Muons from Open Heavy-flavour Decays in pp, Pb-Pb and p-Pb Collisions with ALICE

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Rencontres, QGP-France-13, Etretat, 9-12 Septembre 2013

Outline

- Heavy-Flavour Physics at the LHC
- Heavy-Flavour Measurements with ALICE
- Muon analysis results in p-p, Pb-Pb and p-Pb collisions
- Conclusions and Outlooks

Part 1:
Introduction

Heavy-Flavour Physics at the LHC

- Heavy flavours in **pp collisions**
  - ✓ baseline for pA and AA collisions
  - ✓ test NLO pQCD in a new energy domain

$$R_{AA} = \frac{1}{< T_{AA} >} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

- Heavy flavours in **AA collisions:** tomography of QCD medium
  - ✓ Nuclear modification factor
    - ☐ mass and color charge dependence of parton energy loss;

$$\boxed{\begin{array}{c}\Delta E_g > \Delta E_{q\approx c} > \Delta E_b \\ R^h_{AA} < R^D_{AA} < R^B_{AA}\end{array}}$$

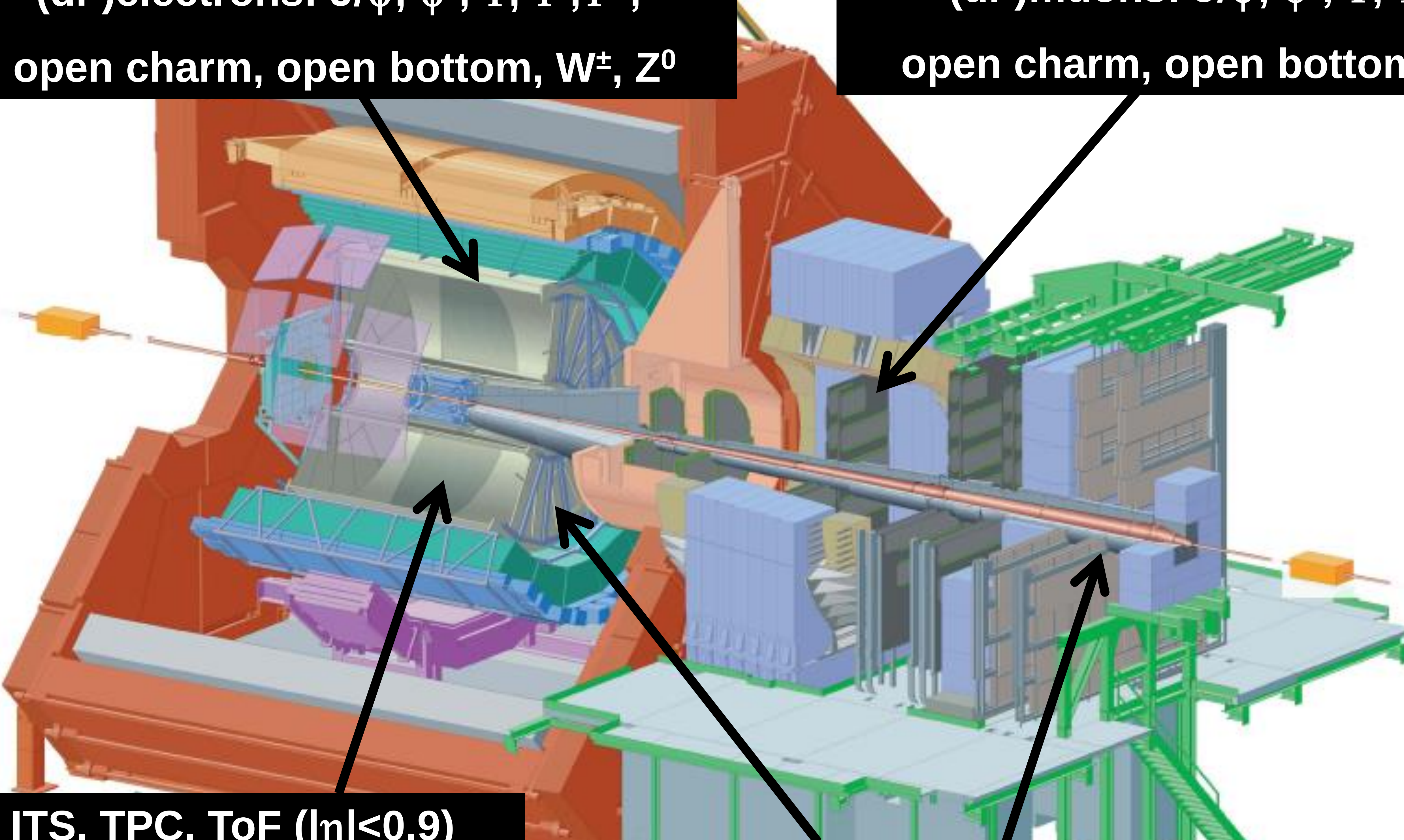
  - ✓ azimuthal anisotropic flow
    - ☐ low p_T region: initial conditions of QCD medium, degree of thermalization of heavy quarks in QGP,
    - ☐ high p_T region: path length dependence of heavy flavour energy loss;

- Heavy flavours in **pA collisions**
  - ✓ "correct" R_{AA} for shadowing effects: deviation of R_{pA} from unity reveals the presence of cold nuclear matter (CNM) effect

Heavy-flavour Measurements with ALICE

ITS, TPC, TRD, ToF, EMCal ($|\eta|<0.9$)
(di-)electrons: J/ψ, ψ', Υ, Υ', Υ'',
open charm, open bottom, $W^{\pm}$, Z^0

muon spectrometer ($-4<\eta<-2.5$)
(di-)muons: J/ψ, ψ', Υ, Υ', Υ'',
open charm, open bottom, $W^{\pm}$, Z^0

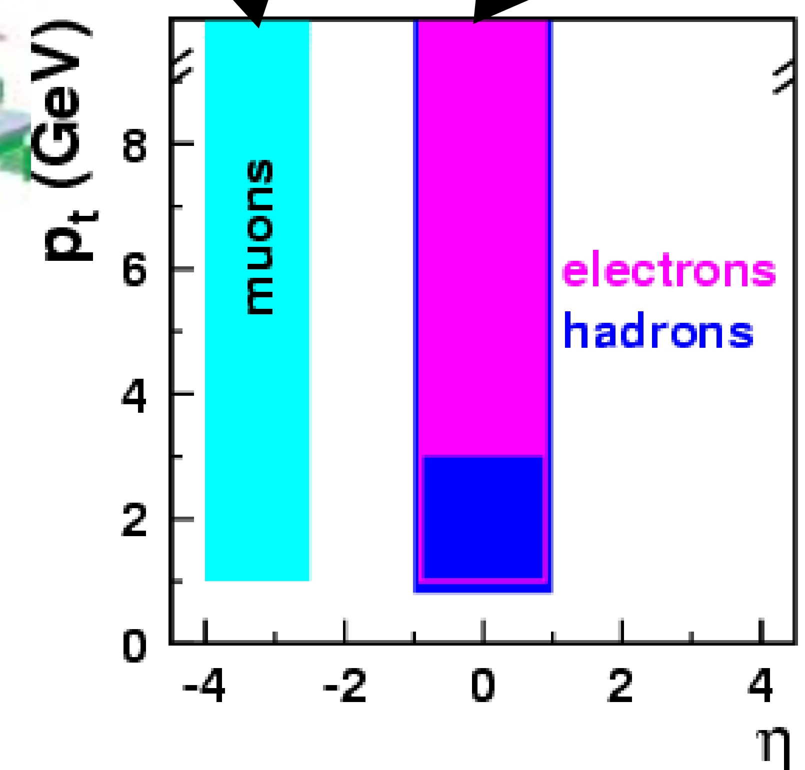


ITS, TPC, ToF ($|\eta|<0.9$)
hadrons: D^0, $D^{\pm}$, D^*…

electron-muon coincidences:
open charm & bottom

no 2nd vertex

2nd vertex



The heavy-flavour physics is investigated in several decay channels and large rapidity coverage with ALICE.

