The Event Generator HORACE

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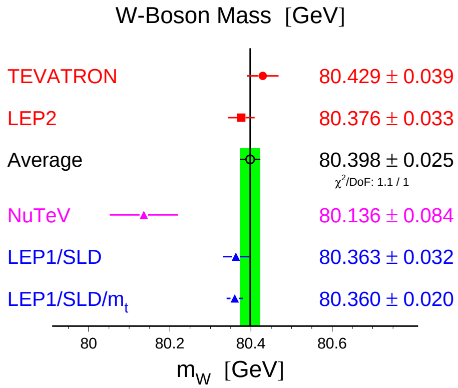
Outline

- The event generator **HORACE**
  http://www.pv.infn.it/hepcomplex/horace.html
  - first version (with a QED Parton Shower)
    C.M.C.C., G. Montagna, O. Nicrosini, M. Treccani, Phys. Rev. **D69**:037301 (2004)
    JHEP 0505:019 (2005)
  - inclusion of exact $\mathcal{O}(\alpha)$ electro-weak corrections
    C.M.C.C., G. Montagna, O. Nicrosini, A. Vicini, JHEP 0612 016 (2006)
    JHEP 0710 109 (2007)
  - results
- Combining EW & QCD corrections
- Quickly translating RC and/or theoretical errors into M_W shifts/uncertainties: the **fitter** program
- A wish list & conclusions

Direct measurement of M_W

- at LEP2, from $e^+e^- \to WW$ (at threshold and higher energies)
- at hadron colliders, from the M_T distribution



Future goals for ΔM_W

- ⋆ Tevatron Run II $\Rightarrow$ 27 MeV
- ⋆ LHC $\Rightarrow$ 15 MeV

Future goals for $\Delta \Gamma_W$

- ⋆ Tevatron Run II $\Rightarrow$ 30 MeV
- ⋆ LHC $\Rightarrow \leq$ 30 MeV

- A small ΔM_W (and Δm_{top}) will constrain the indirect limit on M_H

$\Delta M_W = 27\ [15]$ MeV and $\Delta m_{top} = 2.7\ [1]$ GeV $\to \Delta M_H / M_H \simeq 35\ [18]\%$

Status of QCD calculations (& tools)

- NLO/NNLO corrections to W/Z total production rate

G. Altarelli, R.K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246** (1984) 12

R. Hamberg, W.L. van Neerven, T. Matsuura, Nucl. Phys. **B359** (1991) 343

W.L. van Neerven and E.B. Zijlstra, Nucl. Phys. **B382** (1992) 11

- fully exclusive NLO corrections to W/Z production (and to W/Z + 1 jet, W/Z + 2 jets) (**MCFM**)

J. M. Campbell and R.K. Ellis, Phys. Rev. **D65** 113007

- fully exclusive NNLO corrections to W/Z production (**FEWZ**)

C. Anastasiou et al., Phys. Rev. **D69** (2004) 094008
K. Melnikov and F. Petriello, Phys. Rev. Lett. **96** (2006) 231803
S. Catani, L. Cieri, G. Ferrera, D. de Florian, M. Grazzini **arXiv:0903.2120 [hep-ph]**

- resummation of LL/NLL p_T^W/M_W logs (**RESBOS**)

C. Balazs and C.P. Yuan, Phys. Rev. **D56** (1997) 5558

P. Nadolsky et al. Phys. Rev. **D67** (2003) 073016

- NLO merged with Parton Shower [PS] (**MC@NLO**, **POWHEG**)

S. Frixione and B.R. Webber, JHEP **0206** (2002) 029

Nason, Ridolfi, Oleari et al.

- Matrix elements MC (**ALPGEN**, **SHERPA**,...) matched with PS

M.L. Mangano et al., JHEP **0307**, 001 (2003)

F. Krauss et al., JHEP **0507**, 018 (2005)

EW calculations for W & tools

- $\mathcal{O}(\alpha)$ electroweak corrections to W production
  - ⋆ Pole approximation ($\sqrt{\hat{s}} = M_W$)
    - → D. Wackeroth and W. Hollik, PRD **55** (1997) 6788
    - → U. Baur et al., PRD **59** (1999) 013002
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections
    - → V.A. Zykunov et al., EPJC **3** 9 (2001)
    - → S. Dittmaier and M. Krämer, PRD **65** (2002) 073007 **DK**
    - → U. Baur and D. Wackeroth, PRD **70** (2004) 073015 **WGRAD2**
    - → A. Arbuzov, et al., EPJC **46**, 407 (2006) **SANC**
    - → C.M.C.C. et al., JHEP 0612:016 (2006) **HORACE**
- Multi-photon radiation
  - → C.M.C.C. et al., PRD **69**, 037301 (2004); JHEP 0612:016 (2006) **HORACE**
  - → S. Jadach, W. Płaczek, EPJC **29** 325 (2003) **WINHAC**

