Heavy-Flavour Measurements at the LHC

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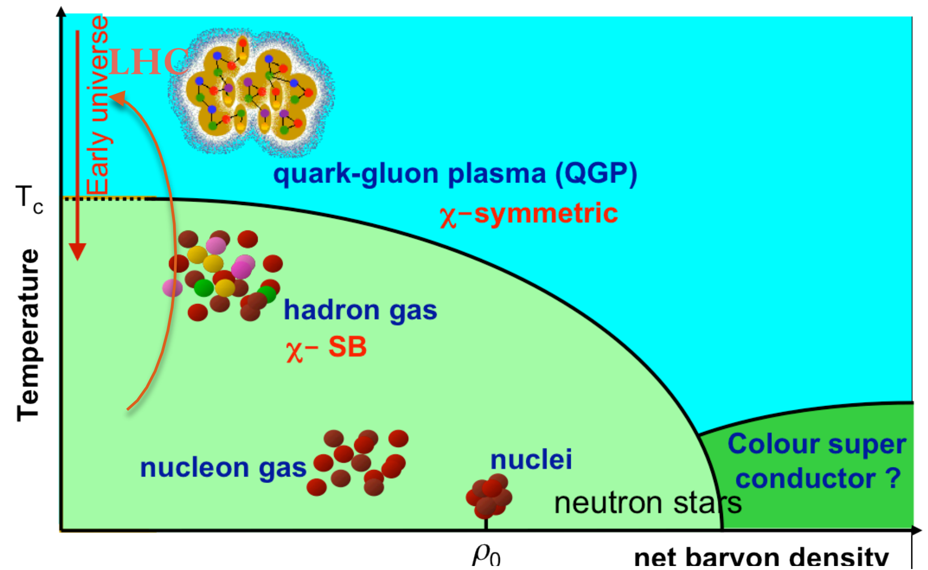
OUTLINE

- Why Heavy flavours in heavy-ion physics
- Heavy-flavour observables
- Overview of heavy-flavour measurements
    - in pp, p-Pb, Pb-Pb collisions
- Summary

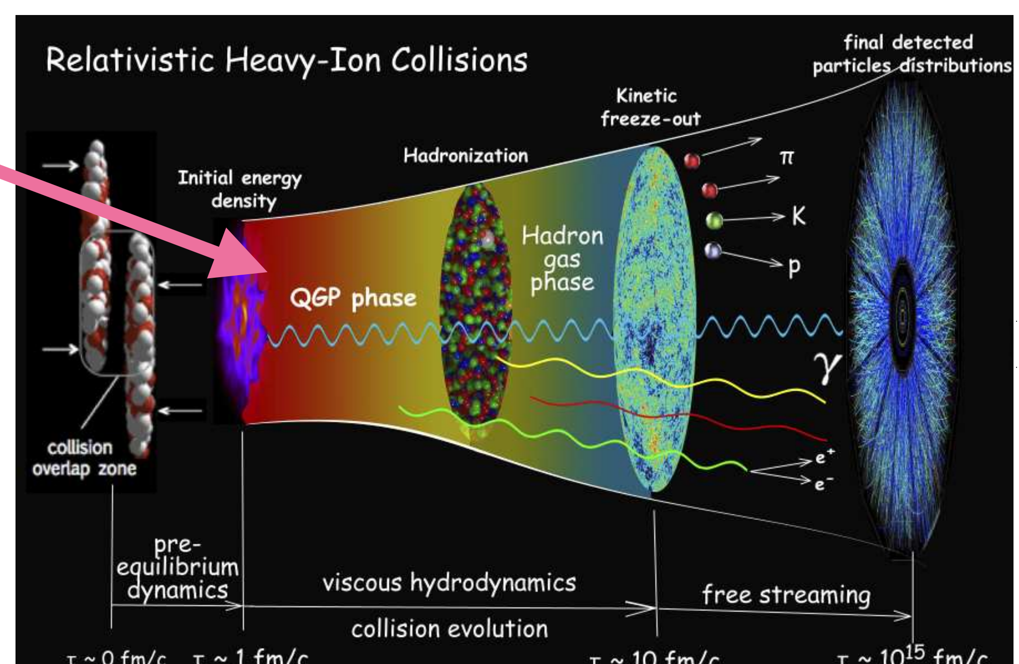
Deconfined QCD matter and its probes

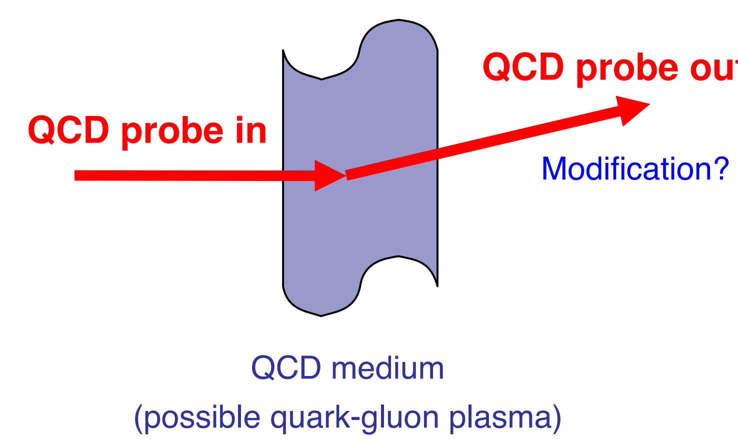
- Heavy-ion (HI) collisions at LHC energies
  - Deconfined QCD matter (Quark-Gluon Plasma phase) is expected (lifetime ~ *O*(10 fm/c))



- Hard (large Q^2, large mass scale) probes are produced at the beginning of the collisions →probe the whole evolution of the collisions

Hard processes:
- Charm, Beauty, W, Z, photons, Jets





Tomographic probes

What's special about heavy quarks

	Pole mass M
Charm	~ 1.3–1.7 GeV
Bottom	~ 4.5–5 GeV
Top	$173.1 \pm 0.6 \pm 1.1$ GeV (?)

PDG; TevEWWG

- Heavy quarks
  - Large mass ($m_q \gg \Lambda_{QCD}$)

    → hard probes even at low p_T

    → produced in the early stages of the HI collision with short formation time;

    $t_{charm} \sim 1/m_c \sim 0.1$ fm/c << $\tau_{QGP} \sim O(10$ fm/$c)$

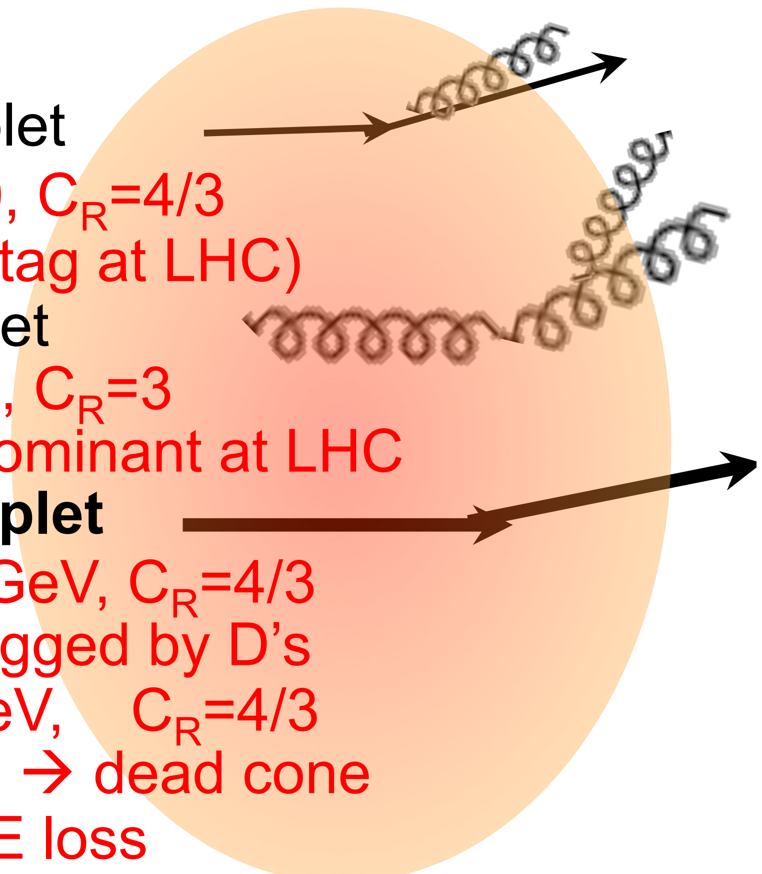
  - Interactions with QGP don't change flavour identity

  - Uniqueness of heavy quarks: cannot be destroyed/created in the medium

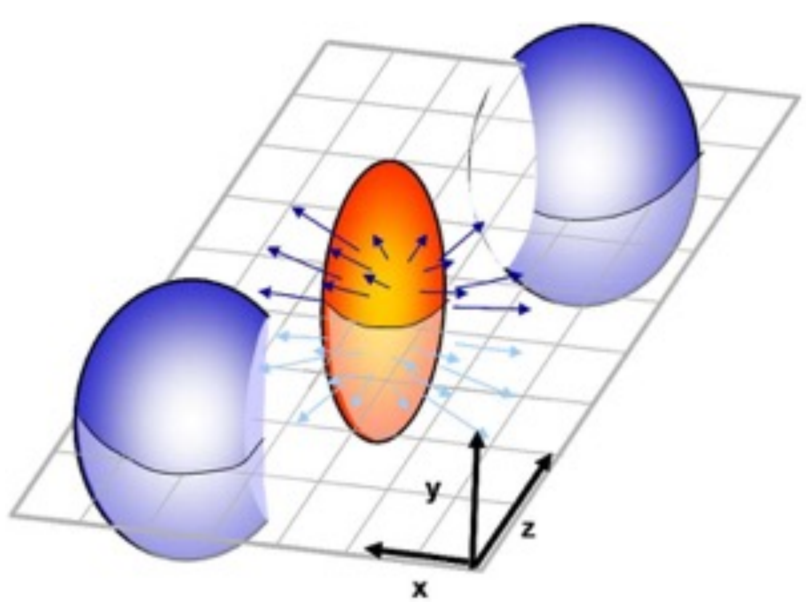
➡traverse the medium interacting with its constituents
→ natural probe of the hot medium created in HI interactions

Heavy quarks as medium probes

q: colour triplet
u,d,s: m~0, C_R=4/3
(difficult to tag at LHC)
g: colour octet
g: m=0, C_R=3
> E loss, dominant at LHC
Q: colour triplet
c: m~1.5 GeV, C_R=4/3
small m, tagged by D's
b: m~5 GeV, C_R=4/3
large mass → dead cone
→ < E loss



'Quark Matter'



Parton Energy Loss by
→ **medium-induced gluon radiation**
→ **collisions with medium constituents**

$$\Delta E(\varepsilon_{medium};C_R,m,L)$$

Prediction: $\Delta E_g > \Delta E_{c\approx q} > \Delta E_b$

Might translate into a hierarchy of nuclear modification factors

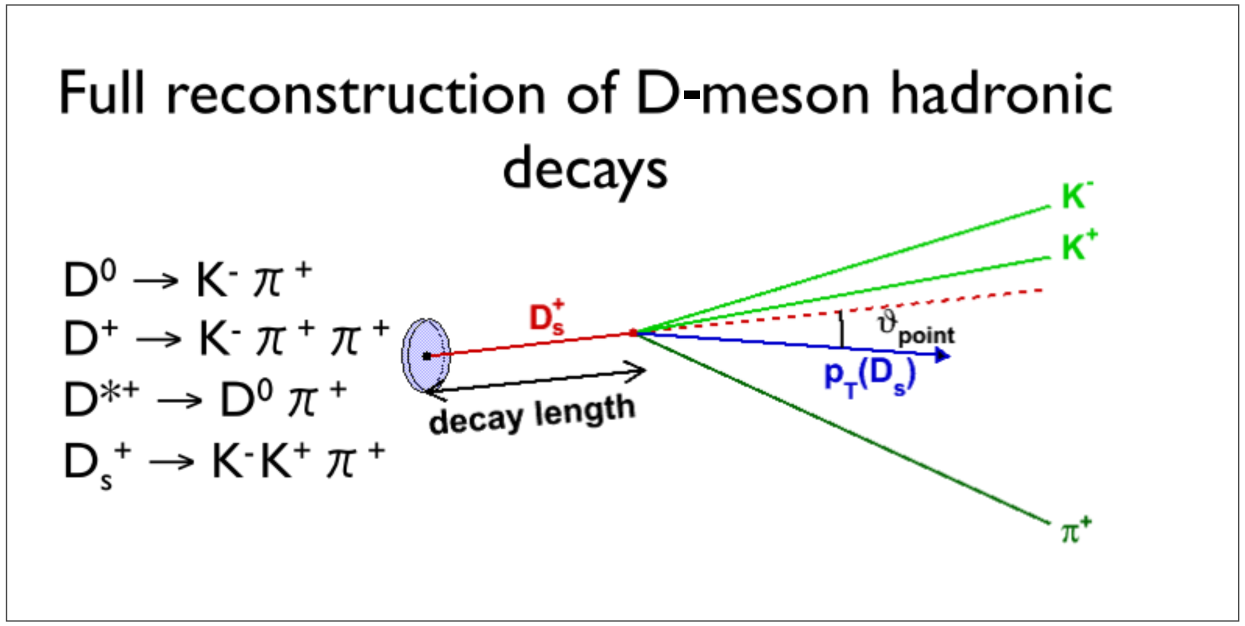
$$R_{AA}^{\pi} < R_{AA}^{D} < R_{AA}^{B}?$$

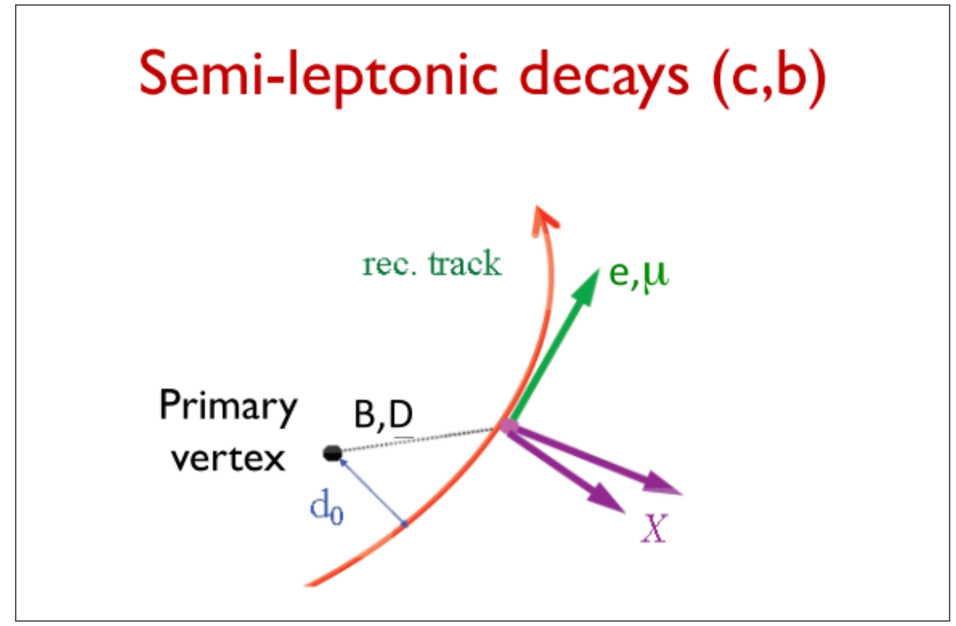
Collectivity in the QGP

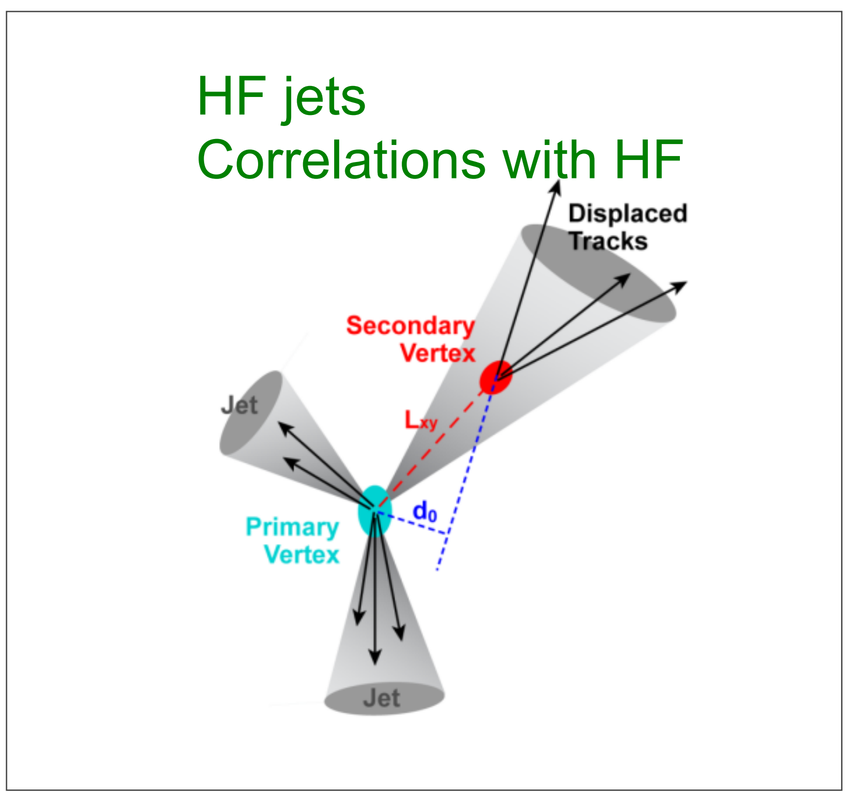
- **in general: initial spatial asymmetry**
  → azimuthal asymmetry of particle emission in momentum space
- **heavy quarks participate in collectivity of the medium in case of sufficient re-scattering**
  → approach to thermalization
- **high p_T: path-length dependence of energy loss introduces azimuthal asymmetry as well**

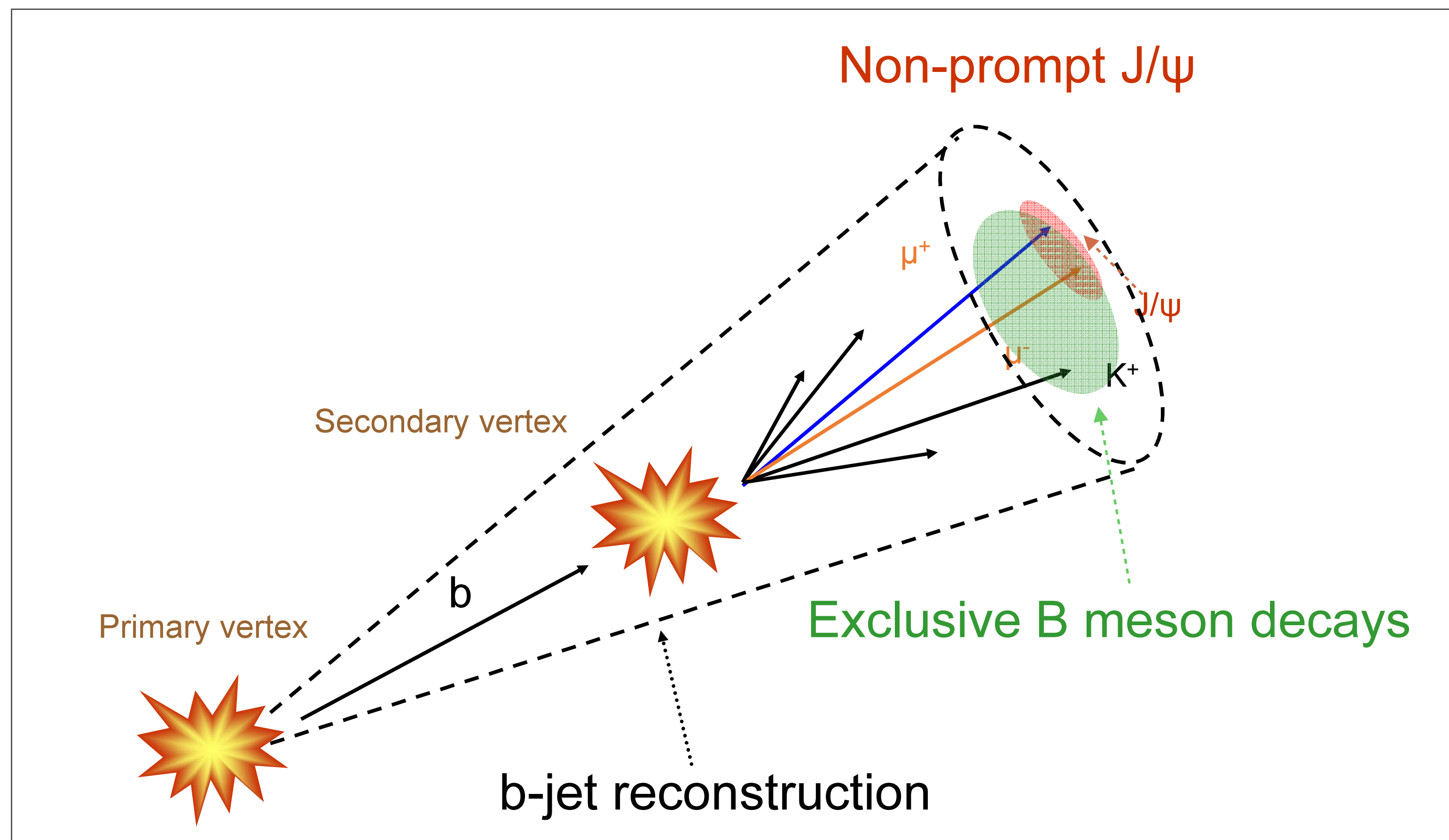
Heavy-flavour Observables: measure decay products

Heavy-flavor hadrons decay via weak interaction: lifetimes $c\tau$ ~ few 100 μm







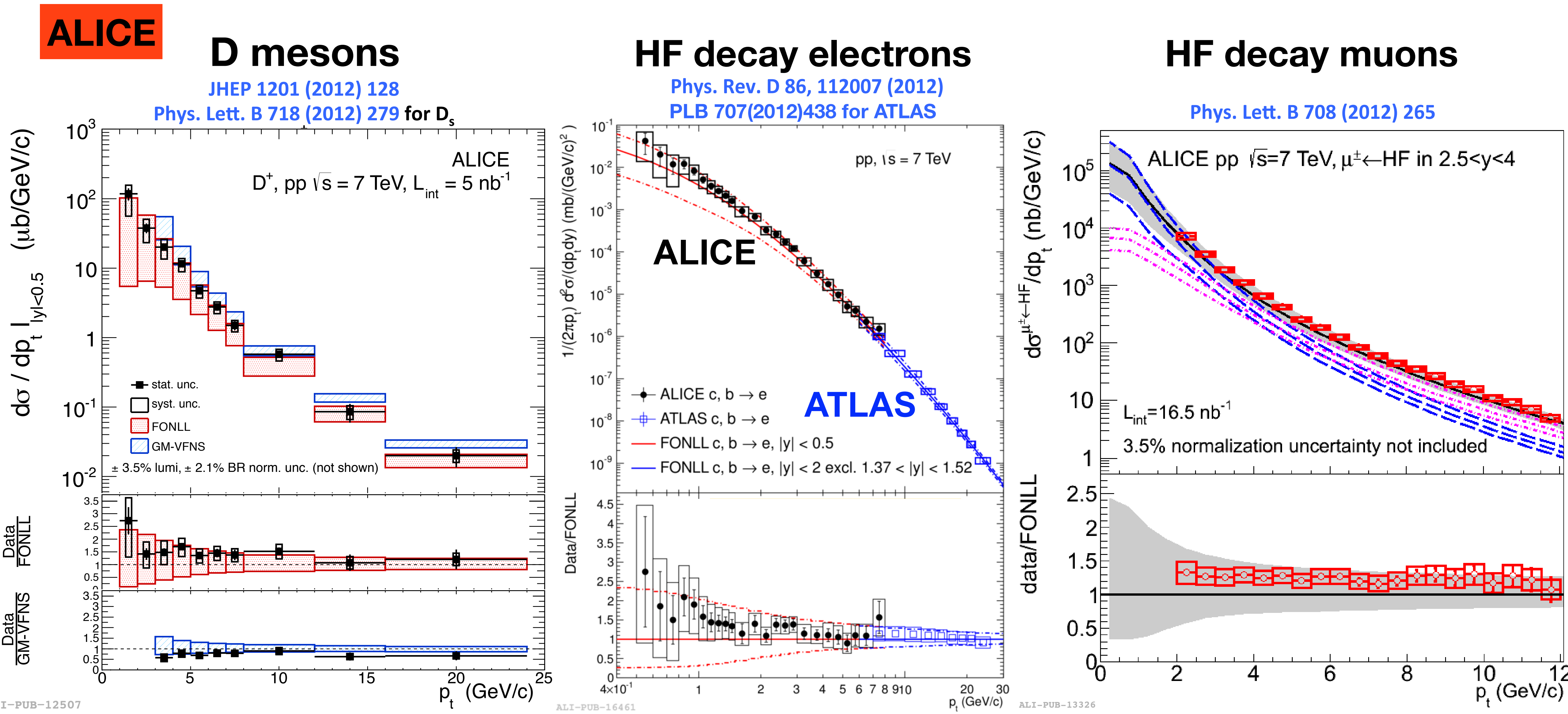


Heavy flavours

Results in pp collisions at $\sqrt{s}$ = 7 TeV and $\sqrt{s}$ = 2.76 TeV

Baseline for AA and p-A collisions
Test perturbative QCD calculations

Heavy-flavour cross section in pp at $\sqrt{s}$ = 7, 2.76 TeV



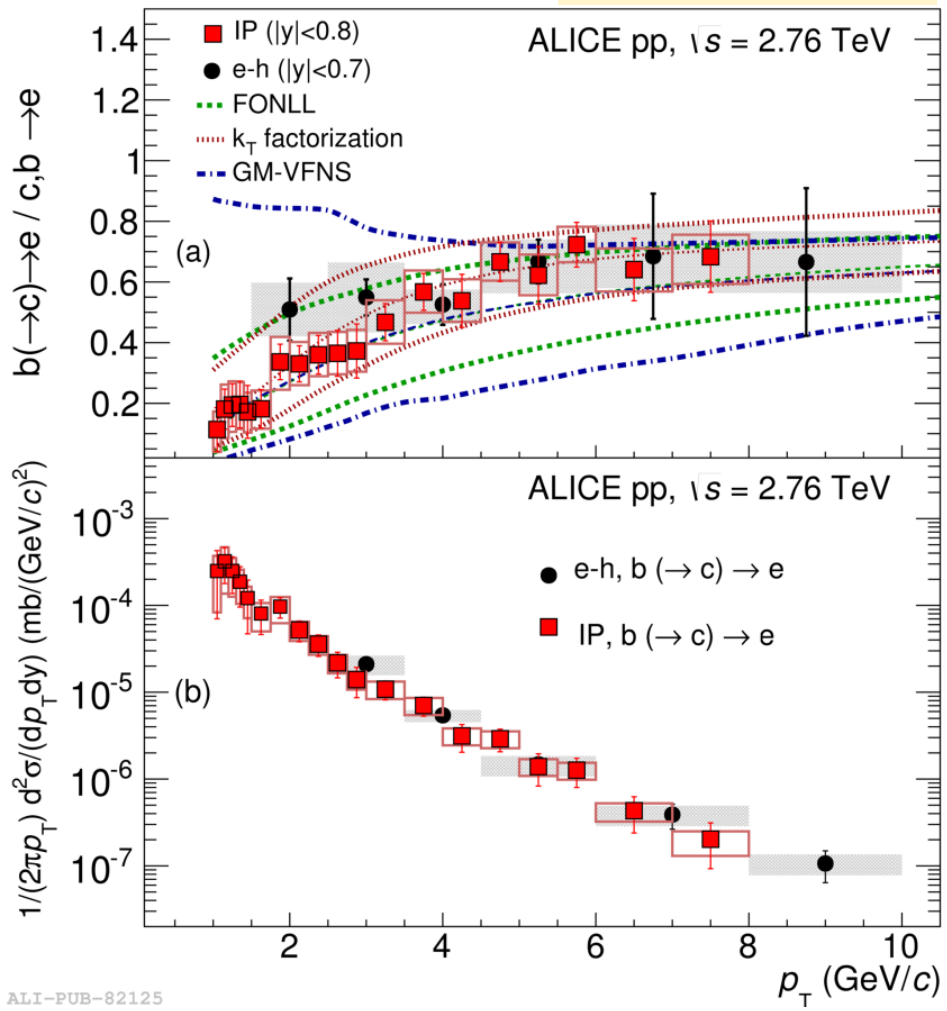
- Heavy-flavour cross section measured in various channels
- pQCD-based calculations (FONLL, GM-VFNS, k_T factorization) compatible with data FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033
- Similar conclusion at $\sqrt{s}$ = 2.76 TeV

