

IPPP

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

- general structure of NLO calculation for N -body production

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

- phase space factorisation assumed here ($\phi_{\mathcal{R}} = \phi_{\mathcal{B}} \otimes \phi_1$)

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

- process independent subtraction kernels

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

with universal $\mathcal{S}_1(\Phi_B \otimes \Phi_1)$ and $\mathcal{I}_1^{(S)}(\Phi_B)$

- in Catani–Seymour invertible phase space mapping

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

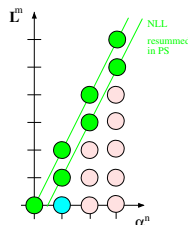
ME CORRECTIONS

- analyse **first** emission, given by

$$d\sigma_B = d\Phi_N \mathcal{B}_N(\Phi_N)$$

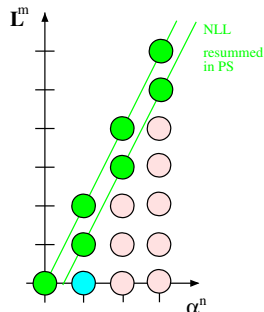
$$\cdot \underbrace{\left\{ \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2, t_0) + \int_{t_0}^{\mu_N^2} d\Phi_1 \left[\frac{\mathcal{R}_N(\Phi_N \times \Phi_1)}{\mathcal{B}_N(\Phi_N)} \Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2, t(\Phi_1)) \right] \right\}}_{\text{once more: integrates to unity} \rightarrow \text{"unitarity" of parton shower}}$$

- 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”:
 $\mu_N \rightarrow E_{pp}$ and apply ME correction

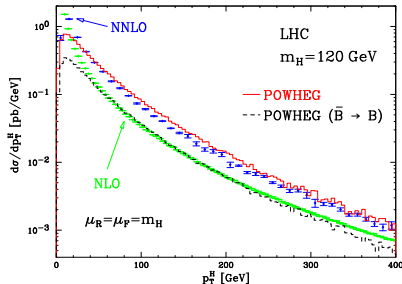


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- parton shower resums logarithms
fair description of collinear/soft emissions
jet evolution (where the logs are large)
- matrix elements exact at given order
fair description of hard/large-angle emissions
jet production (where the logs are small)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



- IPPP



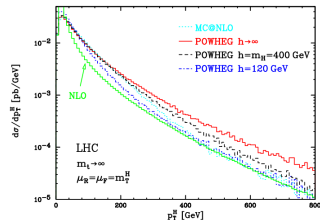
- large enhancement at high $p_{T,h}$
- can be traced back to large NLO correction
- fortunately, NNLO correction is also large $\rightarrow \sim$ agreement

- improving POWHEG
- split real-emission ME as

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

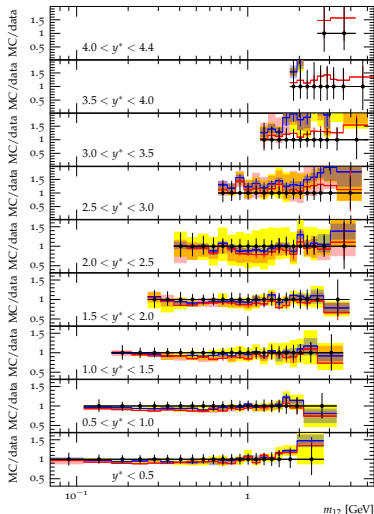
- can “tune” h to mimick NNLO - or other (resummation) result
- differential event rate up to first emission

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

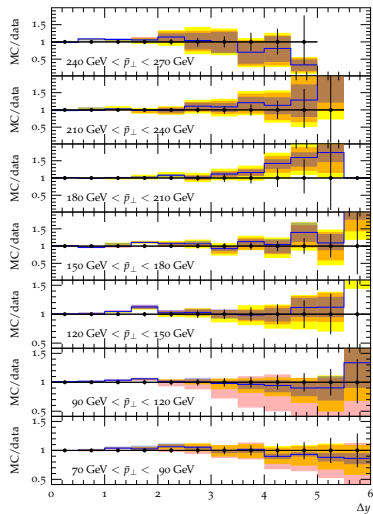
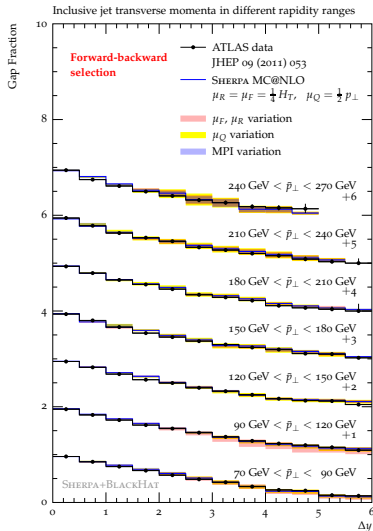


