Status of Parton Shower Simulations

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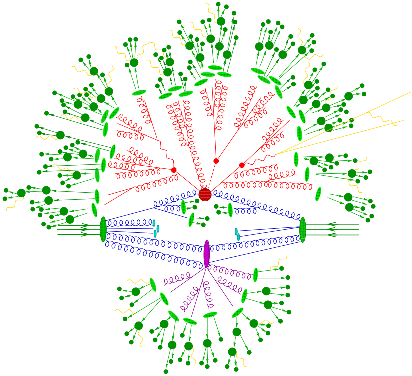
Outline

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



Reminder: Ingredients of simulations

Cross sections at the LHC: Born approximation

$$\mathrm{d}\sigma_N = \mathrm{d}\Phi_N \mathcal{B}_N$$
$$= \sum_{a,b} \int_0^1 \mathrm{d}x_a \mathrm{d}x_b f_a(x_a,\mu_F) f_b(x_a,\mu_F) \frac{1}{2\hat{s}} \int_{\text{cuts}} \mathrm{d}\phi_N |\mathcal{M}_{ab\to N}(\phi_N;\,\mu_F,\mu_R)|^2$$

- 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 $\mathcal{M}_{ab\to N}$ (summed/averaged over polarisations)
- renormalisation and factorisation scales μ_R and μ_F
- complexity demands numerical methods for large N

Reminder: Structure of an NLO calculation

- sketch of cross section calculation (by now fully automated)

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

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

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

S. Frixione, Z. Kunszt & A. Signer, Nucl.Phys.B467

S. Catani & M. Seymour, Nucl.Phys.B485

- result: terms in both brackets separately infrared finite

Probabilistic treatment of emissions

- probability for **no decay** in $[t_0,\ t]$: Sudakov form factor

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

- decay width for parton $i(j) \to ik(j)$ (spectator j)

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

- evolution parameter t defined by kinematics

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

- resummation of leading (and next-to leading) logarithms $\log t$
- 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

- shorthand 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

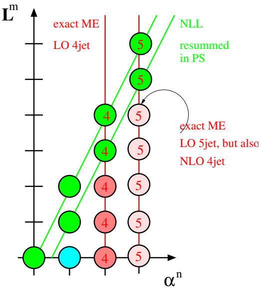
$$\mathrm{d}\sigma_B = \mathrm{d}\Phi_N\, \mathcal{B}_N(\Phi_N) \underbrace{\left\{ \Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \left[\mathcal{K}_N(\Phi_1) \Delta_N^{(\mathcal{K})}(\mu_N^2, t(\Phi_1)) \right] \right\}}_{\text{integrates to unity} \longrightarrow \text{“unitarity”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

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

NLO improvements: Matching

NLO matching: Basic idea

- parton shower resums logarithms
  fair description of collinear/soft emissions
  jet evolution (where the logs are large)
- matrix elements exact at given order
  fair description of hard/large-angle emissions
  jet production (where the logs are small)
- adjust ("match") terms:
  - cross section at NLO accuracy
  - correct hardest emission in PS to exactly reproduce ME at order α_S ($\mathcal{R}$-part of the NLO calculation)



The POWHEG-trick (I): Matrix-element reweighting

M. Bengtsson & T. Sjostrand, Phys.Lett.B 185& M. Seymour, Comp.Phys.Comm.90

P. Nason, JHEP 0411 & S. Frixione, P. Nason & C. Oleari, JHEP 0711

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

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

- 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

The POWHEG-trick (II): Local K-factors

P. Nason, JHEP 0411 & S. Frixione, P. Nason & C. Oleari, JHEP 0711

- start from Born configuration Φ_N with NLO weight:

("local K-factor")

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

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

(relevant for MC@NLO)

NLO accuracy in radiation pattern

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

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

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

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

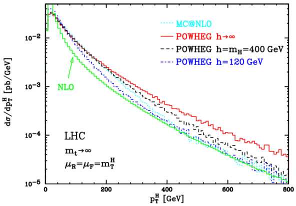
Improved POWHEG: Constraining the phase space

S. Alioli, P. Nason, C. Oleari, & E. Re, JHEP 0904

- 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 resummation result
- differential event rate up to first emission



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

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

Resummation in MC@NLO

S. Frixione & B. Webber, JHEP 0602

S. Hoeche, FK, M. Schoenherr, & F. Siegert, JHEP 1209

- 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)

