Production of muons from heavy-flavour hadron decays with ALICE at the CERN-LHC

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First China LHC Physics workshop (CLHCP)
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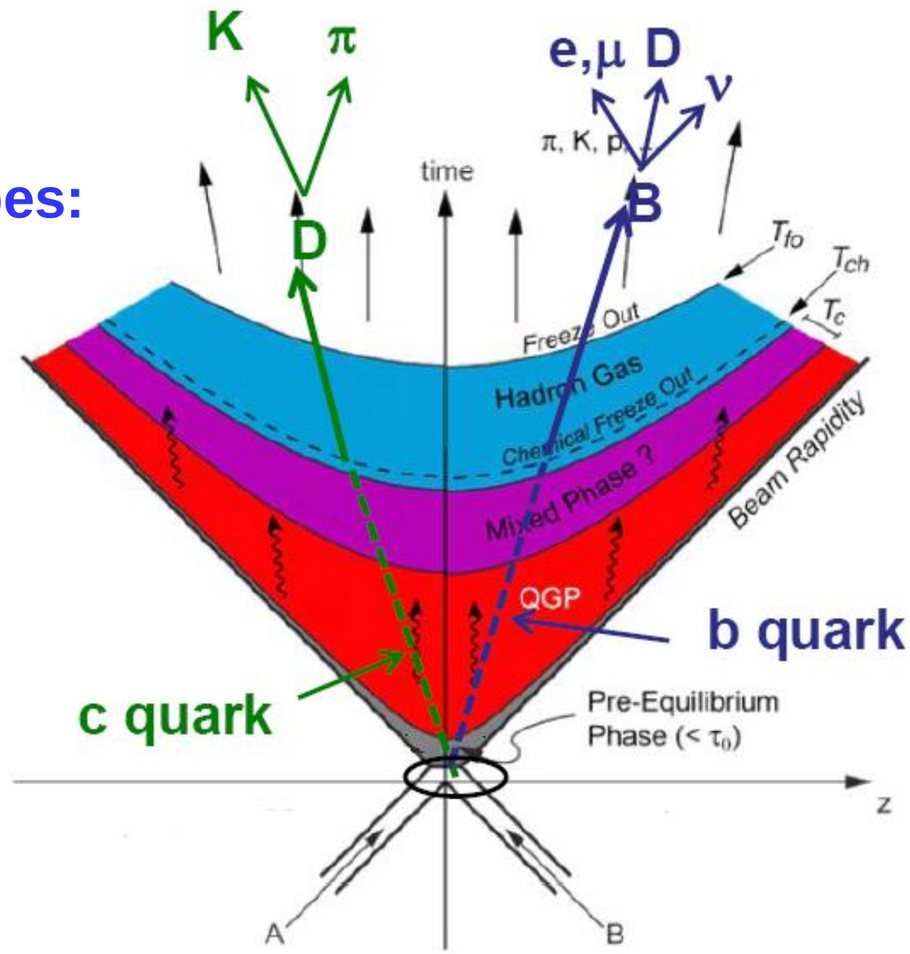
Outline

- Physics motivations
- ALICE setup
- Selection of measurements of muons from heavy-flavour hadron decays in pp, p-Pb and Pb-Pb collisions with ALICE detector
- Summary and outlook

Relevance of open heavy flavours in heavy-ion collisions at the LHC

- **Heavy quarks (charm and beauty) are produced in initial hard scatterings on a short time scale and experience the whole evolution of the system**



Interaction of heavy quarks with the hot/dense medium probes:

- **Parton energy loss via (in)elastic processes**
  - ✓ expected: $\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$
  - ✓ reflected into: $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?
  - ✓ caveats:
    - different shapes of parent parton p_T distributions in pp collisions
    - different fragmentation functions
- **Collectivity in the QGP**
  - ✓ initial spatial asymmetry → azimuthal asymmetry of particle emission in momentum space
  - ✓ low p_T : participation of heavy quarks in the collective expansion of the system
  - ✓ high p_T: path-length dependence of energy loss → azimuthal asymmetry

$$R_{AA}(p_T) = \frac{d\sigma_{AA}/dp_T}{< N_{coll} > d\sigma_{pp}/dp_T}$$

$$\frac{dN}{d\varphi} \propto [1 + 2v_1 cos(\varphi - \Psi_1) + 2v_2 cos[2(\varphi - \Psi_2)] + \cdots]$$

Relevance of open heavy flavours in pp and p-Pb collisions

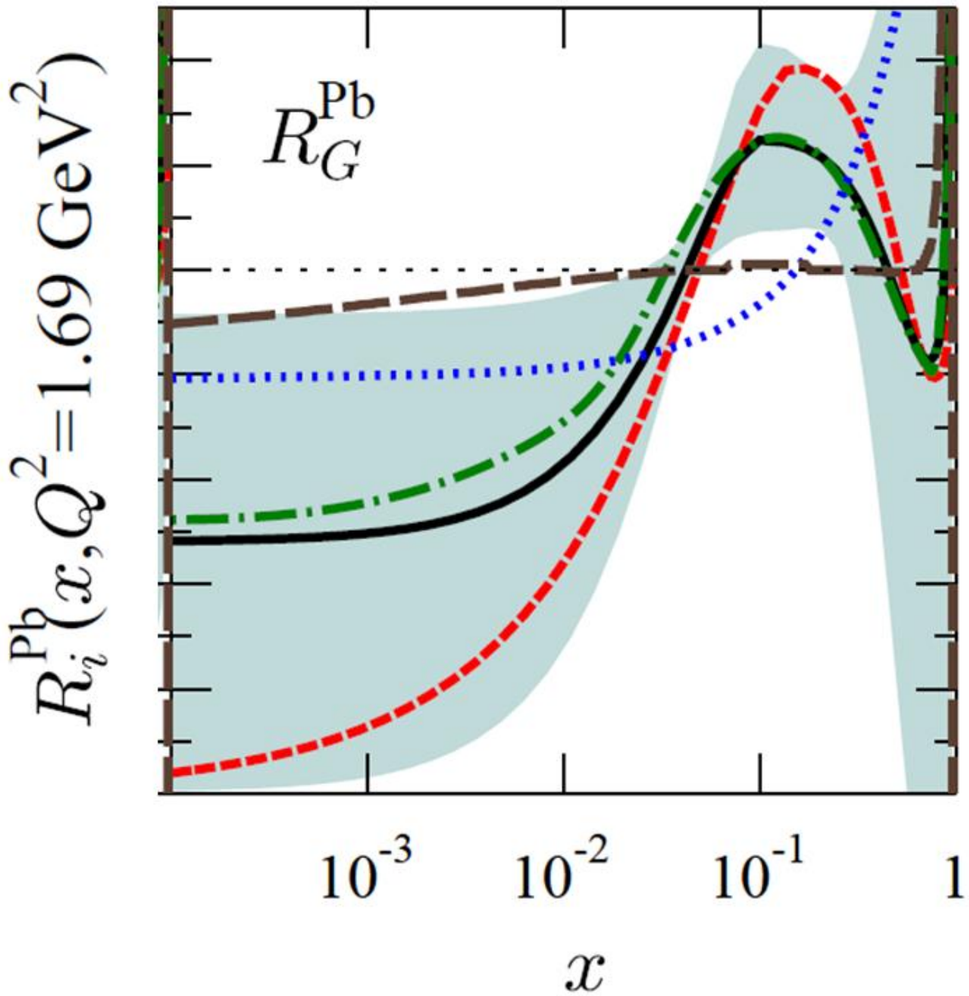
Comprehensive understanding of Pb-Pb data needs data from:

p-Pb collisions

- **Control experiment for Pb-Pb collisions**
- **Quantify cold nuclear matter effects**
  - ✓ parton Distribution Functions (PDF) (shadowing / gluon saturation)
  - ✓ k_T broadening
  - ✓ energy loss in cold nuclear matter
  - ✓ possible other final-state effects
- **Explore nPDFs at different x ranges**

  [arXiv:1512.01528]

JHEP 0904 (2009) 65



pp collisions

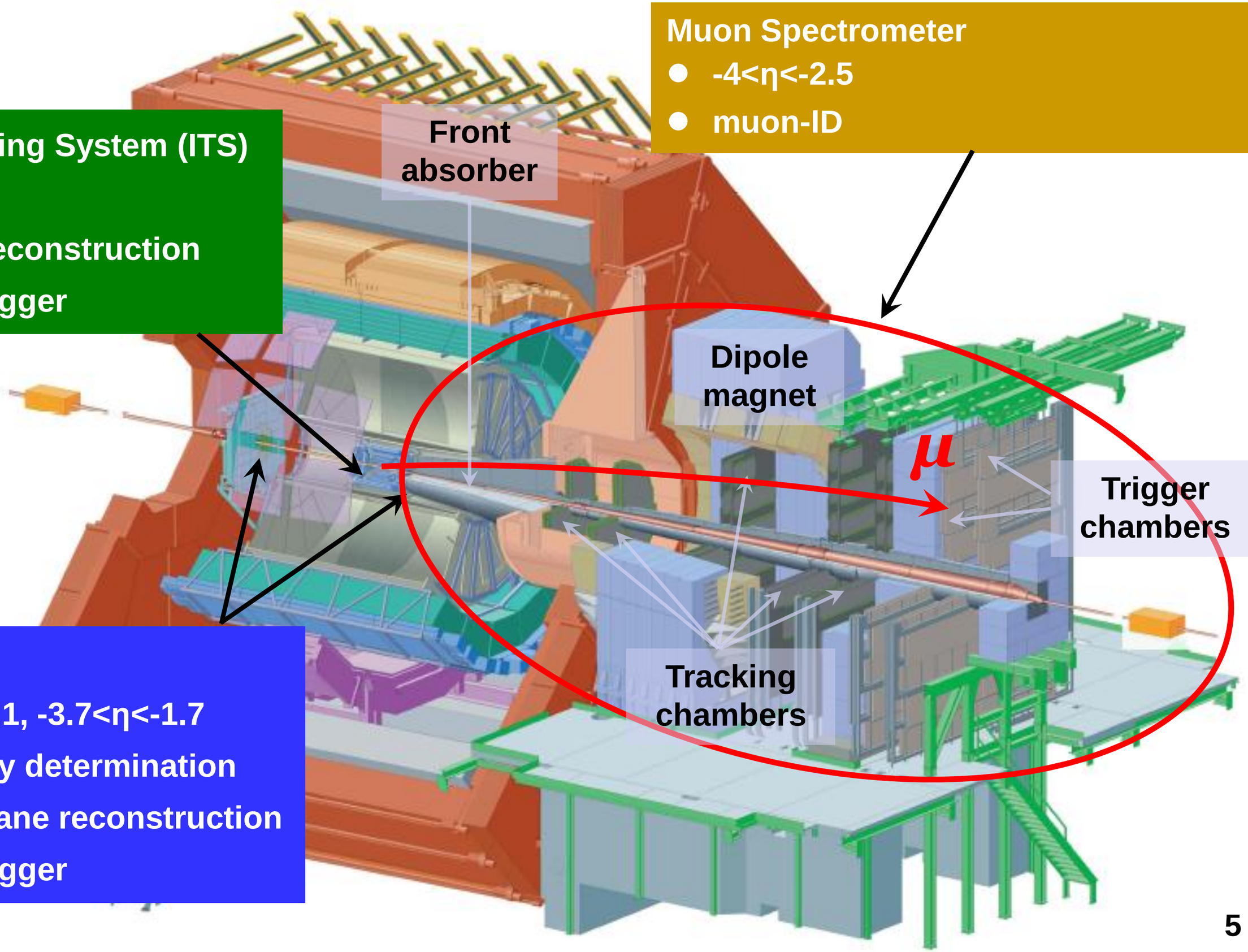
- **Reference for Pb-Pb and p-Pb collisions**
- **Test of perturbative QCD calculations**
- **Insights into production mechanisms at the parton level**

ALICE: A Large Ion Collider Experiment

Inner Tracking System (ITS)
- $|\eta|<0.9$
- vertex reconstruction
- event trigger

Muon Spectrometer
- $-4<\eta<-2.5$
- muon-ID

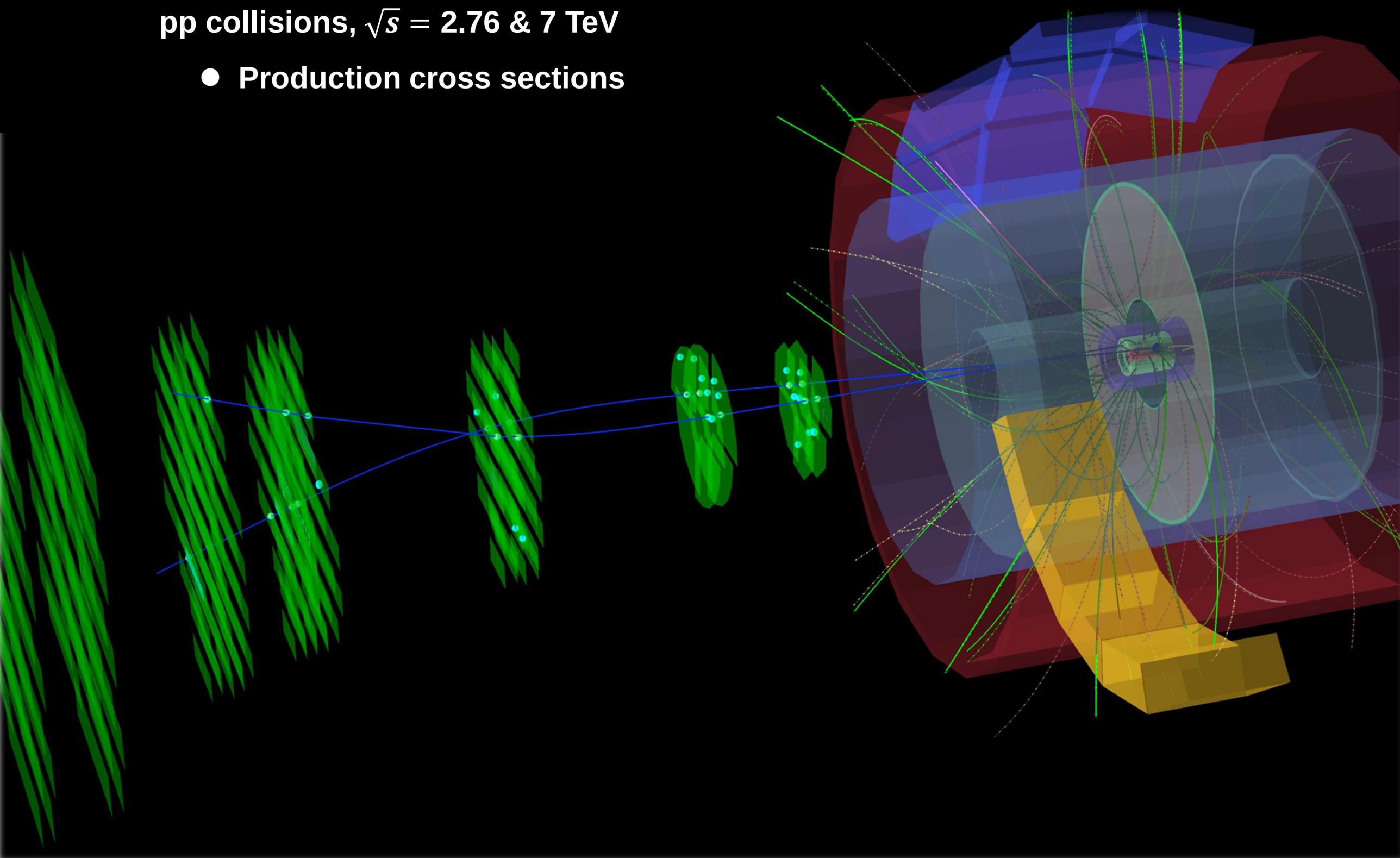
VZERO
- $2.8<\eta<5.1$, $-3.7<\eta<-1.7$
- centrality determination
- event plane reconstruction
- event trigger



