

Multi-jet merging with Parton Branching TMD evolution

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in collaboration with

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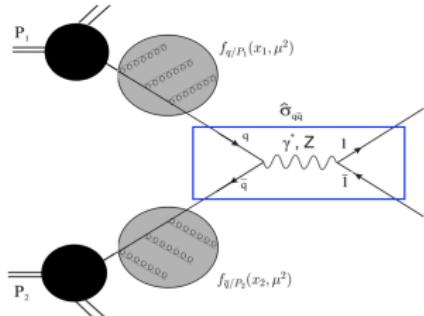
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May 3, 2022



Introduction: TMD factorization

Collinear factorization



$$\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, \mu^2) \hat{\sigma}_{ab}(x_1, x_2, Q^2, \mu^2) f_b(x_2, \mu^2)$$

- $\hat{\sigma}$ fixed order calculation in α_s
- evolution of $f_i(x, \mu^2)$ described by DGLAP

Multiple soft-gluon emissions call for effects **beyond fixed order!**

Transverse momentum dependent (TMD) factorization

- low- q_t factorization: CSS (resum $\alpha_s^n \ln^m(Q^2/q_T^2)$)
- high energy ($k_{\perp}-$) factorization: CCFM, BFKL (resum $(\alpha_s \ln \sqrt{s}/Q)^n$)
- Recent ('17) development: practical application in **Monte Carlo** approaches:
Parton branching (PB) method JHEP 01 (2018) 070 [arXiv:1708.03279]

$$\sigma = \sum_{a,b} \int dx_1 dx_2 \int d^2 k_{t,1} d^2 k_{t,2} \underbrace{\mathcal{A}_a(x_1, \mathbf{k}_{t,1}, \mu^2)}_{\text{TMD}} \hat{\sigma}_{ab}(x_1, x_2, \mathbf{k}_{t,1}, \mathbf{k}_{t,2}, Q^2, \mu^2) \underbrace{\mathcal{A}_b(x_2, \mathbf{k}_{t,2}, \mu^2)}_{\text{TMD}}$$

The Parton Branching (PB) method

JHEP 01 (2018) 070 [arXiv:1708.03279]

PB evolution equation for TMDs $\tilde{A}_a(x, k_t^2, \mu^2)$ can be solved iteratively with the Monte Carlo method:

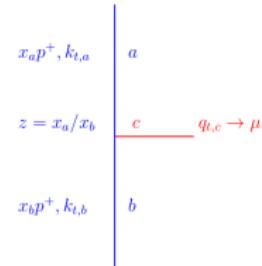
$$\begin{aligned} \tilde{A}_a(x, k_t^2, \mu^2) &= \Delta_a(\mu^2, \mu_0^2) \tilde{A}_a(x, k_{t,0}^2, \mu_0^2) + \\ &+ \sum_b \left[\int \frac{d^2 \mu'}{\pi \mu'^2} \int_x^{z_M(\mu')} dz \Theta(\mu^2 - \mu'^2) \Theta(\mu'^2 - \mu_0^2) \right. \\ &\times \left. \frac{\Delta_a(\mu^2, \mu_0^2)}{\Delta_a(\mu'^2,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

$P_{ab}^{(R)}(\alpha_s, z)$ real splitting function (resolvable branching probability),
 $\Delta_a(\mu^2, \mu_0^2)$ Sudakov (no branching probability)

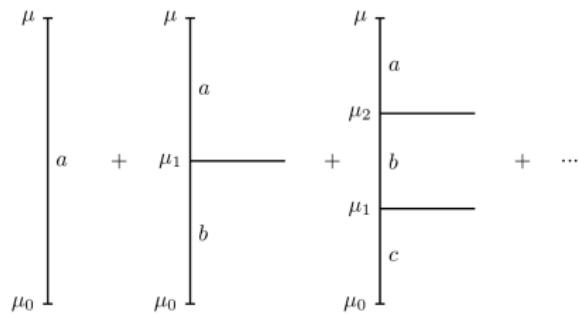
$$P_{ab}^{(R)}(\alpha_s, z) = \sum_{n=1}^{\infty} \left(\frac{\alpha_s}{2\pi} \right)^n P_{ab}^{(R)n-1}(z)$$

$$\Delta_a(\mu^2, \mu_0^2) = \exp \left(- \sum_b \int \frac{d\mu^2}{\mu^2} \int_0^{z_M} dz z P_{ab}^{(R)}(z, \alpha_s) \right)$$

