Recent developments in the PDF2ISR method in PYTHIA 8

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… for the PB TMD group

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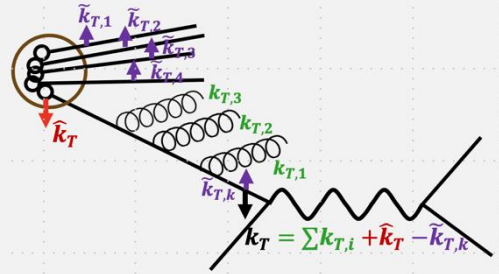
22.10.2026

Outline

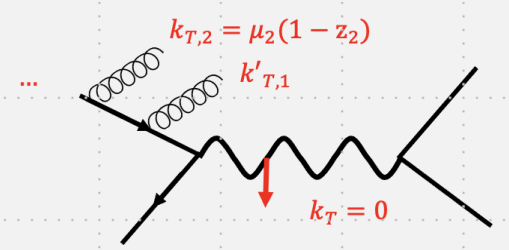
1) Introduction to Parton Branching and PDF2ISR

2) Properties of PDF2ISR: EPJ.C 86 (2026) 6, 727 arXiv 2602.17533

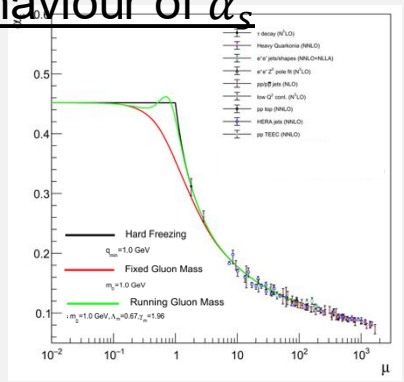
<u>Default primordial k_T treatment</u>



<u>Relation of q_s as a function of $\sqrt{s}$</u>



<u>Non-perturbative behaviour of α_s</u>



3) Jet merging with PDF2ISR

Intrinsic transverse momentum and soft gluons

DY $p_T(ll)$: benchmark process to study multiple QCD effects:

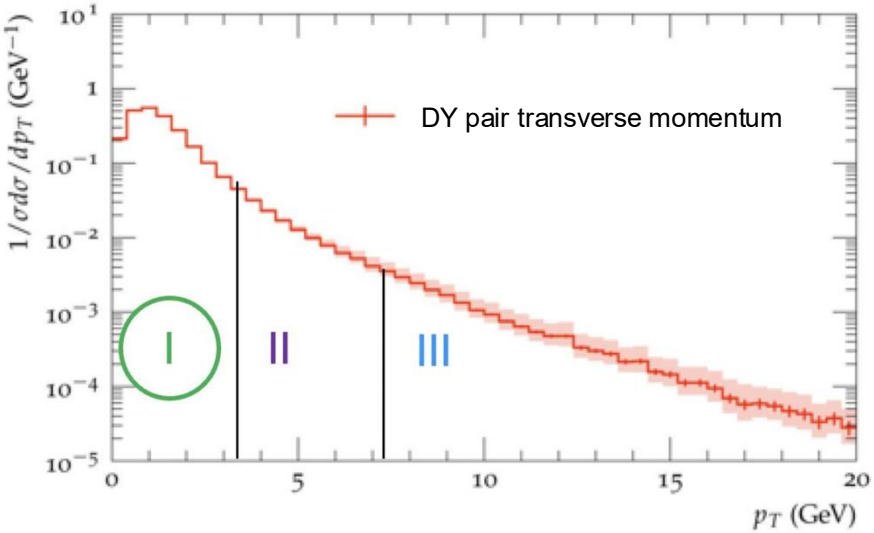
III) Perturbative. Higher order terms dominating

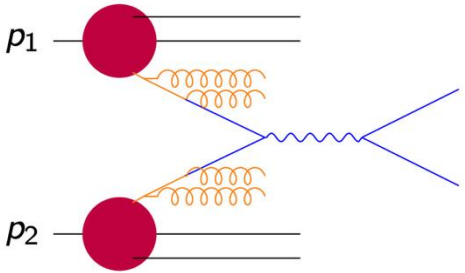
II) Transition region

I) Non-perturbative region. Interplay between:

a) Intrinsic transverse momentum (k_T)

b) Soft gluon radiation from initial-state parton evolution





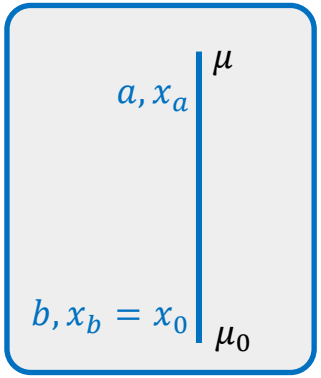
The parton branching method

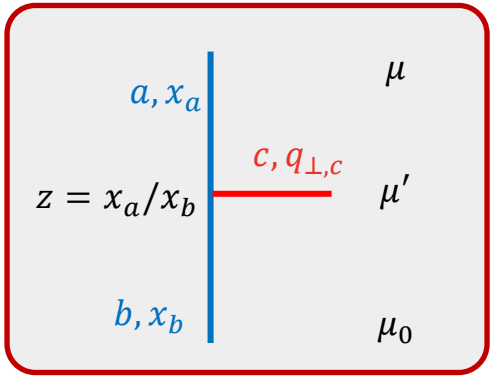
- Parton branching (PB) method: transverse momentum dependent PDF (TMD) generated from the DGLAP PDF evolution in an iterative way (MC)
- Introduces the transverse degree of freedom (k_T) at the parton distribution level

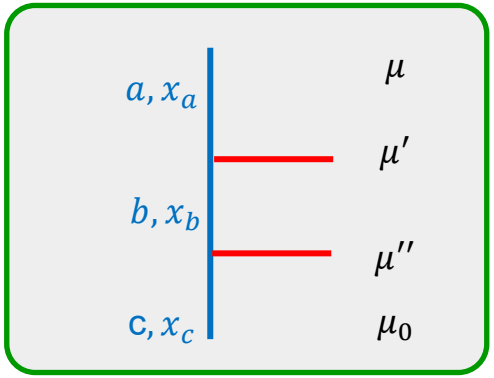
$$\tilde{A}_a(x,\boldsymbol{k},\mu^2) = A(x,\boldsymbol{k},\mu_0^2)\Delta_a(\mu^2) + \sum_b \int_{\mu_0}^{\mu} \frac{d^2\mu'}{\pi\mu'} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \Theta(\mu^2-\mu'^2)\Theta(\mu'^2-\mu_0^2)$$
$$\times \int_x^{z_M} \frac{dz}{z} P_{ab}^{(R)}(\alpha_s,z)\, \tilde{A}_b\left(\frac{x}{z}, \boldsymbol{k}+(1-z)\boldsymbol{\mu'}, \mu'^2\right) \Delta_b(\mu'^2) + \cdots$$

arXiv 1704.01757

JHEP 01 (2018) 070





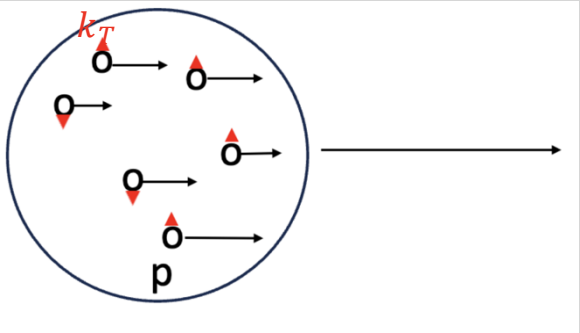


$0 < z < z_M$: longitudinal momentum transfer; $\tilde{A} = xA$

Branchings non-resolvable for $z > z_M$

Transverse momentum interpreted from the evolution scale $\mu' = q_\perp/(1-z) \Rightarrow$ angular ordered

Intrinsic transverse momentum and soft gluons



Starting scale of the evolution: intrinsic k_T.
Generated from a Gaussian distribution with width σ.
In PB model/PYTHIA, it is expressed via parameter q_s: $\sigma^2 = q_s^2/2$

TMD as initial scale:

$$A_a(x, k_0, \mu_0^2) = f_a(x, \mu_0^2) \cdot \frac{\exp(-\frac{|k_0^2|}{q_s^2})}{(\pi q_s^2)^{1/2}}$$

The initial distribution must be fitted to data:

- Collinear part PB-NLO with HERA DIS data with xFitter Phys.Rev.D 99 (2019) 7, 074008
- TMD part with DY data (see talk by Laurent Favart) EPJ C 84 (2024) 154

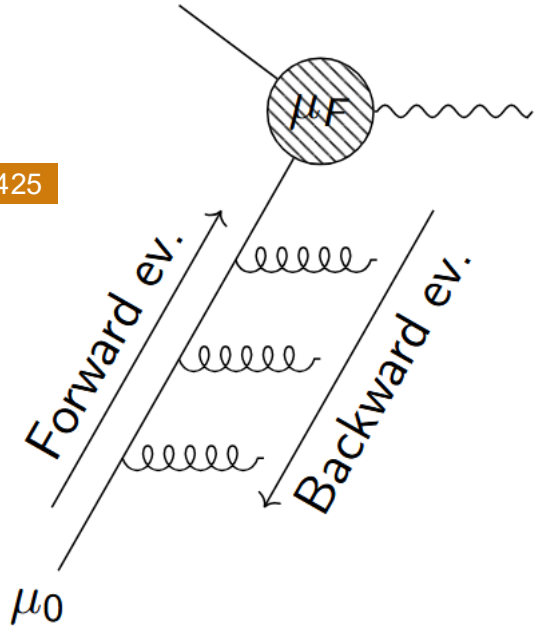
Two sets of PB branching sets depend on the scaling of α_s

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

Forward and backward evolution

TMD can be obtained from:

- parton branching (PB) – **forward evolution**
  e.g CASCADE event generator arXiv 2101.10221 EPJ C (2021) 81:425
- initial state radiation (ISR) – **backward evolution**
  e.g. PDF2ISR as studied in the talk arXiv 2504.10243 EPJ C (2025) 85:870



Sudakov form factor:

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

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

$f_{i/b}(x_b, \mu)$ – PDF;

Cross validation of PDF2ISR

PDF2ISR method: constructs the ISR to exactly follow the evolution of the collinear parton density, i.e. the PB Method

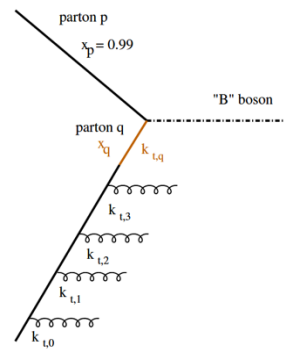
arXiv 2504.10243
EPJ C (2025) 85:870

Modification of PYTHIA 8 ISR shower to make it consistent with the PDF and PB method. PB-NLO-Set2 PDF set was used.

