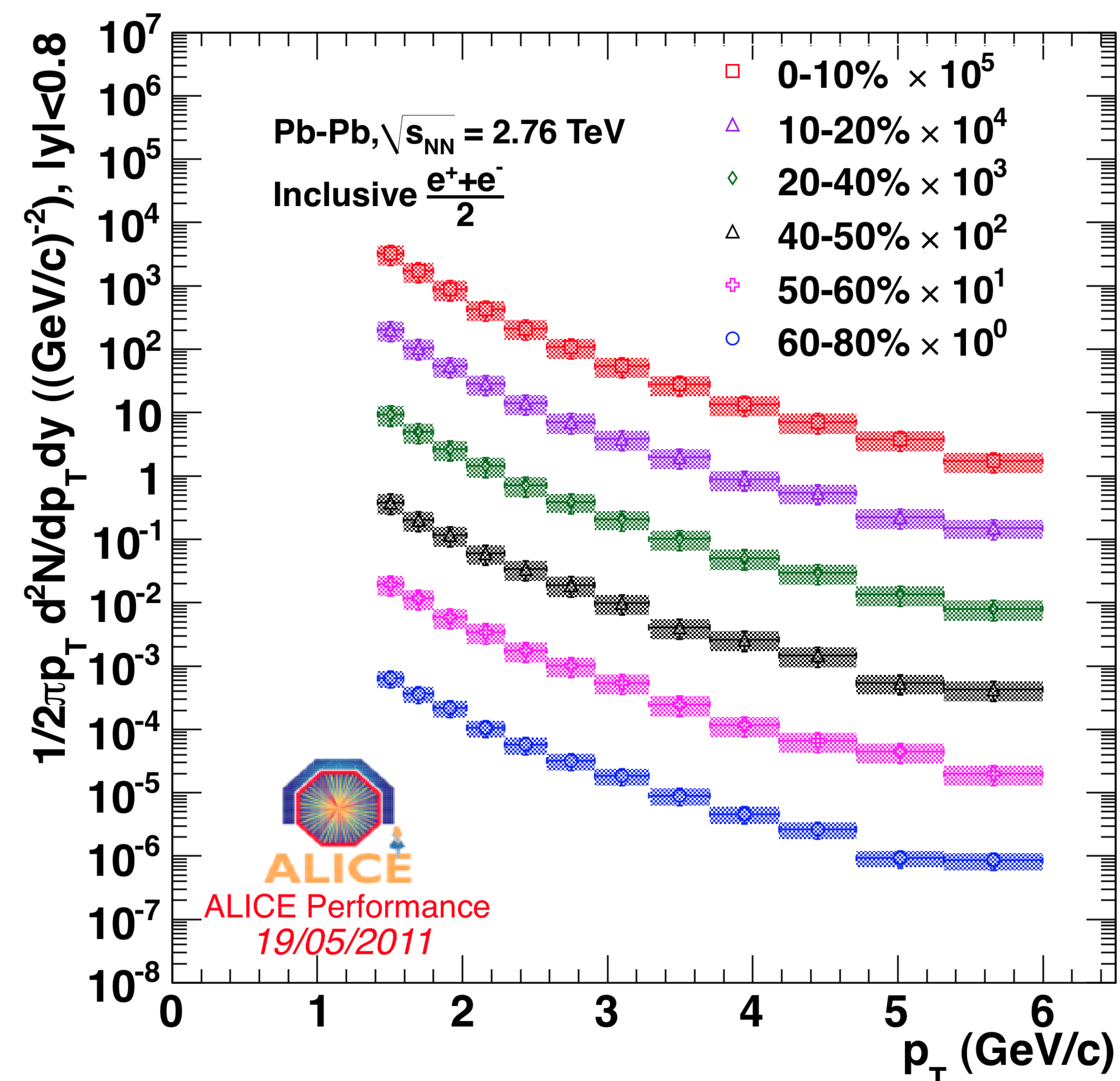
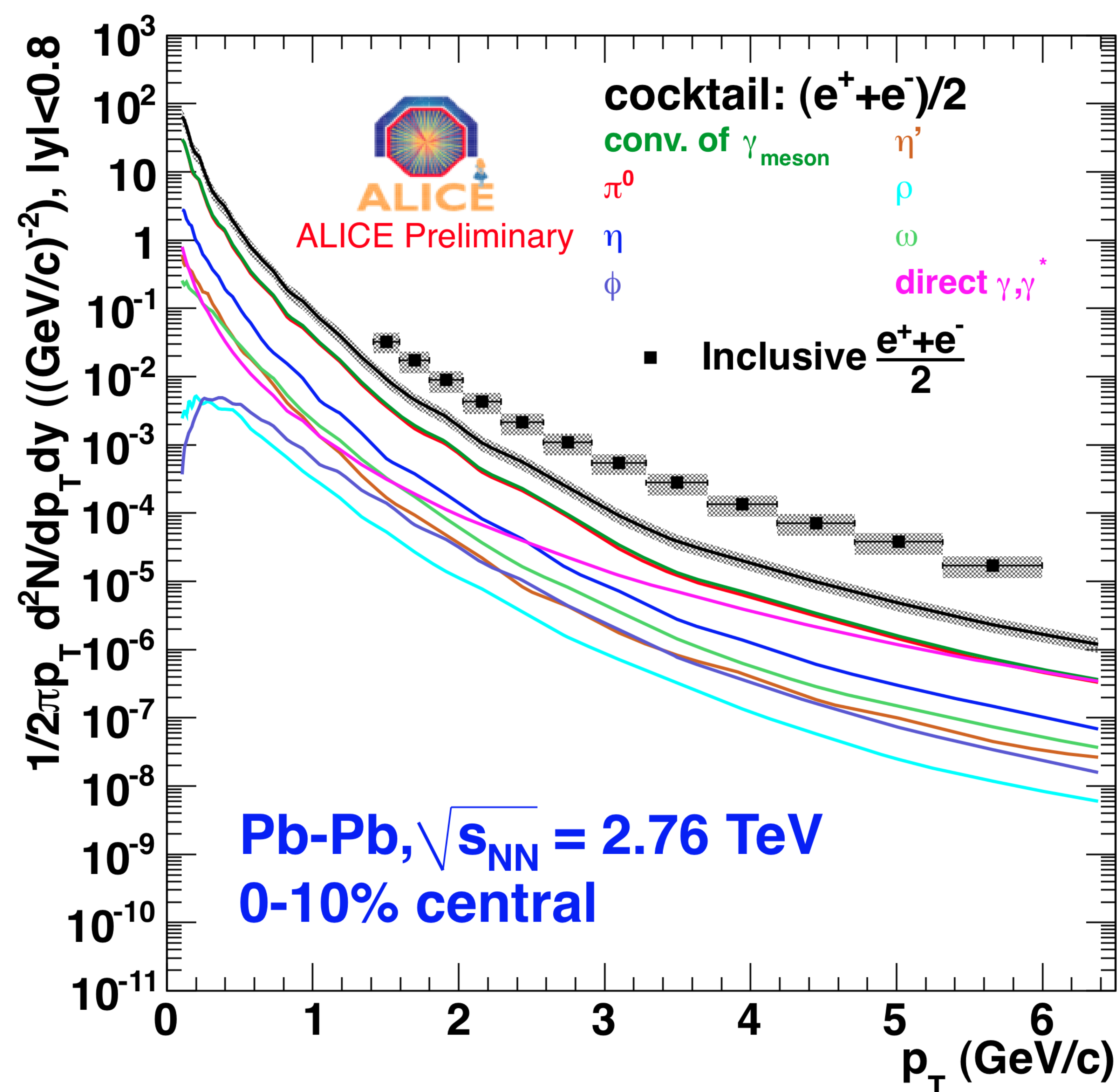
ALI-PERF-6379



ALI-PERF-2329

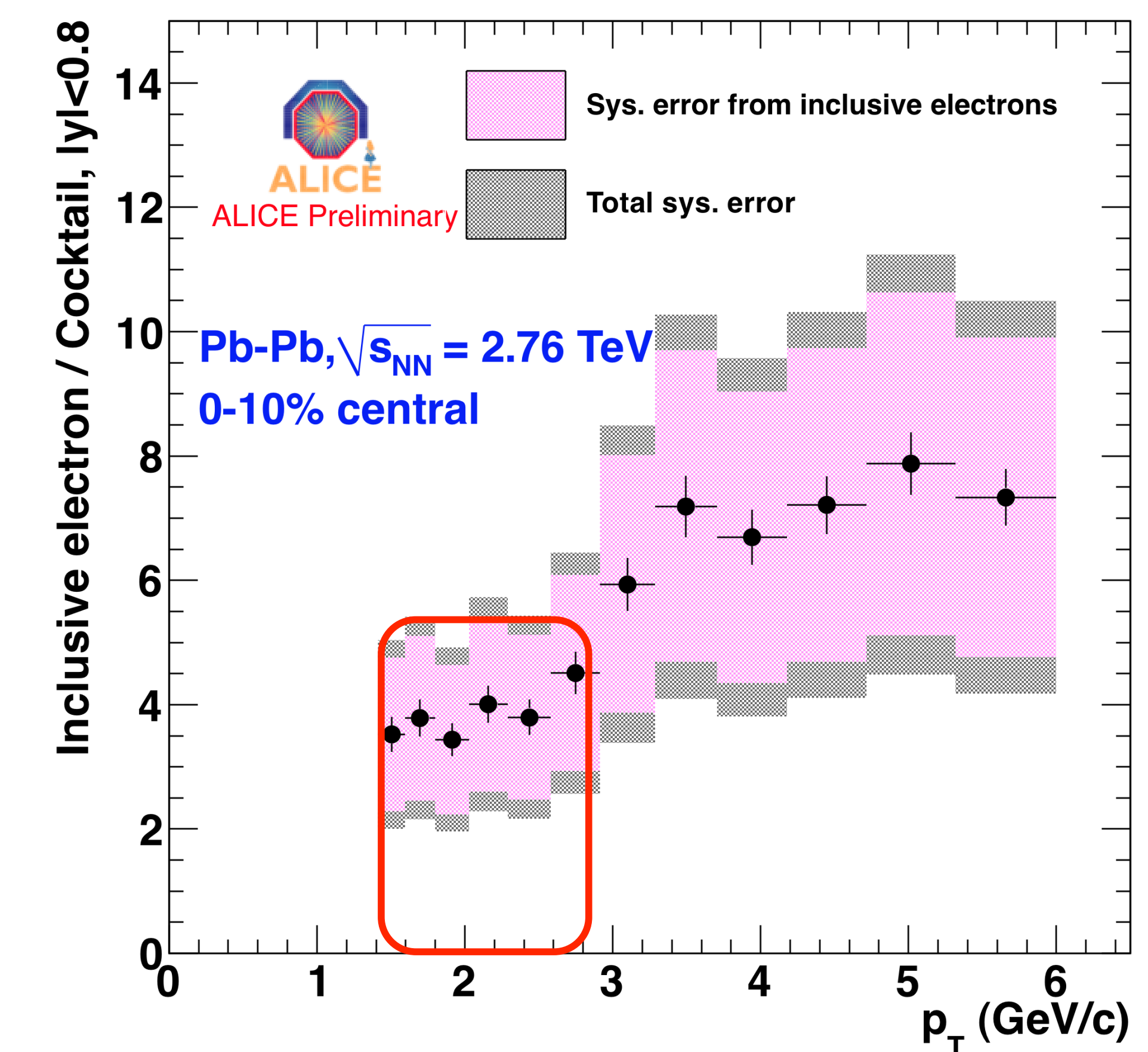
