# How to break EW symmetry naturally?

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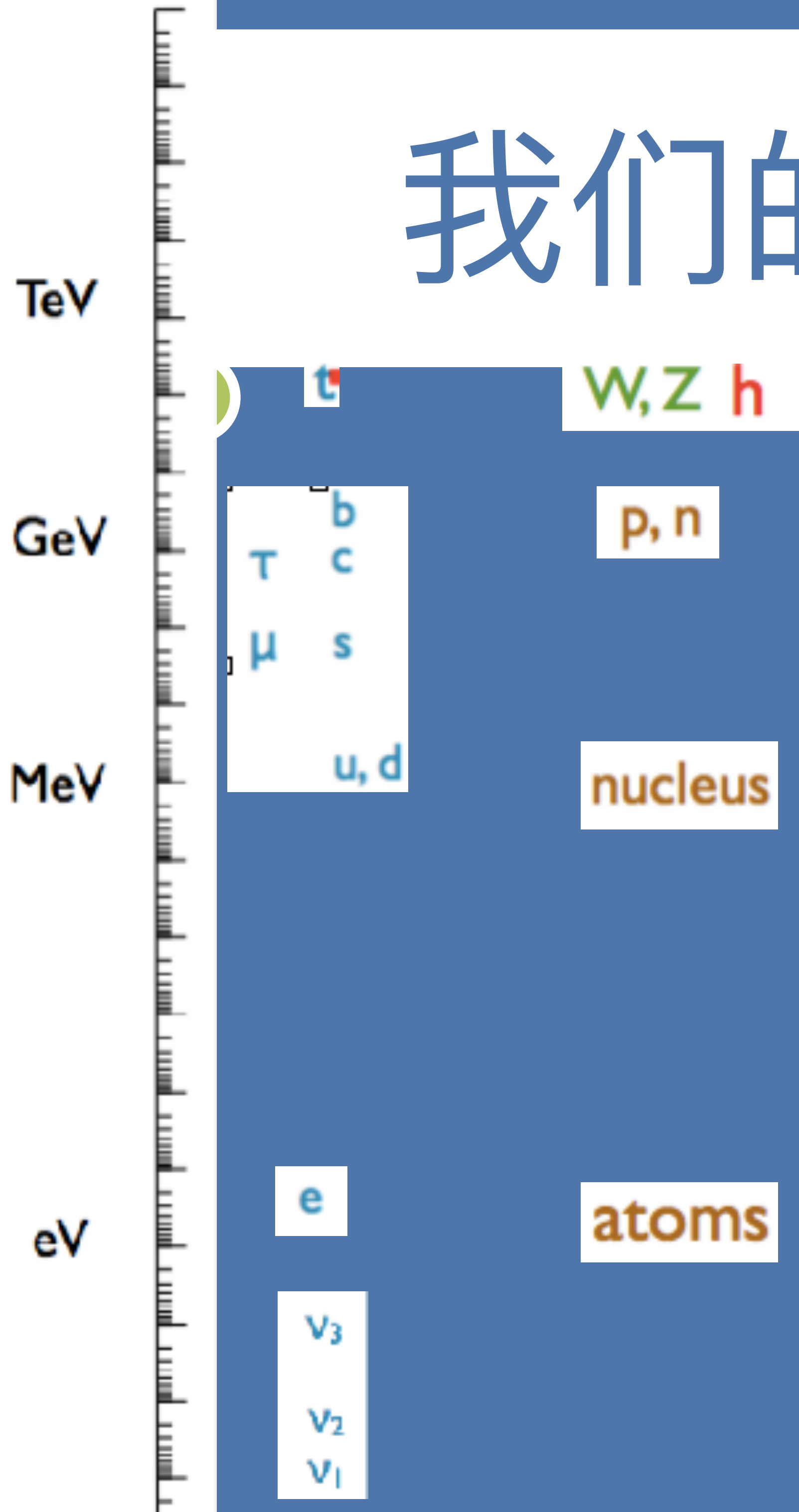
# 简介

- 电弱对称性破缺问题简介?
- 我们究竟需要解决什么问题？疑难在哪里?
- 电弱对称性破缺的有效拉氏量，非线性组合。
- 最大对称性下的复合Higgs模型。
- 未来展望。

# 电弱对称性破缺起源

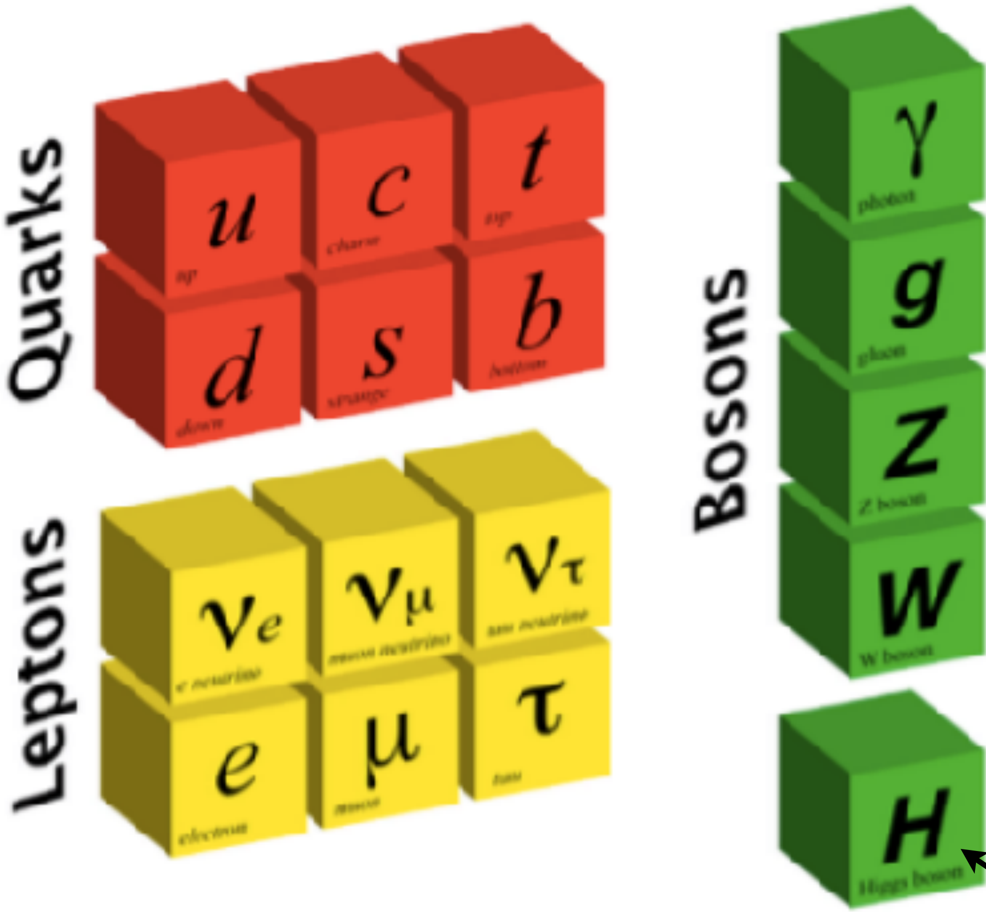
# 我们的高能物理




未来高能量前沿
继续探索未知

过去一个世纪
的高能物理学

# 我们已知的“旧”物理




## The Weinberg-Salam Model

$$\mathcal{L} = \bar{E}_L(i\partial\!\!\!/)E_L + \bar{e}_R(i\partial\!\!\!/)e_R + \bar{Q}_L(i\partial\!\!\!/)Q_L + \bar{u}_R(i\partial\!\!\!/)u_R + \bar{d}_R($$

$$+ g(W^+_\mu J^{\mu+}_W + W^-_\mu J^{\mu-}_W + Z^0_\mu J^\mu_Z) + eA_\mu J^\mu_{EM},$$

$$J^{\mu+}_W = \frac{1}{\sqrt{2}}(\bar{\nu}_L\gamma^\mu e_L + \bar{u}_L\gamma^\mu d_L);$$

$$J^{\mu-}_W = \frac{1}{\sqrt{2}}(\bar{e}_L\gamma^\mu \nu_L + \bar{d}_L\gamma^\mu u_L); \qquad e = \frac{gg'}{\sqrt{g^2+g'^2}}$$

$$J^\mu_Z = \frac{1}{\cos\theta_w}\Big[\bar{\nu}_L\gamma^\mu(\tfrac{1}{2})\nu_L + \bar{e}_L\gamma^\mu(-\tfrac{1}{2}+\sin^2\theta_w)e_L + \bar{e}_R\gamma^\mu($$

$$+ \bar{u}_L\gamma^\mu(\tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_w)u_L + +\bar{u}_R\gamma^\mu(-\tfrac{2}{3}\sin^2\theta_w)$$

