Precision Monte Carlo

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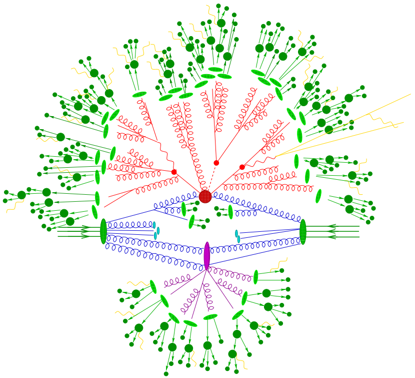
INTRODUCTION

Improving event generators

The inner working of event generators

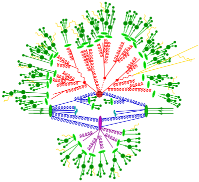
. . . simulation: divide et impera

- 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

Example: 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

INGREDIENTS

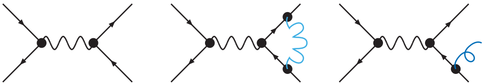
Cross sections at the LHC: Born approximation

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

- 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

Including higher order corrections

- 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)

- general structure of NLO calculation for N-body production

$$\begin{aligned} \mathrm{d}\sigma &= \mathrm{d}\Phi_{\mathcal{B}}\mathcal{B}_N(\Phi_{\mathcal{B}}) + \mathrm{d}\Phi_{\mathcal{B}}\mathcal{V}_N(\Phi_{\mathcal{B}}) + \mathrm{d}\Phi_{\mathcal{R}}\mathcal{R}_N(\Phi_{\mathcal{R}}) \\ &= \mathrm{d}\Phi_{\mathcal{B}}\left(\mathcal{B}_N + \mathcal{V}_N + \mathcal{I}_N^{(\mathcal{S})}\right) + \mathrm{d}\Phi_{\mathcal{R}}\left(\mathcal{R}_N - \mathcal{S}_N\right) \end{aligned}$$

- phase space factorisation assumed here ($\Phi_{\mathcal{R}} = \Phi_{\mathcal{B}} \otimes \Phi_1$)

$$\int \mathrm{d}\Phi_1 \mathcal{S}_N(\Phi_{\mathcal{B}} \otimes \Phi_1) = \mathcal{I}_N^{(\mathcal{S})}(\Phi_{\mathcal{B}})$$

- process independent subtraction kernels

$$\begin{aligned} \mathcal{S}_N(\Phi_{\mathcal{B}} \otimes \Phi_1) &= \mathcal{B}_N(\Phi_{\mathcal{B}}) \otimes \mathcal{S}_1(\Phi_{\mathcal{B}} \otimes \Phi_1) \\ \mathcal{I}_N^{(\mathcal{S})}(\Phi_{\mathcal{B}} \otimes \Phi_1) &= \mathcal{B}_N(\Phi_{\mathcal{B}}) \otimes \mathcal{I}_1^{(\mathcal{S})}(\Phi_{\mathcal{B}}) \end{aligned}$$

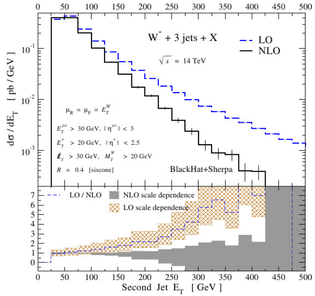
  with universal $\mathcal{S}_1(\Phi_{\mathcal{B}} \otimes \Phi_1)$ and $\mathcal{I}_1^{(\mathcal{S})}(\Phi_{\mathcal{B}})$
- in Catani–Seymour invertible phase space mapping

$$\Phi_{\mathcal{R}} \longleftrightarrow \Phi_{\mathcal{B}} \otimes \Phi_1$$

Aside: choices . . .

- common lore: NLO calculations reduce scale uncertainties
- this is, in general, true. however:

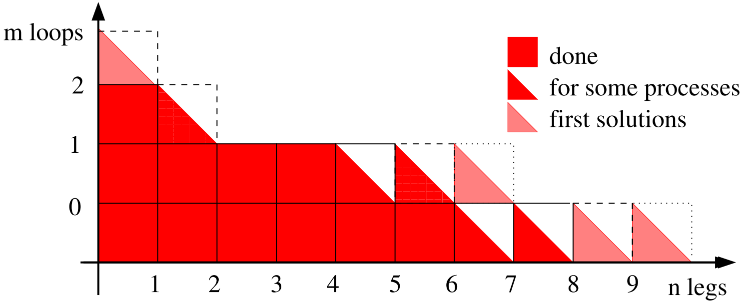
  unphysical scale choices will yield unphysical results



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

Availability of exact calculations (hadron colliders)

- fixed order matrix elements ("parton level") are exact to a given perturbative order. (and often quite a pain!)
- important to understand limitations:
  only tree-level and one-loop level fully automated, beyond: prototyping



Parton showers, compact notation

- Sudakov form factor (**no-decay** probability)

$$\Delta^{(\mathcal{K})}_{ij,k}(t,t_0) = \exp\left[-\int\limits_{t_0}^{t}\frac{\mathrm{d}t}{t}\frac{\alpha_s}{2\pi}\int\mathrm{d}z\frac{\mathrm{d}\phi}{2\pi}\underbrace{\mathcal{K}_{ij,k}(t,z,\phi)}_{\substack{\text{splitting kernel for}\\ (ij)\to ij\ (\text{spectator } k)}}\right]$$

- evolution parameter t defined by kinematics

generalised angle (HERWIG ++) or transverse momentum (PYTHIA, SHERPA)

- will replace $\frac{\mathrm{d}t}{t}\mathrm{d}z\frac{\mathrm{d}\phi}{2\pi}\longrightarrow\mathrm{d}\Phi_1$
- scale choice for strong coupling: $\alpha_s(k_\perp^2)$ — resums classes of higher logarithms
- regularisation through cut-off t_0

- "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 $Q^2 = t$ of previous emission

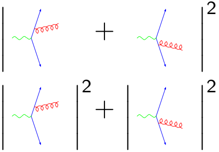
ME CORRECTIONS

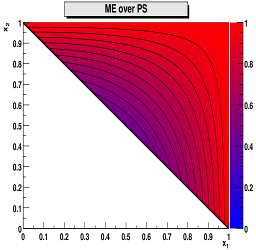
Matrix element corrections

- parton shower ignores interferences typically present in matrix elements
- pictorially

ME :

PS :



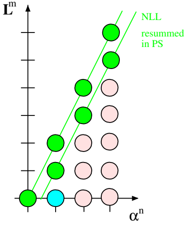


- form many processes $\mathcal{R}_N < \mathcal{B}_N \times \mathcal{K}_N$
- typical processes: $q\bar{q}' \to V$, $e^-e^+ \to q\bar{q}$, $t \to bW$
- practical implementation: shower with usual algorithm, but reject first/hardest emissions with probability $\mathcal{P} = \mathcal{R}_N/(\mathcal{B}_N \times \mathcal{K}_N)$

- analyse **first** emission, given by

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

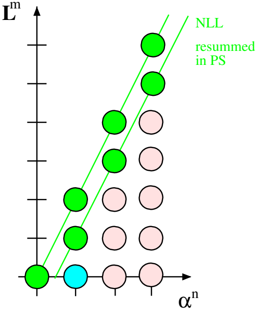
- radiation given by $\mathcal{R}_N$ (correct at $\mathcal{O}(\alpha_s)$)
  (but modified by logs of higher order in α_s from $\Delta_N^{(\mathcal{R}/\mathcal{B})}$)
- emission phase space constrained by μ_N
- also known as “soft ME correction”
  hard ME correction fills missing phase space
- used for “power shower”:
  $\mu_N \to E_{pp}$ and apply ME correction



NLO 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)
    (this is relatively trivial)
  - maintain (N)LL-accuracy of parton shower
    (this is not so simple to see)



POWHEG

- 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

- define local K-factors
- start from Born configuration Φ_N with NLO weight:

("local K-factor")

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

$$= \mathrm{d}\Phi_N \left\{ \mathcal{B}_N(\Phi_N) + \underbrace{\mathcal{V}_N(\Phi_N) + \mathcal{B}_N(\Phi_N) \otimes \mathcal{S}}_{\tilde{\mathcal{V}}_N(\Phi_N)} + \int \mathrm{d}\Phi_1 \left[\mathcal{R}_N(\Phi_N \otimes \Phi_1) - \mathcal{B}_N(\Phi_N) \otimes \mathrm{d}\mathcal{S}(\Phi_1) \right] \right\}$$

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

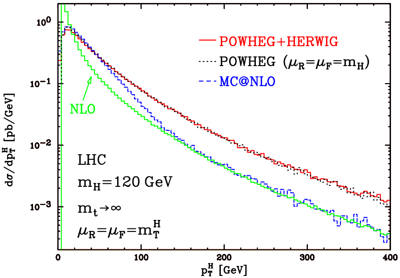
(relevant for MC@NLO)

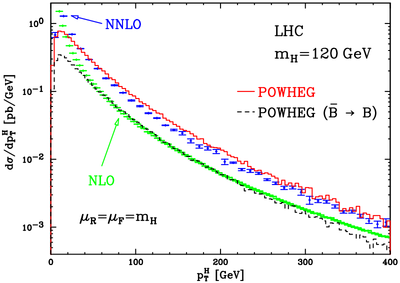
- analyse accuracy of radiation pattern
- generate emissions with $\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, t_0)$:

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

- 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 $p_\perp$?)

