LHC Electroweak Working Group Meeting, CERN, June 2018

NLOPS with TMDs

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• work in progress with A. Bermudez Martinez, H. Jung, A. Lelek and R. Zlebcik

A study of NLO-matched parton showers versus TMD resummation
for electroweak gauge boson production and jets

MOTIVATION

- How to relate parton-shower calculations and resummed calculations?
- How to estimate uncertainties on theoretical predictions based on NLO-matched parton showers?

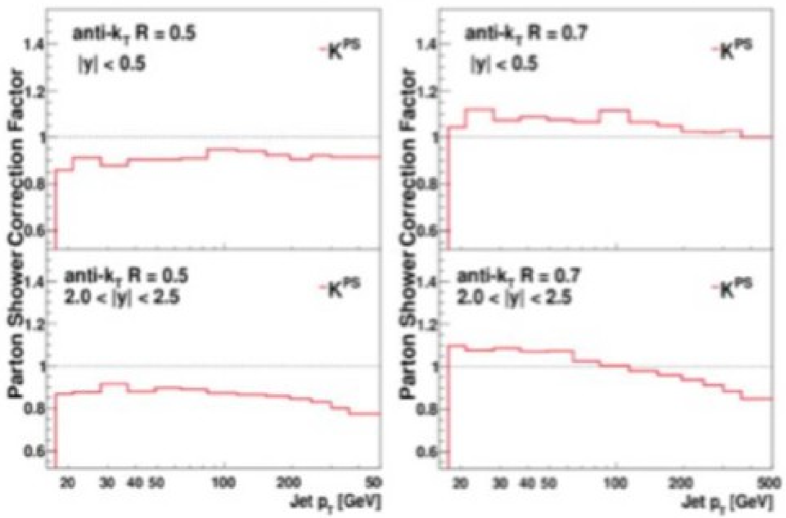
Ex.: Dasgupta, Dreyer, Hamilton, Monni, Salam
"Logarithmic accuracy of parton showers:
a fixed-order study" arXiv:1805.09327

analysis of final-state shower effects

MOTIVATION

Parton-showering corrections to associated jets can be large even at large pT

S. Dooling et al., PRD87 (2013) 094009

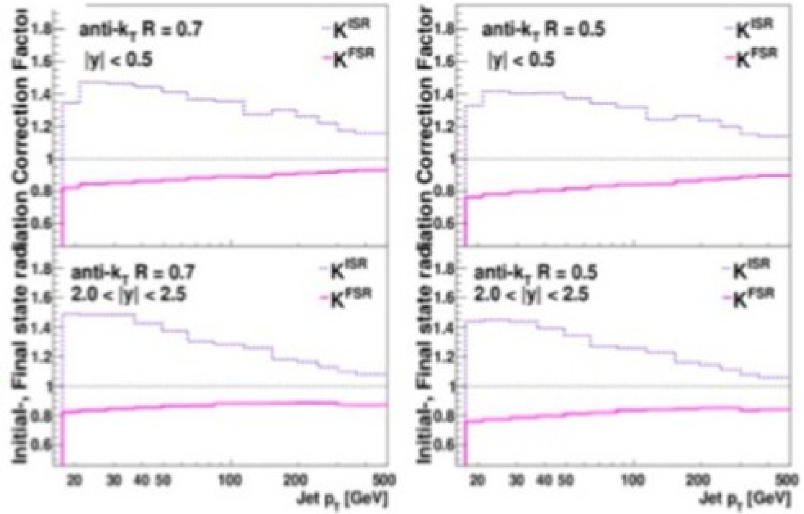


$$K^{PS} = K^{(ps)}_{NLO-MC} / K^{(0)}_{NLO-MC}$$

- Depends on rapidity and p_T especially in the forward region
- Finite effect also at large p_T

- Initial and Final State Parton Shower considered independently
- But they are interconnected: The combined effects cannot be obtained by adding the individual contributions
- ISR largest at low p_T, FSR significant for all p_T

[S. Dooling, talk at DIS 2013]