EW calculations for Z

- $\mathcal{O}(\alpha)$ electroweak corrections to Z production
  - ⋆ QED corrections
    - → U. Baur, *et al.*, Phys. Rev. **D57** (1998) 199 (**ZGRAD**)
  - ⋆ Complete $\mathcal{O}(\alpha)$ corrections
    - → U. Baur, *et al.*, Phys. Rev. **D65** (2002) 033007 (**ZGRAD2**)
    - → C.M.C.C. et al, JHEP 0710:109 (2007) (**HORACE**)
    - → Bardin et al., **arXiv:0711.0625 [hep-ph]** (**SANC**)
- Multi-photon radiation
  - → C.M.C.C. et al., JHEP 0505:019 (2005) + JHEP 0710:109 (2007) (**HORACE**)
  - → W. Płaczek et al., in preparation (**ZINHAC**)

⋆ all the independent EW calculations have been successfully cross-checked by tuned comparisons during TeV4LHC, LH 2005, LH 2007 workshops ⋆

arXiv:0705.3251 [hep-ph]
hep-ph/0604120
arXiv:0803.0678 [hep-ph]

Les Houches comparisons, varying $p_\perp^\ell$ cut

C. Buttar et al., hep-ph/0604120

$pp \to \nu_l l^+ (+\gamma)$ @ $\sqrt{s} = 14$ TeV (with MRSTQED04)

$p_{T,l}$/GeV	25–∞	50–∞	100–∞	200–∞	500–∞	1000–∞
σ_0/pb						
DK	2112.2(1)	13.152(2)	0.9452(1)	0.11511(2)	0.0054816(3)	0.00026212(1)
HORACE	2112.21(4)	13.151(6)	0.9451(1)	0.11511(1)	0.0054812(4)	0.00026211(2)
SANC	2112.22(2)	13.1507(2)	0.94506(1)	0.115106(1)	0.00548132(6)	0.000262108(3)
WGRAD	2112.3(1)	13.149(1)	0.94510(5)	0.115097(5)	0.0054818(2)	0.00026209(2)
$\delta_{e+\nu_e}$/%						
DK	−5.19(1)	−8.92(3)	−11.47(2)	−16.01(2)	−26.35(1)	−37.92(1)
HORACE	−5.23(1)	−8.98(1)	−11.49(1)	−16.03(1)	−26.36(1)	−37.92(2)
WGRAD	−5.10(1)	−8.55(5)	−11.32(1)	−15.91(2)	−26.1(1)	−38.2(2)
$\delta_{\mu+\nu_\mu}$/%						
DK	−2.75(1)	−4.78(3)	−8.19(2)	−12.71(2)	−22.64(1)	−33.54(2)
HORACE	−2.79(1)	−4.84(1)	−8.21(1)	−12.73(1)	−22.65(1)	−33.57(1)
SANC	−2.80(1)	−4.82(2)	−8.17(2)	−12.67(2)	−22.63(2)	−33.50(2)
WGRAD	−2.69(1)	−4.53(1)	−8.12(1)	−12.68(1)	−22.62(2)	−33.6(2)
δ_{recomb}/%						
DK	−1.73(1)	−2.45(3)	−5.91(2)	−9.99(2)	−18.95(1)	−28.60(1)
HORACE	−1.77(1)	−2.51(1)	−5.94(1)	−10.02(1)	−18.96(1)	−28.65(1)
SANC	−1.89(1)	−2.56(1)	−5.97(1)	−10.02(1)	−18.96(1)	−28.61(1)
WGRAD	−1.71(1)	−2.32(1)	−5.94(1)	−10.11(2)	−19.08(3)	−28.73(6)
$\delta_{\gamma q}$/%						
DK	+0.071(1)	+5.24(1)	+13.10(1)	+16.44(2)	+14.30(1)	+11.89(1)

HORACE: first version

- The Monte Carlo event generator **HORACE** was originally developed to simulate QED multi-photon radiation in DY (W & Z) processes in Leading-Log accuracy, by means of a QED Parton Shower [PS]. Only final state radiation was accounted for

