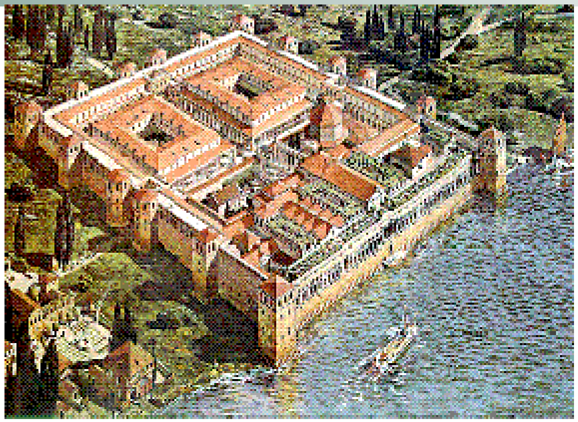
2022 LHC Days in Split

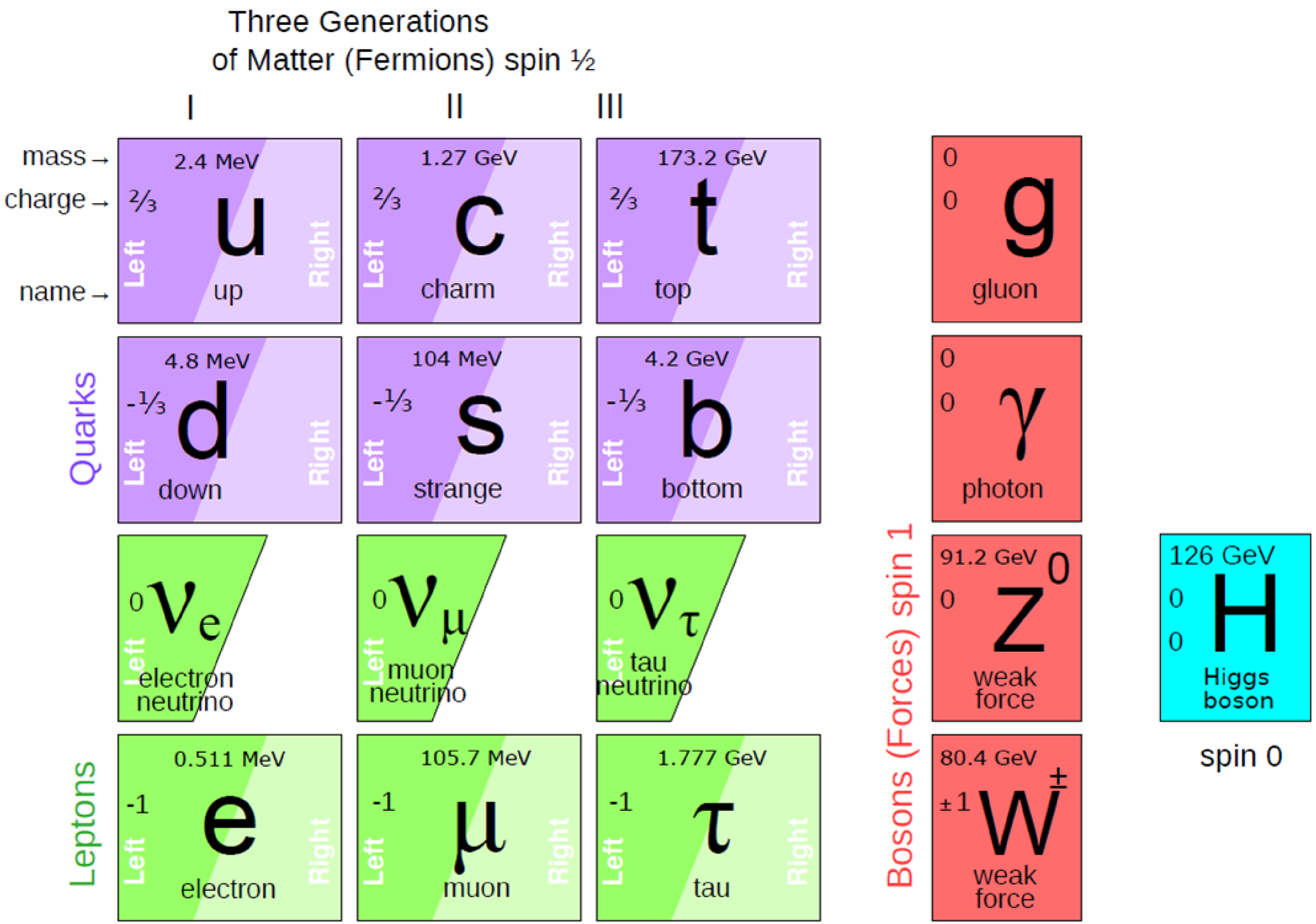


Electroweak Theory

Ivica Picek
University of Zagreb

Split, 6 October 2022

EW Theory – 10 yrs from Higgs-discovery



From EW Model to EW Theory

- Discovery of W, Z and Higgs boson at CERN;
- Experiments on front of
  - Precision,
  - Energy,
  - Statistics;
- Opened questions require:

Beyond EW (QCD, DM, DE)

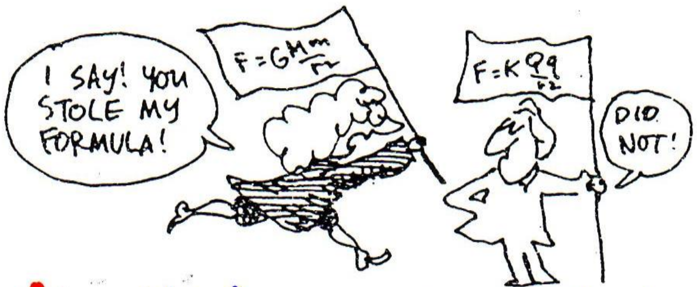
Use of artificial inteligence

Need for a jump in thinking.

Unification attempt by M. Faraday (1850)
- to relate the gravity to electricity

UNIFICATION PREHISTORY

GRAVITATION & ELECTRICITY



- Newton (1642-1727) vs Coulomb (1736-1806)

  the inverse square, $1/r^2$ LAW

- Faraday's attempt (1791-1867)
- Kaluza (1919) & Klein

may be generalized to unify gravity with the other three interactions ?

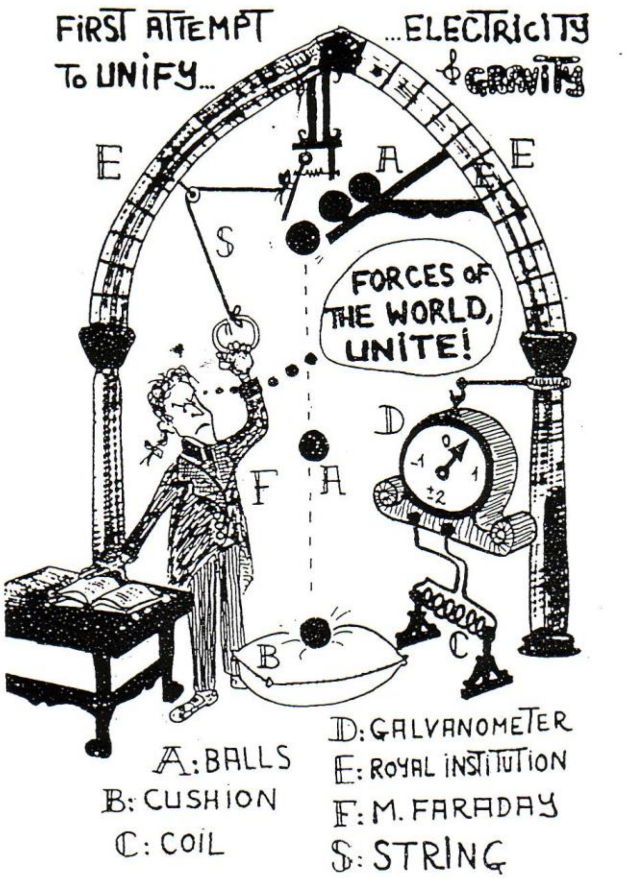
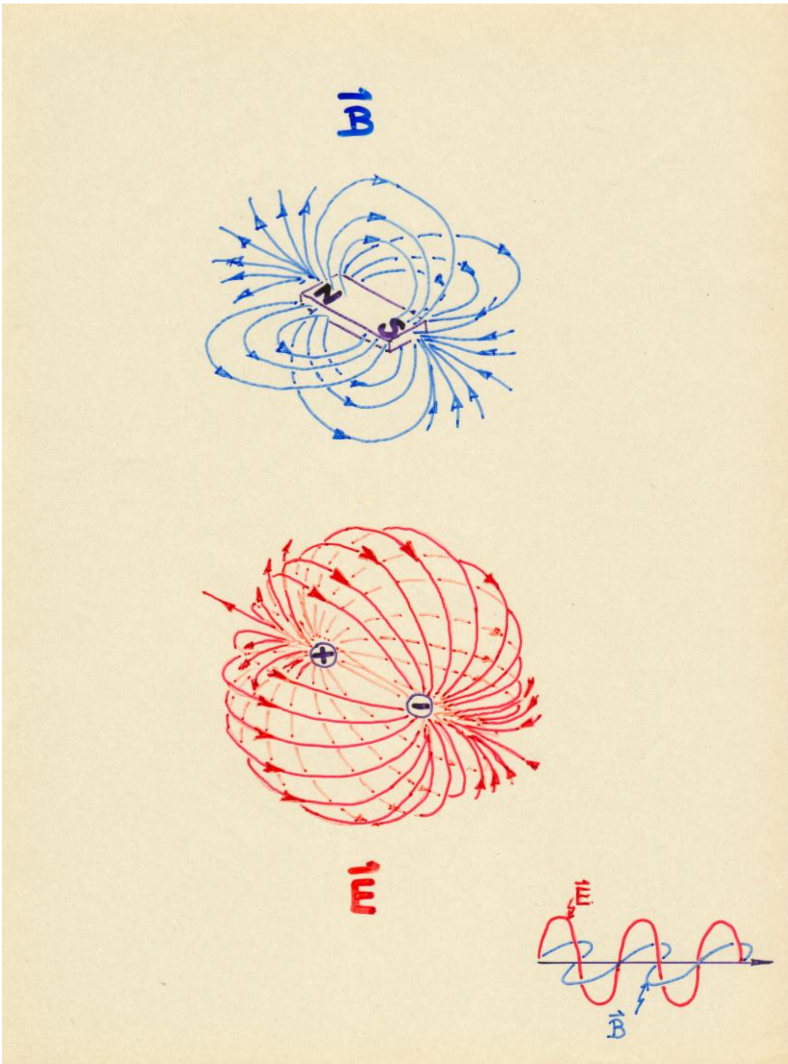
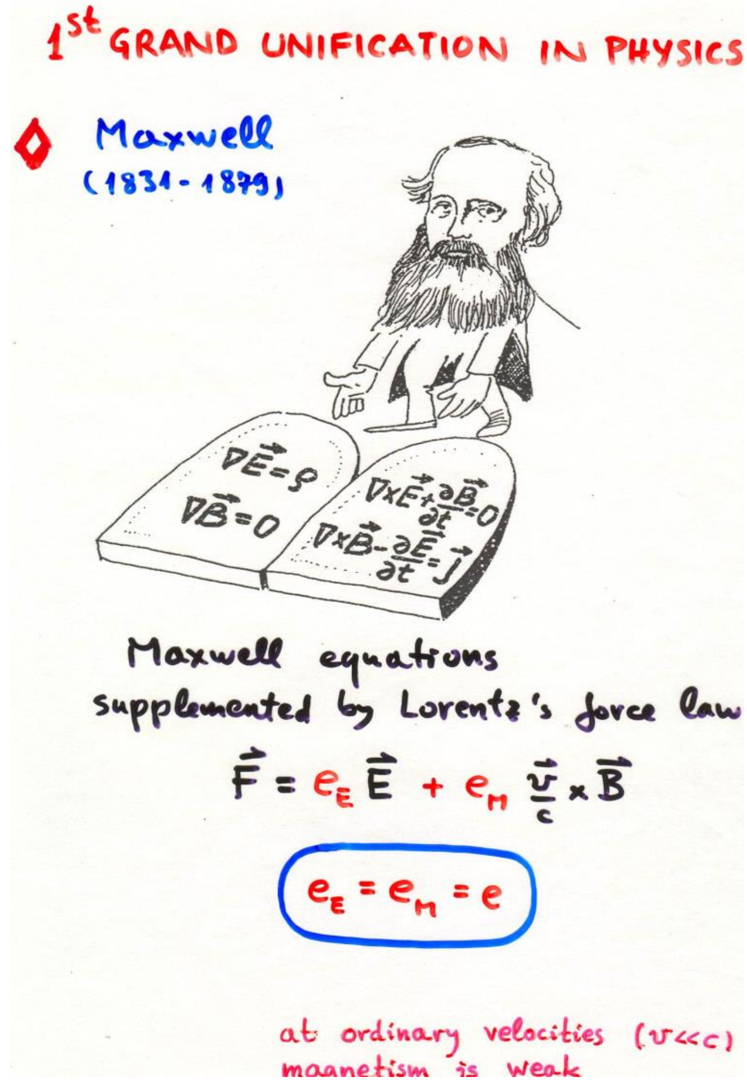


Figure 18.5. Cartoon depicting Michael Faraday at the Royal Institution. Due to A. de Rujula.

