Precision simulations in SHERPA

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HP^2, GGI Florence, 3.9.2014

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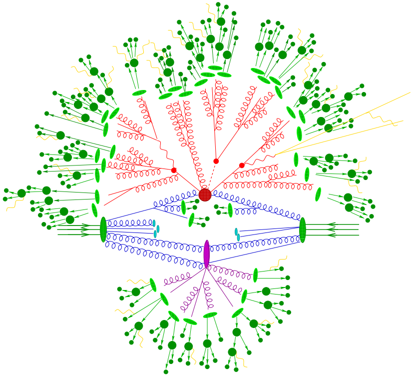
The inner working of event generators . . .

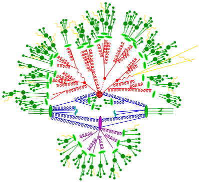
simulation: divide et impera

- hard process:
  fixed order perturbation theory
  traditionally: Born-approximation
- bremsstrahlung:
  resummed perturbation theory
- hadronisation:
  phenomenological models
- hadron decays:
  effective theories, data
- "underlying event":
  phenomenological models



. . . and possible improvements

possible strategies:



- improving the phenomenological models:
  - "tuning" (fitting parameters to data)
  - replacing by better models, based on more physics

    (my hot candidate: "minimum bias" and "underlying event" simulation)

- improving the perturbative description:
  - inclusion of higher order exact matrix elements and correct connection to resummation in the parton shower:

    "NLO-Matching" & "Multijet-Merging"

  - systematic improvement of the parton shower: next-to leading (or higher) logs & colours

Reminder: Ingredients of simulations at NLO

Structure of an NLO calculation

- sketch of cross section calculation

$$\mathrm{d}\sigma_N^{(\mathrm{NLO})} = \underbrace{\mathrm{d}\Phi_N \mathcal{B}_N}_{\substack{\text{Born}\\ \text{approximation}}} + \underbrace{\mathrm{d}\Phi_N \mathcal{V}_N}_{\substack{\text{renormalised}\\ \text{virtual correction}\\ \text{IR-divergent}}} + \underbrace{\mathrm{d}\Phi_{N+1} \mathcal{R}_{N+1}}_{\substack{\text{real correction}\\ \text{IR-divergent}}}$$

$$= \mathrm{d}\Phi_N \left[\mathcal{B}_N + \mathcal{V}_N + \mathcal{B}_N \otimes \mathcal{S}\right] + \mathrm{d}\Phi_{N+1} \left[\mathcal{R}_{N+1} - \mathcal{B}_N \otimes \mathrm{d}\mathcal{S}\right]$$

- subtraction terms $\mathcal{S}$ (integrated) and $\mathrm{d}\mathcal{S}$: exactly cancel IR divergence in $\mathcal{R}$ – process-independent structures
- result: terms in both brackets separately infrared finite
- in SHERPA: virtual parts provided by some great other codes: BLACKHAT, GOSAM, NJET, OPENLOOPS, ... + some process-specific codes interfaced

Probabilistic treatment of emissions

- Sudakov form factor (no-emission probability)

$$\Delta_{ij,k}(t,t_0) = \exp\left[-\int\limits_{t_0}^{t} \mathrm{d}\Gamma_{ij,k}(t)\right]$$

- decay width for parton $i(j) \to ik(j)$ (spectator j for 4-momentum conservation)

$$\mathrm{d}\Gamma_{ij,k}(t) = \frac{\mathrm{d}t'}{t'}\,\frac{\alpha_S(k_\perp^2)}{2\pi}\int\limits_{z_-(t'/t)}^{z_+(t'/t)}\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\underbrace{\mathcal{K}_{ij,k}(t,\,z,\,\phi)}_{\text{splitting kernel}}$$

- comparison with Q_T-resummation:
  Sudakov form factor contains terms A_1, A_2 and B_1