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



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



Inclusive & exclusive observable calculations with PB

The PB method is implemented in event generator CASCADe3

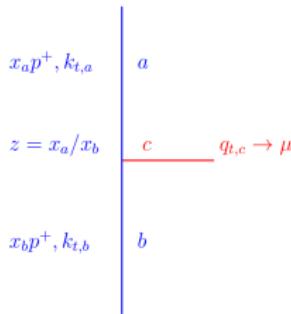
S. Baranov, MvK et al. Eur. Phys. J. C 81, 425 (2021)

- 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
- Backward evolution *unfolds* the TMD distribution

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

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

- Total transverse momentum:

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

Combining PB with higher orders

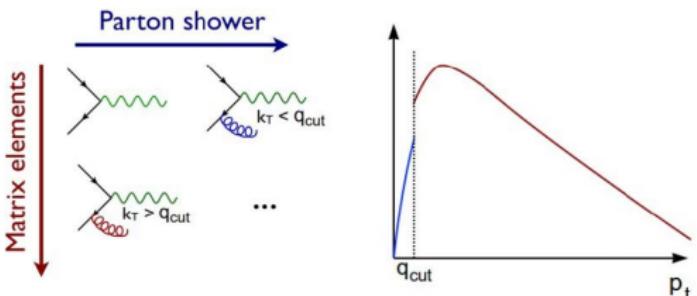
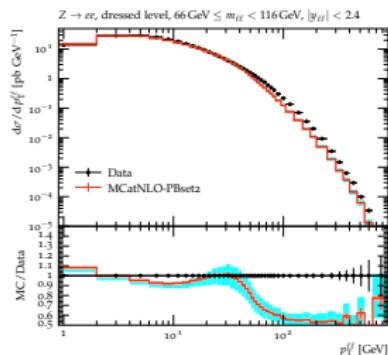
Matching TMD and NLO

- Match with MC@NLO procedure, subtraction terms HERWIG6
- Intermediate p_T region described
- Deficit at large p_T

Multi-jet merging at TMD level New!

- Include higher fixed-order calculations: **multi-jets**
- Make ME exclusive by Sudakov suppression
- Avoid double counting between initial state TMD evolution & hard emissions

figure by A. Bermudez Martinez →



$$\text{- 1st emission PS: } \mathcal{R}^{PS}(p_t^2) \times \exp \left[- \int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}} \right]$$

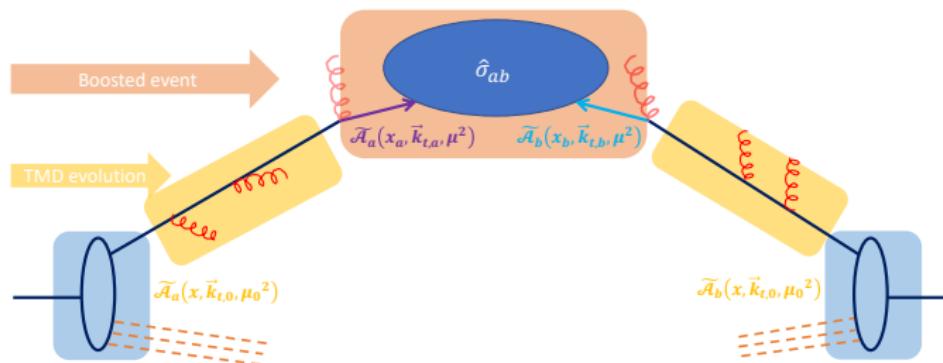
$$\text{- 1st emission ME: } \mathcal{R}(p_t^2) \rightarrow \mathcal{R}(p_t^2) \times \exp \left[- \int_{p_t^2} dp_t'^2 \frac{\mathcal{R}^{PS}(p_t'^2)}{\mathcal{B}} \right]$$

