STRONG DYNAMICS AND EWSB: STATUS AND PROSPECTS

Jamison Galloway
LHC Higgs Signal Implications
UC Davis, April 2013

Work in collaboration with A. Azatov, R. Contino, A. Di Iura

SAPIENZA
UNIVERSITÀ DI ROMA

EWSB: PAST AND PRESENT

What did we know (prior to LHC)?

- Massive W and Z
- $\Rightarrow$ Nonlinear sigma model at energies below some cutoff Λ_{NLSM}

What did we want to know (from the LHC)?

- Does the NLSM survive to its strongly coupled scale $\Lambda_{\mathrm{NLSM}} \sim 4\pi v$?
- Or does new perturbative physics intervene?

What clues did we have going in (from other data)?

- LEP gave some answer to question of strong coupling: "probably not"
- The problem: Electroweak Precision, contributions from IR

$$\Delta \mathrm{EWP} \propto \log\left(\frac{\Lambda_{\mathrm{NLSM}}}{m_Z}\right)$$

- Data were indicating $\Lambda_{\mathrm{NLSM}} \lesssim v$

Simplest, most economical though potentially unnatural, solution:
a light Higgs

EWSB: PAST AND PRESENT

Given the lessons of LEP, a model-independent Higgs-like Lagrangian becomes a handy tool for thorough exploration of the weak scale.

Chiral expansion: $\mathcal{L}_{\text{eff}} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \dots$

$$\left.\begin{aligned}\Delta\mathcal{L}^{(2)} = &\left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v} + \mathcal{O}(h^2)\right) \\ &+ \sum_\psi m_\psi \psi^c \psi \left(1 + c\frac{h}{v} + \mathcal{O}(h^2)\right) + \text{h.c.}\end{aligned}\right\} \quad \begin{aligned} a = c = 1 \\ \Rightarrow \text{SM}\end{aligned}$$

Ref:
Contino et al,
JHEP 1005 (2010)

$$\Delta\mathcal{L}^{(4)} = \frac{h}{v} \times \left(c_{\gamma\gamma}\gamma_{\mu\nu}^2 + c_{gg}G_{\mu\nu}^2 + c_{Z\gamma}Z_{\mu\nu}\gamma^{\mu\nu}\right)$$

EWSB: PAST AND PRESENT

Given the lessons of LEP, a model-independent Higgs-like Lagrangian becomes a handy tool for thorough exploration of the weak scale.

Chiral expansion: $\mathcal{L}_{\text{eff}} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \ldots$

$$\left.\begin{aligned}\Delta\mathcal{L}^{(2)} &= \left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v} + \mathcal{O}(h^2)\right) \\ &\quad + \sum_\psi m_\psi \psi^c \psi \left(1 + c\frac{h}{v} + \mathcal{O}(h^2)\right) + \text{h.c.}\end{aligned}\right\} \begin{aligned} a = c = 1 \\ \Rightarrow \text{SM}\end{aligned}$$

Ref:
Contino et al,
JHEP 1005 (2010)

$$\Delta\mathcal{L}^{(4)} = \frac{h}{v} \times \left(c_{\gamma\gamma}\gamma_{\mu\nu}^2 + c_{gg} G_{\mu\nu}^2 + c_{Z\gamma} Z_{\mu\nu}\gamma^{\mu\nu}\right)$$

Indicators of naturalness in composite models:

$$\delta a, \delta c \propto v^2/f^2$$

$$\text{tuning} \sim 1/\delta$$

x% tuning corresponds to x% deviation in vector coupling

EWSB: PAST AND PRESENT

Given the lessons of LEP, a model-independent Higgs-like Lagrangian becomes a handy tool for thorough exploration of the weak scale.

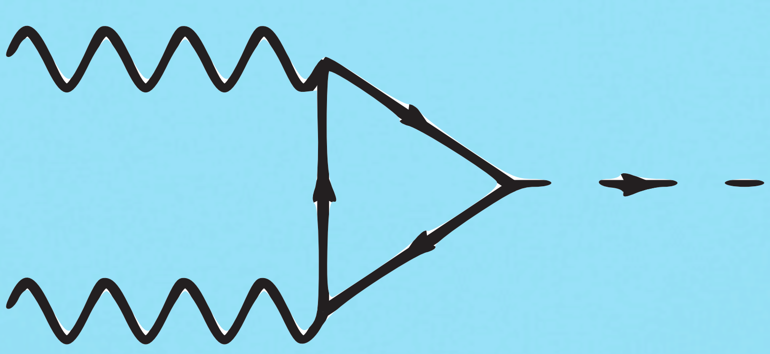
Chiral expansion: $\mathcal{L}_{\text{eff}} = \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \ldots$

$$\left.\begin{aligned}\Delta\mathcal{L}^{(2)} = & \left(m_W^2 W_\mu W^\mu + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right)\left(1 + 2a\frac{h}{v} + \mathcal{O}(h^2)\right) \\ & + \sum_\psi m_\psi \psi^c \psi \left(1 + c\frac{h}{v} + \mathcal{O}(h^2)\right) + \text{h.c.}\end{aligned}\right\} \begin{aligned} a = c = 1 \\ \Rightarrow \text{SM}\end{aligned}$$

Ref:
Contino et al,
JHEP 1005 (2010)

$$\Delta\mathcal{L}^{(4)} = \frac{h}{v} \times \left(c_{\gamma\gamma}\gamma_{\mu\nu}^2 + c_{gg}G_{\mu\nu}^2 + c_{Z\gamma}Z_{\mu\nu}\gamma^{\mu\nu}\right)$$

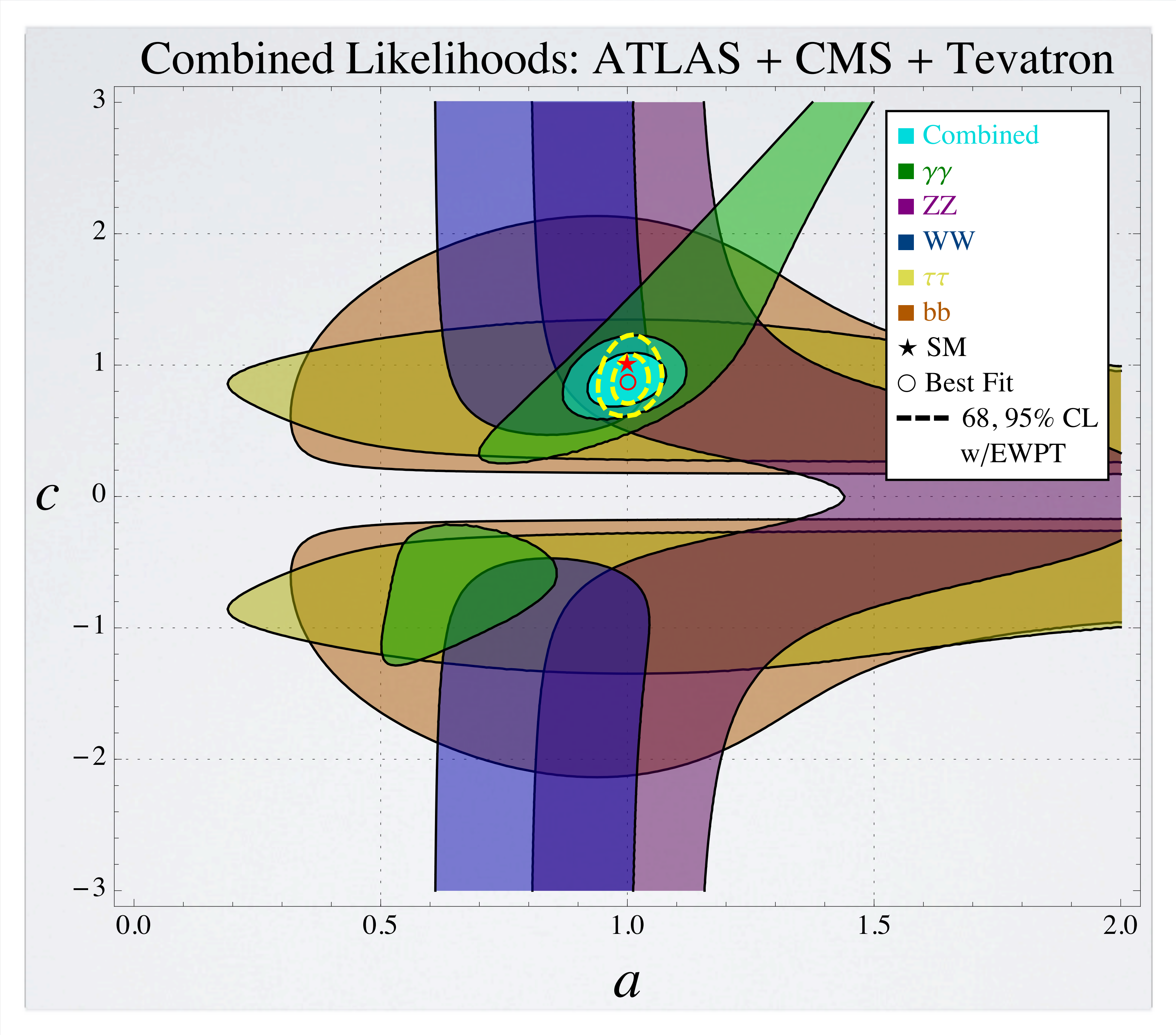
Indicators of naturalness in models with new matter
(SUSY, partial compositeness, ...)



EWSB: PAST AND PRESENT

Ref:
Azatov, J.G.
IJMPA (2012)

Where do we stand?

