W + jet production at NLO QCD and electroweak accuracy matched to Parton Shower

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Outline

1. Introduction
    - Motivations
    - What are we aiming at?
2. `POWHEG + MiNLO` method
    - The `POWHEG` method
    - Treatment of Resasonance in `VRES`
    - `MiNLO` method
3. Matching to Parton Shower
    - Strategy
    - Phenomenological results at the LHC
4. Summary

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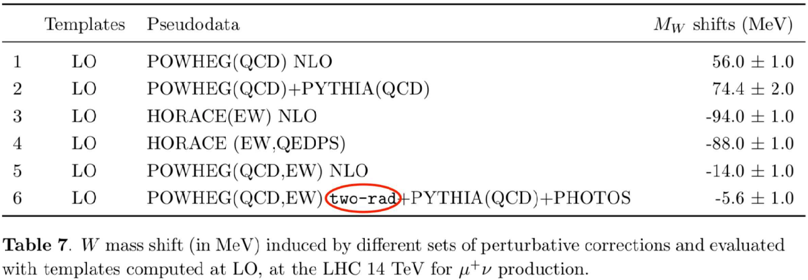
Implementation in `POWHEG-BOX-RES`

- `POWHEG-BOX-RES` generator: a resonance-aware implementation of the `POWHEG` algorithm ⇒ improve the treatment of processes with real radiation in the presence of decaying resonances
  - e.g., Wj: improves prediction around W-resonance

Precision Measurement of the W–Boson Mass:
Theoretical Contributions and Uncertainties

C. Carloni Calame *et al.* Phys.Rev. **D96** (2017) no.9, 093005



	Templates	Pseudodata	M_W shifts (MeV)
1	LO	POWHEG(QCD) NLO	56.0 ± 1.0
2	LO	POWHEG(QCD)+PYTHIA(QCD)	74.4 ± 2.0
3	LO	HORACE(EW) NLO	-94.0 ± 1.0
4	LO	HORACE (EW,QEDPS)	-88.0 ± 1.0
5	LO	POWHEG(QCD,EW) NLO	-14.0 ± 1.0
6	LO	POWHEG(QCD,EW) `two-rad`+PYTHIA(QCD)+PHOTOS	-5.6 ± 1.0

Table 7. W mass shift (in MeV) induced by different sets of perturbative corrections and evaluated with templates computed at LO, at the LHC 14 TeV for $\mu^+\nu$ production.

W + 1 jet NLO QCD + EW using `POWHEG + MiNLO`

- Full set of NLO QCD + electroweak corrections to W + 1 jet
  1. NLO QCD ($\mathcal{O}\left(\alpha^2\alpha_s^2\right)$) + EW ($\mathcal{O}\left(\alpha^3\alpha_s\right)$) for Wj
  2. NLO QCD ($\mathcal{O}\left(\alpha^3\alpha_s\right)$) for $W\gamma$
  3. Photon-induced & mixed interference contributions ($\mathcal{O}\left(\alpha^3\alpha_s\right)$)
- Relevant calculations are implemented in the `RES` version of POWHEG-BOX using `POWHEG + MiNLO` approach
  1. Inclusion of contributions of electroweak nature and treatment of reasonances developed in `POWHEG-RES`: a step further w.r.t. QCD NLO+PS result
  2. Use of `MiNLO` (**M**ulti-scale **i**mproved **NLO**) enables the predictions for inclusive W production at finite transverse momentum (small p_T cut ≈ inclusive result)

Outline

Master Formula and Algorithm

- `POWHEG`: **PO**sitive **W**eight **H**ardest **E**mission **G**enerator

  P.Nason (2004); S.Frixione *et al.* (2007); S.Alioli *et al.* (2010)

