Muons from Open Heavy-flavour Decays in p-Pb Collisions at $\sqrt{s_{NN}}$=5.02 TeV with ALICE

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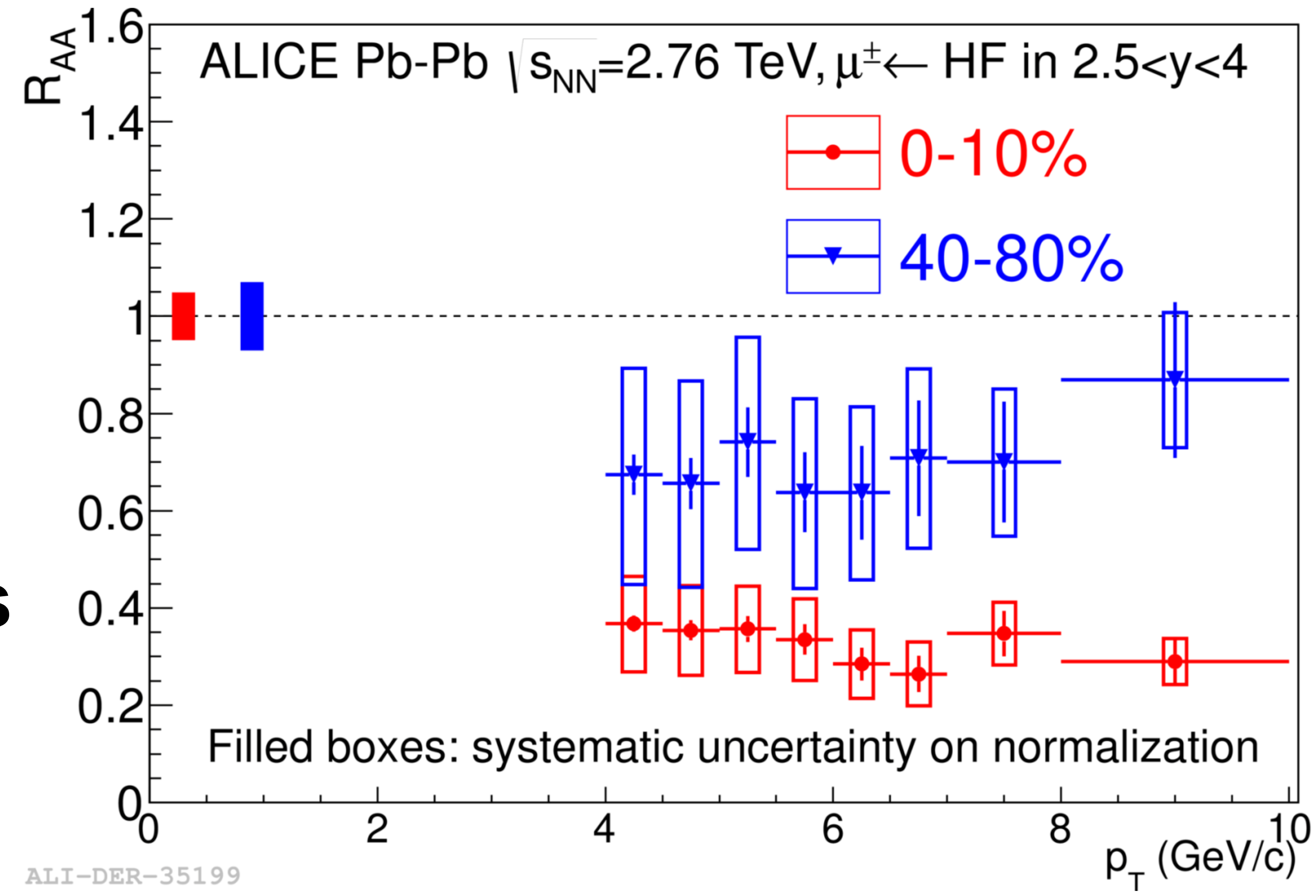
Outline

- Motivation
- Heavy-flavour decay muons with ALICE
- Heavy-flavour decay muons in p-Pb collisions
    - ✓ Production cross section
    - ✓ Nuclear modification factor
    - ✓ Forward-to-backward ratio
- Conclusion

Heavy flavours in p-Pb collisions: motivation

- **Heavy quarks (charm and beauty) produced in initial hard scatterings and experience the full evolution of the medium**

- **Suppression observed in central Pb-Pb collisions: cold + hot nuclear matter effect**



Phys. Rev. Lett. 109, 112301 (2012)

- **Cold nuclear matter effects in p-Pb collisions**
  - ✓ nuclear modification of PDFs
    - ☐ shadowing / gluon saturation at low Bjorken-*x*

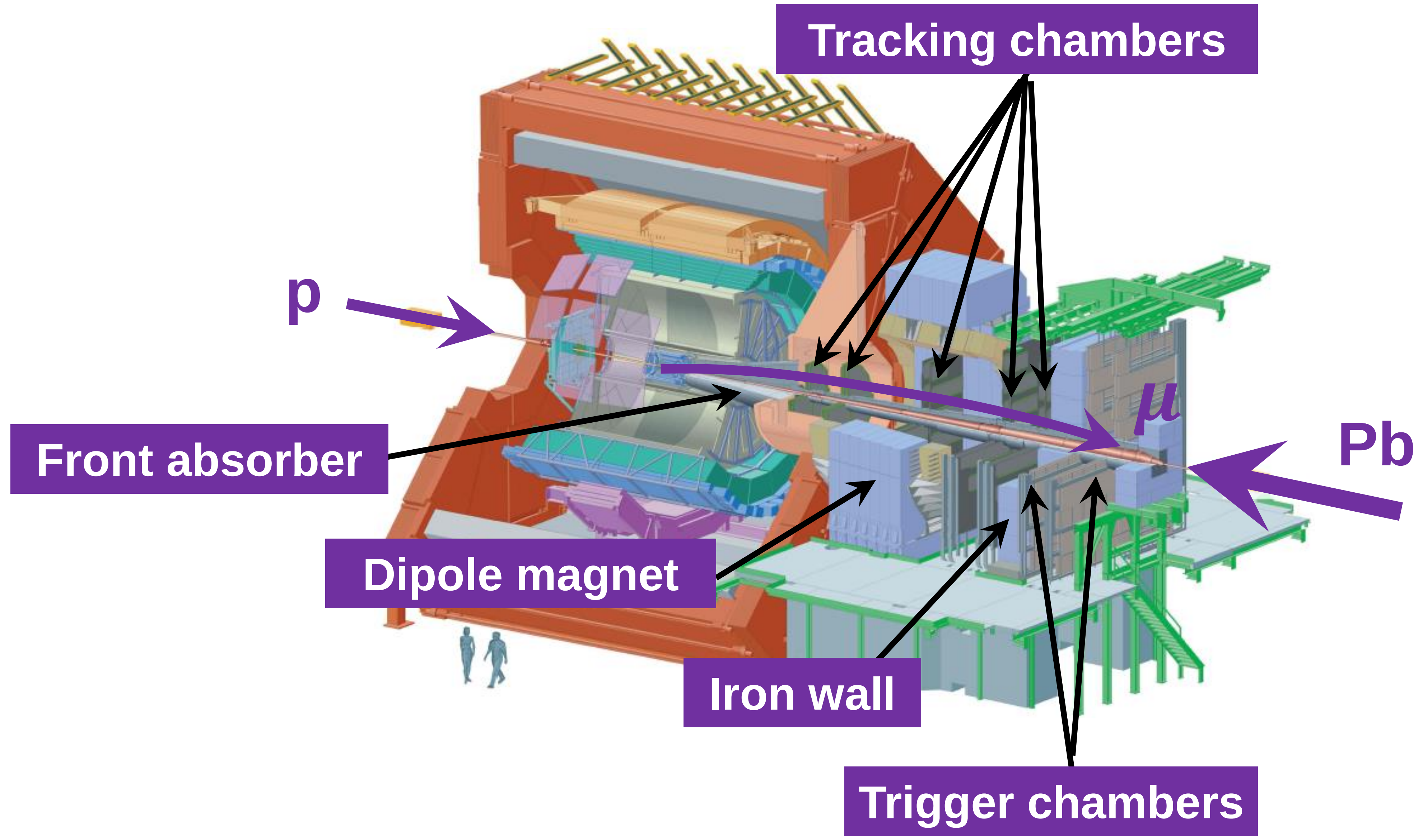
      H. Fujii and K. Watanabe, Nucl. Phys. A915 (2013) 1
  - ✓ parton energy loss — I. Vitev, Phys. Rev. C75 (2007) 064906
  - ✓ multiple collisions — A.M. Glenn et al., Phys. Lett. B 644 (2007) 119

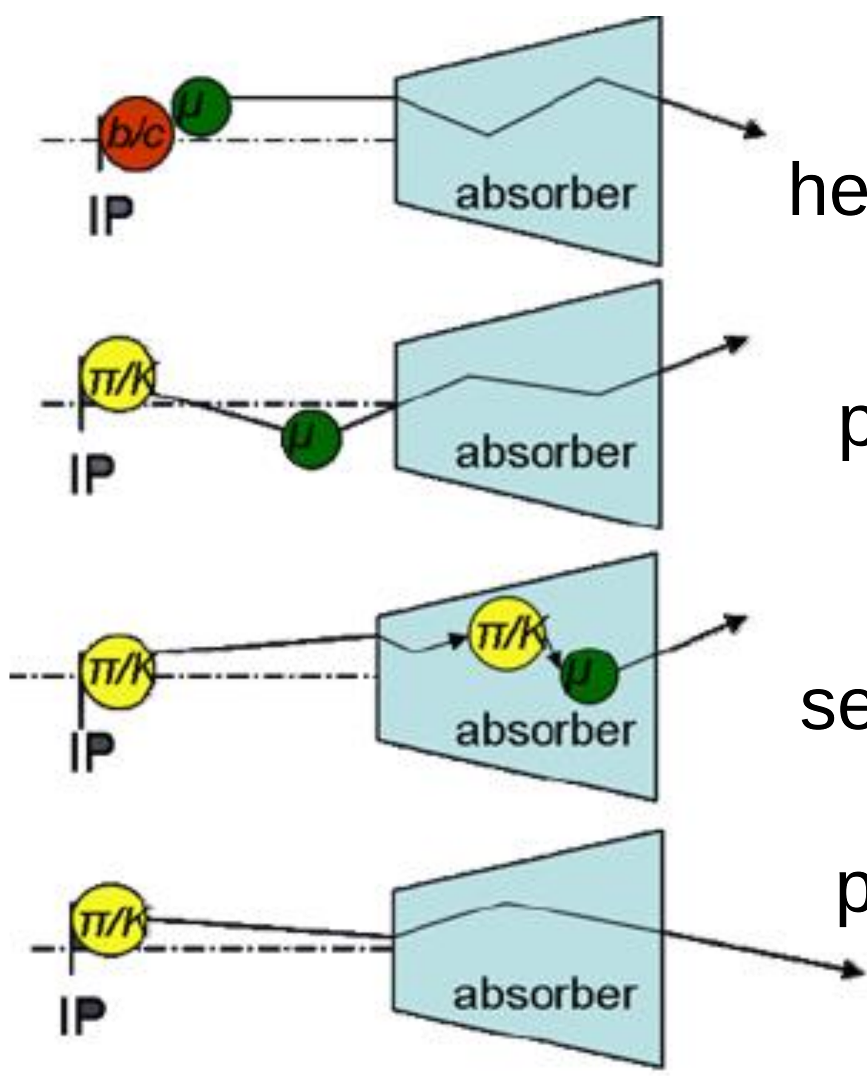
- **Investigation by means of the nuclear modification factor and the forward-to-backward ratio**

$$R_{\mathrm{pPb}} = \frac{1}{\mathrm{A}} \frac{\mathrm{d}\sigma_{\mathrm{pA}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}} \qquad R_{\mathrm{FB}} = \frac{\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}\,(\mathrm{Forward})}{\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}(\mathrm{Backward})}$$

Heavy-flavour decay muons at forward rapidity in ALICE

- $D, B, \Lambda_c \rightarrow \mu + X$
- Muon spectrometer
  - ✓ acceptance and geometrical cuts
  - ✓ matching between tracking and trigger chambers
  - ✓ correlation between momentum and distance of closest approach (DCA) to remove further background