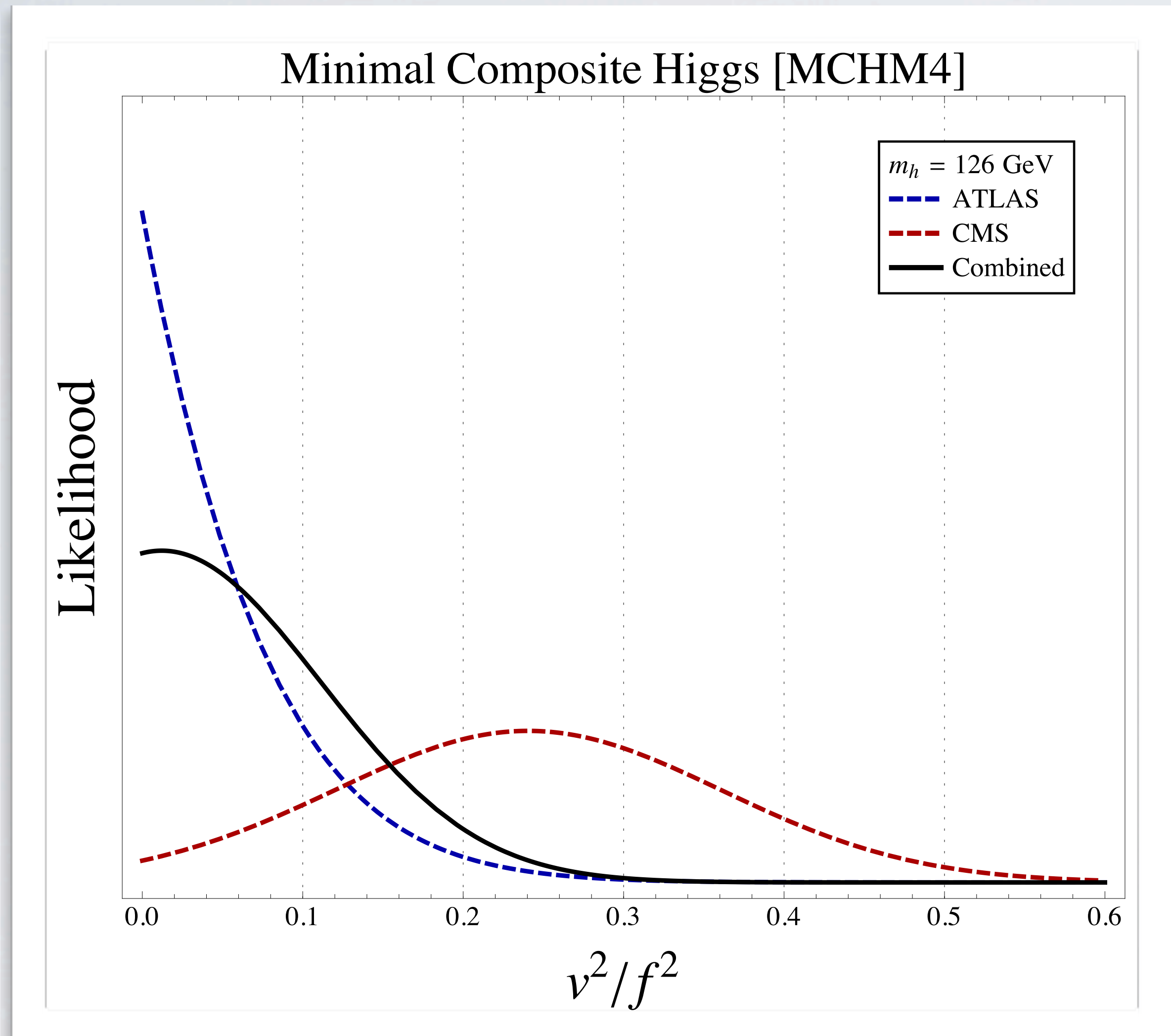


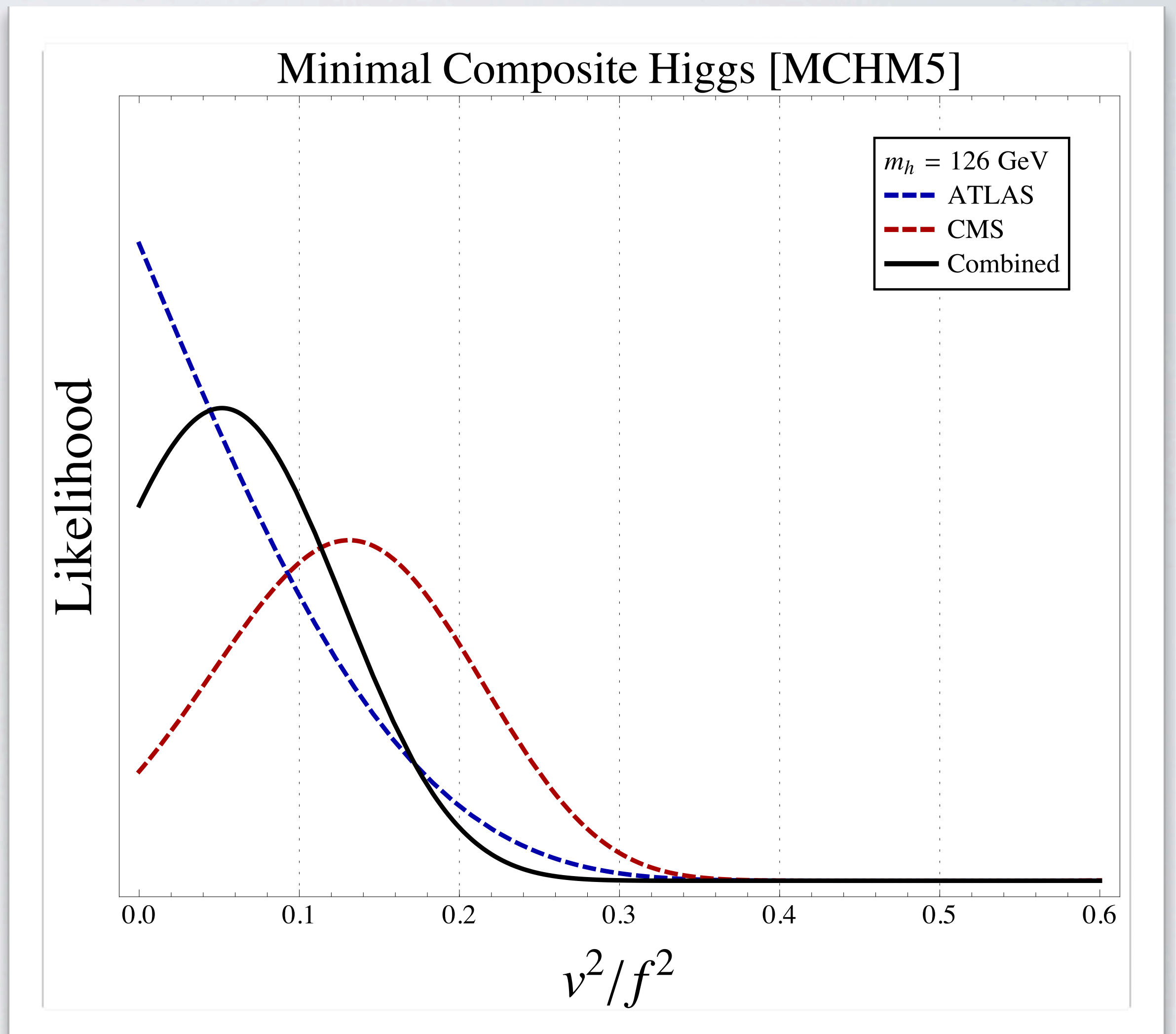
(rather accidental that a previous 'second solution' has dematerialized)

EWSB: PAST AND PRESENT

Explicit models: $SO(5)/SO(4)$ with fermions in $\mathbf{4}, \mathbf{5}$

Ref: Azatov, J.G. IJMPA (2012)

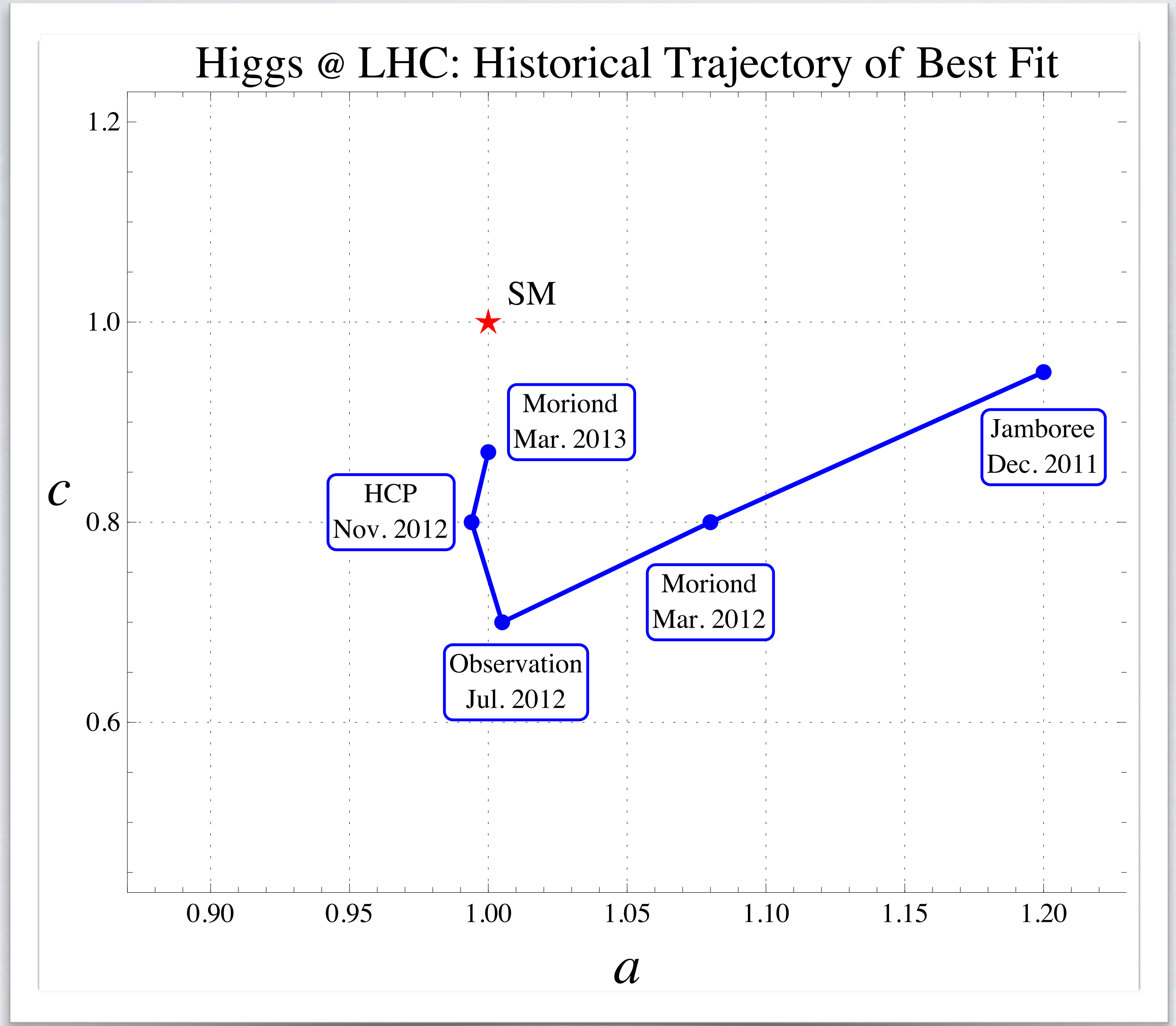




(strong cutoff at > 20 (10) TeV, respectively)

EWSB: PAST AND PRESENT

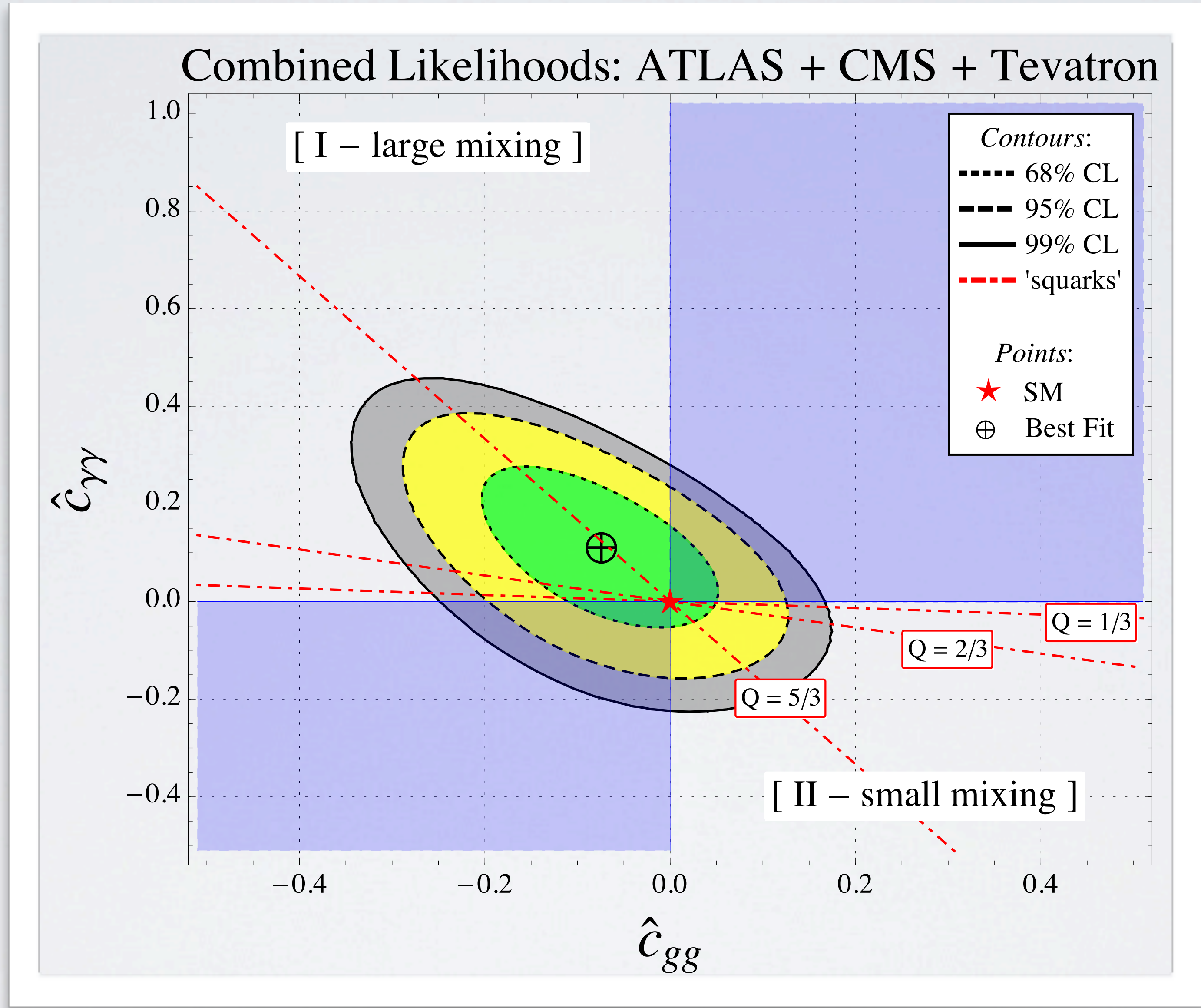
For 'fun': What's the forecast like?



Will the red point get connected?

WHAT ABOUT LOOPS?

$$\Delta\mathcal{L}^{(4)} = \frac{h}{v} \times \left(c_{\gamma\gamma}\gamma_{\mu\nu}^2 + c_{gg}G_{\mu\nu}^2 + c_{Z\gamma}Z_{\mu\nu}\gamma^{\mu\nu}\right)$$



Ref:
Azatov, J.G.
IJMPA (2012)

BUT these are understandably small for a composite Higgs...

