



Current state of QCD simulations

a biased view of recent progress

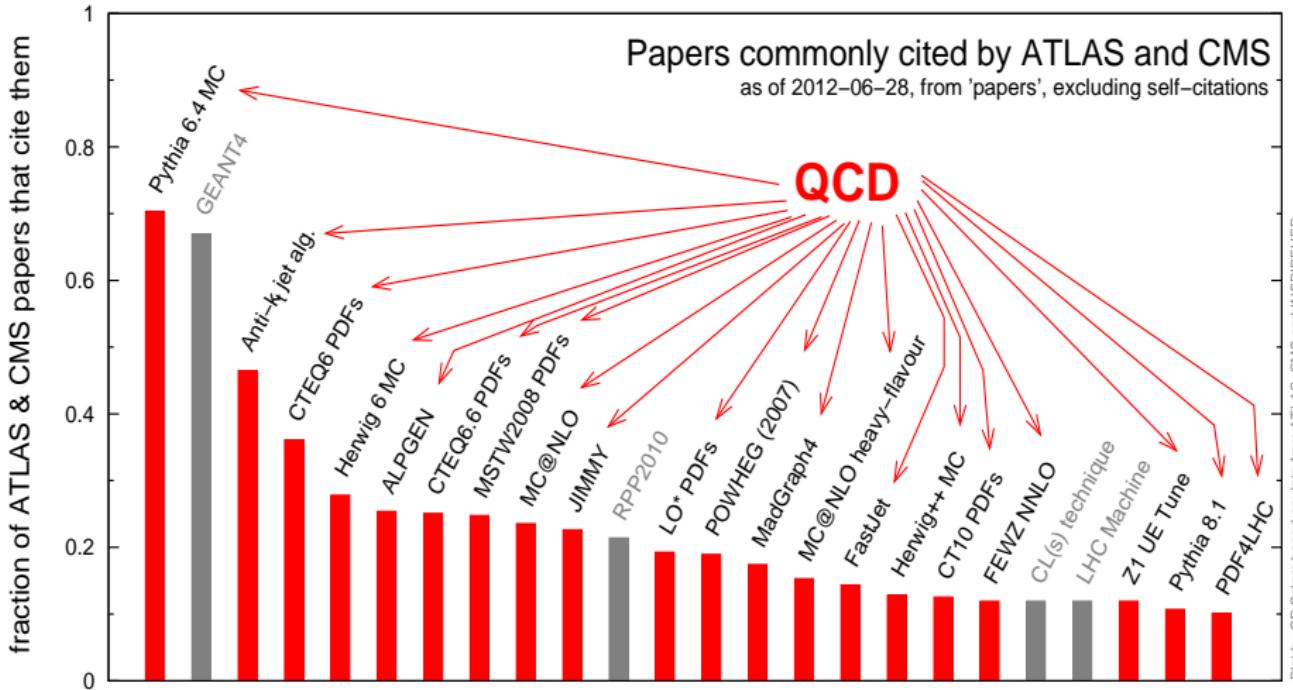


Stefan Höche

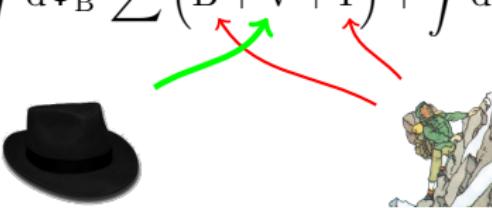
SLAC

ATLAS Physics Jamboree

SLAC, 11/12/14



NLO calculations: The art of collaboration

$$\sigma_{\text{NLO}} = \int d\Phi_B \sum (B + \tilde{V} + I) + \int d\Phi_R \sum (R - S)$$


- ▶ One-Loop Engines (OLEs) compute virtual piece
- ▶ ME generator takes care of Born, real emission, subtraction phase-space integration and event generation
- ▶ Interface provided by BLHA(2)

[Binoth et al.] arXiv:1001.1307 [Alioli et al.] arXiv:1308.3462

$W+5\text{jets}$ – brought to you by BlackHat+Sherpa

[BlackHat] PRD88(2013)014025, arXiv:1407.6564

- ▶ $W+\text{jets}$ at 7 TeV, $E_T^e > 20 \text{ GeV}$, $|\eta^e| < 2.5$, $E_T > 20 \text{ GeV}$
 $p_T^j > 25 \text{ GeV}$, $|\eta^j| < 3$, $M_T^W > 20 \text{ GeV}$

Jets	$\frac{W^- + (n+1)}{W^- + n}$		$\frac{W^+ + (n+1)}{W^+ + n}$	
	LO	NLO	LO	NLO
1	0.2949(0.0003)	0.238(0.001)	0.3119(0.0005)	0.242(0.002)
2	0.2511(0.0005)	0.220(0.001)	0.2671(0.0004)	0.235(0.002)
3	0.2345(0.0008)	0.211(0.003)	0.2490(0.0005)	0.225(0.003)
4	0.218(0.001)	0.200(0.006)	0.2319(0.0008)	0.218(0.006)

- ▶ Fit to straight line gives (for $n \geq 2$)

$$R_{n/(n-1)}^{\text{NLO}, W^-} = 0.248 \pm 0.008 - (0.009 \pm 0.002) n$$

$$R_{n/(n-1)}^{\text{NLO}, W^+} = 0.263 \pm 0.009 - (0.009 \pm 0.003) n$$

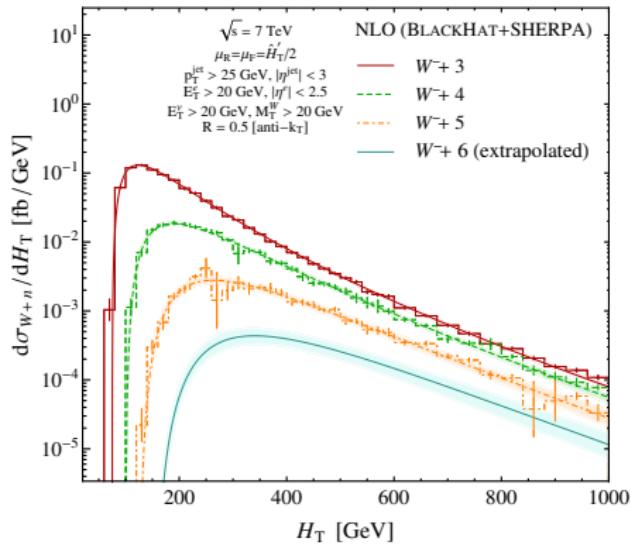
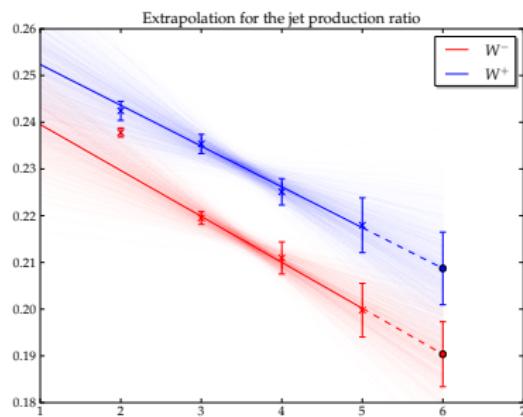
- ▶ Extrapolate to six jets

