Matching and merging QCD matrix elements and parton showers at NLO accuracy

SLAC Theory Seminar, 11 Jan 2013

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Based on

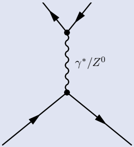
- arXiv:1207.5031 (Stefan Höche, Frank Krauss, Marek Schönherr, FS)
- arXiv:1207.5030 (Thomas Gehrmann, Stefan Höche, Frank Krauss, Marek Schönherr, FS)
- arXiv:1201.5882 (Stefan Höche, Frank Krauss, Marek Schönherr, FS)
- arXiv:1111.1220 (Stefan Höche, Frank Krauss, Marek Schönherr, FS)

LHC phenomenology

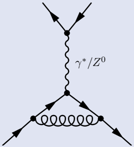
- Higgs/BSM signals with heavy particles decaying into high multiplicity final states
- Backgrounds from simple SM processes with many additional jets

⇒ Need good understanding of higher order QCD corrections to SM processes

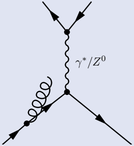
Typical framework: Calculation to fixed order in α_s, e.g. NLO



Born level matrix element



Virtual matrix element



Real emission matrix element

This talk

Improving approximate resummation of the series with exact fixed order corrections

Table of Contents

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 cross section at NLO:

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

- Subtraction terms $\mathcal{D}$ and their integrated form $\mathcal{I}$
  e.g. Frixione, Kunszt, Signer (1995); Catani, Seymour (1996)
- Subtraction defines phase space mappings $\Phi_R \underset{r_{\widetilde{\imath\jmath}}}{\overset{b_{ij}}{\rightleftharpoons}} (\Phi_B, \Phi_1)$

Resummation in parton showers

Factorisation of collinear QCD emissions

- Universal factorisation of QCD real emission ME in collinear limit:

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

- Differential branching probability: $\mathrm{d}\sigma_{\mathrm{branch}}^{\widetilde{ij}} = \sum_{f_i} \mathrm{d}\Phi_1(t, z, \varphi) \, \frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}}$
- Assume multiple independent emissions (Poisson statistics) $\Rightarrow$ Exponentiation yields total no-branching probability down to evolution scale t:

$$\Delta^{(\mathrm{PS})}(t) = \prod_{\widetilde{ij}} \exp\left\{ - \sum_{f_i = q,g} \int \mathrm{d}\Phi_1 \, \Theta\left(t(\Phi_1) - t\right) \frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}} \right\}$$

Cross section up to first emission

$$\mathrm{d}\sigma^{(\mathrm{B})} = \mathrm{d}\Phi_B \, \mathcal{B} \left[\underbrace{\Delta^{(\mathrm{PS})}(t_0)}_{\text{unresolved}} + \underbrace{\sum_{\widetilde{ij}} \sum_{f_i} \int_{t_0}^{\mu_F^2} \mathrm{d}\Phi_1 \, \frac{\mathcal{D}_{ij}^{(\mathrm{PS})}}{\mathcal{B}} \Delta^{(\mathrm{PS})}(t)}_{\text{resolved}} \right]$$

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Merging and matching fixed-order and resummation: Classification

NLO+PS matching

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

ME+PS@LO merging

- Multiple LO+PS simulations for processes of different jet multiplicity e.g. $W, Wj, Wjj, \ldots$
- Objectives:
  - combine into one inclusive sample by making them exclusive
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Combination of the two approaches above: ME+PS@NLO

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

From fixed order to resummation

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

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

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

$$\bar{\mathcal{B}}^{(\mathrm{A})} = \mathcal{B} + \tilde{\mathcal{V}} + \sum_{\{\widetilde{ij}\}} \mathcal{I}_{\widetilde{ij}}^{(\mathrm{S})} + \sum_{\{\widetilde{ij}\}} \sum_{f_i=q,g} \int \mathrm{d}\Phi_1 \left[\mathcal{D}_{ij}^{(\mathrm{A})} - \mathcal{D}_{ij}^{(\mathrm{S})} \right]$$

- $\mathcal{D}_{ij}^{(\mathrm{A})}$ must have same kinematics mapping as $\mathcal{D}_{ij}^{(\mathrm{S})}$
- Exact choice of $\mathcal{D}_{ij}^{(\mathrm{A})}$ will specify e.g. MC@NLO vs. POWHEG
- Difference between $\mathcal{D}^{(\mathrm{A})}$ and $\mathcal{D}^{(\mathrm{S})}$ will allow later to determine how much emission phase space is exponentiated