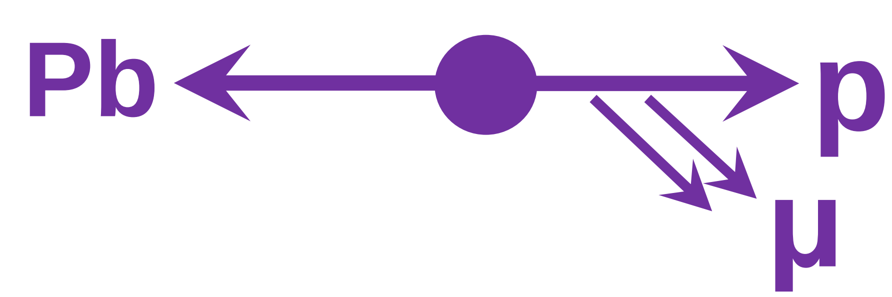
μ from heavy flavours

μ from primary K/π

μ from secondary K/π

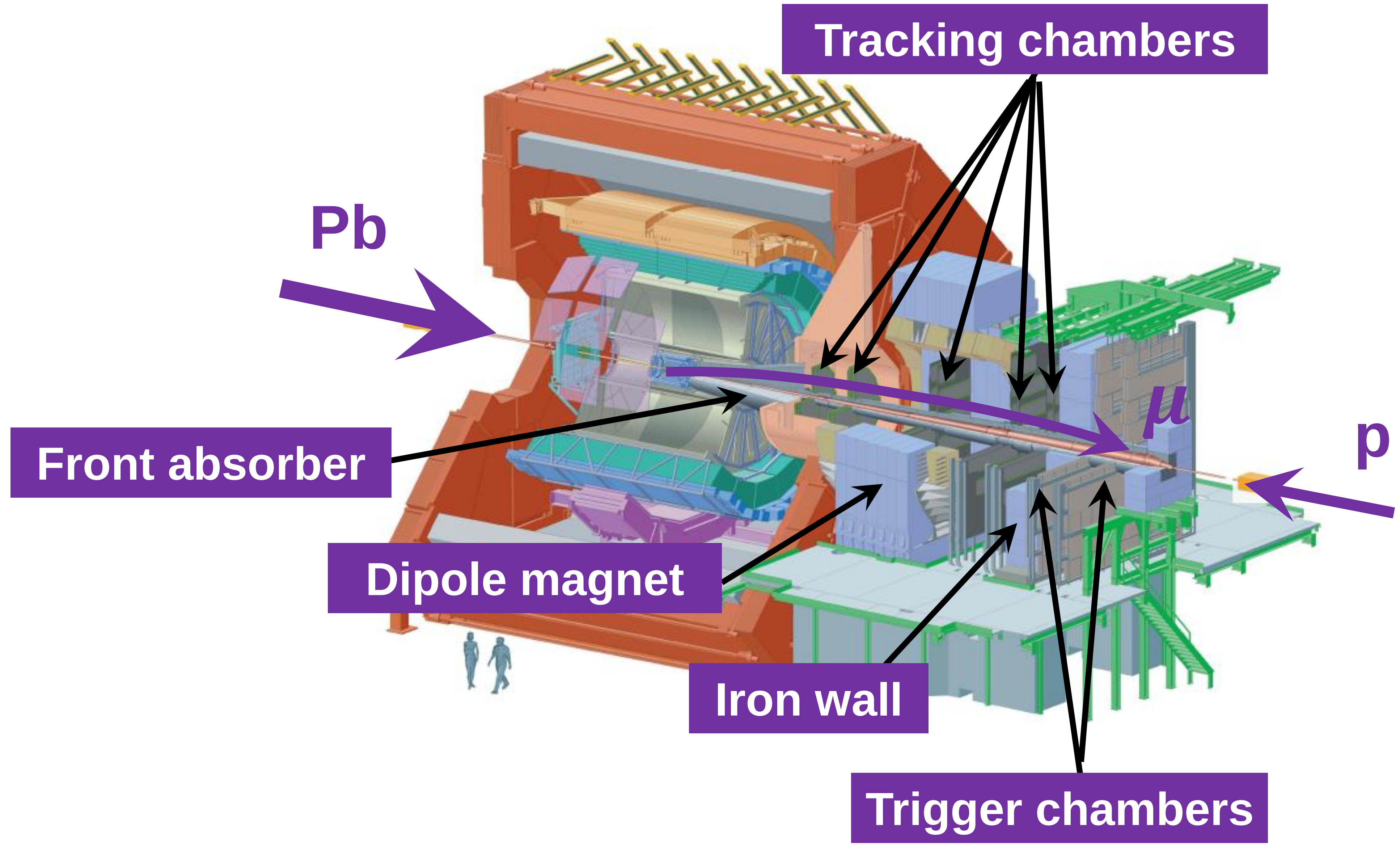
punch through hadrons

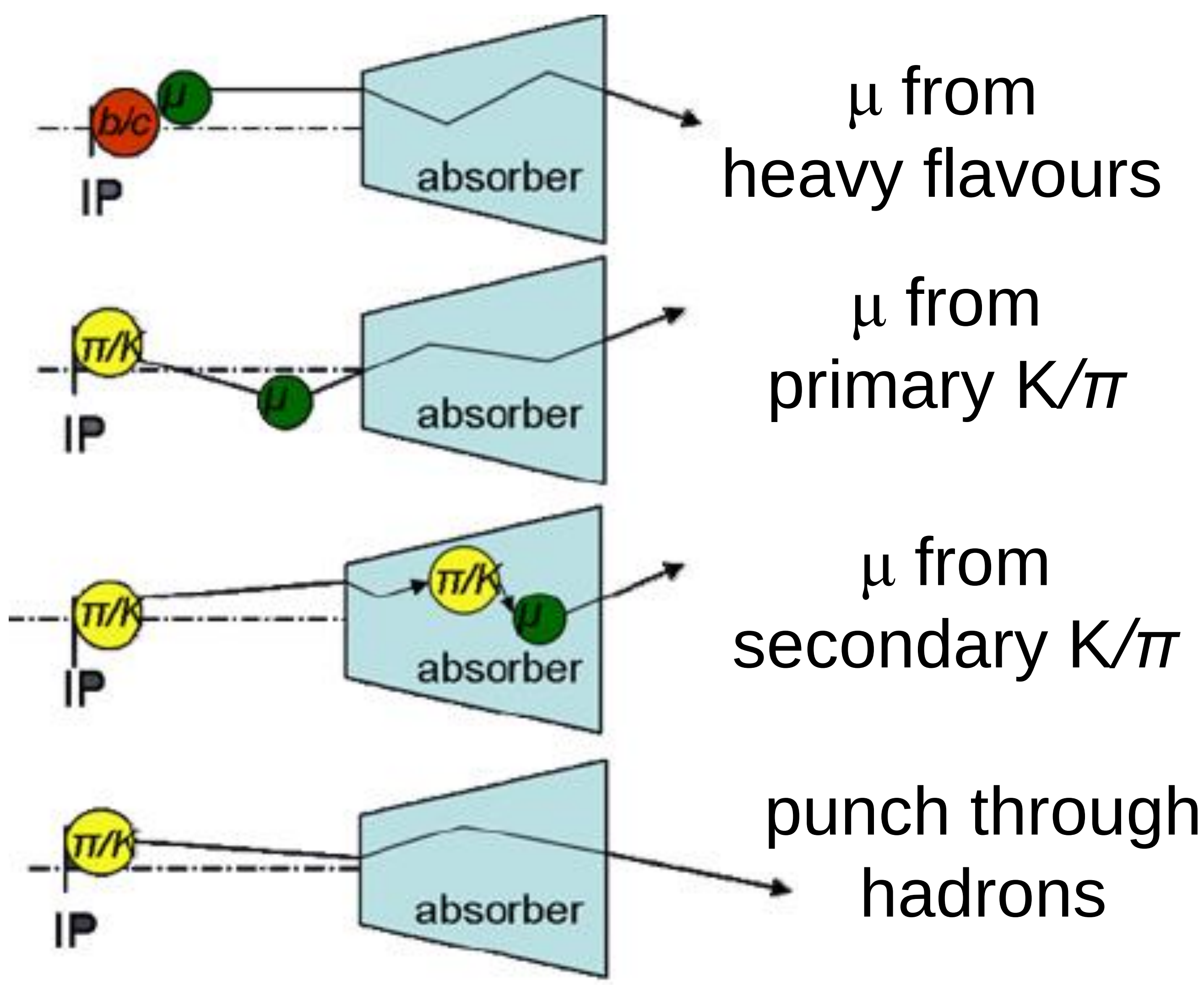
- Rapidity shift of the center-of-mass of 0.465 units in the p direction
- Background (mainly from $\pi^{\pm}$ and $K^{\pm}$ decays) estimated at **forward rapidity (p-going direction, 2.03<y_{cms}<3.53)**



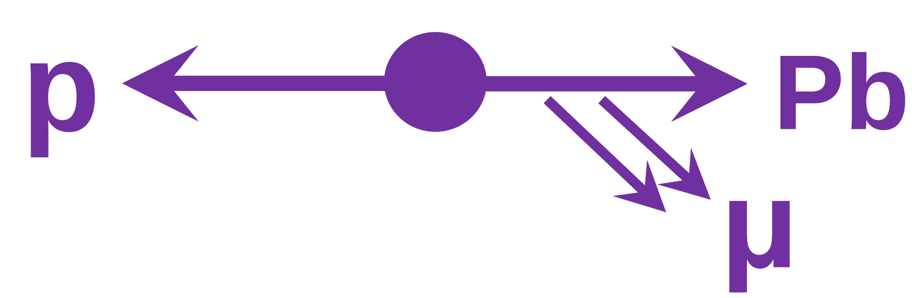
Heavy-flavour decay muons at backward rapidity in ALICE

- $D, B, \Lambda_c \rightarrow \mu + X$
- Muon spectrometer
  - ✓ acceptance and geometrical cuts
  - ✓ matching between tracking and trigger chambers
  - ✓ correlation between momentum and distance of closest approach (DCA) to remove further background





- Rapidity shift of the center-of-mass of 0.465 units in the p direction
- Background (mainly from $\pi^{\pm}$ and $K^{\pm}$ decays) estimated at **backward rapidity (Pb-going direction, -4.46<y_{cms}<-2.96)**



Analysis strategy: data sample

- p-Pb collisions at 5.02 TeV collected in 2013
  - ✓ forward (p-going side): muon single low (MSL) & muon single high (MSH)
  - ✓ backward (Pb-going side): MSL & MSH

		p_T threshold at 50% efficiency (GeV/c)	statistics	integrated luminosity (μb^{-1})
forward	MSL	~0.5	1.5×10^7	196
	MSH	~4.2	1×10^7	4.9×10^3
backward	MSL	~0.5	2.6×10^7	254
	MSH	~4.2	1.5×10^7	5.8×10^3

- σ_{MB} = 2.09 b (2.12 b) at forward (backward) rapidity

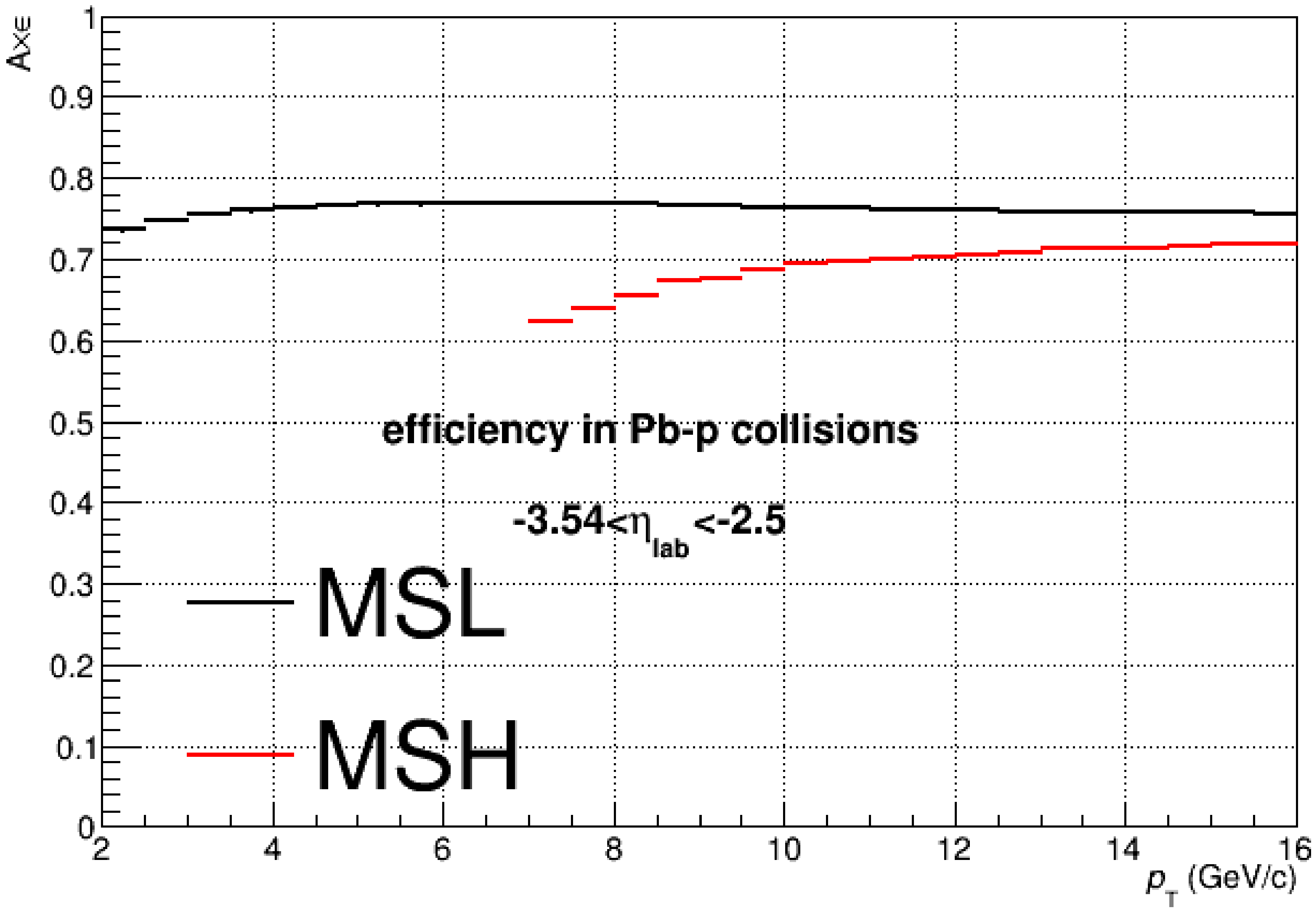
Analysis strategy: normalization

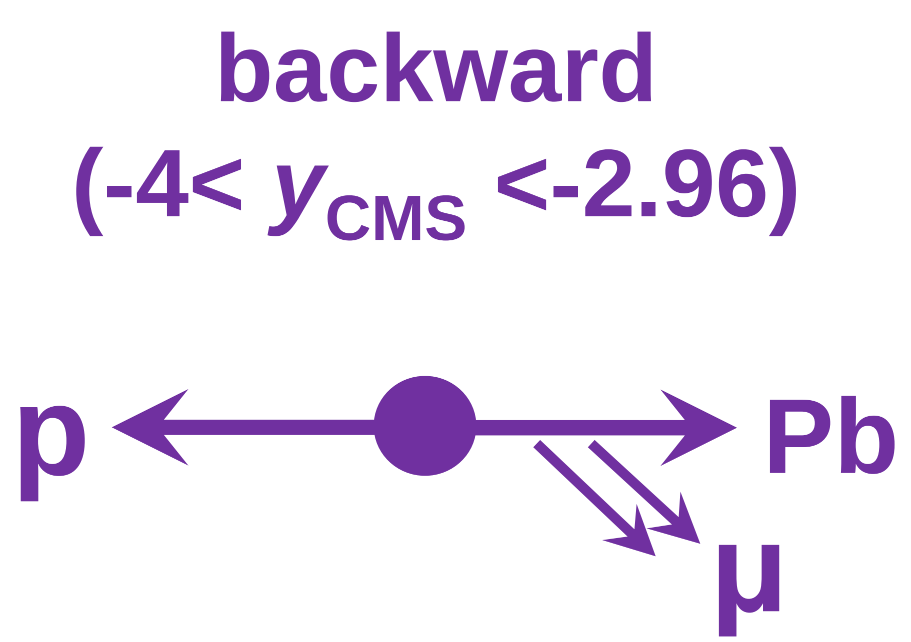
$$\frac{d\sigma}{dp_T} = \frac{1}{F_{norm}\, N_{evt}} \cdot \frac{dN}{dp_T} \cdot \sigma_{MB}$$

- Two methods implemented to obtain the number of equivalent Minimum-Bias (MB) events from the Muon Single Low (MSL) and Muon Single High (MSH) triggers
  - ✓ offline method based on AOD [https://indico.cern.ch/event/287038]
  - ✓ scaler method based on OCDB [https://indico.cern.ch/event/240961]

F_{norm}(0-100%)	forward rapidity	backward rapidity
MSL	28.2±0.3%(stat.) ±0.5%(syst.)	20.5±0.2%(stat.) ±0.3%(syst.)
MSH	1032.8±0.7%(stat.) ±1.1%(syst.)	798.3±0.6%(stat.) ±0.4%(syst.)

