Open heavy-flavour and electroweak boson measurements via the (di-)muonic decay channel with ALICE at the LHC

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National Research Foundation

iThemba LABS
Laboratory for Accelerator Based Sciences

ALICE

Why heavy flavours?

Heavy quarks (**charm** and **beauty**) are produced at the beginning of the collision in high-Q^2 scatterings

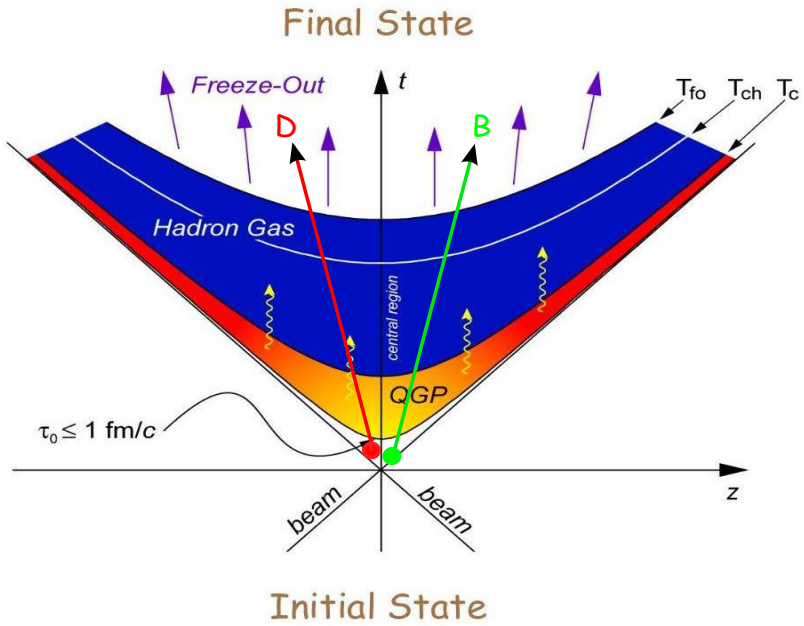
In **proton-proton collisions**:

- high cross section at the LHC w.r.t to RHIC

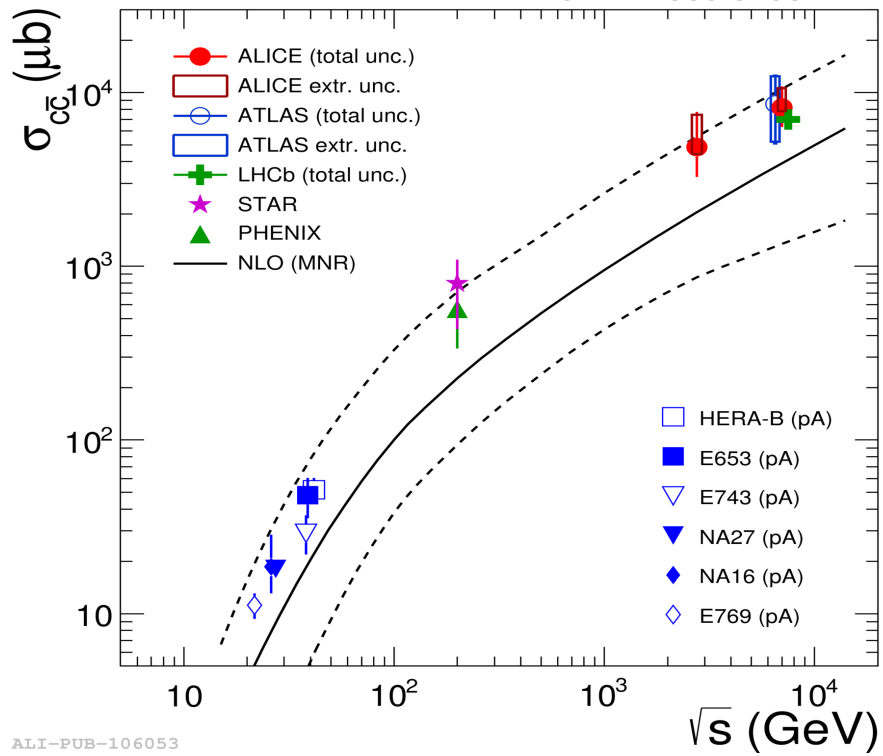
  $\sigma_{c\bar{c}}(LHC) \sim 10\sigma_{c\bar{c}}(RHIC)$ JHEP 07 (2012) 191

  $\sigma_{b\bar{b}}(LHC) \sim 50\sigma_{b\bar{b}}(RHIC)$

- test for pQCD calculations and reference for heavy-ion collisions



arXiv:1605.07569



· · · in **heavy-ion collisions**:

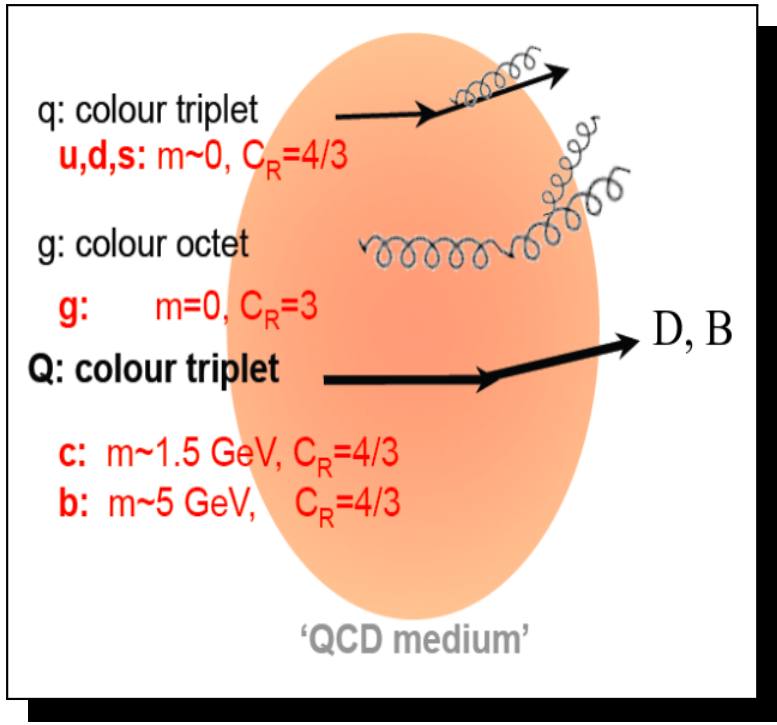
- experience the whole evolution of the QGP
- ideal probe for all the stages of the collision

Probing the medium with heavy flavours

- Heavy quarks lose energy in the medium via radiative and collisional processes
- Medium-induced radiative energy loss depends on:
  - the medium properties and path length (L)

    in the medium Nucl. Phys. B, 483:291–320, 1997
  - Casimir factor, C_R (color charge effect)

    Nucl. Phys. B, 483:291–320, 1997



  - dead-cone effect (mass of the partons, $\triangle E_{u,d,s} > \triangle E_c > \triangle E_b$) PLB 519 (2001) 199

Average energy loss: $\langle \triangle E \rangle \propto \alpha_s C_R L^2$, α_s - strong coupling constant

Phys. Rev. Lett. 30 (1973) 1343

Observables

Nuclear modification factor

Test whether A–A (p–A) can be described by incoherent superposition of $\langle N_{\rm coll} \rangle$ binary collisions

$$R_{AA(pA)} = \frac{1}{\langle T_{AA(pA)} \rangle} \frac{{\rm d}N_{AA}/{\rm d}p_{\rm T}}{{\rm d}\sigma_{\rm pp}/{\rm d}p_{\rm T}}$$

$\langle T_{AA(pA)} \rangle = N_{\rm coll}/\sigma_{NN}$, nuclear overlap function arXiv:nucl-ex/0302016

$R_{AA} = 1$ no medium effects

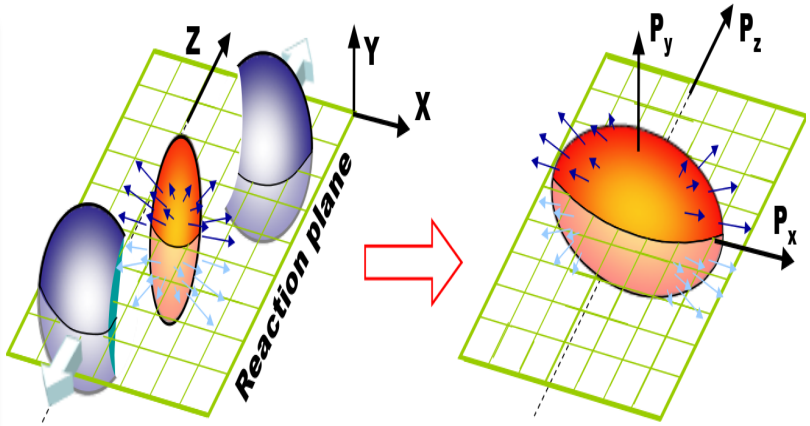
$R_{AA} < 1$: suppression of the yield

$R_{AA} > 1$: enhancement

Azimuthal anisotropy

$$\frac{{\rm d}N}{{\rm d}\varphi} = \frac{N_0}{2\pi}(1+2\cdot v_1 cos(\varphi-\psi_1)+2\cdot v_2 cos[2(\varphi-\psi_2)]+\cdots)$$

v_2 - collective motion (flow) of heavy quarks at low $p_{\rm T}$ and path-length dependence of heavy quark energy loss at high $p_{\rm T}$



Why electroweak bosons?

