Precision Monte Carlo event generators for Higgs boson production in gluon fusion

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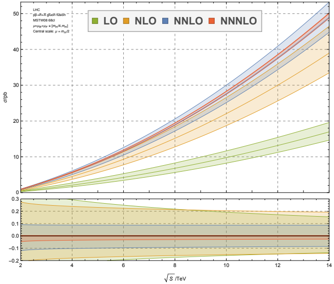
Higgs-boson production in gluon fusion

- Gluon fusion dominant Higgs production mode at LHC
- In large m_t limit described by effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{QCD}} - \frac{C}{4}\, H\, G^a_{\mu\nu}\, G_a^{\mu\nu}$$

- C known to N^{4}LO [Chetyrkin,Kniehl,Steinhauser 1998], [Schröder,Steinhauser 2006], [Chetyrkin,Kühn,Sturm 2006]
- Inclusive and fully differential NNLO known [Anastasiou,Melnikov 2002], [Harlander,Kilgore 2002], [Anastasiou,Melnikov,Petriello 2005], [Catani,Grazzini 2007]
- Mixed QCD+EW corrections known [Anastasiou,Boughezal,Petriello 2009], [Actis,Passarino,Sturm,Uccirati 2008]
- Total cross section known to N^{3}LO [Anastasiou,Duhr,Dulat,Herzog,Mistlberger 2015]
- Fully differential H+jet known to NNLO [Boughezal,Caola,Melnikov,Petriello,Schulze 2013] [Chen,Gehrmann,Glover,Jacquier 2014] [Boughezal,Focke,Giele,Liu,Petriello 2015]
- NNLO scale uncertainty still $\mathcal{O}(10\%)$
  Comparable to exp uncertainty Run I



MC Toolkit

SLAC

Fully differential NNLO

- FEHiP [Anastasiou,Melnikov,Petriello] hep-ph/0501130 / FEHiPro / eHiXS
- HNNLO [Catani,Grazzini,Sargsyan] arXiv:0801.3232, arXiv:0802.1410, arXiv:1306.4581
- Sherpa [Li,Prestel,SH] arXiv:1407.3773

Resummation

- HqT [de Florian,Ferrera,Grazzini,Tommasini] hep-ph/0512025, arXiv:1109.2109
- HRes [de Florian,Ferrera,Grazzini,Tommasini] arXiv:1203.6321

NLO matched to parton showers

- POWHEG Box [Alioli,Nason,Oleari,Re] arXiv:0812.0578
- HERWIG [Hamilton,Richardson,Tully] arXiv:0903.4345
- Sherpa [Krauss,Schönherr,Siegert,SH] arXiv:1008.5399

Merging of NLO matched calculations

- Sherpa [Gehrmann,Krauss,Schönherr,Siegert,SH] arXiv:1207.5031, arXiv:1207.5030
- Pythia [Lönnblad,Prestel] arXiv:1211.7278
- MG5_aMC@NLO [Frederix,Frixione] arXiv:1209.6215

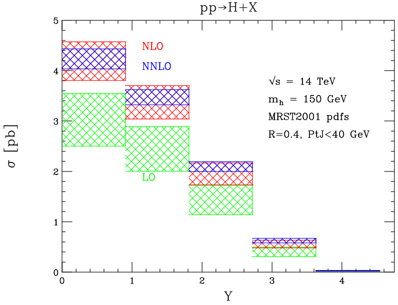
NNLO matched to parton showers

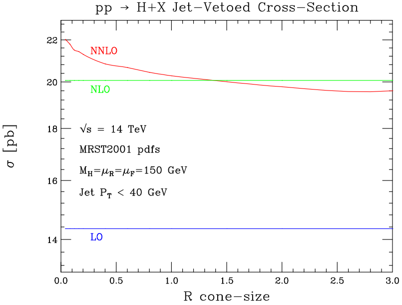
- POWHEG/MINLO [Hamilton,Nason,Zanderighi] arXiv:1309.0017, arXiv:1501.04637
- Sherpa [Li,Prestel,SH] arXiv:1407.3773

Fixed-order NNLO – FEHiP

[Anastasiou,Melnikov,Petriello] hep-ph/0409088, hep-ph/0501130
[Anastasiou,Lazopoulos,Stöckli] FEHiPro, [Herzog] eHiXS

- Inclusive result from [Harlander,Kilgore] hep-ph/0201206, [Anastasiou,Melnikov] hep-ph/0207004, [Ravindran,Smith,vanNeerven] hep-ph/0302135
- Double real from $(\quad)_+$ expansion [Anastasiou,Melnikov,Petriello] hep-ph/0311311 combined with sector decompostition [Binoth,Heinrich] hep-ph/0004013
- Allowed for the first time to apply cuts on final state

