Matching and merging fixed orders and parton showers

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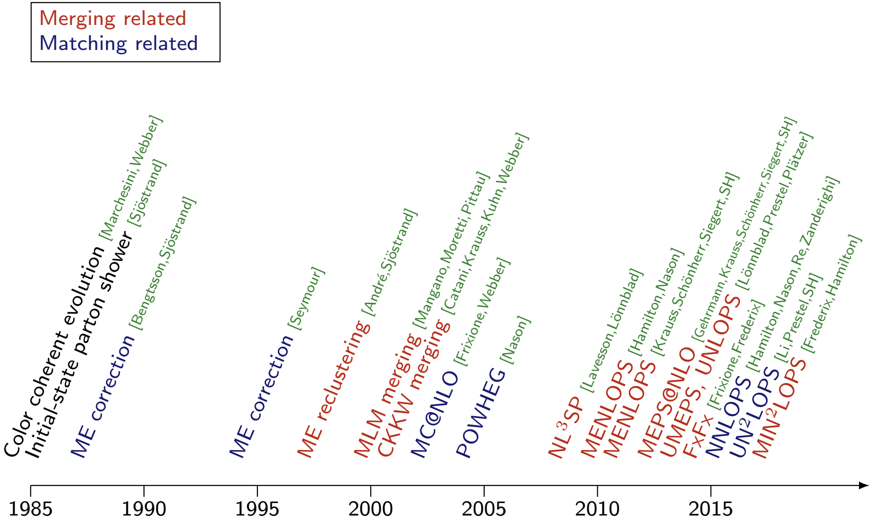
Stress-testing the SM at the LHC

Santa Barbara, 05/24/2016

The long road to precise Monte-Carlo simulations



NLO+PS matching – Basics

- Leading-order calculation for observable O

$$\langle O\rangle = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\,O(\Phi_B)$$

- NLO calculation for same observable

$$\langle O\rangle = \int \mathrm{d}\Phi_B\left\{\mathrm{B}(\Phi_B)+\tilde{V}(\Phi_B)\right\}O(\Phi_B)+\int \mathrm{d}\Phi_R\,\mathrm{R}(\Phi_R)\,O(\Phi_R)$$

- Parton-shower result (zero and one emission)

$$\langle O\rangle = \int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left[\Delta^{(\mathrm{K})}(t_c)\,O(\Phi_B)+\int_{t_c}\mathrm{d}\Phi_1\,\mathrm{K}(\Phi_1)\,\Delta^{(\mathrm{K})}(t(\Phi_1))\,O(\Phi_R)\right]$$

$$\stackrel{\mathcal{O}(\alpha_s)}{\to}\int \mathrm{d}\Phi_B\,\mathrm{B}(\Phi_B)\left\{1-\int_{t_c}\mathrm{d}\Phi_1\mathrm{K}(\Phi_1)\right\}O(\Phi_B)+\int_{t_c}\mathrm{d}\Phi_B\mathrm{d}\Phi_1\,\mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1)\,O(\Phi_R)$$

Phase space: $\mathrm{d}\Phi_1 = \mathrm{d}t\,\mathrm{d}z\,\mathrm{d}\phi\,J(t,z,\phi)$
Splitting functions: $\mathrm{K}(t,z)\to\alpha_s/(2\pi t)\,\sum\mathrm{P}(z)\,\Theta(\mu_Q^2-t)$
Sudakov factors: $\Delta^{(\mathrm{K})}(t)=\exp\left\{-\int_t\mathrm{d}\Phi_1\mathrm{K}(\Phi_1)\right\}$

NLO+PS matching – MC@NLO

[Frixione,Webber] hep-ph/0204244

- Subtract $\mathcal{O}(\alpha_s)$ PS terms from subtracted NLO result ($t_c \to 0$)
  $1/N_c$ corrections faded out in soft region by smoothing function

$$\bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B) = \mathrm{B}(\Phi_B) + \tilde{\mathrm{V}}(\Phi_B) + \mathrm{I}(\Phi_B) + \int \mathrm{d}\Phi_1 \left[\mathrm{S}(\Phi_R) - \mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1) \right] f(\Phi_1)$$

$$\mathrm{H}^{(\mathrm{K})}(\Phi_R) = \left[\mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\,\mathrm{K}(\Phi_1) \right] f(\Phi_1)$$

