NLO+PS matching for non-trivial processes

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Motivation for NLO+PS matching

Two approaches to higher-order corrections

Fixed order ME calculation

+ Exact to fixed order
+ Includes all interferences
+ $N_C = 3$ (summed or sampled)
+ Includes virtual contributions
– Perturbation breaks down in logarithmically enhanced regions

Parton Shower

+ Resums logarithmically enhanced contributions to all orders
+ High-multiplicity final state
+ Allows for exclusive hadron-level events
– Only approximation for emission ME
– Large N_C limit

$\Downarrow$

Goal: Combine advantages

- Include virtual contributions and first hard emission from **NLO ME**
- Add further parton evolution with the **PS**

Resummation in parton-showers

Factorisation of collinear QCD emissions

Universal factorisation of QCD real emission ME in collinear limit:

$$\mathcal{R} \overset{ij \text{ collinear}}{\longrightarrow} \mathcal{D}_{ij}^{(\text{PS})} = \mathcal{B} \times \left(\frac{1}{2p_ip_j} \, 8\pi\alpha_s \, \mathcal{K}_{ij}(p_i, p_j) \right)$$

- $\frac{1}{2p_ip_j}$ from massless propagator
  Evolution variable of shower $t \sim 2p_ip_j$ (e.g. $k_\perp$, angle, $\ldots$)
- $\mathcal{K}_{ij}$ splitting kernel for branching $\widetilde{ij} \to i + j$
  Specific form depends on scheme of the factorisation, e.g.:
  - Altarelli-Parisi splitting functions
  - Dipole terms from Catani-Seymour subtraction (in $N_C \to \infty$)
  - Antenna functions

Radiative phase space factorisation:

$$\mathrm{d}\Phi_R \to \mathrm{d}\Phi_B \, \mathrm{d}\Phi_{R|B}^{ij} \overset{\text{e.g.}}{=} \mathrm{d}\Phi_B \, \frac{1}{16\pi^2} \, \mathrm{d}t \, \mathrm{d}z \frac{\mathrm{d}\phi}{2\pi}$$

Resummation in parton-showers

Differential branching probability

$$\mathrm{d}\sigma^{\widetilde{ij}}_{\texttt{branch}} = \sum_{f_i=q,g} \mathrm{d}\Phi^{ij}_{R|B} \frac{\mathcal{D}^{(\mathrm{PS})}_{ij}}{\mathcal{B}}$$

(Symmetry factors/PDFs ignored)

Differential probability for single branching of subterm ij in interval $\mathrm{d}\Phi^{ij}_{R|B}$

Total "survival" probability of parton ensemble

- Integrate single branching probability down to scale t in terms of $t(\Phi^{ij}_{R|B})$
- Assume multiple independent emissions (Poisson statistics) ⇒ Exponentiation

subterm:
$$\Delta^{(\mathrm{PS})}_{\widetilde{ij}}(t) = 1 - \int \mathrm{d}\sigma^{\widetilde{ij}}_{\texttt{branch}}\, \Theta\left(t(\Phi^{ij}_{R|B}) - t\right) + \ldots$$
$$= \exp\left\{ - \sum_{f_i=q,g} \int \mathrm{d}\Phi^{ij}_{R|B}\, \Theta\left(t(\Phi^{ij}_{R|B}) - t\right) \frac{\mathcal{D}^{(\mathrm{PS})}_{ij}}{\mathcal{B}} \right\}$$

event:
$$\Delta^{(\mathrm{PS})}(t) = \prod_{\widetilde{ij}} \Delta^{(\mathrm{PS})}_{\widetilde{ij}}(t)$$

Resummation in parton-showers

Cross section up to first emission in a parton shower

$$\langle O\rangle^{(\mathrm{PS})} = \int \mathrm{d}\Phi_B\, \mathcal{B}\Bigg[\underbrace{\Delta(t_0)\,O(\Phi_B)}_{\text{unresolved}} + \underbrace{\sum_{\widetilde{ij}}\sum_{f_i}\int_{t_0}^{\mu_F^2} \mathrm{d}\Phi_{R|B}^{ij}\,\frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}}\,\Delta(t)\,O\left(r_{\widetilde{ij}}(\Phi_B)\right)}_{\text{resolved}}\Bigg]$$

Generating events for $\langle O\rangle^{(\mathrm{PS})}$

- Generate Born ME event $\mathcal{B}$ at μ_F^2
- Generate t according to survival probability $\Delta(t)/\Delta(\mu_F^2)$
- Stop if $t < t_0$
- Generate remaining kinematics of the branching (z, φ) according to $\mathcal{D}_{ij}^{(\mathrm{PS})}/\mathcal{B}$

Features of $\langle O\rangle^{(\mathrm{PS})}$

- Unitarity: $[\ldots]|_{O=1} = 1$
  $\Rightarrow$ LO cross section preserved
- "Unresolved" part:
  No emissions above cutoff t_0
- "Resolved" part:
  Emission between t_0 and μ_F^2 in PS approximation

Fixed order NLO calculations

Reminder + Notation: Subtraction method

- Contributions to NLO cross section: $\mathcal{B}$orn, $\mathcal{V}$irtual and $\mathcal{R}$eal emission
- $\mathcal{V}$ and $\mathcal{R}$ divergent in separate phase space integrations
  $\Rightarrow$ Subtraction method for expectation value of observable O at NLO:

$$\langle O\rangle^{(\mathrm{NLO})} = \sum_{\vec{f}_\mathrm{B}} \int \mathrm{d}\Phi_B \left[\mathcal{B}(\Phi_B) + \tilde{\mathcal{V}}(\Phi_B) + \sum_{\widetilde{ij}} \mathcal{I}^{(\mathrm{S})}_{\widetilde{ij}}(\Phi_B)\right] O(\Phi_B)$$
$$+ \sum_{\vec{f}_\mathrm{R}} \int \mathrm{d}\Phi_R \left[\mathcal{R}(\Phi_R)\, O(\Phi_R) - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{S})}_{ij}(\Phi_R)\, O(b_{ij}(\Phi_R))\right]$$

