The MC4TMD project

Determining Transverse Momentum Dependent Parton Distribution Functions (TMDs/ TMD PDFs) with Monte Carlo generators

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DESY.

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Motivation

From Collinear PDFs to TMD PDFs

Collinear PDFs

- 1-D probe
- Integrated over k_t with a dependence solely on x and scale factor
- Utilize collinear fact. and resummation to predict observables
- ordering dependence(virtuality or angular)

V.S.

TMD PDFs

- 3-D probe
- Unintegrated PDF with dependence on (x, k_t, μ^2)
- TMD fact. extends beyond collinear fact.
- accounts for multi-parton radiation
- conserves momentum in cross section calculations
- ordering dependence (virtuality or angular)

WHY TMDS?

- Some cases collinear fact and predictions for observables are inaccurate ——> TMD Factorization formalism and resummation is required
- Multi-parton radiation in transverse directions is the cause of these inaccuracies
- Necessary to conserve E/momentum from beginning to retain kinematics

Two experimental cases of this :

Deep Inelastic Scattering (DIS) @ high energies
low q_t region for Drell-Yan and Semi inclusive DIS

Reference:
Angeles-Martinez et al. Transverse Momentum Dependent (TMD) Parton Distribution Functions: Sta-tus and Prospects.Acta Physica Polonica B, 46(12):2501, January 2015

Theory

Parton Branching (PB) Method & Parton Showering (PS)

- **PB is a method that solves DGLAP evolution equations in iterative steps from small to large energy scales (μ^2) .**
- **PS is the reverse process of PB, evolving from large scale to small scale**

The Integrated f/Δ_s form of DGLAP:

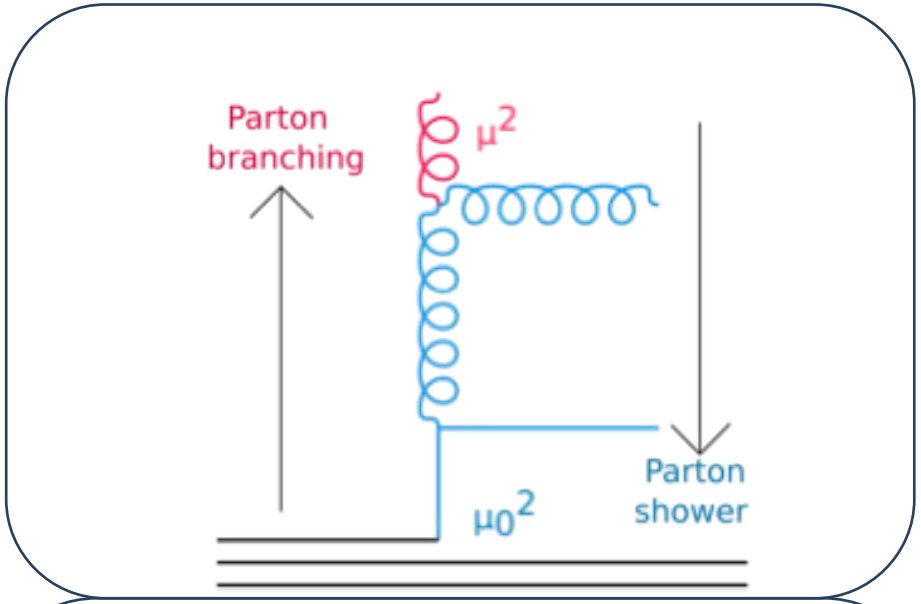
$$f(x,t) = f(x,t_0)\Delta(t) + \int \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \frac{\alpha_s(t')}{2\pi} \int \frac{dz}{z} P^R(z) f\left(\frac{x}{z}, t'\right)$$

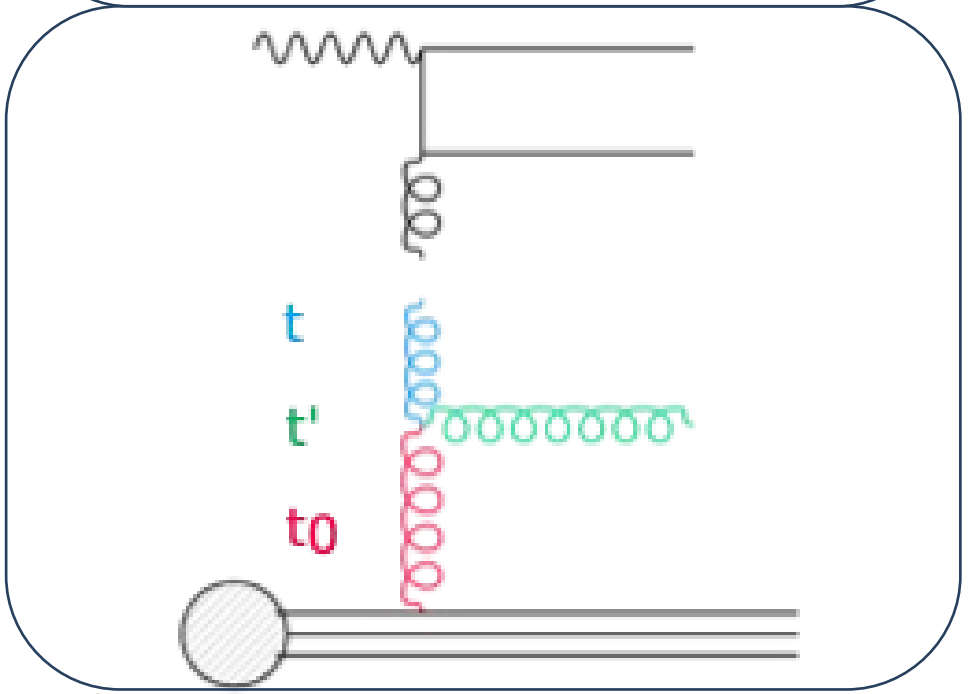
where Δ_s is the Sudakov form factor and $t=Q^2$

PB/PS allows us to :

- Define transverse momentum k_t at each step in iteration
- Retain and obtain kinematics for each splitting
- Investigate PS effects and ordering conditions
- Determine TMDs

MC generators with PS such as PYTHIA and CASCADE can be used to generate TMDs and validate PB method.
A new method, PS2TMD , can be applied to study backward evolution with MC PS to determine effective TMDs .





References:
Melanie Schmitz. *Drell-Yan Production with Transverse Momentum Dependent Parton Densities. MastersThesis*, 2019.

Methodology

PS2TMD Method

X_1: momentum fraction carried by parton 1 compared to the proton it belongs to

k_t: transverse wavevector/momentum

Toy model based on Drell-Yan process:

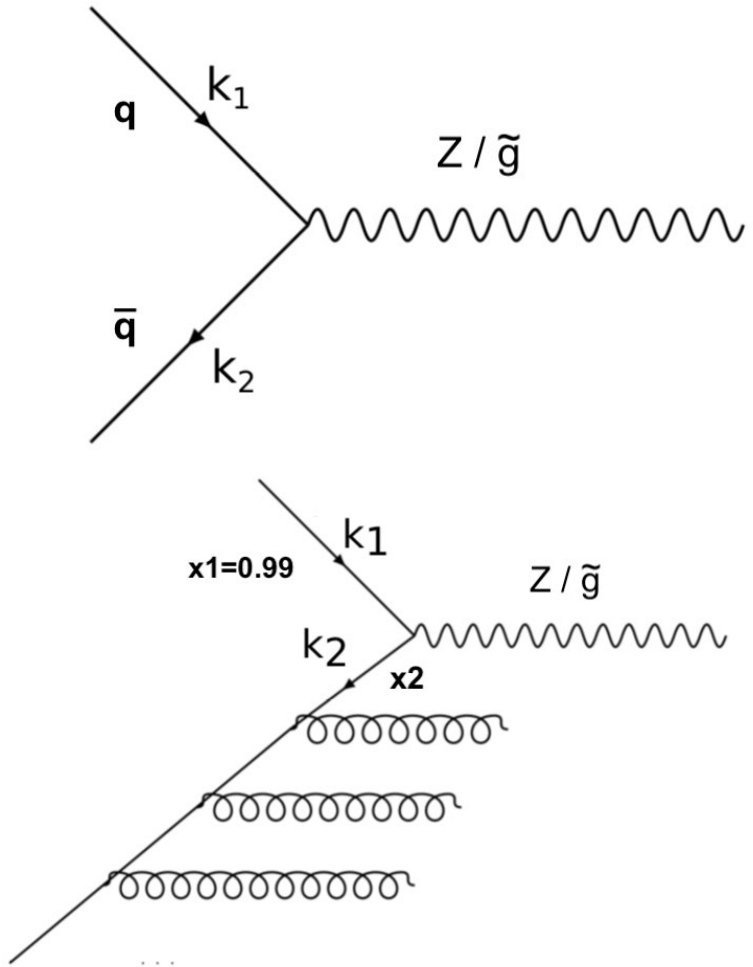
- Parton 1 is fixed (x_1=0.99 & k_t =0)
- Initial state radiation (ISR) on Parton 2
- k_z= k_1 +k_2

TMDs from MC generators:

1. Produce PS
2. Reconstruct TMDs from PS
3. Plot and Compare TMDs

How to obtain TMDs from MC generators?