  (up to some power-like corrections $\propto t'/t$

- evolution parameter t' defined by kinematics:
  gen. angle (HERWIG++) or transverse momentum (PYTHIA, SHERPA)

Emissions off a Born matrix element

- "compound" splitting kernels $\mathcal{K}_n$ and Sudakov form factors $\Delta_n^{(\mathcal{K})}$ for emission off n-particle final state:

$$\mathcal{K}_n(\Phi_1) = \frac{\alpha_S}{2\pi} \sum_{\text{all } \{ij,k\}} \mathcal{K}_{ij,k}(\Phi_{ij,k}) \,, \quad \Delta_n^{(\mathcal{K})}(t,t_0) = \exp\left[-\int\limits_{t_0}^{t} \mathrm{d}\Phi_1\, \mathcal{K}_n(\Phi_1)\right]$$

- consider first emission only off Born configuration (N ext. particles)

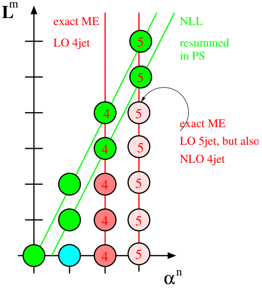
$$\mathrm{d}\sigma_B = \mathrm{d}\Phi_N\, \mathcal{B}_N(\Phi_N)$$
$$\cdot \underbrace{\left\{\Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \left[\mathcal{K}_N(\Phi_1)\Delta_N^{(\mathcal{K})}(\mu_N^2, t(\Phi_1))\right]\right\}}_{\text{integrates to unity} \longrightarrow \text{“unitarity” of parton shower}}$$

- further emissions by recursion with $\mu_N^2 \longrightarrow t$ of previous emission

NLO improvements: Matching & Merging

NLO matching: Basic idea

- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- adjust ("match") terms:
  - cross section at NLO accuracy
  - correct hardest emission in PS to exactly reproduce ME at order α_S ($\mathcal{R}$-part of the NLO calculation)



Matching a la MC@NLO

(S. Frixione & B. Webber, JHEP 0602 (2002) 029)

(S. Hoeche, F. Krauss, M. Schoenherr, & F. Siegert, JHEP 1209 (2012) 049)

- divide $\mathcal{R}_N$ in soft (“S”) and hard (“H”) part:

$$\mathcal{R}_N = \mathcal{R}_N^{(S)} + \mathcal{R}_N^{(H)} = \mathcal{B}_N \otimes \mathrm{d}\mathcal{S}_1 + \mathcal{H}_N$$

- identify subtraction terms and shower kernels $\mathrm{d}\mathcal{S}_1 \equiv \sum\limits_{\{ij,k\}} \mathcal{K}_{ij,k} \equiv \mathcal{K}_N$

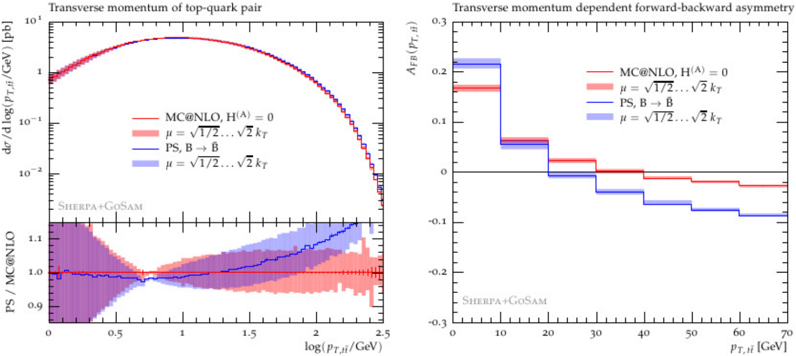
(modify $\mathcal{K}$ in 1^{st} emission to account for colour)

$$\begin{aligned}\mathrm{d}\sigma_N \;&=\; \mathrm{d}\Phi_N \left[\mathcal{B}_N + \mathcal{V}_N + \mathcal{B}_N \otimes \mathcal{S}_1\right] \\ &\qquad \otimes \left[\Delta_N^{(\mathcal{K})}(\mu_N^2,\, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1\, \mathcal{K}_N(\Phi_1)\, \Delta_N^{(\mathcal{K})}(\mu_N^2,\, k_\perp^2)\right] \\ &\quad + \mathrm{d}\Phi_{N+1}\, \mathcal{H}_N\end{aligned}$$

