OPEN HEAVY FLAVOR PRODUCTION AT LHC WITH ALICE

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EMMI

OUTLINE

- Heavy flavors at LHC
  - motivations
  - energy loss in a hot and dense medium
  - energy loss studies with ALICE
- The ALICE detector and the heavy flavor measurements
  - Open charm in its hadronic decays
  - heavy flavors in their semi leptonic decays:
    - heavy flavor electrons
    - heavy flavor muons
- Conclusions

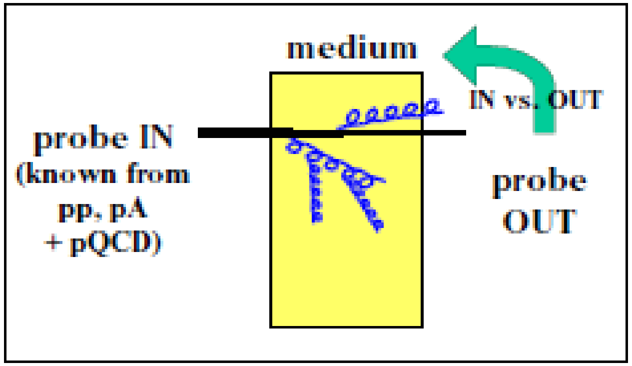
HEAVY FLAVORS

- *In p-p collisions:*
  - measure charm and beauty cross section
  - test of pQCD predictions in a new energy domain
  - necessary baseline for Pb-Pb

first results in this talk

- *In Pb-Pb collisions:* probe the properties of the medium
  - created in the hard initial collision → **experience the whole collision history**
  - possible comparison heavy quarks/light partons

  → **energy loss:**



$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

Casimir factor, dead cone

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

$$R_{AA}(p_t) = \frac{1}{\langle N_{coll} \rangle} \times \frac{\mathrm{d}N_{AA}/\mathrm{d}p_t}{\mathrm{d}N_{pp}/\mathrm{d}p_t}$$

pp reference essential!

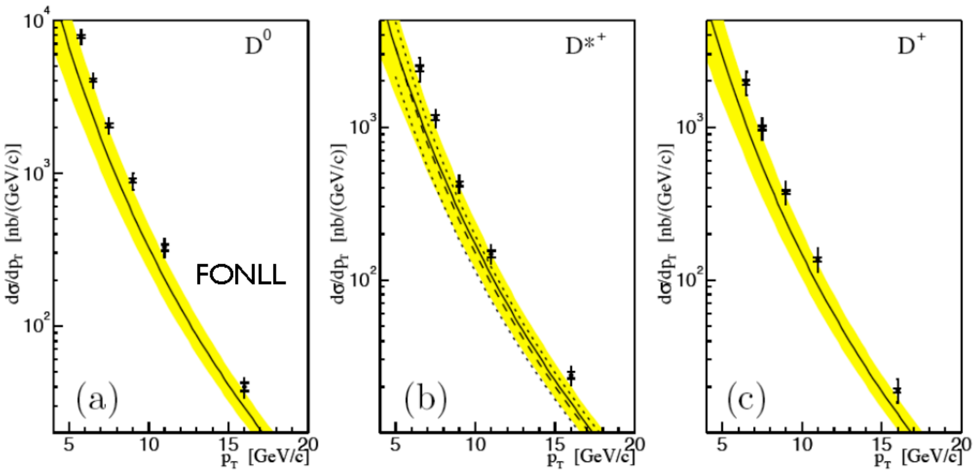
HEAVY FLAVOR PRODUCTION@LHC

Theoretical predictions (NLO) → charm & beauty reference

MNR code (FO NLO): Mangano, Nason, Ridolfi, NBP373 (1992) 295

Pairs per Event	RHIC Au+Au 0.2 TeV (0-5)%	LHC p+p 7 TeV	LHC p+p 14 TeV	LHC Pb+Pb 2.76 TeV	LHC Pb+Pb 5.5 TeV (0-5%)
$c\bar{c}$	10	0.10	0.16	56	90
$b\bar{b}$	0.05	0.003	0.006	2	3.7

$\sigma_{c\bar{c}}$ @LHC grows by a factor 10 wrt RHIC, $\sigma_{b\bar{b}}$ by a factor 50!



charm production at the limit of theoretical predictions at Tevatron and RHIC

CDF RunII: c->D , PRL 91:241804 (2003)

RHIC:Eur.Phys. J. C (2009 62: 3-7)

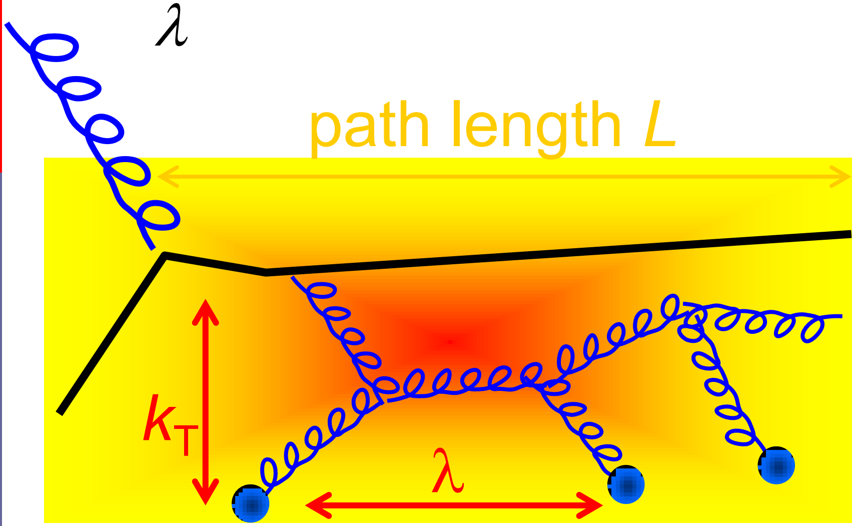
HEAVY QUARK ENERGY LOSS

$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$

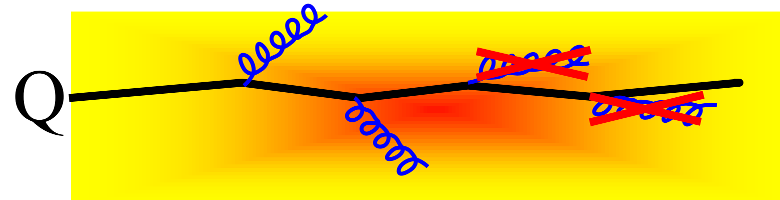
Energy loss

color coupling factor: 4/3 for q, 3 for g

$$\frac{\langle k_T^2 \rangle}{\lambda}$$ medium transport coefficient

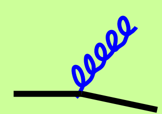


"Dead cone" effect for heavy quarks:



- ✓ in vacuum, gluon radiation suppressed at $q < m_Q/E_Q$
- ✓ in medium, dead cone implies lower energy loss
- ✓ similar mass effect expected for collisional energy loss

Gluonsstrahlung probability

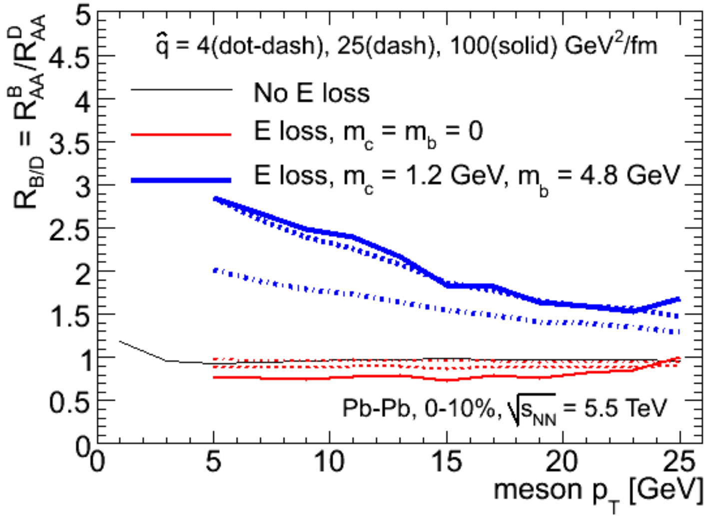


$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

Baier, Dokshitzer, Mueller, Peigne', Schiff, NPB 483 (1997) 291. Salgado, Wiedemann, PRD 68(2003) 014008. Dokshitzer and Kharzeev, PLB 519 (2001) 199. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.

BEAUTY TO CHARM RATIO

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



- c and b have the same color charge → the mass effect is the enhancement of factor ~2, <u>independent</u> of $\hat{q}$ (for $\hat{q} > 20\ \mathrm{GeV}^2/\mathrm{fm}$)

Adapted from Armesto, Dainese, Salgado, Wiedemann, PRD71 (2005) 054027

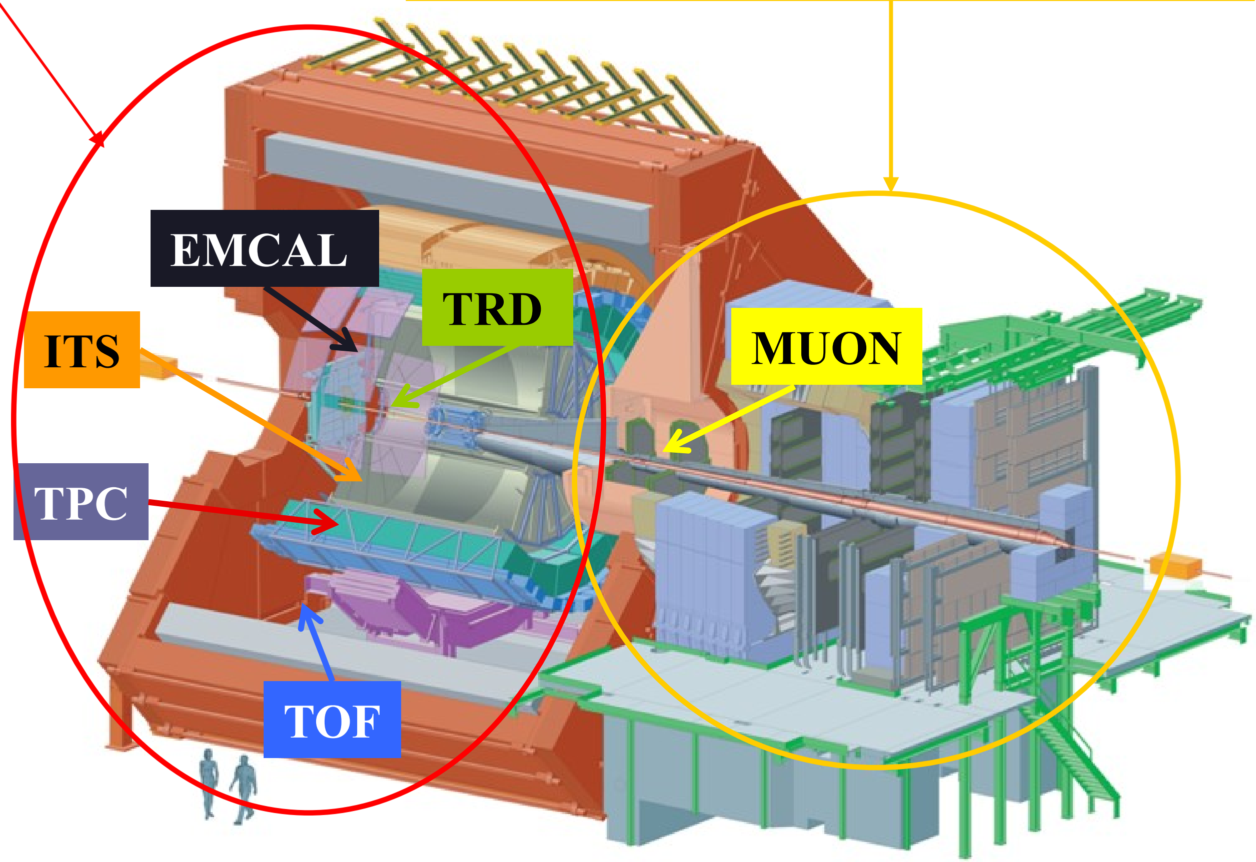
THE ALICE DETECTOR

Muon spectrometer ($-4 < \eta < -2.5$)

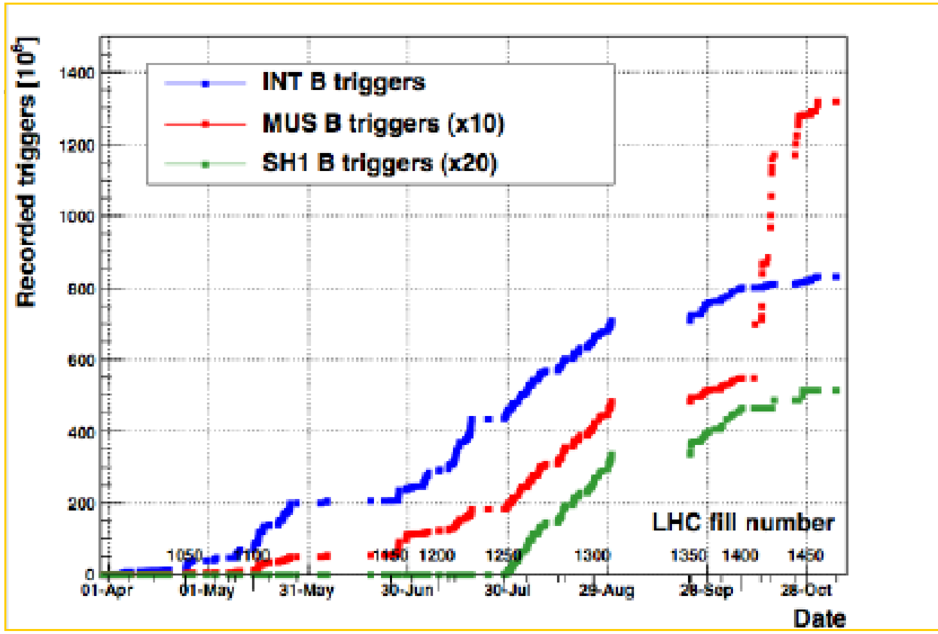
- Absorber
- Muon trigger
- Muon tracker