- Subtraction terms $\mathcal{D}$ and their integrated form $\mathcal{I}$
  e.g. Frixione, Kunszt, Signer (1995); Catani, Seymour (1996)
- Subtraction defines phase space mappings $\Phi_R \underset{r_{\widetilde{ij}}}{\overset{b_{ij}}{\rightleftharpoons}} \left(\Phi_B, \Phi^{ij}_{R|B}\right)$

From fixed order to resummation

Problem

- Applying PS resummation to LO event is simple ✓
- Can the same simply be done separately for $\mathcal{B}$ and $\mathcal{V}+\mathcal{I}$ and $\mathcal{R}-\mathcal{D}$ at NLO?

$$\langle O\rangle^{(\mathrm{NLO})} = \sum_{\vec{f}_\mathrm{B}}\int \mathrm{d}\Phi_B \left[\mathcal{B}(\Phi_B)+\tilde{\mathcal{V}}(\Phi_B)+\sum_{\widetilde{\imath\jmath}}\mathcal{I}^{(\mathrm{S})}_{\widetilde{\imath\jmath}}(\Phi_B)\right] O(\Phi_B)$$

$$+\sum_{\vec{f}_\mathrm{R}}\int \mathrm{d}\Phi_R \left[\mathcal{R}(\Phi_R)\,O(\Phi_R)-\sum_{\{ij\}}\mathcal{D}^{(\mathrm{S})}_{ij}(\Phi_R)\,O(b_{ij}(\Phi_R))\right]$$

- Different observable dependence in $\mathcal{R}$ and $\mathcal{D}$ but if showered separately ⇒ "double counting" ✗

Solution: Let's in the following ...

Frixione, Webber (2002)

- rewrite $\langle O\rangle^{(\mathrm{NLO})}$ a bit
- add PS resummation into the game leading to $\langle O\rangle^{(\mathrm{NLO+PS})}$ and claim that:
  - $\langle O\rangle^{(\mathrm{NLO+PS})} = \langle O\rangle^{(\mathrm{NLO})}$ to $\mathcal{O}(\alpha_s)$
  - $\langle O\rangle^{(\mathrm{NLO+PS})}$ contains the first step of a PS evolution which can then be continued trivially with a regular PS
- sketch how $\langle O\rangle^{(\mathrm{NLO+PS})}$ is being generated in MC@NLO formalism

From fixed order to resummation

First rewrite: Additional set of subtraction terms $\mathcal{D}^{(\mathrm{A})}$

$$\langle O\rangle^{(\mathrm{NLO})} = \sum_{\vec{f}_B}\int \mathrm{d}\Phi_B\, \bar{\mathcal{B}}^{(\mathrm{A})}(\Phi_B)\, O(\Phi_B) + \sum_{\vec{f}_R}\int \mathrm{d}\Phi_R \left[\mathcal{R}(\Phi_R)\, O(\Phi_R) - \sum_{\{ij\}} \mathcal{D}^{(\mathrm{A})}_{ij}(\Phi_R)\, O\left(b_{ij}(\Phi_R)\right)\right]$$

with $\bar{\mathcal{B}}^{(\mathrm{A})}(\Phi_B)$ defined as:

$$\bar{\mathcal{B}}^{(\mathrm{A})}(\Phi_B) = \mathcal{B}(\Phi_B) + \tilde{\mathcal{V}}(\Phi_B) + \sum_{\{\widetilde{ij}\}} \mathcal{I}^{(\mathrm{S})}_{\widetilde{ij}}(\Phi_B) + \sum_{\{\widetilde{ij}\}}\sum_{f_i=q,g}\int \mathrm{d}\Phi^{ij}_{R|B}\left[\mathcal{D}^{(\mathrm{A})}_{ij}(r_{\widetilde{ij}}(\Phi_B)) - \mathcal{D}^{(\mathrm{S})}_{ij}(r_{\widetilde{ij}}(\Phi_B))\right]$$

- $\mathcal{D}^{(\mathrm{A})}_{ij}$ must have same kinematics mapping as $\mathcal{D}^{(\mathrm{S})}_{ij}$
- Exact choice of $\mathcal{D}^{(\mathrm{A})}_{ij}$ will specify e.g. MC@NLO vs. POWHEG
- Issue with different observable kinematics not yet solved → next step

From fixed order to resummation

Second rewrite: Make observable correction term explicit

$$
\begin{aligned}
\langle O\rangle^{(\mathrm{NLO})} =& \sum_{\vec{f}_B} \int \mathrm{d}\Phi_B\, \bar{\mathcal{B}}^{(\mathrm{A})}(\Phi_B)\, O(\Phi_B) \\
&+ \sum_{\vec{f}_R} \int \mathrm{d}\Phi_R \left[\mathcal{R}(\Phi_R) - \sum_{\{ij\}} \mathcal{D}_{ij}^{(\mathrm{A})}(\Phi_R)\right] O(\Phi_R) \\
&+ \langle O\rangle^{(\mathrm{corr})}
\end{aligned}
$$

with $\langle O\rangle^{(\mathrm{corr})}$ defined as:

$$
\langle O\rangle^{(\mathrm{corr})} = \sum_{\vec{f}_R} \int \mathrm{d}\Phi_R \sum_{\{ij\}} \mathcal{D}_{ij}^{(\mathrm{A})}(\Phi_R) \left[O(\Phi_R) - O(b_{ij}(\Phi_R))\right]
$$