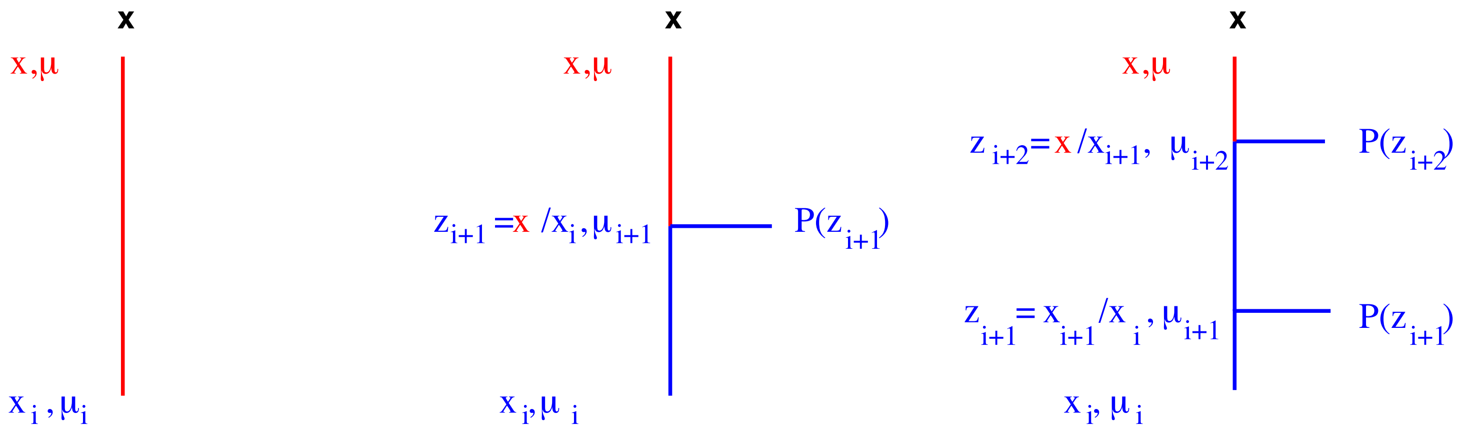


INITIAL STATE SHOWERS
QCD evolution and soft-gluon resolution scale

[Jung, Lelek, Radescu, Zlebcik & H, PLB772 (2017) 446]

$$\widetilde{f}_a(x,\mu^2) = \Delta_a(\mu^2)\ \widetilde{f}_a(x,\mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz\ P_{ab}^{(R)}(\alpha_{\mathrm{S}}(\mu'^2),z)\ \widetilde{f}_b(x/z,\mu'^2)$$

$$\text{where} \quad \Delta_a(z_M,\mu^2,\mu_0^2) = \exp\left(- \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\ z\ P_{ba}^{(R)}(\alpha_{\mathrm{S}}(\mu'^2),z) \right)$$



▷ soft-gluon resolution parameter z_M separates resolvable and nonresolvable branchings

▷ no-branching probability Δ; real-emission probability $P^{(R)}$

INITIAL STATE SHOWERS
qT recoils and transverse momentum dependence

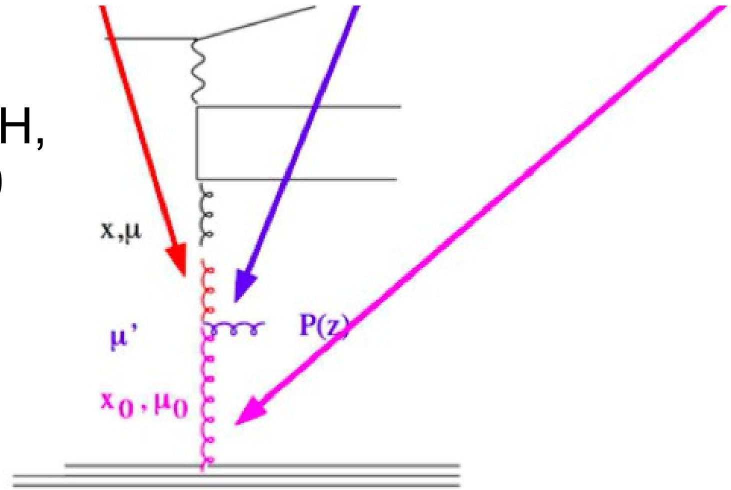
$$\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu^2) = \Delta_a(\mu^2)\,\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu_0^2) + \sum_b \int \frac{d^2\mathbf{q}'}{\pi\mathbf{q}'^2}\,\frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$
$$\times \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2),z)\,\widetilde{\mathcal{A}}_b(x/z,\mathbf{k}+(1-z)\mathbf{q}',\mathbf{q}'^2)$$