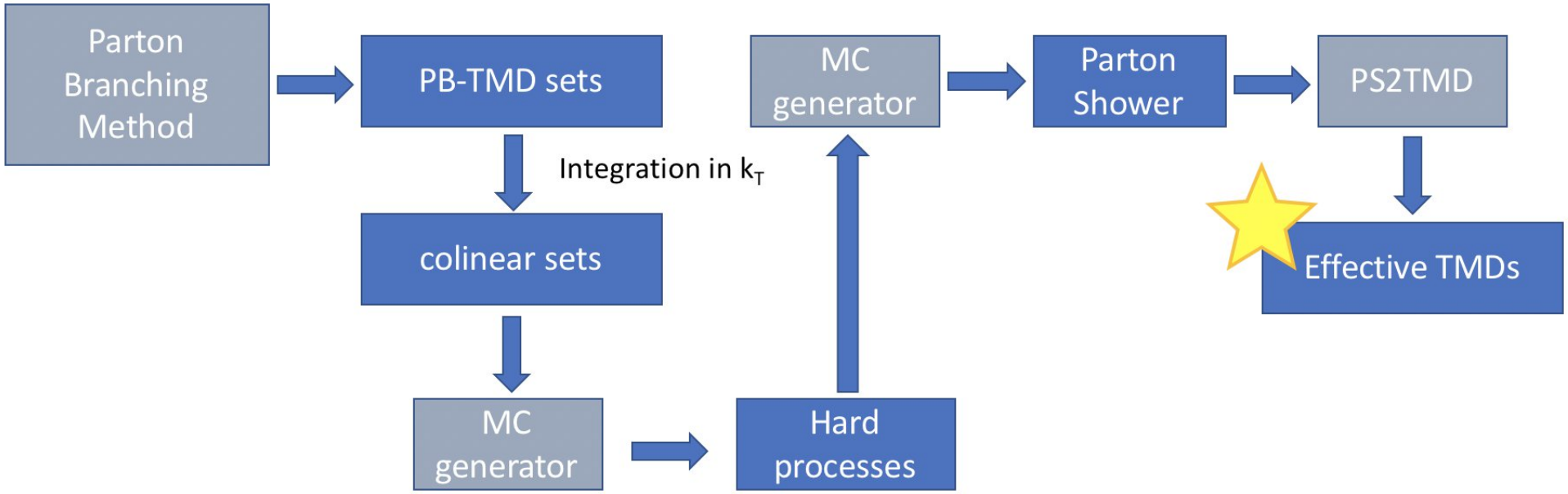
Is the reconstruction routine reliable?



Reference:
Melanie Schmitz. *Drell-Yan Production with Transverse Momentum Dependent Parton Densities. MastersThesis*, 2019.

Methodology

Validation of PS2TMD



DESY.

How to obtain TMDs from MC generators?

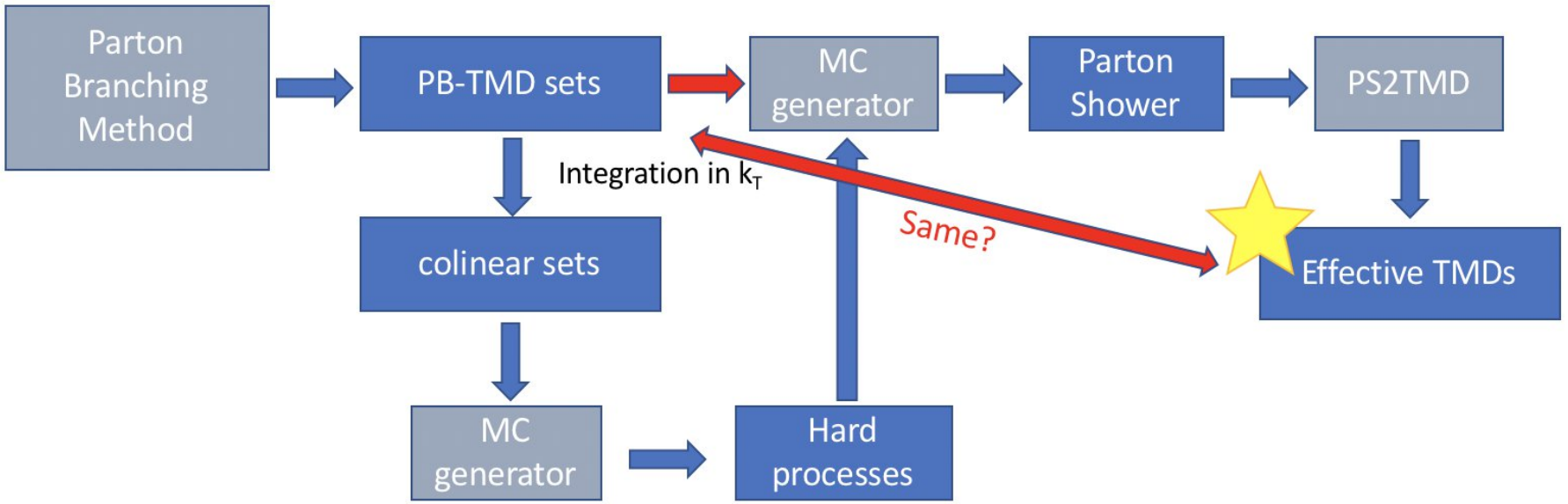
Collinear sets -> Hard processes -> Parton Shower

One complete run of this process is called 1 ‘job’. To ensure enough statistics, 2000 jobs are performed and their results are added together for the final plot.

Methodology

Validation of PS2TMD

We can also ask MC generators to produce PS following a given TMD set!
If PS2TMD reconstruction routine is valid, the reconstructed TMDs must be identical to the original TMDs fed into the MC generators.



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Methodology

Implementation of PS2TMD

PB-TMD sets used in this study:

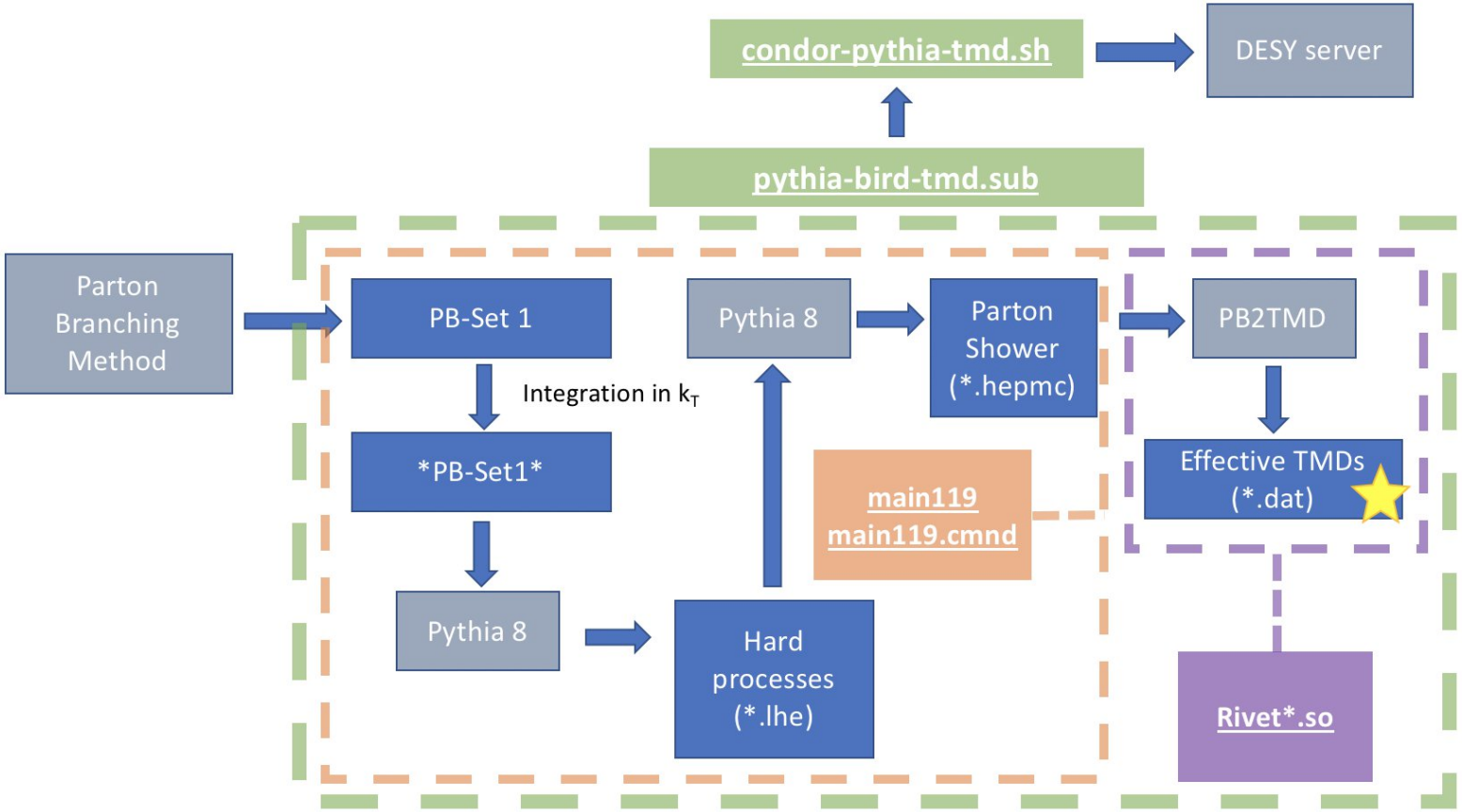
- PB-NLO-HERAI+II-2018-set1
- PB-NLO-HERAI+II-2018-set2

Both obtained from PB method + fitting to inclusive HERA DIS precision measurements

The two sets, along with their corresponding collinear sets, are called PB-Set1 and PB-set2.

