Heavy quarks in a Quark-Gluon Plasma at the LHC

- charm and beauty production in pp collisions
  at the LHC
- energy loss of partons in a QGP
  - light quarks
  - charm and beauty quarks
- elliptic flow of heavy quarks

Johanna Stachel, Physikalisches Institut, Universität Heidelberg
Workshop on QCD Thermodynamics in High-Energy Collisions
Central China Normal University, China, July 27-31, 2015

charm quarks in the quark gluon plasma

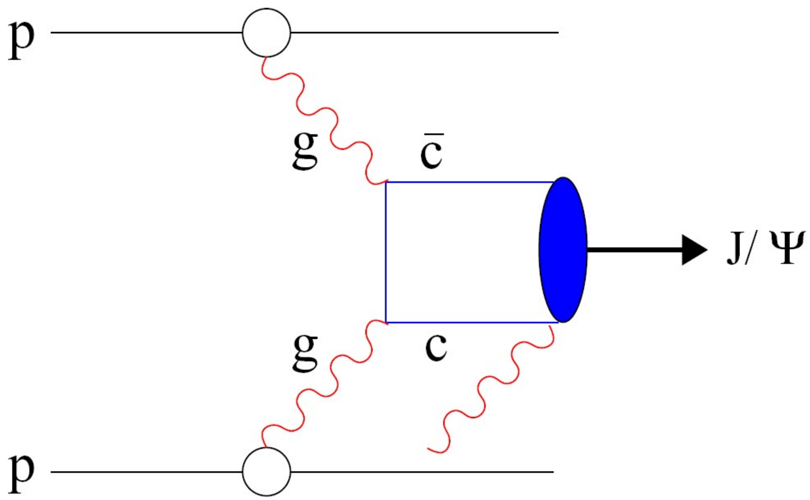
interest 2-fold:

transport coefficient for heavy quarks?
also energy loss of heavy quark (radiative energy loss should be suppressed due to large mass (1.2 GeV); in vaccum gluon radiation into angles $\theta \leq \frac{m_q}{E_q}$ suppressed (Dokshitzer and Kharzeev)
and Casimir factor $C_q = 4/3$ vs $C_{gluon} = 3$

need total charm cross section for understanding of charmonia (ccbar states)

in pp and pA charm physics interesting on it's own right, tests pQCD and parton distribution functions as well as nuclear effects

Production of charm quarks and charmonia in hadronic collisions

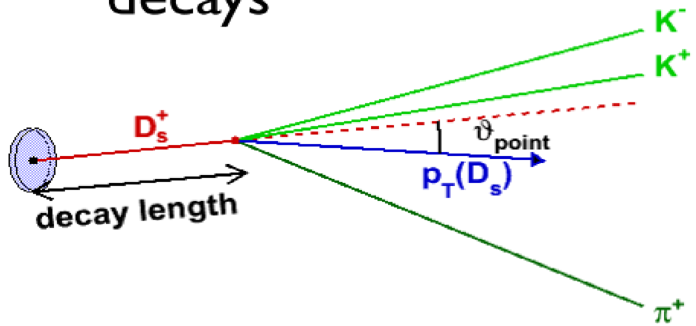


- charm and beauty quarks are produced in early hard scattering processes
time scale $\tau \approx 1/2m_q \approx 0.02 - 0.1$ fm
- most important Feynman diagram: gluon fusion
- formation of quarkonia: with about 1% probability the c and cbar form ^{3}1S state = J/ψ - requires transition to a color singlet state
not pure perturbative QCD anymore, some modelling required
CEM Color Evaporation Model
CSM Color Singlet Model
now overall reasonably successful modelling

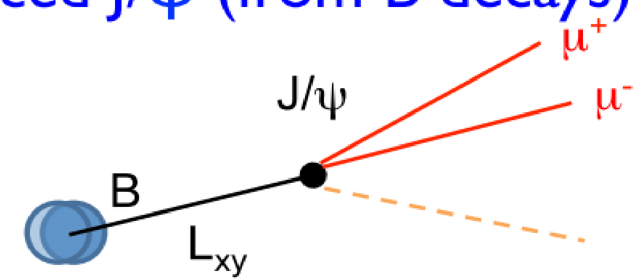
How to measure open heavy flavor production

Full reconstruction of D meson hadronic decays

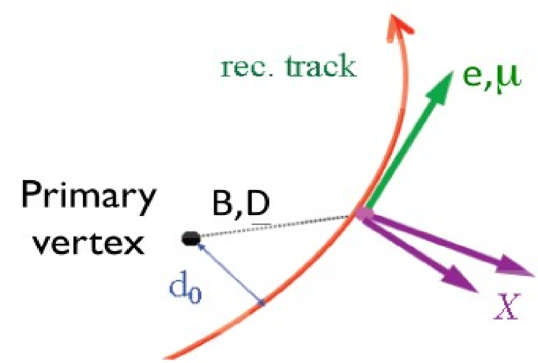
$D^0 \rightarrow K^- \pi^+$
$D^+ \rightarrow K^- \pi^+ \pi^+$
$D^{*+} \rightarrow D^0 \pi^+$
$D_s^+ \rightarrow K^- K^+ \pi^+$



Displaced J/ψ (from B decays)



Semi-leptonic decays (c,b)



need good PID (in particular e, mu, also K) and vertexing capabilities (sub 100 μm)

Measurement of heavy flavor production

reconstruction of hadronic decays: $|\eta| < 0.5$ PID TPC, TOF

$D^0 \rightarrow K\pi$ $D^{\pm} \rightarrow K\pi\pi$ $D^* \rightarrow D\pi$ $D_s \rightarrow Kk\pi$ $\Lambda_c \rightarrow \Lambda\pi$

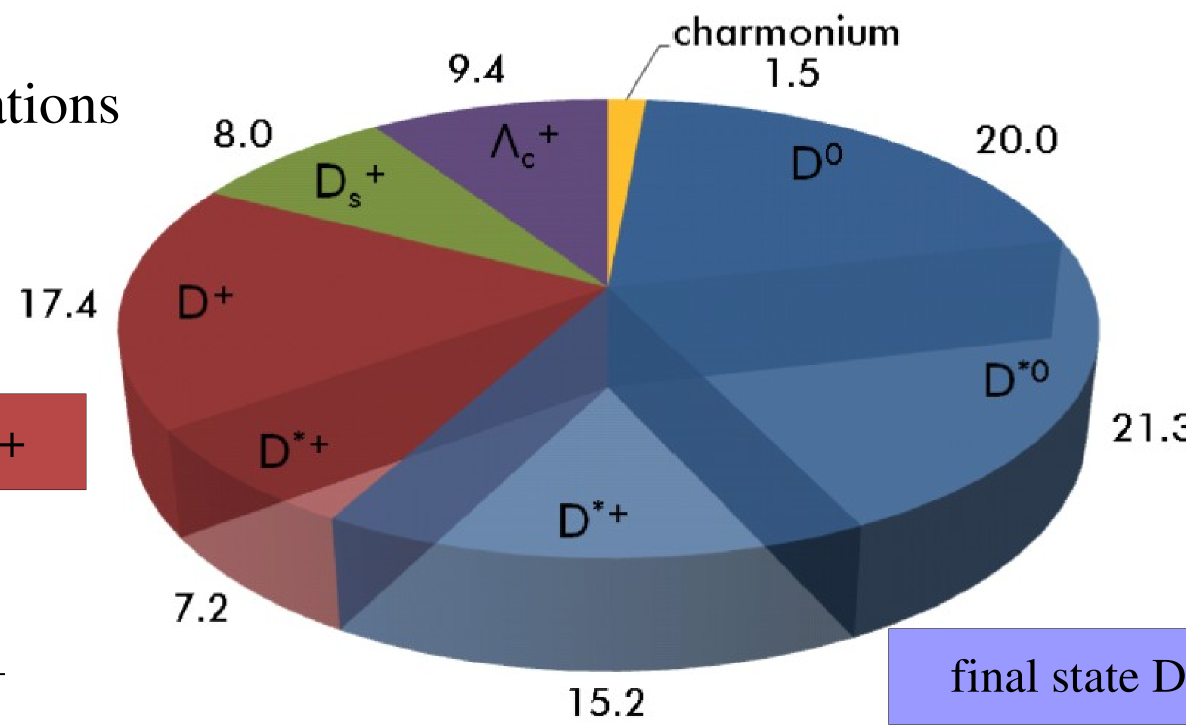
semi-leptonic decays:

$c,b \rightarrow e$ $|\eta| < 0.8$ PID TPC, TRD, TOF, EMCal

$c,b \rightarrow \mu$ $|\eta| = 2.5–4.0$ PID muon RPCs

beauty from secondary J/ψ

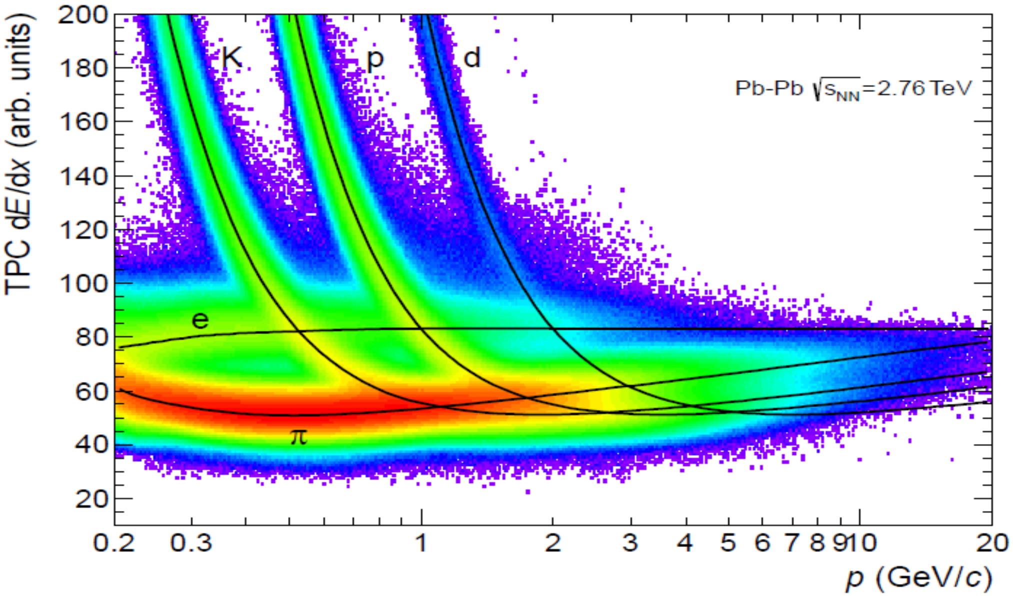
beauty from e-hadron correlations

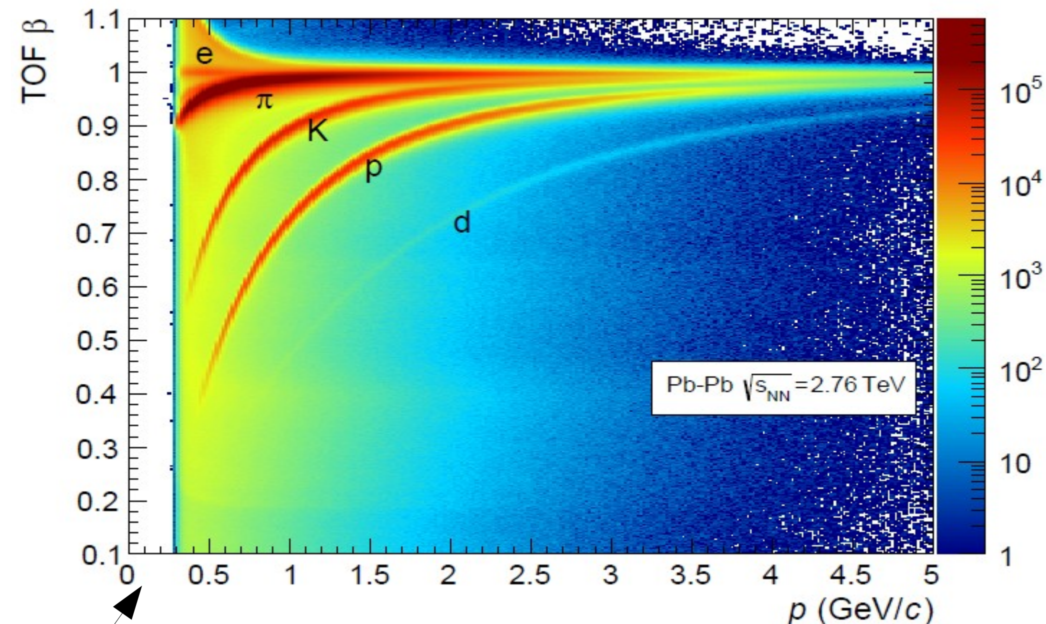


final state D+

final state D0

Particle identification in ALICE central barrel

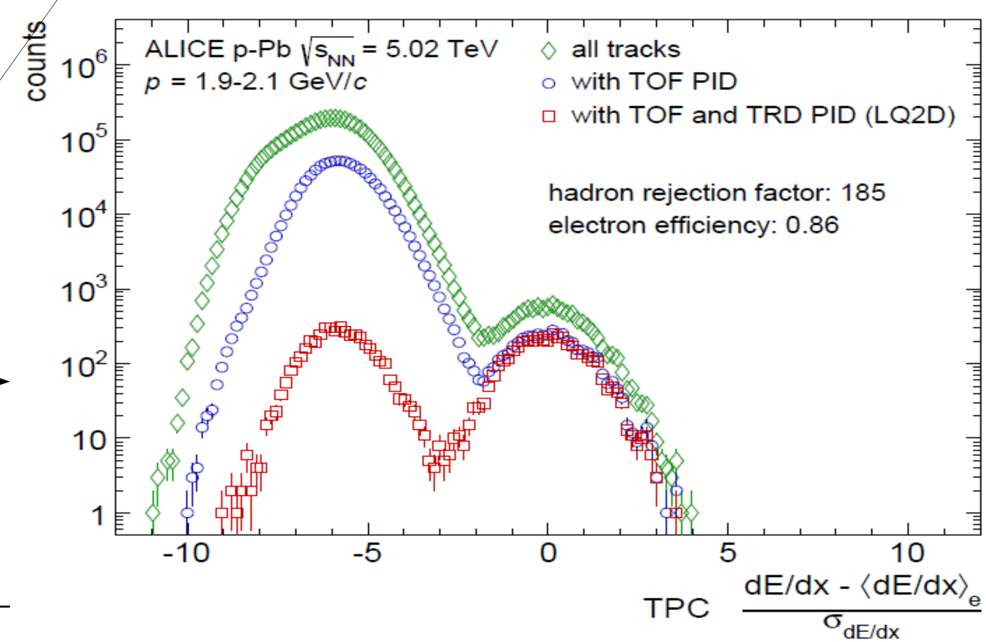




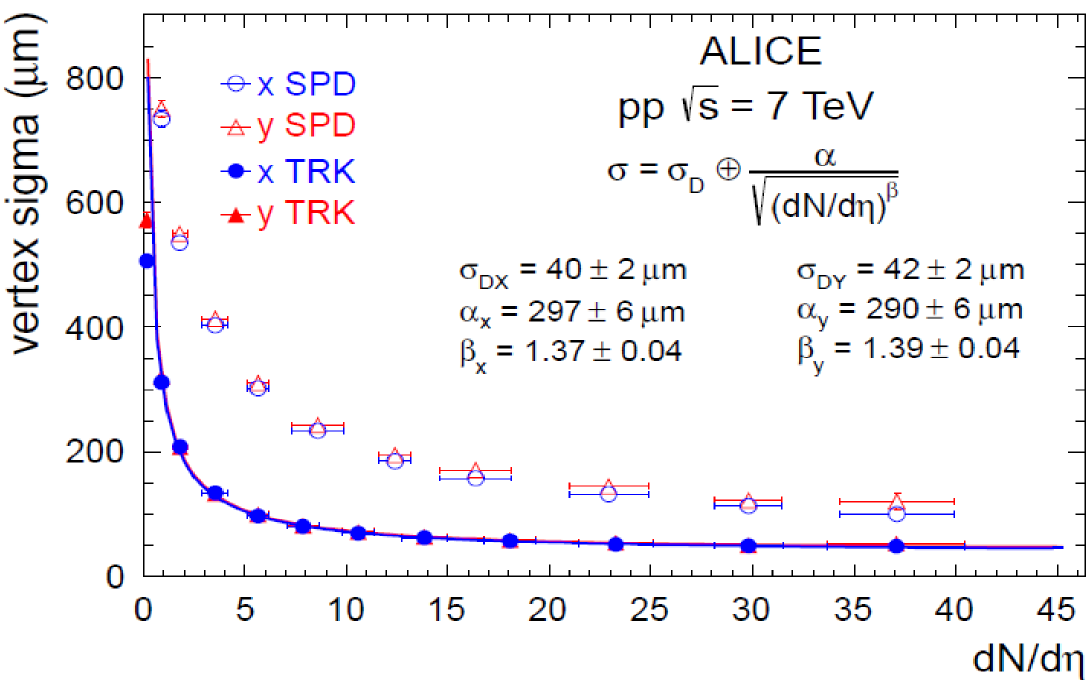
specific energy loss in TPC

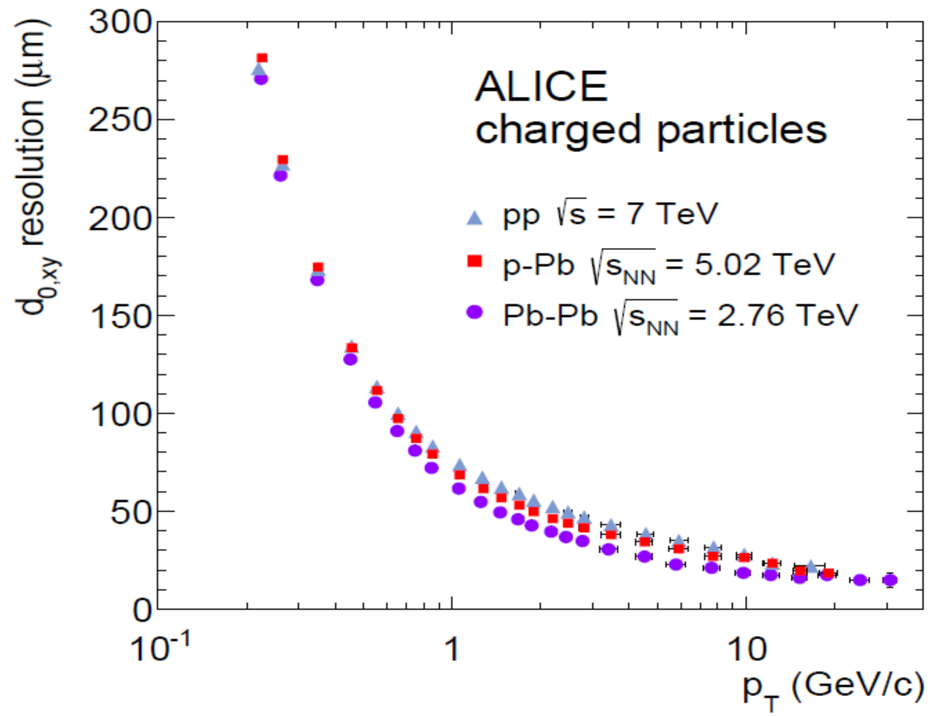
time-of-flight TOF

transition radiation with TRD



tracking performance – ITS system





resolution of transverse distance to interaction vertex of global ITS-TPC tracks
after careful alignment of Silicon Pixel Detectors
expected vertex and impact parameter resolution reached