Aside: impact of full colour

(S. Hoeche, J. Huang, G. Luisoni, M. Schoenherr, & J. Winter, arXiv:1306.2703 [hep-ph])

- effect of full colour treatment in Sudakov form factor, MC@NLO without **H**-part vs. parton shower with $\mathcal{B} \longrightarrow \tilde{\mathcal{B}}$
- take $t\bar{t}$ production (red = full colour, blue = "PS" colours)

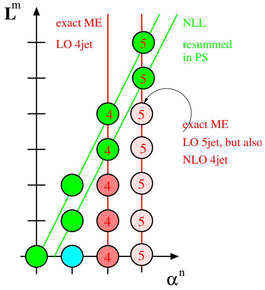


Multijet merging @ leading order

Multijet merging: basic idea

(S. Catani, F. Krauss, R. Kuhn, B. Webber, JHEP 0111 (2001) 063,
L. Lonnblad, JHEP 0205 (2002) 046, & F. Krauss, JHEP 0208 (2002) 015)

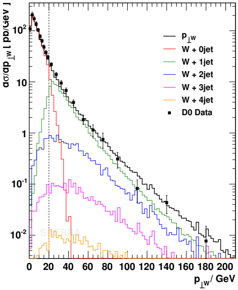
- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- combine ("merge") both:
  result: "towers" of MEs with increasing number of jets evolved with PS
  - multijet cross sections at Born accuracy
  - maintain (N)LL accuracy of parton shower



Separating jet evolution and jet production

- separate regions of jet production and jet evolution with jet measure Q_J

  ("truncated showering" if not identical with evolution parameter)
- matrix elements populate hard regime
- parton showers populate soft domain



First emission(s), again

(S. Hoeche, F. Krauss, S. Schumann, F. Siegert, JHEP 0905 (2009) 053)

$$\begin{aligned} d\sigma \;=\; & d\Phi_N\,\mathcal{B}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,\,t_0) + \int\limits_{t_0}^{\mu_N^2} d\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,\,t_{N+1})\Theta(Q_J - Q_{N+1})\right] \\ & + d\Phi_{N+1}\,\mathcal{B}_{N+1}\,\Delta_N^{(\mathcal{K})}(\mu_{N+1}^2,\,t_{N+1})\Theta(Q_{N+1} - Q_J) \end{aligned}$$

- note: $N+1$-contribution includes also $N+2$, $N+3$, ...

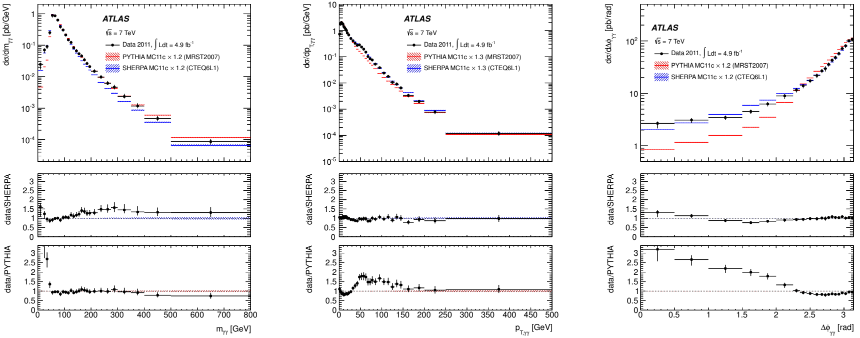
  (no Sudakov suppression below t_{n+1}, see further slides for iterated expression)