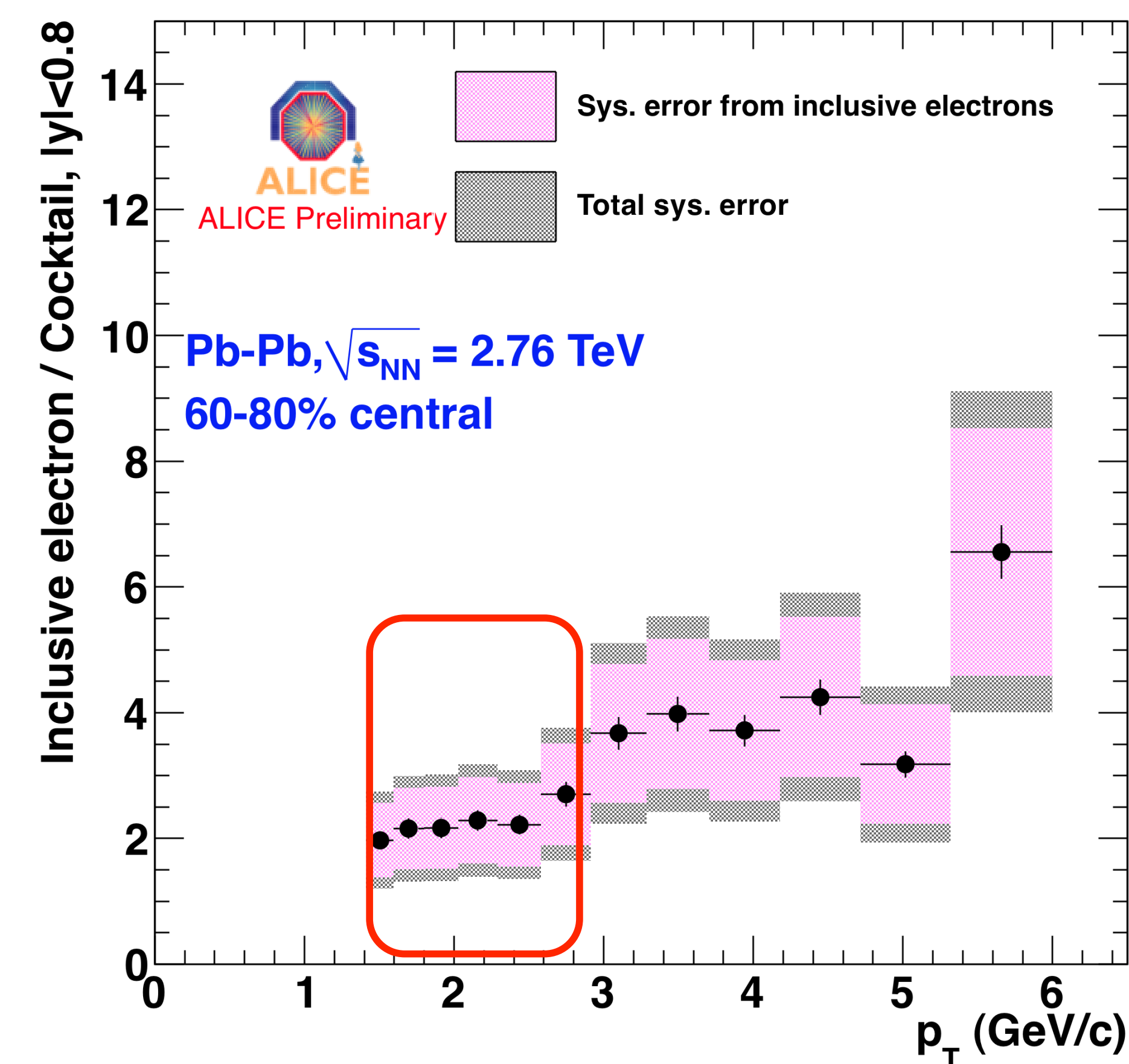
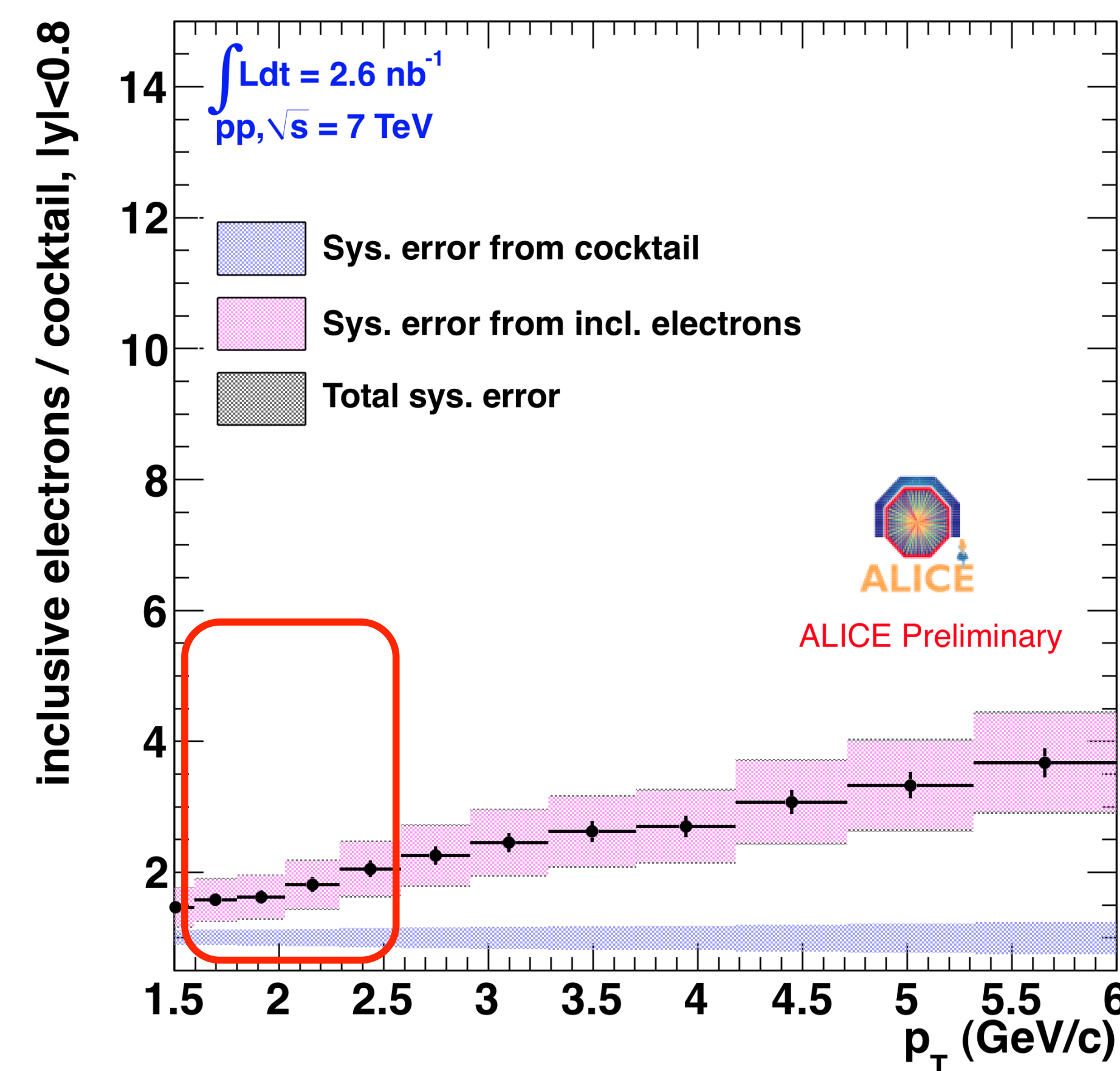
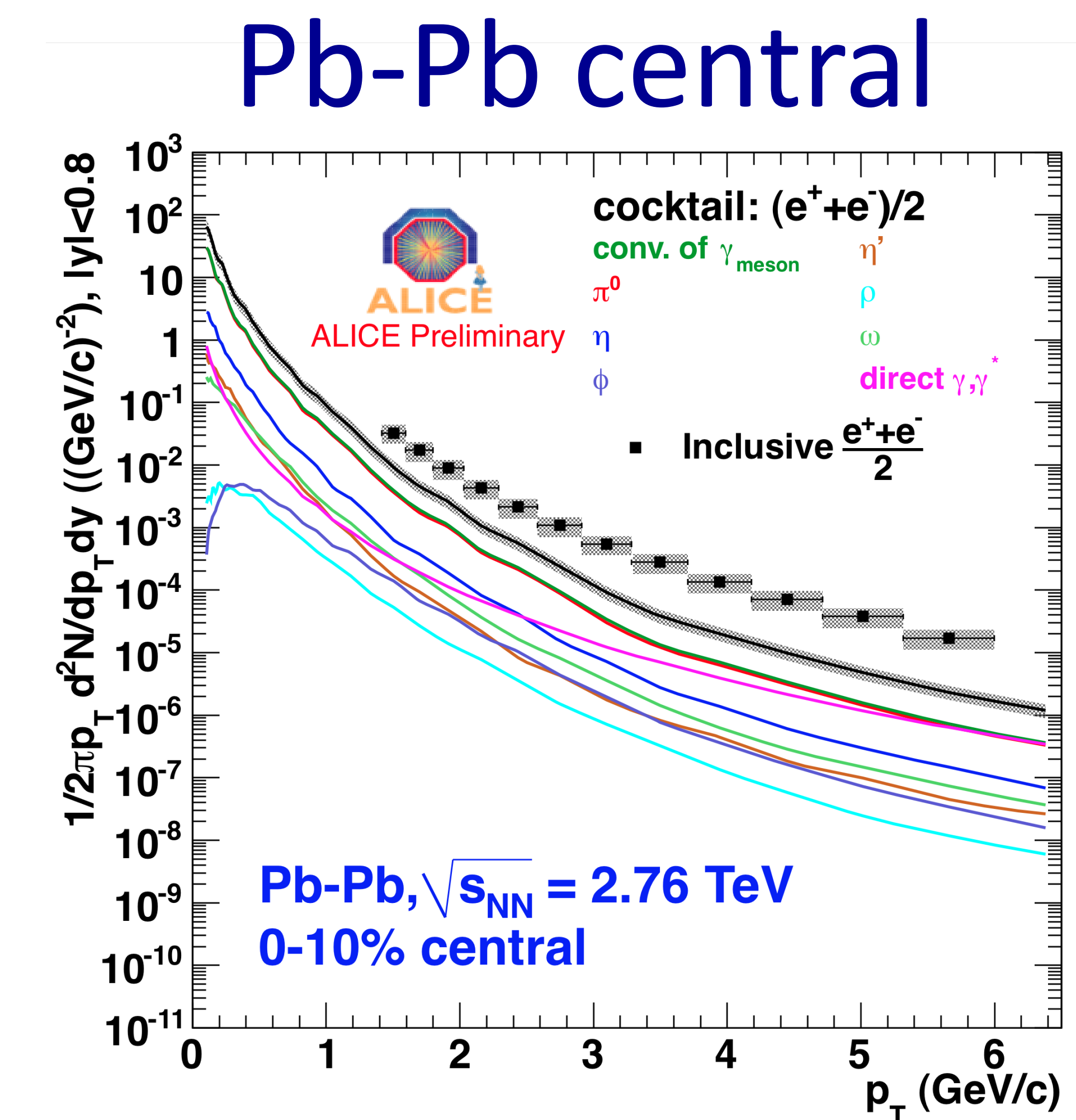
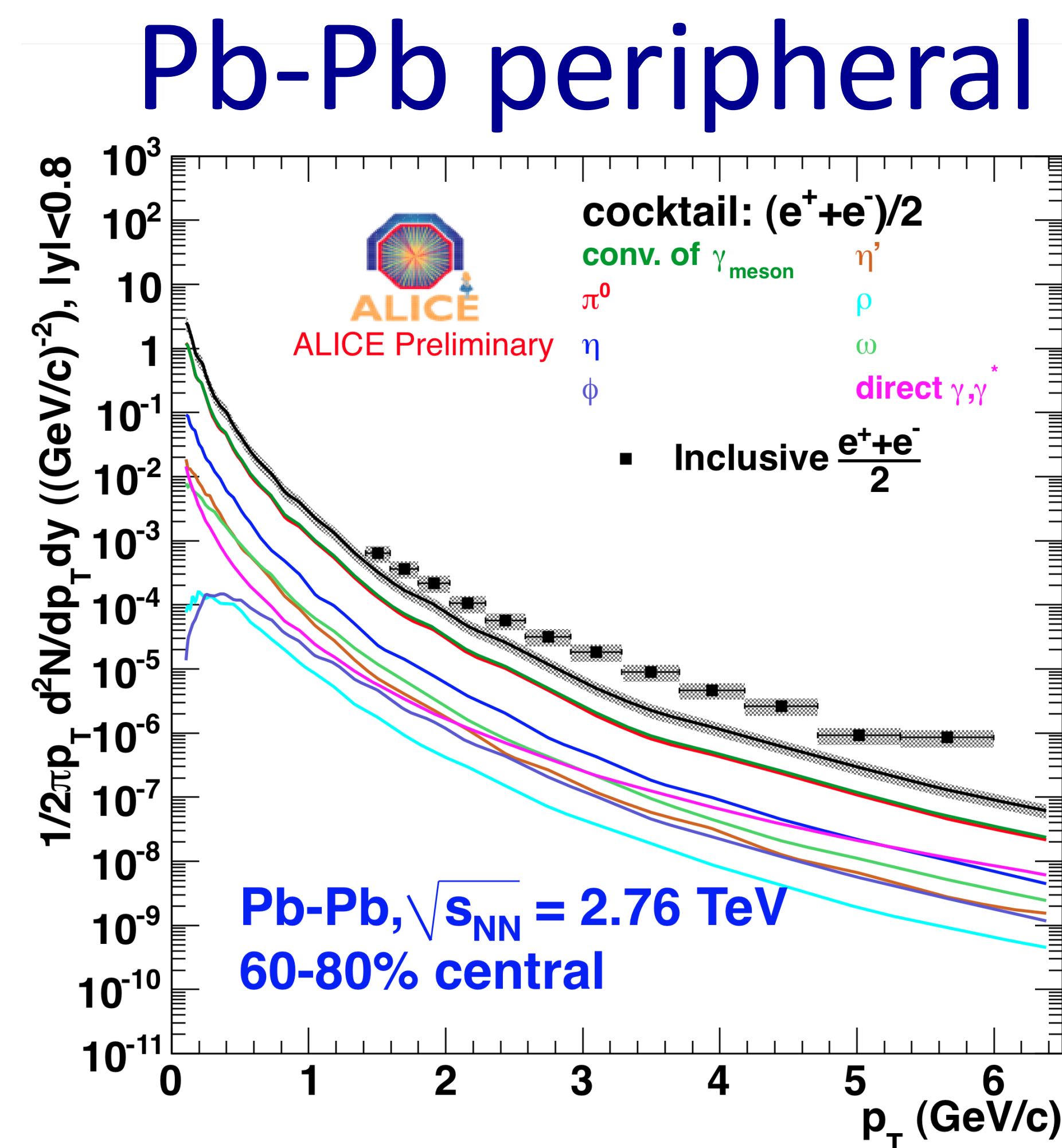
