Heavy Flavour Production in Small and Large Systems measured with ALICE

MinJung Kweon
Inha University

HIM Meeting
April 22, 201

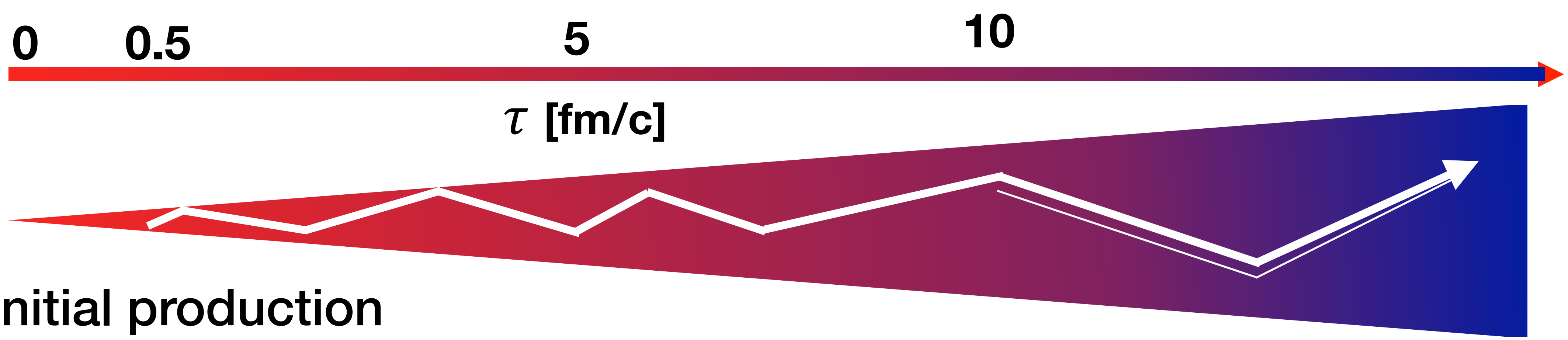
OUTLINE

- **Why Heavy flavours in heavy-ion physics**
- **Heavy-flavour observables**
- **Main and recent heavy-flavour measurements**
  - **in pp, p-Pb collisions**
  - **in Pb-Pb collisions**
- **Future plans**

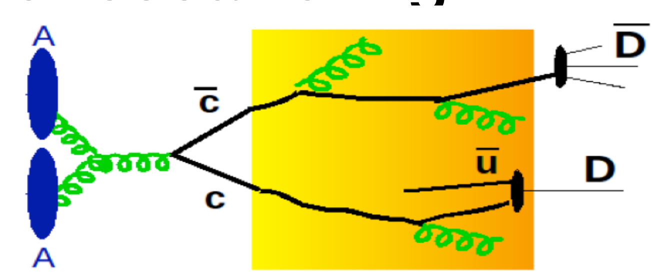
Basic scales of heavy flavour

- $m_{c,b} \gg \Lambda_{QCD}$ **pQCD initial production**
- $m_{c,b} \gg T_{RHIC,LHC}$ **negligible thermal production**
- $\tau_0 \approx 1/2m_Q$ (<0.1 fm/c) $\ll \tau_{QGP}$ (O(10fm/c)) **witness of all the QGP**

⇨ **"Calibrated probes" of the medium**



- Initial production
  - pQCD-NLO
  - MC-NLO
  - CNM effect
- Dynamics in QGP
  - energy loss via radiative ("gluon Bremsstrahlung") and collisional processes
    - color charge (Casimir factor)
    - quark mass (dead-cone effect)
    - path length and medium density
- Hadronization
  - via quark coalescence and/ or fragm.
  - hadronic rescattering



Heavy quark energy loss

Dead Cone Effect

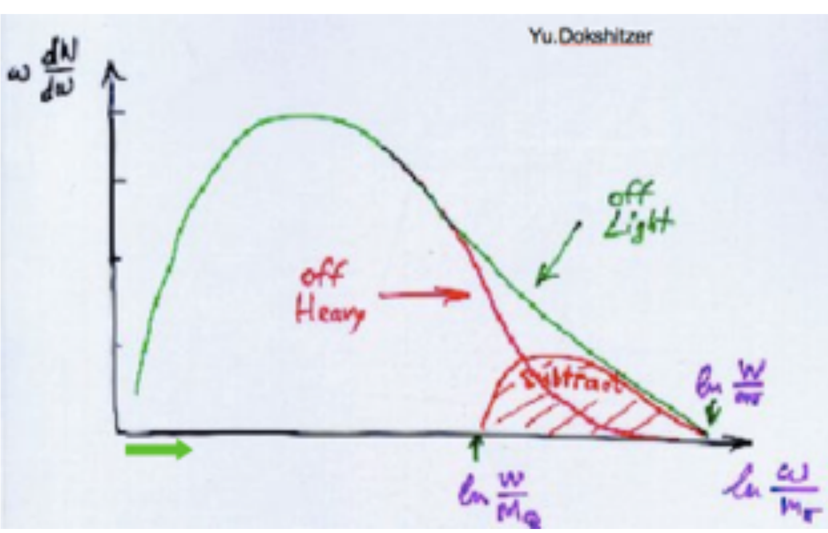
- **Gluon radiation is suppressed at angles smaller than the ratio of the quark mass M_Q to its energy E_Q ($\theta < M_Q/E_Q$)**
- **In medium, dead cone implies lower energy loss**

(Dokshitzer and Kharzeev, PLB 519 (2001) 199.)

gluon radiation spectrum by the quark propagation in the medium:

$$\omega \frac{dI}{d\omega}\bigg|_{Heavy\ in\ Medium} = \omega \frac{dI}{d\omega}\bigg|_{Light\ in\ Medium} \cdot \left(1 + \left(\frac{M_Q}{E_Q}\right)^2 \frac{1}{\theta^2}\right)^{-2}$$

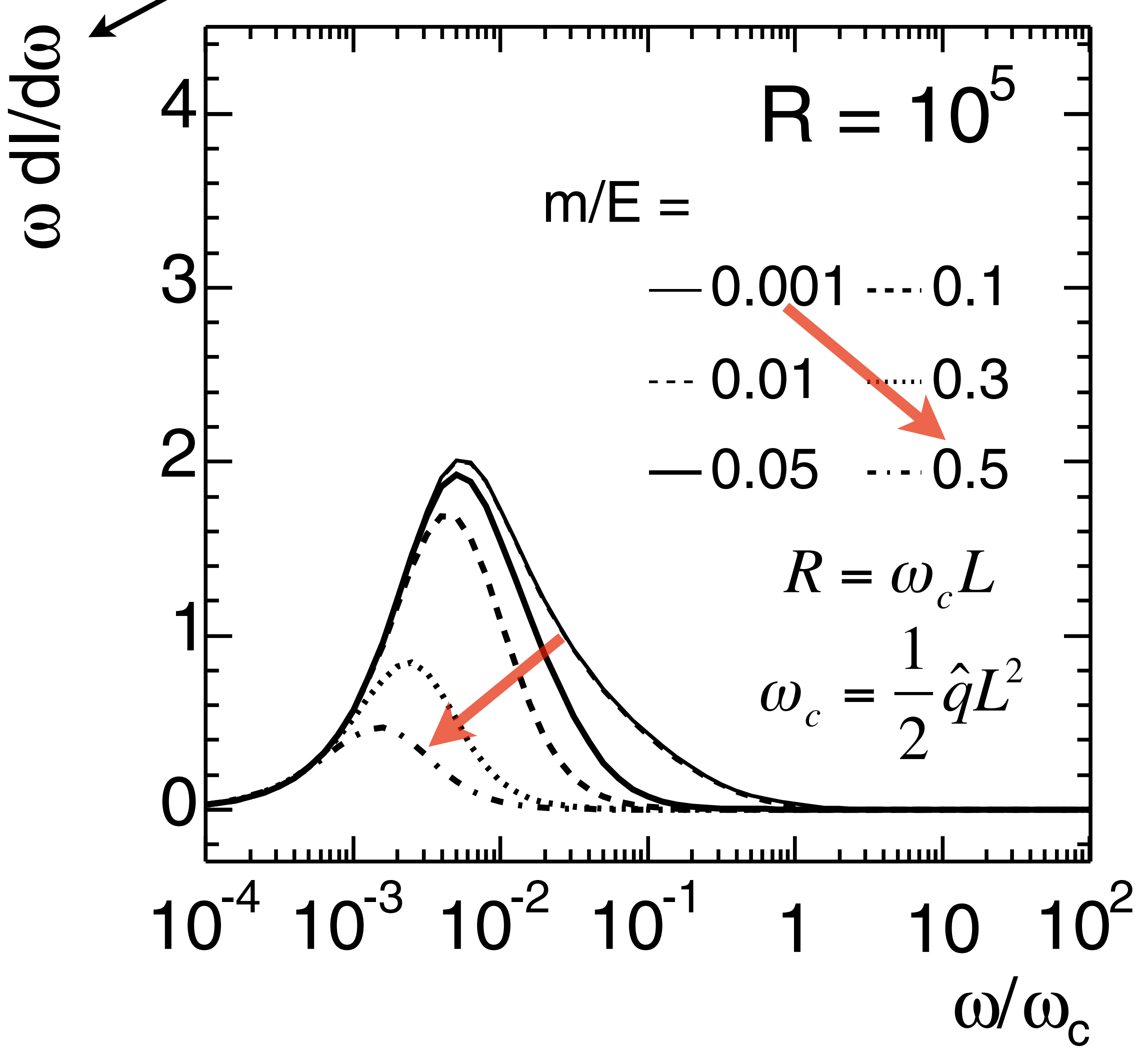
$$, where \quad \theta \simeq \frac{k_T}{\omega} \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$$



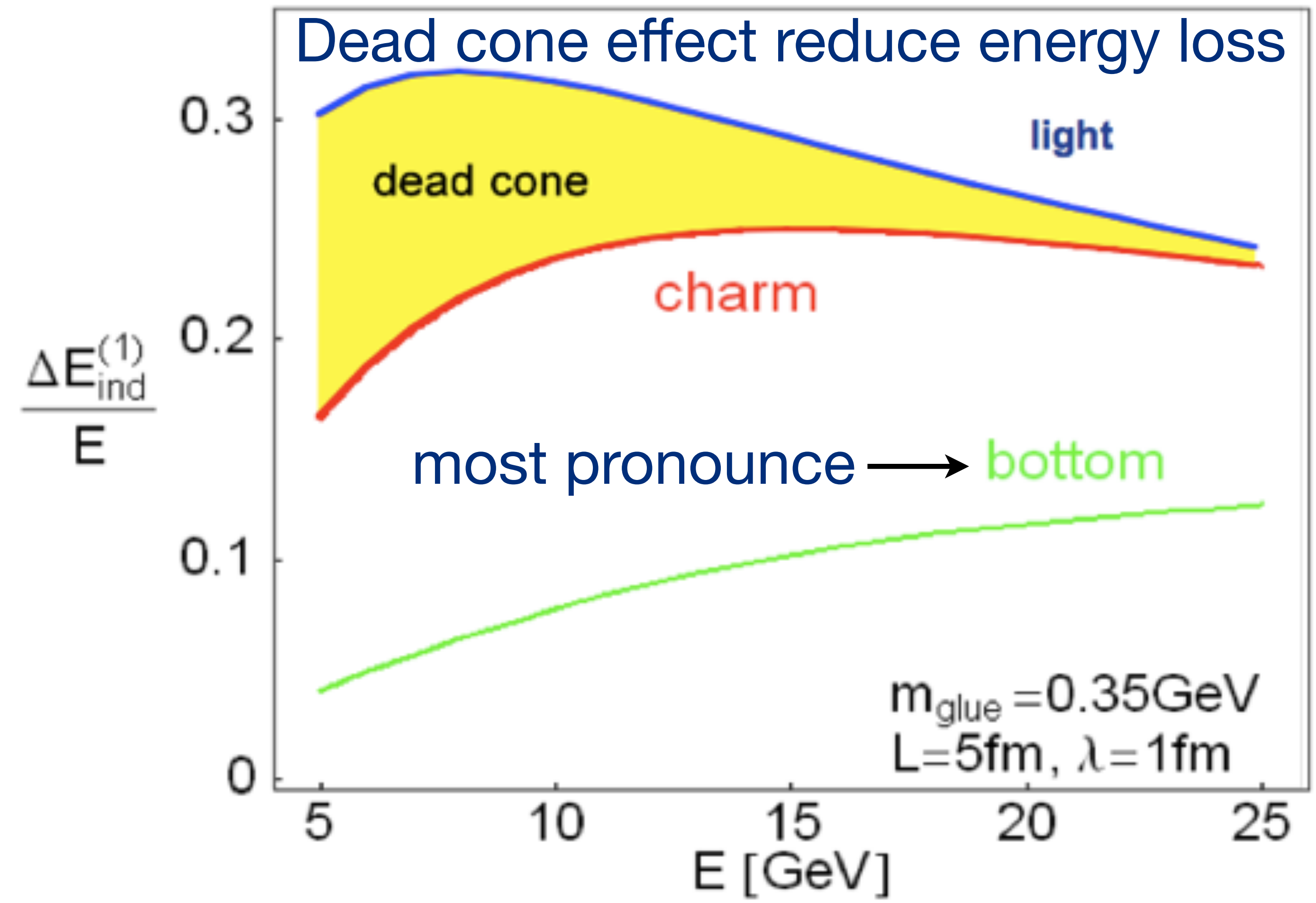
⇒ suppression of high-energy tail for heavy quarks
⇒ more pronounced for beauty

Dead cone effect in other model

medium induced gluon energy distribution



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



M.Djordjevic J.Phys.G30:S1183-S1188,2004

Baier, Dokshitzer, Mueller, Peigne‘, Schiff, NPB 483 (1997) 291. Salgado, Wiedemann, PRD 68(2003) 014008. Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003.

Massive calculation confirms this qualitative feature

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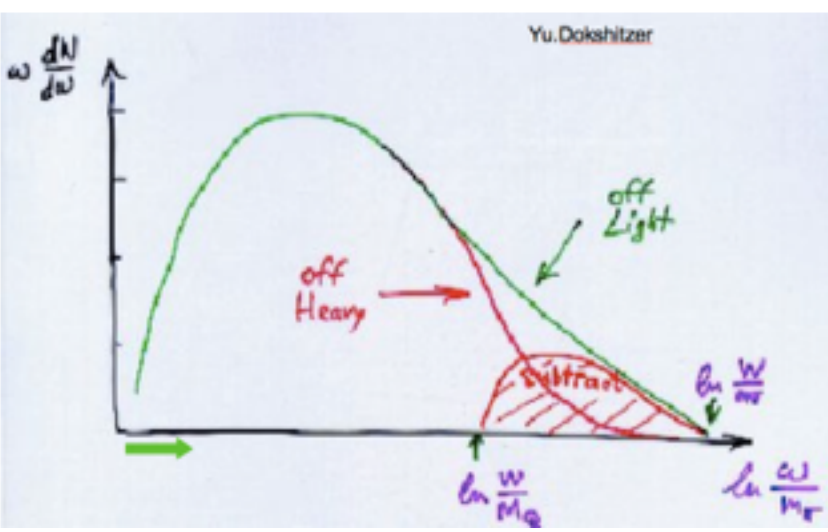

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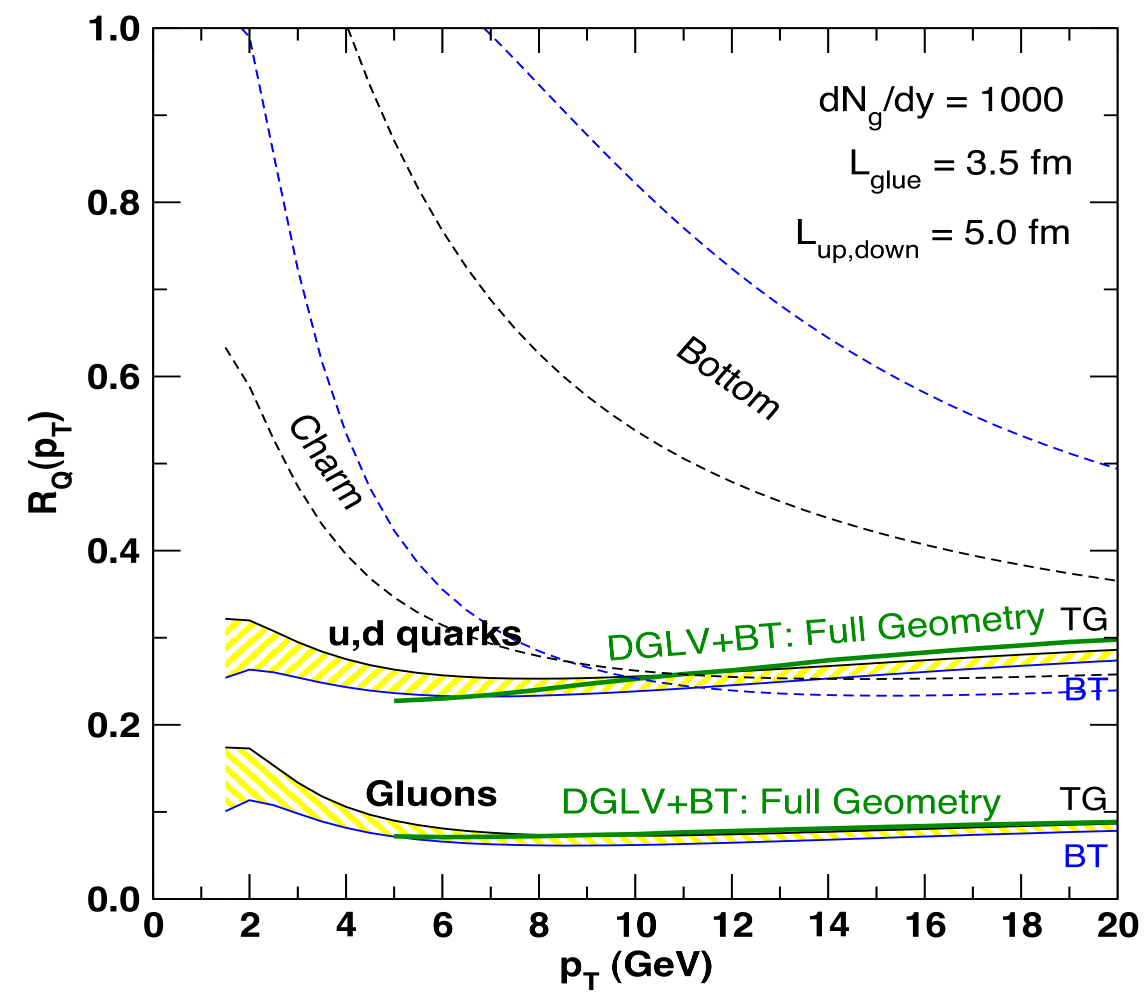
⇒ more pronounced for beauty

Color charge dependence of energy loss

gluon radiation spectrum by the parton propagation in the medium:

$$\omega \frac{dI}{d\omega} \propto \alpha_s C_R f(\omega)$$

$$,where \quad C_R = 3 \ for\ g, \ \frac{4}{3} \ for\ q$$



here, $R_Q = d\sigma_Q^{final} / d\sigma_Q^{initial}$ (partonic modification factor before hadronization)

Heavy quark energy loss

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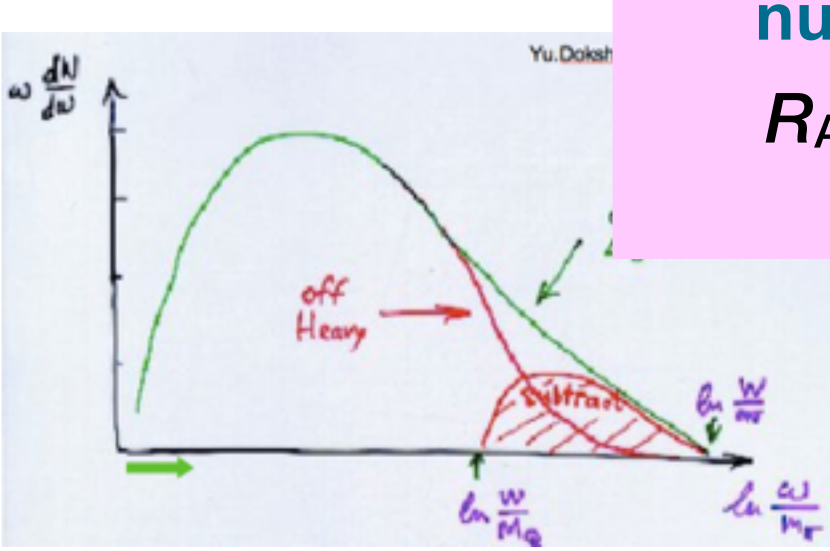
$, w$



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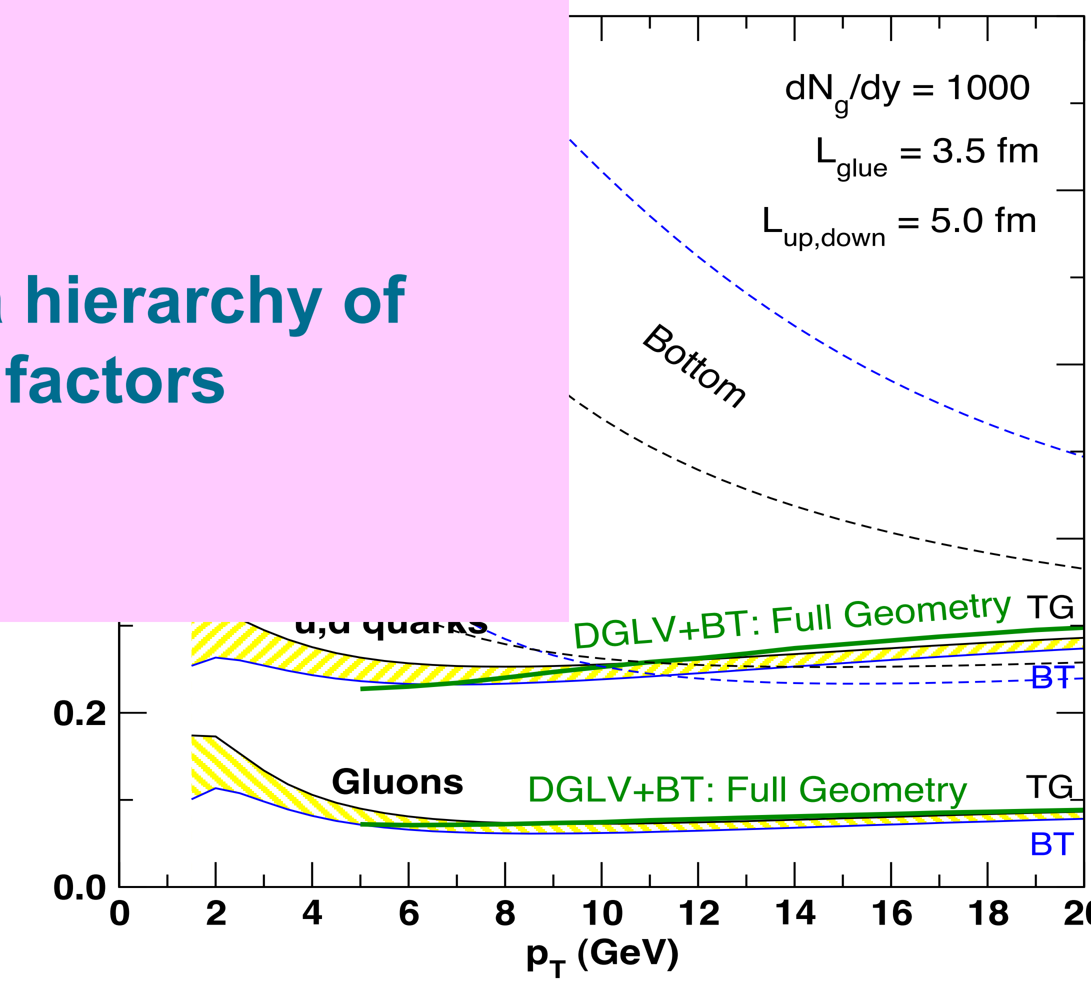
$$\Delta E(\varepsilon_{medium}; C_R, m, L)$$

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

Might translate into a hierarchy of nuclear modification factors

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



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How can we measure medium effects?

