Azimuthal correlations of open heavy-flavour decay muons in large and small systems at the LHC

Xiaoming Zhang (Central China Normal University)

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Outline

- **Challenge for preparing this talk (main part)**
- **Results and discussions**

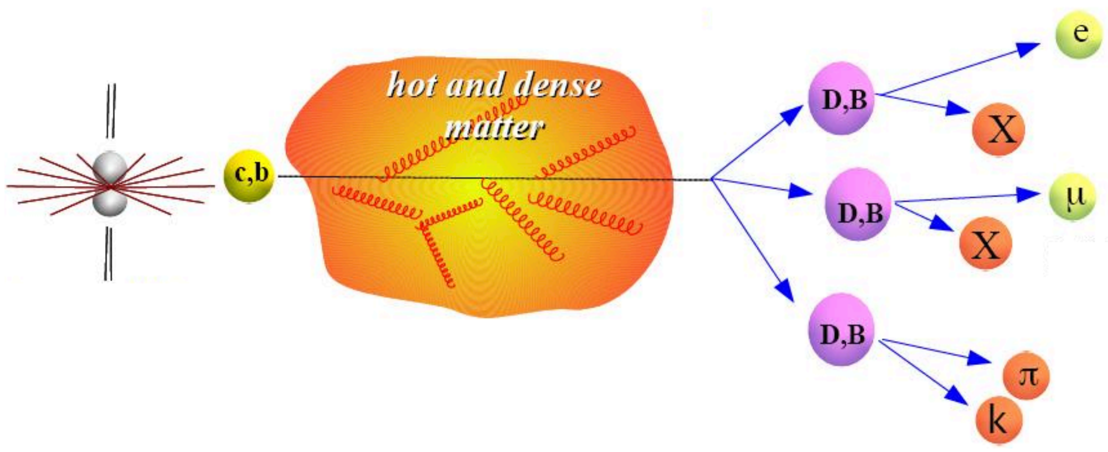
References

- **ATLAS Collaboration**, "Measurement of the suppression and azimuthal anisotropy of muons from heavy-flavor decays in Pb+Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the ATLAS detector", [arXiv:1805.05220]
- **ALICE Collaboration**, "Elliptic flow of muons from heavy-flavour hadron decays at forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", *Phys. Lett.* **B753** (2016) 41
- **ALICE Collaboration**, "Forward-central two-particle correlations in p–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV", *Phys. Lett.* **B753** (2016) 126

- Only three publications are found related to this topic in the entire LHC heavy-ion publications up to now
- All them are using the LHC RUN-I data (2009 – 2013)
- Two of them (for the ALICE Collaboration) are published in the same volume of same journal

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)



Total charm cross section in A–A collisions is expected to scale w. r. t. the number of binary collisions in pp-like collisions

Charm Hadron		Cross Section dσ/dy (μb)
Au+Au 200 GeV (10-40%)	D^0	41 ± 1 ± 5
	D^+	18 ± 1 ± 3
	D_s^+	15 ± 1 ± 5
	Λ_c^+	78 ± 13 ± 28*
	Total	**152 ± 13 ± 29**
p+p 200 GeV	**Total**	**130 ± 30 ± 26**

*** derived using Λ_c^+ / D^0 ratio in 10-80%** **STAR Preliminary**

- Produced in initial hard scatterings (high Q^2) at the early stage of heavy-ion collisions: $\tau_{c/b}$ ~0.01 — 0.1 fm/c < τ_{QGP} (~0.3 fm/c)
- Production cross section calculable with pQCD (m_c, $m_b \gg \Lambda_{QCD}$)
- Experience the entire evolution of the QCD medium — probe transport properties of the deconfined medium

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)

Nuclear modification factor (*R_{AA}*): heavy quark in-medium energy loss

- Elastic (radiative) vs. inelastic (collisional) processes
- Radiative energy loss: color charge (Casimir factor) and mass (dead cone effect) dependence

$$R_{\rm AA}(p_{\rm T}) = \frac{{\rm d}N_{\rm AA}/{\rm d}p_{\rm T}}{< T_{\rm AA} > {\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm T}}$$

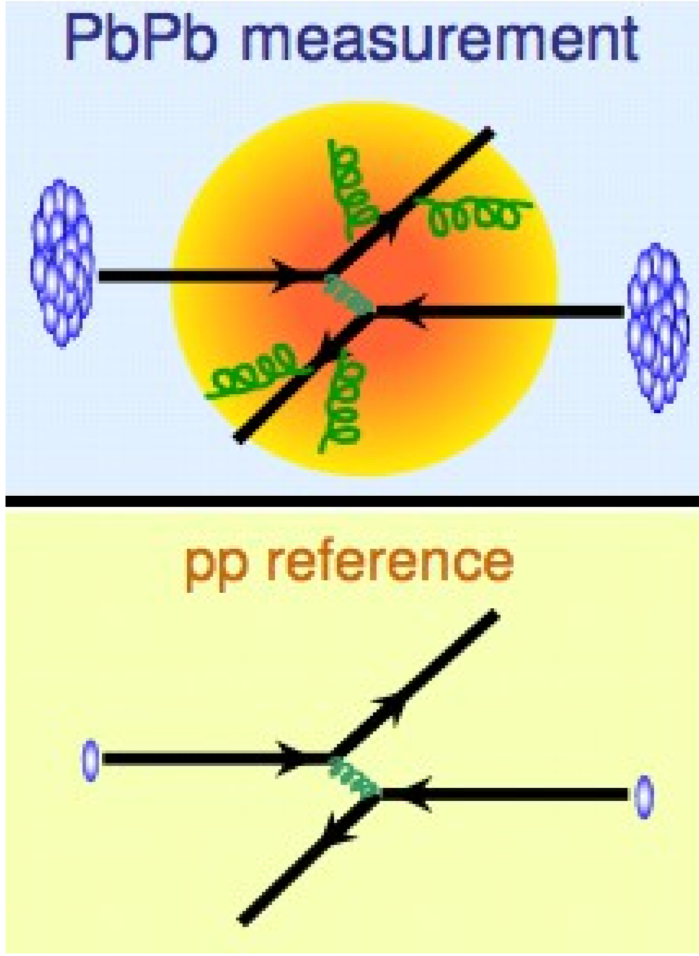
QCD medium

QCD vacuum

- R_{AA} = 1, if no medium modification

$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$

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



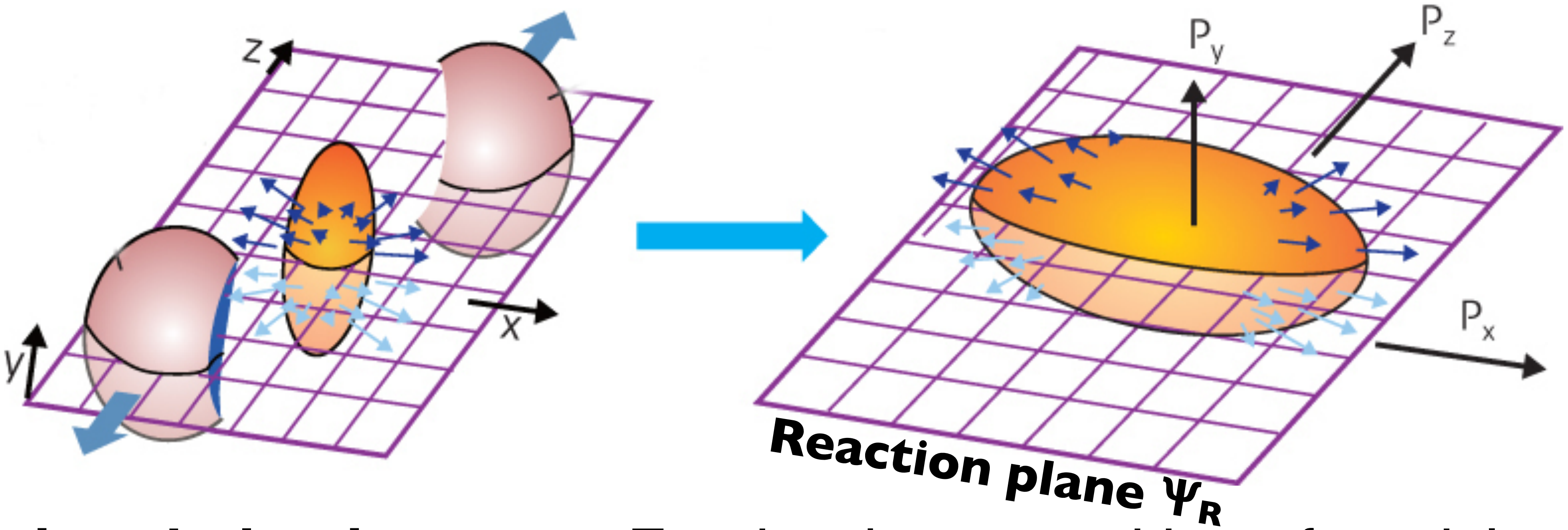
Medium modification of heavy-flavour hadron formation

- Hadronization via quark coalescence which may modify the D_s^+ /non-strange D ratio

Introduction

Heavy quarks (charm and beauty): powerful probes of the Quark-Gluon Plasma (QGP)

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



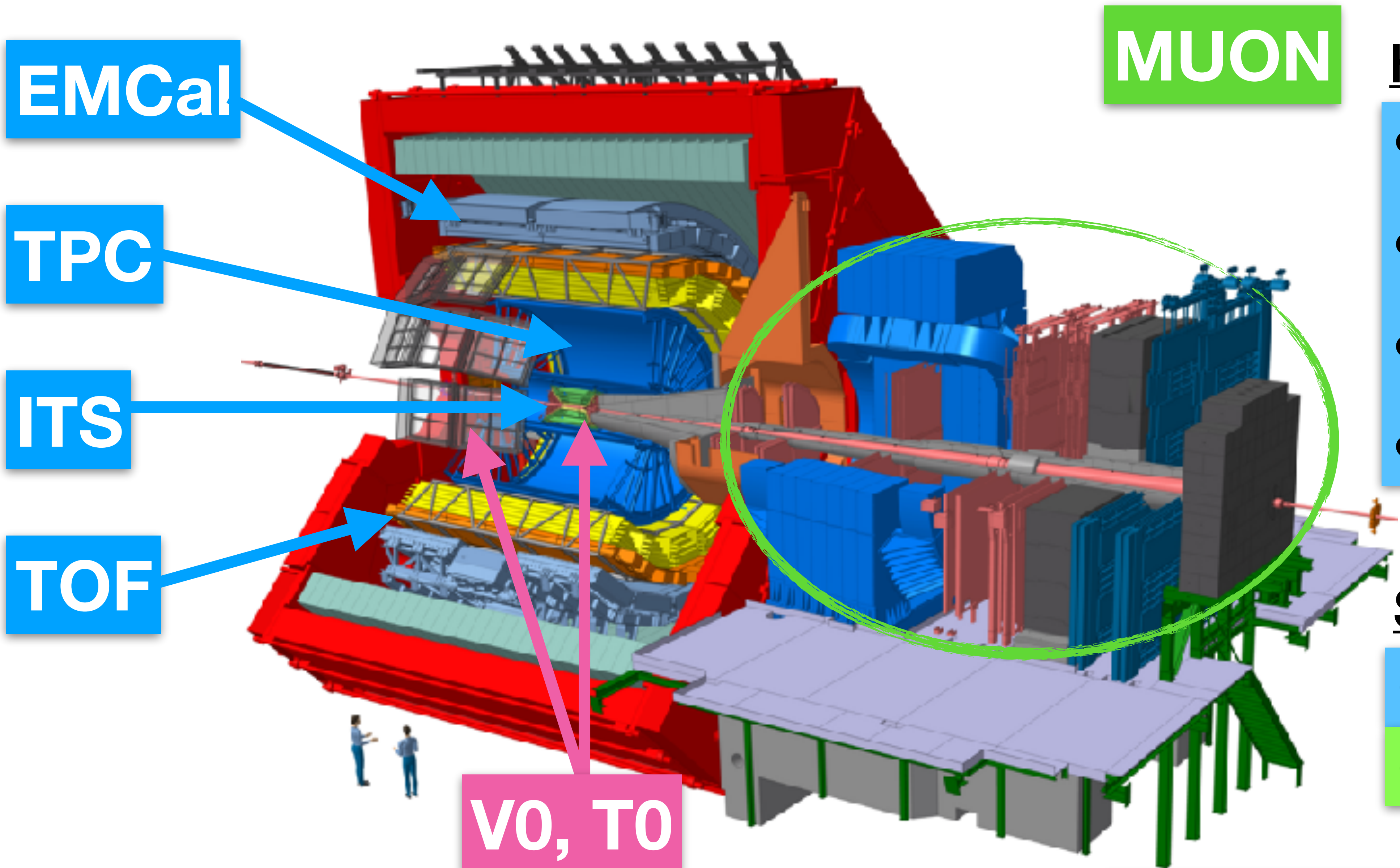
Azimuthal anisotropy: Fourier decomposition of particle azimuthal distribution relative to the reaction plane (Ψ_{RP})

- Elliptic flow (v_2): coefficient of second order harmonic

➡ Low and intermediate p_T: collective motion and possible heavy-quark thermalization in the QCD medium

➡ High p_T: path-length dependence of heavy-quark in-medium energy loss

ALICE open heavy flavour program



Hadronic decays:

- $D^0 \rightarrow K^- \pi^+$
- $D^+ \rightarrow K^- \pi^+ \pi^+$
- $D^{*+} \rightarrow D^0 \pi^+$
- $D^+_s \rightarrow \phi \pi^+ \rightarrow K^- K^+ \pi^+$

Semi-leptonic decays:

- D, B→e+X
- D, B→μ+X

Mid-rapidity ($|\eta|<0.9$)

- ITS, TPC, TOF: vertexing, tracking, PID
- EMCal: high-p_T electron trigger, PID

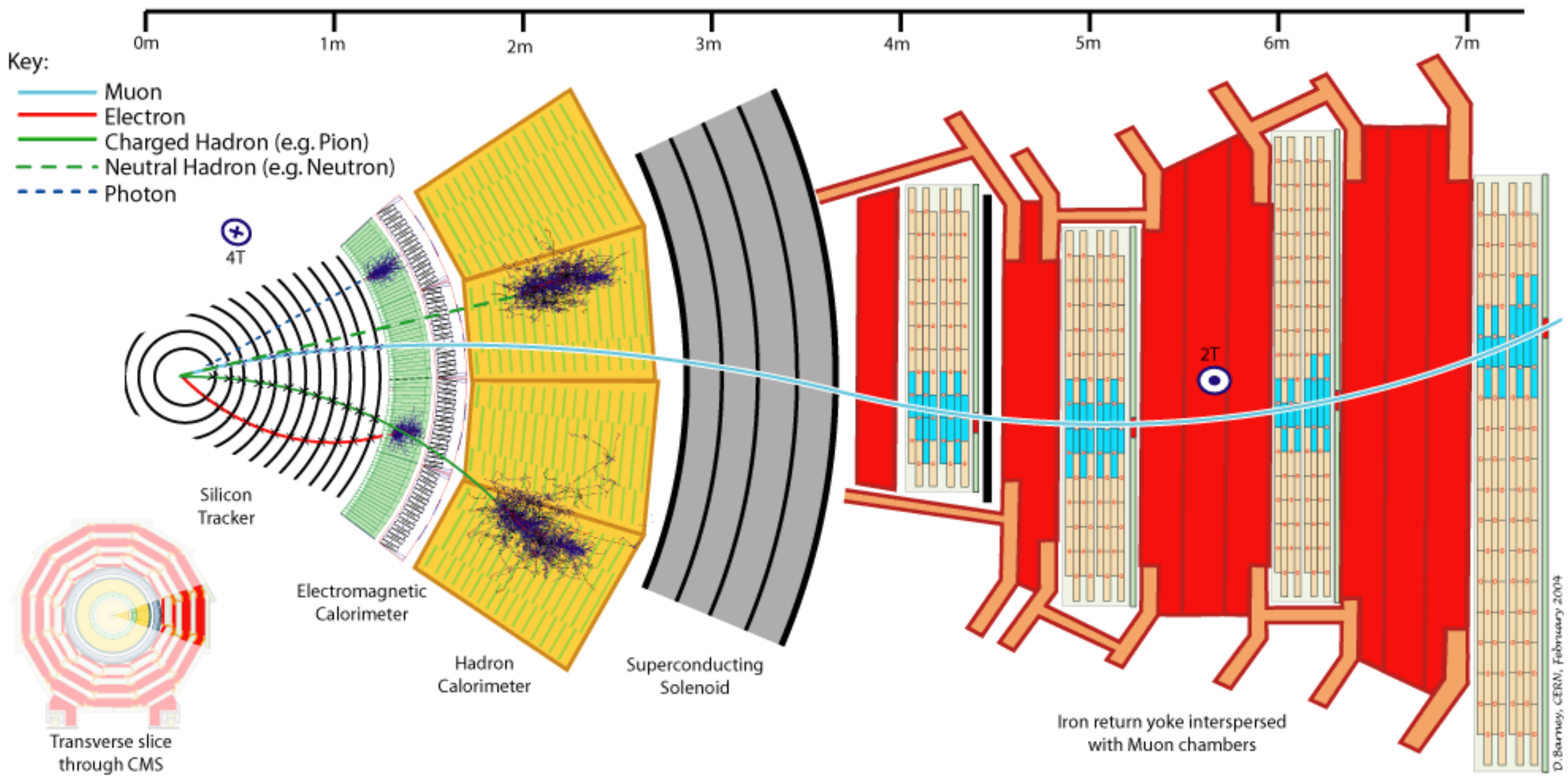
Forward MUON ($-4<\eta<-2.5$)

