Production of muons from open heavy-flavor decays in Pb-Pb collisions at 5.02 TeV

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- Physics motivation
- ALICE detector
- Overview in Run I
- Analysis strategy
- Results in Run II
- Summary and outlook

Why open heavy flavour?

- Heavy quarks (charm and beauty) are produced in initial hard scatterings with a short formation time

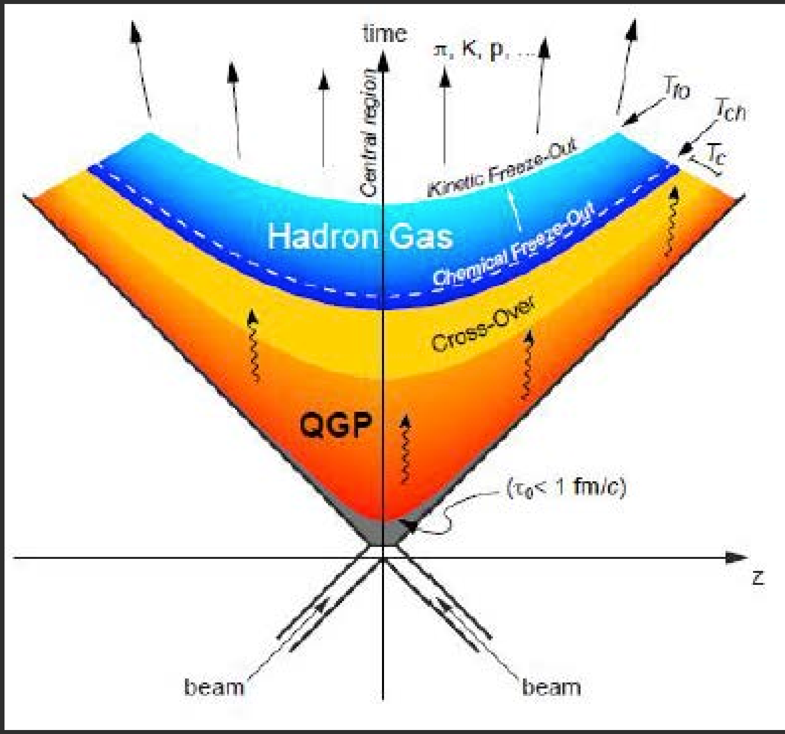
  $\tau_f \sim 1/m_{c/b}$ (~ 0.02-0.1 fm/c) << τ_{QGP} (~ 5-10 fm/c)
- Involved in the full evolution of the QCD medium

  sensitive probes of the medium properties

✓ Open heavy flavours in A-A collisions:

investigate the hot nuclear matter effects

- energy loss in the medium via gluon radiation and elastic collisions:
  - parton color-charge and mass dependence
  - expected: $\Delta E_g > \Delta e_{u,d,s} > \Delta E_c > \Delta E_b$ $R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$
- participation in the collective expansion of the system



Observables

- Central-to-peripheral nuclear modification factor:

$$R_{CP}(p_T) = \langle T_{AA} \rangle_P \Big/ \langle T_{AA} \rangle_C \times \frac{dN^C_{AA}/dp_T}{dN^P_{AA}/dp_T}$$

- Nuclear modification factor:

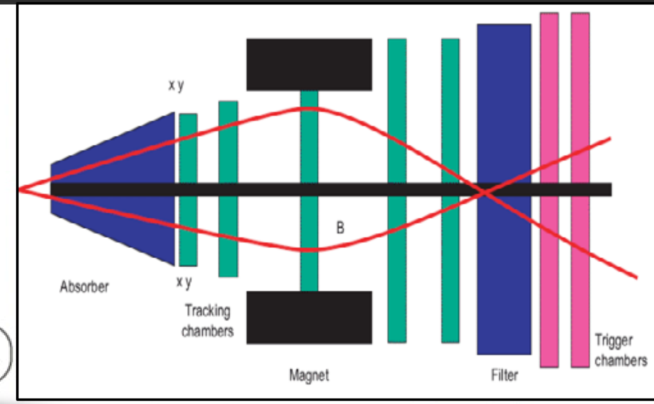
$$R_{AA}(p_T) = \frac{1}{\langle T_{AA} \rangle} \times \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T}$$

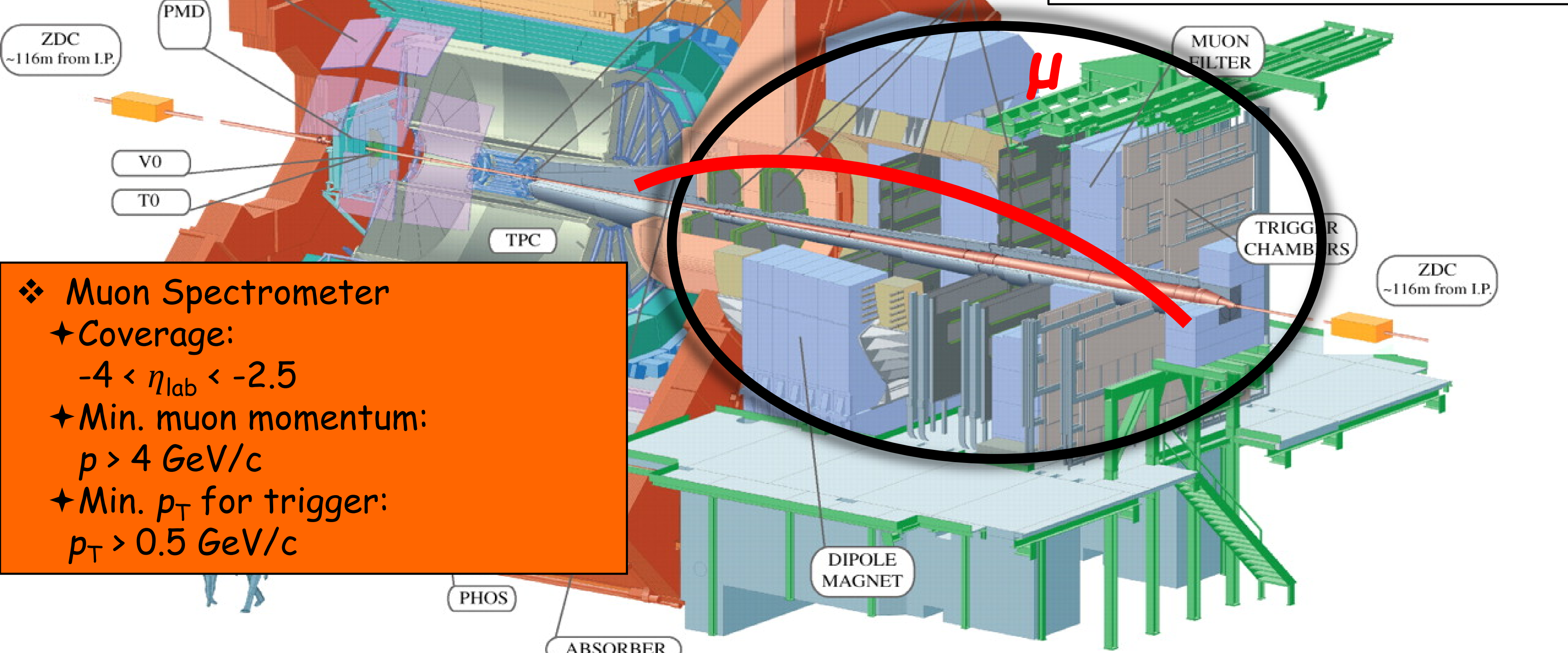
- Elliptic flow, v_2:

$$v_2 = \langle \cos[2(\varphi - \Psi_n)] \rangle$$

ALICE detector layout

- Detectors used to reconstruct muons from open heavy flavour, W-boson and Z-boson decay