Unification of electricity and magnetism (Maxwell)
- ended in Quantum Electro Dynamics (QED)





WEAK FORCE: Fermi theory → IVB theory

$$M_{fi} = [\tfrac{g_W}{\sqrt{2}}\overline{\psi}\tfrac{1}{2}\gamma^{\mu}(1-\gamma^5)\psi]\frac{g_{\mu\nu}-q_{\mu}q_{\nu}/m_W^2}{q^2-m_W^2}[\tfrac{g_W}{\sqrt{2}}\overline{\psi}\tfrac{1}{2}\gamma^{\nu}(1-\gamma^5)\psi]$$

which for $q^2 \ll m_W^2$ becomes:

$$M_{fi} = \frac{g_W^2}{8m_W^2}g_{\mu\nu}[\overline{\psi}\gamma^{\mu}(1-\gamma^5)\psi][\overline{\psi}\tfrac{1}{2}\gamma^{\nu}(1-\gamma^5)\psi]$$

$$\Rightarrow \boxed{\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}}$$

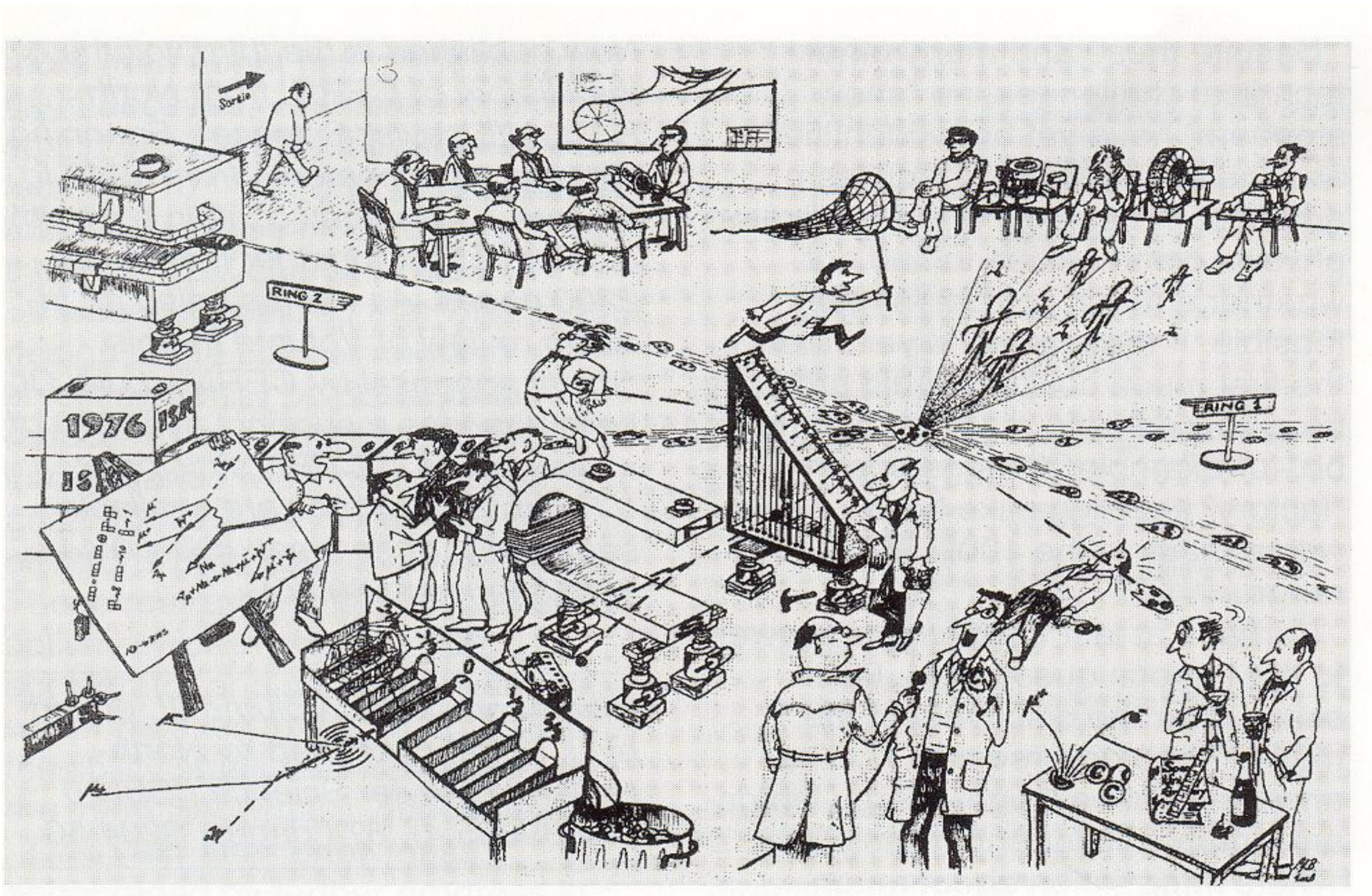
$$m_W = 80.403 \pm 0.029\,\mathrm{GeV}$$

$$\Rightarrow \alpha_W = \frac{g_W^2}{4\pi} = \frac{8m_W^2 G_F}{4\sqrt{2}\pi} = \frac{1}{30}$$

Road to EW (QED-like) model

- In 1964: Brout-Englert-Higgs (BEH) & Guralnik-Hagen-Kibble proposed gauge-boson masses trough SSB;
- In 1967: Weinberg's EW „Model of leptons";
- In 1970: Glashow, Iliopoulos & Maiani extended GWS model to quarks; Physics of flavour becomes the flavour of physics;
- In 1971: 't Hooft & Veltman showed that SSB theories are renormalizable

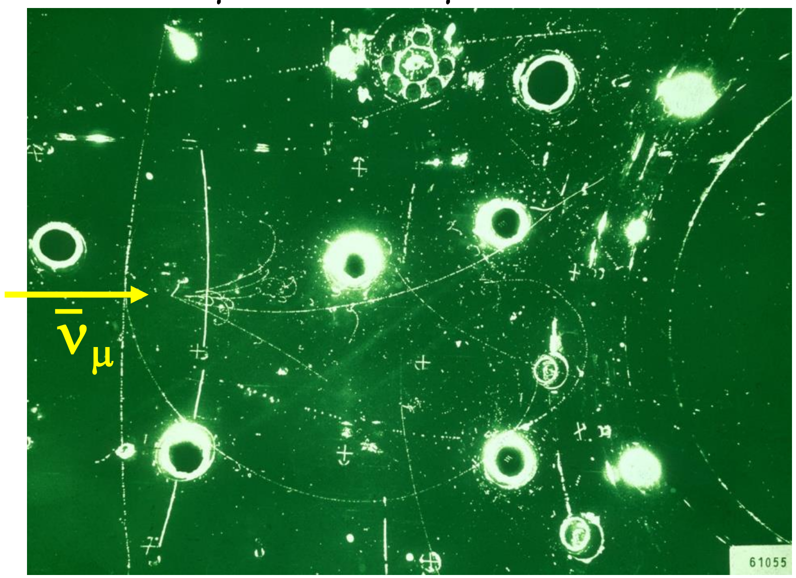
ROLE of CERN: ISR (1971-84) in discovery of the force mediators



WEAK NEUTRAL CURRENT

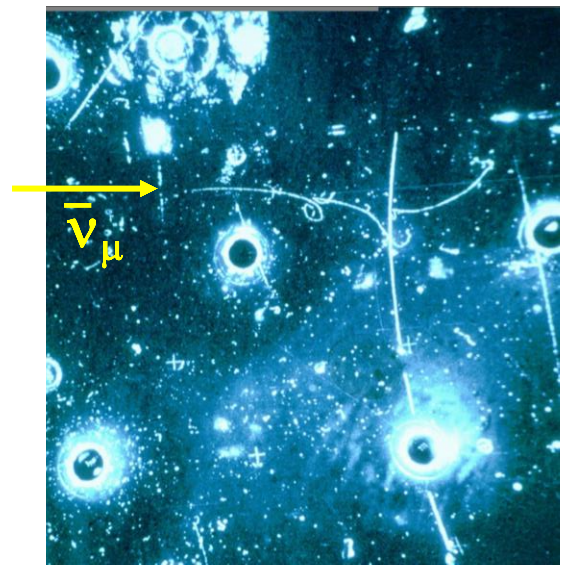
Neutrinos also interact via the Neutral Current. First observed in the Gargamelle bubble chamber in 1973. Interaction of muon neutrinos produce a final state muon

$$\overline{\nu}_\mu + N \rightarrow \overline{\nu}_\mu + \text{hadrons}$$



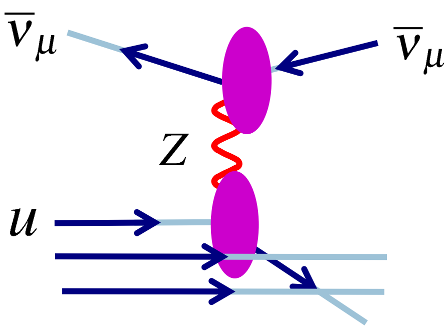
F.J. Hasert et al., Phys. Lett. 46B (1973) 138

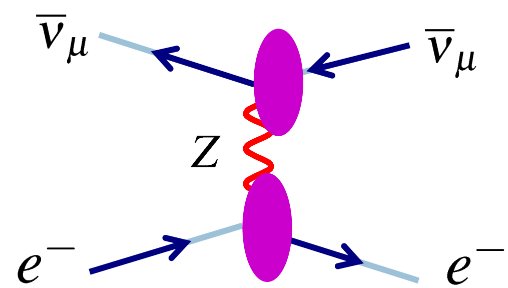
$$\overline{\nu}_\mu + e^- \rightarrow \overline{\nu}_\mu + e^-$$



