Open heavy-flavour production with the ALICE experiment at the LHC

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- Aim of ALICE: study of the Quark Gluon Plasma formed in ultra-relativistic heavy-ion collisions

A–A collisions

- Heavy flavours are probes of the medium

p–A collisions

- Disentangle the initial state effects

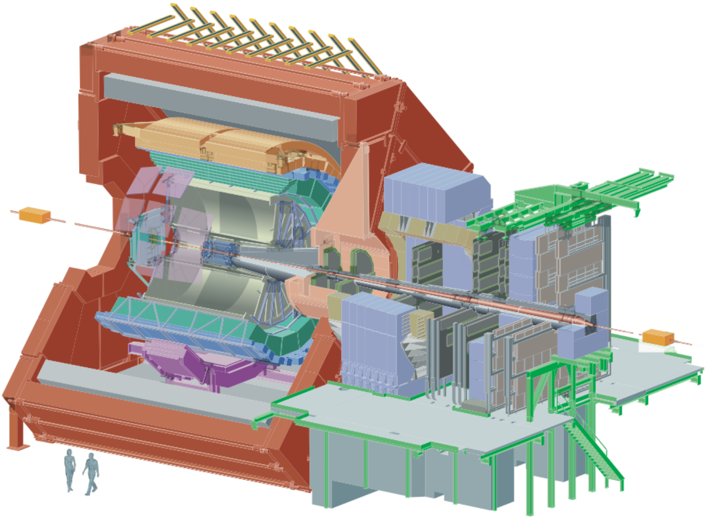
p–p collisions

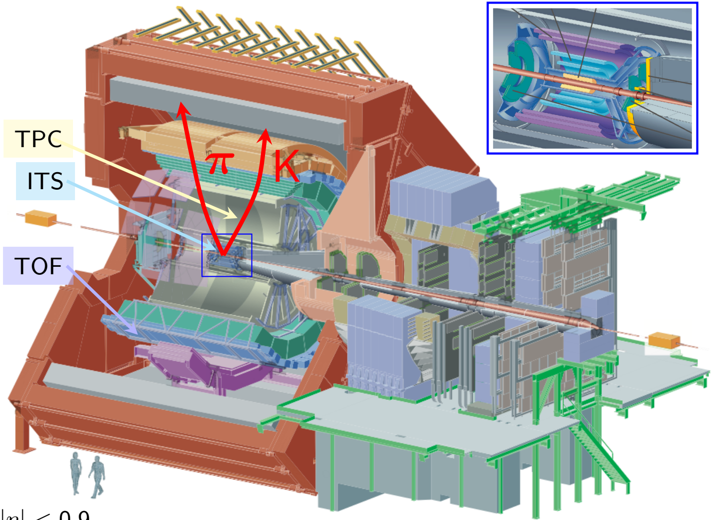
- Reference to study the effects in A–A collisions
- Test of perturbative QCD

The ALICE uniqueness: acceptance down to low p_{T}

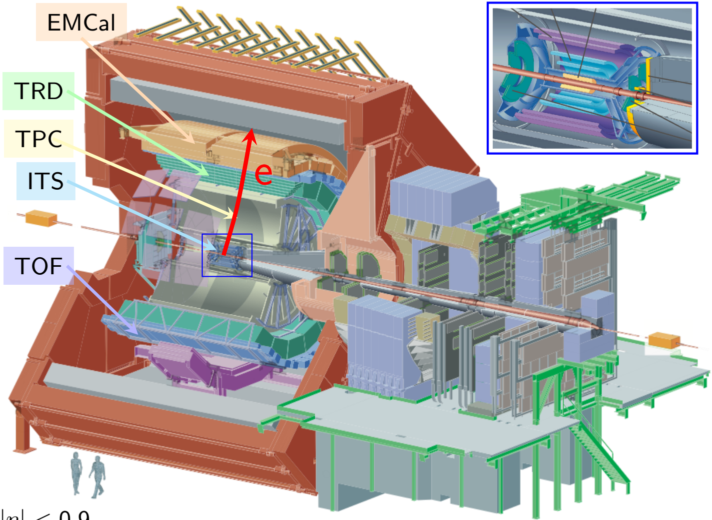
- ≥ 1 GeV/c for charm hadrons
- ≥ 1 GeV/c for b-decay electrons