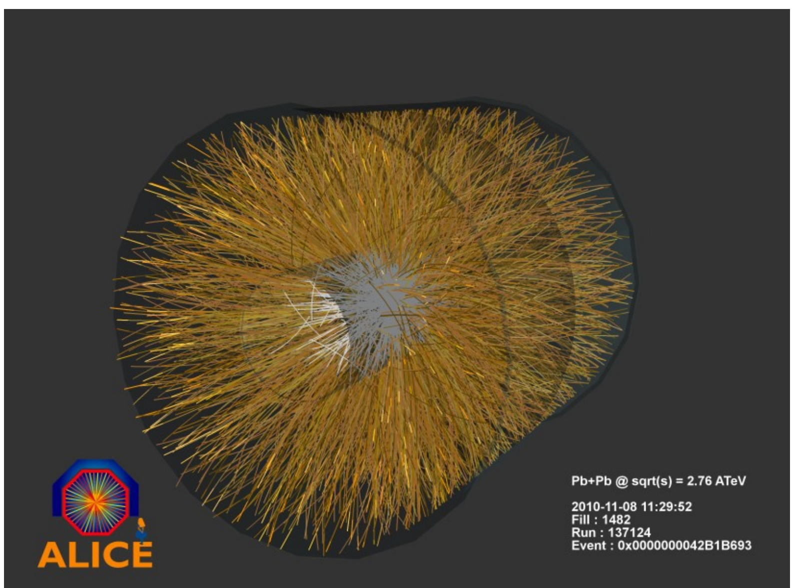
Central barrel ($|\eta| < 0.9$):

- ITS for vertexing, tracking, PID
- TPC for tracking, PID
- TOF for PID
- TRD, EMCAL for e/π separation



DATA TAKING





Data taking in 2009 – 2010:

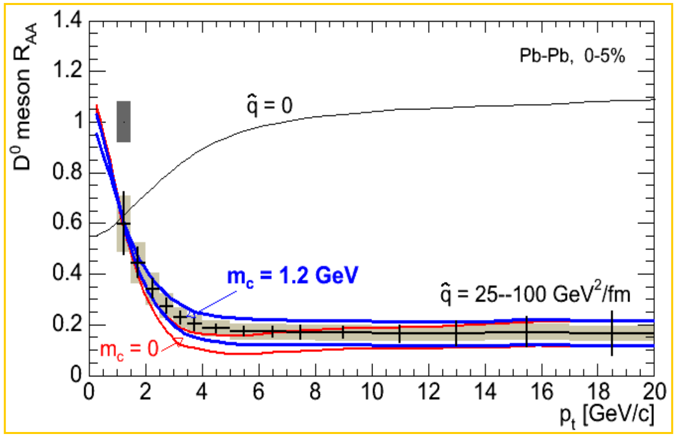
p-p interactions:

- 0.9 TeV : 7M events
- 2.36 TeV: 30k events
- 7 TeV: 800M events min bias (L~7.5 nb^{-1}) + 130M muon triggers
- 2.76 TeV: 74M events min bias + 9M muon trigger

Pb-Pb interactions:

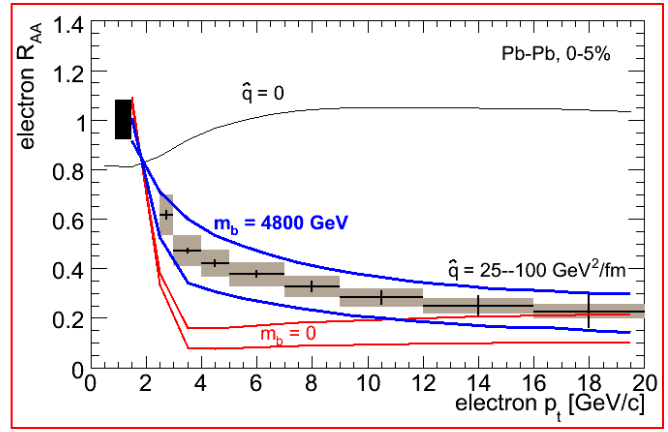
- 2.76 TeV: 50M events

HEAVY TO LIGHT RATIOS IN ALICE



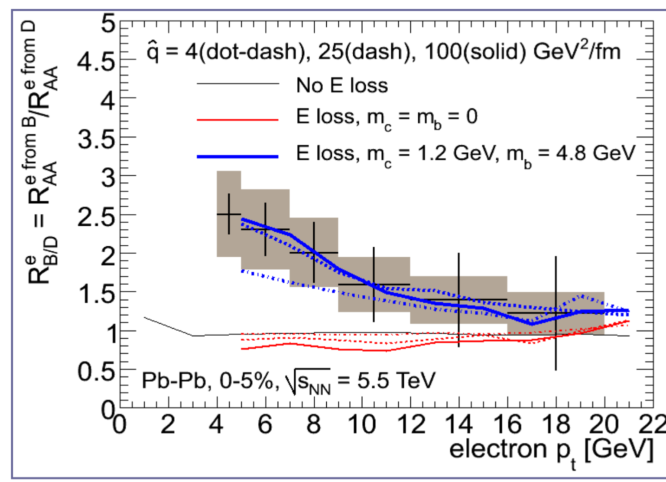
R_{AA} D^0

R_{AA} electrons



$$R_{B/D}(p_t) = R_{AA}^{\text{e from B}}(p_t) \big/ R_{AA}^{\text{e from D}}(p_t)$$

- ALICE can separate b & c contributions!
- expectations for 1 year at nominal luminosity (10^7 central Pb-Pb events @ 5.5 TeV, 10^9 pp events)



E loss calc.: Armesto, Dainese, Salgado, Wiedemann

HEAVY FLAVOR MEASUREMENTS

✓ *Open charm :*

$D^0 \rightarrow K\pi$,
$D^+ \rightarrow K\pi\pi$,
$D_s \rightarrow KK\pi$,
$D^* \rightarrow D^0\pi$,
$D^0 \rightarrow K3\pi$,
$\Lambda_c \rightarrow \pi K p$

✓ *quarkonium:* → ee , μμ

✓ *charm & beauty → e + X*

✓ *charm & beauty → μ+ X*

✓ *outlook:*

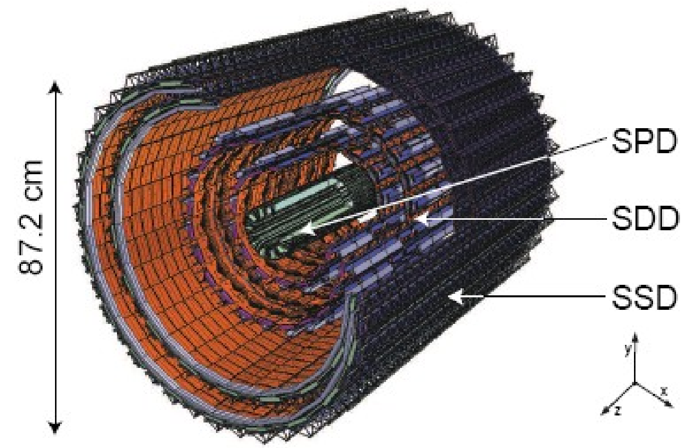
✓ *Beauty:* $B \rightarrow e + X$,
$B \rightarrow X\ J/Psi$

Features	**What is needed to detect them**
"Rare" decays	excellent tracking (TPC + ITS) √
Displaced secondary vertex as signature of heavy-quark decay: $c\tau$ = 60μm – 300μm	good vertexing + impact parameter resolution (ITS) √
High combinatorial background	good Particle IDentification (TPC, ITS, TOF,TRD) √

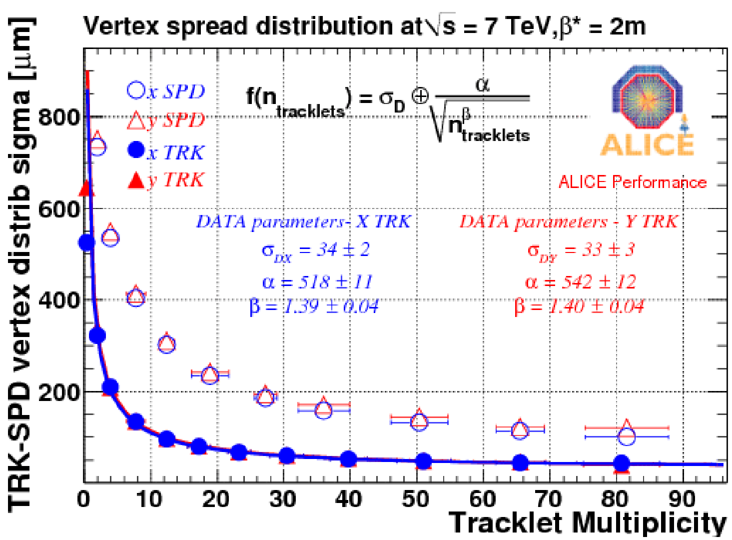
→ *The ALICE detector has all we need!*

TRACKING & VERTEXING PERFORMANCE

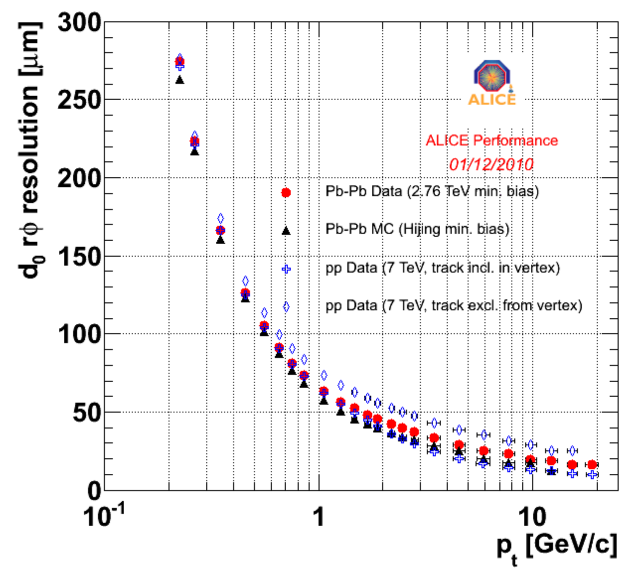
- 3 different technologies used:
  - Silicon Pixel Detector
  - Silicon Drift Detector
  - Silicon Strip Detector



Vertex

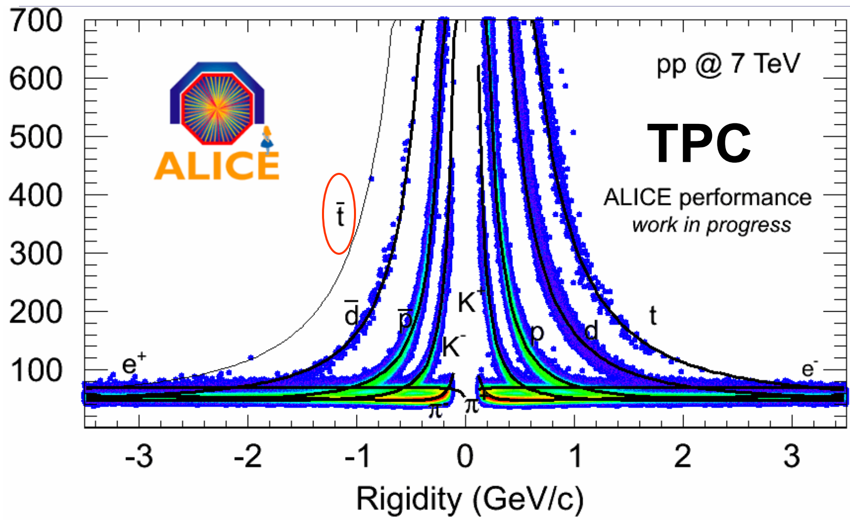


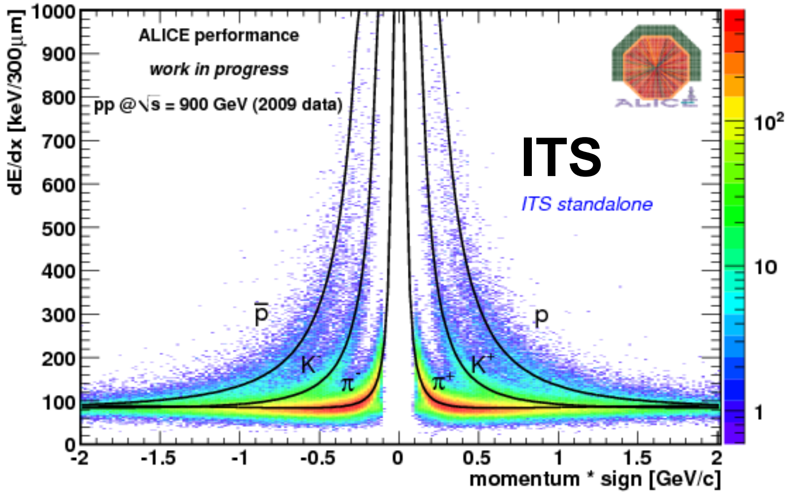
Impact parameters



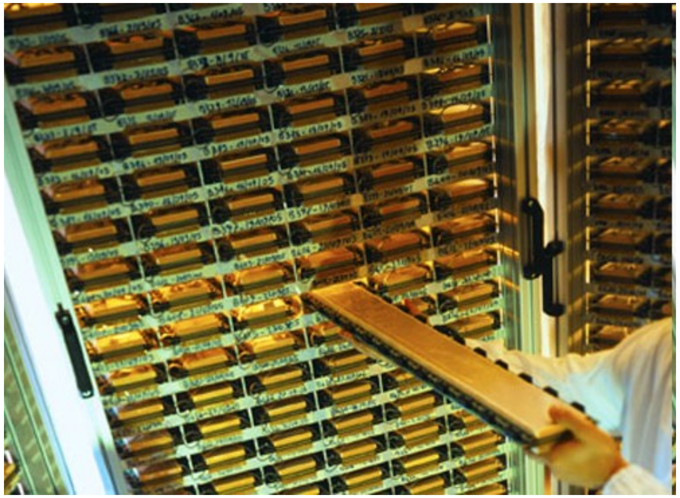
Excellent vertexing and good impact parameter resolution!