- Explicit correction term due to observable kinematics: $\langle O\rangle^{(\mathrm{corr})}$
- Essence of NLO+PS
  - Ignore $\langle O\rangle^{(\mathrm{corr})}$ for the time being
  - Apply PS resummation to first line using $\Delta^{(\mathrm{A})}$ in which $\mathcal{D}^{(\mathrm{PS})} \to \mathcal{D}^{(\mathrm{A})}$

From fixed order to resummation

Master formula for NLO+PS up to first emission

$$\langle O\rangle^{(\mathrm{NLO+PS})} = \sum_{\vec{f}_B}\int \mathrm{d}\Phi_B\,\bar{\mathcal{B}}^{(\mathrm{A})}(\Phi_B)\Bigg[\underbrace{\Delta^{(\mathrm{A})}(t_0)}_{\text{unresolved}}\;O(\Phi_B)$$

$$+\sum_{\{\widetilde{ij}\}}\sum_{f_i}\int_{t_0}\mathrm{d}\Phi^{ij}_{R|B}\,\underbrace{\frac{\mathcal{D}^{(\mathrm{A})}_{ij}(r_{\widetilde{ij}}(\Phi_B))}{\mathcal{B}(\Phi_B)}\,\Delta^{(\mathrm{A})}(t)}_{\text{resolved, singular}}\;O(r_{\widetilde{ij}}(\Phi_B))\Bigg]$$

$$+\sum_{\vec{f}_R}\int \mathrm{d}\Phi_R\,\underbrace{\Bigg[\mathcal{R}(\Phi_R)-\sum_{ij}\mathcal{D}^{(\mathrm{A})}_{ij}(\Phi_R)\Bigg]}_{\text{resolved, non-singular}\,\equiv\,\mathcal{H}^{(\mathrm{A})}}\;O(\Phi_R)$$

- This is generated in the following way:
  - Generate seed event according to first or second line of $\langle O\rangle^{(\mathrm{NLO})}$ on last slide
  - Second line: $\mathbb{H}$-event with Φ_R is kept as-is $\to$ resolved, non-singular term
  - First line: $\mathbb{S}$-event with Φ_B is processed through one-step PS with $\Delta^{(\mathrm{A})}$ $\Rightarrow$ emission (resolved, singular) or no emission (unresolved) above t_0
- To $\mathcal{O}(\alpha_s)$ this reproduces $\langle O\rangle^{(\mathrm{NLO})}$ including the correction term
- Resolved cases: Subsequent emissions can be generated by ordinary PS

Special case: POWHEG

Original POWHEG

- Choose additional subtraction terms as

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

- $\mathbb{H}$-term vanishes
- $\bar{\mathcal{B}}^{(\mathrm{A})}$ remains complicated now, includes real-emission integration (may be done by Monte-Carlo method)
- 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

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

- Allows to generate the non-singular cases of $\mathcal{R}$ without underlying $\mathcal{B}$
- More control over how much is exponentiated

Special case: MC@NLO

To prove NLO accuracy:
$\mathcal{D}^{(\mathrm{A})}$ needs to be identical in shower algorithm and real-emission events

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

Frixione, Webber (2002)

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

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

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

Höche, Krauss, Schönherr, FS (2011)

- \+ "Non-singular" piece fully free of divergences
- \+ $\bar{\mathcal{B}}^{(\mathrm{A})}$ function simplifies
- – Splitting kernels in shower algorithm become negative

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

⇓
Used in the following

Results for $W + n$-jet production at the LHC (arXiv:1201.5882)

Event generation setup

- SHERPA's MC@NLO for $W + 0$, $W + 1$, $W + 2$ and $W + 3$-jet production
- Virtual corrections from BLACKHAT, leading-colour approximation for the $W + 3$-jet virtual
- For $n > 0$ regularise requiring k_T jets with $p_\perp > 10$ GeV
- Exponentiation region restricted using $\alpha = 0.01$-cut in dipole terms (cf. later)
- CTEQ6.6 NLO PDF
- $\mu_R = \mu_F = 1/2\, \hat{H}'_T$, where $\hat{H}'_T = \sqrt{\sum p^2_{T,j} + E^2_{T,W}}$.
- Three levels of event simulation:

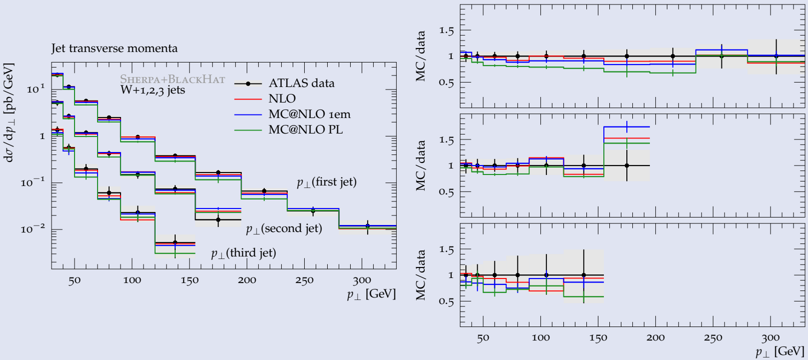
"NLO"	Fixed-order
"MC@NLO 1em"	MC@NLO including hardest emission
"MC@NLO PL"	MC@NLO including full PS