  C.M.C.C. et al., PRD **69** 037301 (2004)

  C.M.C.C et al., JHEP 0505:019 (2005)

- as in QCD, the QED PS solves the QED DGLAP equation, allowing for
  - ⋆ inclusion of QED LL corrections up to all orders (resummation)
  - ⋆ fully exclusive event generation (up to ∞ photons)

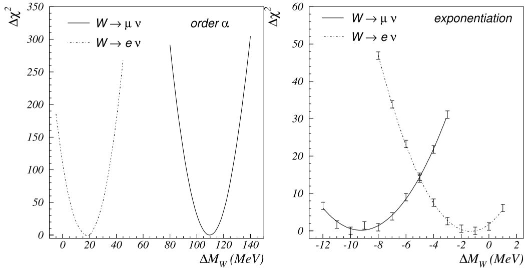
⋆ the QED PS is very (very!) similar to the package **PHOTOS**

→ e.g., by comparing the resummed PS and its $\mathcal{O}(\alpha)$ truncation, the effects purely due to QED higher-orders in the extraction of M_W from $M_\perp^W$ can be disentangled

M_W shift induced by h.o. QED RC

C.M.C.C. et al., PRD **69**, 037301 (2004)

- we performed an exercise by including (naive) detector effects to estimate the impact of QED RC on M_W extraction from M_T^W distribution



$\Delta M_W^{\alpha,e} \sim 20$ MeV
$\Delta M_W^{\alpha,\mu} \sim 110$ MeV

$\Delta M_W^{\infty,e} \sim 2$ MeV
$\Delta M_W^{\infty,\mu} \sim 10$ MeV

- for the electron, a recombination criterium was adopted $\rightarrow$ smaller effect
- W-mass shift due to multiphoton radiation is about 10% of that caused by one photon emission $\rightarrow$ non negligible for precise W mass!

Matching $\mathcal{O}(\alpha)$ RC with multi-photon radiation

- a matching of the LL QED PS with the exact EW $\mathcal{O}(\alpha)$ calculation is necessary, in order to
  - ⋆ preserve PS advantages (multi-photon effects, exclusive event generation)
  - ⋆ go beyond its approximation (LL accuracy, missing contributions already at $\mathcal{O}(\alpha)$)
- the matching has to avoid the double counting of $\mathcal{O}(\alpha)$ LL, already accounted for by the PS, and to "produce" a formula well suited for Monte Carlo generation
- the issue has a long story also in QCD (e.g. **MC@NLO**, **POWHEG**)

PS and exact $\mathcal{O}(\alpha)$ matrix elements (at parton level)

Consider the LL [$LL \equiv PS$] resummed, LL $\mathcal{O}(\alpha)$ and exact $\mathcal{O}(\alpha)$ cross sections

- $d\sigma^{\infty}_{LL} = \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ |\mathcal{M}_{n,LL}|^2\ d\Phi_n$
- $d\sigma^{\alpha}_{LL} = [1 + C_{\alpha,LL}]\,|\mathcal{M}_0|^2 d\Phi_0 + |\mathcal{M}_{1,LL}|^2 d\Phi_1 \equiv d\sigma_{SV}(\varepsilon) + d\sigma_H(\varepsilon)$
- $d\sigma^{\alpha}_{exact} = [1 + C_{\alpha}]\,|\mathcal{M}_0|^2 d\Phi_0 + |\mathcal{M}_1|^2 d\Phi_1$
- $F_{SV} = 1 + (C_\alpha - C_{\alpha,LL}) \qquad F_H = 1 + \frac{|\mathcal{M}_1|^2 - |\mathcal{M}_{1,LL}|^2}{|\mathcal{M}_{1,LL}|^2}$
- $d\sigma^{\alpha}_{exact} \overset{\text{at } \mathcal{O}(\alpha)}{=} F_{SV}(1 + C_{\alpha,LL})|\mathcal{M}_0|^2 d\Phi_0 + F_H|\mathcal{M}_{1,LL}|^2 d\Phi_1$

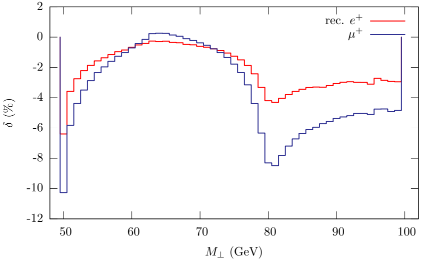
$$d\sigma^{\infty}_{matched} = F_{SV}\ \Pi(Q^2,\varepsilon)\ \sum_{n=0}^{\infty} \frac{1}{n!}\ \left(\prod_{i=0}^{n} F_{H,i}\right)\ |\mathcal{M}_{n,LL}|^2\ d\Phi_n$$