$$W^- + 6 \text{ jets} : 0.15 \pm 0.01 \text{ pb}$$

$$W^+ + 6 \text{ jets} : 0.30 \pm 0.03 \text{ pb}$$

$W+6\text{jets}$ – brought to you by BlackHat+Sherpa

[BlackHat] arXiv:1407.6564

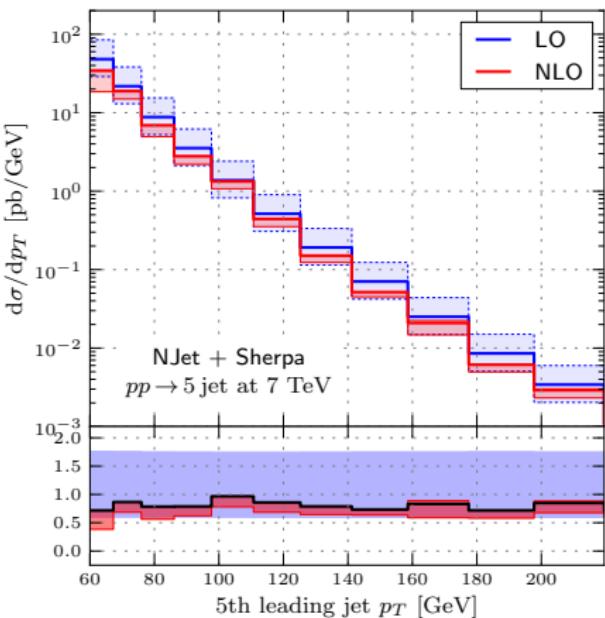
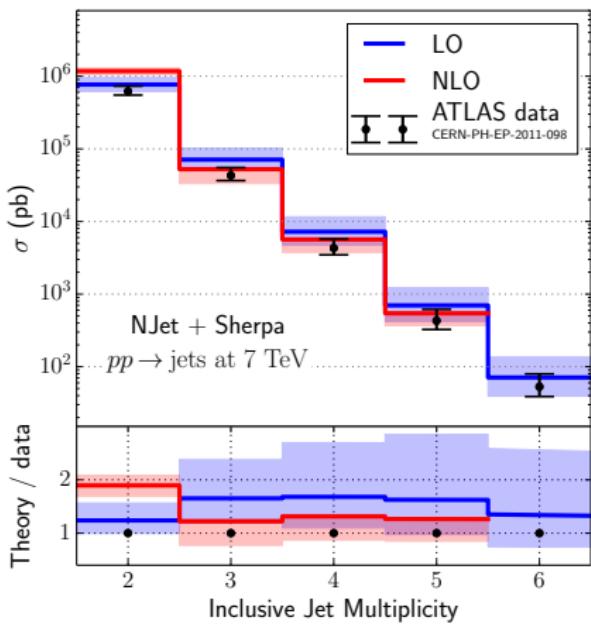


- ▶ Extrapolation of jet rate ratio and H_T spectrum
- ▶ Scaling hypothesis supported by resummation (\nearrow backup slide)

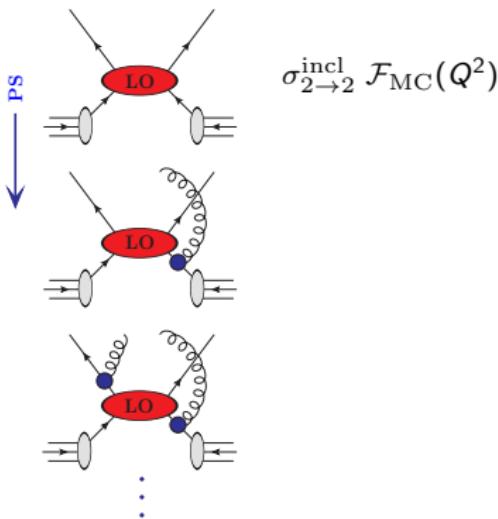
5jets – brought to you by NJet+Sherpa

[NJet] arXiv:1309.6585

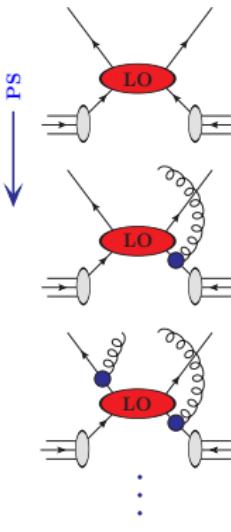
- ▶ Can help constrain PDFs with LHC data
- ▶ Can be used to understand jet scaling patterns → BSM searches



QCD Parton showers



QCD Parton showers



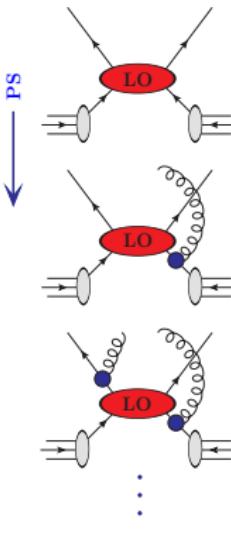
$$\sigma_{2 \rightarrow 2}^{\text{incl}} \left[\Delta(t_c, Q^2) \right.$$

$$+ \int_{t_c}^{Q^2} \frac{dt}{t} \int dz \frac{\alpha_s}{2\pi} P(z) \Delta(t, Q^2)$$

$$+ \frac{1}{2} \left(\int_{t_c}^{Q^2} \frac{dt}{t} \int dz \frac{\alpha_s}{2\pi} P(z) \right)^2 \Delta(t, Q^2)$$

$$+ \dots$$

QCD+EW Parton showers



$$\sigma_{2 \rightarrow 2}^{\text{incl}} \left[\Delta^{(QCD+EW)}(t_c, Q^2) \right.$$