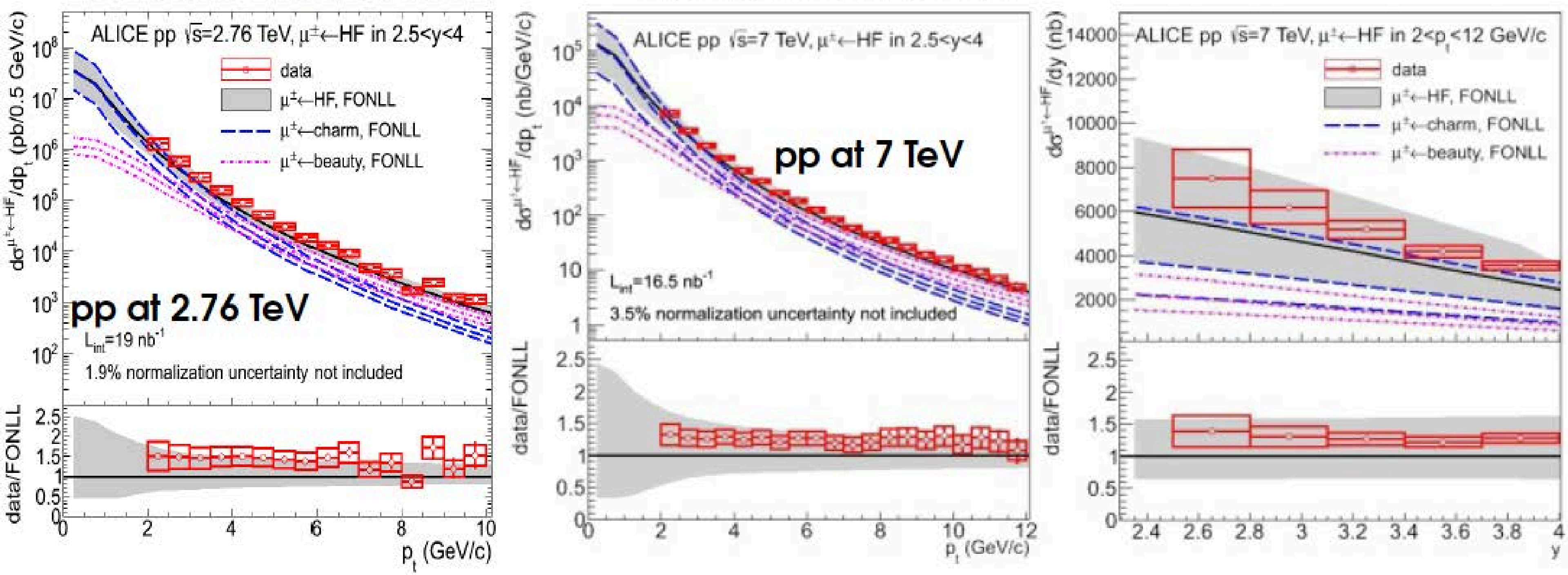
- Muon Spectrometer
  - Coverage: $-4 < \eta_{lab} < -2.5$
  - Min. muon momentum: $p > 4$ GeV/c
  - Min. p_T for trigger: $p_T > 0.5$ GeV/c

Overview in Run I

	pp	p-Pb	Pb-Pb
Run I (2009 - 2013)	0.9, 2.76, 7, 8 TeV	5.02 TeV	2.76 TeV
Run II (2015 - now)	5.02, 13 TeV	5.02, 8.16 TeV	5.02 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 uncertainties at both energies

arXiv:1205.6344

R_{AA} and v_2

ALICE

- Suppressed by a factor 3 – 4 in the most central collisions for p_T > 4 GeV/c
- Less suppression in peripheral collisions
- R_{pPb} is consistent with unity within uncertainties
- The suppression observed at high p_T in central Pb-Pb collisions results from final-state effects related to parton energy loss

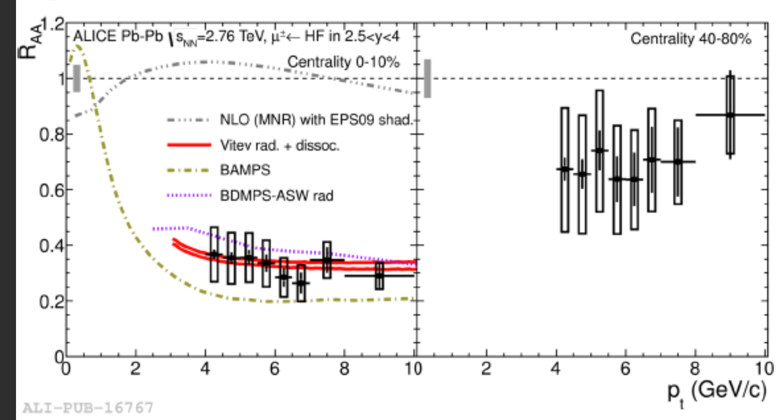
- ✓ v_2 is non-compatible with 0 at intermediate p_T
- ✓ Models reproduce measurement

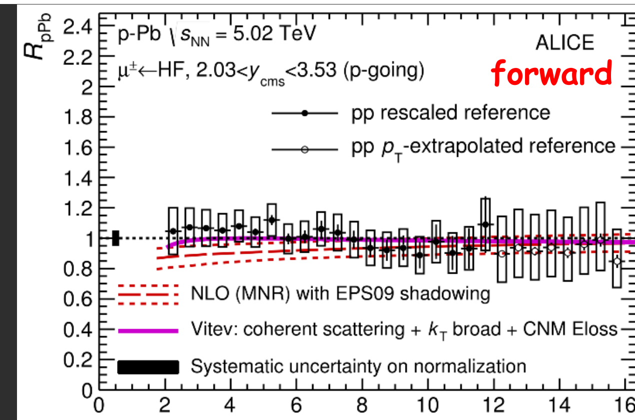
BAMPS: transport model with collisional process

MC@sHQ+EPOS: collisional and radiative energy loss

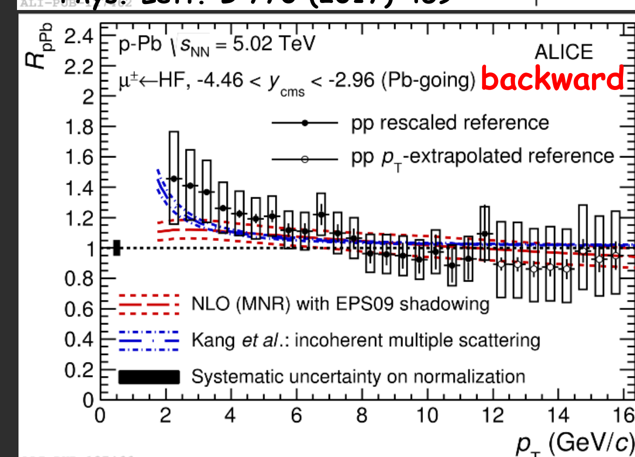
TAMU: transport model including only collisional processes

