QCD+EW corrections to DY in POWHEG

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also on behalf of C. Bernaciack & D. Wackeroth

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Recent efforts in QCD $\oplus$ EW $N^{(n)}LO$ for DY

$$d\sigma = d\sigma_0 + d\sigma_{\alpha_s} + d\sigma_{\alpha} + d\sigma_{\alpha_s^2} + d\sigma_{\alpha\alpha_s} + \ldots$$

Fixed order MC:

- FEWZ: $\alpha_s^2 (+\alpha$ for neutral DY) — Melnikov & Petriello, **PRL** 96 (2006) 231803; Li & Petriello, arXiv:1208.5967
- SANC: $\alpha_s + \alpha$ — Bardin & al., arXiv:1207.4400

Matching realized using different generators:

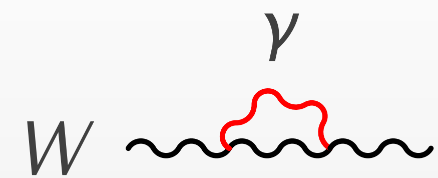
- PYTHIA8/HERWIG++ $\oplus$ SANC — Richardson & al., **JHEP** 1206 (2012) 090
- MC@NLO $\oplus$ HORACE — Balossini & al., **JHEP** 1001 (2010) 013

NLO matched to PS (POWHEG):

- W_EW-BMNNP — L. B. & al., **JHEP** 1204 (2012) 037
- W_EW-BW — Bernaciack & Wackeroth, **PRD** 85 (2012) 093003
  - Z in progress (preliminary results)

General features of EW radiative corrections

- Unstable particles ($\Gamma \neq 0$) in the loops
  $\rightarrow$ avoid gauge invariance violation!
  $\rightarrow$ Complex Mass (for DY simpler schemes)



- $m_\gamma = m_q = 0 \Rightarrow$ IR singularities (regularized):

Soft $\rightarrow$ cancel between R and V

IS collinear $\rightarrow$ redefinition of PDFs ~~$\log(Q^2/m_q^2)$~~

FS collinear $\rightarrow$ $\log(Q^2/m_\ell^2)$ are physical:

- $\circ$ $\mu^\pm$ "always" separated from γ

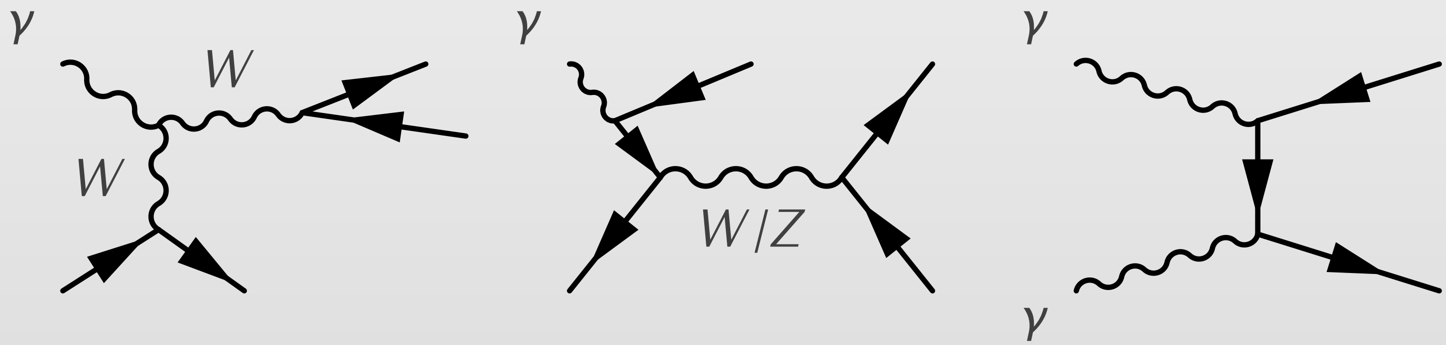
corrections enhanced

- $\circ$ $e^\pm - \gamma$ recombined ("electromagnetic jet")

General features of EW radiative corrections

- at $\sqrt{\hat{s}} \sim M_{W/Z}$ QED corrections important
  $\rightarrow$ QED structure functions
  $\rightarrow$ QED PS $\rightarrow$ `HORACE` / `PHOTOS` — Golonka & Was, **EPJC**45 (2006) 97; Carloni & al., **JHEP** 0612 (2006) 016
  $\rightarrow$ YFS $\rightarrow$ `WINHAC` + `SANC` — Jadach & Placzek, **EPJC**29 (2003) 325

- γ induced processes



$\rightarrow$ only `MRSTQED2004` provides photon distribution function

QCD/EW NLO Cross section

$$d\sigma_{NLO} = \Bigg\{ B(\Phi_n) + \overbrace{V^b(\Phi_n)}^{-\infty}$$

$$+ \int \overbrace{R(\Phi_n, \Phi_{rad})}^{\infty} d\Phi_{rad}$$

$$+ \int \frac{dz}{z} G^{\oplus}(\Phi_{n,\oplus}) + \int \frac{dz}{z} G^{\ominus}(\Phi_{n,\ominus}) \Bigg\} d\Phi_n$$

$$\equiv \boxed{\bar{B}\, d\Phi_n}$$

$$V^b = V^b_{EW} + V^b_{QCD} \quad R = R_{EW} + R_{QCD} \quad G = G_{EW} + G_{QCD}$$

QCD/EW NLO Cross section

$$d\sigma_{NLO} = \Bigg\{ \underbrace{B(\Phi_n) + \overbrace{V^b(\Phi_n)}^{-\infty} + \overbrace{\int C(\Phi_n, \Phi_{rad}) d\Phi_{rad}}^{\infty}}_{\text{finite}}$$

$$+ \sum_{\alpha_r} \int \underbrace{\Bigg[\overbrace{R^{\alpha_r}(\Phi_n, \Phi_{rad})}^{\infty} - \overbrace{C^{\alpha_r}(\Phi_n, \Phi_{rad})}^{\infty} \Bigg]}_{\text{finite}} d\Phi_{rad}$$

