GAUGE BOSON PAIRS at the LHC: ELECTROWEAK CORRECTIONS and MONTE CARLO IMPLEMENTATION

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SFB TR9

RADCOR 2013

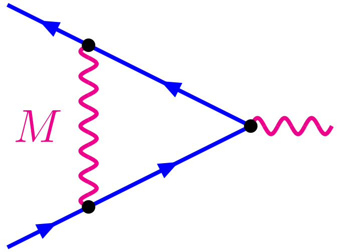
I. Introduction

"Typical" size of electroweak corrections: $\frac{\alpha_{\text{weak}}}{\pi} \approx 10^{-2}$

new aspects at LHC: $\sqrt{\hat{s}} \approx$ 1-2TeV $\gg M_{W,Z}$

strong enhancement of negative corrections

one-loop example: massive U(1)



$$\Rightarrow \quad \text{Born} * \left[1 + \frac{\alpha}{4\pi}\left(-\ln^2\frac{s}{M^2} + 3\ln\frac{s}{M^2} - \frac{7}{2} + \frac{\pi^2}{3}\right)\right]$$

$\frac{s}{M^2}$	$-\ln^2\frac{s}{M^2}$	$+3\ln\frac{s}{M^2}$	$-\frac{7}{2}+\frac{\pi^2}{3}$	Σ	$*\,4\,\frac{\alpha_{\text{weak}}}{4\pi}$
$\left(\frac{1000}{80}\right)^2$	-25.52	$+15.15$	-0.21	-10.6	-13%
$\left(\frac{2000}{80}\right)^2$	-41.44	$+19.31$	-0.21	-22.3	-27%

(four-fermion cross section $\Rightarrow$ factor 4)

- leading $\log^2$ multiplied by (charge)$^2 = I(I+1) = \begin{cases} 3/4 & I = 1/2 \\ 2 & I = 1 \end{cases}$
  $\Rightarrow$ further enhancement for W-pairs by nearly factor 2.

- important subleading logarithms (NLL+...)

- One-loop up to $\mathcal{O}(40\%) \to$ two-loop terms may be relevant

- interplay between electroweak and QCD corrections

- important differences between fermions and electroweak gauge bosons

- important differences between long. and transverse gauge bosons ($I = 1/2$ vs. $I = 1$)

- Small transverse momenta, close to WW threshold!
  $\to$ complete calculation with masses required

Gauge Boson Pair Production: W^+W^-, $W^\pm Z$, ZZ, $\gamma\gamma$

Two Approaches:

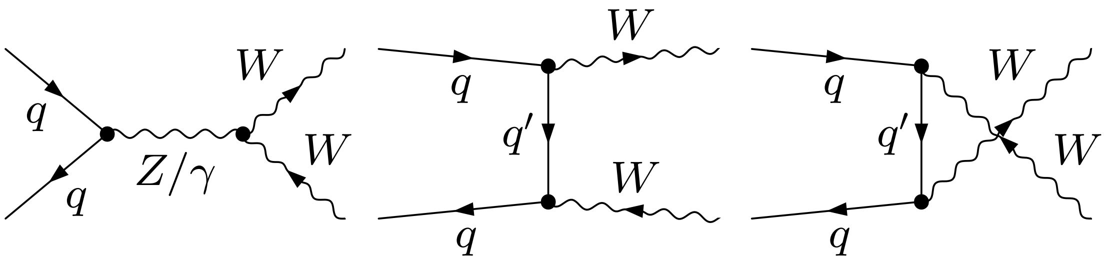
- dominant, logarithmically enhanced terms via evolution equation & separation of QED
  $\Rightarrow$ one- and two-loop terms in NNLL
  J.H.K., Metzler, Penin, Uccirati: JHEP 1106 (2011) 143
  related work based on SCET: Manohar,...

- one-loop calculation, including $M_W^2/\hat{s}$ terms and real radiation: full NLO
  Bierweiler, Kasprzik, J.H.K., Uccirati
  (JHEP 1211 (2012)093[arXiv:1208.3147], arXiv:1208.3404, arXiv:1305.5402)
  earlier work: logarithmically enhanced terms only, including W decays and off-shell effects
  Accomando, Denner, Kaiser

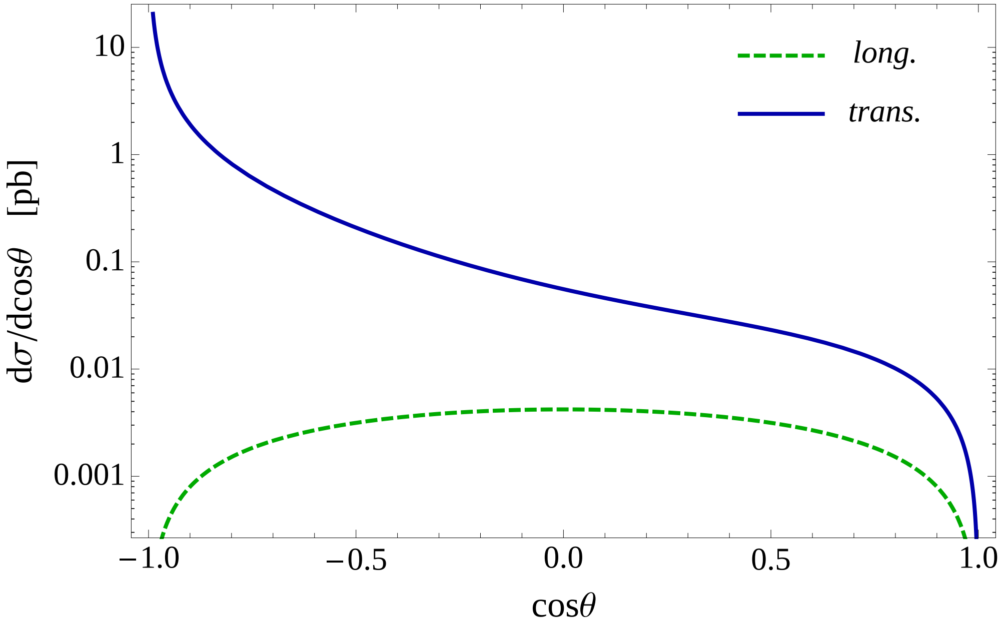
- Aim: Combine the two approaches
  $\rightarrow$ Implementation in Monte Carlo

II. One-Loop Results

II.1. W-Pairs: Leading Order

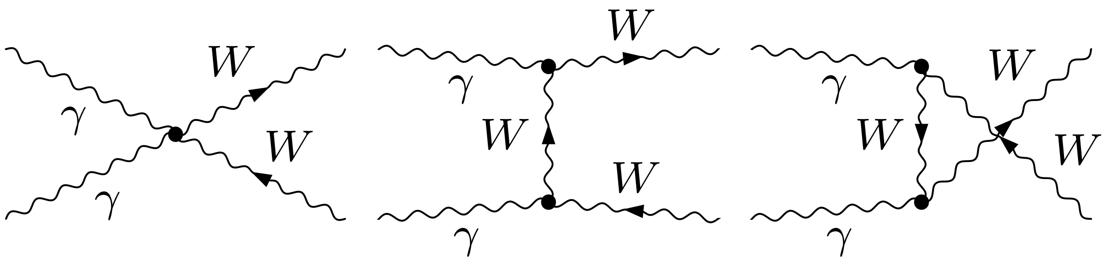


$u\bar{u} \to W^+W^-,\ \sqrt{s} = 1$ TeV

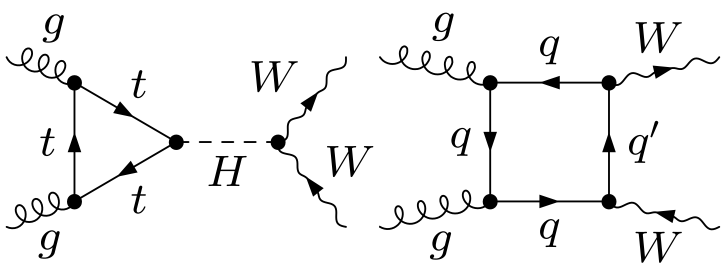


- Strong enhancement for $\Theta \to 180^\circ$
- dominance of transverse W

Also included: $\gamma\gamma \to WW$



also included: $gg \to WW$



One Loop Corrections

- On-shell, G_μ-scheme (M_W, M_Z, G_μ)

- virtual and real photon radiation included
  remaining collinear singularities "absorbed" in PDFs
  ($q\bar{q}$: MSTW2008LO; $\gamma\gamma$: MRST2004QED/NNPDF2.3QED)

