Nuclear Modification Factor and Elliptic Flow of Muons from Heavy-flavour Decays in Pb−Pb Collisions at $\sqrt{s_{NN}}$=2.76 TeV with ALICE

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Outline

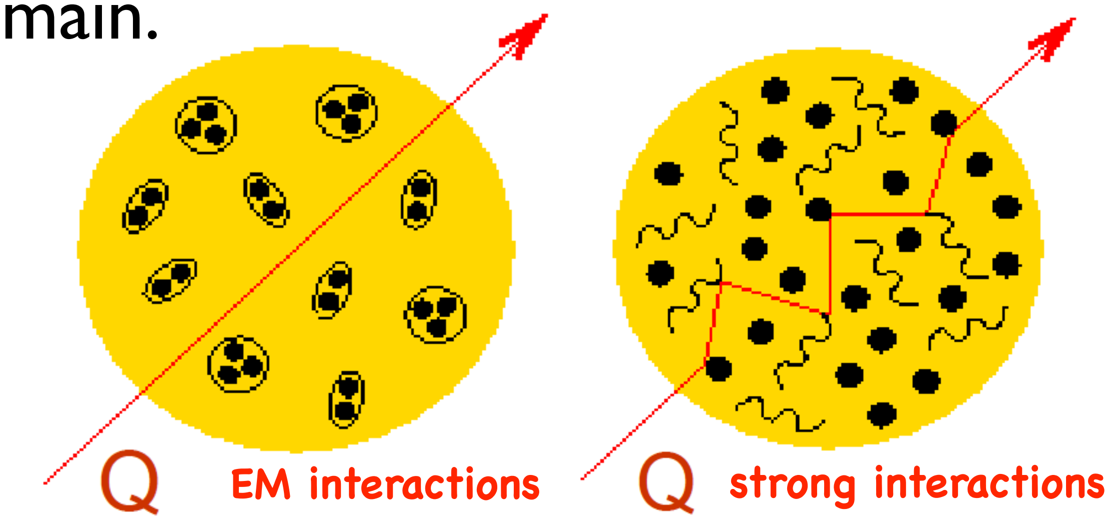
- Heavy-Flavour Physics at the LHC
- ALICE Setup
- R_{AA} of Muons from Heavy-Flavour Decays
- Elliptic Flow of Muons From Heavy-Flavour Decays
- Summary

Heavy-Flavour Physics at LHC

Heavy-flavours in pp collisions:

- baseline for p−A and A−A collisions;
- test NLO perturbative QCD in a new energy domain.

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



Heavy-flavours in p−A collisions:

- investigate cold nuclear matter effects.

Heavy-flavours in AA collisions:

- tomography of QCD medium,
  - ➡ mass and color charge dependence of parton energy loss;

[Phys. Rev. D69 (2004) 114003, Phys. Rev. D71 (2005) 054027]

- azimuthal anisotropic flow, $v_n(p_T,\eta)$,
  - ➡ 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;
- results at RHIC leave some open questions… **[PHENIX Collaboration PRL 98 (2007) 172301 STAR Collaboration PRL 98, (2007) 192301]**

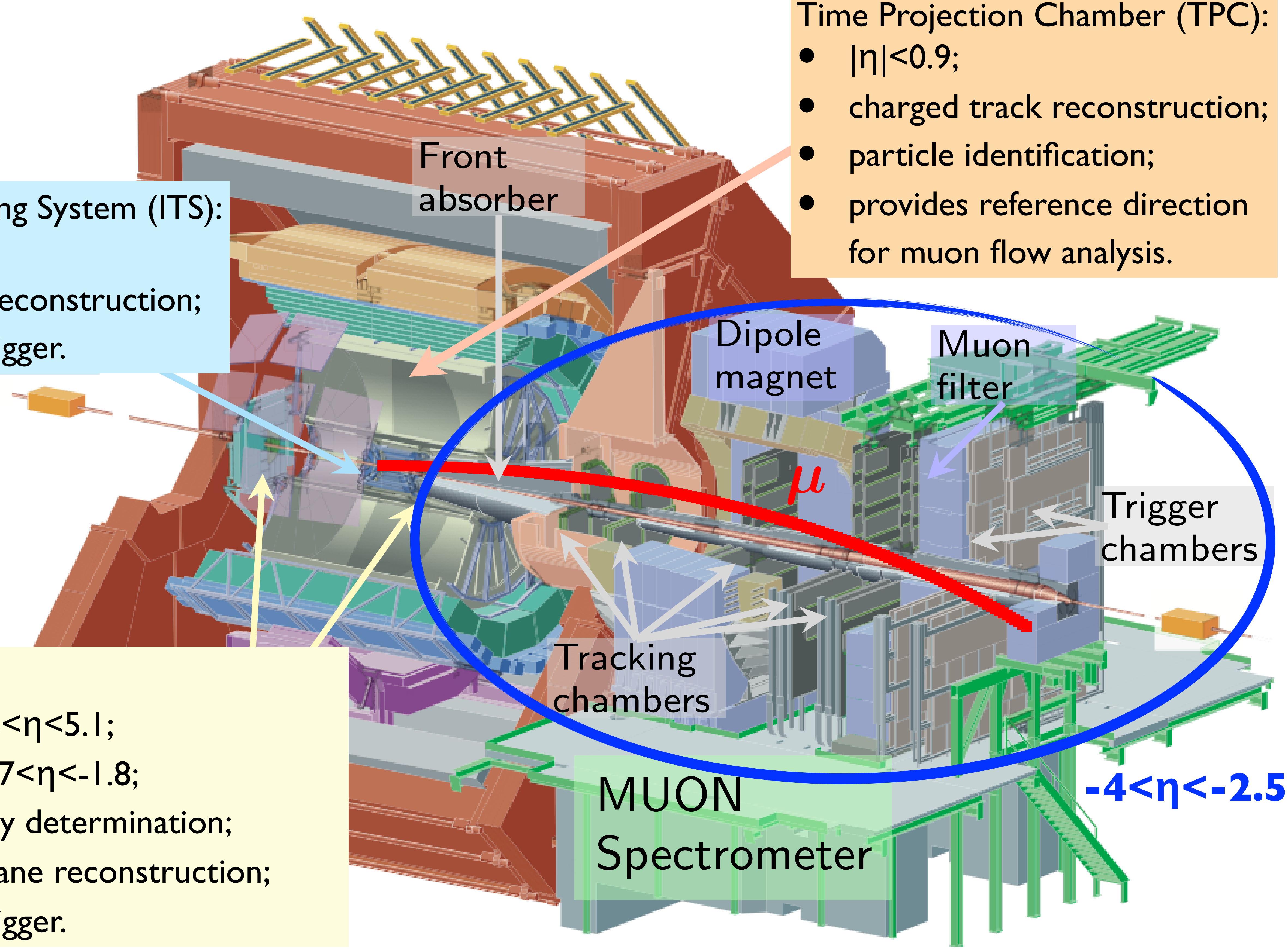
ALICE Setup

Time Projection Chamber (TPC):

- $|\eta|<0.9$;
- charged track reconstruction;
- particle identification;
- provides reference direction for muon flow analysis.

Inner Tracking System (ITS):

- $|\eta|<0.9$;
- vertex reconstruction;
- event trigger.

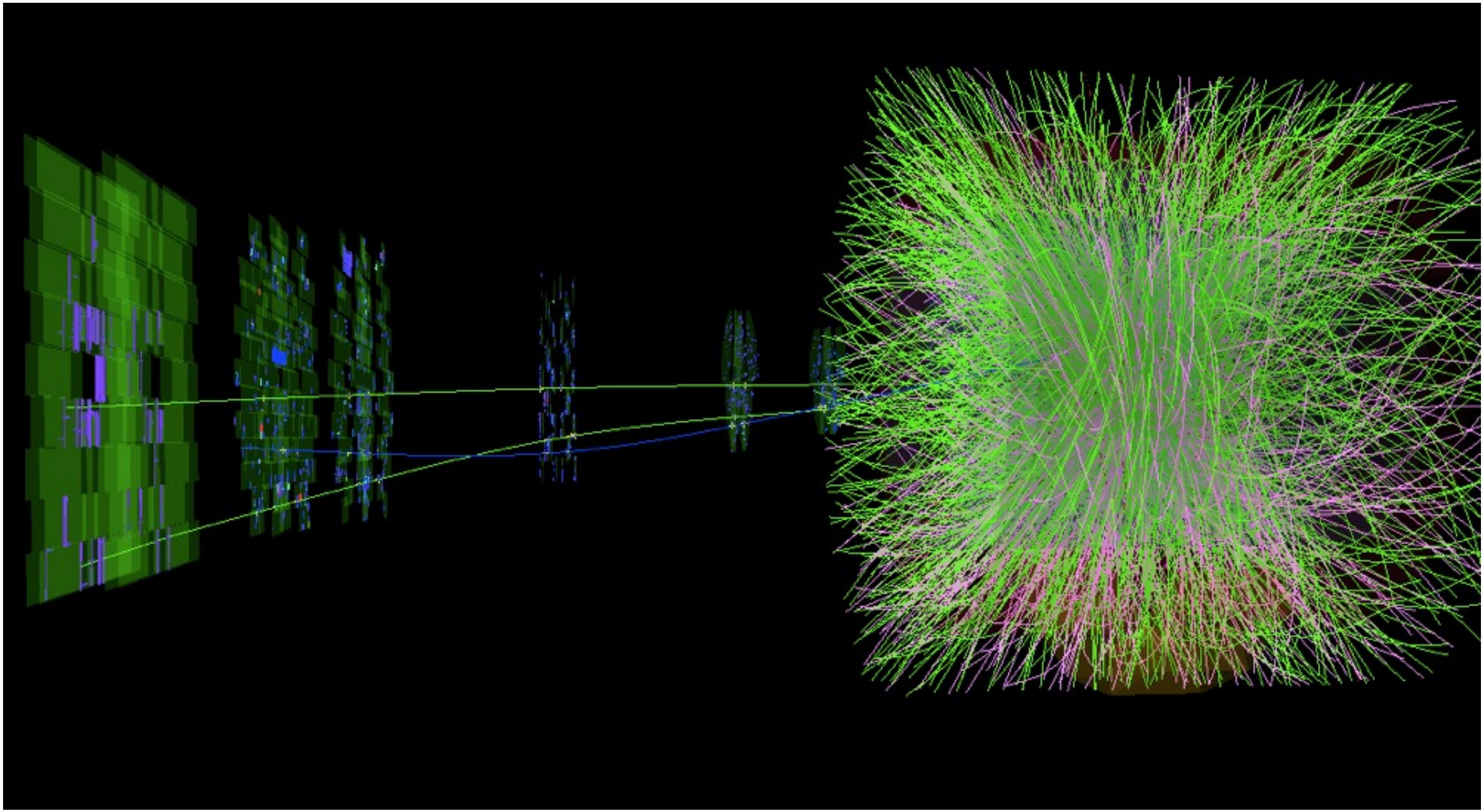


VZERO:

