Azimuthal correlations in high p_T processes with the TMD Parton Branching method at NLO

ICHEP 2022

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July 9, 2022

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Based on:
Eur.Phys.J.C 82 (2022) 1, 36, arXiv:2112.10465
& arXiv:2204.01528

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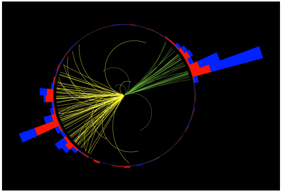
ICHEP 2022 BOLOGNA
ICHEP 2022 XLI
International Conference on High Energy Physics
Bologna (Italy)
6 13 07 2022

Introduction

Dijet & Z+jet processes at 13 TeV @LHC

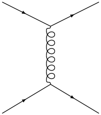
Azimuthal correlations $\Delta\phi_{jj}$ / $\Delta\phi_{Zj}$:

- LO: delta-peak at $\Delta\phi = \pi$
- Higher order QCD radiation smears δ-peak
- $\Delta\phi$ near π: soft gluon radiation, $\Delta\phi$ away from π: hard radiation

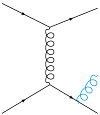


CMS figure of jets in back-to-back $\Delta\phi$ region

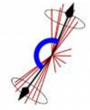
α_s^2

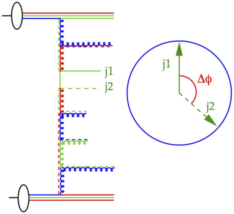


α_s^3



$\alpha_s^n \ln^m Q/q_T$

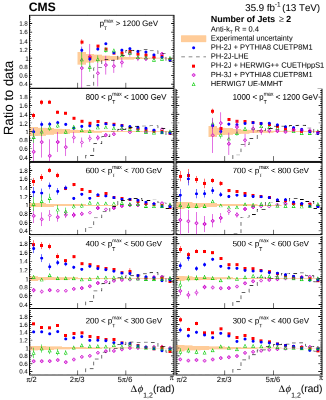




- Small $\Delta\phi$ region is treatable with fixed-order QCD calculations (NLO, NNLO etc)
- Large $\Delta\phi$ region requires soft-gluon resummation to all orders (e.g. Sun, Yuan, Yuan [Phys. Rev. D 92, 094007 (2015)])

$\Delta\phi_{12}$ with high p_T jets

- Current comparisons theory/data show significant deviations up to 50% in medium $\Delta\phi$ and 10% in the back-to-back region: need to understand better.
- Soft gluon resummation probes small transverse momenta of incoming partons, described by TMD distributions.



Analysis of $\Delta\phi_{jj}$ and $\Delta\phi_{Zj}$ at high p_T with NLO + Parton Branching (PB) approach to TMDs

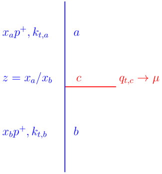
- High leading jet p_T, perturbative effects dominate. Even in the back-to-back region! CMS coll. [Eur. Phys. J. C 78 (2018) 566]
- Further interest: it has been suggested that the back-to-back region is affected by soft-gluon initial-state/final-state correlations: so-called *factorization-breaking* effects (Collins-qiu arXiv:0705.2141, Vogelsang-yuan arXiv:0708.4398, Rogers-Mulders arXiv:1001.2977)

The Parton Branching (PB) method

Hautmann et al. [JHEP 01 (2018) 070]

The **PB method** provides evolution equations for TMDs $\tilde{\mathcal{A}}_a$:

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



Non-perturbative distribution $\tilde{\mathcal{A}}_a(x, k_{t,0}^2, \mu_0^2)$ includes intrinsic k_t:

$$f_a(x, \mu_0) e^{-k_t^2/2\sigma^2}$$

Kinematics in each branching governed by momentum conservation: $k_{t,b} = k_{t,a} + q_{t,c}$

- DGLAP splitting functions $P_{ab}(\alpha_s, z)$

$$P_{ab}^{(R)}(\alpha_s, z) = \frac{k_a(\alpha_s)\delta_{ab}}{1 - z} + R_{ab}(\alpha_s, z)$$

resolvable emission probability

- Sudakov form factor (non-resolvable / no-emission probability):

$$\Delta_a^{(PB)}(\mu, \mu_0) = \exp\left\{ -\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M(\mu')} dz \; z \; P_{ba}^{(R)}(\alpha_s(q_t), z) \right\}$$

