Open heavy-flavour hadron decay muon production with ALICE at the LHC

MD SAMSUL ISLAM

Indian Institute of Technology Bombay

for the ALICE Collaboration

10th Asian Triangle Heavy-Ion Conference (ATHIC 2025), 13-16 January
IISER Berhampur, Odisha, India

Outline:

=> **Motivation**

=> **Energy loss mechanism**

=> **Results**

=> **Summary**

Motivation

=> Both charm and beauty quarks ($m_c \approx$ 1.29 GeV and $m_b \approx$ 4.19 GeV) are heavy compared to the light u, d, and s quarks and significantly exceed the QCD scale parameter of 0.2 GeV.

=> The heavy-flavour (charm and beauty) hadron production can be theoretically calculated within the framework of perturbative Quantum Chromodynamics (pQCD) over all momenta.

=> The measurements of heavy-flavour production in proton-proton (pp) collisions at the LHC provide stringent test for pQCD calculations.

=> Additionally, studies in pp collisions serve as a necessary baseline for the same measurement in proton-nucleus (p-A) and nucleus-nucleus (A-A) collisions in order to investigate the influence of cold and hot nuclear matter effects on heavy-flavour production.

Heavy quark production in A-A collisions

==> Investigation of strongly-interacting matter at high energy density and temperature in ultra-relativistic heavy-ion collisions.

==> Heavy-quarks (charm and beauty) are very important probe to study such QGP properties.

i) due to their large mass, predominantly produced in the early stage on a time scale (about 1 fm/c) before the QGP formation.

$$\tau_f^{\mathrm{q}} < \frac{\hbar}{m_{\mathrm{q}}} \quad (m_{\mathrm{c}} \approx 1.29 \text{ GeV}, \; m_{\mathrm{b}} \approx 4.19 \text{ GeV}, \quad \hbar c = 0.197 \text{ GeV. fm})$$

ii) experience the full evolution of the hot and dense QCD medium.

iii) lose energy via radiative and collisional processes during their propagation through the medium.

==> The energy loss of the heavy-quarks passing through the hot and dense medium produced in heavy-ion collisions can be quantified in terms of Nuclear Modification Factor (R_{AA}) of final state particles, e.g. muons from heavy-flavour (HF) hadron decays

$$R_{\mathrm{AA}}(p_{\mathrm{T}}, \mathrm{y}) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \times \frac{d^2N_{\mathrm{AA}}/dp_{\mathrm{T}}dy}{d^2N_{\mathrm{pp}}/dp_{\mathrm{T}}dy} ,$$

$\langle N_{\mathrm{coll}} \rangle$ being average number of binary nucleon-nucleon collisions

==> Hadronisation of heavy quarks into heavy-flavour hadrons,

i) Open heavy-flavour hadrons: heavy quarks and anti-quarks fragment (or coalesce) into hadrons.
ii) Quarkonia: heavy quark and anti-quark pair forms a bound state. (typically 1-2%)

Energy loss mechanism

==> Radiative energy loss :

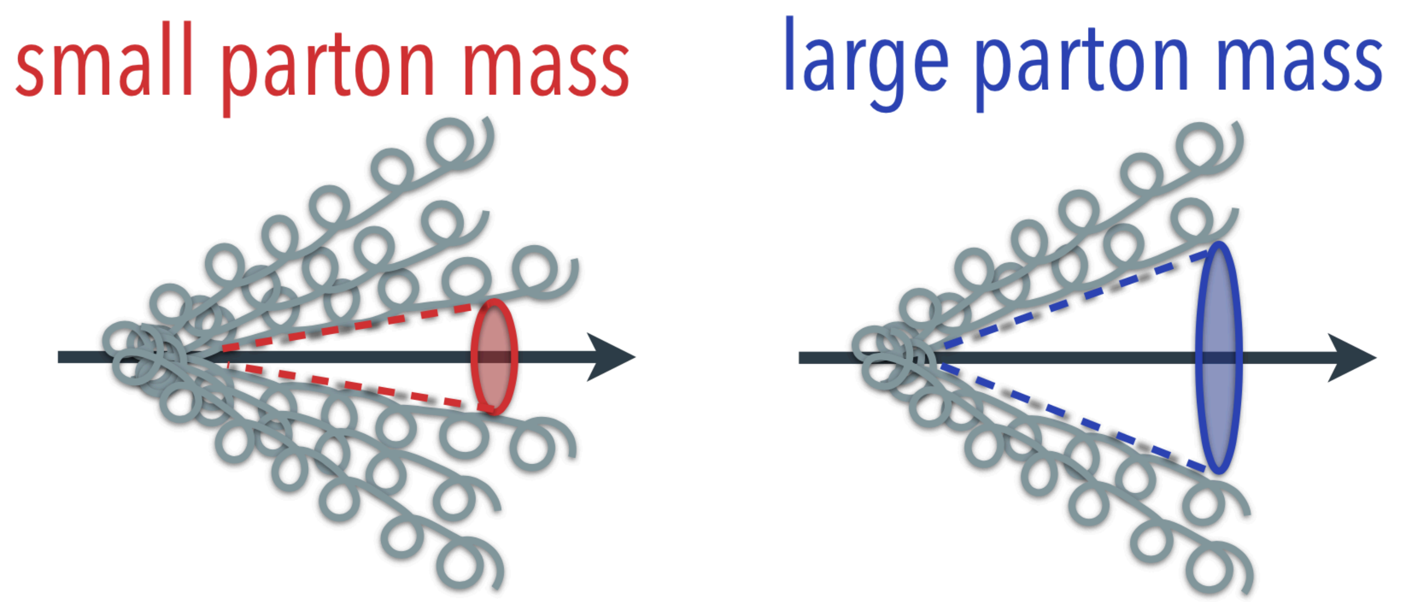
i) Heavy quarks emit gluons during their propagation, losing energy.

ii) Gluons exhibit a larger color coupling factor than quarks and so the energy loss of quarks is expected to be smaller than that of gluons.

ii) Heavy quark energy loss is reduced compared to light quarks due to dead-cone effect (gluon radiation at small angles $(\theta < m_q/E_q)$ with respect to the quark momentum vector is suppressed).

==> distinct mass hierarchy, $(R_{\mathrm{AA}})_{\text{light quarks}} < (R_{\mathrm{AA}})_{\mathrm{c}} < (R_{\mathrm{AA}})_{\mathrm{b}}$

….. Radiative energy loss is more relevant at higher momenta.



$$\theta_{cone} \equiv \frac{m_q}{P_q} \simeq \frac{m_q}{E_q}$$

Energy loss mechanism ….

==> Collisional process :

Heavy quarks also lose energy through elastic scattering with the light quarks, antiquarks, and gluons in the QGP.

i) Elastic scattering : preserve the identity of heavy quarks.

ii) Depends on the path length and medium density, transport coefficients (like spatial diffusion coefficient, momentum broadening etc.)

iii) More significant at lower momentum

==> Combined (radiative + collisional) effect:

