Z boson production in proton-lead collisions at the LHC

Accounting for transverse momenta of initial partons

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26/11/19

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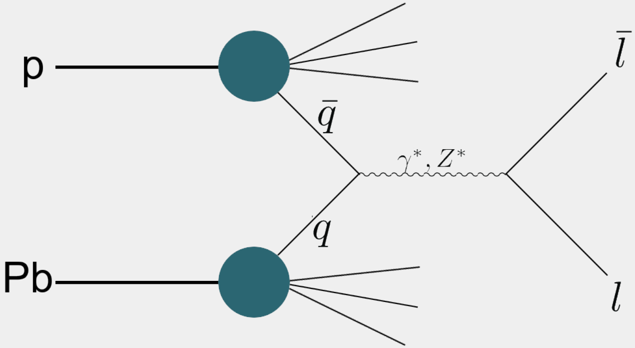
Framework



Process

$$p\mathrm{Pb} \to (Z/\gamma^*) \to \ell\bar{\ell}$$

Fiducial Region

- $\sqrt{s} = 5.02$ TeV
- $|\eta^{l}_{lab}| < 2.4$
- $p^{l}_{T} > 20$ GeV
- 60 Gev$< m_{ll} <$ 120 GeV

CMS Collaboration. STUDY OF Z BOSON PRODUCTION IN PPB COLLISIONS AT SQRT (S_NN)= 5.02 TEV.

***PHYSICAL LETTERS*, B759:36–57, 2016**

$k_{i\in 1,2} = x_i p_i + k_{t,i}$ where 1 refers to p and 2 to Pb.

Formulation

$$d\sigma = \sum_{a,b} \int \frac{d^2\mathbf{k}_{t,1}}{\pi} dx_1 \frac{d^2\mathbf{k}_{t,2}}{\pi} dx_2 \mathcal{A}_{a,1}(x_1, \mathbf{k}_{t,1}, \mu) \mathcal{A}_{b,2}(x_2, \mathbf{k}_{t,2}, \mu) \times$$
$$\times\ \sigma_{a,b}(x_1, \mathbf{k}_{t,1}, x_2, \mathbf{k}_{t,2}, \mu)$$

S Catani, M Ciafaloni, and F Hautmann. HIGH-ENERGY FACTORIZATION IN QCD AND MINIMAL SUBTRACTION SCHEME.
***Physics Letters B*, 307(1-2):147–153, 1993**

k_t-FACTORIZATION

$k_{i\in 1,2} = x_i p_i + k_{t,i}$ where 1 refers to p and 2 to Pb.

Formulation

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Objects needed

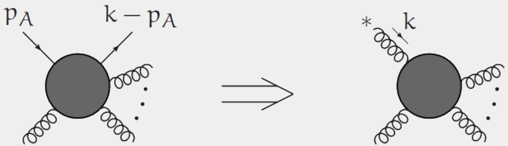
- TMDs to describe partons in p
- nTMDs to describe partons in Pb
- Off-shell matrix elements

KaTie

Katie

- Monte-Carlo events generator
- Suitable for k_t-dependent initial states
- Calculates partonic tree-level off-shell matrix elements

A. van Hameren. KATIE: FOR PARTON-LEVEL EVENT GENERATION WITH KT-DEPENDENT INITIAL STATES.
COMPUTER PHYSICS COMMUNICATIONS, 224:371–380, 2018



Simple oveview

1. "Replace" the off-shell gluon by an eikonal quark line
2. Calculate the amplitude with color ordered eikonal Feynman rules
3. Apply some appropriate kinematic / prescription

A Van Hameren, P Kotko, and K Kutak. Helicity amplitudes for high-energy scattering.

Journal of High Energy Physics, 2013(1):78, 2013

Parton Distribution Functions

Principle

- Use a known PDF at a fixed μ_0, $k_{t,0}$ as a starting distribution.
- Consider a factorized Gaussian k_t dependence.
- Apply iteratively DGLAP evolution equation.
  $\Rightarrow$ Equivalent to space-like parton shower

Evolution Equation

Evolution Equation :

$$x\mathcal{A}_a^{\mathrm{Pb}}(x, k_t^2, \mu^2) = \int dx' \mathcal{A}_{0,b}^{\mathrm{Pb}}(x', k_{t,0}^2, \mu_0^2) \frac{x}{x'} \mathcal{K}_{ba}\left(\frac{x}{x'}, k_{t,0}^2, k_t^2, \mu_0^2, \mu^2\right)$$