$\Rightarrow$ Low-p_{T} region dominates the total cross section





- $|\eta| < 0.9$
- ITS, TPC, TOF: vertex, hermetic tracking, PID



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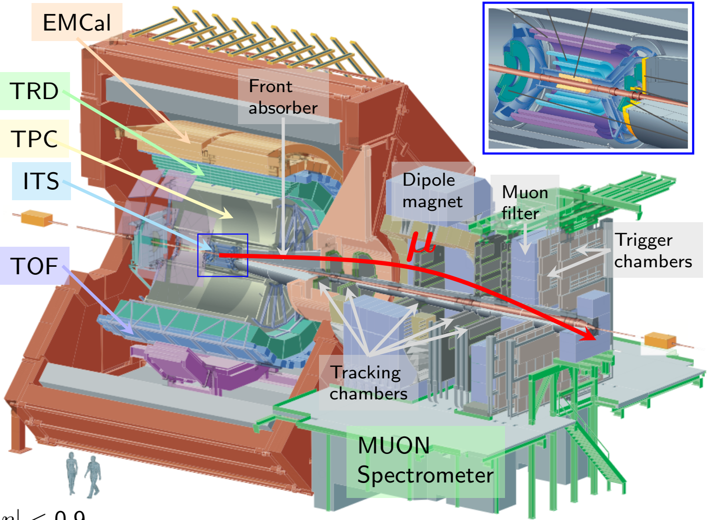
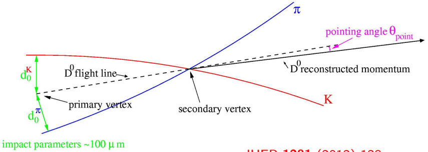
- TRD, EMCal: electron PID



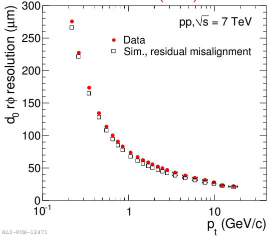
- $|\eta| < 0.9$
- ITS, TPC, TOF: vertex, hermetic tracking, PID
- TRD, EMCal: electron PID
- Muon Spectrometer: tracking and PID in $-4 < \eta < -2.5$

- Search for secondary vertices displaced of few hundreds μm

D^0	$\rightarrow K^-\pi^+$	$c\tau \sim 123\ \mu m$
D^+	$\rightarrow K^-\pi^+\pi^+$	$c\tau \sim 312\ \mu m$
D^{*+}	$\rightarrow D^0\pi^+$	
D_s^+	$\rightarrow K^+K^-\pi^+$	$c\tau \sim 150\ \mu m$



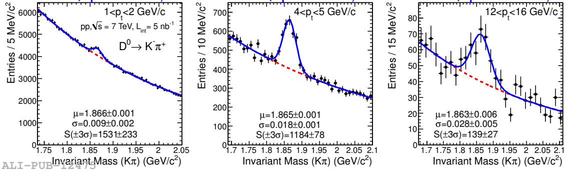
JHEP **1201** (2012) 128



- Selection criteria:
  - p_T and impact parameters of tracks
  - pointing angle
  - distance between primary and secondary vertices
  - kaon ID to reduce background at low p_T

- Signal extraction through fit of the invariant mass of the decay products

$1 < p_T < 2$ GeV/c $\quad$ $4 < p_T < 5$ GeV/c $\quad$ $12 < p_T < 16$ GeV/c



JHEP **1201** (2012) 128

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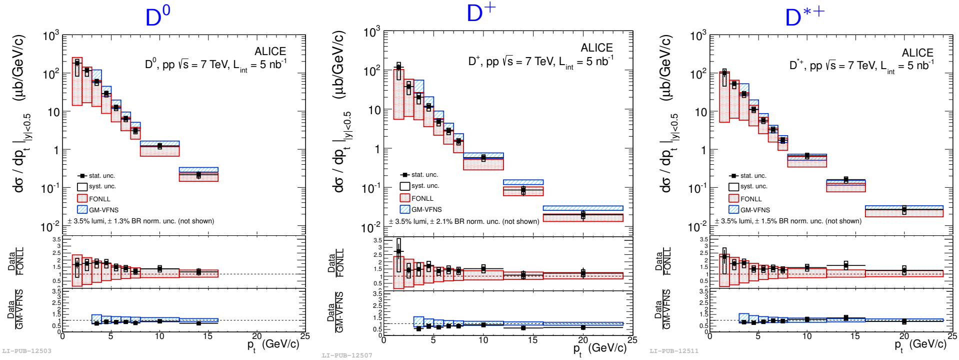
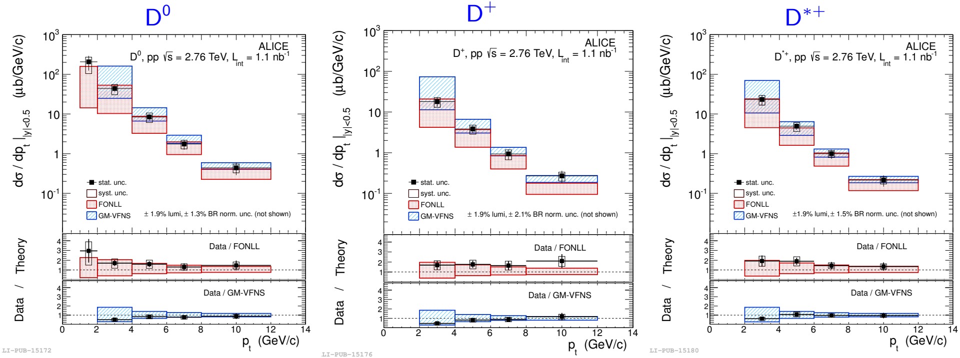