- V0A, $2.8<\eta<5.1$;
- V0C, $-3.7<\eta<-1.8$;
- centrality determination;
- event plane reconstruction;
- event trigger.

R_{AA} of Muons From-Heavy Flavour Decays

Phys. Rev. Lett. 109 (2012) 112301



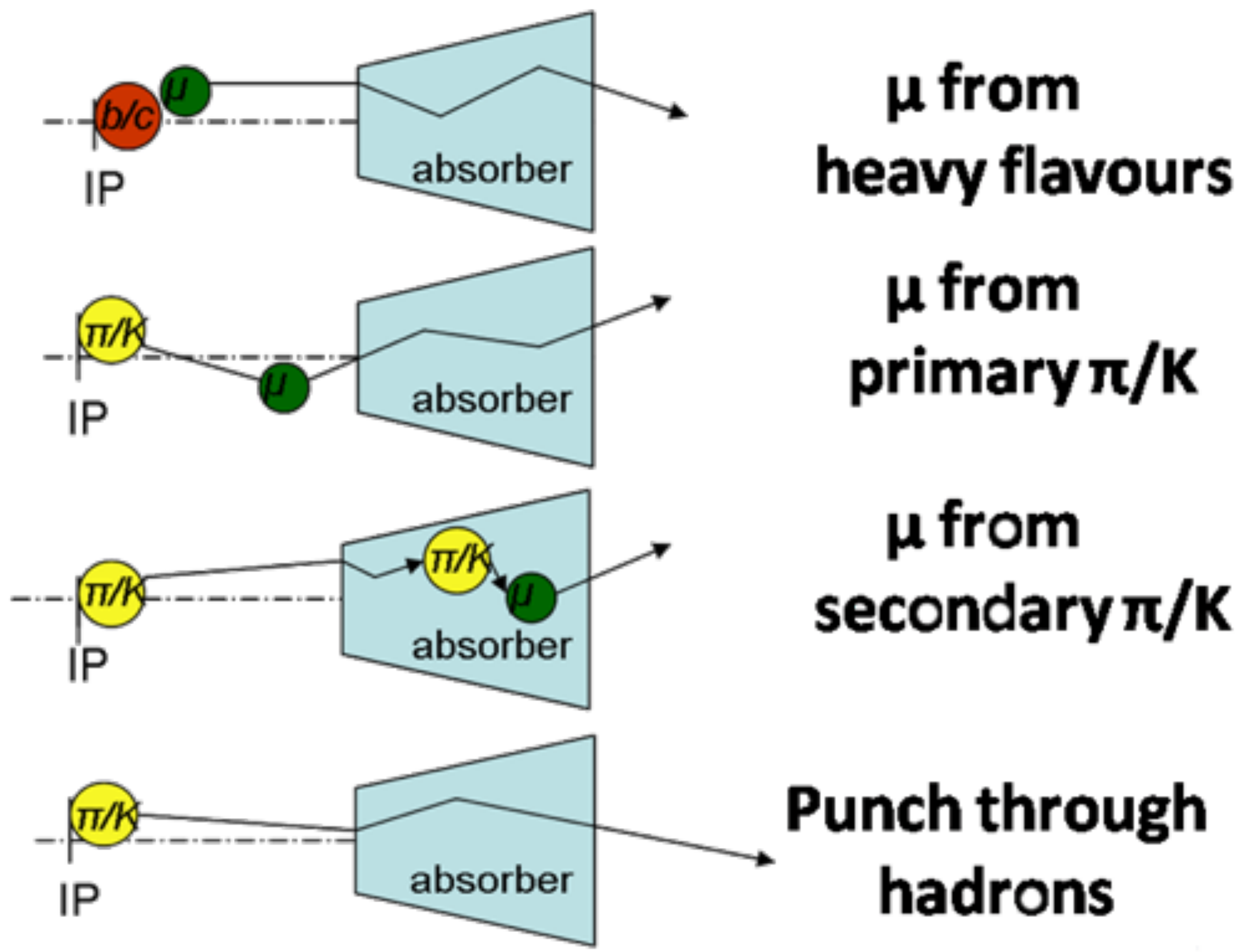
Data Sample and Muon Selection

Data Samples:

- pp collisions, muon trigger, $\mathcal{L}_{int}$=19 nb^{-1};
- Pb–Pb collisions taken in 2010, minimum bias trigger, $\mathcal{L}_{int}$=2.7 μb^{-1}.

Track selection:

- -4<η<-2.5: acceptance of ALICE MUON spectrometer;
- muon trigger matching: reject hadrons that cross the absorber;
- pointing angle to the vertex: remove beam-gas and particles produced in the absorber.



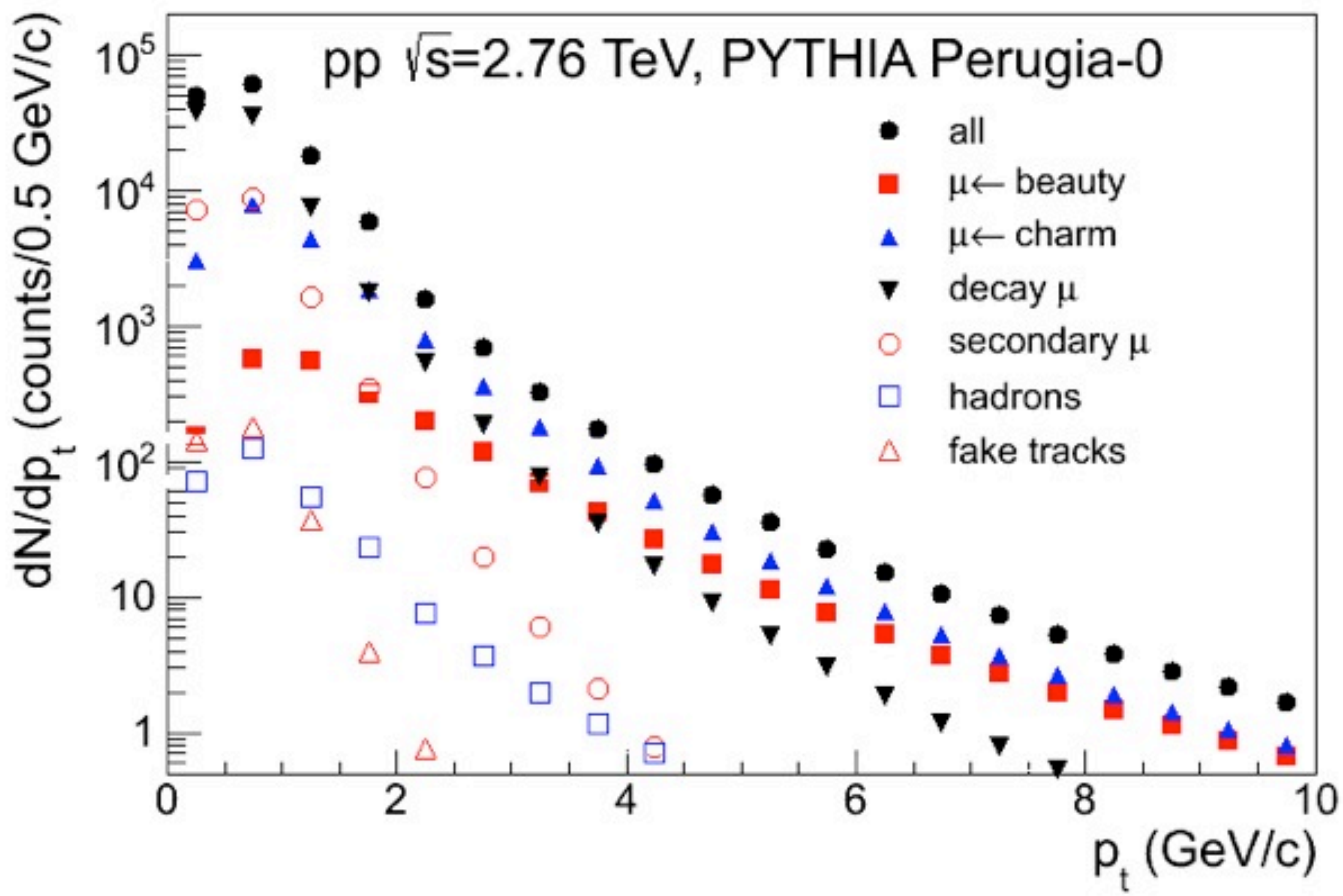
Background Subtraction: pp

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%.