Analysis strategy: efficiency correction

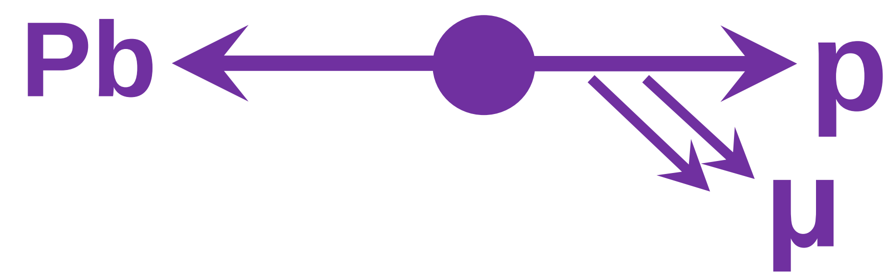




- Realistic simulations using beauty signals as inputs
  (negligible difference between efficiencies of charm and beauty decay muons)

- Uncertainty on misalignment: 1% x p_T (p_T in GeV/c)

Analysis strategy : background subtraction (1/2)



- **Forward rapidity (2.5< y_{CMS} <3.54)**

  ✓ input: K/π spectra in p-Pb collisions measured at mid-rapidity ($|y_{CMS}|$<0.3, $p_T^{K/\pi} < 15\ \mathrm{GeV}/c$) with ALICE

  ☐ extrapolate K/π spectra to higher p_T ($p_T^{\pi} < 24\ \mathrm{GeV}/c$, $p_T^{\pi} < 40\ \mathrm{GeV}/c$) in order to have the decay muons in $p_T^{\mu} < 16\ \mathrm{GeV}/c$

  ✓ extrapolate K/π spectra in p-Pb collisions to forward rapidity by means of Monte-Carlo simulations according to

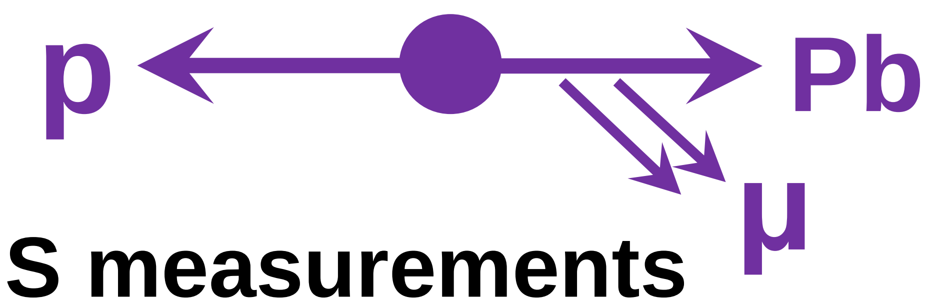
$$\frac{dN_{pPb}^{K/\pi}}{dp_T dy}(p_T, y) = \frac{dN_{pPb}^{K/\pi}}{dp_T dy}(p_T, |y_{\mathrm{CMS}}| < 0.3) \times F_{extra.}(p_T, y)$$

  the rapidity extrapolation factor ($F_{extra.}$) is estimated via the ratio of forward to mid-rapidity ($|y_{CMS}|$<0.3) yields from DPMJET simulations

  ☐ use HIJING to estimate the systematic uncertainty

  ✓ produce the K/π decay muon background by means of fast simulations of decay kinematics and absorber effect

Analysis strategy : background subtraction (2/2)



- **Backward rapidity (-4< y_{CMS} <-2.96)**

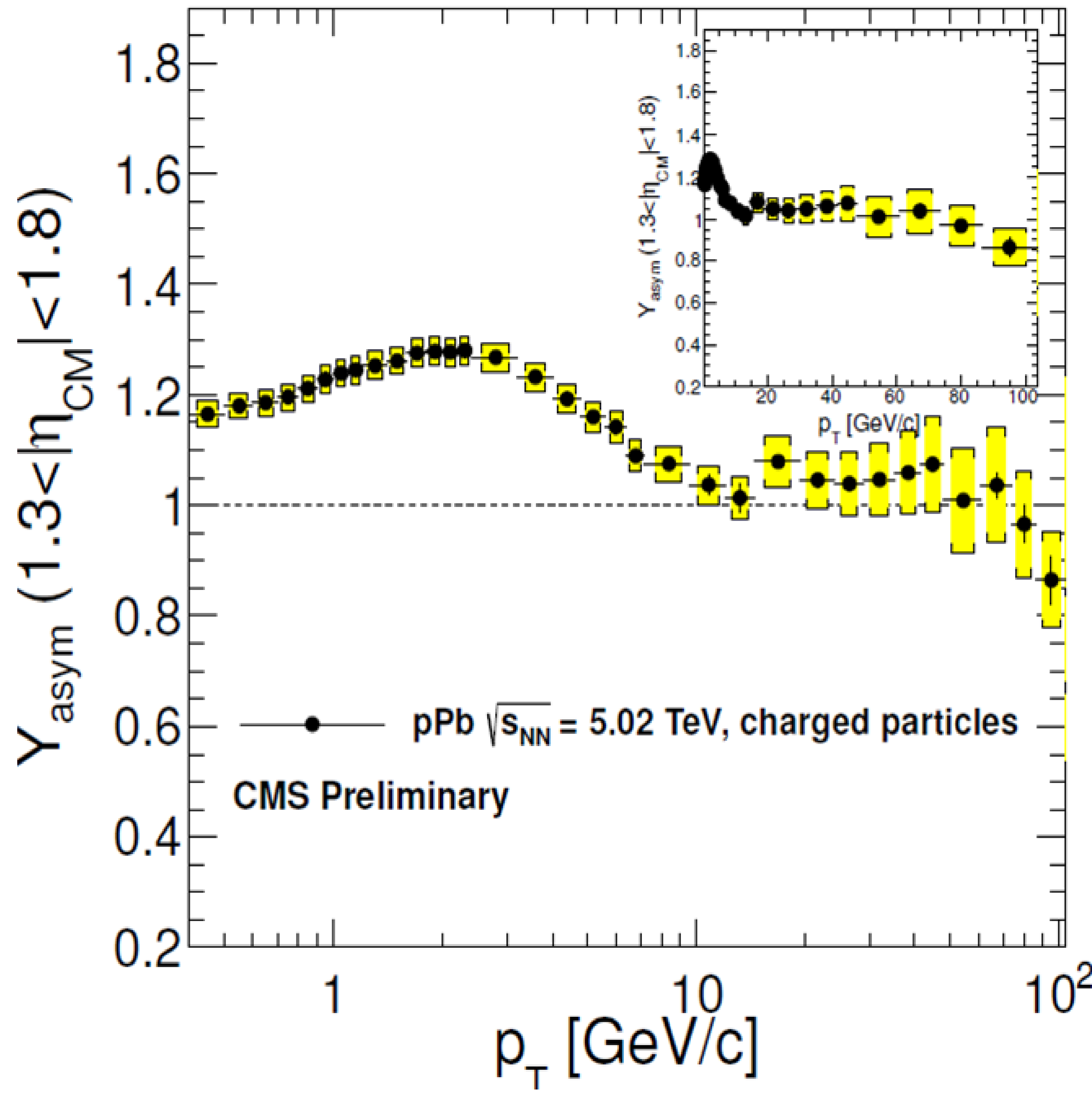
scale K/π spectra to backward rapidity according to CMS measurements

✓ lower limit of decay muons: $Y_{asym} = 1$

✓ upper limit: 2 x the asymmetry measured by CMS (maximum of the upper limit is ~2.6)

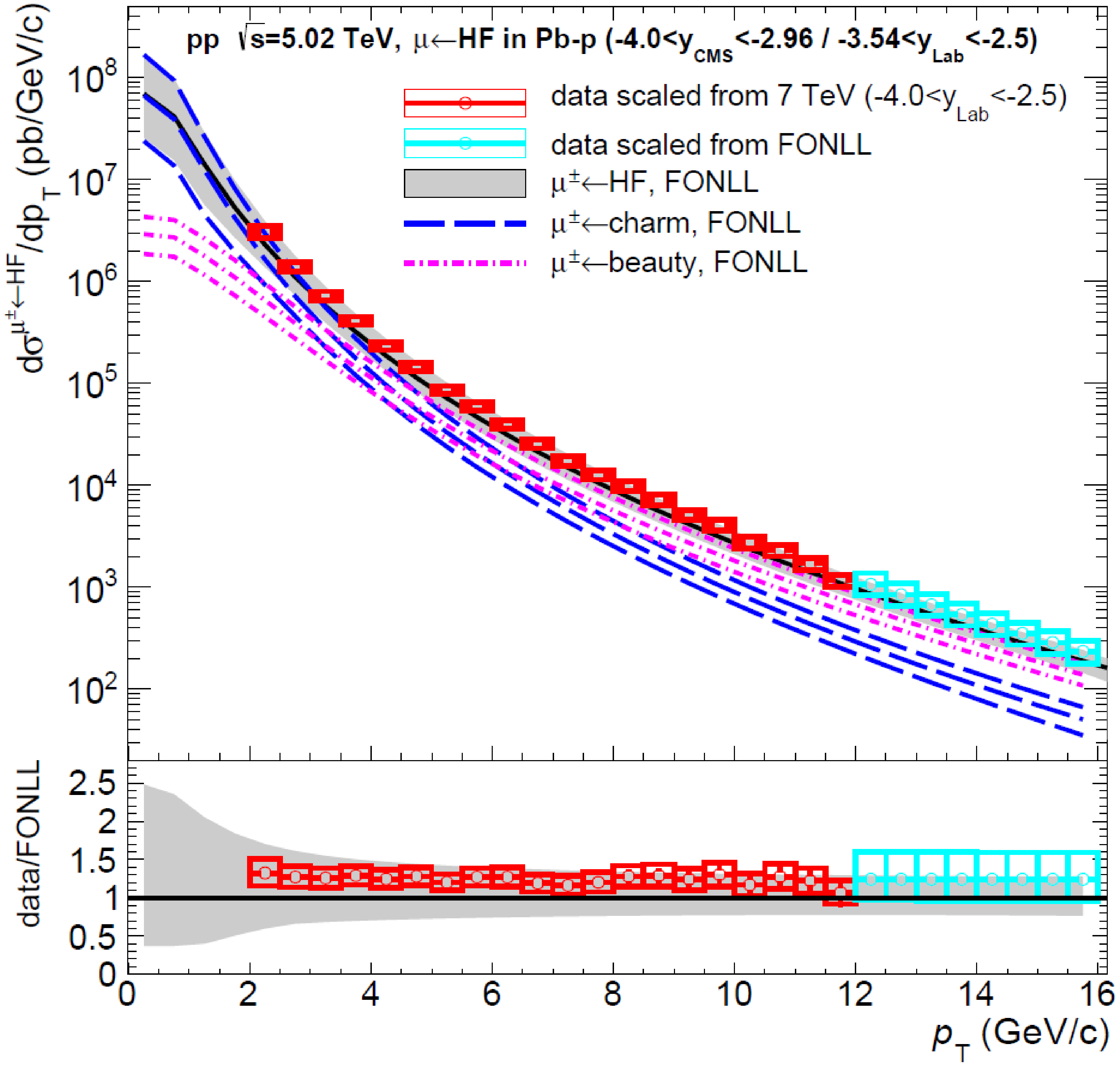
$$F_{mean} = \frac{a+b}{2} \qquad \sigma^2_{mean} = \frac{(a-b)^2}{12}$$

(where, a and b are the lower and upper limit, respectively; mean value with systematic uncertainty by assuming a uniform distribution.)

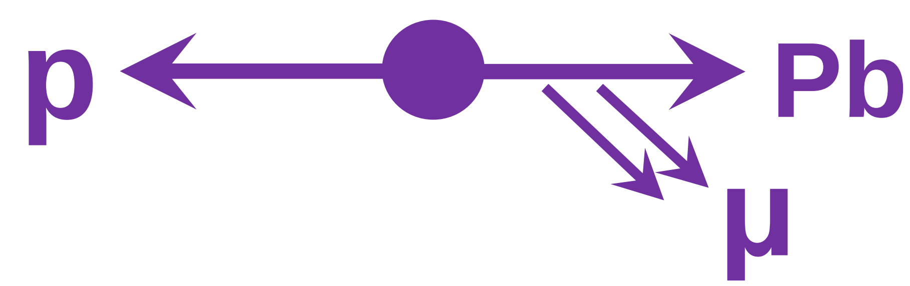


backward-to-forward ratio of charged particles within symmetric η bins [CMS PAS HIN-12-017]

Analysis strategy: pp reference



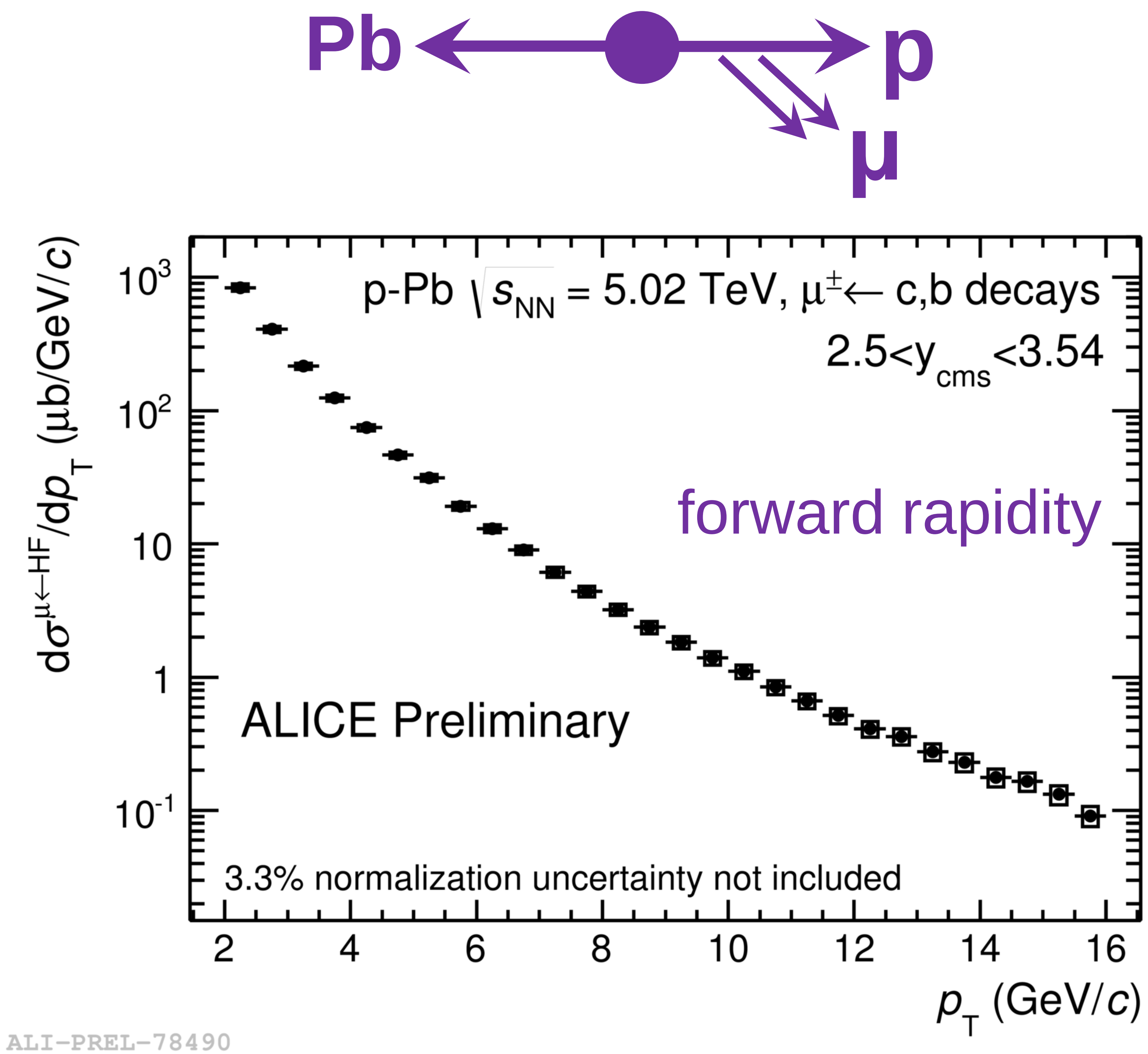
backward
(-4< y_{CMS} <-2.96)