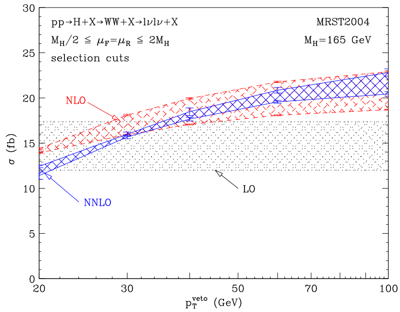


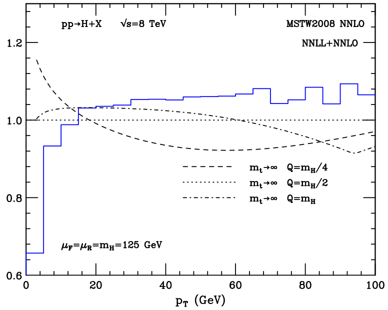


Fixed-order NNLO – HNNLO

[Catani,Grazzini] arXiv:0801.3232, arXiv:0802.1410

- Real/real-virtual corrections from q_T subtraction [Catani,Grazzini] hep-ph/0703012
- Includes heavy quark mass effects [Grazzini,Sargsyan] arXiv:1306.4581

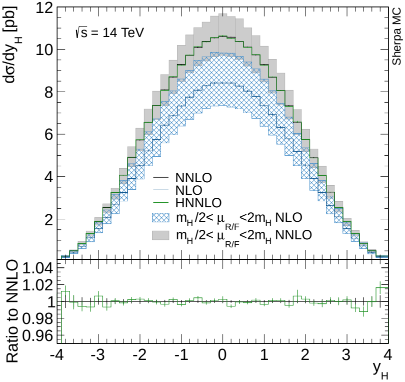


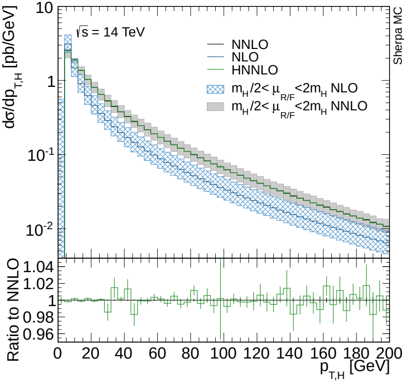


Fixed-order NNLO – Sherpa

[Li,Prestel,SH] arXiv:1407.3773

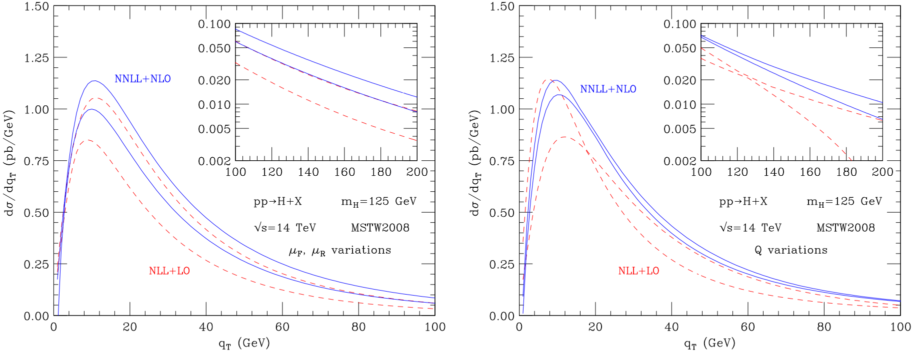
- Real/real-virtual correction from q_T cutoff method [Gao,Li,Zhu] arXiv:1210.2808 using [Becher,Neubert] arXiv:1007.4005 [Gehrmann,Lübbert,Yang] arXiv:1209.0682, arXiv:1403.6451
- Tree-level like terms from automated generators Amegic or Comix [Krauss,Kuhn,Soff] hep-ph/0109036, [Gleisberg,Krauss] arXiv:0709.2881; [Gleisberg,SH] arXiv:0808.3674
- Virtual corrections from [Ravindran,Smith,vanNeerven] hep-ph/0201114





[Grazzini] hep-ph/0512025
[de Florian,Ferrera,Grazzini,Tommasini] arXiv:1109.2109

- NNLL matched to NLO ($m_t \to \infty$)
- All perturbative coefficients up to $\mathcal{O}(\alpha_s^4)$