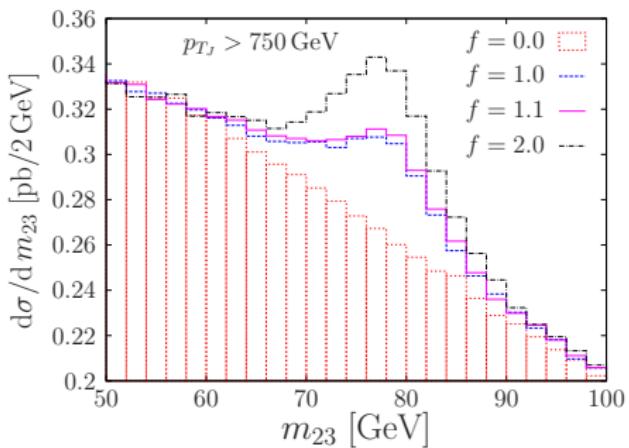
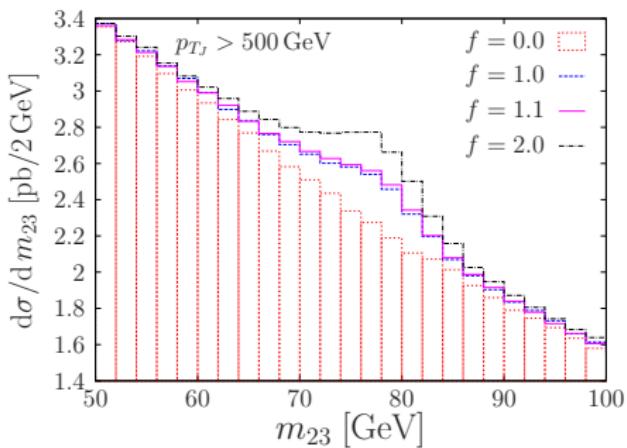
$$+ \int_{t_c}^{Q^2} \frac{dt}{t} \int dz \frac{\alpha_s}{2\pi} (P^{(QCD)}(z) + P^{(EW)}(z)) \Delta^{(QCD+EW)}(t_c, Q^2)$$

$$+ \frac{1}{2} \left(\int_{t_c}^{Q^2} \frac{dt}{t} \int dz \frac{\alpha_s}{2\pi} (P^{(QCD)}(z) + P^{(EW)}(z)) \right)^2 \Delta^{(QCD+EW)}(t_c, Q^2)$$

$$+ \dots$$

Electroweak showers in Sherpa

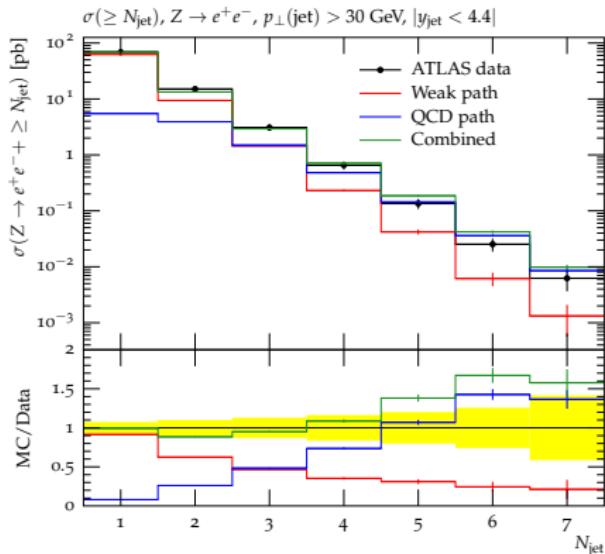
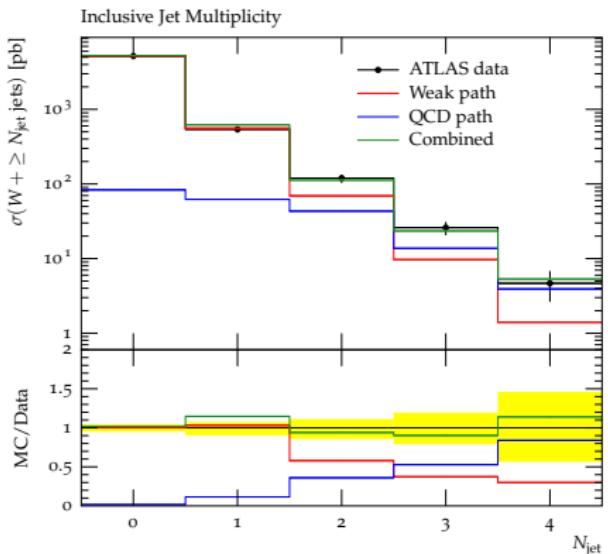
[Krauss,Petrov,Schönherr,Spannowsky] arXiv:1403.4788



- ▶ W masses as reconstructed from sub-jets in boosted topologies
- ▶ Enhance factors (f) for EW-splittings allow to check tagger response
- ▶ Spin averaged splitting functions used, but ok for a single emission

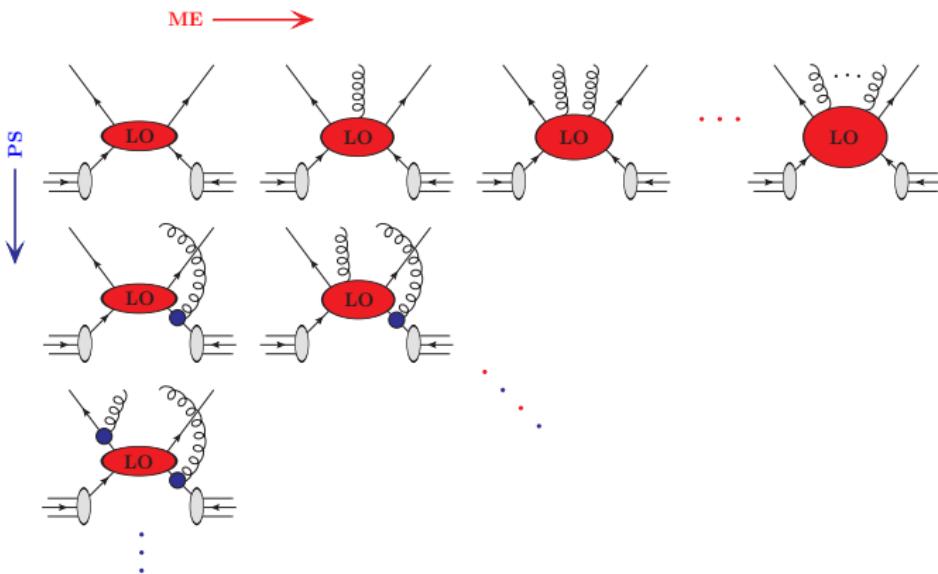
Electroweak showers in Pythia

[Christiansen,Sjöstrand] arXiv:1401.5238



- ▶ Jet multiplicity in W/Z +multi-jet events well described
 - ▶ Shower results now similar to leading order ME \oplus PS merging
 - ▶ Full matrix-element correction for first EW splitting