Heavy ion data from the LHC

PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV   ALICE, ATLAS, CMS

2010 about 9 μb^{-1}

2011 about 150 μb^{-1} ≅ 10^9 collisions

pPb at $\sqrt{s_{NN}}$ = 5.02 TeV   ALICE, ATLAS, CMS, LHCb

2013 about 30 nb^{-1} ≅ $5 \cdot 10^{10}$ collisions

total of about 12 weeks in 3 years of running

pp reference at $\sqrt{s}$=7 TeV   ALICE

2010 about 5 nb^{-1} min bias and 16.5 nb^{-1} muon trigger

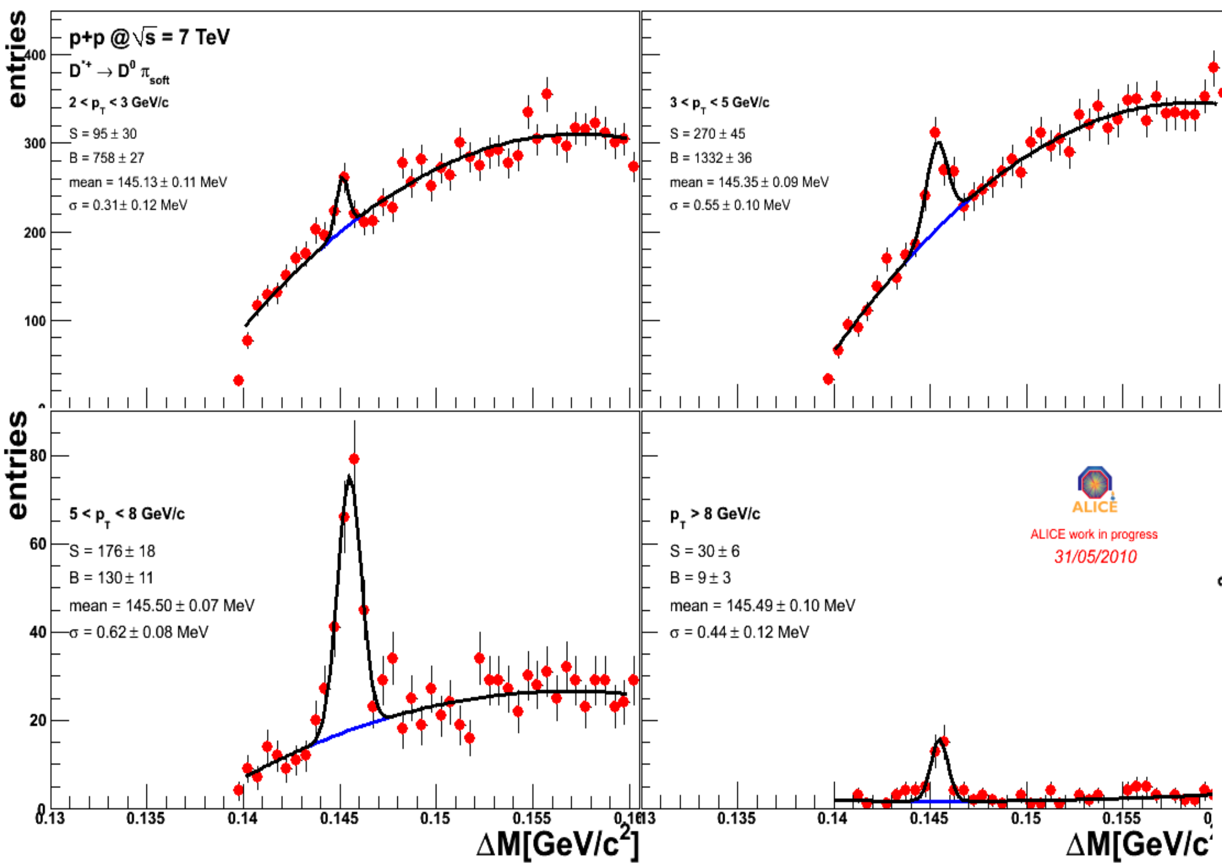
pp ref. at $\sqrt{s}$=2.76 TeV   ALICE

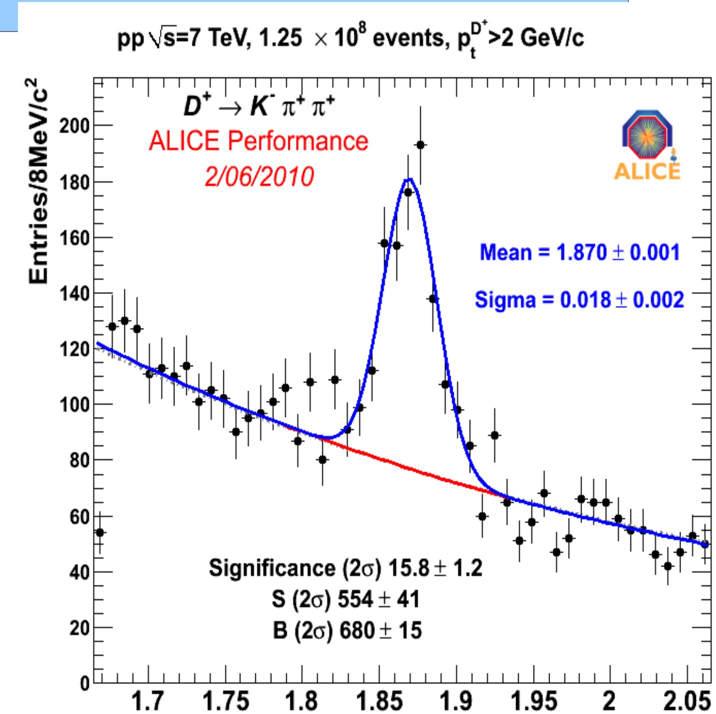
2011 about 1.1 nb^{-1} min bias and 19 nb^{-1} muon trigger

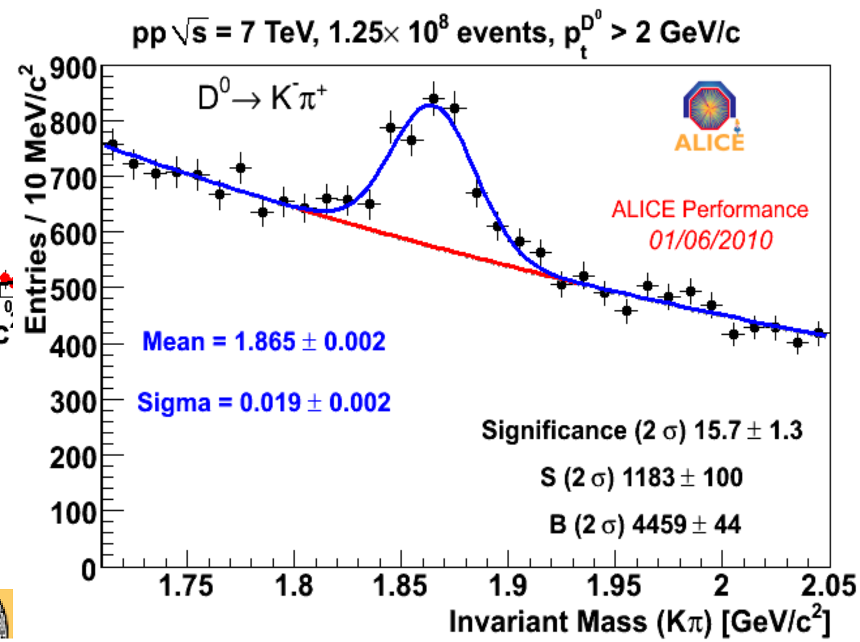
Charm and beauty in pp at the LHC

D^0, D^+ and D^{0*} in 7 TeV pp data

1.25 10^8 events

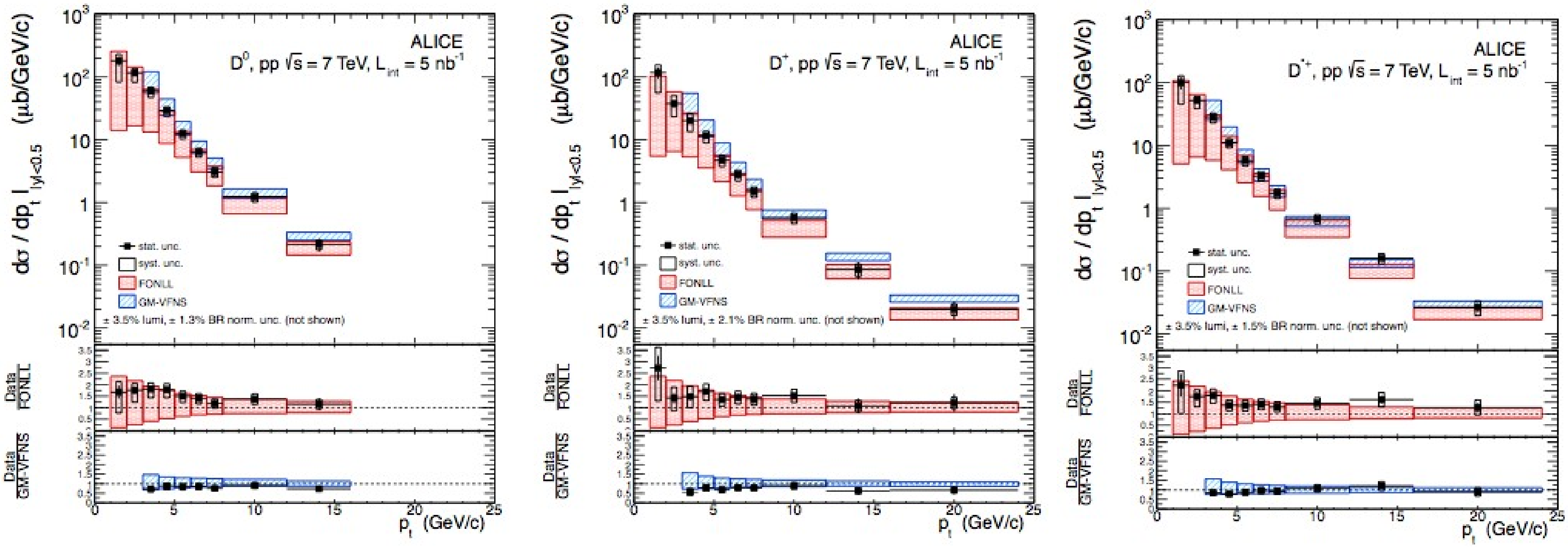






for 10^9 events, expect to measure open charm
for p_t = 0.5 – 15 GeV/c

Measurements agree well with state of the art pQCD calculations



JHEP1201(2012)128

data are compared to perturbative QCD calculations
reasonable agreement
- at upper end of FONLL and at lower end of GM-VFNS
measure 80% of charm cross section for |y| < 0.5

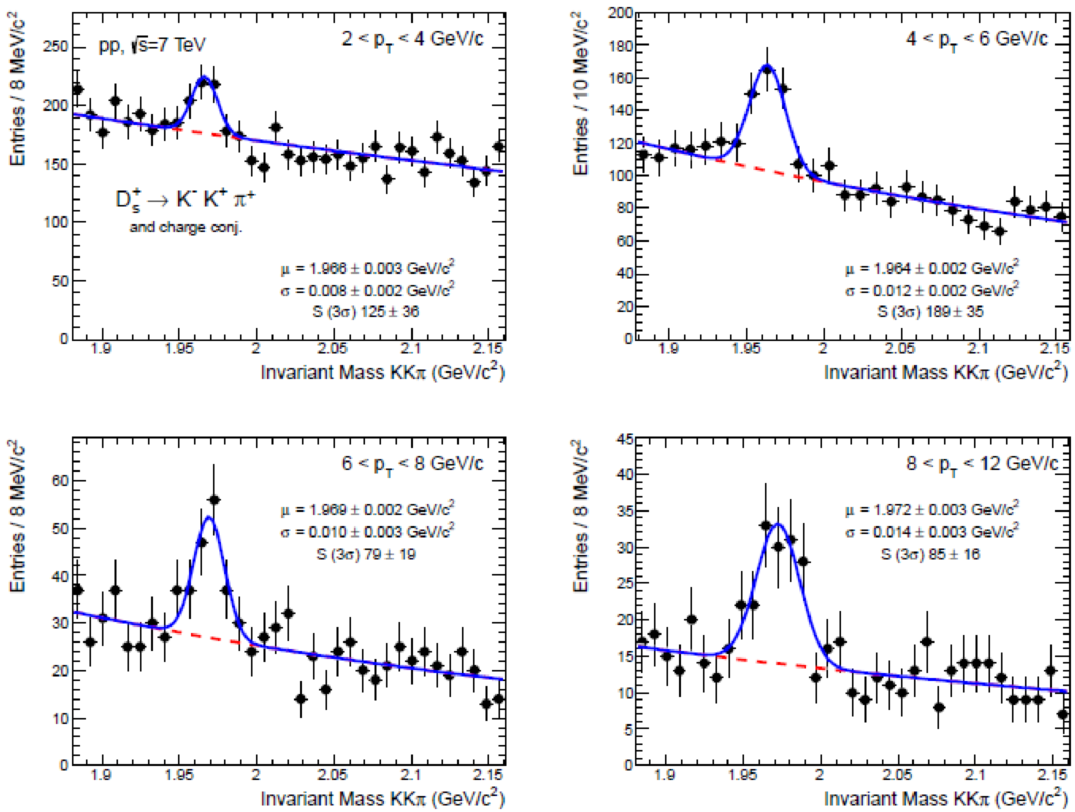
FONLL: Cacciari et al., arXiv:1205.6344
GM-VFNS: Kniehl et al., arXiv:1202.0439

mid-y cross sections: $d\sigma^{D^0}/dy = 516 \pm 41(\text{stat.})^{+\ 69}_{-175}(\text{syst.}) \pm 18(\text{lumi.}) \pm 7(\text{BR})^{+120}_{-\ 37}(\text{extr.})\ \mu b,$

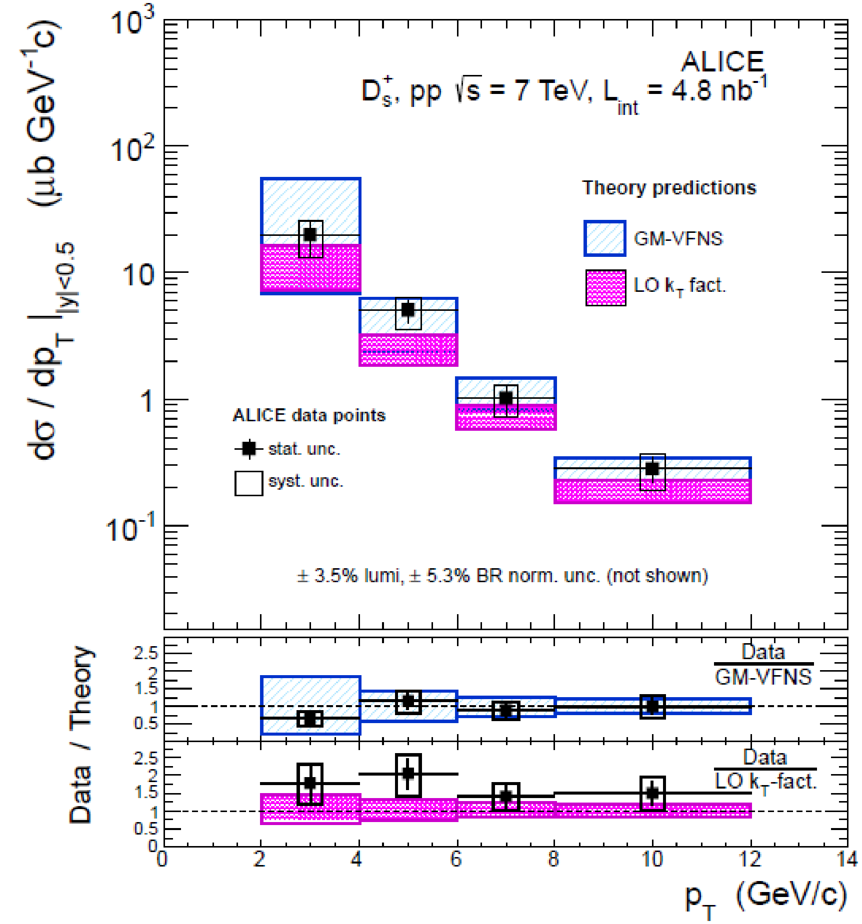
$$d\sigma^{D^+}/dy = 248 \pm 30(\text{stat.})^{+52}_{-92}(\text{syst.}) \pm 9(\text{lumi.}) \pm 5(\text{BR})^{+57}_{-18}(\text{extr.})\ \mu b,$$

$$d\sigma^{D^{*+}}/dy = 247 \pm 27(\text{stat.})^{+36}_{-81}(\text{syst.}) \pm 9(\text{lumi.}) \pm 4(\text{BR})^{+57}_{-16}(\text{extr.})\ \mu b.$$

D_s p_t spectrum compared to pQCD



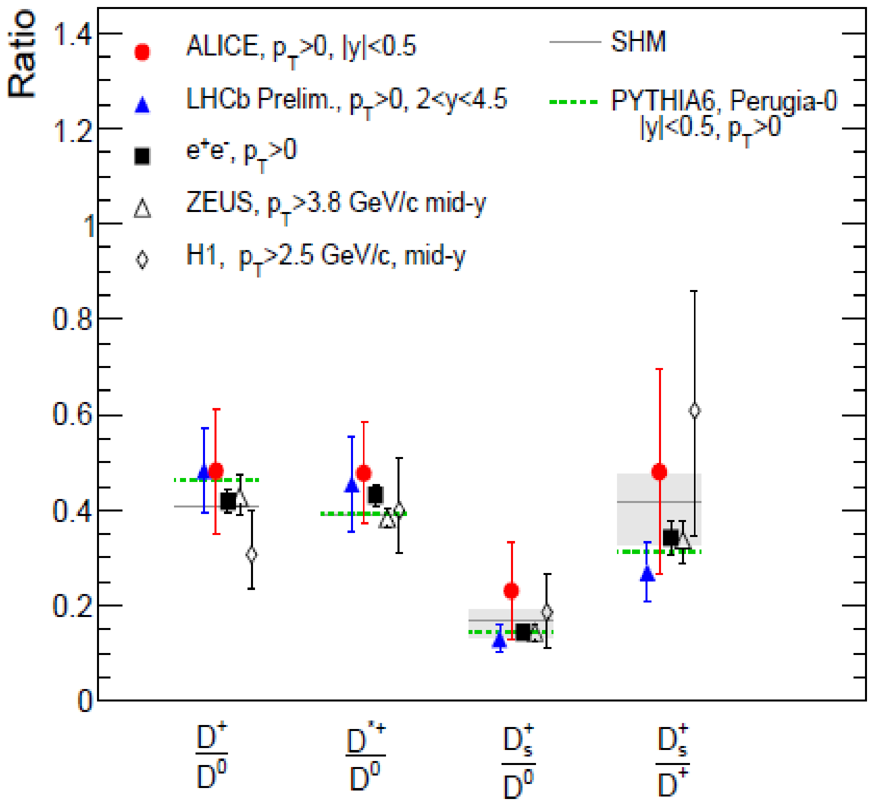
PLB718 (2012) 279 arXiv1208.1948

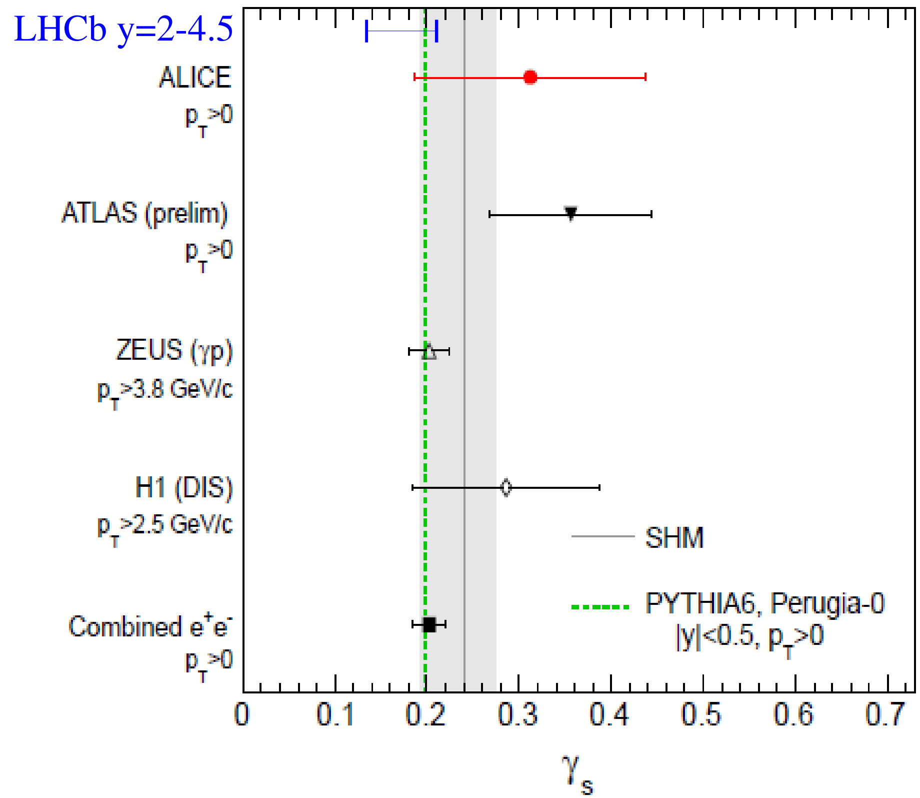


$$d\sigma^{D_s^+}/dy = 118 \pm 28(\text{stat.})^{+28}_{-34}(\text{syst.}) \pm 4(\text{lumi.}) \pm 6(\text{BR})^{+38}_{-35}(\text{extr.})\ \mu b$$

GM-VFNS: Kniehl et al., arXiv:1202.0439

Comparison of D-meson yields among experiments and to models





canonical statistical model (SHM) with T=164 MeV, V=30±10 fm3, strangeness fugacity 0.60±0.04

Andronic, Beutler, Braun-Munzinger, Redlich, JS, PLB 678 (2009) 350

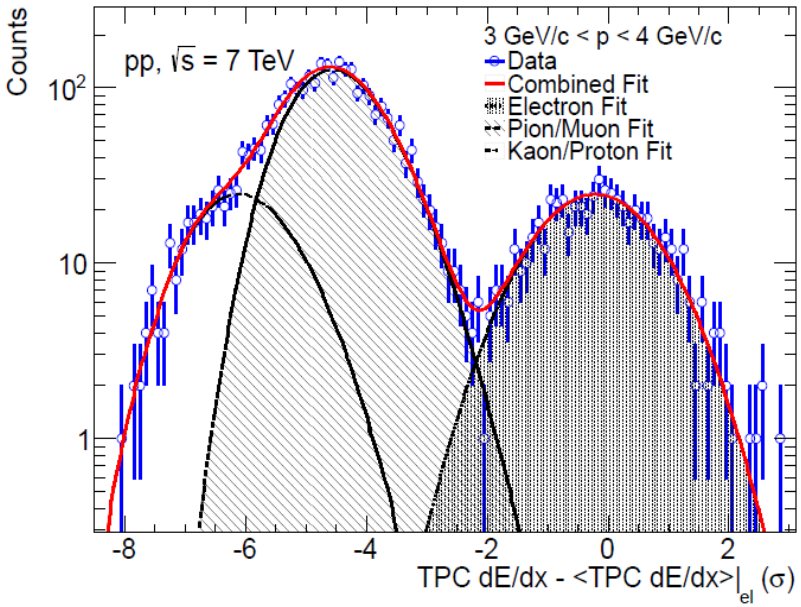
$$\gamma_s = \frac{2\, d\sigma(D_s^+)/dy}{d\sigma(D^0)/dy + d\sigma(D^+)/dy}$$

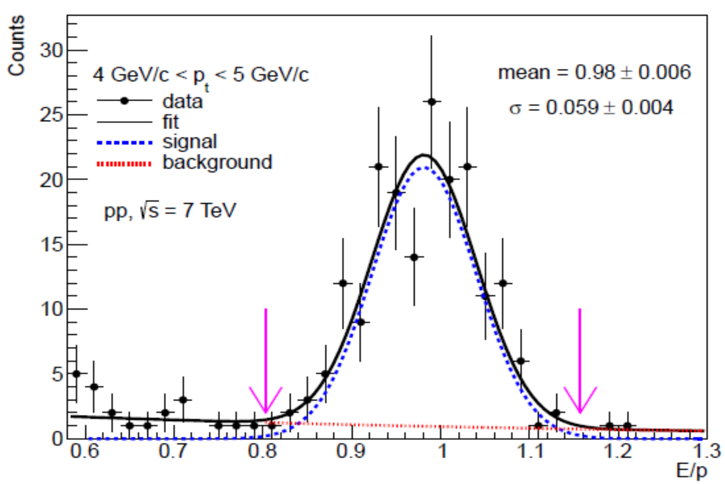
- very similar number LHCb in B-sector: f_s/f_d = 0.267+0.021-0.020
- within current errors no evidence for lifting of strangeness suppression at LHC energy