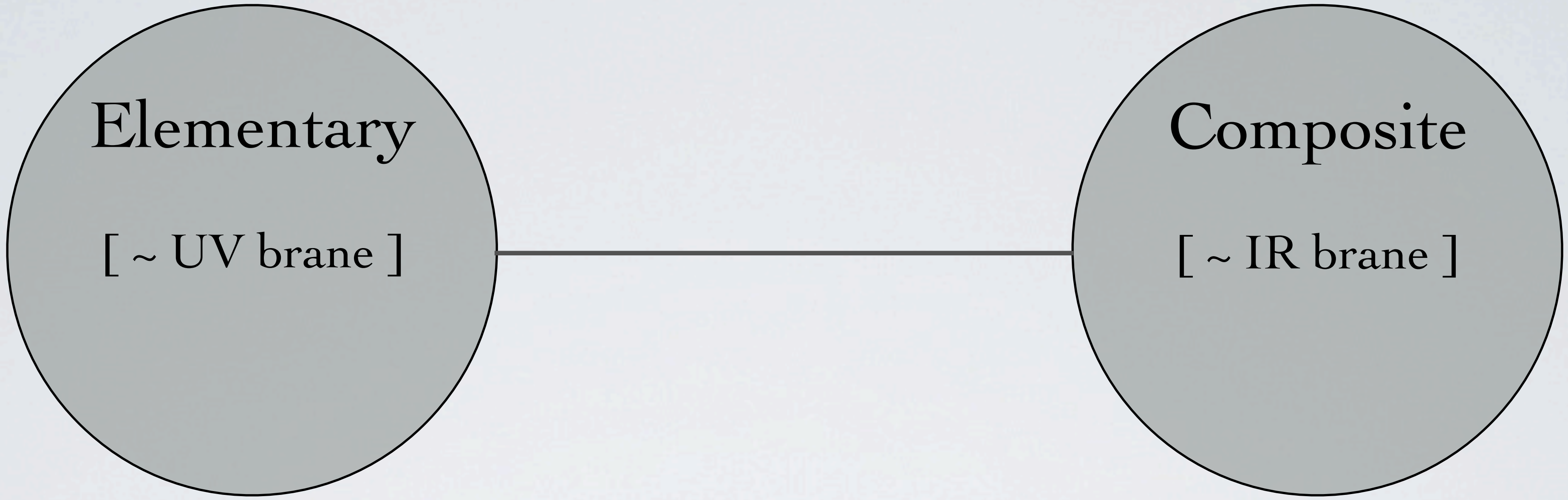
WHAT ABOUT LOOPS?

$$\Delta\mathcal{L}^{(4)} = \frac{h}{v} \times \left(c_{\gamma\gamma}\gamma_{\mu\nu}^2 + c_{gg}G_{\mu\nu}^2 + c_{Z\gamma}Z_{\mu\nu}\gamma^{\mu\nu}\right)$$

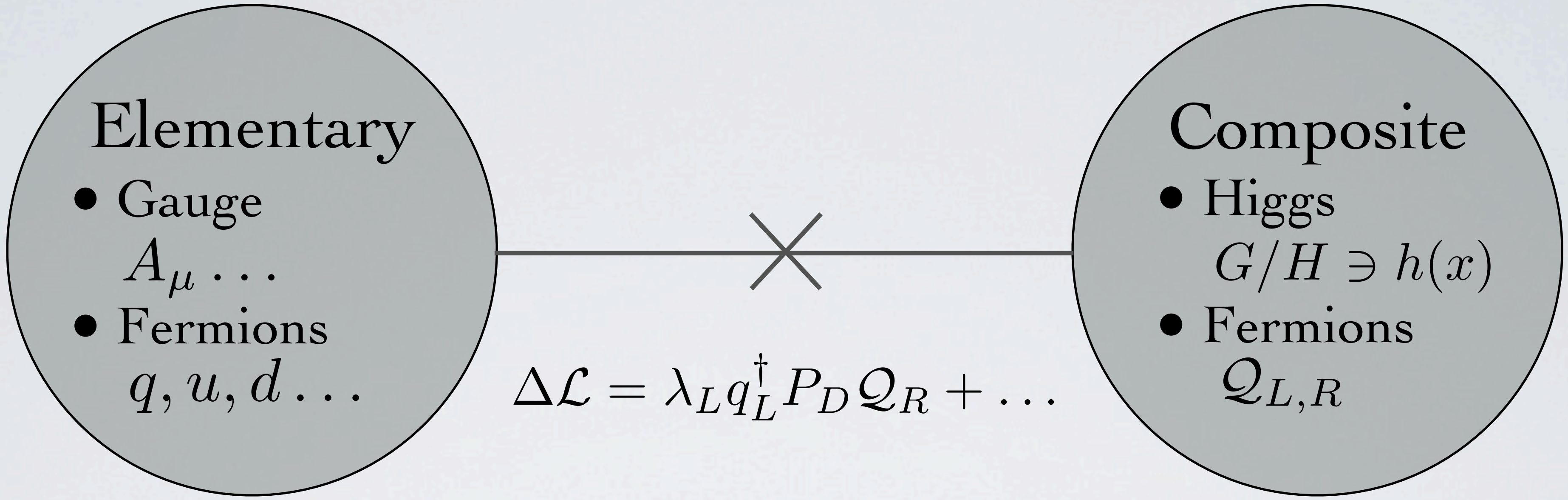
These are understandably small for a composite Higgs...

...so we'll turn our attention to the final one in the list.

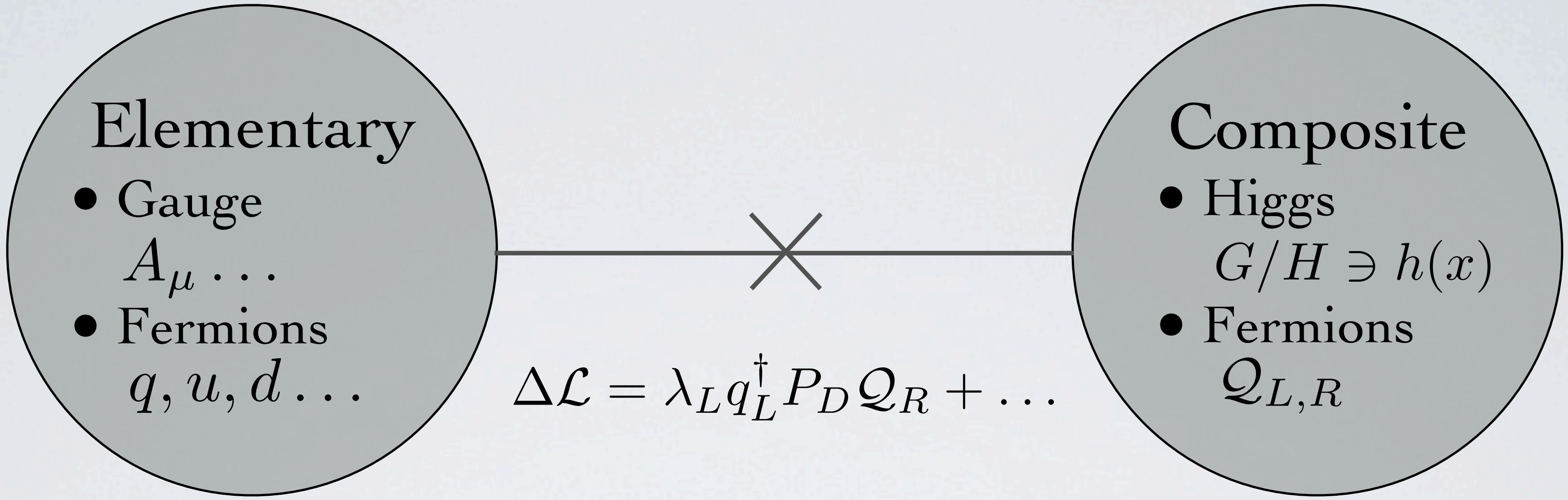
MOVING TO LOOP LEVEL: (PARTIAL) COMPOSITENESS



MOVING TO LOOP LEVEL: (PARTIAL) COMPOSITENESS



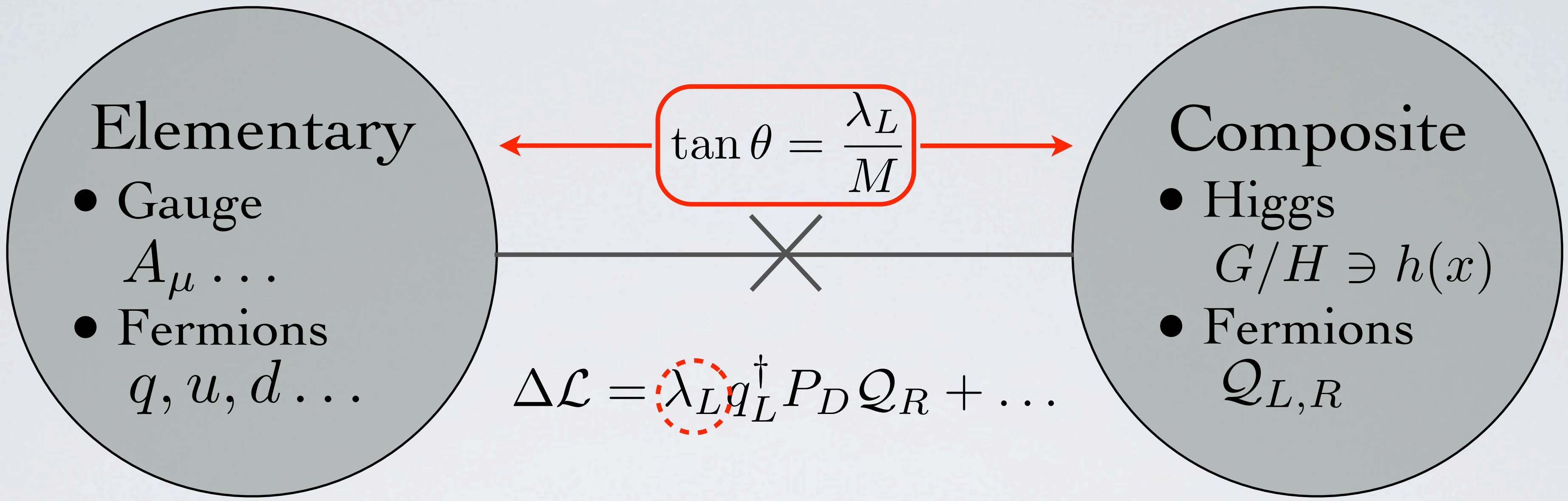
MOVING TO LOOP LEVEL: (PARTIAL) COMPOSITENESS



$$\Delta\mathcal{L} = \lambda_L q_L^\dagger P_D \mathcal{Q}_R + \dots$$

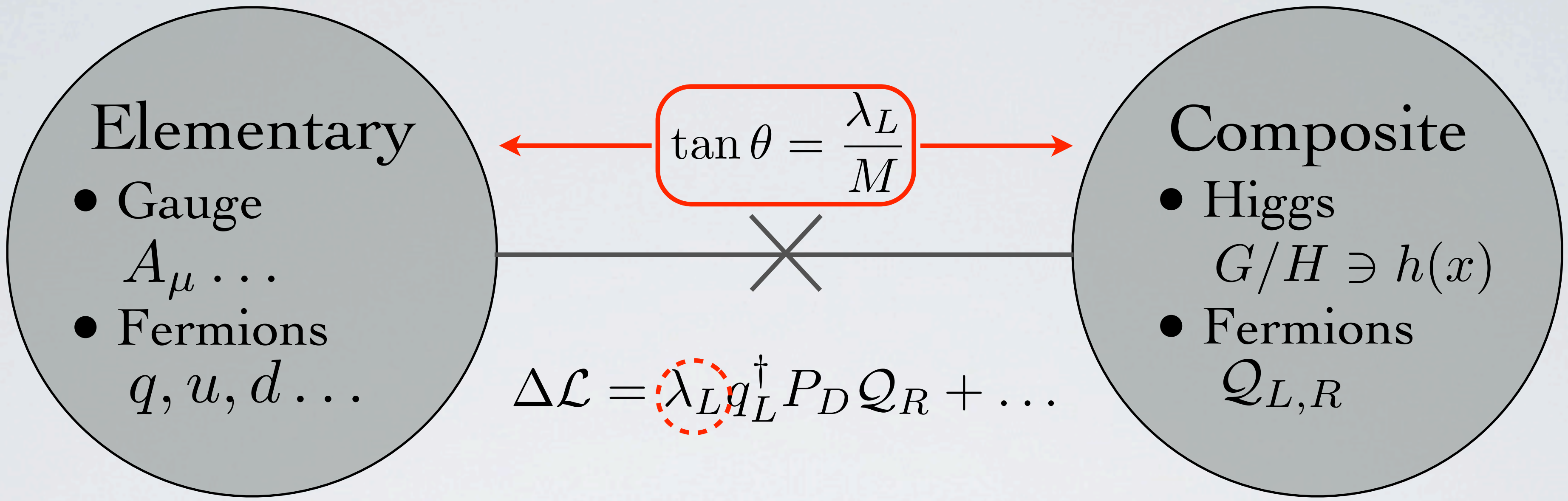
$$\Delta\mathcal{L} = M(\mathcal{Q}_L^\dagger \mathcal{Q}_R + \text{h.c.}) + \text{mixing} \quad \Longrightarrow \quad \begin{pmatrix} Q_L \\ q_L^{\text{SM}} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} P_D \mathcal{Q}_L \\ q_L \end{pmatrix}$$

