TMD Monte Carlo for EIC: The CASCADE 3 generator

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on behalf of the CASCADE team

Outline

- Overview: CASCADE3 and TMDs
- PB formulation of TMD evolution
- TMDlib, TMDplotter, RIVET
- From fixed target to LHC
- TMD-MC4EIC
- Outlook and Summary

Overview

Traditional approaches

- Fixed order calculations limited in application
- **Collinear PDFs** from gobal fits
- Analytical **resummation** applicable to few observables
- Traditional MC have many parameters to be tuned (**parton shower**, MPI, hadronization)

CASCADE3

S. Baranov et al. [Eur. Phys. J. C 81 (2021) 425]

- **TMD parton density based** MC event generator
- Fully exclusive events (**TMD parton shower**)
- Both internal **off-shell process**, and external (e.g. Katie, Pegassus) via LHE format
- **On-shell matrix lement** via HE format
- **Matching/merging** to higher order fixed orders (MC@NLO, TMD merging)
- TMD shower has **no free parameters** (fixed by TMD)

Overview

Why TMDs?

R. A. Martinez et al. [APP B46 (2015) 12, 2501–2534]

- Small transverse momentum phenomena
- Small-x phenomena
- Semi-inclusive DIS and DY
- Transverse momentum effects from intrinsic kt and evolution

Parton Branching method

FH et al. [PLB 772 (2017) 446–451]
FH et al. [JHEP 2018, 70 (2018)]
ABM et al. [PRD 99, 074008 (2019)]

- Evolution of TMDs (and collinear PDFs)
- Resummation of soft gluons at LL and NLL
- Solution valid at LO, NLO and NNLO
- Determination of TMDs from the fully exclusive solution
- **Backward evolution fully determines the TMD shower**

→ consistently treats perturbative and non-perturbative transverse momentum effects

PB formulation of TMD evolution

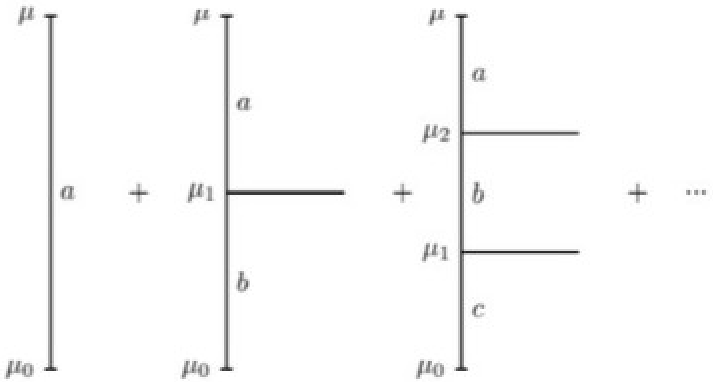
Forward evolution

FH et al. [PLB 772 (2017) 446–451]
FH et al. [JHEP 2018, 70 (2018)]
ABM et al. [PRD 99, 074008 (2019)]

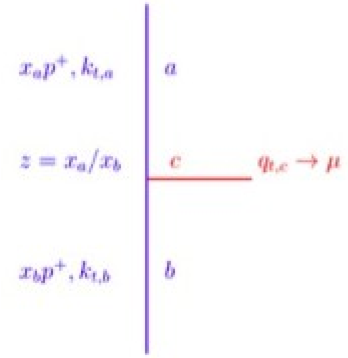
PB-TMD evolution equation:

$$\tilde{\mathcal{A}}_a(x, k_t^2, \mu^2) = \Delta_a(\mu^2, \mu_0^2)\tilde{\mathcal{A}}_a(x, k_{t,0}^2, \mu_0^2) + \\ + \sum_b \left[\int \frac{d^2\mu'}{\pi\mu'^2} \int_x^{z_M(\mu')} dz \Theta(\mu^2 - \mu'^2)\Theta(\mu'^2 - \mu_0^2) \right. \\ \left. \times \frac{\Delta_a(\mu^2, \mu_0^2)}{\Delta_a(\mu'^2, \mu_0^2)} P_{ab}^{(R)}(\alpha_s(q_t), z)\tilde{\mathcal{A}}_b\left(\frac{x}{z}, \underbrace{k_{t,b} - q_{t,c}}_{k_{t,a}}, \mu'^2\right)\right]$$

Solve iteratively with MC method:



Splitting kinematics:

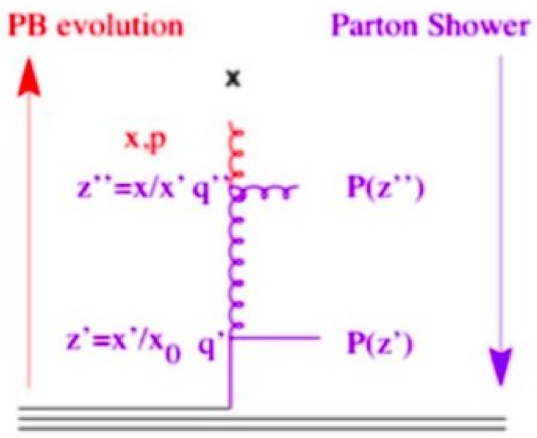


$$\begin{aligned} \boldsymbol{k_{t,b}} &= \boldsymbol{k_{t,a}} + \boldsymbol{q_{t,c}} \\ &= \boldsymbol{k_{t,a}} + (1 - z)\mu \end{aligned}$$

