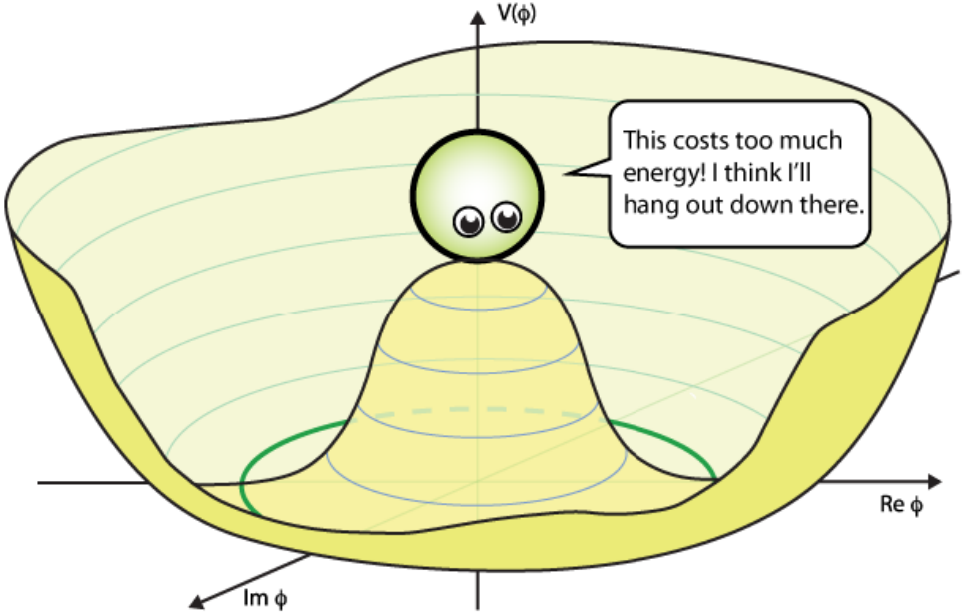
SERC School: SM & Higgs Theory



$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

$$\text{For } \mu^2 < 0, \quad \text{minimum } v = \sqrt{-\frac{\mu^2}{2\lambda}}$$

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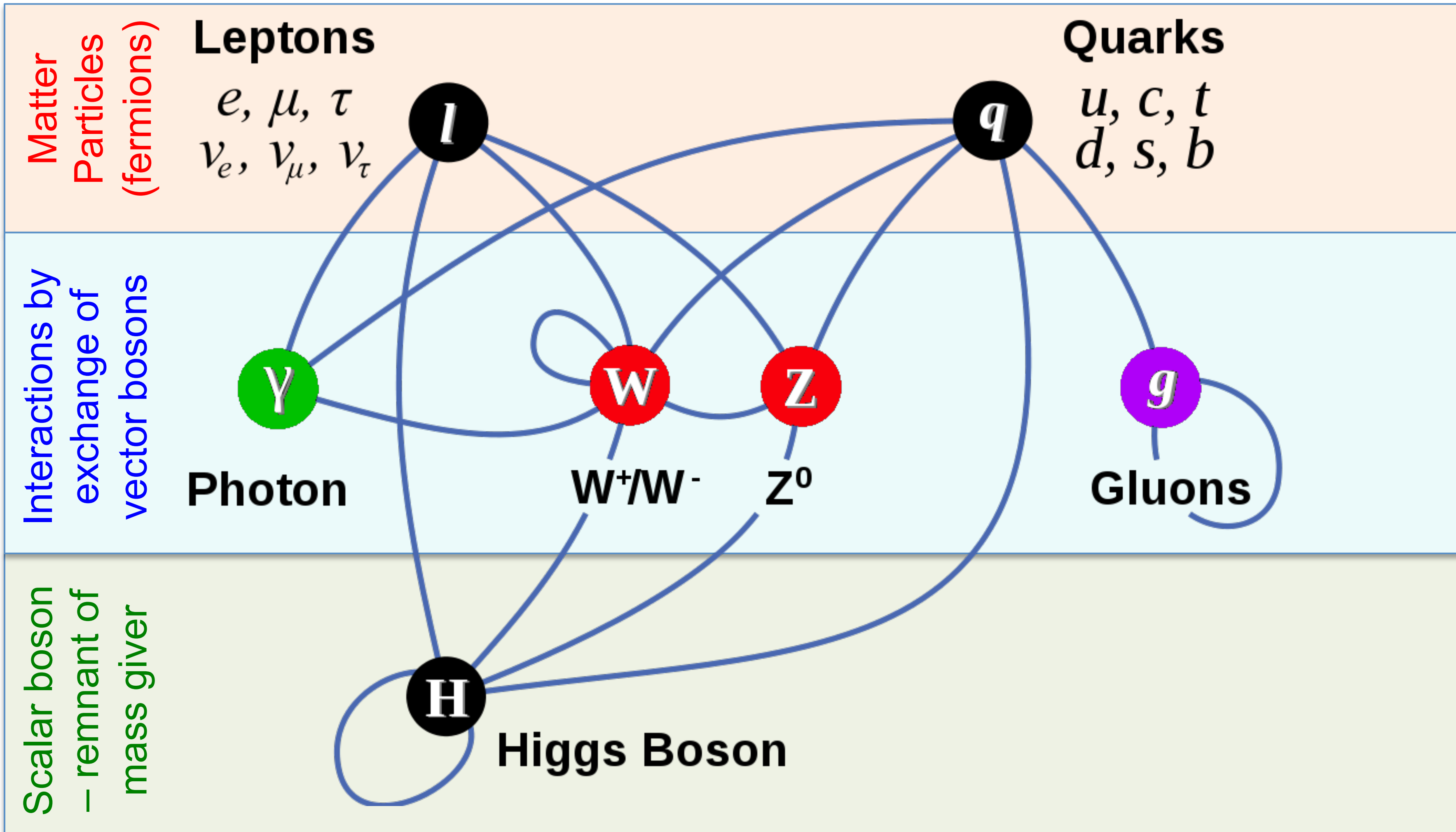
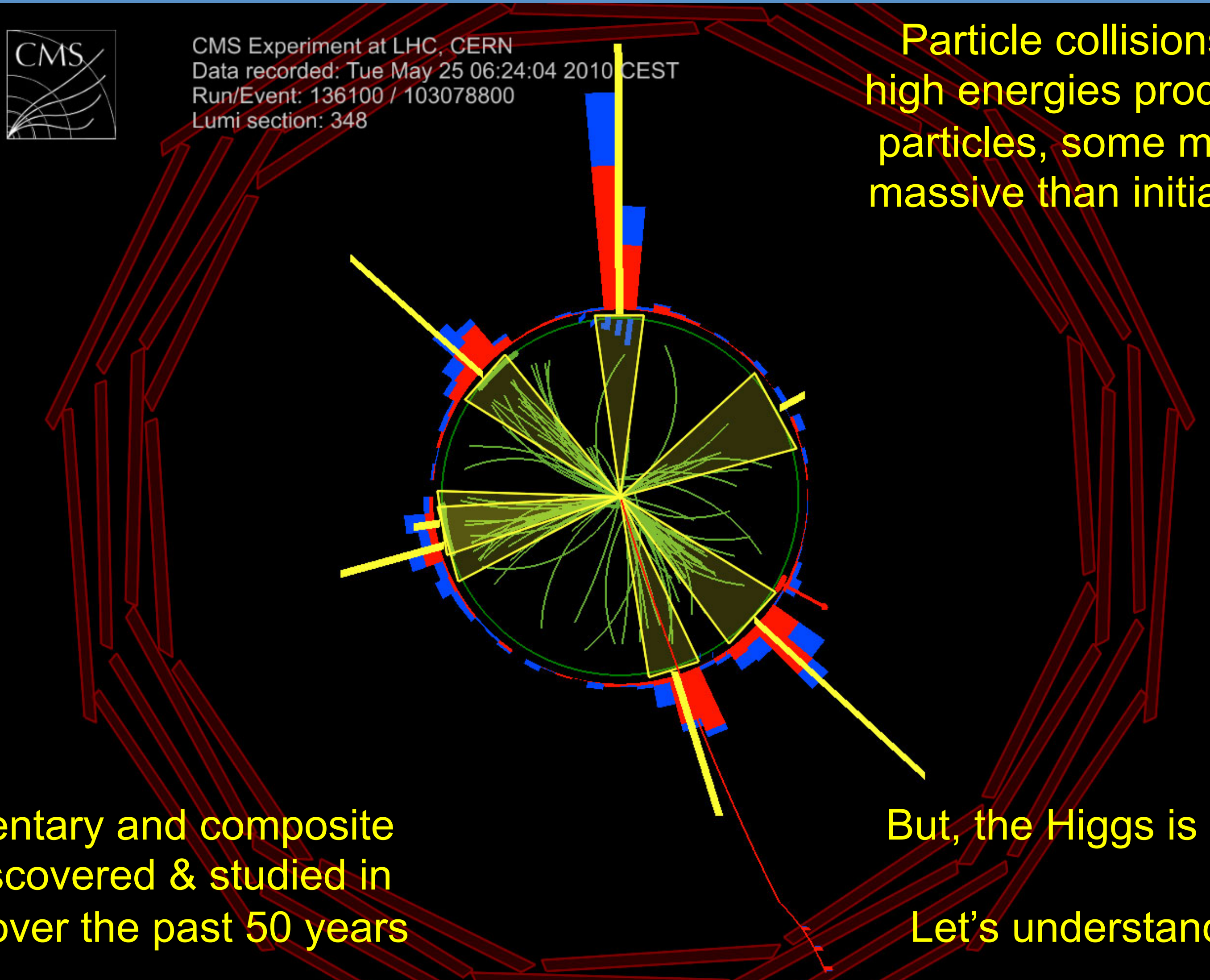


Relativistic Collisions



Particle collisions at very high energies produce many particles, some much more massive than initial particles

Many elementary and composite particles discovered & studied in great detail over the past 50 years

But, the Higgs is Special!

Let's understand why?

Relativistic Kinematics

Einstein's famous equation: $E = M$

The collision energy can manifest as mass!

For particles in motion: $E^2 - P_x^2 - P_y^2 - P_z^2 = M^2$

Energy-Momentum is conserved in collisions

Speed of light, $c = 1$

We use a common unit for mass, energy and momentum GeV

Relativistic Quantum World

Quantum Fields permeate all space-time

- EM field vibrations → photons (light quanta)

Given sufficient energy matter fields create quanta (particles), that can be long lived or ephemeral

- Matter-anti-matter pairs manifest out of vacuum

Particles interact with each other exchanging quanta

- Photons, Gluons, W and Z, (graviton)

Works beautifully for massless quanta – QED, QCD

- W & Z quanta are massive – decay promptly
- Mass terms in lagrangian break gauge invariance

Quantum Field Theory

Describes Elementary Particle Dynamics

All the fifty years of conscious brooding have brought me no closer to the answer to the question, "What are light quanta?" Of course today every rascal thinks he knows the answer, but he is deluding himself.

– Albert Einstein (1951)

Like silicon chips of more recent years,
the Feynman diagram was bringing computation
[of quantum field theory amplitudes]
to the masses.