- IPPP

Dijet invariant mass spectra in different rapidity ranges



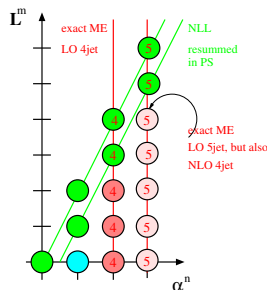
MC@NLO for light jets: jet vetoes



MULTIJET MERGING

Multijet merging: basic idea

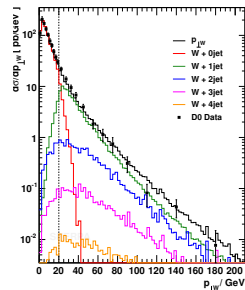
- parton shower resums logarithms
fair description of collinear/soft emissions
jet evolution (where the logs are large)
- matrix elements exact at given order
fair description of hard/large-angle emissions
jet production (where the logs are small)
- combine (“merge”) both:
result: “towers” of MEs with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

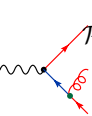
- matrix elements populate hard regime
- parton showers populate soft domain



Why it works: jet rates with the parton shower

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



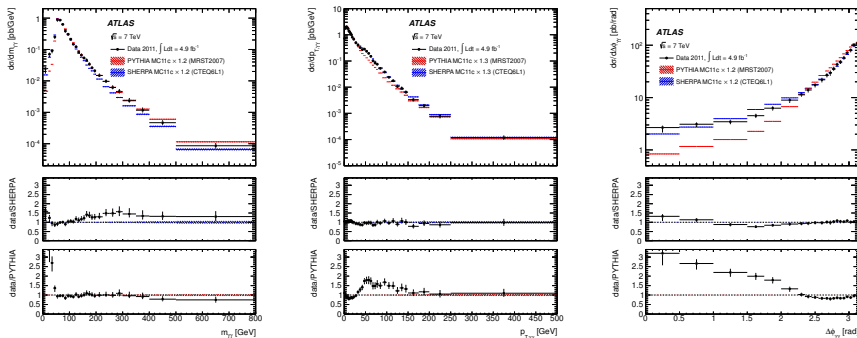
$$\mathcal{R}_2(Q_J) = [\Delta_q(E_{\text{c.m.}}^2, Q_J^2)]^2$$


$$\mathcal{R}_3(Q_J) = 2\Delta_q(E_{\text{c.m.}}^2, Q_J^2) \int_{Q_J^2}^{E_{\text{c.m.}}^2} \frac{dk_{\perp}^2}{k_{\perp}^2} \left[\frac{\alpha_s(k_{\perp}^2)}{2\pi} dz \mathcal{K}_q(k_{\perp}^2, z) \right. \\ \left. \times \Delta_q(E_{\text{c.m.}}^2, k_{\perp}^2) \Delta_q(k_{\perp}^2, Q_J^2) \Delta_g(k_{\perp}^2, Q_J^2) \right]$$

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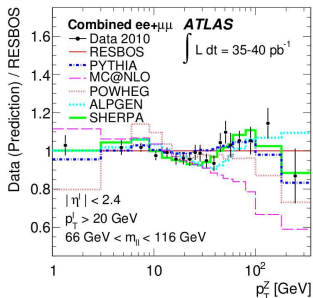
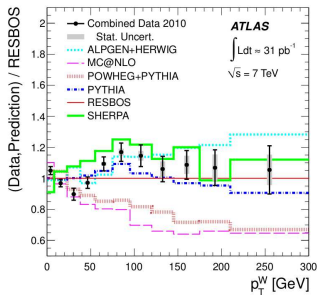
Di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$ in showers

(arXiv:1211.1913 [hep-ex])



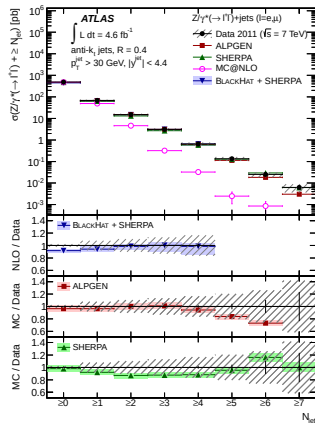
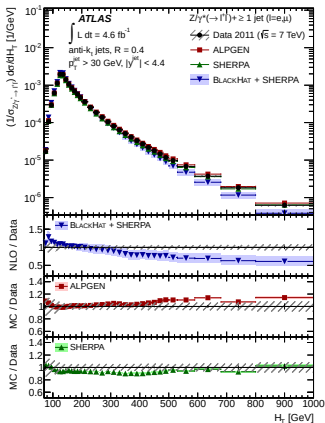
Transverse momentum of W & Z boson

