Physics at the LHC

Abdelhak DJOUADI (LPT Orsay)

- **Standard Physics at the LHC**

  1. **The Standard Model**
  2. **QCD at the LHC**
  3. **Tests of the SM at the LHC**

- **The SM Higgs at the LHC**
- **SUSY and SUSY–Higgs at the LHC**

1. The Standard Model: brief introduction

The SM is based on a local gauge symmetry: invariance under

$$\mathrm{G_{SM} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y}$$

- The group $\mathrm{SU(3)_C}$ describes the strong force:

– interaction between q, q , q which are SU(3) triplets

– mediated by 8 gluons, G_μ^a corresponding to 8 generators of $\mathbf{SU(3)_C}$

Gell-Man 3×3 matrices: $[\mathbf{T^a}, \mathbf{T^b}] = \mathbf{i f^{abc} T_c}$ with $\mathrm{Tr}[\mathbf{T^a T^b}] = \frac{1}{2}\delta_{\mathbf{ab}}$

– asymptotic freedom: interaction "weak" at high energy, $\alpha_\mathbf{s} = \frac{\mathbf{g_s^2}}{\mathbf{4\pi}} \ll \mathbf{1}$

The Lagrangian of the theory is given by:

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}\mathbf{G^a_{\mu\nu} G_a^{\mu\nu}} + \mathbf{i}\sum_\mathbf{i} \mathbf{\bar{q}_i}(\partial_\mu - \mathbf{i g_s T_a G^a_\mu})\gamma^\mu \mathbf{q_i}(-\sum_\mathbf{i} \mathbf{m_i \bar{q}_i q_i})$$

with $\mathbf{G^a_{\mu\nu}} = \partial_\mu \mathbf{G^a_\nu} - \partial_\nu \mathbf{G^a_\mu} + \mathbf{g_s\, f^{abc} G^b_\mu G^c_\nu}$

– fermion gauge boson couplings : $-g_i \overline{\psi} V_\mu \gamma^\mu \psi$

– triple gauge boson couplings : $i g_i\, \mathrm{Tr}(\partial_\nu V_\mu - \partial_\mu V_\nu)[V_\mu, V_\nu]$

– quartic gauge boson couplings : $\frac{1}{2} g_i^2\, \mathrm{Tr}[V_\mu, V_\nu]^2$

1. The SM: brief introduction

• $\mathrm{SU(2)_L \times U(1)_Y}$ **describes the electroweak interaction:**

– between the three familles of quarks and leptons

$$\mathbf{I_f^{3L,3R} = \pm\tfrac{1}{2}, 0 \quad \Rightarrow L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L,\ R = e_R^-,\ Q = \begin{pmatrix} u \\ d \end{pmatrix}_L,\ u_R,\ d_R}$$

$$\mathbf{Y_f = 2Q_f - 2I_f^3 \Rightarrow Y_L = -1, Y_R = -2, Y_Q = \tfrac{1}{3}, Y_{u_R} = \tfrac{4}{3}, Y_{d_R} = -\tfrac{2}{3}}$$

Same holds for the two other generations: $\mu, \nu_\mu, \mathbf{c}, \mathbf{s};\ \tau, \nu_\tau, \mathbf{t}, \mathbf{b}$.

There is no $\nu_\mathbf{R}$ **(and neutrinos are and stay exactly massless)!**

– mediated by the $\tilde{\mathrm{W}}_\mu$ **(isospin) and** B_μ **(hypercharge) gauge bosons**

the gauge bosons, corresp. to generators, are exactly massless

$$\mathbf{T^a = \tfrac{1}{2}\tau^a\,; \quad [T^a, T^b] = i\epsilon^{abc}T_c \ \ \text{and} \ \ [Y, Y] = 0}$$

Lagrangian simple: with fields strenghs and covariant derivatives

$$\mathbf{W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2 \epsilon^{abc} W^b_\mu W^c_\nu,\ B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu}$$

$$\mathbf{D_\mu \psi = \left(\partial_\mu - igT_a W^a_\mu - ig'\tfrac{Y}{2}B_\mu\right)\psi\,, \quad T^a = \tfrac{1}{2}\tau^a}$$

$$\mathcal{L}_{\mathrm{SM}} = \mathbf{-\tfrac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{F}_{Li}\, iD_\mu\gamma^\mu\, F_{Li} + \bar{f}_{Ri}\, iD_\mu\gamma^\mu\, f_{R_i}}$$

1. The Higgs in the SM: the potential

But if gauge boson and fermion masses are put by hand in $\mathcal{L}_{\rm SM}$

$\frac{1}{2}{\rm M_V^2} V^\mu V_\mu$ **and/or $\rm m_f \bar{f}_L f_R$ terms: breaking of gauge symmetry.**

We need a less "brutal" way to generate particle masses in the SM.

In the SM, for the mechanism of spontaneous EW symmetry breaking,

$\Rightarrow$ introduce a doublet of complex scalar fields

$$\mathbf{\Phi} = \begin{pmatrix} \phi^+ \\ \phi^{\mathbf{0}} \end{pmatrix} \quad \text{with} \quad \mathbf{Y_\Phi = +1}$$

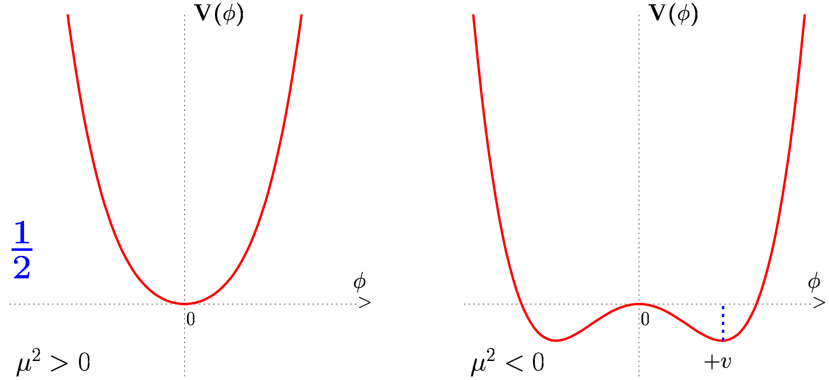
with a Lagrangian that is invariant under $\mathbf{SU(2)_L \times U(1)_Y}$

$$\mathcal{L}_{\mathbf{S}} = (\mathbf{D}^\mu \mathbf{\Phi})^\dagger (\mathbf{D}_\mu \mathbf{\Phi}) - \mu^2 \mathbf{\Phi}^\dagger \mathbf{\Phi} - \lambda (\mathbf{\Phi}^\dagger \mathbf{\Phi})^2$$

$\mu^2 > 0$: **4 scalar particles.**

$\mu^2 < 0$: Φ **develops a vev:**

$$\langle 0 | \Phi | 0 \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \quad v = \left(-\frac{\mu^2}{\lambda}\right)^{\frac{1}{2}}$$



1. The Higgs in the SM: the physical fields

To obtain the physical states, write $\mathcal{L}_S$ with the true vacuum:

- Write Φ in terms of four fields $\theta_{1,2,3}(\mathrm{x})$ and H(x) at 1st order:

$$\Phi(\mathrm{x}) = \mathrm{e}^{\mathrm{i}\theta_\mathrm{a}(\mathrm{x})\tau^\mathrm{a}(\mathrm{x})/\mathrm{v}} \, \frac{1}{\sqrt{2}}\binom{0}{\mathrm{v}+\mathrm{H}(\mathrm{x})} \simeq \frac{1}{\sqrt{2}}\binom{\theta_2+\mathrm{i}\theta_1}{\mathrm{v}+\mathrm{H}-\mathrm{i}\theta_3}$$

- Make a gauge transformation on Φ to go to the unitary gauge:

$$\Phi(\mathrm{x}) \to \mathrm{e}^{-\mathrm{i}\theta_\mathrm{a}(\mathrm{x})\tau^\mathrm{a}(\mathrm{x})} \, \Phi(\mathrm{x}) = \frac{1}{\sqrt{2}}\binom{0}{\mathrm{v}+\mathrm{H}(\mathrm{x})}$$