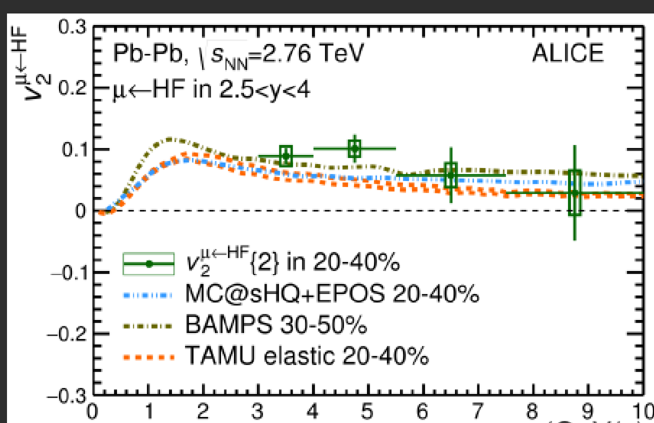
Phys.Rev.Lett. 109 (2012) 112301





Phys. Lett. B 770 (2017) 459



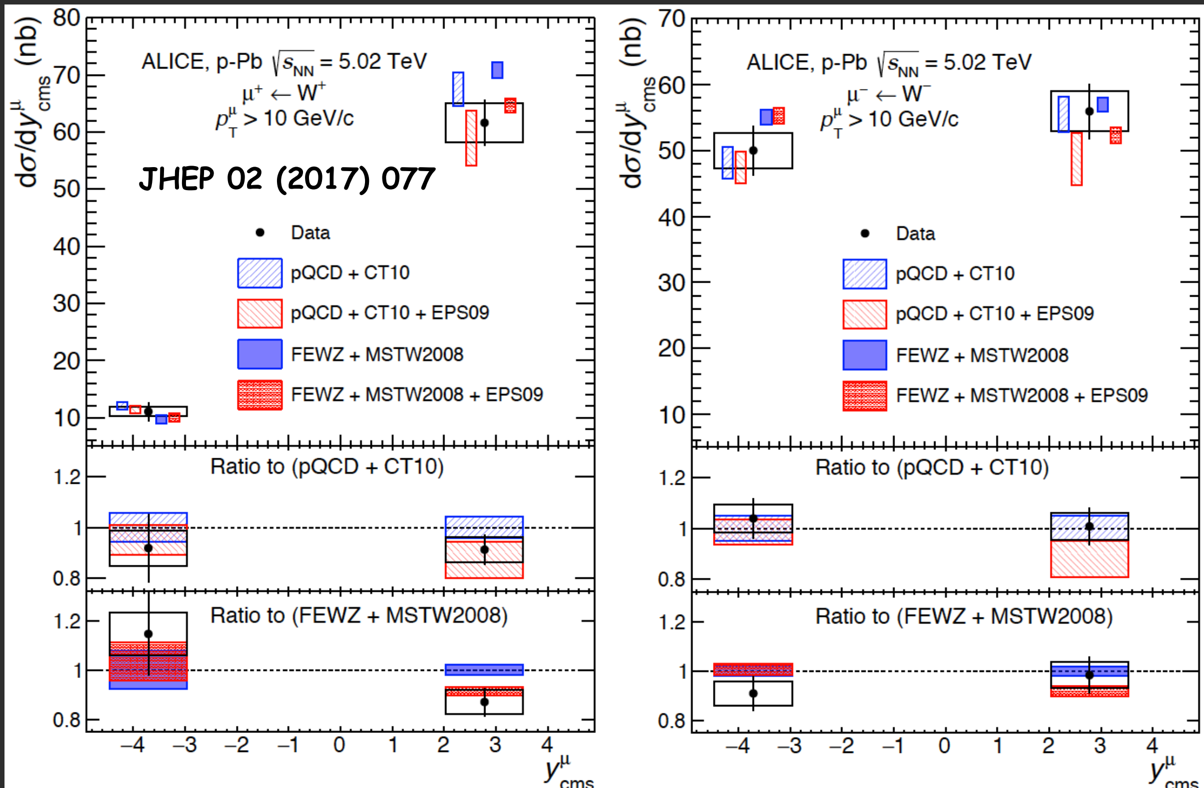


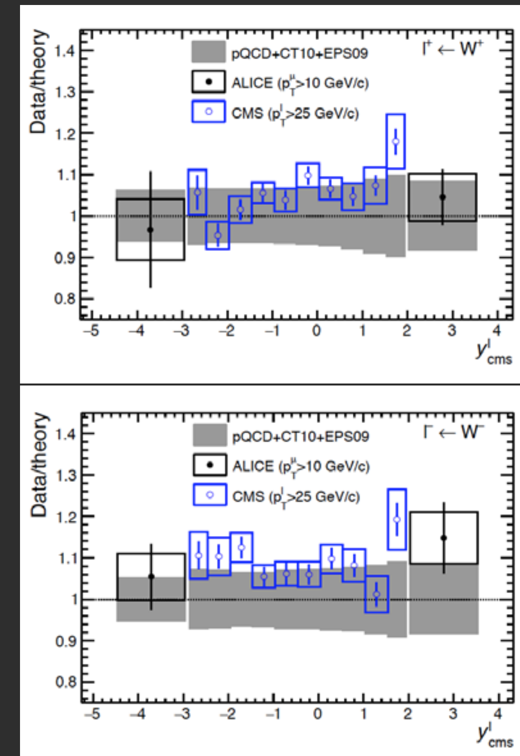
Phys. Lett. B753 (2016) 41-56

W in p-Pb

pQCD: JHEP 1103 (2011) 071
FEWZ: Comput. Phys. Commun. 182 (2011) 2388-2403

CMS: [Phys. Lett. B 750 (2015) 565]

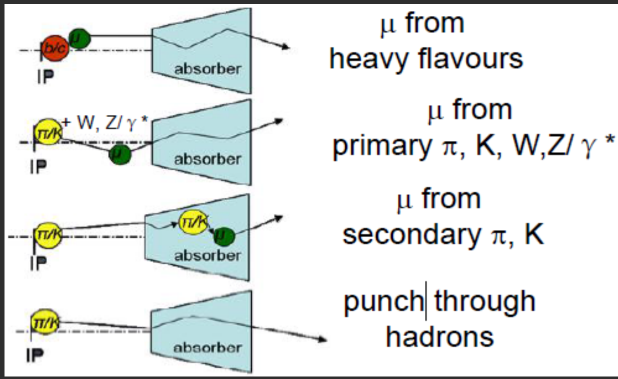




- The inclusion of nPDFs results in a slightly lower value of cross section, especially at forward rapidity
- Both the NLO pQCD calculations with CT10 PDFs and NNLO FEWZ calculations with MSTW2008 PDFs describe the data within uncertainties
- The smaller cross-section of W^+ at backward rapidity
- The cross section divided by the NLO pQCD calculations with nPDFs are shown together with CMS
- The calculations describe data over the full rapidity interval explored

Analysis Strategy for pp

- **Data sample:** 2015 pp collisions at $\sqrt{s}$ = 5.02 TeV
- **Trigger condition:** signal in the two V0 arrays (MB trigger) with
  - ✓ MSL: at least one muon with a low p_T threshold of 0.5 GeV/*c*
  - ✓ MSH: at least one muon with a high p_T threshold of 4.2 GeV/*c*
- **Muon track selection:**
  - acceptance & geometrical cuts: select tracks in the acceptance
  - p_T cut at 2 GeV/*c*: reject μ from secondary π, K
  - track matched with trigger: reject hadrons crossing the absorber
  - pxDCA in 6σ: reject beam-gas interactions & particles produced in the absorber



1. Normalize muon triggered events to the equivalent number of MB events
2. Acceptance x efficiency correction:
   - parameterize p_T and η distributions of muons from open HF hadron decays given by FONLL
3. Background subtraction:
   - muons from charged K/π decays
     - ➢ extrapolate ALICE measured charged K/π p_T spectrum at mid-rapidity to forward rapidity
   - muons from J/Ψ decays
     - ➢ extrapolate ALICE measured J/Ψ p_T and rapidity at forward rapidity by fits with power-law and pol2, respectively, to take into account fiducial effects
   - muons from W and Z/γ^* decays
     - ➢ estimated using p_T -differential production cross section given by POWHEG simulations with CT10 PDFs
4. Systematic uncertainties estimation
5. Compare with model calculations