Electroweak bosons (W and Z) are produced via hard processes at the early stage of the collisions

In **proton-proton collisions**:

- Known with good precision
- Give access to parton distributions functions (PDFs) at high-Q^2

In **heavy-ion collisions**:

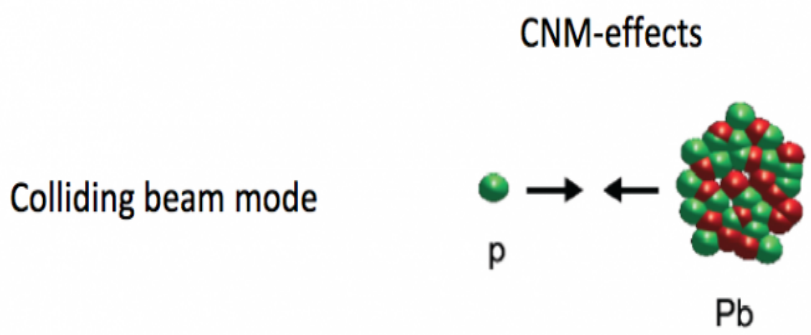
- Large cross sections at LHC energies
- Electroweak bosons do not interact strongly with the medium
- Thus they constitute clean probes of the initial state
- Test of the scaling of hard processes with the number of binary collision $\langle N_{\mathrm{coll}} \rangle$
- Help to constrain nuclear PDFs (nPDFs)

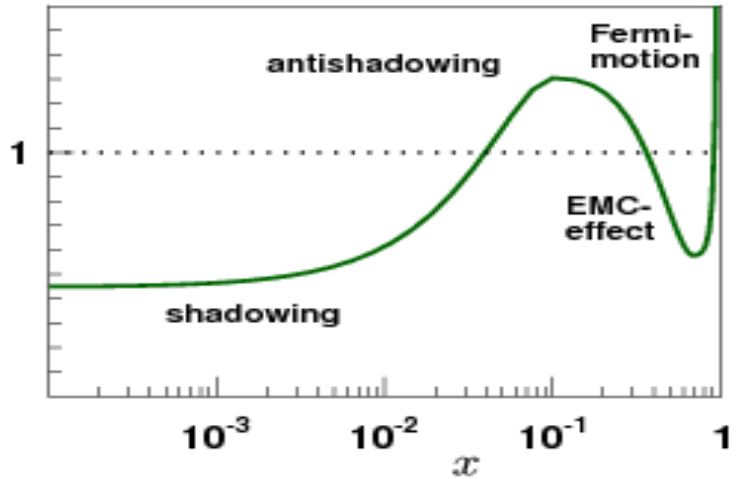
Phys.Rev.Lett. 106 (2011) 212301, Phys.Lett. B715 (2012) 66-87

Observables

- **Cross sections**: used to constrain nPDFs
- N_{coll}-normalized yield: test binary scaling of hard probes

Do we have a control experiment?



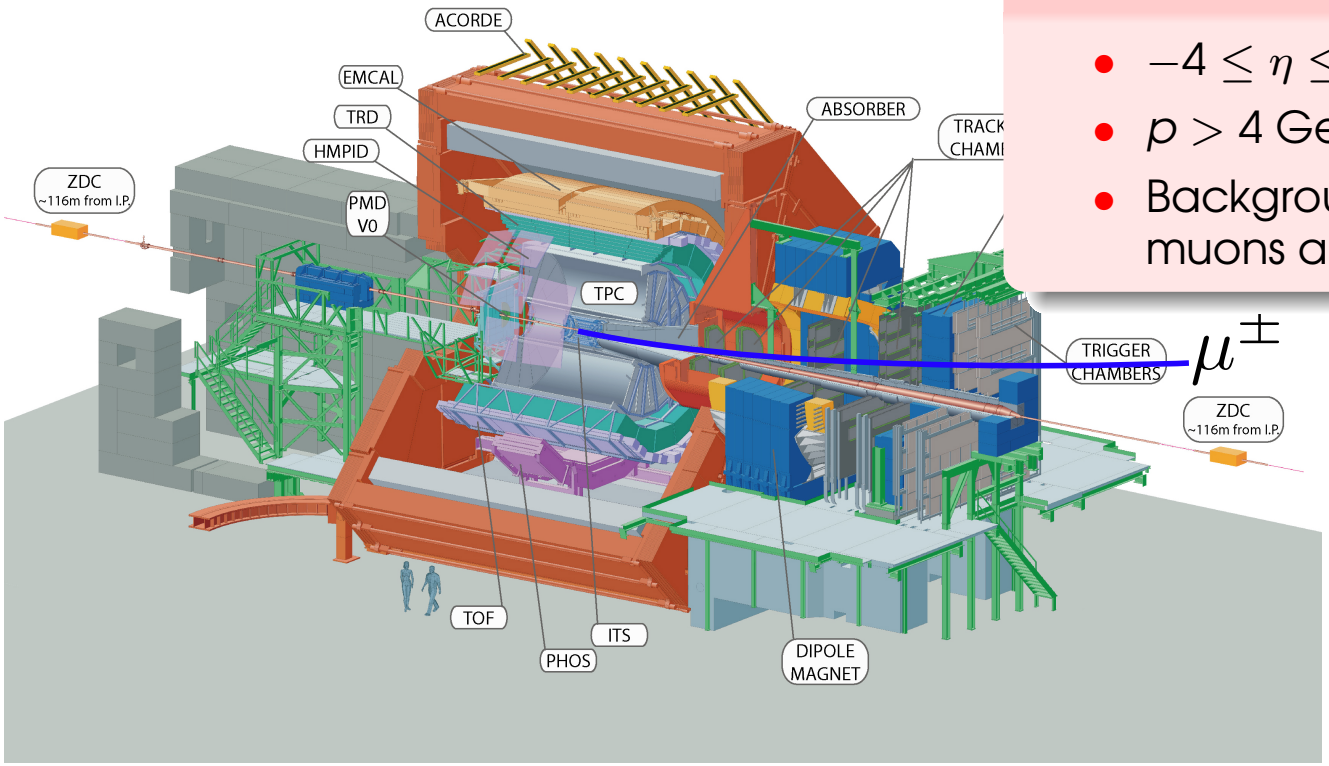


- Open heavy-flavours and electroweak bosons are initial-state probes
- In proton-lead collisions their production provides an excellent tool to study:

Cold Nuclear Matter (CNM) effects

- nuclear modification of the PDFs, known as shadowing and anti-shadowing
  $\Rightarrow$ refer to the modification of PDFs in nuclei
- other effects are: isospin, absorption, EMC effect, Fermi motion and neutron skin effects (arXiv:1412.2930,Eur. Phys. J. C (2015) 75:426), k_{T}-broadening (Cronin effects), energy loss in the initial and final states Phys.Rev. D68 (2003) 094013, arXiv:0212148v2
- these are parametrized by nPDFs

Muon measurements in ALICE



Muons

- $-4 \leq \eta \leq -2.5$
- $p > 4$ GeV/c
- Background: π and K decay muons are dominant at low-p_{T}

Event characterization

Centrality, event plane and triggering

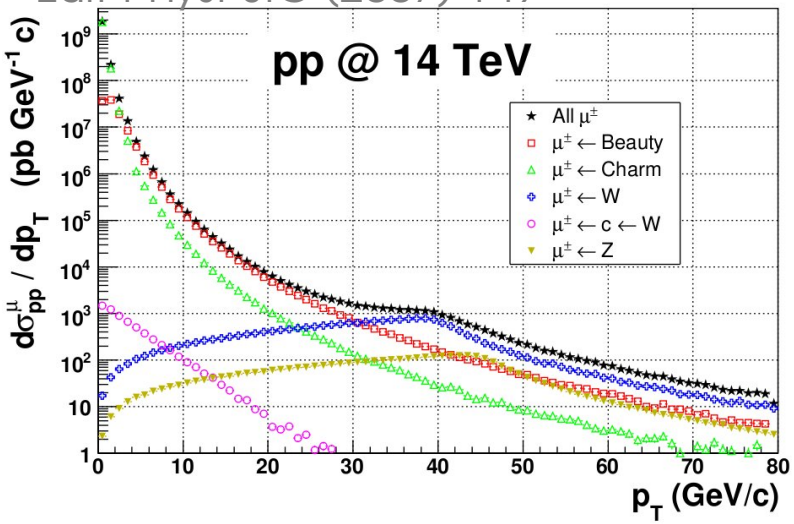
- Forward detectors: V0-A(C) and Zero Degree Calorimeter (ZDC)
- TPC: used for event plane determination Phys. Lett. B753 (2016) 41-56
- Silicon Pixel Detector (SPD)

