TECHNISCHE UNIVERSITÄT DRESDEN

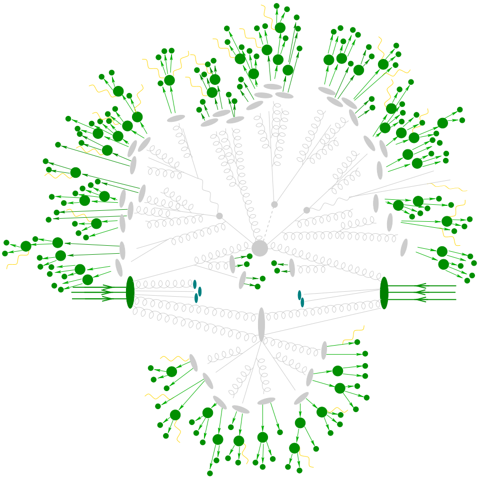
Fakultät Mathematik und Naturwissenschaften Institut für Kern- und Teilchenphysik

NLO + parton shower matching and merging in four-lepton + jets production

Frank Siegert

Universität Mainz, Theorie-Palaver, 12.11.2013

Motivation



- We want:
  Simulation of $pp \to$ full hadronised final state
- Factorisation into stages:
  MC event representation
- We know from first principles:
  - Hard scattering at fixed order in perturbation theory (**Matrix Element**)
  - Approximate resummation of QCD corrections to all orders (**Parton Shower**)
- Missing bits:
  Hadronisation/Underlying event (ignored in this talk)

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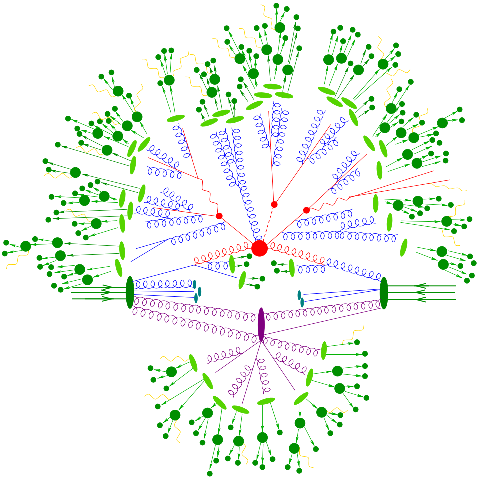

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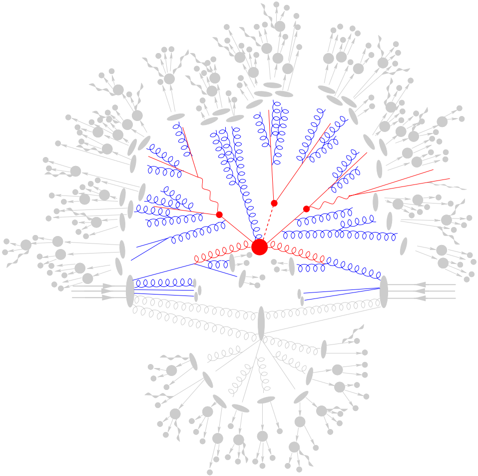

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Outline

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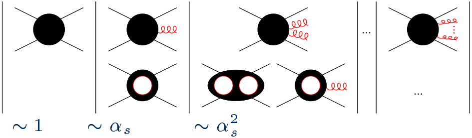
- QCD: We can only calculate parts of the perturbative series in α_s



- Exact calculations possible up to $\mathcal{O}(\alpha_s^2)$ for some processes
- Why is that not always enough?

Large logarithms from infrared divergences

- KLN: inclusive observables calculable at fixed-order
- If not inclusive $\Rightarrow$ Finite remainders of infrared divergences:

$$\text{logarithms of } \frac{\mu^2_{\text{hard}}}{\mu^2_{\text{resolution}}} \text{ with each } \mathcal{O}(\alpha_s)$$

can become large and spoil convergence of perturbative series

$\Rightarrow$ Need to resum the series to all orders

Since nobody is smart enough yet, only resum the logarithmically enhanced terms:
Parton shower evolution between μ^2_{hard} and $\mu^2_{\text{hadronisation}}$

Construction of a parton shower

Universal collinear factorisation of QCD emissions

- Matrix element $\mathcal{M}^{(n+1)} \to \mathcal{D}_{ij}^{(\mathrm{PS})} = \mathcal{M}^{(n)} \times \left[\frac{1}{2p_i p_j}\, 8\pi\alpha_s\, \mathcal{K}_{ij}\right]$
- Radiative phase space $\mathrm{d}\Phi^{(n+1)} = \mathrm{d}\Phi^{(n)} \times \mathrm{d}\Phi^{(1)} \sim \mathrm{d}\Phi_n\ \mathrm{d}t$

  $\Rightarrow$ "Evolution variable" $t \sim 2\, p_i p_j$ as measure of collinearity (e.g. angle)