Analysis setup

- Comparing to ATLAS W+jets measurement arXiv:1201.1276
- Using implementation in Rivet arXiv:1003.0694
- Lepton with $p_\perp > 20$ GeV, $|\eta| < 2.5$
- $E_T^{\text{miss}} > 25$ GeV
- $m_{\text{T}}^{\text{W}} > 40$ GeV
- Anti-k_t jets with $R = 0.4$ and $p_\perp > 30$ GeV

Results for $W + n$-jet production at the LHC (arXiv:1201.5882)

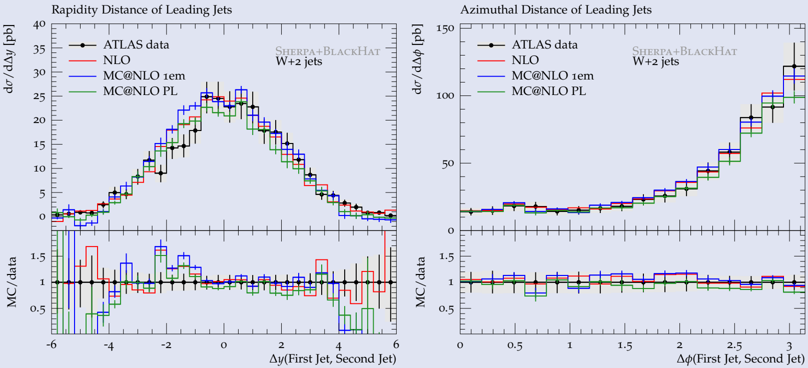
Transverse momenta of jets



Transverse momentum of the first, second and third jet (from top to bottom) in $W^\pm + \geq 1, 2, 3$ jet production as measured by ATLAS compared to predictions from the corresponding fixed order and MC@NLO simulations.

Results for $W + n$-jet production at the LHC (arXiv:1201.5882)

Angular correlations of leading jets



Angular correlations of the two leading jets in $W^{\pm} + \geq 2$ jet production as measured by ATLAS compared to predictions from the $W^{\pm} + 2$ jet fixed order and MC@NLO simulations.

NLO+PS uncertainties

Höche, Krauss, Schönherr, FS (2011)

Perturbative uncertainties

- Unknown higher-order corrections
- Can be estimated by scale variations, e.g. $\mu_F = \mu_R = \frac{1}{2}\mu \ldots 2\mu$

Non-perturbative uncertainties

- Model uncertainties in hadronisation, hadron decays, multiple parton interactions
- Can be estimated by variation of parameters/models within tuned ranges

Exponentiation uncertainties

- Arbitrariness of $\mathcal{D}^{(\mathrm{A})}$ and thus of the exponent in $\Delta^{(\mathrm{A})}$
- Estimated here using SHERPA by:
  - Comparing MC@NLO and POWHEG prescription
  - Using MC@NLO with variable cut-off in dipole terms $\mathcal{D}^{(\mathrm{S})}$

Exponentiation uncertainties

Recall NLO+PS expression and its resummation evolution:

$$\langle O\rangle = \int \mathrm{d}\Phi_B\, \bar{\mathcal{B}}^{(\mathrm{A})} \left[\underbrace{\Delta^{(\mathrm{A})}(t_0)}_{\text{unresolved}} O(\Phi_B) + \sum_{\{\widetilde{ij}\}} \int_{t_0} \mathrm{d}\Phi^{ij}_{R|B}\, \underbrace{\frac{\mathcal{D}^{(\mathrm{A})}_{ij}}{\mathcal{B}} \Delta^{(\mathrm{A})}(t)}_{\text{resolved, singular}} O(r_{\widetilde{ij}}(\Phi_B)) \right]$$

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

- Upper limit of this integration $\hat{=}$ Starting scale in traditional parton shower
- Determines how much emission phase space is exponentiated

How to implement and vary this consistently in NLO+PS?

Cuts in dipole terms

Basic idea: Implement upper cut-off in resummation kernels $\mathcal{D}_{ij}^{(\mathrm{A})}$

Dipole α cut

+ Integrated dipole terms with α cut are known Nagy (2003)
  $\Rightarrow$ Can apply cut universally in $\mathcal{D}^{(\mathrm{A})} = \mathcal{D}^{(\mathrm{S})}$
– α different from PS evolution variable k_T
  $\Rightarrow$ Functional form of resummation scale not ideal

Höche, Krauss, Schönherr, FS (2011)

k_T cut-off

+ Consistently restricts resummation region in the PS evolution variable k_T
– Integrated dipole terms not known with cut
  $\Rightarrow$ $\mathcal{D}^{(\mathrm{S})}$ has to remain unchanged
  $\Rightarrow$ $\mathcal{D}^{(\mathrm{A})} \neq \mathcal{D}^{(\mathrm{S})}$
  $\Rightarrow$ Integral in $\bar{\mathcal{B}}^{(\mathrm{A})}$ has to be re-instated

Höche, Schönherr (in prep.)

