Answering some Monte Carlo questions

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Outline

1. NLO Monte Carlo developments
2. Dealing with photons
3. Gluon splitting $g \to Q\bar{Q}$
4. W polarisation
5. Proposal for systematic evaluation of systematic errors
6. Concluding remarks

reminder: ingredients

Reminder: structure of an NLO calculation

- sketch of cross section calculation

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

IR-divergent (virtual correction) IR-divergent (real correction)

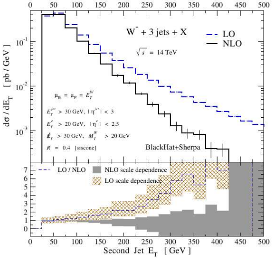
$$= \mathrm{d}\Phi_N \left[\mathcal{B}_N + \mathcal{V}_N + \mathcal{B}_N \otimes \mathcal{S}\right] + \mathrm{d}\Phi_{N+1}\left[\mathcal{R}_N - \mathcal{B}_N \otimes \mathrm{d}\mathcal{S}\right]$$

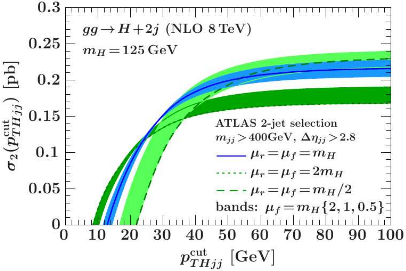
- subtraction terms $\mathcal{S}$ (integrated and differential): exactly cancel IR divergence in $\mathcal{R}$ – process-independent structures
- result: terms in both brackets separately infrared finite

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

Reminder: parton shower

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

$$\Delta^{(\mathcal{K})}_{ij,k}(t,t_0) = \exp\left[-\int\limits_{t_0}^{t}\frac{\mathrm{d}t}{t}\,\frac{\alpha_S}{2\pi}\int\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,\underbrace{\mathcal{K}_{ij,k}(t,\,z,\,\phi)}\right]$$

splitting kernel for
$(ij) \to ij$ (spectator k)

- 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

Emissions off a Born matrix element

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

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

- consider first emission only off Born configuration

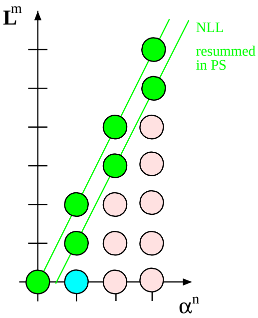
$$d\sigma_B = d\Phi_N\, \mathcal{B}_N(\Phi_N)$$
$$\cdot \underbrace{\left\{\Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int_{t_0}^{\mu_N^2} d\Phi_1 \left[\mathcal{K}_N(\Phi_1)\Delta_N^{(\mathcal{K})}(\mu_N^2, t(\Phi_1))\right]\right\}}_{\text{integrates to unity} \longrightarrow \text{"unitarity" of parton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

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

NLO 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)



The POWHEG-trick: modifying the Sudakov form factor

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

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

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

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

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

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

Local K-factors

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

- start from Born configuration Φ_N with NLO weight:

("local K-factor")

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

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

(relevant for MC@NLO)

NLO accuracy in radiation pattern

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

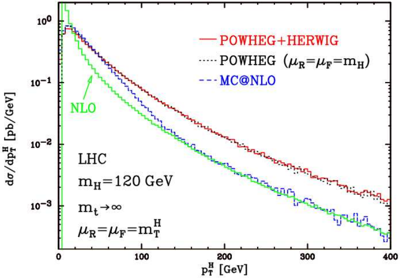
- generate emissions with $\Delta_N^{(\mathcal{R}/\mathcal{B})}(\mu_N^2,\, t_0)$:

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

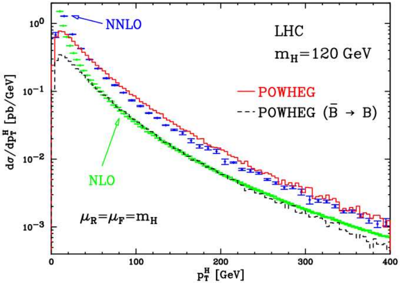
- radiation pattern like in ME correction
- pitfall, again: choice of upper scale μ_N^2 (this is vanilla POWHEG!)
- apart from logs: which configurations enhanced by local K-factor

