# Electroweak Precision Predictions in the LHC Era - Part 1

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# Electroweak Physics - a prelude

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,a} + \sum_{j=1}^{f} \bar{q}^j(x) i\gamma^\mu (\partial_\mu + i g_s G^a_\mu(x) \frac{\lambda^a}{2}) q^j(x)$$

$$\mathcal{L}_{EW} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+ \frac{g}{2\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2 s^2_w Q_f - I^3_f \gamma_5) \Psi_f Z_\mu +$$

$$- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

$$- ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + igc_w(W^+_\mu Z_\nu - W^+_\nu Z_\mu)|^2 +$$

$$- \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + igc_w(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

$$- \frac{1}{2} M^2_H H^2 - \frac{g M^2_H}{8 M_W} H^3 - \frac{g^2 M^2_H}{32 M^2_W} H^4 + |M_W W^+_\mu + \frac{g}{2} H W^+_\mu|^2 +$$

$$+ \frac{1}{2} |\partial_\mu H + i M_Z Z_\mu + \frac{ig}{2c_w} H Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f H$$

Glashow (1961); Higgs (1964,1966); Brout and Englert (1964); Guralnik, Hagen and Kibble (1964); Kibble (1967), Weinberg (1967); Salam (1968); 't Hooft, Veltman (1971)

*Is this really it and is this all ?*

To answer this question, during the last 30+ years the Standard Model has been thoroughly scrutinized with high precision at the quantum level. This was only possible, since

- the SM as a renormalizable Quantum Field Theory is predictive beyond the Born approximation, and
- experiments have been made available with high collision energies and large number of particle collisions (=luminosity) such as LEP/SLC ($e^+e^-$), HERA ($ep$), and Tevatron ($p\bar{p}$).
- The LHC now explores a new energy $E_{CM}$ and precision frontier ($\mathcal{L}_{int}$):

$$\text{number of events} \ \propto \ L_{int}\,\sigma(E_{CM})$$

This allows us to look for *rare processes (Higgs discovery!)*, heavy particles, measure masses $M_W, m_{top}, M_H$ and test SM predictions with extremely high precision.

# Electroweak Physics - a prelude

Lessons from the LHC so far: again the SM has proven to be very robust!
How can electroweak physics at the LHC help to make 'dent' in the SM?

- With the discovery of the Higgs the SM can be 'squeezed' even more!
  For example, in EW physics global fits to EWPOs are now providing extremely precise predictions for $M_W$ and $\sin^2\theta^l_{eff}$: $\Delta M_W = 11$ MeV and $\Delta\sin^2\theta^l_{eff} = 10\times 10^{-5}$.
  This calls for an improvement of the current experimental accuracy of 15 MeV and $16\times 10^{-5}$.
- LHC is already providing a wealth of EW measurements at very high precision (per mil/percent level), is probing new kinematic regimes, and some *SM processes* for the first time, and there is still more to come.

Here we will mainly discuss two aspects of EW physics at the LHC:

- Electroweak precision observables: $M_W, (\sin^2\theta^l_{\rm eff})$, extracted from single $W$ and $Z$ production in Drell-Yan-like processes.
- Non-standard gauge couplings in multi-gauge boson production.

# Precision physics with $W$ and $Z$ bosons in Drell-Yan-like processes

$W$ and $Z$ production processes are one of the theoretically best understood, most precise experimental probes of the Standard Model (SM):

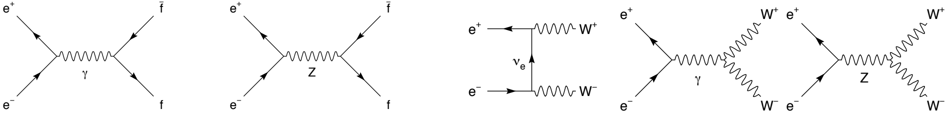
- Detector calibration ($M_Z$); Monte Carlo tuning
- Precision measurement of $M_W$ (and $\sin^2\theta^l_{eff}$): increased sensitivity to indirect signals of Beyond-the-SM (BSM) physics in EW precision observables.
- Search for BSM particles appearing as heavy resonances in $W$ and $Z$ distributions at high energies.
- Sensitive probe of proton structure, e.g., asymmetries in $W^+, W^-$ rapidity distribution probe the d/u ratio.

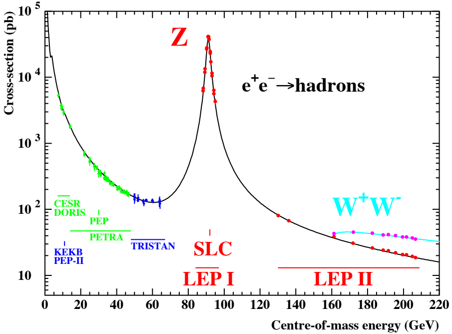
# Multiple EW gauge boson production

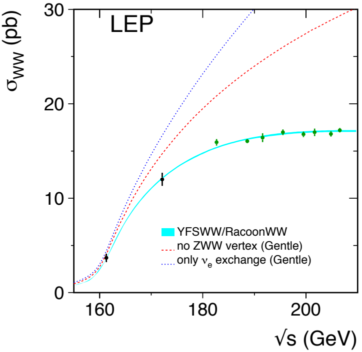
Di-boson and triple gauge boson production processes are sensitive probes of the non-abelian EW gauge structure and the EWSB sector of the SM. For a review see, e.g., K.Hagiwara, NPB282 (1987)

- Search for non-standard gauge boson interactions provide an unique indirect way to look for BSM in a model-independent way.
- Improved constraints on anomalous triple-gauge boson couplings (TGCs) and quartic couplings (QGCs) can probe scales of new physics in the multi-TeV range.
- Important background to Higgs physics and BSM searches.

# Precision EW Physics in the LEP/SLC era




LEP/SLC collab., hep-ex/0509008 LEP2 report, arXiv:1302.3415 [hep-ex]

# EW Precision (Pseudo-)Observables around the $Z$ resonance

Taken from D.Bardin *et al.*, hep-ph/9902452

Pseudo-observables are extracted from “real” observables (cross sections, asymmetries) by de-convoluting them of QED and QCD radiation and by neglecting terms ($\mathcal{O}(\alpha\Gamma_Z/M_Z)$) that would spoil factorization ($\gamma, Z$ interference, $t$-dependent radiative corrections).

The $Zf\bar{f}$ vertex is parametrized as $\gamma_\mu(G_V^f + G_A^f\gamma_5)$ with formfactors $G_{V,A}^f$, so that the partial Z width reads:

$$\Gamma_f = 4N_c^f\Gamma_0(|G_V^f|^2 R_V^f + |G_A^f|^2 R_A^f) + \Delta_{EW/QCD}$$

$R_{V,A}^f$ describe QED, QCD radiation and $\Delta$ non-factorizable radiative corrections.

