RIGA TECHNICAL UNIVERSITY
Institute of Particle Physics and Accelerator Technologies

TMD from Pythia8, intro

Andris Potrebko

DY workshop 2025

Summary of:

M. Mendizabal talk at REF workshop
https://agenda.infn.it/event/43981/contributions/274204/

H. Jung talk at PH Gen meeting
https://indico.cern.ch/event/1548937/#4-a-parton-shower-consistent-w

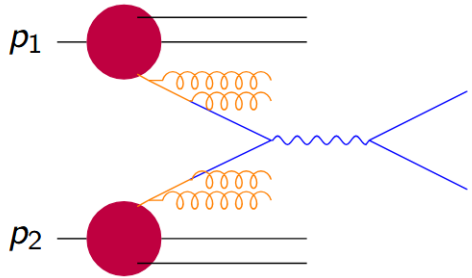
H. Jung, L. Lönnblad, M. Mendizabal, S. Taheri Monfared
arxiv:2504.10243

D. Subotić, H. Jung, N. Raičević talk at QCD at the Extremes
https://indico.cern.ch/event/1539849

06.11.2025

Background

- In PDF if two scales are involved (DY, low p_T), parton transverse momenta become important → Transverse Momentum Dependent parton densities (TMD) are needed



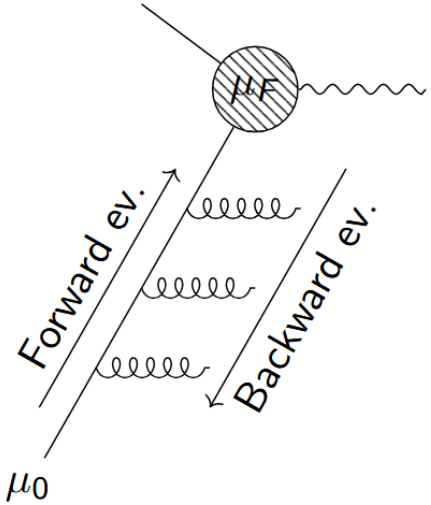
TMD can be obtained from parton branching (PB) – forward evolution – and initial state radiation (ISR) – backward evolution

Sudakov form factor:

$$\Delta_{ib}^{FW} = \exp\left(-\sum_b \int_{\mu_{i-1}}^{\mu} \frac{d^2\mu'}{\mu'} \int_{z_{min}}^{z_{max}} dz\, P_{ib}^R(z, \alpha_s(\mu^2))\right)$$

$$\Delta_{ib}^{BW} = \exp\left(-\sum_b \int_{\mu_{i-1}}^{\mu} \frac{d^2\mu'}{\mu'} \int_{z_{min}}^{z_{max}} dz\, P_{ib}^R(z, \alpha_s(\mu^2)) \frac{f_i(x_b, \mu')}{f_b(x_b, \mu')}\right)$$

μ_{i-1} / μ– starting/final scale; $P_{ib}^R(z, \alpha_s(\mu^2))$ – regularized DGLAP splitting functions ($b \to i$); $f_{i/b}(x_b, \mu)$ – PDF;



Background

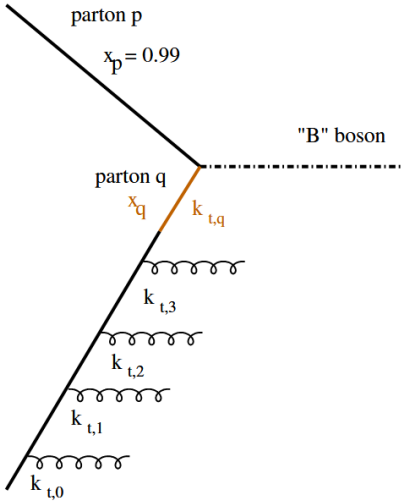
PDF2ISR method: modify the default (SimpleSpaceShower) in PYTHIA8 to follow the same kinematic constraints as in the parton evolution

Two sets of PB branching sets depend on the scaling of α_s

PB-NLO-Set1	$\alpha_s = \alpha_s(\mu)$; μ: evolution scale
PB-NLO-Set2	$\alpha_s = \alpha_s(p_t)$; $p_t = (1-z)\mu$: transverse momentum

