Recent developments in Sherpa

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On behalf of the Sherpa collaboration

SLAC National Accelerator Laboratory

MC4BSM X

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U.S. DEPARTMENT OF ENERGY
Office of Science

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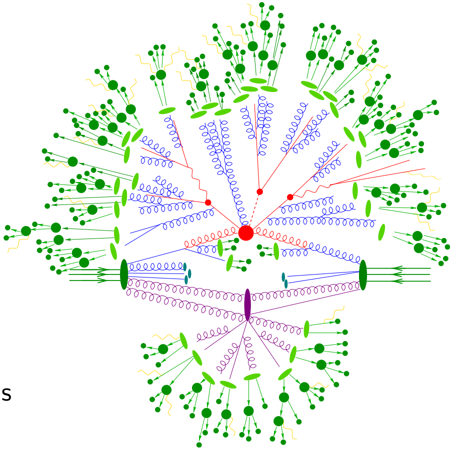
Overview

[Gleisberg,Krauss,Schönherr,Schumann,Siegert,Winter,SH] arXiv:0811.4622
[Bothmann,Krauss,Kuttimalai,Li,Schönherr,Schulz,Schumann,Siegert,Zapp,SH] soon

- Matrix Element generators
  AMEGIC++ (SM)
  and Comix (SM, BSM)
- Parton shower based on
  Catani-Seymour subtraction
  and new dipole-like shower
- Multiple interaction model
  à la Pythia (non-interleaved)
- In-house cluster hadronization
  and interface to PYTHIA string
  fragmentation (cross-checks!)
- Built-in hadron decay package
  $\approx$ 400 hadrons, $\approx$ 2500 channels
- Photon emission generator
  based on YFS formalism



LO calculations

[Kuttimalai,Schumann,Siegert,SH] arXiv:1412.6478

- Until Sherpa 2.2.0 hardcoded models & dedicated FeynRules interface
- Since Sherpa 2.2.0 UFO interface $\rightarrow$ easy & automatic model setup
- Converter script generates Lorentz calculators fully automatically
- Color calculators currently hardwired, working on generalization
- Tested on a large set of processes, including

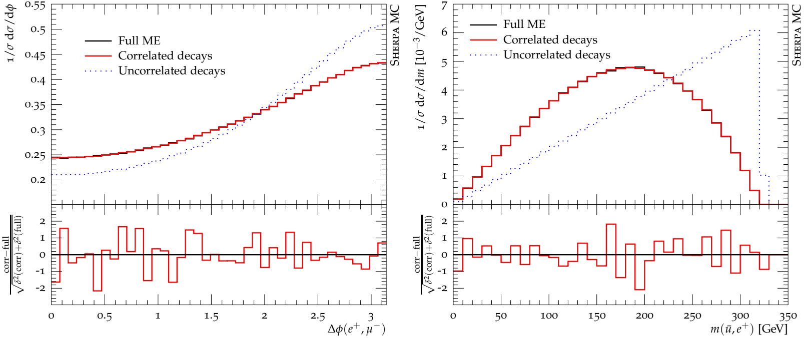
  [Hagiwara et al.] hep-ph/0512260, [Christensen et al.] arXiv:0906.2474

Model	number of processes tested	max. rel. deviation Comix $\leftrightarrow$ MadGraph5
Standard Model	60	$2.3 \cdot 10^{-10}$
Higgs Effective Field Theory	13	$4.3 \cdot 10^{-13}$
MSSM	401	$1.0 \cdot 10^{-10}$
Minimal Universal Extra Dimensions	51	$2.8 \cdot 10^{-12}$
Anomalous Quartic Gauge Couplings	16	$5.9 \cdot 10^{-12}$