`POWHEG` cross section with hardest event generation

$$d\sigma = \sum_{f_b} \bar{B}^{f_b}\left(\boldsymbol{\Phi}_n\right) d\boldsymbol{\Phi}_n \left\{ \Delta^{f_b}\left(\boldsymbol{\Phi}_n, p_T^{\min}\right) \right.$$

$$\left. + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \frac{\left[d\Phi_{\text{rad}} \theta\left(k_T - p_T^{\min}\right) \Delta^{f_b}\left(\boldsymbol{\Phi}_n, k_T\right) R\left(\boldsymbol{\Phi}_{n+1}\right)\right]_{\alpha_r}^{\bar{\boldsymbol{\Phi}}_n^{\alpha_r} = \boldsymbol{\Phi}_n}}{B^{f_b}\left(\boldsymbol{\Phi}_n\right)} \right\}$$

Master Formula and Algorithm

- Cross section at NLO accuracy: $\bar{B}^{f_b}(\mathbf{\Phi}_n)$

$$\begin{aligned}\bar{B}^{f_b}(\mathbf{\Phi}_n) = {} & \left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)\right]_{f_b} \\ & + \sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \left[d\Phi_{\mathrm{rad}} \left\{R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1})\right\}\right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n} \\ & + \sum_{\alpha_\oplus \in \{\alpha_\oplus | f_b\}} \int \frac{dz}{z} G_\oplus^{\alpha_\oplus}(\mathbf{\Phi}_{n,\oplus}) \\ & + \sum_{\alpha_\ominus \in \{\alpha_\ominus | f_b\}} \int \frac{dz}{z} G_\ominus^{\alpha_\ominus}(\mathbf{\Phi}_{n,\ominus})\end{aligned}$$

  - $\left[B(\mathbf{\Phi}_n) + V(\mathbf{\Phi}_n)\right]_{f_b}$: LO + virtual & integrated ct
  - $R(\mathbf{\Phi}_{n+1}) - C(\mathbf{\Phi}_{n+1})$: real contribution - ct
  - $G_\oplus^{\alpha_\oplus}(\mathbf{\Phi}_{n,\oplus})$, $G_\ominus^{\alpha_\ominus}(\mathbf{\Phi}_{n,\ominus})$: collinear remnants – finite leftover after adding PDF ct for IS collinear singularities

Master Formula and Algorithm

- Modified Sudakov form factor: $\Delta^{f_b}\left(\mathbf{\Phi}_n, p_T\right)$

$$\Delta^{f_b}\left(\mathbf{\Phi}_n, p_T\right) = \exp\left\{ -\sum_{\alpha_r \in \{\alpha_r | f_b\}} \int \frac{\left[d\Phi_{\text{rad}}\theta\left(k_T\left(\mathbf{\Phi}_{n+1}\right) - p_T\right) R\left(\mathbf{\Phi}_{n+1}\right)\right]_{\alpha_r}^{\bar{\mathbf{\Phi}}_n^{\alpha_r} = \mathbf{\Phi}_n}}{B^{f_b}\left(\mathbf{\Phi}_n\right)} \right\}$$

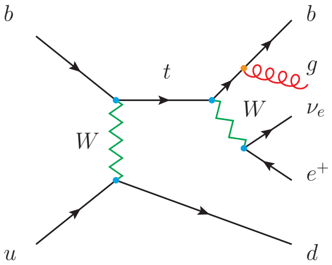
  - $k_T\left(\mathbf{\Phi}_{n+1}\right)$: a function in real phase space and is equal to the transverse momemtun of the emitted parton in soft/collinear limit.

