ALICE/ATLAS/CMS Production and quenching of heavy flavours: pp, pA, AA comparisons

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BEAUTY 2013 – 14th International conference on B-Physics at Hadron Machines

Why Heavy Flavours

Heavy quarks are produced in initial high-Q^2 processes

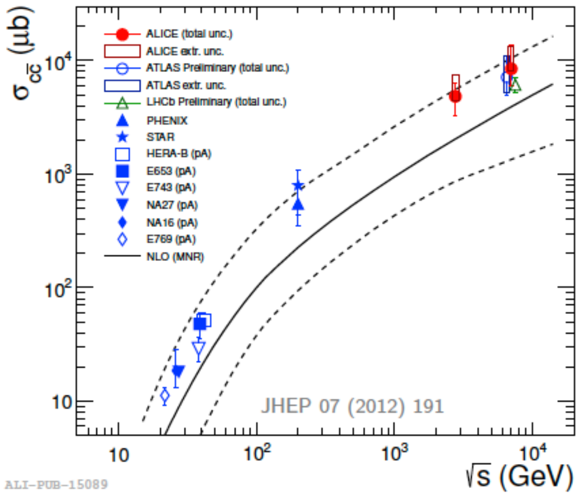
in pp: 1) test for pQCD

At LHC, larger cross-section:

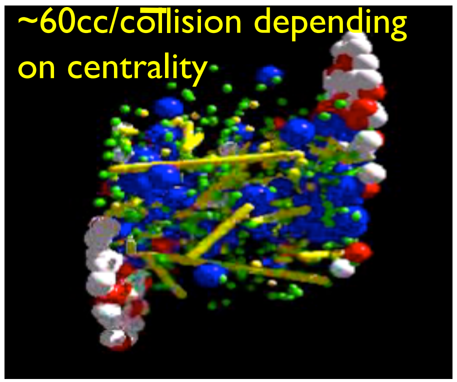
σ_c(LHC)~5-10 σ_c(RHIC)

σ_b(LHC)~ 50 σ_b(RHIC)

2) reference for pA and AA!



in PbPb: *initially-produced probes* exposed to the medium evolution

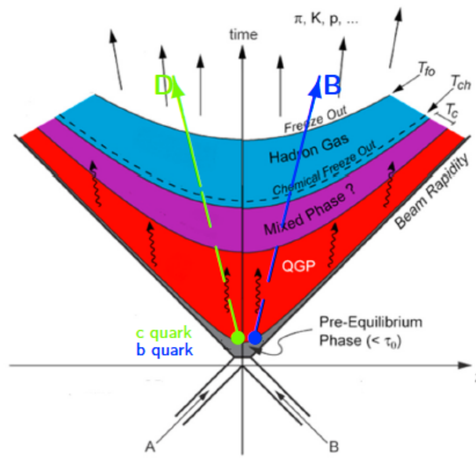


Questions:

How do partons interact with the medium?

How does the energy loss depend on path-length, medium density, parton mass/colour charge?

How to disentangle cold from hot nuclear state effects?

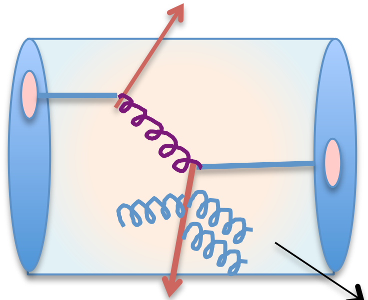


in pPb: reference for cold nuclear matter effects

Heavy Flavours and Heavy-Ion Collisions

- How do partons interact with the medium?
  - Energy loss mechanism via:

    radiative gluon emission and elastic collisions



- What does the energy loss depend on?
  - Medium density, path-length → $\langle \Delta E \rangle \propto \alpha_s C_R \hat{q} L^2$
  - Colour-charge, Mass ("dead-cone")→ $\Delta E_g > \Delta E_{u,d} > \Delta E_c > \Delta E_b$

Dokshitzer and Kharzeev, PLB 519 (2001) 199.

- How to disentangle cold and hot nuclear matter effects?
  - Idea: study nuclear matter under extreme conditions of temperature/energy density via AA collisions
    - Produce a "hot" fireball where quarks and gluons are deconfined (Quark-Gluon Plasma)
    - From Lattice QCD the phase transition occurs at: T_c~170 MeV, ε_c~0.6 GeV/fm^3
      - these conditions are reached at RHIC and the LHC
  - Are there "cold" nuclear matter effects? If yes, need to decouple them. How?

  → pPb collisions: control experiment used as reference (new data from 2013)
    - here, no quark-gluon plasma is expected to be created

Heavy Flavours and Heavy Ion Collisions

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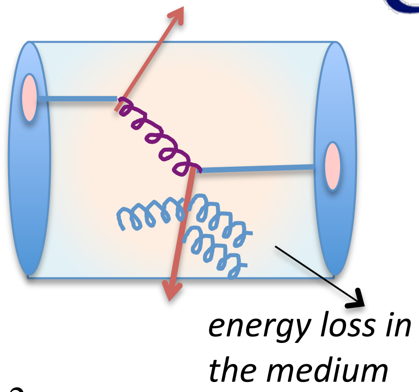

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  - C

519 (2001) 199.

Comparing nuclear effects on heavy quarks (c and b) vs light quarks and gluons in pp/pA/AA → insight into *path-length/flavour/colour-charge dependence of energy loss*

- How
  - Id ensity via AA collisions
    - Produce a "hot" fireball where quarks and gluons are deconfined (Quark-Gluon Plasma)
    - From Lattice QCD the phase transition occurs at: $T_c \sim 170$ MeV, $\varepsilon_c \sim 0.6$ GeV/fm^3
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  → pPb collisions: control experiment used as reference (new data from 2013)
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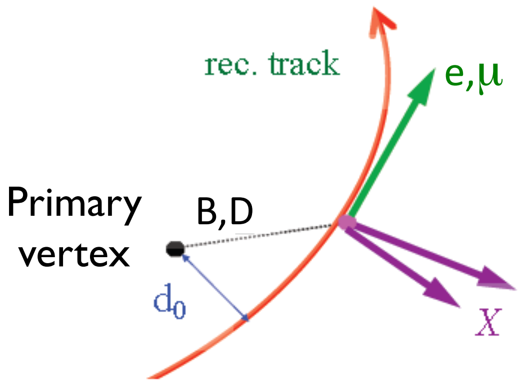
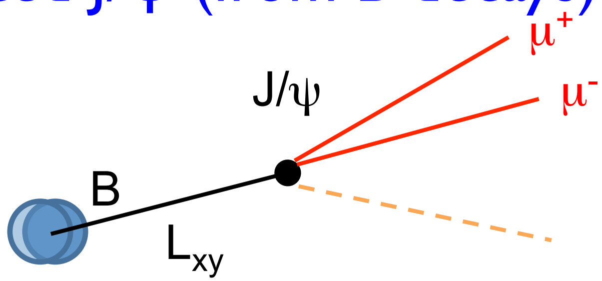
Measurements of Heavy Flavours at the LHC in Pb-Pb (and pp)

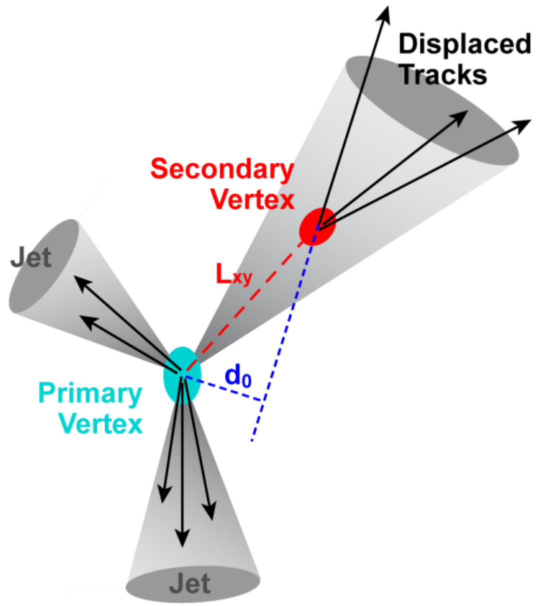
Semi-leptonic decays ((charm,beauty))



Displaced J/ψ (from B decays)



Jet b-tagging



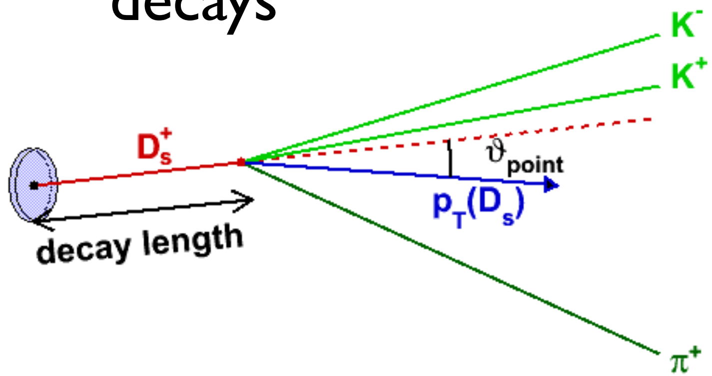
Full reconstruction of D meson hadronic decays

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

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

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

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



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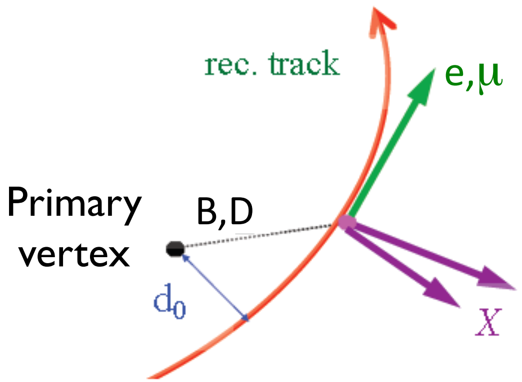

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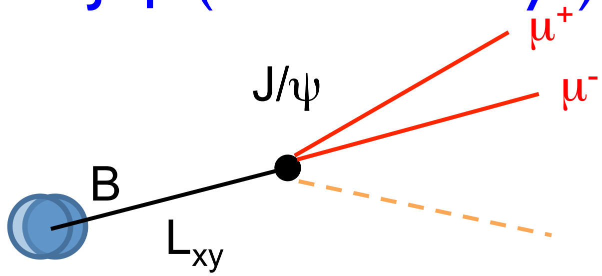

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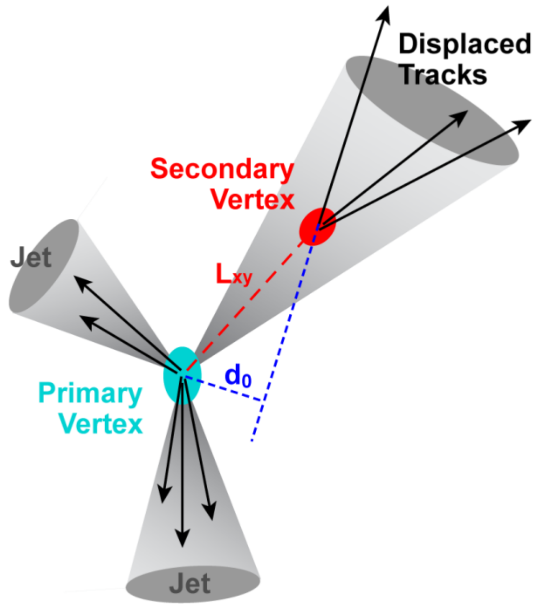

Full reconstruction of beauty decays: **B** and Λ_b hadrons (ATLAS/CMS,LHCb, **only pp**)

$\Lambda_b \rightarrow J/\psi\ \Lambda$
$B^+ \rightarrow J/\psi\ K^+$, $J/\psi\ K\pi$
$B^0 \rightarrow J/\psi\ K^0_s$
$B_s^0 \rightarrow J/\psi\ \phi$

same technique as for D mesons based on displaced vertex topologies

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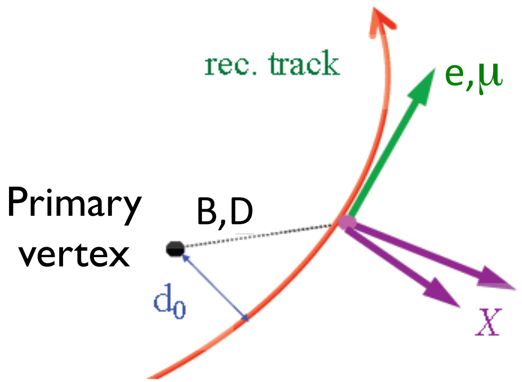
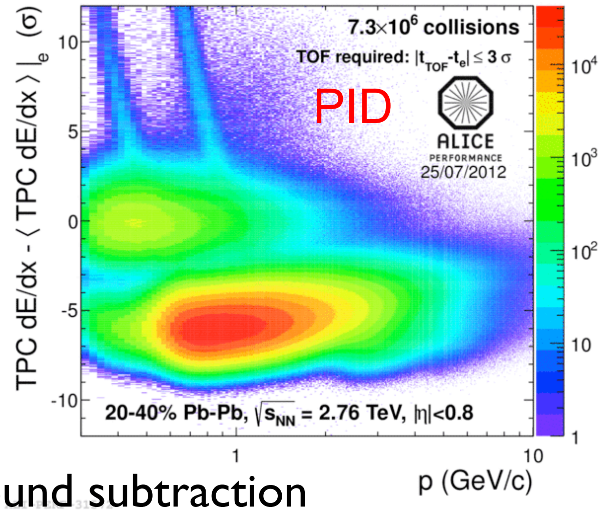


Electrons *(e.g. ALICE)*



Background subtraction

→ *invariant mass method*: to remove π^0, Dalitz decays, photon conversions

→ *cocktail:* different background sources using Monte Carlo hadron-decay generator

Beauty-decay electrons: extra cut on track impact parameter (less hadron contamination) and/or e-h correlations

Muons

Background sources:

μ from charm, Drell-Yan, decays in flight of K, π

Selection strategy (e.g. ATLAS):

Match tracks from Inner Detector and Muon Spectrometer

Discriminant variables with different distribution for signal and background

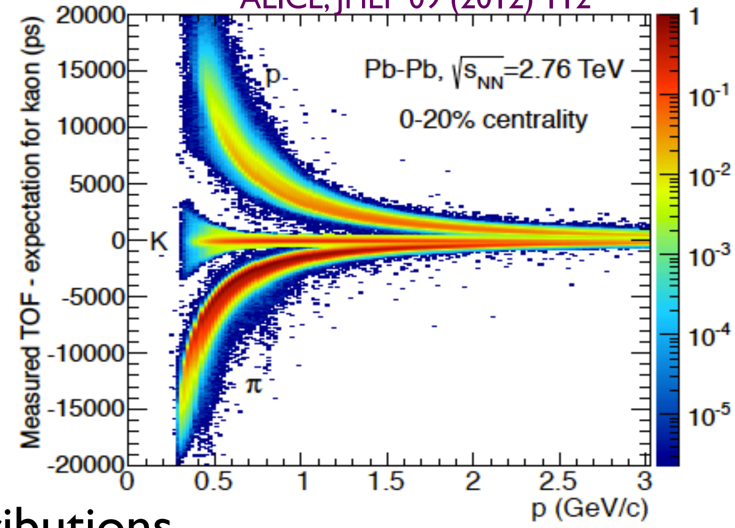
Measurements of Heavy Flavours at the LHC in Pb-Pb (and pp)

(1) Strategy: search for secondary vertices displaced by few hundred μm

(2) Main selection criteria:

- p_T and impact parameter of the single tracks
- PID (π, K, p) for background rejection at low p_T
- pointing angle
- distance primary-secondary vertices

