

# (2) Weak interactions and Electroweak unification



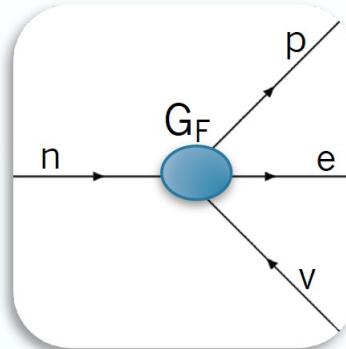
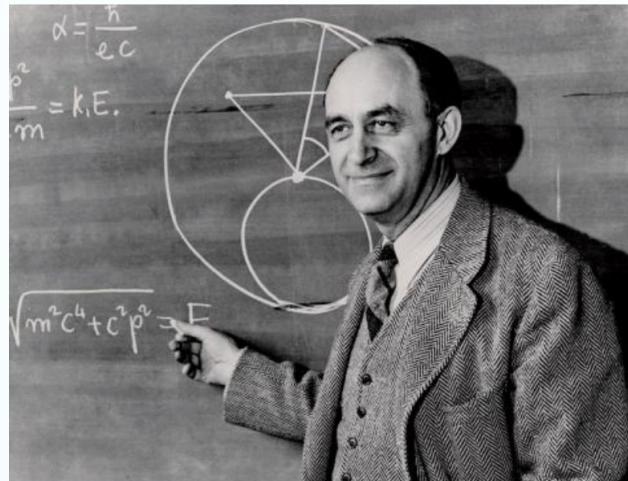
Chien-Shiun Wu

*... it was unthinkable that anyone would question the validity of symmetries under space inversion, charge conjugation and time reversal. It would have been almost sacrilegious to do experiments to test such unholy thoughts*

*Chien-Shiun Wu: discovered parity violation in weak interactions*

# Fermi Theory

Fermi theory of weak interaction, 1933: Effective Field Theory

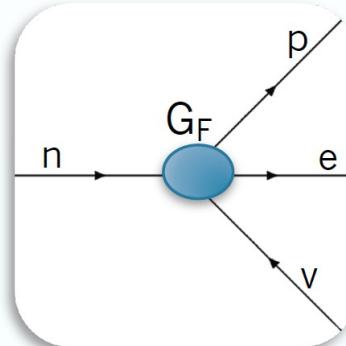
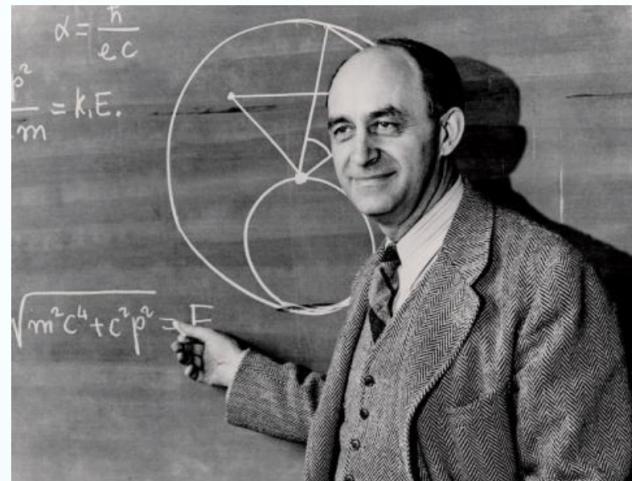


$\beta$  decay of the neutron

$$G_F = 1.17 \times 10^{-5} \text{ GeV}^{-2}$$

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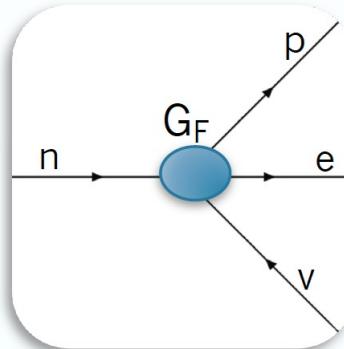
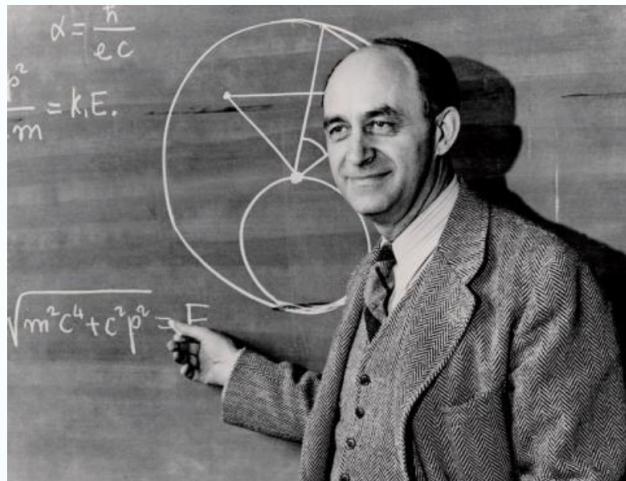


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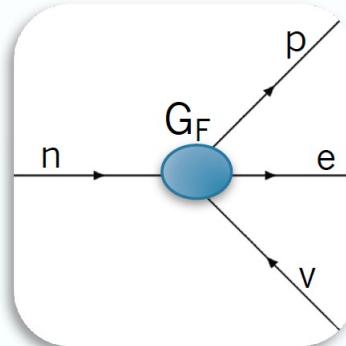
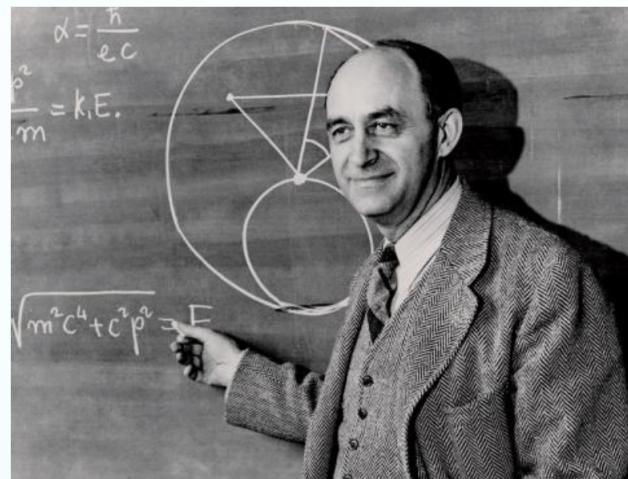
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Today's relation at low energies:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

# Contemporary theory

Contemporary Matrix element (low energy limit): **W boson**

$$\mathcal{M} = \left[ \frac{g_w}{\sqrt{2}} \bar{u}(u) \gamma^\mu \frac{1}{2} (1 - \gamma^5) u(d) \right] \frac{1}{M_W^2 - q^2} \left[ \frac{g_w}{\sqrt{2}} \bar{u}(\nu_e) \gamma_\mu \frac{1}{2} (1 - \gamma^5) u(e) \right]$$

Projection to  
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$M_W \sim 80$  GeV

