Precision simulations for LHC physics in SHERPA

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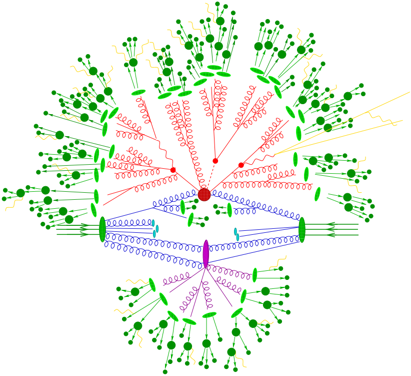
The inner working of event generators . . .

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

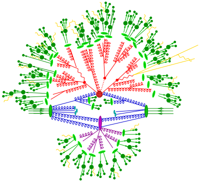


. . . and possible improvements

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

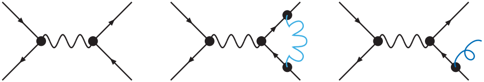
Cross sections at the LHC: Born approximation

$$\mathrm{d}\sigma_{ab\to N} = \int\limits_0^1 \mathrm{d}x_a \mathrm{d}x_b f_a(x_a,\, \mu_F) f_b(x_a,\, \mu_F) \int\limits_{\mathrm{cuts}} \mathrm{d}\Phi_N \frac{1}{2\hat{s}} \left|\mathcal{M}_{p_a p_b \to N}(\Phi_N;\, \mu_F,\, \mu_R)\right|^2$$

- parton densities $f_a(x,\, \mu_F)$ (PDFs)
- phase space Φ_N for N-particle final states
- incoming current $1/(2\hat{s})$
- squared matrix element $\mathcal{M}_{p_a p_b \to N}$ (summed/averaged over polarisations)
- renormalisation and factorisation scales μ_R and μ_F
- complexity demands numerical methods for large N

Higher orders: some general thoughts

- obtained from adding diagrams with additional:
  loops (virtual corrections) or
  legs (real corrections)



- effect: reducing the dependence on μ_R & μ_F
  NLO allows for meaningful estimate of uncertainties
- additional difficulties when going NLO:
  ultraviolet divergences in virtual correction
  infrared divergences in real and virtual correction

  enforce

  UV regularisation & renormalisation
  IR regularisation & cancellation

(Kinoshita–Lee–Nauenberg–Theorem)

Structure of an NLO calculation

- sketch of cross section calculation

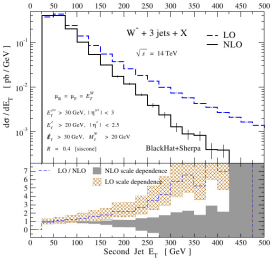
$$\mathrm{d}\sigma_N^{(\mathrm{NLO})} = \underbrace{\mathrm{d}\Phi_N \mathcal{B}_N}_{\substack{\text{Born}\\ \text{approximation}}} + \underbrace{\mathrm{d}\Phi_N \mathcal{V}_N}_{\substack{\text{renormalised}\\ \text{virtual correction}\\ \text{IR-divergent}}} + \underbrace{\mathrm{d}\Phi_{N+1} \mathcal{R}_{N+1}}_{\substack{\text{real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

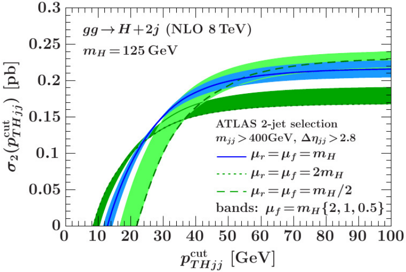
$$= \mathrm{d}\Phi_N \left[\mathcal{B}_N + \mathcal{V}_N + \mathcal{B}_N \otimes \mathcal{S}\right] + \mathrm{d}\Phi_{N+1} \left[\mathcal{R}_{N+1} - \mathcal{B}_N \otimes \mathrm{d}\mathcal{S}\right]$$

- 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

An interesting problem with scales

- common lore: NLO calculations reduce scale uncertainties
- this is, in general, true. however:
  unphysical scale choices will yield unphysical results





- so maybe we have to be a bit smarter than just running NLO code

Probabilistic treatment of emissions

- Sudakov form factor

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

  yields probability for **no decay** between scales t_0 and t
- decay width for parton $i(j) \to ik(j)$ (spectator j)

$$\mathrm{d}\Gamma_{ij,k}(t) = \frac{\mathrm{d}t}{t}\,\frac{\alpha_S}{2\pi}\int \mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,\underbrace{\mathcal{K}_{ij,k}(t,\, z,\, \phi)}_{\text{splitting kernel}}$$

- evolution parameter t defined by kinematics

  generalised angle (HERWIG++) or transverse momentum (PYTHIA, SHERPA)
- scale choice for strong coupling: $\alpha_S(k_\perp^2)$

  resums classes of higher logarithms
- regularisation through cut-off t_0

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

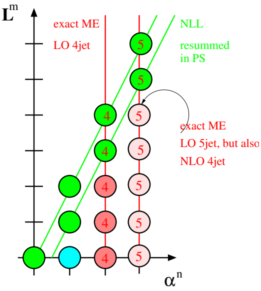
$$\mathrm{d}\sigma_B = \mathrm{d}\Phi_N\, \mathcal{B}_N(\Phi_N)$$
$$\cdot \underbrace{\left\{\Delta_N^{(\mathcal{K})}(\mu_N^2,t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \left[\mathcal{K}_N(\Phi_1)\Delta_N^{(\mathcal{K})}(\mu_N^2,t(\Phi_1))\right]\right\}}_{\text{integrates to unity} \longrightarrow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