– Julian Schwinger

Scalar, Charged Scalar, Spinor & Vector Fields

$$\hat{\mathcal{L}}_{scalar} = \frac{1}{2}\partial^{\mu}\hat{\phi}\,\partial_{\mu}\hat{\phi} - \frac{1}{2}m^2\hat{\phi}^2 \qquad \hat{\mathcal{L}}_{complexScalar} = \frac{1}{2}\partial^{\mu}\hat{\phi}^{\dagger}\partial_{\mu}\hat{\phi} - \frac{1}{2}m^2\hat{\phi}^{\dagger}\hat{\phi}$$

$$\hat{\mathcal{L}}_{Dirac} = \hat{\bar{\psi}}\left(i\gamma^{\mu}\partial_{\mu} - m\right)\hat{\psi} \qquad \hat{\mathcal{L}}_{Vector} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{2}\left(\partial_{\mu}\hat{A}^{\mu}\right)^2$$

Quantization of the field coordinates

- Promote fields and conjugates to operators
- Impose commutation (anti-commutation for Dirac) fields
- Normal mode expansion of the fields – non-interacting
    - Ladder operators
    - Plane wave solutions with definite momenta

Interactions

Construct out of covariant quantities

$$\hat{\mathcal{L}}_{scalar} = \frac{1}{2}\partial^\mu \hat{\phi}\,\partial_\mu \hat{\phi} - \frac{1}{2} m^2 \hat{\phi}^2$$

$$\hat{\phi}^3, \hat{\phi}^4, \partial^\mu \phi, \ldots$$

$$\hat{\mathcal{L}}_{complexScalar} = \frac{1}{2}\partial^\mu \hat{\phi}^\dagger \partial_\mu \hat{\phi} - \frac{1}{2} m^2 \hat{\phi}^\dagger \hat{\phi}$$

$$\left(\hat{\phi}^\dagger \hat{\phi}\right)^2, \hat{j}^\mu_\phi = ie\left(\hat{\phi}^\dagger \partial^\mu \hat{\phi} - \hat{\phi}\,\partial^\mu \hat{\phi}^\dagger\right), \ldots$$

$$\hat{\mathcal{L}}_{Dirac} = \hat{\bar{\psi}}\left(i\gamma^\mu \partial_\mu - m\right)\hat{\psi}$$

$$\hat{\bar{\psi}}\hat{\psi}, \hat{\bar{\psi}}\gamma^5\hat{\psi}, \hat{\bar{\psi}}\gamma^\mu\hat{\psi}, \hat{\bar{\psi}}\gamma^\mu\gamma^5\hat{\psi}, \hat{\bar{\psi}}\sigma^{\mu\nu}\hat{\psi}$$

$$\hat{\mathcal{L}}_{Vector} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{2}\left(\partial_\mu \hat{A}^\mu\right)^2$$

$$\hat{A}^\mu, \hat{F}^{\mu\nu}, \ldots$$

Interactions must respect experimental observations

Gauge Transformation

Potentials are not unique:

$$\vec{A} \rightarrow \vec{A}' = \vec{A} + \vec{\nabla}\chi$$

$$V \rightarrow V' = V - \frac{\partial \chi}{\partial t}$$

Physical quantities, expectation values, should not change

In particular, wavefunction need not stay the same, and in fact does not:

We want: $\left[\frac{1}{2m}\left(-i\vec{\nabla} - q\vec{A}'\right)^2 + qV'\right]\psi'(x,t) = i\frac{\partial}{\partial t}\psi'(x,t)$

Simultaneously transforming $\psi'(x,t) = e^{iq\chi(x,t)}\psi(x,t)$ does the magic

Promoting global phase invariance: $\psi'(x,t) = e^{i\alpha}\psi(x,t)$ to local phase invariance!

Gauge Principle → Interactions

$$\partial^\mu \rightarrow \hat{D}^\mu \equiv \partial^\mu + iq\hat{A}^\mu \qquad \hat{\psi}(x,t) \rightarrow \hat{\psi}'(x,t) = e^{-iq\chi(x,t)}\hat{\psi}(x,t)$$

$$\hat{A}^\mu \rightarrow \hat{A}'^\mu = \hat{A}^\mu + \partial^\mu \hat{\chi} \qquad \hat{\bar{\psi}}' = \hat{\bar{\psi}} e^{iq\hat{\chi}}$$

For Dirac field: $\mathcal{L}_D = \hat{\bar{\psi}}\left(i\gamma^\mu \partial_\mu - m\right)\hat{\psi} \rightarrow \mathcal{L}_{D,local} = \hat{\bar{\psi}}\left(i\gamma^\mu \hat{D}_\mu - m\right)\hat{\psi}$

$$\hat{D}'_\mu \hat{\psi}' = e^{-iq\hat{\chi}}\left(\hat{D}_\mu \hat{\psi}\right) \quad \Rightarrow \left(i\gamma^\mu \hat{D}'_\mu - m\right)\hat{\psi}' = e^{-iq\hat{\chi}}\left(i\gamma^\mu \hat{D}_\mu - m\right)\hat{\psi}$$

$$\hat{\bar{\psi}}'\left(i\gamma^\mu \hat{D}'_\mu - m\right)\hat{\psi}' = \hat{\bar{\psi}} e^{iq\hat{\chi}} e^{-iq\hat{\chi}}\left(i\gamma^\mu \hat{D}_\mu - m\right)\hat{\psi} = \hat{\bar{\psi}}\left(i\gamma^\mu \hat{D}_\mu - m\right)\hat{\psi}$$

$$\mathcal{L}_{D,local} = \hat{\bar{\psi}}\left(i\gamma^\mu \partial_\mu - m\right)\hat{\psi} - q\hat{\bar{\psi}}\gamma^\mu\hat{\psi}\hat{A}_\mu$$

$$\boxed{\mathcal{L}_{\text{int}} = -q\hat{\bar{\psi}}\gamma^\mu\hat{\psi}\hat{A}_\mu = -\hat{j}^\mu_D \hat{A}_\mu}$$

Global gauge invariance led to conserved current

Demanding local invariance results in interaction!

Feynman Rules for QED

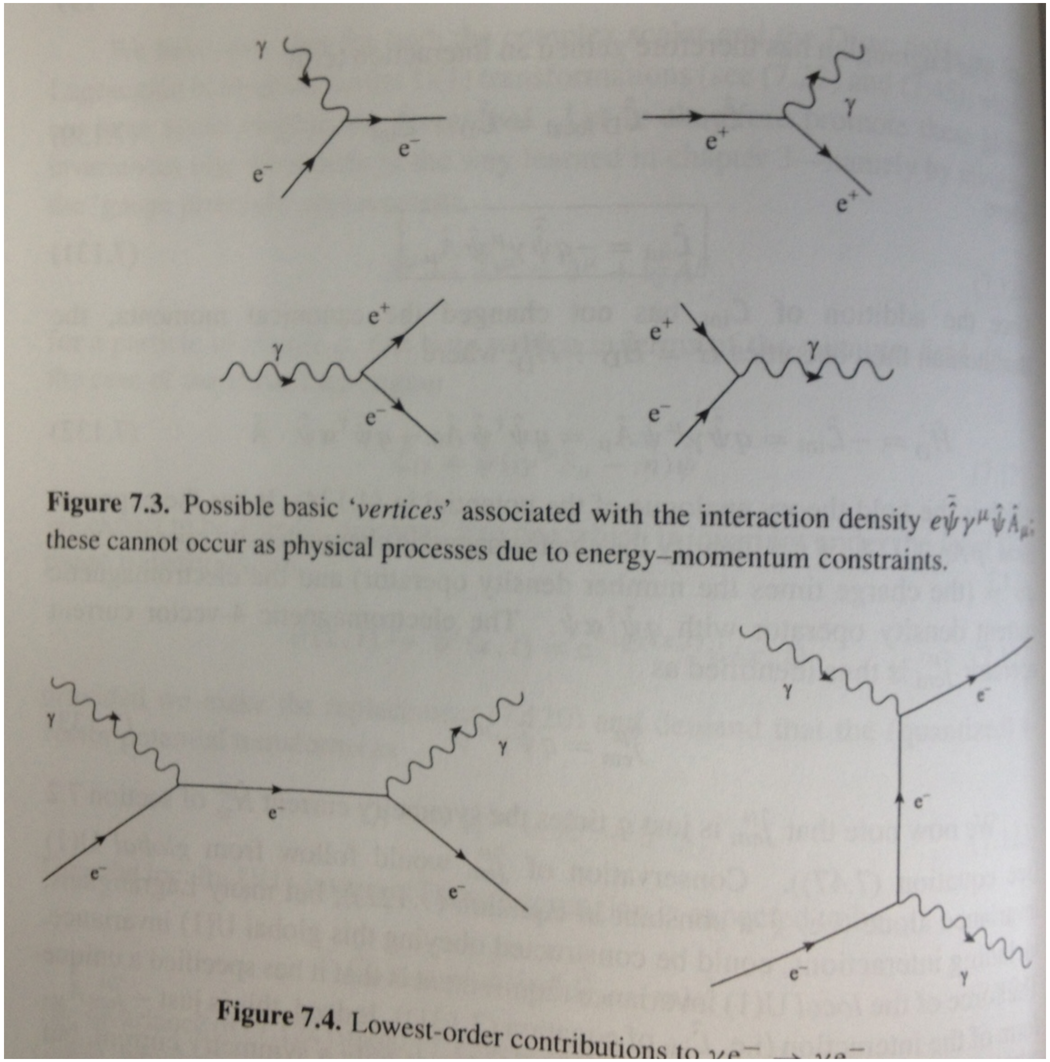


Figure 7.3. Possible basic '*vertices*' associated with the interaction density $e\bar{\hat{\psi}}\gamma^{\mu}\hat{\psi}\hat{A}_{\mu}$; these cannot occur as physical processes due to energy–momentum constraints.

Figure 7.4. Lowest-order contributions to $\gamma e^- \to \gamma e^-$

Electro-Weak Theory

Including weak interactions $(W^{\pm}, Z^0)$ with EM (γ)

Electromagnetic interactions conserve parity

and are accounted by U(1) gauge symmetry

Vector boson mass term

$m^2 A^\mu A_\mu$ is a no-no

Parity violating weak interactions due to $W^{\pm}, Z^0$

can be accommodated in $\mathrm{SU(2)}_L$ – left handed fields

Massive charged fermions should have

both left and right handed components.

$m\bar{\psi}\psi = m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L)$

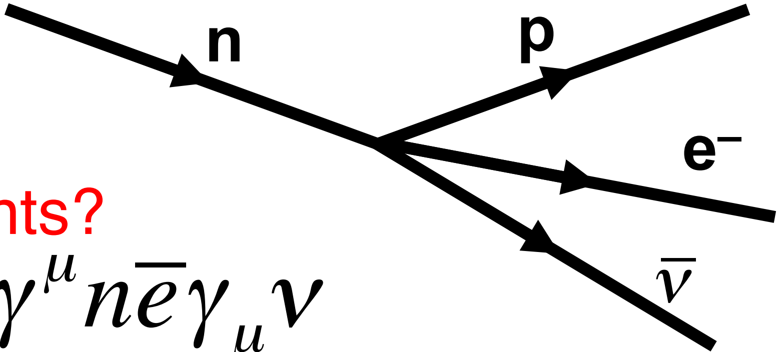
fermion mass term a problem

Glashow, Weinberg and Salam (independently) proposed

$\mathrm{SU(2)}_L \otimes U(1)$ gauge group, with $\mathrm{W}^{\pm}$, Z^0 and γ

But, mass terms for $\mathrm{W}^{\pm}$, Z and fermions violate gauge invariance

Four Fermion Interaction



What interaction can describe this decay?