MOVING TO LOOP LEVEL: (PARTIAL) COMPOSITENESS



$$\Delta\mathcal{L} = M(\mathcal{Q}_L^\dagger \mathcal{Q}_R + \text{h.c.}) + \text{mixing} \quad \Longrightarrow \quad \begin{pmatrix} Q_L \\ q_L^{\text{SM}} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} P_D \mathcal{Q}_L \\ q_L \end{pmatrix}$$

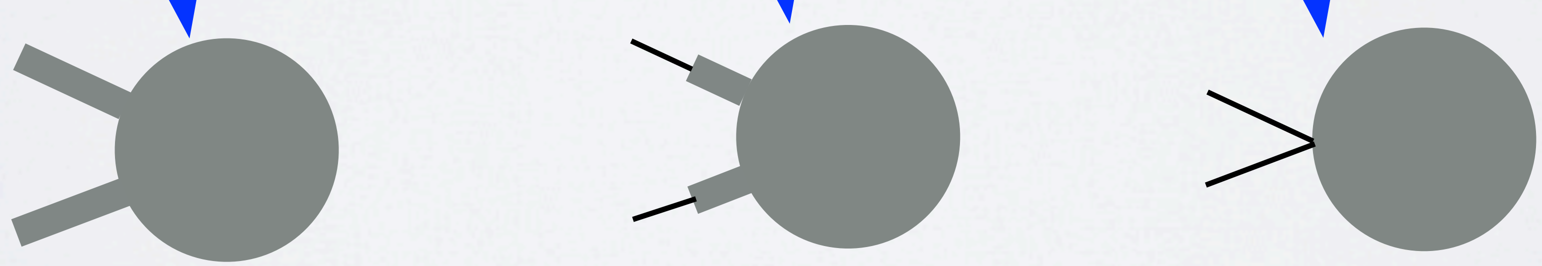
MOVING TO LOOP LEVEL: (PARTIAL) COMPOSITENESS



$$\Delta\mathcal{L} = \lambda_L q_L^\dagger P_D \mathcal{Q}_R + \ldots$$

$$\Delta\mathcal{L} = M(\mathcal{Q}_L^\dagger \mathcal{Q}_R + \text{h.c.}) + \text{mixing} \quad \Longrightarrow \quad \begin{pmatrix} Q_L \\ q_L^{\text{SM}} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} P_D \mathcal{Q}_L \\ q_L \end{pmatrix}$$

Encompasses a broad class of models:
RS, Composite Higgs, Conformal TC, etc.

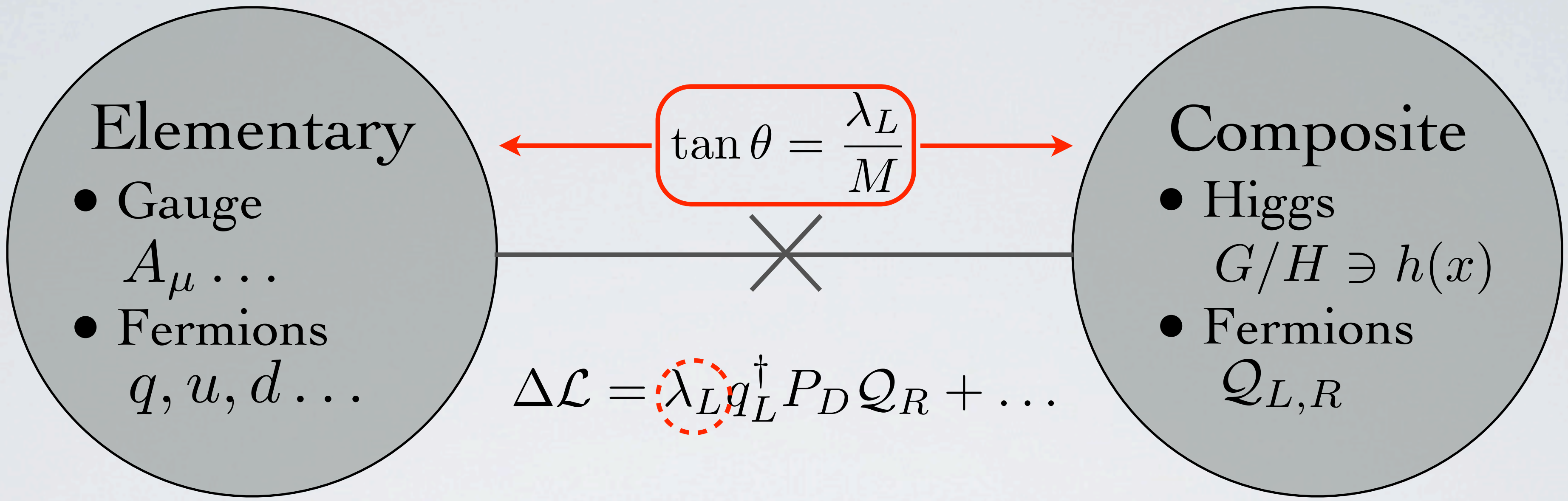


Ref:
Randall, Sundrum
PRL 83 (1999)

Ref:
Contino et al
JHEP 0705 (2007)

Ref:
Luty, Okui
JHEP 0609 (2006)

MOVING TO LOOP LEVEL: (PARTIAL) COMPOSITENESS

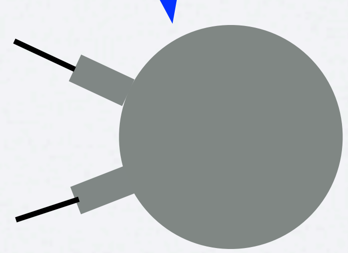


$$\Delta\mathcal{L} = \lambda_L q_L^\dagger P_D \mathcal{Q}_R + \ldots$$

$$\Delta\mathcal{L} = M(\mathcal{Q}_L^\dagger \mathcal{Q}_R + \text{h.c.}) + \text{mixing} \quad \Longrightarrow \quad \begin{pmatrix} Q_L \\ q_L^{\rm SM} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} P_D \mathcal{Q}_L \\ q_L \end{pmatrix}$$

Encompasses a broad class of models:
RS, Composite Higgs, Conformal TC, etc.

VERY LIGHT COMPOSITES (LEP)

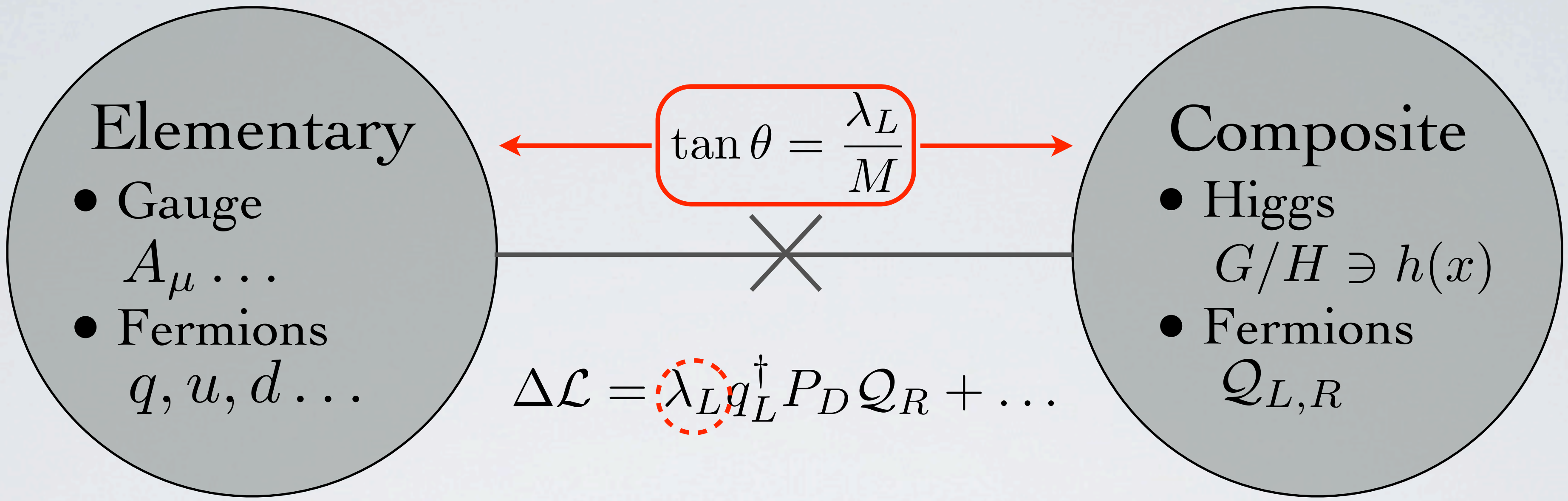


BOUNDS ON O.P.E. (THEORY)

Ref:
Abreu et al
EPJC 8 (1999)

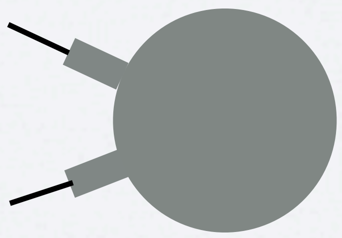
Ref:
Rattazzi et al
JHEP 0812 (2008)

MOVING TO LOOP LEVEL: (PARTIAL) COMPOSITENESS



$$\Delta\mathcal{L} = M(\mathcal{Q}_L^\dagger \mathcal{Q}_R + \text{h.c.}) + \text{mixing} \quad \Longrightarrow \quad \begin{pmatrix} Q_L \\ q_L^{\text{SM}} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} P_D \mathcal{Q}_L \\ q_L \end{pmatrix}$$

Encompasses a broad class of models:
RS, Composite Higgs, Conformal TC, etc.



Lots of (composite) fermions in the TeV-ish spectrum:
even if not directly accessible, may contribute in loops...

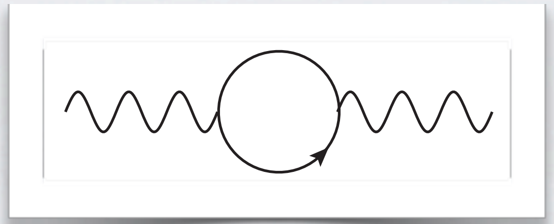
COUPLING CONSIDERATIONS

[Primary tool: low energy theorems]

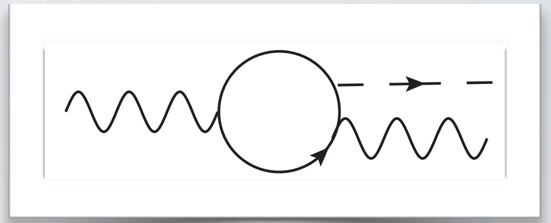
Ref:
Ellis et al (1976)
Shifman et al (1979)

Ideology: treat Higgs as constant background field $\Big\}$ $\lim_{p_{h(x)}\to 0} \mathcal{M}(X \to X + h) \sim \mathcal{M}(X \to X)$

E.g. QED vacuum polarization $\Big\}$ from



to



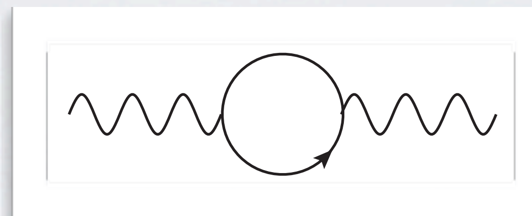
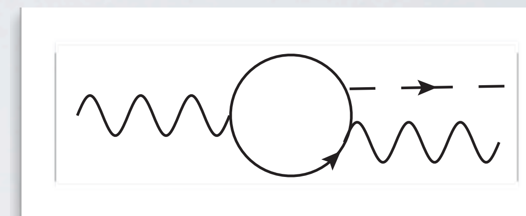
$$-\frac{1}{4}F^2 \times \sum_i b_i \frac{e^2}{16\pi^2} \log\left(\frac{\Lambda^2}{m_i^2}\right) \xrightarrow{\text{expand}} \boxed{b_i \frac{\alpha}{8\pi}\frac{y_i}{m_i} h(x) \times F^2}$$

COUPLING CONSIDERATIONS

[Primary tool: low energy theorems]

Ref:
Ellis et al (1976)
Shifman et al (1979)

