Excess in $h \to Z\gamma$ but not $h \to \gamma\gamma$

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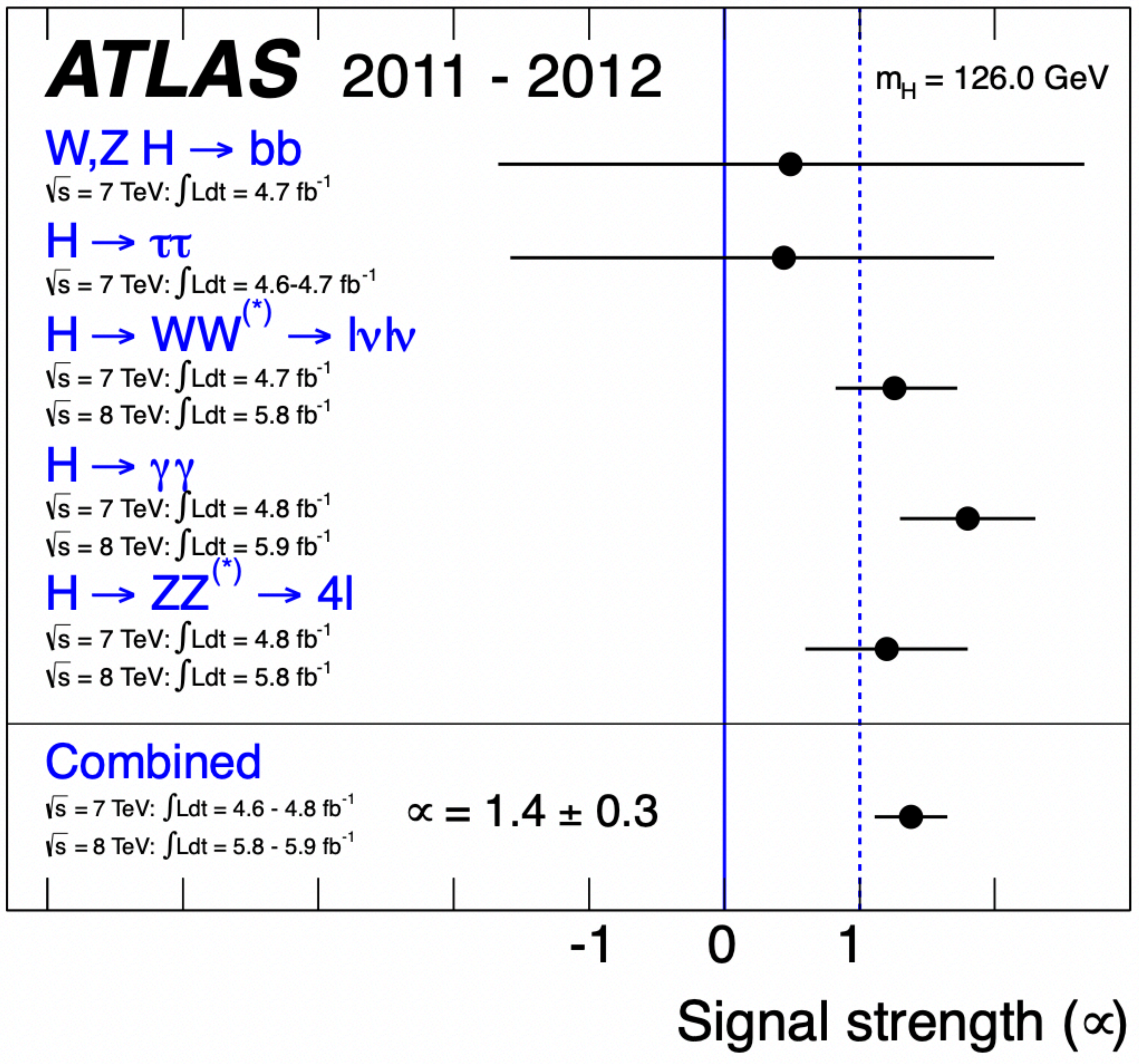
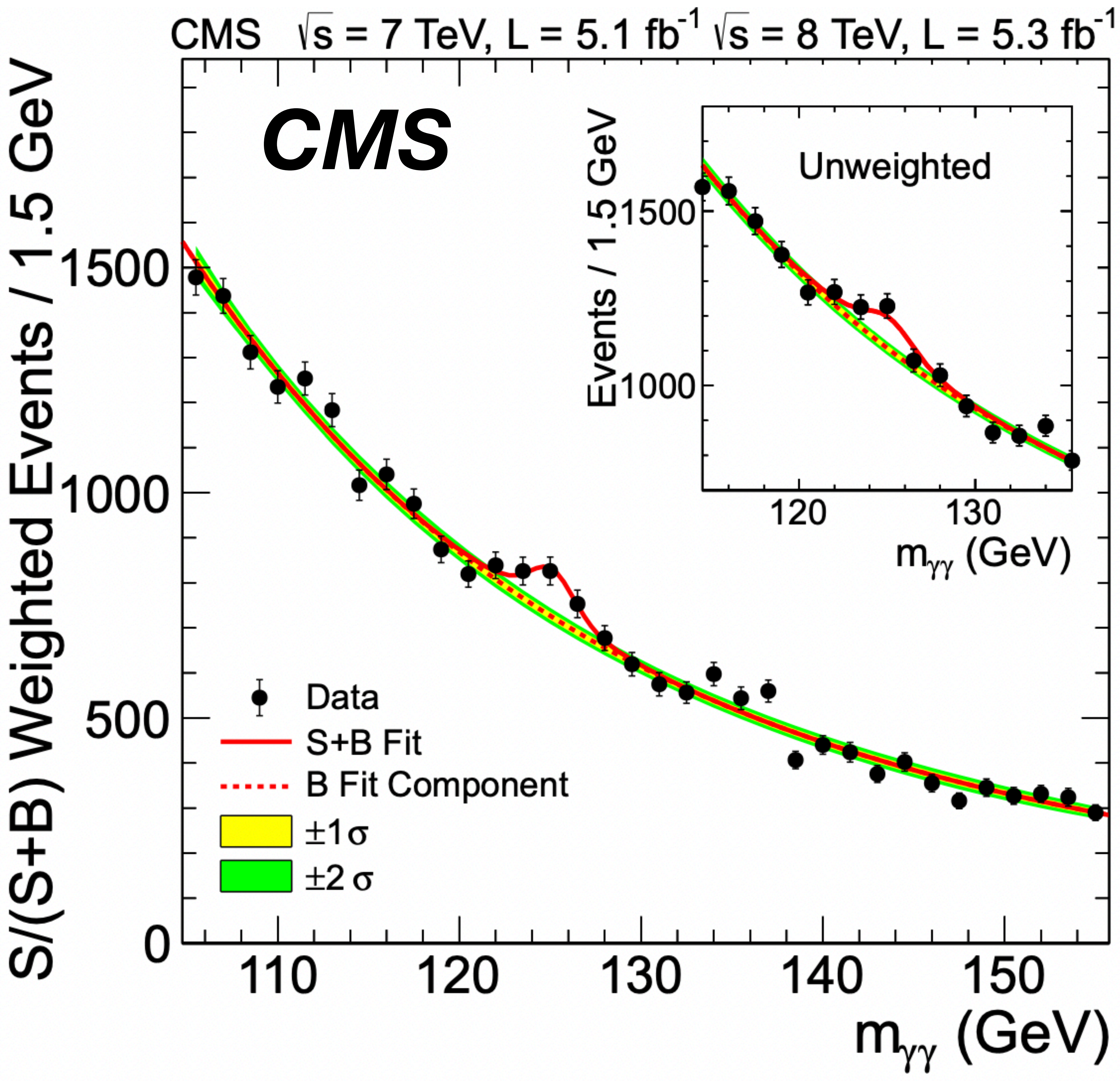
- **Research background**