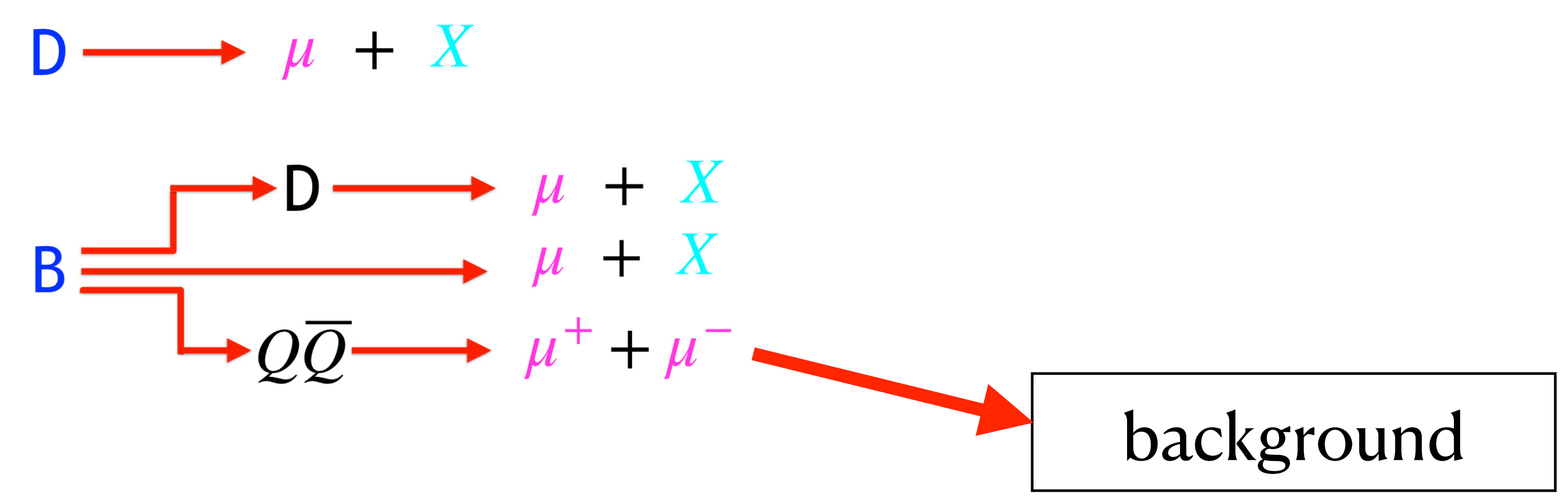
i) charm quarks, being lighter than bottom quarks, generally experience more significant energy loss through both collisional and radiative processes.

ii) total energy loss is reflected in the R_{AA}.

Measurements of open heavy-flavour hadron decay leptons with ALICE

i) Electrons from semi-electronic channel decays at midrapidity.

ii) Muons from semi-muonic channel decays at forward rapidity.



Here we discuss, the results of the open heavy-flavour decay muon (HFM) production at forward rapidity with ALICE.

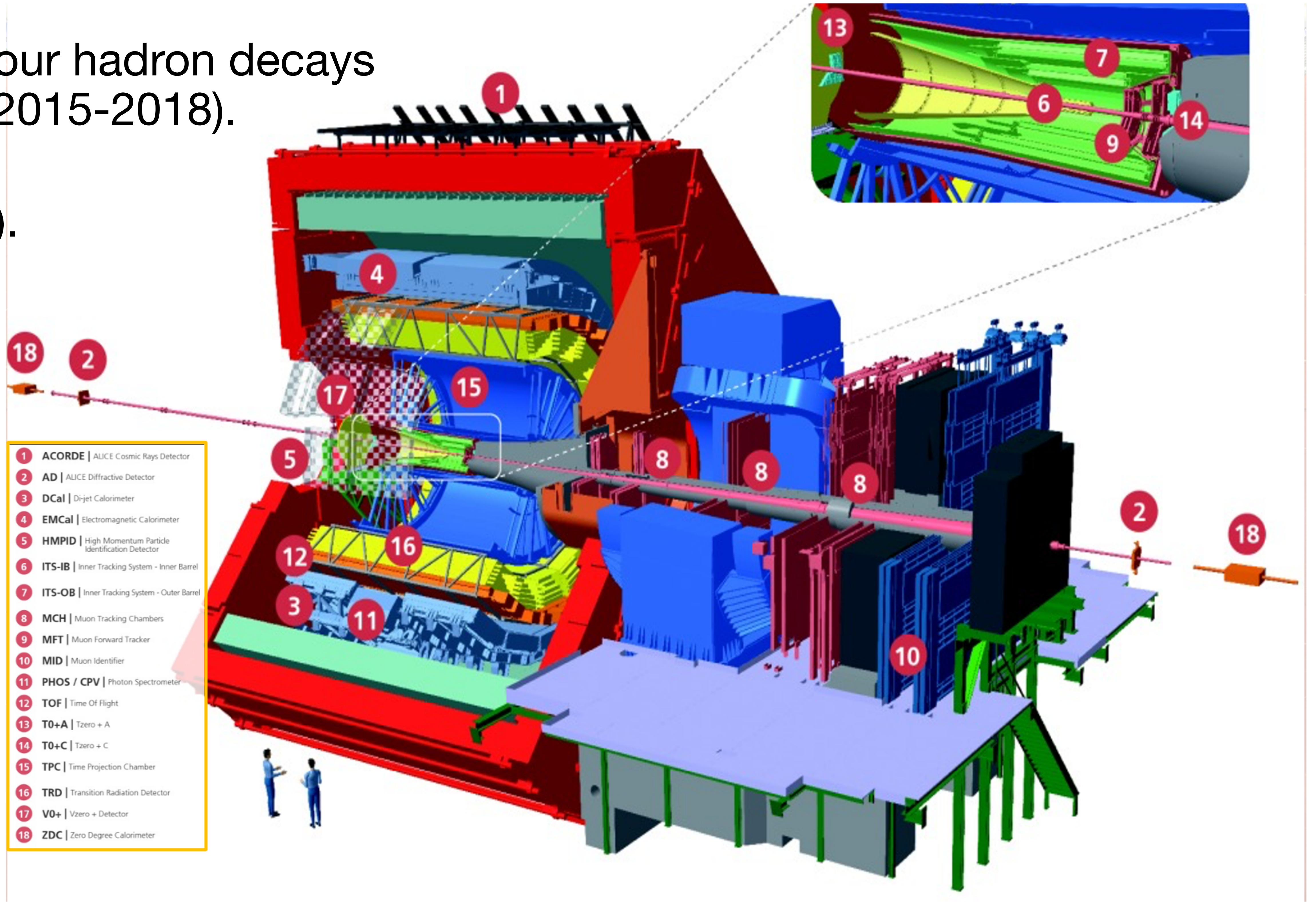
==> ALICE has measured the production of muons from open heavy flavour hadron decays in pp and heavy-ion collisions during Run 1 (2009-2012) and Run 2 (2015-2018).

i) pp collisions at $\sqrt{s}$ = 0.9, 2.76 & 7 TeV (Run 1) and 5.02 TeV (Run 2).

ii) p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV.

iii) Xe-Xe collisions at $\sqrt{s_{\rm NN}}$ = 5.44 TeV.

ii) Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 2.76 TeV and 5.02 TeV.



Analysis procedure

- **Event Selection Cuts :**
  – Physics selection: Offline event selection to reject any background events at the hardware level.
  – Vertex: z-component of vertex selection within $|V_z| < 10$ cm

Muon Triggered events:

Muon Single Low (MSL) => p_T -threshold ~ 1 GeV/c
Muon Single High (MSH) => p_T -threshold ~ 4.2 GeV/c

- **Track Selection Cuts:**
  – Pseudo-rapidity : $-4.0 < \eta < -2.5$
  – Polar angle: $170° < \theta < 178°$
  – track-trigger matching
  – pDCA: 6σ