From fixed order to resummation

Master formula for NLO+PS up to first emission

$$\mathrm{d}\sigma^{(\mathrm{NLO+PS})} = \sum_{\vec{f}_B} \mathrm{d}\Phi_B\, \bar{\mathcal{B}}^{(\mathrm{A})}(\Phi_B) \left[\underbrace{\Delta^{(\mathrm{A})}(t_0)}_{\text{unresolved}} + \sum_{\{\widetilde{ij}\}} \sum_{f_i} \int_{t_0} \mathrm{d}\Phi_1 \underbrace{\frac{\mathcal{D}_{ij}^{(\mathrm{A})}}{\mathcal{B}}\, \Delta^{(\mathrm{A})}(t)}_{\text{resolved, singular}} \right]$$

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

- To $\mathcal{O}(\alpha_s)$ this reproduces $\mathrm{d}\sigma^{(\mathrm{NLO})}$ including the correction term
- Event generation in the following way:
  - Generate seed event according to $\bar{\mathcal{B}}^{(\mathrm{A})}$ or $\mathcal{H}^{(\mathrm{A})}$ according to their XS
  - Second line ("$\mathbb{H}$-event"): kept as-is → resolved, non-singular term
  - First line ("$\mathbb{S}$-event"): from one-step PS with $\Delta^{(\mathrm{A})}$
    ⇒ emission (resolved, singular) or no emission (unresolved) above t_0
- Resolved cases: Subsequent emissions can be generated by ordinary PS

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 $\mathcal{R} - \sum_{ij} \mathcal{D}_{ij}^{(\mathrm{A})}$ 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 $\mathcal{D}^{(\mathrm{S})}$

(only potential difference: phase space cuts)

Höche, Krauss, Schönherr, FS (2011)

- \+ "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

⇓
Used in the following

Special case: POWHEG

Original POWHEG

- Choose additional subtraction terms as

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

- $\mathbb{H}$-term vanishes
- Similar to PS with ME-correction for 1st emission (e.g. Herwig, Pythia)

Mixed scheme

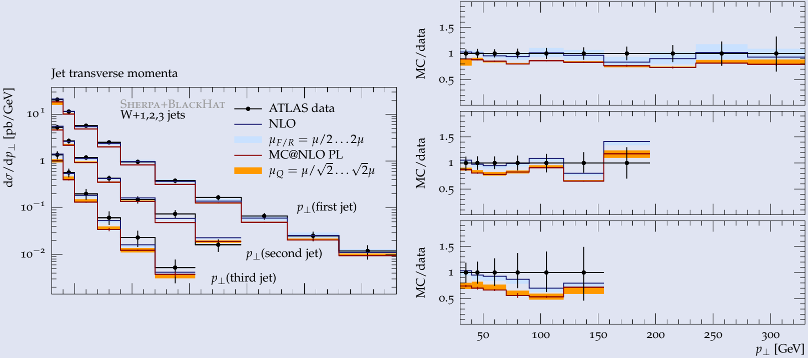
- Subtract arbitrary regular piece from $\mathcal{R}$ and generate separately

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

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

Results for $W + n$-jet production at the LHC

Comparison to ATLAS data



ATLAS measurement (arXiv:1201.1276)
SHERPA+BLACKHAT NLO+PS predictions (arXiv:1201.5882)

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Combination of the two approaches above: ME+PS@NLO

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Tree-level ME+PS merging

Main idea

Phase space slicing for QCD radiation in shower evolution

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

  ⇒ Splitting kernels replaced by exact real emission matrix elements

$$\frac{8\pi\alpha_s}{2p_ip_j}\mathcal{K}_{ij,k}(z,t) \quad\rightarrow\quad \frac{8\pi\alpha_s}{2p_ip_j}\,\mathcal{K}^{\text{ME}}_{ij,k}(z,t) \;=\; \frac{\mathcal{R}_{ij,k}}{\mathcal{B}}$$

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

  ⇒ Retained from parton shower $\quad \mathcal{K}_{ij,k}(z,t) = \mathcal{K}^{\text{PS}}_{ij,k}(z,t)$

Note

Boundary determined by "jet criterion" $Q_{ij,k}$

- Has to identify soft/collinear divergences in MEs, like jet algorithm
- Otherwise arbitrary

Parton shower on top of high-multi ME

Translate ME event into shower language

Why?