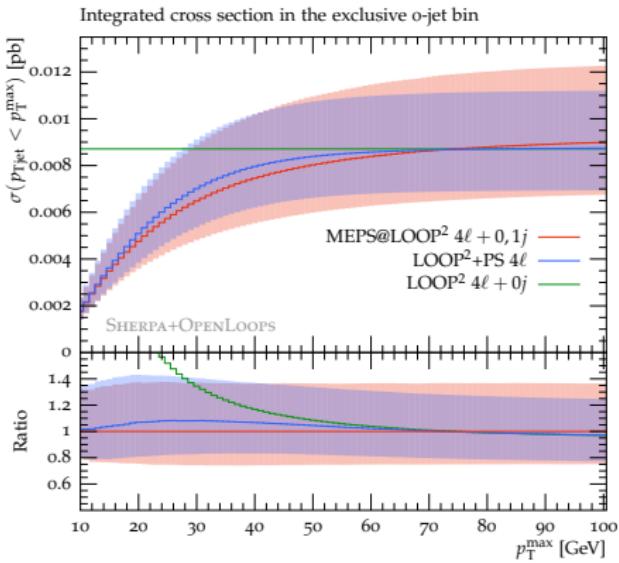
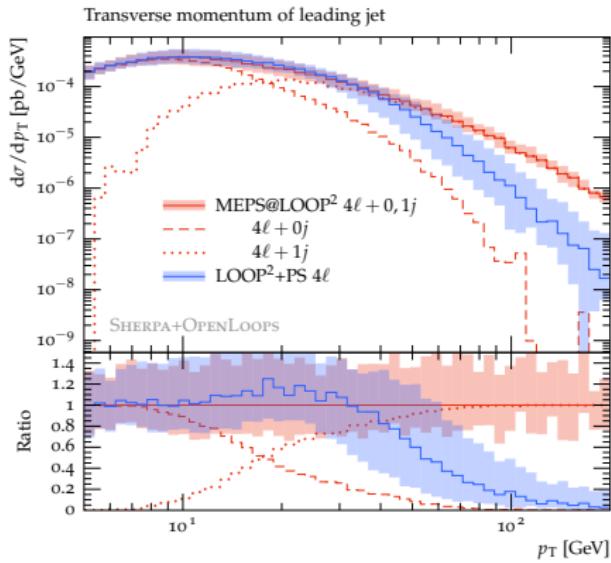
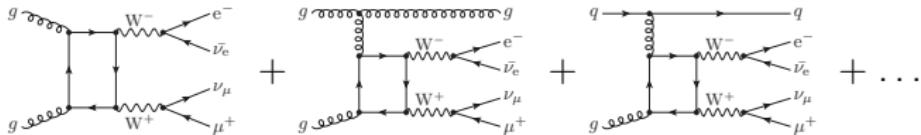
ME+PS merging at leading order