TMD merging

A. Bermudez Martinez, F. Hautmann, M.L. Mangano Phys.Lett.B 822 (2021) 136700

TMD multi-jet merging method

- ① Evaluate n-jet matrix elements: $\hat{\sigma}_{ab}$
- ② Reweighting the strong coupling
- ③ Apply forward PB-TMD evolution with condition: $|k_t|^2 \leq \mu_{min}^2$
- ④ Shower the events using the backward PB evolution
- ⑤ Apply MLM¹ prescription between boosted events and the showered events

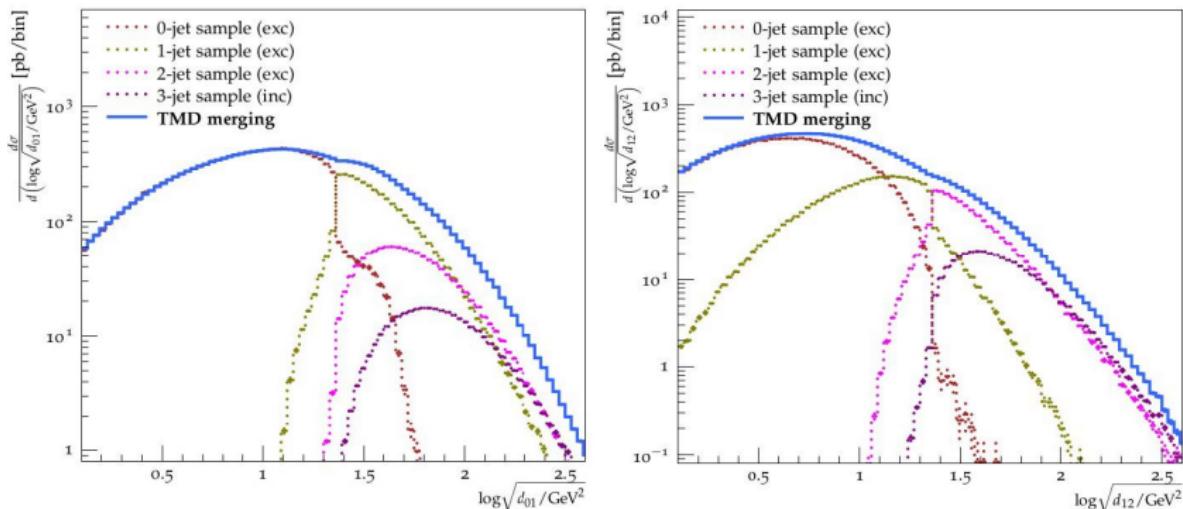


¹Other merging prescriptions can potentially also be used

Differential jet rates: Z+jets

Differential jet rates (DJR) show **smoothness** of the transition between the TMD region / parton shower and matrix element region.

- $d(n, n+1)$: scale at which an n -jet configuration becomes an $(n+1)$ -jet configuration
- merging scale μ_m divides soft and hard region
- transition around merging scale $\mu_m = 23$ GeV should be smooth ($\log(23) = 1.36$)