The last observed **fundamental** *particle in the Standard Model.*

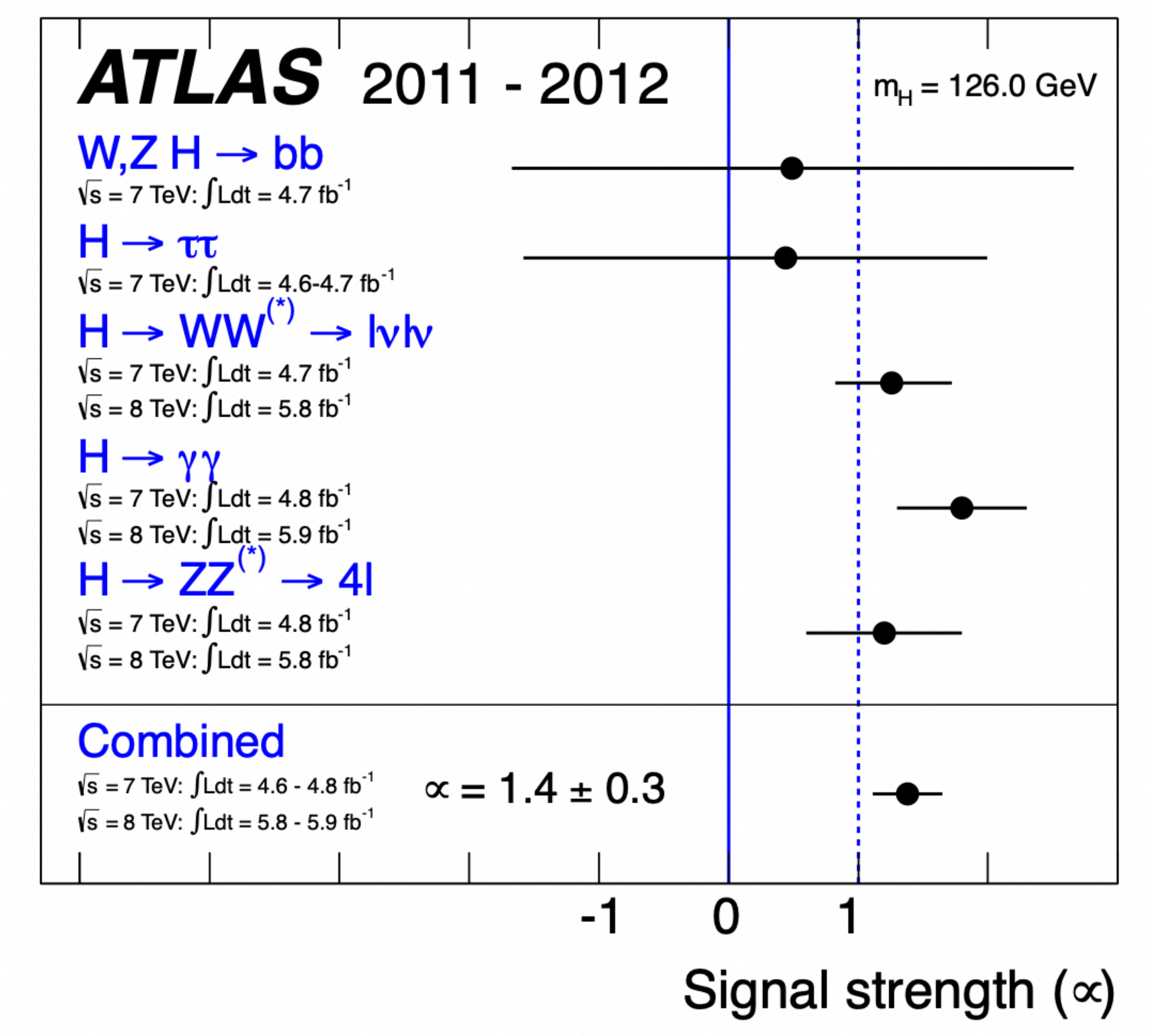




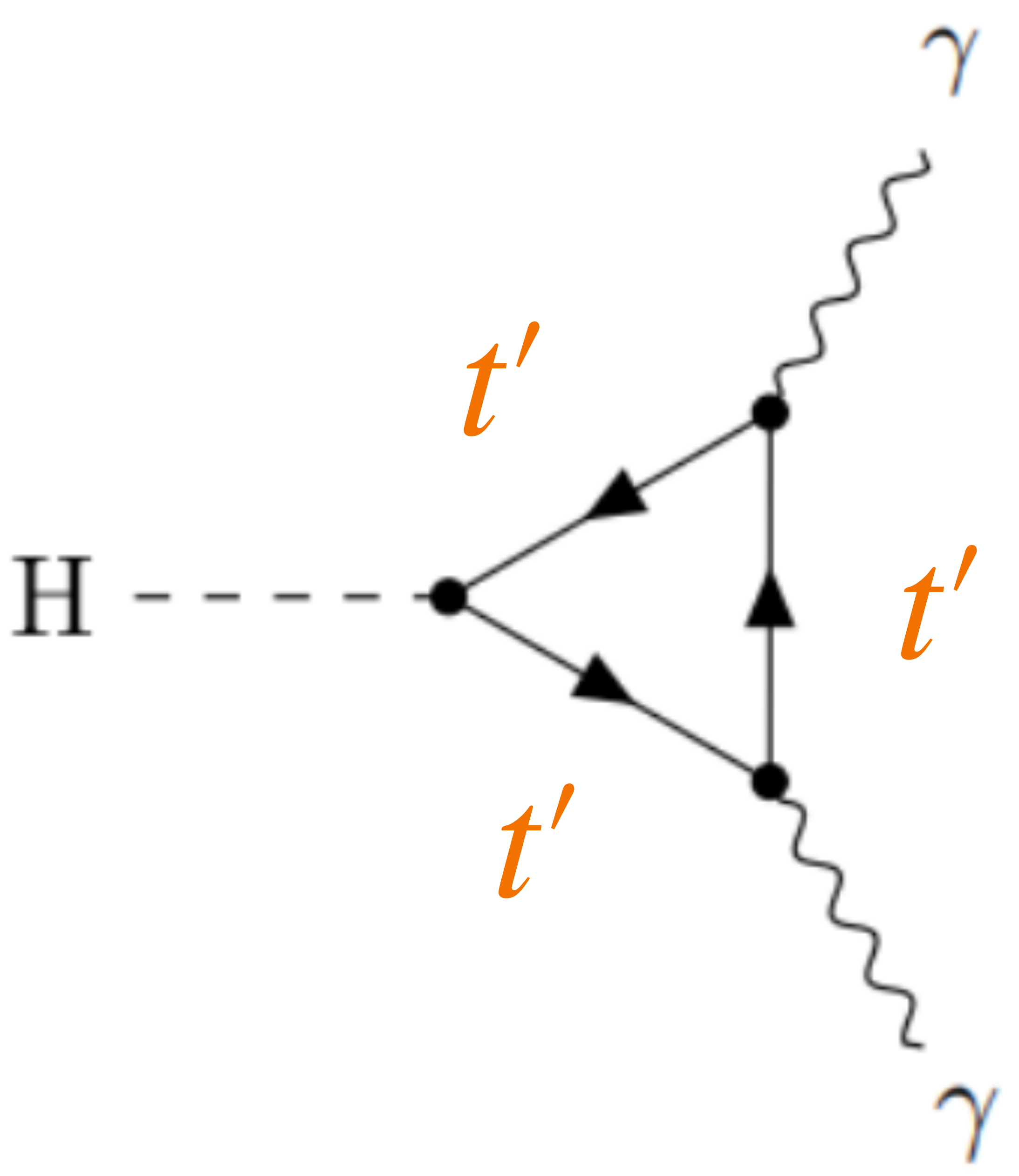
• Research background

Studies of Higgs couplings with gauge bosons are ***important****:*

Provide clear signals:



Testing new physics:



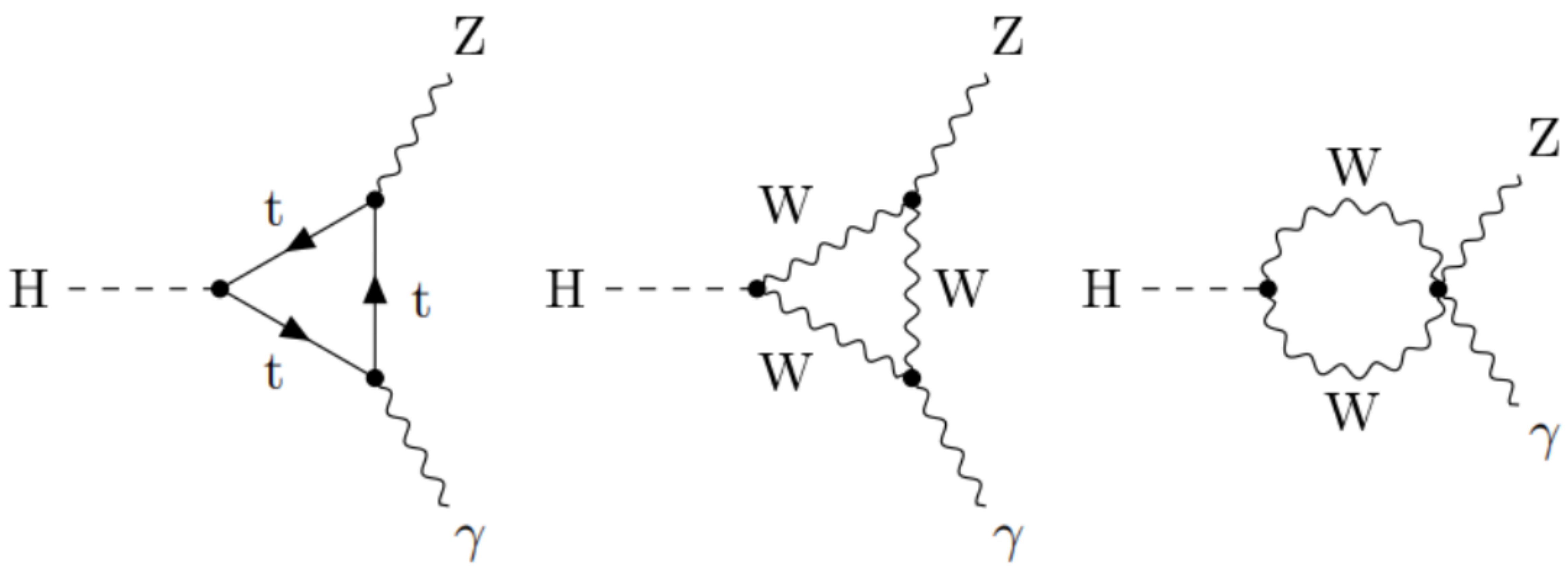
The fourth generation

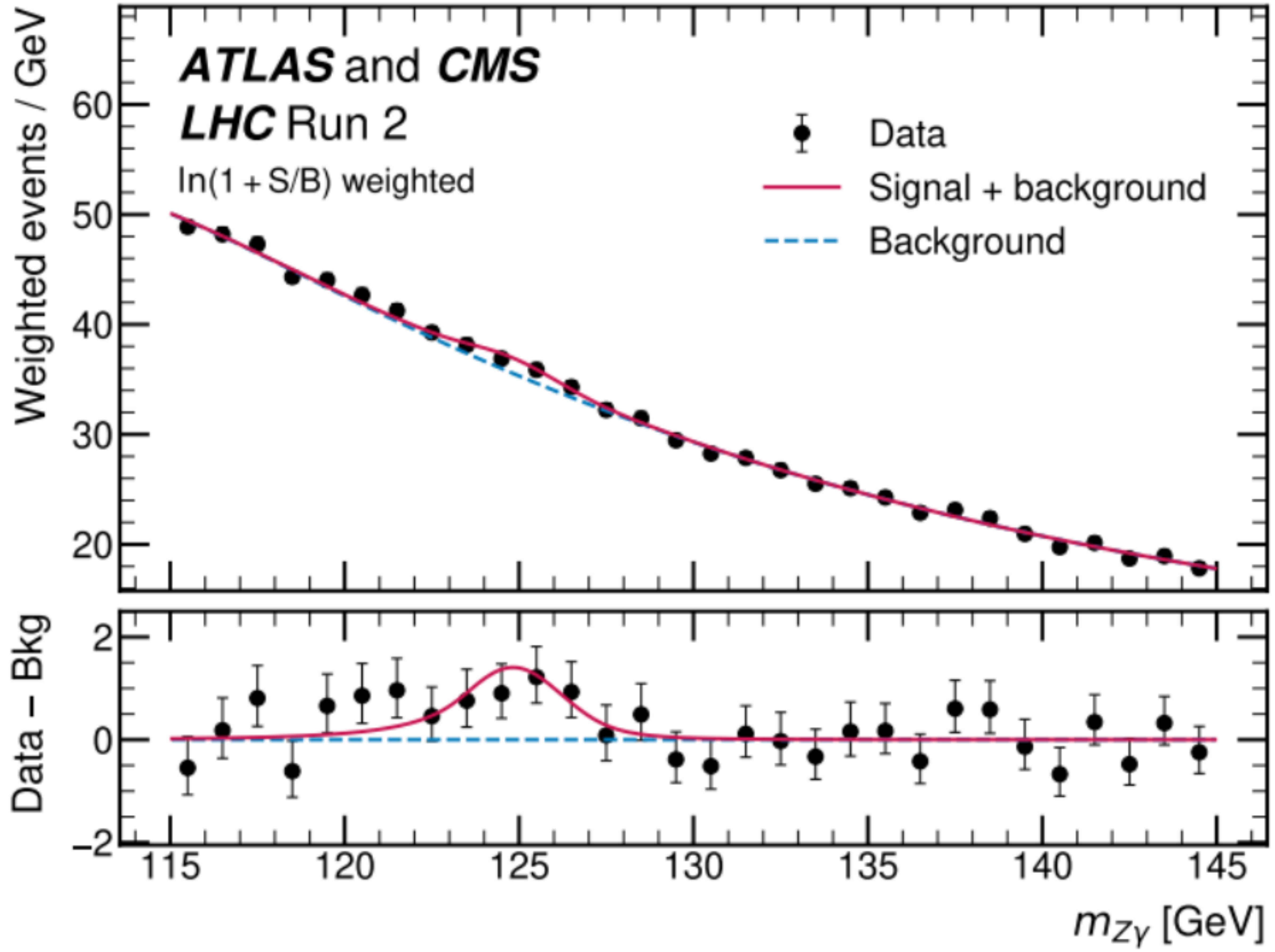
- # Research background

First evidence of $h \to Z\gamma$

$$\mu_{Z\gamma} = (\sigma \cdot Br)_{\text{obs}} / (\sigma \cdot Br)_{\text{SM}} = 2.2 \pm 0.7$$

Induced at loop level in the standard model:



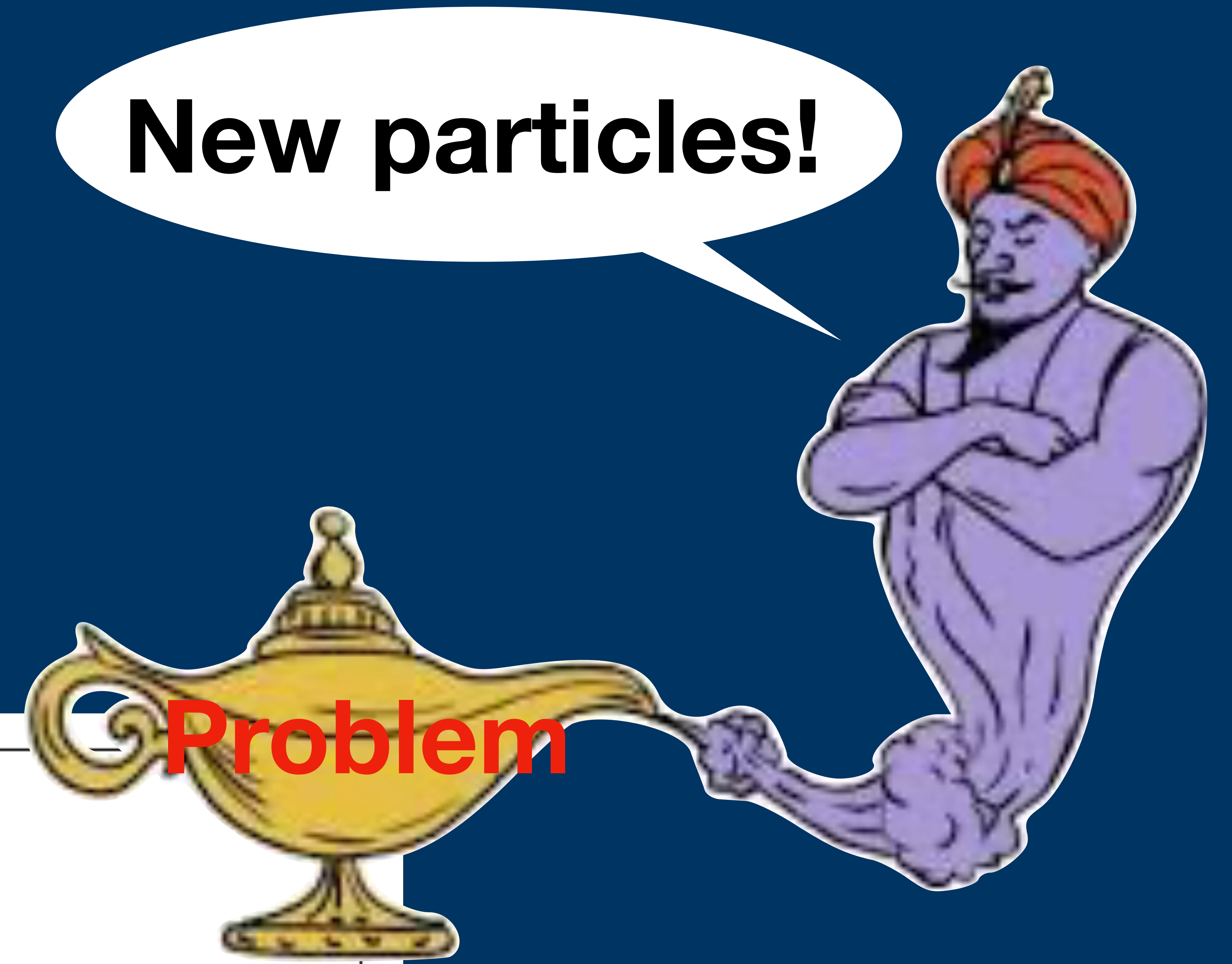


There are 1.7σ deviations in $\mu_{z\gamma}$!

For two-loop calculations, see:
Z. Q. Chen, L. B. Chen, C. F. Qiao and R. Zhu, **PRD 110** L051301(2024).
W. L. Sang, F. Feng and Y. Jia, **PRD 110** L051302(2024).