- 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)



The POWHEG-trick: modifying the Sudakov form factor

(P. Nason, JHEP 0411 (2004) 040 & S. Frixione, P. Nason & C. Oleari, JHEP 0711 (2007) 070)

- reminder: $\mathcal{K}_{ij,k}$ reproduces process-independent behaviour of $\mathcal{R}_N/\mathcal{B}_N$ in soft/collinear regions of phase space

$$\mathrm{d}\Phi_1\,\frac{\mathcal{R}_N(\Phi_{N+1})}{\mathcal{B}_N(\Phi_N)}\;\xrightarrow{\text{IR}}\;\mathrm{d}\Phi_1\,\frac{\alpha_S}{2\pi}\,\mathcal{K}_{ij,k}(\Phi_1)$$

- define modified Sudakov form factor (as in ME correction)

$$\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2, t_0) = \exp\left[-\int\limits_{t_0}^{\mu_N^2}\mathrm{d}\Phi_1\,\frac{\mathcal{R}_N(\Phi_{N+1})}{\mathcal{B}_N(\Phi_N)}\right]\,,$$

- assumes factorisation of phase space: $\Phi_{N+1} = \Phi_N \otimes \Phi_1$
- typically will adjust scale of α_S to parton shower scale

Local K-factors

(P. Nason, JHEP 0411 (2004) 040 & S. Frixione, P. Nason & C. Oleari, JHEP 0711 (2007) 070)

- start from Born configuration Φ_N with NLO weight:

("local K-factor")

$$\begin{aligned} \mathrm{d}\sigma_N^{(\mathrm{NLO})} &= \mathrm{d}\Phi_N\,\bar{\mathcal{B}}(\Phi_N) \\ = \quad & \mathrm{d}\Phi_N \left\{ \mathcal{B}_N(\Phi_N) + \underbrace{\mathcal{V}_N(\Phi_N) + \mathcal{B}_N(\Phi_N)\otimes\mathcal{S}}_{\tilde{\mathcal{V}}_N(\Phi_N)} \right. \\ & \left. + \int \mathrm{d}\Phi_1\left[\mathcal{R}_N(\Phi_N\otimes\Phi_1) - \mathcal{B}_N(\Phi_N)\otimes\mathrm{d}\mathcal{S}(\Phi_1)\right] \right\} \end{aligned}$$

- by construction: exactly reproduce cross section at NLO accuracy
- note: second term vanishes if $\mathcal{R}_N \equiv \mathcal{B}_N \otimes \mathrm{d}\mathcal{S}$

(relevant for MC@NLO)

NLO accuracy in radiation pattern

(P. Nason, JHEP 0411 (2004) 040 & S. Frixione, P. Nason & C. Oleari, JHEP 0711 (2007) 070)

- generate emissions with $\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, t_0)$:

$$\mathrm{d}\sigma_N^{\mathrm{(NLO)}} = \mathrm{d}\Phi_N\, \bar{\mathcal{B}}(\Phi_N)$$

$$\times \underbrace{\left\{\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \frac{\mathcal{R}_N(\Phi_N \otimes \Phi_1)}{\mathcal{B}_N(\Phi_N)} \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, k_\perp^2(\Phi_1))\right\}}_{\text{integrating to yield 1 - ``unitarity of parton shower''}}$$

- radiation pattern like in ME correction
- pitfall, again: choice of upper scale μ_N^2 (this is vanilla POWHEG!)
- apart from logs: which configurations enhanced by local K-factor

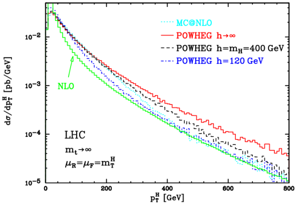
(K-factor for inclusive production of X adequate for $X+$ jet at large $p_\perp$?)

Improved POWHEG

(S. Alioli, P. Nason, C. Oleari, & E. Re, JHEP 0904 (2009) 002)

- split real-emission ME as

$$\mathcal{R} = \mathcal{R}\left(\underbrace{\frac{h^2}{p_\perp^2 + h^2}}_{\mathcal{R}^{(S)}} + \underbrace{\frac{p_\perp^2}{p_\perp^2 + h^2}}_{\mathcal{R}^{(F)}}\right)$$



- can "tune" h to mimick NNLO - or maybe resummation result
- differential event rate up to first emission

$$\mathrm{d}\sigma = \mathrm{d}\Phi_B \bar{\mathcal{B}}^{(\mathrm{R}^{(S)})} \left[\Delta^{(\mathcal{R}^{(S)}/\mathcal{B})}(s,\, t_0) + \int\limits_{t_0}^{s} \mathrm{d}\Phi_1 \frac{\mathcal{R}^{(S)}}{\mathcal{B}} \Delta^{(\mathcal{R}^{(S)}/\mathcal{B})}(s,\, k_\perp^2) \right]$$

$$+\mathrm{d}\Phi_R\, \mathcal{R}^{(F)}(\Phi_R)$$

Resummation in 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 $\mathrm{d}\mathcal{S}_1 \equiv \sum\limits_{\{ij,k\}} \mathcal{K}_{ij,k}$

