A critical appraisal of NLO+PS matching

Particle Physics Seminar, Zürich

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Based on

- arXiv:1111.1220 (Stefan Höche, Frank Krauss, Marek Schönherr, FS)
- arXiv:1008.5399 (Stefan Höche, Frank Krauss, Marek Schönherr, FS)

Teaser

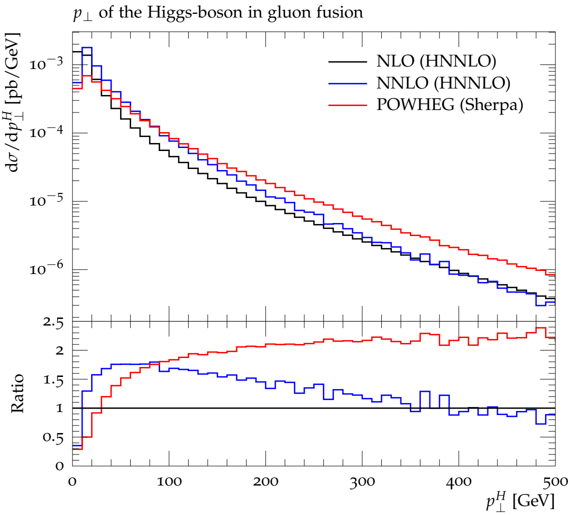

$p_\perp$ of the Higgs-boson in gluon fusion
$d\sigma/dp_\perp^H$ [pb/GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
NLO (HNNLO)
NNLO (HNNLO)
POWHEG (Sherpa)
Ratio
2.5
2
1.5
1
0.5
0
0
100
200
300
400
500
$p_\perp^H$ [GeV]

Table of Contents

A critical appraisal of NLO+PS matching

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
- – Only low FS multiplicity

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 hard QCD radiation from **NLO ME**
- Keep intrajet evolution provided by the **PS**

Fixed order calculations (NLO)

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:

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

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

Resummation in parton-showers

Factorisation of collinear QCD emissions

Universal factorisation of QCD real emission ME in collinear limit:

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

- Sum over subterms ij of the factorisation, e.g. parton lines (DGLAP)
- $\frac{1}{2p_i p_j}$ from massless propagator
  Evolution variable of shower $t \sim 2p_i p_j$ (e.g. $k_\perp$, angle, ...)
- $\mathcal{K}_{ij}$ 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

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

(Symmetry factors/PDFs ignored)

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

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

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

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

From fixed order to resummation

Problem

- Applying PS resummation to $\mathcal{B}$ event was simple ✓ (for some definition of simple)
- At NLO, can the same simply be done separately for $\mathcal{B}, \mathcal{V}+\mathcal{I}, \mathcal{R}-\mathcal{D}$?

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

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

Solution: Let's in the following …

- rewrite $\langle O\rangle^{(\mathrm{NLO})}$ a bit
- add some 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 and POWHEG

From fixed order to resummation

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

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

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

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

- $\mathcal{D}^{(A)}_{ij}$ must have same kinematics mapping as $\mathcal{D}^{(S)}_{ij}$
- Exact choice of $\mathcal{D}^{(A)}_{ij}$ will later specify 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

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

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

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

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

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

- 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: MC@NLO

Choice of $\mathcal{D}^{(\mathrm{A})}$

- Choose the additional subtraction terms as

$$\mathcal{D}_{ij}^{(\mathrm{A})} \to \mathcal{D}_{ij}^{(\mathrm{S})}$$

Comments

- $\bar{\mathcal{B}}^{(\mathrm{A})}$ simplified significantly
- Still non-trivial to implement, need either of:
  - One-step PS algorithm based on subtraction terms $\mathcal{D}_{ij}^{(\mathrm{S})}$
    ! splitting kernels can become negative $\Rightarrow \Delta > 1$!
  - ME subtraction using ordinary PS kernels $\mathcal{D}_{ij}^{(\mathrm{PS})}$
    ! soft divergences (subleading in $\frac{1}{N_C}$) not covered !
- In SHERPA's MC@NLO implementation:
  - $\mathcal{D}^{(\mathrm{S})}$ from Catani-Seymour
  - Weighted $N_C = 3$ one-step PS to generate $\Delta > 1$

