POWHEG: matching NLO QCD with SMC

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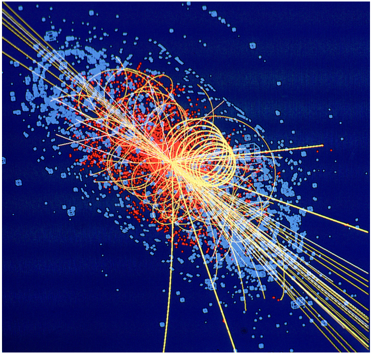
Outline



- The POWHEG method: implementation details and issues
- The POWHEG BOX: overview of available processes
- Practical recipe to merge V+jets NLO samples
- Conclusions & Outlook

The POWHEG method

The POWHEG method [Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

1. **Generates only the hardest emission including full tree level real matrix element and virtual corrections.**
2. **The shower generates subsequent emissions, performing (N)LL resummation of collinear/soft logs.**
3. **Vetoing emissions harder than the first is required to avoid double-counting.**

NLO differential cross section:

- **Phase space factorization :** $d\Phi_{n+1} = d\Phi_n \, d\Phi_{\rm rad} \qquad d\Phi_{\rm rad} \div dt \, dz \, \frac{d\varphi}{2\pi}$
- **NLO cross section at fixed underlying Born kinematics:** $d\sigma_{\tt NLO} = \bar{B}(\Phi_n) d\Phi_n d\Phi_{\rm rad}$

$$d\sigma_{\tt NLO} = \left\{ B(\Phi_n) + V(\Phi_n) + \left[\underbrace{\overbrace{R(\Phi_n,\Phi_{\rm rad})}^{\rm IRdivergent} - \overbrace{C(\Phi_n,\Phi_{\rm rad})}^{\rm IRdivergent}}_{\rm finite} \right] d\Phi_{\rm rad} \right\} d\Phi_n$$

$$V(\Phi_n) = \underbrace{\overbrace{V_b(\Phi_n)}^{\rm IRdivergent} + \overbrace{\int C(\Phi_n,\Phi_{\rm rad}) \, d\Phi_{\rm rad}}^{\rm IRdivergent}}_{\rm finite}$$

The POWHEG method

[Nason JHEP,2004] [Frixione,Nason,Oleari JHEP,2007]

SMC differential cross section for first emission:

$$d\sigma_{\texttt{SMC}} = \overbrace{B(\Phi_n)}^{Born}\, d\Phi_n \left\{ \Delta_{\texttt{SMC}}(t_0) + \Delta_{\texttt{SMC}}(t) \overbrace{\frac{\alpha_S(t)}{2\pi}\frac{1}{t}P(z)}^{\lim_{k_T\to 0} R(\boldsymbol{\Phi}_{n+1})/B(\boldsymbol{\Phi}_n)} d\Phi_{\rm rad}^{\texttt{SMC}} \right\}$$

$$\Delta_{\texttt{SMC}}(t) = \underbrace{\exp\left[-\int d\Phi'_{\rm rad}\frac{\alpha_S(t')}{2\pi}\frac{1}{t'}P(z')\,\theta(t'-t)\right]}_{\texttt{SMC}\ Sudakov}$$

- **The event weight is $B(\Phi_n)$**
- **$\Delta_{\texttt{SMC}}(t)$ is the probability of not emitting at a scale greater than t (q^2, θ^2, p_T^2)**
- **Unitarity ensures that what is inside $\left\{\ldots\right\}$ does not change the cross section (up to t_0 power suppressed terms)**

The POWHEG differential cross section :

$$d\sigma_{\mathtt{POWHEG}} = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta_{\mathtt{POWHEG}}(\Phi_n, p_{\mathrm{T}}^{\mathrm{min}}) + \Delta_{\mathtt{POWHEG}}(\Phi_n, k_{\mathrm{T}}) \frac{R(\Phi_n, \Phi_{\mathrm{rad}})}{B(\Phi_n)}\, d\Phi_{\mathrm{rad}} \right\}$$

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✓ **NLO cross section for inclusive quantities. Event weight is** $\bar{B}(\Phi_n)$

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- ✓ **NLO cross section for inclusive quantities. Event weight is** $\bar{B}(\Phi_n)$
- ✓ $\bar{B} = B(\Phi_n) + V(\Phi_n) + \int \left[R(\Phi_n, \Phi_{\mathrm{rad}}) - C(\Phi_n, \Phi_{\mathrm{rad}})\right] d\Phi_{\mathrm{rad}} < 0$

  Negative weights where NLO $>$ LO, i.e. where perturbative expansion breaks down!

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$$\Delta_{\texttt{POWHEG}}(\Phi_n, p_{\mathrm{T}}) = \exp\left[- \int d\Phi'_{\mathrm{rad}} \frac{R(\Phi_n, \Phi'_{\mathrm{rad}})}{B(\Phi_n)} \theta\left(k_{\mathrm{T}}(\Phi_n, \Phi'_{\mathrm{rad}}) - p_{\mathrm{T}}\right) \right]$$

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- ✓ **It has the same logarithmic accuracy of the SMC. In the soft/collinear region** $k_T \to 0$

$$\frac{R(\Phi_n, \Phi_{\rm rad})}{B(\Phi_n)} d\Phi_{\rm rad} \approx \frac{\alpha_S(t)}{2\pi} \frac{1}{t} P(z)\, dt\, dz\, \frac{d\varphi}{2\pi} \qquad \textbf{and} \qquad \bar{B} \approx B\left(1 + \mathcal{O}(\alpha_S)\right)$$

The POWHEG method

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✓ **The accuracy of NLO is preserved in the hard region, since $\Delta_{\texttt{POWHEG}}(\Phi_n, p_T) \approx 1$ and**

$$d\sigma_{\texttt{POWHEG}} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\Phi_n, \Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad} \approx R(\Phi_n, \Phi_{\rm rad})\,(1 + \mathcal{O}(\alpha_S))\, d\Phi_n\, d\Phi_{\rm rad}$$

NLO accuracy of POWHEG formula (1)

- **Use the POWHEG formula**

$$d\sigma = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) + \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)}\, \theta(k_T - p_T^{\min})\, d\Phi_{\rm rad} \right\}$$

- **to calculate the expectation value of a generic observable** $< \mathcal{O} > =$

$$= \int \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_T^{\min}) O_n(\Phi_n) + \int_{p_T^{\min}} \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} O_{n+1}(\Phi_{n+1})\, d\Phi_{\rm rad} \right\}$$

$$= \int \bar{B}(\Phi_n)\, d\Phi_n \left\{ \left[\Delta(\Phi_n, p_T^{\min}) + \int_{p_T^{\min}} \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)}\, d\Phi_{\rm rad} \right] O_n(\Phi_n) \right.$$

$$\left. + \int_{p_T^{\min}} \Delta(\Phi_n, k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \left[O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n) \right]\, d\Phi_{\rm rad} \right\}$$