- two independent calculations

- NLO QCD recalculated
  $\rightarrow$ giant corrections from events with soft W and hard jet: jet or p_T-veto to select "balanced" pairs

(related results: Baglio, Ninh, Weber)

- surprisingly large contribution from $\gamma\gamma \to WW$ at large $\hat{s}$ and **large** rapidity (small $\hat{t}$)

- large negative corrections at large $\hat{s}$ and small rapidity

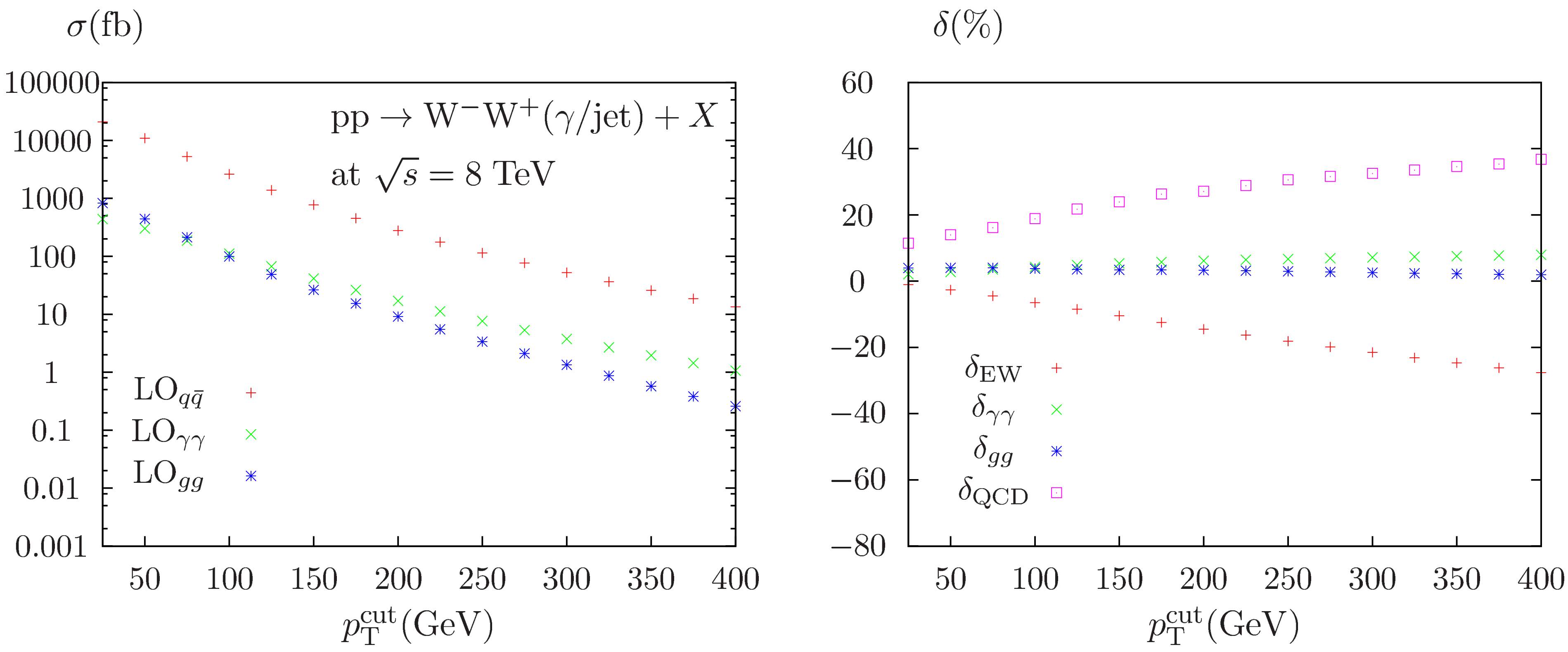
- pronounced modification of angular distribution ($\to$ mimics anomalous couplings) (compare Accomando, Denner, Kaiser)

- sizable QCD corrections

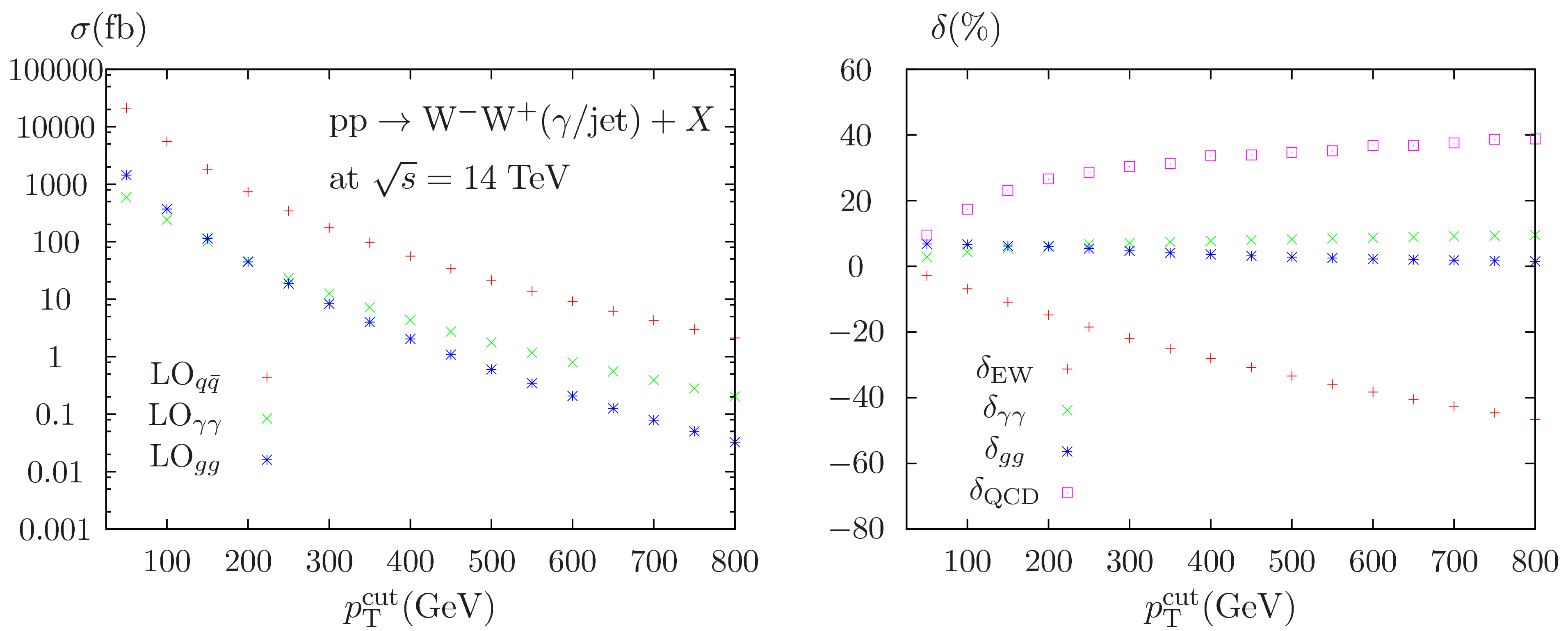
- combination of QCD and EW corrections? additive vs. multiplicative!

One-Loop Results

Total cross sections LHC8, $p_T > p_{T,\text{cut}}$ ($\int \mathcal{L} dt = 25$ fb^{-1} per experiment)