MC generators:

- Validation: PYTHIA (Hard processes), CASCADE (PS)
- Main study: PYTHIA for both

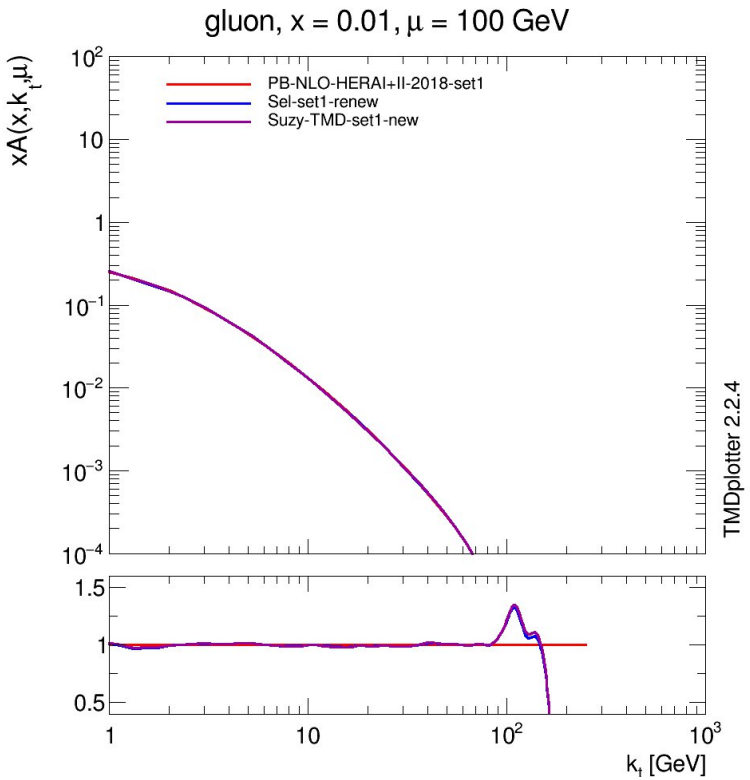


This study investigates how different configurations of PYTHIA8 PS affect the obtained TMDs.

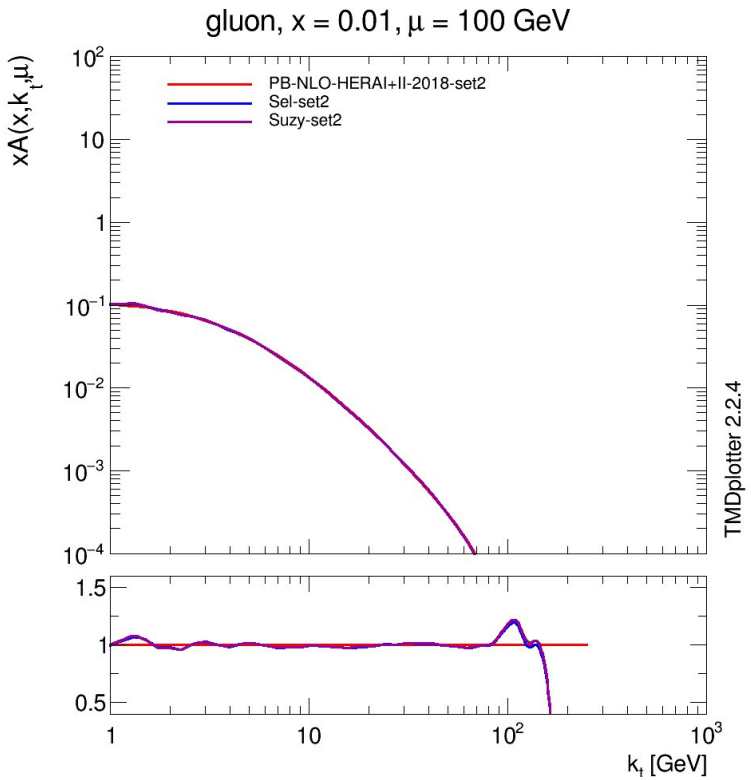
TMD PDFs in k_t will be given in this study.

Results

Validation of TMDs with Cascade and PB sets 1 & 2



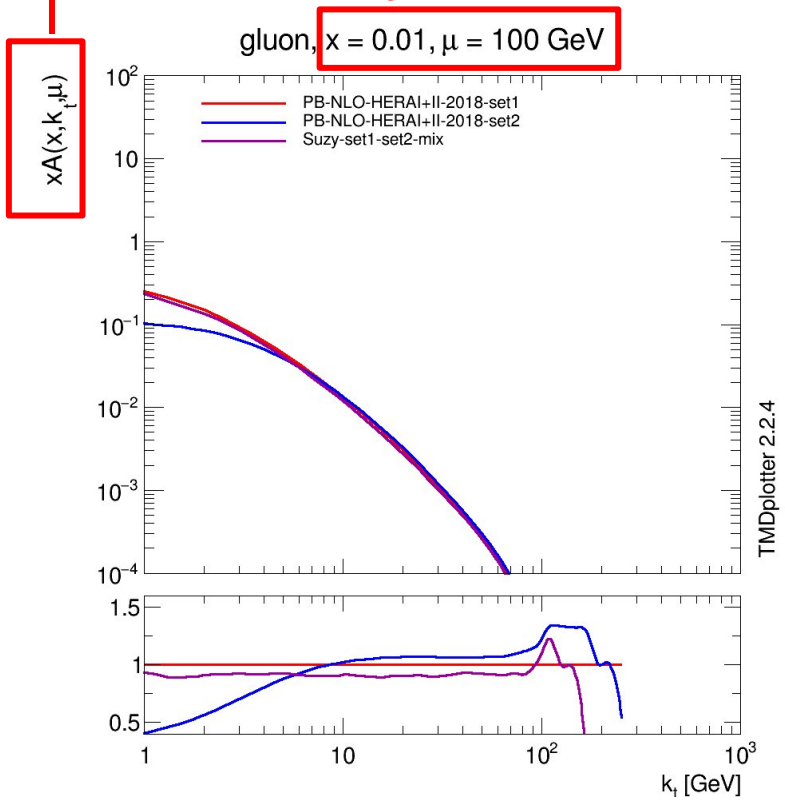
Set 1



Set 2

x*(TMD PDF)

X and μ are fixed to study k_t distribution



Mixed

Reference of TMD plotter:
N. A. Abdulov et al.TMDlib2 and TMDplotter: a platform for 3D hadronstructure studies. 2021. arXiv:2103.09741 [hep-ph].

Results

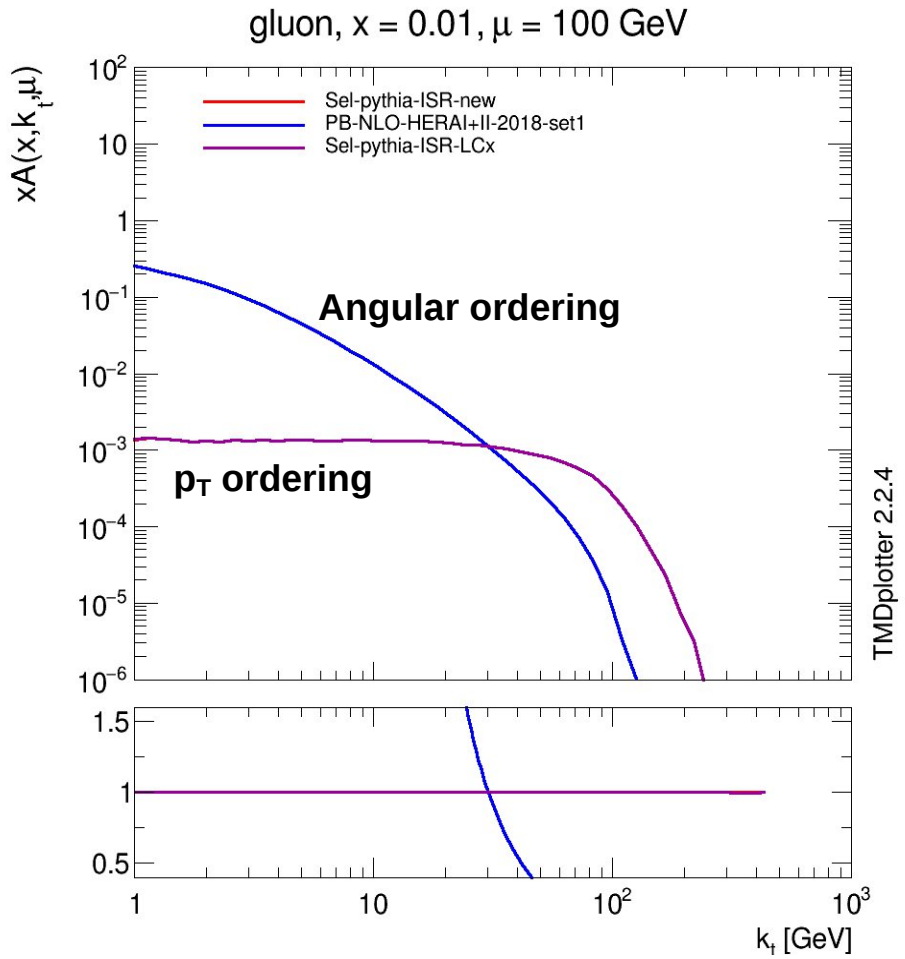
Z boson Check with Pythia Showering Configurations

The following configuration settings are investigated @ 100,000 events & 2000 jobs each:

- Multi-Parton Interations - MPI (default: off)
- Primodial kT (default: on)
- Rapidity ordering (default: on)
- α_s ordering (default = 1; can be set to 0 - 2)