- **Angular ordering**: $\mu' = q_t/(1 - z)$ in z_M, $k_{t,a}$ and α_s

Collinear limits of the PB method

Integration of the PB evolution equation over transverse momentum gives

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

Coincide with approach by **Catani, Marchesini and Webber for coherent branching** [Nucl. Phys. B349 (1991) 635]) by using:

- dynamical resolution scale $z_M(\mu') = 1 - q_0/\mu'$
  Hautmann, Keersmaekers, Lelek, MvK [Nucl.Phys.B 949 (2019) 114795]
- $\alpha_s(q_t)$

Recover **DGLAP** in limits (Hautmann et al. [JHEP 1801 (2018) 070]):

- $z_M(\mu') \to 1$
- $\alpha_s(q_t) \to \alpha_s(\mu')$

PB TMD sets fitted to data, available in TMDLIB N.A. Abdulov et al. [Eur.Phys.J.C 81 (2021) 8, 752]

- Set 1: PB-NLO-HERAI+II-2018-set1 has $\alpha_s(\mu')$
- Set 2: PB-NLO-HERAI+II-2018-set2 has $\alpha_s(q_t)$

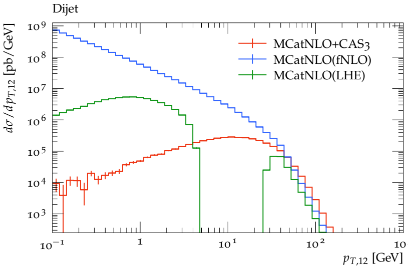
A. Bermudez Martinez et al. [Phys. Rev. D 99, 074008]

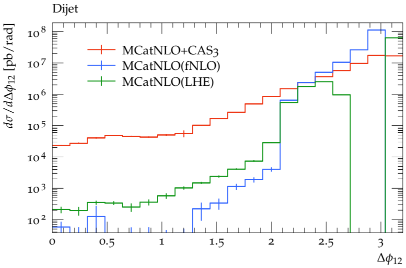
Matching PB evolution to NLO matrix elements

A. Bermudez Martinez et al. [Phys. Rev. D 100, 074027 (2019)]

- PB-TMDs and TMD shower implemented in CASCADE3

  S. Baranov et al. [Eur.Phys.J.C 81 (2021) 5, 425]
- Avoid double counting in the MC@NLO manner with HERWIG6 subtraction terms (angular ordered evolution)
- Associate k_t to partons in the hard process according to the TMD
- TMD parton shower that unfolds TMD distribution



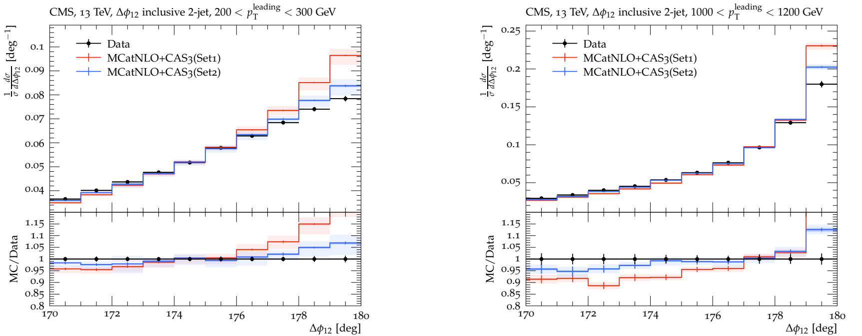


Similar distributions for Z boson + jet [arXiv:2204.01528]

Scale of strong coupling in TMD evolution

In the back-to-back region, both perturbative and non-perturbative effects.
$p_T^{leading} > 200$ GeV: **perturbative effects dominate**

- MC@NLO matched to PB-TMD-set1: $\alpha_s(\mu)$
- MC@NLO matched to PB-TMD-set2: $\alpha_s(q_T)$