	Default PYTHIA 8	PB method and PDF2ISR
Ordering	p_T-ordered, $q_\perp^2 = \mu^2$	Angular-ordered, $q_\perp^2 = (1-z)^2\mu^2$
Phase space	$0 < z < z_{\mathrm{dyn}}^{P8}$	$0 < z < z_{\mathrm{M}} \approx 1 - 10^{-5}$
Splitting Functions	LO	NLO
α_s NLO treatment	PDG parametrisation	QCDNUM numeric

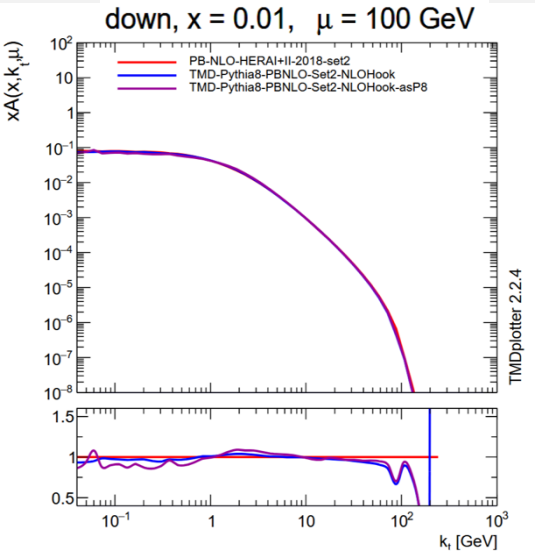
- Both PB method and PDF2ISR are fast, robust and flexible methods for TMD resummation
- Unlike CASCADE (PB method), PDF2ISR includes the full event description including Underlying Event (UE), hadronization (within PYTHIA 8): can be used can be used as a general-purpose MC generator

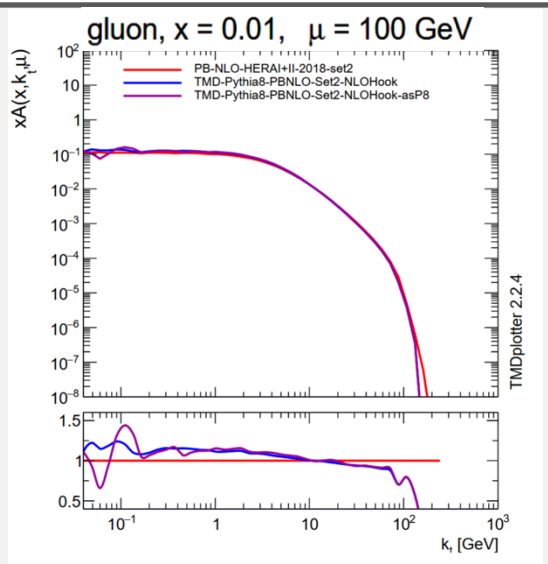
Cross-validation



Cross validation was performed using a toy model: $p + q \rightarrow B$:

- B: colourless boson used to easily calculate the kinematics
- p: parton that does not develop a parton shower; q: develops a parton shower
- Transverse kinetics: $k_{t,q} = p_{t,B}$
- Compare $p_{t,B}$ distribution from PDF2ISR with the TMDs obtained by PB





- Remarkable agreement between the FW evolution (PB method) and BW evolution (PDF2ISR)
- Blue: consistent α_s treatment
- Violet: PYTHIA 8 α_s treatment
- Gluon differences: different frame definitions when generating transverse moment (see further slides)

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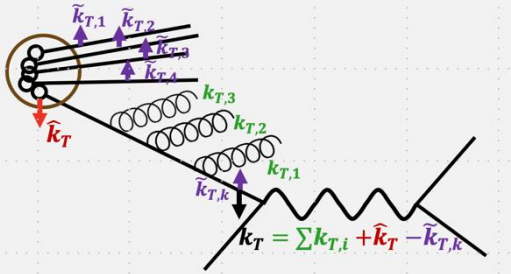

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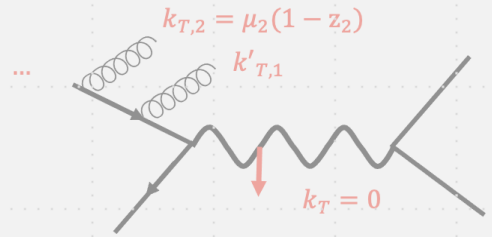

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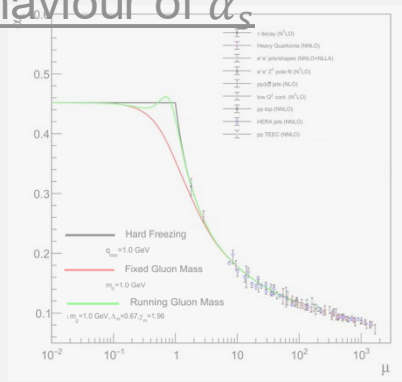

3) Jet merging with PDF2ISR

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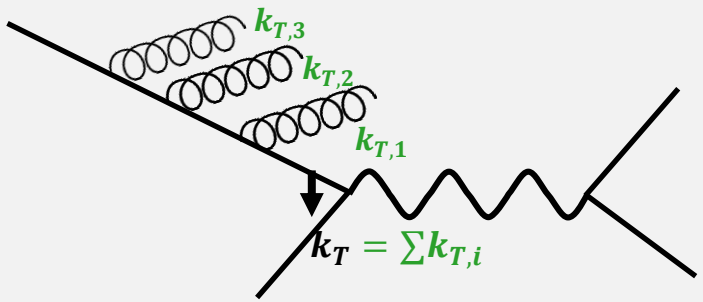
Primordial k_T recoil prescriptions

1. Shower is performed, keeping track of all the $k_{T,i}$ at each splitting
2. Primordial k_T ($\hat{k}_T$) sampled from the Gaussian distribution
3. Momentum conservation: recoil subtracted

Default primordial k_T treatment

Compensation redistributes the net k_T over all the beam partons



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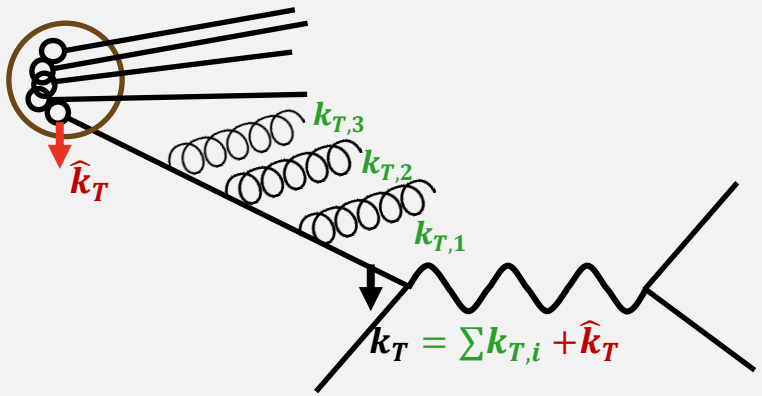

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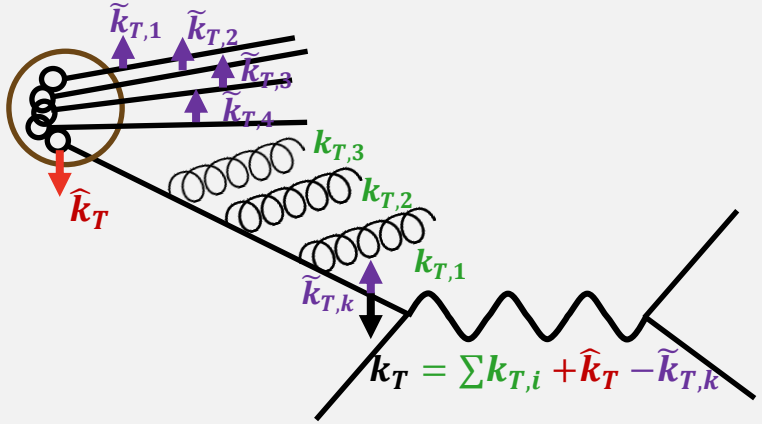