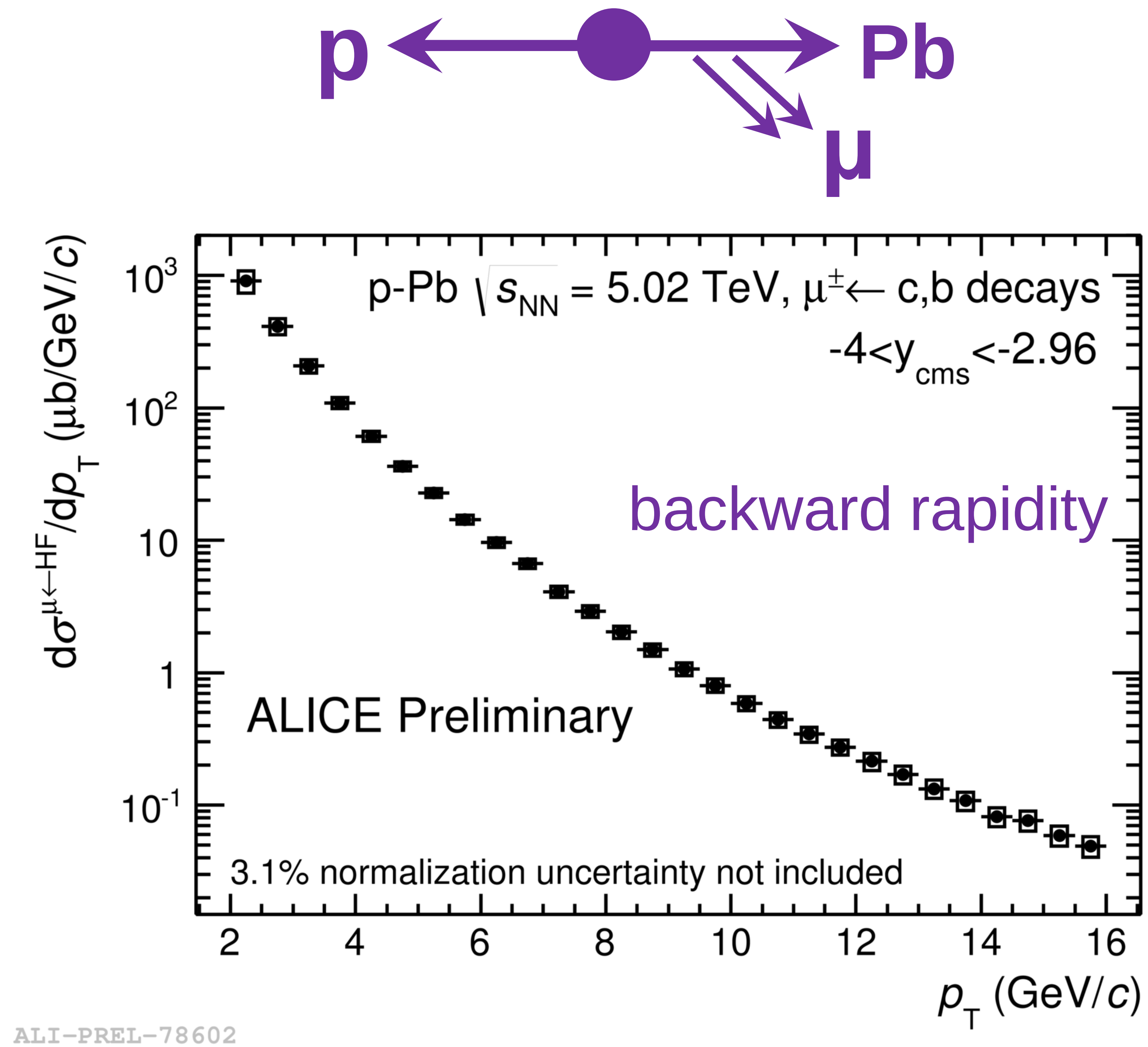


- obtained by a pQCD-based energy scaling of the p_T-differential cross sections measured at $\sqrt{s}$ = 7 TeV and extrapolated to higher p_T by using pQCD calculations when no measurement is available

arXiv:1107.3243 [hep-ph]

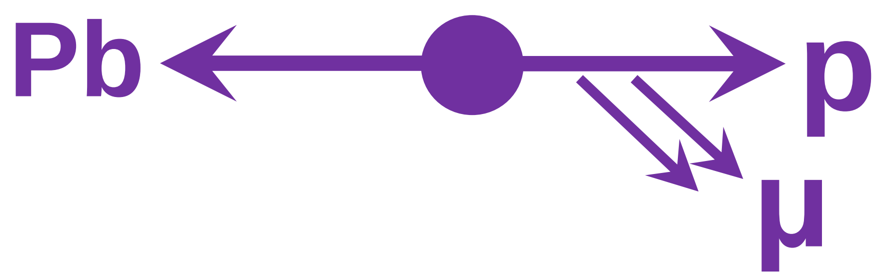
Heavy-flavour decay muons: p_T-differential cross sections

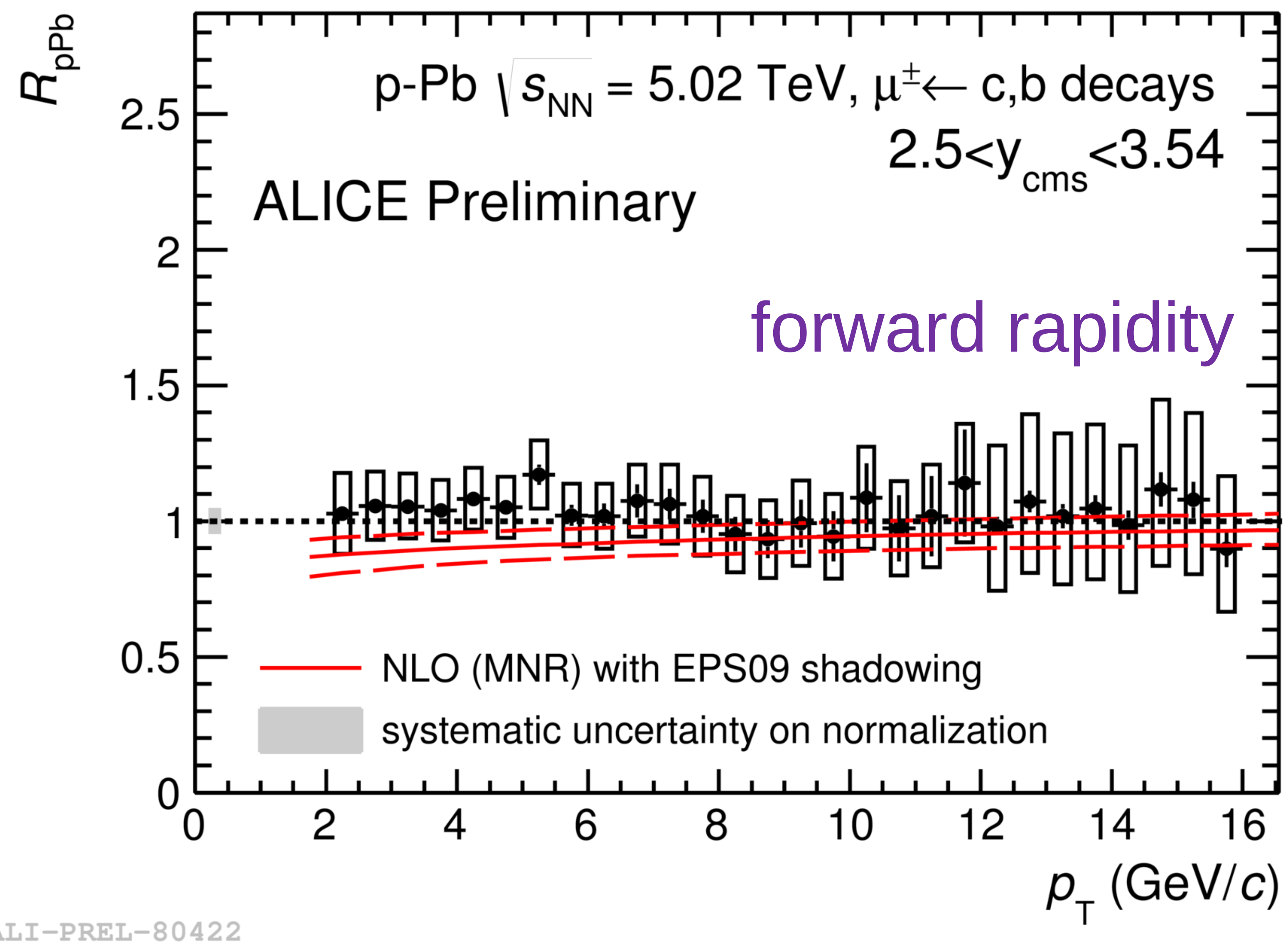


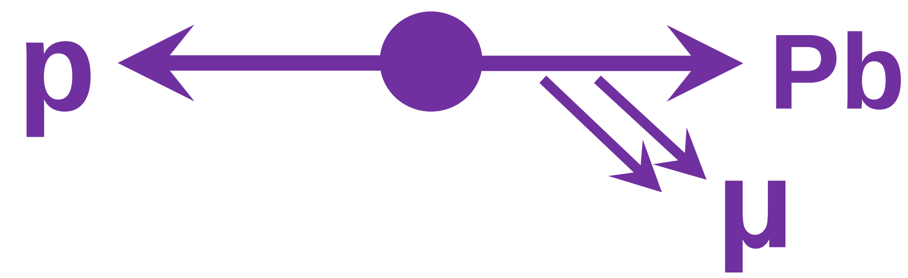


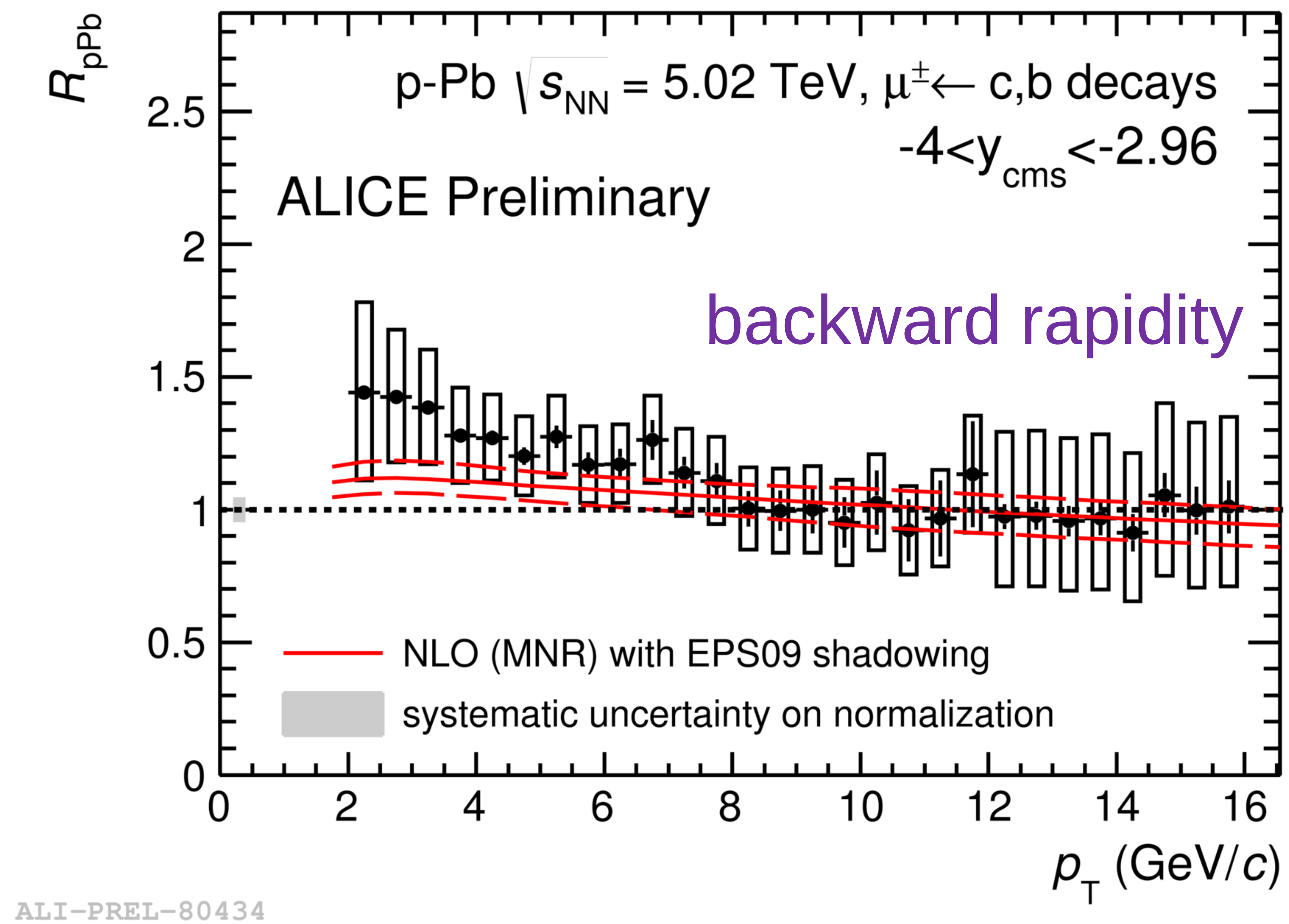
- p_T-differential production cross sections measured for heavy-flavour decay muons at forward and backward rapidities in $2<p_T<16$ GeV/c