ATLAS, arXiv:1108.6308, arXiv:1107.2381



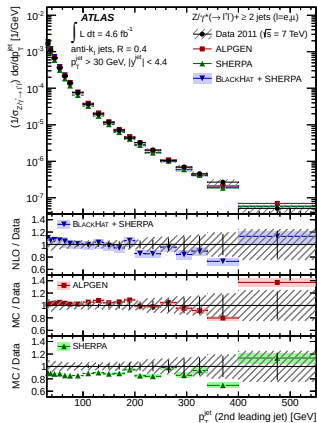
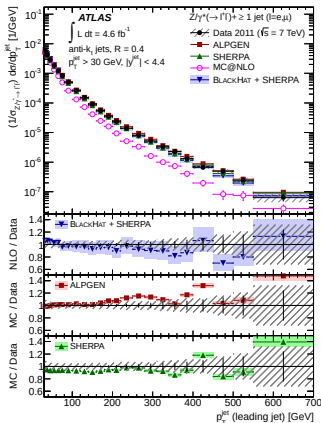
Z+jets: inclusive quantities

ATLAS, arXiv:1111.2690



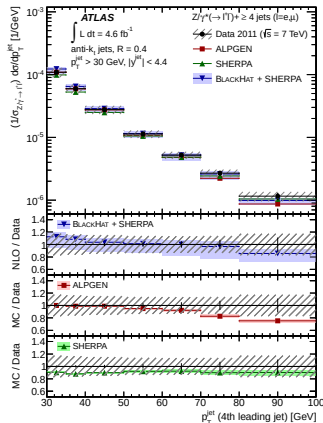
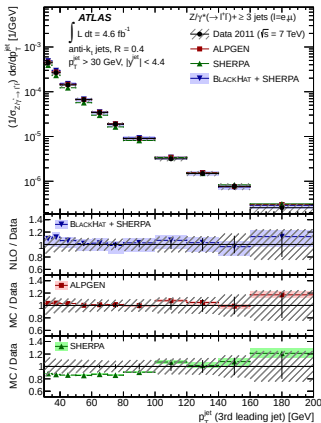
Z+jets: jet transverse momenta

ATLAS, arXiv:1111.2690



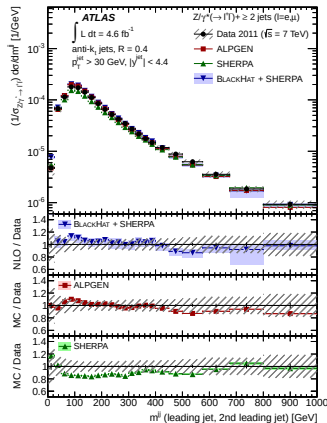
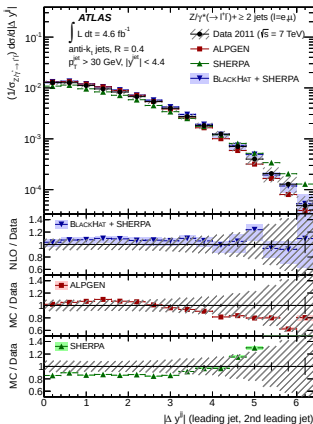
Z+jets: jet transverse momenta

ATLAS, arXiv:1111.2690

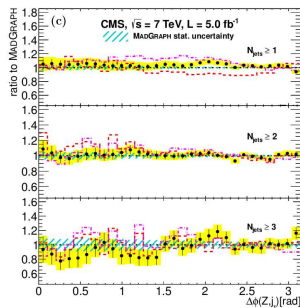


Z+jets: correlation of leading jets

ATLAS, arXiv:1111.2690

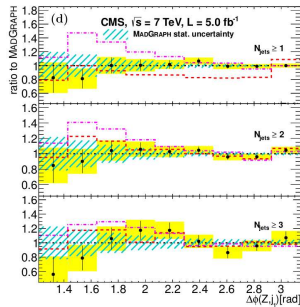
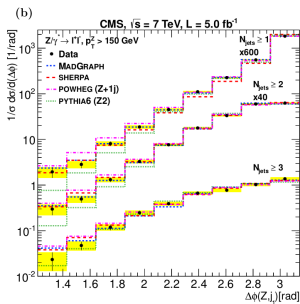