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

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

- effect: only resummed parts modified with local K-factor

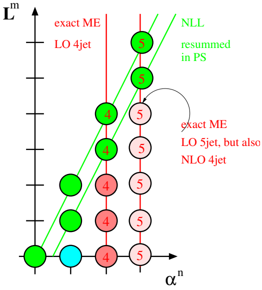
Multijet merging @ leading order

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)

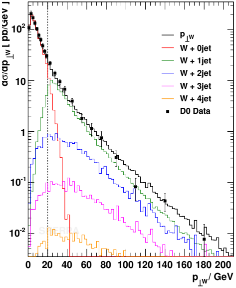
- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- combine ("merge") both:
  result: "towers" 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)

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

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

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

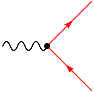
- potential occurence of different shower start scales: $\mu_{N,N+1,\dots}$
- “unitarity violation” in square bracket: $\mathcal{B}_N\mathcal{K}_N \longrightarrow \mathcal{B}_{N+1}$

(cured with UMEPS formalism, L. Lonnblad & S. Prestel, JHEP 1302 (2013) 094 &

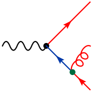
S. Platzer, arXiv:1211.5467 [hep-ph] & arXiv:1307.0774 [hep-ph])

Why it works: jet rates with the parton shower

- consider jet production in $e^+e^- \to$ hadrons
  Durham jet definition: relative transverse momentum $k_\perp > Q_J$
- fixed order: one factor α_S and up to $\log^2 \frac{E_{\rm c.m.}}{Q_J}$ per jet
- use Sudakov form factor for resummation &
  replace approximate fixed order by exact expression:



$$\mathcal{R}_2(Q_J) \;=\; \left[\Delta_q(E^2_{\rm c.m.},\,Q_J^2)\right]^2$$

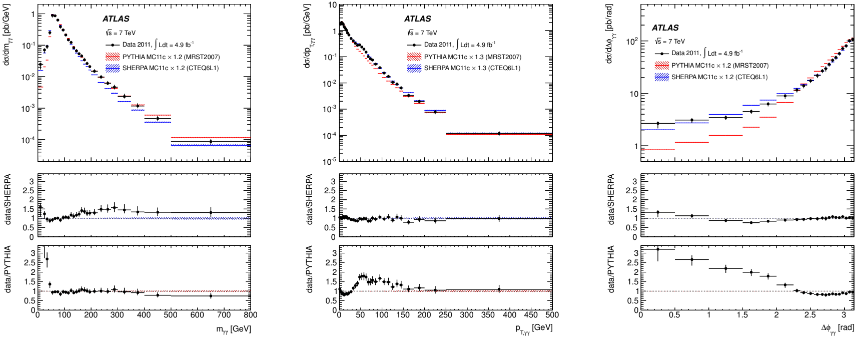


$$\mathcal{R}_3(Q_J) \;=\; 2\Delta_q(E^2_{\rm c.m.},\,Q_J^2)\int\limits_{Q_J^2}^{E^2_{\rm c.m.}}\frac{{\rm d}k_\perp^2}{k_\perp^2}\left[\frac{\alpha_S(k_\perp^2)}{2\pi}{\rm d}z\mathcal{K}_q(k_\perp^2,z)\right.$$

$$\left.\times\;\Delta_q(E^2_{\rm c.m.},\,k_\perp^2)\Delta_q(k_\perp^2,\,Q_J^2)\Delta_g(k_\perp^2,\,Q_J^2)\right]$$

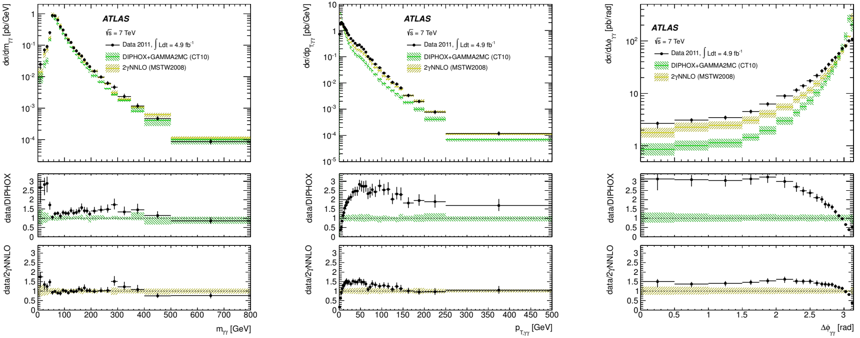
Di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$ in showers