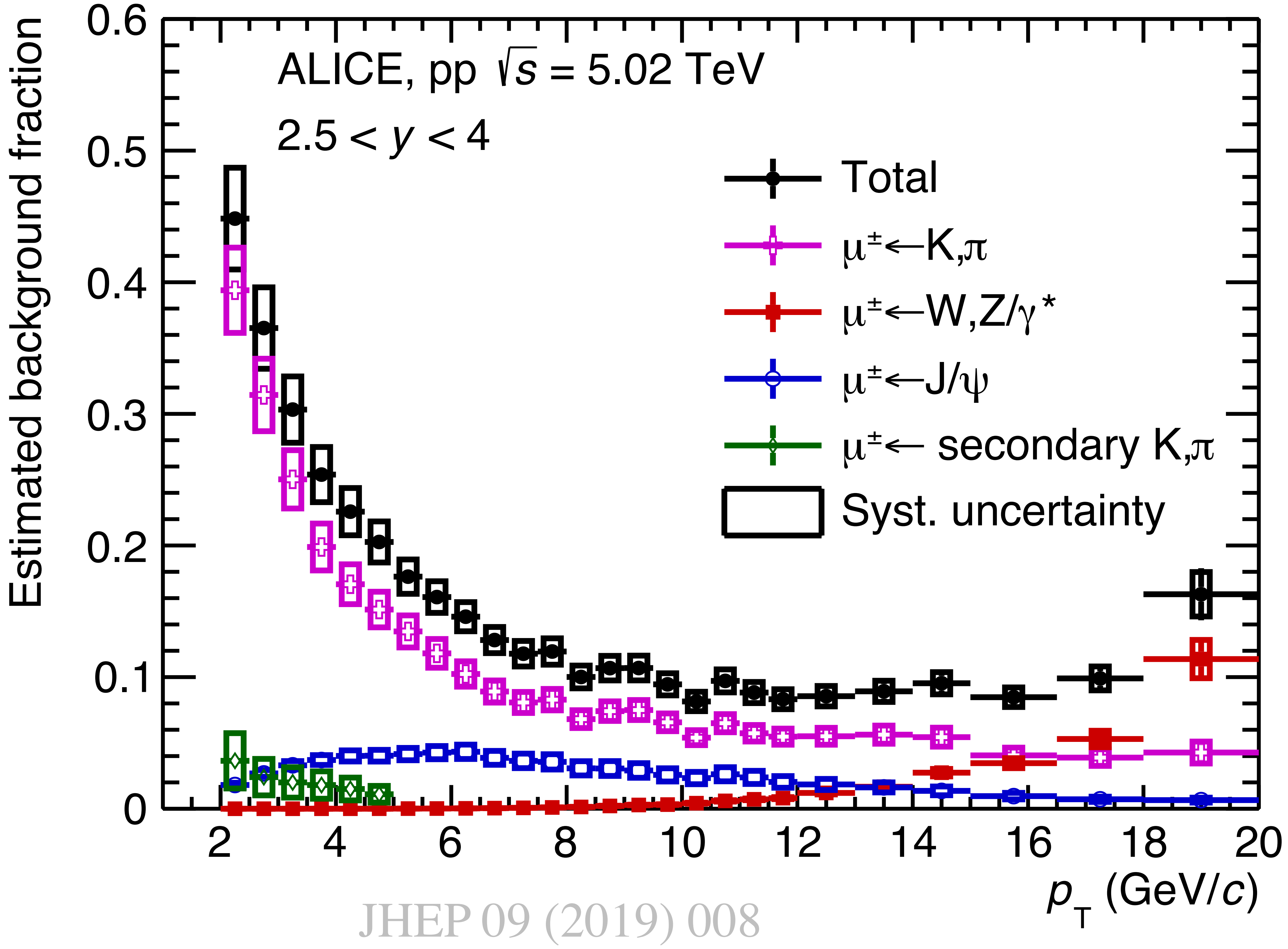
- A beam-induced background track does not point towards the interaction vertex
- Multiple coulomb scattering inside the front absorber => tracks pointing toward interaction vertex => DCA distribution follows Gaussian => width of gaussian proportional to $1/p$ => proposed to study p x DCA distribution

The p_T-differential R_{AA} of muons from open heavy-flavour hadron decays in a given centrality class

$$R_{AA}(p_T, y) = \frac{\left(\frac{d^2N^{\mu^\pm}}{dp_T dy} - \sum \frac{d^2N^{\text{non-HF}\rightarrow\mu^\pm}}{dp_T dy}\right)_{\text{Pb-Pb}}}{\langle N_{\text{coll}}\rangle \times \left(\frac{d^2N^{c,b\rightarrow\mu^\pm}}{dp_T dy}\right)_{pp}}$$

$$\sum \frac{d^2N^{\text{non-HF}\rightarrow\mu^\pm}}{dp_T dy} = \frac{d^2N^{\mu\leftarrow\pi,K}}{dp_T dy} + \frac{d^2N^{\sec\ \mu}}{dp_T dy} + \frac{d^2N^{\mu\leftarrow J/\psi}}{dp_T dy} + \frac{d^2N^{\mu\leftarrow W/Z/\gamma^*}}{dp_T dy}$$

Background contributions in heavy-flavour decay muon measurement



JHEP 09 (2019) 008

pp collisions @ $\sqrt{s}$ = 5.02 TeV

i) The total contribution of muons from primary $\pi^{\pm}$ and $K^{\pm}$ decays decreases with increasing p_T from about 39% at p_T = 2 GeV/c down to about 4% at p_T = 20 GeV/c.

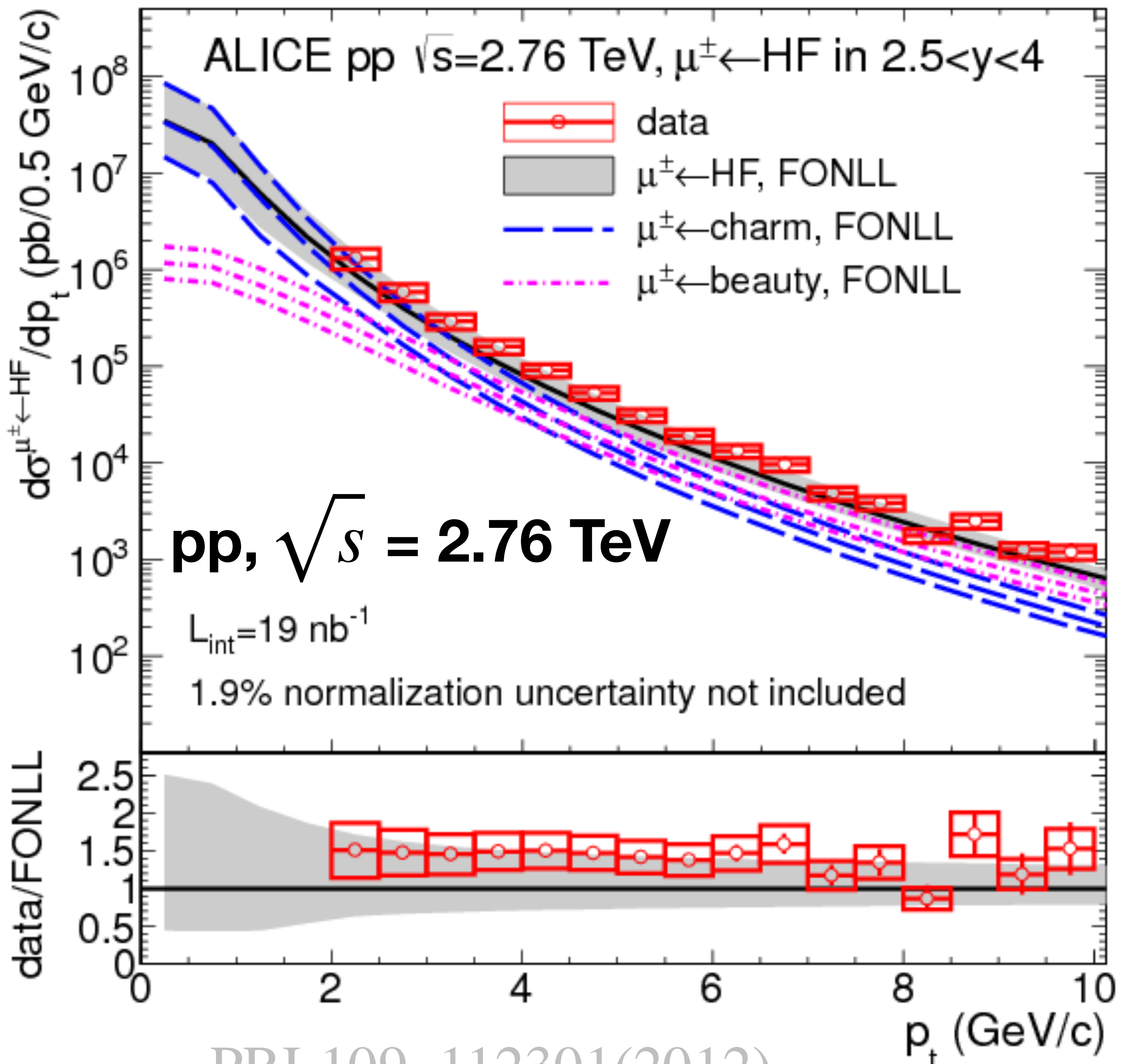
ii) Muons from secondary $\pi^{\pm}$ and $K^{\pm}$ decays relative to the inclusive muon yield decreases with increasing p_T from about 4% at p_T = 2 GeV/c to less than 1% at p_T = 5 GeV/c.