Singular zones of R

$$+ \int \frac{dz}{z} G^{\oplus}(\Phi_{n,\oplus}) + \int \frac{dz}{z} G^{\ominus}(\Phi_{n,\ominus}) \Bigg\} d\Phi_n$$

$$\equiv \bar{B}\, d\Phi_n$$

$$V^b = V^b_{EW} + V^b_{QCD} \quad R = R_{EW} + R_{QCD} \quad G = G_{EW} + G_{QCD}$$

- Subtraction procedure $\rightarrow C = C_{QCD} + C_{QED}$

Virtual part (W_EW-BMNNP)

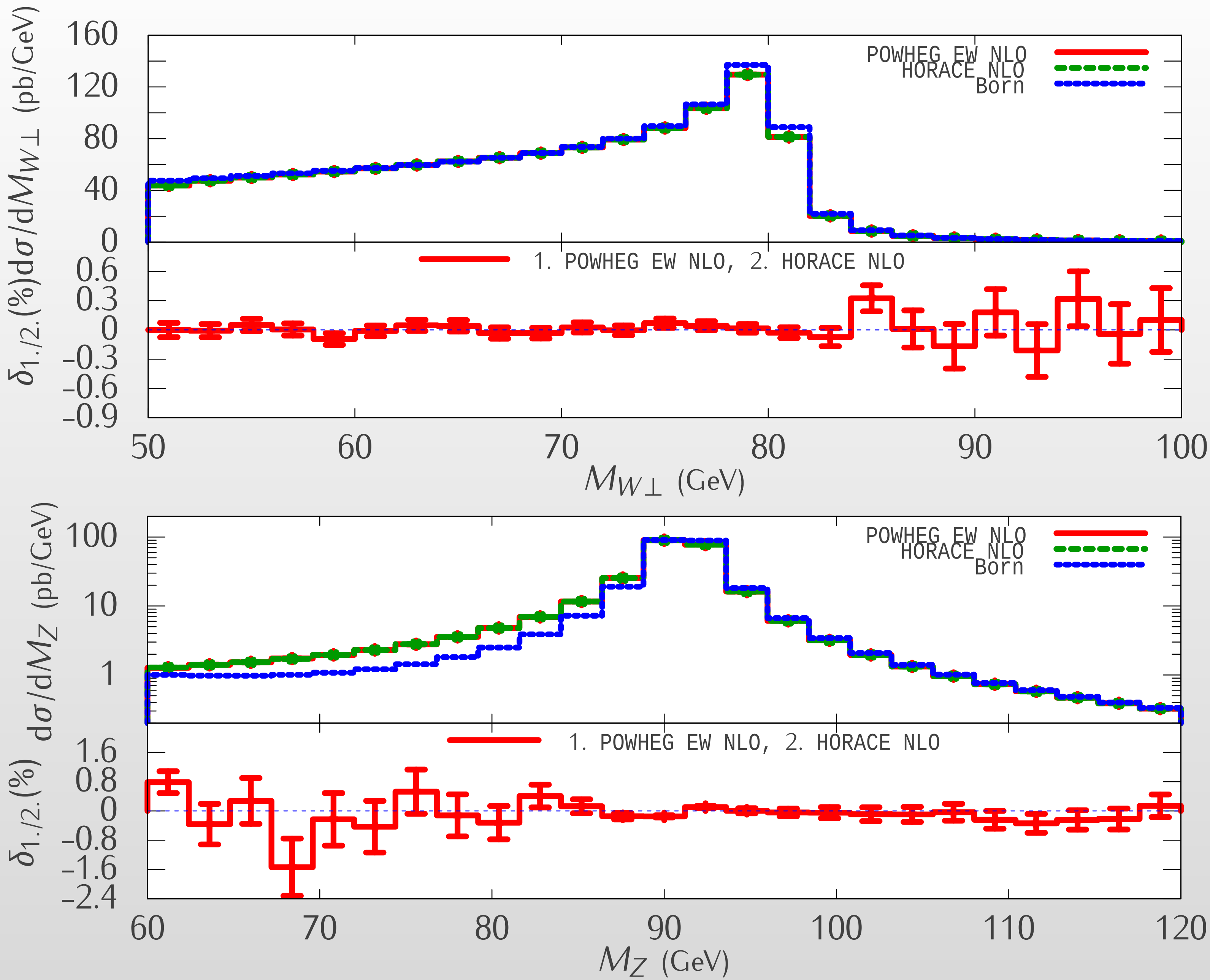
- V^b_{EW} calculated (cross-checked) in different ways
  - We chose to use:
    - **Dittmaier & Krämer** - 2002 for W **PRD**65 073007
    - **Dittmaier & Huber** - 2010 for Z/γ^* **JHEP** 1001 060
    - finite part of dimensional regularization of IR divergent scalar functions $(m_q^{in} = m_\gamma = 0, m_\ell \neq 0)$ Denner, Dittmaier **NPB** 844:199-242, 2011 Dittmaier **NPB** 565:69-122, 2000
    - factorizing out $\mathcal{N} = \frac{(4\pi)^\epsilon}{\Gamma(1-\epsilon)}(\frac{\mu_R^2}{Q^2})^\epsilon$

  $\Rightarrow$ direct extension of subtraction procedure

C/G_{QCD} in POWHEG with FKS algorithm $\rightarrow C/G_{QED}$

NLO Checked with **HORACE**

Carloni & al., **JHEP** 10 (2007) 190
Carloni & al., **JHEP** 12 (2006) 016



Virtual part II (W_EW-BW)