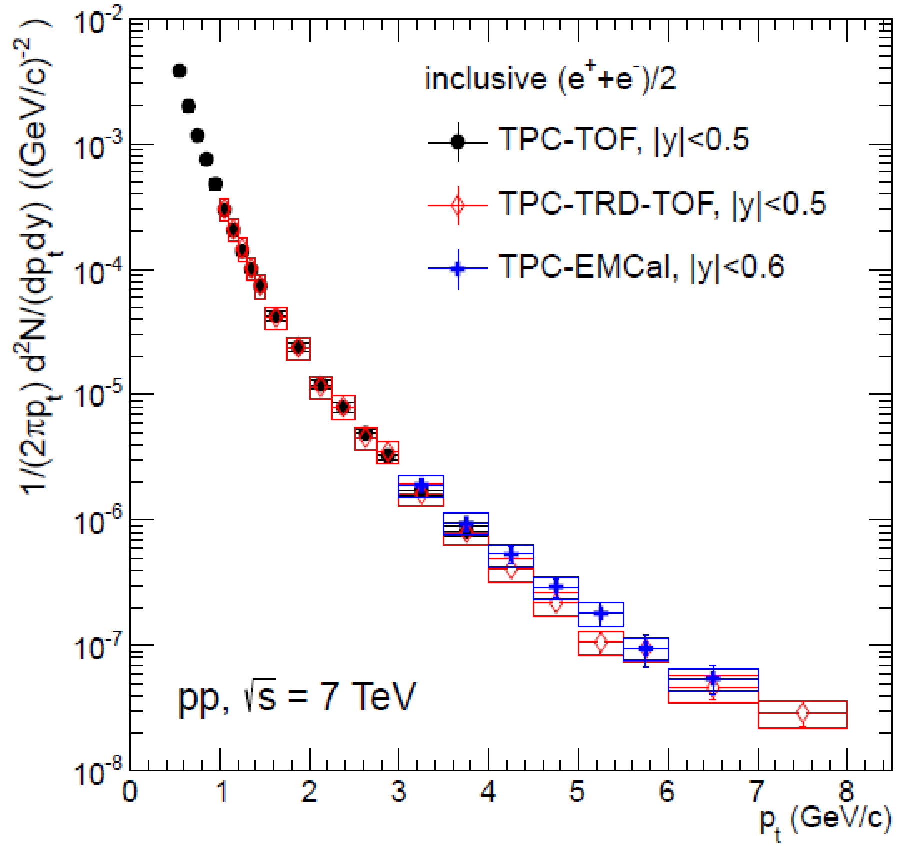
Semi-leptonic decays of charm and beauty mesons

mid-rapidity electrons: TPC-TOF, TPC-TRD-TOF, TPC-EMCal analyses combined

very good agreement, cover p_t = 0.5-8 GeV/c



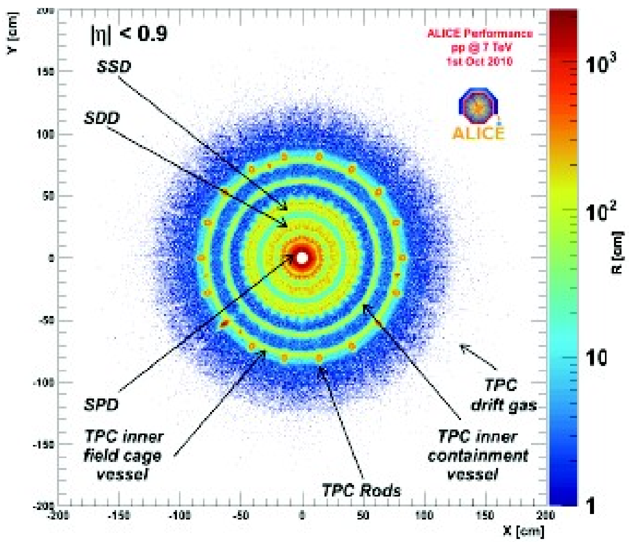




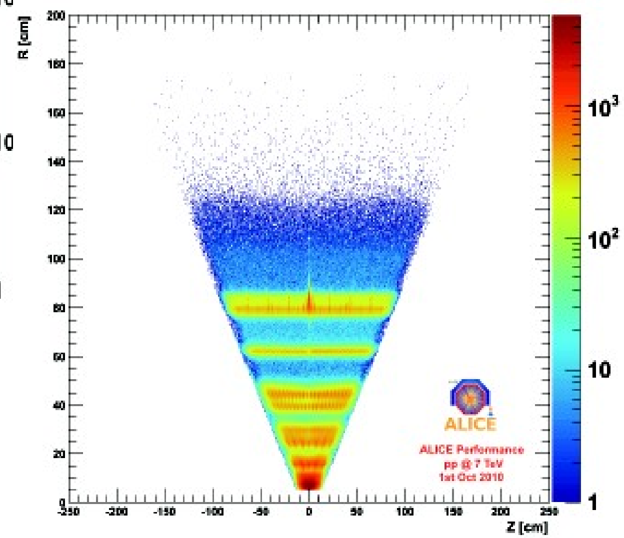
next: precision subtraction of electrons from conversion and Dalitz decays

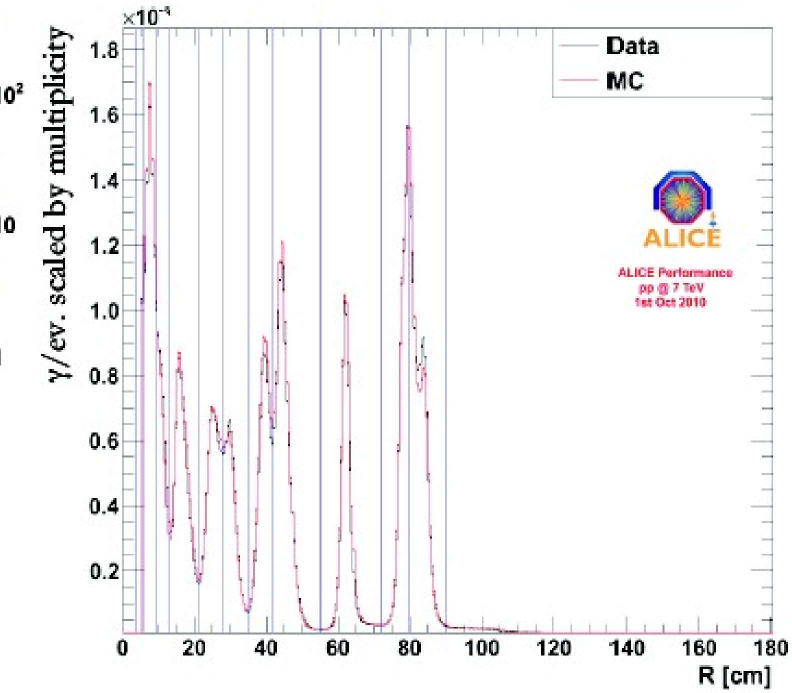
use conversion method for π^0, η measurement plus precision determination of material thickness

Gamma-ray tomography of ALICE



Conversions provide a γ-ray tomography of ALICE.
Very useful tool to check the material budget.
For ALICE this is very well known (down to ± 6% accuracy).

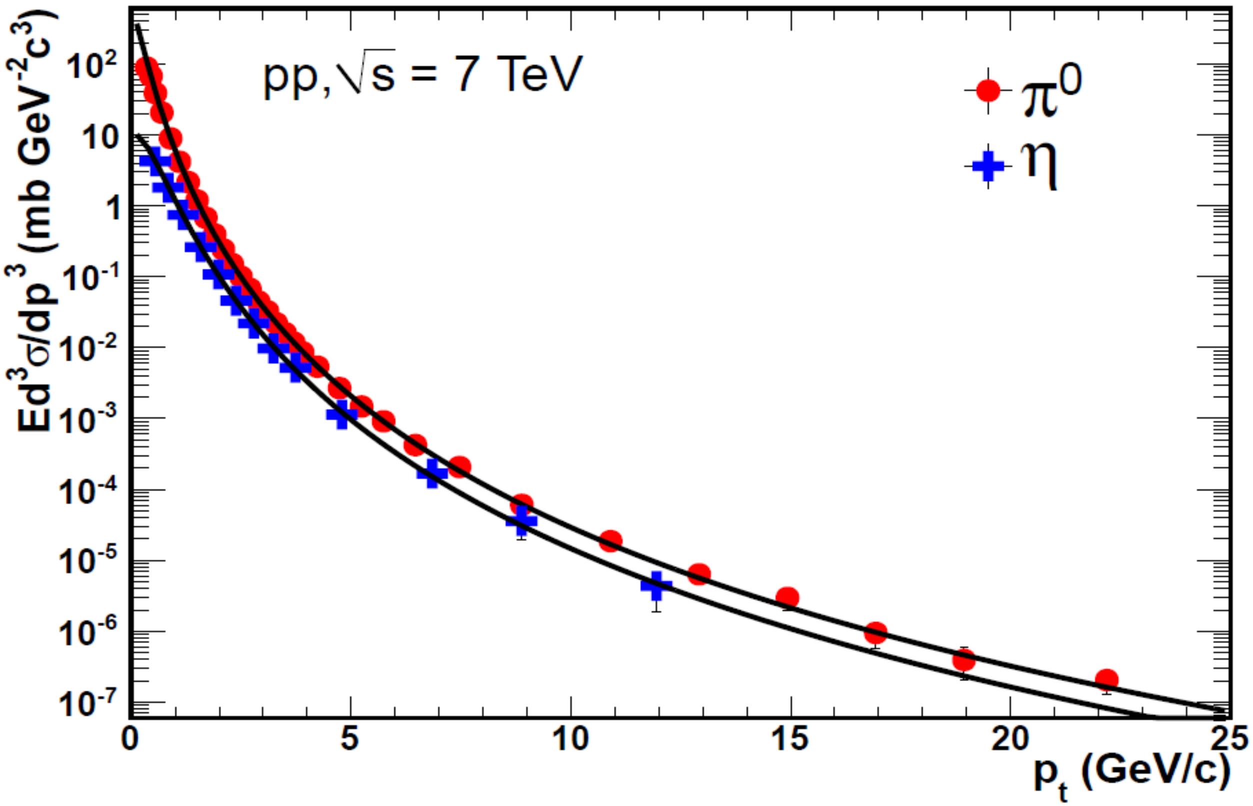




Resolution:
Better than 3 cm in R, 1.5 cm in Z and 2.5 mrad in Φ.

pi0 and eta measurement in ALICE

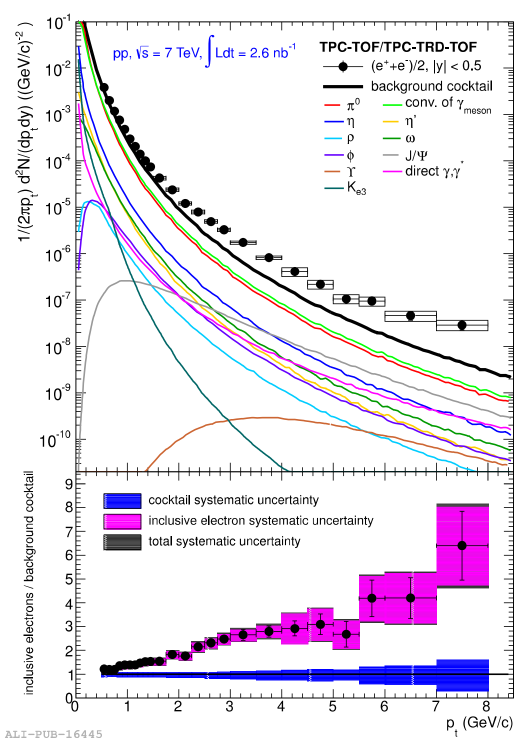
ALICE PLB717 (2012) 162 arXiv 1205.5724

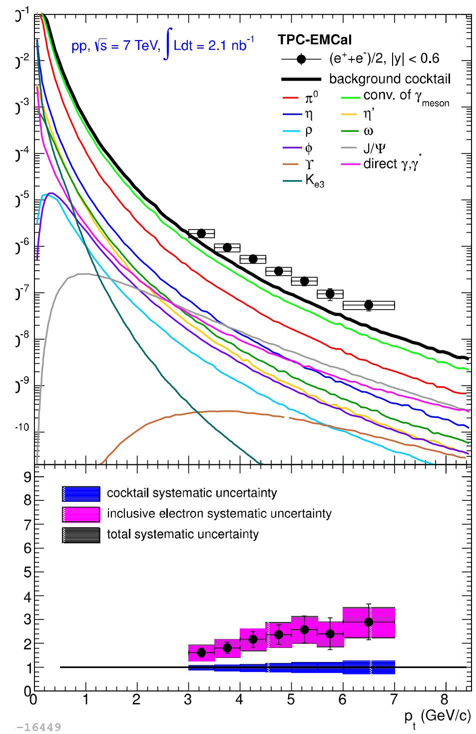


data plus Tsallis parameterisation for hadron cocktail

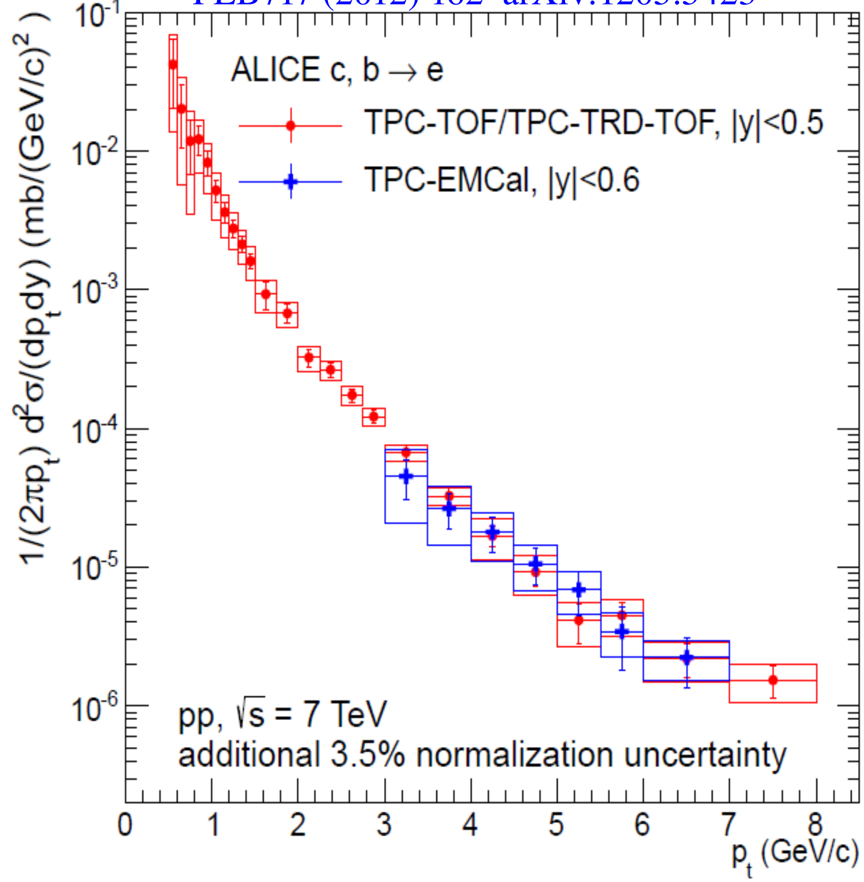
Charm and beauty via semi-leptonic decays

inclusive electron spectrum from 2 PID methods: TPC-TOF-TRD and TPC-EMCAL





PLB717 (2012) 162 arXiv:1205.5423

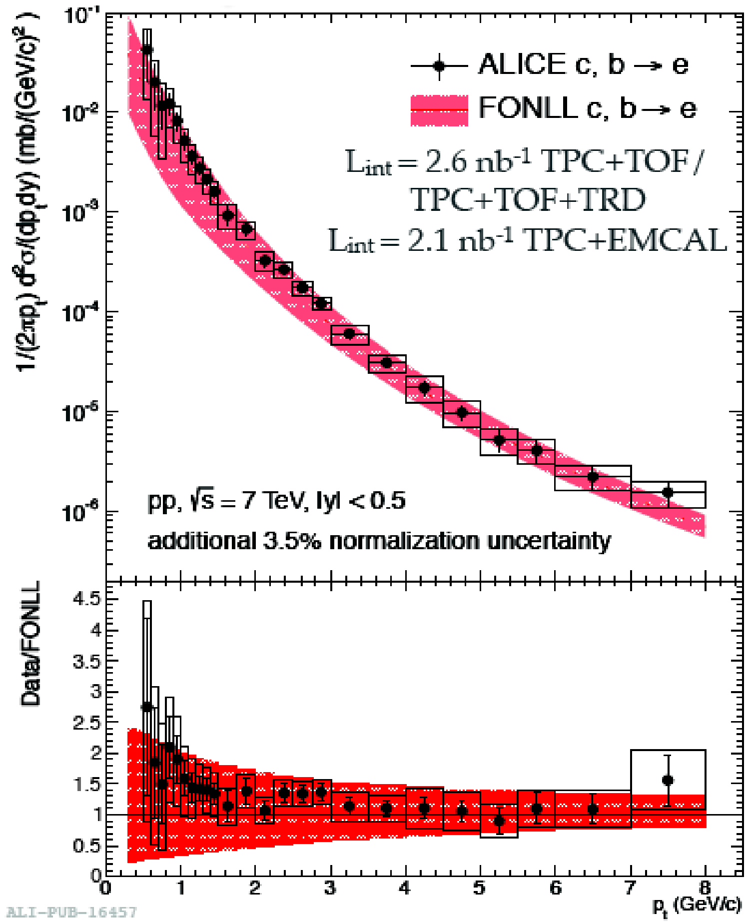


subtract hadronic decay cocktail using measurements where possible (π^0, η, m_t scaling for other mesons, J/ψ), direct γ from pQCD

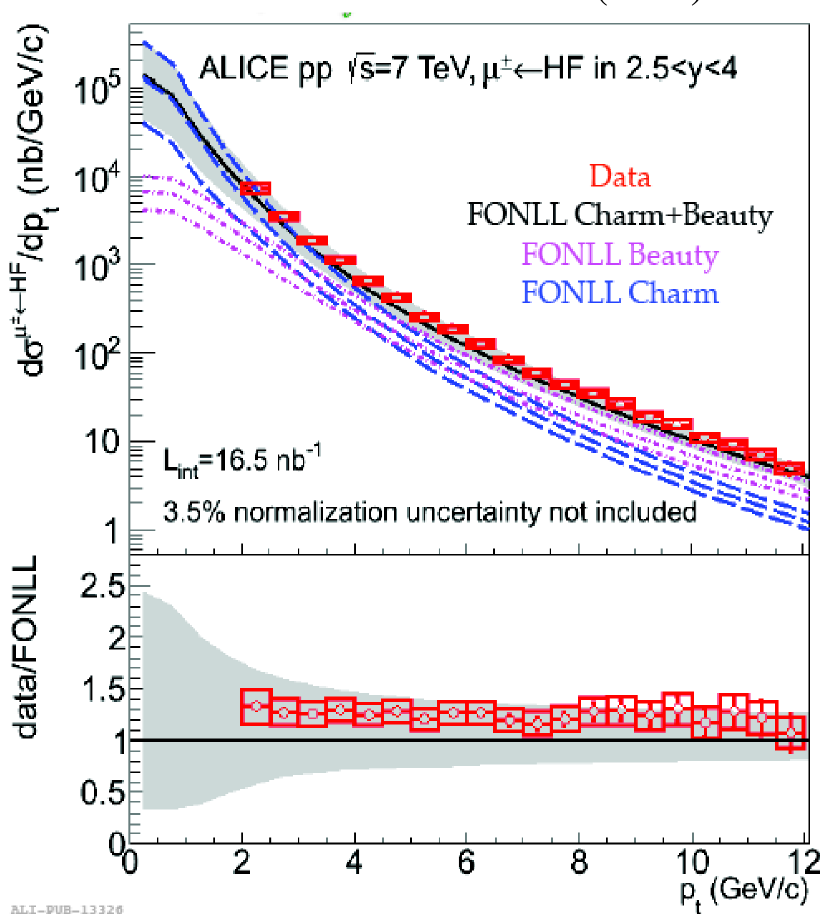
electrons from c and b decays

Heavy flavor decay leptons compared to pQCD

PRD86 (2012)112007 arXiv 1205.5423



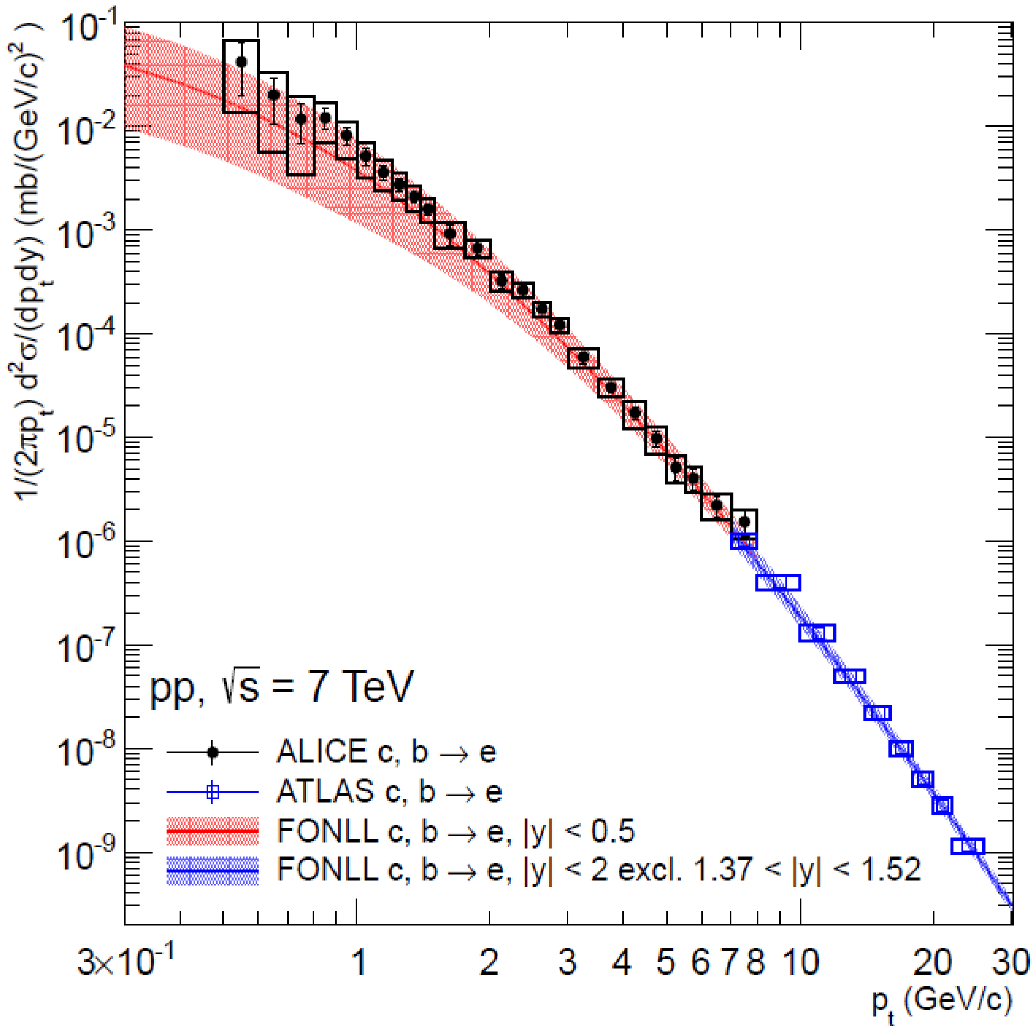
PLB 708 (2012) 2651



data well described by pQCD (FONLL)