Angular ordering condition: $\boxed{q_t^2 = (1 - z)^2\mu'^2}$

PB formulation of TMD evolution

Backward evolution

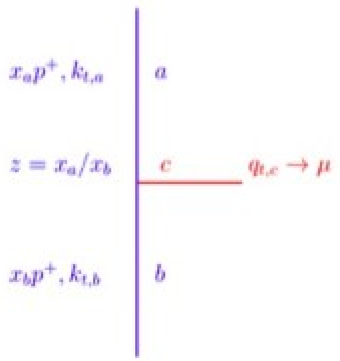


Use the PB-TMD backward evolution equation:

$$\frac{\partial}{\partial \ln \mu^2}\left(\frac{\tilde{A}_a(x,k_t,\mu)}{\Delta_a(\mu)}\right)=\sum_b\int_x^{z_M} dz P_{ab}^{(R)}\frac{\tilde{A}_b(x/z,k_t',\mu)}{\Delta_a(\mu)}$$

No-branching probability:

$$\Delta_{bw}(x,k_t,\mu_i,\mu_{i-1})=\exp\left\{-\sum_b\int_{\mu_{i-1}^2}^{\mu_i^2}\frac{d\mu'^2}{\mu'^2}\int_x^{z_M} dz P_{ab}^{(R)}\frac{\tilde{A}_b(x/z,k_t',\mu')}{\tilde{A}_a(x,k_t,\mu')}\right\}$$



Splitting kinematics:

$$\begin{aligned}\mathbf{k}_{t,b} &= \mathbf{k}_{t,a}+\mathbf{q}_{t,c}\\ &= \mathbf{k}_{t,a}+(1-z)\mu\end{aligned}$$

Implemented in the CASCADE event generator

S. Baranov et al. [Eur. Phys. J. C 81 (2021) 425]

TMDlib, TMDplotter, RIVET

Where to find/store/analize TMDs

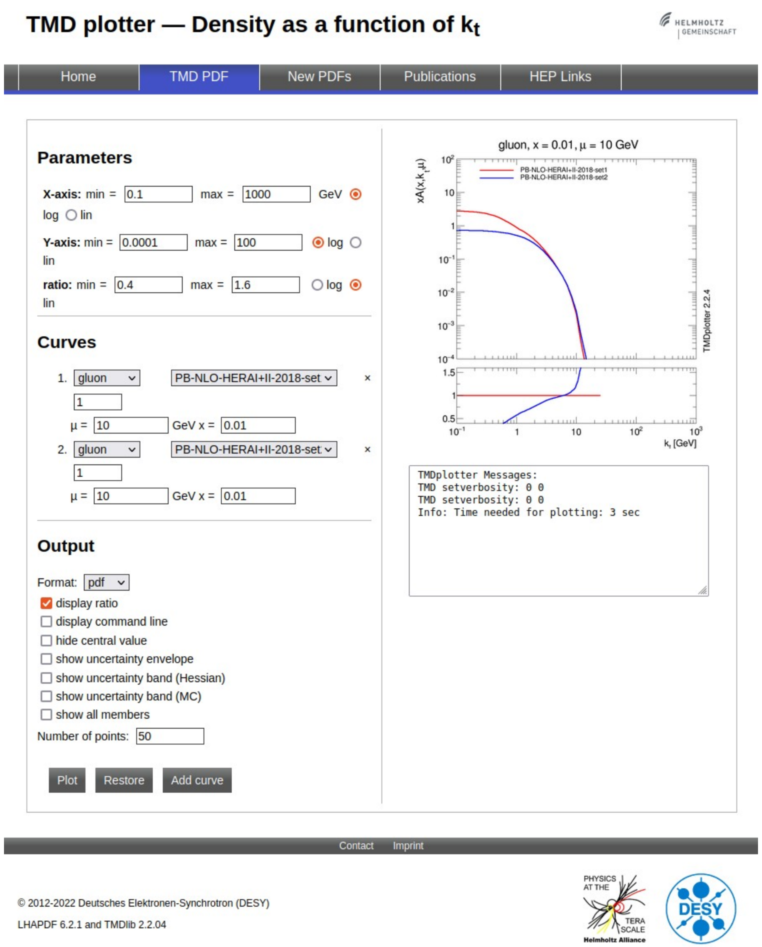
TMDlib

- Proposed in 2014 as part of the REF workshop and developed since
- Library of parametrization of TMDs and uPDFs
- Collinear and integrated TMDs also available
- **Pick your TMD and use it in CASCADE3**

http://tmdlib.hepforge.org

http://tmdplotter.desy.de/

TMDplotter

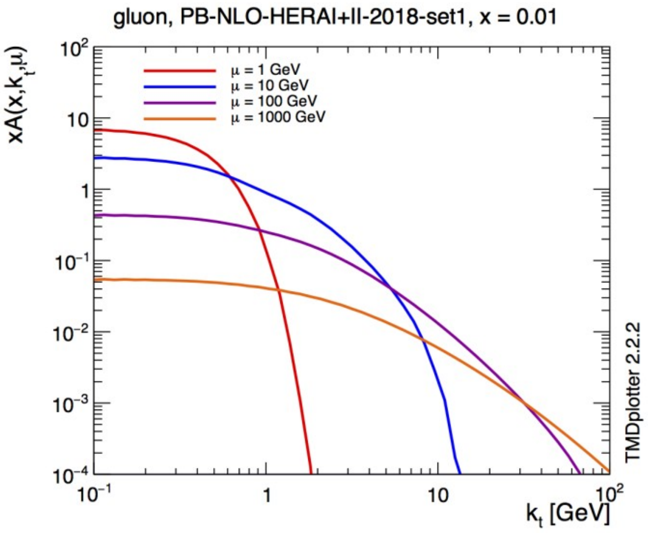


RIVET

- CASCADE outputs .HEPMC
- It can now output .YODA

From fixed target to LHC

Pert. and non-pert. PB TMD contributions



- ISR broadens initial distribution

ABM et al. [PRD 99, 074008 (2019)]