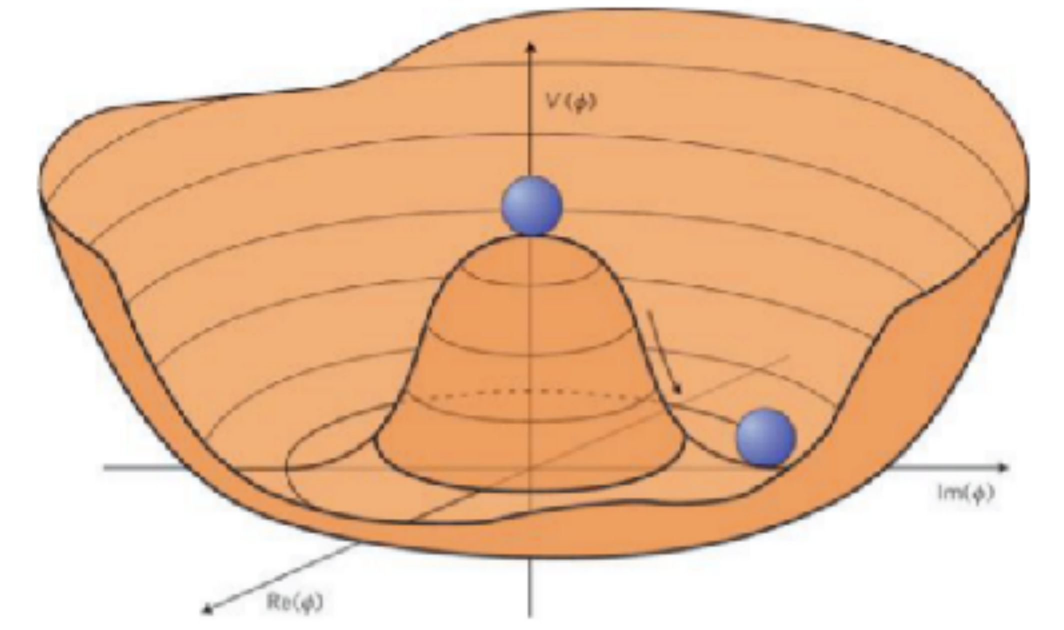
$$+ \bar{d}_L\gamma^\mu(-\tfrac{1}{2}+\tfrac{1}{3}\sin^2\theta_w)d_L + \bar{d}_R\gamma^\mu(\tfrac{1}{3}\sin^2\theta_w)d$$

$$J^\mu_{EM} = \bar{e}\gamma^\mu(-1)e + \bar{u}\gamma^\mu(+\tfrac{2}{3})u + \bar{d}\gamma^\mu(-\tfrac{1}{3})d.$$

基本粒子图谱

The chosen one!

# 为什么Higgs是上帝粒子




Higgs 粒子的势能项

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

自发性电弱对称性破缺（Higgs机制）

规范对称性自发破缺

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

Higgs机制给予所有基本粒子质量

发现Higgs让我们对质量起源了解更多

# “旧”物理中的未知?

Higgs的势能

$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

Laudau-Ginzberg 势能（超导）

$$m_h^2(h^\dagger h) + \frac{1}{2}\lambda(h^\dagger h)^2 + \frac{1}{3!\Lambda^2}(h^\dagger h)^3$$

必须是一个负数，
有原因么

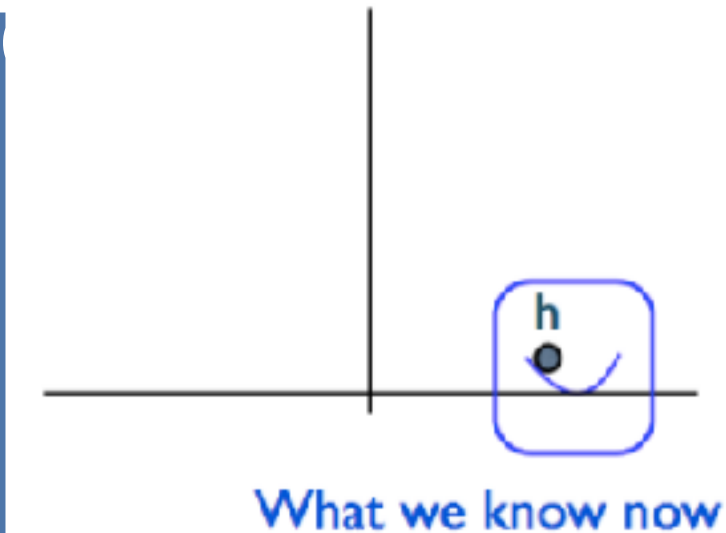
$$\frac{1}{2}\lambda(h^\dagger h)^2 \log\left[\frac{(h^\dagger h)}{m^2}\right]$$

$$V(h) \simeq -\gamma\, s_h^2 + \beta\, s_h^4\,.$$

我们其实从来也不知道，更不知道
为什么会有电弱对称性破缺

粒子物理最核心
最现实的问题

# “旧”物理中的未知？




对于Higgs势能的量子涨落，泰勒展开式

h^3　　h^4　　h^5。。。。。h^9

未来对撞机的探测重点

暂时实验上看不到希望


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

相同的对撞机信息，不同的势能

$$V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$$

# 为什么这是一个问题?

$\Lambda$

质量起源的能标

- Higgs的势能究竟是啥样?
- 电弱破缺机制的势能究竟是怎么来的?

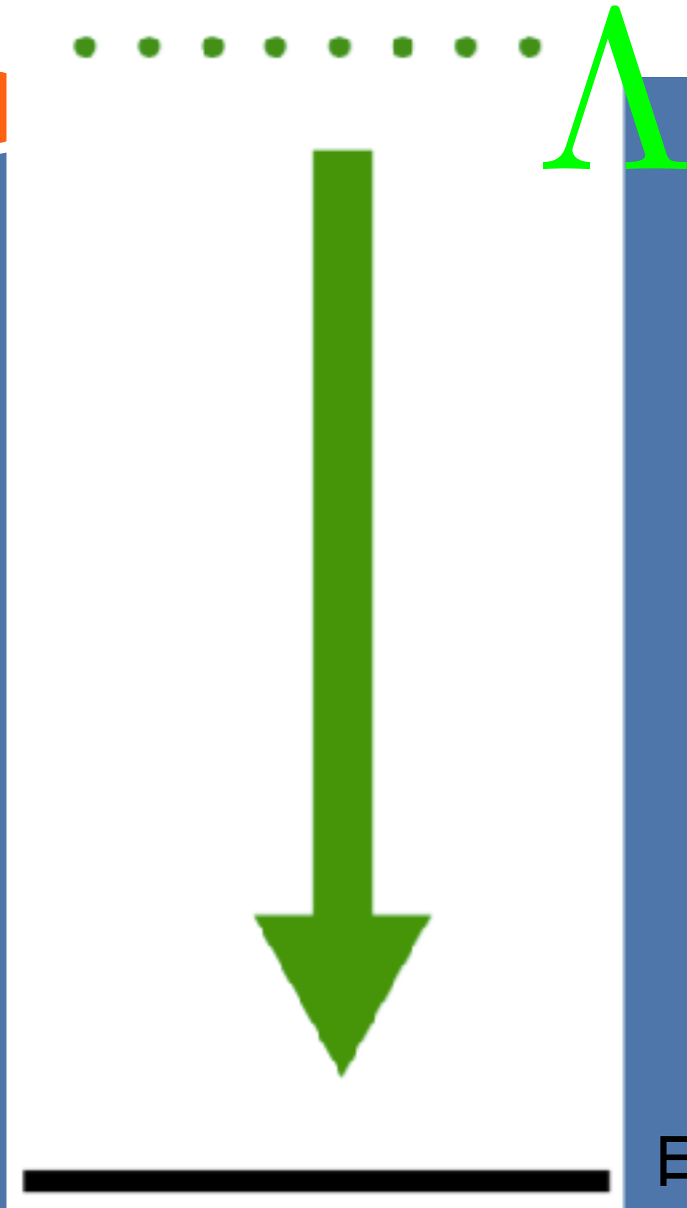
我们不断向上探索的能量

$$m_{phys}^2 = m_0^2 + c\Lambda^2 + \ldots$$

电弱能标

Top, Higgs, W, Z, etc

# 为什么这是一个问题?




电弱能标

$$m_{phys}^2 = m_0^2 + c\Lambda^2 + \ldots$$

- 如果Lambda是我们的某些基本高能标（Plank? GUT? etc), 可怕的相消. 规范等级度的问题（Gauge Hierarchy Problem)
- Lambda如果很低呢? OK 我们的新物理也许并不远!