[Cacciari et al. JHEP 05 (1998) 007,
Cacciari et al. JHEP 07 (2001) 006,
Cacciari et al arXiv:1205.6344 (2012)]

Charm and beauty electrons compared to pQCD

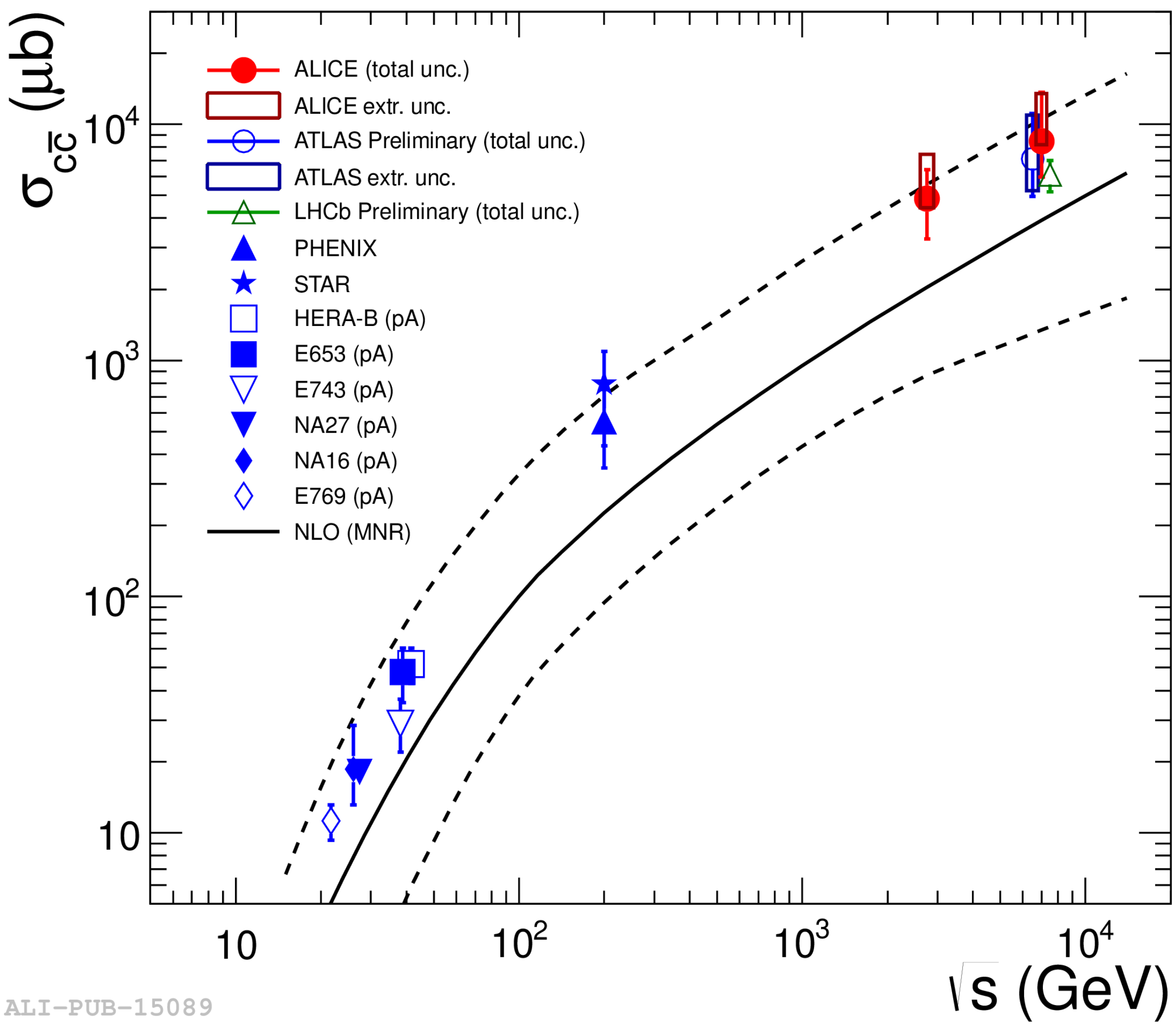


- ALICE data complementary to ATLAS measurement at higher pt (somewhat larger y-interval)
- good agreement with pQCD
- at upper end of FONLL range for p_t < 3 GeV/c where charm dominates

PRD76 (2012) 112007 arXiv:1205.5423
ATLAS: PLB707 (2012) 438
FONLL: Cacciari et al., arXiv:1205.6344

a first try at the total ccbar cross section in pp collisions

JHEP 1207 (2012) 191 arXiv:1205.4007

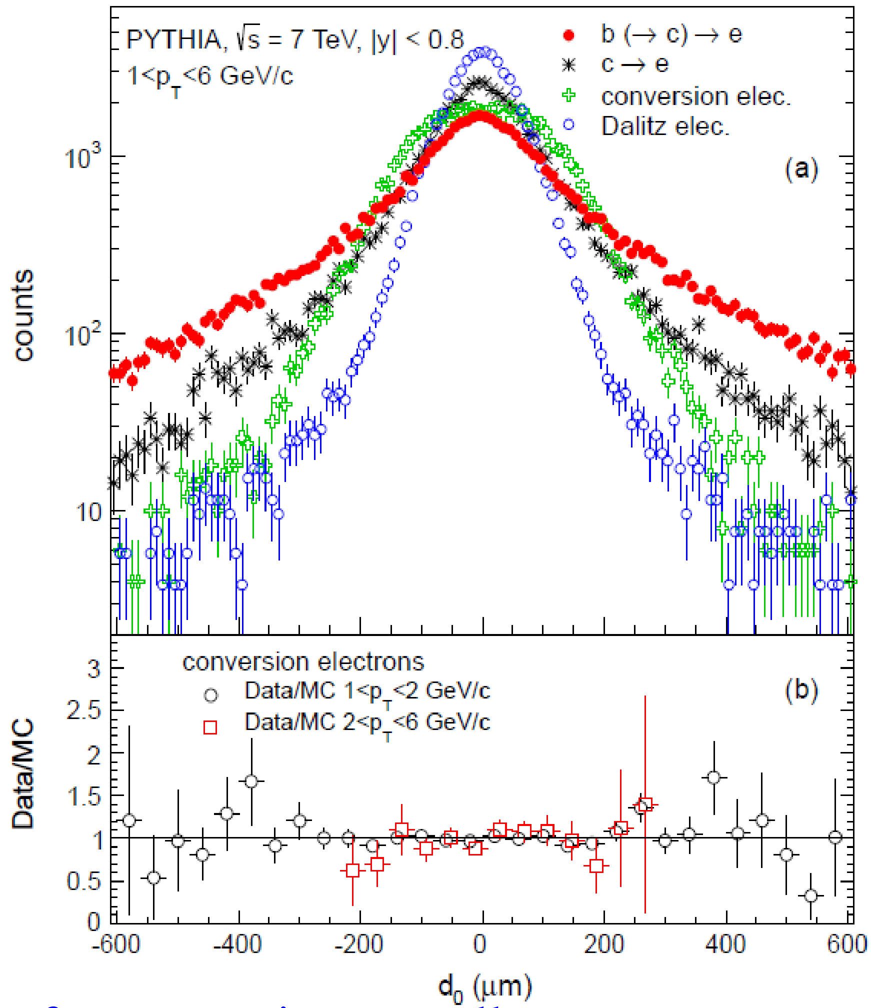


- good agreement between ALICE, ATLAS and LHCb
- large syst error due to extrapolation to low pt, need to push measurements in that direction
- data factor 2 ± 0.5 above central value of FONLL but well within uncertainty
- beam energy dependence follows well FONLL

Separation of charm and beauty via minimum impact parameter cut

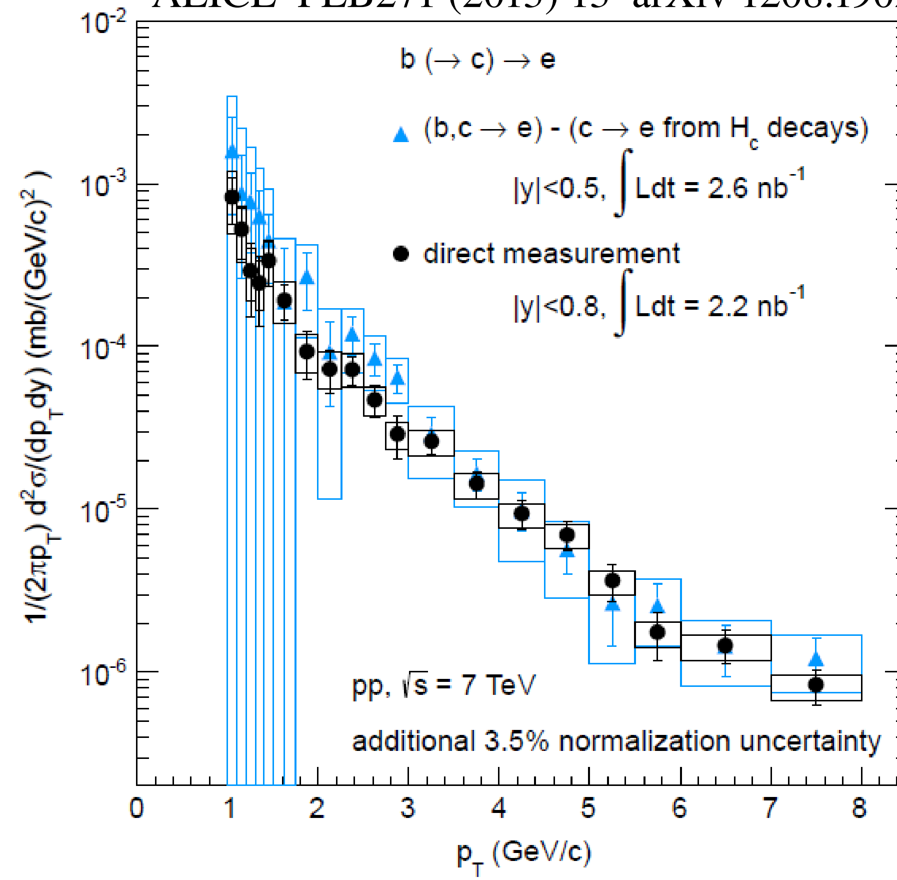
via cut in transverse impact parameter d_0

resolution better 80 (20) μm for p_t = 1 (10) GeV/c



for conversions excellent agreement between data and MC

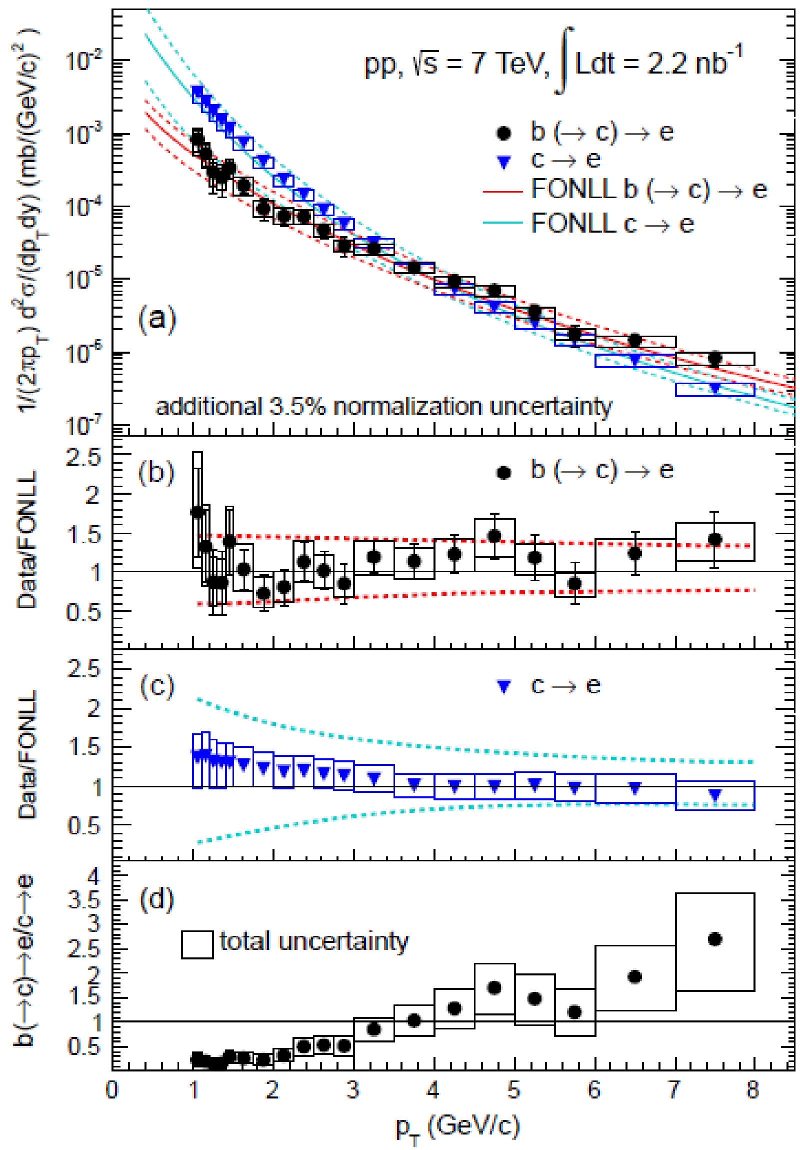
ALICE PLB271 (2013) 13 arXiv 1208.1902



cross check: compare spectrum with min. d0 cut to spectrum where decays from charm were subtracted using measured D cross sections and FONLL for unmeasured parts → very good agreement

Comparison electrons from beauty and charm decays

ALICE PLB721 (2013) 12 arXiv 1208.1902

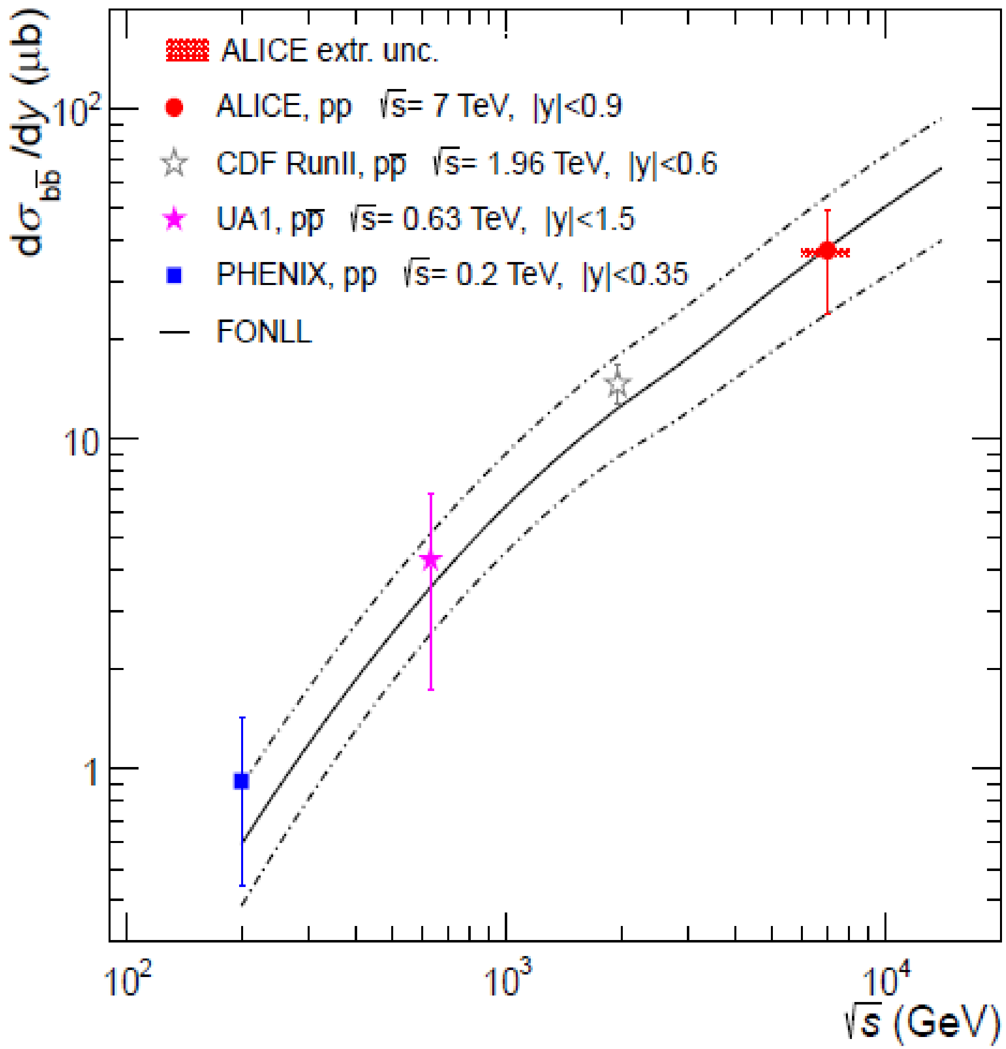


electron from charm and beauty decays measured separately from 1-8 GeV/c

beyond 4 GeV/c beauty larger than charm

good agreement with pQCD, data lie in upper half of FONLL band

Beauty cross section in pp and ppbar collisions



rapidity density of beauty cross section in excellent agreement with pQCD

total bbar cross section

$$\sigma_{b\bar{b}} = 280 \pm 23(\mathrm{stat})^{+81}_{-79}(\mathrm{sys})^{+7}_{-8}(\mathrm{extr}) \pm 10(\mathrm{BR})\ \mu\mathrm{b}$$

well consistent with ALICE measurement of J/psi from displaced secondary vertices

$$\sigma_{b\bar{b}} = 282 \pm 74(\mathrm{stat})^{+58}_{-68}(\mathrm{sys})^{+8}_{-7}(\mathrm{extr})\ \mu\mathrm{b}$$