(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

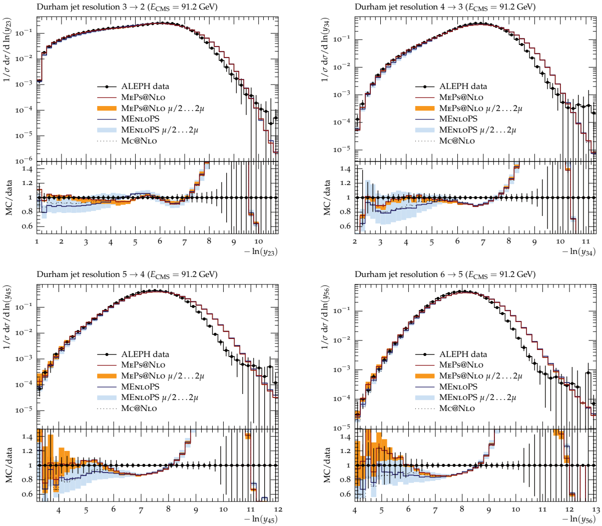
maintain NLO and LL accuracy of ME and PS

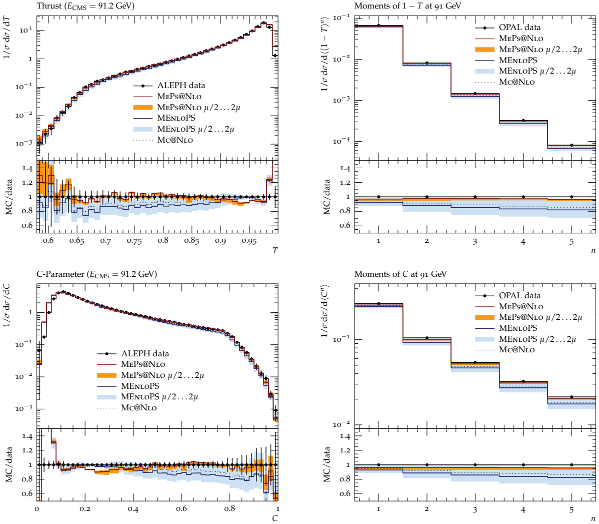
- this effectively translates into a merging of MC@NLO simulations and can be further supplemented with LO simulations for even higher final state multiplicities

First emission(s), once more

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

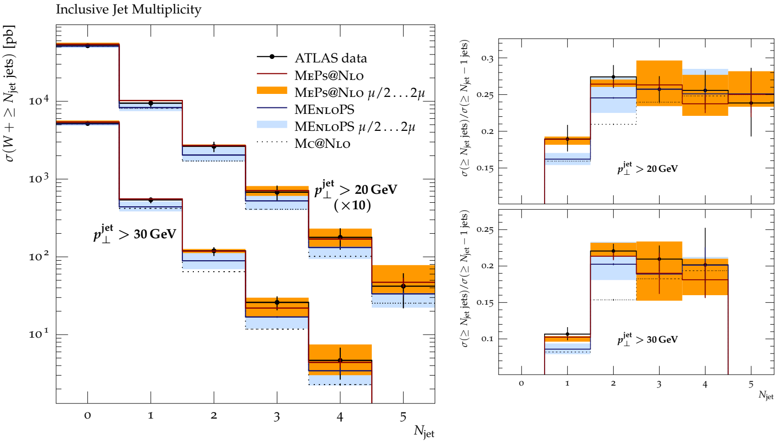
MEPS@NLO: validation in $e^-e^+ \to$ hadrons

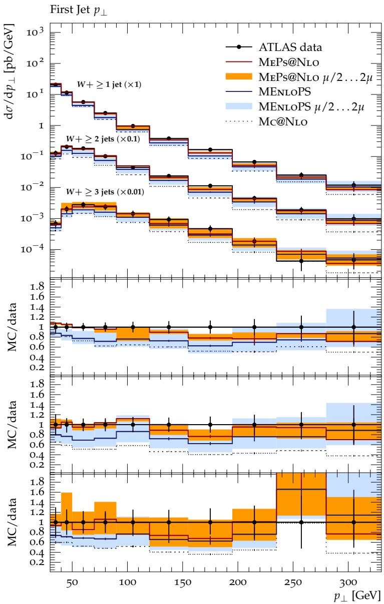


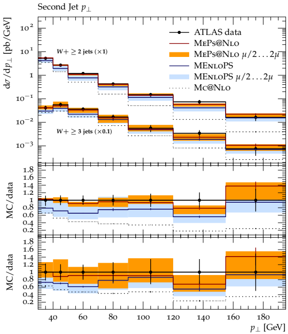

Thrust (E_{CMS} = 91.2 GeV)
$1/\sigma\, d\sigma/dT$
ALEPH data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
MC/data
T
Moments of $1-T$ at 91 GeV
$1/\sigma\, d\sigma/d\langle(1-T)^n\rangle$
OPAL data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
MC/data
n
C-Parameter (E_{CMS} = 91.2 GeV)
$1/\sigma\, d\sigma/dC$
ALEPH data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
MC/data
C
Moments of C at 91 GeV
$1/\sigma\, d\sigma/d\langle C^n\rangle$
OPAL data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
MC/data
n