LO calculations

[Kuttimalai,Schumann,Siegert,SH] arXiv:1412.6478

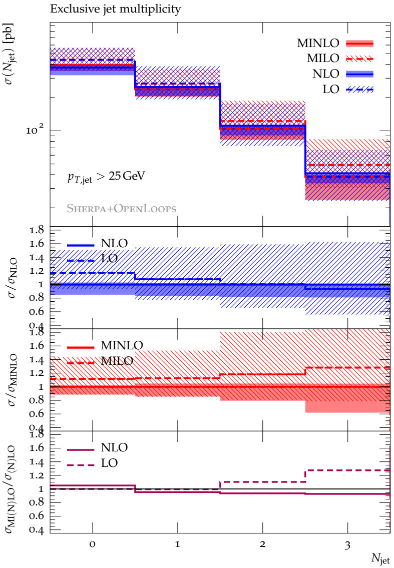
- Spin correlation algorithm for decay chains [Richardson] hep-ph/0110108
- Examples: $pp \to t\bar{t} \to b e^+ \nu_e \bar{b} \mu^- \bar{\nu}_\mu$ in SM,
  $pp \to \tilde{u}\tilde{u}^* \to d\,\chi_1^0\,\mu^+\,\nu_\mu\,\bar{u}\,e^+\,e^-\,\chi_1^0$ in MSSM



NLO QCD calculations

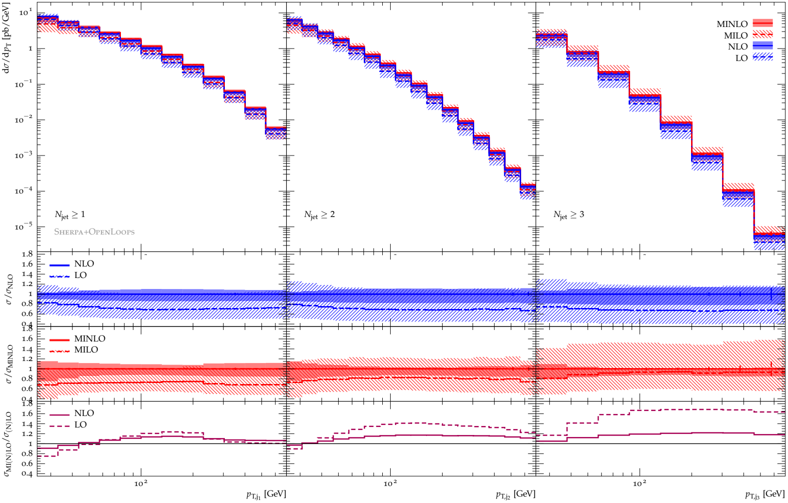
[Maierhöfer,Moretti,Pozzorini,Siegert,SH] in preparation

- First computation of $t\bar{t}$+3 jets at NLO / MINLO accuracy
- Sherpa NLO MC framework using Comix [Gleisberg,SH] arXiv:0808.3674 combined with OpenLoops [Cascioli,Maierhöfer,Pozzorini] arXiv:1111.5206
- Public results in NTuple format [BlackHat collaboration] arXiv:1310.7439 for easy analysis & recycling will be made available at NERSC
- Scale dependence studied using $H_{T,m} = \sum m_\perp$ and MINLO [Hamilton,Nason,Zanderighi] arXiv:1206.3572 extended to massive partons



NLO QCD calculations

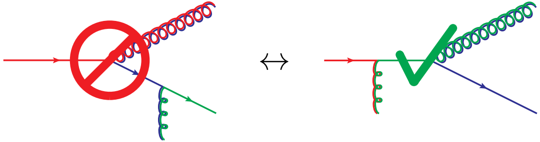
[Maierhöfer,Moretti,Pozzorini,Siegert,SH] in preparation



Color coherence and the color dipole picture

[Marchesini,Webber] NPB310(1988)461

- Individual color charges inside a color dipole cannot be resolved by gluons of wavelength larger than the dipole size
  $\rightarrow$ emission off combined mother parton instead



- Net effect is destructive interference outside cone with opening angle defined by emitting color dipole
  $\rightarrow$ Soft anomalous dimension halved due to reduced phase space
- Formerly implemented by angular ordering / angular veto
- Alternative description in terms of color dipoles

  [Gustafsson,Pettersson] NPB306(1988)746, [Kharraziha,Lönnblad] hep-ph/9709424
  [Winter,Krauss] arXiv:0712.3913

The midpoint between dipole and parton showers

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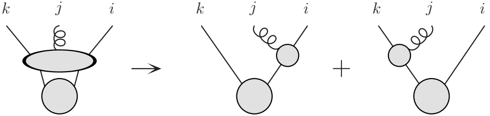
- Angular ordered / vetoed parton shower does not fill full phase space
  Dipole shower lacks parton interpretation $\rightarrow$ prefer alternative to both
- Can preserve parton picture by partial fractioning soft eikonal
  $\leftrightarrow$ soft enhanced part of splitting function [Catani,Seymour] hep-ph/9605323