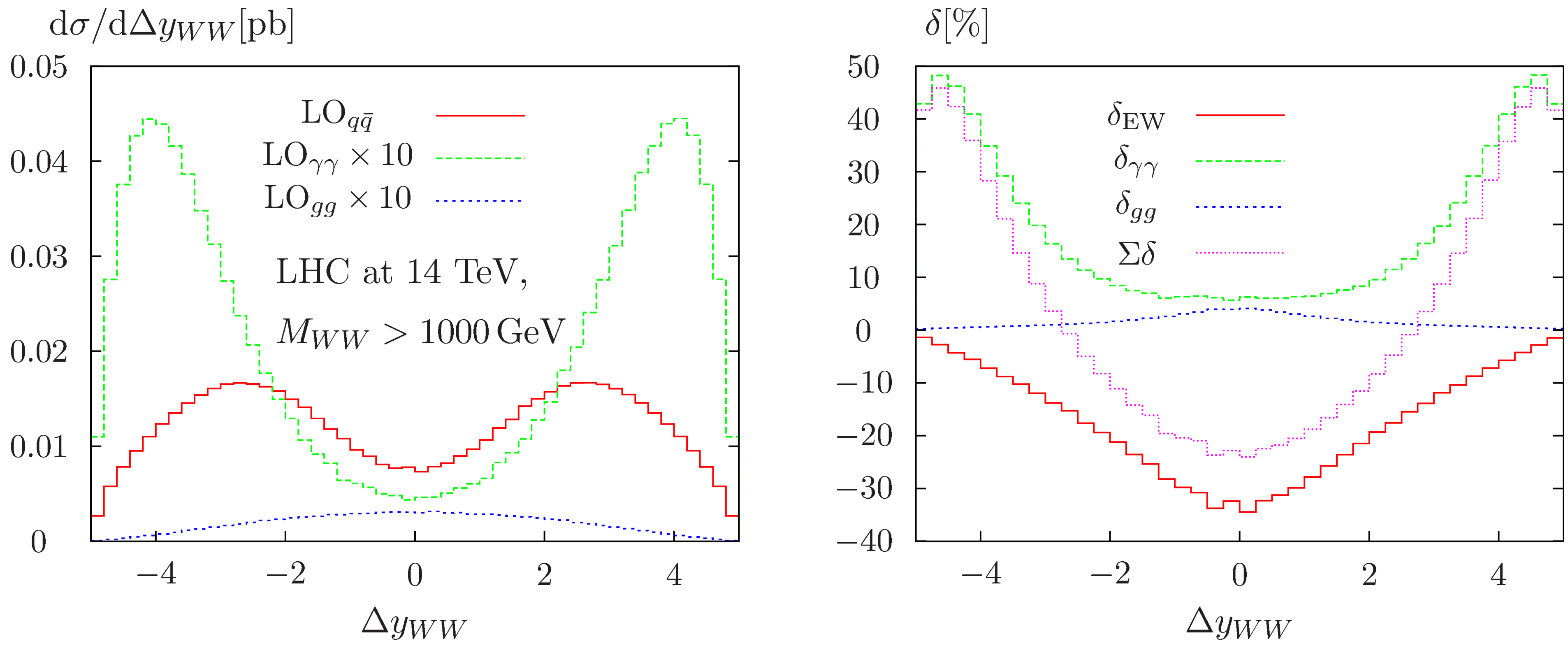


Total cross sections LHC14, $p_T > p_{T,\text{cut}}$
(Hope for $\int \mathcal{L}dt = 300$ fb^{-1} per experiment)



assume 10% efficiency

$\rightarrow$ up to $p_{\text{T}}^{\text{cut}} \sim 800$ GeV



Differential LO cross sections for the W-boson rapidity gap with a minimal invariant mass of 1000 GeV at the LHC14. On the right-hand-side, the corresponding relative rates due to photon- and gluon-induced channels w.r.t. the $q\bar{q}$-contributions are shown, as well as the EW corrections.

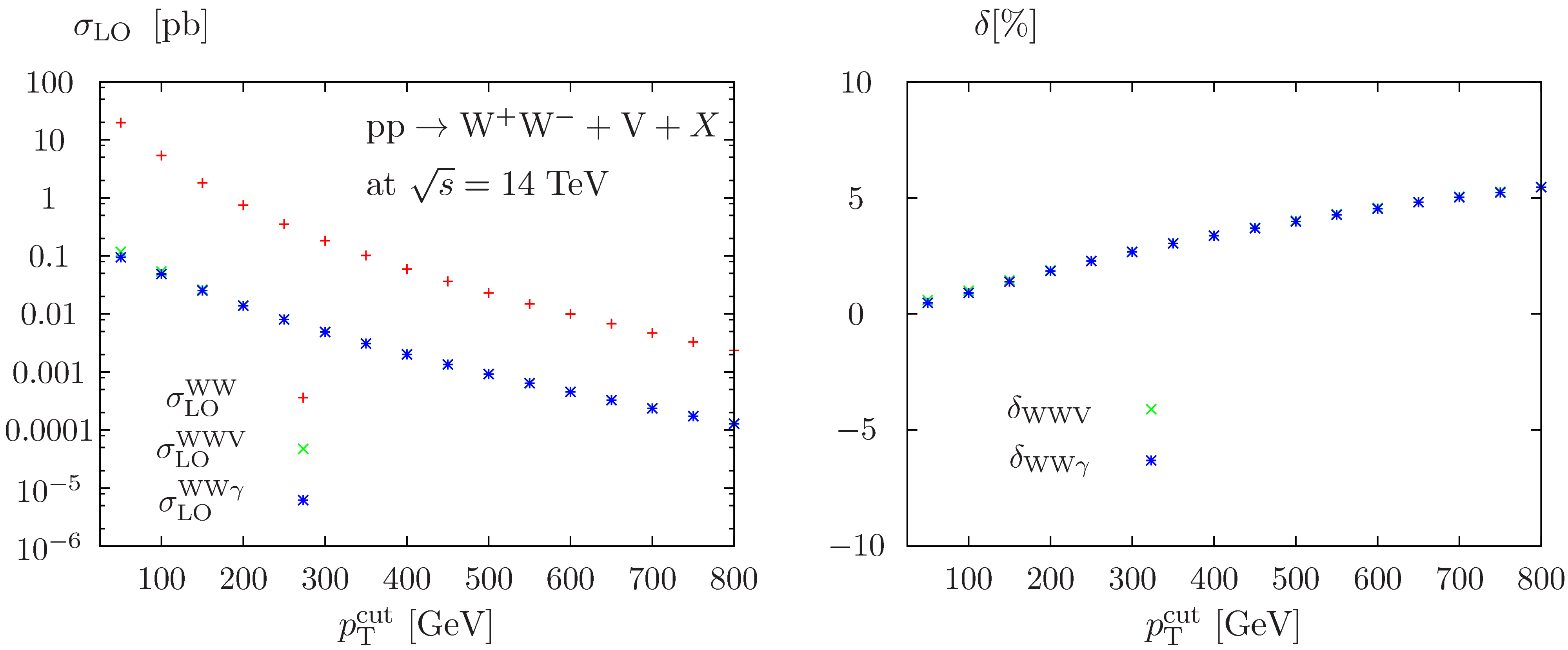
Real W, Z Radiation: Compensation?

- soft and/or collinear radiation may (partly) compensate or overcompensate virtual corrections:

- model study (Bell, J.K., Rittinger arXiv:1004.4117; EPJC)
strong dependence on cuts!
asymptotic energies (multi-TeV)

- semi-realistic evaluation (on-shell W, Z) (Bierweiler, Kasprzik, J.K.)
$q\bar{q} \longrightarrow W^+W^-(\gamma)$ (Born + one-loop)
vs. $q\bar{q} \longrightarrow W^+W^-Z$
$q\bar{q} \longrightarrow W^+W^-W^+$ + c.c.

- request large invariant mass of V-pair
or large p_{T} of both Vs



Aim: real radiation taken care of by MC $\Rightarrow$ different final states:

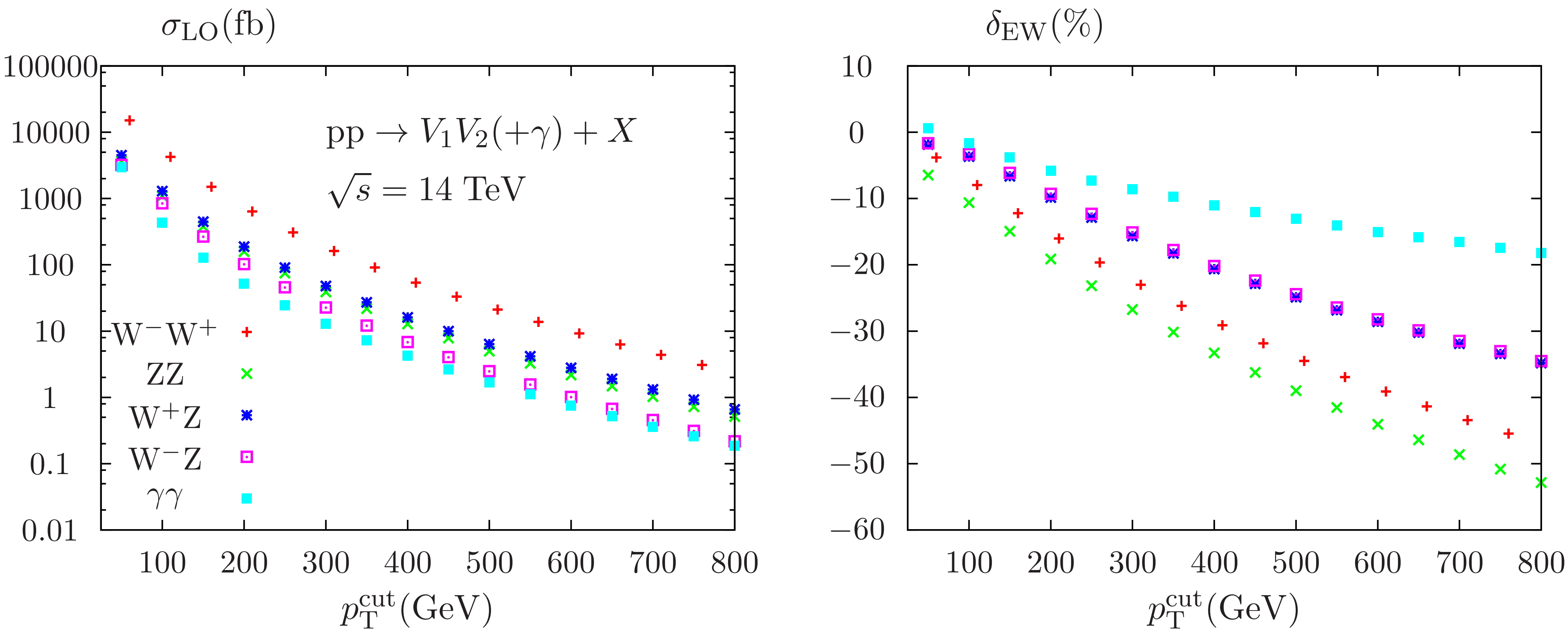
$\rightarrow$ different angular distributions