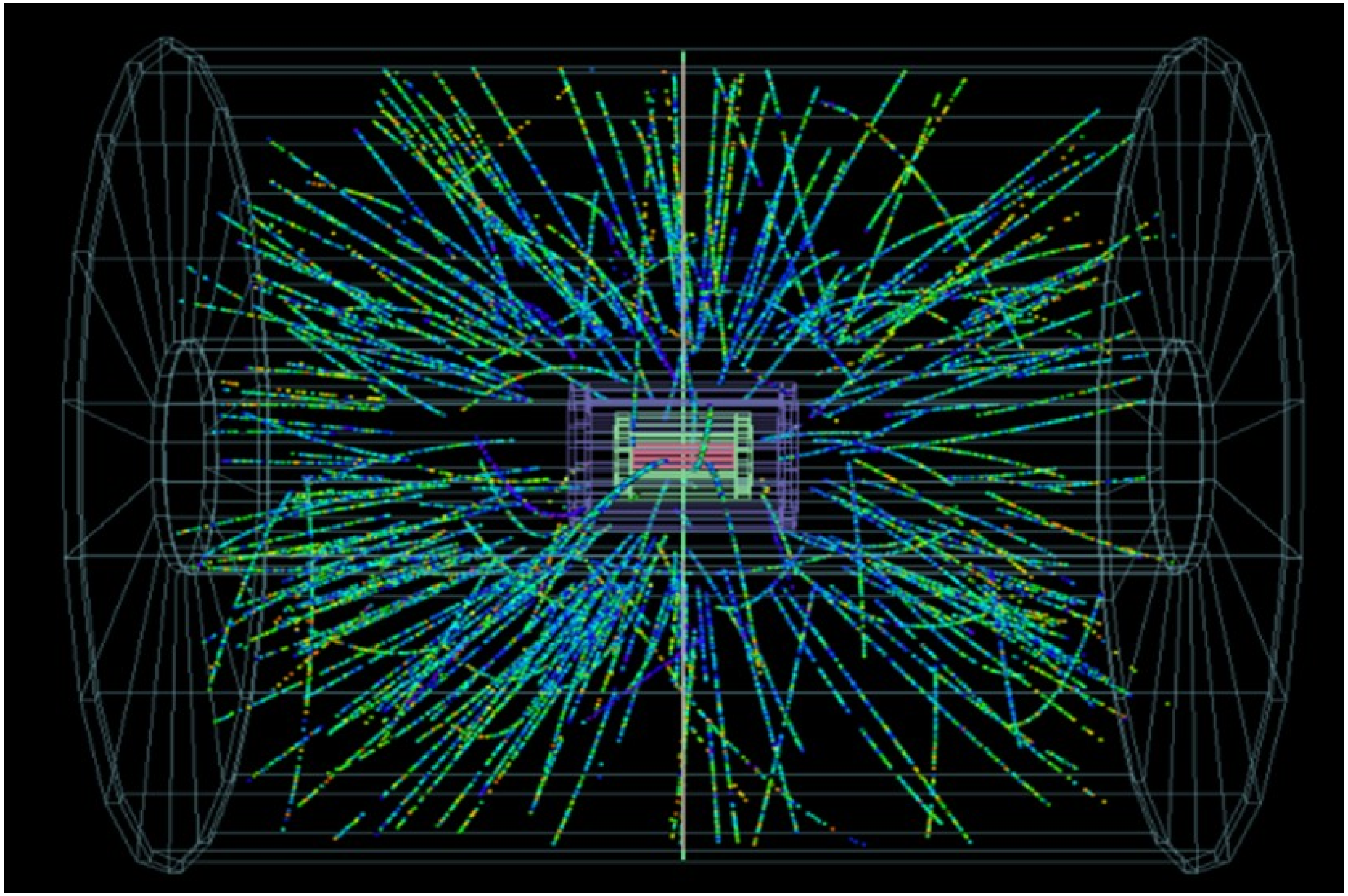
compared to FONLL

$$\sigma_{b\bar{b}} = 259^{+120}_{-96}\ \mu\mathrm{b}$$

collisions of pPb as baseline for PbPb

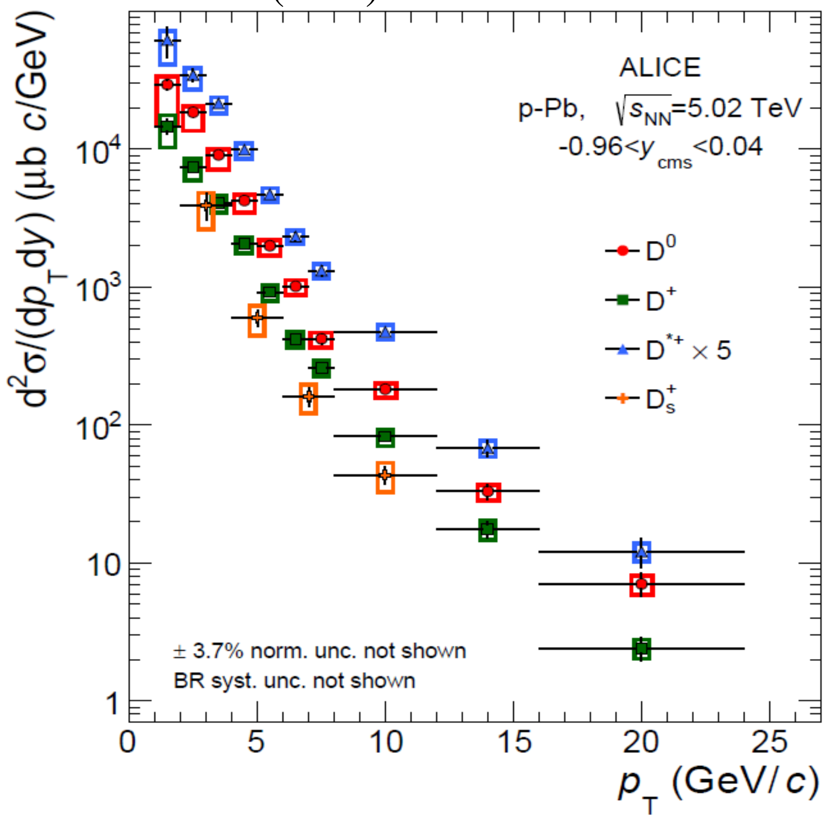
p Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

heavy flavor measurements via: D-mesons, heavy flavor decay electrons and muons



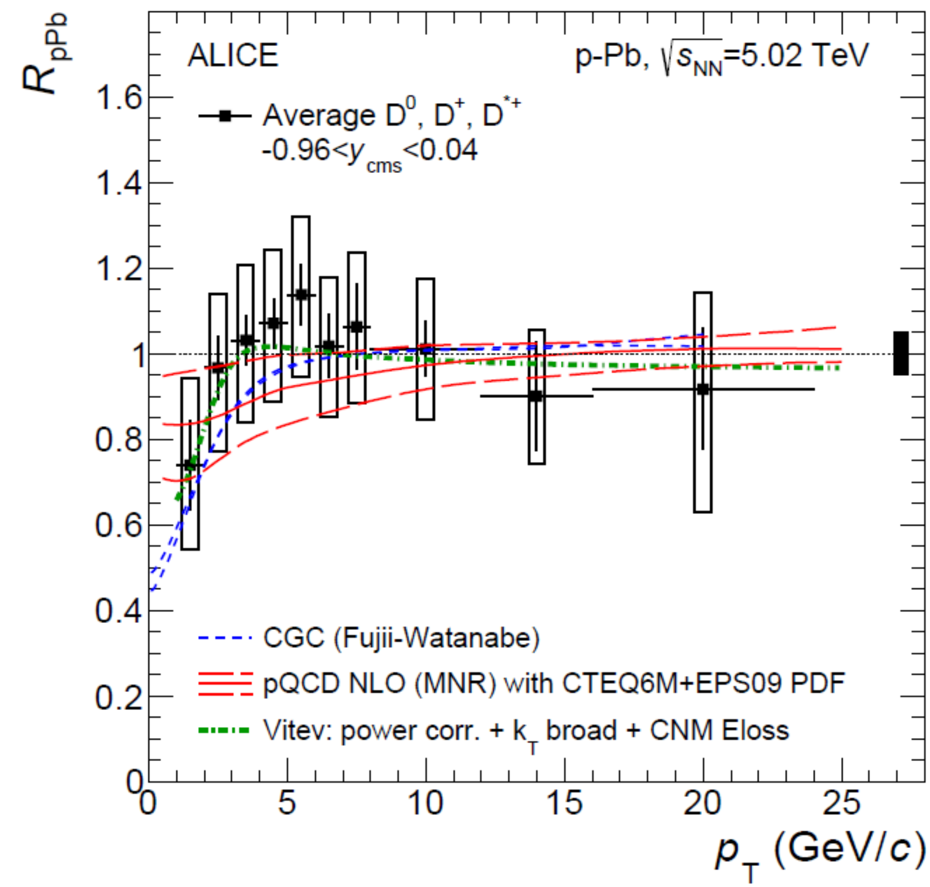
collisions of pPb - D meson spectra

PRL 113 (2014) 232301 arXiv:1405.3452



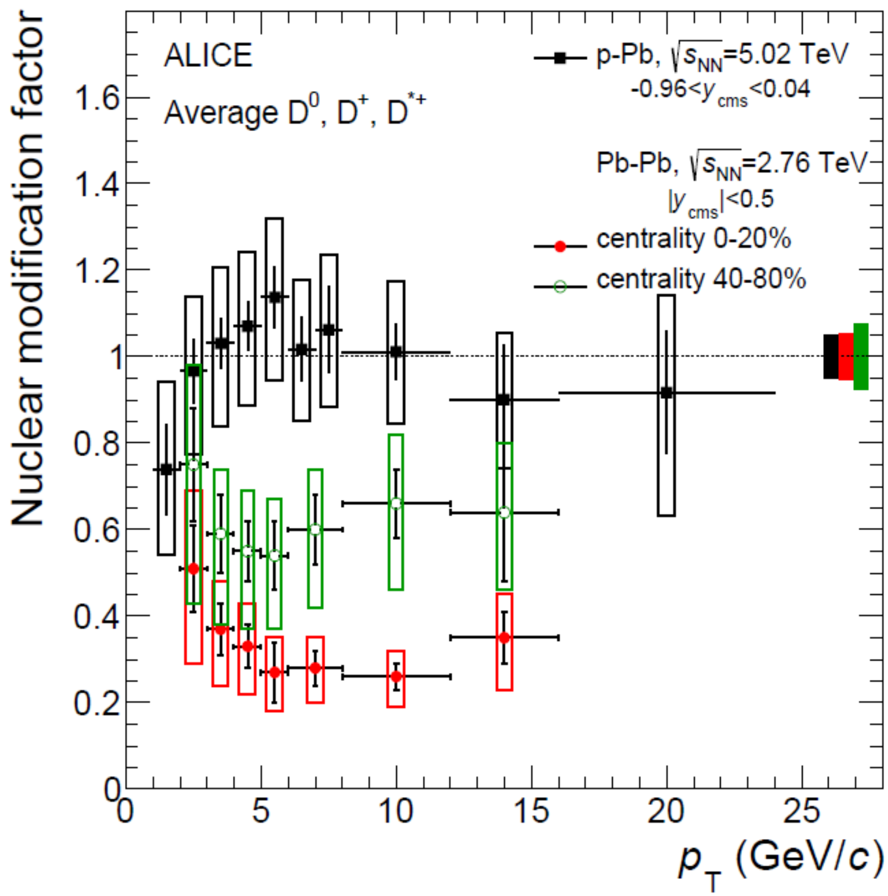
prompt spectra of D_0, D^+, D^{*+}, D_s^+ and their conjugates (b subtracted via FONLL)

various calculations describe data comparably well, nuclear effects small from moderate pt upwards



collisions of pPb as baseline for PbPb

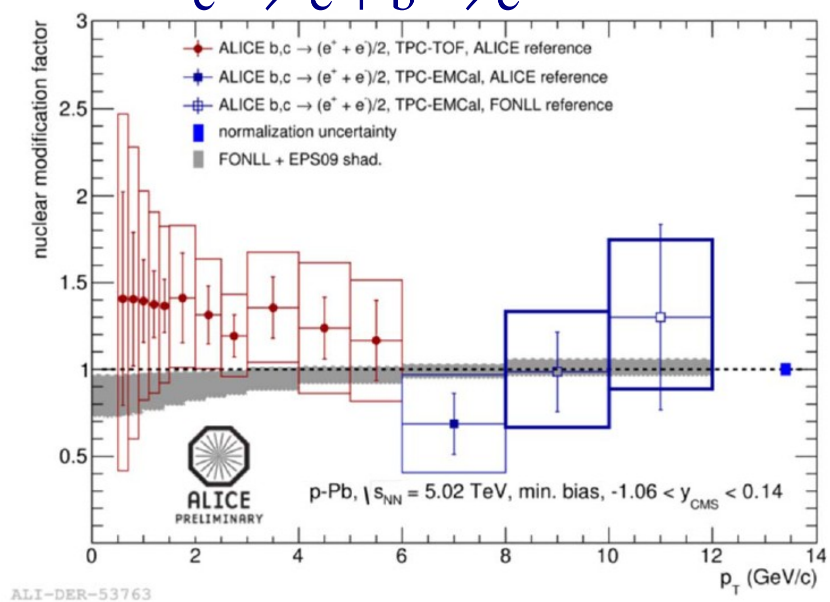
PRL 113 (2014) 232301 arXiv:1405.3452



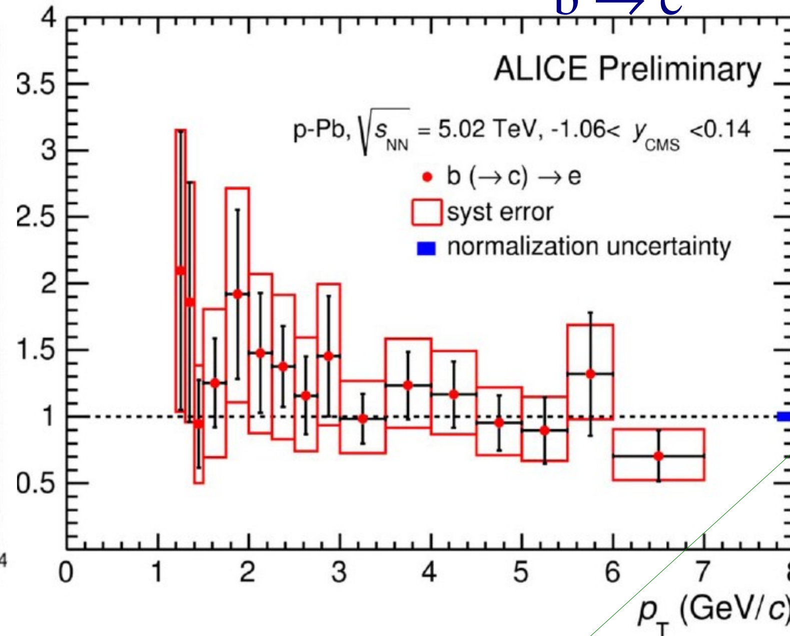
p Pb data consistent with unity
strong suppression in nuclear collision is final state (QGP) effect

Heavy flavor decay electrons and muons in pPb

$c \to e + b \to e$

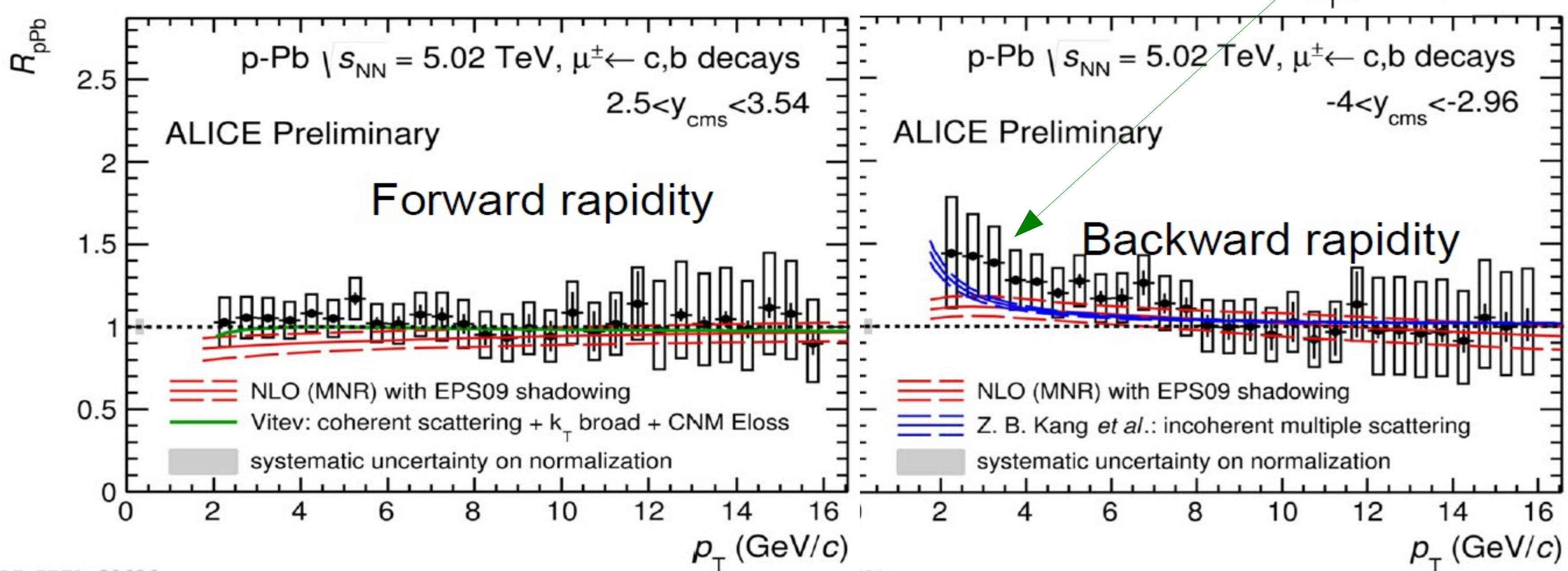


$b \to e$

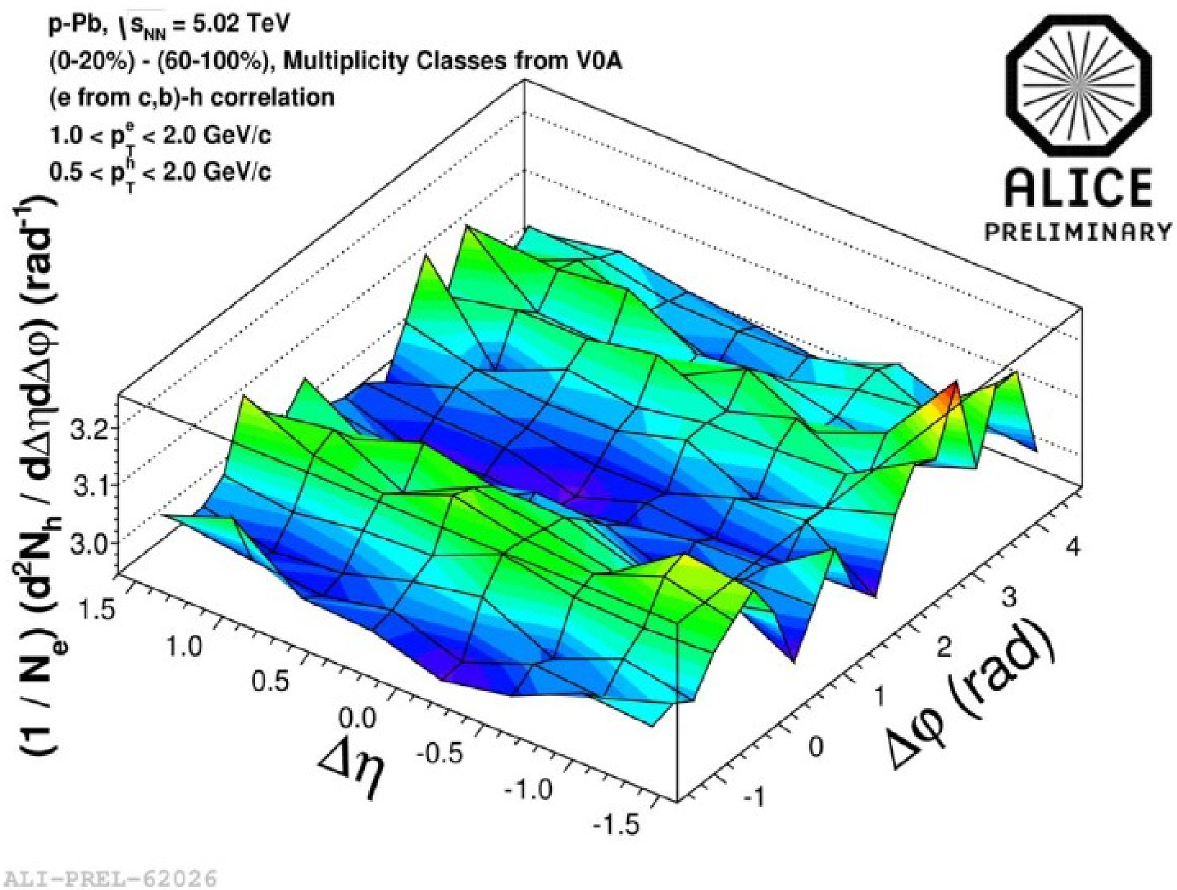


all consistent with unity – nuclear effects are small

only slight enhancement in Pb-going direction at low p_t



Double-ridge structure also apparent in heavy flavor electrons in pPb collisions



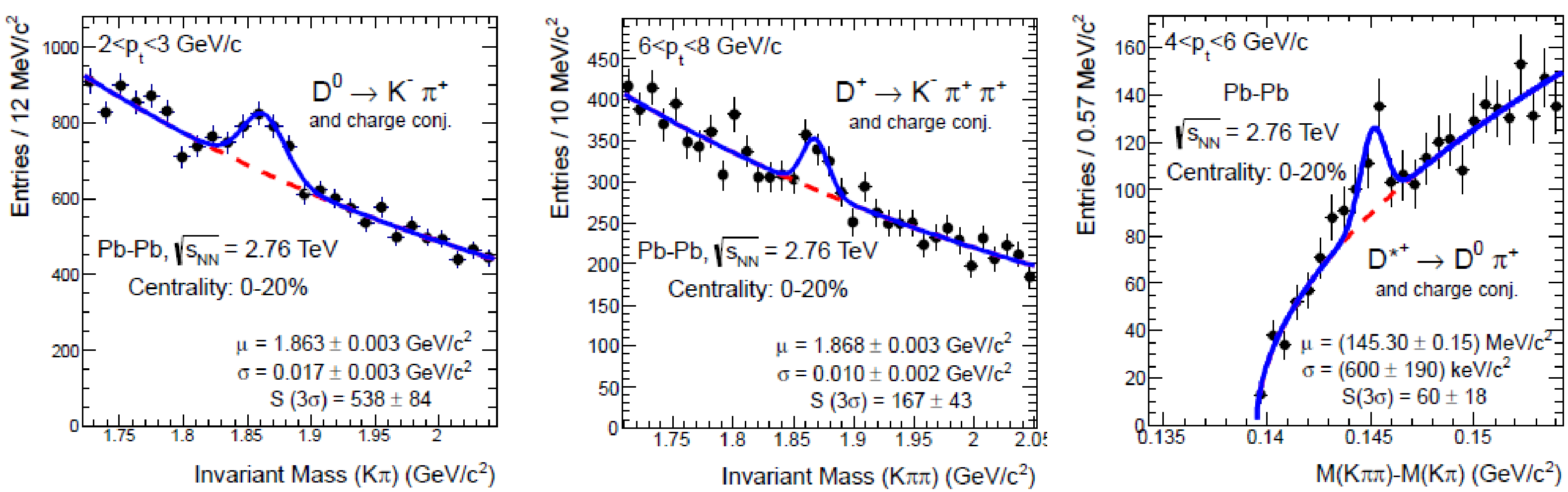
- trigger particle: heavy flavor decay electron
- associated particle: ch. Hadron
- jet correlations removed by subtracting from the highest multiplicity class (0-20%) the angular correlation of the lowest multiplicity class (60-100%)

results very similar to light flavor sector
explanation? Collective expansion? CGC?