- Algorithm for generation of radiation
  - i The probability of generating the hardest radiation $\propto\ d\Delta^{f_b}$
  - ii Each singular region has a Sudakov form factor $\Delta^{f_b} = \prod_{\alpha_r \in \{\alpha_r | f_b\}} \Delta_{\alpha_r}^{f_b}$
  - iii Use the so called "highest bid method" to generate one p_T for each singular region and then pick the largest one
  - iv Following the hardest radiation, subsequent radiations are simulated via PS, and are vetoed if harder than the `POWHEG` generated radiation

Problems to be addressed

- Up-to-date framework `POWHEG-BOX-RES` T.Ježo and P.Nason (2015)
  - The subtraction method and nd resonances
  - NLO + PS and resonances

I subtraction method and resonances



Catani-Seymour subtraction scheme

$$\bar{k}_b = k_b + k_g - k_\oplus \frac{(k_b + k_g)^2}{2\,(k_b + k_g)\cdot k_\oplus}, \ \bar{k}_b^2 = 0$$

$$\bar{k}_\oplus = k_\oplus - k_\oplus \frac{(k_b + k_g)^2}{2\,(k_b + k_g)\cdot k_\oplus}$$

$$\Delta k_t = k_\oplus \frac{(k_b + k_g)^2}{2\,(k_b + k_g)\cdot k_\oplus} \approx \frac{m_{bg}^2}{E_{bg}}$$

Real and subtraction terms match only if: $\boxed{m_{bg}^2 \ll \Gamma_t E_{bg}}$

Problems to be addressed

II NLO + PS and resonances

Radiation is generated according to a Sudakov form factor

$$\Delta\left(p_T^2\right) = \exp\left[-\int d\Phi_{\rm rad}\theta\left(k_T\left(\Phi_{\rm rad}\right) - p_T\right)\frac{R\left(\mathbf{\Phi}_{n+1}\right)}{B\left(\mathbf{\Phi}_n\right)}\right]$$

- Mapping of the real phase space $\mathbf{\Phi}_{n+1} \mapsto \Phi_{\rm rad} \otimes \mathbf{\Phi}_n$ is the same as in NLO subtraction precedure, and it will not preserve reasonance masses, so that R and B in general are not on the reasonance peak at the same time. E.g., R is on reasonance peak while B is not $(R/B \to \infty)$ $\Rightarrow$ badly violates collinear approximation.
- A further problem arises when interfacing NLO + PS caculation to a shower generator to generate next-to-hardest radiation. Radiation should have a reasonance assignment to instruct SMC to preserve the mass of the reasonances.

Reasonance-aware implementation in VRES generator

- New phase space mappings have been introduced to preserve the invariant masses of reasonances, and the corresponding soft/collinear subtraction terms have been modified accordingly.

- The hardest radiation is selected for each one of the resonances of the underlying Born (UB) process.

MiNLO method[1]

- **M**ulti-scale **i**mproved **NLO**
- Originally developed as an algorithm for the optimal choice of scales in NLO QCD calculations (massive colorless systems + $n-$jets; MiNLO formulation on backup slides)

Scale choice in QCD processes

$$P = \frac{d\sigma}{d\Phi} = \alpha_s^N(\mu_R)\,B + \alpha_s^{N+1}(\mu_R)\left[V + N\ b_0 \log\frac{\mu_R^2}{Q^2}\ B\right] + \alpha_s^{N+1}(\mu_R)\,R,$$

$$\frac{\partial P}{\partial \log \mu_R} = -N\ b_0 \alpha_s^{N+1}(\mu_R)\,B + N\ b_0 \alpha_s^{N+1}(\mu_R)\,B + \mathcal{O}\left(\alpha_s^{N+2}\right)$$

$$\alpha_s^N(\mu_R)\,B \Rightarrow \prod_{i=1}^{N} \alpha_s(q_i)\,B; \quad \mu_R \to \mu_R \doteq \left[\prod_{i=1}^{N} q_i\right]^{1/N}$$

- As a byproduct, it provides the suppression for the QCD singularities of the LO process preserving the NLO accuracy of the calculation

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[1] K.Hamilton *et al.*, JHEP **1210** (2012), JHEP **1305** (2013)

Wj production using `MiNLO`: remark

- `MiNLO` is mandatory for Wj UB

- For $W\gamma$ UB `MiNLO` is used in order to improve the α_s scale choice in the QCD corrections