Pseudo-observables are then defined as ($g_{V,A}^f = Re G_{V,A}^f$)

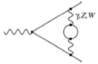
- $\sigma_h^0 = 12\pi\frac{\Gamma_e\Gamma_h}{M_Z^2\Gamma_Z^2}$ , $R_{q,l} = \Gamma_{q,h}/\Gamma_{h,l}$
- $A_{FB}^f = \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} \to A_{FB}^{f,0} = \frac{3}{4}A_e A_f, A_f = 2\frac{g_V^f g_A^f}{(g_V^f)^2+(g_A^f)^2}$
- $A_{LR}(SLD) = \frac{N_L-N_R}{N_L+N_R}\frac{1}{<P_e>} \to A_{LR}^0(SLD) = A_e$

and $4|Q_f|\sin^2\theta_{eff}^f = 1 - \frac{g_V^f}{g_A^f}$ with $g_{V,A}^f$ being *effective* couplings including radiative corrections.

# Status of predictions for EWPOs

To match or better exceed the experimental accuracy, EWPOs had to be calculated beyond NLO, some up to leading 4-loop corrections, but complete NNLO EW for all EWPOs is not available (yet).
Some of the most important EWPOs and their present-day and future estimated theory errors: see discussion by A.Freitas in EW WG Snowmass report, arXiv:1310.6708

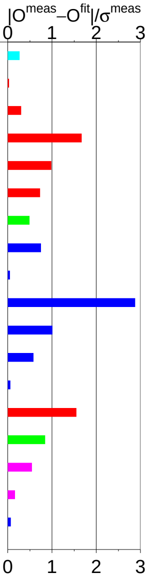
| Quantity | Current theory error | Leading missing terms | Est. future theory error |
|---|---|---|---|
| $\sin^2\theta^l_{\rm eff}$ | $4.5\times10^{-5}$ | $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$ | $1...1.5\times10^{-5}$ |
| $R_b$ | $\sim2\times10^{-4}$ | $\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$ | $\sim1\times10^{-4}$ |
| $\Gamma_Z$ | few MeV | $\mathcal{O}(\alpha^2)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$ | $<1$ MeV |
| $M_W$ | 4 MeV | $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq2}\alpha^3)$ | $<\sim1$ MeV |



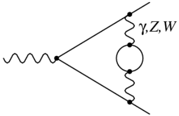

New: Fermionic 2-loop order is now complete: $\Delta\Gamma_Z\sim0.5MeV$ A.Freitas, 1401.2477 [hep-ph]

# Measurements vs SM predictions of EWPOs

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha^{(5)}_{had}(m_Z)$ | $0.02750 \pm 0.00033$ | 0.02759 |
| $m_Z$ [GeV] | $91.1875 \pm 0.0021$ | 91.1874 |
| $\Gamma_Z$ [GeV] | $2.4952 \pm 0.0023$ | 2.4959 |
| $\sigma^0_{had}$ [nb] | $41.540 \pm 0.037$ | 41.478 |
| $R_l$ | $20.767 \pm 0.025$ | 20.742 |
| $A^{0,l}_{fb}$ | $0.01714 \pm 0.00095$ | 0.01645 |
| $A_l(P_\tau)$ | $0.1465 \pm 0.0032$ | 0.1481 |
| $R_b$ | $0.21629 \pm 0.00066$ | 0.21579 |
| $R_c$ | $0.1721 \pm 0.0030$ | 0.1723 |
| $A^{0,b}_{fb}$ | $0.0992 \pm 0.0016$ | 0.1038 |
| $A^{0,c}_{fb}$ | $0.0707 \pm 0.0035$ | 0.0742 |
| $A_b$ | $0.923 \pm 0.020$ | 0.935 |
| $A_c$ | $0.670 \pm 0.027$ | 0.668 |
| $A_l$(SLD) | $0.1513 \pm 0.0021$ | 0.1481 |
| $\sin^2\theta^{lept}_{eff}(Q_{fb})$ | $0.2324 \pm 0.0012$ | 0.2314 |
| $m_W$ [GeV] | $80.385 \pm 0.015$ | 80.377 |
| $\Gamma_W$ [GeV] | $2.085 \pm 0.042$ | 2.092 |
| $m_t$ [GeV] | $173.20 \pm 0.90$ | 173.26 |




March 2012




New: ferm. 2-loop corr. reduce $R_b$ by approx. exp. error

Freitas, Huang, 1205.0299

SM predictions for the Z pole EWPOs provided by ZFITTER

Bardin et al (1999)

using as input parameters:

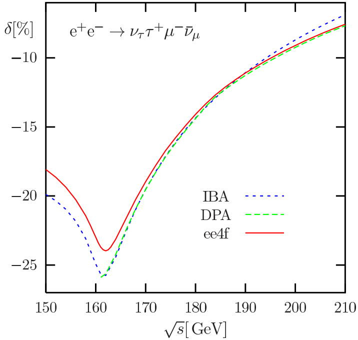
$\Delta\alpha^{(5)}_{had}, \alpha_s(M_Z), M_Z, m_f, M_H, G_\mu$

Also: GFITTER M.Baak *et al* arXiv:1209.2716

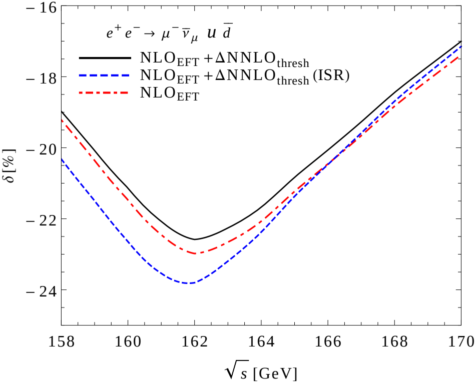
and GPP J.Erler *et al*, PDG 2012

and M. Ciuchini *et al.*, arXiv:1306.4644

# Extracting $M_W$ from $W$ pairs in $e^+e^-$ collisions




A.Denner *et al*, hep-ph/0502063



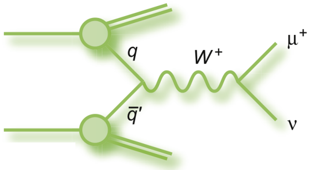

S.Actis *et al*, arXiv:0807.0102 [hep-ph]

One needs NLO EW to $e^+e^- \to 4f$, careful inclusion of finite width, and dominant NNLO corr. at threshold.

Theory uncert. due to missing NNLO corr.: $\Delta M_W \approx 3$ MeV at threshold

see discussion by C.Schwinn in Snowmass EW WG report, arXiv:1310.6708.