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

POWHEG features



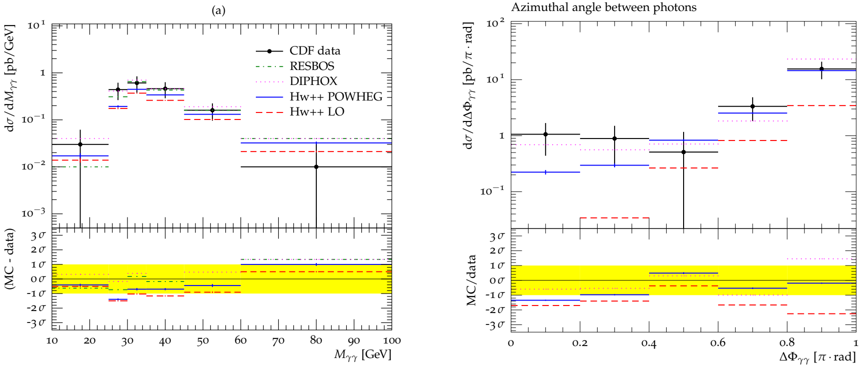
S. Alioli, P. Nason, C. Oleari, & E. Re, JHEP 0904 (2009) 002



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

Other implementations: di-photon production in HERWIG++

(L. D'Errico & P. Richardson, JHEP 1202 (2012) 130)

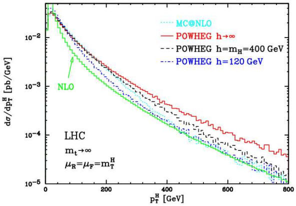


Improved POWHEG

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

- split real-emission ME as

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



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

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

Resummation in MC@NLO

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

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

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

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

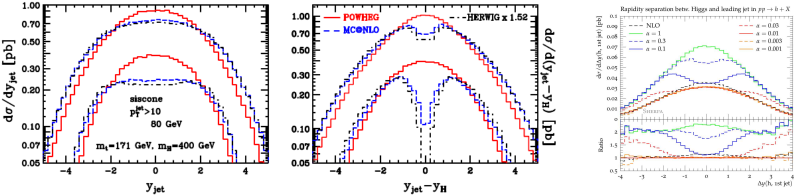
$$\mathrm{d}\sigma_N = \mathrm{d}\Phi_N \underbrace{\tilde{\mathcal{B}}_N(\Phi_N)}_{\mathcal{B}+\tilde{\mathcal{V}}} \left[\Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \, \mathcal{K}_{ij,k}(\Phi_1) \, \Delta_N^{(\mathcal{K})}(\mu_N^2, k_\perp^2) \right]$$
$$+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

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

Aside: phase space/K-factor effects

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

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

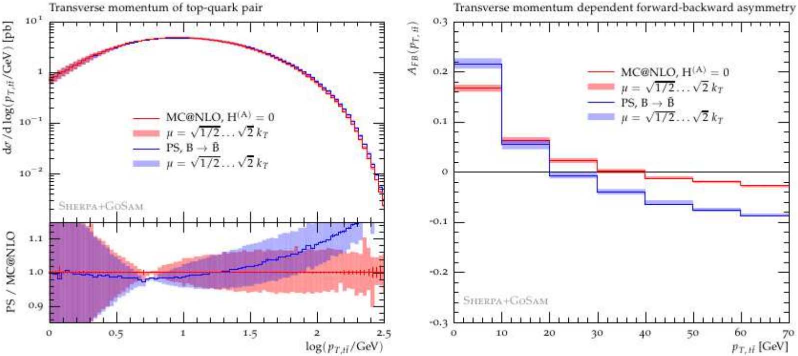


- problem: impact of subtraction terms on local K-factor (filling of phase space by parton shower)
- studied in case of $gg \to H$ above
- proper filling of available phase space by parton shower paramount

Aside': impact of full colour

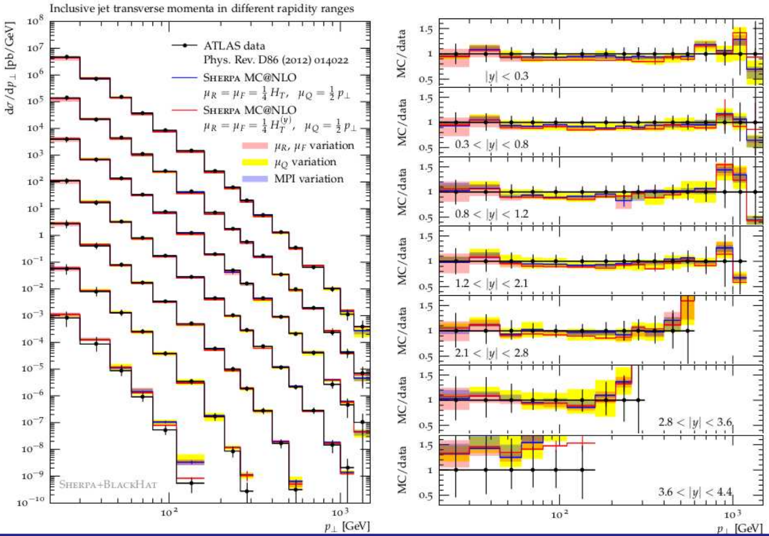
(S. Hoeche, J. Huang, G. Luisoni, M. Schoenherr, & J. Winter, arXiv:1306.2703 [hep-ph])

