NLO EW corrections in the POWHEG-BOX

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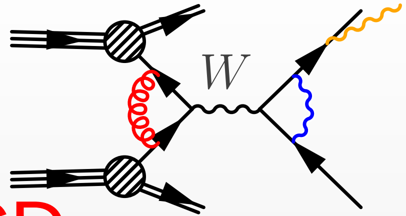
NLO & PS comparison



NLO QCD

Normalization at order α_s

Accurate shapes also of high $p_\perp$

Reduced dependence on $\mu_{R/F}$

PS QCD

Accurate shapes of low $p_\perp$

Realistic events

NLO EW

Normalization at order $\alpha_{EW} \sim \alpha_s^2$

M_W shift $\sim$ 100 MeV

EW Sudakov logs

PS QED

exp NLO $\rightarrow M_W$ shift $\sim$ 10 MeV

(LHC $\Delta M_W \sim$ 15 MeV)

We need a NLO EW+QCD Monte Carlo event generator with mixed QED & QCD parton shower:

- unified tool for pheno studies / data analysis
- $\mathcal{O}(\alpha_{EW}\alpha_{QCD})$ NLL estimate

Exact NLO$\otimes$shower corrections

- $\mathcal{O}(\alpha_s)\otimes$QCD shower →
  - POWHEG-BOX$\oplus$SMC JHEP 0711 (2007) 070 / JHEP 1006 (2010) 043
  - MC@NLO$\otimes$HERWIG JHEP 0206 (2002) 029
  - $\otimes$PYTHIA JHEP 04 (2010) 110
  - SHERPA$\otimes$POWHEG JHEP 04 (2011) 24
- $\mathcal{O}(\alpha_{EW})\otimes$QED shower →
  - HORACE JHEP 0612 (2006) 016
  - WINHAC$\otimes$SANC Acta Phys.Polon B40 (2009)
- $\mathcal{O}(\alpha_{EW})\otimes$QED+QCD shower → SANC$\otimes$HERWIG++/PYTHIA8 arXiv:1011.5444
- $\mathcal{O}(\alpha_s)\otimes$QCD resummation$\oplus\gamma$FSR → RESBOSa PRL 93:042001(2004)
- QCD$\otimes$QED YFS resummation & IR-improved DGLAP → HERWIRI PRD 81 (2010) 076008
- Mixed EW & QCD (HORACE$\otimes/\oplus$MC@NLO) JHEP 1001 (2010) 013

Presently no QCD + EW with PS event generator

QCD/EW NLO (subtraction procedure)

$$d\sigma_{LO} = B \, d\Phi_n$$

$$d\sigma_{NLO} = \Bigg\{ B(\Phi_n) + \underbrace{\overbrace{V^b(\Phi_n)}^{-\infty} + \overbrace{\int C(\Phi_n, \Phi_{rad}) d\Phi_{rad}}^{\infty}}_{<\infty} + \int \underbrace{\left[\overbrace{R(\Phi_n, \Phi_{rad})}^{\infty} - \overbrace{C(\Phi_n, \Phi_{rad})}^{\infty} \right]}_{<\infty} d\Phi_{rad} \Bigg\} d\Phi_n$$

$$V^b = V^b_{EW} + V^b_{QCD}$$

$$R = R_{EW} + R_{QCD} \quad C = C_{QED} + C_{QCD}$$

$$d\sigma_{NLO} \equiv \tilde{B} \, d\Phi_n$$

Virtual part (process dependent)

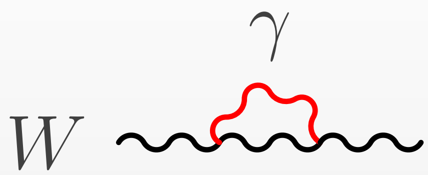
$$V^b = V^b_{QCD} + V^b_{EW}$$

✓ V^b_{QCD} already implemented in `POWHEG-BOX`

- V^b_{EW} calculated and checked from different groups.
  - ○ We chose to use **Dittmaier & Krämer** - 2002
    - finite part of dimensional regularization of IR divergent scalar functions Denner, Dittmaier NPB 844:199242, 2011 Dittmaier NPB 565:69122, 2000 ($m_q^{in} = m_\gamma = 0, m_\ell \neq 0$)
    - factorizing out $\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)} \left(\frac{\mu_R^2}{Q^2}\right)^\epsilon$

