Connection between diphoton and 3-boson channels

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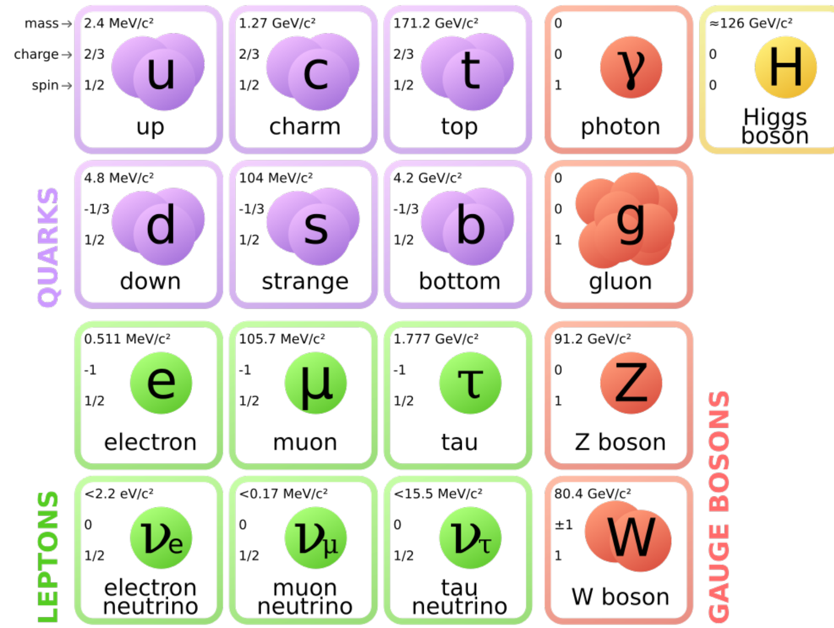
The Standard Model

- The Standard Model is a successful model of particle physics that combines three (electromagnetic, weak and strong) of four fundamental forces together