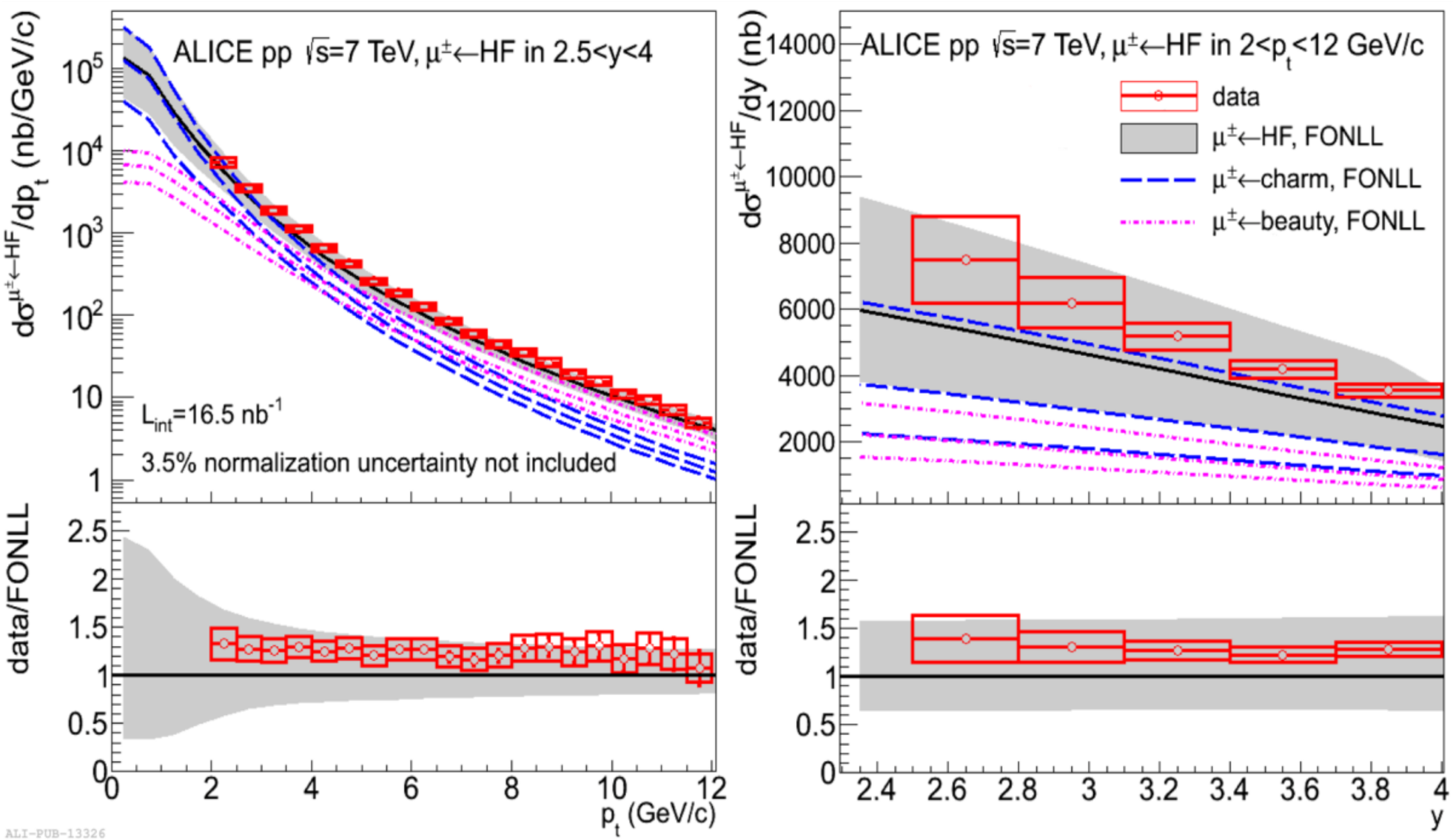
Measurements of muons from heavy-flavour hadron decays in pp collisions

pp collisions, $\sqrt{s} = 2.76$ & 7 TeV

- Production cross sections



Test for pQCD and reference for p-A and A-A collisions



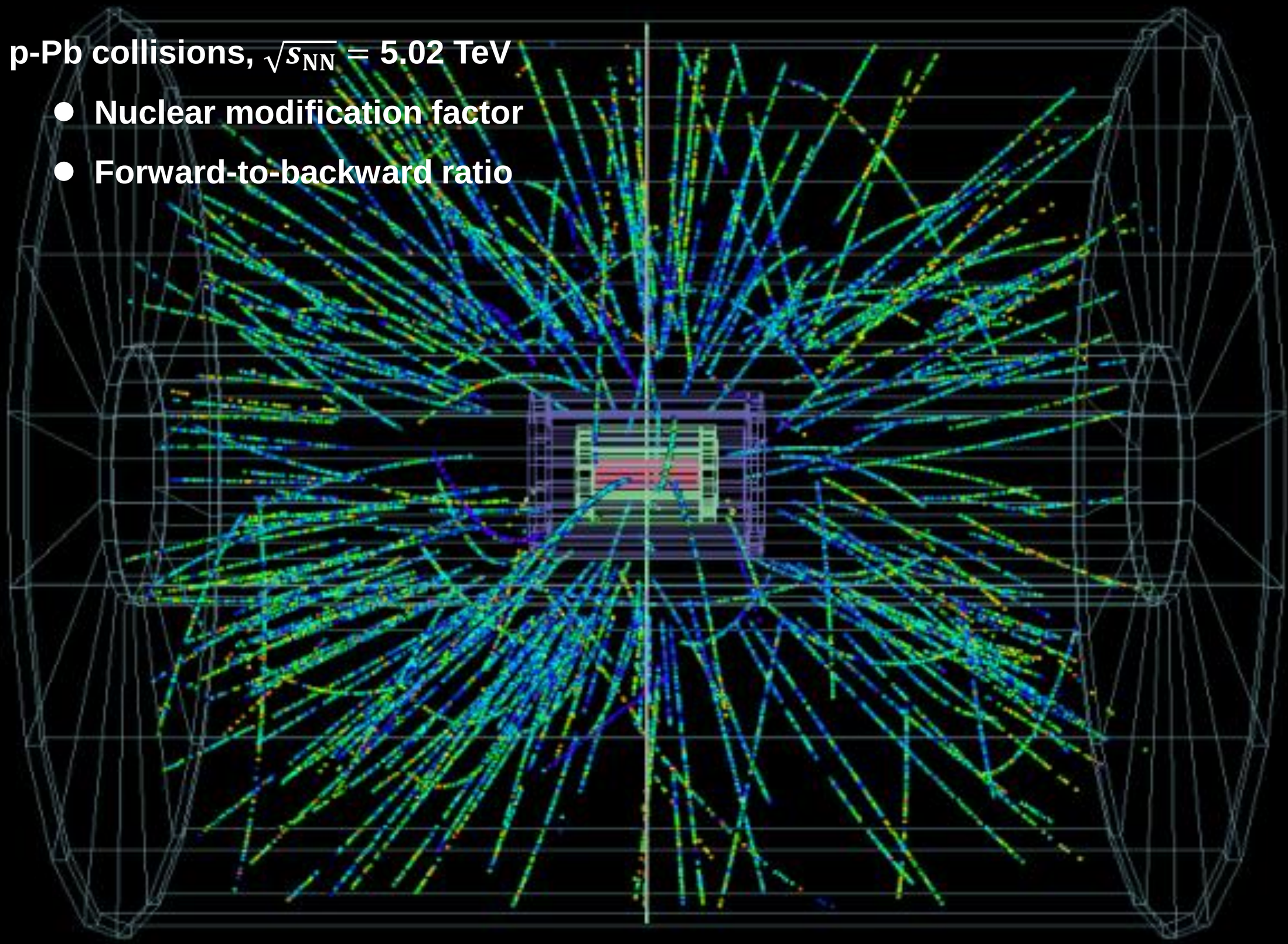
- pQCD calculations are compatible with the p_T- and y-differential measurements at $\sqrt{s} = 7$ TeV
- Similar conclusion found for pp collisions at $\sqrt{s} = 2.76$ TeV

[Data: PLB 708 (2012) 265; FONLL: JHEP 1210 (2012) 137]

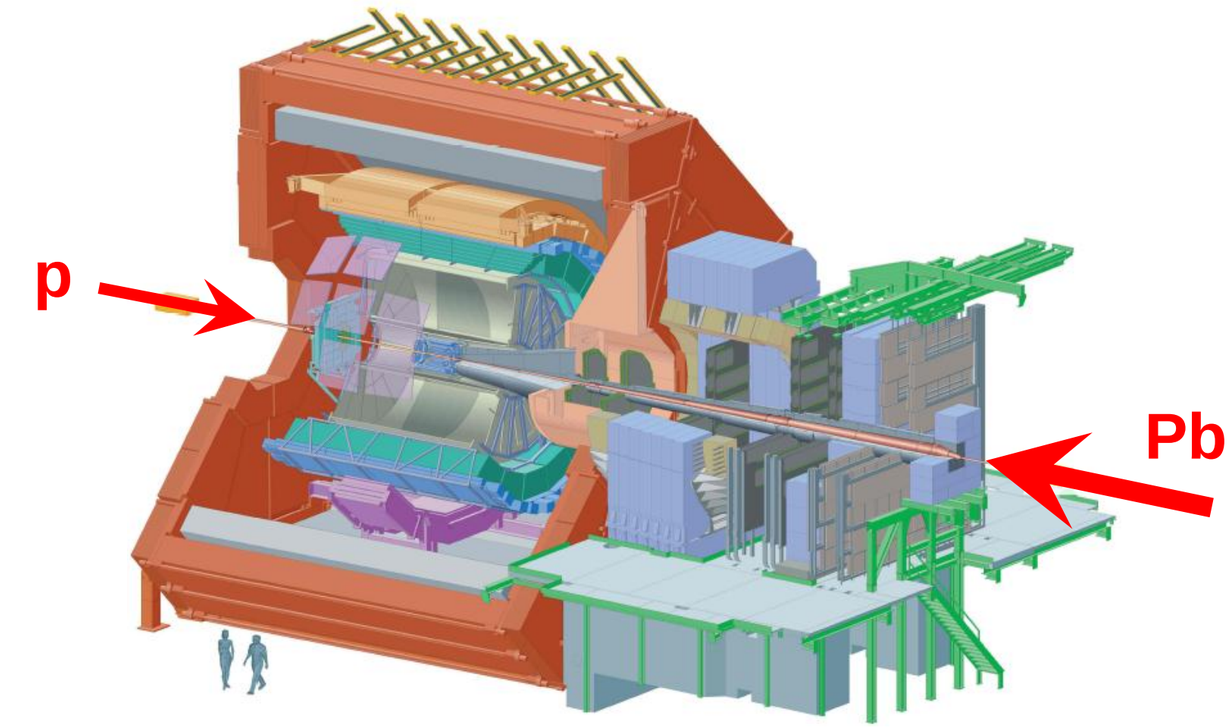
Measurements of muons from heavy-flavour hadron decays in p-Pb collisions

p-Pb collisions, $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- Nuclear modification factor
- Forward-to-backward ratio

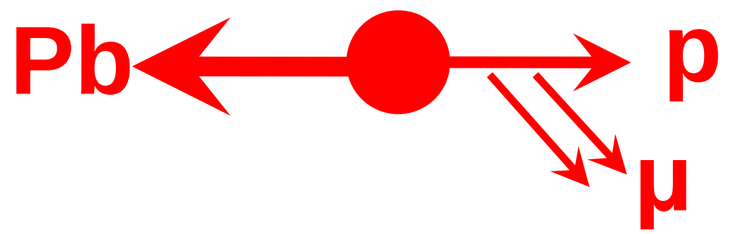


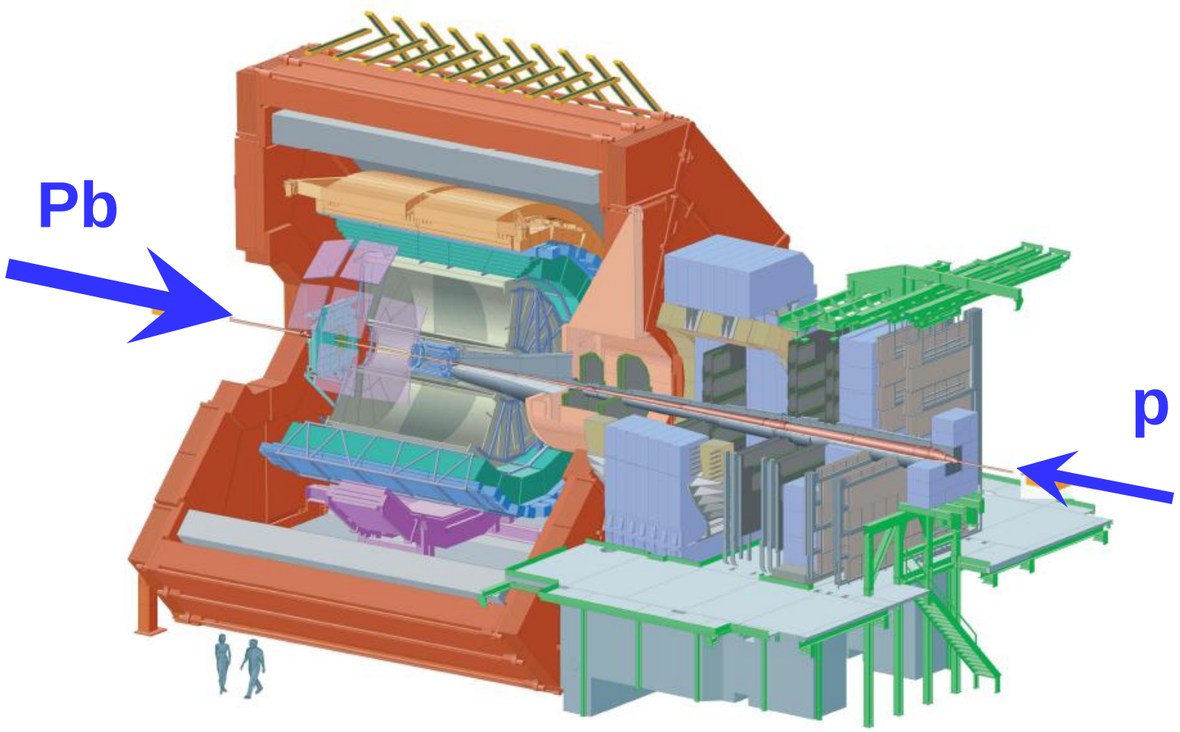
p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



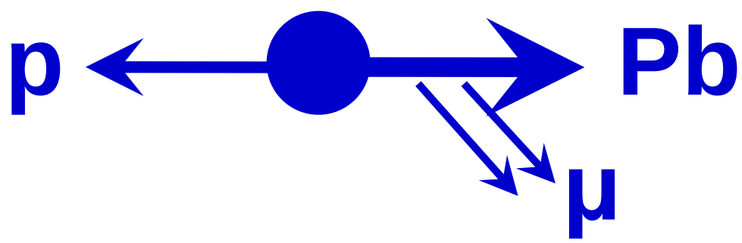
- Rapidity shift of the center-of-mass of 0.465 units in the proton direction