Considering multiple emissions

$\rightarrow$ Analogy to radioactive decay

Radioactive decay

- Constant decay probability

  $f(t) \equiv \lambda = \text{const}$
- Survival probability $\mathcal{N}(t)$

  $-\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}t} = \lambda\,\mathcal{N}(t)$

  $\Rightarrow \mathcal{N}(t) \sim \exp(-\lambda t)$

Parton shower branching

- Branching probability

  $f(t) \equiv \mathcal{D}_{ij}^{(\mathrm{PS})}(t)$
- Survival probability $\mathcal{N}(t)$

  $-\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}t} = f(t)\,\mathcal{N}(t)$

  $\Rightarrow \mathcal{N}(t) \sim \exp\left(-\int_0^t f(t')\mathrm{d}t'\right)$

Construction of a parton shower

Definition of main parton shower ingredients

- "Sudakov factor" $\equiv$ Survival probability of ensemble between two scales:

$$\Delta(t', t'') = \prod_{\{ij\}} \exp\left(- \int_{t'}^{t''} \mathrm{d}t \; \mathcal{D}_{ij}^{(\mathrm{PS})} \right)$$

- Evolution variable t: not time, but collinearity from hard to soft
- Starting scale μ_Q^2 (time $t = 0$ in radioactive decay) defined by hard scattering
- Cutoff scale related to hadronisation scale $t_0 \sim \mu_{\mathrm{had}}^2$

$\Rightarrow$ Differential cross section (up to first emission)

$$\mathrm{d}\sigma^{(\mathrm{LO})} = \mathrm{d}\Phi_B \, \mathcal{B} \left[\underbrace{\Delta^{(\mathrm{PS})}(t_0, \mu_Q^2)}_{\text{unresolved}} + \underbrace{\sum_{\{ij\}} \int_{t_0}^{\mu_Q^2} \mathrm{d}t \; \mathcal{D}_{ij}^{(\mathrm{PS})} \Delta^{(\mathrm{PS})}(t, \mu_Q^2)}_{\text{resolved}} \right]$$

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$$\mathrm{d}\sigma^{(\mathrm{LO+PS})} = \mathrm{d}\Phi_B \, \mathcal{B} \left[\underbrace{\Delta^{(\mathrm{PS})}(t_0, \mu_Q^2)}_{\text{unresolved}} + \underbrace{\sum_{\{ij\}} \int_{t_0}^{\mu_Q^2} \mathrm{d}t \; \mathcal{D}_{ij}^{(\mathrm{PS})} \Delta^{(\mathrm{PS})}(t, \mu_Q^2)}_{\text{resolved}} \right]$$

Higher precision for parton showers

NLO+PS matching

- Parton shower on top of NLO prediction
(e.g. inclusive W production)
- Objectives:
  - avoid double counting
  - inclusive NLO accuracy

ME+PS@LO merging

- Multiple LO+PS simulations for processes of different jet multi
(e.g. $W, Wj, Wjj, \ldots$)
- Objectives:
  - combine into inclusive sample
  - preserve resummation accuracy

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Combination: ME+PS@NLO

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Reminder + Notation: NLO cross section

$$\mathrm{d}\sigma^{\text{(NLO)}} = \mathrm{d}\Phi_B \left[\mathcal{B} + \tilde{\mathcal{V}} + \sum_{\{ij\}} \mathcal{I}^{(\mathrm{S})}_{(ij)} \right] + \mathrm{d}\Phi_R \left[\mathcal{R} - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{S})}_{ij} \right]$$

Idea of NLO+PS matching

- Apply PS separately for $\mathcal{B}$ and $\mathcal{V}$ and $\mathcal{R}$ at NLO? $\Rightarrow$ **double counting**
- Instead: subtract additional PS(-like) terms $\mathcal{D}^{(\mathrm{A})}_{ij}$

$$\mathrm{d}\sigma^{\text{(NLO sub)}} = \mathrm{d}\Phi_B\ \bar{\mathcal{B}}^{(\mathrm{A})} + \mathrm{d}\Phi_R \left[\mathcal{R} - \sum \mathcal{D}^{(\mathrm{A})}_{ij} \right]$$

$$\text{with } \bar{\mathcal{B}}^{(\mathrm{A})} = \mathcal{B} + \tilde{\mathcal{V}} + \sum \mathcal{I}^{(\mathrm{S})}_{(ij)} + \sum \int \mathrm{d}t \left[\mathcal{D}^{(\mathrm{A})}_{ij} - \mathcal{D}^{(\mathrm{S})}_{ij} \right]$$

and add them back by PS(-like) resummation on $\mathrm{d}\sigma^{\text{(NLO sub)}}$ events:

$$\mathrm{d}\sigma^{\text{(NLO+PS)}} = \mathrm{d}\Phi_B\ \bar{\mathcal{B}}^{(\mathrm{A})} \left[\underbrace{\Delta^{(\mathrm{A})}(t_0, \mu_Q^2)}_{\text{unresolved}} + \underbrace{\sum \int_{t_0}^{\mu_Q^2} \mathrm{d}t\ \frac{\mathcal{D}^{(\mathrm{A})}_{ij}}{\mathcal{B}} \Delta^{(\mathrm{A})}(t, \mu_Q^2)}_{\text{resolved, singular}} \right]$$

$$+ \mathrm{d}\Phi_R \underbrace{\left[\mathcal{R} - \sum \mathcal{D}^{(\mathrm{A})}_{ij} \right]}_{\text{resolved, non-singular} \equiv \mathcal{H}^{(\mathrm{A})}}$$