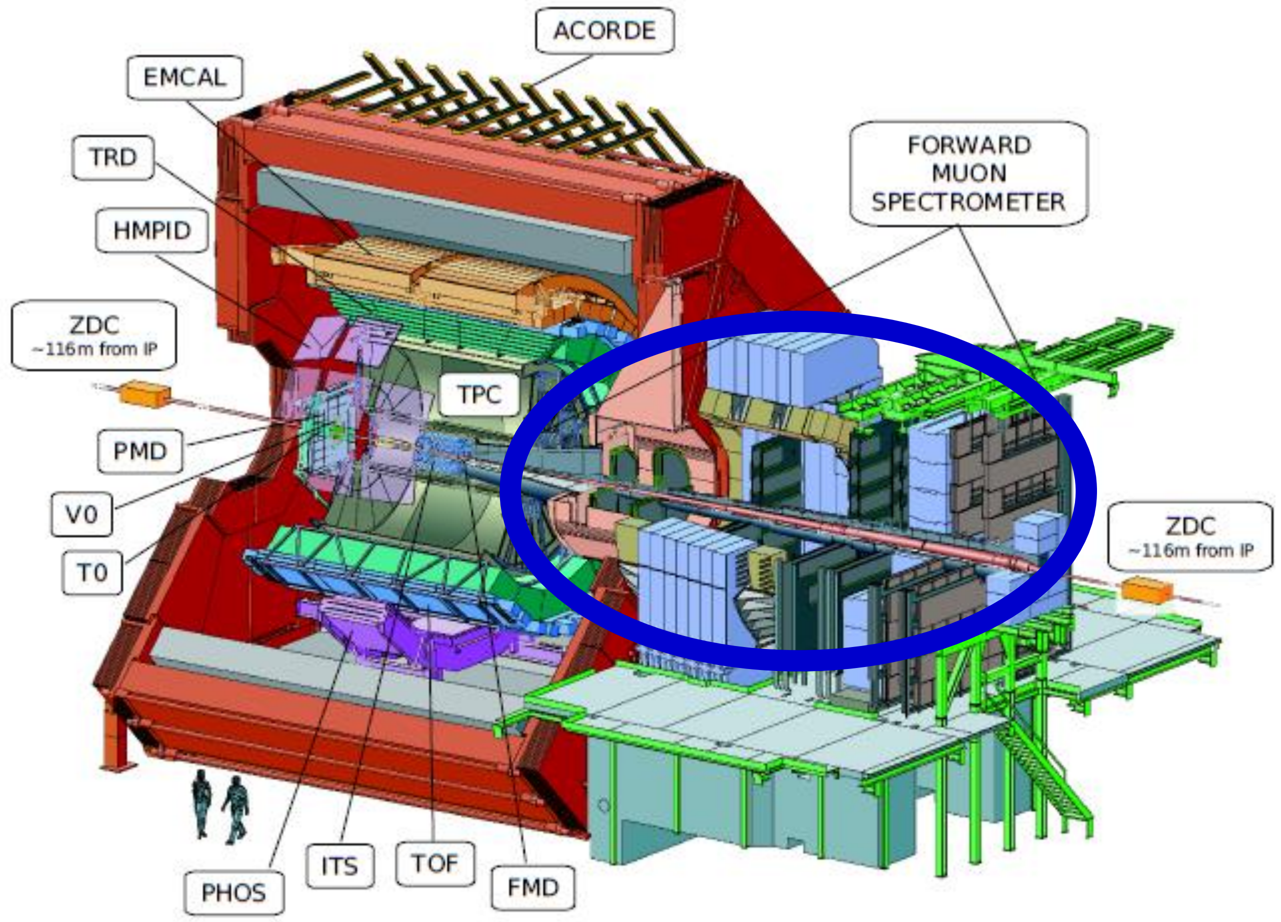
Data samples

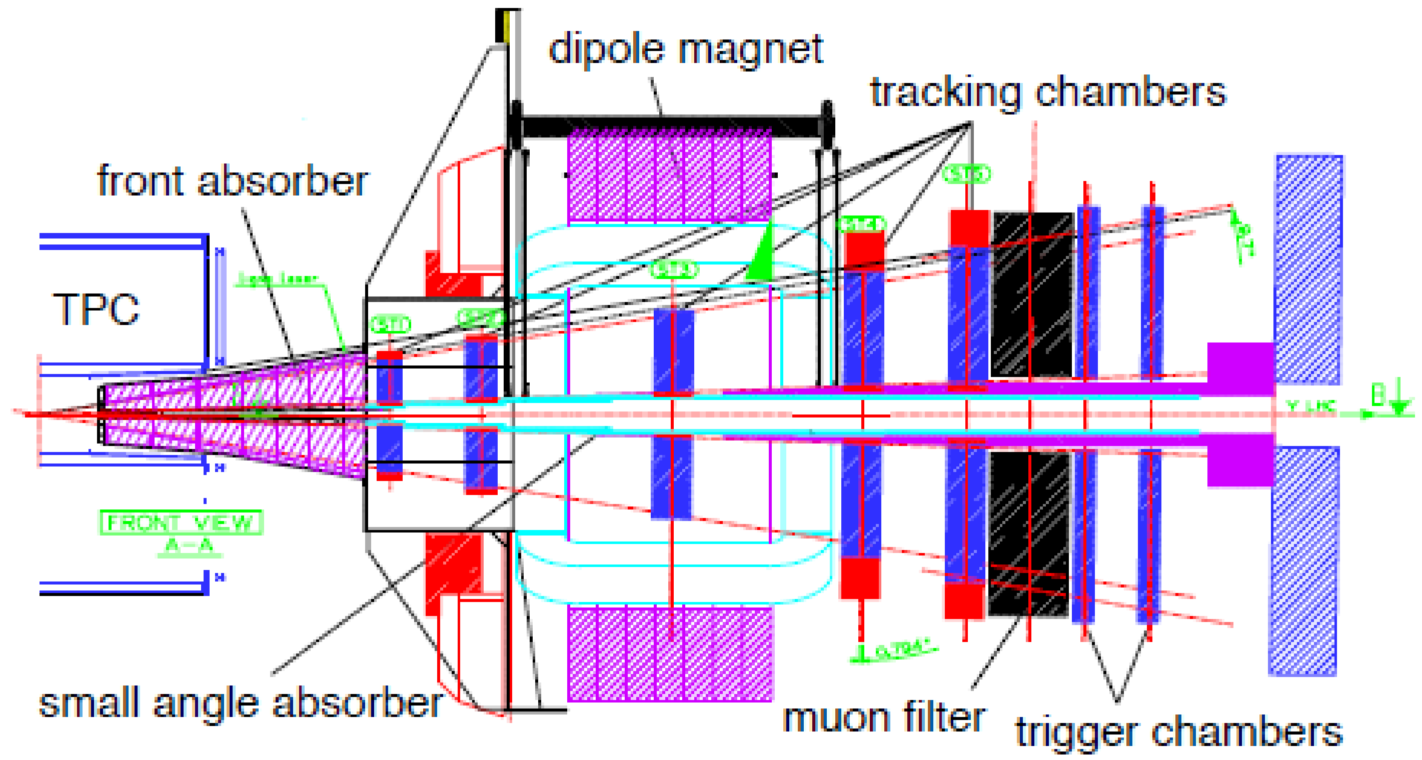
- pp collisions @ $\sqrt{s_{NN}}$ = 7 TeV: data collected in 2010, muon trigger events;

- Pb-Pb collisions @ $\sqrt{s_{NN}}$ = 2.76 TeV
  - ✓ R_{AA}: data collected in 2010, min.bias events;
  - ✓ v_2: data collected in 2011, central and semi-central events;

- p-Pb/Pb-p collisions @ $\sqrt{s_{NN}}$ = 5.02 TeV: data collected in 2013, muon trigger events.