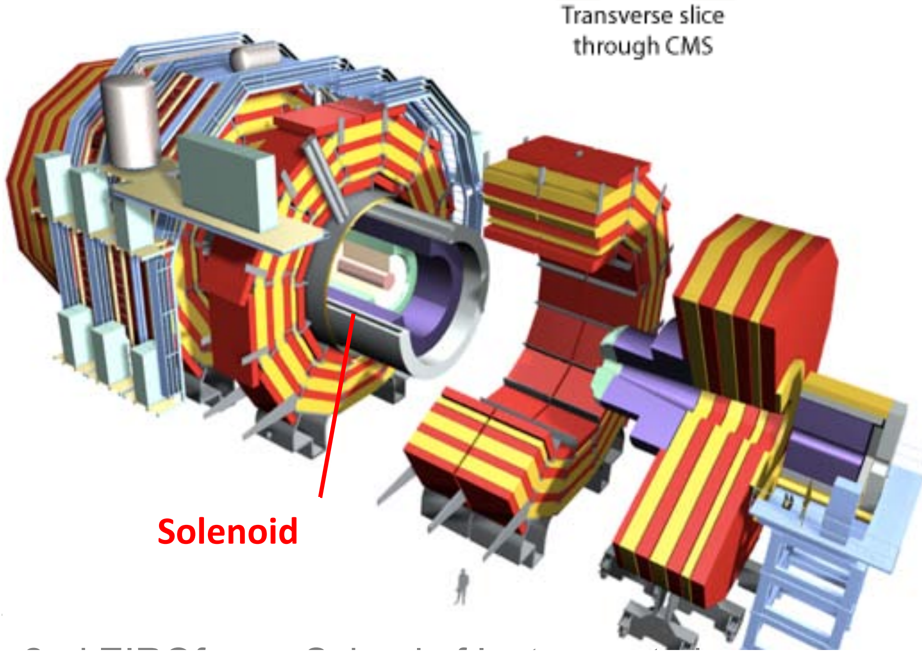
- Muon trigger, tracking, PID

Smaller detectors: V0, T0, ZDC

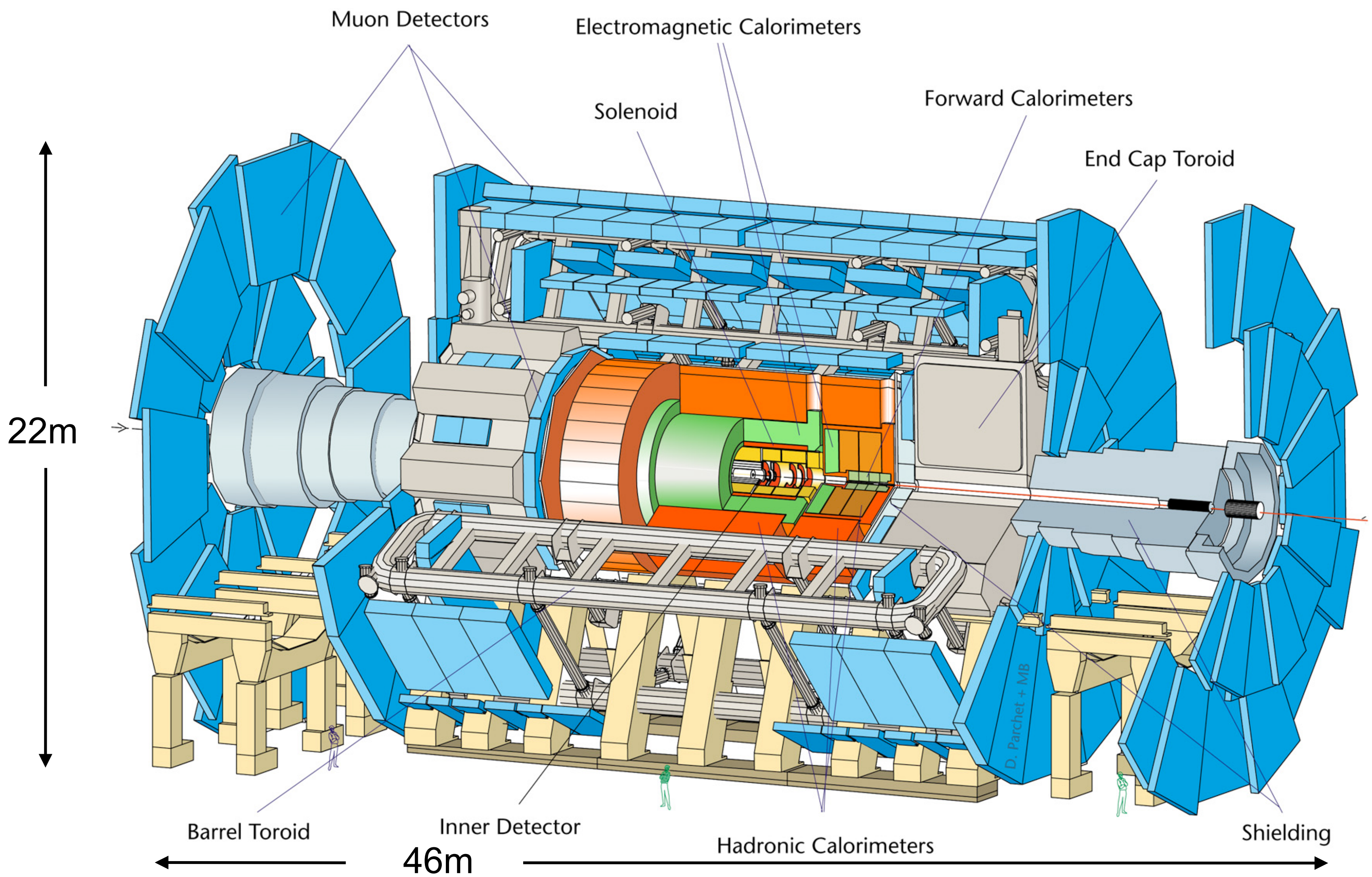
- Event trigger, characterization

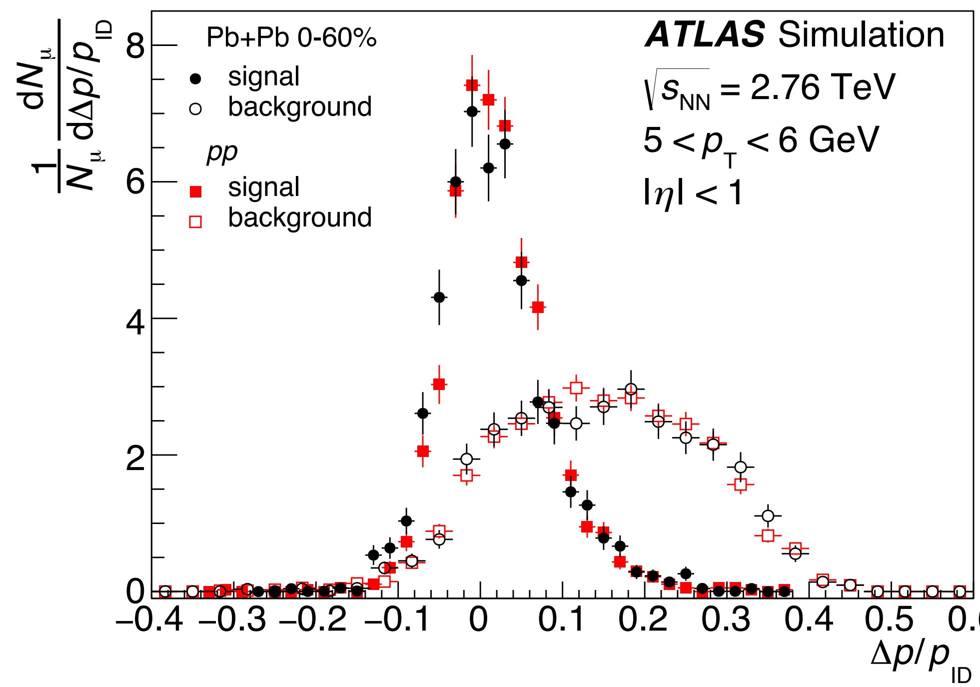
Muon measurement with CMS





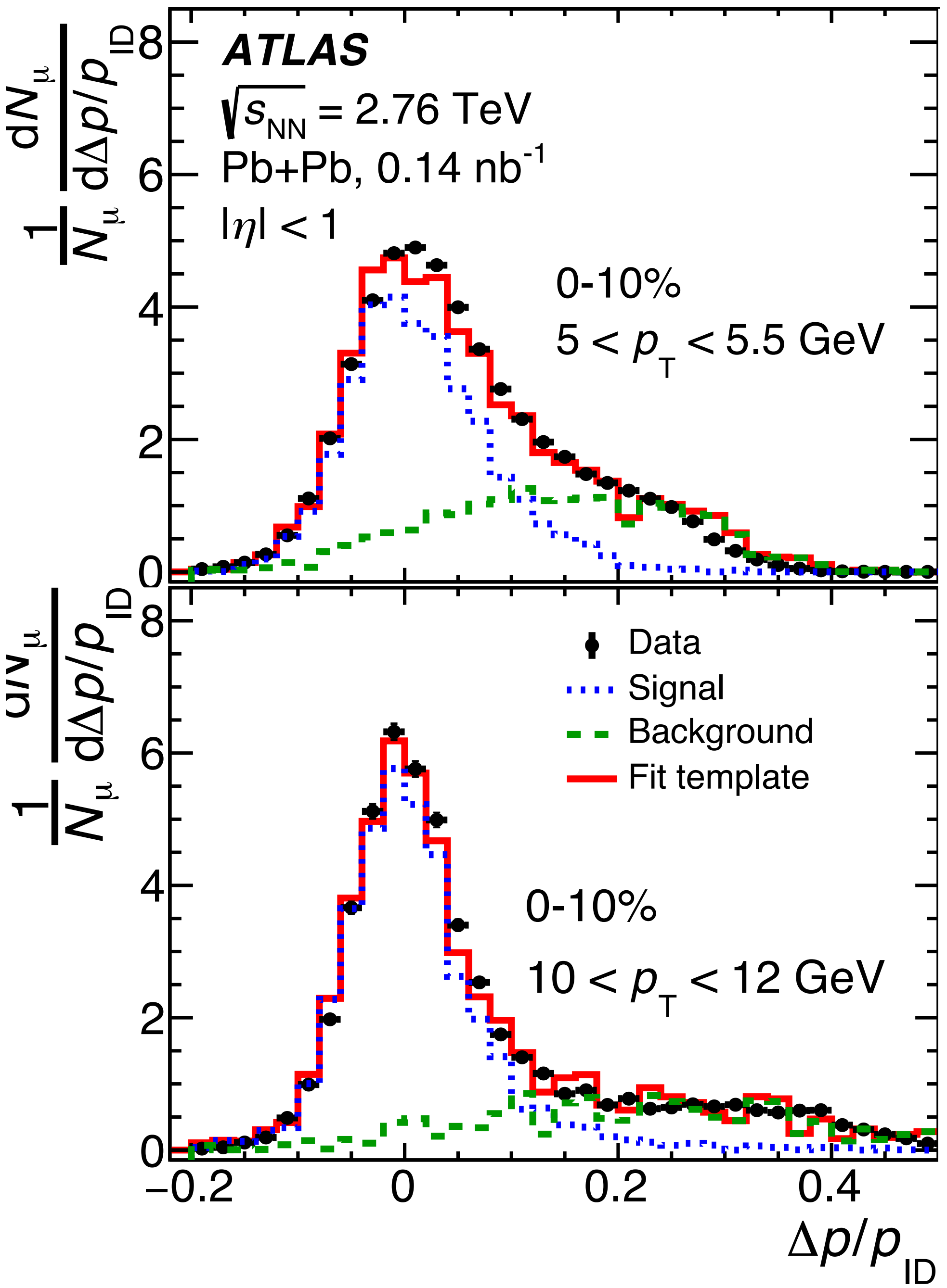
Muon measurement with ATLAS

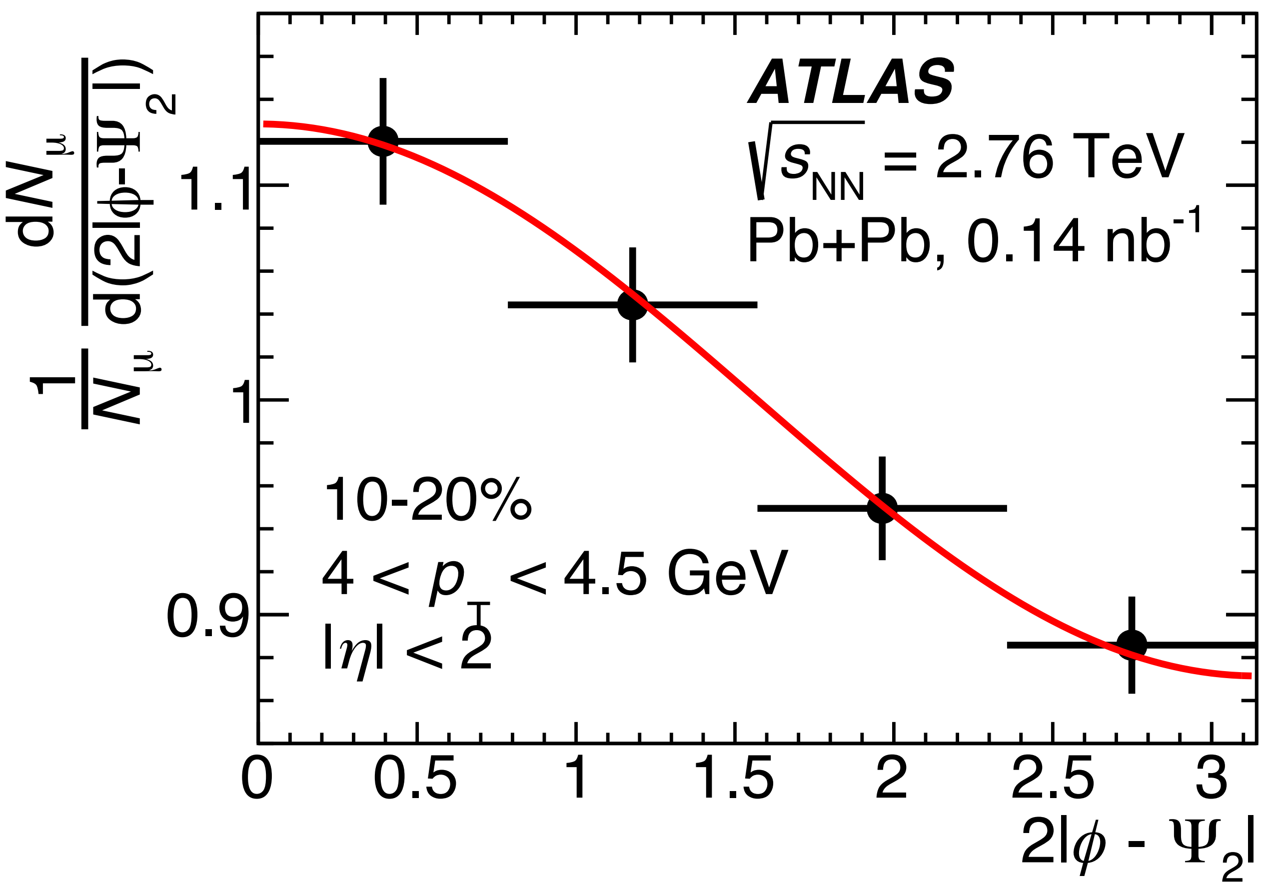




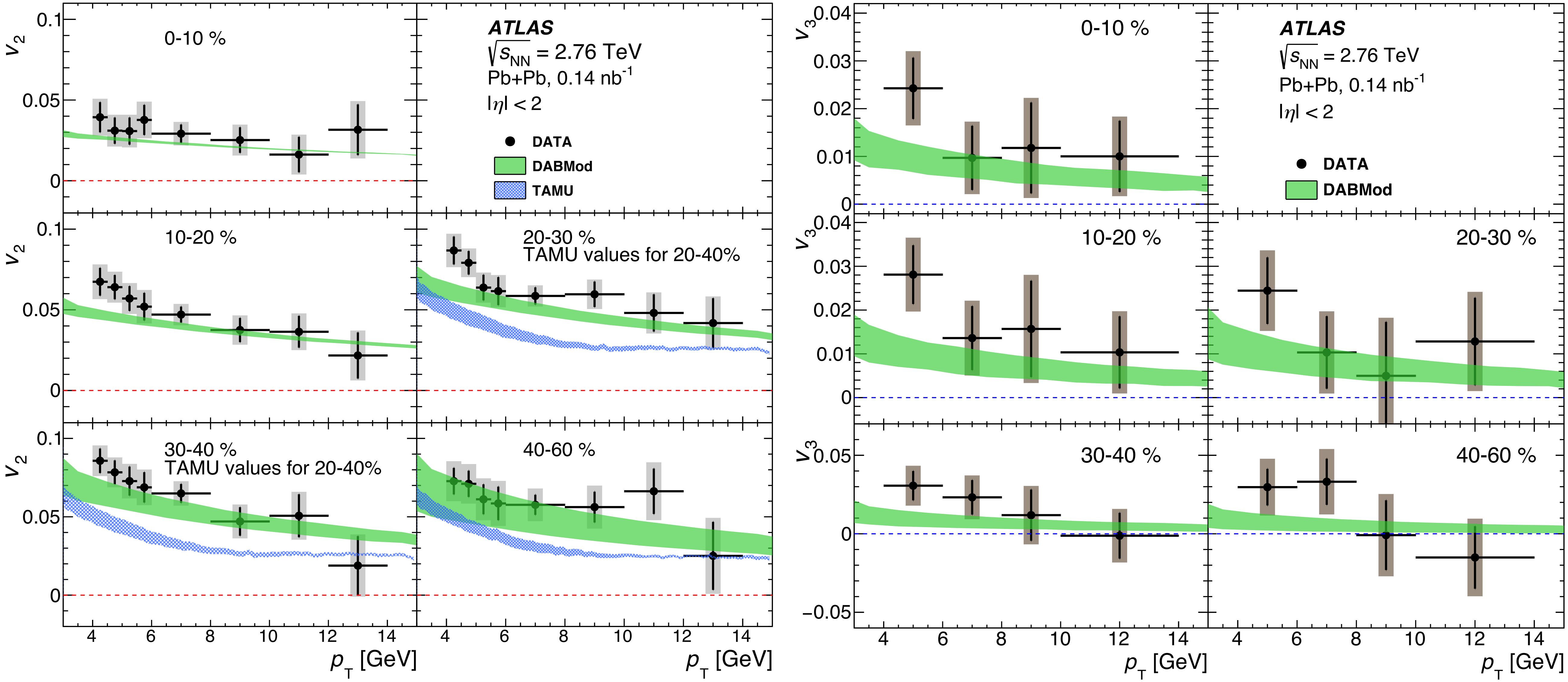
$$\frac{\Delta p}{p_{\mathrm{ID}}} = \frac{p_{\mathrm{ID}} - p_{\mathrm{MS}} - \Delta p_{\mathrm{calo}}(p, \eta, \phi)}{p_{\mathrm{ID}}}$$

Muon measurement with ATLAS



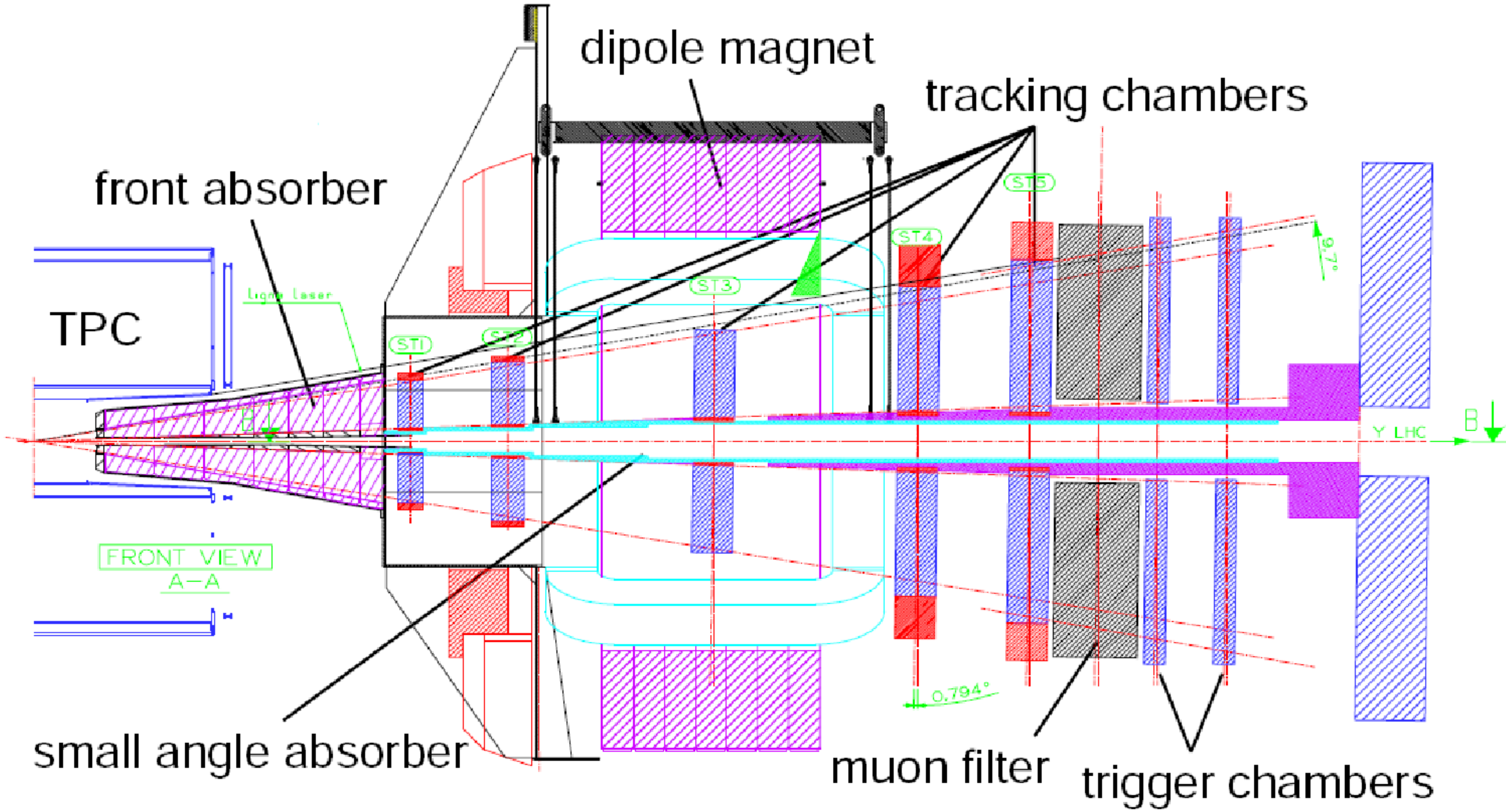


v_2 and v_3 of HF decay muons (ATLAS)



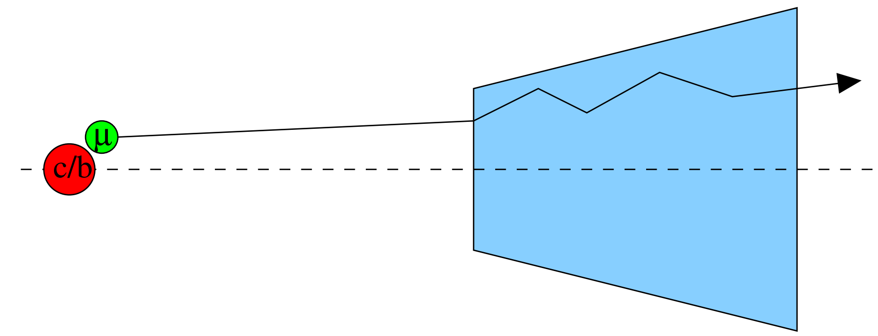
DABMod: with initial state fluctuations, better reproduces the data

ALICE muon spectrometer



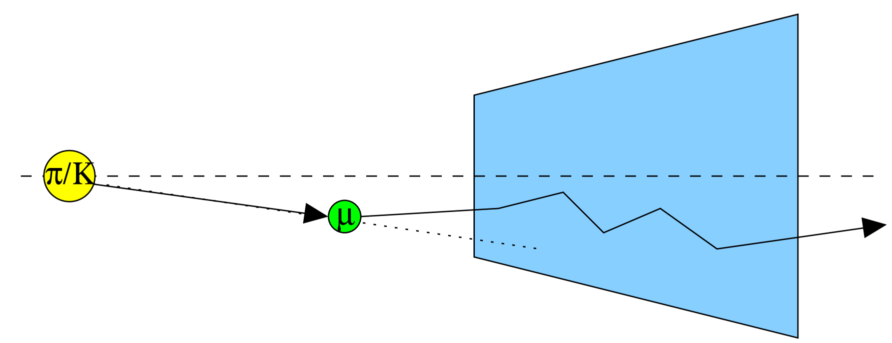
Muon measurement with ALICE

$$\frac{\mathrm{d}^2 N_\mu^{c/b}}{\mathrm{d}p_\mathrm{t}\mathrm{d}z_\mathrm{v}} \simeq \rho(z_\mathrm{v}) \int \mathrm{d}p'_\mathrm{t}\; P_{c/b}(p_\mathrm{t}, p'_\mathrm{t})\, \frac{\mathrm{d}N_{c/b}}{\mathrm{d}p'_\mathrm{t}} = \rho(z_\mathrm{v})\; B_{c/b}(p_\mathrm{t})$$