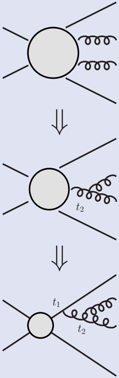
- Need starting scales t for PS evolution
- Have to embed existing emissions into PS evolution

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: factorisation scale μ_F^2 and shower cut-off t_o

Master formula

Cross section up to first emission in ME+PS

$$\mathrm{d}\sigma = \mathrm{d}\Phi_B\,\mathrm{B}\left[\underbrace{\Delta^{(\mathrm{PS})}(t_0,\mu^2)}_{\text{unresolved}} + \sum_{ij,k}\frac{1}{16\pi^2}\int_{t_0}^{\mu^2}\mathrm{d}t\int_{z_-}^{z_+}\mathrm{d}z\int_0^{2\pi}\frac{\mathrm{d}\phi}{2\pi}\,\Delta^{(\mathrm{PS})}(t,\mu^2)\right.$$
$$\left.\times\left(\underbrace{\frac{8\pi\,\alpha_s}{2p_ip_j}\,\mathcal{K}_{ij,k}^{(\mathrm{PS})}(z,t)\,\Theta(Q_{\mathrm{cut}}-Q_{ij,k})}_{\text{resolved, PS domain}} + \underbrace{\frac{\mathrm{R}_{ij,k}}{\mathrm{B}}\,\Theta(Q_{ij,k}-Q_{\mathrm{cut}})}_{\text{resolved, ME domain}}\right)\right]$$

Features

- LO weight B for Born-like event
- Unitarity slightly violated due to mismatch of $\Delta^{(\mathrm{PS})}$ and R/B
  $[\ldots] \approx 1 \Rightarrow$ LO cross section only approximately preserved
- Unresolved emissions as in parton shower approach
- Resolved emissions now sliced into PS and ME domain
- Only for one emission here, but possible up to high number of emissions

Features and shortcomings

Example

Diphoton production at Tevatron

- Recently published by DØ Phys.Lett.B690:108-117,2010
- Isolated hard photons
- Azimuthal angle between the diphoton pair

ME+PS simulation using SHERPA with QCD+QED interleaved shower and merging

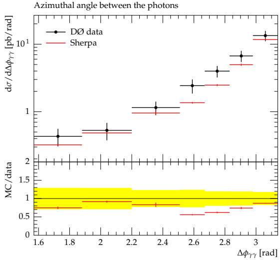
Höche, Schumann, FS (2010)

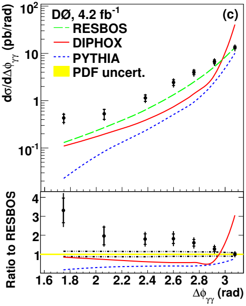
Conclusions

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. $\Delta\Phi_{\gamma\gamma} \to \pi$

Total cross section too low $\Rightarrow$ Virtual MEs needed





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Basic idea

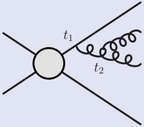
Concepts continued from ME+PS merging at LO

- 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: $k = 1$



Master formula

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

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

Results for $e^+e^- \to$ hadrons: Setup

General setup

- ME generators (tree-level and dipole subtraction): AMEGIC++ and COMIX
- Virtual corrections from BLACKHAT
- MC@NLO-like generator built into SHERPA with full colour treatment
- Parton shower based on Catani-Seymour dipole factorisation
- Hadronisation model AHADIC++, not tuned for ME+PS@NLO yet
  $\Rightarrow$ Deviations in hadronisation sensitive regions
- Comparison to ALEPH and OPAL measurements:
  Eur. Phys. J. C35 (2004), 457-486, Eur.Phys.J. C40 (2005), 287-316, Eur. Phys. J. C20 (2001), 601-615