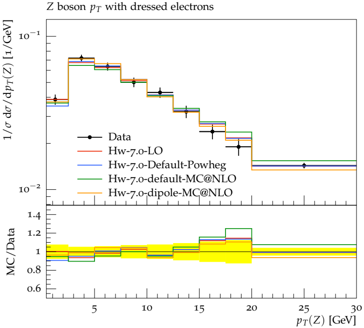
$$\mathrm{d}\sigma_N = \mathrm{d}\Phi_N \underbrace{\tilde{\mathcal{B}}_N(\Phi_N)}_{\mathcal{B}+\tilde{\mathcal{V}}} \left[\Delta_N^{(\mathcal{K})}(\mu_N^2, t_0) + \int\limits_{t_0}^{\mu_N^2} \mathrm{d}\Phi_1 \, \mathcal{K}_{ij,k}(\Phi_1) \, \Delta_N^{(\mathcal{K})}(\mu_N^2, k_\perp^2) \right]$$
$$+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

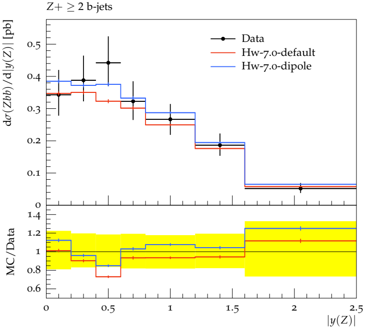
- effect: only resummed parts modified with local K-factor

Example results: inclusive Z-$p_\perp$ and $Zb\bar{b}$

snapshot of upcoming HERWIG ++ 3.0

- MC@NLO vs. POWHEG implemented in HERWIG ++
  with two different parton showers (ang.ordered & CS dipole)



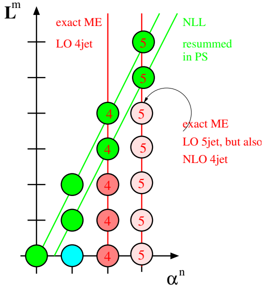


Multijet merging

Multijet merging: basic idea

S. Catani, FK, R. Kuhn, & B. Webber, JHEP 0111 & L. Lonnblad, JHEP 0205 & FK, JHEP 0208

- 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



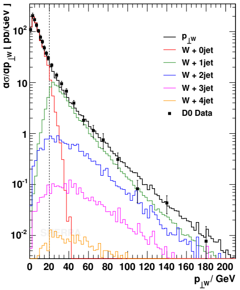
Separating jet evolution and jet production

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

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

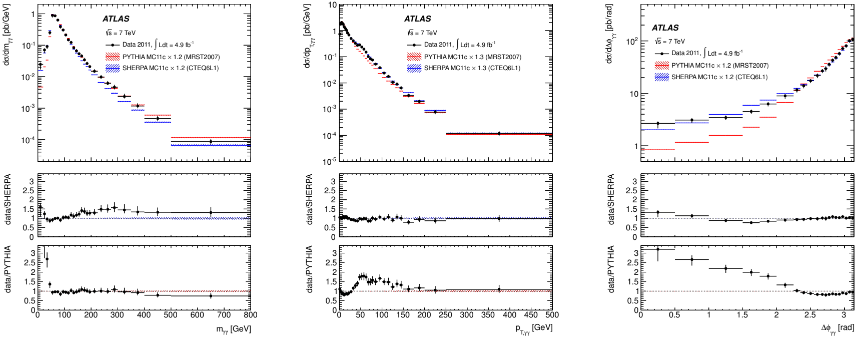
- matrix elements populate hard regime
- parton showers populate soft domain
- plot from first practical implementation for hadron colliders

FK, A. Schaelicke, S. Schumann, G. Soff, Phys.Rev.D70



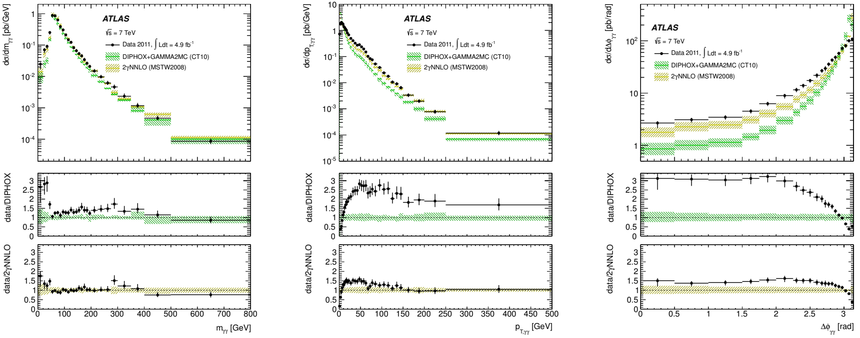
Di-photons @ ATLAS: $m_{\gamma\gamma}$, $p_{\perp,\gamma\gamma}$, and $\Delta\phi_{\gamma\gamma}$ in showers

arXiv:1211.1913 [hep-ex]



Aside: Comparison with higher order calculations

arXiv:1211.1913 [hep-ex]