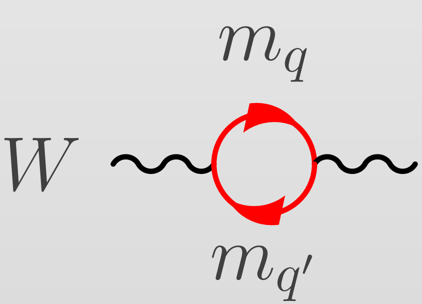
  $\Rightarrow$ direct extension of subtraction procedure

Virtual part - details



$$\propto \log(\hat{s} - M_W^2) \xrightarrow{\hat{s}\to M_W^2} \infty$$

- Dyson resummation $\Rightarrow M_W^2 \to M_W^2 - i\Gamma_W M_W$
  - substitute M_W only in $\log(\hat{s} - M_W^2)$
  - complex mass scheme Denner, Dittmaier, Roth & Wieders NPB 724:247294, 2005



$f(m_q, m_{q'})$ $\to M_W, M_Z, G_\mu$ as input

($m_{q(')} \neq 0$ in loops)

(correct $\Delta\alpha_{had}$)

Subtraction part (process independent)

$$\begin{array}{rcl} C(\Phi_n, \Phi_{rad}) & \to & R \quad \text{if} \quad R \to \infty \\ \int C(\Phi_n, \Phi_{rad}) \mathrm{d}\Phi_{rad} & \to & -V^b \quad \text{if} \quad V^b \to -\infty \end{array}$$

$$C = C_{QCD} + C_{QED}$$

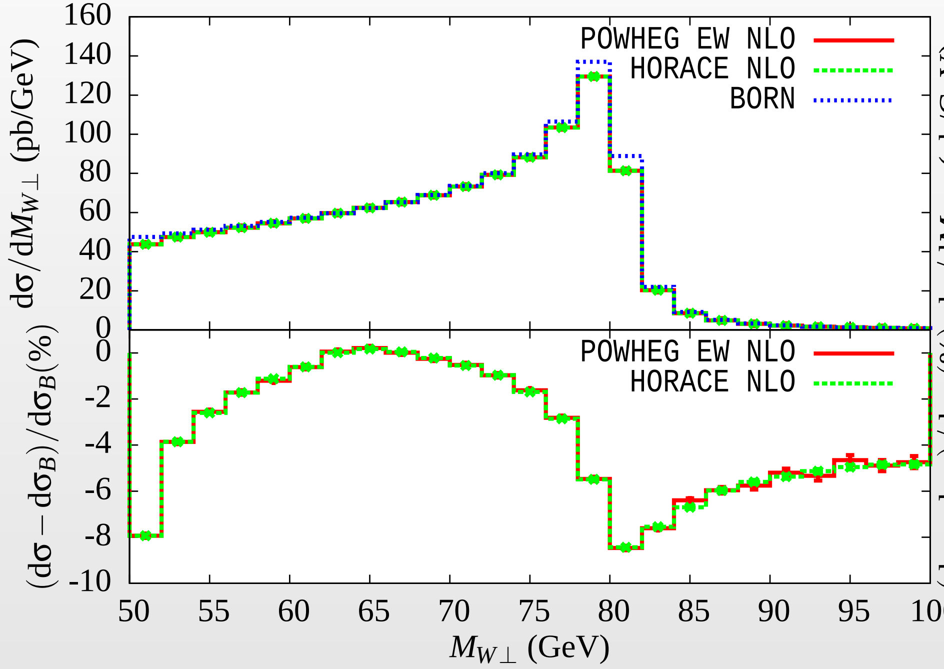
✓ C_{QCD}, $\int C_{QCD}$ implemented in `POWHEG-BOX` for every process by means of FKS algorithm