Results

ISR results



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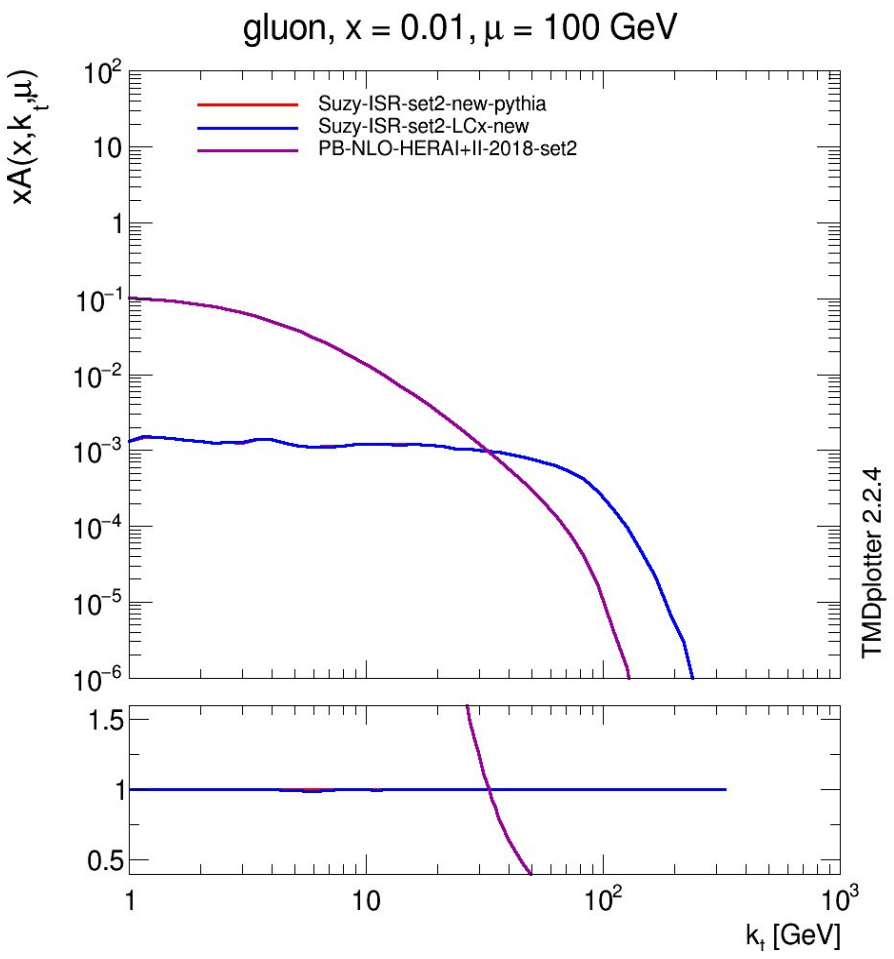
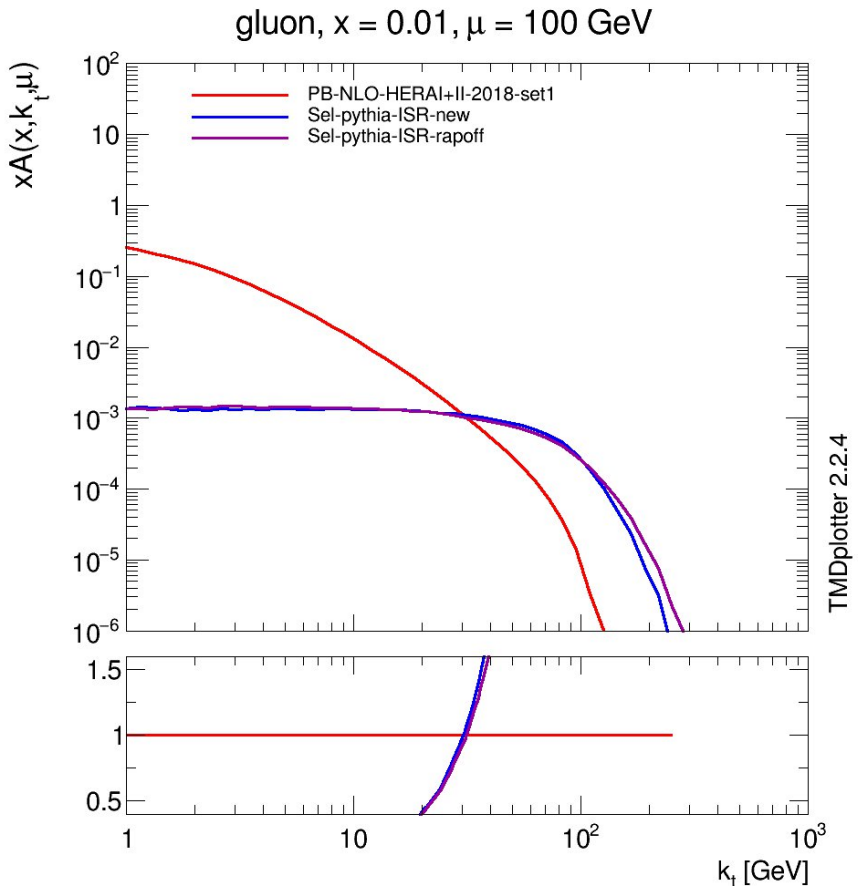


Set 2

Reference:
N. A. Abdulov et al.TMDlib2 and TMDplotter: a platform for 3D hadronstructure studies. 2021. arXiv:2103.09741 [hep-ph].

Results

ISR + Rapidity Ordering OFF results



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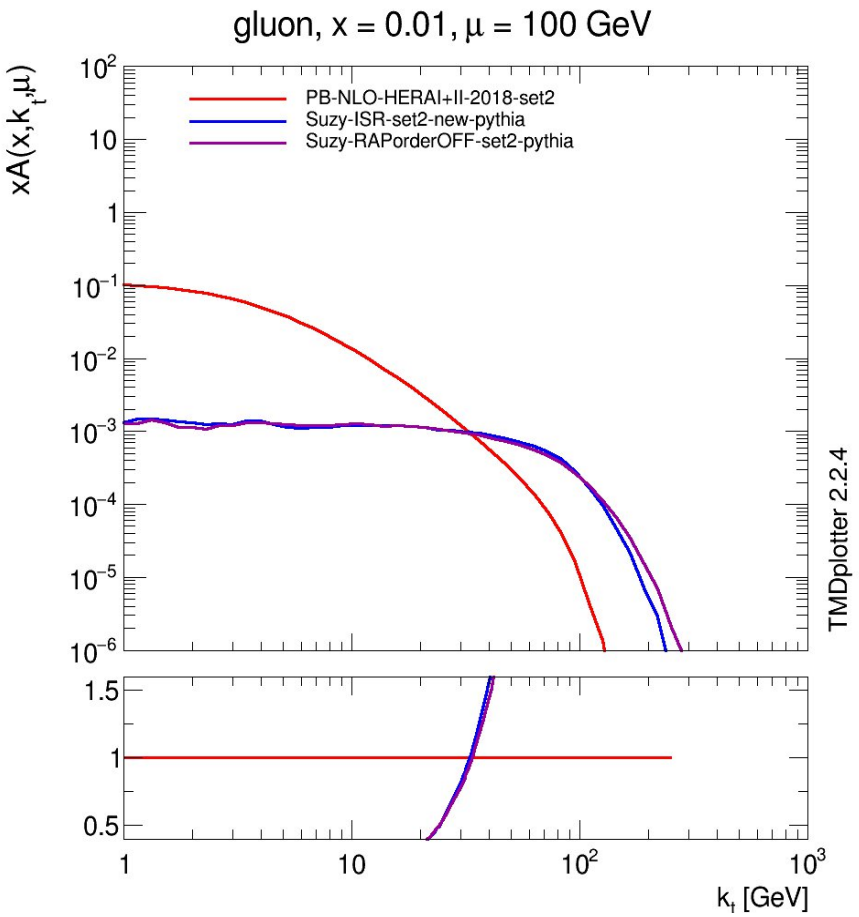

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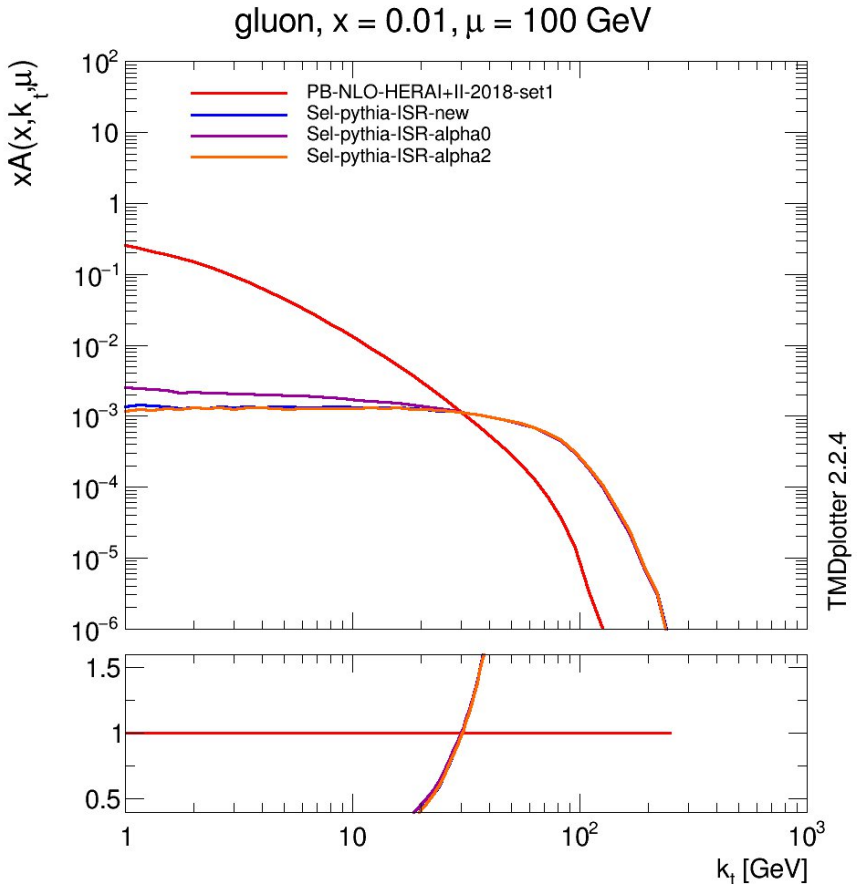
Reference of TMD plotter:
N. A. Abdulov et al.TMDlib2 and TMDplotter: a platform for 3D hadronstructure studies. 2021. arXiv:2103.09741 [hep-ph].

