Nuclear shadowing and electroweak-boson production in heavy-ion collisions

Particle Physics Day 2020

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Outline

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1. Motivation
2. Electroweak-boson production in p+p, p+Pb and Pb+Pb
3. Glauber modelling and data-preferred value for $\sigma_{\mathrm{nn}}^{\mathrm{inel}}$
4. Eikonal minijet model with nuclear shadowing
5. Summary & Outlook

Motivation

ATLAS Pb+Pb data from Run 2

- $W^{\pm}$ production (0-80%)

  [EPJC 79 (2019) 11, 935]

- Z production (0-100%)

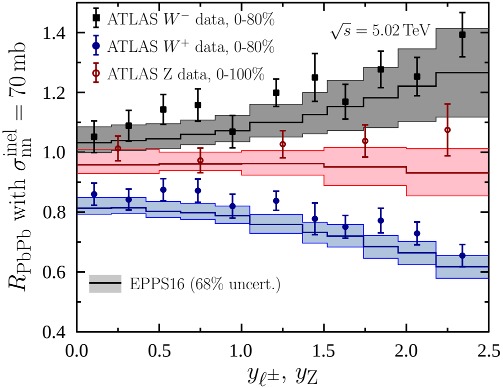
  [PLB 802 (2020) 135262]

- Percent-level uncertainties
- Not sensitive to QGP

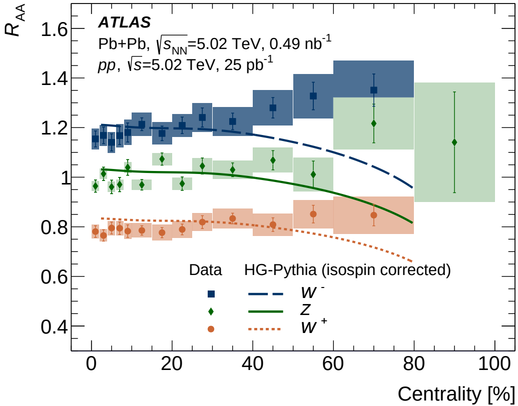
⇒ Allows precision studies for

- Initial state nuclear effects
- Glauber model calibration/validation

  [Paukkunen, Salgado, JHEP 03 (2011) 071]



Motivation



[ATLAS: PLB 802 (2020) 135262]

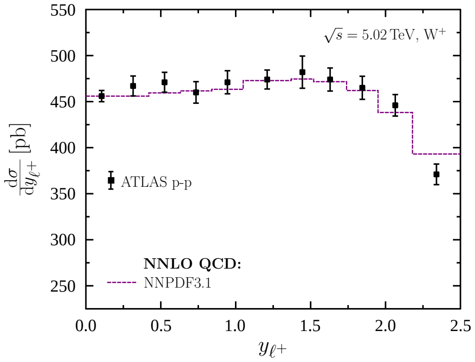
Also centrality-dependent data

- Unexpected rise of R_{AA} towards more peripheral events
- Similar for W^+, W^- and Z
- Geometrical and selection biases (HG-Pythia) suggest an opposite behaviour

Electroweak-boson production in p+p

Theoretically well-constrained

- High-scale processes ($Q^2 = M_Z^2, M_W^2 \sim 10\,000$ GeV^2) $\Rightarrow$ Can treat perturbatively
- Next-to-next-to-leading order (NNLO) calculations available [MCFM: EPJC 77 (2017) 1, 7]
- Proton PDFs available at NNLO [NNPDF3.1: EPJC 77 (2017) 10, 663]
- Very good agreement with p+p data at $\sqrt{s} = 5.02$ TeV when using NNPDF3.1 for W^+



[ATLAS: EPJC 79 (2019) 2, 128]

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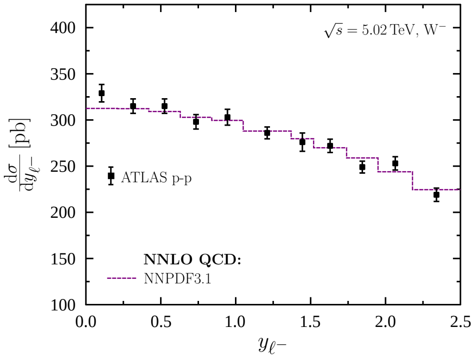