两种情况都在我们的世界完美体现

# 电子质量的启示

我们先看看第一种情况：

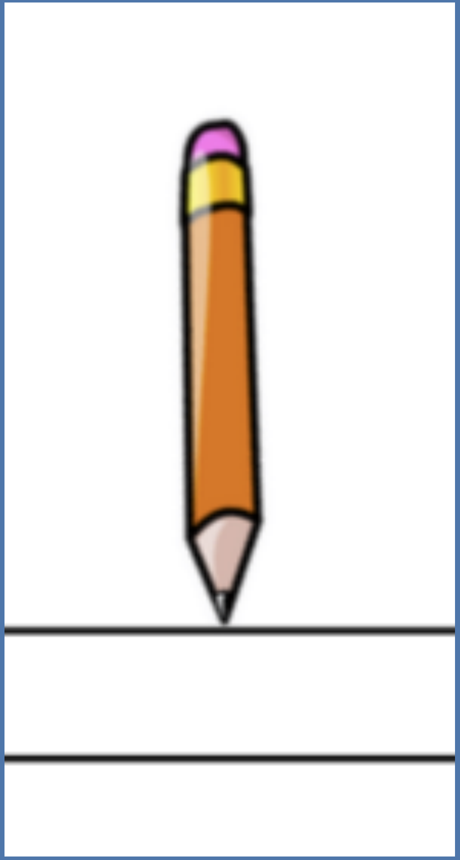
$$m^2_{phys} = m^2_0 + c\Lambda^2 + \ldots$$

如果我们的理论(SM?), 在能标Lambda下也成立

如果$\Lambda \sim M_{plank}$公式右边相除要达到10^{32}

Higgs真空期望值对于量子辐射修正大大的不稳定

Huge!!!



# 电子质量的启示

如果我们不能扔很多个这种铅笔的话（人择原理）

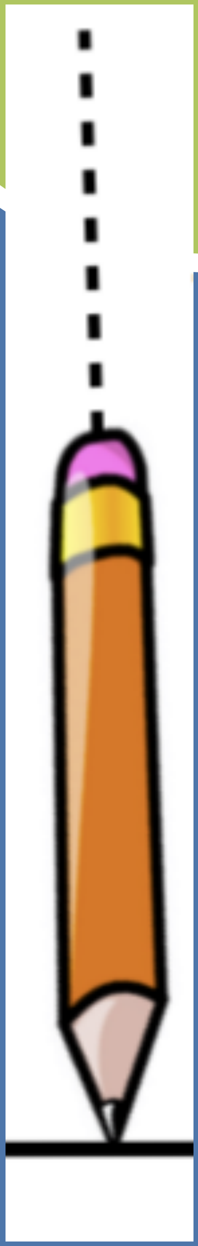
事实上对称性能够保证（Higgs势能）
对于量子辐射修正的稳定性

$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$$

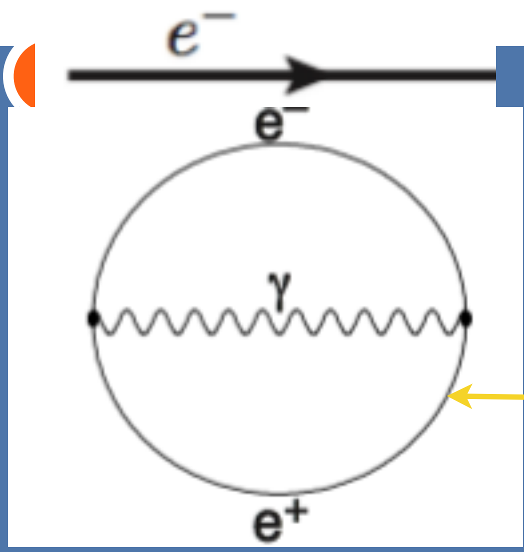
$$\delta m_e = \int_{r=\Lambda^{-1}} d^3r\,\vec{E}^2 \simeq \alpha\Lambda$$

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_{\text{Coulomb}}.$$

电子质量项
线性发散



# 电子质量的启示

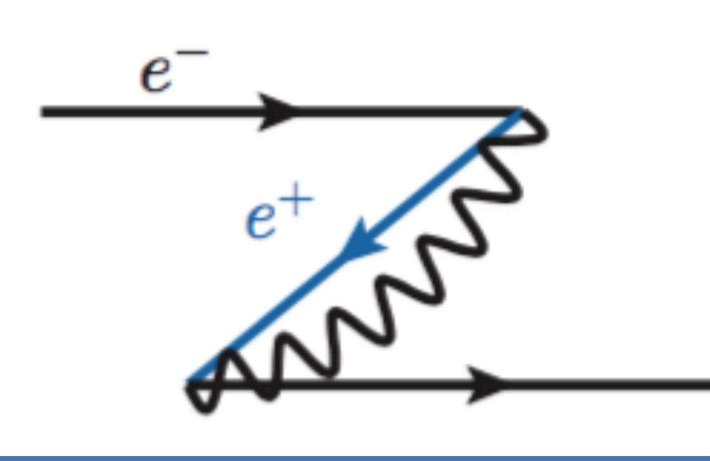



$$\Delta E_{\text{pair}} = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$$

Weisskopf 1939

量子涨落引入了正电子

$$\delta m_e \simeq \frac{\alpha}{\pi} m_e \log\left(\frac{\Lambda}{m_e}\right)$$




忽略质量的情况下，电子正电子满足

Chiral symmetry

Lambda取Plank质量，修正项只有10%

# 有关Higgs的对称性

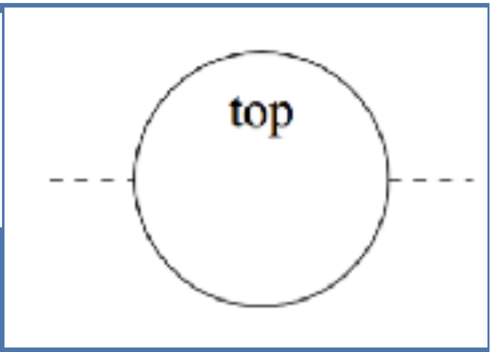
手征对称性：　电子 ⇔ 正电子

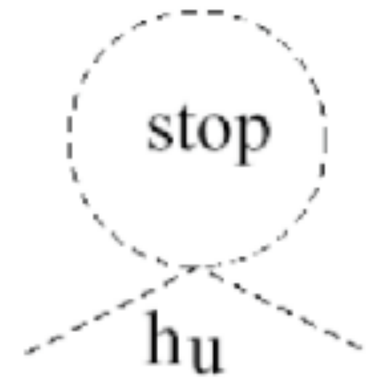
超对称　波色子 ⇔ 费米子

| | spin | | | spin |
|---|---|---|---|---|
| gluon, g | 1 | gluino | $\tilde{g}$ | 1/2 |
| $W^{\pm}$, Z | 1 | gaugino | $\tilde{W}^{\pm}, \tilde{Z}$ | 1/2 |
| quark | 1/2 | squark | $\tilde{q}$ | 0 |
| .... | | .... | | |
| Standard Model particles | | superpartners | | |

# 超对称性

$$m_h^2 \simeq m_{\rm SUSY}^2 \left(1 - \frac{y_{\rm top}^2}{16\pi^2} \log\left[\frac{\Lambda^2}{m_{\rm W,Z}^2}\right] + \cdots\right)$$




微小的量子辐射修正

$$16\pi^2\mu\frac{d}{d\mu}m_{H_u}^2 = 3X_t - 6g_2^2M_2^2 - \frac{6}{5}g_1^2M_1^2,$$

$$16\pi^2\mu\frac{d}{d\mu}m_{H_d}^2 = -6g_2^2M_2^2 - \frac{6}{5}g_1^2M_1^2,$$

$$16\pi^2\mu\frac{d}{d\mu}m_{Q_3}^2 = X_t - \frac{32}{3}g_3^2M_3^2 - 6g_2^2M_2^2 - \frac{2}{15}g_1^2M_1^2,$$

$$16\pi^2\mu\frac{d}{d\mu}m_{U_3}^2 = 2X_t - \frac{32}{3}g_3^2M_3^2 - \frac{32}{15}g_1^2M_1^2.$$

$$X_t = 2h_t^2(m_{H_u}^2 + m_{Q_3}^2 + m_{U_3}^2)$$

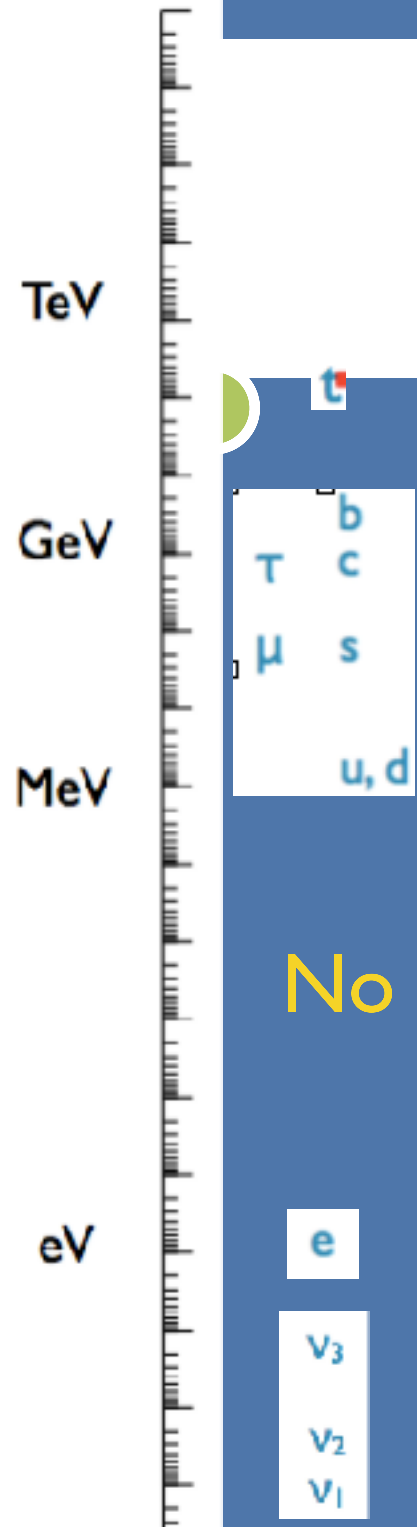
完整的SUSY RGE

负数

SUSY中的质量起源

GUT能标下的初条件?