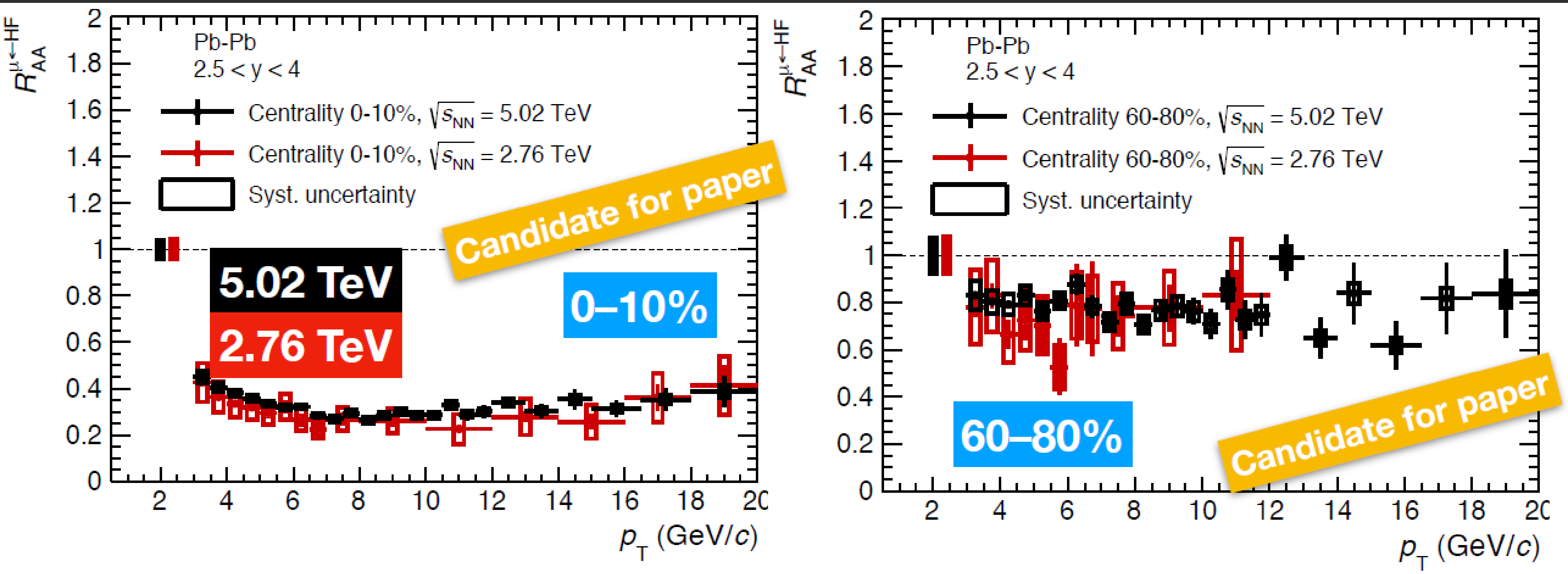
Analysis Strategy for Pb-Pb

- Data sample: 2015 Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV
- Trigger condition:
  - ✓ MSL with $p_{T,trigger}$ ~ 1 GeV/c
  - ✓ MSH with $p_{T,trigger}$ ~ 4 GeV/c
- Same muon track selection as pp collisions

1. Normalize muon triggered events to the equivalent number of MB events on a run by run basis
2. Acceptance x efficiency correction:
   - from simulations using heavy-flavor signals from NLO pQCD predictions
   - centrality dependence of tracking efficiency estimated by embedding procedure, ~6% difference from 60-80% to 0-10% centrality class
3. Background subtraction:
   - muons from charged K/π decays
     - similar as pp, consider the uncertainty on quenching strength
   - muons from J/Ψ decays
     - similar as pp
   - muons from W and Z/γ^* decays
     - similar as pp, add EPS 09 CNM effect parameterization
4. Systematic uncertainties estimation
5. Compare with model calculations

Compare with RUN-I

- pp and Pb-Pb paper proposals are accepted by ALICE



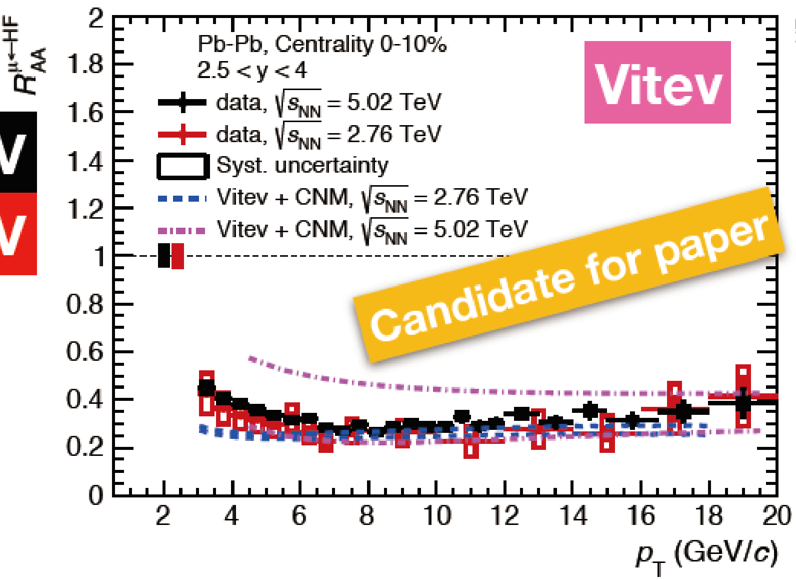
- Compare with RUN-I: higher precision
- R_{AA} between the two energies are consistent within uncertainties