In both cases: Variation gives handle on resummation uncertainty in NLO+PS

Exponentiation uncertainties in the example of $gg \to h$

Example setup

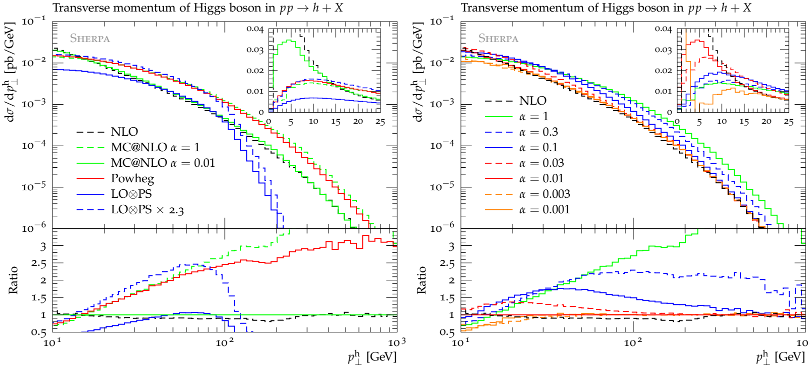
- $gg \to h \to \tau\tau$ at LHC with $\sqrt{s} = 7$ TeV and $m_h = 120$ GeV, $\mu = m_h$
- Analysed with $p_\perp^\tau > 25$ GeV and $|n^\tau| < 3.5$
- Jets defined using inclusive $k_\perp$ with $R = 0.7$ and $p_\perp > 20$ GeV

Studies at parton shower level

1. Validate NLO+PS against fixed NLO predictions
2. Comparison with LO parton shower (LO+PS)
3. MC@NLO vs. POWHEG
4. MC@NLO with $0.001 \leq \alpha_{\text{cut}} \leq 1$ variation

$\Rightarrow$ Very busy plots
(SORRY!)

Exponentiation uncertainties in the example of $gg \to h$



- With large α variation: Huge NLO+PS uncertainties especially at large $p_\perp^h$
- POWHEG and unrestricted MC@NLO similar
- Decreasing exponentiation of non-singular pieces with $\alpha_{\text{cut}} \lesssim 0.01$ recovers NLO behaviour
- Resummation region $p_\perp^h \to 0$ strongly affected by α_{cut} variation: side effect of imperfect functional form of α (vs. parton shower $t \sim k_\perp^2$)

MENLOPS: Merging NLO+PS with higher-order tree-level MEs

$\langle O\rangle$ up to first emission in MENLOPS

$$\langle O\rangle = \int \mathrm{d}\Phi_n\, \bar{\mathcal{B}}_n^{(\mathrm{A})}\left[\Delta_n^{(\mathrm{A})}(t_0)\, O(\Phi_n) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathcal{D}_n^{(\mathrm{A})}(\Phi_n,\Phi_1)}{\mathcal{B}_n(\Phi_n)}\, \Delta_n^{(\mathrm{A})}(t)\, \Theta(Q_\mathrm{cut}-Q)\, O(\Phi_{n+1})\right]$$

$$+ \int \mathrm{d}\Phi_{n+1}\, \mathcal{H}_n^{(\mathrm{A})}(\Phi_{n+1})\, \Theta(Q_\mathrm{cut}-Q)\, O(\Phi_{n+1})$$

$$+ \int \mathrm{d}\Phi_{n+1}\, k_n^{(\mathrm{A})}(\Phi_{n+1})\, \mathcal{B}_{n+1}(\Phi_{n+1})\, \Delta_n^{(\mathrm{PS})}(t)\, \Theta(Q-Q_\mathrm{cut})\, O(\Phi_{n+1})$$

- Introduce parton separation criterion Q for $n+1$ partons
  - $Q < Q_\mathrm{cut} \Rightarrow$ Treat as n parton process (here: MC@NLO)
  - $Q > Q_\mathrm{cut} \Rightarrow$ Treat as $n+1$ parton process (here: Tree-level ME)
- Sudakov from (truncated) shower to preserve logarithmic accuracy of the shower
- Local "K-factor" k_n for smooth $\frac{\bar{\mathcal{B}}}{\mathcal{B}}$ matching

Höche, Krauss, Schönherr, FS (2010)

MEPS@NLO: Sneak preview

$\langle O \rangle$ for merging n with $n+1$ partons in MEPS@NLO

$$
\begin{aligned}
\langle O \rangle \;=\; & \int \mathrm{d}\Phi_n\, \bar{\mathcal{B}}_n^{(\mathrm{A})} \left[\Delta_n^{(\mathrm{A})}(t_0)\, O(\Phi_n) + \int_{t_0}^{\mu_Q^2} \mathrm{d}\Phi_1\, \frac{\mathcal{D}_n^{(\mathrm{A})}(\Phi_n, \Phi_1)}{\mathcal{B}_n(\Phi_n)}\, \Delta_n^{(\mathrm{A})}(t)\, \Theta(Q_{\mathrm{cut}} - Q)\, O(\Phi_{n+1}) \right] \\
& + \int \mathrm{d}\Phi_{n+1}\, \mathcal{H}_n^{(\mathrm{A})}(\Phi_{n+1})\, \Theta(Q_{\mathrm{cut}} - Q)\; O(\Phi_{n+1}) \\
& + \int \mathrm{d}\Phi_{n+1}\, \bar{\mathcal{B}}_{n+1}^{(\mathrm{A})} \left[1 + \frac{\mathcal{B}_{n+1}}{\bar{\mathcal{B}}_{n+1}^{(\mathrm{A})}} \left(\int_{t}^{\mu_Q^2} \mathrm{d}\Phi_1\, \mathcal{K}_n(\Phi_1) \right) \right] \Delta_n^{(\mathrm{PS})}(t)\, \Theta(Q - Q_{\mathrm{cut}})\; O(\Phi_{n+1}) \\
& + \int \mathrm{d}\Phi_{n+2}\, \mathcal{H}_{n+1}^{(\mathrm{A})}(\Phi_{n+2})\, \Delta_n^{(\mathrm{PS})}(t)\, \Theta(Q - Q_{\mathrm{cut}})\; O(\Phi_{n+2})
\end{aligned}
$$

- Difference to MENLOPS:
  Tree-level ME with local K-factor replaced by exact $n+1$ NLO result
- [. . .] on line 3: Correct parts otherwise generated by the parton shower