Tests were performed using a toy model: $p + q \to B$:

- B: colourless boson used to calculate the kinematics and for easy identification in the event record, non-physical
- p: parton that does not develop a parton shower
- q: develops a parton shower
- Transverse kinetics: $k_{t,q} = p_{t,B}$

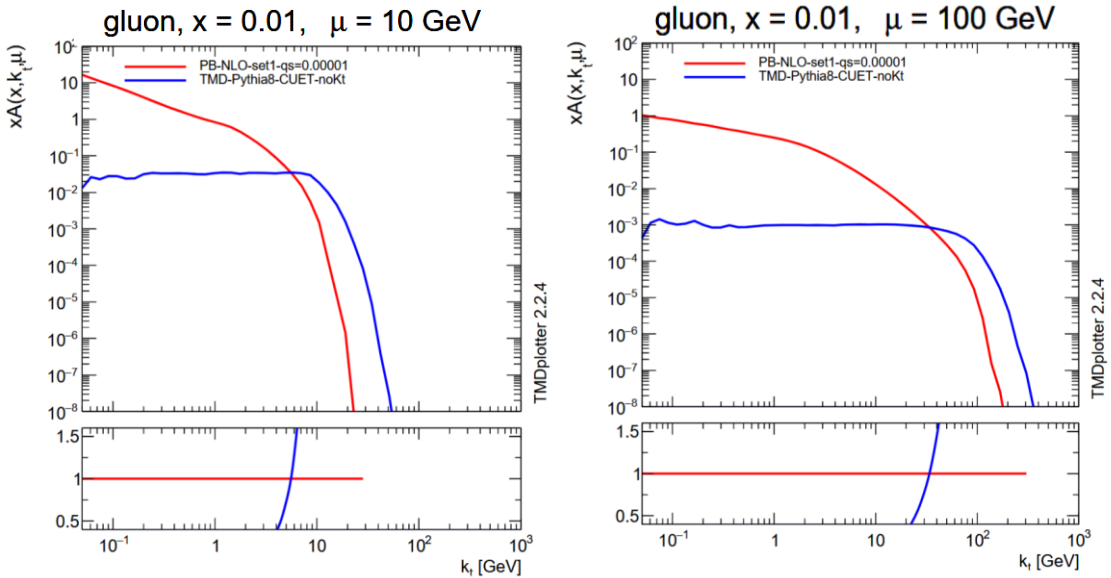


PB-TMD and effective TMD from PYTHIA8

Default setting in Pythia8 and PB method

μ – evolution scale

	PYTHIA8	PB method
Ordering	p_T-ordered, $q_\perp^2 = \mu^2$	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$
Phase space	$0 < z < z_{dyn}^{P8}$	$0 < z < z_M \approx 1 - 10^{-5}$
Splitting Functions	LO	NLO
α_s NLO treatment	PDG parametrisation	QCDNUM numeric



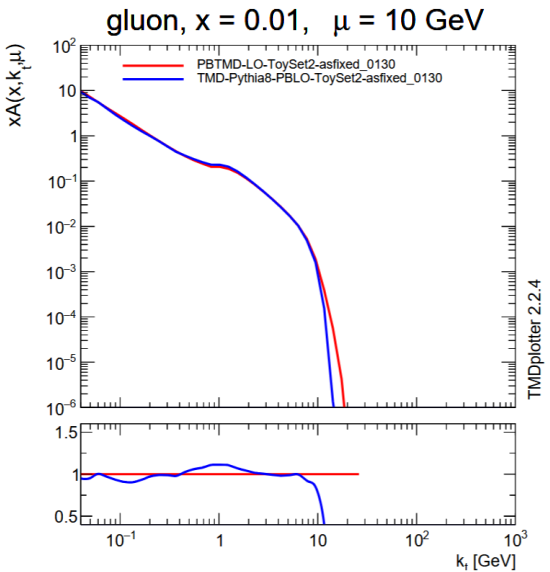
- Initial tries to introduce PDF in a PS and get a TMD produced bad agreement