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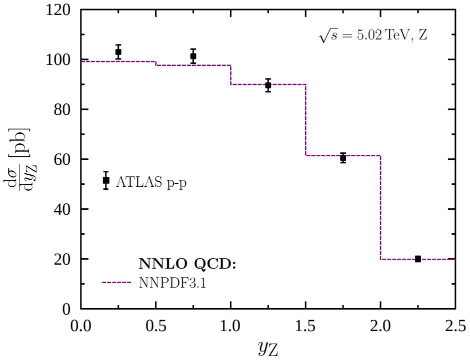
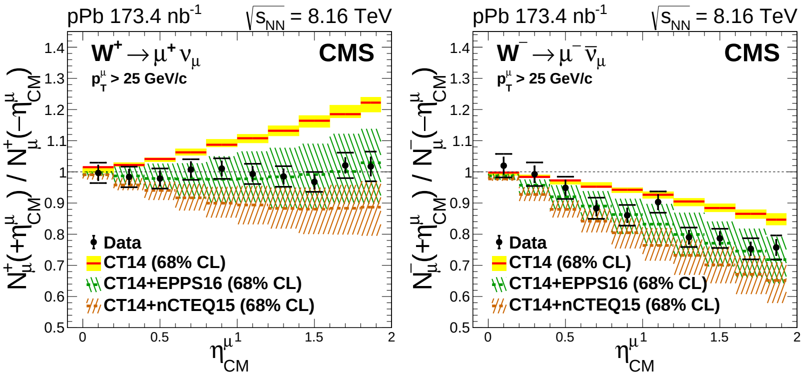


[ATLAS: EPJC 79 (2019) 2, 128]

Electroweak-boson production in p+Pb

[CMS: Phys.Lett.B 800 (2020) 135048]



- Collinear factorization ⇒ Absorb nuclear effects into nuclear PDFs (nPDFs)
- Excellent agreement with CMS $W^{\pm}$ data and EPPS16 nPDFs in p+Pb

Electroweak-boson production in Pb+Pb

State-of-the-art framework

- Calculate the cross sections at NNLO in pQCD using MCFM
  [version 8.0, EPJC 77 (2017) 1, 7]
- NNLO free proton PDFs from NNPDF3.1 analysis
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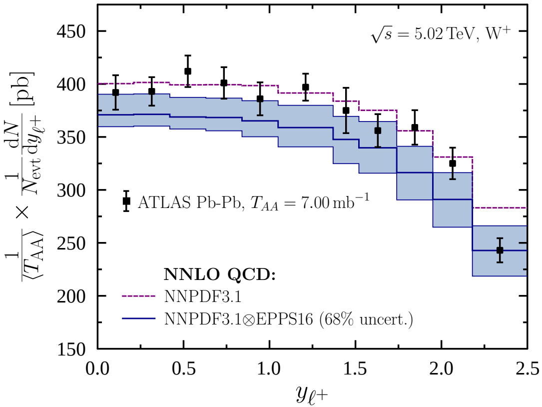
- Nuclear modifications from EPPS16 NLO analysis
  [EPJC 77 (2017) 3, 163]



- Shapes well described, slight systematic offset in normalization

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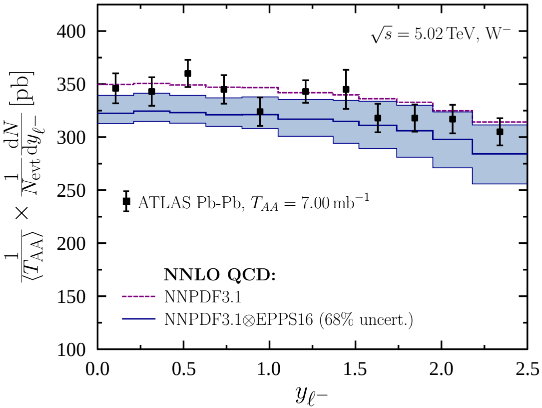

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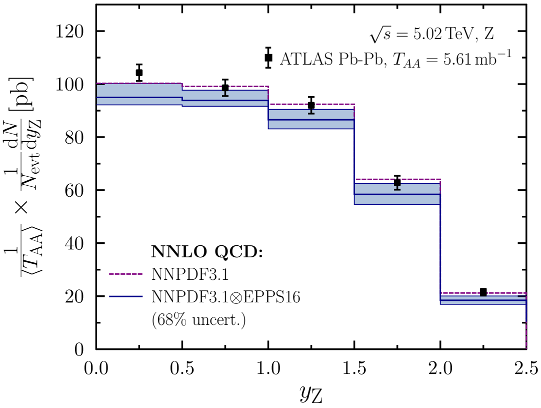