Ideology: treat Higgs as constant background field $\Big\}$ $\lim_{p_{h(x)}\to 0} \mathcal{M}(X \to X + h) \sim \mathcal{M}(X \to X)$

E.g. QED vacuum polarization $\Big\}$ from  to 

$$-\frac{1}{4}F^2 \times \sum_i b_i \frac{e^2}{16\pi^2} \log\left(\frac{\Lambda^2}{m_i^2}\right) \xrightarrow{\text{expand}} \boxed{b_i \frac{\alpha}{8\pi}\frac{y_i}{m_i} h(x) \times F^2}$$

A calculational simplification $\Big\}$

$$\frac{\alpha}{8\pi}\frac{y_i}{m_i} h(x) \times F^2 = \frac{\alpha}{8\pi}\frac{h(x)}{v}\frac{\partial \log m}{\partial \log v} \times F^2$$

$$\xrightarrow{\text{sum species}} \boxed{F^2 \times \frac{\alpha}{16\pi}\frac{h(x)}{v}\frac{\partial}{\partial \log v} \log\det \mathbf{M}^\dagger \mathbf{M}}$$

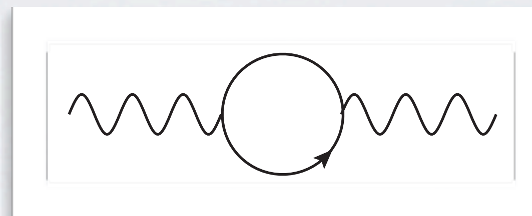
COUPLING CONSIDERATIONS

[Primary tool: low energy theorems]

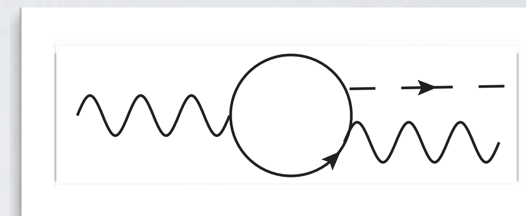
Ref:
Ellis et al (1976)
Shifman et al (1979)

Ideology: treat Higgs as constant background field $\Big\}$ $\lim_{p_{h(x)}\to 0} \mathcal{M}(X \to X + h) \sim \mathcal{M}(X \to X)$

E.g. QED vacuum polarization $\Big\}$ from



to



$$-\frac{1}{4}F^2 \times \sum_i b_i \frac{e^2}{16\pi^2} \log\left(\frac{\Lambda^2}{m_i^2}\right) \xrightarrow{\text{expand}} \boxed{b_i \frac{\alpha}{8\pi}\frac{y_i}{m_i} h(x) \times F^2}$$

A calculational simplification $\Big\}$

$$\frac{\alpha}{8\pi}\frac{y_i}{m_i} h(x) \times F^2 = \frac{\alpha}{8\pi}\frac{h(x)}{v}\frac{\partial \log m}{\partial \log v} \times F^2$$

$$\xrightarrow{\text{sum species}} \boxed{F^2 \times \frac{\alpha}{16\pi}\frac{h(x)}{v}\frac{\partial}{\partial \log v} \log\det \mathbf{M}^\dagger \mathbf{M}}$$

Can compute corrections to loop-induced processes very simply...

COUPLING CONSIDERATIONS

[Primary tool: low energy theorems]

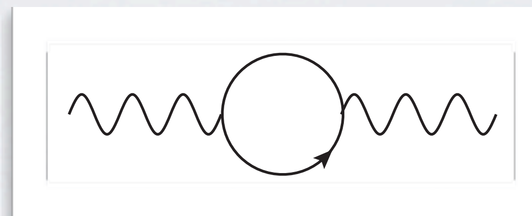
Ref:
Ellis et al (1976)
Shifman et al (1979)

Ideology: treat Higgs as constant background field

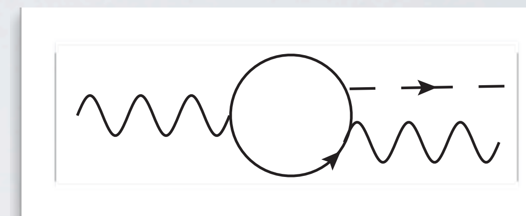
$$\lim_{p_{h(x)}\to 0} \mathcal{M}(X \to X + h) \sim \mathcal{M}(X \to X)$$

E.g. QED vacuum polarization

from



to



$$-\frac{1}{4}F^2 \times \sum_i b_i \frac{e^2}{16\pi^2} \log\left(\frac{\Lambda^2}{m_i^2}\right) \xrightarrow{\text{expand}} \boxed{b_i \frac{\alpha}{8\pi}\frac{y_i}{m_i} h(x) \times F^2}$$

A calculational simplification

$$\frac{\alpha}{8\pi}\frac{y_i}{m_i} h(x) \times F^2 = \frac{\alpha}{8\pi}\frac{h(x)}{v}\frac{\partial \log m}{\partial \log v} \times F^2$$

$$\xrightarrow{\text{sum species}} \boxed{F^2 \times \frac{\alpha}{16\pi}\frac{h(x)}{v}\frac{\partial}{\partial \log v} \log\det \mathbf{M}^\dagger \mathbf{M}}$$

...so what can we expect to produce with these sorts of interactions?
(very naively it looks like $O(1)$ corrections should be typical)

CONTACT OPERATORS $h\gamma\gamma$ AND hgg FROM COMPOSITES

Suffices to examine mass matrix
e.g. minimal coset $SO(5)/SO(4)$:

$$\mathbf{5} = \begin{pmatrix} T & \chi \\ B & T' \end{pmatrix} \oplus \tilde{T} \quad \Rightarrow \quad \text{four top states}$$

a particularly transparent basis:

$$\mathcal{M}^2 = \left(\begin{array}{c|ccc} 0 & \dots & \lambda_L v & \dots \\ \hline \vdots & & & \\ \lambda_R v & & F(M,Y,f) & \\ \vdots & & & \end{array}\right)$$

$$\Rightarrow \quad \det \mathcal{M}^2 = f(\lambda v) \times F(M,Y,f);$$
$$\hookrightarrow \partial_v \log \det \mathcal{M}^2 = f'(\lambda v)$$

Ref:
Low et al, JHEP 1004 (2004)
Low & Vichi PRD (2011)
Azatov, J.G. PRD (2012)

symmetry understanding: two spurions $\lambda_{L,R} \quad \Rightarrow \quad$ single inv't to build $\mathcal{M}^2$

Conclusions:
In cases of partial compositeness where individual charge species mix with *a single* composite representation, VEV and composite mass dependence factorize; no M-dependence in effective contact operators

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$G : T^A \qquad H : T^a \qquad G/H : T^{\hat{a}}$$

$$\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f) \mapsto U_{(G)}\xi(x)V^\dagger_{(H)}$$

LE theory built from ξ and gauge via Cartan form

$$D_\mu = \partial_\mu - i\mathcal{A}_\mu$$

$$C_\mu = i\xi^\dagger(x)D_\mu\xi(x) = (C^\perp_\mu)^{\hat{a}}T^{\hat{a}} + (C^\parallel_\mu)^a T^a$$

$$C^\perp_\mu \mapsto VC^\perp_\mu V^\dagger$$

$$C^\parallel_\mu \mapsto V(C^\parallel_\mu + i\partial_\mu)V^\dagger$$

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$G : T^A$$
$$H : T^a$$
$$G/H : T^{\hat{a}}$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)}$$
$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$D_\mu = \partial_\mu - i\mathcal{A}_\mu$$
$$C_\mu = i\xi^\dagger(x)D_\mu\xi(x)$$
$$= (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$
$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:

Construct field strength, cov'nt deriv.

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ... $\Bigg\}$

$$G : T^A \qquad H : T^a \qquad G/H : T^{\hat{a}}$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)} \mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form $\Bigg\}$

$$D_\mu = \partial_\mu - i\mathcal{A}_\mu$$

$$C_\mu = i\xi^\dagger(x)D_\mu\xi(x) = (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$

$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:

Construct field strength, cov'nt deriv.

e.g. $\Bigg\}$

$$f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 \implies \text{masses, kinetic}$$

$$\mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) \implies S \text{ parameter}$$

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$\left.\begin{array}{rl} G & : T^A \\ H & : T^a \\ G/H & : T^{\hat{a}} \end{array}\right\}$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)}$$

$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$\left.\begin{array}{l} D_\mu = \partial_\mu - i\mathcal{A}_\mu \\ C_\mu = i\xi^\dagger(x)D_\mu\xi(x) \\ \quad = (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a \end{array}\right\}$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$

$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

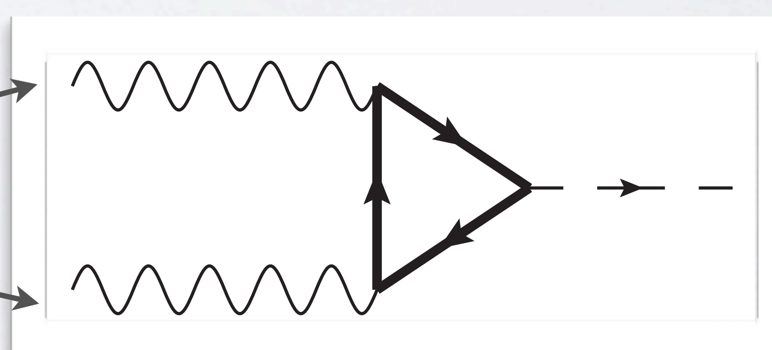
$\hookrightarrow$ Gauge field of $SO(4)$:
Construct field strength, cov'nt deriv.

e.g.

$$\left.\begin{array}{lcl} f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 & \Longrightarrow & \text{masses, kinetic} \\ \mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) & \Longrightarrow & S \text{ parameter} \end{array}\right\}$$

[Coming back to the question of how to generate loops]

Coupling to unbroken directions (glue, photon) requires breaking of Goldstone symmetry



[$\Delta\mathcal{L} \sim G^2 H^\dagger H,\ F^2 H^\dagger H$]

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$\left.\begin{array}{r} G : T^A \\ H : T^a \\ G/H : T^{\hat{a}} \end{array}\right.$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)}$$

$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$D_\mu = \partial_\mu - i\mathcal{A}_\mu$$

$$C_\mu = i\xi^\dagger(x)D_\mu\xi(x) = (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a$$

$$\boxed{C_\mu^\perp \mapsto V C_\mu^\perp V^\dagger}$$

$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:

Construct field strength, cov'nt deriv.

e.g.

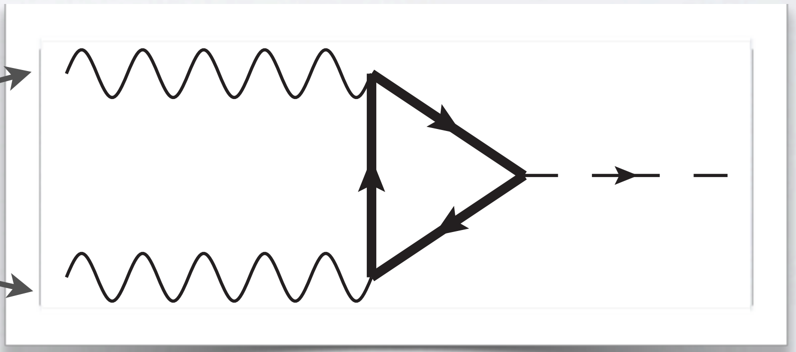
$f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 \implies$ masses, kinetic

$\mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) \implies$ S parameter

[Coming back to the question of how to generate loops]

$\partial_v \log\det \mathbf{M}^2$

independent of composite spectrum!



[$\Delta\mathcal{L} \sim G^2 H^\dagger H,\ F^2 H^\dagger H$]

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$\left.\right\} \begin{aligned} G &: T^A \\ H &: T^a \\ G/H &: T^{\hat{a}} \end{aligned}$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)}$$
$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$\left.\right\} \begin{aligned} D_\mu &= \partial_\mu - i\mathcal{A}_\mu \\ C_\mu &= i\xi^\dagger(x)D_\mu\xi(x) \\ &= (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a \end{aligned}$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$
$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:
Construct field strength, cov'nt deriv.