ONE OF THE ALICE SPECIALTIES: Particle IDentification!

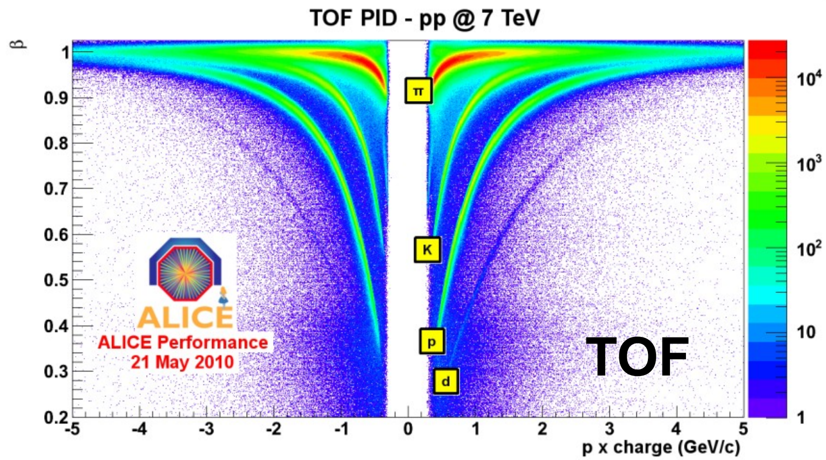




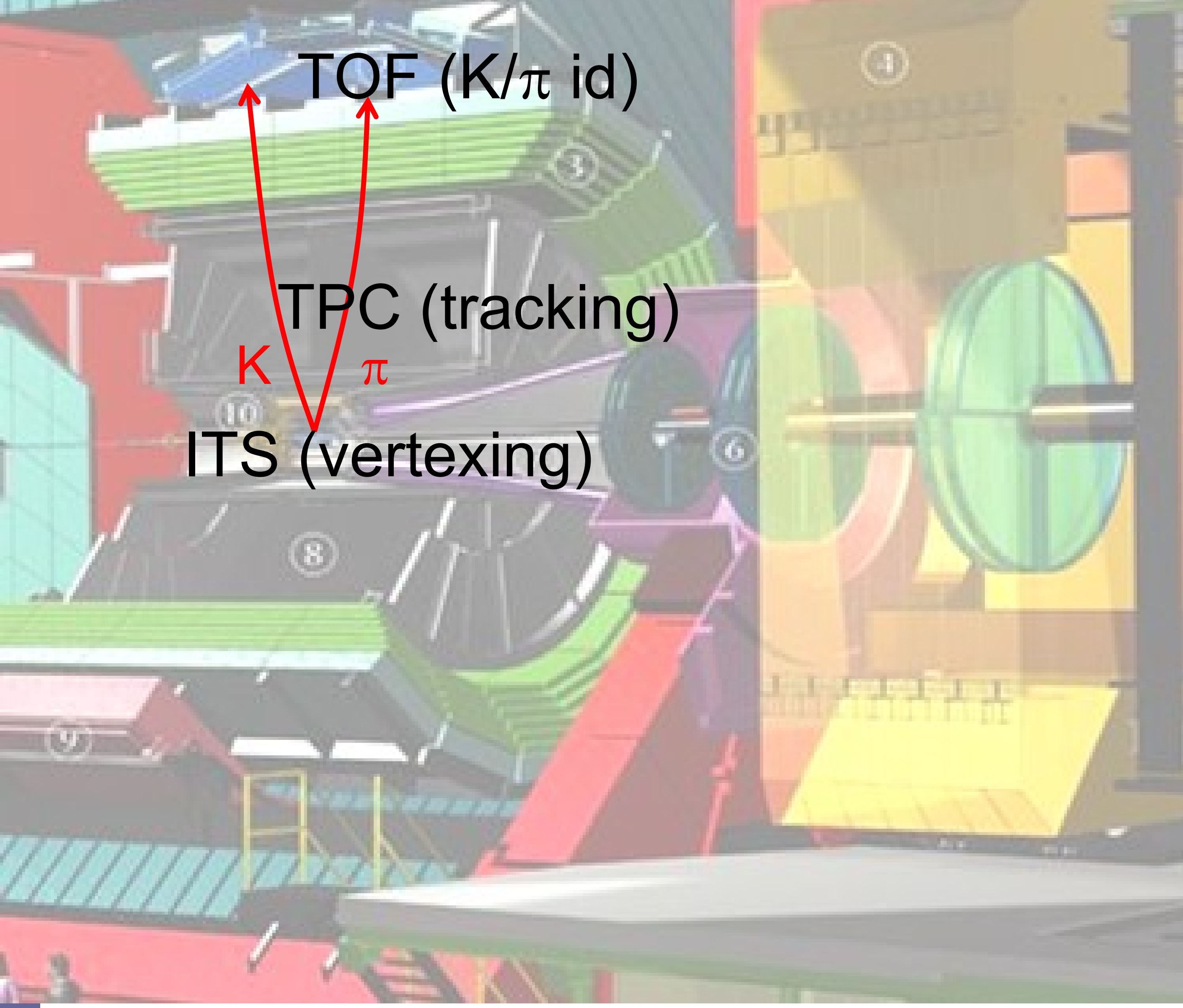
The detectors are complementary and cover the whole p_T range



TOF



OPEN CHARM IN ITS HADRONIC DECAYS



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

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

$D^{*+} \rightarrow D^0\pi^+$

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

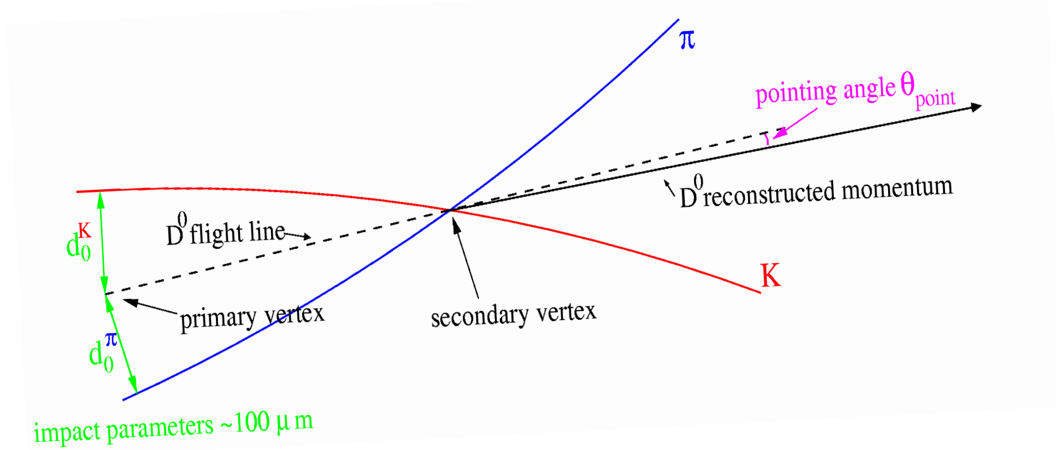
$D_s \rightarrow K^-K^+\pi^+$

$\Lambda_c{}^+ \rightarrow pK^-\pi^+$

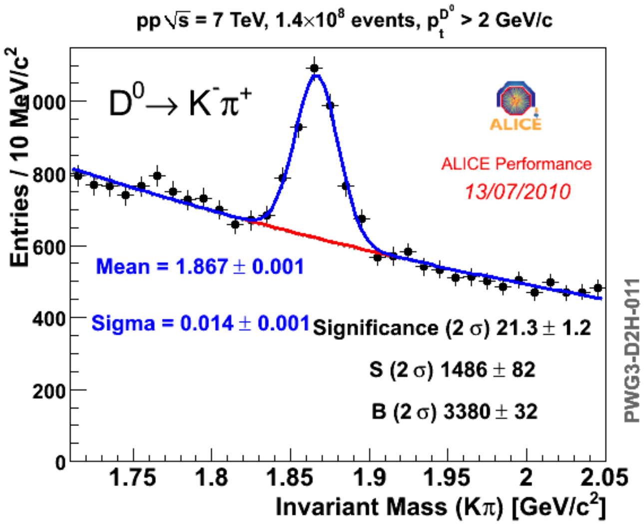
ANALYSIS STRATEGY

Charm candidates "production" (vertexing) → Raw signal extraction → Corrections (efficiencies, acceptance, feed-down from B)

- Topological cuts to reduce background
- Invariant mass analysis to extract the raw signal yield
- 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