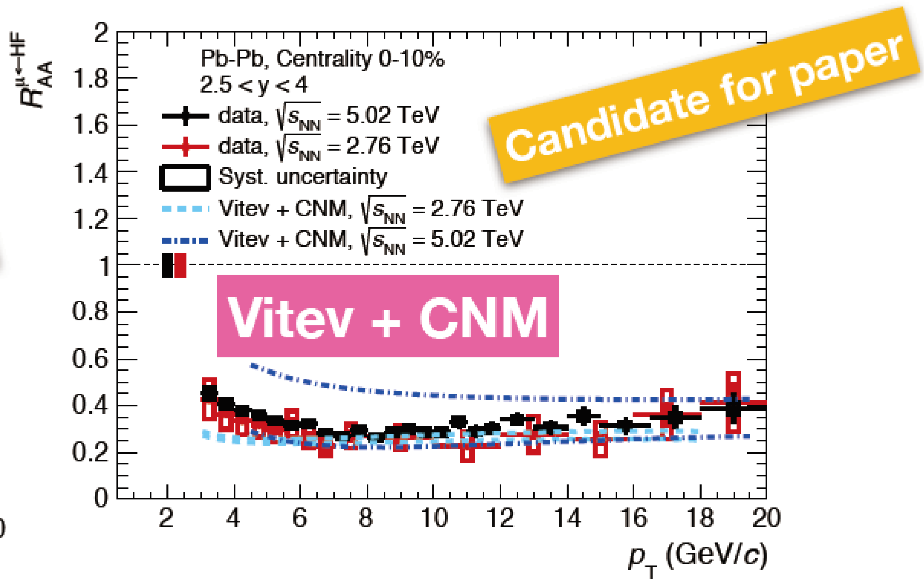
Compare with model

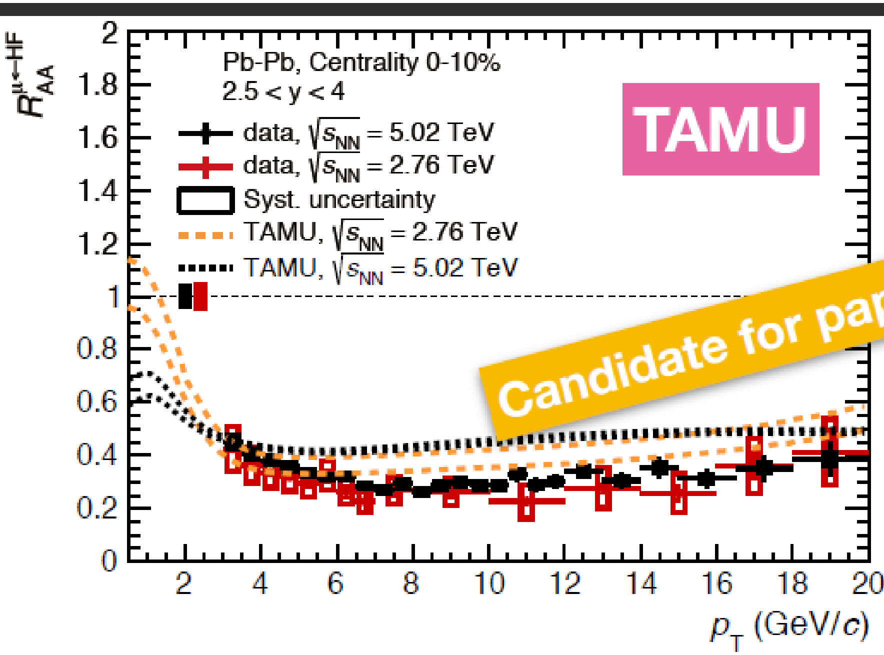
5.02 TeV

2.76 TeV

0–10%

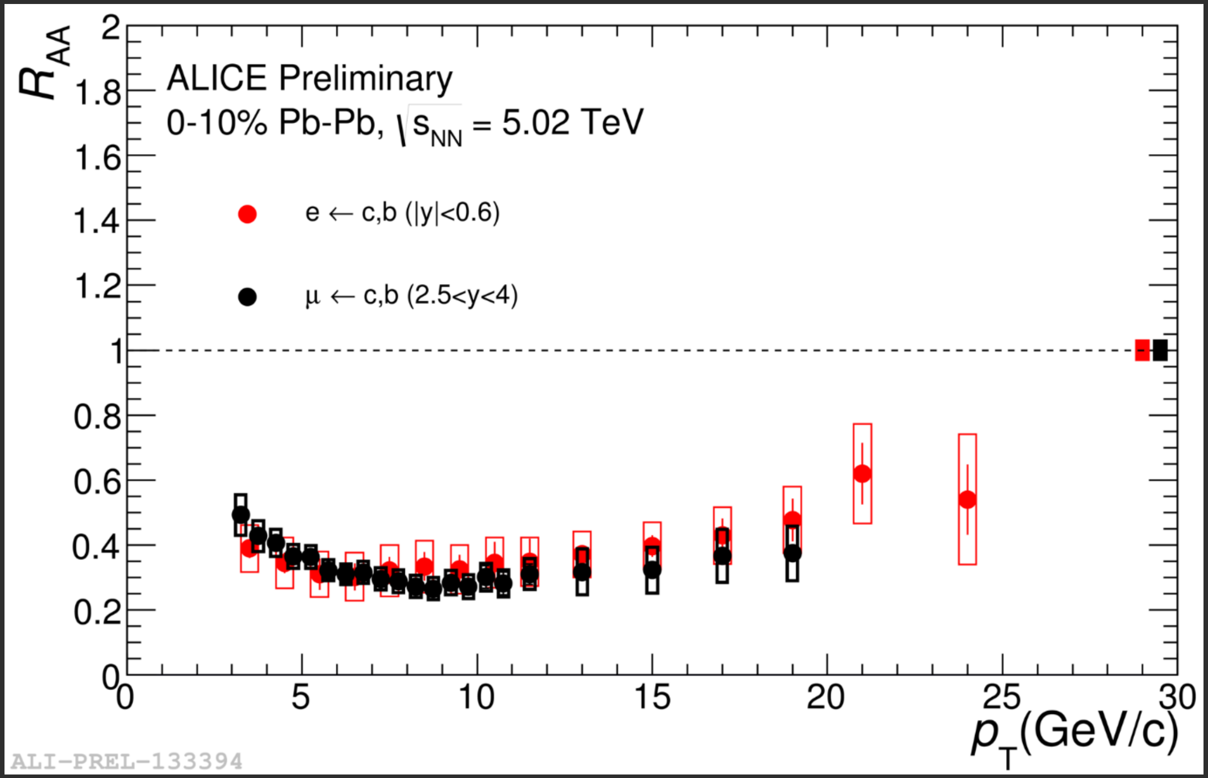






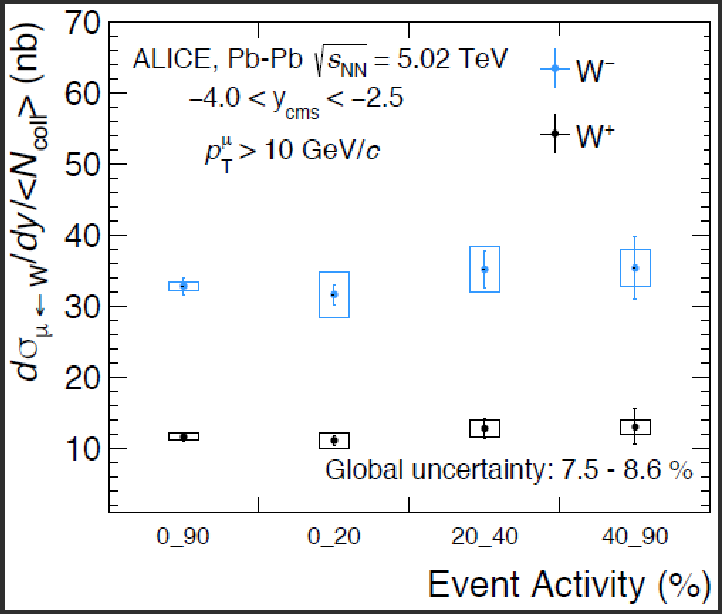
- Vitev model catches the data well within uncertainty
- TAMU with no radiative energy loss overestimated data
- High precision data set stringent constraints to models

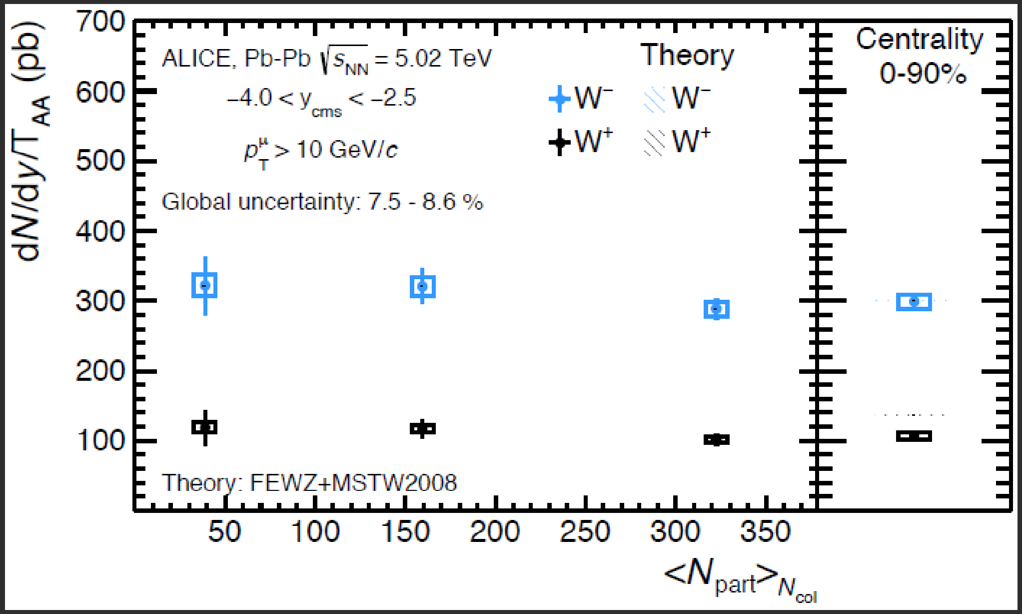
Compare with HFE



- p_T > 5-6 GeV/c: dominated by beauty decay leptons
- Strong suppression in most 10% central collisions for heavy-flavor decay electrons at mid-rapidity (|y| < 0.6) and heavy-flavor decay muons at forward rapidity (2.5 < y < 4.0)
- Suppression of heavy-flavor decay muons is compatible with heavy-flavor decay electrons within uncertainties
  - ✓ Indication that heavy quarks suffered strong interactions in the QCD medium in a wide rapidity range

W in Pb-Pb at 5.02 TeV



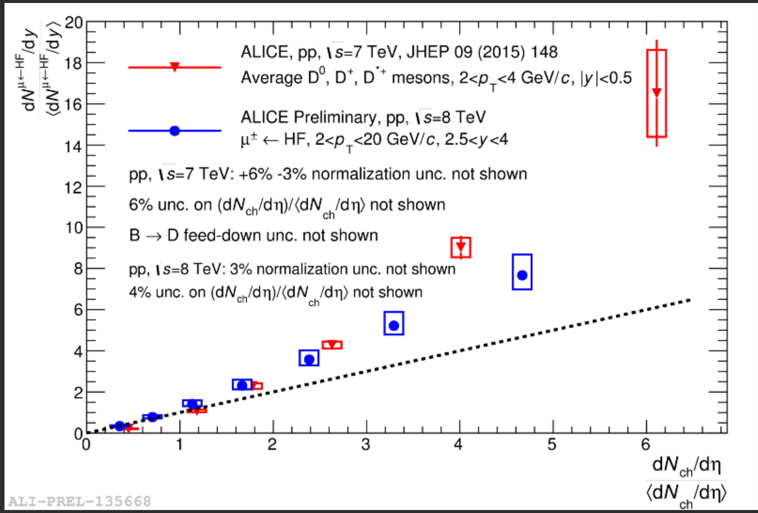


- ✓ First measurement of W production in Pb-Pb collisions at forward rapidity at LHC
- ✓ Cross-section normalized to the number of binary collisions vs. centrality
  - independent with the collision centrality
- ✓ Yield normalized to the nuclear-overlap function T_{AA} vs. average number of participants
  - independent with the collision centrality