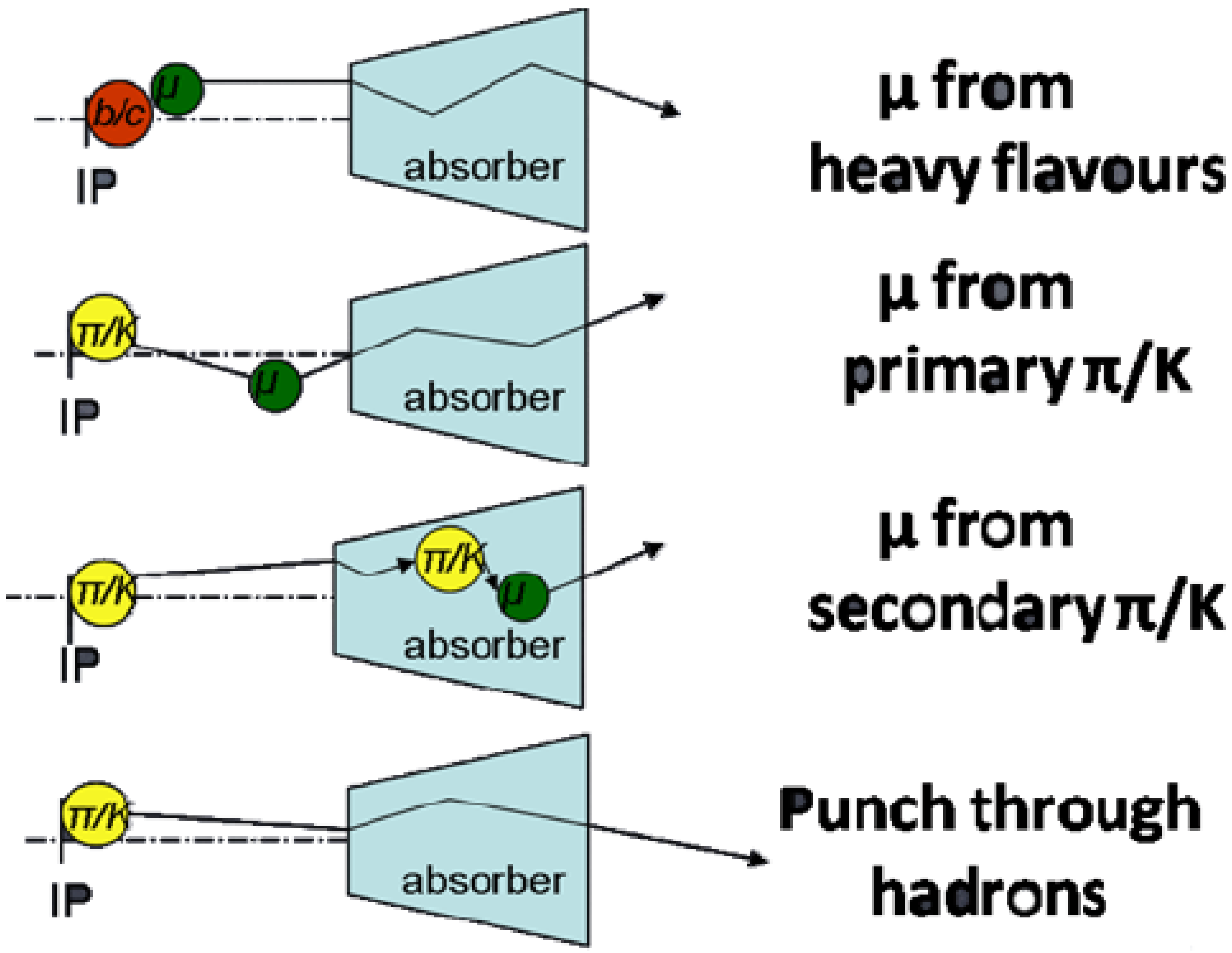
Muon selection





Track selection

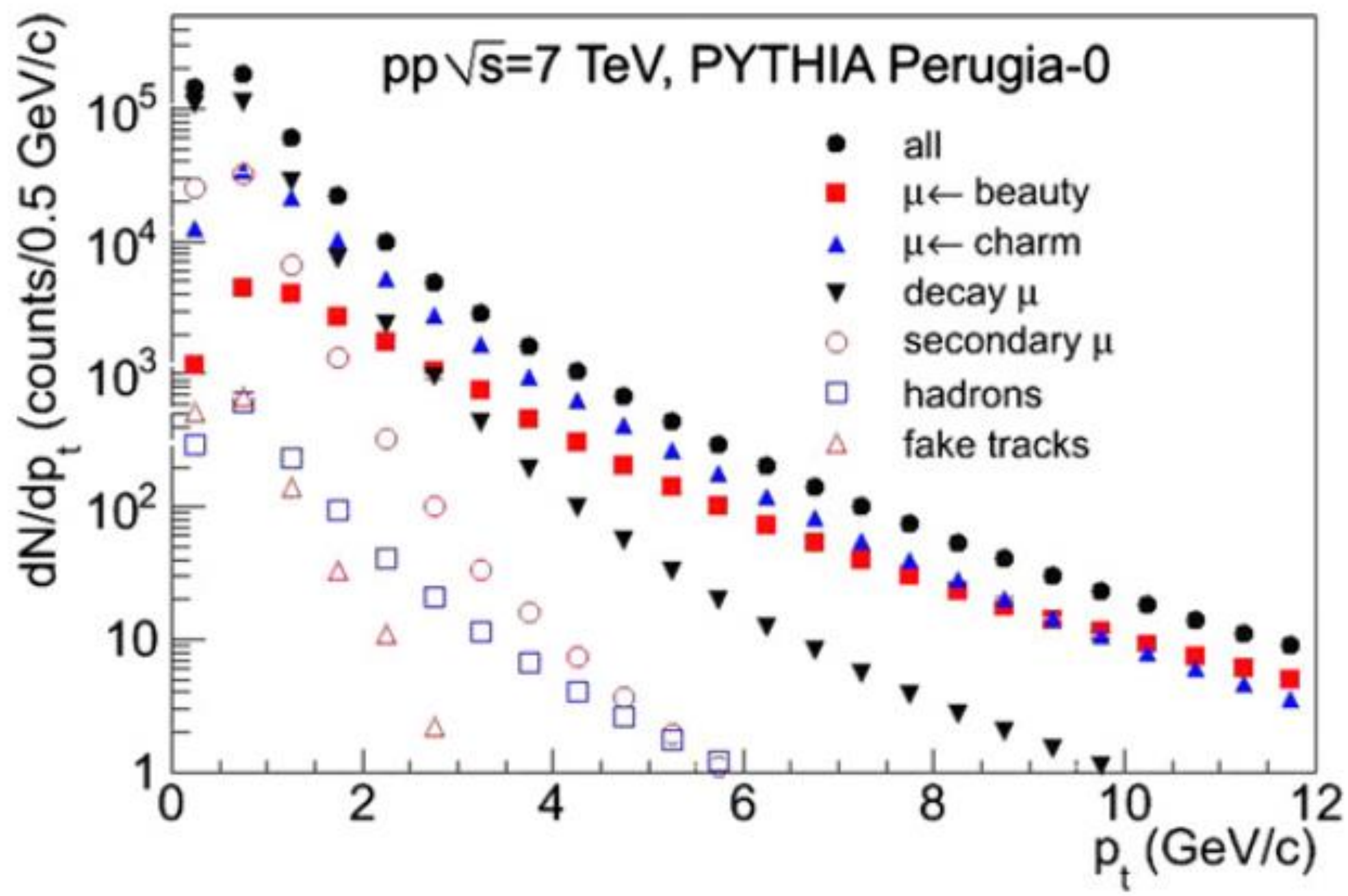
- $-4 < \eta_{lab} < -2.5$: acceptance of ALICE MUON spectrometer;
- $170^0 < \theta_{abs} < 178^0$: geometry of the spectrometer;
- muon trigger matching: reject hadrons that cross the absorber;
- pxDCA: remove beam-gas and particles produced in the absorber.



Decay Muon Subtraction in p-p Collisons

- **Strategy:**
  - ✓ extract dN/dp_T of K/π decay muons from simulation (PYTHIA or Phojet);
  - ✓ normalize it to measured muon yield at low p_T;
  - ✓ subtract from inclusive dN/dp_T to obtain heavy flavour decay muon spectrum;

- **Systematic uncertainty:**
  - ✓ models: estimated by using different inputs;
  - ✓ transport codes, estimated by varying yield of muons from secondary K/π between 0 and 200%.



Decay Muon Subtraction in Pb-Pb Collisons

- **Strategy:**
  - ✓ input: K/π spectra in pp collisions and R_{AA} in Pb–Pb collisions at central rapidity measured with ALICE; **[J. Phy. G, G38 (2011) 124014 & 124080]**
  - ✓ extrapolate K/π spectra in pp collisions to forward rapidity by means of Monte-Carlo simulations according to

$$d^2N_{pp}^{\pi^\pm,K^\pm}/dp_t dy = [d^2N_{pp}^{\pi^\pm,K^\pm}/dp_t dy]_{y=0} \exp\left(\frac{-y^2}{2\sigma_y^2}\right)$$

  - ✓ get K/π spectra in Pb–Pb collisions at forward rapidity by scaling the extrapolated charged K/π spectra with their R_{AA} at central rapidity

$$dN_{\mathrm{PbPb}}^{\pi^\pm,K^\pm}/dp_t = \langle T_{AA}\rangle (d\sigma_{pp}^{\pi^\pm,K^\pm}/dp_t)[R_{AA}^{\pi^\pm,K^\pm}(p_t)]_{y=0}$$

    vary K/π R_{AA} between 0 and 200% to estimate the systematic uncertainty on unknown quenching effect at forward rapidity;

  - ✓ produce the K/π decay muon background by means of fast simulation.

Decay Muon Subtraction in p-Pb Collisons

- **Strategy:**
  - ✓ input: *K/π* spectra in p-Pb collisions at central rapidity measured with ALICE;
  - ✓ extrapolate *K/π* spectra in p-Pb collisions to forward rapidity by means of Monte-Carlo simulations according to

$$\left.\frac{1}{N_{AA}^{ev}}\frac{dN_{pA}^{k/\pi}}{dp_t}\right|_{FW} = \left.\frac{1}{N_{AA}^{ev}}\frac{dN_{pA}^{k/\pi}}{dp_t}\right|_{CB} \times F_{extra.}$$

$$F_{extra.} = \left.\frac{1}{N_{AA}^{ev}}\frac{dN_{AA}^{k/\pi}}{dp_t}\right|_{a}^{b} \Big/ \left.\frac{1}{N_{AA}^{ev}}\frac{dN_{AA}^{k/\pi}}{dp_t}\right|_{0}^{0.5}$$

by using the *non-parameterized* rapidity extrapolation factor;

  - ✓ produce the *K/π* decay muon background by means of fast simulation.

$$\left.\frac{1}{N_{AA}^{ev}}\frac{dN_{pA}^{\mu\leftarrow k/\pi}}{dp_t}\right|_{FW\ (\Delta p_t)} = \left.\left\{\frac{\left.\frac{1}{N_{AA}^{ev}}\frac{dN_{pA}^{k/\pi}}{dp_t}\right|_{FW}}{\frac{dN_{pA}^{flat\ k/\pi}}{dp_t}} \times \left.\frac{dN_{pA}^{\mu\leftarrow flat\ k/\pi}}{dp_t}\right|_{FW\ (\Delta p_t)}\right\}\right|_{(\Delta p_t)}$$

Normalization to Min. Bias events

➢ **Strategy:** two methods are used to obtain the number of equivalent Min. Bias events from the MSL/MSH triggers: about 1% difference

- Offline method from AOD

$$F_{norm}(MSL) = \frac{N_{MB} \times F_{pile-up}}{N_{(MB\ \&\&\ 0MSL)}}$$

$$F_{norm}(MSH) = \frac{N_{MB} \times F_{pile-up}}{N_{(MB\ \&\&\ 0MSL)}} \times \frac{N_{MSL}}{N_{(MSL\ \&\&\ 0MSH)}}$$

- Scaler method from OCDB: used in the following

$$F_{norm} = \frac{L0b_{MB} \times purity_{MB} \times F_{pile-up}}{L0b_{MSL(MSH)} \times PS_{MSL(MSH)}}$$

N.B. $L0b$ is the value of *L0b* counter for selected trigger;

PS is the fraction of physics selection accepted triggers;

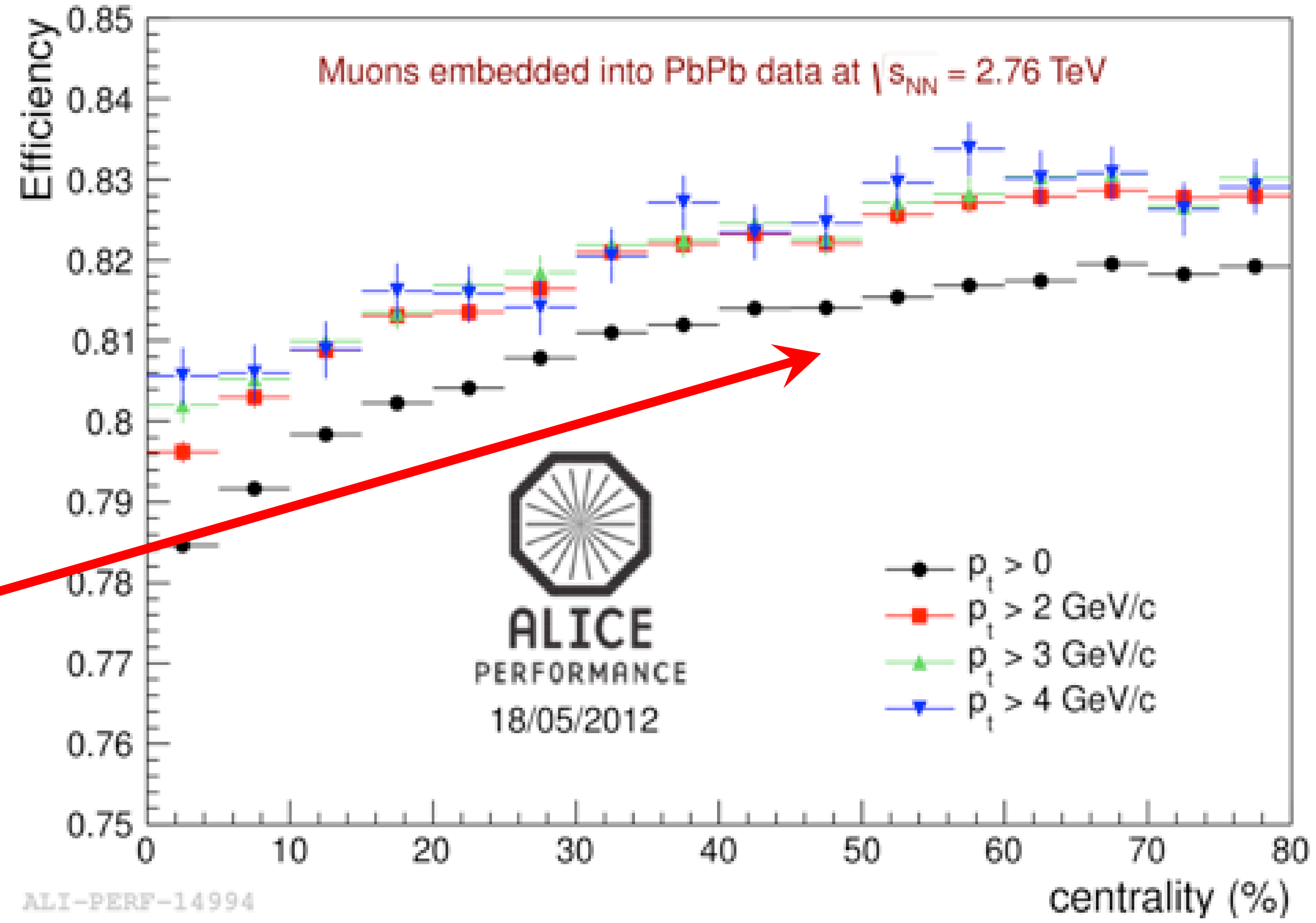
purity is the fraction of events which satisfy V0 timing cut (that is better than 99% for most of the runs

$$F_{pile-up} = \mu/e^{-\mu}, \quad \mu = -\ln(1 - purity_{MB} * \frac{L0bRate_{MB}}{N_{colliding} * f_{LHC}})$$