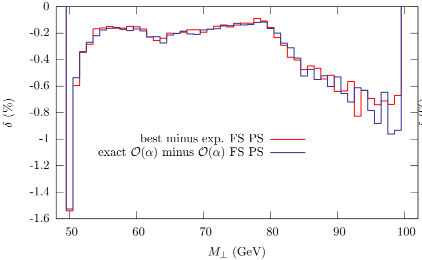
The new event generator HORACE

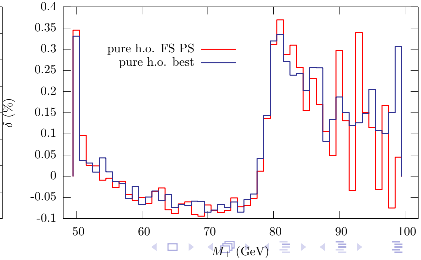
- **www.pv.infn.it/hepcomplex/horace.html**
- current version: 3.1 + bug fixes
- it is an event generator implementing SM EWK RC to charged- and neutral-current DY processes
  - ⋆ exact $\mathcal{O}(\alpha)$ RC, consistently matched with
  - ⋆ multi-photon radiation (h.o. QED corrections)
  - ⋆ and including photon-induced processes
- it's a true, fully exclusive event generator
- events saved in a Les Houches compliant format
  - → easy interface to QCD showering & hadronization programs like **HERWIG** and **PYTHIA**
- interfaced to the **LHAPDF** package

HORACE results for W

- M_T^W distribution, $\mathcal{O}(\alpha)$ effect at peak, PS $\mathcal{O}(\alpha)$ vs exact $\mathcal{O}(\alpha)$ and h.o. QED effects at peak

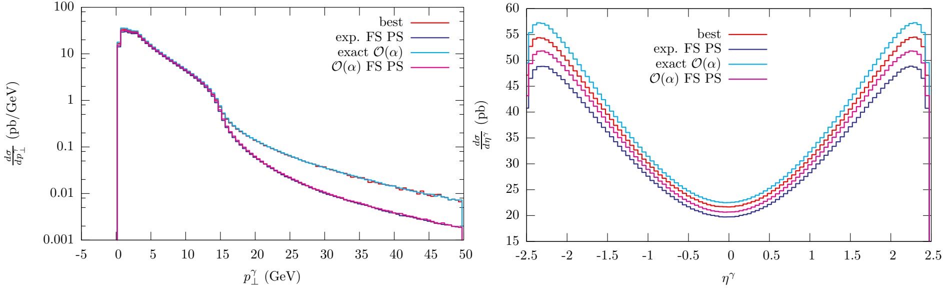






Photonic observables ($W\gamma$ events)

- besides leptonic cuts, we require $|\eta_\gamma| < 2.5$ and $E_\gamma > 3$ GeV for the hardest photon
- this signature can be used e.g. to study the $WW\gamma$ trilinear vertex



- as expected, the exact real emission ME gives large corrections w.r.t. the LL approximation
- here radiative events (one more α) are selected

Combining EW and QCD corrections

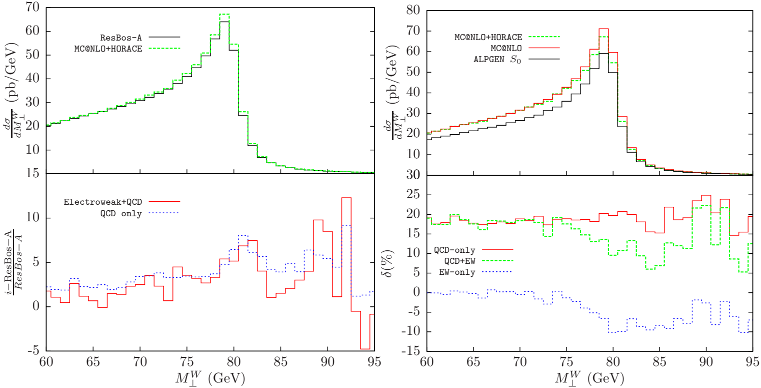
work in progress: Balossini, CMCC, Montagna, M. Moretti, Nicrosini, Piccinini, Treccani, Vicini