Heavy-flavour cross section in pp at $\sqrt{s}$ = 2.76, 7 TeV

ALICE

Beauty decay electrons

PLB 738(2014)97



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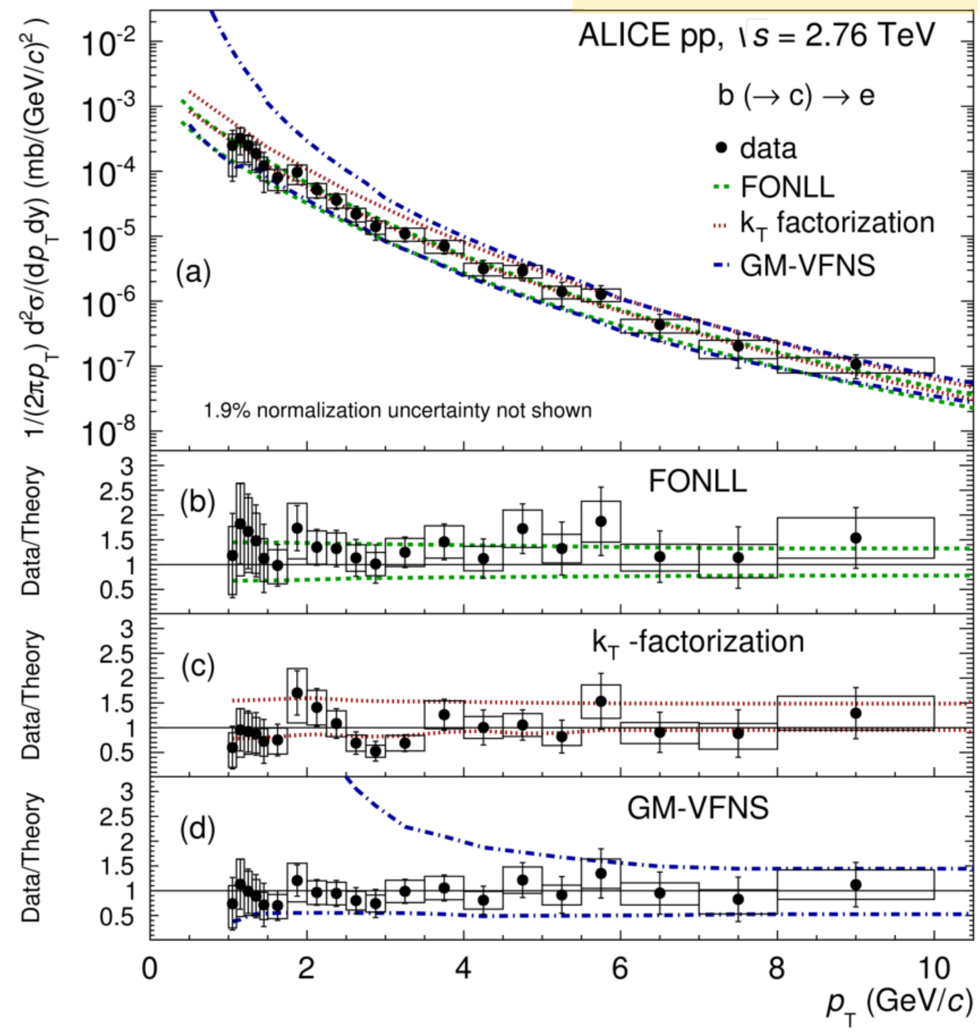
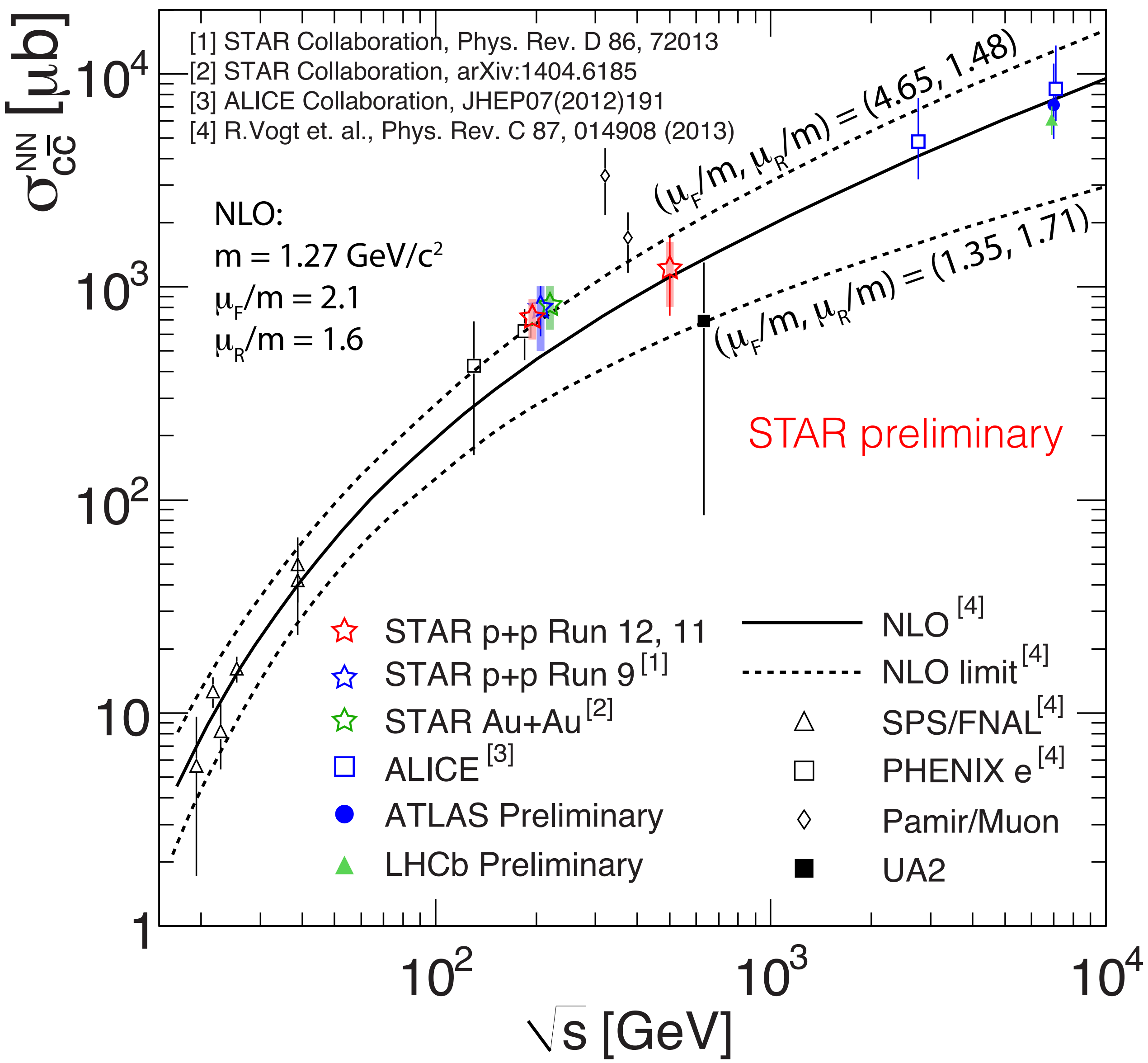


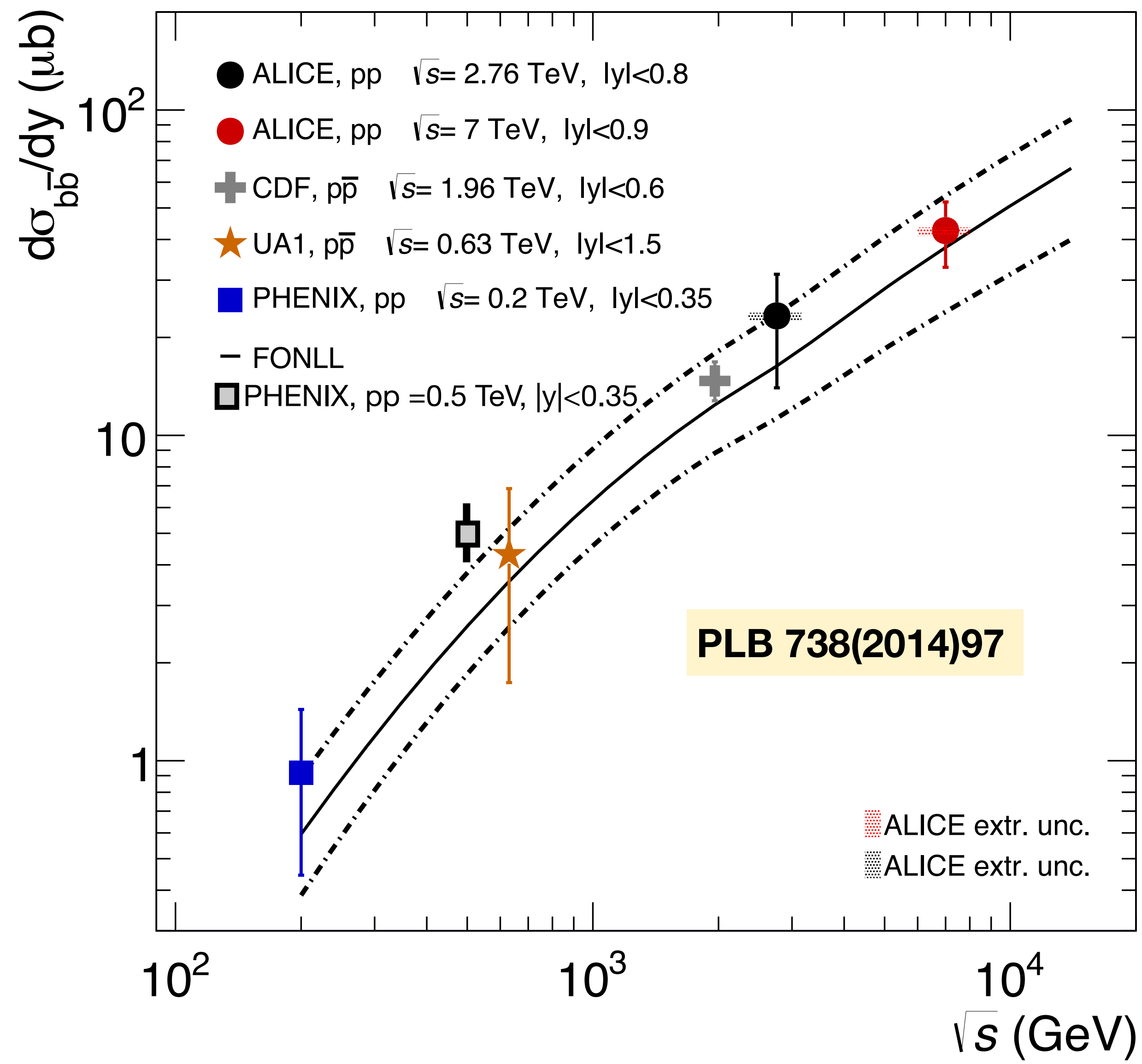
- Statistical separation of $e^{\pm}$ from charm and beauty decays using displaced secondary vertex and electron-hadron angular correlation
- Relative contributions of charm and beauty decays as well as beauty decay electron cross section reproduced by pQCD-based calculations (FONLL, GM-VFNS, k_T factorization), similar conclusion at $\sqrt{s}$ = 7 TeV

Phys. Lett. B 721 (2013) 13–23

FONLL: JHEP 1210 (2012) 137, GM-VFNS: Eur. Phys. J. C 72 (2012) 2082, k_T factorisation: arXiv:1301.3033

Heavy-flavour production cross sections

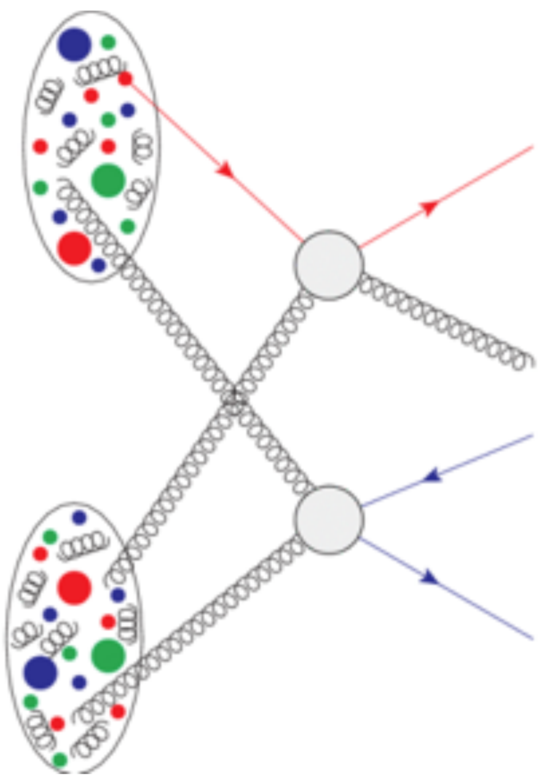




- Calculation based on pQCD (ex. FONLL) describes consistently energy dependence of total cross sections
- Charm (beauty) x~10 (~100) from RHIC (200 GeV) to LHC
- Precision measurement required for quarkonia reference!

More on production mechanism:
Multiplicity dependence of heavy-flavour production

ALICE



Particle production in pp collisions at the LHC shows **a better agreement with models including Multi-Parton Interactions (MPIs)**

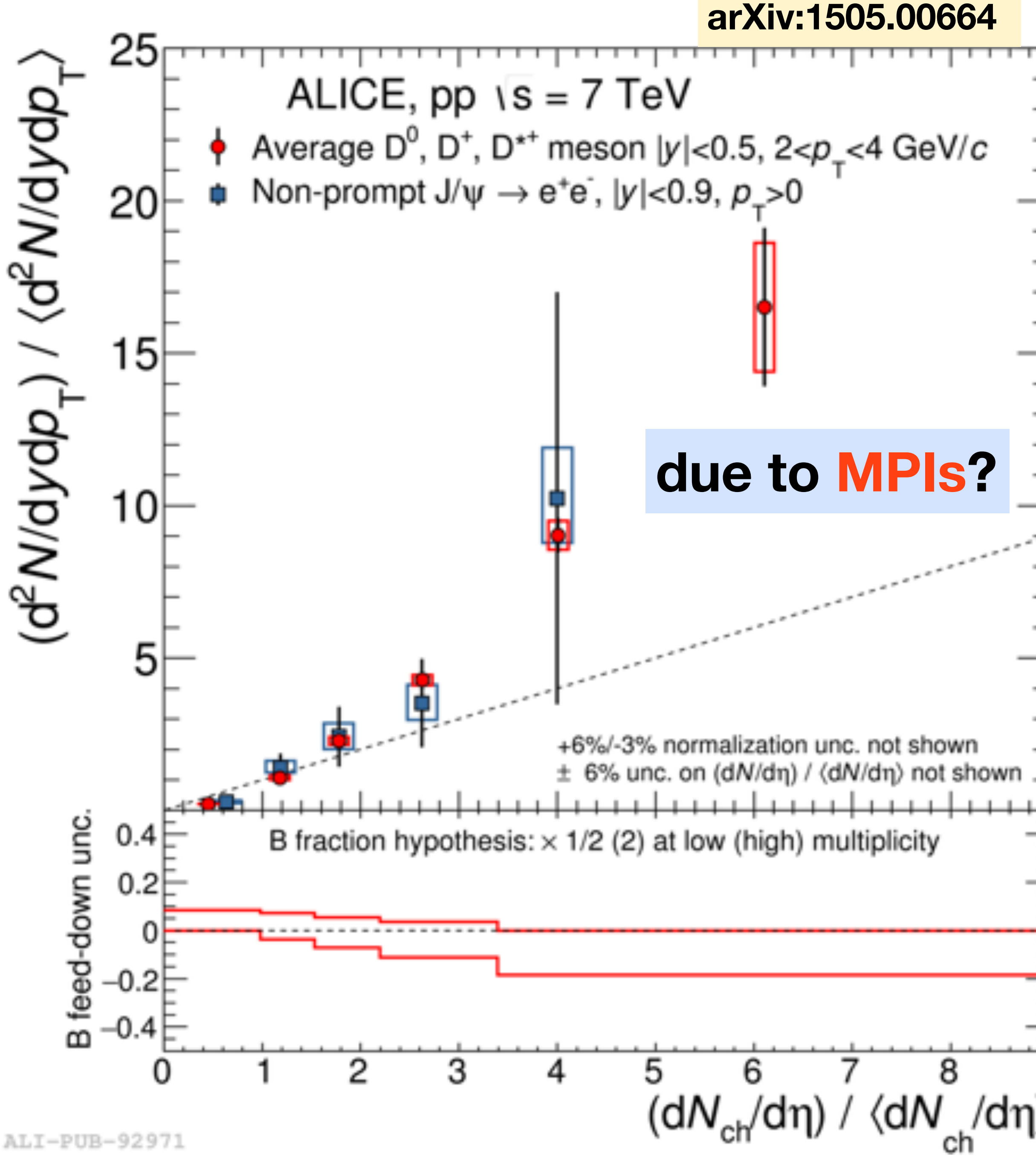
Eur. Phys. J. C 73 (2013) 2674

For heavy flavours:

- LHCb: double charm production agrees **better with models including double parton scattering**

J. High Energy Phys., 06 (2012) 141

arXiv:1505.00664

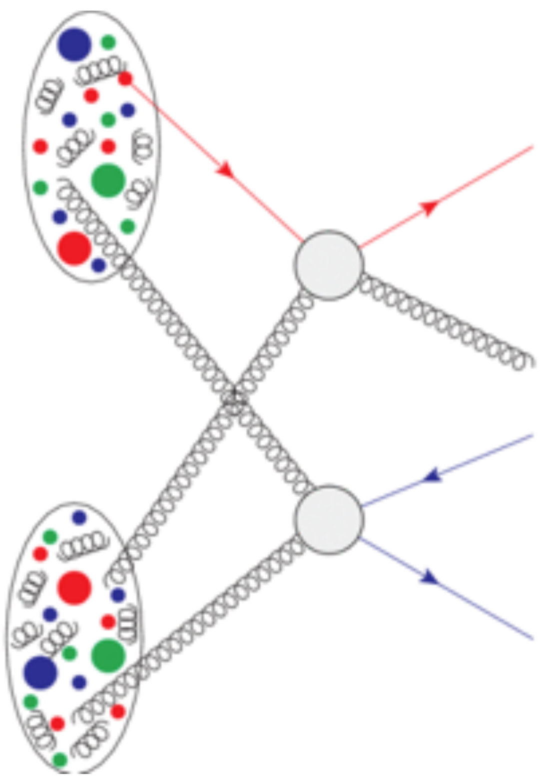


due to MPIs?

MPIs involving only light quarks and gluons, or for heavy-flavour production?

- D-meson, non-prompt J/ψ yields increase with charged-particle multiplicity
→ presence of MPIs and contribution on the harder scale?

More on production mechanism: Multiplicity dependence of heavy-flavour production



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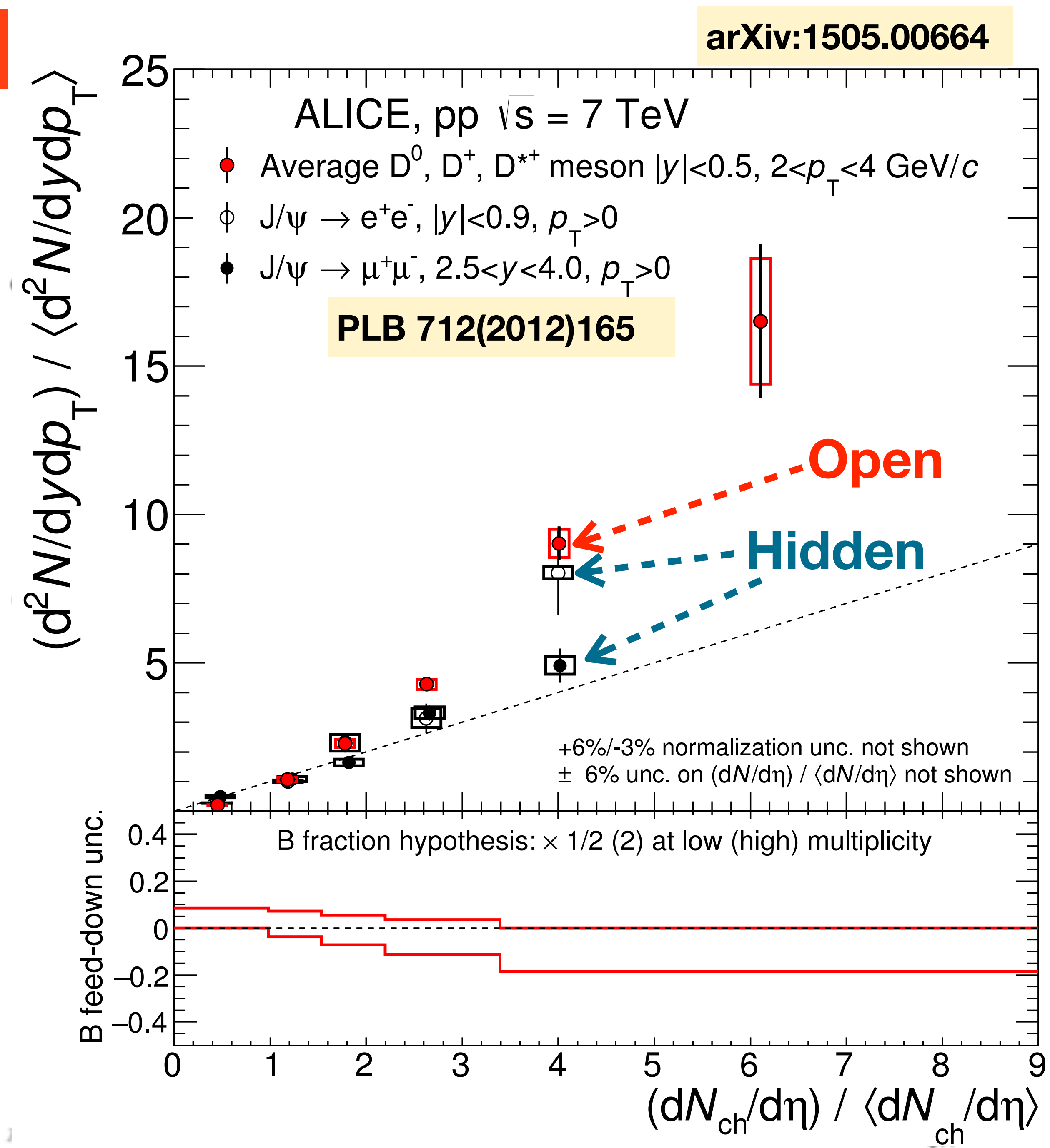
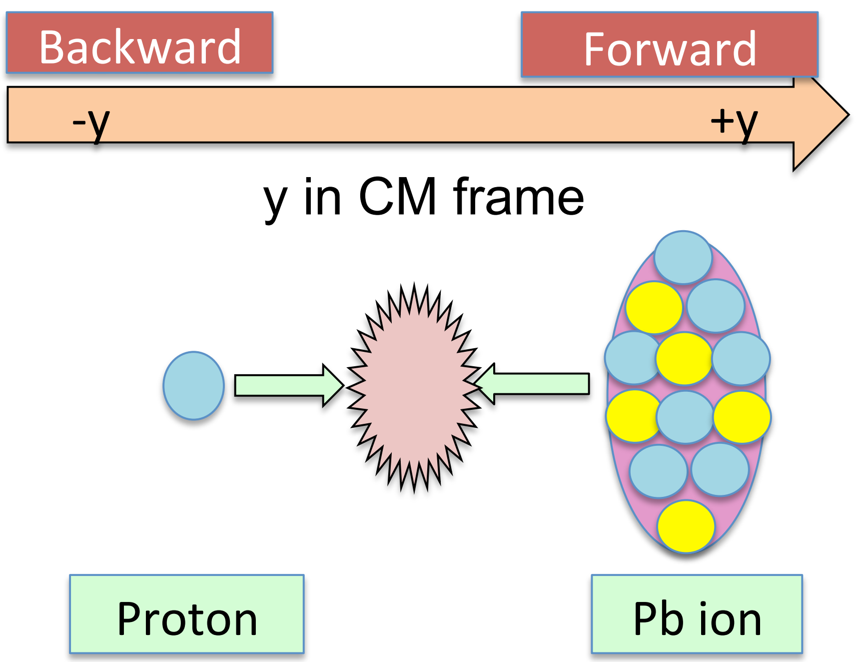


MPIs involving only light quarks and gluons, or for heavy-flavour production?

Same behavior for open and hidden charm production

→ this behaviour is most likely related to the $c\bar{c}$ and $b\bar{b}$ production processes, but not significantly influenced by hadronisation!

Heavy flavours
Results in p-Pb collisions



y_{CMS} = 0.465 in the p-beam direction

Cold nuclear matter effects

- Modification of the parton distribution functions inside nucleus
- k_T broadening via collisions inside the nucleus
- Energy loss in cold nuclear matter…

$$\frac{dN^D_{PbPb}}{dp_T} = PDF(x_1)PDF(x_2) \otimes \frac{d\hat{\sigma}^c}{dp_T} \otimes P(\Delta E) \otimes D_{c\to D}(z)$$

Nuclear modification factor

$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

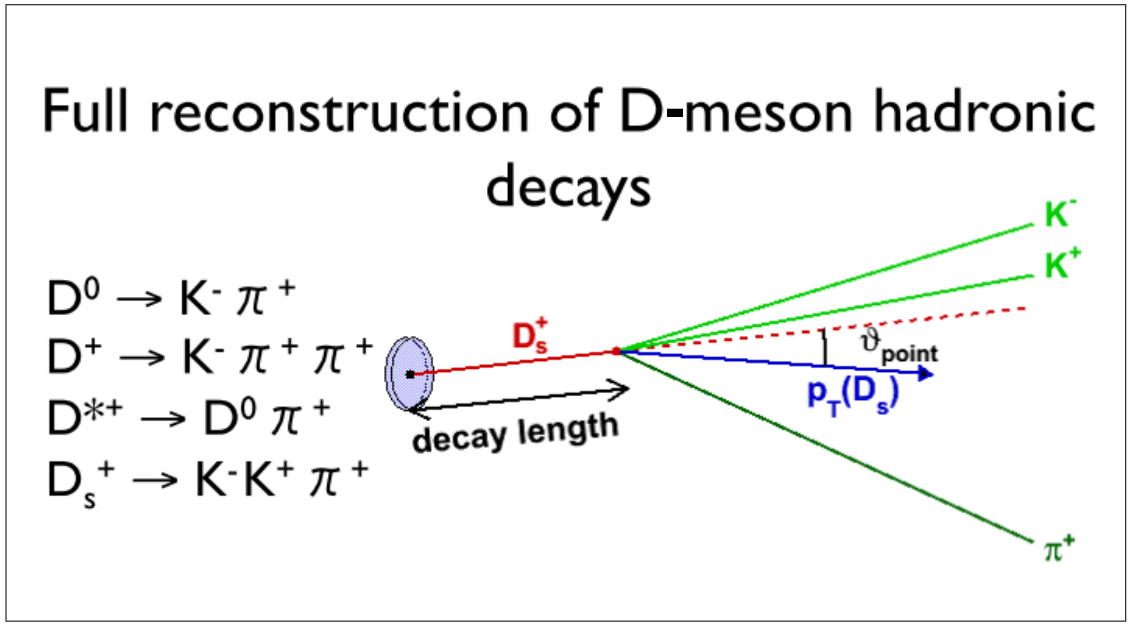
Binary scaling based on the Glauber Model

R_{AA} = 1: binary scaling
R_{AA} ≠ 1: medium effect

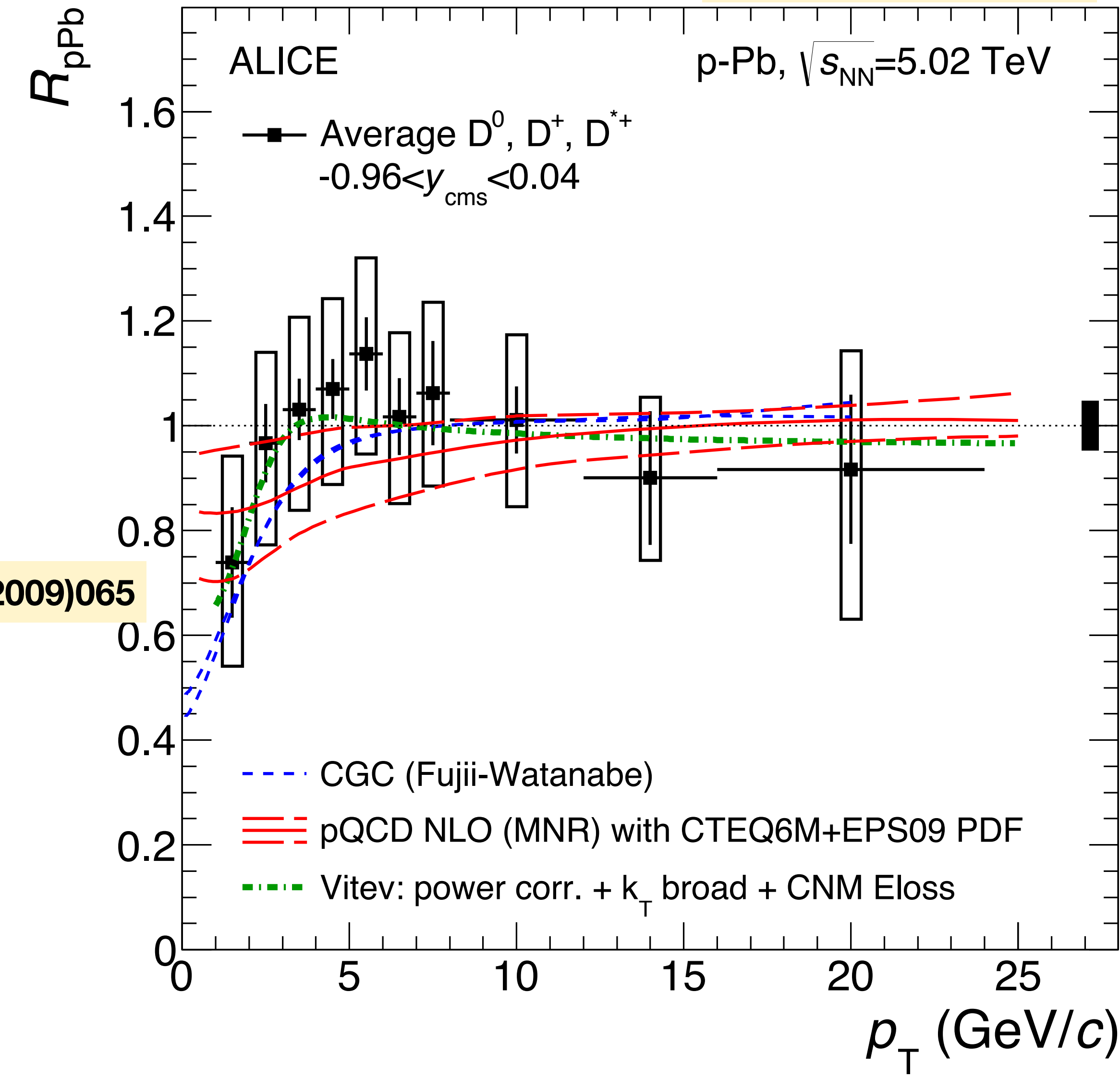
Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