Nuclear modification factor (R_{AA}): compare particle production in Pb-Pb with that in pp scaled by a geometrical 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**

Trivial but important caveat:

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

- Initial-state effects: $PDF(x_1)PDF(x_2)$
- "Vacuum" parton spectra: $\frac{\mathrm{d}\hat{\sigma}^{c}}{\mathrm{d}p_T}$
- Parton interaction with the medium: $P(\Delta E)$
- (Modified?) hadronization: $D_{c \to D}(z)$
- What we want to probe: $P(\Delta E) \otimes D_{c \to D}(z)$

Measured spectra in AA collisions result from a convolution of many pieces

⇒ interpretation of the results requires **comparison with models**

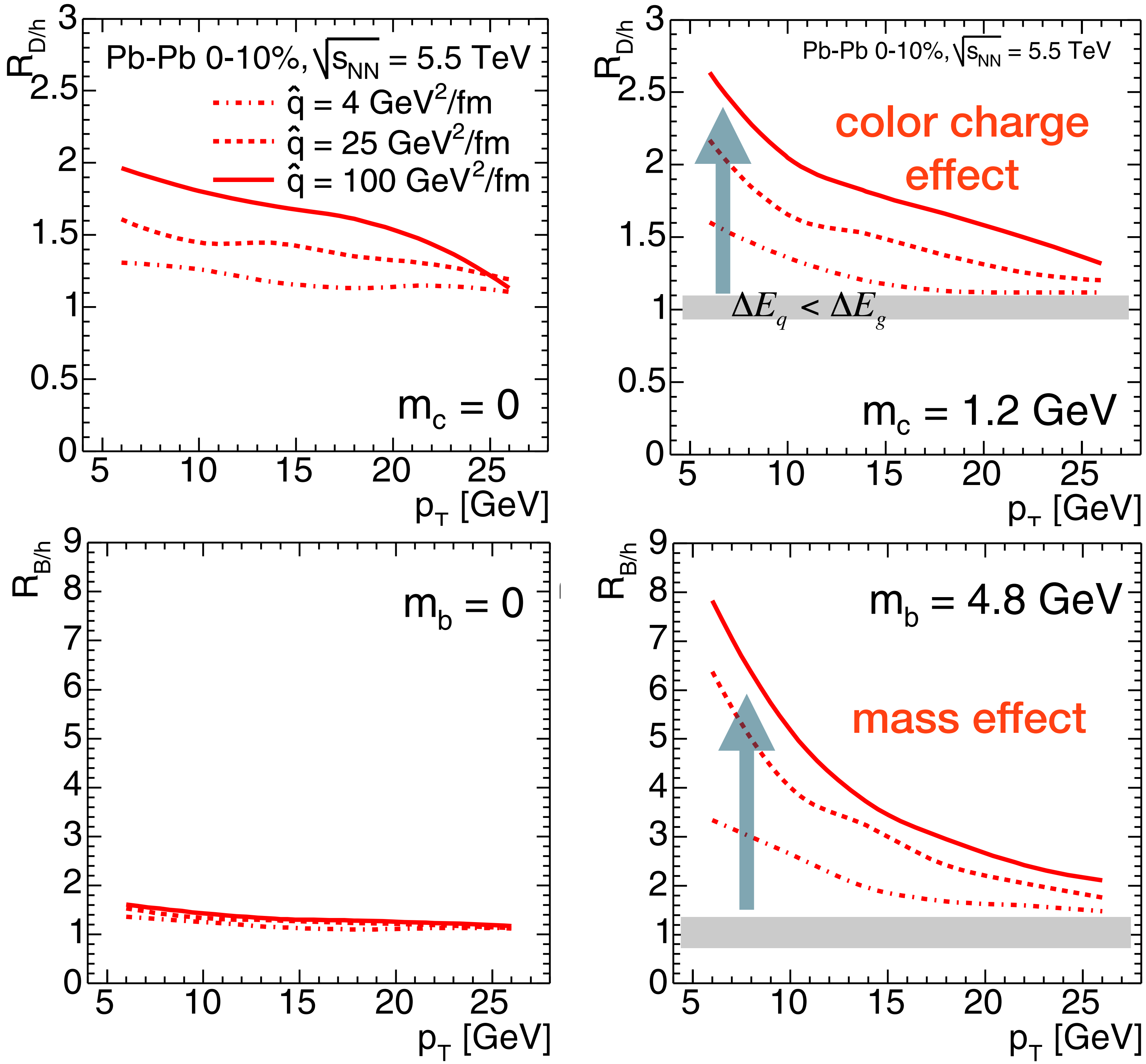
⇒ must measure **observables with different sensitivity** to the various ingredients

Color charge effect and mass effect

Heavy-to-light ratios: $R_{D(B)/h}(p_T) = R_{AA}^{D(B)}(p_t) / R_{AA}^{h}(p_t)$

(Light flavour hadrons mainly from gluons)

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



Note:

At p_T > 10 GeV, the charm mass dependence of parton energy loss becomes negligible since $m_c/p_T \to 0$

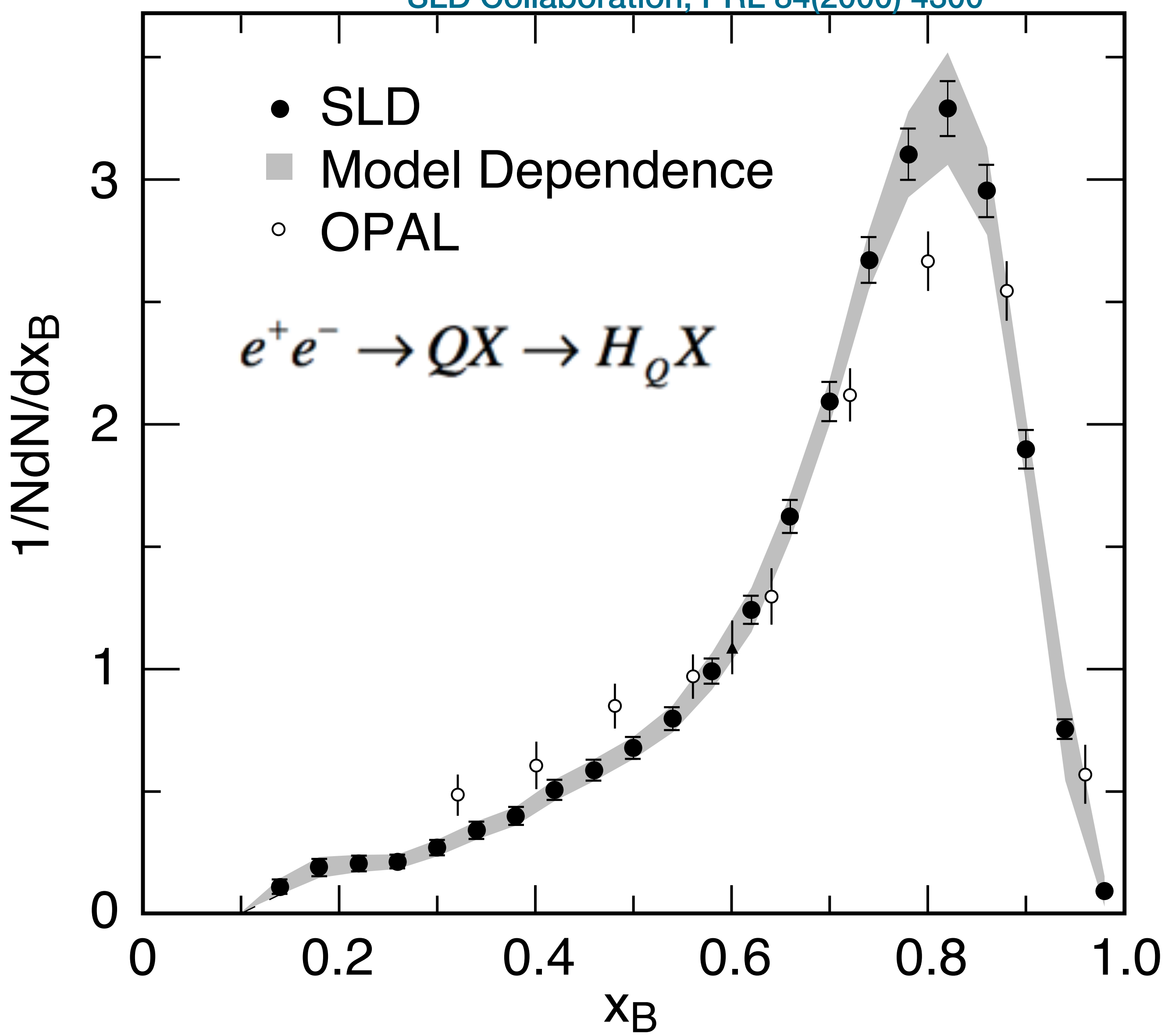
At smaller Bjorken x, a larger fraction of the produced light-flavored hadrons have gluon parents and thus the color charge dependence of parton energy loss can leave a much more sizable effect in the heavy-to-light ratio $R_{D/h}$ at LHC

$R_{D/h}$ enhancement probes colour-charge dependence of energy loss

$R_{B/h}$ enhancement probes mass dependence of energy loss

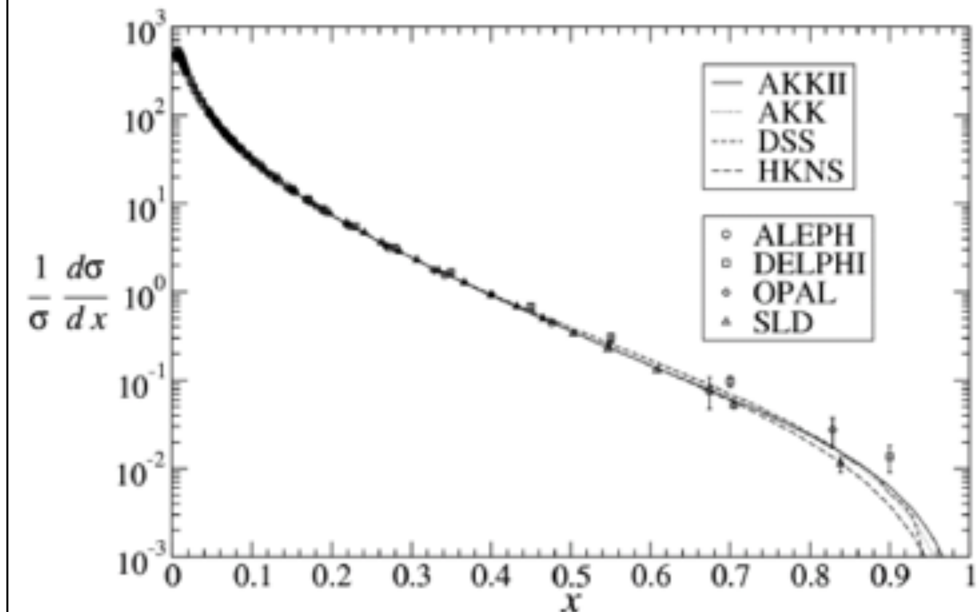
b quark fragmentation

SLD Collaboration, PRL 84(2000) 4300



b-quark fragments much harder than light quarks(due to dead cone effect in the vacuum)

for gluon

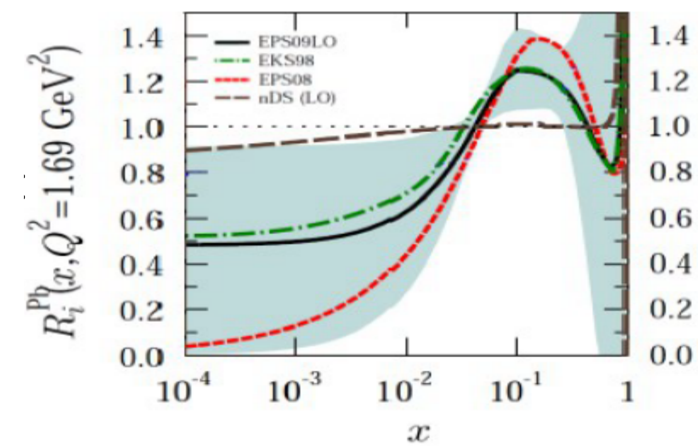


- Hard fragmentation
  ➜ measured meson properties closer to parton ones
  ➜ Jet energy can be measured more precisely
  ⇒better handle on the fragmentation function to extract medium modification effect

pp and p-Pb collisions (small systems!)

pp collisions

- Testing ground for perturbative QCD calculations
- Relevant production mechanisms on the parton level
  - LO: gluon fusion, quark-antiquark annihilation
  - NLO: gluon splitting, flavor excitation
  - Multi Parton Interactions (MPI)
- Reference for p-Pb and Pb-Pb collisions



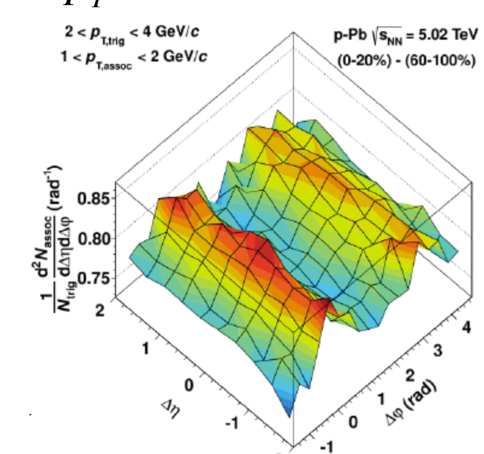
K. J. Eskola et al: JHEP04(2009)065

p-Pb collisions

- Quantify cold nuclear matter effects: measure effects, not due to QGP formation, that can modify the yield of hard probes in nuclear collisions

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

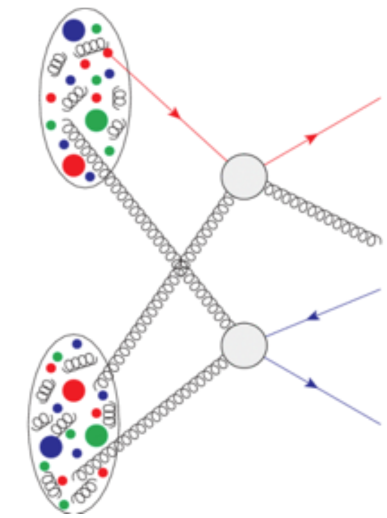
  - nuclear modification of Parton Distribution Functions (shadowing, gluon saturation)
  - k_T broadening via multiple scattering of the parton before the hard scattering
  - energy loss in cold nuclear matter
- Final state effects? (e.g. from system collectivitiy/hydro)



charged particles: long range correlation

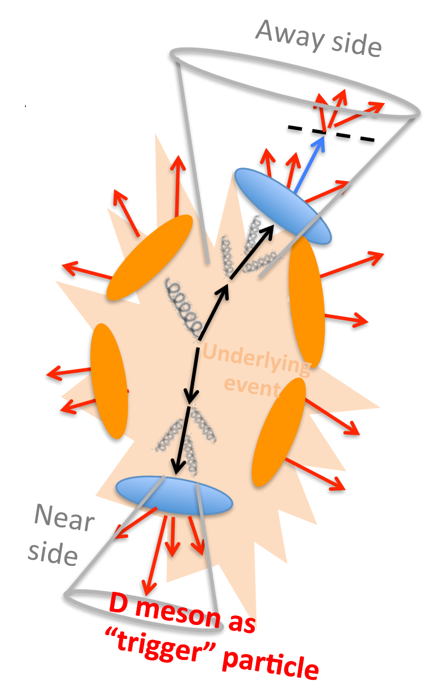
pp and p-Pb collisions, more differential measurements

HF production vs. multiplicity in pp and p-Pb collisions

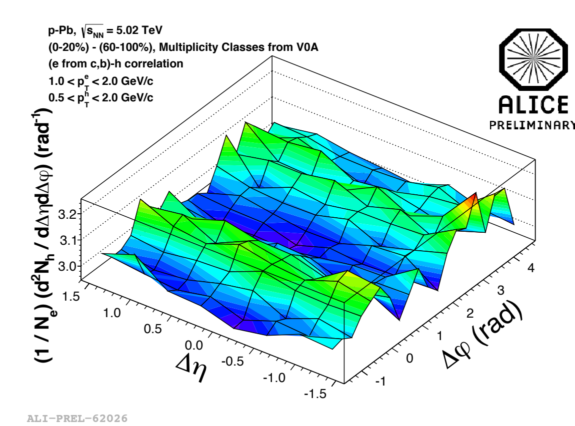


- Interplay between **hard and soft** processes in particle production
- Study the role of **multi-parton interactions (MPI)** in the **heavy-flavour** sector
- Investigate a **possible centrality dependence** of the modification of the p_T spectra in p-Pb w.r.t. pp collisions

Azimuthal correlation of D meson with charged particles in pp and p-Pb collisions



- Sensitive to **charm quark fragmentation** properties → address charm jet properties
- **Modification of angular correlations** in p-Pb w.r.t. pp collisions?
  - may arise from both initial and final-state effects
- **Reference** for Pb-Pb measurements → **complementary** information to R_{AA} and v_2 measurements to study in-medium energy loss (e.g. path-length dependence)



Heavy flavours

Results in pp and p-Pb collisions

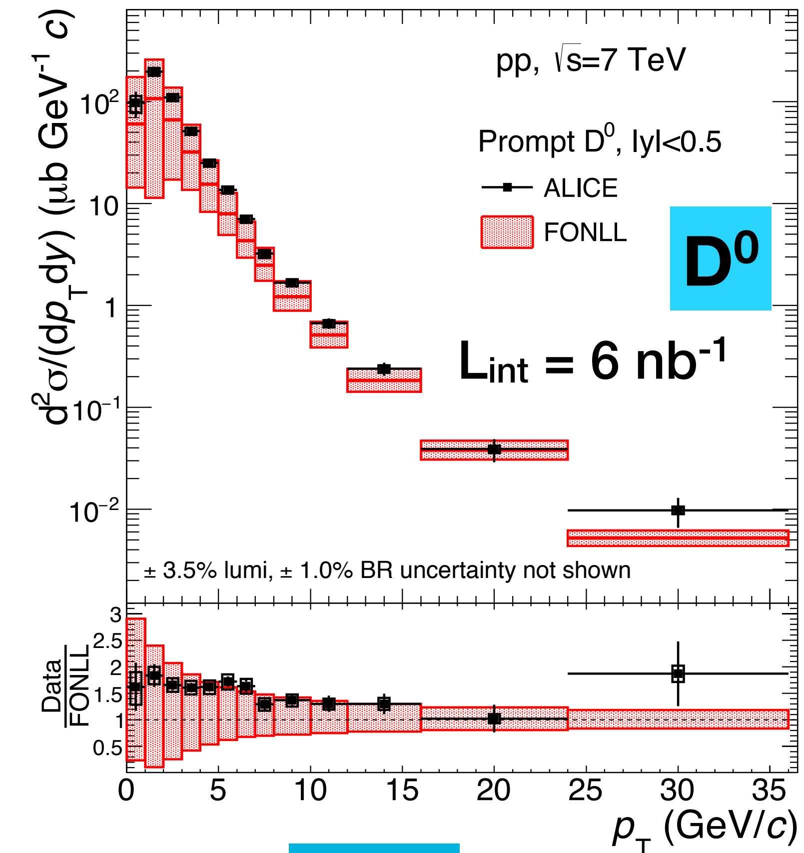
Small systems!