ALICE, JHEP 09 (2012) 112



(3) Signal extracted from fits to invariant mass distributions

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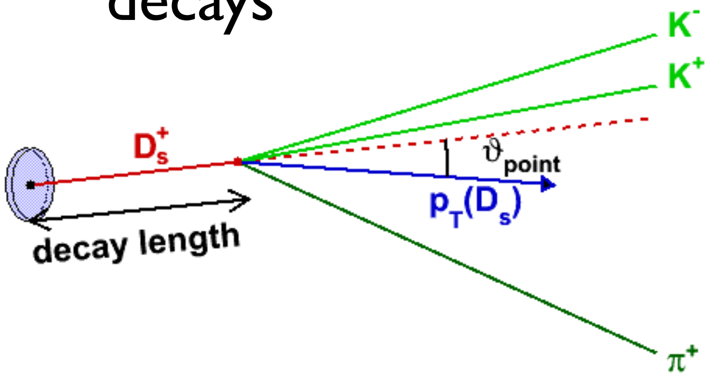
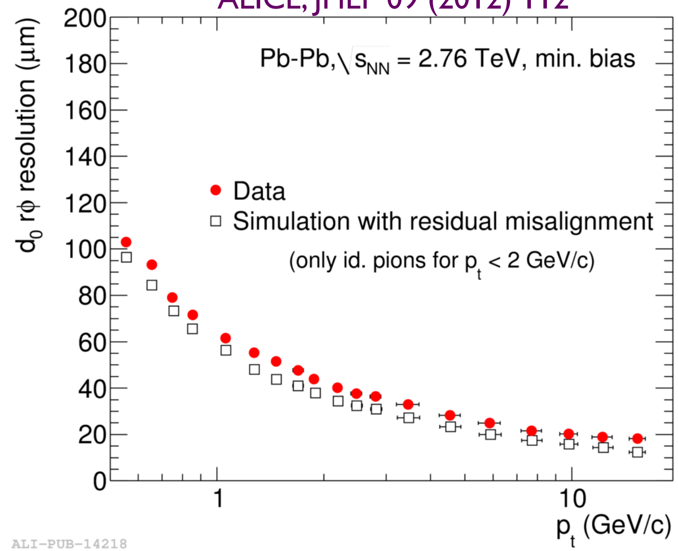


ALICE, JHEP 09 (2012) 112



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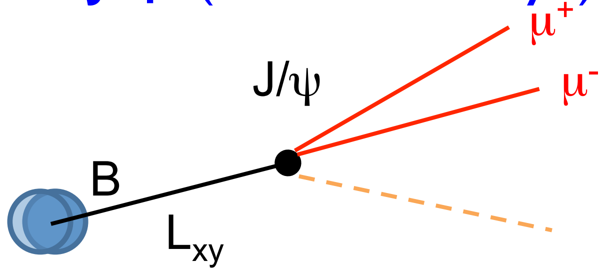
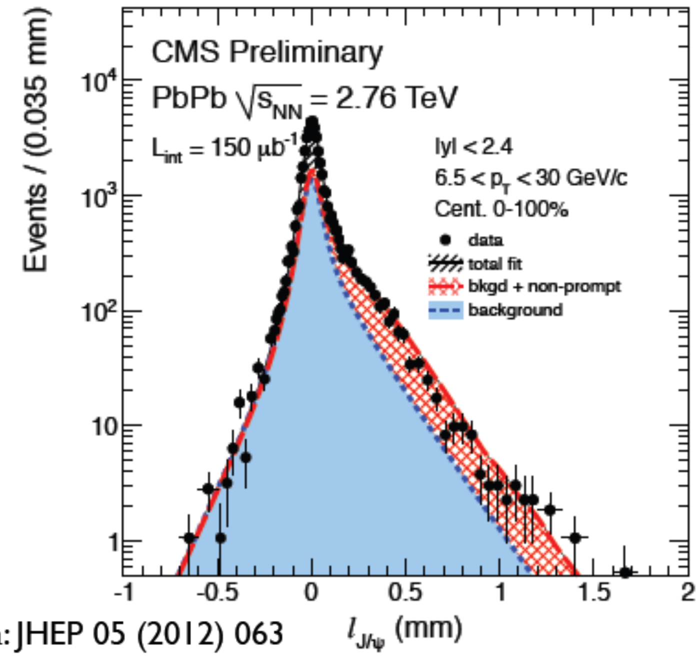


Yield of non-prompt J/ψ becomes significant towards high p_T

Reconstruct $\mu^+\mu^-$ vertex

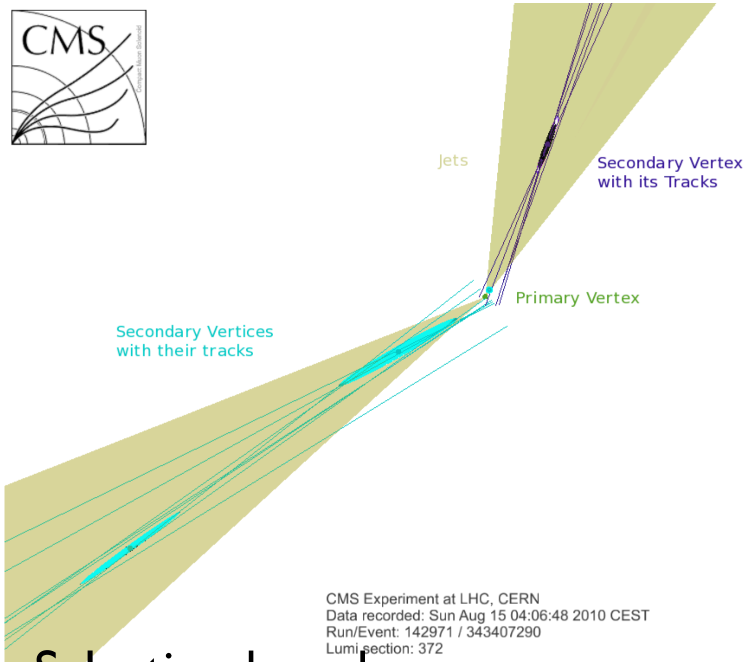
Simultaneous fit to $\mu^+\mu^-$ mass and pseudo-proper decay length $\ell_{J/\psi}$

$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$



2010 data: JHEP 05 (2012) 063
2011 data: CMS PAS HIN-12-014

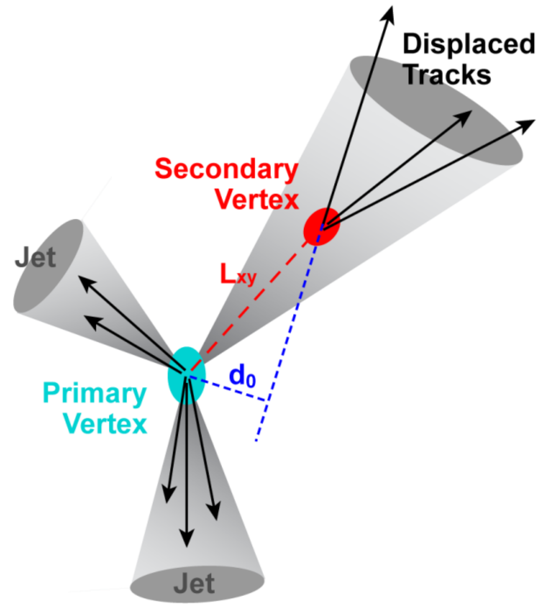
Measurements of Heavy Flavours at the LHC in Pb-Pb (and pp)



CMS Physics Analysis Summary HIN-12-003
CMS Physics Analysis Summary BTV-11-004

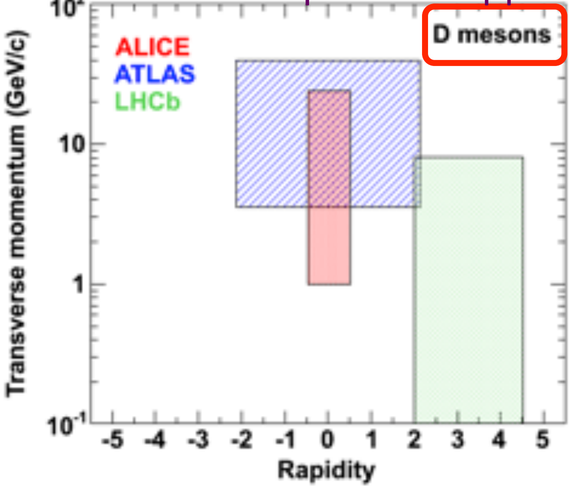
Selection based on:
- search of secondary vertices
- flight distance
- rejection of long-lived particles
- b-jet *purity* is derived from a fit to the vertex mass distribution (MC templates)
- Alternative cross-check method based on track impact parameter

Jet b-tagging

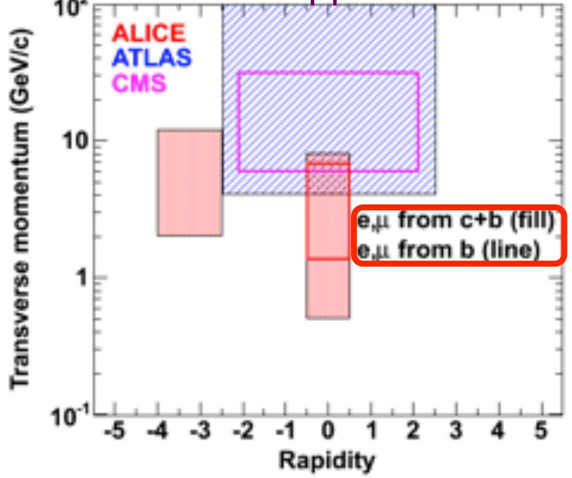


The Heavy-Ion LHC experiments

refers to published pp



for pp



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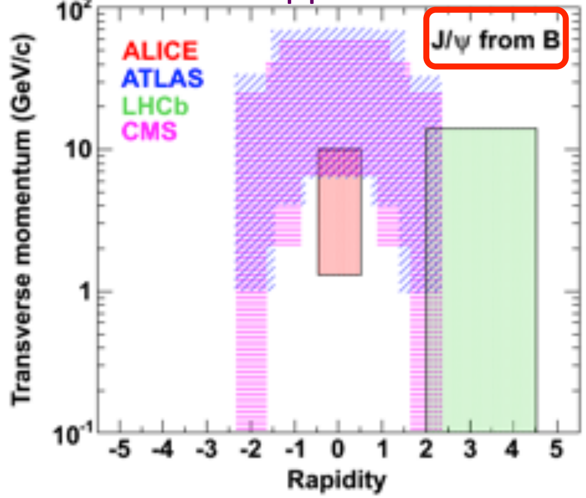


Complementary rapidity and p_T coverage:

ALICE: unique low-p_T reach (thanks to tracking and PID)

ATLAS/CMS: large rapidity coverage. High momentum space explored. Low momentum reachable with secondary J/ψ but not at mid-rapidity (CMS).

LHCb (only pp): unique large momentum coverage at forward rapidity

The Results: pp

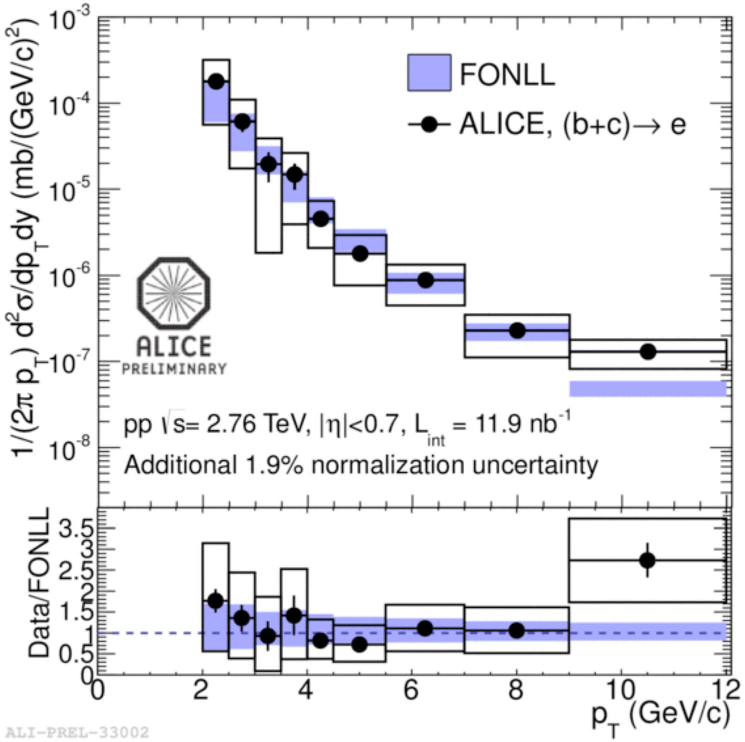
7 TeV (Run 2010)

2.76 TeV (Run 2011)

1) Electrons and muons from Heavy Flavour (c+b) decay
2) Open Charm
3) Open Beauty
4) Beauty Jets

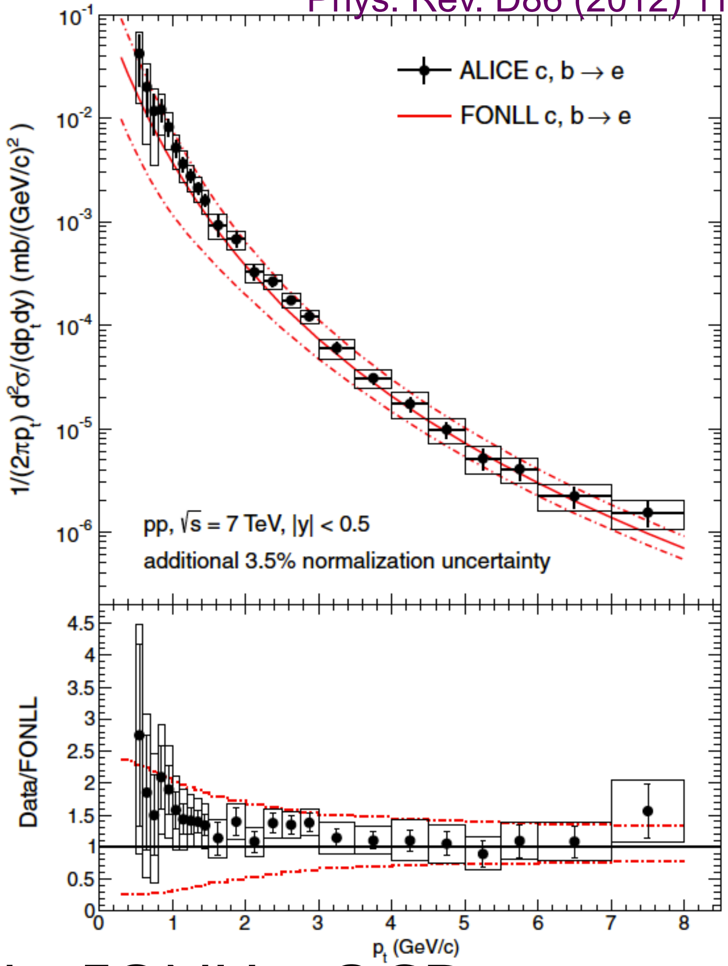
Heavy-Flavour (b+c) decay electrons

pp @ 2.76 TeV (TPC+TOF+EMCal)



pp @ 7 TeV (TPC+TOF+TRD+EMCal)

Phys. Rev. D86 (2012) 112007



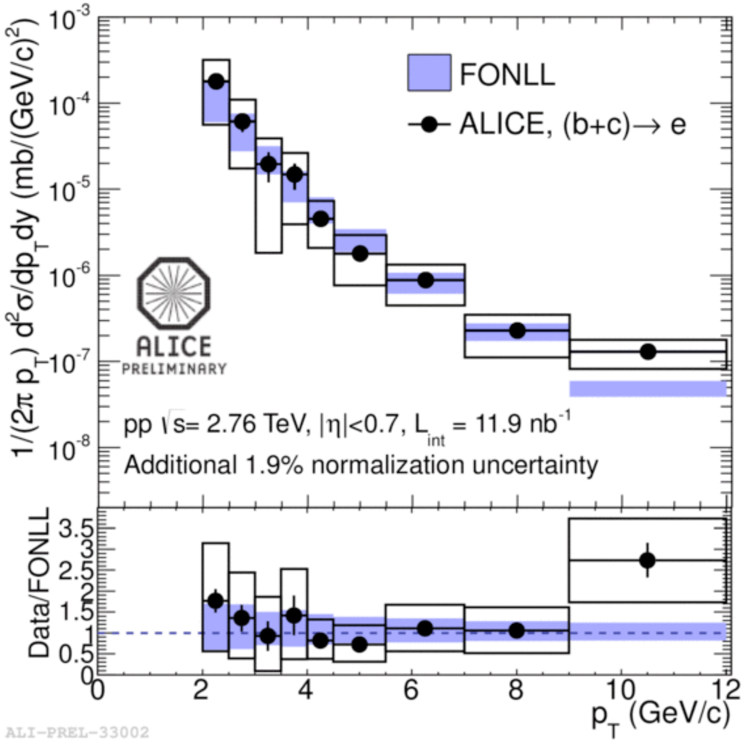
Data at both energies well described by FONLL pQCD