- potential occurence of different shower start scales: $\mu_{N,N+1,\dots}$
- "unitarity violation" in square bracket: $\mathcal{B}_N\mathcal{K}_N \longrightarrow \mathcal{B}_{N+1}$

  (cured with UMEPS formalism, L. Lonnblad & S. Prestel, JHEP 1302 (2013) 094 & S. Platzer, arXiv:1211.5467 [hep-ph] & arXiv:1307.0774 [hep-ph])

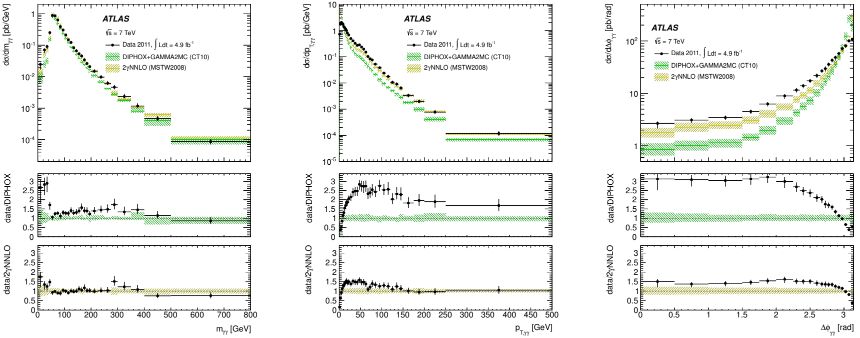
Di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$ in showers

(arXiv:1211.1913 [hep-ex])



Aside: Comparison with higher order calculations

(arXiv:1211.1913 [hep-ex])



Multijet merging @ next-to leading order

Multijet-merging at NLO: MEPS@NLO

(arXiv: 1207.5030, 1207.5031 [hep-ph])

- basic idea like at LO: towers of MEs with increasing jet multi (but this time at NLO)
- combine them into one sample, remove overlap/double-counting

maintain NLO and LL accuracy of ME and PS

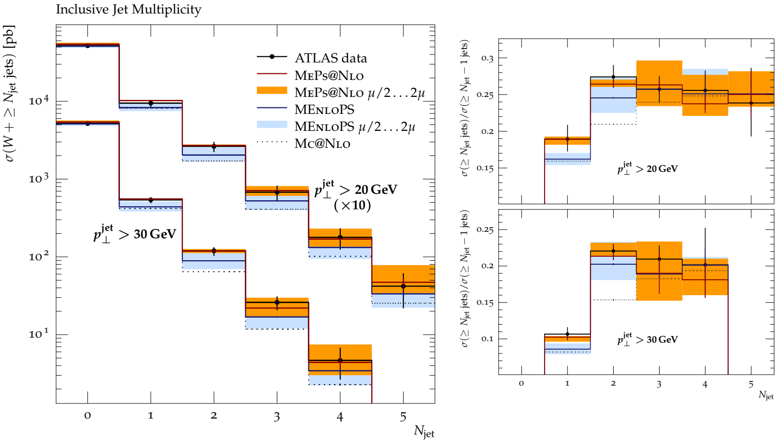
- this effectively translates into a merging of MC@NLO simulations and can be further supplemented with LO simulations for even higher final state multiplicities

