Azimuthal correlations in dijet events at NLO with the parton branching method

CPHI-2022

Aron Mees van Kampen

on behalf of
the CASCADE developer team
& participants of the Monte Carlo school: PB TMDs with CASCADE

University of Antwerp, Belgium

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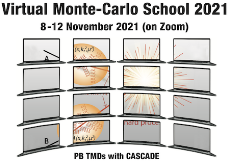
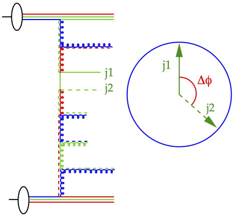
Universiteit Antwerpen

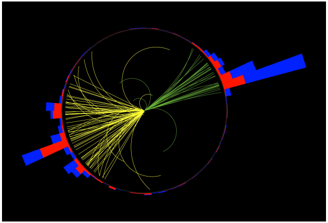


Introduction

Azimuthal correlation of dijets at the LHC: $\Delta\phi_{12}$ Abdulhamid et al. [Eur.Phys.J.C 82 (2022) 1, 36]

- PP collisions @13 TeV
- High p_T of leading jet(s): $p_T^{\text{leading}} > 200$ GeV
- fixed order calculation not sufficient

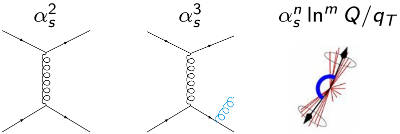




CMS figure of jets in back-to-back $\Delta\phi$ region

Calculation of $\Delta\phi_{12}$:

1. LO: only 2 jets ($\Delta\phi = \pi$)
2. NLO: middle $\Delta\phi$ region
3. Resummation approach ($\Delta\phi \to \pi$)



Resummation in CSS manner by Sun, Yuan, Yuan [Phys. Rev. D 92, 094007 (2015)]
Possible *factorization breaking* effects towards $\Delta\phi \to \pi$

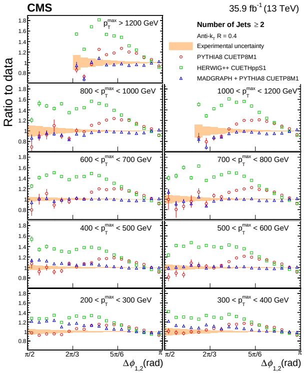
$\Delta\phi_{12}$ with high p_T dijets using Parton Branching

General purpose event generators results

Tunes needed!

Deviations up to 50% in medium $\Delta\phi$ & up to 10% in $\Delta\phi \to \pi$ region

Experimental uncertainty smaller than theoretical deviations



CMS coll. [Eur. Phys. J. C 78 (2018) 566]

Parton branching formalism for TMD evolution very suitable!

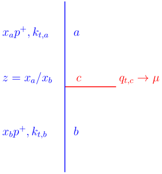
- Initial parton radiation: moves $\delta(\Delta\phi_{12} - \pi)$-peak
- Resums large logarithms
- Matching to NLO matrix elements

The Parton Branching (PB) method

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

The **parton branching (PB) method** provides evolution equations for TMDs $\tilde{\mathcal{A}}_a(x, k_t^2, \mu^2)$:

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



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

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

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

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

Hautmann, MvK et al. [Nucl.Phys.B 949 (2019) 114795]

- DGLAP splitting functions $P_{ab}(\alpha_s, z)$ ($P_{ab}^{(R)}$ are real emission probabilities)
- Sudakov form factor (non-resolvable / no-emission probability):

$$\Delta_a^{(PB)}(Q^2, q_0^2) = \exp\left\{ -\int_{q_0^2}^{Q^2} \frac{dq_t^2}{q_t^2} \left[\frac{1}{2} \ln\left(\frac{Q^2}{q_t^2}\right) k_a(\alpha_s(q_t^2)) - d_a(\alpha_s(q_t^2)) \right] \right\}$$

resummation up to at least NLL accuracy!

The Parton Branching (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 **CMW for coherent branching** (Catani-Marchesini-Webber, [Nucl. Phys. B349 (1991) 635]) by using:

- dynamical resolution scale $z_M(\mu') = 1 - q_0/\mu'$
- $\alpha_s(q_t^2)$

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, MvK 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 $\alpha_s(q_t)$

Matching PB evolution to NLO matrix elements

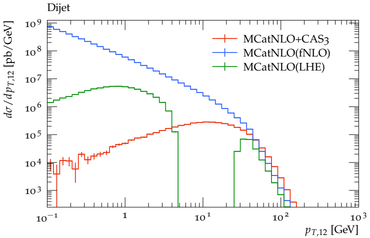
Matching NLO from MADGRAPH_AMC@NLO with PB

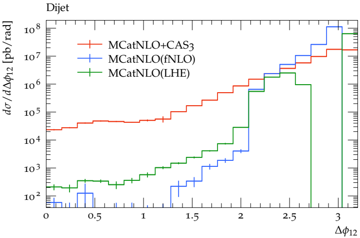
A. Bermudez Martinez et al. [Phys. Rev. D 100, 074027 (2019)]