- 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)



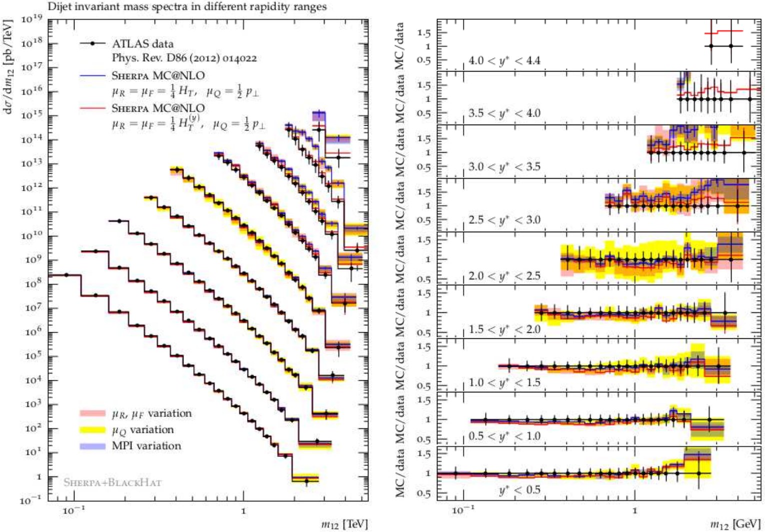
MC@NLO for light jets: jet-$p_\perp$

(S. Hoeche & M. Schoenherr, Phys. Rev. D86 (2012) 094042)



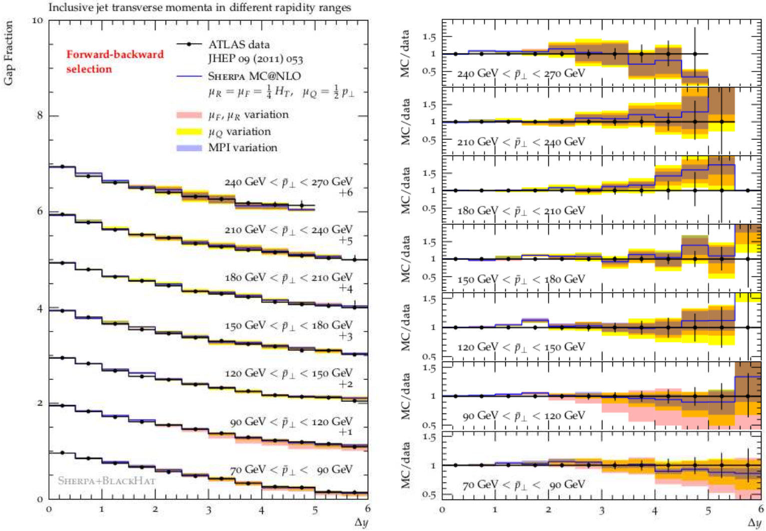
MC@NLO for light jets: dijet mass

(S. Hoeche & M. Schoenherr, Phys. Rev. D86 (2012) 094042)



MC@NLO for light jets: jet vetoes

(S. Hoeche & M. Schoenherr, Phys. Rev. D86 (2012) 094042)

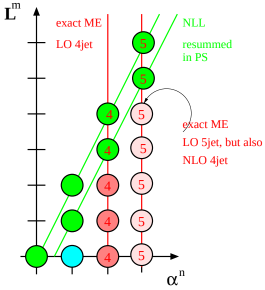


Multijet merging LO

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)

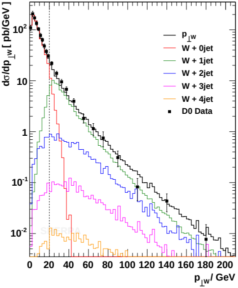
- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- combine ("merge") both:
  result: "towers"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