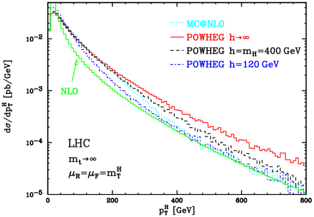




- large enhancement at high $p_{T,h}$
- can be traced back to large NLO correction
- fortunately, NNLO correction is also large $\to\sim$ agreement

- improving POWHEG
- 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 other (resummation) result
  - differential event rate up to first emission

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

MC@NLO

- MC@NLO paradigm: divide $\mathcal{R}_N$ in soft ("S") and hard ("H") part:

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

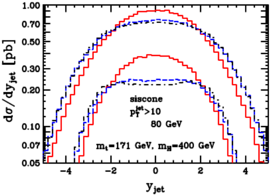
- identify subtraction terms and shower kernels $\mathrm{d}\mathcal{S}_1 \equiv \sum\limits_{\{ij,k\}} \mathcal{K}_{ij,k}$

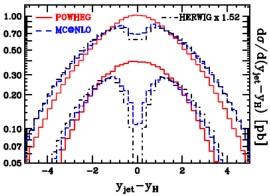
(modify $\mathcal{K}$ in 1st emission to account for colour)

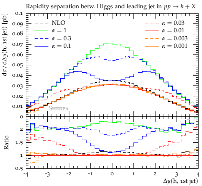
$$\begin{aligned}\mathrm{d}\sigma_N \quad = \quad & \mathrm{d}\Phi_N \underbrace{\tilde{\mathcal{B}}_N(\Phi_N)}_{\mathcal{B}+\tilde{\mathcal{V}}} \left[\Delta_N^{(\mathcal{K})}(\mu_N^2,\, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1\, \mathcal{K}_{ij,k}(\Phi_1)\, \Delta_N^{(\mathcal{K})}(\mu_N^2,\,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

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

- phase space effects: shower vs. fixed order

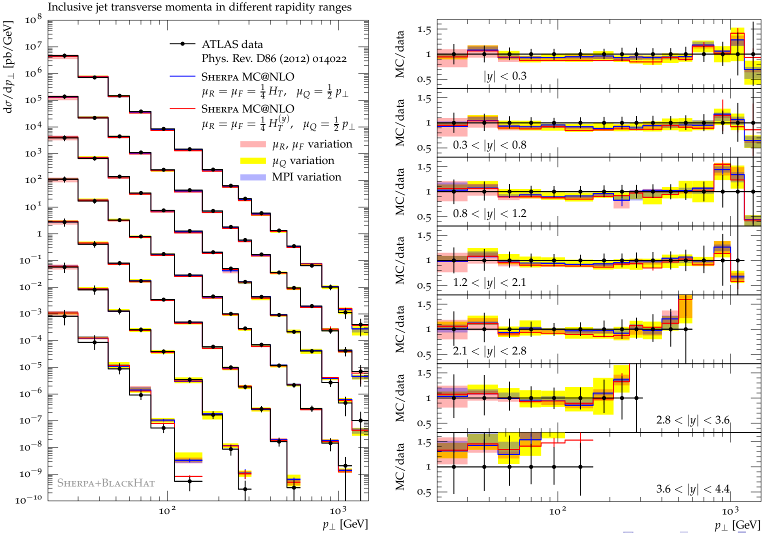




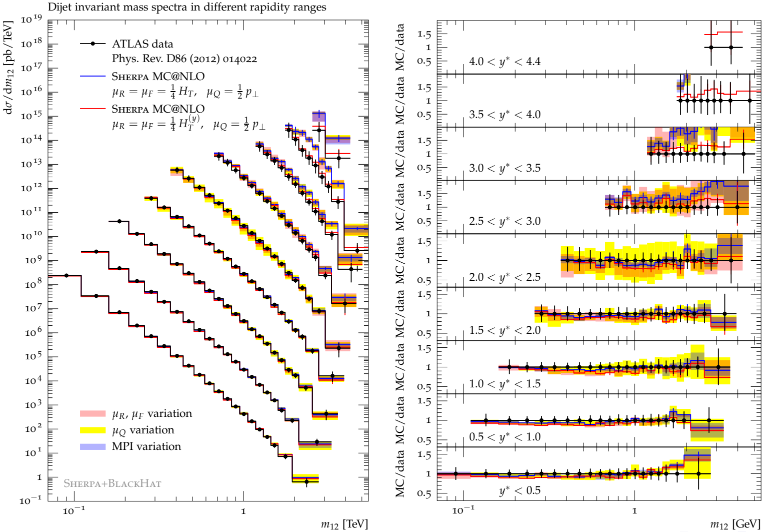


- problem: impact of subtraction terms on local K-factor (filling of phase space by parton shower)
- studied in case of $gg \to H$ above
- proper filling of available phase space by parton shower paramount