Multijet merging at NLO

Multijet-merging at NLO: MEPS@NLO, FXFX, & UNLOPS

S. Hoeche, FK, M. Schoenherr, & F. Siegert, JHEP 1304, arXiv 1207.5030

R. Frederix & S. Frixione, JHEP 1212, arXiv 1209.6215

L. Lonnblad & S. Prestel, arXiv 1211.7278

- basic idea like at LO: towers of MEs with increasing jet multi (but this time at NLO)
- combine them into one sample, remove overlap/double-counting

maintain NLO and LL accuracy of ME and PS

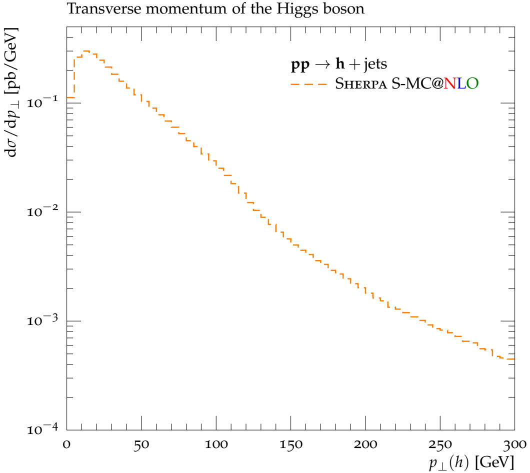
- towers of MC@NLO simulations without double-counting

(possibly further supplemented with LO simulations for even higher final state multiplicities)

First emission(s) in NLO-merged samples

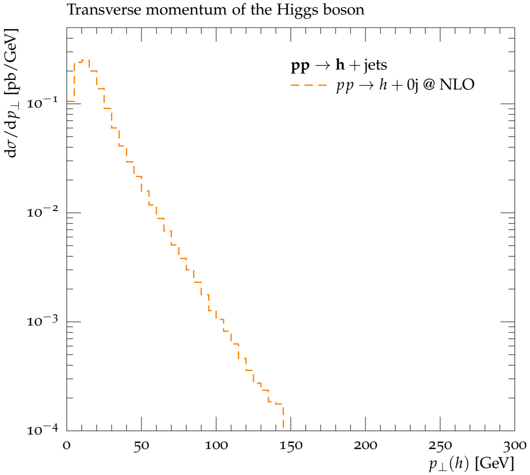
$$
\begin{aligned}
\mathrm{d}\sigma \;=\;& \mathrm{d}\Phi_N\,\tilde{\mathcal{B}}_N\left[\Delta_N^{(\mathcal{K})}(\mu_N^2,t_0)+\int\limits_{t_0}^{\mu_N^2}\mathrm{d}\Phi_1\,\mathcal{K}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\right]\\
&+\mathrm{d}\Phi_{N+1}\,\mathcal{H}_N\Delta_N^{(\mathcal{K})}(\mu_N^2,t_{N+1})\Theta(Q_J-Q_{N+1})\\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

$p_\perp^H$ in MEPS@NLO



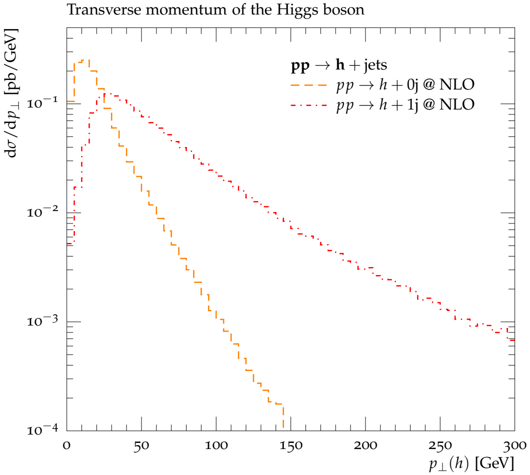
- first emission by MC@NLO

$p_\perp^H$ in MEPS@NLO



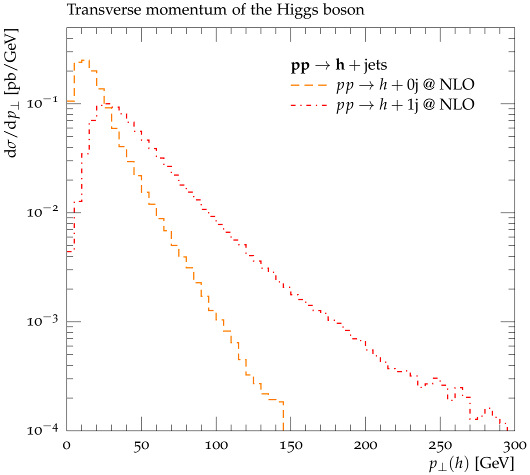
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\rm cut}$