- Large p_{T} coverage:
  - D^0: $1 < p_{\mathrm{T}} < 16$ GeV/c
  - D^+, D^{*+}: $1 < p_{\mathrm{T}} < 24$ GeV/c
- Agreement with pQCD calculations within errors

  FONLL: M. Cacciari *et al.*, JHEP **1210** (2012) 137
  GM–VFNS: B. A. Kniehl *et al.*, Eur. Phys. J. C **72** (2012) 2082
  k_t factorisation: R. Maciula and A. Szczurek, arXiv:1301.3033 [hep-ph]

JHEP **1207** (2012) 191

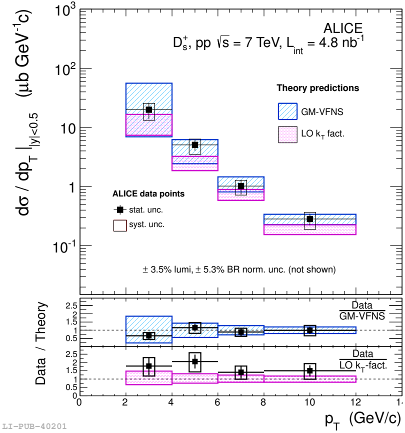


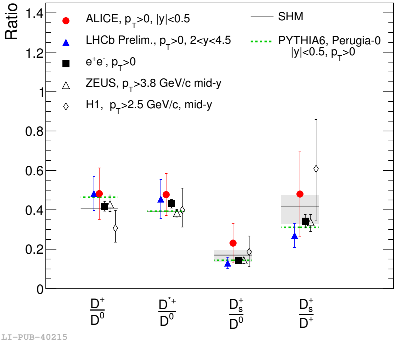
- p_T coverage: $2 < p_T < 12$ GeV/c
- Agreement with pQCD calculations within errors

  FONLL: M. Cacciari *et al.*, JHEP **1210** (2012) 137

  GM–VFNS: B. A. Kniehl *et al.*, Eur. Phys. J. C **72** (2012) 2082

Phys. Lett. B **718** (2012) 279





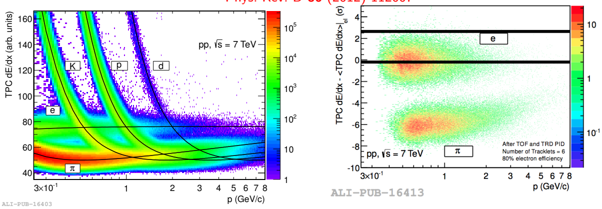
- p_T coverage: $2 < p_T < 12$ GeV/c
- Agreement with model calculations within errors
  GM–VFNS: B. A. Kniehl *et al.*, Eur. Phys. J. C **72** (2012) 2082
  k_t factorisation: R. Maciula *et al.*, EPJ Web Conf. **37** (2012) 06008

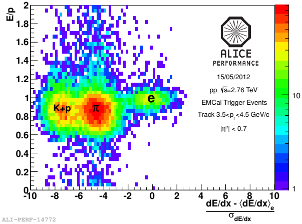
- Agreement with LHCb [LHCb, Nucl. Phys. B **871** (2013) 1]
- Ratios comparable in pp, ep [H1, Eur. Phys. J. C **38**, 447 (2005) ; ZEUS, Eur. Phys. J. C **44** (2005) 351] and e^+e^- [L. Gladilin, hep-ex/9912064]
- Ratios well described by Statistical Hadronization Model [A. Andronic *et al.*, Phys. Lett. B **678** (2009) 350]