D meson signals in Pb Pb collisions

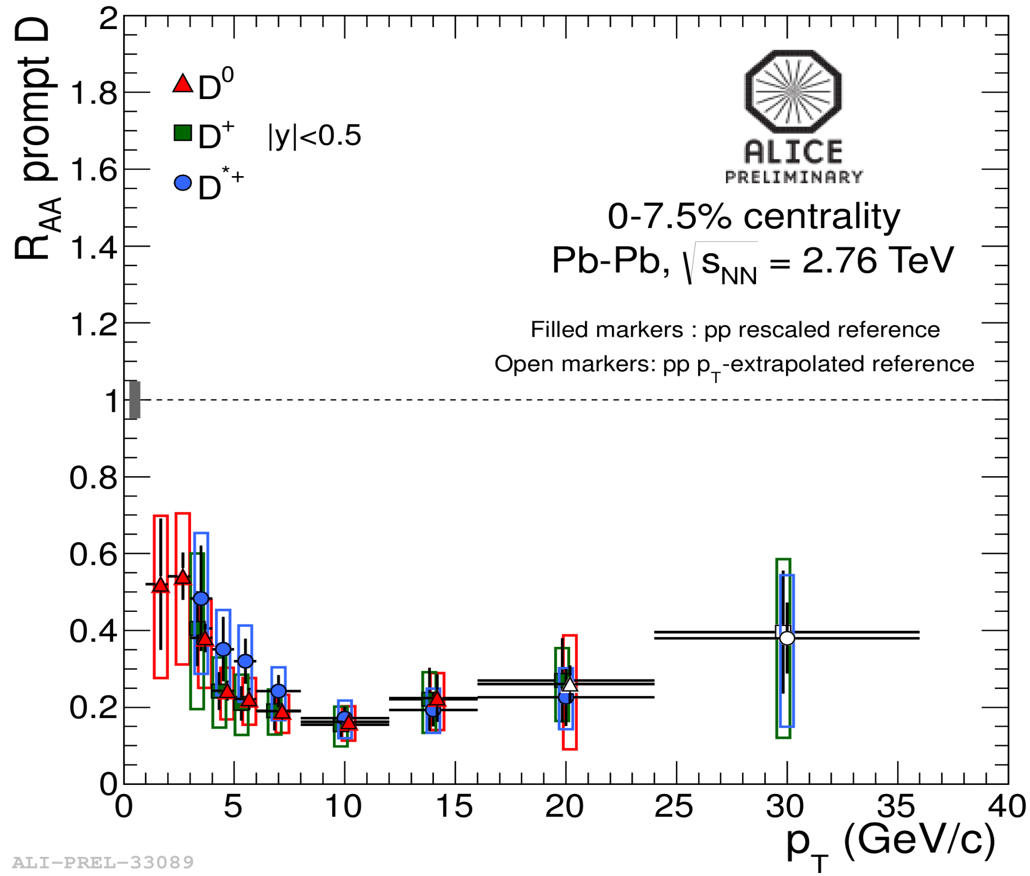
measurement:
reconstruction of hadronic decays of D-mesons (ALICE)
semi-leptonic decays into electrons (ATLAS, ALICE)
    “   into muons (ATLAS, ALICE)
J/ψ from secondary vertex from B-decay

data: ALICE JHEP 1209 (2012) 112 arXiv:1203.2160



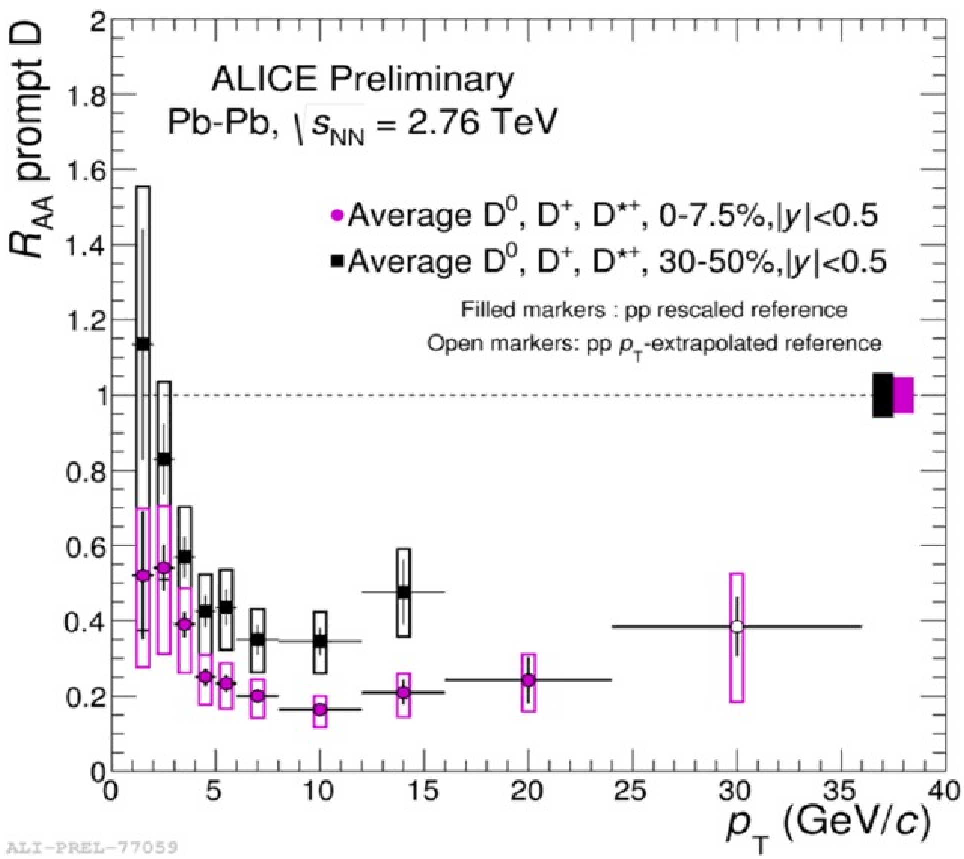
Suppression of charm at LHC energy

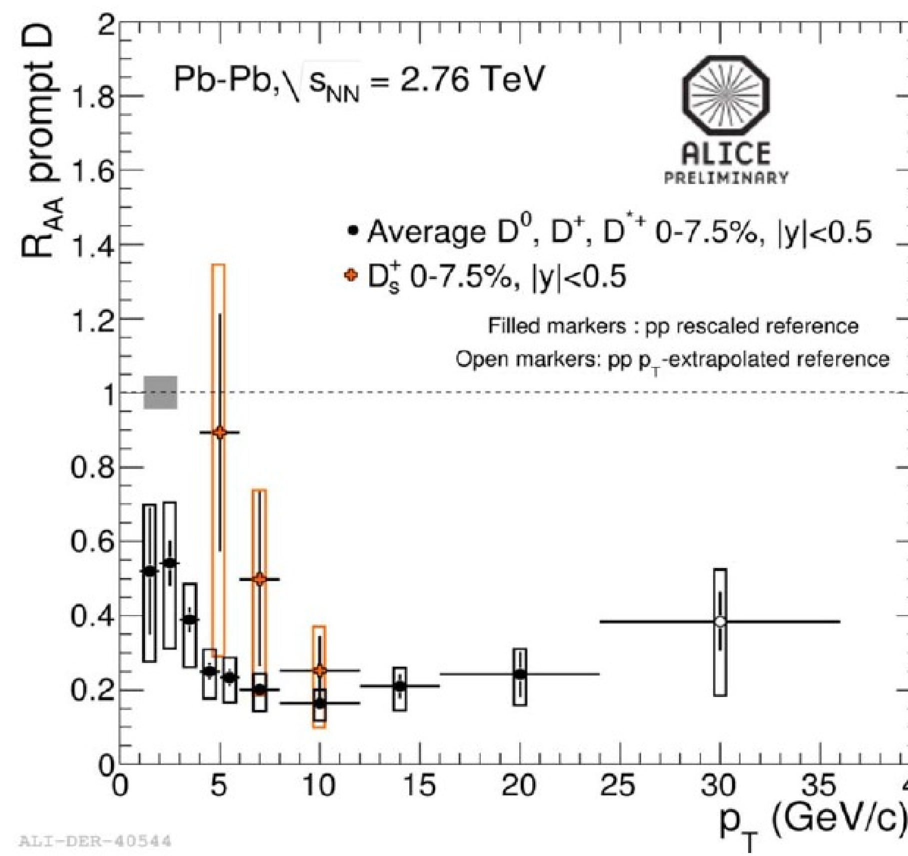
pp reference at 2.76 TeV: measured 7 TeV spectrum scaled with FONLL
cross checked with 2.76 TeV measurement (large uncertainty due to limited luminosity



energy loss for all species of D-mesons within errors equal - not trivial
energy loss of central collisions very significant - suppr. factor 5 for 5-15 GeV/c

Comparing D_s to D^0, D^+, D^{*+}





- R_{AA} all D^0, D^+, D^{*+} averaged: centrality dependence as for charged particles
- energy loss of D_s comparable, less at low p_t?

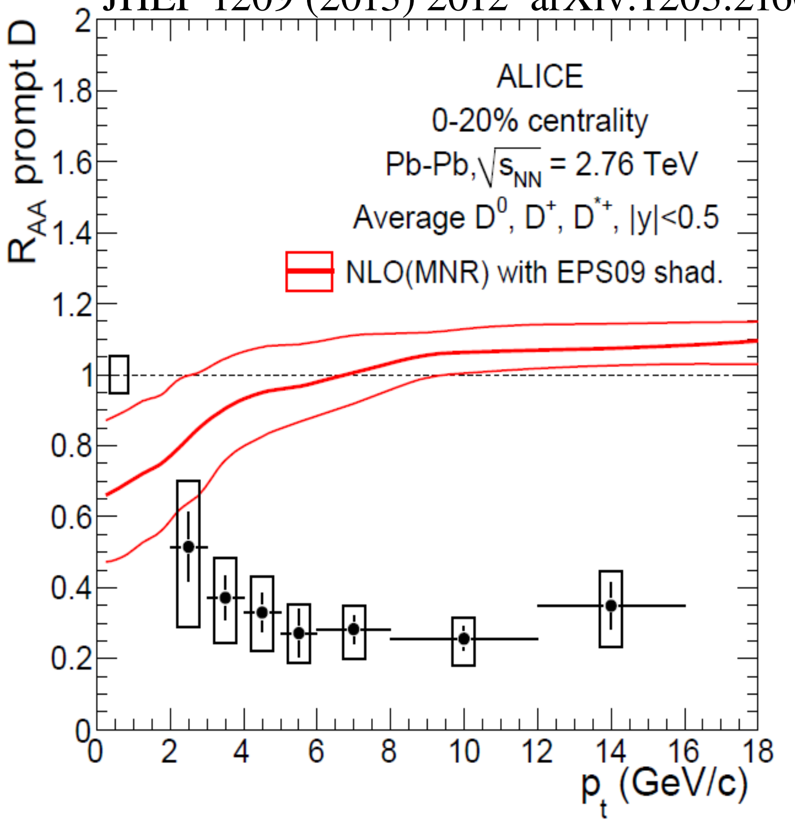
interest in D_s yield: standard stat. hadronization vs enhancement reflecting strangeness in QGP and in possible enhancement of RAA at intermediate pt due to coalescence

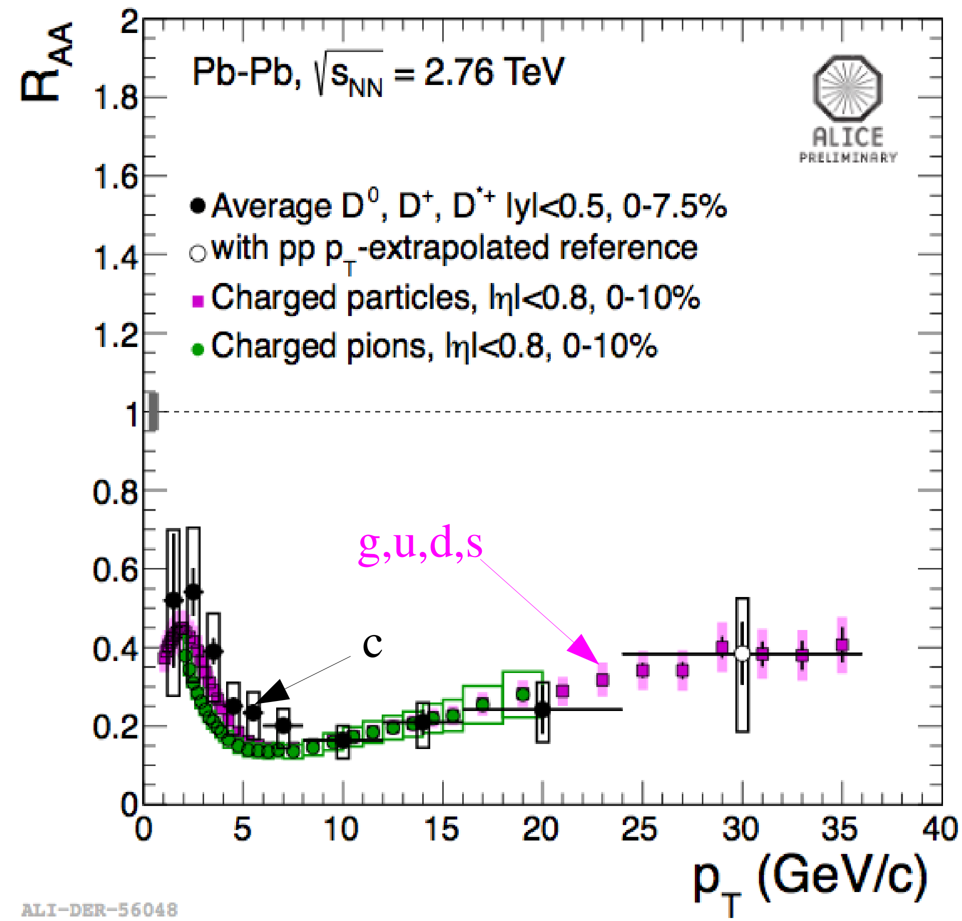
Kuznetsova, Rafelski, EPJ C 51 (2007) 113; He et al., PRL 110 (2013) 112301; Andronic et al., PLB 659 (2008) 149

Suppression of charm at LHC energy

comparison to EPS09 shadowing:
suppression not an initial state effect
will be measured directly in pPb collisions

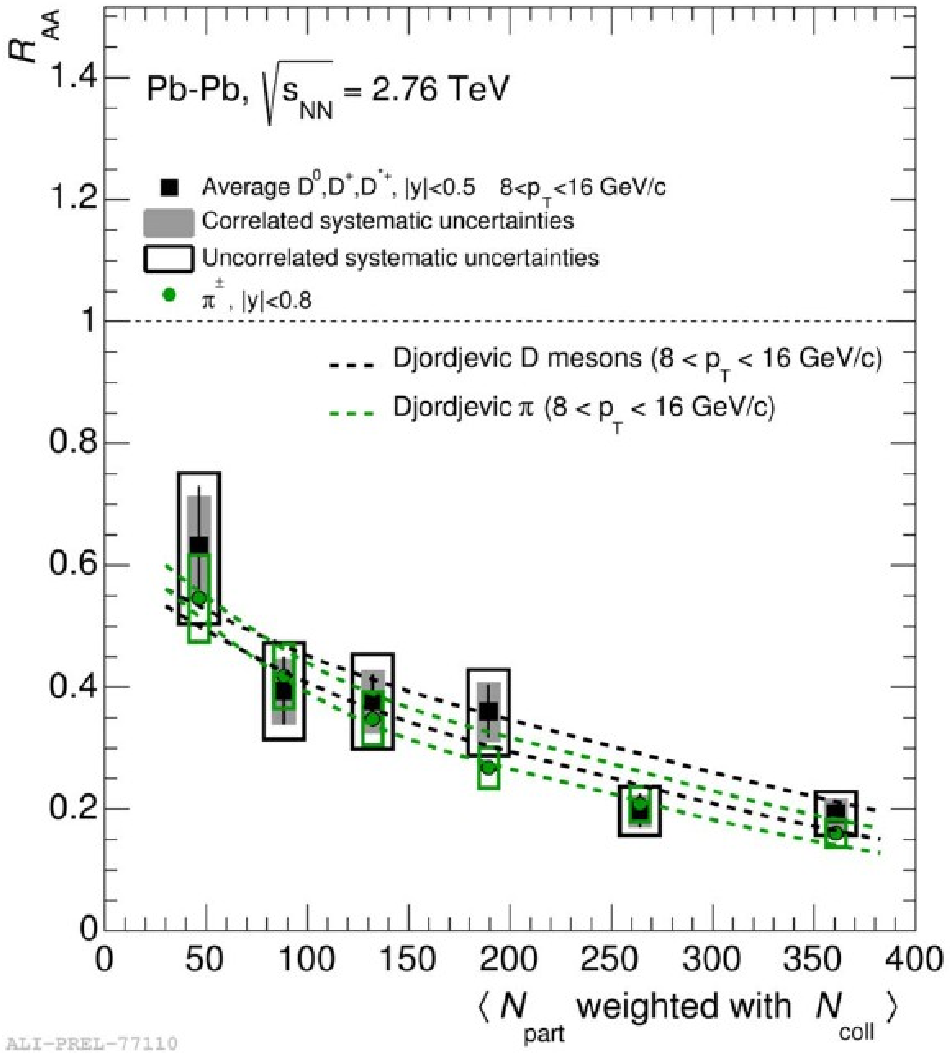
JHEP 1209 (2013) 2012 arXiv:1203.2160





energy loss of charm quarks only slightly less than that for light quark → thermalization

Centrality dependence of charm suppression

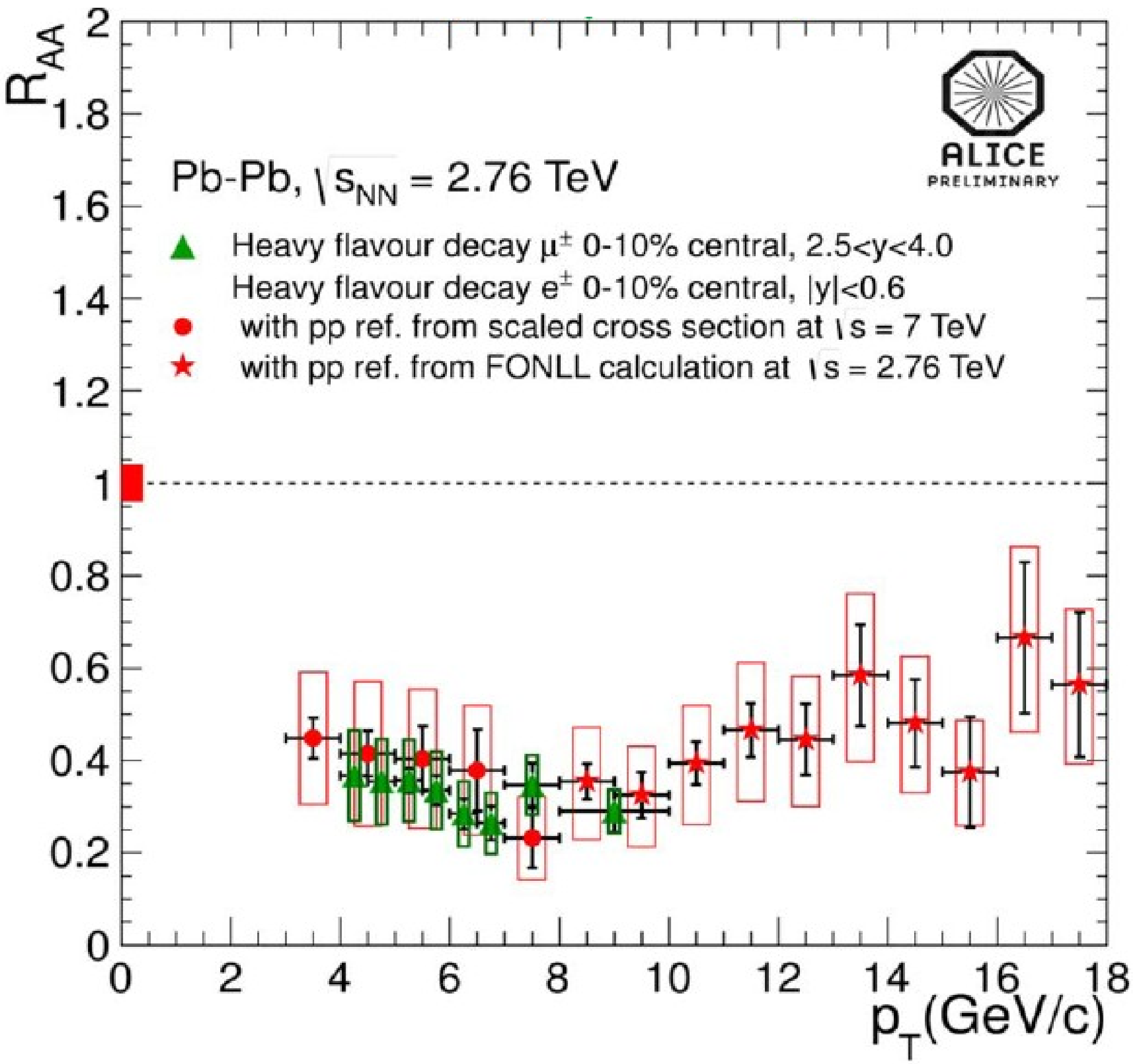


absolute values and centrality dependence similar between D and π

in agreement with models implementing
$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c$
and taking into account different shapes of parton distributions and fragmentation functions