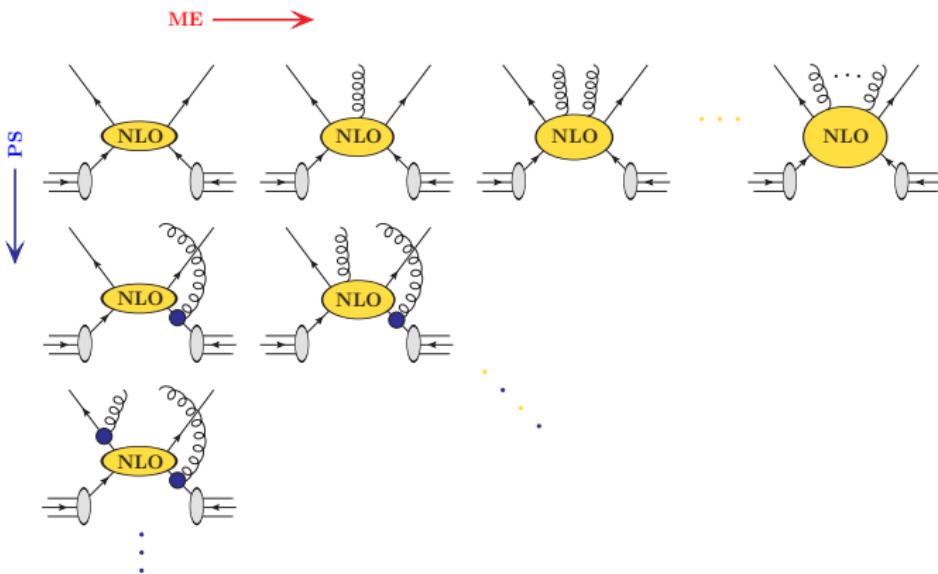
Squared-loop ME \oplus PS merging

[Cascioli,Krauss,Maierhöfer,Pozzorini,Siegert,SH] arXiv:1309.0500

► Combine

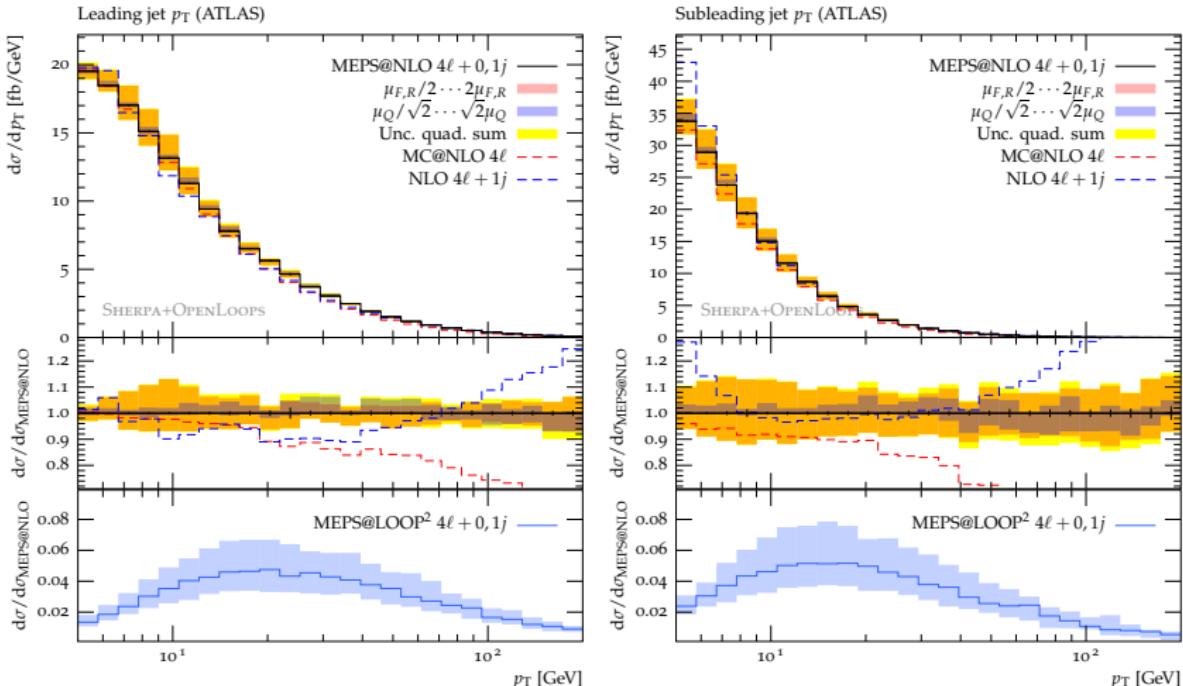


ME+PS merging at next-to-leading order



Four lepton production at the LHC

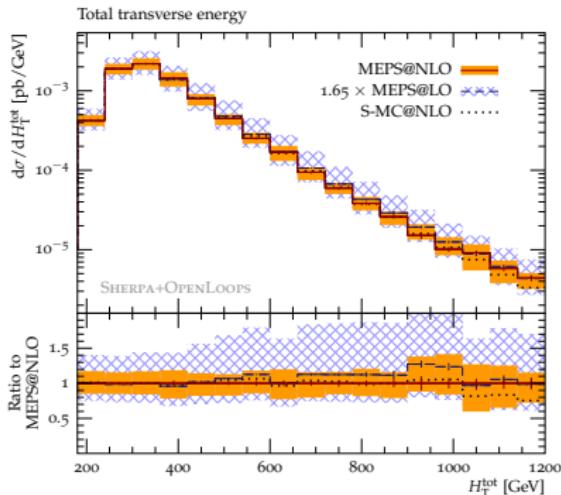
[Cascioli,Krauss,Maierhöfer,Pozzorini,Sieger,SH] arXiv:1309.0500



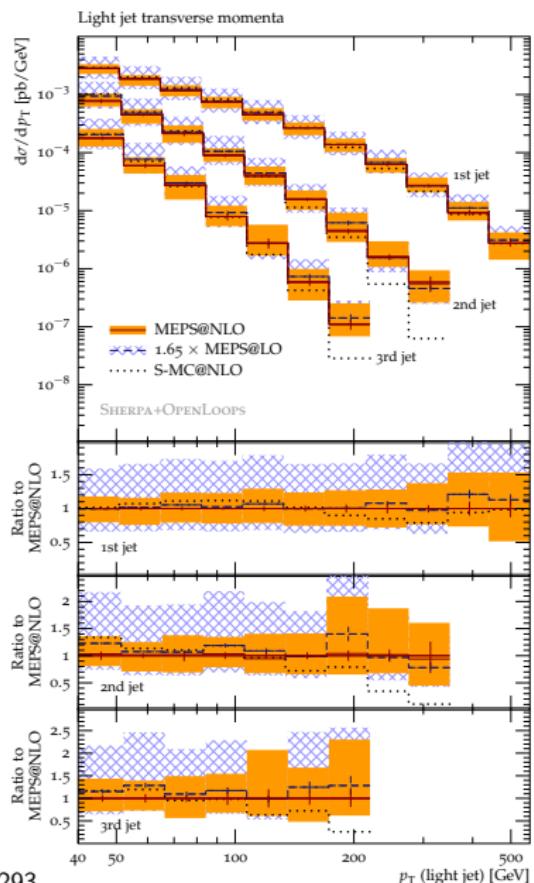
- ME \oplus PS@NLO with 0&1 jet at NLO plus 2 jet at LO
- ME \oplus PS@LOOP² with 0&1 jet at LOOP²

Top quark pair production

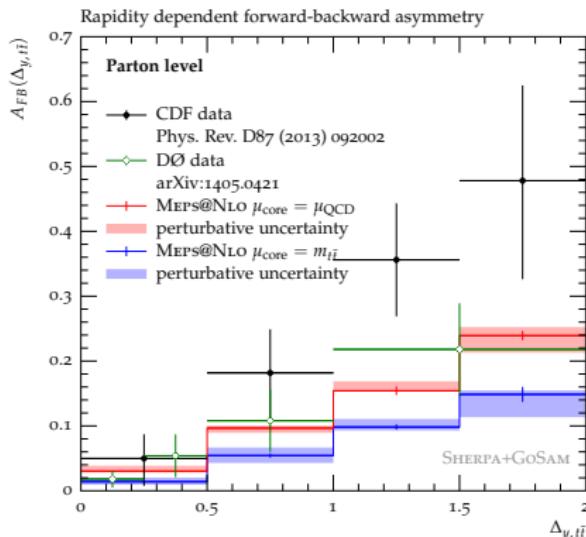
- ▶ First matched/merged sim for $t\bar{t}+2j$
full result has $t\bar{t}+0,1,2j @ \text{NLO}$, $3j @ \text{LO}$
- ▶ Largely reduced theory uncertainty
for both for measurement (p_T , N_{jet})
and BSM search (H_T) observables