- Then fully develop the term $|\mathrm{D}_\mu\Phi)|^2$ of the Lagrangian $\mathcal{L}_S$:

$$|\mathrm{D}_\mu\Phi)|^2 = \left|\left(\partial_\mu - \mathrm{i}\mathrm{g}_1\frac{\tau_\mathrm{a}}{2}\mathrm{W}_\mu^\mathrm{a} - \mathrm{i}\frac{\mathrm{g}_2}{2}\mathrm{B}_\mu\right)\Phi\right|^2$$

$$= \frac{1}{2}\left|\begin{pmatrix} \partial_\mu - \frac{\mathrm{i}}{2}(\mathrm{g}_2\mathrm{W}_\mu^3+\mathrm{g}_1\mathrm{B}_\mu) & -\frac{\mathrm{i}\mathrm{g}_2}{2}(\mathrm{W}_\mu^1-\mathrm{i}\mathrm{W}_\mu^2) \\ -\frac{\mathrm{i}\mathrm{g}_2}{2}(\mathrm{W}_\mu^1+\mathrm{i}\mathrm{W}_\mu^2) & \partial_\mu+\frac{\mathrm{i}}{2}(\mathrm{g}_2\mathrm{W}_\mu^3-\mathrm{g}_1\mathrm{B}_\mu)\end{pmatrix}\binom{0}{\mathrm{v}+\mathrm{H}}\right|^2$$

$$= \frac{1}{2}(\partial_\mu\mathrm{H})^2 + \frac{1}{8}\mathrm{g}_2^2(\mathrm{v}+\mathrm{H})^2|\mathrm{W}_\mu^1+\mathrm{i}\mathrm{W}_\mu^2|^2 + \frac{1}{8}(\mathrm{v}+\mathrm{H})^2|\mathrm{g}_2\mathrm{W}_\mu^3-\mathrm{g}_1\mathrm{B}_\mu|^2$$

- Define the new fields $\mathrm{W}_\mu^\pm$ and Z_μ [A_μ is the orthogonal of Z_μ]:

$$\mathrm{W}^\pm = \frac{1}{\sqrt{2}}(\mathrm{W}_\mu^1 \mp \mathrm{W}_\mu^2)\,,\ \mathrm{Z}_\mu = \frac{\mathrm{g}_2\mathrm{W}_\mu^3-\mathrm{g}_1\mathrm{B}_\mu}{\sqrt{\mathrm{g}_2^2+\mathrm{g}_1^2}}\,,\ \mathrm{A}_\mu = \frac{\mathrm{g}_2\mathrm{W}_\mu^3+\mathrm{g}_1\mathrm{B}_\mu}{\sqrt{\mathrm{g}_2^2+\mathrm{g}_1^2}}$$

$$\sin^2\theta_\mathrm{W} \equiv \mathrm{g}_2/\sqrt{\mathrm{g}_2^2+\mathrm{g}_1^2} = \mathrm{e}/\mathrm{g}_2$$

1. The Higgs in the SM: the masses

- And pick up the terms which are bilinear in the fields $W^\pm, Z, A$:

$$M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu + \frac{1}{2} M_A^2 A_\mu A^\mu$$

$\Rightarrow$ 3 degrees of freedom for $W_L^\pm, Z_L$ and thus $M_{W^\pm}, M_Z$:

$$M_W = \frac{1}{2} v g_2 \,,\; M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2} \,,\; M_A = 0 \,,$$

with the value of the vev given by: $v = 1/(\sqrt{2} G_F)^{1/2} \sim 246\ \mathrm{GeV}$.

$\Rightarrow$ The photon stays massless, $\mathrm{U(1)_{QED}}$ is preserved.

- For fermion masses, use same doublet field Φ and its conjugate field $\tilde{\Phi} = i\tau_2 \Phi^*$ and introduce $\mathcal{L}_{\rm Yuk}$ which is invariant under SU(2)xU(1):

$$\mathcal{L}_{\rm Yuk} = -f_e (\bar{e}, \bar{\nu})_L \Phi e_R - f_d (\bar{u}, \bar{d})_L \Phi d_R - f_u (\bar{u}, \bar{d})_L \tilde{\Phi} u_R + \cdots$$

$$= -\frac{1}{\sqrt{2}} f_e (\bar{\nu}_e, \bar{e}_L) \binom{0}{v+H} e_R \cdots = -\frac{1}{\sqrt{2}} (v+H) \bar{e}_L e_R \cdots$$

$$\Rightarrow m_e = \frac{f_e\, v}{\sqrt{2}} \,,\; m_u = \frac{f_u\, v}{\sqrt{2}} \,,\; m_d = \frac{f_d\, v}{\sqrt{2}}$$

With same Φ, we have generated gauge boson and fermion masses, while preserving SU(2)xU(1) gauge symmetry (which is now hidden)!

What about the residual degree of freedom?

1. The Higgs in the SM: the Higgs boson

It will correspond to the physical spin–zero scalar Higgs particle, H.

The kinetic part of H field, $\frac{1}{2}(\partial_\mu H)^2$, comes from $|D_\mu \Phi)|^2$ term.

Mass and self-interaction part from $V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$:

$$V = \frac{\mu^2}{2}(0, v + H)\binom{0}{v+H} + \frac{\lambda}{2}|(0, v + H)\binom{0}{v+H})|^2$$

Doing the exercise you find that the Lagrangian containing H is,

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu H)(\partial^\mu H) - V = \frac{1}{2}(\partial^\mu H)^2 - \lambda v^2 H^2 - \lambda v H^3 - \frac{\lambda}{4} H^4$$

The Higgs boson mass is given by: $M_H^2 = 2\lambda v^2 = -2\mu^2$.

The Higgs triple and quartic self–interaction vertices are:

$$g_{H^3} = 3i\, M_H^2/v \, , \; g_{H^4} = 3iM_H^2/v^2$$

What about the Higgs boson couplings to gauge bosons and fermions?

They were almost derived previously, when we calculated the masses:

$$\mathcal{L}_{M_V} \sim M_V^2(1 + H/v)^2 \;\; , \; \mathcal{L}_{m_f} \sim -m_f(1 + H/v)$$

$$\Rightarrow g_{Hff} = im_f/v \, , \; g_{HVV} = -2iM_V^2/v \, , \; g_{HHVV} = -2iM_V^2/v^2$$

Since v is known, the only free parameter in the SM is M_H or λ.

2. Status of the SM: parameters at tree—level

In the SM, there are 18 free parameters ($+\theta_{\rm QCD}+\nu$ sector):

- **9 fermions masses, 4 CKM parameters (see below for details).**
- **3 coupling g_s, g_2, g_1 and 2 parameters from scalar potential μ, λ**

More precise inputs, $\alpha_s, \alpha(M_Z^2), G_F, M_Z$ and M_H (unknown)

Weak interactions of fermions with gauge bosons

$$\mathcal{L}_{\rm NC} = eJ_\mu^{\rm A}A^\mu + \frac{g_2}{\cos\theta_W}J_\mu^Z Z^\mu \ , \ \mathcal{L}_{\rm CC} = \frac{g_2}{\sqrt{2}}(J_\mu^+ W^{+\mu} + J_\mu^- W^{-\mu})$$

$$J_\mu^A = Q_f \bar{f}\gamma_\mu f \ , \ J_\mu^Z = \frac{1}{4}\bar{f}\gamma_\mu[\hat{v}_f - \gamma_5 \hat{a}_f]f \ , \ J_\mu^+ = \frac{1}{2}\bar{f}_u\gamma_\mu(1-\gamma_5)f_d$$

with $v_f = \frac{\hat{v}_f}{4s_W c_W} = \frac{2I_f^3 - 4Q_f s_W^2}{4s_W c_W} \ , \ a_f = \frac{\hat{a}_f}{4s_W c_W} = \frac{2I_f^3}{4s_W c_W}$

3-families: complication in CC as current eigenstates $\neq$ mass eigenstates

connected by a unitary transformation: $(d', s', b') = V_{\rm CKM}(d, s, b)$

$V_{\rm CKM} \equiv 3\times3$ **unitarity matrix; NC are diagonal in both bases (GIM).**