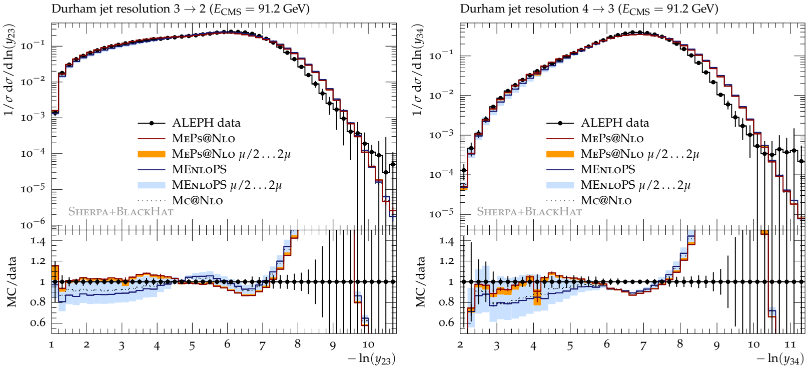
Comparison of three runs

MC@NLO: NLO+PS prediction for $2 \to 2$

MENLOPS: MC@NLO for $2 \to 2$ + ME+PS up to $2 \to 6$
μ_R variation indicated by blue band

MEPS@NLO: MC@NLO for $2 \to 2, 3, 4$ + ME+PS for $2 \to 5, 6$
μ_R variation indicated by orange band

Results for $e^+e^- \to$ hadrons: Differential Durham jet rates



- Significant reduction of MEPS@NLO scale uncertainties in perturbative region
- Improved agreement with experimental data

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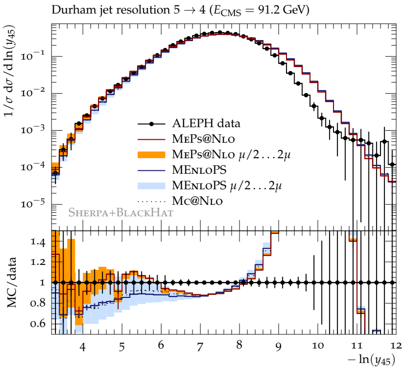
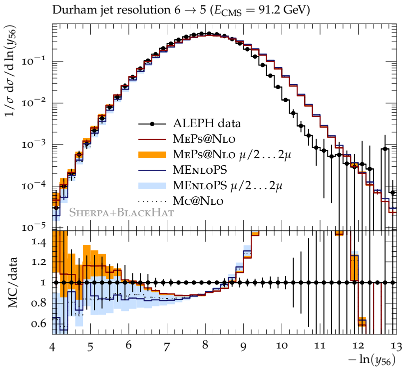
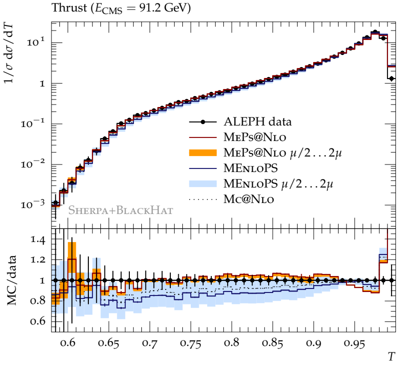
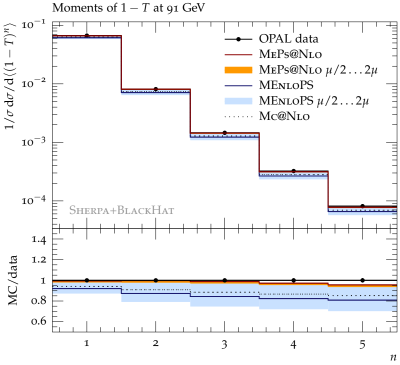




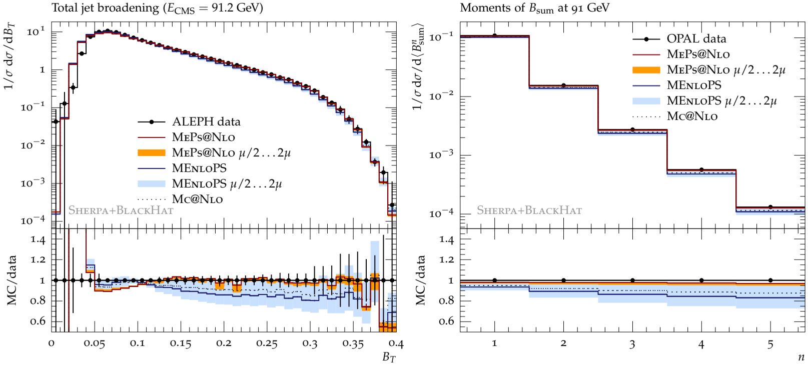
- Scale uncertainty not reduced, due to sensitivity to $2 \to 5, 6$ partons (LO)