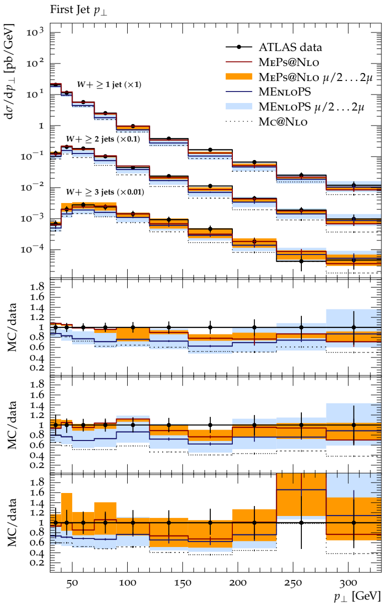
First emission(s), once more

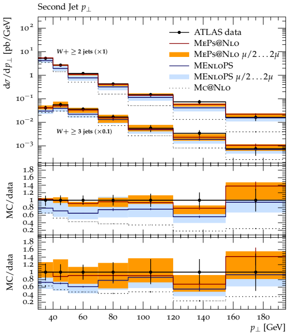
$$
\begin{aligned}
d\sigma \;=\; & d\Phi_N\,\tilde{\mathcal{B}}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,t_0)+\int\limits_{t_0}^{\mu_N^2} d\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\right]\\
& +d\Phi_{N+1}\,\mathcal{H}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\\
& +d\Phi_{N+1}\,\tilde{\mathcal{B}}_{N+1}\left(1+\frac{\mathcal{B}_{N+1}}{\tilde{\mathcal{B}}_{N+1}}\int\limits_{t_{N+1}}^{\mu_N^2} d\Phi_1\,\mathcal{K}_N\right)\Theta(Q_{N+1}-Q_J)\\
& \quad\cdot\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\cdot\left[\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_0)+\int\limits_{t_0}^{t_{N+1}} d\Phi_1\,\mathcal{K}_{N+1}\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_{N+2})\right]\\
& +d\Phi_{N+2}\,\mathcal{H}_{N+1}\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Delta_{N+1}^{(\mathcal{K})}(t_{N+1},t_{N+2})\Theta(Q_{N+1}-Q_J)+\dots
\end{aligned}
$$

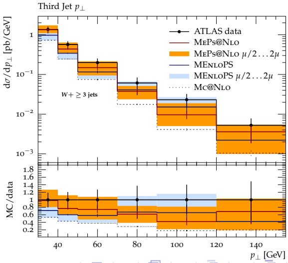
MEPS@NLO: validation in W+jets

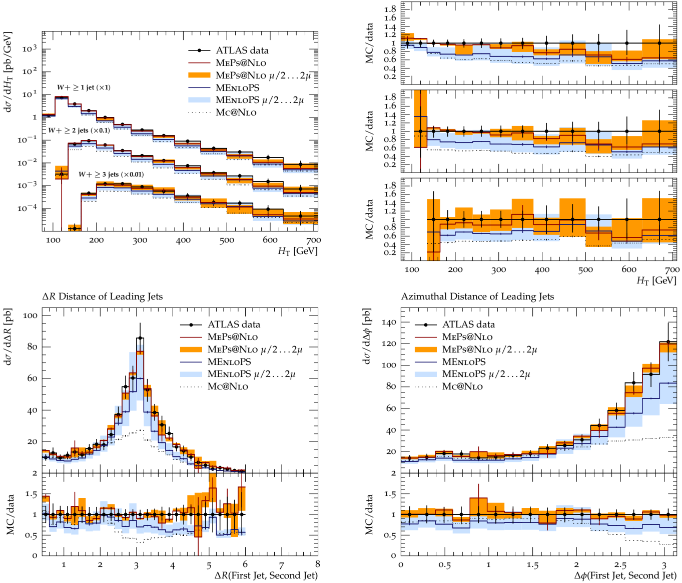
(S. Hoeche, F. Krauss, M. Schoenherr & F. Siegert, JHEP 1304 (2013) 027)




First Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 1$ jet ($\times 1$)
$W+\geq 2$ jets ($\times 0.1$)
$W+\geq 3$ jets ($\times 0.01$)
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]