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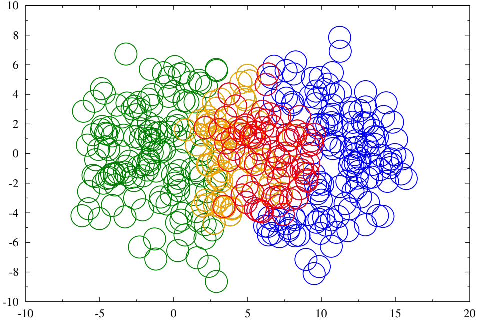
Monte-Carlo (MC) Glauber model for heavy-ion collisions



MC Glauber simulations

- Sample nucleon positions
- Sample impact parameter b
- Calculate N_{bin} and N_{part},
  N-N collision if $d < \sqrt{\sigma_{\mathrm{nn}}^{\mathrm{inel}}/\pi}$
- Classify collisions based on multiplicity and calculate $\langle N_{\mathrm{bin}} \rangle_c$

⇒ Normalization for a centrality class c: $\langle T_{\mathrm{PbPb}} \rangle = \langle N_{\mathrm{bin}} \rangle_c / \sigma_{\mathrm{nn}}^{\mathrm{inel}}$

- We use TGlauberMC (version 2.4)
  [SoftwareX 1-2 (2015) 13-18]

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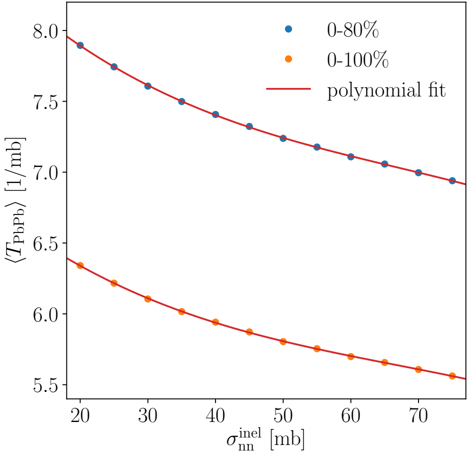

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Electroweak-boson production in Pb+Pb

To study nuclear effects it is useful to consider nuclear modification ratio R_{AA}

Experimental definition

$$R^{\text{exp}}_{\text{PbPb}}(y) = \frac{1}{\langle T_{\text{PbPb}}\rangle} \frac{\frac{1}{N_{\text{evt}}} \mathrm{d}N^{W^\pm,Z}_{\text{PbPb}}/\mathrm{d}y}{\mathrm{d}\sigma^{W^\pm,Z}_{\text{pp}}/\mathrm{d}y}$$

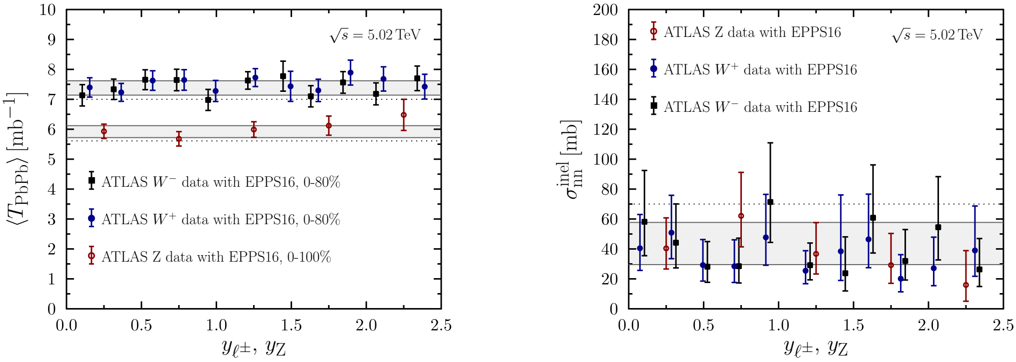
- $\langle T_{\text{PbPb}}\rangle = \langle N_{\text{bin}}\rangle_c / \sigma^{\text{inel}}_{\text{nn}}$
- $\langle N_{\text{bin}}(\sigma^{\text{inel}}_{\text{nn}})\rangle_c$ from MC Glauber
- Conventionally $\sigma^{\text{inel}}_{\text{nn}} = \sigma^{\text{inel}}_{\text{pp}}$ ($\approx 70 \pm 5$ mb at $\sqrt{s} = 5.02$ TeV)