- V^b_{EW} taken from WGRAD2 Baur & Wackeroth, **PRD** 70, 073015, 2004
  - Mass regularization ($m_q \neq 0$, $m_\gamma \neq 0$)
  - 2-cutoff (δ_c, δ_s) phase space slicing

    m_q, m_γ, δ_c, δ_s must cancel in physical result

$$d\sigma^{EW}_{NLO} = \left\{ B(\Phi_n) + \underbrace{(V+s)(\Phi_n)}_{\sim\delta_s} + \int_{1,2} \frac{dz}{z} \underbrace{HC(\Phi_n, z)}_{\sim\delta_c} + \int_{\delta_s,\delta_c} d\Phi_{rad} H\bar{C}(\Phi_n, \Phi_{rad}) \right\} d\Phi_n$$

Within POWHEG-BOX:

$$\bar{B} = B + V_{QCD} + V_{s,EW} + R_{QCD} + R_{EW} + G_{QCD} + G_{EW}$$

NLO Checks

	Tevatron, W^+	LHC, W^+	LHC, W^-
WGRAD2	362.55(2) pb	1059.6(1) pb	759.26(3) pb
W_EW-BW	362.4(2) pb	1059.0(5) pb	758.7(8) pb

(δ_s, δ_c)	Tevat, W^+	LHC, W^+	LHC, W^-
0.01, 0.005	362.4(2) pb	1059.0(5) pb	758.7(8) pb
0.01, 0.001	362.4(2) pb	1059.1(7) pb	759.2(5) pb
0.001, 0.0005	362.3(2) pb	1059.4(9) pb	759.4(5) pb
0.001, 0.0001	362.3(2) pb	1059.2(8) pb	759.3(5) pb

NLO + PS with POWHEG

Nason, JHEP 0411 (2004) 040

Mapping $(\Phi_n, \Phi_{rad}) \leftrightarrow \Phi_{n+1}$ → Radiated particle

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

$$\Delta = \exp\left\{ -\sum_{\alpha_r} \int \frac{R^{\alpha_r}(\Phi_{n+1})\vartheta(p_\perp^{\alpha_r}(\Phi_{n+1}) - p_\perp^{min})\, d\Phi_{rad}}{B(\Phi_n)} \right\}$$

Singular zones of R

Cross section after the first emission:

$$d\sigma = \bar{B}(\Phi_n)\, d\Phi_n \left[\Delta(\Phi_n, p_\perp^{min}) + \sum_{\alpha_r} \Delta(\Phi_n, p_\perp^{\alpha_r}) \frac{R^{\alpha_r}(\Phi_n, \Phi_{rad})}{B(\Phi_n)} d\Phi_{rad} \right].$$

$p_\perp$ veto on shower emissions ⇒ **no double-counting**

QCD/EW NLO + PS in W_EW-BMNNP

$$\{\alpha_r\} = \{\alpha_r^{QED}, \alpha_r^{QCD}\}$$

$$\Delta_{\max(k_\perp, p_\perp)} \equiv \Delta_{k_\perp}^{EW} \Delta_{p_\perp}^{QCD}$$

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

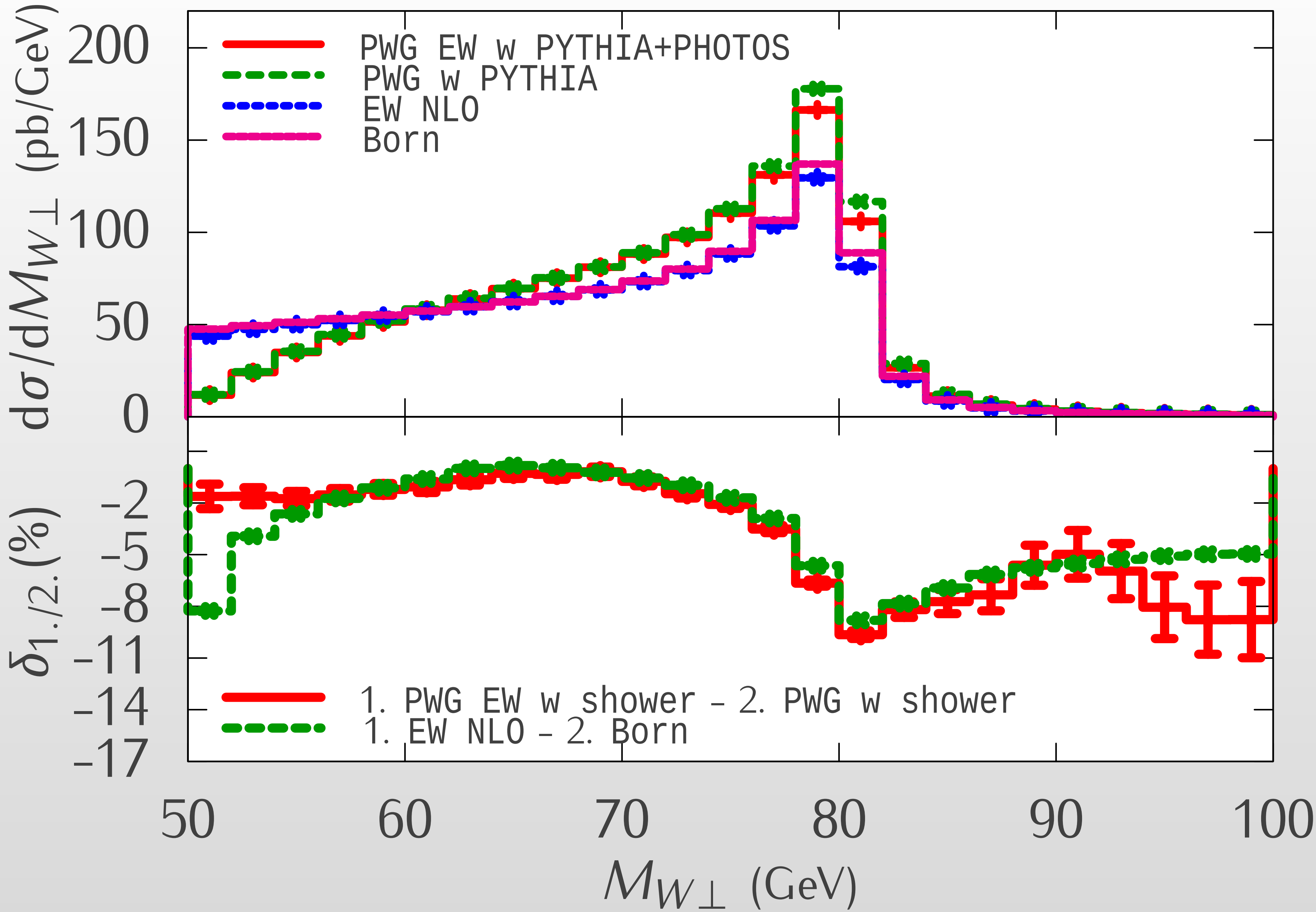
$$\Delta_{p_\perp}^{QCD} = \exp\left\{-\int \frac{R_{QCD}}{B} \vartheta(p'_\perp - p_\perp)\, d\Phi'_{rad}\right\}$$

