Precision simulations for Higgs physics in SHERPA

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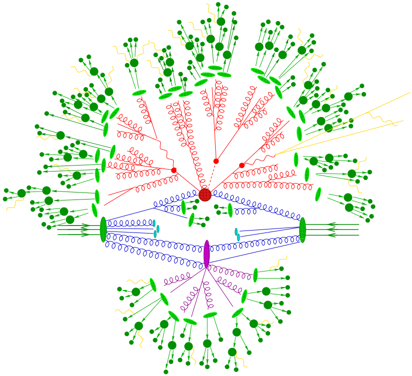
The inner working of event generators . . .

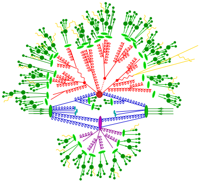
simulation: divide et impera

- 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

QCD precision in Higgs physics

- after discovery: time for precision studies of the newly found boson
  is it the SM Higgs boson or something else?
  relevant: spin/parity, couplings to other particles
- Higgs signal suffers from different backgrounds, depending on production and decay channel considered in the analysis
- decomposing in bins of different jet multiplicities yields
  - different signal composition (e.g. WBF vs. ggF)
  - different backgrounds (most notably: $t\bar{t}$ in WW final states)
- to this end: must understand jet production in big detail
  name of the game: uncertainties and their control

despite far-reaching claims: analytic resummation and fixed-order calculations will not be sufficient

Reminder: Ingredients of simulations

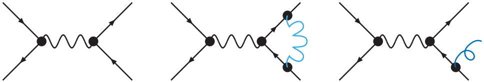
Cross sections at the LHC: Born approximation

$$\mathrm{d}\sigma_{ab\to N} = \int_0^1 \mathrm{d}x_a \mathrm{d}x_b f_a(x_a,\,\mu_F) f_b(x_a,\,\mu_F) \int_{\text{cuts}} \mathrm{d}\Phi_N \frac{1}{2\hat{s}} \left|\mathcal{M}_{p_a p_b \to N}(\Phi_N;\,\mu_F,\,\mu_R)\right|^2$$

- 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

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

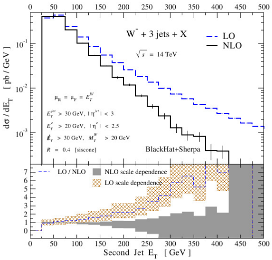
$$= \mathrm{d}\Phi_N \left[\mathcal{B}_N + \mathcal{V}_N + \mathcal{B}_N \otimes \mathcal{S}\right] + \mathrm{d}\Phi_{N+1} \left[\mathcal{R}_{N+1} - \mathcal{B}_N \otimes \mathrm{d}\mathcal{S}\right]$$

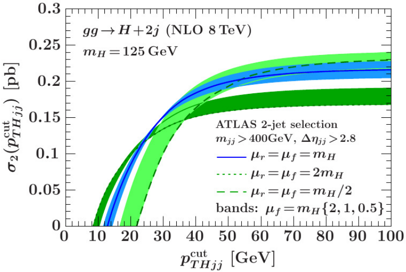
- subtraction terms $\mathcal{S}$ (integrated) and $\mathrm{d}\mathcal{S}$:
  exactly cancel IR divergence in $\mathcal{R}$ – process-independent structures
- result: terms in both brackets separately infrared finite

Aside: 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:

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

- consider first emission only off Born configuration

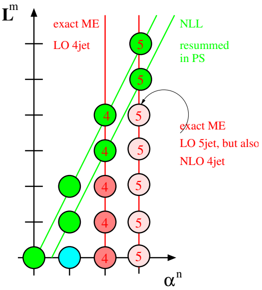
$$\mathrm{d}\sigma_B = \mathrm{d}\Phi_N\, \mathcal{B}_N(\Phi_N) \cdot \underbrace{\left\{\Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \left[\mathcal{K}_N(\Phi_1)\Delta_N^{(\mathcal{K})}(\mu_N^2, t(\Phi_1))\right]\right\}}_{\text{integrates to unity} \longrightarrow \text{“unitarity”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

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

NLO improvements: Matching

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 with 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 $\mathrm{d}\mathcal{S}_1 \equiv \sum_{\{ij,k\}} \mathcal{K}_{ij,k}$

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

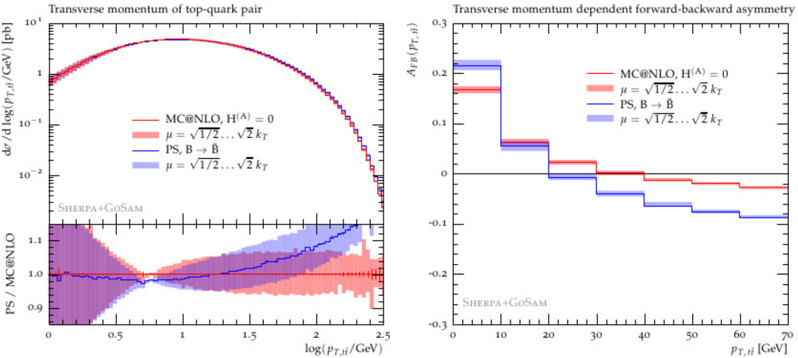
$$\mathrm{d}\sigma_N = \mathrm{d}\Phi_N \underbrace{\tilde{\mathcal{B}}_N(\Phi_N)}_{\mathcal{B}+\tilde{\mathcal{V}}} \left[\Delta_N^{(\mathcal{K})}(\mu_N^2,\, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1\, \mathcal{K}_{ij,k}(\Phi_1)\, \Delta_N^{(\mathcal{K})}(\mu_N^2,\, k_\perp^2)\right] + \mathrm{d}\Phi_{N+1}\,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