Results

ISR + α_s ordering results



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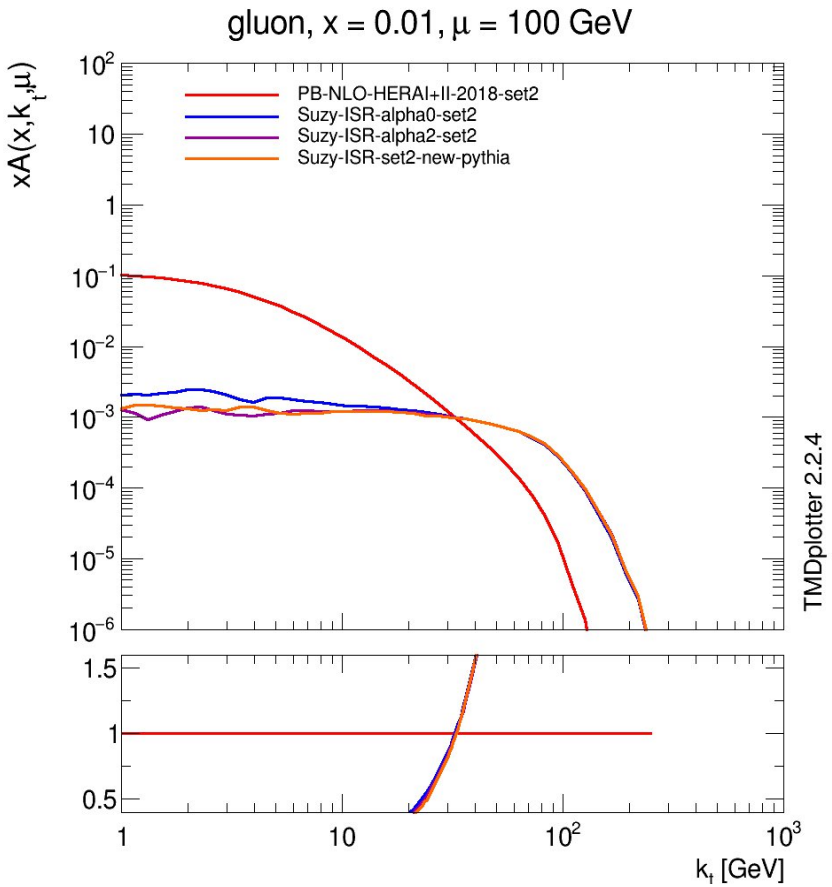


Set 2

Reference of TMD plotter:
N. A. Abdulov et al.TMDlib2 and TMDplotter: a platform for 3D hadronstructure studies. 2021. arXiv:2103.09741 [hep-ph].

Summary

- **Validated that the PS2TMD method can be used to reconstruct TMDs from Monte-Carlo parton showers**
- **Demonstrated that different ordering conditions give noticeable differences in TMD sets**
- **Investigated how PYTHIA8 PS configurations affect the TMDs obtained**
- **Further investigations in angular ordering MC generators (Herwig)**
- **Comparison between gluino and Z boson**
- **Discrepancy between different x2 definition**

DESY.

Reference to PYTHIA8 , CASCADE, Rivet

Pythia 8:

Torbj¨orn Sj¨ostrand et al. “An introduction to PYTHIA 8.2”. In:ComputerPhysics Communications191 (June 2015), pp. 159–177.issn: 0010-4655.doi:10.1016/j.cpc.2015.01.024.url:http://dx.doi.org/10.1016/j.cpc.2015.01.024

Torbj¨orn Sj¨ostrand, Stephen Mrenna, and Peter Skands. “PYTHIA 6.4physics and manual”. In:Journal of High Energy Physics2006.05 (May2006), pp. 026–026.issn: 1029-8479.doi:10.1088/1126-6708/2006/05/026.url:http://dx.doi.org/10.1088/1126-6708/2006/05/026

CASCADE 3:

S. Baranov et al. “CASCADE3 A Monte Carlo event generator based onTMDs”. In:The European Physical Journal C81.5 (May 2021).issn: 1434-6052.doi:10.1140/epjc/s10052-021-09203-8.url:http://dx.doi.org/10.1140/epjc/s10052-021-09203-8

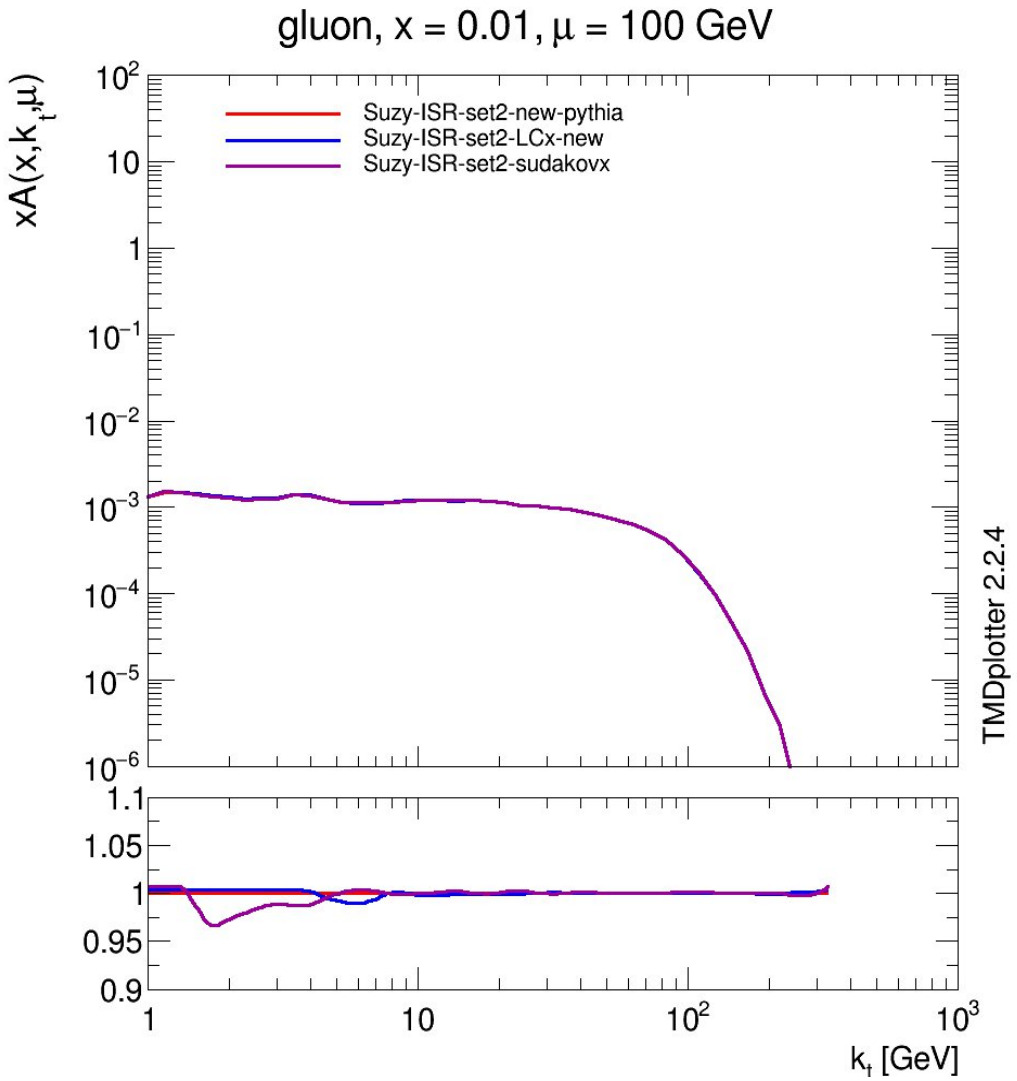
RIVET:

Christian Bierlich et al. Robust Independent Validation of Experiment and Theory: Rivet version 3.SciPost Phys., 8:026, 2020.

Thank you

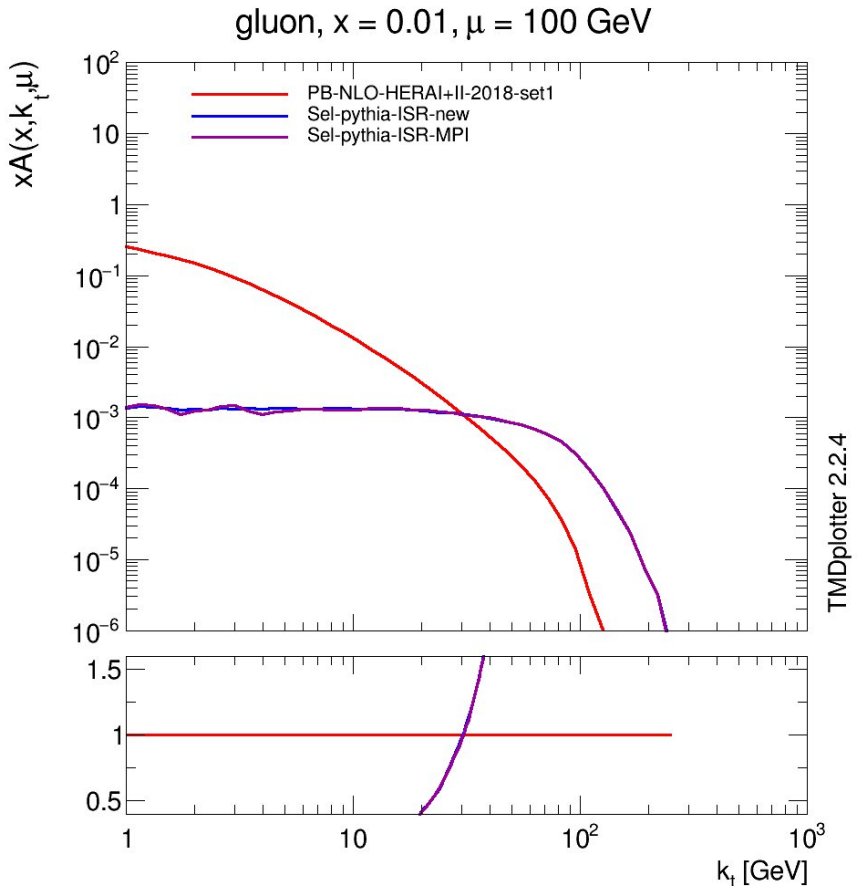
DESY.