Theoretical definition

$$R^{\text{theor}}_{\text{PbPb}}(y) = \frac{1}{(208)^2} \frac{\mathrm{d}\sigma^{W^\pm,Z}_{\text{PbPb}}/\mathrm{d}y}{\mathrm{d}\sigma^{W^\pm,Z}_{\text{pp}}/\mathrm{d}y}$$

- Min.bias $\mathrm{d}\sigma_{\text{PbPb}}$ normalized with number of nucleons
- Nuclear effects for $\mathrm{d}\sigma_{\text{PbPb}}$ derived from nuclear PDFs (nPDFs)

Our idea: Use EW bosons as a standard candle and equate ∼min.bias $R^{\text{exp}}_{\text{PbPb}}$ with $R^{\text{theor}}_{\text{PbPb}}$ to obtain data-preferred values for $\langle T_{\text{PbPb}}\rangle$ and $\sigma^{\text{inel}}_{\text{nn}}$ in Pb+Pb

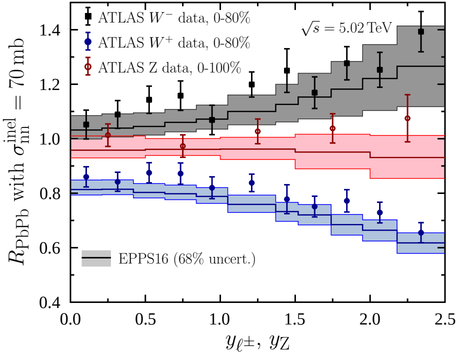


- Data points obtained from equating $R_{\mathrm{PbPb}}^{\mathrm{exp}}$ with $R_{\mathrm{PbPb}}^{\mathrm{theor}}$ and solving for $\langle T_{\mathrm{PbPb}} \rangle$

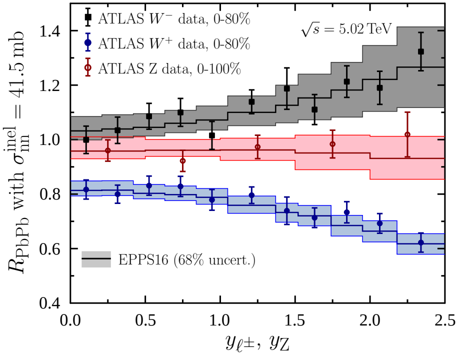
Result: $\sigma_{\mathrm{nn}}^{\mathrm{inel}} = 41.5^{+16.2}_{-12.0}$ mb instead of $\sigma_{\mathrm{pp}}^{\mathrm{inel}} = 70 \pm 5$ mb used by ATLAS

Resulting $R_{\mathrm{PbPb}}^{W^\pm,Z}$

Original analysis

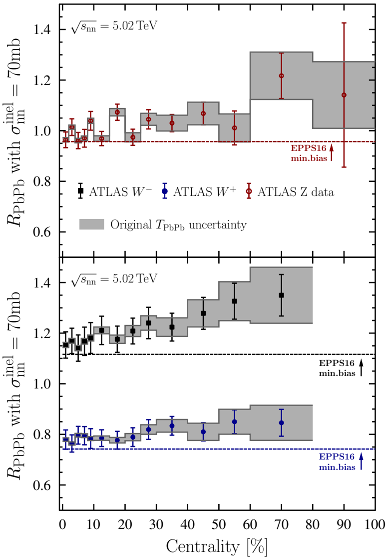


Fitted $\sigma_{\mathrm{nn}}^{\mathrm{inel}}$



- Original data lie systematically above the theory predictions
- Data re-normalized with $\langle T_{\mathrm{PbPb}} \rangle$ using $\sigma_{\mathrm{nn}}^{\mathrm{inel}} = 41.5$ mb is well described with the theory setup