- effect: resummed parts modified with local K-factor

Aside: impact of full colour

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

- evaluate effect of full colour treatment, 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)

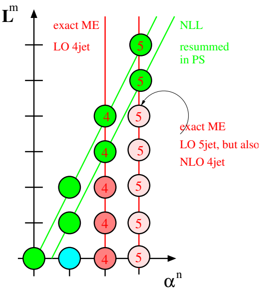


Multijet merging @ leading order

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

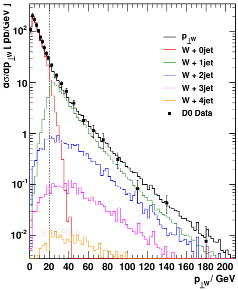


Separating jet evolution and jet production

- 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)

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

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

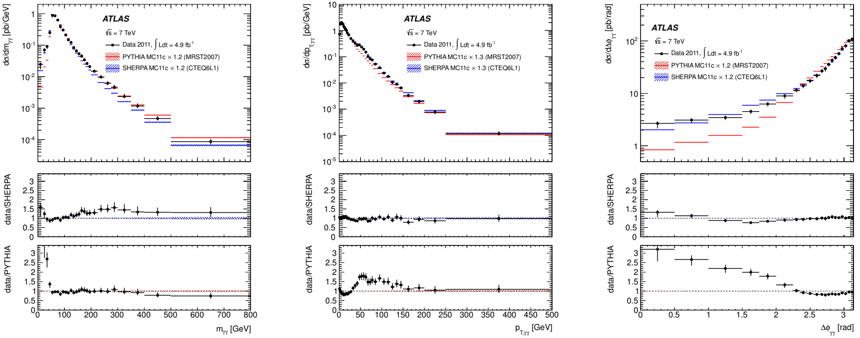
  (no Sudakov suppression below t_{n+1}, see further slides for iterated expression)

- 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]) – see next talks

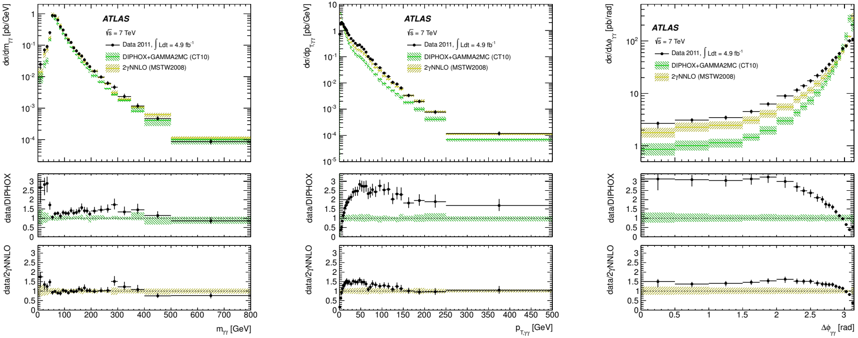
Di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$ in showers

(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

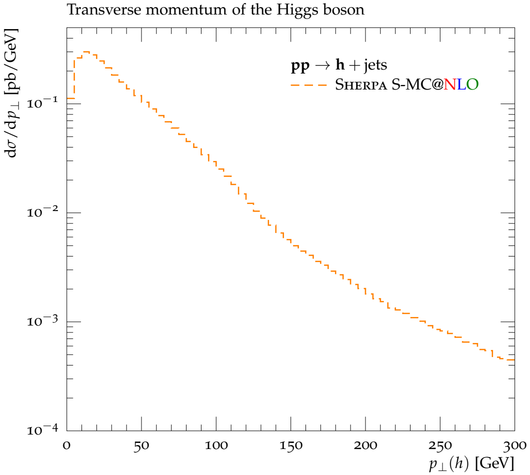
maintain NLO and LL accuracy of ME and PS

- 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

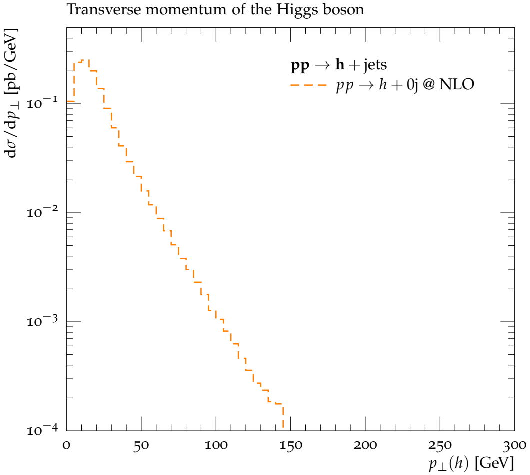
$$
\begin{aligned}
\mathrm{d}\sigma \;=\; & \mathrm{d}\Phi_N\,\tilde{\mathcal{B}}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,t_0)+\int\limits_{t_0}^{\mu_N^2}\mathrm{d}\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\right]\\
& +\mathrm{d}\Phi_{N+1}\,\mathcal{H}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\\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