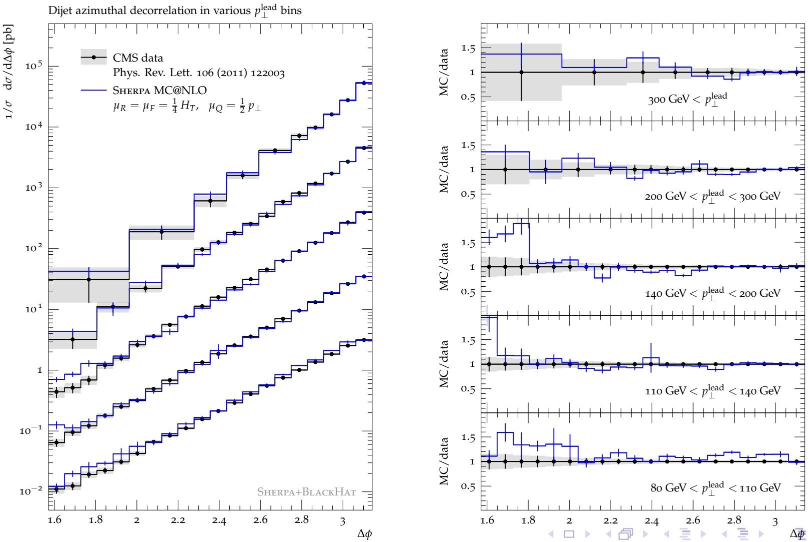
MC@NLO for light jets: jet-$p_\perp$



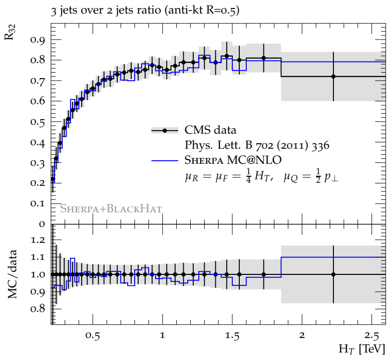
MC@NLO for light jets: dijet mass

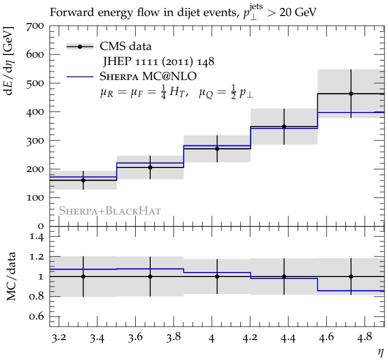


MC@NLO for light jets: azimuthal decorrelations

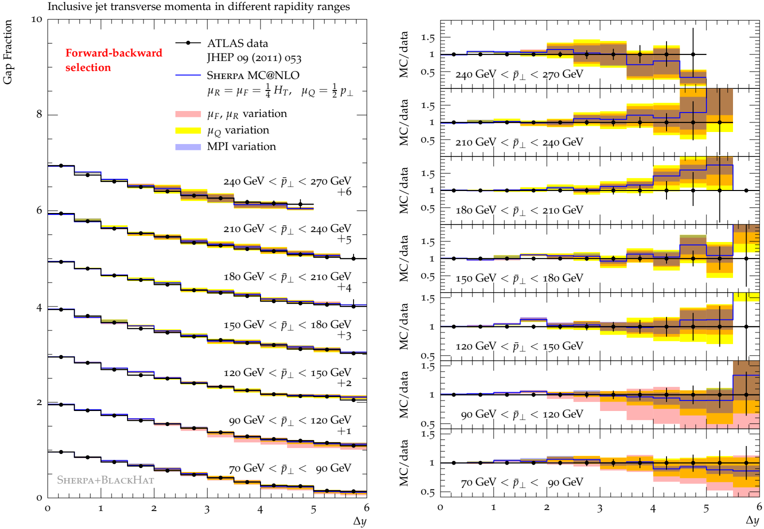


MC@NLO for light jets: R_{32} & forward energy flow





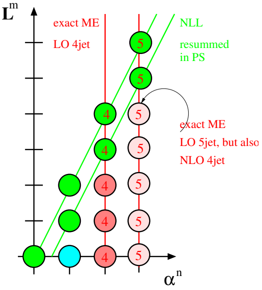
MC@NLO for light jets: jet vetoes



MULTIJET MERGING

Multijet merging: basic idea

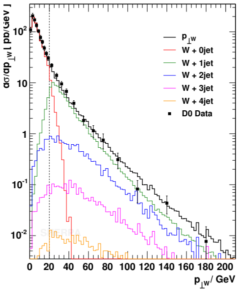
- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- combine ("merge") both:
  result: "towers"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



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

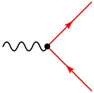
  ("truncated showering" if not identical with evolution parameter)

- matrix elements populate hard regime
- parton showers populate soft domain

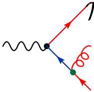


Why it works: jet rates with the parton shower

- 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:



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



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

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

Multijet merging at LO

- expression for first emission

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

- 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: $\mu_{N,N+1,\ldots}$
- "unitarity violation" in square bracket: $\mathcal{B}_N\mathcal{K}_N \longrightarrow \mathcal{B}_{N+1}$

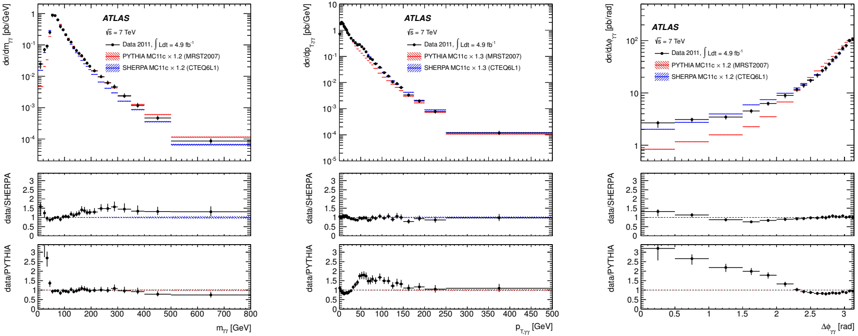
(cured with UMEPS formalism, L. Lonnblad & S. Prestel, JHEP 1302 (2013) 094 &

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

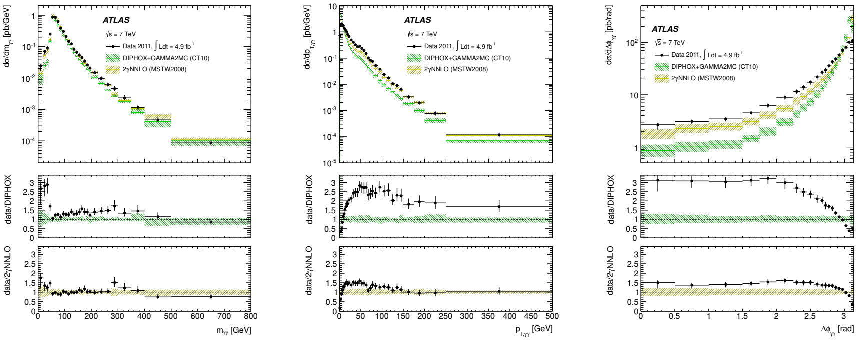
$$
\begin{aligned}
\mathrm{d}\sigma \;=\; \sum_{n=N}^{n_{\max}-1} \Bigg\{ & \mathrm{d}\Phi_n\,\mathcal{B}_n \overbrace{\left[\prod_{j=N}^{n-1} \Theta(Q_{j+1}-Q_J)\right]}^{(n-N)\text{ extra jets}} \overbrace{\left[\prod_{j=N}^{n-1} \Delta_j^{(\mathcal{K})}(t_j,\,t_{j+1})\right]}^{\text{no emissions off internal lines}} \\
& \times \Bigg[\underbrace{\Delta_n^{(\mathcal{K})}(t_n,t_0)}_{\text{no emission}} + \underbrace{\int\limits_{t_0}^{t_n} \mathrm{d}\Phi_1\,\mathcal{K}_n \Delta_n^{(\mathcal{K})}(t_n,t_{n+1})\Theta(Q_J-Q_{n+1})}_{\text{next emission no jet \& below last ME emission}} \Bigg] \\
& + \mathrm{d}\Phi_{n_{\max}}\,\mathcal{B}_{n_{\max}} \left[\prod_{j=N}^{n_{\max}-1} \Theta(Q_{j+1}-Q_J)\right] \left[\prod_{j=N}^{n_{\max}-1} \Delta_j^{(\mathcal{K})}(t_j,\,t_{j+1})\right] \\
& \times \left[\Delta_{n_{\max}}^{(\mathcal{K})}(t_{n_{\max}},t_0) + \int\limits_{t_0}^{t_{n_{\max}}} \mathrm{d}\Phi_1\,\mathcal{K}_{n_{\max}} \Delta_{n_{\max}}^{(\mathcal{K})}(t_{n_{\max}},t_{n_{\max}+1})\right]
\end{aligned}
$$

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



A step towards multijet-merging at NLO: MeNLoPs

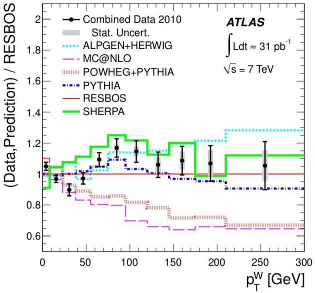
- combine matching for lowest multiplicity with multijet merging
- interpolating local K-factor for reweighting hard emissions

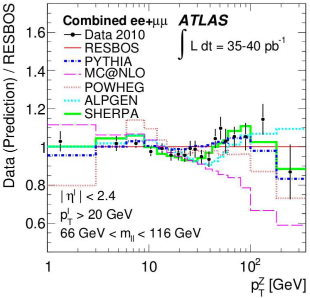
$$k_N(\Phi_{N+1}) = \frac{\tilde{\mathcal{B}}_N}{\mathcal{B}_N}\left(1-\frac{\mathcal{H}_N}{\mathcal{B}_{N+1}}\right)+\frac{\mathcal{H}_N}{\mathcal{B}_{N+1}} \longrightarrow \begin{cases} \tilde{\mathcal{B}}_N/\mathcal{B}_N & \text{for soft emission} \\ 1 & \text{for hard emission} \end{cases}$$