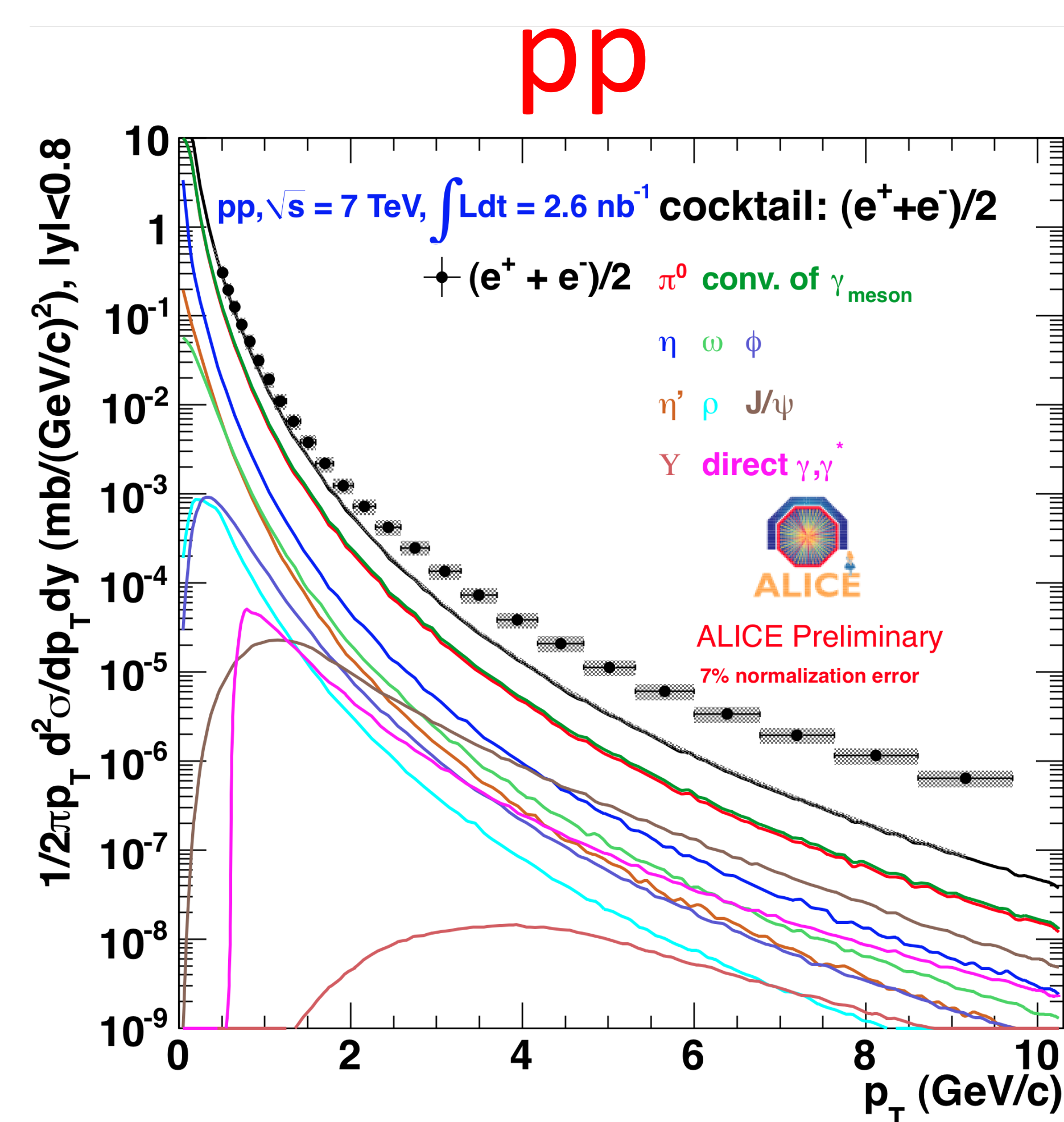
# Electron spectra in Pb-Pb

- Inclusive electron  $p_t$  spectra in six centrality bins