- Add parton shower, described by generating functional $\mathcal{F}_{\mathrm{MC}}$

$$\langle O \rangle = \int \mathrm{d}\Phi_B\, \bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B)\, \mathcal{F}^{(0)}_{\mathrm{MC}}(\mu_Q^2, O) + \int \mathrm{d}\Phi_R\, \mathrm{H}^{(\mathrm{K})}(\Phi_R)\, \mathcal{F}^{(1)}_{\mathrm{MC}}(t(\Phi_R), O)$$

- Expansion of matched result up to first emission

$$\langle O \rangle = \int \mathrm{d}\Phi_B \bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B) \Bigg[\Delta^{(\mathrm{K})}(t_c)\, O(\Phi_B) + \int_{t_c} \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1) \Delta^{(\mathrm{K})}(t(\Phi_1))\, O(\Phi_r) \Bigg] + \int \mathrm{d}\Phi_R\, \mathrm{H}^{(\mathrm{K})}(\Phi_{n+1})\, O(\Phi_R)$$

NLO+PS matching – POWHEG

[Nason] hep-ph/0409146
[Frixione,Nason,Oleari] arXiv:0709.2092

- Replace $\mathrm{BK} \to \mathrm{R} \Rightarrow \mathrm{H}^{(\mathrm{R})}$ zero, $\bar{\mathrm{B}}^{(\mathrm{R})}$ positive in physical region

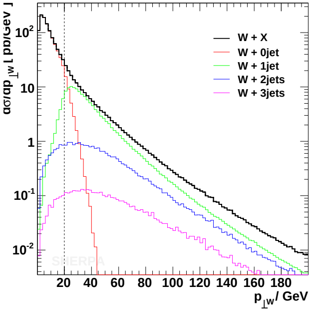
$$\langle O \rangle = \int \mathrm{d}\Phi_B \bar{\mathrm{B}}^{(\mathrm{R})}(\Phi_B) \Bigg[\Delta^{(\mathrm{R})}(t_c, s_{\mathrm{had}})\, O(\Phi_B) + \int_{t_c}^{s_{\mathrm{had}}} \mathrm{d}\Phi_1 \frac{\mathrm{R}(\Phi_R)}{\mathrm{B}(\Phi_B)} \Delta^{(\mathrm{R})}(t(\Phi_1), s_{\mathrm{had}})\, O(\Phi_R) \Bigg]$$

- μ_Q^2 changed to hadronic centre-of-mass energy squared, s_{had}, to cover full phase space for real-emission correction
- Absence of hard events $\to$ enhanced high-p_T region ($K = \bar{\mathrm{B}}/\mathrm{B}$)
  Formally beyond NLO, but often sizeable $\to$ Avoid by split $\mathrm{R} \to \mathrm{R}^s + \mathrm{R}^f$

$$\langle O \rangle = \int \mathrm{d}\Phi_B \bar{\mathrm{B}}^{(\mathrm{R}^{\mathrm{s}})}(\Phi_B) \Bigg[\Delta^{(\mathrm{R}^{\mathrm{s}})}(t_c, s_{\mathrm{had}})\, O(\Phi_B) + \int_{t_c}^{s_{\mathrm{had}}} \mathrm{d}\Phi_1 \frac{\mathrm{R}^{\mathrm{s}}(\Phi_R)}{\mathrm{B}(\Phi_B)} \Delta^{(\mathrm{R}^{\mathrm{s}})}(t(\Phi_1), s_{\mathrm{had}})\, O(\Phi_R) \Bigg] + \int \mathrm{d}\Phi_R\, \mathrm{R}^{\mathrm{f}}(\Phi_R)$$