$p_\perp^H$ in MEPS@NLO



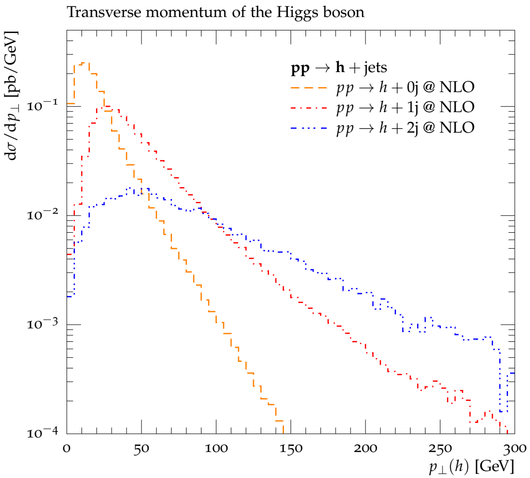
- first emission by MC@NLO , restrict to $Q_{n+1} < Q_{\text{cut}}$
- MC@NLO $pp \to h + \text{jet}$ for $Q_{n+1} > Q_{\text{cut}}$

$p_\perp^H$ 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 $Q_{n+2} < Q_{\rm cut}$

$p_\perp^H$ in MEPS@NLO



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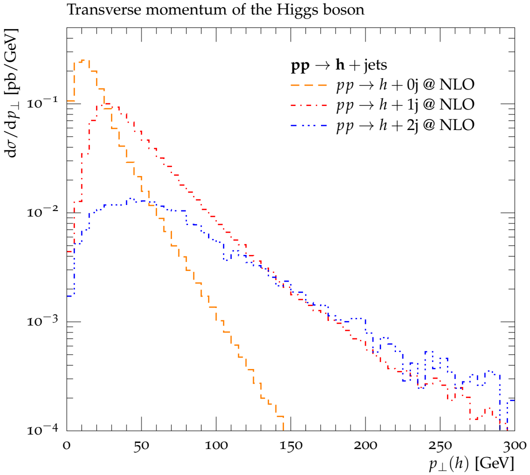
- MC@NLO $pp \to h+$2jets for $Q_{n+2} > Q_{\rm cut}$

$p_\perp^H$ in MEPS@NLO



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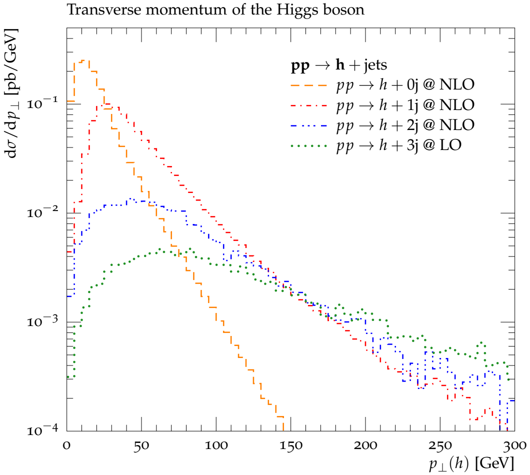
- restrict emission off $pp \to h + \text{jet}$ to $Q_{n+2} < Q_{\rm cut}$
- MC@NLO $pp \to h + 2\text{jets}$ for $Q_{n+2} > Q_{\rm cut}$
- iterate

$p_\perp^H$ in MEPS@NLO



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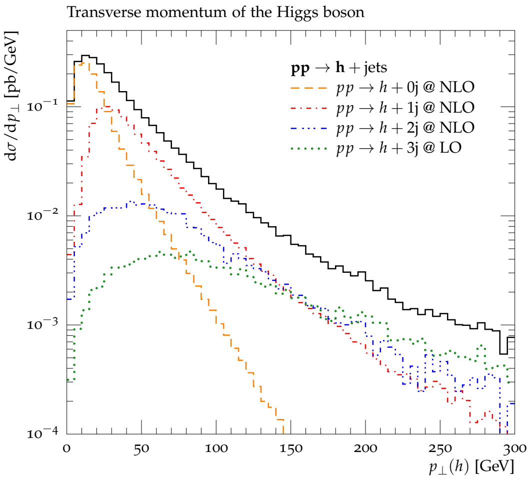
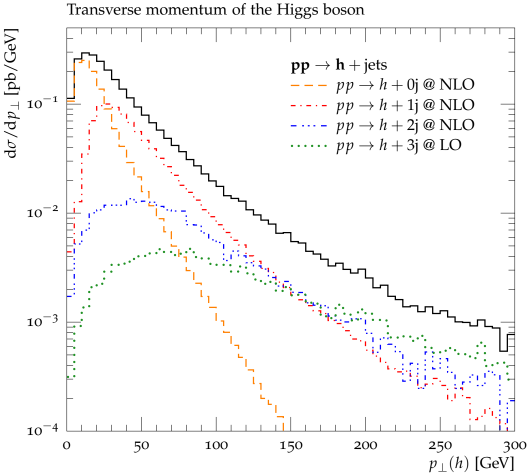
- iterate