Special case: Mc@Nlo

Frixione, Webber (2002)

Original idea: $\mathcal{D}^{(\mathrm{A})}$ = PS splitting kernels

+ Shower algorithm for Born-like events easy to implement
– "Non-singular" piece $\mathcal{R} - \sum_{ij} \mathcal{D}_{ij}^{(\mathrm{A})}$ is actually singular:
  - Collinear divergences subtracted by splitting kernels ✓
  - Remaining soft divergences in non-trivial processes at sub-leading N_c ✗

Workaround: $\mathcal{G}$-function dampens soft limit in non-singular piece
$\Leftrightarrow$ Loss of formal NLO accuracy
(but heuristically only small impact)

Höche, Krauss, Schönherr, FS (2011)

Alternative idea: $\mathcal{D}^{(\mathrm{A})}$ = Catani-Seymour subtraction terms $\mathcal{D}^{(\mathrm{S})}$

+ "Non-singular" piece fully free of divergences
– Splitting kernels in shower algorithm become negative

Solution: Weighted $N_C = 3$ one-step PS based on subtraction terms

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Used in Sherpa

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ME+PS@LO merging

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Parton shower on top of high-multi ME

Translate ME event into shower language

Why?

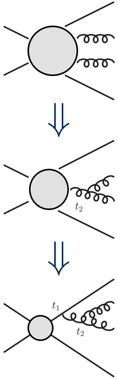
- Need starting scales t for PS evolution
- Have to embed existing emissions into PS evolution

Problem: ME only gives final state, no history

Solution: Backward-clustering (running the shower reversed), similar to jet algorithm:

1. Select last splitting according to shower probablities
2. Recombine partons using inverted shower kinematics $\rightarrow$ N-1 particles + splitting variables for one node
3. Reweight $\alpha_s(\mu^2) \rightarrow \alpha_s(p_\perp^2)$
4. Repeat 1 - 3 until core process ($2 \rightarrow 2$)

Example:



Truncated shower

- Shower each (external and intermediate!) line between determined scales
- "Boundary" scales: resummation scale μ_Q^2 and shower cut-off t_0

Tree-level ME+PS merging

Main idea

Catani, Krauss, Kuhn, Webber (2001); Höche, Krauss, Schumann, FS (2009)

Phase space slicing for QCD radiation in shower evolution

- Hard emissions $Q_{ij}(z,t) > Q_{\text{cut}}$
  - Events rejected
  - Compensated by events starting from higher-order ME regularised by Q_{cut}

  $\Rightarrow$ Splitting kernels replaced by exact real-emission matrix elements

$$\mathcal{D}_{ij}^{(\mathrm{PS})} \quad \rightarrow \quad \mathcal{R}_{ij}$$

(But Sudakov form factors $\Delta^{(\mathrm{PS})}$ remain unchanged)

- Soft/collinear emissions $Q_{ij,k}(z,t) < Q_{\text{cut}}$

  $\Rightarrow$ Retained from parton shower $\quad \mathcal{D}_{ij}^{(\mathrm{PS})} = \mathcal{B} \times \left[\frac{1}{2p_ip_j}\, 8\pi\alpha_s\, \mathcal{K}_{ij}(p_i,p_j)\right]$

$$\mathrm{d}\sigma^{(\text{ME+PS})} = \mathrm{d}\Phi_B\, \mathcal{B}\left[\underbrace{\Delta^{(\mathrm{PS})}(t_0,\mu_Q^2)}_{\text{unresolved}} + \sum_{\{ij\}}\int_{t_0}^{\mu_Q^2} \mathrm{d}t\, \Delta^{(\mathrm{PS})}(t,\mu^2)\right.$$
$$\left.\times\left(\underbrace{\frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}}\,\Theta(Q_{\text{cut}}-Q_{ij})}_{\text{resolved, PS domain}} + \underbrace{\frac{\mathcal{R}_{ij}}{\mathcal{B}}\,\Theta(Q_{ij}-Q_{\text{cut}})}_{\text{resolved, ME domain}}\right)\right]$$

Features and shortcomings

Example

Diphoton production at Tevatron

- Measured by CDF
  Phys.Rev.Lett. 110 (2013) 101801
- Isolated hard photons
- Azimuthal angle between the photons

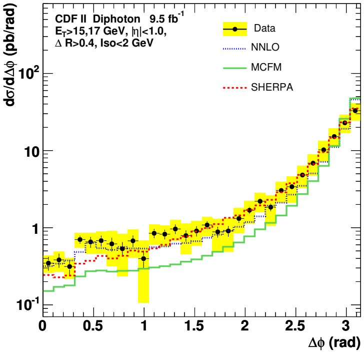
ME+PS simulation using SHERPA vs. (N)NLO