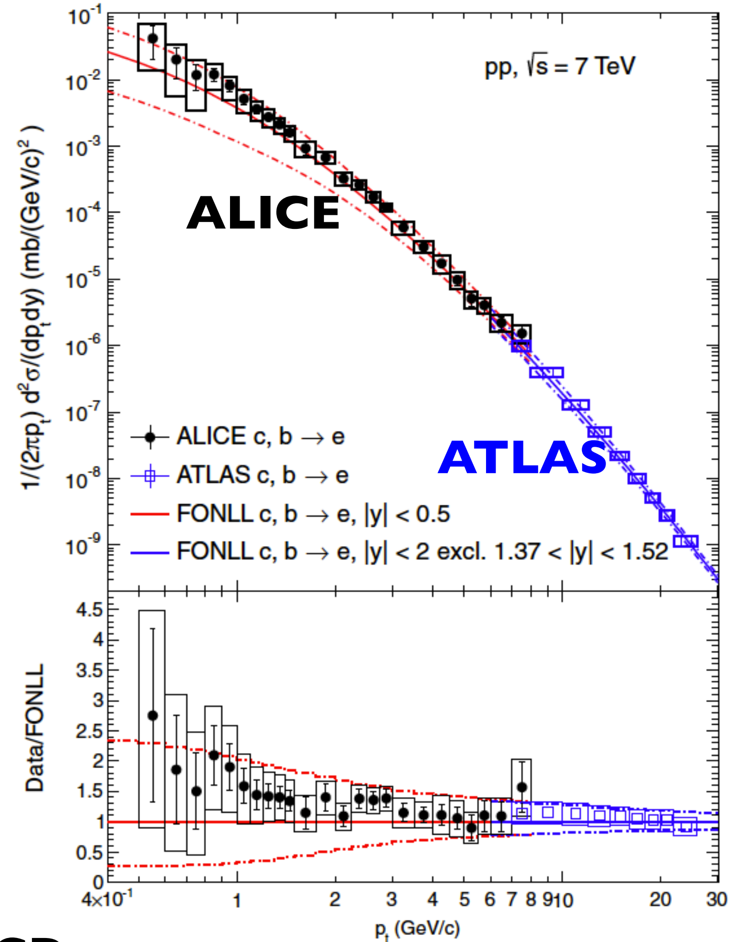
Cacciari et al., arXiv:1205.6344

7 TeV measurement scaled to 2.76 TeV and used as R_{AA} reference

Heavy-Flavour (b+c) decay electrons

pp @ 2.76 TeV (TPC+TOF+EMCal)





(ALICE) Phys. Rev. D86 (2012) 112007
(ATLAS) PLB 707 (2012) 438

Both energies well described by FONLL pQCD Cacciari et al., arXiv:1205.6344

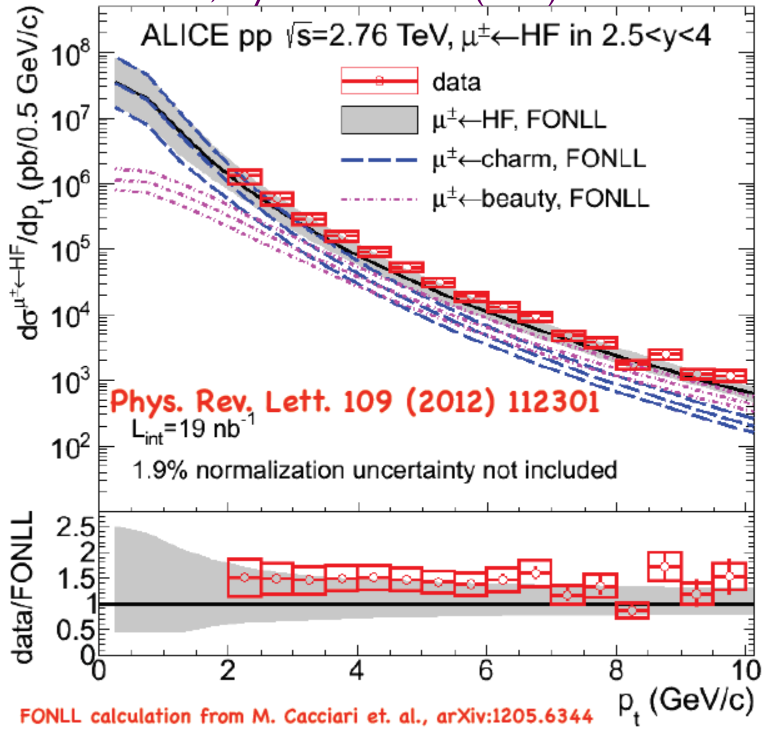
7 TeV measurement scaled to 2.76 TeV (via pQCD predictions) and used as R_{AA} reference

Nice complementarity with ATLAS at high p_T

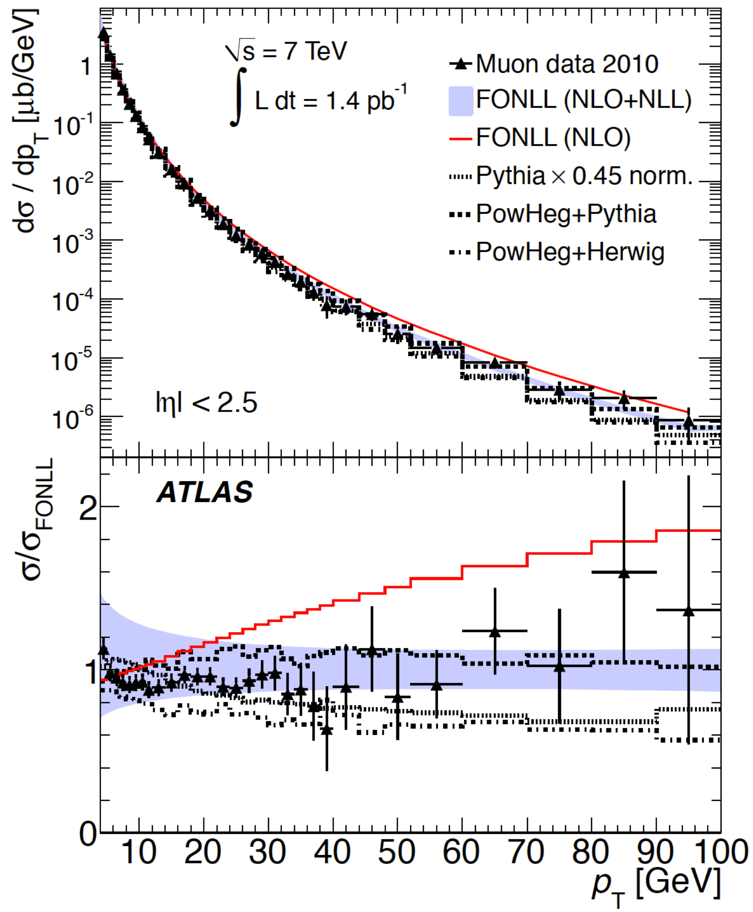
Heavy-Flavour (b+c) decay muons

ALICE, pp @ 2.76 TeV

ALICE, Phys. Rev. Lett. 109 (2012) 112301



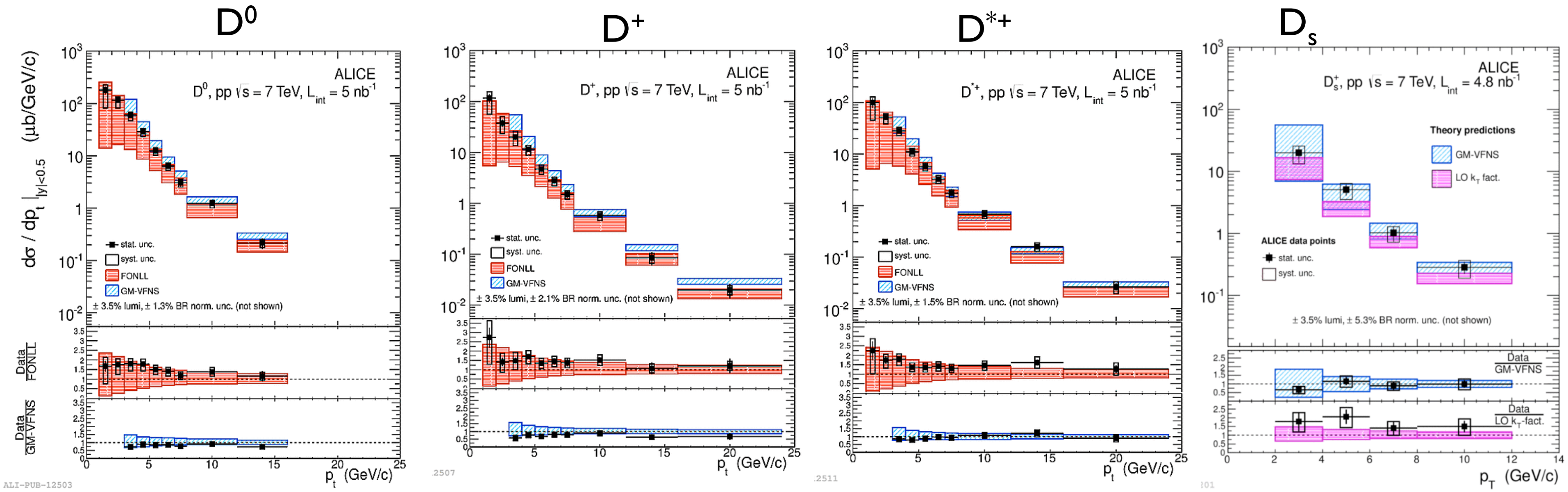
ATLAS, pp @ 7 TeV



CMS, JHEP 06 (2012) 110
CMS, JHEP 1103 (2011) 090
ATLAS, PLB 707 (2012) 438

Perturbative calculations are sensitive to NLL resummations
FONLL (NLO+NLL) gives a better description over a broad momentum range

Open Charm in pp @ 7 TeV



ALICE Coll. JHEP 01 (2012) 128
arXiv : 1208.1948

cross-sections for D mesons:

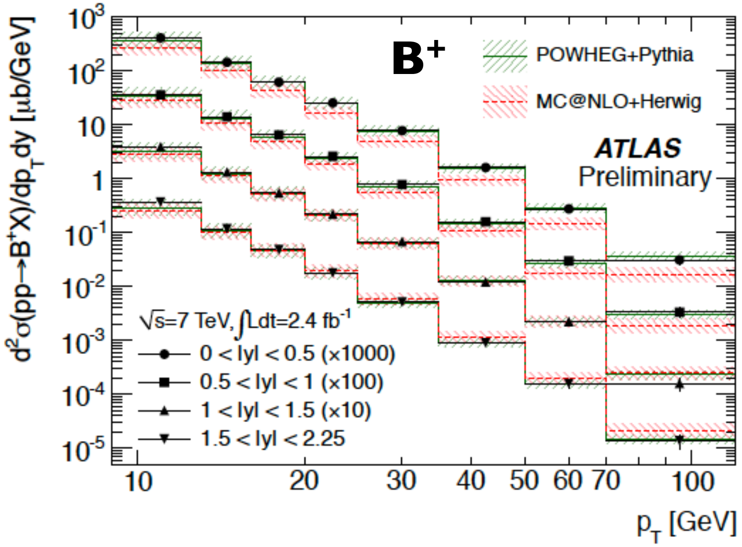
- D^0 $1<p_T<16$ GeV/c
- D^+, D^{*+} $1<p_T<24$ GeV/c
- D_s $2<p_T<12$ GeV/c

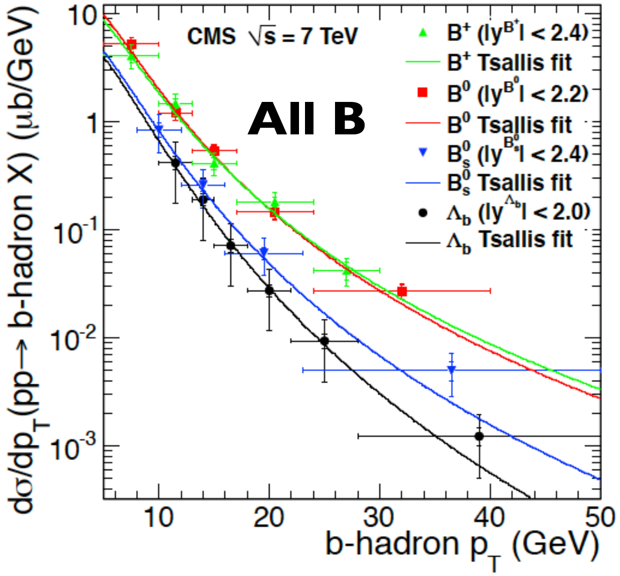
Within uncertainties described by FONLL/GM-VFNS pQCD calculations and kt-factorization approach

Cacciari et al., arXiv:1205.6344
Kniehl et al., arXiv: 1202.0439
Maciula, et al, arXiv:1208.6126

Open Beauty in pp @ 7 TeV

ATLAS-CONF-2013-008





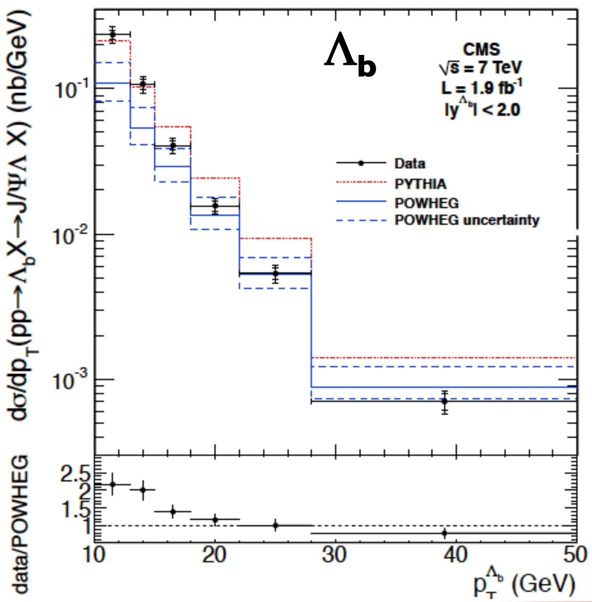
B mesons:

Good agreement for POWHEG+Pythia. Theory tends to be on the low side (MC@NLO).

p_T spectrum steeper for heavier hadrons.

Λ_b:

Reasonable description by theory. Measured p_T spectrum falls faster than theory predictions.