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Chien-Shiun Wu

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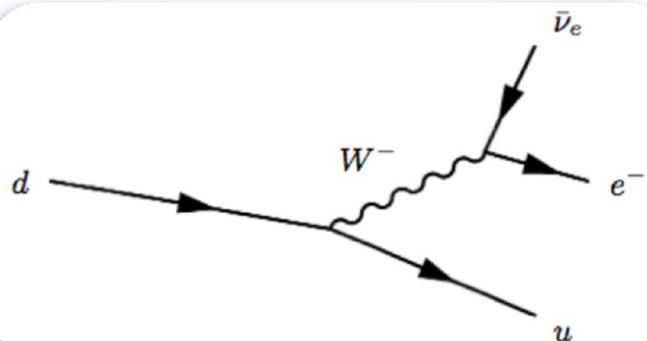
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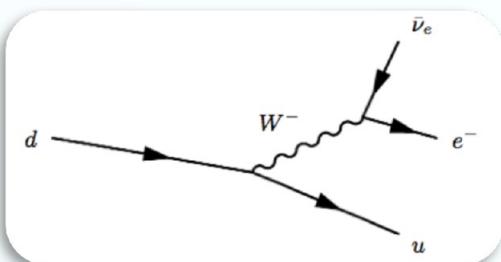
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The W couples with **pairs of  
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Chien-Shiun Wu

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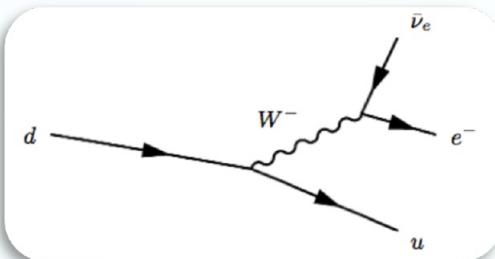
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Nicola  
Cabibbo

**CKM matrix:**  
connection between  
weak and mass  
eigen states

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$



Toshihide  
Maskawa



Makoto  
Kobayashi

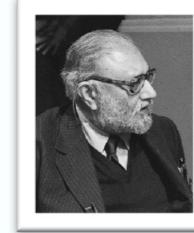
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Require the Dirac Lagrangian to be invariant under a local  $SU(2)_L \times U(1)_Y$  transformation.

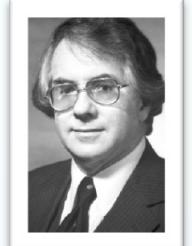
$$\mathcal{L}_{Dirac} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi$$



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Weinberg



Abdus  
Salam



Sheldon.  
Glashow

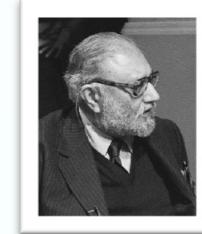
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$SU(2)_L$ : only transforms left-handed fermion-doublets  
generators of  $SU(2)$  are the Pauli matrices:

$$T_i = \frac{1}{2}\sigma_i$$

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

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$$SU(2) \ni U = \exp(i\alpha_i \sigma_i)$$

# Electroweak unification

→ New covariant derivative  $D_\mu$ : one gauge field per generator: 3 W fields, 1 B field

$$L : D_\mu = \partial_\mu + ig_w \frac{\sigma_i}{2} W_\mu^i + ig \frac{Y}{2} B_\mu$$
$$\psi_R, \psi'_R : D_\mu = \partial_\mu + ig \frac{Y}{2} B_\mu$$

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$$\left( \begin{array}{c} \nu_e \\ e \end{array} \right)_L \quad \left( \begin{array}{c} \nu_\mu \\ \mu \end{array} \right)_L \quad \left( \begin{array}{c} \nu_\tau \\ \tau \end{array} \right)_L \quad \left( \begin{array}{c} u \\ d' \end{array} \right)_L \quad \left( \begin{array}{c} c \\ s' \end{array} \right)_L \quad \left( \begin{array}{c} t \\ b' \end{array} \right)_L$$

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Physical fields are linear combinations of the original gauge fields:

$$W_\mu^\pm = \frac{1}{\sqrt{2}} [W_\mu^1 \mp iW_\mu^2]$$
$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_w & \sin \theta_w \\ -\sin \theta_w & \cos \theta_w \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}$$

$\theta_W$ : Weinberg angle

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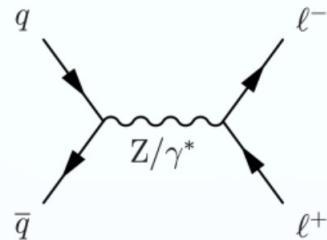
In order to obtain the QED current for  $A_\mu$ , the Weinberg angle needs to be:

$$\cos \theta_w = \frac{g_w}{\sqrt{g_w^2 + g^2}} \quad \sin \theta_w = \frac{g}{\sqrt{g_w^2 + g^2}}$$

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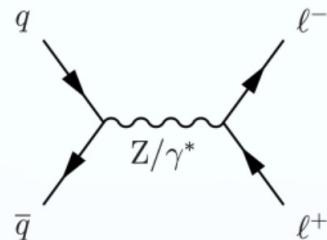


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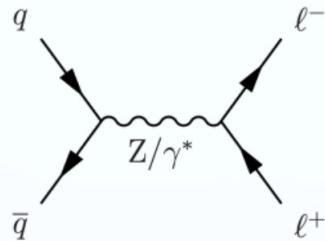
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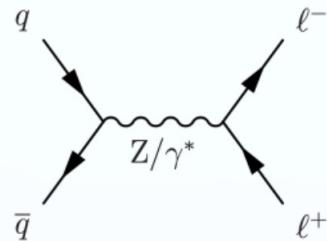
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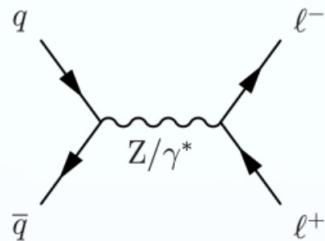
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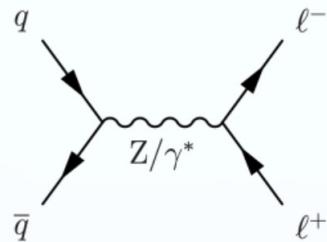
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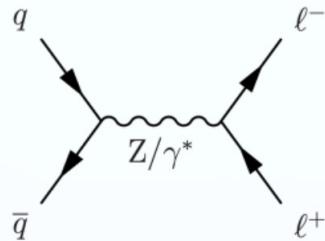
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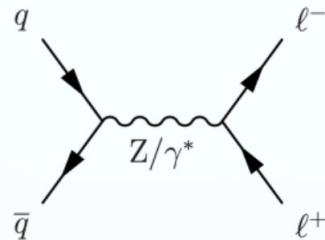
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$$c_V(e, \mu, \tau) = -0.04 \text{ and } c_A(e, \mu, \tau) = -0.5$$

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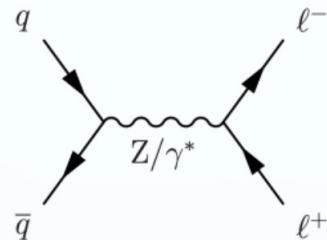
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Couplings are averages for right and left handed fermions