- O_n, O_{n+1} **are the actual forms of** $\mathcal{O}$ **in the** $n, n+1$**-body phase space.**
- $\mathcal{O}$ **is required to be infrared-safe and to vanish fast enough when two singular regions are approached at the same time**

NLO accuracy of POWHEG formula (2)

- **Now observe that**

$$\int_{p_T^{\min}} d\Phi_{\rm rad} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, k_T) = \int_{p_T^{\min}}^{\infty} dp'_T \int d\Phi_{\rm rad}\, \delta(k_T - p'_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} \Delta(\Phi_n, p'_T)$$

$$= -\int_{p_T^{\min}}^{\infty} dp'_T \Delta(\Phi_n, p'_T) \frac{d}{dp'_T} \int_{p_T^{\min}} d\Phi_{\rm rad}\, \theta(k_T - p'_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)}$$

$$= \int_{p_T^{\min}}^{\infty} dp'_T \frac{d}{dp'_T} \Delta(\Phi_n, p'_T) = 1 - \Delta(\Phi_n, p_T^{\min})$$

- **Furthermore we can replace** $\bar{B}(\Phi_n) \approx B(\Phi_n)\,(1 + \mathcal{O}(\alpha_S))$
- **and also** $\Delta(\Phi_n, k_T) \approx 1 + \mathcal{O}(\alpha_S)$ **since** $[O_{n+1} - O_n] \to 0$ **at small** k_T**'s**
- **The final result is (up to** $p_T^{\min}$ **power-suppressed terms)**

$$< \mathcal{O} > = \int d\Phi_n \bar{B}(\Phi_n)\, 1\, O_n(\Phi_n)$$

$$+ \int 1 \frac{R(\Phi_{n+1})}{1} [O_{n+1}(\Phi_{n+1}) - O_n(\Phi_n)]\; d\Phi_{\rm rad} + \mathcal{O}(\alpha_S)$$

Does we have to exponentiate the full real contribution ?

- **No, separate the singular part of real contribution** $R = R^{\text{sing.}} + R^{\text{remn.}}$

$$
\begin{aligned}
d\sigma &= \overbrace{\bar{B}_{\text{sing.}}(\Phi_n)}^{\text{NLO}} \, d\Phi_n \overbrace{\left\{ \Delta_{\text{sing.}}(t_0) + \Delta_{\text{sing.}}(t) \frac{R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})}{B(\Phi_n)} \, d\Phi_{\text{rad}} \right\}}^{\text{sum to 1 by unitarity}} \\
&+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) \right]}_{\text{NLO}} d\Phi_n \, d\Phi_{\text{rad}}
\end{aligned}
$$

$$
\begin{aligned}
\bar{B}_{\text{sing}}(\Phi_n) &= B(\Phi_n) + V(\Phi_n) + \int \left[R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) - C(\Phi_n, \Phi_{\text{rad}}) \right] \, d\Phi_{\text{rad}} \\
\Delta_{\text{sing.}}(t) &= \exp\left[-\int d\Phi'_{\text{rad}} \frac{R^{\text{sing.}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta\left(t' - t\right) \right]
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$$+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}) - R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) \right]}_{\text{NLO}} d\Phi_n\, d\Phi_{\text{rad}}$$

- **In POWHEG :** $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}}) = F(\Phi_n, \Phi_{\text{rad}}) \times R(\Phi_n, \Phi_{\text{rad}})$**, with** $0 \leq F \leq 1$**, and** $F(\Phi_n, \Phi_{\text{rad}}) \to 1$ **in the soft/collinear limit.**

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Example: ***e.g.*** $F = h^2/(h^2 + p_T^2)$**. The value of** h **must be chosen considering that**

- **For** $h \to 0 \implies F \to 0$ **one recovers pure NLO results, but the Sudakov region is squeezed and distorted. Positivity may also be lost.**
- $h \to \infty \implies F \to 1$ **corresponds to the exponentiation of all the real contributions. The simplest choice** $F \equiv 1$ **is often adopted.**

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- **No, separate the singular part of real contribution** $R = R^{\text{sing.}} + R^{\text{remn.}}$

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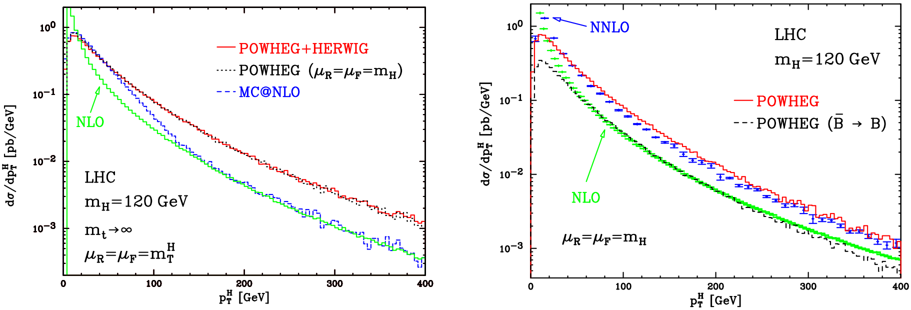
- **In MC@NLO :** $R^{\text{sing.}}(\Phi_n,\Phi_{\text{rad}}) = R_{\text{SMC}}(\Phi_n,\Phi_{\text{rad}}^{\text{SMC}})$ **is the shower approximation of a real emission**

Example: Higgs high$-p_{\rm T}$ behaviour



$$\bar{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int [R(\Phi_n,\Phi_{\rm rad}) - C(\Phi_n,\Phi_{\rm rad})]\, d\Phi_{\rm rad}$$

$$d\sigma = \bar{B}(\Phi_n)\, d\Phi_n \left\{ \Delta(\Phi_n, p_{\rm T}^{\rm min}) + \Delta(\Phi_n, p_{\rm T}) \frac{R(\Phi_n,\Phi_{\rm rad})}{B(\Phi_n)}\, d\Phi_{\rm rad} \right\}$$

if $p_{\rm T} >> 1 \quad \Rightarrow \quad \Delta(\Phi_n, p_{\rm T}) \approx 1$ **and**

$$d\sigma_{\bf rad} \approx \frac{\bar{B}(\Phi_n)}{B(\Phi_n)} R(\Phi_n,\Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad} \approx \underbrace{\{1+O(\alpha_{\rm S})\}}_{\approx\, 2 \text{ for } gg\to H} R(\Phi_n,\Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad}$$

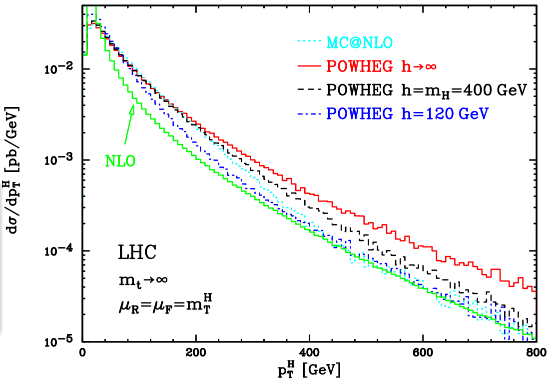
Reduction of real contribution entering the Sudakov FF

$$R = \underbrace{R \times F}_{singular} + \underbrace{R \times (1-F)}_{regular}$$
$$= R_{\bar{B}} + R_{\mathbf{reg}}$$