MEPS@NLO



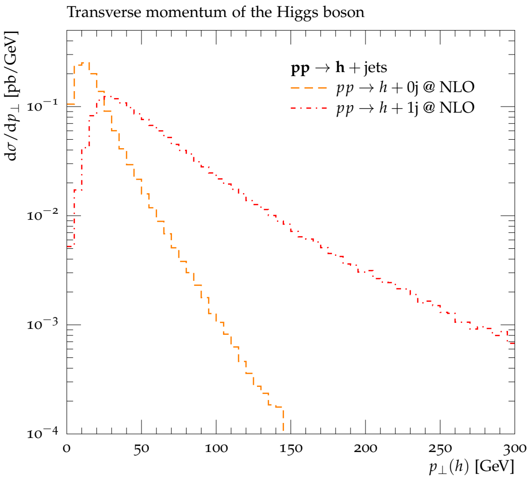
- first emission by MC@NLO

MEPS@NLO



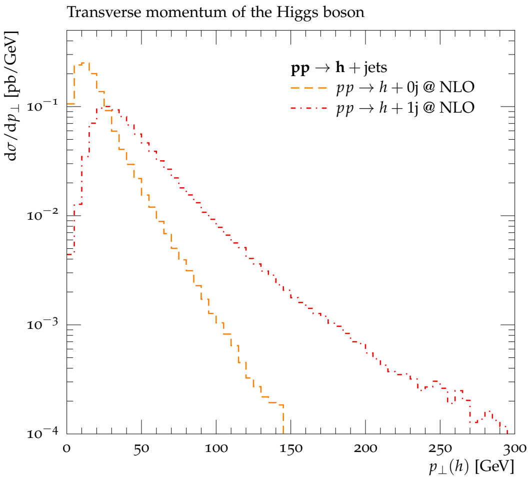
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\mathrm{cut}}$

MEPS@NLO



- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$

MEPS@NLO



- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\rm cut}$

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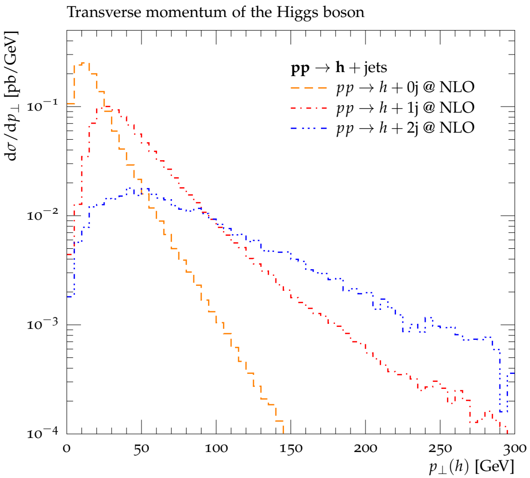

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- MC@NLO $pp \to h +$ jet for $Q_{n+1} > Q_{cut}$
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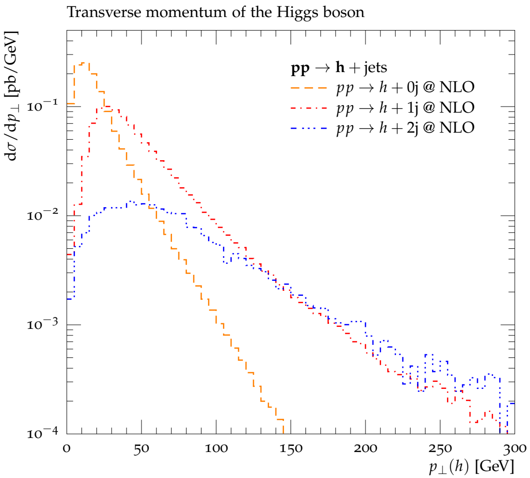
- MC@NLO $pp \to h +$ 2jets for $Q_{n+2} > Q_{cut}$

MEPS@NLO



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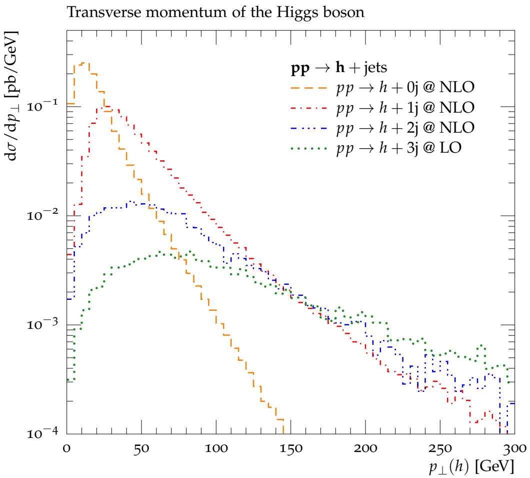
- restrict emission off $pp \to h+$jet to $Q_{n+2} < Q_{\text{cut}}$
- MC@NLO $pp \to h+$2jets for $Q_{n+2} > Q_{\text{cut}}$
- iterate

MEPS@NLO



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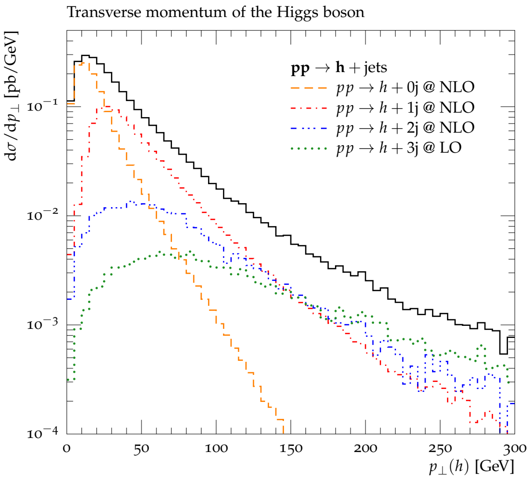
MEPS@NLO