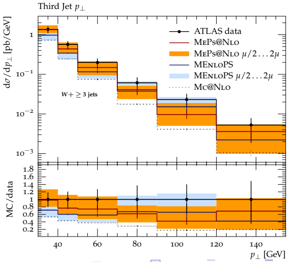
MEPS@NLO: validation in W+jets

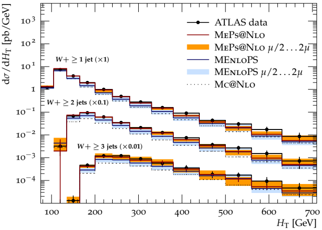
(S. Hoeche, F. Krauss, M. Schoenherr & F. Siegert, JHEP 1304 (2013) 027)

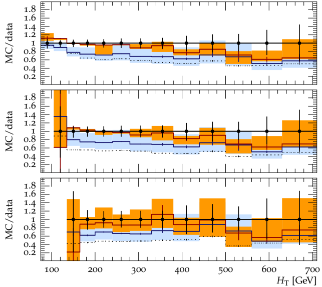



First Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 1$ jet ($\times 1$)
$W+\geq 2$ jets ($\times 0.1$)
$W+\geq 3$ jets ($\times 0.01$)
10^3
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
MC/data
MC/data
MC/data
50
100
150
200
250
300
$p_\perp$ [GeV]

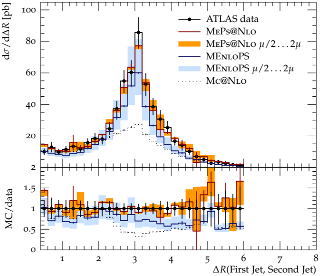

Second Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 2$ jets ($\times 1$)
$W+\geq 3$ jets ($\times 0.1$)
10^2
10^1
1
10^{-1}
10^{-2}
10^{-3}
MC/data
MC/data
40
60
80
100
120
140
160
180
$p_\perp$ [GeV]


Third Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 3$ jets
1
10^{-1}
10^{-2}
10^{-3}
MC/data
40
60
80
100
120
140
$p_\perp$ [GeV]

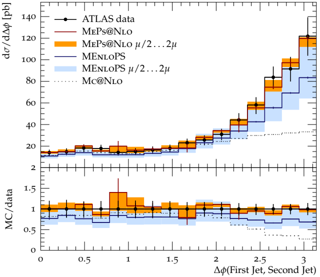




ΔR Distance of Leading Jets



Azimuthal Distance of Leading Jets

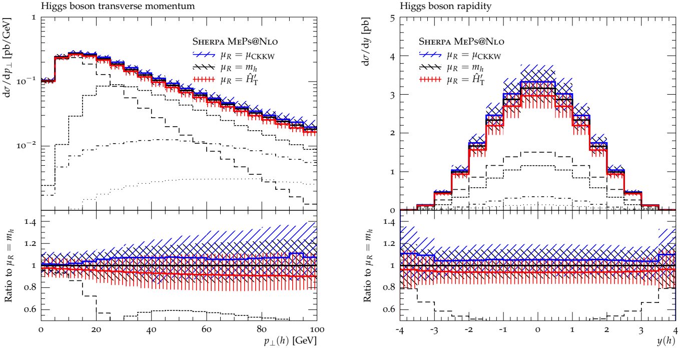


Multijet merging @ next-to leading order: $gg \to H$

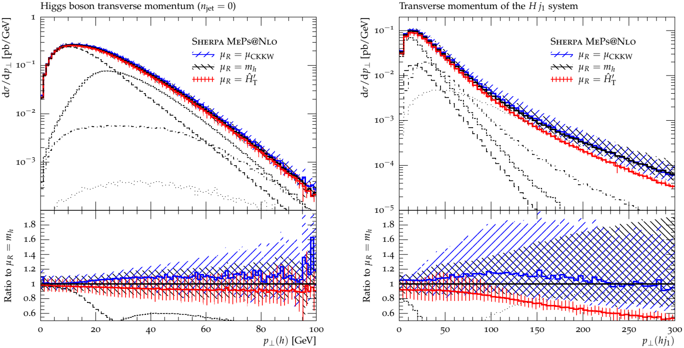
Results for Higgs boson production through gluon fusion

- parton-shower level, Higgs boson does not decay
- setup & cuts:
  jets: anti-kt, $p_\perp \geq 20$ GeV, $R = 0.4$, $|\eta| \leq 4.5$
  dijet cuts: at least 2 jets with $p_\perp \geq 25$ GeV
  WBF cuts: $m_{jj} \geq 400$ GeV, $\Delta y_{jj} \geq 2.8$
- jet multiplicity plots:
  0-jet excl.: no jet with $p_\perp \geq \{20, 25, 30\}$ GeV
  2-jet incl.: at least two jets with $p_\perp \geq \{20, 25, 30\}$ GeV
- SHERPA with $H + \{0,1,2\}^{(NLO)} + \{3\}^{(LO)}$ jets, $Q_{\rm cut} = 20 GeV$