Conclusions

Shapes described very well even for this non-trivial process/observable for both:

- Hard region, e.g. $\Delta\Phi_{\gamma\gamma} \to 0$
- Soft region, e.g. $\Delta\Phi_{\gamma\gamma} \to \pi$

Scale variations high $\Rightarrow$ NLO needed



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Höche, Krauss, Schönherr, FS (2012)

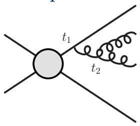
Concepts continued from NLO+PS and ME+PS@LO

- For each event select jet multiplicity k according to its inclusive NLO cross section
- Reconstruct branching history and nodal scales $t_0 \ldots t_k$
- Truncated vetoed parton shower, but with peculiarities (cf. below)

Differences for NLO merging

- For each event select type ($\mathbb{S}$ or $\mathbb{H}$) according to absolute XS
  $\Rightarrow$ Shower then runs differently
- $\mathbb{S}$ event:
  1. Generate MC@NLO emission at t_{k+1}
  2. Truncated "NLO-vetoed" shower between t_0 and t_k:
     First hard emission is only ignored, no event veto
  3. Continue with vetoed parton shower
- $\mathbb{H}$ event:
  (Truncated) vetoed parton shower as in tree-level ME+PS

Example: $k = 1$



For the sake of completeness...

ME+PS@NLO prediction for combining NLO+PS samples of multiplicities n and $n+1$

$$
\begin{aligned}
\mathrm{d}\sigma^{(\text{ME+PS@NLO})} = {} & \mathrm{d}\Phi_n\ \bar{\mathrm{B}}_n^{(\mathrm{A})}\left[\Delta_n^{(\mathrm{A})}(t_c,\mu_Q^2) + \int_{t_c}^{\mu_Q^2} \mathrm{d}\Phi_1\ \frac{\mathrm{D}_n^{(\mathrm{A})}}{\mathrm{B}_n}\ \Delta_n^{(\mathrm{A})}(t_{n+1},\mu_Q^2)\ \Theta(Q_{\text{cut}} - Q_{n+1})\right] \\
& + \mathrm{d}\Phi_{n+1}\ \mathrm{H}_n^{(\mathrm{A})}\ \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\ \Theta(Q_{\text{cut}} - Q_{n+1}) \\
& + \mathrm{d}\Phi_{n+1}\ \bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}\ \underbrace{\left(1 + \frac{\mathrm{B}_{n+1}}{\bar{\mathrm{B}}_{n+1}^{(\mathrm{A})}} \int_{t_{n+1}}^{\mu_Q^2} \mathrm{d}\Phi_1\ \mathrm{K}_n\right)}_{\text{MC counterterm} \,\to\, \text{NLO-vetoed shower}}\ \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\ \Theta(Q_{n+1} - Q_{\text{cut}}) \\
& \times\left[\Delta_{n+1}^{(\mathrm{A})}(t_c,t_{n+1}) + \int_{t_c}^{t_{n+1}} \mathrm{d}\Phi_1\ \frac{\mathrm{D}_{n+1}^{(\mathrm{A})}}{\mathrm{B}_{n+1}}\ \Delta_{n+1}^{(\mathrm{A})}(t_{n+2},t_{n+1})\right] \\
& + \mathrm{d}\Phi_{n+2}\ \mathrm{H}_{n+1}^{(\mathrm{A})}\ \Delta_{n+1}^{(\mathrm{PS})}(t_{n+2},t_{n+1})\ \Delta_n^{(\mathrm{PS})}(t_{n+1},\mu_Q^2)\ \Theta(Q_{n+1} - Q_{\text{cut}})\ + \ \ldots
\end{aligned}
$$

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Four-lepton + jets production

Precise predictions for $pp \to \ell\ell\nu\nu$ + jets

- As signal: SM measurements, vector-boson scattering, anomalous gauge couplings, …
- As background: Higgs production, BSM searches

Background to $H \to WW^* \to \ell^+\nu\ell^-\bar{\nu}$ + jets

Higgs analyses in exclusive $0, 1, 2$-jet bins ($\Rightarrow$ jet vetoes)

$\to$ Better control over backgrounds (WW^* vs. $t\bar{t}$)

$\to$ Disentangle production modes ($gg \to H$ vs. VBF)

Non-trivial theoretical issues

- Precise predictions for jet production $\Rightarrow$ beyond inclusive NLO QCD
- Exclusive jet bins $\Rightarrow$ Sudakov effects, resummation
- Offshell WW^* production $\Rightarrow$ non-resonant and interference effects
- Loop-induced processes like $gg \to WW^*$ sizeable in Higgs signal regions

Calculation with SHERPA+OPENLOOPS

Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, FS; arXiv: 1309.0500

Toolkit

- SHERPA including its automated dipole subtraction and merging a la MEPS@NLO
- OPENLOOPS automated 1-loop QCD matrix elements including the COLLIER tensor integral reduction Cascioli, Maierhöfer, Pozzorini; arXiv:1111.5206 Denner, Dittmaier, Hofer; in prep.