F.J. Hasert et al., Phys. Lett. 46B (1973) 121

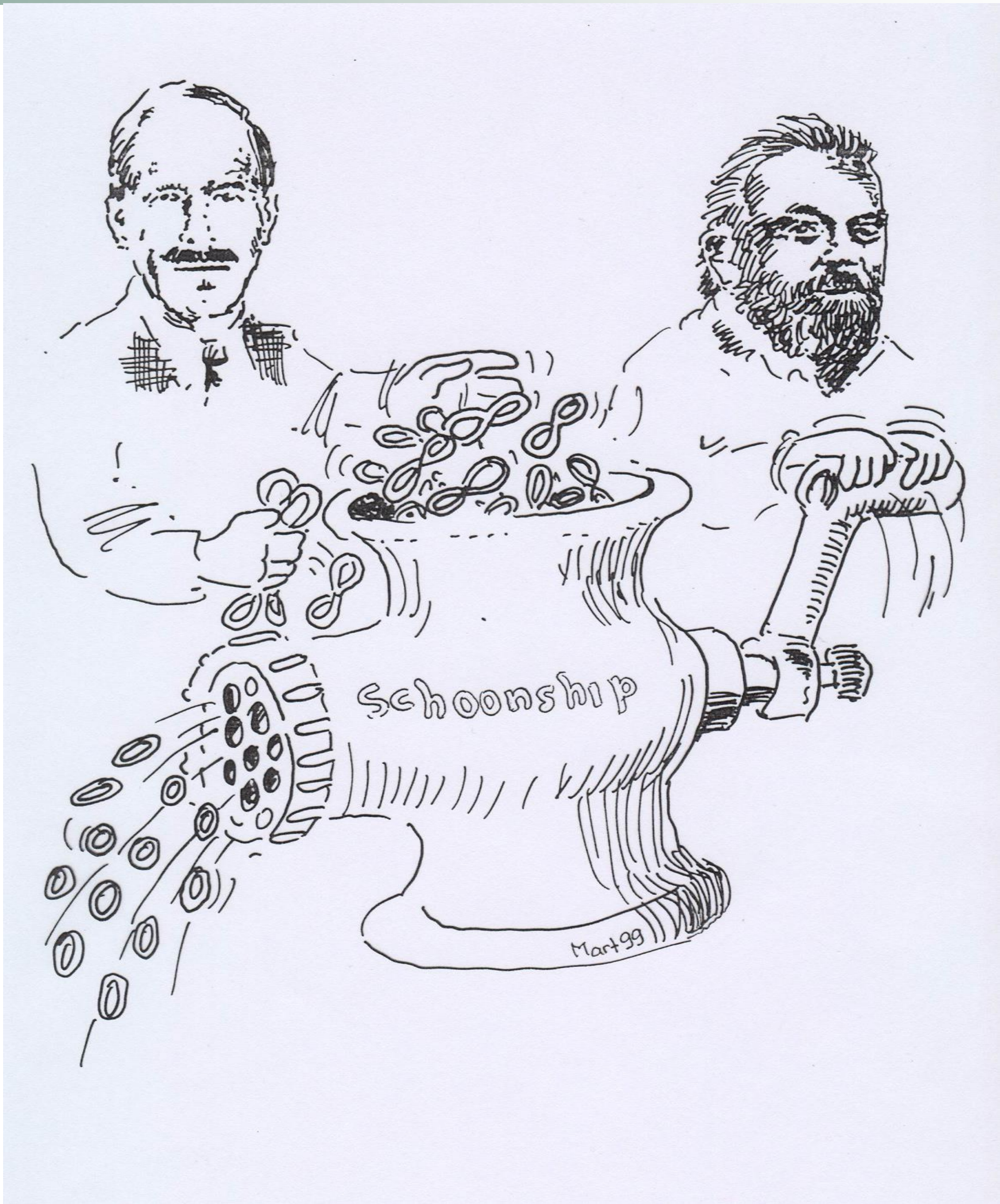
Cannot be due to W exchange - first evidence for Z boson



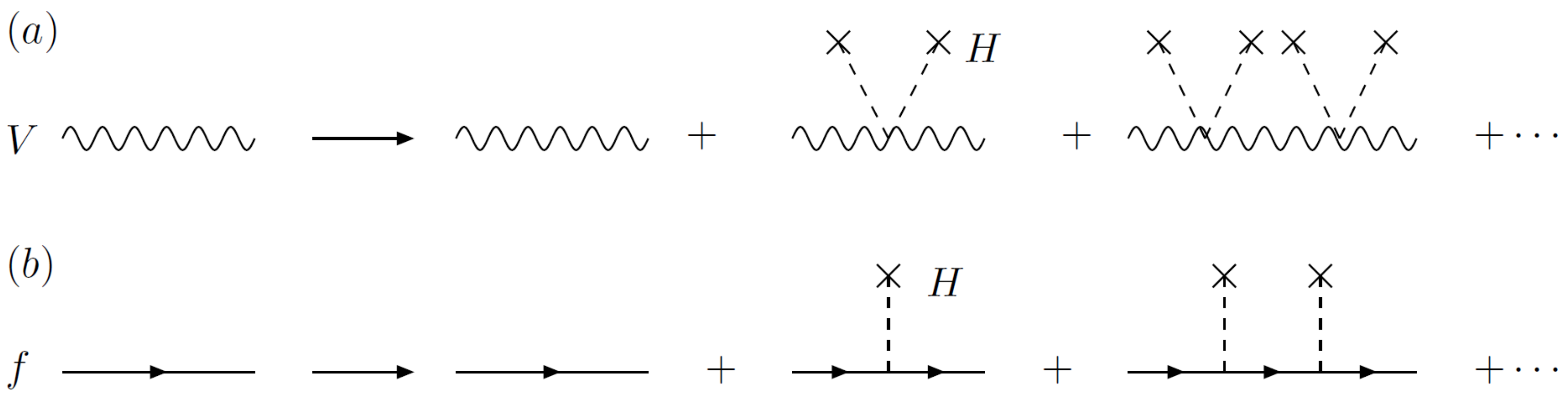


Nobel prize in physics for 1999.

Renormaliza-bility boost: promotes EW model into EW theory ('t Hooft & Veltman)



Massless fields acquire their masses in interaction with the background scalar field passing trough SSB (0 -> v)

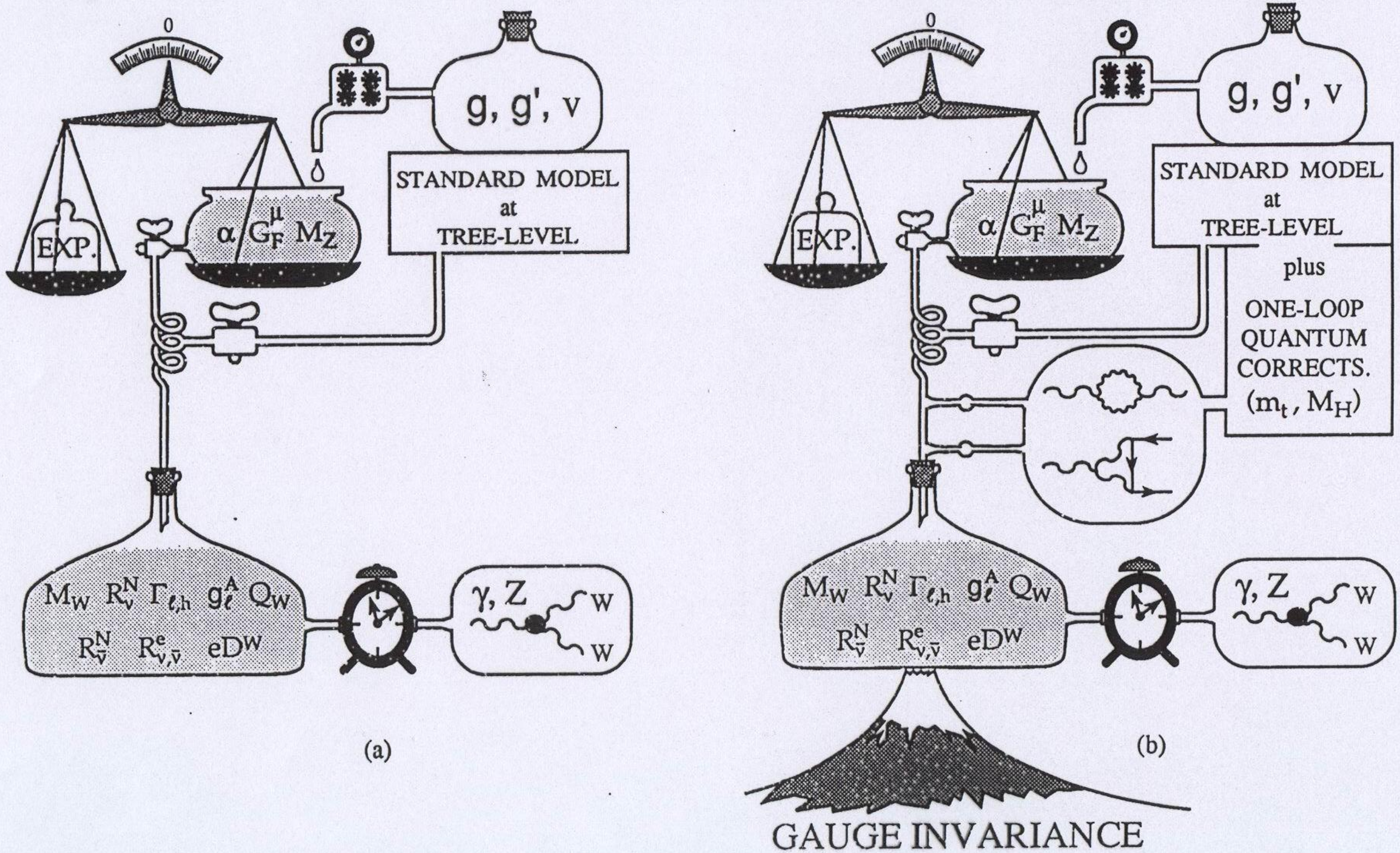


$$(a) \quad \frac{1}{q^2} \rightarrow \frac{1}{q^2} + \sum_j \frac{1}{q^2}\left[\left(\frac{gv}{2}\right)^2 \frac{1}{q^2}\right]^j = \frac{1}{q^2 - M^2} \quad : \quad M^2 = g^2 \frac{v^2}{4}$$

$$(b) \quad \frac{1}{\not{q}} \rightarrow \frac{1}{\not{q}} + \sum_j \frac{1}{\not{q}}\left[\frac{g_f v}{\sqrt{2}} \frac{1}{\not{q}}\right]^j = \frac{1}{\not{q} - m_f} \quad : \quad m_f = g_f \frac{v}{\sqrt{2}}$$

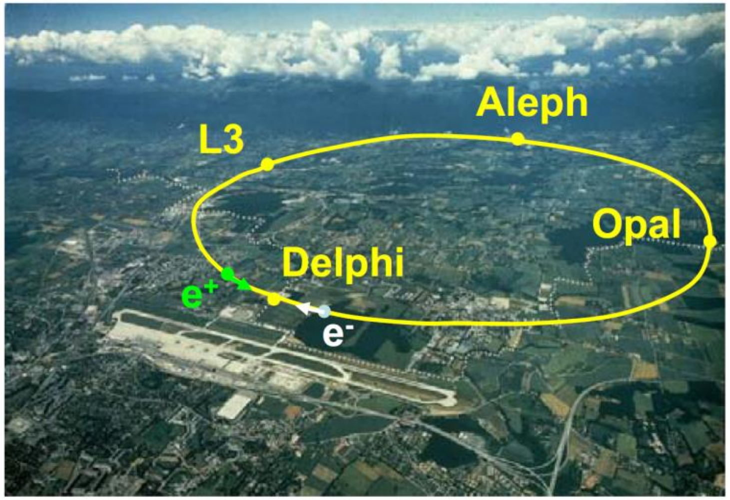
SU(2)⊗U(1) ELECTROWEAK MODEL

SU (2) ⊗ U (1) ELECTROWEAK THEORY



(a) (b)

EW MEASUREMENTS @ LEP (1989-2000)



- 26 km circumference accelerator straddling French/Swiss boarder
- Electrons and positrons collided at 4 interaction points
- 4 large detector collaborations (each with 300-400 physicists):
  - ALEPH,
  - DELPHI,
  - L3,
  - OPAL

Basically a large Z and W factory:

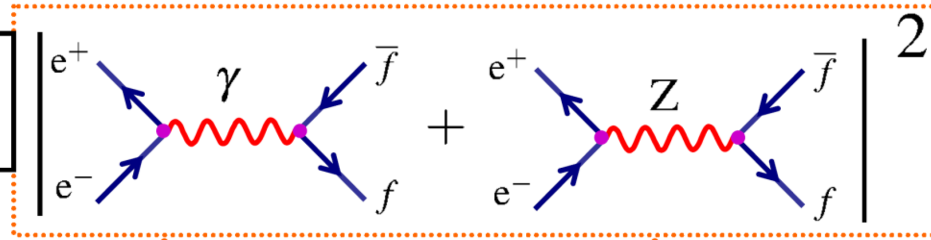
★ 1989-1995: Electron-Positron collisions at $\sqrt{s}$ = 91.2 GeV
- 17 Million Z bosons detected