Djordjevic, PLB 734 (2014) 286;
Wicks, Horowitz, Djordjevic, NPA 872 (2011) 265

R_{AA} of decay electrons and muons from heavy flavor mesons

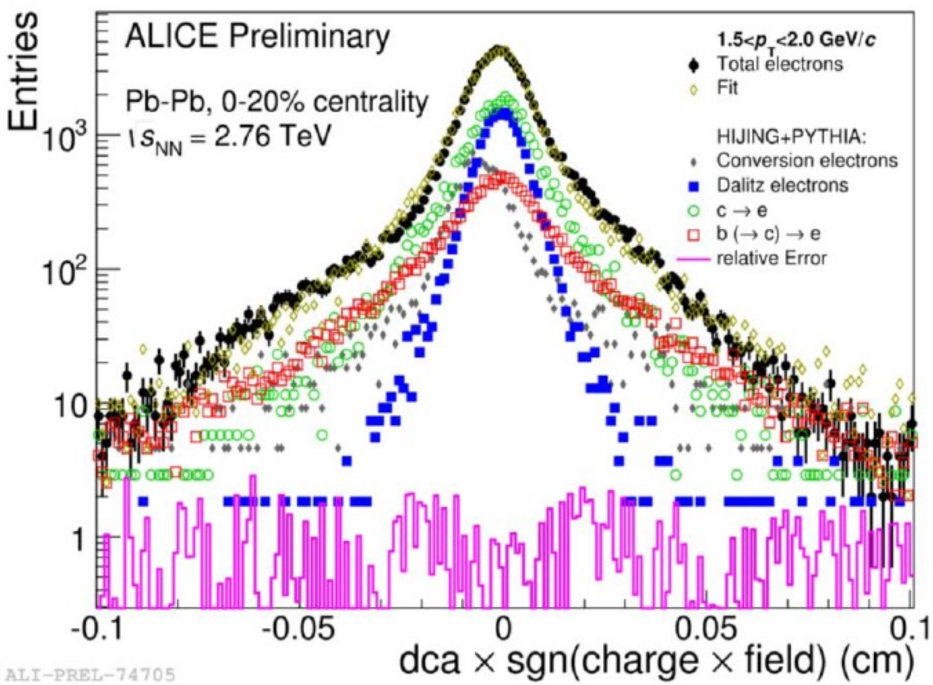


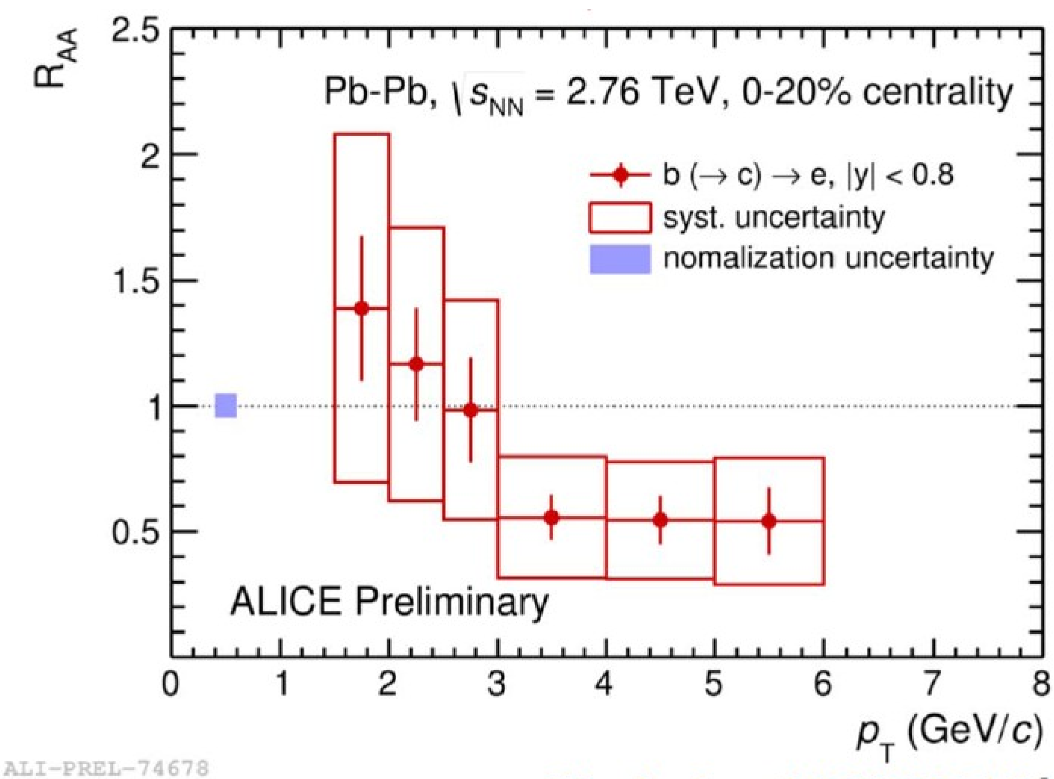
for central collisions (most central 10 %) very significant suppression – factor 2-4 for pt > 3 GeV/c - also for electrons and muons from c and b decays

indicative of significant energy loss

suppression for mid-y
(electrons at |y|<0.6)
and forward y
(muons at 2.5 < y < 4.0) very similar

What about b-quark energy loss and thermalization?

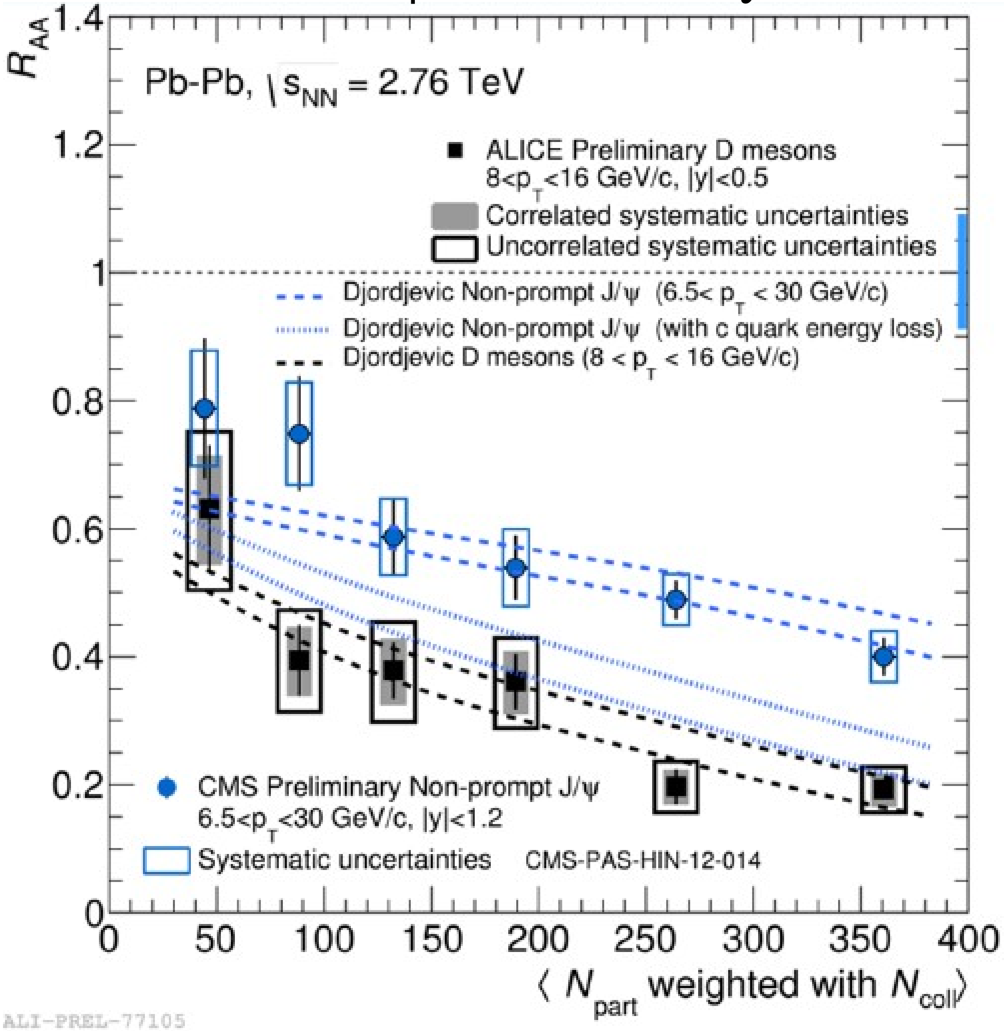




- separation of electrons from b-decay via fit of dca distribution of electrons with templates from measured impact parameter distributions
- for most central 10% collisions, electrons from b-decay show suppression for p_t > 3 GeV/c

Comparison c and b-quark energy loss with theory

above 6.5 GeV/c in PbPb collisions, b-quark suppression established by CMS via J/ψ from B-decay

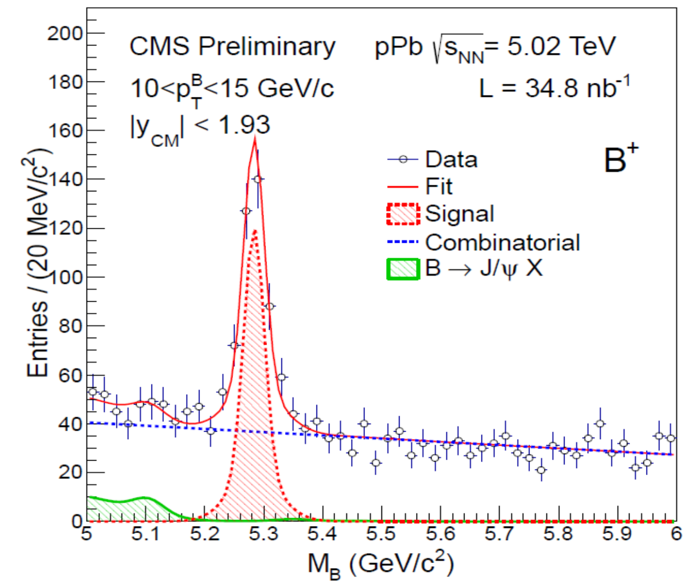


non-prompt J/ψ less suppressed than D in line with expectation $\Delta E_c > \Delta E_b$ mean p_t of D and contributing B mesons as well as rapidity range are similar

pQCD based calculation of energy loss in QGP reproduces data well (M. Djordjevic PLB 734 (2014) 286)

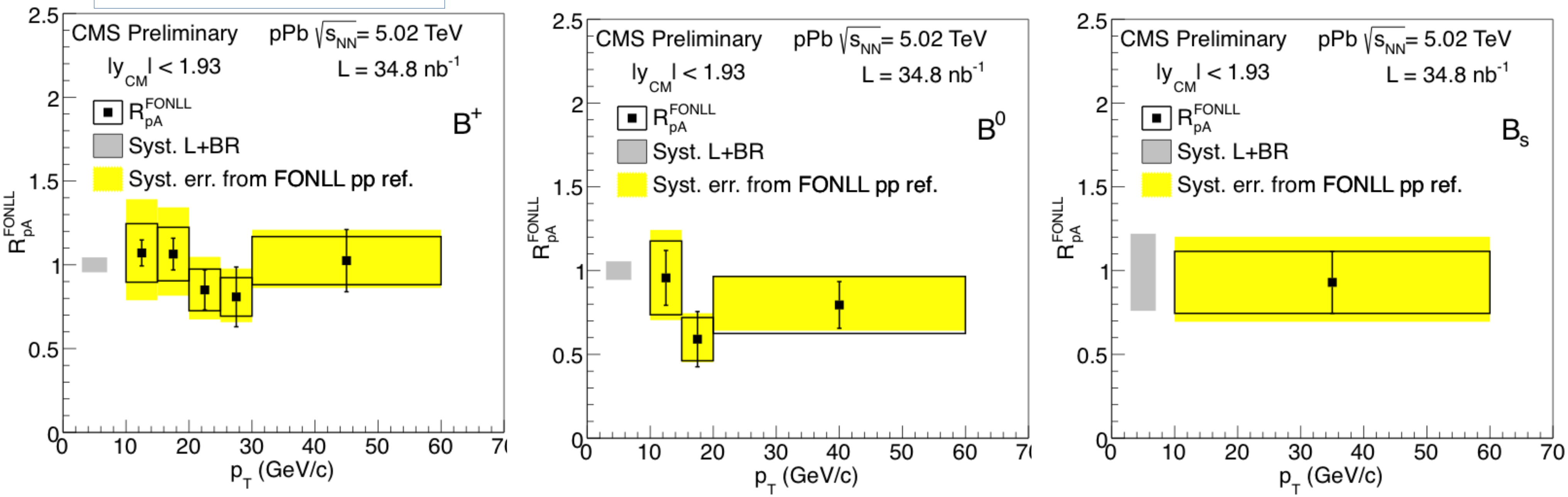
other calculations (TAMU, BAMPS, WHDG, MC@sHQ+EPOS2) give similar trends

Future: reconstruction of B-mesons



CMS recent result: first B-meson direct reconstruction in pPb collisions!

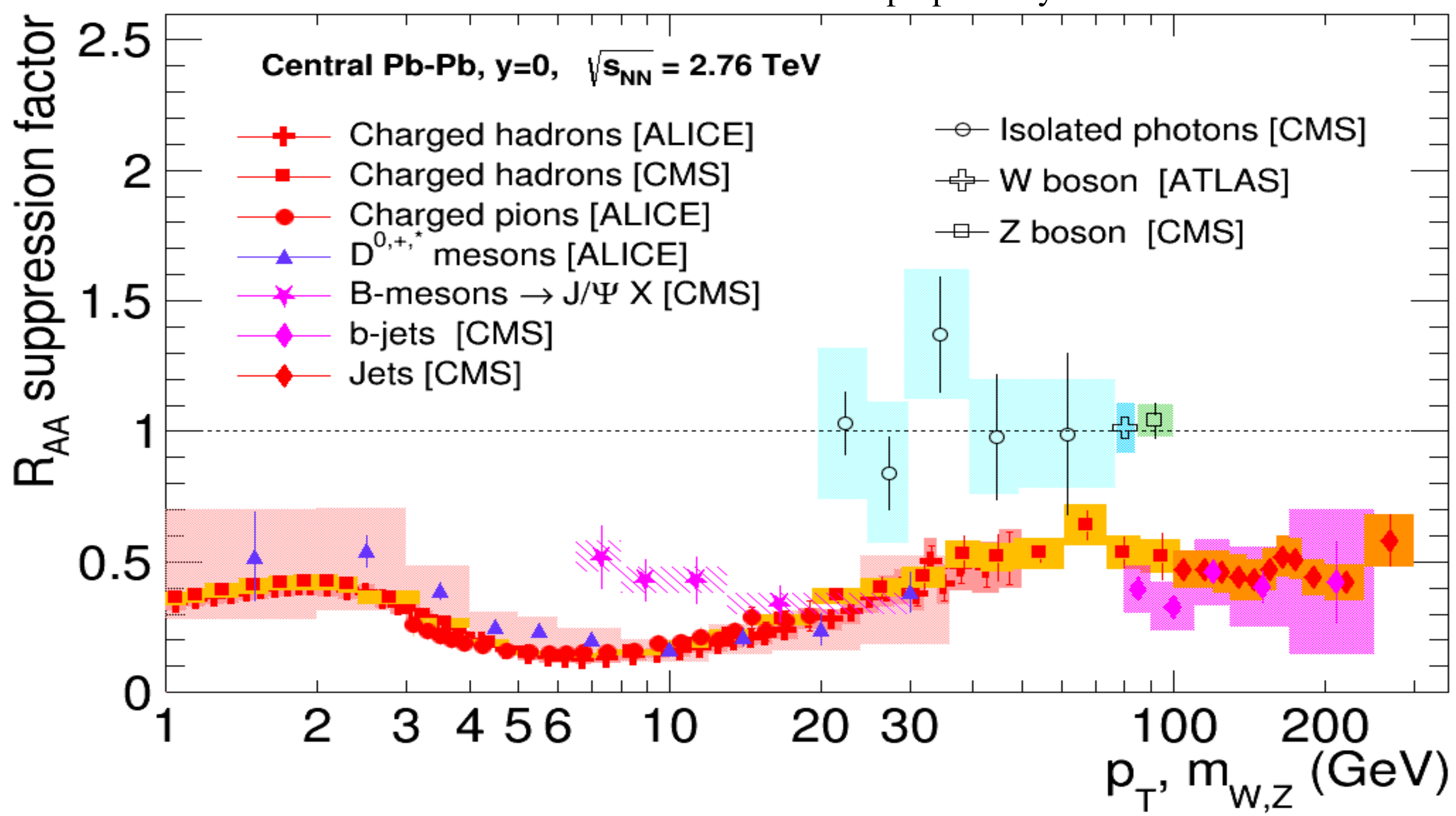
CMS-PAS-HIN-14-004



data for pPb important baseline for PbPb data -
to be repeated in Run2/3 for PbPb by all CMS, ALICE, LHCb...

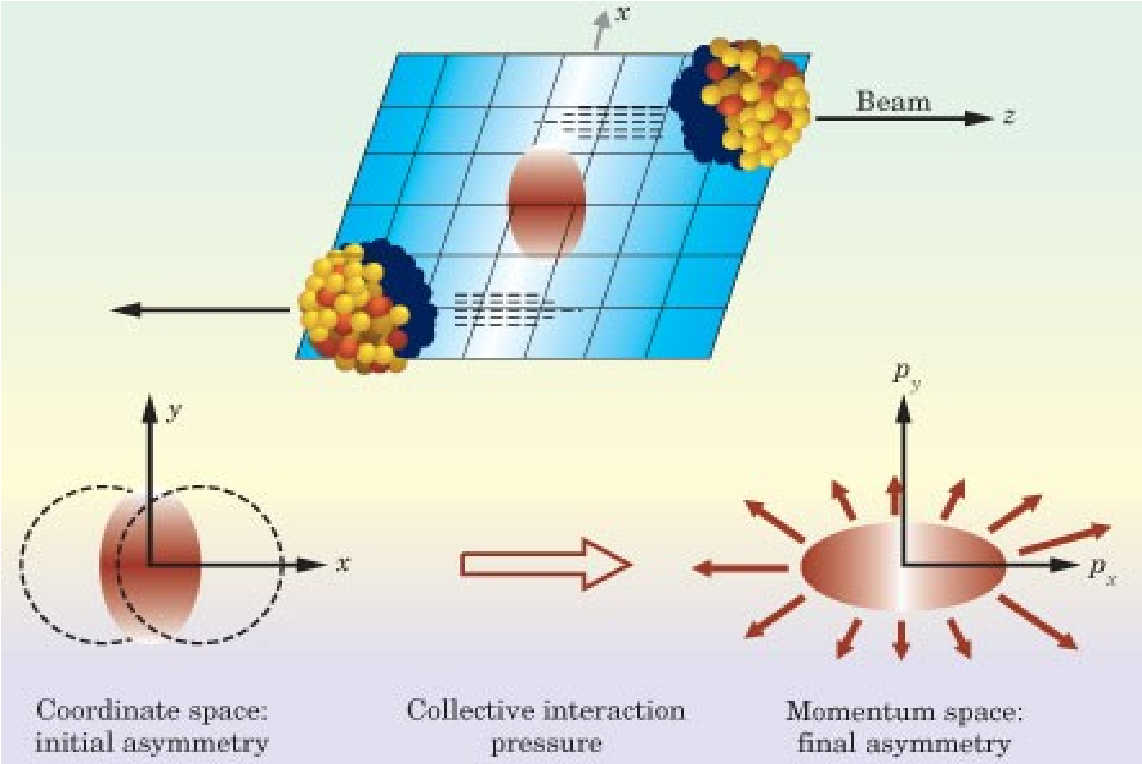
Suppression only for Strongly Interacting Hard Probes

prepared by D. d'Enterria for ICFA2014



photons, Z and W scale with number of binary collisions in PbPb – not affected by medium
→ demonstrates that charged particle suppression is medium effect: energy loss in QGP

Azimuthal Anisotropy of Transverse Spectra



Fourier decomposition of momentum distributions rel. to reaction plane:

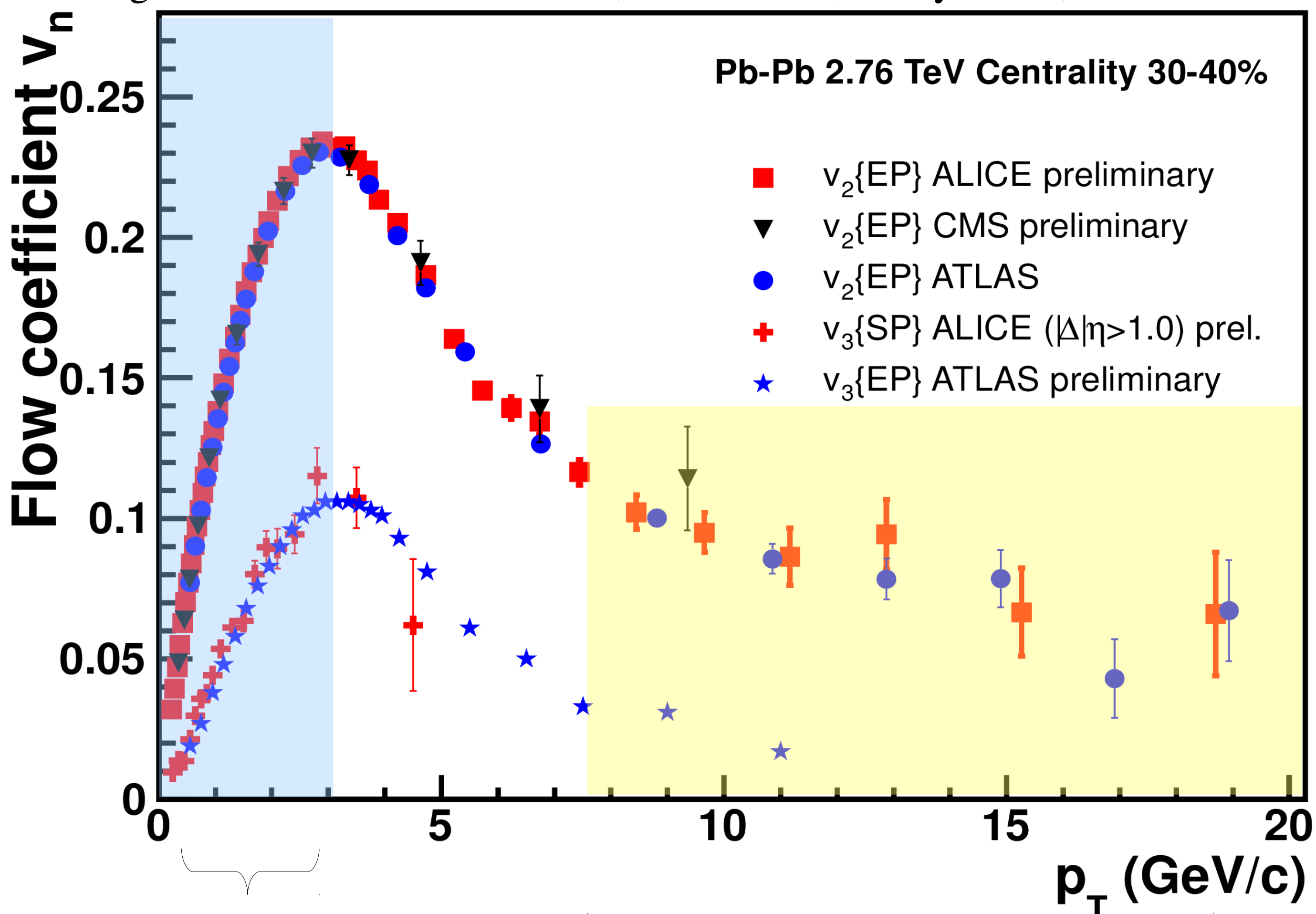
$$\frac{dN}{dp_t\, dy\, d\phi} = N_0 \cdot \left[1 + \sum_{i=1} 2 v_i(y, p_t) \cos(i\phi) \right]$$

quadrupole component v_2
"elliptic flow"
effect of expansion (positive v_2) seen from top AGS energy

the v_n are the equivalent of the power spectrum of cosmic microwave rad.