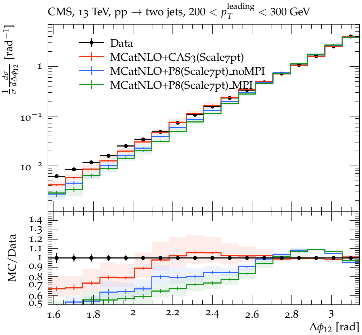


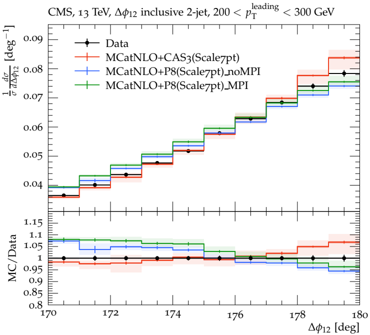
- TMD important in the back-to-back region

Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3- jet events in pp collisions at 13 TeV, CMS Collaboration [Eur.Phys.J. C79 (2019) no.9, 773]

Comparison PB-TMD with PYTHIA8

- Madgraph_aMC@NLO with PYTHIA8
- Check results with and without MPI
- Strong difference in shape
- collinear vs. TMD factorization

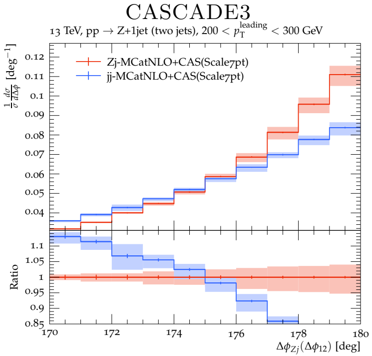


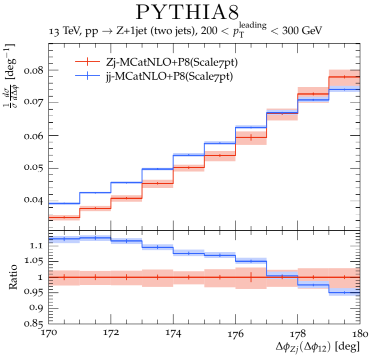


- PB uncertainties: TMD + scale uncertainties
- Pythia uncertainties: $\mu_{R,F}$ in ME + μ_R variation in PS
- Small $\Delta\phi$ region: multi-jet merging (TMD merging, A. Bermudez Martinez et al. [Phys.Lett.B 822 (2021) 136700])

Dijet versus Z boson+jet $\Delta\phi$

200 GeV $< p_T^{\text{leading}} <$ 300 GeV

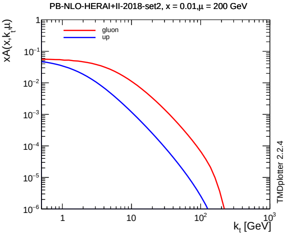




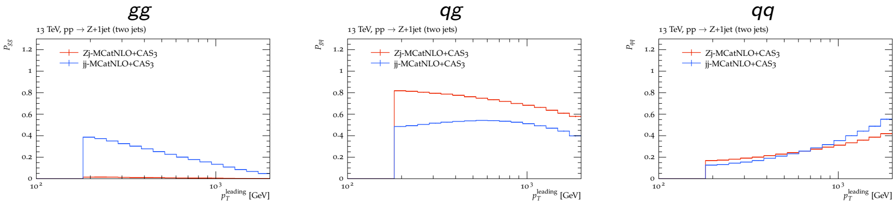
- differences Z+jet and multijet: different flavor composition in initial and final state
- CASCADE3 compared to PYTHIA8: different treatment of transverse momentum in initial state. Shape of the ratio Zj/jj is similar for CAS3 and P8
- Zj is more strongly correlated than jj

Flavor contributions to jj and Z+j

- TMD distributions differ for different flavors
- This causes different transverse momenta of the hard system



Relative contribution to cross section from initial parton channels:

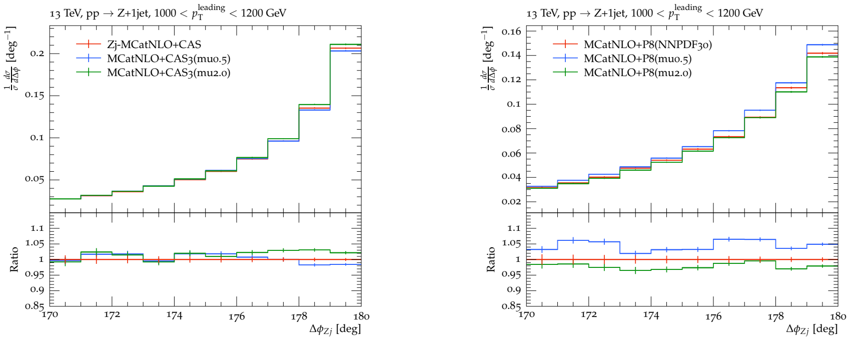


- @$p_T^{\text{leading}} > 1000$ GeV, *qq* channel becomes important for both *jj* and $Z + j$
- @$p_T^{\text{leading}} > 200$ GeV, *gg* and *qg* channels are dominant for multijet production