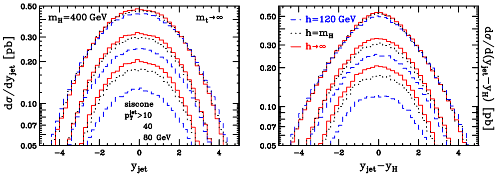
$F < 1, \qquad F \to 1$ **when** $p_T \to 0$,

$F \to 0$ **when** $p_T \to \infty$

$\Rightarrow \; F = \frac{h^2}{p_T^2 + h^2}$

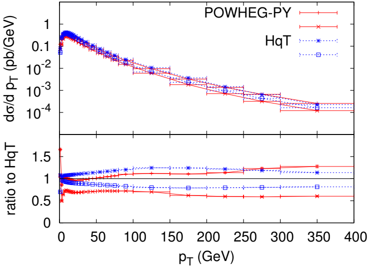


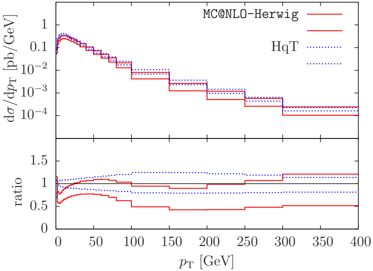
$$\sigma = \sigma_{\bar{B}} + \sigma_{\mathbf{reg}}$$
$$\sigma_{\bar{B}} = \int d\Phi_n \Big\{ B(\Phi_n) + V(\Phi_n) + \left[R_{\bar{B}}(\Phi_n, \Phi_{\rm rad}) - C(\Phi_n, \Phi_{\rm rad}) \right] d\Phi_{\rm rad} \Big\}$$
$$\sigma_{\mathbf{reg}} = \int R_{\mathbf{reg}}(\Phi_n, \Phi_{\rm rad})\, d\Phi_n\, d\Phi_{\rm rad}$$



Reduction of real contribution entering the Sudakov FF

- **Are we completely free in choosing the $R^{\text{sing.}}, R^{\text{remn.}}$ separation ? Giving up theoretical errors ? No, the resummed results can tell us where the separation is reasonable and where it's not.**

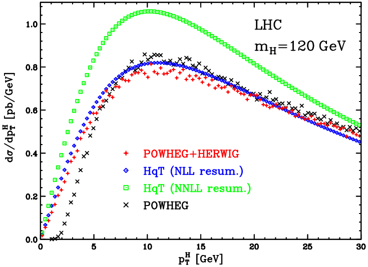




- **NLL for < 4 colored partons via**

$$\alpha_S \to \alpha_S \left\{ 1 + \frac{\alpha_S}{2\pi} \left[\left(\frac{67}{18} - \frac{\pi^2}{6} \right) C_A - \frac{5}{9} n_f \right] \right\}$$

[Catani et al., Nucl.Phys.B349]



- **MC@NLO in the POWHEG language**

$$d\sigma_{\texttt{MC@NLO}} = \overbrace{\bar{B}_{\texttt{SMC}}(\Phi_n)}^{\texttt{MC@NLO}\ \mathcal{S}-\text{event}} \quad d\Phi_n \overbrace{\left\{\Delta_{\texttt{SMC}}(t_0) + \Delta_{\texttt{SMC}}(t)\frac{R_{\texttt{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\texttt{SMC}})}{B(\Phi_n)}\, d\Phi_{\text{rad}}^{\texttt{SMC}}\right\}}^{\texttt{SMC}}$$

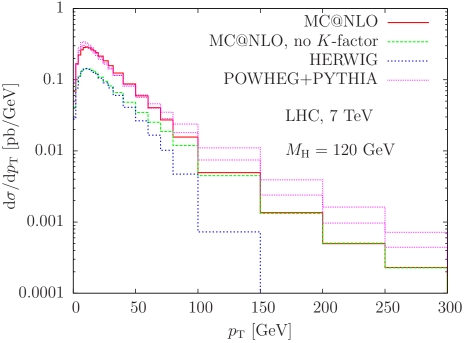
$$+ \quad \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}^{\texttt{SMC}}) - R_{\texttt{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\texttt{SMC}})\right]}_{\texttt{MC@NLO}\ \mathcal{H}-\text{event}} d\Phi_n\, d\Phi_{\text{rad}}^{\texttt{SMC}}$$

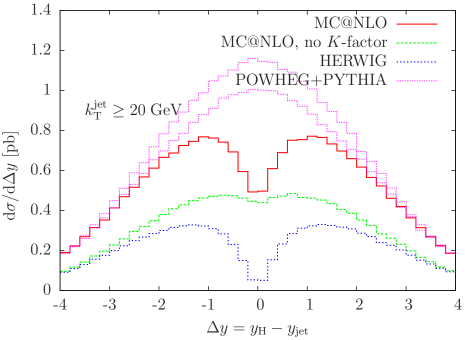
$$\bar{B}_{\texttt{SMC}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R_{\texttt{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\texttt{SMC}}) - C(\Phi_n, \Phi_{\text{rad}}^{\texttt{SMC}})\right] d\Phi_{\text{rad}}^{\texttt{SMC}}$$

$$\Delta_{\texttt{SMC}}(t) = \exp\left[-\int d\Phi'_{\text{rad}} \frac{R_{\texttt{SMC}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta\left(t' - t\right)\right] \quad \Leftarrow \textbf{HERWIG or PYTHIA Sudakov!}$$

MC@NLO

- **Difference arise formally only starting at NNLO. However, they may turn out to be sizable**





[Nason&Webber arXiv:1202.1251]

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$$+ \underbrace{\left[R(\Phi_n, \Phi_{\text{rad}}^{\text{SMC}}) - R_{\text{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\text{SMC}}) \right]}_{\text{MC@NLO } \mathcal{H}-\text{event}} d\Phi_n \, d\Phi_{\text{rad}}^{\text{SMC}}$$

$$\bar{B}_{\text{SMC}}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int \left[R_{\text{SMC}}(\Phi_n, \Phi_{\text{rad}}^{\text{SMC}}) - C(\Phi_n, \Phi_{\text{rad}}^{\text{SMC}}) \right] \, d\Phi_{\text{rad}}^{\text{SMC}}$$

$$\Delta_{\text{SMC}}(t) = \exp\left[- \int d\Phi'_{\text{rad}} \frac{R_{\text{SMC}}(\Phi_n, \Phi'_{\text{rad}})}{B(\Phi_n)} \theta\left(t' - t\right) \right]$$ $\Leftarrow$ **HERWIG or PYTHIA Sudakov!**

- **Difference arise formally only starting at NNLO. However, they may turn out to be sizable**