- R_{pPb} measured in various channels
- R_{pPb} consistent with unity within uncertainties

ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, (arXiv:1308.1258) pQCD calculations with EPS09 nuclear PDF (JHEP 04(2009)065 and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening (PRC 75(2007)064906)



PRL 113(2014)232301



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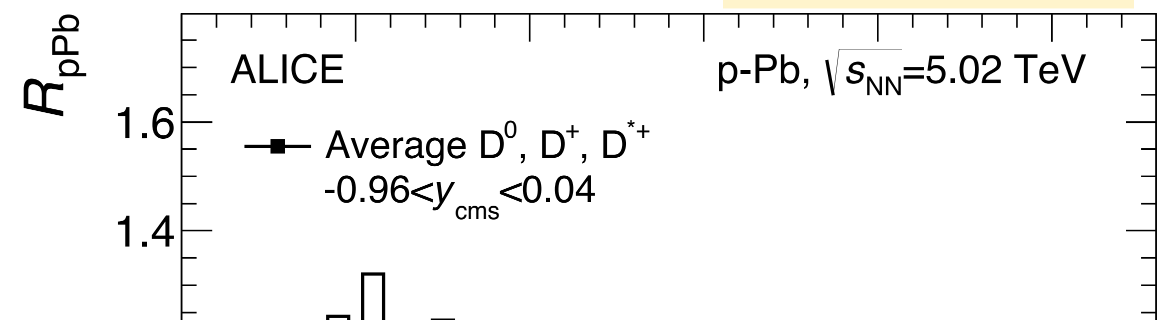
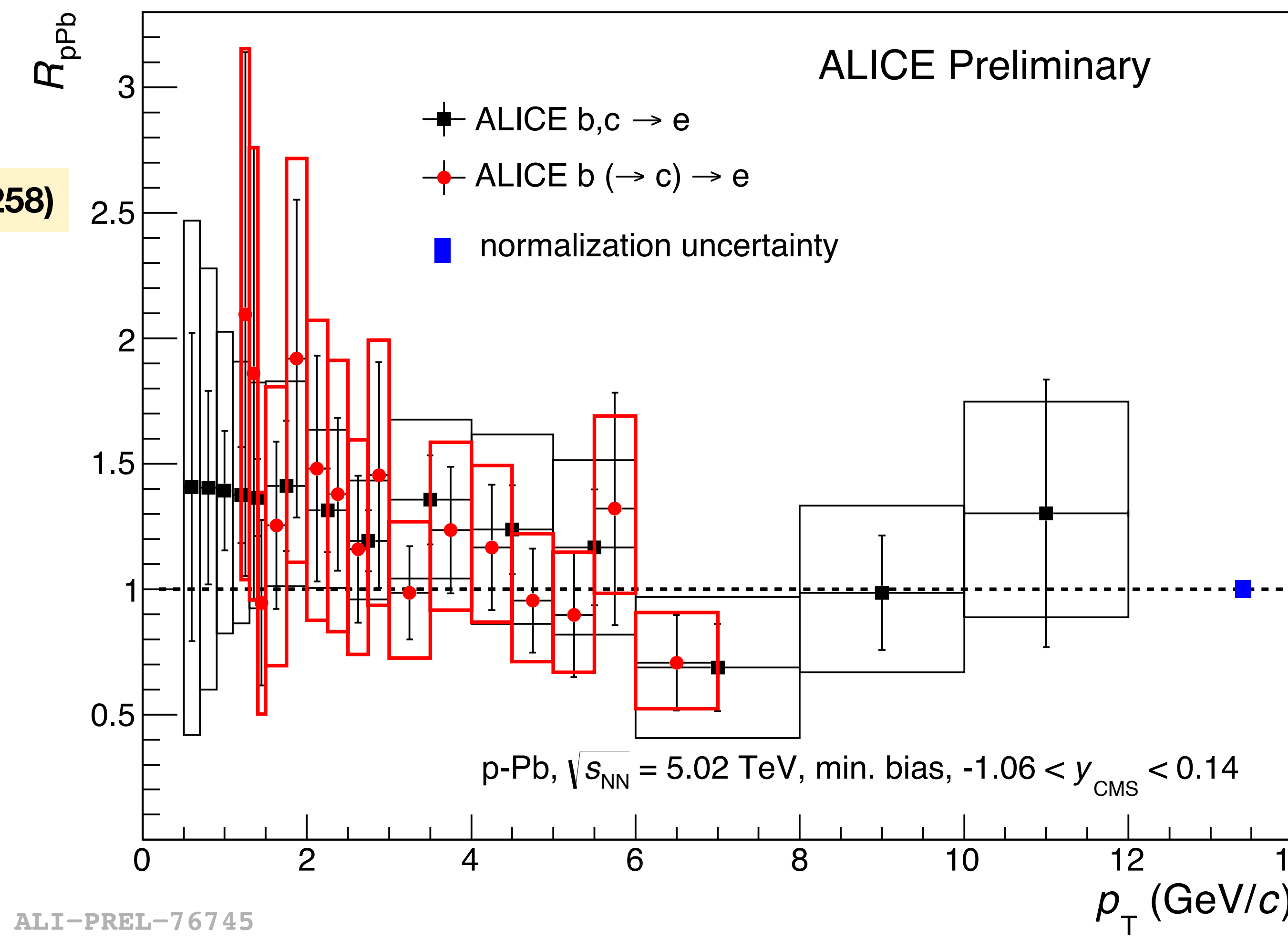
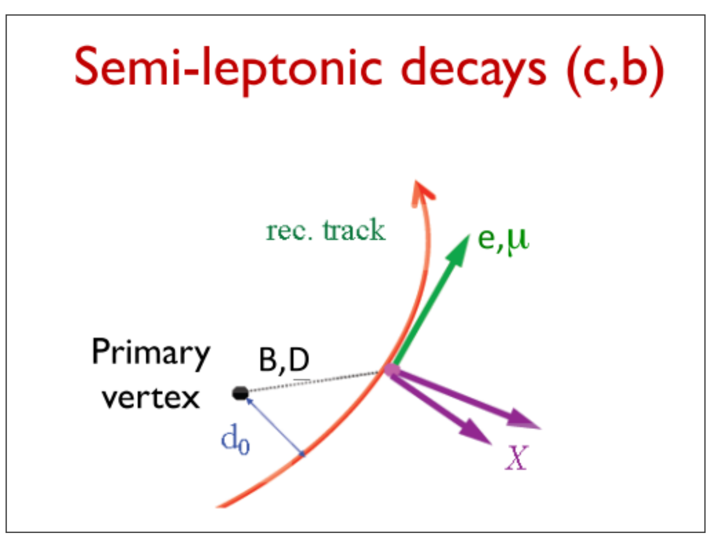
- ◉ c,b→e & b→e (mid rapidity)

PRL 113(2014)232301







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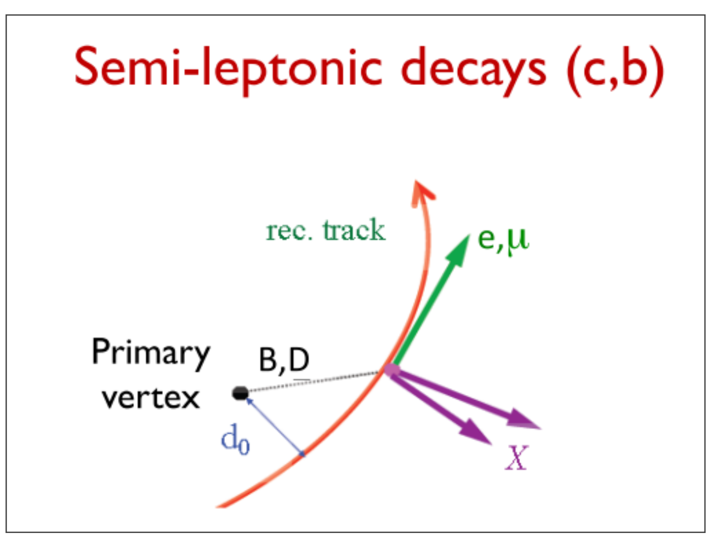
- ◉ c,b→e & b→e (mid rapidity)
- ◉ c,b→μ (forward, backward rapidity)



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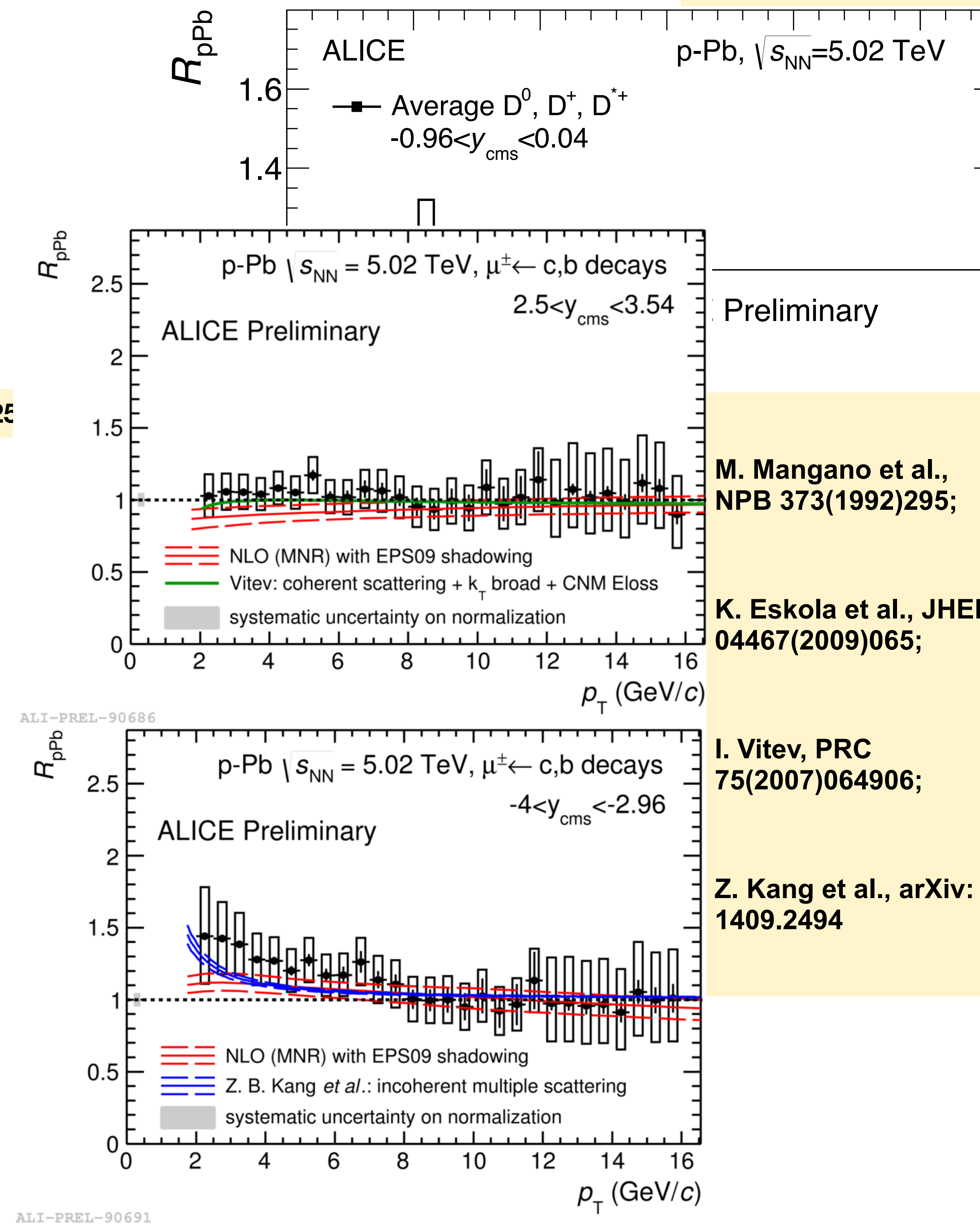


M. Mangano et al., NPB 373(1992)295;

K. Eskola et al., JHEP 04467(2009)065;

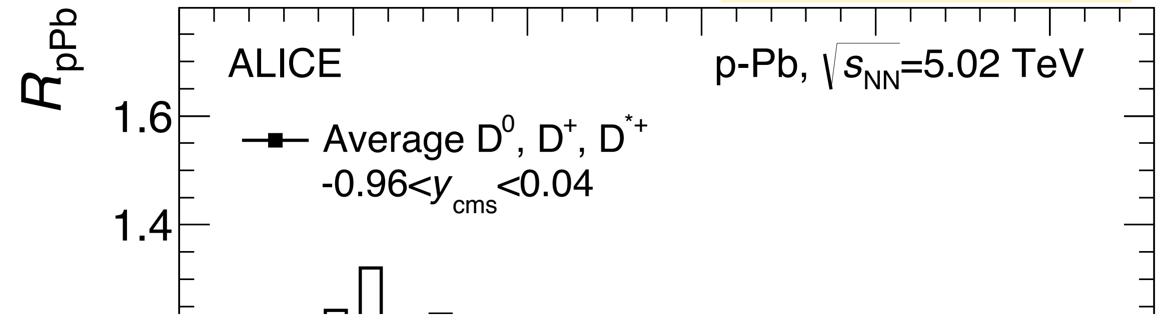
I. Vitev, PRC 75(2007)064906;

Z. Kang et al., arXiv: 1409.2494

Slightly larger than unity at backward rapidity for 2 < p_T < 4 GeV/c

Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

PRL 113(2014)232301



- R_{pPb} measured in various channels
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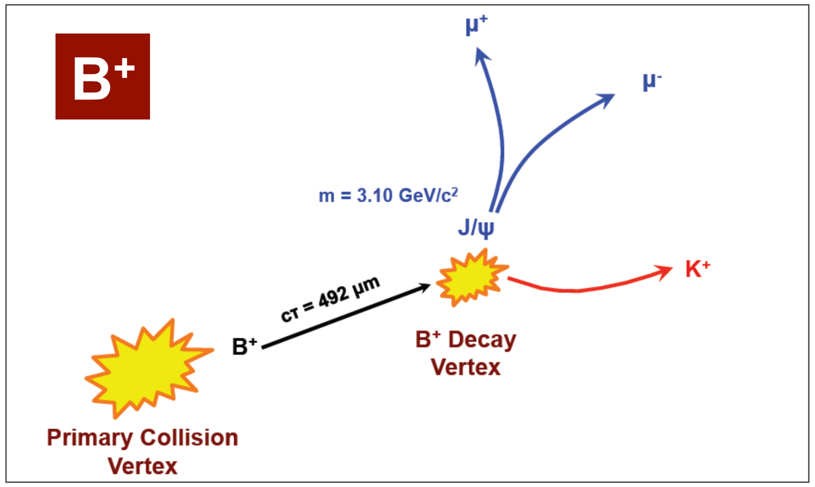
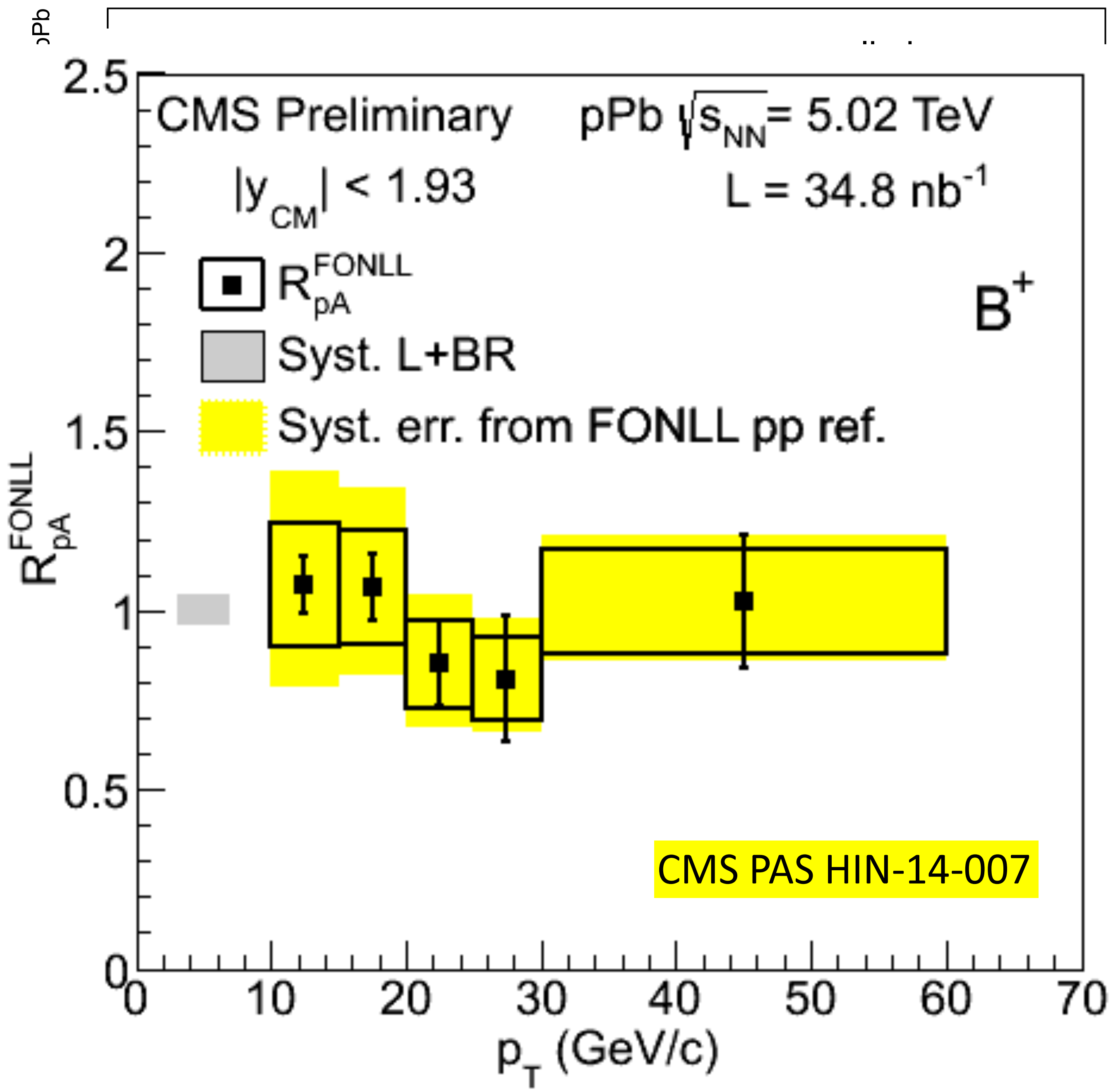
ALICE
- D^0, D^+, D^{*+} mesons (mid rapidity): can be described by CGC calculations, (arXiv:1308.12 pQCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening (PRC 75(2007)064906)
- c,b→e & b→e (mid rapidity)
- c,b→μ (forward, backward rapidity)

CMS
- B^+, B^0, B_s (mid rapidity): FONLL expectation as a pp reference





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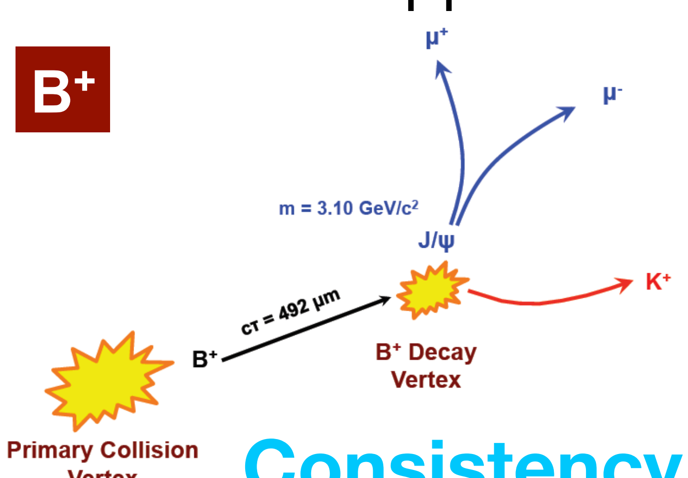

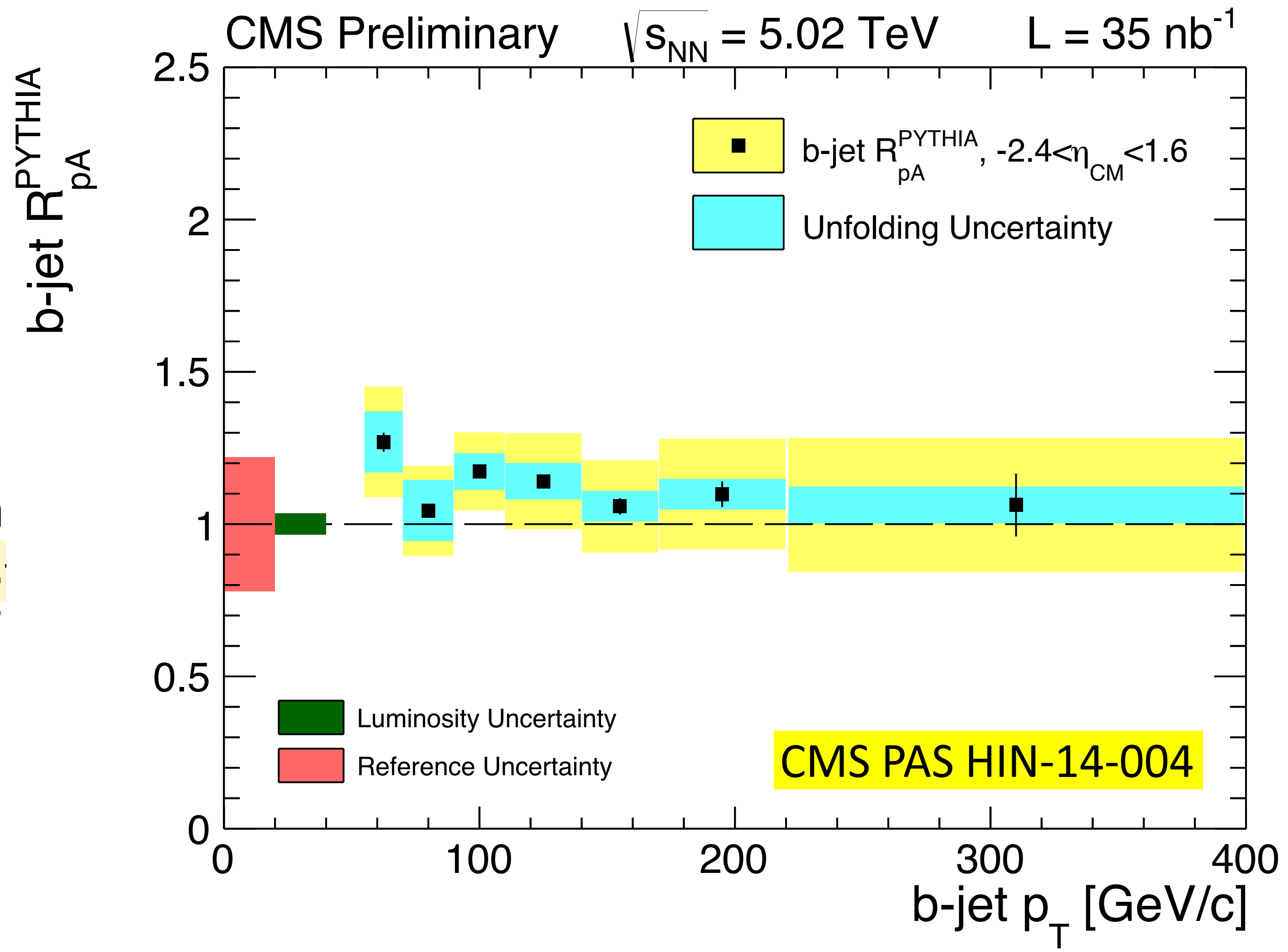

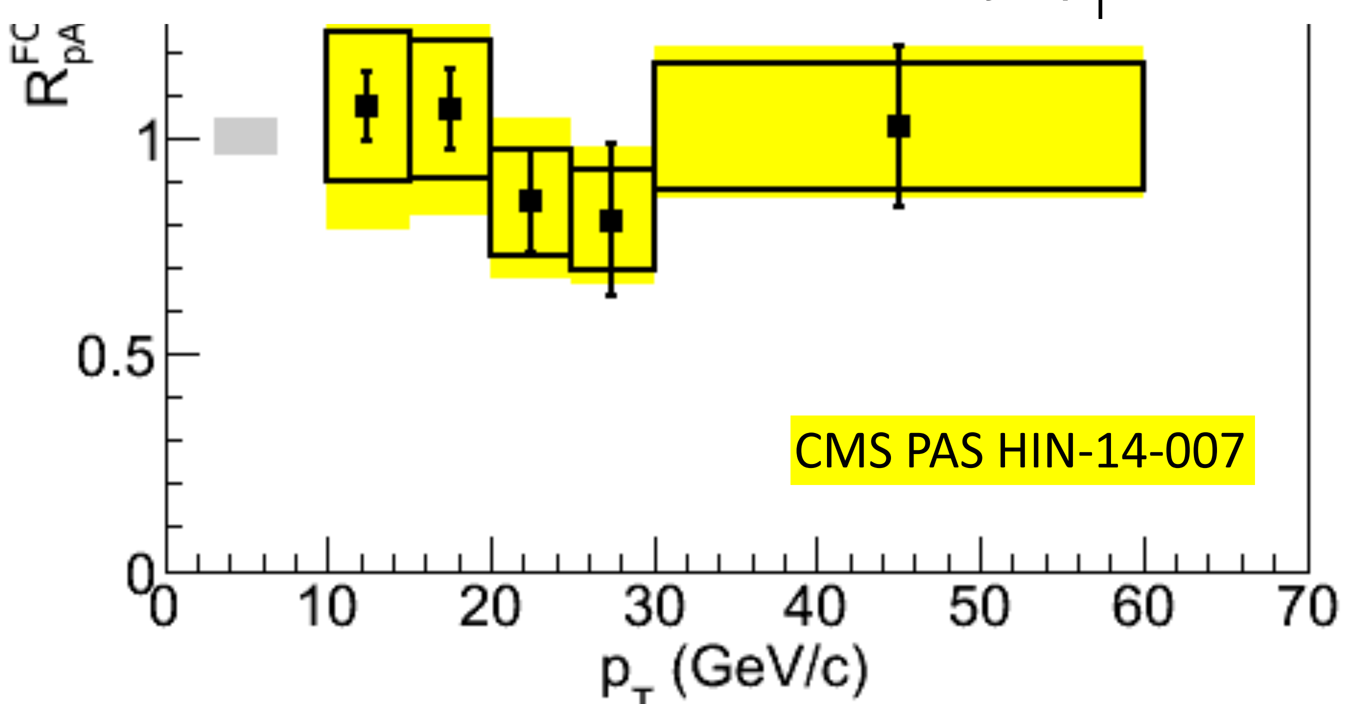

Consistency with b-jet measurement

Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

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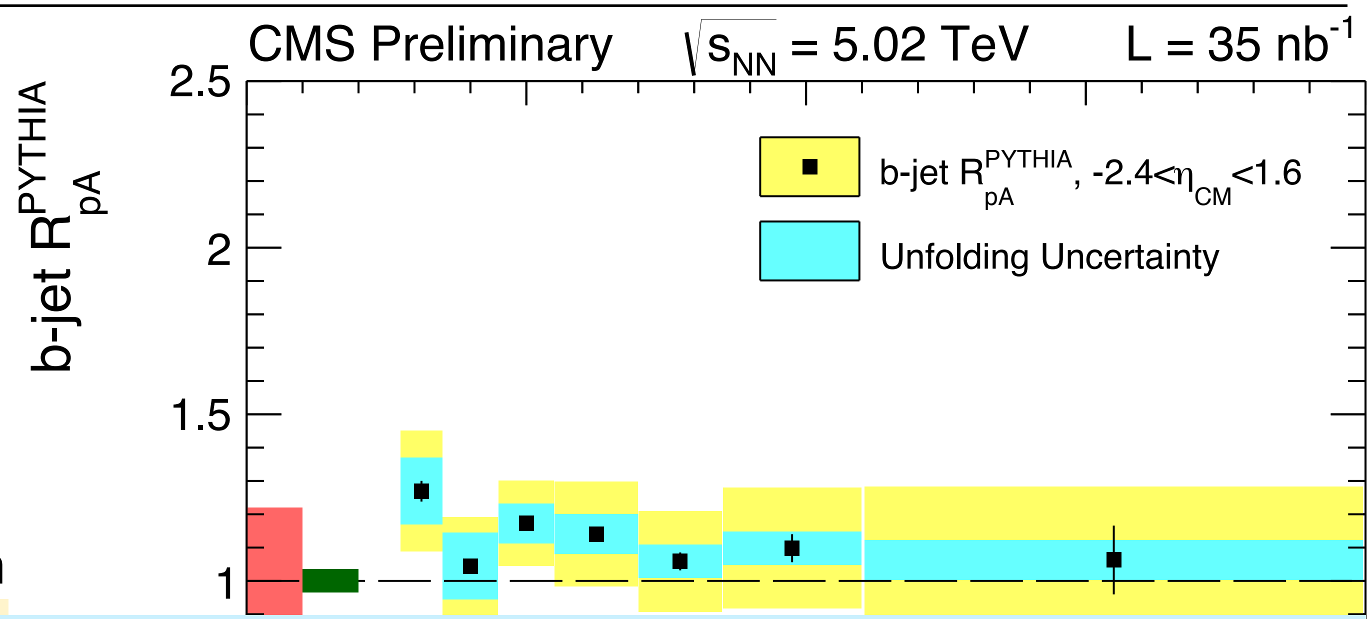
ALICE ◉ D^0, D^+, D^{*+} mesons (mid rapidity): can