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

Transverse momentum of W & Z boson

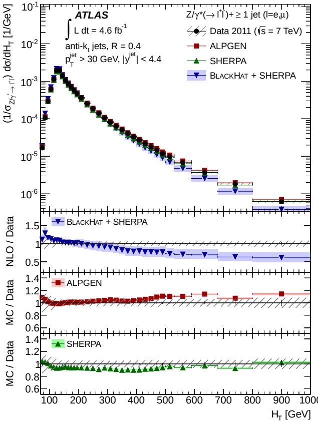
ATLAS, arXiv:1108.6308, arXiv:1107.2381

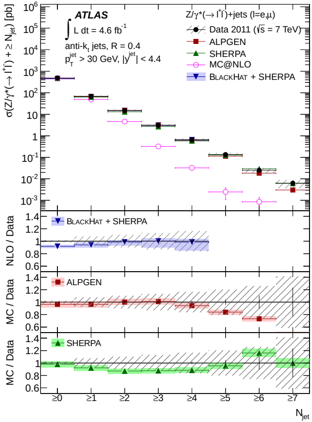




Z+jets: inclusive quantities

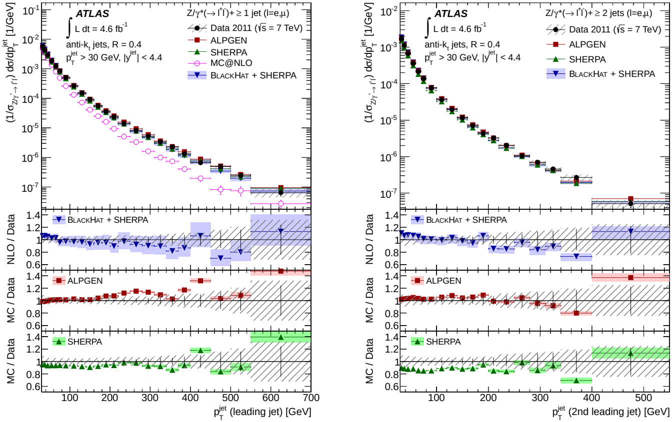
ATLAS, arXiv:1111.2690





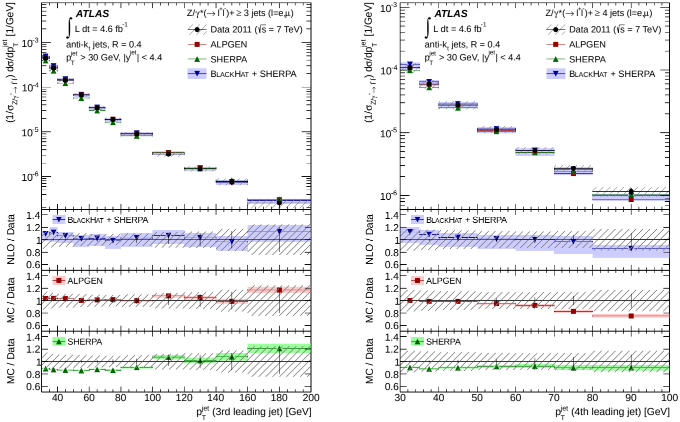
Z+jets: jet transverse momenta

ATLAS, arXiv:1111.2690



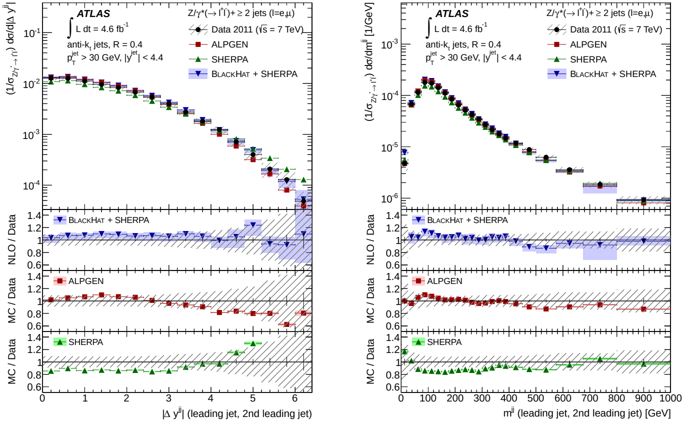
Z+jets: jet transverse momenta

ATLAS, arXiv:1111.2690



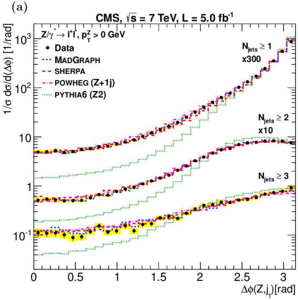
Z+jets: correlation of leading jets

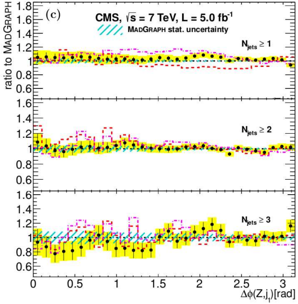
ATLAS, arXiv:1111.2690



Z+jets: $\Delta\phi_{Zj}$ in unboosted sample

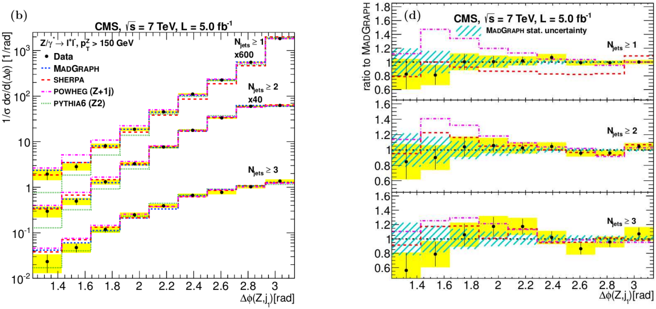
CMS, arXiv:1301.1646





Z+jets: $\Delta\phi_{Zj}$ in boosted sample

CMS, arXiv:1301.1646



Multijet-merging at NLO: MEPS@NLO

- 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

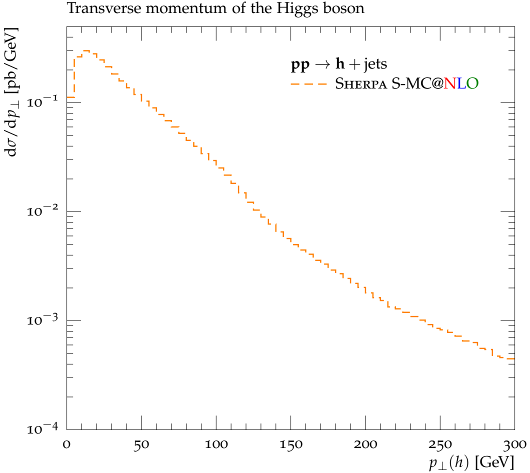
maintain NLO and (N)LL accuracy of ME and PS

- 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

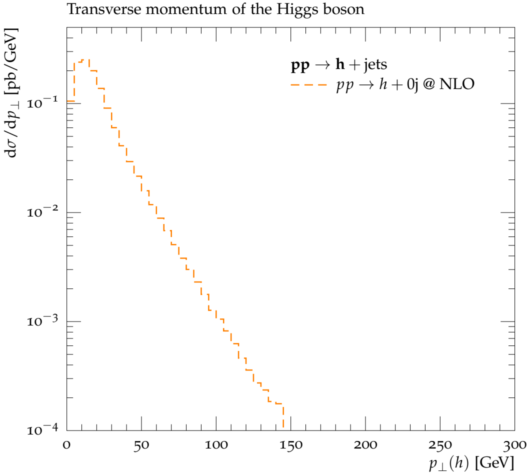
$$
\begin{aligned}
d\sigma = & \; d\Phi_N\,\tilde{\mathcal{B}}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,t_0)+\int\limits_{t_0}^{\mu_N^2}d\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\right]\\
& +d\Phi_{N+1}\,\mathcal{H}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\\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