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

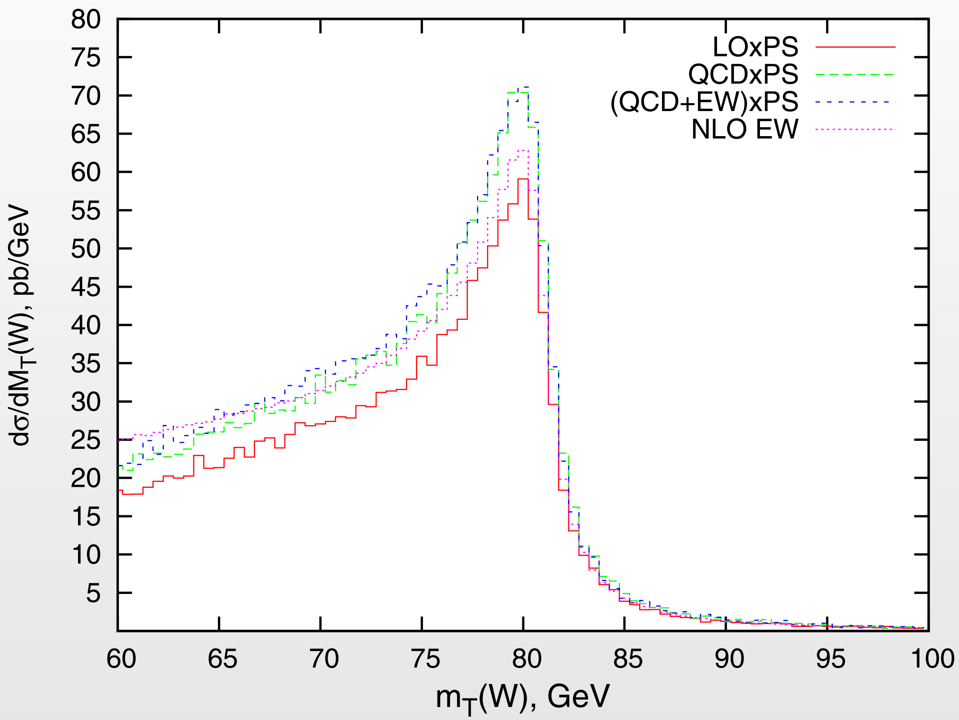
$$\text{if} \begin{cases} \text{emitted}\, \gamma/g/q\ (p_\perp \gtrsim \Lambda_{QCD}) \Rightarrow \text{veto}\ \gamma/g/q \text{ with } p'_\perp > p_\perp \\ \text{emitted}\, \gamma \qquad (p_\perp \lesssim \Lambda_{QCD}) \Rightarrow \text{veto} \begin{cases} g/q \\ \gamma \text{ with } p'_\perp > p_\perp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

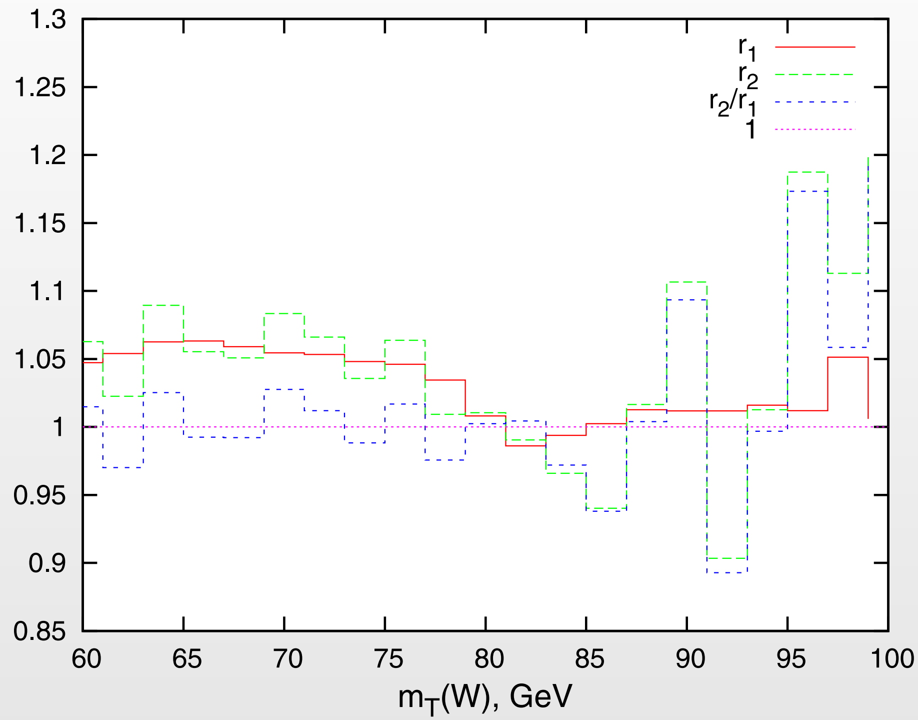
Interfaced to PYTHIA / (HERWIG) $\oplus$ PHOTOS