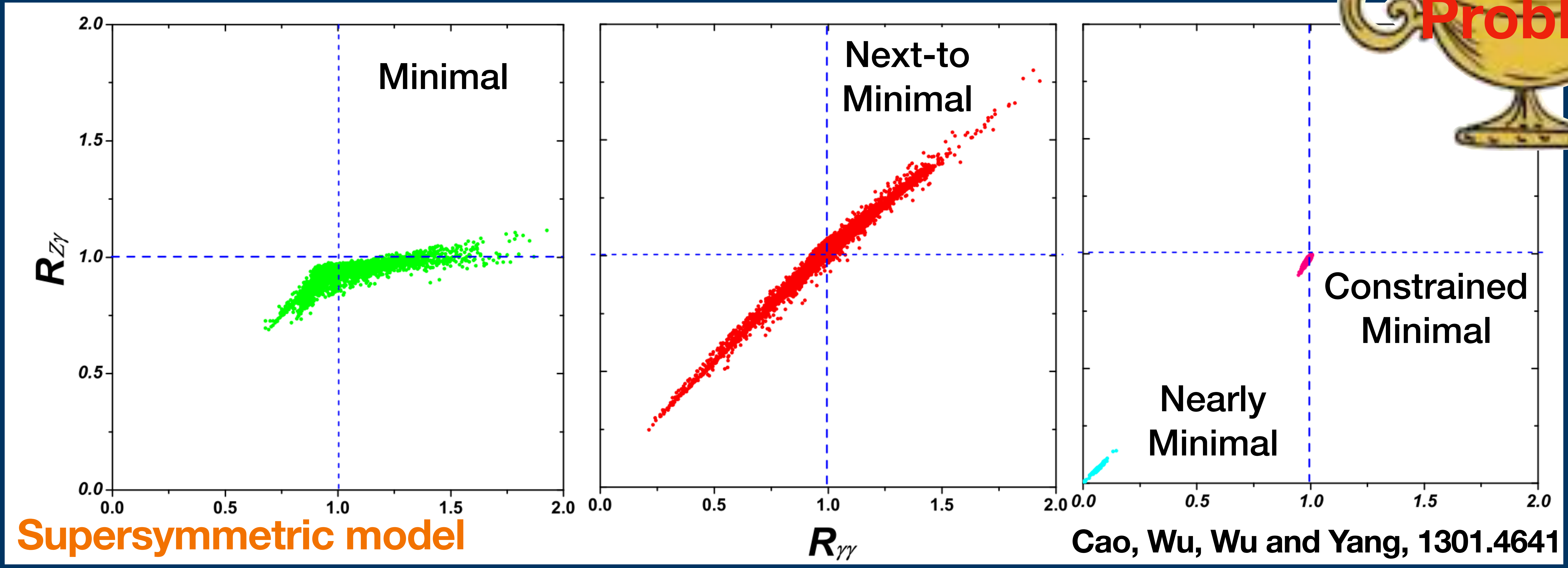
PRD 132 021803(2024).

Explain data with NP?



$$\mu_{Z\gamma}^{\text{exp}} = 2.2 \pm 0.7 \qquad \mu_{\gamma}^{\text{exp}} = 1.10 \pm 0.07$$

$$Z_\mu = \cos\theta_W W_\mu^3 + \sin\theta_W B_\mu \qquad A_\mu = \cos\theta_W B_\mu - \sin\theta_W W_\mu^3$$



Other studies in NP $\mu_{Z\gamma} < 1.5$: μνSSM, 2002.04370; U(1)XSSM, 2205.14880; 3-3-1 models, 1307.5572 ,1907.06735; left-right symmetric model, 2312.11045.

- ## Formalism

We start with the standard model effective field theory with Λ the NP scale.

It must respect the $SU(3) \times SU(2) \times U(1)$ gauge symmetry in the SM.

$$\mathscr{L}_{\rm eff} = c_{BB}\frac{g'^2}{2\,\Lambda^2}\,H^\dagger\,H\,B_{\mu\nu}B^{\mu\nu} + c_{WW}\frac{g^2}{2\,\Lambda^2}\,H^\dagger\,H\,W_{a\,\mu\nu}W_a^{\mu\nu} + c_{WB}\frac{g'\,g}{2\,\Lambda^2}\,H^\dagger\,\tau_a\,H\,W_a^{\mu\nu}B_{\mu\nu}$$

$$= \frac{\alpha_{em}}{8\pi v}(c_\gamma^{\rm SM} + \delta c_\gamma)F_{\mu\nu}F^{\mu\nu}h + \frac{\alpha_{em}}{4\pi v}(c_Z^{\rm SM} + \delta c_Z)Z_{\mu\nu}F^{\mu\nu}h + \cdots$$

$$\delta c_\gamma = \left(\frac{4\,\pi v}{\Lambda}\right)^2\left(c_{BB} + c_{WW} - c_{WB}\right)\,, \qquad \delta c_Z = \left(\frac{4\,\pi v}{\Lambda}\right)^2\left(\cot\theta_W c_{WW} - \tan\theta_W c_{BB} - \cot 2\,\theta_W c_{WB}\right)$$

Goal: $\delta c_\gamma \approx 0$ but $\delta c_Z \sim c_Z^{SM}$

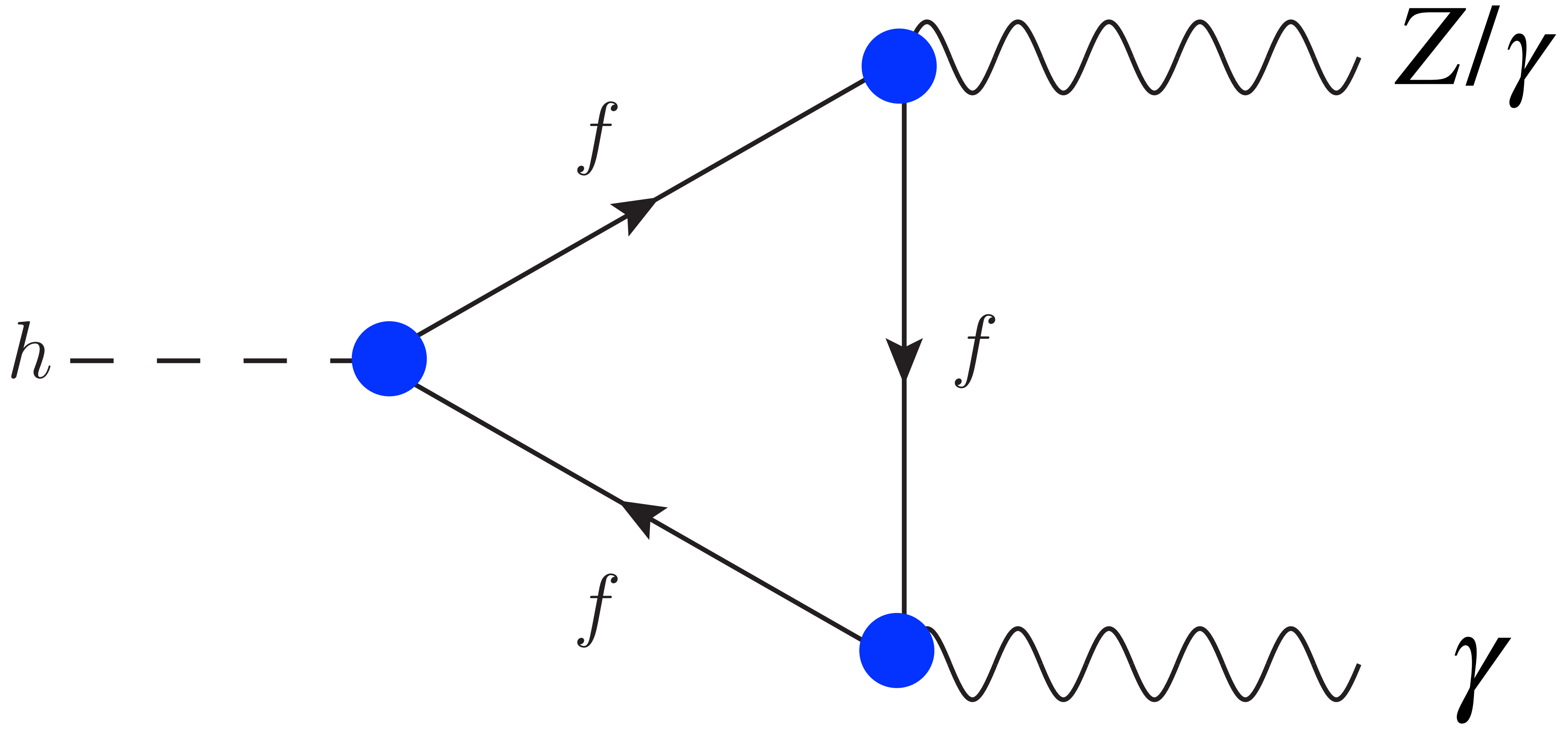
Possible to fine tune Wilson coefficients to achieve $\delta c_\gamma = 0$, but ***no simple*** solutions.