Systematics: matching scale

The matching scale μ_m limits the hardness of parton shower emissions: source of uncertainty

- Vary μ_m
- Same exercise with collinear approach of PYTHIA8



- Matching scale uncertainty decreases for higher $p_T^{leading}$ for CASCADE3
- In angular ordered TMD shower, μ_m limits **all emissions**
- In transverse momentum ordered shower, μ_m limits only the **first emission**

Discussion and conclusions

First time TMD predictions are compared to high jet p_T data from the LHC.
The PB approach for TMDs takes into account both perturbative and non-perturbative effects.
In high p_T dijets and $Z + j$, perturbative effects dominate, even at $\Delta\phi_{12} \sim \pi$.

- PB gives a good description of *jj* data in the back-to-back region. This is non-trivial, since PYTHIA8 does not describe it well.

- Back-to-back region potentially sensitive to factorization breaking effects
- These would affect differently boson-jet and jet-jet azimuthal correlations
- We propose to compare the Zj / jj ratio with data to access potential factorization breaking effects

- Systematic uncertainties dominated by scale uncertainties, while TMD uncertainties are small
- Matching scale variations lead to smaller uncertainties in MC@NLO+PB case compared to MC@NLO+PYTHIA8

Back-up slides

Inclusive & exclusive observable calculations with PB

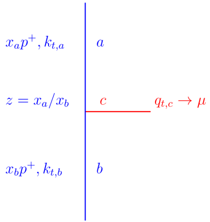
The PB method is implemented in event generator CASCADE3 Eur. Phys. J. C 81, 425 (2021) [arXiv:2101.10221v1]

- Two modes for hard scattering events (LHE input): on-shell and off-shell
- Associate k_t to partons in the hard process according to the TMD
- Two modes for parton shower: PB and CCFM shower

TMD parton shower based on PB by constructing the *backward Sudakov*:

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

This is the no-branching probability in the TMD parton shower.



- In each splitting

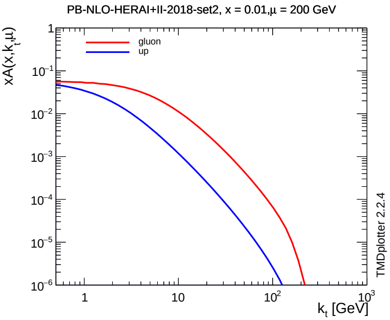
$$\begin{aligned} \boldsymbol{k_{t,b}} &= \boldsymbol{k_{t,a}} + \boldsymbol{q_{t,c}} \\ &= \boldsymbol{k_{t,a}} + (1-z)\mu \end{aligned}$$

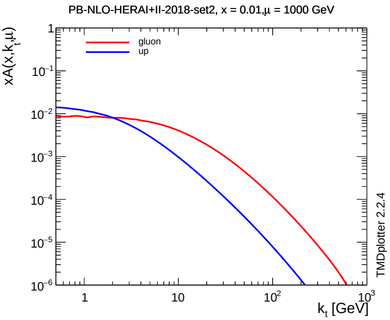
- Total transverse momentum:

$$\boldsymbol{k_t} = \boldsymbol{k_{t,0}} + \sum_c q_{t,c}$$

TMD distributions - gluon vs quark

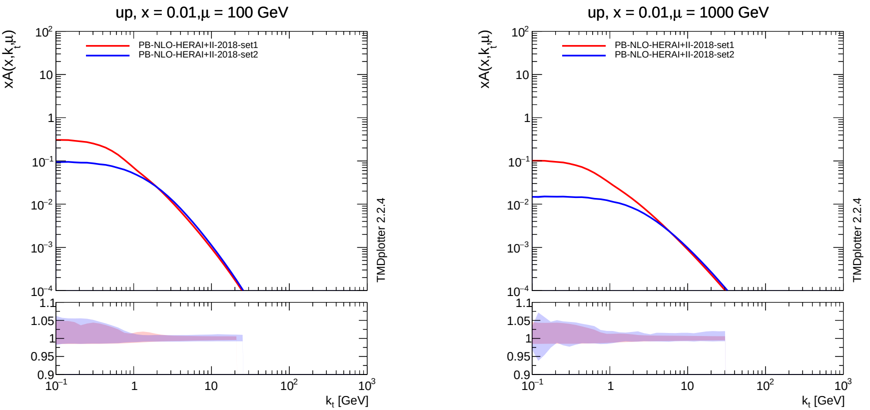
TMD distributions for gluon and valence (up) quark