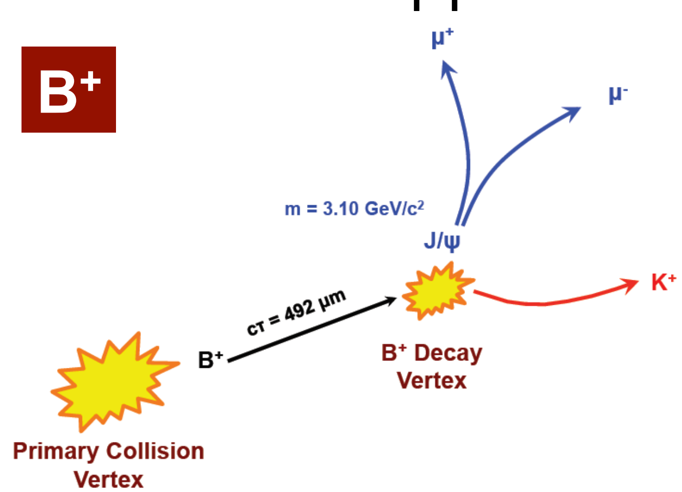


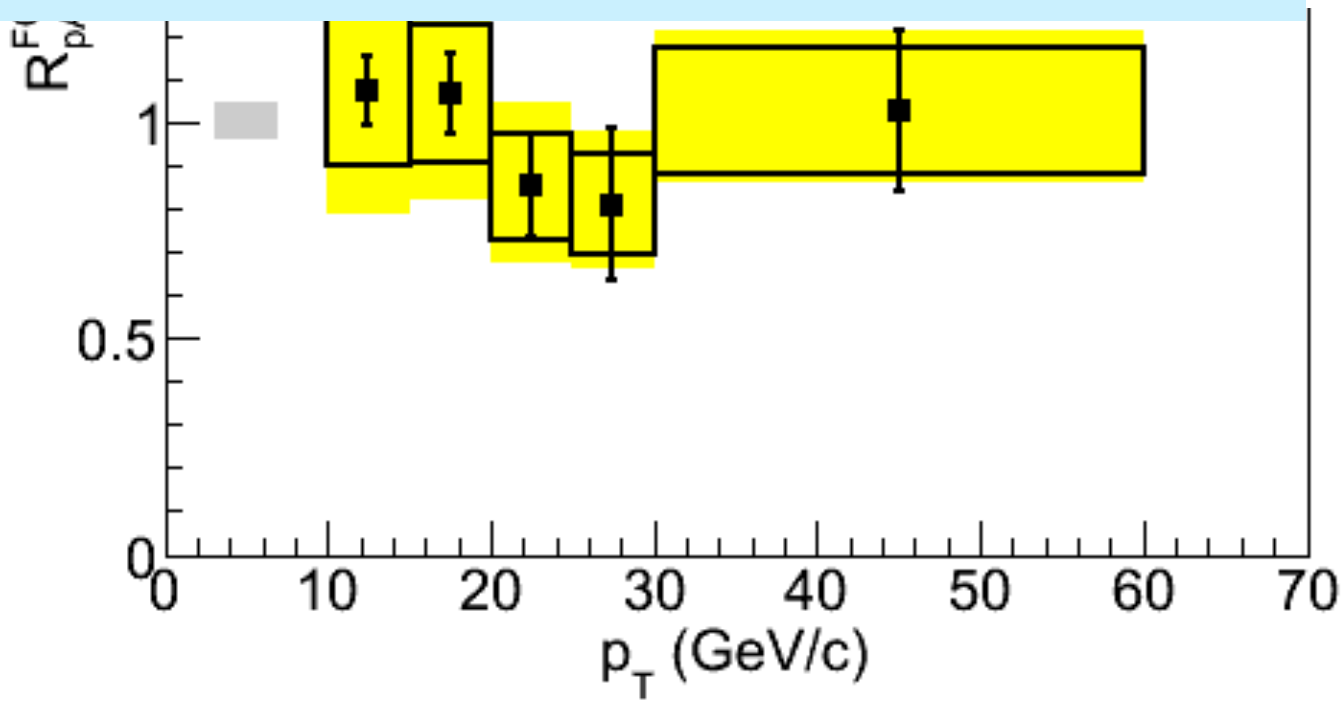
Described by pQCD models including cold nuclear matter effects

Cold nuclear matter effects are small at high p_T!

◉ c,b→e & b→e (forward, backward rapi

CMS ◉ B^+, B^0, B_s (mid rapidity): FONLL expectation as a pp reference





Heavy flavours

Results in Pb-Pb collisions

Peripheral from 100% — Centrality → Central to 0%

Dense/hot partonic medium effect

Nuclear modification factor

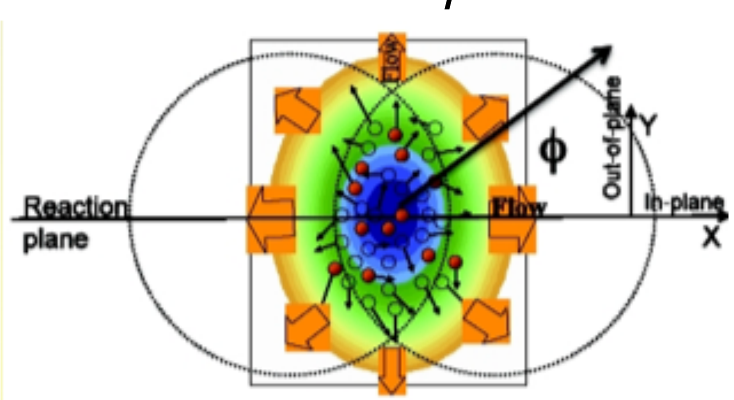
$$R_{AA} = \frac{dN_{AA}/dp_T}{\langle N_{coll}\rangle \times dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{\langle T_{AA}\rangle \times d\sigma_{pp}/dp_T}$$

Binary scaling based on the Glauber Model

- $R_{AA} = 1$: binary scaling
- $R_{AA} \neq 1$: medium effect

Anisotropic flow: v_2

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

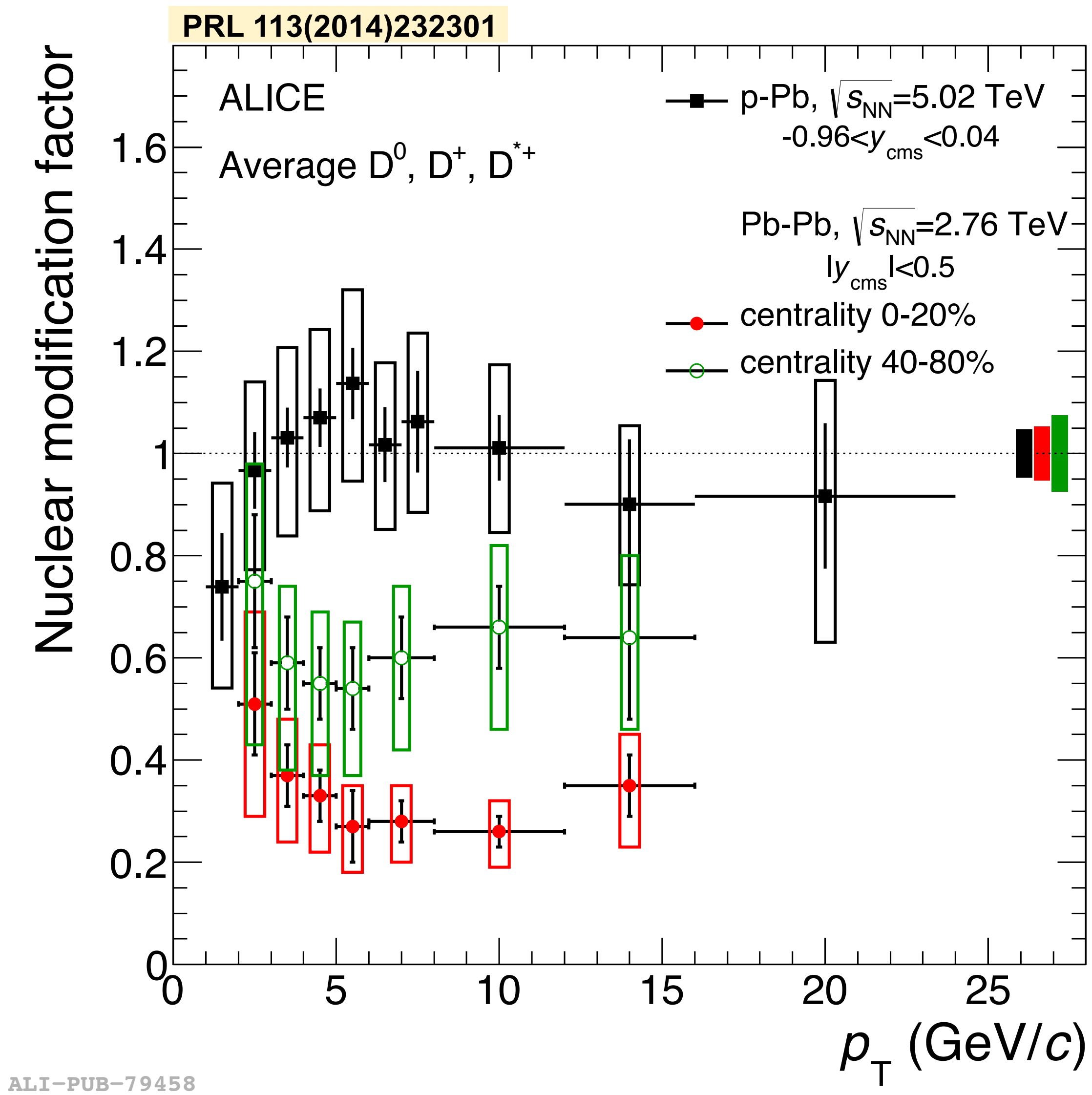


Initial spatial anisotropy $\xrightarrow{\text{via re-scatterings}}$ momentum anisotropy of particle emission

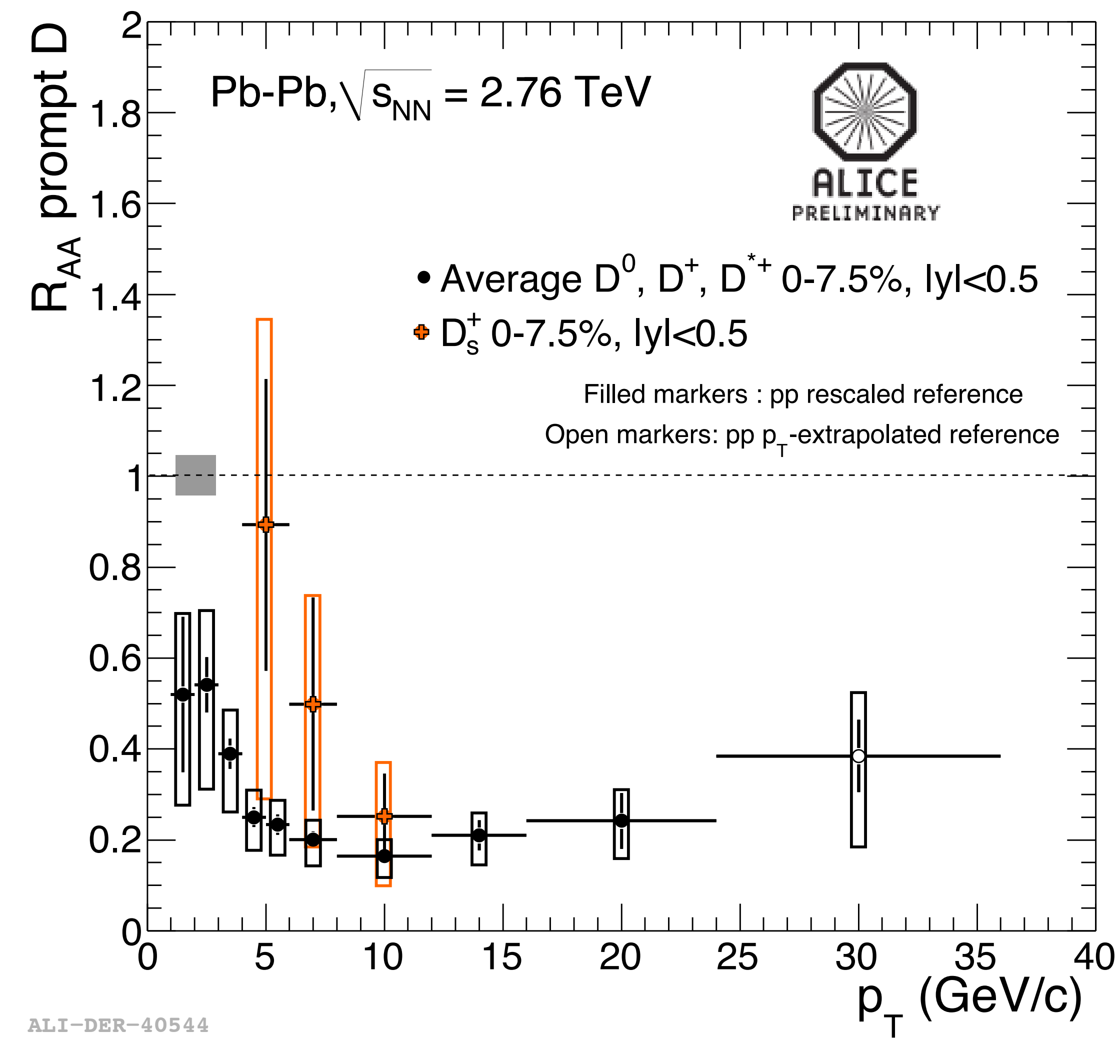
The anisotropy is quantified via a Fourier expansion in azimuthal angle (φ) with respect to the reaction plane (Ψ_{RP})

D-meson R_{AA} in p-Pb and Pb-Pb

Talk by Paola PAGANO on Wednesday!



ALICE



- p-Pb results indicate that the suppression observed in Pb-Pb comes from strong interaction of charm quarks with the medium

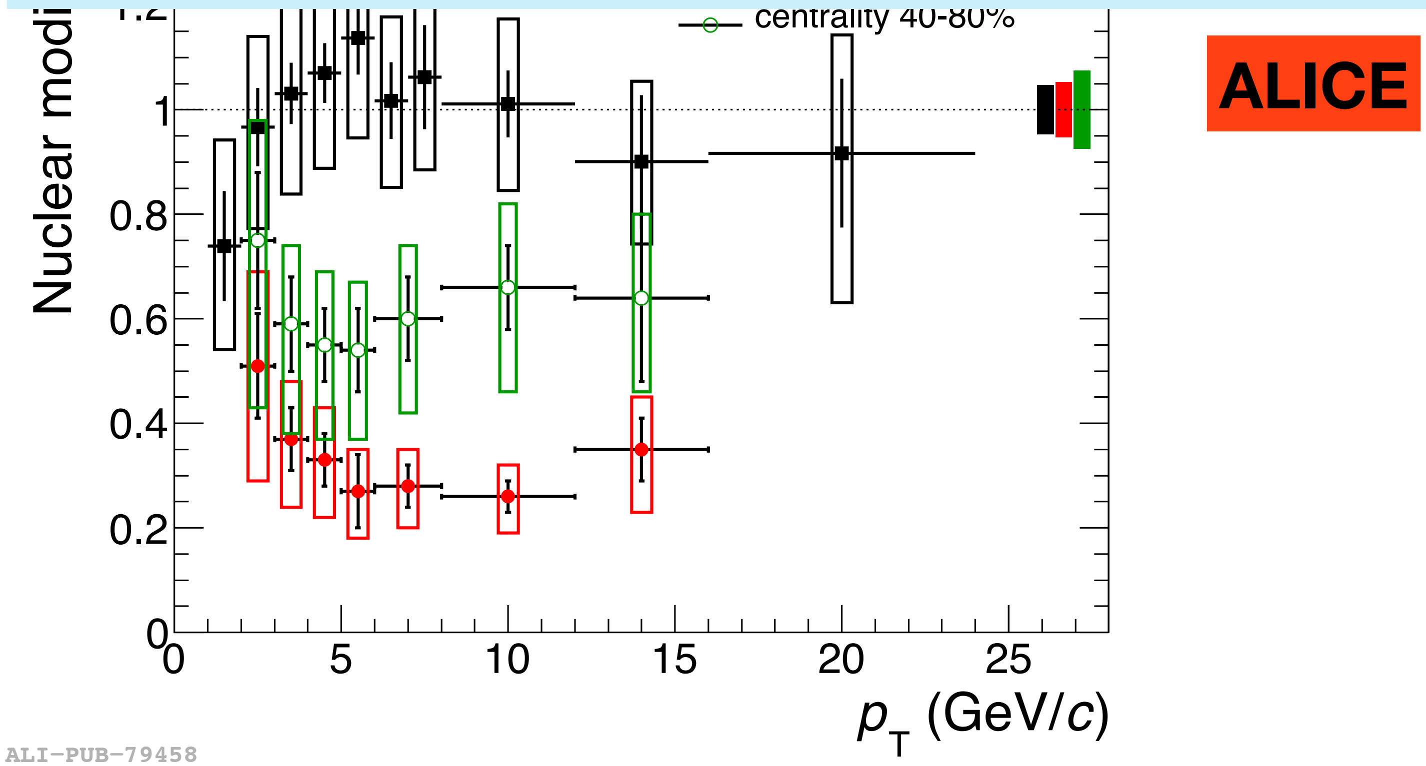
- D_s^+ suppressed by a factor ~3 for $8 < p_T < 12$ GeV/c
  - more statistics needed at low p_T where an enhancement of D_s^+/D due to coalescence is predicted:

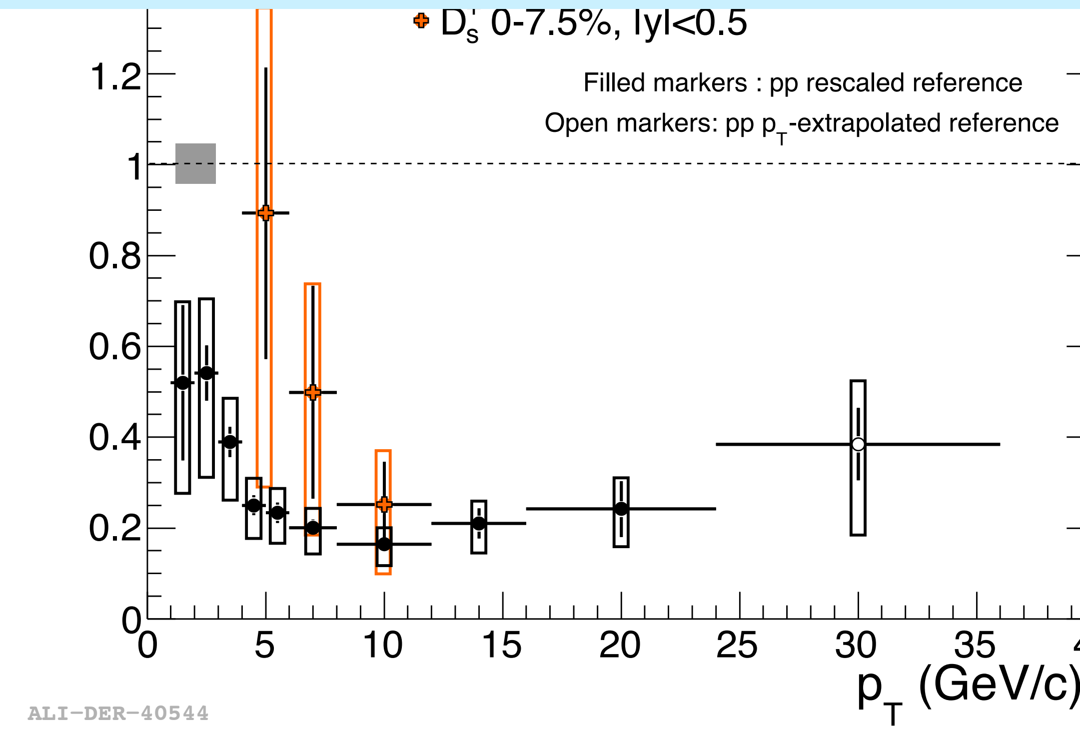
Kuznetsova, Rafelski EPJ C 51 (2007) 113
He et al. PRL 110 (2013) 112301
Andronic et al. PLB 659 (2008) 149

D-meson R_{AA} in p-Pb and Pb-Pb

Cold nuclear matter effects are small (R_{pPb} ~ 1)

Suppression due to dense/hot partonic medium effect!





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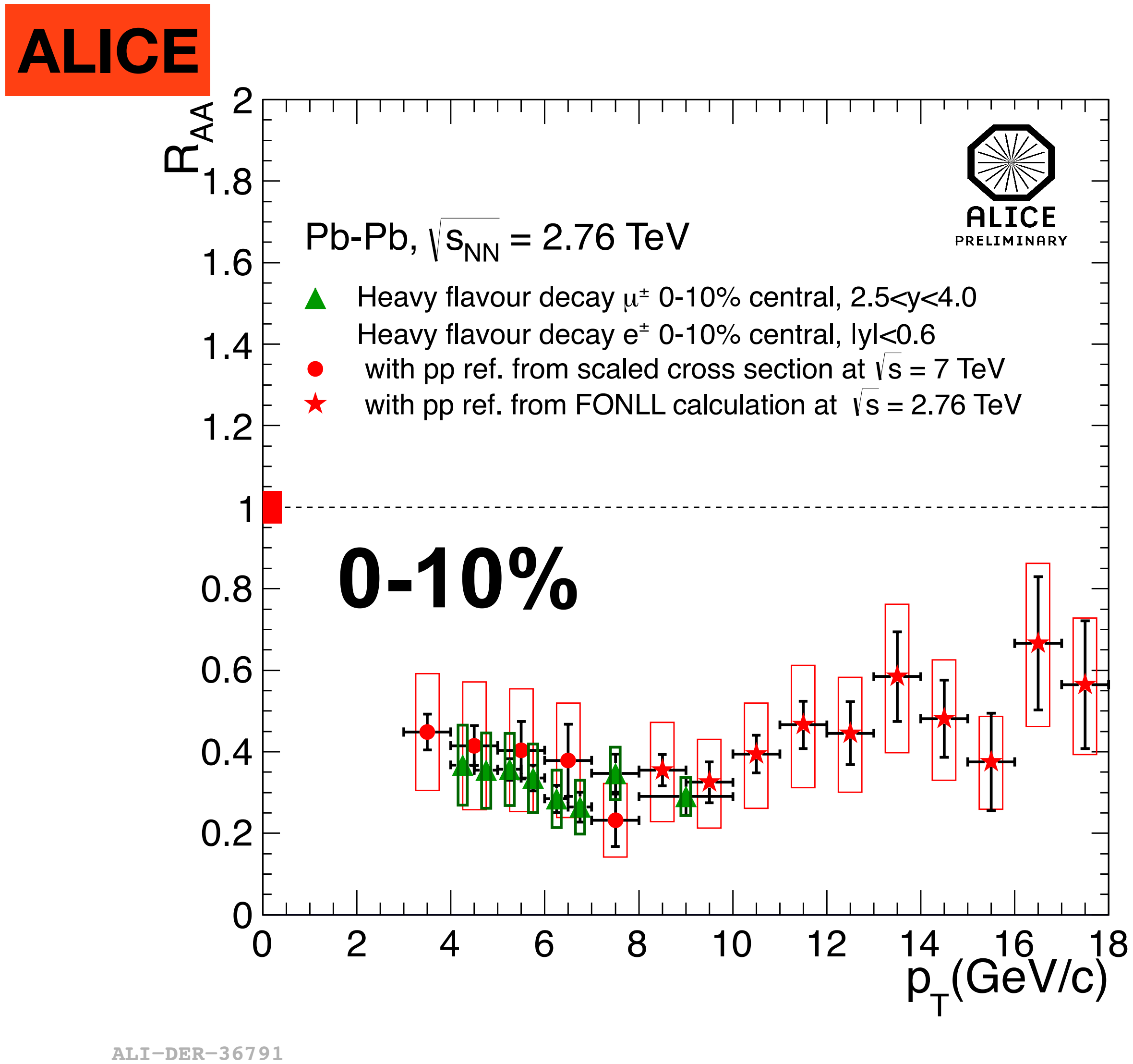
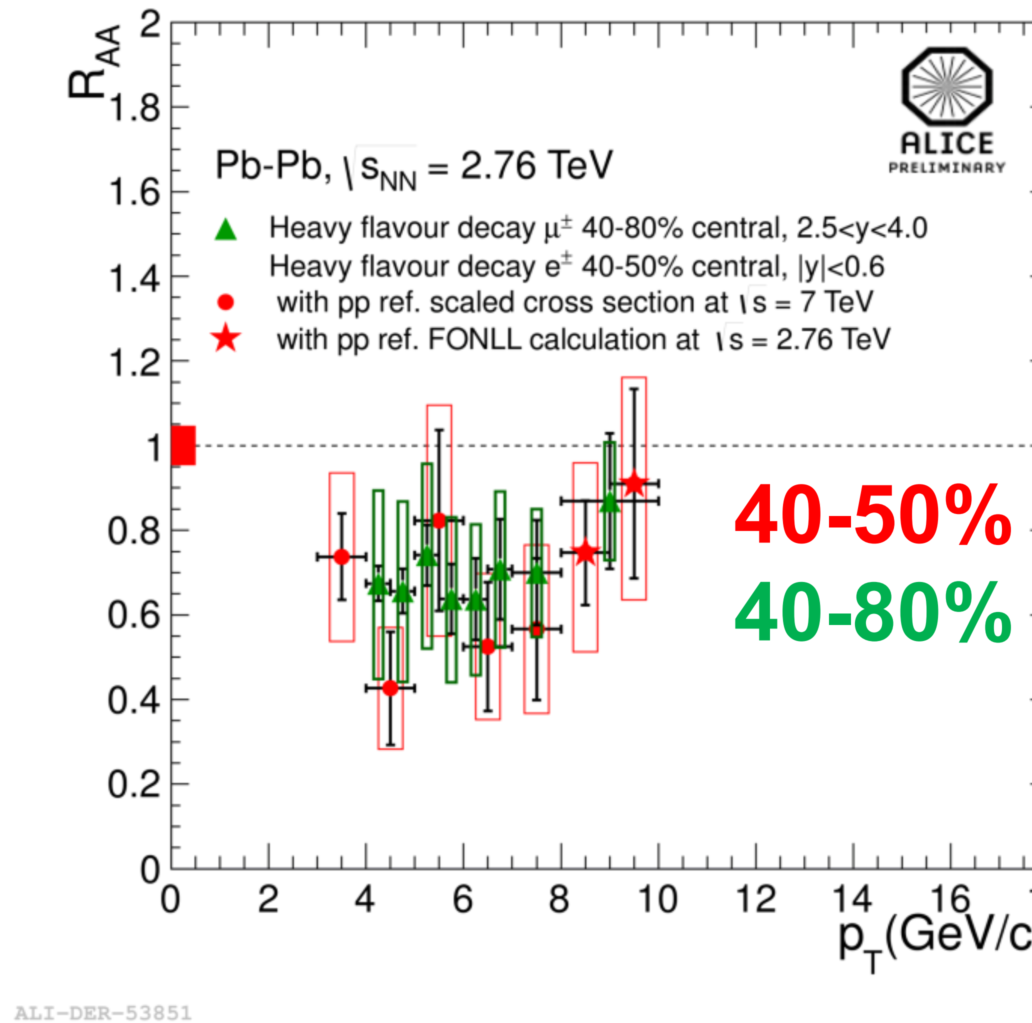
Heavy-flavour decay lepton R_{AA}