D mesons down to p_T=0

[1] JHEP 05 (1998) 007, JHEP10(2012)137

arXiv:1702.00766

pp, $\sqrt{s}$ = 7 TeV

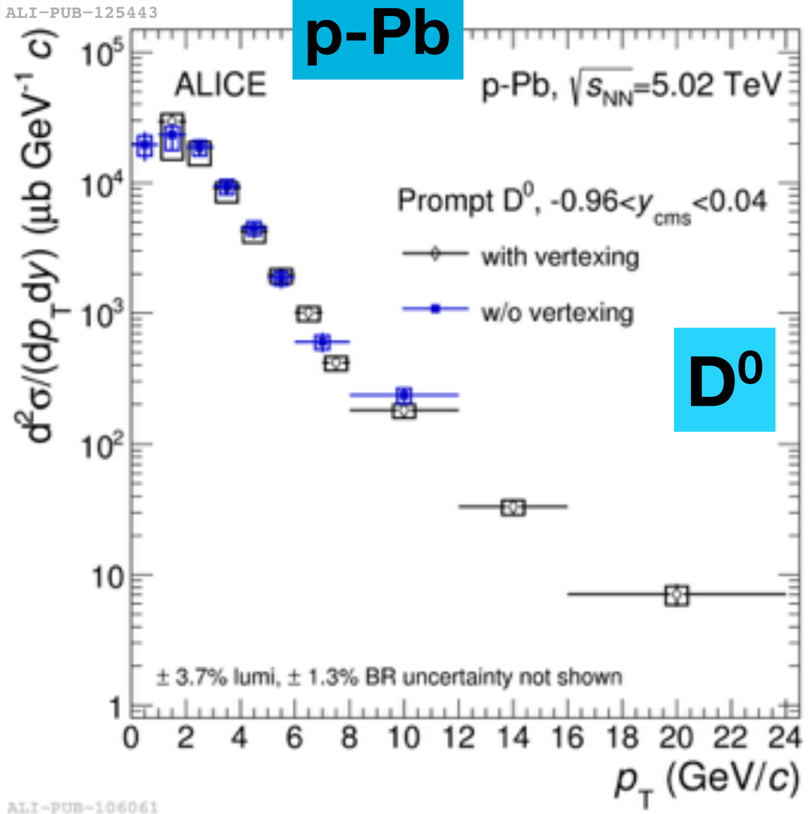


New analysis of 2010 pp data at $\sqrt{s}$ = 7 TeV (D^0,D^+,D^{*+},D^+_s)

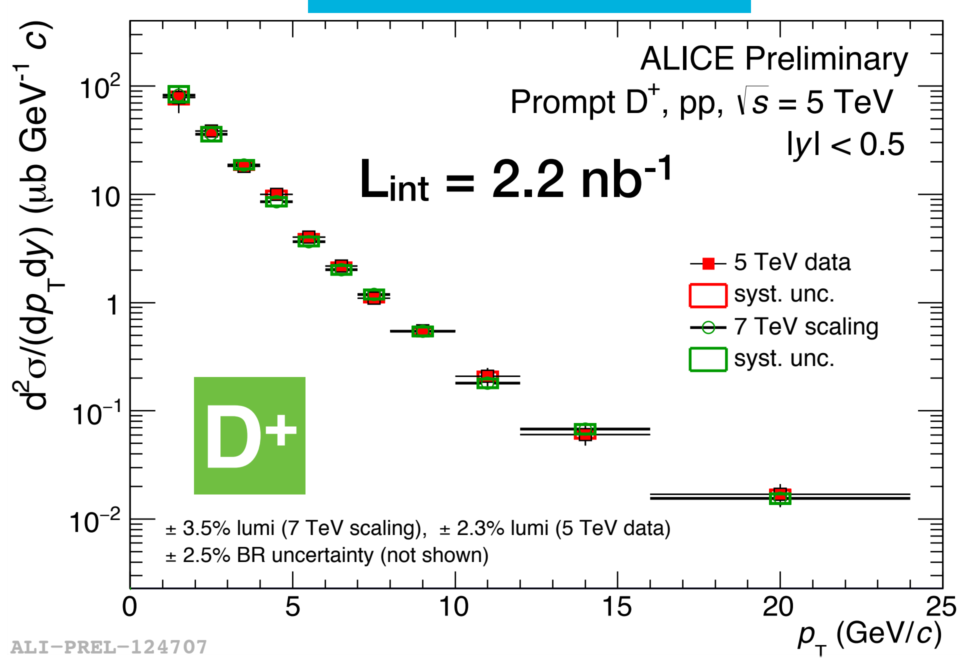
Extended p_T coverage w.r.t. previous analysis systematic uncertainty **reduced by a factor 2!**

- **pQCD-based** theoretical calculations reproduce the data
- **Data much more precise** than theoretical calculations!

p-Pb



pp, $\sqrt{s}$ = 5 TeV

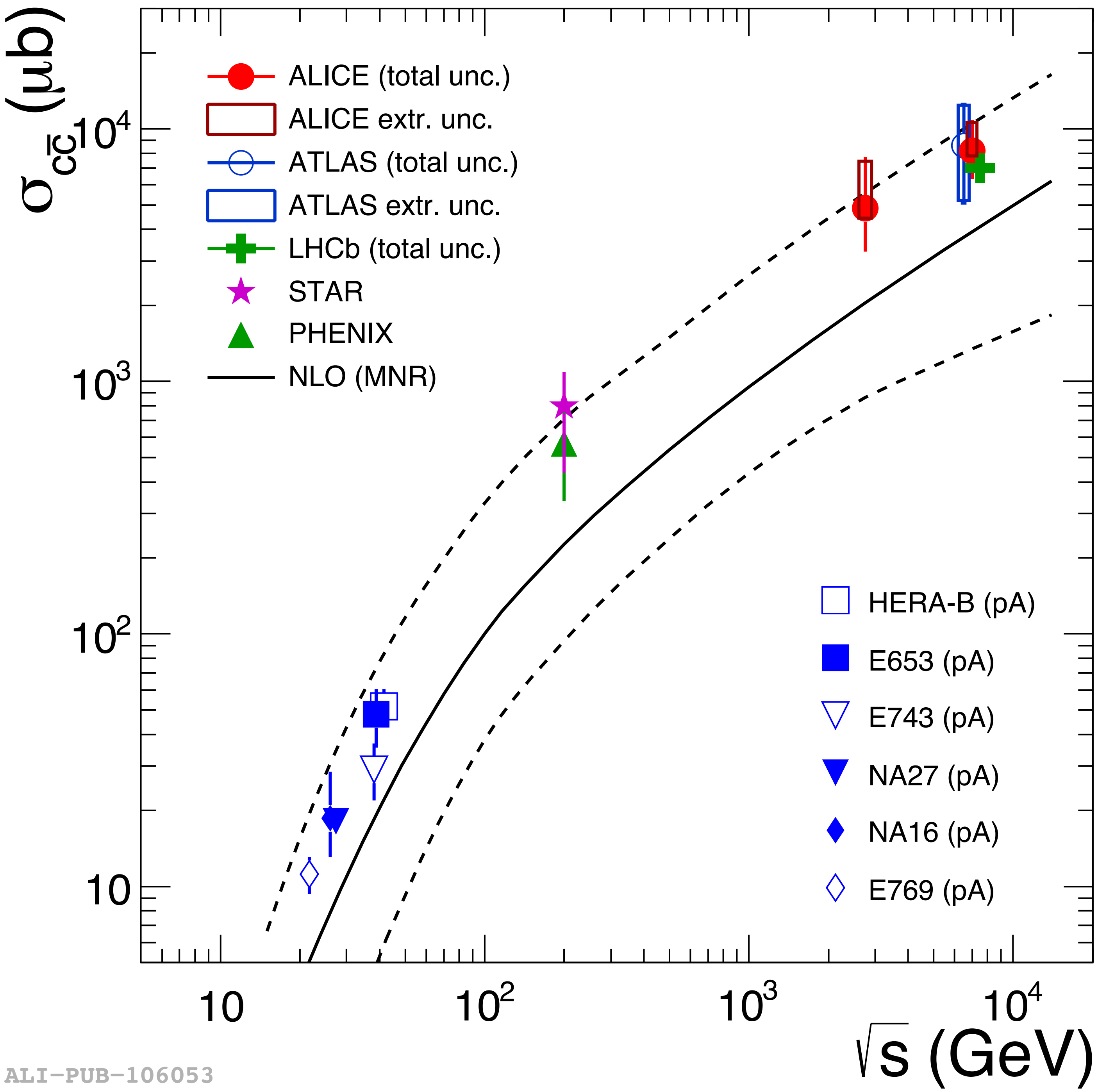


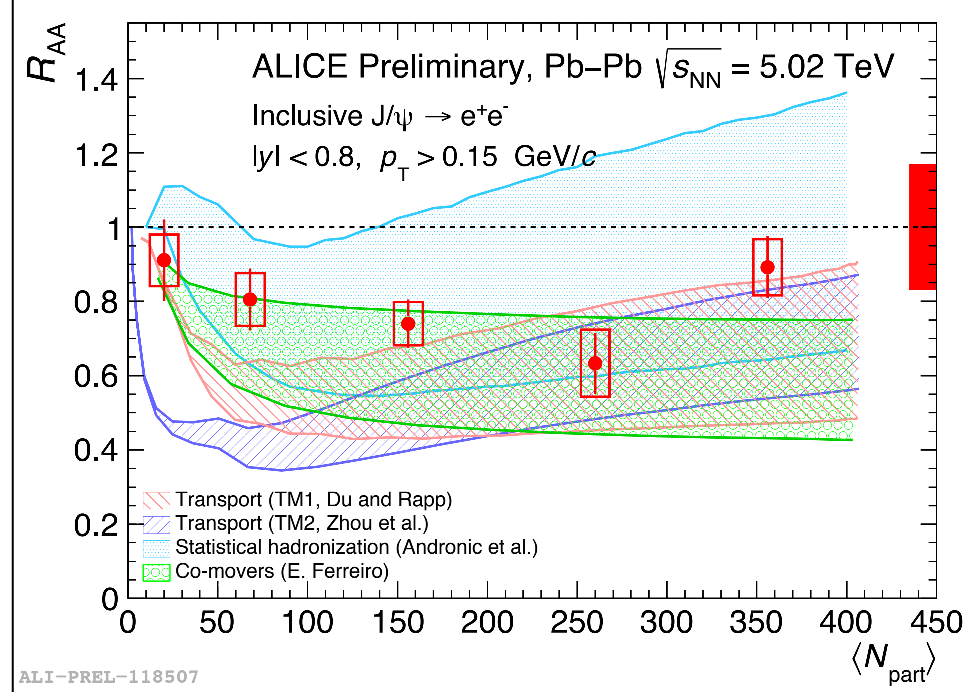
New analysis of 2015 pp data at $\sqrt{s}$ = 5.02 TeV

D-meson cross sections in pp at 5 TeV **compatible** within uncertainties with FONLL[1] predictions at 5 TeV and with extrapolated cross section from 7 TeV data

Total Charm Cross Section

arXiv:1605.07569





Transport and statistical models have large uncertainties (shadowing+open charm cross section)

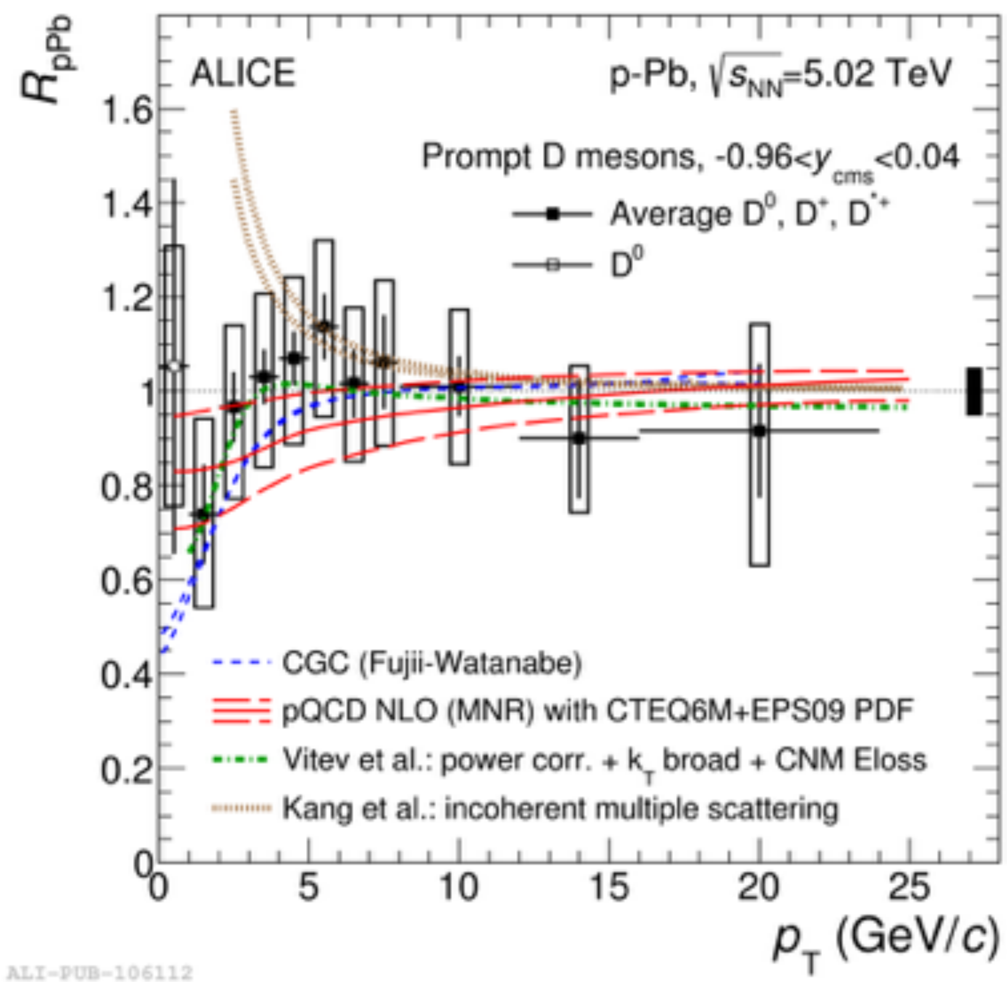
Factor ~2 reduction on systematic uncertainty

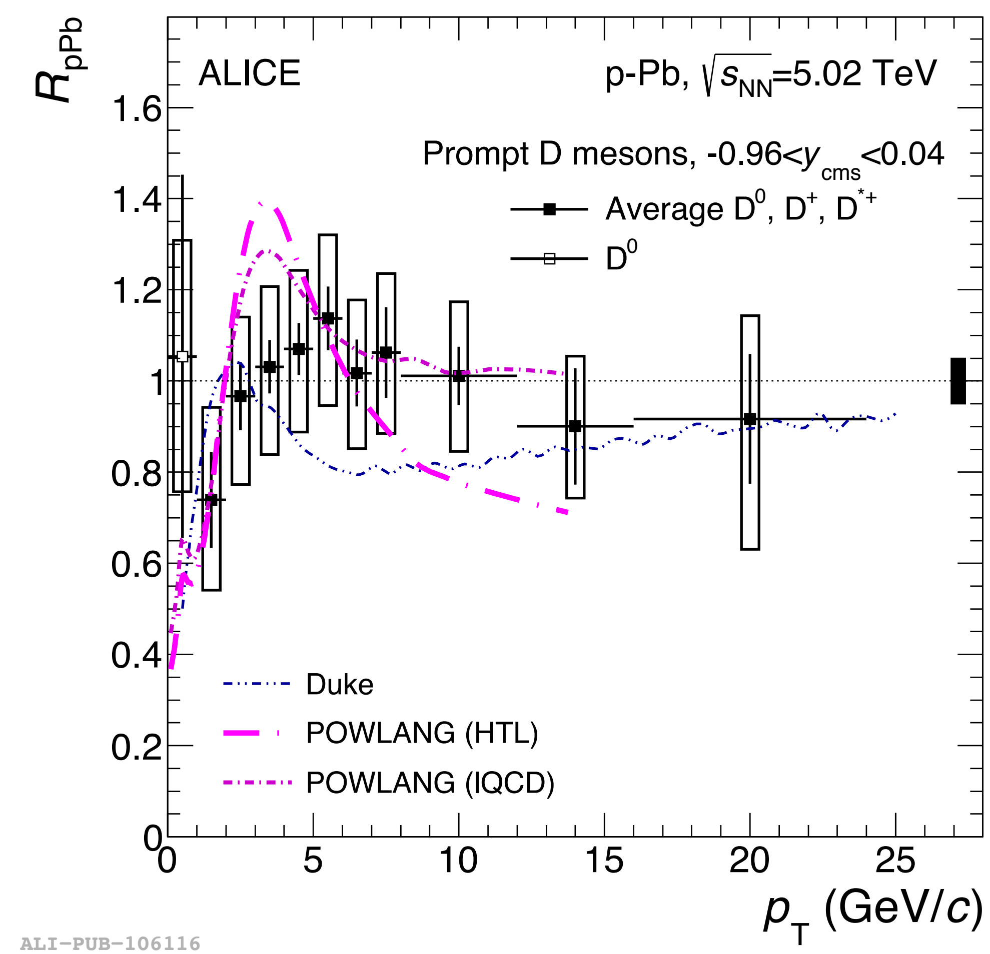
Important input for model!

D-meson R_{pPb}

D^0 and D-mesons

arXiv:1605.07569



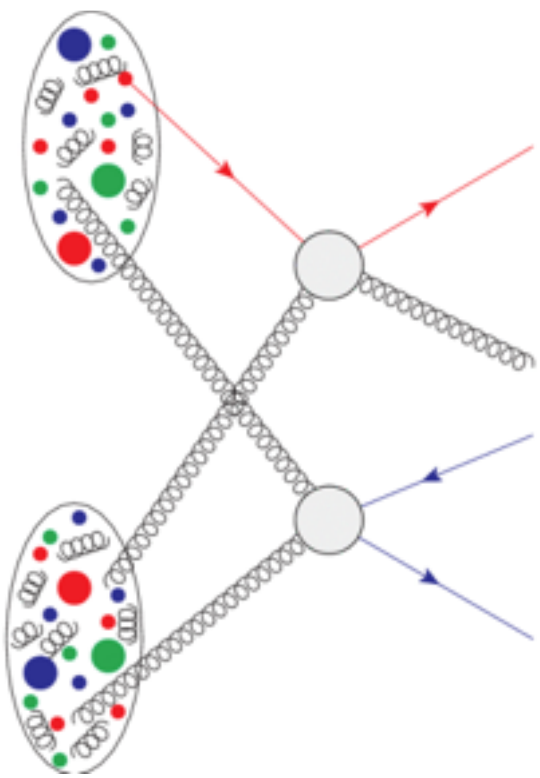


- D-meson R_{pPb} **compatible with unity** within uncertainties
- Data are described by models **including initial-state and cold nuclear matter effects** **(left panel)**, as well as by models assuming the formation of a **small-size QGP** in p-Pb collisions **(right panel)**
- **Need larger samples** of both p-Pb and pp collisions @5 TeV for constraining models at low p_T where predictions differentiate.

Results in pp and p-Pb collisions:

Toward more differential measurements!

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



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

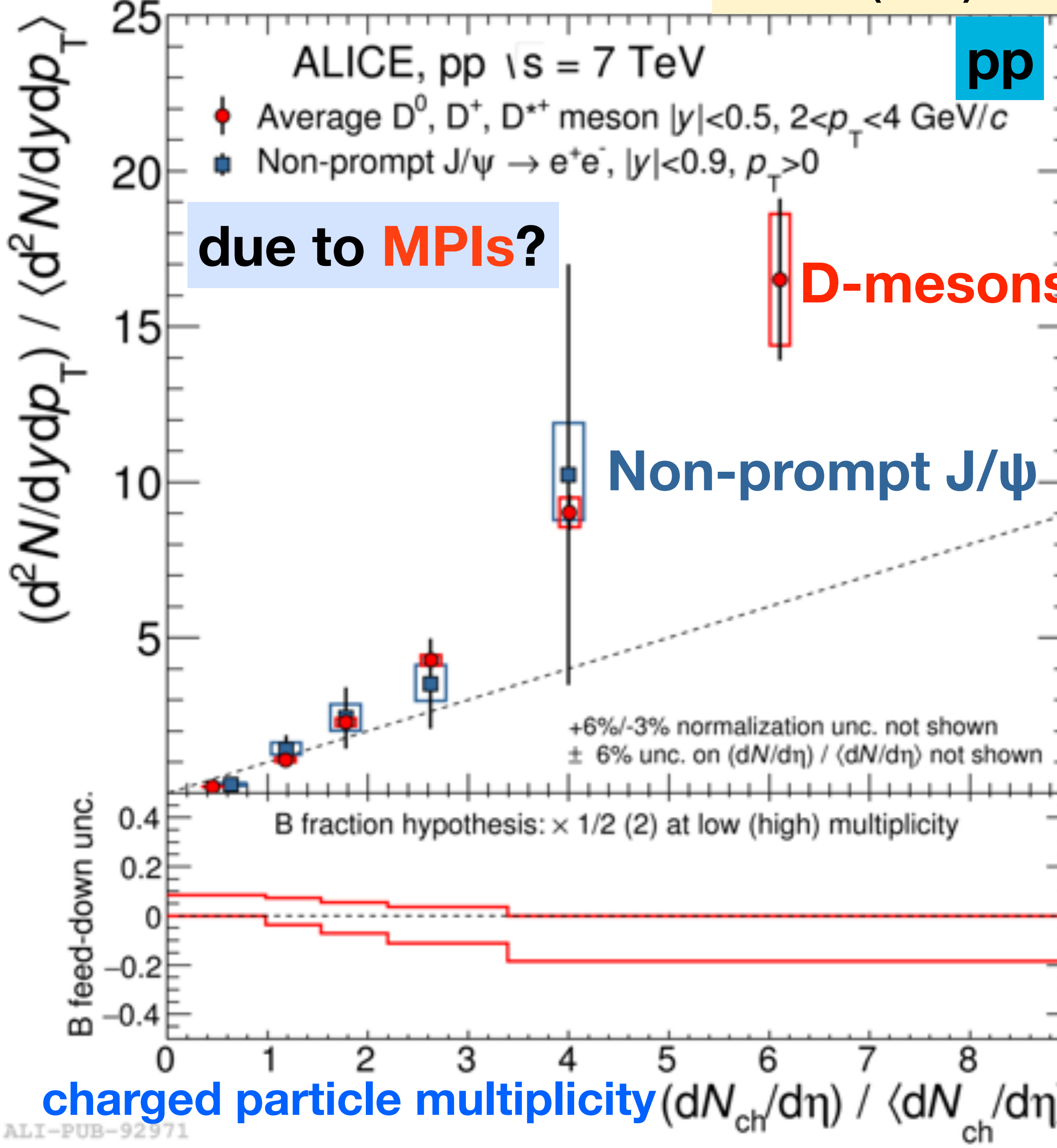
↓

For heavy flavours:

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

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

JHEP09 (2015) 148

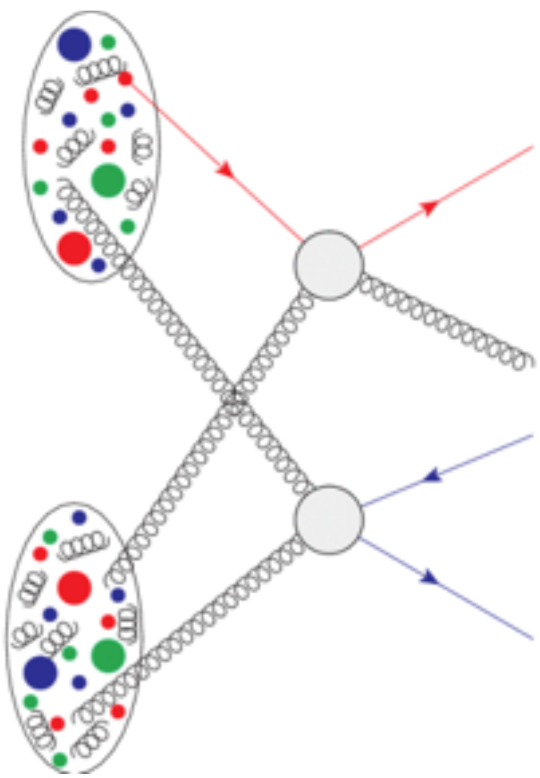


MPIs involving only light quarks and gluons, or for heavy-flavour production?