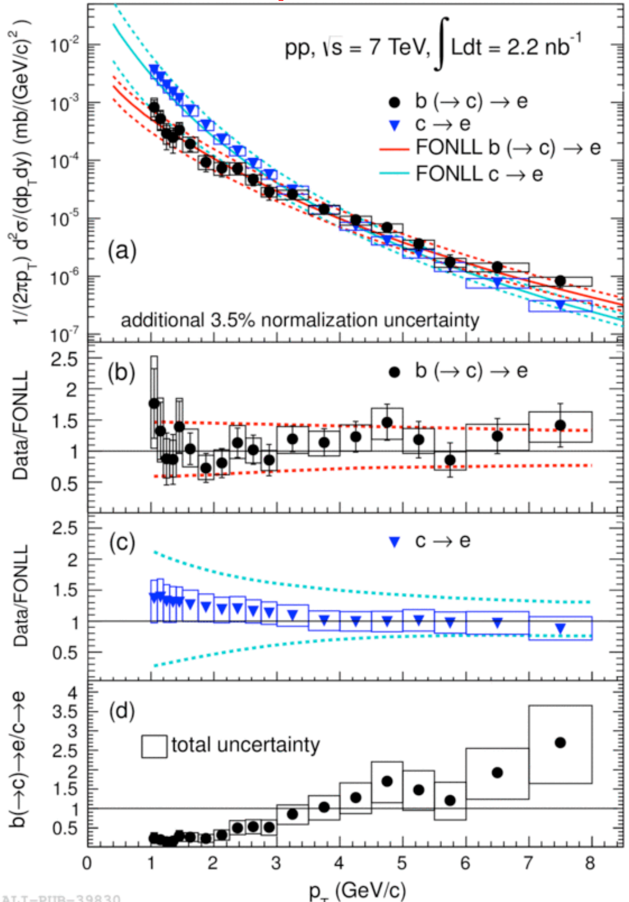


CMS: PLB 714 (2012) 136

ATLAS: arXiv: 1207.2284

Inclusive Beauty

Beauty electrons

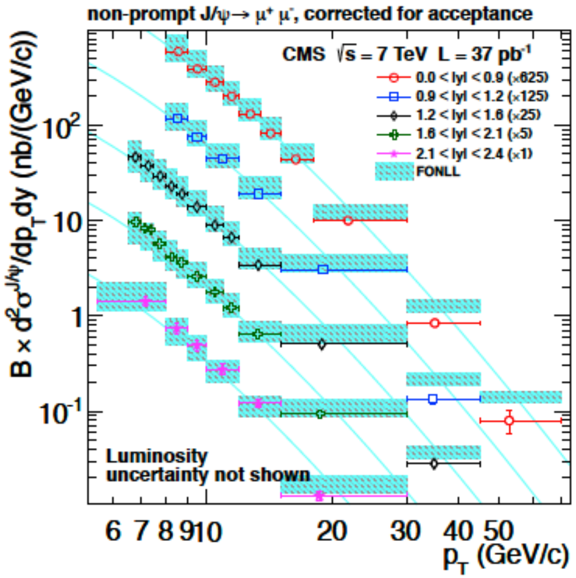


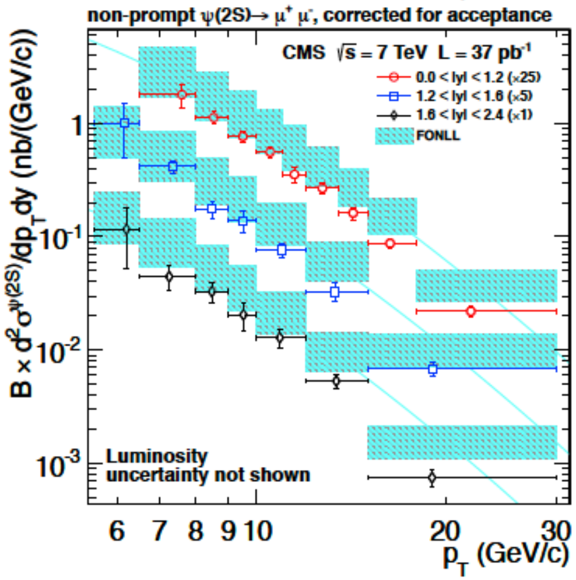
ALICE, Phys. Lett. B721 (2013) 12

Beauty cross-section in pp @ 7 TeV

FONLL pQCD reliable for beauty also at low p_T at LHC

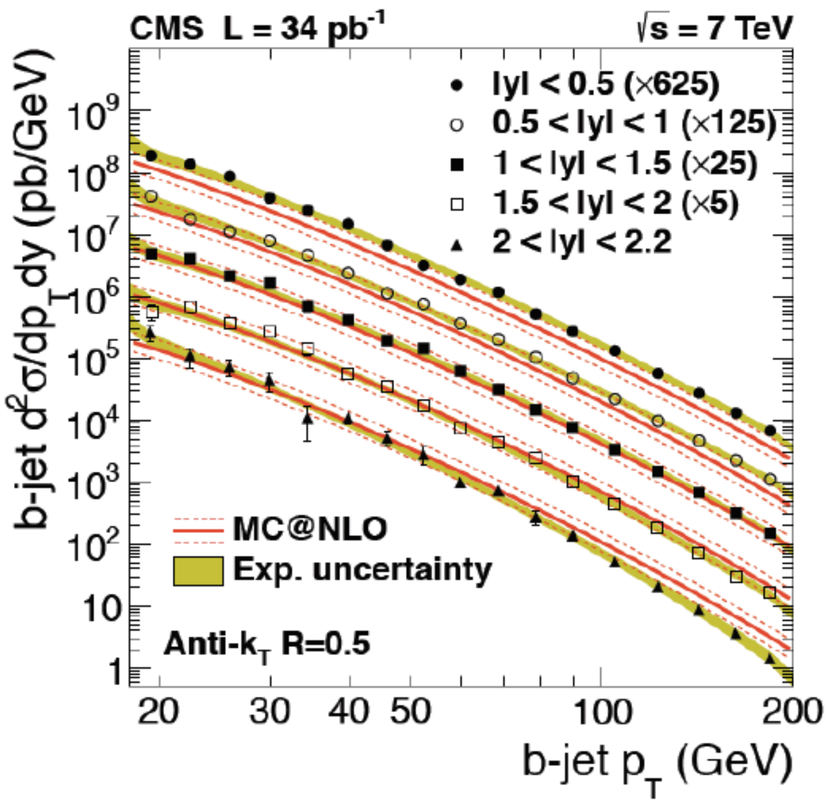
Non-prompt Charmonium

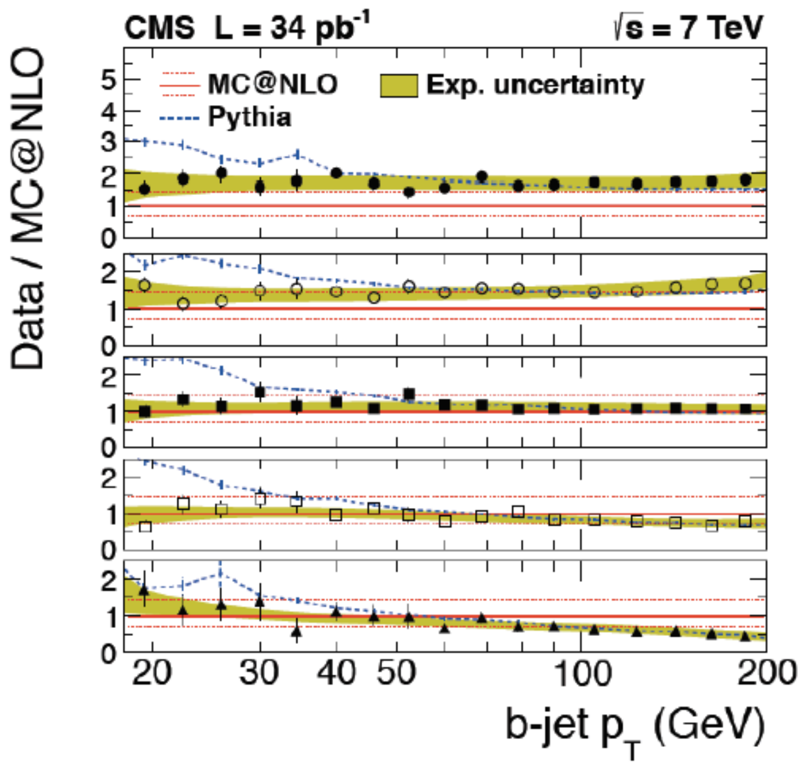




CMS, JHEP 02 (2012) 011
ATLAS, NPB 850 (2012) 387

Beauty Jets





MC@NLO agreement at the edge of uncertainties

Pythia overshoots at low p_T, agrees well at high p_T

pp measurements provide a well calibrated probe

now we can look at Pb-Pb

The Results: Pb-Pb

2.76 TeV (Run 2010)

2.76 TeV (Run 2011)

The experimental observables

Goal: measure the energy loss of different parton species

How:

1) measure particle production in PbPb and compare to pp

Nuclear modification factor

$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

PbPb

pp

Nuclei overlap function

If $\mathbf{R_{AA}=1}$ → no nuclear effects

if $\mathbf{R_{AA}\neq 1}$ → binary scaling broken. Energy loss gives rise to *$R_{AA}<1$ at high p_T* → *Hot nuclear matter effect*

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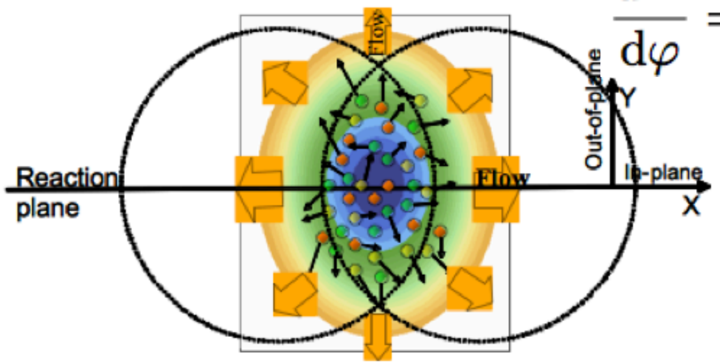
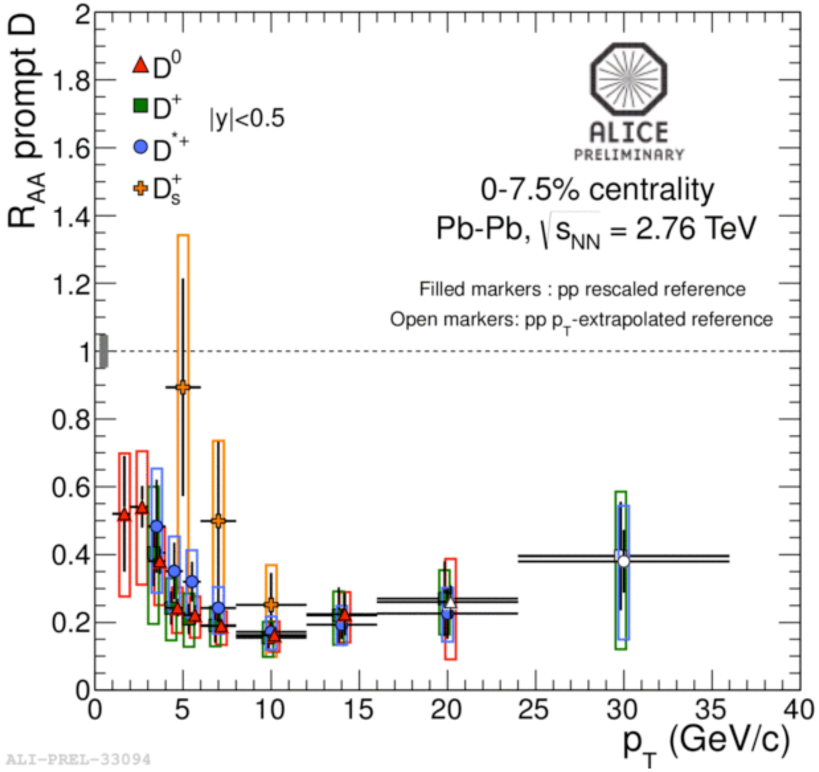
2) more differentially: look at azimuthal anisotropy



$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_1) + 2v_2\cos[2(\varphi - \Psi_2)] + \ldots\right)$$

non-isotropic emission can originate from *path-length dependence of energy loss (high-p_T)* and/or *thermalization/collective motion (low p_T)*

D meson R_{AA}



$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}^{D}/dp_T}$$

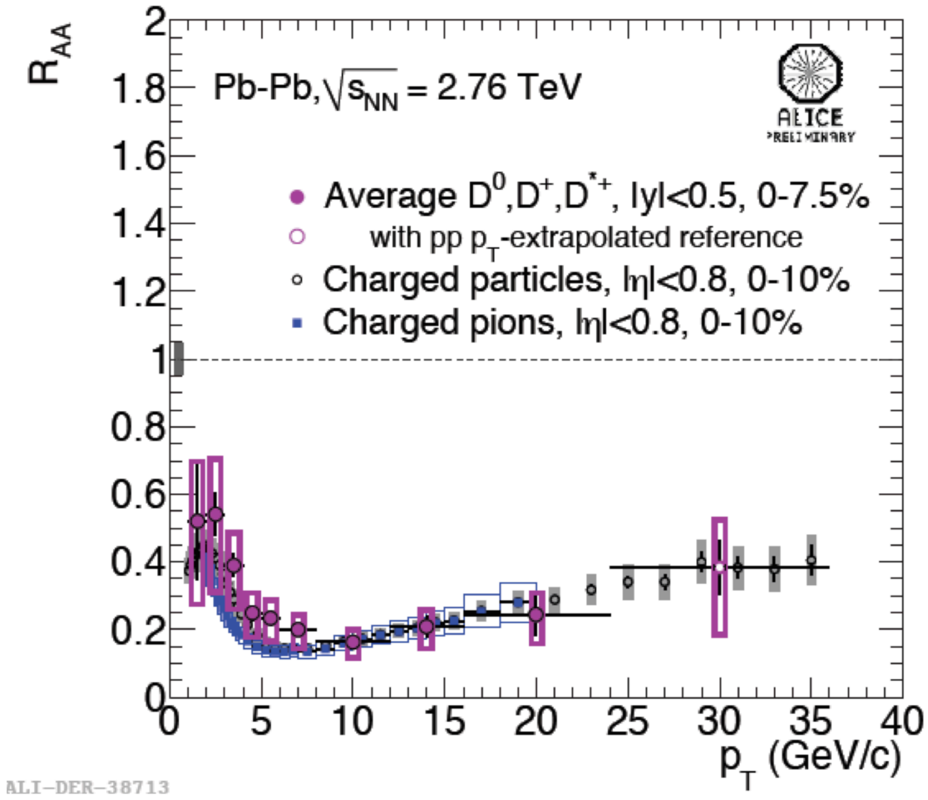
D^0, D^+, D^{*+} R_{AA} compatible within errors

Large suppression in a wide p_T range:
→*factor of 4-5 in 5<p_T<15 GeV/c*

First measurement of D_s in Pb-Pb with 2011 Run
→*suppression by factor 3-5 in 8-12 GeV/c*
→more statistics needed to conclude on the expected enhancement of low-p_T D_s due to c-quark coalescence with the abundant strange quarks

Kuznetsova & Rafelski, EPJ C51(2007)113;
He et al., arXiv:1204.4442;
Andronic et al., arXiv:0708.1488

D meson R_{AA}



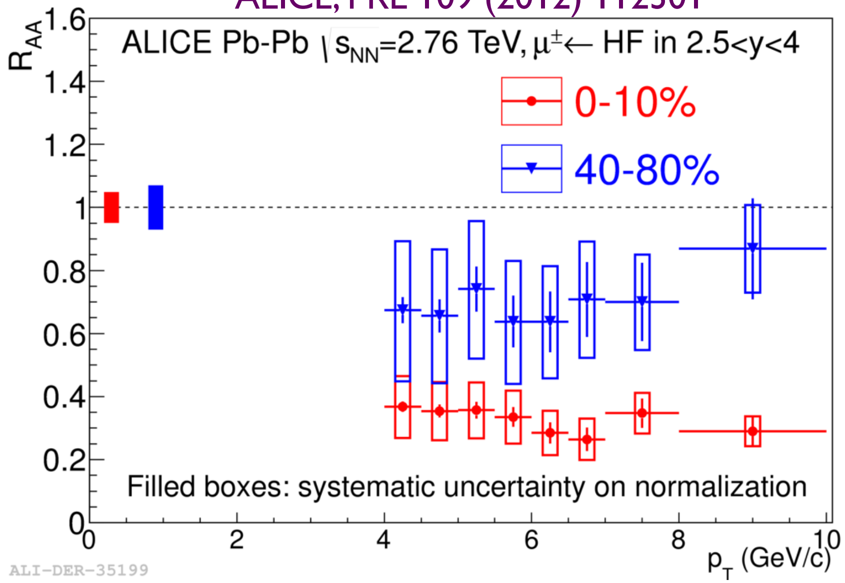
$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D}/dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}^{D}/dp_T}$$