Iterating the emissions

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

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

Multijet merging NLO

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

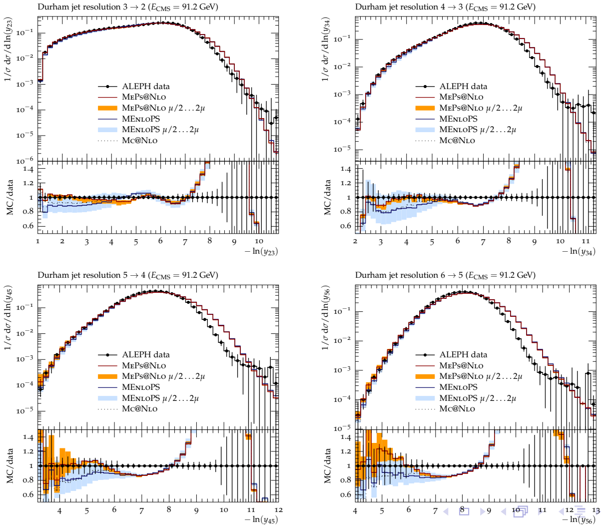
First emission(s), once more

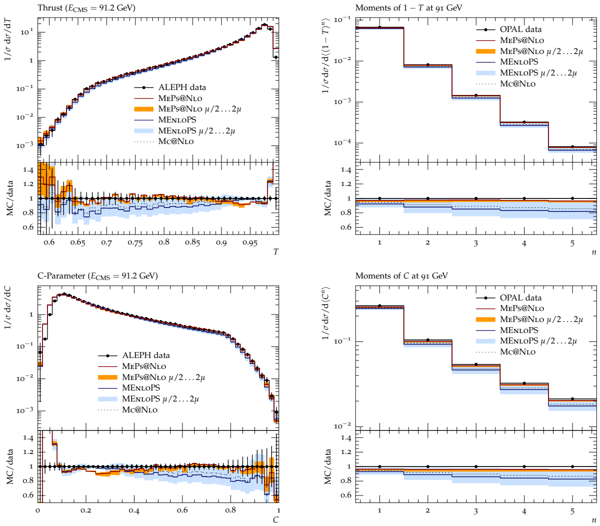
(S. Hoeche, F. Krauss, M. Schoenherr, and F. Siegert, JHEP 1304 (2013) 027, MEs from BLACKHAT)

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

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

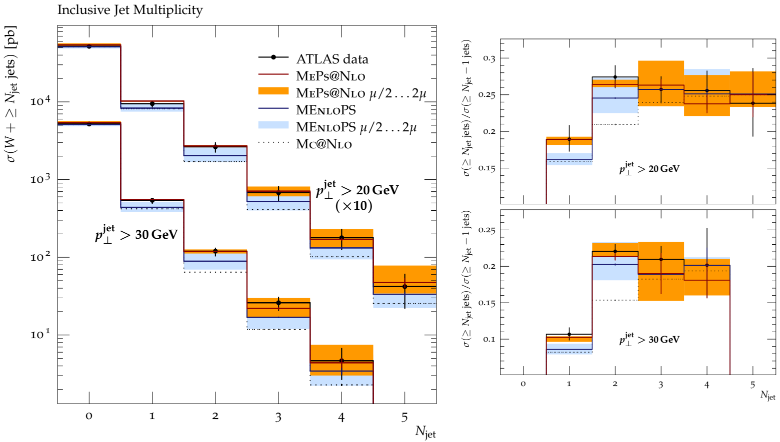
(S. Hoeche, T. Gehrmann, F. Krauss, M. Schoenherr, and F. Siegert, JHEP 1301 (2013) 144, MEs from BLACKHAT)

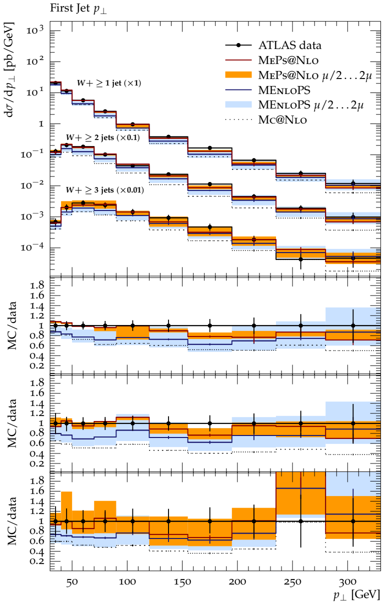


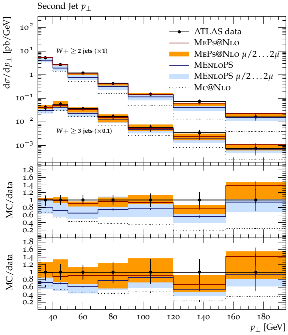

Thrust (E_{CMS} = 91.2 GeV)
ALEPH data
MEPs@NLO
MEPs@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
1/σ dσ/dT
MC/data
T
Moments of 1 − T at 91 GeV
OPAL data
1/σ dσ/d⟨(1 − T)^n⟩
n
C-Parameter (E_{CMS} = 91.2 GeV)
1/σ dσ/dC
C
Moments of C at 91 GeV
1/σ dσ/d⟨C^n⟩