- How about – charged currents?

$$J^{\mu}_{CC,h} J_{CC,l,\mu} = A\bar{p}\gamma^{\mu} n \bar{e}\gamma_{\mu}\nu$$

- Discovery of beta+ decays – hermitian conjugate

$$A\bar{n}\gamma^{\mu} p \bar{\nu}\gamma_{\mu} e$$

- Works Surprisingly well!
- But, not perfectly, both ΔJ=0 and 1 seen
  - This implied potential other forms of interaction

$$A\bar{n}p\bar{\nu}e \text{ or } A\bar{n}\sigma^{\mu\nu} p \sigma_{\mu\nu}\bar{\nu}e \text{ with } \sigma_{\mu\nu} = \frac{i}{2}\left(\gamma_{\mu}\gamma_{\nu} - \gamma_{\nu}\gamma_{\mu}\right)$$

Pseudoscalars and Axial Vectors

What is the correct interaction?

- Weak interactions found to be violating parity

Parity on Vector: $V^{\mu} = \left(V^{0}, \vec{V}\right) \rightarrow V'^{\mu} = PV^{\mu} = \left(V^{0}, -\vec{V}\right)$

Parity on Axial Vector: $A^{\mu} = \left(A^{0}, \vec{A}\right) \rightarrow A'^{\mu} = PA^{\mu} = \left(-A^{0}, \vec{A}\right)$

$A^{\mu}A_{\mu}$ & $V^{\mu}V_{\mu}$ are scalars

$A_{\mu}V^{\mu}$ is pseudoscalar

$$V^{\mu} = \bar{\psi}\gamma^{\mu}\psi$$

$$A^{\mu} = \bar{\psi}\gamma^{\mu}\gamma^{5}\psi$$

Discovery of Maximal P Violation

Resulted in identification of interaction as V-A!

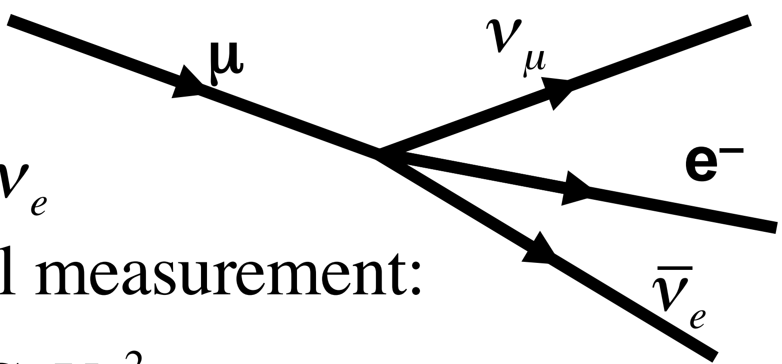
$$J^{\mu}(\mathrm{e}) = \bar{\nu}_e \gamma^{\mu}\left(1-\gamma^5\right)e$$

$$J^{\mu}_{CC}(\mathrm{leptons}) = J^{\mu}_{CC}(\mathrm{e}) + J^{\mu}_{CC}(\mu) + J^{\mu}_{CC}(\tau)$$

Universal coupling – same for all leptons

$$\mathcal{H}^{\mathrm{leptons}}_{CC} = \frac{G_F}{\sqrt{2}} J^{\mu}_{CC}(\mathrm{leptons}) J^{\dagger}_{CC,\mu}(\mathrm{leptons})$$

Describe muon decay with:



$$\mathcal{H}^{\mathrm{leptons}}_{CC} = \frac{G_F}{\sqrt{2}} \bar{\nu}_\mu \gamma^{\mu}(1-\gamma^5)\mu \bar{e}\gamma_\mu(1-\gamma^5)\nu_e$$

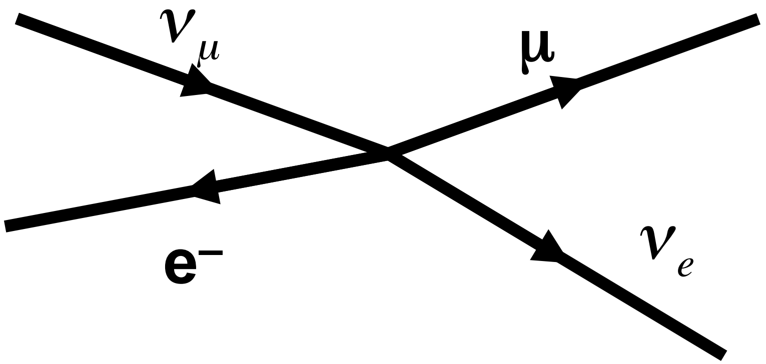
From experimental measurement:

$$G_F \simeq 1.166 \times 10^{-5}\, GeV^{-2}$$

Neutrino – Electron Scattering

$$\mathcal{M} = -i\frac{G_F}{\sqrt{2}}\bar{u}\gamma^\mu(1-\gamma^5)\nu_\mu\bar{\nu}_e\gamma_\mu(1-\gamma^5)e$$

$$\sigma = \frac{G_F}{\pi}s$$



Cross section grows with energy $\Rightarrow$ not renormalizable.

As an effective theory at low energy, V - A was successful in describing weak interactions between leptons and quarks

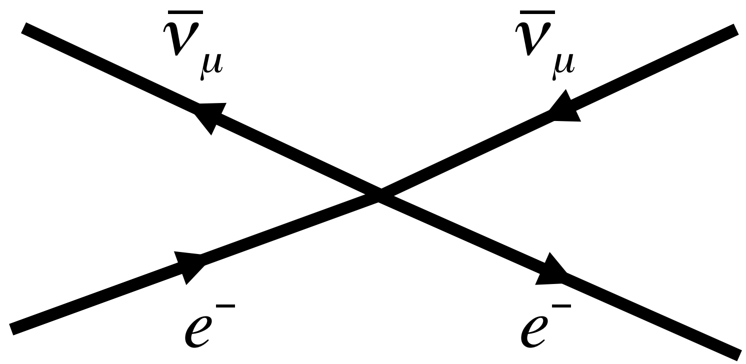
Quark charged current has additional complications due to mixing

$$j^\mu_{Cabibbo} = \cos\theta_C\bar{u}\gamma^\mu\frac{1-\gamma^5}{2}d + \sin\theta_C\bar{u}\gamma^\mu\frac{1-\gamma^5}{2}s$$

Neutral Currents

Discovery of neutral current process:

$$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$$



New currents of the form:

$$g_N c^{\nu_l} \bar{\nu}_l \gamma^\mu \left(\frac{1-\gamma^5}{2}\right) \nu_l \text{ for } l = e, \mu, \tau$$

New currents of the form:

$$g_N \bar{l} \gamma^\mu \left[c_L^l \left(\frac{1-\gamma^5}{2}\right) + c_R^l \left(\frac{1+\gamma^5}{2}\right) \right] l \text{ for } l = e, \mu, \tau$$

Possible NC:

$$\nu_\mu e^- \rightarrow \nu_\mu e^-$$

$$\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_\mu e^-$$

Possible NC & CC:

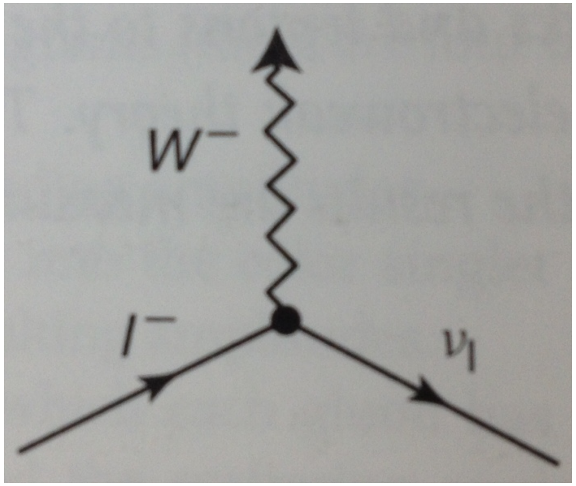
$$\nu_e e^- \rightarrow \nu_e e^-$$

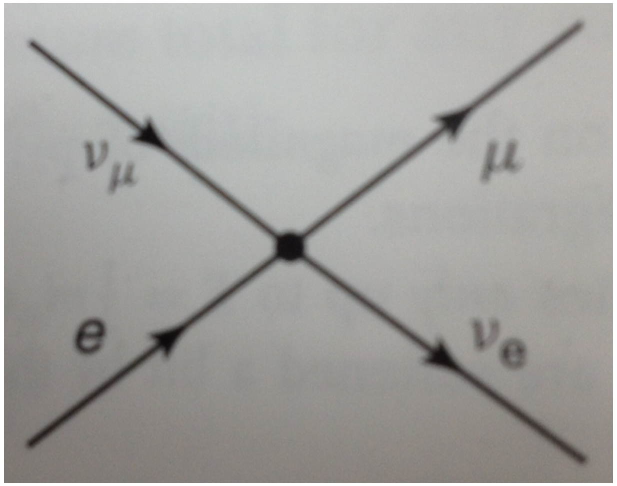
$$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$$

Introducing Weak Isospin symmetry, SU(2) predicted triplet of currents: CC, $CC^\dagger$ & *NC*

Intermediate Vector Bosons

Introducing:





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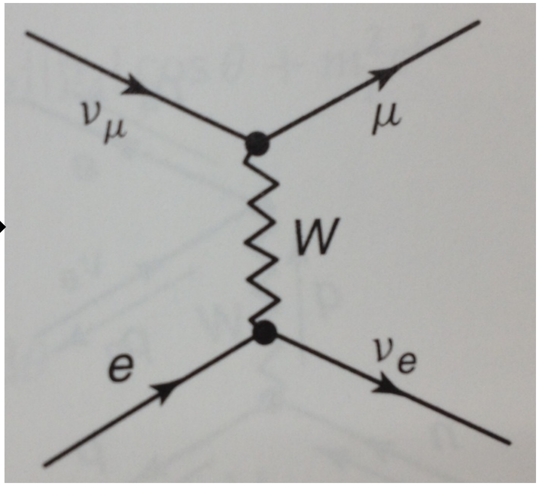


Lepton "weak isospin" doublets:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}$$

W^+ & W^- change lepton charge but NOT flavor

Z^0 mediates neutral current interactions

$M_{W^\pm}$ & $M_{Z^0} \gg 0$ for short distance weak interaction

Propagator: $$\frac{-i(g_{\mu\nu} - q_\mu q_\nu / M^2)}{q^2 - M^2}$$

Quark Weak Isospin Doublets

Using mixed field (weak quark-state with mixed flavor)

$$\hat{d}' = \cos\theta_C \hat{d} + \sin\theta_C \hat{s} \qquad j^{\mu}_{Cabibbo}(\mathrm{u,d,s}) = \bar{u}\gamma^{\mu}\frac{1-\gamma^5}{2}d'$$

Invoking quark-lepton symmetry GIM proposed

weak isospin doublets, predicting charm quark:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix} \qquad \hat{s}' = -\sin\theta_C \hat{d} + \cos\theta_C \hat{s}$$

$$j^{\mu}_{GIM}(\mathrm{u,d,s,c}) = \bar{u}\gamma^{\mu}\frac{1-\gamma^5}{2}d' + \bar{c}\gamma^{\mu}\frac{1-\gamma^5}{2}s'$$

GIM mechanism solves a bigger problem.