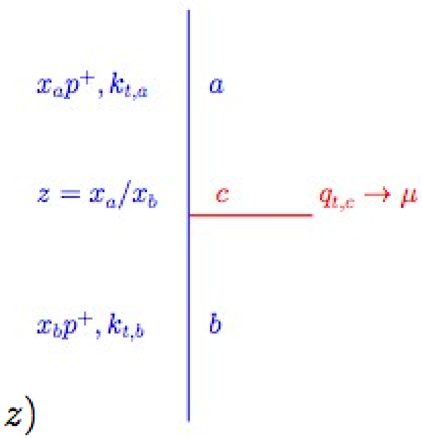
Solve iteratively : $\widetilde{\mathcal{A}}_a^{(0)}(x,\mathbf{k},\mu^2) = \Delta_a(\mu^2)\,\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu_0^2)$,

$$\widetilde{\mathcal{A}}_a^{(1)}(x,\mathbf{k},\mu^2) = \sum_b \int \frac{d^2\mathbf{q}'}{\pi\mathbf{q}'^2}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$
$$\times \frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)} \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2),z)\,\widetilde{\mathcal{A}}_b(x/z,\mathbf{k}+(1-z)\mathbf{q}',\mu_0^2)\,\Delta_b(\mathbf{q}'^2)$$

NB: angular ordering

Jung, Lelek, Radescu, Zlebcik & H, JHEP 01 (2018) 070





$\mu = |\mathbf{q}_c|/(1-z)$

- Drell-Yan pT spectrum from convolution of two transverse momentum dependent distributions

- Comparison of parton branching results with analytic TMD resummation (Collins-Soper-Sterman method)

COMPARISON WITH TMD RESUMMATION

Resummed DY differential cross section:

$$\frac{d\sigma}{d^2\mathbf{q}dM^2dy} = \sum_{q,\bar{q}} \frac{\sigma^{(0)}}{s} H(\alpha_S) \int \frac{d^2\mathbf{b}}{(2\pi)^2}\, e^{i\mathbf{q}\cdot\mathbf{b}} \mathcal{A}_q(x_1,\mathbf{b},M)\mathcal{A}_{\bar{q}}(x_2,\mathbf{b},M) + \mathcal{O}\left(\frac{|\mathbf{q}|}{M}\right)$$

where $H(\alpha_S) = 1 + H^{(1)}\,\frac{\alpha_S}{\pi} + H^{(2)}\left(\frac{\alpha_S}{\pi}\right)^2 + \ldots$ and

$$\mathcal{A}_i(x,\mathbf{b},M) = \exp\left\{\frac{1}{2}\int_{c_0/b^2}^{M^2} \frac{d\mu'^2}{\mu'^2}\left[A_i(\alpha_S(\mu'^2))\ln\left(\frac{M^2}{\mu'^2}\right) + B_i(\alpha_S(\mu'^2))\right]\right\}\exp\left(\frac{-\mathbf{b}^2}{2\lambda^2}\right)$$
$$\times \sum_j \int_x^1 \frac{dz}{z} C_{ij}\left(z, \alpha_S\left(\frac{c_0}{\mathbf{b}^2}\right)\right) f_j\left(\frac{x}{z}, \frac{c_0}{\mathbf{b}^2}\right)$$

with $A_i(\alpha_S) = A_i^{(1)}\,\frac{\alpha_S}{\pi} + A_i^{(2)}\left(\frac{\alpha_S}{\pi}\right)^2 + A_i^{(3)}\left(\frac{\alpha_S}{\pi}\right)^2 + \ldots,$

$$B_i(\alpha_S) = B_i^{(1)}\,\frac{\alpha_S}{\pi} + B_i^{(2)}\left(\frac{\alpha_S}{\pi}\right)^2 + \ldots,$$

$$C_{ij}(z,\alpha_S) = \delta(1-z)\delta_{ij} + C_{ij}^{(1)}\frac{\alpha_S}{\pi} + C_{ij}^{(2)}\left(\frac{\alpha_S}{\pi}\right)^2 + \ldots.$$