arXiv:2407.09145

- ## Formalism

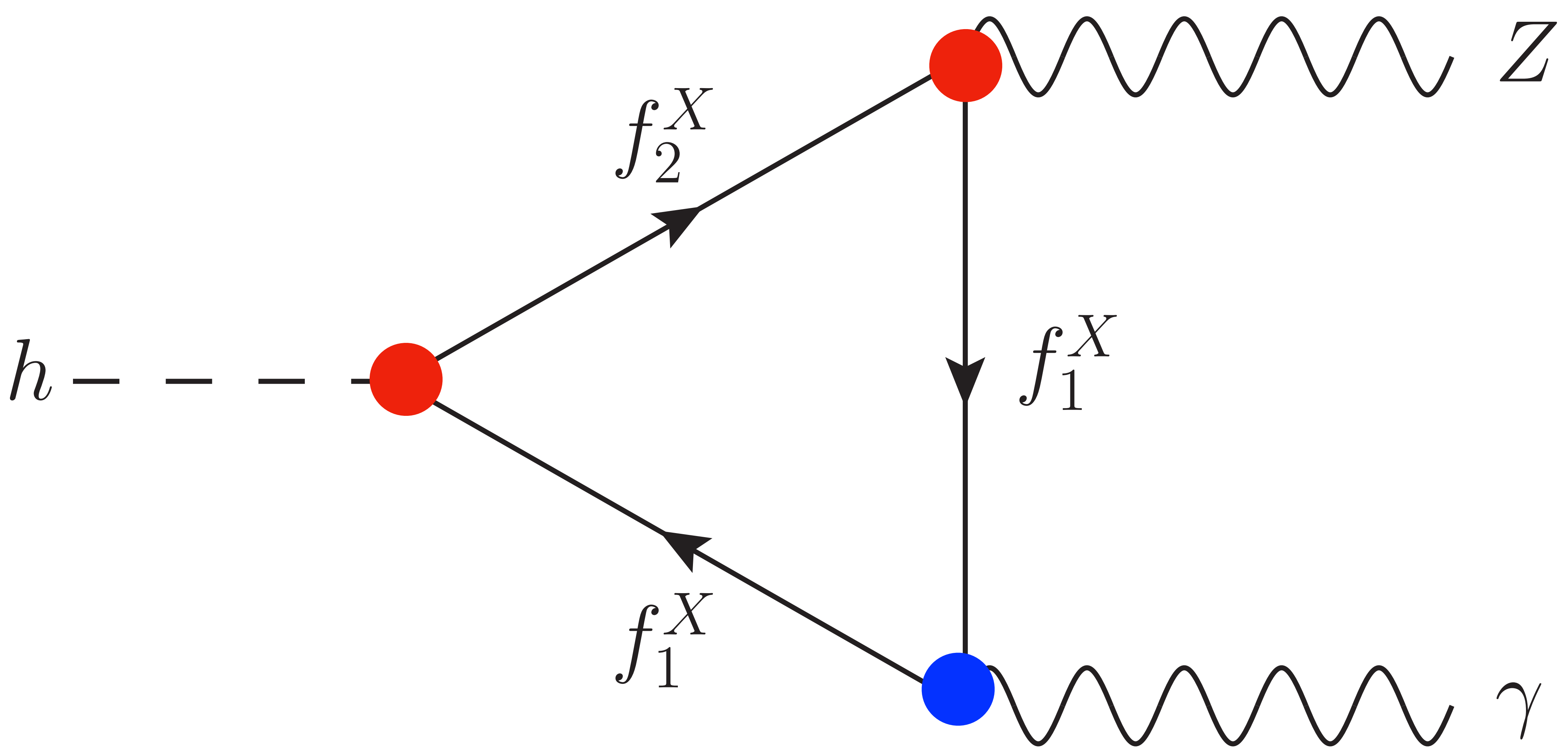
In general, if we want to introduce new fermions to solve the problem, we will encounter two type of diagrams…

Flavor-**conserving** diagrams



Contribute to **both** processes.

Flavor-**changing** diagrams



Contribute to $h \to Z\gamma$ **exclusively**.
($A^\mu \bar{f}_2 \gamma_\mu f_1$ violates the Ward identity)

Formalism

Vector-like Leptons

	$SU(3)_c$	$SU(2)$	$U(1)_Y$
$(f_S^{Y+1})_{L,R}$	**1**	**1**	$Y+1$
$(f_D)_{L,R}$	**1**	**2**	$Y+1/2$
$(f_S^Y)_{L,R}$	**1**	**1**	Y

- Left and right-handed leptons are introduced; color singlet to avoid gluon fusion.
- Gauge **anomalies** are canceled.
- Assuming **CP** symmetry, tightly constrained by electric dipole moments.

$$\mathscr{L}_{H+M} = -m_D \bar{f}_D f_D - m_S^Y \bar{f}_S^Y f_S^Y - m_S^{Y+1} \bar{f}_S^{Y+1} f_S^{Y+1} - \left(c_f^Y \bar{f}_D f_S^Y H + c_f^{Y+1} \bar{f}_D f_S^{Y+1} \tilde{H} + (\text{h.c.}) \right),$$

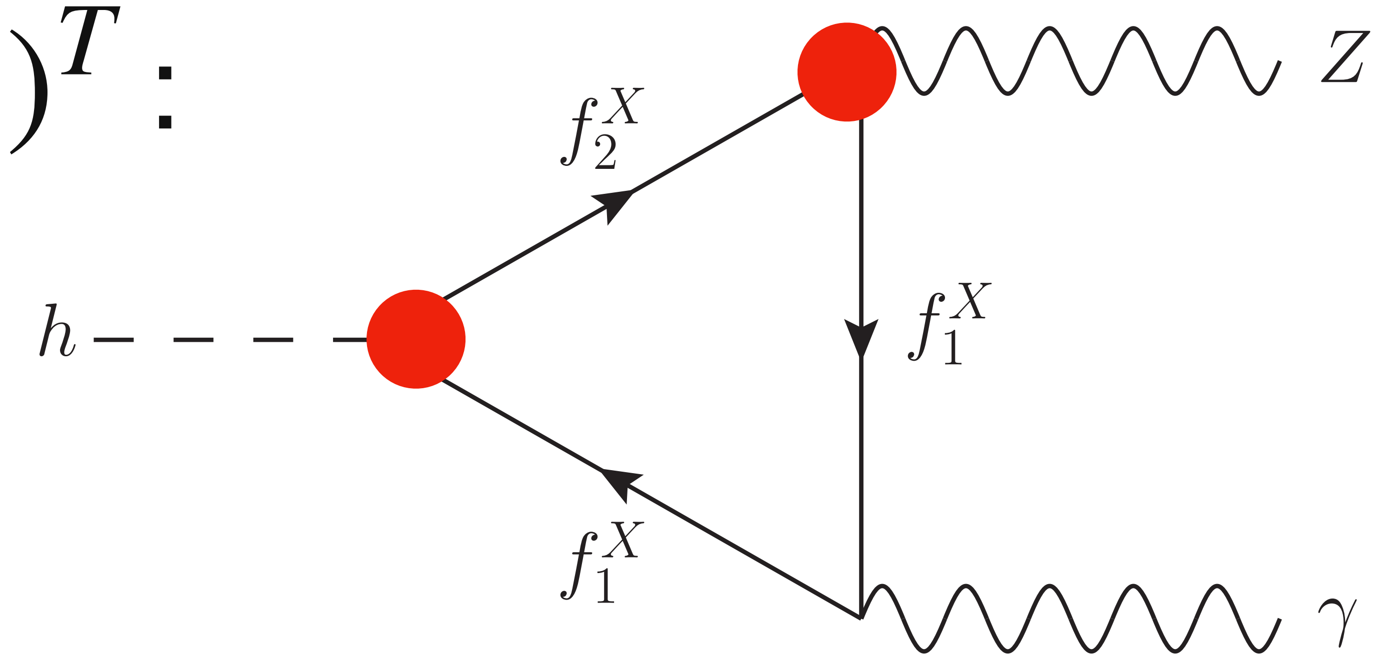
$$\mathscr{L}_V = g' B^\mu \left(Y \bar{f}_S^Y \gamma_\mu f_S^Y + \left(Y + \frac{1}{2} \right) \bar{f}_D \gamma_\mu f_D + (Y+1) \bar{f}_S^{Y+1} \gamma_\mu f_S^{Y+1} \right) + \frac{g}{2} W_i^\mu \bar{f}_D \gamma_\mu \sigma_i f_D$$

Formalism

Vector-like Leptons

	$SU(3)_c$	$SU(2)$	$U(1)_Y$
$(f_S^{Y+1})_{L,R}$	**1**	**1**	$Y+1$
$(f_D)_{L,R}$	**1**	**2**	$Y+1/2$
$(f_S^Y)_{L,R}$	**1**	**1**	Y

Contribute to $h \to Z\gamma$ solely.



- **Spontaneously symmetry breaking**, $H \to (0, v + h(x))^T$:

$$\begin{pmatrix} f_1^X \\ f_2^X \end{pmatrix} = \begin{pmatrix} \cos\theta_X & \sin\theta_X \\ -\sin\theta_X & \cos\theta_X \end{pmatrix} \begin{pmatrix} f_D^X \\ f_S^X \end{pmatrix}, \ X = Y, Y+1.$$