1. **enhancement by the ratio $\bar{B}(\Phi_n)/B(\Phi_n) \approx 1 + \mathcal{O}(\alpha_s)$**
2. **different scale choice used in different part of the process**
3. **different Sudakov factor $\Delta(p_{\rm T})$, which always reduce high-$p_{\rm T}$ spectrum $\Delta \leq 1$.**

- **All major differences found tracked back to 1. or 2. Exponentiation of different $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})$ does not seem to yield large differences since in the $p_T \to 0$ region which dominates the integral, all the $R^{\text{sing.}}(\Phi_n, \Phi_{\text{rad}})$ must be the same.**

Color coherence - truncated showers

- When interfaced to angular-ordered showers, POWHEG needs truncated showers to fully restore color coherence. This accounts for radiation larger in angle but smaller in p_{T} wrt the first one.
- If interfaced to $p_{\mathrm{T}}-$ordered showers, no such problem
- General feature of ME-shower matching with angular order: similar problem in CKKW approach.
- Truncated shower implemented in HERWIG$++$
- Are there visible effects due to lack of large angle soft-gluons ?

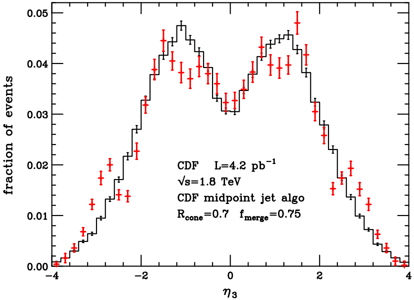
Color coherence produces a dip at $\eta_3 = 0$

$$|\eta_1|, |\eta_2| < 0.7,$$

$$||\phi_1 - \phi_2| - \pi| < 20^\circ$$

$$E_{\mathrm{T},1} > 110 \text{ GeV}$$

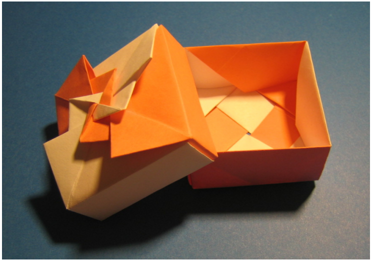
$$E_{T,3} > 10 \text{ GeV.}$$



[CDF Phys. Rev. D50]

The POWHEG BOX

The POWHEG BOX [S.A., Nason,Oleari,Re, JHEP 1006:043,2010]



- Framework for the implementation of a POWHEG generator for a generic NLO process
- Practical implementation of the theoretical construction of the POWHEG general formulation presented in [Frixione,Nason,Oleari,JHEP 0711:070, 2007]
- FKS subtraction approach automatically implemented, hiding all the technicalities
- Code publicly available at the web page http://powhegbox.mib.infn.it
- Few other groups implement their own version (SHERPA ,HERWIG++) or use the POWHEG BOX interfaced to specific NLO calculator (POWHEL)

Towards full automation

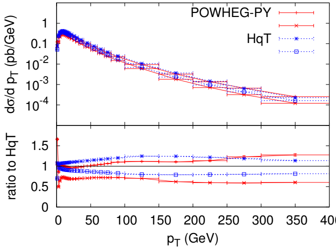
- To implement new processes the user was required to provide a few inputs. Now (almost) everything has been fully automated.
- However, the freedom of using dedicated routines at any stage is left.
- Ingredients:
    - The list of flavour of Borns and Reals $\Longleftarrow$ Madgraph
    - The Born phase space $\Longleftarrow$ Dedicated routines, recursive FKS, multi-channel
    - The Born squared amplitudes $\mathcal{B} = |\mathcal{M}|^2$, the color-ordered Born squared amplitudes $\mathcal{B}_{jk}$ and the helicity correlated Born squared amplitudes $\mathcal{B}_{k,\mu\nu}$ $\Longleftarrow$ Madgraph
    - The Real squared amplitudes $\mathcal{R}$ $\Longleftarrow$ Madgraph
    - The finite part of the interference of Born and virtual amplitude contributions $\mathcal{V}_{\mathrm{b}} = 2\mathrm{Re}\{\mathcal{B} \times \mathcal{V}\}$ $\Longleftarrow$ GoSam, BlackHat, MadLoop

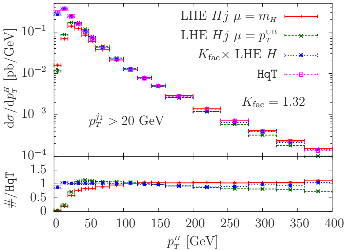
- Given these ingredients the `POWHEG BOX` automatically finds singular regions, performs the FKS subtraction and outputs the results of a NLO analysis.
- Then it produces events with a single extra radiation (or not), ready to be showered with your preferred SMC, via the Les Houches interface.
- Drivers for fortran SMC provided. Support of open standards allow for easy interface to modern `C++` SMC (`Pythia8, Herwig++`) and to the `Rivet` analysis toolkit

Overview of available processes :

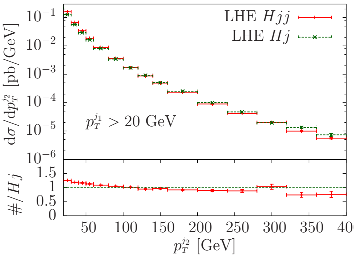
Higgs production

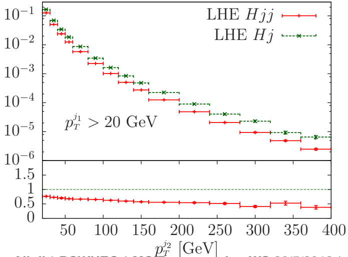
- **Gluon Fusion (Effective Theory) : H, H+1 jet , H +2 jets** [SA, Nason, Oleari & Re, JHEP 0904, 2009]
  [Campbell,Ellis, Frederix, Nason, Oleari & Williams, arXiv:1202.5475]





Results consistent with `Hqt`. Scale choice important for H+jets ($\mu = m_H$ vs. $\mu = p_{\rm T}^B, \hat{H}_T$)





Higgs production

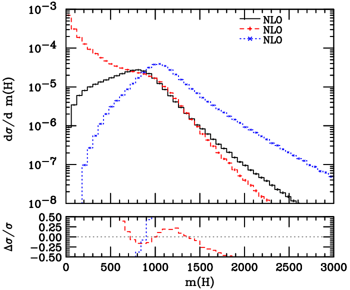
- **Included Higgs lineshape corrections in complex pole mass scheme [Passarino's prescription]**

$$\frac{M\Gamma(M)}{(M^2-\mu_H^2)^2+\mu_H^2\gamma_H^2}$$

$$M_H,\Gamma_H \Rightarrow \mu_H,\gamma_H$$

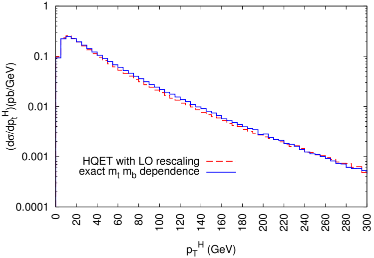
complex pole at $\mu_H + i\gamma_H$

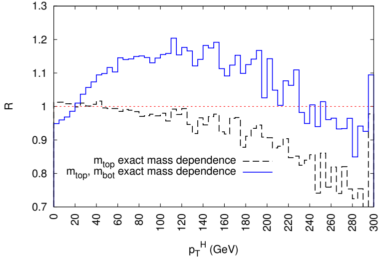
$M_H = 1$ TeV$, \Gamma_H = 647$ GeV



- **Scalar and Pseudo-Scalar production via gluon fusion in the SM and MSSM, including full m_t and m_b dependence**