- 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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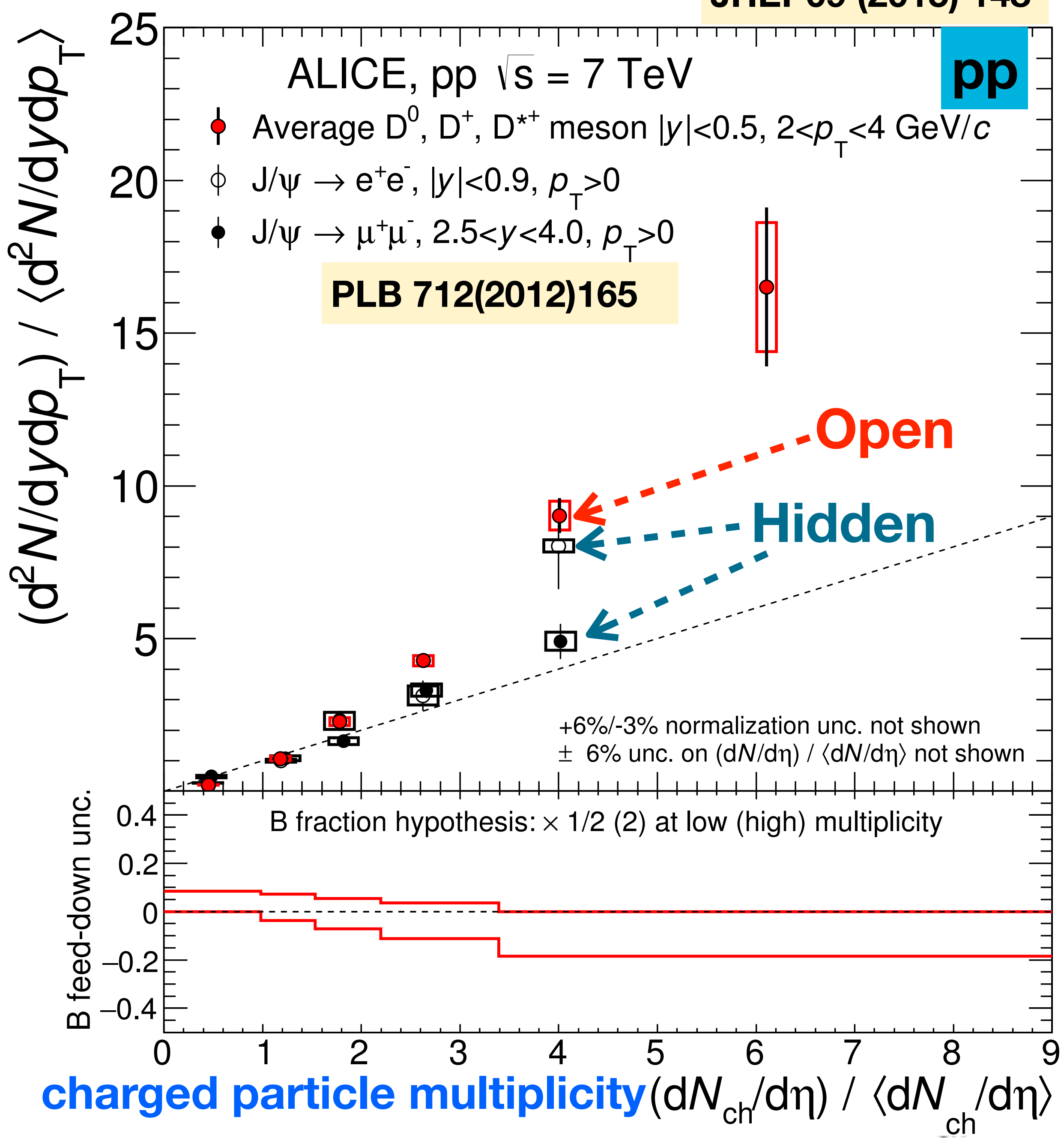
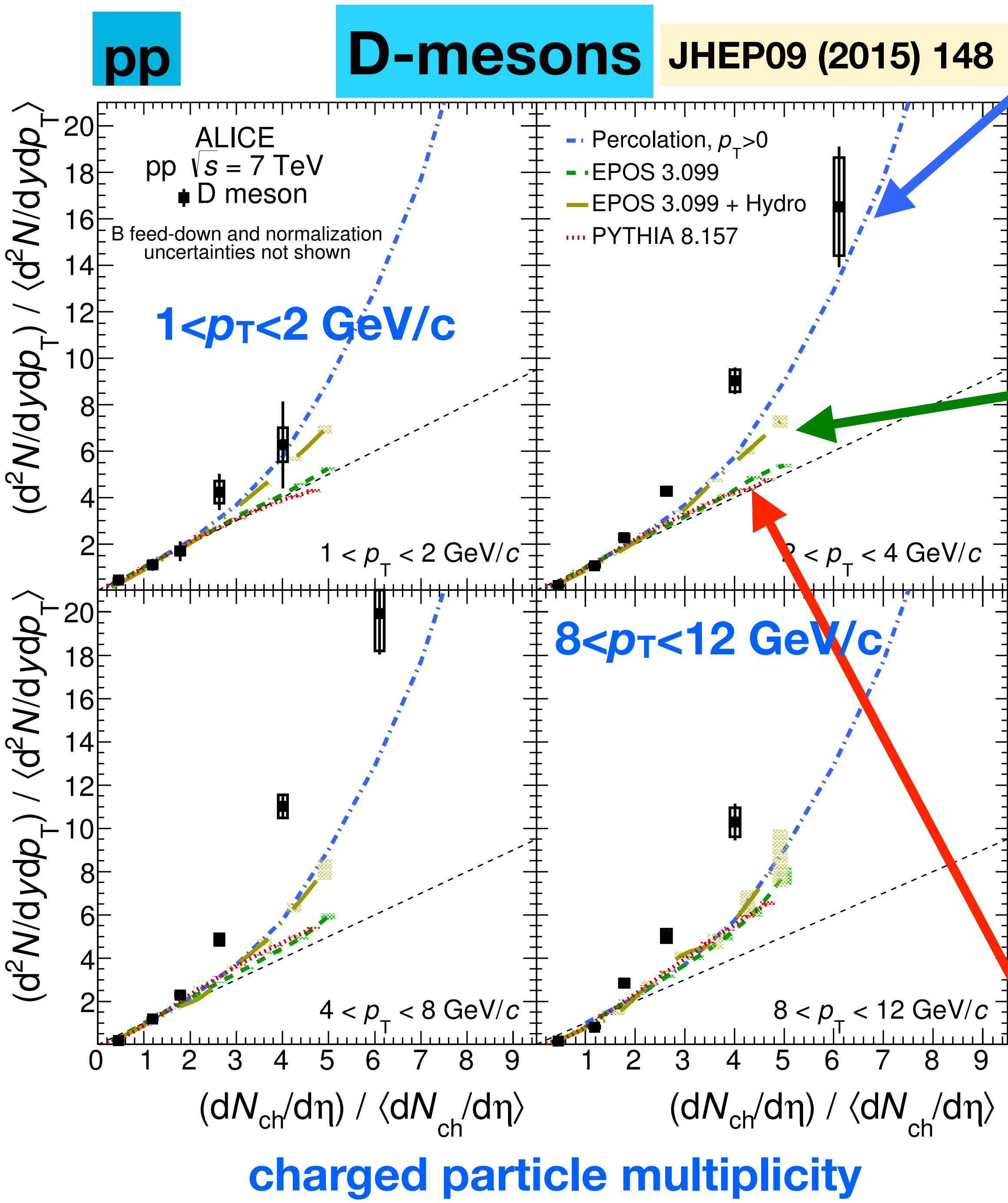


MPIs involving only light quarks and gluons, or for heavy-flavour production?

- 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!**

D-meson yields vs. multipicity: comparison with models (pp)



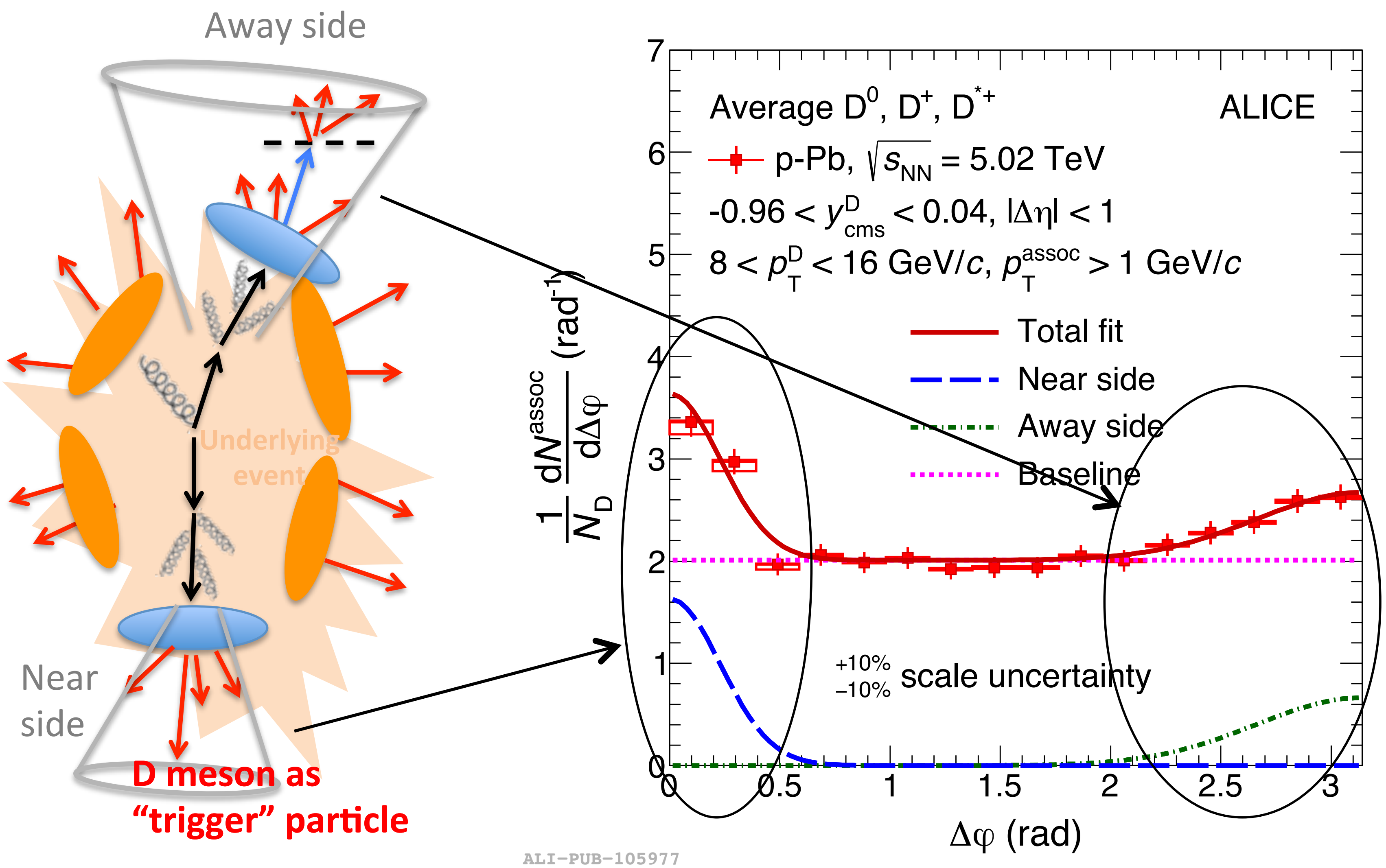
- **Percolation** (Ferreiro, Pajares, PRC 86 (2012) 034903)

  Particle production via exchange of colour sources between projectile and target (close to MPI scenario) → Faster than linear increase

- **EPOS 3.099** (Werner et al., PRC 89 (2014) 064903)
  - Gribov-Regge multiple-scattering formalism
  - Saturation scale to model non-linear effects
  - Number of MPI directly related to multiplicity → slightly faster than linear
  - With hydrodynamical evolution applied to the core of the collision→faster than linear increase

- **PYTHIA 8** (Sjostrand et al., Comput. Phys. Commun. 178 (2008) 852)
  - Soft-QCD tune
  - Colour reconnection
  - MPI

More differential information:
Azimuthal correlations of D mesons with charged particles



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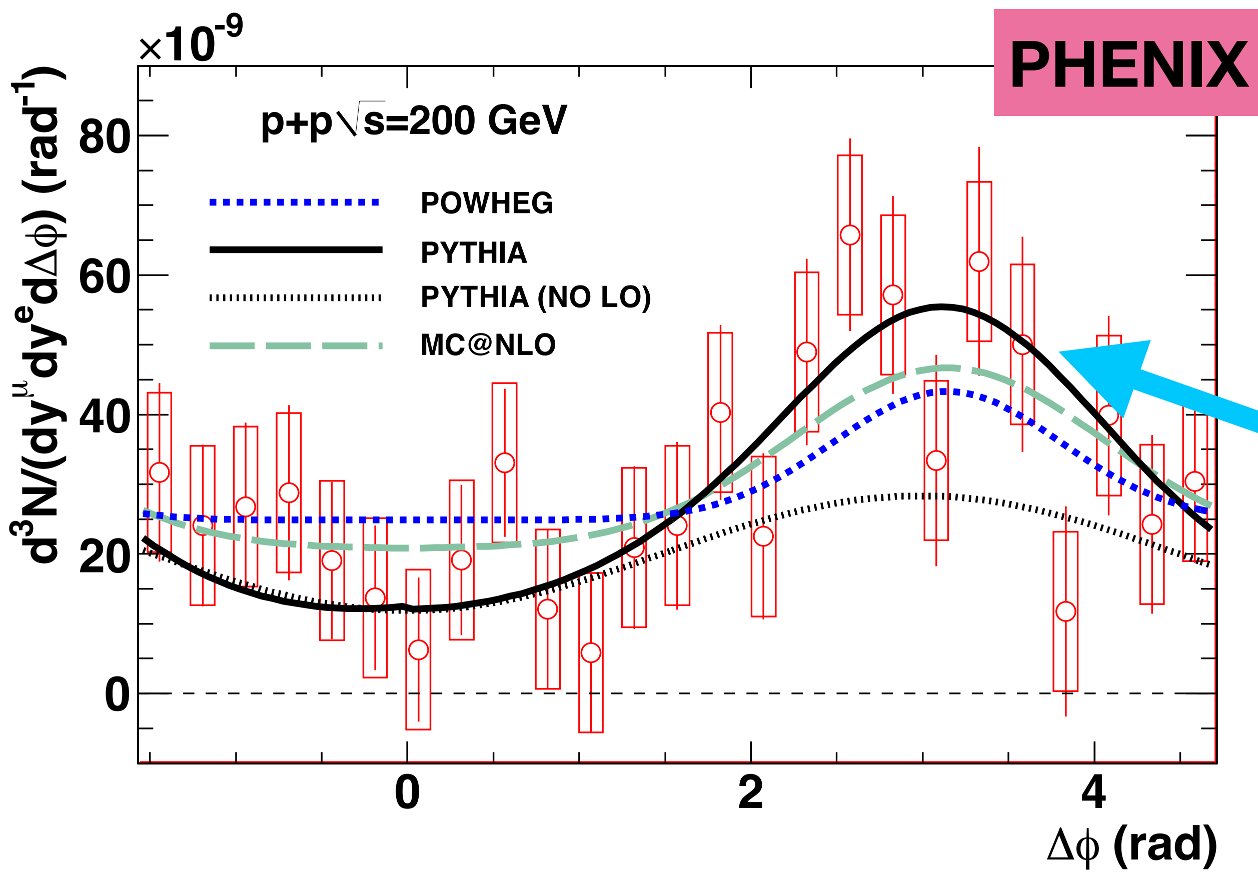
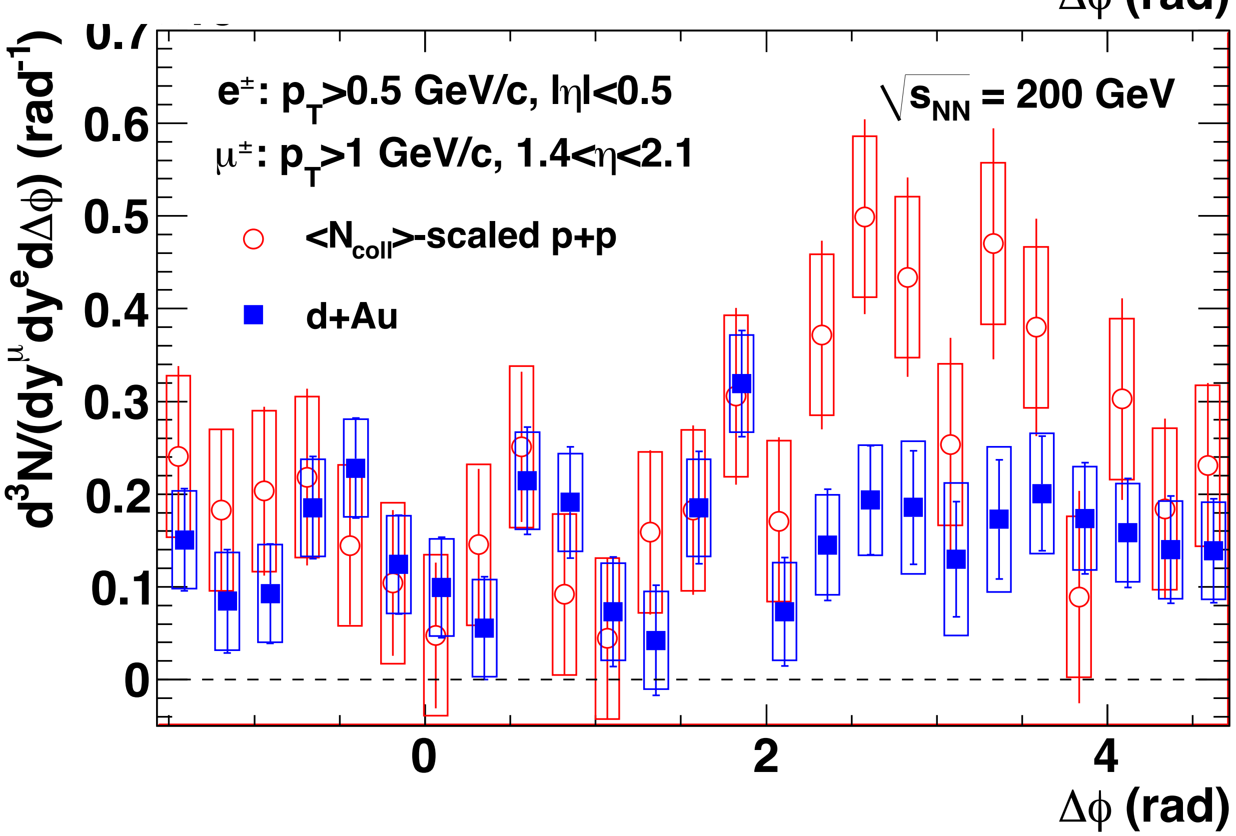
More differential information:
Heavy-flavour electron-muon correlation in d+Au



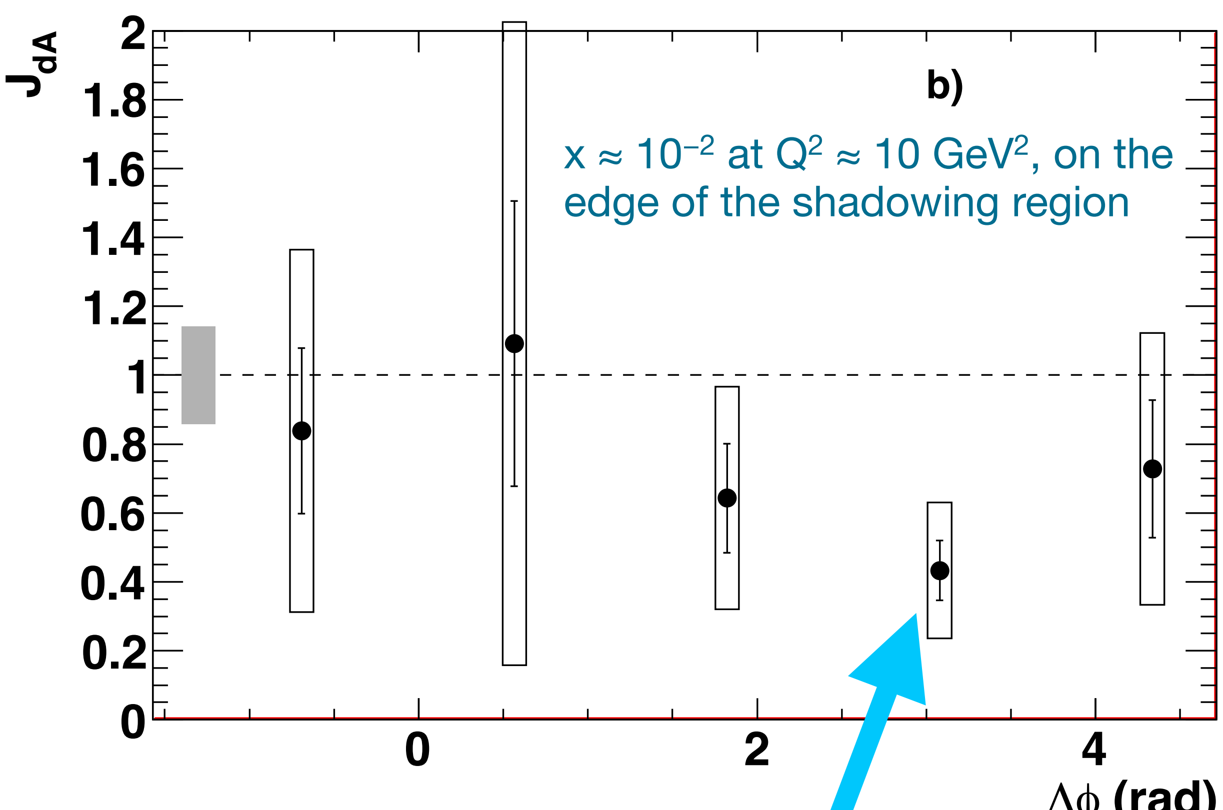
Access to the *g*-PDF?

$$\sigma_{cc} = 538 \pm 46(\text{stat}) \pm 197(\text{data sys}) \pm 174(\text{model sys})\mu b$$

Peak by leading order gluon fusion
Continuum by higher order processes



$$J_{dA} = \frac{d + \text{Au pair yield}}{\langle N_{\text{coll}} \rangle \; p + p \text{ pair yield}}$$