COMPARISON WITH TMD RESUMMATION

▷ The parton branching TMD contains Sudakov form factor in terms of

$$P_{ab}^{(R)}(\alpha_S, z) = K_{ab}(\alpha_S)\,\frac{1}{1-z} + R_{ab}(\alpha_S, z) \quad \text{where}$$

$$K_{ab}(\alpha_S) = \delta_{ab} k_a(\alpha_S)\,, \quad k_a(\alpha_S) = \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{2\pi}\right)^n k_a^{(n-1)}\,, \quad R_{ab}(\alpha_S, z) = \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{2\pi}\right)^n R_{ab}^{(n-1)}(z)$$

▷ Via momentum sum rules, use unitarity to re-express this in terms of

$$P^{(V)} = P - P^{(R)}\,, \quad \text{where}$$

$$P_{ab}(\alpha_S, z) = D_{ab}(\alpha_S)\delta(1-z) + K_{ab}(\alpha_S)\,\frac{1}{(1-z)_+} + R_{ab}(\alpha_S, z)$$

is full splitting function (at LO, NLO, etc.)

$$\text{with} \quad D_{ab}(\alpha_S) = \delta_{ab} d_a(\alpha_S)\,, \quad d_a(\alpha_S) = \sum_{n=1}^{\infty} \left(\frac{\alpha_S}{2\pi}\right)^n d_a^{(n-1)}$$

▷ Identify $d_a(\alpha_S)$ and $k_a(\alpha_S)$ with resummation formula coefficients (LL, NLL, . .)

- $d_a(\alpha_S)$ and $k_a(\alpha_S)$ perturbative coefficients

$$\mathrm{one-loop}\ :$$

$$d_q^{(0)} = \frac{3}{2}\,C_F \quad , \quad k_q^{(0)} = 2\;C_F$$

$$\mathrm{two-loop}\ :$$

$$d_q^{(1)} = C_F^2\left(\frac{3}{8} - \frac{\pi^2}{2} + 6\;\zeta(3)\right) + C_F C_A\left(\frac{17}{24} + \frac{11\pi^2}{18} - 3\;\zeta(3)\right) - C_F T_R N_f\left(\frac{1}{6} + \frac{2\pi^2}{9}\right)\ ,$$

$$k_q^{(1)} = 2\;C_F\;\Gamma\ , \quad \mathrm{where}\ \ \Gamma = C_A\left(\frac{67}{18} - \frac{\pi^2}{6}\right) - T_R N_f\,\frac{10}{9}$$

REMARKS

- Comparison carried out for DY pT spectrum – need broader comparisons
- TMD parton distribution consistent by construction with TMD parton shower
- First implementation using NLO matrix elements from POWHEG