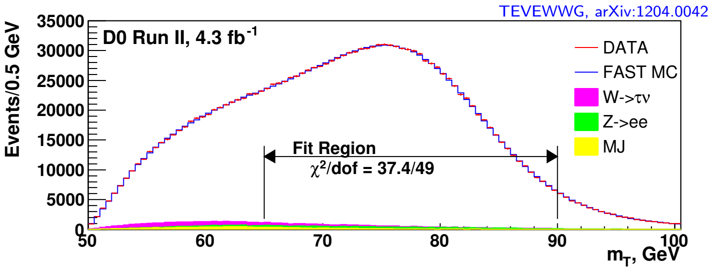
# Most precise $M_W$ measurement to date is from the Tevatron



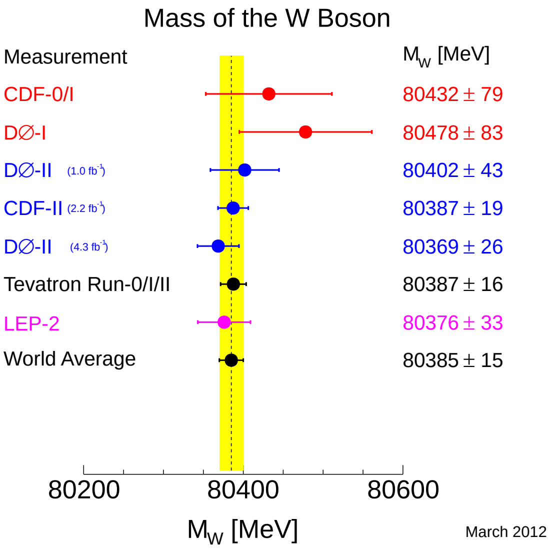

$M_W$ from the transverse mass of the $l\nu$ pair in $p\bar{p} \to W \to l\nu$:

$M_T(l\nu_l) = \sqrt{p_T^l p_T^\nu (1 - \cos(\Phi_l - \Phi_\nu))}$

$\delta M_W = 16$ MeV with 7.6 $fb^{-1}$



# A new era of EW precision physics: $\delta M_W^{exp} \approx 0.02\%$




TEVEWWG March 2012

# Projected uncertainties in the measurement of $M_W$ at the Tevatron

| $\Delta M_W$ [MeV] | CDF | D0 | combined | final CDF | final D0 | combined |
|---|---|---|---|---|---|---|
| $\mathcal{L}$[fb] | 2.2 | 4.3 (+1.1) | 7.6 | 10 | 10 | 20 |
| PDF | 10 | 11 | 10 | 5 | 5 | 5 |
| QED rad. | 4 | 7 | 4 | 4 | 3 | 3 |
| $p_T(W)$ model | 5 | 2 | 2 | 2 | 2 | 2 |
| other systematics | 10 | 18 | 9 | 4 | 11 | 4 |
| $W$ statistics | 12 | 13 | 9 | 6 | 8 | 5 |
| Total | 19 | 26 (23) | 16 | 10 | 15 | 9 |

From the Snowmass 2013 EW WG report, arXiv:1310.6708.

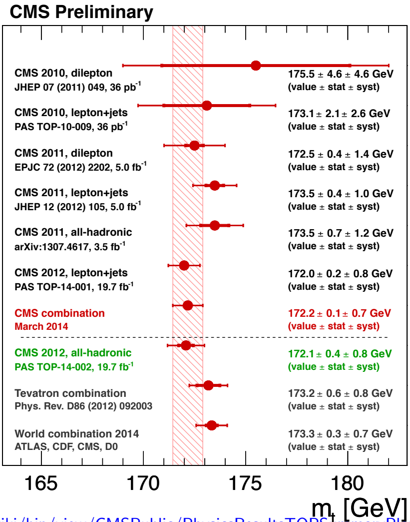
- CDF, arXiv:1203.0275: $\delta M_W$(QED)=4 MeV
  ResBos+PHOTOS, HORACE used to assess the impact of the missing $\mathcal{O}(\alpha)$ corrections
- D0, arXiv:1203.0293: $\delta M_W$(QED)=7 MeV
  ResBos+PHOTOS, WGRAD used to assess the impact of the missing EW $\mathcal{O}(\alpha)$ corrections
- How about uncertainties due to missing higher-order corrections?
- PDF uncertainty is the limiting factor!

# Projected uncertainties in the measurement of $M_W$ at the LHC

| $\Delta M_W$ [MeV] | LHC | | |
|---|---|---|---|
| $\sqrt{s}$ [TeV] | 8 | 14 | 14 |
| $\mathcal{L}$[fb] | 20 | 300 | 3000 |
| PDF | 10 | 5 | 3 |
| QED rad. | 4 | 3 | 2 |
| $p_T(W)$ model | 2 | 1 | 1 |
| other systematics | 10 | 5 | 3 |
| $W$ statistics | 1 | 0.2 | 0 |
| Total | 15 | 8 | 5 |

From the Snowmass 2013 EW WG report, arXiv:1310.6708.

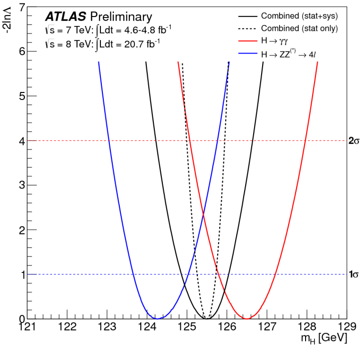
# A new era of EW precision physics: $\delta m_{top}^{exp} \approx 0.54\%$

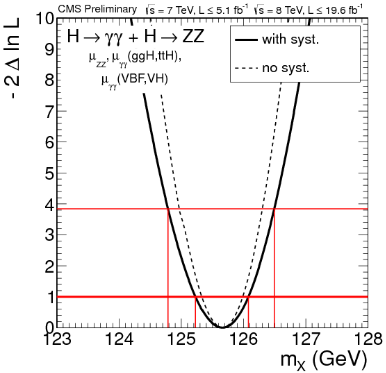



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryPlots

see also https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP

# A new era of EW precision physics: $\delta M_H^{exp} \approx 0.51\%$

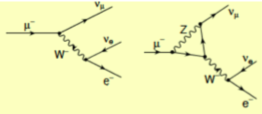



$M_H = 125.7 \pm 0.3 \pm 0.3$ GeV (CMS) CMS-PAS-HIG-13-005

$M_H = 125.5 \pm 0.2^{+0.5}_{-0.6}$ GeV (ATLAS) ATLAS-CONF-2013-014,ATLAS-CONF-2013-025

# What can we learn from a precise $M_W$ measurement?



Predicting the $W$ boson mass from an implicit equation for $M_W$:

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\alpha(0)M_Z^2}{2(M_Z^2 - M_W^2)M_W^2}[1 + \Delta r(\alpha, M_W, M_Z, m_t, M_H, \ldots)]$$

$\Delta r$ describes the loop corrections to muon decay ($c_W = M_W/M_Z$):

$$\Delta r = \Delta\alpha - \frac{c_w^2}{s_w^2}\Delta\rho(0) + 2\Delta_1 + \frac{s_w^2 - c_W^2}{s_w^2}\Delta_2 + \mathrm{boxes,\ vertices,\ higher\,orders}$$

$\Delta\rho(0)$ at 1-loop is given in terms of 1-PI EW gauge boson self energies, $\Pi^T_{V_1V_2}$:

$$\Delta\rho(0) = \frac{\Pi^T_{WW}(0)}{M_W^2} - \frac{\Pi^T_{ZZ}(0)}{M_Z^2} - 2\frac{s_W}{c_W}\frac{\Pi^T_{Z\gamma}(0)}{M_Z^2}$$

$\Delta\alpha$ describes contributions to the running of $\alpha$: $\Delta\alpha = \Delta\alpha_{lep} + \Delta\alpha_{top} + \Delta\alpha^{(5)}_{had} + \ldots$.

# Parametric and theory uncertainties: $M_W$ and $\sin^2\theta^l_{\rm eff}$

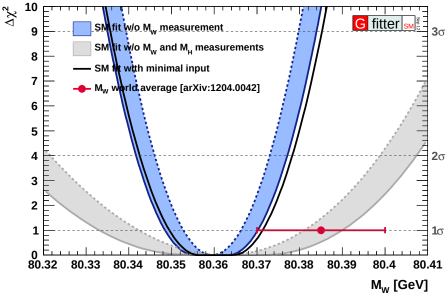
Theory uncertainty is due to missing 3-loop corrections of $\mathcal{O}(\alpha^2\alpha_s)$, $\mathcal{O}(N_f^{\geq 2}\alpha^3)$.
Parametric uncertainties (Awramik *et al*, hep-ph/0311148; hep-ph/0608099):

$$M_W = M_W^0 - c_1 \ln\left(\frac{M_H}{100\mathrm{GeV}}\right) + c_6\left(\frac{m_t}{174.3\mathrm{GeV}}\right)^2 - 1 + \ldots$$

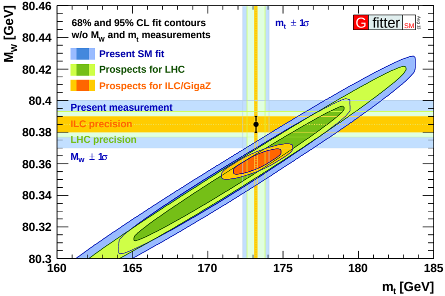
| | $\Delta M_W$ [MeV] | | $\Delta\sin^2\theta^l_{\rm eff}[10^{-5}]$ | |
|---|---|---|---|---|
| | present | future | present | future |
| $\Delta m_t = 0.9; 0.5(0.1)$ GeV | 5.4 | 3.0(0.6) | 2.8 | 1.6(0.3) |
| $\Delta(\Delta\alpha_{\rm had}) = 1.38(1.0); 0.5\cdot 10^{-4}$ | 2.5(1.8) | 1.0 | 4.8(3.5) | 1.8 |
| $\Delta M_Z = 2.1$ MeV | 2.6 | 2.6 | 1.5 | 1.5 |
| missing h.o. | 4.0 | 1.0 | 4.5 | 1.0 |
| total | 7.6(7.4) | 4.2(3.0) | 7.3(6.5) | 3.0(2.6) |

From Snowmass EW WG report arXiv:1310.6708 [hep-ph].

# How well do we need to measure $M_W$?




$M_W$ from global fit to EWPOs before (gray band) and after (blue) $M_H$ measurement is included in the fit.




Indirect determination is now more precise than direct measurements!

Fit result: $\Delta M_W = 11$ MeV (present)

Fit result: $\Delta M_W = 5.8$ MeV (LHC)

Fit result: $\Delta M_W = 3.6$ MeV (GigaZ)

GFITTER, arXiv:1209.2716

Snowmass EW WG report, arXiv:1310.6708

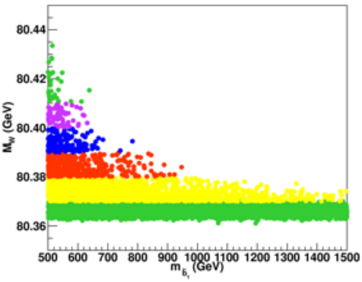
# Search for indirect signals of BSM physics in EWPOs

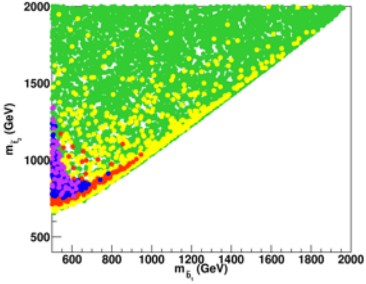
- Consider a specific BSM model, which is predictive beyond tree-level, and calculate complete BSM loop contributions to EWPOs ($Z$ pole observables, $M_W$, ...). Example: MSSM
- In many new physics models, the leading BSM contributions to EWPOs are due to modifications of the gauge boson self energies which can be described by the *oblique* parameters $S$, $T$, $U$ Peskin, Takeuchi (1991):

$$\Delta r \approx \Delta r^{\mathrm{SM}} + \frac{\alpha}{2 s_W^2} \Delta S - \frac{\alpha c_W^2}{s_W^2} \Delta T + \frac{s_W^2 - c_W^2}{4 s_W^4} \Delta U$$

$$\sin^2 \theta^l_{eff} \approx (\sin^2 \theta^l_{eff})^{\mathrm{SM}} + \frac{\alpha}{4(c_W^2 - s_W^2)} \Delta S - \frac{\alpha s_W^2 c_W^2}{c_W^2 - s_W^2} \Delta T$$

# What else can be learned from a more precise $M_W$ measurement?




Assumption: a light stop is found with $m_{\tilde{t}_1} = 400 \pm 40$ GeV: green points: all points in the scan with $M_h = 125.6 \pm 3.1$ GeV and $m_{\tilde{t}_1} = 400 \pm 40$ GeV, and
$M_W = 80.375 \pm 0.005$ GeV (yellow), $M_W = 80.385 \pm 0.005$ GeV (red),
$M_W = 80.395 \pm 0.005$ GeV (blue), and $M_W = 80.405 \pm 0.005$ GeV (purple).
S.Heinemeyer *et al*, Snowmass EW WG report arXiv:1310.6708 [hep-ph].