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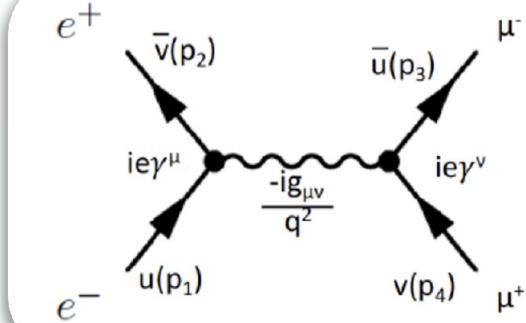
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Different couplings for right/left handed fermions

$$c_V = c_L + c_R \quad c_A = c_L - c_R$$

# Electroweak unification

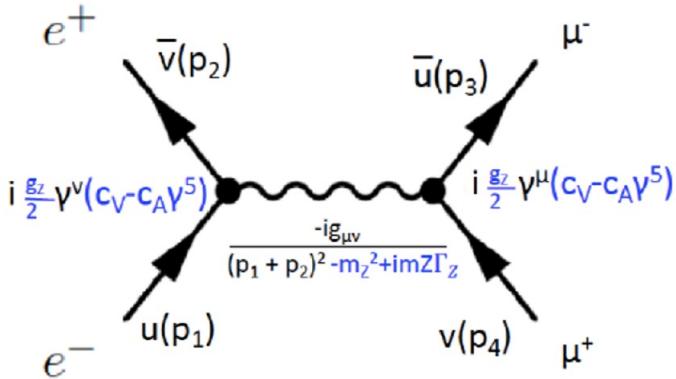
reminder:  $e^+e^- \rightarrow \gamma \rightarrow \mu^+\mu^-$ :



$$\mathcal{M} = \frac{-e^2}{(p_1 + p_2)^2} [\bar{u}(p_3)\gamma^\mu v(p_4)][\bar{v}(p_2)\gamma_\mu u(p_1)]$$

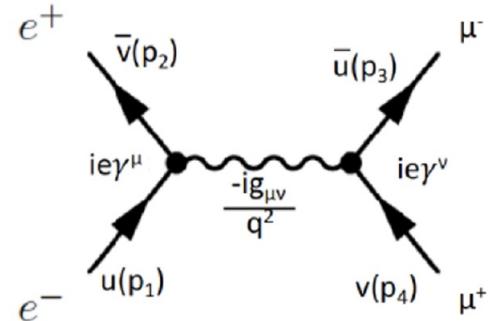
# Electroweak unification

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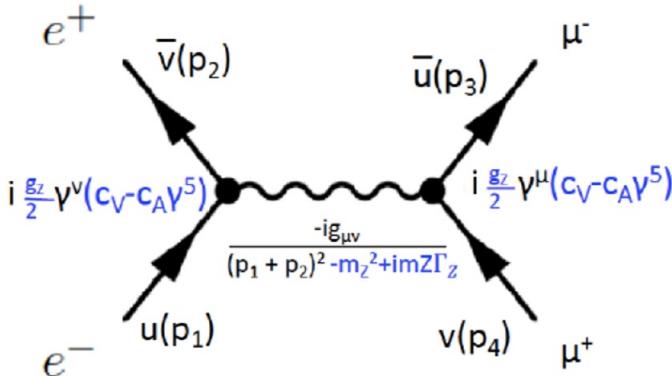
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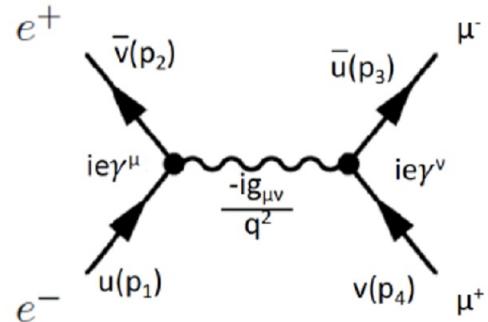
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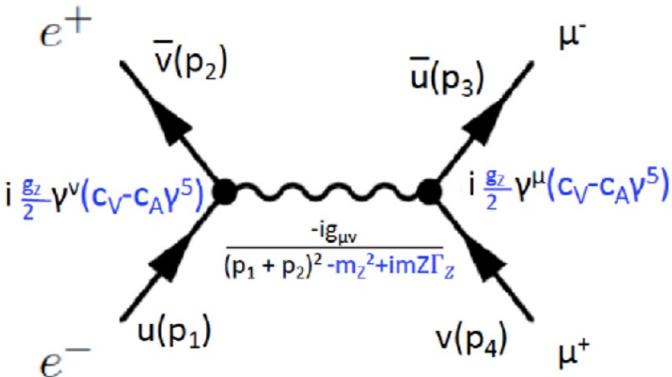
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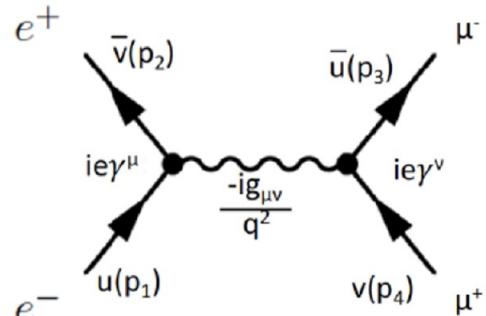
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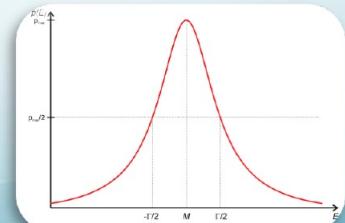
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Breit-Wigner Resonanz

$$\rightarrow \sigma(e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-) = \frac{12\pi s}{m_Z^2} \frac{\Gamma_{e^+e^-}\Gamma_{\mu^+\mu^-}}{(s - m_Z^2)^2 + m_Z^2\Gamma_Z^2}$$



# Electroweak unification

$$\sigma \sim \left| \begin{array}{c} e^- \\ \downarrow \\ e^+ \end{array} \right\rangle \left( \begin{array}{c} \text{wavy line} \\ \gamma \\ + \\ Z \end{array} \right) \left( \begin{array}{c} f \\ \downarrow \\ \bar{f} \end{array} \right) \left| \begin{array}{c} e^- \\ \downarrow \\ e^+ \end{array} \right\rangle \left( \begin{array}{c} \text{wavy line} \\ \gamma \\ + \\ Z \end{array} \right) \left( \begin{array}{c} f \\ \downarrow \\ \bar{f} \end{array} \right) \right|^2$$

Z- $\gamma$  interference

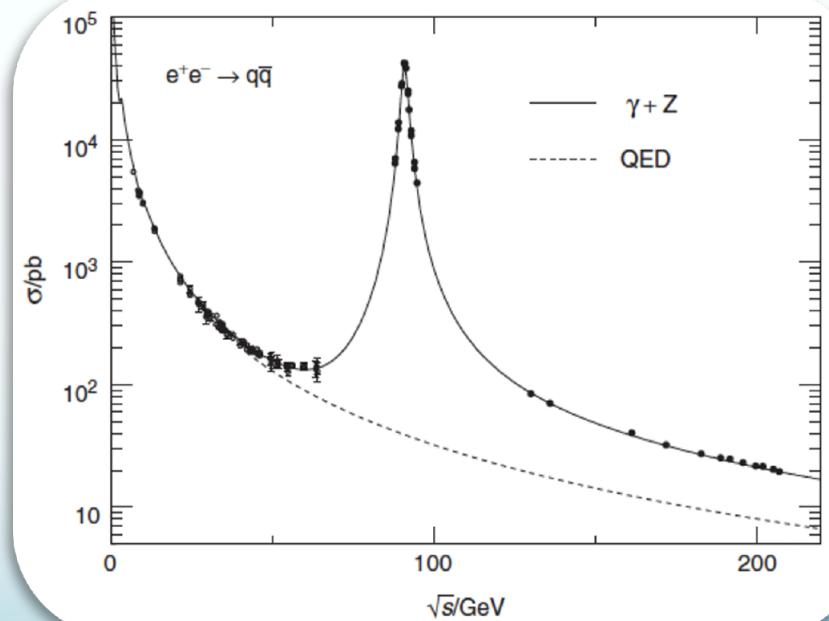
# Electroweak unification

$$\sigma \sim \left| \begin{array}{c} e^- \\ | \\ \text{---} \\ e^+ \end{array} \right\rangle \left( \begin{array}{c} \gamma \\ | \\ \text{---} \\ f \end{array} \right) + \left( \begin{array}{c} e^- \\ | \\ \text{---} \\ e^+ \end{array} \right) \left( \begin{array}{c} Z \\ | \\ \text{---} \\ f \end{array} \right) \right|^2$$