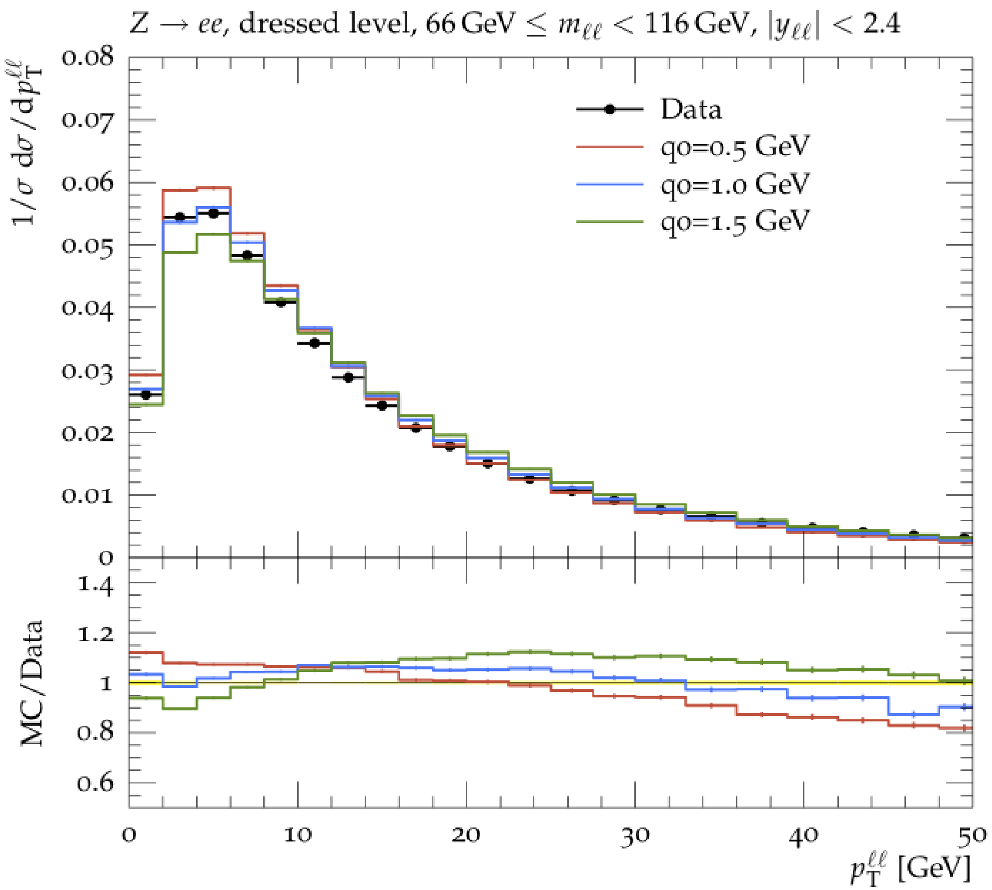
Z-boson pT spectrum from parton branching TMD

- Parton branching TMD defined by using angular ordering
  - Scale in running coupling also by angular ordering