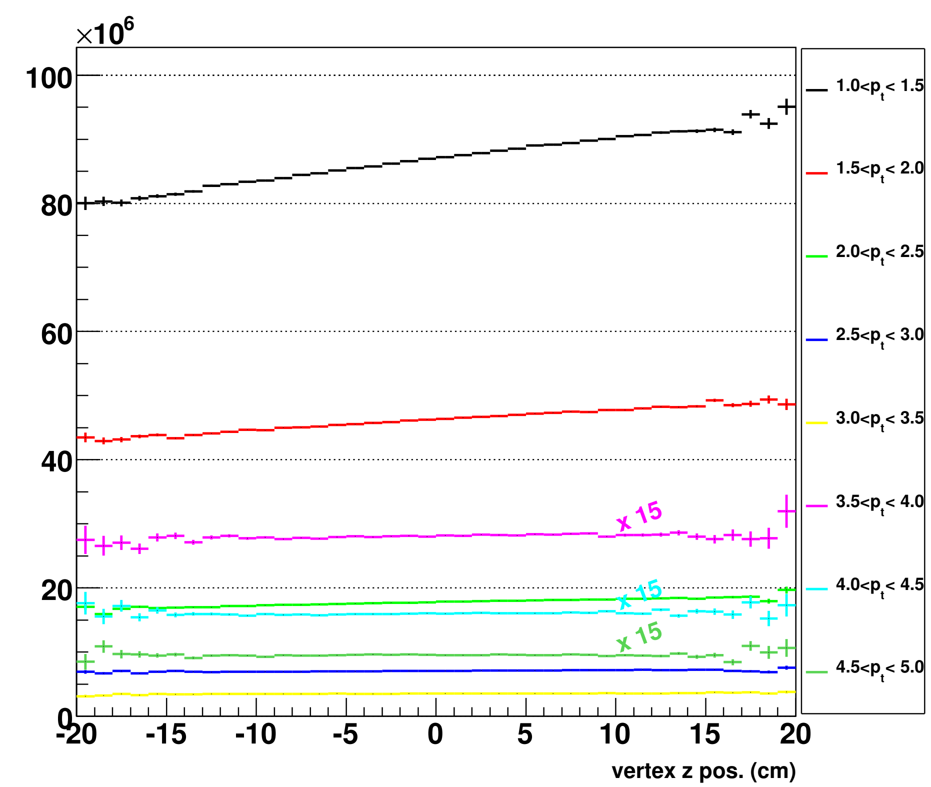
(a) Heavy flavor muons

$$\frac{\mathrm{d}^2 N_\mu^{\pi/\mathrm{K}}}{\mathrm{d}p_\mathrm{t}\mathrm{d}z_\mathrm{v}} = \rho(z_\mathrm{v}) \int \mathrm{d}\theta \int \mathrm{d}p'_\mathrm{t}\; P_{\pi/\mathrm{K}}(p_\mathrm{t}, p'_\mathrm{t})\, \frac{\mathrm{d}^2 N_{\pi/\mathrm{K}}}{\mathrm{d}p'_\mathrm{t}\mathrm{d}\theta} \times \left[1 - \exp\left(-\frac{d\, m_{\pi/\mathrm{K}} \tan\theta}{c\tau\, p'_\mathrm{t}}\right)\right]$$



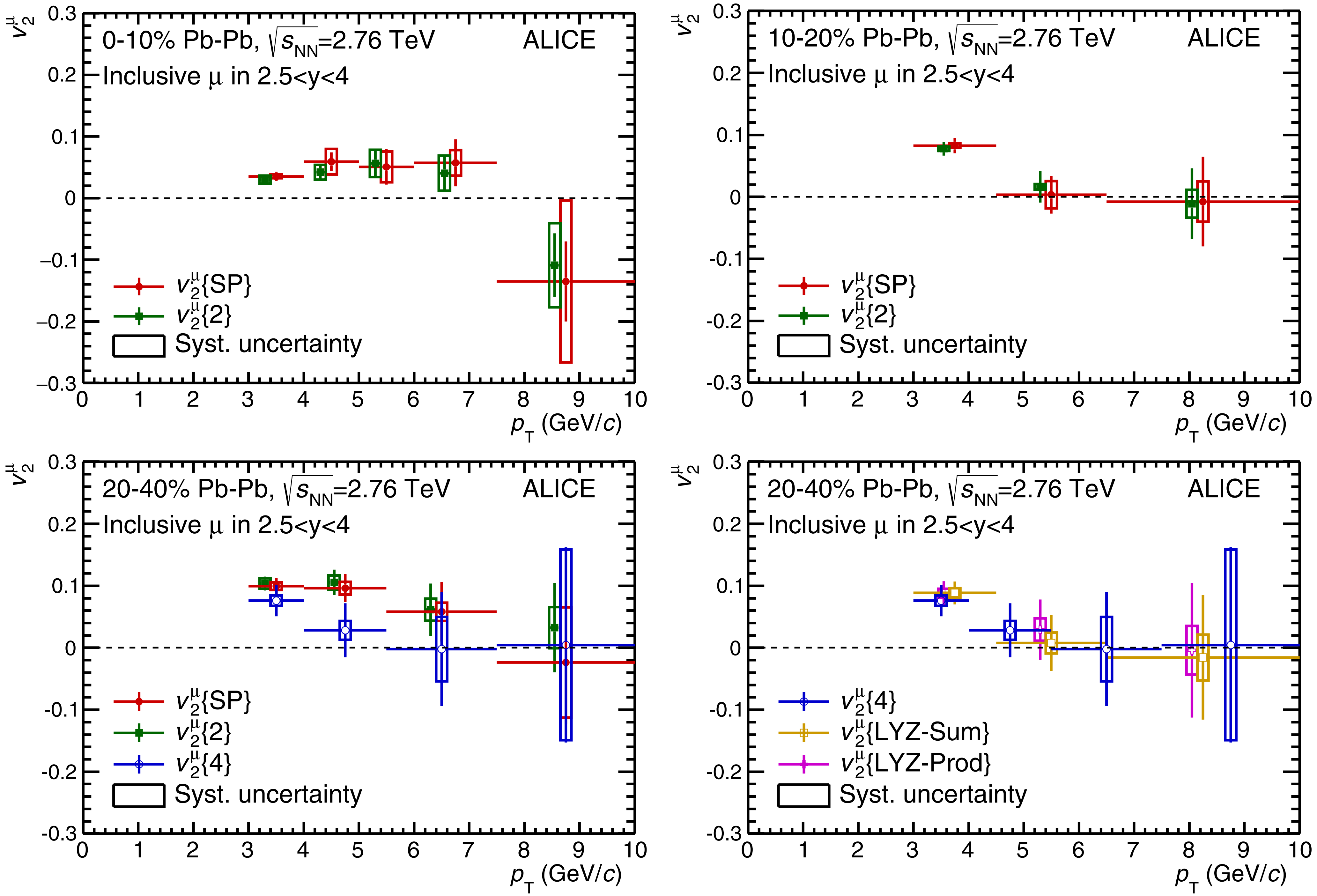
(b) Decay muons

$$\frac{\mathrm{d}^2 N_\mu^{\pi/\mathrm{K}}}{\mathrm{d}p_\mathrm{t}\mathrm{d}z_\mathrm{v}} \simeq d\,\rho(z_\mathrm{v}) \int \mathrm{d}\theta \int \mathrm{d}p'_\mathrm{t}\; P_{\pi/\mathrm{K}}(p_\mathrm{t}, p'_\mathrm{t})\, \frac{\mathrm{d}^2 N_{\pi/\mathrm{K}}}{\mathrm{d}p'_\mathrm{t}\mathrm{d}\theta}\, \frac{m_{\pi/\mathrm{K}} \tan\theta}{c\tau\, p'_\mathrm{t}} = \rho(z_\mathrm{v})\; A_{\pi/\mathrm{K}}(p_\mathrm{t})\; d$$