W^+ Transverse Mass at LHC W_EW-BMNNP



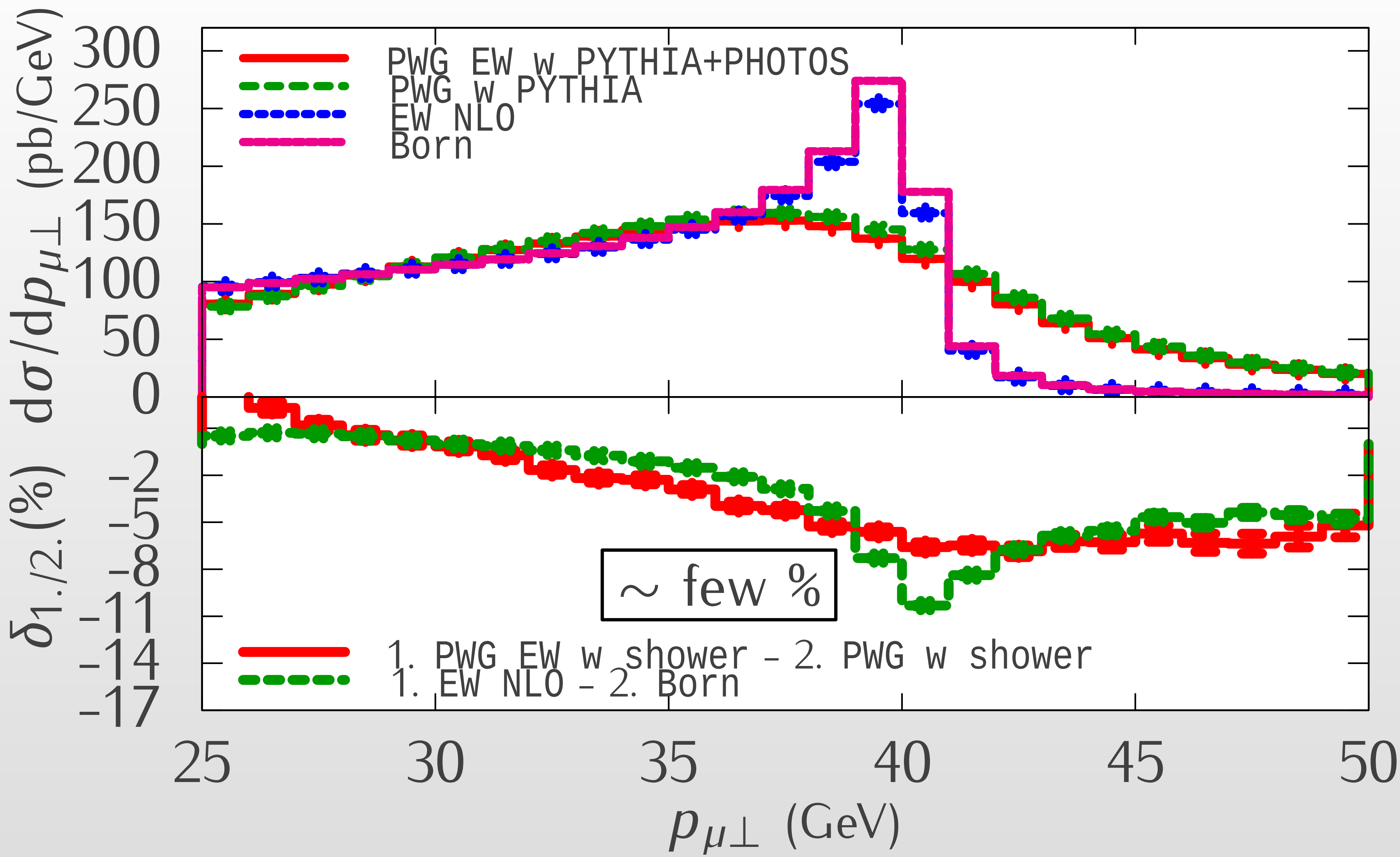
W^+ Transverse Mass at LHC W_EW-BW





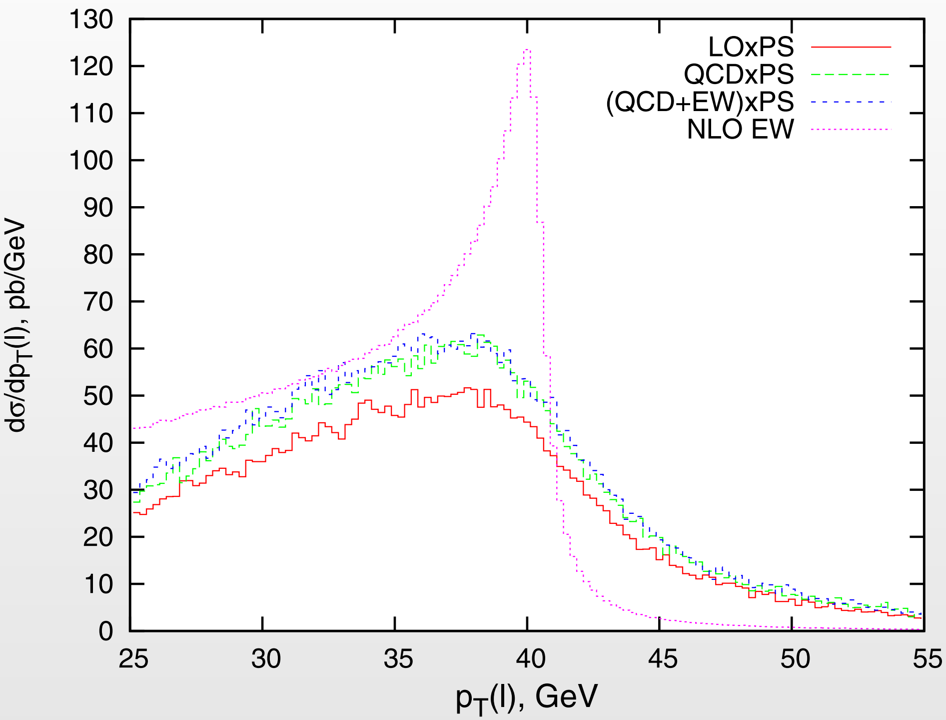
W transverse mass is an observable inclusive over QCD radiation
$\Rightarrow \mathcal{O}(\alpha\alpha_s)$ leading logs $\sim$ cancel.