Starting distribution : $\mathcal{A}_{0,b}^{\mathrm{Pb}}(x, k_{t,0}^2, \mu_0^2) = f_{0,b}^{\mathrm{Pb}}(x, \mu_0^2) \cdot \exp(-|k_{t,0}^2|/\sigma^2)$

From TMDs to Collinear PDFs

$$f_a(x, \mu^2) = \int \frac{d^2 k_t}{\pi} \mathcal{A}_a(x, k_t, \mu^2)$$

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- Starting scale μ_0

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- Scale of the running constant α_S

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TMD Set1

$\mu_0 = 1.9\text{GeV}^2$
$\alpha_S(\mu^2)$

TMD Set2

$\mu_0 = 1.4\text{GeV}^2$
$\alpha_S(|q^2_{t,i}|)$

Proton TMD

- PB-NLO-HERAI+II-2018

"Hybrid" TMD

- PB-NLO_ptoPb208

TMD sets

- $\texttt{Set1}: \mu_0 = 1.9\text{GeV}^2$
  $\alpha_S(\mu^2)$
- $\texttt{Set2}: \mu_0 = 1.4\text{GeV}^2$
  $\alpha_S(|q_{t,i}^2|)$

Nuclear TMDs (*n*TMDs)

- PB-EPPS16nlo_CT14nl_Pb208
- PB-nCTEQ15FullNuc_208_82
- PB-gluon_D_c_ncteq1568CL_Pb

Proton TMD

- **PB-NLO-HERAI+II-2018**

"Hybrid" TMD

- PB-NLO_ptoPb208

Reference

A. Bemudez Martinez et al. COLLINEAR AND TMD PARTON DENSITIES FROM FITS TO PRECISION DIS MEASUREMENTS IN THE PARTON BRANCHING METHOD. ***Physical Review D*, 99(7):074008, 2019**

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Construction

$$\mathcal{A}^{Pb} = \frac{82}{208}\mathcal{A}^{p} + \frac{126}{208}\mathcal{A}^{n}$$

with $\mathcal{A}^{n}$ obtained by isospin symmetry.

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K.J. Eskola, P. Paakkinen,
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EPPS16: Nuclear parton distributions with LHC data.
The European Physical Journal C, 77(3):163, 2017

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A. Kusina, J.P. Lansberg, I. Schienbein, and H.S. Shao. Gluon shadowing in heavy-flavor production at the LHC.

***Physical review letters*, 121(5):052004, 2018**

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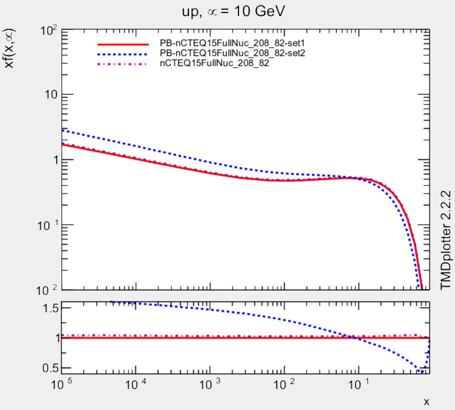
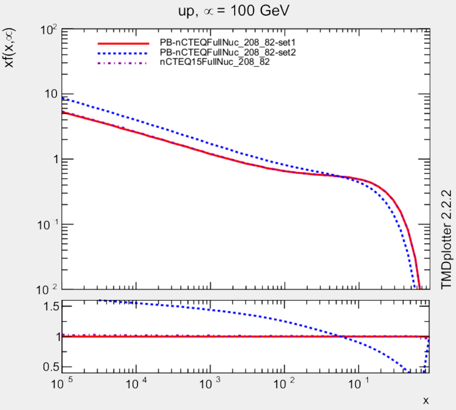
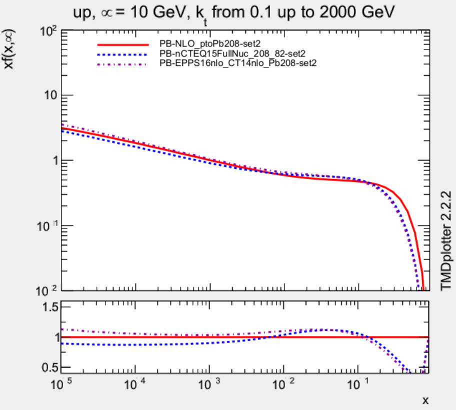
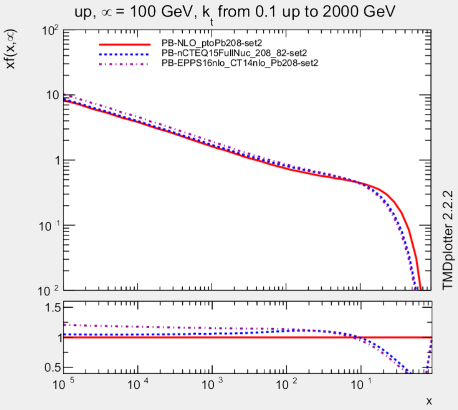
*n*TMDs in details