Results for $e^+e^- \to$ hadrons: Thrust event shape

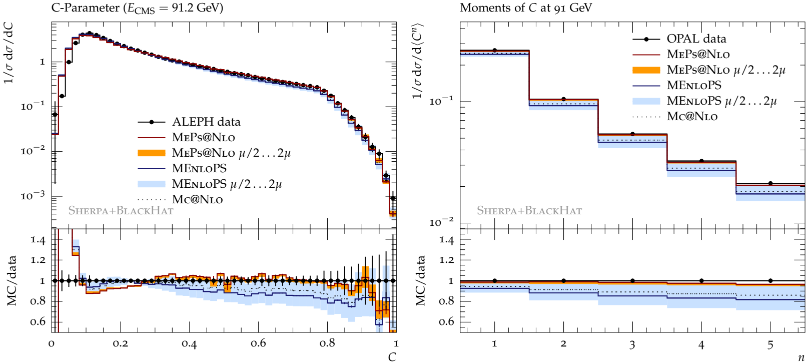




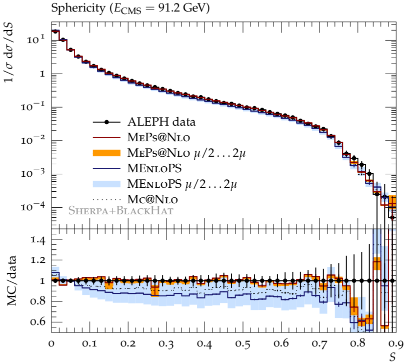
Results for $e^+e^- \to$ hadrons: Total jet broadening event shape

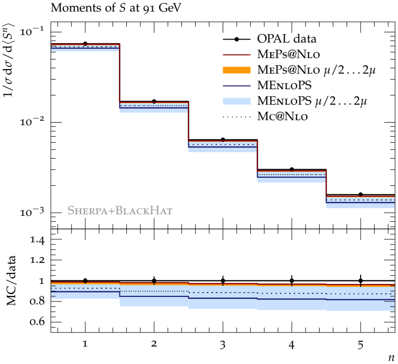


Results for $e^+e^- \to$ hadrons: C parameter event shape

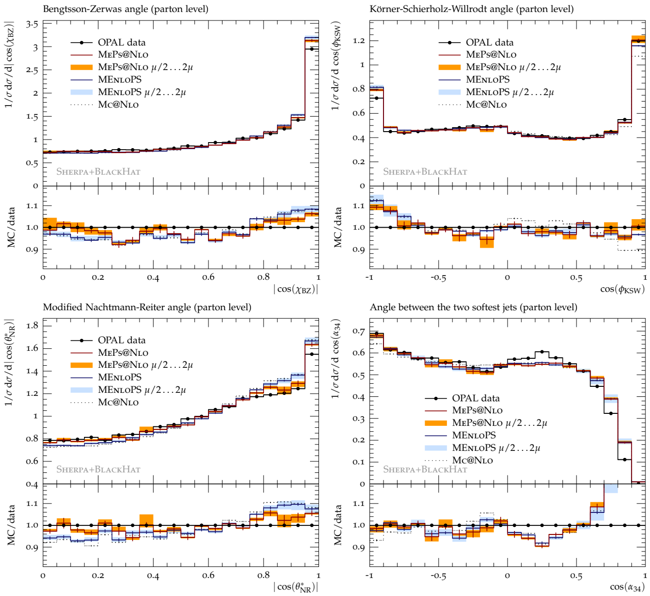


Results for $e^+e^- \to$ hadrons: Sphericity event shape





Results for $e^+e^- \to$ hadrons: Four-jet angles



Results for W + jets: Setup

General setup

- ME generators (tree-level and dipole subtraction): AMEGIC++ and COMIX
- Virtual corrections from BLACKHAT
- MC@NLO-like generator built into SHERPA with full colour treatment
- Parton shower based on Catani-Seymour dipole factorisation
- Hadronisation and multiple parton interactions not taken into account (observables almost insensitive)
- CT10 PDF set
- Central scales $\mu_{F,R}$ from clustering onto $2 \to 2$ configuration