- Measurements performed at **forward rapidity (p-going direction, $2.03 < y_{\mathrm{cms}} < 3.53$) → x~$10^{-5}$**



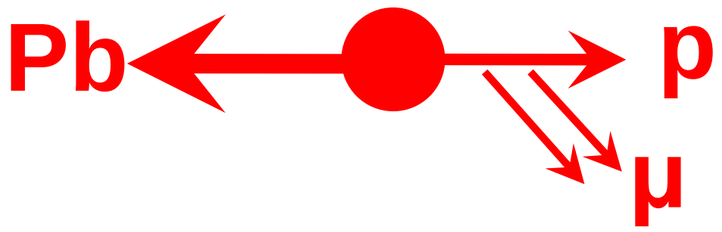


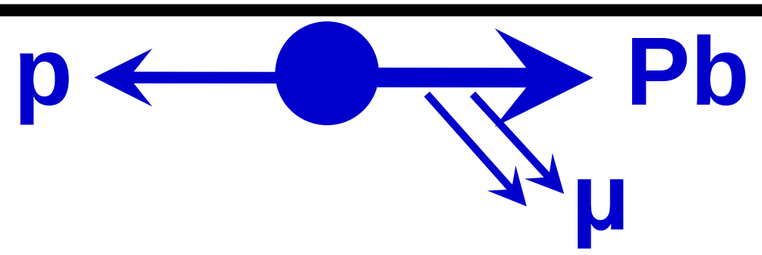
- Measurements performed at **backward rapidity (Pb-going direction, $-4.46 < y_{\mathrm{cms}} < -2.96$) → x~$10^{-2}$**

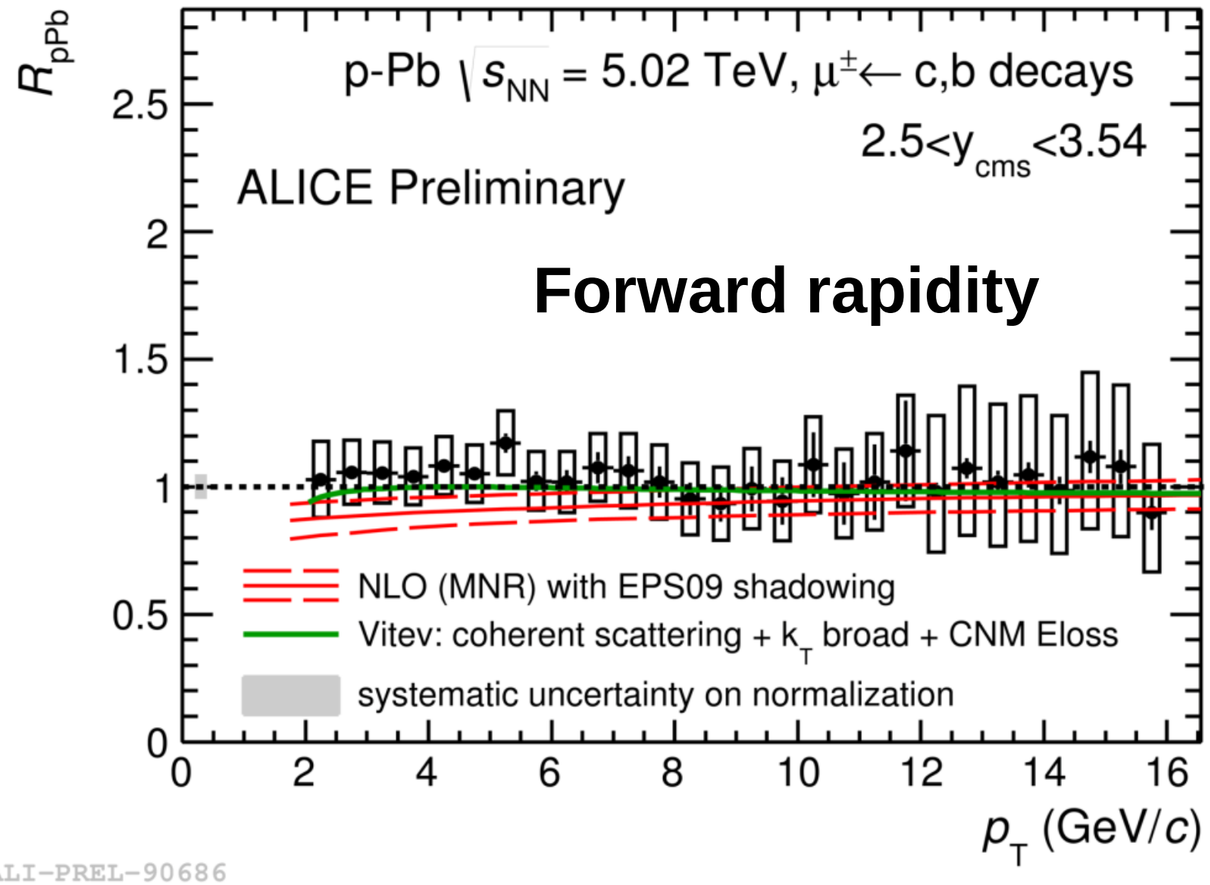


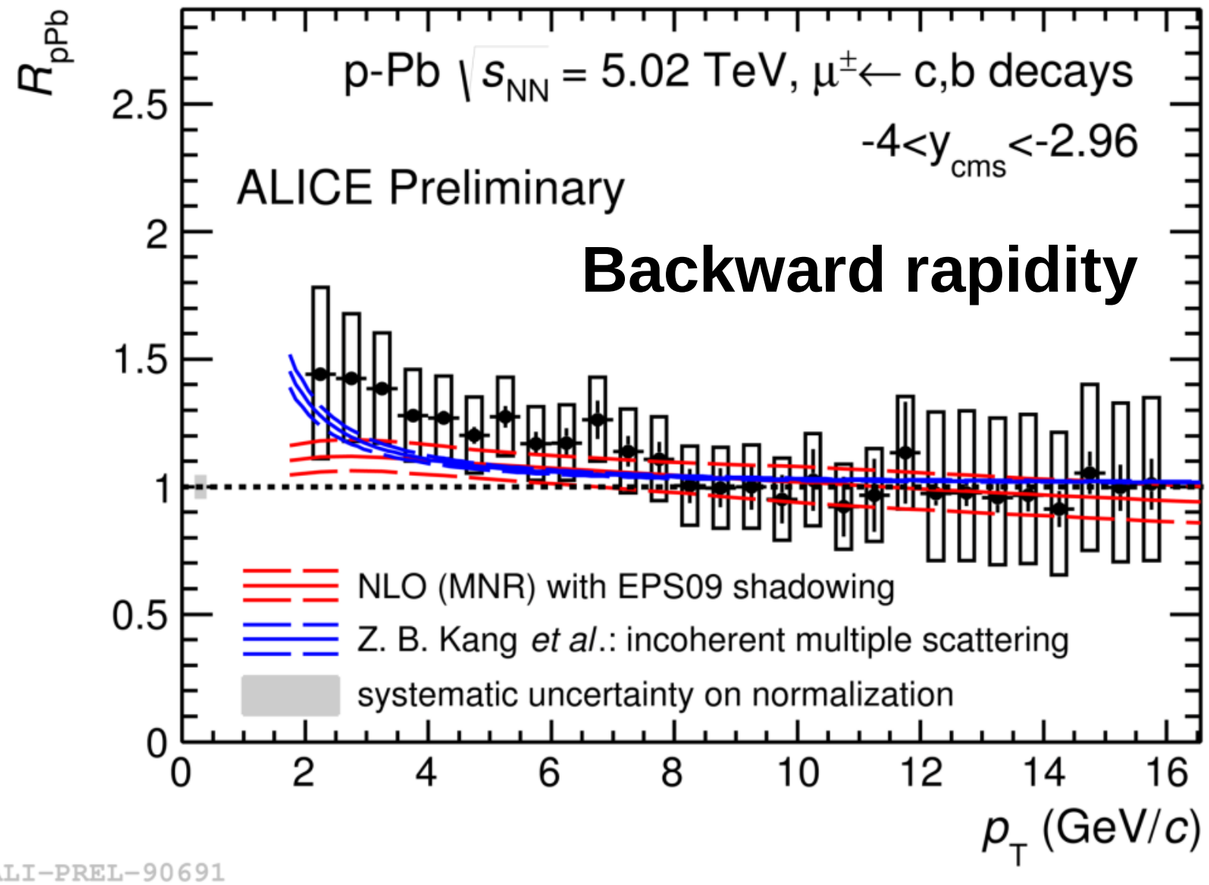
R_{pPb} vs p_T

$$R_{pPb} = \frac{1}{A} \times \frac{d\sigma_{pPb}}{dp_T} \Big/ \frac{d\sigma_{pp}}{dp_T}$$









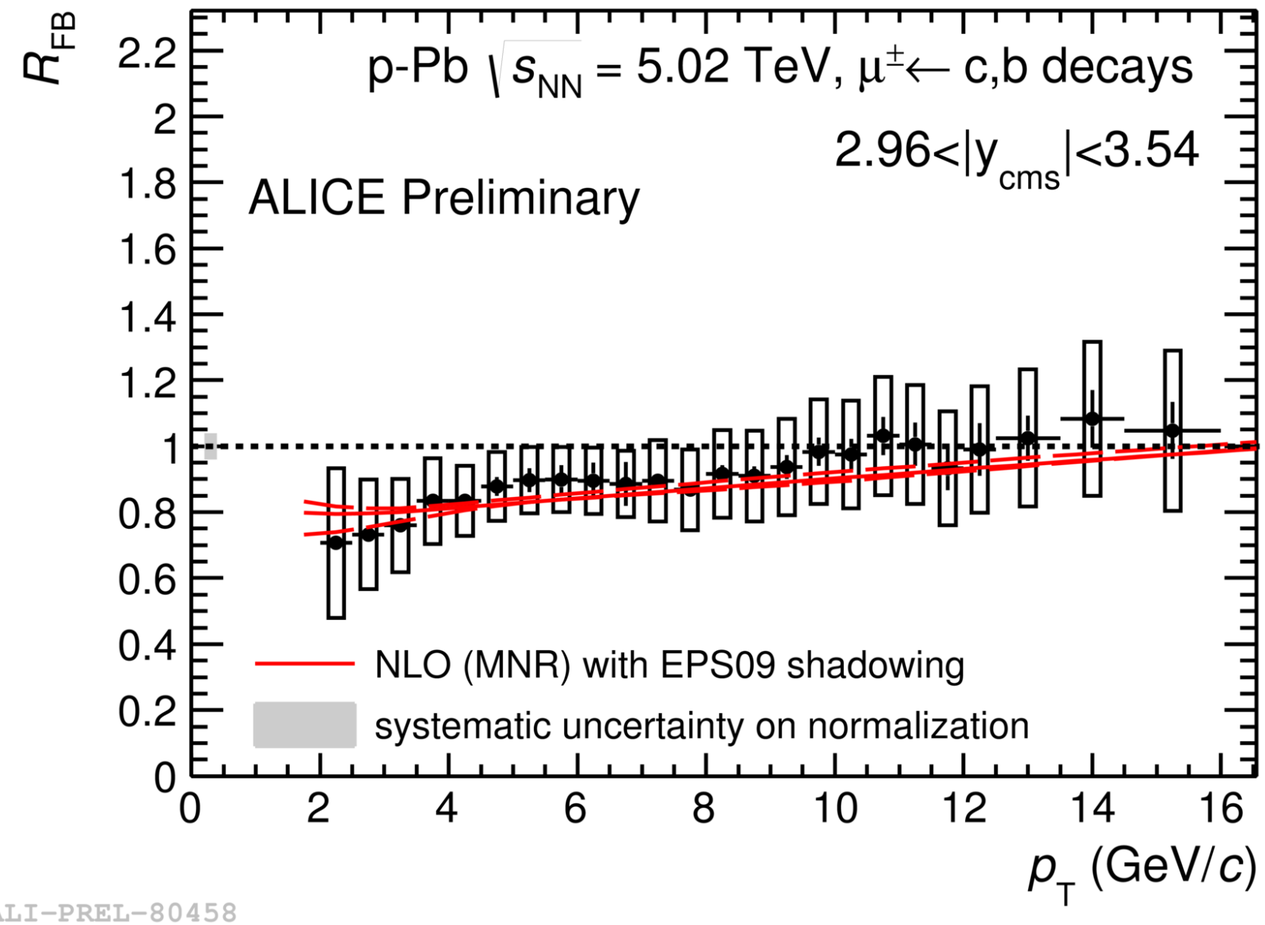
- R_{pPb} at forward rapidity*:* consistent with unity within uncertainties over the whole measured p_T range
- R_{pPb} at backward rapidity*:* slightly larger than unity in $2<p_T<4$ GeV/c and close to unity at higher p_T
- R_{pPb}~1 indicates small cold nuclear matter effects (at least at high-p_T)
- Good agreement between data and models including cold nuclear matter effects

[pQCD NLO (MNR): NPB 373 (1992) 295; EPS09: JHEP 04 (2009) 065
PRC 80 (2009) 054902; PRC 87 (2013) 044905
PLB 740, (2015) 23; PR D 88 (2013) 054010]

R_{FB} vs p_T

Forward-to-backward ratio

$$R_{\mathrm{FB}}(2.96 < |y_{cms}| < 3.54) = \frac{\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}\,[\mathrm{Forward}(2.96 < y_{\mathrm{cms}} < 3.54)]}{\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}[\mathrm{Backward}(-3.54 < y_{cms} < -2.96)]}$$