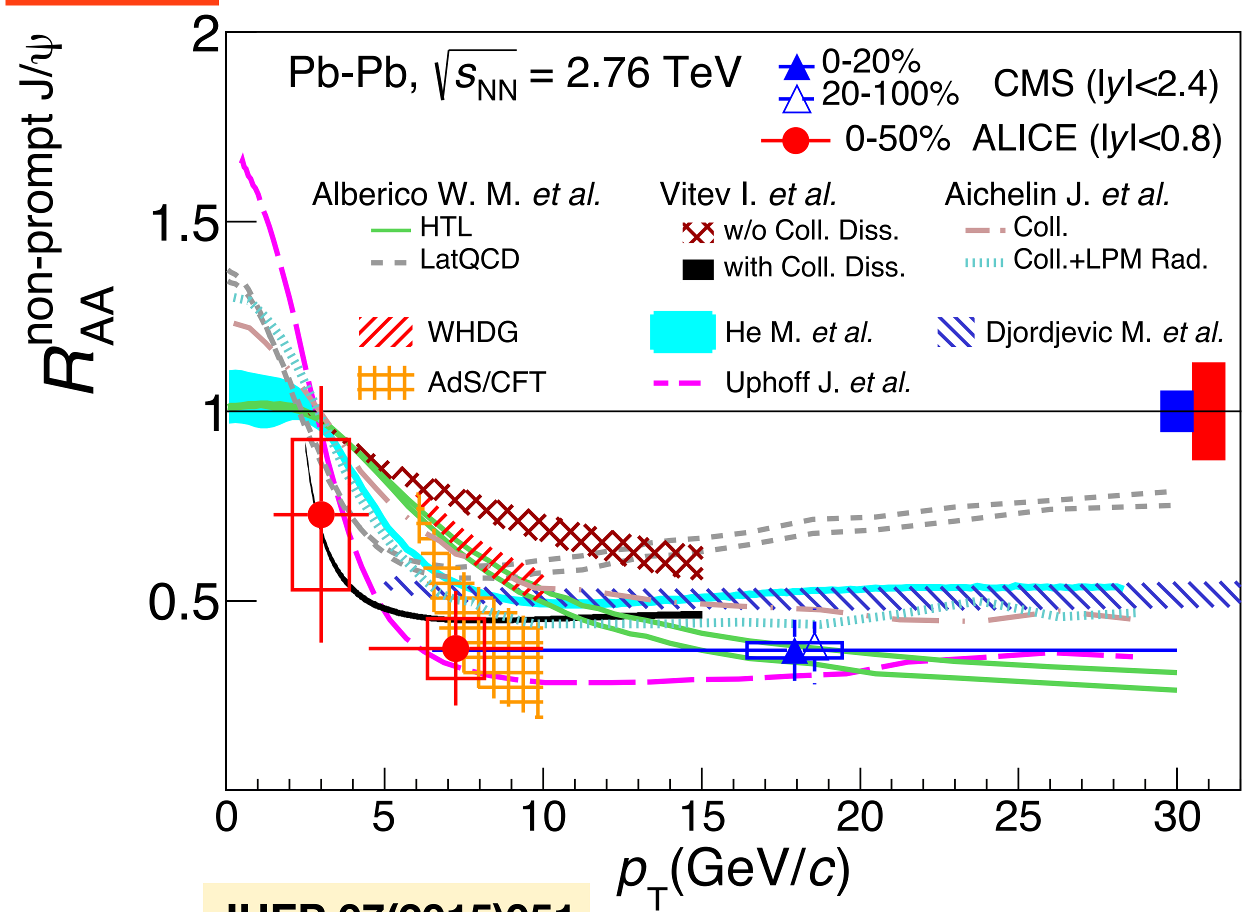




- Significant suppression at high p_T in central Pb-Pb collisions w.r.t. binary scaled pp collisions
  - HF decay electrons (|y| < 0.6) and muons (2.5 < y < 4) R_{AA} are similar
  - Less suppression in more peripheral collisions

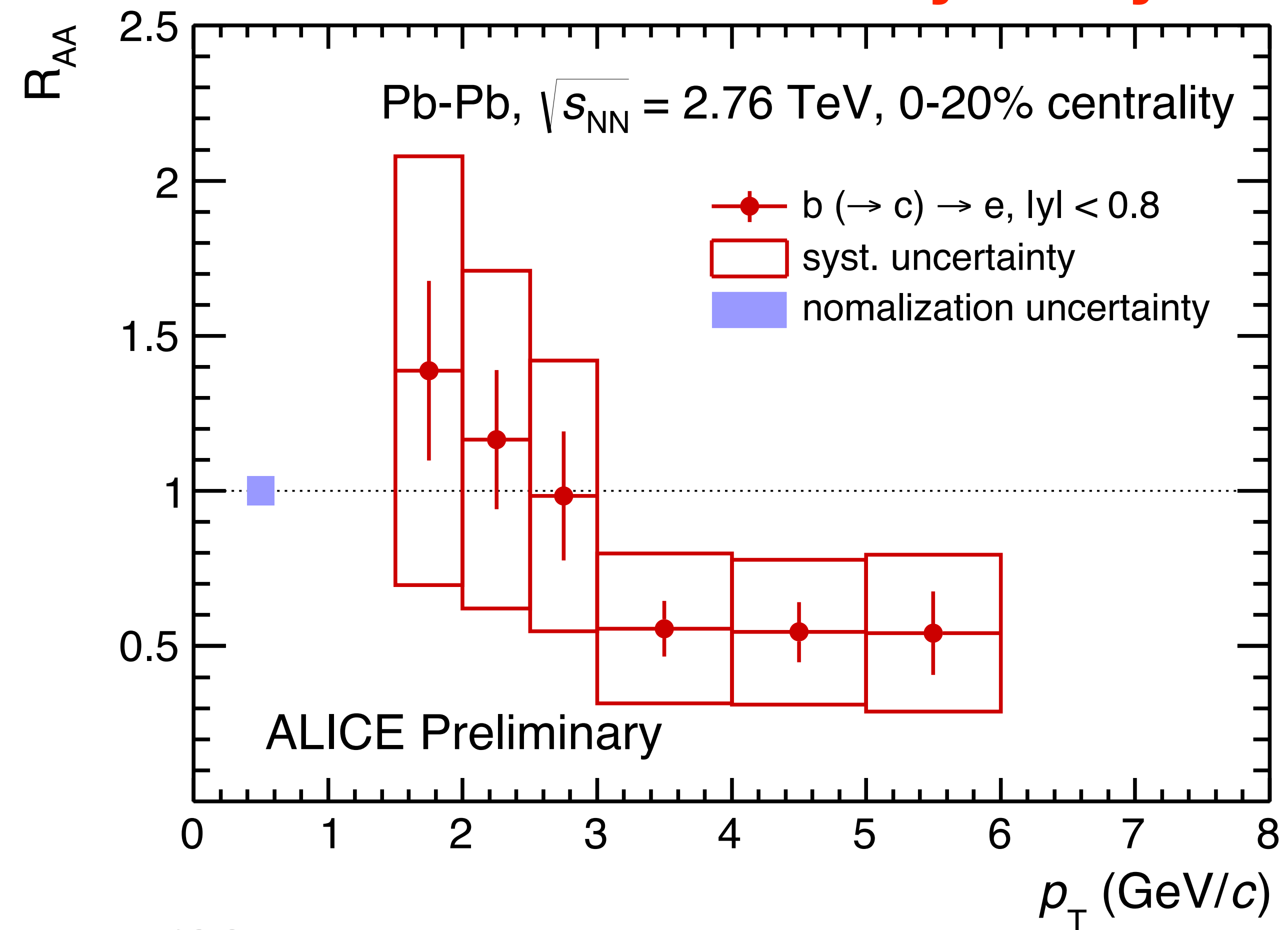
Heavy-flavour decay lepton R_{AA}

ALICE **0-50% non-prompt J/ψ R_{AA}**



JHEP 07(2015)051

0-20% electrons from beauty decays R_{AA}



ALI-PREL-74678

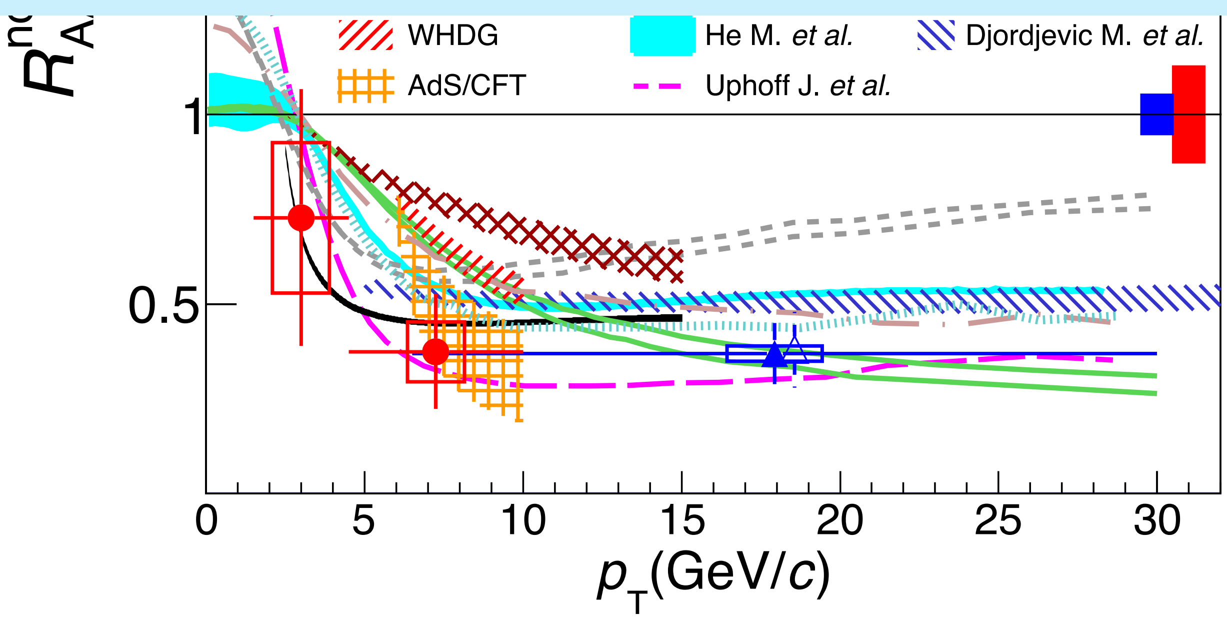
- Significant suppression at high p_T in central Pb-Pb collisions w.r.t. binary scaled pp collisions
  - HF decay electrons (|y| < 0.6) and muons (2.5 < y < 4) R_{AA} are similar
  - Less suppression in more peripheral collisions
  - R_{AA} of non-prompt J/ψ , electrons from beauty decays shows

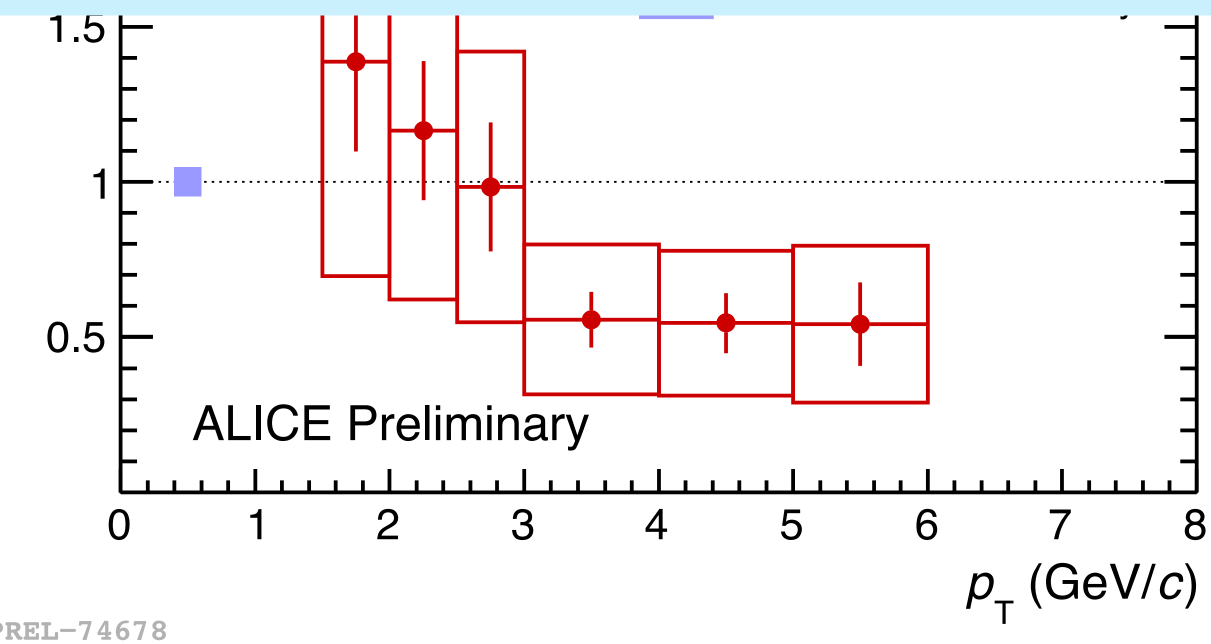
hint of suppression

Heavy-flavour decay lepton R_{AA}

Cold nuclear matter effects are small (R_{pPb} ~ 1)

Suppression due to dense/hot partonic medium effect!





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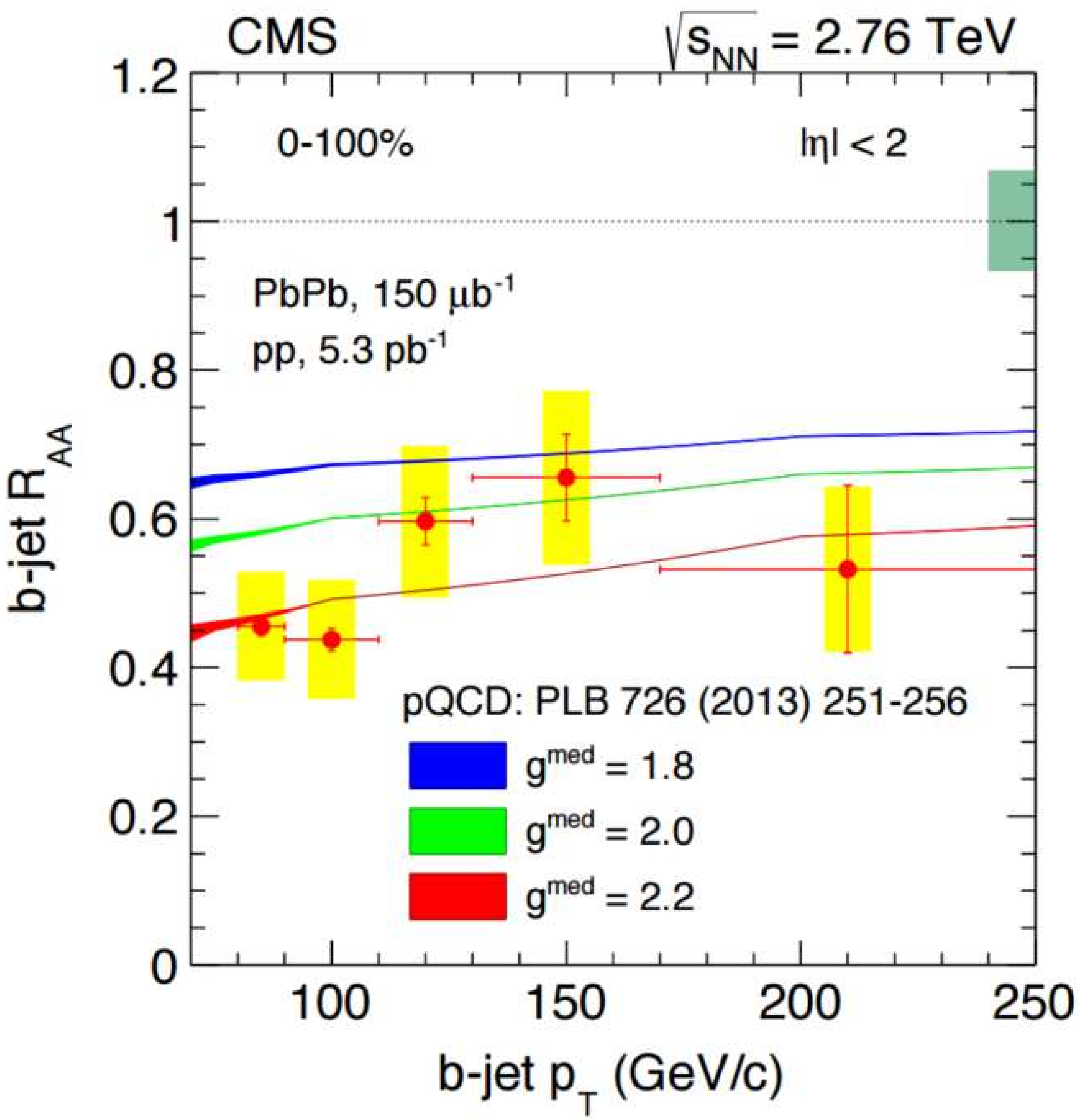
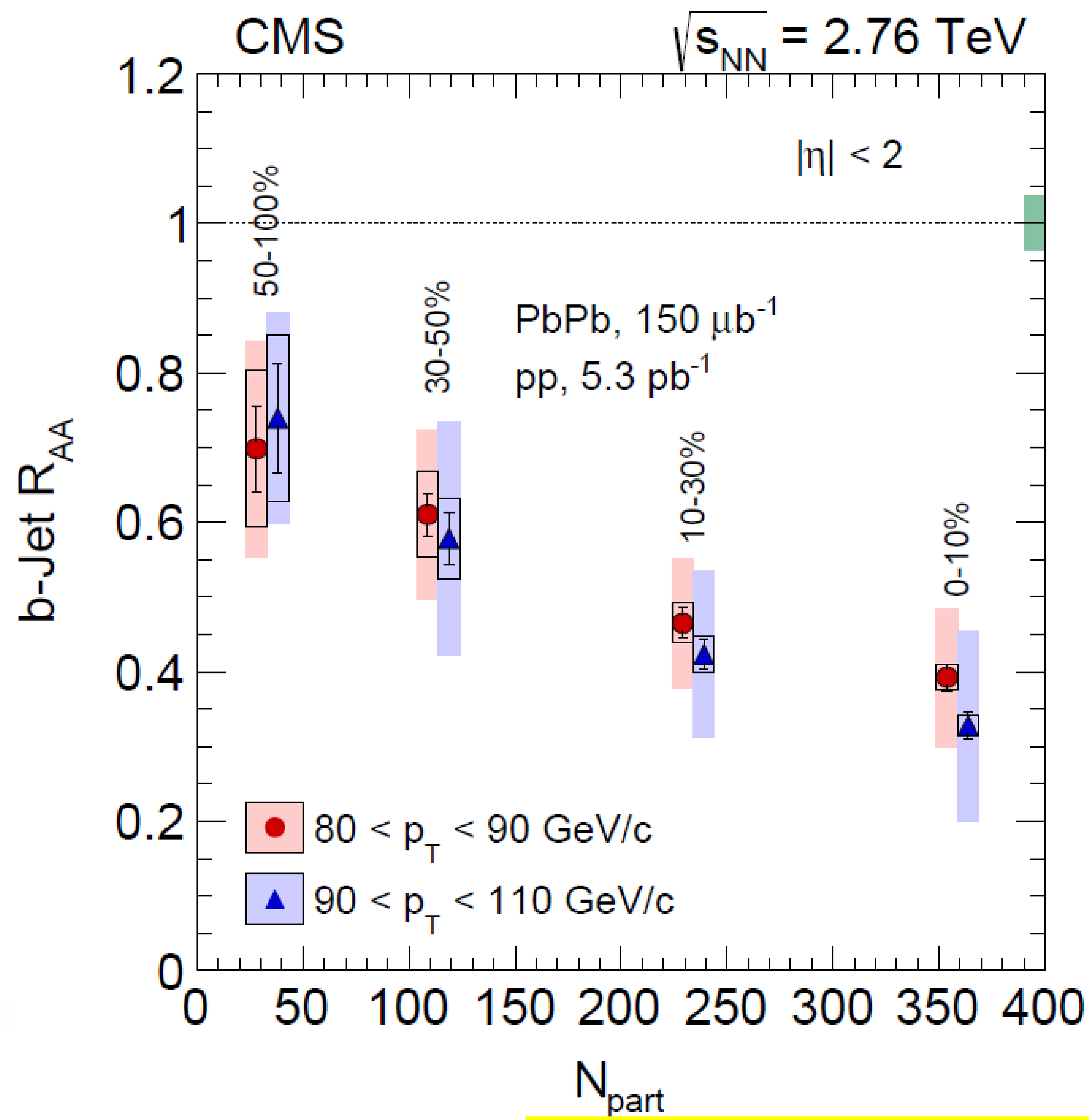
b-Jet R_{AA}

CMS





CMS HIN-12-003
PRL 113, 132301 (2014)

- Evidence of b-jet suppression in PbPb collisions
- Suppression favors pQCD model with stronger jet-medium coupling

b-Jet R_{AA}

CMS

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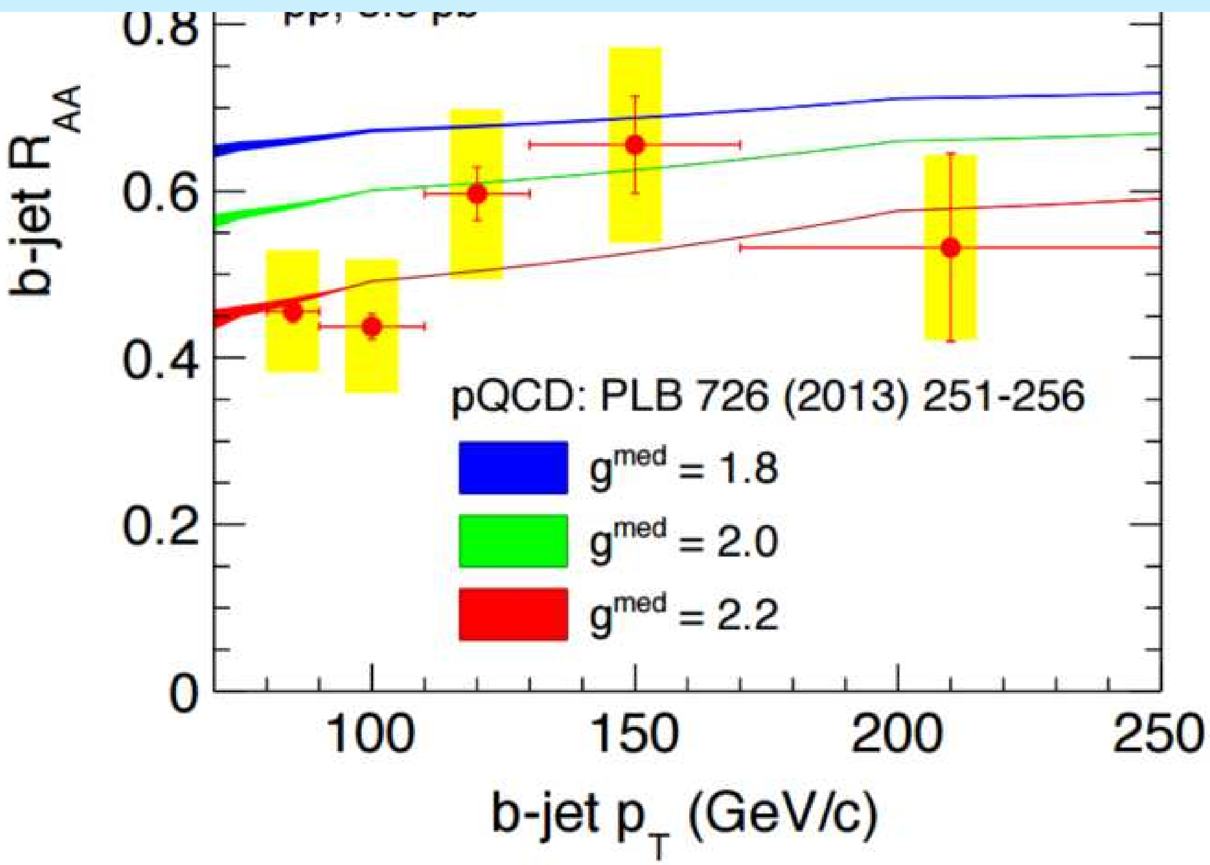