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

Subtleties to note

Exponentiation uncertainty

- Have to exponentiate full subtraction terms $\mathcal{D}_{ij}^{(\mathrm{S})}$ (MC@NLO) or even $\mathcal{R}$ (POWHEG) for NLO accuracy
- Exponent contains arbitrary terms beyond all-orders singular pieces
  = Systematic theory uncertainty in NLO+PS

$\Rightarrow$ Studied in detail in Results later

Renormalisation scale choice in NLO vs. PS

- First emission partly done by NLO matrix element, partly by PS
- $\alpha_s^{(\mathrm{NLO})}(\mu_R)$ taken at fixed scale
- $\alpha_s^{(\mathrm{PS})}(k_\perp)$ taken at transverse momentum of the branching
  (partially resums soft higher-order contributions)

$\Rightarrow$ Only noted here without solution, critical for smooth NLO$\otimes$NLO merging

NLO+PS uncertainties

Perturbative uncertainties

- Unknown higher-order corrections
- Estimated here by simultaneous scale variations
  $\mu_F = \mu_R = \frac{1}{2}\mu \ldots 2\mu$

$\rightsquigarrow pp \to h$ + jet later

Non-perturbative uncertainties

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

$\rightsquigarrow pp \to W$ + jet later

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
  - Using MC@NLO with variable "dipole α_{cut}" restriction in $\mathcal{D}^{(\mathrm{S})}$:
    $\alpha_{\mathrm{cut}} \to 0$ decreases phase space for non-singular contributions

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

Example setup

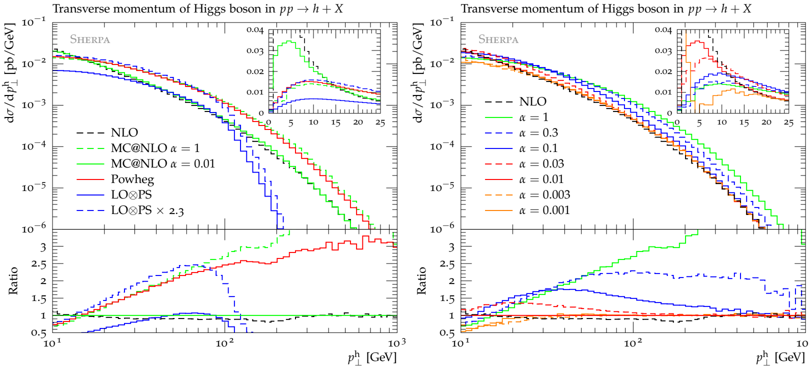
- $gg \to h \to \tau\tau$ at LHC with $\sqrt{s} = 7$ TeV and $m_h = 120$ GeV, $\mu = m_h$
- Analysed with $p_\perp^\tau > 25$ GeV and $|n^\tau| < 3.5$
- Jets defined using inclusive $k_\perp$ with $R = 0.7$ and $p_\perp > 20$ GeV

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 $0.001 \le \alpha_{\text{cut}} \le 1$ variation

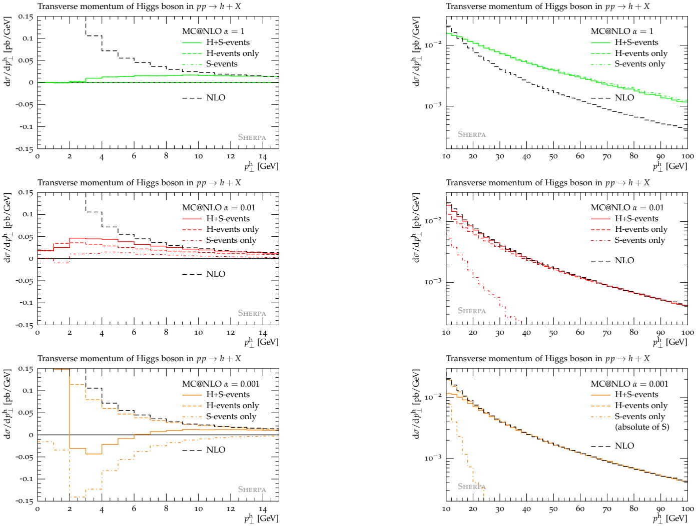
$\Rightarrow$ Very busy plots
(SORRY!)