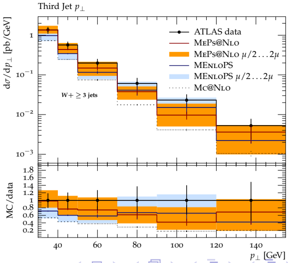
Example: MEPS@NLO for W+jets

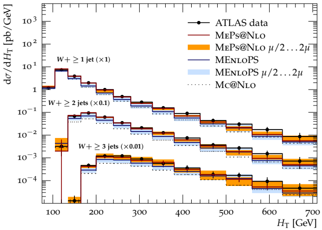
(S. Hoeche, F. Krauss, M. Schoenherr, and F. Siegert, JHEP 1304 (2013) 027, MEs from BLACKHAT)

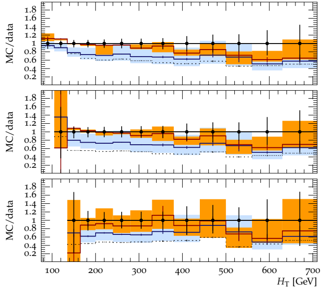



First Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 1$ jet ($\times 1$)
$W+\geq 2$ jets ($\times 0.1$)
$W+\geq 3$ jets ($\times 0.01$)
MC/data
$p_\perp$ [GeV]

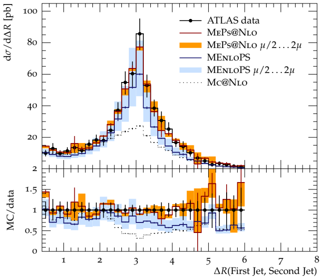

Second Jet $p_\perp$
$d\sigma/dp_\perp$ [pb/GeV]
ATLAS data
MEPs@NLO
MEPs@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 2$ jets ($\times 1$)
$W+\geq 3$ jets ($\times 0.1$)
MC/data
$p_\perp$ [GeV]


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

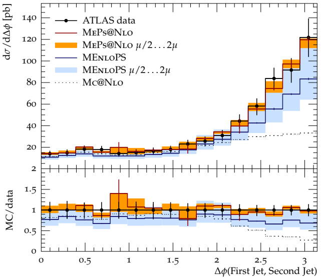




ΔR Distance of Leading Jets

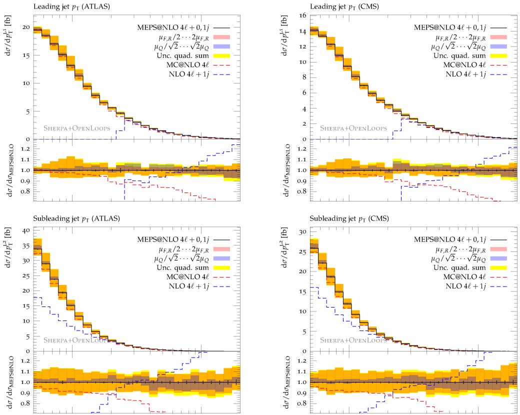


Azimuthal Distance of Leading Jets



Example: MEPS@NLO for W^+W^-+jets

(F. Cascioli et al., arXiv:1309.0500, up to one jet @ NLO, virtuals from OPENLOOPS, all interferences, $gg \to WW(+j)$ included, no Higgs)

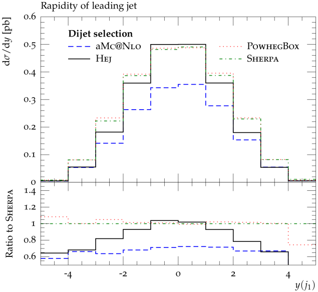


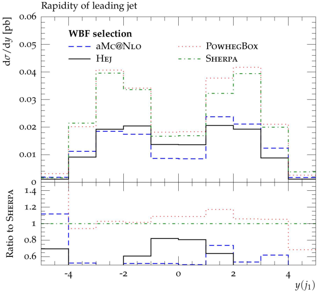
Results for Higgs boson production through gluon fusion

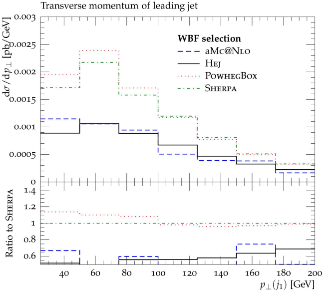
- parton-shower level, Higgs boson does not decay
- setup & cuts:
  - jets: anti-kt, $p_\perp \geq 20$ GeV, $R = 0.4$, $|\eta| \leq 4.5$
  - dijet cuts: at least 2 jets with $p_\perp \geq 25$ GeV
  - WBF cuts: $m_{jj} \geq 400$ GeV, $\Delta y_{jj} \geq 2.8$
- jet multiplicity plots:
  - 0-jet excl.: 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 $H + \{0,1\}^{(NLO)} + \{2,3\}^{(LO)}$ jets, $Q_{\rm cut} = 20 GeV$
- $H + \{0,1,2\}^{(NLO)}$ jets being finalised as we speak