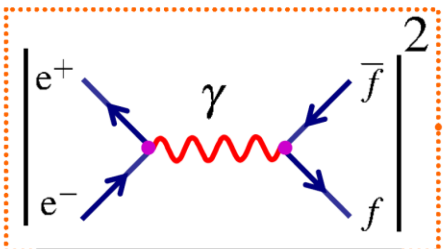
★ 1996-2000: Electron-Positron collisions at $\sqrt{s}$ = 161-208 GeV
- 30000 W^+W^- events detected

ELECTRON-POSITRON ANNIHILATION

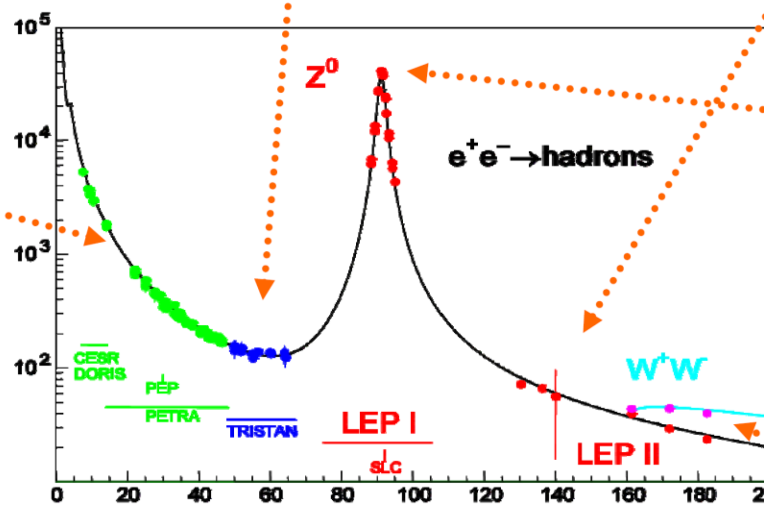
e^+e^- Annihilation in Feynman Diagrams

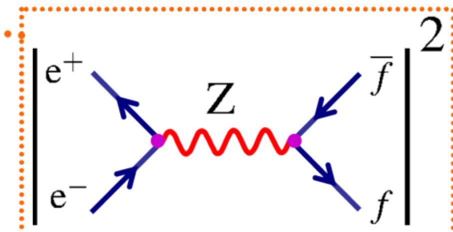
In general e^+e^- annihilation involves both photon and Z exchange : + interference





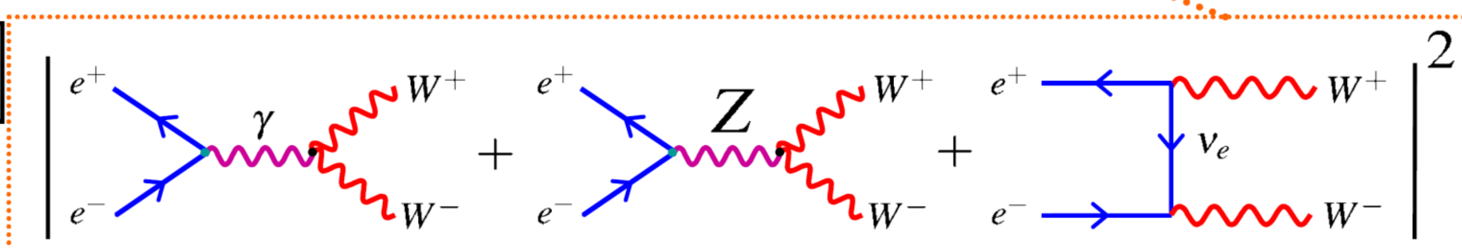
Well below Z: photon exchange dominant





At Z resonance: Z exchange dominant

High energies: WW production



PRECISELY MEASURED

Basic set: α_{em}, G_F, M_Z

↕

fantastic exp. accuracy:

- $(g-2)_e$
- τ_μ
- Z line shape

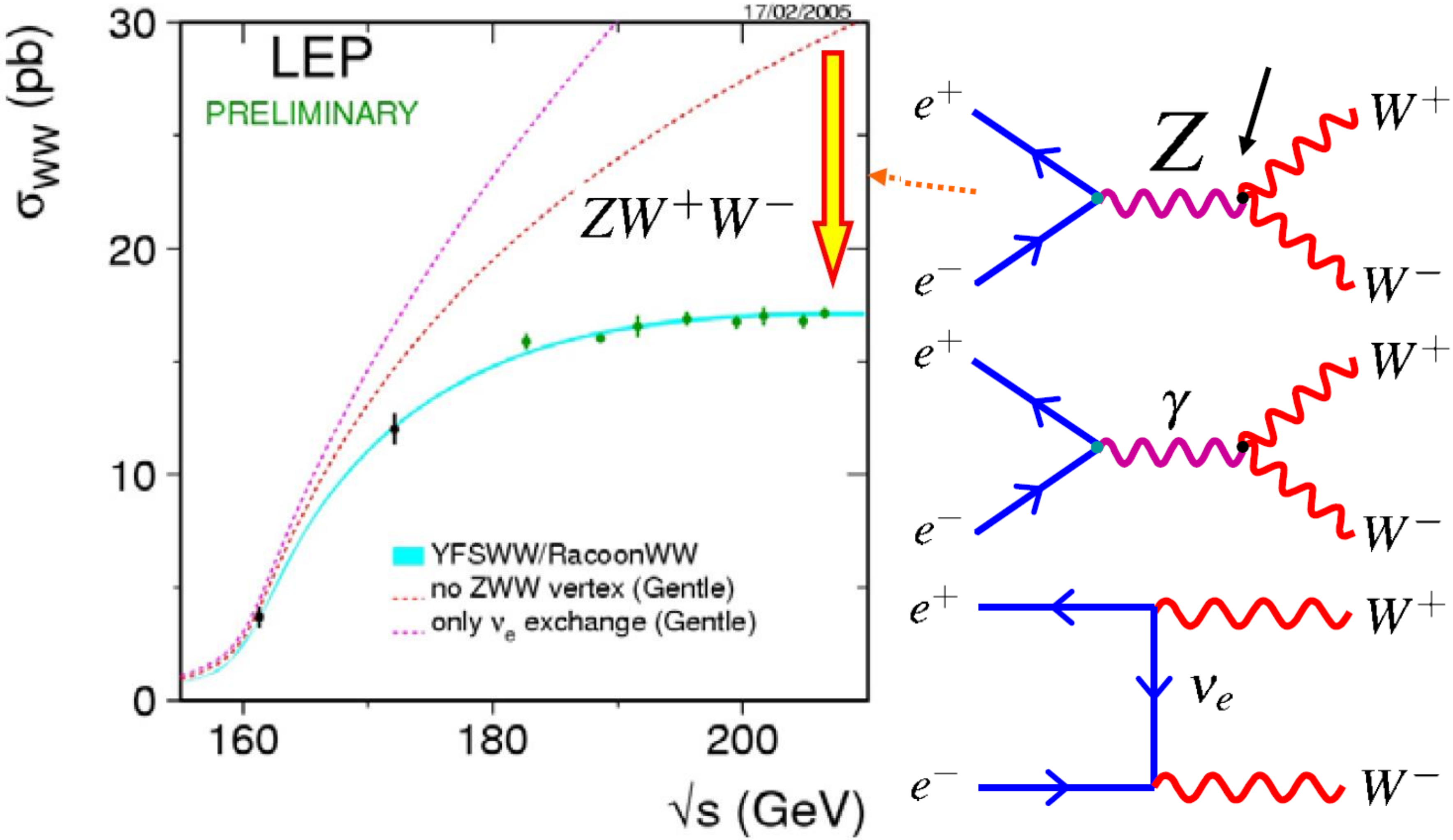
g, g', v

$$\alpha^{-1} = 137.035\,999\,710 \pm 0.000\,000\,096$$

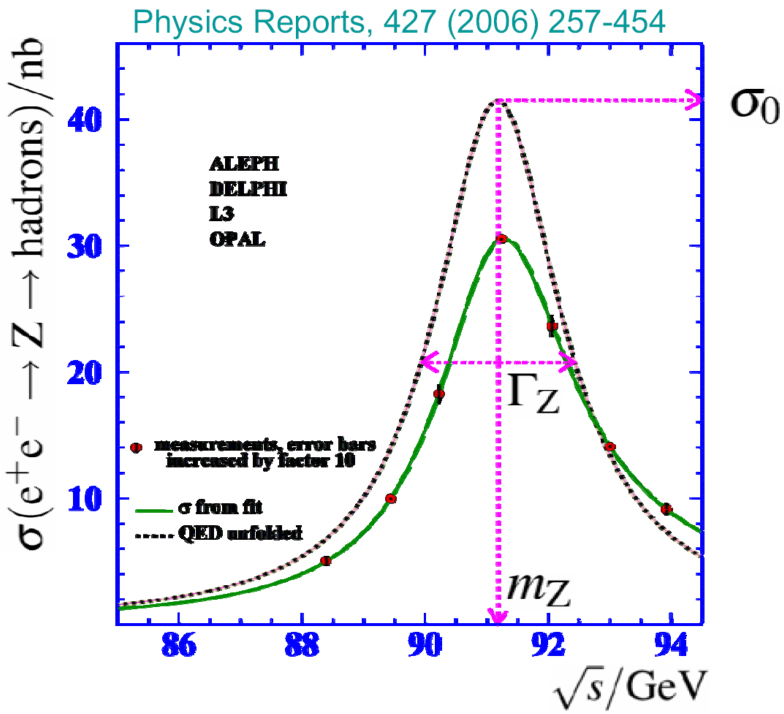
$$G_F = (1.166\,371 \pm 0.000\,006) \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$

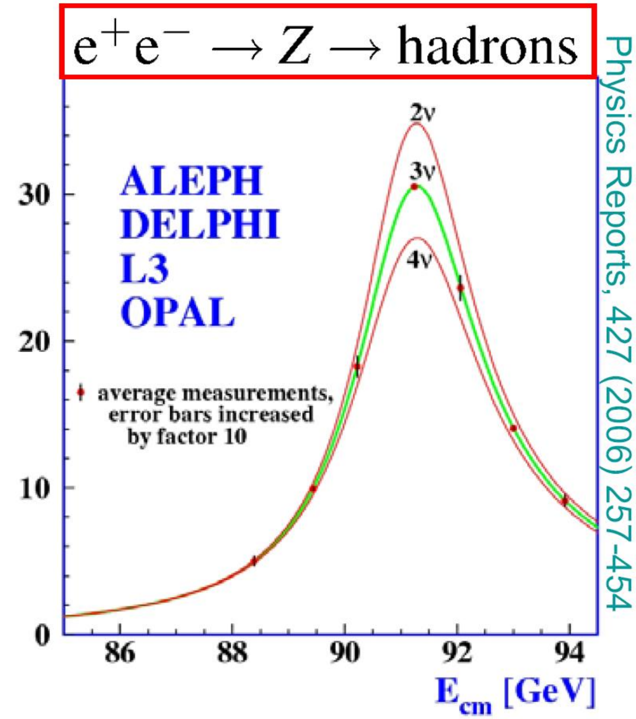
$$M_Z = (91.1875 \pm 0.0021)\ \mathrm{GeV}$$