Matching at NLO – MC@NLO

[Frixione,Webber] hep-ph/0204244

- Separate NLO calculation into standard and hard events

$$\mathbb{S} \;\to\; \bar{\mathrm{B}}^{(\mathrm{K})}(\Phi_B) = \mathrm{B}(\Phi_B) + \tilde{\mathrm{V}}(\Phi_B) + \mathrm{B}(\Phi_B)\int \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)$$

$$\mathbb{H} \;\to\; \mathrm{H}^{(\mathrm{K})} = \mathrm{R}(\Phi_R) - \mathrm{B}(\Phi_B)\mathrm{K}(\Phi_1)$$

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: $\Delta^{(\mathrm{K})}(t) = \exp\left\{-\int_t \mathrm{d}\Phi_1 \mathrm{K}(\Phi_1)\right\}$

- MC counterterms cancel against Sudakov expanded to $\mathcal{O}(\alpha_s)$

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

where $\mathcal{F}^{(n)}_{\mathrm{MC}}$ - generating functional of PS off n partons, observable O

$$\mathcal{F}^{(n)}_{\mathrm{MC}}(t, O) = \Delta^{(\mathrm{K})}(t_c)\, O_n + \int_{t_c} \mathrm{d}\Phi_1\, \mathrm{K}(\Phi_1)\, \mathcal{F}^{(n+1)}_{\mathrm{MC}}(t(\Phi_1), O)$$

Matching at NLO – POWHEG

[Frixione,Nason,Oleari] arXiv:0709.2092

- Separate NLO correction into IR singular and IR finite events

$$\mathbb{S} \;\to\; \bar{\mathrm{B}}(\Phi_B) = \mathrm{B}(\Phi_B) + \tilde{\mathrm{V}}(\Phi_B) + \int \mathrm{d}\Phi_1 \mathrm{R}^{(\mathrm{s})}(\Phi_R)$$

$$\mathbb{H} \;\to\; \mathrm{H} = \mathrm{R}(\Phi_R) - \mathrm{R}^{(s)}(\Phi_R)$$

Phase space: $\mathrm{d}\Phi_1 = \mathrm{d}t\,\mathrm{d}z\,\mathrm{d}\phi\,J(t,z,\phi)$
Singular/finite separation: $\mathrm{R}^{(s)}(\Phi_R) = \mathrm{R}(\Phi_R)\,\mathrm{F}(\Phi_R)$, e.g. $\mathrm{F} = h^2/(p_T^2 + h^2)$
Sudakov factors: $\Delta^{(\mathrm{R})}(t,\Phi_B) = \exp\Big\{ -\int_t \mathrm{d}\Phi_1 \mathrm{R}^{(s)}(\Phi_R)\Big\}$

- Cancel MC counterterms at NLO against expanded Sudakov form factor

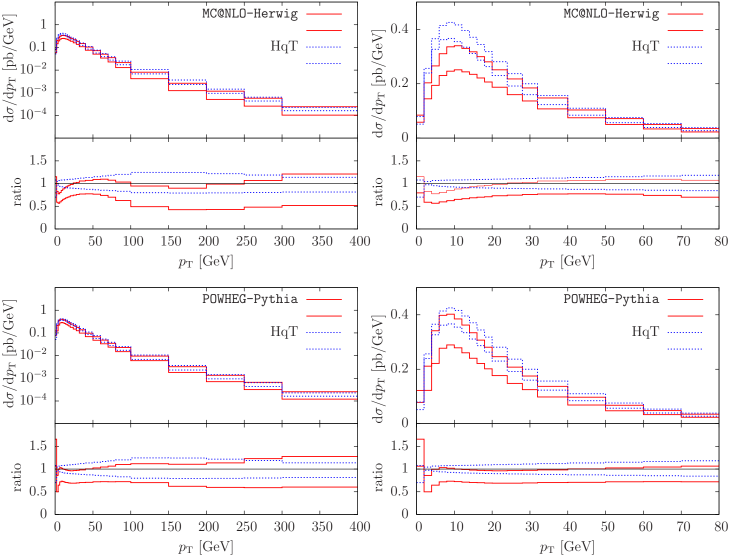
$$\langle O \rangle = \int \mathrm{d}\Phi_B\,\bar{\mathrm{B}}(\Phi_B)\,\bar{\mathcal{F}}_{\mathrm{MC}}(\mu_Q^2, O) + \int \mathrm{d}\Phi_R\,\mathrm{H}(\Phi_R)\,\mathcal{F}_{\mathrm{MC}}^{(1)}(t(\Phi_R), O)$$

where $\bar{\mathcal{F}}_{\mathrm{MC}}^{(n)}(t,O)$ - generating functional of POWHEG

$$\bar{\mathcal{F}}_{\mathrm{MC}}(t,O) = \Delta^{(\mathrm{R})}(t_c)\,O_0 + \int_{t_c} \mathrm{d}\Phi_1\,\frac{\mathrm{R}^{(s)}(\Phi_R)}{\mathrm{B}(\Phi_B)}\,\mathcal{F}_{\mathrm{MC}}^{(1)}(t(\Phi_1), O)$$