Basic idea of ME+PS merging

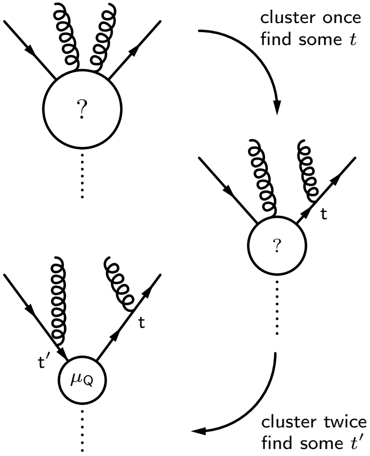
- Separate phase space into "hard" and "soft" region
- Matrix elements populate hard domain
- Parton shower populates soft domain
- Need criterion to define "hard" & "soft" $\rightarrow$ jet measure Q and corresponding cut, Q_{cut}



Parton-shower histories

[André,Sjöstrand] hep-ph/9708390

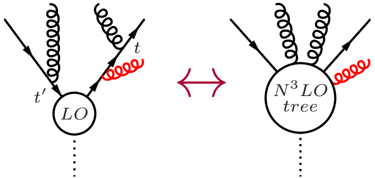
- Start with some "core" process for example $e^+e^- \to q\bar{q}$
- This process is considered inclusive It sets the resummation scale μ_Q^2
- Higher-multiplicity ME can be reduced to core by clustering
- Clustering algorithm uniquely defined by requiring exact correspondence between ME & PS
    - Identify most likely splitting according to PS emission probability
    - Combine partons into mother according to PS kinematics
    - Continue until no clustering possible



Truncated & vetoed parton showers

[Catani,Krauss,Kuhn,Webber] hep-ph/0109231
[Lönnblad] hep-ph/0112284, arXiv:1211.7204

- Higher-multiplicity MEs that can be reduced to core process are included in core's inclusive cross section (unitarity of PS)
- Sudakov suppression factors needed to make inclusive MEs exclusive
- Most efficiently computed with pseudo-showers
  - Start PS from core process
  - Evolve until predefined branching ↔ truncated parton shower
  - Emissions producing additional hard jets lead to event veto/weight



$$\Delta^{(\mathrm{K})}(t; > Q_{\mathrm{cut}}) = \exp\left\{ -\int_t \mathrm{d}\Phi_1\, \mathrm{K}(\Phi_1)\, \Theta(Q - Q_{cut}) \right\}$$

ME+PS merging

- ME⊕PS for 0+1-jet in Mc@Nlo notation

$$\langle O\rangle = \int \mathrm{d}\Phi_B \mathrm{B}(\Phi_B)\Big[\Delta^{(\mathrm{K})}(t_c)\,O(\Phi_B) + \int_{t_c} \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)\,\Delta^{(\mathrm{K})}(t)\,\Theta(Q_{\mathrm{cut}} - Q)\,O(\Phi_R)\Big]$$
$$+ \int \mathrm{d}\Phi_R\,\mathrm{R}(\Phi_R)\,\Delta^{(\mathrm{K})}(t(\Phi_R); > Q_{\mathrm{cut}})\,\Theta(Q - Q_{\mathrm{cut}})\,O(\Phi_R) + \ldots$$

- Reorder by parton multiplicity k, change notation $\mathrm{R}_k \to \mathrm{B}_{k+1}$
- Analyze exclusive contribution from k hard partons only $(t_0 = \mu_Q^2)$

$$\langle O\rangle_k^{\mathrm{excl}} = \int \mathrm{d}\Phi_k\,\mathrm{B}_k \prod_{i=0}^{k-1} \Delta_i^{(\mathrm{K})}(t_{i+1}, t_i; > Q_{\mathrm{cut}})\,\Theta(Q_k - Q_{\mathrm{cut}})$$
$$\times \Big[\Delta_k^{(\mathrm{K})}(t_c, t_k)\,O_k + \int_{t_c}^{t_k} \mathrm{d}\Phi_1\,\mathrm{K}_k\,\Delta_k^{(\mathrm{K})}(t_{k+1}, t_k)\,\Theta(Q_{\mathrm{cut}} - Q_{k+1})\,O_{k+1}\Big]$$