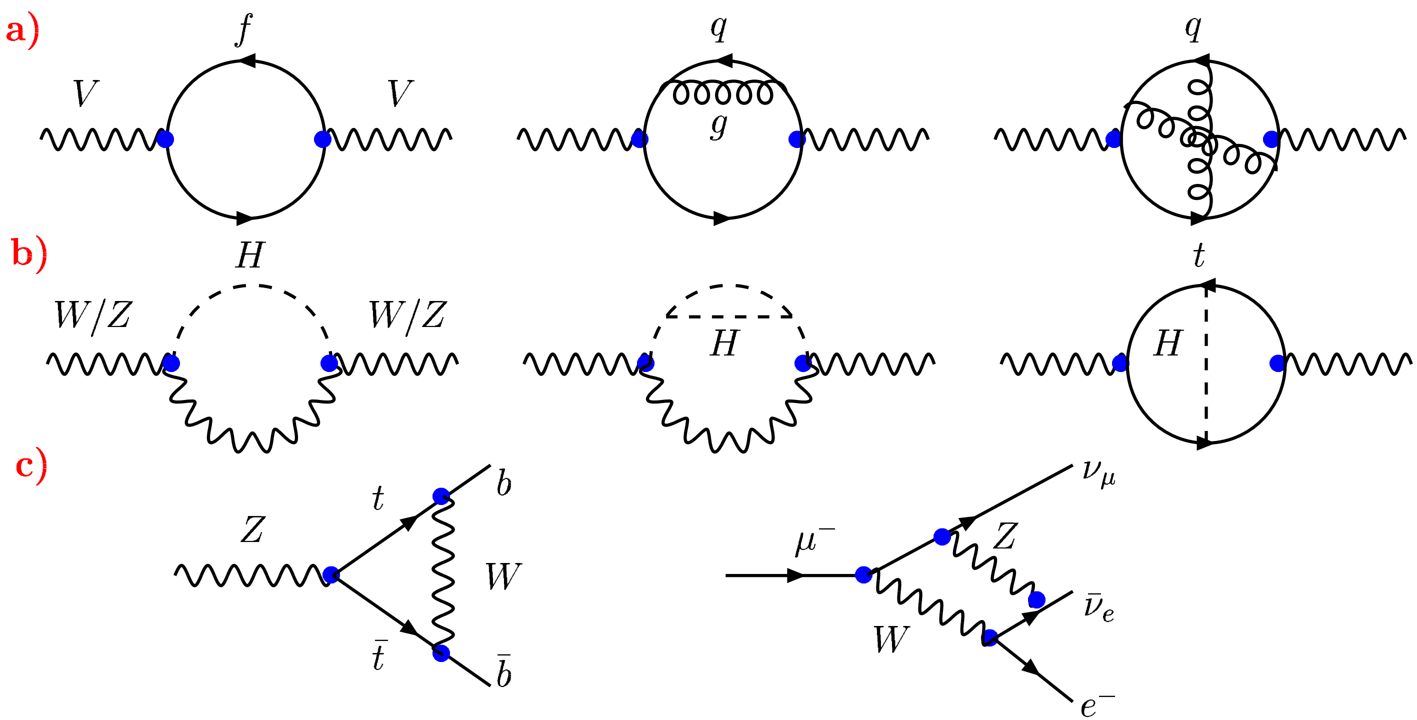
Parametrized by 3 angles and 1 CPV phase: tests at B–factories.

2. Status of the SM: precision tests

M_W **and** $\sin^2\theta_W$ **predicted:** $\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha(M_Z^2)}{2M_W^2(1-M_W^2/M_Z^2)}$; $\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$

In fact, they are related by $\rho = \frac{M_W^2}{c_W^2 M_Z^2} \equiv 1$ **at tree–level in the SM**

To have very precise predictions, include the radiative corrections:



The dominant correction is, besides $\Delta\alpha$**, the one to the** ρ **parameter**

$$\rho = \frac{1}{1-\Delta\rho}\ ,\ \Delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} = \frac{3G_\mu m_t^2}{8\sqrt{2}\pi^2} - \frac{G_\mu M_W^2}{8\sqrt{2}\pi^2}\log\frac{M_H^2}{M_W^2} + \cdots$$

2. Status of the SM: high–precision data

- Z boson lineshape parameters at LEP1 ($\sqrt{\rm s} \sim \rm M_Z$):

$$M_Z, \Gamma_Z, \sigma(e^+e^- \to \text{hadrons})$$

- Partial decay widths and asymmetries in Z decays at LEP1:

$$\Gamma(Z \to f\bar{f}) = \frac{2\alpha}{3} N_c M_Z (v_f^2 + a_f^2)\ ,\ A_{FB}^f = \frac{3}{4} \frac{2a_e v_e}{v_e^2+a_e^2} \frac{2a_f v_f}{v_f^2+a_f^2}$$

- Left–right polarized asymmetries in Z decays at SLC:

$$A_{LR} = \frac{2a_e v_e}{v_e^2+a_e^2}\ ,\ A_{LR/FB}^f = \frac{3}{4} \frac{2a_f v_f}{v_f^2+a_f^2}$$

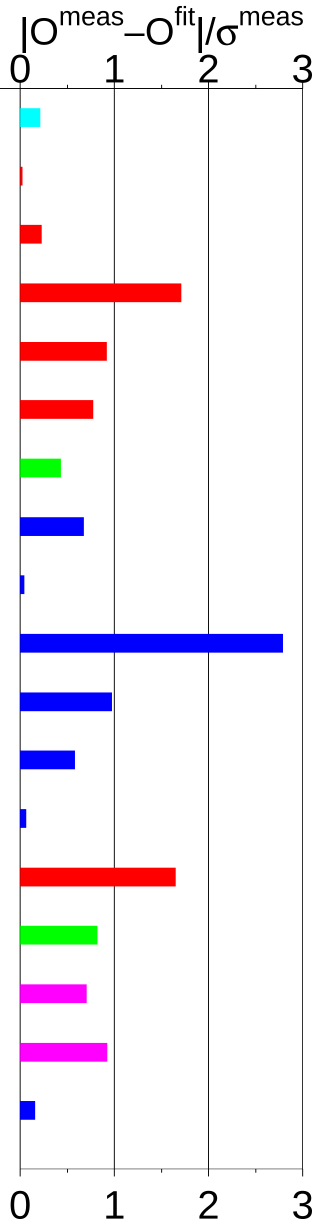
- W boson parameters: M_W and Γ_W at LEP2 and Tevatron.
- Other observables at low–energy: ν_e DIS, PV in Cs and Th ...
- Use top quark mass value from Tevatron $m_t = 171 \pm 2$ GeV
- Use value of α_s from LEP and elsewhere: $\alpha_s = 0.1172 \pm 0.002$
- Use $\alpha(M_Z)$ with $\Delta\alpha = 0.028 \pm 0.00036$ from low–energy data

$\Rightarrow$ Very high precision tests of the SM at the quantum level: 1%–0.1%

SM describes precisely (almost) all available experimental data!

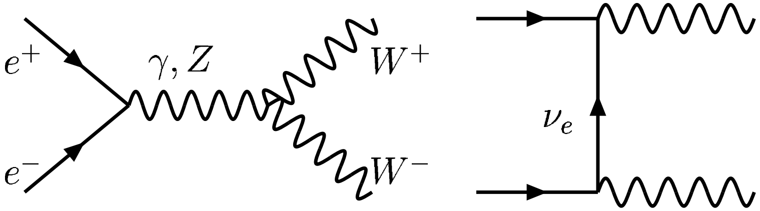
2. Status of the SM: high–precision tests

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02766
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ_{had}^{0} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01640
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479
R_b	0.21629 ± 0.00066	0.21585
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1479
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.392 ± 0.029	80.371
Γ_W [GeV]	2.147 ± 0.060	2.091
m_t [GeV]	171.4 ± 2.1	171.7



2. Tests of the SM: gauge structure

WW production at at LEP2:



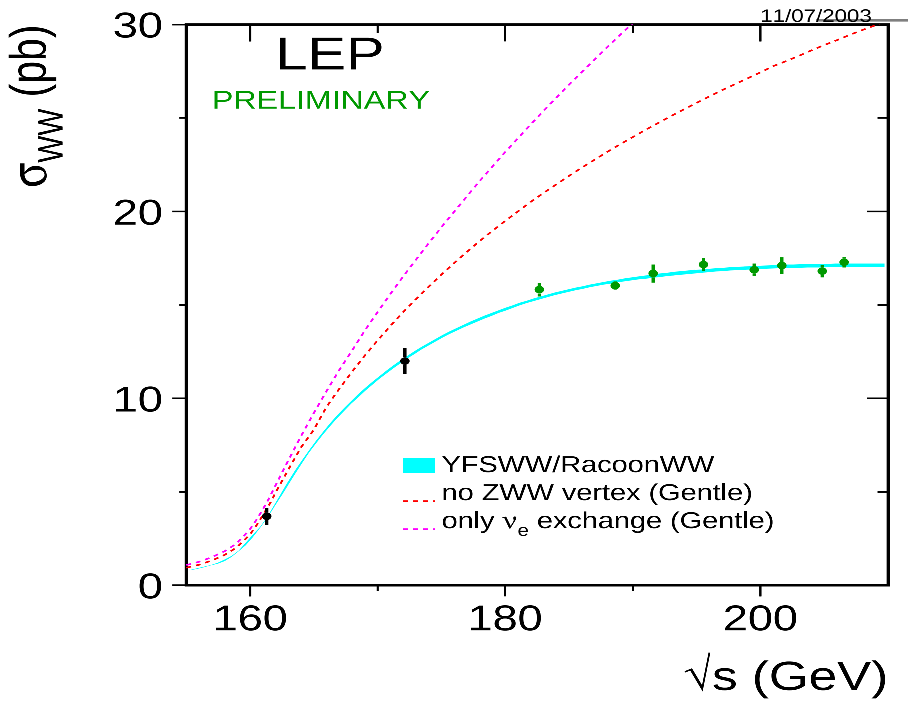
General CPC WWV coupling given by:

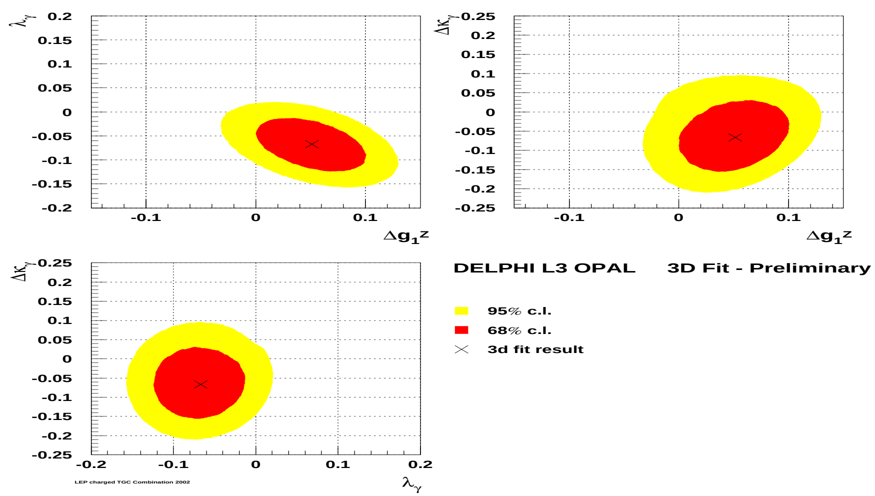
$$\mathcal{L}_{\rm eff}^{WWV} \propto g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu}\right)$$
$$+\kappa_V W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu}$$

In SM: $g_1^V = 1, \kappa_V = 1, \lambda_V = 0$

$\mathbf{SU(2)_L \times U(1)_Y}$ gauge structure checked rather precisely at LEP2

Note: QCD also very precisely tested!
– running of α_s from m_τ to LEP2.
– 3 gluon vertex determined at LEP1.





3. Physics at LHC: generalities

LHC: pp collider

$\sqrt{s}=7+7=14$ TeV $\Rightarrow \sqrt{s}_{\rm eff} \sim \sqrt{s}/3 \sim 5$ TeV

$\mathcal{L} \sim 10\,{\rm fb}^{-1}$ first years and 100 fb^{-1} later

- **Huge cross sections for QCD processes.**
- **Small cross sections for EW Higgs signal.**

S/B $\gtrsim 10^{10} \Rightarrow$ **a needle in a haystack!**

- **Need some strong selection criteria:**

Trigger: get rid of uninteresting events...

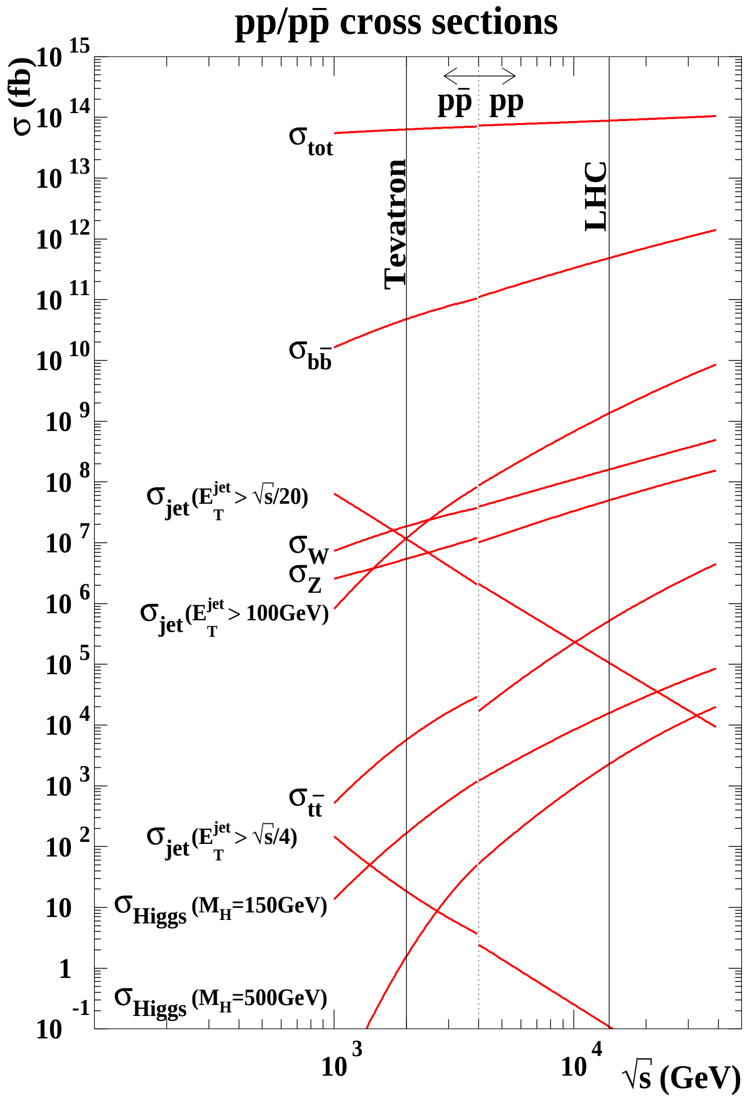
Select clean channels: $\mathbf{H} \to \gamma\gamma, \mathbf{VV} \to \ell$

Use different kinematic features for Higgs

Combine different decay/production channels

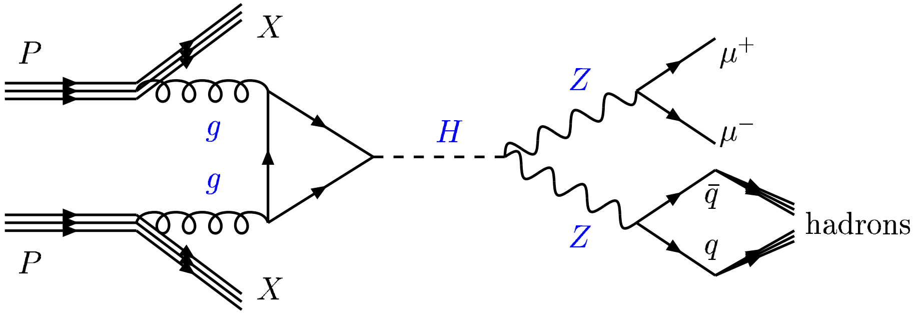
Have a precise knowledge of S and B rates.