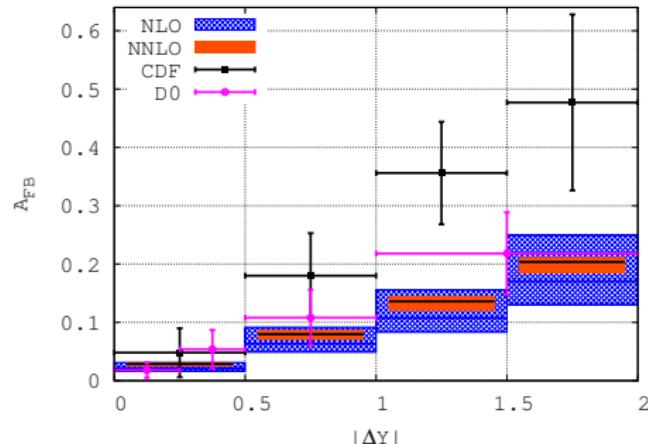
[Krauss, Maierhöfer, Pozzorini, Schönherr, Siegert, SH] arXiv:1402.6293



The top quark forward-backward asymmetry



[Huang,Luisoni,Schönherr,Winter,SH] arXiv:1306.2703



[Czakon,Fiedler,Mitov] Top Workshop 2014, Cannes

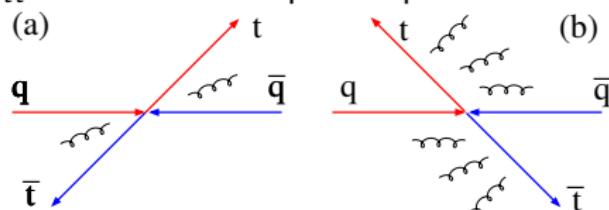
- ME \oplus PS@NLO merged result and full NNLO both agree well with DØ data
- Scale choice should take QCD dynamics into account (\nearrow next slide)
Use method from [Marchesini,Webber] NPB310(1988)461

A_{FB} from a parton shower viewpoint

[Skands, Webber, Winter] arXiv:1205.1466

[Huang, Luisoni, Schönherr, Winter, SH] arXiv:1306.2703

- Parton-shower unitarity broken by splitting of emission phase space
- Events with $\Delta y_{t\bar{t}} > 0$ have fewer phase space for radiation



- But inclusive asymmetry is mainly generated by momentum mapping

$$\Delta\sigma_{+-} = -2 \int \underbrace{d\sigma_{LO}|_{\Delta y > 0} (1 - \Delta_+) P_{+-}}_{\text{subdominant as } \Delta_- < \Delta_+ ((b) \text{ vs. (a)})} + 2 \int \underbrace{d\sigma_{LO}|_{\Delta y < 0} (1 - \Delta_-) P_{-+}}_{\text{dominant as } \Delta_+ > \Delta_- ((a) \text{ vs. (b)})}$$

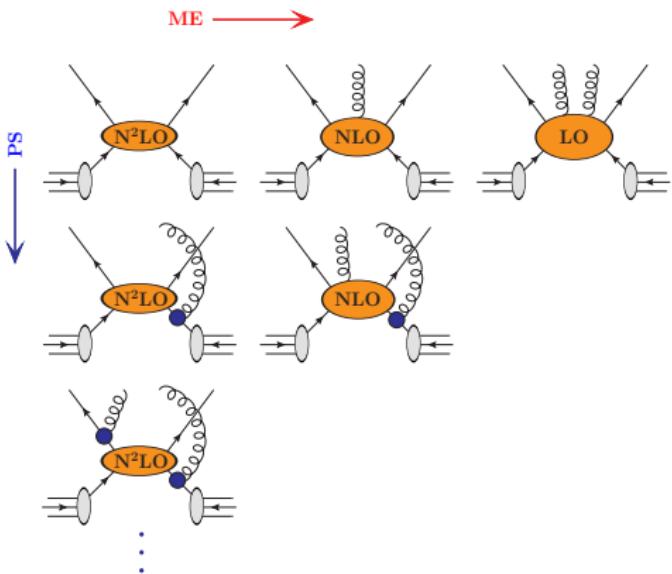
P_{-+}/P_{+-} - probabilities for Δy to increase / decrease in splitting

- Dipole showers generate positive rapidity shift in each emission

$$\Delta y_t = \frac{1}{2} \ln \left(1 + \frac{u_i}{1 - u_i} \left(\frac{1 - x_{ik,a}}{x_{ik,a}} - \frac{2m_k^2}{Q^2 - m_k^2} \right) \frac{\tilde{p}_{ai}^+}{\tilde{p}_k^+} \right) > 0$$

Similar finding for any dipole-like recoil scheme \rightarrow positive asymmetry

Combining NNLO calculations and parton showers



Unitary Matrix-Element Parton-Shower merging

[Lönnblad, Prestel] arXiv:1211.4827

- ▶ PS expression for infrared safe observable, O

$$\langle O \rangle = \int d\Phi_0 B_0 \mathcal{F}_0(\mu_Q^2, O)$$

$$\mathcal{F}_n(t, O) = \Pi_n(t_c, t) O(\Phi_n) + \int_{t_c}^t d\hat{\Phi}_1 K_n \Pi_n(\hat{t}, t) \mathcal{F}_{n+1}(\hat{t}, O)$$

- ▶ Add ME correction to first emission ($B_0 K_0 \rightarrow B_1$) & unitarize

$$+ \int_{t_c}^t d\Phi_1 \Pi_0(t_1, \mu_Q^2) B_1 \mathcal{F}_1(t_1, O) - \int_{t_c}^t d\Phi_1 \Pi_0(t_1, \mu_Q^2) B_1 O(\Phi_0)$$

- ▶ ME evaluated at fixed scales $\mu_{R/F} \rightarrow$ need to adjust to PS

$$w_1 = \frac{\alpha_s(b t_1)}{\alpha_s(\mu_R^2)} \frac{f_a(x_a, t_1)}{f_a(x_a, \mu_F^2)} \frac{f_{a'}(x_{a'}, \mu_F^2)}{f_{a'}(x_{a'}, t_1)}$$

- ▶ Replace B_0 by vetoed xs $\bar{B}_0^{t_c} = B_0 - \int_{t_c}^t d\Phi_1 B_1$

$$\begin{aligned} \langle O \rangle = & \left\{ \int d\Phi_0 \bar{B}_0^{t_c} + \int_{t_c}^t d\Phi_1 \left[1 - \Pi_0(t_1, \mu_Q^2) w_1 \right] B_1 \right\} O(\Phi_0) \\ & + \int_{t_c}^t d\Phi_1 \Pi_0(t_1, \mu_Q^2) w_1 B_1 \mathcal{F}_1(t_1, O) \end{aligned}$$