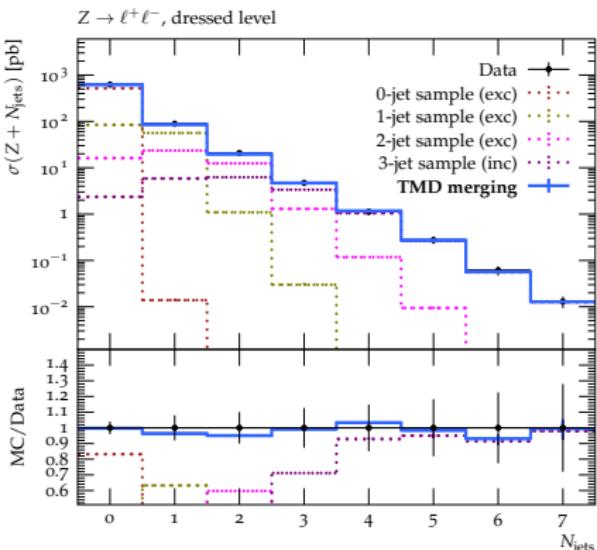
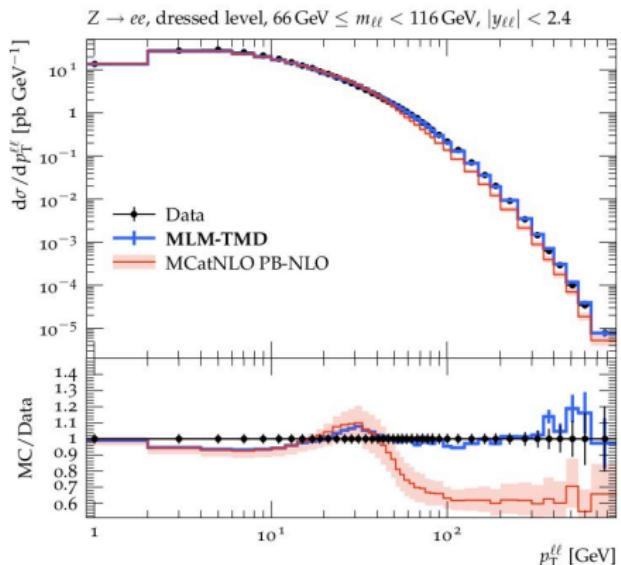


Bermudez Martinez et al. Phys.Lett.B 822 (2021) 136700 [arXiv:2107.01224v1]

Z boson p_T spectrum & jet multiplicity

Bermudez Martinez et al. Phys.Lett.B 822 (2021) 136700 [arXiv:2107.01224v1]

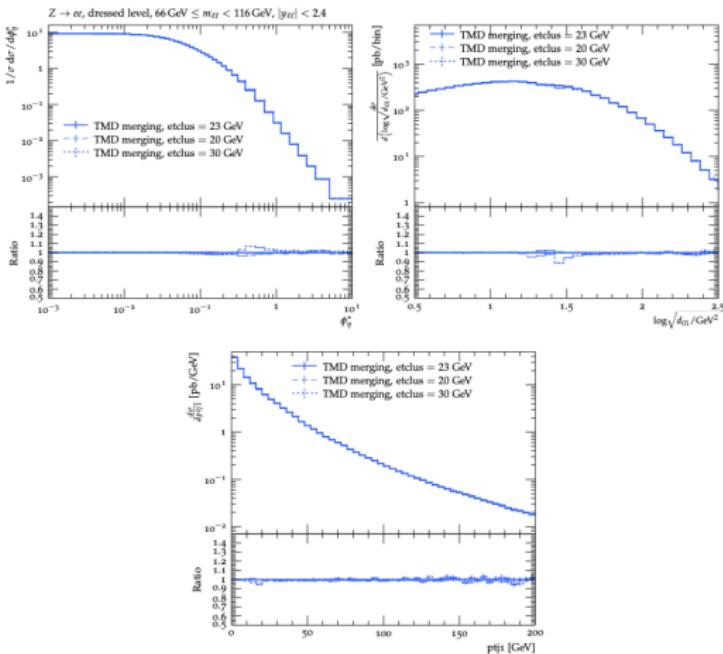
- Z + 1,2,3 jets in matrix element
- @Z mass peak: $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$



- Consistent with PB+MC@NLO at low p_T
- Uncertainty NLO from scale variations

- Also jet multiplicity well described
- Accurate at $N_{\text{jets}} = 7$!