CMS, arXiv:1301.1646

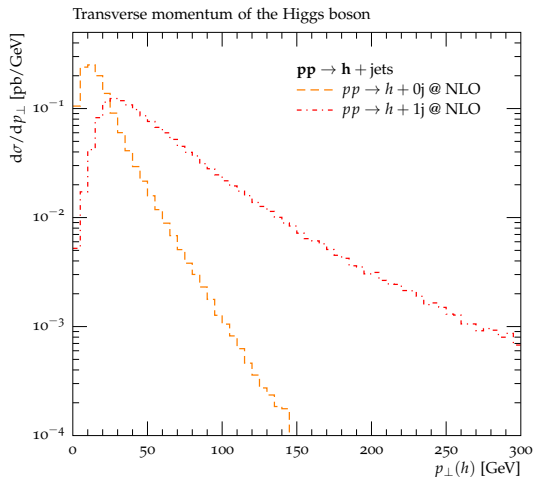


$Z+\text{jets}$: $\Delta\phi_{Zj}$ in boosted sample

CMS, arXiv:1301.1646

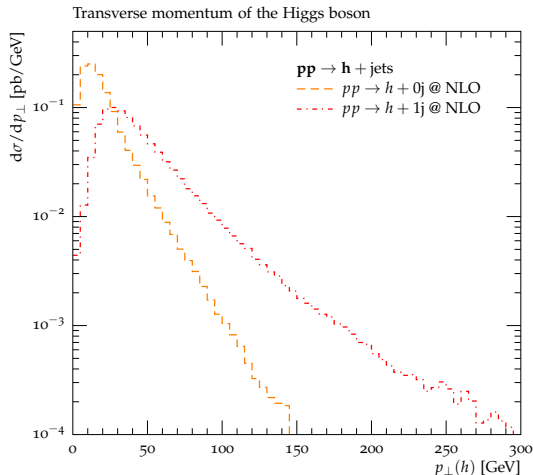


$p_{\perp}^H$ in MEPS@NLO



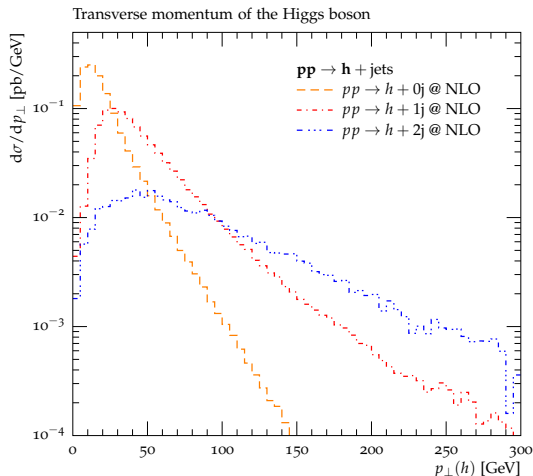
- first emission by MC@NLO, restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$

p_T^H in MEPS@NLO



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

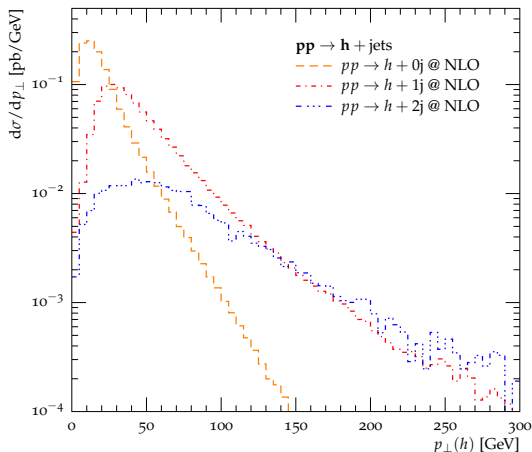
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- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- MC@NLO $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$