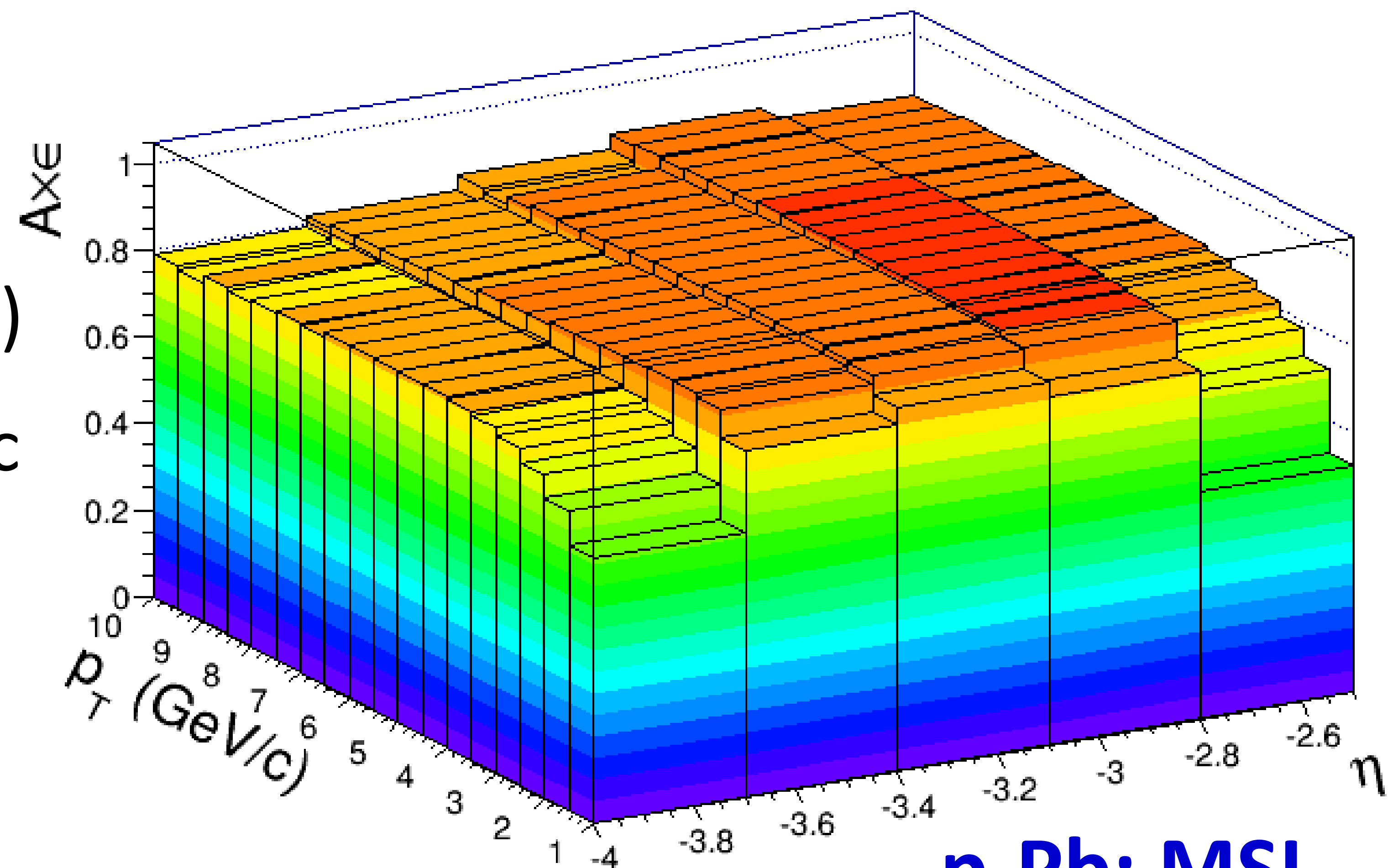
F_{norm}(0-100%)	p-Pb		Pb-p	
	Offline	Scaler	Offline	Scaler
MSL	28.1	28.5	20.4	20.4
MSH	1024.3	1040.8	795.2	794.2

Acceptance x Efficiency Correction

- **Reminder for Pb-Pb collisions**
  - the centrality dependence of tracking efficiency is estimated via embedding procedure
  - efficiency drops by 4±1% in the 10% most central collisions w.r.t. peripheral collisions



- **Follow same strategy as in pp collisions**
  - no dependence on centrality expected (Javier, Jpsi2mumu PAG meeting, 31/05/2013)
  - simulations using beauty signals with realistic detector condition as inputs
  - systematic uncertainty on misalignment: 1%xp_T (p_T in GeV/c)