Background Subtraction: Pb−Pb

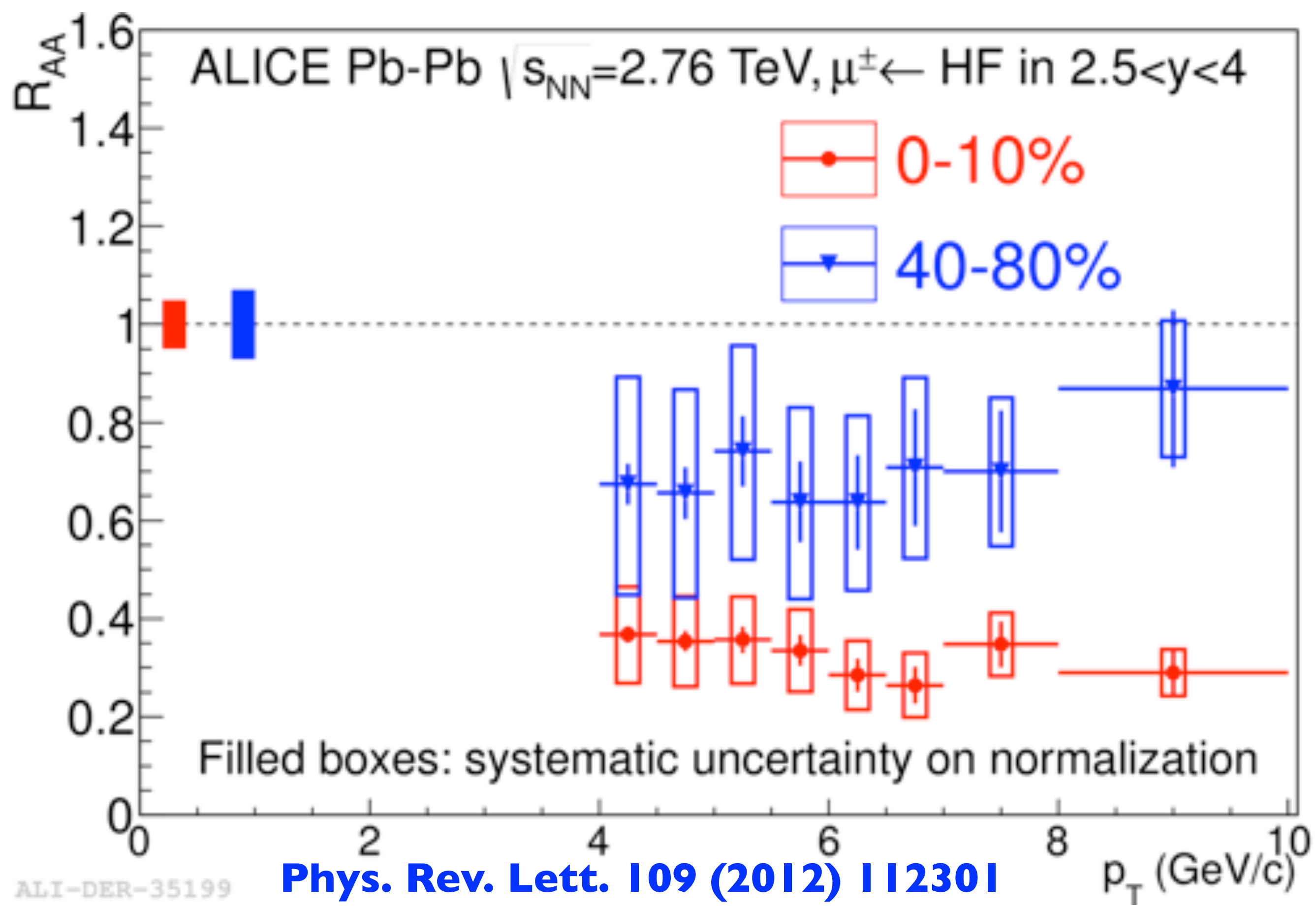
- Input: charged K/π spectra in pp collisions and R_{AA} in Pb−Pb collisions at central rapidity measured with ALICE; **[J. Phy. G, G38 (2011) 124014 & 124080]**

- extrapolate charged K/π spectra in pp collisions to forward rapidity with the extrapolation factor obtained in Monte-Carlo predictions (PYTHIA and PhoJet);
  [Phys. Rev., D76, (2007) 092002]

- get K/π spectra in Pb−Pb collisions at forward rapidity by scaling the extrapolated charged K/π spectra with their nuclear modification factor R_{AA} measured at central rapidity,
  ➡ varying charged 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 a fast Monte-Carlo simulation.

R_{AA} of Heavy-flavour Muons at Forward Rapidity



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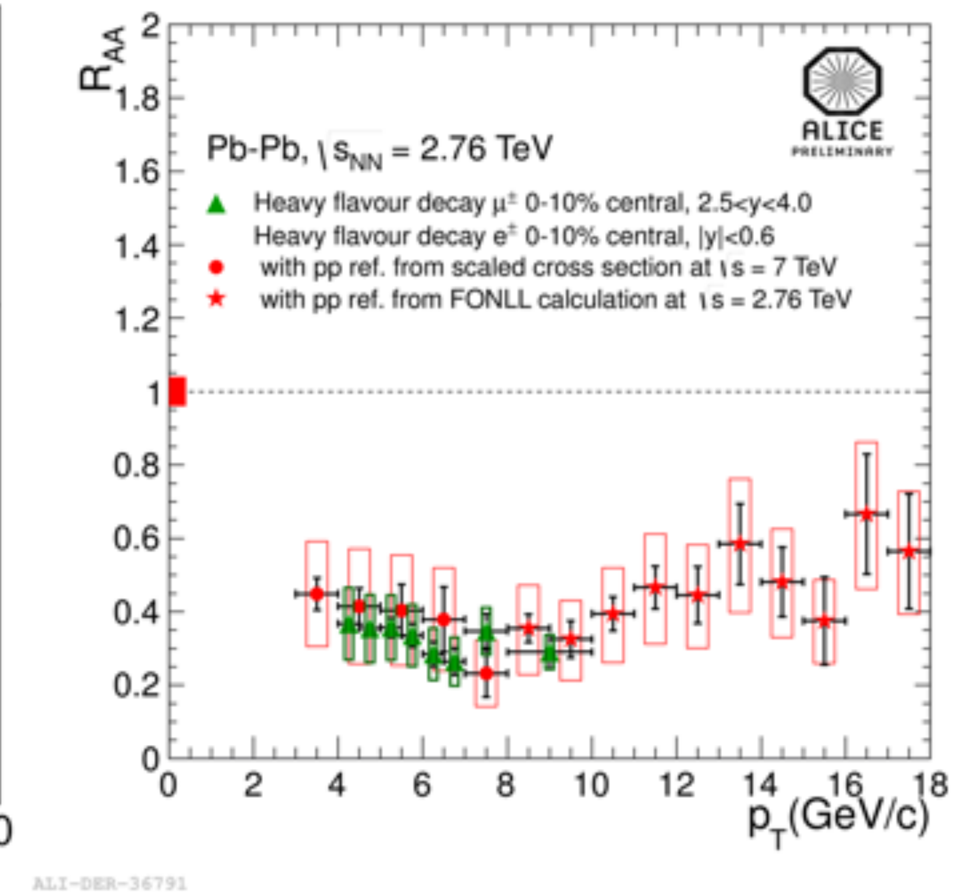
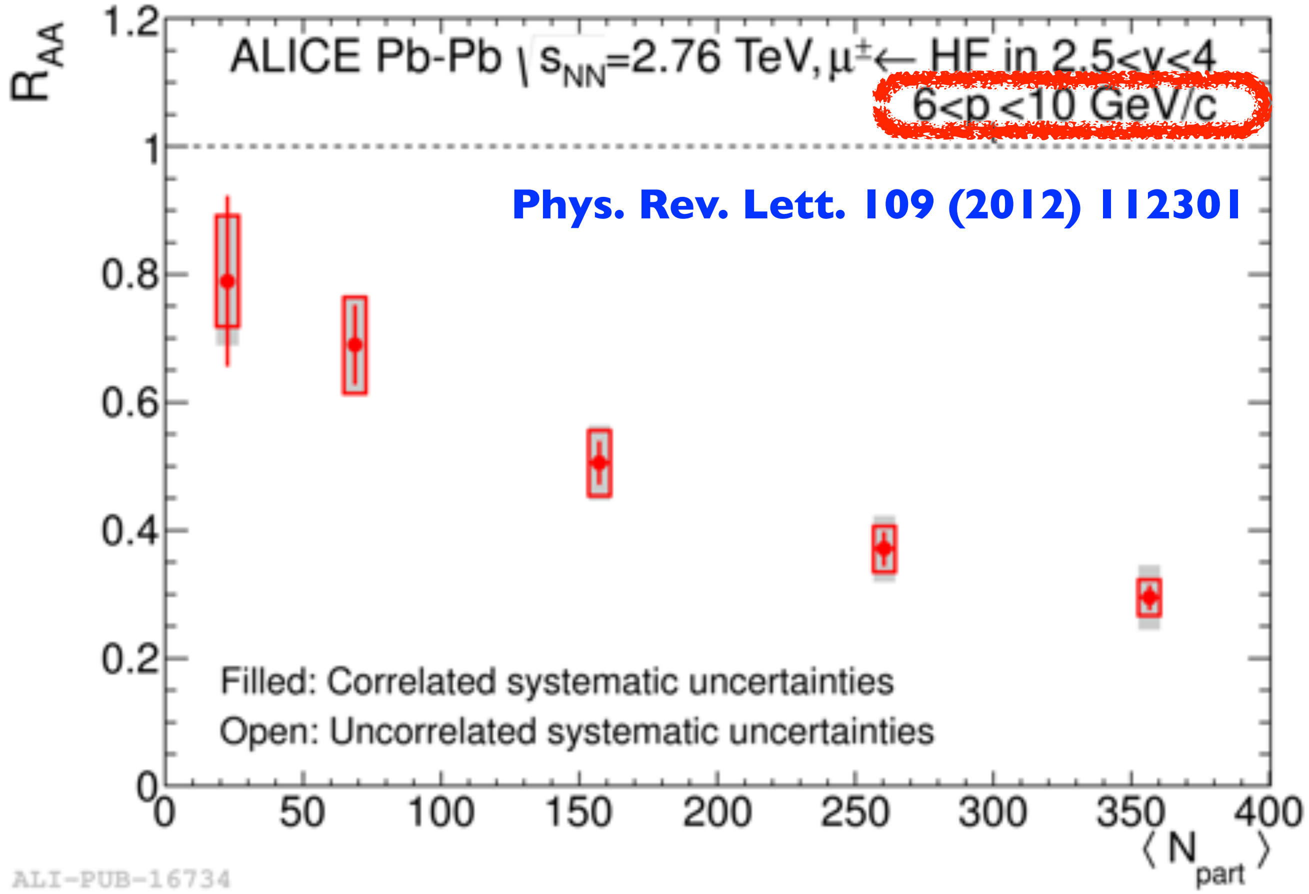
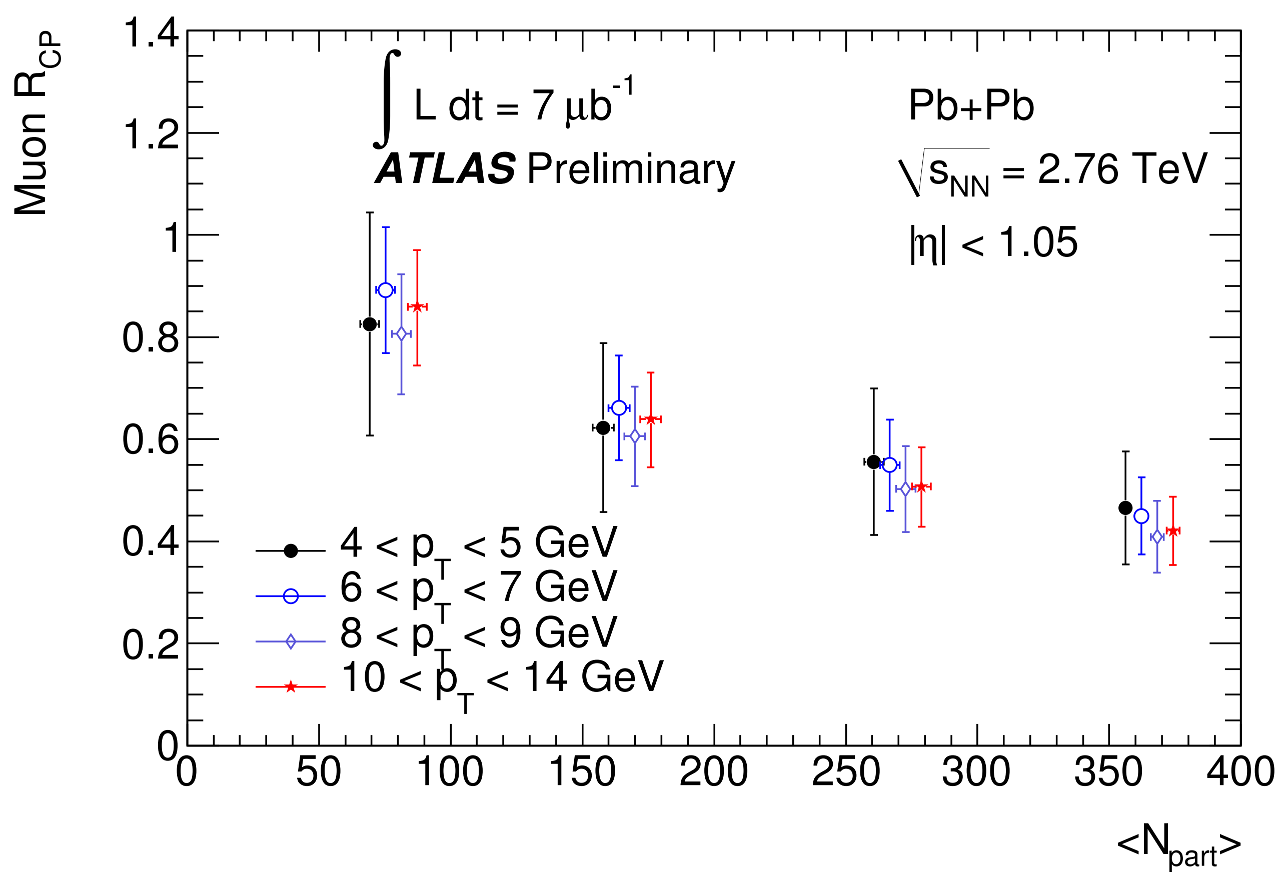