- DIS measurements from HERA I+II
- fitting procedure in a nutshell:
  - parametrize the integrated distribution at Q_0
  - with the PB method evolve the TMD to $Q > Q_0$ (implemented in xFitter)
  - fit the measurements and extract the initial parametrization
  - store the TMD in a grid for later use (TMDlib, complementary slides)

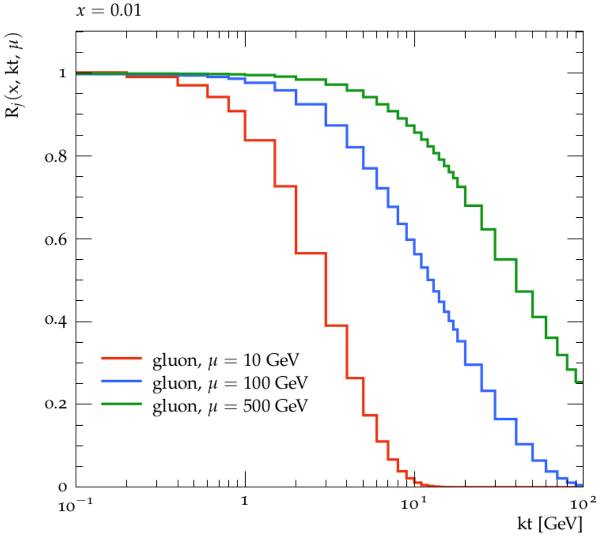
N. A. Abdulov et al. [Eur. Phys. J. C 81 (2021) 752]

Consider the integrated distribution above the jet pT scale:

$$a_j(x, \boldsymbol{k}, \mu^2) = \int \frac{d^2\boldsymbol{k}'}{\pi} \mathcal{A}_j(x, \boldsymbol{k}', \mu^2)\, \Theta(\boldsymbol{k}'^2 - \boldsymbol{k}^2)$$

- e.g. probability of 0.3 that the gluon develops a kt larger than 20 GeV, for μ = 100 GeV

- TMD evolution effects crucial at describing jet production



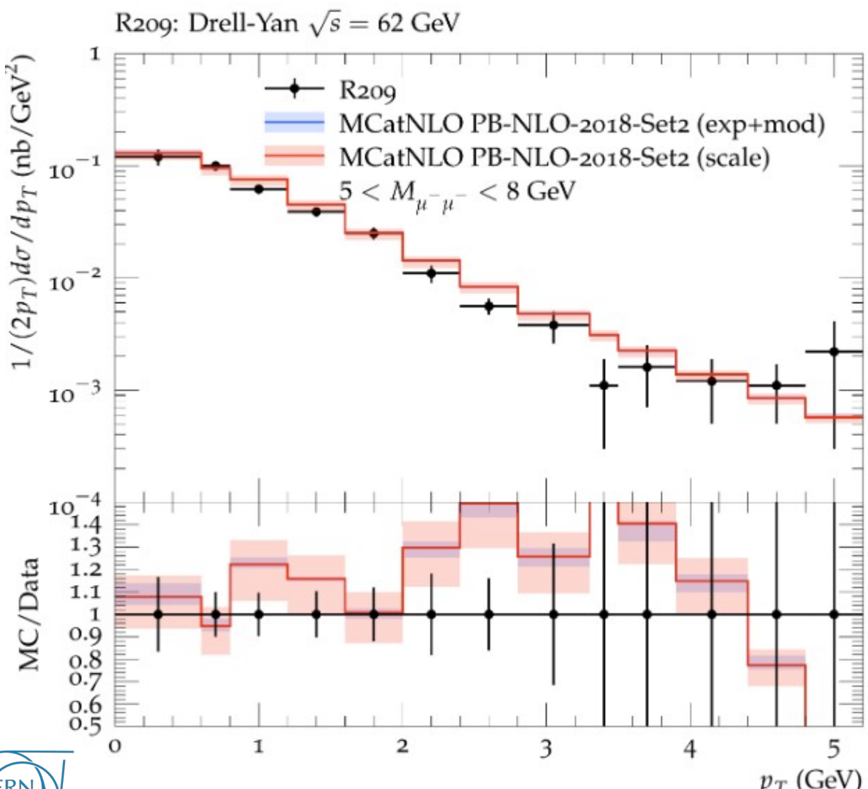
ABM et al. [arXiv:2107.01224]