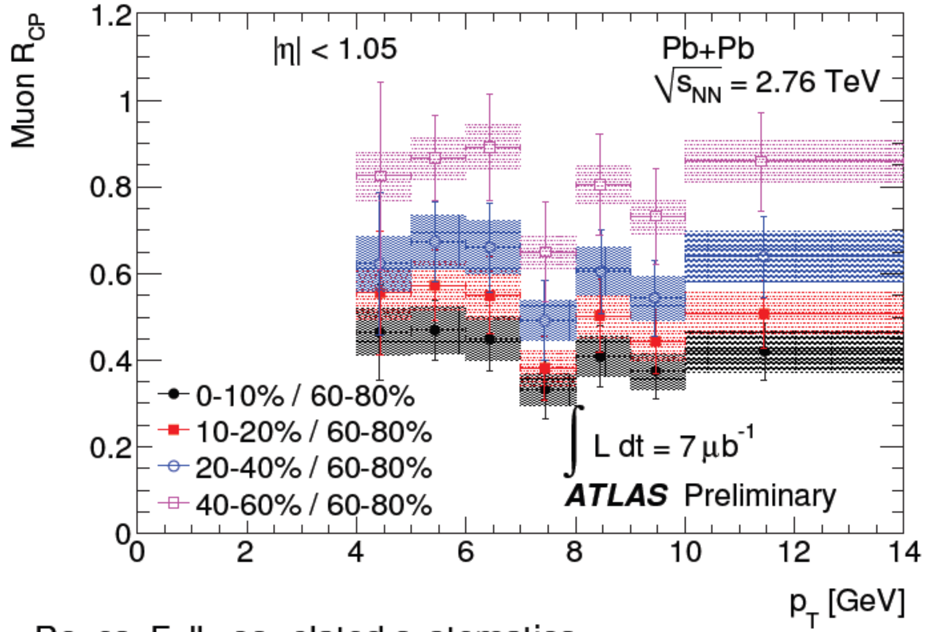
Similar suppression of D mesons as light hadrons, hint of difference below 5 GeV/c

→more statistics needed to extract flavour dependence of energy loss [R_{AA}(D)>R_{AA}(pion) expected from mass hierarchy –slide 3]

R_{AA} of Heavy-Flavour decay muons

ALICE, PRL 109 (2012) 112301





Boxes: Fully correlated systematics
Error bars: uncorrelated combined statistical+systematic

ALICE: forward rapidity

Suppression by a factor 2-4 in 0-10% centrality

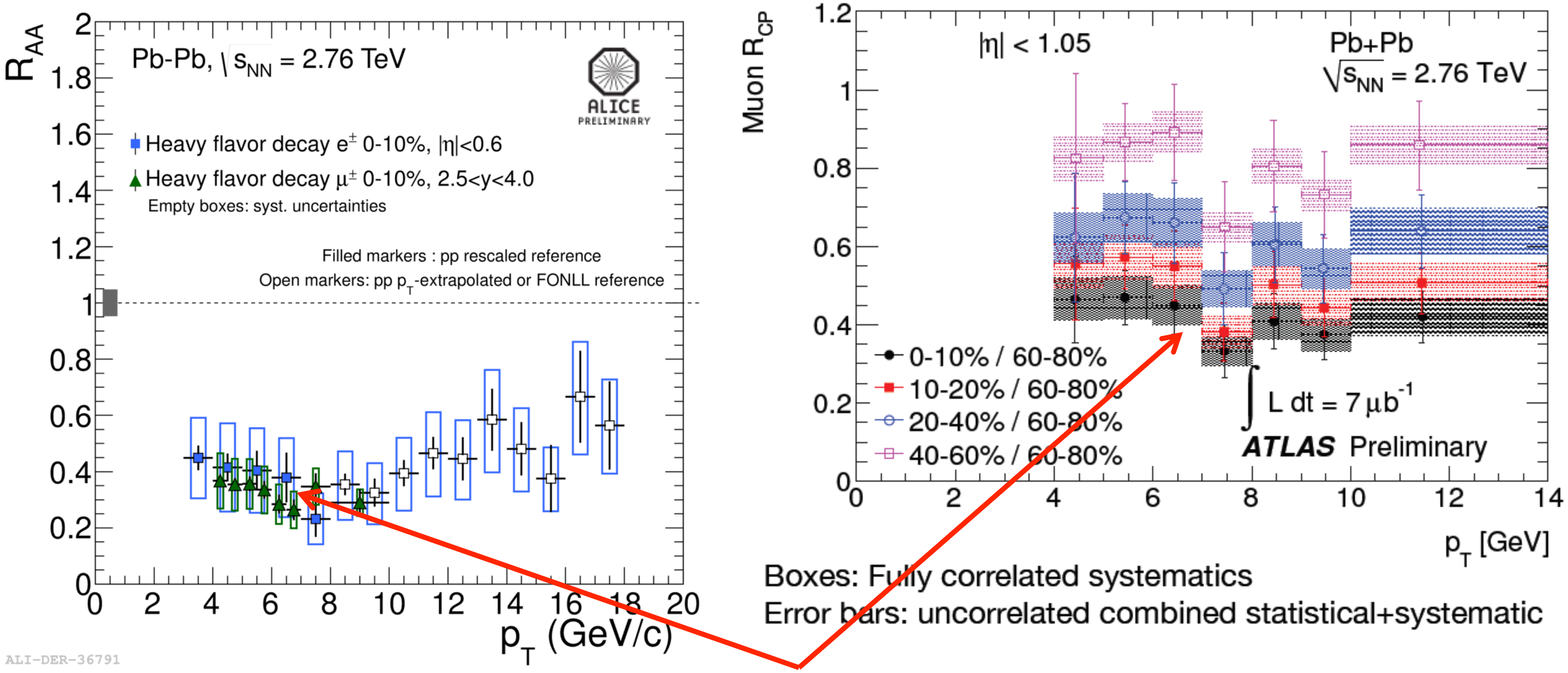
Less suppression in peripheral collisions

ATLAS: mid rapidity

$$R_{CP}(p_T) = \frac{\langle N_{coll} \rangle_{Per}}{\langle N_{coll} \rangle_{Cent}} \frac{dN/dp_T|_{Cent}}{dN/dp_T|_{Per}}$$

Approximately flat vs. p_T

R_{AA} of electrons vs muons

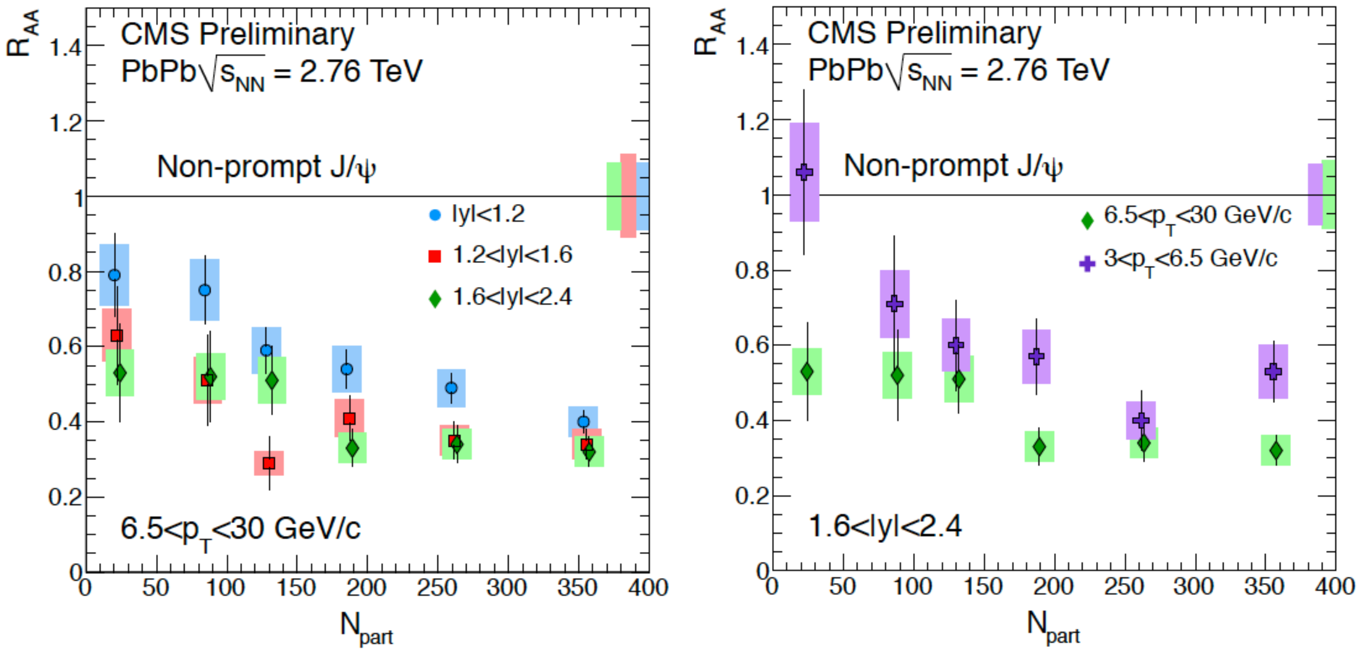


HF electrons (|y|<0.6) vs HF muons (2.5<y<4)→ *similar R_{AA} for 0-10%*

Direct comparison of muon R_{AA} (ALICE) and R_{CP} (ATLAS) not straightforward
→ Assuming ~no suppression for 60-80% centrality → same order of suppression for electrons in |η|<0.6 and muons in |η|<1.05 in 0-10%

Non-prompt J/ψ R_{AA}

CMS PAS HIN-12-014

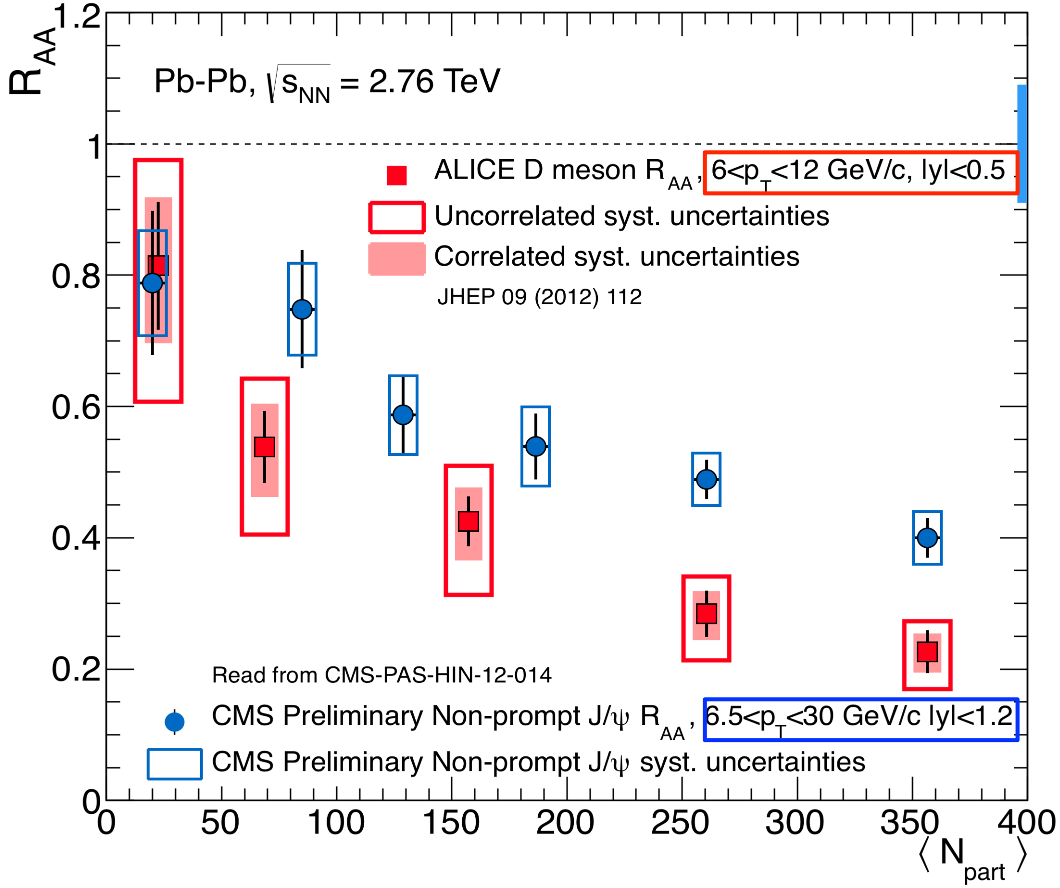


Centrality dependence of R_{AA} is similar in different rapidity ranges

At forward rapidity: can access low p_T (3<p_T<6.5 GeV/c) compared to 6.5<p_T<30 GeV/c accessible at mid-rapidity

Slightly less suppression in most central collisions at low p_T compared to high p_T

R_{AA}: Charm vs Beauty



[ALICE Coll. JHEP 09 (2012) 112]
[CMS Coll., JHEP 05 (2012) 063]

ALICE D mesons vs CMS J/ψ from B decays

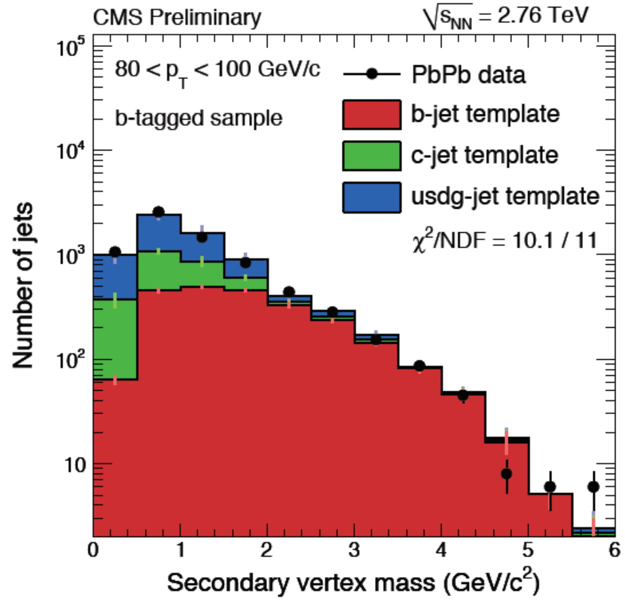
Charm vs Beauty difference observed in central collisions

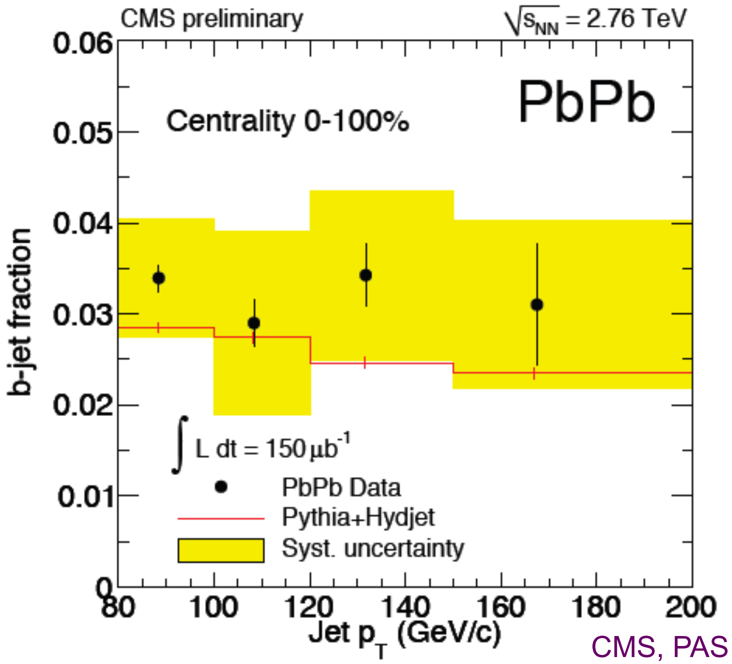
[R_{AA}(B)>R_{AA}(D) expected from mass hierarchy –slide 3]