GIM Mechanism

Only $|\Delta s| = 1$ & $\Delta s = \Delta Q$ transitions seen experimentally!

i.e. Only charged current mediates flavor change.

Only suppressed by $\sin\theta_C$. Experimentally $K^0 \to \mu^+\mu^-$ is too small.

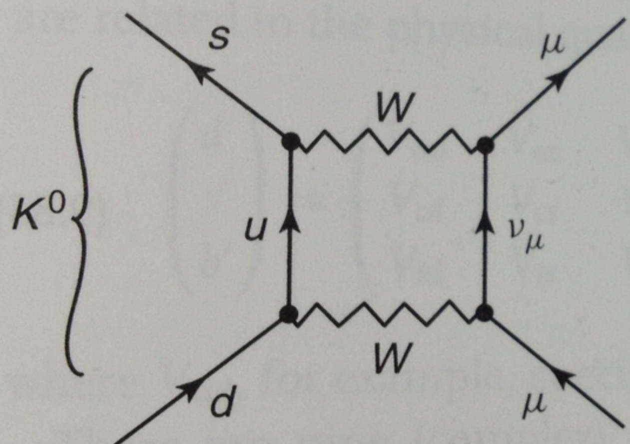


Fig. 9.4 The decay $K^0 \to \mu^+ + \mu^-$.

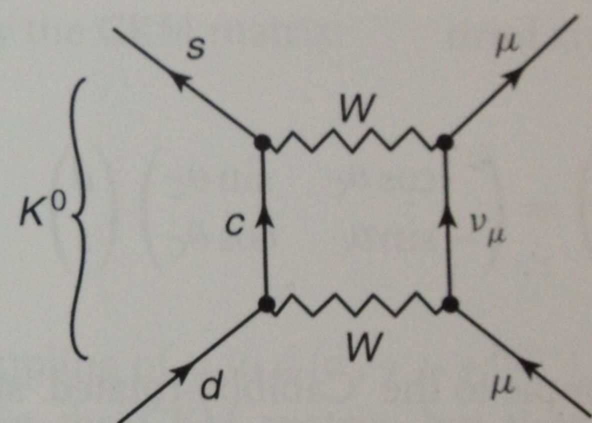
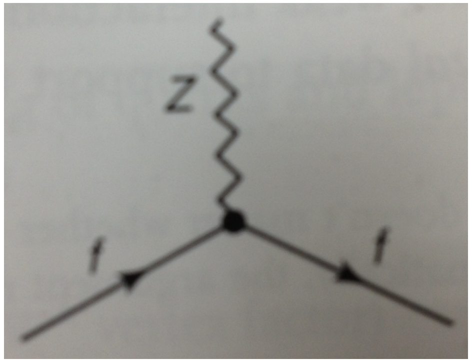


Fig. 9.5 The GIM mechanism. This diagram cancels Figure 9.4. Note the virtual *c* quark replacing the *u*.

Weak Neutral Currents

Lepton neutral currents:

$$g_N c^{\nu_l} \bar{\nu}_l \gamma^\mu \left(\frac{1-\gamma^5}{2} \right) \nu_l \text{ for } l = e, \mu, \tau$$



Similar to leptons, we have both $V - A$ and $V + A$:

$$g_N \sum_{q=u,c,d,s} \bar{q} \gamma^\mu \left[c_L^q \left(\frac{1-\gamma^5}{2} \right) + c_R^q \left(\frac{1+\gamma^5}{2} \right) \right] q$$

NC mediate interactions only between same flavor

Why not FCNC: $K^+ \to \pi^+ \nu \bar{\nu}$? Experiment: $<10^{-9}\%$

What's the origin of mass?

$W^{\pm}$ & Z^0 must be massive to confine weak interaction to nuclear scale, but that breaks gauge invariance :(

$$G_F \sim \frac{g^2}{M_W^2} \Rightarrow \text{for } g \sim e,\ M_W \sim 90 GeV$$

How do we give mass to vectors in a gauge invariant way?

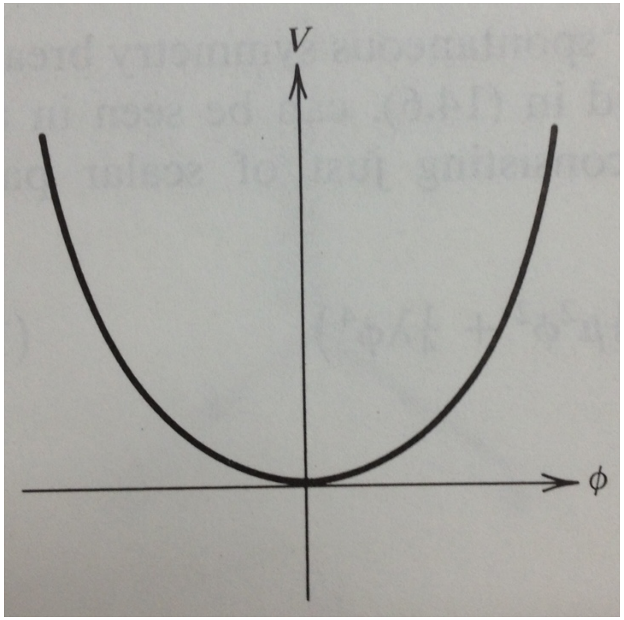
Anderson, Brout, Englert, Higgs, Guralnik, Hagen, Kibble

Ideas of spontaneous symmetry breaking Goldstone, Nambu, ...

Goldstone Model

Consider complex scalar field:

$$\phi = \frac{\phi_1 - i\phi_2}{\sqrt{2}} \ \& \ \phi^\dagger = \frac{\phi_1 + i\phi_2}{\sqrt{2}}$$



Lagrangian:

$$L_G = \left(\partial^\mu \phi^\dagger\right)\left(\partial^\mu \phi\right) - V(\phi)$$

Symmetric case:

$$V(\phi) = \frac{1}{4}\lambda\left(\phi^\dagger\phi\right)^2 + \mu^2\phi^\dagger\phi, \text{ for } \mu^2 > 0 \ \& \ \lambda > 0$$

Lagrangian is invariant under: $\phi \rightarrow \phi' = e^{-i\alpha}\phi$

For $\lambda=0$ there are two degrees of freedom with the same mass μ

For $\lambda > 0$ they interact

Spontaneous Symmetry Breaking

Symmetry breaking case:

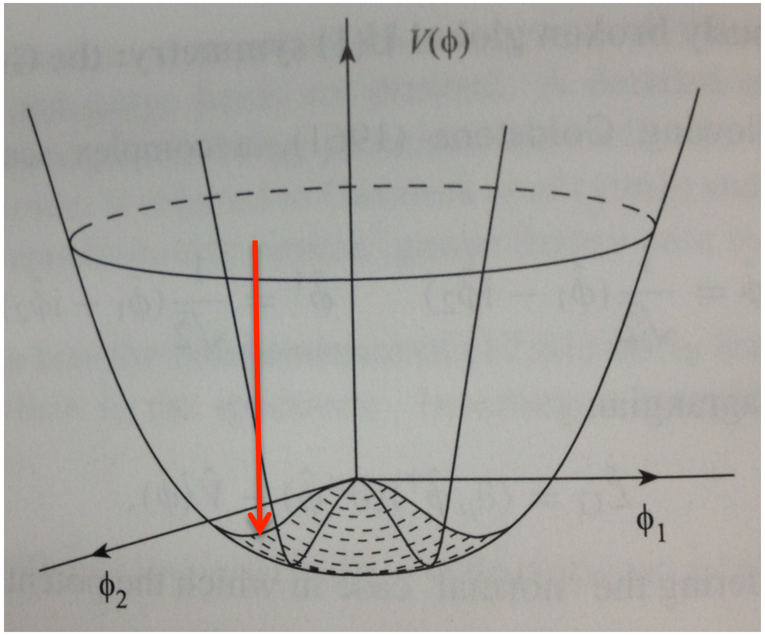
$$V(\phi) = \frac{1}{4}\lambda\left(\phi^\dagger\phi\right)^2 - \mu^2\phi^\dagger\phi, \text{ for } \mu^2 > 0 \;\&\; \lambda > 0$$

$\phi^\dagger\phi = \dfrac{4\mu^2}{\lambda}$ is the minimum

$$\phi_1^2 + \phi_2^2 = \frac{4\mu^2}{\lambda} \equiv v^2 \Rightarrow v = \frac{2|\mu|}{\sqrt{\lambda}}$$

Considering oscillation around stable point (in polar variables):

$$\phi(x) = \frac{1}{\sqrt{2}}\left(v + h(x)\right)e^{-\frac{i\theta(x)}{v}}$$



Unlike the usual expansion about 0

Different Degrees of Freedom!

In terms of $h(x)$ and $\theta(x)$ Lagrangian:

$$L_G = \frac{1}{2}\partial_\mu h \partial^\mu h - \mu^2 h^2 + \frac{1}{2}\partial_\mu \theta \partial^\mu \theta + \frac{\mu^4}{\lambda} + \ldots$$

No mass term for $\theta(x)$ in the Lagrangian

Particle content is different from what we started with.

Looking at $\mathcal{L}$, we now have a massive and a massless boson.

Spontaneously broken symmetry resulted in a massless boson.

This mechanism can be used to preserve gauge invariance of SU(2) theory while giving mass to physical W & Z

EWK Particle Content

$SU(2)_L$ charged W transforms e^- to ν_e ...

e^- & ν_e form a "weak-isospin" doublet ...