Theoretical systematics; $Z + \text{jets}$



A. Bermudez Martinez, F. Hautmann, M.L. Mangano,
[arXiv:2109.08173]

Variation of the merging scale with 10 GeV gives < 2% change in cross sections

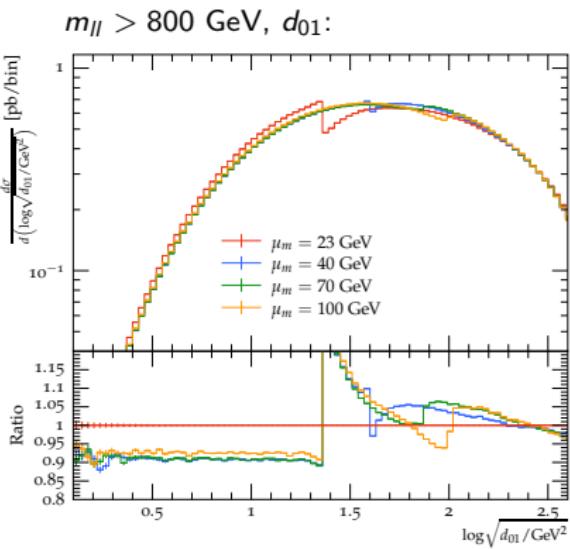
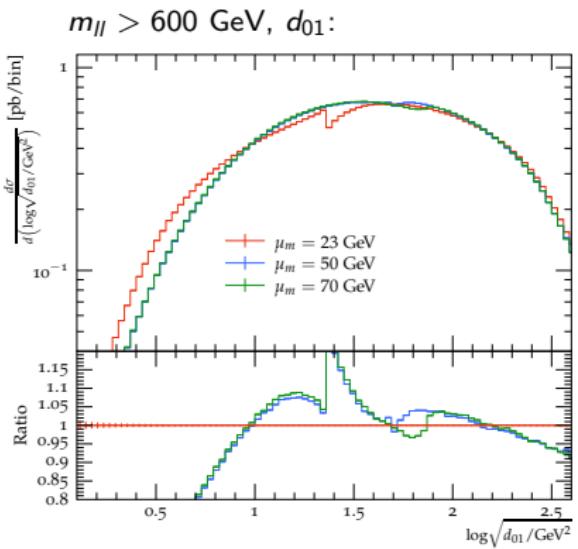
Merging scale [GeV]	$\sigma[\text{tot}]$ [pb]	$\sigma[\geq 1 \text{ jet}]$ [pb]	$\sigma[\geq 2 \text{ jet}]$ [pb]	$\sigma[\geq 3 \text{ jet}]$ [pb]	$\sigma[\geq 4 \text{ jet}]$ [pb]
23.0	573	87.25	20.27	4.84	1.18
33.0	563	86.15	20.48	4.86	1.19

Dynamical merging scale

Understand the relation of the Z boson p_T with the corresponding mass.

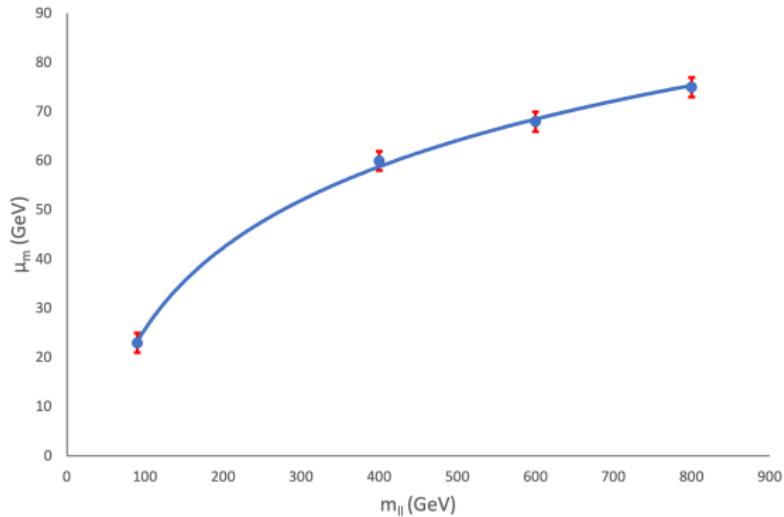
As in studies by B. Bilin et al. in [CMS-PAS-SMP-20-003]