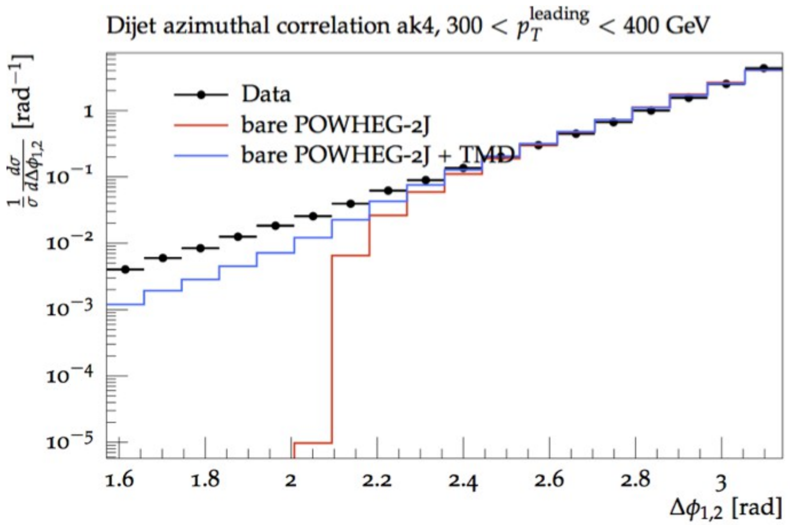
$$\alpha_s(\mu^2 (1-z)^2)$$

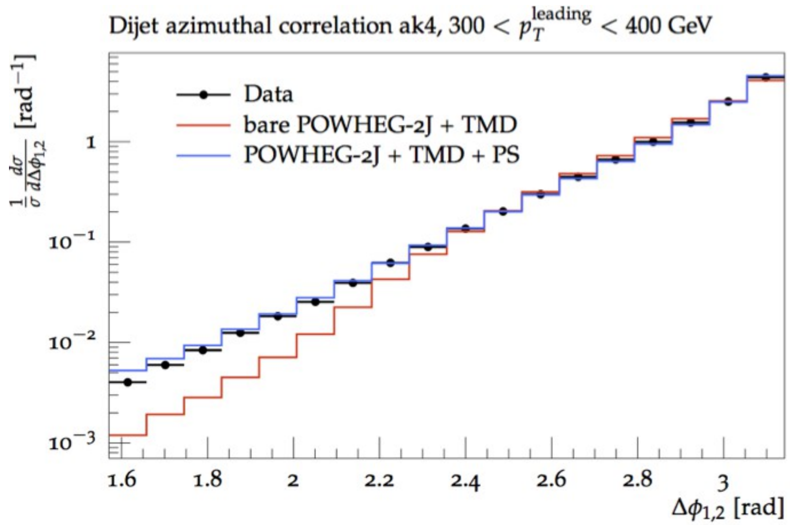
- mu-dependent soft-gluon resolution scale parameter zM

$$z_M(\mu) = 1 - q_0/\mu$$

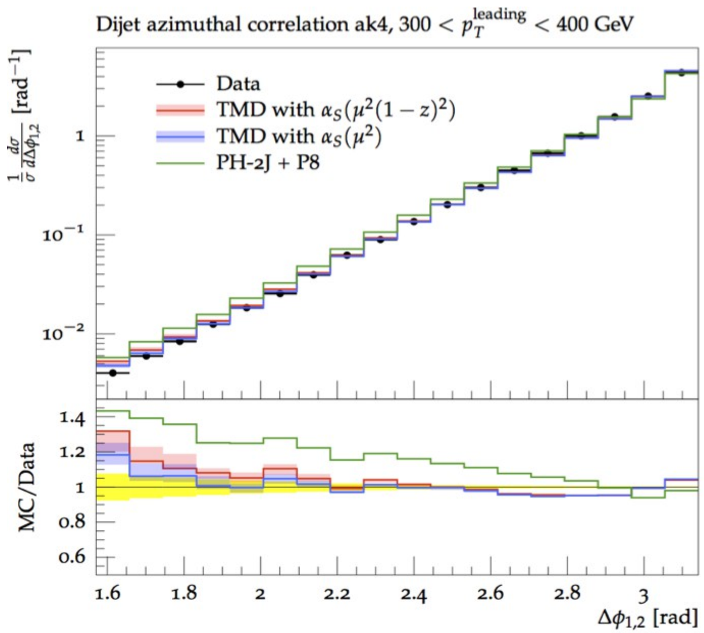


Di-jets from NLOPS with TMDs



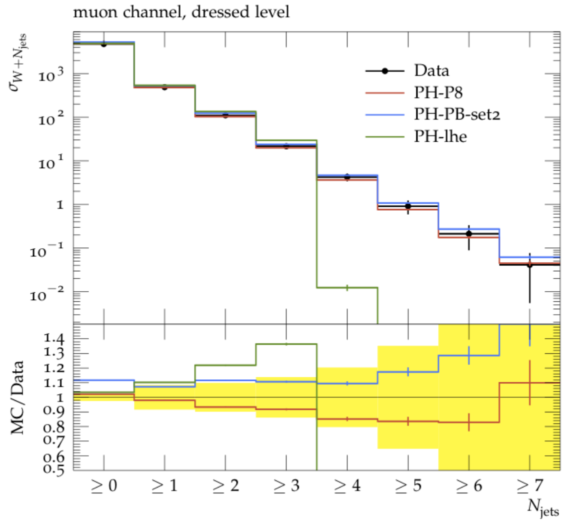


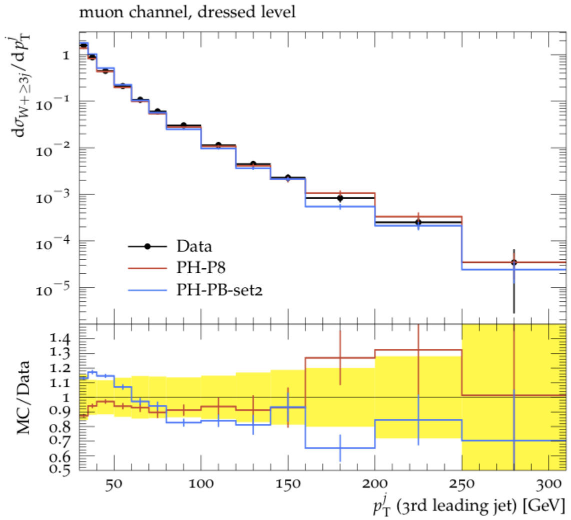
- Events by NLO POWHEG 2 jets
- Parton branching TMD (with angular ordering)
- TMD parton shower