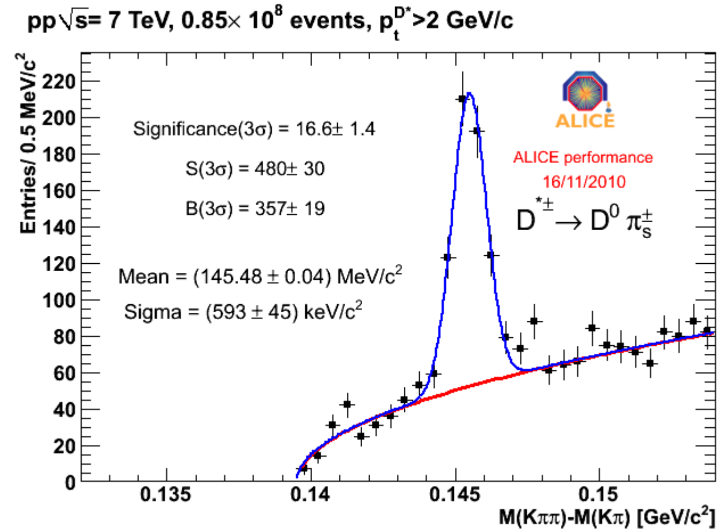


RAW SIGNAL EXTRACTION



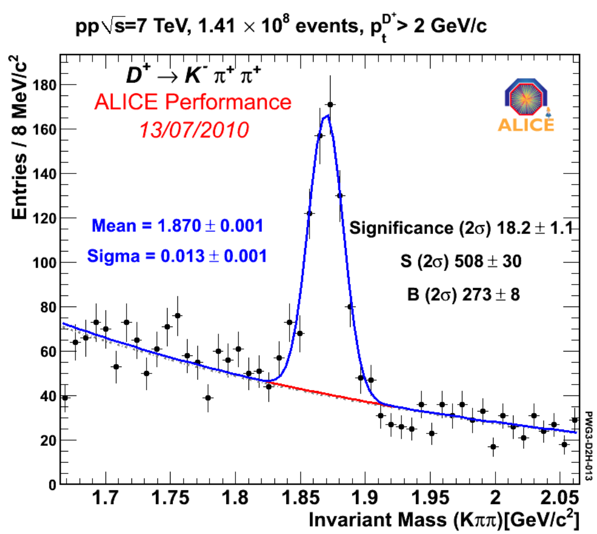
signal in 6 p_T bins

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



$D^0 \rightarrow K\pi$

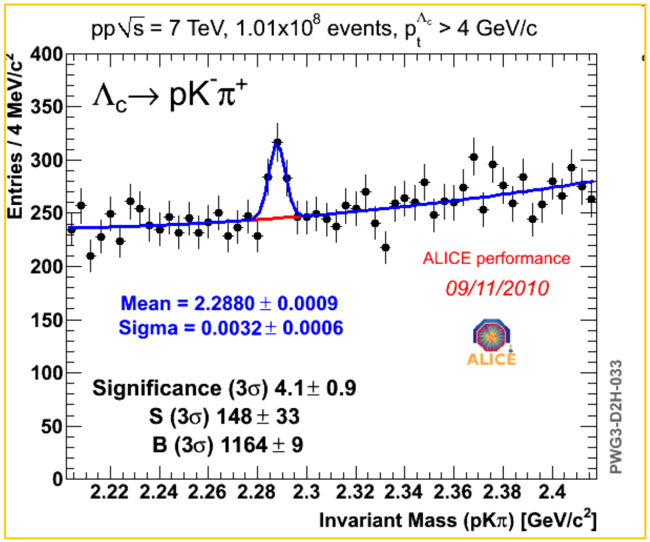
signal in 6 p_T bins



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

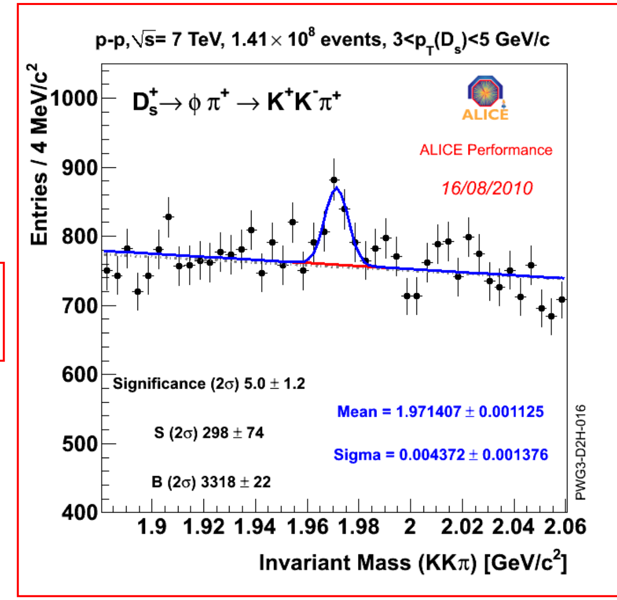
signal in 6 p_T bins

OTHER DECAY CHANNELS UNDER STUDY

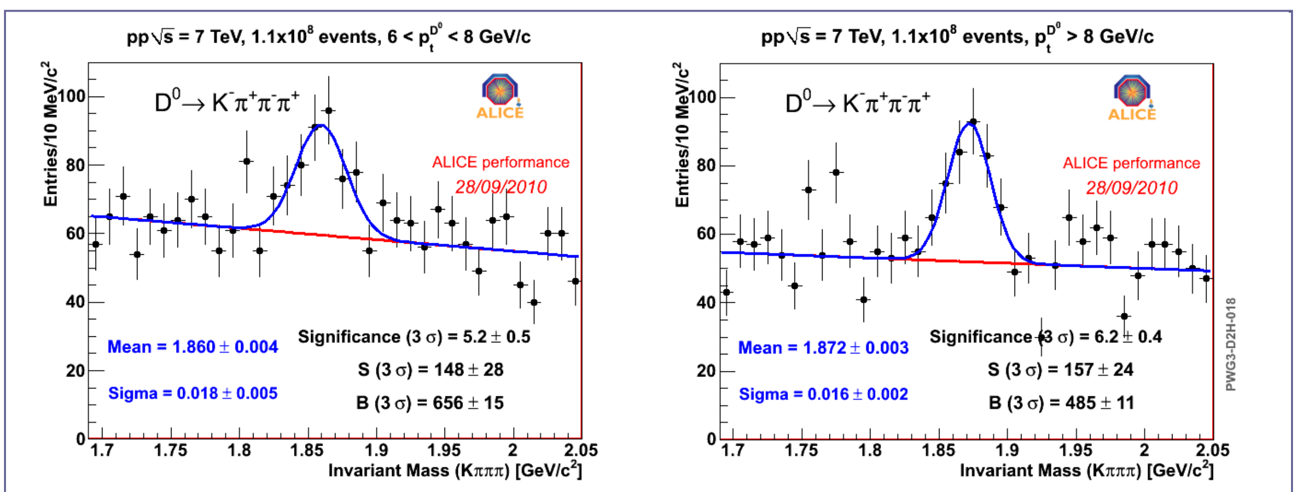


$\Lambda_c \rightarrow pK\pi$

$D_s \rightarrow KK\pi$



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



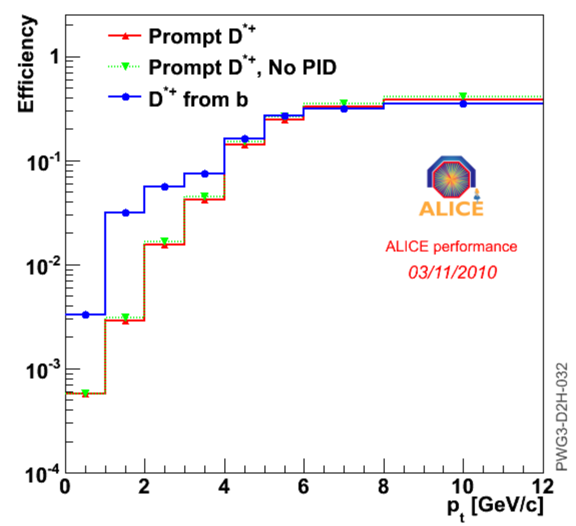
TOWARDS A CROSS SECTION

$$\left.\frac{d\sigma^{D}(p_T)}{dp_T}\right|_{|y|<0.5} = \frac{1}{2}\times\frac{1}{L\times\Delta y(p_T)\times BR}\times\frac{1}{\varepsilon_c}\times f_c\times\left(N^{(D)}(p_T)\right)^{raw}_{|y|<0.5}$$

Integrated luminosity

Efficiencies for prompt charm

- PID efficiency almost 100%



TOWARDS A CROSS SECTION

$$\left.\frac{d\sigma^{D}(p_T)}{dp_T}\right|_{|y|<0.5} = \frac{1}{2}\times\frac{1}{L\times\Delta y(p_T)\times BR}\times\frac{1}{\varepsilon_c}\times f_c\times\left(N^{(D)}(p_T)\right)^{raw}_{|y|<0.5}$$

fraction of prompt D

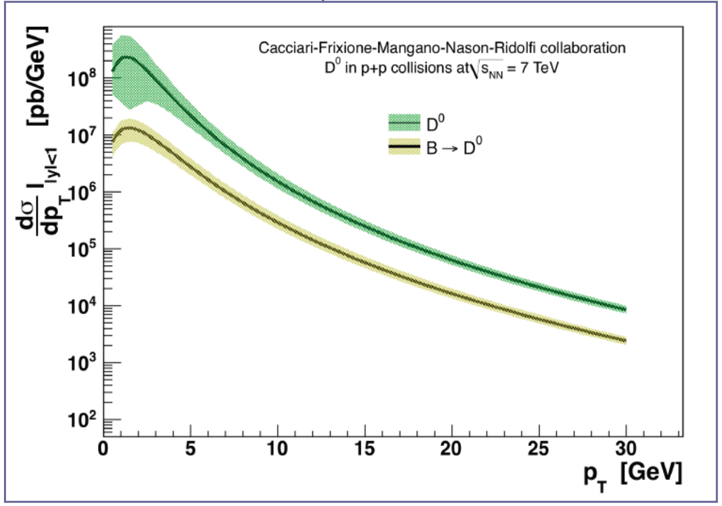
(D ← B 20%)

- "feed down" correction:

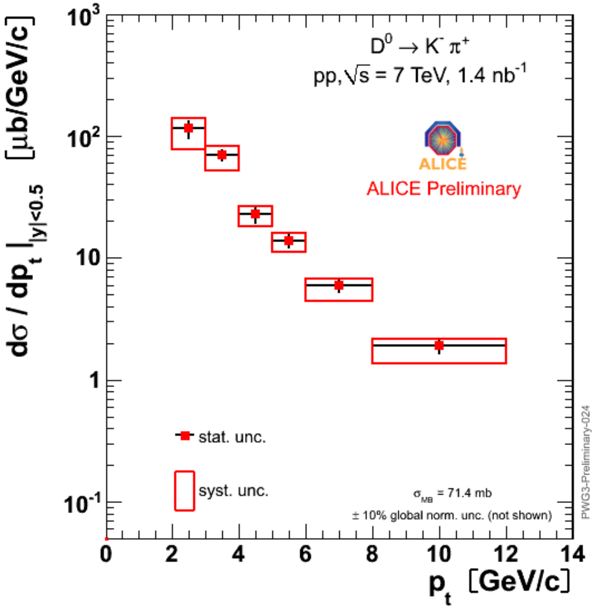
FONLL predictions+ efficiency from MC

✓ FONLL reproduces well B production for CMS and LHCb

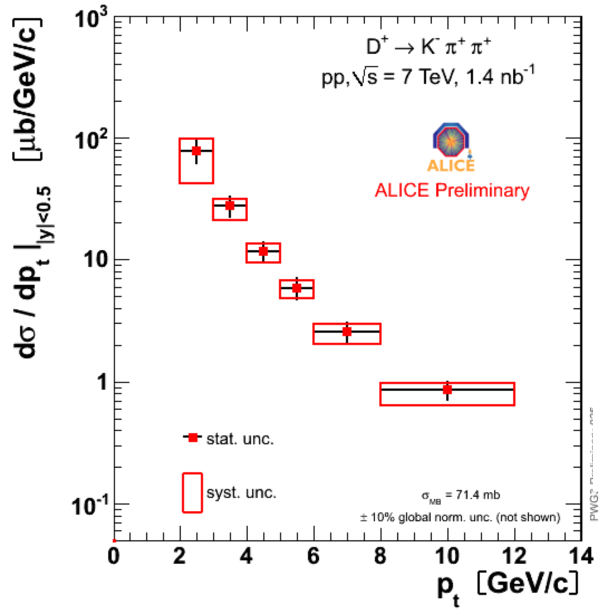
measured raw yield

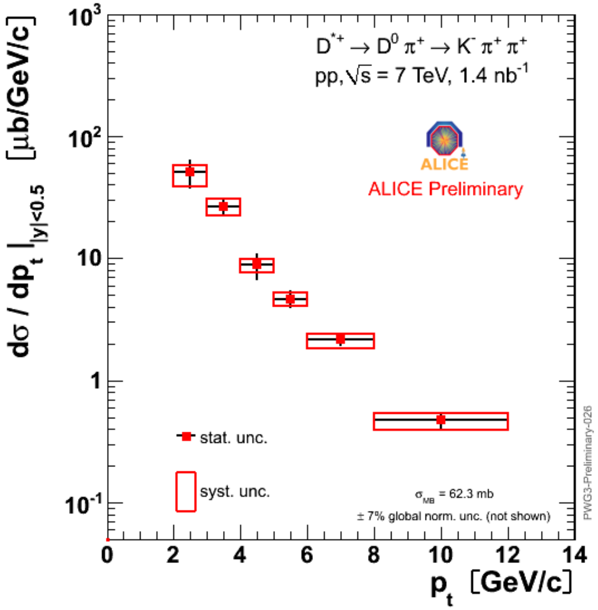


CROSS SECTIONS (I)



D0



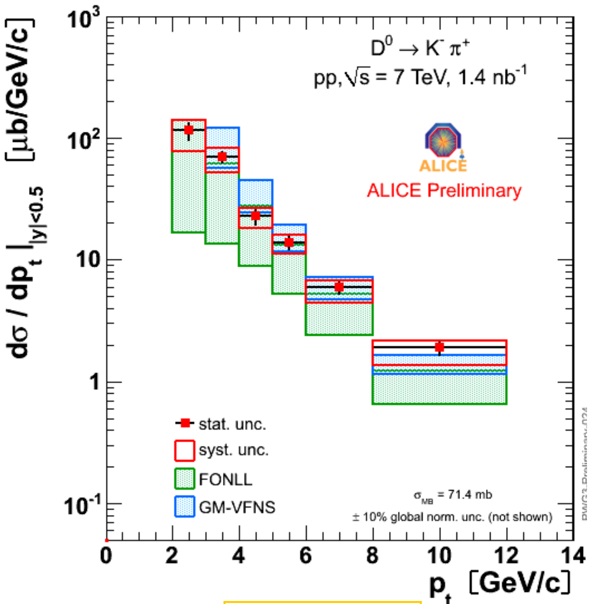


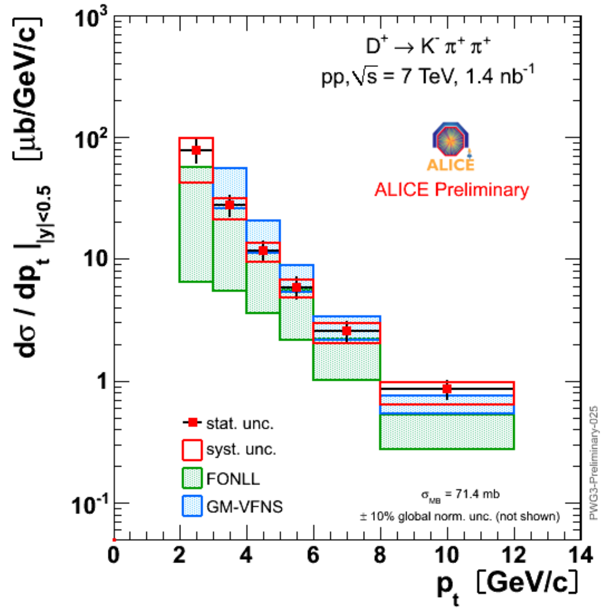
D*

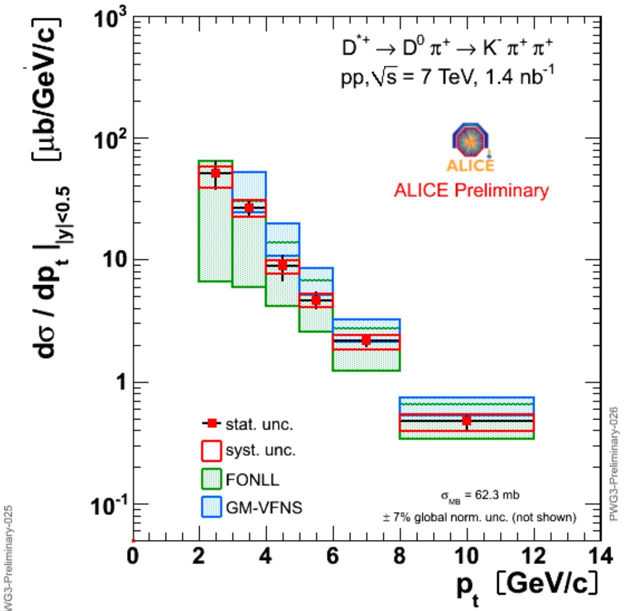
- ✓ Obtained with 1.4 nb^{-1} integrated luminosity
- ✓ $2<p_T<12$ GeV/c
- ✓ systematic errors ~ 20% – 40 %

CROSS SECTIONS (II)

D+







D0

D*

✓pQCD predictions in agreement with data

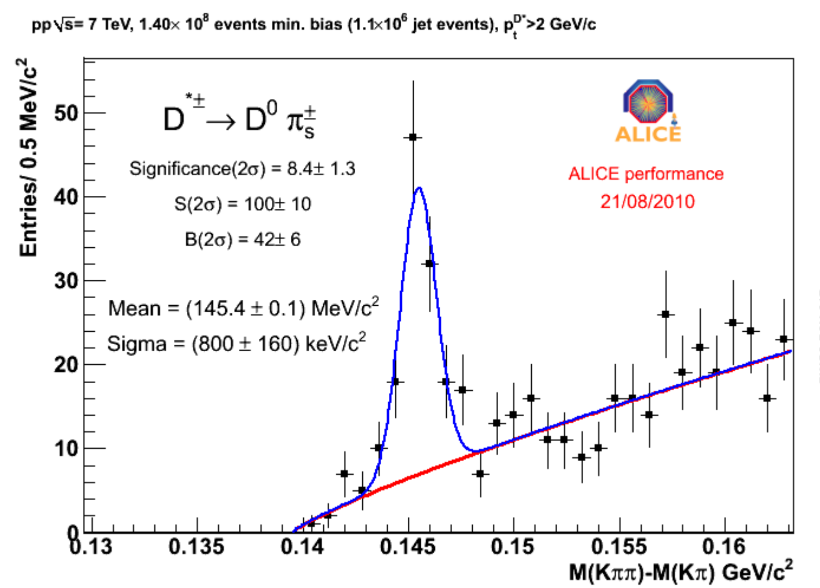
✓ Outlook:

- ✓extend p_T range
- ✓feed down correction using data

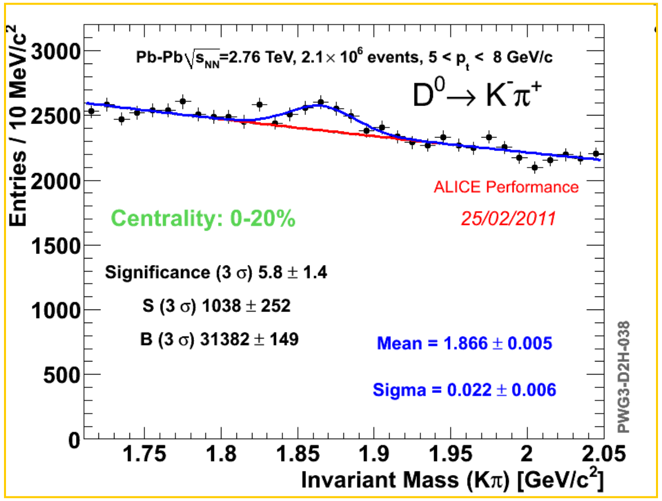
D* IN JETS

- The understanding of D* content in jets can be used to evaluate the gluon splitting ratio in ccbar
- Azimuthal correlation of D* with the jet axis:
  - the gluon splitting contribution is in the near-side peak
  - pair creation in both away - and near- side, but with a different fragmentation characteristic

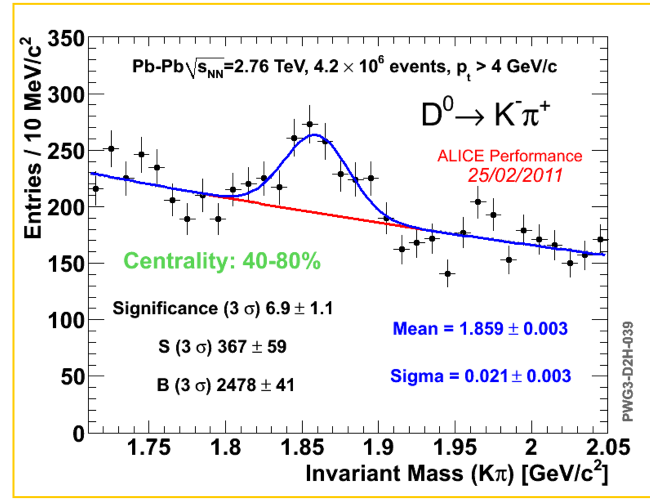
- Jets are reconstructed with UA1: cone size R=0.4, energy threshold of 10 GeV → an example, other algorithms can be used!
- Jet axis is required to have |η|<=0.5
- Only D* candidates with momentum direction inside the jet cone



D MESONS IN Pb-Pb

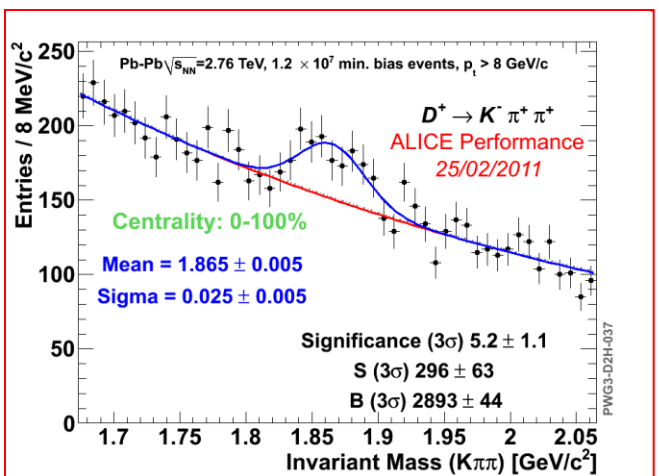


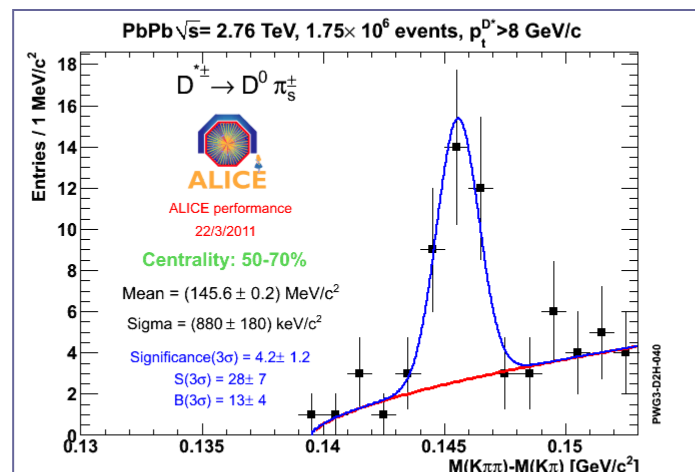
$D^0 \rightarrow K\pi$



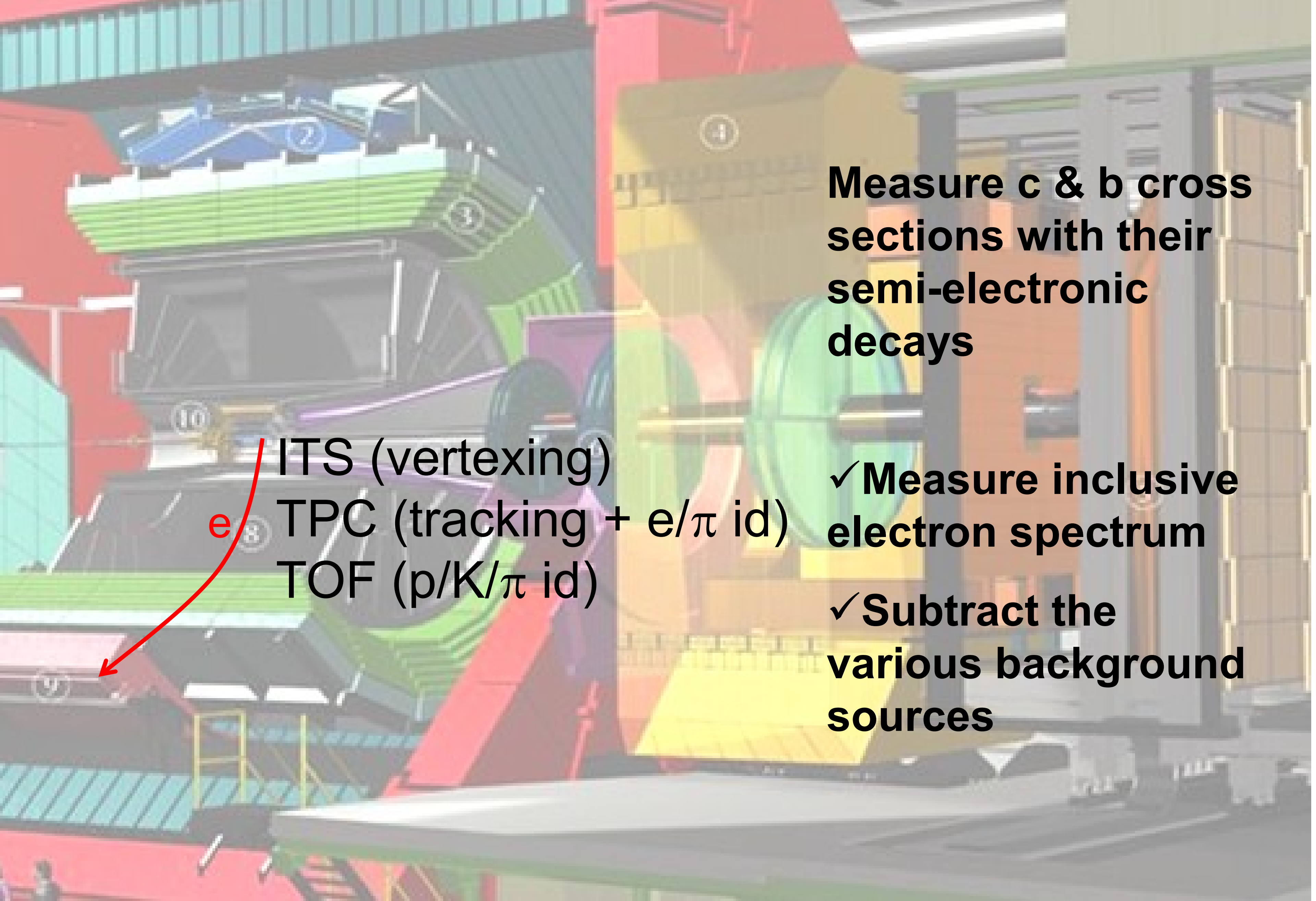
$D^+ \rightarrow K\pi\pi$

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





SINGLE ELECTRONS



ITS (vertexing)
TPC (tracking + e/π id)
TOF (p/K/π id)

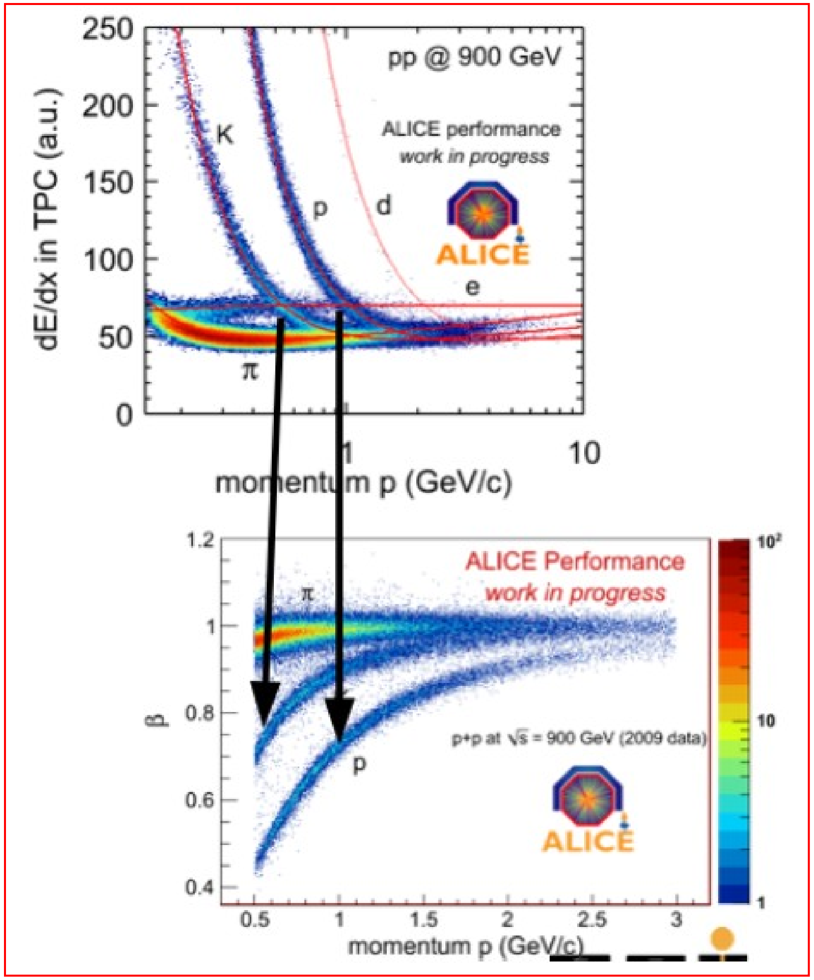
Measure c & b cross sections with their semi-electronic decays

✓Measure inclusive electron spectrum

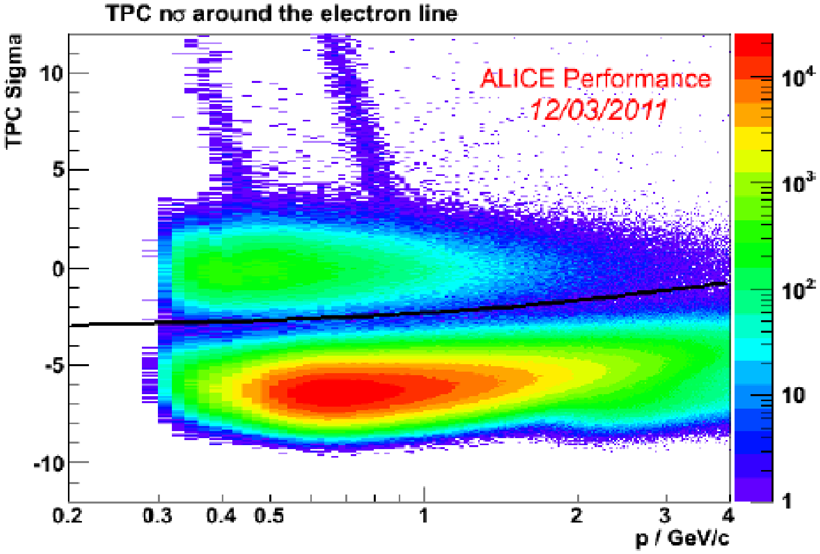
✓Subtract the various background sources

ELECTRON IDENTIFICATION (I)