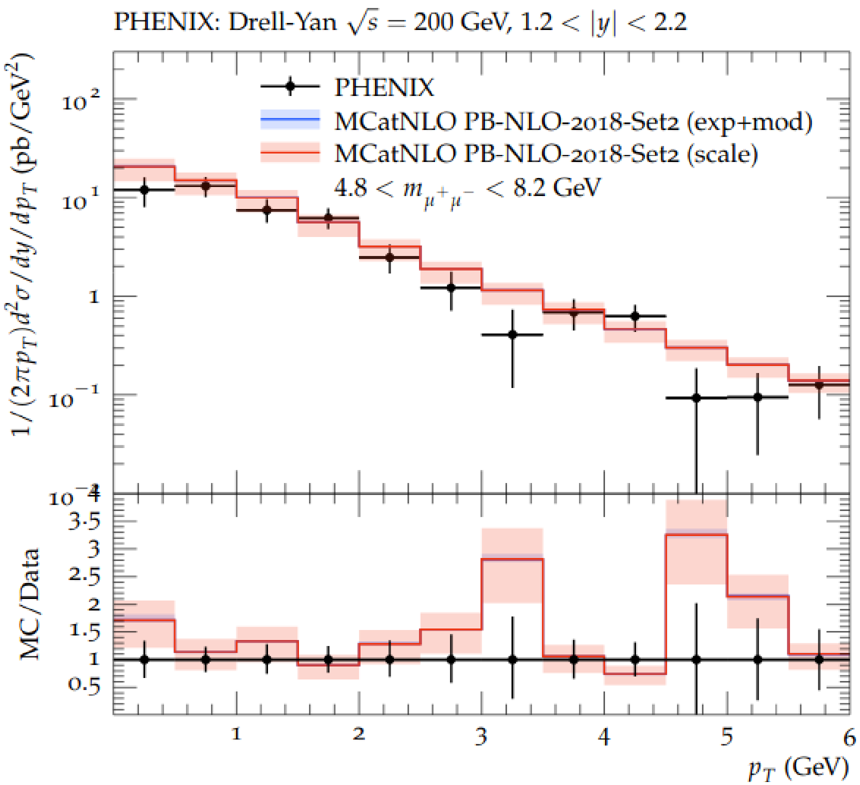
R209, PHENIX, NUSEA, E605

DY pt spectrum at low mass and low sqrt(s)

ABM et al. [PRD 100, 074027 (2019)]
ABM et al. [EPJC 80, 598 (2020)]
ABM et al. [PoS EPS-HEP2021 (2022) 386]

- MC@NLO matching
- **Excellent description of DY pT spectrum**



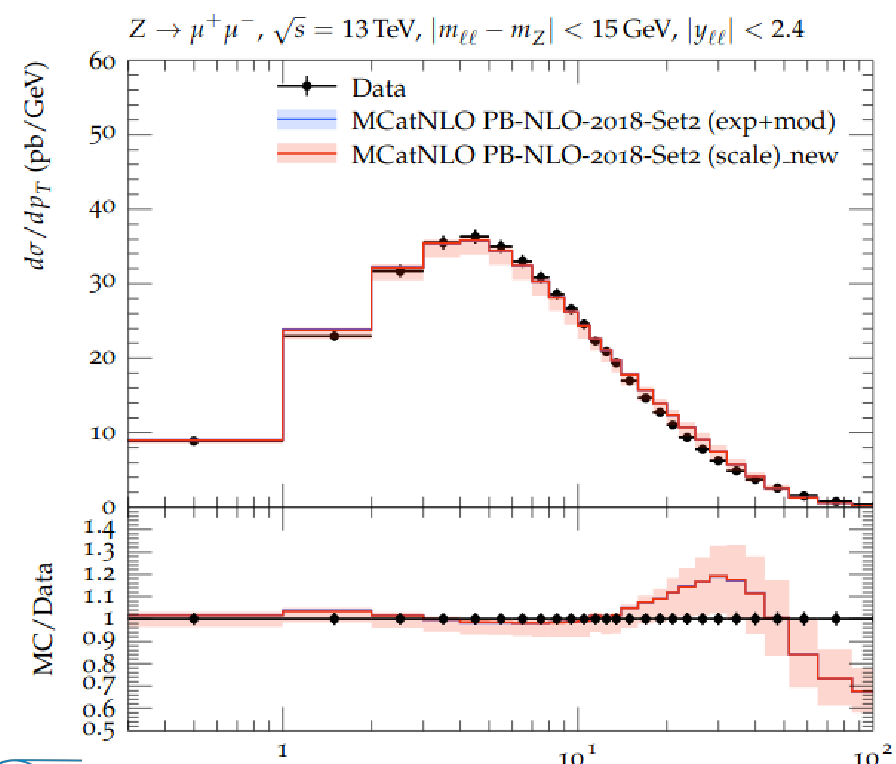


LHC @8 and 13 TeV

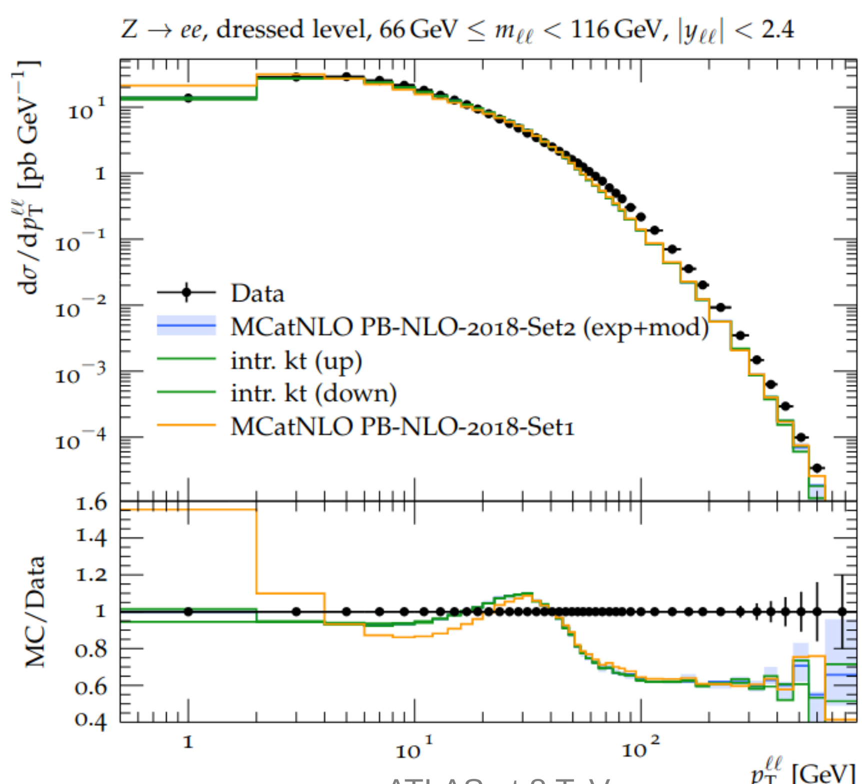
DY pt spectrum at high mass, high sqrt(s)