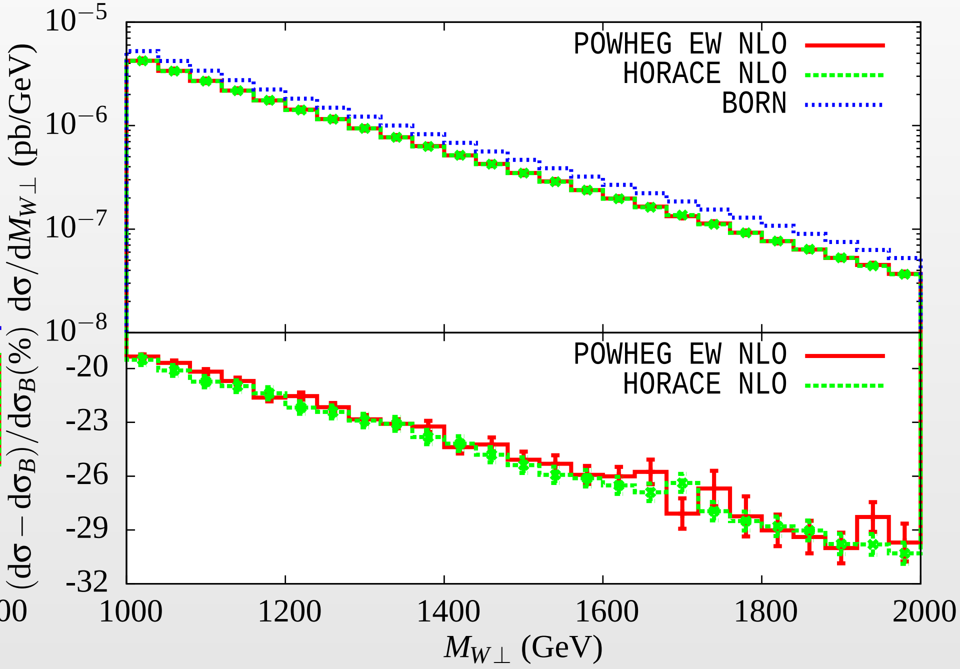
- C_{QED}, $\int C_{QED}$ $\sim$ subsets of C_{QCD} ($q \to qg \sim f \to f\gamma$) (collinear remnants included in C)

generalizing `POWHEG-BOX` FKS subtraction for QED
(in principle) for every EW process
(in dimensional regularization)

NLO EW results (bonus→NLO EW(+QCD) Monte Carlo)

New FSR mapping to describe collinear photons





- ✓ NLO calculation;
- ✓ subtraction procedure.

$$pp \to W^+ \to \mu^+ \nu_\mu$$

$$p_\perp^\mu, \not{E}_\perp \geq 25, |\eta_\mu| \leq 2.5$$

CTEQ6L / LHC @ 7 TeV

HORACE → mass regularization of IR divergencies, $\neq V^b$, $\neq C$ …

QCD/EW NLO + PS

$$\Delta^{\mathtt{POWHEG}}_{\max(k_\perp,p_\perp)} \equiv \Delta^{QCD}_{p_\perp} \Delta^{EW}_{k_\perp}$$

2 different $p_\perp$ scales: $\begin{cases} m_\ell & \text{for leptons} \\ \Lambda_{QCD} & \text{for quarks} \end{cases}$