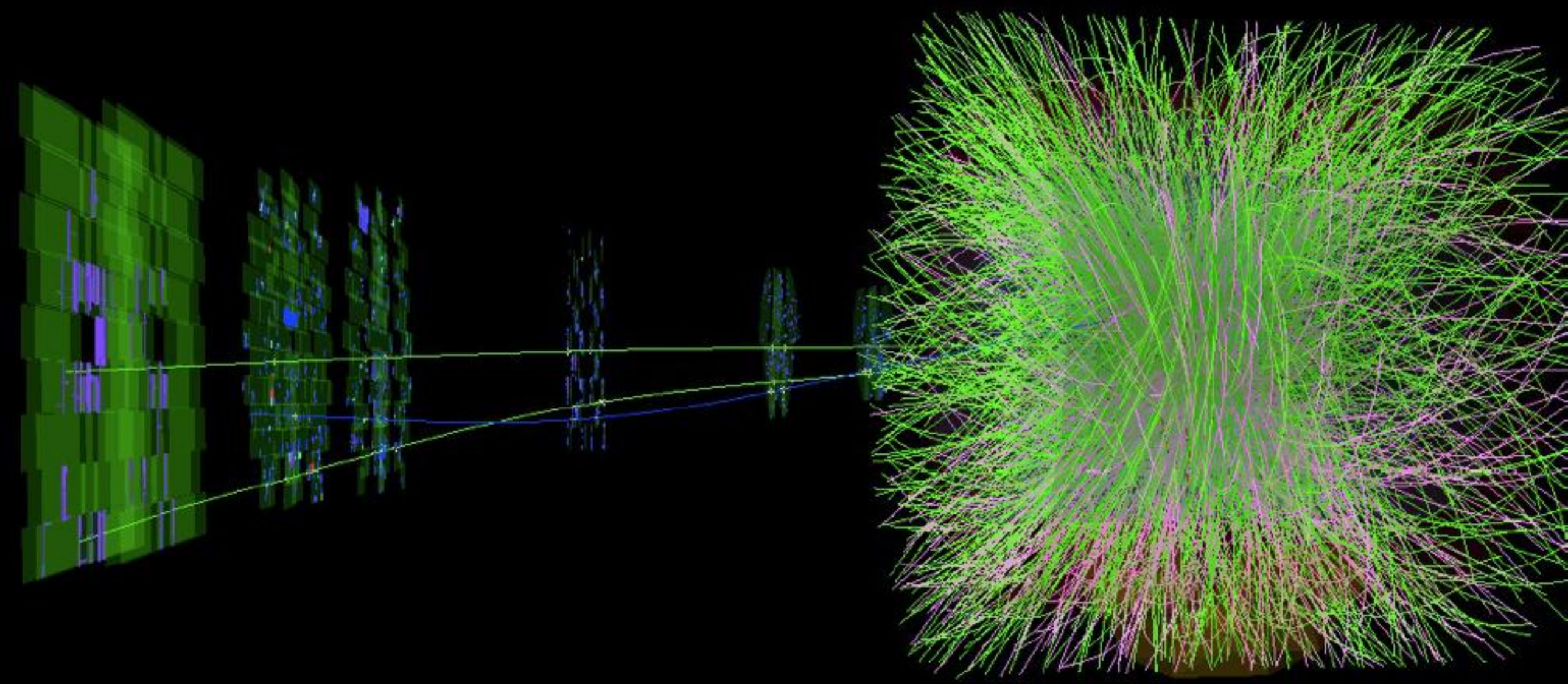
- R_{FB}: systematically smaller than unity in 2<p_T<4 GeV/c and close to unity at higher p_T
- R_{FB}~1 indicates small cold nuclear matter effects (at least at high-p_T)
- Within uncertainties, data can be described by EPS09 predictions

[pQCD NLO (MNR): NPB 373 (1992) 295; EPS09: JHEP 04 (2009) 065]

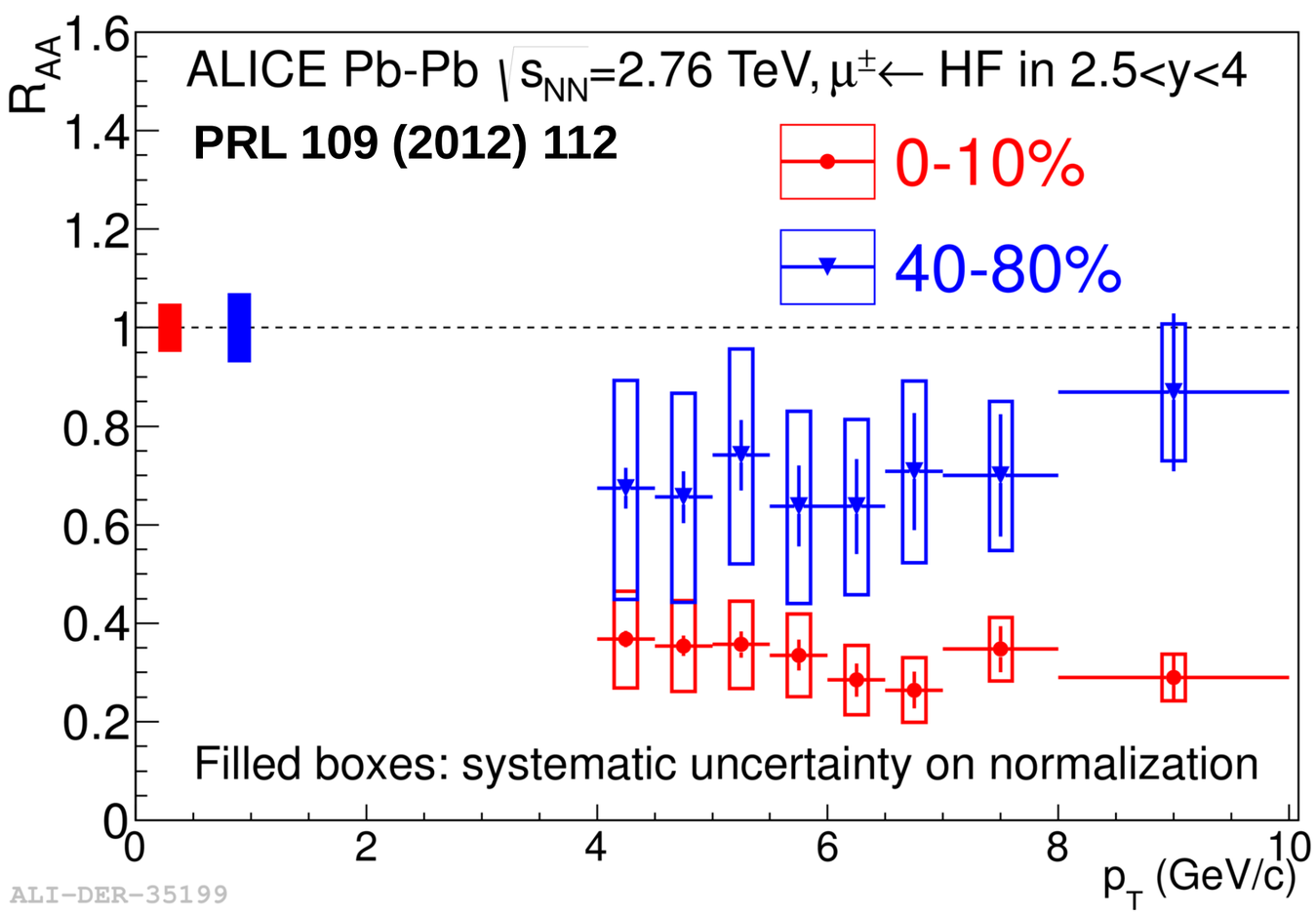
Measurements of muons from heavy-flavour hadron decays in Pb-Pb collisions

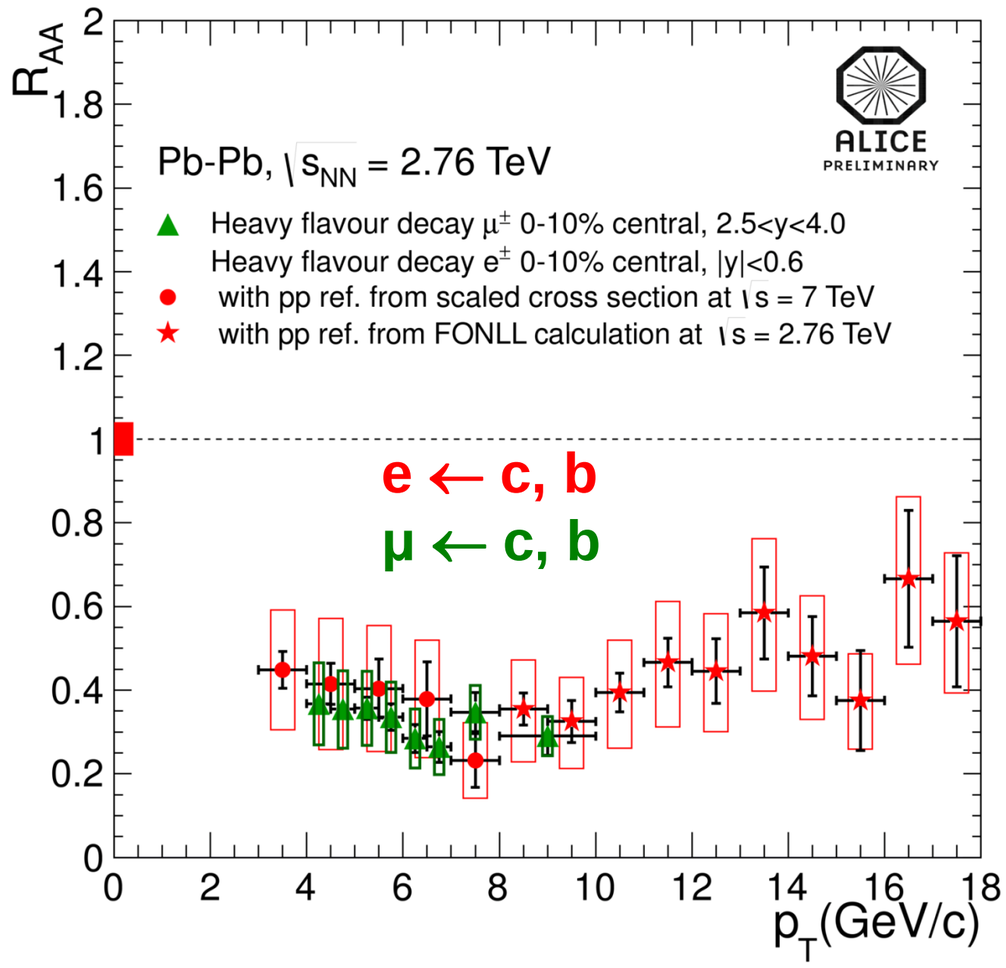
Pb-Pb collisions, $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

- **Nuclear modification factor**
- **Azimuthal anisotropy**



R_{AA} vs p_T

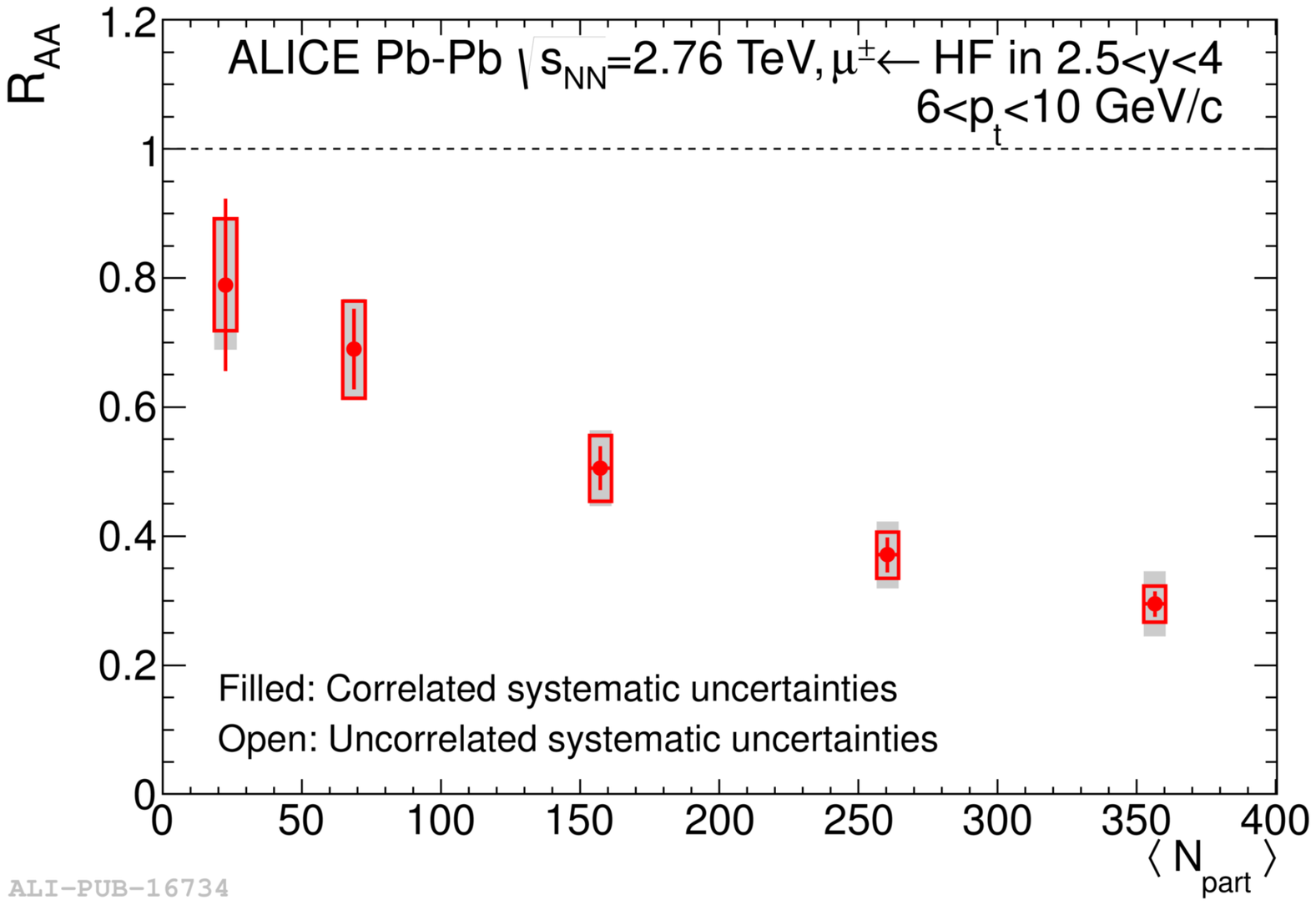




- R_{AA} of of heavy-flavour decay muons is independent of p_T within the measured p_T range
- Stronger suppression in central than in peripheral collisions, reaching a factor of about 3-4 in the 10% most central collisions → results from final-state effects induced by the hot and dense nuclear medium (cold nuclear matter effects are small at high-p_T)
- R_{AA} of heavy-flavour decay muons at forward rapidity (2.5<y<4) is compatible with that of heavy-flavour decay electrons at mid-rapidity (|y|<0.6)

Centrality dependence

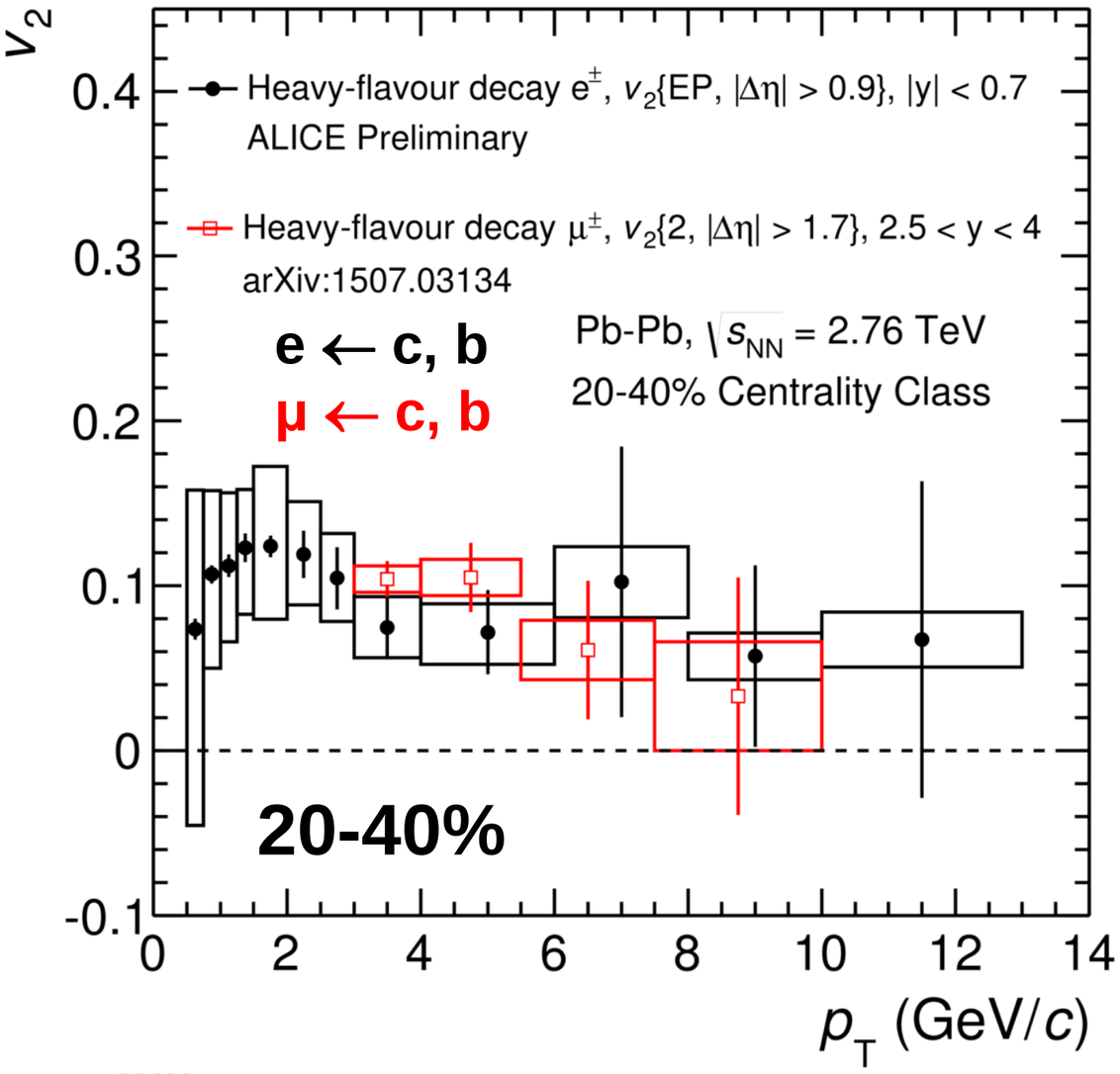
PRL 109 (2012) 112



- The suppression of heavy-flavour decay muons in the high p_T range at forward rapidity exhibits a increase with increasing centrality
- Consistent centrality dependence observed at mid-rapidity with muons measured in the ATLAS collaboration [ATLAS-CONF-2012-050]