- Suppression is observed and is independent of p_T within uncertainties (in the measured p_T interval);
- stronger suppression in central than peripheral collisions, reaching a factor of about 3−4 in the 10% most central collisions;
- R_{AA} of heavy-flavour decay muons at forward rapidity (2.5<y<4) is consistent with that of heavy-flavour decay electrons at mid-rapidity (|y|<0.6).

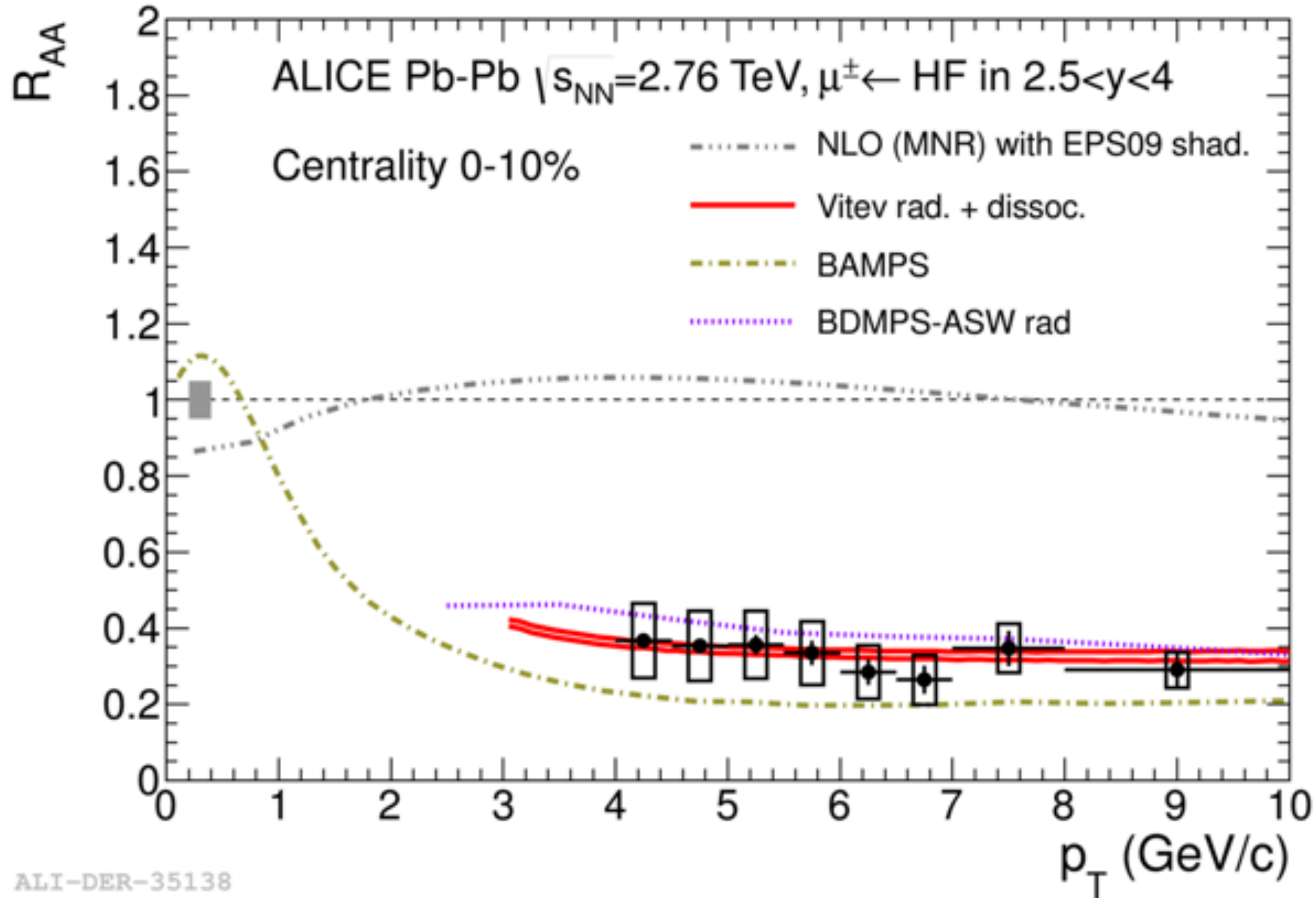
R_{AA} of Heavy-flavour Muons at Forward Rapidity