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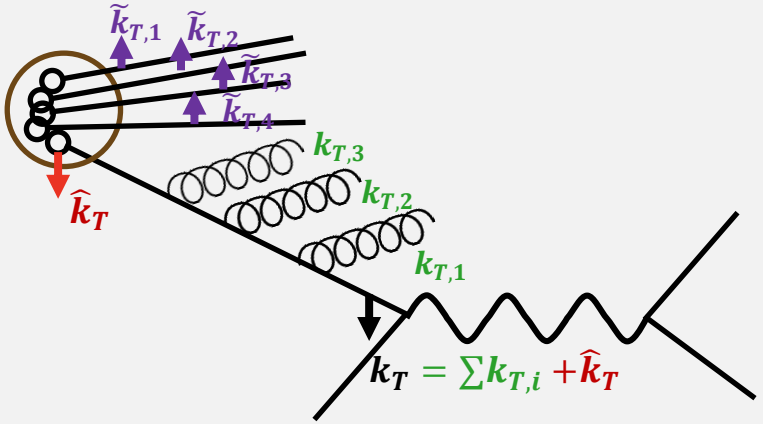
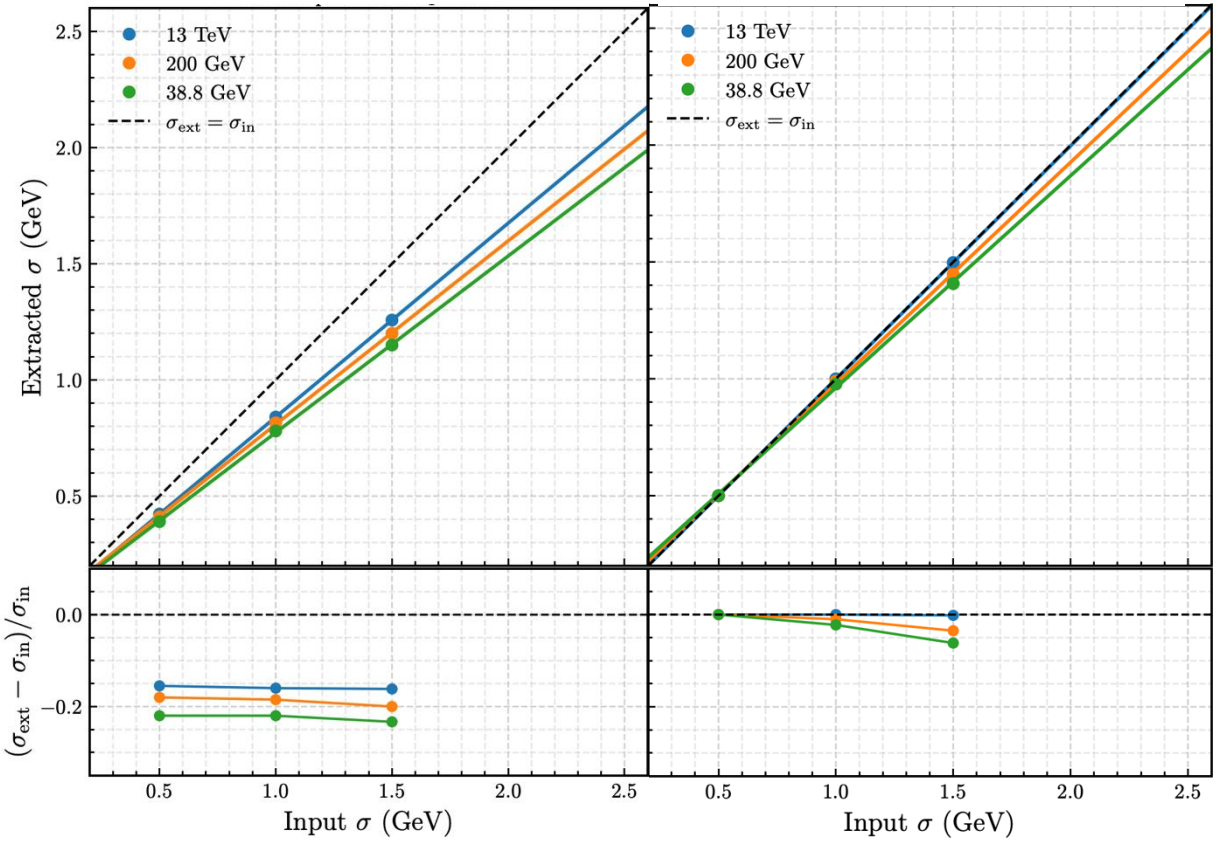


Primordial k_T recoil prescriptions

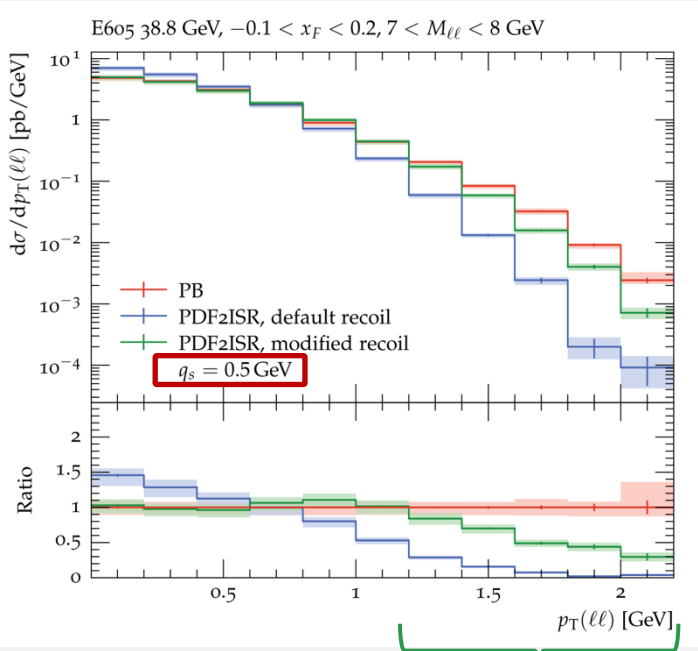
Default primordial k_T treatment

Beam remnants-only treatment



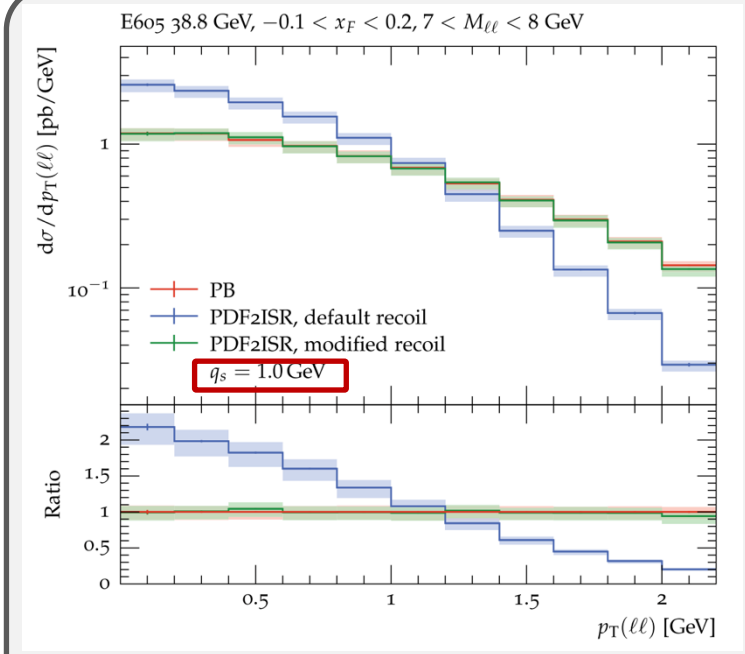
- Only a mild residual $\sqrt{s}$ dependence remains, from energy–momentum conservation in the physical process.

Recoil prescriptions ($p_T(ll)$, no ISR)



- At fixed q_s the modified recoil reproduces PB;
- The default scheme does not

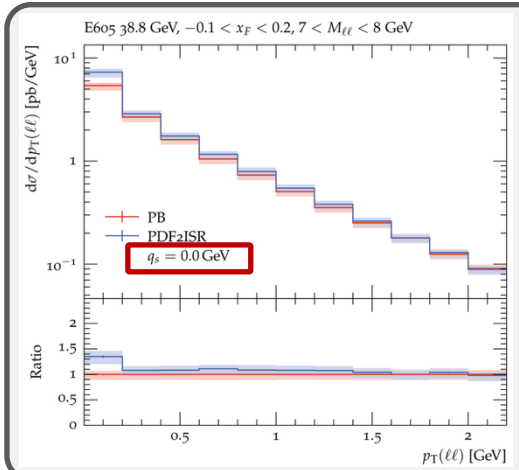
Small shift due to matching to NLO

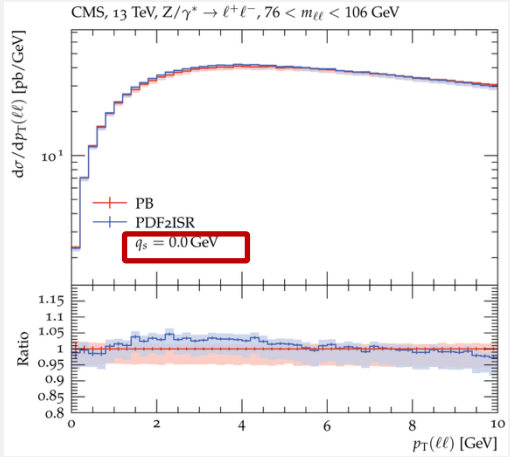


- The default scheme drifts increasingly as q_s grows.

For this and all the following studies the hard process was generated using aMC@NLO at NLO

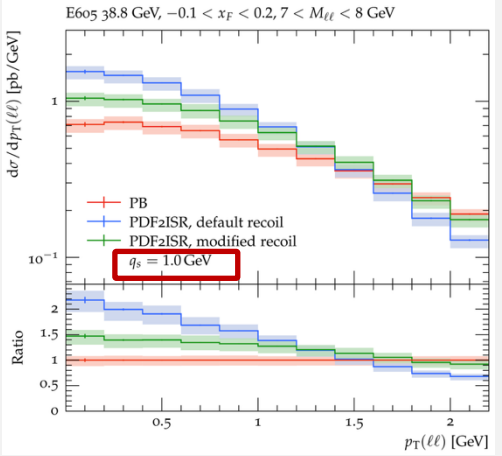
With and without primordial k_T, recoil schemes

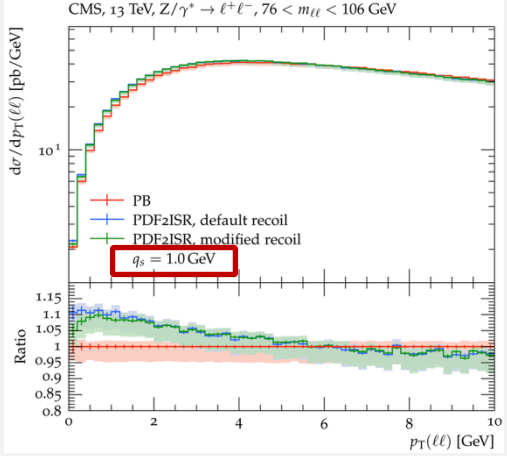




No intrinsic k_T ($q_s = 0$), only ISR

Good agreement between PDF2ISR and PB





Adding intrinsic k_T ($q_s = 1$ GeV) and ISR

Less effect from the modified scheme at large $\sqrt{s}$ than in the default scheme. Still, some of the k_T is absorbed due to the frame definition of the k_T at the splitting (see further)