Summary and outlook

- **First measurement of R_{AA} of muons from open heavy-flavor decays in Pb-Pb collisions at 5.02 TeV:**
  - ✓ A strong suppression in the 10% most central collisions reaching a factor ~3
  - ✓ Results compatible within uncertainties with those obtained at 2.76 TeV
  - ✓ R_{AA} measurement provides new constraints on energy loss models
  - ✓ heavy quarks suffered strong interactions in the QCD medium in a wide rapidity range
- **Outlook:**
  - ✓ We are extending the analysis for more differential observables

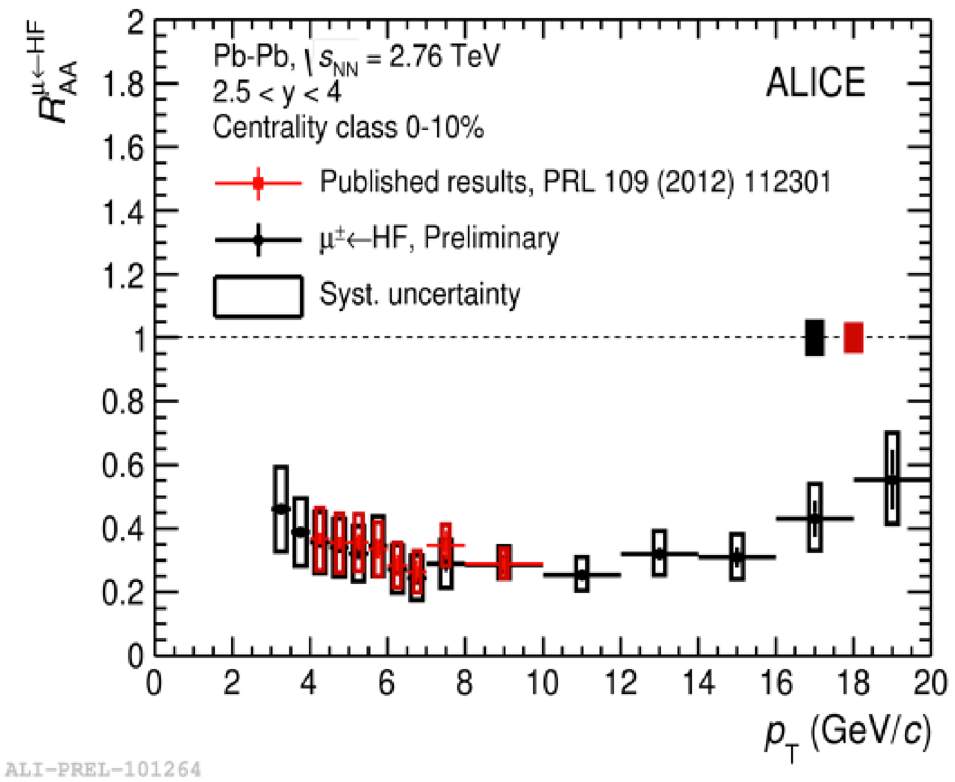
    (HFM vs. multiplicity in pp, flow in p-Pb and higher order of flow in Pb-Pb, Upsilon vs. multiplicity in pp, long-range correlations in pp…)

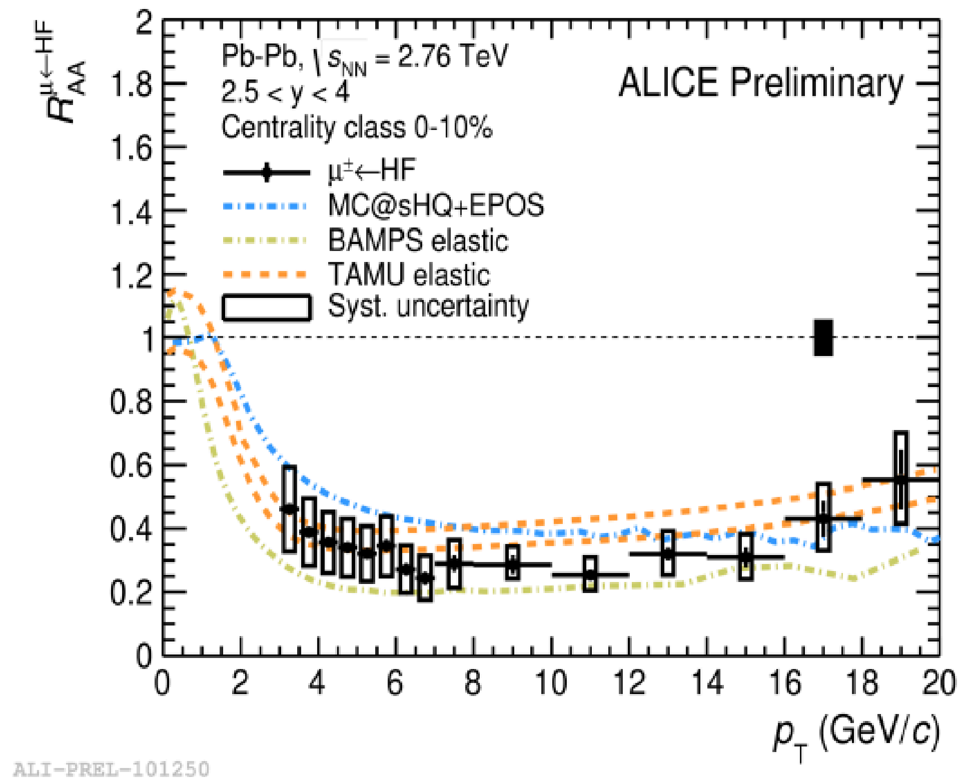


Backup

Nuclear modification of heavy flavour

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





Properties of W and Z boson by PDG

W $J = 1$

Charge $= \pm 1\ e$
Mass $m = 80.385 \pm 0.015$ GeV
$m_Z - m_W = 10.4 \pm 1.6$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV
$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$
$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$
$\langle N_p \rangle = 0.92 \pm 0.14$
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

W^- modes are charge conjugates of the modes below.

W^+ DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
$\ell^+ \nu$	[b]	(10.86 ± 0.09) %		–
$e^+ \nu$		(10.71 ± 0.16) %		40192
$\mu^+ \nu$		(10.63 ± 0.15) %		40192
$\tau^+ \nu$		(11.38 ± 0.21) %		40173
hadrons		(67.41 ± 0.27) %		–
$\pi^+ \gamma$		$< 7 \times 10^{-5}$	95%	40192
$D_s^+ \gamma$		$< 1.3 \times 10^{-3}$	95%	40168
cX		(33.3 ± 2.6) %		–
$c\bar{s}$		(31^{+13}_{-11}) %		–
invisible	[c]	(1.4 ± 2.9) %		–

Z $J = 1$

Charge $= 0$
Mass $m = 91.1876 \pm 0.0021$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0023$ GeV
$\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV [b]
$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]
$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV
$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.0009 \pm 0.0028$
$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 1.0019 \pm 0.0032$ [f]

Average charged multiplicity

$\langle N_{charged} \rangle = 20.76 \pm 0.16 \quad (S = 2.1)$

Couplings to quarks and leptons

$g_V^\ell = -0.03783 \pm 0.00041$
$g_V^u = 0.25^{+0.07}_{-0.06}$
$g_V^d = -0.33^{+0.05}_{-0.06}$
$g_A^\ell = -0.50123 \pm 0.00026$
$g_A^u = 0.50^{+0.04}_{-0.06}$
$g_A^d = -0.523^{+0.050}_{-0.029}$
$g^{\nu_\ell} = 0.5008 \pm 0.0008$
$g^{\nu_e} = 0.53 \pm 0.09$
$g^{\nu_\mu} = 0.502 \pm 0.017$

Asymmetry parameters [g]