DIRECT ZWW-VERTEX TEST



REZONANCE SHAPE
& NEUTRINO NUMBER





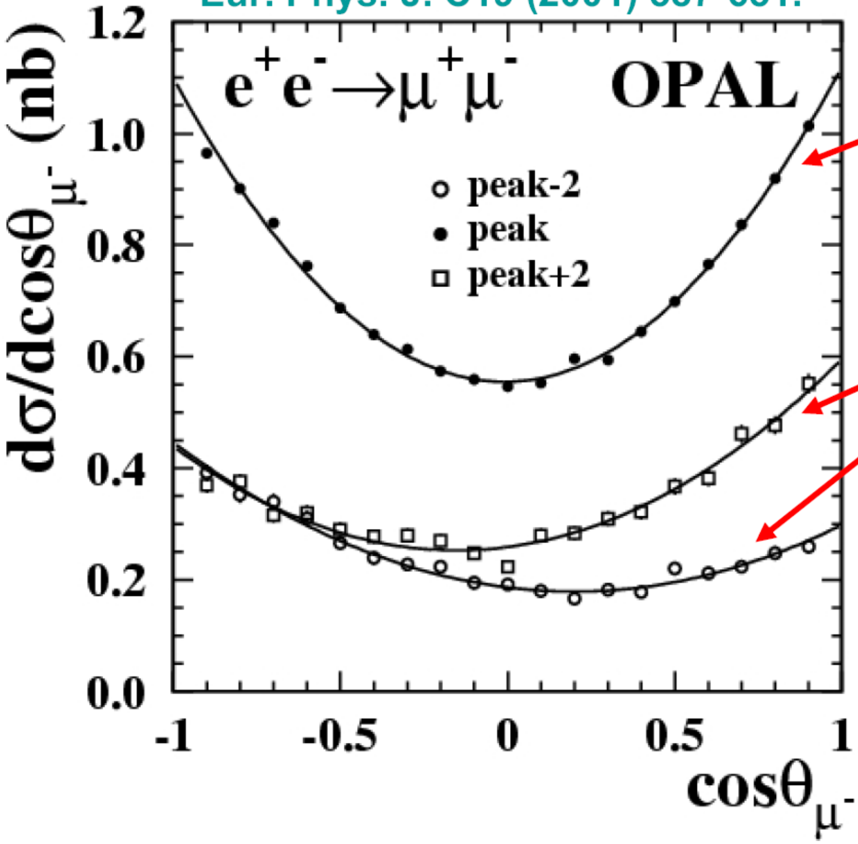
$$m_Z = 91.1875 \pm 0.0021\,\text{GeV}$$

$$N_\nu = 2.9840 \pm 0.0082$$

$$\Gamma_Z = 2.4952 \pm 0.0023\,\text{GeV}$$

MEASUREMENT OF F-B ASYMMETRY on Z-resonance & interferency with γ

OPAL Collaboration,
Eur. Phys. J. C19 (2001) 587-651.



$$e^+e^- \to Z \to \mu^+\mu^-$$

$$e^+e^- \to \gamma \to \mu^+\mu^-$$

★ **LEP data combined:**

$$A_{FB}^{0,e} = 0.0145 \pm 0.0025$$

$$A_{FB}^{0,\mu} = 0.0169 \pm 0.0013$$

$$A_{FB}^{0,\tau} = 0.0188 \pm 0.0017$$

MEASUREMENTS of F-B ASYMMETRIES determine the weak-mixing angle:

- **LEP MEASURES**
- **SLC MEASURES**

$$\left.\begin{aligned} A_{FB}^{0,f} &= \tfrac{3}{4} A_e A_f \\ A_{LR} &= A_e \end{aligned}\right\} \quad A_e, A_\mu, A_\tau, \ldots$$

$$A_e = 0.1514 \pm 0.0019$$
$$A_\mu = 0.1456 \pm 0.0091$$
$$A_\tau = 0.1449 \pm 0.0040$$

$$A_f \equiv \frac{2 c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2} = 2 \frac{c_V / c_A}{1 + (c_V / c_A)^2}$$

$$\frac{c_V}{c_A} = \frac{I_W^3 - 2Q \sin^2\theta_W}{I_W^3} = 1 - 4|Q| \sin^2\theta_W$$

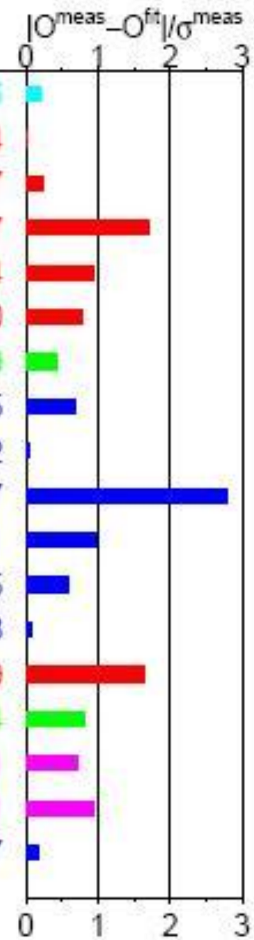
$$\sin^2\theta_W = 0.23154 \pm 0.00016$$

Global fit to EW precision data

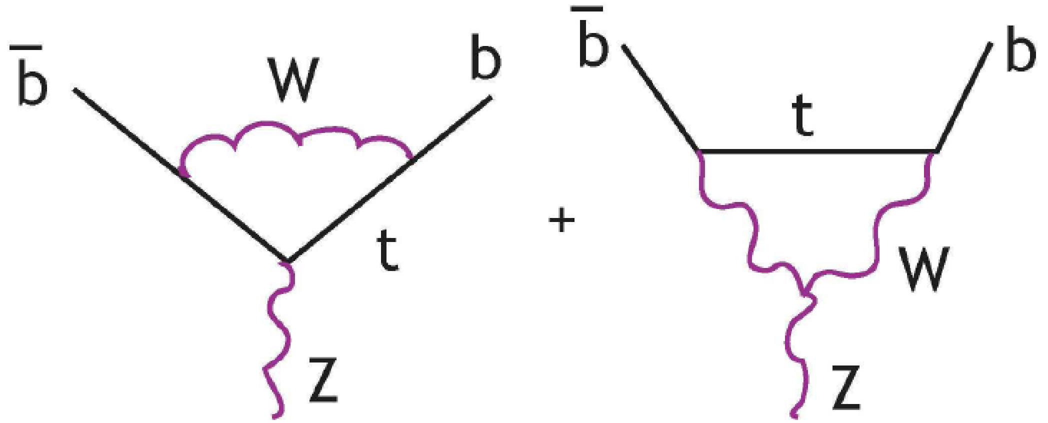
$\chi^2/dof=17.8/13$ (16.6%)

Largest pull is from LEP b-quark forward/backward asymmetry.

	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



There is a special consideration for the b quark. The diagrams



contribute a correction to the b_L Z charge,

$$Q_{ZbL} = -(\frac{1}{2} - \frac{1}{3}s_w^2 - \frac{\alpha}{16\pi s_w^2}\frac{m_t^2}{m_W^2})$$

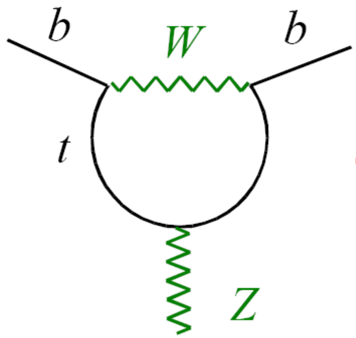
This is a -2% correction to the partial width. It is easier to measure the quantity

$$R_b = \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{ hadrons})}$$

which is almost independent of s_w^2 and so directly tests the above correction.

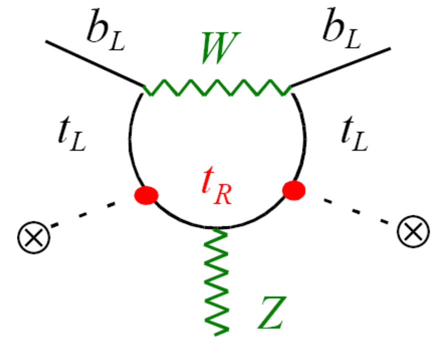
E.g.:

$$R_b = \frac{\Gamma(Z \to bb)}{\Gamma(Z \to \text{had})}$$



leading m_t dep.

driven by



$$R_b = R_0 \,[\, 1 - G_F\, m_t^2 / 2\pi^2\sqrt{2} \; + \ldots \,] \approx 0.2182 - 0.0024$$

$$\sim \frac{g^2\, y_t^2 \langle \phi^+ \phi \rangle Z_\mu b_L \gamma^\mu b_L}{M^2_W}$$

tree−level

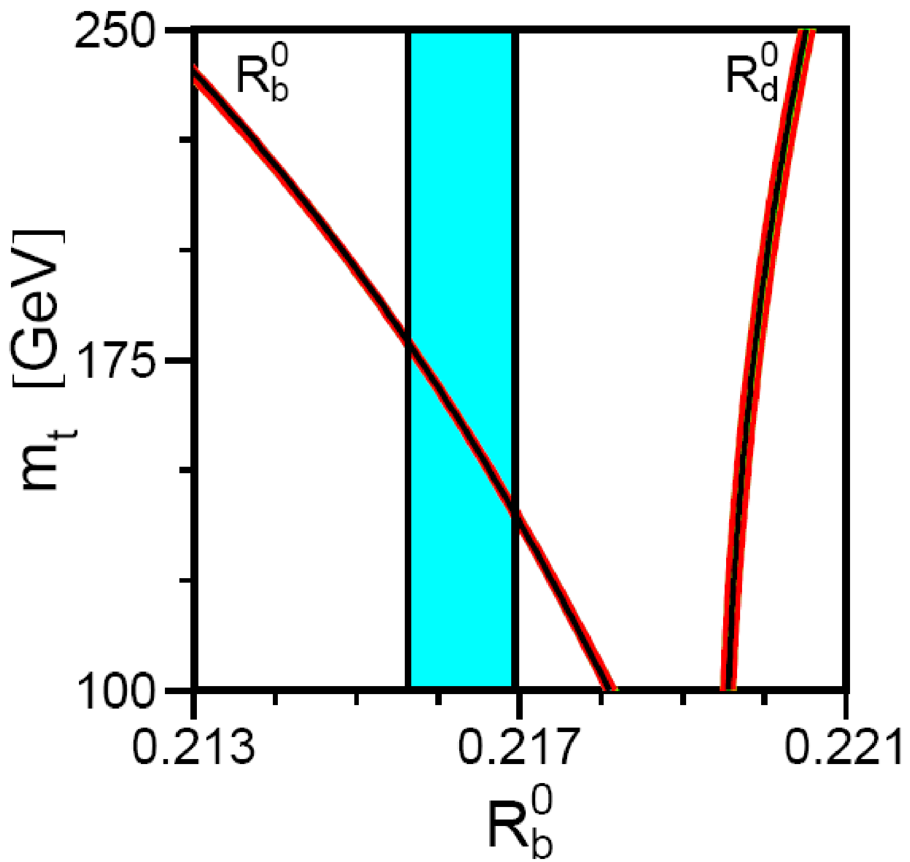
+ flavour−universal corrections

The final result is:

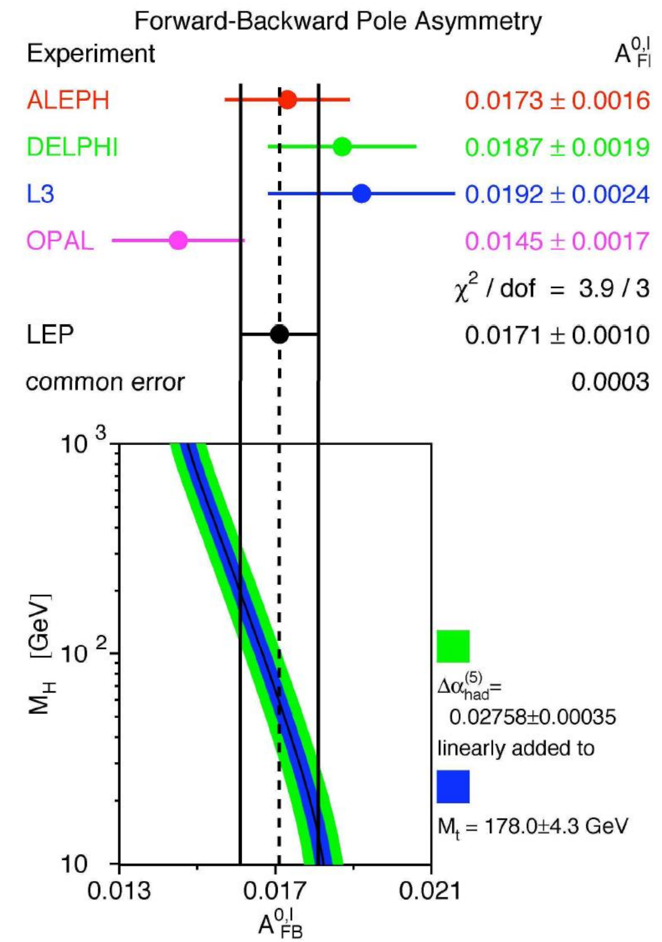
$$R_b = 0.21643 \pm 0.00073$$

in excellent agreement with the Standard Model and confirming the -2% shift due to the t-W diagrams.