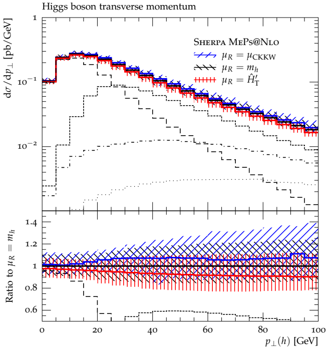

Second Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 2$ jets ($\times 1$)
$W+\geq 3$ jets ($\times 0.1$)
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]


Third Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 3$ jets
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]

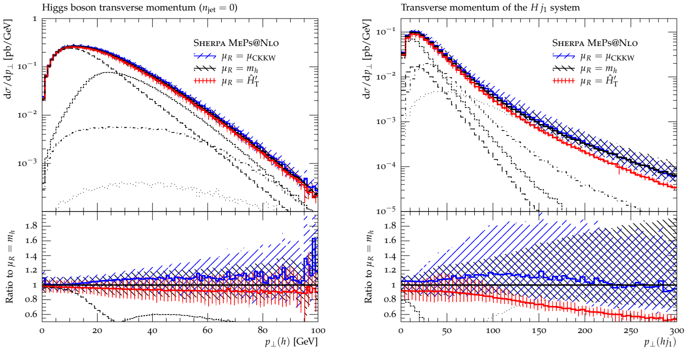

ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 1$ jet ($\times1$)
$W+\geq 2$ jets ($\times0.1$)
$W+\geq 3$ jets ($\times0.01$)
$d\sigma/dH_T$ [pb/GeV]
H_T [GeV]
MC/data
ΔR Distance of Leading Jets
$d\sigma/d\Delta R$ [pb]
ΔR(First Jet, Second Jet)
Azimuthal Distance of Leading Jets
$d\sigma/d\Delta\phi$ [pb]
$\Delta\phi$(First Jet, Second Jet)

Inclusive observables for $gg \to H$

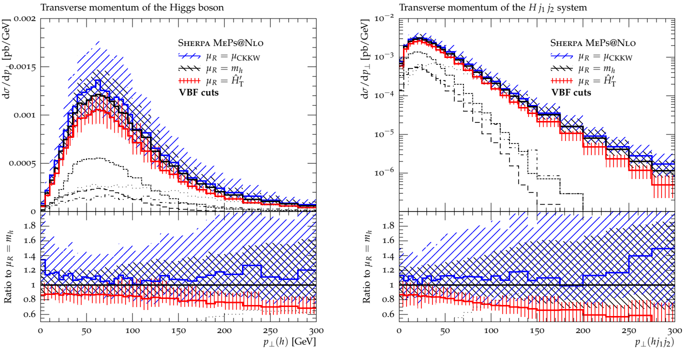
- note: impact of central scale choice!
- uncertainty bands through variation by factor of 2 on $\mu_{F,R}$ and $\sqrt{2}$ on μ_Q