Matching at NLO – MC@NLO vs POWHEG

[Webber,Nason] arXiv:1202.1251



Color coherence and the dipole picture

- Gluons with large wavelength cannot resolve charges within emitting color dipole $\rightarrow$ angular ordering [Marchesini,Webber] NPB310(1988)461 (also known as soft double counting, collinear anomaly, ...)
- Soft radiation pattern correct if evolution reformulated in terms of color dipoles [Gustafsson,Pettersson] NPB306(1988)746, [Kharraziha,Lönnblad] hep-ph/9709424
- Dipole subtraction preserves parton picture by partial fractioning soft enhanced splitting function [Catani,Seymour] hep-ph/9605323

$$\frac{p_ip_k}{(p_ip_j)(p_jp_k)} \rightarrow \underbrace{\frac{1}{p_ip_j}\,\frac{p_ip_k}{(p_i+p_k)p_j}}_{(i,k)\to(ij,k)} + \underbrace{\frac{1}{p_kp_j}\,\frac{p_ip_k}{(p_i+p_k)p_j}}_{(k,i)\to(kj,i)}$$

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

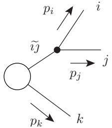
$$\frac{1}{1-z} \rightarrow \frac{1-z}{(1-z)^2+\kappa^2} \qquad \kappa^2 = \frac{k_\perp^2}{Q^2}$$

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

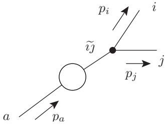
The midpoint between dipole and parton showers

[Prestel,SH] arXiv:1506.05057

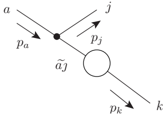
- Choose parametrization such that soft term identical in all dipole types



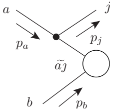
$$\kappa^2 = \frac{p_i p_j \, p_j p_k}{(p_{\widetilde{ij}} p_{\tilde{k}})^2} \qquad z_j = \frac{p_j p_k}{p_{\widetilde{ij}} p_{\tilde{k}}}$$



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



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



$$\kappa^2 = \frac{p_a p_j \, p_j p_b}{(p_a p_b)^2} \qquad z_j = \frac{p_j p_b}{p_a p_b}$$

- z_j - light-cone momentum fraction of gluon (maps to collinear limit)
  $\rightarrow$ Full splitting function from adding collinear bits & enforcing sum rules

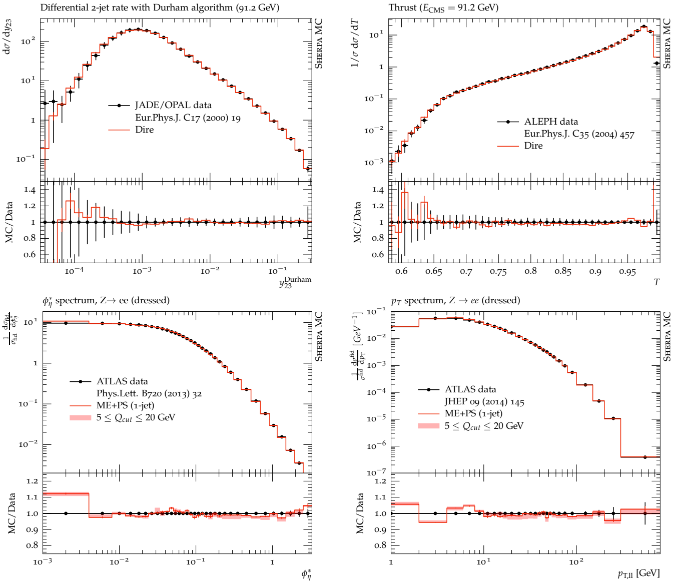
$$P_{qq}(z,\kappa^2) = 2\,C_F \left[\left(\frac{1-z}{(1-z)^2+\kappa^2} \right)_+ - \frac{1+z}{2} \right] + \gamma_q \, \delta(1-z)$$

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

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

The midpoint between dipole and parton showers

[Prestel,SH] arXiv:1506.05057



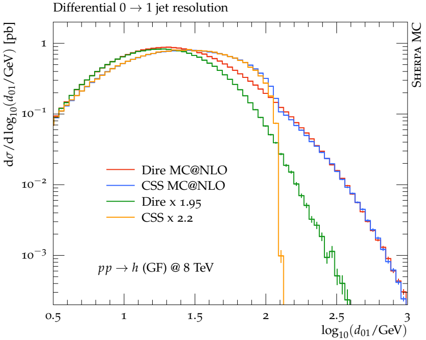
Extension to a subtraction method and MC@NLO

[SH] TBP?