$p_\perp^H$ 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



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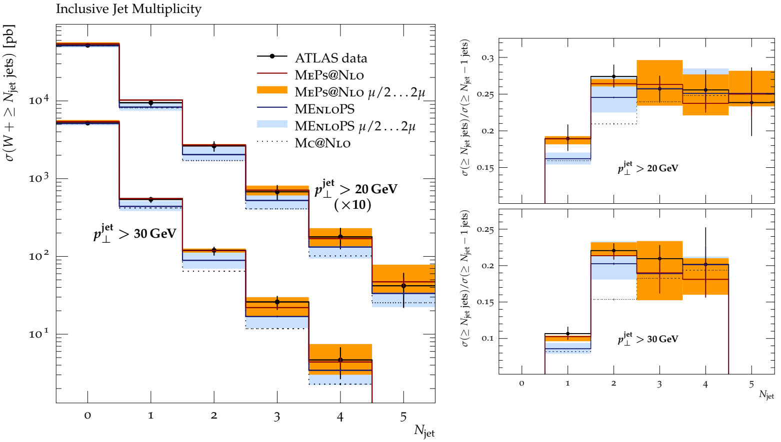
- MC@NLO $pp \to h+$2jets for $Q_{n+2} > Q_{\rm cut}$
- iterate
- sum all contributions
- eg. $p_\perp(h)$>200 GeV has contributions fr. multiple topologies

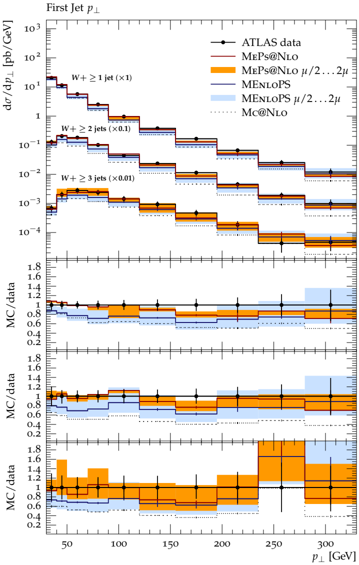
Differences between MEPS@NLO, FxFx, & UNLOPS

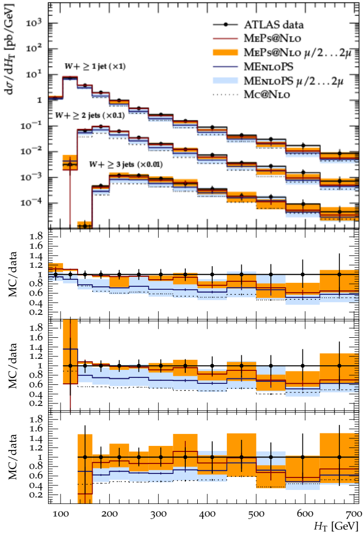
	MEPS@NLO in SHERPA	FxFx with aMC@NLO_MADGRAPH	UNLOPS in PYTHIA/HERWIG
ME	$\mathcal{V}$ external $\mathcal{B}$, $\mathcal{R}$, $\mathcal{S}$ fromCOMIX or AMEGIC++ $\mathcal{V}$ from OPENLOOPS, BLACKHAT, NJET, ...	all internal aMC@NLO_MADGRAPH	all external LH event files
shower	internal CS Shower from SHERPA	external HERWIG or PYTHIA	internal PYTHIA/HERWIG
Δ_N	from PS	analytical	from PS
$\Theta(Q_J)$	per emission	a-posteriori	per emission
Q_J-range	$>$ Sudakov regime	relatively high (but changed)	$\approx$ Sudakov regime

MEPS@NLO: validation in W+jets

S. Hoeche, F. Krauss, M. Schoenherr & F. Siegert, JHEP 1304



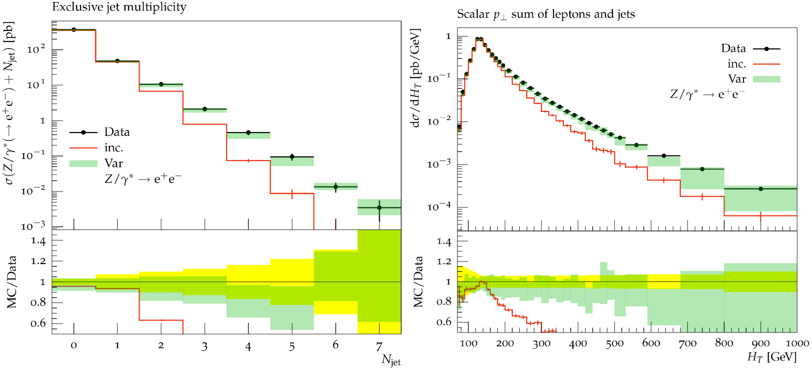

First Jet $p_\perp$
ATLAS data
MEPS@NLO
MEPS@NLO $\mu/2\ldots2\mu$
MENLOPS
MENLOPS $\mu/2\ldots2\mu$
MC@NLO
$W+\geq 1$ jet ($\times 1$)
$W+\geq 2$ jets ($\times 0.1$)
$W+\geq 3$ jets ($\times 0.01$)
$d\sigma/dp_\perp$ [pb/GeV]
MC/data
$p_\perp$ [GeV]