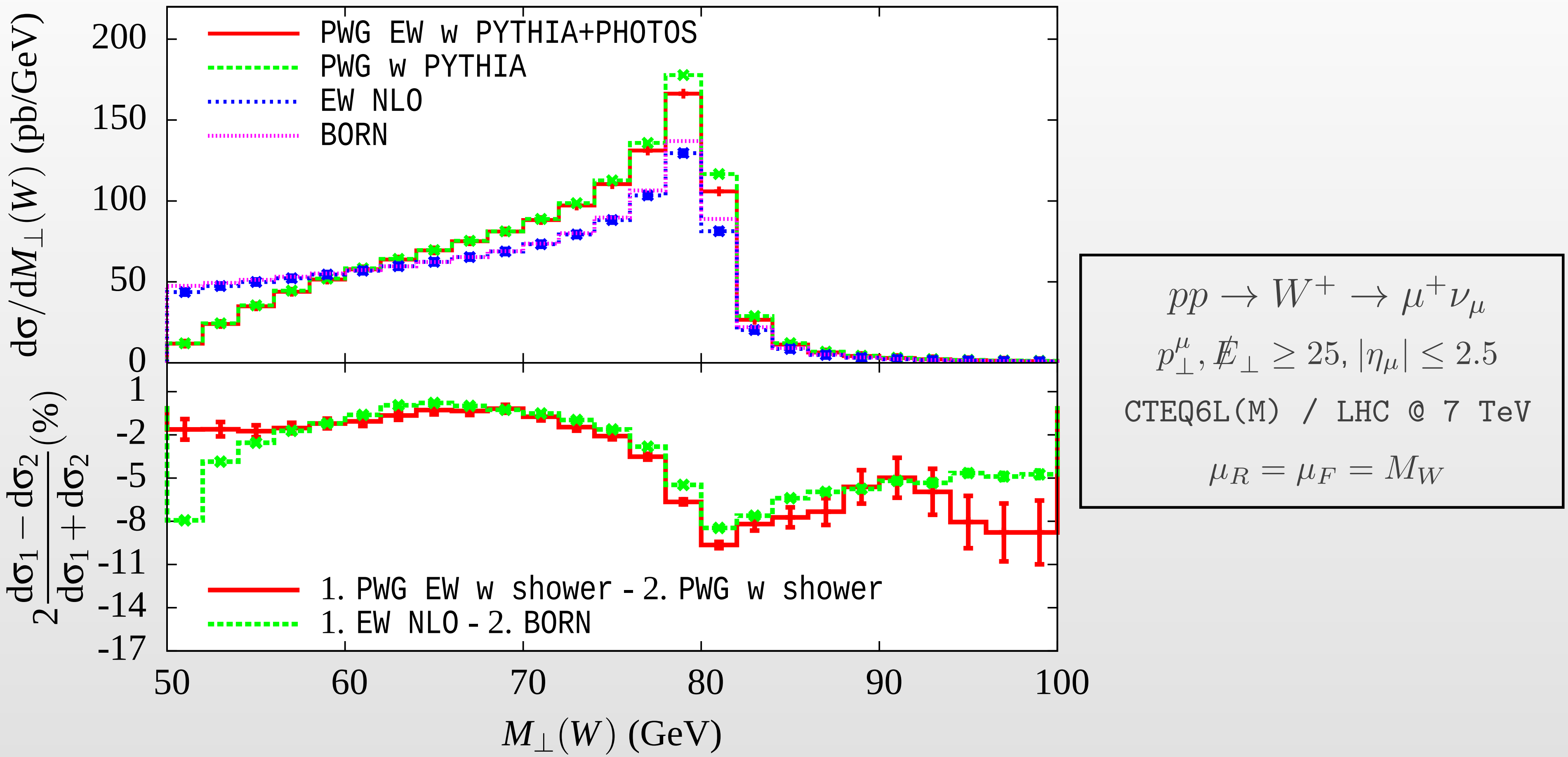
$$\Delta^{QCD}_{p_\perp} = \exp\left\{ - \int \frac{R_{QCD}}{B} \vartheta(p'_\perp - p_\perp)\, \mathrm{d}\Phi'_{rad} \right\}$$

$$\Delta^{EW}_{k_\perp} = \exp\left\{ - \int \frac{R_{EW}}{B} \vartheta(k'_\perp - k_\perp)\, \mathrm{d}\Phi''_{rad} \right\}$$

$$\text{if} \begin{cases} \text{emitted } \gamma/g/q\ (p_\perp \gtrsim \Lambda_{QCD}) \Rightarrow \text{veto } \gamma/g/q \text{ with } p'_\perp > p_\perp \\ \text{emitted } \gamma\ (p_\perp \lesssim \Lambda_{QCD}) \Rightarrow \text{veto} \begin{cases} g/q \\ \gamma \text{ with } p'_\perp > p_\perp \end{cases} \end{cases}$$