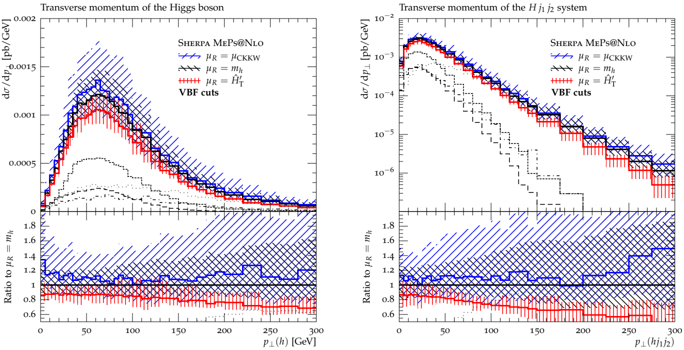
Inclusive observables for $gg \to H$



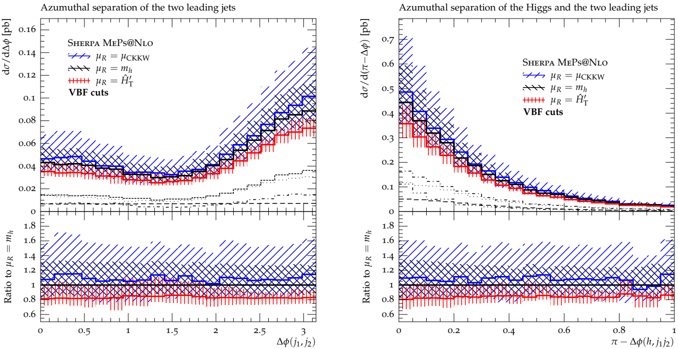
Exclusive observables for $gg \to H$



$gg \to H$ after WBF cuts

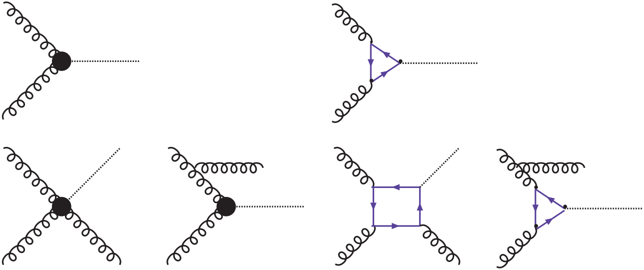


$gg \to H$ after WBF cuts



Quark mass effects

- include effects of quark masses

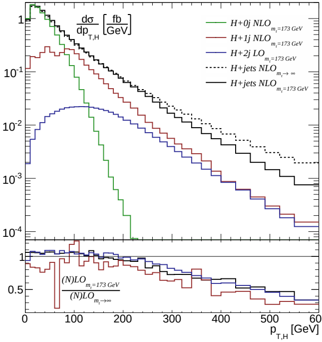


- reweight NLO HEFT with LO ratio:

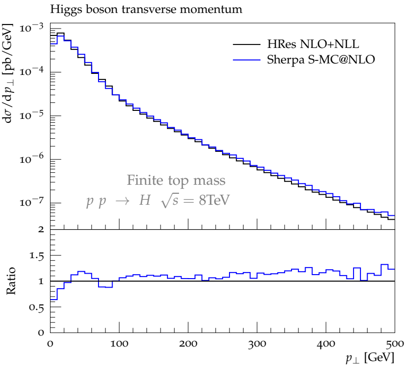
$$\mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{mass}} \approx \mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{HEFT}} \times \frac{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{mass}}}{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{HEFT}}}$$

Quark mass effects – results

- top mass effect in MEPS@NLO (on Higgs–$p_\perp$)

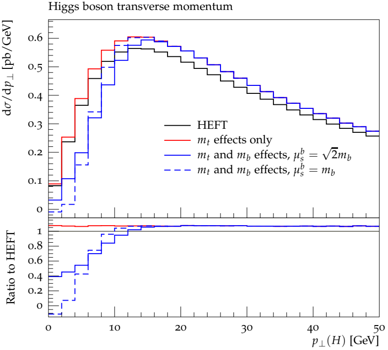


- comparison S-MC@NLO– HRES (top–loop only)

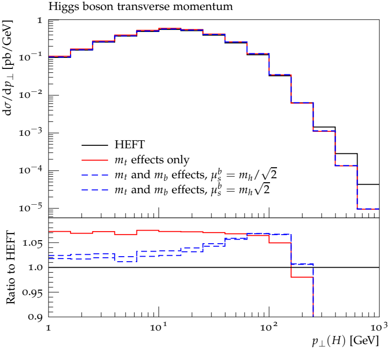


b–mass effects: playtime

vary around $\mu_Q = m_b$

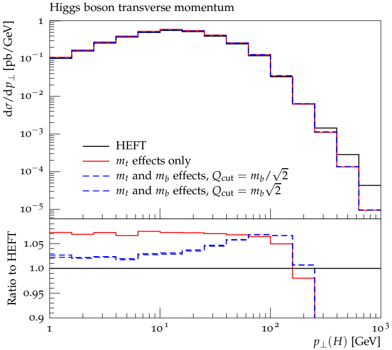


vary around $\mu_Q = m_h$ with $Q_{\rm cut} = m_b$

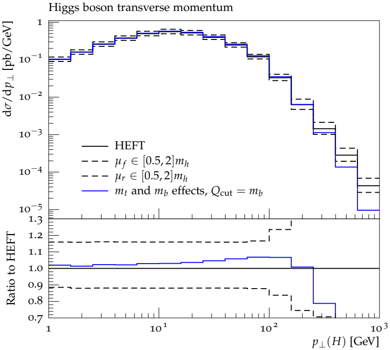


b–mass effects: playtime (cont'd)