- The singularities of $W\gamma$ UB are removed by small generation cuts

$$p_{T,\gamma}^{\text{min}} \ll p_{T,\gamma}^{\text{exp.cut}}, \quad \Delta R^{\text{min}}\left(\gamma, l\right) \ll \Delta R^{\text{exp.cut}}\left(\gamma, l\right)$$

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Strategy for the PS matching

`POWHEG-BOX-RES` generates up to one real radiation for each of reasonance structures of UB under consideration

- Two possible reasonances for W + 1 jet process: W (FS) and initial states + 1 jet (IS)
  1. $pp \to W\gamma$ without radiation;

     QCD & QED PS: `rad_ptsqmin = 0.8` GeV^2
  2. $pp \to W\gamma$ + one IS QCD radiation;

     QCD & QED PS: relative p_T of IS QCD radiation
  3. $pp \to Wj$ without radiation;

     IS PS: `rad_ptsqmin = 0.8` GeV^2; FS QED PS: `rad_ptsqmin_em = ` 10^{-6} GeV^2
  4. $pp \to Wj$ + one IS QCD or QED radiation;

     IS PS: relative p_T of IS radiation; FS QED PS: `rad_ptsqmin_em = ` 10^{-6} GeV^2
  5. $pp \to Wj$ + one FS QED radiation;

     IS PS: `rad_ptsqmin = 0.8` GeV^2; FS QED PS: relative p_T of FS QED radiation
  6. $pp \to Wj$ + one IS QCD or QED radiation + one FS QED radiation.

     IS PS: relative p_T of IS radiation; FS QED PS: relative p_T of FS QED radiation

Strategy for the PS matching

- If the photon-induced processes are included:
  1. New lepton- and (some) photon-induced UB with W exchaged at $t-$channel ⇒ only resonance structure is the hard process itself.
  - Choice: `POWHEG` generates up to one radiation ⇒ as in the case of Wγ UB

- Interface with `PYTHIA8.2`

Showered results compared with $W\gamma$ `V2`

- Perform a tuned comparison between Wj `VRES` and $W\gamma$ `V2` (no EW corrections, photon-induced and mixed interference contributions in Wj `VRES`)
- W production accompanying at least one jet at $\sqrt{S} = 13$ TeV LHC[2] (in order to include photon PDF, we use `NNPDF31_nlo_as_0118_luxqed`)
  1. Muon selection criteria:
  $$p_{T,\mu} > 25 \text{ GeV}, \ |\eta_\mu| < 2.4$$
  2. Jet selection criteria:
  $$p_{T,j} > 30 \text{ GeV}, \ |y_j| < 2.4; \ Anti - k_T, \ R = 0.4$$
  3. Spatial separation between moun and jet:
  $$\Delta R > 0.4$$
  4. Invariant transeverse mass cut:
  $$\begin{aligned} &m_T > 50 \text{ GeV}, \\ &m_T\left(\mu, \vec{p}_T^{\,\text{miss}}\right) \equiv \sqrt{2 p_T^\mu E_T^{\text{miss}} \left(1 - \cos\Delta\phi\right)}, \\ &\cos\Delta\phi = \vec{p}_T^{\,\mu} \cdot \vec{p}_T^{\,\text{miss}} / |\vec{p}_T^{\,\mu}||\vec{p}_T^{\,\text{miss}}| \end{aligned}$$