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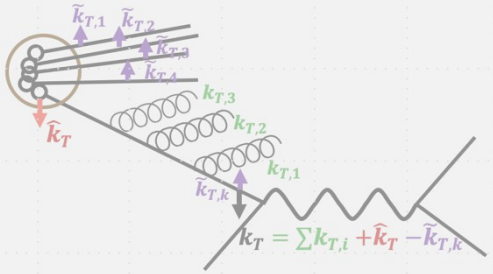

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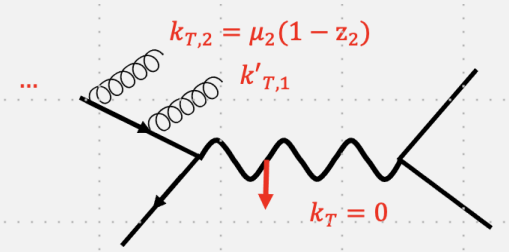

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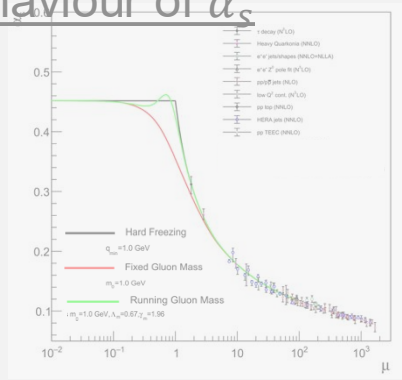

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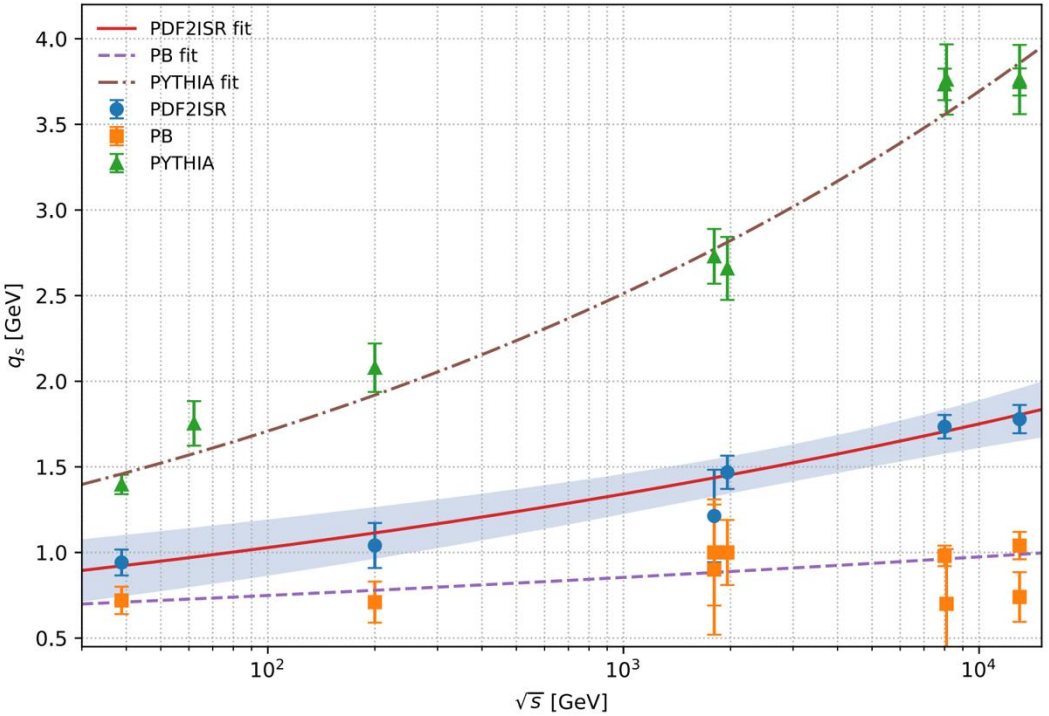
Extracting q_s as a function of $\sqrt{s}$



- In PDF2ISR the extracted $q_s(\sqrt{s})$ rises more steeply than PB, but much flatter than in PYTHIA.

- Backward evolution absorbs part of the p_T into the fitted intrinsic k_T
- $k_{T,i}$ of each splitting defined in the COM frame

Comparison with PYTHIA and PB fits from EPJ C 84 (2024) 154 see also talk by Laurent Favart

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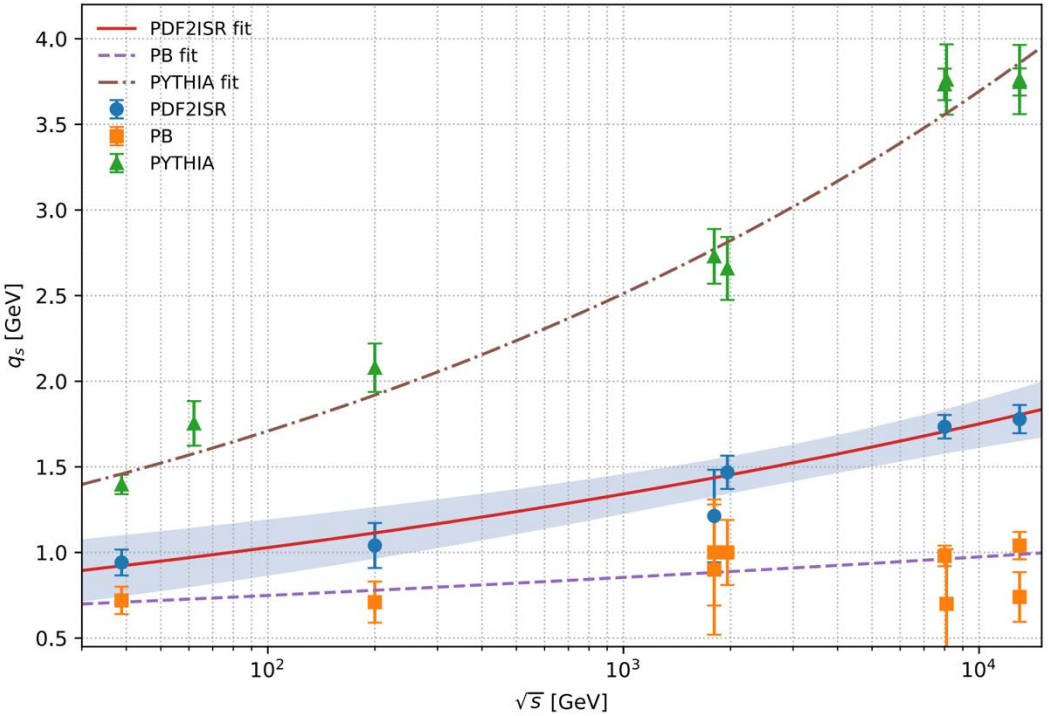

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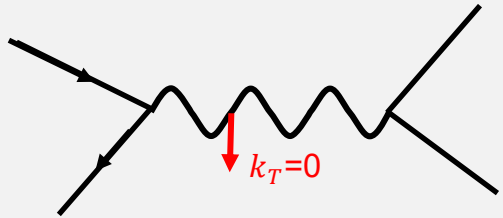

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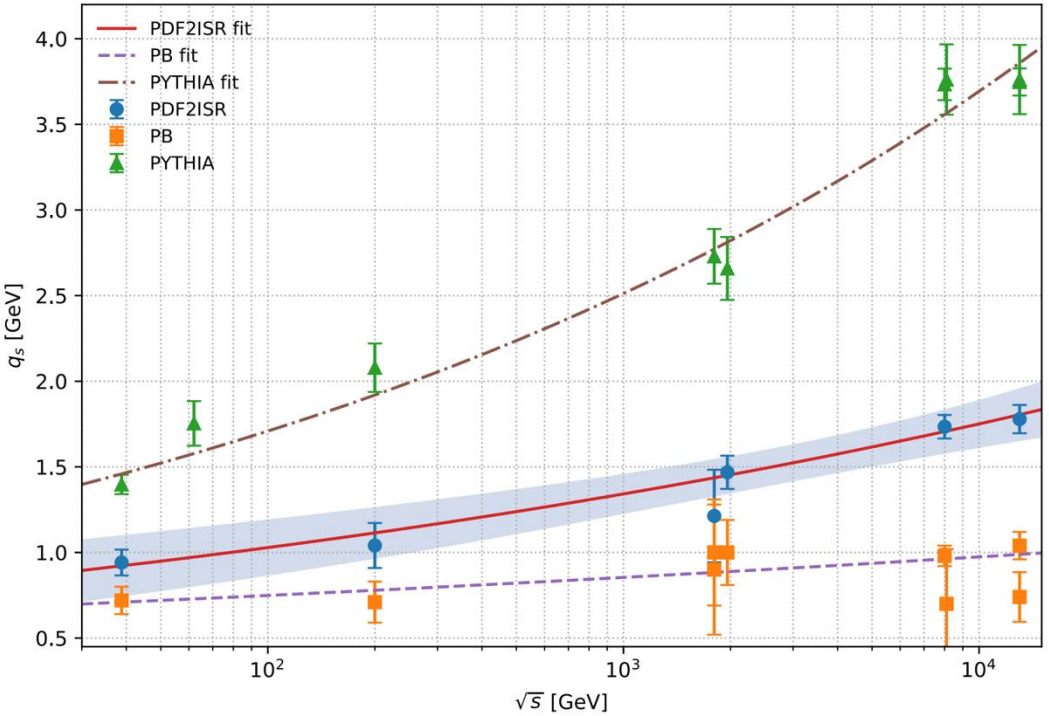

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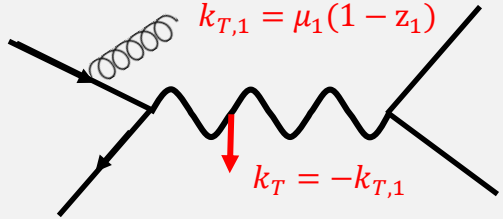