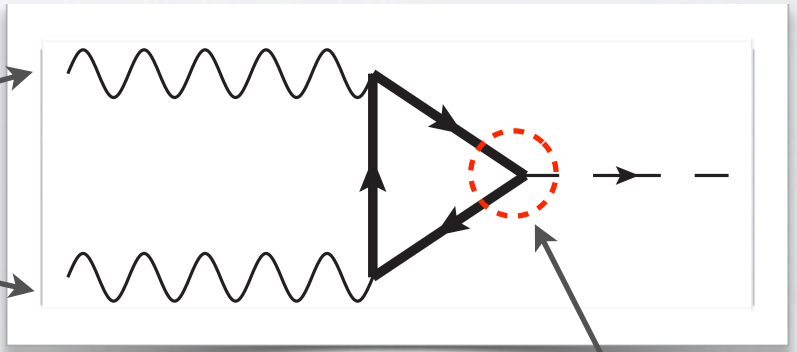
e.g. $\left.\right\}$

$$f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 \implies \text{masses, kinetic}$$
$$\mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) \implies S \text{ parameter}$$

[Coming back to the question of how to generate loops]

$$\partial_v \log\det \mathbf{M}^2$$

$\approx$ Useless as probe of fermionic composites



$$\frac{\delta g}{g} = F(v/f) \Big\}$$ sensitive only to non-linearities

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$\left.\begin{array}{rl} G &: T^A \\ H &: T^a \\ G/H &: T^{\hat a}\end{array}\right\}$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat a}(x)T^{\hat a}/f)}$$

$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$\begin{aligned} D_\mu &= \partial_\mu - i\mathcal{A}_\mu \\ C_\mu &= i\xi^\dagger(x)D_\mu\xi(x) \\ &= (C_\mu^\perp)^{\hat a}T^{\hat a} + (C_\mu^\parallel)^a T^a \end{aligned}$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$

$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:

Construct field strength, cov'nt deriv.

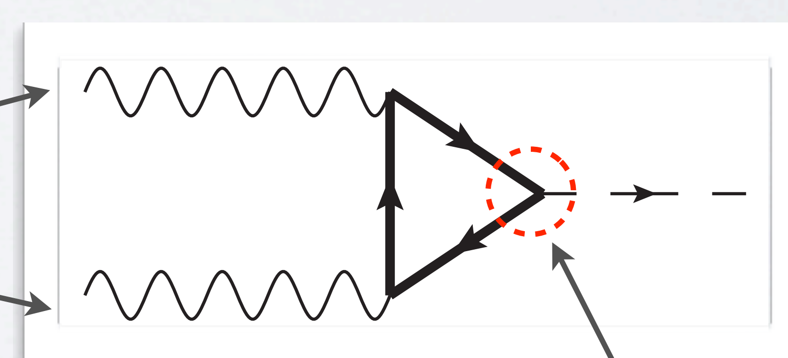
e.g.

$$\left.\begin{array}{lll} f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 & \Longrightarrow & \text{masses, kinetic} \\ \mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) & \Longrightarrow & S \text{ parameter}\end{array}\right.$$

[Coming back to the question of how to generate loops]

$$\partial_v \log\det \mathbf{M}^2$$

$\approx$Useless as probe of fermionic composites



$$\frac{\delta g}{g} = F(v/f)$$

(these measured already in a)

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$\left.\begin{array}{r} G \,:\, T^A \\ H \,:\, T^a \\ G/H \,:\, T^{\hat a} \end{array}\right.$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat a}(x)T^{\hat a}/f)}$$

$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$D_\mu = \partial_\mu - i\mathcal{A}_\mu$$

$$C_\mu = i\xi^\dagger(x)D_\mu\xi(x)$$

$$= (C^\perp_\mu)^{\hat a}T^{\hat a} + (C^\parallel_\mu)^a T^a$$

$$\boxed{C^\perp_\mu \mapsto VC^\perp_\mu V^\dagger}$$

$$\boxed{C^\parallel_\mu \mapsto V(C^\parallel_\mu + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:
Construct field strength, cov'nt deriv.

e.g.

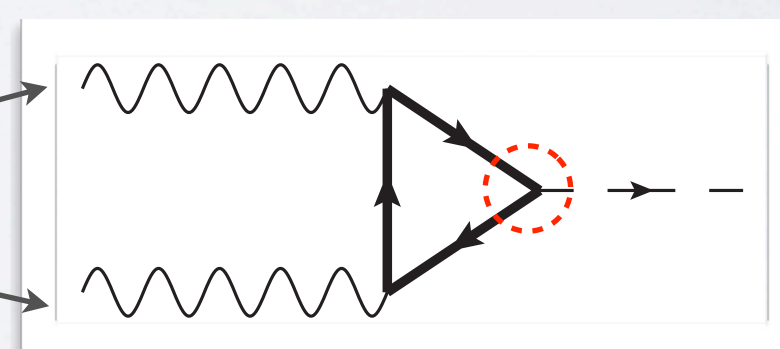
$$f^2\,\mathrm{Tr}\,(C^\perp_\mu)^2 \implies \text{masses, kinetic}$$

$$\mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) \implies S \text{ parameter}$$

[Coming back to the question of how to generate loops]

$$\partial_v \log\det \mathbf{M}^2$$

$\approx$ Useless as probe of fermionic composites



Heuristic moral: fermions respect Goldstone symmetry, can't contribute to *GG*, *FF* operators

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$\left.\begin{array}{r} G \,:\, T^A \\ H \,:\, T^a \\ G/H \,:\, T^{\hat{a}} \end{array}\right\}$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)}$$

$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$\begin{aligned} D_\mu &= \partial_\mu - i\mathcal{A}_\mu \\ C_\mu &= i\xi^\dagger(x)D_\mu\xi(x) \\ &= (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a \end{aligned}$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$

$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:
Construct field strength, cov'nt deriv.

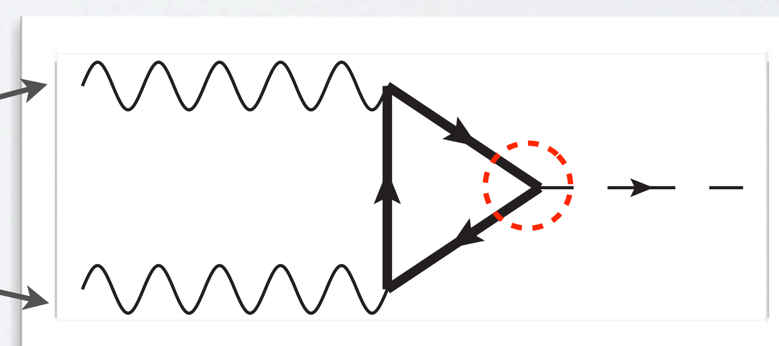
e.g.

$$\left.\begin{array}{lcl} f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 & \Longrightarrow & \text{masses, kinetic} \\ \mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) & \Longrightarrow & S \text{ parameter} \end{array}\right.$$

[Coming back to the question of how to generate loops]

$$\partial_v \log\det \mathbf{M}^2$$

$\approx$Useless as probe of fermionic composites



(Careful moral: two spurions imply a single invariant => Det[M] factorizes)

INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$G : T^A$$
$$H : T^a$$
$$G/H : T^{\hat{a}}$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)}$$
$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$D_\mu = \partial_\mu - i\mathcal{A}_\mu$$
$$C_\mu = i\xi^\dagger(x)D_\mu\xi(x)$$
$$= (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$
$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:
Construct field strength, cov'nt deriv.

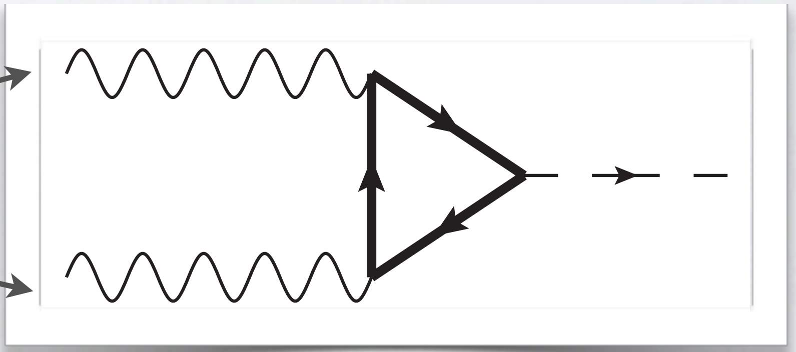
e.g.

$$f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 \implies \text{masses, kinetic}$$
$$\mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) \implies S \text{ parameter}$$

[Coming back to the question of how to generate loops]

Coupling to *broken* directions, however...

$$\mathrm{Tr}\left(C_\mu^\perp C_\nu^\perp C^{\mu\nu}\right)$$
$$\supset Z_\mu\partial_\nu h F^{\mu\nu}$$



INTERLUDE: SOME NECESSARY FORMALISM (CCWZ)

Recall the Higgs as Goldstone of G/H ...

$$\left.\begin{array}{r} G : T^A \\ H : T^a \\ G/H : T^{\hat{a}} \end{array}\right.$$

$$\boxed{\xi(x) = \exp(i\sqrt{2}\pi^{\hat{a}}(x)T^{\hat{a}}/f)}$$
$$\mapsto U\xi(x)V^\dagger$$

LE theory built from ξ and gauge via Cartan form

$$D_\mu = \partial_\mu - i\mathcal{A}_\mu$$
$$C_\mu = i\xi^\dagger(x)D_\mu\xi(x)$$
$$= (C_\mu^\perp)^{\hat{a}}T^{\hat{a}} + (C_\mu^\parallel)^a T^a$$

$$\boxed{C_\mu^\perp \mapsto VC_\mu^\perp V^\dagger}$$
$$\boxed{C_\mu^\parallel \mapsto V(C_\mu^\parallel + i\partial_\mu)V^\dagger}$$

$\hookrightarrow$ Gauge field of $SO(4)$:

Construct field strength, cov'nt deriv.

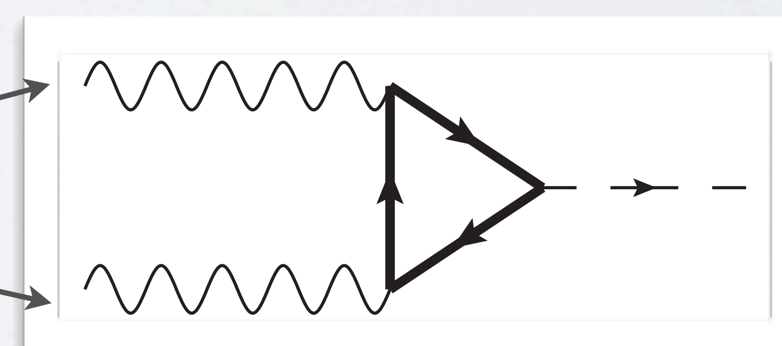
e.g.

$$f^2\,\mathrm{Tr}\,(C_\mu^\perp)^2 \implies \text{masses, kinetic}$$
$$\mathrm{Tr}\,(C_{\mu\nu}C^{\mu\nu}) \implies S \text{ parameter}$$

[Coming back to the question of how to generate loops]

Coupling to *broken* directions, however...

$$\mathrm{Tr}\left(C_\mu^\perp C_\nu^\perp C^{\mu\nu}\right)$$
$$\supset Z_\mu\partial_\nu hF^{\mu\nu}$$



might realize large corrections

we lose the slick calculational tool

RECAP

1. Higgs low-energy theorems allow us to almost trivially see that important loop-induced couplings cannot be modified by composite spectrum in a way that illuminates its 'flavor' structure...

2. ...having to do with the fact that the crucial couplings involve a Higgs coupling to two *unbroken* directions (thus Goldstone suppressed)

3. A hope may remain when looking at interactions that involve at least one *broken* direction: Goldstone symmetry can be respected and spurion suppression can therefore be absent

THE ANATOMY OF $h \to Z\gamma$

[with Azatov, Contino, Di Iura; in preparation]

THE ANATOMY OF $h \to Z\gamma$

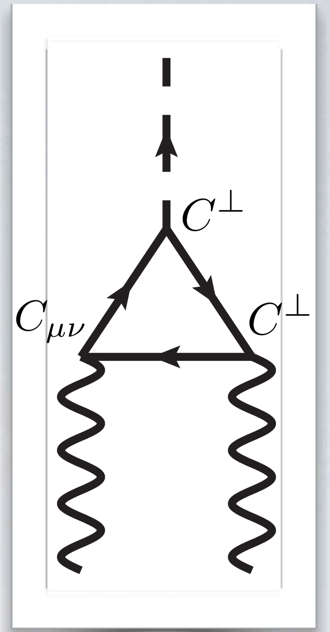
Two pertinent operators to consider

[assuming $G \supset SU(2)_L \times SU(2)_R$]

$$c_\pm \,\mathrm{Tr}\left[C_\mu^\perp C_\nu^\perp (C_L^{\mu\nu} \pm C_R^{\mu\nu})\right]$$

$\cancel{P_{LR}}$ $\quad$ P_{LR}

$\boxed{c_- \;:\; h \to Z\gamma}$ $\quad$ $\boxed{c_+ \;:\; h \to ZZ}$



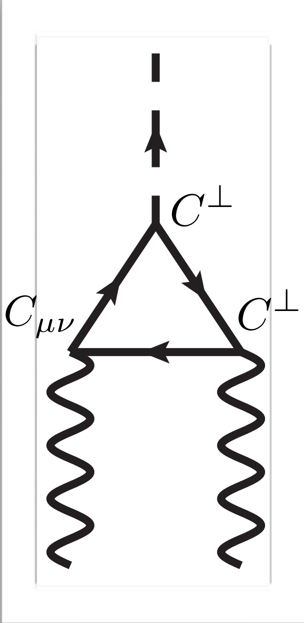
THE ANATOMY OF $h \to Z\gamma$

Two pertinent operators to consider
[assuming $G \supset SU(2)_L \times SU(2)_R$]

$$\boxed{c_\pm \operatorname{Tr}\left[C^\perp_\mu C^\perp_\nu (C^{\mu\nu}_L \pm C^{\mu\nu}_R)\right]}$$