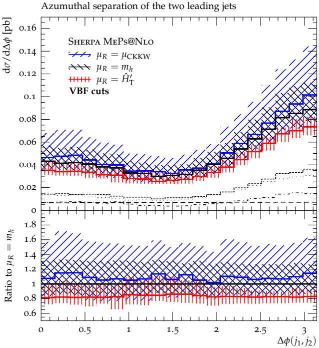
Exclusive observables for $gg \to H$

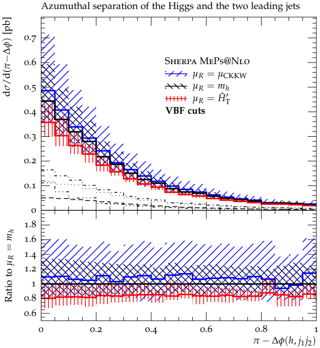


$gg \to H$ after WBF cuts

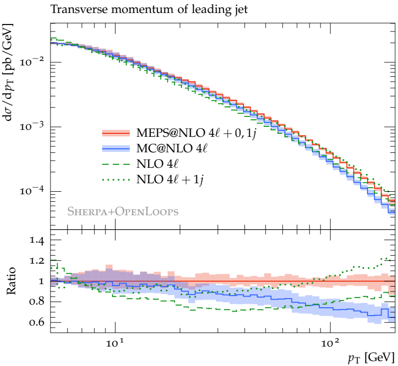


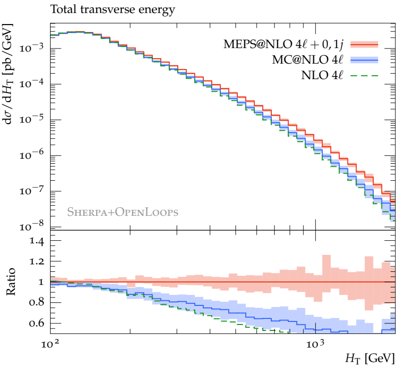
$gg \to H$ after WBF cuts





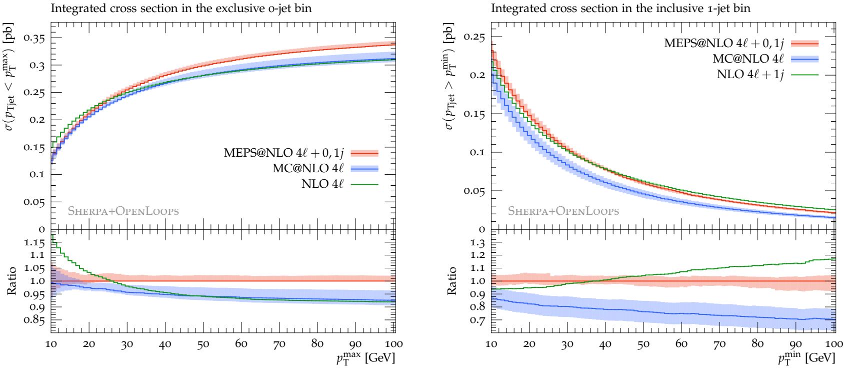
Higgs backgrounds: inclusive observables in W^+W^-+jets





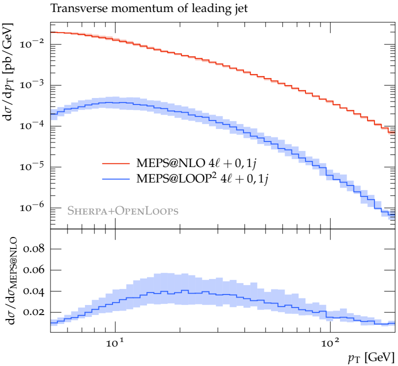
Higgs backgrounds: jet vetoes in W^+W^-+jets

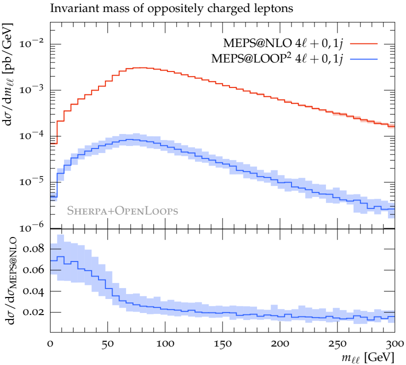
- integrated cross sections in 0/1-jet bin in dependence on p_T of jet



Higgs backgrounds: gluon-induced processes W^+W^-+jets

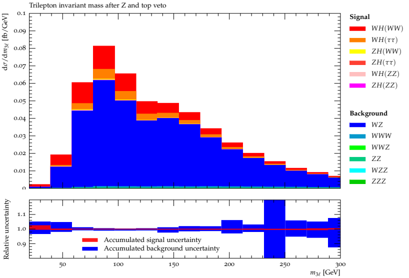
- include (LO-) merged loop^2 contributions of $gg \to VV$ (+1 jet)