- 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

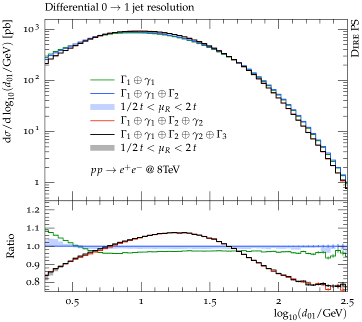


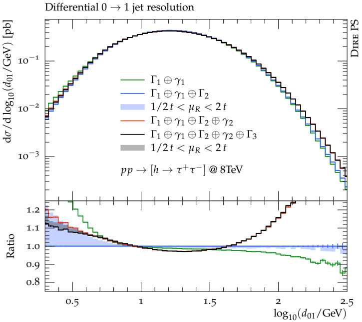
Towards higher logarithmic accuracy

[Krauss,Li,Prestel,Schönherr,SH] TBP!

- Big drawback of parton showers is lack of higher-order kernels
- Start improving with spacelike NLO splitting functions

  [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





NLO merging

[Lavesson,Lönnblad] arXiv:0811.2912, [Lönnblad,Prestel] arXiv:1211.7278
[Gehrmann et al.] arXiv:1207.5031, [Krauss et al.] arXiv:1207.5030
[Frederix,Frixione] arXiv:1209.6215

NL^{3}SP / UNLOPS (Pythia)

- CKKW-L simulation upgraded to NLO by substituting individual ME's
- NLO matched events reweighted to CKKW scales $\mu_{R/F}$, $\mathcal{O}(\alpha_s)$ subtracted
- Exact NLO cross sections recovered by unitarization (UNLOPS)

MEPS@NLO (Sherpa)

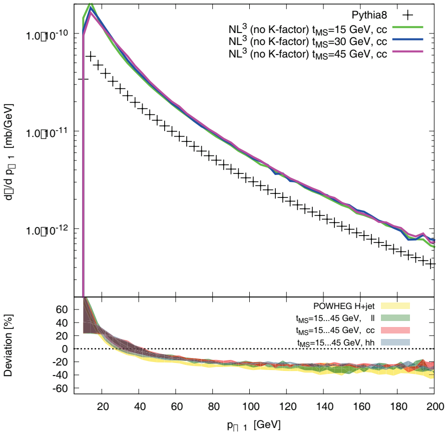
- CKKW-L simulation with NLO matched input events
- Events evaluated at CKKW μ_R, reweighted to μ_F, $\mathcal{O}(\alpha_s)$ subtracted
- Sudakov factor also multiplies NLO corrections

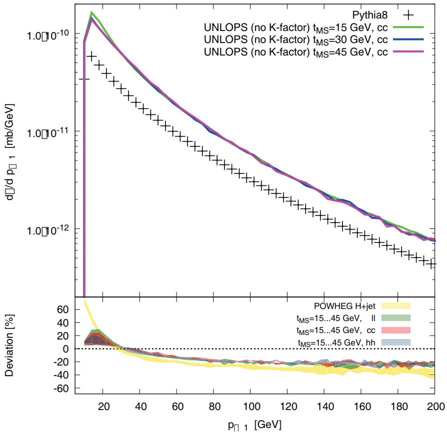
FxFx (MG5_aMC@NLO)