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



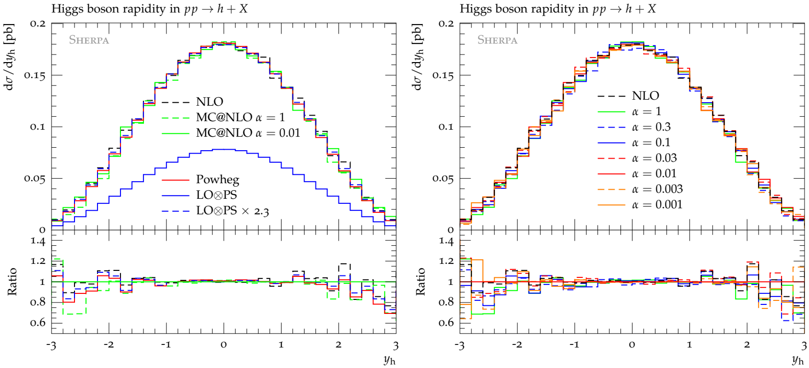
- Surprising result: Huge NLO+PS uncertainties especially at large $p_\perp^h$
- POWHEG and unrestricted MC@NLO similar
- Decreasing exponentiation of non-singular pieces with $\alpha_{\text{cut}} \lesssim 0.01$ recovers NLO behaviour
- Resummation region $p_\perp^h \to 0$ strongly affected by α_{cut}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

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



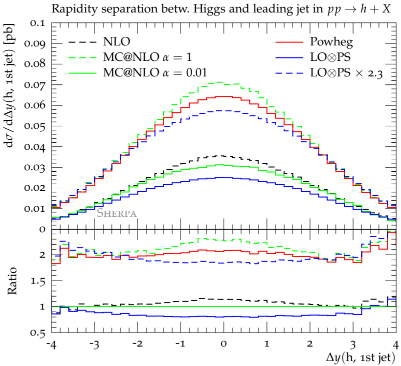
- Predictions separated by $\mathbb{H}$ and $\mathbb{S}$ events for illustration purposes

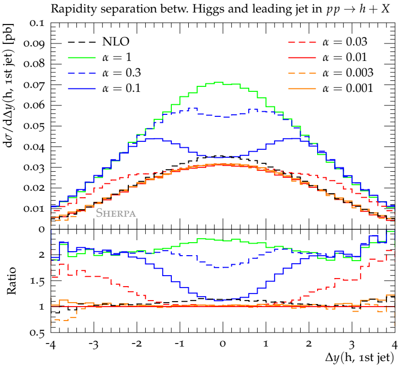
Exponentiation uncertainties in the example of $gg \to h$



- Predictions much more stable for y_h than for $p_\perp^h$
- Observable already exists at LO, thus described at NLO here

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





- Large uncertainties for $\Delta y(h, j)$
- Interesting dip structure in MC@NLO due to cuts on exponentiated phase space
  Surprisingly similar to effect from dead zones in MC@NLO with HERWIG

Predictions for $pp \to h + \text{jet}$

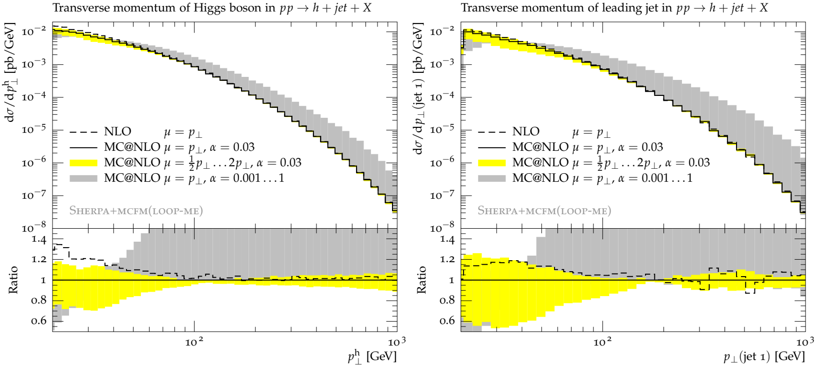
Example setup

- $pp \to h[\to \tau\tau] + \text{jet}$ at LHC with $\sqrt{s} = 7$ TeV and $m_h = 120$ GeV, $\mu = p_\perp^{j_{\text{lead}}}$
- Virtual matrix element interfaced from MCFM
- Generated ME level with $p_\perp > 10$ GeV for inclusive $k_\perp$ jets with $R = 0.5$
- 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