⇒ Full QCD NLO automation with SHERPA+OPENLOOPS
Already available within ATLAS and CMS

Phenomenological setup: $pp \to e^- \bar{\nu}_e \mu^+ \nu_\mu$ + jets

- Predictions for LHC $\sqrt{s} = 8$ TeV, using CT10 PDFs
- QCD NLO accuracy for $\ell\ell\nu\nu + 0, 1$ jets
- Squared quark-loop contributions merged for $+\,0, 1$ jets
- Full off-shell, interference and spin-correlation effects
- NLO+PS matching to the parton shower, MEPS@NLO merging into inclusive sample

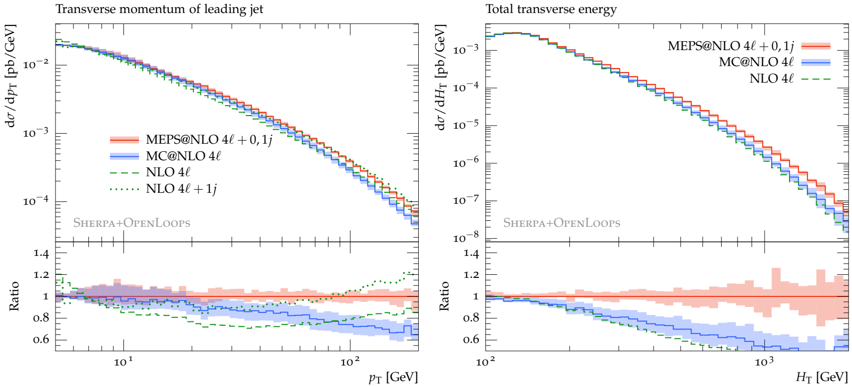
- Central scale choice: $\mu_0 = \frac{1}{2}(E_{T,W^+} + E_{T,W^-})$
- CKKW-like scale prescription in merged jet emissions: $\alpha_s(k_\perp)$
- Independent factor-2 variations of $\mu_{F,R}$ and factor-$\sqrt{2}$ of resummation scale μ_Q

Comparison of different simulation levels

NLO simulations	0-jet	1-jet	2-jet
NLO 4ℓ	NLO	LO	-
NLO $4\ell + 1j$	-	NLO	LO
MC@NLO 4ℓ	NLO+PS	LO+PS	PS
MC@NLO $4\ell + 1j$	-	NLO+PS	LO+PS
MEPS@NLO $4\ell + 0,1j$	NLO+PS	NLO+PS	LO+PS
LOOP^2 simulations	**0-jet**	**1-jet**	**2-jet**
LOOP^2 4ℓ	LO	-	-
LOOP^2 $4\ell + 1j$	-	LO	-
LOOP^2+PS 4ℓ	LO+PS	PS	PS
LOOP^2+PS $4\ell + 1j$	-	LO+PS	PS
MEPS@LOOP^2 $4\ell + 0,1j$	LO+PS	LO+PS	PS

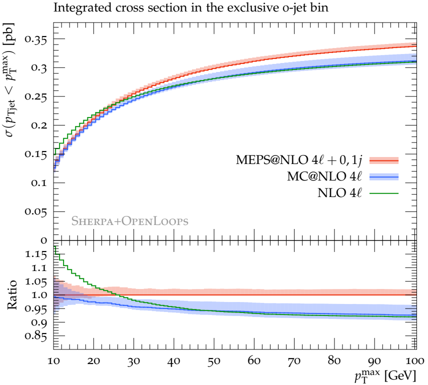
Basic WW^* analysis

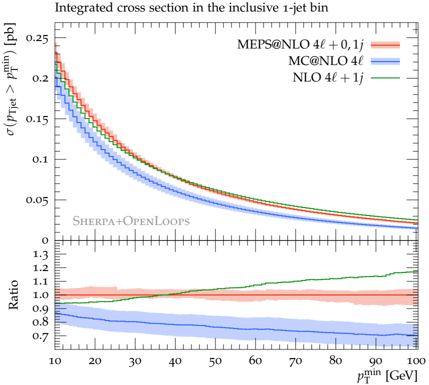
$p_{\perp,\ell} > 25$ GeV, $|\eta_\ell| < 3.5$, $\not{E}_T > 25$ GeV, anti-k_t jets with $R = 0.4$



- NLO 4ℓ and MC@NLO 4ℓ only LO accurate, underestimate hard $p_\perp$ tail
- Resummation necessary for $p_\perp \to 0$ (Sudakov logs)
  - NLO $4\ell \sim 20\%$ effects at $p_\perp = 5$ GeV
  - NLO $4\ell + 1j$ partially includes logs $\Rightarrow$ reduced effect
- Harder tails in fixed-order due to μ_R not dynamic with jet $p_\perp$
- H_T sensitive to combination of different jet multiplicities $\Rightarrow$ merging crucial