[Bagnaschi,De Grassi,Slavich & Vicini, JHEP 1202]

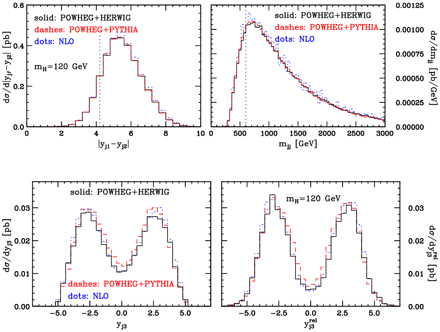




Higgs production

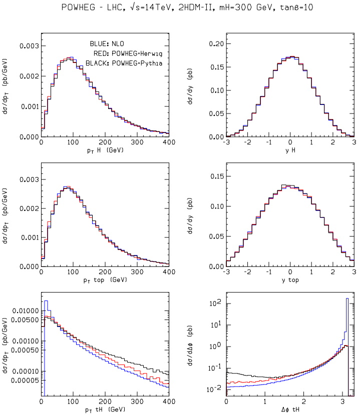
- **Vector Boson Fusion**

[Nason & Oleari,JHEP 1002, 2010]



Associated production top-quark – charged Higgs

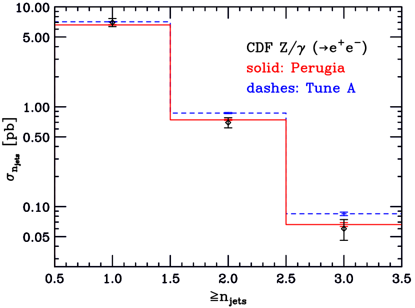
[Klasen, Kovarik, Nason & Weydert arXiv:1203.134]

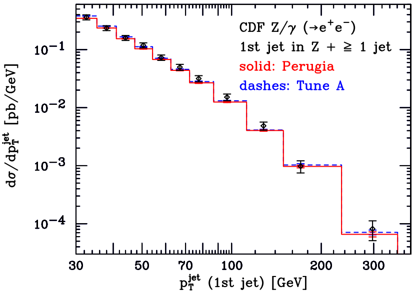


- **Vector Boson, $W, Z/\gamma$ + 0,1 jet, with leptonic decays and correlations**

[SA, Nason,Oleari & Re, JHEP 0807, 2008]

[SA, Nason, Oleari & Re, JHEP 1101, 2011]

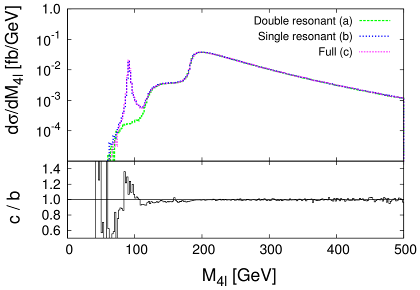


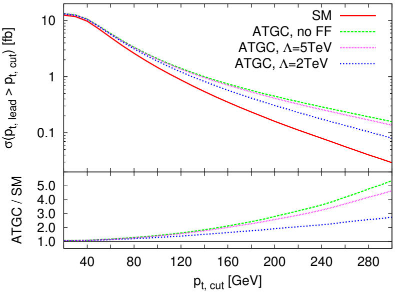


Vector Bosons

- **Vector Boson pairs , ZZ, WW, WZ with Z/γ, identical fermion interference, off-shell effects, ATGC and decays**

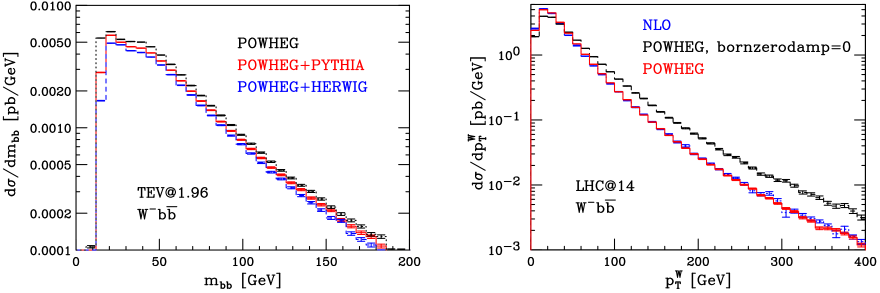
[Melia, Nason, Rontsch, Zanderighi JHEP 1111, 2011]





Vector Bosons

- $Wb\bar{b}$ **with massive** b**'s and** W **leptonic decay** [Oleari, Reina, JHEP 1108]



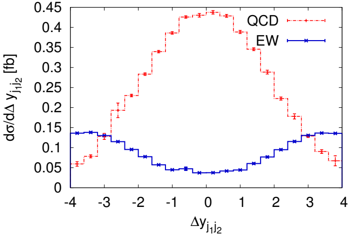
- **High-**$p_{\rm T}$ **enanchemenmt originally attributed to large** $K-$**factor turned out to be due to** $B \to 0$ **in** $R(\Phi_{n+1})/B(\Phi_n)$ **. General solution was already presented for single** W **production (`bornzerodamp`).**

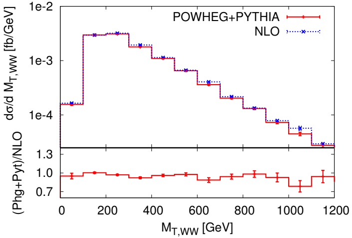
Vector Bosons

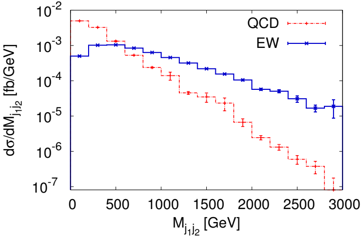
- W^+W^+ **plus two jets (QCD and EW)**

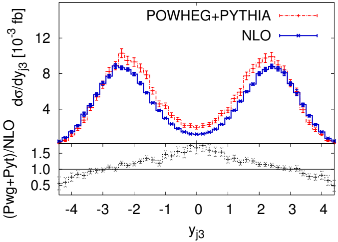
[Melia et al. Eur.Phys.J. C71 (2011) 1670]

[Jaeger,Zanderighi JHEP 1111 (2011) 055]