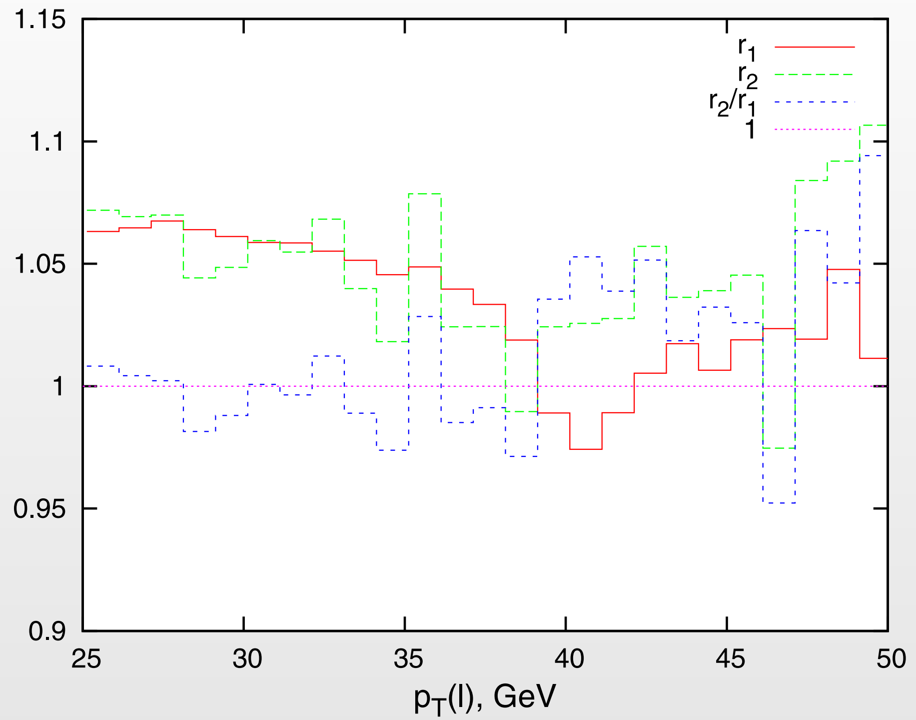
$\mu^+ \perp$ Momentum at LHC W_EW-BMNNP



Effects of $\mathcal{O}(\alpha\alpha_s)$ on M_W measurement?