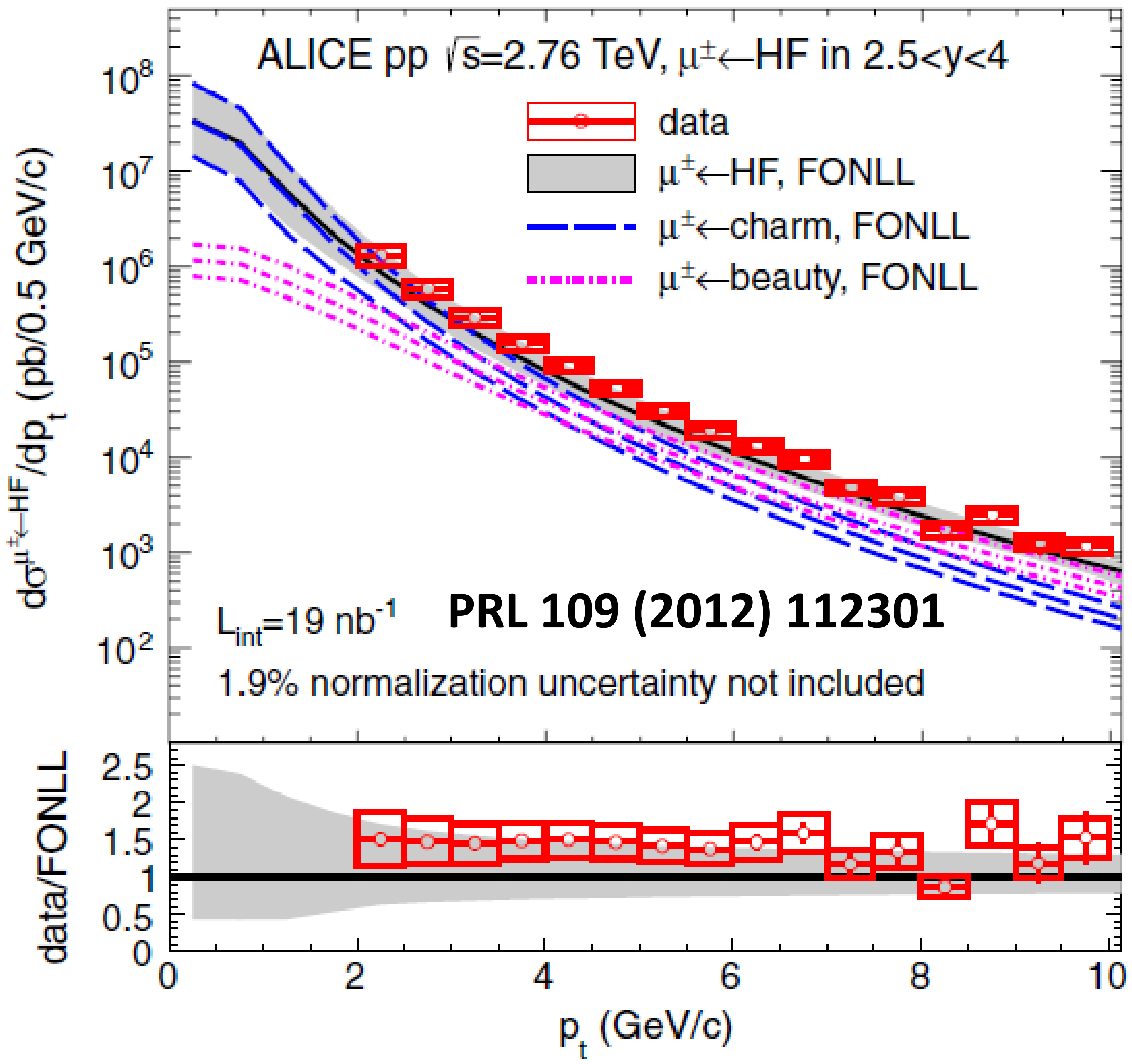


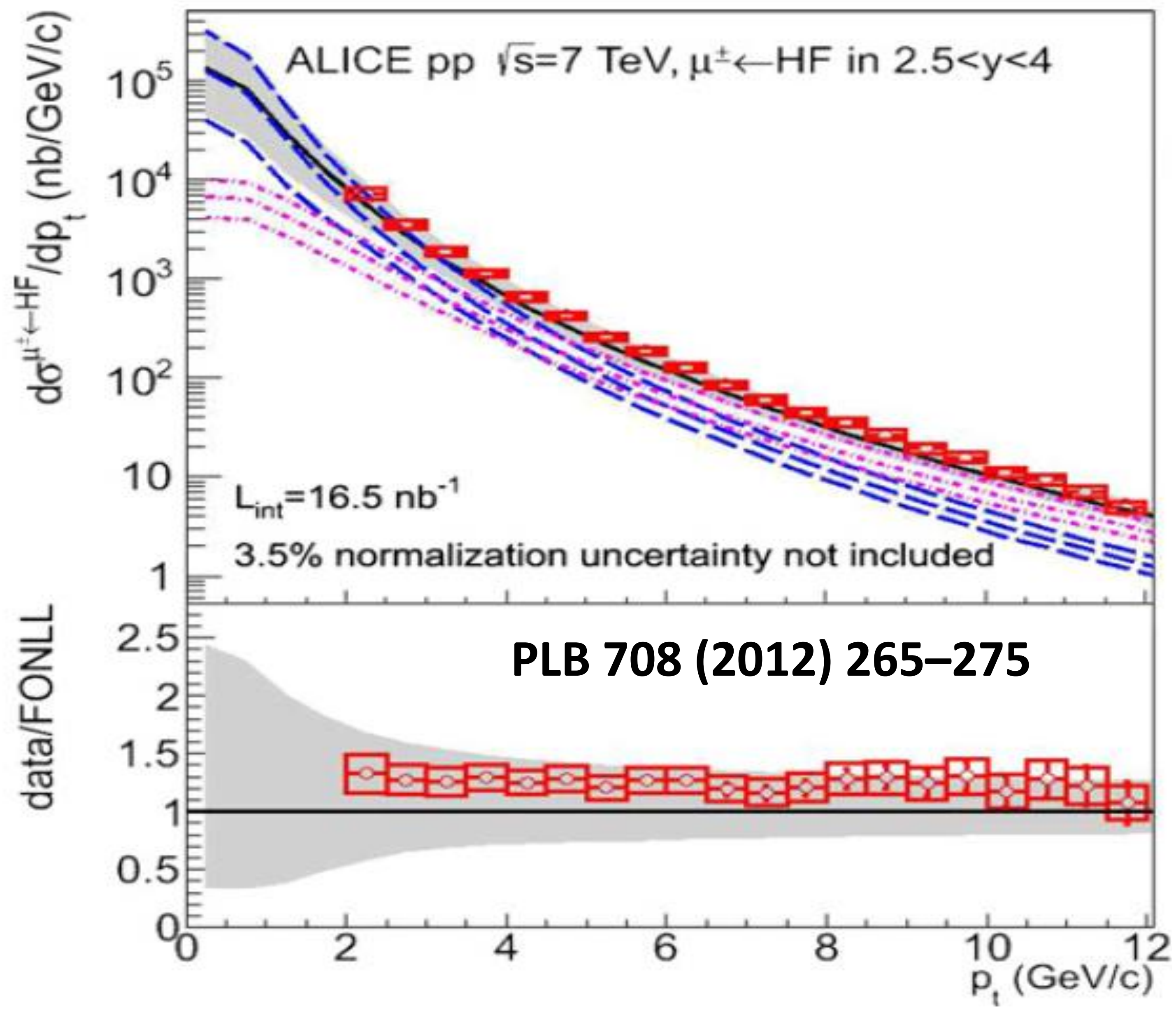
p-Pb: MSL

Part 2:
Results & Discussions

p-p collisions

------ cross section



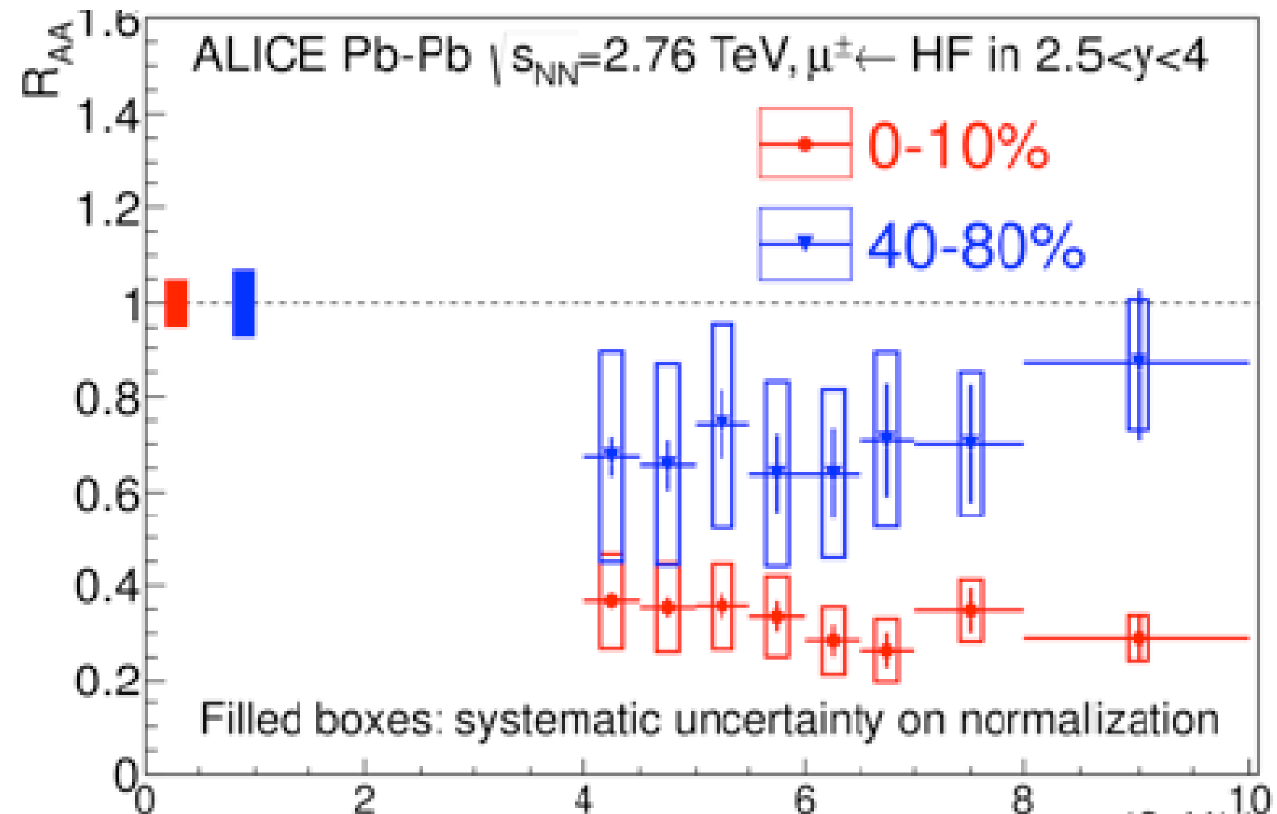


- p_T-differential cross sections of muon from heavy-flavour decays measured at 2.76 and 7 TeV;
- The FONLL pQCD calculations are in good agreement with data within experimental and theoretical uncertainties;
- baseline for the study of heavy quark in-medium effects in Pb-Pb and p-Pb collisions.

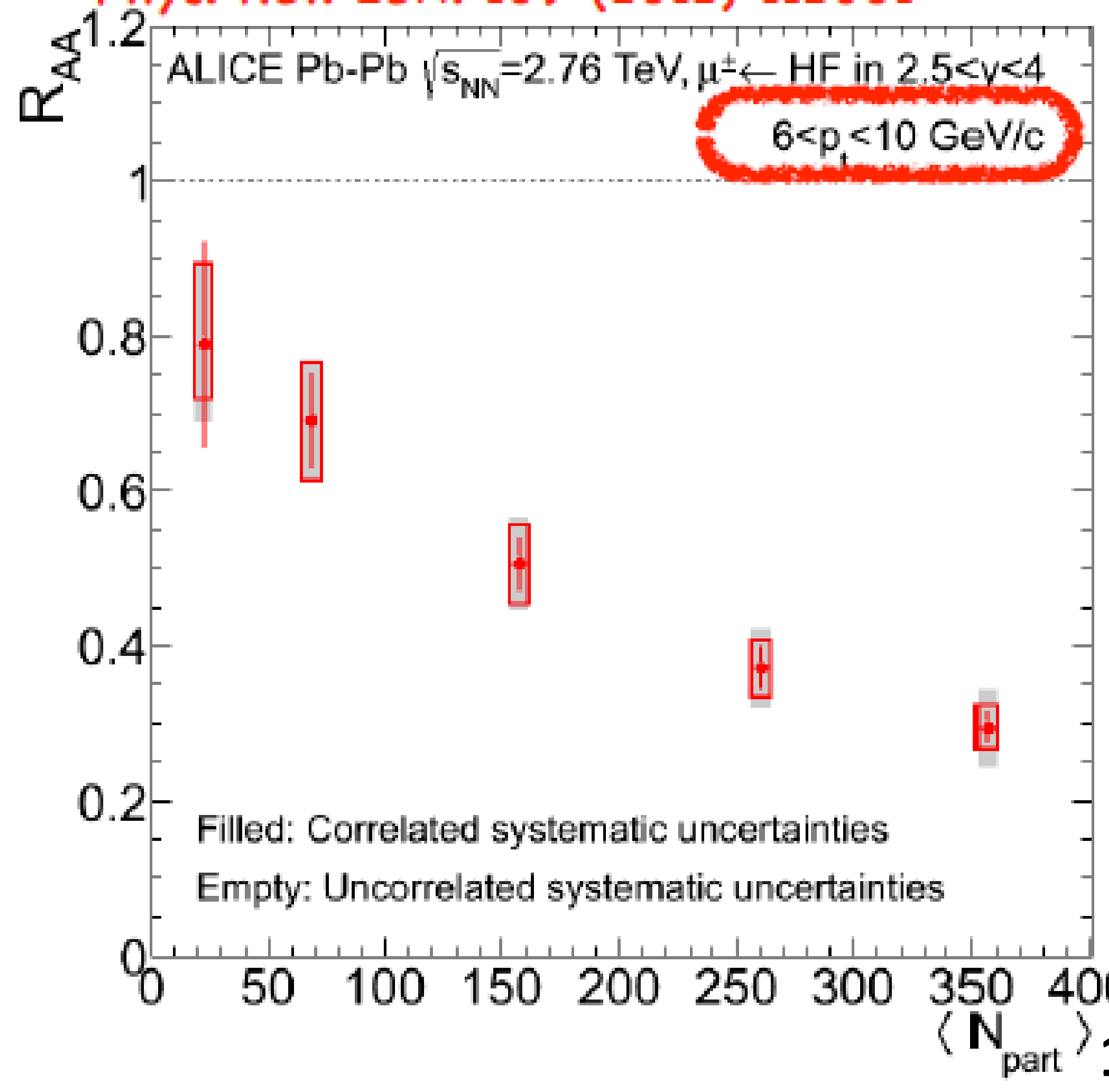
Pb-Pb collisions

------ nuclear modification factor R_{AA}

- suppression is observed and is independent of p_T within uncertainties (in the measured p_T interval);
- stronger suppression in central than peripheral collisions, reaching a factor of about 3–4 in the 10% most central collisions;
- in the p_T region (p_T>6 GeV/c), beauty contribution is dominant in pp collisions, according to FONLL calculations.