- But still have challenge to implement in data

Inclusive muon elliptic flow (ALICE)



Background subtraction (ALICE)

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

- 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)
- 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

Background subtraction (ALICE)

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

Decay muon v_2 estimation:

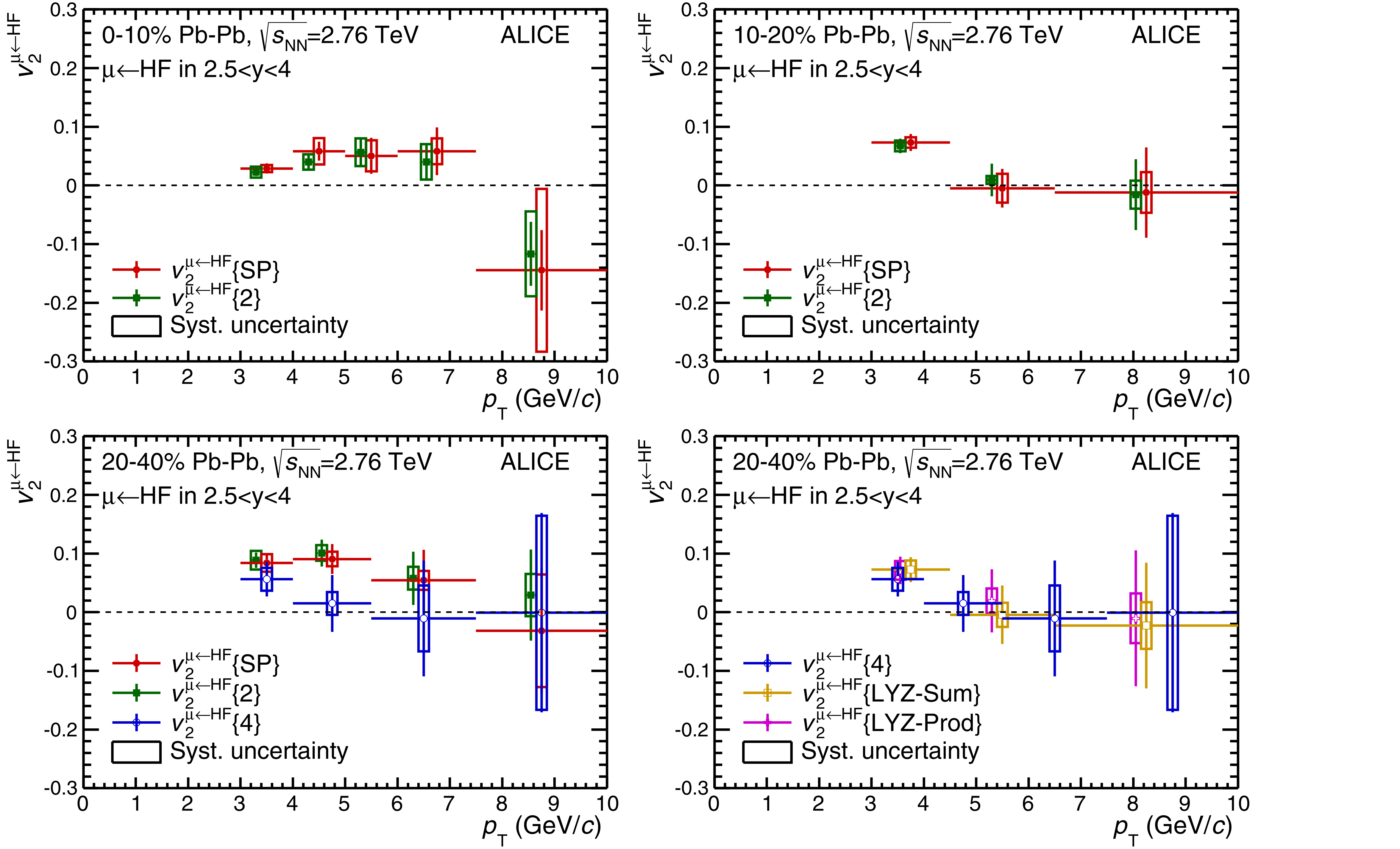
- parameterize the p_T and η dependence of charged hadrons v_2 measured by ATLAS and extrapolate to forward rapidity [ATLAS: Phys. Lett. B707 (2012) 330];
- treat all the charged hadrons as pions and Kaons, separately and produce the v_2 of decay muon in the acceptance of ALICE muon spectrometer via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

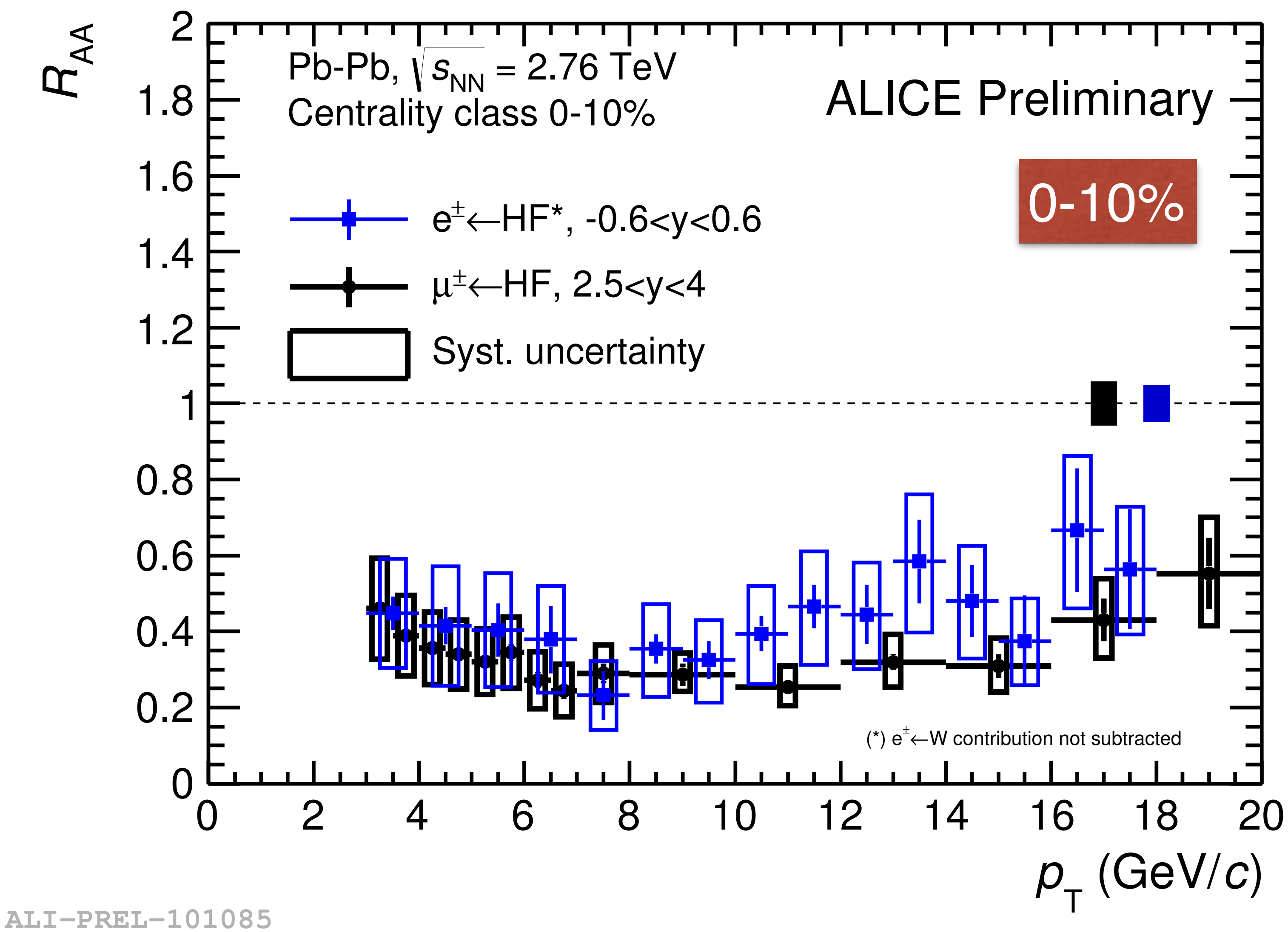
Decay muon fraction with the same method used for R_{AA} analysis:

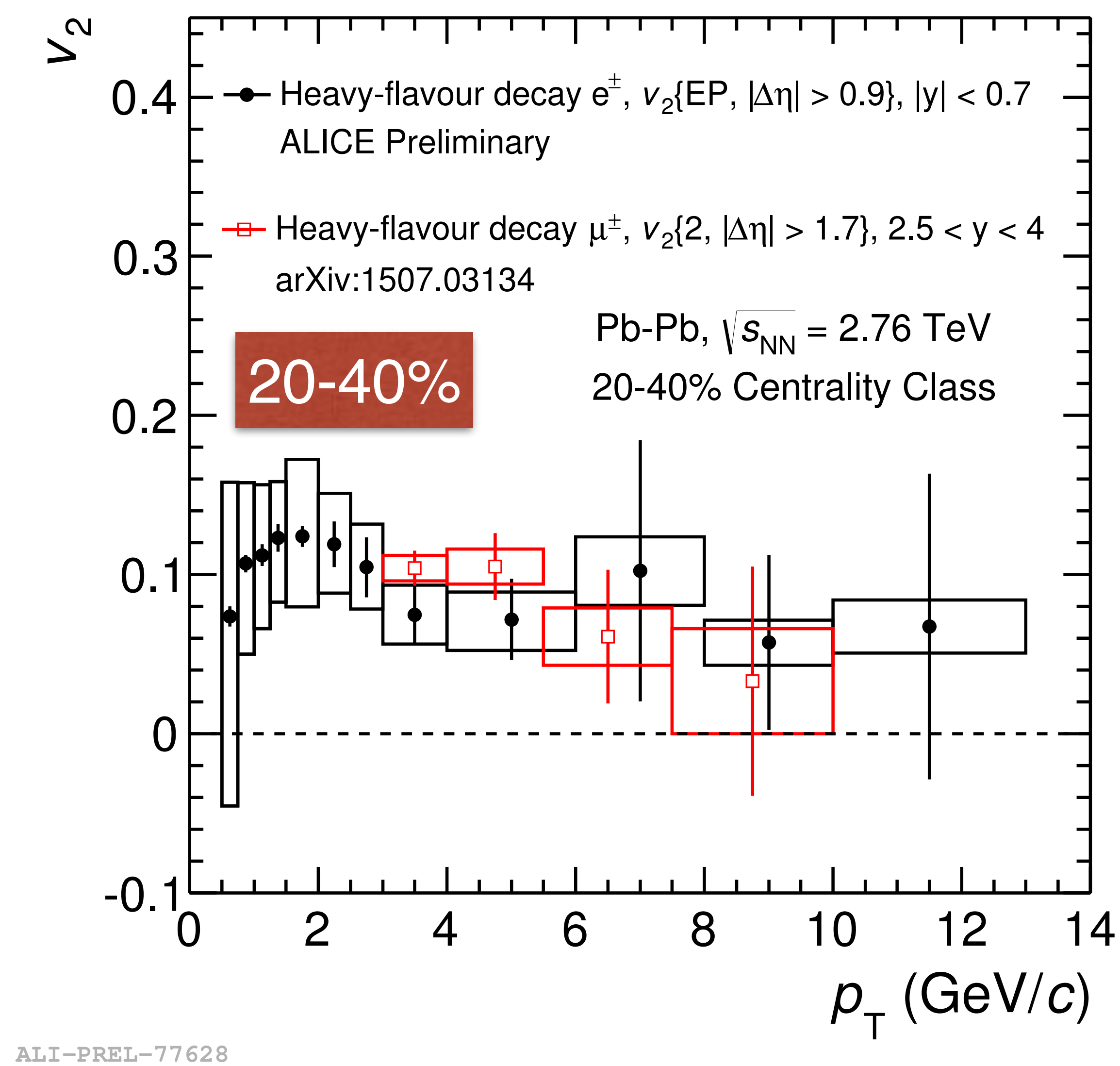
➡ 15% at low p_T, 5% at high p_T.

Elliptic flow of HF decay muons (ALICE)



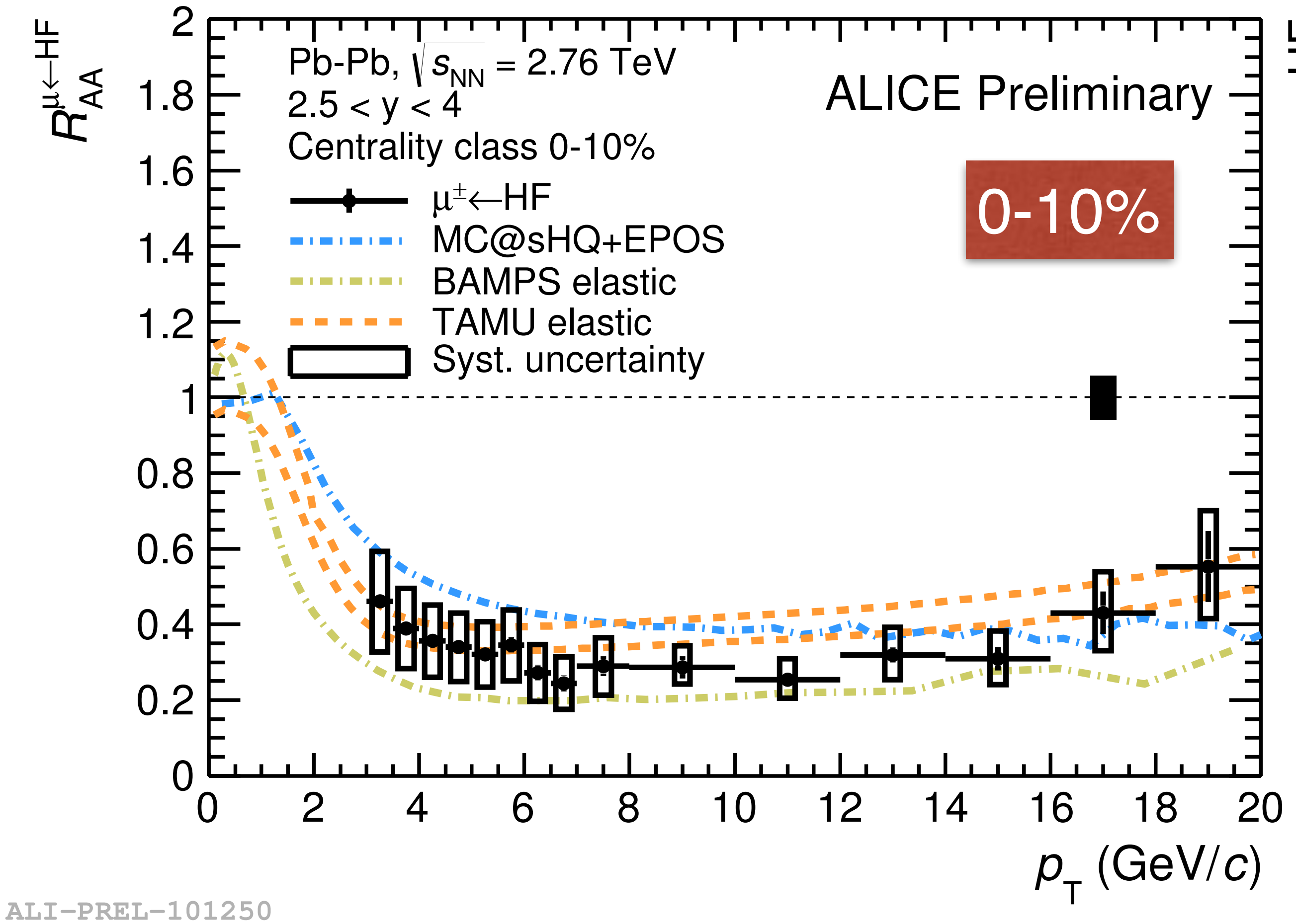
Elliptic flow of HF decay muons (ALICE)