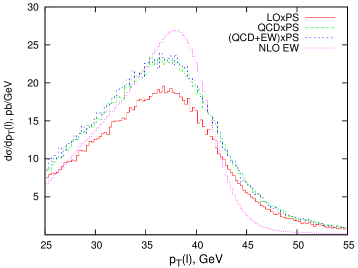
Vector Bosons

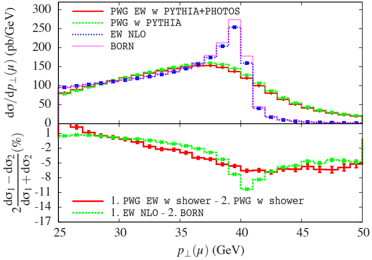
- **Single Vector Boson QCD + EW**

[Bernaciak, Wackeroth, arXiv:1201.4804]

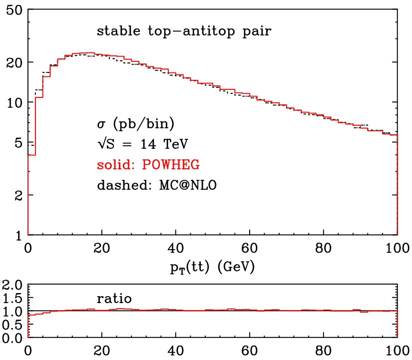
[Barzè, Montagna, Nason, Nicrosini, Piccinini, arXiv:1202.0465]

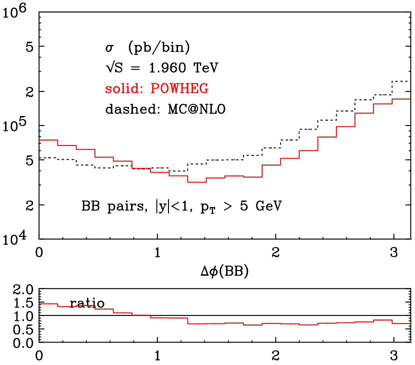
- **Two different implementation: NLO QCD + NLO EW interfaced to QCD and both QCD and QED parton showers**
- **Modification of the POWHEG BOX radiation regions to handle quasi-collinear radiation (crucial given m_e).**





- **Heavy particle pair production:** $c\bar{c},\ b\bar{b},\ t\bar{t}$ [Frixione, Nason & Ridolfi,JHEP 0709, 2007]



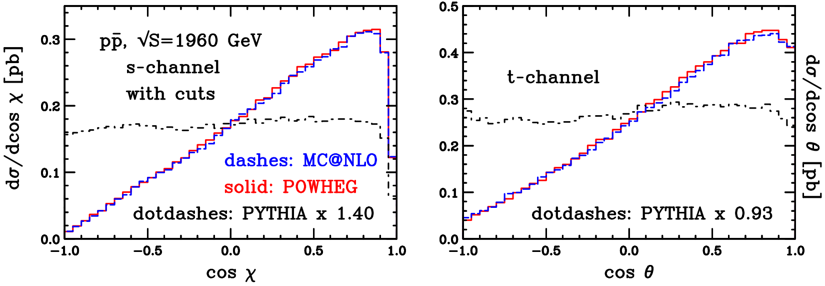


Heavy partons

- **Single-top production in the $s-$, $t-$ and $Wt-$ channels**

[SA,Nason, Oleari & Re, JHEP 0909:111,2009]

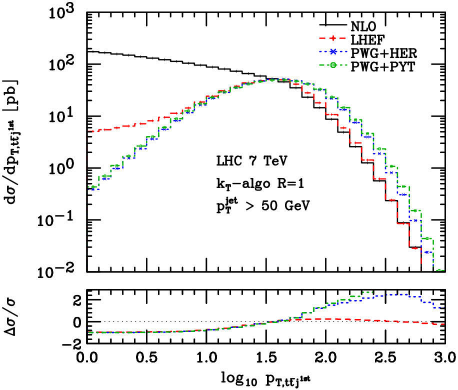
[Re, Eur.Phys.J. C71 ,2011]

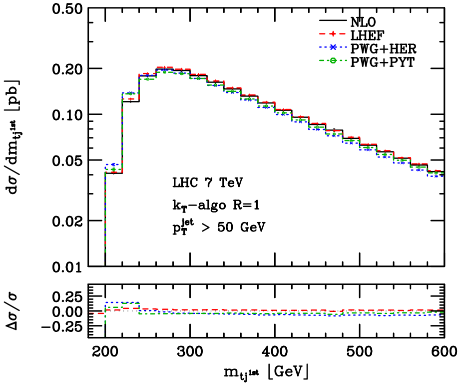


Heavy partons

- **Top pair production plus jet**

[SA, Moch & Uwer, JHEP 1201, 2012]





Dijets

S.A., K.Hamilton, P.Nason, C.Oleari, E.Re [arXiv:1012.3380]

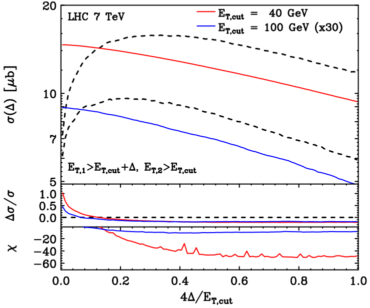
- With symmetric cuts, the (IR safe) NLO cross sec. with $E_{T,1} > E_{T,\text{cut}} + \Delta$, $E_{T,2} > E_{T,\text{cut}}$ is patologic when $\Delta \to 0$.

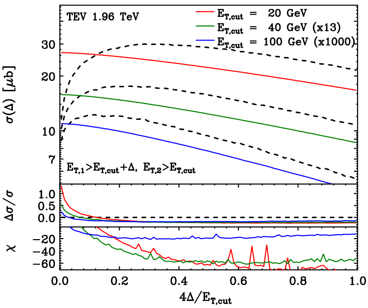
✗ **It does not decrease reducing the available phase space**

- Well known effect, already observed in [Nucl.Phys. B507 (1997), Phys.Rev. D56 (1997)]
- Truncation of perturbative expansion at NLO induces logarithmic Δ terms from unbalanced cancellation of soft gluons between reals and virtual contributions.
- Inclusion of soft gluons resummation fixes this anomalous behaviour
  [Eur. Phys. J. C 23, 13 (2002)]

- Similar resummation performed by `POWHEG`:

--- NLO — POWHEG





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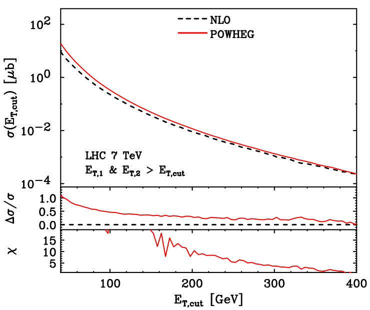
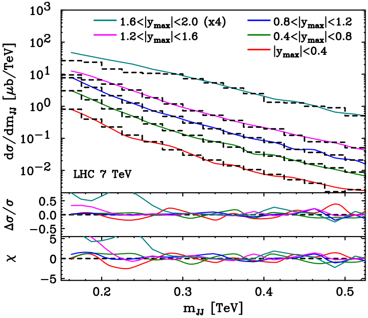
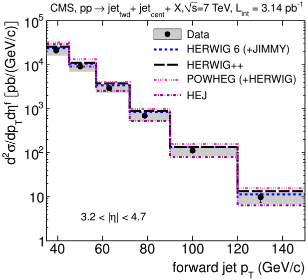
- Inclusion of soft gluons resummation fixes this anomalous behaviour [Eur. Phys. J. C 23, 13 (2002)]
- Effects visible also in physical distributions: $E_T \approx \frac{m_{jj}}{2\cosh|y|}$ symmetric $E_{T,\rm cut} = 40\text{GeV}$

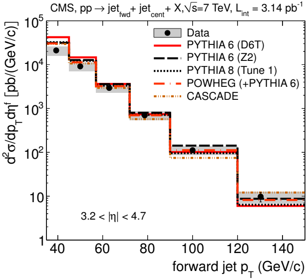


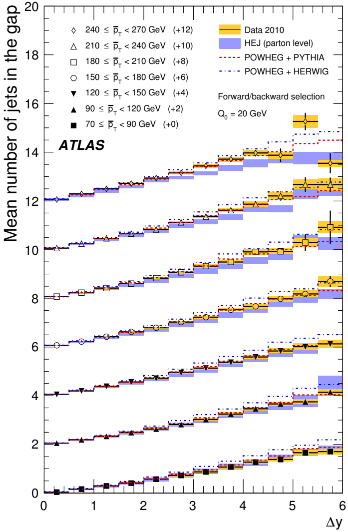


Dijets

- **Already several studies by ATLAS and CMS using** [SA, Hamilton, Nason, Oleari, & Re]
- **Overall good agreement, interesting discrepancies at large Δy, partly related to the scale choice**

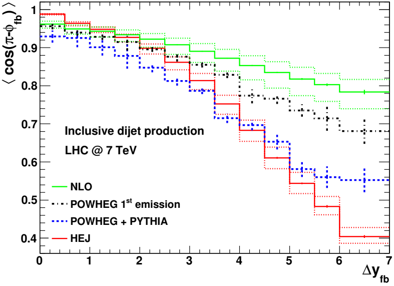


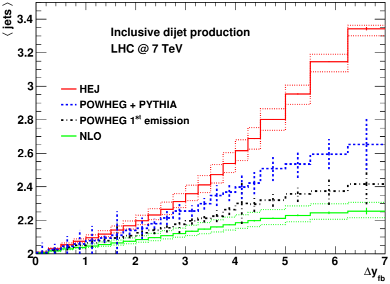


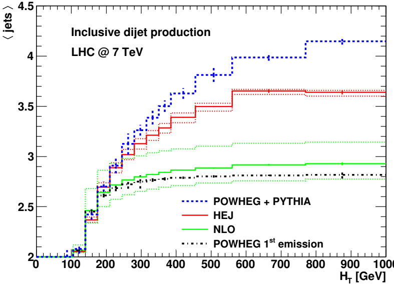


Dijets: higher order effects

- **Experimental effort to distinguish DGLAP resummation effects from BFKL-type ones**
- **NLO vs. POWHEG vs. HEJ comparative study** [Andersen,SA,Oleari,Re,Smillie arXiv:1202.1475]
- **ATLAS and CMS comparisons studies not yet conclusive, new cuts and measurements proposed**







Merging samples with different multiplicities: a practical recipe

- **Case study for $V + 0, 1$ jet** [SA, Hamilton, Re JHEP09 (2011)]

Basic idea: first "improve" both the $V + 0$ jet and $V + 1$ jet samples, then merge them in a smooth way. How?

Merging samples with different multiplicities: a practical recipe

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Basic idea: first "improve" both the $V+0$ jet and $V+1$ jet samples, then merge them in a smooth way. How?

✗ **The $V+0$ jet sample lacks a NLO description of the hardest radiation. No $V+j$ virtuals and next-to-hardest radiation generated by the shower.**

✓ **Improve it by iterating the POWHEG formula after the first emission (now includes $V+2j$ ME)**

$$d\sigma_\infty = \bar{B}_V d\mathbf{\Phi}_V \left\{ \Delta_V\left(p_{\mathrm{T}}^{\min}\right) + \frac{R_{Vj}}{B_V}\Delta_V\left(p_{\mathrm{T},1}\right) d\mathbf{\Phi}_{j_1} \times \right.$$
$$\left. \times \left[\Delta_{Vj}\left(p_{\mathrm{T}}^{\min}\right) + \Delta_{Vj}\left(p_{\mathrm{T},2}\right) \sum_\alpha \frac{R^\alpha_{Vjj}}{B_{Vj}} d\mathbf{\Phi}_{j_2} \right] \right\}$$

Merging samples with different multiplicities: a practical recipe

- **Case study for $V+0,1$ jet** [SA, Hamilton, Re JHEP09 (2011)]

Basic idea: first "improve" both the $V+0$ jet and $V+1$ jet samples, then merge them in a smooth way. How?

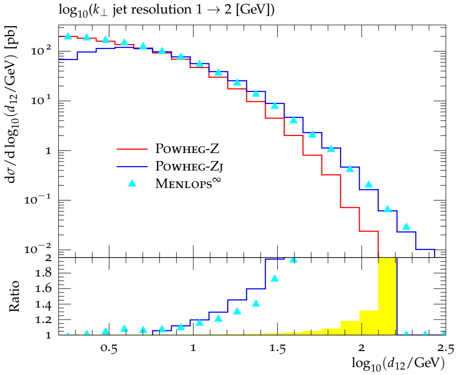
✗ **The $V+1$ jet sample lacks a correct suppression at low V transverse momentum. Only the Sudakov for Vj is present and not the Sudakov for V.**

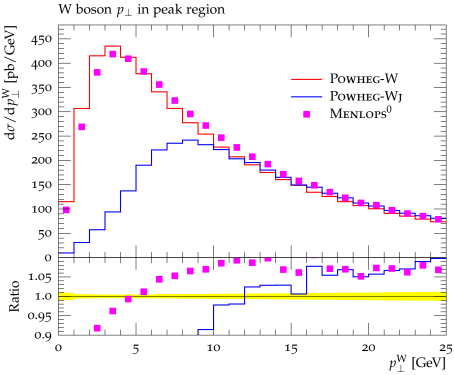
✓ **Improve it by supplementing the correct low-p_{T} behaviour by resummed expression and reweight by $V+0$ jet $K-$ factor to get the total cross section right.**

$$d\sigma_0 = \mathcal{P}(p_{\mathrm{T},1})\, d\sigma^{\mathrm{NLL}}_{Vj} + \left(1-\mathcal{P}(p_{\mathrm{T},1})\right)\, d\sigma_{Vj}$$