Höche, Krauss, Schönherr, FS (in preparation)

Sneak preview: MEPS@NLO for $e^+e^- \to$ hadrons with SHERPA

Höche, Krauss, Schönherr, FS (in preparation)

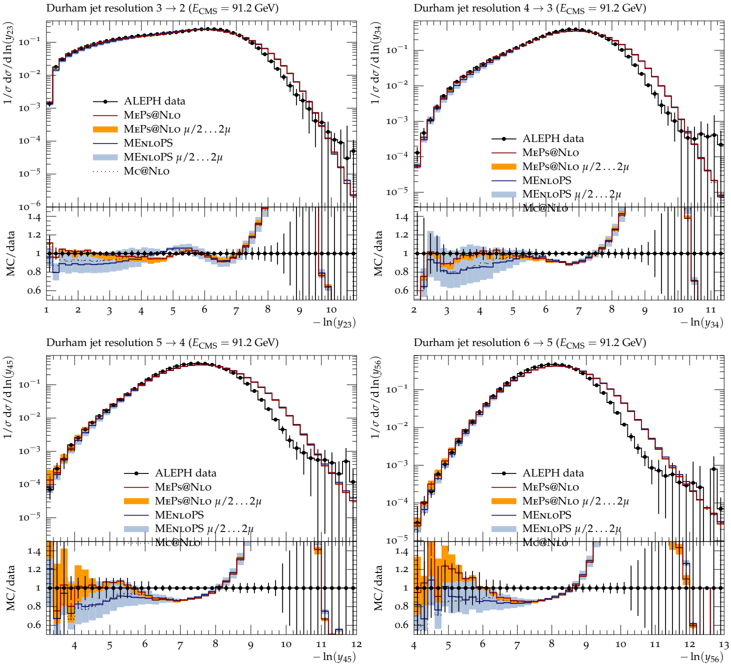
Event generation setup

- $e^+e^- \to$ hadrons at the Z pole
- SHERPA with built-in automatic MC@NLO
- Virtual matrix elements from BlackHat library, analyses from Rivet library

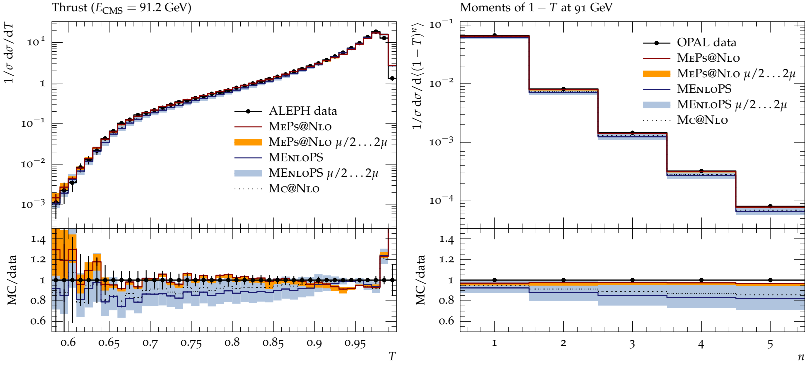
Comparison of approaches

- MC@NLO: One inclusive sample with
  - NLO accuracy for $e^+e^- \to 2$ partons
  - ($\Rightarrow$ LO accuracy for $e^+e^- \to 3$ partons)
- MENLOPS: One inclusive sample with
  - NLO accuracy for $e^+e^- \to 2$ partons
  - LO accuracy for $e^+e^- \to 3, 4, 5, 6$ partons
- MEPS@NLO: One inclusive sample with
  - NLO accuracy for $e^+e^- \to 2, 3, 4$ partons
  - LO accuracy for $e^+e^- \to 5, 6$ partons

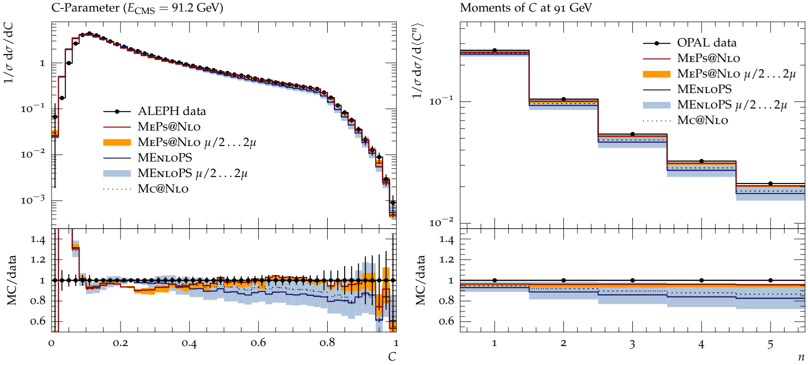
+ Subsequent parton showering and hadronisation in all cases


Durham jet resolution 3 → 2 (E_{CMS} = 91.2 GeV)
Durham jet resolution 4 → 3 (E_{CMS} = 91.2 GeV)
Durham jet resolution 5 → 4 (E_{CMS} = 91.2 GeV)
Durham jet resolution 6 → 5 (E_{CMS} = 91.2 GeV)
ALEPH data
MEPs@NLO
MEPs@NLO $\mu/2 \ldots 2\mu$
MENLOPS
MENLOPS $\mu/2 \ldots 2\mu$
MC@NLO
$1/\sigma\, d\sigma/d\ln(y_{23})$
$1/\sigma\, d\sigma/d\ln(y_{34})$
$1/\sigma\, d\sigma/d\ln(y_{45})$
$1/\sigma\, d\sigma/d\ln(y_{56})$
MC/data
$-\ln(y_{23})$
$-\ln(y_{34})$
$-\ln(y_{45})$
$-\ln(y_{56})$