Heavy-flavour decay muons: p_T-differential R_{pPb}





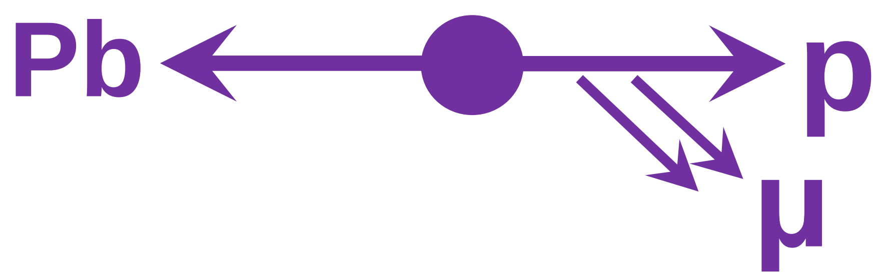


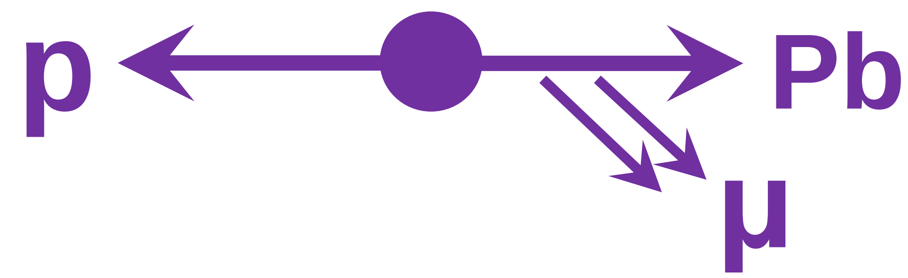


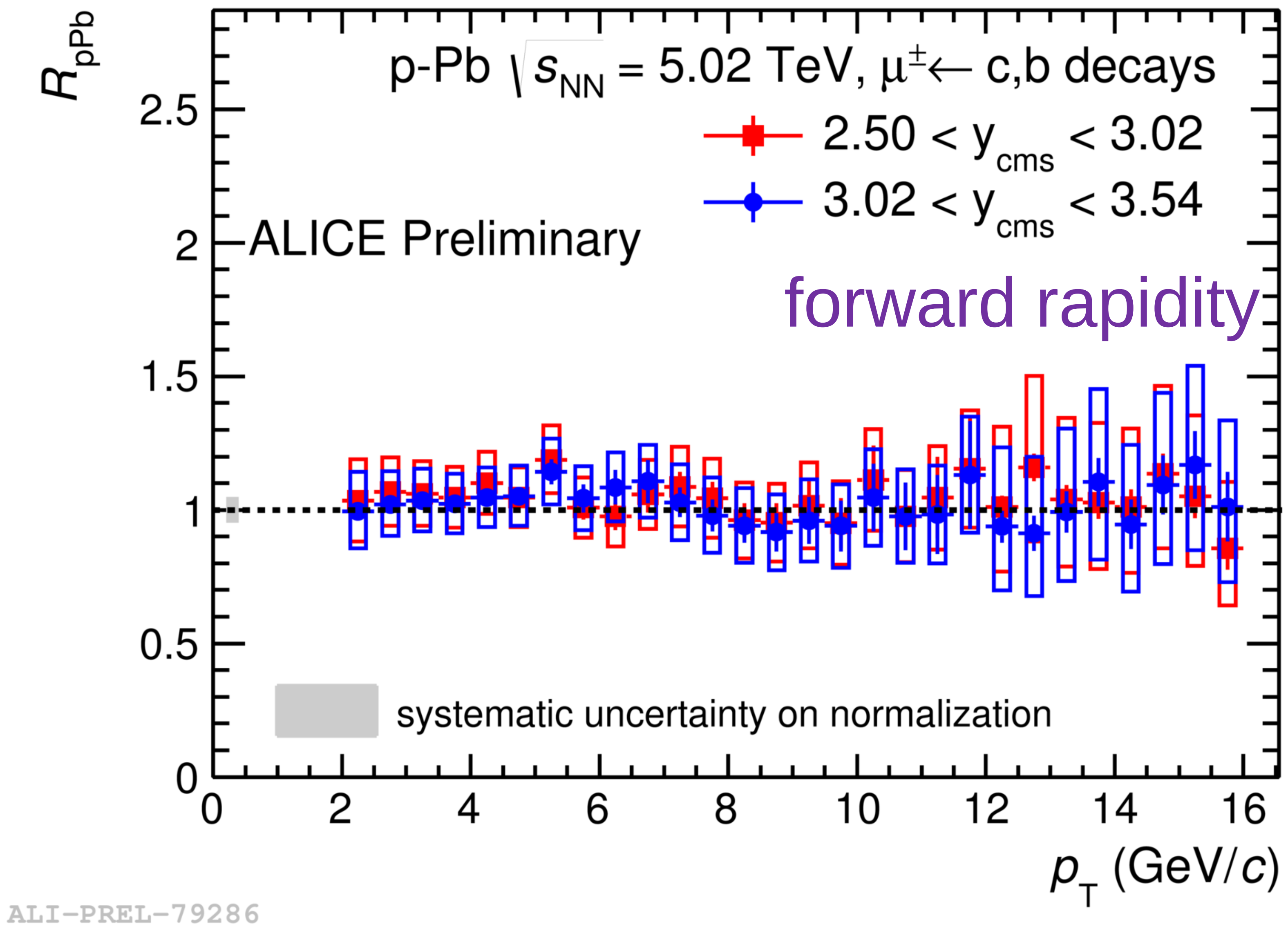
- R_{pPb} at forward rapidity*:* consistent with unity within uncertainties over the whole measured p_T range
- R_{pPb} at backward rapidity*:* slightly larger than unity in $2<p_T<4$ GeV/c and close to unity at higher p_T
- Within uncertainties, data can be described by perturbative QCD calculations with EPS09 parameterization of shadowing

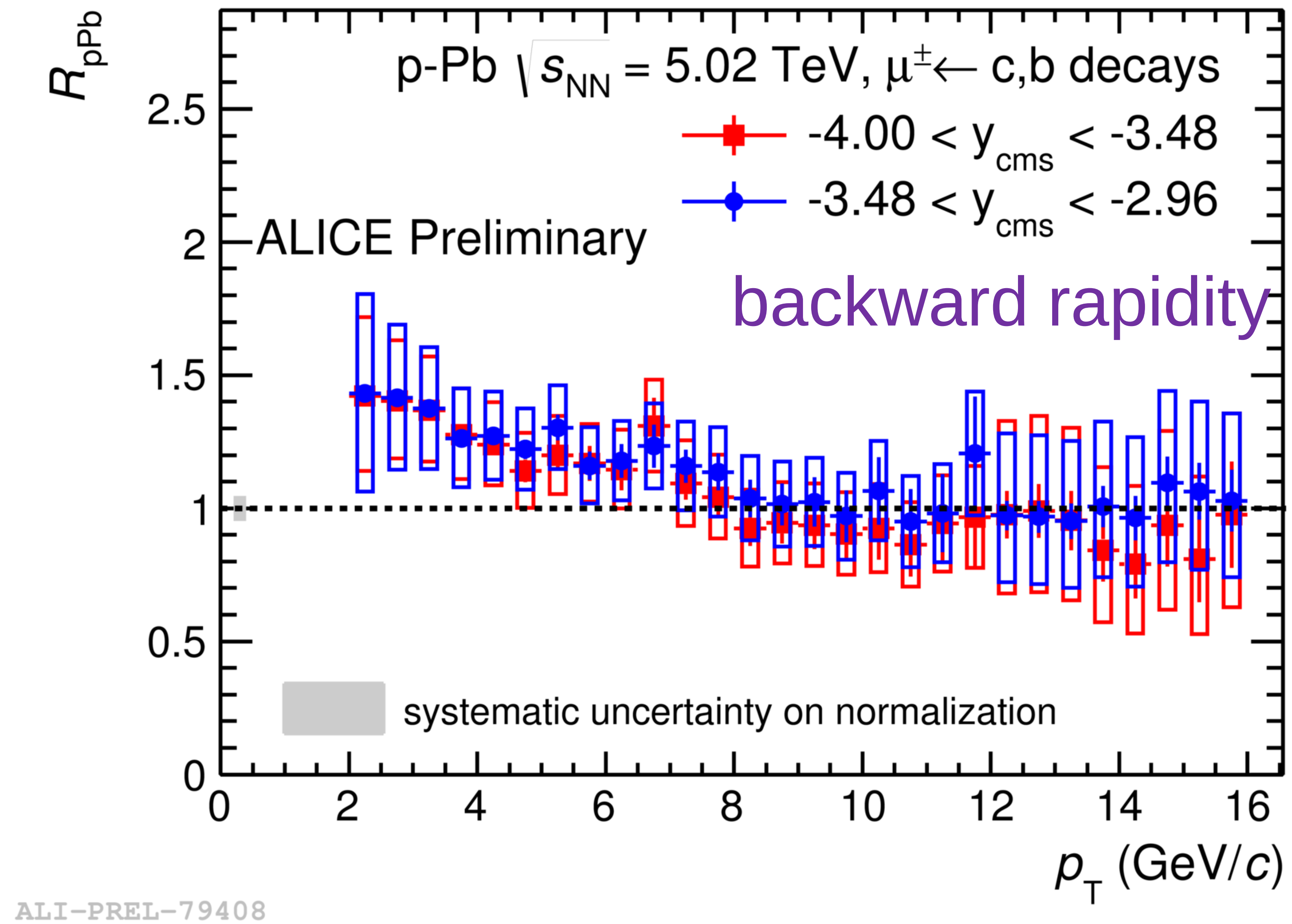
pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065

Heavy-flavour decay muons: R_{pPb} within sub-rapidity bins









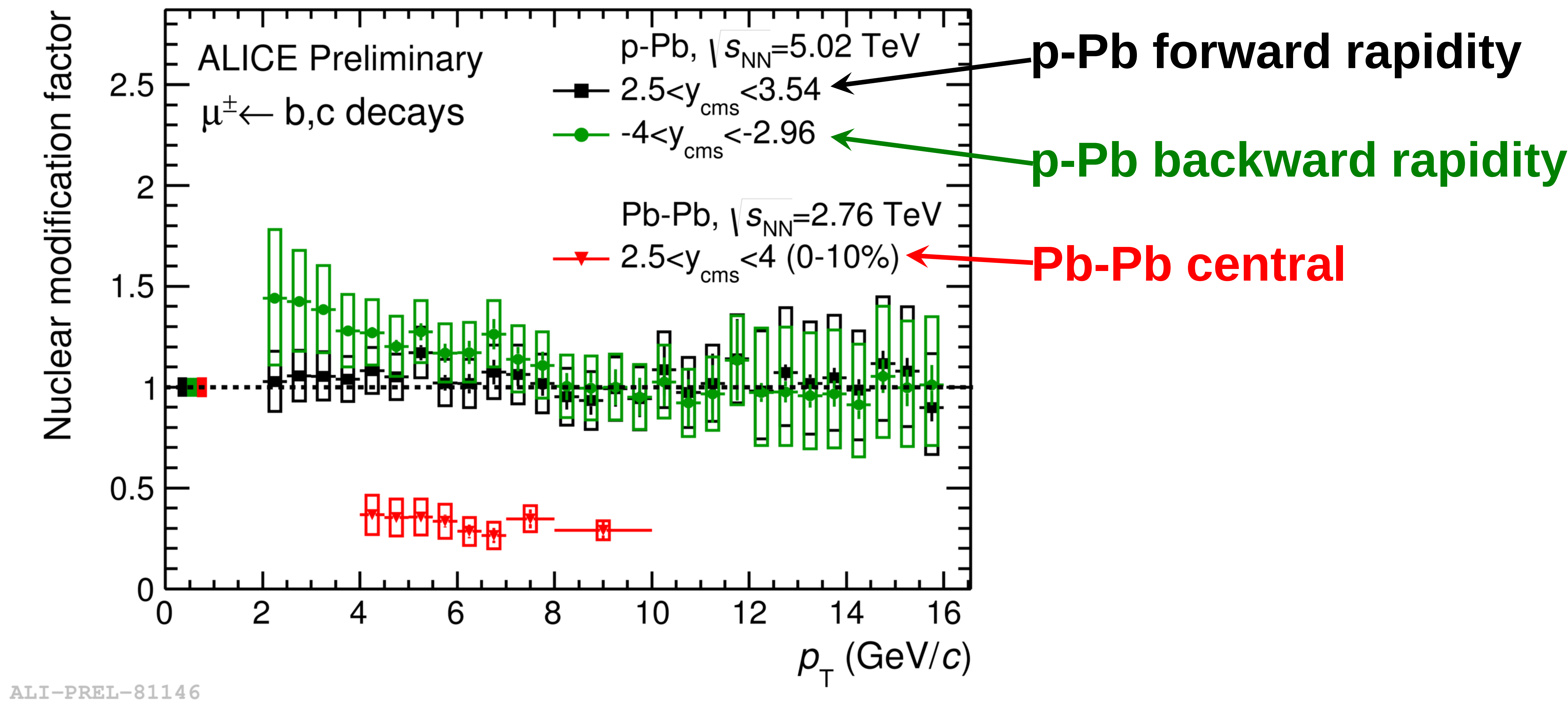
$2.50 < y_{\mathrm{CMS}} < 3.02$
$3.02 < y_{\mathrm{CMS}} < 3.54$

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

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

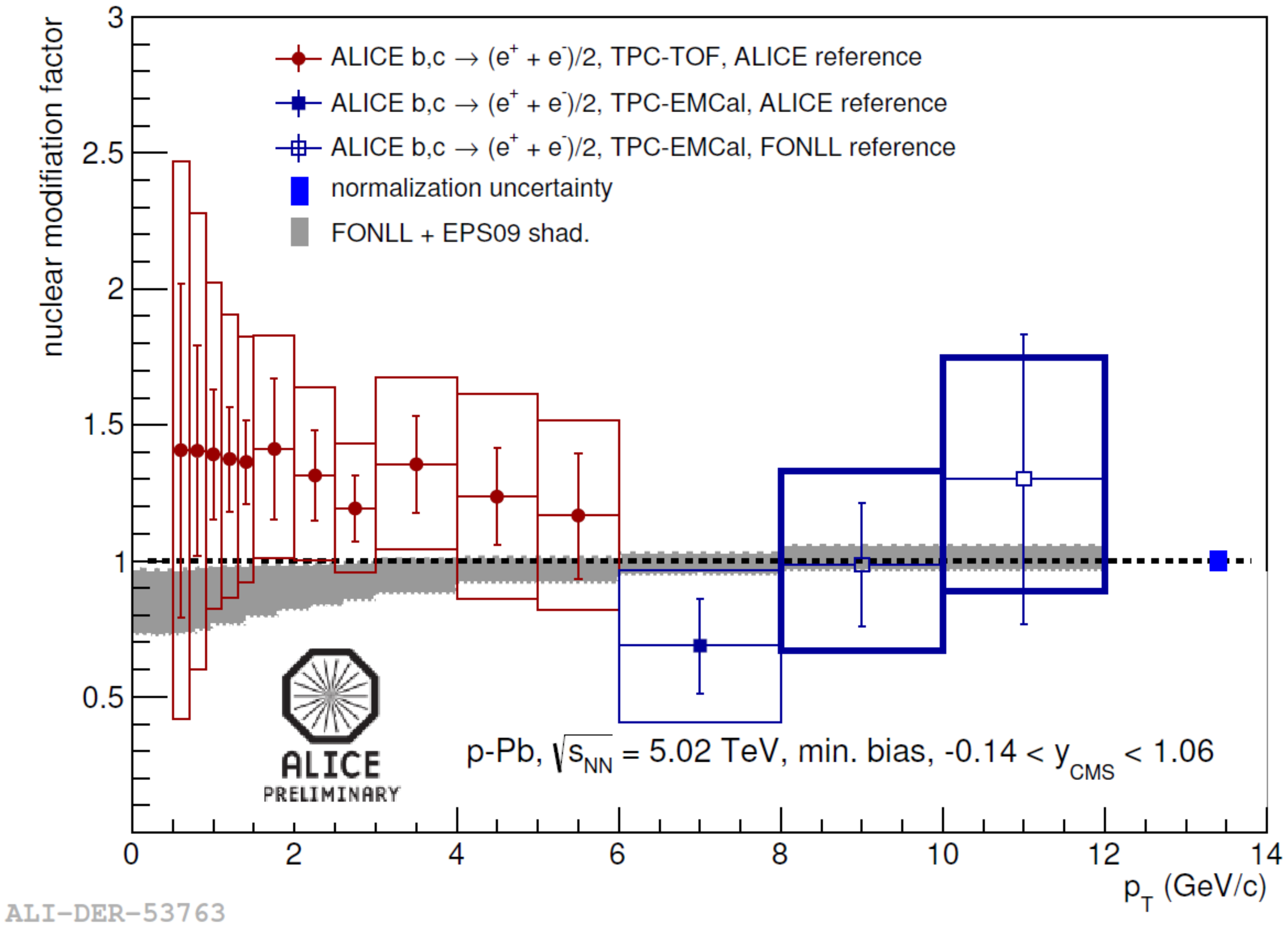
Comparison with R_{PbPb}

Pb-Pb: ALICE Collaboration, Phys. Rev. Lett. 109, 112301 (2012)