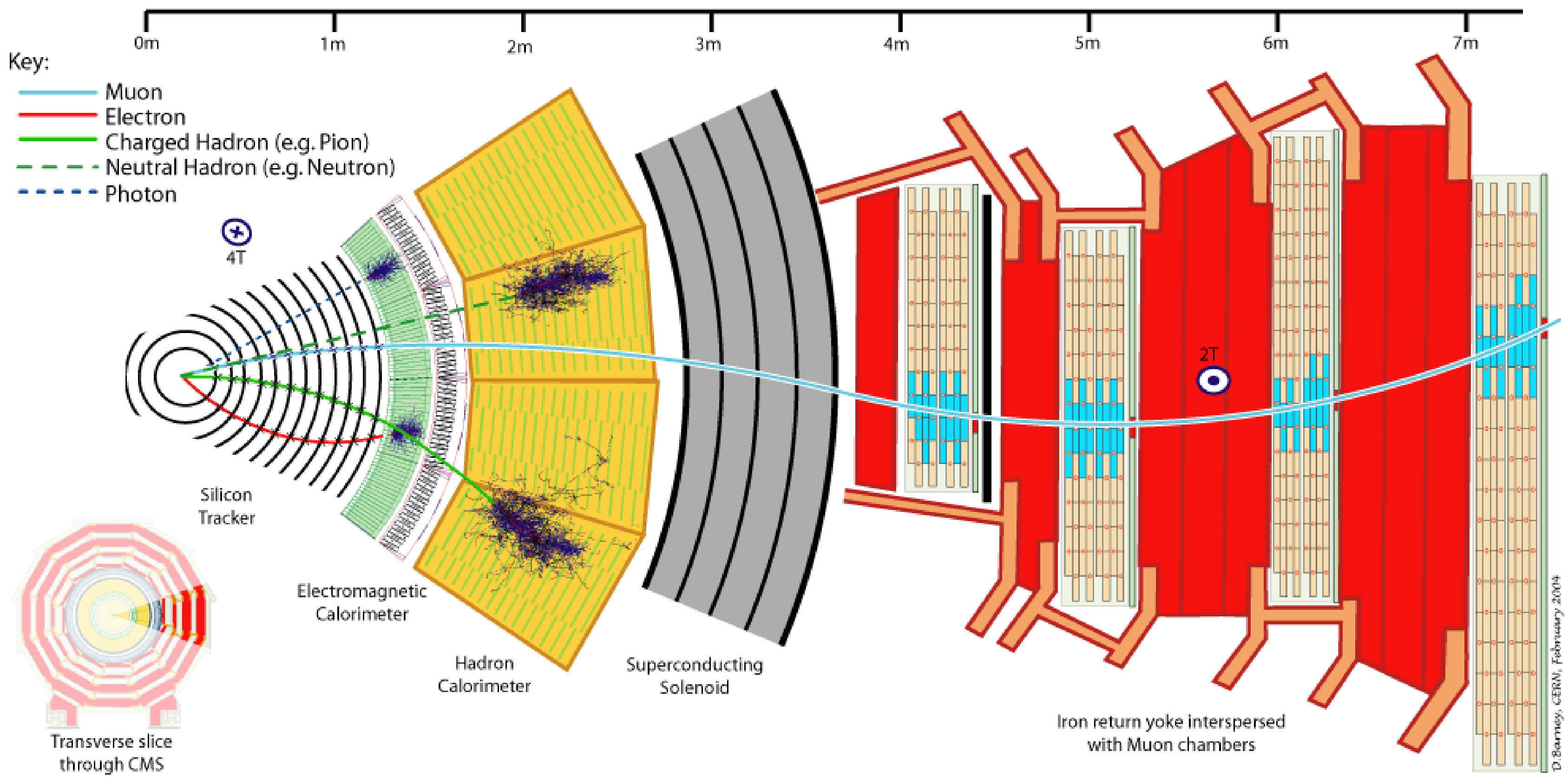


- All predicted particles are found and we do not observe significant deviations from the SM at the collider experiments

- However... There exist well established observational phenomena, **not explained** by the SM: *Neutrino Oscillations, Dark Matter, Baryogenesis*

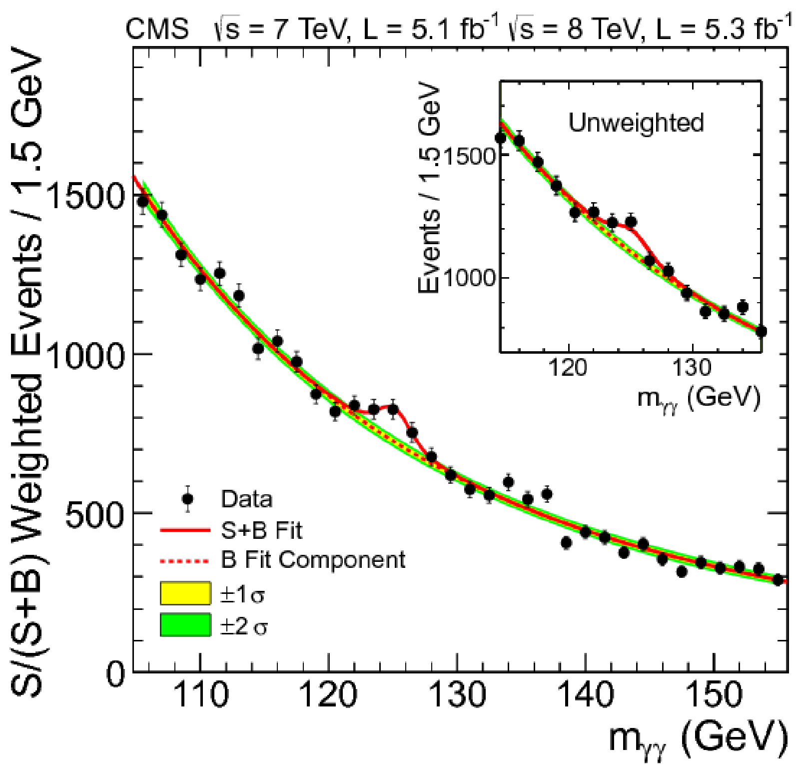
- That is why it is important to examine any beyond the SM signals