Extension to NNLO – UN²LOPS

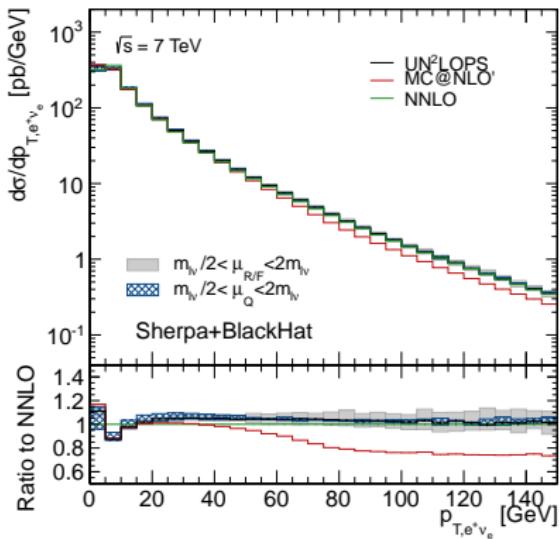
[Lönnblad,Prestel] arXiv:1211.7278
 [Li,Prestel,SH] arXiv:1405.3607

- ▶ Promote vetoed cross section to NNLO
- ▶ Add NLO corrections to B_1 using S-MC@NLO
- ▶ Subtract $\mathcal{O}(\alpha_s)$ term of w_1 and Π_0

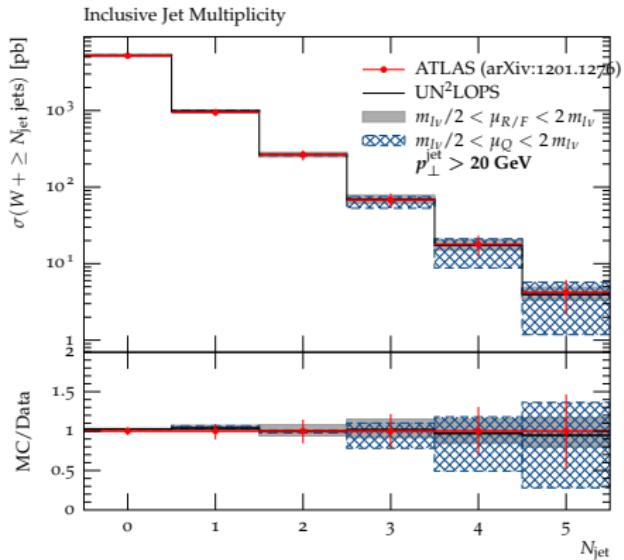
$$\begin{aligned}\langle O \rangle = & \int d\Phi_0 \bar{\mathbb{B}}_0^{t_c} O(\Phi_0) \\ & + \int_{t_c} d\Phi_1 \left[1 - \Pi_0(t_1, \mu_Q^2) \left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1, \mu_Q^2) \right) \right] B_1 O(\Phi_0) \\ & + \int_{t_c} d\Phi_1 \Pi_0(t_1, \mu_Q^2) \left(w_1 + w_1^{(1)} + \Pi_0^{(1)}(t_1, \mu_Q^2) \right) B_1 \bar{\mathcal{F}}_1(t_1, O) \\ & + \int_{t_c} d\Phi_1 \left[1 - \Pi_0(t_1, \mu_Q^2) \right] \tilde{B}_1^R O(\Phi_0) + \int_{t_c} d\Phi_1 \Pi_0(t_1, \mu_Q^2) \tilde{B}_1^R \bar{\mathcal{F}}_1(t_1, O) \\ & + \int_{t_c} d\Phi_2 \left[1 - \Pi_0(t_1, \mu_Q^2) \right] H_1^R O(\Phi_0) + \int_{t_c} d\Phi_2 \Pi_0(t_1, \mu_Q^2) H_1^R \mathcal{F}_2(t_2, O) \\ & + \int_{t_c} d\Phi_2 H_1^E \mathcal{F}_2(t_2, O)\end{aligned}$$

- ▶ $\tilde{B}_1^R = \bar{B}_1 - B_1 = \tilde{V}_1 + I_1 + \int d\Phi_{+1} S_1 \Theta(t_2 - t_1)$
 H_1^R (H_1^E) → regular (exceptional) double real configurations

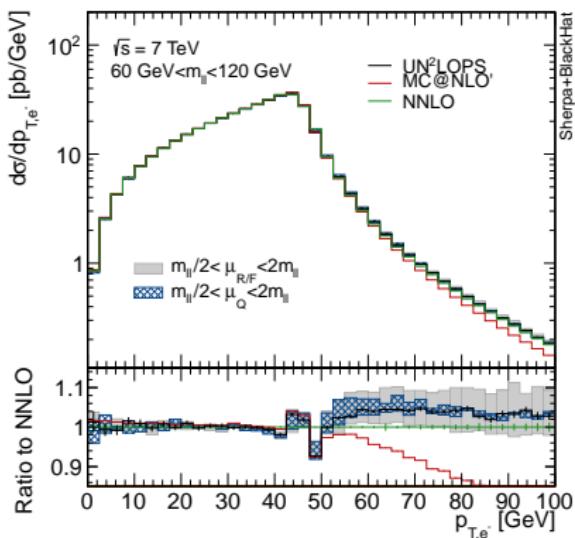
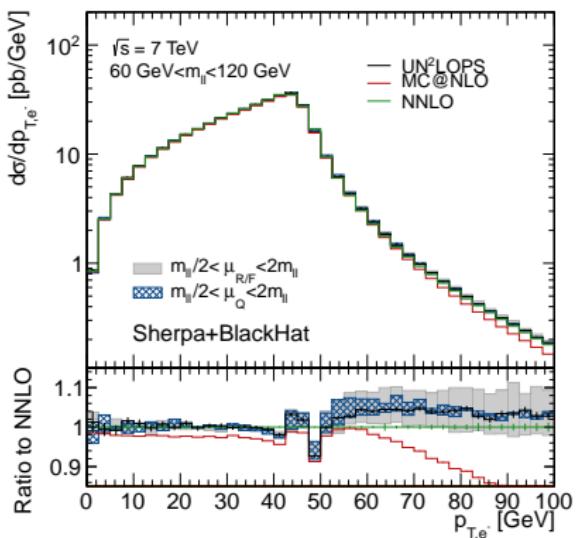
UN²LOPS vs. S-MC@NLO