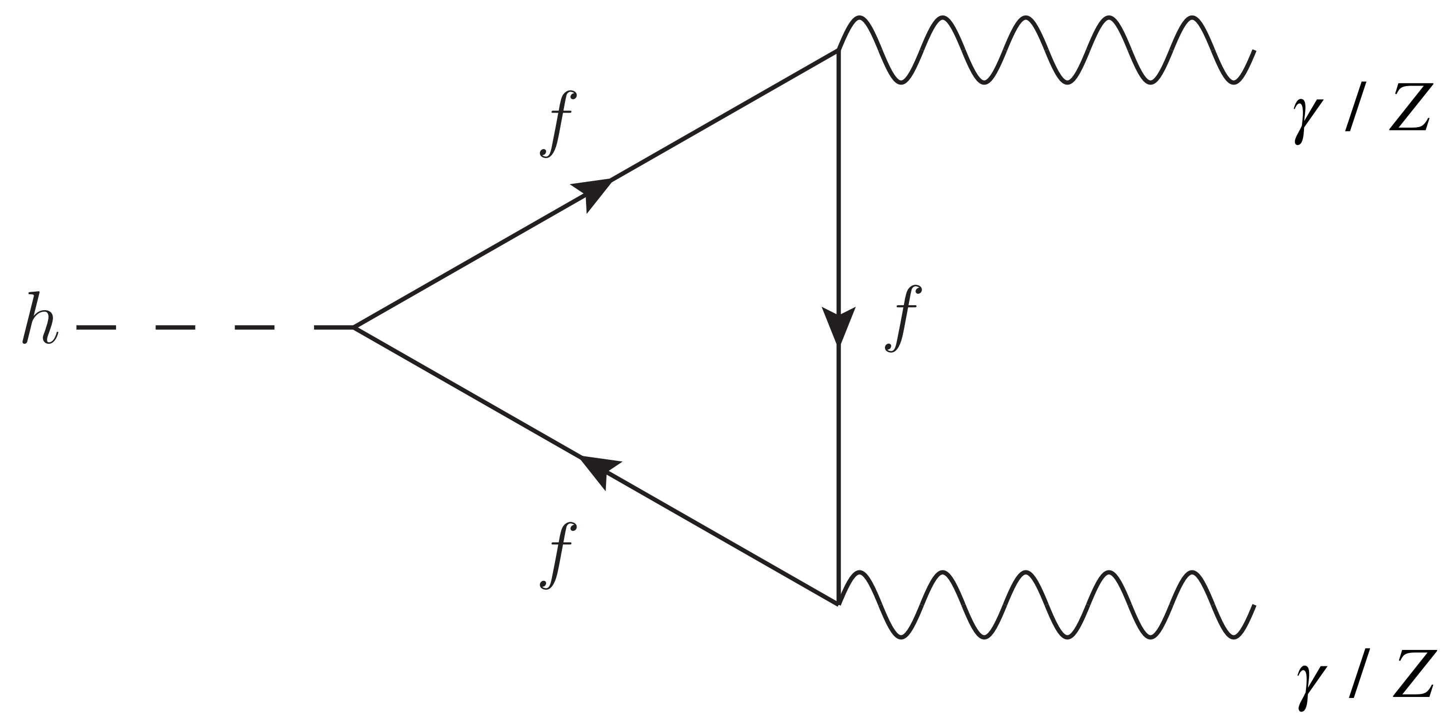
$$\mathscr{L}_h^X = -\frac{c_f^X h}{\sqrt{2}} \bar{f}^X \left(\sin 2\theta_X \sigma_z + \cos 2\theta_X \sigma_x\right) f^X = -\frac{c_f^X h}{\sqrt{2}} \left[\sin 2\theta_X \left(\bar{f}_1^X f_1^X - \bar{f}_2^X f_2^X\right) + \cos 2\theta_X \left(\bar{f}_1^X f_2^X + \bar{f}_2^X f_1^X\right)\right]$$

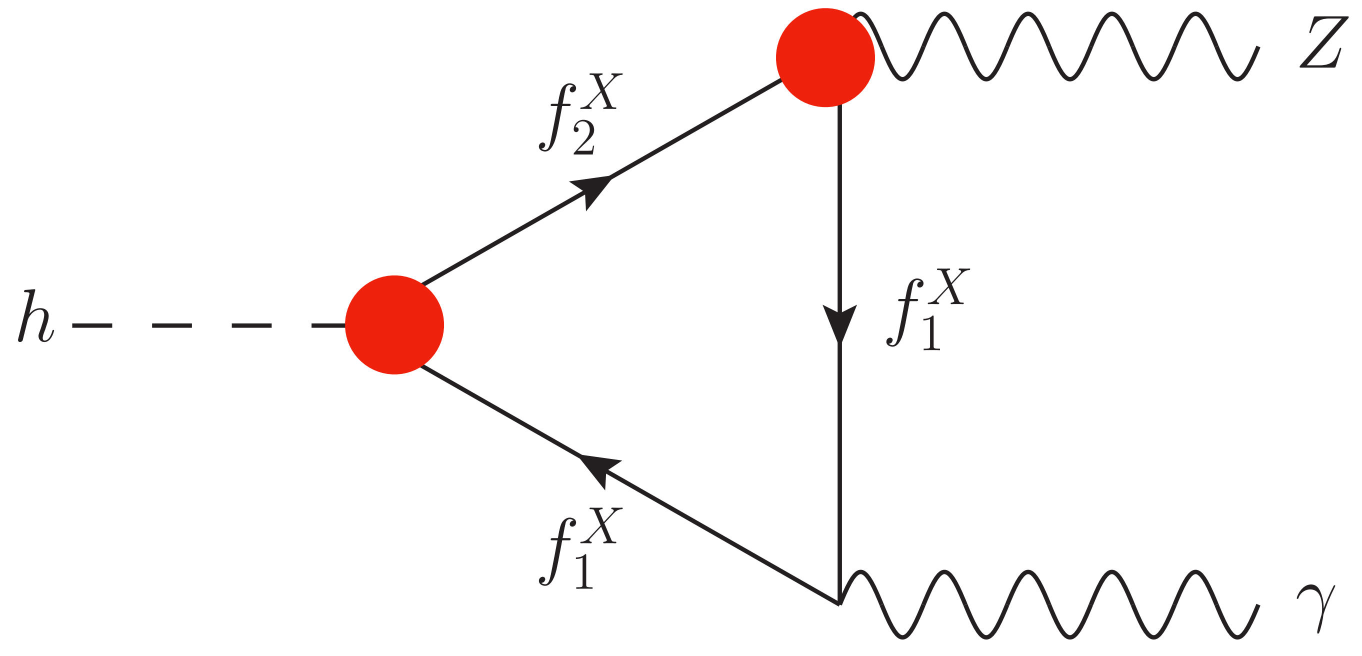
$$\mathscr{L}_Z^X = e\bar{f}^X Z^\mu \gamma_\mu \left[-X \tan\theta_W - \frac{\eta_X}{4\cos\theta_W \sin\theta_W}\left(1 + \cos 2\theta_X \sigma_z - \sin 2\theta_X \sigma_x\right)\right] f^X$$

• Formalism

$$c_\gamma = c_\gamma^{\rm SM}\left(1+\frac{\delta c_\gamma}{c_\gamma^{\rm SM}}\right), \qquad c_\gamma^{\rm SM} = -6.56\,, \quad \frac{\delta c_\gamma}{c_\gamma^{\rm SM}} \approx 0.05\,.$$

$$c_Z = c_Z^{\rm SM}\left(1+\frac{\delta c_Z}{c_Z^{\rm SM}}\right), \qquad c_Z^{\rm SM} = -11.67\,, \quad \frac{\delta c_\gamma}{c_\gamma^{\rm SM}} \approx 0.5\,.$$





- Taking $m_{1,2} \gg m_h$, resulting in ***wrong signs***!

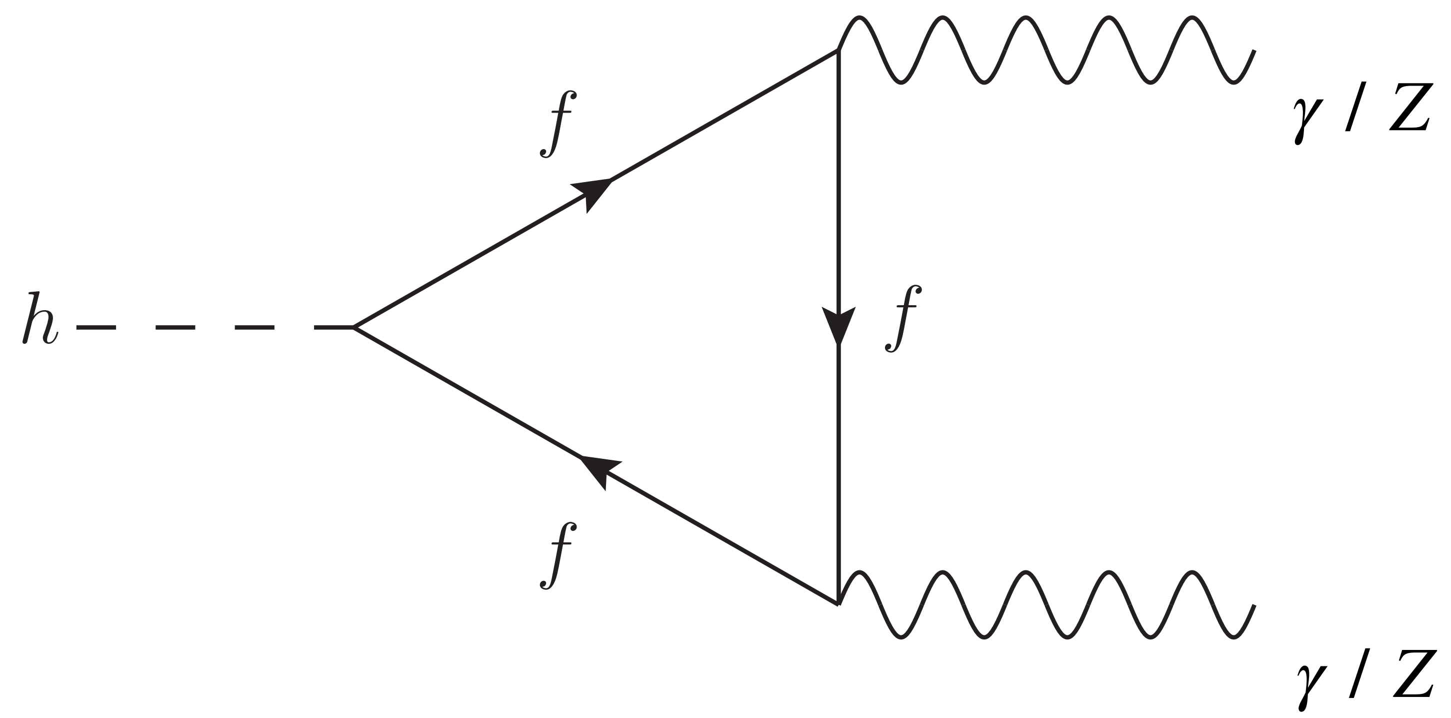
$$\delta c_\gamma = -\frac{4}{3}\left(Y^2\frac{\left(c_f^Y v\right)^2}{m_1^Y m_2^Y} + (Y+1)^2\frac{\left(c_f^{Y+1} v\right)^2}{m_1^{Y+1} m_2^{Y+1}}\right) < 0$$

$$\delta c_Z = -\tan\theta_W \delta c_\gamma + \frac{2}{3\sin\theta_W\cos\theta_W}\left(Y\frac{\left(c_f^Y v\right)^2}{m_1^Y m_2^Y} - (Y+1)\frac{\left(c_f^{Y+1} v\right)^2}{m_1^{Y+1} m_2^{Y+1}}\right) > 0$$