Z- $\gamma$  interference

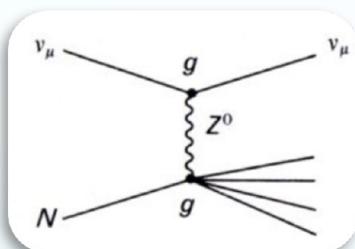
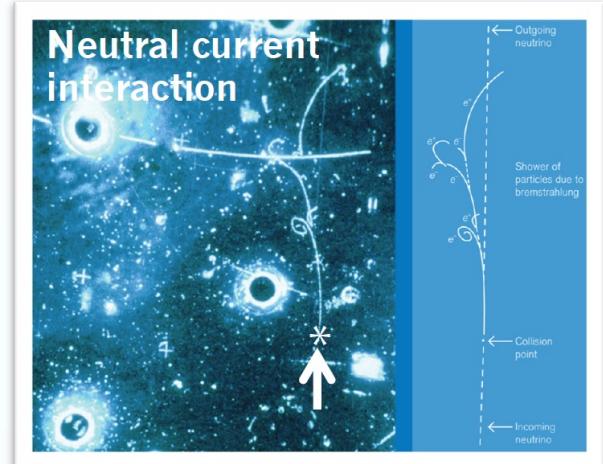
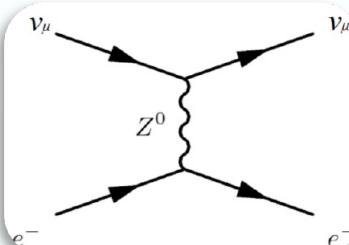
For small energies ( $\sqrt{s} < 50$  GeV), the photon (QED) contribution dominates.

Around the Z mass ( $\sqrt{s} \sim 91$  GeV), the Z contribution dominates.



# Experimental milestones

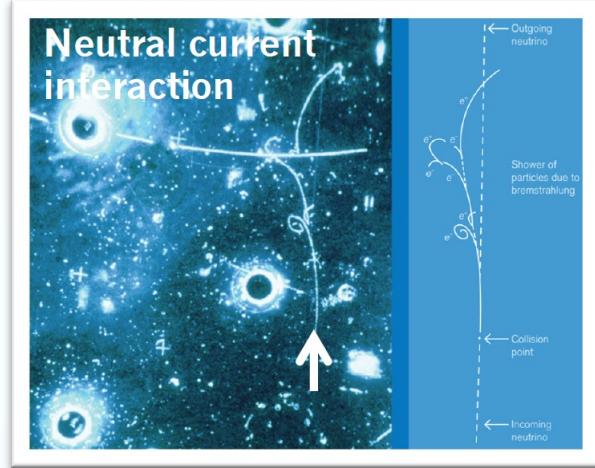
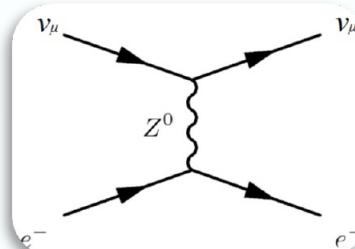
- 1972: Gargamelle: discovery of neutral currents



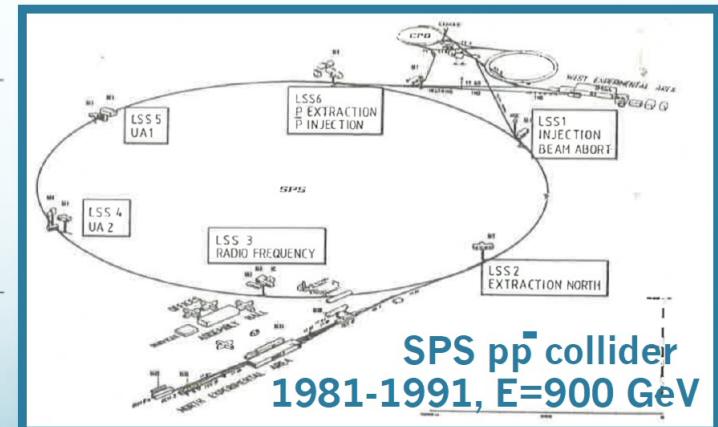
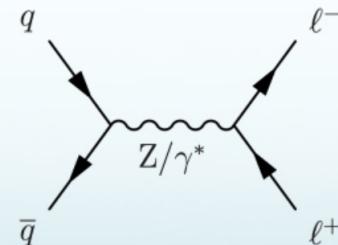
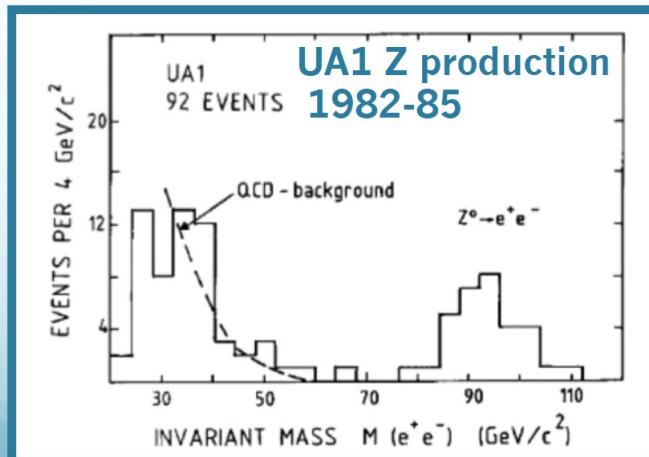
The Neutral Current was not part of Gargamelle's core program  
... but they reacted fast to new challenge

# Experimental milestones

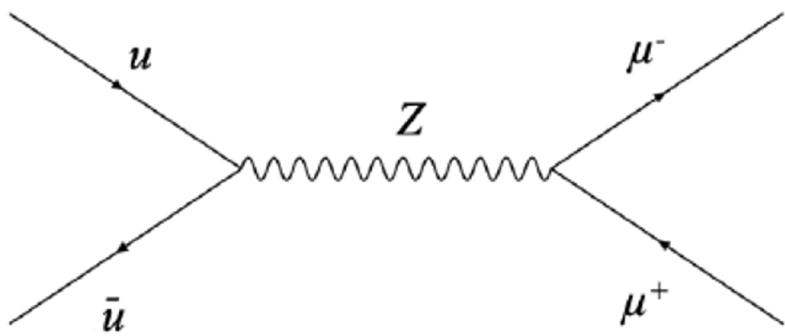
- 1972: Gargamelle: discovery of neutral currents