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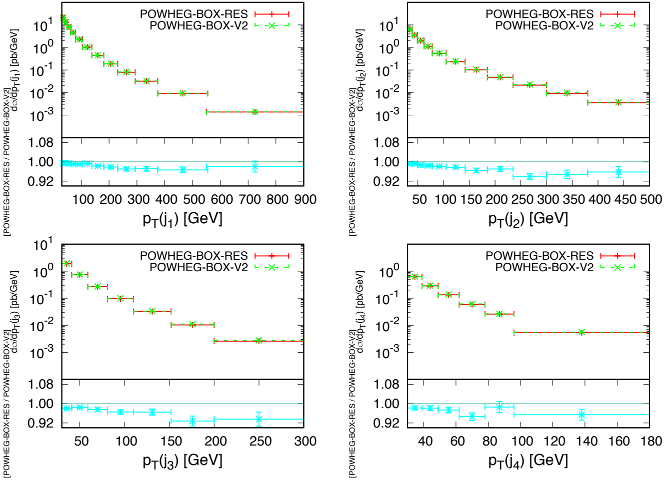
[2] Acceptance cuts are adopted from A.M.Sirunyan *et al.* (CMS Collaboration), Phys. Rev. **D 96**, 072005 (2017)

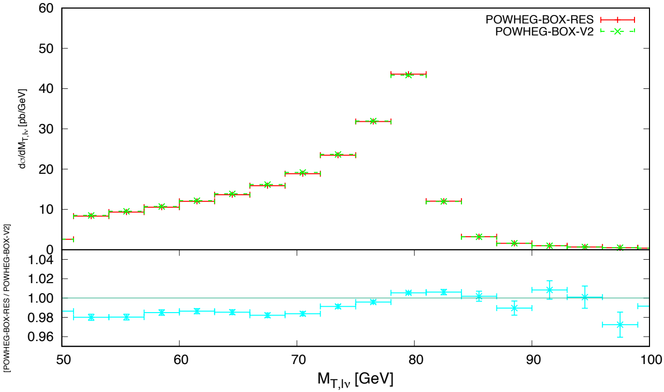
Showered result compared with $W\gamma$ V2

Differential cross section as a function of transverse momentum of the 1st - 4th leading jets



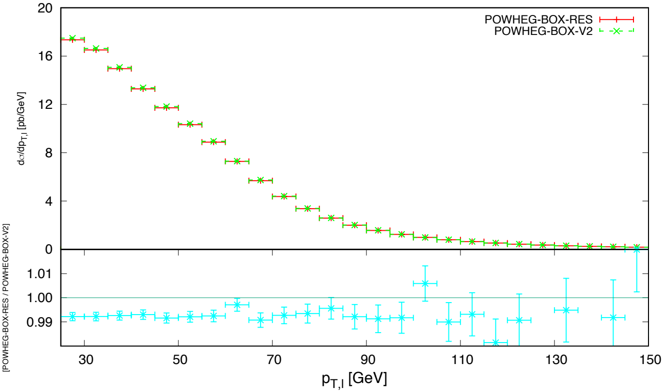
Showered result compared with $W\gamma$ `V2`

Differential cross section as a function of the transverse mass of lepton-neutrino pair



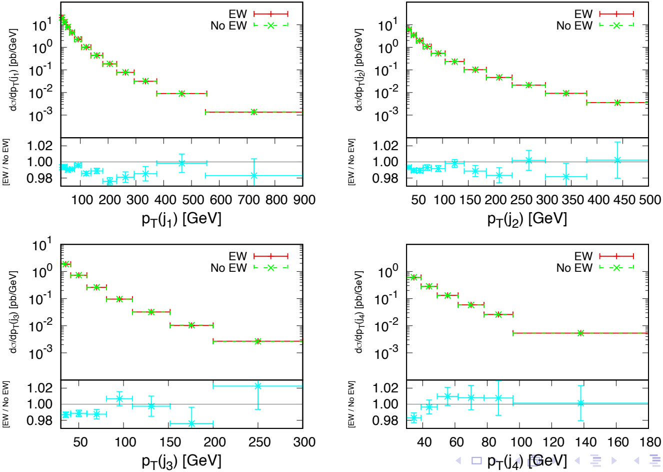
Showered result compared with $W\gamma$ V2

Differential cross section as a function of the transverse momentum of the charged lepton