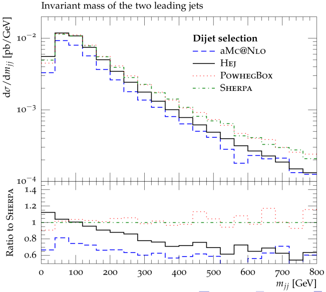
Comparison of different approaches

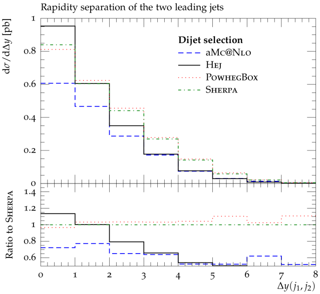
- SHERPA with $H + \{0,1\}^{(NLO)} + \{2,3\}^{(LO)}$ jets, $Q_{\rm cut} = 20 GeV$:
  - NLO accurate, preserving LL accuracy of shower
- aMC@NLO with $H + \{0,1,2\}^{(NLO)}$ jets, $Q_{\rm cut} = 50 GeV$:
  - "FxFx-merging": MLM-inspired overlay of NLO samples
- POWHEG with $H + \{2\}$ jets at NLO, "cut-free"
  - convergence through analytic Sudakov reweighting
- HEJ with $H + \{2,3\}$ jets at LO, $p_\perp \geq 25$ GeV
  - improved by wide-angle resummation, no parton shower

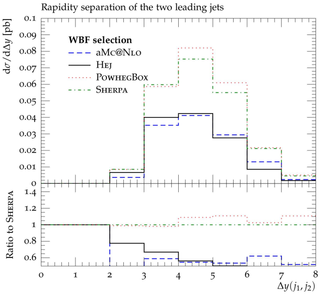

Rapidity of leading jet
Dijet selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
$d\sigma/dy$ [pb]
Ratio to SHERPA
$y(j_1)$

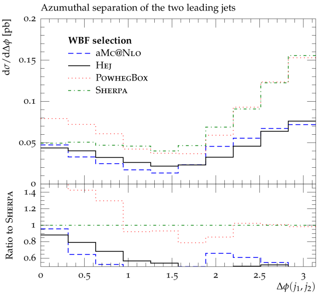

Rapidity of leading jet
WBF selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
$d\sigma/dy$ [pb]
Ratio to SHERPA
$y(j_1)$

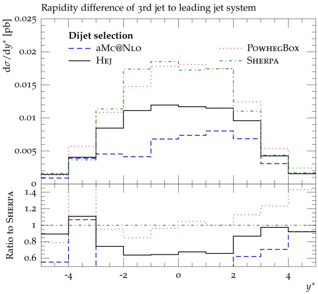

Transverse momentum of leading jet
WBF selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
$d\sigma/dp_\perp$ [pb/GeV]
Ratio to SHERPA
$p_\perp(j_1)$ [GeV]


Invariant mass of the two leading jets
Dijet selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
$d\sigma/dm_{jj}$ [pb/GeV]
Ratio to SHERPA
m_{jj} [GeV]


Rapidity separation of the two leading jets
Dijet selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
dσ/dΔy [pb]
Ratio to SHERPA
Δy(j1, j2)


Rapidity separation of the two leading jets
WBF selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
dσ/dΔy [pb]
Ratio to SHERPA
Δy(j1, j2)


Azimuthal separation of the two leading jets
WBF selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
dσ/dΔφ [pb]
Ratio to SHERPA
Δφ(j1, j2)

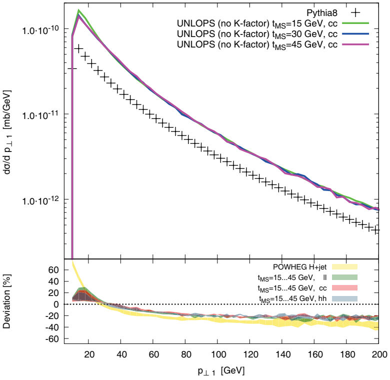

Rapidity difference of 3rd jet to leading jet system
Dijet selection
aMC@NLO
HEJ
POWHEGBOX
SHERPA
dσ/dy* [pb]
Ratio to SHERPA
y*

Aside: restoring unitarity with UMEPS & UNLOPS

(L. Lonnblad, S. Prestel, JHEP1302 (2013) 094)

(L. Lonnblad, S. Prestel, JHEP1303 (2013) 166)