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 ($\times 0.01$)
$d\sigma/dH_T$ [pb/GeV]
MC/data
H_T [GeV]

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)



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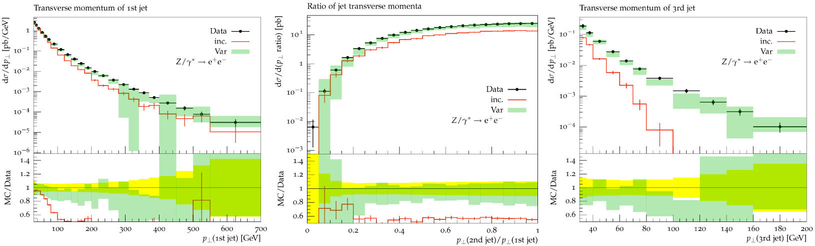
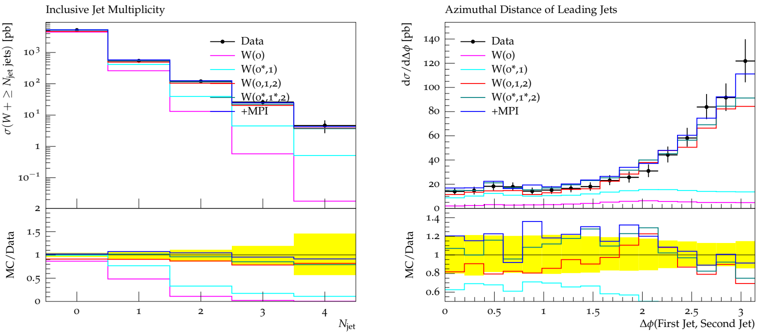


Multijet merging in HERWIG ++: validation in W+jets

Merging algorithm from S. Platzer, JHEP 1308

- compare LO and NLO merging (NLO MEs with *)



Aside: merging without Q_J - the MINLO approach

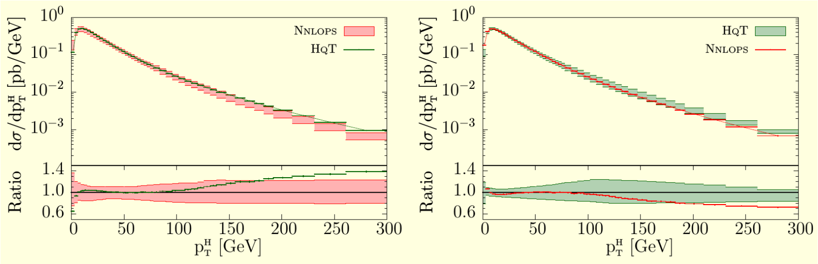
K.Hamilton, P.Nason, C.Oleari & G.Zanderighi, JHEP 1305

- 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
  - scale setting like in multijet merging
  - apply analytic 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

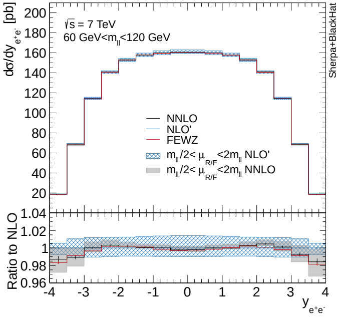
K. Hamilton, P. Nason, E. Re & G. Zanderighi, JHEP 1310

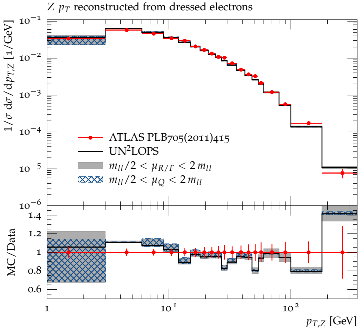


Alternative NNLO+PS: UN^{2}LOPS

S. Hoche, Y. Li, & S. Prestel, Phys.Rev.D90 & D91

- building on UNLOPS logic: add and subtract terms in parton shower





Improving the parton showers

Going dipoles

- first parton showers in PYTHIA and HERWIG based on $1 \to 2$ splittings evolution parameters given by invariant mass (ang.veto) or angle
- antenna shower based on $2 \to 3$ in ARIADNE:

  also in VINCIA (W. Giele, D. Kosover & P. Skands, Phys.Rev.D78)