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L, \begin{pmatrix} c \\ s' \end{pmatrix}_L, \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Invariance under rotation in $SU(2)_L$

$$\begin{pmatrix} \nu'_e \\ e'^- \end{pmatrix}_L = e^{-i\frac{\vec{\tau}.\vec{\alpha}}{2}} \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$$

Gauging $SU(2)_L$, i.e., demanding local invariance leads to interactions between e^-_L and $\nu_{e,L}$

$e^-_R, \mu^-_R, \tau^-_R, u_R, c_R, t_R, \ldots$ ($SU(2)_L$ singlets)

but ν_R dropped in SM - negligible mass

Weak Isospin & Hypercharge

$SU(2)_L$ weak-isospin ($\vec{t}$) & U(1) Hypercharge (y)

Neutral bosons mix to make photon and Z

$$Q = t_3 + \frac{y}{2}$$ (Gellman-Nishijima relation for EWK)

Hypercharge chosen such that the left and right components have same Q

Right handed neutrino assignments shown for "completeness" with the discovery of neutrino mixing.

	t	t_3	y	Q
$\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}$	1/2	1/2	−1	0
$\nu_{eR}, \nu_{\mu R}, \nu_{\tau R}$	0	0	0	0
e_L, μ_L, τ_L	1/2	−1/2	−1	−1
e_R, μ_R, τ_R	0	0	−2	−1
u_L, c_L, t_L	1/2	1/2	1/3	2/3
u_R, c_R, t_R	0	0	4/3	2/3
d'_L, s'_L, b'_L	1/2	−1/2	1/3	−1/3
d'_R, s'_R, b'_R	0	0	−2/3	−1/3
ϕ^+	1/2	1/2	1	1
ϕ^0	1/2	−1/2	1	0

EWK Lagrangian

$$\mathcal{L}_{SM} = \mathcal{L}_G + \mathcal{L}_\phi + \mathcal{L}_{leptons} + \mathcal{L}_{quarks} + \mathcal{L}_{Yukawa}$$

$$\mathcal{L}_G = -\frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu},$$

with $\vec{F}^{\mu\nu} = \partial^\mu \vec{W}^\nu - \partial^\nu \vec{W}^\mu - g\vec{W}^\mu \times \vec{W}^\nu$ (for SU(2)) and

$G^{\mu\nu} = \partial^\mu B^\nu - \partial^\nu B^\mu$ (for U(1))

Introduce scalar SU(2) weak-isospin doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$\mathcal{L}_\phi = \left(D_\mu\phi^\dagger\right)\left(D^\mu\phi\right) + \mu^2\phi^\dagger\phi - \frac{\lambda}{4}\left(\phi^\dagger\phi\right)^2,$$

with $\mu,\lambda > 0$ and $D^\mu = \partial^\mu + ig\frac{\vec{\sigma}.\vec{W}^\mu}{2} + ig'\frac{B^\mu}{2}$

Spontaneous Symmetry Breaking

Similar to the Goldstone model - the minimum of classical potential is not at zero, but at *v*:

$$VEV = \langle 0|\phi|0\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$$

Expansion: $\phi = e^{-i\frac{\vec{\theta}(x).\vec{\sigma}}{2v}} \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} + H(x) \end{pmatrix}$

$$\left(\mathcal{L}_G + \mathcal{L}_\phi\right)^{free} = \frac{1}{2}\partial_\mu H \partial^\mu H - \mu^2 H^2$$
$$-\frac{1}{4}\left(\partial_\mu W_{1\nu} - \partial_\nu W_{1\mu}\right)\left(\partial^\mu W_1^\nu - \partial^\nu W_1^\mu\right) + \frac{1}{8} g^2 v^2 W_{1\mu} W_1^\mu$$
$$-\frac{1}{4}\left(\partial_\mu W_{2\nu} - \partial_\nu W_{2\mu}\right)\left(\partial^\mu W_2^\nu - \partial^\nu W_2^\mu\right) + \frac{1}{8} g^2 v^2 W_{2\mu} W_2^\mu$$
$$-\frac{1}{4}\left(\partial_\mu W_{3\nu} - \partial_\nu W_{3\mu}\right)\left(\partial^\mu W_3^\nu - \partial^\nu W_3^\mu\right)$$
$$-\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \frac{1}{8} v^2 \left(g W_{3\mu} - g' B_\mu\right)\left(g W_3^\mu - g' B^\mu\right)$$

Degenerate states for CC:

$$M_1 = M_2 = M_W = \frac{gv}{2}$$

Combinations ±:

$$W_\pm^\mu = \frac{W_1 \pm i W_2}{\sqrt{2}}$$

Higgs Mass (parameter):

$$M_H = \mu\sqrt{2} = v\sqrt{2\lambda}$$

Z and Photon

Neutral State (EWK) Mixing:

$$Z^\mu = \cos\theta_W W_3^\mu - \sin\theta_W B^\mu$$

$$A^\mu = \sin\theta_W W_3^\mu + \cos\theta_W B^\mu$$

The last two terms from previous page:

$$\mathcal{L}_{Z/\gamma} = -\frac{1}{4}\left(\partial_\mu Z_\nu - \partial_\nu Z_\mu\right)\left(\partial^\mu Z^\nu - \partial^\nu Z^\mu\right) + \frac{1}{8}v^2\left(g^2 + g'^2\right)Z_\mu Z^\mu$$

$$-\frac{1}{4}\left(\partial_\mu A_\nu - \partial_\nu A_\mu\right)\left(\partial^\mu A^\nu - \partial^\nu A^\mu\right)$$

Coupling strengths:

$$e = g\sin\theta_W$$

Mass terms for the Z and A:

$$M_Z = \frac{v\sqrt{g^2 + g'^2}}{2} = \frac{M_W}{\cos\theta_W}$$

$$M_A = 0$$

$$\sin\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad \cos\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

Leptonic Part of $\mathcal{L}$

With L and R charged leptons and L neutrinos :

$$\mathcal{L}_{leptons} = \sum_{f=e,\mu,\tau} \bar{l}_{fL} i \not{D} l_{fL} + \sum_{f=e,\mu,\tau} \bar{l}_{fR} i \not{D} l_{fR}, \text{ where } l_{fL} = \begin{pmatrix} \nu_f \\ f^- \end{pmatrix}_L \ \& \ l_{fR} = e_R, \mu_R, \tau_R$$

Weak interaction with L spinors give : $\gamma^\mu \left(1-\gamma^5\right)$

Expanding the covariant derivative gives interaction terms:

$$\text{CC: } -\frac{g}{\sqrt{2}} \left\{ \sum_{f=e,\mu,\tau} \bar{\nu}_f \gamma^\mu \frac{\left(1-\gamma^5\right)}{2} f \right\} W_\mu + h.c., \text{ with } W^\mu = \frac{W_1^\mu - W_2^\mu}{\sqrt{2}}$$

$$\text{NC: } -\frac{g}{\cos\theta_W} \left\{ \sum_{f=e,\mu,\tau} \bar{f} \gamma^\mu \left[t_3^f \frac{\left(1-\gamma^5\right)}{2} - \sin^2\theta_W Q_f \right] f \right\} Z_\mu \quad \text{EM: } -g\sin\theta_W \sum_{f=e,\mu,\tau} \bar{f} \gamma^\mu f A_\mu$$

These are still massless spinors, because, $m\bar{\psi}\psi = m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

is not invariant, as only ψ_L transform as doublet under SU(2) and not ψ_R

Quark Part of $\mathcal{L}$

With L and R quarks :

$$\mathcal{L}_{quarks} = \sum_{f=u,c,t} \bar{q}_{fL} i\not{D} q_{fL} + \sum_{f=u,c,t} \bar{q}_{fR} i\not{D} q_{fR}, \text{ where } q_{fL} = \begin{pmatrix} u \\ d' \end{pmatrix}_L \ldots \& \; l_{fR} = u_R, d'_R, c_R, s'_R \ldots$$

Weak interaction with L spinors give : $\gamma^\mu \left(1-\gamma^5\right)$

Expanding the covariant derivative gives interaction terms:

$$\text{CC: } -\frac{g}{\sqrt{2}} \left\{ \sum_{f=u,c,t} \bar{u}_f \gamma^\mu \frac{\left(1-\gamma^5\right)}{2} d'_f \right\} W_\mu + h.c., \text{ with } W^\mu = \frac{W_1^\mu - W_2^\mu}{\sqrt{2}}$$

$$\text{NC: } -\frac{g}{\cos\theta_W} \left\{ \sum_{q=u,c,t} \bar{q} \gamma^\mu \left[t_3^f \frac{\left(1-\gamma^5\right)}{2} - \sin^2\theta_W Q_f \right] q \right\} Z_\mu \quad \text{EM: } -g\sin\theta_W \sum_{f=u,c,t} \bar{f}\gamma^\mu f A_\mu$$

These are still massless spinors, because, $m\bar{\psi}\psi = m(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$

is not invariant, as only ψ_L transform as doublet under SU(2) and not ψ_R

Axial and Vector Couplings

$$\text{NC \& } \gamma\text{:}\ \frac{g}{\cos\theta_W}\left\{\sum_f \bar{f}\gamma^\mu\left[c_L^f\frac{(1-\gamma^5)}{2}-c_R^f\frac{(1+\gamma^5)}{2}\right]f\right\}$$

$$\text{NC \& } \gamma\text{:}\ \frac{g}{\cos\theta_W}\left\{\sum_f \bar{f}\gamma^\mu\left[c_V^f-c_A^f\gamma^5\right]f\right\}$$

$$c_L^f = t_3^f - \sin^2\theta_W Q_f$$

$$c_R^f = -\sin^2\theta_W Q_f$$

$$c_V^f = t_3^f - 2\sin^2\theta_W Q_f$$

$$c_A^f = -t_3^f$$

f	c_V	c_A
ν_e, ν_μ, ν_τ	$\frac{1}{2}$	$\frac{1}{2}$
e^-, μ^-, τ^-	$-\frac{1}{2}+2\sin^2\theta_w$	$-\frac{1}{2}$
u, c, t	$\frac{1}{2}-\frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$
d, s, b	$-\frac{1}{2}+\frac{2}{3}\sin^2\theta_w$	$-\frac{1}{2}$

Yukawa Couplings

Left fermions are in an SU(2) doublet

Right fermions are in SU(2) singlet

Use scalar field doublet to form scalar:

$$\mathcal{L}_{Yukawa} = -g_f\left(\bar{f}_L \phi f_R + \bar{f}_R \phi^\dagger f_L\right)$$

After SSB this is mass term:

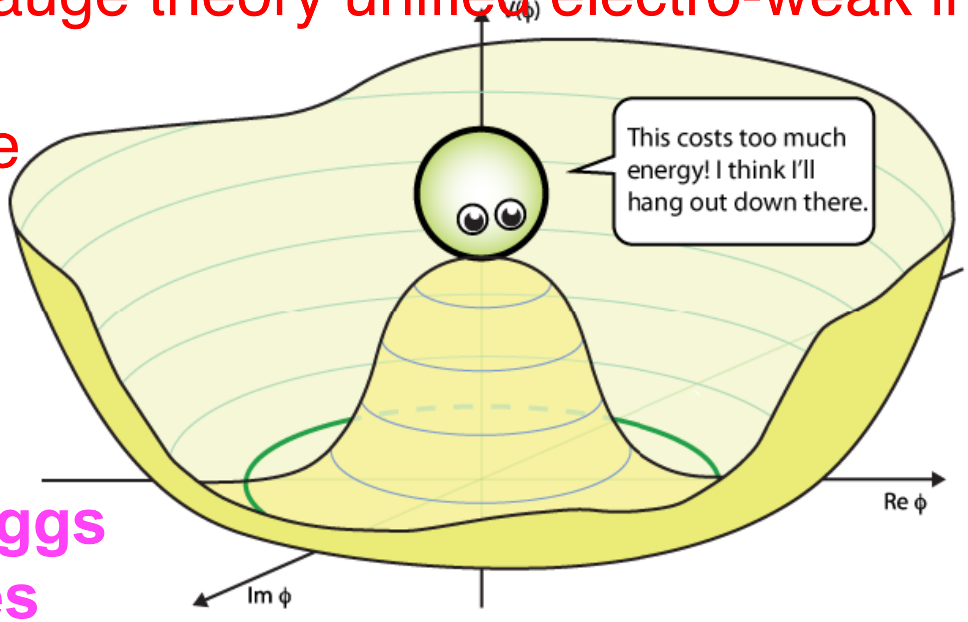
$$\mathcal{L}_{Yukawa} = -\frac{g_f v}{\sqrt{2}}\left(\bar{f}_L f_R + \bar{f}_R f_L\right) - \frac{g_f}{\sqrt{2}} \bar{f} f H$$

Fermion masses: $m_f = g_f \frac{v}{\sqrt{2}}$

Higgs coupling to fermions proportional to mass: $\frac{m_f}{v}$

Electro-Weak Symmetry Breaking

50 years ago, gauge theory unified electro-weak interactions, but could not accommodate non-zero masses for $W^\pm$ & Z



Predicted a remnant scalar particle!