- Present strategy based on TOF and TPC
  - Effective for p_t<4 GeV/c
  - TOF rejects protons up to 3 GeV/c and kaons up to 1.5 GeV/c, i.e where electron dE/dx in TPC crosses kaon and proton curves
- Next step: include TRD and EMCAL to extend the electron identification to higher momenta

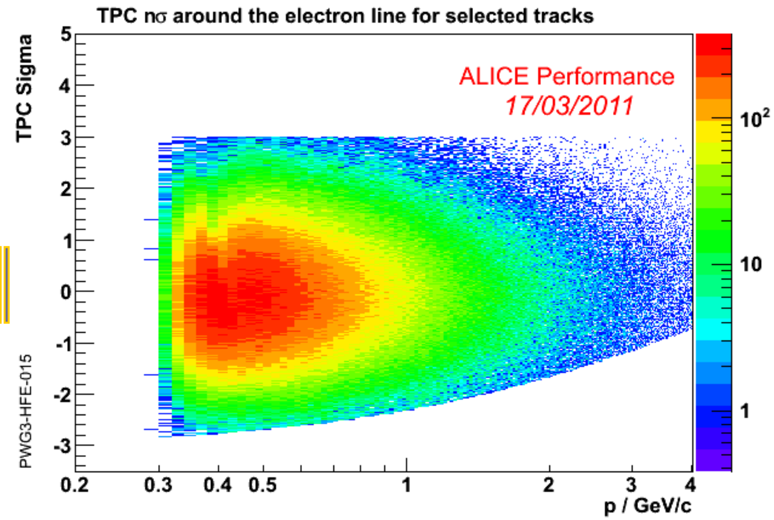


ELECTRON IDENTIFICATION (II)



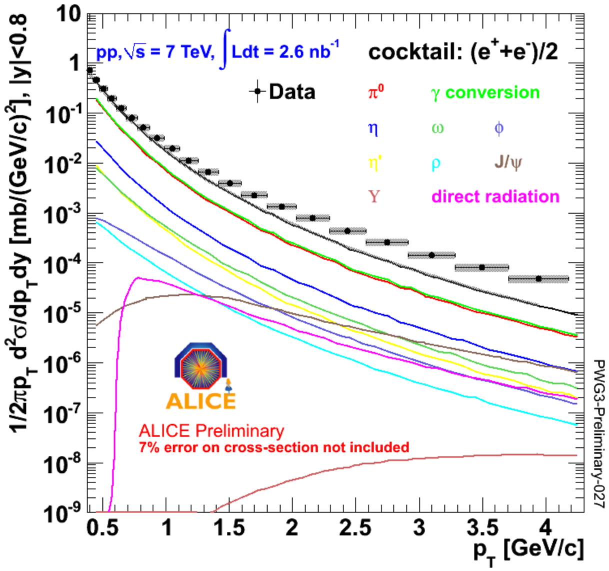
Further hadron rejection with TPC

- n. sigma cut with respect to electron expected dE/dx

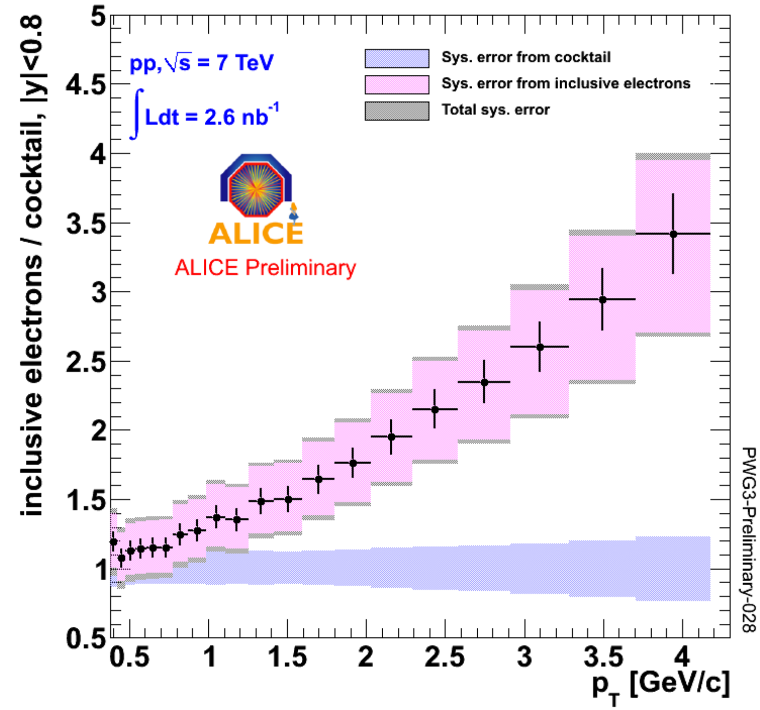


- Remaining hadron contamination estimated from data and subtracted (few % only!)
- Efficiency ~ 30%

ELECTRON SPECTRUM & COCKTAIL



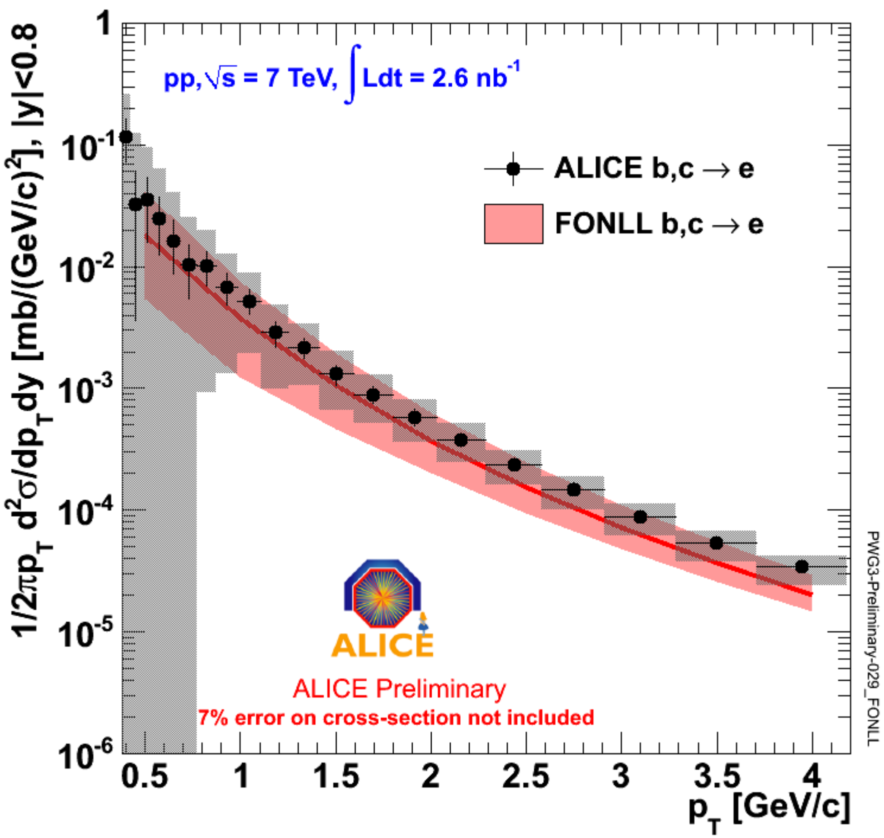
making
a ratio ..



- Ingredients for the cocktail:
  - Dalitz decay of π^0 (from data)
  - heavy mesons (η,η',ρ,Φ,ω,J/ψ)
  - photon conversions (in the beam pipe and in the internal layer of the ITS)

- The excess of electrons comes from charm & beauty

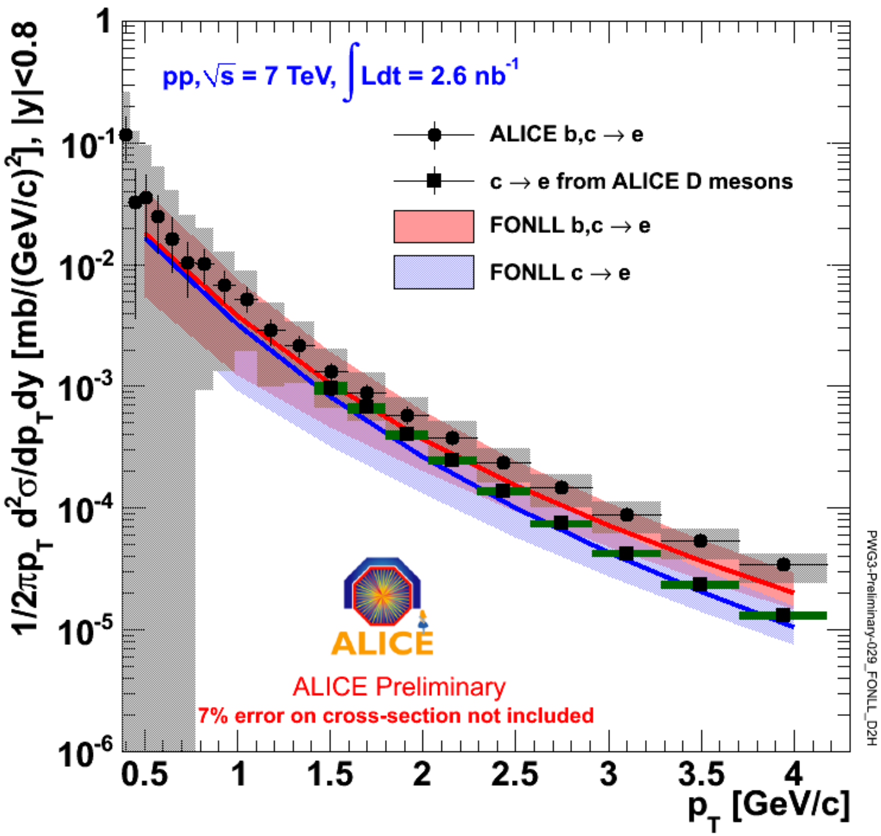
Heavy Flavor Electron CROSS SECTION (I)



✓ Comparison with the FONLL prediction for charm & beauty → e

✓ HFE spectrum harder and in good agreement with the FONLL prediction for charm & beauty → e

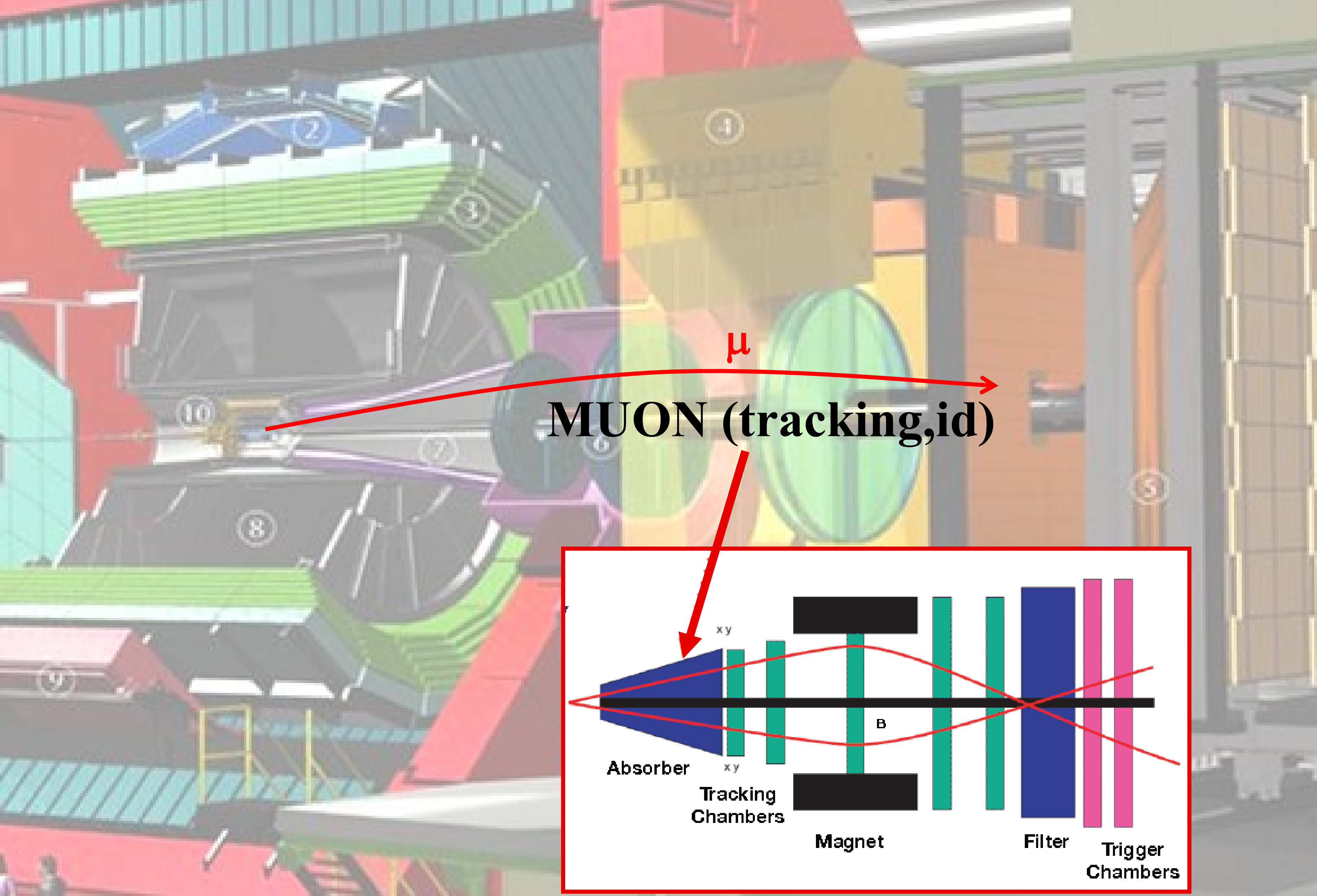
Heavy Flavor Electron CROSS SECTION (II)