# 已知未知对比




GUT scale

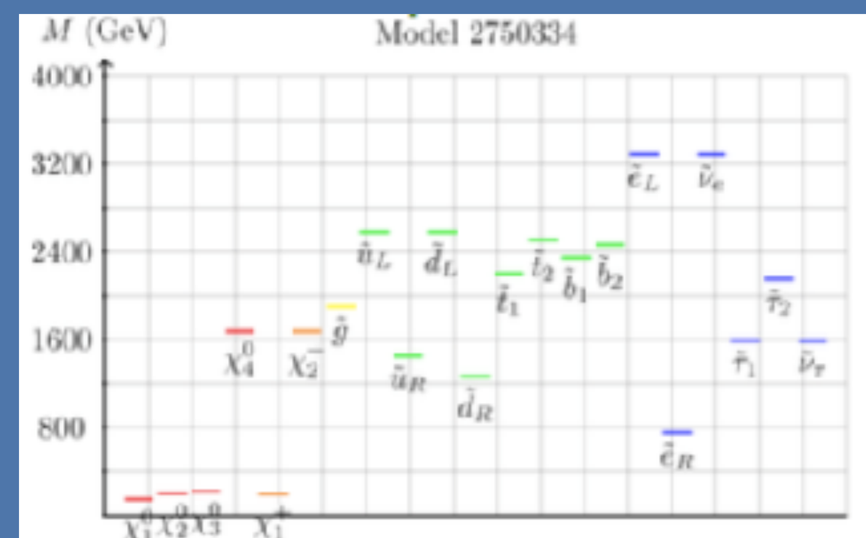
电子质量

a large physics desert

No New Physics

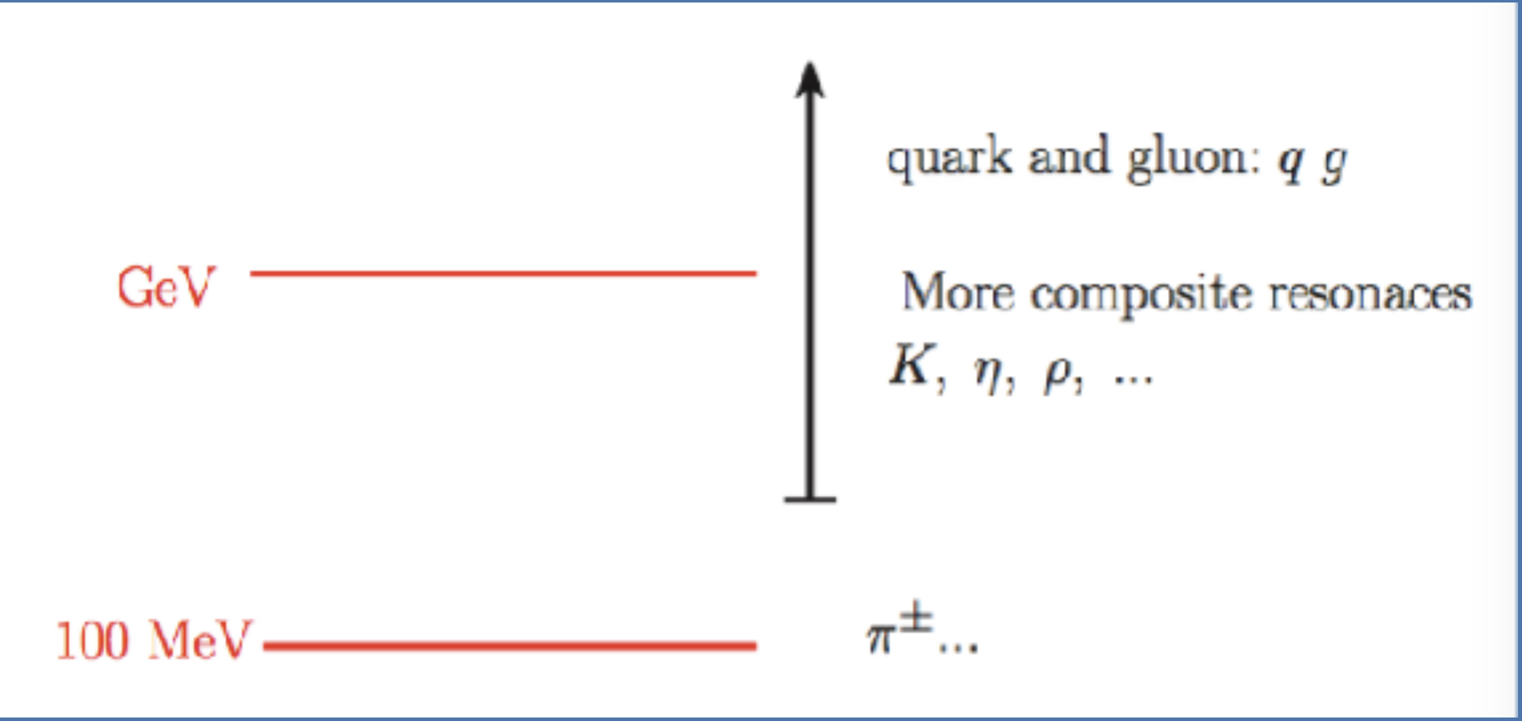
手征对称性

正电子




SUSY particles

# Pi介子质量的启示




QCD

Pi介子是pNGB 通过破坏QCD的味道对称性获得质量

# Higgs粒子的复合性?

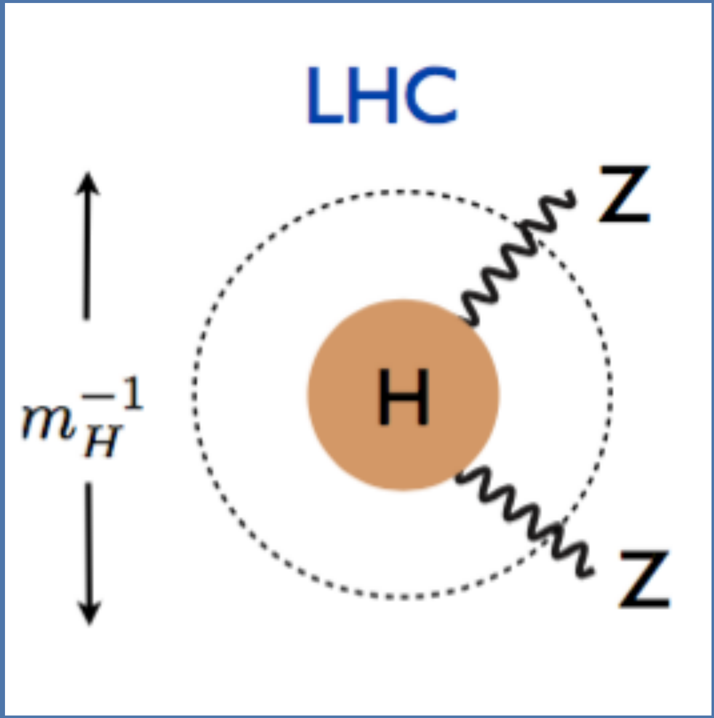
到新物理能标下，我们才能看见复合Higgs的结构（类似QCD Pi介子形状因子的偏移）