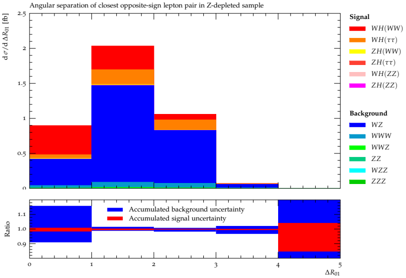




Some fun with $VH \to 3\ell$

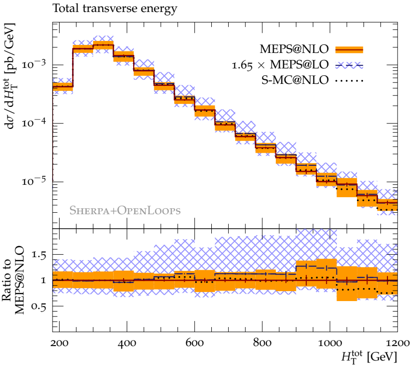
- relevant observables: $\not{E}_T$, m_{123}, and ΔR_{01}
- lots of backgrounds ..., signal and dominant ones multijet-merged

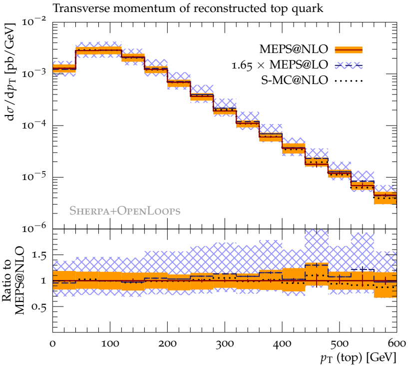




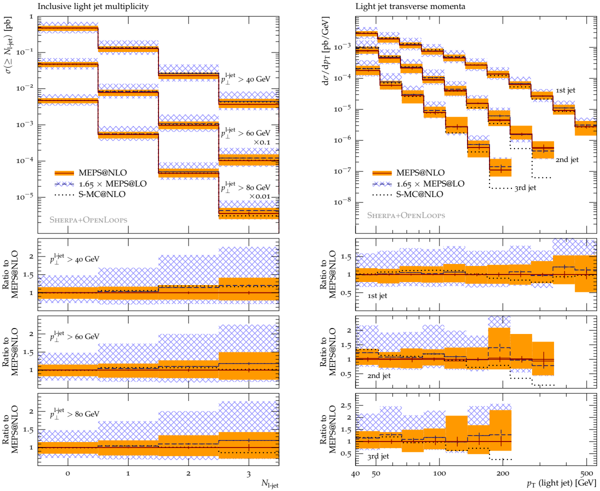
Inclusive observables in $t\bar{t}$ + jets

- multijet merging for $t\bar{t}$ + {0, 1, 2} jets



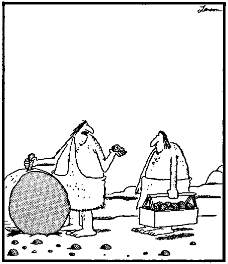


Light jet observables in $t\bar{t}$ + jets



Summary

- Systematic improvement of event generators by including higher orders has been at the core of QCD theory and developments in the past decade:
  - multijet merging (“CKKW”, “MLM”)
  - NLO matching (“MC@NLO”, “POWHEG”)
  - MENLOPS NLO matching & merging
  - MEPS@NLO (“SHERPA”, “UNLOPS”, “MINLO”, “FxFx”)



“So what's this? I asked for a *hammer*! A hammer! *This* is a crescent wrench! ... Well, maybe it's a hammer. ... Damn these stone tools.”

- multijet merging an important tool for many relevant signals and backgrounds - pioneered by SHERPA at LO & NLO

(and excessively validated in a lot of different processes: $V/H/VV/VH/VVV/t\bar{t}/t\bar{t}V$+jets, jets alone, . . .)

- complete automation of NLO calculations done ⟶ benefit from it!

(it's the precision and trustworthy & systematic uncertainty estimates!)