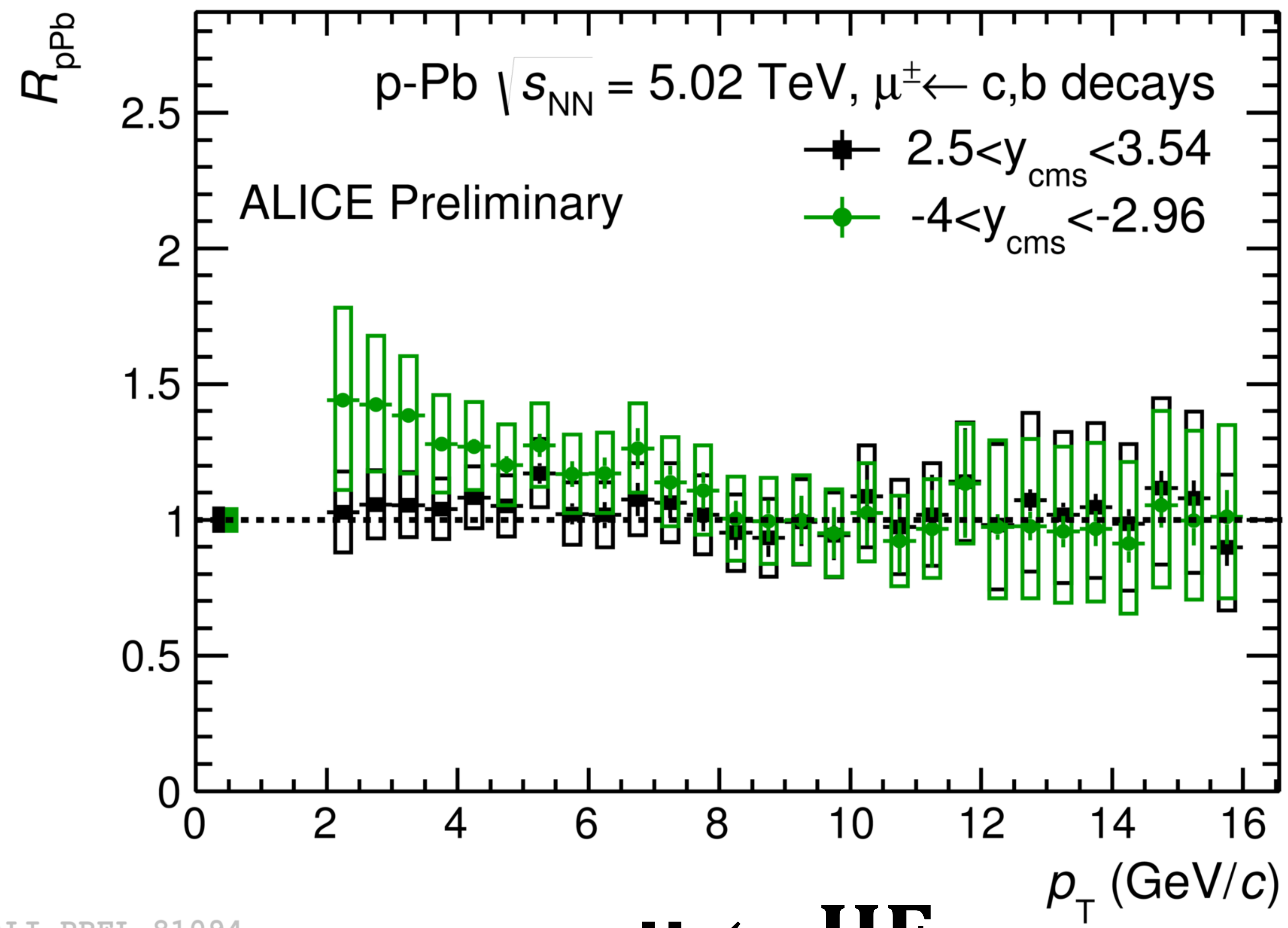


- R_{PbPb}: suppression by a factor of 3-4 in 4<p_T<10 GeV/*c* in the 10% most central collisions
- R_{pPb}: consistent with unity for p_T>4 GeV/c at both forward and backward rapidity
- **Suppression** observed **in central Pb-Pb** collisions is a **hot and dense medium effect**

Comparison with heavy-flavour decay electrons



e ← HF

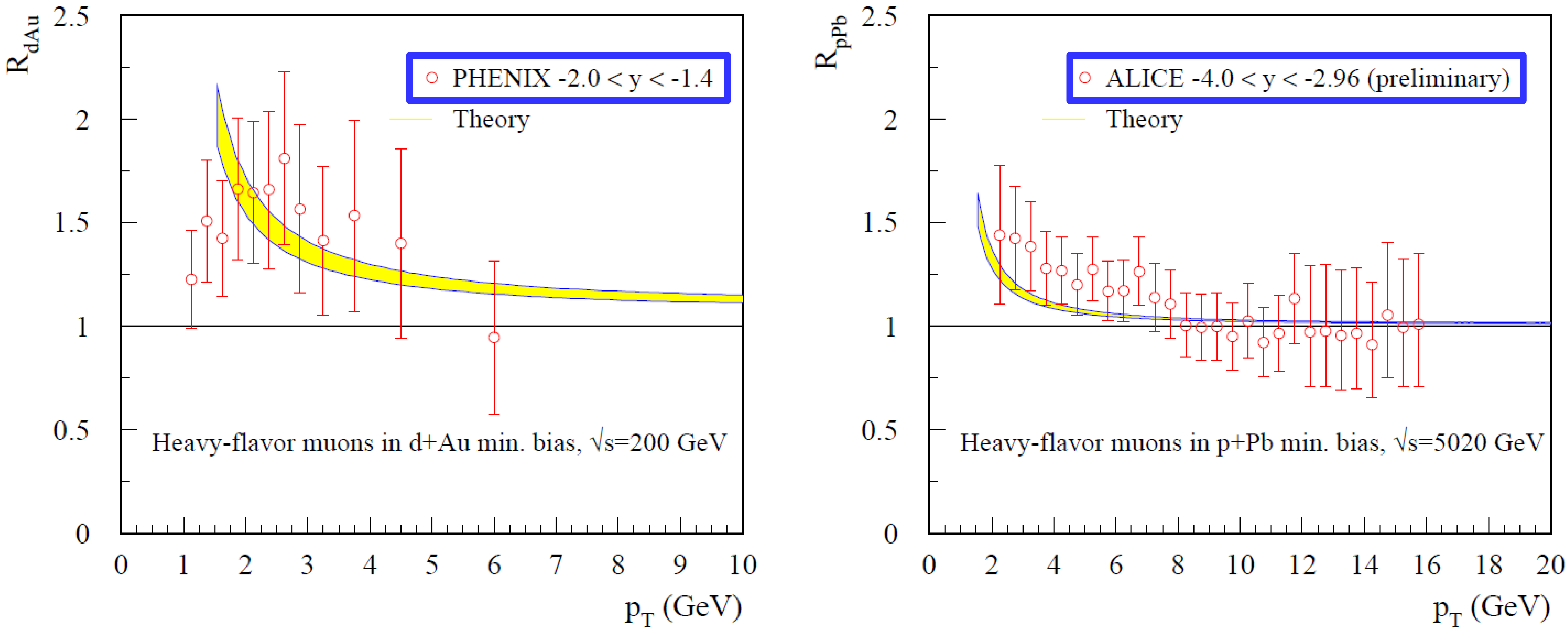


μ ← HF

- Within uncertainties, R_{pPb} of **electrons from heavy-flavour decays**
  - ✓ consistent with unity
  - ✓ data can be described by the perturbative QCD calculations
  - ✓ **consistent** with the ones of **muons from heavy-flavour decays** in the overlap p_T region
- p_T correlation between heavy-flavour meson and electron (at mid-rapidity) is similar with the one between heavy-flavour meson and muon (at forward rapdity)

Comparison with PHENIX at backward rapidity

1409.2494 [hep-ph]

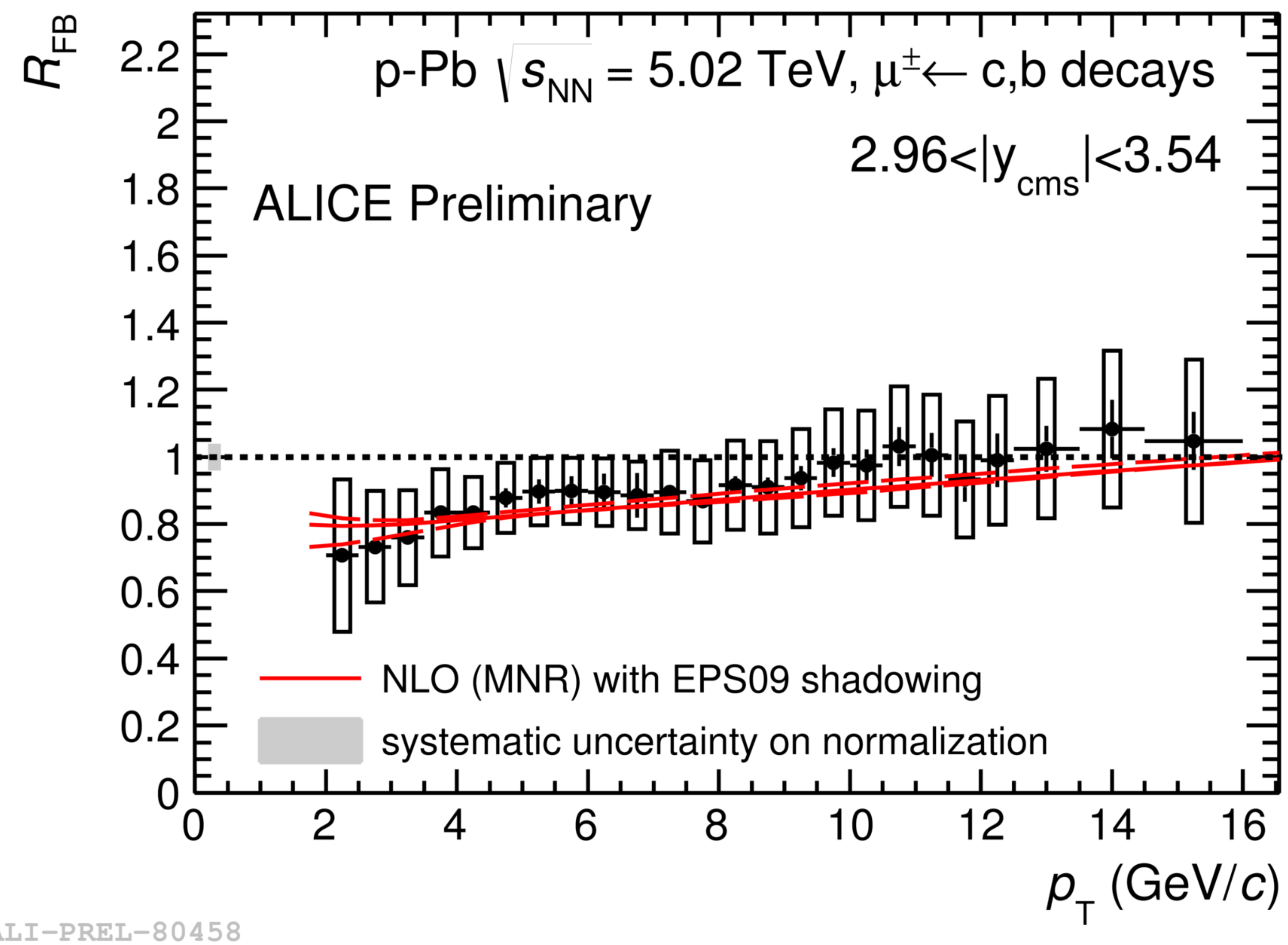


- Results of PHENIX and ALICE are based on different energy and acceptance => compared with the predictions from same model
- Model predictions performed at backward rapidity
  - ✓ perturbative QCD calculations including both initial-state and final-state interactions
  - ✓ incoherent multiple scattering effect can enhance the heavy meson cross section in the intermediate p_T region => enhancement behavior found in the semi-leptonic decay channel
- Within uncertainties, data can be well described => consistent between PHENIX and ALICE

Heavy-flavour decay muons: p_T-differential R_{FB}

Forward-to-backward ratio

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



- R_{FB}: systematically smaller than unity in 2<p_T<4 GeV/c and close to unity at higher p_T
- Within uncertainties, data can be described by perturbative QCD calculations with EPS09 parameterization of shadowing

pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295; EPS09: K. J. Eskola et al., JHEP 04 (2009) 065