ME+PS merging – Unitarization

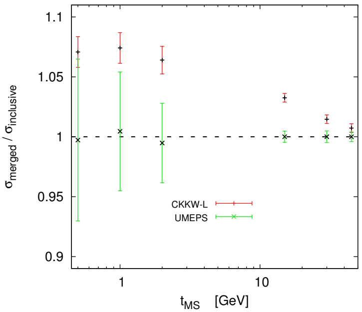
[Lönnblad,Prestel] arXiv:1211.4827, [Plätzer] arXiv:1211.5467

- Unitarity condition of PS:

$$1 = \Delta^{(\mathrm{K})}(t_c) + \int_{t_c} \mathrm{d}\Phi_1\, \mathrm{K}(\Phi_1)\, \Delta^{(\mathrm{K})}(t)$$

- ME+PS(@NLO) violates PS unitarity as ME ratio replaces splitting kernels in emission terms, but not in Sudakovs

$$\mathrm{K}(\Phi_1) \to \frac{\mathrm{R}(\Phi_1, \Phi_B)}{\mathrm{B}(\Phi_B)}$$



- Can be corrected by explicit subtraction

$$1 = \underbrace{\left\{ \Delta^{(\mathrm{K})}(t_c) + \int_{t_c} \mathrm{d}\Phi_1 \left[\mathrm{K}(\Phi_1) - \frac{\mathrm{R}(\Phi_1, \Phi_B)}{\mathrm{B}(\Phi_B)} \right] \Theta(Q - Q_{\mathrm{cut}})\, \Delta^{(\mathrm{K})}(t) \right\}}_{\text{unresolved emission / virtual correction}}$$

$$+ \underbrace{\int_{t_c} \mathrm{d}\Phi_1 \left[\mathrm{K}(\Phi_1)\Theta(Q_{\mathrm{cut}} - Q) + \frac{\mathrm{R}(\Phi_1, \Phi_B)}{\mathrm{B}(\Phi_B)} \Theta(Q - Q_{\mathrm{cut}}) \right] \Delta^{(\mathrm{K})}(t)}_{\text{resolved emission}}$$

ME+PS merging at NLO

- Analyze exclusive contribution from k hard partons

$$
\begin{aligned}
\langle O\rangle_k^{\rm excl} \;=\; & \int \mathrm{d}\Phi_k\,\bar{\mathrm{B}}_k^{(\mathrm{K})} \prod_{i=0}^{k-1} \Delta_i^{(\mathrm{K})}(t_{i+1},t_i;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut}) \\
& \times\left(1+\frac{\mathrm{B}_k}{\bar{\mathrm{B}}_k^{(\mathrm{K})}}\sum_{i=0}^{k-1}\int_{t_{i+1}}^{t_i}\mathrm{d}\Phi_1\mathrm{K}_i\,\Theta(Q_i-Q_{\rm cut})\right) \\
& \times\left[\Delta_k^{(\mathrm{K})}(t_c,t_k)\,O_k+\int_{t_c}^{t_k}\mathrm{d}\Phi_1\;\mathrm{K}_k\,\Delta_k^{(\mathrm{K})}(t_{k+1},t_k)\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}\right] \\
& +\int \mathrm{d}\Phi_{k+1}\,\mathrm{H}_k^{(\mathrm{K})}\,\Delta_k^{(\mathrm{K})}(t_k;>Q_{\rm cut})\,\Theta(Q_k-Q_{\rm cut})\,\Theta(Q_{\rm cut}-Q_{k+1})\,O_{k+1}
\end{aligned}
$$

- Born matrix element $\rightarrow$ NLO-weighted Born
- Add hard remainder function
- Subtract $\mathcal{O}(\alpha_s)$ terms contained in truncated PS