ALICE

- Electron ID with:
  - TPC (dE/dx) + TOF + TRD
  - TPC (dE/dx) + EMCAL

Phys. Rev. D **86** (2012) 112007



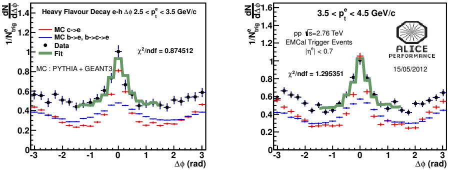


- Background subtraction:
  - e^+e^- invariant mass method: removes Dalitz decay and photon conversion
  - cocktail: MC hadron generator for different background sources

Beauty measurement:

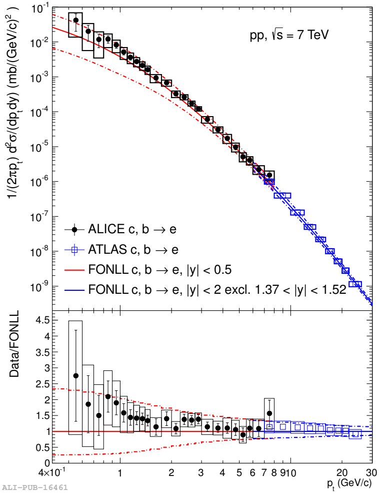
- B decay $c\tau = 500\ \mu$m
- cut on impact parameter to enhance S/B
- subtract residual *e* from D decay: input from measured D mesons

- complementary method based on fit to MC templates of *e*-hadron correlation shapes for D and B (exploit the larger width of the near-side peak for B-hadron decays)

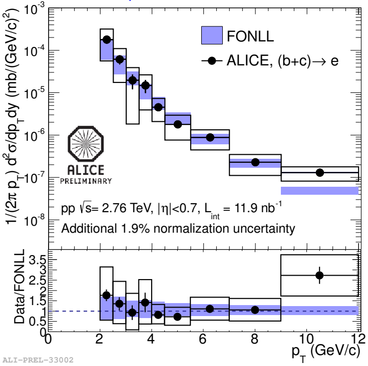


$\sqrt{s} = 7$ TeV

Phys. Rev. D **86** (2012) 112007



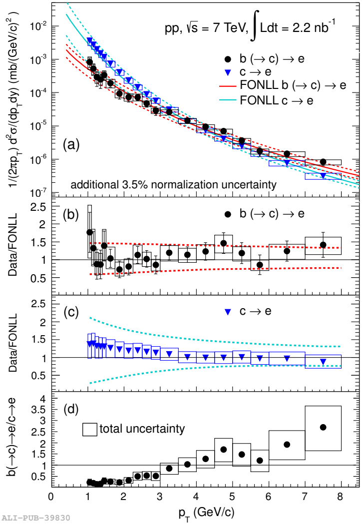
$\sqrt{s} = 2.76$ TeV



- Results at 7 TeV complementary to ATLAS results at high p_{T}
  Phys. Lett. B **707** (2012) 438
- Data at both energies well described by FONLL calculations
  M. Cacciari *et al.*, JHEP **1210** (2012) 137

$\sqrt{s} = 7$ TeV

Phys. Lett. B **721** (2013) 13



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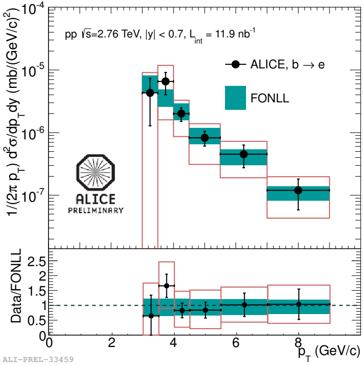
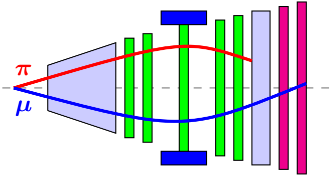


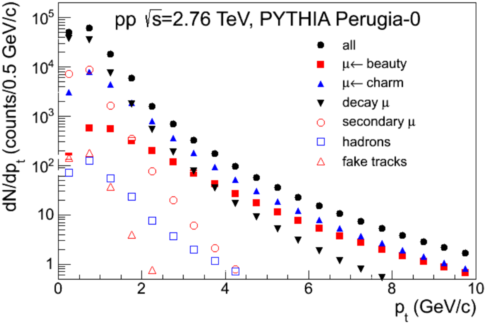
- At 7 TeV, beauty becomes dominant compared to charm from $p_T > 4$ GeV/c
- Beauty production well described by FONLL down to low p_T
  M. Cacciari *et al.*, JHEP **1210** (2012) 137