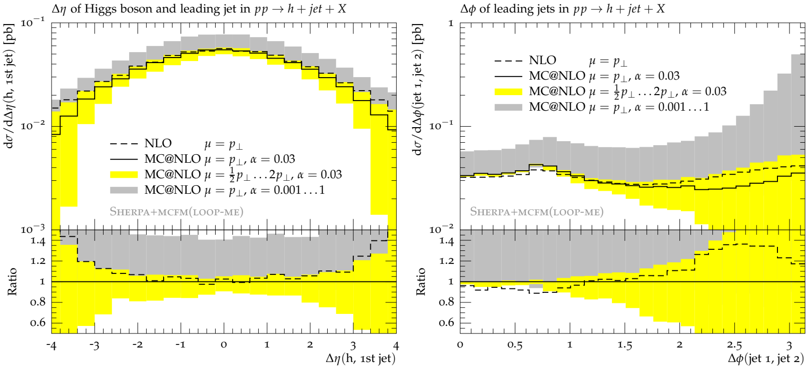
- Includes hadronisation, hadron decays, multiple parton interactions (MPI), QED corrections to $h \to \tau\tau$ decay
- Scale uncertainty band (yellow) from $\mu_F = \mu_R = \frac{1}{2}\mu \ldots 2\mu$
- Exponentiation uncertainty band (gray) from $\alpha_{\text{cut}} = 0.001 \ \ldots \ 1$

Predictions for $pp \to h + \text{jet}$



- Despite NLO accuracy, large exponentiation uncertainty for large $p_\perp$:
  - Large influence from higher-order corrections in Δ where more phase space is exponentiated
  - Additional distortion from scale difference for real-emission: relative $p_\perp$ of partons vs. $p_\perp$ against beam

Predictions for $pp \to h + \text{jet}$



- Milder exponentiation variations in $\Delta\eta(\mathrm{h}, \mathrm{jet})$, mainly normalisation due to larger emission rates with $\alpha_{\mathrm{cut}} \to 1$
- $\Delta\phi(\mathrm{jet}\ 1, \mathrm{jet}\ 2)$: Back-to-back situation amplified due to harder radiation

Non-perturbative effects in W + jet production

Example setup

- $pp \to W[\to e\nu]$ + jet at LHC with $\sqrt{s} = 7$ TeV, $\mu = p_\perp^{j_\text{lead}}$
- Virtual matrix element interfaced from BlackHat
- Exponentiation level fixed at $\alpha_\text{cut} = 0.03$
- Generated ME level with $p_\perp > 10$ GeV for inclusive $k_\perp$ jets with $R = 0.5$
- Analysed jets with $p_\perp > 20$ GeV for inclusive $k_\perp$ jets with $R = 0.7$

Non-perturbative effects

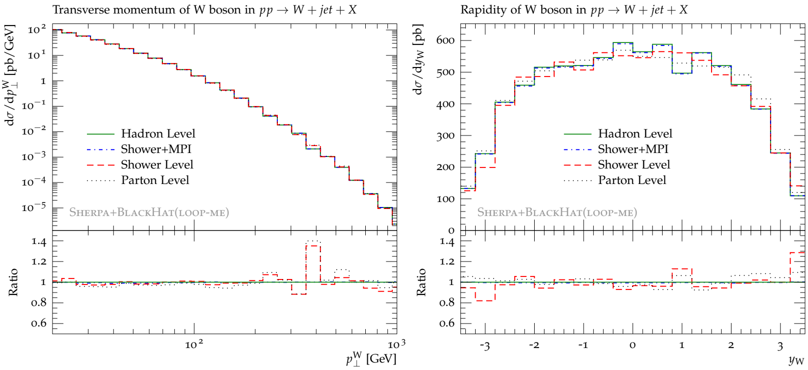
"Parton Level"
: Only seed event + first emission off $\mathbb{S}$-events in MC@NLO