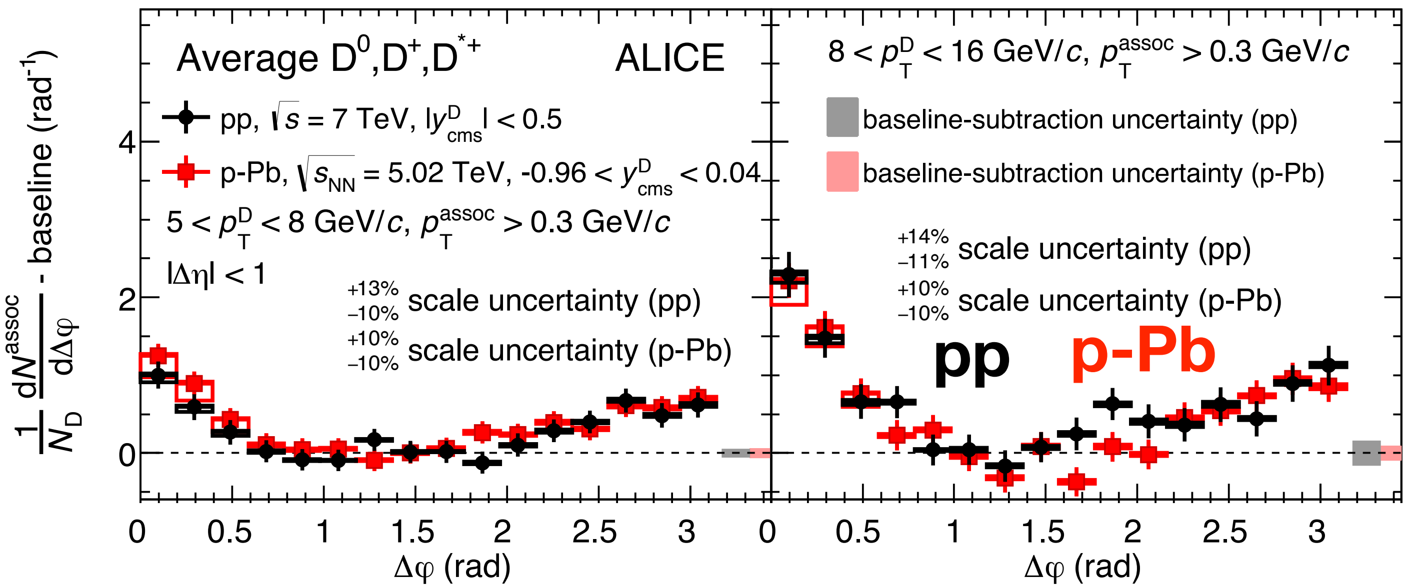


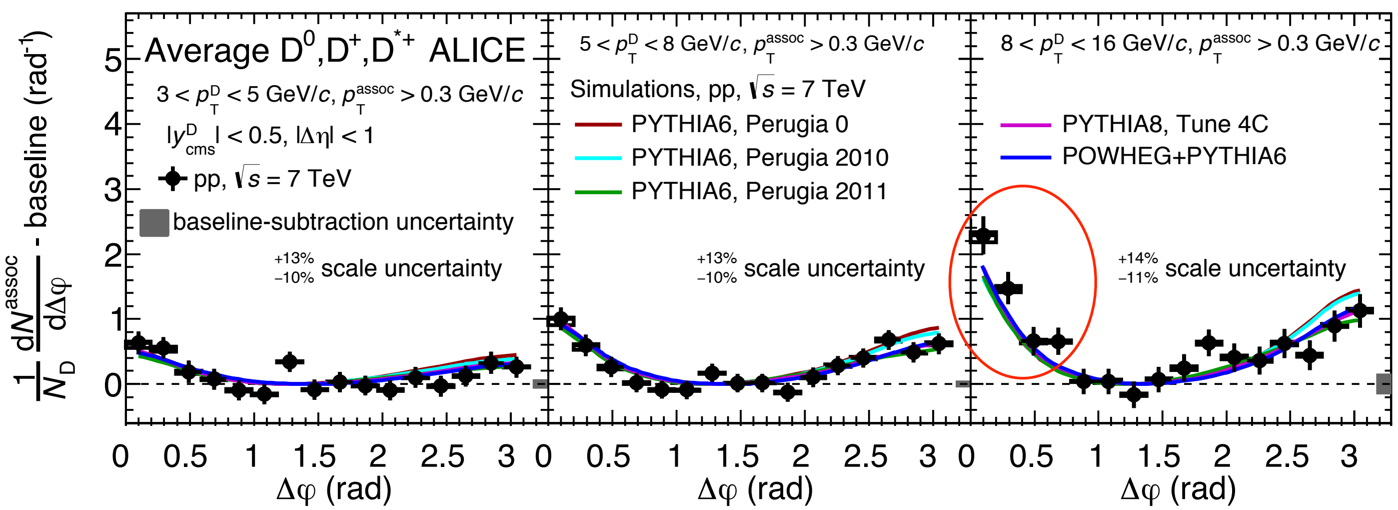
Phys. Rev. C 89, 034915 (2014)

Cold nuclear medium modifies the $c\bar{c}$ correlations

More differential information:
Azimuthal correlations of D mesons with charged particles

arXiv:1605:06963



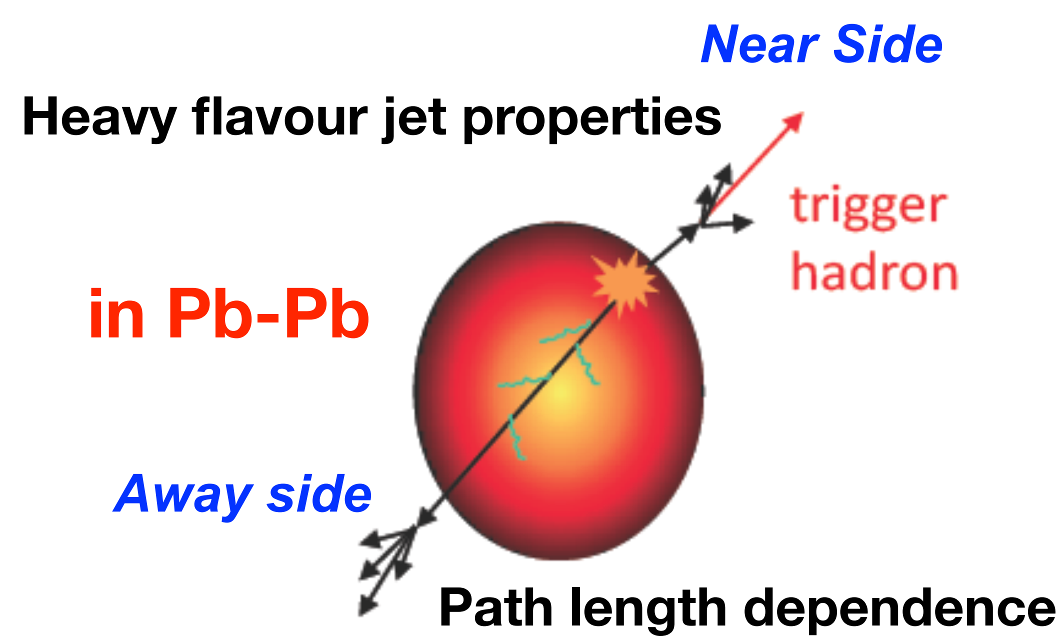


- Baseline-subtracted azimuthal-correlation distributions observed in the **two collision systems are compatible** within uncertainties → **similar initial and final-state effects?**

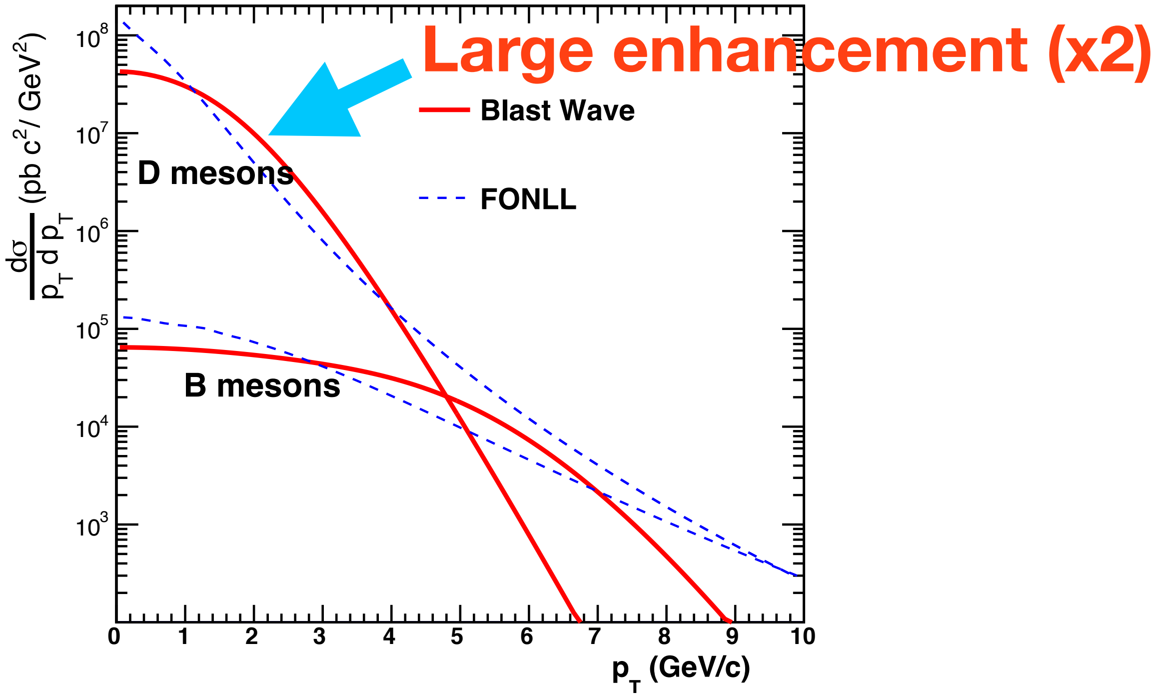
Require precision measurement!

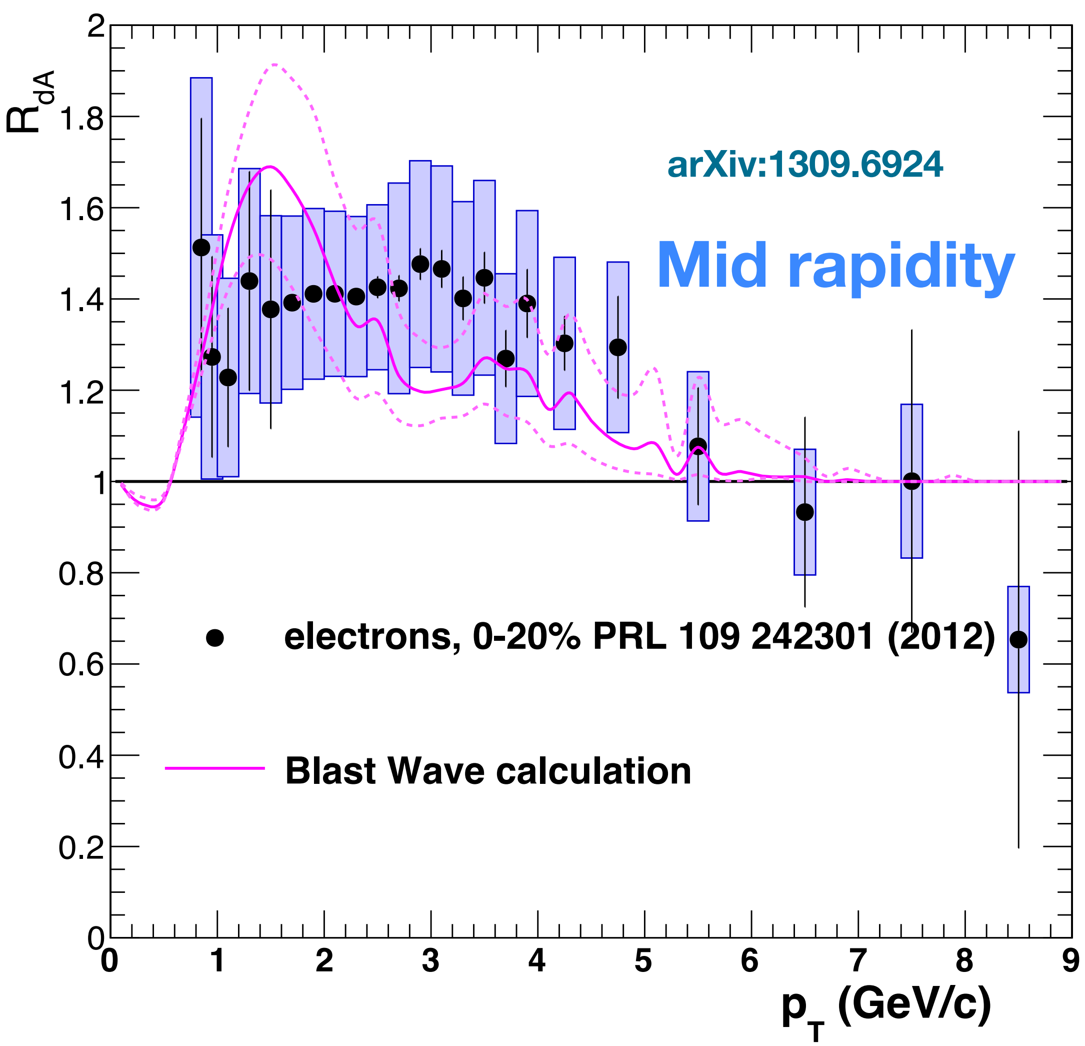
- **MC simulations describe, within the uncertainties**, the data in the whole $\Delta\phi$ range, though a hint for a more **pronounced peak in the near side** in data than in models is present for D mesons at high p_T

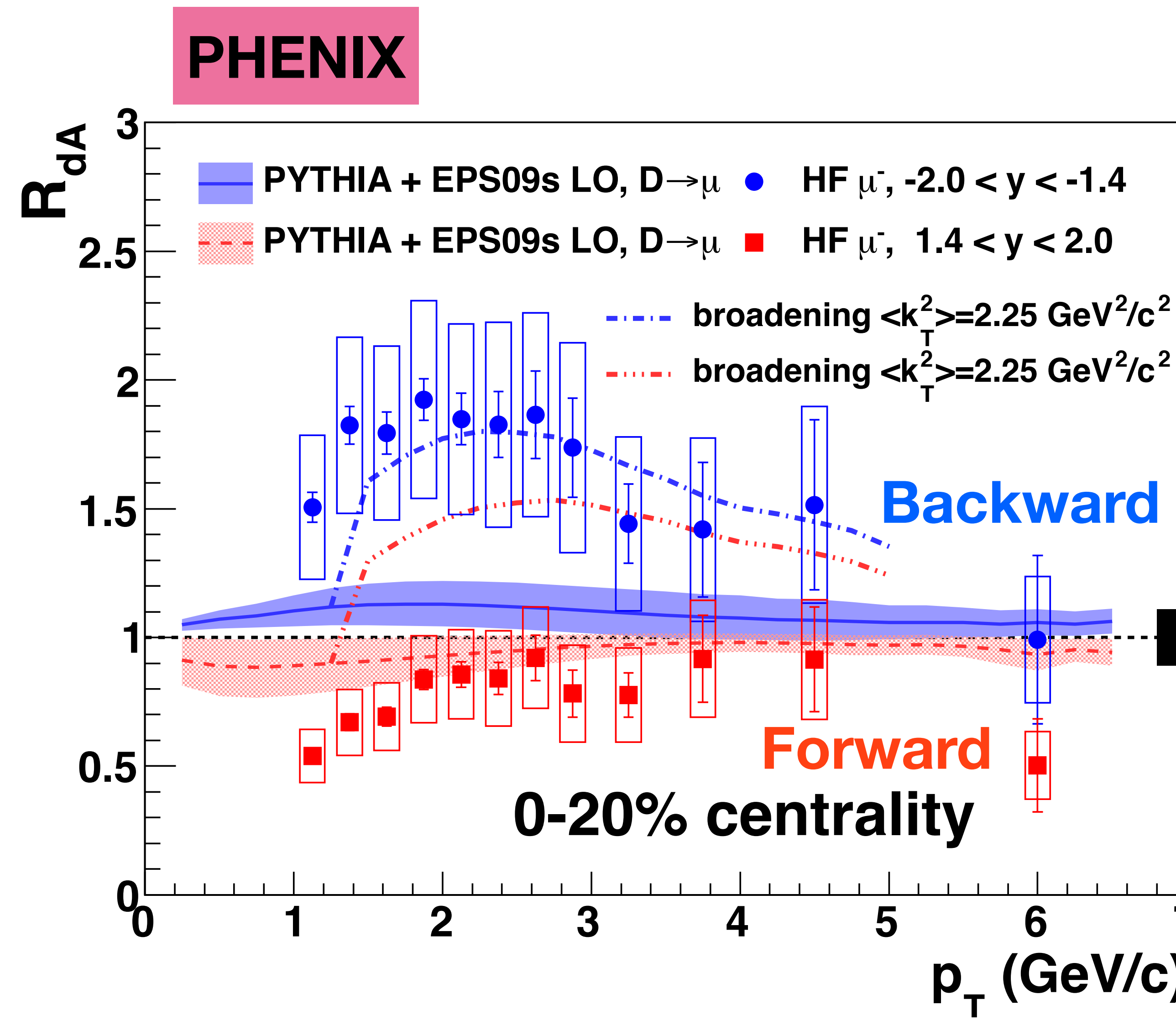
- **Reference for future Pb-Pb measurements** → **complementary** information to R_{AA} and v_2 measurements to study in-medium energy loss (e.g. **path-length dependence**)



More differential information: Hydro?
Enhancement in central d+Au at RHIC







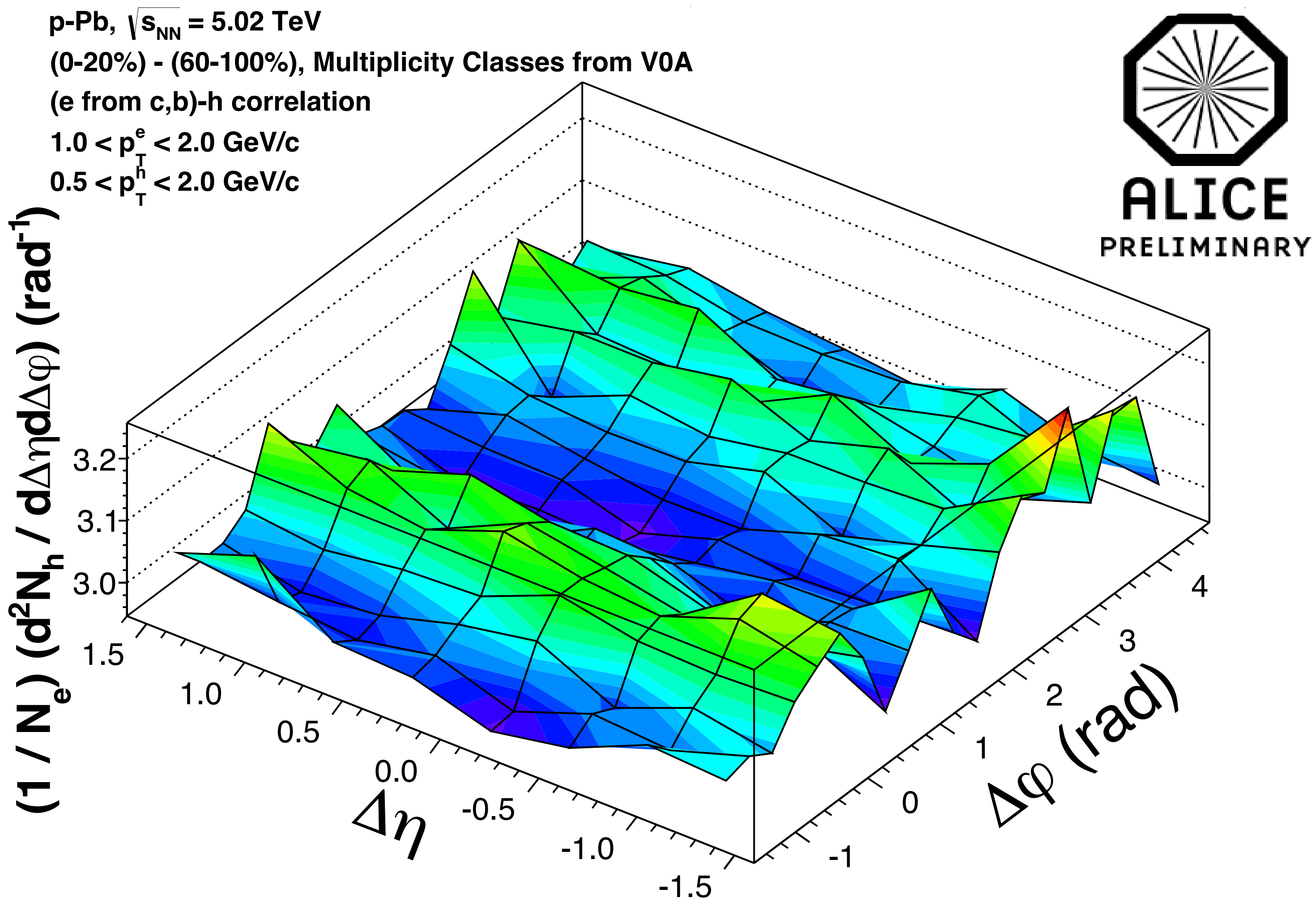
← **Radial flow qualitatively reproduces the data!**

Enhancement at mid- and backward rapidity possibly due to hydrodynamics?