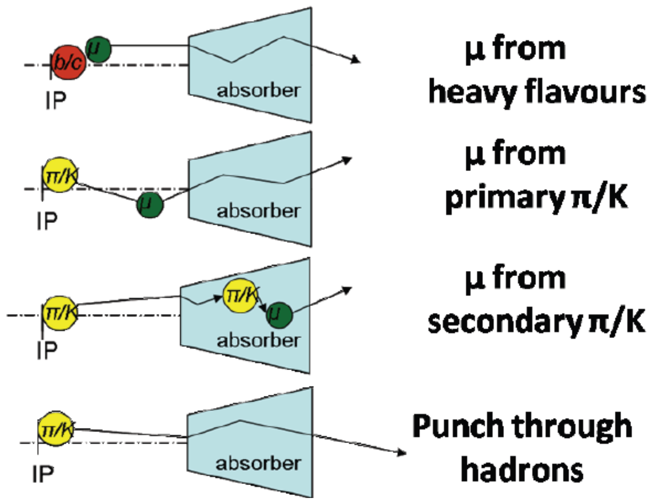
✓ The charm cross section measured with D meson decays is used to produce an electron spectrum

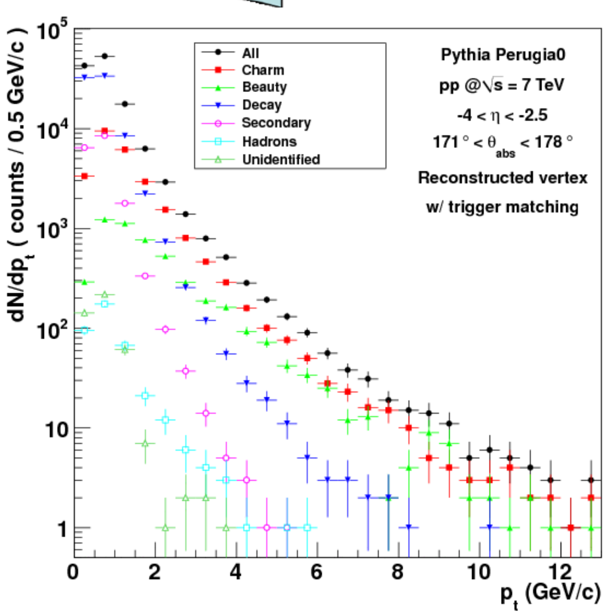
✓ Harder part of the HFE spectrum → contribution from beauty decays

SINGLE MUONS



HEAVY FLAVOR SINGLE MUONS





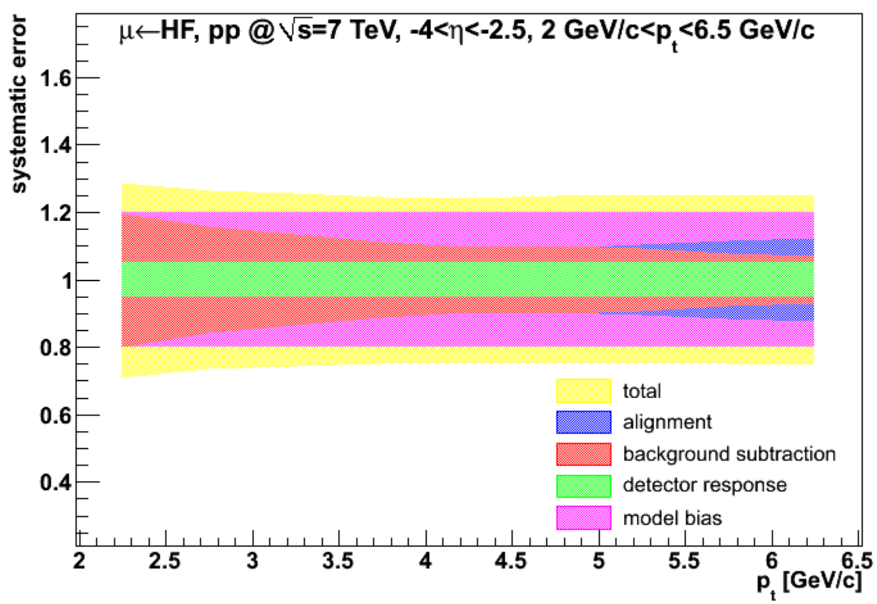
- Analysis strategy:
  - Remove hadrons and low p_t secondary muons that do not make it to the trigger station
  - Remove residual decay muons by subtracting MC dN/dp_t normalized to data at low p_t
    - Alternative method: use muon distance-of-closest-approach to primary vertex

→ What is left are muons from charm and beauty

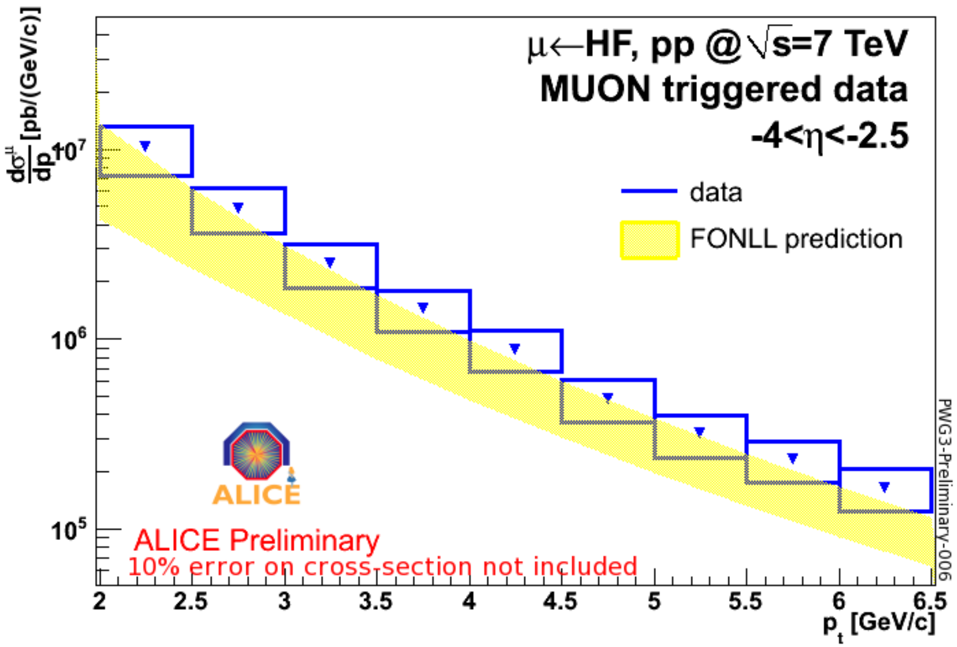
- Apply efficiency corrections

SYSTEMATICS

- Main sources of systematic errors:
  - subtraction of background of decay muons from π and K (≈20% at low p_T)
    - use different PYTHIA tunes (Perugia-0 vs. ATLAS-CSC) and vary secondary yield to estimate systematic error
  - efficiency correction (≈5%)
    - mainly due to the description of the detector response in the MC



HEAVY FLAVOR SINGLE MUONS $d\sigma/dp_t$



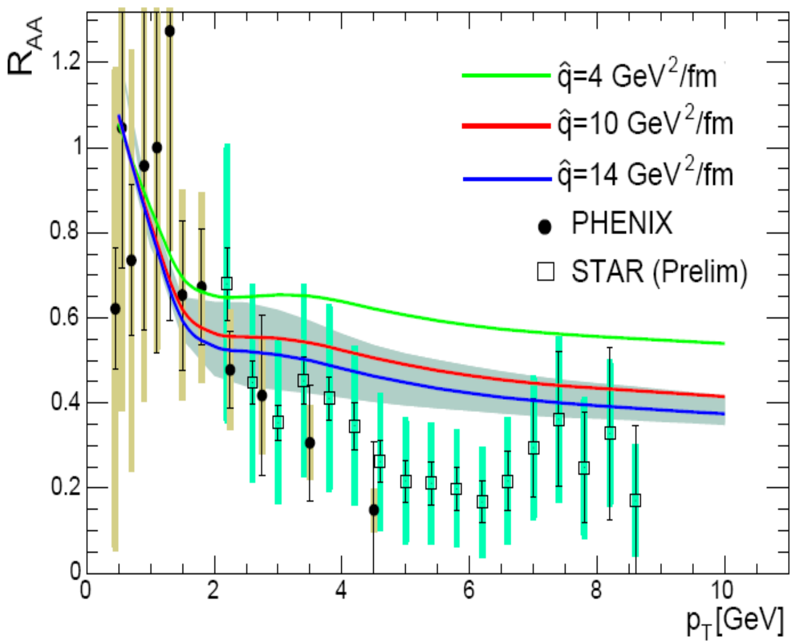
- ✓ p_t differential cross section for muons from B and D decays measured in pt range 2.0-6.5 GeV
- ✓ Obtained with 3.49 nb-1 integrated luminosity → reach 15-20 GeV/c with full 2010 statistics
- ✓ reference for R_{AA} in PbPb
- ✓ pQCD prediction (FONLL) reproduces the shape of measured cross section and is in agreement with data within errors

CONCLUSIONS

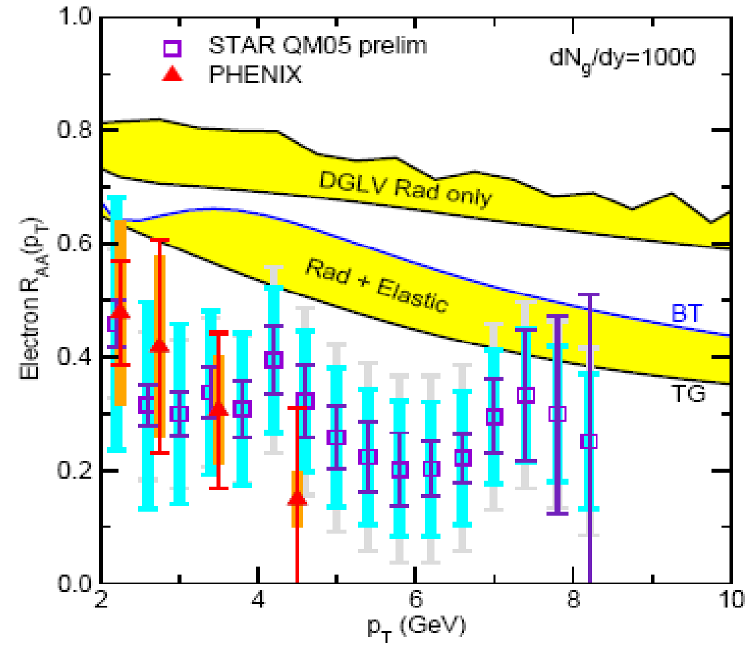
- Heavy flavors are a unique probe
  - to understand the properties of the medium and energy loss studies, in Pb-Pb
  - to test pQCD calculations and provide reference to Pb-Pb, in p-p
- ALICE has a very rich heavy flavor programme:
  - excellent tracking and vertex performances
  - heavy flavor cross section is measured both in the hadronic and semi leptonic channels, in different rapidity regions, down to low pT
- First results on p-p data:
  - cross sections of charmed mesons $D^{0,+,*}$ measured, the pQCD calculations are in agreement with data
  - heavy flavor electron cross section measured and at high p_T we measure the beauty component
  - heavy flavor muons cross section in the forward rapidity region is also measured and compared with pQCD
- Pb-Pb results coming soon!

HFE SUPPRESSED AT RHIC

Indirect measurement: non-γ electrons (Dalitz and conversions subtracted); c / b inclusive (large uncertainty on pp baseline!!)



Radiative



Radiative + Collisional

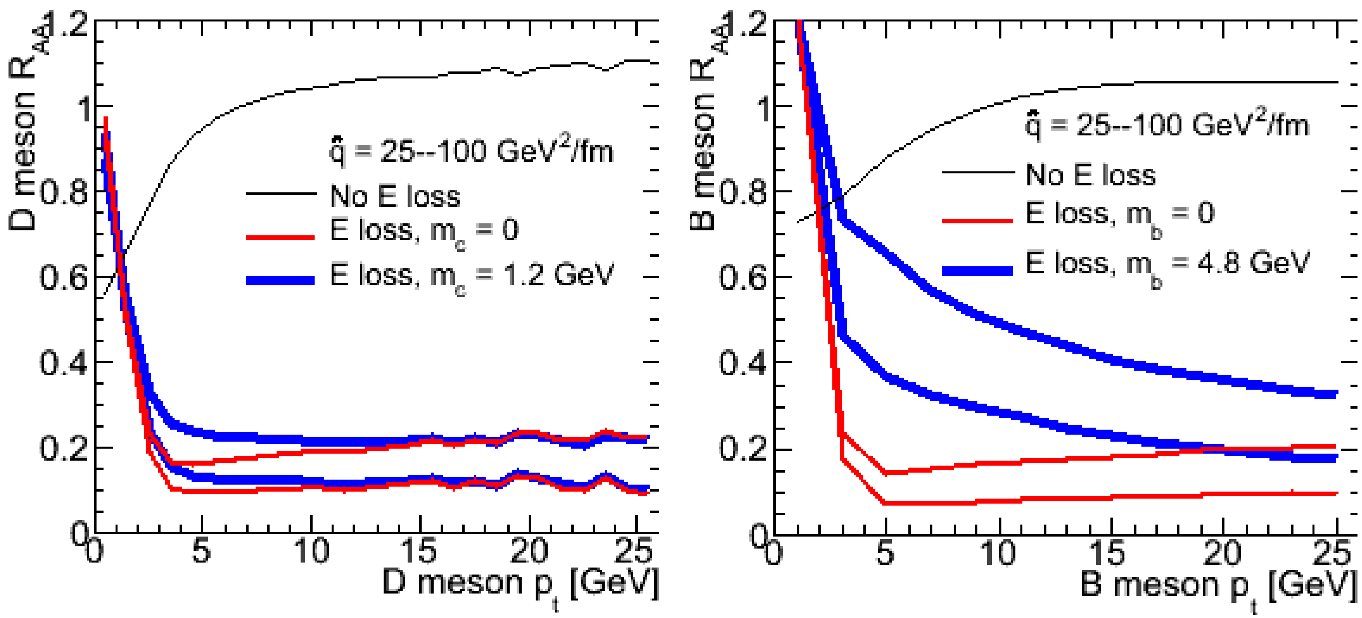
Energy loss calculations tend to underpredict suppression

Armesto, Cacciari, Dainese, Salgado, Wiedemann, PLB637 (06) 326.