- as indicated, MEPS@LO formalism breaks unitarity: inclusive *n*-jet cross sections not maintained due to mismatch of kernels in actual emission term and Sudakov form factor
- can be cured by adding/subtracting shower and ME-like terms
- formulae a bit tricky (worse at NLO)
- allows low merging cut



Dealing with photons

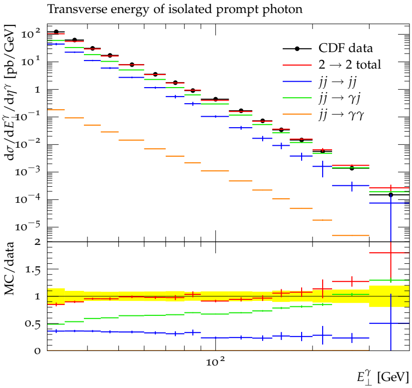
Multi-jet merging for photons

(implemented in S. Hoeche, F. Siegert, and S. Schumann, Phys.Rev. D81 (2010) 034026)

- treat photons and QCD partons fully democratically

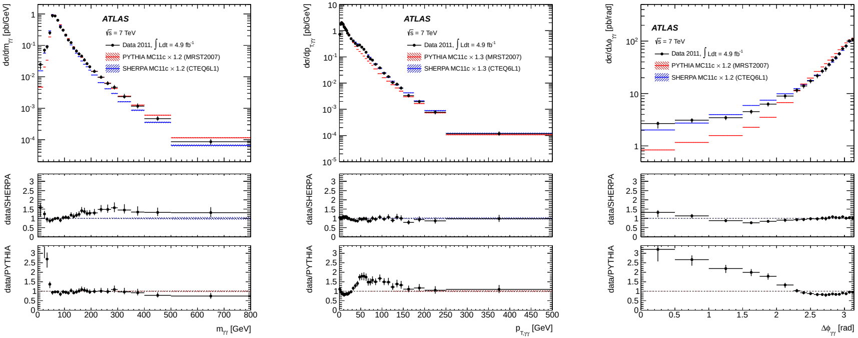
  (Glover, Morgan Z. Phys. C **62** (1994) 311)

- combine matrix elements of different parton/photon multiplicity with
- QCD$\oplus$QED evolution and hadronisation $\rightsquigarrow$ models $D^{\gamma}_{q,g}(z, Q^2)$



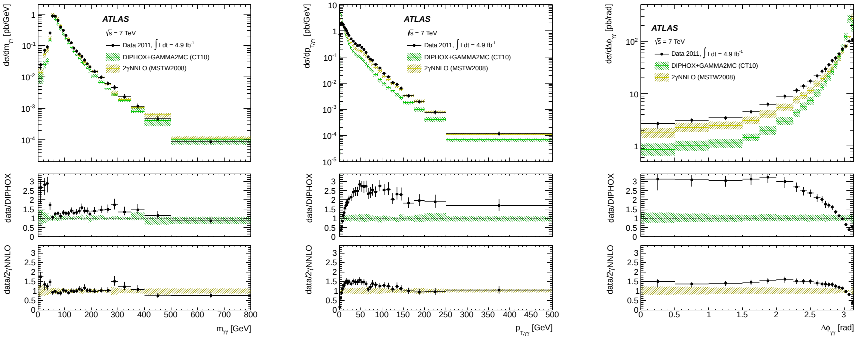
Di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$ in showers

(ATLAS, arXiv:1211.1913 [hep-ex])



Aside: Comparison with higher order calculations

(arXiv:1211.1913 [hep-ex])



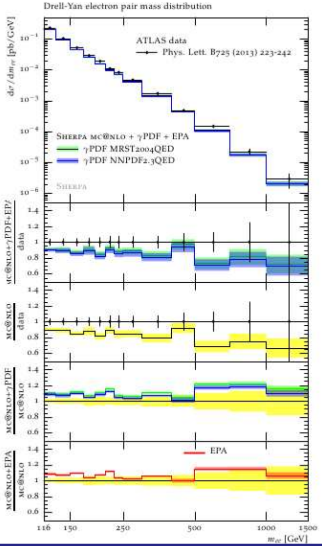
Aside: correcting for QED FSR

- correcting for QED FSR apparently an ongoing issue
- my take: don't do it by default. reasons:
  - correction hard to undo
  - better (future) tools may be more precise
  - scientific principle - publish as closely to data as possible
- suggestion: publish **both** uncorrected with dressed leptons and corrected with best possible tools for comparison with HO tools and for precision measurements

Aside: Initial state photons

- two kinds of initial state photon contributions: PDFs & EPA
- recently a new QED PDF by NNPDF collaboration

  (the only other one dated from 2004)
- for PDF: need to deal with photons in shower: trivial
- for EPA: need to have EPA spectrum and implement quasi-elastic $pp \to Xpp$ process: also trivial