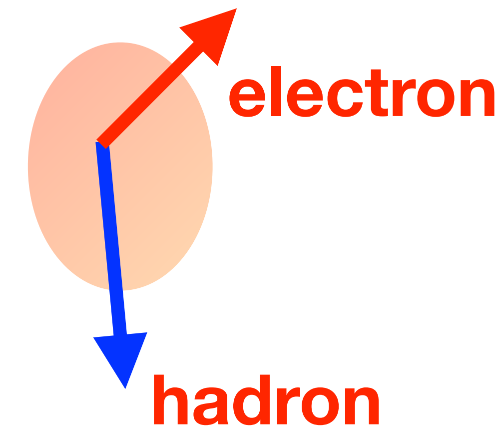
More differential information:
Heavy-flavour electron-hadron correlations

p-Pb

Multiplicity class:
(0-20%) - (60-100%)



ALI-PREL-62026



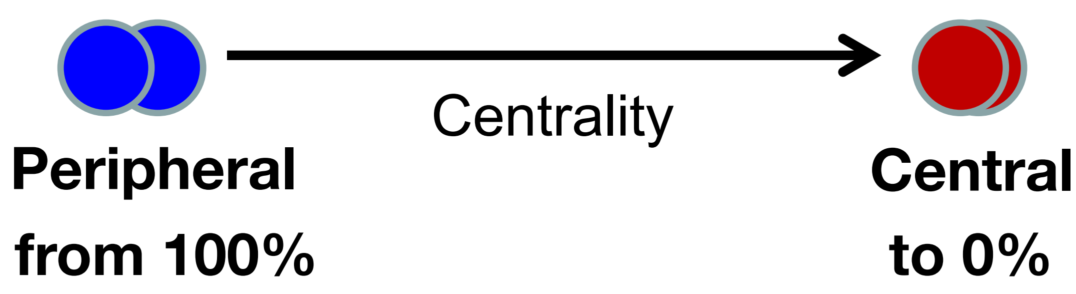
Resembles the structure that in AA is interpreted in terms of collective flow

The double ridge also observed in heavy-flavour sector!

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

Heavy flavours
Results in Pb-Pb collisions

Large systems!



Observables to measure medium effect

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

Parton interaction with the medium

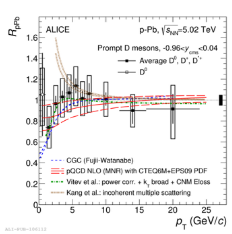
(Modified?) hadronization

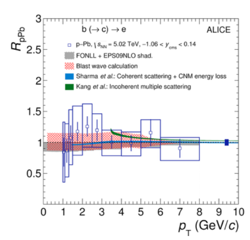
Initial-state effects

"Vacuum" parton spectra

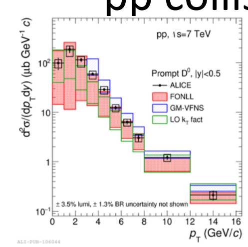
What we want to probe

Constrain models with measurements from p-Pb collisions





pp collisions



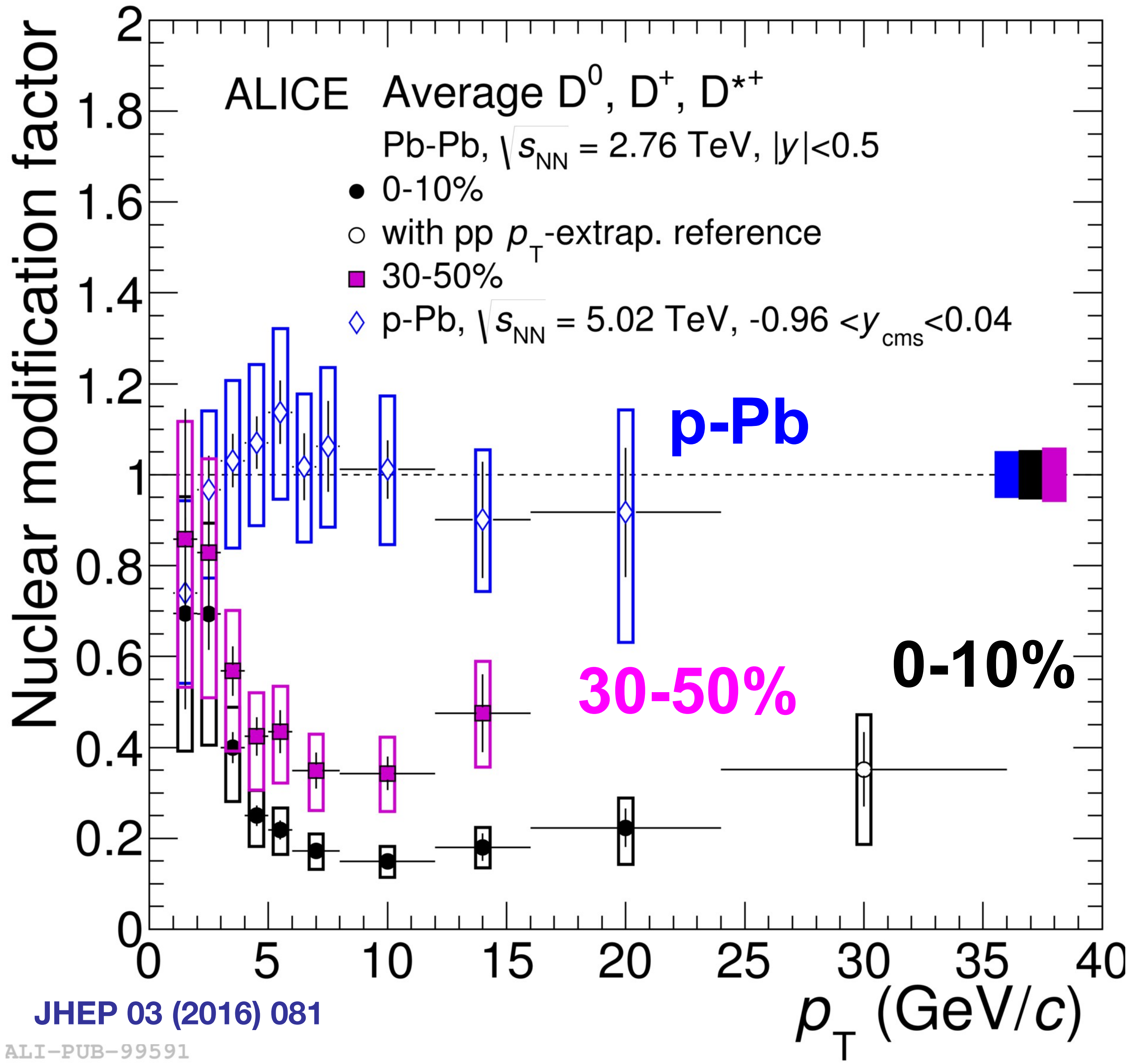
Charm and beauty energy loss

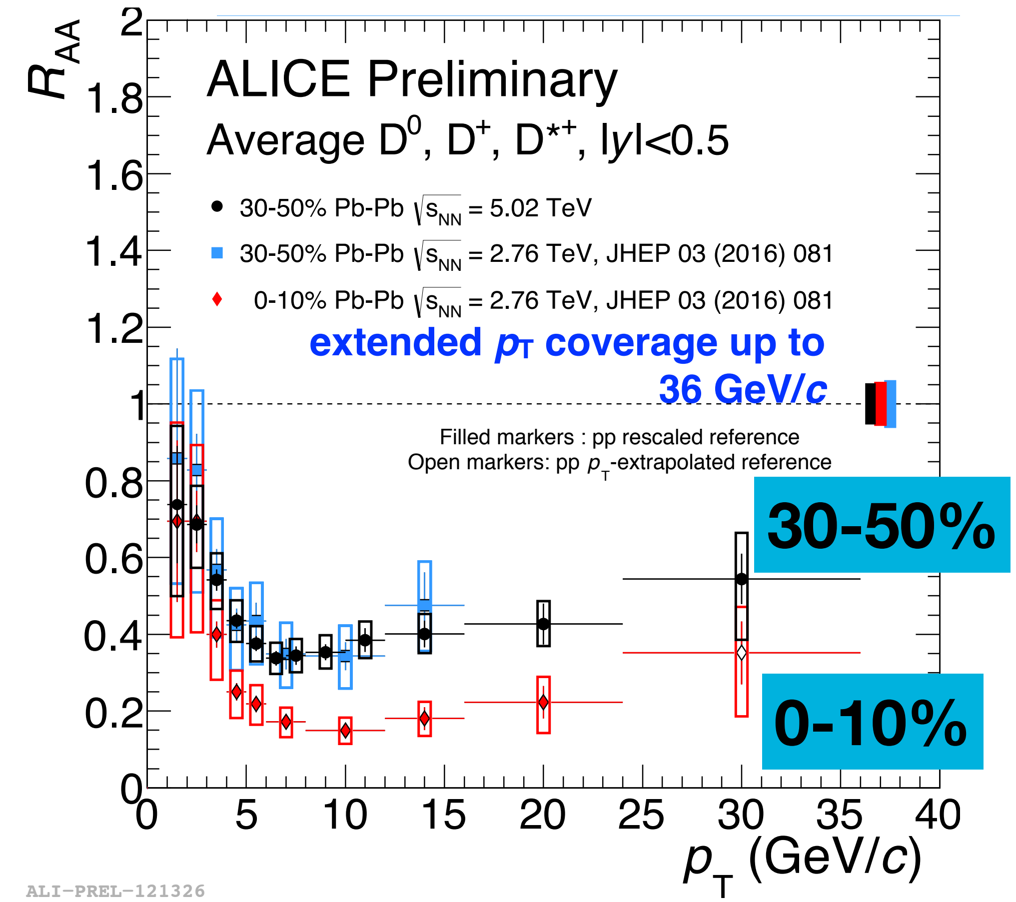
→ via radiative ("gluon Bremsstrahlung") and collisional processes

- quark mass (dead-cone effect)
- color charge (Casimir factor)
- path length and medium density

→ hadronization via coalescence with medium quarks?

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

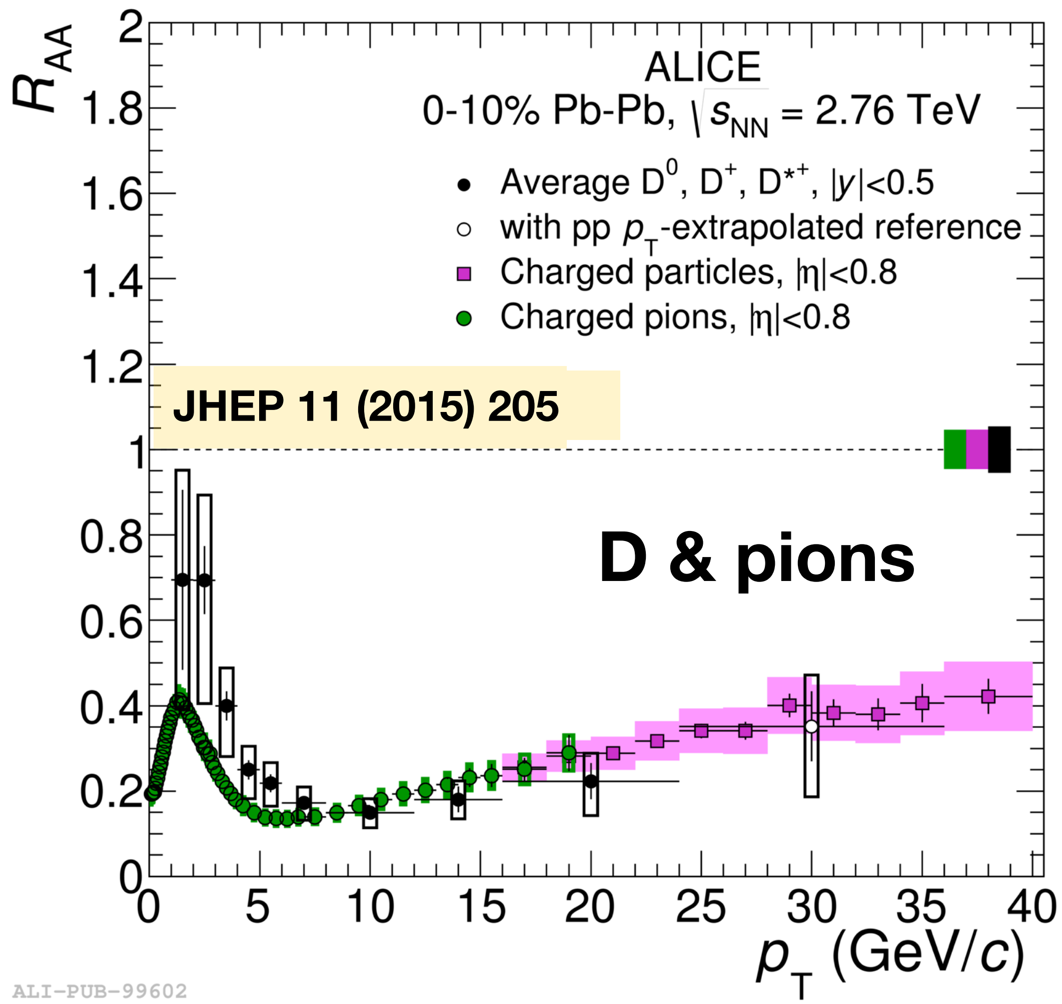


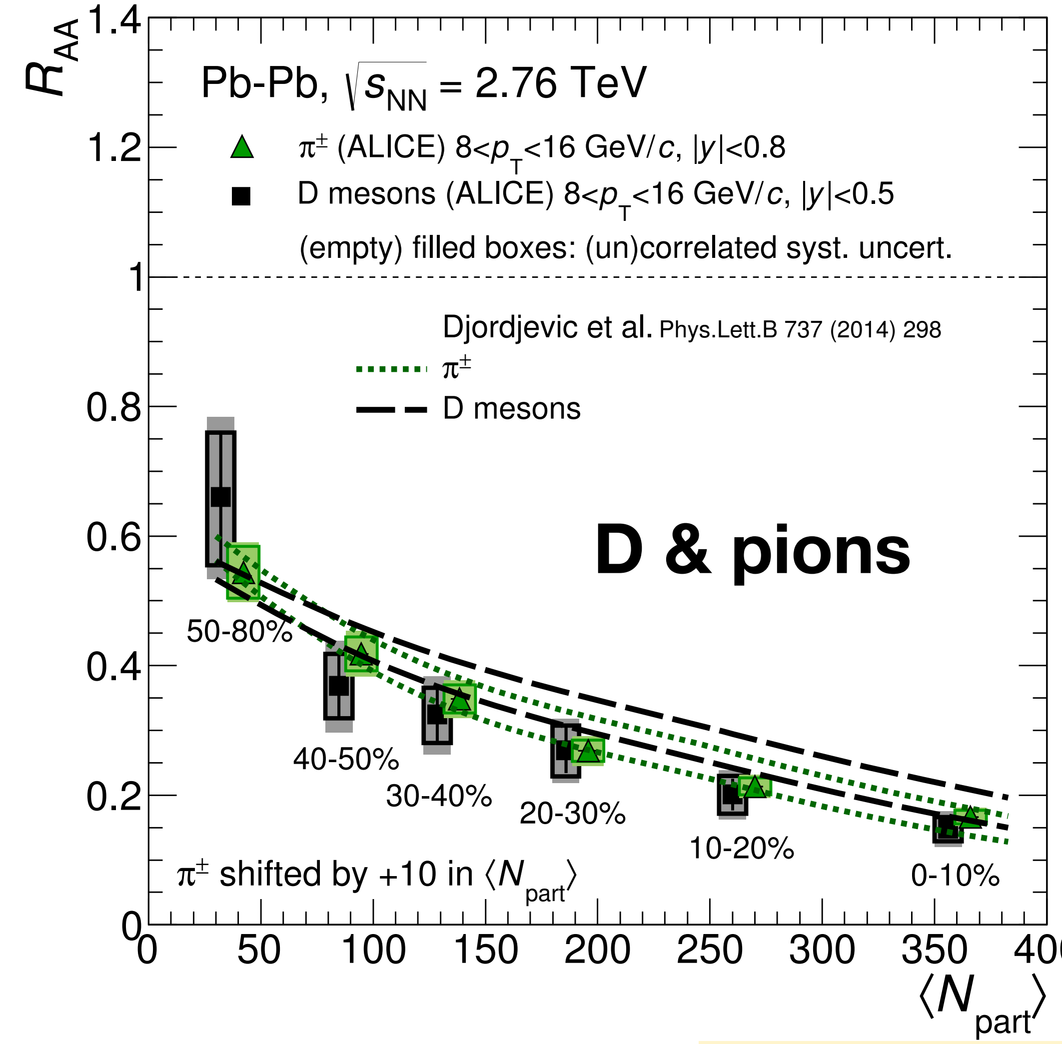


- D-meson R_{pPb} **consistent with unity** within uncertainties
- p-Pb results indicate that the **suppression** observed in **Pb-Pb** comes from **strong interaction of charm quarks with the medium**

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)





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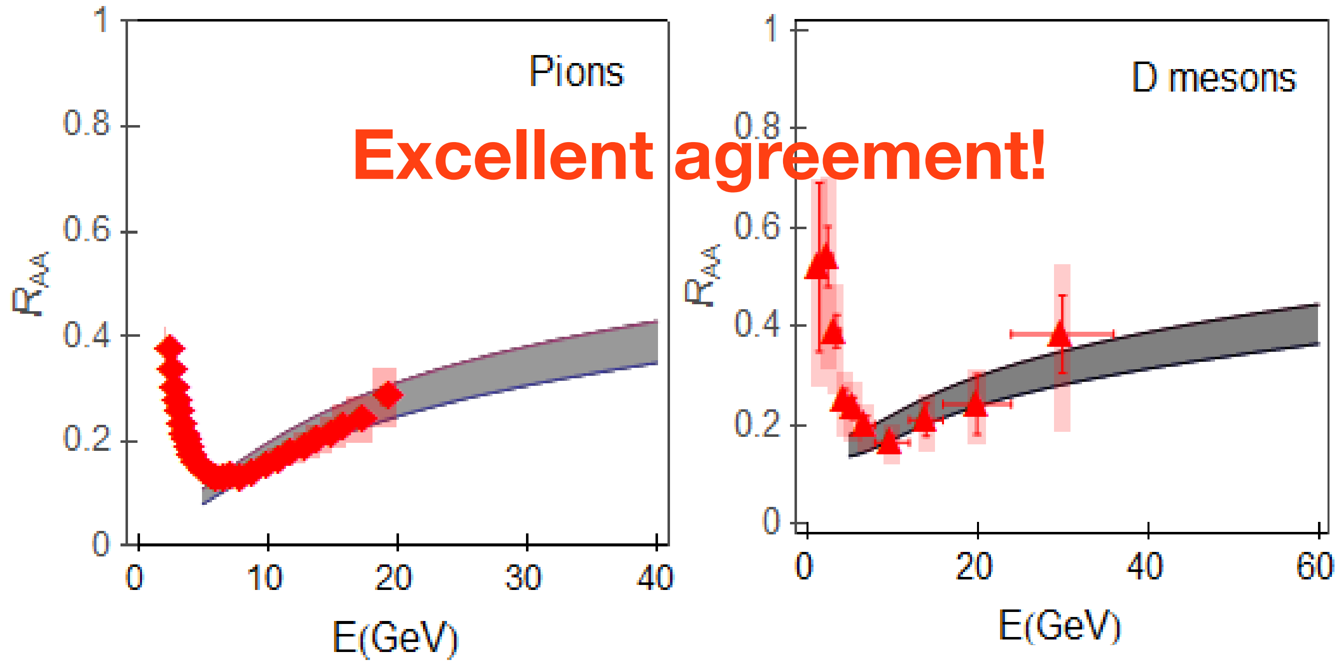
Djordjevic, PRL 112(2014)042302
Wicks et al., NPA 872(2011)265
Djordjevic, PLB 737(2014)298

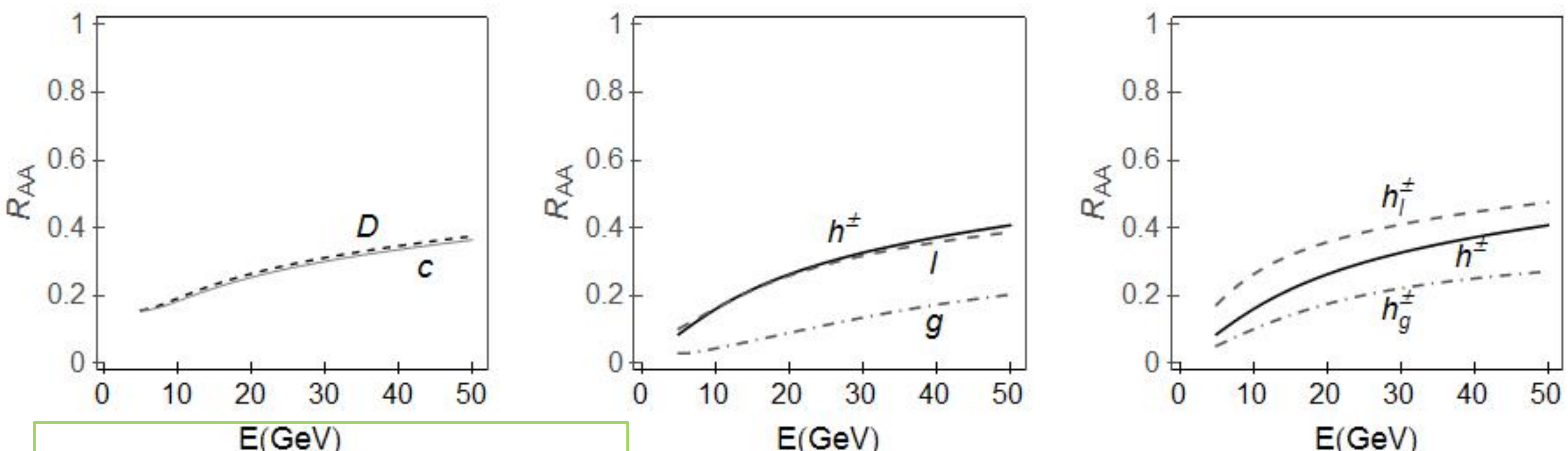
- D-meson and π R_{AA} are compatible within uncertainties
- Agreement with models including energy loss hierarchy: ΔE(g) > ΔE(u,d,s) > ΔE(c), different shapes of the parton p_T distributions, different fragmentation functions, soft production mechanisms for low-p_T π
- Measurement not yet conclusive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

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



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

Djordjevic, arXiv:1307.4098



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)

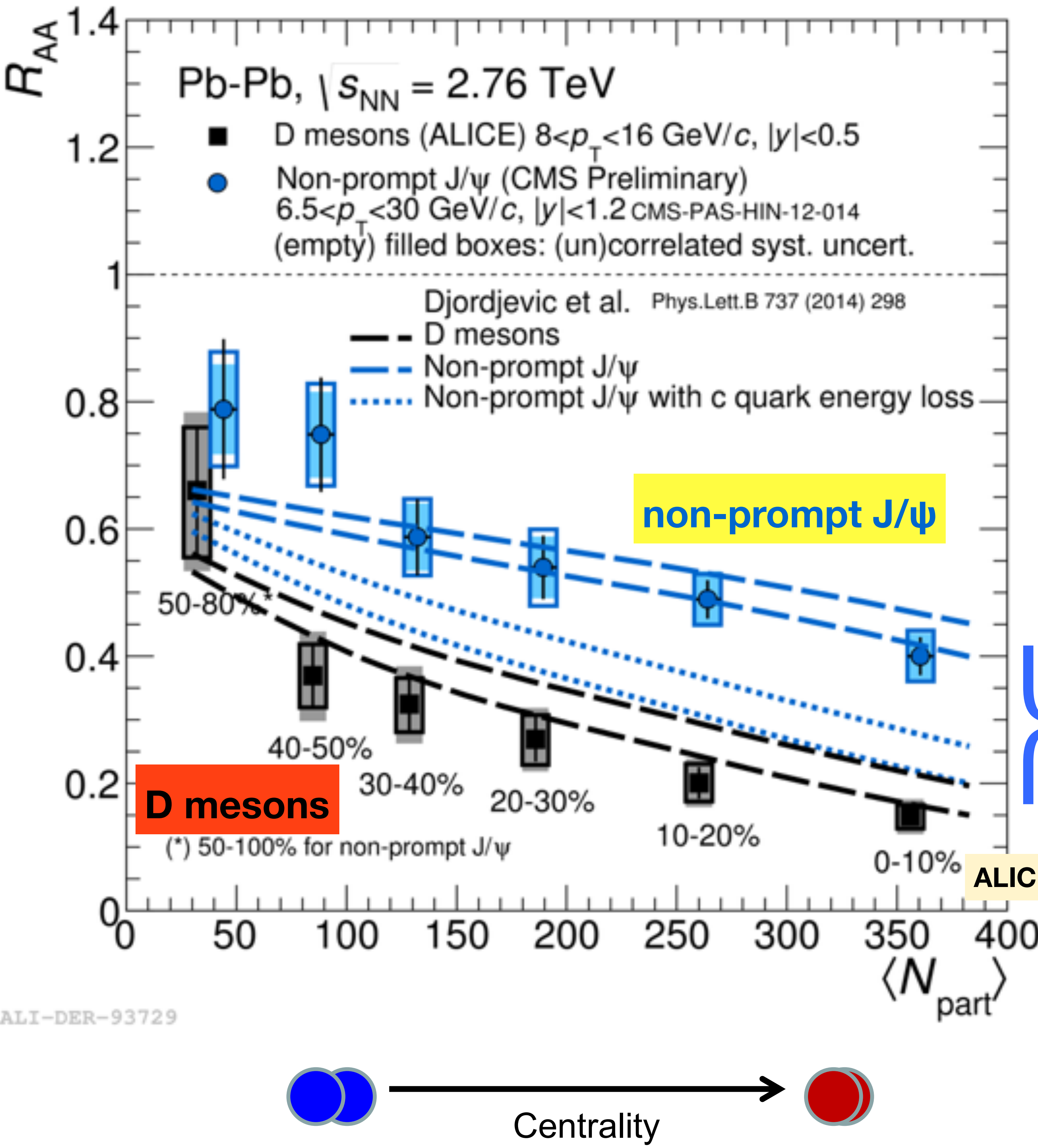
Distortion by fragmentation!