Elliptic Flow of Charged Particles at LHC

figure modified from B. Muller, J. Schukraft, B. Wyslouch, arXiv:1202.3233v1



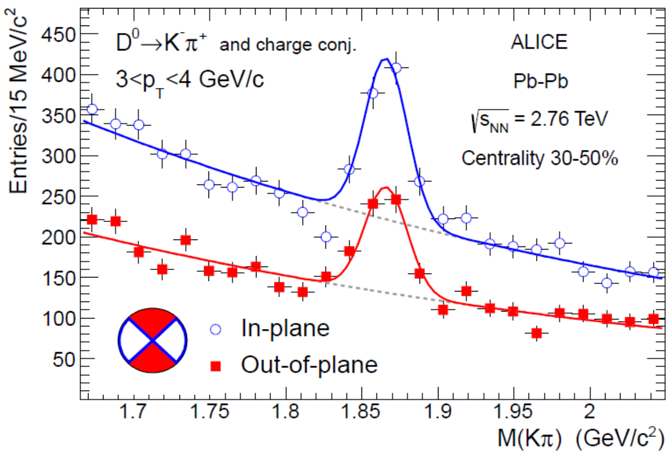
hydrodynamic regime
v2 driven by pressure gradient

jet fragmentation regime
v2 driven by energy loss

elliptic flow (v2) as function of p_t :

- excellent agreement between all 3 LHC experiments
- same for v3

Charm Quarks also Exhibit Elliptic Flow

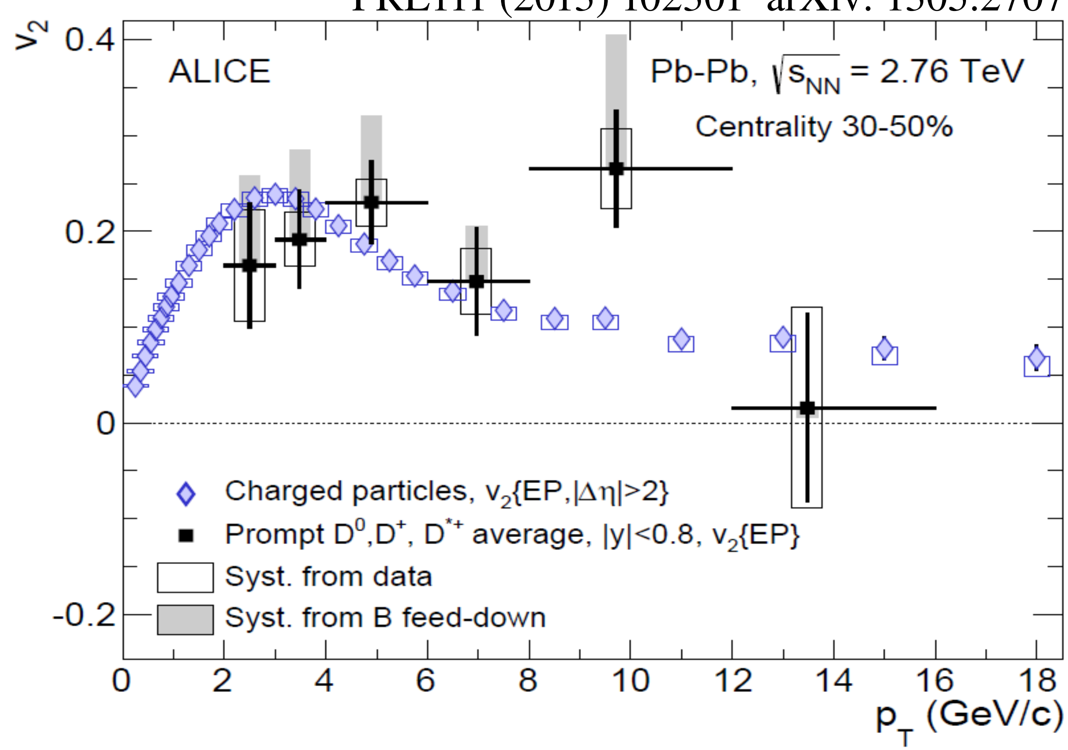


$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N_{\text{in-plane}} - N_{\text{out-of-plane}}}{N_{\text{in-plane}} + N_{\text{out-of-plane}}}$$

$R_2 \cong 0.82$ corrects for reaction plane resolution

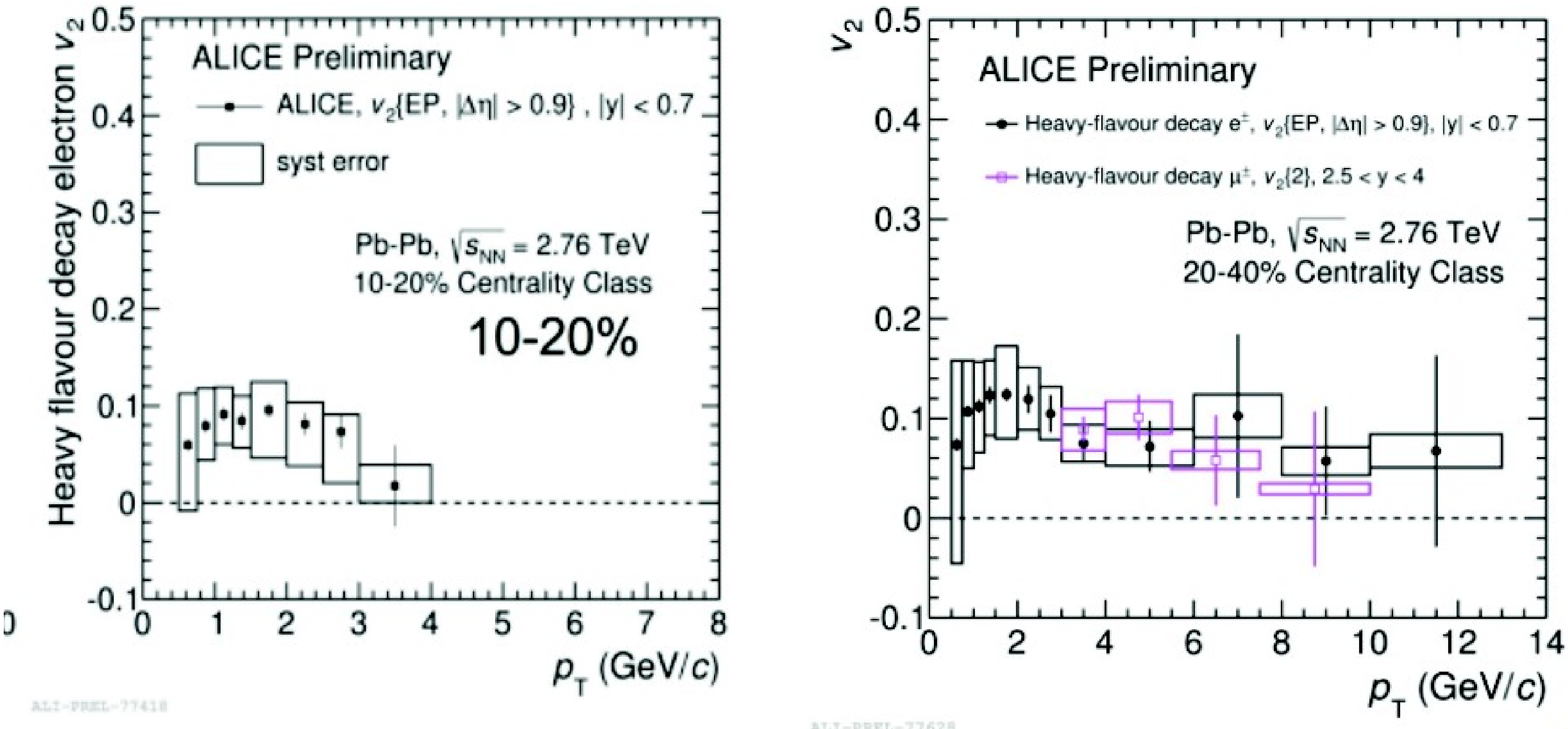
2 centrality classes
event plane from TPC
corrected for B-feed down (FONLL)

PRL111 (2013) 102301 arXiv: 1305.2707



non-zero elliptic flow for 5.7 σ effect for D^0 2-6 GeV/c
within errors charmed hadron v_2 equal to that of all charged hadrons

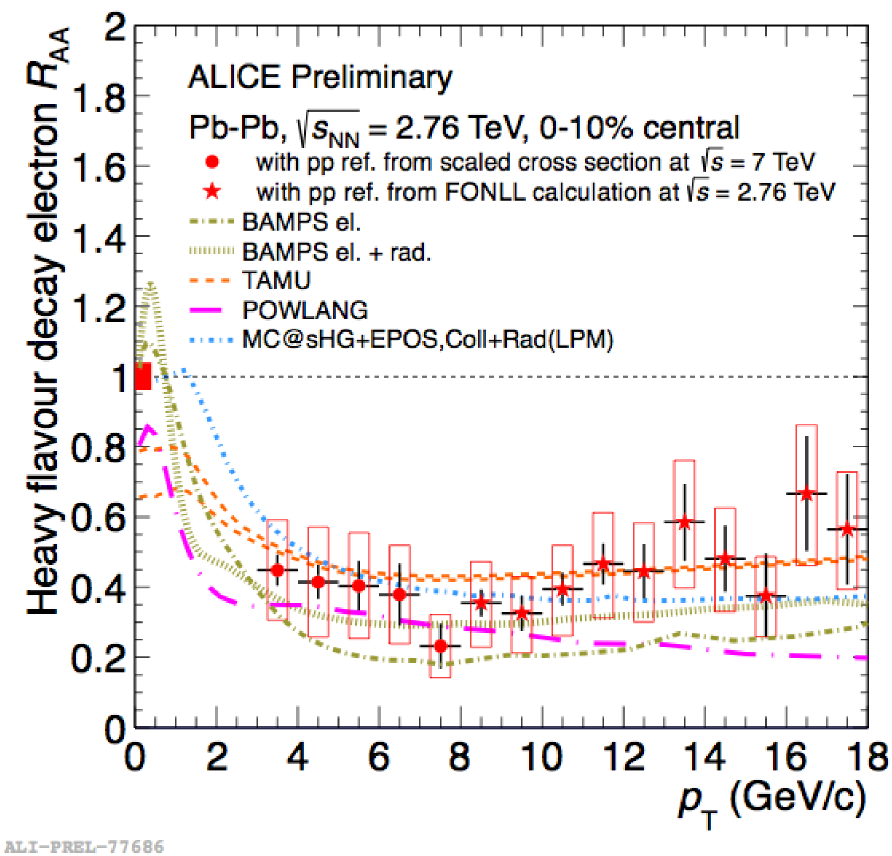
v_2 of leptons from heavy flavor decays

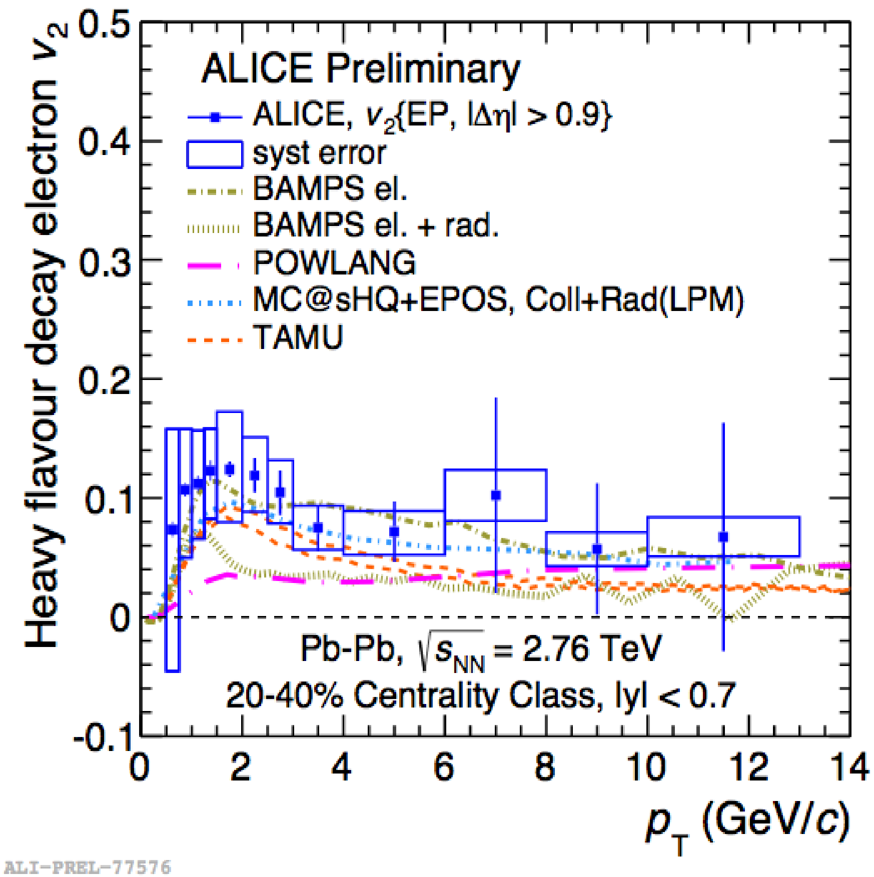


also electrons and muons from heavy flavor decays exhibit elliptic flow similar to D-mesons in magnitude and pt and centrality dependence

low pt c-quark follow collective expansion of QGP

Model Description of Energy Loss and Flow of D-mesons





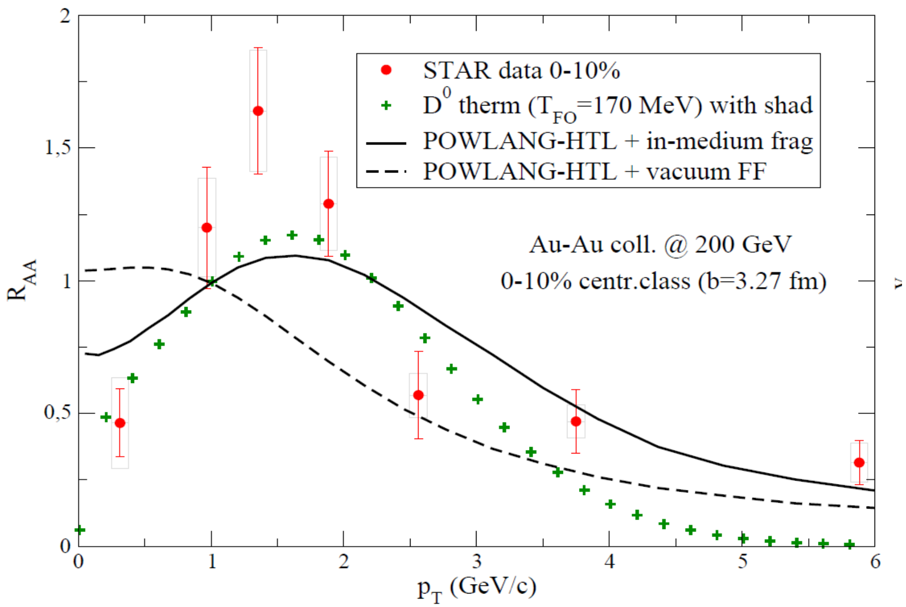
both are determined by transport properties of the medium (QGP)
simultaneous description still a challenge for some models

Energy loss and flow of charm quarks at RHIC energy

STAR D^0 production in $\sqrt{s_{NN}}$=200 GeV AuAu

PRL 113 (2014) 142301

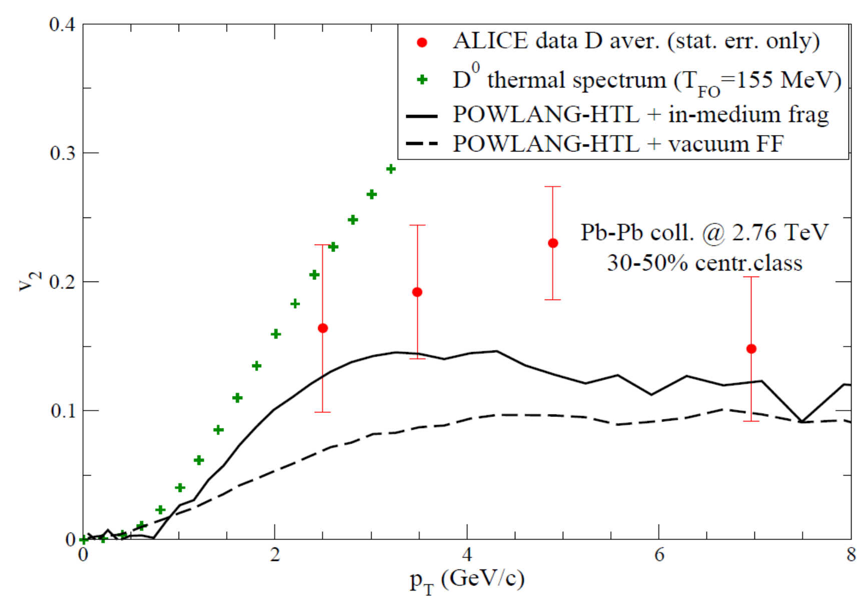
! measurement down to p_t close to 0 !



calc: A. Beraudo et al. 1407.5918, 1410.6082

calculations with charm quark energy loss in QGP using Langevin equation with weak coupling transport coefficients and hadronization in an expanding medium lead to enhancement in low p_t region

current LHC data start above 2 GeV/c but elliptic flow of D mesons reproduced by the same approach wo new parameters



ALICE PbPb $\sqrt{s_{NN}}$=2.76 TeV D mesons

PRL 111 (2013) 102301

The end

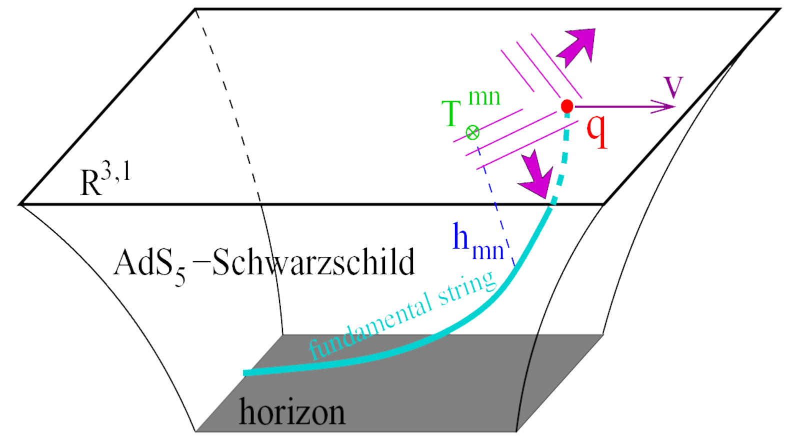
Many heavy flavor observables studied in pp, pPb, PbPb

charm quarks lose energy efficiently in QGP, thermalization

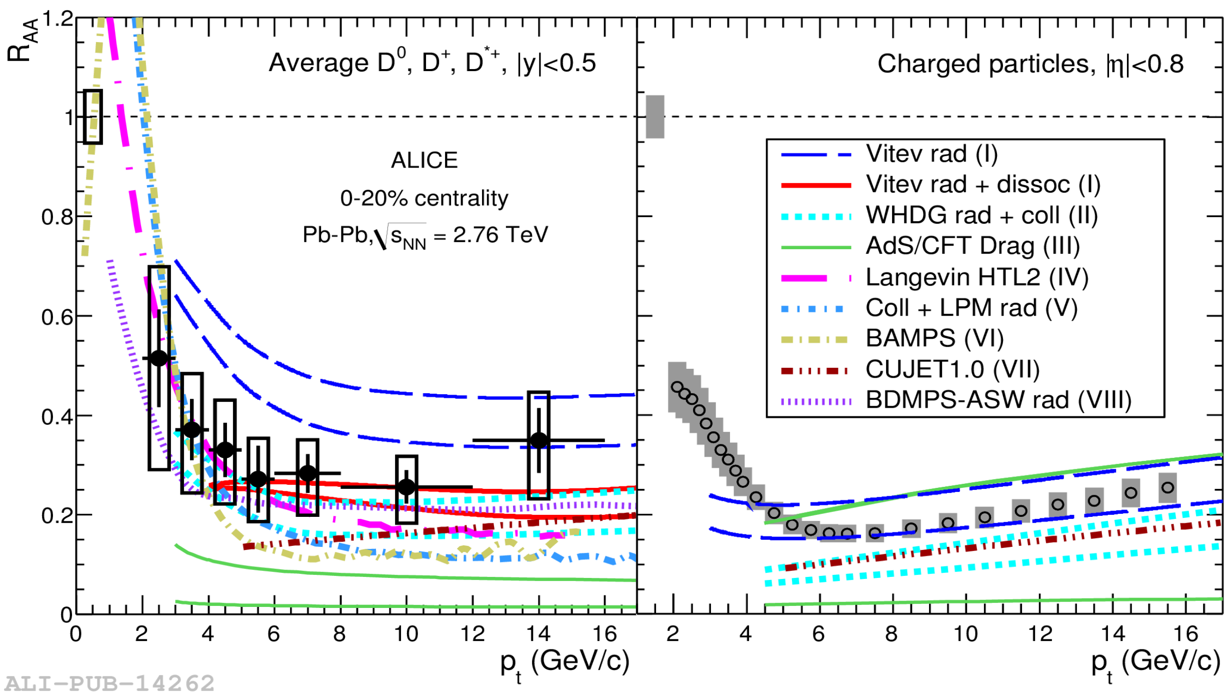
many things still to do
- open charm cross section in PbPb and pp, pPb, precision
- in b-sector field still wide open

exciting years to come

AdSxS5 string theory does not describe charm quark energy loss and elliptic flow at LHC



J Friess, Phys Rev D75 (2007)



systems appears not as strongly coupled!