可能的新物理偏移

$$\delta = c\frac{m_W^2}{M_{\rm NP}^2}, \; c = \mathcal{O}(1)$$

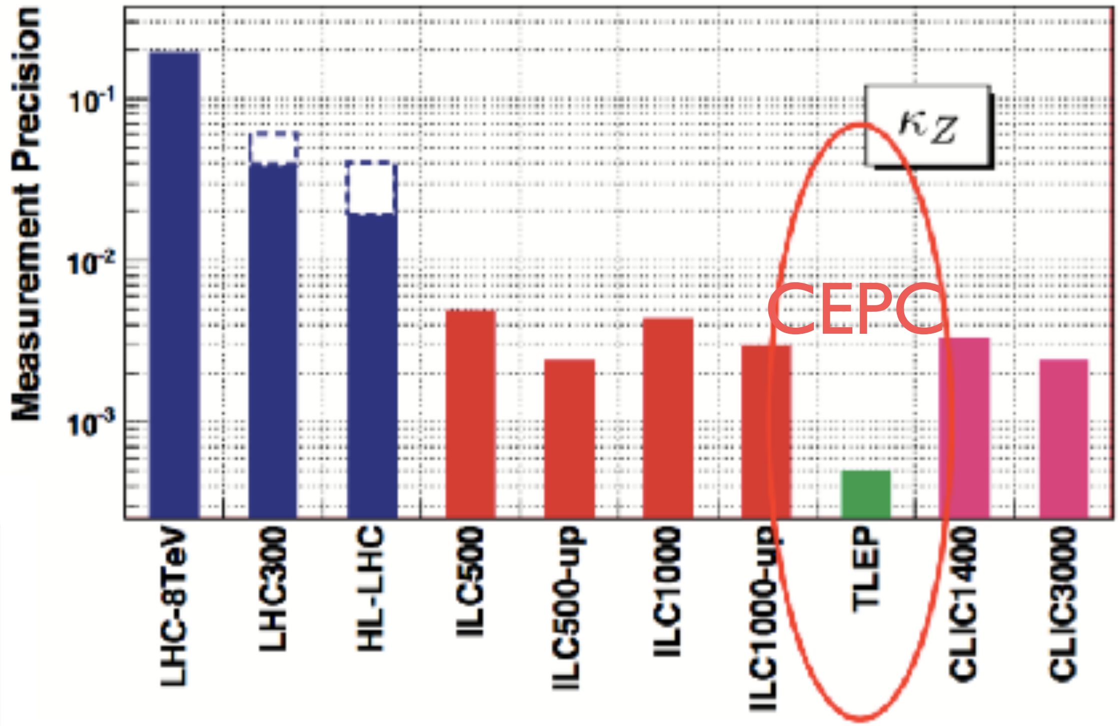
Higgs粒子是可分的，类似Pi介子

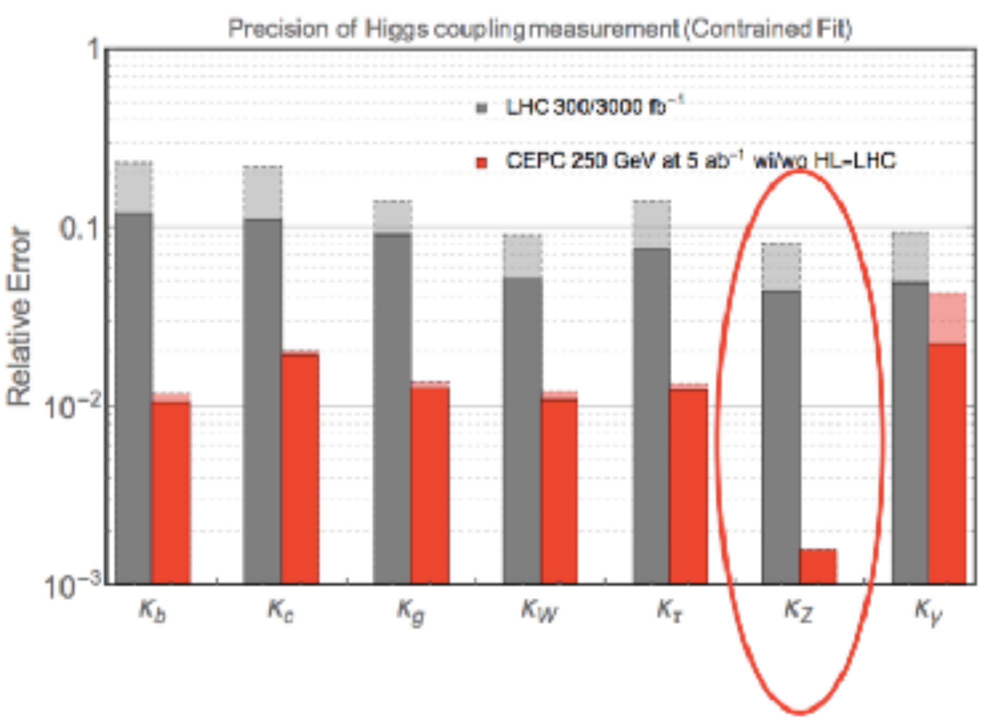
新的层子模型的时代?

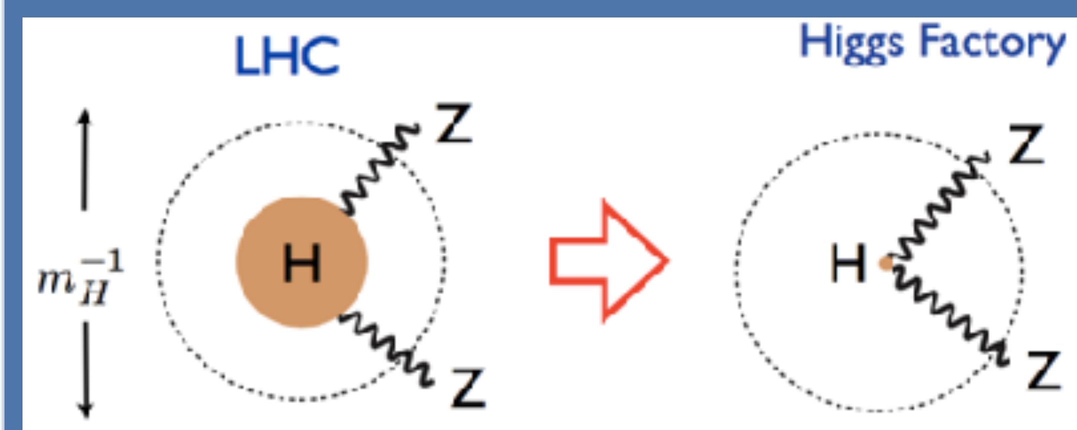


# 未来Higgs精确测量

$$\kappa_Z = \frac{g_{hZ}(\text{Measured})}{g_{hZ}(\text{SM})}$$



# Higgs as a pNGB

# Higgs作为pNGB

全局对称性G自发破缺到H, 会有无质量的波色子(NGB)在培集空间中(coset space), 如果G有直接破缺的效应, NGB将获得小的质量

如果G自发破缺到H是新的禁闭的强作用，pNGB是个复合粒子

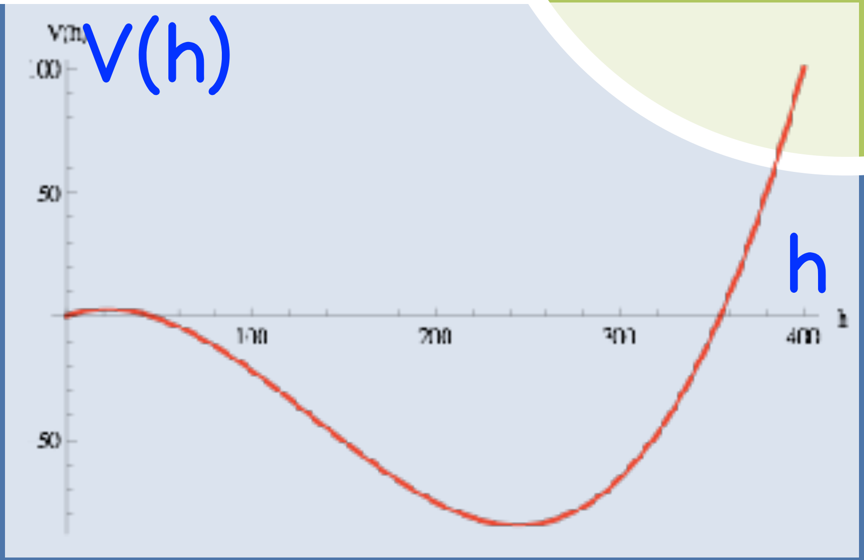
为什么考虑这种情况?　　QCD手征对称性破缺，pi介子

- Higgs质量相对于Higgs结构能标（1~10TeV) 很低
  以前电子对撞机的实验限制
- Higgs势能的起源 (The origin of EWSB)
- 一般性的普适结构 (universal prediction)(Like soft pion theorem)