$p_\perp^H$ in MEPS@NLO



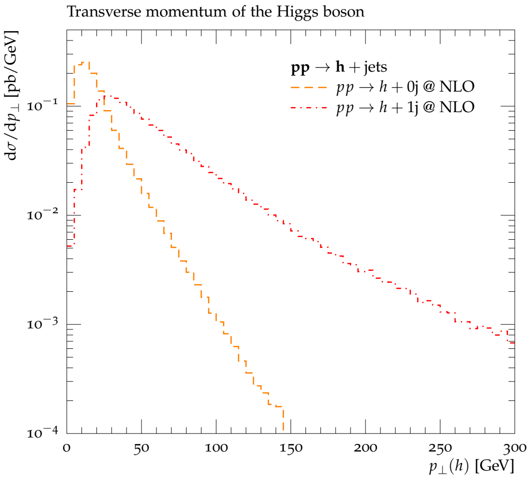
- first emission by MC@NLO

$p_\perp^H$ in MEPS@NLO



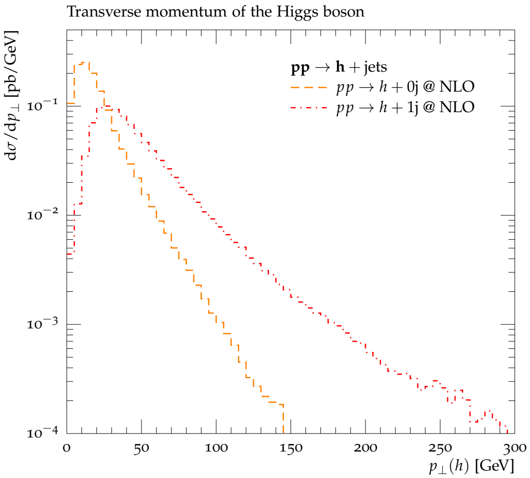
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$

$p_\perp^H$ in MEPS@NLO



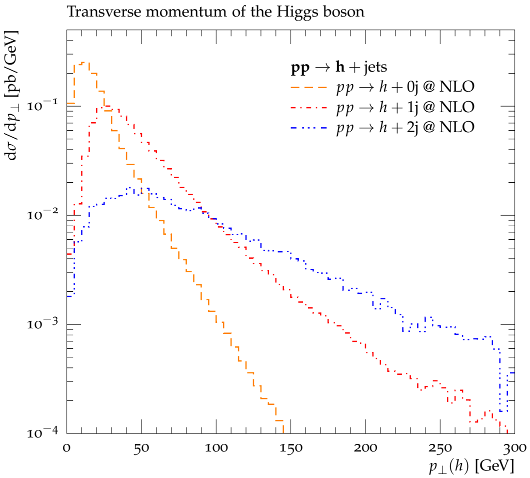
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\rm cut}$

$p_\perp^H$ in MEPS@NLO



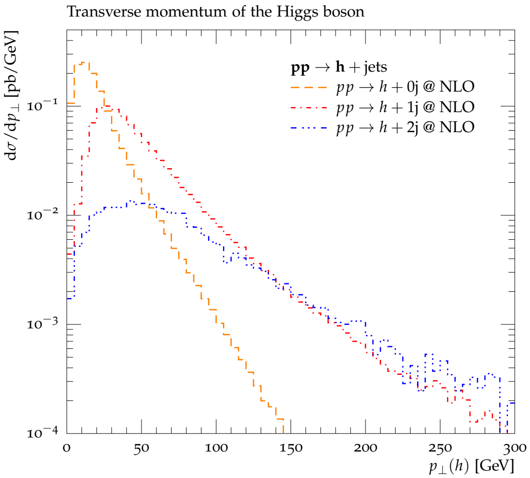
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h+\text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h+\text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$

$p_\perp^H$ in MEPS@NLO



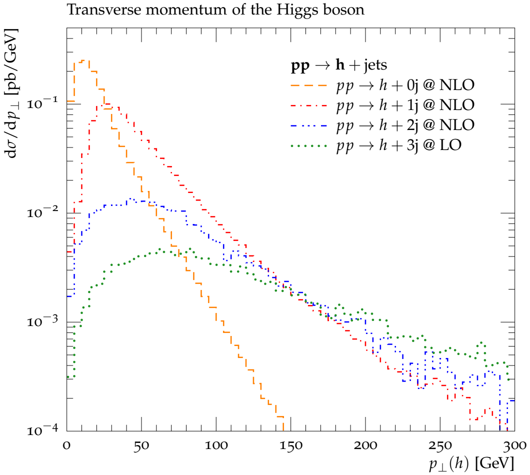
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\rm cut}$

$p_\perp^H$ in MEPS@NLO



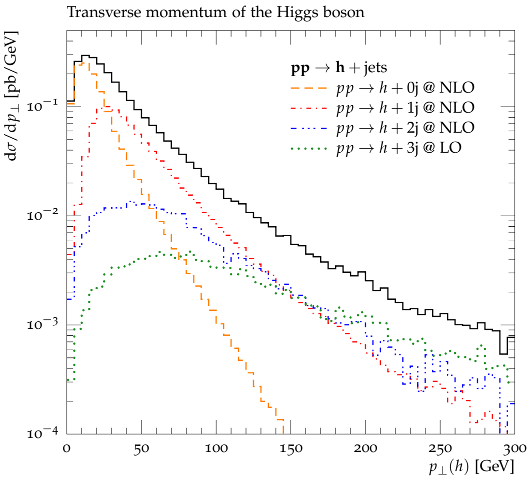
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\rm cut}$
- iterate

$p_\perp^H$ in MEPS@NLO



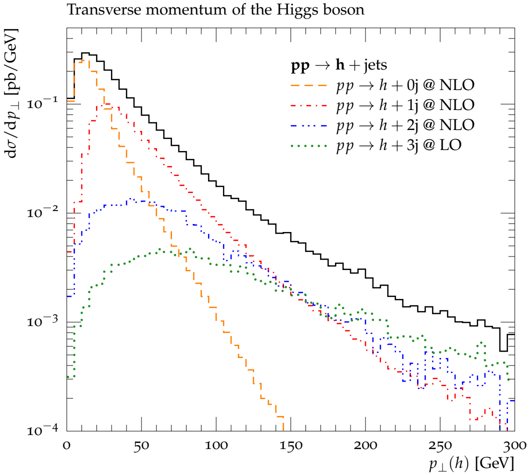
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h +$ jet for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h +$ jet to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h +$ 2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate

$p_\perp^H$ in MEPS@NLO



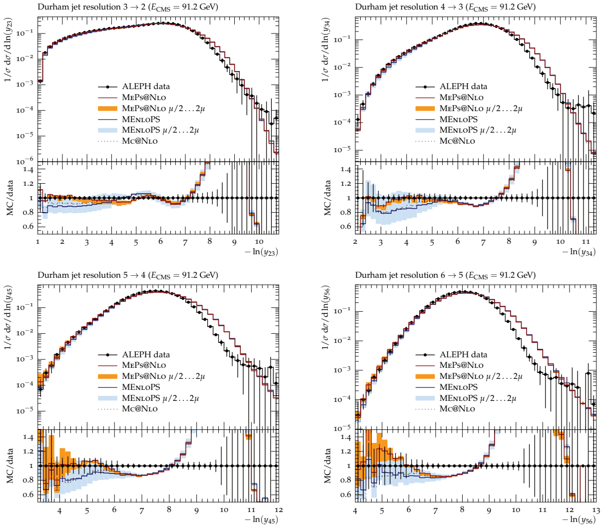
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$
- MC@NLO $pp \to h+$jet for $Q_{n+1} > Q_{\rm cut}$
- restrict emission off $pp \to h+$jet to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h+$2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate
- sum all contributions

$p_\perp^H$ in MEPS@NLO

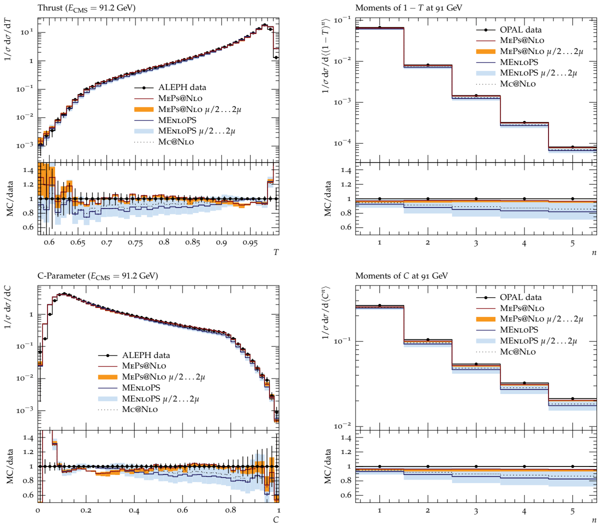


- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h+\text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
- restrict emission off $pp \to h+\text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- MC@NLO $pp \to h+\text{2jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions
- eg. $p_\perp(h)$>200 GeV has contributions fr. multiple topologies