Coupling to Higgs field provides masses to matter particles!!

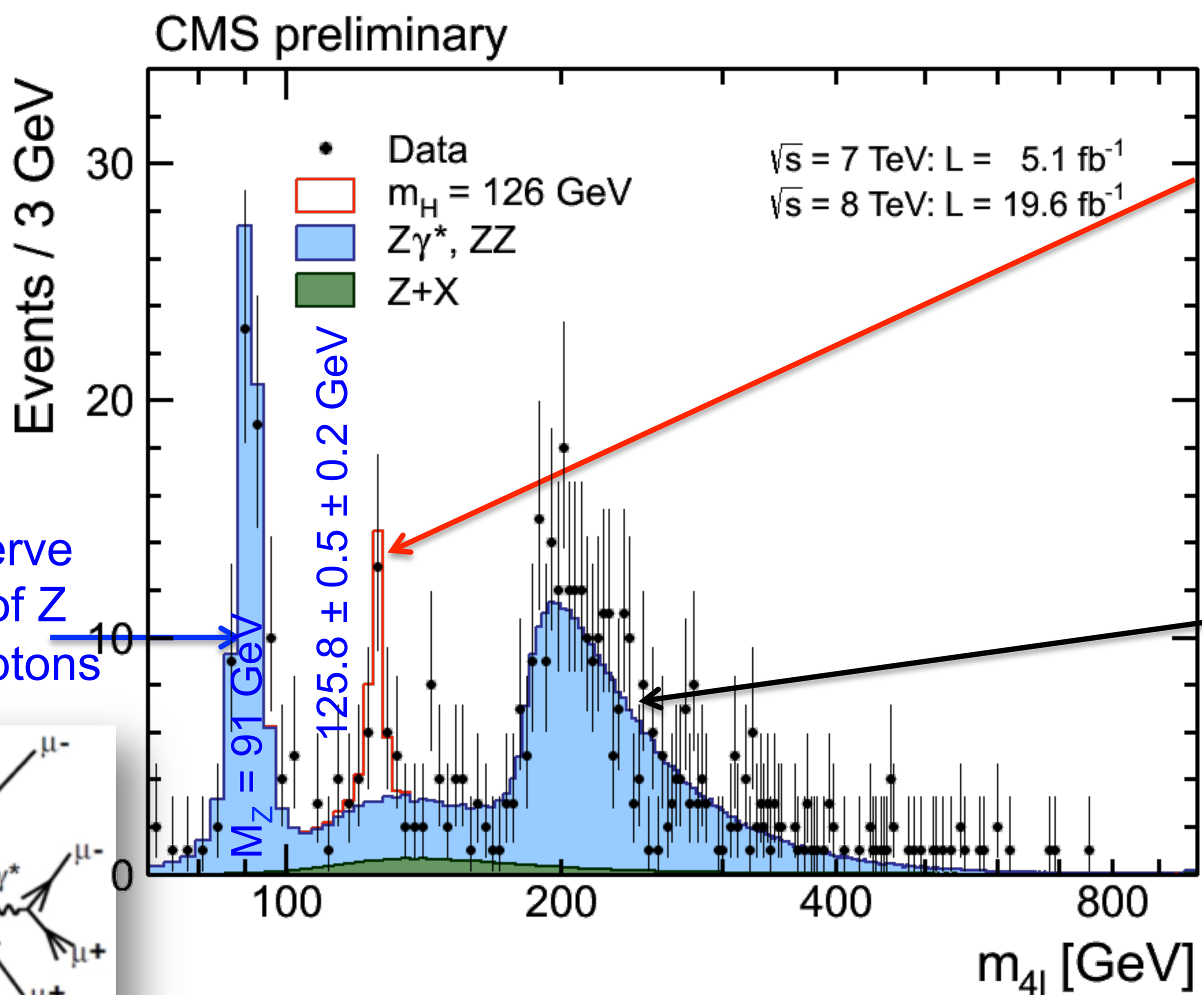
$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2\Phi^2 - \lambda\Phi^4$$

$$\text{For } \mu^2 < 0, \quad \text{minimum } v = \sqrt{-\frac{\mu^2}{2\lambda}}$$

Introduction of a doublet of complex scalar fields with peculiar potential provided masses for $W^\pm$ & Z and left γ massless!

Decays to ZZ to 4-light leptons

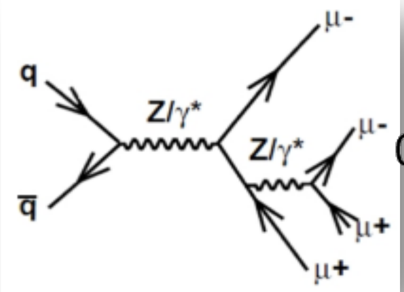
CMS HIG-13-002



Cluster of events rising above the background consistent at 4.7σ level with SM Higgs signal

Clearly observe production of Z decay to 4 leptons

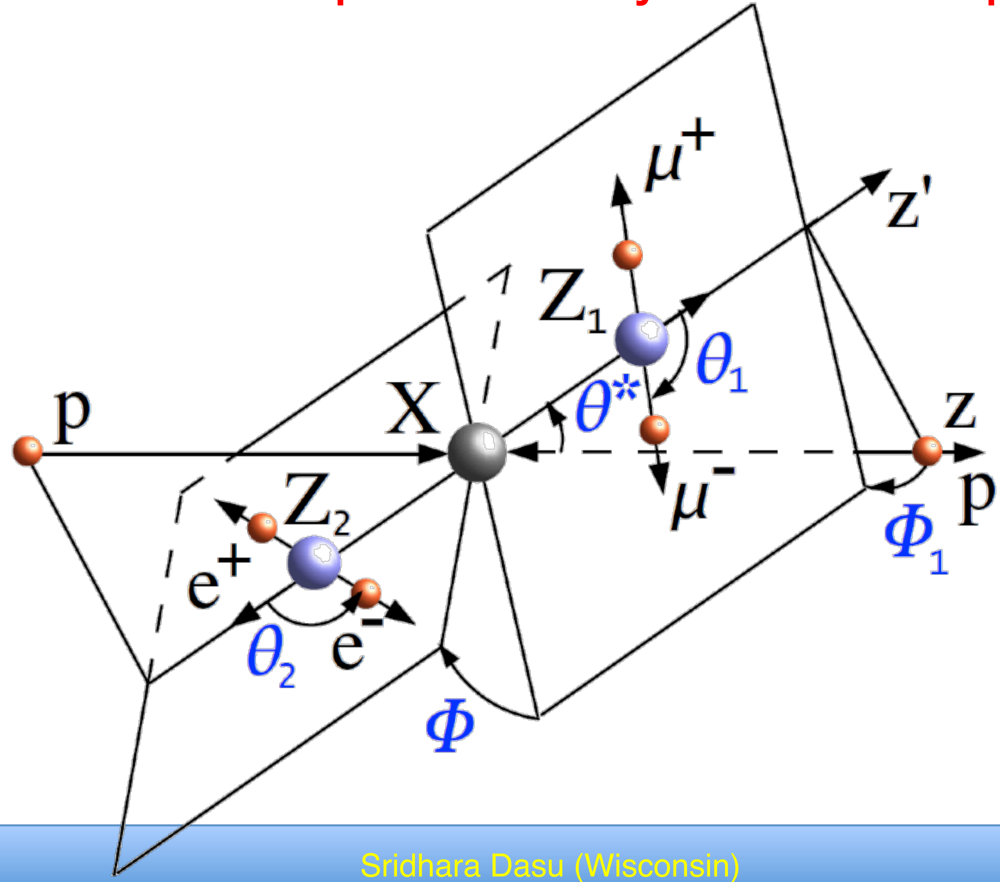
ZZ production for $M_{4l} > 2M_Z$



Use Angular Information

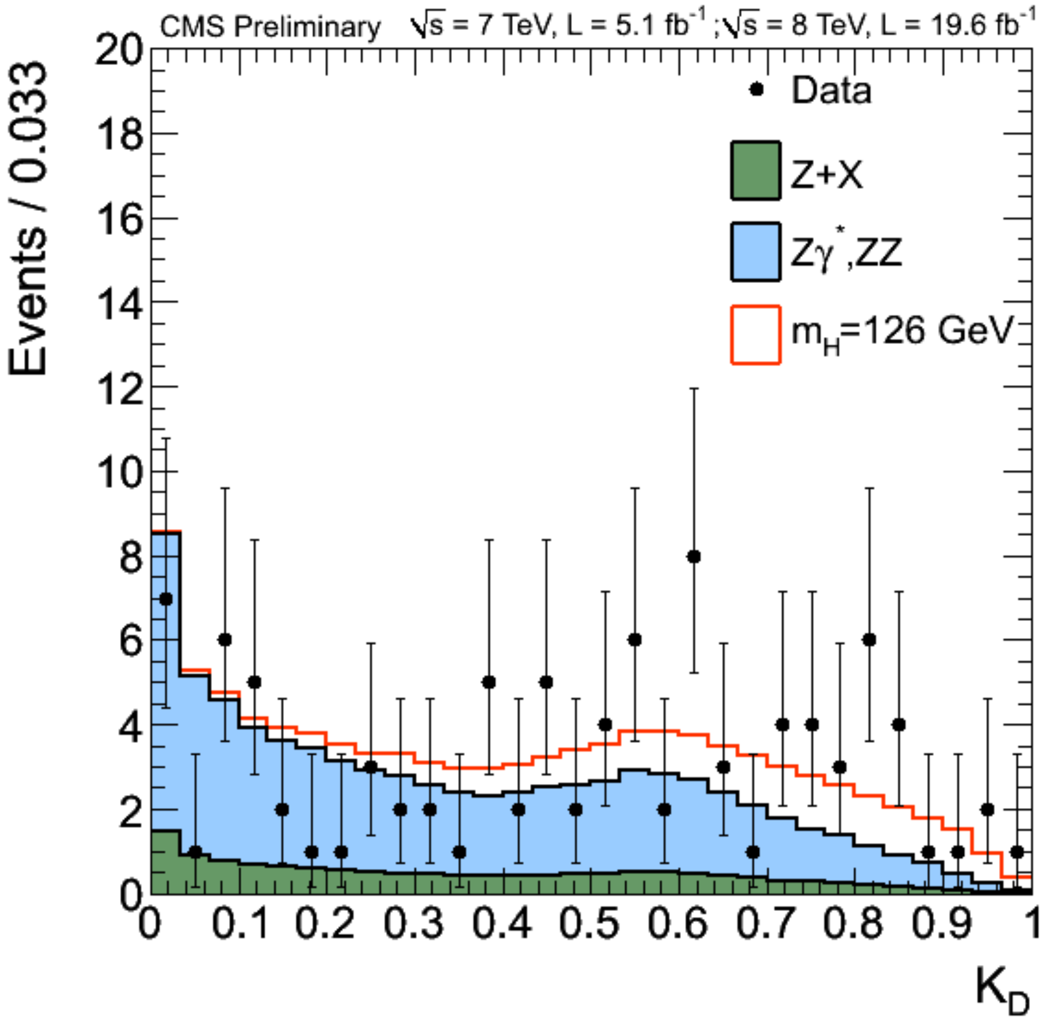
Reduce BG further & study additional properties of these events