- **Gigantic experimental (+theoretical) efforts!**



3. Physics at LHC: generalities

Example of process at LHC to see how things work: $gg \to H$



$$N_{ev} = \mathcal{L} \times P(g/p) \times \hat{\sigma}(gg \to H) \times B(H \to ZZ) \times B(Z \to \mu\mu) \times BR(Z \to qq)$$

For a large number of events, all these numbers should be large!

Two ingredients: hard process (σ, B) and soft process (PDF, hadr).

Factorization theorem! Here discuss production/decay process.

The partonic cross section of the subprocess, $gg \to H$, is:

$$\hat{\sigma}(gg \to H) = \int \frac{1}{2\hat{s}} \times \frac{1}{2 \cdot 8} \times \frac{1}{2 \cdot 8} |\mathcal{M}_{Hgg}|^2 \frac{d^3 p_H}{(2\pi)^3 2E_H} (2\pi^4) \delta^4 (q - p_H)$$

Flux factor, color/spin average, matrix element squared, phase space.

Convolute with gluon densities to obtain total hadronic cross section

$$\sigma = \int_0^1 dx_1 \int_0^1 dx_2 \frac{\pi^2 M_H}{8\hat{s}} \Gamma(H \to gg) g(x_1) g(x_2) \delta(\hat{s} - M_H^2)$$

3. Physics at LHC: generalities

The calculation of $\sigma_{\rm born}$ is not enough in general at pp colliders:

need to include higher order radiative corrections which introduce terms of order $\alpha_s^n \log^m(Q/M_H)$ where Q is either large or small...

- **Since α_s is large, these corrections are in general very important.**
- **Choose a (natural scale) which absorbs/resums the large logs.**

Since we truncate pert. series: only NLO/NNLO corrections available.

- **The (hopefully) not known HO corrections induce a theoretical error.**
- **The scale variation is a (naive) measure of the HO: must be small.**

Also, precise knowledge of σ is not enough: need to calculate some kinematical distributions (e.g. $p_T, \eta, \frac{d\sigma}{dM}$) to distinguish S from B.

In fact, one has to do this for both the signal and background (unless directly measurable from data): the important quantity is $\sigma = \frac{N_S}{\sqrt{N_{bjg}}}$

$\Rightarrow$ a lot of theoretical work is needed!

But most complicated thing is to actually see the signal for S/B$\ll$1!

4. SM physics at the LHC

Tests of the SM and background calibration for New Physics search

- **High–p_T jets, γ physics and QCD:**

– allows to measure α_s, PDFs and check perturbation theory

– c, b, t production for QCD dynamics (resummation, quarkonia).

- **The physics of the bottom quarks:**

– study of QCD (as above), CKM matrix and CP violation (LHCb).

- **The physics of the top quark:**

– plays a key role origin of EWSB and clue to SM flavour problem?

– since lifetime shorter than hadronisation scale, QCD laboratory

- **The physics of W, Z bosons:**

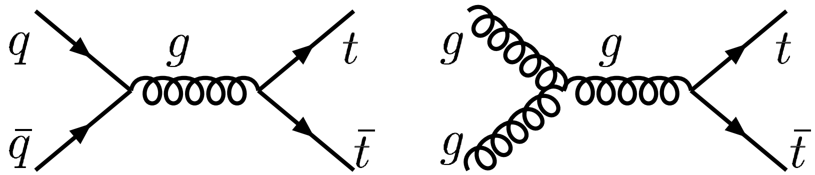
– W, Z production allow to measure precisely M_W and Γ_W

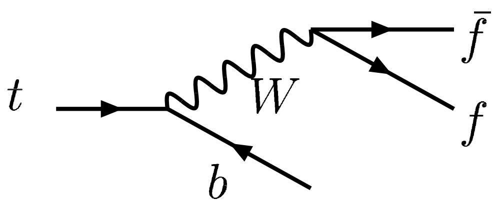
– $WW, WZ(\gamma), ZZ(\gamma)$ allow to measure the TGC.

– VV and $VV \to VV$ allow to test a strong interaction sector.

4. SM physics: the top quark

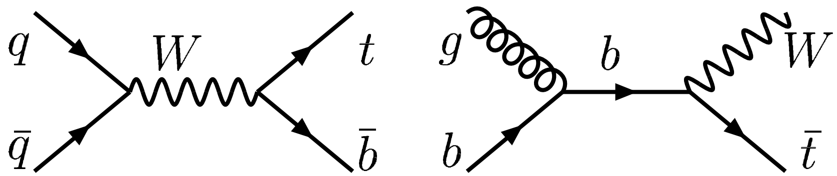
Top quark pair production: $pp \to t\bar{t}$