Open heavy-flavour and electroweak boson measurements

Open heavy-flavour (*B* and *D*) signal

- Measured via the single muon decay channel

Eur. Phys. J.C (2007) 149

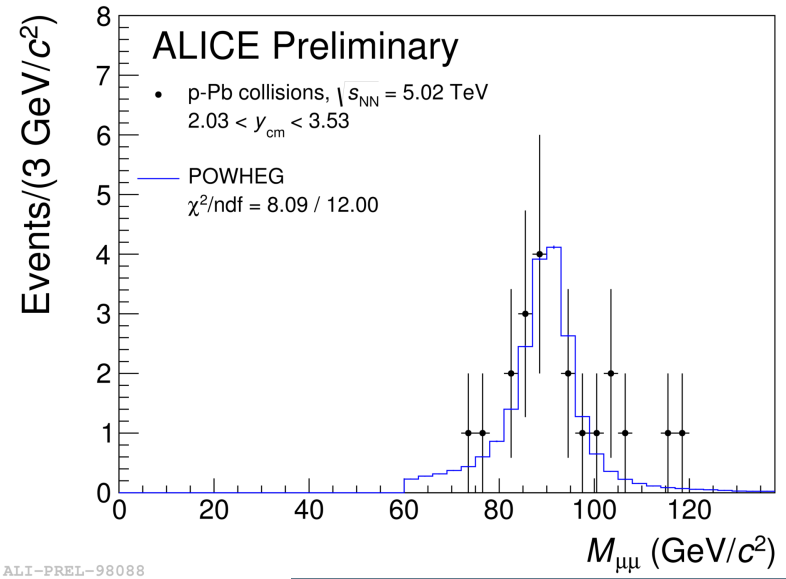


W-boson signal

- Via the semi-muonic decay channel
- Main source of muons above $p_{\mathrm{T}} \approx 30$ GeV/c
- The signal is a Jacobean peak in an inclusive single muon p_{T}-differential spectrum at $p_{\mathrm{T}} = M_{\mathrm{W}}/2$

Z-boson signal

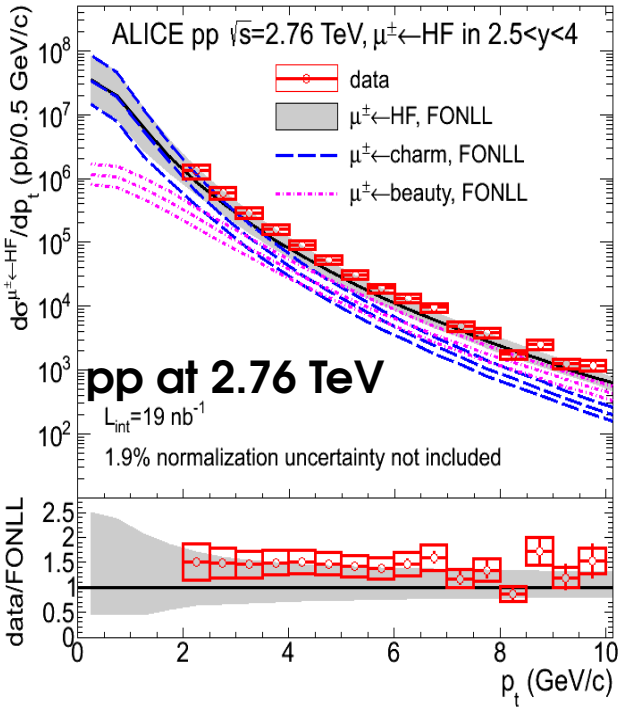
- Is observed in the invariant mass distribution of unlike-sign muon pairs as a peak around the Z-boson mass
- Compared with POWHEG Next-to-Leading Order (NLO) event generator JHEP 0807 (2008) 060



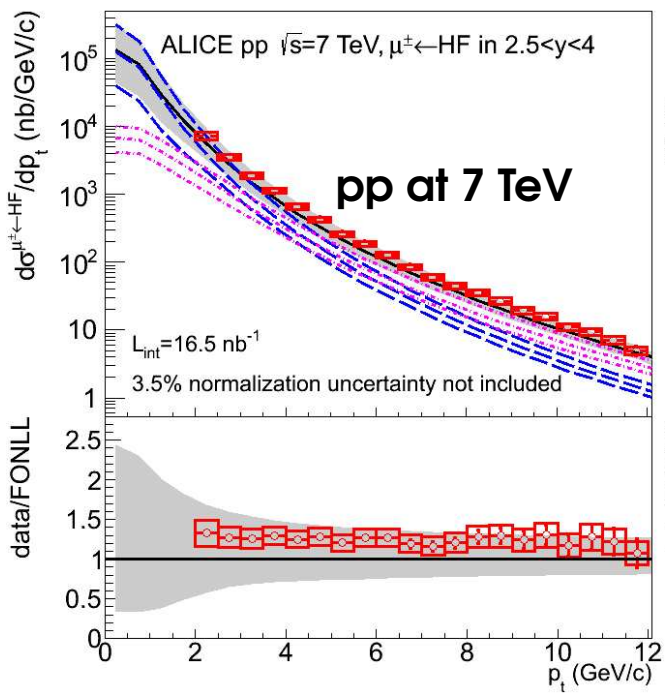
ALI-PREL-98088

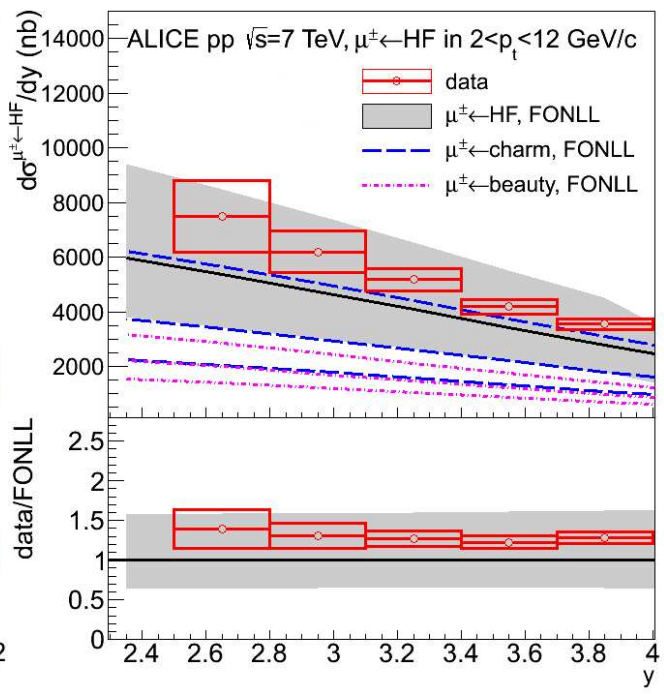
Open heavy-flavours: pp collisions at $\sqrt{s} = 2.76$ TeV and 7 TeV

Phys.Rev.Lett. 109 (2012) 112301



Phys.Lett. B708 (2012) 265-275



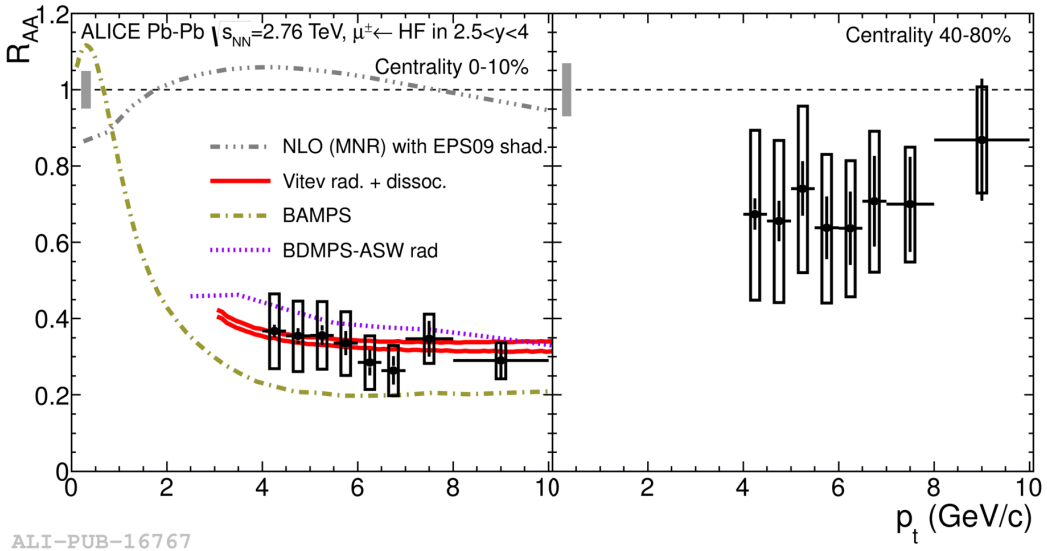


- Open heavy-flavour decay muons at forward rapidity versus p_{T} and rapidity
- ALICE measurements are described by pQCD within uncertainities at both energies