- Extension of MLM method to NLO
- Logarithmic accuracy not quantified

NLO merging – UNLOPS

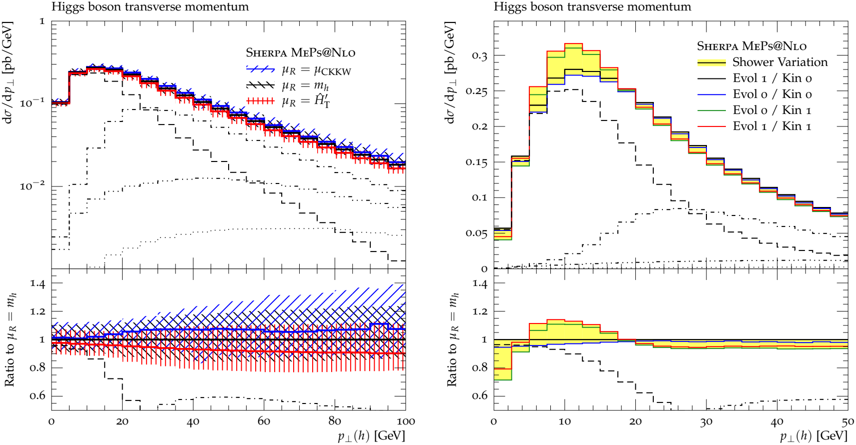
[Lönnblad,Prestel] arXiv:1211.7278





- NL^3 vs. UNLOPS merging – both parametrically $\mathcal{O}(\alpha_s)$ correct

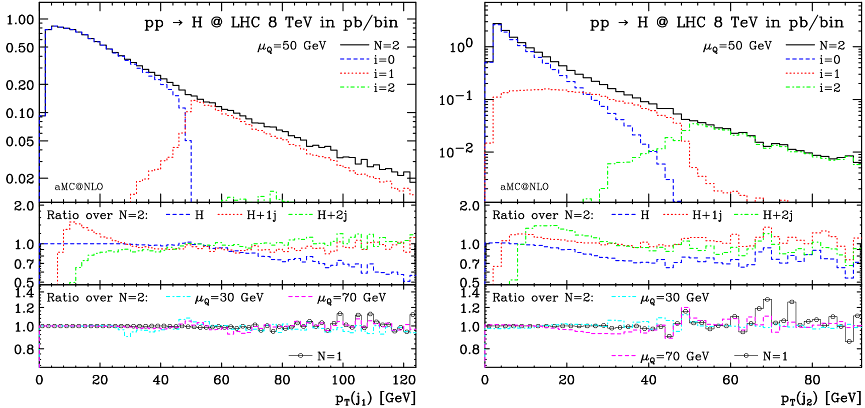
[Krauss,Schönherr,SH] arXiv:1401.7971



- Residual fixed-order/resummation uncertainties in inclusive events

NLO merging – FxFx

[Frederix,Frixione] arXiv:1209.6215



Multi-scale improved NLO – MINLO

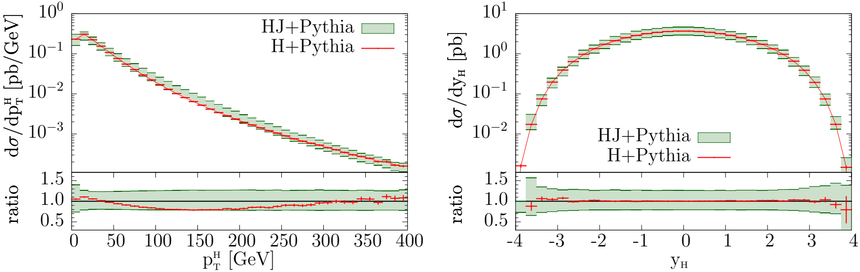
[Hamilton,Nason,Zanderighi] arXiv:1206.3572

- Interpret NLO event in terms of QCD branchings, like in a parton-shower
  Assign transverse momentum scales q to splittings
- Evaluate α_s at nodal scales, multiply by Sudakov factors

  Maintain NLO accuracy by subtracting $\mathcal{O}(\alpha_s)$ expansion $\left(L = \log Q^2/p_T^2\right)$

$$\frac{d\sigma_{\rm MINLO}}{dp_T^2 dy} = \Delta^2(Q, p_T)\,\frac{\alpha_s(p_T)}{\alpha_s(Q)}\left[\frac{d\sigma}{dp_T^2 dy} + \frac{d\sigma}{dp_T^2 dy}\bigg|_{\rm LO}\frac{\alpha_s}{2\pi}\left(A_1\,L^2 + B_1\,L - \beta_0\,L\right)\right]$$

- h+jet MINLO NLO accurate for h+jet and h inclusive
  [Hamilton,Nason,Oleari,Zanderighi] arXiv:1212.4504



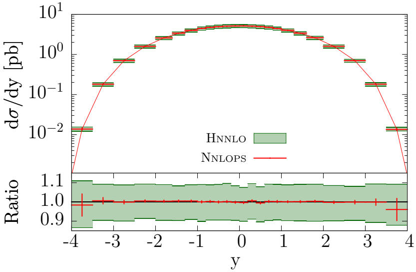
From MINLO to NNLOPS

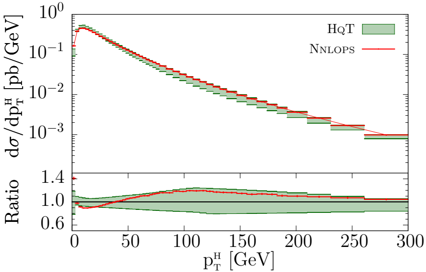
[Hamilton,Nason,Re,Zanderighi] arXiv:1309.0017

- Reweighting of MINLO h+jet result with differential K-factor

$$\mathrm{d}\sigma_{\mathrm{NNLOPS}} = \mathrm{d}\sigma_{\mathrm{MINLO}}\, K(y_h) \qquad K(y_h) = \frac{\mathrm{d}\sigma_{\mathrm{NNLO}}/\mathrm{d}y_h}{\mathrm{d}\sigma_{\mathrm{MINLO}}/\mathrm{d}y_h}$$