ABM et al. [PRD 100, 074027 (2019)]
ABM et al. [EPJC 80, 598 (2020)]
ABM et al. [PoS EPS-HEP2021 (2022) 386]

- MC@NLO matching
- **Excellent description of DY pT spectrum**
- **First simultaneous description of both low and high-mass DY pT spectrum**
- **No more low pT crisis** **Bacchetta et al. [PRD 100 (2019) 014018]; ABM et al. [EPJC 80, 598 (2020)]**



CMS at 13 TeV



ATLAS at 8 TeV

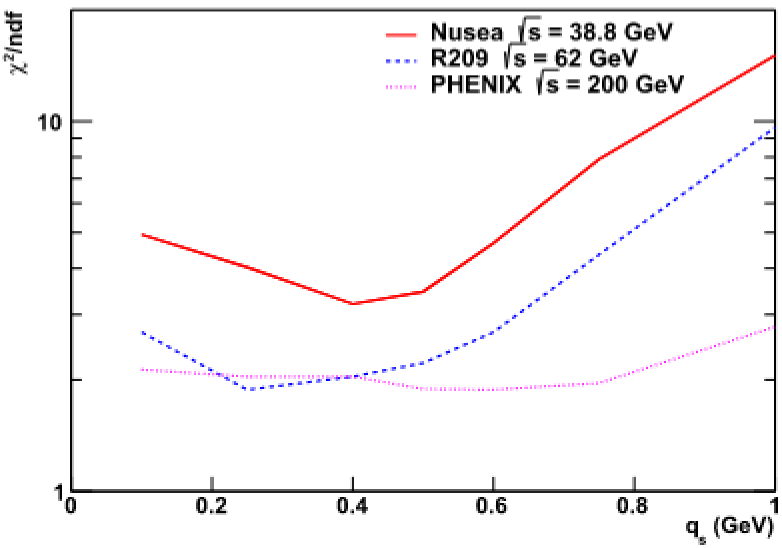
R209, PHENIX, NUSEA, E605, CMS, ATLAS

DY pt spectrum

ABM et al. [PRD 100, 074027 (2019)]
ABM et al. [EPJC 80, 598 (2020)]
ABM et al. [PoS EPS-HEP2021 (2022) 386]
CMS Collaboration [CMS-PAS-SMP-20-003]

- **The same setup works in a wide range of DY mass and comE**

comE [GeV]	DY mass [GeV]
38.8	~4.7
38.8	~7.5
62.0	~6.5
200.0	~6.6
8000.0	~91.2
13000.0	~63.0
13000.0	~91.2
13000.0	~138.0
13000.0	~260.0
13000.0	~675.0



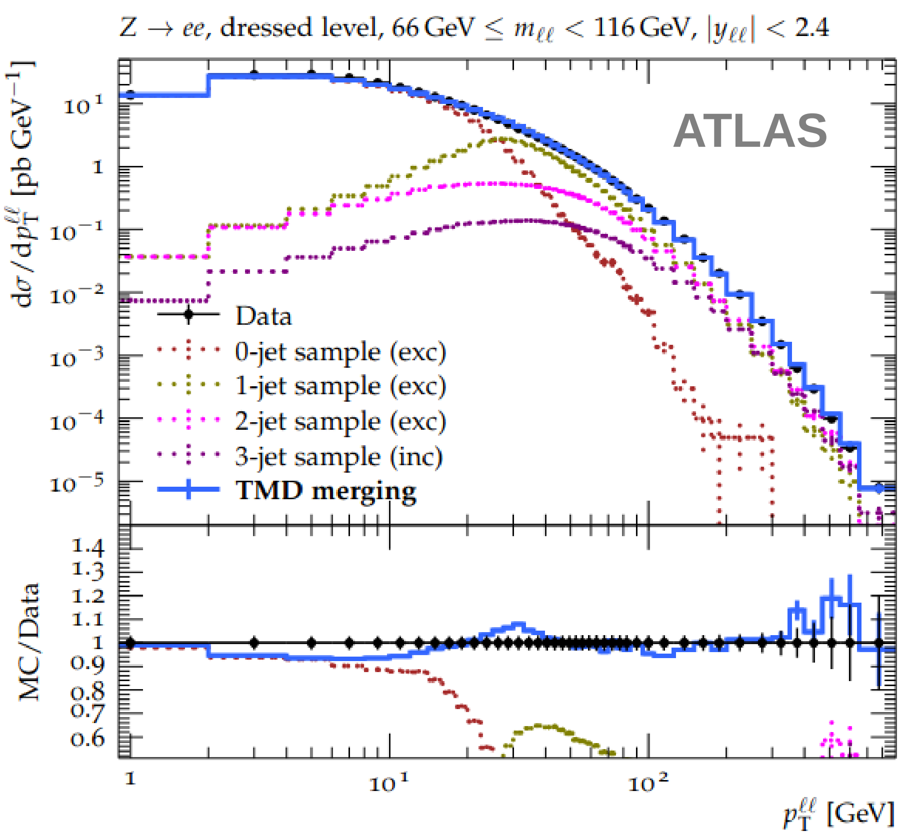
- **Pulled intrinsic kt ~ 0.3 GeV (q0/sqrt(2))**