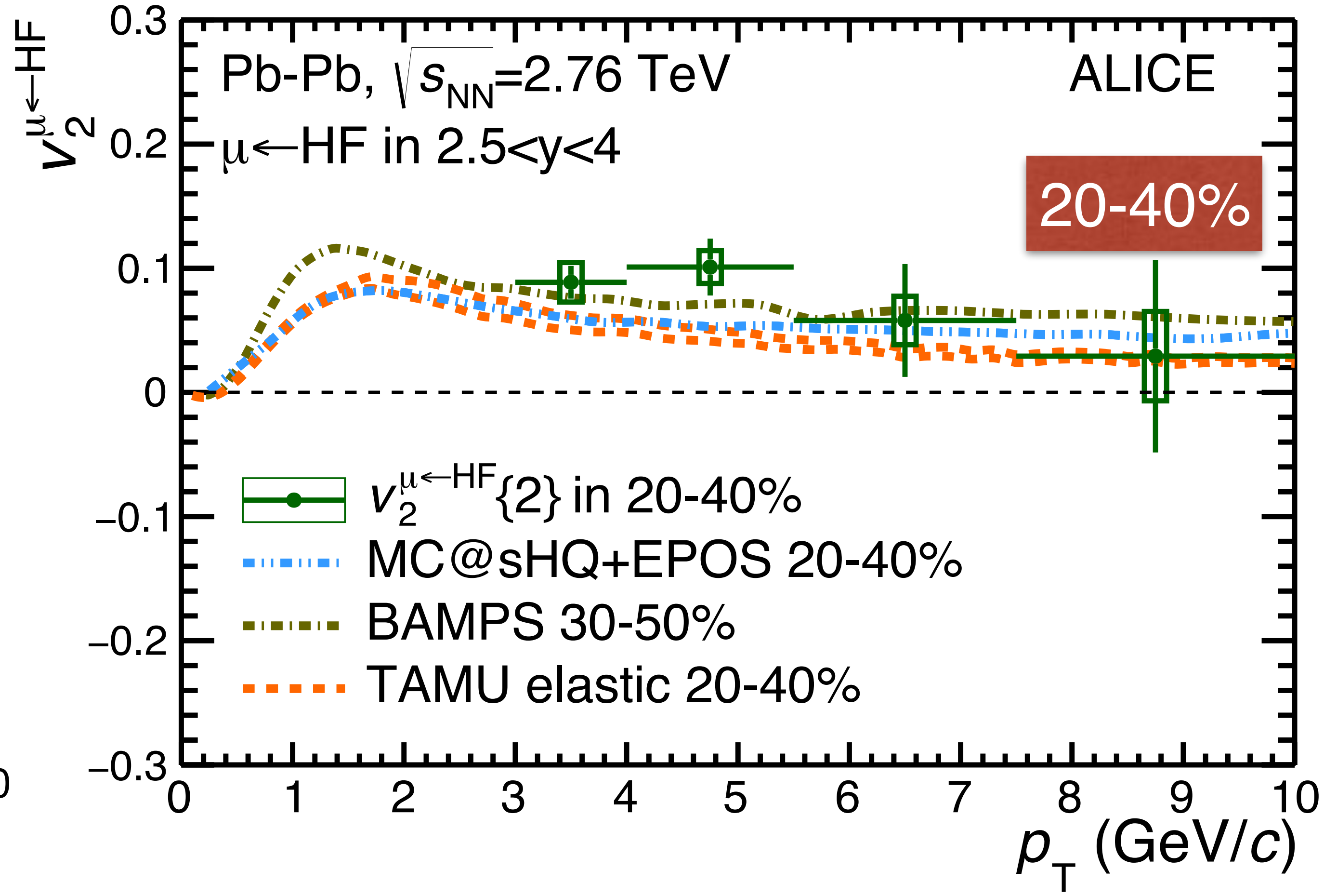




- Both R_{AA} and v_2 of heavy-flavour decay muons at forward rapidity ($2.5<y<4$) are compatible with heavy-flavour decay electrons at mid-rapidity ($|y|<0.6$ or <0.7)
- Large suppression of R_{AA} in central collisions — final-state effect
- Observed positive v_2 (3σ effect) — similar as for D mesons — confirms the significant interaction of heavy quarks with the medium

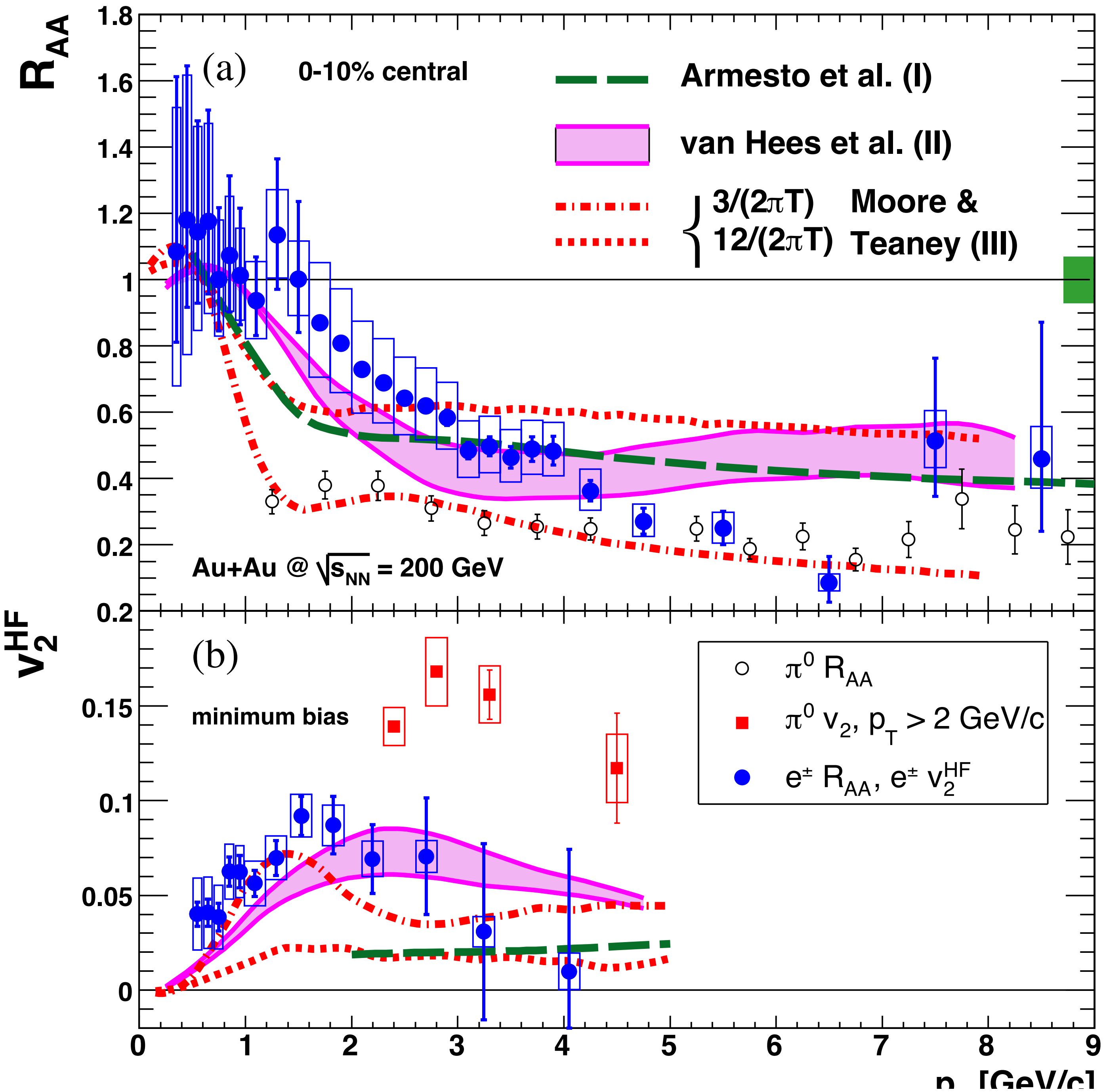
Elliptic flow of HF decay muons (ALICE)

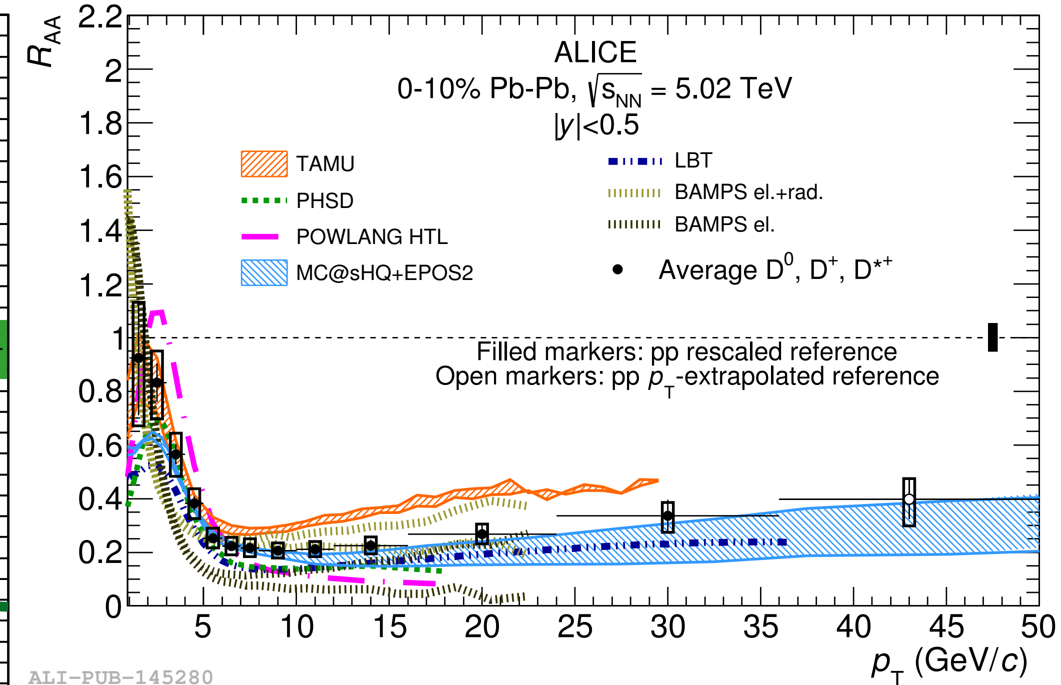


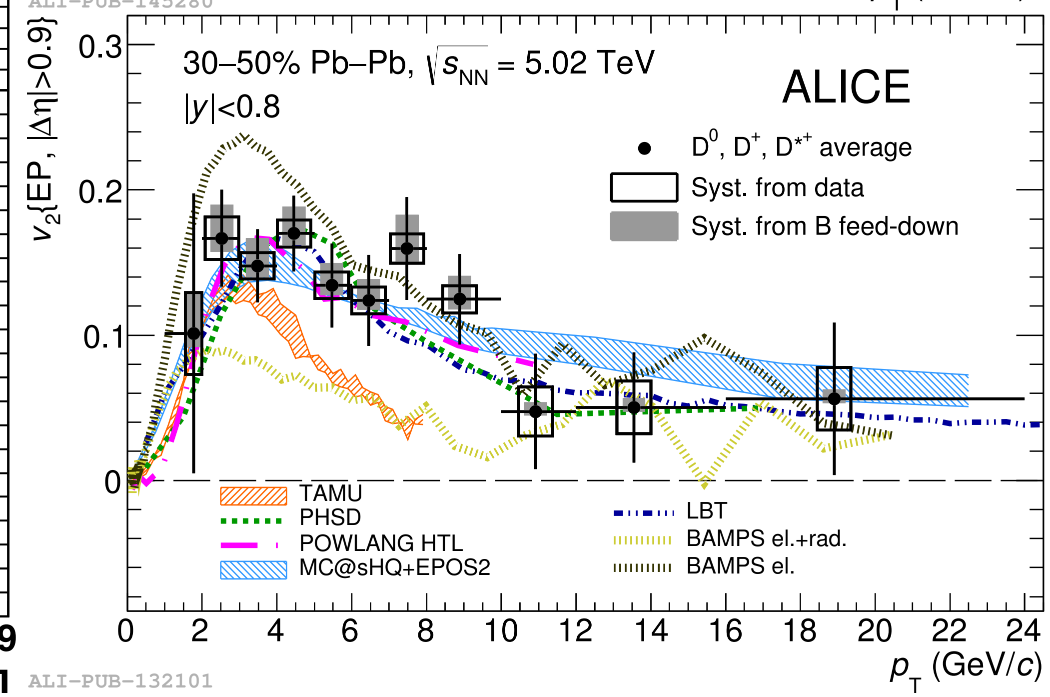


- The simultaneous description of R_{AA} and v_2 of heavy-flavour decay muons is challenging
  - Same picture for D-mesons and heavy-flavour decay electrons at mid-rapidity
  - R_{AA} and v_2 measurements together provide constraints for models

AOB



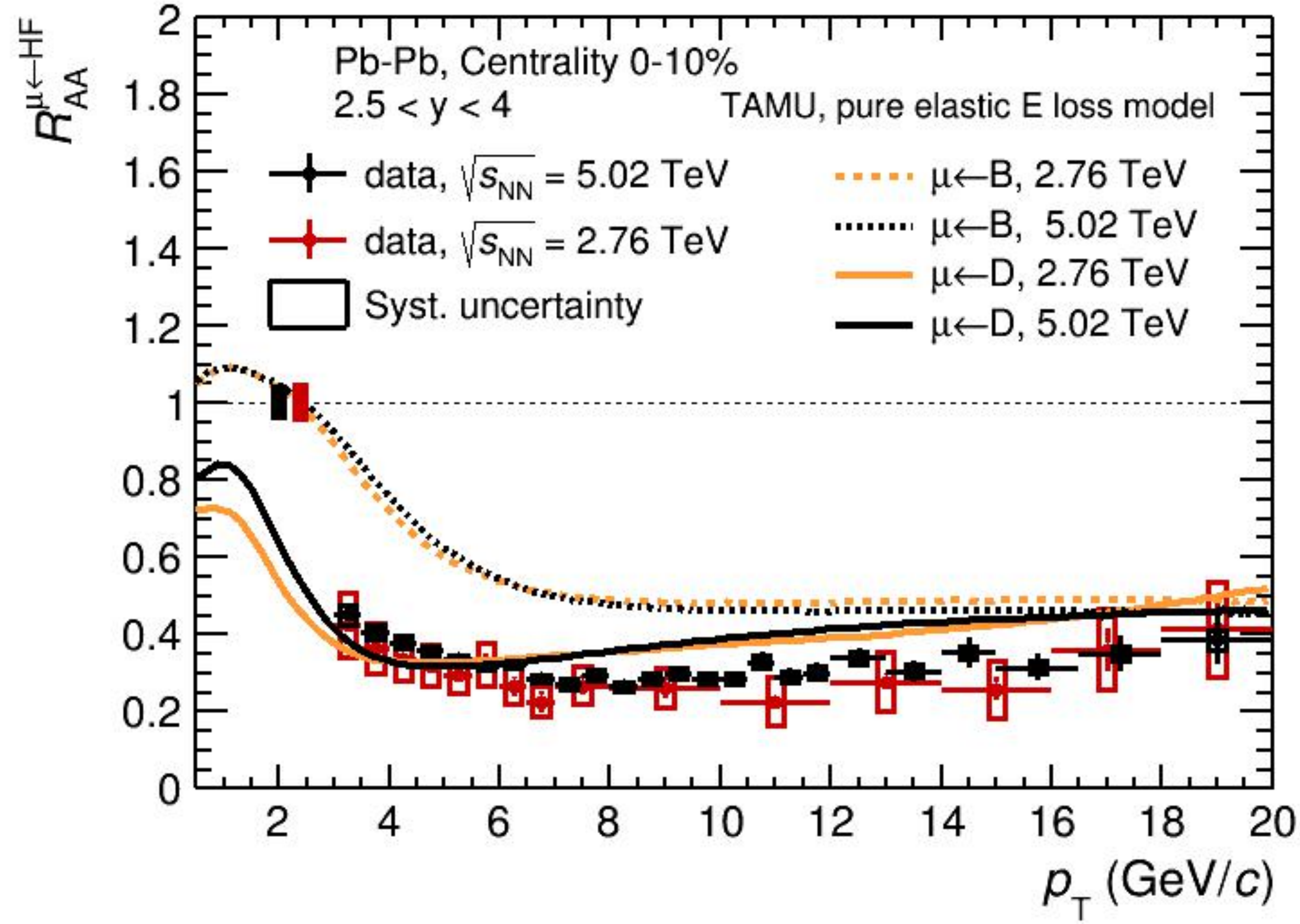




Heavy quark diffusion coefficient

- RHIC: $(4 - 6) / 2\pi T$ for $0.2 < T < 0.4$ GeV
- LHC: $(1.5 - 7) / 2\pi T$ for $T = T_c$