$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \rightarrow \frac{1}{p_i p_j}\,\frac{p_i p_k}{(p_i + p_k) p_j} + \frac{1}{p_k p_j}\,\frac{p_i p_k}{(p_i + p_k) p_j}$$



- "Spectator"-dependent kernels, singular in soft-collinear region only
  $\rightarrow$ capture dominant coherence effects (3-parton correlations)

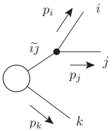
$$\frac{1}{1-z} \rightarrow \frac{1-z}{(1-z)^2 + \kappa^2} \qquad \kappa^2 = \frac{k_\perp^2}{Q^2}$$

- For correct soft evolution, ordering variable must be identical at both "dipole ends" ($\rightarrow$ recover soft eikonal at integrand level)

The midpoint between dipole and parton showers

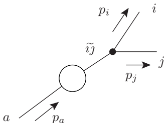
Choose parametrization such that soft term is $\frac{1-z}{(1-z)^2+\kappa^2}$ in all dipole types

(1) FF



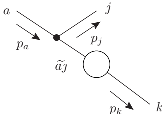
$$\kappa^2 = \frac{p_ip_j\,p_jp_k}{(p_{\widetilde{ij}}p_{\tilde{k}})^2} \qquad z_j = \frac{p_jp_k}{p_{\widetilde{ij}}p_{\tilde{k}}}$$

(2) FI



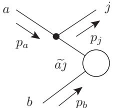
$$\kappa^2 = \frac{p_ip_j\,p_jp_a}{(p_{ij}p_a)^2} \qquad z_j = \frac{p_jp_a}{p_{ij}p_a}$$

(3) IF



$$\kappa^2 = \frac{p_ap_j\,p_jp_k}{(p_{jk}p_a)^2} \qquad z_j = \frac{p_jp_k}{p_{jk}p_a}$$

(4) II



$$\kappa^2 = \frac{p_ap_j\,p_jp_b}{(p_ap_b)^2} \qquad z_j = \frac{p_jp_b}{p_ap_b}$$

Preserve collinear anomalous dimensions & sum rules → splitting functions fixed

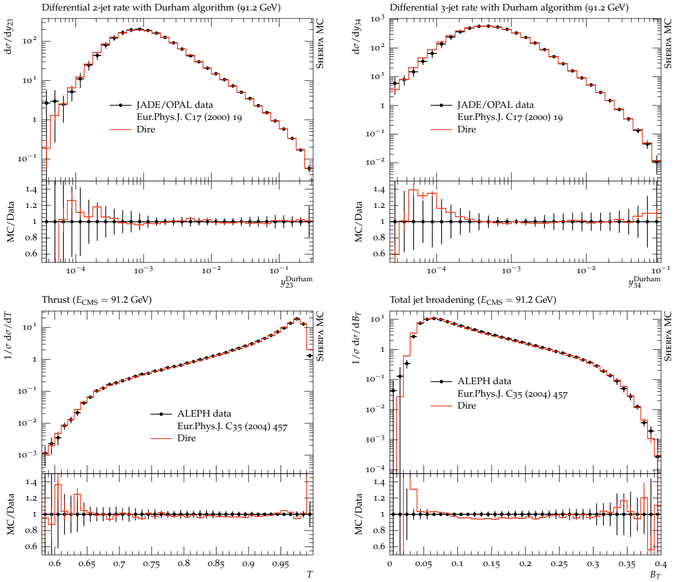
$$P_{qq}(z,\kappa^2) = 2\,C_F\left[\left(\frac{1-z}{(1-z)^2+\kappa^2}\right)_+ - \frac{1+z}{2}\right] + \gamma_q\,\delta(1-z)$$

$$P_{gg}(z,\kappa^2) = 2\,C_A\left[\left(\frac{1-z}{(1-z)^2+\kappa^2}\right)_+ + \frac{z}{z^2+\kappa^2} - 2 + z(1-z)\right] + \gamma_g\,\delta(1-z)$$

$$P_{qg}(z,\kappa^2) = 2\,C_F\left[\frac{z}{z^2+\kappa^2} - \frac{2-z}{2}\right] \qquad P_{gq}(z,\kappa^2) = T_R\left[z^2+(1-z)^2\right]$$