*n*TMDs\ Integration over k_T

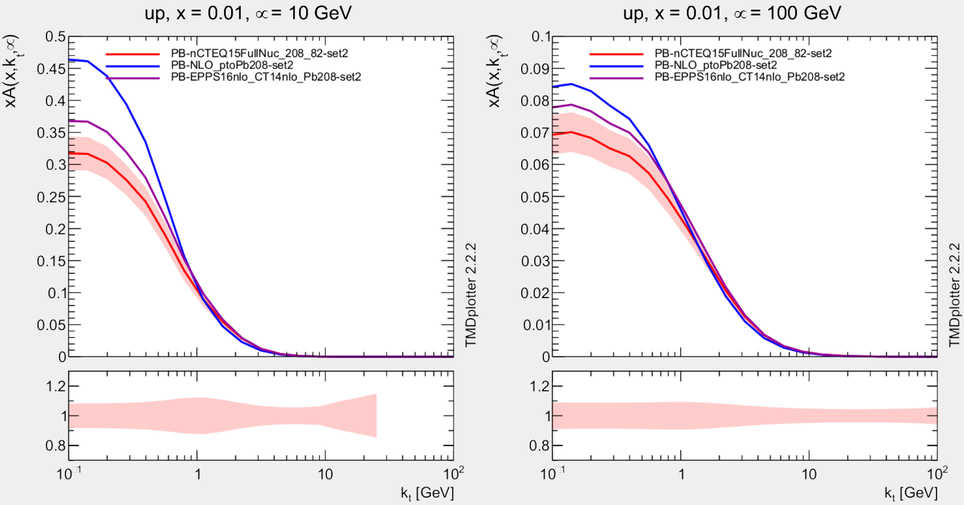


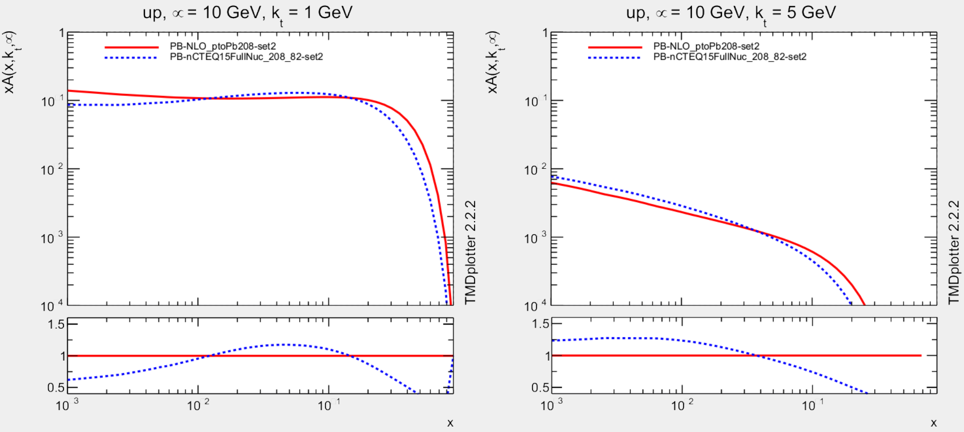



up, ∝ = 10 GeV, k_t from 0.1 up to 2000 GeV
PB-NLO_ptoPb208-set2
PB-nCTEQ15FullNuc_208_82-set2
PB-EPPS16nlo_CT14nlo_Pb208-set2
xf(x,∝)
TMDplotter 2.2.2
x