- NLO accuracy of $\mathrm{d}\sigma_{\mathrm{MINLO}}/\mathrm{d}y_h$ implies $K(y_h) = 1 + \mathcal{O}(\alpha_s^2)$
  $\rightarrow$ preserves NLO accuracy of MINLO prediction
- Improve agreement with NNLO by damping $F = (\beta m_h)^\gamma/((\beta m_h)^\gamma + p_T^\gamma)$





Unitary Matrix-Element Parton-Shower merging

[Lönnblad,Prestel] arXiv:1211.4827

- PS expression for infrared safe observable, O

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

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

- Add ME correction to first emission $(\mathrm{B}_0\mathrm{K}_0 \to \mathrm{B}_1)$ & unitarize

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

- ME evaluated at fixed scales $\mu_{R/F}$ $\to$ 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 $\bar{\mathrm{B}}_0^{t_c} = \mathrm{B}_0 - \int_{t_c} \mathrm{d}\Phi_1 \mathrm{B}_1$

$$\langle O\rangle = \left\{ \int \mathrm{d}\Phi_0\, \bar{\mathrm{B}}_0^{t_c} + \int_{t_c} \mathrm{d}\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\, w_1\right] \mathrm{B}_1 \right\} O(\Phi_0)$$

$$+ \int_{t_c} \mathrm{d}\Phi_1\, \Pi_0(t_1,\mu_Q^2)\, w_1\, \mathrm{B}_1\, \mathcal{F}_1(t_1,O)$$

Extension to NNLO – UN^{2}LOPS

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

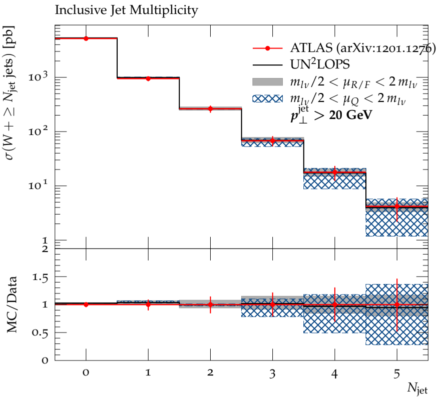
- Promote vetoed cross section to NNLO
- Add NLO corrections to B_1 using S-MC@NLO
- Subtract $\mathcal{O}(\alpha_s)$ term of w_1 and Π_0

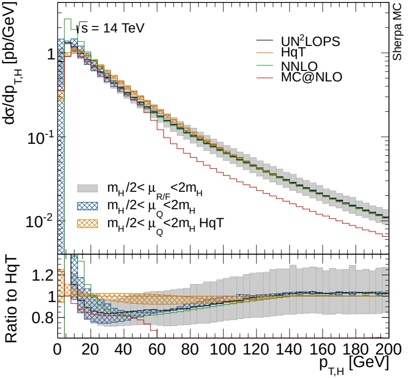
$$
\begin{aligned}
\langle O\rangle =& \int \mathrm{d}\Phi_0\, \bar{\bar{\mathrm{B}}}_0^{t_c}\, O(\Phi_0) \\
&+ \int_{t_c} \mathrm{d}\Phi_1 \left[1 - \Pi_0(t_1,\mu_Q^2)\, w_1 \left(1 + w_1^{(1)} + \Pi_0^{(1)}(t_1,\mu_Q^2)\right)\right] \mathrm{B}_1\, O(\Phi_0) \\
&+ \int_{t_c} \mathrm{d}\Phi_1\, \Pi_0(t_1,\mu_Q^2)\,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

- $\tilde{\mathrm{B}}_1^{\mathrm{R}} = \bar{\mathrm{B}}_1 - \mathrm{B}_1 = \tilde{\mathrm{V}}_1 + \mathrm{I}_1 + \int \mathrm{d}\Phi_{+1}\mathrm{S}_1\Theta(t_2 - t_1)$
  $\mathrm{H}_1^{\mathrm{R}}$ ($\mathrm{H}_1^{\mathrm{E}}$) $\rightarrow$ regular (exceptional) double real configurations