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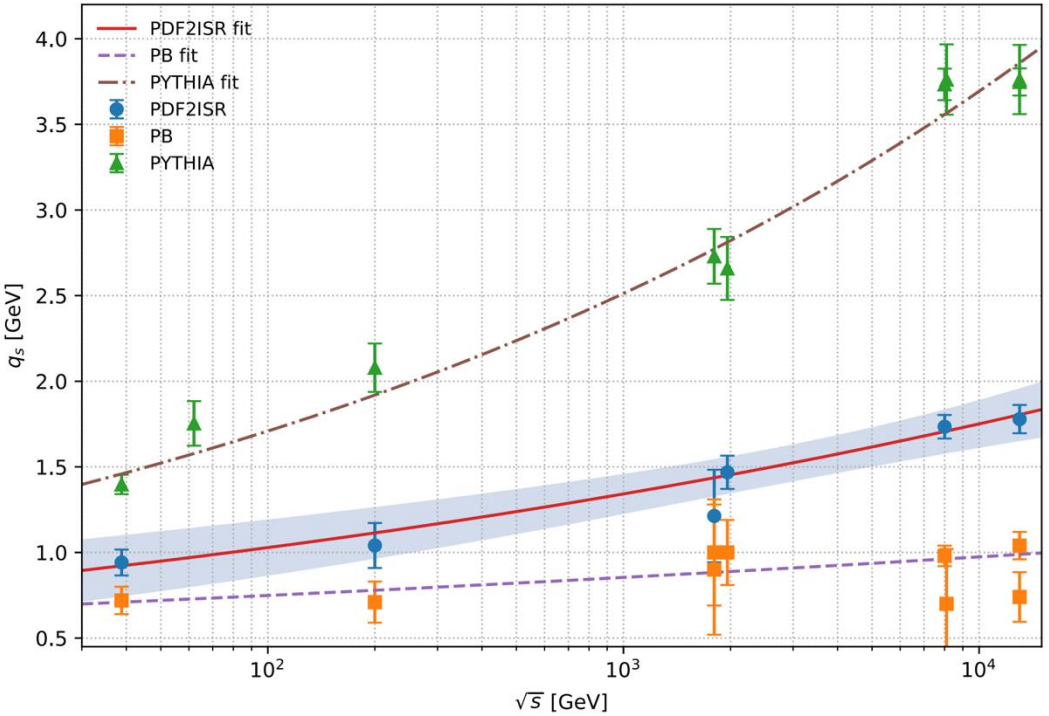

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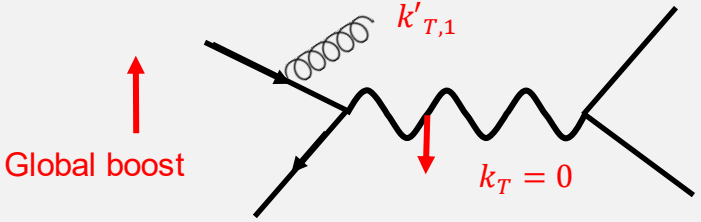

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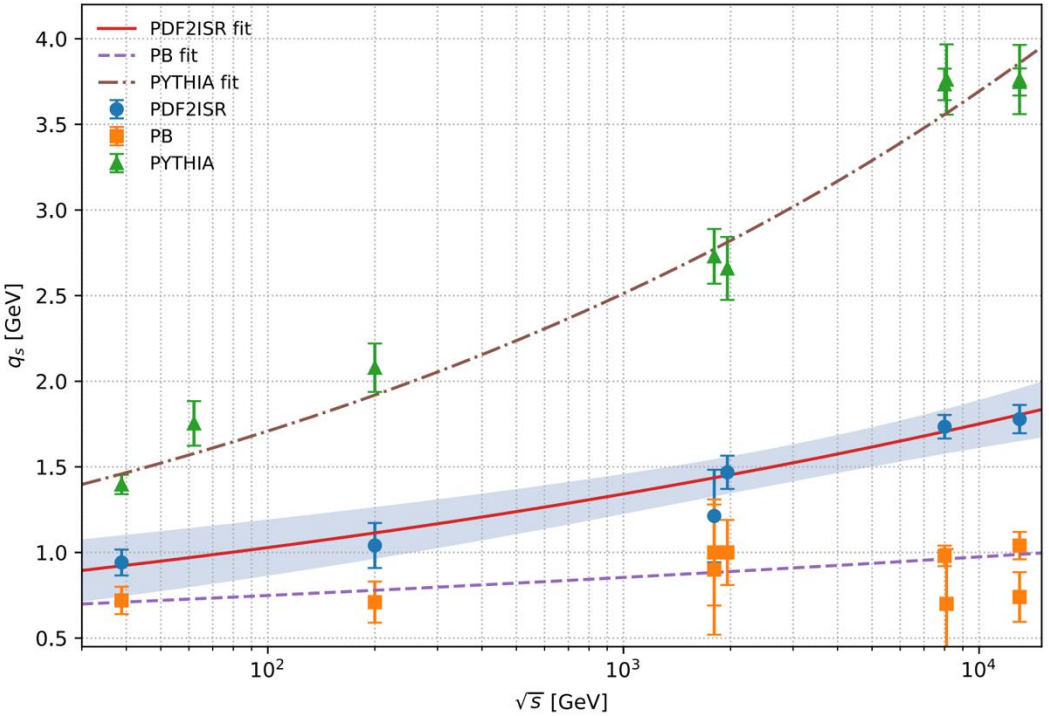

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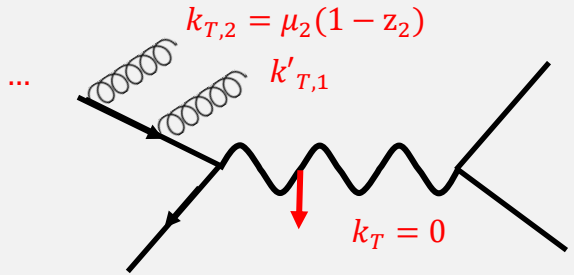

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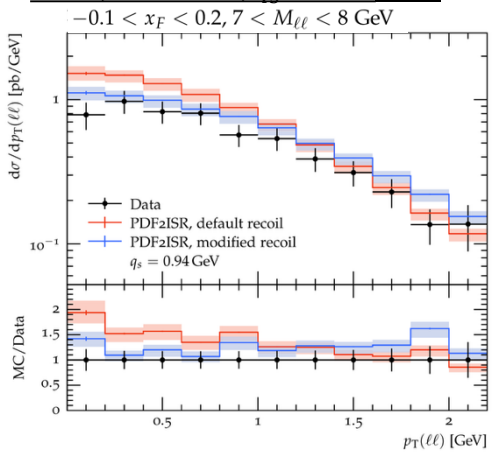
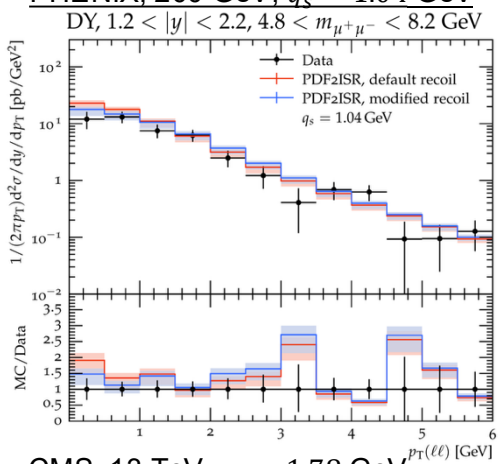
PDF2ISR shows good agreement across various scales

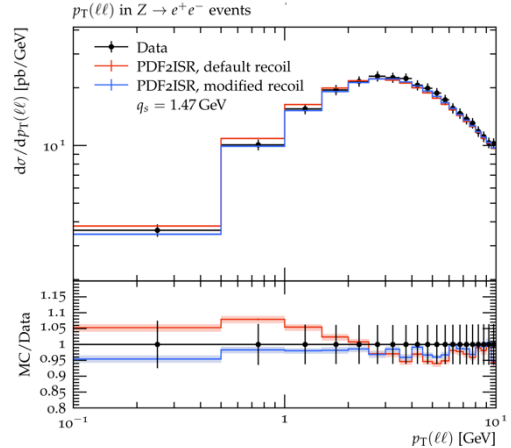
E605, 38.8 GeV, $q_s = 0.94$ GeV



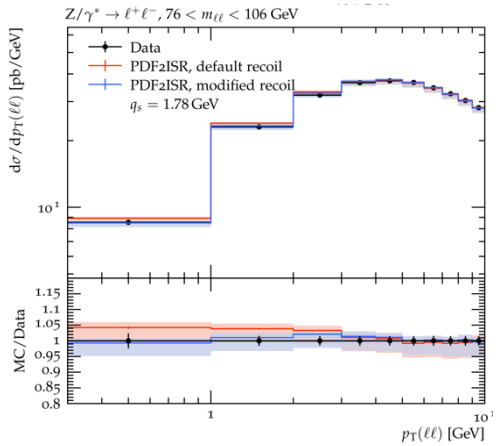
PHENIX, 200 GeV, $q_s = 1.04$ GeV



CDF, 1960 GeV, $q_s = 1.47$ GeV



CMS, 13 TeV, $q_s = 1.78$ GeV



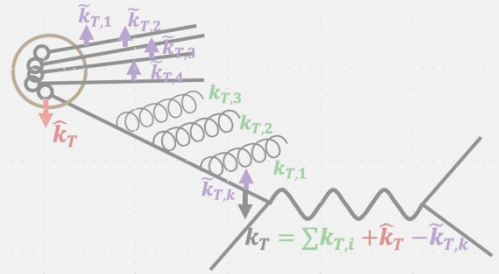
- Good description of data across centre-of-mass energies from 38 GeV to 13 TeV when using the fitted q_s values
- Only comparison in low $p_T(ll)$ is shown sensitive to primordial k_T and soft gluon radiation

Outline

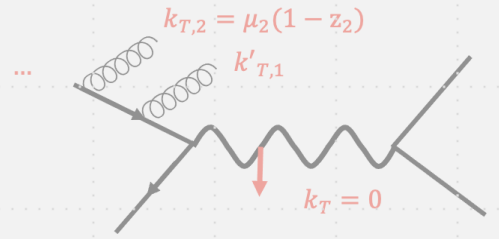
1) Introduction to Parton Branching and PDF2ISR