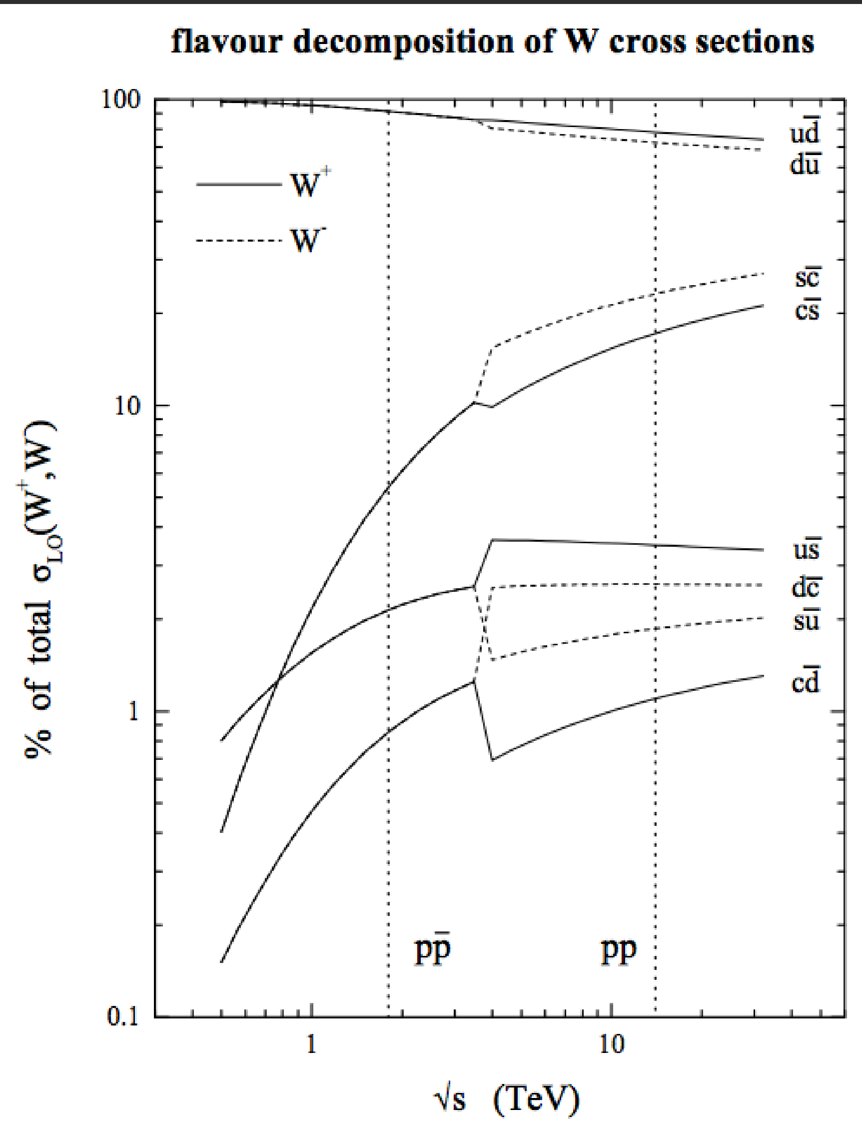
$A_e = 0.1515 \pm 0.0019$
$A_\mu = 0.142 \pm 0.015$
$A_\tau = 0.143 \pm 0.004$
$A_s = 0.90 \pm 0.09$
$A_c = 0.670 \pm 0.027$
$A_b = 0.923 \pm 0.020$

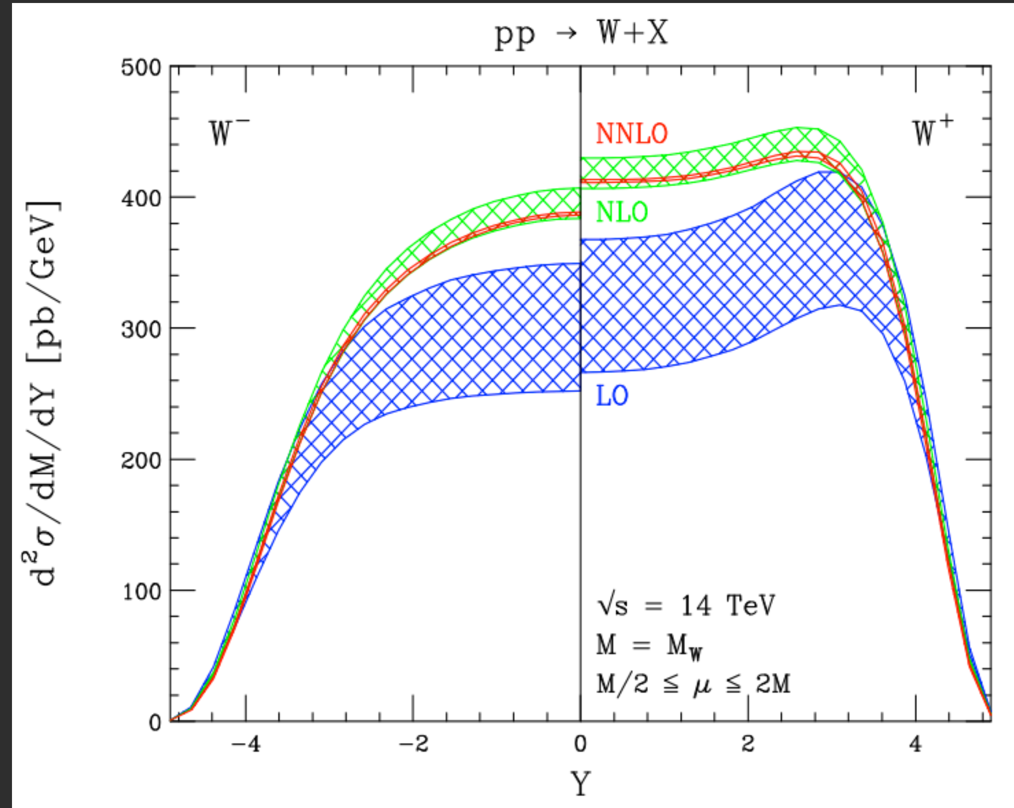
Charge asymmetry (%) at Z pole

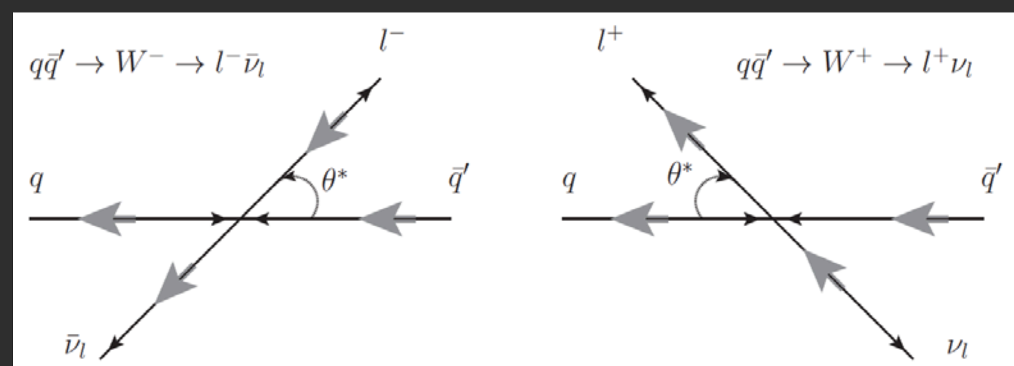
$A_{FB}^{(0\ell)} = 1.71 \pm 0.10$
$A_{FB}^{(0u)} = 4 \pm 7$
$A_{FB}^{(0s)} = 9.8 \pm 1.1$
$A_{FB}^{(0c)} = 7.07 \pm 0.35$
$A_{FB}^{(0b)} = 9.92 \pm 0.16$

Z DECAY MODES		Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
e^+e^-		(3.363 ± 0.004) %		45594
$\mu^+\mu^-$		(3.366 ± 0.007) %		45594
$\tau^+\tau^-$		(3.370 ± 0.008) %		45559
$\ell^+\ell^-$	[b]	(3.3658 ± 0.0023) %		–

Why smaller W^+ at backward rapidity?