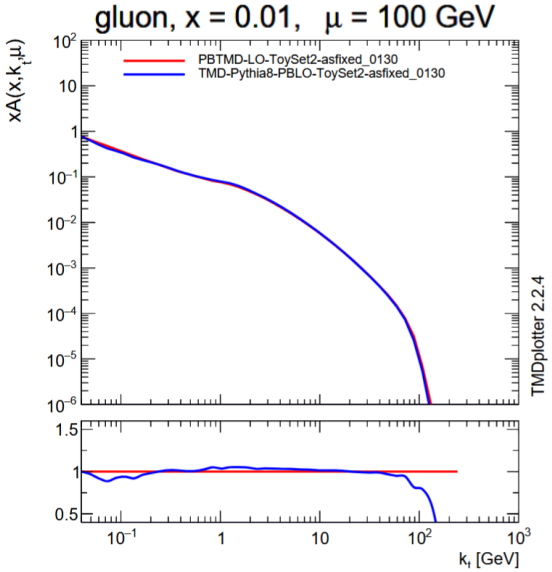
Method to extract TMDs from PS ISR:
H. Jung, S. Steel, S. Taheri Monfared, Y. Zhou arxiv:2112.11248

PDF2ISR: tuning phase space

Default setting in Pythia8 and PB method

	PYTHIA8	PB method
Ordering	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$
Phase space	$0 < z < z_M \approx 1 - 10^{-5}$	$0 < z < z_M \approx 1 - 10^{-5}$
Splitting Functions	LO	NLO
α_s treatment	$\alpha_s^{\text{fixed}} = 0.130$	$\alpha_s^{\text{fixed}} = 0.130$