# Higgs势能起源

Pi介子没有真空期望值

只有正的质量项




Higgs势能可能的源：

- 复合Higgs中基本部分子的质量
- SM粒子的（主要是Top夸克的）量子辐射修正（圈图效应）？

以后讨论focus在top sector

# Higgs as pNGB

$E$

$\Lambda$

$f$ $SO(5)/SO(4)$

$v = f \sin(\langle \pi \rangle / f)$

$SO(4)/SO(3)$

Consider the minimal group G/H

$$\boxed{SO(5) \times U(1)_X \rightarrow SO(4) \times U(1)_X}$$

at the scale f > v

$$\boxed{\xi \equiv \frac{v^2}{f^2}}$$

There are four NGBs: $\pi^{\hat{a}}$, with $\hat{a} = 1, 2, 3, 4.$

They transform as a 4 of $SO(4)$

(2,2) of $SU(2)$ x $SU(2) \sim SO(4)$.

$$Y = T_{3R} + X$$

$SU(2)_L \times U(1)_Y \subset SU(2)_L \times SU(2)_R \times U(1)_X \sim \boxed{SO(4)' \times U(1)_X}$

# Goldstone Lag

Consider the most general Goldstone interaction which has a custodial symmetry

(only the gauge sector) $SU(2)_L \times SU(2)_R$

$$\Sigma(x) = \exp(i\sigma^a \chi^a(x)/v)$$ Goldstone interaction

$$\mathcal{L} = \frac{v^2}{4} Tr[(D_\mu \Sigma)^\dagger D^\mu \Sigma]$$ Consider a physical scalar h

$$\mathcal{L}_H = \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{4} Tr[(D_\mu \Sigma)^\dagger (D_\mu \Sigma)](1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + ...)$$
$$-\frac{v}{\sqrt{2}} \Sigma[1 + c_j \frac{h}{v} + \cdots] \begin{pmatrix} y^u_{ij} u^j_R \\ y^d_{ij} d^j_R \end{pmatrix} + h.c.$$

# Higgs physics

$$
\begin{aligned}
f^2 \sin^2 \frac{h}{f} =& f^2 \left[ \sin^2 \frac{\langle h \rangle}{f} + 2 \sin \frac{\langle h \rangle}{f} \cos \frac{\langle h \rangle}{f} \left( \frac{h}{f} \right) \right. \\
& \left. + \left( 1 - 2 \sin^2 \frac{\langle h \rangle}{f} \right) \left( \frac{h}{f} \right)^2 + \dots \right] \\
=& v^2 + 2v\sqrt{1-\xi}\, h + (1-2\xi)\, h^2 + \dots
\end{aligned}
$$

W boson mass

modification of hVV coupling

$a = \sqrt{1-\xi}$ $\quad b = 1 - 2\xi$

Similarly for fermions.

$$m_f(h) \propto \sin\left(\frac{2h}{f}\right)$$

$c = \frac{1-2\xi}{\sqrt{1-\xi}}$

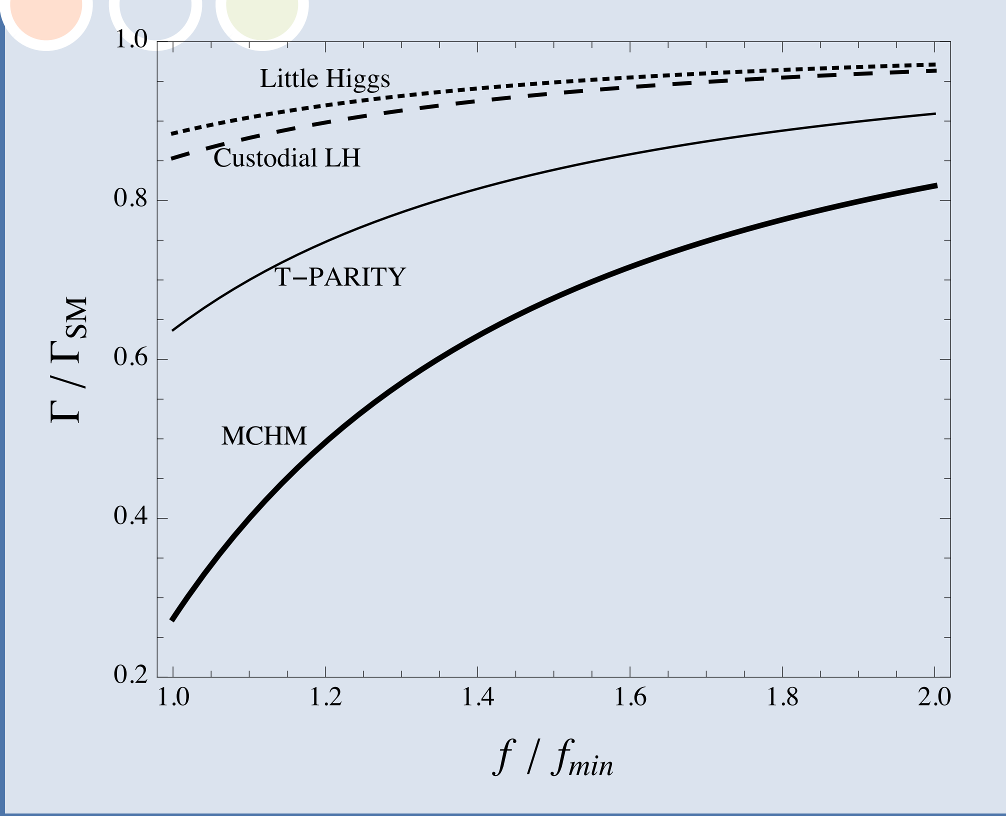
5, 10

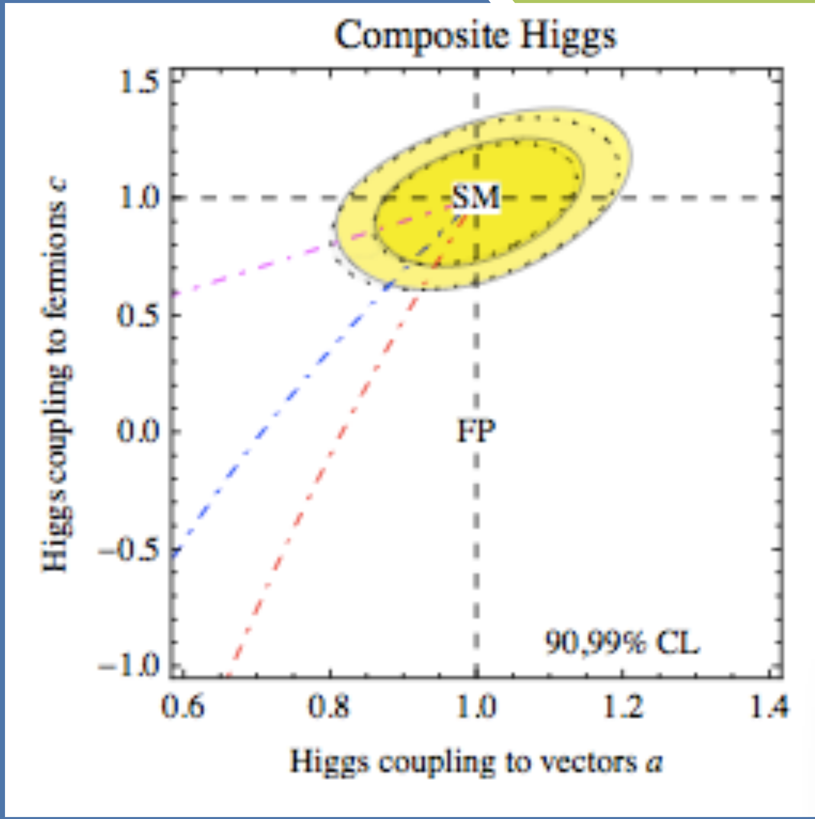
$$m_f(h) \propto \sin\left(\frac{h}{f}\right)$$

$c = \sqrt{1-\xi}$

Spinorial 4

# Higgs fits




P. Giardino, et al, arxiv: 1303.3570

Suppressed production rate

Overall Higgs fit $\xi < 0.2$

# Picture of CHMs

Elementary

SM

Explicitly break G: source of higgs potential

W/Z ⟷ mixture ⟷ Spin one: rho, axi-rho, etc

Top, b, tau, etc ⟷ mixture ⟷ Spin 1/2: composite fermions

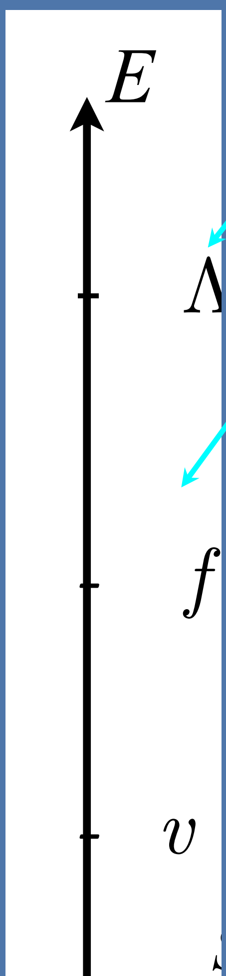
Composite

Strong dynamics

Global symmetry breaking pattern (G/H)

The mixture measures how composite the light states are

# Spin-one Resonances




The theory make sense up to $\Lambda = 4\,\pi\,\mathrm{f}$

We assume that a given number of resonances in the composite sector are lighter than $\Lambda$ so that it appears in the effective action.