  - hadron contamination <10% up to 6 GeV/c



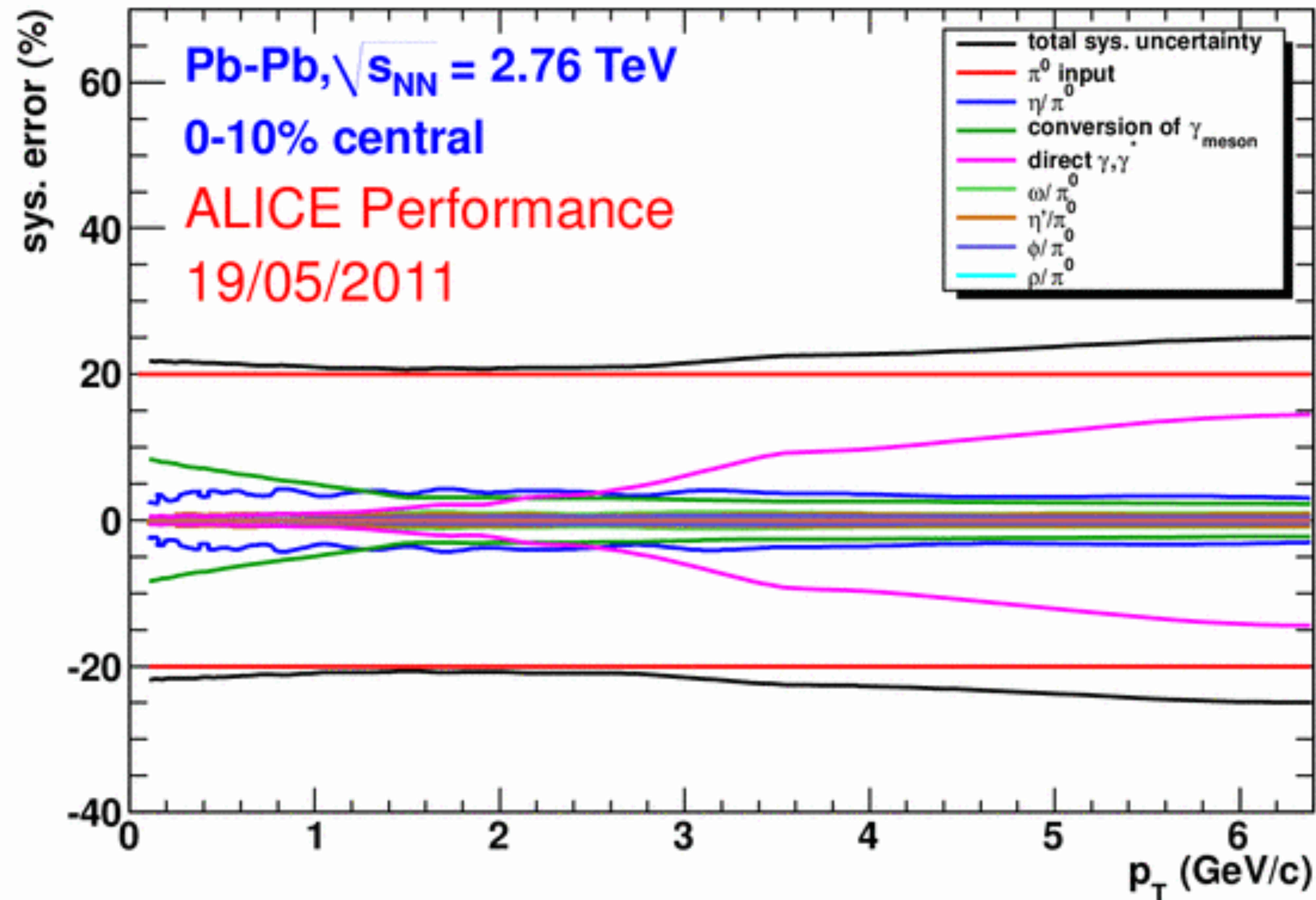
- Background electron cocktail, based on  $\pi^\pm$  spectra +  $m_t$ -scaling + pQCD direct photons
- Subtract background cocktail. The resulting electron spectrum is dominated by c and b decays for  $p_t > 3,4$  GeV/c.

# Electron spectra in PbPb vs cocktail



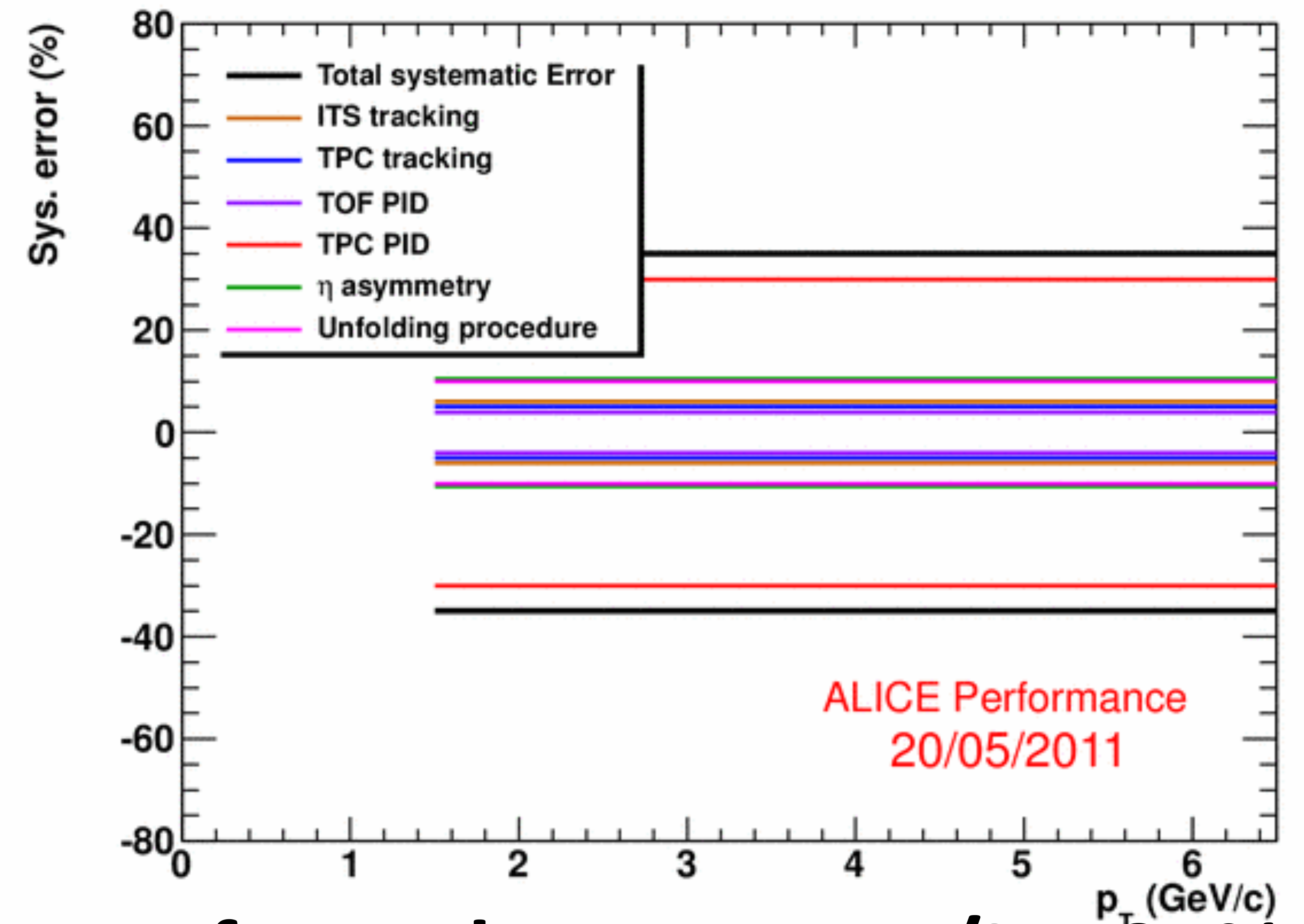
- Hint of an **electron excess** at low  $p_T$  (beyond our systematic errors, mainly from e ID)