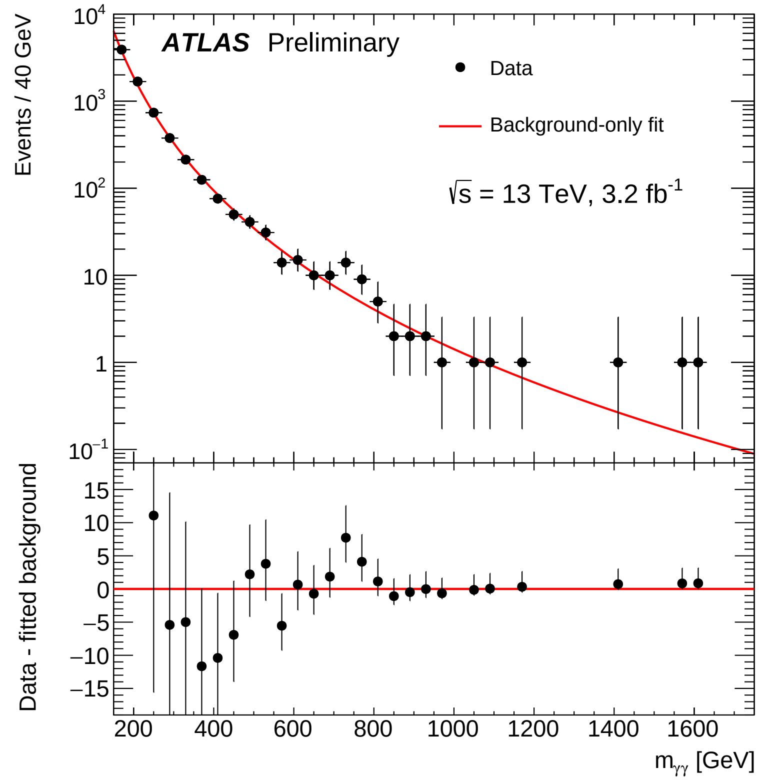
Particle Detection



- Particles that reach the detector: ν, $\mu^{\pm}$, hadrons, $e^{\pm}$, γ

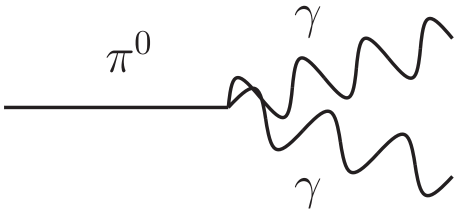
Examples of the Diphoton Signals





- Higgs was found in the diphoton channel, despite the fact that the branching ratio for $H \to \gamma\gamma$ channel is $\sim 10^{-3}$
- 750 GeV resonance (which vanished with more data) had been observed in the diphoton channel

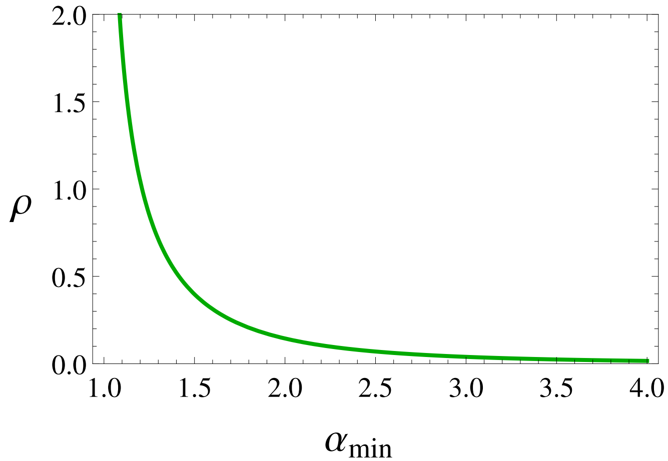
- For a scalar relativistic particle, the distribution of decay products in the rest frame are isotropic



- In the laboratory frame, the relativistic particle has the Lorentz factor $\gamma = E/m$
- The distribution in α-angle between two photons is

$$\frac{dN_\gamma}{d\alpha} = \frac{1}{2\sqrt{\gamma^2 - 1}} \frac{\cos(\alpha/2)}{\sin(\alpha/2)} \frac{1}{\sqrt{\gamma^2 \sin^2(\alpha/2) - 1}} \quad (1)$$

- The minimal angle $\alpha_{\text{min}} = 2/\gamma$
- 95% of the photon pairs have the opening angle $\delta\theta < 6/\gamma$



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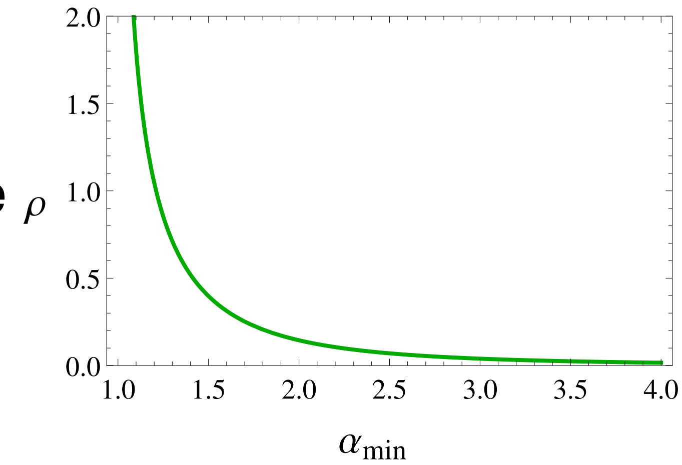
Misidentification

- 95% of the photon pairs have the opening angle $\delta\theta < 6/\gamma$



- The angular resolution of the detector is always finite!
- The detectors at LHC: CMS and ATLAS are *different*
- The granularity for them are