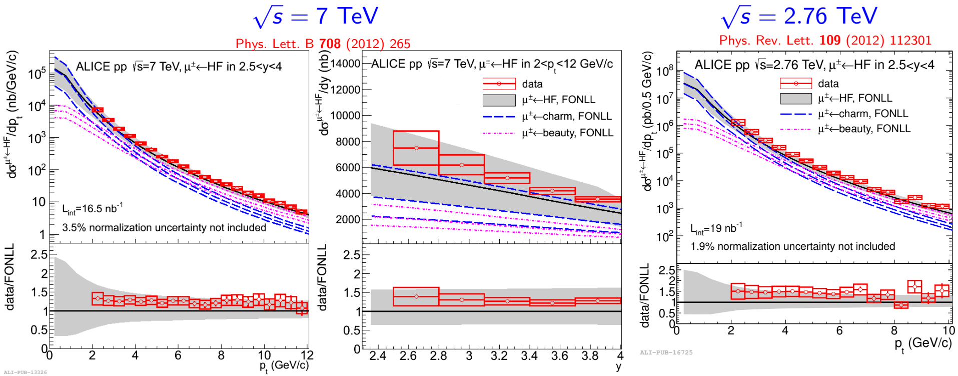
ALICE

- Track selection:
  - Match track with tracklet in the trigger chambers ⇒ reject punch-through hadrons
  - $p \times$ DCA cut ⇒ reject tracks from beam-gas interaction

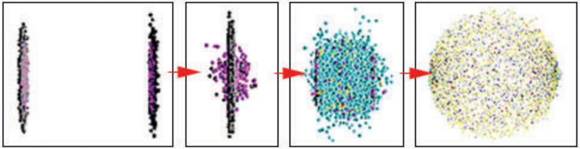


- Background subtraction:
  - bkg. contribution decreases with p_T ⇒ focus on $p_T \geq 2$ GeV/c
  - main background source: muons from pion and kaon decays
  - subtraction using MC simulations as input (Pythia, Phojet)





- According to FONLL, beauty decay contributes more than charm decay to the muon yield at $p_{\mathrm{T}} \gtrsim 6$ GeV/c
- Data at both energies well described by FONLL calculations
  M. Cacciari *et al.*, JHEP **1210** (2012) 137



- Heavy quarks are hard probes of the medium:
  - produced in the initial hard scattering processes (large Q^2)
  - experience the evolution of the "fireball"
  - interact strongly with the medium
- QCD models describing collisional and radiative energy loss in the medium predict:

$$E_{loss}(\text{light hadrons}) > E_{loss}(c) > E_{loss}(b)$$

- Experimental observable:

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

  No medium effects $\Rightarrow$ production in A–A collisions = production in p–p collisions $\times$ average number of nucleon collisions* $\Rightarrow$ $\mathrm{R_{AA}} = 1$

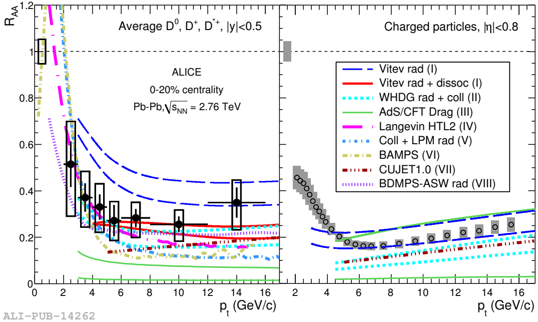
- The mass hierarchy in the energy loss translates into:

$$\mathrm{R_{AA}}(\text{light hadrons}) < \mathrm{R_{AA}}(c) < \mathrm{R_{AA}}(b)$$

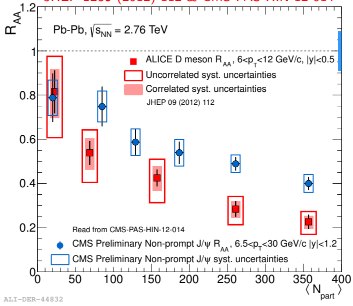
*neglecting initial state effects, to be estimated with p–A collisions