- 1984: UA1/UA2: observation of W and Z bosons

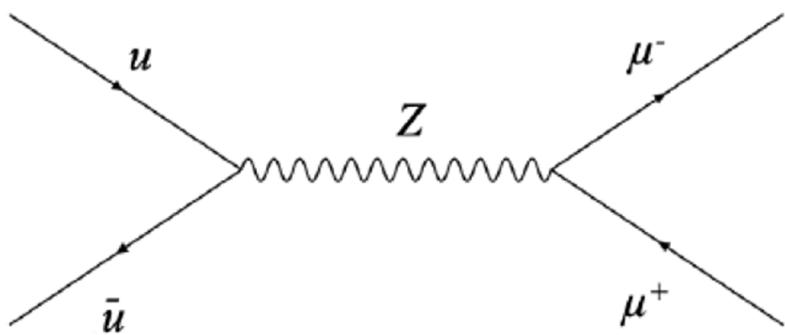


# Z production at hadron colliders



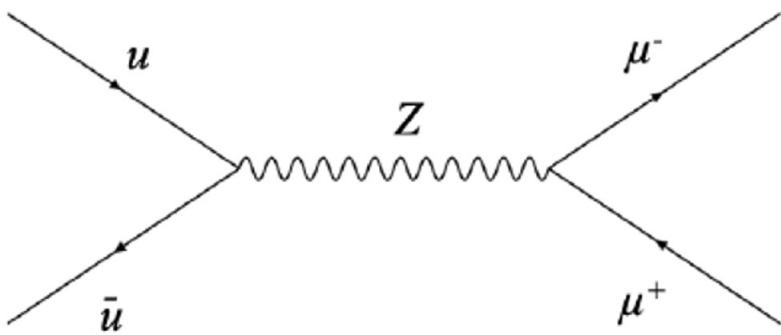
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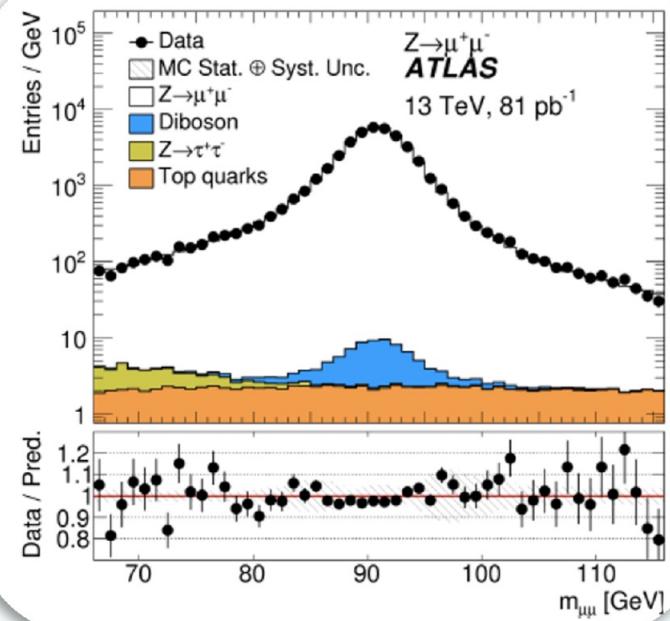


- ▶ At hadron colliders the  $Z$  boson can be produced via the Drell-Yan Process, e.g.  $u\bar{u} \rightarrow Z \rightarrow \mu^+\mu^-$
- ▶ As the quarks can carry a wide range of the proton energy fraction, we automatically scan the mass range

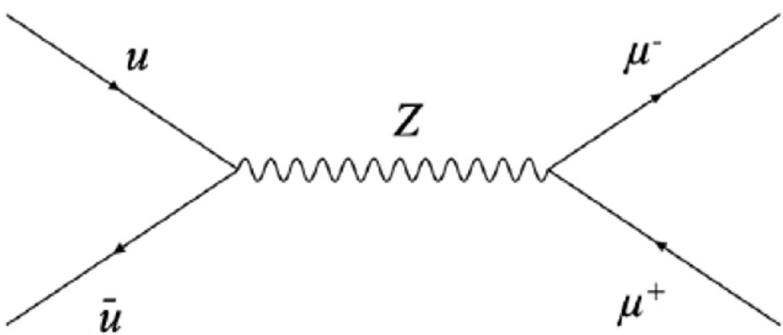
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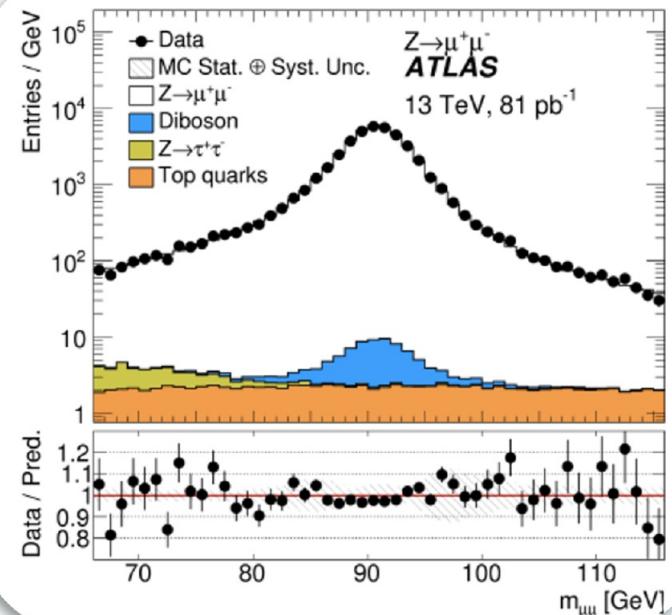
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- ▶ As the quarks can carry a wide range of the proton energy fraction, we automatically scan the mass range
- ▶ Similar to LEP, the cross section results from an interference between photon and  $Z$



# Electroweak gauge fields

→ Lagrangian of free gauge fields

$$\mathcal{L}_{gauge}^{EW} = -\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

with:

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

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$$\left[ \frac{\sigma_a}{2}, \frac{\sigma_b}{2} \right] = i \epsilon_{abc} \frac{\sigma_c}{2}$$

*W/Z bosons carry  
EM and/or weak charges*

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Leads to triple and quartic gauge boson couplings:

$$\begin{aligned} \mathcal{L}_{gauge}^{EW} = & -\frac{1}{4} [(W_{\mu\nu}^-)^\dagger W^{-\mu\nu} + (W_{\mu\nu}^+)^{\dagger} W^{+\mu\nu} + Z_{\mu\nu} Z^{\mu\nu} + A_{\mu\nu} A^{\mu\nu}] \\ & -ig_w [(\cos \theta_w Z^\mu + \sin \theta_w A^\mu)(W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) \\ & \quad + (\cos \theta_w Z_{\mu\nu} + \sin \theta_w A_{\mu\nu}) W^{+\mu} W^{-\nu}] \\ & -\frac{g_w^2}{2} [2 \cos^2 \theta_w (W_\mu^+ W^{-\mu} Z_\nu Z^\nu - W_\mu^+ W^{-\nu} Z_\nu Z^\mu) \\ & \quad + 2 \sin^2 \theta_w (W_\mu^+ W^{-\mu} A_\nu A^\nu - W_\mu^+ W^{-\nu} A_\nu A^\mu) \\ & \quad + 2 \cos \theta_w \sin \theta_w (2 W_\mu^+ W^{-\mu} Z_\nu A^\nu - W_\mu^+ W^{-\nu} Z_\nu A^\mu - W_\mu^+ W^{-\nu} A_\nu Z^\mu) \\ & \quad - W_\mu^+ W^{+\mu} W_\nu^- W^{-\nu} + W_\mu^+ W^{-\mu} W_\nu^- W^{+\nu}] \end{aligned}$$