There have been a number of different ways introduced in the literature to paramaterize non-standard couplings.

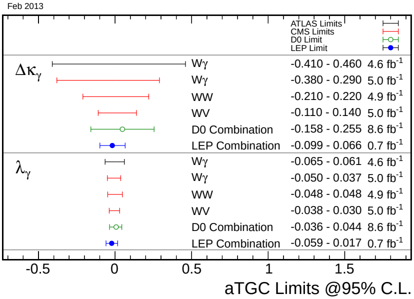
The anomalous couplings approach of Hagiwara et al (1987) was introduced for LEP physics and is based on the Lagrangian ($V = \gamma, Z$)

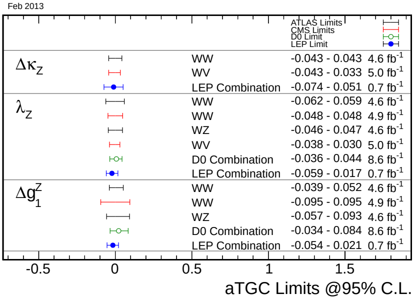
$$\begin{aligned}\mathcal{L} =& i g_{WWV} \Bigg( g_1^V (W^+_{\mu\nu} W^{-\mu} - W^{+\mu} W^-_{\mu\nu}) V^\nu + \kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} W^{\nu +}_\mu W^{-\rho}_\nu V^\mu_\rho \\ & + i g_4^V W^+_\mu W^-_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - i g_5^V \epsilon^{\mu\nu\rho\sigma} (W^+_\mu \partial_\rho W^-_\nu - \partial_\rho W^+_\mu W^-_\nu) V_\sigma \\ & + \tilde{\kappa}_V W^+_\mu W^-_\nu \tilde{V}^{\mu\nu} + \frac{\tilde{\lambda}_V}{m_W^2} W^{\nu +}_\mu W^{-\rho}_\nu \tilde{V}^\mu_\rho \Bigg) \, ,\end{aligned}$$

$V = \gamma, Z$; $W^\pm_{\mu\nu} = \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $g_{WW\gamma} = -e$ and $g_{WWZ} = -e \cot\theta_W$.

SM: $g_1^Z = \kappa_V = 1; \lambda_V = \tilde{\lambda}^V = \tilde{\kappa}_V = 0$.

# LEP/Tevatron/LHC limits on aTGCs

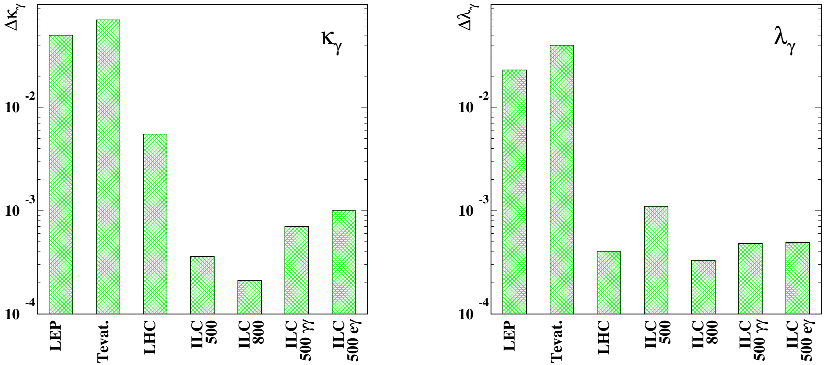



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMPaTGC

# Sensitivity to anomalous couplings: LHC vs ILC

Comparison of $\Delta\kappa_\gamma$ and $\Delta\lambda_\gamma$ at different machines: A.Freitas et al (2013)



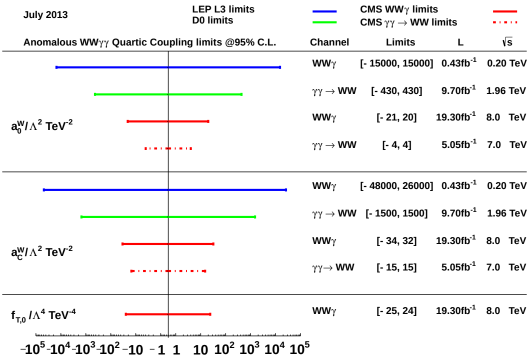
# Probing the non-abelian gauge structure of the SM: genuine aQGCs

For LEP-II studies genuine anomalous quartic couplings involving two photons have been introduced as follows (Sterling et al (1999)):

$$\mathcal{L}_0 = -\frac{e^2}{16\pi\Lambda^2} a_0 F_{\mu\nu} F^{\mu\nu} \vec{W}^{\alpha} \vec{W}_{\alpha}$$

$$\mathcal{L}_c = -\frac{e^2}{16\pi\Lambda^2} a_c F_{\mu\alpha} F^{\mu\beta} \vec{W}^{\alpha} \vec{W}_{\beta}$$

with $F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$ and $\vec{W}_\mu = (\frac{1}{\sqrt{2}}(W^+_\mu + W^-_\mu), \frac{i}{\sqrt{2}}(W^+_\mu - W^-_\mu), \frac{Z_\mu}{\cos\theta_W})$



# New interactions in multi-boson production: the EFT approach

Effective field theory (EFT): Weinberg (1979); Buchmueller, Wyler (1986)
EFT Lagrangians parametrize in a model independent way the low–energy effects of possible BSM physics with characteristic energy scale $\Lambda$. Residual new interactions among light degrees of freedom, ie the particles of mass $M << \Lambda$, can then be described by higher-dimensional operators:

$$\mathcal{L}_{\mathcal{EFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \sum_j \frac{f_j}{\Lambda^4}\mathcal{O}_j + \ldots$$

- Implemented in public codes MadGraph, Whizard, VBFNLO, and in dedicated calculations for multiple EW gauge boson production.
- The choice of higher-dimensional operators is not unique (different basis, symmetry group, ...) and different methods to unitarize the cross sections have been used (form factors, K-matrix unitarization, ...).
- Relations between EFT coefficients $c_i, f_j$ and anomalous couplings have been derived.

Snowmass 2013 EW WG report, arXiv:1310.6708; C.Degrande *et al*, arXiv:1309.7890

# Genuine dimension eight operators

- The lowest dimension operator that leads to quartic interactions but does not exhibit two or three weak gauge boson vertices is of dimension eight.
- Effective operators possessing QCGs but no TGCs can be generated at tree level by new physics at a higher scale (see Arzt et al.(1995)), in contrast to operators containing TGCs that are generated at loop level.