Djordjevic, Gyulassy, Wicks, nucl-th/0512076

Heavy Flavour R_{AA} at LHC

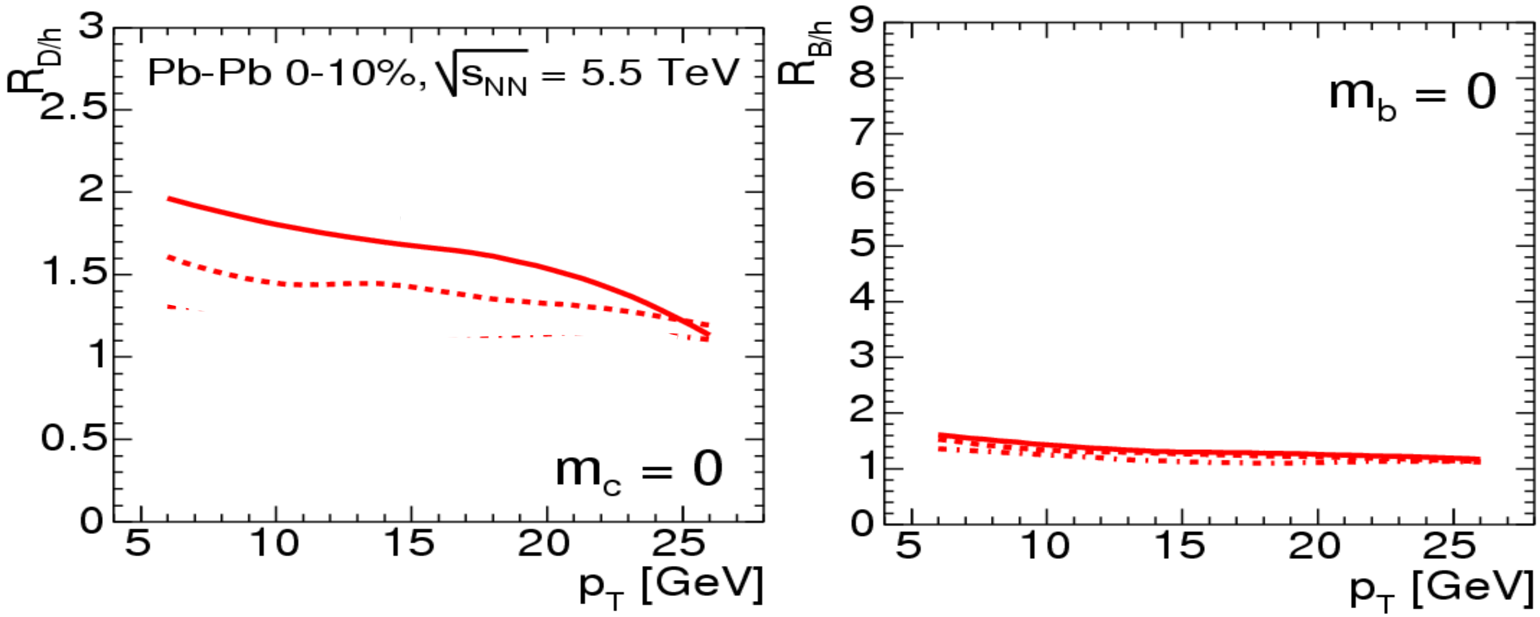
- Baseline: PYTHIA, with EKS98 shadowing, tuned to reproduce c and b p_T distributions from NLO pQCD (MNR)
- (m/E)-d



$$\hat{q}_{LHC} \approx 7^{*} \times \hat{q}_{RHIC} = 25 \div 100 \text{ GeV}^2/\text{fm}$$

Armesto, Dainese, Salgado, Wiedemann, PRD 71 (2005) 054027.

* EKRT Saturation model:
Eskola, Kajantie, Ruuskanen, Tuominen, NPB 570 (2000) 379.



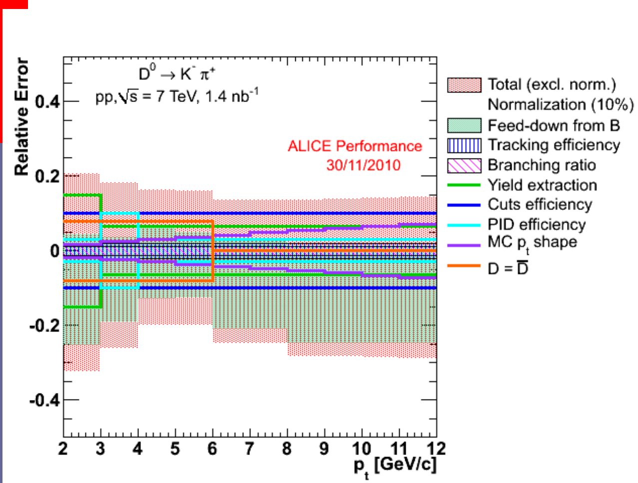
Pb-Pb 0-10%, $\sqrt{s_{NN}}$ = 5.5 TeV
$R_{D/h}$
$m_c = 0$
p_T [GeV]
$R_{B/h}$
$m_b = 0$
p_T [GeV]

SYSTEMATIC ERRORS

- Main sources of systematic errors
  - Tracking efficiency
  - yield extraction
  - selections (topological and PID)
  - normalization
  - Feed down from B

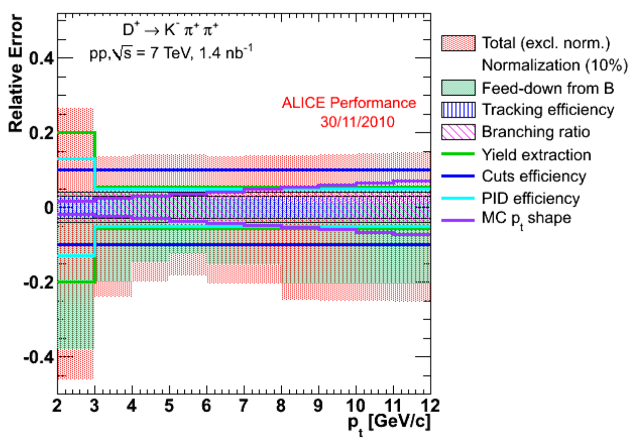
TOTAL: ~ 20-40%

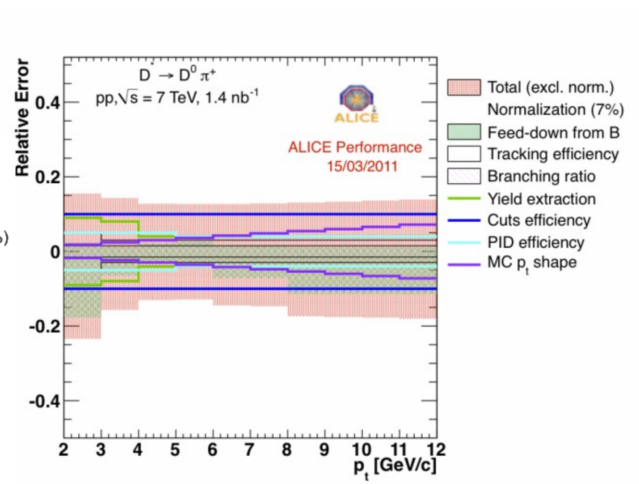
To be reduced with statistics



D^0

D^+

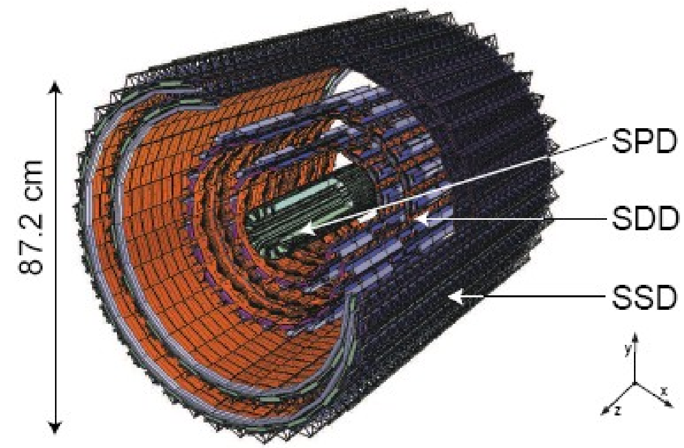




D^*

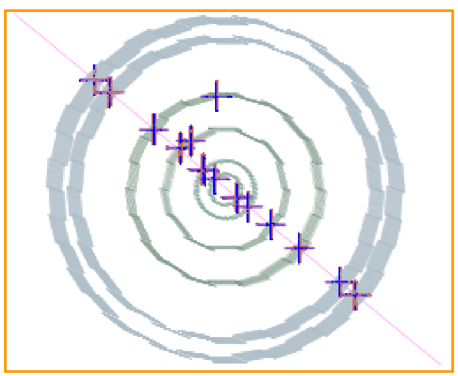
Inner Tracking System

- 3 different technologies used:
  - Silicon Pixel Detector
  - Silicon Drift Detector
  - Silicon Strip Detector

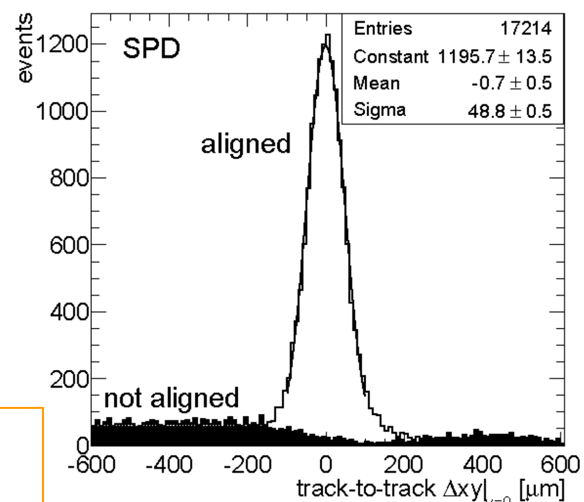


Good alignment is needed to get excellent tracking and vertexing!

For example : SPD Alignment



Δ_{xy} → distance between 2 half tracks in the xy plane at y=0



2010 JINST P03003

- $\sigma_{r\varphi} \approx$14 mm
- misalignment < 10 mm

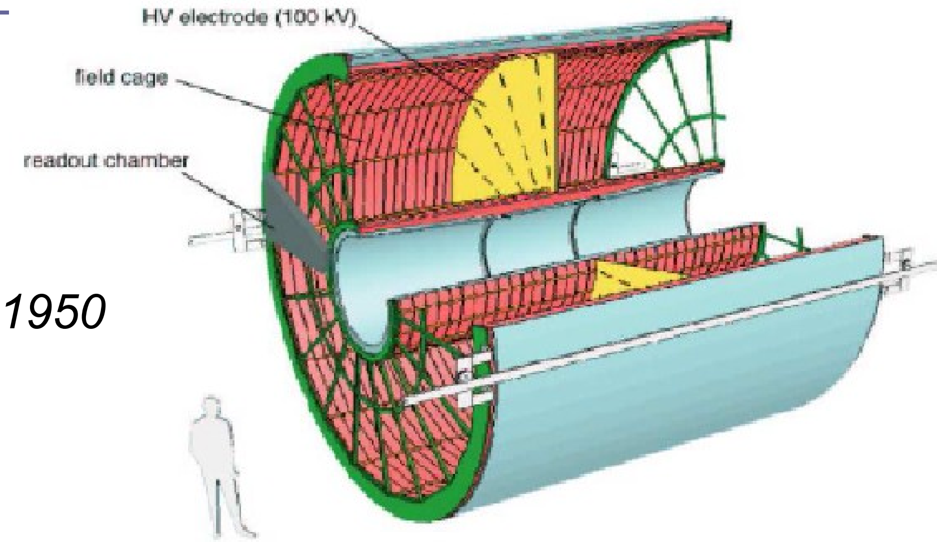
→close to design values

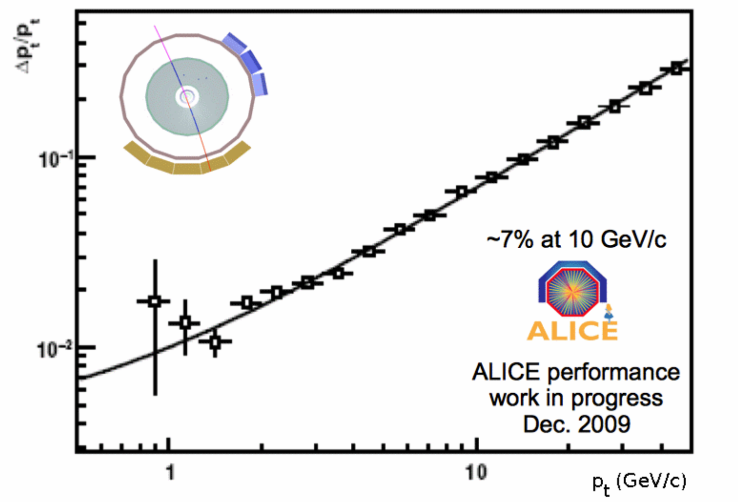
Time Projection Chamber

Challenge: reconstruct 15000 primary tracks in heavy ion collisions!

- biggest ever built!
- minimal material budget
- first calibration completed before data taking!

arXiv:1001.1950





- match two segments of cosmic tracks
- momentum resolution very close to detector design:
  - 7% at 10 GeV/c
  - < 1% at p_T< 1 GeV/c confirmed from K^0_s measurement