- PB-TMDs and TMD shower implemented in CASCADE3

S. Baranov et al. [Eur.Phys.J.C 81 (2021) 5, 425]

- Avoid double counting: HERWIG6 subtraction terms (angular ordered shower)
- Associate k_t to partons in the hard process according to the TMD
- Two modes for parton shower: PB and CCFM shower



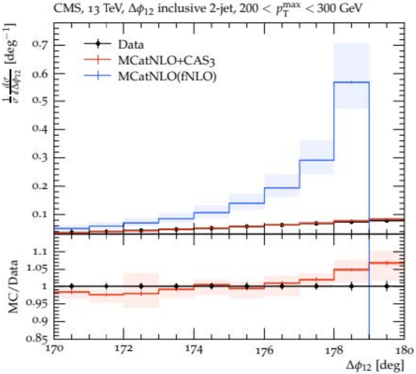


DY p_T results see next talk by A. Lelek

Now apply this method to dijets

Results: fixed order NLO versus NLO+PB

- fNLO: no subtraction terms
- CAS3: include subtraction terms, TMD

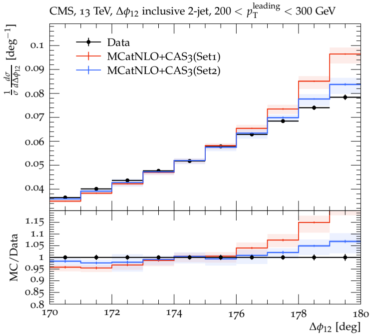


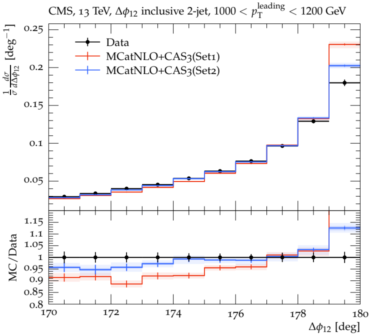
Q. Wang, REF workshop 2021

Results: back-to-back region $\Delta\phi \in [170, 180]^\circ$

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: $\alpha_s(q_T)$



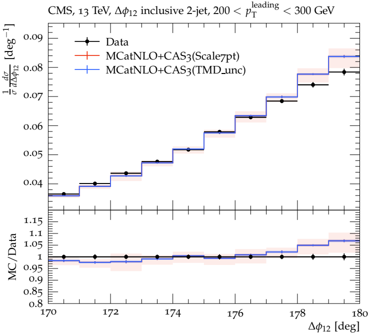


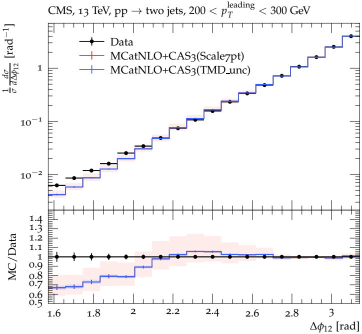
- TMD important in the back-to-back region
- ISR not important for inclusive 2-jet calculation

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

Results: theoretical uncertainties

- Scale uncertainties: μ_R and μ_F; 7-point scale variations
- TMD uncertainties: uncertainty from fit to data

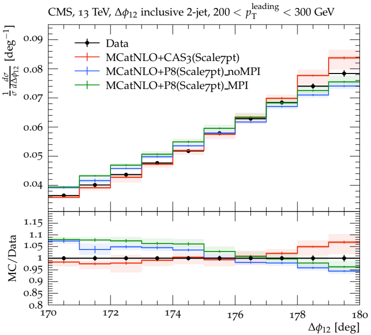


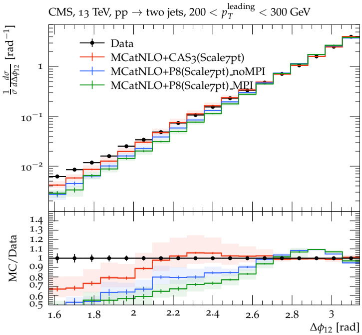


Azimuthal correlations for inclusive 2-jet, 3-jet, and 4-jet events in pp collisions at 13 TeV
Eur.Phys.J. C78 (2018) no.7, 566

Results: comparison PB-TMD with PYTHIA8

- Madgraph_aMC@NLO with PYTHIA8
- Check results with and without MPI
- Tune in PYTHIA needed, not needed for PB!