- our exercise (preliminary results) is based on the following formula

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{QCD}\oplus\text{EW}} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{\text{best QCD}} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{best EW}} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{\text{Born}}\right\}_{\texttt{HERWIG}\text{ PS}}$$

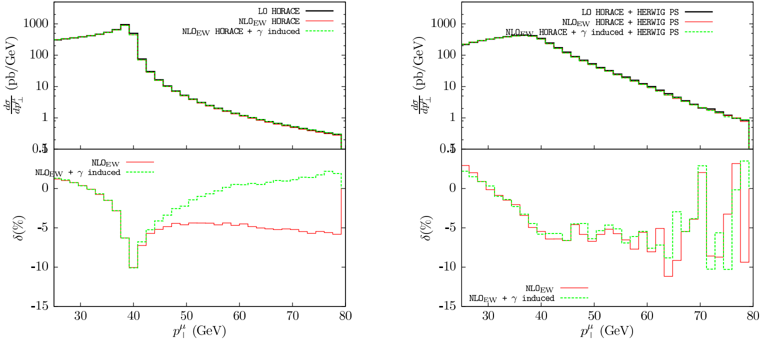
- best QCD ⇒ **MC@NLO**, **ALPGEN** (with PS matching according to MLM prescription, `0+1 jet`, `0+1+2 jets`), **RESBOS**
- EW part (**HORACE**) is interfaced to **HERWIG** PS (EW ⊕ QCD LL)
  - ⋆ NLO EW is convoluted with QCD LL parton shower ⇒ $\mathcal{O}(\alpha\alpha_s)$ corrections not reliable where hard non log QCD corrections are important (e.g. high $p_\perp$ lepton distribution without cut on the W transverse mass). In this case a two-loop calculation needed for a sound estimate of $\mathcal{O}(\alpha\alpha_s)$ effects

⋆ we consider the charged Drell-Yan process



- **Resbos-A** vs **HORACE+MC@NLO**
- effects of QCD NLO and combined EW ⊕ QCD

Convolution of EW & QCD corrections (LHC)



- non trivial effect due to the QCD showering of EW corrected events

A tool to estimate M_W shifts: **fitter** (PRELIMINARY)

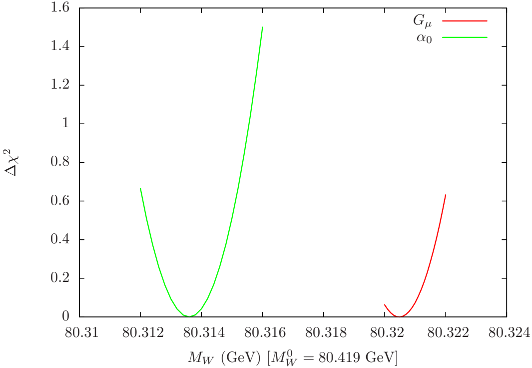
- how do the various RC effects and/or theoretical errors translate into M_W shifts? Can they be quickly estimated?
- the following procedure can be used:
  - ⋆ dump a sample of LO weighted events in LHA format with $M_W = M_W^{(0)}$
  - ⋆ produce a set of (e.g.) $M_\perp^W$ distributions with n M_W's reweigthing the events

$$w \to w \times f(M_W^{(0)}, M_W^{(n)}) \frac{(s - M_W^{(0)2})^2 + \Gamma_W^2 M_W^{(0)2}}{(s - M_W^{(n)2})^2 + \Gamma_W^2 M_W^{(n)2}}$$

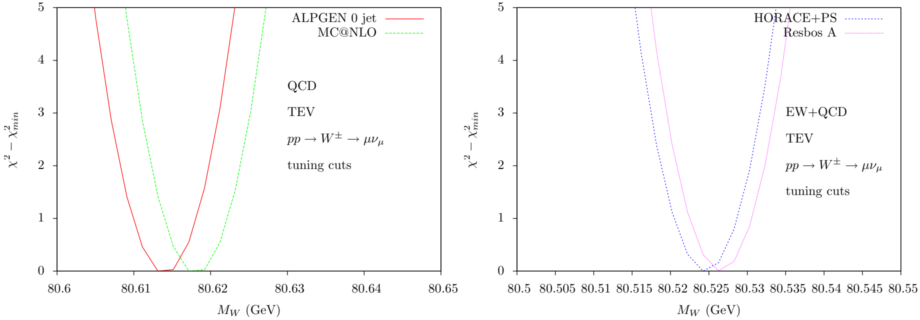
  - ⋆ produce the $M_\perp^W$ distribution by including the effect to be estimated (e.g. EW RC)
  - ⋆ fit that distribution with the n replica
  - ⋆ read the shift in M_W
- a preliminary code is available, **fitter**