$$d\sigma^{\mathrm{NLL}}_{Vj} = \mathcal{K}\, B\left(\mathbf{\Phi}_V\right)\Big|_{\mu_F = m_V}\, d\mathbf{\Phi}_V \left[\frac{R\left(\mathbf{\Phi}_{Vj}\right)}{B\left(\mathbf{\Phi}_V\right)}\, \delta\left(k_{\mathrm{T}}\left(\mathbf{\Phi}_{Vj}\right) - p_{\mathrm{T},1}\right) \Delta\left(\mathbf{\Phi}_V,\, p_{\mathrm{T},1}\right) d\mathbf{\Phi}_{j_1}\, dp_{\mathrm{T},1} \right.$$
$$\left. \times \left\{ \Delta\left(\mathbf{\Phi}_{Vj},\, p_{\mathrm{T}}^{\mathrm{min}}\right) + \Delta\left(\mathbf{\Phi}_{Vj},\, p_{\mathrm{T},2}\right) \sum_{\alpha} \frac{R^{\alpha}\left(\mathbf{\Phi}^{\alpha}_{Vjj}\right)}{B\left(\mathbf{\Phi}_{Vj}\right)}\, \delta\left(k^{\alpha}_{\mathrm{T}}\left(\mathbf{\Phi}^{\alpha}_{Vjj}\right) - p_{\mathrm{T},2}\right) d\mathbf{\Phi}_{j_2}\, dp_{\mathrm{T},2} \right\} \right]$$

Merging samples with different multiplicities: examples





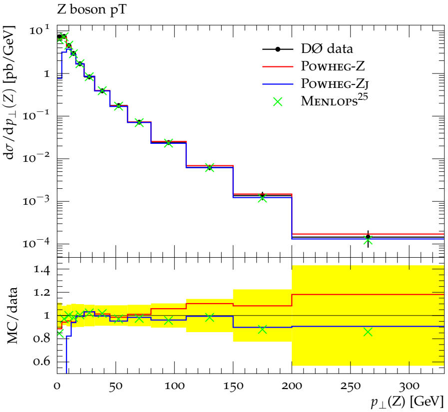
✗ **At this point both samples are “improved“, but none of them is both NLO accurate for both V and Vj.**

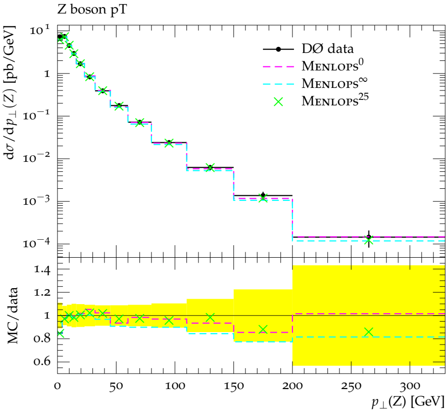
✗ **MENLOPS$^\infty$ is not formally NLO for Vj**

✗ **MENLOPS^0 is only LO + NLL for V**

Practical recipe to merge samples with different multiplicities

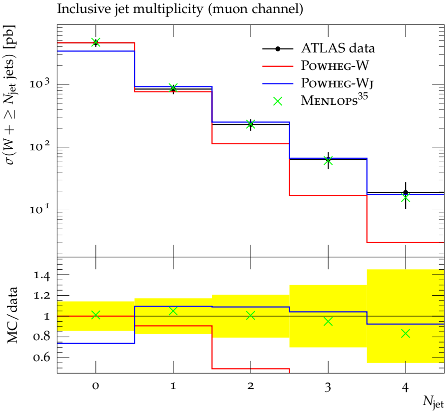
- ✓ **To create a sample which is formally NLO accurate in both cases, we merge the two, requiring that the fractions of events from the MENLOPS^0 sample is $\leq \alpha_S$**
- $\Rightarrow$ **lower bound on the merging scale**
- ✓ **Dependence on the merging scale no worse than usual MEPS**
- ▸ **Comparisons with Tevatron data:**

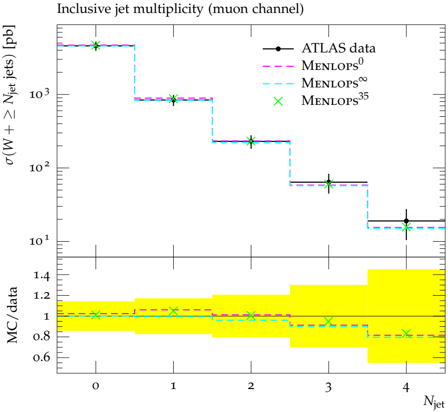




Practical recipe to merge samples with different multiplicities

- **Comparisons with LHC data:**





- **In both cases we see and improved description of data and a smooth behaviour near the merging point**
- **Theoretical uncertainty at NLO** $\approx 20\%$ **compatible with NLL+LO for** $p_{\mathrm{T}} < 40$ GeV

[Bozzi et al., NPB 2009]

Practical recipe to merge samples with different multiplicities

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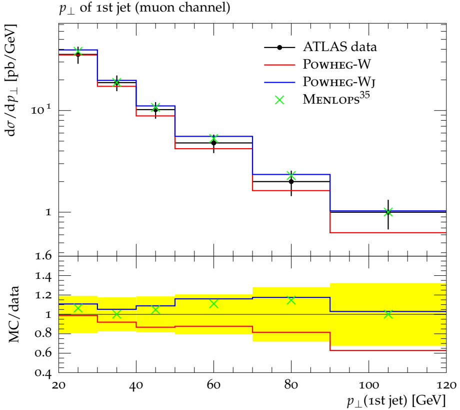

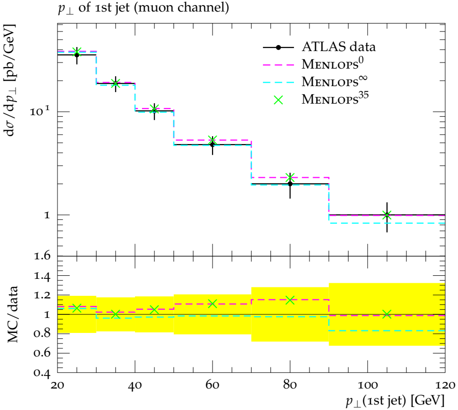

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Conclusions and Outlook

- POWHEG is a well established method to implement NLO corrections into SMC programs. Extensively tested by independent groups, similarities and differences with alternative approaches thoroughly investigated!
- The POWHEG BOX allows the implementation of an arbitrary process in the FKS subtraction approach.
- Several processes already implemented into the POWHEG BOX : it can be used as a tool to obtain NLO+SMC predictions.

Outlook :

- Complete automation with external automated NLO calculators almost completed.
- Dedicated tuning of NLO+SMC to data: uncharted territory ...
- Merging NLO + Parton Shower with ME corrections and samples with different multiplicities. Practical recipe of [SA, Hamilton, Re JHEP09 (2011)] worked for $V, V+j$. Extendible to other processes ?
- Looking forward to experimental community for feedbacks and required improvements.

Thank you for your attention!