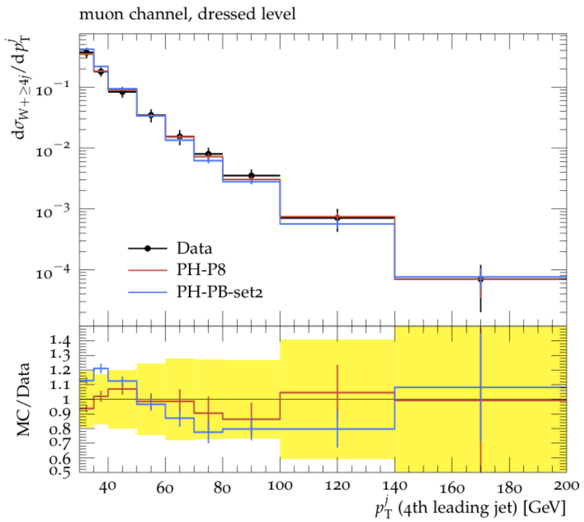


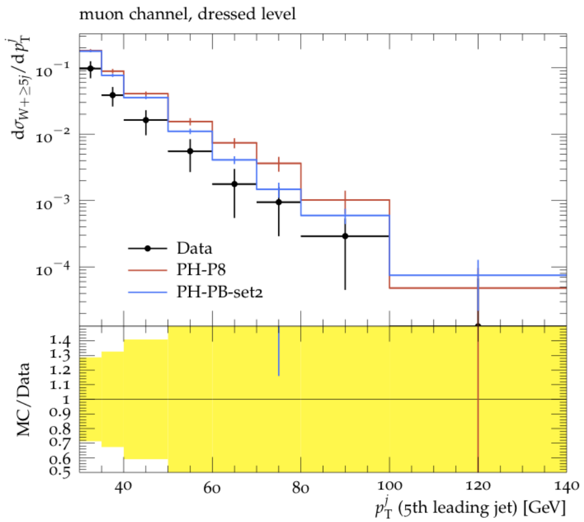
W + n jets from NLOPS with TMDs

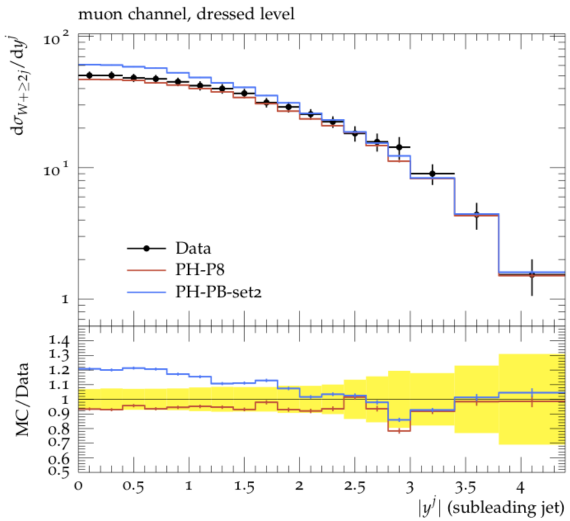
- POWHEG
  NLO W+2 jets
- TMD shower











Conclusions

- First steps toward NLO parton showers with TMDs: method to take into account simultaneously soft-gluon emission ($z \longrightarrow 1$) and transverse momentum q_T recoils in the parton branchings along the QCD cascade

- potentially relevant for estimating theoretical uncertainties and comparing parton shower calculations with resummation results

- terms in powers of ln ($1 - z_M$) can be related to large-x resummation $\rightarrow$ relevant to near-threshold, rare processes to be investigated at high luminosity

- numerical examples for W/Z production and jets

  $\longrightarrow$ systematic studies of ordering effects and color coherence