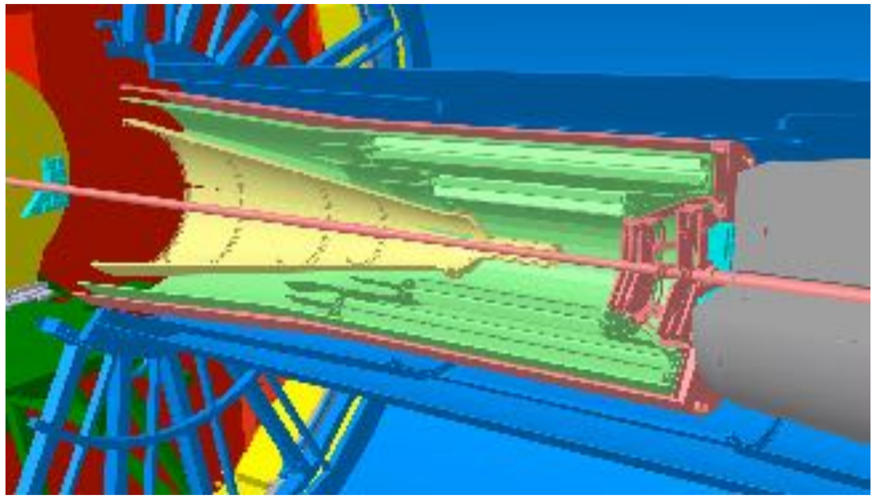
AOB



- Near future: 2018 Pb–Pb data
  - Improved uncertainty in ALICE LHC RUN-II

AOB

- Not so far future
  - ALICE LHC RUN-III

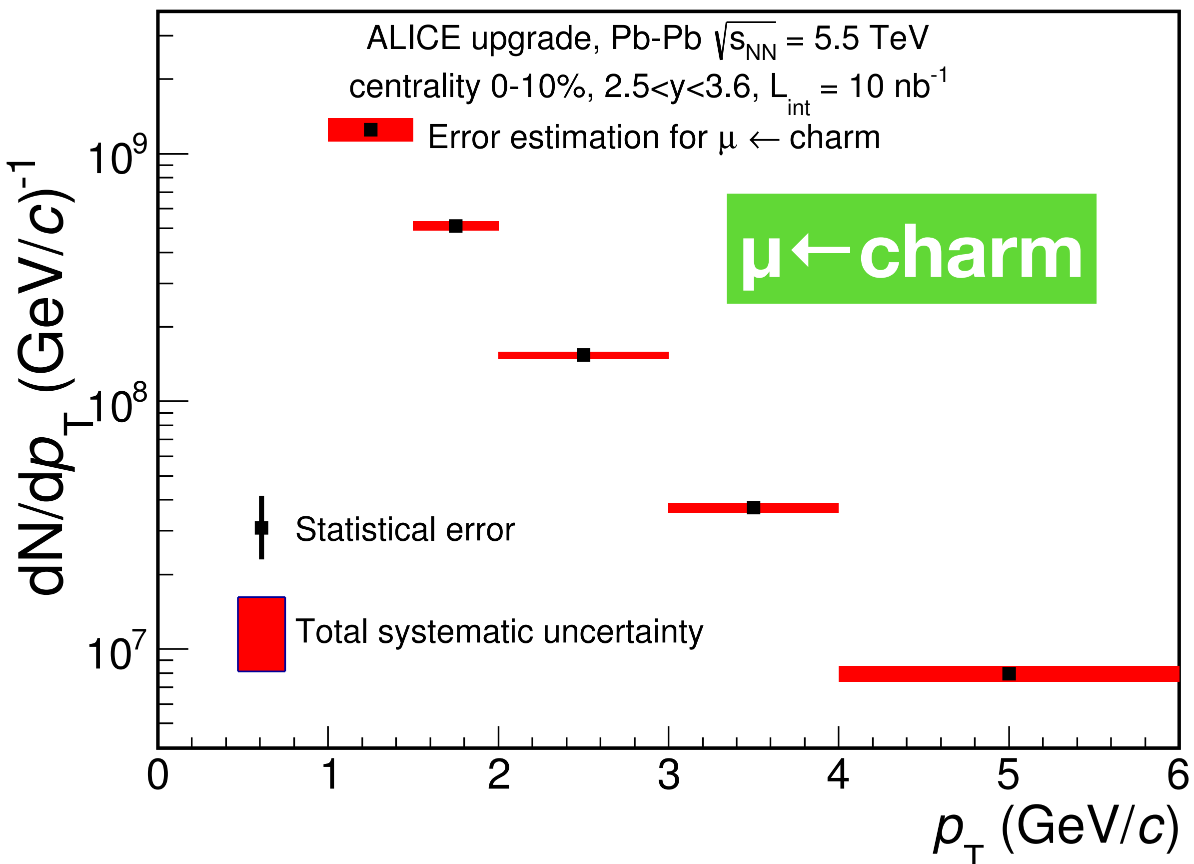


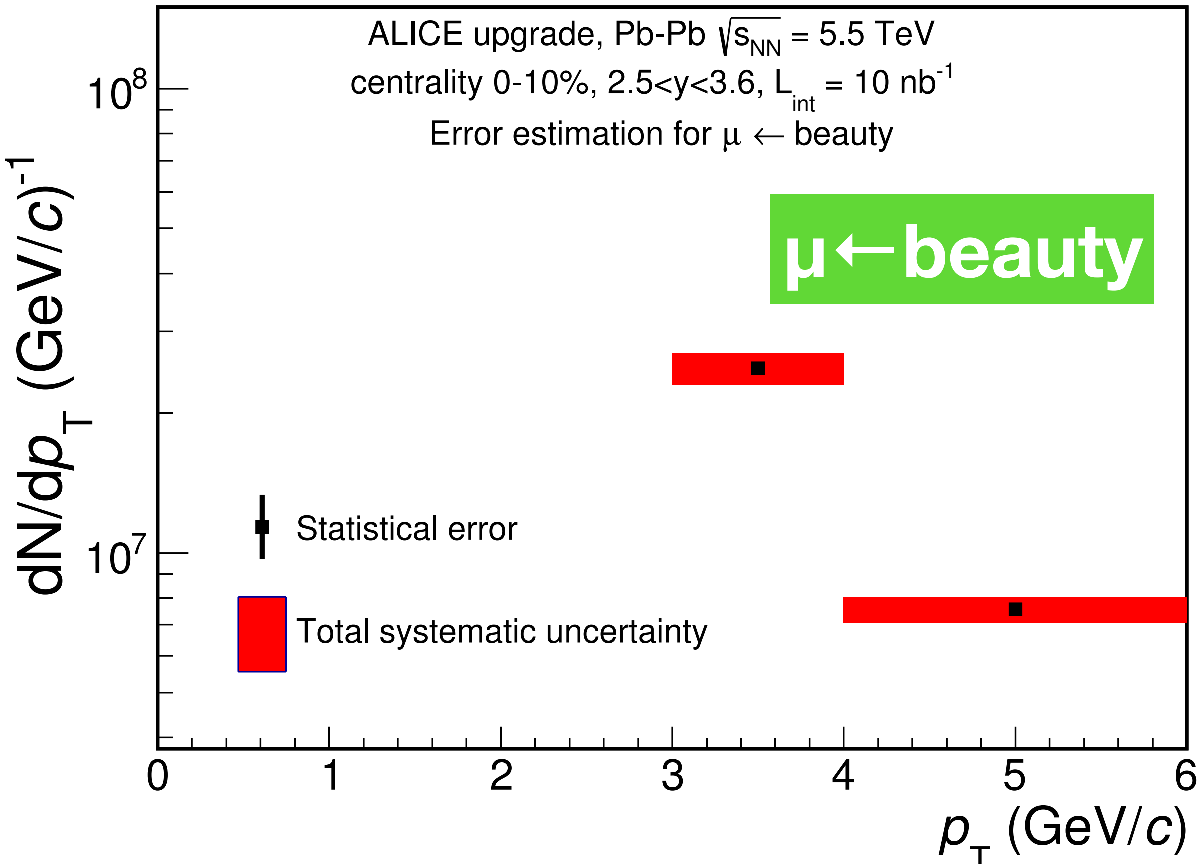
- Muon forward tracker + muon spectrometer

➡ Capability to separate charm and beauty production down to low p_T

- Promising update — displacement beauty decays alone z-axis (for any p_T, even for $p_T = 0$) due to the rapidity boost

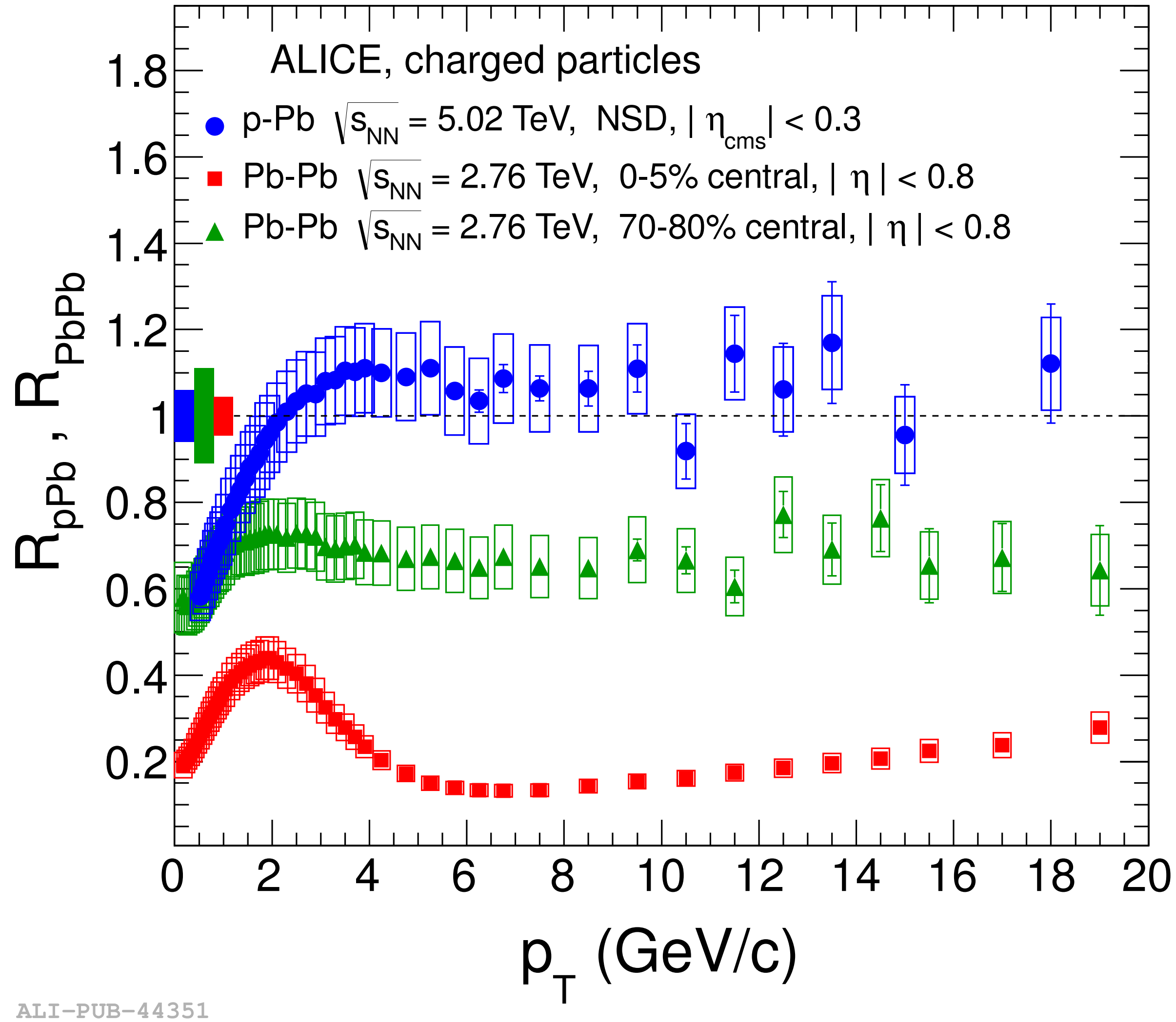
➡ Recover total charm and beauty cross section — crucial for quarkonia regeneration



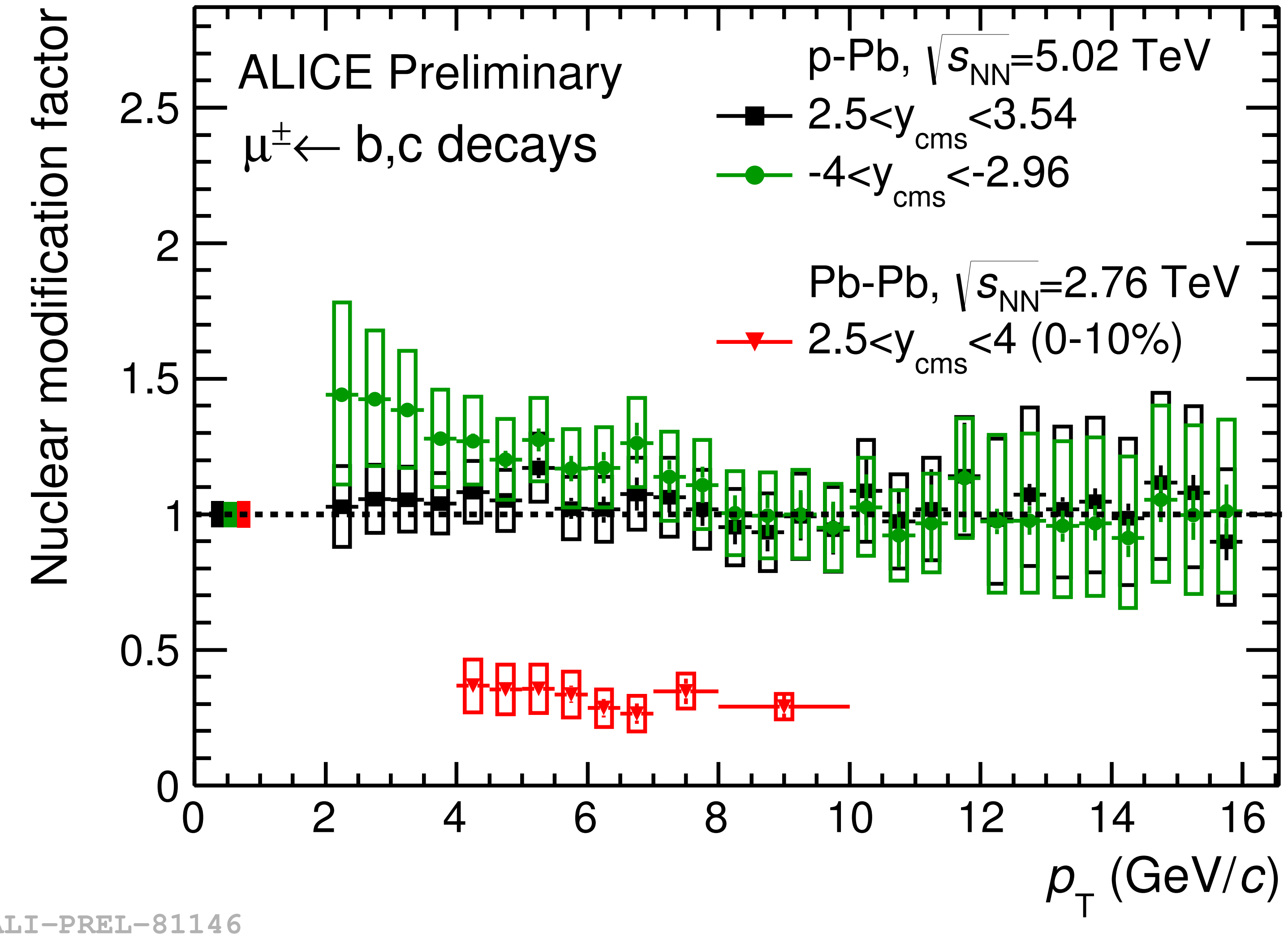


Control experiment

Charged particles $|\eta_{CMS}|<0.3$



HF muons $2.5<y_{CMS}<3.54$, $-4<y_{CMS}<-2.96$



Phys. Rev. Lett. 110 (2013) 082302

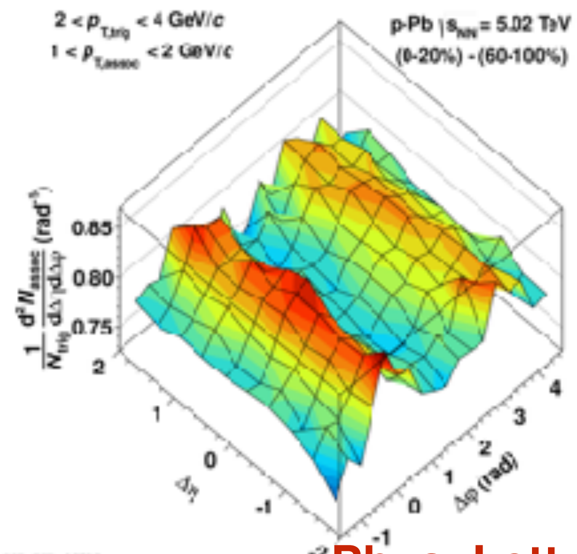
Phys. Lett. B770 (2017) 459

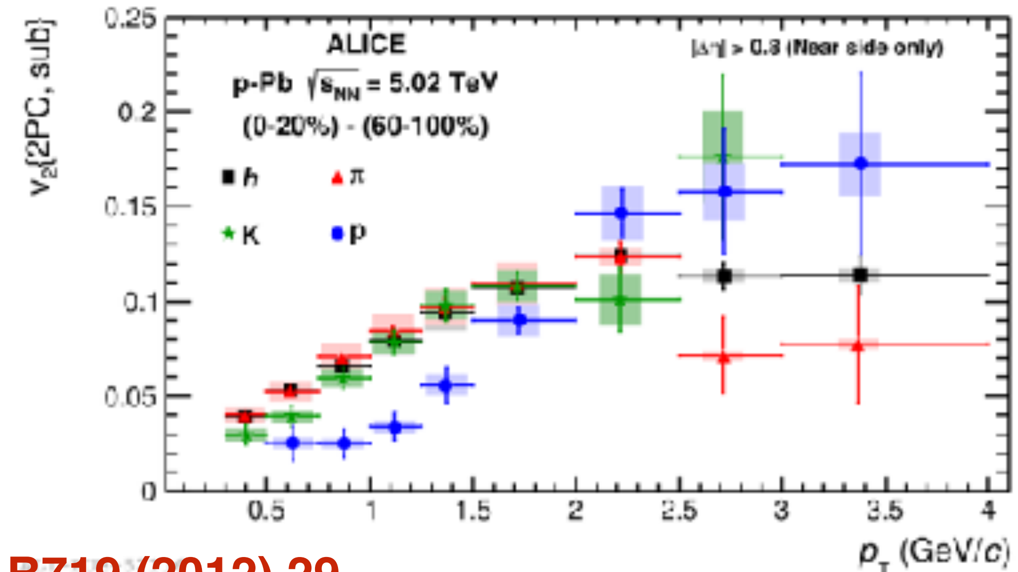
- R_{pPb} consistent with unity — strong suppression observed in central Pb–Pb collisions at mid-rapidity and forward rapidity is due to the hot medium