Examples:

$$\mathcal{O}_{M,0} = \mathrm{Tr}\left[W_{\mu\nu} W^{\mu\nu}\right] \times \left[\left(D_\beta \Phi\right)^\dagger D^\beta \Phi\right]$$

$$\mathcal{O}_{M,1} = \mathrm{Tr}\left[W_{\mu\nu} W^{\nu\beta}\right] \times \left[\left(D_\beta \Phi\right)^\dagger D^\mu \Phi\right]$$

with $D_\mu \equiv \partial_\mu + i\frac{g'}{2} B_\mu + igW^i_\mu \frac{\tau^i}{2}$
For the $WW\gamma\gamma$-vertex one finds:

$$\frac{f_{M,0}}{\Lambda^4} = \frac{a_0}{\Lambda^2}\frac{1}{g^2 v^2}$$

$$\frac{f_{M,1}}{\Lambda^4} = -\frac{a_c}{\Lambda^2}\frac{1}{g^2 v^2}$$

$$\frac{f_{M,2}}{\Lambda^4} = \frac{a_0}{\Lambda^2}\frac{2}{g^2 v^2}$$

# aQGCs and heavy resonances

See Snowmass 2013 EW WG report (contribution by J.Reuter), arXiv:1310.6708

BSM physics could enter in the EW sector in form of very heavy resonances that leave only traces in the form of deviations in the SM couplings, ie they are not directly observable. But such deviations can be translated into higher-dimensional operators that affect triple and quartic gauge couplings in multi-boson processes.

For example, a scalar resonance $\sigma$, whose Lagrangian is given by ($\mathbf{V} = \Sigma(D\Sigma)^\dagger, \mathbf{T} = \Sigma\tau^3\Sigma^\dagger$)

$$\mathcal{L}_\sigma = -\frac{1}{2}\left[\sigma(M_\sigma^2 + \partial^2)\sigma - g_\sigma v \mathbf{V}_\mu \mathbf{V}^\mu - h_\sigma \mathbf{T}\mathbf{V}_\mu \mathbf{T}\mathbf{V}^\mu\right]$$

leads to the effective Lagrangian after integrating out the scalar,

$$\mathcal{L}_\sigma^{\text{eff}} = \frac{v^2}{8M_\sigma^2}\left[g_\sigma \mathbf{V}_\mu \mathbf{V}^\mu + h_\sigma \mathbf{T}\mathbf{V}_\mu \mathbf{T}\mathbf{V}^\mu\right]^2$$

ie integrating out $\sigma$ generates the following anomalous quartic couplings

$$\alpha_5 = g_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_7 = 2g_\sigma h_\sigma\left(\frac{v^2}{8M_\sigma^2}\right) \qquad \alpha_{10} = 2h_\sigma^2\left(\frac{v^2}{8M_\sigma^2}\right)$$

# aQGCs and heavy resonances

For strongly coupled, broad resonances, one can then translate bounds for anomalous couplings directly into those of the effective Lagrangian:

$$\alpha_5 \leq \frac{4\pi}{3}\left(\frac{v^4}{M_\sigma^4}\right) \approx \frac{0.015}{(M_\sigma \text{ in TeV})^4} \quad \Rightarrow \quad 16\pi^2\alpha_5 \leq \frac{2.42}{(M_\sigma \text{ in TeV})^4}$$

From the Snowmass 2013 EW WG report (ATLAS study):
For a different choice of operator basis:

$$\alpha_4 = \frac{f_{S0}}{\Lambda^4}\frac{v^4}{16} \;\; ; \;\; \alpha_5 = \frac{f_{S1}}{\Lambda^4}\frac{v^4}{16}$$

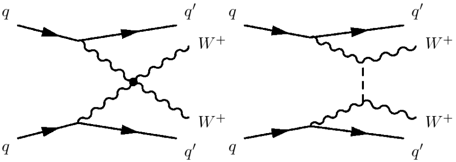
For example, $W^\pm W^\pm$ scattering at 14 TeV and 3000 $fb^{-1}$ can constrain $f_{S0}/\Lambda^4$ to 0.8 TeV$^{-4}$ at 95% CL which translates to

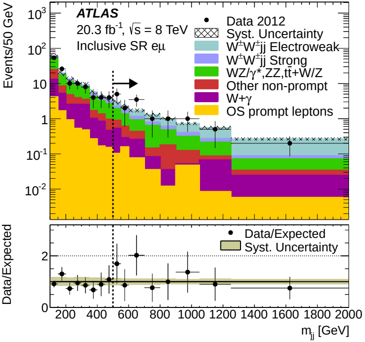
| Type of resonance | LHC 300 fb$^{-1}$ | | LHC 3000 fb$^{-1}$ | |
|---|---|---|---|---|
| | $5\sigma$ | 95% CL | $5\sigma$ | 95% CL |
| scalar $\phi$ | 1.8 TeV | 2.0 TeV | 2.2 TeV | 3.3 TeV |
| vector $\rho$ | 2.3 TeV | 2.6 TeV | 2.9 TeV | 4.4 TeV |
| tensor $f$ | 3.2 TeV | 3.5 TeV | 3.9 TeV | 6.0 TeV |

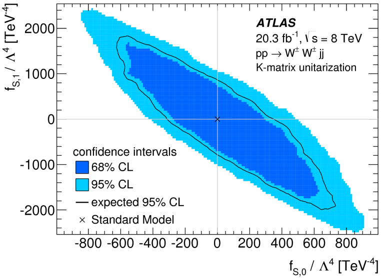
# First evidence for $W^{\pm}W^{\pm}jj$ production

The ATLAS collaboration, arXiv:1405.6241

NLO QCD implemented in POWHEG B.Jaeger, G.Zanderighi, arXiv:1108.0864



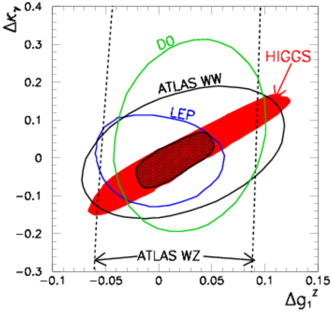



# Combined tests of gauge and Higgs interactions

$$\mathcal{L}_{eff} = \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n$$

TGCs in terms of $f_n$ (dim 6 operators):

$$\Delta\kappa_\gamma \propto (f_W + f_B)\frac{v^2}{\Lambda^2} \quad , \quad \Delta g_1^Z \propto f_W \frac{v^2}{\Lambda^2}$$




| | ZWW | AWW | HWW | HZZ | HZA | HAA | WWWW | ZZWW | ZAWW | AAWW |
|---|---|---|---|---|---|---|---|---|---|---|
| $\mathcal{O}_{WWW}$ | X | X | | | | | X | X | X | X |
| $\mathcal{O}_W$ | X | X | X | X | X | | X | X | X | |
| $\mathcal{O}_B$ | X | X | | X | X | | | | | |
| $\mathcal{O}_{\Phi d}$ | | | X | X | | | | | | |
| $\mathcal{O}_{\Phi W}$ | | | X | X | X | X | | | | |
| $\mathcal{O}_{\Phi B}$ | | | | X | X | X | | | | |