- Angles shown carry information of scalar (SM H), pseudo-scalar vs spin-2 decay versus ZZ production



Kinematic Discriminator

CMS HIG-13-002

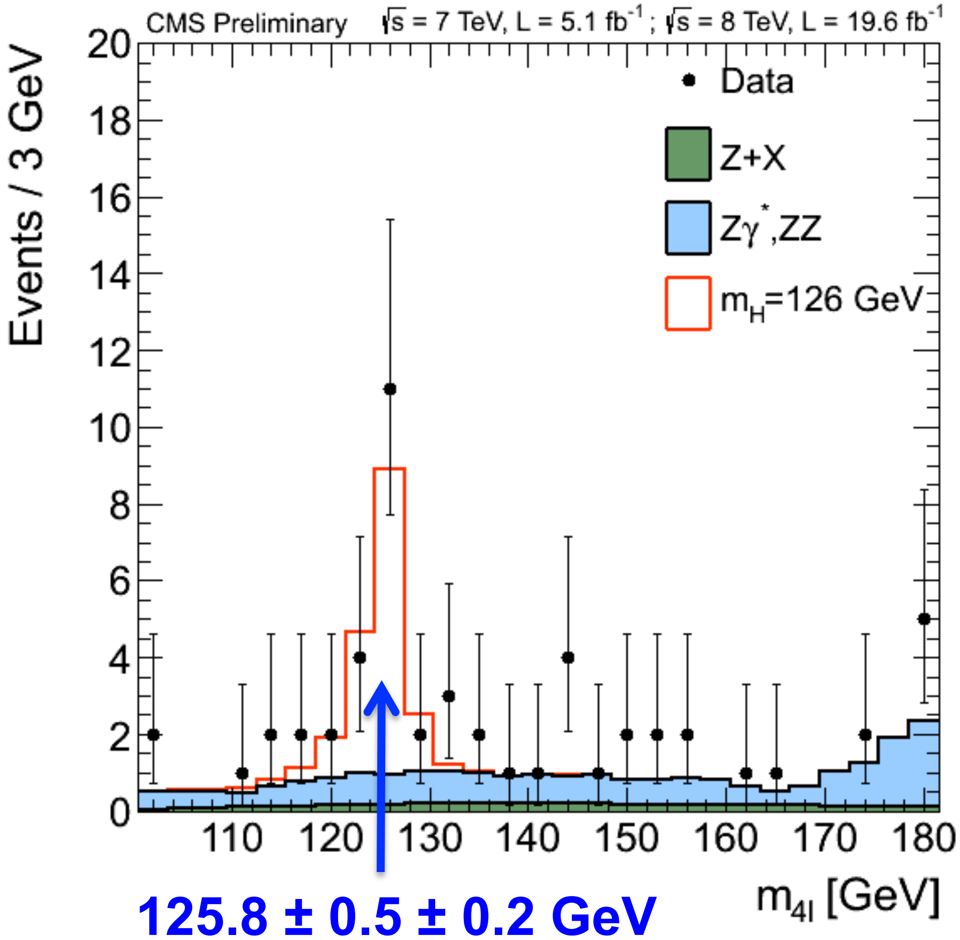


Strong Evidence in decays to ZZ

CMS HIG-13-002

Boost using angular information from 4.7 to 6.7 sigma

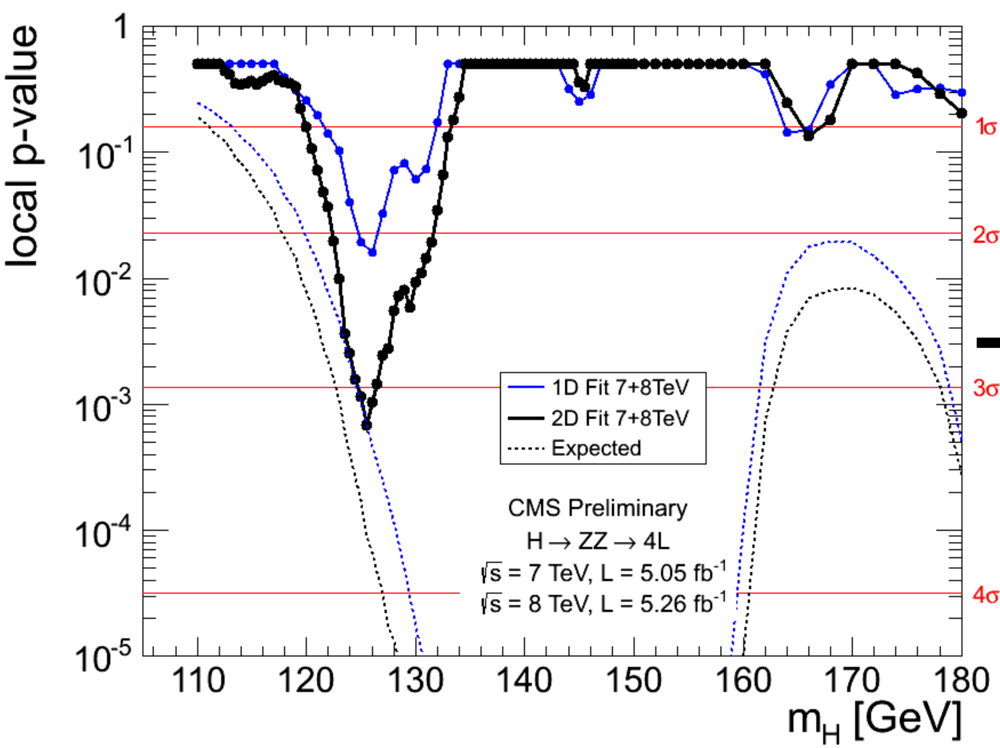
- Reduce background, while keeping signal-like events