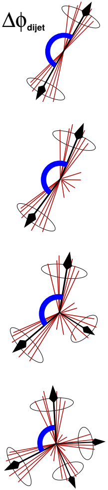
The midpoint between dipole and parton showers

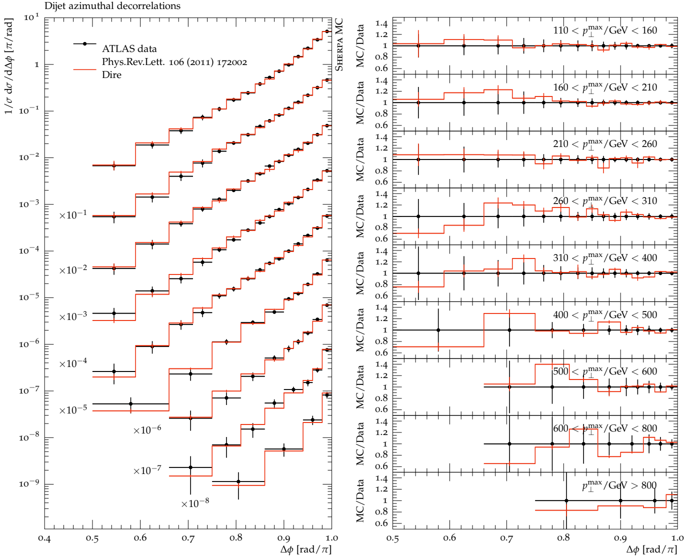
[Prestel,SH] arXiv:1506.05057



Predictions for the LHC

[Prestel,SH] arXiv:1506.05057





Extension to a subtraction method and MC@NLO

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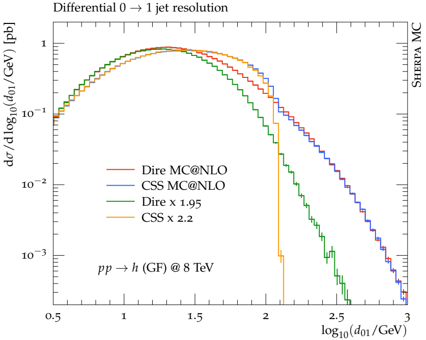
[SH] NTBP

- Can view new shower model as modification of CS subtraction
- IR-finite counterterms computed and implemented in Sherpa (improved cancellation in $pp \to h + j$ due to regulated $1/z$ terms)

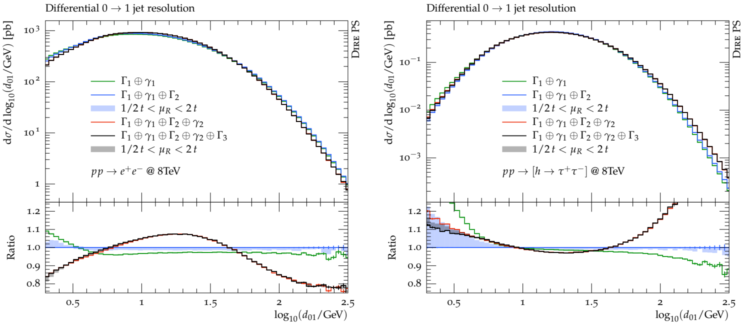
- Sherpa MC@NLO based on exponentiation of CS dipole subtraction terms

  [Krauss,Siegert,Schönherr,SH] arXiv:1111.1220, arXiv:1208.2815
- Dire modified CS subtraction automatically available for MC@NLO matching
- Interesting differences due to evolution variables and kernels



Towards higher logarithmic accuracy

- Big drawback of parton showers is lack of higher-order kernels
- Start improving with spacelike NLO kernels
  [Curci,Furmanski,Petronzio] NPB175(1980)27, PLB97(1980)437
- 2-loop cusp term subtracted & combined with LO soft contribution (similar to CMW rescaling [Catani,Marchesini,Webber] NPB349(1991)635)
- Implemented using weighting algorithms [Schumann,Siegert,SH] arXiv:0912.3501



Uncertainty estimates

Explicit variations

- Can be done for any scale or PDF dependence
- Functional form can be changed
- Separate runs with changed input