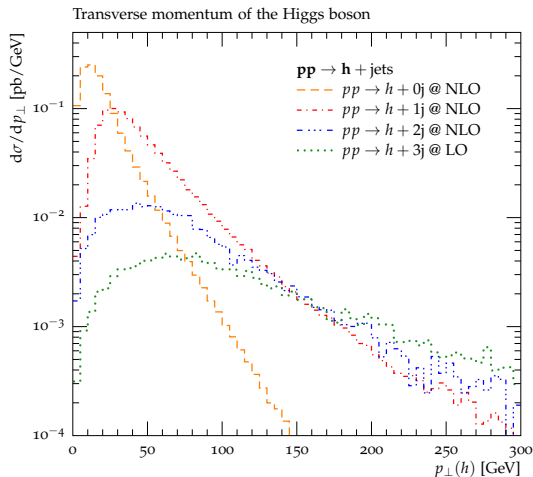
p_T^H in MEPS@NLO

Transverse momentum of the Higgs boson



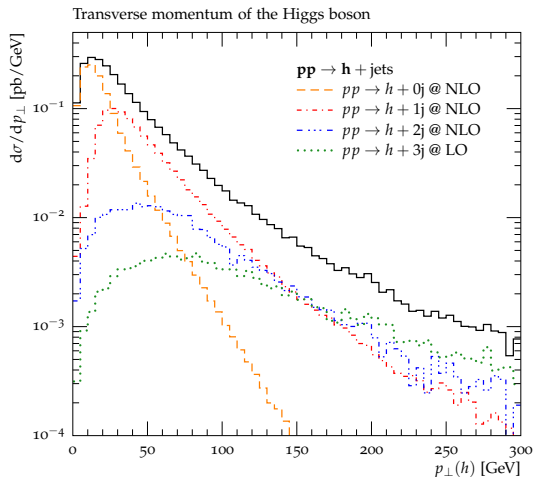
- first emission by MC@NLO, restrict to $Q_{n+1} < Q_{\text{cut}}$
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- restrict emission off $pp \rightarrow h + \text{jet}$ to $Q_{n+2} < Q_{\text{cut}}$
- MC@NLO $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate

$p_{\perp}^H$ in MEPS@NLO



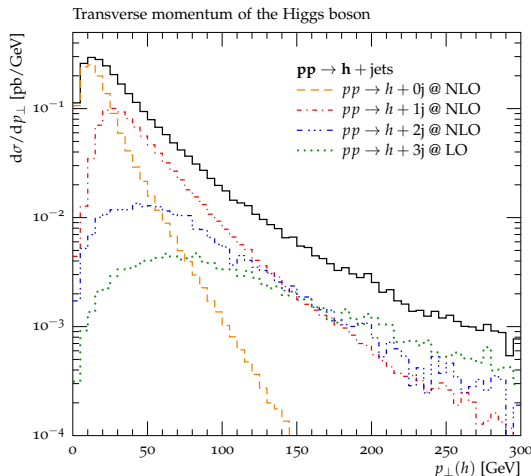
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$p_{\perp}^H$ in MEPS@NLO

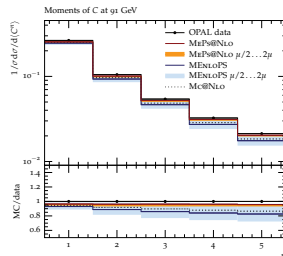
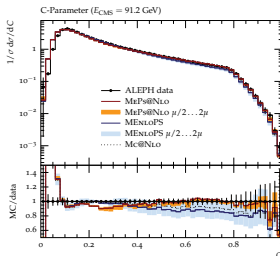
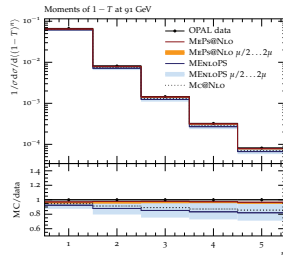
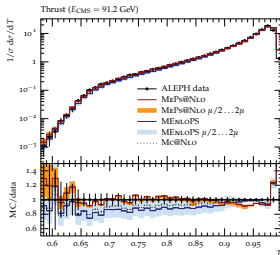


- first emission by MC@NLO, restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \rightarrow h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$
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- MC@NLO $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions

$p_{\perp}^H$ in MEPS@NLO

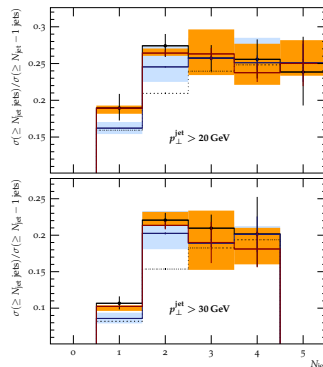
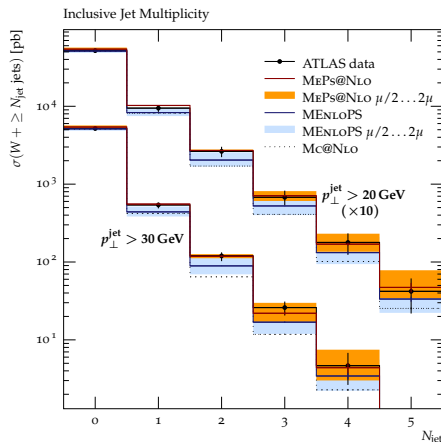


- first emission by MC@NLO, restrict to $Q_{n+1} < Q_{\text{cut}}$
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- MC@NLO $pp \rightarrow h + 2\text{jets}$ for $Q_{n+2} > Q_{\text{cut}}$
- iterate
- sum all contributions
- eg. $p_{\perp}(h) > 200$ GeV has contributions fr. multiple topologies