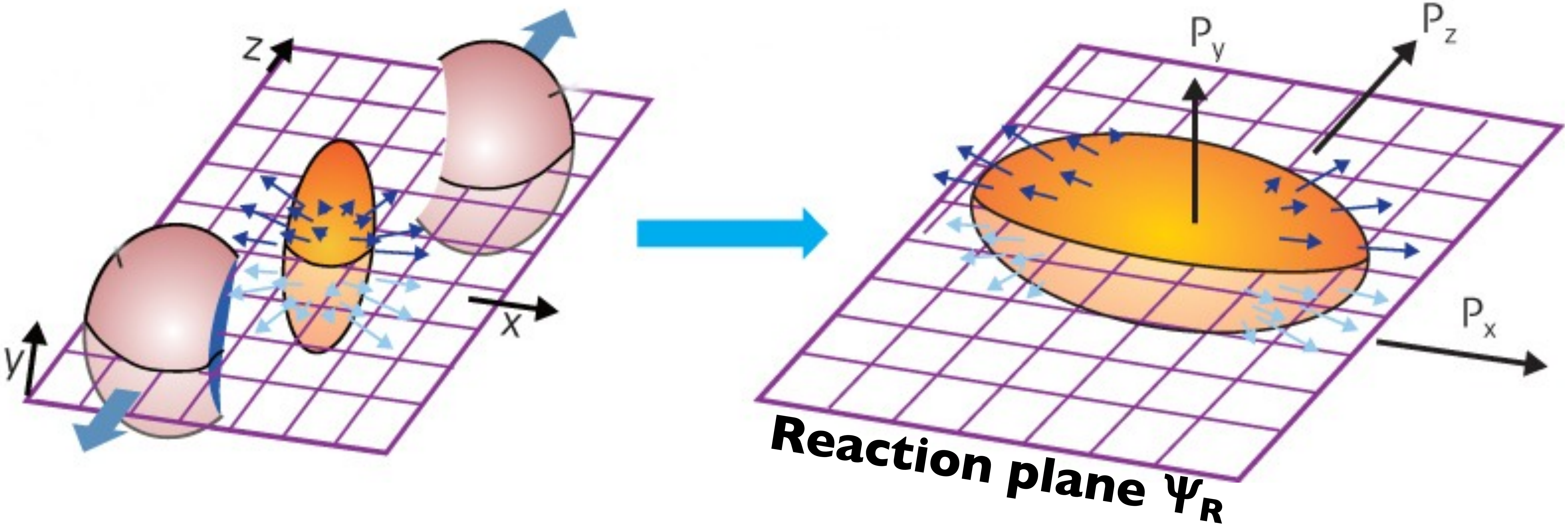
- The suppression of heavy-flavour decay muons at high p_T range at forward rapidity exhibits a strong increase with increasing centrality;
- according to FONLL calculations, in pp collisions beauty hadron decays are the dominant source of heavy-flavour decay muons in $6<p_T<10$ GeV/c;
- results consistent with R_{CP} measured by ATLAS.

Comparison with Model Predictions



- Data can be described by models implementing radiative energy loss (BDMPS-ASW) and rad.+dissoc. (Vitev);
- small contribution from shadowing is expected.

Elliptic Flow of Muons From Heavy Flavour Decays



$$E\frac{d^3\sigma}{d^3\vec{p}} = \frac{d^2\sigma}{2\pi p_T dp_T dy}[1 + \sum_{n=0}^{\infty} 2v_n \cos n(\phi - \Psi_R)]$$

$$v_2 = < \cos 2(\phi - \Psi_R) >$$

Data Sample and Analysis Strategy

Data sample: Pb−Pb collisions at 2.76 TeV taken in 2011,

- central trigger, 0-10%, 8.7×10^6 events;
- semi-central trigger, 10-40%, 8.0×10^6 events.

Particle selection:

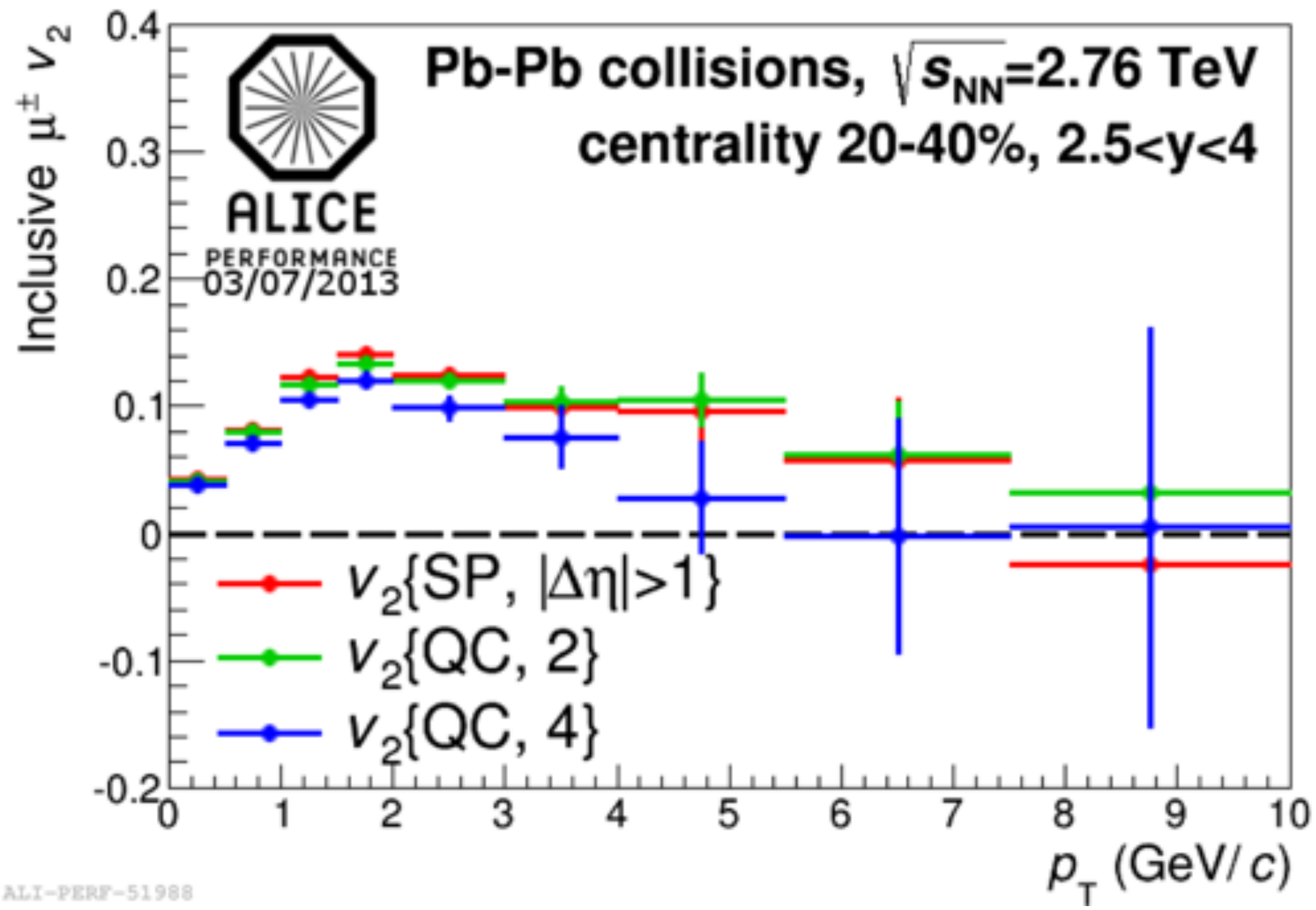
- particles of interest,
  - ➡ muon tracks at forward rapidity, $-4<\eta<-2.5$,
  - ➡ the same selection criteria as used in R_{AA} analysis;
- reference particles: measured in TPC and provides reference for muon flow analysis,
  - ➡ charged tracks measured at mid-rapidity, $|\eta|<0.8$,
  - ➡ various selection and acceptance cuts are used to estimate the uncertainty on reference flow.

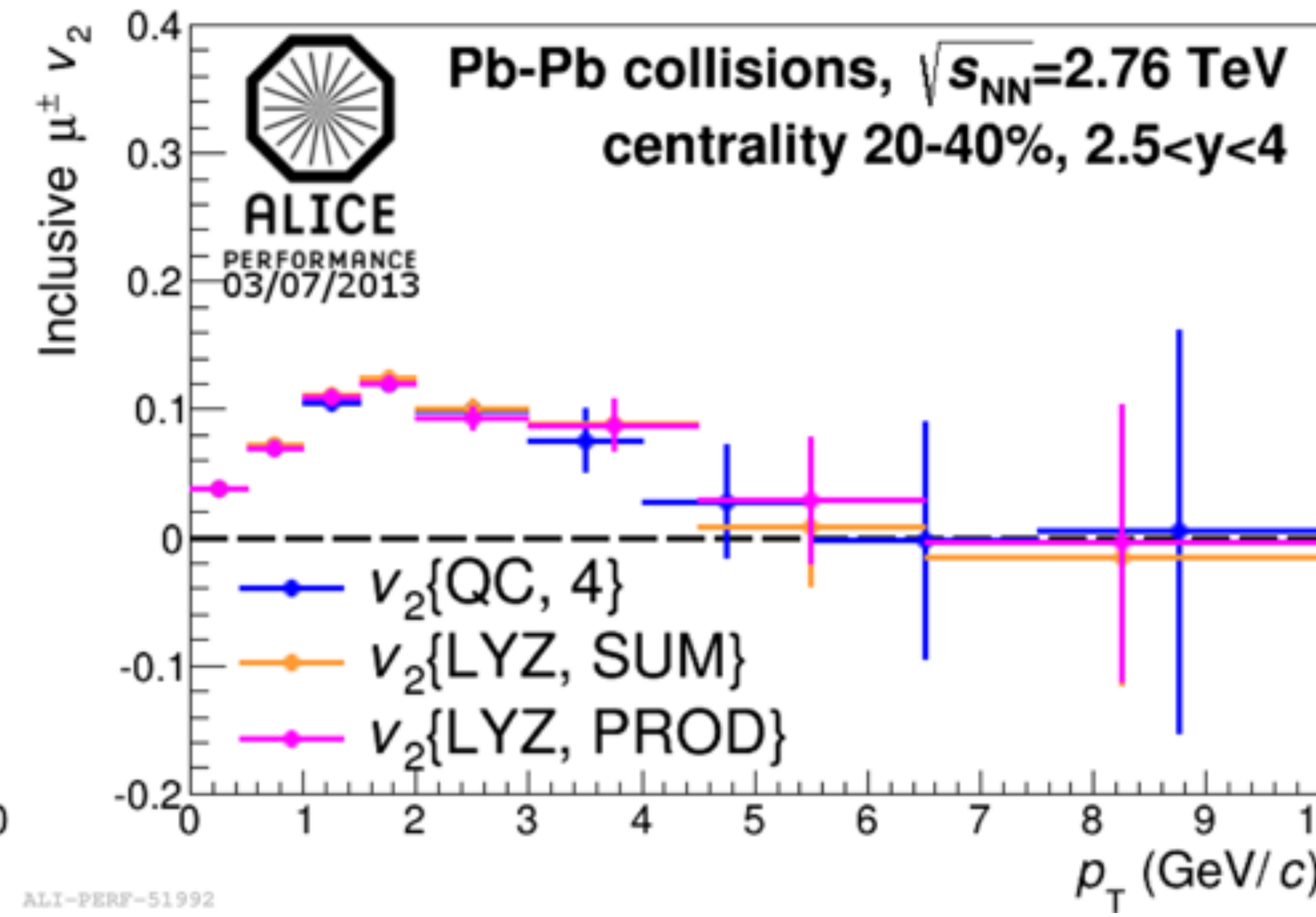
Analysis methods:

- two particle methods:
  - ➡ scalar product (SP) with $\Delta\eta>1$,
  - ➡ 2^{nd} order Q-cumulant (QC2);
- multi-particle methods:
  - ➡ 4^{th} order Q-cumulant (QC4),
  - ➡ Lee-Yang-Zeros (LYZ) with sum and product generating functions.

[Phys. Rev. C83 (2011) 044913, Phys. Lett. B580 (2004) 157]

Inclusive Muon v_2





- Inclusive muon v_2 is measured up to 10 GeV/c;
- results from QC4 are systematically lower than those from two particle methods (SP and QC2):

  ➡ due to different contributions of non-flow correlations and fluctuations;
- results from multi-particle methods (QC4 and LYZ) are consistent within uncertainties.

Background Flow Estimation

$$v_2^{\mu\leftarrow \mathrm{HF}} = \frac{v_2^{\mathrm{inclusive}\ \mu} - v_2^{\mathrm{decay}\ \mu} \cdot f_{\mathrm{decay}\ \mu}}{1 - f_{\mathrm{decay}\ \mu}}$$

Decay muon v_2 estimation:

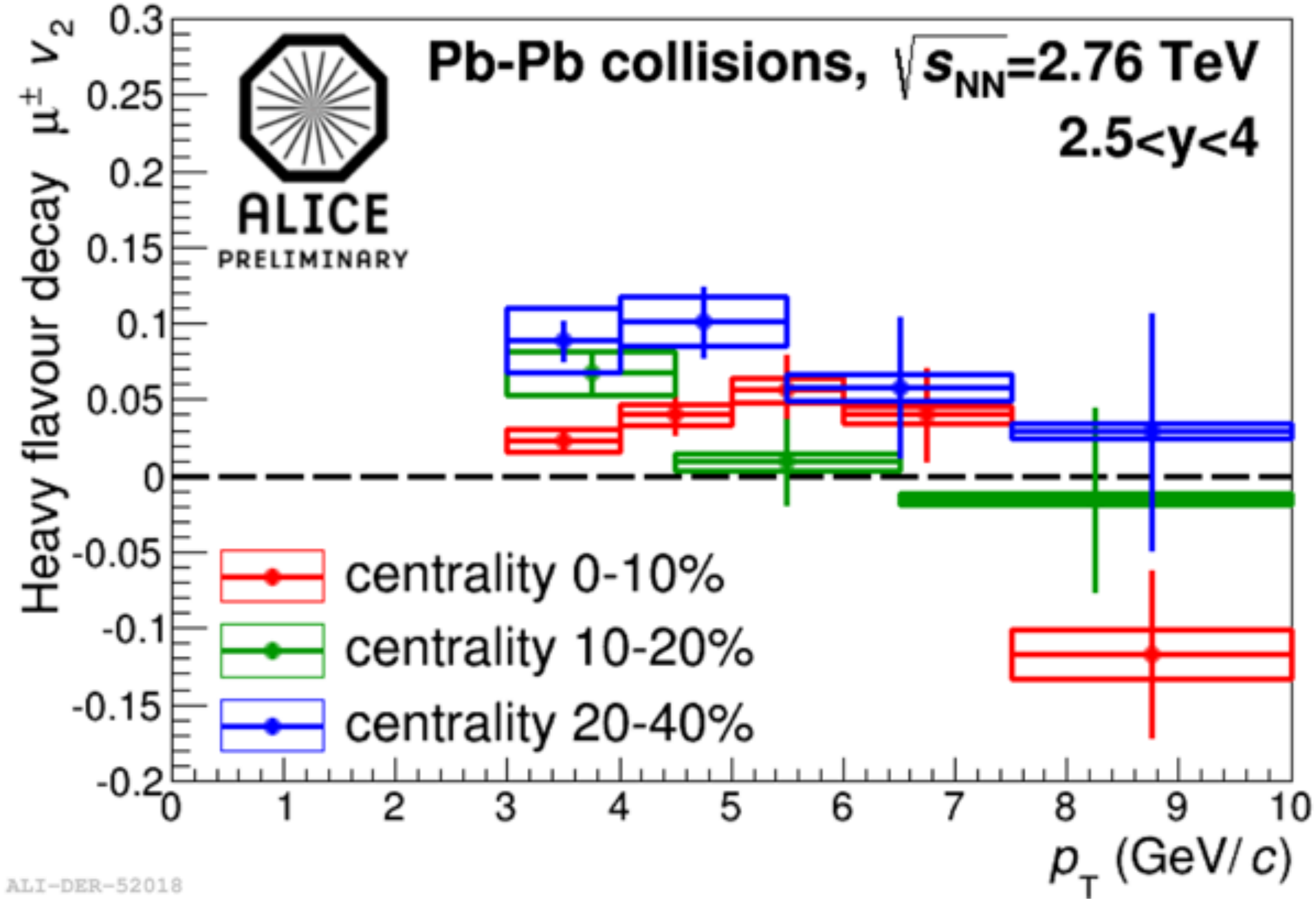
- parameterize the p_T and η dependence of charged hadrons v_2 measured by ATLAS and extrapolate to forward rapidity **[ATLAS: Phys. Lett. B707 (2012) 330]**;
- treat all the charged hadrons as pions and Kaons, separately and produce the v_2 of decay muon in the acceptance of ALICE muon spectrometer via the same fast simulation strategy as in R_{AA} analysis.

Systematic uncertainty on decay muons v_2	
input v_2 bias	~9%
extrapolation	9%–12%
data fluctuations	13%–15% (in high p_T)
K/π weights	<1%

Decay muon fraction with the same method used for R_{AA} analysis:

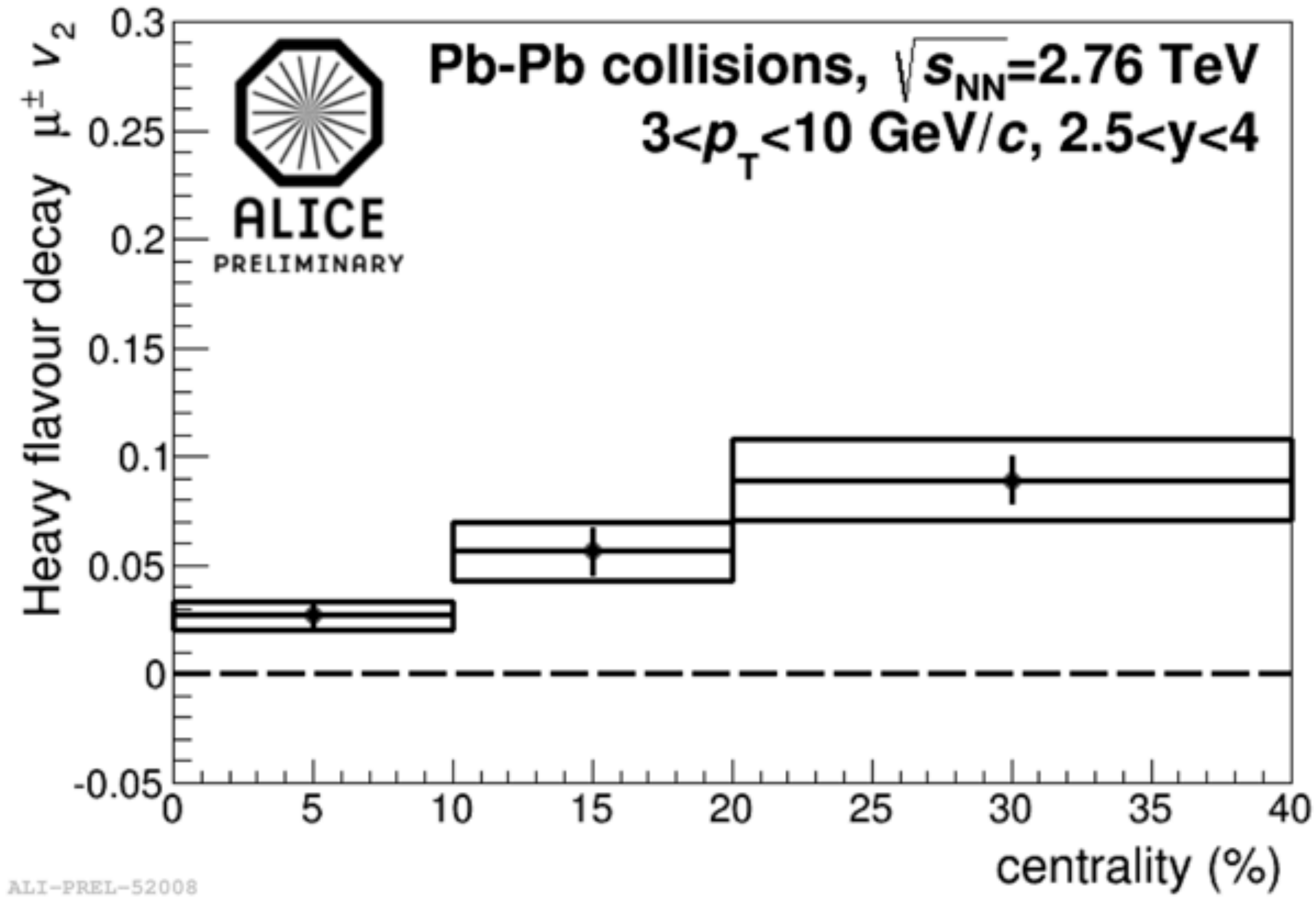
➡ 15% at low p_T, 5% at high p_T.