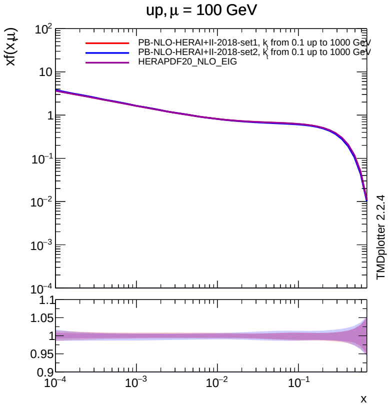


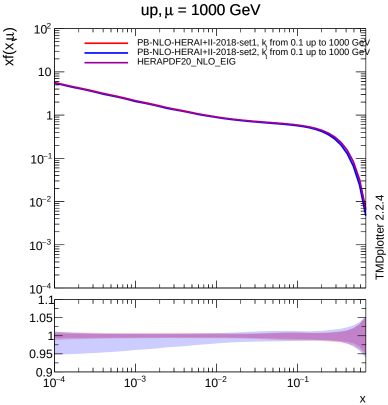
TMD distributions - set1 vs set2

up quark distributions for different PB-TMD fits



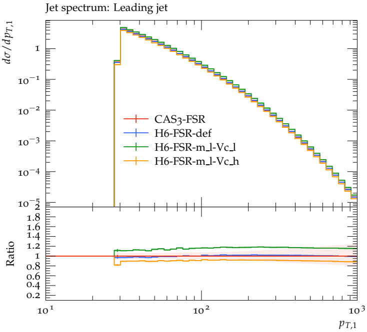
integrated TMD distributions

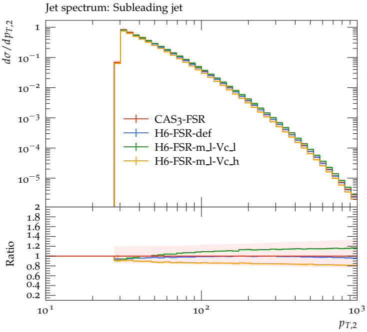




CASCADE3 and HERWIG6 parton showers

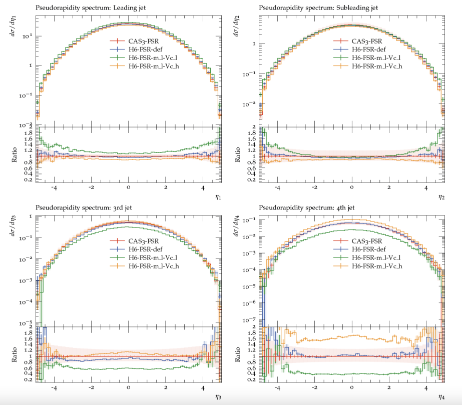
pT of first 2 jets with only final state radiation:

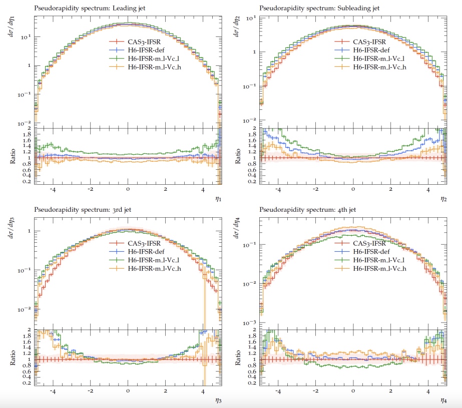




CASCADE3and HERWIG6 parton showers

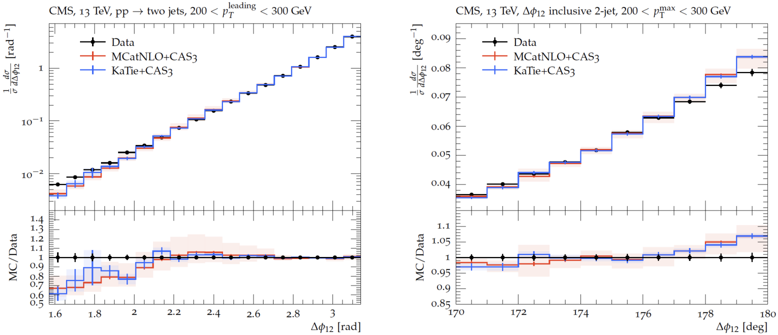
Rapidity distributions of first 4 emissions with CASCADE3and HERWIG6





On-shell versus off-shell matrix elements

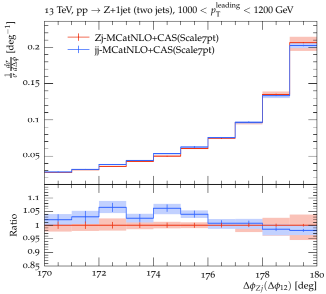
KaTie calculates LO matrix elements with off-shell partons. Compare with PB-TMD with MC@NLO.

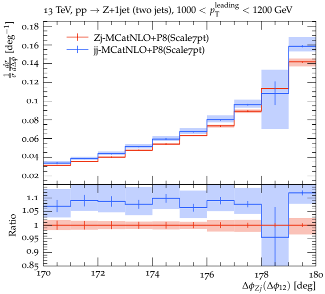


- at high $\Delta\phi$: off-shellness / TMD more important than higher orders of α_s in calculation
- at smaller $\Delta\phi$: relatively good description with off-shellness / TMD

Dijet - boson+jet $\Delta\phi$

$1000\,GeV < p_T^{\text{leading}} < 1200\,GeV$



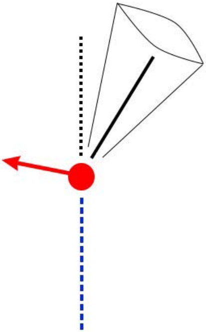


TMD multi-jet merging

TMD merging is a new LO multi-jet merging algorithm
A. Bermudez Martinez et al. [Phys.Lett.B 822 (2021) 136700].

Steps of TMD merging

1. Matrix elements for n-jet production
2. Reweight the strong coupling according to the parton shower: $\alpha_s(Q) \rightarrow \alpha_s(Q) \cdot \frac{\alpha_s(q_T)}{\alpha_s(Q)}$
3. Apply forward PB evolution to incoming partons with condition $k_t^2 \leq \mu_{min}^2$
4. TMD parton showering of the events
5. Apply MLM merging procedure
   M. L. Mangano [NPB 632 (2002) 343–362]
   Compare hard partonic event with showered event and avoid double counting

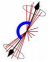


This mainly increases accuracy at large p_T and small $\Delta\phi$ regions

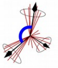
TMD multi-jet merging

Work in progress!

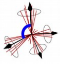
Dijet with soft radiation:



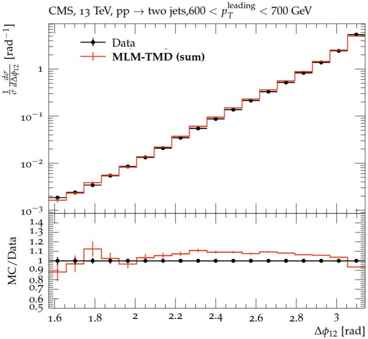
Dijet + 1 jet + additional radiation:



Dijet + 2 jets + additional radiation:

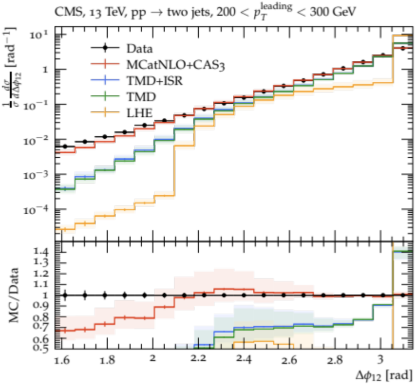


Preliminary result by A. Bermudez Martinez



Effects of TMD and parton shower

- Study effect of
  - TMD,
  - initial state TMD shower



- TMD is very important in back-to-back region as well as in small $\Delta\phi$
- ISR does not play a big role.