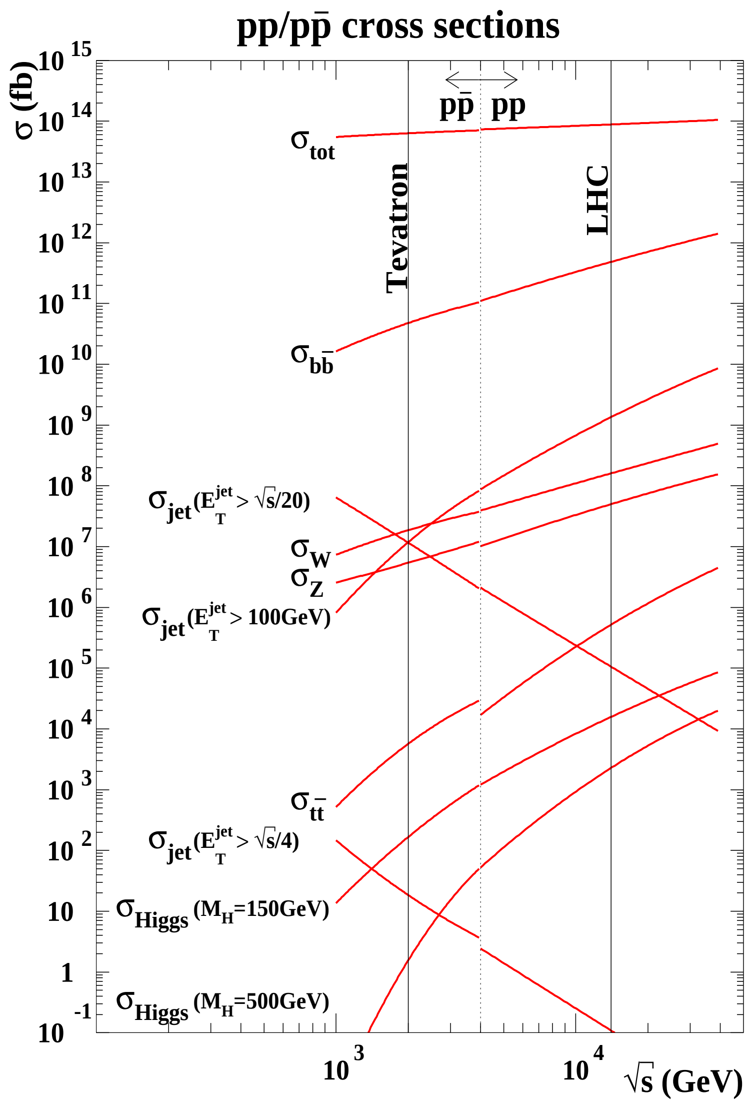


M_t measurement: $\Delta M_t \sim \pm 1$ GeV

Single top production: $pp \to t + X$

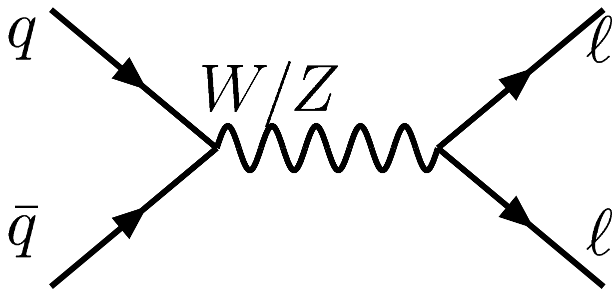


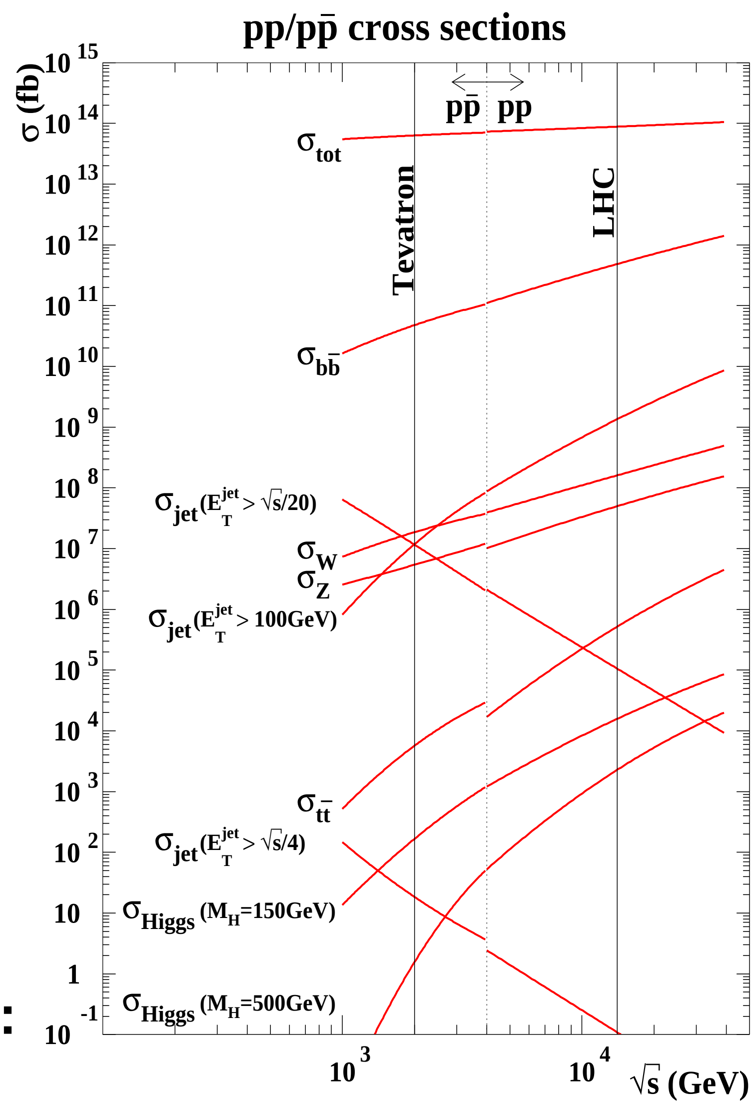
Much smaller rates by enough events
for precise $V_{bt}^{\rm CKM}$ measurement....



4. SM physics: the W/Z bosons

Single W/Z production: $\mathrm{pp} \to \mathrm{q\bar{q}} \to \mathbf{V}$





Very large number of events $\sim 10^9$:

Include RC: $K_V = \sigma_{\mathrm{NNL0}}/\sigma_{\mathrm{LO}} \sim 1.4$

Systematical errors ($\mathcal{L}$, PDF's, etc..)

cancell in the ratio $\sigma(\mathbf{W})/\sigma(\mathbf{Z})$

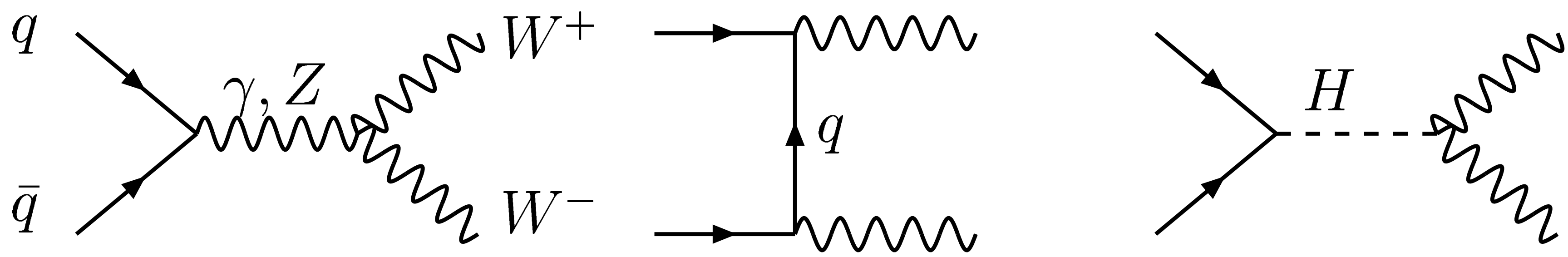
Use Z parameters from LEP1/SLC

Precise measurements of W parameters:

Ex: $\Delta M_W \approx 15$ MeV (30 MeV now).....

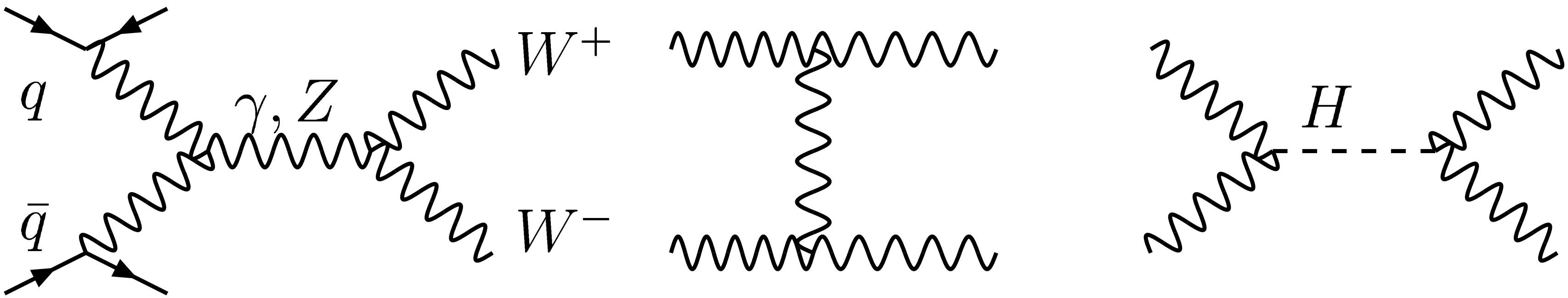
4. SM physics: W boson Physics

WW/ZZ/Zγ production important to check SM gauge structure



WW/ZZ scattering important to check a strongly interacting sector

(in case where there is no Higgs boson found at the LHC!!)



4. SM physics: TGCs

General form of the trilinear gauge boson couplings:

$$\mathcal{L}_{\rm eff}^{WWV} = i g_{WWV} \Big[g_1^V V^\mu \left(W^-_{\mu\nu} W^{+\nu} - W^+_{\mu\nu} W^{-\nu} \right) + \kappa_V \, W^+_\mu W^-_\nu V^{\mu\nu}$$

$$+ \frac{\lambda_V}{M_W^2} V^{\mu\nu} W^{+\rho}_{\nu} W^-_{\rho\mu} + i g_5^V \varepsilon_{\mu\nu\rho\sigma} \left((\partial^\rho W^{-\mu}) W^{+\nu} - W^{-\mu} (\partial^\rho W^{+\nu}) \right) V^\sigma$$

$$+ i g_4^V W^-_\mu W^+_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) - \frac{\tilde{\kappa}_V}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_V}{2 m_W^2} W^-_{\rho\mu} W^{+\mu}{}_{\nu} \varepsilon$$

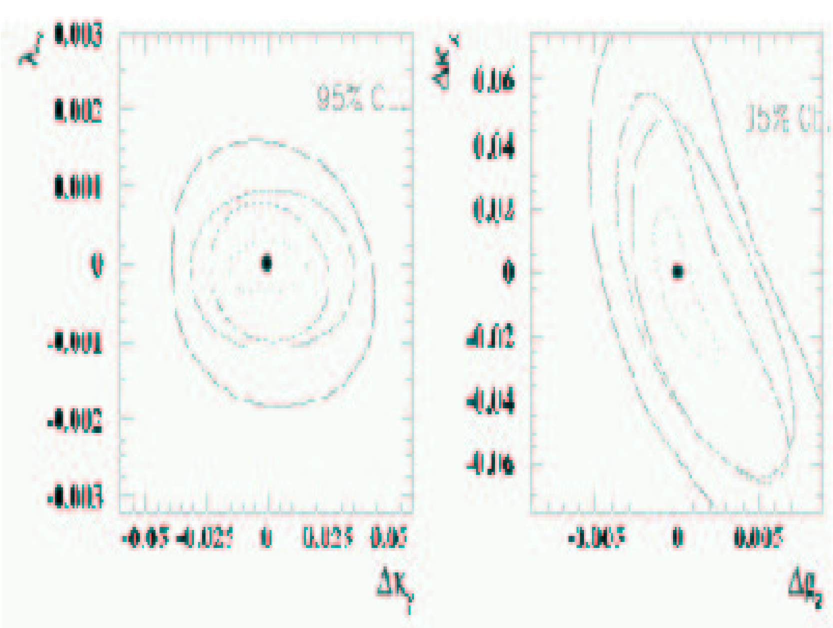
with overall couplings $g_{WW\gamma} = e$ **and** $g_{WWZ} = e \cot \theta_W$