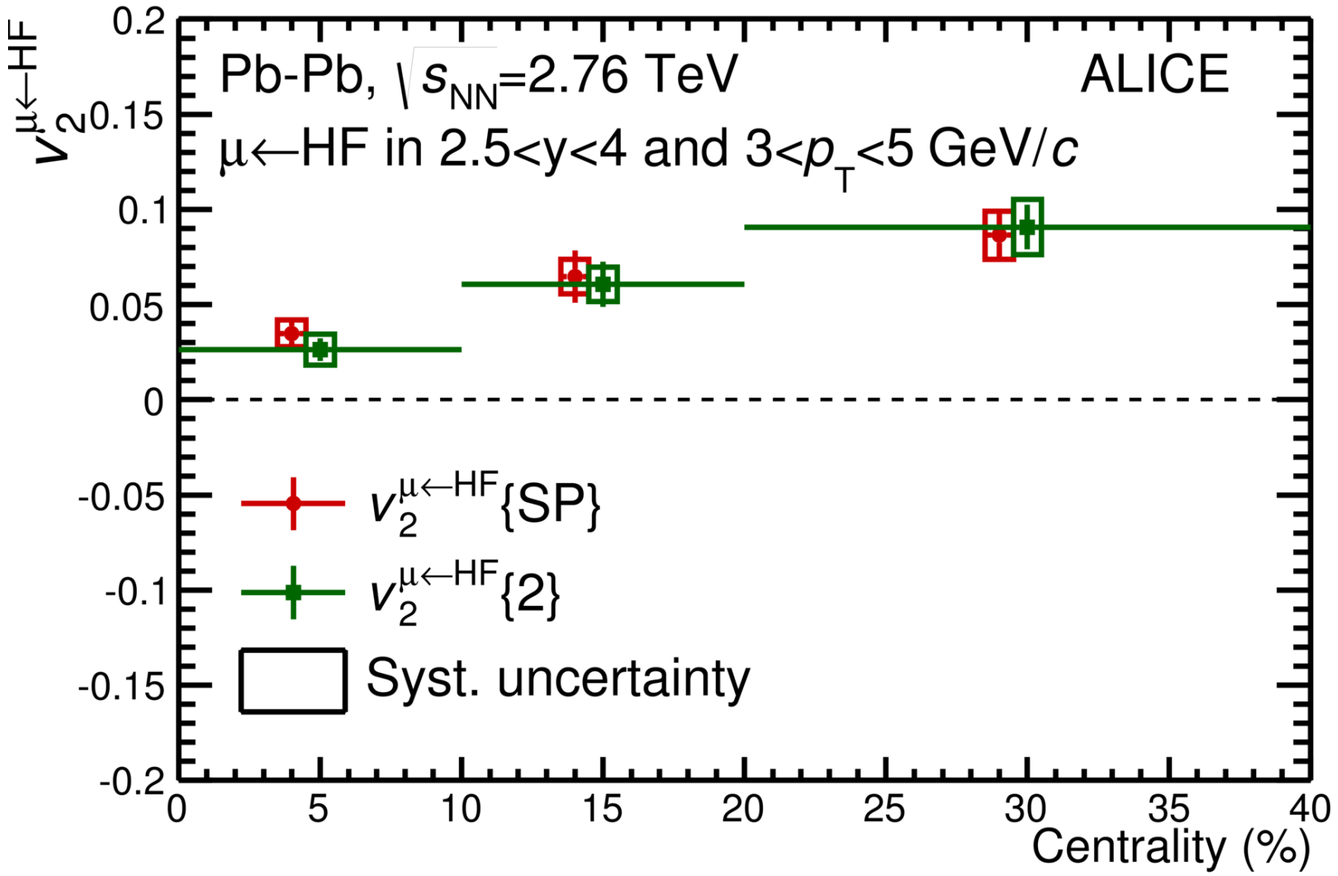
v_2 vs p_T

$$v_2 = < \cos 2(\varphi - \Psi_{RP}) >$$



ALI-PREL-77628

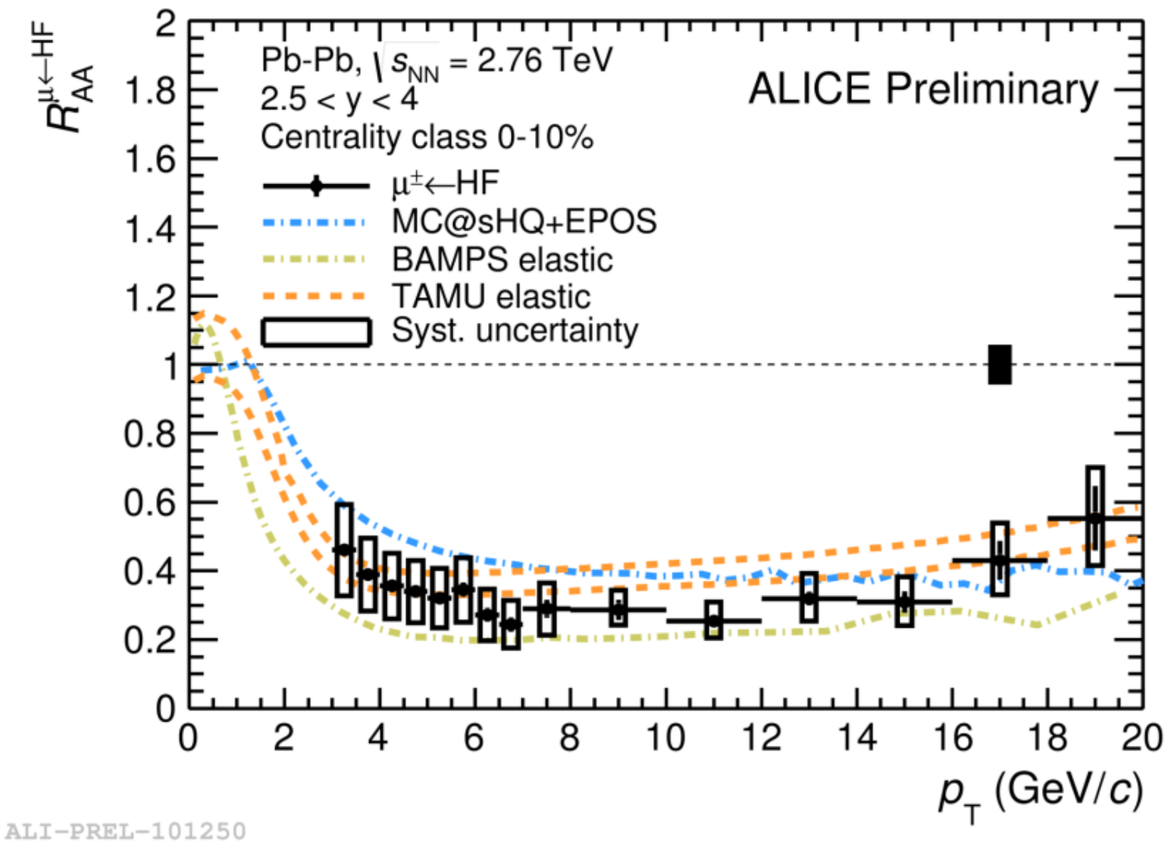
muons: 1507.03134

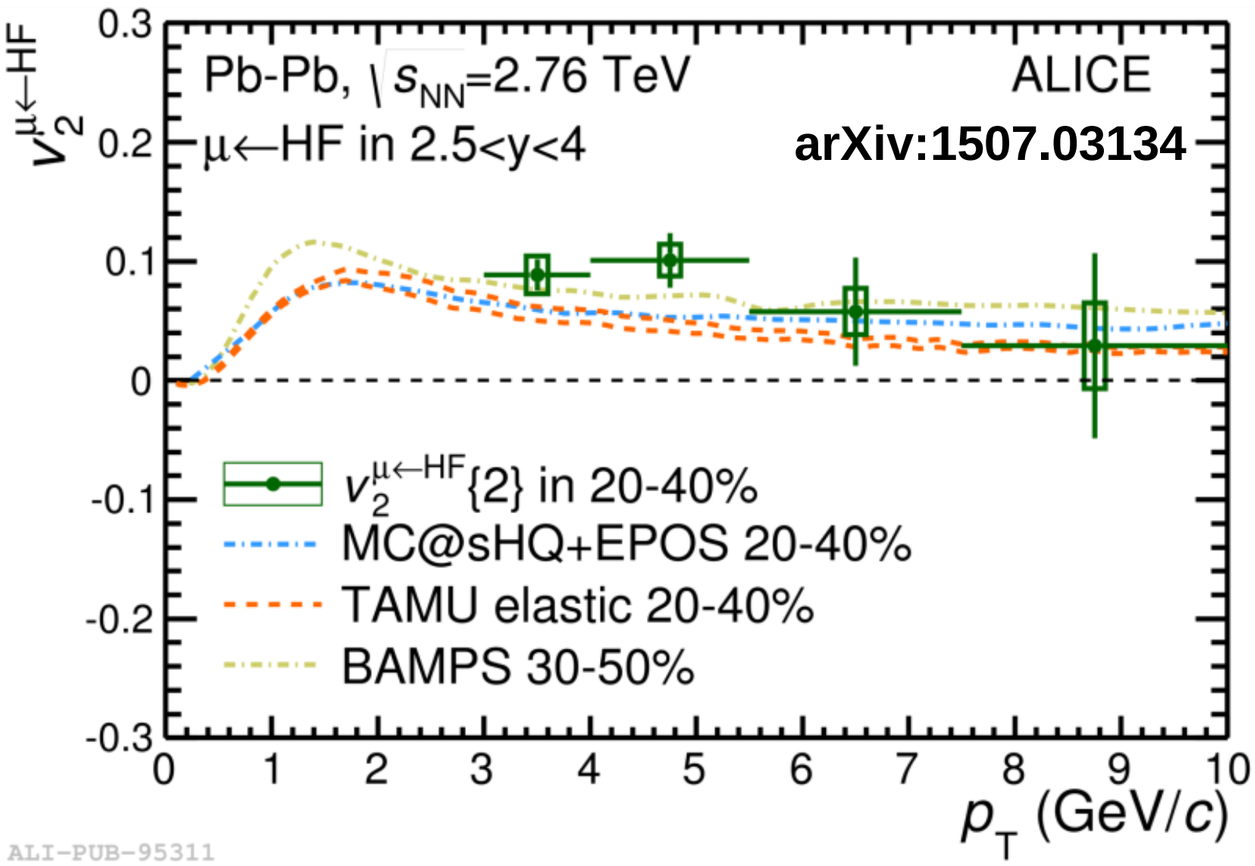


ALI-PUB-103047

- Heavy-flavour hadron decay muon v_2 is positive in $3 < p_T < 5$ GeV/c in 20-40% with a significance larger than 3σ when combining statistical and systematic uncertainties
  - ✓ consistent results with e ← c, b measured at mid-rapidity
- Confirmation of significant interaction of heavy quarks with the medium
  - ✓ same conclusion found for D-meson measured at mid-rapidity [PRC 90 (2014) 034904]
- Increase of v_2 from central to semi-central collisions, in the centrality range 0-40%

Model comparisons





- Simultaneous R_{AA} and v_2 measurements starts to provide constraints to energy-loss models
- Similar picture for D mesons and electrons observed at mid-rapidity

  [PRL 111 (2013) 102301; arXiv:1509.06888]

[MC@ sHQ+EPOS, Coll + Rad (LPM): PRC89 (2014) 014905;
BAMPS PLB 717 (2012) 430;
TAMU elastic: arXiv: 1401.3817]

Summary of heavy-flavour hadron decay muons from Run 1

pp collisions:

- Reference system, test for pQCD at LHC energies
- Insights into production mechanisms at parton level

p-Pb collisions:

- Control experiment for Pb-Pb collisions
- Investigate cold nuclear matter effects within small & large Bjorken-x ranges
  - ✓ cold nuclear matter effects are small (at least at high-p_T)

Pb-Pb collisions:

- Strong interaction of heavy quarks with the medium
  - ✓ suppression of heavy-flavour hadron decay muon yields at high p_T in central collisions: medium effect related to in-medium parton energy loss
  - ✓ participation of heavy quarks (charm, mainly) in the collective expansion of the system
- Simultaneous description of different observables (R_{AA}, v_2) provides constraints on models including energy loss