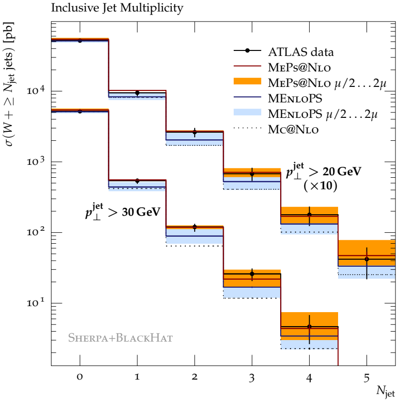
Comparison of three runs

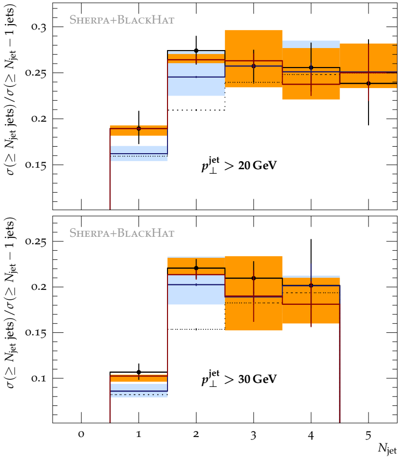
MC@NLO: NLO+PS prediction for $2 \to 2$

MENLOPS: MC@NLO for $2 \to 2$ + ME+PS up to $2 \to 6$
$\mu_{F,R}$ variation indicated by blue band

MEPS@NLO: MC@NLO for $2 \to 2, 3, 4$ + ME+PS for $2 \to 5, 6$
$\mu_{F,R}$ variation indicated by orange band

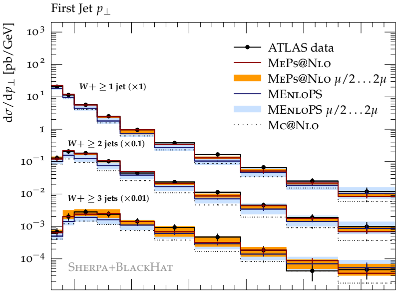
Results for W + jets: Jet multiplicities

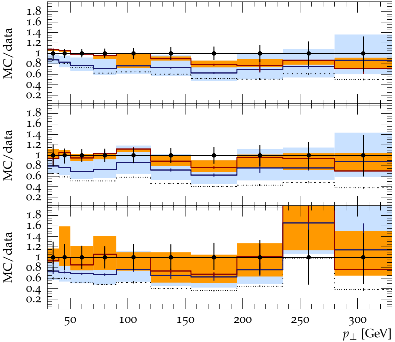




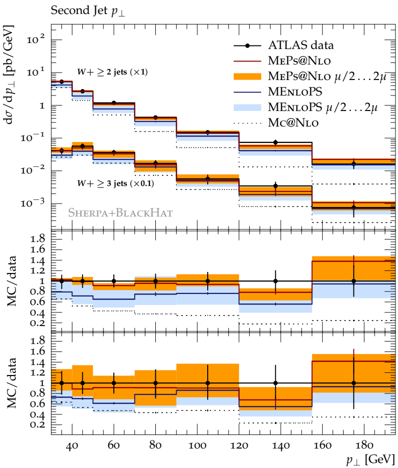
- Comparison to ATLAS measurement Phys.Rev. D85 (2012), 092002
- Significant reduction of MEPS@NLO scale uncertainties in "NLO" multiplicities
- Improved agreement with experimental data

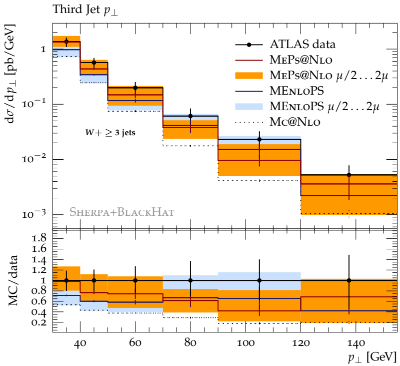
Results for W + jets: Leading jet transverse momentum