  CMS: 0.0174×0.0174

  ATLAS: 0.0031×0.1

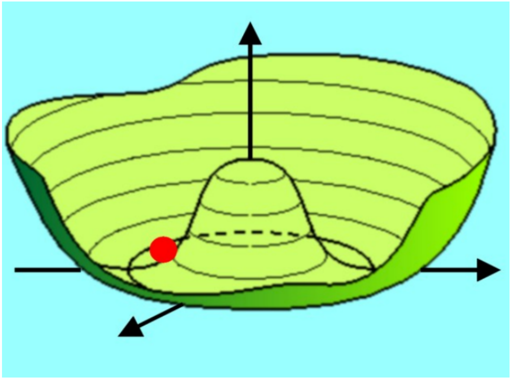
- For large enough γ factor the misidentification take place - two photons detected as a single photon

Example of Misidentification: The Axion Model

- Consider the *complex scalar field* ϕ with the spontaneously symmetry breaking. Let us write ϕ in the following form

$$\phi = (f + s)e^{i\frac{a}{f}}, \qquad (2)$$

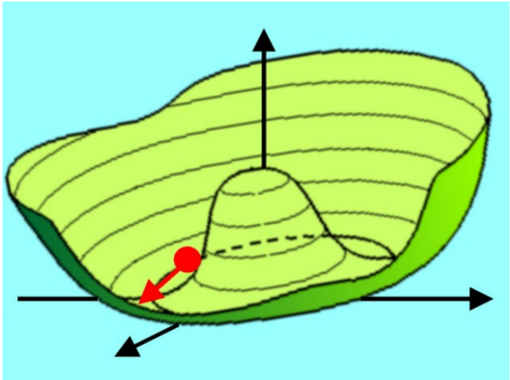
where f is the vacuum expectation value



- We expect the *massive particle* s and *massless particle* a (the Goldstone boson), which comes from the Peccei-Quinn symmetry

Example of Misidentification: The Axion Model

- If the Peccei-Quinn symmetry is *slightly broken*, the axion becomes massive, but much lighter that the heavy scalar particle s



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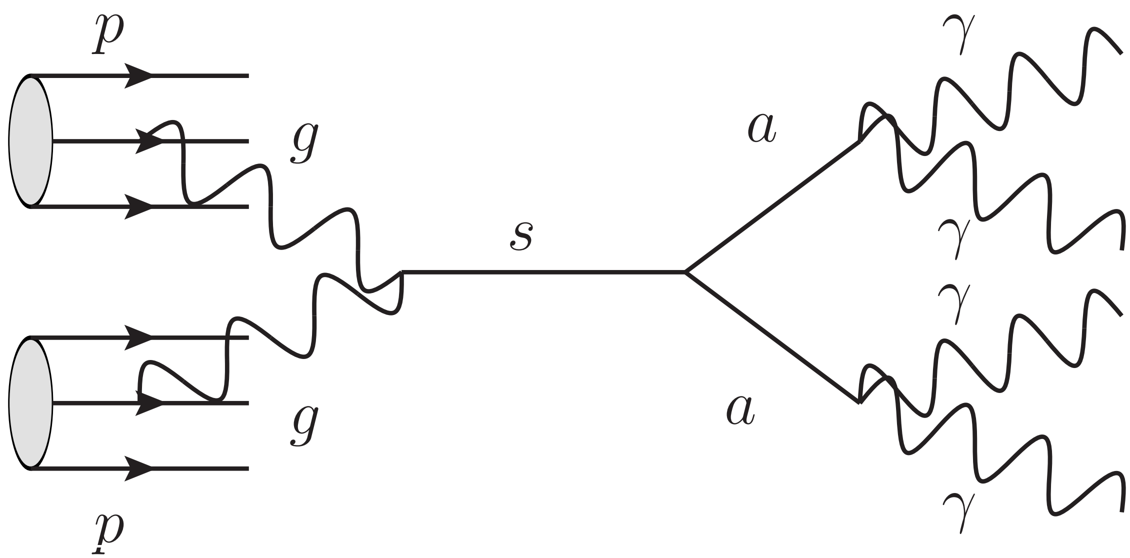
- The Lagrangian of interaction is

$$\mathcal{L}_{\text{int}} = \frac{c_g \alpha_s s}{12\pi f} G_{\mu\nu} G^{\mu\nu} + \frac{3\alpha c_\gamma a}{4\pi f} \epsilon^{\alpha\beta\gamma\delta} F_{\alpha\beta} F_{\gamma\delta} + s \frac{(\partial_\mu a)^2}{f} \quad (3)$$

- The last term in the interaction Lagrangian has interesting origin. It comes from the kinetic term of field ϕ. That is why it *does not have coupling constants*

Example of Misidentification: 750 GeV



- A scalar particle s with a mass $M_s = 750$ GeV decays into two very light particles a (axions)

- Each axion decays into two photons, but these particles are very **relativistic** and photons from its decay are highly collimated. The detector misidentify two photons as one