"Shower Level"
: PL + all QCD emissions in the parton shower and QED emissions in the YFS approach

"Shower+MPI"
: SL + multiple parton interactions and intrinsic $p_\perp$ of the beam hadron

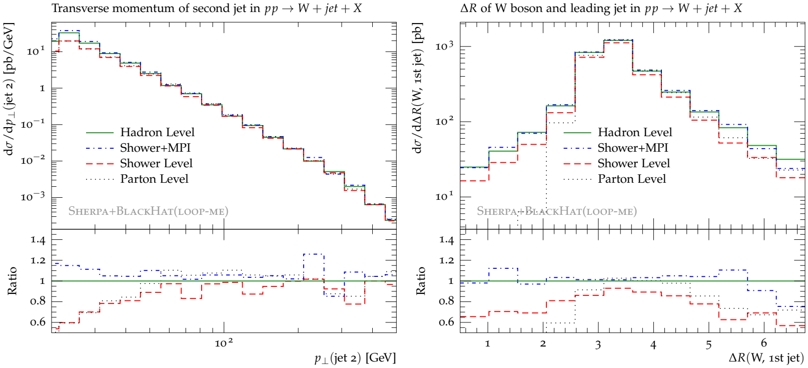
"Hadron Level"
: Additionally, hadronisation and hadron decays are included

Non-perturbative effects in W + jet production



- Properties of the W-boson virtually unaffected

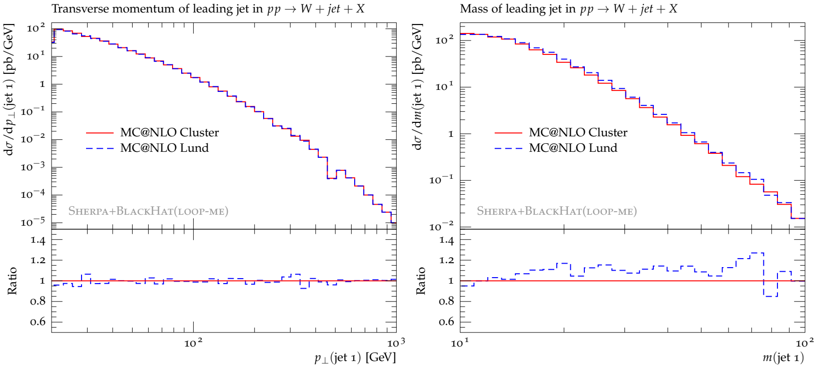
Non-perturbative effects in W + jet production



- Jet properties changed significantly by non-perturbative effects
- Hadronisation and MPI partially compensate each other, depends on jet algorithm

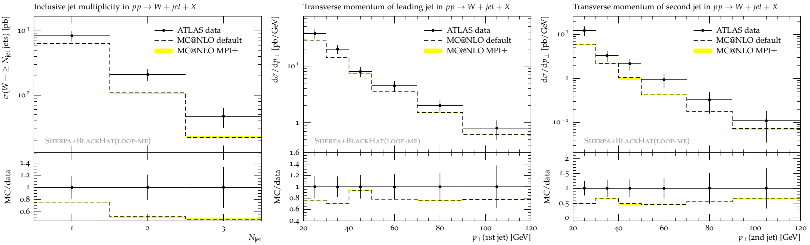
$\Rightarrow$ How large is the uncertainty?

Hadronisation uncertainties in W + jet production



- Probe hadronisation uncertainties by switching from SHERPA default cluster fragmentation to Lund string
- Differences negligible for all jet observables studied, except the specifically sensitive jet mass

Comparison to data for W + jet production



- Comparison to ATLAS data (arXiv:1012.5382): Good agreement in shape, discrepancies in jet rates
- Especially two/three jet rates too low: Only predicted at LO/PS
- MPI parameter variations plotted as yellow band ⇒ negligible