2) Properties of PDF2ISR: EPJ.C 86 (2026) 6, 727 arXiv 2602.17533

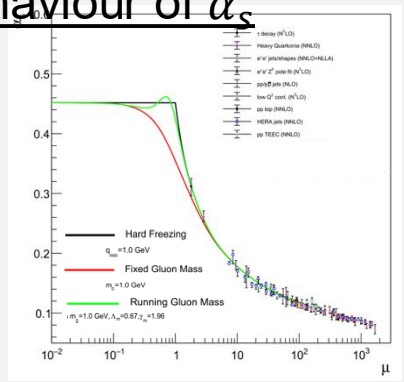
Default primordial k_T treatment



Relation of q_s as a function of $\sqrt{s}$



Non-perturbative behaviour of α_s



3) Jet merging with PDF2ISR

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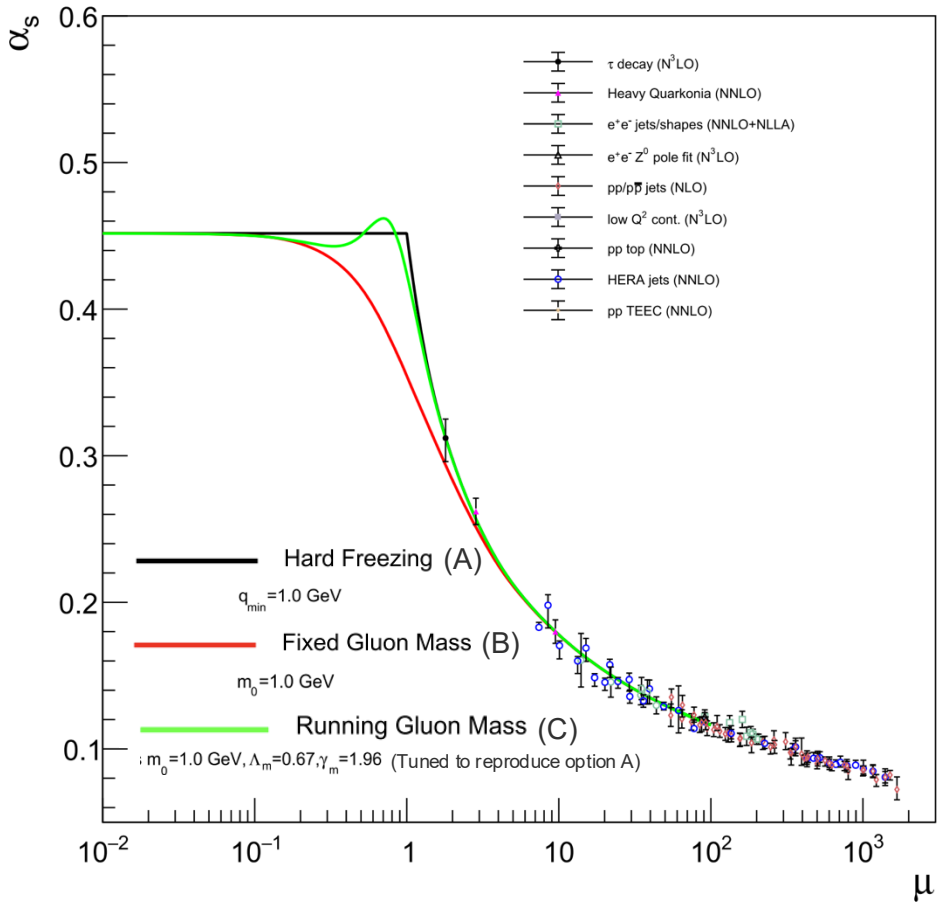
Infrared behaviour of α_s



- The goal is not to prefer an infrared form, but to quantify how much low-p_T Drell–Yan responds to the transition region

A. Hard freezing (PB-NLO-2018 default)

$$\alpha_s = \alpha_s(\max(q_T^2, \mu^2_{\min}))$$

B. Fixed gluon mass (smooth transition)

$$\alpha_s = \alpha_s(m_0^2 + \mu^2)$$

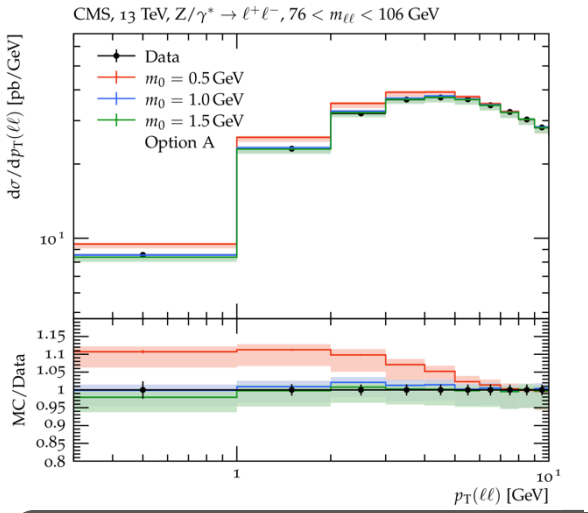
arXiv hep-ph/9408261 Phys. Lett. B 348, 190 (1995)

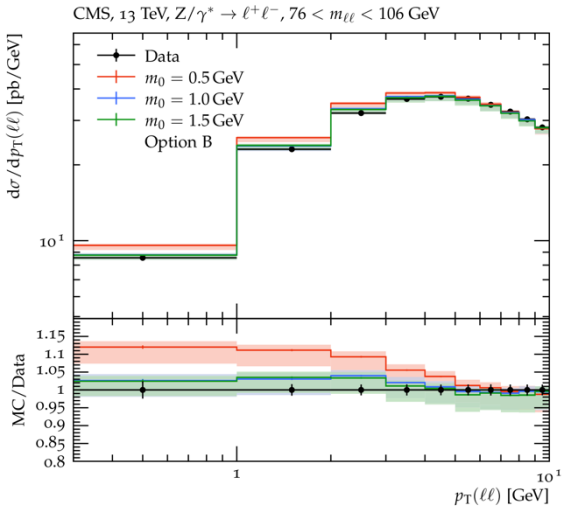
C. Running gluon mass (scale-dependent mass)

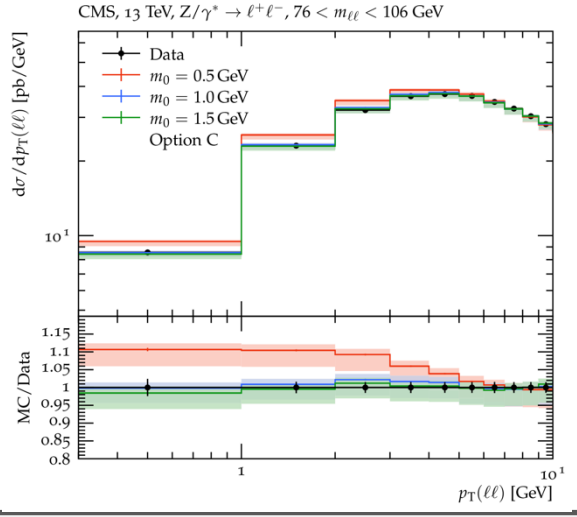
$$\alpha_s = \alpha_s(m^2(\mu^2) + \mu^2),\ m^2(\mu^2) = m_0^2/(1 + \left(\frac{\mu^2}{\Lambda_m^2}\right)^{\gamma})$$

arXiv 1401.3631 Phys. Rev. D 89, 085032

$p_T(ll)$ dependance on the α_s non-perturbative behaviour







- $m_0 = 0.5$ GeV overshoots in all three prescriptions. A stronger low-scale coupling enhances soft ISR.
- $m_0 = 1.0$ and 1.5 GeV are similar. Once the infrared coupling is moderated, further changes of the scale affect the spectrum only weakly
- Fixed mass (option B) deviates more (but within the 7-point band).
- DY could be a probe of α_s complementary to the event shapes and jet observables

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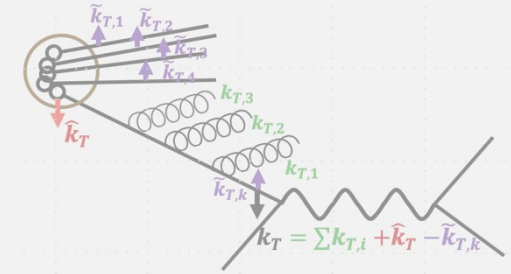

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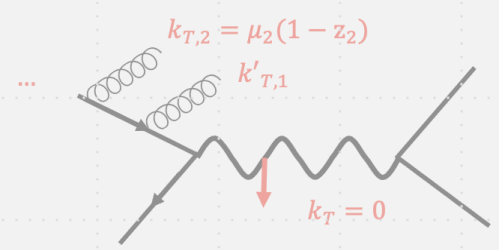
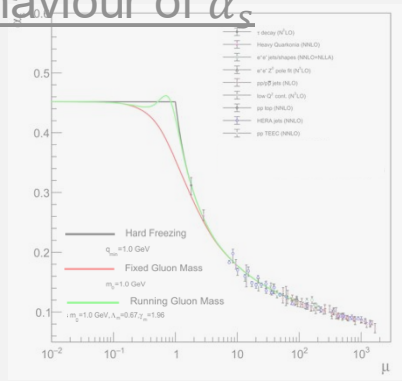


Non-perturbative behaviour of α_s



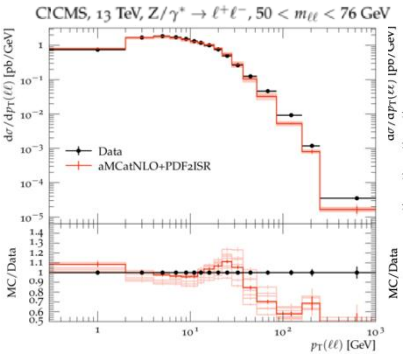
3) Jet merging with PDF2ISR

andris.potrebko@cern.ch

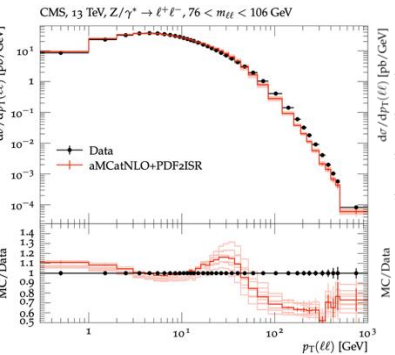
PDF2ISR shows a good agreement with the data