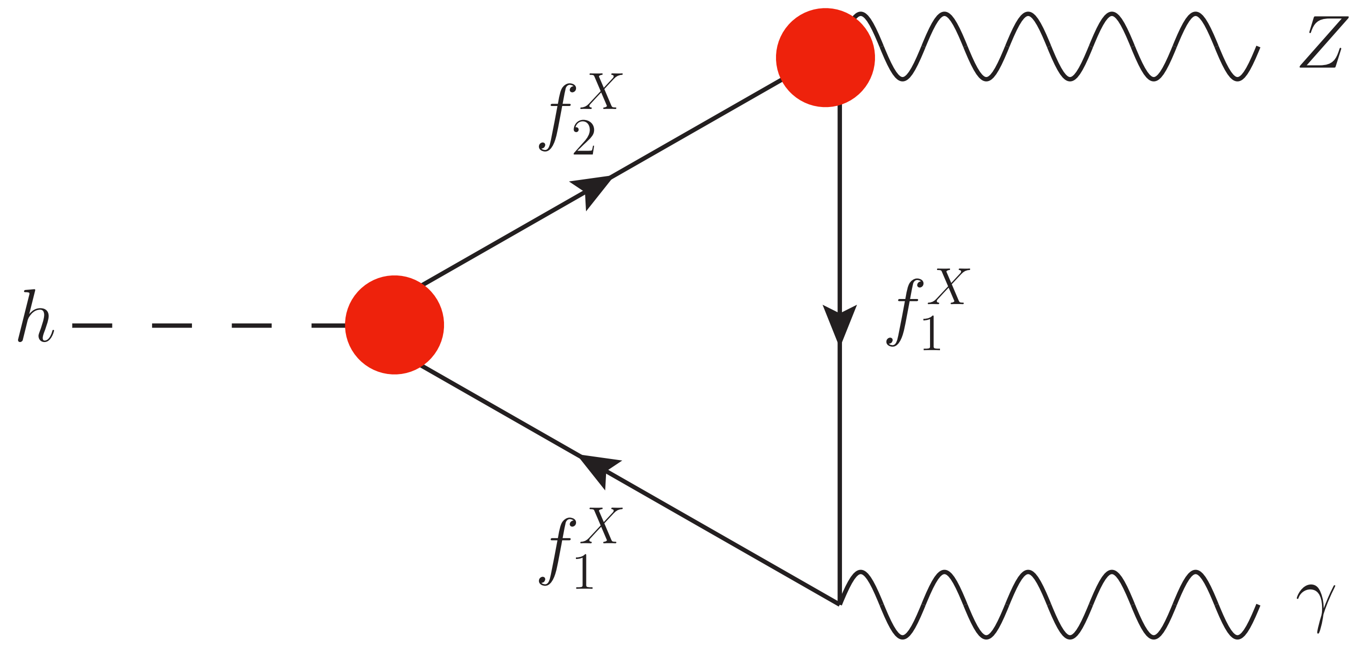
- A naive thought is to take one of the mass to be **negative** **(?)**

• Formalism

$$c_\gamma = c_\gamma^{\rm SM}\left(1 + \frac{\delta c_\gamma}{c_\gamma^{\rm SM}}\right), \qquad c_\gamma^{\rm SM} = -6.56\,, \quad \frac{\delta c_\gamma}{c_\gamma^{\rm SM}} \approx 0.05\,.$$



$$c_Z = c_Z^{\rm SM}\left(1 + \frac{\delta c_Z}{c_Z^{\rm SM}}\right), \qquad c_Z^{\rm SM} = -11.67\,, \quad \frac{\delta c_\gamma}{c_\gamma^{\rm SM}} \approx 0.5\,.$$



- Taking $|m_{1,2}| \gg m_h$ and $m_2^{Y+1}, Y < 0$:

$$\delta c_\gamma = -\frac{4}{3}\left(Y^2\frac{\left(c_f^Y v\right)^2}{m_1^Y m_2^Y} - (Y+1)^2\frac{\left(c_f^{Y+1} v\right)^2}{m_1^{Y+1}\,|m_2^{Y+1}|}\right) \sim 0$$

$$\delta c_Z = -\tan\theta_W \delta c_\gamma + \frac{2}{3\sin\theta_W\cos\theta_W}\left(Y\frac{\left(c_f^Y v\right)^2}{m_1^Y m_2^Y} - (Y+1)\frac{\left(c_f^{Y+1} v\right)^2}{m_1^{Y+1} m_2^{Y+1}}\right) < 0$$

- A naive thought is to take one of the mass to be **negative** **(?)**

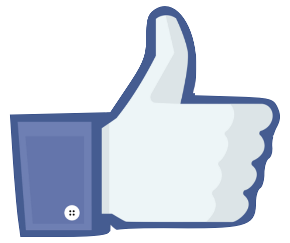
- ## Formalism

- To take account of $m_2^{Y+1} < 0$, we have to take $f_2^{Y+1} \rightarrow e^{\frac{i}{2}(1-\gamma_5)\pi} f_2^{Y+1} = \gamma_5 f_2^{Y+1}$:

$$\mathscr{L}_M^{Y+1} = -\, m_1^{Y+1} \bar{f}_1^{Y+1} f_1^{Y+1} - m_2^{Y+1} \bar{f}_2^{Y+1} f_2^{Y+1} \quad \rightarrow \quad \mathscr{L}_M^{Y+1} = -\, m_1^{Y+1} \bar{f}_1^{Y+1} f_1^{Y+1} - |m_2^{Y+1}| \bar{f}_2^{Y+1} f_2^{Y+1}$$

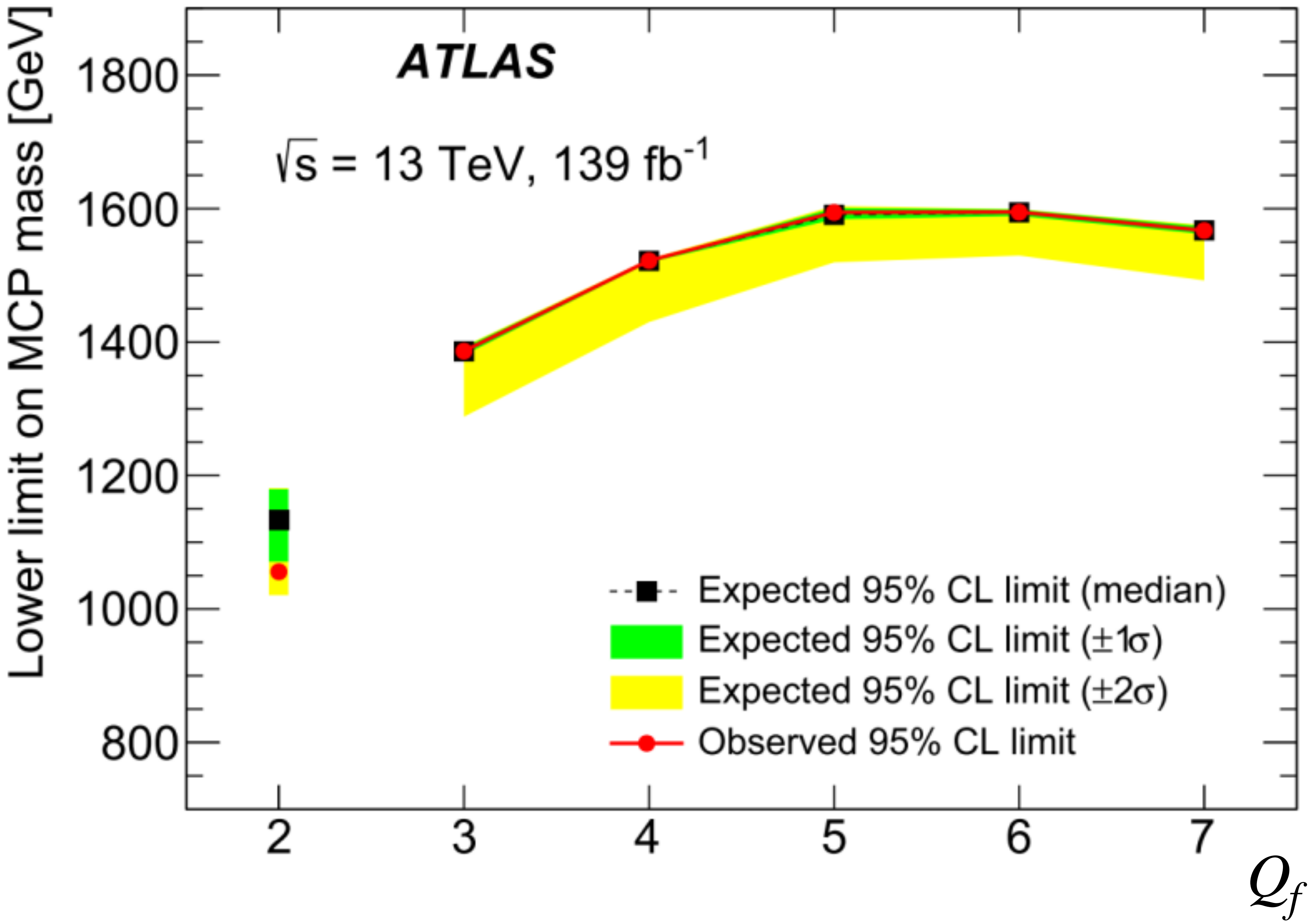
$$\mathscr{L}_h^{Y+1} = -\frac{c_f^{Y+1} h}{\sqrt{2}} \bar{f}^{Y+1} \left(\sin 2\theta \sigma_z + \cos 2\theta \sigma_x\right) f^{Y+1} \rightarrow \mathscr{L}_h^{Y+1} = -\frac{c_f^{Y+1} h}{\sqrt{2}} \bar{f}^{Y+1} \left(\sin 2\theta 1 + \cos 2\theta i \sigma_y \gamma_5\right) f^{Y+1}$$