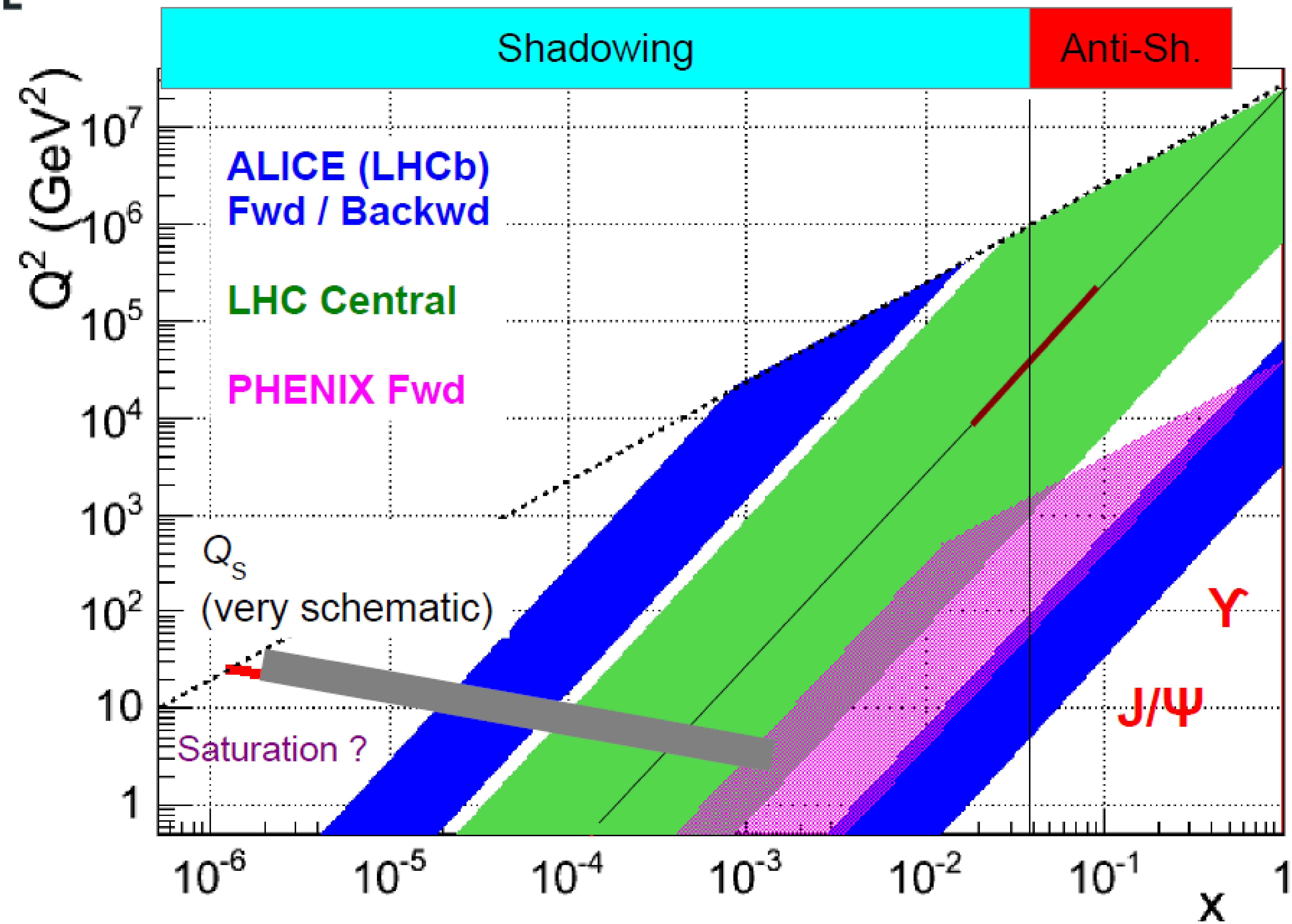
Conclusion

- Cold nuclear matter effects on heavy-flavour decay muons assessed at forward and backward rapidity via the nuclear modification factor R_{pPb} and forward-to-backward ratio R_{FB}
- R_{pPb}
  - ✓ forward (=p-going) rapidity: compatible with unity in the measured p_{T} range
  - ✓ backward (=Pb-going) rapidity: compatible with unity for p_{T} >4 GeV/c, slightly larger than unity in 2< p_{T} <4 GeV/c
- R_{FB}
  - ✓ systematically smaller than unity in 2<p_{T}<4 GeV/*c* and close to unity at higher p_{T}
- Models implementing cold nuclear matter effects describe the data within uncertainties
- **Suppression** observed **in central Pb-Pb** collisions at forward rapidity is due to **hot and dense medium effect**
- Paper proposal done, writing of first draft ongoing

Analysis ongoing: measurements vs. event activity

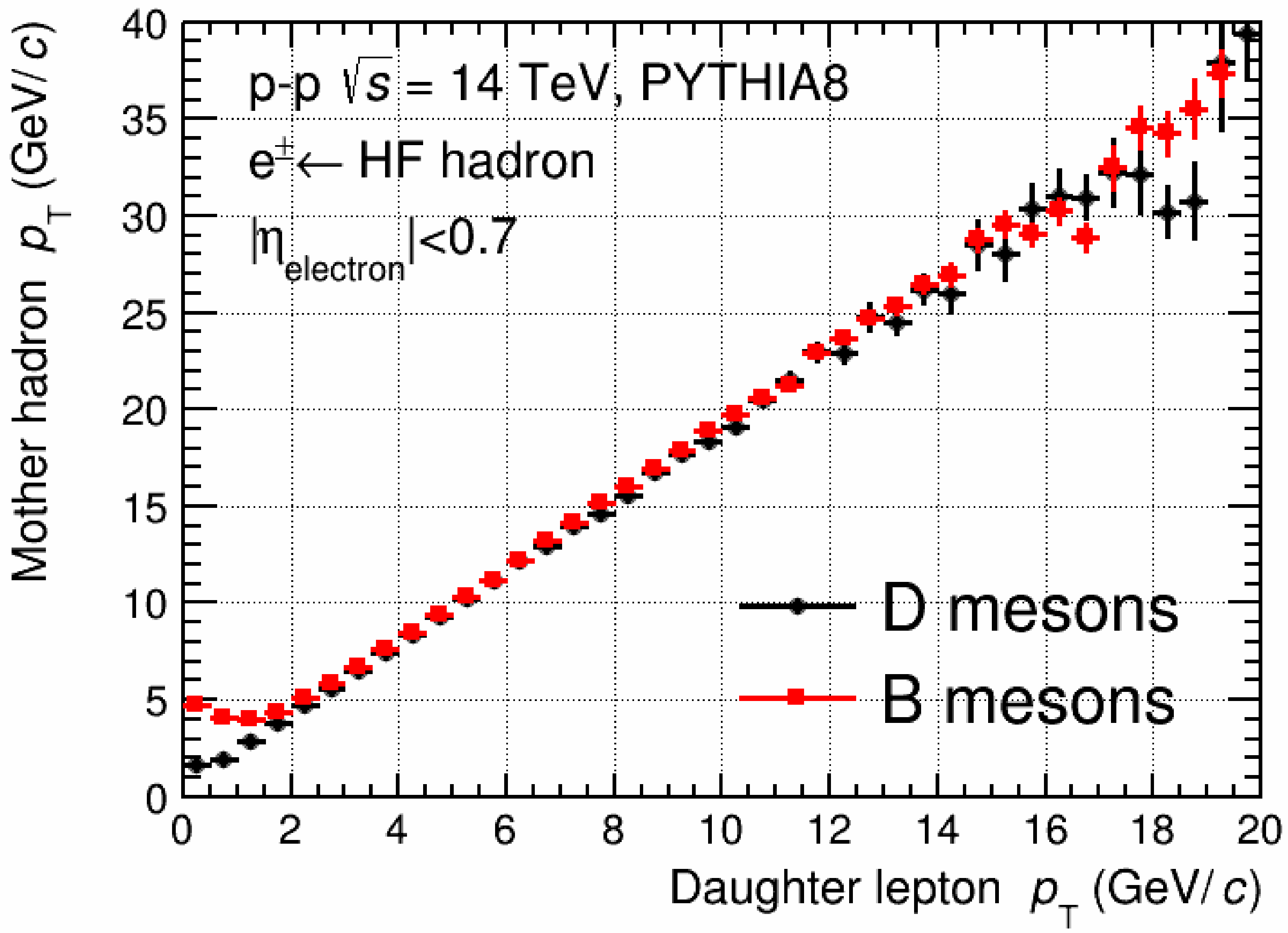
Backup

Where are we ?

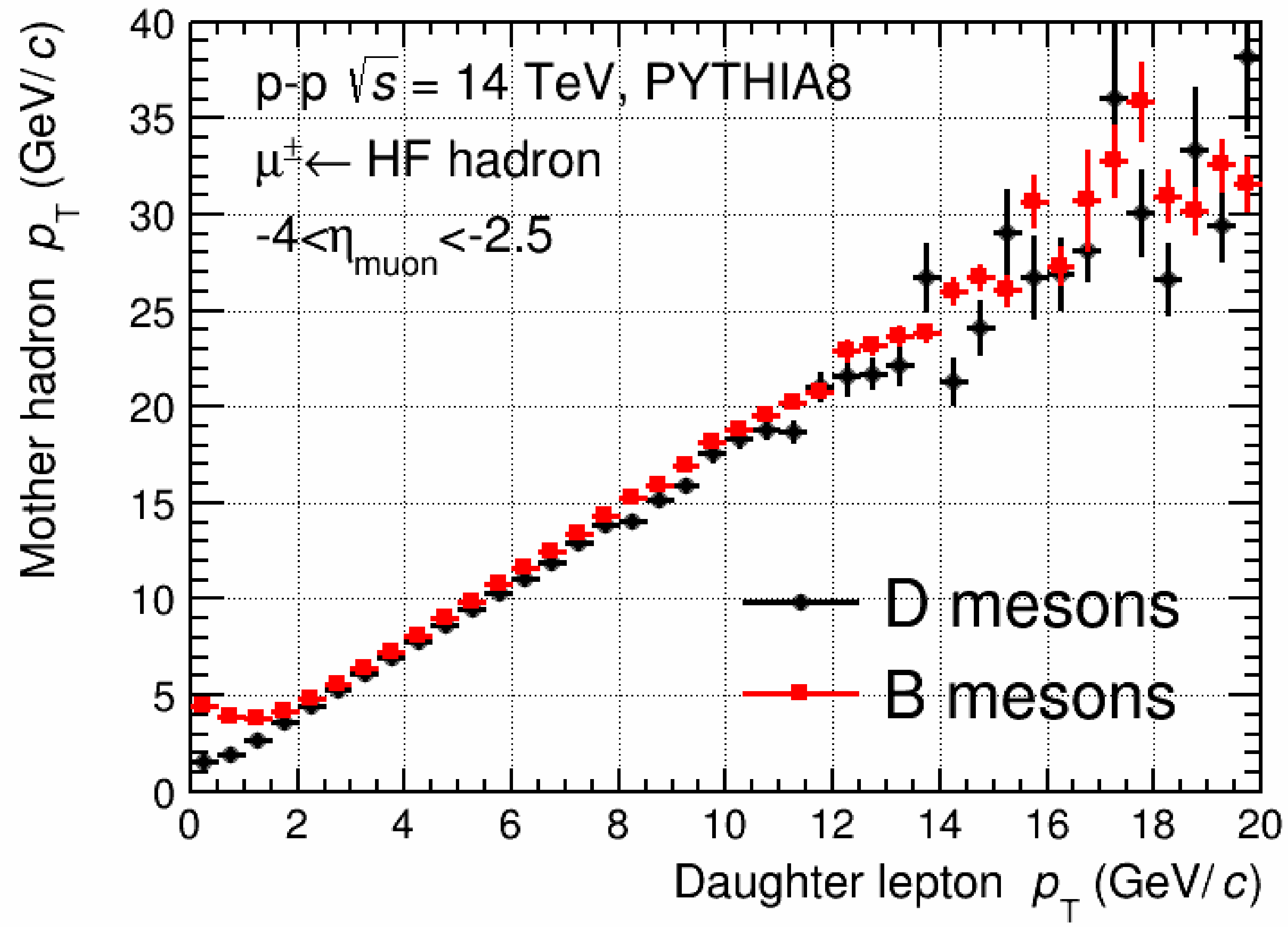


Possibility to approach saturation scale in perturbative region.
Most of measurement performed in shadowing region.