- Increases with centrality
- Might be explained by thermal photons (cfr. PHENIX, PRL104)

# Electrons: systematic uncertainties PbPb



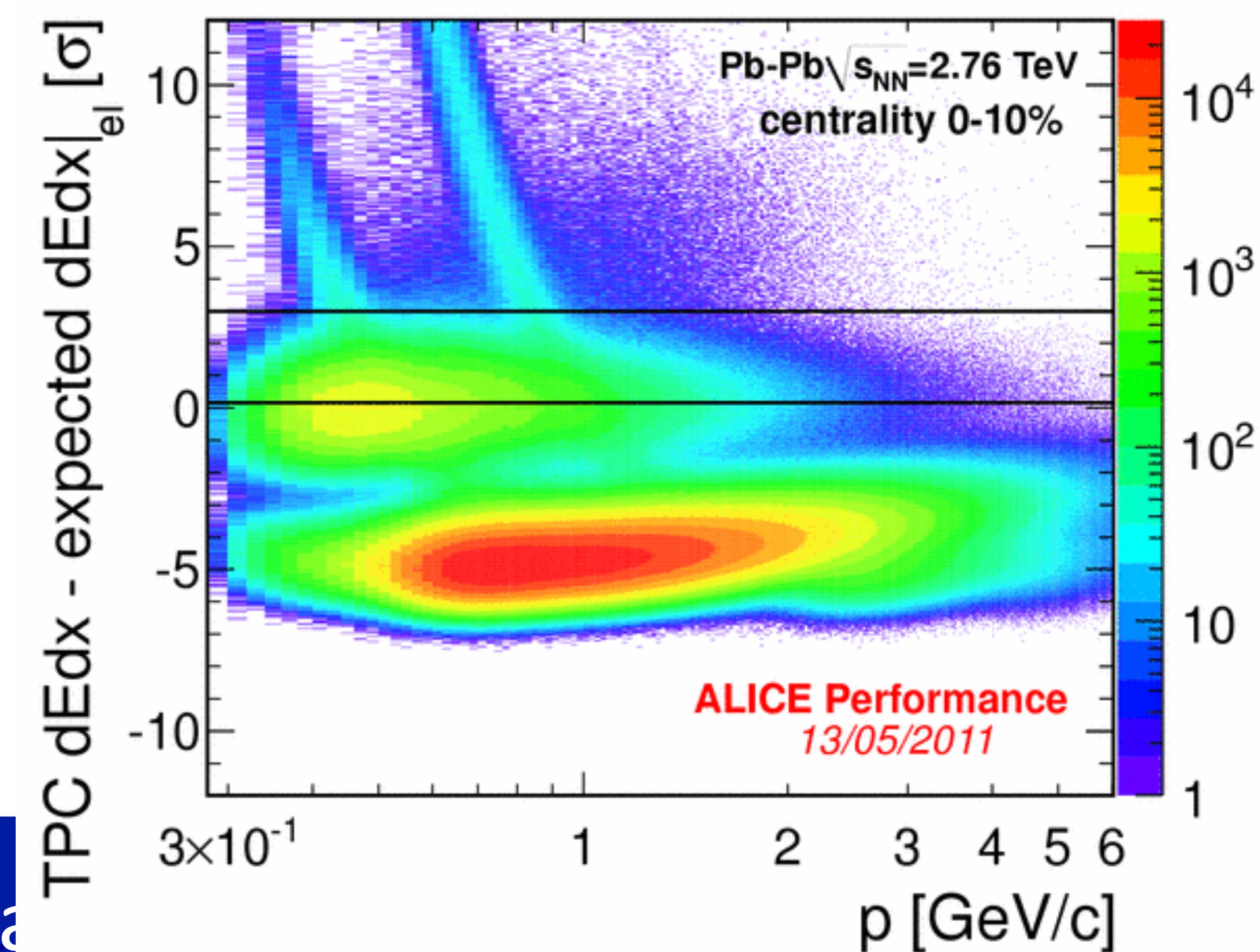
from cocktail : 25%

ALI-PERF-3466



from electron reco/ID: 35%

ALICE Performance  
20/05/2011



gdgdggd