CAVEAT: different y and p_T ranges of D and B

b-jets in Pb-Pb

- First measurement of fully reconstructed beauty jets in heavy-ion collisions by CMS
- Tagging method based on reconstruction of displaced secondary vertices in the jets.
- Contribution of b quarks from template fits to the invariant mass of secondary vertices





CMS, PAS HIN-12-003

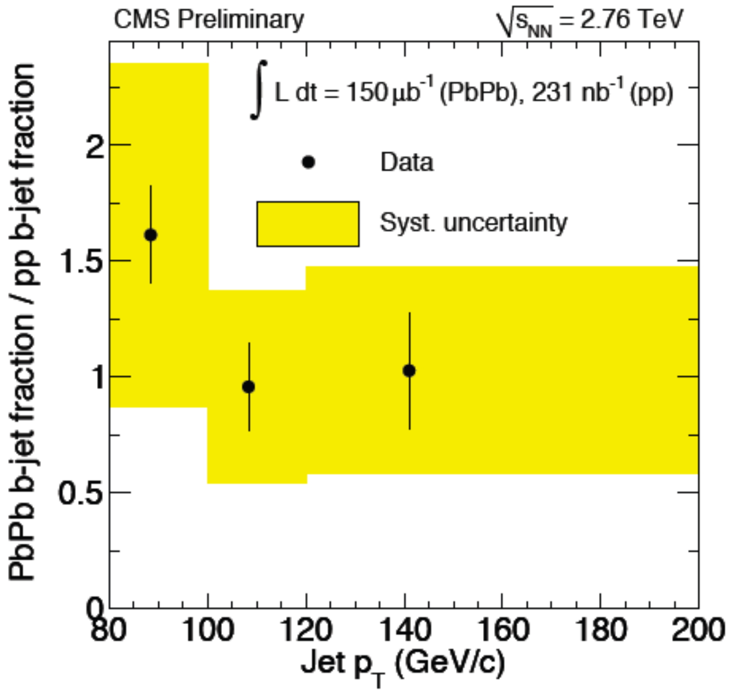
b-jet fraction = # tagged jets * purity / efficiency

b-jet fraction in PbPb larger than MC, but consistent within uncertainties
→ pp data are also consistent with MC

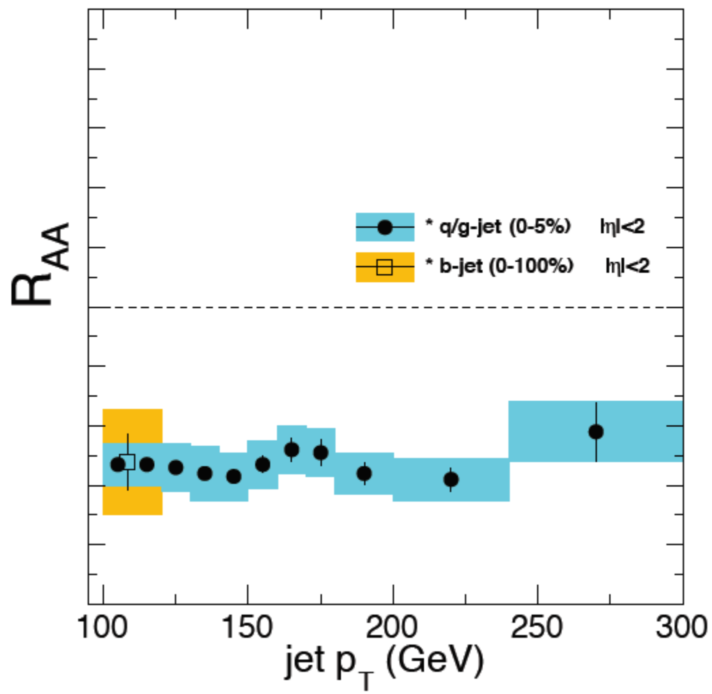
No strong centrality dependence of b-jet fraction

b-jet R_{AA}

double ratio:
b-jet fraction PbPb / b-jet fraction pp



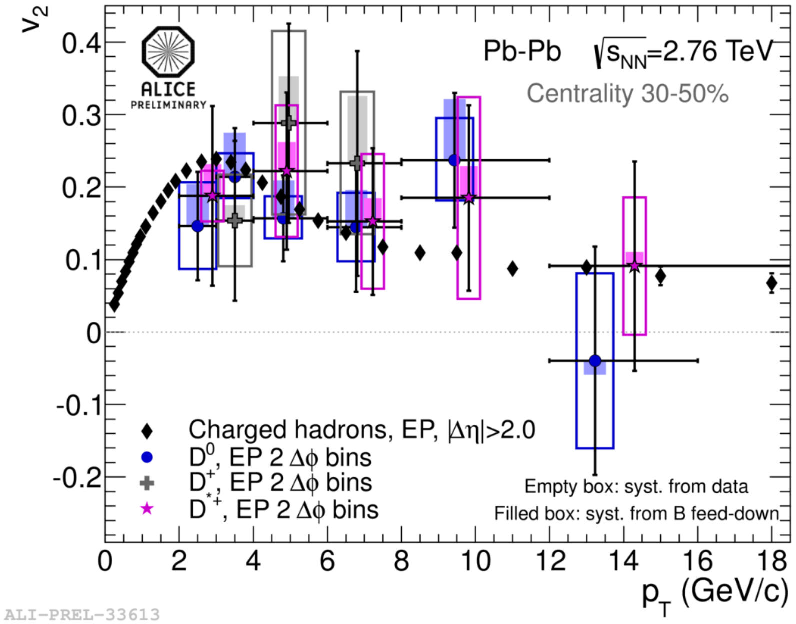
b-jet R_{AA}:
inclusive jet R_{AA} * double ratio



At high p_T (100-120 GeV/c): similar suppression of light vs b jets, as expected

Further analysis pushing to lower p_T jets, muon-jets, double b-tagged dijets

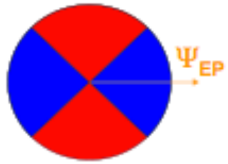
D meson v_2



ALICE: Use event plane method

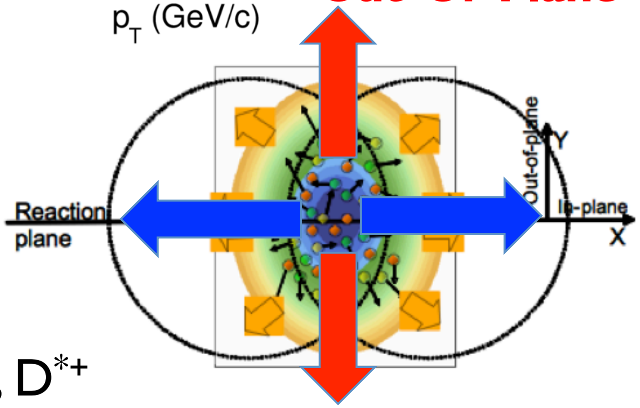
$$v_2 = \frac{1}{R_2}\frac{\pi}{4}\frac{N^{\text{In-Plane}} - N^{\text{Out-Ot-Plane}}}{N^{\text{In-Plane}} + N^{\text{Out-Ot-Plane}}}$$

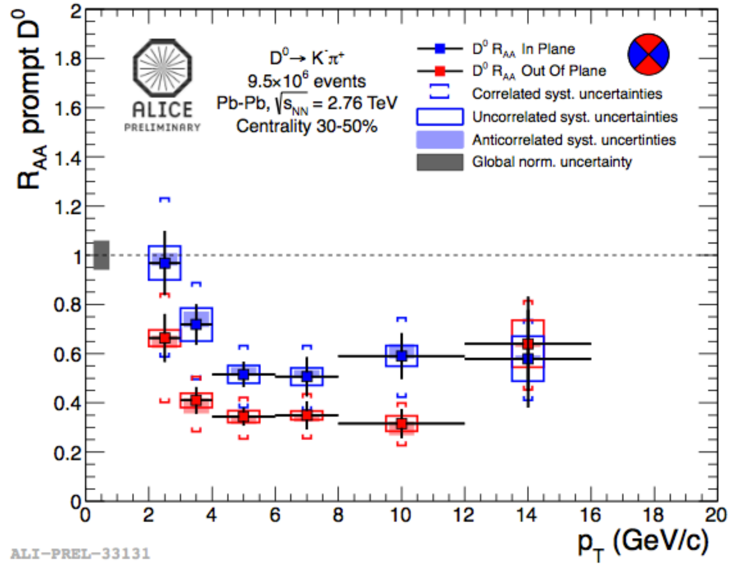
R_2 : event plane resolution



Out-Of-Plane

In-Plane





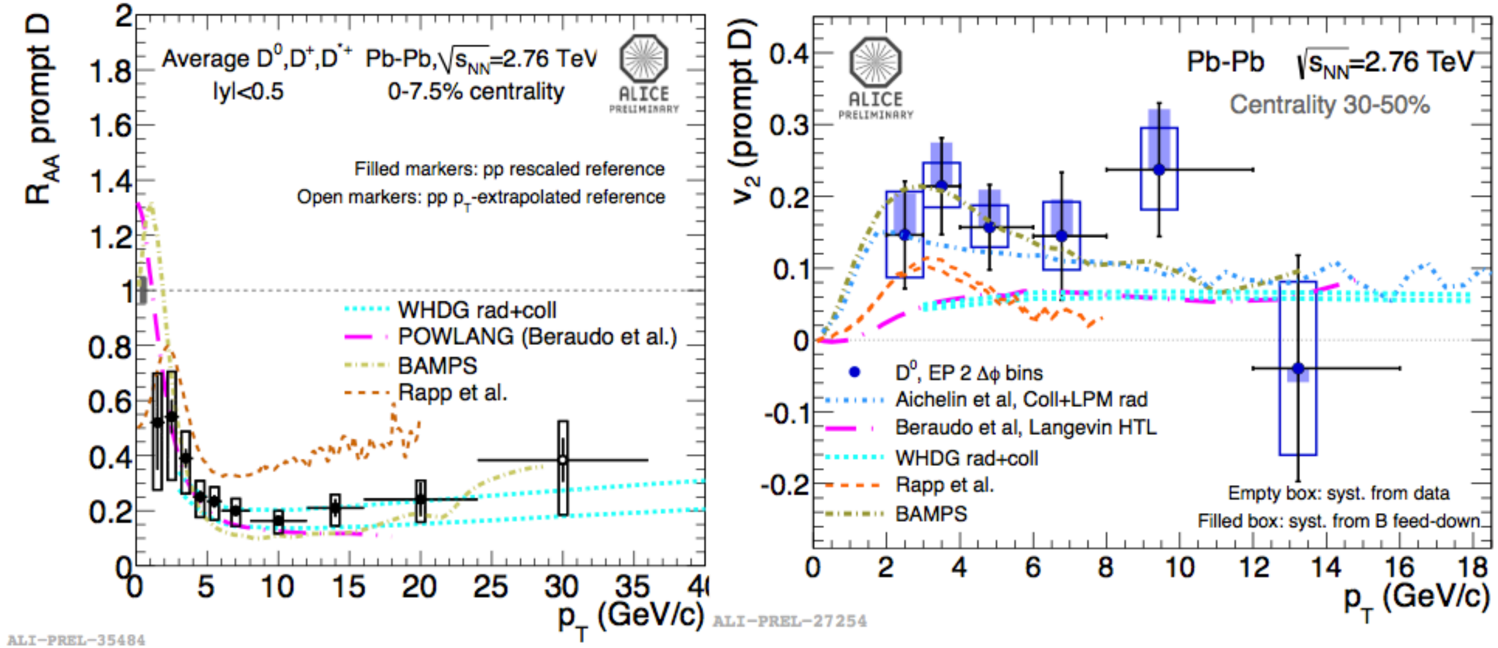
v_2 consistent for D^0, D^+, D^{*+}

D meson v_2>0 at low p_T (3σ effect for 2<p_T<6 GeV/c)

D^0 mesons *more suppressed* **Out-Of-Plane** than **In-Plane**

Hint for collective motion (low p_T) and/or path-length dependent energy loss (high p_T)

The challenge for the models



Theoretical models of in-medium parton energy loss reproduce reasonably R_{AA} but are challenged by simultaneously reproducing results from heavy-flavour R_{AA} and v_2

From the experimental side, reducing statistical and systematic errors will help to disentangle among different models

Armesto et al. PRD71 (2005) 054027
Horowitz et al., JPhys G38 (2011) 124114
Alberico et al., Eur.Phys.J C71 (2011) 1666
van Hees et al., PRC73 (2006) 034913
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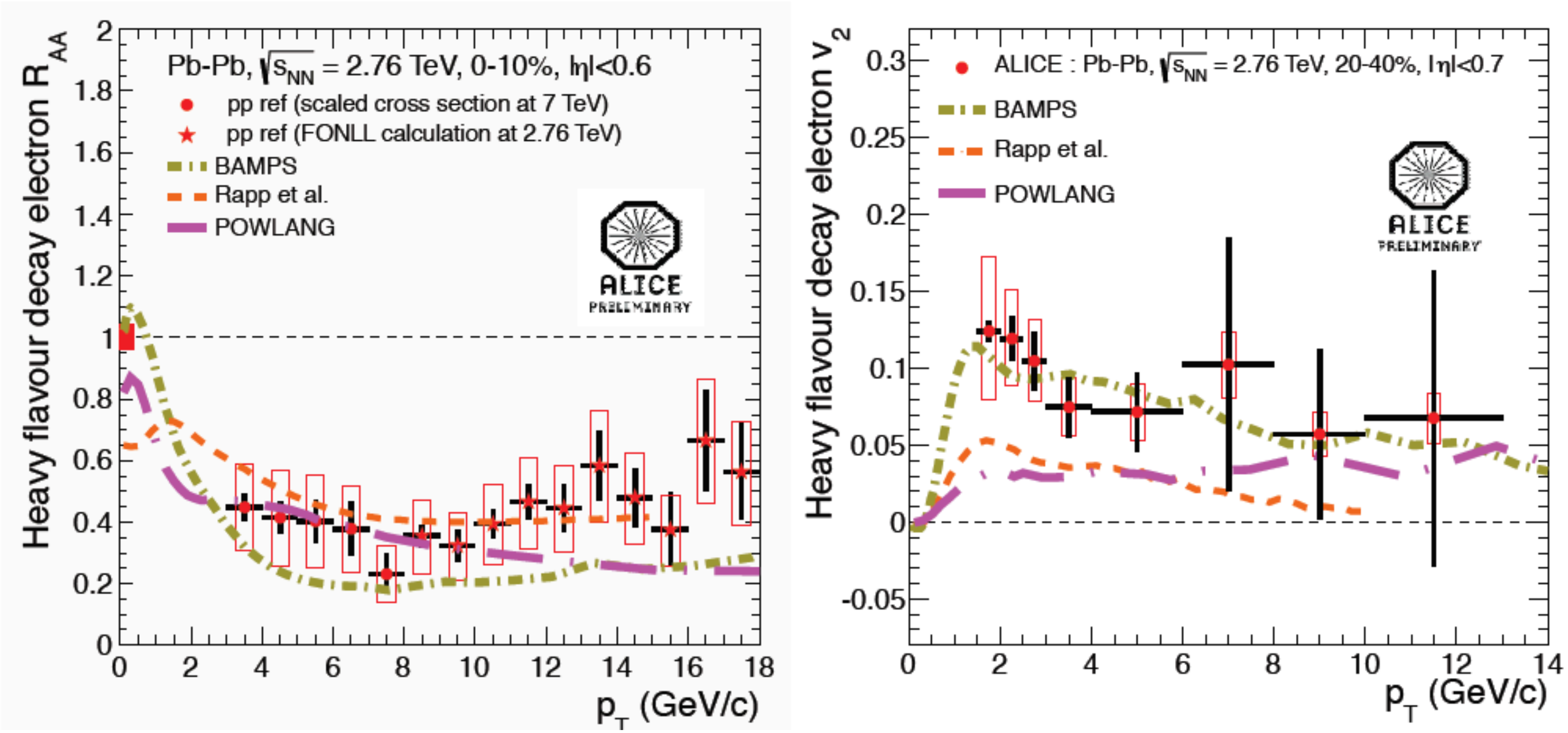
Sharma et al.,PRC80 (2009) 054902
He et al., PLB713 (2012) 224