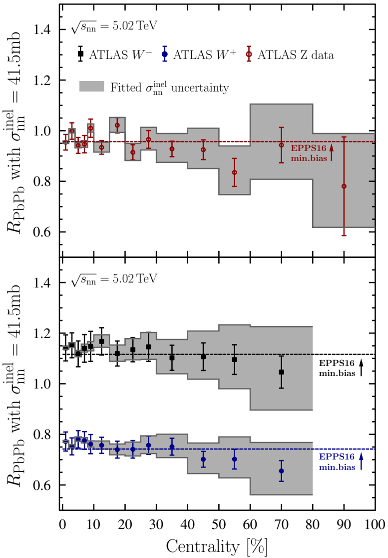
Impact on centrality dependence



ATLAS result

- R_{PbPb} rise towards more peripheral collisions
- Large variations in σ_{nn}^{inel} cause modest changes in $\langle T_{PbPb} \rangle$ for (close to) minimum bias

Impact on centrality dependence



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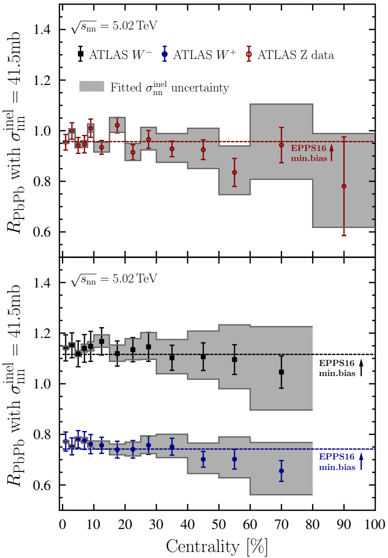

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- Large variations in σ_{nn}^{inel} cause modest changes in $\langle T_{PbPb} \rangle$ for (close to) minimum bias
- The unexpected rise turns into flat (or even slightly decreasing) trend
- Also some other centrality-dependent effects expected

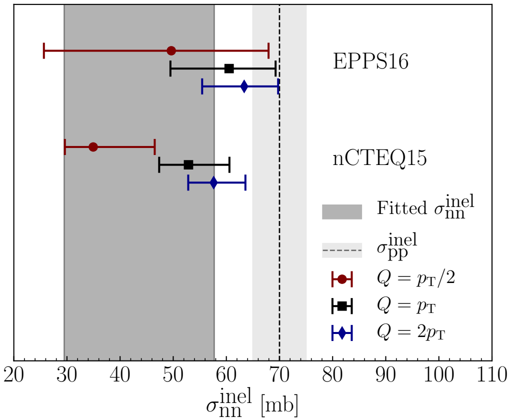
An eikonal minijet model

- No soft component, all cross section purely from (LO) pQCD

$$
\begin{aligned}
\sigma_{\mathrm{nn}}^{\mathrm{inel}}(s, p_0, \lambda, Q) &= \pi \int_0^\infty \mathrm{d}b^2 \left[1 - \mathrm{e}^{-\sigma_{\mathrm{jet}}(s,p_0,Q)T_{\mathrm{pp}}(b,\lambda)}\right] \\
\sigma_{\mathrm{jet}}(s, p_0, Q) &= \int_{p_0} \mathrm{d}p_{\mathrm{T}} \sum_{i,j,k,l} f_i(Q) \otimes f_j(Q) \otimes \hat{\sigma}_{ij\to kl}(Q) \\
T_{\mathrm{pp}}(b, \lambda) &= \frac{1}{4\pi\lambda^2} \mathrm{e}^{-\frac{b^2}{4\lambda^2}}
\end{aligned}
$$

- Fit cut off p_0 to $\sigma_{\mathrm{pp}}^{\mathrm{inel}}$ and fix width parameter λ using $\sigma_{\mathrm{pp}}^{\mathrm{tot}}$
- Apply nPDFs to compute $\sigma_{\mathrm{nn}}^{\mathrm{inel}}(s, p_0, \lambda, Q)$ in Pb+Pb

Results from eikonal minijet model



Nuclear suppression from shadowing

- Two nPDF sets, EPPS16 and nCTEQ15, error bands scaled to 68% cl.
- Three scale choices, $Q = p_T/2, p_T, 2p_T$
- Suppression derived from ATLAS EW data in line with nuclear shadowing