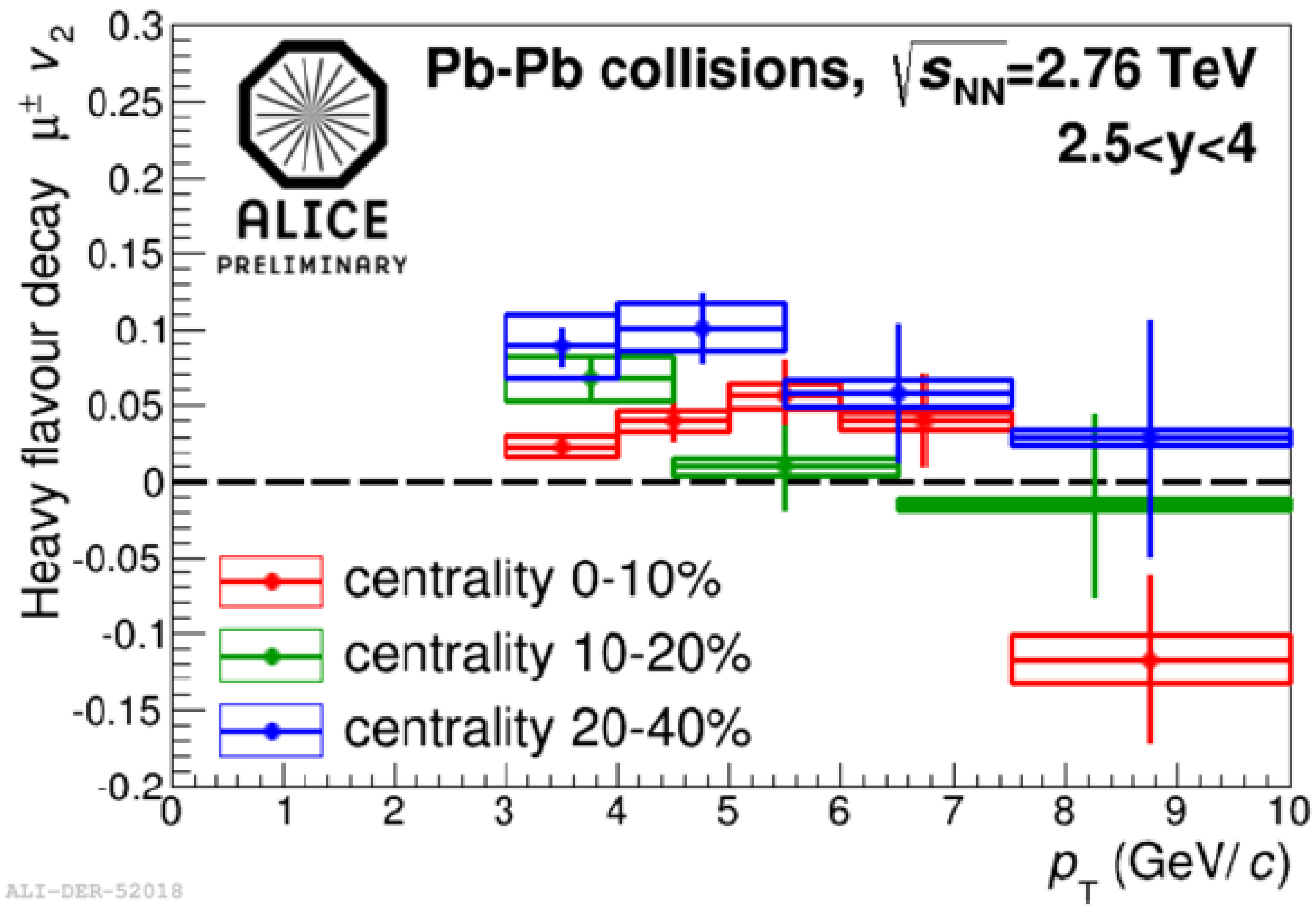


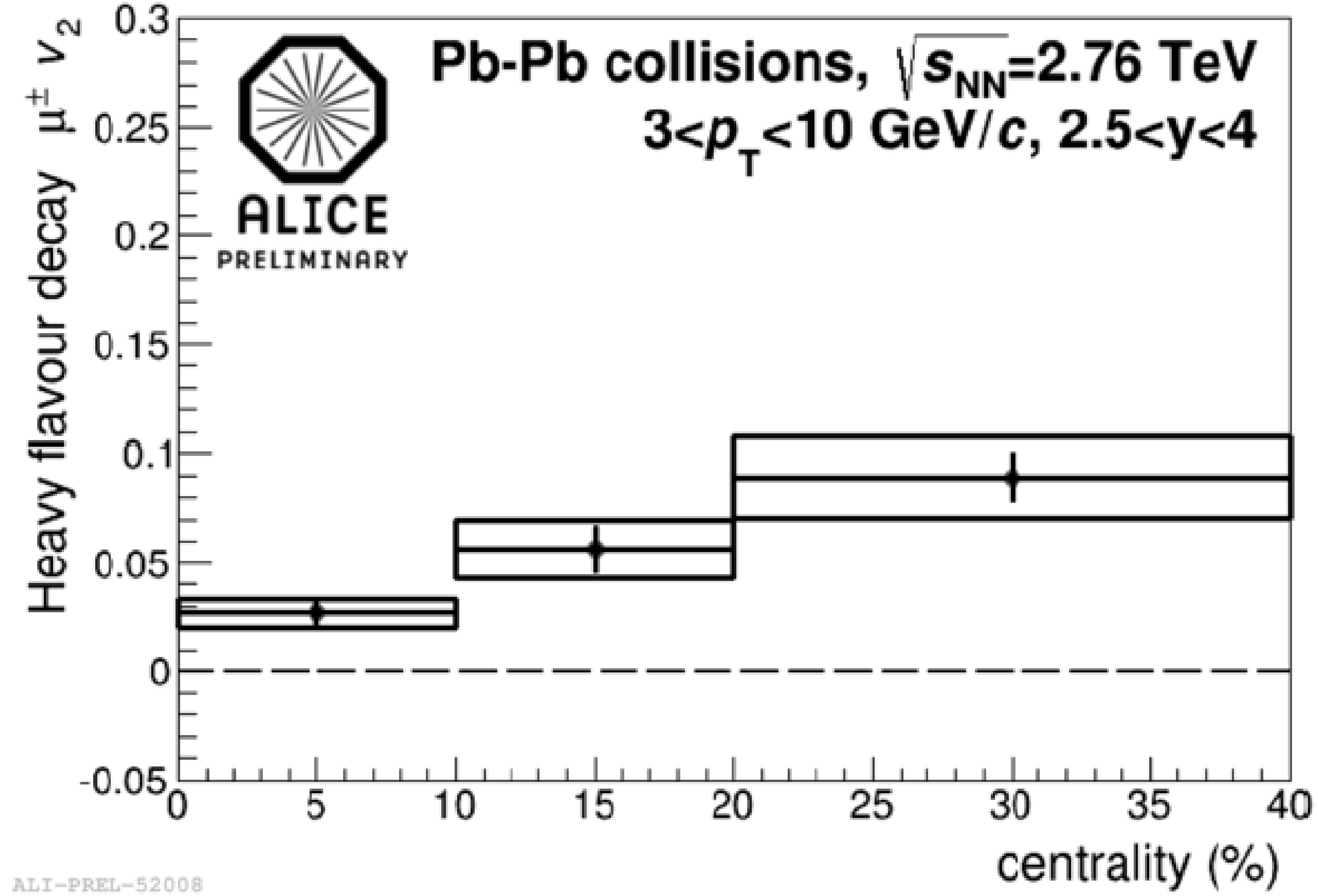
Phys. Rev. Lett. 109 (2012) 112301



Pb-Pb collisions

------ azimuthal anisotropic flow





- Left: differential v_2 vs p_T
  - ✓ v_2 of muons from heavy-flavour decays in semi-central collisions (20-40%) is systematically larger than that in central collisions (0-10%);
  - ✓ non-zero v_2 (3σ effect) in 3<p_T<5 GeV/c and 20-40% centrality class;

- Right: integrated v_2 (in 3<p_T<10 GeV/c) *vs* centrality
  - ✓ v_2 of muons from heavy-flavour decays increases from central to peripheral collisions;
  - ✓ non-zero v_2 (3σ effect) in semi-central collisions (20-40%).

p-Pb collisions

----- nuclear modification factor R_{pA}

Conclusion

- **cross section of muons from heavy-flavour decays measured in pp collisions:**
  - ✓ FONLL predictions in good agreement with data within uncertainties;
  - ✓ baseline for the study of AA and pA collisions

- **R_{AA} of muons from heavy flavour decays measured as a function of p_T and centrality:**
  - ✓ a strong suppression of high p_T muons from heavy-flavour decays is observed in central collisions;
  - ✓ no significant dependence on p_T in $4<p_T<10$ GeV/c;

- **v_2 of muons from heavy-flavour decays:**
  - ✓ v_2 in 20-40% centrality class is larger than that in the most central collisions
  - ✓ non-zero v_2 (3σ effect) in $3<p_T<5$ GeV/c and 20-40% centrality class;

- **R_{pA} of muons from heavy-flavour decays in 0-100%:**

Ongoing work

- implement the similar strategy of the background estimation in Pb-p collisions;
- measure the R_{Ap};
- get the forward to backward ratio R_{FB}.