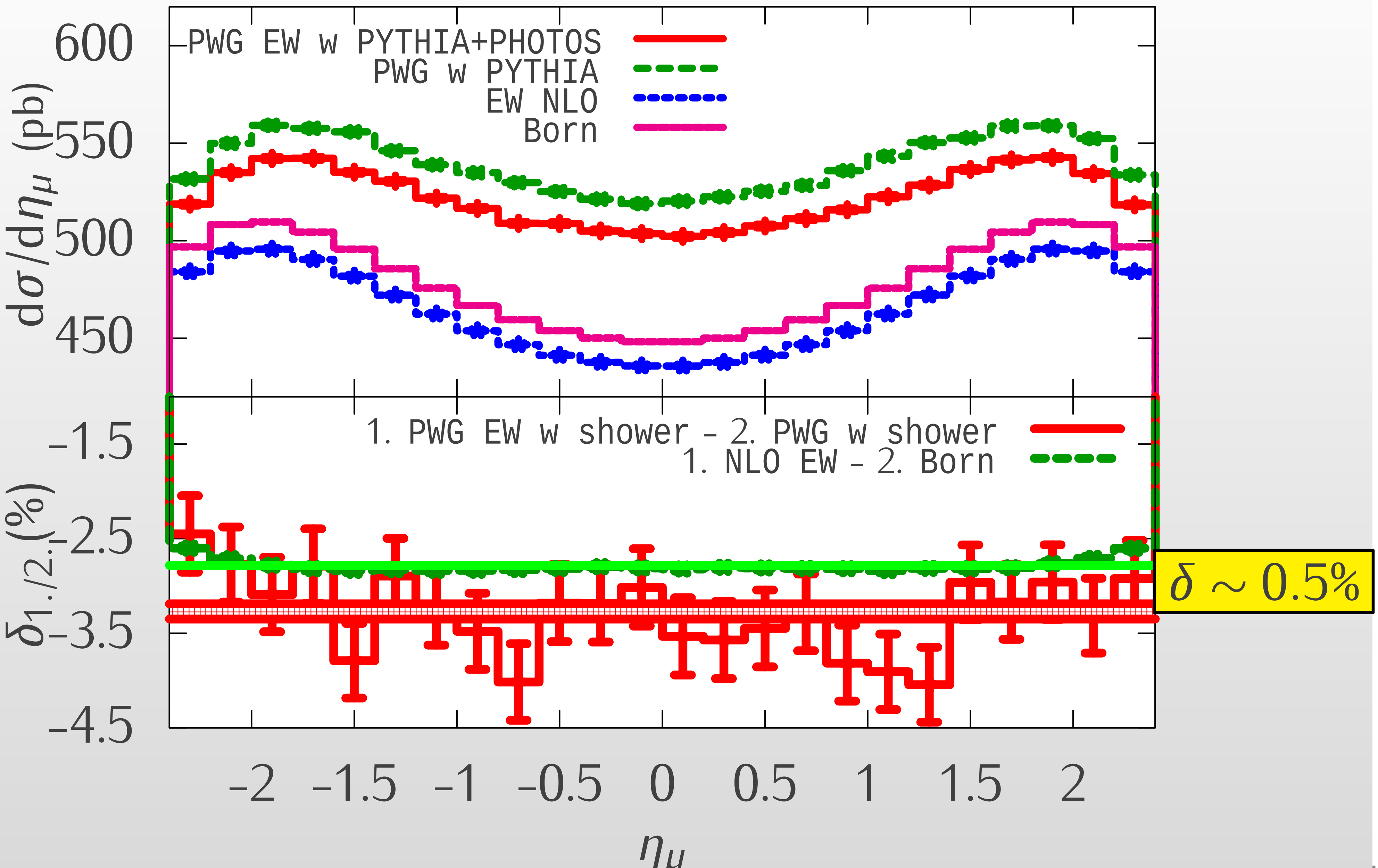
$\mu^+ \perp$ Momentum at LHC W_EW-BW





μ transverse momentum isn't an observable inclusive over QCD radiation
$\Rightarrow \mathcal{O}(\alpha\alpha_s)$ leading logs important.

W^+ Total Cross Section at LHC W_EW-BMNNP



W^+ Total Cross Section at LHC **W_EW-BW**

σ_{LO}	1024.0(1) pb	
σ_{NLOEW}	1059.0(5) pb	
	PYTHIA	HERWIG
$\sigma_{QCD\otimes PS}$	1014(3) pb	1027(3) pb
$\sigma_{(QCD+EW)\otimes PS}$	1052(3) pb	1066(3) pb

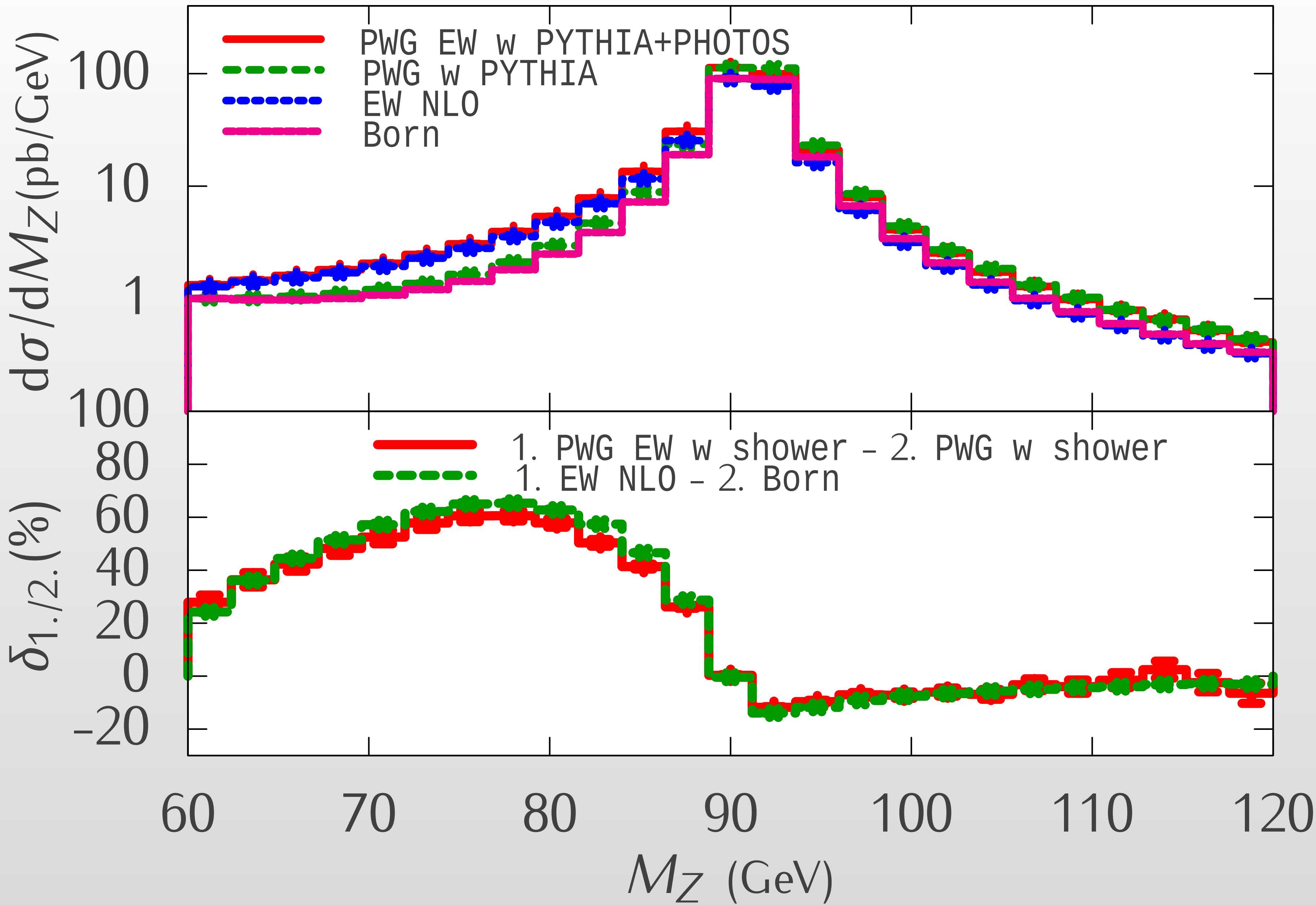
$$\left| \frac{\sigma_{NLOEW} - \sigma_{LO}}{\sigma_{LO}} - \frac{\sigma_{(QCD+EW)\otimes PS} - \sigma_{QCD\otimes PS}}{\sigma_{QCD\otimes PS}} \right| \sim 0.5\%$$

Same order of Balossini & al., **JHEP** 1001 (2010) 013.