ME+PS merging – Practical implementations

- LO schemes

Method	Shower Generator	Unitary	References
MLM	Herwig/Pythia	No	[Mangano,Moretti,Pittau] hep-ph/0108069 [Alwall et al.] arXiv:0706.2569
CKKW	Apacic	No	[Catani,Krauss,Kuhn,Webber] hep-ph/0109231
CKKW-L	Ariadne/Pythia	No	[Lönnblad] hep-ph/0112284 [Lönnblad,Prestel] arXiv:1109.4829
METS	Sherpa CSS	No	[Krauss,Schumann,Siegert,SH] arXiv:0903.1219
CKKW'	Herwig++	No	[Hamilton,Richardson,Tully] arXiv:0905.3072
UMEPS	Pythia/Herwig++	Yes	[Lönnblad,Prestel] arXiv:1211.4827 [Plätzer] arXiv:1211.5467

- NLO schemes

Method	Shower Generator	Unitary	References
NL^3	Ariadne/Pythia	No	[Lavesson,Lönnblad] arXiv:0811.2912
MEPS@NLO	Sherpa CSS	No	[Krauss,Schönherr,Siegert,SH] arXiv:1207.5030 [Gehrmann,Krauss,Schönherr,Siegert,SH] 5031
FxFx	Herwig(++)/Pythia	No	[Frederix,Frixione] arXiv:1209.6215
UNLOPS	Pythia/Herwig++	Yes	[Lönnblad,Prestel] arXiv:1211.7278

NNLO matching methods

NNLOPS

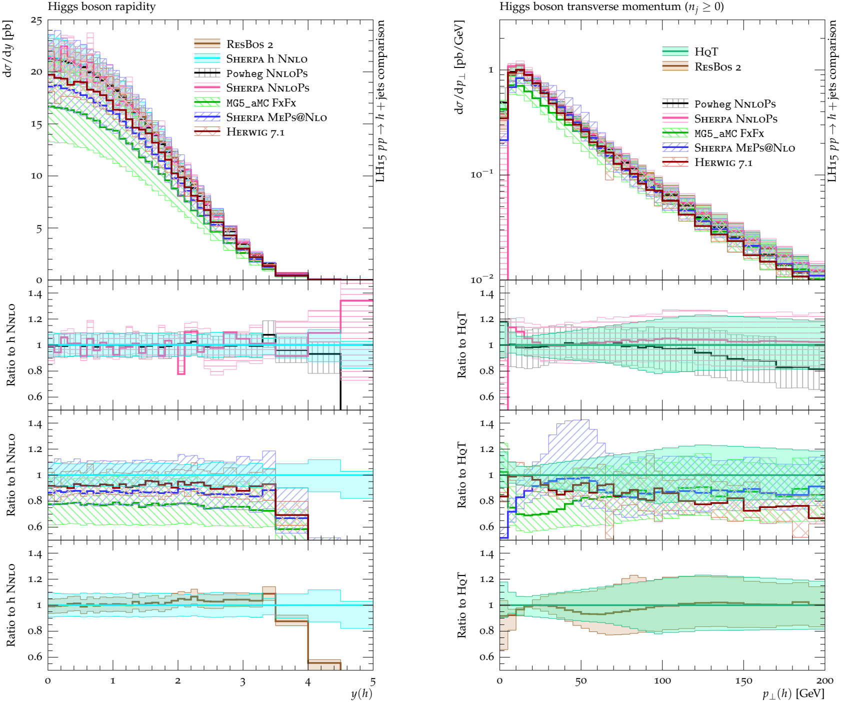
[Hamilton,Nason,Zanderighi] arXiv:1212.4504
[Hamilton,Nason,Re,Zanderighi] arXiv:1309.0017

- Based on MINLO procedure
  [Hamilton,Nason,Zanderighi] arXiv:1206.3572
- Extended to NNLL resummation and reweighted to NNLO differentially in Born phase space