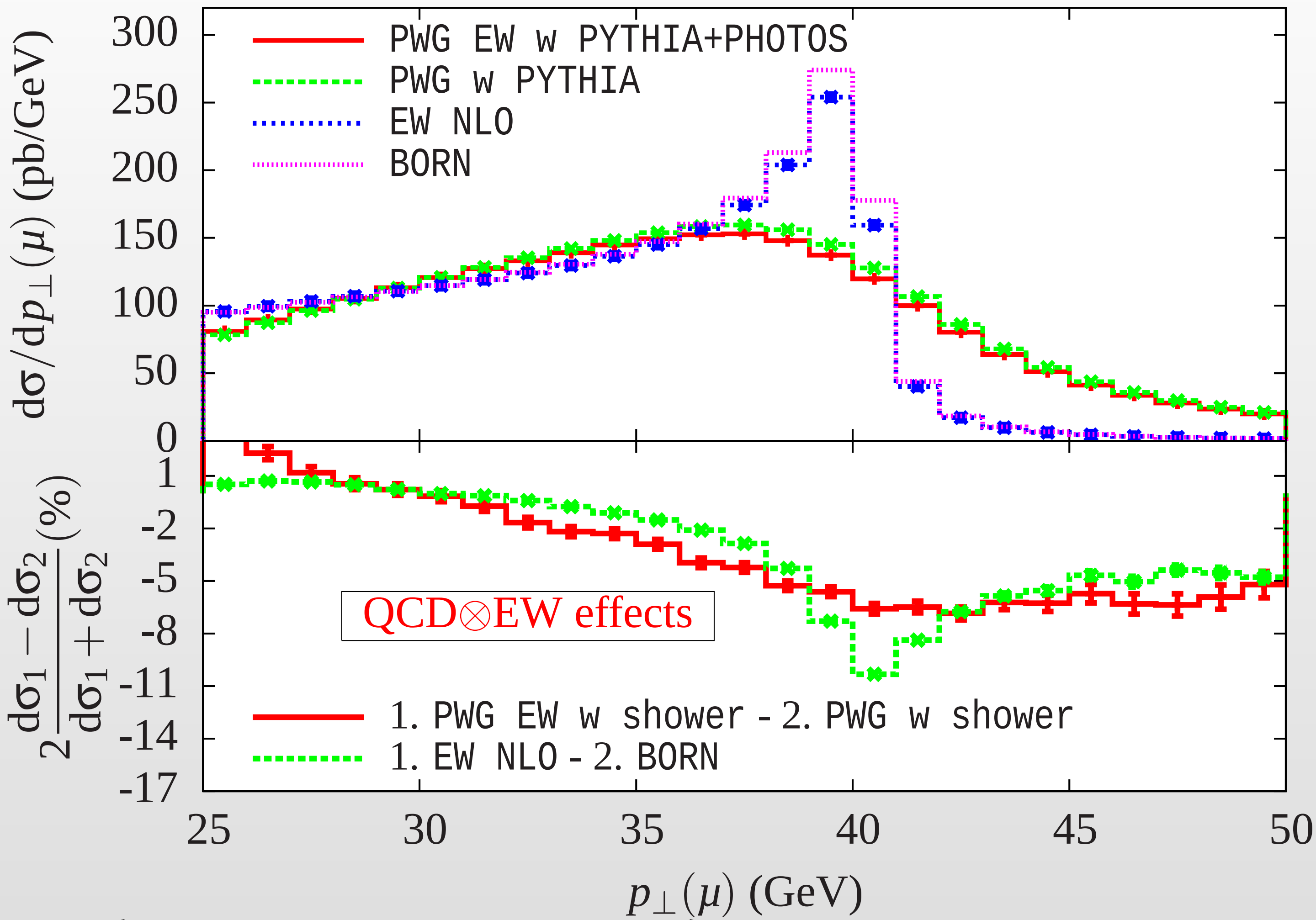
Interfaced to PYTHIA / (HERWIG) $\oplus$ PHOTOS