ALICE

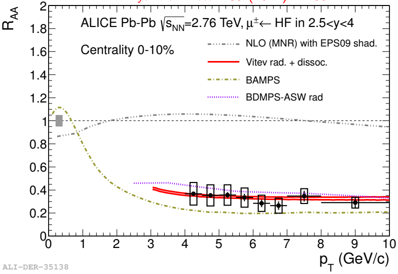
JHEP **1209** (2012) 112



JHEP **1209** (2012) 112 & CMS-PAS-HIN-12-014



Phys. Rev. Lett. **109** (2012) 112301



- Strong reduction of yields observed at high p_T
- The measurements challenge the models describing the interaction of heavy flavours with the medium: should simultaneously reproduce the results in different kinematic ranges, of different hadron species and of different variables (e.g. azimuthal anisotropy)

ALICE

- The ALICE experiment measured heavy-flavour production in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV: results are well described by pQCD calculations

D mesons at mid-rapidity

- Measured down to $p_{\mathrm{T}} = 1$ GeV/c
- D-meson ratios agree with LHCb, ep and e^+e^- experiments

Electrons from heavy-flavour hadron decays at mid-rapidity

- Measured down to $p_{\mathrm{T}} = 0.5$ GeV/c. Complementary to ATLAS
- Electrons from beauty decay measured down to $p_{\mathrm{T}} = 1$ GeV/c

Muons from heavy-flavour hadron decays at forward rapidity

- Measured in $2.5 < y < 4$, down to $p_{\mathrm{T}} = 2$ GeV/c

- Results used as a reference for Pb–Pb collisions: the aim is the understanding of the mechanisms of the propagation and energy loss of heavy quarks in the hot and dense medium formed

Outlook

- Measurement of $\Lambda_c \rightarrow pK^-\pi^+$ and $\Lambda_c \rightarrow K^0_s p$
- Measurement in p–Pb collisions (disentangle initial state effects)

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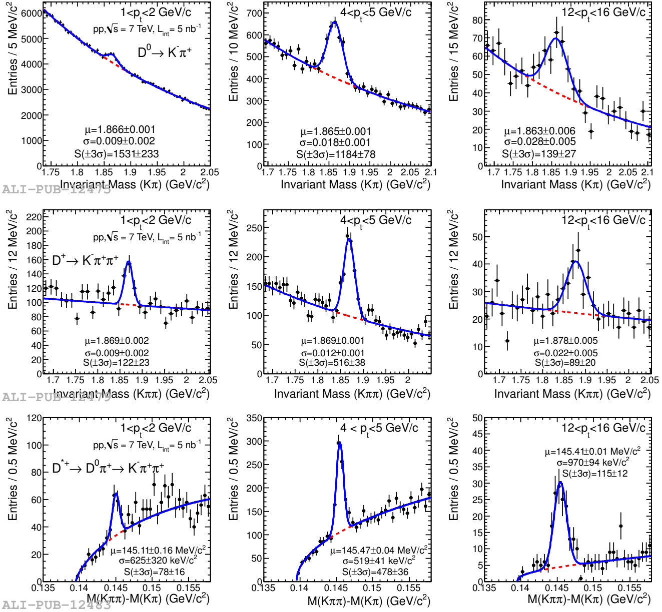
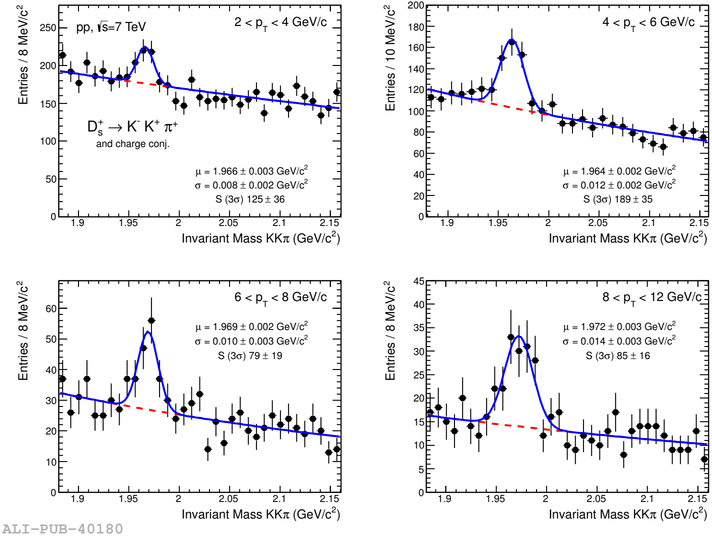
D^0