UN^{2}LOPS

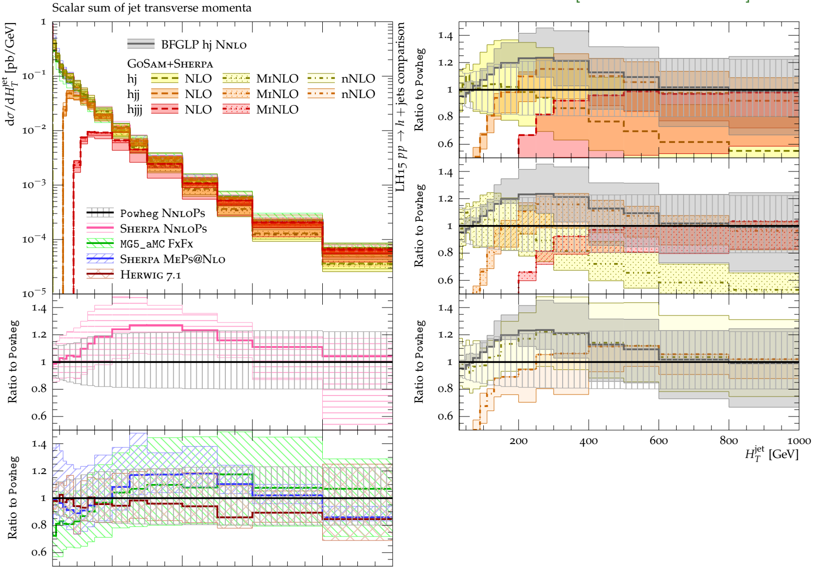
[Li,Prestel,SH] arXiv:1405.3607

- Based on UNLOPS merging
  [Lönnblad,Prestel] arXiv:1211.7278
- q_T-cutoff technique for NNLO, combined with subtracted MC@NLO for 1-jet contribution


Higgs boson rapidity
ResBos 2
Sherpa h NNLO
Powheg NNLOPs
Sherpa NNLOPs
MG5_aMC FxFx
Sherpa MePs@NLO
Herwig 7.1
dσ/dy [pb]
LH15 pp → h + jets comparison
Ratio to h NNLO
y(h)
Higgs boson transverse momentum ($n_j \geq 0$)
HqT
dσ/dp⊥ [pb/GeV]
Ratio to HqT
p⊥(h) [GeV]

Comparison of approaches

[Les Houches SM WG] arXiv:1605.04692



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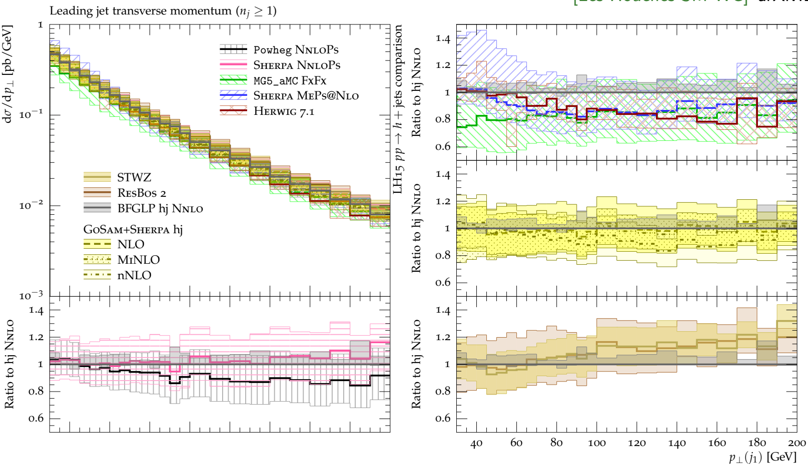