Summary & Outlook

Summary

- Using EW boson data in Pb+Pb collisions and a state-of-the-art pQCD-based calculation we have obtained a nuclear-modified value for $\sigma_{\rm nn}^{\rm inel}$
- ATLAS data prefer significantly suppressed $\sigma_{\rm nn}^{\rm inel}$ at $\sqrt{s_{\rm nn}} = 5.02$ TeV

$$\sigma_{\rm nn}^{\rm inel} = 70 \pm 5 \text{ mb} \to 41.5^{+16.2}_{-12.0} \text{ mb}$$

- In line with an eikonal minijet model including nuclear shadowing of PDFs
- Explains also unexpected centrality dependence of $R_{\rm PbPb}^{W^\pm,Z}$

Outlook

- Preliminary CMS Z-boson data show the opposite centrality dependence, is the tension real or related to different MC Glauber modelling?
- Study further by including other centrality-dependent effects

Backup slides

Fitting procedure for $\sigma_{\rm nn}^{\rm inel}$

Fit $\sigma_{\rm nn}^{\rm inel}$ by minimizing χ^2 defined as

$$\chi^2 = \sum_i \left[\frac{R_{{\rm PbPb},i}^{\rm exp} \frac{\langle T_{\rm PbPb}^i(\sigma_{\rm pp}^{\rm inel})\rangle}{\langle T_{\rm PbPb}^i(\sigma_{\rm nn}^{\rm inel})\rangle} - R_{{\rm PbPb},i}^{\rm theor} + \sum_k f_k \beta_i^k}{\delta_i^{\rm exp} \frac{\langle T_{\rm PbPb}^i(\sigma_{\rm pp}^{\rm inel})\rangle}{\langle T_{\rm PbPb}^i(\sigma_{\rm nn}^{\rm inel})\rangle}} \right]^2 + T \sum_k f_k^2$$

wrt. $\sigma_{\rm nn}^{\rm inel}$ and f_k (1+20 parameters)

- $\beta_i^k = \frac{1}{2}[R_i^{\rm theor}(S_k^+) - R_i^{\rm theor}(S_k^-)]$ accounts for EPPS16 uncertainties
- $T = 1.645^2$ from scaling the uncertainties from 90% into 68% confidence level
- Monte-Carlo (MC) Glauber maps $\sigma_{\rm nn}^{\rm inel}$ to $\langle T_{\rm PbPb}\rangle$ for both centrality classes, 0-80% for $W^\pm$ and 0-100% for Z

Glauber results for $\langle T_{\mathrm{PbPb}} \rangle$

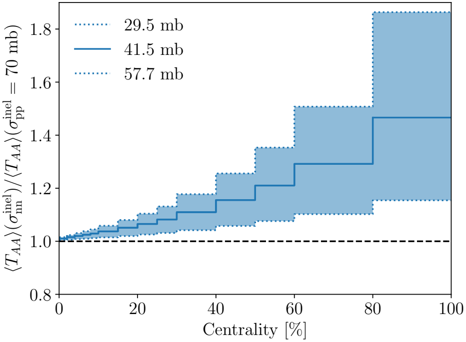
ATLAS and suppressed $\sigma_{\mathrm{nn}}^{\mathrm{inel}}$

centrality	ATLAS	70.0 mb	57.7 mb	41.5 mb	29.5 mb
0 – 2%	28.30	28.26	28.39	28.55	28.69
2 – 4%	25.47	25.51	25.67	25.91	26.10
4 – 6%	23.07	23.09	23.28	23.55	23.80
6 – 8%	20.93	20.94	21.14	21.45	21.73
8 – 10%	18.99	19.00	19.23	19.56	19.86
10 – 15%	16.08	16.08	16.31	16.67	17.02
15 – 20%	12.59	12.58	12.83	13.22	13.59
20 – 25%	9.77	9.762	10.01	10.40	10.78
25 – 30%	7.50	7.487	7.722	8.102	8.469
30 – 40%	4.95	4.933	5.138	5.474	5.808
40 – 50%	2.63	2.628	2.780	3.036	3.300
50 – 60%	1.28	1.281	1.378	1.550	1.733
60 – 80%	0.39	0.395	0.435	0.510	0.595
80 – 100%	0.052	0.052	0.060	0.076	0.096
0 – 80%	7.00	6.993	7.143	7.385	7.624
0 – 100%	5.61	5.605	5.726	5.923	6.118