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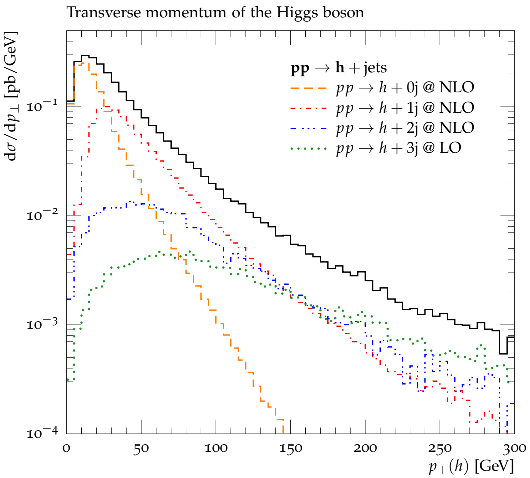
- iterate
- sum all contributions

MEPS@NLO



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- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions
- eg. $p_\perp(h) > 200$ GeV has contributions fr. multiple topologies

Parameter / Scale choices – $\mu_{R/F}$, μ_Q

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\rm core}^2)\,\alpha_s(t_1)\cdots\alpha_s(t_n) \qquad \mu_{F,a/b}^2 = t_{{\rm ext},a/b} \qquad \mu_Q^2 = \mu_{\rm core}^2$$

Free choices

1. $\mu_{\rm core}$ – scale of core process identified through clustering with inverse parton shower

Parameter / Scale choices – $\mu_{R/F}$, μ_Q

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\rm core}^2)\,\alpha_s(t_1)\cdots\alpha_s(t_n) \qquad \mu_{F,a/b}^2 = t_{{\rm ext},a/b} \qquad \mu_Q^2 = \mu_{\rm core}^2$$

Free choices

1. $\mu_{\rm core}$ – scale of core process identified through clustering with inverse parton shower
2. $\mu_{R/F}$ beyond 1-loop running
   - calculate with chosen $\mu_{R/F}$
   - include renormalisation and factorisation terms to shift the 1-loop running to above

$$\mathrm{B}_n\,\frac{\alpha_s(\mu_R)}{\pi}\,\beta_0\,\left(\log\frac{\mu_R}{\mu_{\rm CKKW}}\right)^{2+n}$$

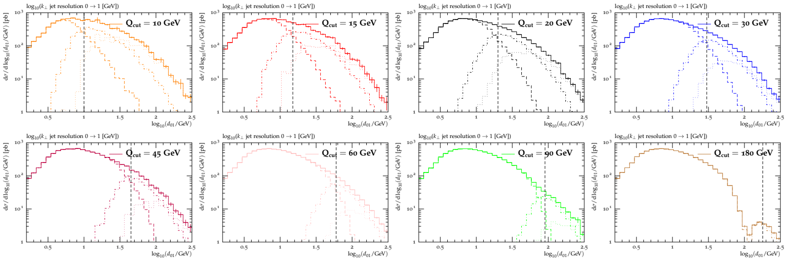
and

$$\mathrm{B}_n\,\frac{\alpha_s}{2\pi}\,\log\frac{\mu_F}{t_{\rm ext}}\sum_{c=q,g}\int_{x_a}^1\frac{\mathrm{d}z}{z}\,P_{ac}(z)f_c(x_a/z,\mu_F^2)$$

$\to$ same as in UNLOPS– see later

Parameter / Scale choices – Q_{cut}

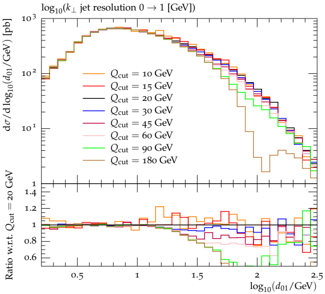
Merging cut Q_{cut} dependence ($pp \to Z+$jets MEPS@LO, up to 2 in ME):



- parton shower is trusted to corectly describe emissions $\lesssim Q_{\text{cut}}$
- changes the region where higher accuracy is used for calculation
  $\to$ part of the uncertainty is due to degraded accuracy for large Q_{cut}
- all samples are identical for $Q < Q_{\text{cut}}^{\text{smallest}}$ and $Q > Q_{\text{cut}}^{\text{largest}}$ by construction
- for $Q \geq 45$ GeV shower approximation breaks down (earlier in other obs.)

Parameter / Scale choices – $Q_{\rm cut}$

Merging cut $Q_{\rm cut}$ dependence ($pp \to Z +$ jets MEPS@LO, up to 2 in ME):



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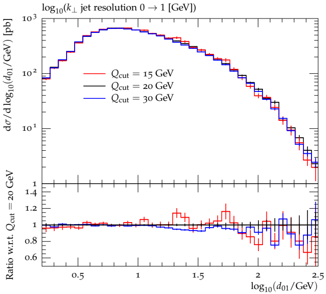