Basic WW^* analysis





Exclusive 0-jet bin

- Few-% agreement between MC@NLO and MEPS@NLO
- Moderate Sudakov effects in comparison of NLO 4ℓ and MC@NLO 4ℓ
- Low uncertainties → good control wrt higher orders/logs

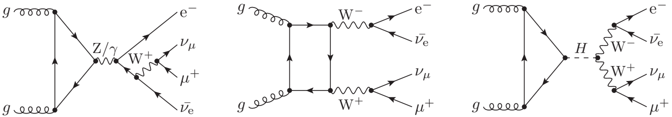
Inclusive 1-jet bin

- Sizable differences between MC@NLO and MEPS@NLO, similar to jet $p_\perp$
- NLO $4\ell + 1j$ excess in tail due to α_s scale differences again

Loop^2 contributions

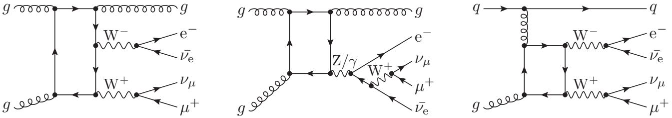
- Finite, gauge-invariant subset of NNLO contributions: squared quark loops like $gg \to 4\ell$
- Relevant at LHC due to gluonic initial states, particularly in Higgs signal regions

0-jet production: Examples for $gg \to 4\ell$ diagrams

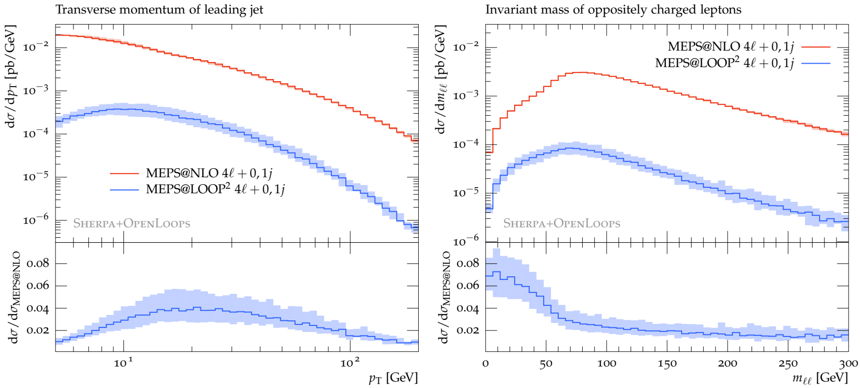


1-jet production

- For the first time we merge 0-jet and 1-jet squared-loop contributions
- Tree-level merging techniques since all MEs are finite
- Shower on top of $gg \to 4\ell \Rightarrow$ consistency requires MEs for qg, $\bar{q}g$ and $q\bar{q}$ initial states
- Example diagrams (requirement: vector bosons coupling to pure quark loop)



Impact of LOOP^2 contributions



- Inclusive contribution of a few %
- Shape distortions: more significant impact in Higgs signal region (e.g. low $m_{\ell\ell}$)

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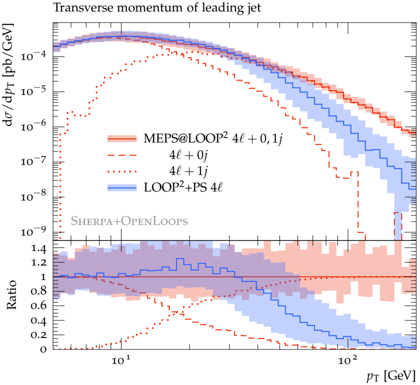
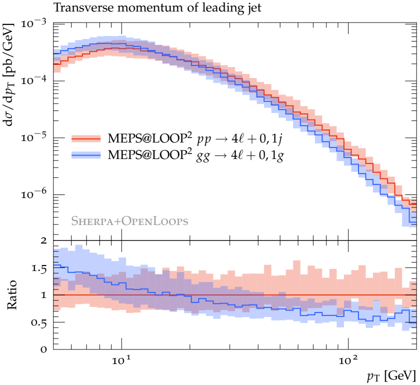
Features of LOOP^2 contributions





Merging effects

- Inclusion of LOOP^2 $4\ell + 1j$ in merging: harder $p_\perp$ spectrum
- Significant reduction of uncertainties (wrt resummation scale) in high-$p_\perp$ region

Non-gluonic initial states

- Inclusion of quark-channels $\longrightarrow$ harder tail
- Naturally, lower Sudakov suppression without quark splittings
- Shape distortion
  $\Rightarrow$ opposite effects in 0/1 jet bins