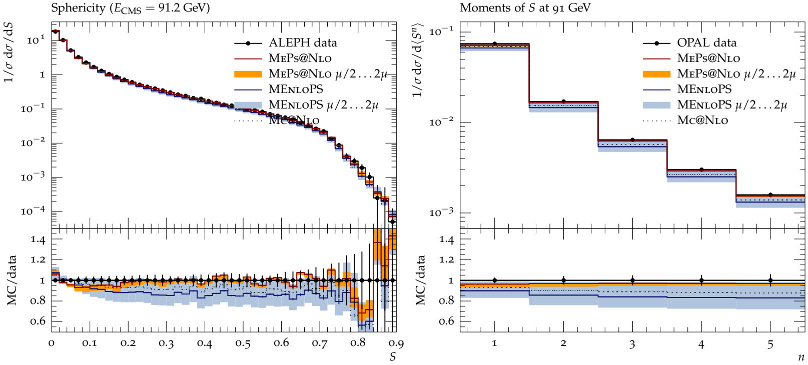
Thrust (ALEPH, 2004) and its moments (OPAL, 2004)

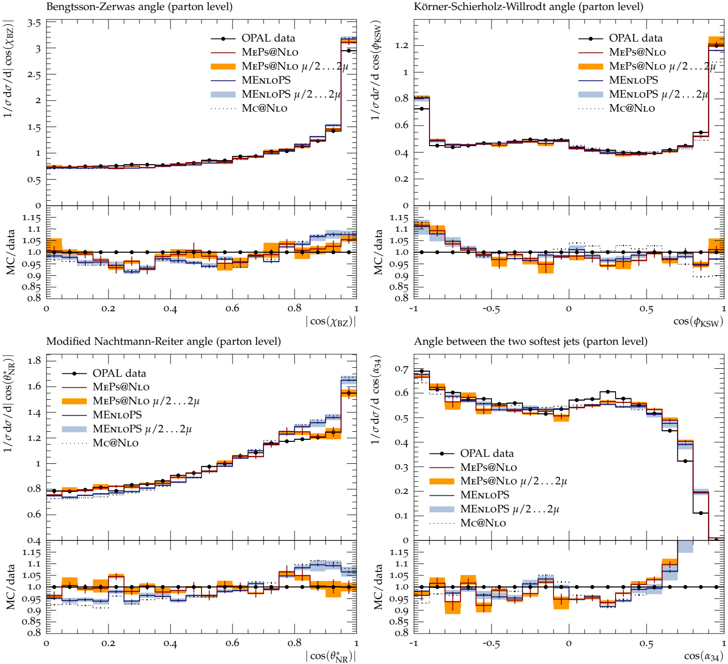


C-Parameter (ALEPH, 2004) and its moments (OPAL, 2004)



Sphericity (ALEPH, 2004) and its moments (OPAL, 2004)





Bengtsson-Zerwas angle (parton level)
OPAL data
MEPs@NLO
MEPs@NLO μ/2...2μ
MENLOPS
MENLOPS μ/2...2μ
MC@NLO
1/σ dσ/d|cos(χBZ)|
MC/data
|cos(χBZ)|
Körner-Schierholz-Willrodt angle (parton level)
1/σ dσ/d cos(φKSW)
cos(φKSW)
Modified Nachtmann-Reiter angle (parton level)
1/σ dσ/d|cos(θ*NR)|
|cos(θ*NR)|
Angle between the two softest jets (parton level)
1/σ dσ/d cos(α34)
cos(α34)

Sneak preview: NLO merging for $W + 0, 1, 2$-jet production with SHERPA

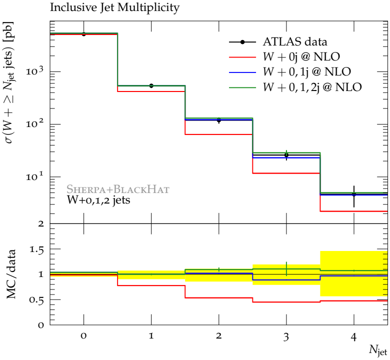
Höche, Krauss, Schönherr, FS (in preparation)

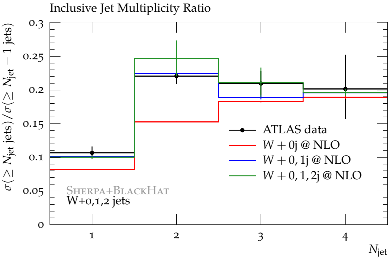
Event generation setup

- $pp \to W$ + jets at 7 TeV
- SHERPA with built-in automatic MC@NLO
- Virtual matrix elements from BlackHat library, analyses from Rivet library
- Displayed here:
  - MC@NLO
  - MEPS@NLO with $W + 0, 1$ partons
  - MEPS@NLO with $W + 0, 1, 2$ partons

Sneak preview: NLO merging for $W + 0, 1, 2$-jet production with SHERPA

NLO merging predictions compared to ATLAS W+jets measurement (arXiv:1201.1276)





Höche, Krauss, Schönherr, FS (in preparation)

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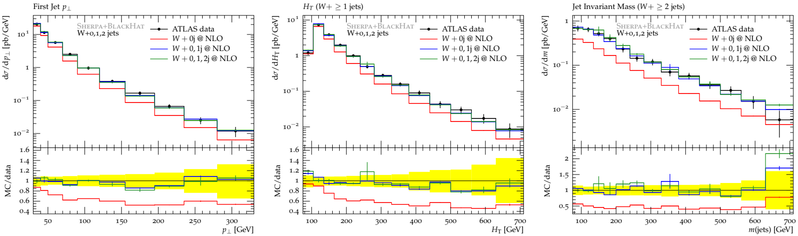