Backup


gluon, x = 0.01, μ = 100 GeV
xA(x,k_t,μ)
Suzy-ISR-set2-new-pythia
Suzy-ISR-set2-LCx-new
Suzy-ISR-set2-sudakovx
TMDplotter 2.2.4
k_t [GeV]

Results

ISR + MPI results



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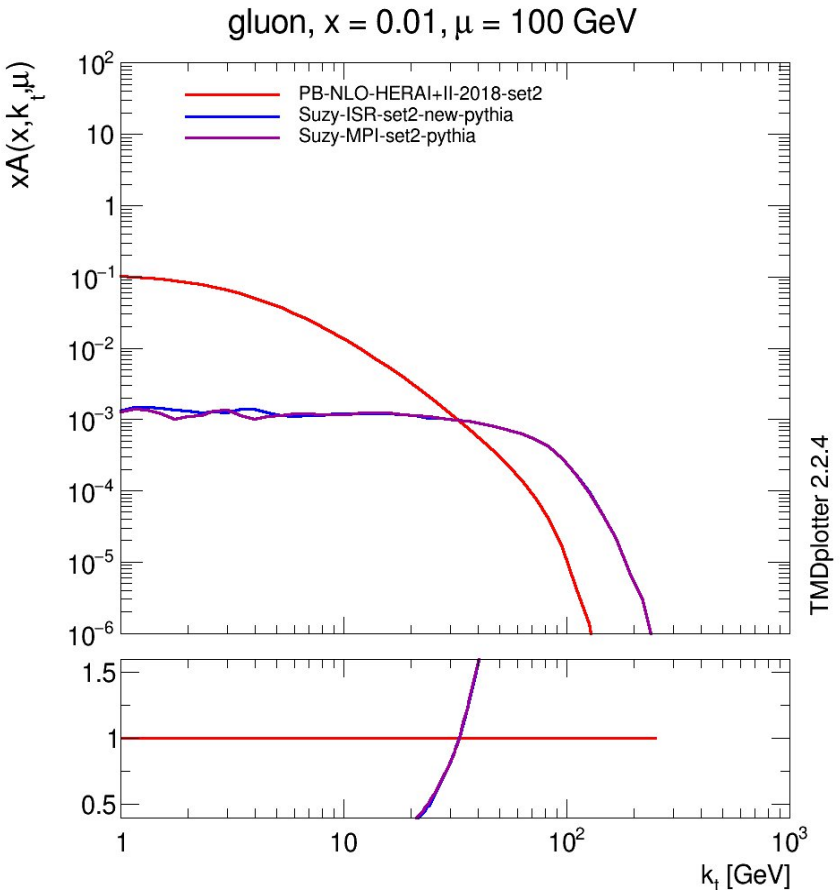
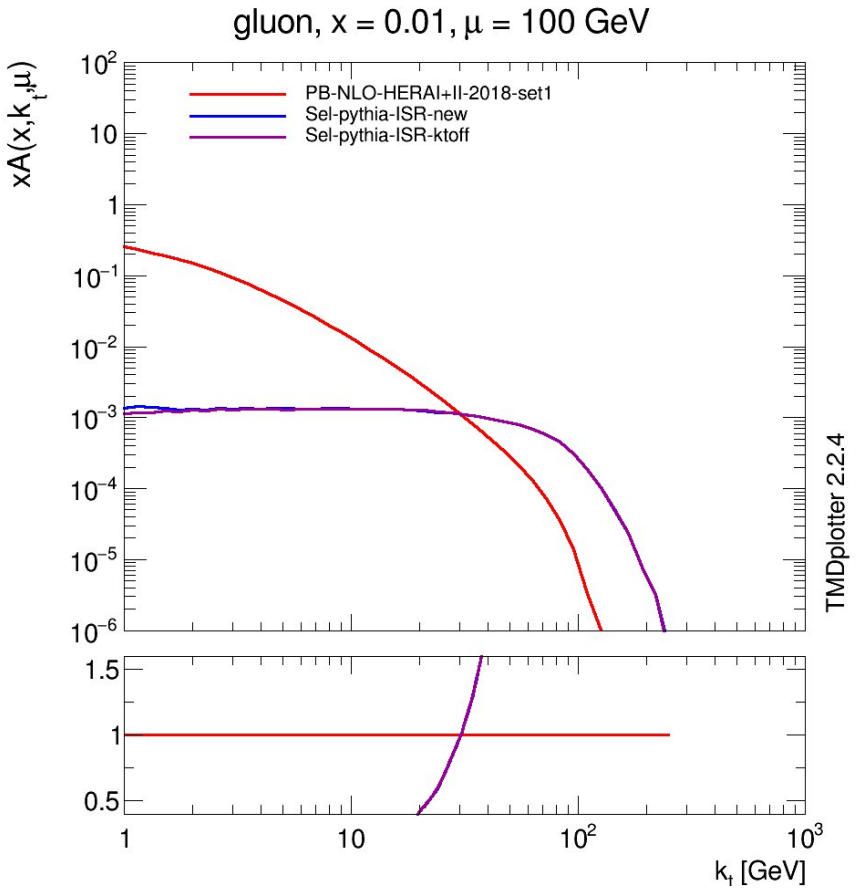


Set 2

Reference:
F. Hautmann, H. Jung, M. Krämer, P. J. Mulders, E. R. Nocera, T. C. Rogers, and A. Signori. TMDliband TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions.Eur. Phys. J. C, 74:3220, 2014

Results

ISR + Primodial KT OFF results



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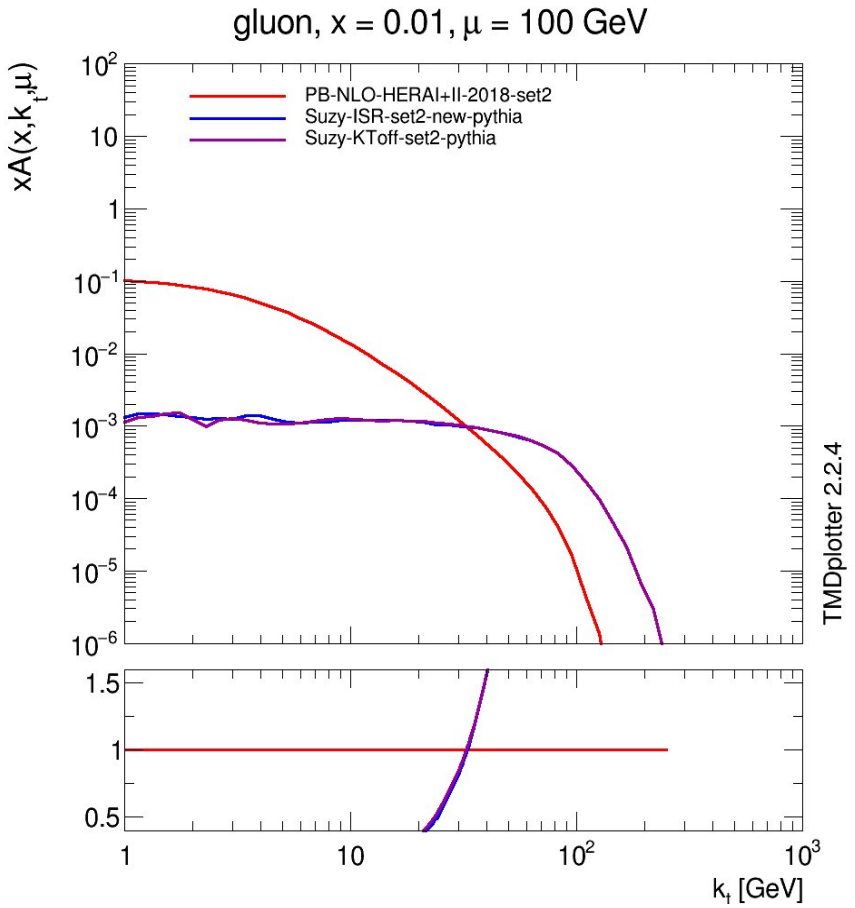