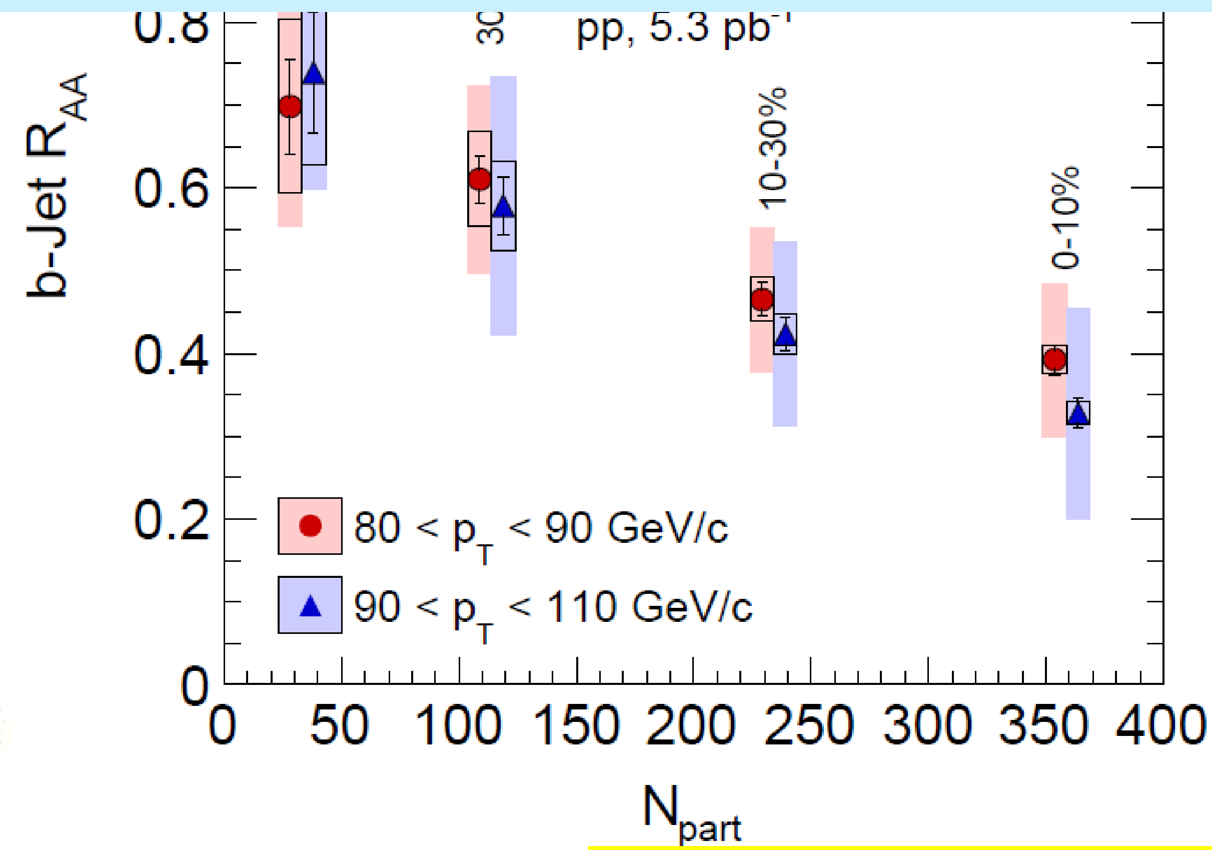

CMS HIN-12-003
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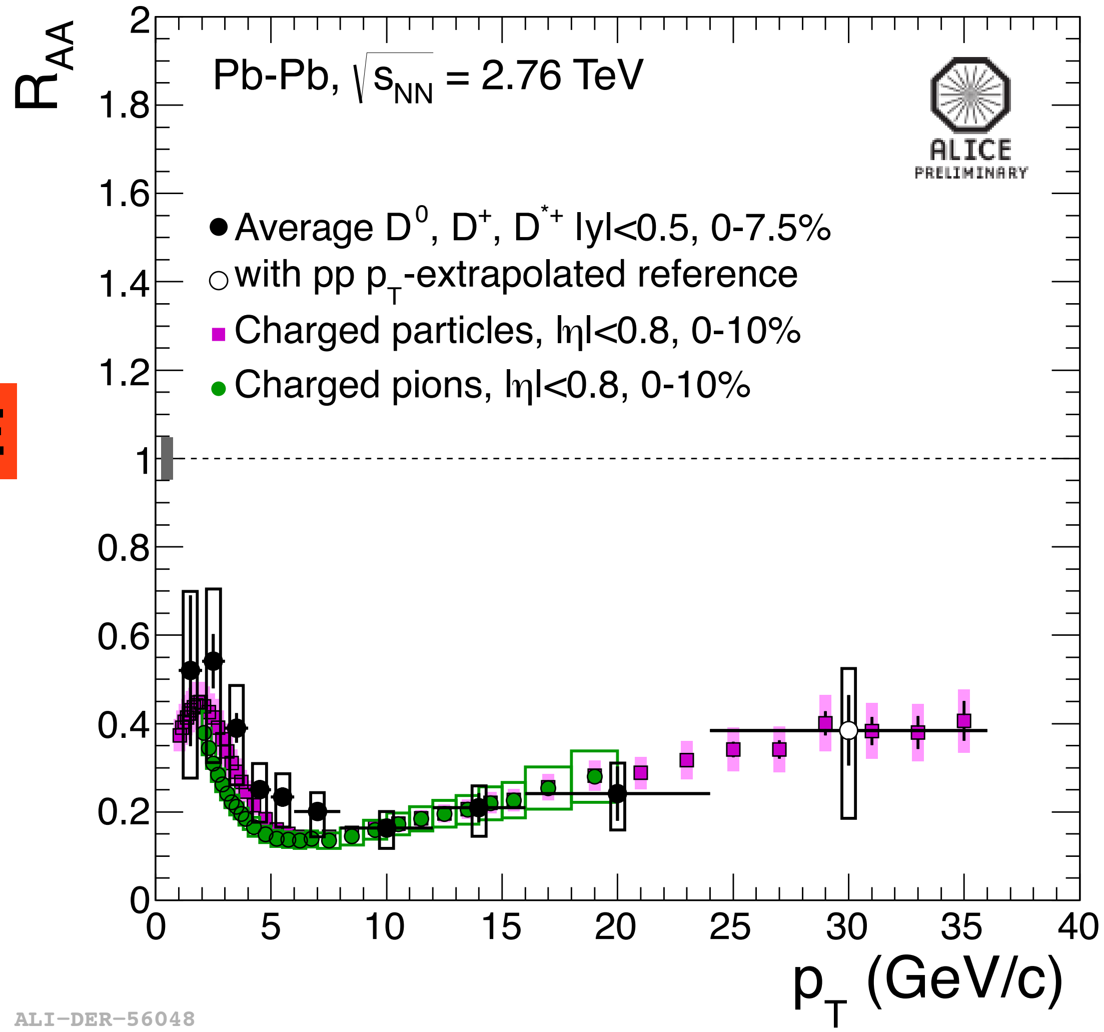
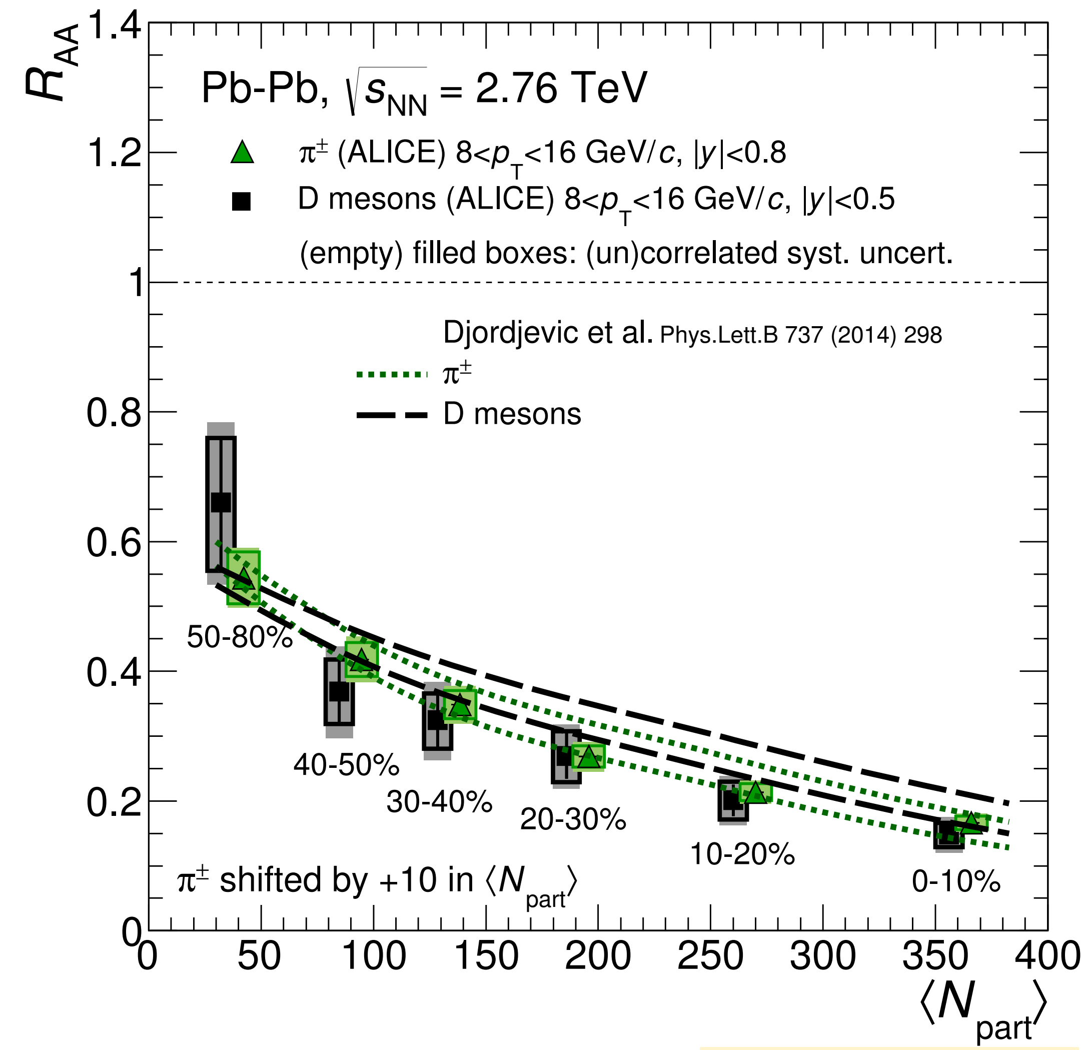
Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$

ΔE(g) > ΔE(u,d,s) > ΔE(c) > ΔE(b) could be reflected in R_{AA}(B) > R_{AA}(D) > R_{AA}(π)

ALICE





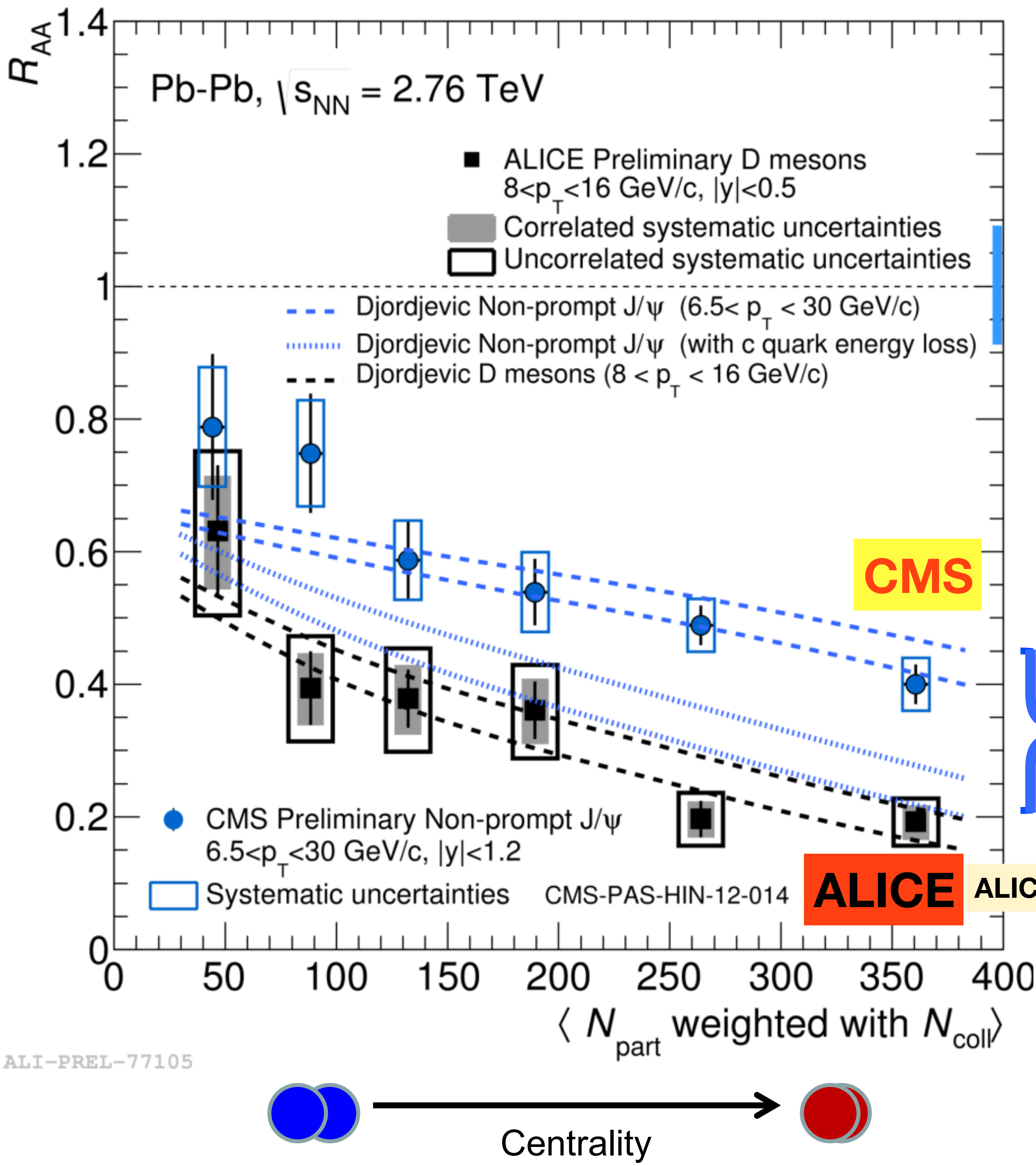
arXiv:1506.06604

- D-meson and π R_{AA} are compatible within uncertainties
- Agreement with models including energy loss hierarchy: ΔE(g) > ΔE(u,d,s) > ΔE(c), different shapes of the parton p_T distributions, different fragmentation functions, soft production mechanisms for low-p_T π
- Measurement not yet conclusive → precision measurement required!

Djordjevic, PRL 112(2014)042302
Wicks et al., NPA 872(2011)265
Djordjevic, PLB 737(2014)298

Quark mass dependence?: D-meson R_{AA} vs. non-prompt J/ψ

$\Delta E(g) > \Delta E(u,d,s) > \Delta E(c) > \Delta E(b)$ could be reflected in $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$



ALICE, arXiv:1506.06604

- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons <p_T>~10 GeV/c, slightly different rapidity ranges
- Clear indication of $R_{AA}^{B\leftarrow J/\psi} > R_{AA}^{D}$

No trivial relation between ΔE and R_{AA}

(Djordjevic, PLB 734(2014)286)

consequence of mass differences of c and b quarks

pQCD model including mass-dependent rad+coll energy loss predict a difference

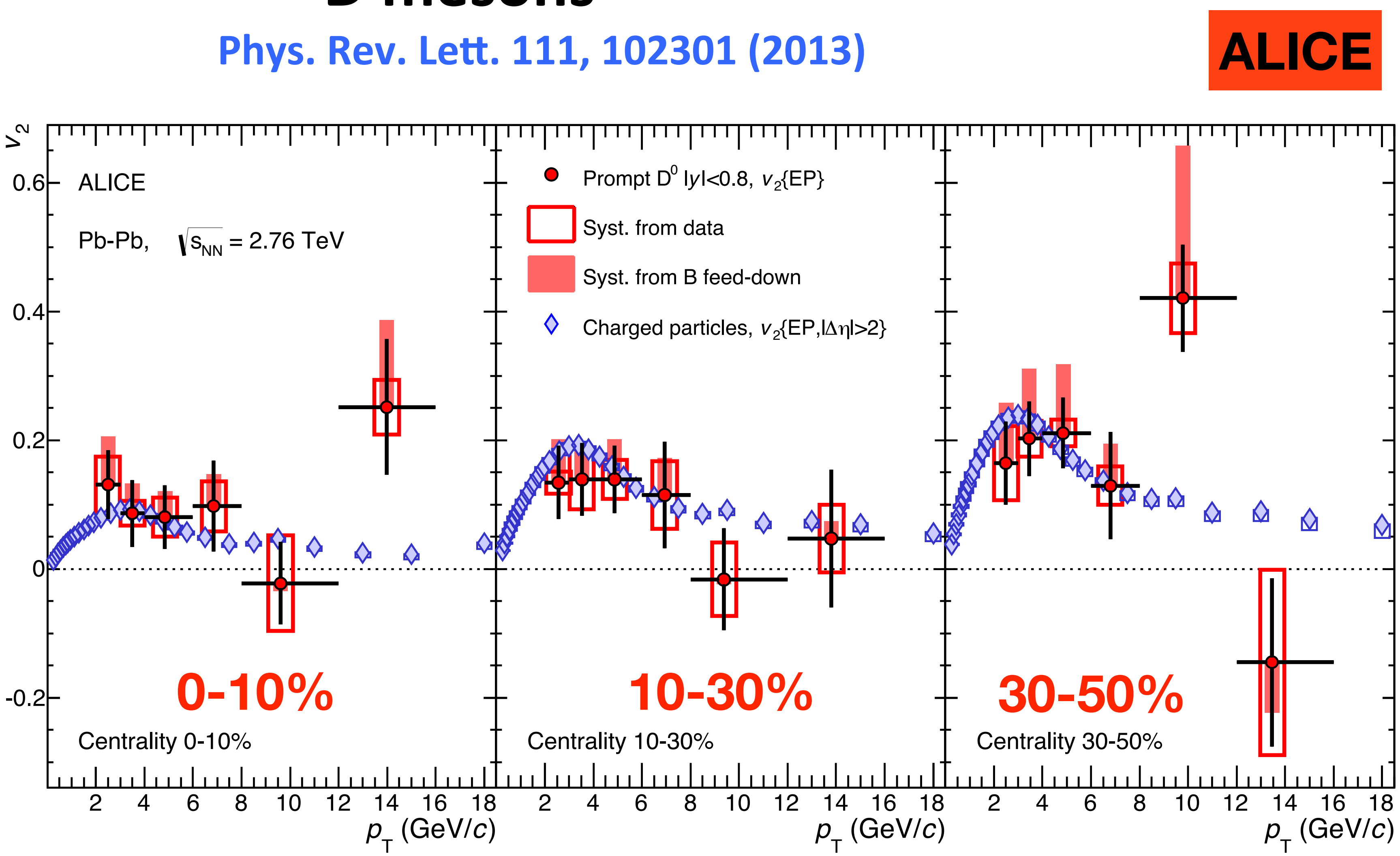
Similar pattern from other calculations

(e.g. BAMPS, WHDG, Vitev et al.).

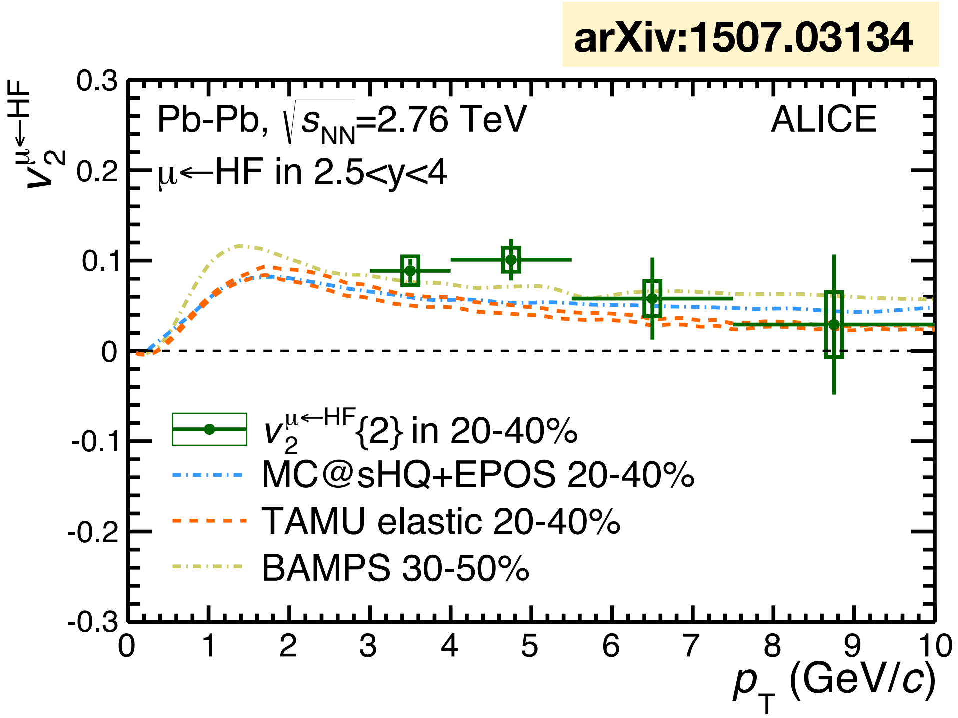
Azimuthal anisotropy of heavy flavours

D mesons

Phys. Rev. Lett. 111, 102301 (2013)



HF decay muons



Similar to electrons

- Positive v_2 for D mesons and leptons from heavy-flavor hadron decays
- Similar v_2 for D mesons and charged-particles
- Hint for increasing flow from central to semi-central collisions
- Confirmation of significant interaction of charm quarks with the medium

Azimuthal anisotropy of heavy flavours

ALICE

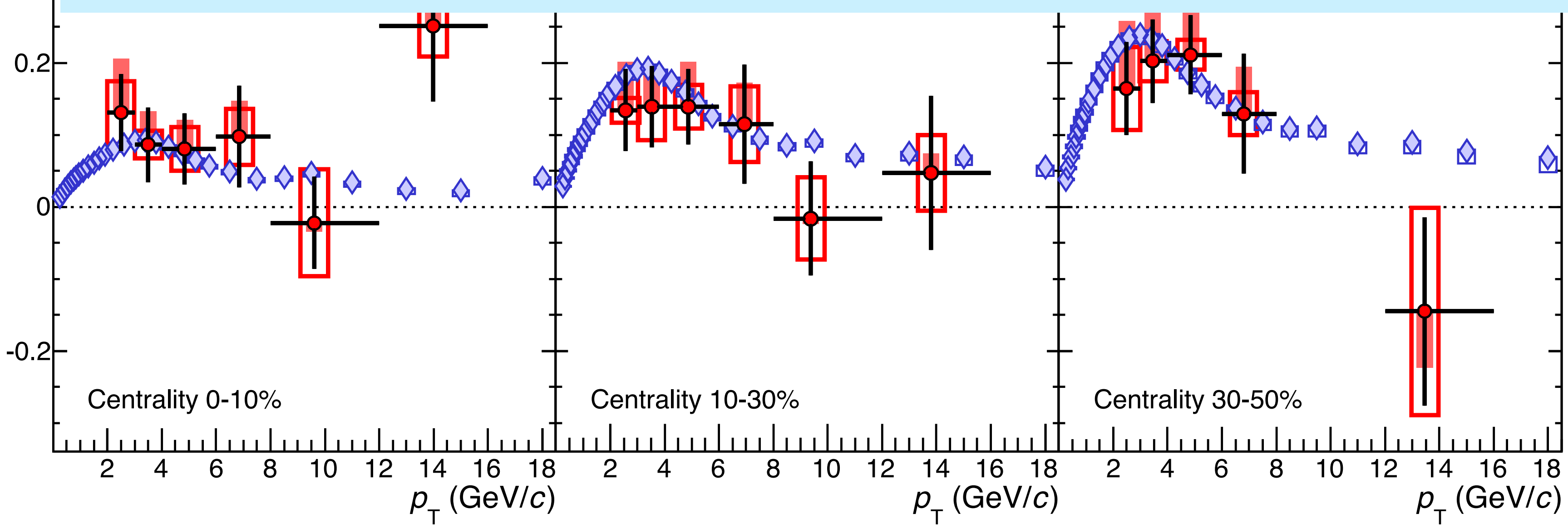
D mesons

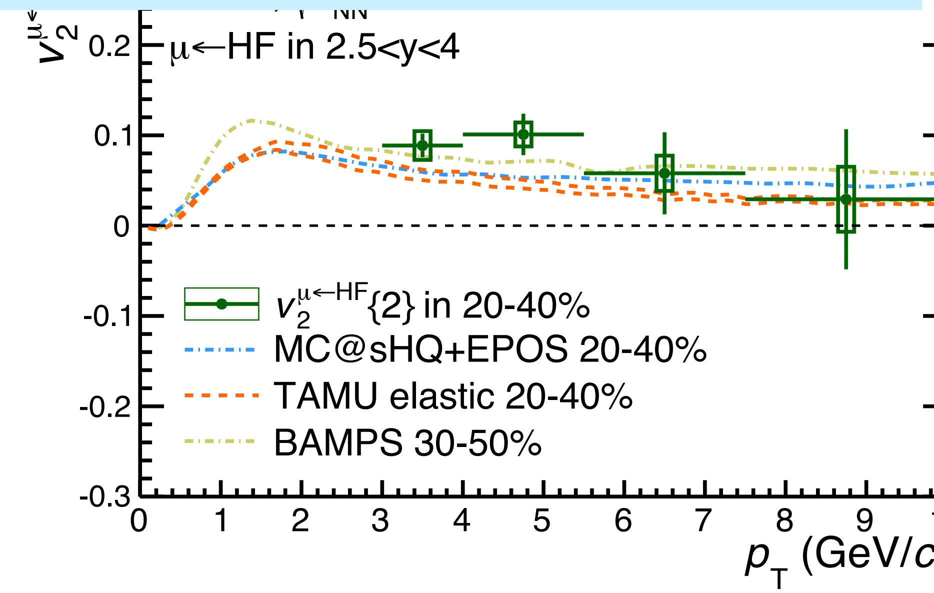
Phys. Rev. Lett. 111, 102301 (2013)

ALICE

HF decay muons

Heavy quarks participate in collective motion of the medium with sufficient re-scatterings





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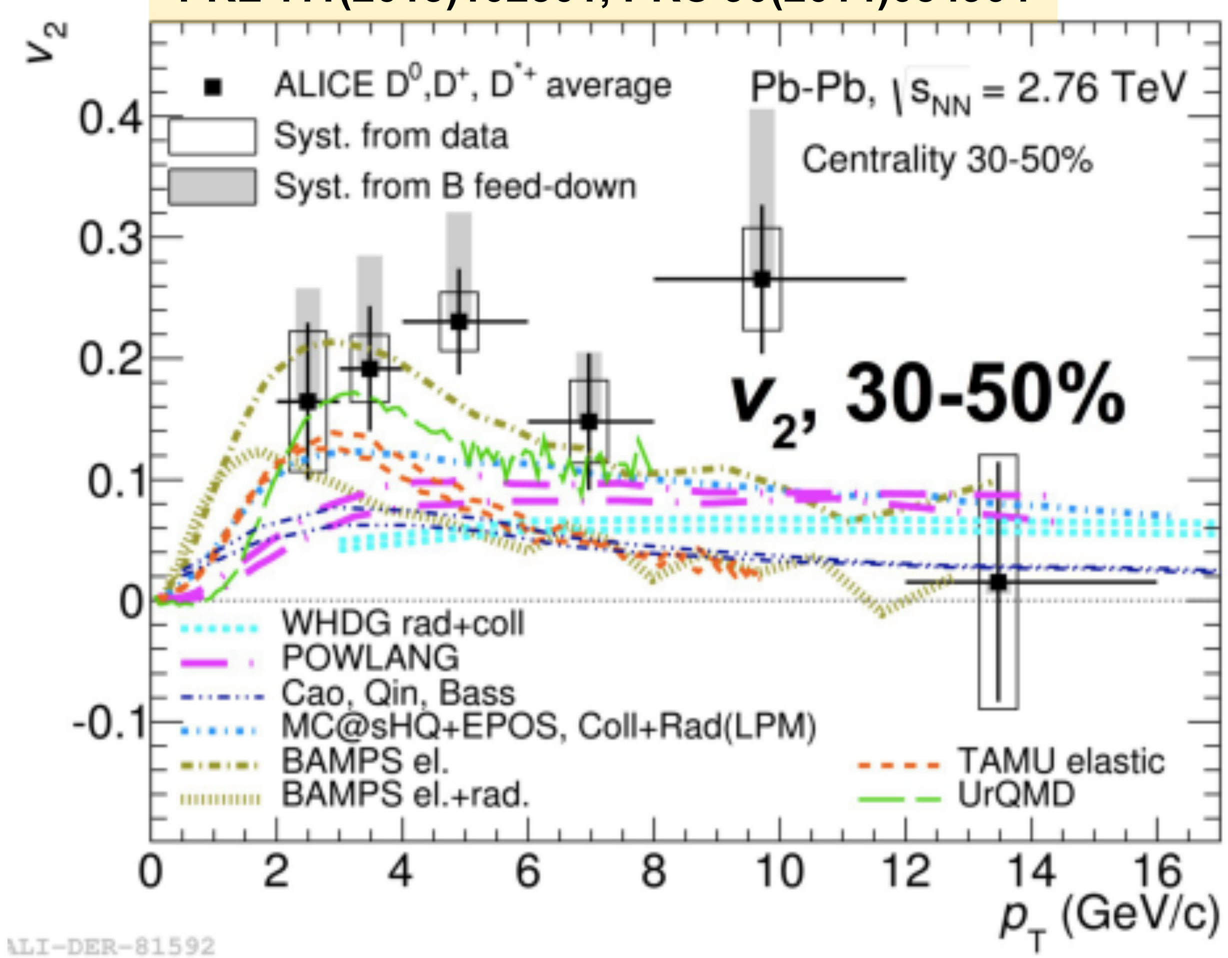
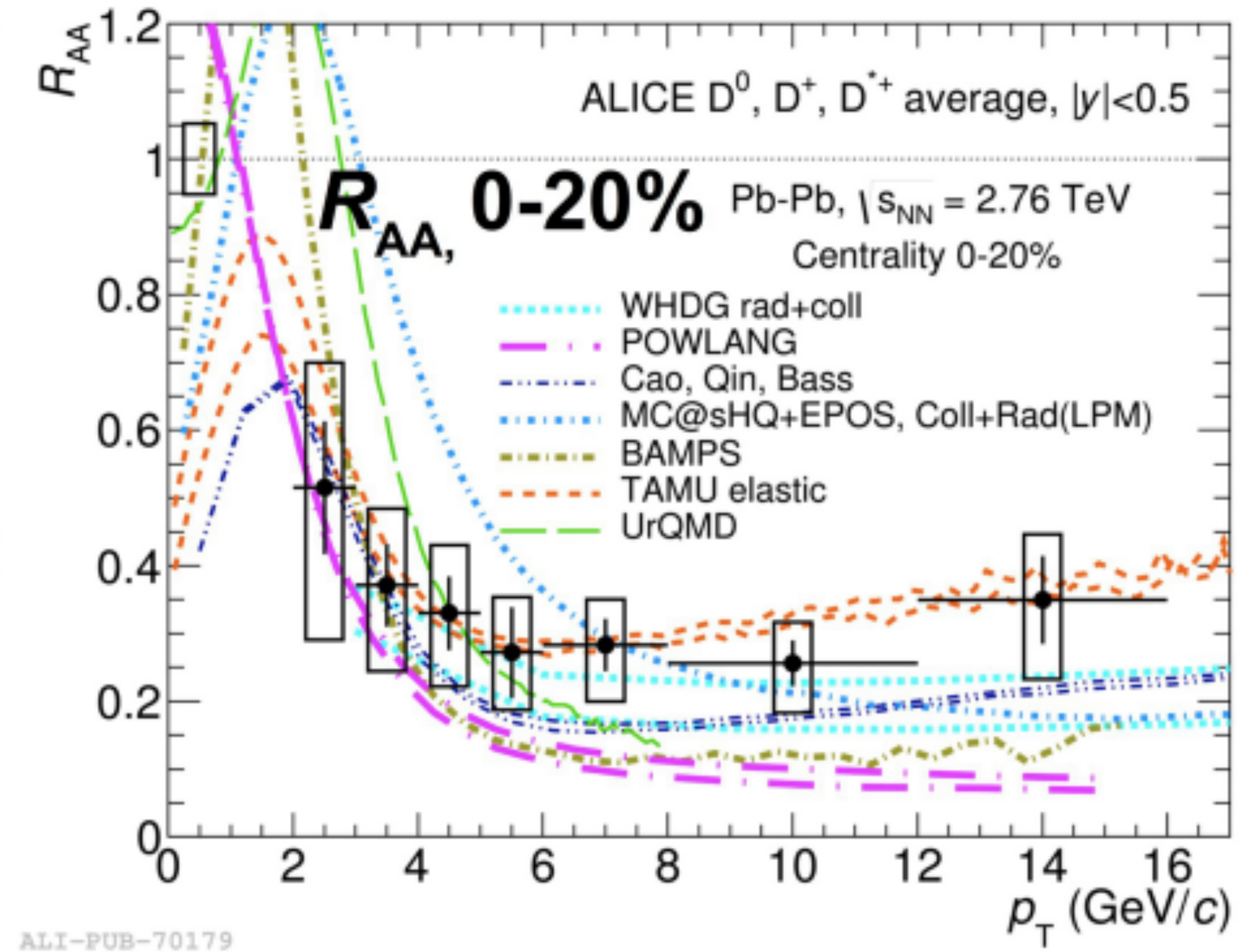
R_{AA} and v_2: Comparison with models