iii) The relative contribution of muons from W and Z/γ^* with respect to inclusive muons is negligible for p_T < 12 GeV/c and increases with p_T from about 1% at p_T = 12 GeV/c up to 12% in 18 < p_T < 20 GeV/c.

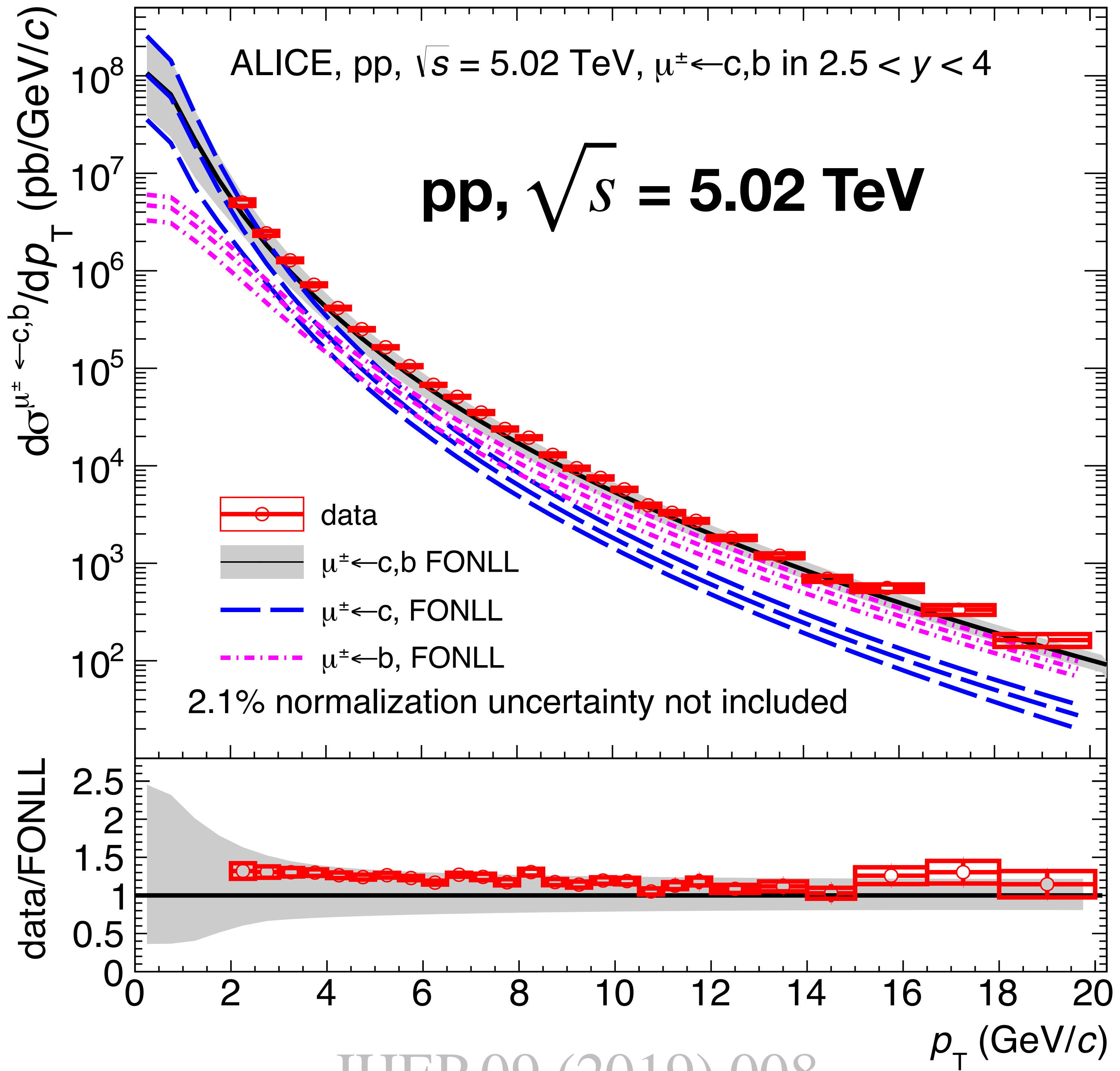
iv) The relative contribution of J/ψ decay muon to the inclusive muons yield varies from 4% to less than 1%, with the maximum fraction at intermediate p_T (4 < p_T < 6 GeV/c).

p_T -differential production cross-section of open heavy-flavour decay muons with ALICE

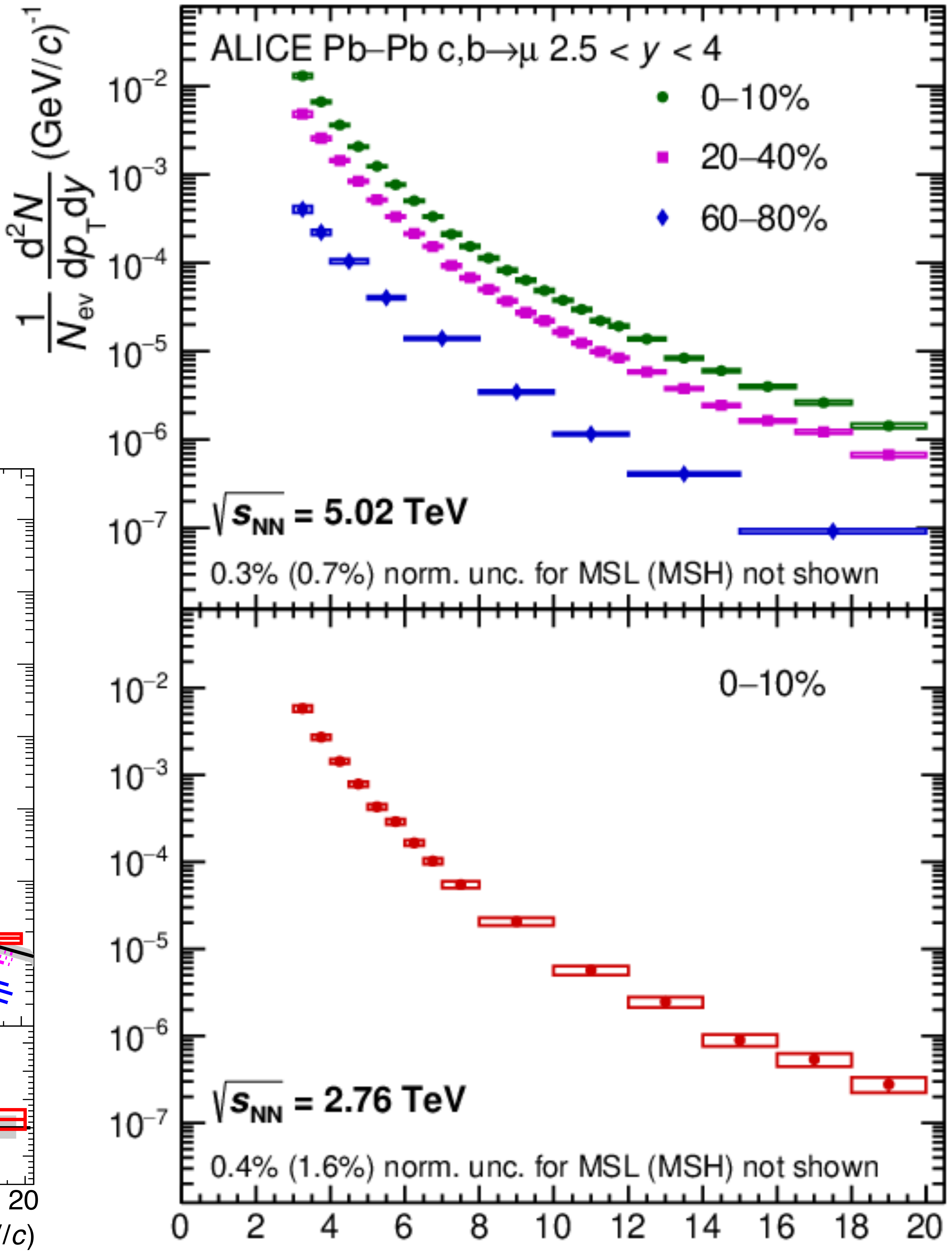
- The measured production cross section of muons decaying from heavy-flavour hadrons are compared with FONLL (Fixed-Order + Next-to-Leading Logarithms) calculations.
- FONLL predictions are provided for muons from charm and beauty decays, separately.
- FONLL predictions are compatible with data within uncertainties.