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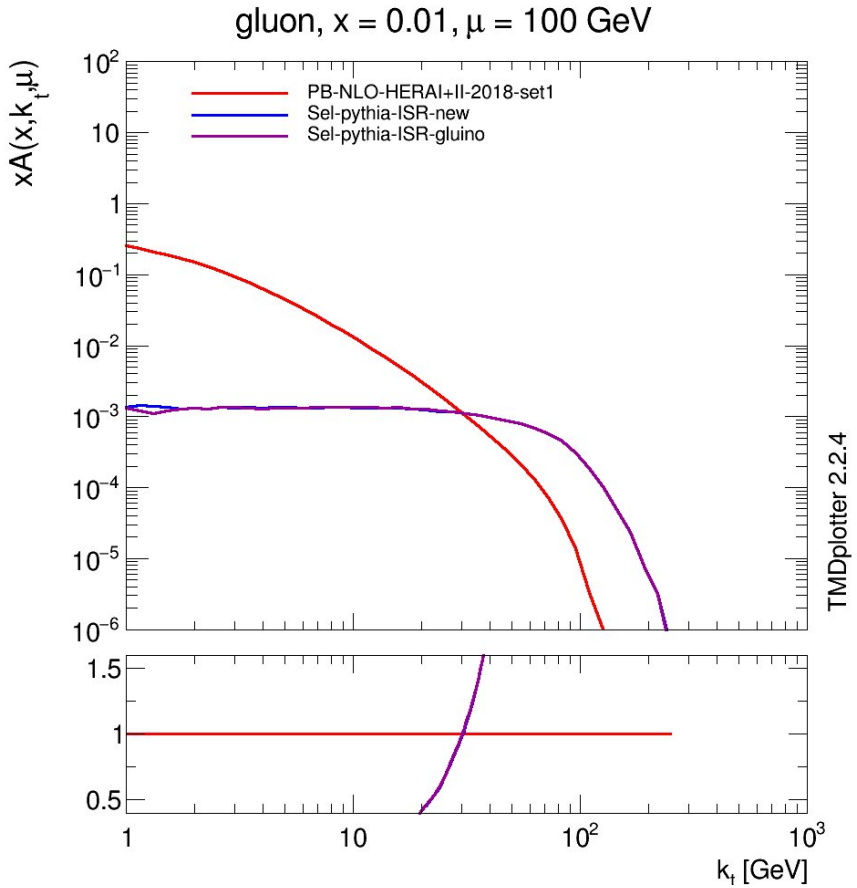
F. Hautmann, H. Jung, M. Krämer, P. J. Mulders, E. R. Nocera, T. C. Rogers, and A. Signori. TMDliband TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions.Eur. Phys. J. C, 74:3220, 2014

Results

Z boson-Gluino Comparison with Pythia Showering Parameters



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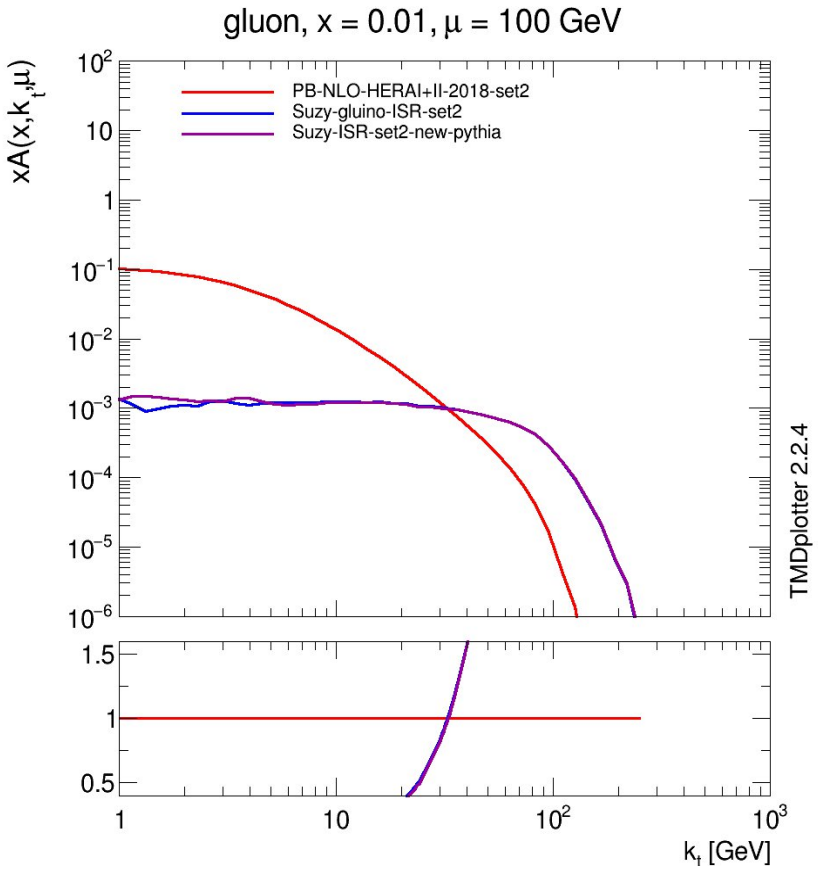

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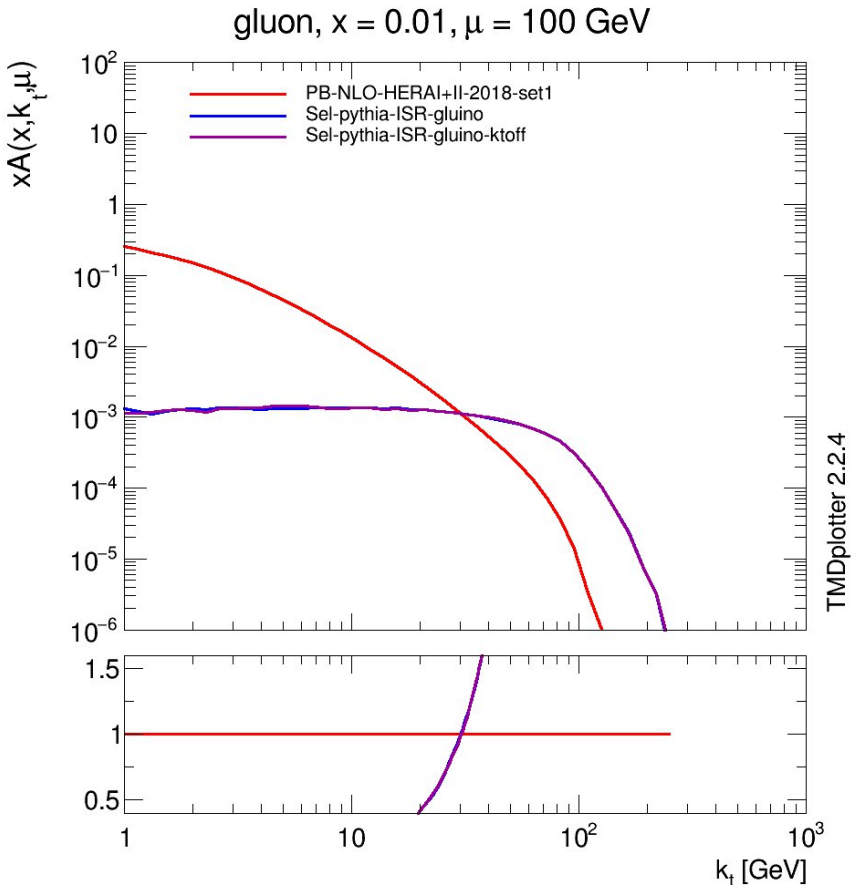
More about gluinos

ISR + Primodial KT Ordering OFF results for gluino



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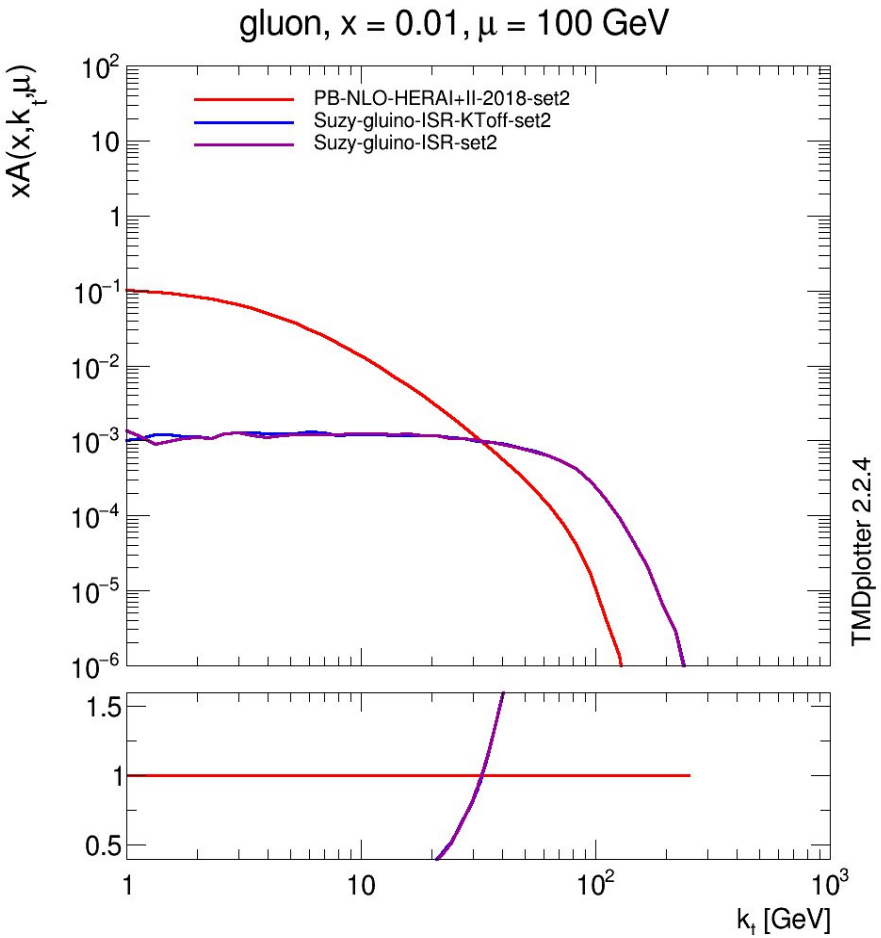

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Theory-DUPLICATE -

Parton Branching (PB) Method & Parton Showering

PB is a method that solves DGLAP evolution equations in iterative steps:

1) DGLAP evolution equation:

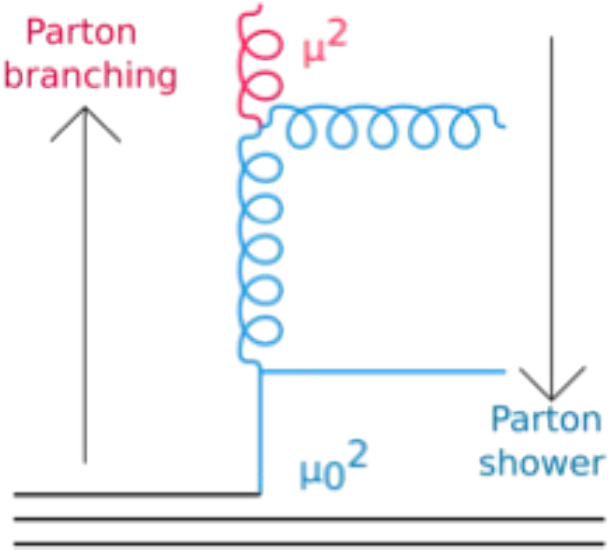
$$t\frac{\partial}{\partial t}\frac{f(x,t)}{\Delta_s} = \int \frac{dz}{z}\frac{1}{\Delta_s}\frac{\alpha_s}{2\pi}P(z)f\left(\frac{x}{z},t\right)$$

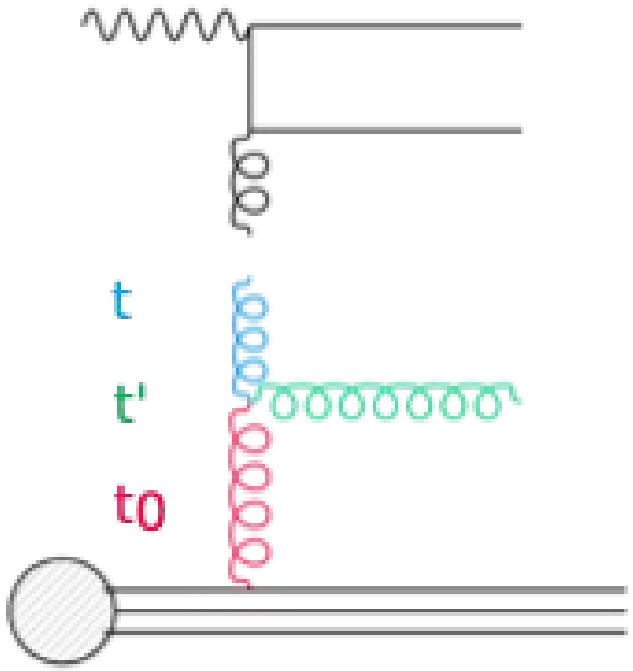
2) Use Sudakov Form Factor ($t=^2$) and put DGLAP in the form f/

$$\Delta_s(t) = \exp\left(-\int_x^{z_{max}} dz \int_{t_0}^{t}\frac{\alpha_s}{2\pi}\frac{dt'}{t'}\tilde{P}(z)\right)$$

3) Integrate f/ form of DGLAP:

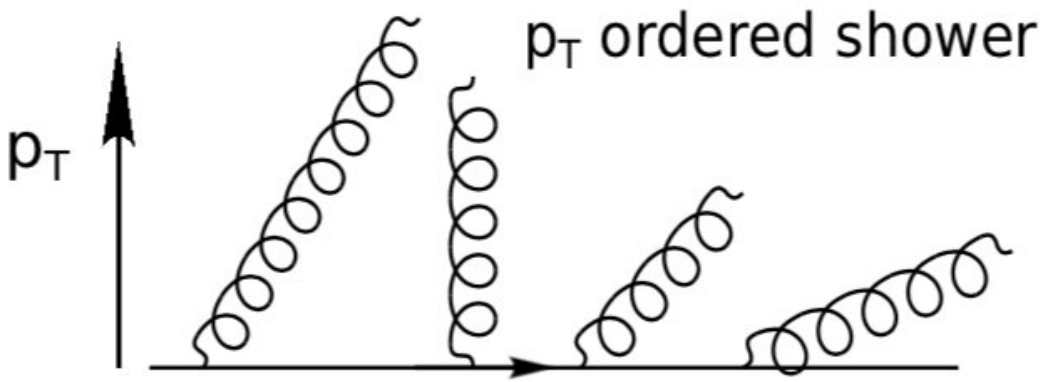
$$f(x,t) = f(x,t_0)\Delta(t) + \int \frac{dt'}{t'}\frac{\Delta(t)}{\Delta(t')}\frac{\alpha_s(t')}{2\pi}\int \frac{dz}{z}P^R(z)f\left(\frac{x}{z},t'\right)$$



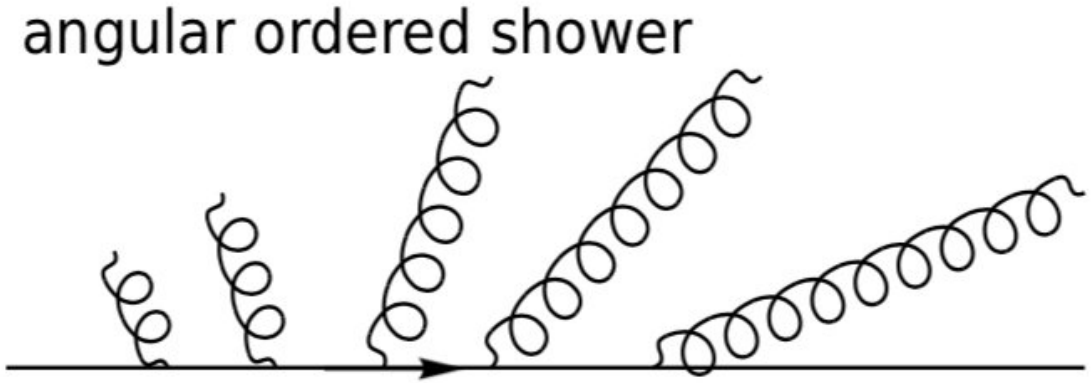


Ordering scheme

PT ordering vs Angular ordering



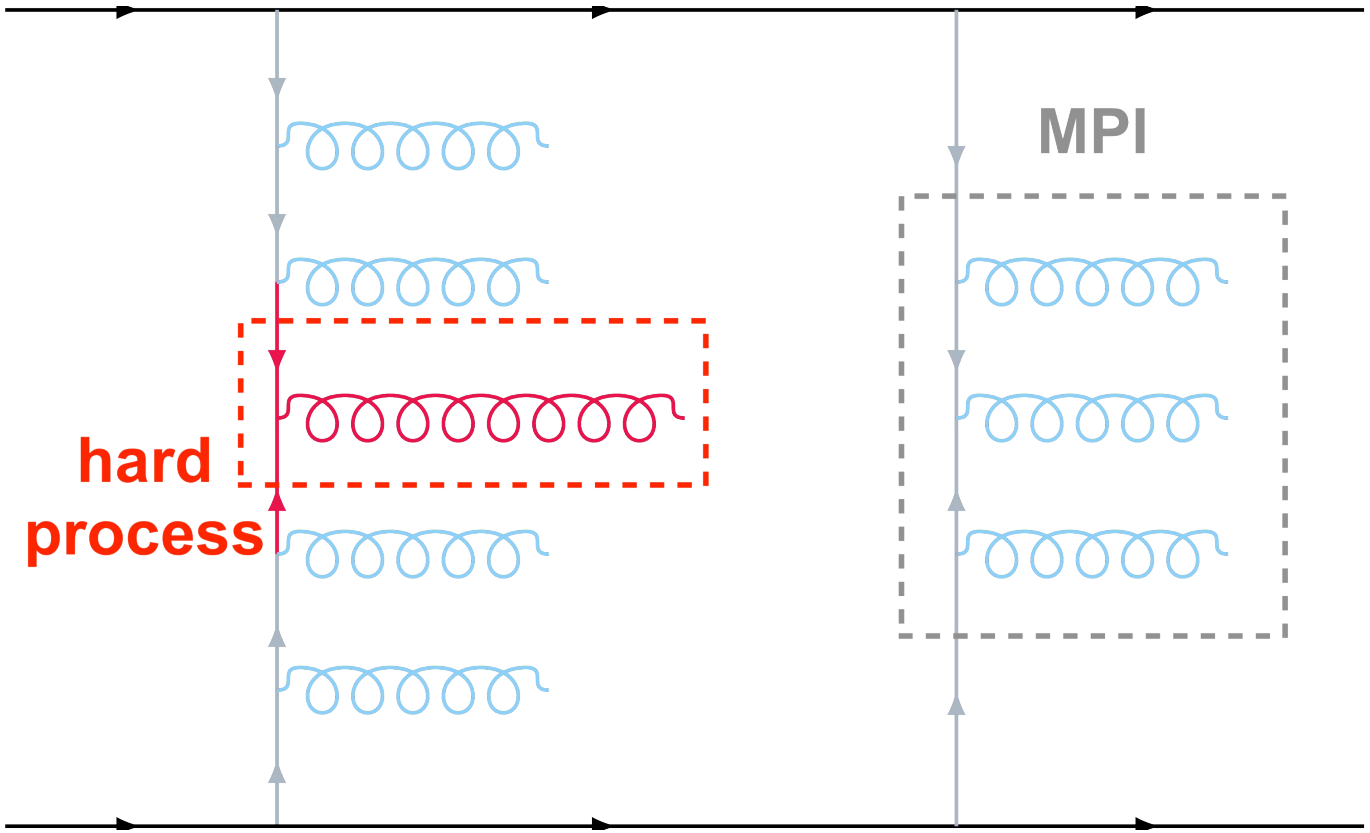
direction of evolution



direction of evolution

MPI - why doesn’t it matter?

Why MPI doesn’t matter



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