Collectivity in small systems

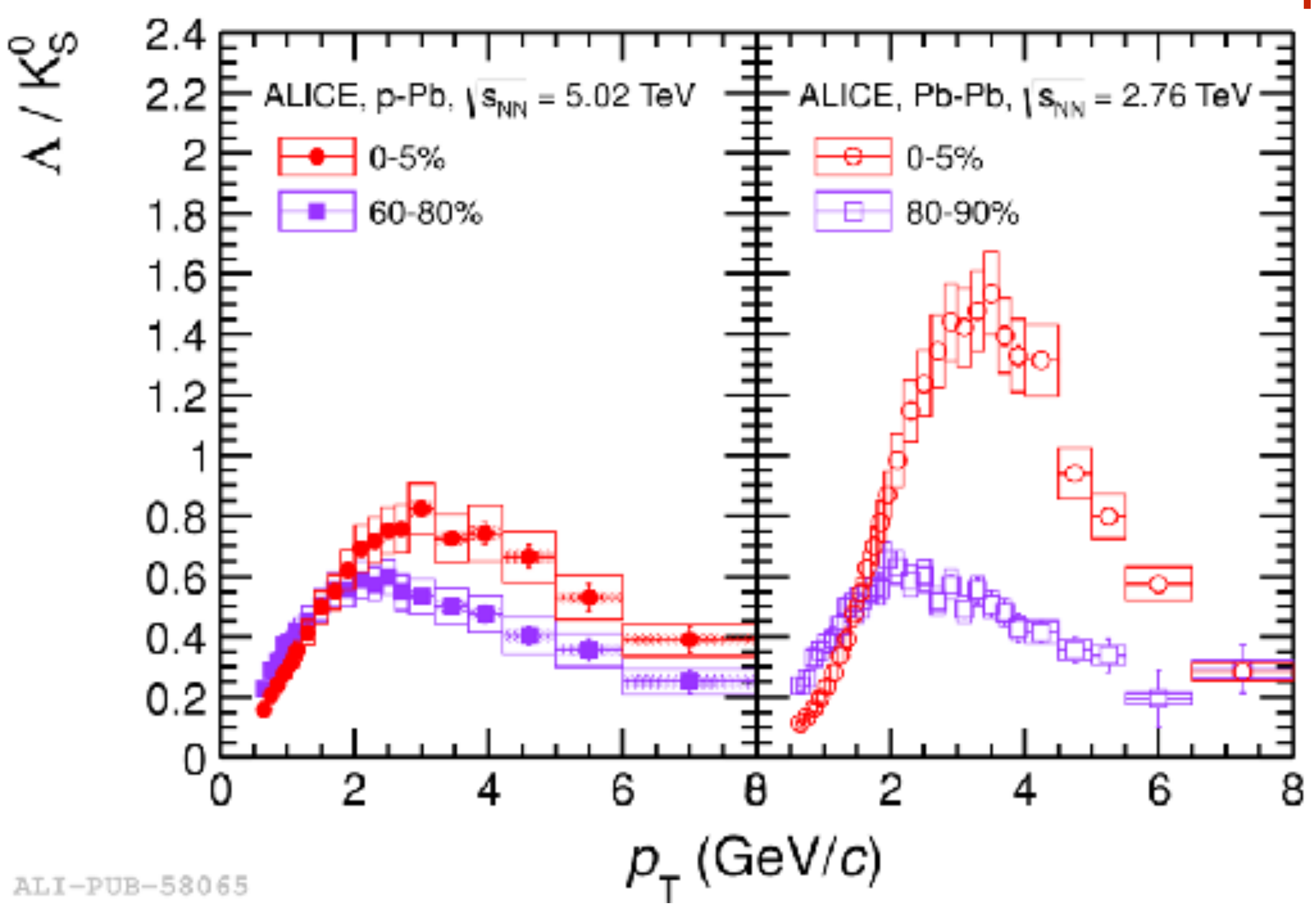
High multiplicity p–Pb and Pb–Pb collisions - similarities

- double ridge structure
- $v_2 > 0$ and PID dependent





Phys. Lett. B719 (2012) 29



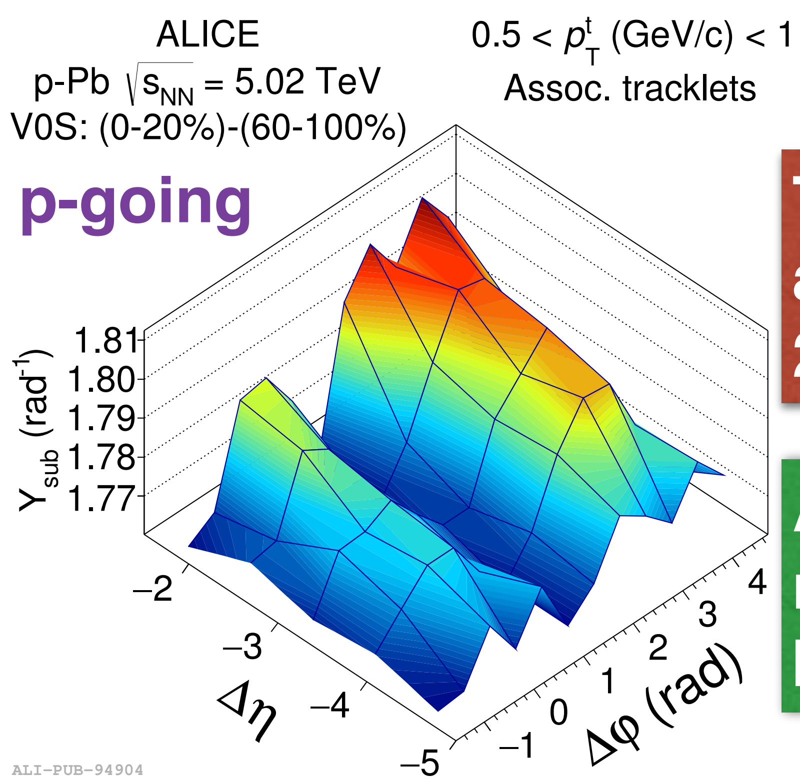
How about heavy-flavour particles?

Phys. Lett. B728 (2014) 25

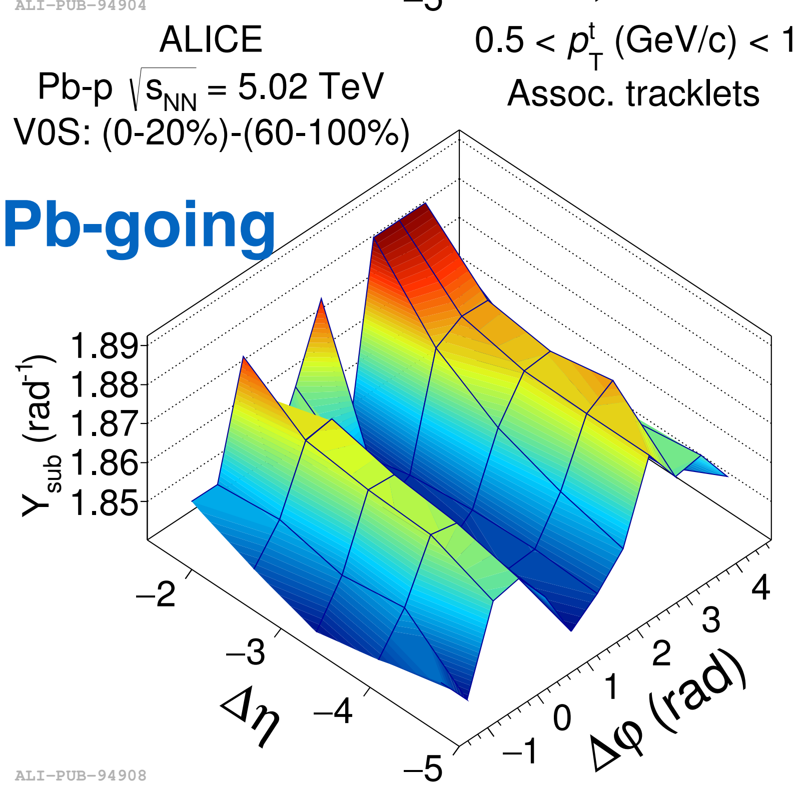
Forward Muon Flow in p–Pb Collisions

ALICE, Phys. Lett. B753 (2016) 126

p-going

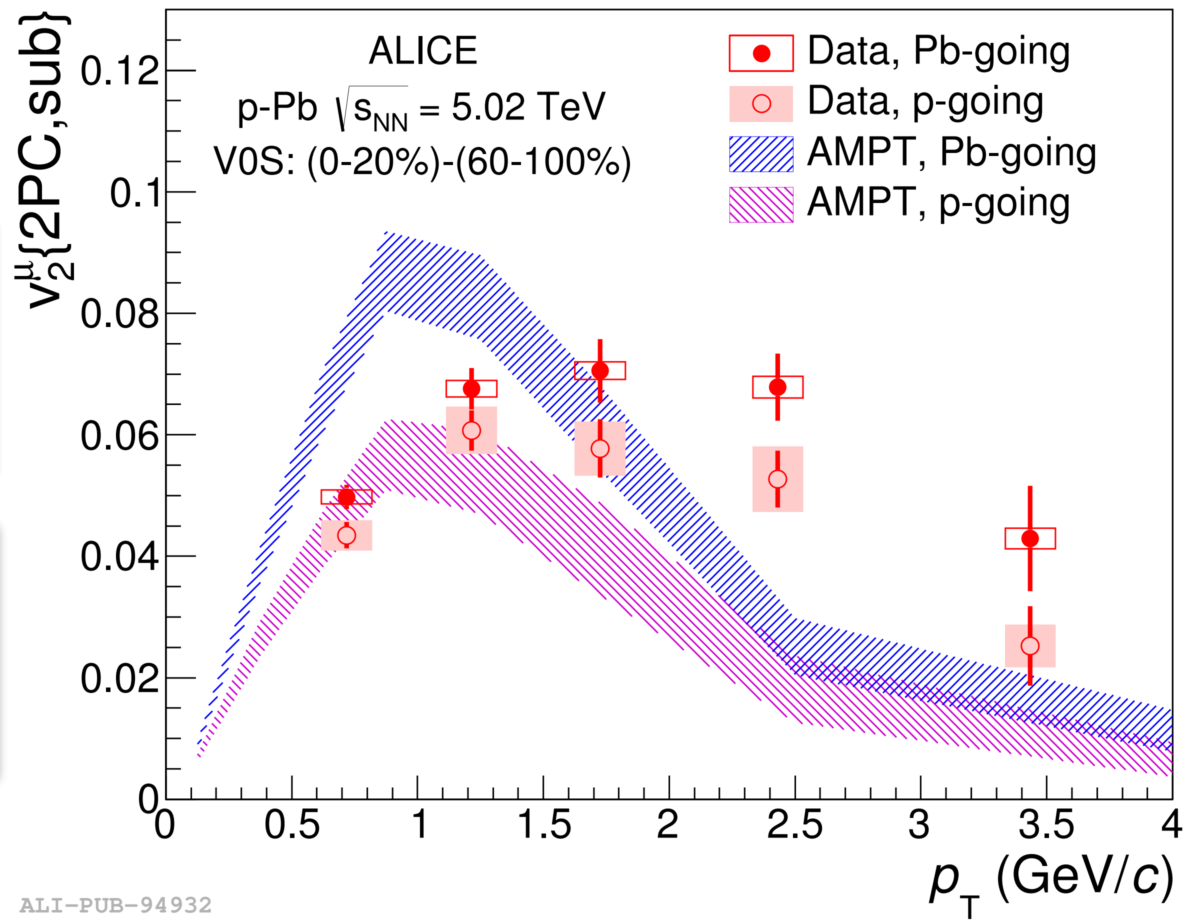


Pb-going



Trigger particle: muon at forward rapidity 2.5<|η|<4

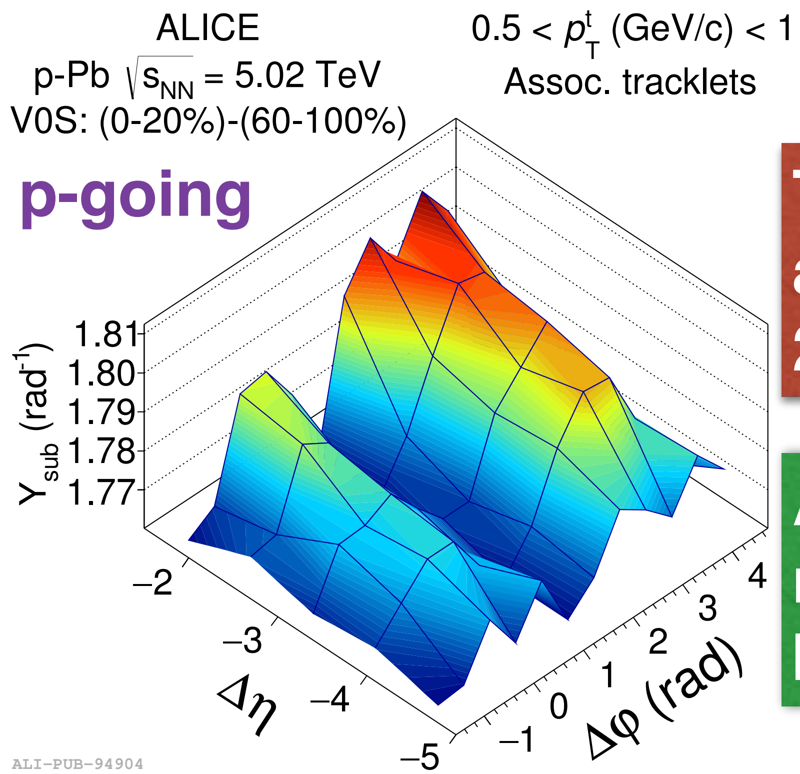
Associate particle: mid-rapidity tracklet |η|<1