Outlook: towards Run 2 and Run 3

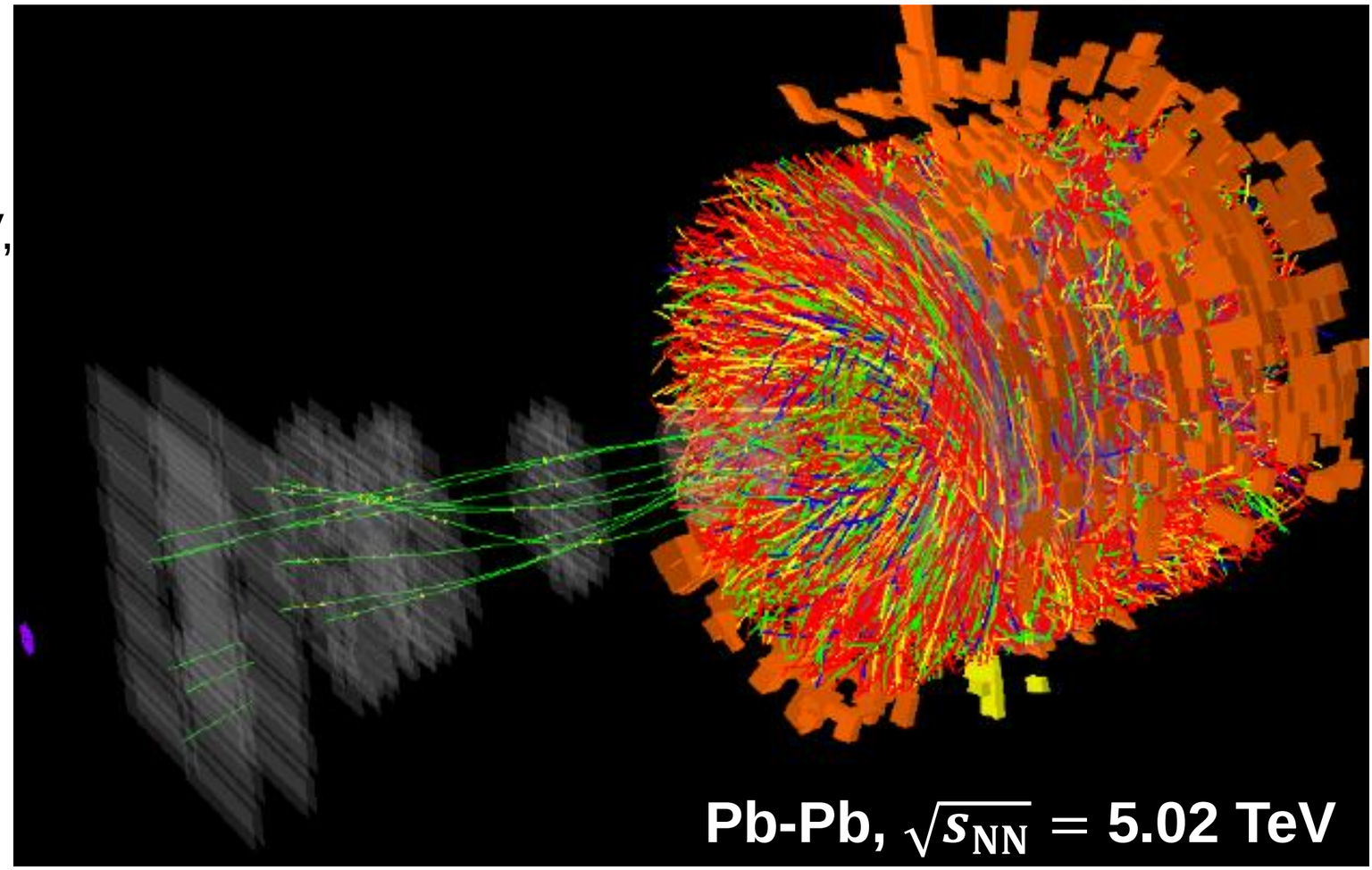
Run 2: 2015-2018

- pp collisions at $\sqrt{s} = 5.02$ and 13 TeV,

  Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV,

  as well as p-Pb collisions
- Significant increase of statistics

  (L~1 nb^{-1} for Pb-Pb collisions)



Run 3: 2020-2023

- ~10 times more statistics w.r.t. Run 2 (L > 10 nb^{-1})
- New MFT (Muon Forward Tracker)
  - ✓ separate μ ← c and μ ← b components at forward rapidity

Outlook: towards Run 2 and Run 3

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- pp collisions at $\sqrt{s} = 5.02$ and 13 TeV,

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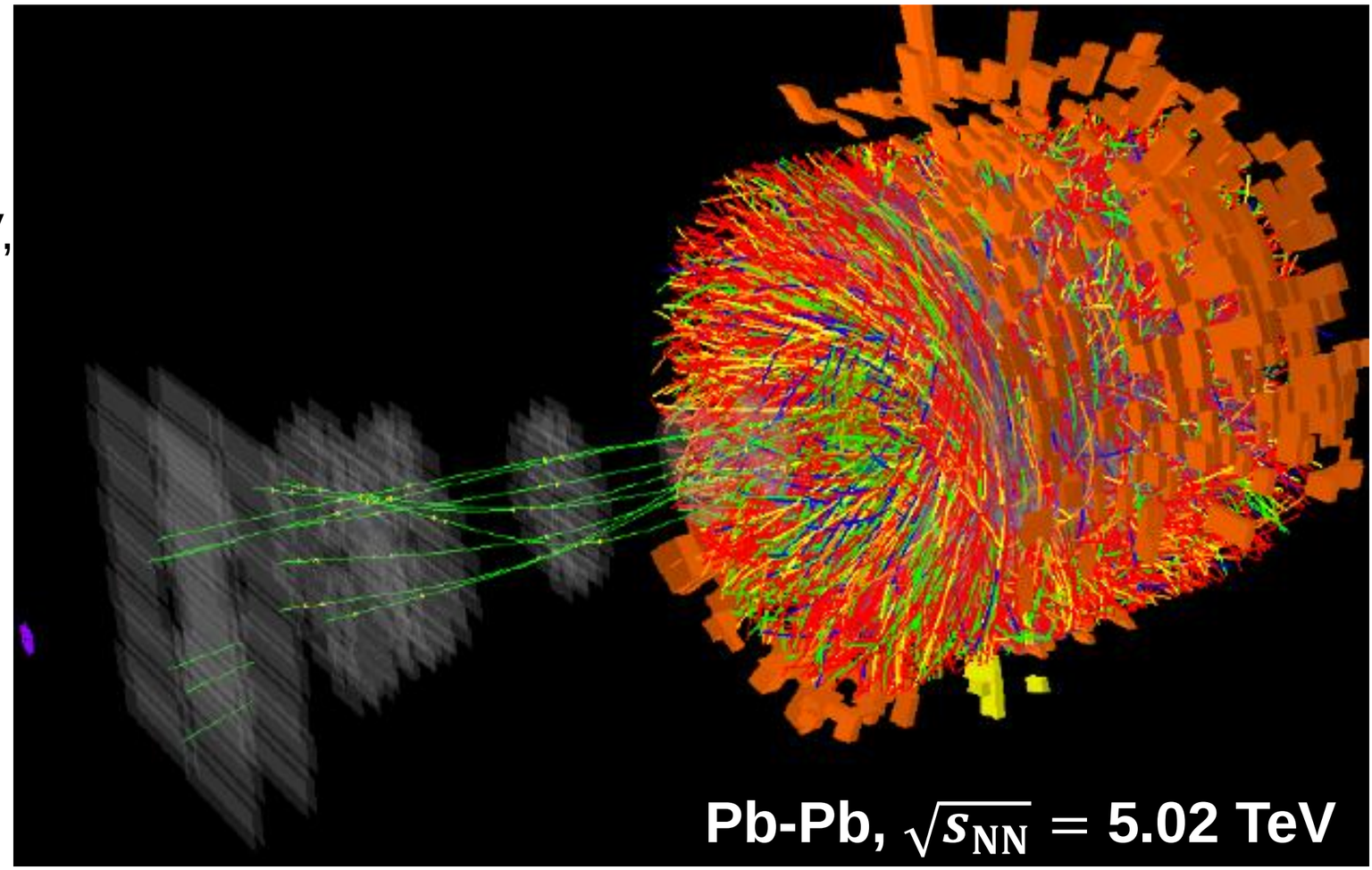

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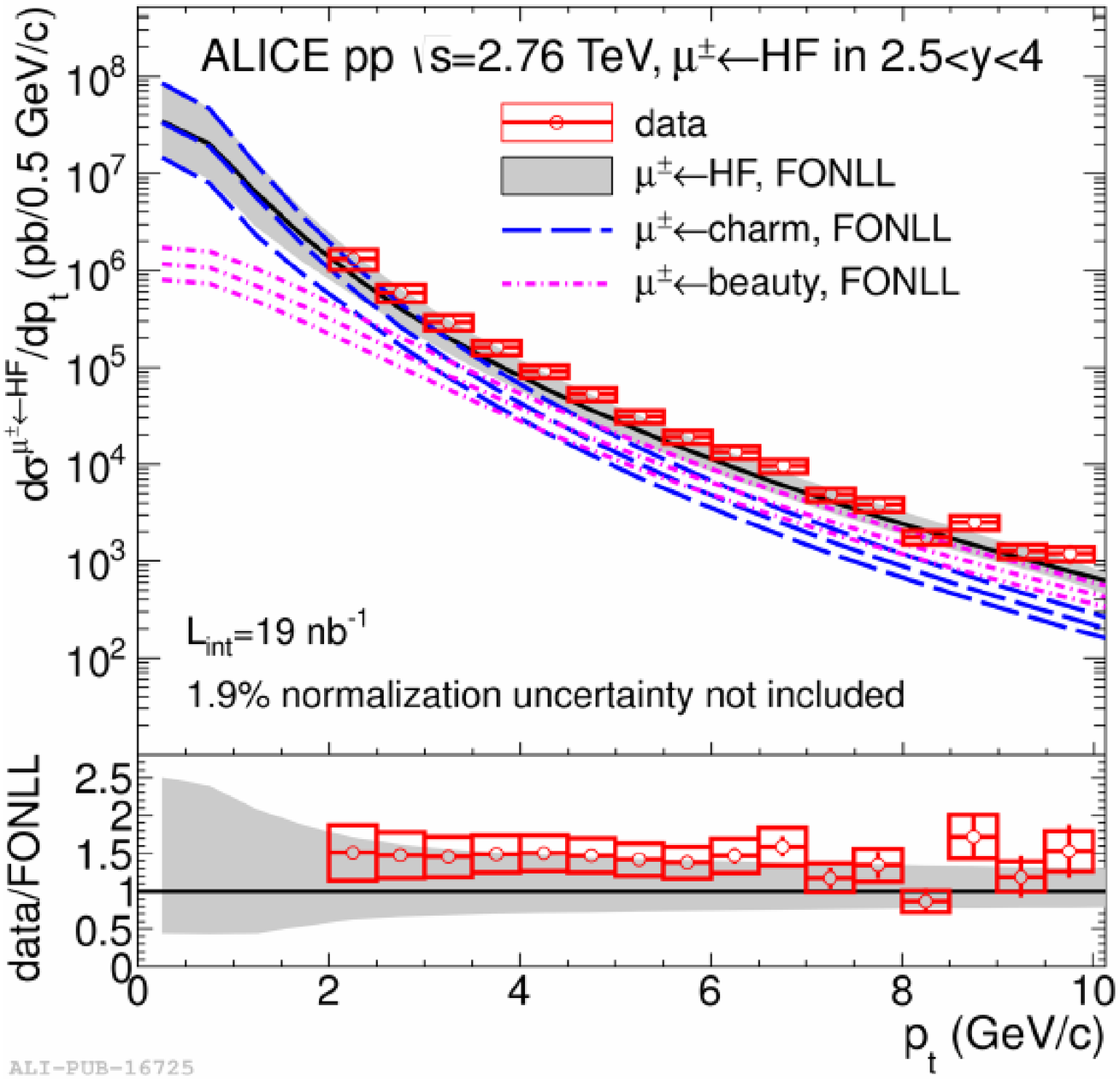
Thank you for the attention!

Backup

Test for pQCD and reference for p-A and A-A collisions (1/2)

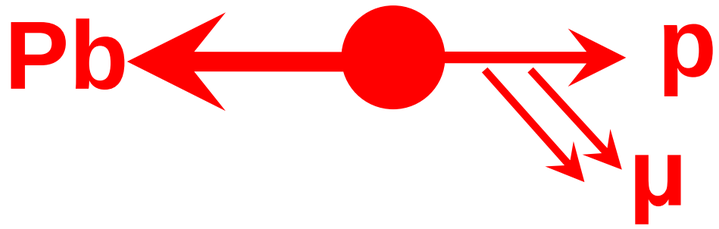


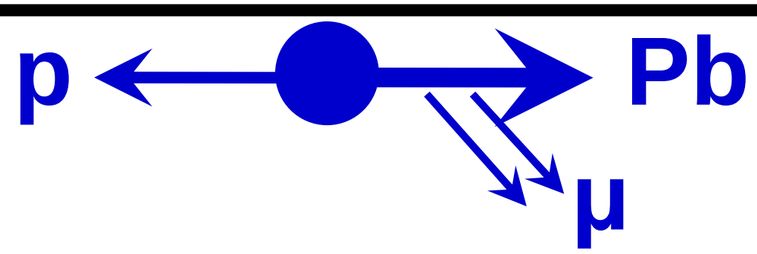
- Within uncertainties, pQCD calculations in reasonable agreement with data at $\sqrt{s} = 2.76$ TeV