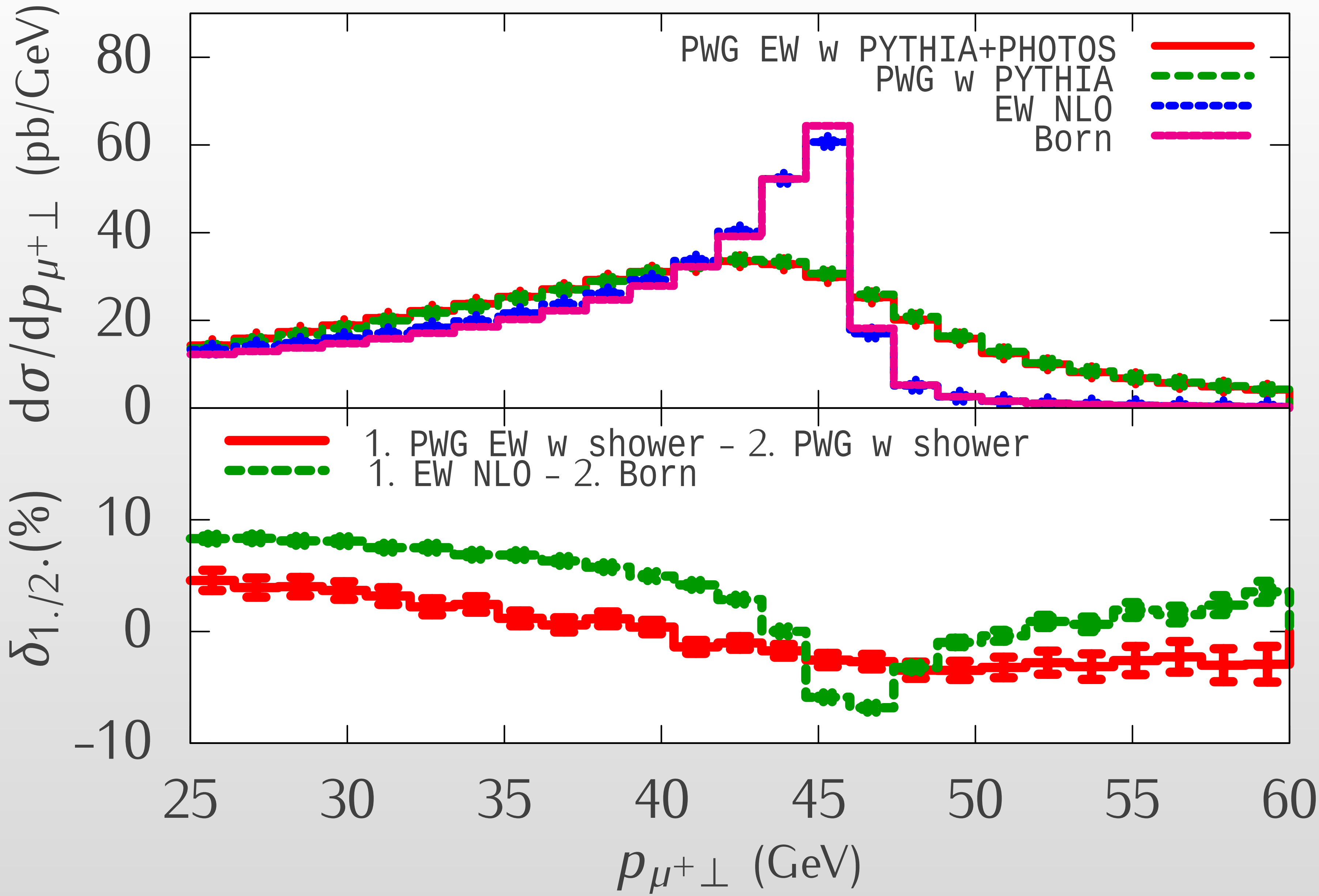
Cuts & parameters different

$\Rightarrow$ Comparison needed.

Z preliminary results W_EW-BMNNP



Z (very) preliminary results **W_EW-BMNNP**



Summary

POWHEG-BOX for CC DY with QCD & EW at NLO

- normalization with NLO QCD $\oplus$ EW accuracy;
- matched mixed QCD $\otimes$ QED PS;
- leading part of mixed $\mathcal{O}(\alpha\alpha_s)$ corrections
  $\rightarrow$ important contribution for some observables;
- similar results from different approaches
  $\rightarrow$ comparison ongoing.

For NC DY ongoing work

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For NC DY ongoing work

THANK YOU!!

Differences? Multiple photon radiation

$\bar{B}^{\texttt{W\_EW-BMNNP}} = \bar{B}^{\texttt{W\_EW-BW}}$ ⇒ Normalization OK

$$d\sigma = \bar{B}(\Phi_n)\, d\Phi_n \left[\Delta(p_\perp^{min}) + \sum_{\alpha_r} \Delta(p_\perp^{\alpha_r}) \frac{R^{\alpha_r}(\Phi_{rad})}{B} d\Phi_{rad} \right]$$

$$\{\alpha_r\}_{\texttt{BMNNP}} = \left\{ \alpha_r^{QED}, \alpha_R^{QCD} \right\} \qquad \{\alpha_r\}_{\texttt{BW}} = \left\{ \alpha_R^{QCD} \right\}$$

W_EW-BMNNP: try to generate γs as hardest particle
→ consistent to use QED shower

W_EW-BW: do not try to generate γs
→ double counting if QED shower

- It is much more likely to generate g / q instead of γ → Small effects