Comparison of approaches

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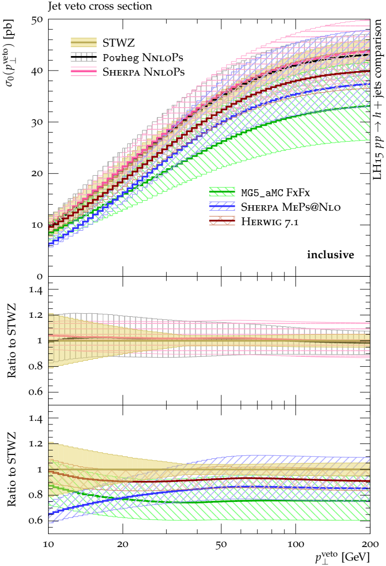
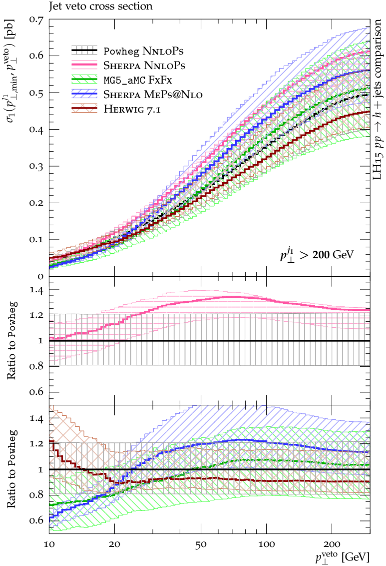
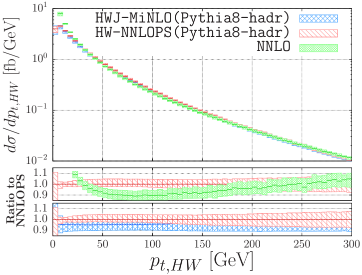
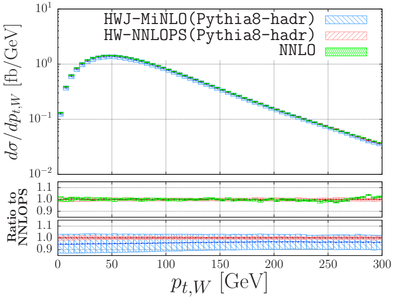


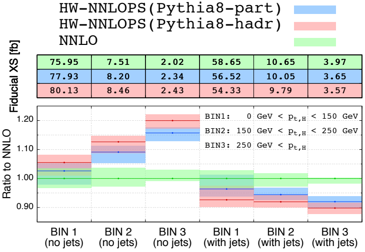


NNLO+PS for WH production

[Astill,Bizon,Re,Zanderighi] arXiv:1603.01620





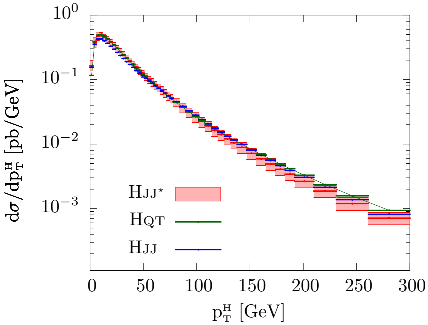


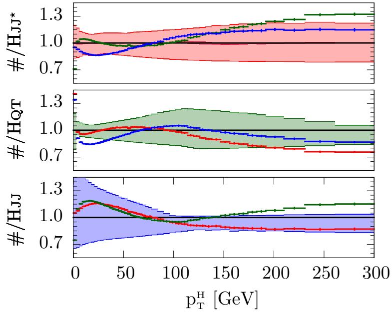
- Using NNLOPS technique
- Small corrections on Born-type observables, but visible effects e.g. on jet veto xs

Merged MINLO simulations

[Frederix,Hamilton] arXiv:1512.02663

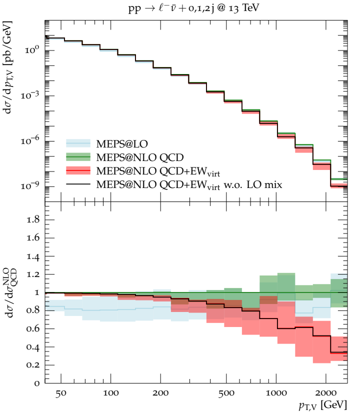
- First method to combine NNLO matched simulation with higher-multiplicity NLO matched simulation
- NNLOPS for H/HJ and modified MINLO for HJJ production