W^+W^-: $q\bar{q} \to W^+W^-Z,\ \ W^+W^-W^\pm$

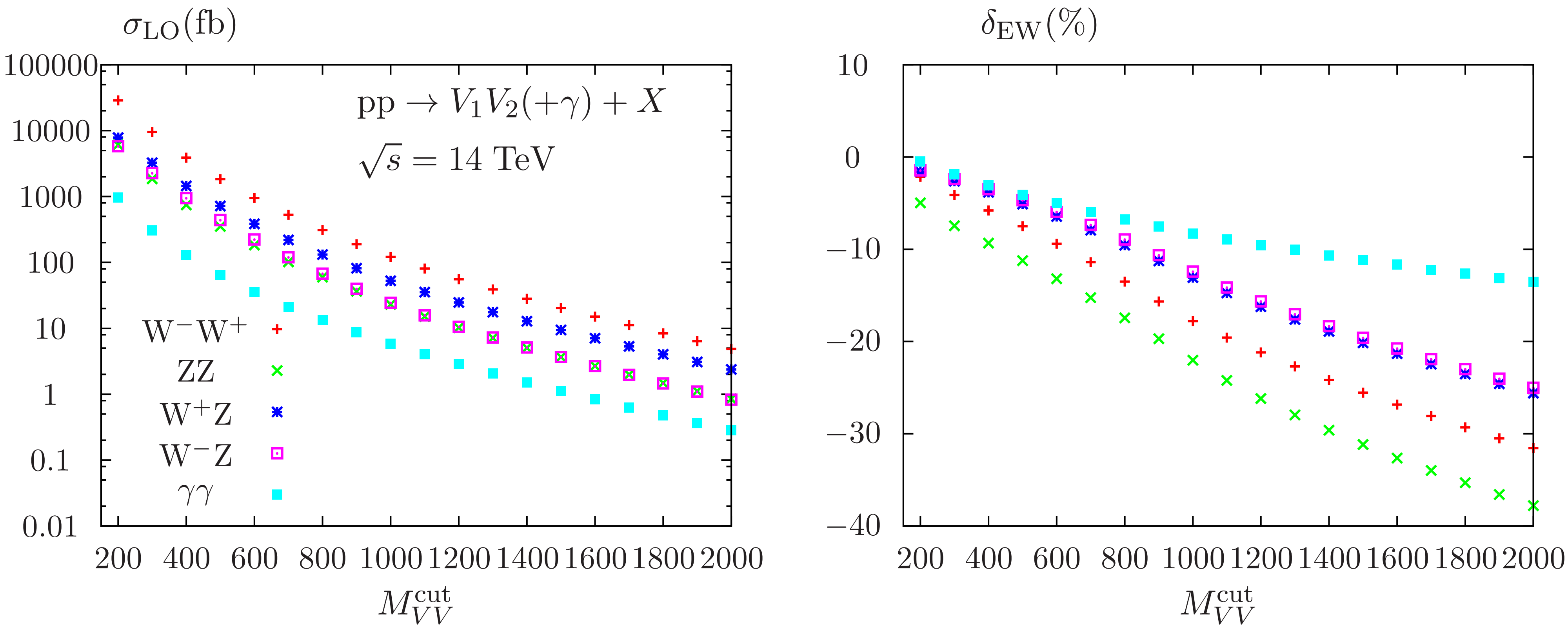
($\delta_{VV\gamma}$ strongly depends on cuts; here: $p_{T,\gamma} > 15$ GeV, $|y_\gamma| < 2.5$)

II.2. ZZ, WZ, $\gamma\gamma$

Similar setup, qualitative similar results

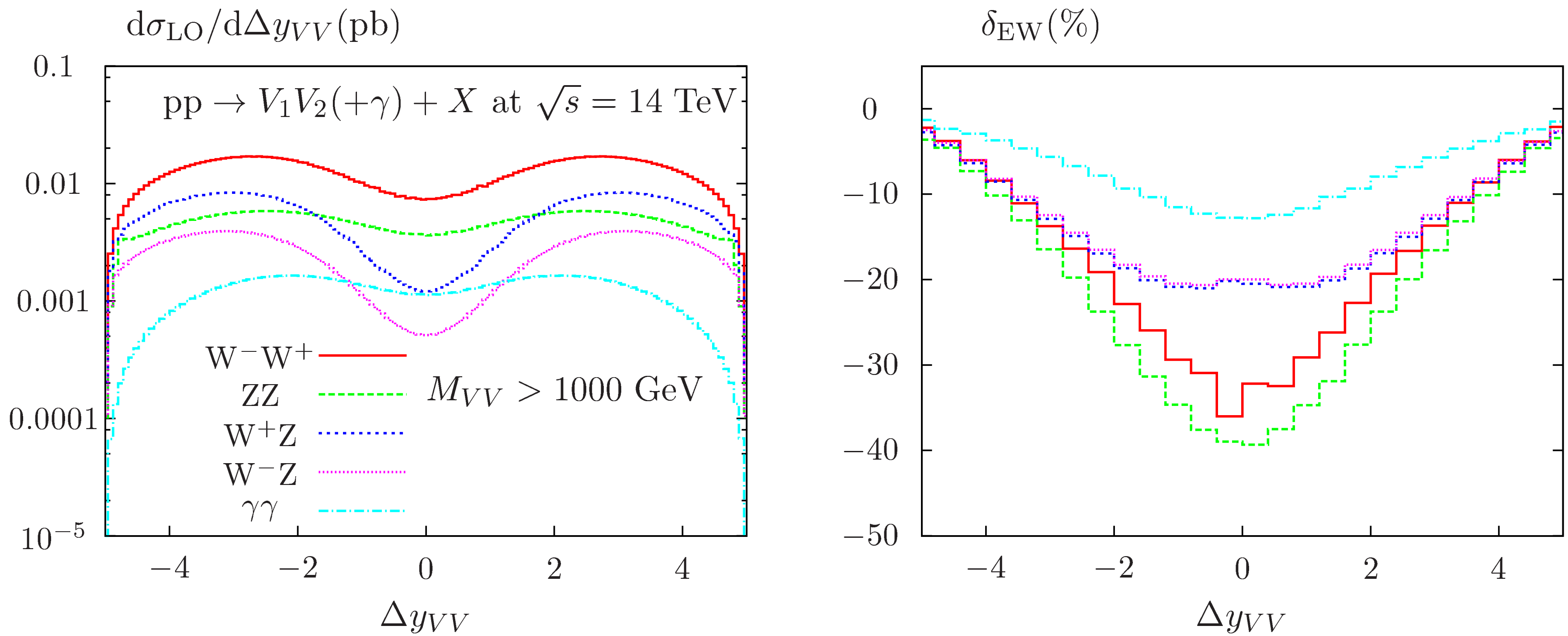


particularly large corrections for ZZ at large p_T: $\sim -40\%$
small p_T: $\sim -4\%$



particularly large corrections for ZZ at large M_{ZZ}: $\sim -40\%$

small M_{ZZ}: $\sim -4\%$



large effects on $\Delta y \equiv y_{V_1} - y_{V_2}$ distribution for large $M_{V_1 V_2}$

$\frac{d\sigma}{d\Delta y}\,|_{M_{V_1 V_2}} \,\hat{=}$ angular distribution in $V_1 V_2$ restframe

$\longrightarrow$ impact on search for anomalous couplings

ZZ production: polarization and decays

Impact of NLO corrections?