$\cancel{P_{LR}}$ $\quad$ P_{LR}

$$\boxed{c_- \; : \; h \to Z\gamma} \qquad \boxed{c_+ \; : \; h \to ZZ}$$



Goldstone symmetry can be preserved, but in this case we need a sizable breaking of possible parity symmetry within the strong sector

e.g. $G/H = SO(5)/SO(4)$

$$4 = (2,2)$$
$$5 = (2,2) \oplus 1$$
$$\boxed{10 = (2,2) \oplus (3,1) \oplus (1,3)}$$
$$\vdots$$

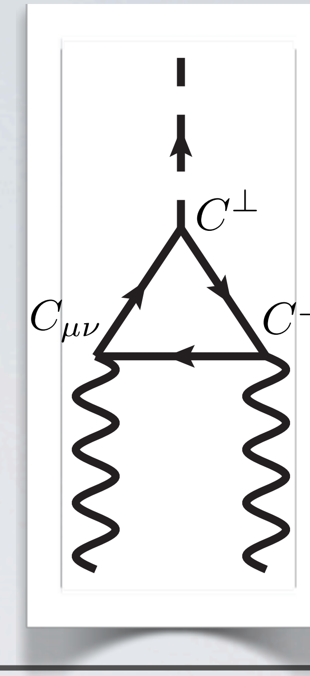
THE ANATOMY OF $h \to Z\gamma$

Two pertinent operators to consider
[assuming $G \supset SU(2)_L \times SU(2)_R$]

$$c_{\pm} \mathrm{Tr}\left[C_\mu^\perp C_\nu^\perp (C_L^{\mu\nu} \pm C_R^{\mu\nu})\right]$$

$\cancel{P_{LR}}$ $\quad$ P_{LR}

$c_- \ : \ h \to Z\gamma$ $\qquad$ $c_+ \ : \ h \to ZZ$



Goldstone symmetry can be preserved, but in this case we need a sizable breaking of possible parity symmetry within the strong sector

e.g. $G/H = SO(5)/SO(4)$

$$4 = (2,2)$$
$$5 = (2,2) \oplus 1$$
$$10 = (2,2) \oplus (3,1) \oplus (1,3)$$
$$\vdots$$

Specializing to the minimal coset $SO(5)/SO(4)$

$$\Delta\mathcal{L} = i\, c_- \times \frac{v \cos\theta}{\sqrt{2} f^2} \times Z_{[\mu}(x)\partial_{\nu]} h(x) F^{\mu\nu}$$

We're left with a simple question: What sorts of UV physics can break the strong sector's LR symmetry in the right way?

PARITY BREAKING: WHAT DOES THE JOB?

Some obvious thoughts

1. Gauge couplings
2. Composite-elementary mixing
3. Mass splitting within matter multiplets

PARITY BREAKING: WHAT DOES THE JOB?

Some obvious thoughts }

1. Gauge couplings
2. Composite-elementary mixing
3. Mass splitting within matter multiplets

1. Gauge couplings, take one: X gauge boson

$$\mathrm{Tr}\left(C^{\perp}_{[\mu}C^{\perp}_{\nu]}X^{\mu\nu}\right) = \mathrm{Tr}\,(\underbrace{C^{\perp}_{[\mu}C^{\perp}_{\nu]}}_{T^A})X^{\mu\nu} = 0$$

PARITY BREAKING: WHAT DOES THE JOB?

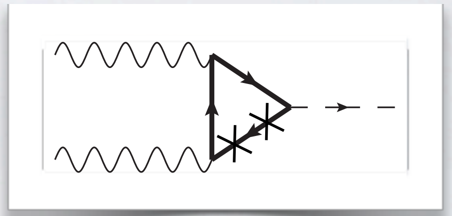
Some obvious thoughts $\Bigg\}$

1. Gauge couplings
2. Composite-elementary mixing
3. Mass splitting within matter multiplets

1. Gauge couplings, take one: X gauge boson

$$\mathrm{Tr}\left(C^{\perp}_{[\mu}C^{\perp}_{\nu]}X^{\mu\nu}\right)=\mathrm{Tr}\,(\underbrace{C^{\perp}_{[\mu}C^{\perp}_{\nu]}}_{T^A})X^{\mu\nu}=0$$

2. Mass Mixing with a **5**



$$\Delta\mathcal{L}=\lambda_L q_L^{\dagger}P_D\mathcal{Q}_R+\lambda_R t_R^{\dagger}P_S\mathcal{Q}_L+\text{h.c.}$$

Two new spurions can be constructed to respect LR $\Bigg\}$

$$S_L=\lambda_L P_D\mapsto S_L\times P_{LR};\quad S_R=\lambda_R P_S\mapsto S_R\times P_{LR}$$

$$\Rightarrow\Delta\mathcal{L}_{\text{eff}}=\mathrm{Tr}\left[C^{\perp}_{\mu}C^{\perp}_{\nu}(S_L+S_R)C_{+}^{\mu\nu}\right]=0\quad\text{(accidental)}$$

PARITY BREAKING: WHAT DOES THE JOB?

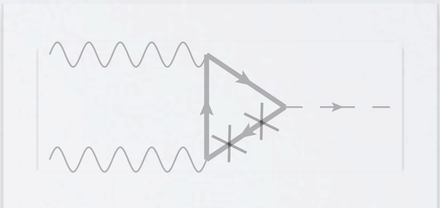
Some obvious thoughts

1. Gauge couplings
2. Composite-elementary mixing
3. Mass splitting within matter multiplets

1. Gauge couplings, take one: X gauge boson

$$\mathrm{Tr}\left(C^{\perp}_{[\mu}C^{\perp}_{\nu]}X^{\mu\nu}\right) = \mathrm{Tr}\,(\underbrace{C^{\perp}_{[\mu}C^{\perp}_{\nu]}}_{T^A})X^{\mu\nu} = 0$$

2. Mass Mixing with a **5**



$$\Delta\mathcal{L} = \lambda_L q_L^\dagger P_D \mathcal{Q}_R + \lambda_R t_R^\dagger P_S \mathcal{Q}_L + \mathrm{h.c.}$$

Two new spurions can be constructed to respect LR

$$S_L = \lambda_L P_D \mapsto S_L \times P_{LR};\quad S_R = \lambda_R P_S \mapsto S_R \times P_{LR}$$

$$\Rightarrow \Delta\mathcal{L}_{\text{eff}} = \mathrm{Tr}\left[C^{\perp}_{\mu}C^{\perp}_{\nu}(S_L + S_R)C_+^{\mu\nu}\right] = 0$$ (accidental)

ADDITIONAL *LR* BREAKING NEEDED

PARITY BREAKING: WHAT DOES THE JOB?

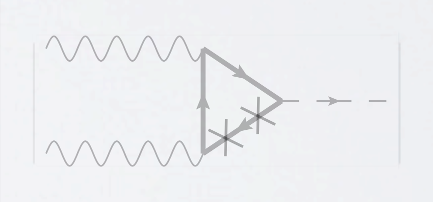
Some obvious thoughts }
1. Gauge couplings
2. Composite-elementary mixing
3. Mass splitting within matter multiplets

1. Gauge couplings, take one: X gauge boson

$$\mathrm{Tr}\left(C^{\perp}_{[\mu}C^{\perp}_{\nu]}X^{\mu\nu}\right) = \mathrm{Tr}\,(\underbrace{C^{\perp}_{[\mu}C^{\perp}_{\nu]}}_{T^A})\,X^{\mu\nu} = 0$$

2. Mass Mixing with a **5**

$$\Delta\mathcal{L} = \lambda_L q_L^\dagger P_D Q_R + \lambda_R t_R^\dagger P_S Q_L + \text{h.c.}$$



Ref:
Djouadi et al
EPJC 1 (1998)

...ions can be ...respect LR }

$$S_L = \lambda_L P_D \mapsto S_L \times P_{LR};\quad S_R = \lambda_R P_S \mapsto S_R \times P_{LR}$$

...TIONAL *LR* BREAKING NEEDED

$$\Rightarrow \Delta\mathcal{L}_{\text{eff}} = \mathrm{Tr}\left[C^{\perp}_{\mu}C^{\perp}_{\nu}(S_L + S_R)C_+^{\mu\nu}\right] = 0$$ (accidental)

3. Mass Splitting

$$\boxed{10 = (2,2)\oplus(3,1)\oplus(1,3)}$$

$$\Delta\mathcal{L} = \sum_{i=4,3L,3R}\bar{\chi}_i(i\,\nabla\!\!\!\!/ - m_i)\chi_i + i\alpha_L\chi_4^\dagger\,C\!\!\!/^{\perp}\,\chi_{3L} + i\alpha_R\chi_4^\dagger\,C\!\!\!/^{\perp}\,\chi_{3R} + \text{h.c.}$$

Schematically:

$$c_- \sim \frac{1}{16\pi^2}\,\frac{\alpha_L^2 m_{3L}^2 - \alpha_R^2 m_{3R}^2}{m_4^2}$$

PARITY BREAKING: WHAT DOES THE JOB?

Some obvious thoughts $\Big\}$

1. Gauge couplings
2. Composite-elementary mixing
3. Mass splitting within matter multiplets

---

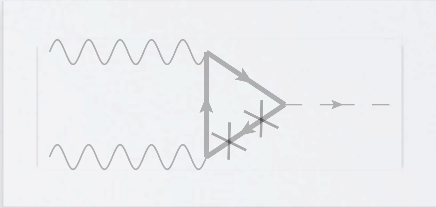
1. Gauge couplings, take one: X gauge boson

$$\mathrm{Tr}\left(C^{\perp}_{[\mu}C^{\perp}_{\nu]}X^{\mu\nu}\right) = \mathrm{Tr}\,(\underbrace{C^{\perp}_{[\mu}C^{\perp}_{\nu]}}_{T^A})X^{\mu\nu} = 0$$

---

2. Mass Mixing with a **5**

$$\Delta\mathcal{L} = \lambda_L q_L^\dagger P_D Q_R + \lambda_R t_R^\dagger P_S Q_L + \text{h.c.}$$



Ref: Djouadi et al EPJC 1 (1998)

...ions can be ...respect LR $\Big\}$ $S_L = \lambda_L P_D \mapsto S_L \times P_{LR}; \quad S_R = \lambda_R P_S \mapsto S_R \times P_{LR}$

$\Rightarrow \Delta\mathcal{L}_{\text{eff}} = \mathrm{Tr}\left[C^{\perp}_{\mu}C^{\perp}_{\nu}(S_L + S_R)C_+^{\mu\nu}\right] = 0$ (accidental)

...TIONAL *LR* BREAKING NEEDED

---

3. Mass Splitting

$$\boxed{10 = (2,2)\oplus(3,1)\oplus(1,3)}$$

$$\Delta\mathcal{L} = \sum_{i=4,3L,3R} \bar{\chi}_i(i\,\not{\nabla} - m_i)\chi_i + i\alpha_L \chi_4^\dagger\,\not{C}^\perp\,\chi_{3L} + i\alpha_R\chi_4^\dagger\,\not{C}^\perp\,\chi_{3R} + \text{h.c.}$$

Explicit calculation: $\left.\dfrac{\text{composites}}{\text{top}}\right|_{m_{3L}-m_{3R}\ll m_4}$

$$\simeq \sum_{\text{exotics}} \frac{v^2}{f^2}\times\frac{T_Z(\text{exotic})}{T_Z(\text{top})}\times\frac{Q(\text{exotic})}{Q(\text{top})}\times\frac{m_{3L}-m_{3R}}{m_4}$$

PARITY BREAKING: WHAT DOES THE JOB?