- What happens at very large masses: $Q^2 \gg M_Z^2$?
- Change the merging scale μ_m



Dynamical merging scale

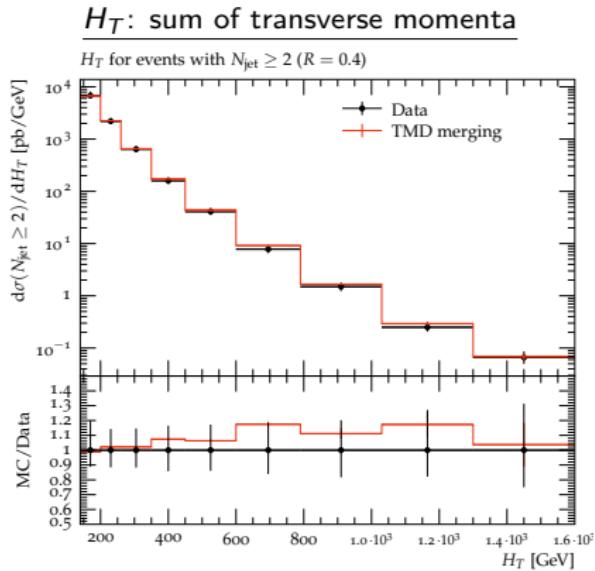
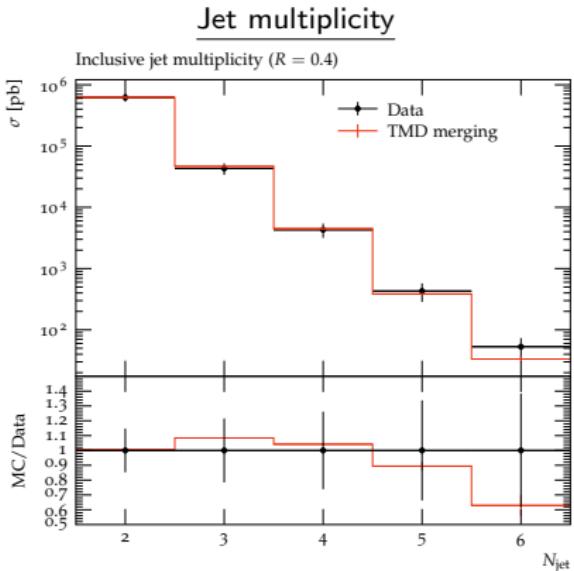
- Merging scale depends on hard scale: $\mu_m \sim \log(m_{\parallel})$



Work in progress

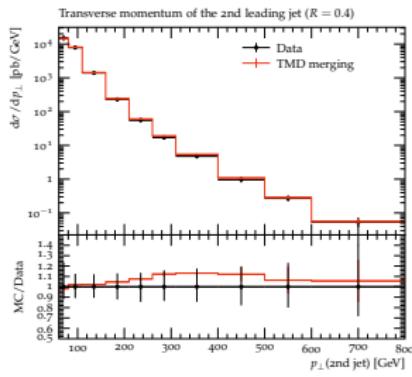
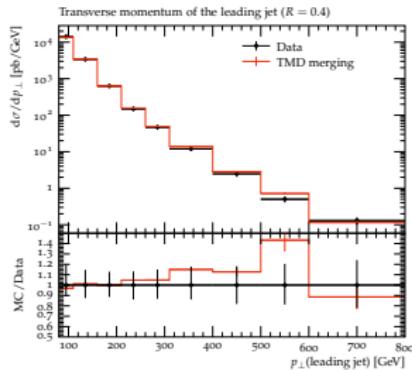
Di-jet production