CMS compared to suppressed $\sigma_{\mathrm{nn}}^{\mathrm{inel}}$

centrality	CMS	70.0 mb	57.7 mb	41.5 mb	29.5 mb
0 – 5%	25.70	26.24	26.39	26.61	26.79
5 – 10%	20.40	20.48	20.69	21.00	21.29
10 – 20%	14.39	14.33	14.57	14.95	15.30
20 – 30%	8.80	8.624	8.866	9.251	9.623
30 – 40%	5.12	4.933	5.138	5.474	5.808
40 – 50%	2.78	2.628	2.780	3.036	3.300
50 – 70%	0.996	0.9223	0.9986	1.134	1.281
70 – 90%	0.165	0.1519	0.1708	0.2073	0.2509
0 – 90%	6.27	6.225	6.359	6.577	6.793
0 – 100%	5.65	5.605	5.726	5.923	6.118

Impact to centrality dependence



Suppressed σ_{nn}^{inel}

- Small effect for central collisions
- More pronounced effect for peripheral collisions

Other possible effects

- Neutron-skin effect
- Decreasing shadowing towards more peripheral collisions
- Geometrical bias
- Selection bias

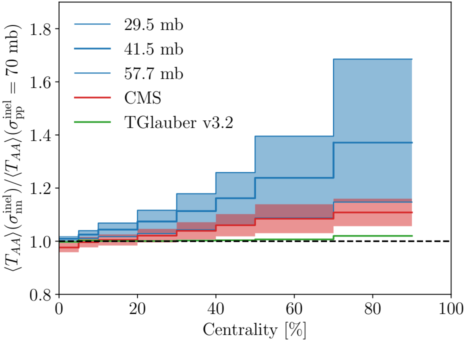
CMS Glauber simulations

Resulting $\langle T_{\mathrm{PbPb}} \rangle$

- Compare CMS results to ATLAS-type setup with nominal and suppressed values of $\sigma_{\mathrm{nn}}^{\mathrm{inel}}$
- Different centrality dependence between ATLAS and CMS

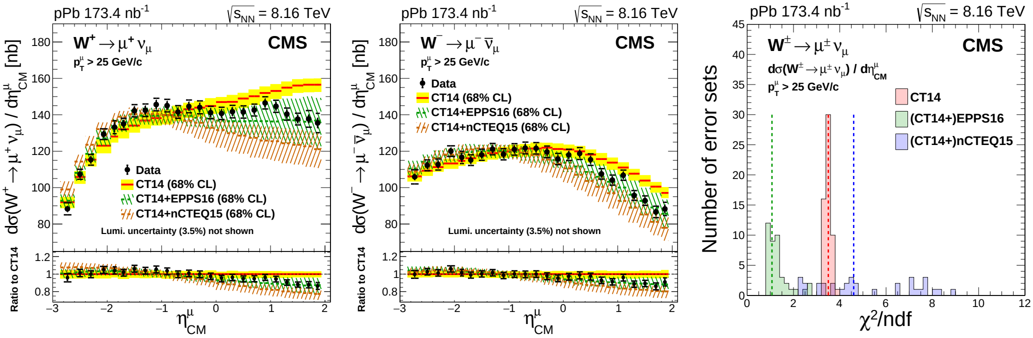
⇒ Part of the mismatch with ATLAS due to Glauber simulations but not enough to resolve the tension

- TGlauber version (2.4 vs 3.2) does not make much difference

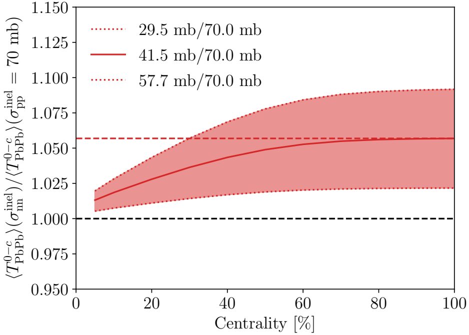


Electro-weak boson production in p+Pb

[CMS: Phys.Lett.B 800 (2020) 135048]



How the effect accumulates towards peripheral collisions

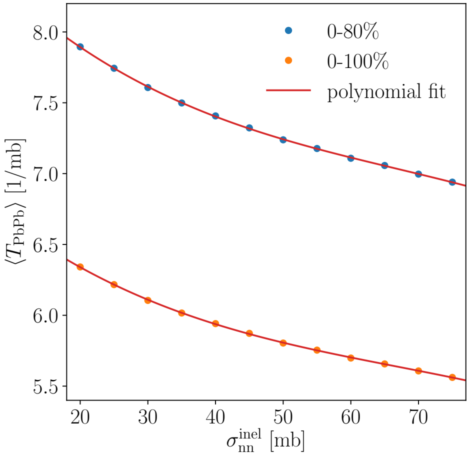


Integrate from 0 to c%

- Most of the modification builds up already from 0–60%
- Less weight from peripheral collisions