Höche, Krauss, Schönherr, FS (in preparation)

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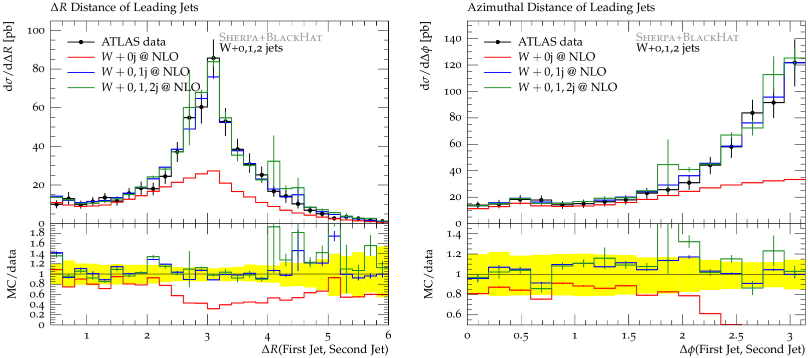


Höche, Krauss, Schönherr, FS (in preparation)

Conclusions

Summary

- Introduced common formalism for NLO+PS matching
- Application in $W + 1, 2, 3$-jet production at LHC
- Uncertainties from resummation can be sizable in NLO+PS predictions

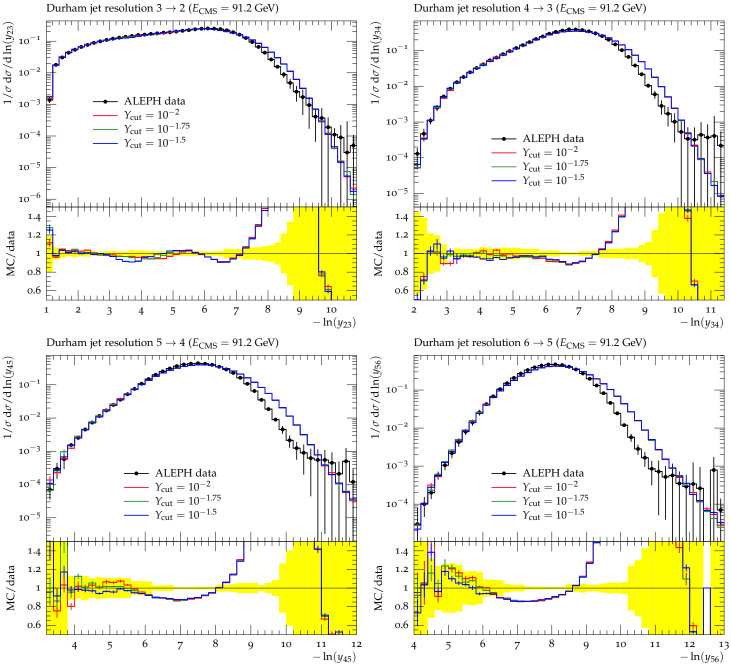
- Merging of NLO+PS with higher multiplicities at tree-level and NLO
- Significant reduction of perturbative uncertainties in MEPS@NLO

  $\Rightarrow$ Very good agreement with data in $e^+e^- \to$ hadrons and W + jets production

Outlook

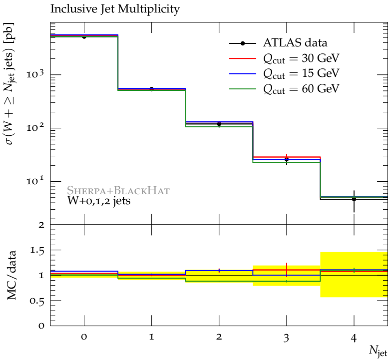
- Publication of MEPS@NLO formalism and results imminent
- Code and documentation release in Sherpa 2.0 in the near future
- Application to more processes relevant for LHC phenomenology

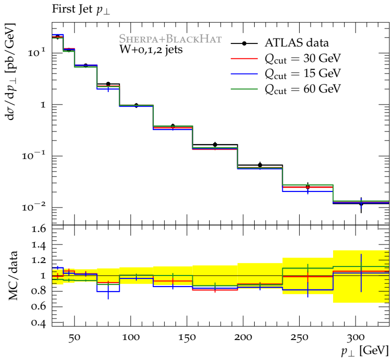
  $\Rightarrow$ Interfacing to more virtual MEs
- After these improvements at fixed order: Improvements of resummation


Durham jet resolution 3 → 2 (E_{CMS} = 91.2 GeV)
Durham jet resolution 4 → 3 (E_{CMS} = 91.2 GeV)
Durham jet resolution 5 → 4 (E_{CMS} = 91.2 GeV)
Durham jet resolution 6 → 5 (E_{CMS} = 91.2 GeV)
ALEPH data
$Y_{cut} = 10^{-2}$
$Y_{cut} = 10^{-1.75}$
$Y_{cut} = 10^{-1.5}$
$1/\sigma\, d\sigma/d\ln(y_{23})$
$1/\sigma\, d\sigma/d\ln(y_{34})$
$1/\sigma\, d\sigma/d\ln(y_{45})$
$1/\sigma\, d\sigma/d\ln(y_{56})$
MC/data
$-\ln(y_{23})$
$-\ln(y_{34})$
$-\ln(y_{45})$
$-\ln(y_{56})$

Sneak preview: NLO merging for $W + 0, 1, 2$-jet production with SHERPA

Uncertainties from Q_{cut} variations





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