Top mass from Rb measurement (LEP,SLD)

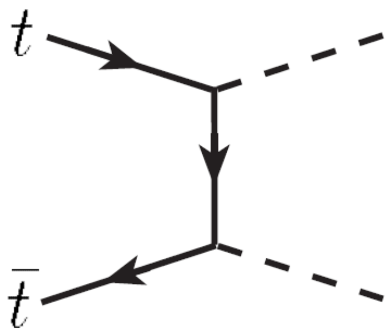


Higgs mass from asymmetry measurement

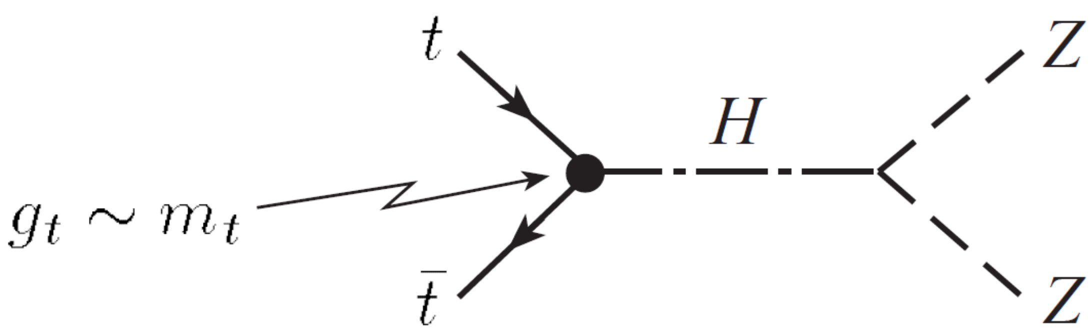


Higgs needed to avoid unitarity violation in top quark annihilation into Z's

$$\frac{d\sigma}{d\Omega}\left[\vphantom{\int}\right.$$



$$\left.+\ \text{crossed diagram}\right] = \frac{\alpha^2 m_t^2}{m_Z^4}$$

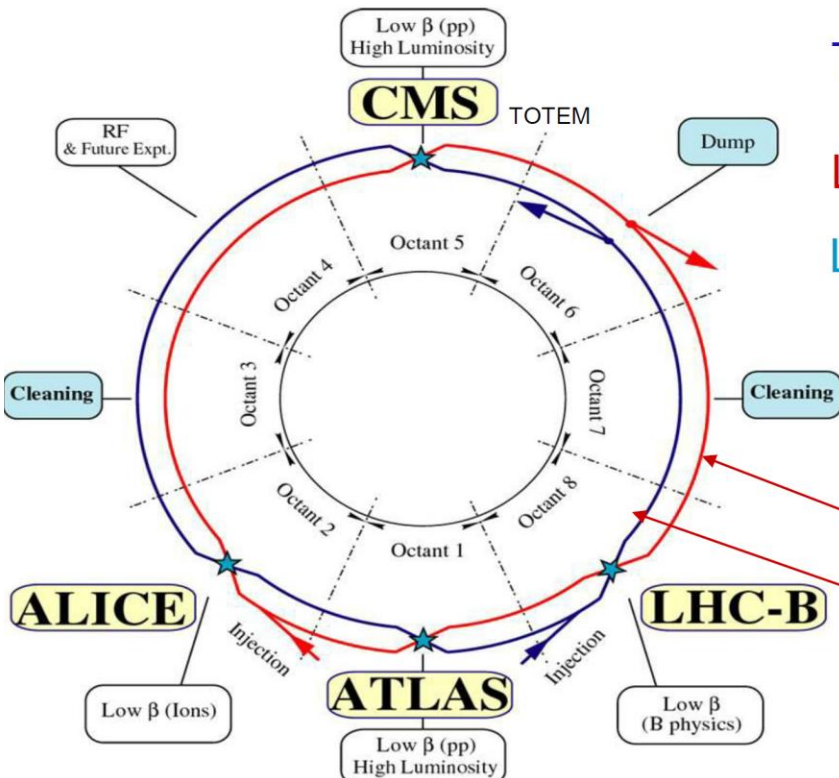


$$\sim \frac{g_t^2}{m_Z^4}$$

2nd EW MILESTONE – Higgs @ LHC

Series of CMS & LHC Days in Split

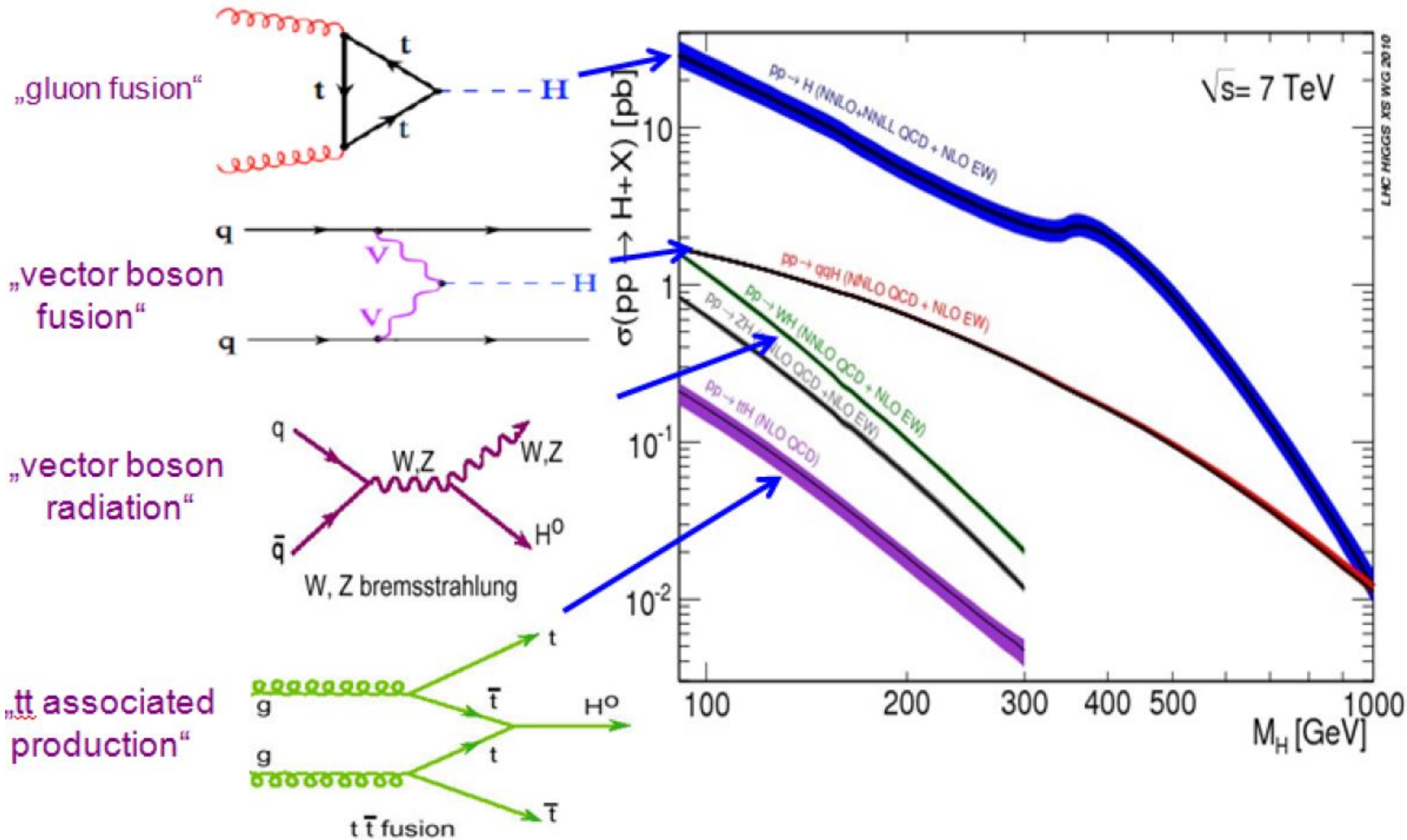
~ 65% of the 27 km long circumference covered with 1232 2-in-1 superconducting dipoles of 14.3m length operated at 1.9 °K giving a field of B = 8.3T , 500 2-in-1 quadrupoles with 215T/m, altogether 1200 tons of superconducting cable and 40.000 tons of material at 1.9 °K superfluid He temperature!.



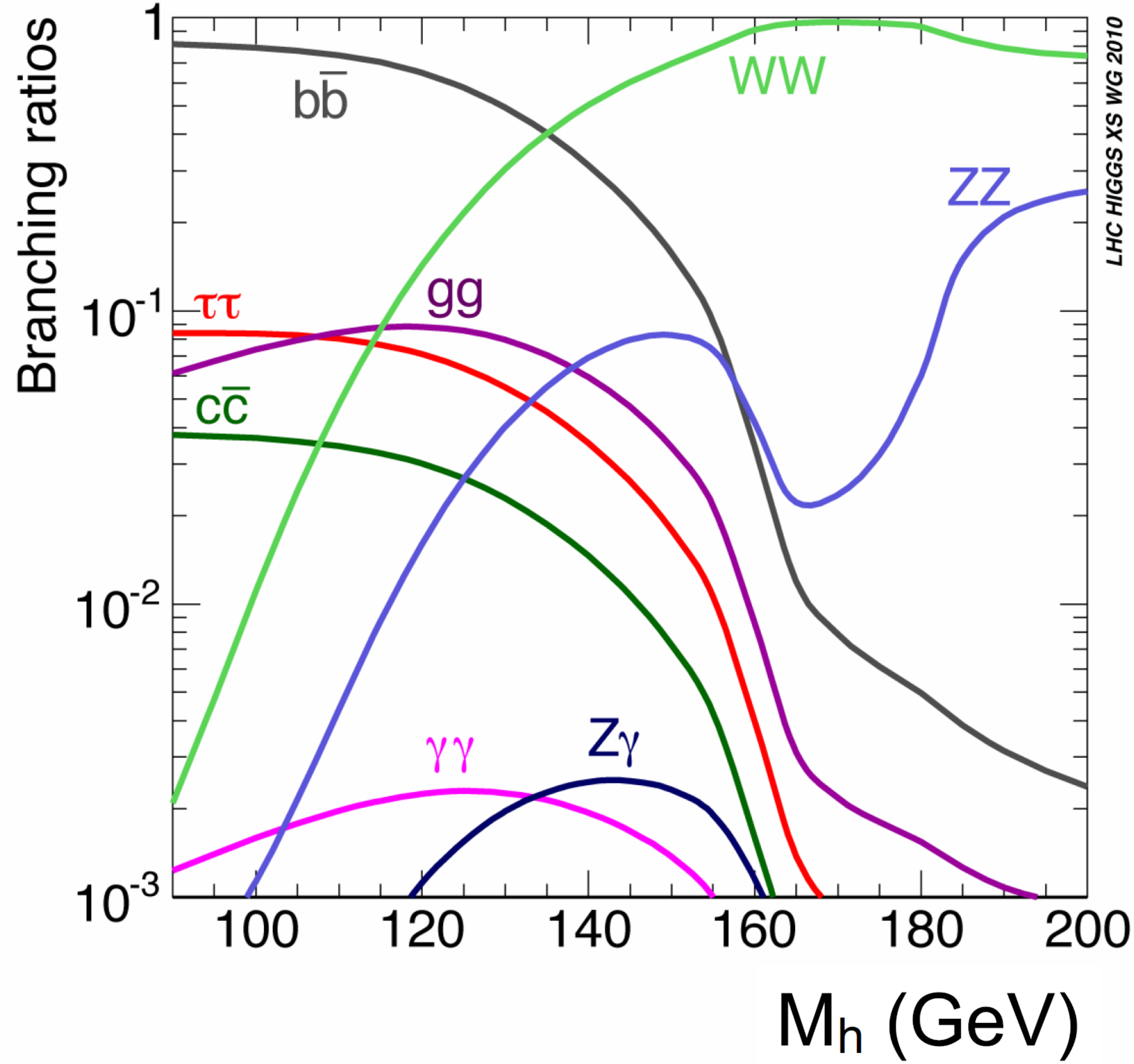
Tevatron	p-p	2.000 GeV	$3*10^{32}$ cm^{-2} s^{-1}
LHC	pp	14.000 GeV	10^{34} cm^{-2} s^{-1}
LHC in 2010/2011	pp	7.000 GeV	$\sim10^{32}$ cm^{-2} s^{-1}