  Cacciari et al., arXiv:1205.6344

Open heavy-flavours: Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

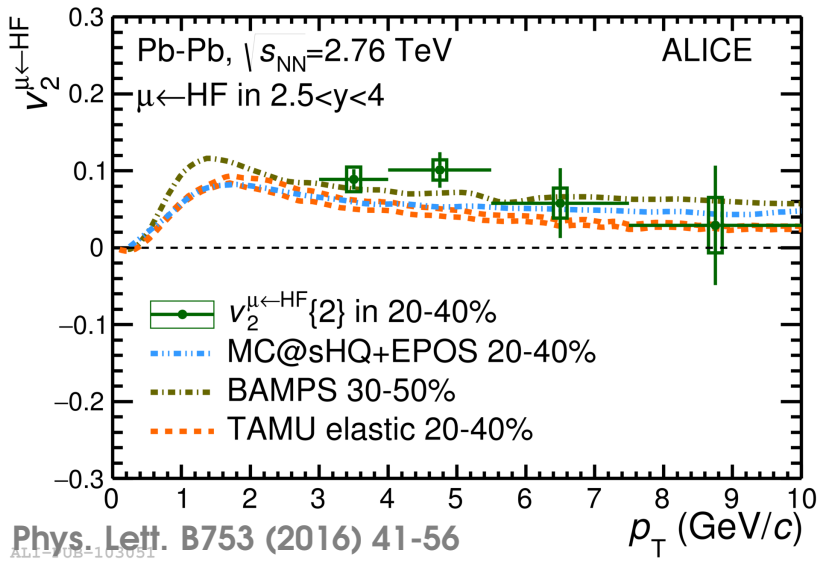
Phys.Rev.Lett. 109 (2012) 112301



- **Suppressed by a factor 3 - 4 in the most central collisions for p_T>4 GeV/c**
- **Less suppression in peripheral collisions**

  Preliminary results up to 20 GeV/c are also available (see backup)

BAMPS: transport model with collisional process
Vitev: radiative+collisional processes



Phys. Lett. B753 (2016) 41-56

- v_2 is non-compatible with 0 at intermediate p_T (2< p_T <6 GeV/c)
- Models reproduce measurement

MC@sHQ+EPOS: transport with collisional and radiative energy loss
TAMU: transport model including only collisional processes

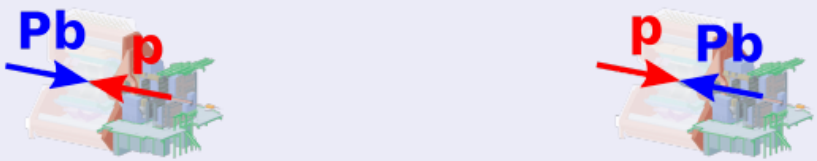
Open heavy-flavours: p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Does the initial state play a role or are the results in Pb–Pb due to the medium-only effects?

How are parton distribution functions modified in nuclei?

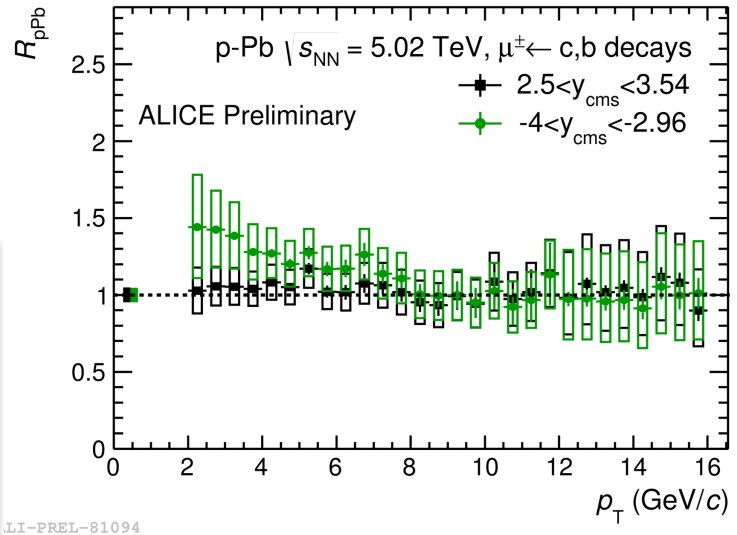
- Beam-energy asymmetry: different rapidity coverage for the two beam configurations

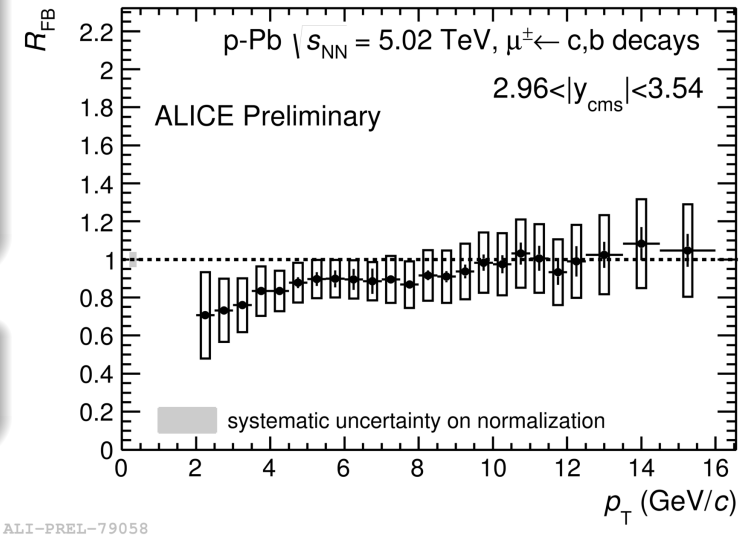
  Backward rapidity **Forward rapidity**



- **Forward rapidity**: R_{pPb} consistent with unity
- **Backward rapidity**: R_{pPb} consistent with unity, within uncertainty at low p_{T}

- Forward to backward ratio (R_{FB}) of open heavy-flavour decay muons





Open heavy-flavours: p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV

Does the initial state play a role or are the results in Pb–Pb due to the medium-only effects?

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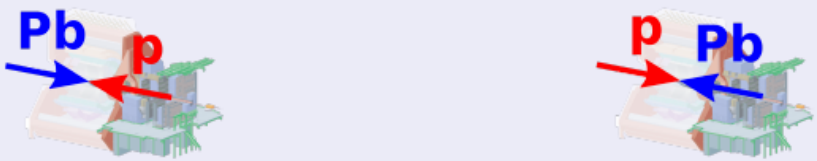
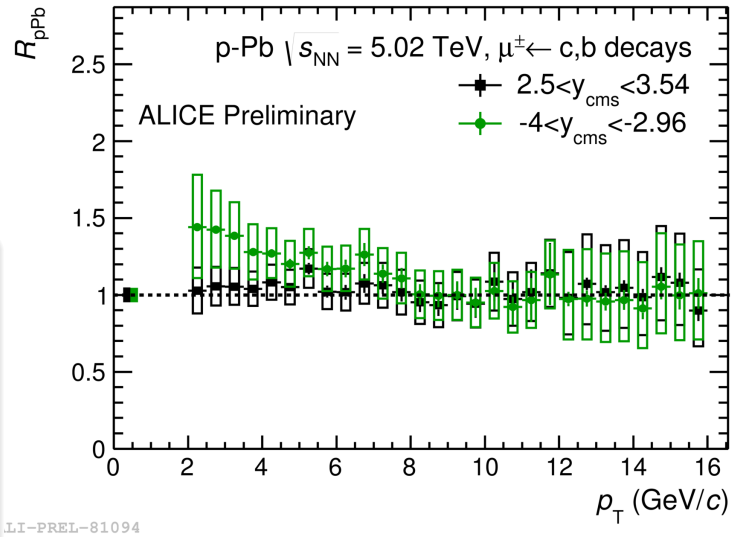
- Beam-energy asymmetry: different rapidity coverage for the two beam configurations