MEPS@NLO: example results for $e^-e^+ \to$ hadrons

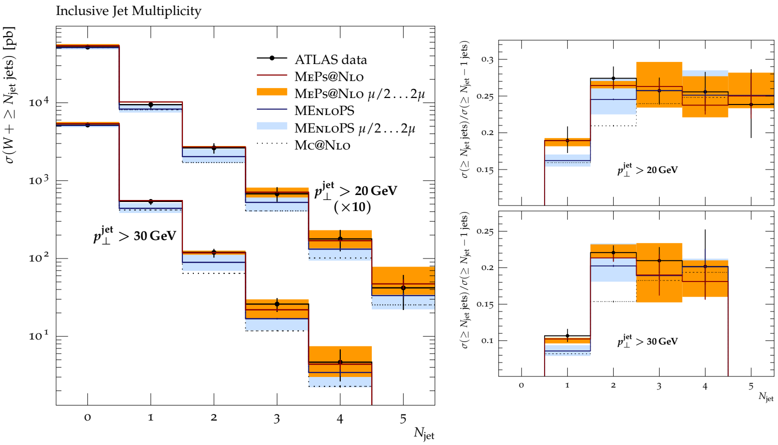


MEPS@NLO: example results for $e^-e^+ \to$ hadrons

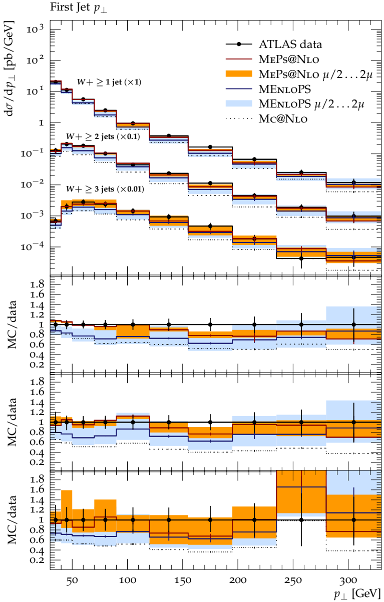


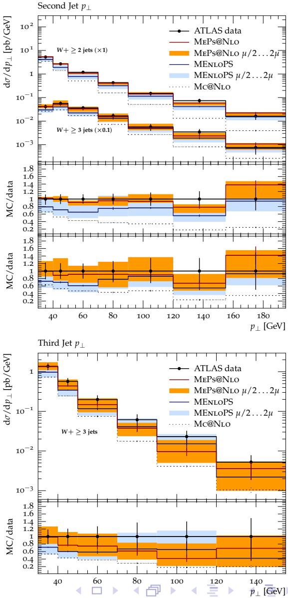
Example: MEPS@NLO for W+jets

(up to two jets @ NLO, from BLACKHAT, see arXiv: 1207.5031 [hep-ex])

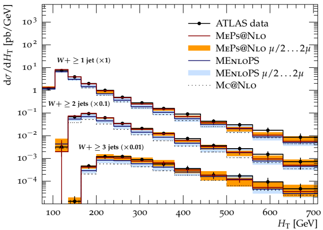


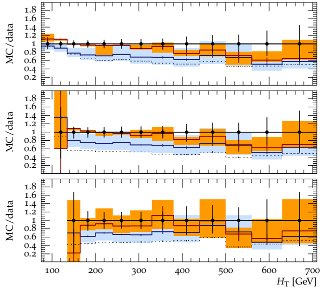
Multijet merging at NLO

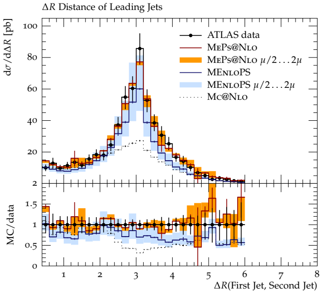


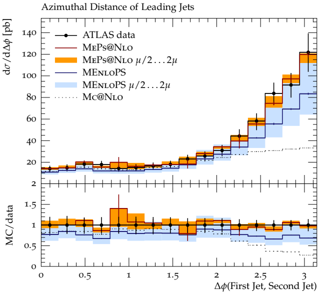


Multijet merging at NLO





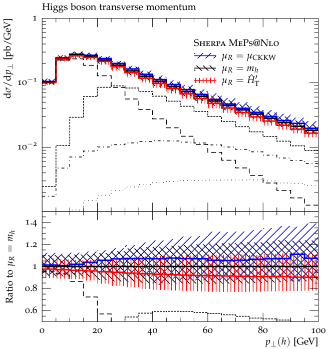


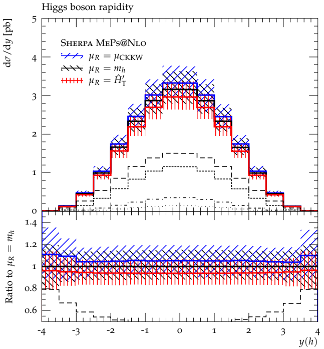


Results for Higgs boson production through gluon fusion

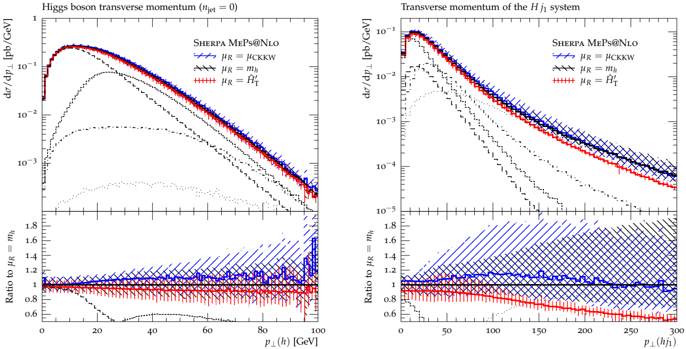
- parton-shower level, Higgs boson does not decay
- setup & cuts:
  - jets: anti-kt, $p_\perp \geq 20$ GeV, $R = 0.4$, $|\eta| \leq 4.5$
  - dijet cuts: at least 2 jets with $p_\perp \geq 25$ GeV
  - WBF cuts: $m_{jj} \geq 400$ GeV, $\Delta y_{jj} \geq 2.8$
- jet multiplicity plots:
  - 0-jet excl.: 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 $gg \to H$

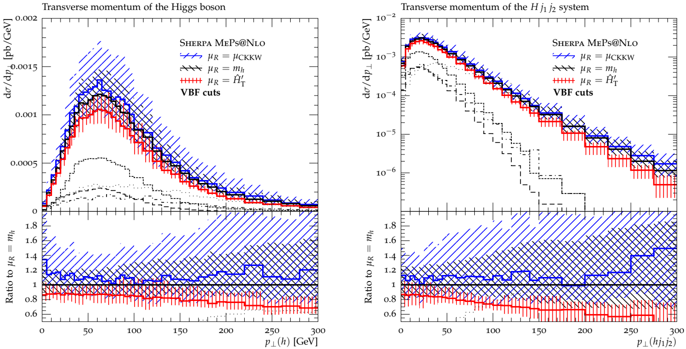




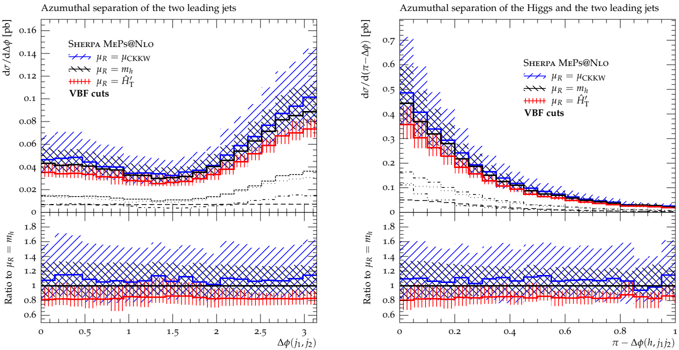
Exclusive observables for $gg \to H$



$gg \to H$ after WBF cuts

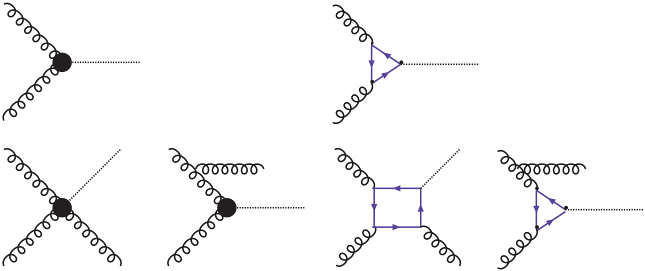


$gg \to H$ after WBF cuts



Quark mass effects

- include effects of quark masses

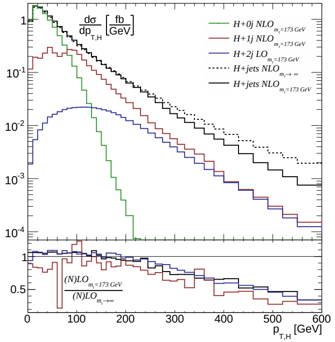


- reweight NLO HEFT with LO ratio:

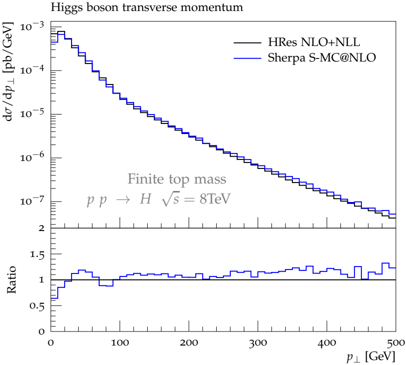
$$\mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{mass}} \approx \mathrm{d}\sigma^{(\mathrm{NLO})}_{\mathrm{HEFT}} \times \frac{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{mass}}}{\mathrm{d}\sigma^{(\mathrm{LO})}_{\mathrm{HEFT}}}$$

Quark mass effects – results

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



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

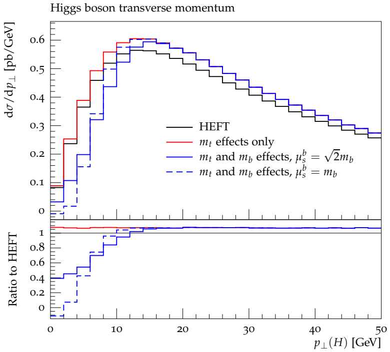


b–mass effects

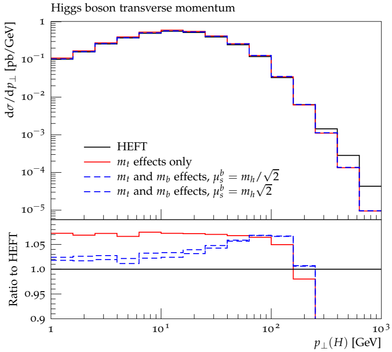
- b–mass effects more tricky
- relevant only for (negative) interference of top– and bottom–loops (bottom^2 double Yukawa - supressed)
- but: cannot start shower at m_H
  radiation "sees" bottom at all scales above m_b
  $\Longrightarrow$ must use full theory there
- p_T spectrum naively "squeezed" –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

b–mass effects: playtime

vary around $\mu_Q = m_b$

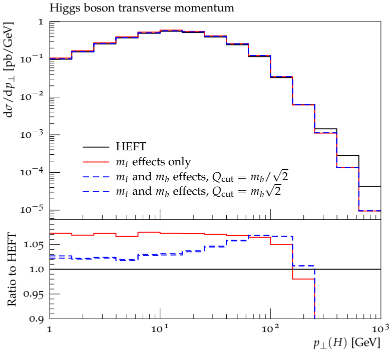


vary around $\mu_Q = m_h$ with $Q_{\rm cut} = m_b$

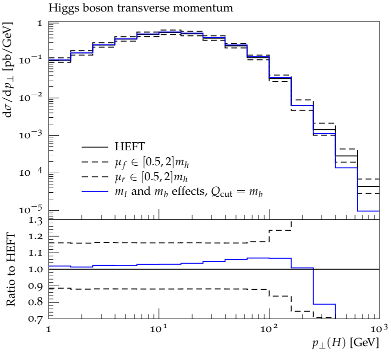


b–mass effects: playtime (cont'd)

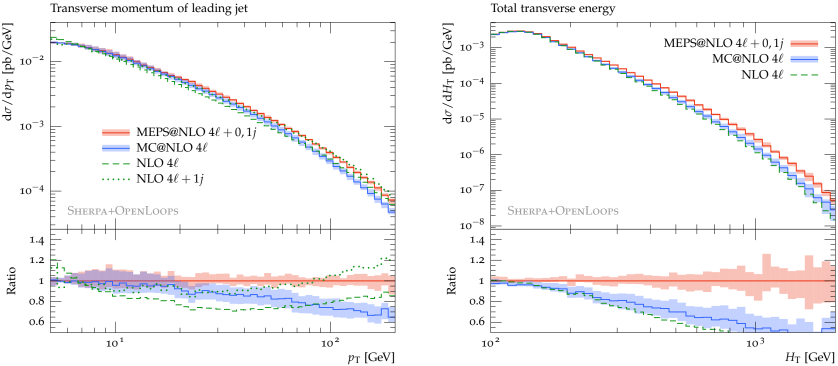
vary around $Q_{\rm cut} = m_b$ with $\mu_Q = m_h$



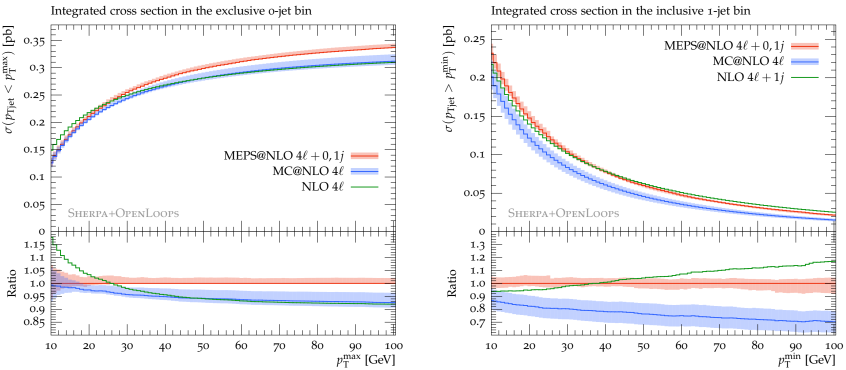
vary $\mu_{F,R}$



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

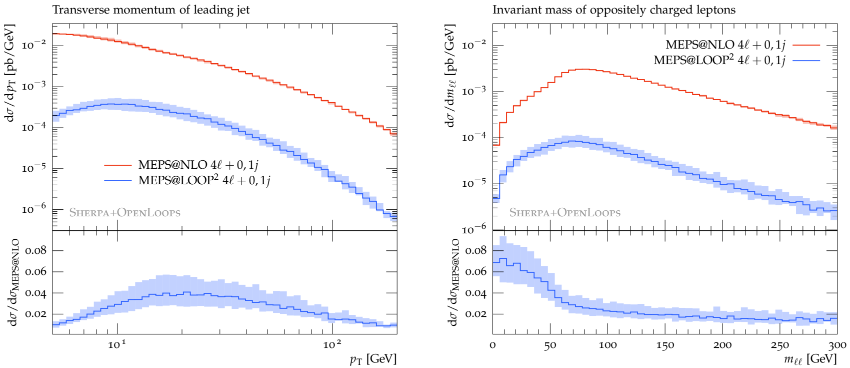


Higgs backgrounds: jet vetoes in W^+W^-+jets

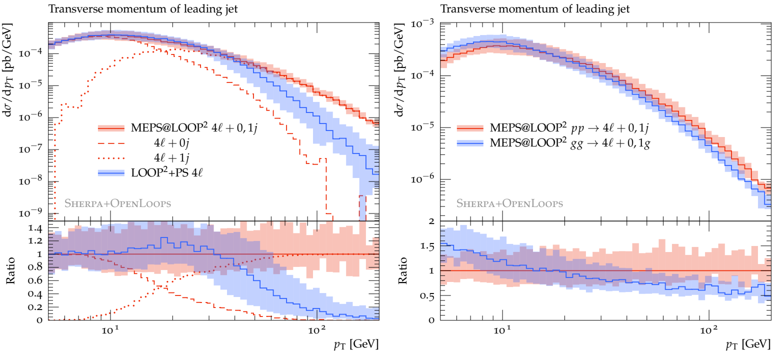


Higgs backgrounds: gluon-induced processes W^+W^-+jets

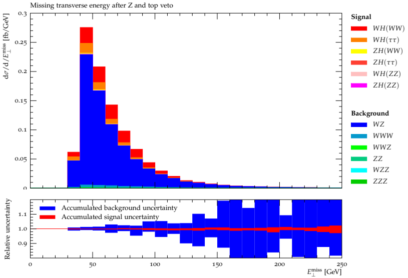
- include (LO-) merged loop^2 contributions of $gg \to VV$ (+1 jet)