- Shown is the full range of p_T over different m_{ll} bins at $\sqrt{s} = 13$ TeV
- Intrinsic k_T width $q_s = 1.04$ GeV
- Good description at low $p_T(ll)$ (non-perturbative region) over different m_{ll}
- High $p_T(ll)$: disagreement due to missing higher-order terms in α_s

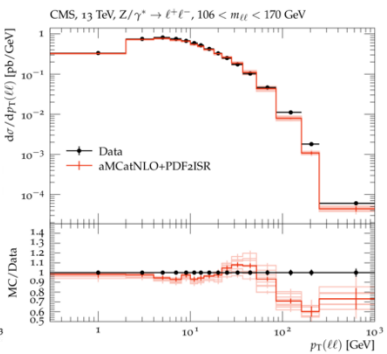
$50 < m_{ll} < 76$ GeV



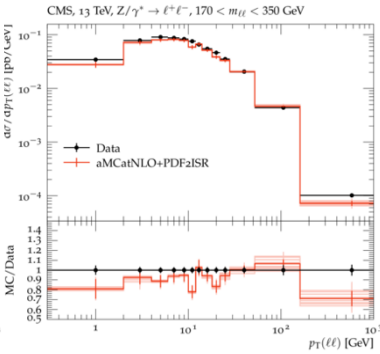
$76 < m_{ll} < 106$ GeV



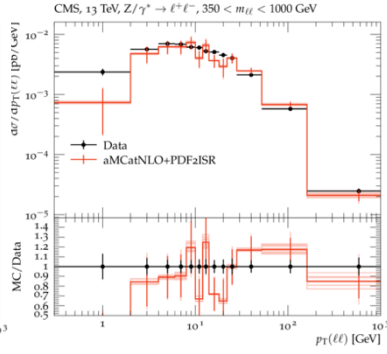
$106 < m_{ll} < 170$



$170 < m_{ll} < 350$

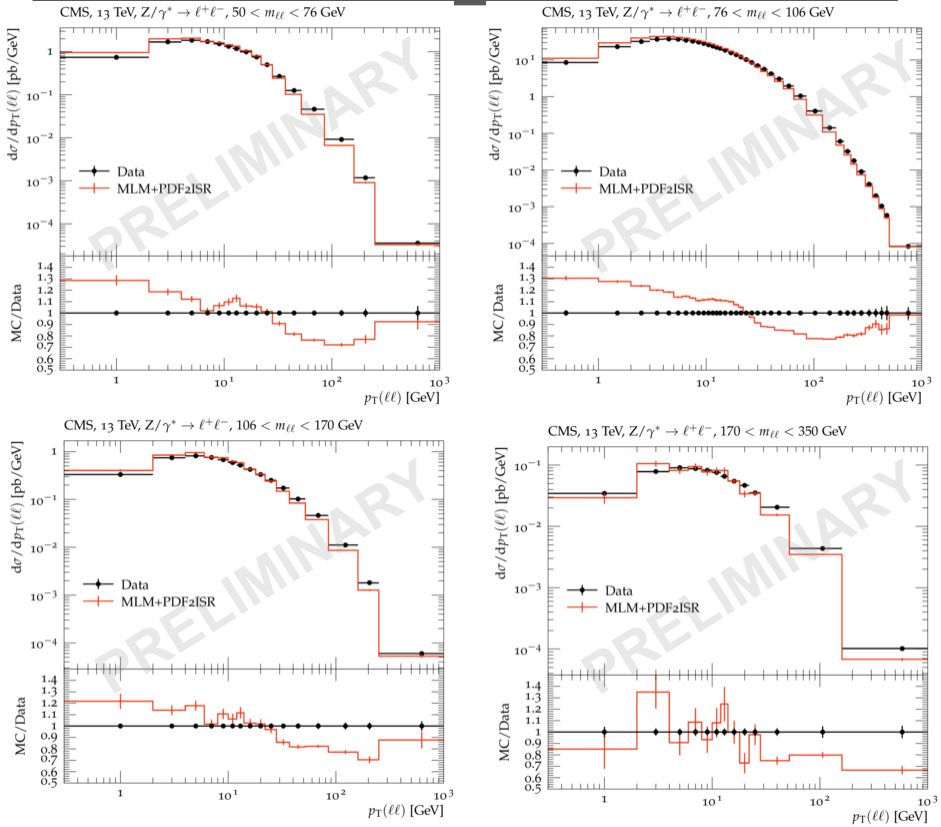


$350 < m_{ll} < 1000$



Towards the usage of PDF2ISR as full-pledged generator

Warning: work in progress
NNPDF3.1 used instead of PB-TMD-Set2.



- PDF2ISR is a fast, robust and flexible method for TMD resummation
- Validation with further complexity is necessary:
  - Validation of the framework with jet merging at LO and NLO
  - Updating the Underlying Event (UE) tune
  - Validation in terms of other processes

- So far: aMC@NLO (1 jet at NLO) + PDF2ISR
- Left: MLM merging (0,…4 jets at LO) + PDF2ISR.
  Note: Changing the shower to angular-ordered keeps the jet merging consistent

Summary

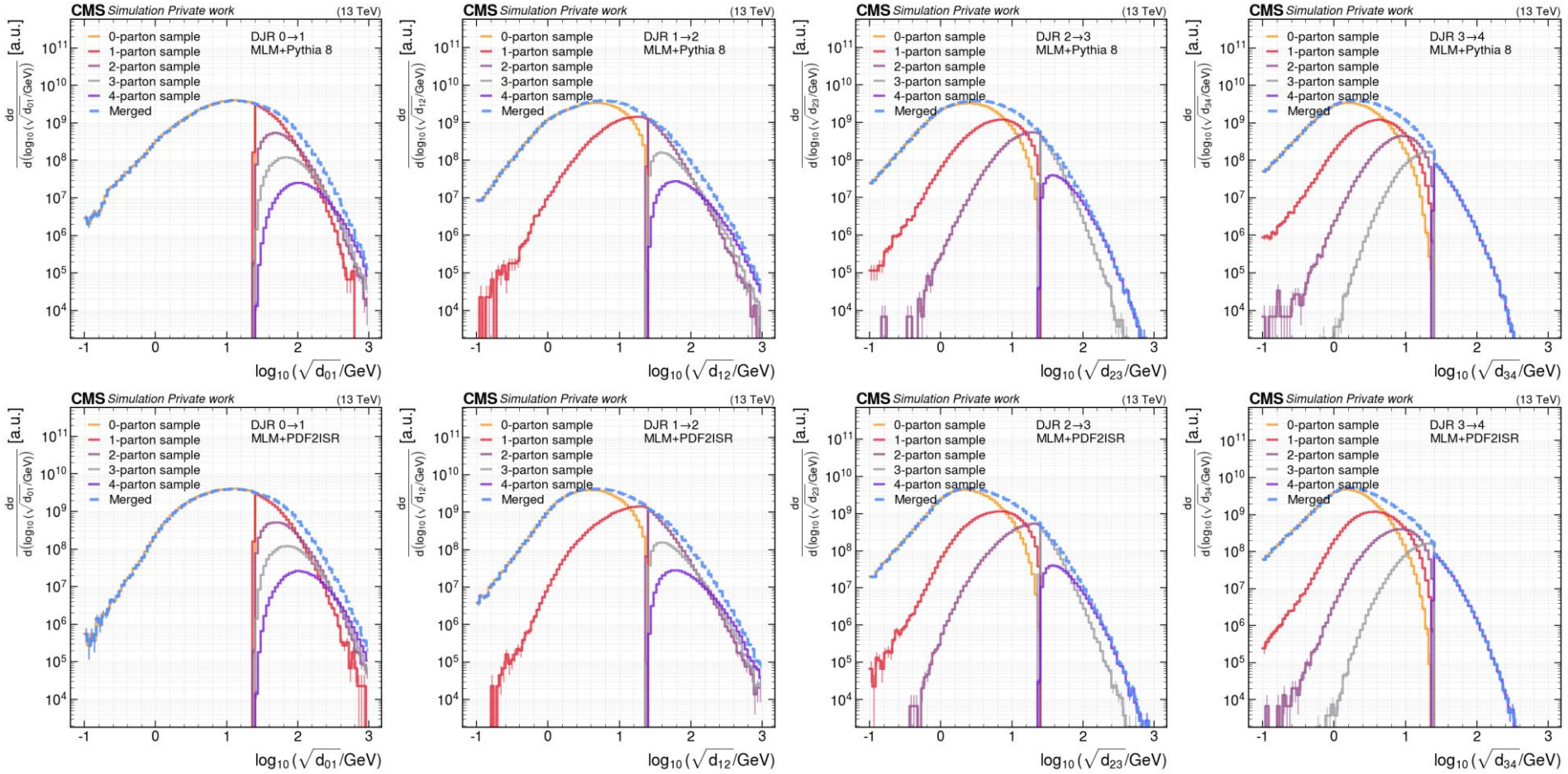
We have presented:

- PDF2ISR: a parton shower consistent with TMD parton densities
- Low-p_T Drell–Yan data are well described from 38.8 GeV to 13 TeV
- A recoil prescription in PDF2ISR that preserves intrinsic k_T
- $q_s(\sqrt{s})$ from PDF2ISR is steeper than in PB, absorbed by the kinematics in the shower
- At the highest energies, low-p Drell–Yan probes the α_s transition region

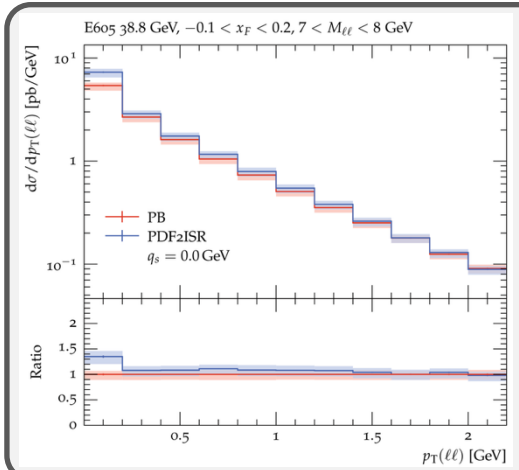
Outlook:

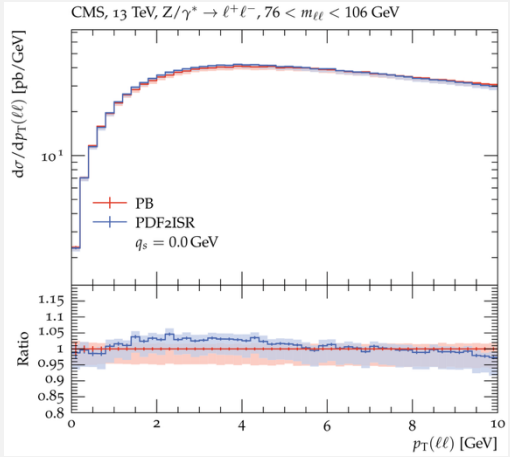
- Low p_T behaviour of MLM+PDF2ISR to be understood better (and with NLO multijet merging)
- Retuning of the underlying event is necessary for use by experiments
- PDF2ISR method with HERWIG 7 would be a good test for $q_s(\sqrt{s})$ extraction

DJR distribution MLM merging



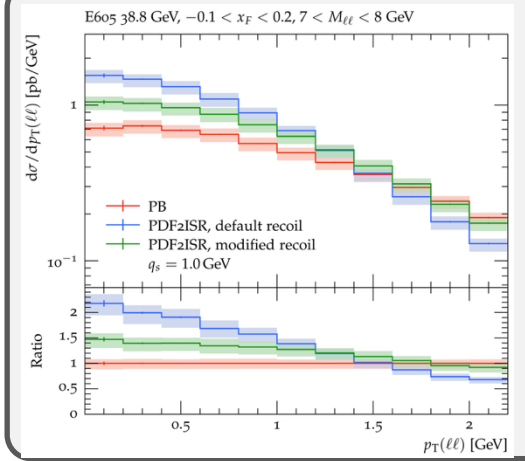
With and without primordial k_T, recoil schemes

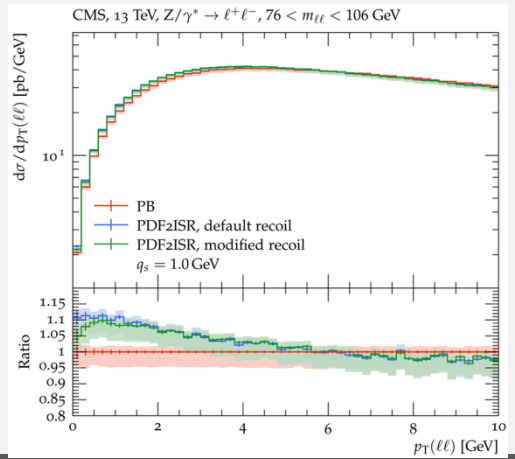




No intrinsic k_T ($q_s = 0$), only ISR

Good agreement between the two showers

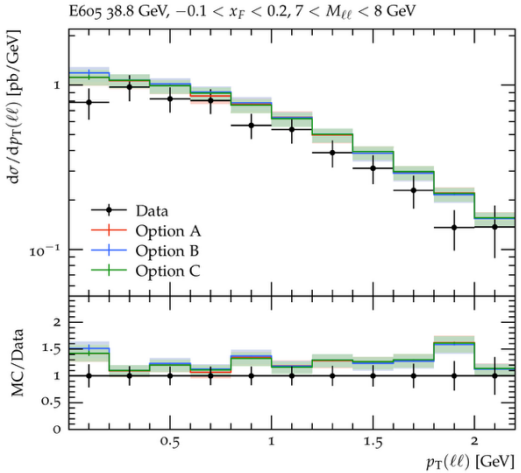


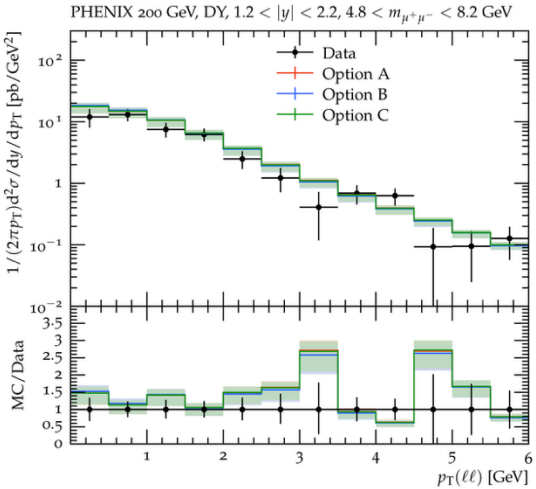


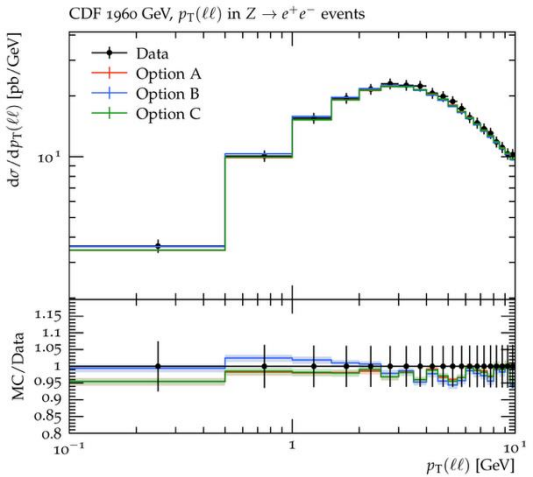
Adding intrinsic k_T ($q_s = 1$ GeV) and ISR

Less effect from the modified scheme at large $\sqrt{s}$.
Still, some of the k_T absorbed due to the frame definition of the k_T at the splitting

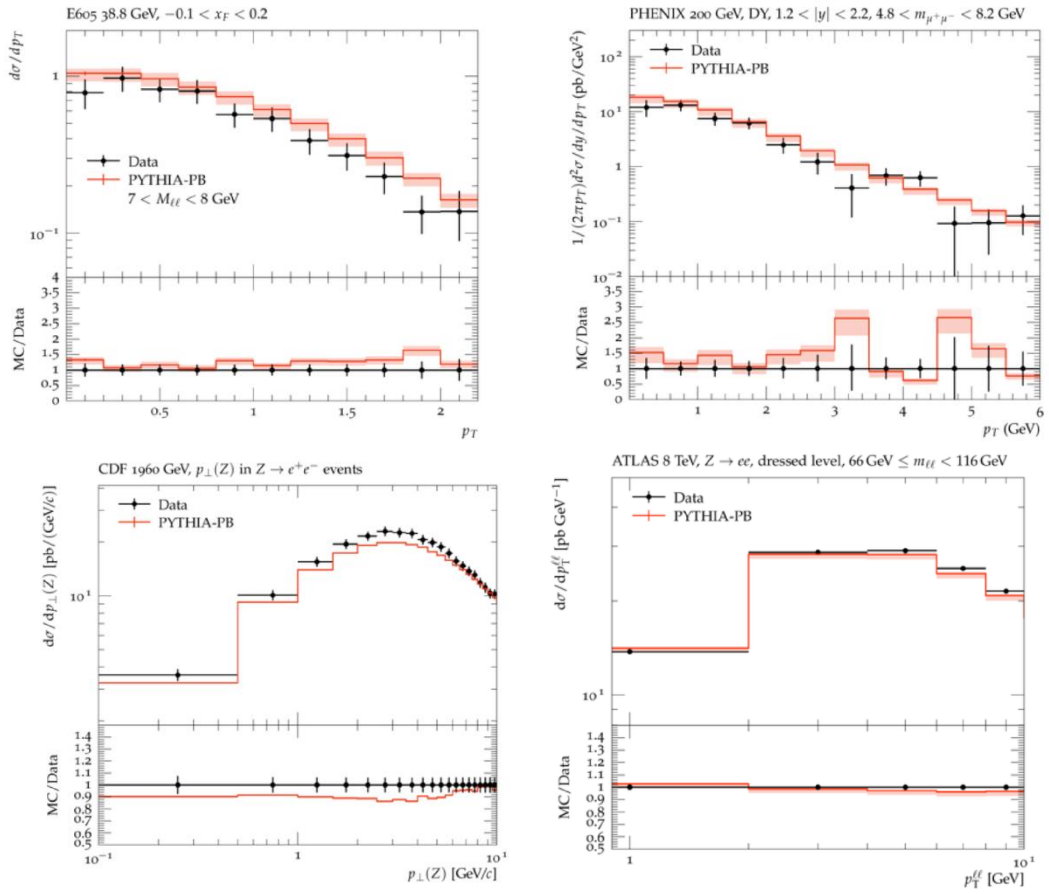
$p_T(ll)$ dependance on the α_s non-perturbative behaviour

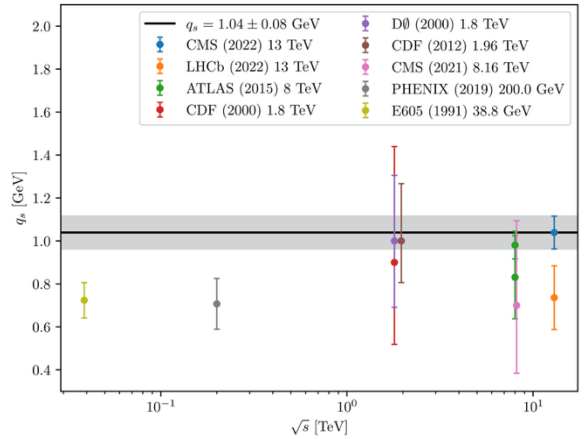






Agreement over $\sqrt{s}$ ($q_s = 1.04$)





- Same $q_s = 1.04$ used as obtained from the fit in

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- Good agreement is seen across centre-of-mass energies from 38 GeV to 13 TeV

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