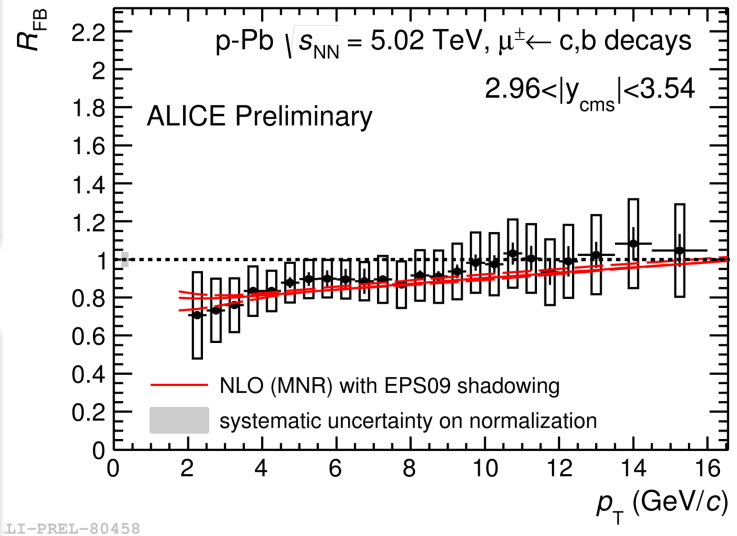
Backward rapidity **Forward rapidity**



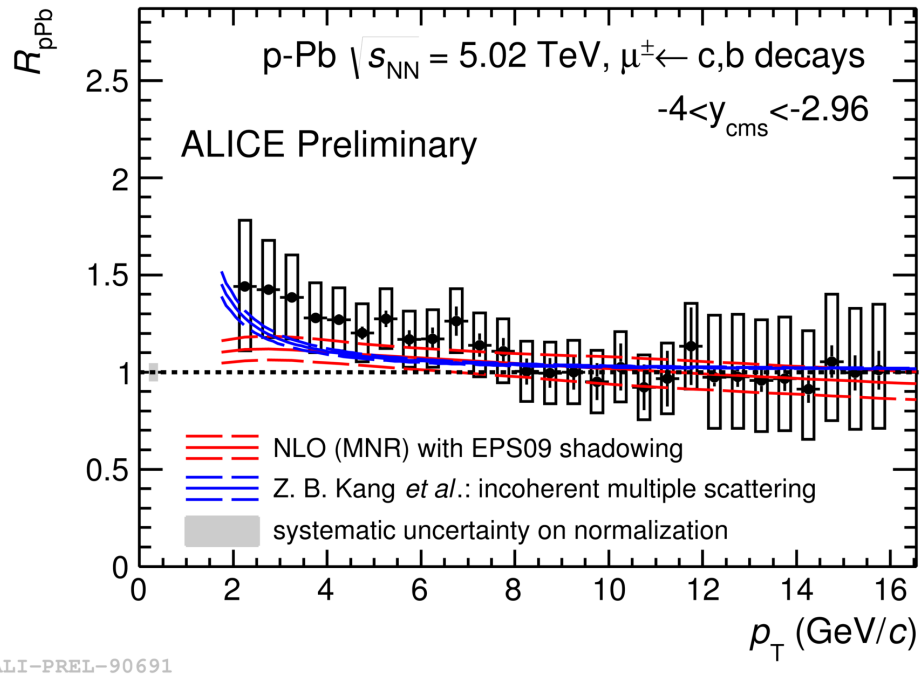
- **Forward rapidity**: $R_{\rm pPb}$ consistent with unity
- **Backward rapidity**: $R_{\rm pPb}$ consistent with unity, within uncertainty at low $p_{\rm T}$

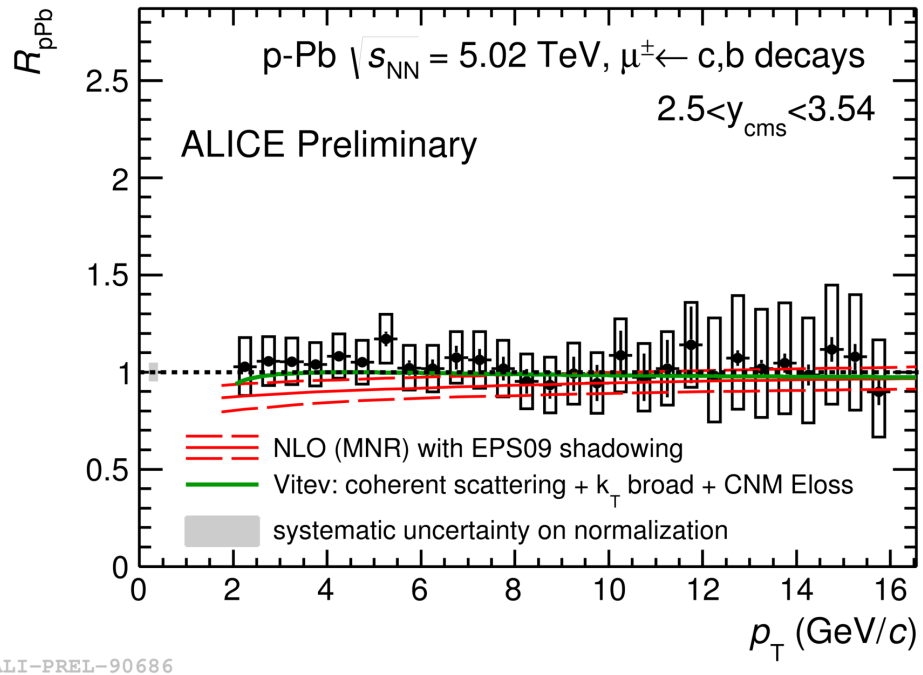
- Forward to backward ratio ($R_{\rm FB}$) of open heavy-flavour decay muons
- Well reproduced by a pQCD calculation including the EPS09 Nucl. Phys. B 373 (1992) 295





Open heavy-flavours: p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

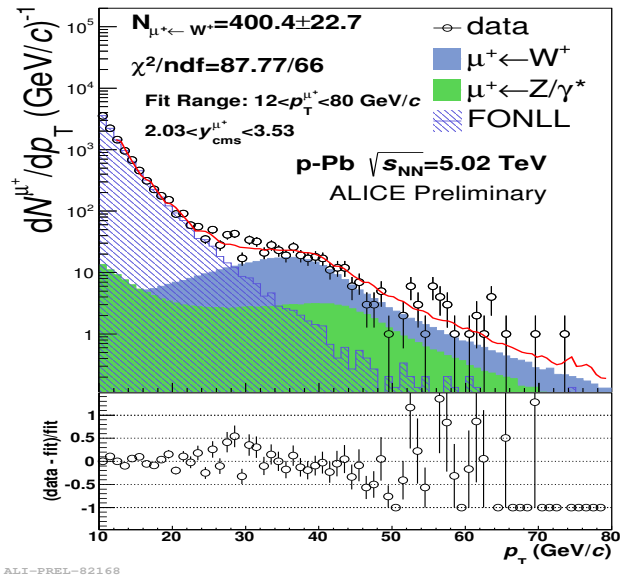




- Models including cold nuclear matter effects reproduce the data:
  - pQCD with EPS09 nPDF NPB 373 (1992) 295, JHEP 04467 (2009) 065
  - I. Vitev: coherent scattering, k_T-broadening and CNM energy loss PRC 75 (2007) 064906
  - Z.B. Kang et al.: incoherent multiple scattering PLB 740 (2015) 23
- Small evidence of CNM effects: **are there other probes?**

Electroweak bosons: p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

W bosons



Signal extraction based on a combined fit

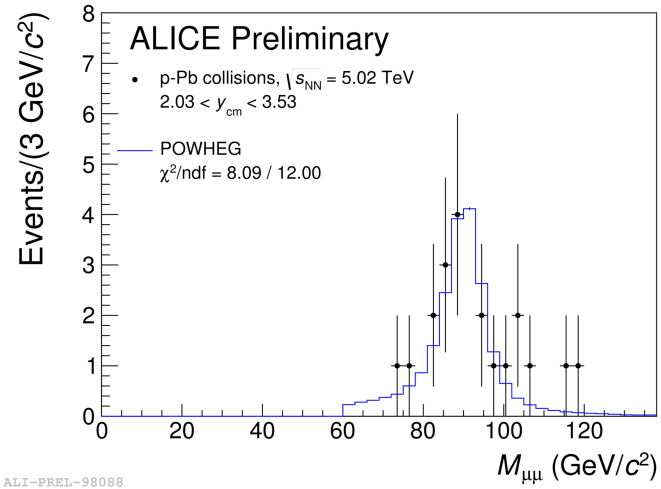
FONLL and phenomenological function (ATLAS-COM-CONF-2011-088): c, b description