Gluon splitting $g \to Q\bar{Q}$

Issues with gluon splitting $g \to Q\bar{Q}$

- "accuracy" in parton shower: next-to leading logs

  (from comparing Sudakov form factor with CSS resummation)

- $g \to Q\bar{Q}$ borderline
- PS paradigms like angular ordering, scale choice in α_S do not necessarily apply
- LEP measured splitting probability $\mathcal{P}_{g\to b\bar{b}}$:

$$\mathcal{P}_{g\to b\bar{b}} \approx 0.0025 \pm 0.0005 \quad (\text{JETSET}) : \mathcal{P}_{g\to b\bar{b}} \approx 0.0015 \qquad (1)$$

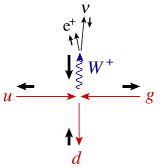
- my suggestion: measure it, especially in light of new ME+PS tools at LO and NLO.

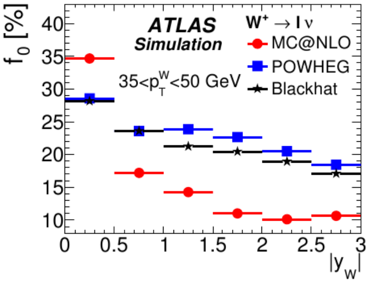
W polarisation

Simulating W polarisation

- showers with polarisation treatment not available now
- some work in HERWIG++ and in PYTHIA
- but maybe not necessary due to HO methods?
- example: MC@NLO ↔ POWHEG in W-polarisation measurement

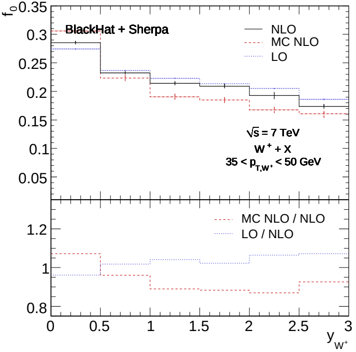
(ATLAS, arXiv:1203.2165)



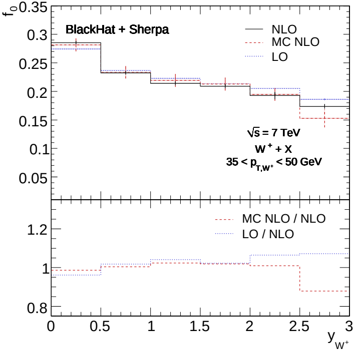


Simulating W polarisation

W+0j MC@NLO ✗



W+1j MC@NLO ✓



Evaluating systematic errors

Proposal for estimating systematic perturbative error

(implicit: with NLO tools)

- systematic error estimates paramount in quest for precision
- at the moment allow for independent variation of 4 scales:
  - factorisation and renormalisation scales: $\mu_{F,R}$
    $\longrightarrow$ advisable in matrix element only
    (old standard method of factor 2 yielded unnaturally large errors in parton shower; some new ideas of how to propagate this into shower)
  - merging scale of ME and PS: $\mathbf{Q}_{\rm cut}$
    (preliminary: dependence typically significantly reduced w.r.t. LO)
  - resummation scale: μ_Q
    (starting scale of shower: impact typically quite visible)
- PDF uncertainties on ME with PDF4LHC accord
  (simple: effectively PDF-weight vectors for each phase space point, inclusion of PDF uncertainties in shower a bit more tricky)

Proposal for estimating systematic non-perturbative error

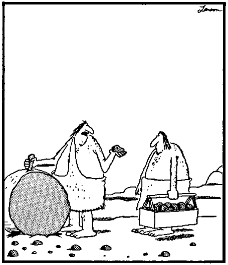
- important: right now, there is
  no first-principles theory for hadronisation & underlying event
- instead: models with lots of parameters, tuned to data
- two classes of hadronisation models: string & cluster
  however, they became increasingly similar in past two decades
- only one idea for underlying event: multi-parton interactions
- all tuned to **same data**,
  likely with lots of under-constrained parameters
- therefore: using different good tunes will **underestimate error**
- instead:
  tunes differing from data in a controlled and pre-defined way

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”)

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

(last method 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.”

- complete automation of NLO calculations done
  $\longrightarrow$ must benefit from it!

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

- maybe time to turn back to parton showers:
  higher log-accuracy (theory work), $g \to Q\bar{Q}$ (data-driven)
- need to work on agreement on non-perturbative uncertainties:
  "hadro-chemistry" of jets (K/π, p/π, etc.), underlying event
- start looking at "awkward" corners:
  - extreme phase spaces
  - jet vetoes
  - photon-induced processes
  - other electroweak corrections
    (TeV region = EW Sudakov zone!)