vary around $\mu_Q = m_h$ with $Q_{\text{cut}} = m_b$

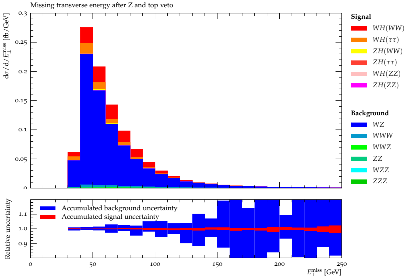


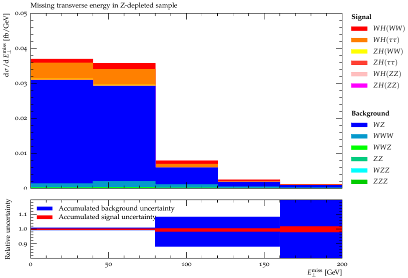
vary $\mu_{F,R}$



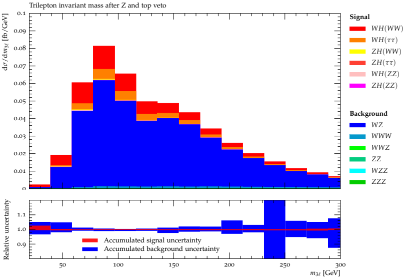
Multijet merging @ next-to leading order: $VH \to 3\ell$

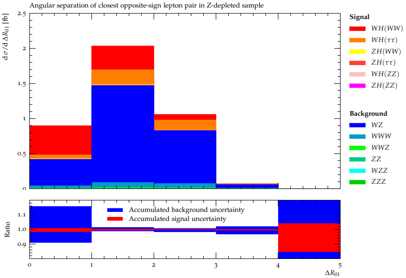
Relevant observables for $VH \to 3\ell$: $\not{E}_T$



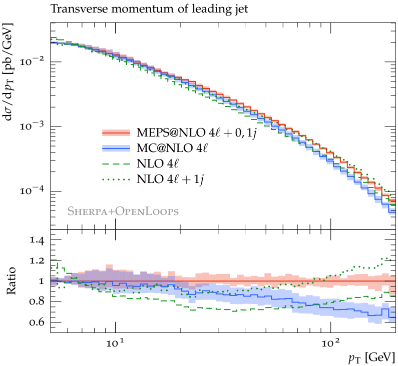


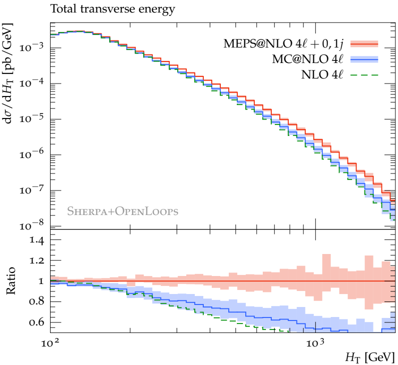
Relevant observables for $VH \to 3\ell$: m_{123} & ΔR_{01}



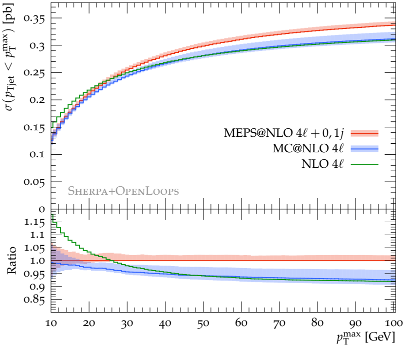


Higgs backgrounds: inclusive observables in W^+W^-+jets

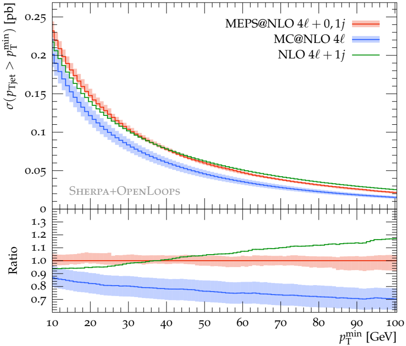

Transverse momentum of leading jet


Total transverse energy

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



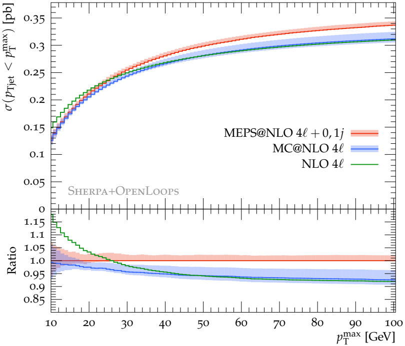
Integrated cross section in the exclusive 0-jet bin



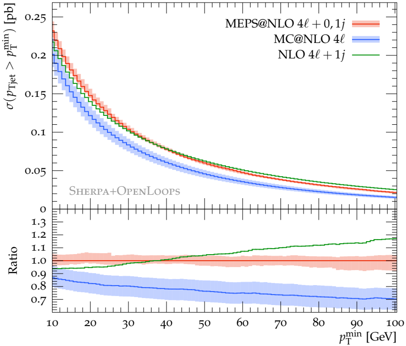
Integrated cross section in the inclusive 1-jet bin