- Good agreement with S-MC@NLO at low $p_{T,W}$
- $W+1\text{-jet}$ K -factor at high $p_{T,W}$



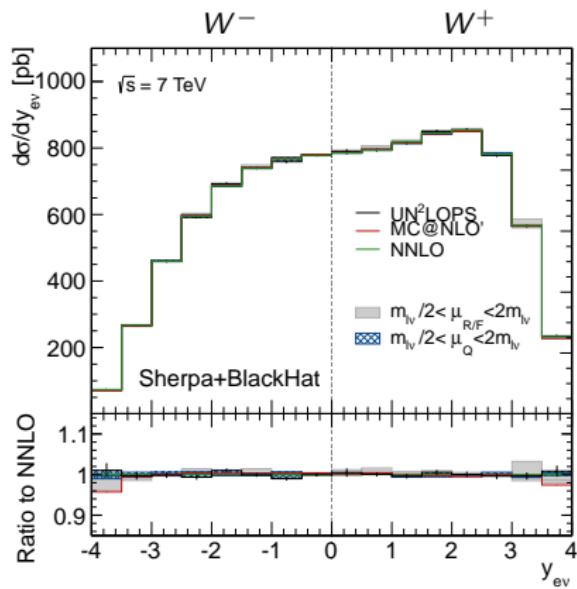
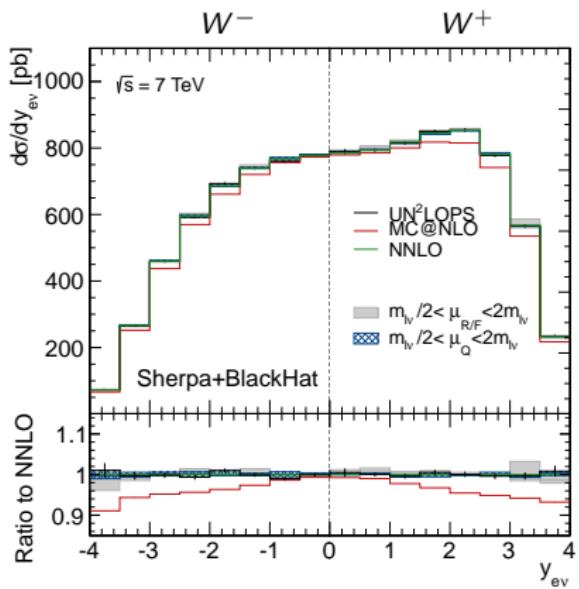
Impact of PDFs



► S-MC@NLO with NLO PDFs

► S-MC@NLO with NNLO PDFs

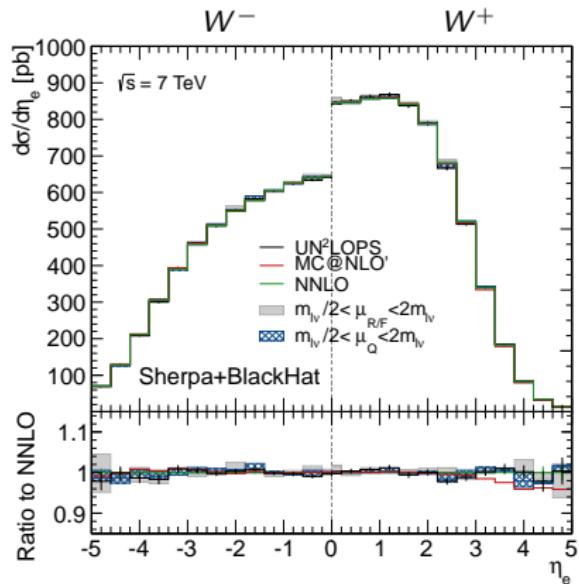
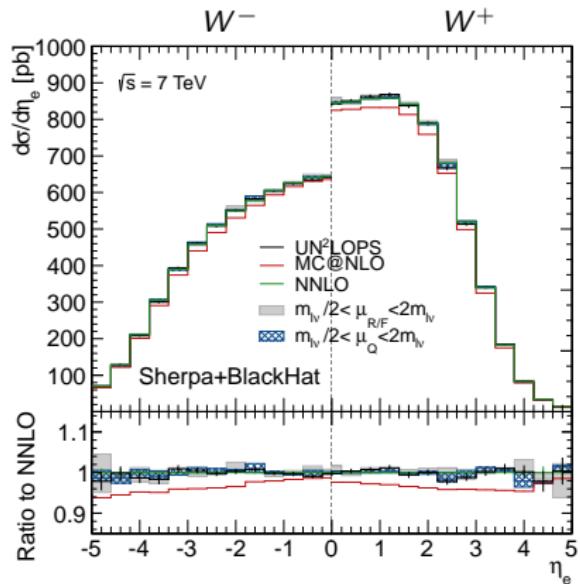
Impact of PDFs



► S-MC@NLO with NLO PDFs

► S-MC@NLO with NNLO PDFs

Impact of PDFs



► S-MC@NLO with NLO PDFs

► S-MC@NLO with NNLO PDFs

Summary

On the bright side

- ▶ NLO (sometimes NNLO) fixed-order calculations are standard
- ▶ Most MC tools include NLO calculations fully automatically

On the dark side

- ▶ Parton showers lack precision compared to analytical resummation
- ▶ Unfortunately, they are most important for getting jet shapes right

We already automated precision calculations at fixed-order
Need to catch up on automating precision resummation

Jet ratio scaling patterns

- ▶ Consider “core” process (e.g. W -production) plus n jets
- ▶ Cross section ratios

$$R_{(n+1)/n} = \frac{\sigma_{n+1}^{\text{excl}}}{\sigma_n^{\text{excl}}}$$

~ stable against QCD corrections [Gerwick et al.] JHEP10(2012)162

▶ Staircase Scaling:

$$R_{(n+1)/n} = \text{const} \quad (\sigma_n = \sigma_0 R^n)$$

- ▶ First predicted for $W/Z + \text{jets}$
[Berends,Giele,Kuijf] NPB321(1989)39
- ▶ Induced by democratic jet cuts
[Gerwick et al.] JHEP10(2012)162

▶ Poisson Scaling:

$$R_{(n+1)/n} = \frac{\bar{n}}{n+1} \quad (\sigma_n = \frac{\bar{n}^n e^{-\bar{n}}}{n!})$$

- ▶ Independent emission picture
(like soft γ radiation in QED)
- ▶ Driven by large emission probability
[Gerwick et al.] JHEP10(2012)162