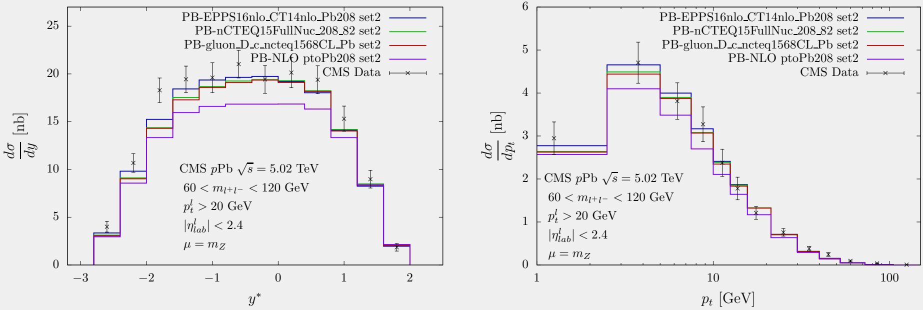

up, ∝ = 100 GeV, k_t from 0.1 up to 2000 GeV
PB-NLO_ptoPb208-set2
PB-nCTEQ15FullNuc_208_82-set2
PB-EPPS16nlo_CT14nlo_Pb208-set2
xf(x,∝)
TMDplotter 2.2.2
x

nTMDs \ k_T-DEPENDENCE




up, ∝ = 10 GeV, k_t = 1 GeV
PB-NLO_ptoPb208-set2
PB-nCTEQ15FullNuc_208_82-set2
xA(x,k_t,∝)
TMDplotter 2.2.2
x
up, ∝ = 10 GeV, k_t = 5 GeV
PB-NLO_ptoPb208-set2
PB-nCTEQ15FullNuc_208_82-set2
xA(x,k_t,∝)
TMDplotter 2.2.2
x

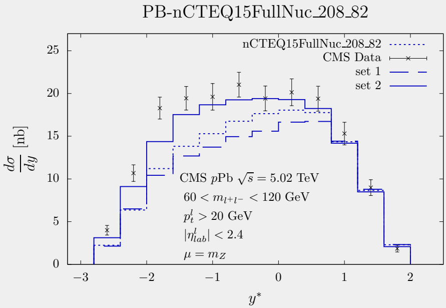
Results

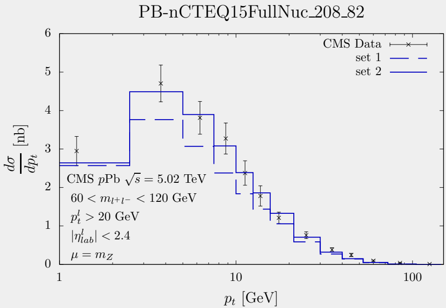


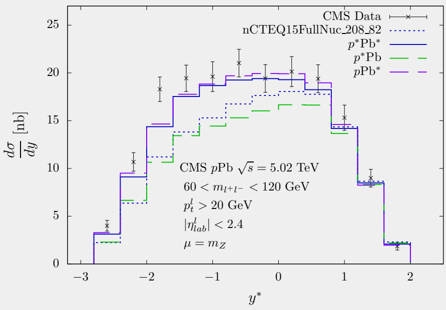
TMDs used

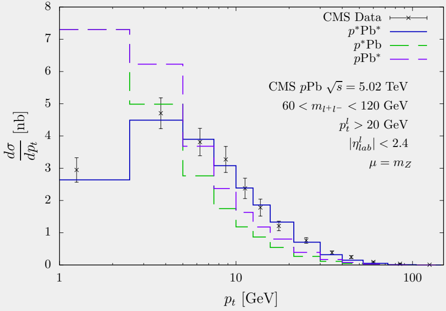
- PB-EPPS16nlo_CT14nl_Pb208
- PB-gluon_D_c_ncteq1568CL_Pb
- PB-nCTEQ15FullNuc_208_82
- PB-NLO_ptoPb208

Results \ Set1 vs Set 2 vs Collinear






CMS Data
nCTEQ15FullNuc_208_82
p^*Pb*
p^*Pb
pPb*
CMS pPb $\sqrt{s} = 5.02$ TeV
$60 < m_{l^+l^-} < 120$ GeV
$p_t^l > 20$ GeV
$|\eta_{lab}^l| < 2.4$
$\mu = m_Z$
$\frac{d\sigma}{dy}$ [nb]
y^*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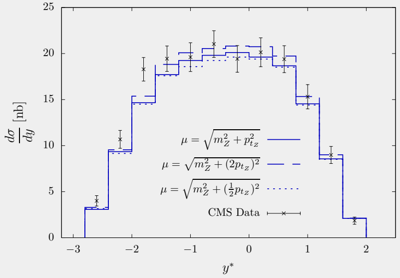
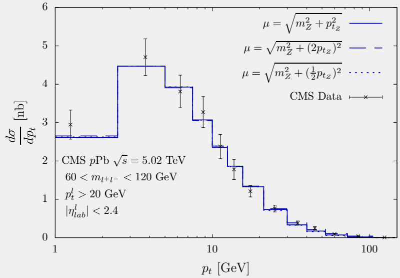
$\mu = m_Z$
$\frac{d\sigma}{dp_t}$ [nb]
p_t [GeV]