PRL109, 112301(2012)

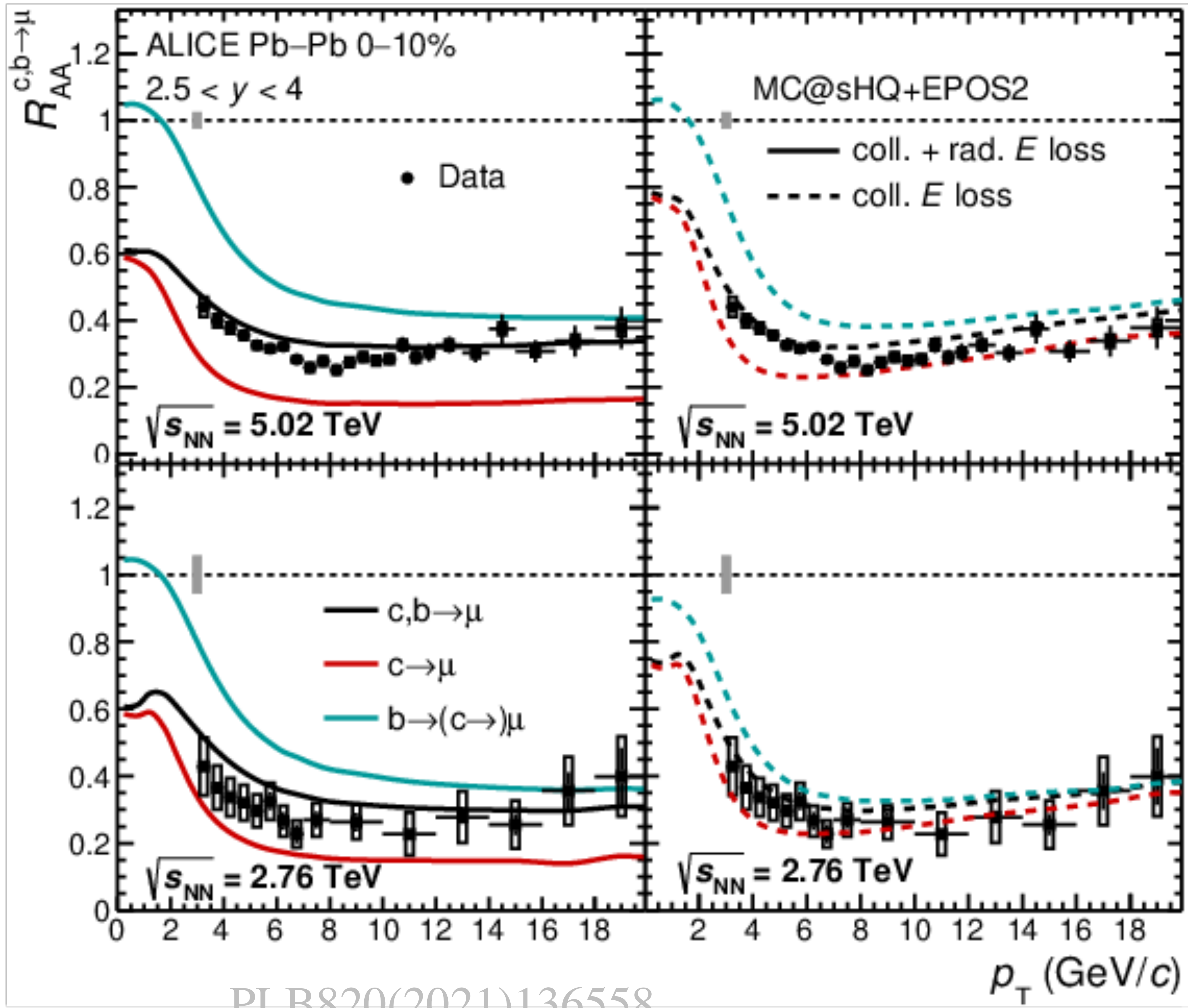


JHEP 09 (2019) 008



PLB 820 (2021) 136558

Comparison of R_{AA} to models without and with radiative energy



PLB820(2021)136558

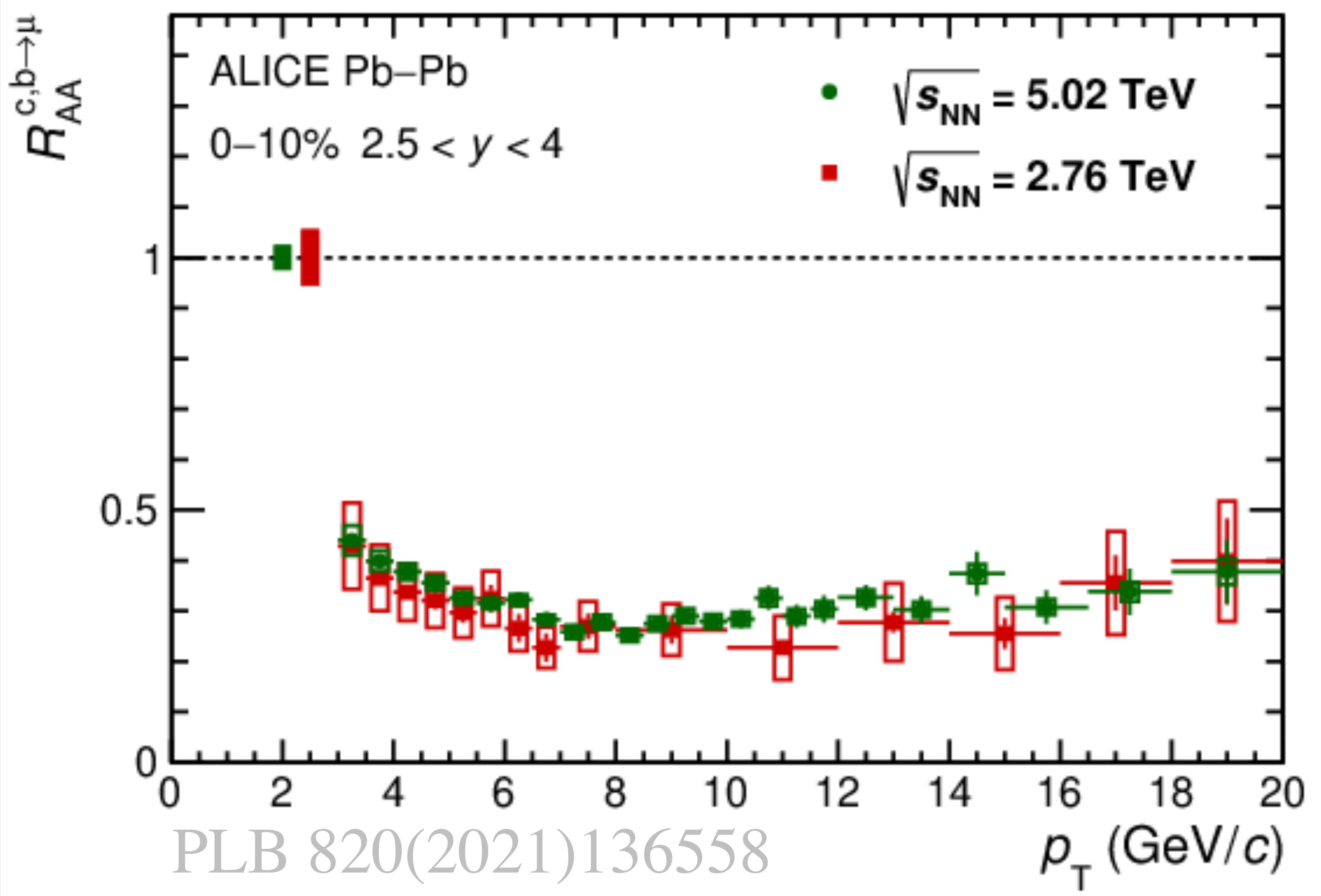
=> HFM distributions are predominantly sensitive to the charm in-medium energy loss for $p_T < 5$ GeV/c.