p_T–differential v_2 of Heavy-Flavour Decay Muons



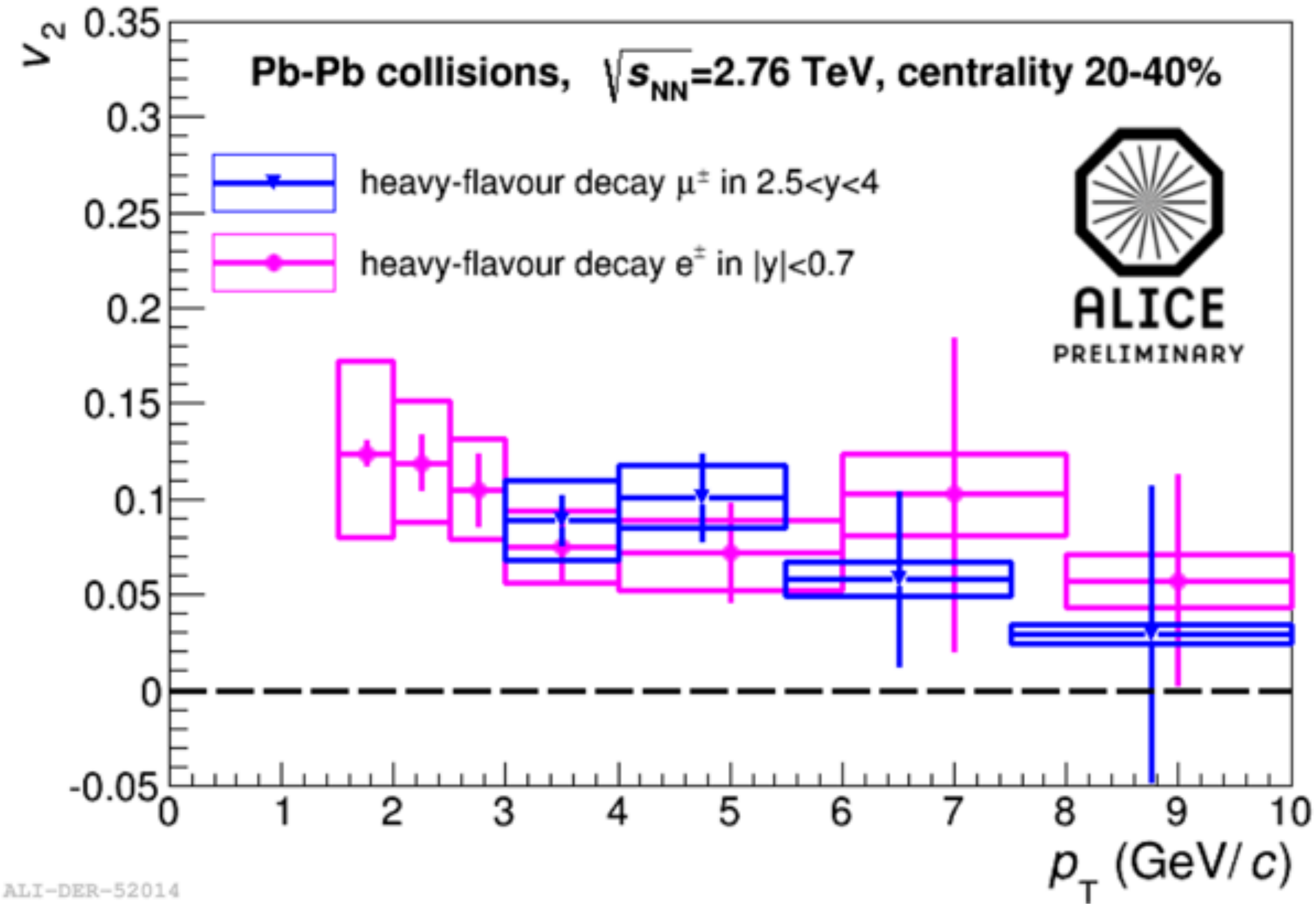
- results are obtained with QC2 method;
- v_2 of muons from heavy-flavour decays in semi-central collisions (20-40%) is systematically larger than that in central collisions (0-10%);
- non-zero v_2 (3σ effect) in $3<p_T<5$ GeV/c and 20-40% centrality class.

v_2 of Heavy-flavour Muons at Forward Rapidity



- in the measured range, integrated v_2 in 3<p_T<10 GeV/c of muons from heavy-flavour decays increases from central to peripheral collisions;
- non-zero v_2 (3σ effect) in semi-central collisions (20-40%).

Compare with v_2 of Heavy-flavour Decays Electrons



- 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.

Summary

- 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,
  - ➡ no significant dependence on p_T in $4<p_T<10$ GeV/c,
  - ➡ p−Pb analysis to quantify the cold nuclear effect, results are expected soon.
- v_2 of muons from heavy-flavour decays is shown for the first time:
  - ➡ 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.

Backup

Heavy-Flavour Physics at LHC

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

Heavy-flavours in pp collisions:

- baseline for p–A and A–A collisions;
- test NLO pQCD in a new energy domain.

Heavy-flavours in p–A collisions:

- investigate cold nuclear matter effects,

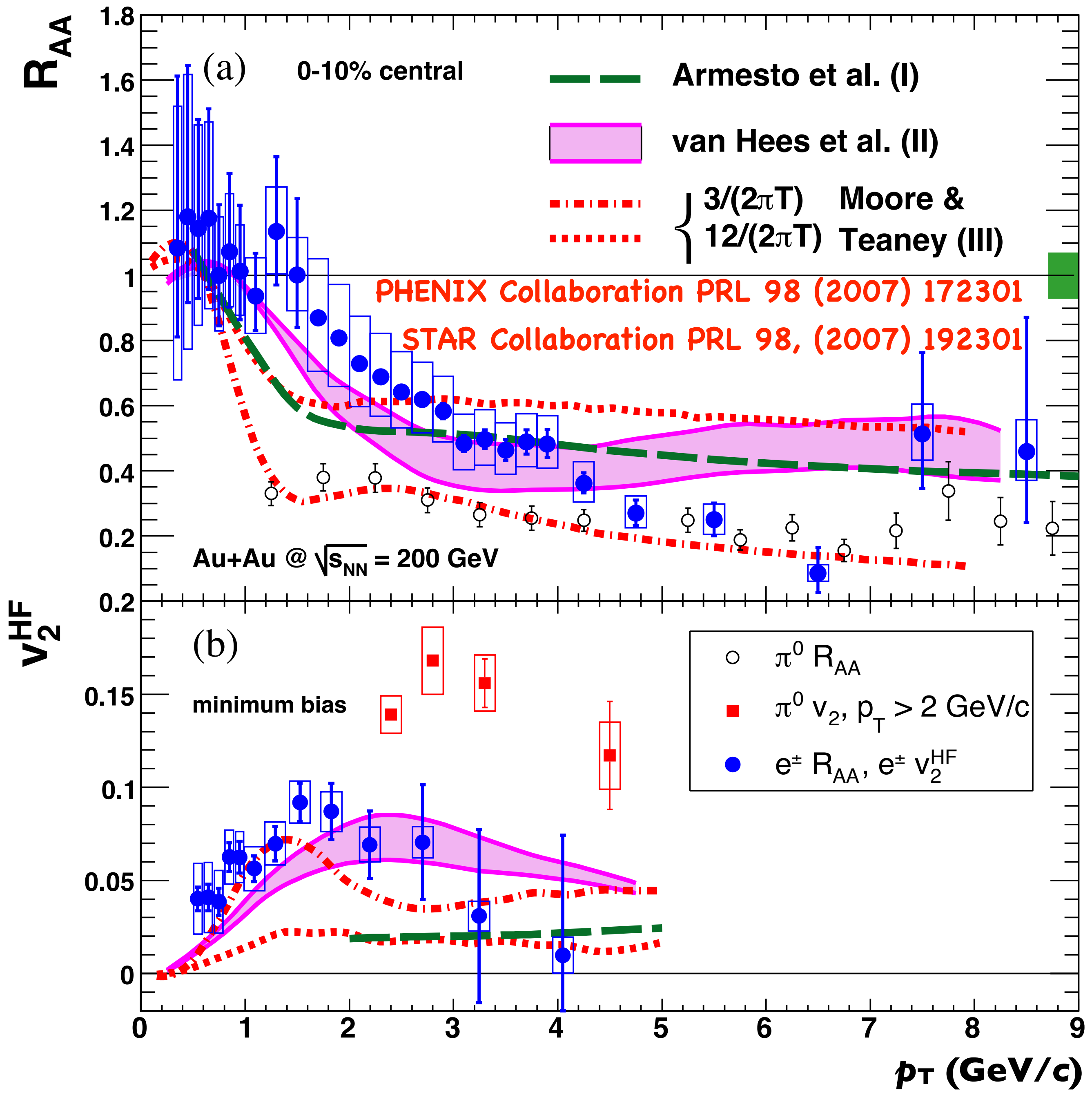
Heavy-flavours in AA collisions:

- tomography of QCD medium,
  - ➡ mass and color charge dependence of parton energy loss,

    R_{AA}(light hadron)<R_{AA}(D)<R_{AA}(B)

[Phys. Rev. **D69** (2004) 114003, Phys. Rev. **D71** (2005) 054027];

- azimuthal anisotropic flow, $v_n(p_t,\eta)$,
  - ➡ 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.