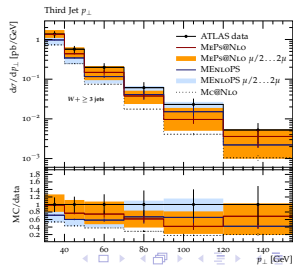
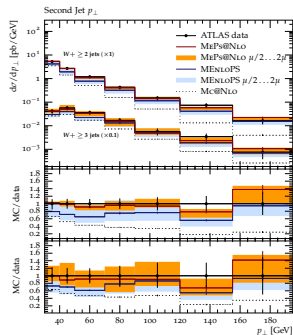
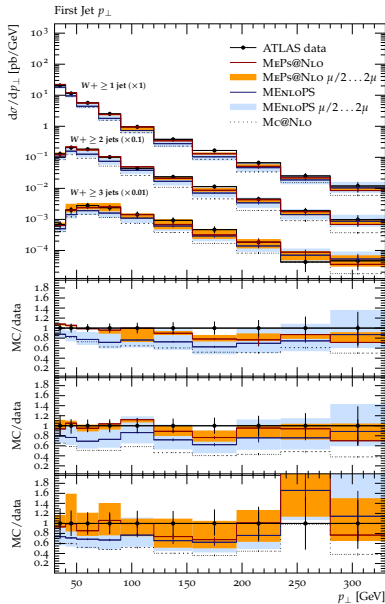
MEPs@NLO: example results for $e^-e^+ \rightarrow \text{hadrons}$ 

Example: MEPS@NLO for $W + \text{jets}$

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



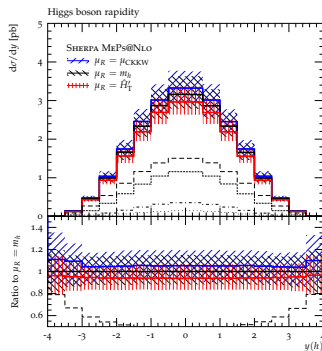
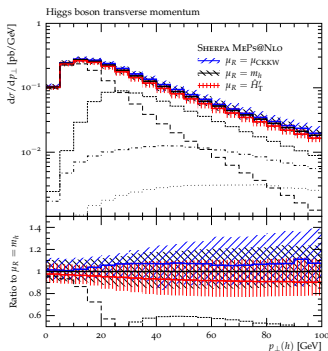
Multijet merging at NLO



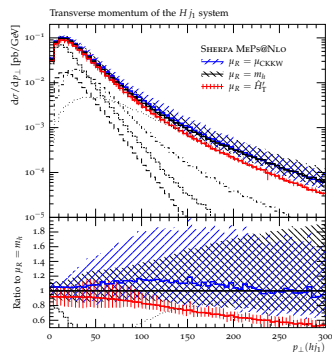
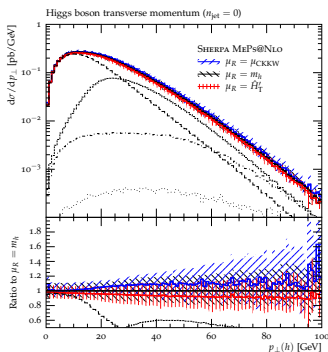
Results for Higgs boson production through gluon fusion

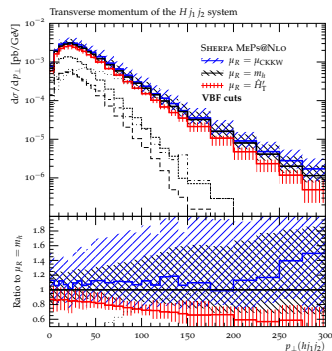
- parton-shower level, Higgs boson does not decay
- setup & cuts:
 - jets: anti-kt, $p_{\perp} \geq 20$ GeV, $R = 0.4$, $|\eta| \leq 4.5$
 - dijet cuts: at least 2 jets with $p_{\perp} \geq 25$ GeV
 - WBF cuts: $m_{jj} \geq 400$ GeV, $\Delta y_{jj} \geq 2.8$
- jet multiplicity plots:
 - 0-jet excl.: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

Inclusive observables for $gg \rightarrow H$

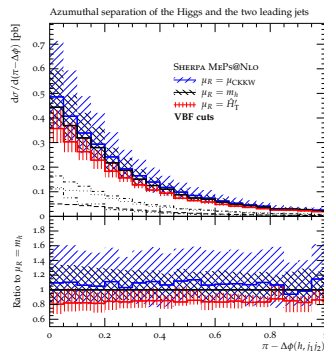
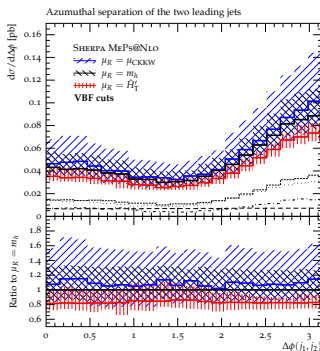