$\text{pp} \to \text{ZZ} + X$					
ZZ polarizations	summed	LL	L+	++	+−
LHC14					
default cuts $\sigma_{\text{LO}}/\text{pb}$ $\delta\sigma_{\text{weak}}/\text{pb}$	7.067 -0.338(-0.292)	0.402 -0.015(-0.014)	0.734 -0.029(-0.025)	0.100 -0.004(-0.003)	4.997 -0.257(-0.223)
$p_{\text{T,Z}} > 500$ GeV $\sigma_{\text{LO}}/\text{pb}$ $\delta\sigma_{\text{weak}}/\text{pb}$	$10^{-2} \times [0.499$ $-0.195(-0.148)]$	$10^{-7} \times [0.921$ $-4.70(+5.577)]$	$10^{-4} \times [0.334$ $-0.087(-0.067)]$	$10^{-7} \times [0.230$ $-0.426(-0.185)]$	$10^{-2} \times [0.492$ $-0.192(-0.147)]$
$p_{\text{T,Z}} > 1000$ GeV $\sigma_{\text{LO}}/\text{pb}$ $\delta\sigma_{\text{weak}}/\text{pb}$	$10^{-3} \times [0.146$ $-0.088(-0.062)]$	$10^{-9} \times [0.189$ $-4.319(+30.04)]$	$10^{-6} \times [0.306$ $-0.126(-0.090)]$	$10^{-10} \times [0.475$ $-2.953(+2.295)]$	$10^{-3} \times [0.146$ $-0.088(-0.062)]$

low p_{T}: universal corrections $\sim -4\%$

$\Longrightarrow$ angular distribution unchanged

high p_{T}: large corrections, only one combination $(+-)$ survives

$\Longrightarrow$ angular distribution unchanged

$\Longrightarrow$ **universal correction factor**

III. Implementation into HERWIG++

Assumption: factorization of EW and QCD corrections

$$\mathrm{d}\sigma_{\mathrm{QCD}\times\mathrm{EW}} = K_{\mathrm{weak}}(\hat{s},\hat{t}) \times \mathrm{d}\sigma_{\mathrm{QCD}}$$

$\mathrm{d}\sigma_{\mathrm{QCD}} \hat{=}$ best prediction for QCD-corrected cross section

- $\widehat{s}, \widehat{t}$ from matching of kinematics:

$$\widehat{s} = M^2_{V_1V_2}; \qquad \widehat{t} = ?$$

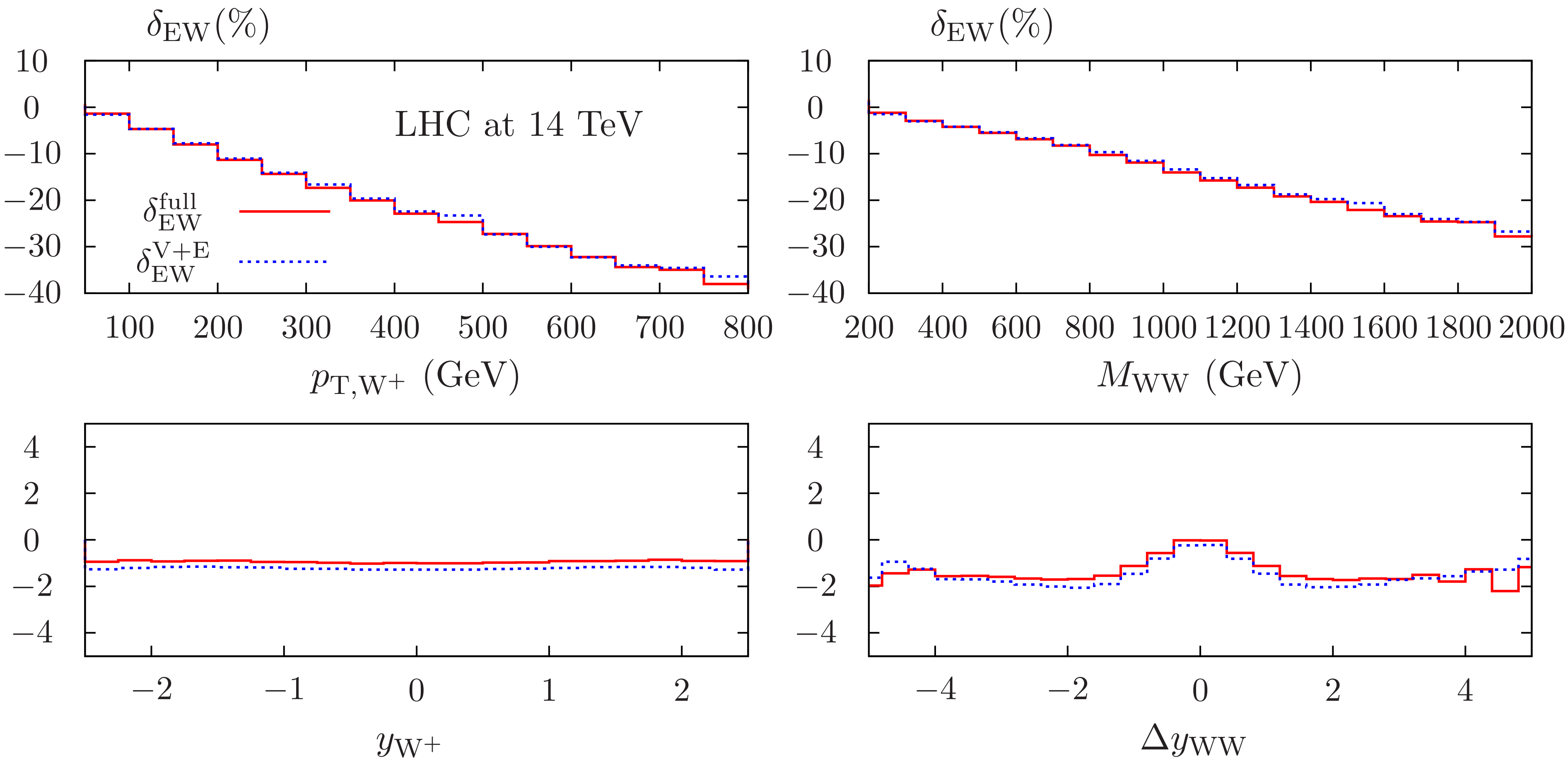
  – small $p_{\rm T}$ of V_1V_2 $\Longrightarrow$ $\widehat{\Theta}$ = scattering angle in V_1V_2 restframe (collinear or soft QCD corrections)

  – large $p_{\rm T}$ of V_1V_2 (assosiated with hard jet!)
  define directions of incoming protons in V_1V_2 restframe
  $\mathbf{e}^*_{1,2} \equiv \frac{\mathbf{p}^*_{1,2}}{|\mathbf{p}^*_{1,2}|}$
  scattering axis: $\widehat{\mathbf{e}}^* \equiv \frac{\mathbf{e}^*_1 - \mathbf{e}^*_2}{|\mathbf{e}^*_1 - \mathbf{e}^*_2|}$
  scattering angle: $\cos\widehat{\Theta} = \frac{\mathbf{p}^*_{V_1}}{|\mathbf{p}^*_{V_1}|} \cdot \widehat{\mathbf{e}}^*$

- or (HERWIG)
  $\widehat{s}, \widehat{t}$ provided by the generator

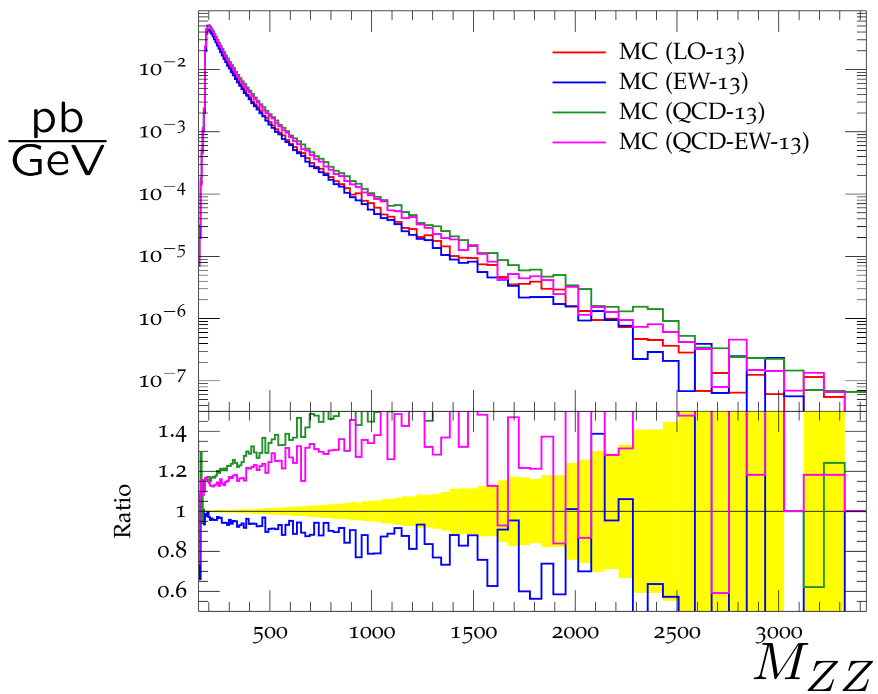
NLO corrections (electroweak) with full QED replaced by virtual + endpoint subtraction. (Dittmaier)
(remainder = real radiation - endpoint subtraction < 1%)