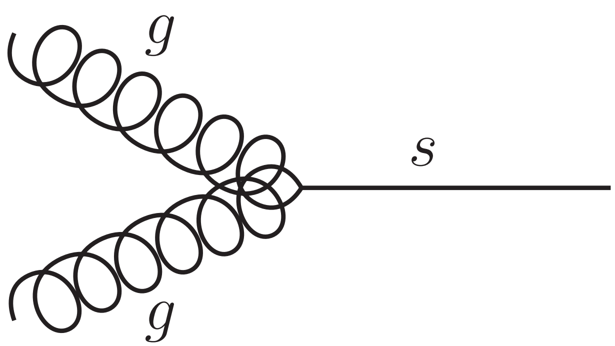
Connection between the diphoton channel and 3 boson channel

- The *diphoton signal* is always connected with WW, ZZ or γZ signals because of the gauge invariance of the SM

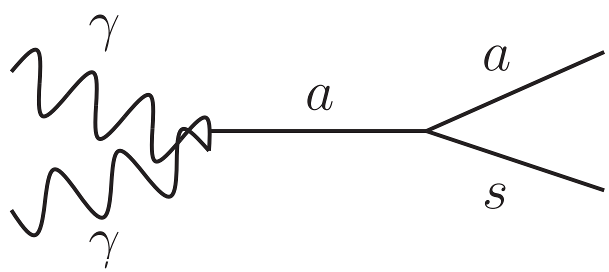
- Due to the misidentification, observation of *two photon signal* can be related with *three boson signal*

- Let us consider more careful the phenomenological model with axions

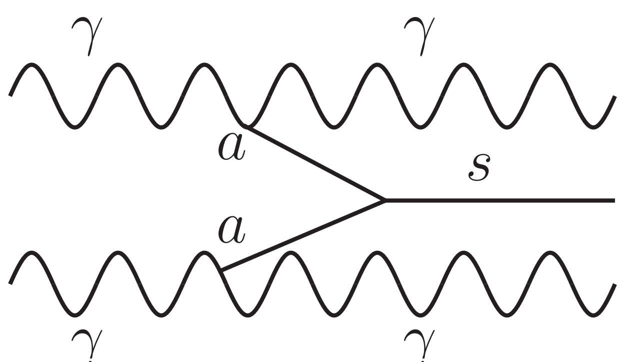
Production channels of s



(a) $\sigma_{\text{gluon}} \propto c_g^2/f^2$



(b) $\sigma_{\text{assoc}} \propto c_\gamma^2/f^4$



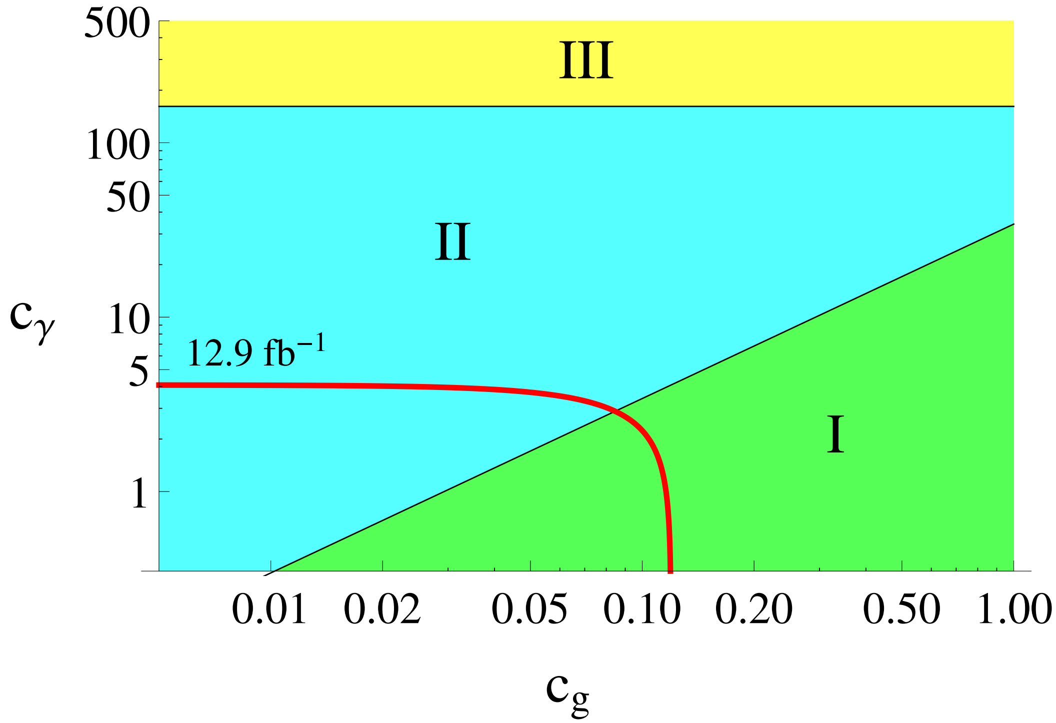
(c) $\sigma_{\text{fusion}} \propto c_\gamma^4/f^6$