Decay kinematics



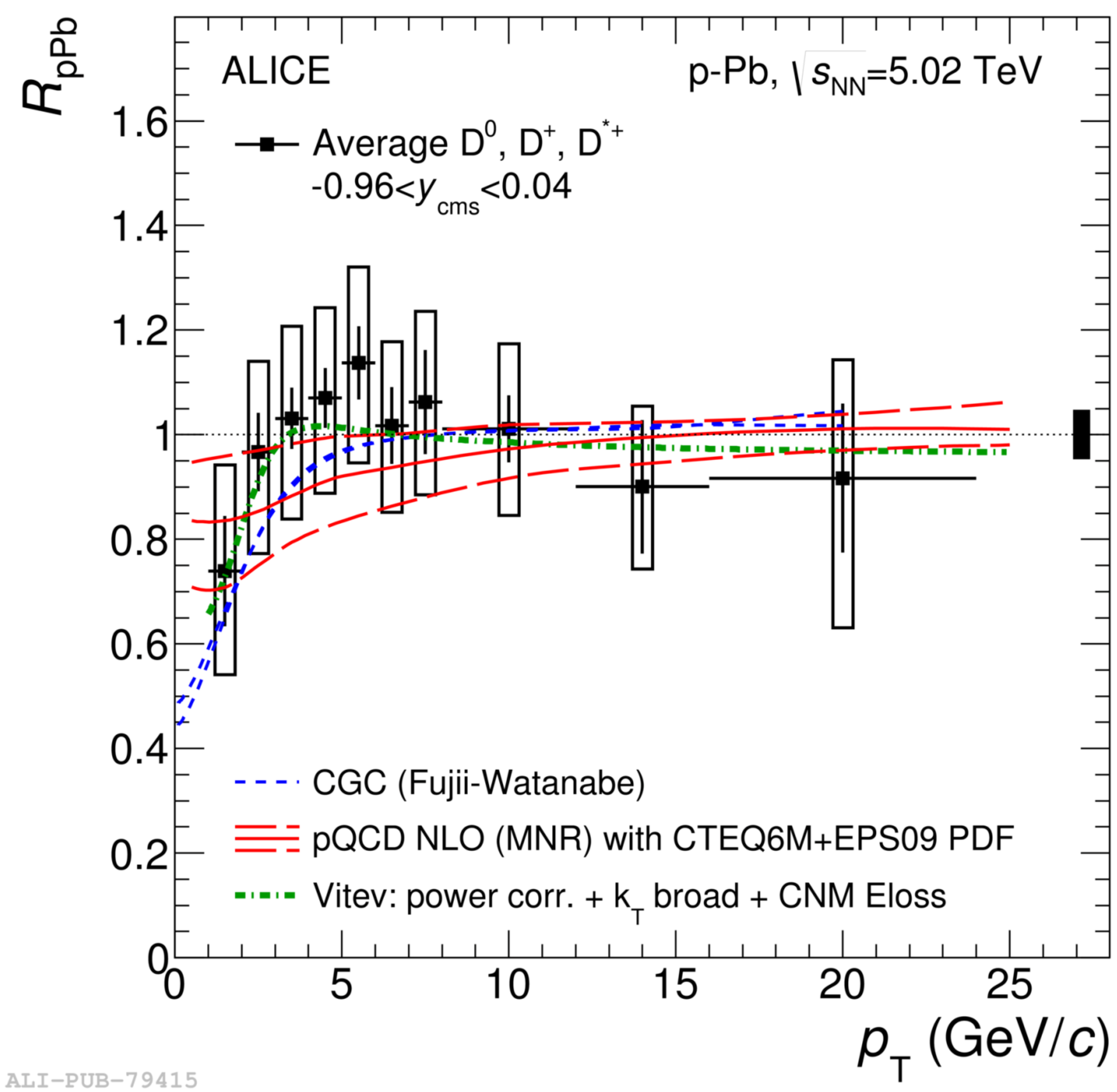
e ← HF

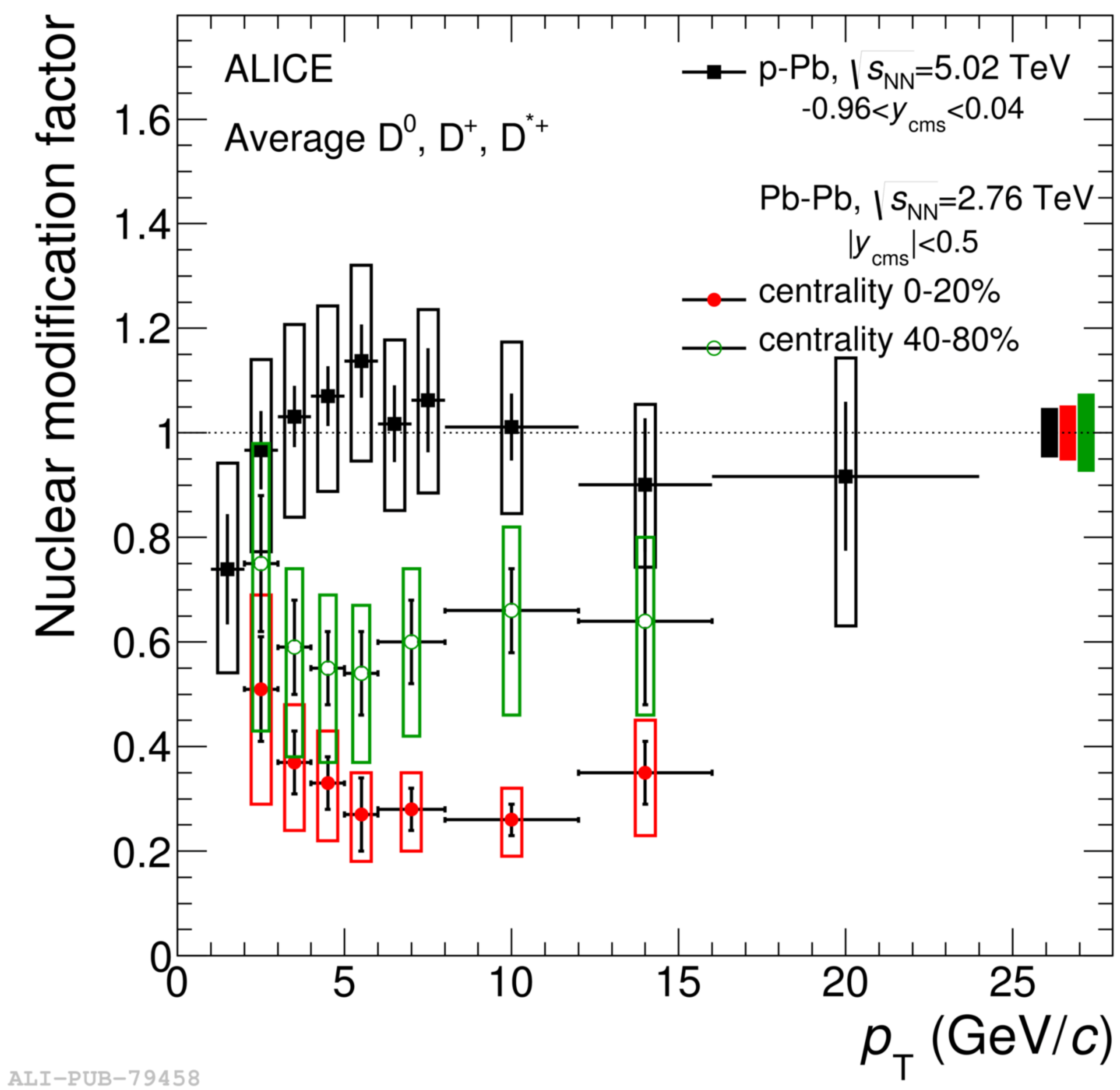


μ ← HF

Results of D-meson

ALICE Collaboration, arXiv:1405.3452 [nucl-ex]





- D-meson R_{pPb} can be described by Color Glass Condensate (CGC) calculations, perturbative QCD calculations with EPS09 nuclear PDF and a model including energy loss in cold nuclear matter, nuclear shadowing and k_T-broadening
- R_{AA}: suppression by a factor of 4-5 at p_T ~ 10 GeV/c in the 20% most central collisions
- **Suppression** observed **in central Pb-Pb** collisions is a **hot medium effect**

CGC: H.Fujii and K. Watanable, arXiv: 1308.1258; pQCD NLO (MNR): Nucl. Phys. B 373 (1992) 295
EPS09: K. J. Eskola et al., JHEP 04 (2009) 065; Vitev: Phys. Rev. C75 (2007) 064906

Heavy-flavour hadron decay muons: systematic uncertainty on R_{pPb}

Systematics	p-Pb (forward rapidity)	p-Pb (backward rapidity)
T_{pA}	3.6% (for 0-100%)	
Normalization to Min. Bias	1%	
Background subtraction	32% maximum (p_{T}<12 GeV/c)	40% maximum (p_{T}<12 GeV/c)
Trigger efficiency	1% (5%) for Low (High) p_{T} Muon Events	
Tracking efficiency	2%	3%
Matching efficiency	0.5%	
Misalignment	1% x p_{T}	
pp reference	< 15% (30%) maximum in p_{T} <12 GeV/c (p_{T}>12 GeV/c); < 3% for rapidity extrapolation	
Additional uncertainty on signal (no background in p_{T}>12 GeV/c)	3%	6%

- $\mathrm{K}^{\pm}/\pi^{\pm}$ decay muon background and pp reference are the dominant sources of systematic uncertainties

Reference between D-meson and HFM (1/3)

D-meson

$$\frac{d\sigma^{\mu\leftarrow HF}_{pp\,(5\,TeV)}}{dp_T} = \frac{\frac{d\sigma^{FONLL}_{pp\,(5\,TeV)}}{dp_T}}{\frac{d\sigma^{FONLL}_{pp\,(7\,TeV)}}{dp_T}} \cdot \frac{d\sigma^{\mu\leftarrow HF}_{pp\,(7\,TeV)}}{dp_T} \qquad (0 < p_T < 25\ GeV/c)$$

pp@ 5.02 TeV

energy scaling factor

inputs from pp@ 7 TeV

measurement at 7 TeV

$$\frac{d\sigma^{\mu\leftarrow HF}_{pp\,(7\,TeV)}}{dp_T} = \begin{cases} \frac{d\sigma^{\mu\leftarrow HF}_{pp\,(7\,TeV,\ data)}}{dp_T} & (p_T < 16\ GeV/c) \\ K_{7\,TeV} \cdot \frac{d\sigma^{FONLL}_{pp\,(7\,TeV)}}{dp_T} & (16 < p_T < 25\ GeV/c) \end{cases}$$

shape from FONLL

scaling factor: match pp data at 7 TeV in $5 < p_T < 16$ GeV/c

Reference between D-meson and HFM (2/3)

energy scaling factor

measurement pp@ 7 TeV

HFM

$$\frac{d\sigma^{\mu\leftarrow HF}_{pp\,(5\,TeV)}}{dp_T} = \begin{cases} \dfrac{\frac{d\sigma^{FONLL}_{pp\,(5\,TeV)}}{dp_T}}{\frac{d\sigma^{FONLL}_{pp\,(7\,TeV)}}{dp_T}} \cdot \dfrac{d\sigma^{\mu\leftarrow HF}_{pp\,(7\,TeV)}}{dp_T} & (0 < pT < 12\ GeV/c) \\[2ex] K_{5\,TeV} \cdot \dfrac{d\sigma^{FONLL}_{pp\,(5\,TeV)}}{dp_T} & (12 < p_T < 16\ \mathrm{GeV}/c) \end{cases}$$

pp@ 5.02 TeV

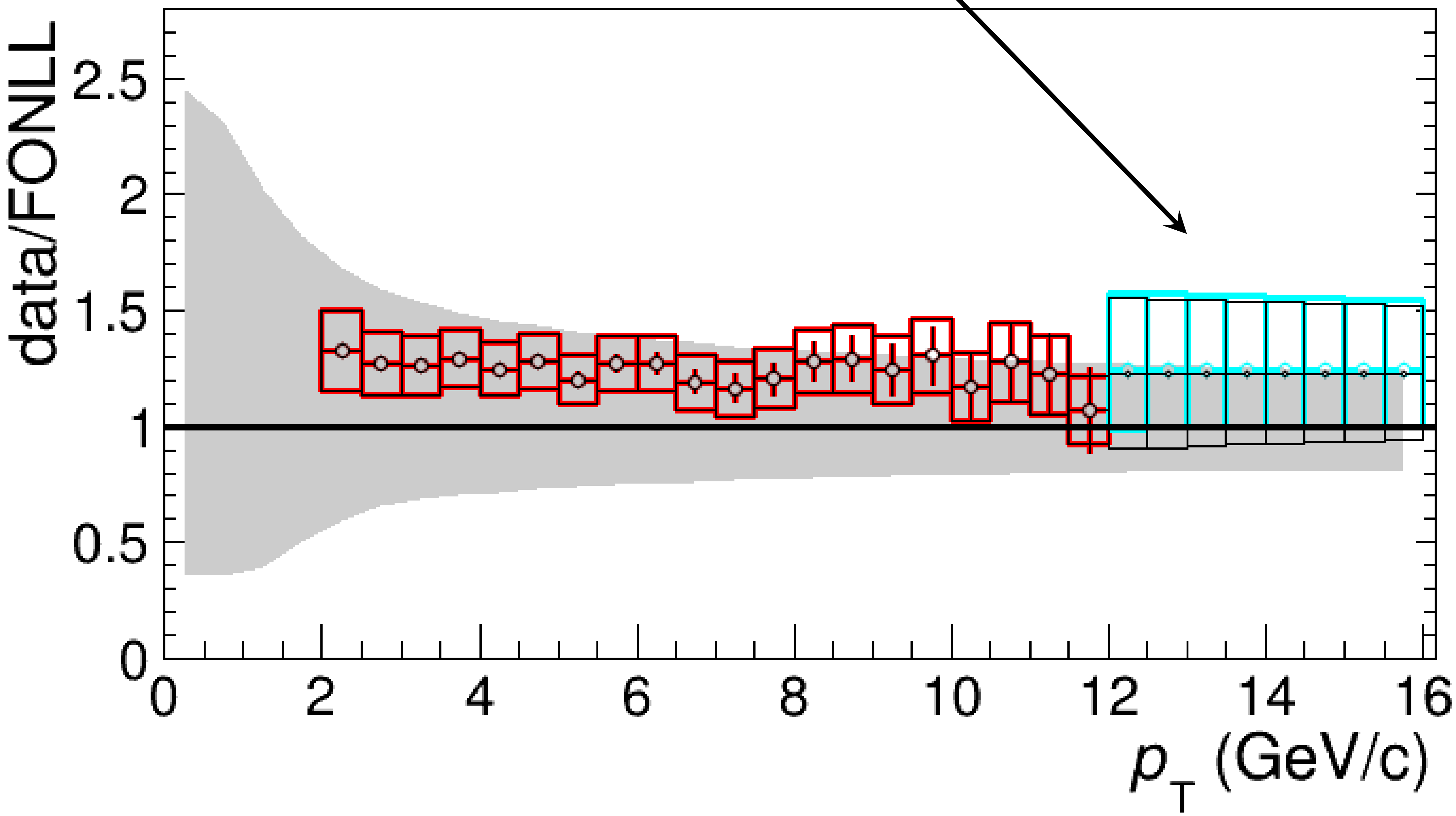
shape from FONLL

scaling factor: match pp@ 5.02 TeV in 6<p_T<12 GeV/c

- parameter K indicates the deviation of data w.r.t the FONLL prediction
  - ✓ if there is no energy dependence, i.e. K(E) ~ const., the two strategies would be similar

reference between D-meson and HFM (3/3)

- parameter K
  - ✓ 1.24 and 1.23 using D-meson and HFM strategy, respectively;
  - ✓ 0.8% deviation;



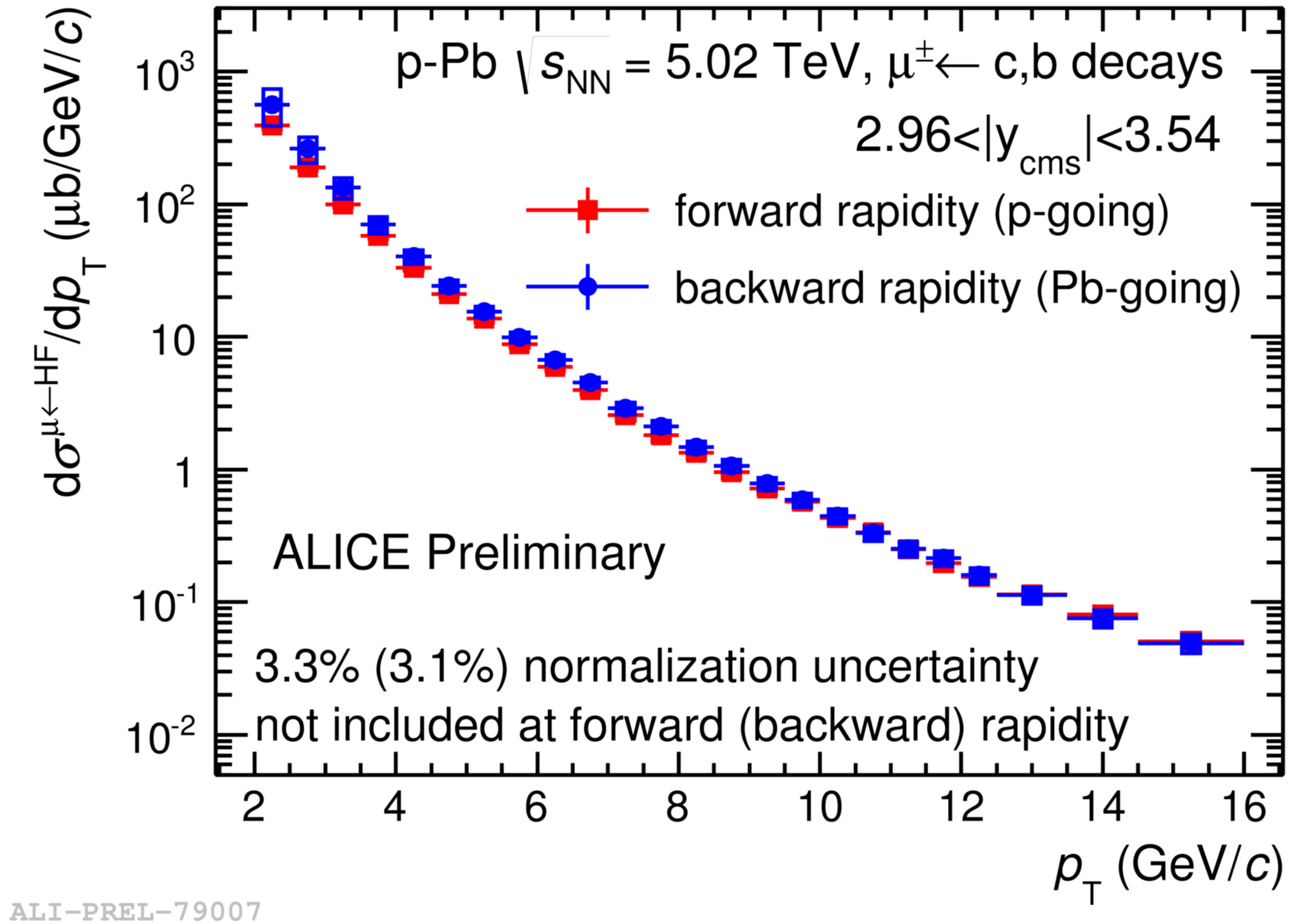
Black: using D-meson strategy in $2<p_T<16$ GeV/c

Red: using HFM strategy in $2<p_T<12$ GeV/c

Light blue: using HFM strategy in $12<p_T<16$ GeV/c

- same results expected between the two strategies in $2<p_T<12$ GeV/c
- similar results found between the two strategies in $12<p_T<16$ GeV/c: controlled by the parameter K

Cross section within overlap acceptance



PHENIX results

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