p = ReB

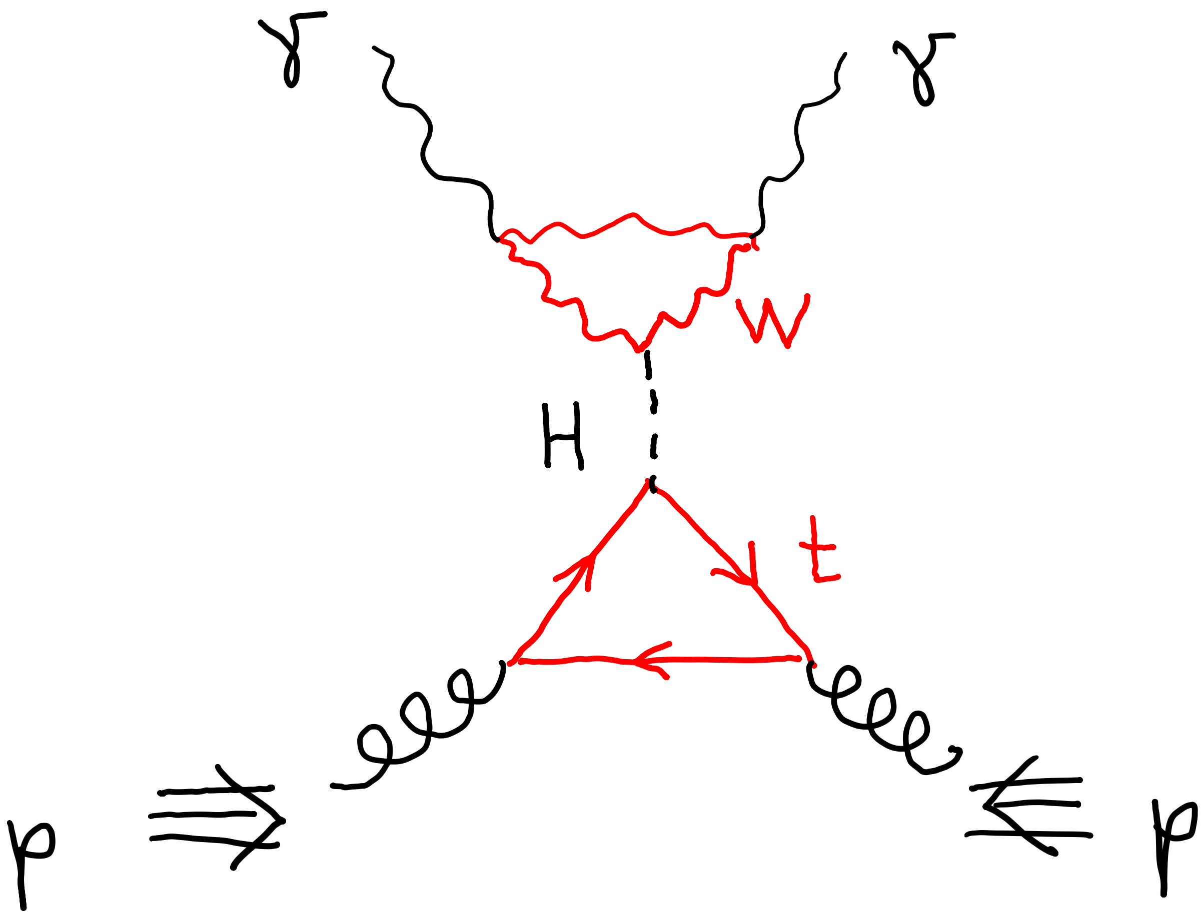
Higgs production @ LHC



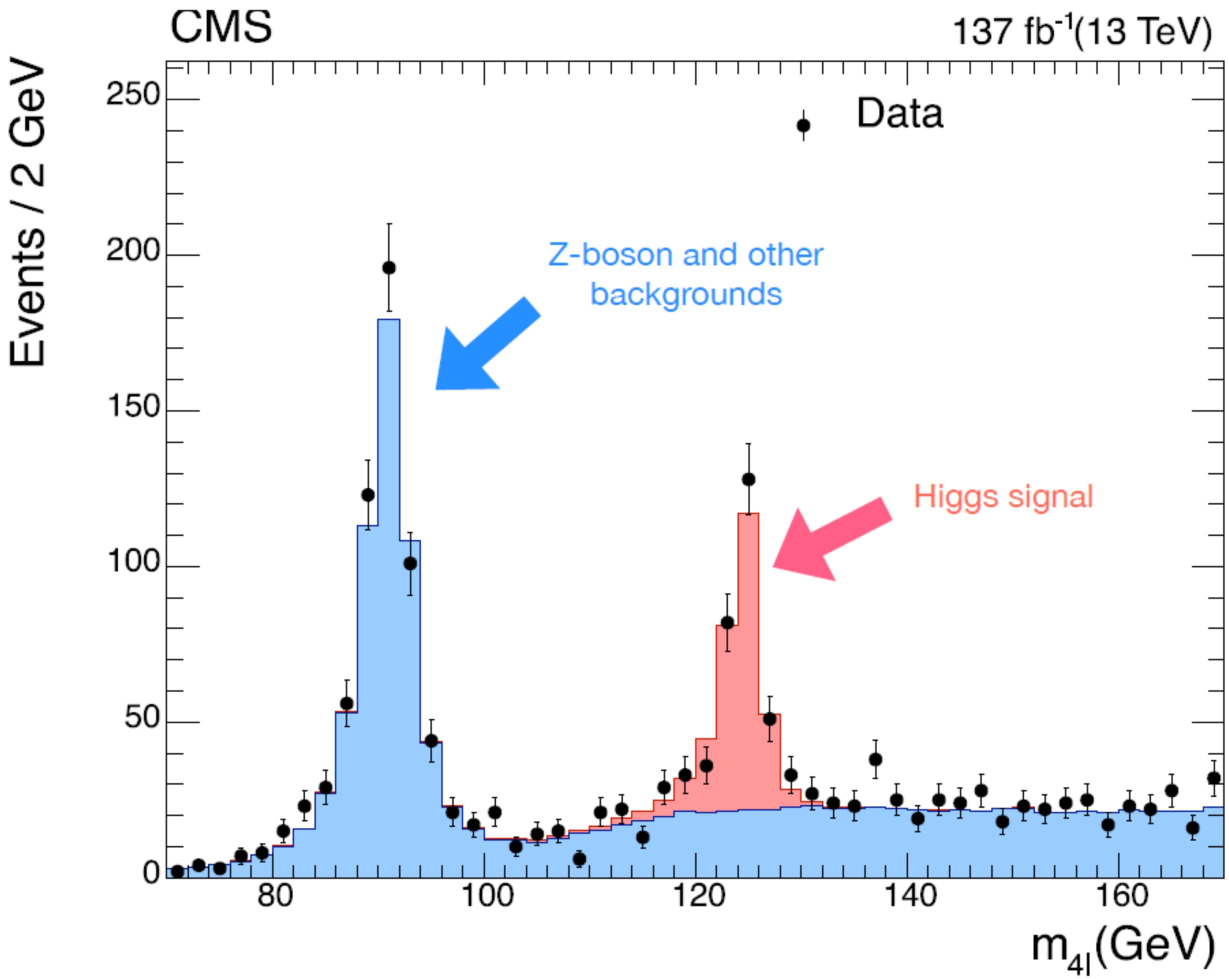
Decay modes of SM Higgs



Virtual physcs @ LHC: a rare two-photon decay



CM energy of 4-leptons - 91.2 and 125 GeV peaks



Higgs-boson discovery
opens new questions:

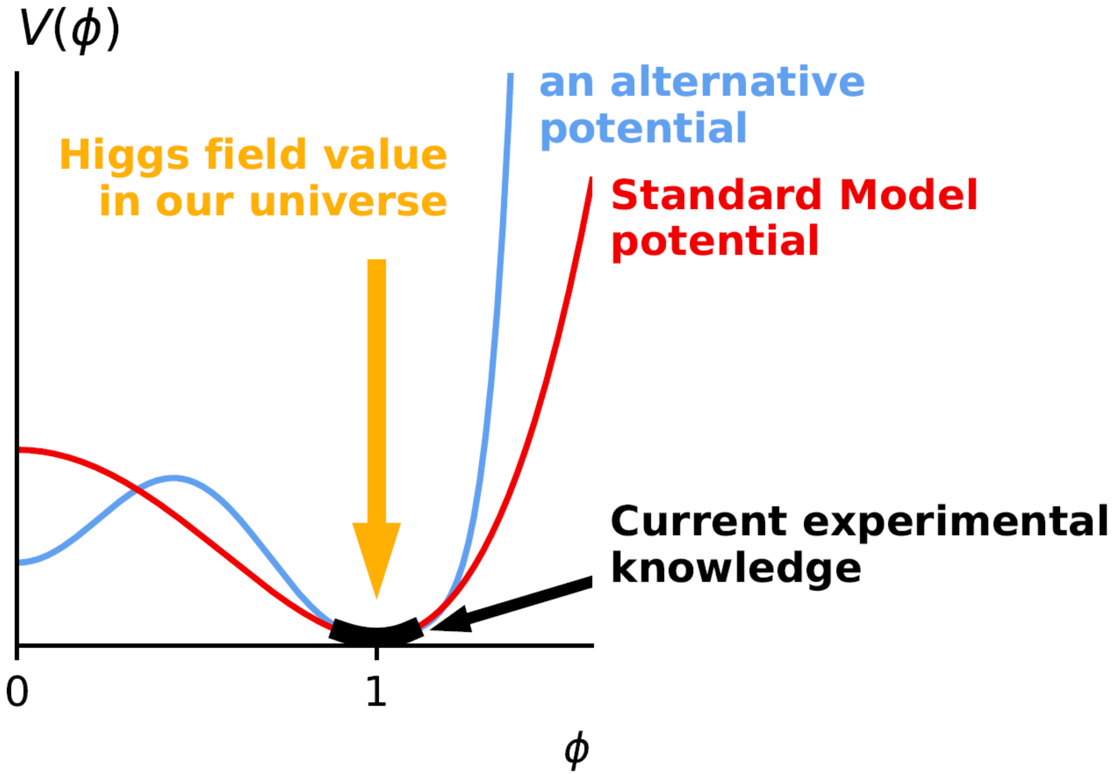
- Huge disparity among SM fermion masses
- Lightness of neutrinos
- ctuning in the Higgs potential:

$$V = \text{const.} + m_H^2 |H|^2 + \lambda |H|^4$$

- Cosmological constant problem
- Higgs naturalness problem
- Vacuum stability problem

What happened at the EW phase transition in the early universe – smooth crossover or 1st order PT?

Depends on Higgs self-interaction, to be probed at a future collider!