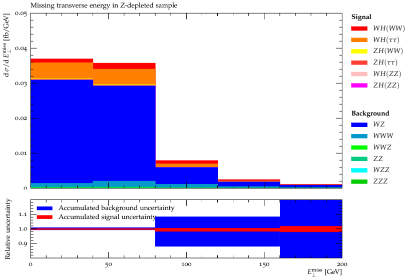


Higgs backgrounds: jet vetoes in W^+W^-+jets

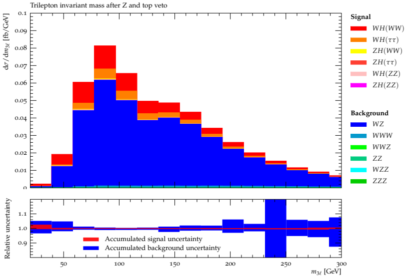


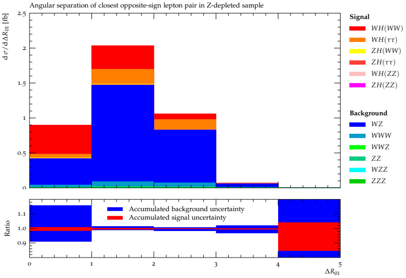
Relevant observables for $VH \to 3\ell$: $\not{E}_T$





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





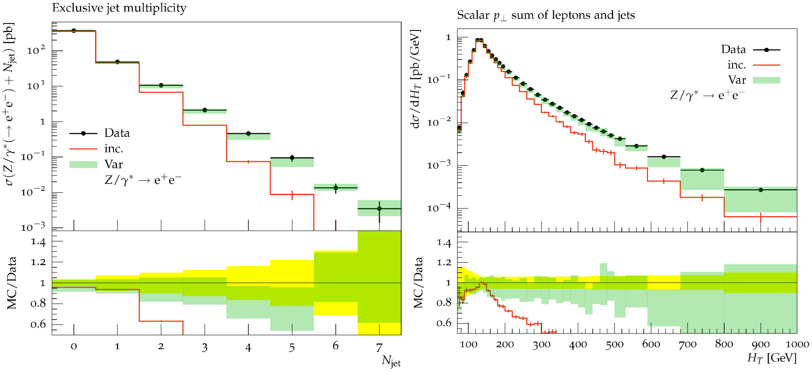
Differences between MEPS@NLO, UNLOPS & FxFx

	FxFx	MEPS@NLO	UNLOPS
ME	all internal aMC@NLO_MADGRAPH	$\mathcal{V}$ external COMIX or AMEGIC++ $\mathcal{V}$ from OPENLOOPS, BLACKHAT, MJET, ...	all external
shower	external HERWIG or PYTHIA	intrinsic	intrinsic PYTHIA
Δ_N $\Theta(Q_J)$	analytical a-posteriori	from PS per emission	from PS per emission
Q_J-range	relatively high (but changed)	$>$ Sudakov regime $\approx$ 10%	$\approx$ Sudakov regime $\approx$ 10%

FxFx: validation in Z+jets

(Data from ATLAS, 1304.7098, aMC@NLO_MADGRAPH with HERWIG++)

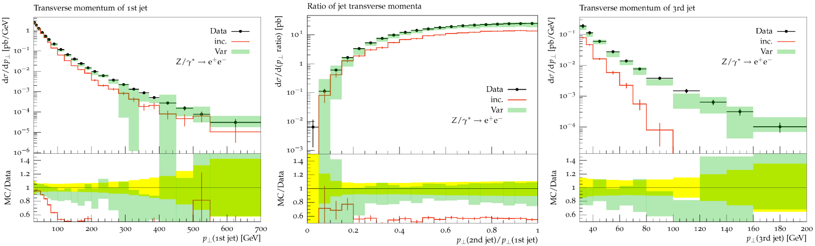
(green: 0, 1, 2 jets + uncertainty band from scale and PDF variations, red: MC@NLO)



FxFx: validation in Z+jets

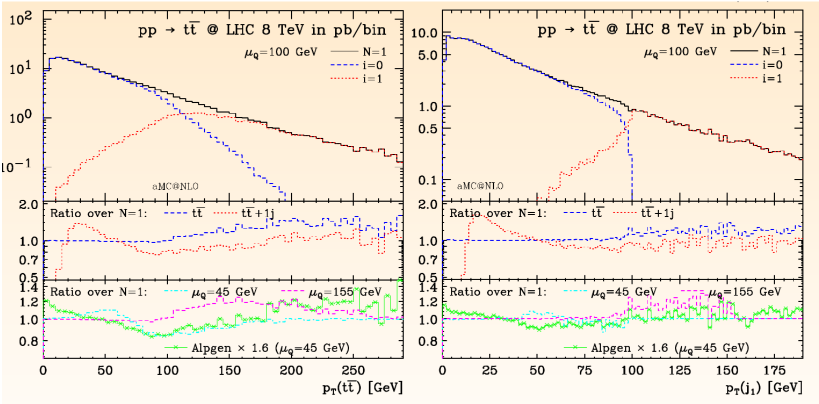
(Data from ATLAS, 1304.7098, aMC@NLO_MADGRAPH with HERWIG++)

(green: 0, 1, 2 jets + uncertainty band from scale and PDF variations, red: MC@NLO)



FxFx: Q_J dependence in $t\bar{t}$

(R.Frederix & S.Frixione, JHEP 1212 (2012) 061)



Aside: merging without Q_J - the MINLO approach

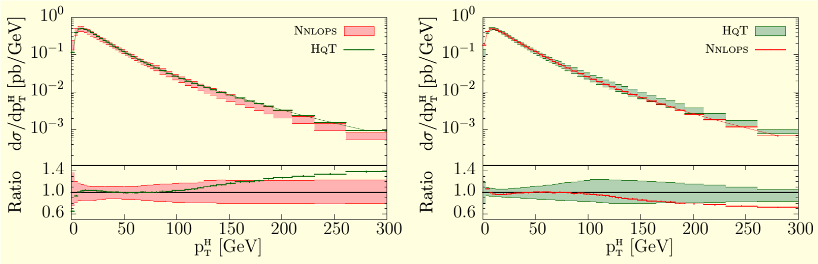
(K.Hamilton, P.Nason, C.Oleari & G.Zanderighi, JHEP 1305 (2013) 082)

- based on POWHEG + shower from PYTHIA or HERWIG
- up to today only for singlet S production, gives NNLO + PS
- basic idea:
  - use S+jet in POWHEG
  - push jet cut to parton shower IR cutoff
  - apply analytical NNLL Sudakov rejection weight for intrinsic line in Born configuration

    (kills divergent behaviour at order α_S)
  - don't forget double-counted terms
  - reweight to NNLO fixed order

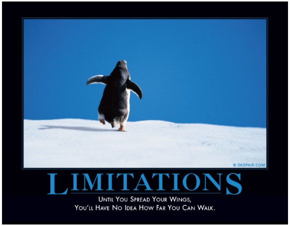
NNLOPs for H production

(K.Hamilton, P.Nason, E.Re & G.Zanderighi, JHEP 1310 (2013) 222)



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")



- multijet merging an important tool for many relevant signals and backgrounds - pioneering phase at LO & NLO over
- complete automation of NLO calculations done
  $\longrightarrow$ must benefit from it!

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

Famous last screams

- in Run-II we're in for a ride:

  more statistics
  more energy
  more channels
  more precision
  more fun

- . . . and all with QCD . . .

oh, and btw.: all tools are public & used