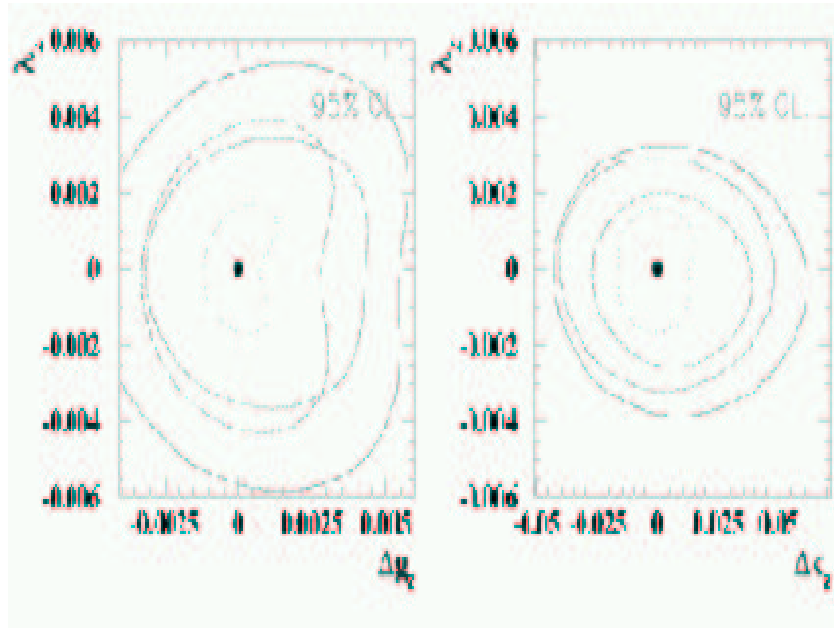
In practice: introduce deviations from their tree–level SM values

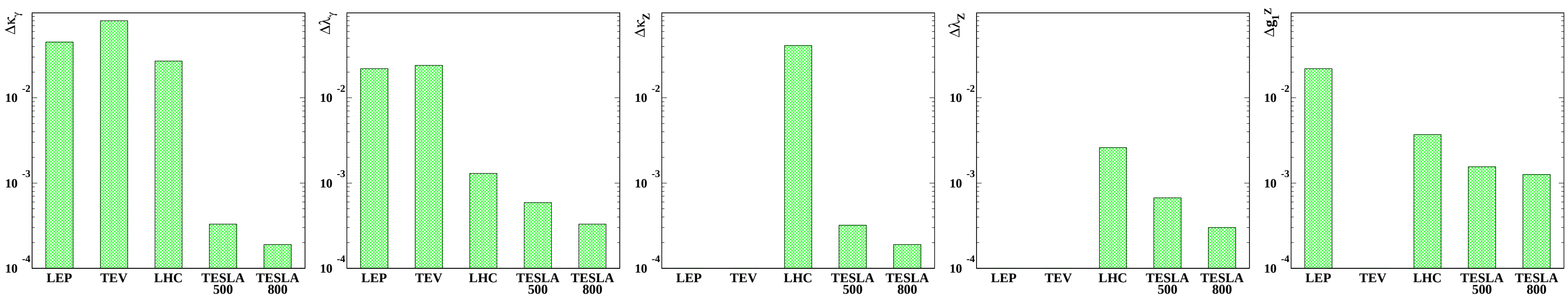
$$\Delta g_1^Z \equiv (g_1^Z - 1) \, , \;\; \Delta \kappa_\gamma \equiv (\kappa_\gamma - 1) \, , \;\; \Delta \kappa_Z \equiv (\kappa_Z - 1)$$

Use all production processes, W/Z **decays, distributions and spin–correlations (many observables!) to probe** Δx**.**

4. SM physics: constraints on TGCs







4. SM physics: strong W/Z sector

In SM with Higgs field integrated out (too heavy or absent), non–linear realisation of EWSB and $\mathcal{L}^{\rm eff}_{\rm SM}$at scale below $\Lambda_{\textsf{EWSB}} = 4\pi v \approx 3\,{\rm TeV}$ (and if no resonance appears) is given by

$$L_1 = \frac{\alpha_1}{16\pi^2}\frac{gg'}{2}B_{\mu\nu}\,{\rm tr}\Big(\sigma_3 W^{\mu\nu}\Big)\ ,\ L_2 = \frac{\alpha_2}{16\pi^2}{\rm i}g' B_{\mu\nu}\,{\rm tr}\Big(\sigma_3 V^\mu V$$

$$L_3 = \frac{\alpha_3}{16\pi^2}2{\rm i}g\,{\rm tr}\Big(W_{\mu\nu}V^\mu V^\nu\Big)\ ,\ L_4 = \frac{\alpha_4}{16\pi^2}\,{\rm tr}\Big(V_\mu V_\nu\Big)\,{\rm tr}\Big(V^\mu V$$

$$L_5 = \frac{\alpha_5}{16\pi^2}\,{\rm tr}\Big(V_\mu V^\mu\Big)\,{\rm tr}\Big(V_\nu V^\nu\Big)\ ,\ \cdots L_{6,7,8,9,10}\ ({\rm C/P\ non-conservin}$$

Coefficients α_i related to the NP scale Λ_i^* by $\frac{\alpha_i}{16\pi^2} = \left(\frac{v}{\Lambda_i^*}\right)^2$

- **Some operators, $L_{1,2,...}$, constrained by precisison data ($\Delta\rho$, ..).**
- **$L_{1,2,3}$ contribute to TGC; probed in $qq \to WW, ZZ, Z\gamma$, ...**
- **$L_{3,4,5}$ contribute to quartic couplings and parametrize strongly interacting gauge bosons; probed in $qq \to WWqq, ZZqq$**

4. SM physics: strong W/Z sector

Propagators of gauge and Goldstone bosons in a general ζ gauge:

$\longrightarrow q$ $\quad \frac{-i}{q^2-M_V^2+i\epsilon}\left[g_{\mu\nu}+(\zeta-1)\frac{q_\mu q_\mu}{q^2-\zeta M_V^2}\right]$

$\zeta=\infty$: **Landau gauge**

$\zeta=1$: **'t Hooft-Feynman**

$\omega^\pm, \omega^0$:

$\longrightarrow q$ $\quad \frac{-i}{q^2-\zeta M_V^2+i\epsilon}$

- **In unitary gauge, Goldstones do not propagate and gauge bosons have usual propagators of massive spin–1 particles (old IVB theory).**
- **At very high energies, $\mathrm{s} \gg \mathrm{M_V^2}$, an approximation is $\mathrm{M_V} \sim 0$. The $\mathrm{V_L}$ components of V can be replaced by the Goldstones, $\mathrm{V_L} \to \omega$.**
- **In fact, the electroweak equivalence theorem tells that at high energies, massive vector bosons are equivalent to Goldstones. In VV scattering e.g**

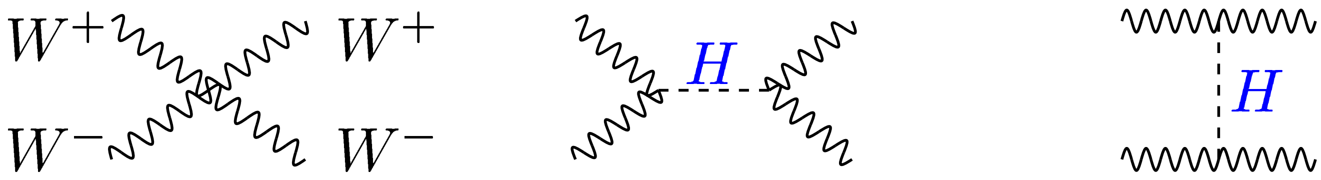
$$\mathbf{A(V_L^1 \cdots V_L^n \to V_L^1 \cdots V_L^{n'}) = (i)^n(-i)^{n'}A(w^1 \cdots w^n \to w^1 \cdots w^{n'}}$$

Thus, we simply replace V by w in the scalar potential and use w:

$$\mathbf{V = \frac{M_H^2}{2v}(H^2+w_0^2+2w^+w^-)H + \frac{M_H^2}{8v^2}(H^2+w_0^2+2w^+w^-)^2}$$

4. SM physics: strong W/Z sector

Scattering of massive gauge bosons $V_L V_L \to V_L V_L$ at high-energy



Because w interactions increase with energy (q^μ terms in V propagator),

$s \gg M_W^2 \Rightarrow \sigma(w^+w^- \to w^+w^-) \propto s$: $\Rightarrow$ unitarity violation possible!