THEORETICAL PROBLEMS

Still, the SM Higgs potential is "ugly" and hides the most serious *theoretical problems* of this highly successful theory:

$$V(\phi) = - \mu^2 \phi^+\phi + \lambda (\phi^+\phi)^2 + Y^{ij} \psi_L^{\,i} \psi_R^{\,j} \phi$$

vacuum instability

possible <u>internal inconsistency</u> of the model ($\lambda < 0$) at large energies

[*key dependence on* m_h]

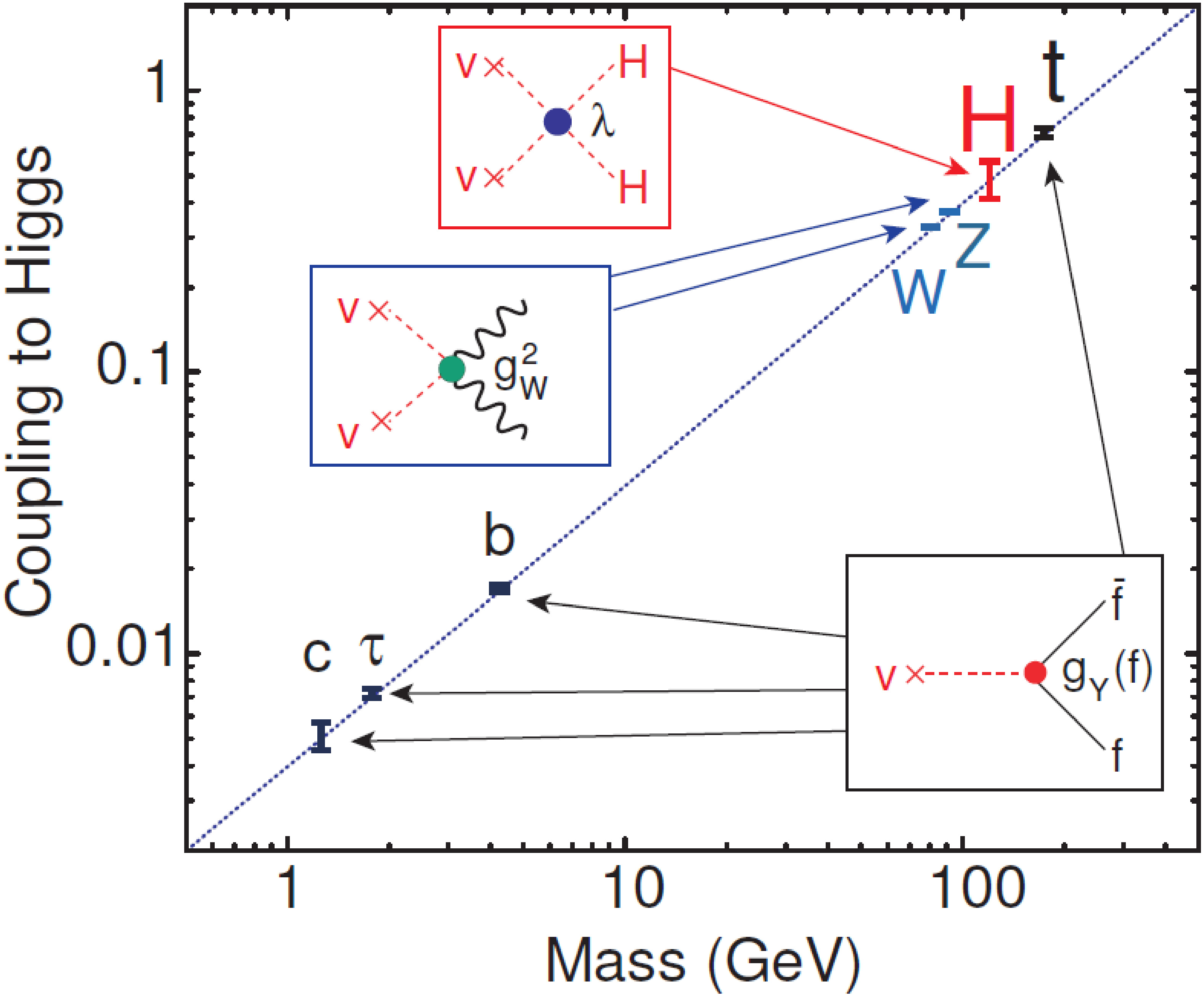
Quadratic sensitivity to the cut-off

$\Delta\mu^2 \sim \Delta m_h^2 \sim \Lambda^2$

(indication of *new physics* close to the electroweak scale ?)

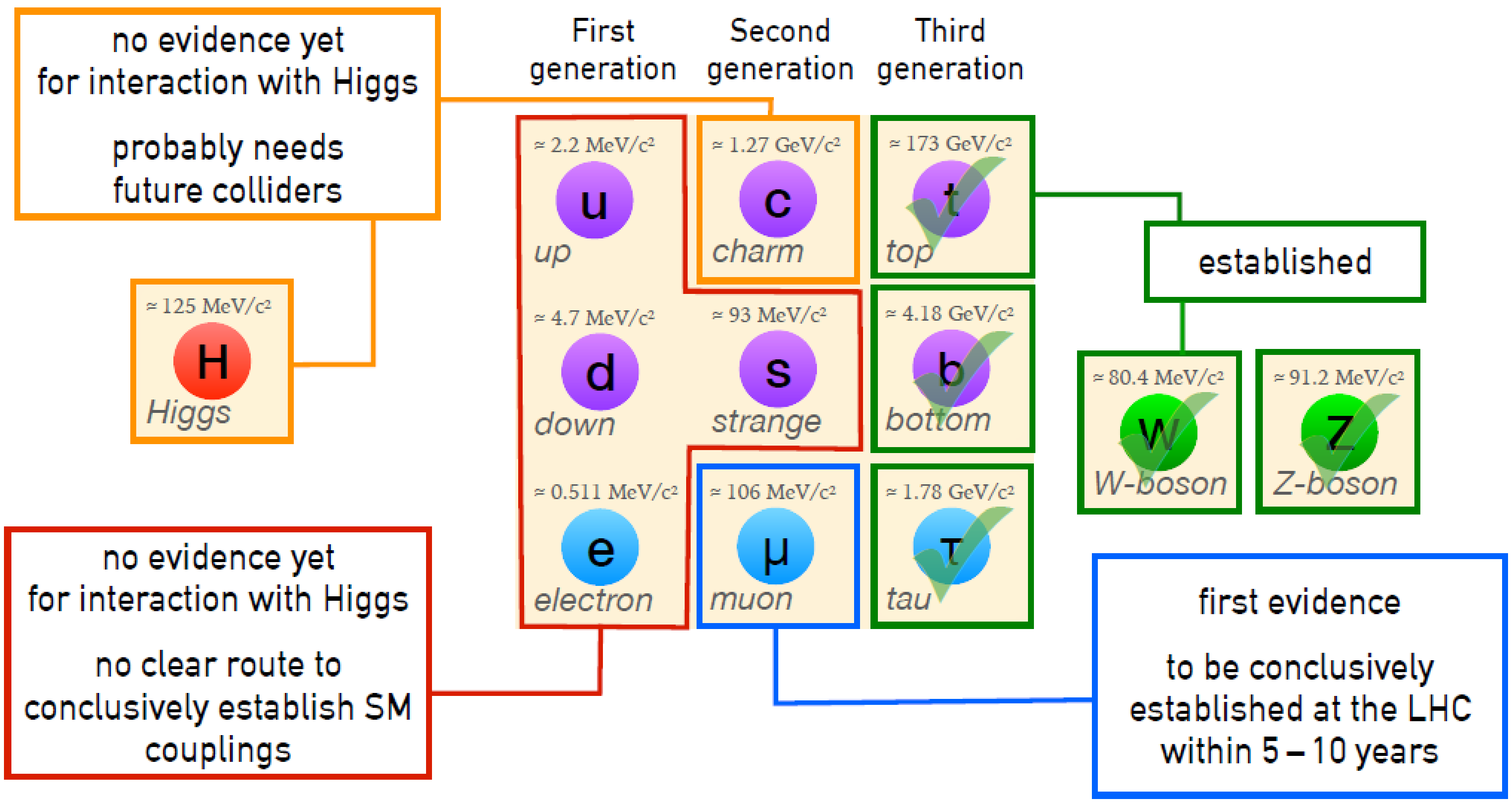
SM flavour problem

(unexplained span over 5 orders of magnitude and strongly hierarchical structure of the Yukawa coupl.)

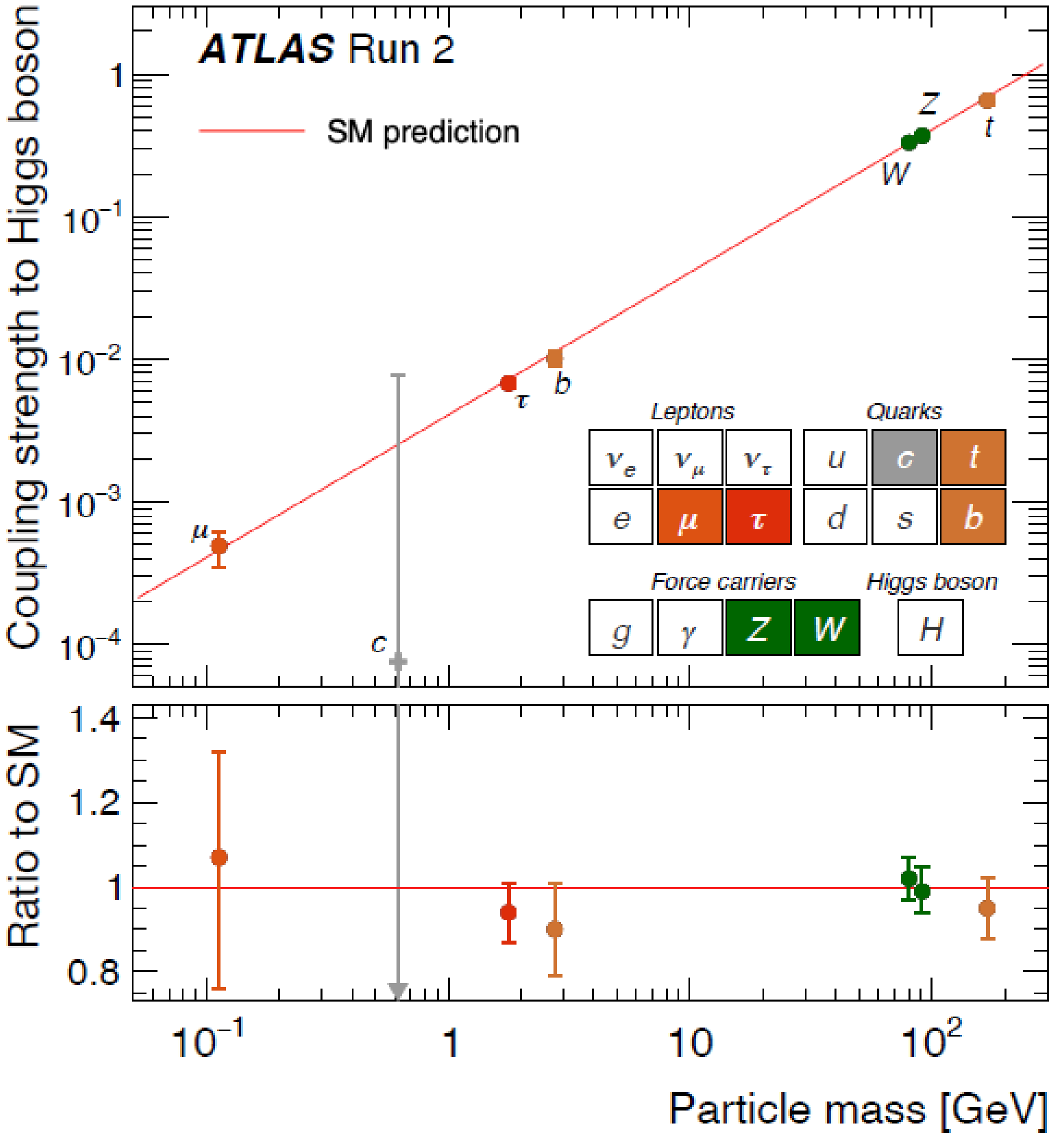


Coupling to Higgs
Mass (GeV)
1
0.1
0.01
1
10
100
v
H
λ
g$_W^2$
g$_Y$(f)
f̄
f
H
t
W
Z
b
c
τ

Summary of known Higgs interactions



Higgs interaction strength vs particle mass



Conclusion

- Higgs discovery reveals:
  - Spin-zero particle
  - SSB mechanism that makes W & Z massive,
  - and confirmes that it gives masses to 3rd generation fermions;
- Return of Yukawa force not deduced from a symmetry principle;
- Naturalness of light Higgs:

either new particles are keeping it light,
or the universe is fine tuned
for our existence

T \ S	0	$\frac{1}{2}$	1	$\frac{3}{2}$	2
0	?	q_R, l_R $\nu_R(?)$	Gluon	??	??
$\frac{1}{2}$	Higgs	Q_L, L_L	?	??	??
1	?	?	W, Z	??	??