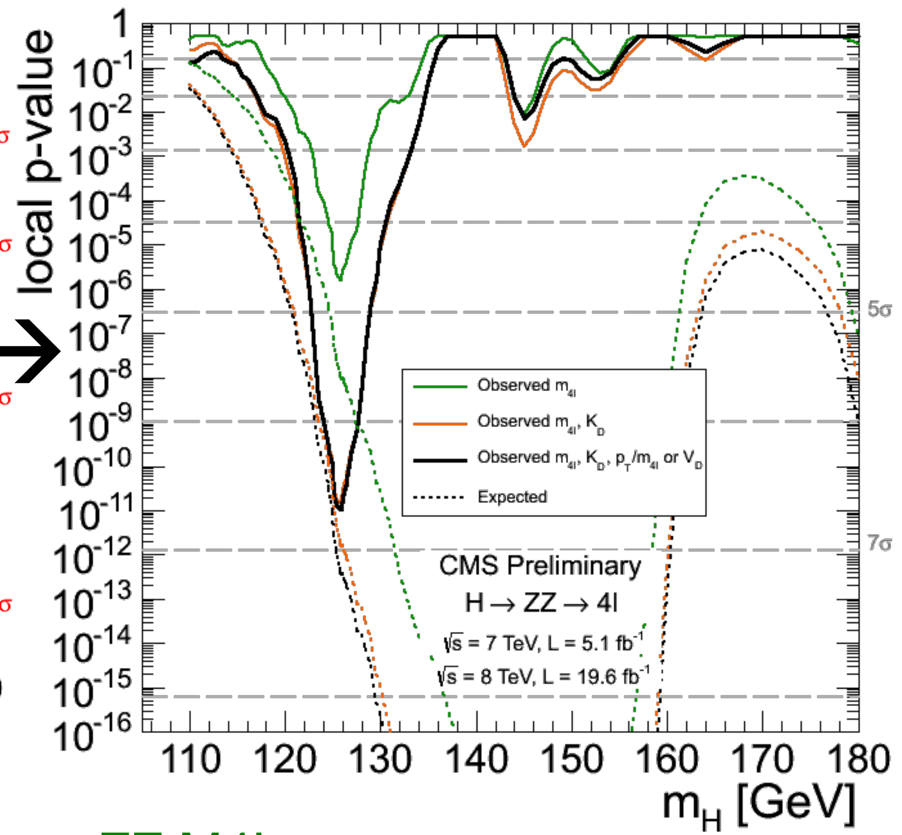


ZZ Signal Strength

CMS HIG-13-002

Adding statistics → Cleaned up nicely





ZZ M4L

ZZ M4L & MELA

ZZ M4L

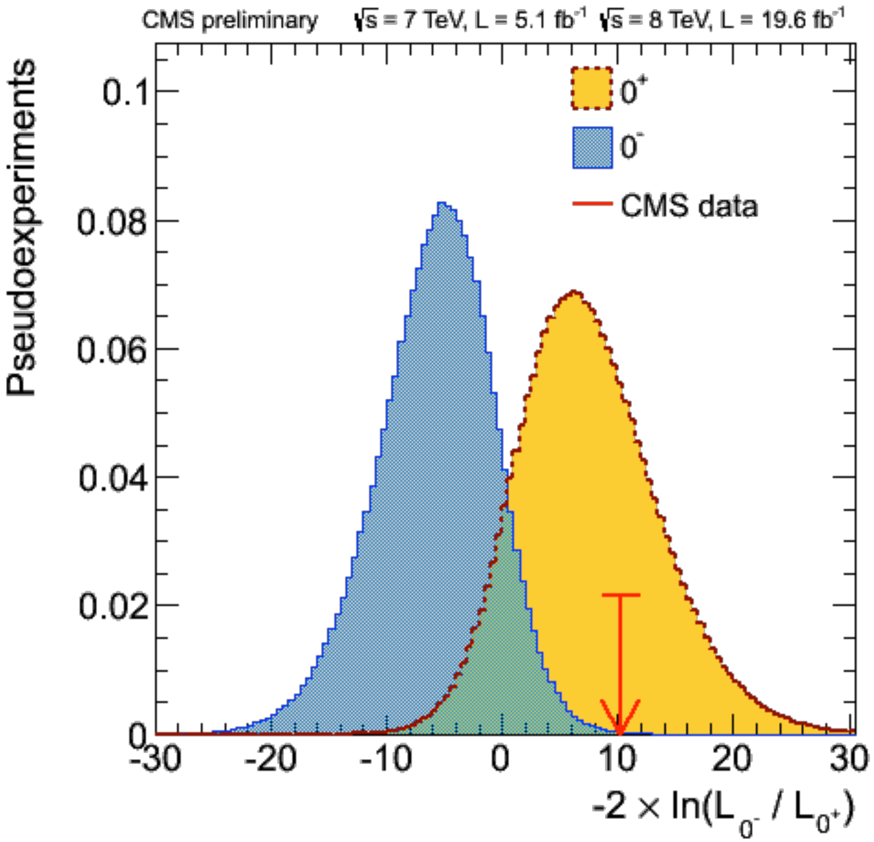
ZZ M4L, KD and P_T

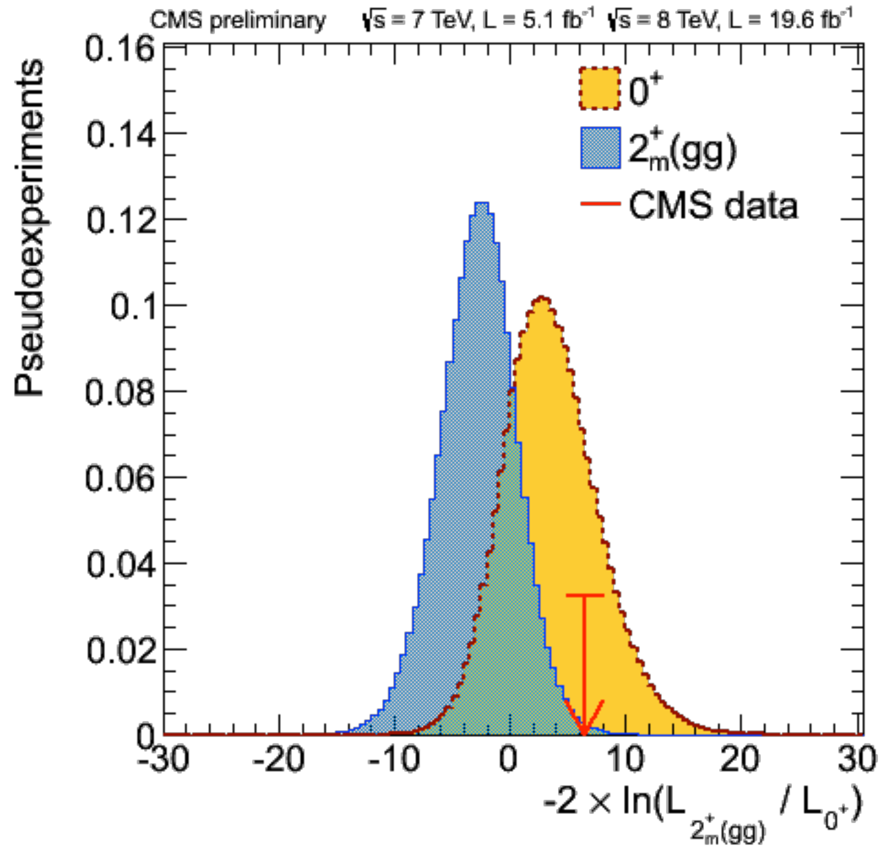
The new boson is scalar like!

CMS HIG-13-002

Angular analysis of ZZ using KDs for 0^+, 0^-, 1 and 2^+

Disfavors 0^- over 0^+ by CL_S value of 0.16% and 2^+ by 1.5%





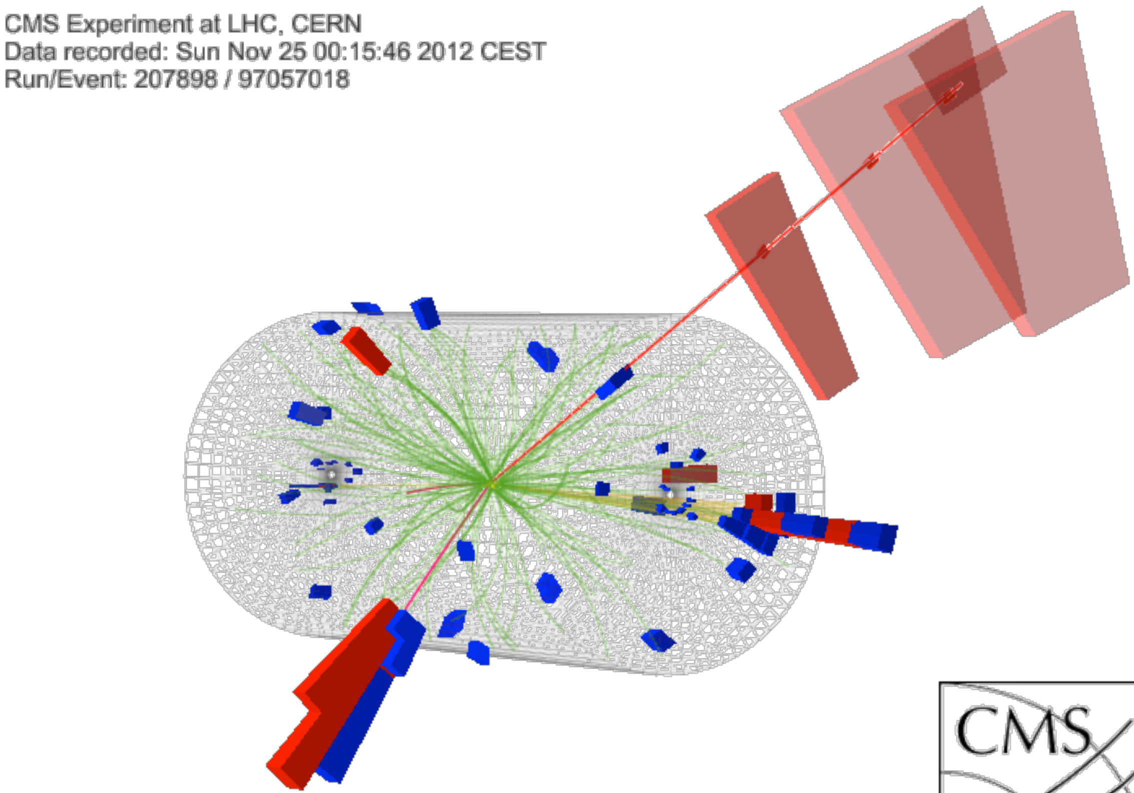
Spin 1 disfavored by a lot

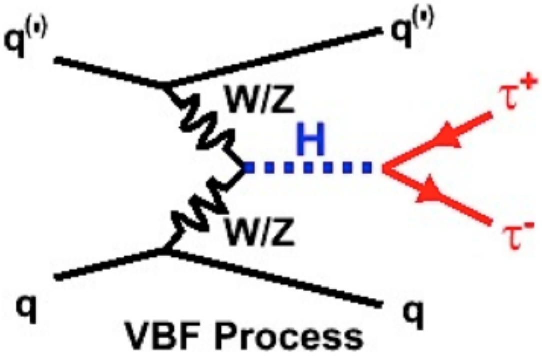
Higgs Decay to Tau Pairs

CMS HIG-13-004

Taus with high branching fraction can probe in all production modes:

W and Z boson fusion; Gluon fusion and W, Z, top associated production





Final states VBF + GF:

$e\mu$, $\mu\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

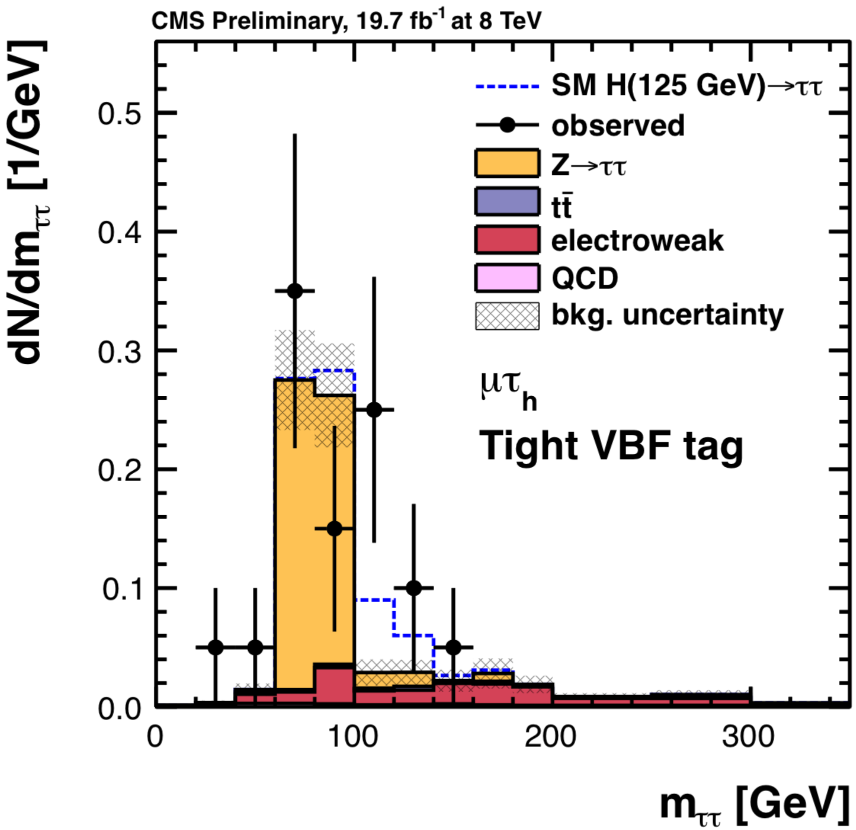
Also, VH (WH & ZH)

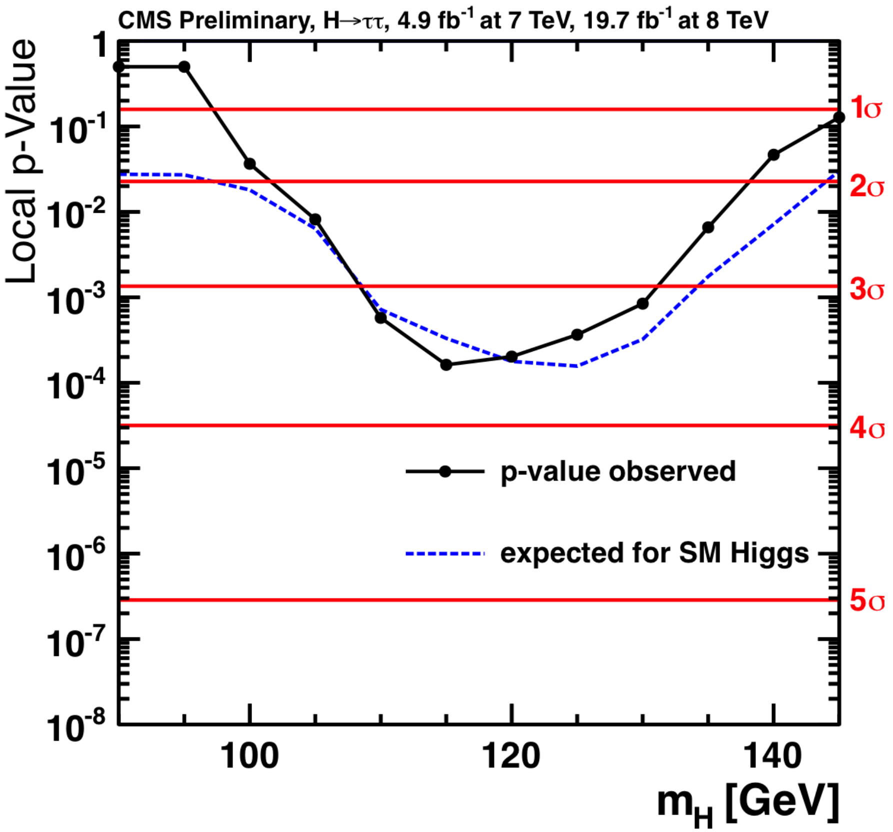
$\ell\ell\tau_h$, $\ell\tau_h\tau_h$, $\ell\ell\tau_h\tau_h$

Combination of ττ All Categories + Channels

CMS HIG-13-004

A 3.4σ signal @ 125 GeV emerging (expected 3.9σ)





>4 σ evidence for fermion coupling combined with bb.

Couplings Scan

CMS HIG-13-005

Details on CMS Higgs combination: Roberto Covarelli's talk in parallel session.