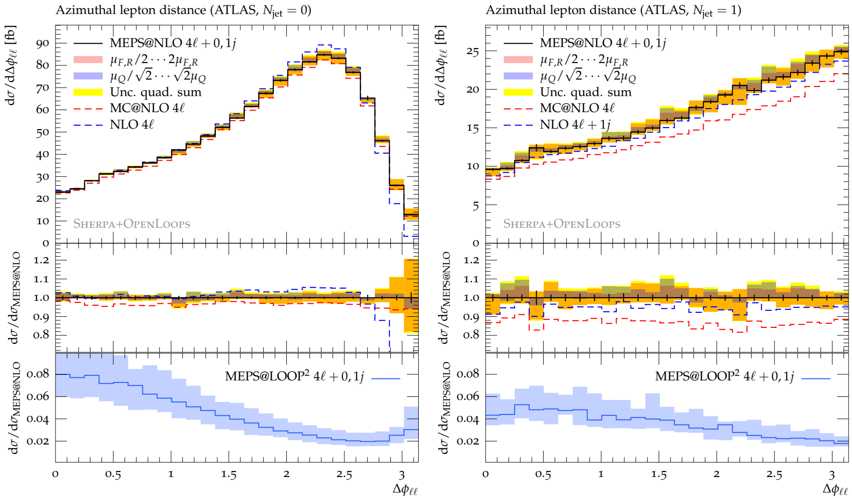
Rivet implementation of Higgs analyses

- 8 separate analyses: $\{$ATLAS,CMS$\} \times \{$0-jet, 1-jet$\} \times \{$signal region, control region$\}$
- Differential predictions in relevant observables: $p_\perp^j$, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_T

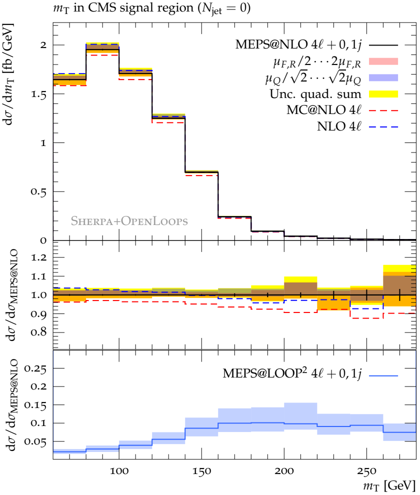
Findings

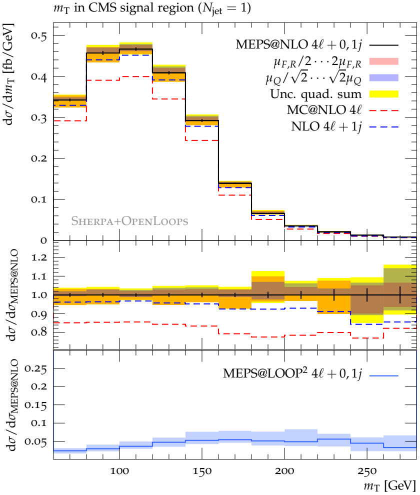
- Different simulation levels agree well in 0-jet bin (where they are NLO accurate)
- Fixed-order agrees with matched/merged predictions in most regions $\to$ Sudakov logs not dominant, except e.g. $\Delta\phi_{\ell\ell} \to \pi$
- Pure MC@NLO predictions underestimates rate in 1-jet bins
- Uncertainty bands for best prediction (MEPS@NLO) from $\mu_{R,F} \oplus \mu_Q$ variations at the few-% level

Example from ATLAS analysis



Example from CMS analysis





Signal/control cross sections in exclusive jet bins

- Relevant for background extrapolation from control to signal region in data-driven methods
- Example: ATLAS analysis

0-jet bin	NLO $4\ell\,(+1j)$	MC@NLO 4ℓ	MEPS@NLO $4\ell+0,1j$	MEPS@LOOP^2 $4\ell+0,1j$
σ_{S} [fb]	$34.28(9)\,^{+2.1\%}_{-1.6\%}$	$32.52(8)\,^{+2.1\%}_{-0.8\%}\,^{+1.2\%}_{-0.7\%}$	$33.81(12)\,^{+1.4\%}_{-2.2\%}\,^{+2.0\%}_{-0.4\%}$	$1.98(2)\,^{+23\%}_{-16.5\%}\,^{+27\%}_{-20\%}$
σ_{C} [fb]	$55.76(9)\,^{+2.0\%}_{-1.7\%}$	$52.28(9)\,^{+1.4\%}_{-0.7\%}\,^{+1.4\%}_{-1.1\%}$	$54.18(15)\,^{+1.4\%}_{-1.9\%}\,^{+2.5\%}_{-0.4\%}$	$2.41(2)\,^{+22\%}_{-17\%}\,^{+27\%}_{-18\%}$

1-jet bin	NLO $4\ell\,(+1j)$	MC@NLO 4ℓ	MEPS@NLO $4\ell+0,1j$	MEPS@LOOP^2 $4\ell+0,1j$
σ_{S} [fb]	$8.99(4)\,^{+4.9\%}_{-9.5\%}$	$8.02(4)\,^{+8.5\%}_{-6.4\%}\,^{+0\%}_{-3.1\%}$	$9.37(9)\,^{+2.6\%}_{-2.7\%}\,^{+2.5\%}_{-0.0\%}$	$0.46(1)\,^{+40\%}_{-18\%}\,^{+2.2\%}_{-6.3\%}$
σ_{C} [fb]	$26.50(8)\,^{+6.4\%}_{-12.5\%}$	$24.58(8)\,^{+6.1\%}_{-6.5\%}\,^{+1.2\%}_{-3.0\%}$	$28.32(13)\,^{+3.1\%}_{-4.7\%}\,^{+4.1\%}_{-0.0\%}$	$0.79(1)\,^{+33\%}_{-20\%}\,^{+15\%}_{-7\%}$