D^+

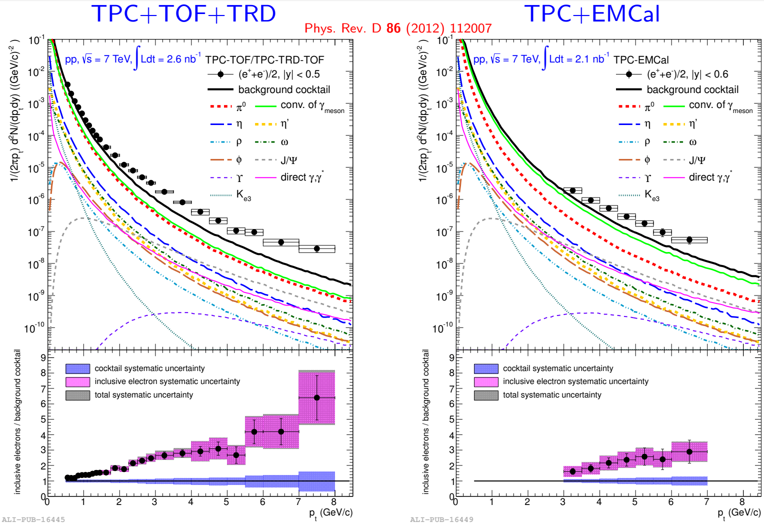
D^{*+}



Phys. Lett. B **718** (2012) 279

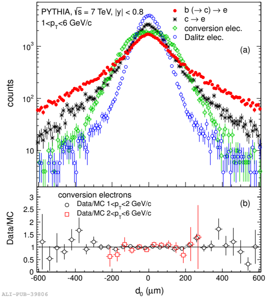


Heavy-flavour electrons: the electron background cocktail



- π^0 input: measurement with ALICE
- Heavier mesons: m_T scaling
- J/ψ and Υ: measurement with ALICE and CMS
- Ratio Conversions/Dalitz: from known material budget

Phys. Lett. B **721** (2013) 13

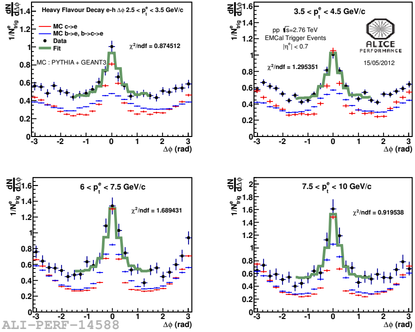


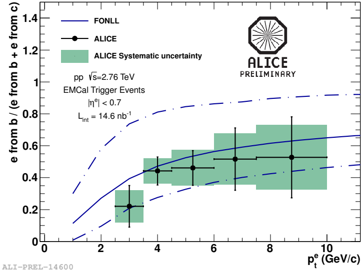
Method 1

- Cut on d_0 to enhance the S/B:
  - hadron contamination $< 3\%$
  - electron background gives S/B $\sim 1/3$ (~ 5) at 1 (8) GeV/c

Method 2

- Extract the beauty signal from a fit of the electron-hadron correlation (fit functions tuned on Pythia MC simulations)





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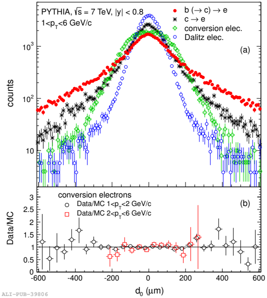

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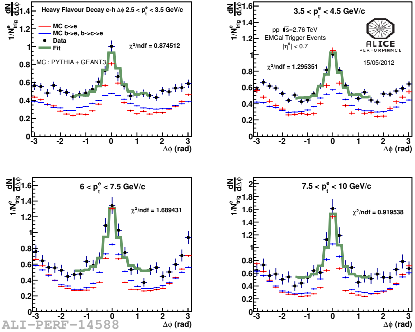

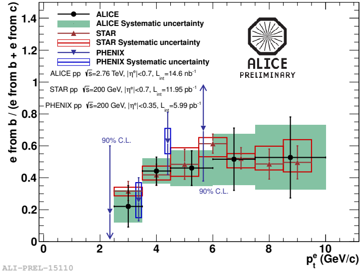

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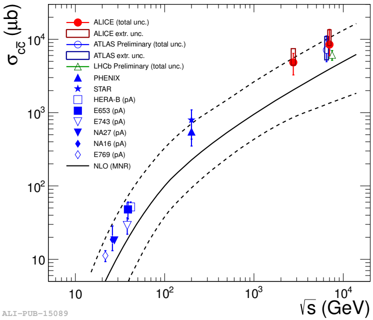