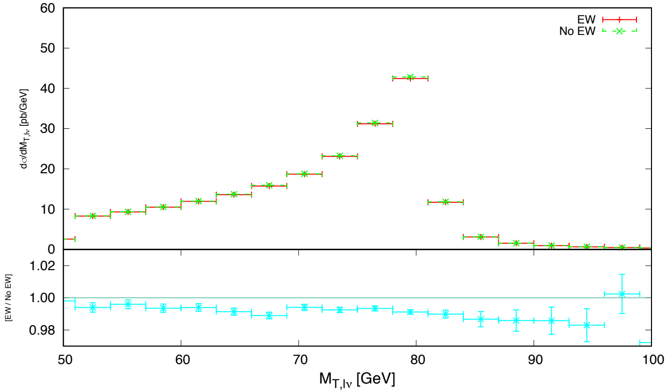
Estimate the significance of the EW contribution

- Comparison between Wj production with and without EW corrections; events are generated by `VRES`
- Transverse momentum of jets distribution



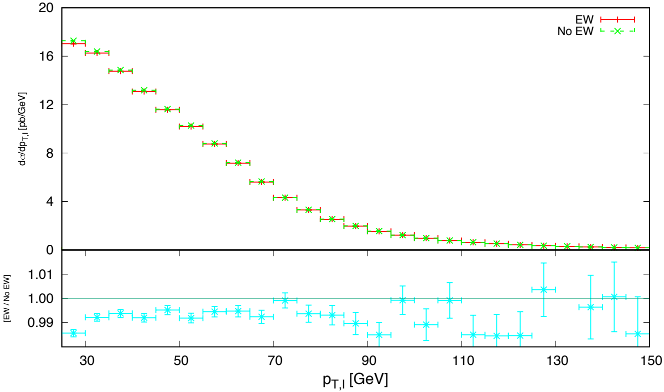
Estimate the significance of the EW contribution

- Transverse mass of lepton-neutrino pair distribution



Estimate the significance of the EW contribution

- Transverse momemtum of the charged lepton



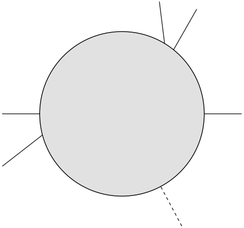
Outline

Summary

- Brief introduction of the `POWHEG-RES` machinery and `MiNLO` approach
- `POWHEG` merging (with `PYTHIA8.2`)
- Comparison between `POWHEG V2` and `POWHEG VRES` versions
- Electroweak corrections to W + jet production
- Remark: the (relative) EW corrections are expected as a few percent ⇒ error needs be under well control (current result with 1.44×10^8 events ⇒ ? $\sim$ 1 billion)

MiNLO method[3]

- **M**ulti-scale **i**mproved **NLO**
- Originally developed as an algorithm for the optimal choice of scales in NLO QCD calculations (massive colorless systems + $n-$jets)
- As a byproduct, it provides the suppression for the QCD singularities of the LO process preserving the NLO accuracy of the calculation



☐ Primary system + n partons
  - $m+n$ powers of α_s
  - $m \in$ primary system (typically 0)
  - $n \in$ QCD splitting
  - $M_{LO} \doteq \alpha_s^{m+n}(\mu)\,B$

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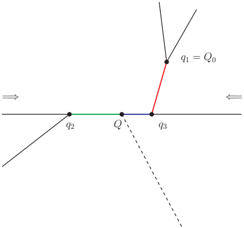
[3] K.Hamilton *et al.*, JHEP **1210** (2012), JHEP **1305** (2013)

MiNLO formulation



- Primary system + n partons
  - Cluster external partons (k_T algorithm)
  - $Q \doteq$ virtuality of primary system
  - $Q_0 \doteq q_1$ resolution scale
  - $\alpha_s^{m+n}(\mu)\,B \Rightarrow \alpha_s^m(Q)\prod_{i=1}^{n}\alpha_s(q_i)\,B$