- PDF and TMD combined with PYTHIA8 parton shower machinery: PDF2ISR
- Very good agreement, PDF2ISR successfully reproduces PB-method

PDF2ISR: tuning phase space

Default setting in Pythia8 and PB method

	PYTHIA8	PB method
Ordering	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$
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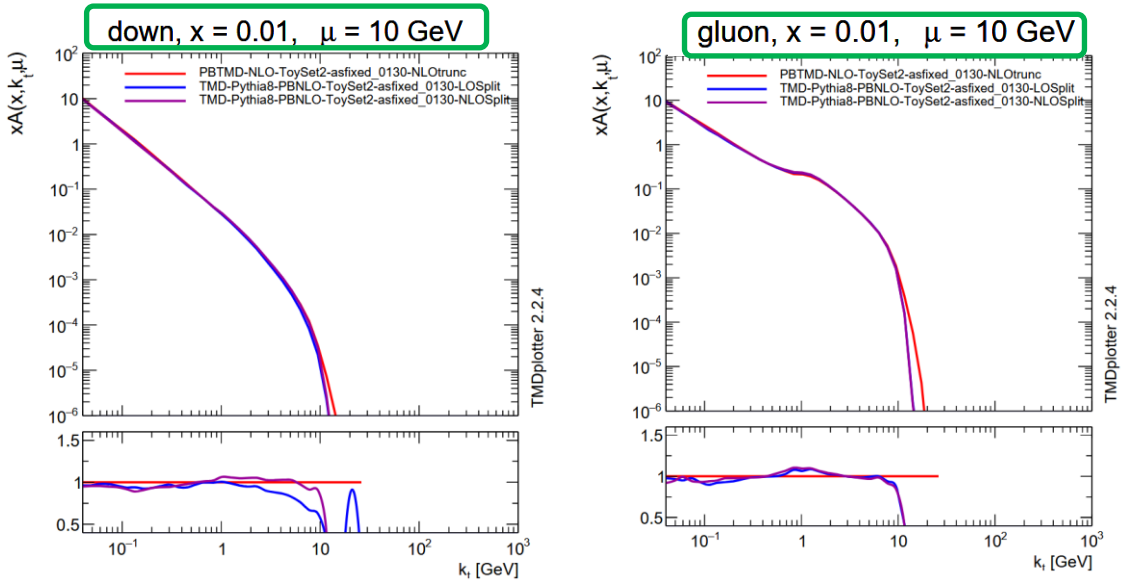
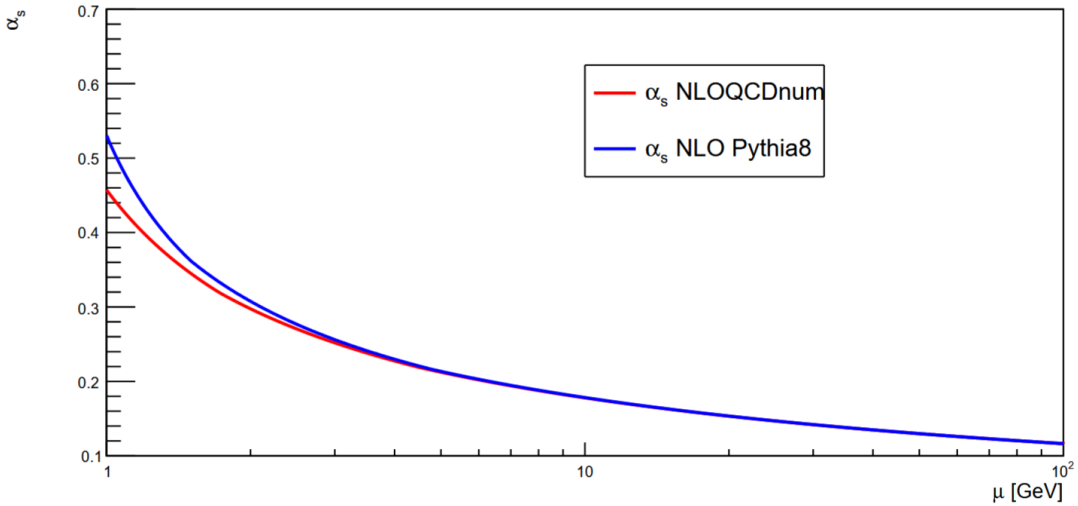