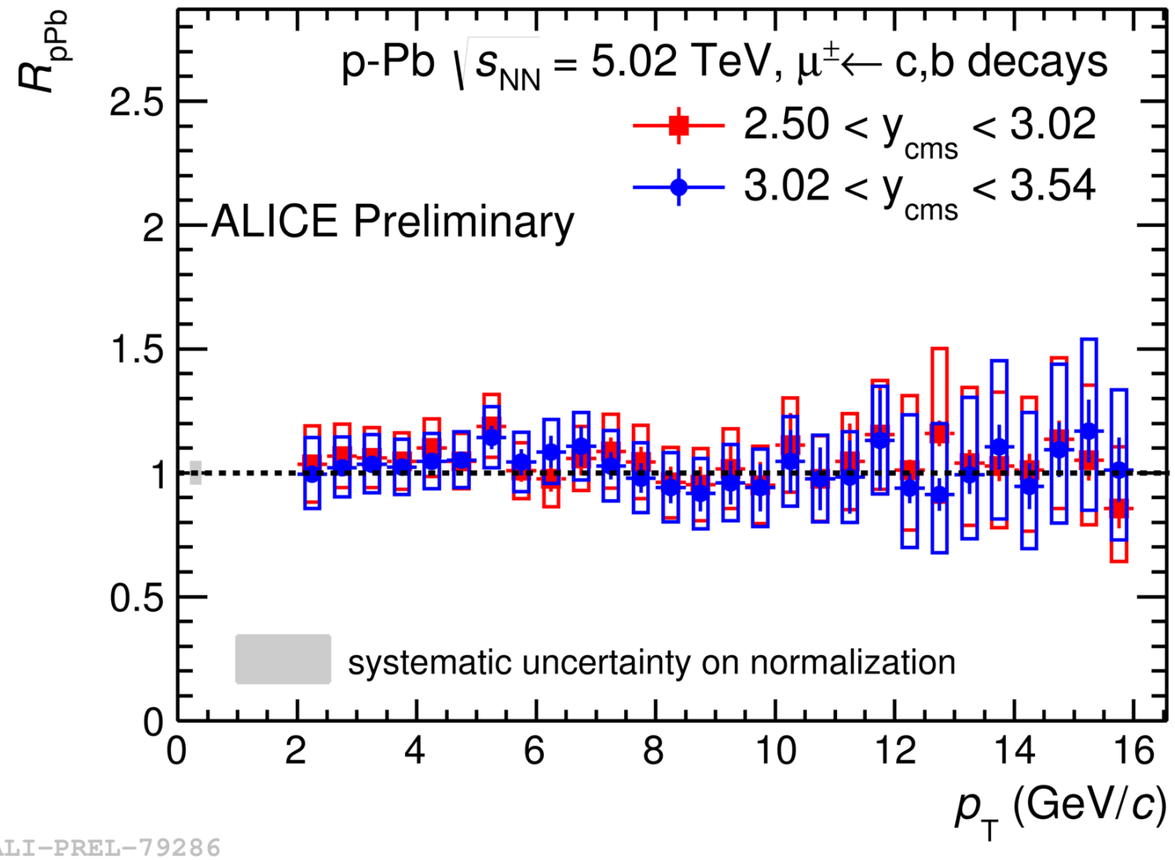
Data: PRL 109 (2012) 112

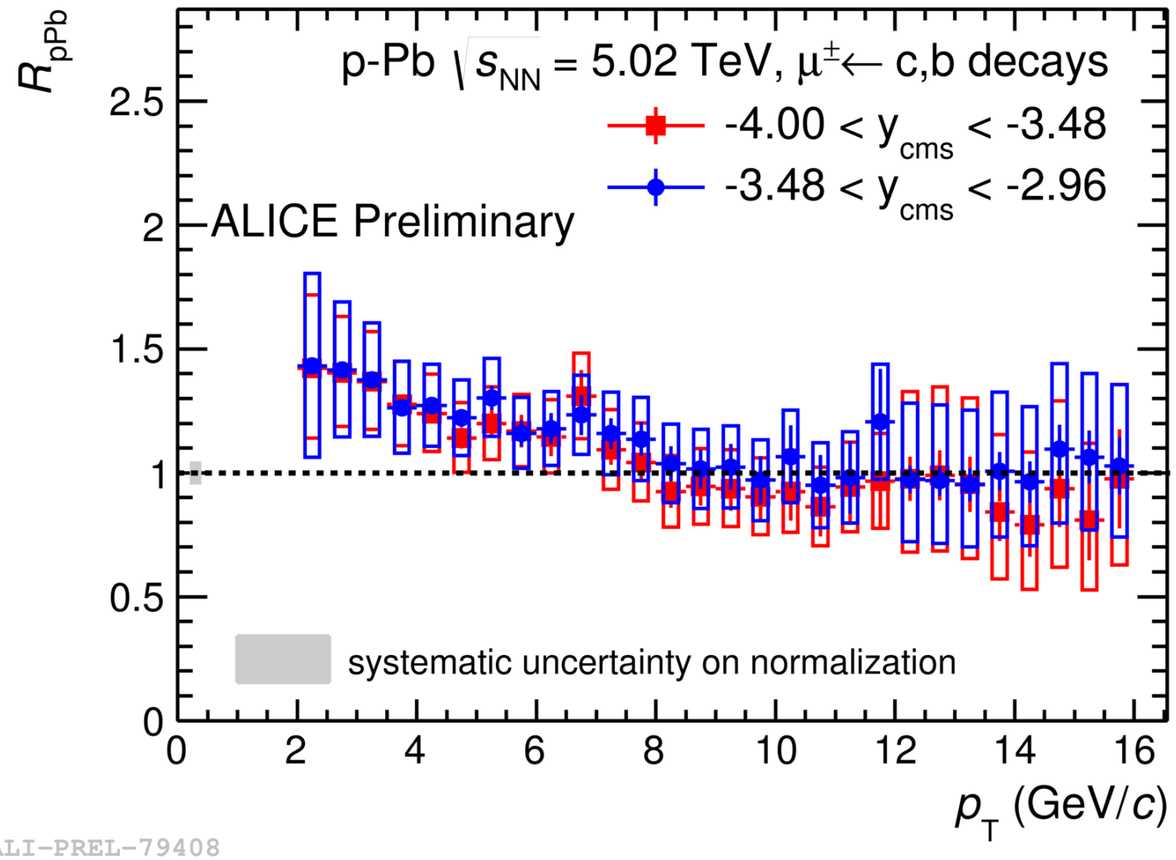
FONLL: JHEP 1210 (2012) 137

R_{pPb} within sub-rapidity bins







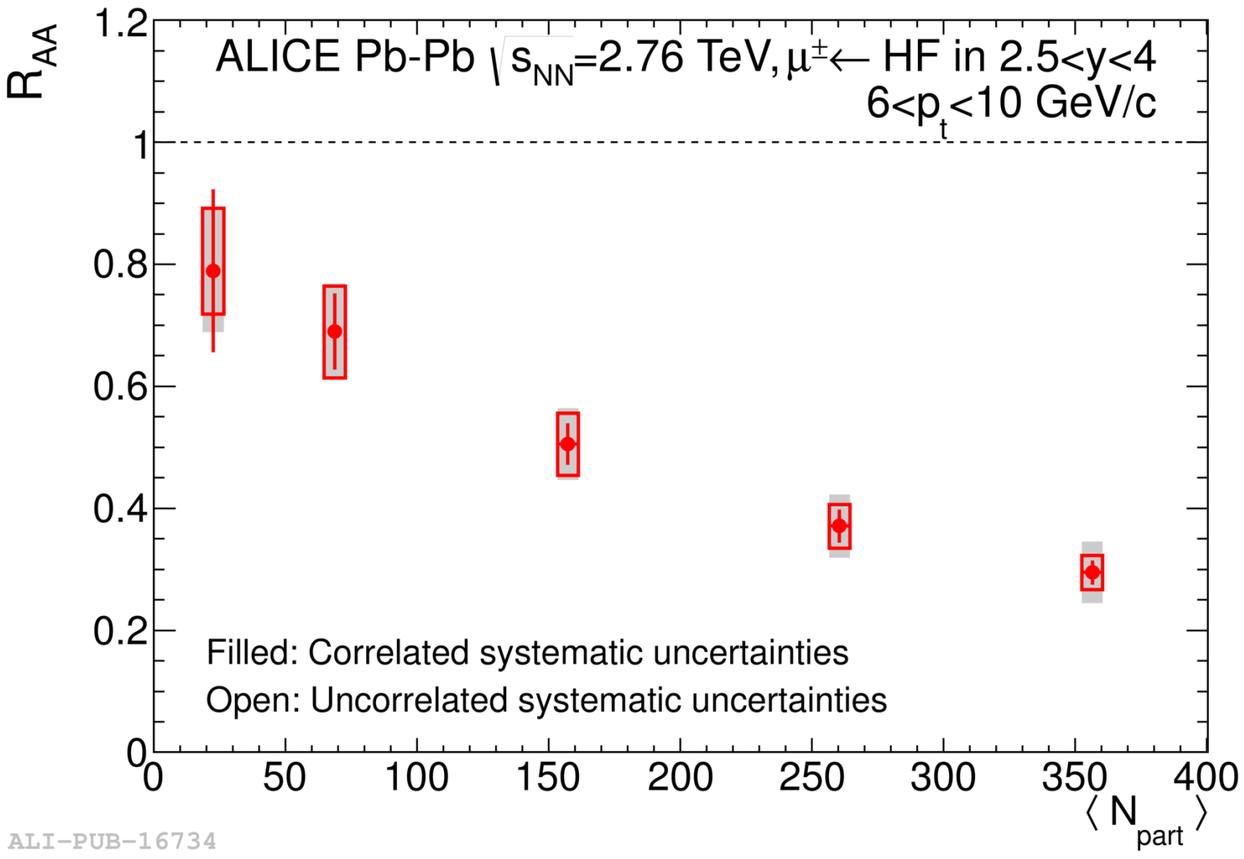


$2.50 < y_{CMS} < 3.02$
$3.02 < y_{CMS} < 3.54$

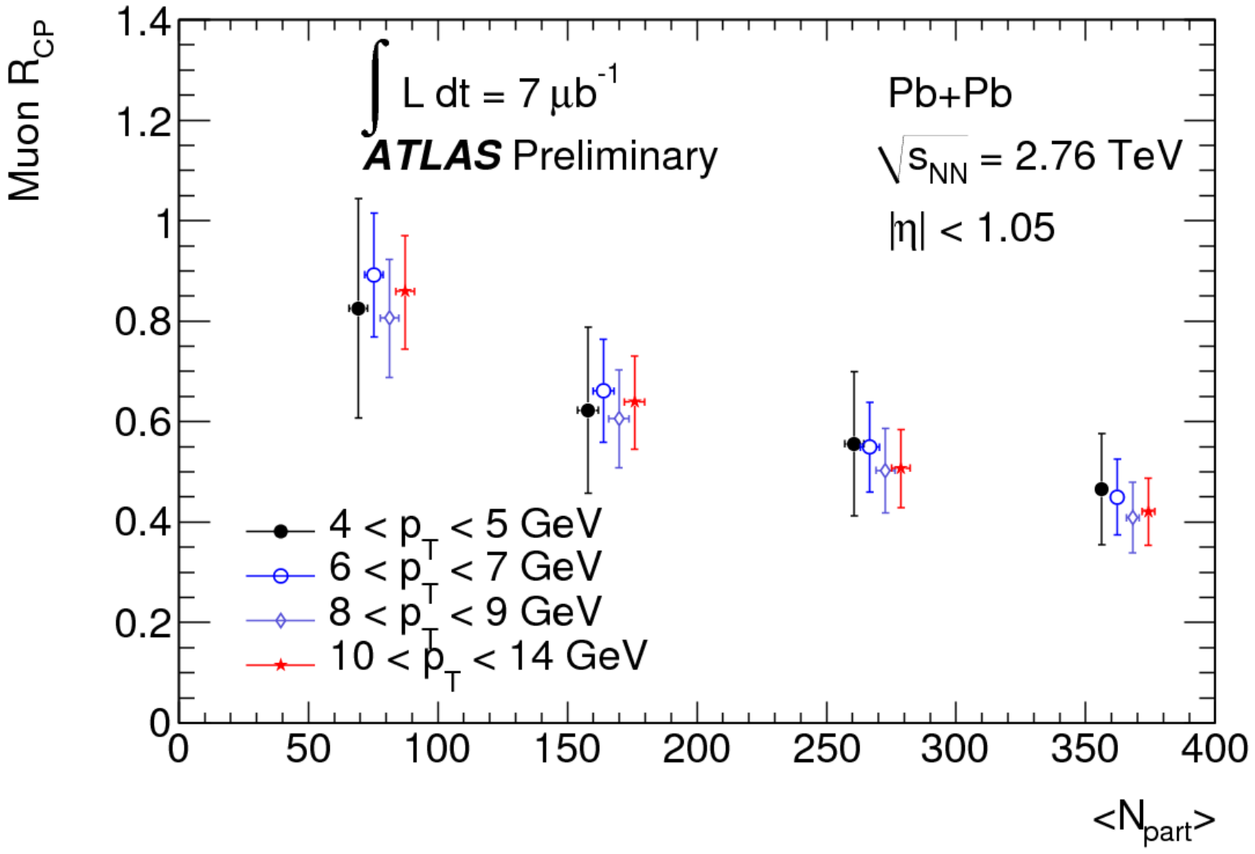
$-4.00 < y_{CMS} < -3.48$
$-3.48 < y_{CMS} < -2.96$

- Within uncertainties, similar results in sub-rapidity bins for R_{pA} at both forward and backward rapidity