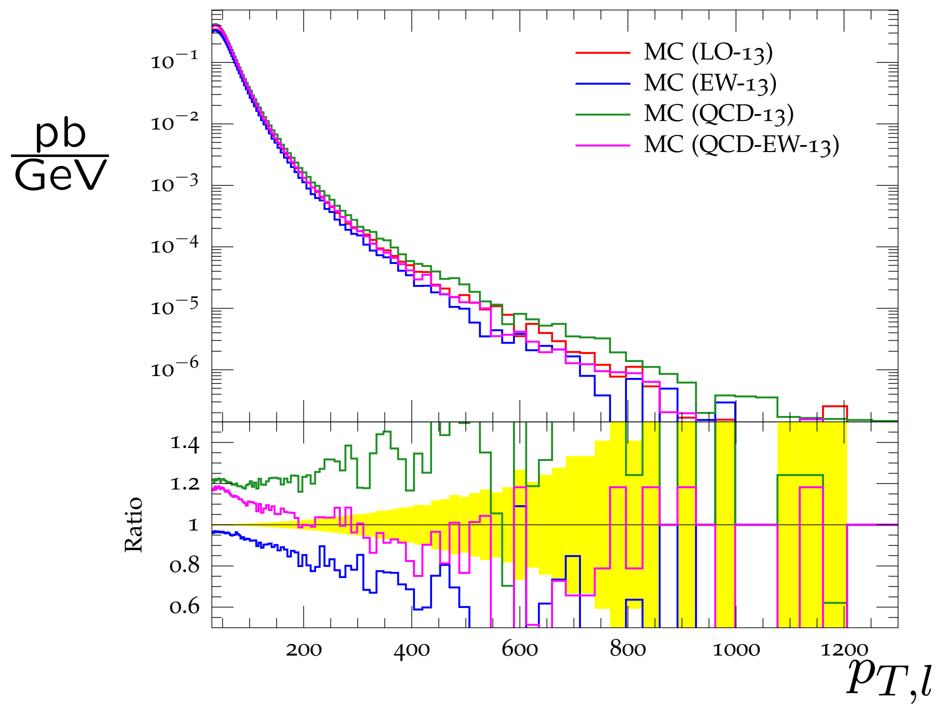
$pp \to WW$ at 14 TeV:



Results (preliminary)

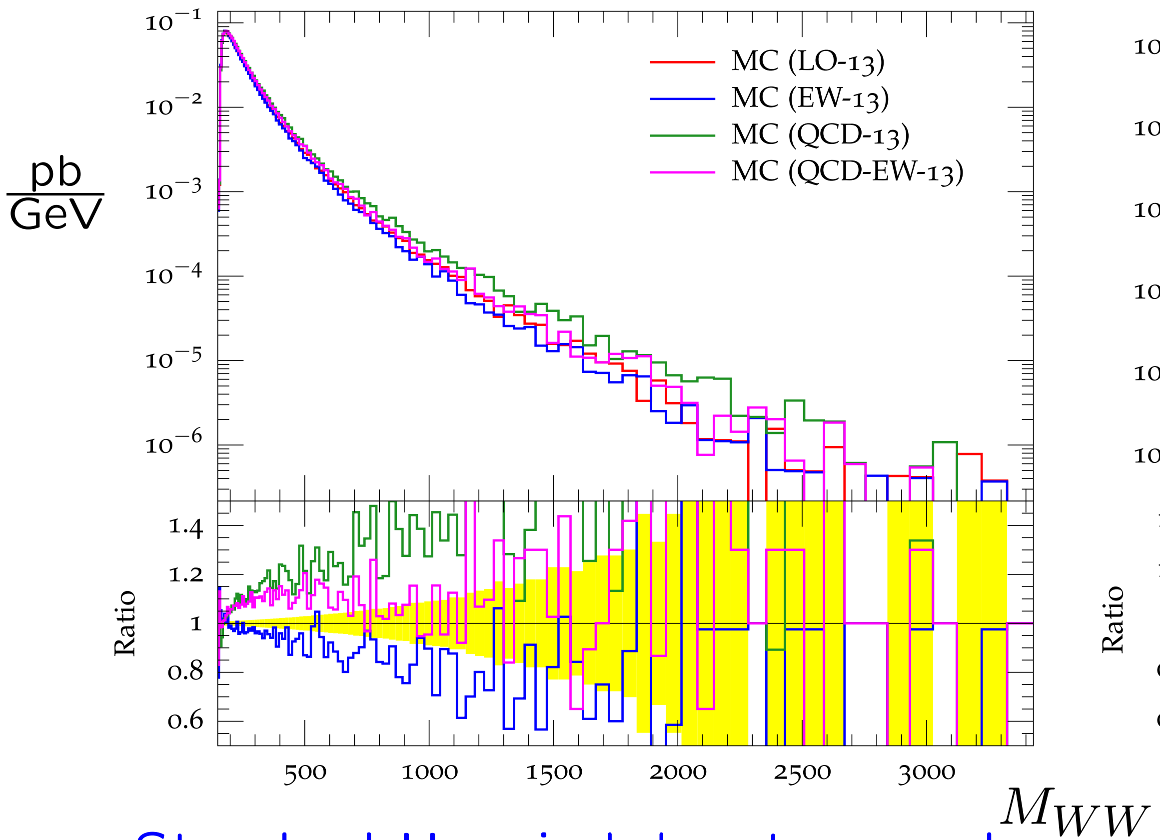
Simulation for $\mathrm{pp} \to ZZ \to e^+e^-\mu^+\mu^- + X$ at 13 TeV,
M_{ZZ} and $p_{\mathrm{T},l}$ (average lepton p_T) distributions