- NLO splitting functions in PDF evolution but LO splitting function in PS (blue): disagreement for quarks; gluons are fine
- NLO splitting function applied consistently (violet): good agreement
- 0.1% branchings with negative weights: ignored for now

PDF2ISR: tuning α_s evolution

Default setting in Pythia8 and PB method

	PYTHIA8	PB method
Ordering	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$
Phase space	$0 < z < z_M \approx 1 - 10^{-5}$	$0 < z < z_M \approx 1 - 10^{-5}$
Splitting Functions	NLO	NLO
α_s NLO treatment	PDG param. → QCDNUM num.	QCDNUM numeric



At NLO by default

- PYTHIA8: PDG evolution (parametrization)
- PB: QCDNUM numerical integration
- Introducing NLO splitting function in PS requires reweighting
  S. Mrenna, P. Skands arxiv:1605.08352

PDF2ISR: tuning α_s evolution

Default setting in Pythia8 and PB method

	PYTHIA8	PB method
Ordering	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$
Phase space	$0 < z < z_M \approx 1 - 10^{-5}$	$0 < z < z_M \approx 1 - 10^{-5}$
Splitting Functions	NLO	NLO
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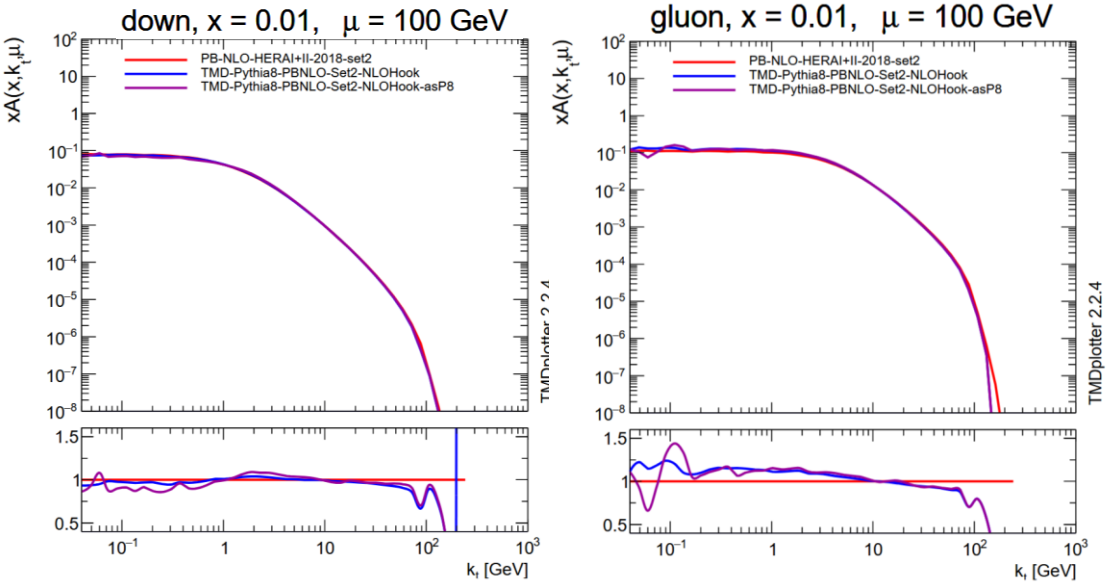

- Blue: consistent α_s treatment
- Violet: Pythia8 α_s treatment
- Remarkable agreement for quarks
- Gluon differences: different frame definitions when generating transverse moment (can be treated as systematic uncertainty)

PDF2ISR: tests on DY dataset

- Using the same phase space as in the recent CMS DY measurement
- All processes, except for ISR are switched off
- Good agreement between PB and Pythia-PB (PDF2ISR)

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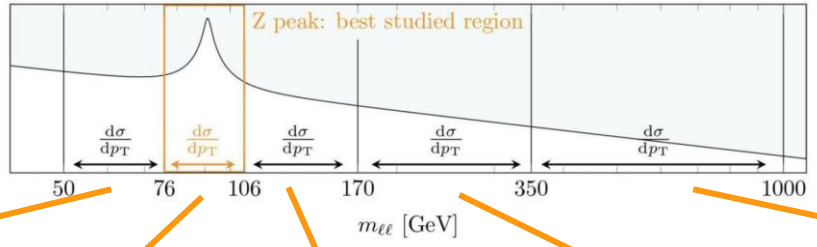
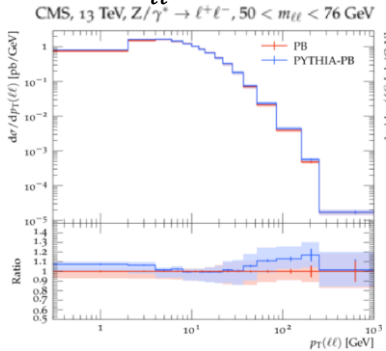
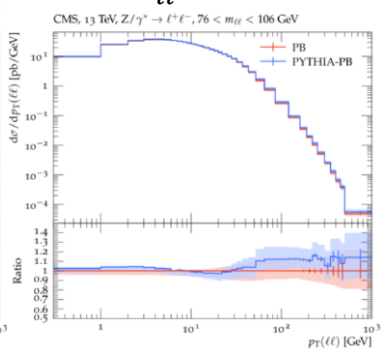
Eur. Phys. J. C 83 (2023) 628