W^+ transverse mass



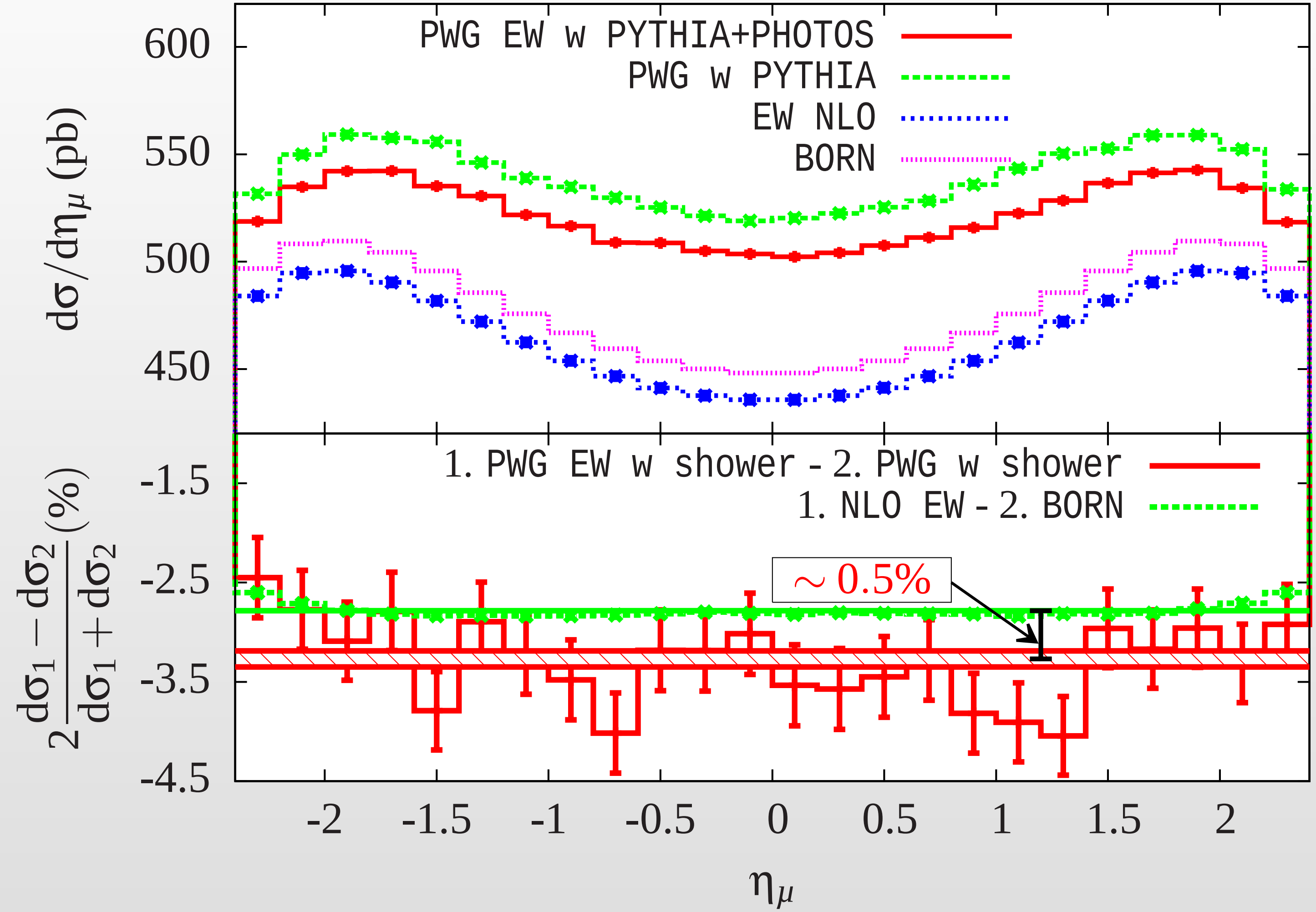
- $M_\perp$ is invariant under a longitudinal boost
  $\Rightarrow$ QCD doesn't modify shape in first approximation

μ^+ transverse momentum



$$\sigma \propto \exp\left\{-\int (R_{EW} + R_{QCD})/B\right\}$$
$$\propto \left(1 + \sum_n \mathcal{O}^n(\alpha_{EW}) + \sum_n \mathcal{O}^n(\alpha_{QCD}) + \sum_n \mathcal{O}^n(\alpha_{QCD}\alpha_{EW}) + \ldots\right)$$

μ^+ pseudorapidity



$\mathcal{O}(\alpha_{EW}\alpha_{QCD}) \sim$ 0.5 %

Balossini & al. - JHEP 1001 (2010) 013

Conclusions / Future developments

☑ Extended POWHEG-BOX to include EW processes
$\Rightarrow$ unified NLO EW & QCD Monte Carlo w PS
$\Rightarrow$ general framework;

☑ EW NLO calculation for W production
$\Rightarrow$ checked with HORACE NLO;

☑ QCD & EW mixing (for some observables is important)
$\Rightarrow$ checked **Balossini & al. - JHEP 1001 (2010) 013**;

☐ add other processes (neutral current, ...).

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THANK YOU!!