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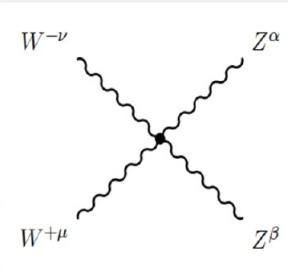
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quartic gauge boson coupling



$$\left[ \frac{\sigma_a}{2}, \frac{\sigma_b}{2} \right] = i \epsilon_{abc} \frac{\sigma_c}{2}$$

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→ Lagrangian of free gauge fields

$$\mathcal{L}_{gauge}^{EW} = -\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu}$$

with:

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

$$F_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a - g_w \epsilon_{abc} W_\mu^b W_\nu^c$$

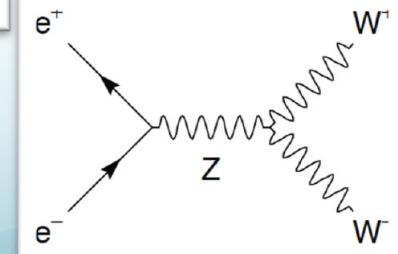
Leads to triple and quartic gauge boson couplings:

$$\begin{aligned} \mathcal{L}_{gauge}^{EW} = & -\frac{1}{4} [(W_{\mu\nu}^-)^\dagger W^{-\mu\nu} + (W_{\mu\nu}^+)^{\dagger} W^{+\mu\nu} + Z_{\mu\nu} Z^{\mu\nu} + A_{\mu\nu} A^{\mu\nu}] \\ & -ig_w [(\cos \theta_w Z^\mu + \sin \theta_w A^\mu)(W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu}) \\ & + (\cos \theta_w Z_{\mu\nu} + \sin \theta_w A_{\mu\nu}) W^{+\mu} W^{-\nu}] \\ & -\frac{g_w^2}{2} [2 \cos^2 \theta_w (W_\mu^+ W^{-\mu} Z_\nu Z^\nu - W_\mu^+ W^{-\nu} Z_\nu Z^\mu) \\ & + 2 \sin^2 \theta_w (W_\mu^+ W^{-\mu} A_\nu A^\nu - W_\mu^+ W^{-\nu} A_\nu A^\mu) \\ & + 2 \cos \theta_w \sin \theta_w (2 W_\mu^+ W^{-\mu} Z_\nu A^\nu - W_\mu^+ W^{-\nu} Z_\nu A^\mu - W_\mu^+ W^{-\nu} A_\nu Z^\mu) \\ & - W_\mu^+ W^{+\mu} W_\nu^- W^{-\nu} + W_\mu^+ W^{-\mu} W_\nu^- W^{+\nu}] \end{aligned}$$

$$\left[ \frac{\sigma_a}{2}, \frac{\sigma_b}{2} \right] = i \epsilon_{abc} \frac{\sigma_c}{2}$$

*W/Z bosons carry  
EM and/or weak charges*

triple gauge boson coupling



# Electroweak gauge fields

→ Lagrangian of free gauge fields

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with:

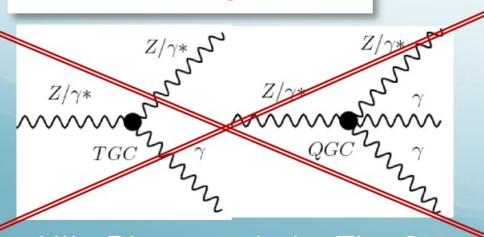
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No vertex with  
3 or 4  $Z/\gamma$

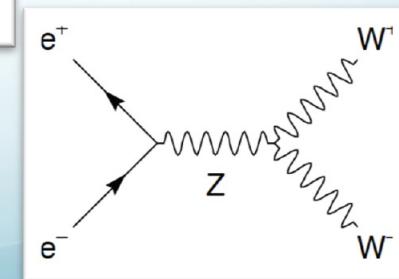
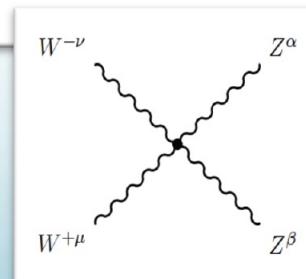


Ulla Blumenschein, The Standard Model, Hasco summer school

$\left[ \frac{\sigma_a}{2}, \frac{\sigma_b}{2} \right] = i \epsilon_{abc} \frac{\sigma_c}{2}$

*W/Z bosons carry EM and/or weak charges*

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# SM precision at LEPII

LEP2 (1996-2000): WW, ZZ,  $\gamma\gamma$

- ◆ W leptonic and hadronic BF
- ◆ W mass and width
- ◆ Triple gauge couplings:WWZ, WW $\gamma$   
& anomalous TGC: ZZZ, ZZ $\gamma^*$