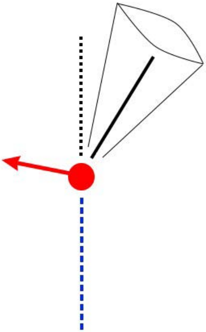
- PB uncertainties: TMD + scale uncertainties
- Pythia uncertainties: $\mu_{R,F}$ in ME + μ_R variation in PS

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

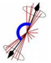
1. Matrix elements for n-jet production
2. Reweight the strong coupling according to the parton shower: $\alpha_s(Q) \rightarrow \alpha_s(Q) \cdot \frac{\alpha_s(q_T)}{\alpha_s(Q)}$
3. Apply forward PB evolution to incoming partons with condition $k_t^2 \leq \mu_{min}^2$
4. TMD parton showering of the 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



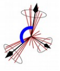
This mainly increases accuracy at large p_T and small $\Delta\phi$ regions

TMD multi-jet merging

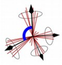
Dijet with soft radiation:



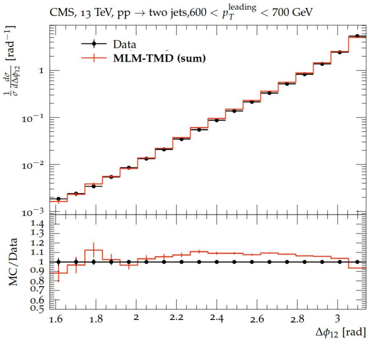
Dijet + 1 jet + additional radiation:



Dijet + 2 jets + additional radiation:



Preliminary result



To be continued...

Conclusions

The PB approach for TMDs takes into account both perturbative and non-perturbative effects.

- Perturbative: soft gluon emissions ($z \to 1$) and all transverse momenta ($q_\perp$) from branchings in the QCD evolution
- Non-perturbative: intrinsic transverse momentum, subject to perturbative evolution

In high p_T dijets perturbative effects dominate, even at $\Delta\phi_{12} \sim \pi$.

Parton branching TMDs matched to NLO matrix elements

- Good description of dijet azimuthal back-to-back region
- No tuning needed
- Small TMD uncertainties

- TMD evolution important at back-to-back region
- PB-TMD-set1 significantly different from PB-TMD-set2: $\alpha_s(q_t)$
- Multi-jet TMD merging increases accuracy at small $\Delta\phi$

Back-up slides

Inclusive & exclusive observable calculations with PB

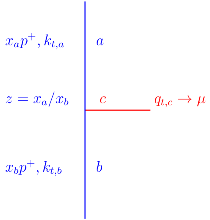
The PB method is implemented in event generator CASCADE3 Eur. Phys. J. C 81, 425 (2021) [arXiv:2101.10221v1]

- 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

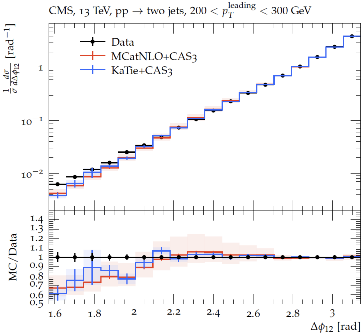
$$\boldsymbol{k_{t,b}} = \boldsymbol{k_{t,a}} + \boldsymbol{q_{t,c}} = \boldsymbol{k_{t,a}} + (1-z)\mu$$

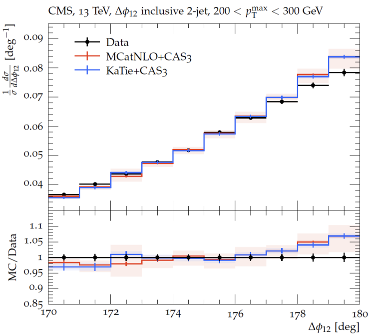
- Total transverse momentum:

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

Results: on-shell versus off-shell matrix elements

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

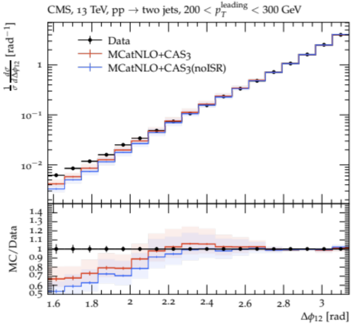


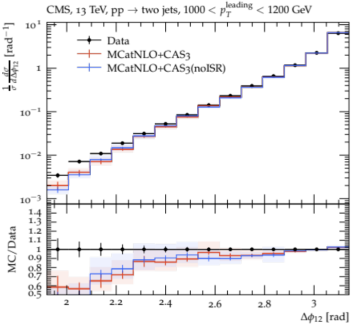


- at high $\Delta\phi$: off-shellness / TMD more important than higher orders of α_s in calculation
- at smaller $\Delta\phi$: relatively good description with off-shellness / TMD

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 since we look at 2 leading jets.

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  - TMD,
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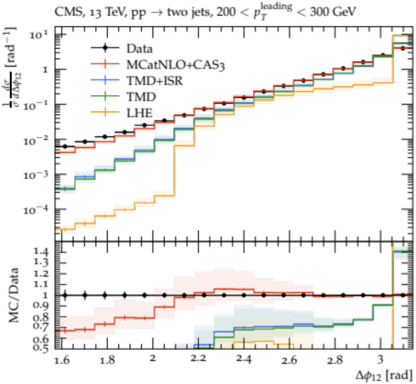

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