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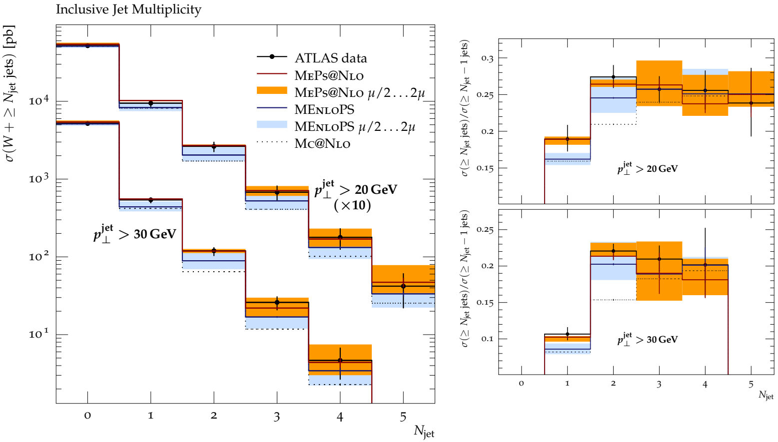
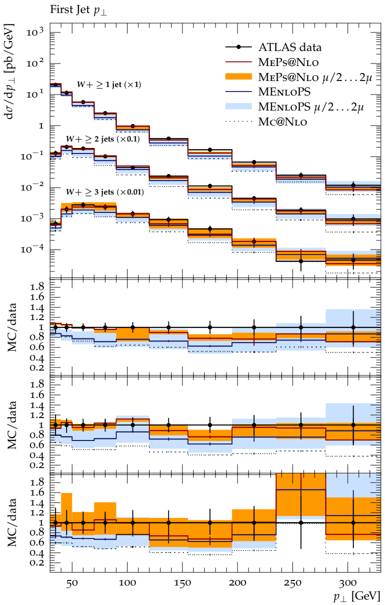
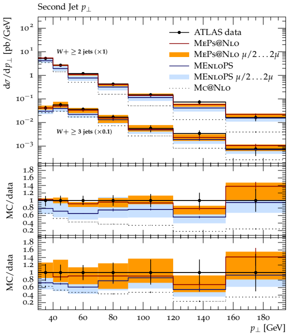
- all samples are identical for $Q < Q_{\rm cut}^{\rm smallest}$ and $Q > Q_{\rm cut}^{\rm largest}$ by construction
- for $Q \geq 45$ GeV shower approximation breaks down (earlier in other obs.)
- $Q_{\rm cut}$ dependence usually small

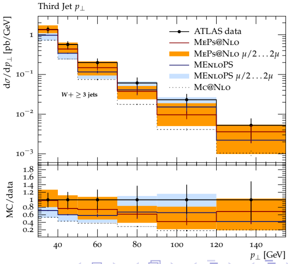
MEPS@NLO: validation in W+jets

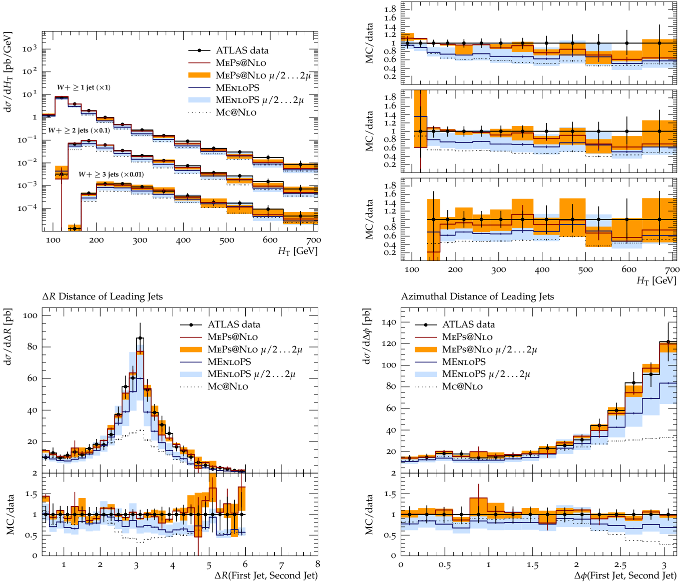
(S. Hoeche, F. Krauss, M. Schoenherr & F. Siegert, JHEP 1304 (2013) 027)




First Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\dots2\mu$
MENLOPS
MENLOPS $\mu/2\dots2\mu$
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 $\mu/2\dots2\mu$
MENLOPS
MENLOPS $\mu/2\dots2\mu$
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 $\mu/2\dots2\mu$
MENLOPS
MENLOPS $\mu/2\dots2\mu$
MC@NLO
$W+\geq 3$ jets
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]

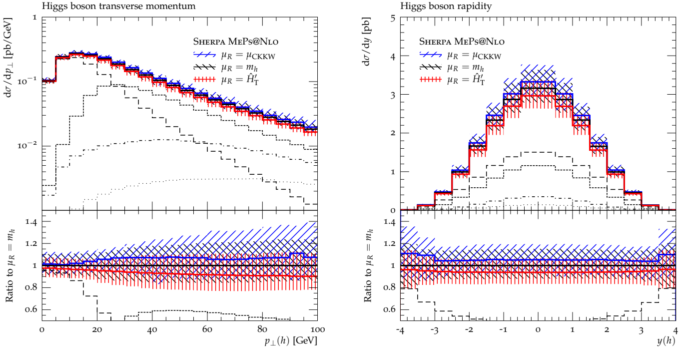

ATLAS data
MEPS@NLO
MEPS@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
W+ ≥ 1 jet (×1)
W+ ≥ 2 jets (×0.1)
W+ ≥ 3 jets (×0.01)
dσ/dH_T [pb/GeV]
H_T [GeV]
MC/data
ΔR Distance of Leading Jets
dσ/dΔR [pb]
ΔR(First Jet, Second Jet)
Azimuthal Distance of Leading Jets
dσ/dΔφ [pb]
Δφ(First Jet, Second Jet)