⇒ Uncertainties in the periphery do not have large impact in $\sigma_{\mathrm{nn}}^{\mathrm{inel}}$ determination from min. bias data

MC Glauber model for heavy-ion collisions



MC Glauber simulations

- We use TGlauberMC (version 2.4)
  [SoftwareX 1-2 (2015) 13-18]
- Centrality classification with two-component model including negative binomial fluctuations

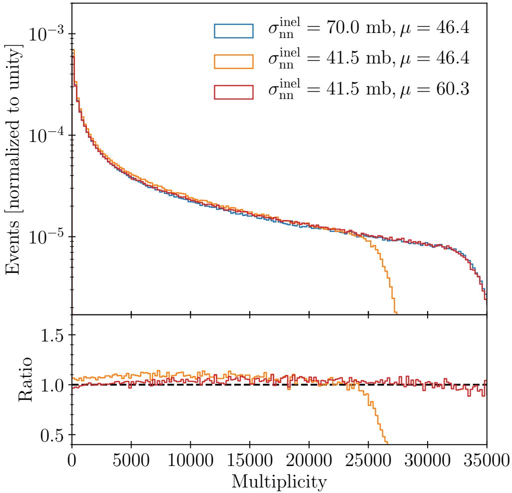
$$N_{\mathrm{ancest}} = \lfloor x\, N_{\mathrm{part}} + (1-x)\, N_{\mathrm{bin}} \rfloor$$

$$N_{\mathrm{final}} = \sum_{i=1}^{N_{\mathrm{ancest}}} P^{n}_{\mathrm{NBD}}(\mu, \kappa)$$

with $x = 0.801$, $\mu = 46.4$, $\kappa = 1.5$

[ALICE-PUBLIC-2018-011]

Does modified σ_{nn}^{inel} ruin Glauber fits?

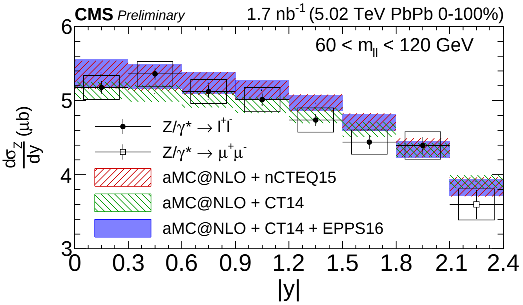


Centrality classification

- Fit multiplicity (or ΣE_T) to fix Glauber parameters
  - x, fractions of N_{part} and N_{bin}
  - μ, mean of NBD
  - κ, width of NBD

  [ALICE-PUBLIC-2018-011]
- Reduced σ_{nn}^{inel} $\Rightarrow$ less multiplicity
- Can be compensated by increasing μ
- Very small impact on $\langle T_{PbPb} \rangle$

Preliminary CMS data for Z



[CMS PAS HIN-19-003]

CMS result

- Also min.bias behaviour is somewhat different from ATLAS
- Is normalization from measured luminosity or Glauber simulations?

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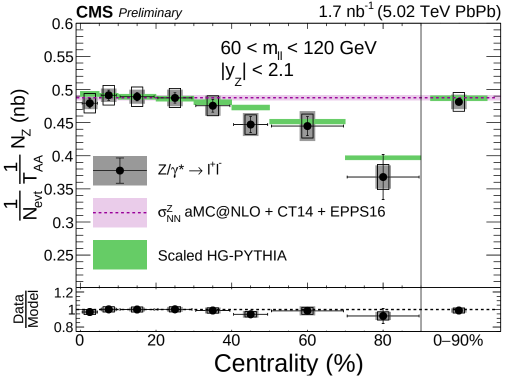

[CMS PAS HIN-19-003]

CMS result

- Decreasing normalized yield with centrality (opposite to ATLAS)
- Data consistent with HG-PYTHIA accounting for geometrical (HIJING) and selection biases (PYTHIA)
- No support for σ_{nn}^{inel} suppression