PRL 111(2013)102301, PRC 90(2014)034904





- Simultaneous reproduction of R_{AA} and v_2 challenging for models

⇒ provide understanding of heavy-quark energy loss mechanism, the degree of thermalization of heavy-quarks within the medium

- Task to us: Precision measurements! → reduction of stat. and sys. uncertainties of data

BAMPS Uphoff et al. arXiv: 1112.1559, Aichelin et al. Aichelin et al. Phys. Rev. C 79 (2009) 044906,
WHDG W. A. Horowitz et al. J. Phys. G38, 124064 (2011), POWLANG W. M. Alberico et al. Eur. Phyis J. C 71, 1666 (2011), TAMU M. He, R. J. Fries and R. Rapp, arXiv:1204.4442[nucl-th],
UrQMD arXiv:1211.6912, J. Phys. Conf. Ser. 426, 012032 (2013), Cao, Quin, Bass arXiv:1308.0617

Summary and Outlook

Summary

- pp data are described by perturbative QCD ⇒ Heavy flavours are a calibrated probe
- Pb-Pb data:
  - Hints of a stronger suppression for charm than for beauty at intermediate/high p_T.
  - No strong conclusions drawn yet from the comparison of D-meson and pion R_{AA}, given the current uncertainties
  - Positive flow of charm hadrons and heavy-flavour decay leptons ⇒ participating in collectivity of the medium with sufficient re-scatterings
- p-Pb data:
  - Results consistent with pQCD + shadowing ⇒ the observed suppression in Pb-Pb collisions is due to a dense/hot partonic medium effect

Outlook

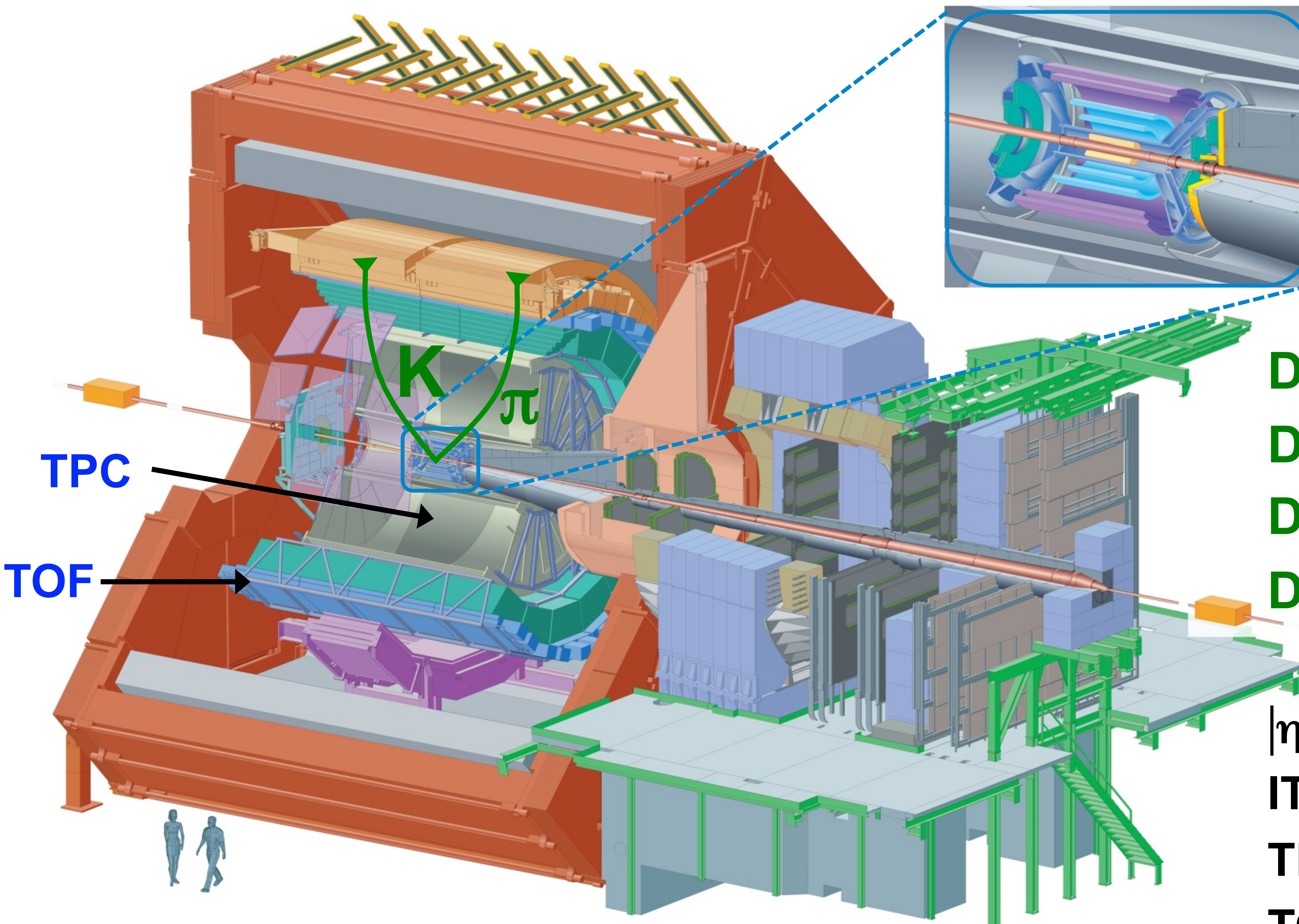
- High precision, more statistics, extended p_T coverage (high and low p_T)
- Smaller uncertainties and new differential measurements will help to
  - constrain model calculations quantitatively
  - address open questions concerning the flavour dependence of parton energy loss, their path-length dependence, thermalization of charm and beauty, heavy-flavour jet pair asymmetries and angular correlations, heavy-flavour jet fragmentation functions/subjet structure, coalescence including heavy quarks ...

LHC run II, III, IV data will answer to the open questions

Thank you for your attention!

Extra Slides

ALICE detectors : D mesons



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

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

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

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

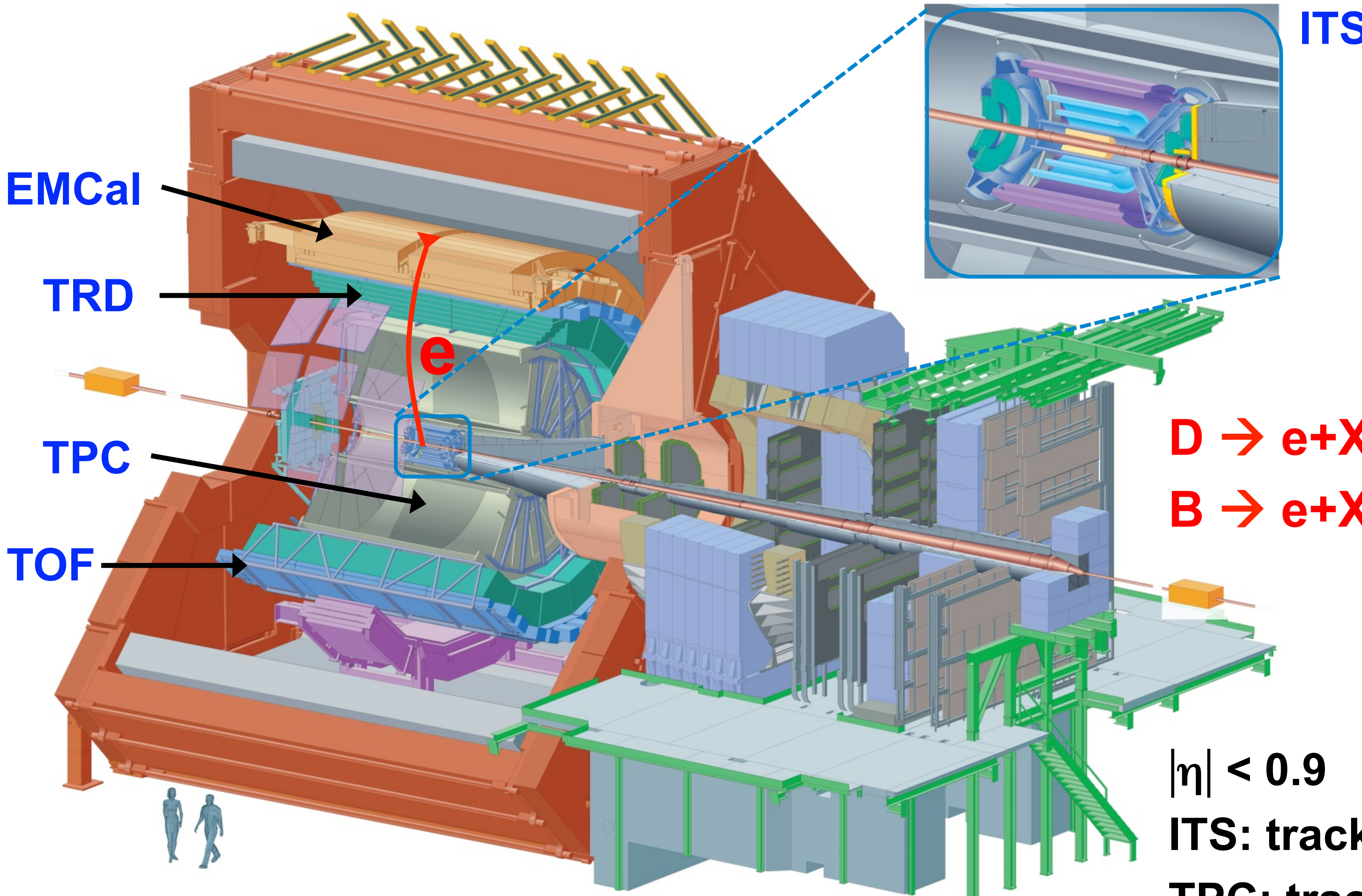
$|\eta| < 0.9$

ITS: tracking, vertexing

TPC: tracking, PID

TOF: K-ID

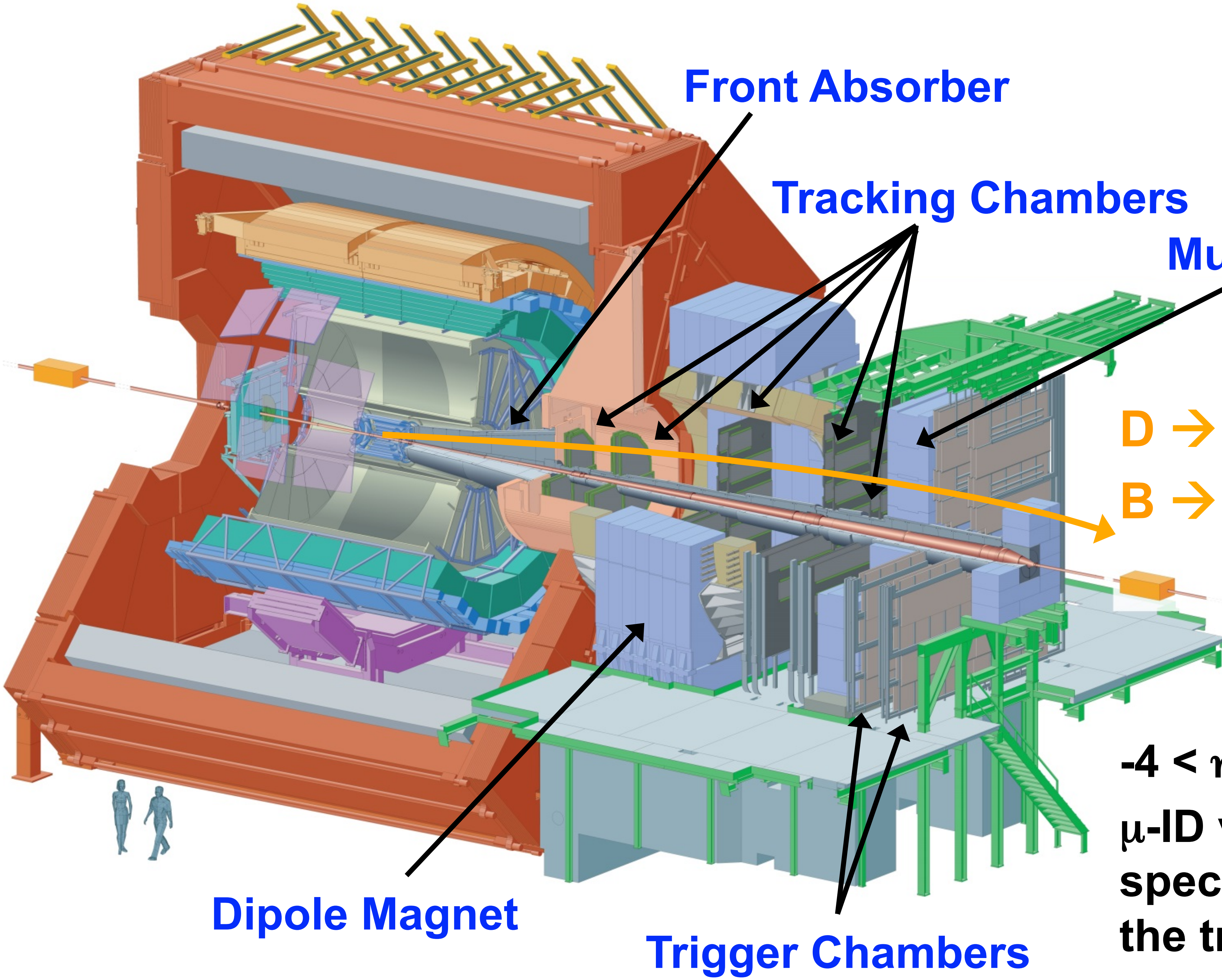
ALICE detectors : Heavy-flavour decay electrons



D → e+X, BR ~ 10%
B → e+X, BR ~ 11%

$|\eta| < 0.9$
ITS: tracking, vertexing, PID
TPC: tracking, PID
TOF, EMCal, TRD: e-ID

ALICE detectors : Heavy-flavour decay muons



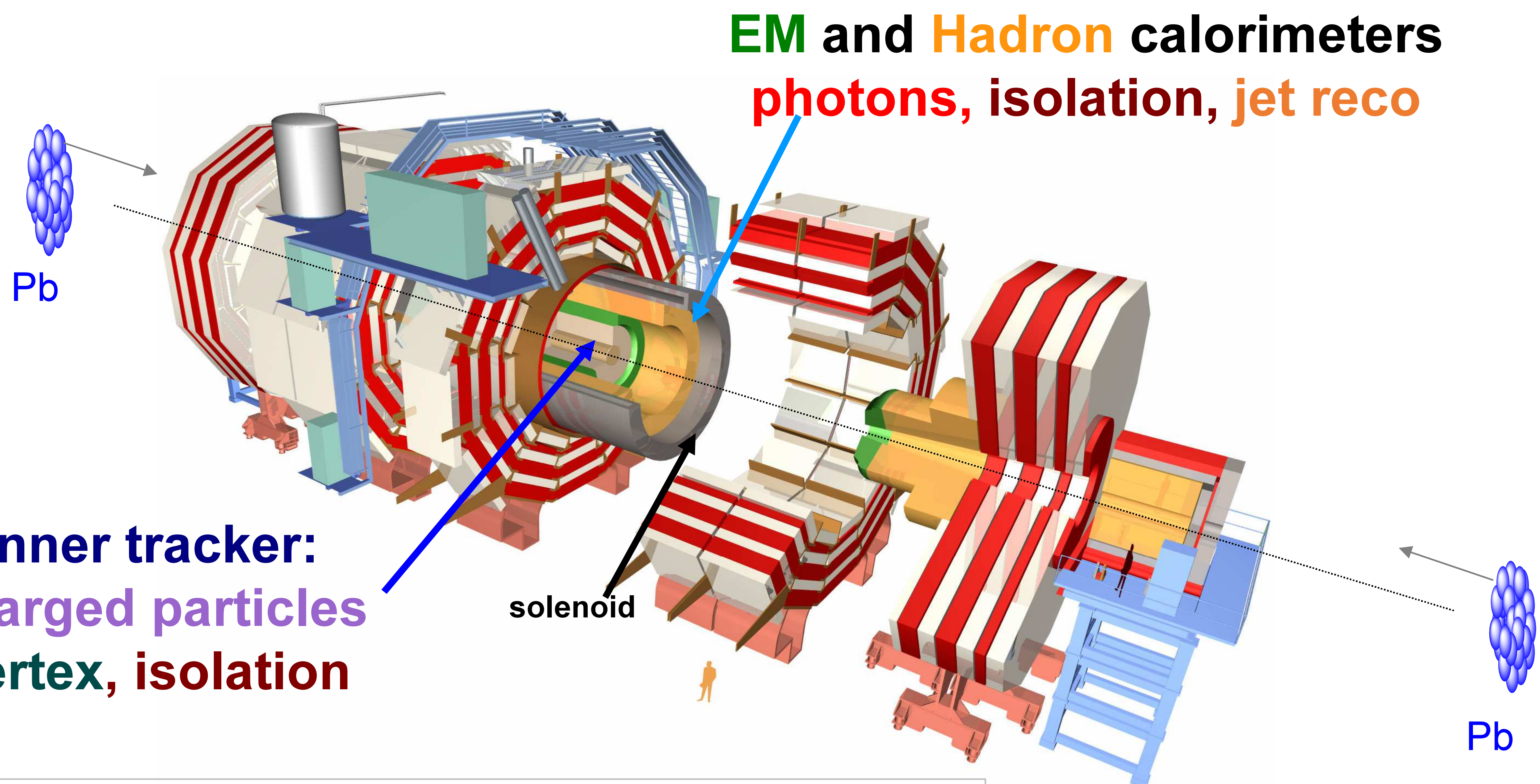
$D \rightarrow \mu + X$, BR ~ 10%

$B \rightarrow \mu + X$, BR ~ 11%

$-4 < \eta < -2.5$

μ-ID via tracks in the muon spectrometer matched with the trigger system

CMS detectors



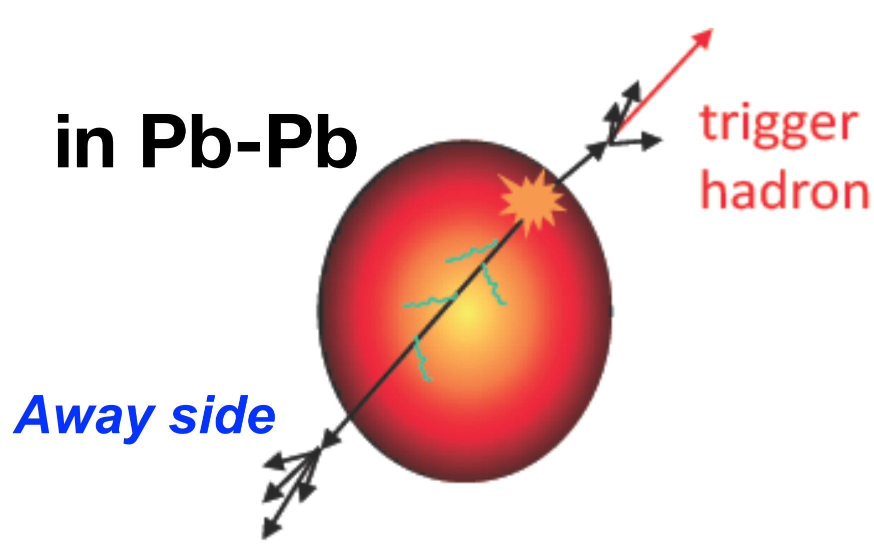
Muon	$|\eta| < 2.4$
HCAL	$|\eta| < 5.2$
ECAL	$|\eta| < 3.0$
Tracker	$|\eta| < 2.5$

Track impact parameter resolution

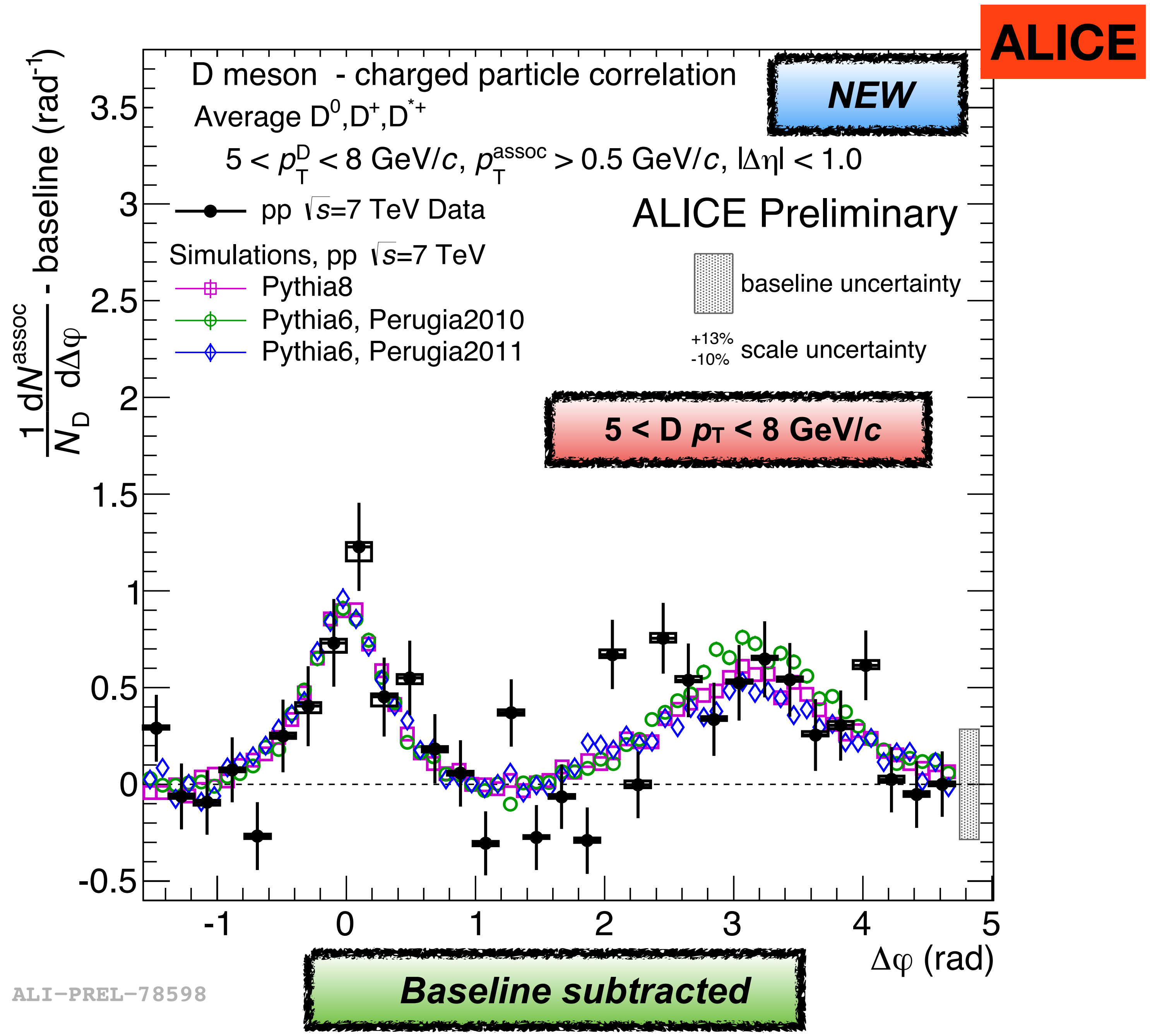
- 100 μm @ 1 GeV/c
- 20 μm @ 20 GeV/c

More differential information:
Heavy flavour correlations

Heavy flavour jet properties



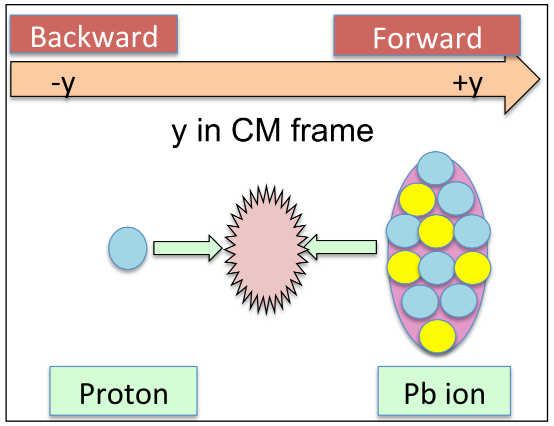
Path length dependence



- D-hadron correlations in pp show good agreement with expectations from Pythia (different tunes)

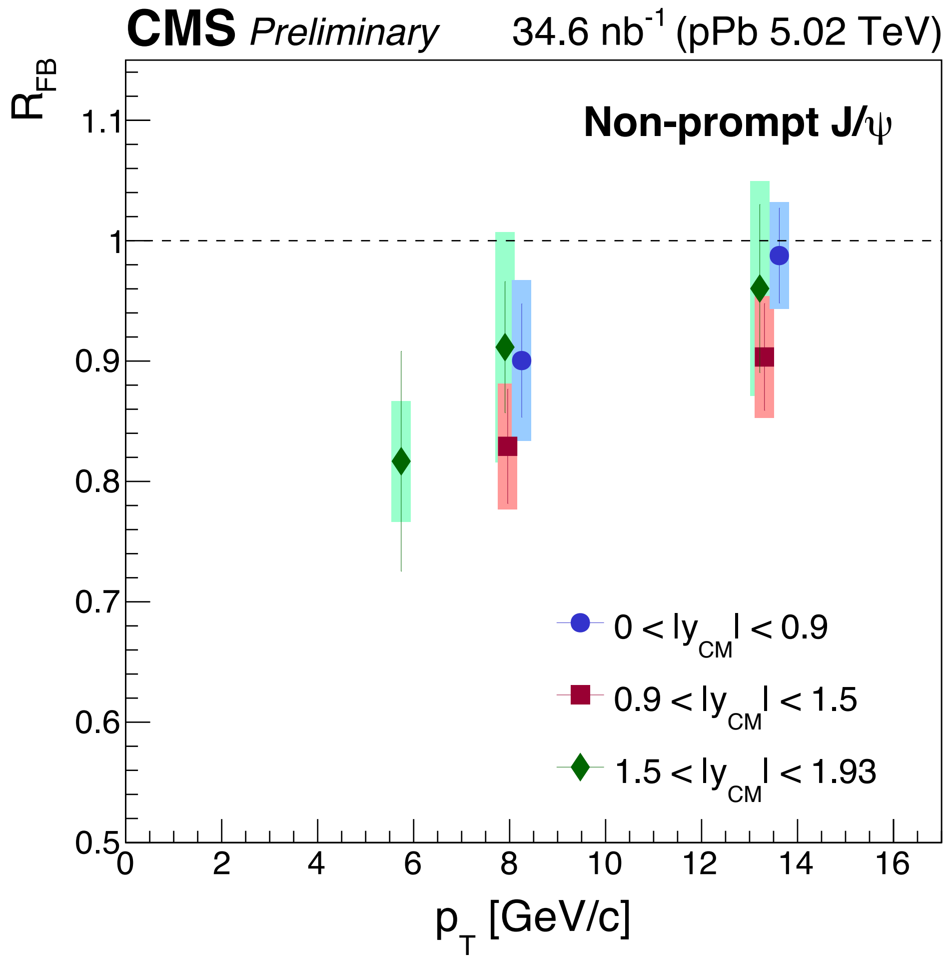
Heavy flavours in p-Pb collisions at the LHC at 5.02 TeV

- non-prompt J/ψ:
  - at forward, modest suppression
  - at backward, consistent with unity within uncertainties



$$R_{FB} = \frac{N^{fit}_{forward}}{N^{fit}_{backward}} \cdot \frac{A_{backward} \cdot \varepsilon_{backward}}{A_{forward} \cdot \varepsilon_{forward}}$$