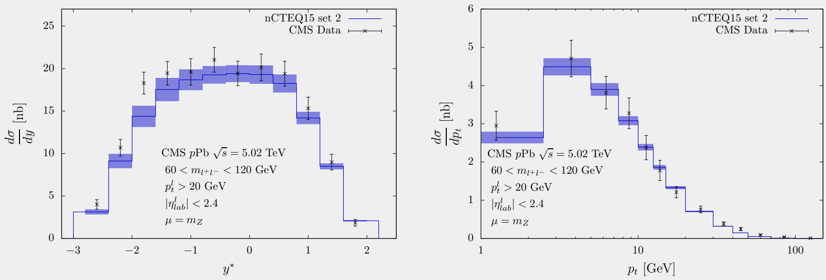




Estimation of NLO corrections

- Scale : $\mu = \sqrt{m_Z^2 + (ap_{tZ})^2}$ [1]
- Scale variation : $a \in [\frac{1}{2}, 2]$

[1] S. Dooling, F. Hautmann, and H. Jung. Hadroproduction of electroweak gauge boson plus jets and TMD parton density functions. *Physics Letters B*, 736:293–298, 2014



Uncertainty calculation

$$\Delta X = \frac{1}{2}\sqrt{\sum_{k=1}^{N}(X(f_k^+) - X(f_k^-))^2}, \text{ with } f_k^\pm = f\left(a_i^0 \pm \sqrt{\frac{\Delta\chi^2}{\lambda_k}}V_i^{(k)}\right)$$ [2]

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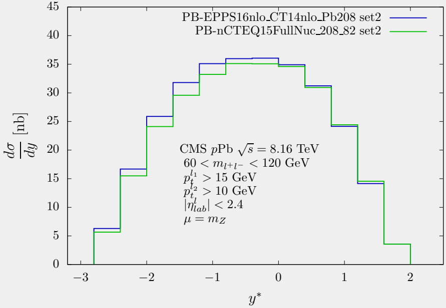
[2] K. Kovařík et al. NCTEQ15: GLOBAL ANALYSIS OF NUCLEAR PARTON DISTRIBUTIONS WITH UNCERTAINTIES IN THE CTEQ FRAMEWORK. *PHYSICAL REVIEW D*, 93(8):085037, 2016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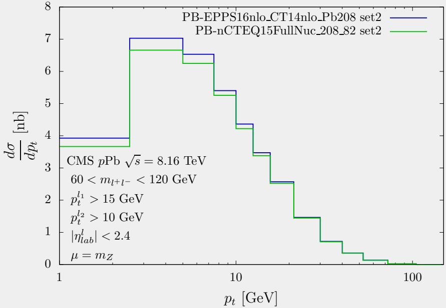
y^*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$\mu = m_Z$
$\frac{d\sigma}{dp_t}$ [nb]
p_t [GeV]

Conclusion

- 1st set of nTMDs (available on **TMDlib**)
- Made possible prediction for *p*Pb collision in the framework of k_T-factorization
- Prediction of Z boson production in very good agreement with CMS data.
- Agreement for shape and also normalization

For more details : E. Blanco, A. van Hameren, H. Jung, A. Kusina, and K. Kutak. Z BOSON PRODUCTION IN PROTON-LEAD COLLISIONS AT THE LHC ACCOUNTING FOR TRANSVERSE MOMENTA OF INITIAL PARTONS.
***Physical Review D*, 100(5):054023, 2019**

Outlook

These should be tested on other data :

- ATLAS data with similar configuration ($\sqrt{s} = 5.02$TeV)
- upcoming analysis on CMS data at $\sqrt{s} = 8.16$TeV

Thanks for your attention!

References I

A. Bemudez Martinez et al.
Collinear and TMD parton densities from fits to precision DIS measurements in the parton branching method.
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References III

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