  - no discrimination of splitter & spectator
  - transverse momentum as ordering parameter
  - for $e^-e^+ \to$ hadrons and DIS only
  - extension to initial states in J. Winter & FK, JHEP 0807
- dipole showers based on subtraction kernels:
  - based on $2 \to 3$ kinematics with splitter–spectator identification
  - transverse momentum as ordering parameter
  - first proposed to alleviate NLO matching (MC@NLO)

    Z. Nagy & D. Soper, JHEP 0510
  - implemented stand-alone and as part of SHERPA and HERWIG ++

    M. Dinsdale, M. Ternick, & S. Weinzierl, Phys.Rev.D76

    S. Schumann & FK, JHEP 0803 & S. Platzer & S. Gieseke, Eur.Phys.C72

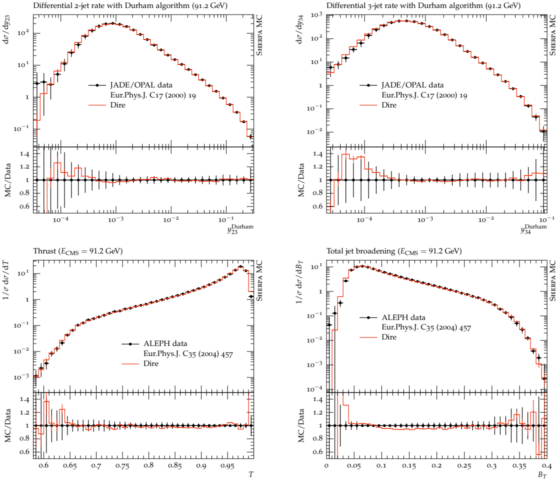
A new hybrid shower between dipole and parton shower

S. Hoeche & S. Prestel, arXiv 1506.05057

- use transverse momentum defined in soft instead of collinear regime: amounts to dynamical rescaling of trivial $k_\perp$
  the exact inverse of soft eikonal
- enforce collinear anomalous dimensions
- two independent implementations in SHERPA and PYTHIA
- LO multijet merging already available

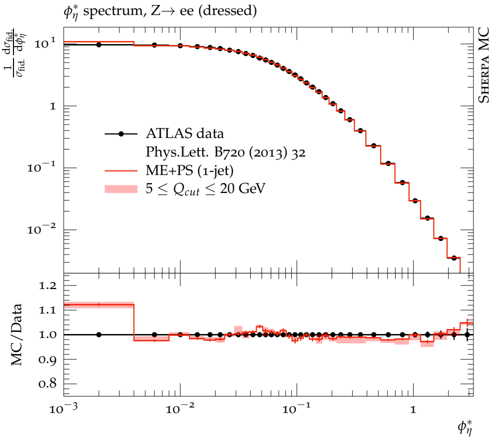
Validation of DIRE in $e^-e^+ \to$ hadrons

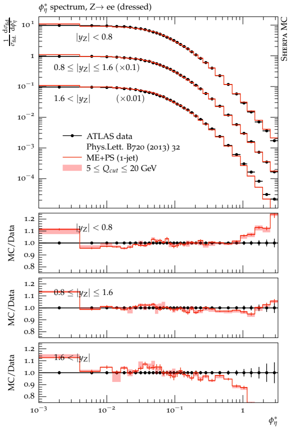
S. Hoche, Y. Li, & S. Prestel, Phys.Rev.D90 & D91



Validation of DIRE in Drell-Yan

S. Hoche, Y. Li, & S. Prestel, Phys.Rev.D90 & D91





Including higher orders in $1/N_c$

- parton showers are formulated in the large–N_c limit
- sum over external colour factors for gluon emission

$$\sum_{j\neq i} \mathbf{T}_i \mathbf{T}_j^\dagger = |\mathbf{T}_i|^2$$

- replace $|\mathbf{T}_i|^2$ with explicit sum — i.e. full colour insertion operators of dipole subtraction
- implemented in dipole shower in HERWIG ++

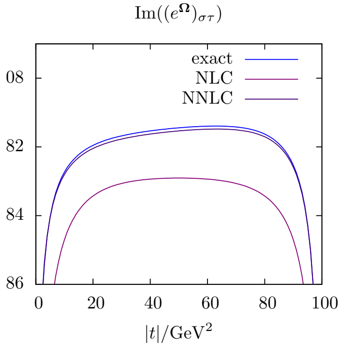
S. Platzer & M.Sjodahl, JHEP 1207

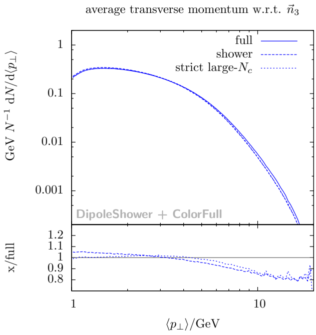
- also (slightly different) in DEDUCTOR — Z. Nagy & D. Soper, JHEP 1206
- usually small contribution (see next slide) –
  only relevant for observables driven by non–global logarithms