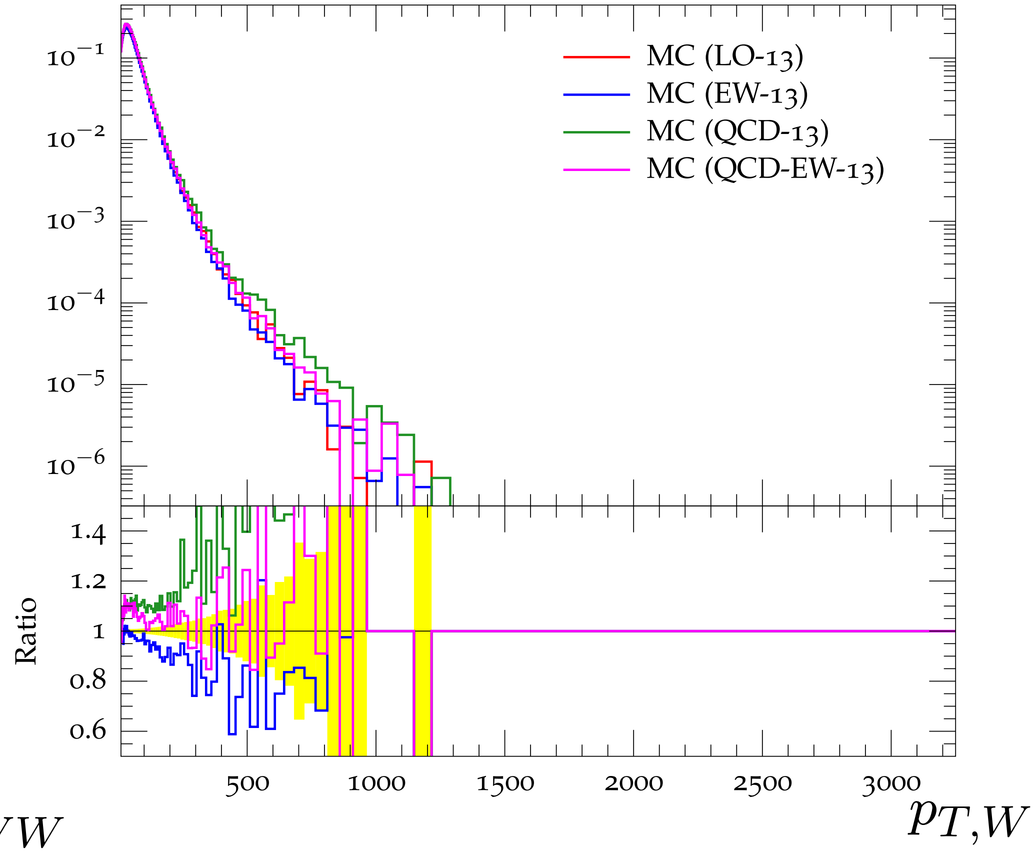




- Standard HERWIG++ setup used
  (v2.6.3, with simple add-on for EW corrections, 2M events), ZZ at NLO QCD matched with parton showers, hadronization included, underlying event switched off
- huge QCD corrections at large $p_{\mathrm{T,Z}}$, factorized ansatz not justified
  $\to$ jet veto, cut on $p_{\mathrm{T,ZZ}}$; veto: $|\sum_i \mathbf{p}^i_{T,l}| < 0.3 \sum_i |\mathbf{p}^i_{T,l}|$

Simulation for $\mathrm{pp} \to (\mathrm{W}^+ \to) e^+ \nu_e \, (\mathrm{W}^- \to) \mu^- \bar{\nu}_\mu + X$ at 13 TeV, M_{WW} and leading-W $p_{\mathrm{T,W}}$ distributions





- Standard Herwig++ setup used
  (v2.6.3, with simple add-on for EW corrections, 2M events), WW at NLO QCD $\oplus$ parton shower, hadronization included, underlying event switched off

- V+E approximate results consistent with arXiv:1208.3147

IV. Two Loop Results (Sudakov Logarithms)

one-loop: $\sim -40\%$
two-loop: $\sim ?$

(Vast amount of literature since ~ 2000)

Karlsruhe (Jantzen, J.K., Metzler, Penin, Smirnov, Uccirati)

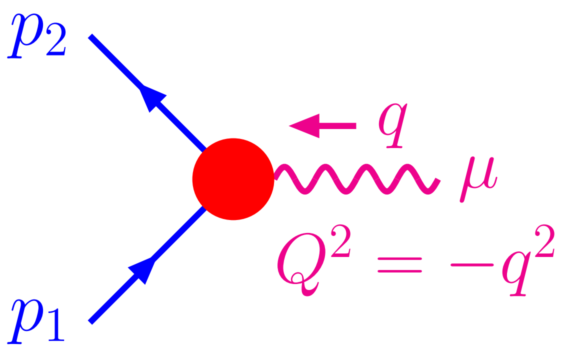
Fadin, Lipatov, Martin, Melles

PSI (Denner, Melles, Pozzorini, . . .)

Ciafaloni, . . .

Manohar, . . .

A) Form Factor and Evolution Equations



Born:

$\mathcal{F}_{\text{Born}} = \bar{\psi}(p_2)\gamma_\mu\psi(p_1)$

$$\frac{\partial}{\partial \ln Q^2}\mathcal{F} = \left[\int_{M^2}^{Q^2}\frac{\mathrm{d}x}{x}\gamma(\alpha(x)) + \zeta(\alpha(Q^2)) + \xi(\alpha(M^2))\right]\mathcal{F}$$

Collins, Sen

$$\Rightarrow\ \mathcal{F} = \mathcal{F}_{\text{Born}}\, F_0(\alpha(M^2))\, \exp\left\{\int_{M^2}^{Q^2}\frac{\mathrm{d}x}{x}\left[\int_{M^2}^{x}\frac{\mathrm{d}x'}{x'}\gamma(\alpha(x')) + \zeta(\alpha(x)) + \xi(\alpha(M^2))\right]\right\}$$

aim: N^{4}LL $\quad\Rightarrow\quad$ corresponds to all terms of the form:

$$\alpha^n \left[\underset{\text{LL}}{\mathcal{L}^{2n}} + \underset{\text{NLL}}{\mathcal{L}^{2n-1}} + \underset{\text{NNLL}}{\mathcal{L}^{2n-2}} + \underset{\text{N}^3\text{LL}}{\mathcal{L}^{2n-3}} + \underset{\text{N}^4\text{LL}}{\mathcal{L}^{2n-4}} \right]$$

$$\mathcal{L} \equiv \ln(Q^2/M^2)$$

NNLL requires running of α (i.e. β_0 and β_1) and:

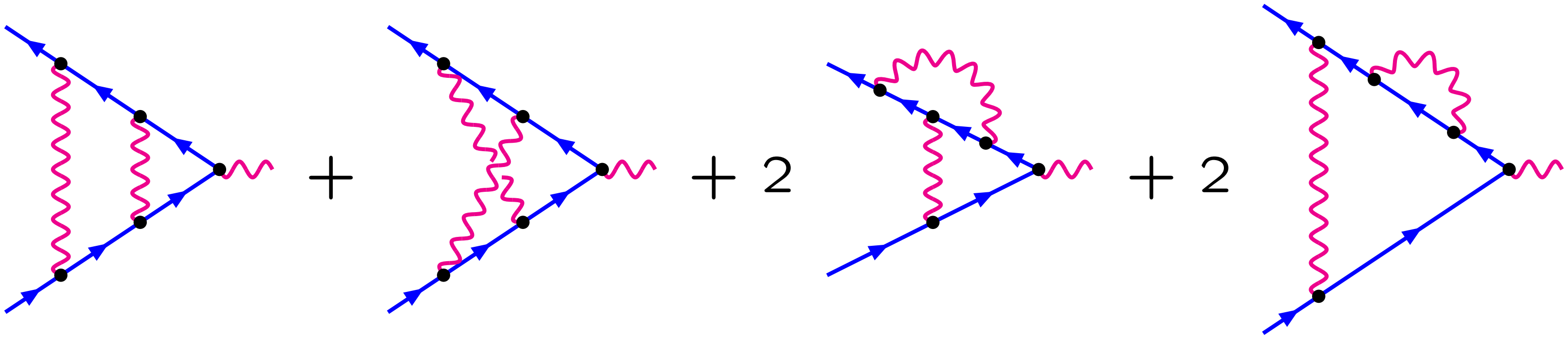
$\zeta(\alpha)$, $\xi(\alpha)$, $F_0(\alpha)$	up to $\mathcal{O}(\alpha)$	(one-loop)
$\gamma(\alpha)$	up to $\mathcal{O}(\alpha^2)$	(massless two loop)

N^{3}LL requires two-loop calculation in high-energy limit including linear logarithms (available for non-abelian theory)

N^{4}LL requires complete two-loop calculation in high-energy limit (available for abelian theory)

B) Two-Loop Results: Massive U(1) Model

$$\mathcal{F}_\alpha(M,Q) = \mathcal{F}_{\text{Born}}\left[1 + \frac{\alpha}{4\pi} f^{(1)} + \left(\frac{\alpha}{4\pi}\right)^2 f^{(2)} + \ldots\right]$$