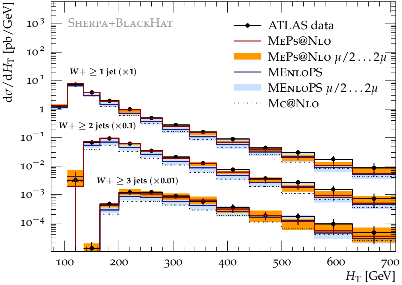


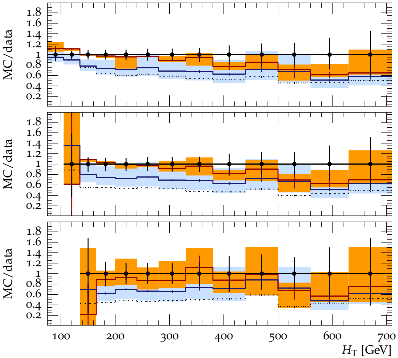
Results for W + jets: Subleading jets transverse momenta





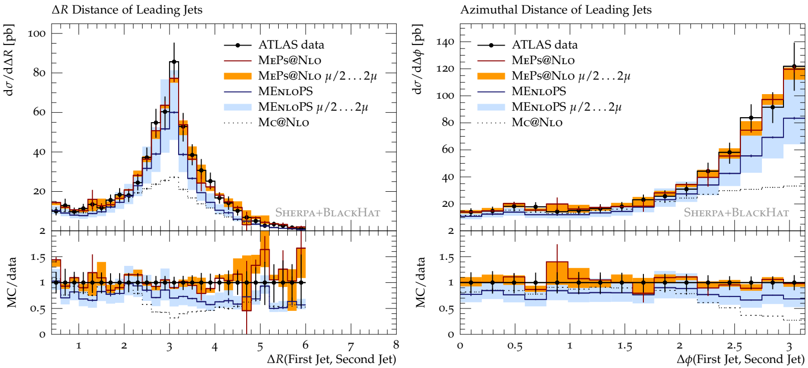
Results for W + jets: Scalar transverse momentum sum H_T





- High H_T region affected by higher multiplicities ⇒ Larger scale uncertainty

Results for W + jets: Angular correlations



- Pure Mc@Nlo simulation misses correlations between the two leading jets

Conclusions

Summary

- Several approaches for higher-order QCD effects have been introduced:
  - NLO+PS matching for NLO and parton showers
  - ME+PS merging of high-multiplicity tree-level matrix-elements with parton showers
  - ME+PS@NLO merging, combining the two approaches above
- Results have been presented for ME+PS@NLO in $ee \to$ hadrons at LEP and W+jets production at the LHC
- Significant improvements in the description of experimental data have been found

Outlook

- Apply ME+PS@NLO to other processes (e.g. $gg \to h$+jets, $t\bar{t}$+jets, diboson+jets)
- Devise sound prescription to study uncertainties (perturbative, resummation, non-perturbative)
- Incorporate EW NLO corrections into matching and merging

Backup: ME+PS@NLO correction term

Correction term of ME+PS@NLO wrt MC@NLO at given jet multiplicity k:

$$\langle O\rangle^{\text{corr}}_{n+k} = \int \mathrm{d}\Phi_{n+k+1}\,\Theta(Q_{n+k+1}-Q_{\text{cut}})\,\tilde{\Delta}^{(\text{PS})}_{n+k+1}(t_c,\mu_Q^2)\,O_{n+k+1}$$
$$\times\left\{\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k}\left[1-\frac{\tilde{\mathrm{B}}^{(\mathrm{A})}_{n+k}}{\mathrm{B}_{n+k}}\,\frac{\Delta^{(\mathrm{A})}_{n+k}(t_{n+k+1},t_{n+k})}{\Delta^{(\text{PS})}_{n+k}(t_{n+k+1},t_{n+k})}\right]\right.$$
$$\left.-\,\mathrm{B}_{n+k+1}\left[1-\frac{\tilde{\mathrm{B}}^{(\mathrm{A})}_{n+k+1}}{\mathrm{B}_{n+k+1}}\,\frac{\Delta^{(\mathrm{A})}_{n+k+1}(t_c,t_{n+k+1})}{\Delta^{(\text{PS})}_{n+k+1}(t_c,t_{n+k+1})}\right]\right\}\,.$$

with compound subtraction term

$$\tilde{\mathrm{D}}^{(\mathrm{A})}_{n+k} = \mathrm{D}^{(\mathrm{A})}_{n+k}\,\Theta(t_{n+k}-t_{n+k+1}) + \mathrm{B}^{(\mathrm{A})}_{n+k}\sum_{i=n}^{n+k-1}\mathrm{K}_i\,\Theta(t_i-t_{n+k+1})\,\Theta(t_{n+k+1}-t_{i+1})\,,$$