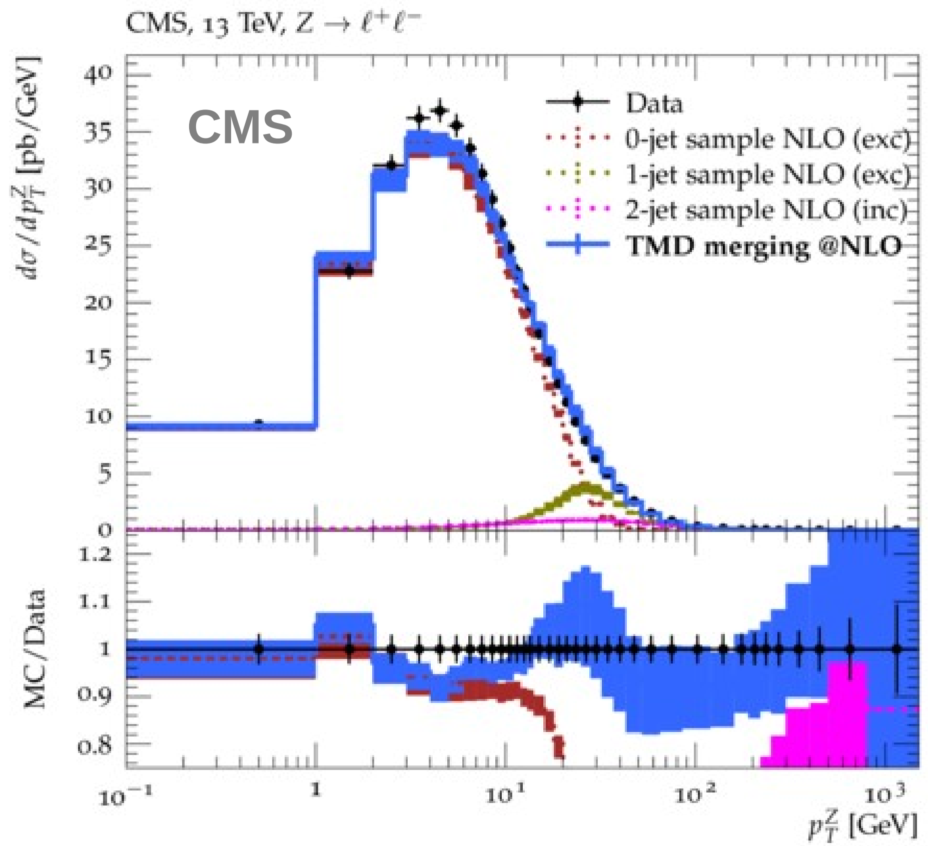
TMD multi-jet merging @LO and @NLO

DY pt spectrum

ABM et al. [Phys.Lett.B 822 (2021) 136700]
ABM et al. [JHEP 09 (2022) 060]
ABM et al. [**in preparation**]

- **Consistency between LO and NLO**
- **Consistent with MCatNLO PB-NLO at low pT**