Constraints from the Diphoton Signal

- There is a constraint on the diphoton channel, that puts a constraint on the s decay into 2 axions

$$\sigma_{\text{gluon}} + \sigma_{\text{assoc}} + \sigma_{\text{fusion}} \leq \sigma_{\gamma\gamma}, \quad (4)$$

where $\sigma_{\gamma\gamma}$ was taken from the experimental data



Gauge Invariant Action

- The term $\frac{3\alpha c_\gamma a}{4\pi f}\epsilon^{\alpha\beta\gamma\delta}F_{\alpha\beta}F_{\gamma\delta}$ in the interaction Lagrangian (3) is not gauge invariant under $SU(2)\times U(1)$ symmetry of the SM

- The gauge invariant form is

$$\boxed{\mathcal{L}_{\text{int}}^{\text{gauge}} = -\frac{c_1}{4f}\epsilon^{\alpha\beta\gamma\delta}aW^i_{\alpha\beta}W_{\gamma\delta,i} - \frac{c_2}{4f}\epsilon^{\alpha\beta\gamma\delta}aB_{\alpha\beta}B_{\gamma\delta}}, \qquad (5)$$

The coupling constants c_1 and c_2 are related to c_γ as

$$c_\gamma = \frac{\pi}{3\alpha}(c_1\sin^2\theta_W + c_2\cos^2\theta_W), \qquad (6)$$

The strength tensors for the gauge fields are

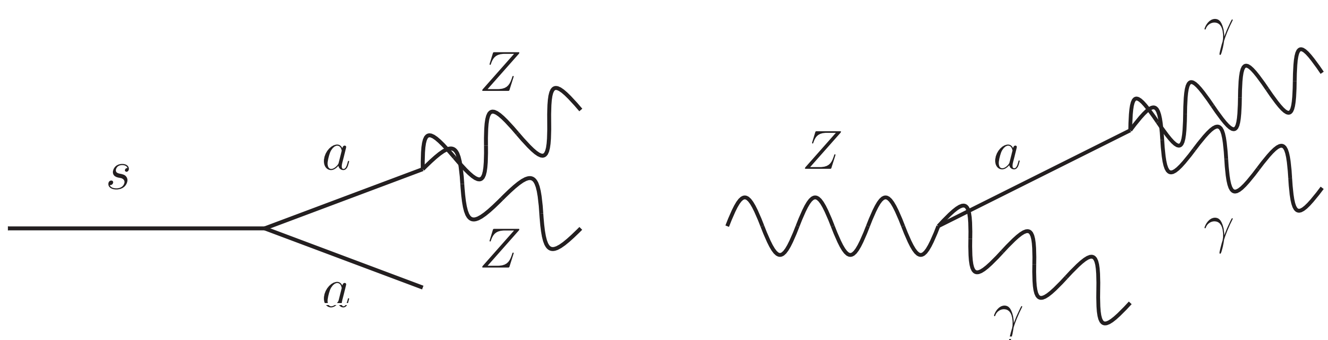
$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu, \qquad (7)$$

$$W^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + c_g\epsilon^{ijk}W^j_\mu W^k_\nu. \qquad (8)$$

Gauge Invariant Action

- Thus, if we have an interaction of a new particle with photons $\boxed{a\gamma\gamma}$, the $SU(2) \times U(1)$ symmetry predicts other **additional interactions** with vector bosons of the SM and **additional channels**

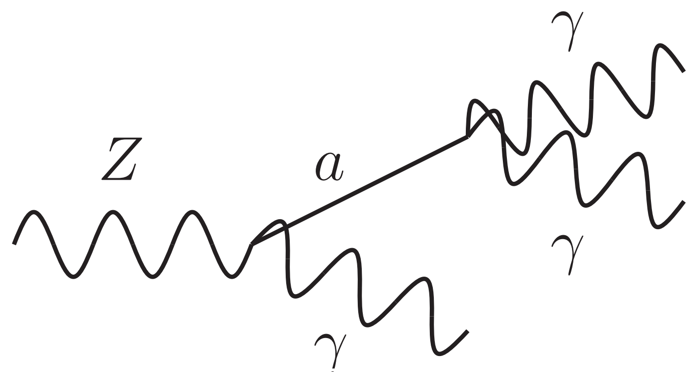
$$\mathcal{L}_{gauge} = c_{\gamma\gamma}\boxed{a\gamma\gamma} + c_{ZZ}\boxed{aZZ} + c_{\gamma Z}\boxed{a\gamma Z} + c_{WW}\boxed{aW^+W^-} + c_{WW\gamma}\boxed{aW^+W^-\gamma} + c_{WWZ}\boxed{aW^+W^-Z}$$



Example of Misidentification: Z Boson Decay

- The *Landau-Yang theorem* forbids the decay of Z boson into two photons

- However, if Z boson interacts with some light particle a, it *could decay into two photons* (from the experimental point of view)



- Interesting channel to search for new non-SM particles!