POWHEG-based templates: W- and Z-boson

- Acceptance and efficiency correction

Signal extracted for $p_{\mathrm{T}}^{\mu} > 10$ GeV/c

Z bosons

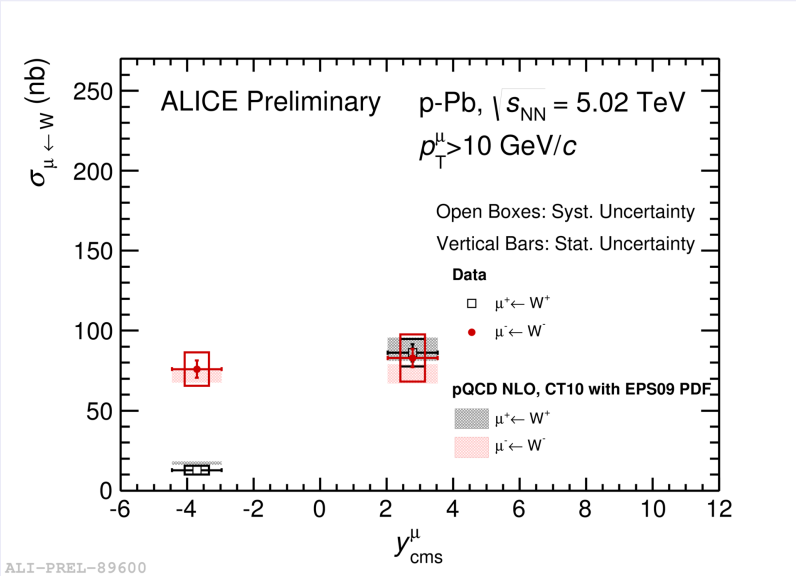


Muons with $p_{\mathrm{T}}^{\mu} > 20$ GeV/c are selected

$N_{\mu\mu\leftarrow Z}$ is extracted between 60–120 GeV/c^2

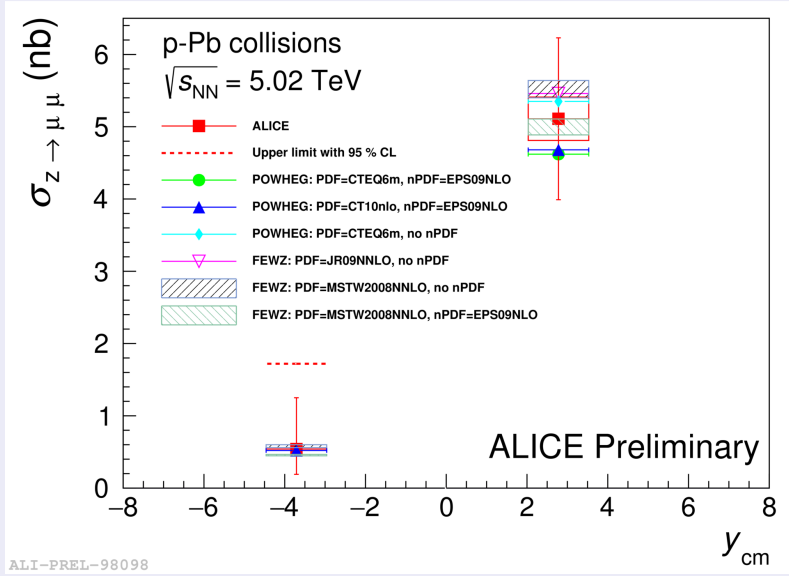
Z-boson candidates is the number of entries (consistent with the integral of a Gaussian fit) POWHEG:JHEP 0807(2008)060

Electroweak bosons: p–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV



- $\mu^{\pm} \leftarrow \mathrm{W}^{\pm}$ cross sections measured both at backward and forward rapidity
- Isospin effect visible at backward rapidity
- NLO pQCD calculation with CT10 and EPS09 reproduce the measurement within uncertainties

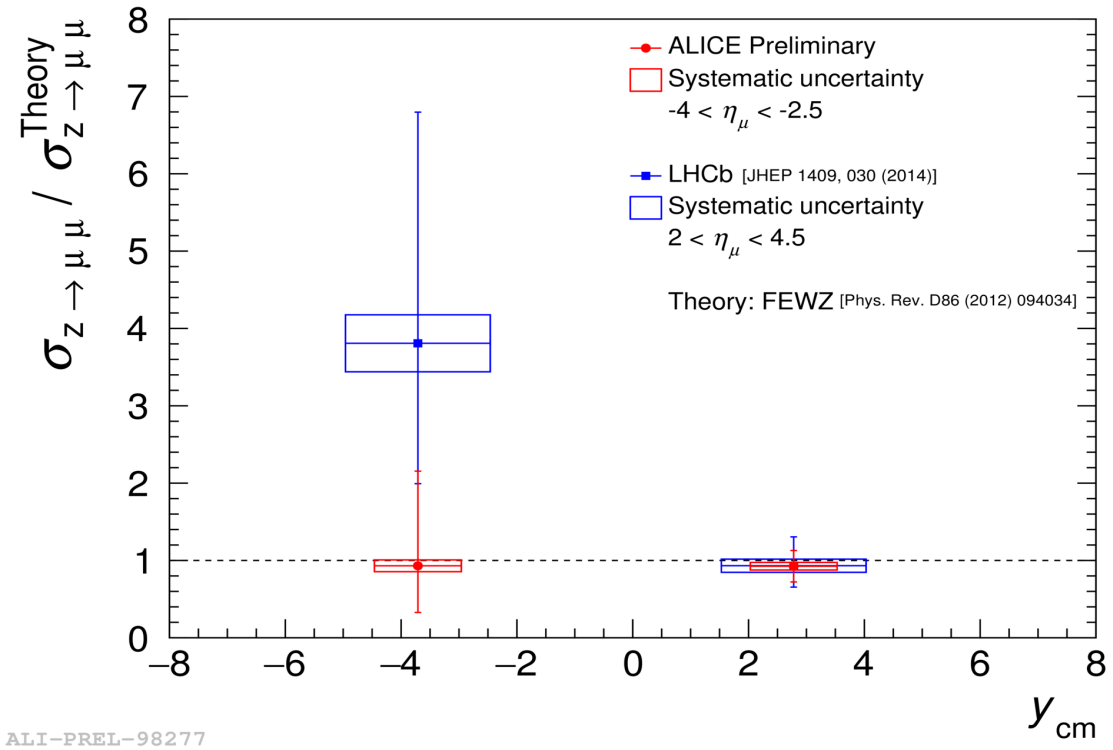
pQCD: JHEP 1103 (2011) 071, CT10: arXiv:1101.0561, EPS09: JHEP 0904(2009)065



- $Z \rightarrow \mu^+\mu^-$ cross section at forward and backward rapidity
- NLO and Next-to-NLO pQCD calculations (POWHEG and FEWZ, respectively) with different PDFs and/or nuclear PDFs (EPS09) reproduce the measurement

FEWZ: Phys. Rev. D86 (2012) 094034, JR09: Phys. Rev. D79 (2009) 074023, MSTW: Eur. Phys. J. C64 (2009) 653-680, CTEQ: Rept. Prog. Phys. 70 (2007) 89

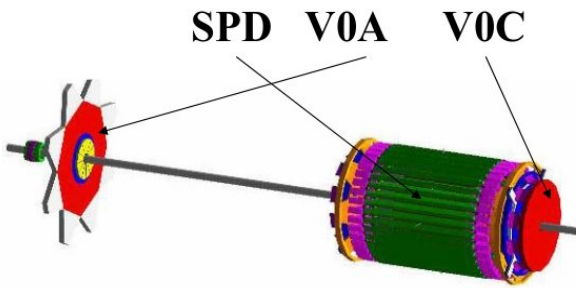
Electroweak bosons: p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



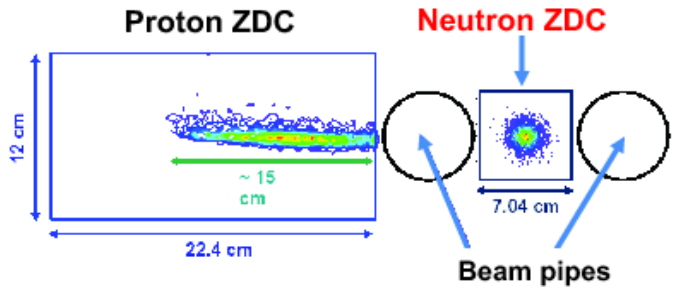
- The ratio of measured cross section by ALICE and LHCb to the FEWZ theoretical predictions are shown
- The ratios are compatible with unity at forward rapidity for both ALICE and LHCb
- The ALICE point at backward rapidity is also compatible with unity

Test of binary scaling

- Production of W bosons is a hard process, thus is expected to scale with the number of colliding nucleons ($\langle N_{\mathrm{coll}} \rangle$)
- $\langle N_{\mathrm{coll}} \rangle$ is expected to be correlated with event activity (centrality of the collision)
- Different estimators with different approaches were used to classify event activity:
  - Glauber Model + Negative Binomial Distribution fit to the signal in the VZEROs and the clusters in the first layer of the SPD