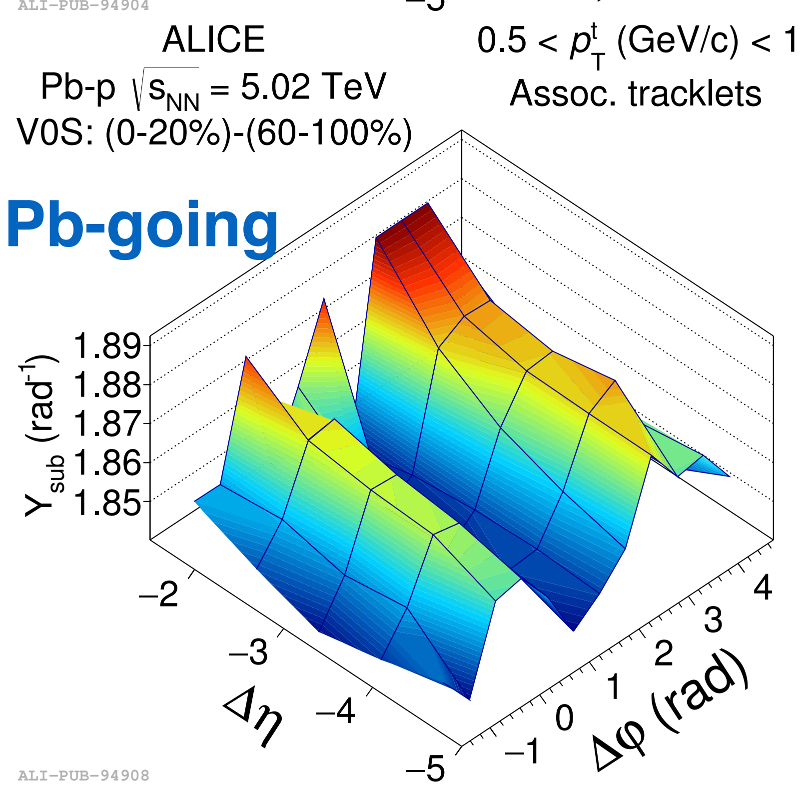


- Double ridge extends up to Δη ~ 5
- Inclusive muon v_2 on Pb-side is larger (~16%) than on p-side, qualitatively consistent with expectations from hydrodynamics (AMPT)

Forward Muon Flow in p–Pb Collisions

ALICE, Phys. Lett. B753 (2016) 126





Trigger particle: muon at forward rapidity 2.5<|η|<4

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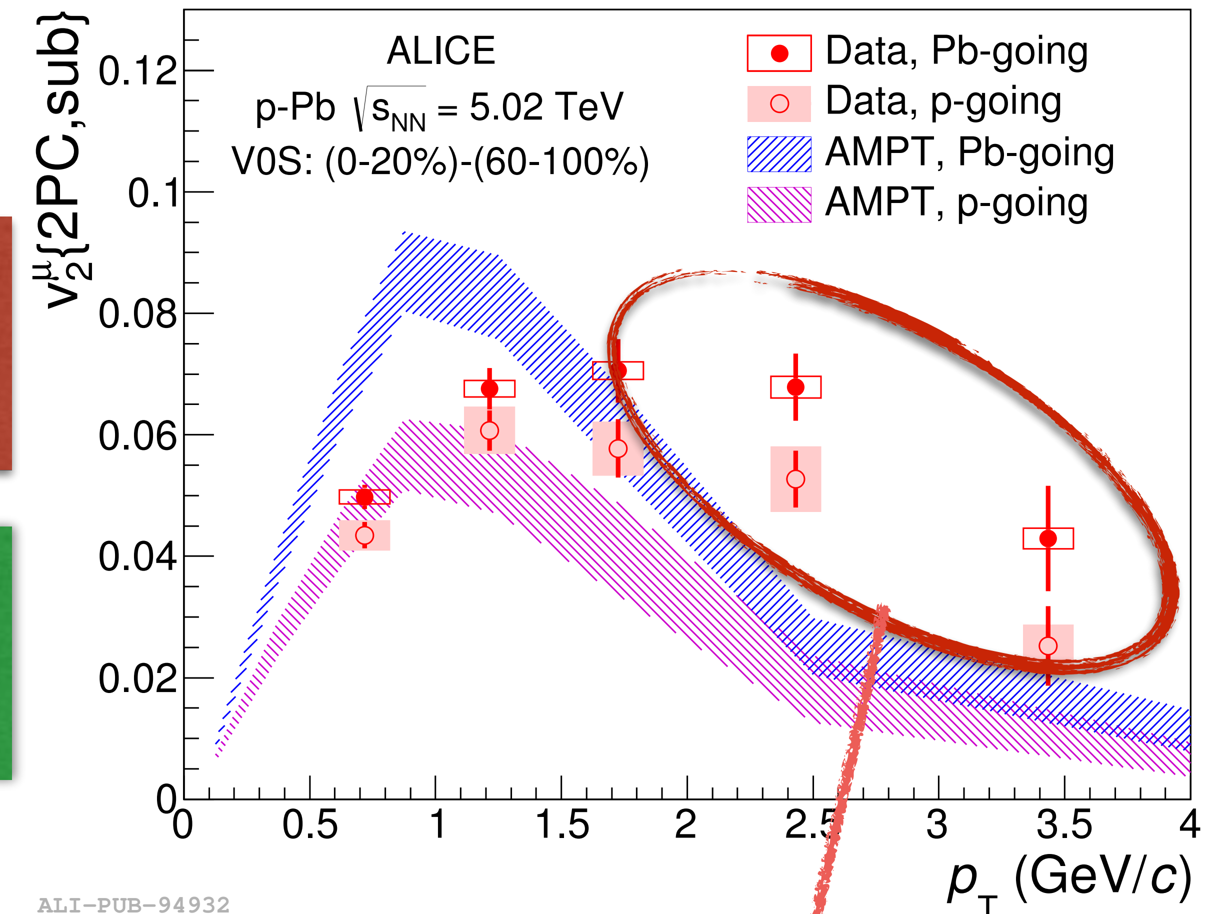
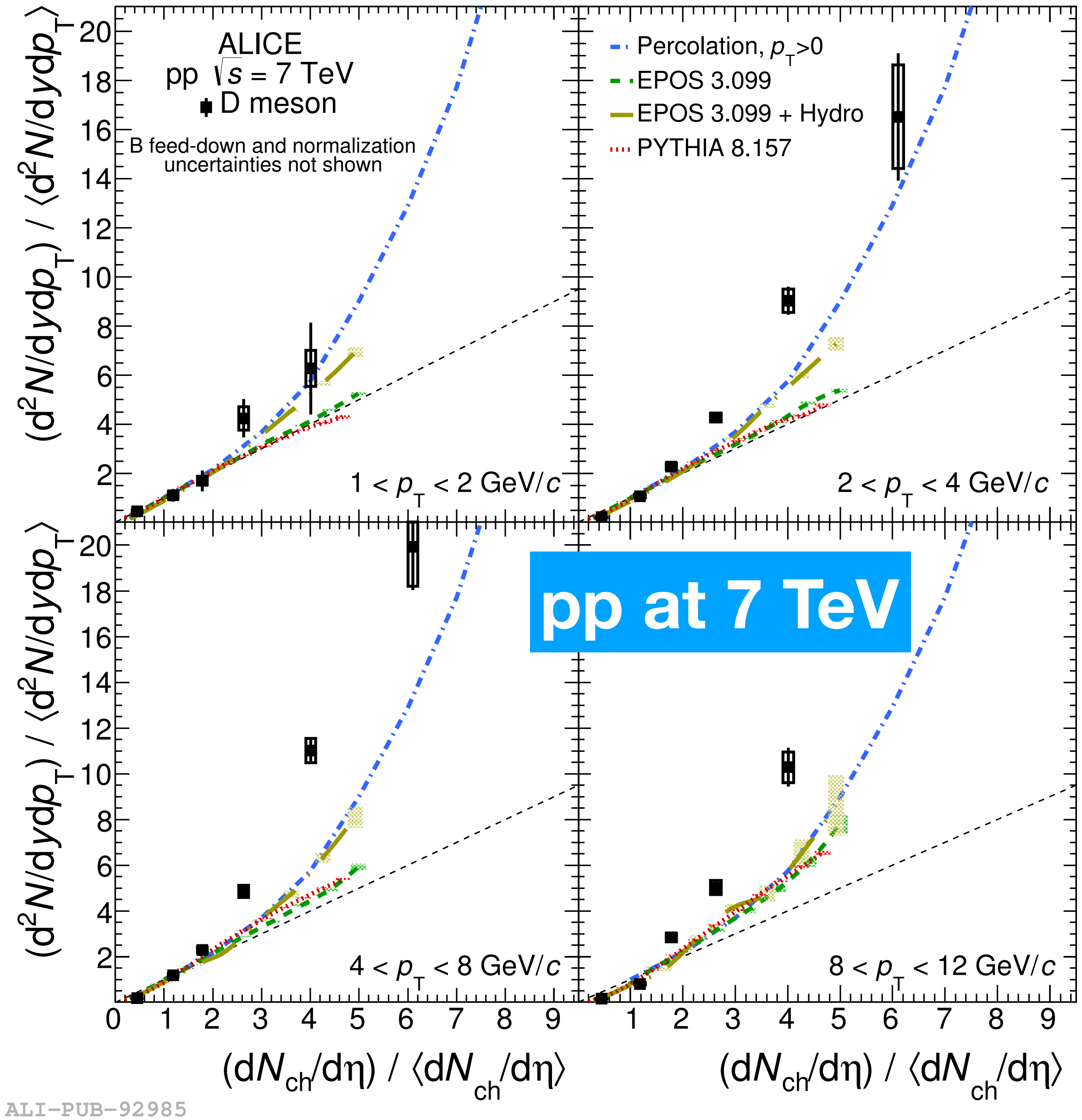
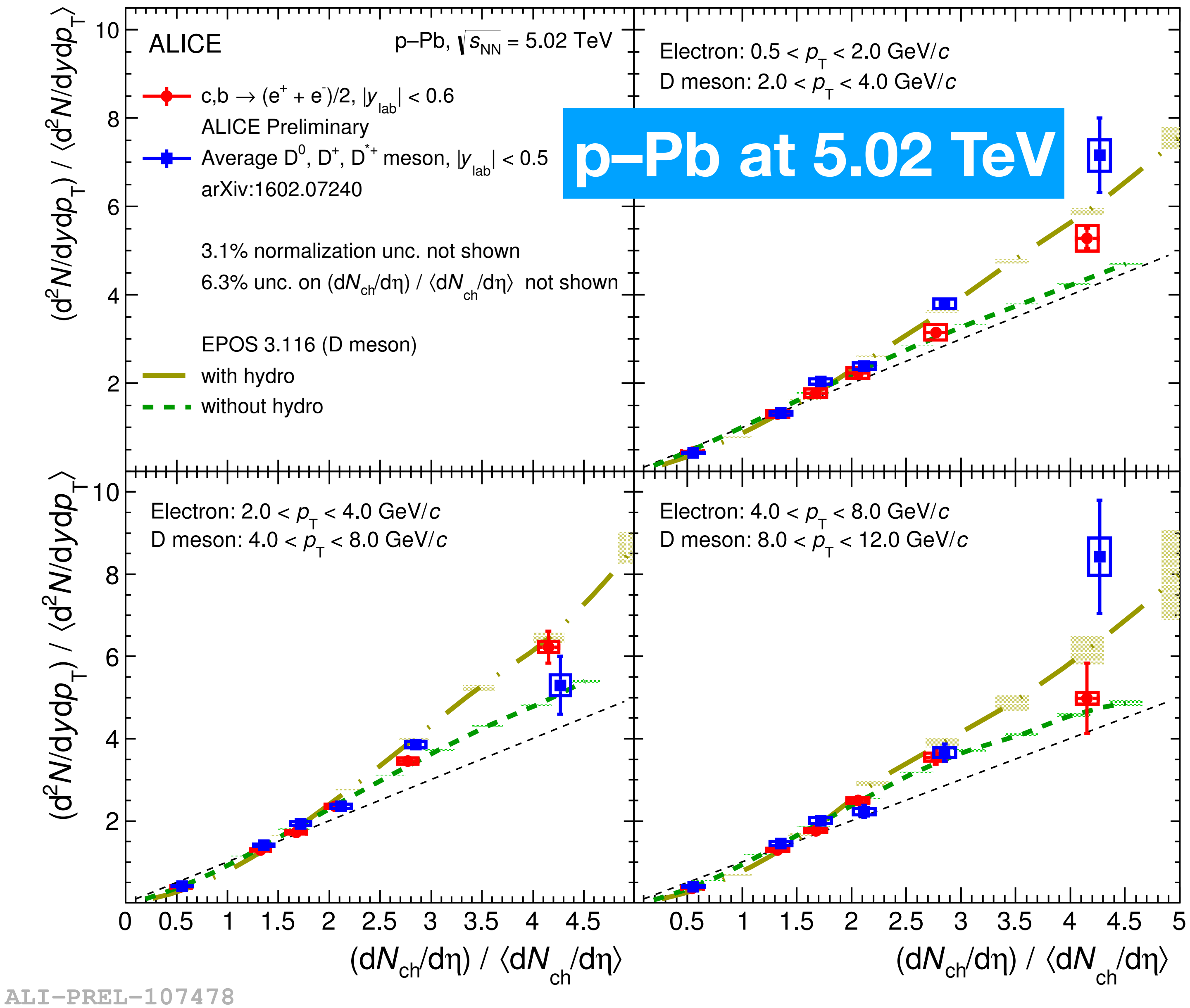


- Double ridge extends up to Δη ~ 5
- Inclusive muon v_2 on Pb-side is larger (~16%) than on p-side, qualitatively consistent with expectations from hydrodynamics (AMPT)
- p_T>2 GeV/c, dominated by (>60%) HF decay muons
  - Non-zero v_2 of HF muons as in Pb–Pb collisions (?)

Open heavy flavour production vs. multiplicity

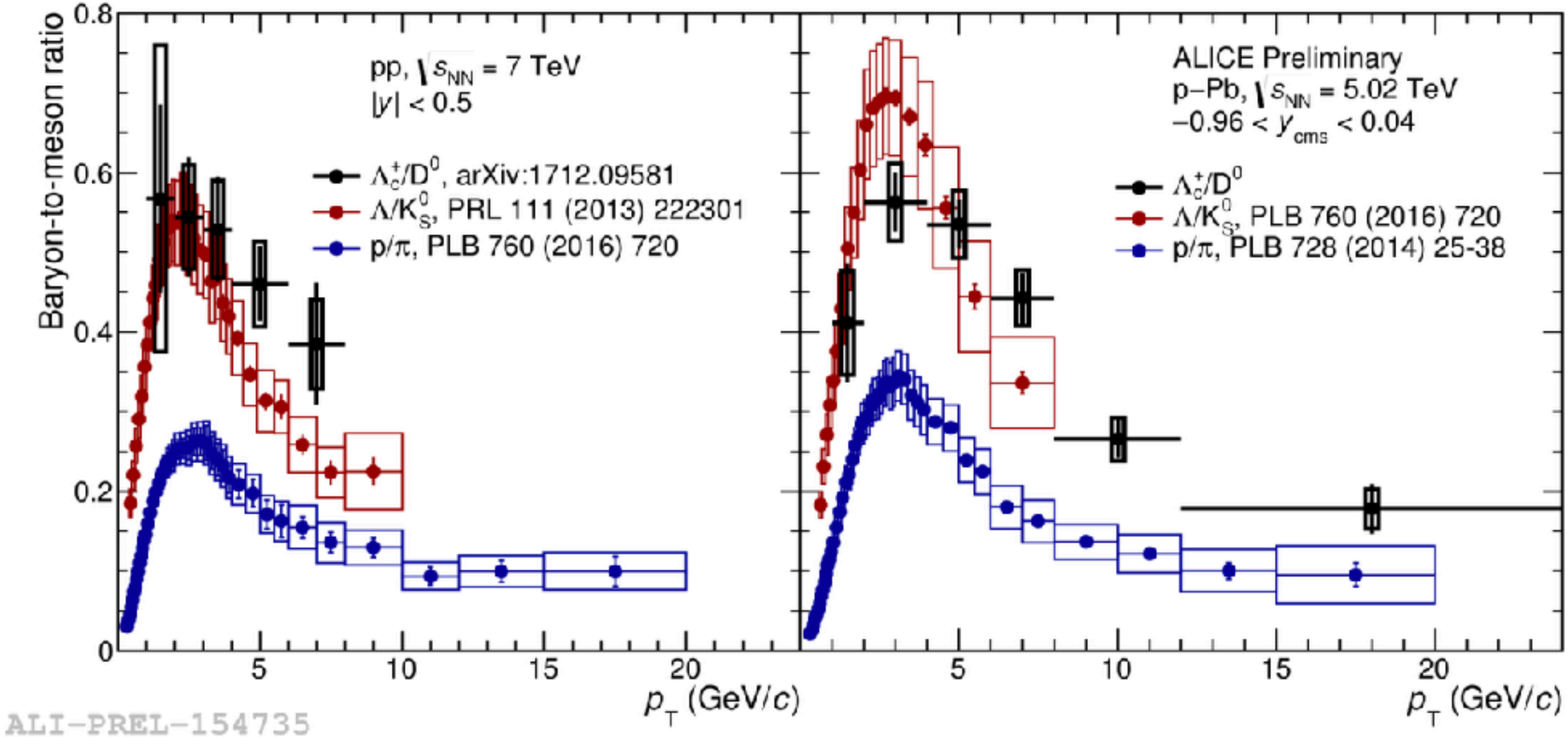
JHEP 09 (2015) 148





- Faster-than-linear increase of self-normalized D-meson and heavy-flavour decay electron yields as a function of the charged-particle multiplicity at mid-rapidity
- Model with hydrodynamics describes fairly data in both pp and p–Pb collisions

Baryon to meson ratios in small systems



- Remarkable similarities of baryon to meson ratio in the charm sector with light flavor results