Z Boson Decay

- The decay width is given by

$$\Gamma_{Z\to a\gamma} = \frac{1}{24\pi f^2}(c_1 - c_2)^2 \cos^2\theta_W \sin^2\theta_W M_Z^3 \tag{9}$$

- The measurement of the Z boson decay into 2 photons was done by the CDF collaboration. Obtained constraint is

$$\text{BR}(Z \to \gamma\gamma) \leq 1.5 \cdot 10^{-5} \tag{10}$$

- $Z \to \gamma\gamma$ decay puts the following constraint on the model parameters

$$|c_1 - c_2| \leq 0.05 \left(\frac{f}{320\ \text{GeV}}\right) \tag{11}$$

3 boson channels

- The decay widths in the limit $M_s \gg m_Z, m_W$ are

$$\Gamma_{s\to Z\gamma a} = \frac{M_s^2}{16\pi^2}\left(\frac{(c_1 - c_2)\sin\theta_W\cos\theta_W}{f}\right)^2 \Gamma_{s\to aa} \quad (12)$$

$$\Gamma_{s\to ZZa} = \frac{M_s^2}{32\pi^2}\left(\frac{c_1\cos^2\theta_W + c_2\sin^2\theta_W}{f}\right)^2 \Gamma_{s\to aa} \quad (13)$$

$$\Gamma_{s\to WWa} = \frac{M_s^2}{16\pi^2}\left(\frac{c_1}{f}\right)^2 \Gamma_{s\to aa} \quad (14)$$

- Branching ratios for these channels depending on the ratio between the coupling constants c_1, c_2

- Taking into account the constraint on $|c_1 - c_2|$

$$\text{BR}(s \to Z\gamma a) \leq 1.5 \cdot 10^{-5}\left(\frac{M_s}{750\text{ GeV}}\right)^2 \quad (15)$$

3 boson channels

- The channel $s \to Z\gamma a$ is highly suppressed compare to the diphoton channel
- It is *possible* to expect 3-boson channels ($s \to ZZa$ or $s \to WWa$) *before the diphoton channel* if the condition $c_1 = c_2 = c$ holds
- In this case we have a constraint on c from the diphoton search at the LHC

$$c \leq 0.035 \left(\frac{f}{320\ \text{GeV}}\right)^2 \frac{1}{\sqrt{\text{BR}(s \to aa)}} \tag{16}$$

- To observe a signal in the 3-boson channel before the diphoton one, the required a condition on f

$$\boxed{f \geq 4 \times 10^4\ \text{GeV} \left(\frac{750\ \text{GeV}}{M_s}\right)} \tag{17}$$

Example of Misidentification: η meson

- The background for any particle is *smoothly decrease* with *increasing* of energy

- The misidentification *may change* our expectation in the following way

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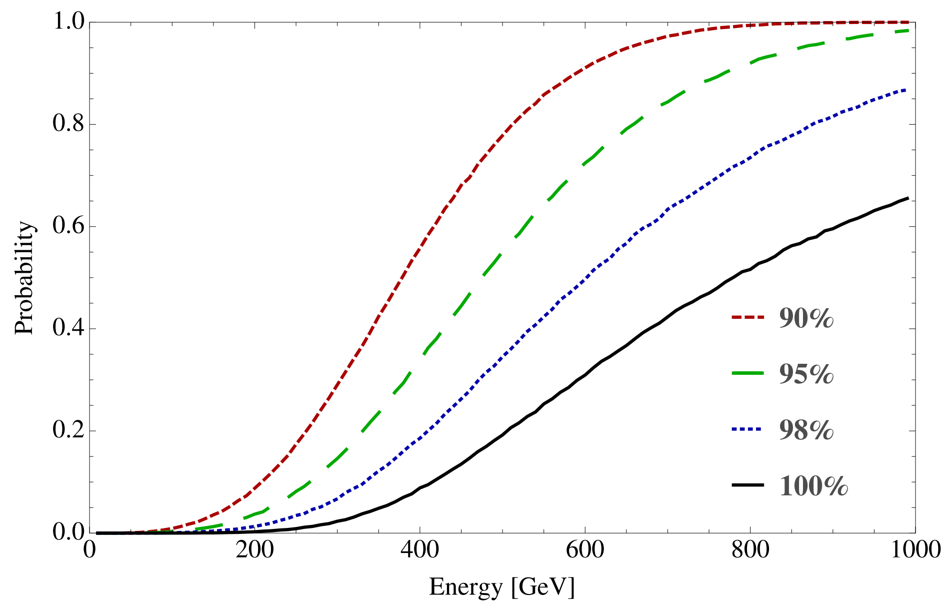
- Consider neutral mesons which decay into photons:

  - $\pi^0 \to 2\gamma$

  - $\eta \to 6\gamma$

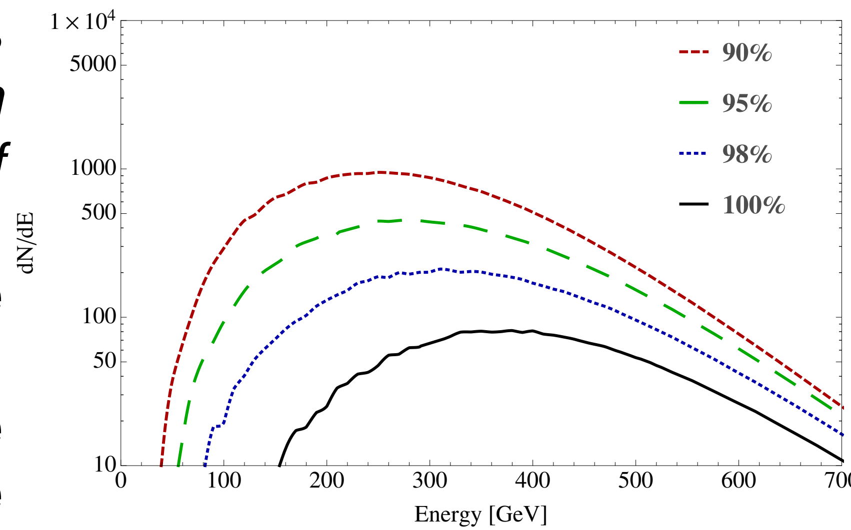


Example of Misidentification: η meson

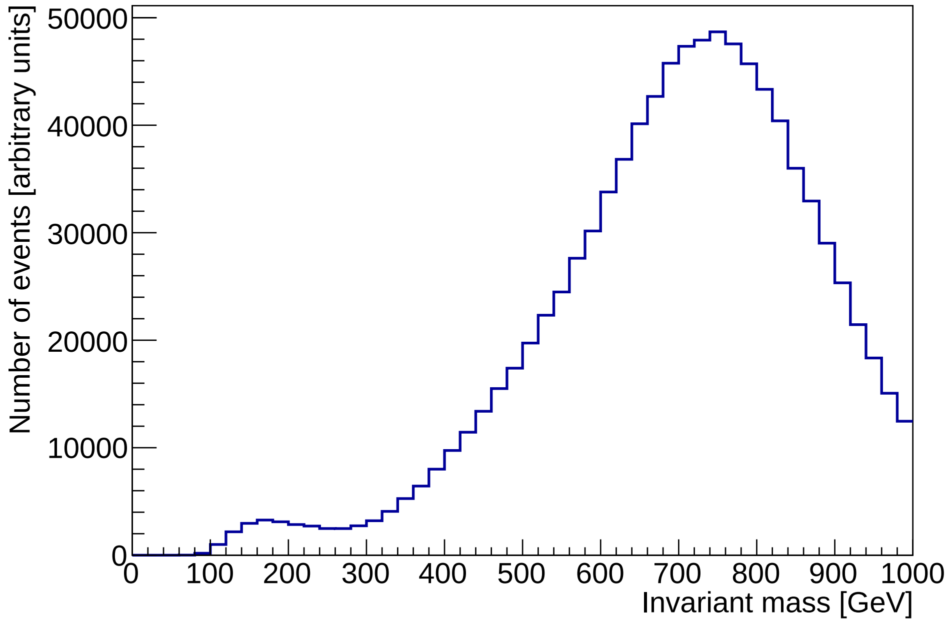
- When the energy of mesons increase, their amounts decrease. The simulations gives the approximated formula for number of η mesons

$$\frac{dN_\eta}{dE} \propto e^{-E/84\ \text{GeV}} \quad (18)$$

- The probability to observe the misidentification of photons is the production of the *distribution function* and the *probability of misidentification of the meson*. Because one function increase with the energy of the incoming neutral meson and the other one drops fast, at some place in the spectrum we can get a pick



Example of Misidentification: η meson



- Misidentification can give a resonance-like feature in the diphoton invariant mass distribution

- The position of this pick depends on three main factors: size of the calorimeter's granularity, the type of the neutral meson and the strategy of phopton identification

Conclusions

- We have shown, using the axion model, that two photon channel may be connected with 3 boson channel because of the misidentification of photons at detectors
- The observing of Z boson decay into two photons might be not an evidence of the violation of the Landau-Yang theorem but an indication of a new light particle
- We have proved that 3 boson channel is an interesting channel for searching of physics beyond the SM at the LHC