backup

Convert the spectra to muon level

same method as using in R_{AA} and flow analysis

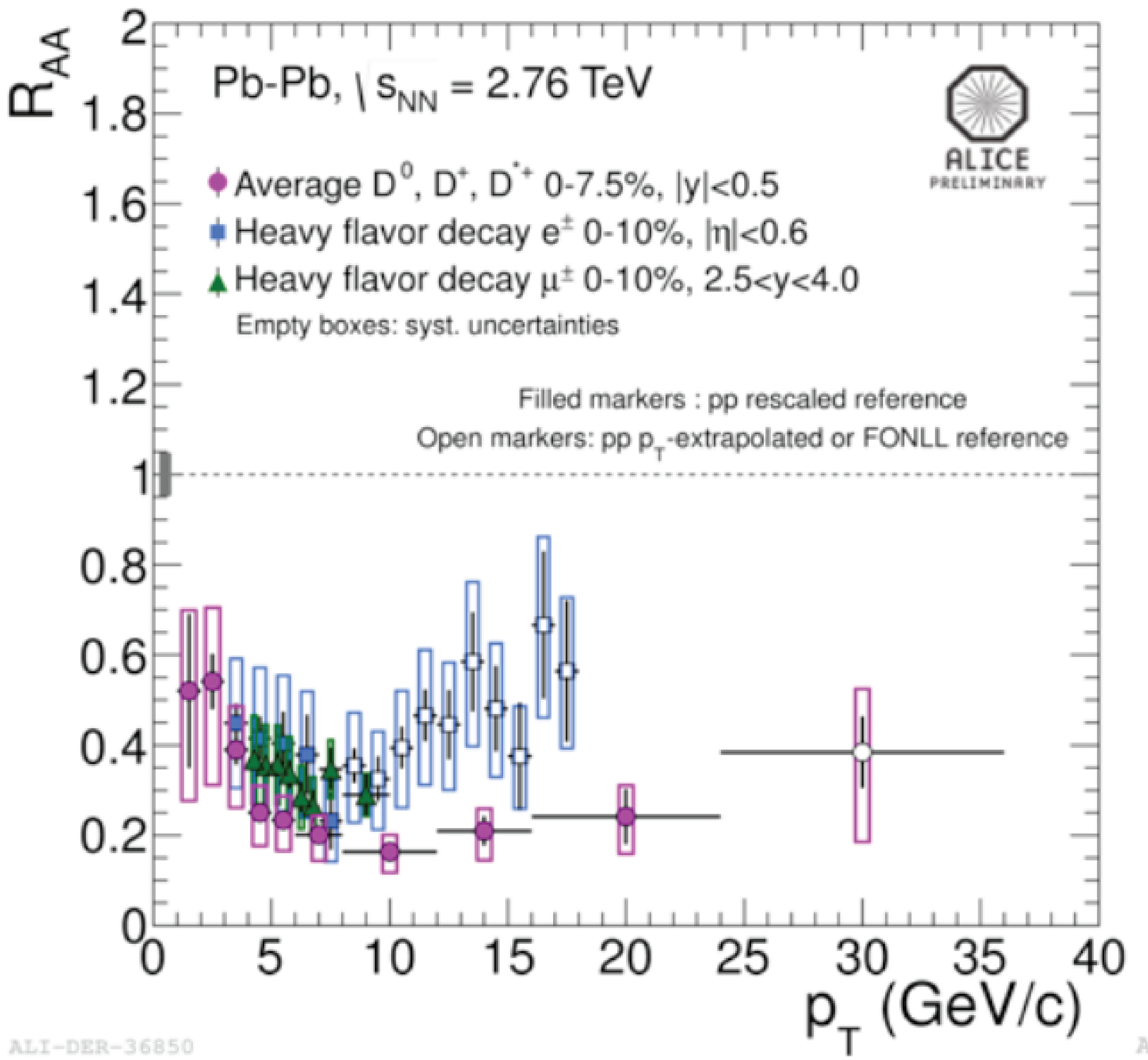
✓ weighting procedure: $p_t^{flat\ k/\pi} \leftrightarrow p_t^{\mu\leftarrow flat\ k/\pi}$;

- for each muon we get the transverse momentum of its mother K/pi ($p_t^{flat\ k/\pi}$)
- weight the above muon spectra according to the bin content at $p_t = p_t^{flat\ k/\pi}$ in the given K/pi distribution, and then re-fill it;
- systematics uncertainties on the given K/pi spectrm and rapidity extrapolation factor are taken into account, and also the absorber effect;
- finally, we normalize the weighted muon distribution with the total number of generated mother K/pi .

charged hadron in forward rapidities

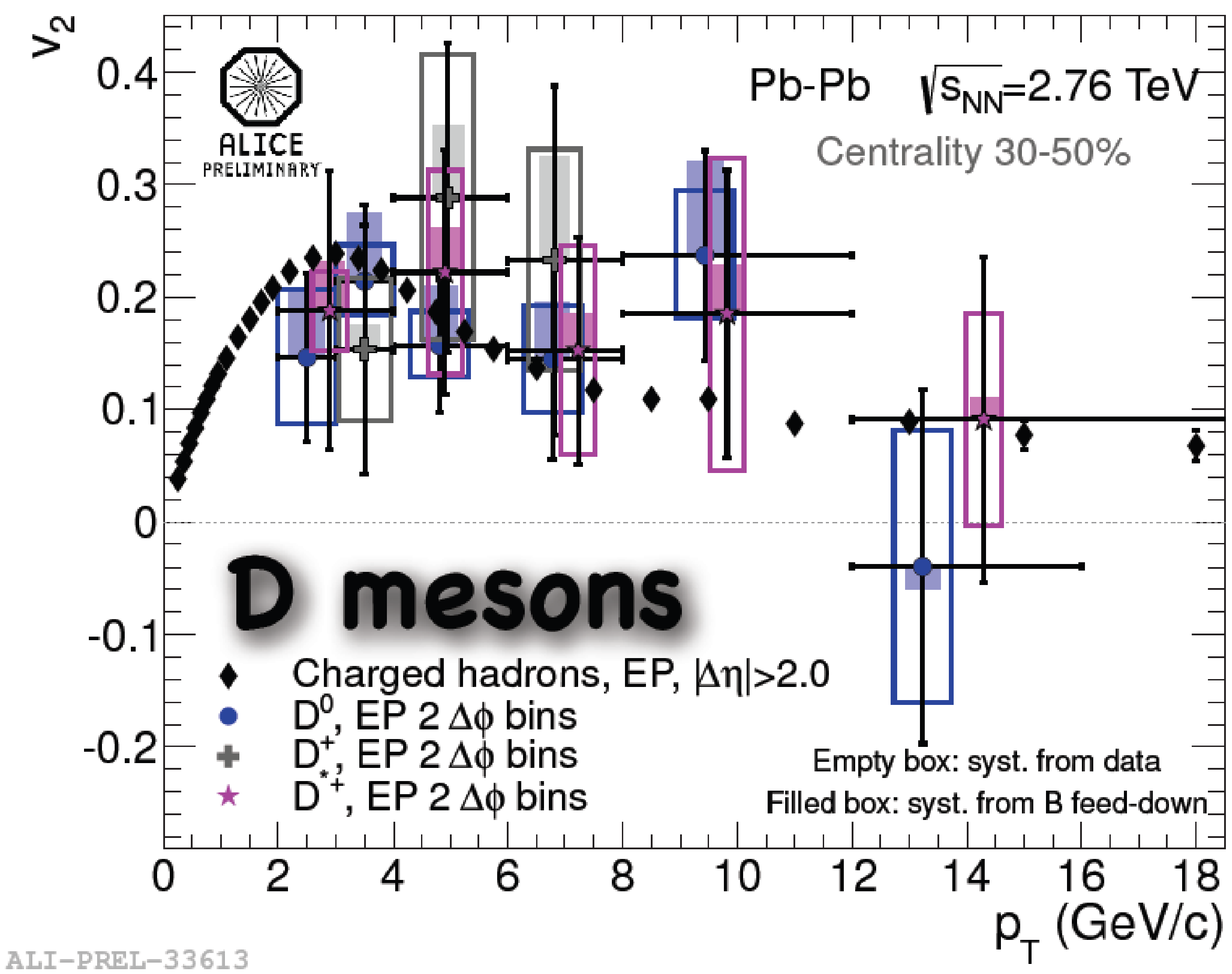
$$\frac{1}{N_{AA}^{ev}}\frac{dN_{pA}^{\mu\leftarrow k/\pi}}{dp_t}\Bigg|_{FW\ (\Delta p_t)} = \left\{\frac{\boxed{\left.\frac{1}{N_{AA}^{ev}}\frac{dN_{pA}^{k/\pi}}{dp_t}\right|_{FW}}}{\frac{dN_{pA}^{flat\ k/\pi}}{dp_t}} \times \frac{dN_{pA}^{\mu\leftarrow flat\ k/\pi}}{dp_t}\Bigg|_{FW\ (\Delta p_t)}\right\}\Bigg|_{(\Delta p_t)}$$

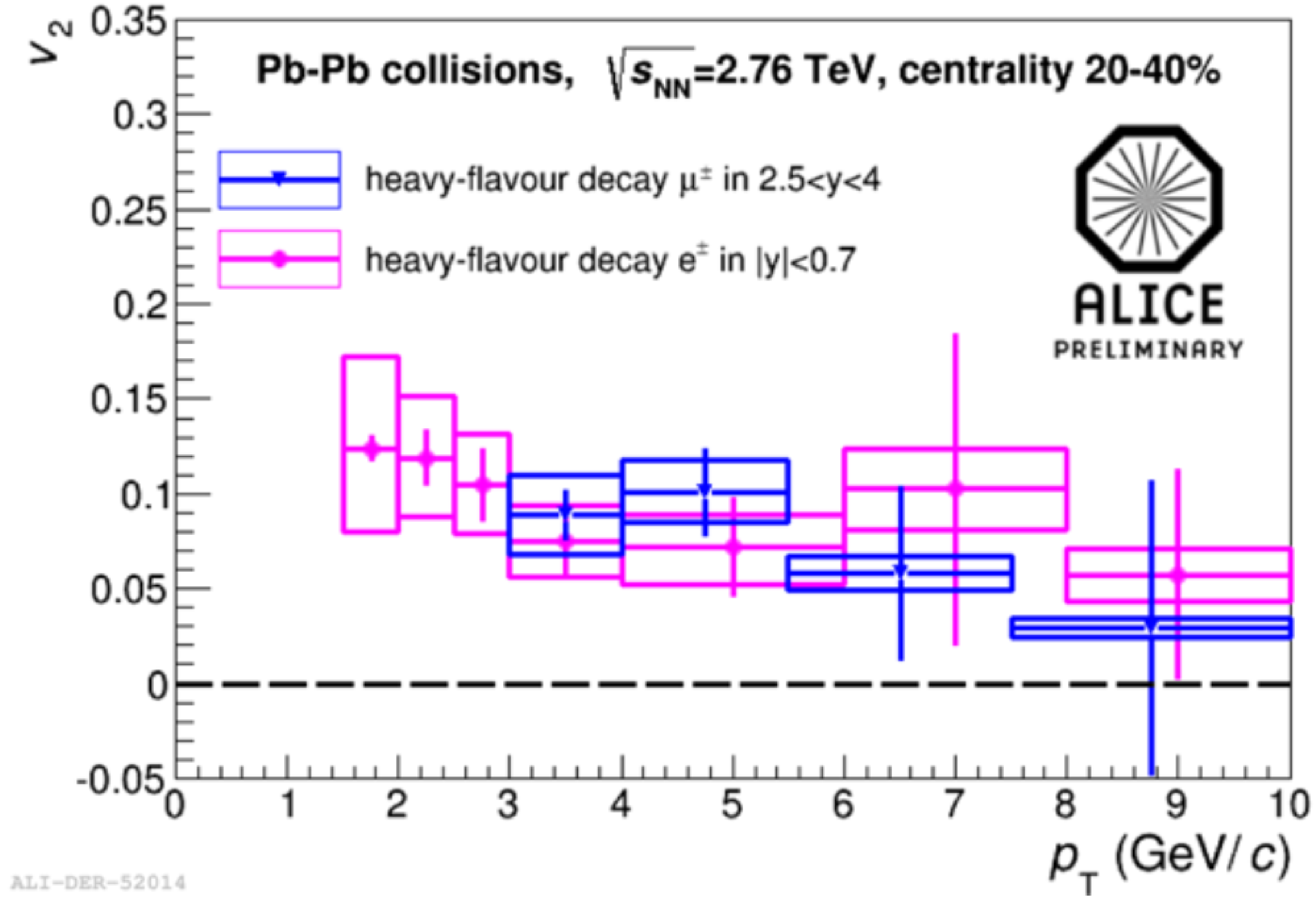
p_T-differential R_{AA} of Heavy Flavours