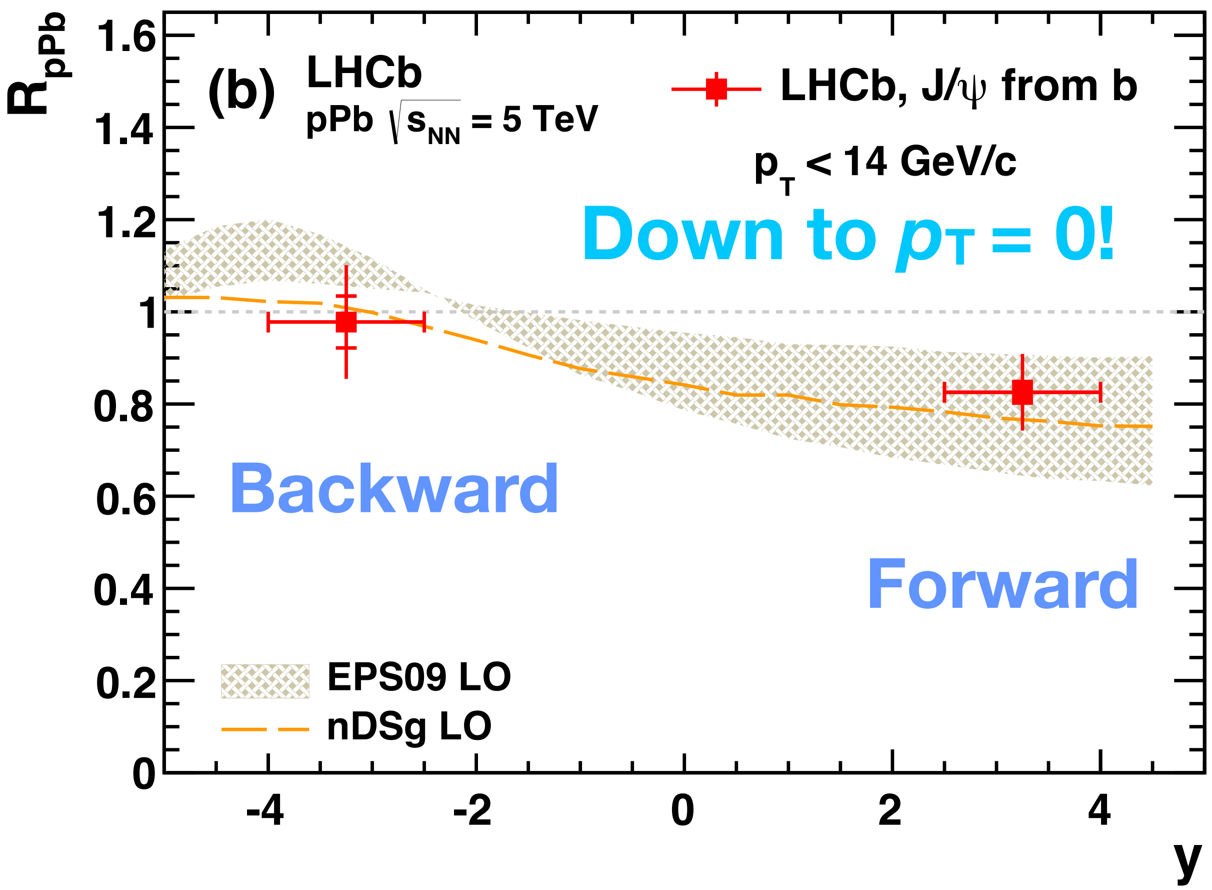
CMS



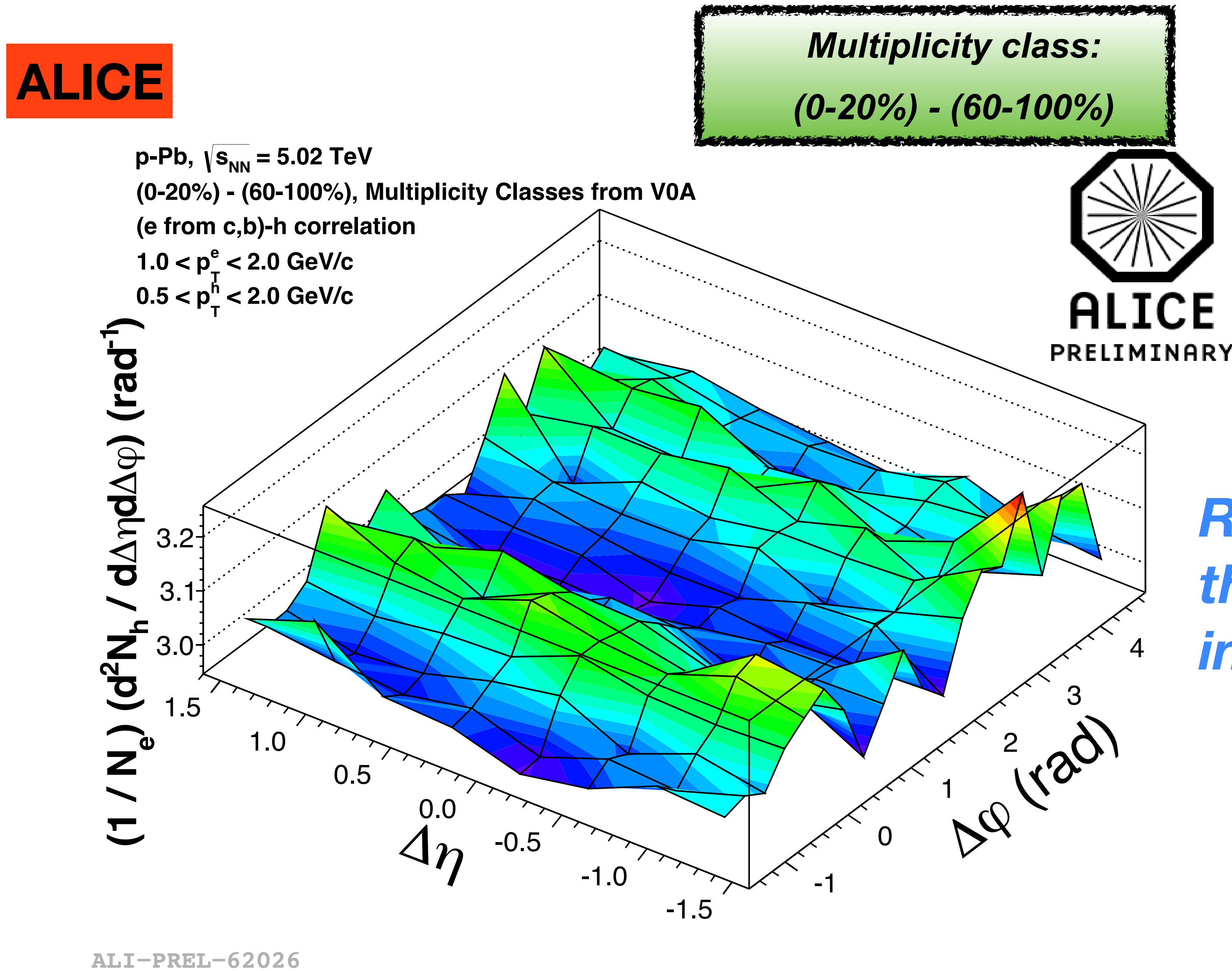
CMS PAS HIN-14-009

- nPDF depleted compared to proton PDF at low *x*

← Characterized by forward/backward asymmetry



More differential information:
Heavy-flavour electron-hadron correlations



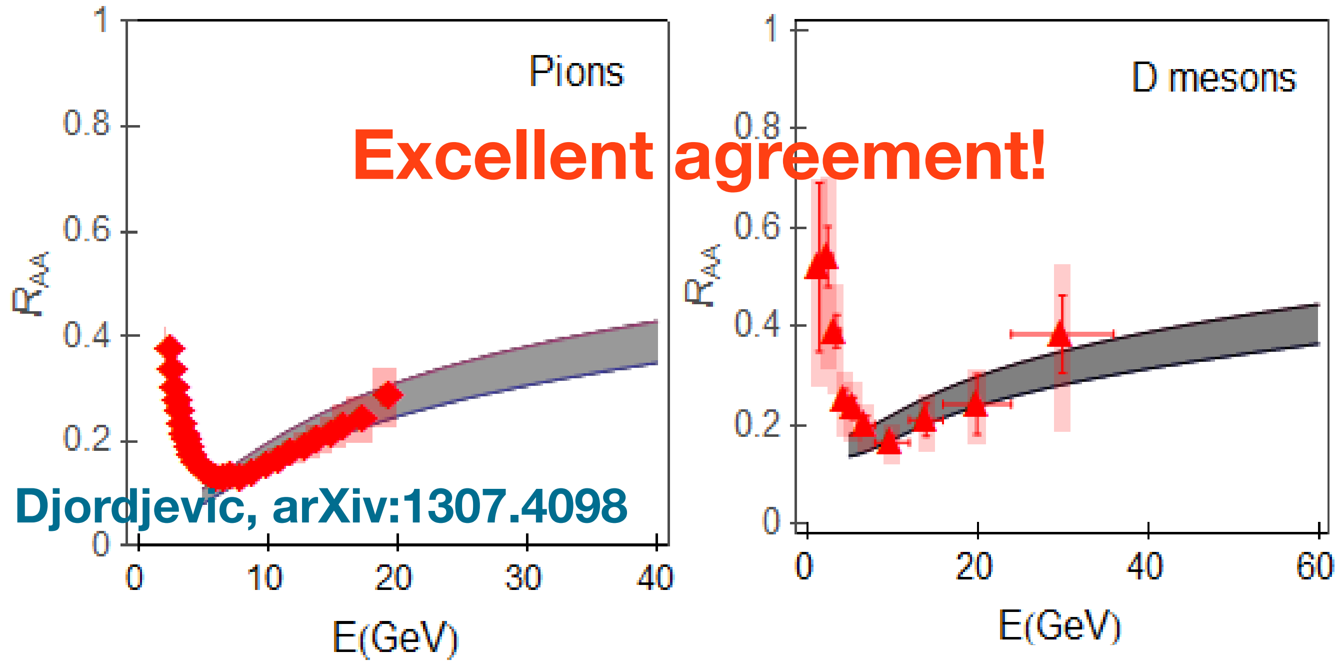
supporting?

Resembles the structure that in AA is interpreted in terms of collective flow

The double ridge also observed in heavy-flavour sector!

The mechanism (CGC? Hydro?) that generates it affects also HF

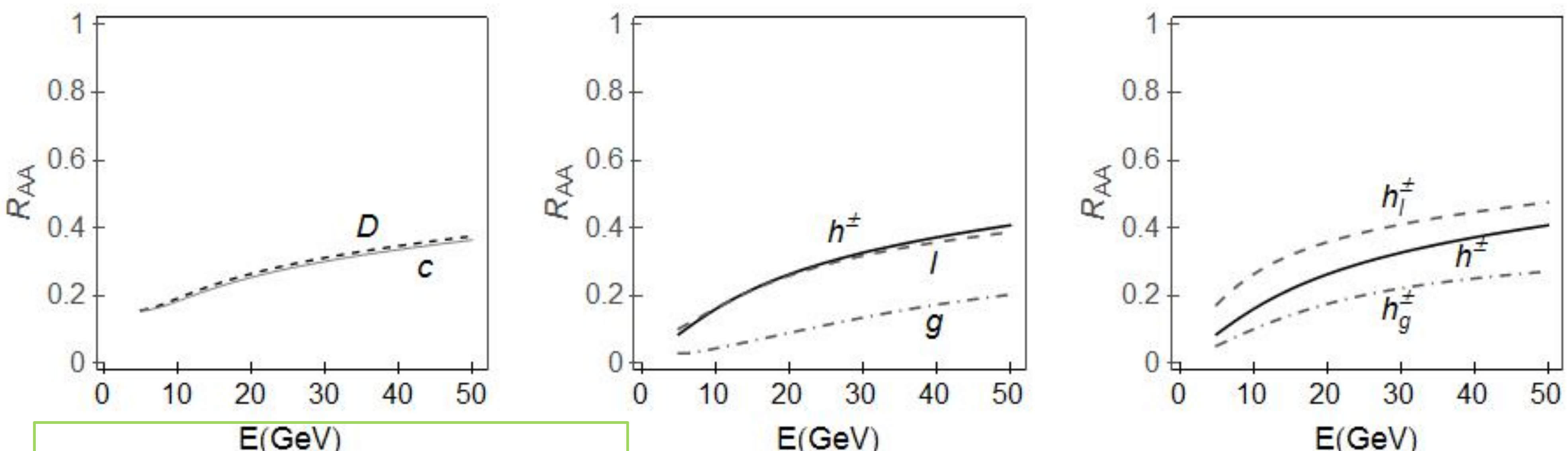
Color charge dependence?: D-meson R_{AA} vs. $\pi^{\pm}$



Excellent agreement!

Djordjevic, arXiv:1307.4098

Calculation by M. Djordjevic (rad+coll energy loss) can describe both R_{AA}



Shows strong colour charge effect in partonic R_{AA} (g vs. light and c)

R_{AA} (D) = R_{AA} (charm)

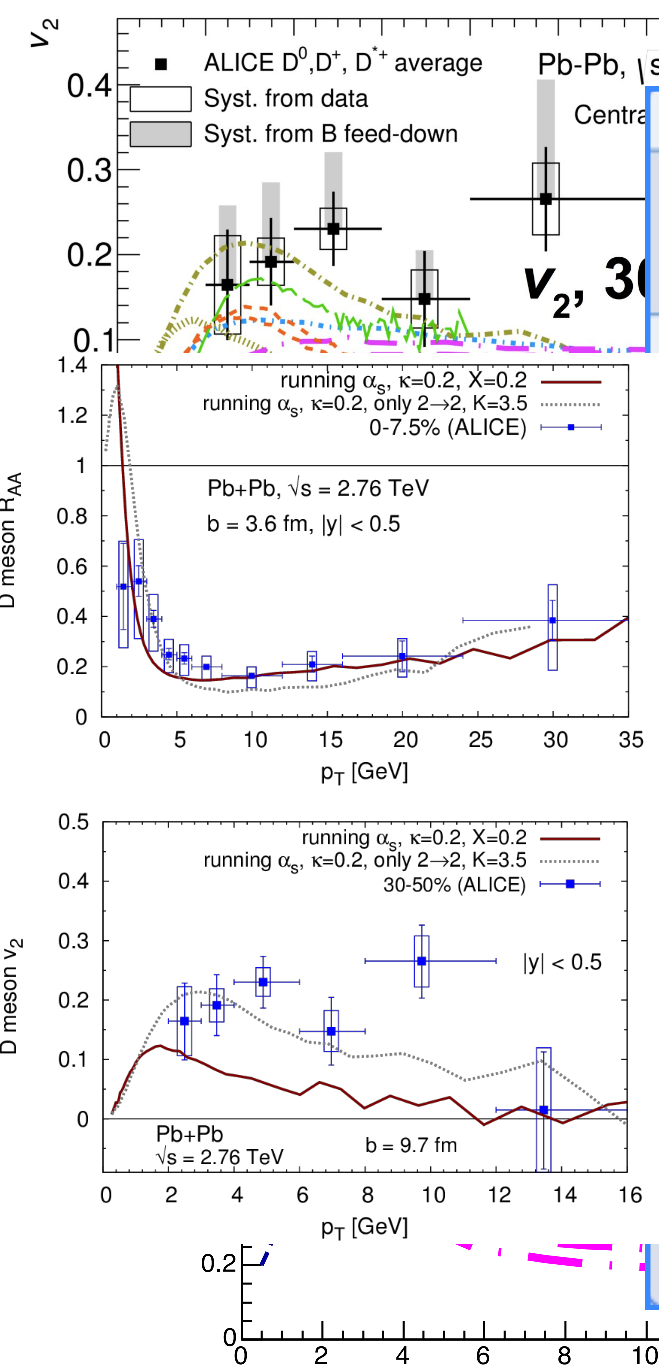
R_{AA} (light quarks) = R_{AA} (charm)

Distortion by fragmentation!

R_{AA} ($h^{\pm}$) = R_{AA} (D)

Colour charge effect plays!

Observables constraining models



	HQ production	Medium Modeling	Heavy quarks interactions	Hadronization
WHDG (AIP Conf Proc. 1441 (2012) 889	FONLL, no shadowing	Glauber model collision geometry, no hydro evolution	radiative + collisional energy loss	fragmentation
POWLANG (J. Phys. G 38 (2011) 124144)	POWEG (NLO) + EPS09 shadowing	2+1d expanding medium with viscos hydro evolution	HQ transport (Langevin) + collisional energy loss	fragmentation
Cao, Quin, Bass (Phys Rev C 88 (2013) 044907)	LO pQCD + EPS09 shadowing	2+1d expanding medium with viscous hydro evolution	HQ transport (Langevin) + quasi elastic scattering + radiative energy loss	recombination + fragmentation
MC@sHQ+EPOS2 (Phys Rev C 89 (2014) 014905)	FONLL, no shadowing	3+1d fluid dynamical expansion (EPOS)	HQ transport (Boltzmann) + radiative + collisional energy loss.	recombination + fragmentation
BAMPS (Phys Lett B 717 (2012) 430)	MC@NLO, no shadowing	3+1d fully dynamic parton transport model	HQ transport (Boltzmann) + collisional energy loss (w/ & w/o radiative)	fragmentation
TAMU elastic (arXiv:1401.3817)	FONLL + EPS09 shadowing	transport + 3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss + diffusion in hadronic phase	recombination + fragmentation
UrQMD (arXiv:1211.6912)	PYTHIA, no shadowing	3+1d ideal hydro evolution	HQ transport (Langevin) + collisional energy loss	recombination + fragmentation

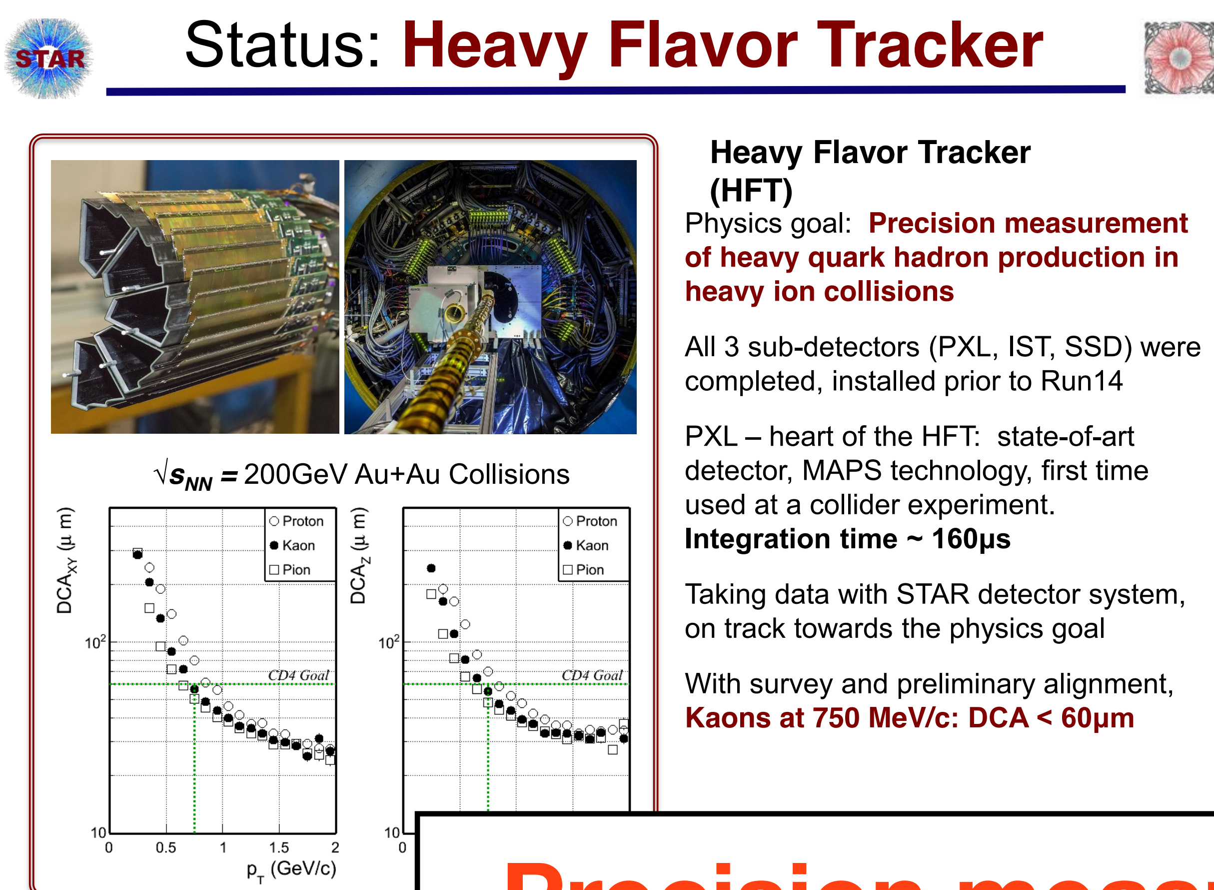
Summarized by Davide Caffarri

ALI-PREL-77576

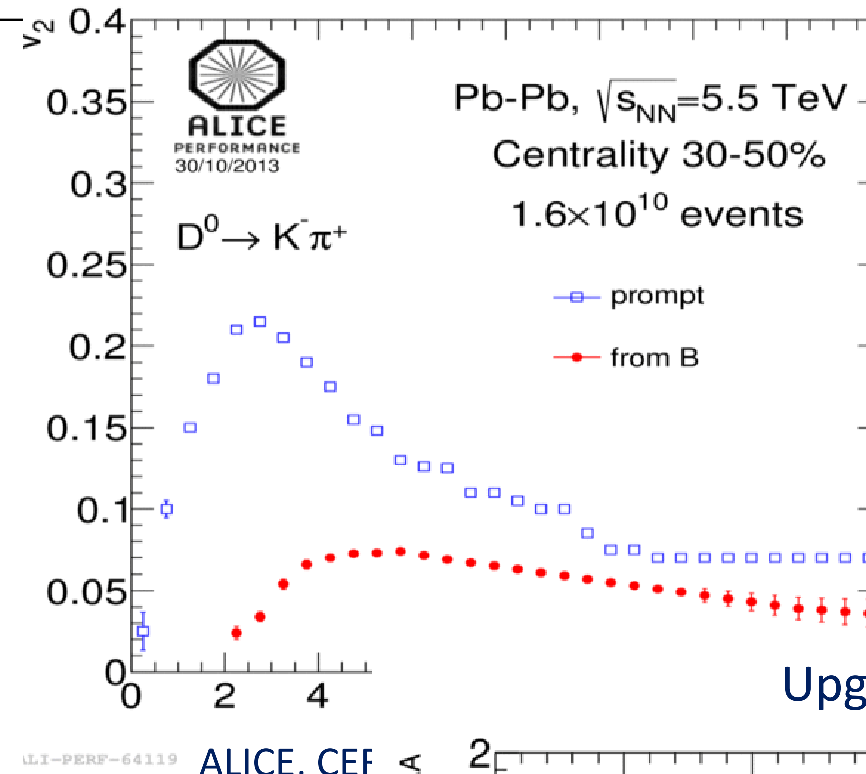
- TAMU elastic: arXiv:1401.3817
- Djordjevic: arXiv:1307.4098
- Cao, Qin, Bass: PRC 88 (2013) 044907
- WHDG rad+coll: Nucl. Phys. A 872 (2011) 265
- MC@sHQ+EPOS: PRC 89 (2014) 014905
- Vitev, rad+dissoc: PRC 80 (2009) 054902
- POWLANG: JPG 38 (2011) 124144
- BAMPS: PLB 717 (2012) 430

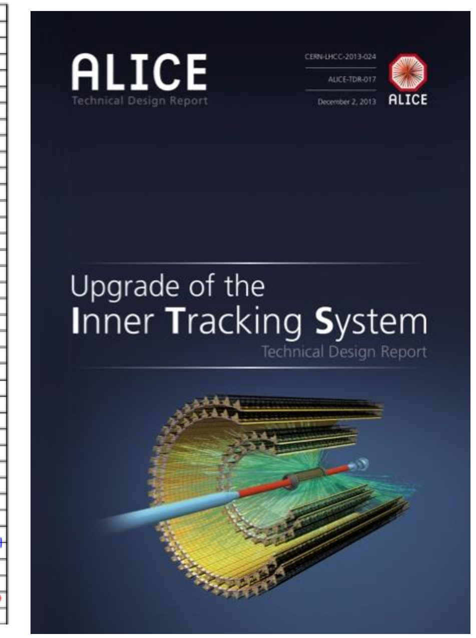
Various observables provide constraints for the models

Outlook

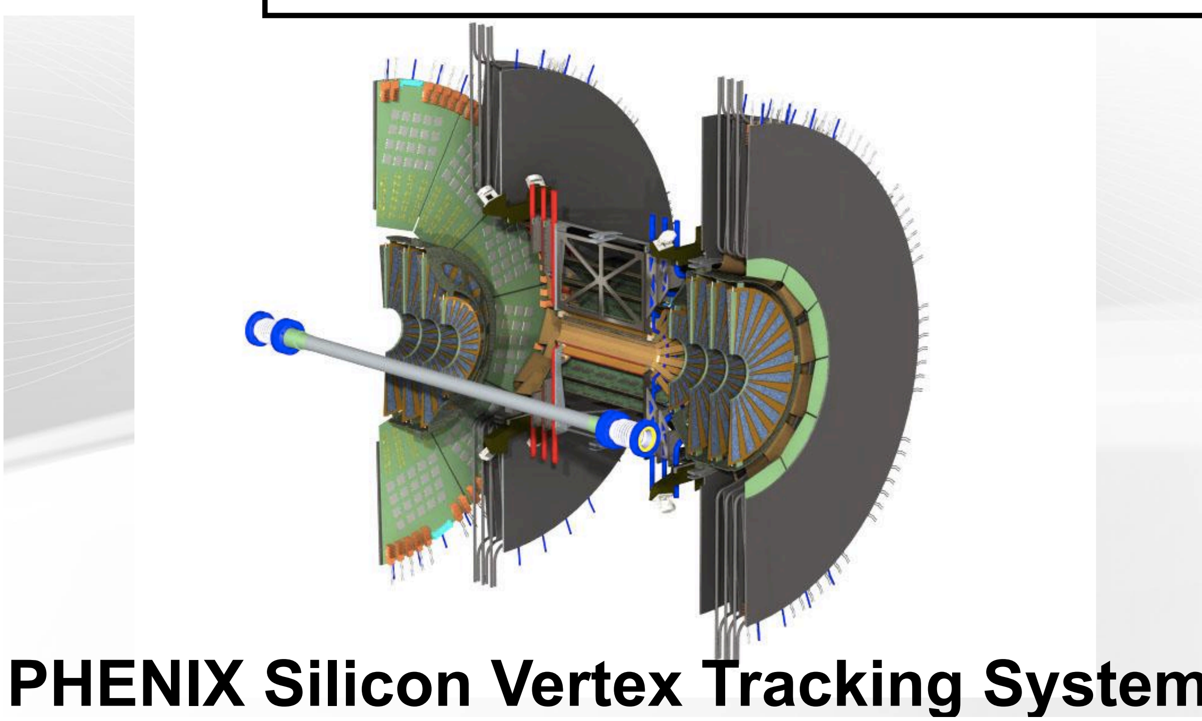


Upgrade





Precision measurements



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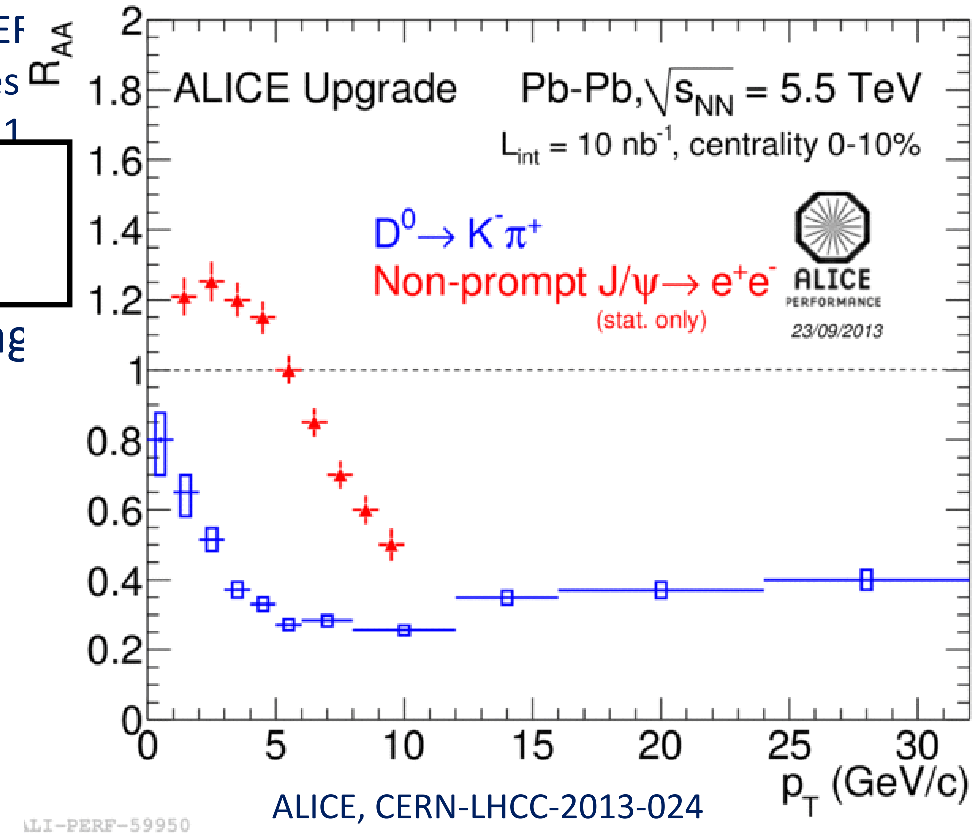

ALICE, CERN-LHCC-2013-024

Charm and beauty R_{AA} down to p_T~0 using D^0 and B-decay J/ψ