BACKUP SLIDES

POsitive Weight Hardest Event Generator

Method to interface NLO with PS (Nason - 2004):

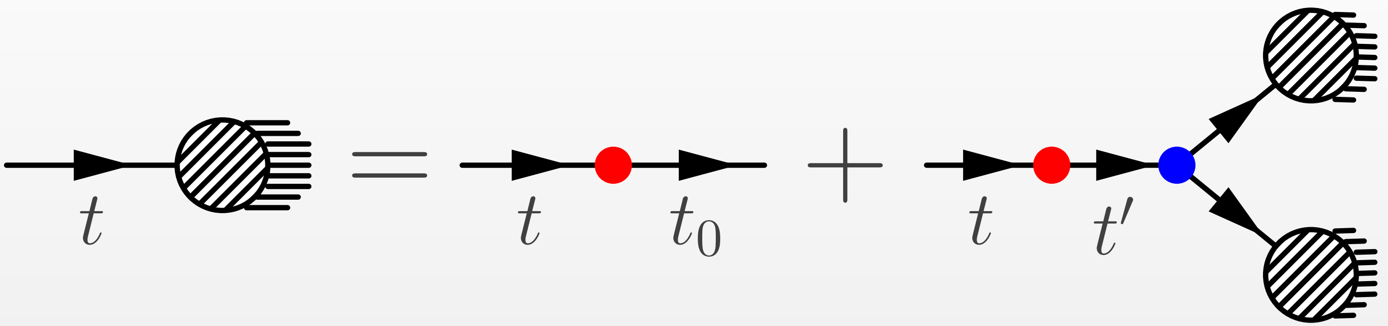
- generate with NLO accuracy the hardest emission;
- events have positive weights;
- shower Monte Carlo interfaced (PYTHIA, HERWIG, ...).

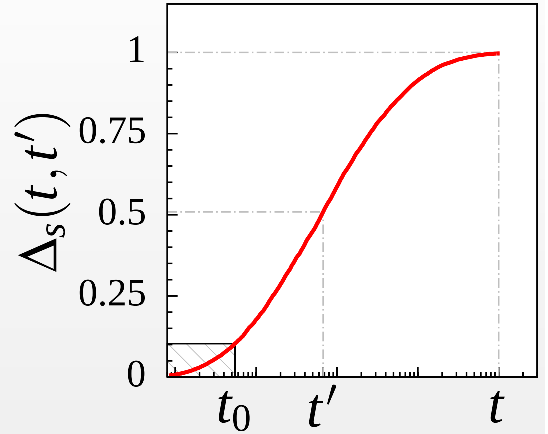
POWHEG-BOX (Alioli, Nason, Oleari, Re - 2009) program:

- identifies all the singular regions;
- projects real contributions over the singular regions;
- general FKS subtraction;
- ISR and FSR phase space;
- calculates upper bounds for the generation of radiation;
- generates radiation.

$\sim$ process independent $\longrightarrow$ Needs only $B_{(jk)}$, R, $\mathrm{d}\Phi_n$ and V^b

Parton Shower





First emission:

$$\Delta_t^{SMC} = \exp\left\{ -\int \frac{\alpha_s(t')}{2\pi}\frac{1}{t'}\mathcal{P}(z')\,\vartheta(t'-t)\,\mathrm{d}\Phi'_{rad} \right\}$$

$$\mathrm{d}\sigma_{SMC} = \overbrace{B\,\mathrm{d}\Phi_n}^{\mathrm{d}\sigma_{LO}} \left[\Delta_{t_0}^{SMC} + \Delta_t^{SMC}\frac{\alpha_s(t)}{2\pi}\frac{1}{t}\mathcal{P}(z)\mathrm{d}\Phi_{rad} \right]$$

Subsequent emissions $t \geq t'' \geq t''' \ldots$

NLO + PS with POWHEG

In POWHEG $p_\perp$ of hardest radiation generated according to:

$$\Delta_{p_\perp} = \exp\left\{ -\int \frac{R}{B}\,\vartheta(p'_\perp - p_\perp)\,\mathrm{d}\Phi'_{rad} \right\}$$

$p_\perp$ veto of subsequent emissions $\Rightarrow$ **no double-counting**

$$\mathrm{d}\sigma = \overbrace{\tilde{B}\,\mathrm{d}\Phi_n}^{\mathrm{d}\sigma_{NLO}} \left[\Delta_{p_\perp^-} + \Delta_{p_\perp} \frac{R}{B} \mathrm{d}\Phi_{rad} \right]$$

Small $p_\perp \quad \rightarrow \quad \tilde{B} \simeq B(1 + \mathcal{O}(\alpha)), \; \frac{R}{B} \rightarrow \frac{\alpha}{2\pi}\frac{1}{t}\mathcal{P}$

Large $p_\perp \quad \rightarrow \quad \mathrm{d}\sigma \simeq \tilde{B}\frac{R}{B} \simeq R(1 + \mathcal{O}(\alpha))$

NLO accuracy