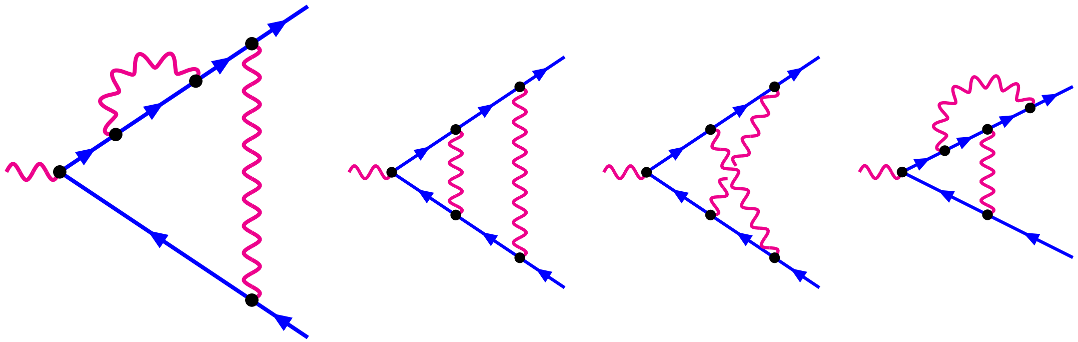


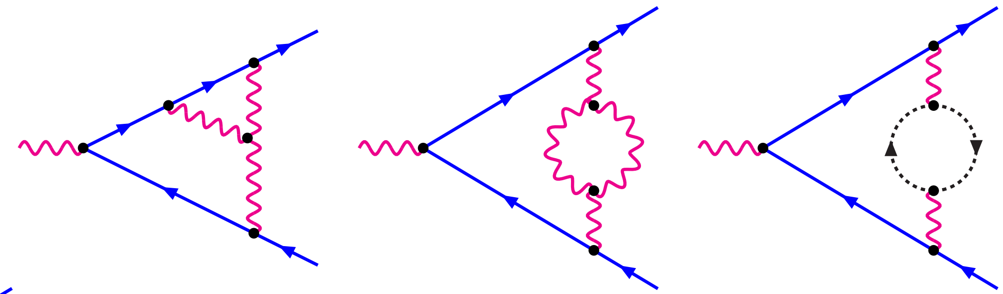
$$f^{(2)} = \frac{1}{2}\mathcal{L}^4 - 3\,\mathcal{L}^3 + \left(8 + \frac{2}{3}\pi^2\right)\mathcal{L}^2 - \left(9 + 4\pi^2 - 24\zeta_3\right)\mathcal{L}$$
$$+\frac{25}{2} + \frac{52}{3}\pi^2 + 80\zeta_3 - \frac{52}{15}\pi^4 - \frac{32}{3}\pi^2\ \ln^2 2 + \frac{32}{3}\ \ln^4 2 + 256\,\text{Li}_4\left(\frac{1}{2}\right)$$

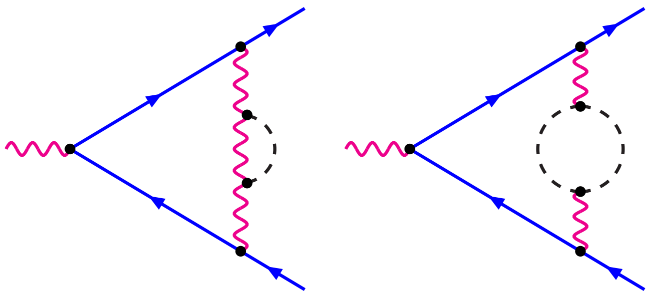
$\mathcal{L} \equiv \ln(Q^2/M^2)$

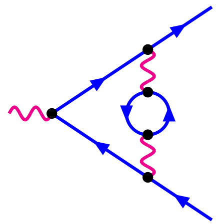
C) Massive SU(2) form factor in 2-loop approximation

2-loop vertex diagrams (massless fermions, massive bosons):

Abelian (C_F^2): 

non-Abelian ($C_F C_A$): last 2 + 

Higgs: 

fermion ($C_F T_F n_f$): 

+ 1-loop$\times$1-loop corrections + renormalization

$$f_2 = +\frac{9}{32}\mathcal{L}^4 - \frac{19}{48}\mathcal{L}^3 - \left(-\frac{7}{8}\pi^2 + \frac{463}{48}\right)\mathcal{L}^2$$
$$+ \left(\frac{39}{2}\frac{\mathrm{Cl}_2\left(\frac{\pi}{3}\right)}{\sqrt{3}} + \frac{45}{4}\frac{\pi}{\sqrt{3}} - \frac{61}{2}\zeta_3 - \frac{11}{24}\pi^2 + 29\right)\mathcal{L}$$

Extensions to four-fermion scattering (Penin et al.) and W-pair production (J.K., Metzler, Penin, Uccirati)

General form (for transverse W) :

$$\mathcal{A} = \alpha(\mu_{\mathsf{T}}) \mathcal{Z}_{\Psi} \mathcal{Z}_{W} \tilde{\mathcal{A}}$$

$\mathcal{Z}_{W,\Psi}$ = form factors of quark or W-field

$\tilde{\mathcal{A}}$ = reduced amplitude (matrix in isospin space)

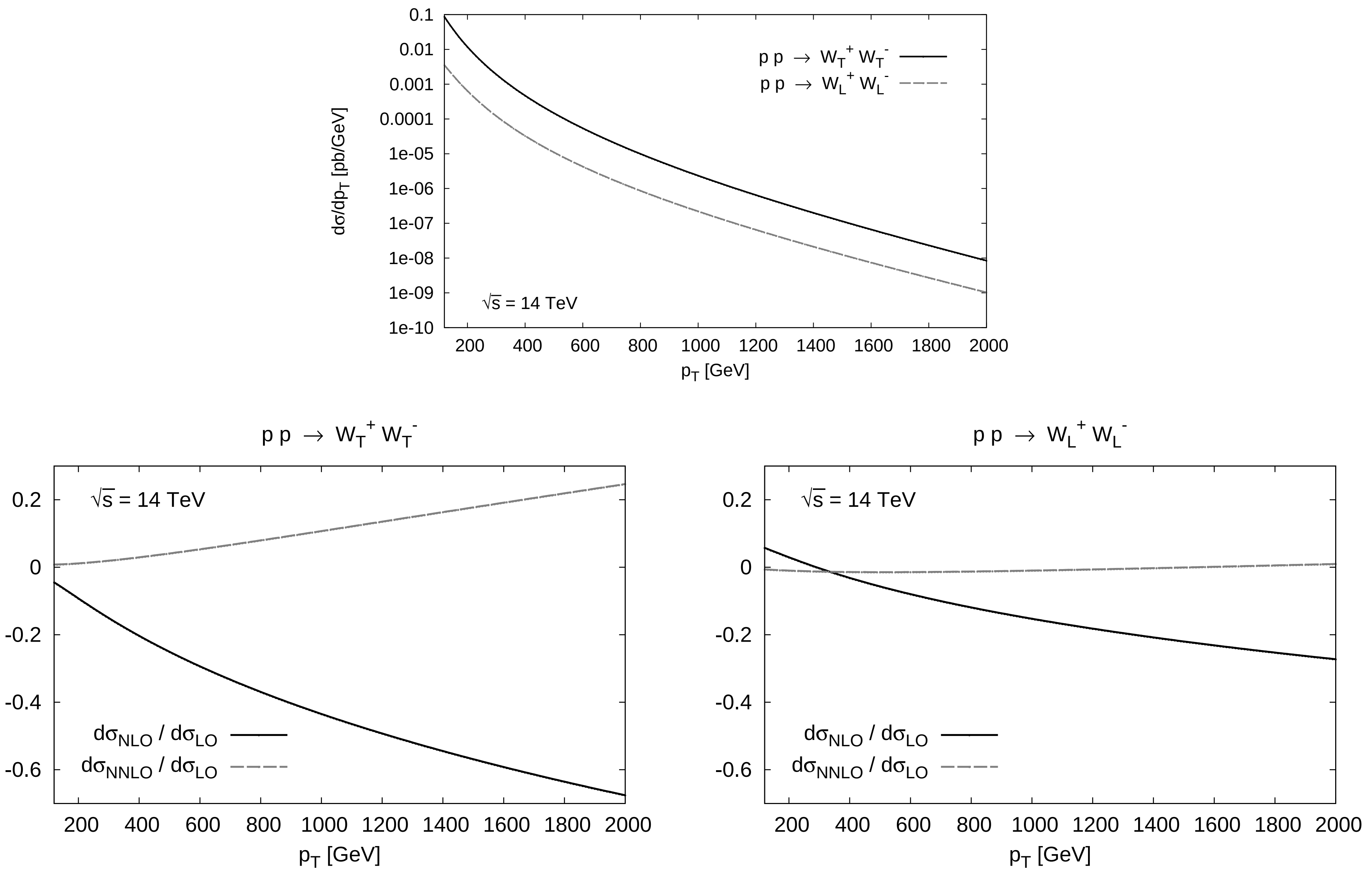
Solution of

$$\frac{\partial}{\partial \ln Q^2} \tilde{\mathcal{A}} = \chi(\alpha(Q^2)) \tilde{\mathcal{A}}$$

($\chi \equiv$ anomalous dimension matrix)

up to quadratic logarithms only one-loop terms ($\ln^2, \ln^1, \ln^0$) of $q\bar{q} \longrightarrow WW$ and the two-loop term $\gamma^{(2)}$ of the anomalous dimension (form factor!) required.

Complication: massless photon! $\Rightarrow$ QED subtracted



($W_{T,L}$: Isospin $I = 1, 1/2$; $\Rightarrow$ relative factor 6/11)

V. Summary

- Weak corrections at LHC14 may reach -40%

- complicated impact on differential distributions
  $\Longrightarrow$ fake anomalous couplings; sensitive to cuts

- first steps toward combination of QCD and EW corrections in Monte Carlo generator

- dominant two-loop corrections (partially) available