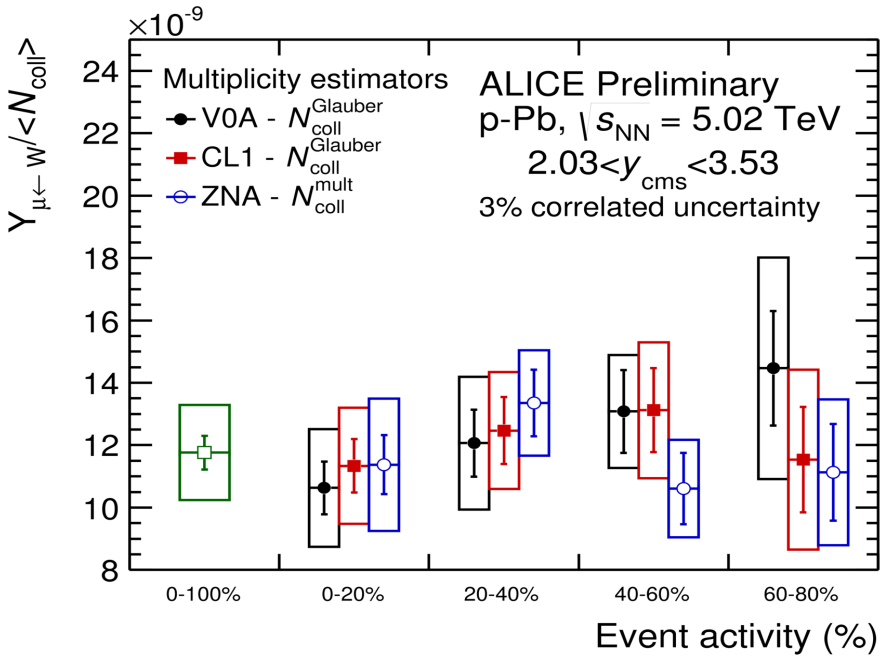
  - Hybrid method: scaling N_{coll} in minimum-bias collisions by the ratio between the average multiplicity density measured at mid-rapidity in a given ZDC energy event class and the one measured in minimum bias collisions



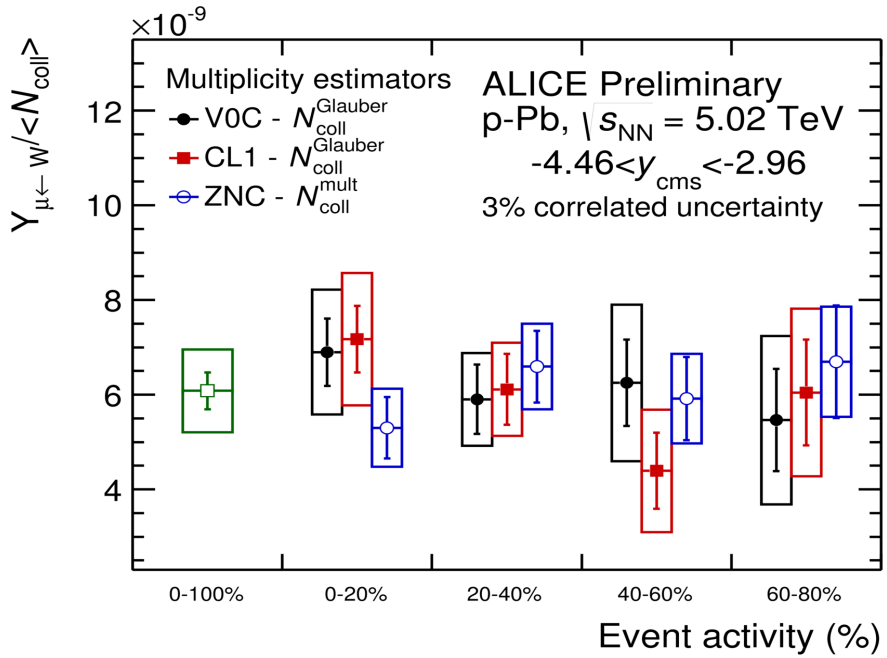
- $\langle N_{\mathrm{coll}} \rangle$ systematic is multiplicity bin dependent, varies between 8 - 24%

$\langle N_{\mathrm{coll}} \rangle$ dependence of W-boson yield in p–Pb collisions

- Yield is normalized to $\langle N_{\mathrm{coll}} \rangle$ to test binary scaling



ALI-PREL-79988



ALI-PREL-80001

- The yield per binary collision is independent of event activity within uncertainties
- Use of different event activity estimators leads to the same conclusion

Summary

Open heavy-flavour in pp, p–Pb and Pb–Pb collisions

pp collisions

* pQCD calculations reproduce measurements within uncertainties

Pb–Pb collisions

* Stronger suppression in the central than peripheral collisions
* Participate in the collective expansion of the medium
* Models reproduce both the R_{AA} and v_2 within uncertainties

p–Pb collisions

* R_{pPb} of heavy-flavour muons consistent with unity: suppression in Pb–Pb due to final-state effects
* Models reproduce the data within uncertainties

W- and Z-boson in p–Pb collisions

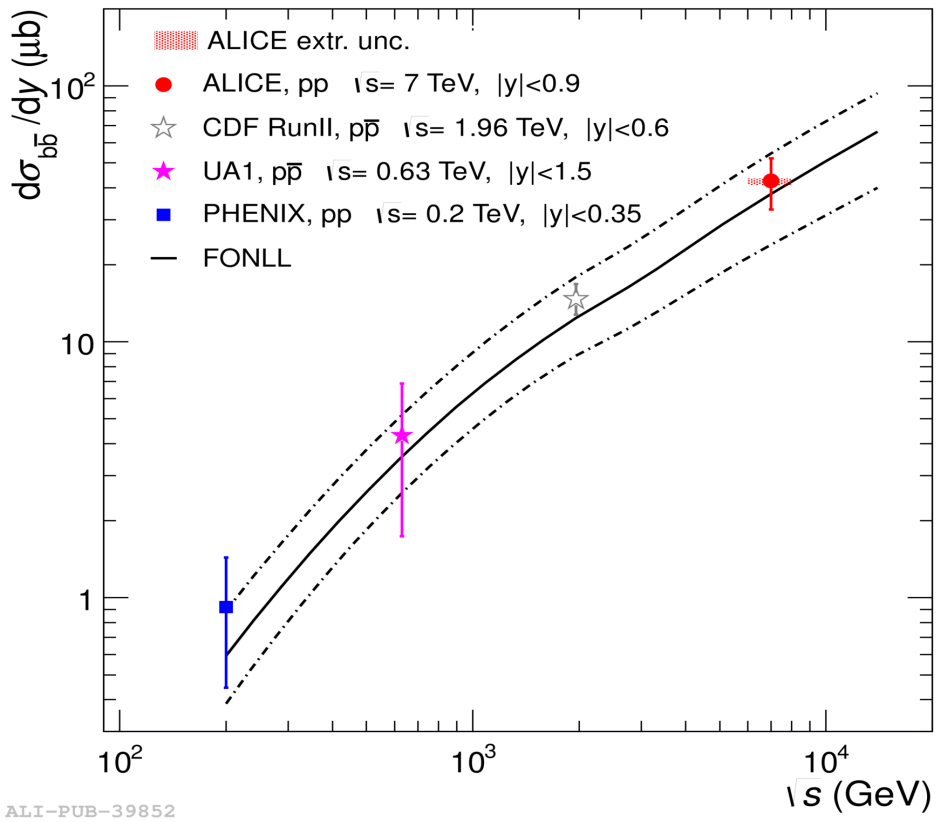
- The measured cross sections are consistent with pQCD theoretical predictions with and without shadowing within large uncertainties
- Large uncertainties: not possible to constrain nPDFs
- W-boson yields exhibit a flat behaviour versus event activity: binary-collision scaling of hard processes holds

Backup

Why heavy flavours?