Effect of subleading colours in $e^-e^+ \to$ hadrons

Merging algorithm from S. Platzer, JHEP 1308

- comparing soft matrix elements for various accuracies in $1/N_c$ (left)
- average $p_\perp$ distribution w.r.t. an axis orthogonal to event plane





Including higher logarithms

S. Hoeche, FK, S. Prestel, M. Schonherr, in prep

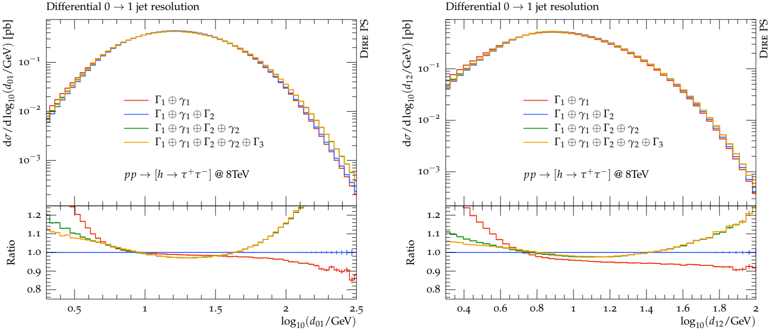
- compare with Q_T resummation in Collins–Soper–Sterman scheme:
  - Sudakov form factor given by

$$\Delta(t,t_0) = \exp\left\{-\int\limits_{t_0}^{t}\frac{\mathrm{d}k_\perp^2}{k_\perp^2}\left[A(k_\perp^2)\log\frac{k_\perp^2}{t_0} + B(k_\perp^2)\right]\right\}$$

    where A and B have expansion in α_S
  - parton showers usually include terms $A^{(1,2)}$ and $B^{(1)}$ ("NLL") in differential form, all process–independent
  - can try to include $A^{(3)}$ process–independent parts of $B^{(2)}$

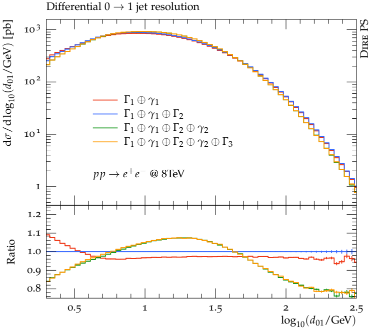
Effect of higher logarithms in Drell-Yan

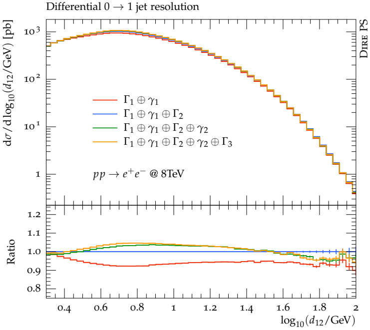
S. Hoeche, FK, S. Prestel, M. Schonherr, in prep



Effect of higher logarithms in $gg \to H$

S. Hoeche, FK, S. Prestel, M. Schonherr, in prep





Adding spin correlations, weak emissions

- can also add spin correlations – needs large matrix multiplications

  Z. Nagy & D. Soper, JHEP 1206 & HERWIG ++, in prep.

- attempts to include electroweak emissions in shower:
  - photon in shower are trivial, multijet merging available

    S. Hoeche, S. Schumann, & F. Siegert, Phys.Rev.D81

  - W and Z emission more tricky, due to spin structure
  - emission of single boson ok, second boson much harder
  - some implementations in PYTHIA and SHERPA

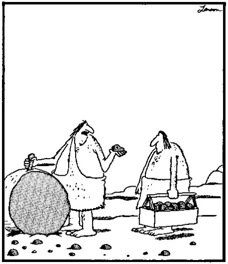
    J. R. Christiansen & T. Sjostrand, JHEP 1404 & FK, P. Petrov, M. Schoenherr, & M. Spannowsky, Phys.Rev.D89

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")
  - MEPS@NLO ("SHERPA", "UNLOPS", "FxFx")
  - NNLOPS feasible for simple processes

(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."

- multijet merging at NLO for relevant signals and backgrounds
- complete automation of NLO calculations done
  $\longrightarrow$ must benefit from it! (it's the precision and trustworthy & systematic uncertainty estimates!)
- first steps towards systematic improvement of parton showers: $1/N_c$ corrections, spin correlations, higher logarithms