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

Colour charge effect helps!

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 $R_{AA}^{J/\psi \leftarrow B} > R_{AA}^{D}$

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.).

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

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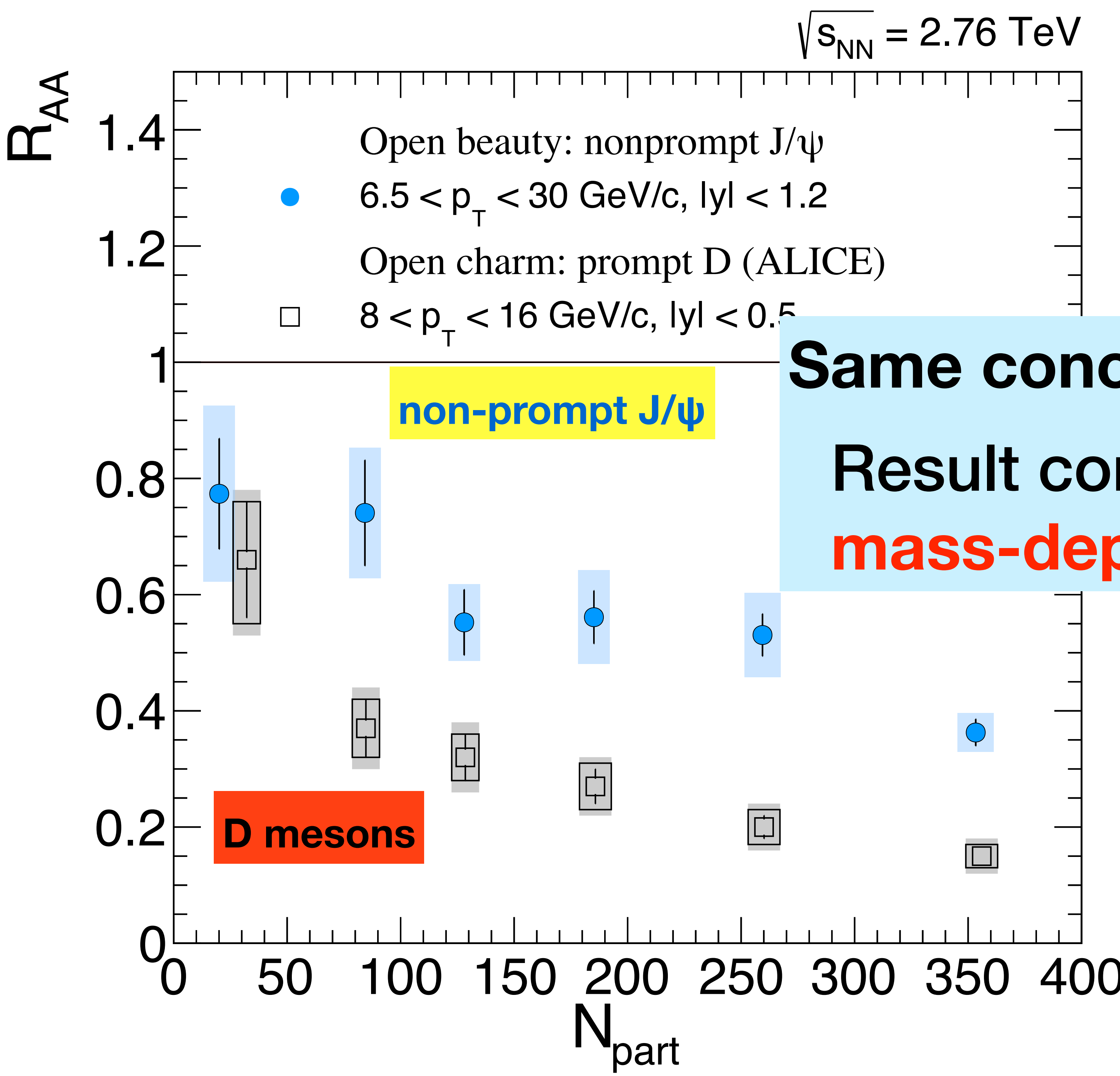

- ALICE prompt D mesons & CMS non-prompt J/ψ:
  - B and D mesons <p_T>~10 GeV/c, slightly different rapidity ranges

Same conclusion with final CMS results!

Result consistent with the picture of **mass-dependent** energy loss

No trivial relation between ΔE and R_{AA}

(Djordjevic, PLB 734(2014)286)

consequence of mass differences of c and b quarks

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Similar pattern from other calculations

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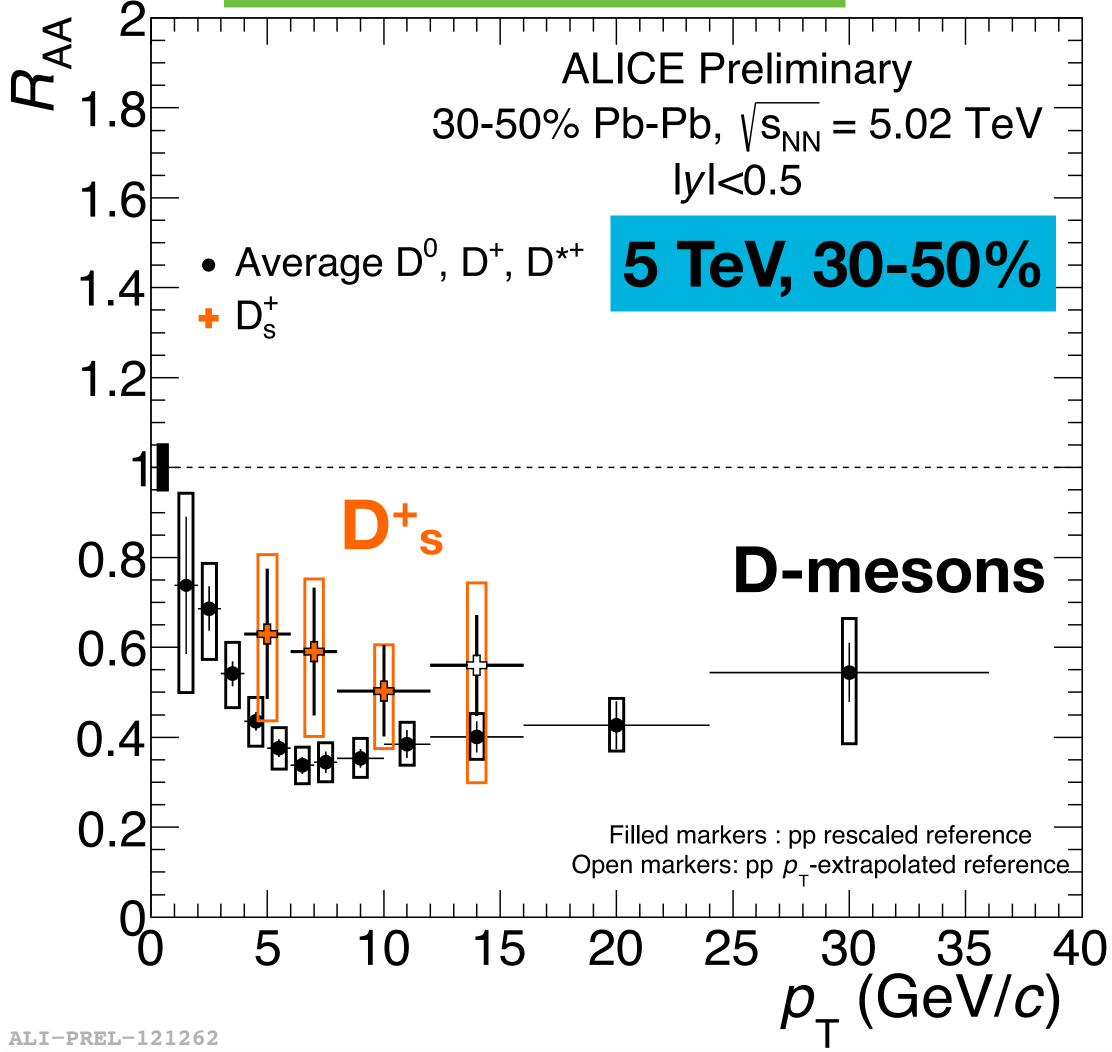
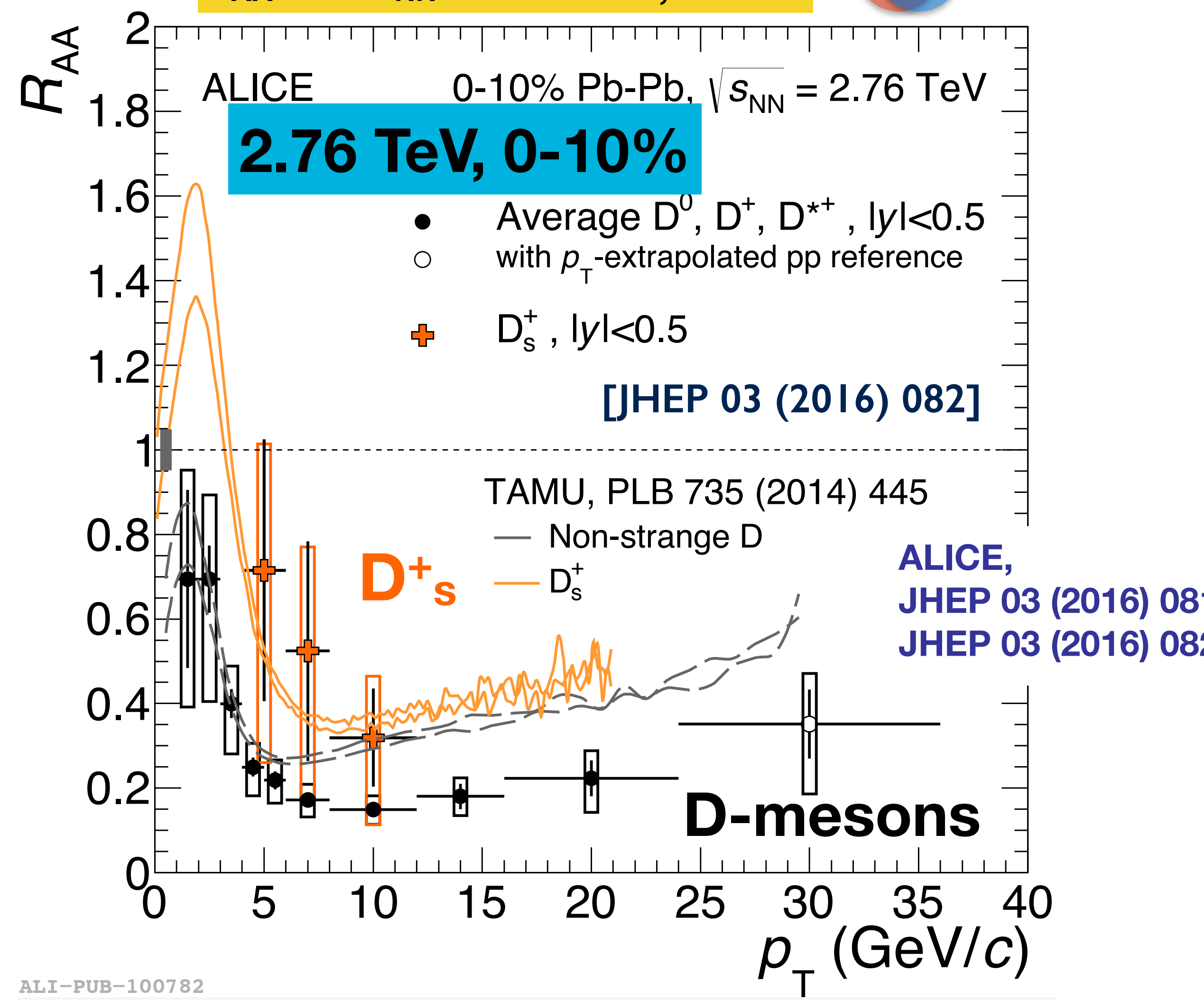
Ds vs. non-strange D mesons

D^0,D^+,D^{*+} average + D^+_s R_{AA}@ $\sqrt{s_{NN}}$ = 5.02 TeV, 30-50%



R_{AA} @ $\sqrt{s_{NN}}$ = 2.76 TeV, 0-10%



- Charm hadronization through **recombination** in medium? → **strangeness enhancement** (predicted in models)
- Hint of R_{AA}(D) < R_{AA}(D_s^+) in data, to be confirmed **with higher precision measurements**

Observables to measure medium effect

Parton interaction with the medium

(Modified?) hadronization

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

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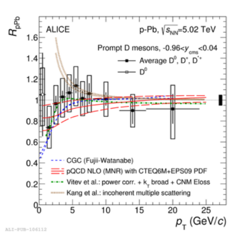
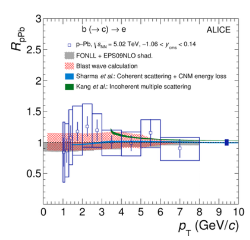
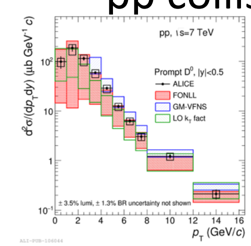
"Vacuum" parton spectra

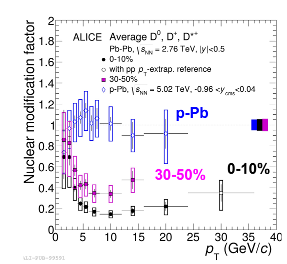
Constrain models with measurements from p-Pb collisions

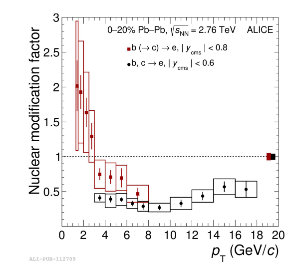




pp collisions

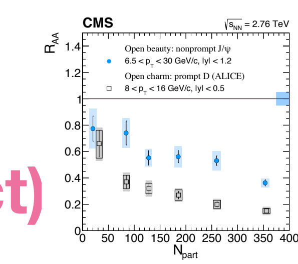


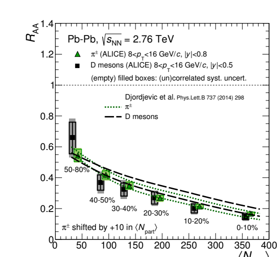




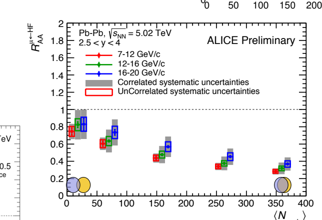
Charm and beauty energy loss

→ via radiative ("gluon Bremsstrahlung") and collisional processes

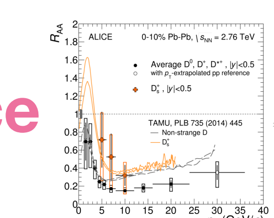




- quark mass (dead-cone effect)
- color charge (Casimir factor)
- path length and medium density

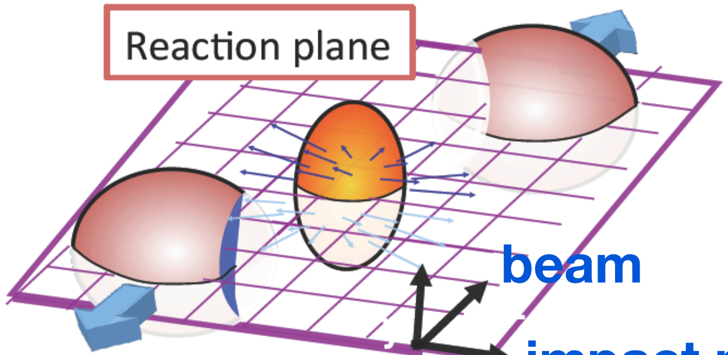


→ hadronization via coalescence



→ collective motion ⇒ azimuthal anisotropy

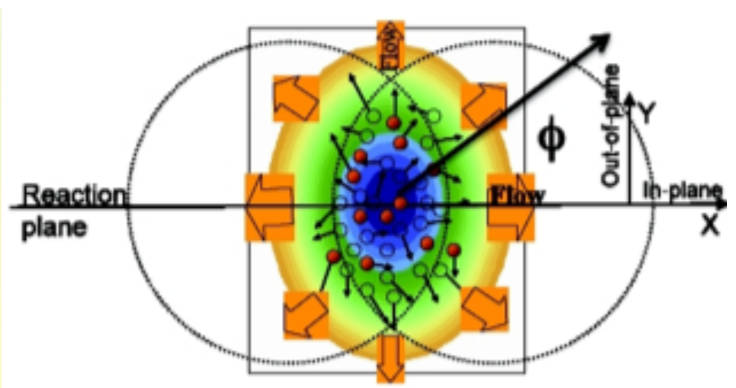
Elliptic flow (azimuthal anisotropy)



Study **azimuthal distribution** of produced particles w.r.t. the reaction plane (Ψ_{RP})

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 —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})

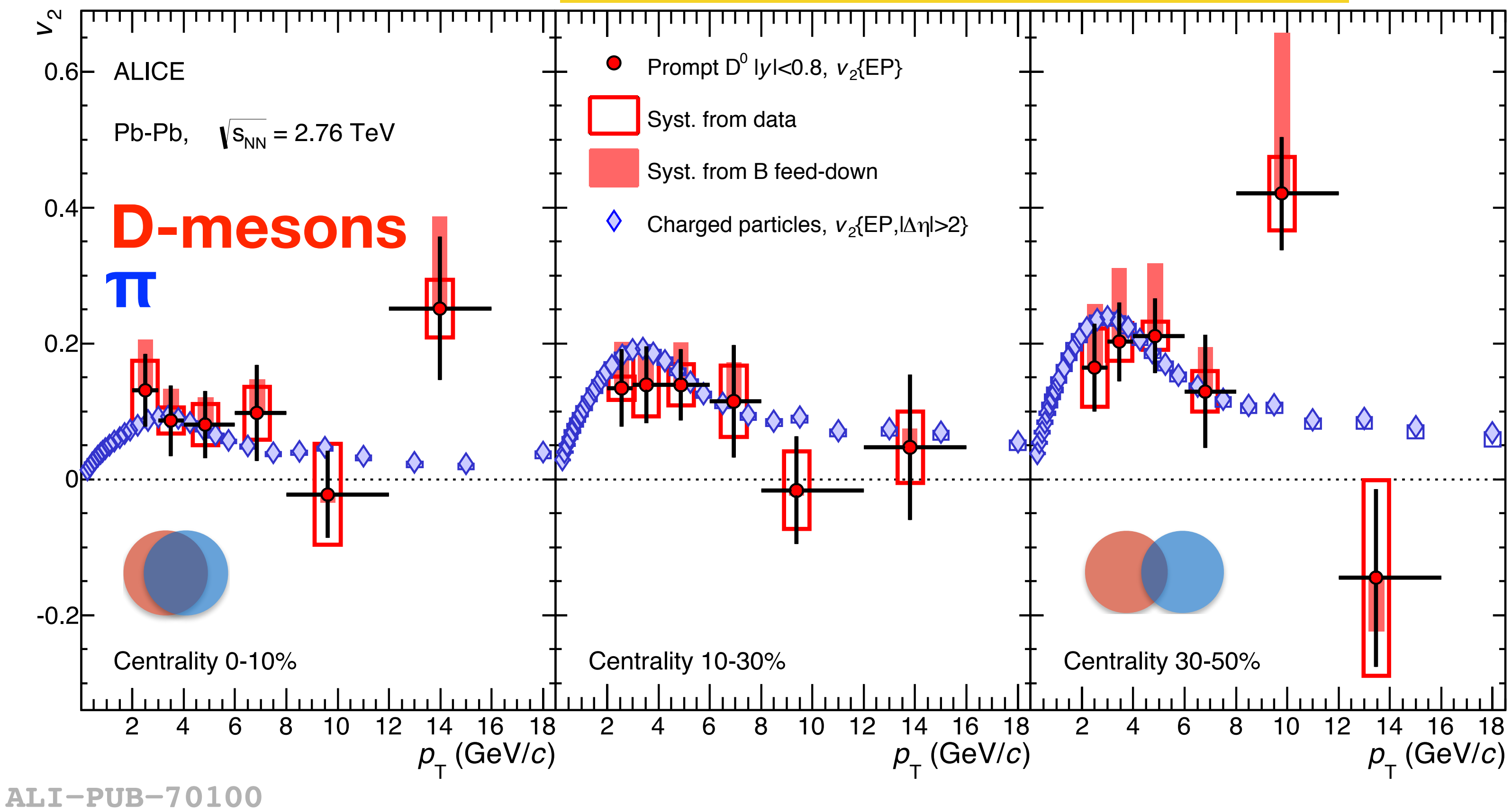
v_2>0
- → Thermalization/collective motion (at low p_T)
- → Path length dependence of energy loss (at high p_T)

v_2+ R_{AA}: complementary information → improve sensitivity to relative contribution of collisional and radiative energy losses and to coalescence