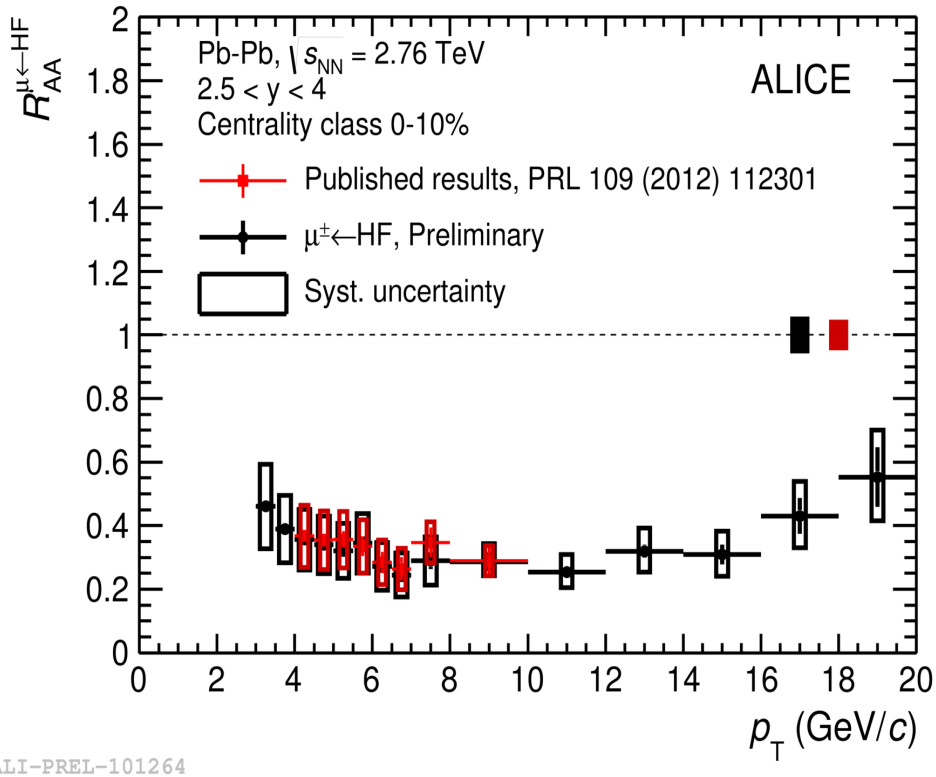
JHEP 1211 (2012) 065

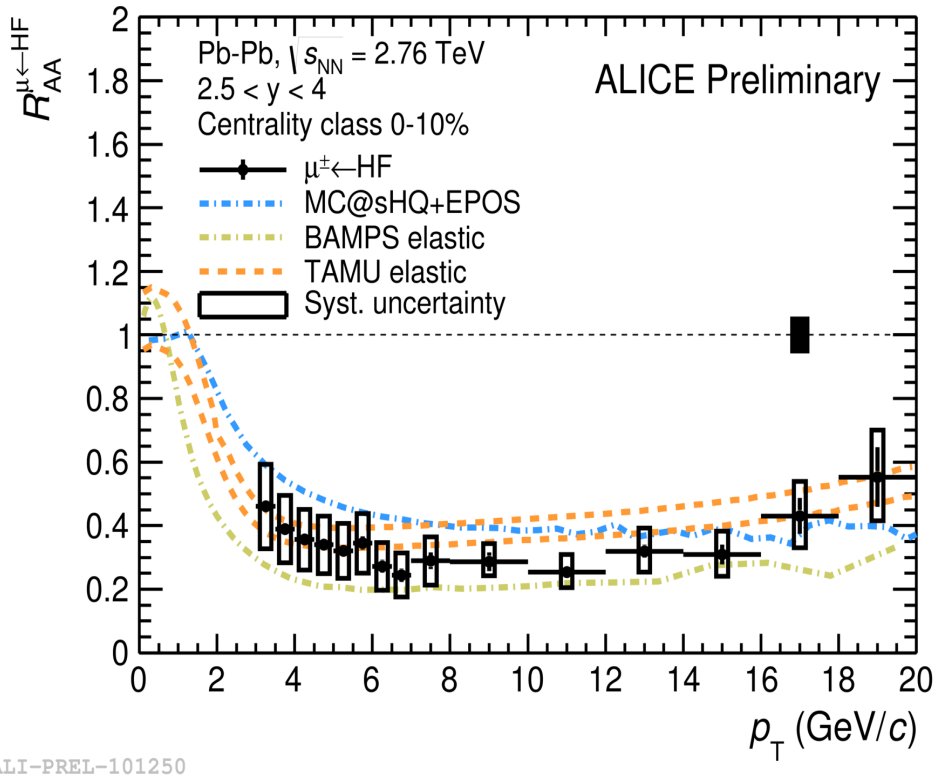
B-hadron cross section



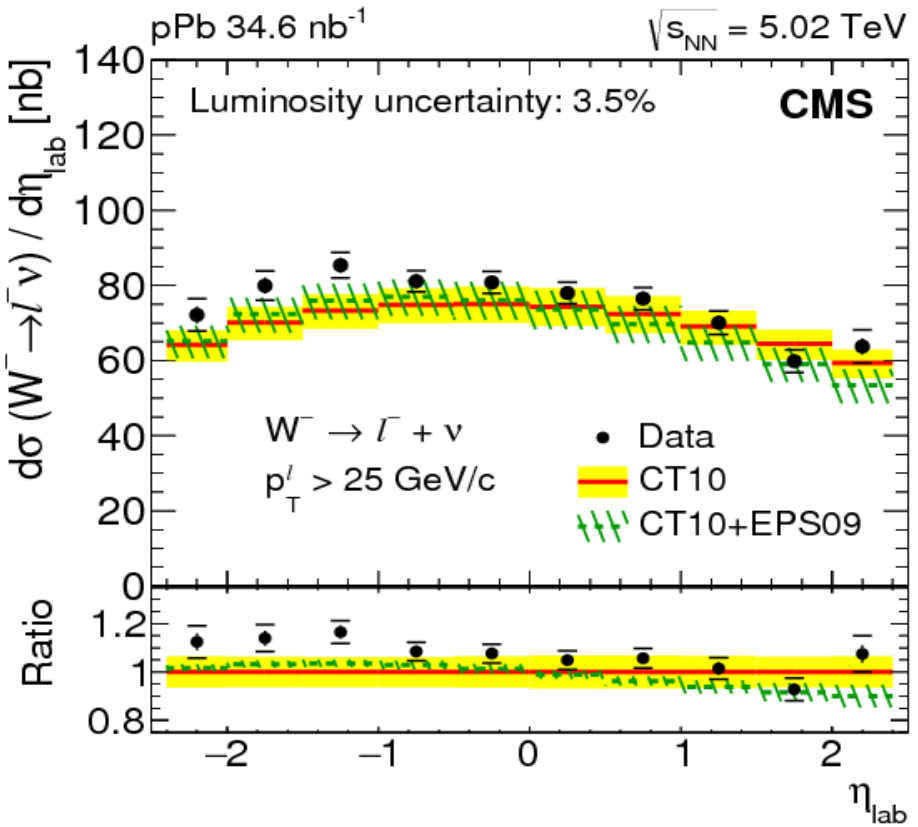
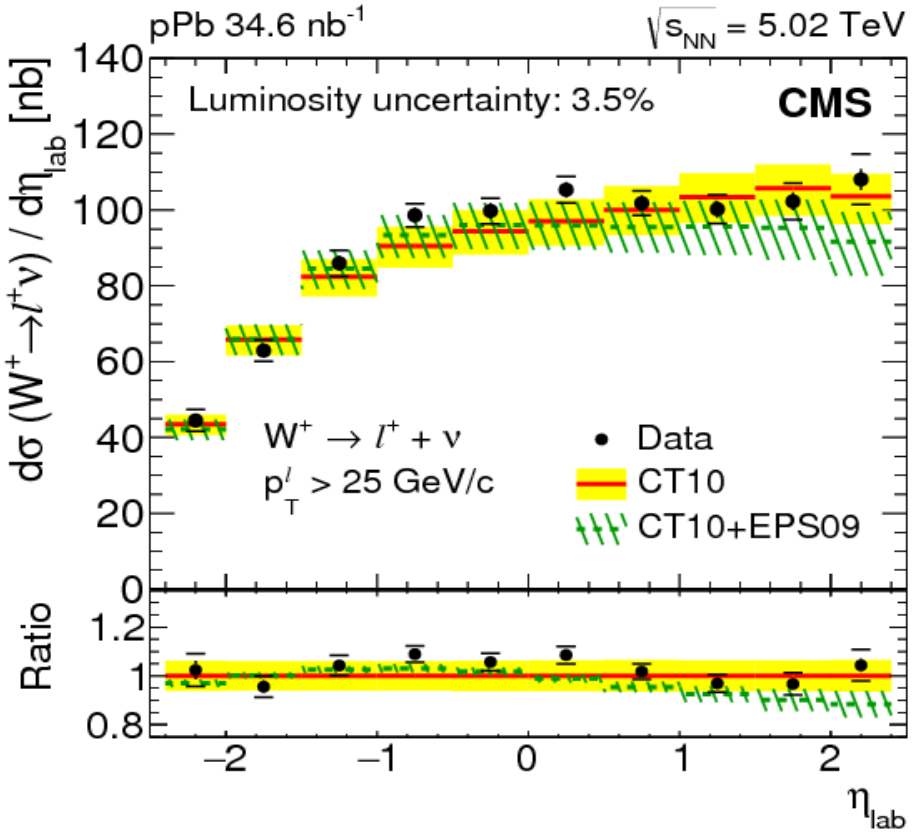
Nuclear modification of heavy flavours

R_{AA} of heavy flavour decay muons extended to high p_T





W-boson measurement in p–Pb: CMS

Cross section of W-boson W^- (left) and W^+ (rigth)

Theoretical predictions with and without shadowing reproduce the measurements within uncertainties