Consider Spin-1 resonances in the $SU(2)_L \times SU(2)_R$ representation

$\rho_L\!: \ (\mathbf{3},\mathbf{1}) \qquad \rho_R\!: \ (\mathbf{1},\mathbf{3}) \qquad a\!: \ (\mathbf{2},\mathbf{2})$

``Vector Resonances'' ``Axial Resonances''

$1 \ll g_\rho,\, g_a \ll 4\,\pi$ strong but perturbative

# Spin 1/2 Resonances

There are many ways to generate the fermion masses

Bilinear: $\mathcal{L} = \lambda \bar{q} q \langle \bar{\Psi} \Psi \rangle$ techicolor, conformal techicolor, etc

Here we only consider the "partial compositeness"

Linear mixing: $\mathcal{L}_{mix} = \lambda \bar{q}_i \mathcal{O}_i$

Good for flavor physics

$\mathcal{O}_i \sim U \Psi_i$ Composite operators

$\Psi_i$ Composite fermions sit in the representation of SO(4)

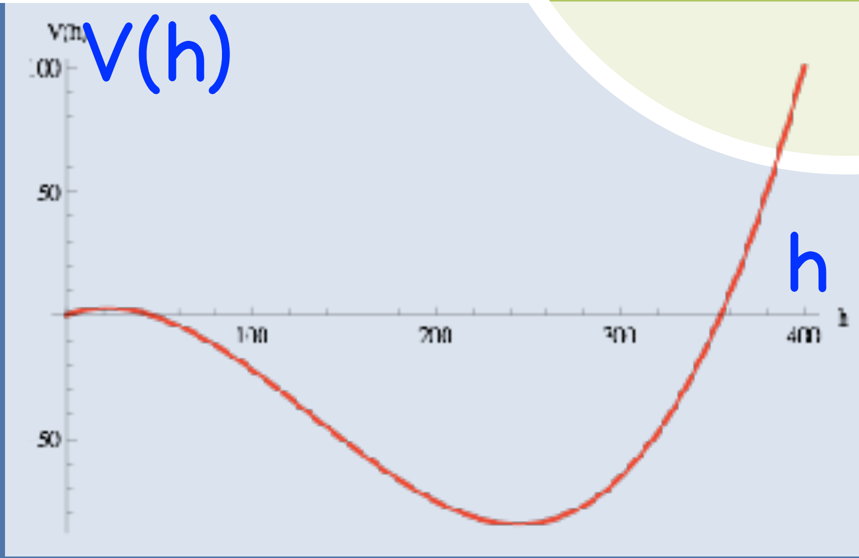
Maximally suppressed the FCNC by the small fermion mass

$Q_j$ bi-doublet $S_i$ Singlet

# Higgs势能起源

Pi介子没有真空期望值

只有正的质量项

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# 电弱对称破缺机制二

Higgs 势能: 辐射修正

$$V_f(h) \simeq -\gamma_f s_h^2 + \beta_f s_h^4,$$

$$\sin^2\langle H\rangle/f = \xi \ll 1$$

$$m_H^2 = 8\,\xi(1-\xi)\,\beta\,.$$

$$\gamma_g = -\frac{3}{8(4\pi)^2}\int_0^\infty dp_E^2\, p_E^2\left(\frac{3}{\Pi_0}+\frac{c_X^2}{\Pi_B}\right)\Pi_1,$$

$$\beta_g = -\frac{3}{64(4\pi)^2}\int_{\mu_g^2}^\infty dp_E^2\, p_E^2\left(\frac{2}{\Pi_0^2}+\left(\frac{1}{\Pi_0}+\frac{c_X^2}{\Pi_B}\right)^2\right)\Pi_1^2.$$

规范波色子贡献

$$\gamma_f = \frac{2N_c}{(4\pi)^2}\int_0^\infty dp_E^2\, p_E^2\left(\frac{\Pi_{1Q}}{\Pi_Q}+\frac{\Pi_{1S}}{\Pi_S}+\frac{\Pi_{QS}^2}{p_E^2\Pi_Q\Pi_S}\right),$$

$$\beta_f = \frac{N_c}{(4\pi)^2}\int_{\mu_f^2}^\infty dp_E^2\, p_E^2\left(\left(\frac{\Pi_{QS}^2}{p_E^2\Pi_Q\Pi_S}+\frac{\Pi_{1Q}}{\Pi_Q}+\frac{\Pi_{1S}}{\Pi_S}\right)^2-\frac{2(p_E^2\Pi_{1Q}\Pi_{1S}-\Pi_{QS}^2)}{p_E^2\Pi_Q\Pi_S}\right).$$

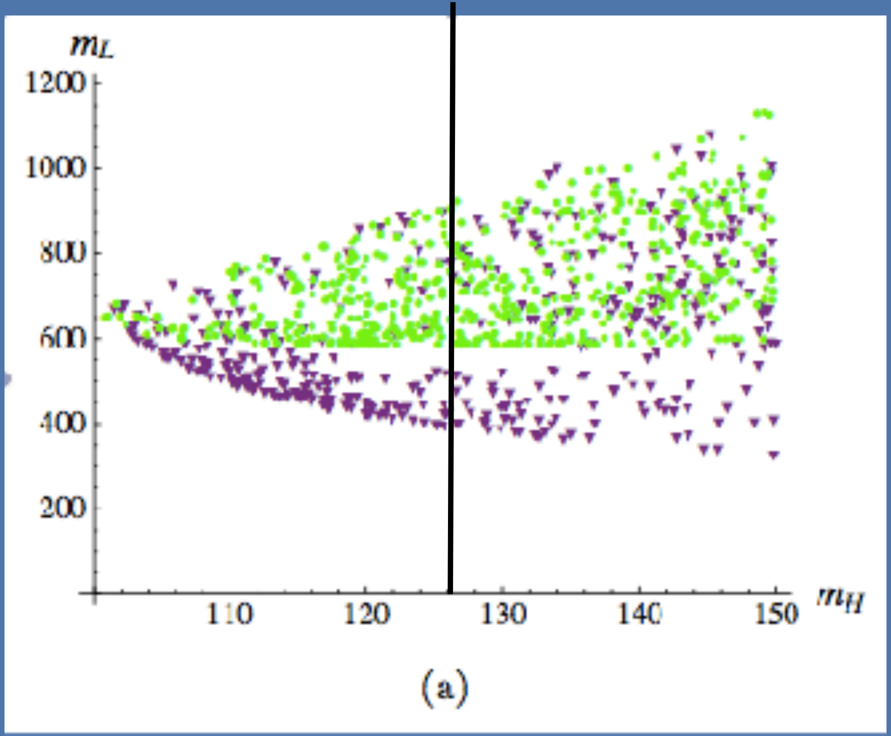
费米子贡献

$$M_t^2(q^2,\langle h\rangle) = \frac{\left|\Pi_{t_L t_R}(q^2,\langle h\rangle)\right|}{\sqrt{\Pi_{t_L}(q^2,\langle h\rangle)\,\Pi_{t_R}(q^2,\langle h\rangle)}}.$$

Top 夸克质量

# 轻的Top伴随子

数值扫描:




D. Marzocca, M. Serone, J.S, JHEP, 1208, (2012) 013

参数空间扫描

$$\xi = 0.1$$

$m_L$ < 900 GeV

最轻的Top伴随子

双-二重态 Q

单态 S

寻找轻的Top伴随子

# 简单的理解

$$m_H^2 = \frac{8\beta}{f_\pi^2}\sin^2(v/f_\pi)\cos^2(v/f_\pi) \simeq \frac{2N_c y^4}{16\pi^2} f_\pi^2 \sin^2(2v/f_\pi)\,,$$