Comparison to data for Z + jet production

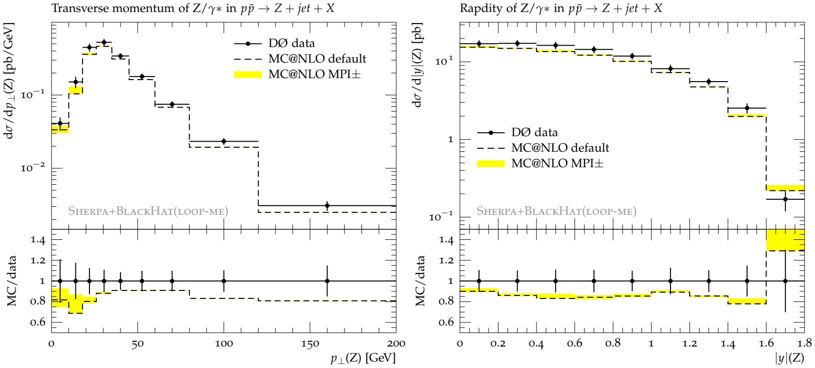
Example setup

- $pp \to Z$ + jet at Tevatron with $\sqrt{s} = 1.96$ TeV, $\mu = p_\perp^{j_\text{lead}}$
- Virtual matrix element interfaced from BlackHat
- Exponentiation level fixed at $\alpha_\text{cut} = 0.03$
- Generated ME level with $p_\perp > 10$ GeV for inclusive $k_\perp$ jets with $R = 0.5$

Tevatron analyses

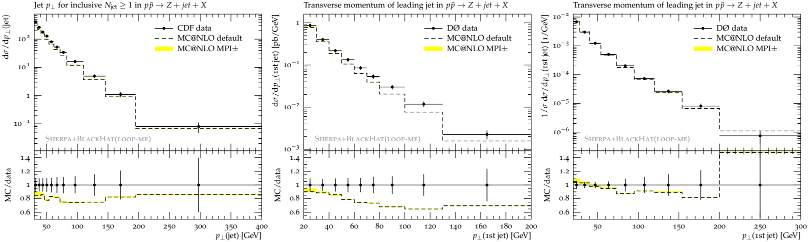
- CDF Z+jets arXiv:0711.3717
- DØ Z+jet arXiv:0808.1296
- DØ Z+jets arXiv:0903.1748
- DØ Z+jet arXiv:0907.4286

Comparison to data for Z + jet production



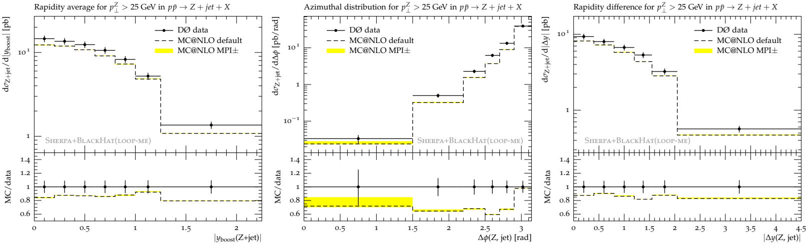
- Z-boson properties in Z+jet+X production
- Fair agreement, 10% rate deficiency
- MPI uncertainties largest at low $p_\perp(Z)$

Comparison to data for Z + jet production



- One-jet-rate too low by 10-20%
- Not conclusive on shape of leading jet $p_\perp$
- Reminder: Large exponentiation uncertainties

Comparison to data for Z + jet production



- Angular correlations of Z-boson and leading jet
- Shape of rapidity distributions matched fairly well
- Significant deviations for azimuthal correlation:
  Back-to-back works, but $\Delta\phi < \pi$ is underestimated.
  That region is generated by emissions beyond the first one $\Rightarrow$ only LO/PS accuracy

Conclusions

Summary

- NLO+PS matching was presented in common formalism
- POWHEG and MC@NLO developed as special cases
- Uncertainties from exponentiation ambiguities are large but understood
- Scale and non-perturbative uncertainties relatively small
- First NLO+PS predictions for h + jet
- W/Z + jet compared to experimental data

Outlook

- Improved functional form of dipole α could allow for better limitation of exponentation
- Merging NLO+PS with higher-multiplicity tree-level MEs can provide better description of multi-jet final states ($\rightarrow$ e.g. MENLOPS)
- Ultimate goal: Merging of NLO at different multiplicities + parton shower