On-the-fly variations

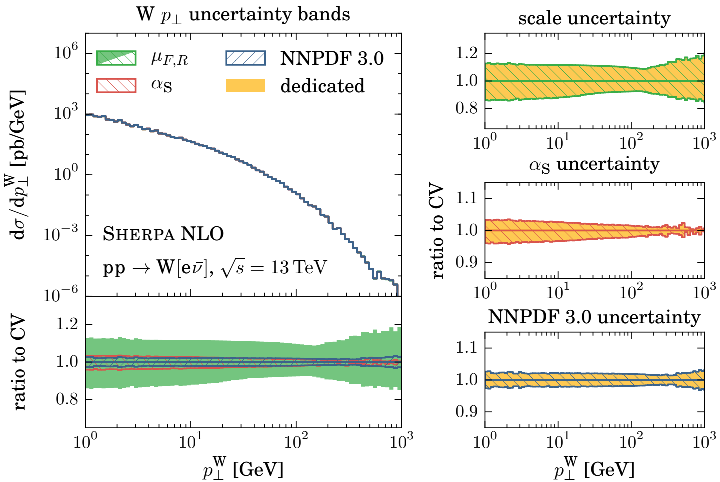
- Can be done for $\mu_{R/F}$ and PDF dependence of matrix elements
- Functional form of scale can currently not be changed
- Full syntax cf. Manual, simplified syntax:

```
VARIATIONS 0.25,0.25 4.,4.;
VARIATIONS NNPDF30_nnlo_as_0118[all];
```

- Stored in HepMC::WeightContainer
  using LH naming convention [LesHouches SM WG] arXiv:1405.1067

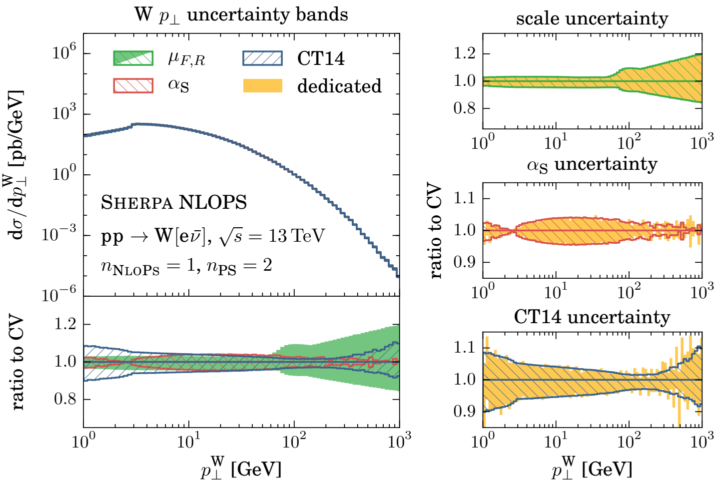
Uncertainty estimates – NLO

[Bothmann,Schönherr,Schumann] arXiv:1606.08753



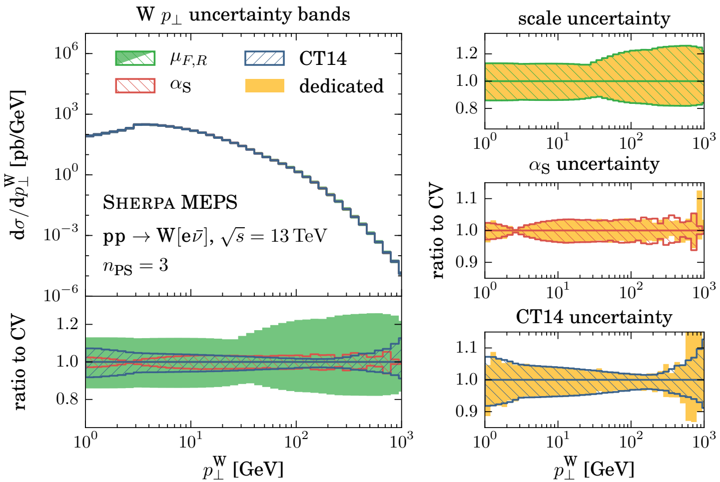
Uncertainty estimates – NLO+PS

[Bothmann, Schönherr, Schumann] arXiv:1606.08753



Uncertainty estimates – ME+PS

[Bothmann,Schönherr,Schumann] arXiv:1606.08753



NLO electroweak corrections

[Kallweit,Lindert,Maierhöfer,Pozzorini,Schönherr] arXiv:1412.5157, arXiv:1511.08692