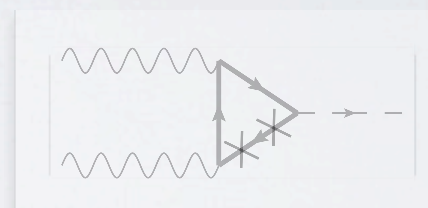
Some obvious thoughts $\Big\}$
1. Gauge couplings
2. Composite-elementary mixing
3. Mass splitting within matter multiplets

1. Gauge couplings, take one: X gauge boson

$$\mathrm{Tr}\left(C^{\perp}_{[\mu}C^{\perp}_{\nu]}X^{\mu\nu}\right) = \mathrm{Tr}\,(\underbrace{C^{\perp}_{[\mu}C^{\perp}_{\nu]}}_{T^A})X^{\mu\nu} = 0$$

2. Mass Mixing with a **5**

$$\Delta\mathcal{L} = \lambda_L q_L^\dagger P_D Q_R + \lambda_R t_R^\dagger P_S Q_L + \text{h.c.}$$



Ref:
Djouadi et al
EPJC 1 (1998)

...ions can be ...respect LR $\Big\}$ $S_L = \lambda_L P_D \mapsto S_L \times P_{LR}; \quad S_R = \lambda_R P_S \mapsto S_R \times P_{LR}$

$\Rightarrow \Delta\mathcal{L}_{\text{eff}} = \mathrm{Tr}\left[C^{\perp}_{\mu}C^{\perp}_{\nu}(S_L + S_R)C_+^{\mu\nu}\right] = 0$ (accidental)

...TIONAL *LR* BREAKING NEEDED

3. Mass Splitting

$$\boxed{\mathbf{10} = (2,2) \oplus (3,1) \oplus (1,3)}$$

$$\Delta\mathcal{L} = \sum_{i=4,3L,3R} \bar{\chi}_i(i\,\nabla\!\!\!\!/ - m_i)\chi_i + i\alpha_L \chi_4^\dagger\, \mathcal{C}\!\!\!/^{\perp}\,\chi_{3L} + i\alpha_R\chi_4^\dagger\,\mathcal{C}\!\!\!/^{\perp}\,\chi_{3R} + \text{h.c.}$$

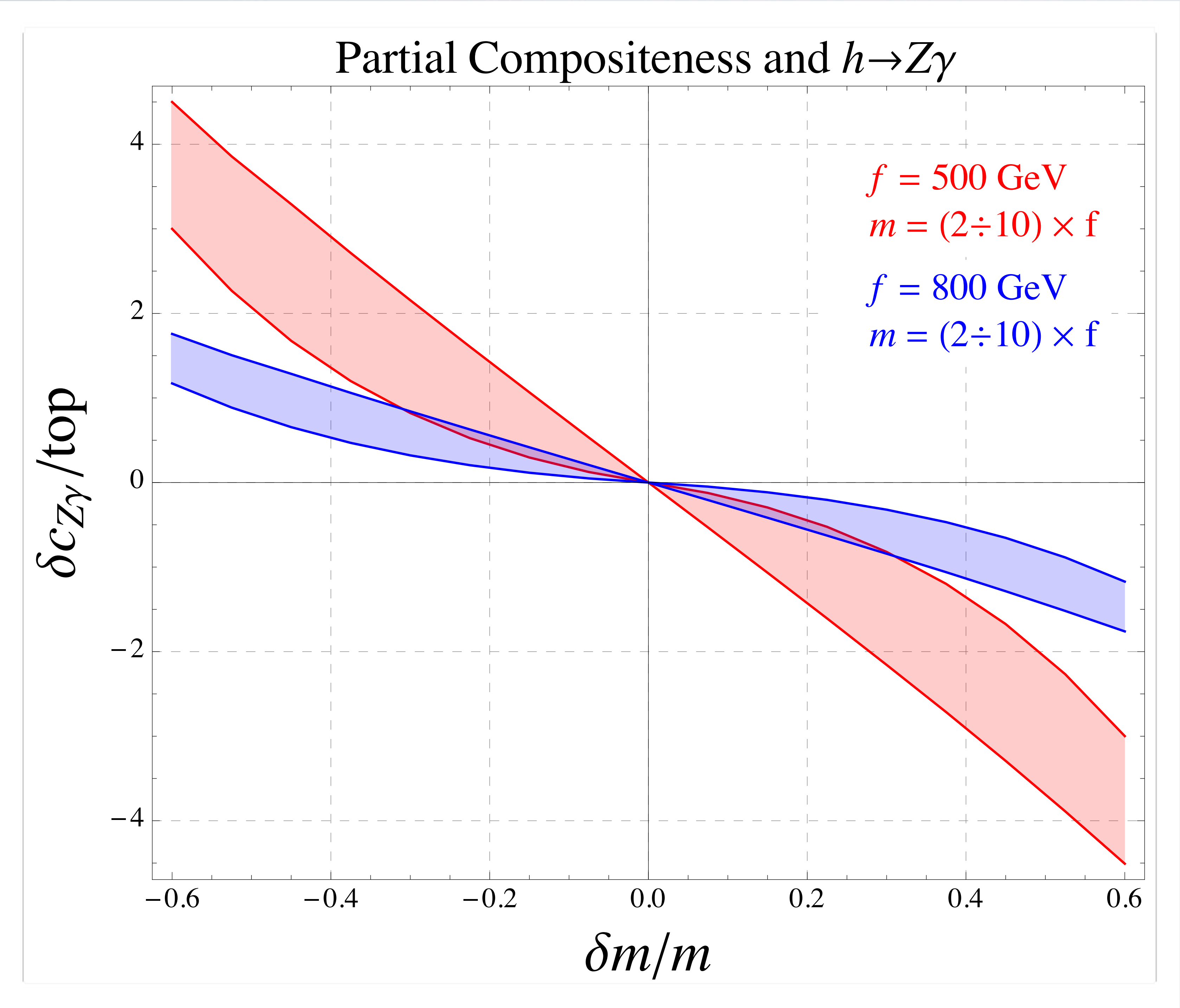
Explicit calculation: $\left.\dfrac{\text{composites}}{\text{top}}\right|_{m_{3L}-m_{3R}\ll m_4}$

$$\boxed{\sim 15\,N_F \times \frac{v^2}{f^2}\times\frac{\Delta m}{m}}$$

Easily $O(1)$

RESULT: MASS SPLITTING WITHIN 10 ALONE

[no additional spurions (or resonances) contributing]



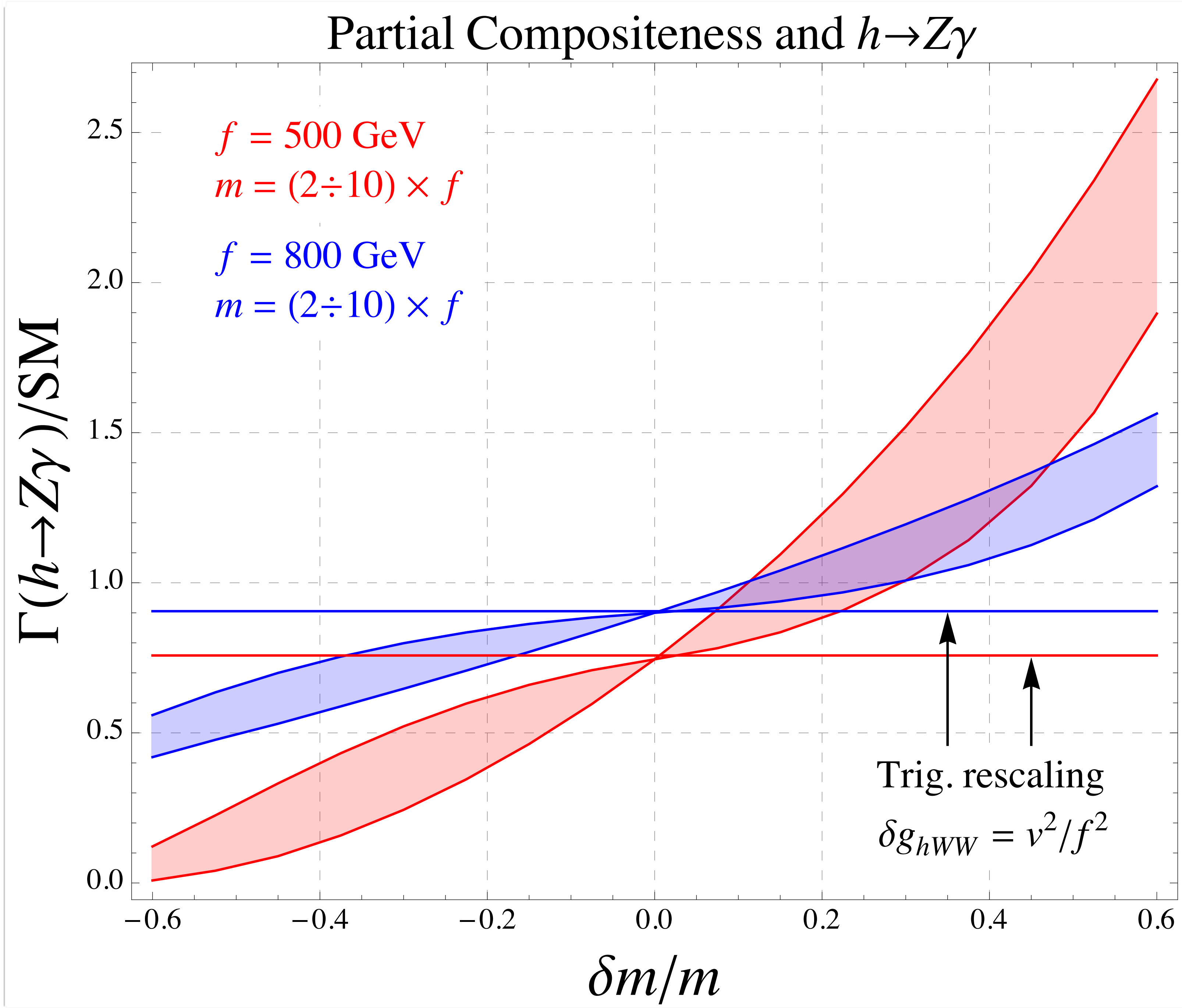
[coupling from a single generation w/10]

Scatter: all composite fermion masses between (2, 10) x f:

LR-symmetric mass moves vertically, (1,3)-(3,1) splitting moves horizontally

RESULT: MASS SPLITTING WITHIN 10 ALONE

[no additional spurions (or resonances) contributing]



[width from all 3 generations]

Conclusion:

Partial width can be significantly enhanced *or* suppressed...

...large deviations possible in either case

CONCLUSION / SPECULATION:

Currently the SM is looking fairly healthy,
loop-induced couplings and all...

...we'll have to look hard at subtler channels

CONCLUSION / SPECULATION:

Currently the SM is looking fairly healthy,
loop-induced couplings and all...

...we'll have to look hard at subtler channels

- Composite Higgs: $h \to \gamma\gamma$ and $h \to GG$ suppressed by Goldstone symmetry

$\Rightarrow$ Poor probe of composite's 'flavor' sector

- New, statistically limited and so relatively unexplored, channels might grant more interesting information (existence proof demonstrated here; perhaps other possibilities are around)

$$\left.\frac{\Delta g_{hZ\gamma}}{g_{hZ\gamma}^{(\mathrm{SM})}} \sim \mathcal{O}(1)\ \right\}$$

From one generation of fermions alone
[additional contribution from resonances]

- Sensitivity to these deviations with increased statistics
[e.g. SM injection gives ~ 0.5 sigma with 20/fb at 8 TeV]

- Despite the lack of early deviations...
We might still (safely) hope for non-SM Higgs behavior in the longer term

RESERVE

PARITY RULES IN CCWZ

E.g. minimal coset $SO(5)/SO(4)$

$$\pi_{1,2,3} \to -\pi_{1,2,3}, \;\; \pi_h \to \pi_h; \qquad A^{\mu\,a}_{L,R} \leftrightarrow A^{\mu\,a}_{R,L}$$

equivalent to $T^A \to \mathcal{P} T^A \mathcal{P}^T; \quad \mathcal{P} = \mathrm{diag}(+1, +1, +1, -1, 1)$

(primary)

from $\xi \to \mathcal{P}\xi\mathcal{P}^T$ and $A^{\mu\,a}_{L,R} \leftrightarrow A^{\mu\,a}_{R,L}$

$\hookrightarrow C_\mu \to \mathcal{P} C_\mu \mathcal{P}^T$ likewise for separate projections

(secondary)

WHAT ABOUT *Zbb*: SHOULD WE WORRY?

Enhancing $h \to Z + \gamma$ requires large parity breaking ...

... but this is the same symmetry that protects Z coupling to b_L.

A safe nonminimal model, without m_t enhancement

$$\left.\begin{aligned} \Delta\mathcal{L} = {} & \lambda_q^{(5)} q_L^\dagger P_D \mathcal{Q}_R^{(5)} + \lambda_t t_R^\dagger P_S \mathcal{Q}_R^{(5)} \\ & + \lambda_q^{(10)} q_L^\dagger P_D \mathcal{Q}_R^{(10)} + \lambda_b b_R^\dagger P_S Q_R^{(10)} \end{aligned}\right\} \begin{aligned} m_t &\sim \lambda_q^{(5)} \lambda_t \\ m_b &\sim \lambda_q^{(10)} \lambda_b \end{aligned}$$

$\boxed{\text{via hierarchy } \lambda_q^{(5)} \gg \lambda_q^{(10)}}$