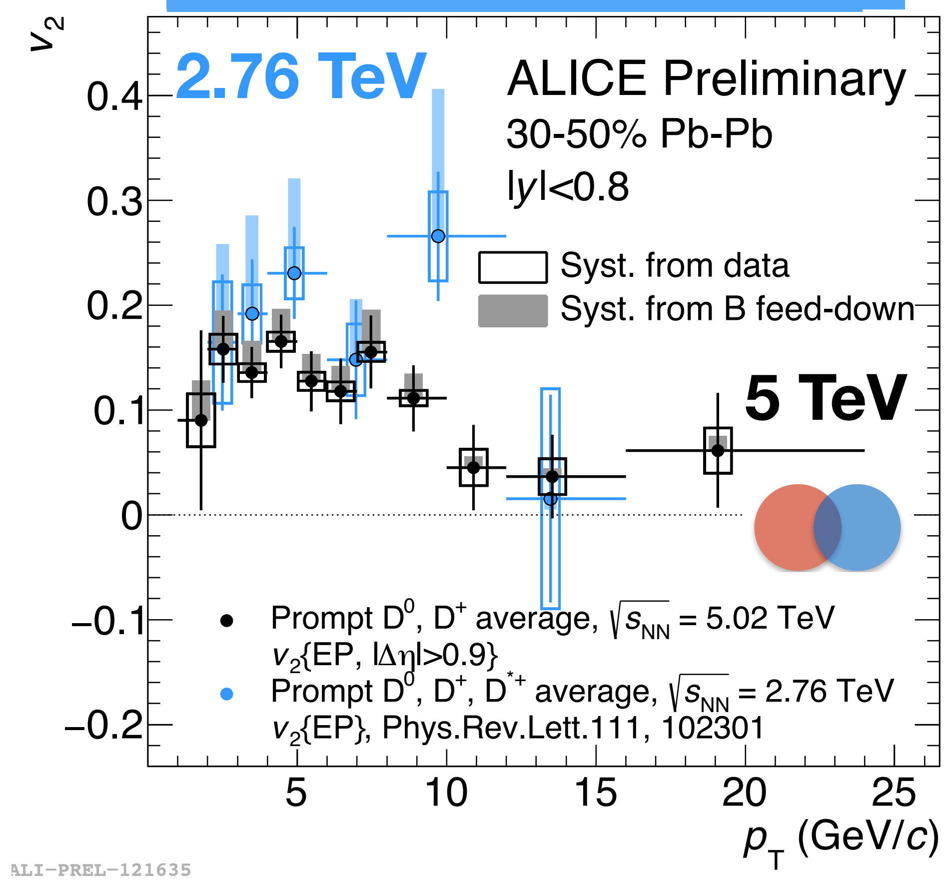
Anisotropic flow v_2 of D mesons

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

D^0, D^+ average v_2 at $\sqrt{s_{NN}}$=2.76 TeV



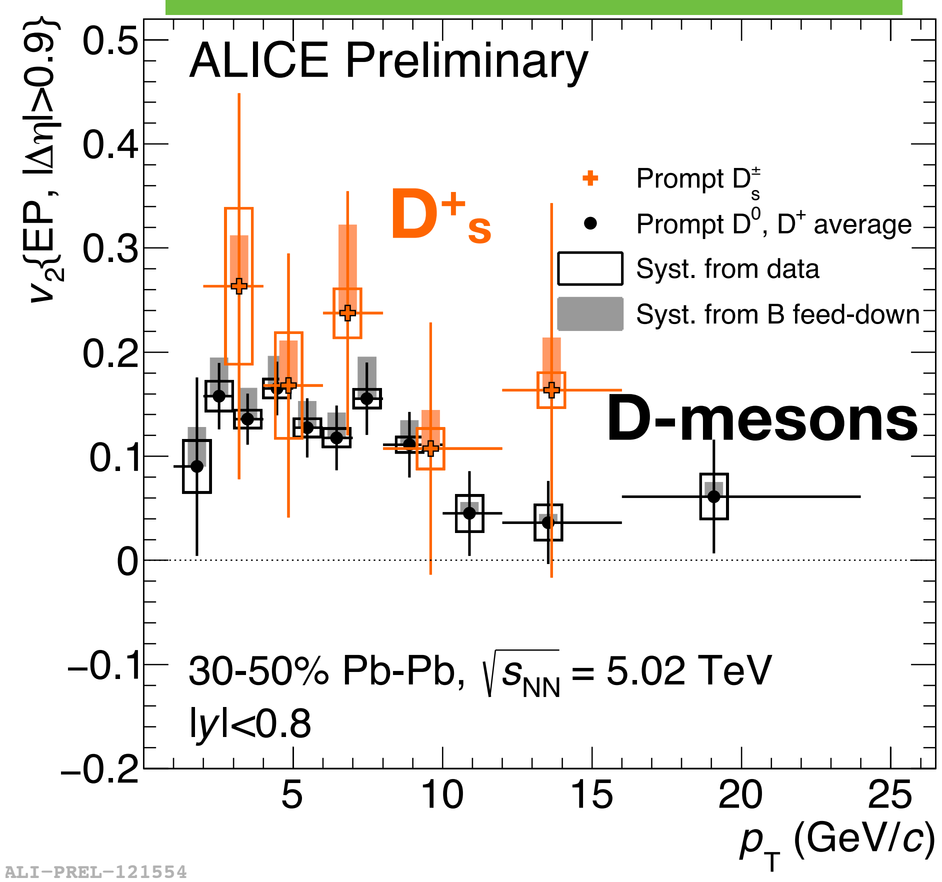
D^0,D^+ average v_2 $\sqrt{s_{NN}}$ = 5.02 vs 2.76 TeV



- Heavy quarks participate in collectivity of the medium in case of **sufficient re-scattering**; accessible via measuring azimuthal asymmetry of particle emission in momentum space, v_2
- **Positive v_2(D)** observed (5σ effect for 2 < p_T < 6 GeV/c in 30-50% centrality class)
- **D-meson v_2** similar to **charged-particle v_2**
  → **Confirms significant interaction of charm quarks with the medium**
- **Similar** v_2 at **different energies** observed (confirmed with better precision at **Run2**!!!)

Anisotropic flow v_2 of D mesons

D^0,D^+ average + D_s v_2 @ $\sqrt{s_{NN}}$ = 5.02 TeV



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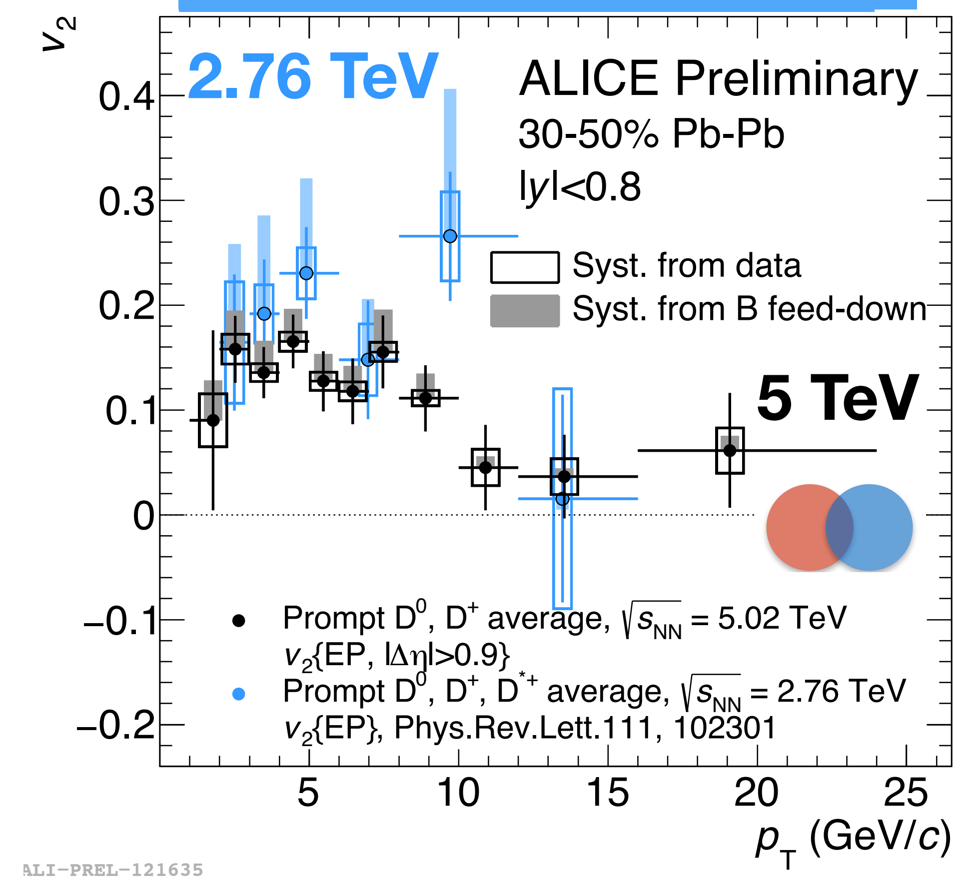

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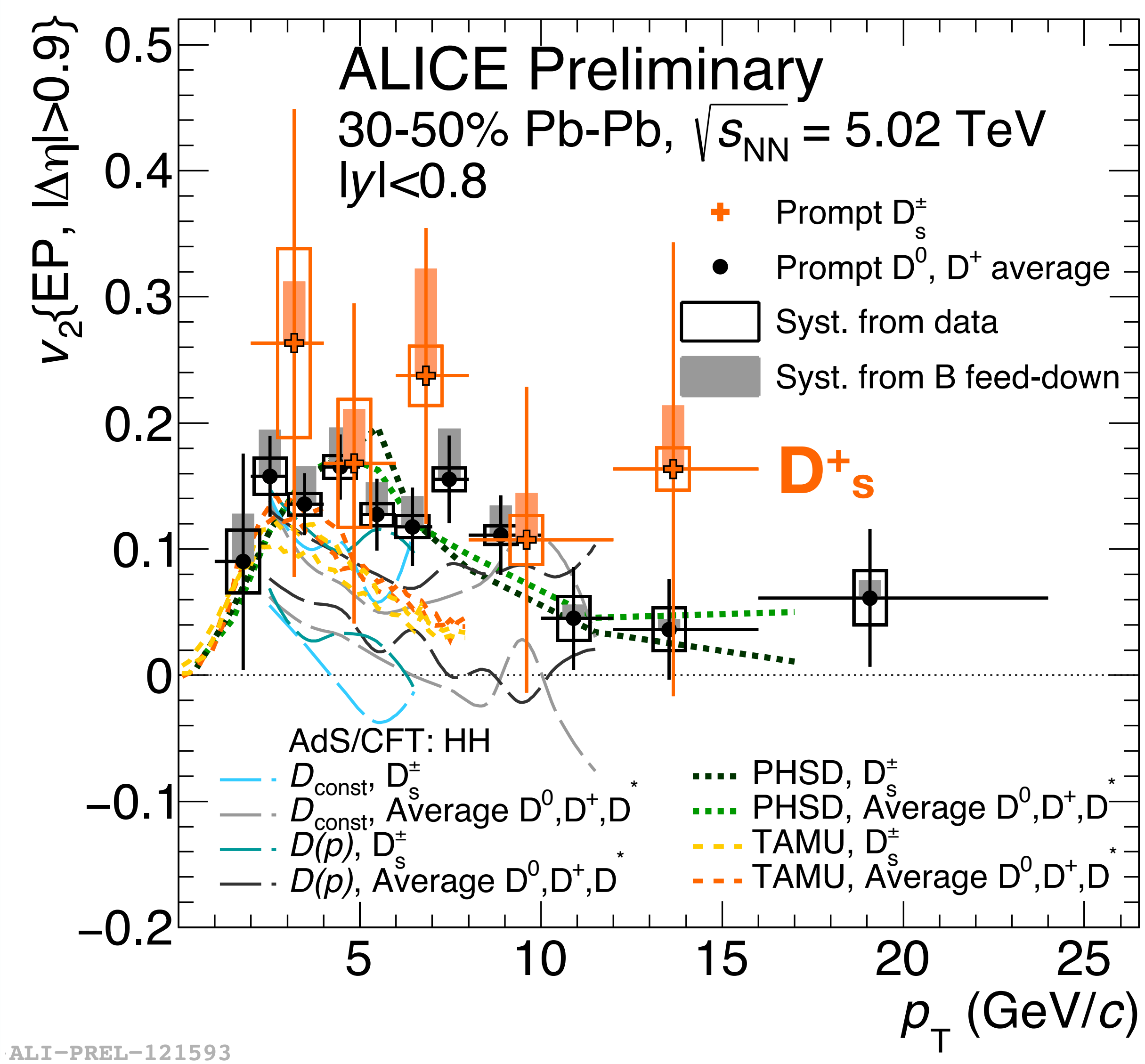
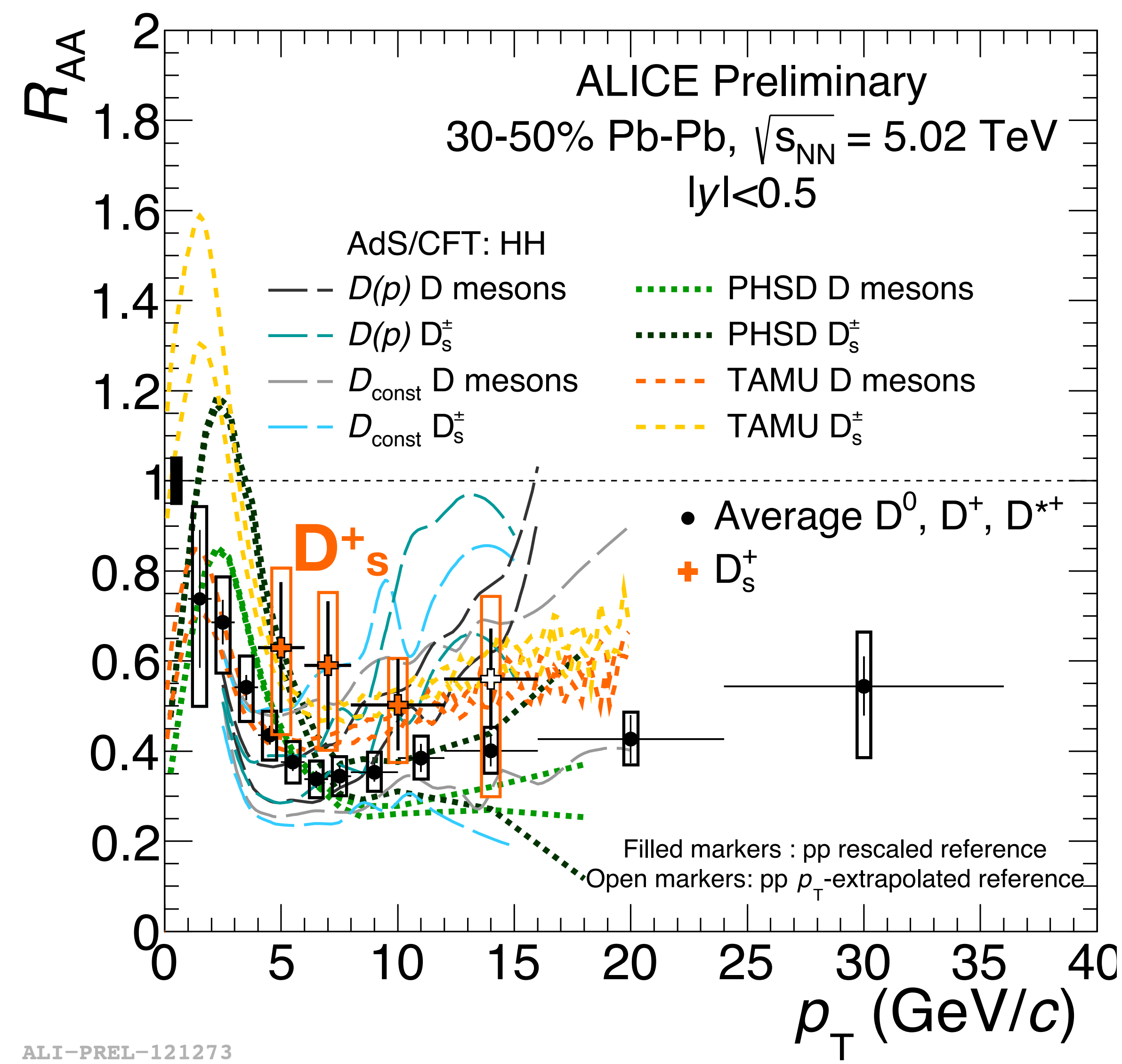
- **Similar** v_2 at **different energies** observed (confirmed with better precision at **Run2**!!!)
- **First** measurement of **D_s-meson** v_2 at the LHC!

Comparison with models





- Highlight **importance** that models include a **realistic description** of the medium evolution and of initial conditions
- **v_2 and R_{AA}** measurements over a wide p_T range can set **stringent constraints to model**
- Experimental results **with improved precision** → potential to constrain models giving a simultaneous description of quenching and collectivity

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(Modified?) hadronization

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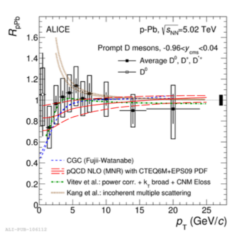
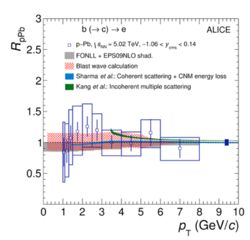
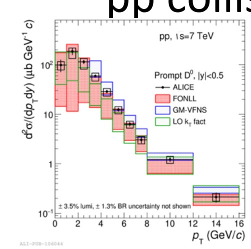
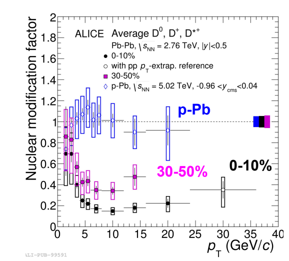
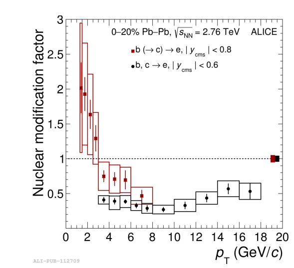

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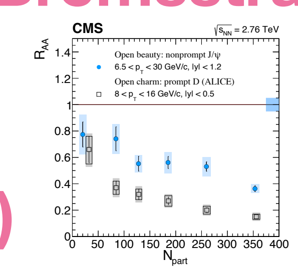
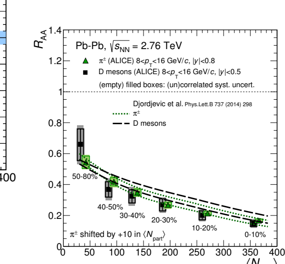

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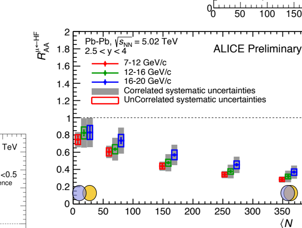

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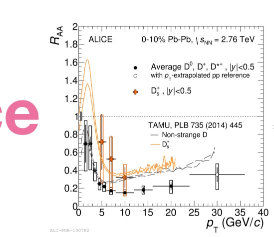
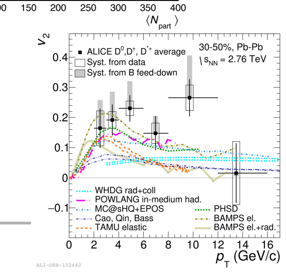


→ collective motion ⇒ azimuthal anisotropy



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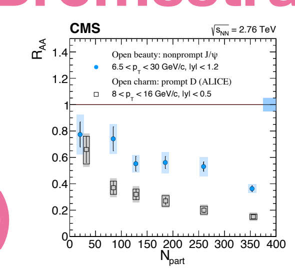
Initial-state effects

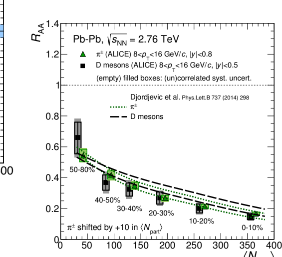
"Vacuum" parton spectra

What we want to probe

We are walking toward differential and precision measurements!

→ energy loss via radiative ("gluon Bremsstrahlung") and collisional processes





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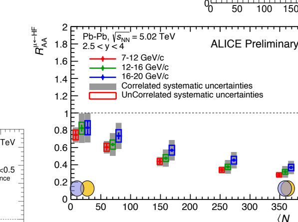
- ✤ path length and medium density



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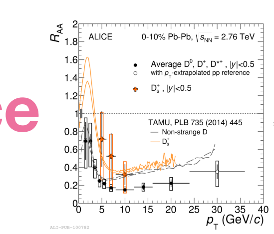

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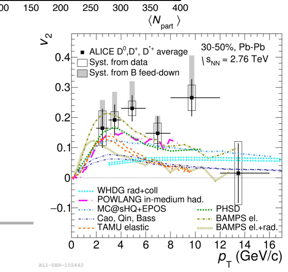

Plans for Run2 and beyond

Goals for ongoing run-2

- **Improve precision** of **multiplicity-differential** studies in pp and p-Pb collisions
- **New** measurements of **azimuthal correlations** in Pb-Pb collisions and **small systems** also as a function of the multiplicity
  - D mesons with charged particles
  - HF-decay electrons with charged particles

Long-shutdown 2 → Detector upgrade

- New ITS, addition of MFT → **improve spatial resolution** at impact point at mid- and forward rapidity
- New readout for several sub-detectors

→ **Tremendous improvement** for reconstructing charm and beauty signals (including D_s, Λ_C, non- prompt J/ψ at mid and forward rapidity, B meson, Λ_b) **down to very low p_T**

Thank you for your attention!