Background Subtraction: Pb–Pb

- 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:

$$\frac{\mathrm{d}^2 N_{\mathrm{pp}}^{\mathrm{K}/\pi}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} = \frac{\mathrm{d}^2 N_{\mathrm{pp}}^{\mathrm{K}/\pi}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}|_{y=0} \times \exp[-\frac{1}{2}(\frac{y}{\sigma_y})^2]$$

[Phys. Rev., D76, (2007) 092002]

with σ_y=3.3 estimated from PYTHIA and PhoJet (error≃15%);

- get K/π spectra in Pb–Pb collisions at forward rapidity via:

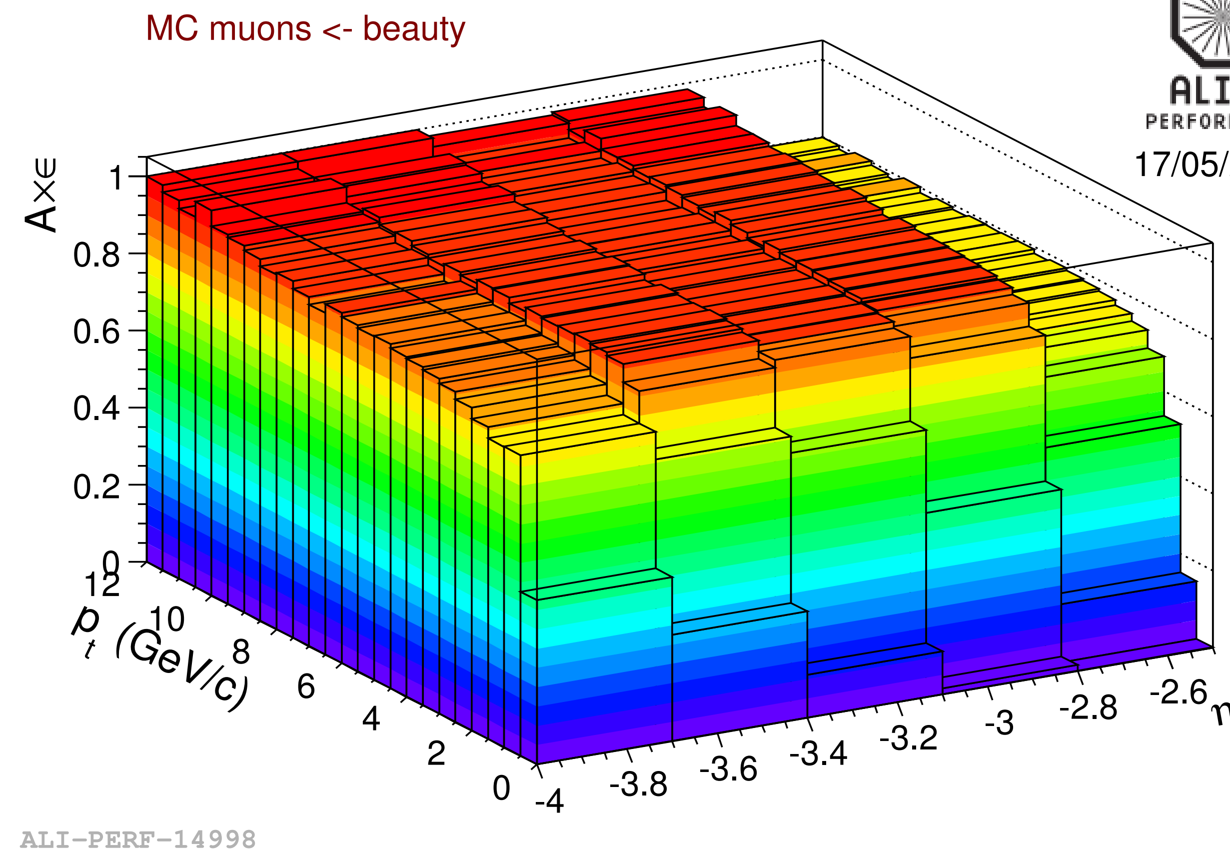
$$\frac{\mathrm{d}^2 N_{\mathrm{AA}}^{\mathrm{K}/\pi}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} =< T_{\mathrm{AA}} > \times R_{\mathrm{AA}}^{\mathrm{K}/\pi}|_{y=0} \times \frac{\mathrm{d}^2 \sigma_{\mathrm{pp}}^{\mathrm{K}/\pi}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}$$

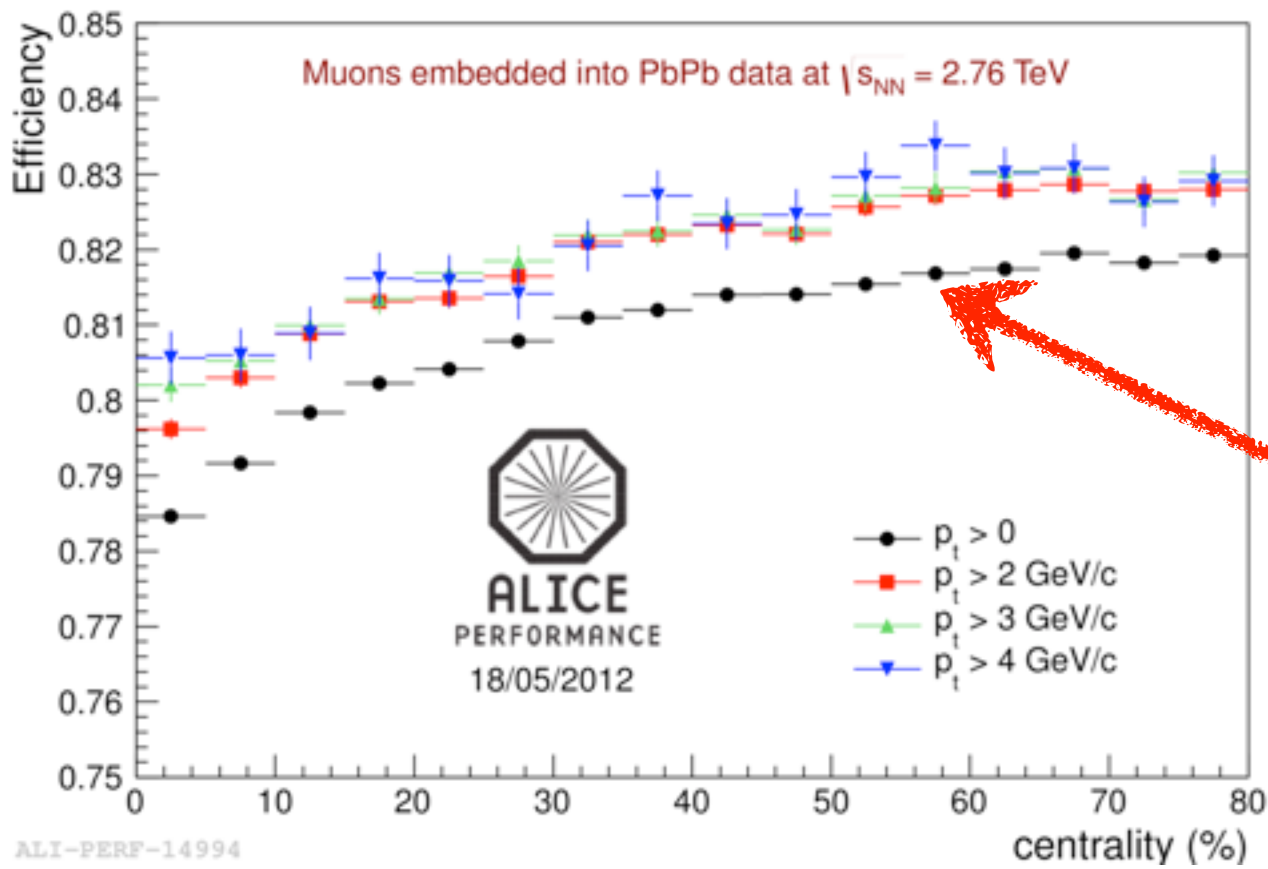
varying K/π R_{AA} between 0 and 200% to estimate the systematic uncertainty on unknown quenching effect at forward rapidity;

- produce the K/π decay muon background in Monte-Carlo with fast detector simulation.

Efficiency Correction

In pp collisions:
efficiency from simulation using beauty signals from NLO pQCD predictions as inputs;
systematic uncertainty on mis-alignment 1%×p_T (in GeV/c).





In Pb–Pb collisions:
the centrality dependence of tracking efficiency is estimated via embedding procedure;
efficiency decreases by 4±1% in the 10% most central collisions w.r.t. peripheral collisions.

Comparisons