Corbett *et al.*, arXiv:1304.1151

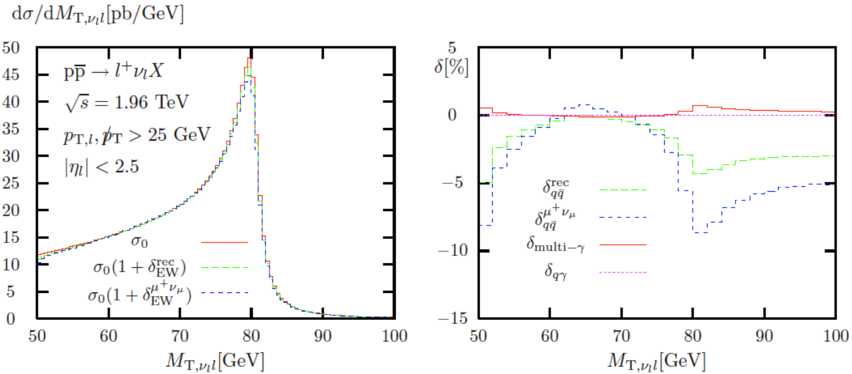
# Why EW radiative corrections ?

Electroweak (EW) radiative corrections are needed

- in modeling signal and background processes for new physics searches either directly or through higher-dimensional operators or the virtual presence of new particles in SM observables,
- in precisely measuring parameters of the SM, e.g., $M_W$, $m_{top}$, $M_H$, $y_{b,t}$, ...,
- in reducing systematic errors, e.g., improve studies of effects of selection/analysis of data, use $\sigma_{W,Z}$ as luminosity monitor, constrain PDFs ($W$ charge asymmetry, $\gamma$, jet production), ...,
- Naturally, electroweak (EW) corrections play an especially important role in EW gauge boson production:
  $Z$ resonance at LEP-I/SLC and W-pair poduction at LEP-II; $V$, $VV$, $VVV$ (+jets) gauge boson production at the Tevatron and LHC.
- Even in QCD dominated processes they can be numerically at least as important as NNLO QCD corrections and in certain kinematic regions they may be the dominant corrections.

See also recent (historic) overview of the role of RCs in EW precision physics by A.Sirlin, A.Ferroglia, Reviews of Modern Phsyics 85 (2013).

# Impact of EW corrections on $M_T(l\nu)$



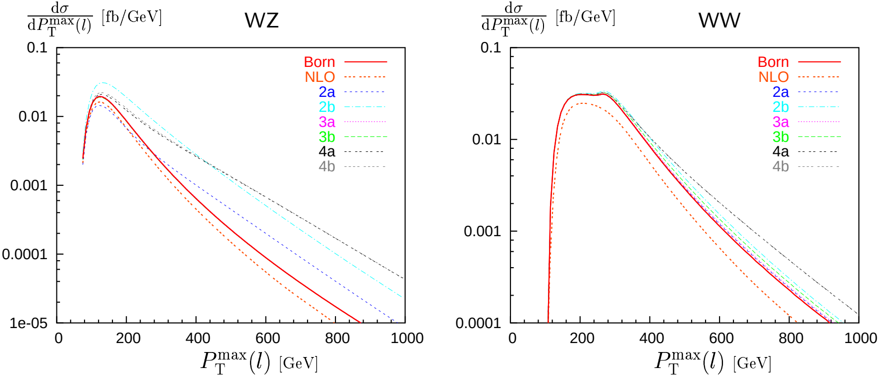

Brensing, Dittmaier, Krämer, Mück (2008)

Shifts in $M_W$: $\delta M_W$(QED FSR) $\approx \mathcal{O}(100)$ MeV

$\delta M_W(mFS) \approx 2, 10$ MeV for $e, \mu$ Carloni-Calame et al (2003)

# Anomalous TGCs in *WZ*/*WW* production at the LHC

SM LO, NLO predictions vs. anomalous couplings scenarios:




E.Accomando, A.Kaiser, hep-ph/0511088

EW corrections can be as large as signals of new physics !

# Status of EW predictions for $pp \to W \to \nu l, pp \to Z, \gamma \to ll$

- Complete EW $\mathcal{O}(\alpha)$ corrections: `HORACE`, `RADY`, `SANC`, `W/ZGRAD2`
  U.Baur *et al*, PRD65 (2002); C.M.Carloni Calame *et al*, JHEP05 (2005)
  U.Baur, D.W., PRD70 (2004); S.Dittmaier, M.Krämer, PRD65 (2002); A.Andonov *et al*, EPJC46 (2006); Arbuzov *et al*, EPJC54 (2008); S.Dittmaier, M.Huber, JHEP60 (2010).
- Multiple final-state photon radiation: `HORACE`, `RADY`, `WINHAC`, `PHOTOS`
  W.Placzek *et al*, EPJC29 (2003); C.M.Carloni Calame *et al*, PRD69 (2004); S.Brensing *et al*, PRD77 (2008)
- EW Sudakov logarithms up to $N^3LL$ Jantzen, Kühn, Penin, Smirnov (2005); brief review: J.H.Kühn, Acta Phys.Polon.B39 (2008)
- NLO EW corrections to $W$ production implemented in POWHEG Bernaciak, W. (2012); Barze et al. (2012) $\Rightarrow$ Study of mixed QED-QCD effects
- NLO EW corrections to $Z$ production implemented in POWHEG Barze et al. (2013) $\Rightarrow$ Study of mixed QED-QCD effects
- NLO EW corrections to $Z$ production implemented in FEWZ (NNLO QCD) Li, Petriello (2012)
- $W + 1j, Z + 1j, Z + 2j$(stable Z) at NLO EW, now with leptonic $W, Z$ decays W.Hollik *et al* (2008); S.Dittmaier *et al* (2009); J.H.Kühn *et al* (2008); A.Denner *et al.* (2010); Actis *et al* (2012); weak Sudakov corr. to $Z+ \leq 3$ jets in Alpgen Chiesa *et al* (2013)
- Toward $W$ and $Z$ production at $\mathcal{O}(\alpha\alpha_s)$ Kotikov *et al* (2008); Bonciani (2011); Kilgore, Sturm (2011); S.Dittmaier, A.Huss, C.Schwinn (2014)

# Status of QCD predictions for $pp \to W \to \nu l, pp \to Z, \gamma \to ll$

- NLO and NNLO QCD (up to $\mathcal{O}(\alpha_s^2)$): total cross sections ($\sigma_{W,Z}$) and fully differential distributions (DYNNLO, FEWZ):

  R.Hamberg *et al.*, NPB359 (1991); W.L.van Neerven *et al*, NBP382 (1992); W.T.Giele *et al*, NPB403 (1993)

  L.Dixon *et al.*, hep-ph/031226; K.Melnikov, F.Petriello, PRL96, PRD74 (2006); S.Catani *et al.*, PRL103 (2009), JHEP1005 (2010); R.Gavin *et al*, 1011.3540

- NLO QCD corrections matched to an all-order resummation of large logarithms $\ln^n(q_T/Q)$ (at NLL and NNLL accuracy) ($Q$: $W/Z$ virtuality, $q_T$: $W/Z$ transverse momentum).