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

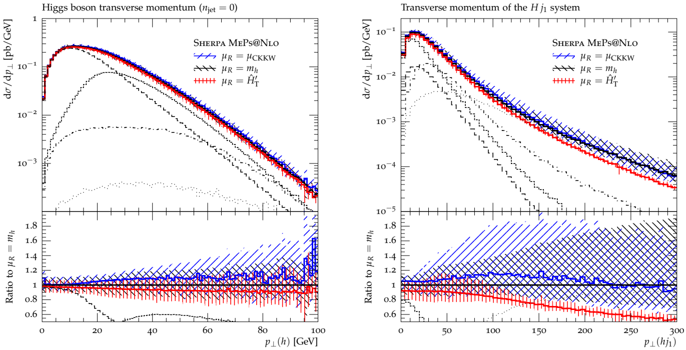
Results for Higgs boson production through gluon fusion

- 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, $Q_{\rm cut} = 20 GeV$

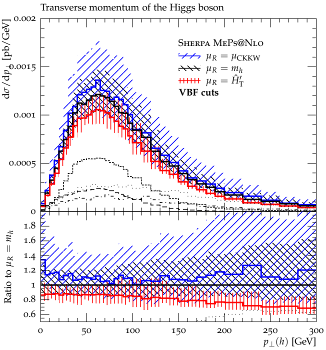
Inclusive observables for $gg \to H$

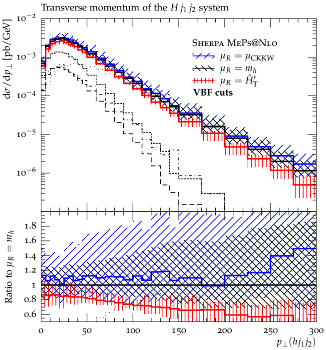


Exclusive observables for $gg \to H$

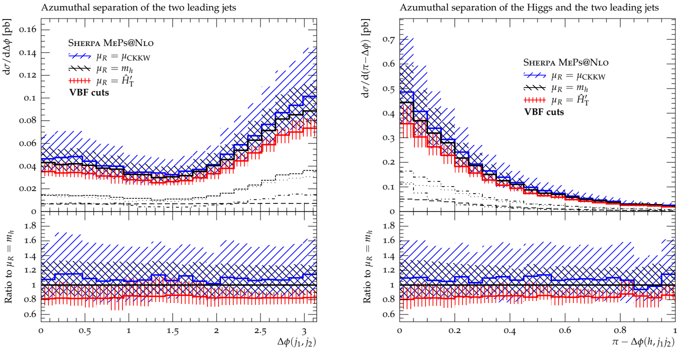


$gg \to H$ after WBF cuts

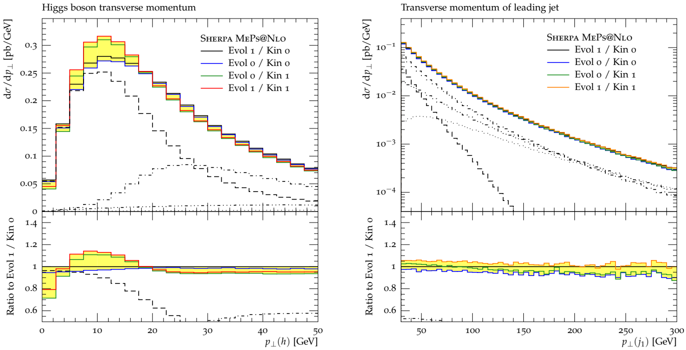




$gg \to H$ after WBF cuts

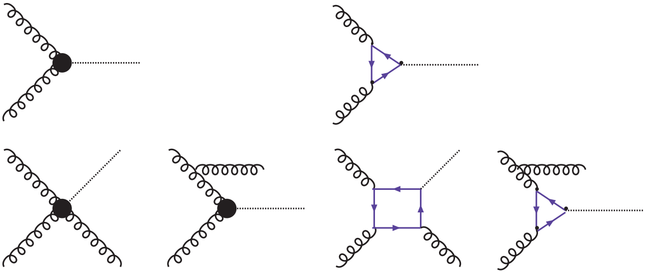


Parton shower uncertainties



Quark mass effects

- include effects of quark masses

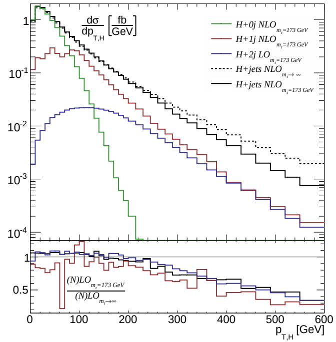


- reweight NLO HEFT with LO ratio:

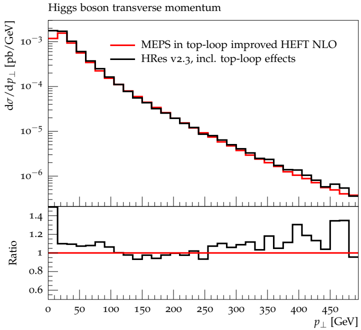
$$\mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{mass}} \approx \mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{HEFT}} \times \frac{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{mass}}}{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{HEFT}}}$$