- Apply to multi-jets: including color in the initial state.
- Produce $pp \rightarrow jj + 1,2 j$

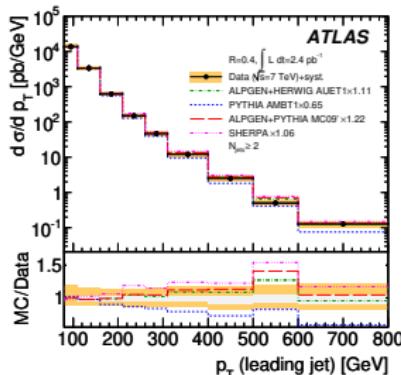


Jet p_T in multi-jet events

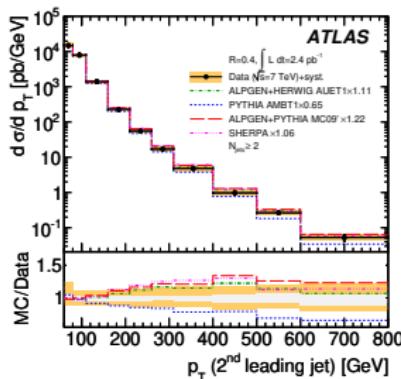
TMD merging up to 2 → 4 matrix elements



Collinear merging up to 2 → 6 matrix elements



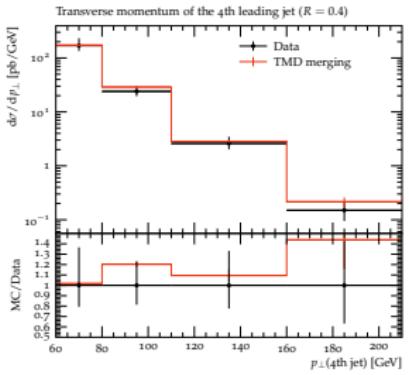
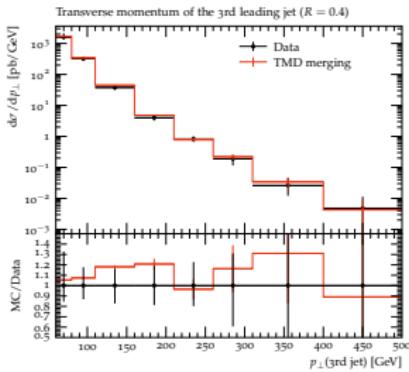
Leading jet p_T



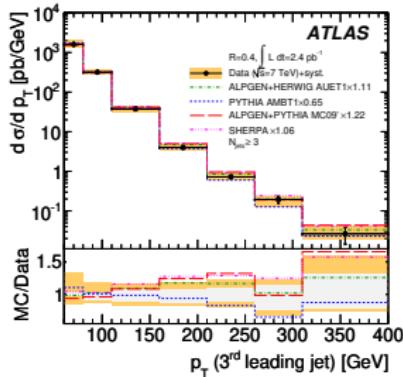
Second leading jet p_T

Jet p_T in multi-jet events

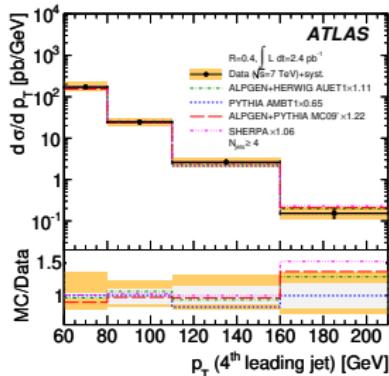
TMD merging up to $2 \rightarrow 4$ matrix elements



Collinear merging up to $2 \rightarrow 6$ matrix elements



Third leading jet p_T



Fourth leading jet p_T

- Parton branching method combined with multi-jet final states
- Exclusive calculations within the TMD framework

TMD multi-jet merging:

- improves description of higher order emissions (large p_T)
- reduces systematic uncertainty
- Merging scale dependence on the DY mass!