- Similar HF decay e ($|y|$<0.6) and μ (2.5<y<4.0) R_{AA} in 0-10%;
- difficulty: comparison of R_{AA} of D mesons and that of HF decay electrons must consider semi-leptonic decay kinematics ($p_T^e \sim 0.5\, p_T^B$ at high p_T);

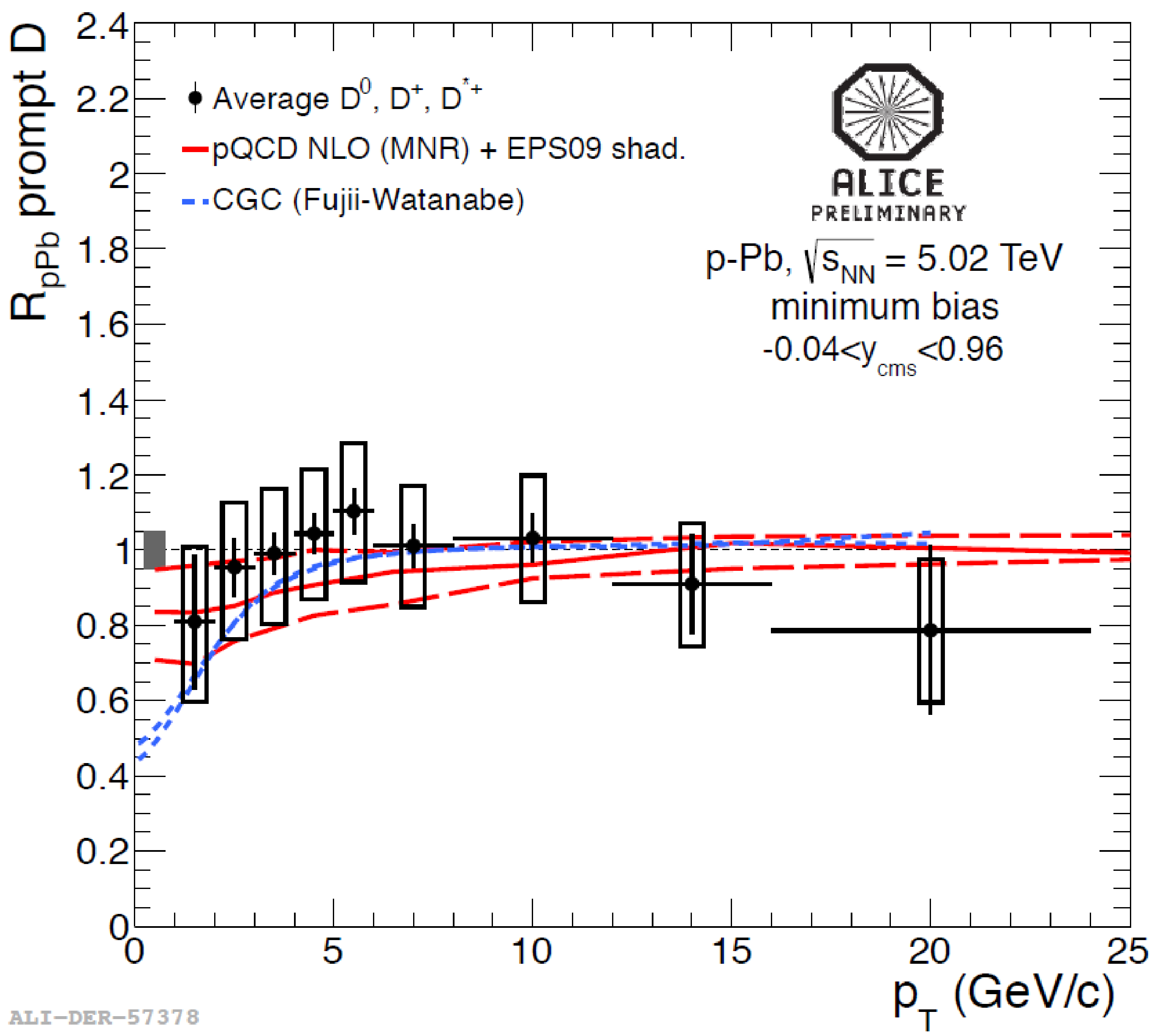
p_T-differential v_2 of Heavy Flavours



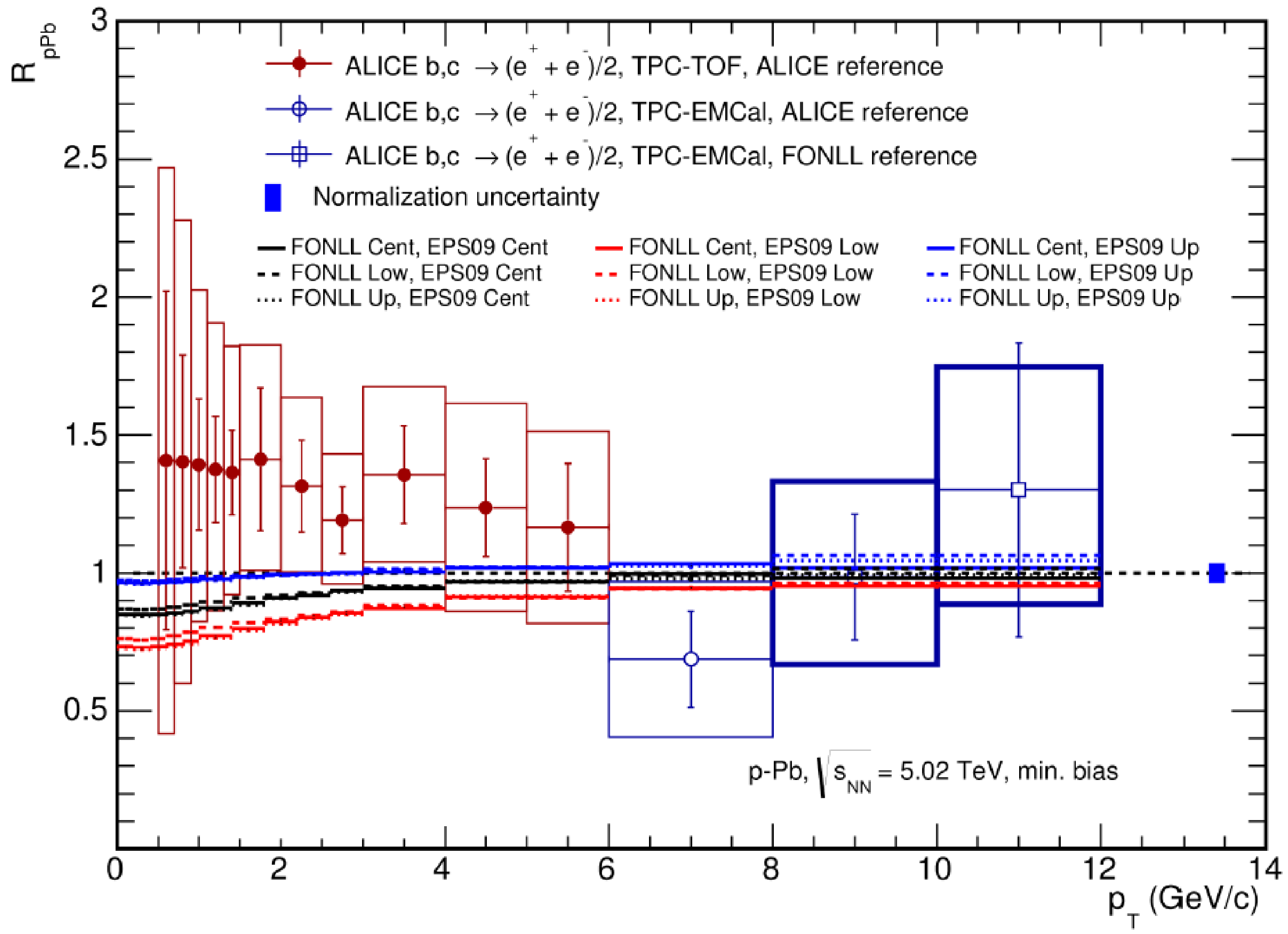


- D measons:
  - ✓ measured with event plane method; consistency among different D mesons; similar v_2 magnitude of D mesons and charged hadrons;
- Heavy-flavour electron:
  - ✓ measured with event plane method;
- non-zero v_2 (3 sigma effect) for D mesons in $2<p_T<6$ GeV/c, heavy flavour electrons in $2<p_T<3$ GeV/c and heavy flavour muons in $3<p_T<5$ GeV/c ;
- v_2 of heavy-flavour muons at forward rapidity ($-4<\eta<-2.5$) is consistent with that of heavy-flavour electrons at mid-rapidity ($|\eta|<0.9$) within uncertainties.

p_T-differential R_{pA} of Heavy Flavours



D measons:
$-0.04<y_{CMS}<0.96$



Heavy-flavour electrons:
$-0.14<y_{CMS}<1.06$

- Within uncertainties, both the results from D mesons and heavy-flavour electrons are around unity, and also consistent with theoretical predictions;