UN^{2}LOPS for Drell-Yan and Higgs production

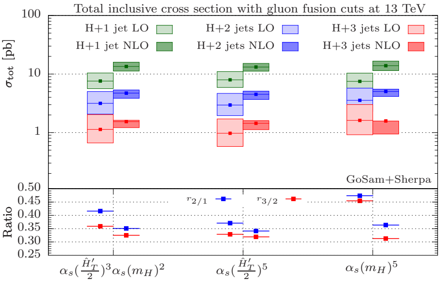
[Li,Prestel,SH] arXiv:1405.3607

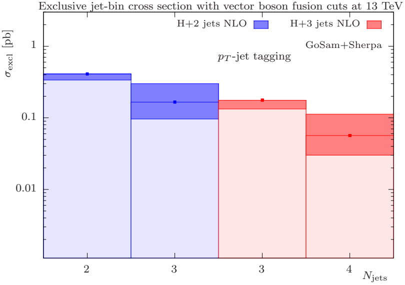


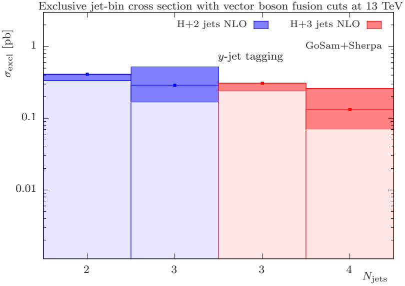


Higgs+3 jets at NLO and VBF backgrounds

[Greiner,Luisoni,Schönherr,Winter,Yundin,SH] arXiv:1506.01016





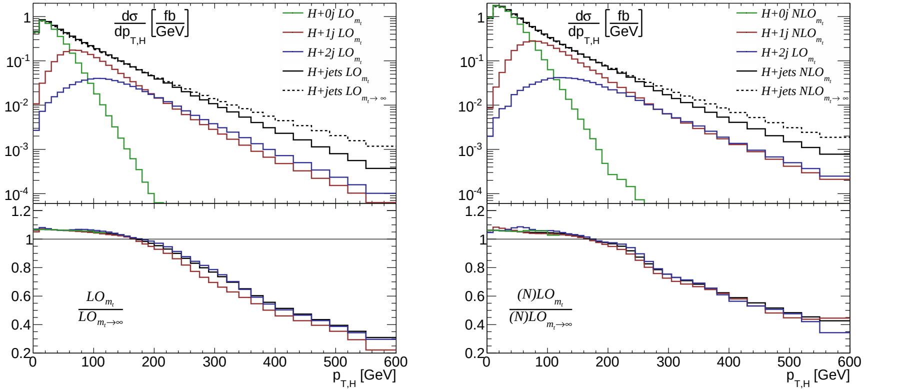


- $H + 2$jets through gluon fusion is irreducible background to VBF $\rightarrow$ get handle on jet veto efficiency through $H + 3$jets at NLO
- Test jet scaling in process with topology similar to Drell-Yan lepton pair production

Heavy quark mass effects

[Buschmann,Goncalves,Kuttimalai,Schönherr,Krauss,Plehn] arXiv:1410.5806

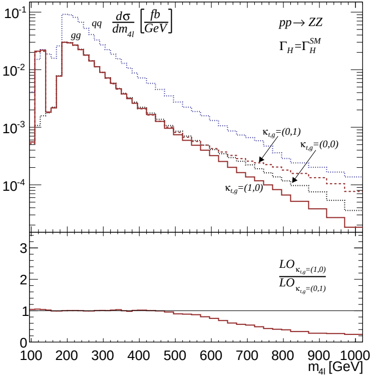
- HQ mass effects change distributions, like Higgs q_T and reconstructed mass
- Simulated by reweighting with SM loop^2 result over HEFT result
  $\rightarrow$ effects factorize for each number of jets in $pp \rightarrow h$+jets
- QCD radiative corrections from HEFT added in factorized form

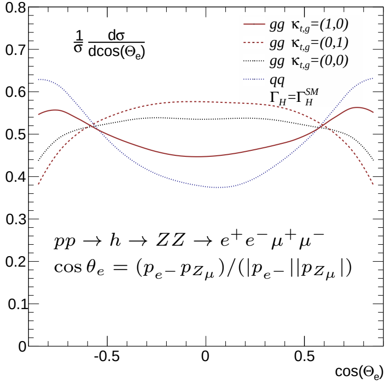


Heavy quark mass effects

[Buschmann,Goncalves,Kuttimalai,Schönherr,Krauss,Plehn] arXiv:1410.5806

- Impact on search for anomalous Higgs couplings $(\mathcal{M} = \kappa_t \mathcal{M}_t + \kappa_g \mathcal{M}_g)$





Summary

- Monte Carlo programs indispensable for pheno & analyses
- NNLO fixed-order standard for $pp \to h$
  Now being incorporated into general-purpose MCs
- NLO (matched & merged) predictions up to $h + 3$ jets available
  Heavy quark effects included by reweighting
- Resummation uncertainties small in analytic approaches
  First attempts on uncertainty reduction in parton showers