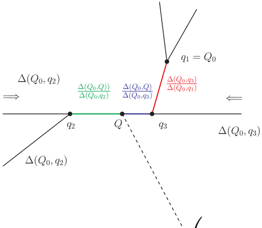
Scale choice in QCD processes

$$P = \frac{d\sigma}{d\Phi} = \alpha_s^N(\mu_R)\,B + \alpha_s^{N+1}(\mu_R)\left[V + N\ b_0 \log\frac{\mu_R^2}{Q^2}\ B\right] + \alpha_s^{N+1}(\mu_R)\,R,$$

$$\frac{\partial P}{\partial \log \mu_R} = -N\ b_0 \alpha_s^{N+1}(\mu_R)\,B + N\ b_0 \alpha_s^{N+1}(\mu_R)\,B + \mathcal{O}\left(\alpha_s^{N+2}\right)$$

MiNLO formulation

- In order to keep this feature, when using multi-scale couplings at LO, i.e., $\alpha_s^{m+n}(\mu_R)\,B \Rightarrow \alpha_s^m(Q)\prod_{i=1}^{n}\alpha_s(q_i)\,B$, in the explicitly scale dependent terms of V set the scale to be the geometric mean of the multi-scale set: $\mu_R \to \mu_R \doteq \left[Q^m \times \prod_{i=1}^{n} q_i\right]^{\frac{1}{m+n}}$



☐ Primary system + n partons

  - Insert a Sudakov form factor for each colored line
  - Subtract effective NLO correction introduced via Sudakovs in the Born term, i.e.,

$$B \Rightarrow B \times \left(1 - \sum_{ij}\left[\Delta^{(1)}_{f_{ij}}(Q_0, q_i) - \Delta^{(1)}_{f_{ij}}(Q_0, q_j)\right] - \sum_{l}\Delta^{(1)}_{f_l}(Q_0, k_l)\right)$$

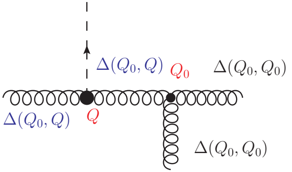
MiNLO example: H + 1 jet

- Pure NLO:

$$d\sigma = \bar{B} d\mathbf{\Phi}_n = \alpha_s^3(\mu_R)\left[B + \alpha_s V(\mu_R) + \alpha_s \int d\Phi_{\mathrm{rad}} R\right] d\mathbf{\Phi}_n$$

- MiNLO:

$$\bar{B} = \alpha_s^2(M_H)\,\alpha_s(q_T)\,\Delta_g^2(q_T, M_H)\left[B\left(1 - 2\Delta_g^{(1)}(q_T, M_H)\right) + \bar{\alpha}_s V(\bar{\mu}_R) + \bar{\alpha}_s \int d\Phi_{\mathrm{rad}} R\right]$$



- $Q = M_H, \quad Q_0 = q_T$
- $\bar{\mu}_R = \left(Q^2\, Q_0\right)^{1/3} = \left(M_H^2\, q_T\right)^{1/3}$
- $\log \Delta_f(Q_0, Q) = -\int_{Q_0^2}^{Q^2} \frac{dq^2}{q^2} \frac{\alpha_s\left(q^2\right)}{2\pi}\left[A_f \log\frac{Q^2}{q^2} + B_f\right]$
- $\Delta_f^{(1)}(Q_0, Q) = -\frac{\alpha_s}{2\pi}\left(\frac{1}{2} A_{1,f} \log^2\frac{Q^2}{Q_0^2} + B_{1,f}\log\frac{Q^2}{Q_0^2}\right)$
- $\bar{\alpha}_s = \frac{1}{3}\left(2\alpha_s(M_H) + \alpha_s(q_T)\right)$
- $\mu_F = Q_0 = q_T$

MiNLO main body