$$m_W = 80.376 \pm 0.033 \text{ GeV}$$

$$\Gamma_W = 2.195 \pm 0.083 \text{ GeV}$$

$$B(W \rightarrow \text{had}) = 67.41 \pm 0.27 \%$$

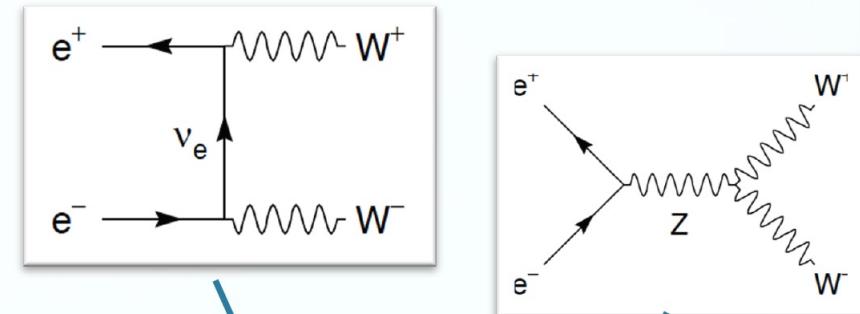
$$g_1^Z = 0.984^{+0.018}_{-0.020}$$

$$\kappa_\gamma = 0.982 \pm 0.042$$

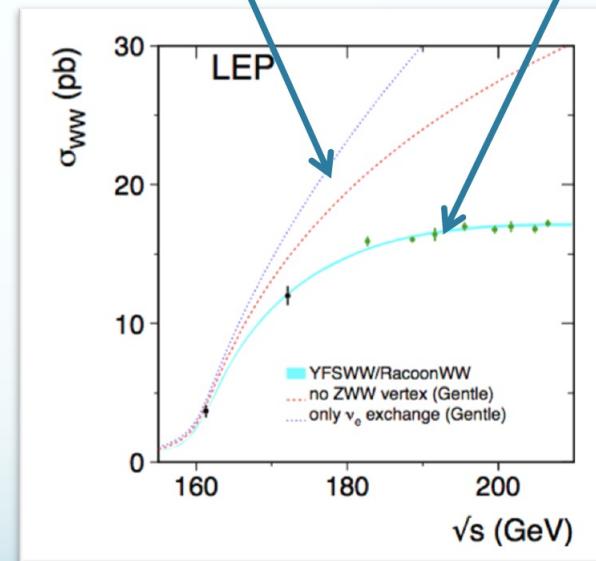
$$\lambda_\gamma = -0.022 \pm 0.019.$$

Phys.Rept.532,119-224, 2013

→ Precise measurement of  
W properties  
→ TGC as predicted in SM



WW cross section



# SM precision at LEPII

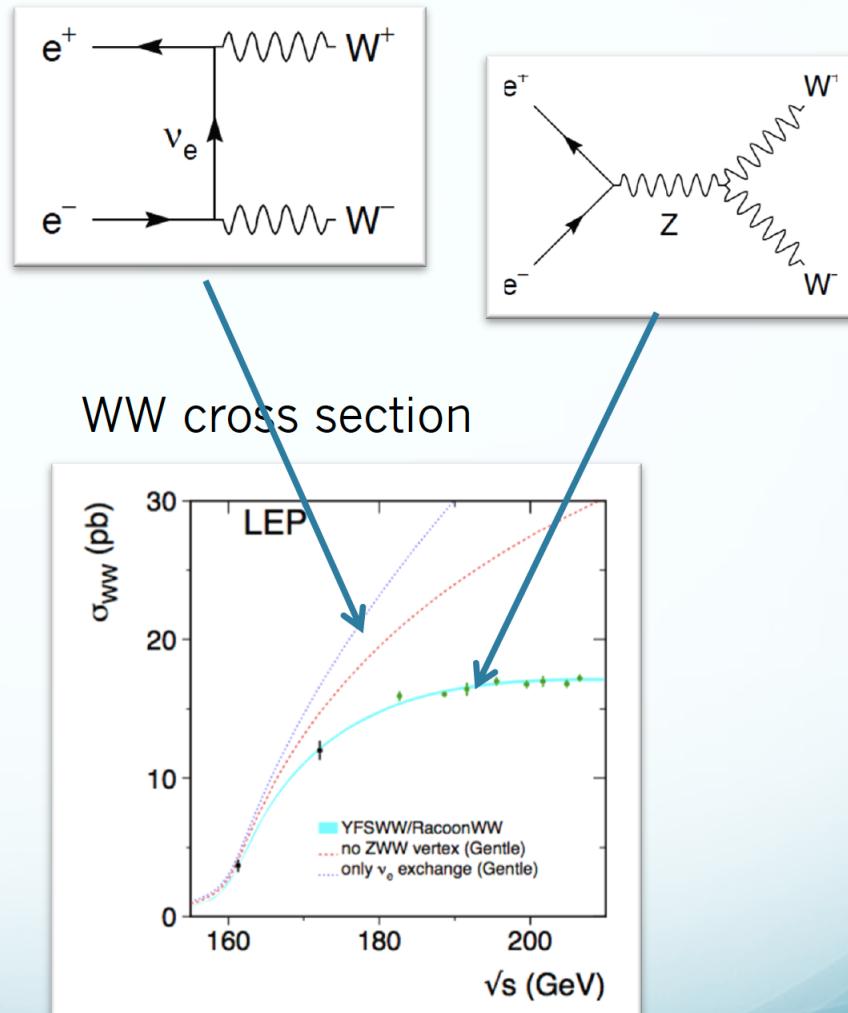
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Phys.Rept.532,119-224, 2013

- Precise measurement of W properties
- TGC as predicted in SM
- QGC measured at the LHC (later)



# [Higgs mechanism]

So far no mass terms for the gauge bosons W,Z as they would destroy the local gauge invariance

→ Mass terms introduced by interaction with a scalar field through the covariant derivative in the kinetic term

$$\mathcal{L}_\phi^{EW} = (D_\mu \phi)^\dagger D^\mu \phi - \left( \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 \right) \quad (\mu^2 < 0, \lambda > 0)$$

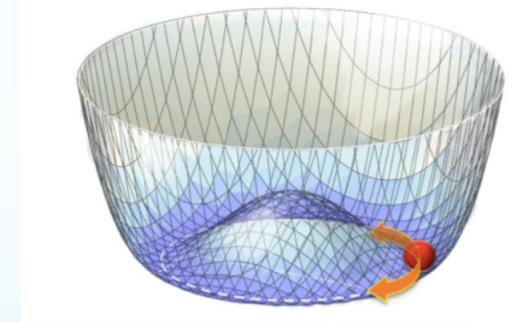


Peter Higgs



Francois Englert

Robert Brout



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Peter Higgs



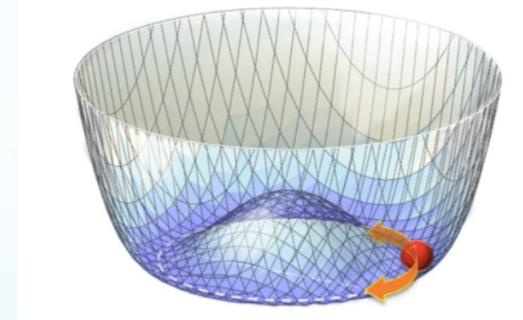
Francois Englert



Robert Brout

reminder:

$$D_\mu = \partial_\mu + ig_w \frac{\sigma_i}{2} W_u^i + ig \frac{Y}{2} B_\mu$$



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Peter Higgs



Francois Englert

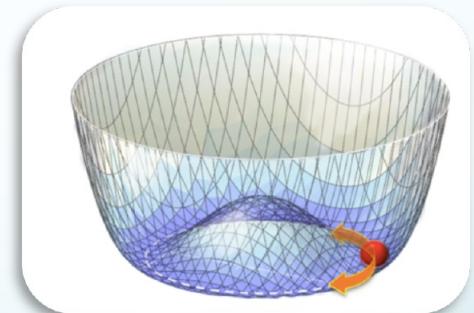


Robert Brout

after assuming a non-zero vacuum expectation value (electroweak symmetry breaking)

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$\langle 0 | \phi^\dagger \phi | 0 \rangle = \frac{v^2}{2} \simeq (174 \text{ GeV})^2$$

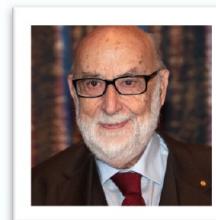


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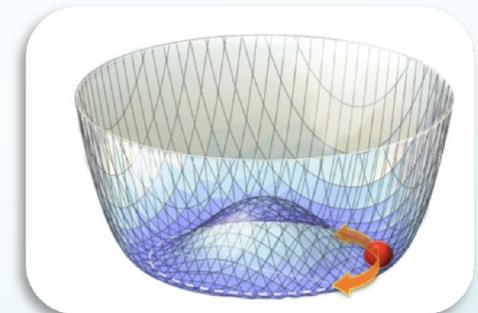
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the **kinematic term** creates mass terms for the W and Z