=> At high p_T the dominant contribution is from beauty-hadron decays rather than charm, so it is more sensitive to the suppression of beauty

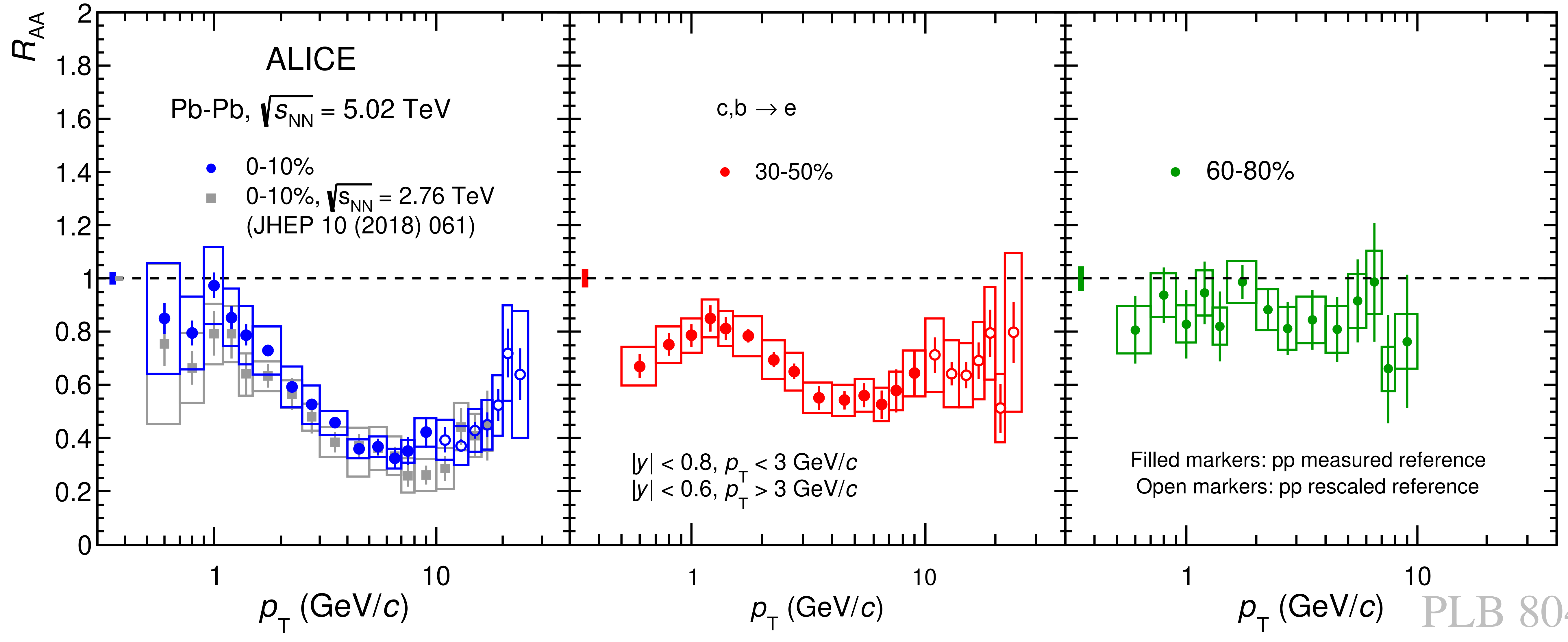
=> MC@sHQ+EPOS2 predictions provide a fair description in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV within uncertainties, while at $\sqrt{s_{NN}}$ = 2.76 TeV, the model tends to slightly overestimate the measured R_{AA} at low/intermediate p_T.

=> MC@sHQ+EPOS2 model reproduces better the data at large p_T when considering both elastic and radiative energy loss.

Comparison of R_{AA} measured at forward and midrapidity



PLB 820(2021)136558



PLB 804 (2020) 135377

=> The observed R_{AA} at mid rapidity (from heavy-flavour decay electrons) and forward rapidity (from heavy-flavour decay muons) are similar.

=> Heavy quarks suffer a strong in-medium energy loss over a wide rapidity interval.