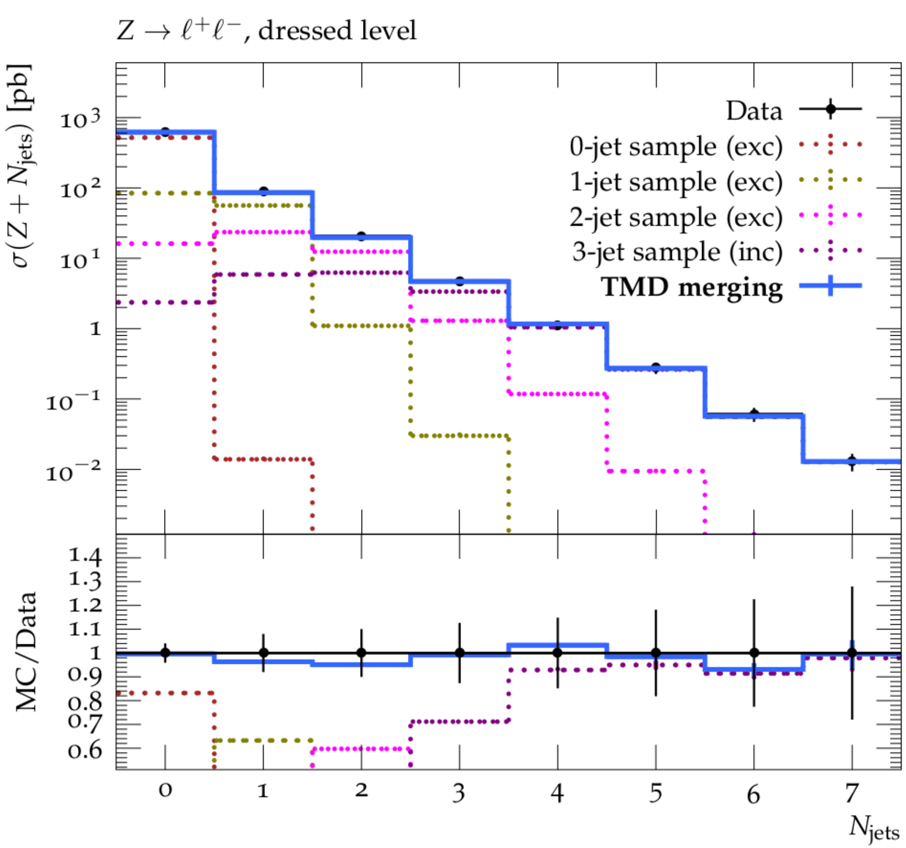


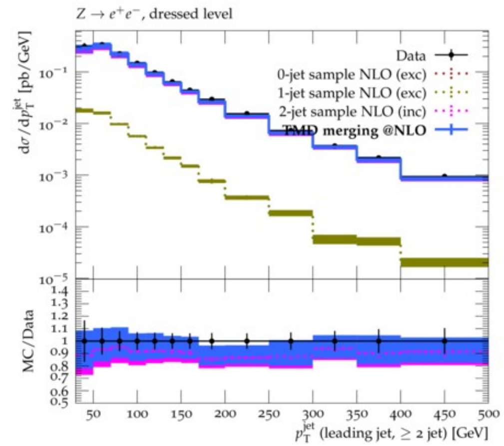
TMD multi-jet merging

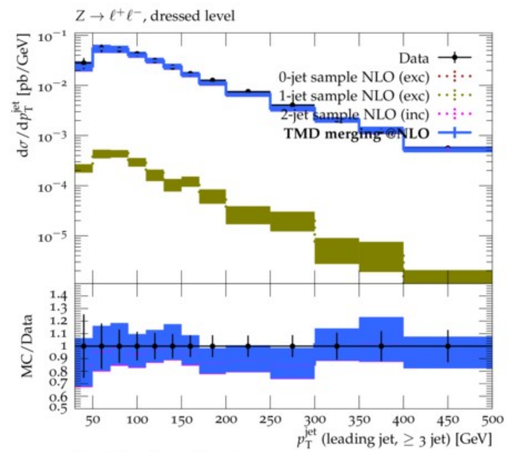
DY + jets production

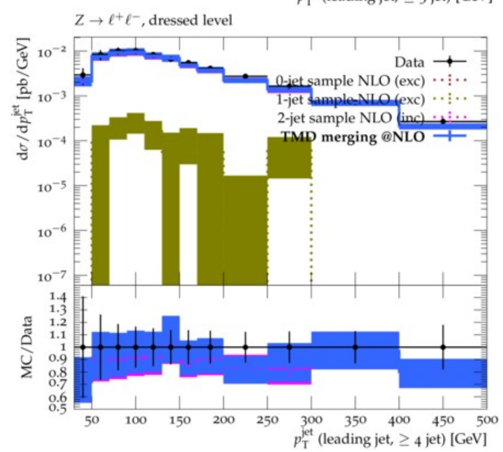
ABM et al. [Phys.Lett.B 822 (2021) 136700]
ABM et al. [JHEP 09 (2022) 060]
ABM et al. [**in preparation**]

- **Consistency between LO and NLO**
- **Consistent with MCatNLO PB-NLO at low pT**
- **Recoil, number of jets, and jet pT well described**









TMD-MC4EIC

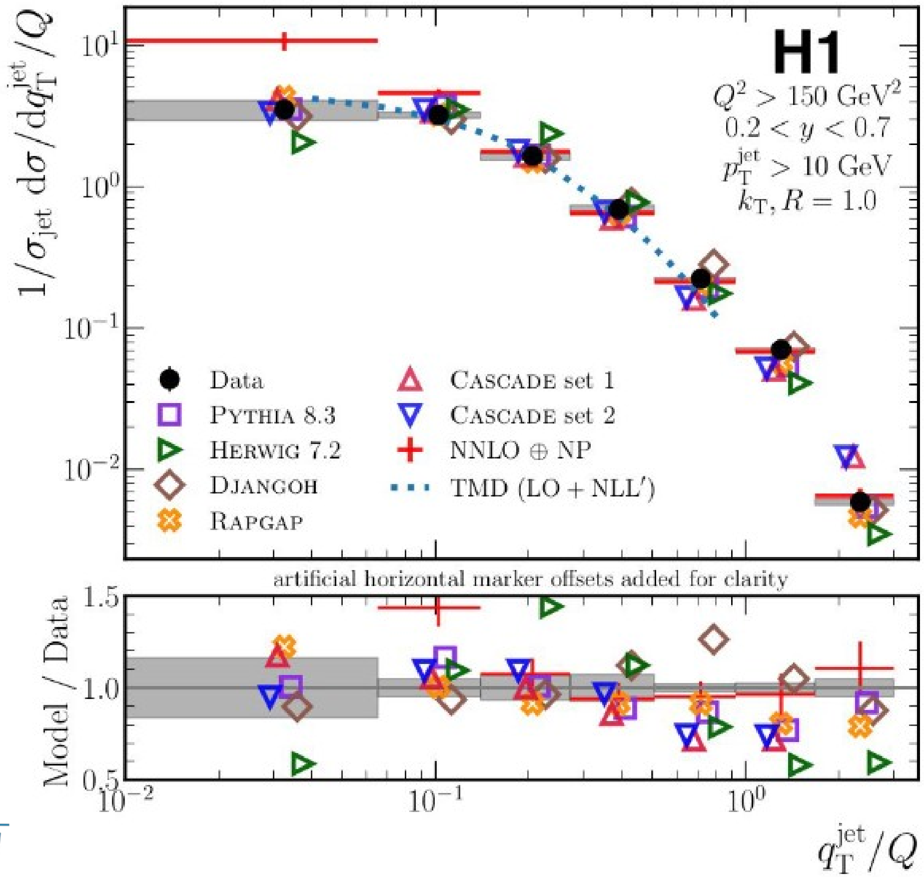
CASCADE3 @HERA

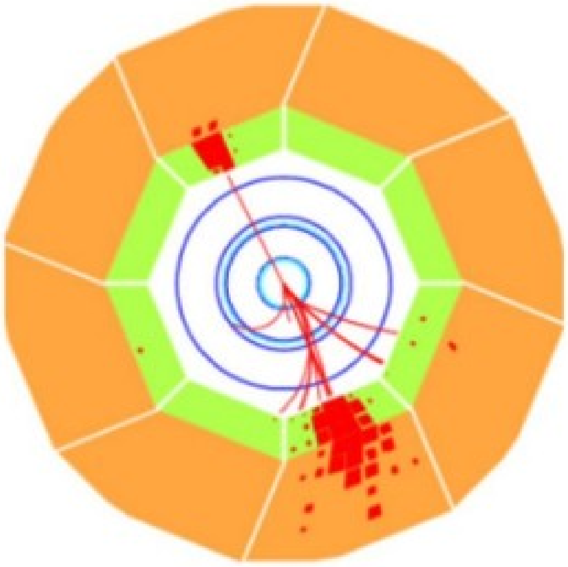
Lepton-jet qT balance

H1 Collaboration [2108.12376]