Decomposition into partial waves and choose J=0 for $s \gg M_W^2$:

$$a_0 = -\frac{M_H^2}{8\pi v^2}\left[1 + \frac{M_H^2}{s - M_H^2} + \frac{M_H^2}{s}\log\left(1 + \frac{s}{M_H^2}\right)\right]$$

For unitarity to be fullfiled, we need the condition $|\mathrm{Re}(a_0)| < 1/2$.

At high energies, $s \gg M_H, M_W$, we have: $a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2}$

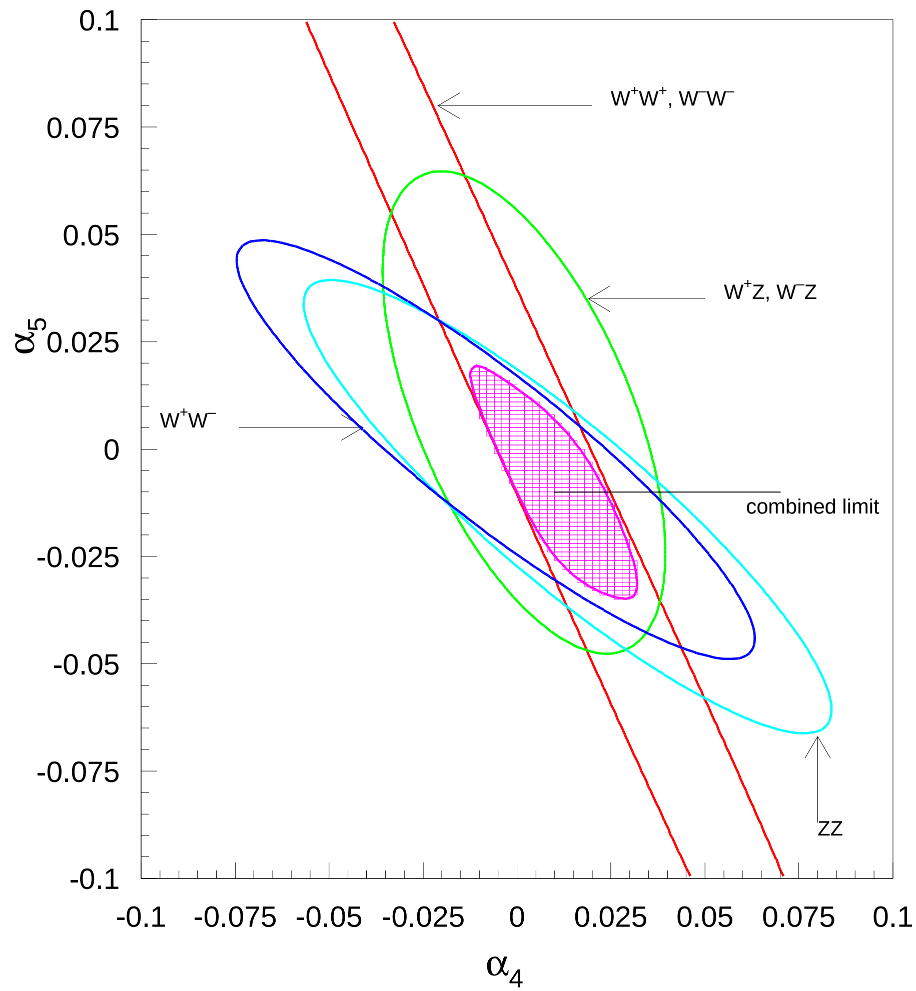
$$\text{unitarity} \Rightarrow M_H \lesssim 870~\text{GeV} \quad (M_H \lesssim 710~\text{GeV})$$

For a very heavy or no Higgs boson, we have: $a_0 \xrightarrow{s \ll M_H^2} -\frac{s}{32\pi v^2}$

$$\text{unitarity} \Rightarrow \sqrt{s} \lesssim 1.7~\text{TeV} \quad (\sqrt{s} \lesssim 1.2~\text{TeV})$$

Otherwise (strong?) New Physics should appear to restore unitarity.

4. SM physics: strong W/Z sector



4. SM physics: strong W/Z sector

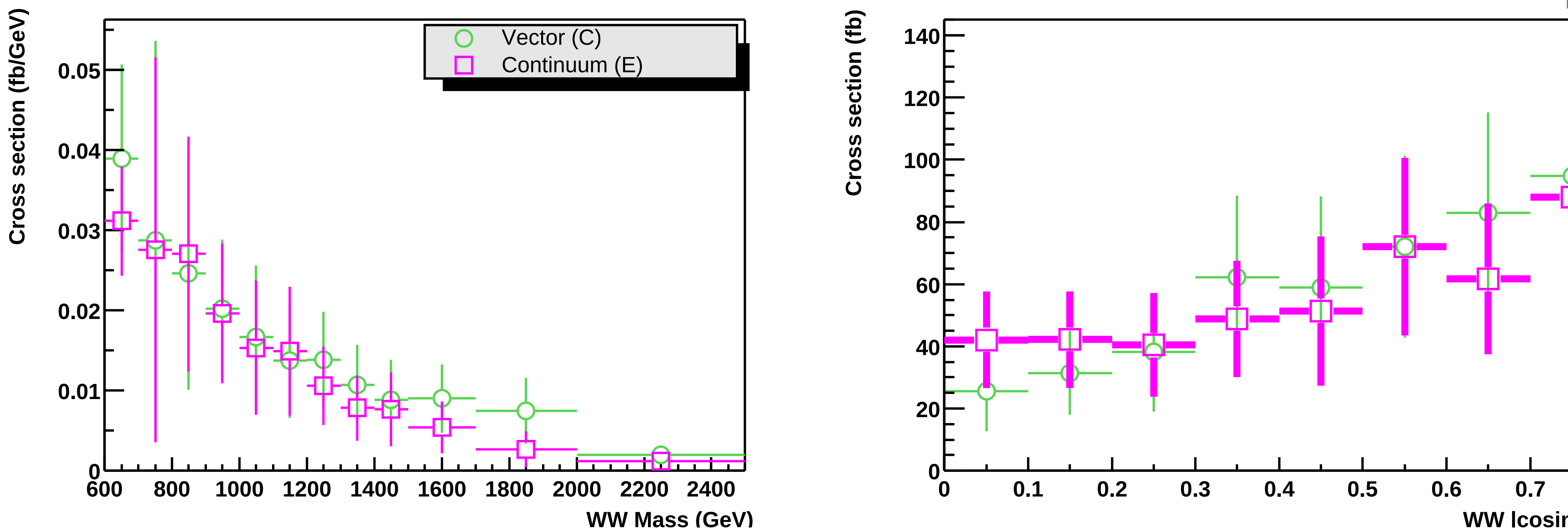


Figure 1: **Differential cross section measurements at LHC assuming $100\ fb^{-1}$ of luminosity and $\sqrt{s} = 14$ TeV: (left) $d\sigma/dM_{WW}$ and (right) $d\sigma/d|\cos\theta^*|$. The green circles are measurements assuming a single 1.9 TeV vector resonance, while the red squares are measurements assuming a model without resonances.**