Exclusive observables for $gg \rightarrow H$



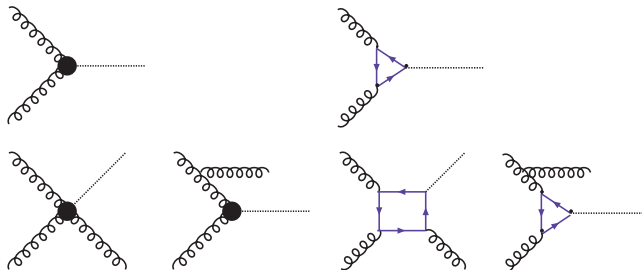


$gg \rightarrow H$ after VBF cuts



Quark mass effects

- include effects of quark masses

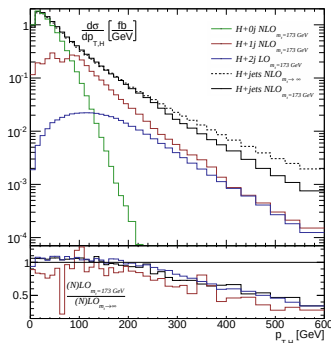


- reweight NLO HEFT with LO ratio:

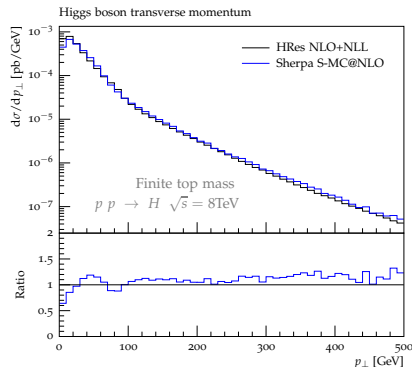
$$d\sigma_{\text{mass}}^{(\text{NLO})} \approx d\sigma_{\text{HEFT}}^{(\text{NLO})} \times \frac{d\sigma_{\text{mass}}^{(\text{LO})}}{d\sigma_{\text{HEFT}}^{(\text{LO})}}$$

Quark mass effects – results

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



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

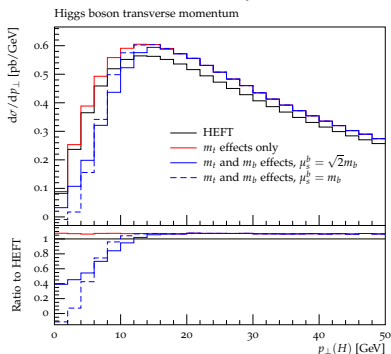


b -mass effects

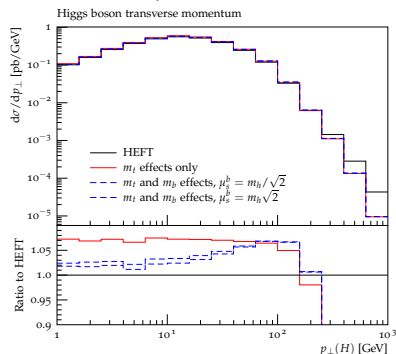
- b -mass effects more tricky
- relevant only for (negative) interference of top- and bottom-loops
(bottom² double Yukawa - suppressed)
- but: cannot start shower at m_H
radiation “sees” bottom at all scales above m_b
⇒ must use full theory there
- p_T spectrum naively “squeezed” – funny shapes
- LO multijet merging improves situation

b-mass effects: playtime

vary around $\mu_Q = m_b$

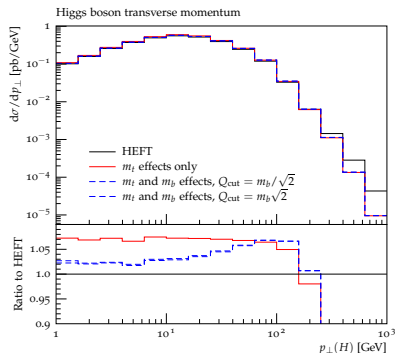


vary around $\mu_Q = m_h$ with $Q_{\text{cut}} = m_b$

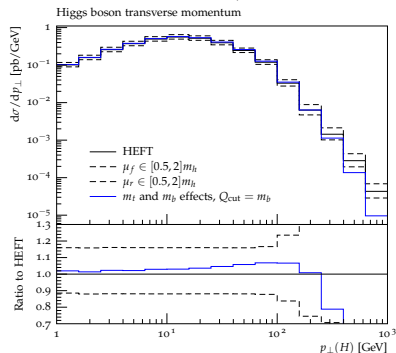


b -mass effects: playtime (cont'd)