  C.Balazs, C.-P.Yuan, PRD56 (1997) (ResBos); G.Bozzi *et al*, NPB815 (2009), arXiv:1007.2351; S.Catani *et al*, 1209.0158

- NLO QCD corrections matched to a parton shower (HERWIG, PYTHIA): MC@NLO, POWEG.

  S.Frixione, B.R.Webber, hep-ph/0612272; S.Alioli *et al*, JHEP0807 (2008)

- NNLO QCD corrections matched to a parton shower: Sherpa+BlackHat Hoeche, Li, Prestel, 1405.3607; POWHEG+MiNLO+DYNNLO Karlberg, Re, Zanderighi, 1407.2940

- $W + n$-jets ($n \leq 5$) and $Z + n$-jets ($n \leq 4$) at NLO QCD (and matched to PS).

  C.F.Berger *et al.* (2010,2009); Z.Bern *et al.* (2013); H.Ita *et al.* (2011); K.Ellis *et al.* (2009); J.Campbell *et al* (2002, 2013 (POWHEG)); B.Jaeger *et al* (2012) (POWHEG); S.Hoeche *et al* (2012)

# Status of predictions for $pp \to VV, VVV$ production

QCD corrections:

- $VV$ (TGCs) and $VVV$ (QGCs) production processes known at NLO QCD
  B.Mele *et al* (1991); J.Ohnemus *et al* (1991); S.Frixione *et al* (1992); U.Baur *et al* (1993,1997); L.Dixon *et al* (1992); J.Campbell *et al* (1999) (MCFM)
  A.Lazopolous *et al.* (2007); V.Hankele *et al.* (2008); F. Campanario (2008); T.Binoth *et al* (2008); G.Bozzi *et al.* (2009, 2011); M.Weber *et al* (2010); S.Dawson *et al* (2013)
  $WW, WZ, ZZ$ implementation in POWHEG Melia *et al*, (2011); P.Nason,J.Zanderighi (2013)
- $\gamma, \gamma, Z\gamma$ and $ZZ$ at NNLO QCD: S.Catani *et al* (2011); M.Grazzini *et al* (2013) and F.Cascioli *et al* (2014)
- $WWj, W\gamma j, WZj, ZZj, W\gamma\gamma j$ known at NLO QCD
  J.Campbell *et al* (2007); S.Dittmaier *et al* (2007,2009); F.Campanario *et al* (2009,2010,2011) (VBFNLO); T.Binoth *et al* (2009); see also brief review by G.Bozzi *et al* 1205.2506 (VBFNLO)

Electroweak corrections:

- Logarithmic EW $\mathcal{O}(\alpha)$ corrections to $WW, WZ, ZZ$ production: E.Accomando *et al* (2004,2005)
  $W$-pair production at NLL+NNLL: J.Kühn *et al.* (2011)
- Complete EW $\mathcal{O}(\alpha)$ corrections to $Z\gamma$ and $WW, WZ, ZZ$ production: W.Hollik *et al.* (2004); Bierweiler *et al* (2012,2013)
  $WW \to 4f$ in DPA M.Biloni *et al* (2013)
  implementation in HERWIG S.Gieseke *et al*, (2013)

# The high precision *wishlist*

| Process | known | desired | details |
|---|---|---|---|
| V | $d\sigma$(lept. V decay) @ NNLO QCD<br>$d\sigma$(lept. V decay) @ NLO EW | $d\sigma$(lept. V decay)<br>@ NNNLO QCD + NLO EW<br>MC@NNLO | precision EW, PDFs |
| V + j | $d\sigma$(lept. V decay) @ NLO QCD<br>$d\sigma$(lept. V decay) @ NLO EW | $d\sigma$(lept. V decay)<br>@ NNLO QCD + NLO EW | Z + j for gluon PDF<br>W + c for strange PDF |
| V + jj | $d\sigma$(lept. V decay) @ NLO QCD | $d\sigma$(lept. V decay)<br>@ NNLO QCD + NLO EW | study of systematics of<br>H + jj final state |
| VV′ | $d\sigma$(V decays) @ NLO QCD<br>$d\sigma$(stable V) @ NLO EW | $d\sigma$(V decays)<br>@ NNLO QCD + NLO EW | off-shell leptonic decays<br>TGCs |
| gg → VV | $d\sigma$(V decays) @ LO QCD | $d\sigma$(V decays)<br>@ NLO QCD | bkg. to $H \to VV$<br>TGCs |
| V$\gamma$ | $d\sigma$(V decay) @ NLO QCD<br>$d\sigma$(PA, V decay) @ NLO EW | $d\sigma$(V decay)<br>@ NNLO QCD + NLO EW | TGCs |
| V$b\bar{b}$ | $d\sigma$(lept. V decay) @ NLO QCD<br>massive b | $d\sigma$(lept. V decay) @ NNLO QCD<br>massless b | bkg. for VH → $b\bar{b}$ |
| VV′$\gamma$ | $d\sigma$(V decays) @ NLO QCD | $d\sigma$(V decays)<br>@ NLO QCD + NLO EW | QGCs |
| VV′V″ | $d\sigma$(V decays) @ NLO QCD | $d\sigma$(V decays)<br>@ NLO QCD + NLO EW | QGCs, EWSB |
| VV′ + j | $d\sigma$(V decays) @ NLO QCD | $d\sigma$(V decays)<br>@ NLO QCD + NLO EW | bkg. to H, BSM searches |
| VV′ + jj | $d\sigma$(V decays) @ NLO QCD | $d\sigma$(V decays)<br>@ NLO QCD + NLO EW | QGCs, EWSB |
| $\gamma\gamma$ | $d\sigma$ @ NNLO QCD | | bkg to $H \to \gamma\gamma$ |

Report of the Snowmass 2013 QCD working group, arXiv:1310.5189

Report of the Les Houches 2013 QCD working group, arXiv:1405.1067