- Fixed-order next-to-leading order electroweak corrections

$$\mathrm{d}\sigma_{NLO} = \int \mathrm{d}\Phi_B \left[B(\Phi_B) + V_{\mathrm{EW}}(\Phi_B) + I_{\mathrm{QED}}(\Phi_B)\right] + \int \mathrm{d}\Phi_R \left[R_{\mathrm{EW}}(\Phi_R) - S_{\mathrm{QED}}(\Phi_R)\right]$$

- Automated implementation, independent cross checks:
  - OpenLoops for virtual corrections
    cross checked against independent private generator
  - Munich for phase space integration (MEs from OpenLoops),
    Sherpa for Born, real emission, subtraction and phase space
- Combine QCD and EW corrections as:

  QCD+EW: $\sigma_{\mathrm{NLO\ QCD+EW}} = \sigma_{\mathrm{LO}}(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{EW}})$
  QCD×EW: $\sigma_{\mathrm{NLO\ QCD\times EW}} = \sigma_{\mathrm{LO}}(1 + \delta_{\mathrm{QCD}})(1 + \delta_{\mathrm{EW}})$

  Use difference as indication of potential size of $\mathcal{O}(\alpha_s\alpha)$ corrections

NLO electroweak corrections

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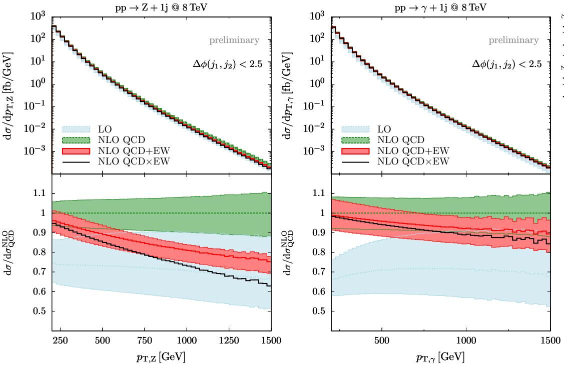
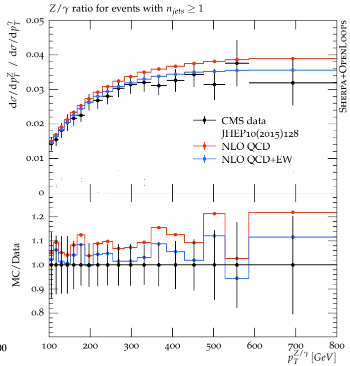
[Kallweit, Lindert, Maierhöfer, Pozzorini, Schönherr] arXiv:1505.05704
[LesHouches SM WG Report] arXiv:1605.04692





- EW corrections differ for Z and γ, affects Z/γ rate

Electroweak merging

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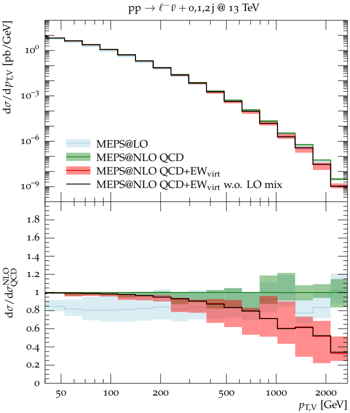
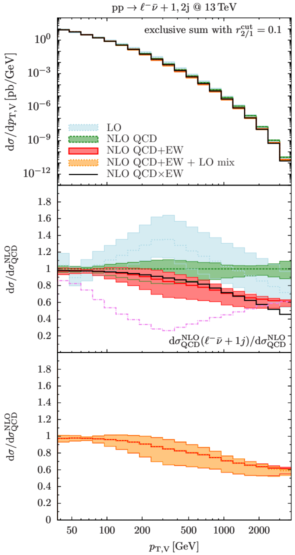
[Kallweit,Lindert,Maierhöfer,Pozzorini,Schönherr] arXiv:1511.08692





- QCD parton shower merged with QCD+EW matrix elements

Summary

Extension of Sherpa's capabilities:

- UFO interface
- Dipole-like parton shower
- On-the-fly variations, (N)LO, (N)LO+PS & MEPS(@NLO)
- Electroweak corrections at fixed order
- Merging of QCD+EW calculations with QCD PS
- MINLO method for massless and massive partons