The challenge for the models



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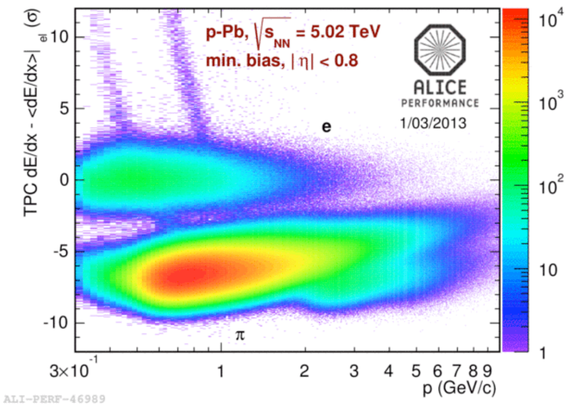
Toward p-Pb

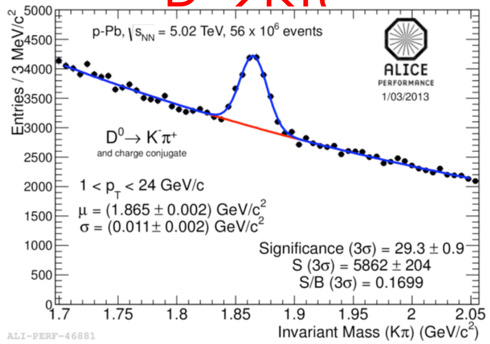
5.02 TeV (Run 2013)

Prospects for p-Pb collisions

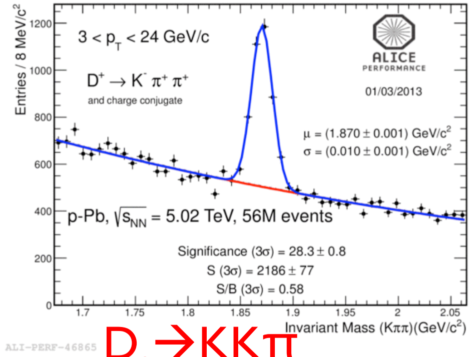
electron PID in TPC



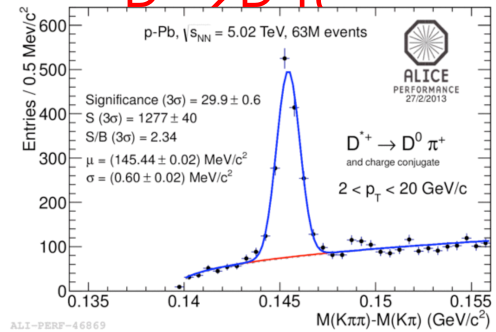
$D^0 \rightarrow K\pi$



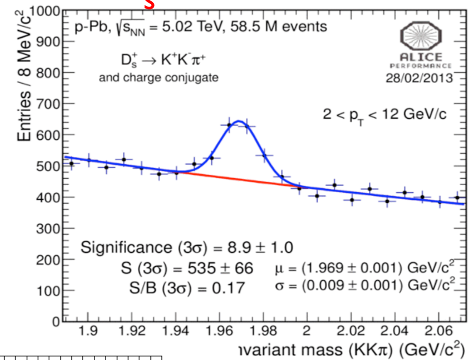
$D^+ \rightarrow K\pi\pi$



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



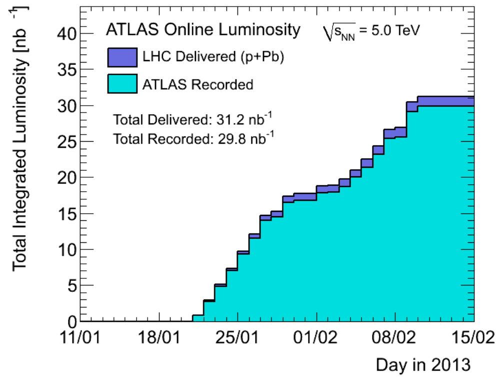
$D_s \rightarrow KK\pi$



Collected statistics:

ALICE:

- ~ 133 M min bias events
- 5.4 nb-1 p-Pb + 6.0nb-1 Pb-p triggered dimuon events



ATLAS: 29.8 nb^{-1} pPb recorded

CMS: 31.13 nb^{-1} pPb recorded

High-quality measurements to assess the cold nuclear matter effect will come soon !

Conclusions

pp data:

- Cross-sections at 7 and 2.76 TeV for D mesons, leptons from HF decays and J/ψ from B decays well reproduced by pQCD → *pp reference under control to compare to Pb-Pb and p-Pb*

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PbPb data:

- *Strong suppression for D mesons (ALICE) and HF electrons (ALICE) and muons (ALICE, ATLAS)* in central Pb-Pb relative to pp (R_{AA})
- *Indication for non-zero v_2 for D mesons (2-6 GeV/c) and HF electrons (2-3 GeV/c)* in semi-peripheral Pb-Pb *(ALICE)* .
- Observed *difference in suppression of D mesons (ALICE) and non-prompt J/ψ from B* meson decays *(CMS)* in central collisions.
- First measurements of *beauty jets (CMS)* at 100-120 GeV/c similar suppression of light vs b jets
- Models of in-medium energy loss predict reasonably well HF R_{AA}. Challenge for theory to reproduce R_{AA} and v_2.

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Coming soon: results from p-Pb (collected in 2013 run) → establish *initial-state effects*

Near future: Pb-Pb at *top energy* in 2015-16

Longer term: LHC and detector *upgrades* (2018) → *high-precision* & *high luminosity*

Extra

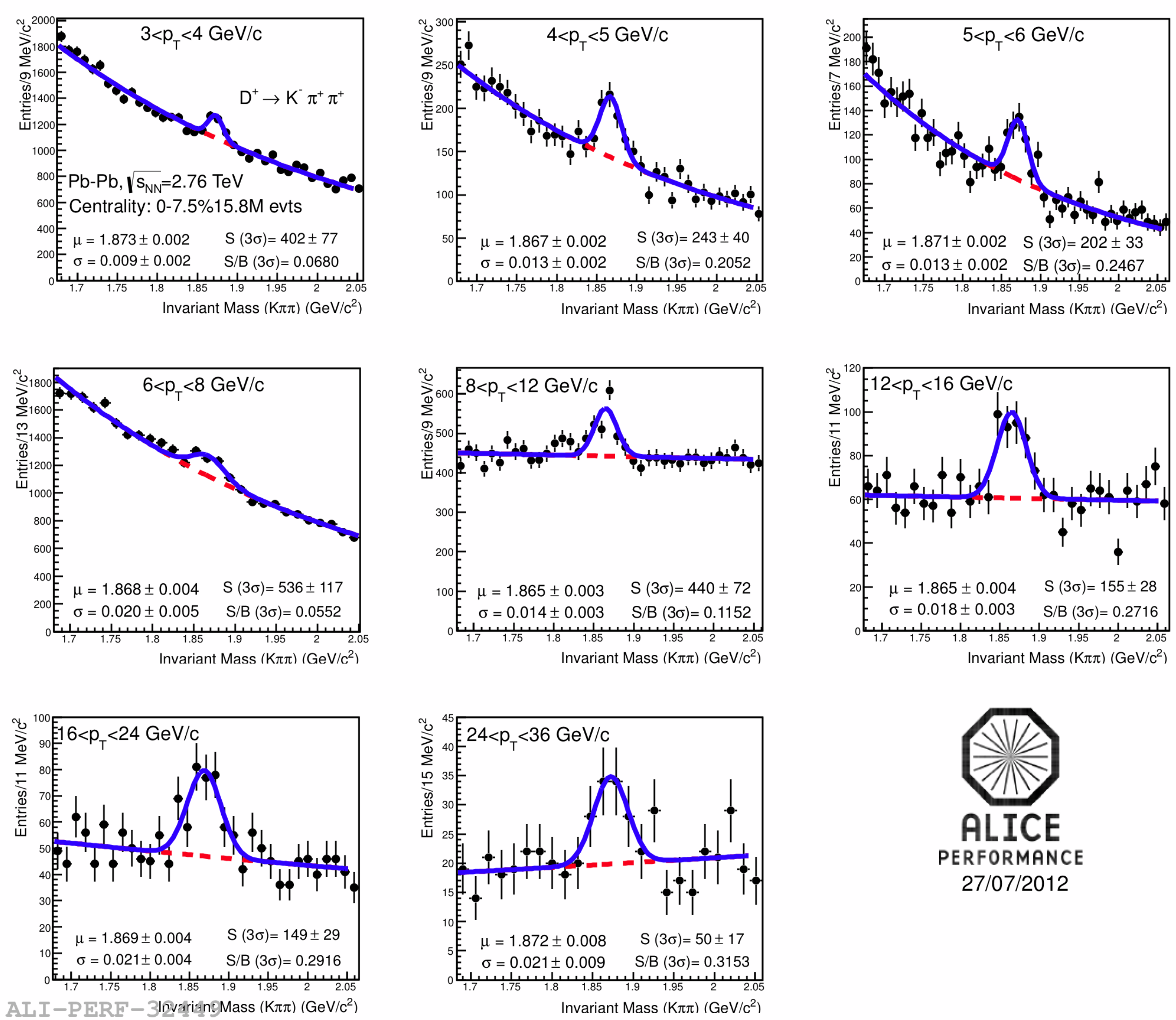
D mesons

~16×10^6 events w/ 2011 run
Centrality 0-7.5%
(MB + centrality trigger)

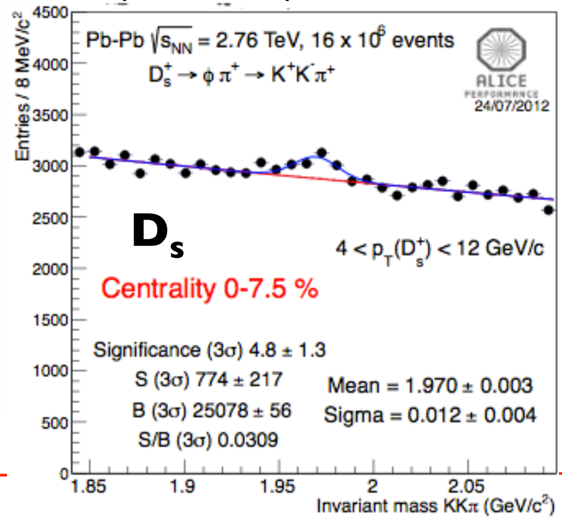
Larger p_T range explored:
D^0 $1<p_T<24$ GeV/c
D^+, D^{*+} $3<p_T<36$ GeV/c
D_s (NEW) $4<p_T<12$ GeV/c

Significance > 30 (D^0),
>11 (D^+, D^{*+})

D^+

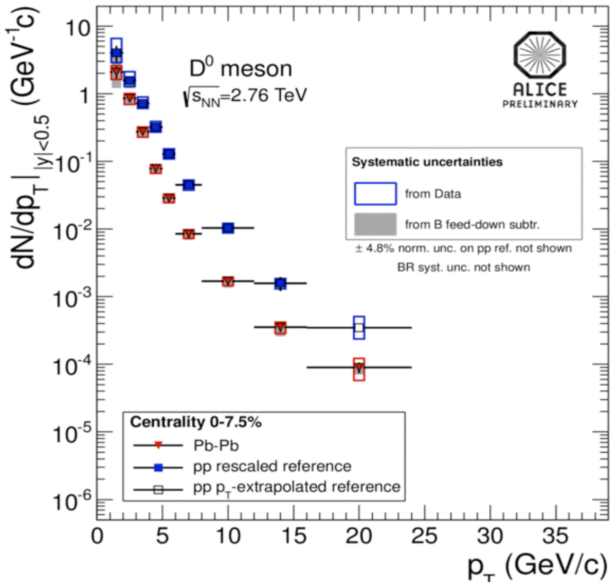


ALICE PERFORMANCE
27/07/2012

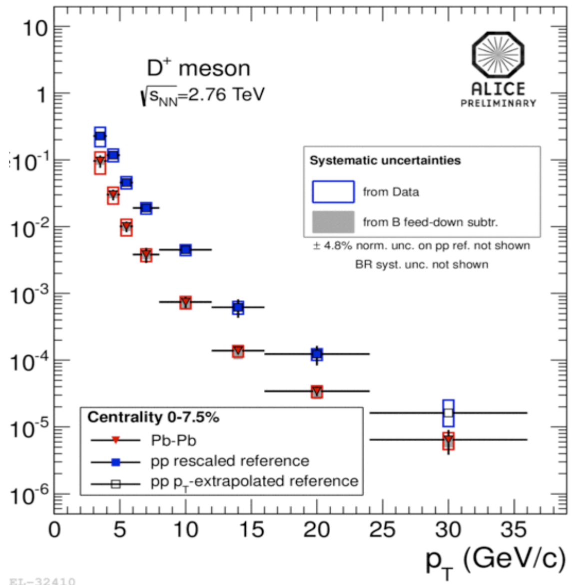


D meson dN/dp_T

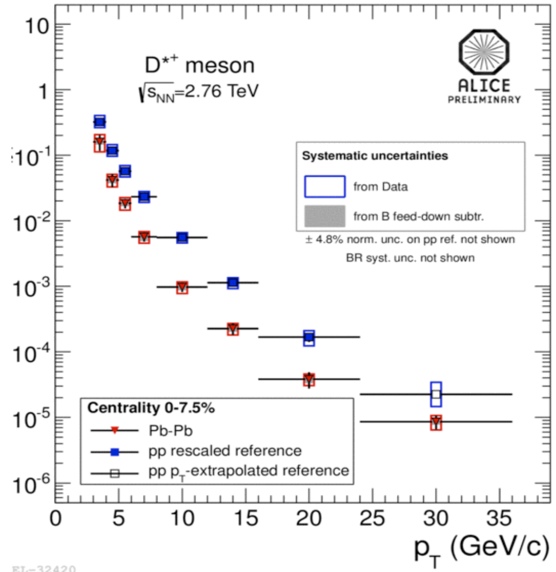
D^0

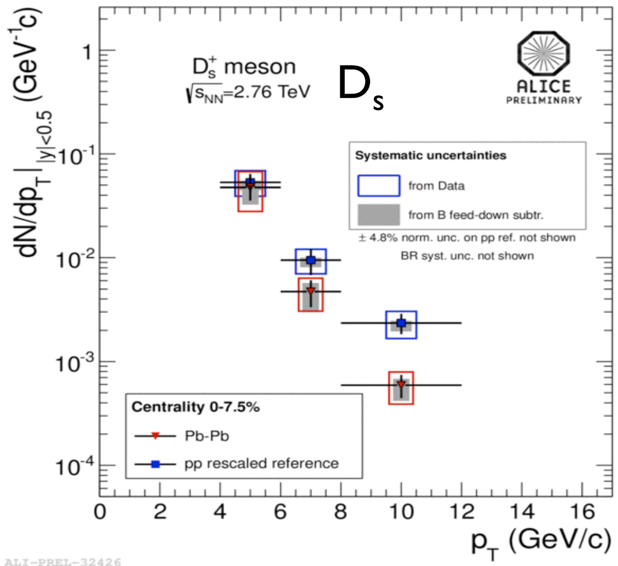


D^+



D^{*+}





prompt D mesons = (inclusive D) – (D from B decays)

- pp: "D from B" yield estimated from pQCD
- Pb-Pb: as for pp, but *uncertainty on unknown B R_{AA}*:

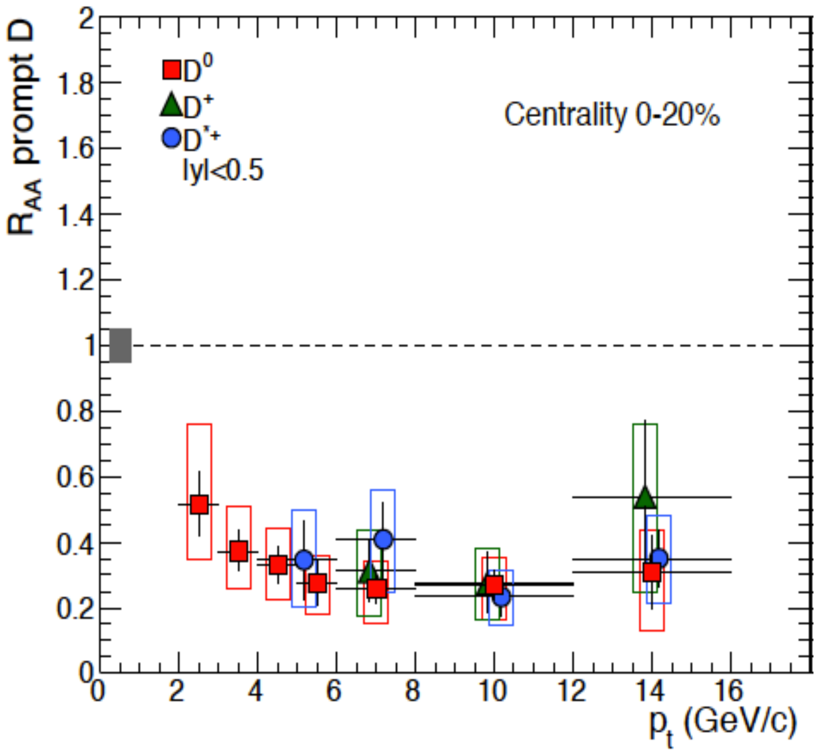
  → R_{AA}(D from B) between 1/3 and 3 x R_{AA}(D)

pp reference from 7 TeV scaled to 2.76 TeV (+ high-p_T FONLL extrapolation) and multiplied by $\langle T_{AA} \rangle$

Large suppression in Pb-Pb relative to pp

D meson R_{AA}

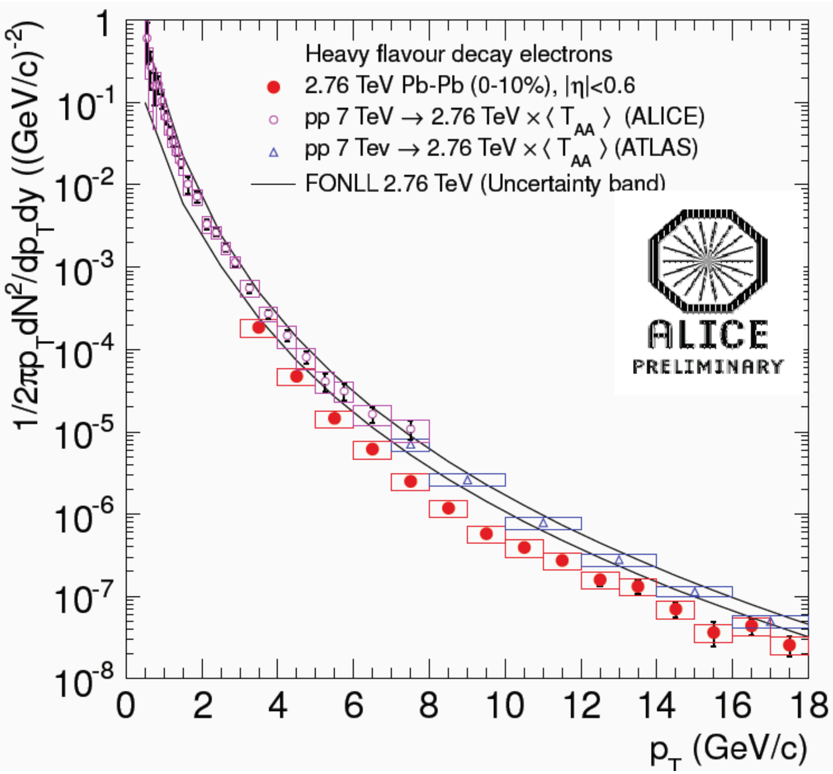
[ALICE Coll. JHEP 09 (2012) 112]

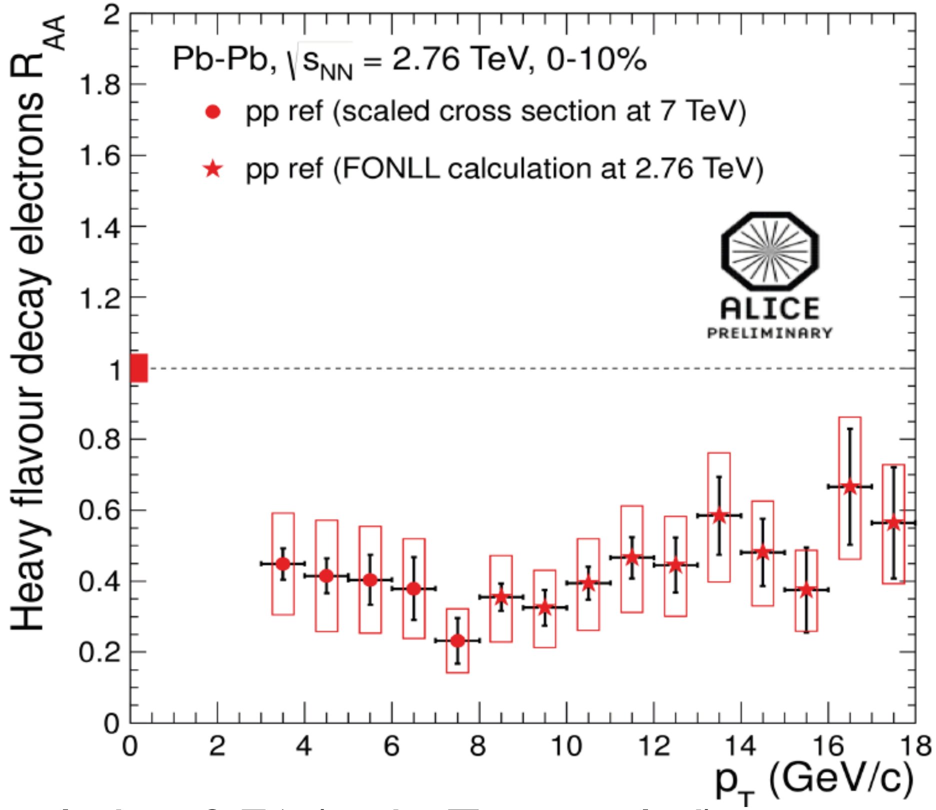


$$R_{AA}^{D}(p_T) = \frac{dN_{AA}^{D} / dp_T}{\langle T_{AA} \rangle \times d\sigma_{pp}^{D} / dp_T}$$

D^0, D^+, D^{*+} R_{AA} compatible within errors

R_{AA} of Heavy-Flavour electrons





HFE pp from ALICE and ATLAS: from 7 TeV scaled to 2.76 (and $<T_{AA}>$ scaled)

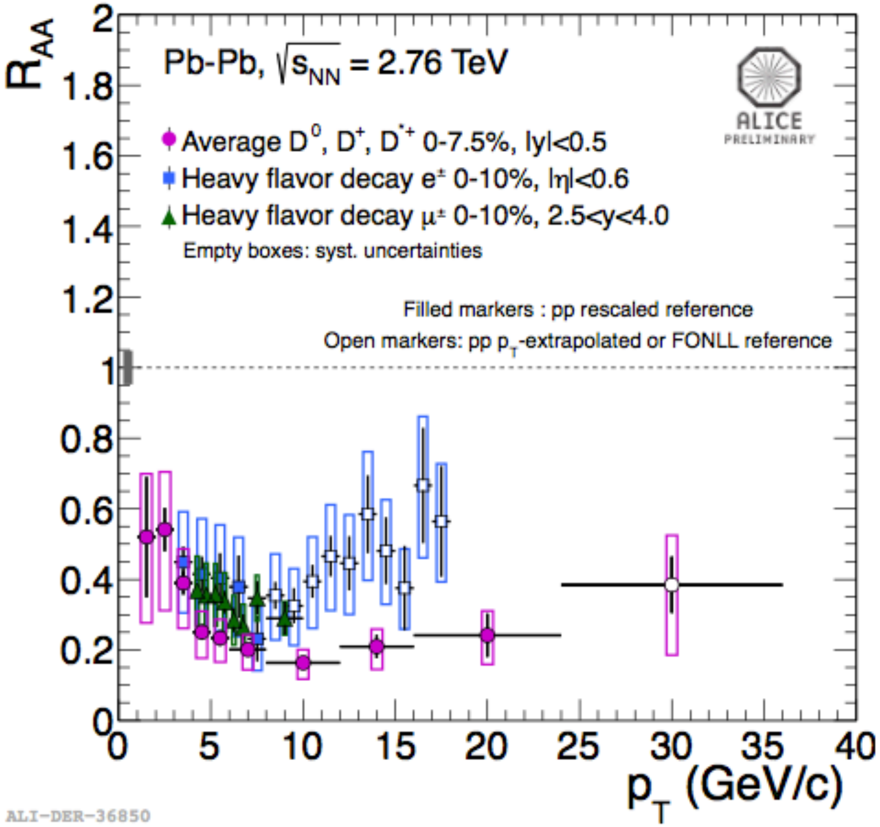
pp reference: p_T< 8 GeV/c from ALICE HFE pp @ 7 TeV (scaled to 2.76 TeV)

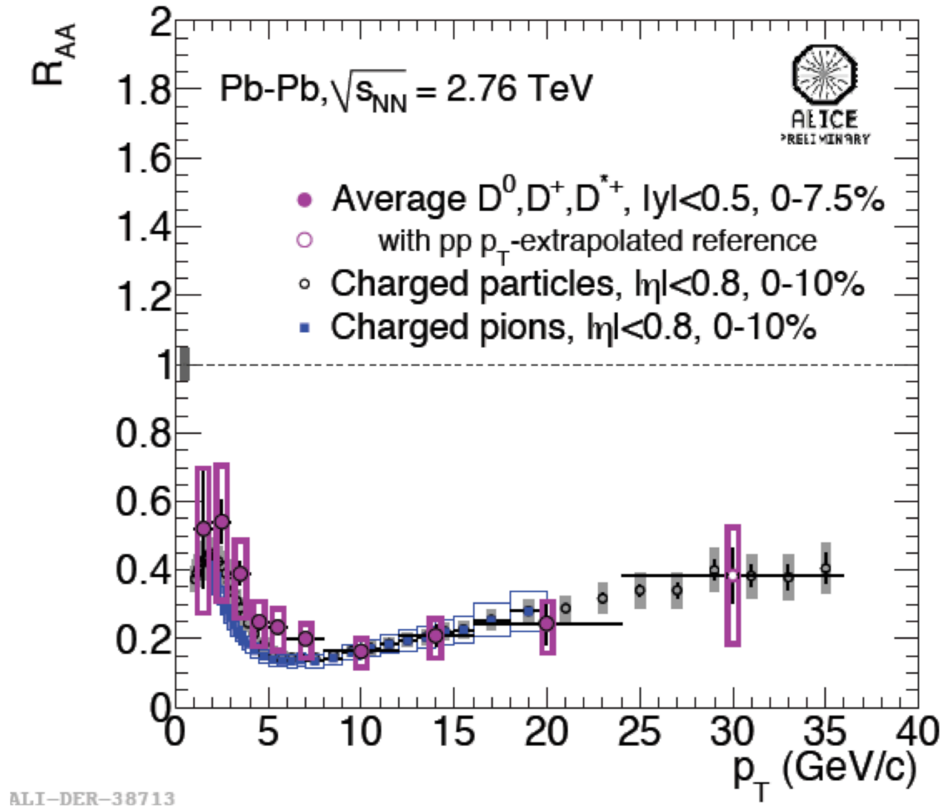
p_T>8 GeV/c FONLL calculation

pp 7 TeV:
(ALICE) arXiv : 1205.5423
(ATLAS) PLB 707 (2012) 438

Clear suppression of HF electrons from 3 up to ~18 GeV/c

R_{AA}: p_T dependence



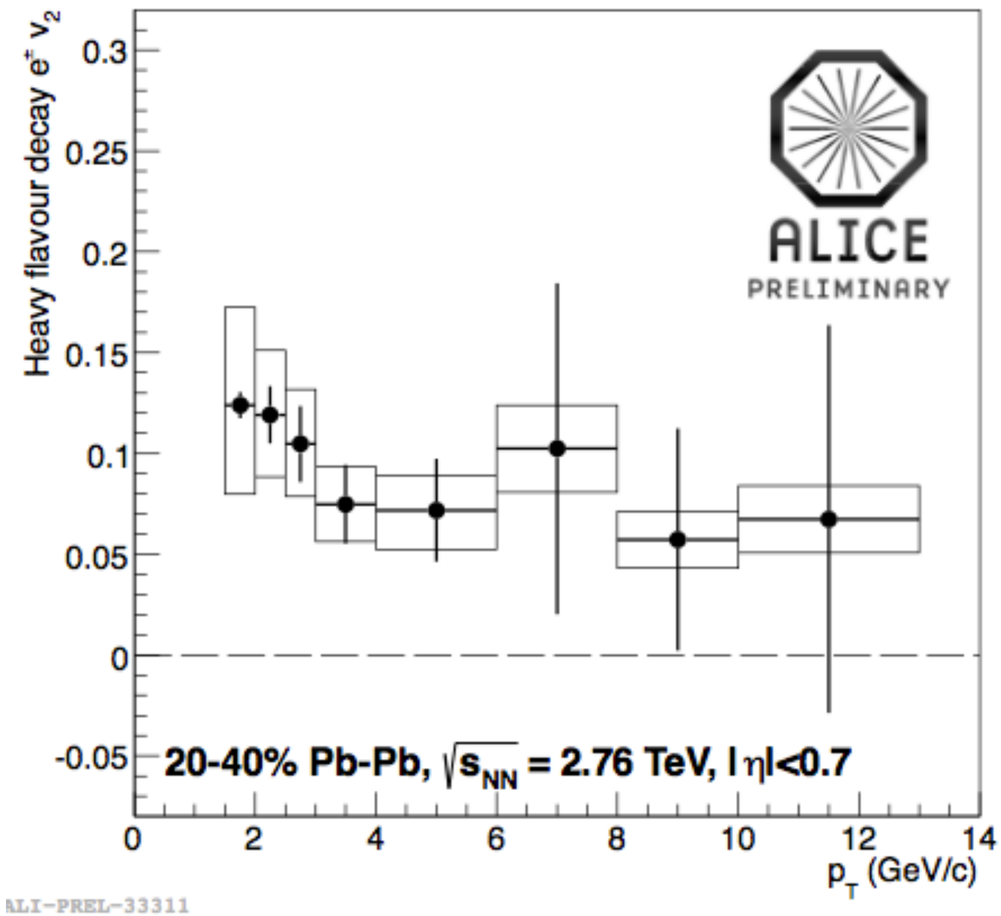


HF leptons vs D → *compatible* given the different kinematics [$p_T(e) \sim 0.5\ p_T(B)$ at high p_T]

Similar suppression as light hadrons, hint of difference below 5 GeV/c

→ more statistics needed to extract flavour dependence of energy loss

Heavy-flavour electron v_2



ALICE: TPC, TOF, EMCal combined

Use event plane method

$$v_2^{\rm HFe} = \frac{(1+\alpha)\, v_2^{\rm e\, inclusive} - v_2^{\rm e\, background}}{\alpha}$$

$$\alpha = N^{\rm HFe} / N^{\rm e\, background}$$

α obtained form cocktail+invariant mass analysis

$v_2^{\rm e\ background}$ obtained from v_2 of background sources (π^0,…)

HF electron v_2>0 at low p_T (3σ effect for 2<p_T<3 GeV/c)