Centrality dependence



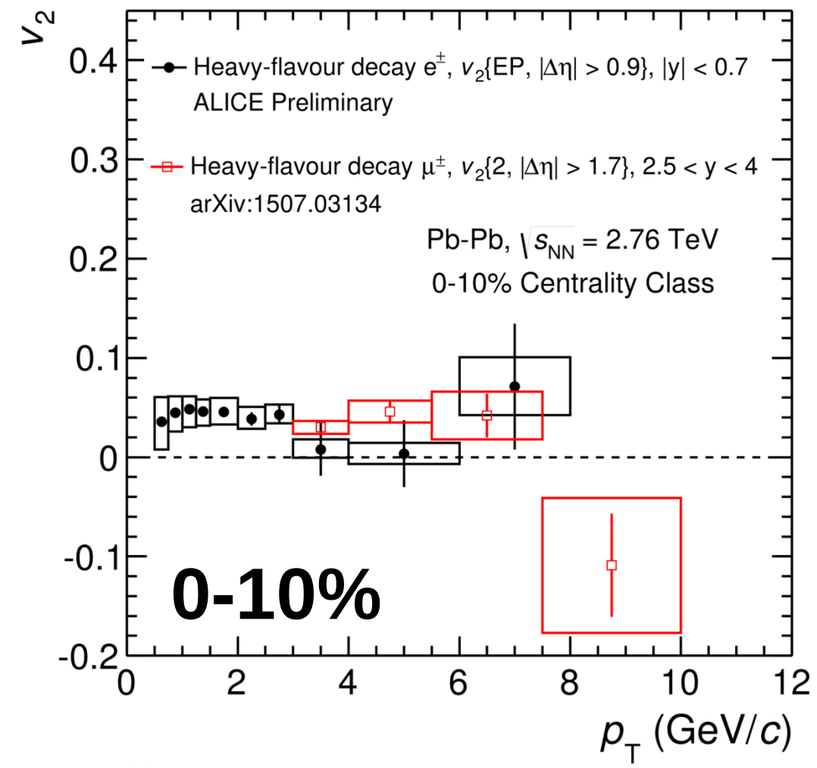
PRL 109 (2012) 112



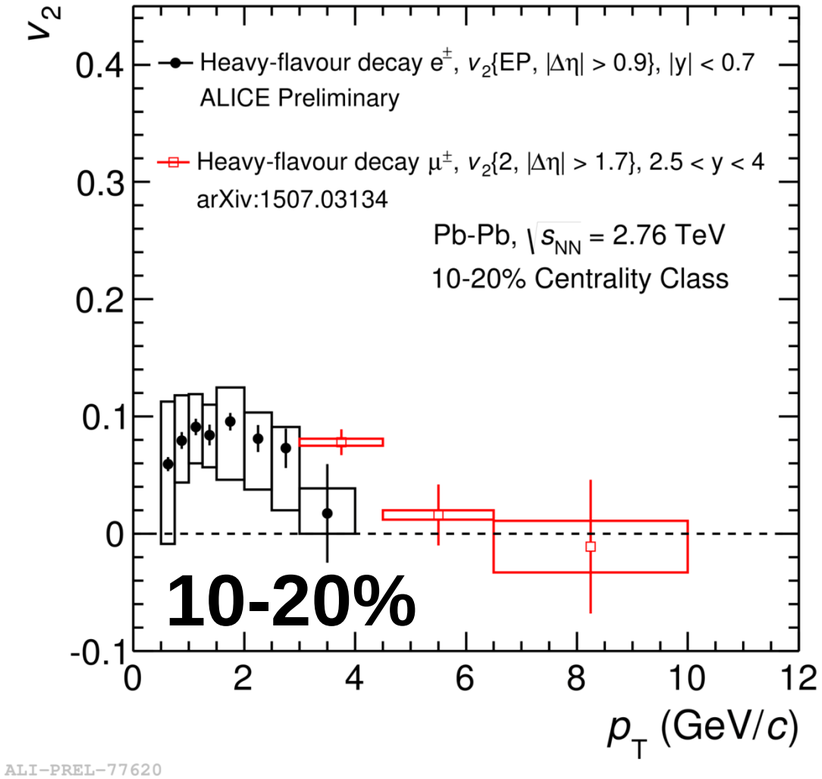
ATLAS-CONF-2012-050

v_2 vs p_T

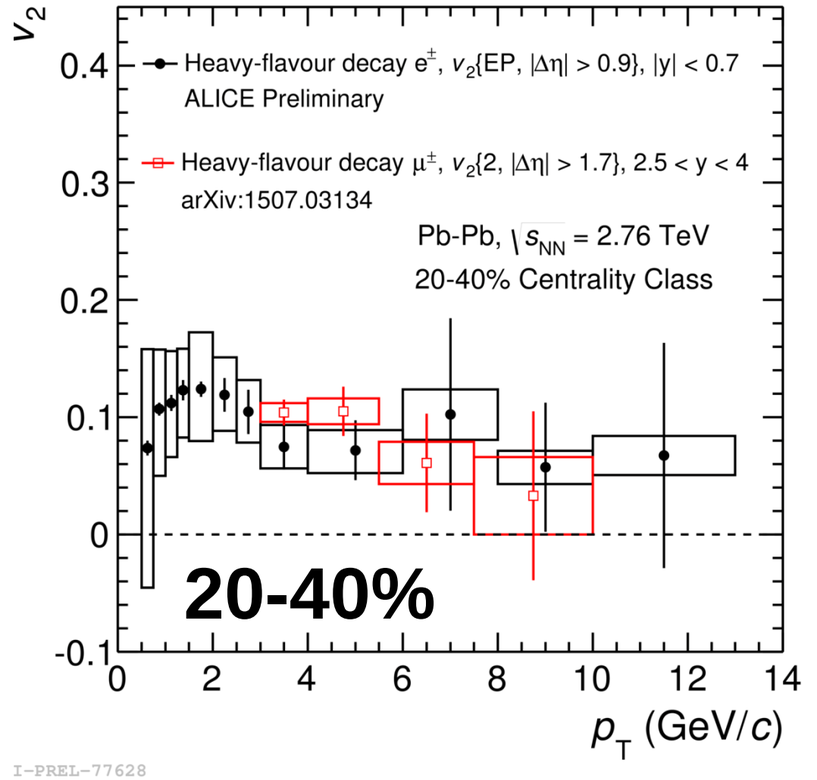
muons: 1507.03134



ALI-PREL-77612

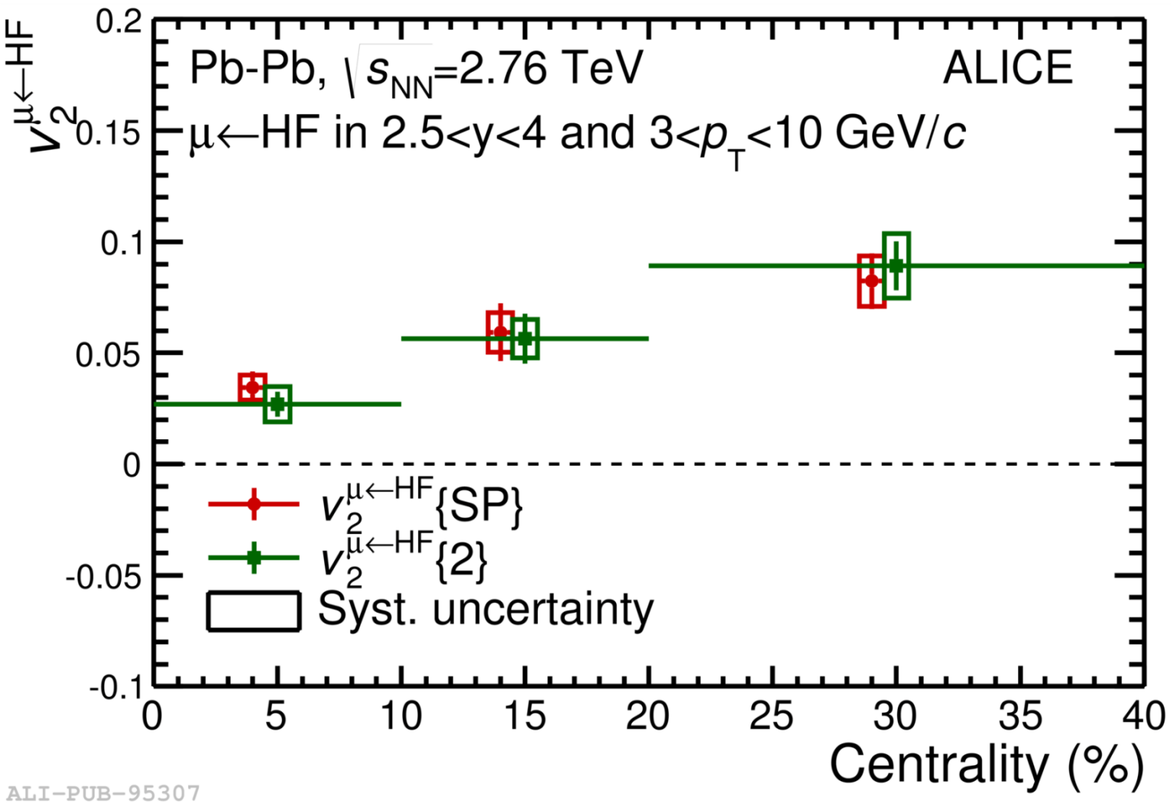


ALI-PREL-77620



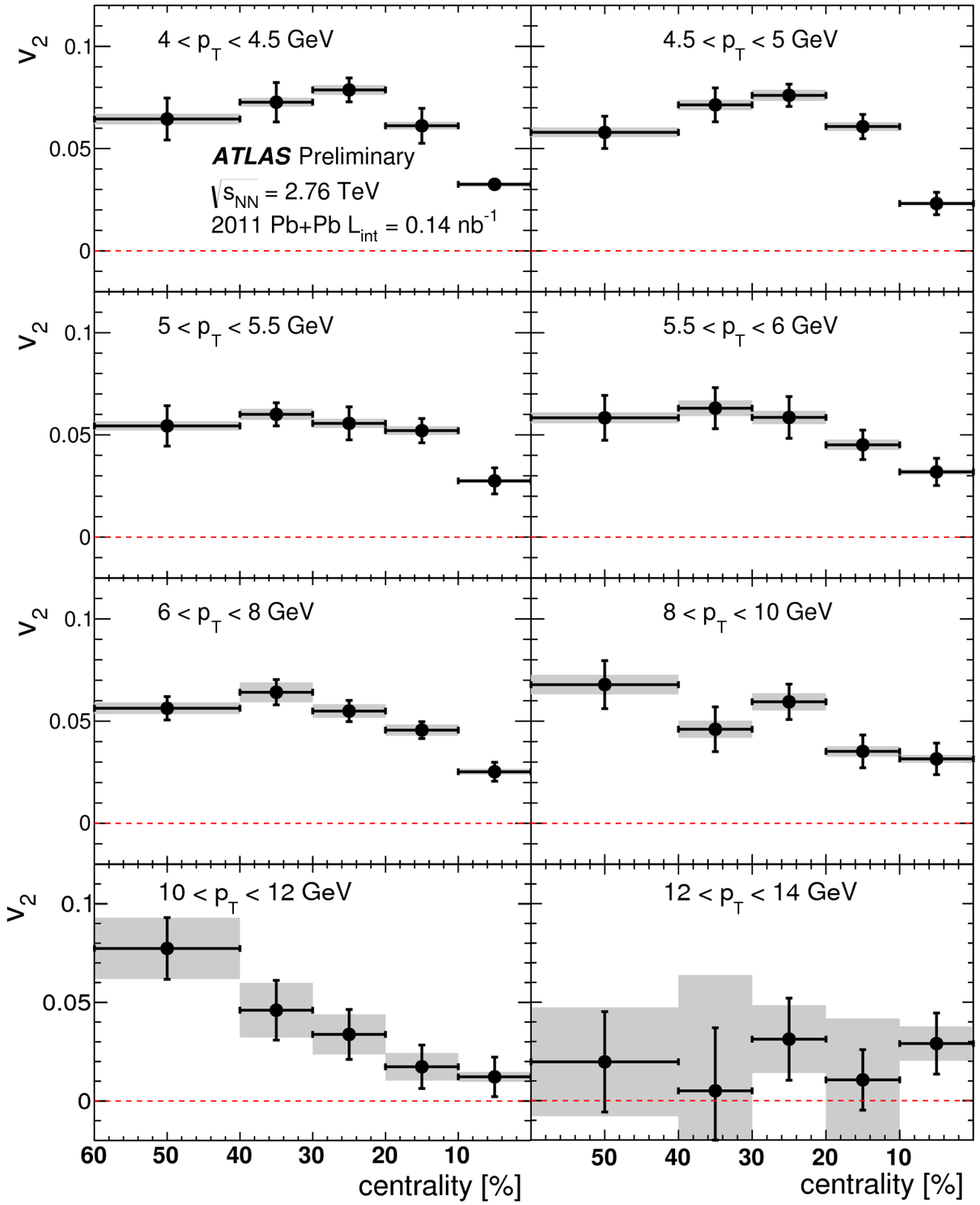
I-PREL-77628

Centrality dependence



ALI-PUB-95307

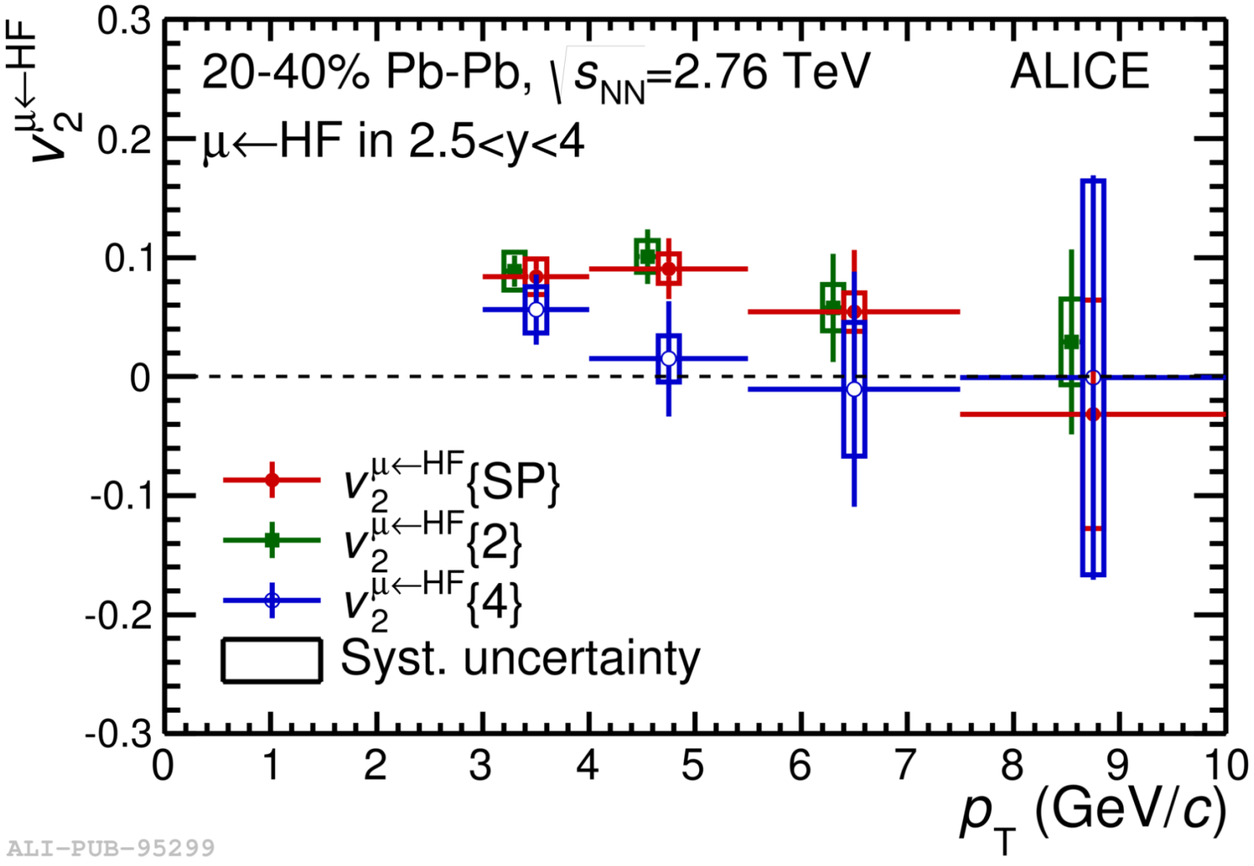
arXiv:1507.03134

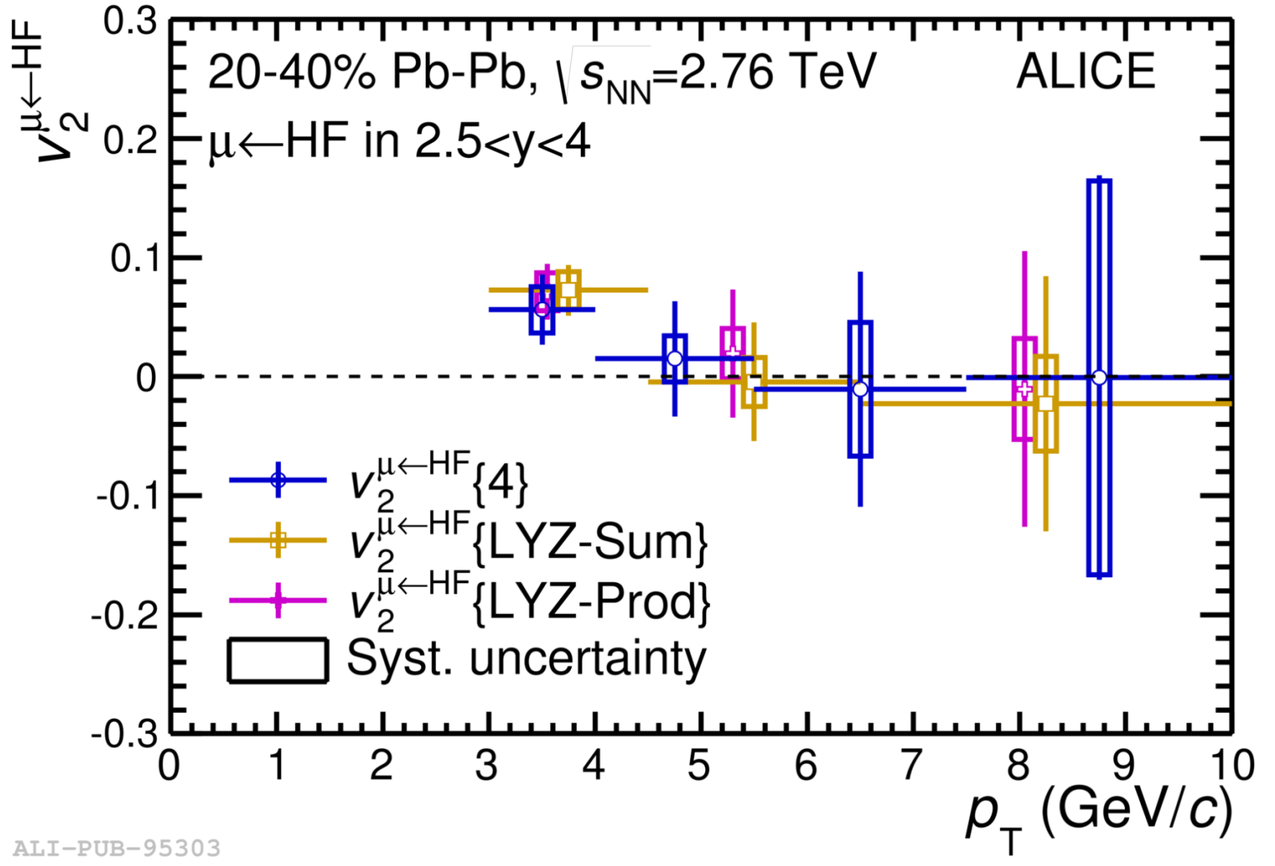


ATLAS-CONF-2015-053

v_2 vs p_T

arXiv:1507.03134





- Results from QC4 are systematically lower than those from SP and QC2

  → due to different contributions of non-flow correlations and flow fluctuations

- 4-particle Q-cumulants give same v_2 as Lee-Yang zeroes within uncertainties

  → indication that non-flow effects are suppressed with 4-particle Q-cumulants

- Smaller v_2 values with multi-particle flow methods than with two-particle methods

  → an indication of flow fluctuation effects