Quark mass effects – results

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



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

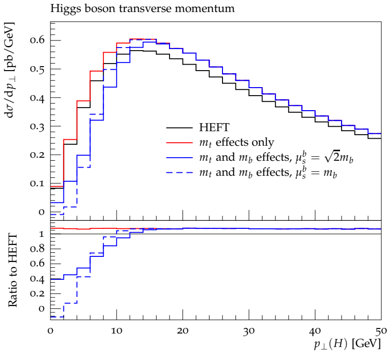


b–mass effects

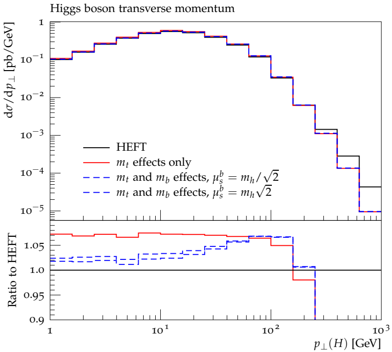
- b–mass effects more tricky
- relevant only for (negative) interference of top– and bottom–loops (bottom^2 double Yukawa - supressed)
- but: cannot start shower at m_H
  radiation "sees" bottom at all scales above m_b
  $\Longrightarrow$ must use full theory there
- p_T spectrum naively "squeezed" – funny shapes
- LO multijet merging improves situation

b–mass effects: playtime

vary around $\mu_Q = m_b$

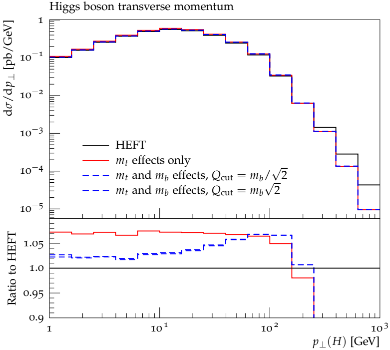


vary around $\mu_Q = m_h$ with $Q_{\rm cut} = m_b$

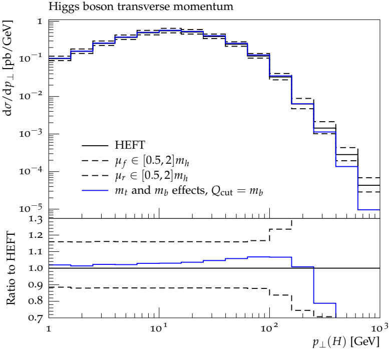


b–mass effects: playtime (cont'd)

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

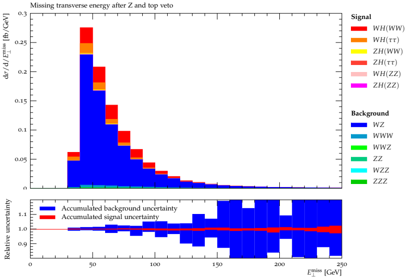


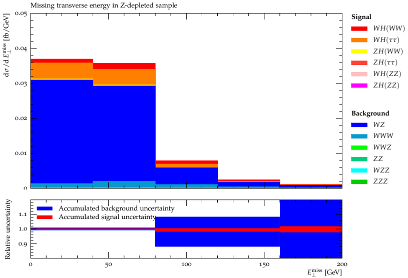
vary $\mu_{F,R}$



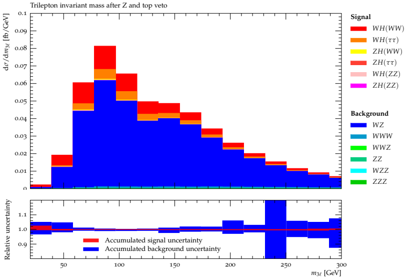
Multijet merging @ next-to leading order: $VH \to 3\ell$

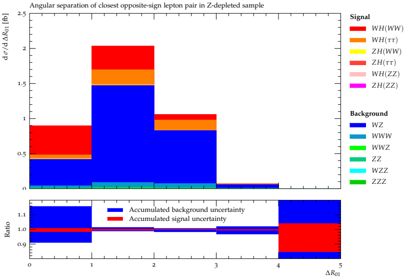
Relevant observables for $VH \to 3\ell$: $\not{E}_T$