- Merged sample reproduces individual NLO cross sections well
- Combined uncertainty on MEPS@NLO best prediction around $3(5)\%$ in 0(1)-jet bin
- LOOP^2 effects larger in **S**ignal than in **C**ontrol region

Conclusions

Summary

- Brief introduction to Monte-Carlo event generators and parton showers
- MEPS@NLO merging as state-of-the-art event simulation method at the hadron level
- Application of MEPS@NLO to $\ell\ell\nu\nu + 0, 1$ jets production
- Inclusion of loop-induced contributions in both multiplicities by MEPS@LOOP^2
- Analysis of predictions and uncertainties as Higgs background

Outlook

- Methods have already been applied to other processes (W/Z+jets, $t\bar{t}$+jets, $t\bar{t}b\bar{b}$), more phenomenology studies being worked on

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Anzeige

- SHERPA 2.0.0 released three weeks ago
- For experimentalists: Includes all features presented here and is available to the LHC experiments together with OPENLOOPS
- For theorists: Interface only your virtual ME, rest comes for free! (tree-level MEs, subtraction, matching, merging, spin-correlated decays)

Algorithmic PS implementation

Radioactive decay

- Constant differential decay probability
  $$f(t) \equiv \lambda = \text{const}$$
- Survival probability $\mathcal{N}(t)$
  $$-\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}t} = \lambda\,\mathcal{N}(t)$$
  $$\Rightarrow \mathcal{N}(t) \sim \exp(-\lambda t)$$
- Resummed decay probability $\mathcal{P}(t)$
  $$\mathcal{P}(t) = f(t)\,\mathcal{N}(t) \sim \lambda\exp(-\lambda t)$$

Parton shower branching

- Differential branching probability
  $$f(t) \equiv \mathcal{D}_{ij}^{(\mathrm{PS})}$$
- Survival probability $\mathcal{N}(t)$
  $$-\frac{\mathrm{d}\mathcal{N}}{\mathrm{d}t} = f(t)\,\mathcal{N}(t)$$
  $$\Rightarrow \mathcal{N}(t) \sim \exp\left(-\int_0^t f(t')\mathrm{d}t'\right)$$
- Resummed branching probability $\mathcal{P}(t)$
  $$\mathcal{P}(t) = f(t)\,\mathcal{N}(t) \sim f(t)\exp\left(-\int_0^t f(t')\mathrm{d}t'\right)$$

Parton shower algorithm

- Recursively generates next emission scale t (after t_{previous}) with probability
  $$\mathcal{P}(t, t_{\text{previous}}) = f(t)\exp\left(-\int_{t_{\text{previous}}}^t f(t')\mathrm{d}t'\right)$$
- Analytically: $t = F^{-1}\left[F(t_{\text{previous}}) + \log(\#_{\text{random}})\right]$ with $F(t) = \int_{t_0}^t \mathrm{d}t'\,f(t')$
- If integral/its inverse are not known: "Veto algorithm" = extension of hit-or-miss
  - Overestimate $g(t) \geq f(t)$ with known integral $G(t)$
    $\rightarrow t = G^{-1}\left[G(t_{\text{previous}}) + \log(\#_{\text{random}})\right]$
  - Accept t with probability $\frac{f(t)}{g(t)}$ using hit-or-miss

Original POWHEG

- Choose additional subtraction terms as

$$\mathcal{D}_{ij}^{(\mathrm{A})} \to \rho_{ij}\,\mathcal{R} \qquad \text{where} \qquad \rho_{ij} = \frac{\mathcal{D}_{ij}^{(\mathrm{S})}}{\sum_{mn}\mathcal{D}_{mn}^{(\mathrm{S})}}$$

- $\mathcal{H}$-term vanishes $\Rightarrow$ No negative weighted events
- Similar to PS with ME-correction for 1st emission (e.g. Herwig, Pythia)

Mixed scheme

- Subtract arbitrary regular piece from $\mathcal{R}$ and generate separately as $\mathbb{H}$-events

$$\mathcal{D}_{ij}^{(\mathrm{A})}(\Phi_R) \to \rho_{ij}(\Phi_R)\,\left[\mathcal{R}(\Phi_R) - \mathcal{R}^r(\Phi_R)\right] \qquad \text{where} \qquad \rho_{ij}\ \text{as above}$$

- Tuning of $\mathcal{R}^r$ to reduce exponentiation of arbitrary terms
- Allows to generate the non-singular cases of $\mathcal{R}$ without underlying $\mathcal{B}$