EW scheme shift

- pseudo-data produced at LO, $M_W = 80.419$ GeV, G_μ EW scheme
- LO$^{G_\mu}$ $\rightarrow$ 1-loop$^{G_\mu}$ shift: 98 MeV
- LO$^{G_\mu}$ $\rightarrow$ 1-loop$^{\alpha_0}$ shift: 105 MeV
- EW scheme dependence shift at 1-loop ~ 7 MeV



QCD & EW $\otimes$ QCD shifts



- QCD PS gives ~ 200 MeV shift ($M_W^{(0)} = 80.419$ GeV)
- QCD NLO gives ~ 10 MeV

Contribution to the wish list

Which are the shifts due to:

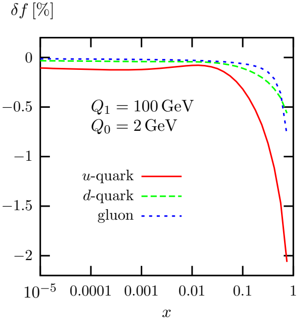
- ⋆ EW input schemes
- ⋆ other EW effects, e.g. photon induced processes
- ⋆ missing higher-orders EW corrections (e.g. pair corrections)
- ⋆ different QCD PS implementations (e.g. **HERWIG** vs **PHYTIA**)
- ⋆ QCD NLO and NNLO corrections
- ⋆ different low $p_\perp$ resummation prescriptions
- ⋆ QCD scale variation
- ⋆ PDFs uncertainties (see J. Rojo's talk)
- ⋆ ...

Conclusions

- The event generator **HORACE** implements
  - ⋆ complete exact 1-loop EW corrections to charged and neutral DY processes
  - ⋆ matching between the exact $\mathcal{O}(\alpha)$ RC and a QED PS, to include h.o. QED radiative corrections
  - ⋆ events are stored in LHA compliant format to be passed through QCD showering MC
  - it's a fully exclusive event generator
- a tool to quickly translate RC/theoretical errors into M_W shifts is now available (for phenomenologists): **fitter**

Subtraction of initial state collinear singularities

- IS quark masses regularize the collinear QED divergencies
- the QED IS singularities have to be subtracted from the hard cross section [in analogy with NLO QCD], since they are already accounted in the (QED) evolution of PDFs
- the set **MRSTQED** (2004) includes the QED evolution



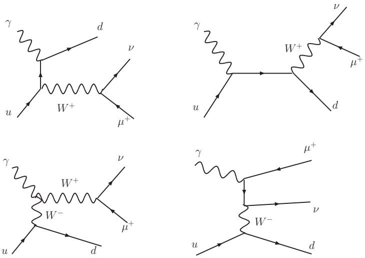
e.g. M. Roth, S. Weinzierl, PLB 590 190 (2004)

⋆ QED evolution modifies PDFs at 0.1% level for $x < 0.1$

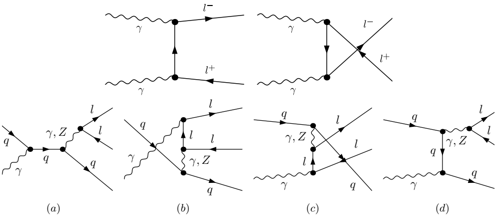
⋆ dynamic generation of photon distr. function. Need to include photon induced processes in DY

Diagrams for photon-induced processes

- for W production



- for Z production



IS subtracted hadron level cross section

$$d\sigma(p\overset{(-)}{p} \to l\nu_l + X) = \sum_{a,b}\int_0^1 dx_1 dx_2 \;\; q_a(x_1, M^2) q_b(x_2, M^2) \left[d\sigma_0 \; + \; d\sigma_\alpha \right] - \\ - \; \left(\Delta q_a(x_1, M^2) q_b(x_2, M^2) + q_a(x_1, M^2) \Delta q_b(x_2, M^2) \right) \; d\sigma_0$$

$$\Delta q_i(x, M^2) \; = \int_z^1 q_i\left(\frac{x}{z}, M^2\right) \frac{\alpha}{2\pi} Q_i^2 \left[P(z) \left(\log\left(\frac{M^2}{m_i^2}\right) - 2\log(1-z) - 1 + f(z) \right) \right]_+ .$$