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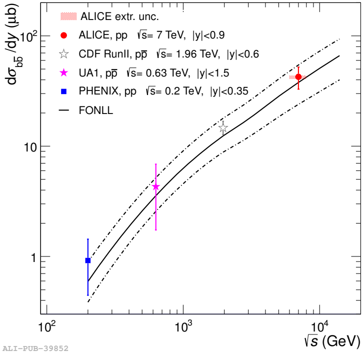


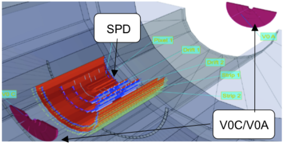
- D mesons cross-section extrapolated to total with FONLL
- $b\bar{b}$ cross-section from J/ψ from B measurement. Total cross-section estimated with FONLL

pp collisions

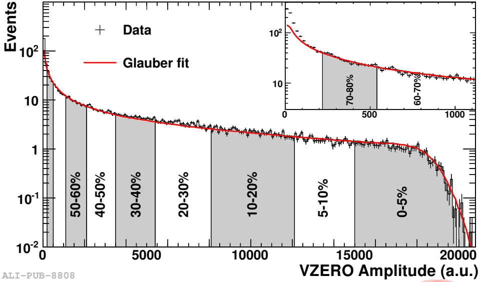
- Minimum Bias (MB): V0A or V0C or SPD
- MUON: MB + single muon trigger

Pb–Pb collisions

- MB: V0A and V0C and SPD
- MUON: MB + single muon trigger

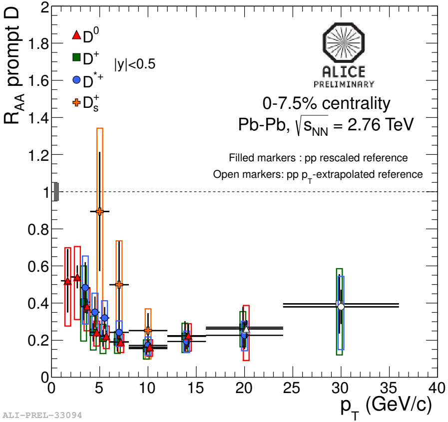


Phys. Rev. Lett. **106** (2011) 032301



- Centrality selection based on a geometrical Glauber model fit of the V0 amplitude

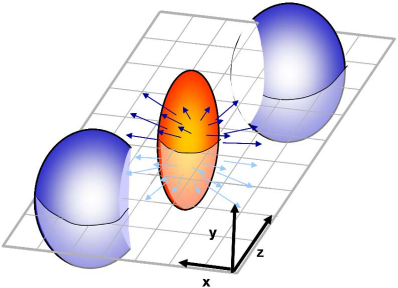
ALICE

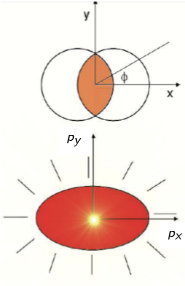


- $p_{\rm T}$ range increased with respect to 2010 data
- D^0, D^+, D^{*+} R_{AA} compatible within errors
- Large suppression factor in a wide $p_{\rm T}$ range

- First measurement of D_s^+ in Pb–Pb collisions
- More statistics needed to conclude on the expected enhancement of low-$p_{\rm T}$ D_s^+

Elliptic flow



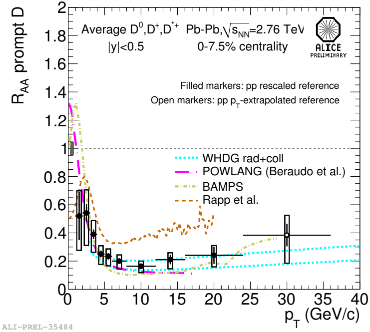


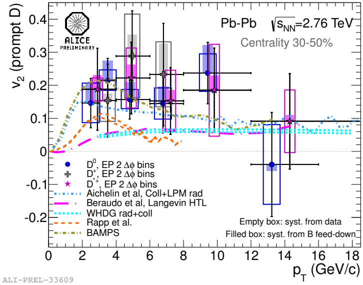
- Spatial anisotropy is converted via multiple collisions into an anisotropic momentum distribution
- Reaction plane (Ψ_{RP}): defined by the beam axis and the impact parameter vector of the two colliding nuclei
- Azimuthal distributions of particles measured with respect to the reaction plane can be expanded in a Fourier series:

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n(\phi - \Psi_{RP})\right)\right)$$

- The elliptic flow is defined as:

$$v_2 = \langle\cos(2(\phi - \Psi_{RP}))\rangle$$





- The challenge for the models: reproduce simultaneously R_{AA} and v_2
- The challenge for experiments: reduce the statistical and systematic errors for a better constraint to models