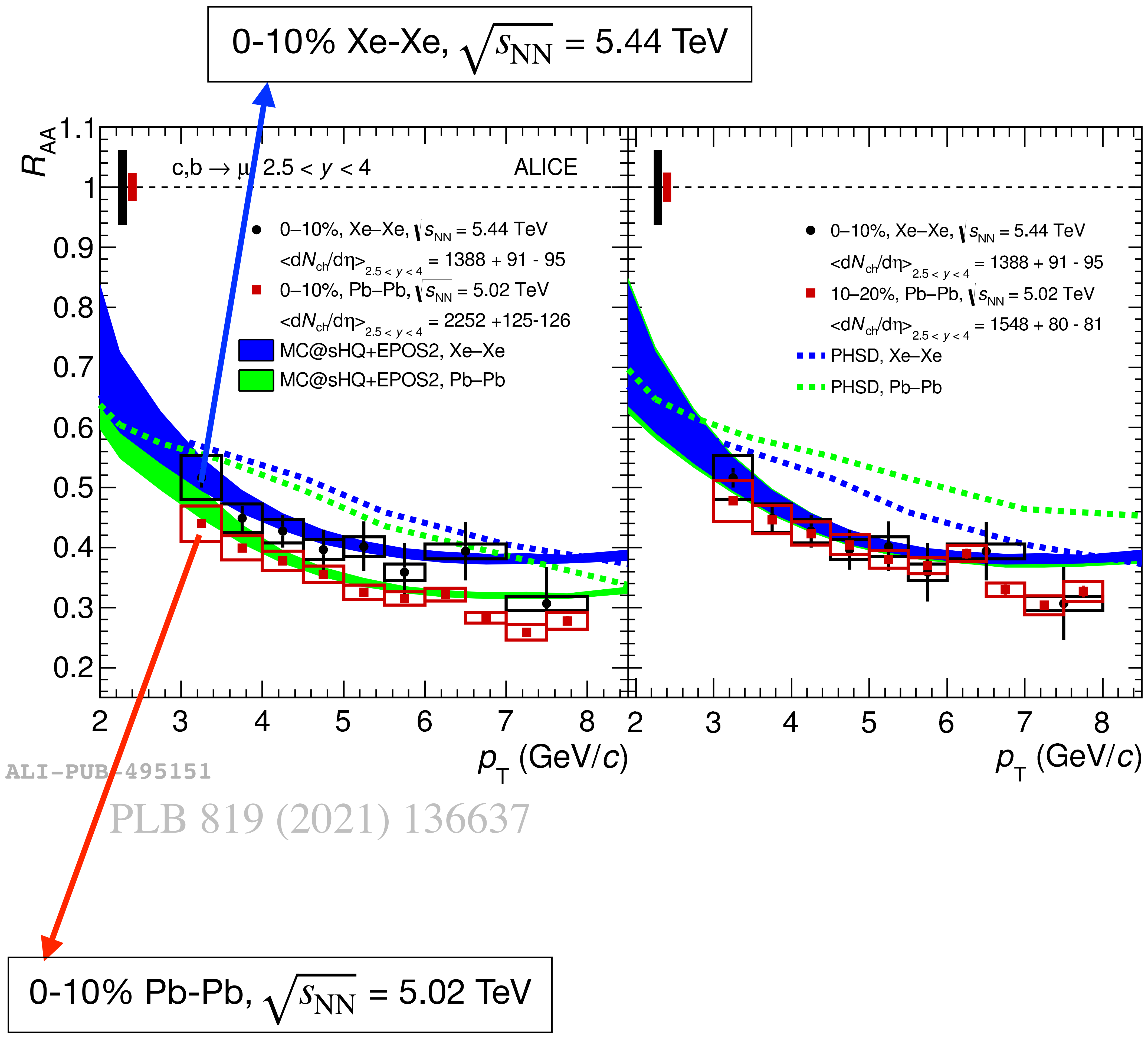
=> In both cases, the measured yield suppression at $\sqrt{s_{NN}}$ = 5.02 TeV is comparable to that observed at $\sqrt{s_{NN}}$ = 2.76 TeV.

=> This similarity of the R_{AA} at two different energies may results from the interplay of the following two effects:

i) a flattening of the p_T spectra of charm and beauty quarks with increasing collision energy, which would reduce the suppression.

ii) a medium temperature estimated to be higher by about 7% at $\sqrt{s_{NN}}$ = 5.02 TeV than at 2.76 TeV —-> would increase the suppression

Comparison of R_{AA} at forward rapidity in Xe-Xe and Pb-Pb collisions



==> Different charged particle multiplicities (and hence energy densities) are present to the same centrality class in Pb-Pb and Xe-Xe collision systems and hence we expect a different suppression in the two collision systems at the same centrality class.

==> The evolution of R_{AA} in Pb-Pb and Xe-Xe collision systems is similar, although the suppression is stronger in Pb-Pb collisions at the same centrality class.

==> The p_T-integrated R_{AA} values in the range $3 < p_T < 8$ GeV/c differ by about 2.5 standard deviations which may result from the difference in the system size.

==> The MC@sHQ+EPOS2 model describes the suppression observed in the data for both Pb–Pb and Xe–Xe systems in central (0–10%) collisions. The PHSD calculations underestimate the measured suppression over the entire p_T interval in these two collision systems.

Scope with MFT+ Muon Spectrometer of ALICE in Run 3

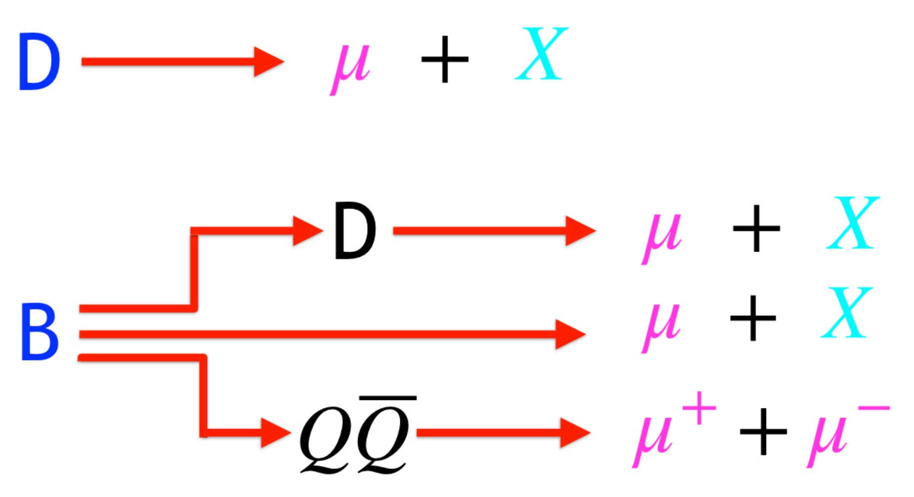
Muon physics program suffered several limitations during Run 1 and Run 2, specially due to the multiple scattering experienced by the muon tracks inside hadron absorber => vertex region is smeared.

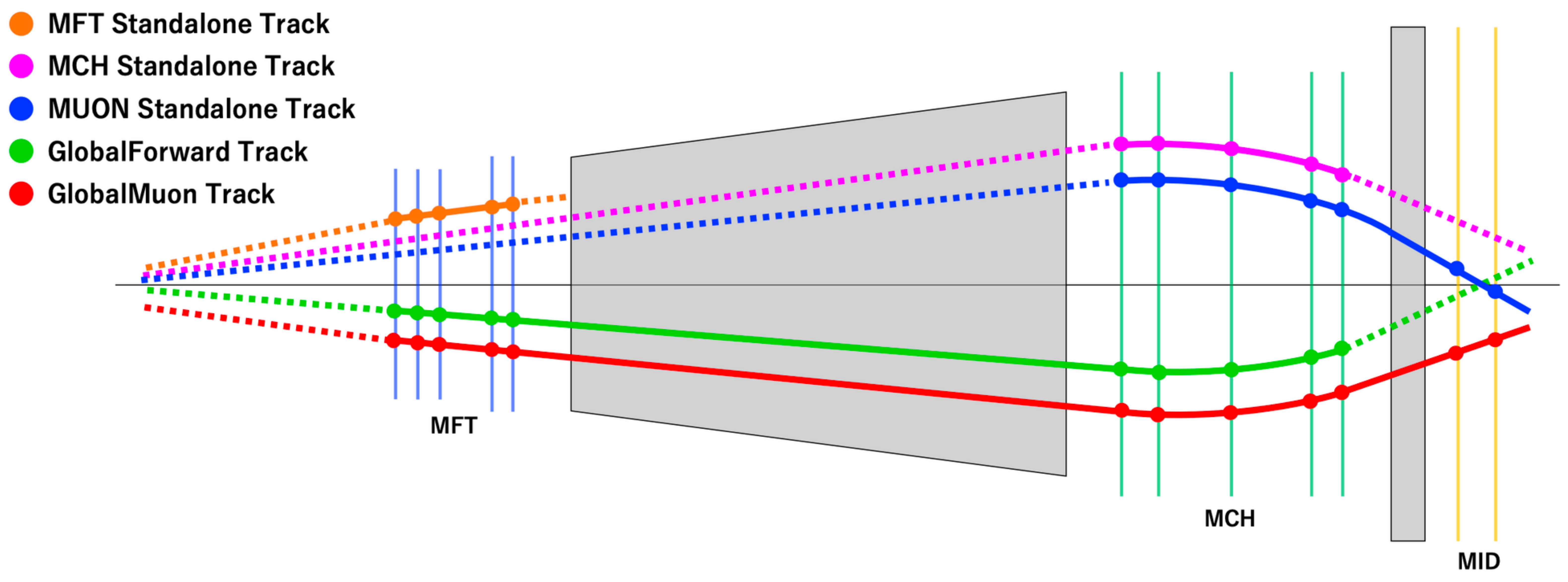
Matching of tracks reconstructed in the tracking system of Muon Spectrometer and that with MFT cluster =>

i) Separation of prompt J/ψ from b-decay J/ψ.

ii) Open charm and open beauty via semi-muonic decays can be distinguished because of the different lifetimes of charm ($c\tau \sim 100\ \mu m$) and beauty ($c\tau \sim 500\ \mu m$) hadrons.