HF, $W^{\pm}$ and Z^0/γ^* MC templates

$W^{\pm}$ and Z^0/γ^*

Simulation configuration :

- $W^{\pm}$ and Z^0/γ^* generated with POWHEG in p-p, p-n & n-p collisions at 5.02 TeV

Generators :

- POWHEG : [JHEP 0807(2008)060]
  - is interfaced with PYTHIA6.4 [JHEP 05(2006)026] to apply showering, CTEQ6m/CT10 PDF
  - shadowing : p or n considered in a Pb nucleus, parameterized with EPS09 [JHEP 0904(2009)065]

Combine p-p & p-n to obtain p-Pb :

- A = 208, Z = 82

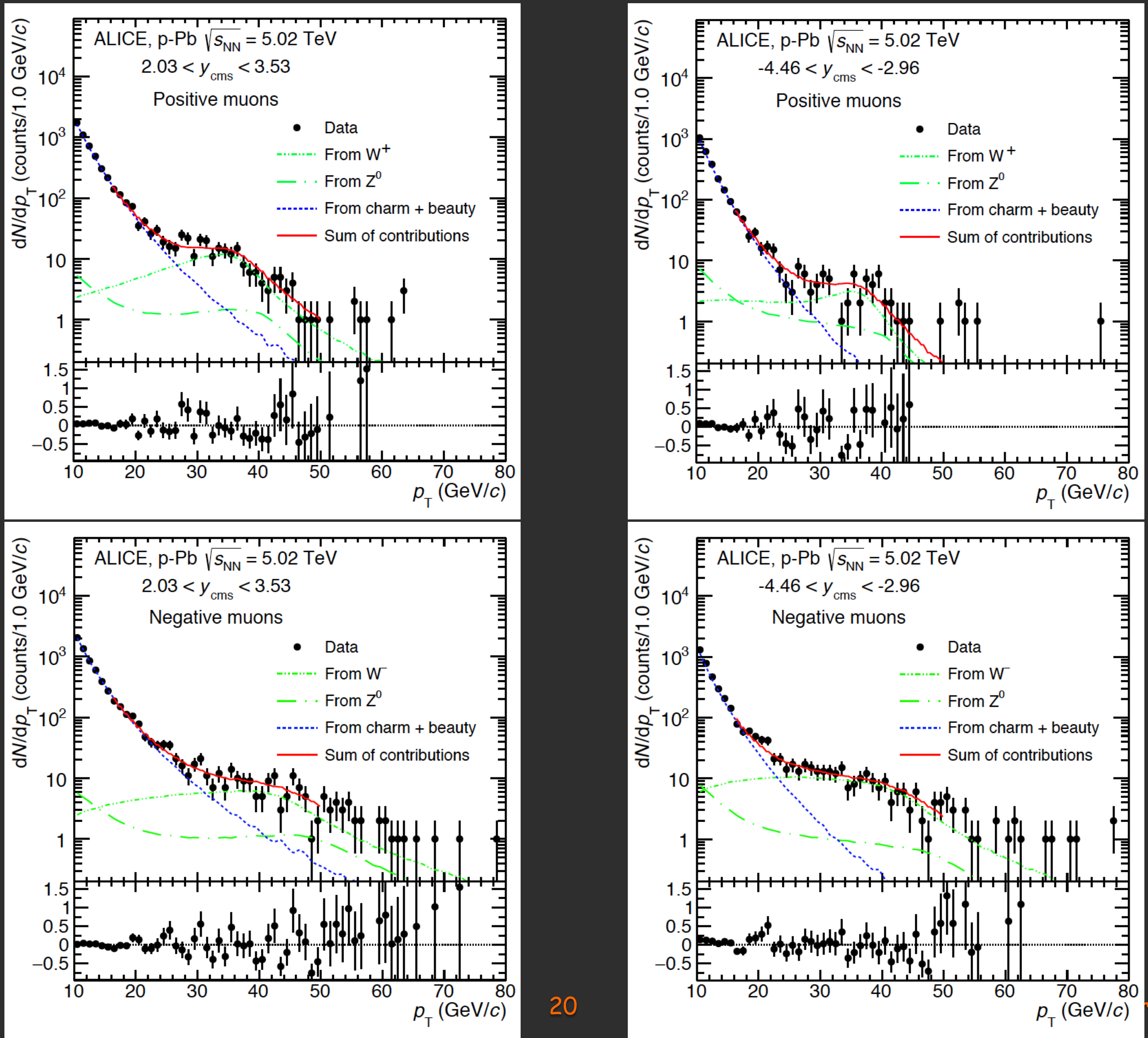
$$\frac{1}{N_{pPb}} \cdot \frac{dN_{pPb}}{dp_T} = \frac{Z}{A} \cdot \frac{1}{N_{pp}} \cdot \frac{dN_{pp}}{dp_T} + \frac{A-Z}{A} \cdot \frac{1}{N_{pn}} \cdot \frac{dN_{pn}}{dp_T}$$

Heavy-flavor (HF)

Simulation configuration :

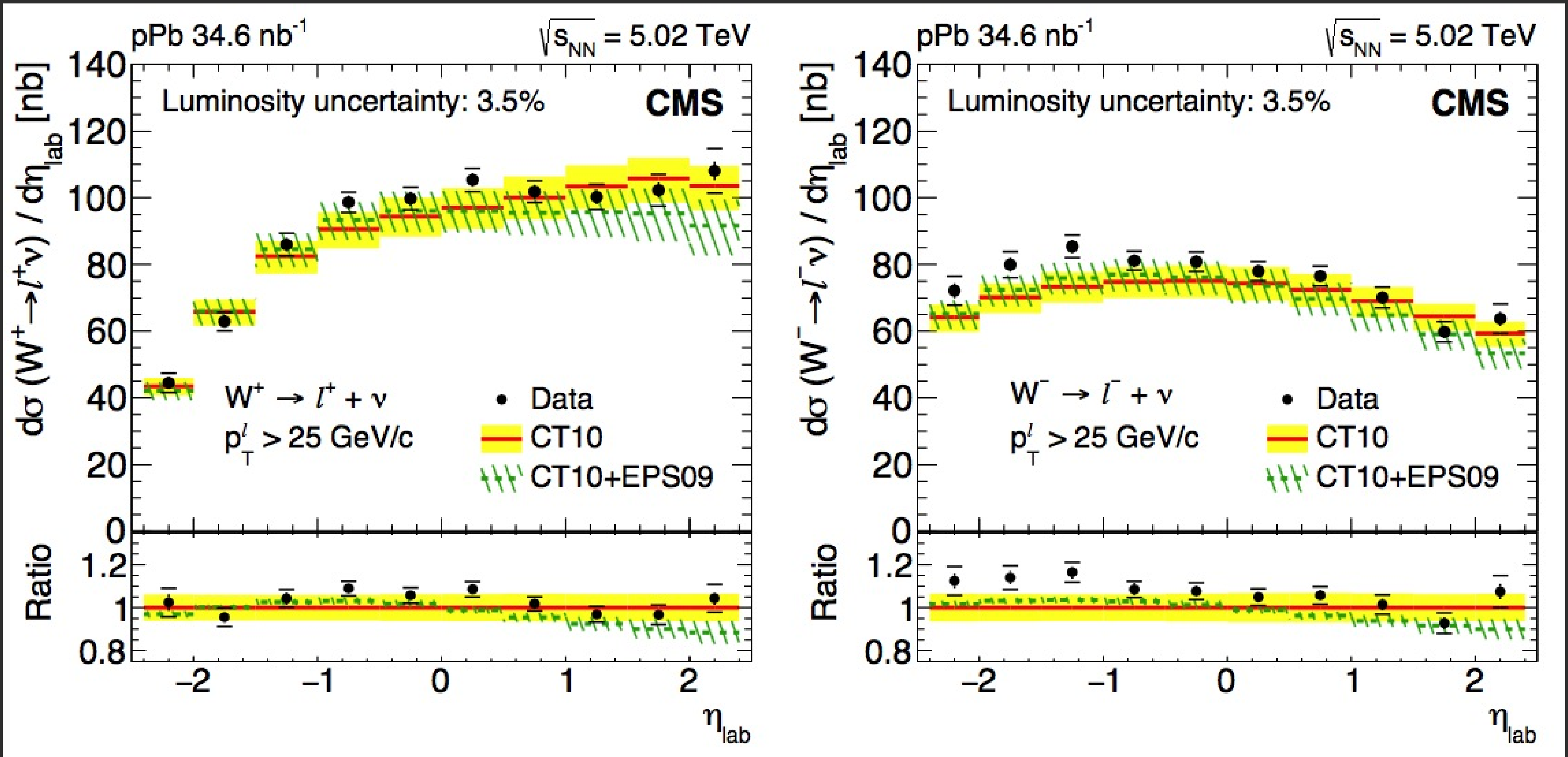
- Based on Fixed Order Next-to-Leading-Log (FONLL) with CTEQ6.6 [JHEP 1210(2012)137]

Examples of combined fit in ALICE



W-boson cross section in CMS

[Phys. Lett. B 750 (2015) 565]



W-boson charge asymmetry in CMS

[Phys. Lett. B 750 (2015) 565]