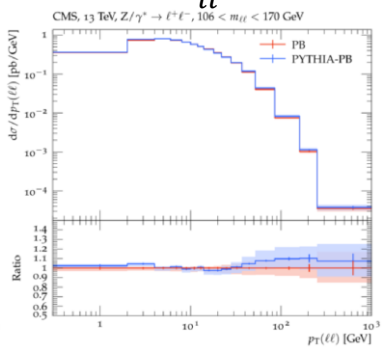
$50 < m_{ll} < 76$ GeV



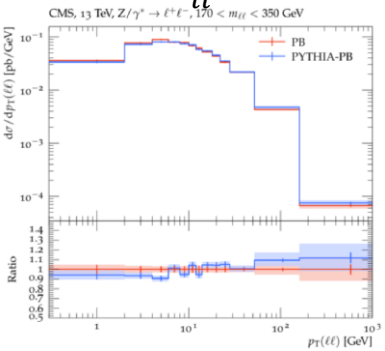
$76 < m_{ll} < 106$ GeV



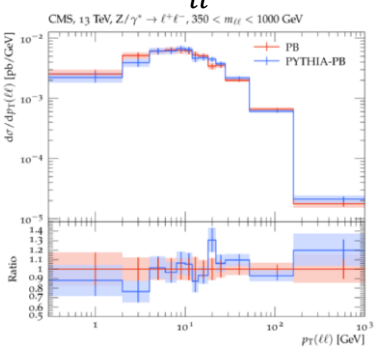
$106 < m_{ll} < 170$



$170 < m_{ll} < 350$



$350 < m_{ll} < 1000$

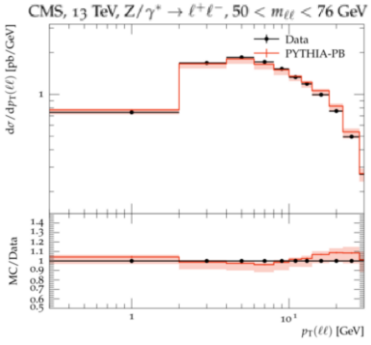


PDF2ISR: DY dataset, comparison with data

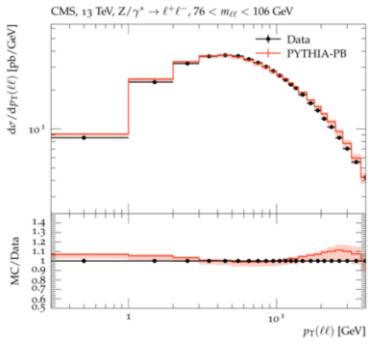
D. Subotić, H. Jung, N. Raičević, talk, QCD at the Extremes https://indico.cern.ch/event/1539849

- FSR turned on
- Intrinsic k_T width $q_0 = 1.04$ GeV
- Good description except for high $p_T(ll)$, missing higher orders
- Note: The plots are cut at high p_T with disagreements: $p_T(ll) < 100$ GeV

$50 < m_{ll} < 76$ GeV



$76 < m_{ll} < 106$ GeV



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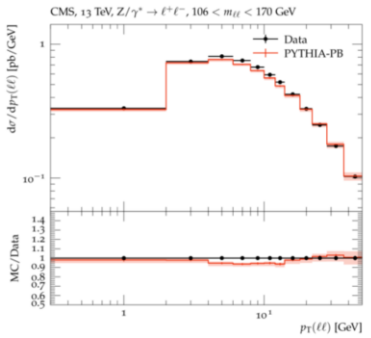

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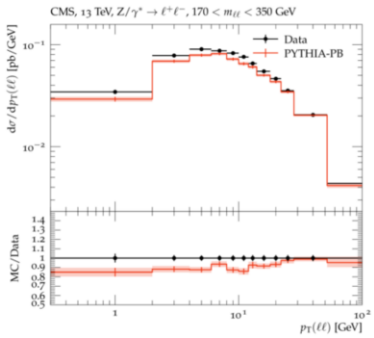

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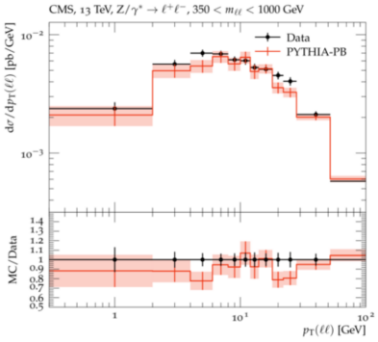

Summary

- PDF2ISR method: forward evolution (PB TMD) and backward (PYTHIA8 PS) can provide consistent results provided the same conditions are applied: angular ordering, kinematic limits, and the scale choice in α_s
- Have to use consistent splitting functions in the PDF and parton shower
- Definition of the frame of reference in k_t matters (worse agreement for gluon x)
- Can be extended to NNLO
- Validated also on DY data