- Good description at low qT
- **High overlap between TMD and collinear approaches**

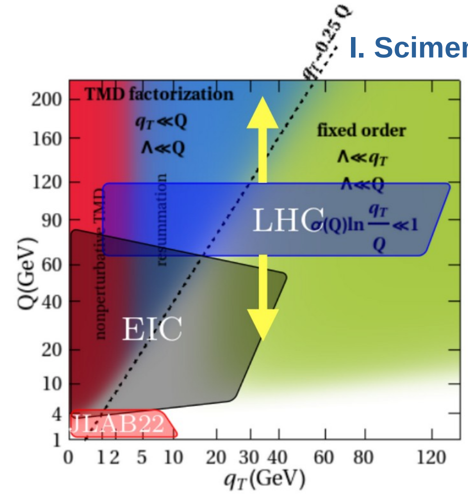
$$q_T = |\vec{p}_T^{\,e} + \vec{p}_T^{\,\text{jet}}|$$





CASCADE3 and TMD factorization

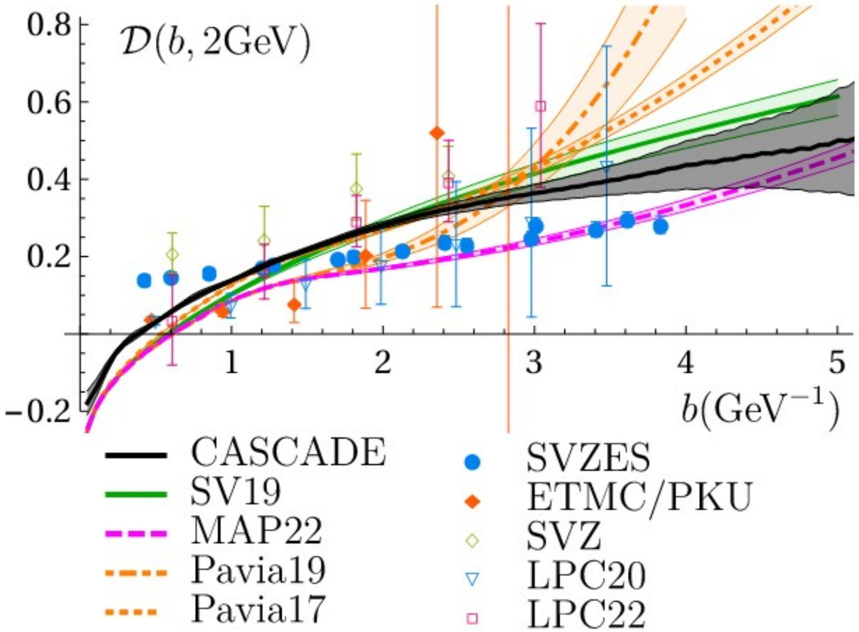
I. Scimemi



CS kernel direct determination

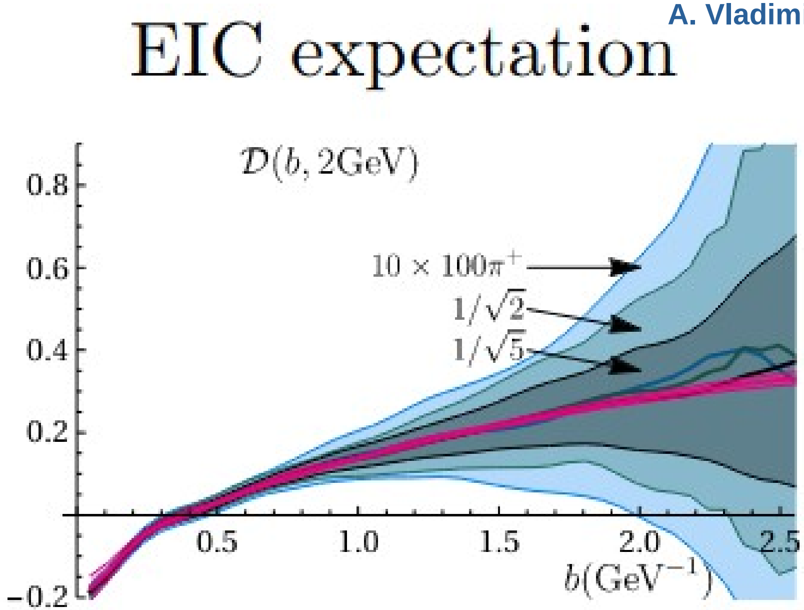
- CASCADE3 agrees with TMD factorization
- New method to determine it from xsec

ABM et al. [2206.01105, accepted in PRD]



$$\mathcal{D}(b,\mu) = \lambda_- \frac{ig}{2} \frac{\int_0^1 d\beta \langle 0|F_{b+}(-\lambda_- n + b\beta) W_{C'}|0\rangle}{\langle 0|W_{C'}|0\rangle} + Z_{\mathcal{D}}(\mu)$$

A. Vladimirov



- **Critical to have a MC to simulate detector response**

Conclusions

- CASCADE3 is a unique MC generator based on TMD evolution
- It has shown very good results for fixed target and LHC measurements, in a wide range of energy scales, for both inclusive and exclusive observables
- qT spectrum is well described for HERA SIDIS
- CASCADE3 agrees with TMD factorization
- General Monte Carlo generator that can be used for detector response, especially for NP sensitive measurements
- CASCADE3 is ready for EIC

Thank you