$$\delta c_\gamma = -\frac{4}{3}\left(Y^2 \frac{\left(c_f^Y v\right)^2}{m_1^Y m_2^Y} + (Y+1)^2 \frac{\left(c_f^{Y+1} v\right)^2}{m_1^{Y+1} m_2^{Y+1}}\right) \longrightarrow \delta c_\gamma = -\frac{4}{3}\left(Y^2 \frac{\left(c_f^Y v\right)^2}{m_1^Y m_2^Y} - (Y+1)^2 \frac{\left(c_f^{Y+1} v\right)^2}{m_1^{Y+1} |m_2^{Y+1}|}\right)$$

- The **naive** expectation holds! 

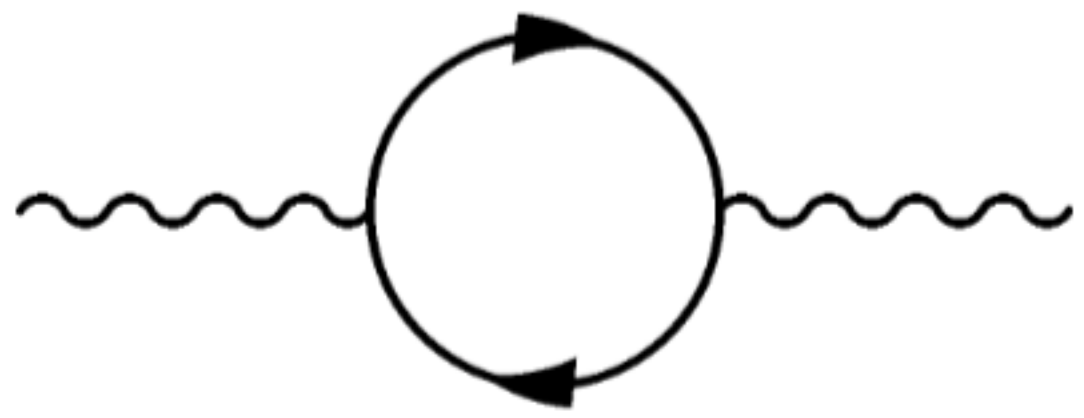
• Numerical results

- Mass constraint on stable charged leptons.



- We set the lowest new fermion mass to 1.6 TeV with $|Q_f| = 8$.

Peskin–Takeuchi parameter



$$S = \frac{1}{6\pi}\left[2 - \left(Y + \frac{1}{2}\right)\log\left(\frac{m_1^{Y+1} m_2^Y}{m_1^Y m_2^{Y+1}}\right)^2\right]$$

$$T = \frac{1}{16\pi c_w^2 s_w^2 m_Z^2}\Bigg(\left(m_1^{Y+1}\right)^2 + \left(m_1^Y\right)^2 - 2\frac{\left(m_1^{Y+1}\right)^2\left(m_1^Y\right)^2}{\left(m_1^{Y+1}\right)^2 - \left(m_1^Y\right)^2}\log\frac{\left(m_1^{Y+1}\right)^2}{\left(m_1^Y\right)^2}$$

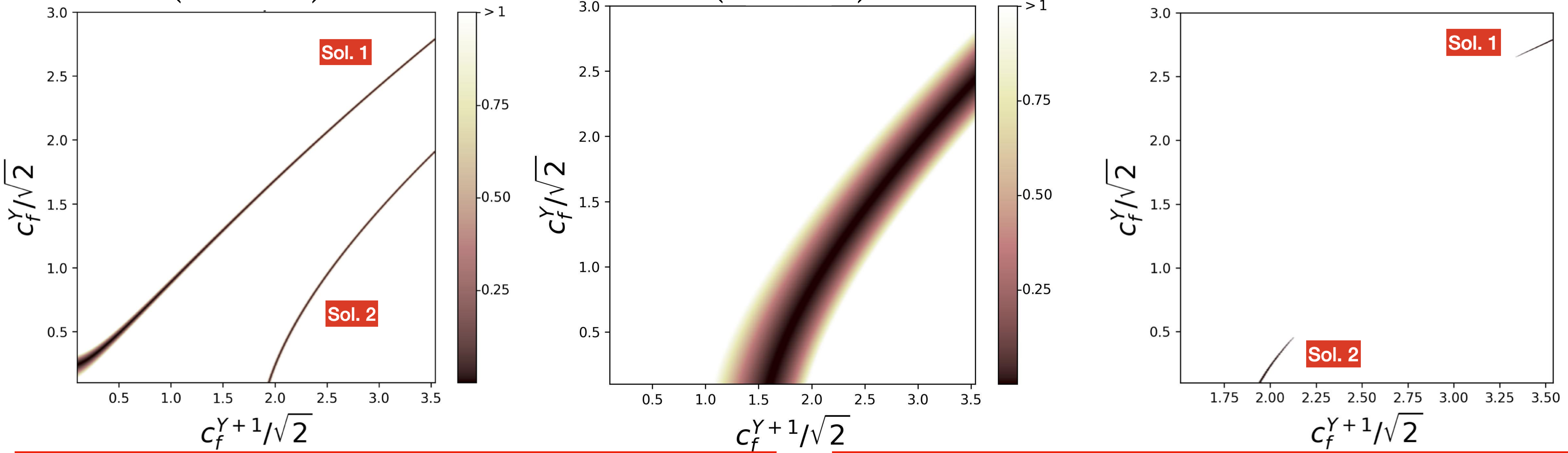
$$+\left(m_2^{Y+1}\right)^2 + \left(m_2^Y\right)^2 - 2\frac{\left(m_2^{Y+1}\right)^2\left(m_2^Y\right)^2}{\left(m_2^{Y+1}\right)^2 - \left(m_2^Y\right)^2}\log\frac{\left(m_2^{Y+1}\right)^2}{\left(m_2^Y\right)^2}\Bigg)$$

- $S \approx T \approx 0$ provided that masses are degenerate. We set $m_S^Y = m_D = -m_S^{Y+1}$.

• Numerical results

$\mu_\gamma^{\rm exp} = 1.10 \pm 0.07$ $\mu_{Z\gamma}^{\rm exp} = 2.2 \pm 0.7$

$\left(\frac{\mu_\gamma^{\rm exp} - \mu_\gamma}{\sigma_\gamma^{\rm exp}}\right)^2$ $\left(\frac{\mu_Z^{\rm exp} - \mu_Z}{\sigma_Z^{\rm exp}}\right)^2$ Intersection of previous two



Sol. 1 $(\mu_\gamma, \mu_Z) = (1.10, 1.55)$

$(m_1^Y, m_2^Y, m_{1,2}^{Y+1}) = (2.8, 1.6, 2.4)$ TeV ,

Has the feature of $\delta c_\gamma \approx 0$.

Sol. 2 $(\mu_\gamma, \mu_Z) = (1.10, 2.88)$

$(m_1^Y, m_2^Y, m_{1,2}^{Y+1}) = (1.6, 1.6, 1.7)$ TeV ,

Has the feature of $\delta c_\gamma \approx -2c_\gamma^{SM}$.

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- **A shortcoming of this simple model**

- The hypercharge is too high $|Q_f| \sim 8$, which my not be natural.

$$g'(\mu) = \frac{g'(\Lambda)^2}{1 - \frac{g^2(\Lambda)}{16\pi^2}\left(\frac{41}{6} + \frac{4}{3}\sum_{\rm NP} Q_Y^2\right)\log\left(\mu^2/\Lambda^2\right)}$$

The ***Landau pole*** occurs at a few tens of TeV.

- The problem can be alleviated by promoting doublets to ***N***-plets.

	$SU(3)_c$	$SU(2)$	$U(1)_Y$
$(f_S^{Y+1})_{L,R}$	$\mathbf{1}$	***N***	$Y+1$
$(f_D)_{L,R}$	$\mathbf{1}$	***N+1***	$Y+1/2$
$(f_S^{Y})_{L,R}$	$\mathbf{1}$	***N***	Y

To achieve $\delta c_\gamma \approx 0$, **chiral rotations** have to be performed.

Summary & Outlook

Chiral rotation is key to explaining the data in the vector-like lepton model.

CEPC and LHC's third run will provide more information.