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

Integrated cross section in the exclusive 0-jet bin

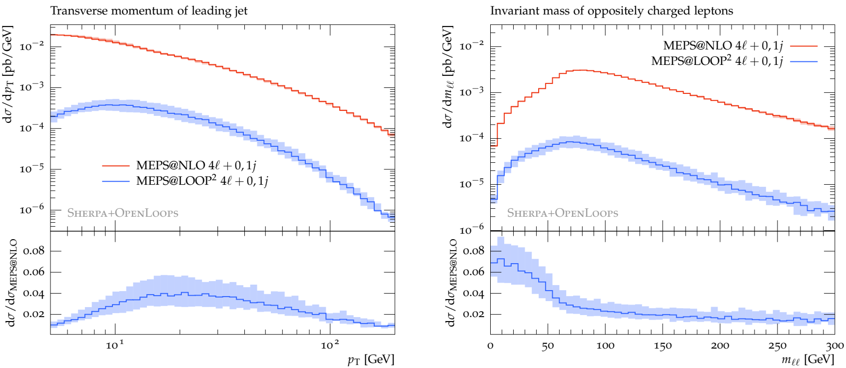


Integrated cross section in the inclusive 1-jet bin

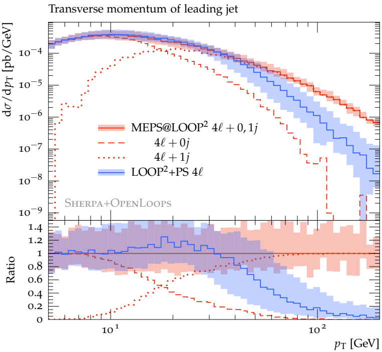


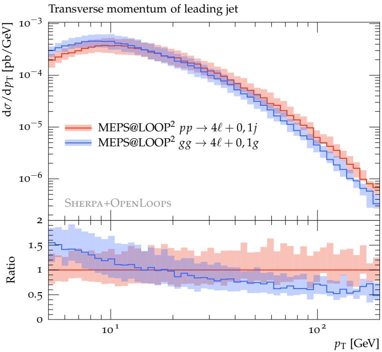
Higgs backgrounds: gluon-induced processes W^+W^-+jets

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

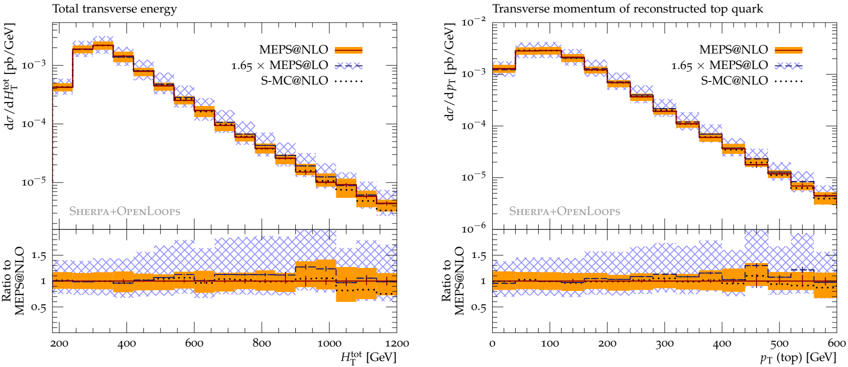


Higgs backgrounds: jet vetoes in W^+W^-+jets

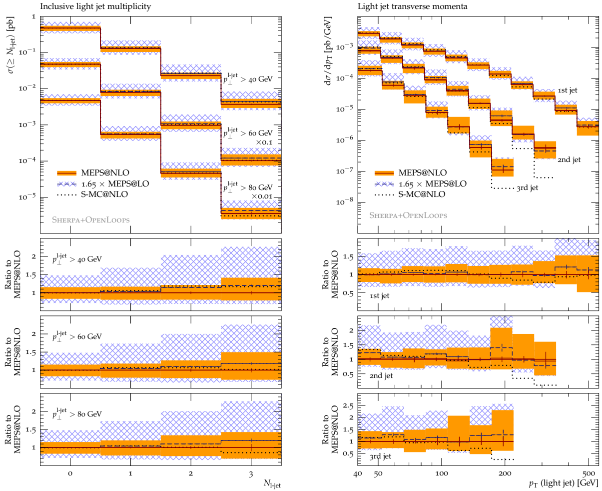

Transverse momentum of leading jet


Transverse momentum of leading jet

Higgs backgrounds: $t\bar{t}$ + jets

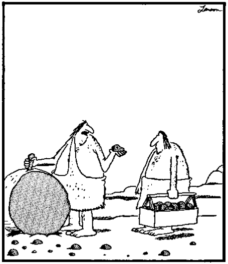


Higgs backgrounds: light jets in $t\bar{t}$ + jets



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."

(first 3 methods are well understood and used in experiments)

(last method need validation etc.)

- multijet merging an important tool for many relevant signals and backgrounds - pioneered by SHERPA at LO & NLO
- complete automation of NLO calculations done
  ⟶ must benefit from it!

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

Famous last screams

- in Run-II we'll be in for a ride:

more statistics
more energy
more channels
more precision
more fun