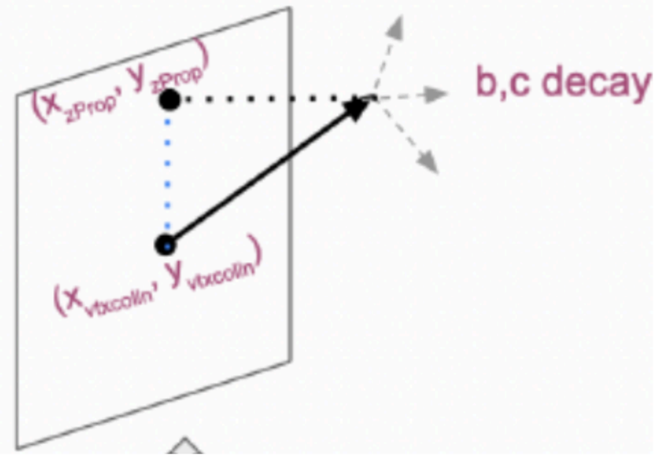
iii) Study of heavy-flavour (HF) using single muons down to p_{T} ~1 GeV/c.





Charm & beauty separation: An analysis of the Offset distribution

The measurement of charm and beauty yields is based on the fit of the distance of closest approach (DCA) distribution.



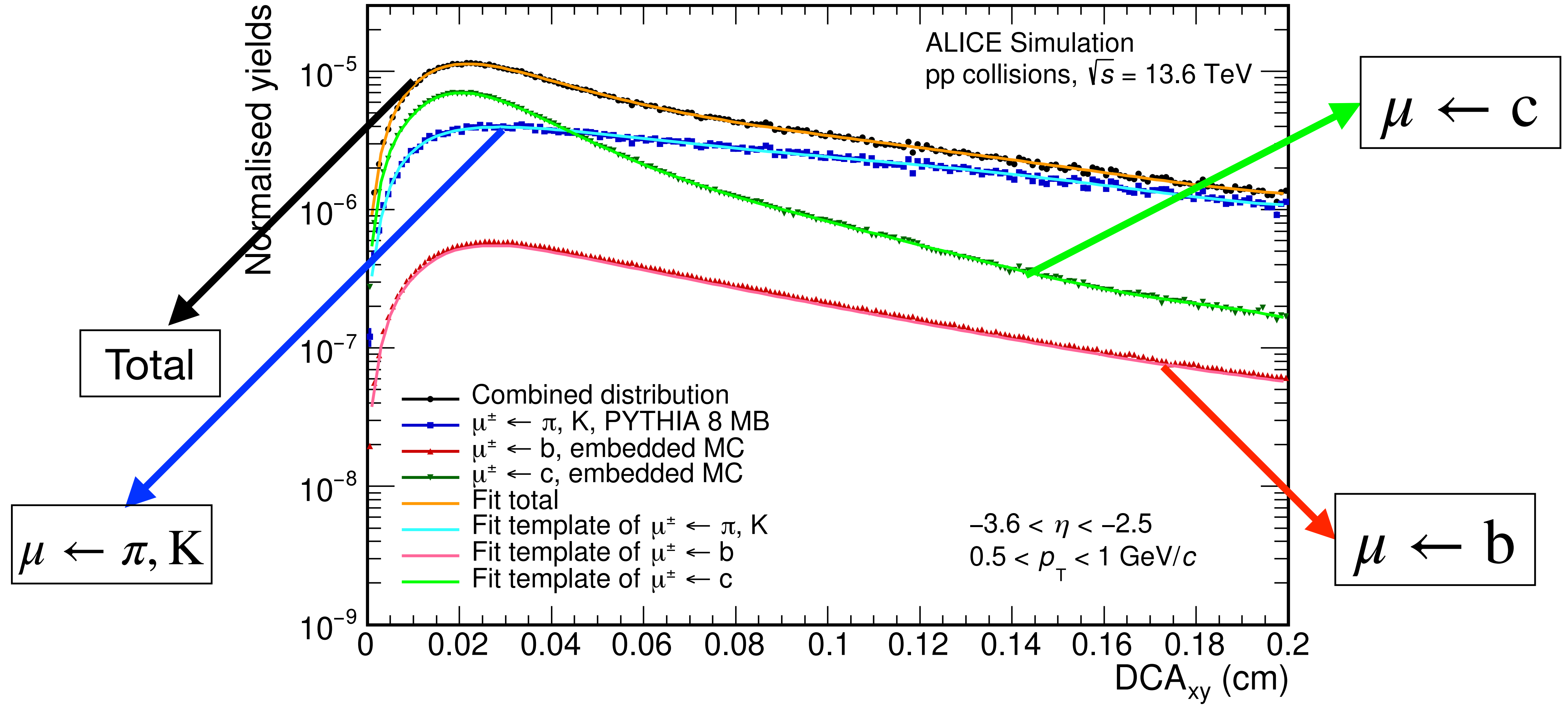
$$DCA_{xy} = \sqrt{(x_V - x_{ext})^2 + (y_V - y_{ext})^2}$$

(x_V, y_V) => Transverse coordinate of the primary vertex (PV) measured by the Inner Tracking System (ITS).
(x_{ext}, y_{ext}) => Coordinates in the plane transverse to the beam line of the extrapolated track evaluated at the z-axis of the PV.

The total DCA distribution are decomposed into three components via a fit with the function:

$$f(DCA_{xy}) = C\,.f_c(DCA_{xy}) + B\,.f_b(DCA_{xy}) + D\,.f_{bkg}(DCA_{xy}) \longrightarrow f_{c/b/bkg}(x) = Ae^{-(x-\mu)^2/2\sigma(x)^2}$$

$f_c(DCA_{xy}),\ f_b(DCA_{xy}),\ f_d(DCA_{xy})$ => Monte Carlo templates for charm(c), beauty(b) and background respectively.
B,C,D => free parameters corresponding to the normalisation of the three components.



ALI-SIMUL-547324

Ongoing Run 3 analyses

==> Multi-differential measurements for $\mu \leftarrow c$, $\mu \leftarrow b$ (vs p_T, y, centrality/multiplicity)

i) production cross-sections, ratios & R_{AA} down to lower p_T and higher p_T compared to Run 2.

ii) Azimuthal anisotropies (v2, v3 and higher harmonics).

Summary

==> ALICE has measured the p_{T}-differential production cross-section of open heavy-flavour decay muon in pp and AA (Pb-Pb & Xe-Xe) collisions in Run 1 & Run 2.

==> The measured R_{AA} shows evidence of a strong suppression, a factor of about 4 in the 10% most central collisions with respect to the binary-scaled pp reference in both collision energies of Pb-Pb collisions while it is upto a factor of 2.5 in the case of Xe-Xe collisions.

==> The observed suppression is compatible with a large in-medium energy loss of heavy-quarks.

==> The suppression becomes weaker from central to peripheral collisions, reflecting the dependence of energy loss on the path length in the QGP.

==> The R_{AA} measurements have the potential to discriminate between different model calculations with different implementation of the dynamics of the heavy-quarks in the QGP.

==> The measured R_{AA} is in fair agreement with transport model calculations that consider both collisional and radiative energy loss.

==> Various multi-differential measurements for $\mu \leftarrow c, \mu \leftarrow b$ are ongoing in Run 3 with much higher statistics compared to Run 2.

thank you