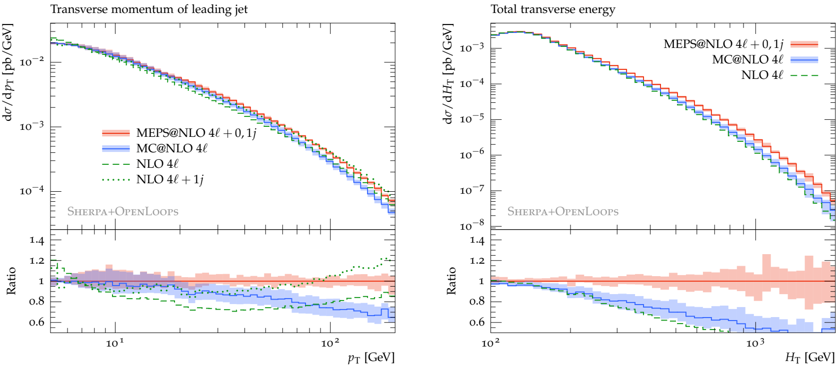


Relevant observables for $VH \to 3\ell$: m_{123} & ΔR_{01}

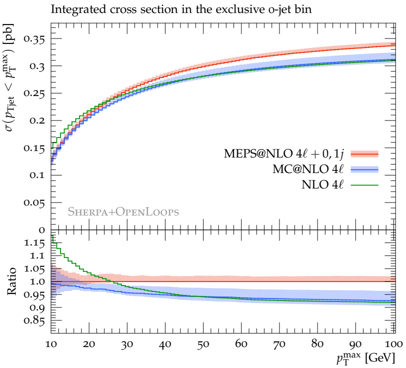


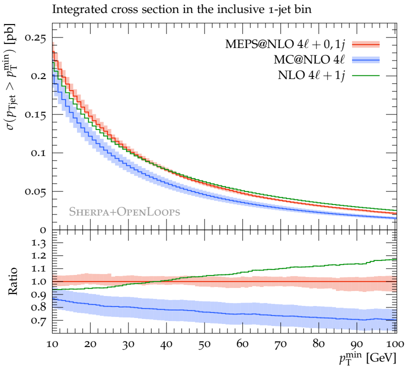


Higgs backgrounds: inclusive observables in W^+W^-+jets



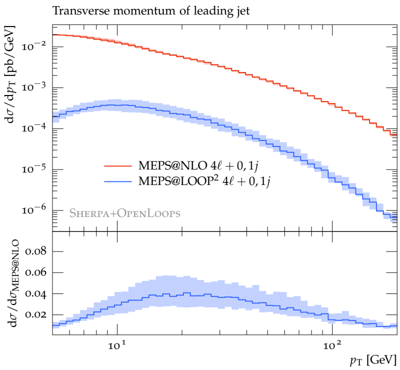
Higgs backgrounds: jet vetoes in W^+W^-+jets

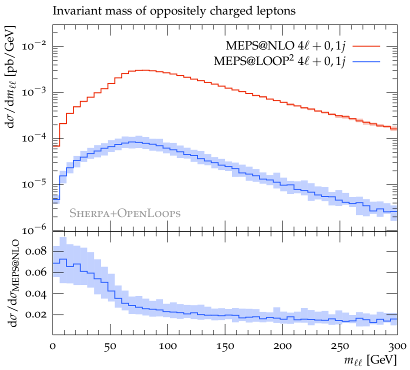




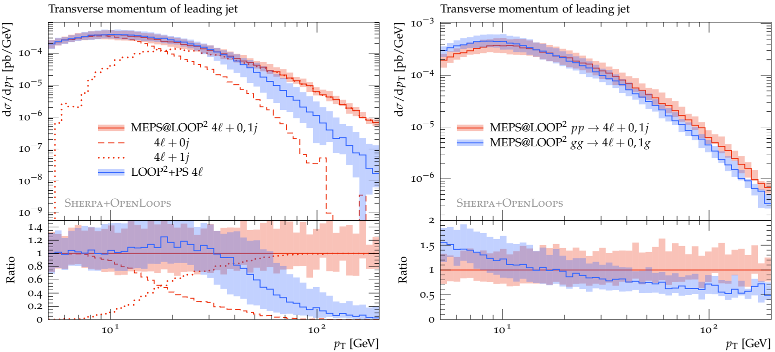
Higgs backgrounds: gluon-induced processes W^+W^-+jets

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

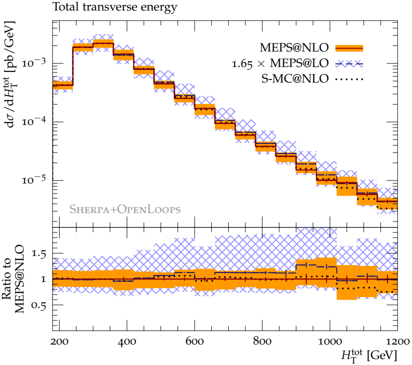


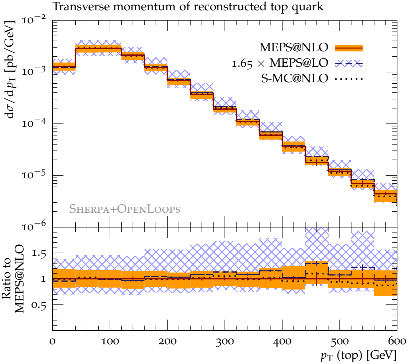


Higgs backgrounds: jet vetoes in W^+W^-+jets

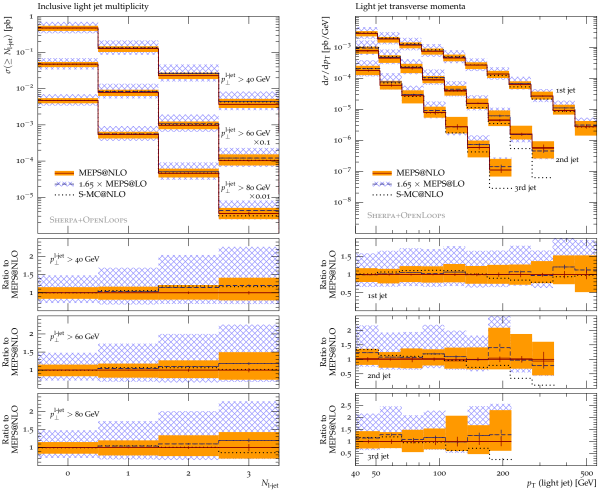


Higgs backgrounds: $t\bar{t}$ + jets





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

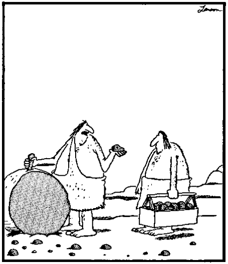


Summary

- Systematic improvement of event generators through higher orders ongoing:
  - multijet merging ("CKKW", "MLM")
  - NLO matching ("MC@NLO", "POWHEG")
  - MENLOPS NLO matching & merging
  - MEPS@NLO ("SHERPA", "UNLOPS", "MINLO", "FXFX")
  - NNLO+PS (two versions)

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

(last two methods need validation etc.)



"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

(next stop: parton shower uncertainties & improvements)

- complete automation of NLO calculations done $\longrightarrow$ 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