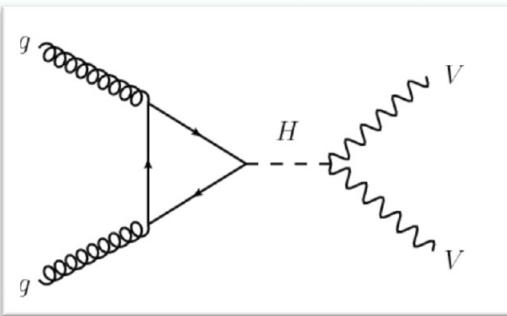
$$m_{W^+} = \frac{g_w v}{2}$$

$$m_{W^-} = \frac{g_w v}{2}$$

$$m_Z = \frac{g_w v}{2 \cos \theta_w} = \frac{m_W}{\cos \theta_w}$$



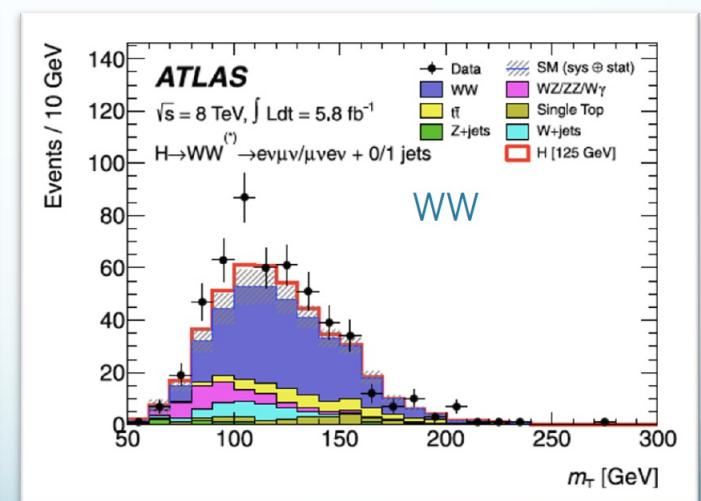
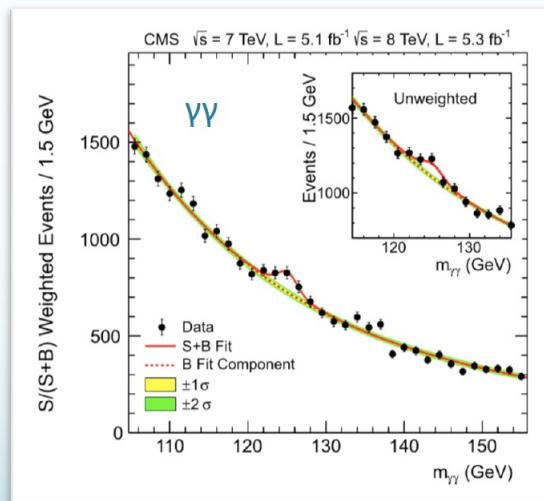
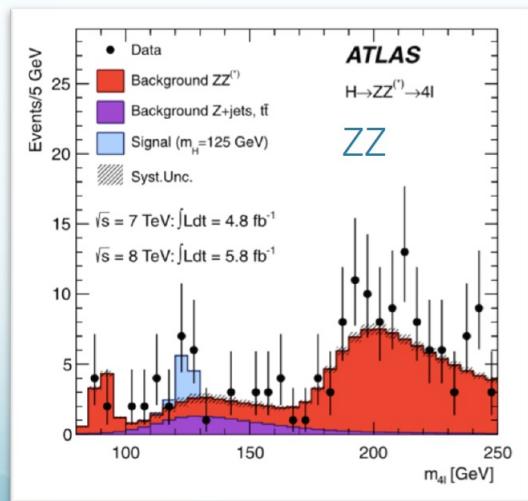
# [LHC: the Higgs boson]



Production:

- gg fusion
- VBF
- bbH, ttH
- ZH, WH

**2012: Higgs boson discovery:  
ATLAS & CMS experiments,  $m_H = 125.1 \pm 0.2$  GeV**



Phys. Lett. B 716 (2012)

Ulla Blumenschein, The Standard Model, Hasco summer school

# Summary Standard Model

Symmetries and fields:

- Lorentz boosts/rotations, translations

matter particles, spin 1/2:  $\Psi$

described by Dirac formalism:

$$\mathcal{L}_{SM} = i\bar{\Psi}_i \gamma^\mu \partial_\mu \Psi_i$$

2x6 leptons: e,  $\nu_e$ ,  $\mu$ ,  $\nu_\mu$ ,  $\tau$ ,  $\nu_\tau$

2x6 quarks: u, d, c, s, b, t

- Local gauge symmetries:

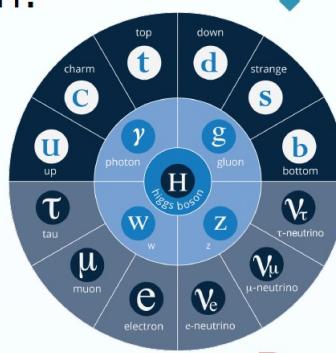
→ force fields: spin 1:  $V$

$SU(2) \times U(1)$  →  $\gamma$ , Z,  $W^\pm$ : EW force

$SU(3)$  → 8 gluons: strong force

$$D_\mu = \partial_\mu + ig_k V_\mu^k$$

- ◆ Relativistic Quantum Field Theory
- ◆ Symmetry requirements
- ◆ Renormalizability

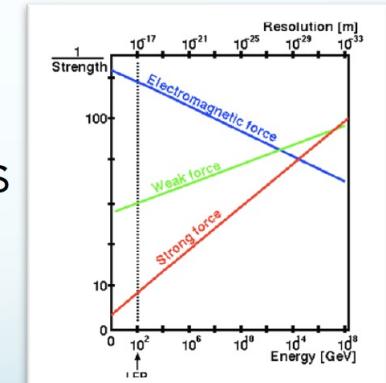


- ◆ Fermions and bosons masses

→ scalar Higgs field  $\varphi$   
EW Symmetry breaking in  
the ground state (vacuum)

## Renormalizability

Effective parameters  
can be adjusted in  
all orders of  
perturbation  
expansion such  
that theory keeps finite



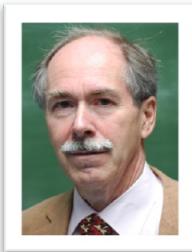
# SM: an international development



Richard Feynman  
(US), QED



Abdus Salam  
(Pakistan)  
EW theory



Gerard 't Hooft  
Netherlands,  
renormalisation



Chien-Shiun Wu  
(China/US)  
Parity violation



Shinichiro Tomonaga  
(Japan) QED



Yang Chen-Ning  
(China) Gauge theories



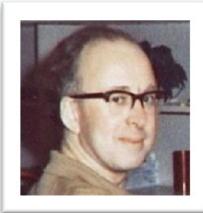
Frank Wilczek  
(US) QCD



Murray Gell-Man  
(US) Quarks



Tsung-Dao Lee  
(China) parity violation



Peter Higgs  
(UK) EWSB



Steven Weinberg  
(US) EW theory



Makoto Kobayashi  
(Japan): Quark mixing



Emmy Noether  
(Germany):  
Symmetries and  
conservation

*“Scientific thought and its creation is the common and shared heritage of mankind.”*

*Abdus Salam*