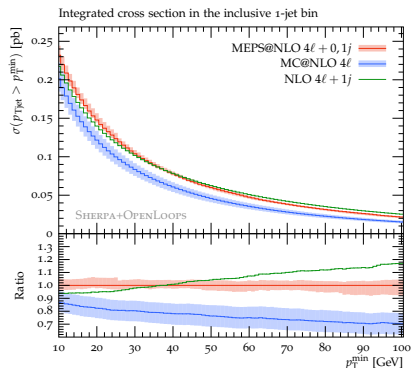
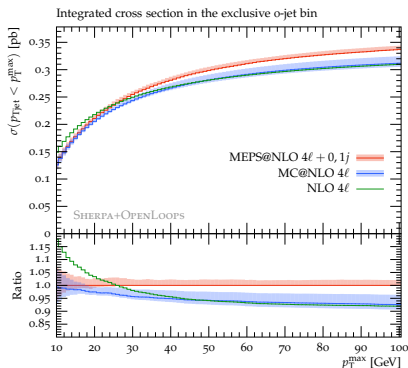
vary around $Q_{\text{cut}} = m_b$ with $\mu_Q = m_h$



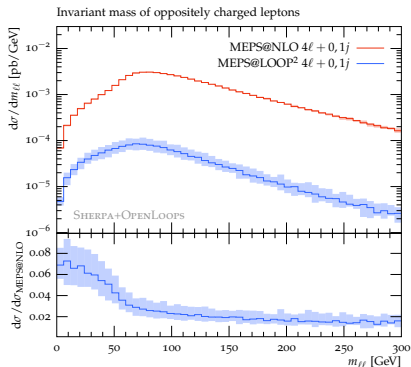
vary $\mu_{F,R}$



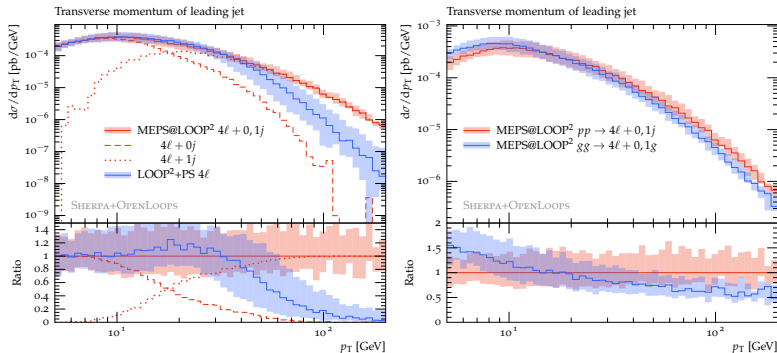
Higgs backgrounds: jet vetoes in W^+W^-+jets



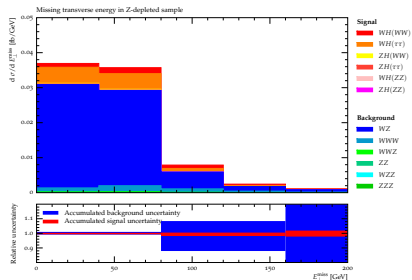
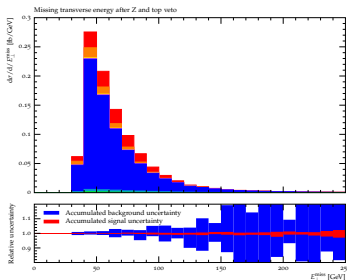
- include (LO-) merged loop² contributions of $gg \rightarrow VV$ (+1 jet)



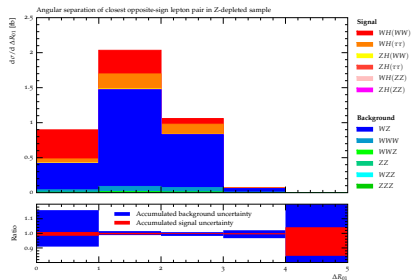
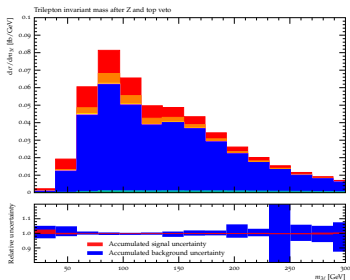
Higgs backgrounds: jet vetoes in $W^+W^- + \text{jets}$



Relevant observables for $VH \rightarrow 3\ell$: E_T



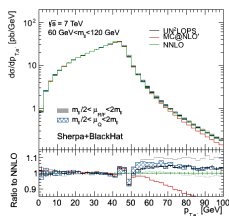
Relevant observables for $VH \rightarrow 3\ell$: m_{123} & ΔR_{01}



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 $\approx 10\%$

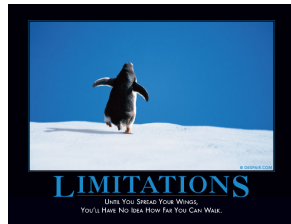
(S.Höche, S.Prestel, Y.Li, Phys.Rev.D91 (2015) 7 074015)



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
→ 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