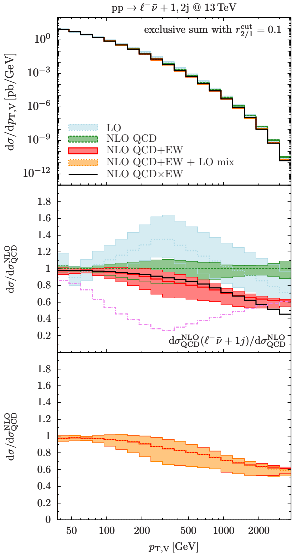




Electroweak merging in Sherpa

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



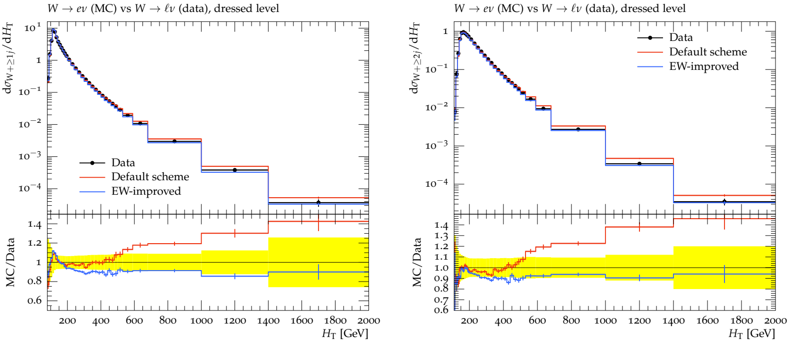


- QCD parton shower merged with QCD+EW matrix elements
- Implemented in Sherpa +OpenLoops framework

Electroweak merging in Pythia

[Christiansen,Prestel] arXiv:1510.01517

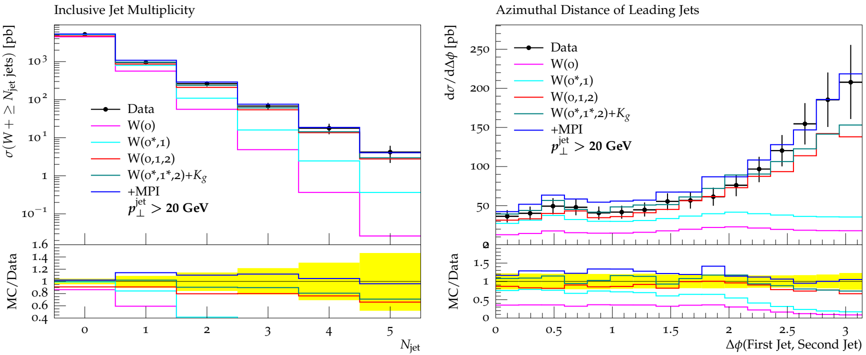
- QCD+EW parton shower implemented in Pythia 8
- Consistently merged to QCD+EW LO matrix elements



NLO merging in Herwig++

[Bellm] PhD thesis

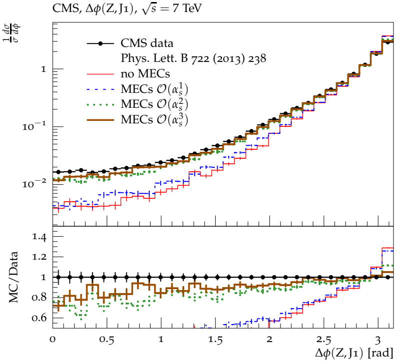
- Unitarized LO and NLO merging implemented in Herwig++

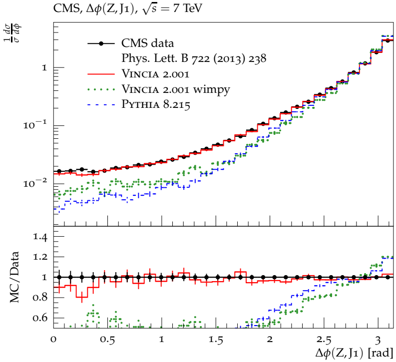


Matrix-element corrections in Vincia

[Fischer,Prestel,Ritzmann,Skands] arXiv:1605.06142

- Alternative to merging → iterative matrix-element corrections
- Implemented in Vincia for both final- and initial-state shower





Outlook

- Matching & merging a very active field
- Most methods come with uncertainty estimates
- Number of tools allows to eliminate “theory bias”
- There is no perfect method just yet ...