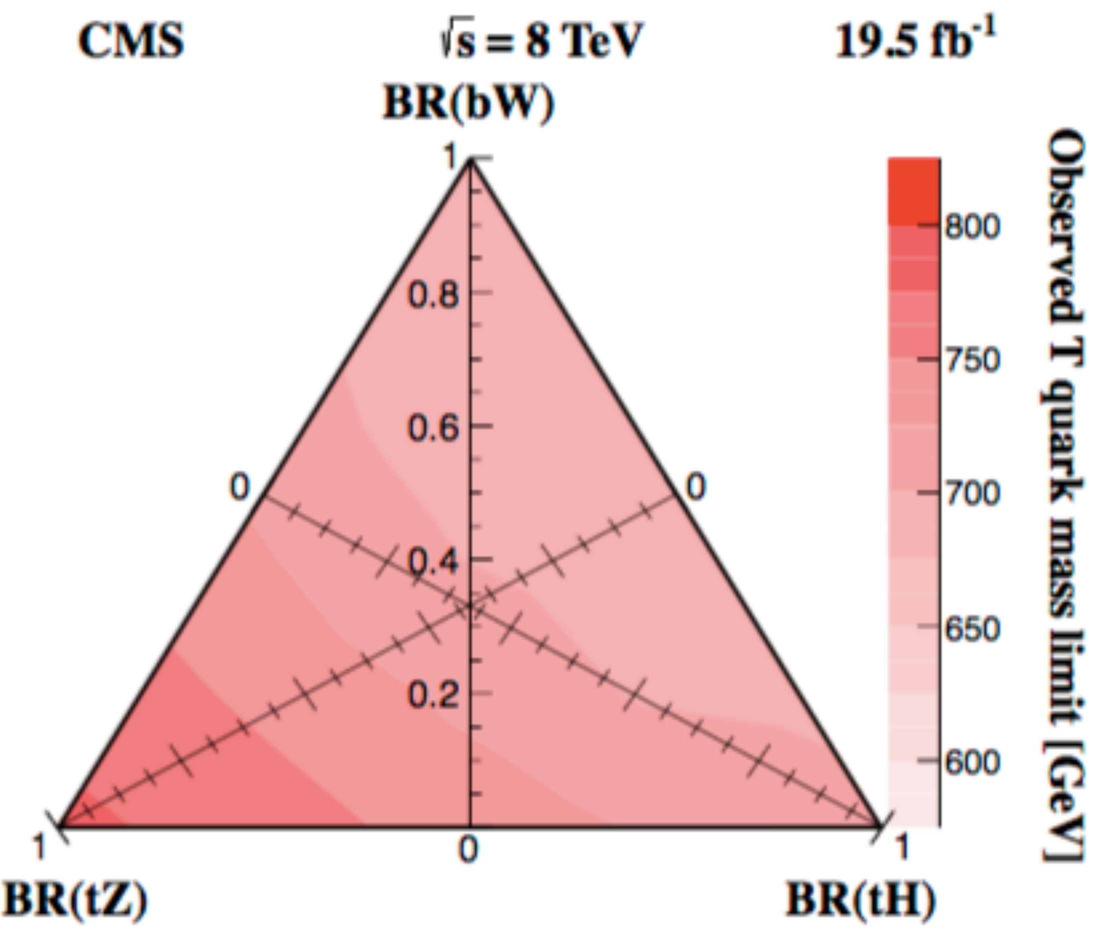
$$m_t \simeq \frac{\max(m_T^*, m_{\tilde{T}}^*)}{2\sqrt{2}} \sin\varphi_L \sin\varphi_R \sin(2v/f_\pi) = \frac{1}{2\sqrt{2}} \frac{y_L y_R f_\pi^2}{\min(m_T, m_{\tilde{T}})} \sin(2v/f_\pi)\,.$$

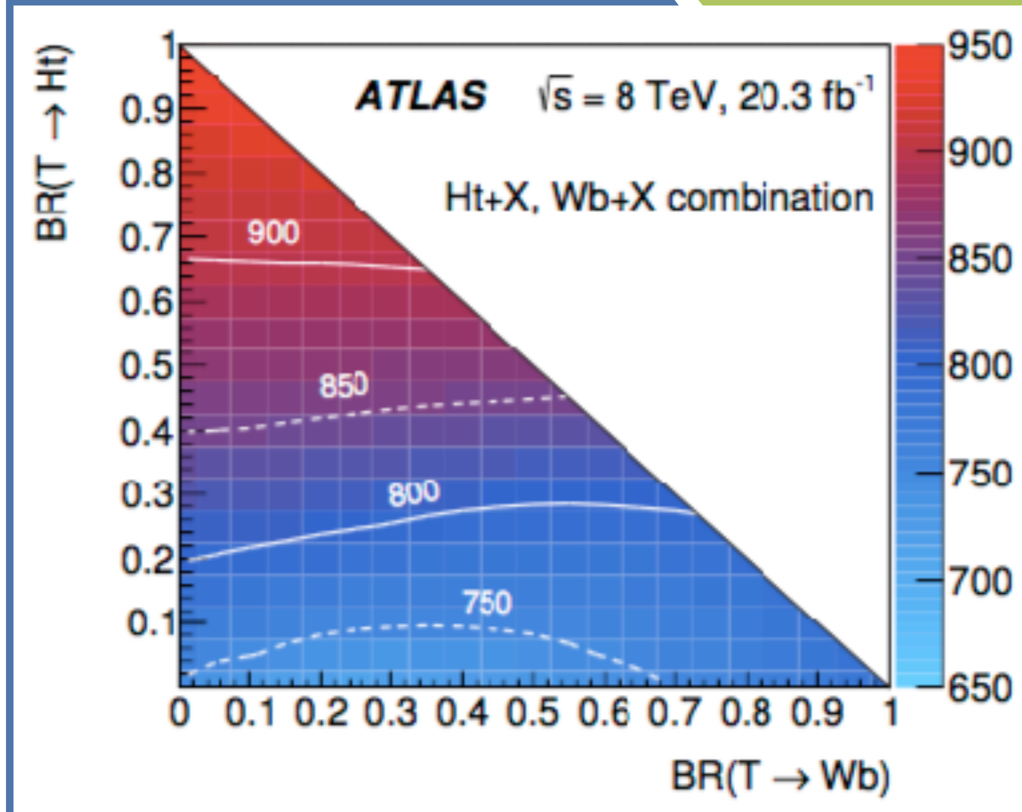
$$m_H \simeq \frac{\sqrt{N_c}}{\pi} \frac{\min(m_T, m_{\tilde{T}})}{f_\pi} m_t \simeq 130\,\mathrm{GeV} \frac{\min(m_T, m_{\tilde{T}})}{1.4 f_\pi}\,.$$

125GeV的Higgs我们有Top伴随子的质量下限，

和模型混合无关

# Top 伴随子的寻找




$$\mathrm{BR}(t' \to th) \approx \mathrm{BR}(t' \to tZ) \approx \mathrm{BR}(t' \to bW)/2 \approx 0.25$$

最新的constrain大约到了1.1TeV左右

# Maximally symmetric composite Higgs

# 新框架下突破

- 得到正确的电弱对称性破缺(v<<f)
  - 得到正确的125 GeV Higgs质量?
  - 对高能标下的物理没有依赖，Higgs势能不依赖于cut off scale下的物理 规范等级度的问题，精细调节
- 从最基本的群论出发，发现Higgs宇称的重要性，提出一套全新最简洁的研究问题的方法 (linear realization in the symmetric coset space) 方法论突破
- 完美的解决上面的所以问题，发现一种新的自带对称性 (Maximal symmetry) 模型的突破

我做了什么

C. Csaki, T. Ma, J. Shu., in preparation

# Symmetric space

对于任意全局G对称性破缺到H

$T^{\hat{a}}(T^a)$ is the (un)broken generator

$[T^a, T^a] \sim T^a, \; [T^a, T^{\hat{a}}] \sim T^{\hat{a}}$

总是满足

$[T^{\hat{a}}, T^{\hat{a}}] \sim T^a$

对称性培集空间

G群存在着一个同构空间(automorphism)

$VT^aV^\dagger = T^a$

$VT^{\hat{a}}V^\dagger = -T^{\hat{a}}$

Higgs 是NG粒子，在G/H培集空间内

Higgs是个负的Higgs宇称（和QCD里面的pi宇称一样）

# 对称性下的变化规律

对于任意全局G对称性破缺到H,
NGB相互作用形式

The CCWZ唯象表示

$$U = \exp\left(\frac{ih^{\hat{a}}T^{\hat{a}}}{f}\right)$$

非线性变换

$$U \to gUh(h^{\hat{a}}, g)^{\dagger}$$

而对于对称性培集空间

$$\Sigma' = U^2 V$$

G/H信息包含在V里面

线性变换

$$\Sigma' \to g\Sigma' g^{\dagger}\ .$$

$$\tilde{U} = VUV^{\dagger} = U^{\dagger}.$$

# 费米子场相互作用

考虑最小复合Higgs模型SO(5)/SO(4)

费米子在基础表示下

$$\Psi_{q_L} = \frac{1}{\sqrt{2}}\begin{pmatrix} b_L \\ -ib_L \\ t_L \\ it_L \\ 0 \end{pmatrix} \qquad \Psi_{t_R} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}$$

$$\Sigma' = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & c_{2h} & -s_{2h} \\ 0 & 0 & 0 & -s_{2h} & -c_{2h} \end{pmatrix}$$

$$\Sigma' \to g\Sigma' g^\dagger \ .$$

最普实的top夸克和Higgs相互作用 $\Sigma'^2 = 1$

$$\Psi \to g\Psi$$

Master formular

$$\begin{aligned} \mathcal{L}_{\text{eff}} = & \bar{\Psi}_{Q_L} \not{p}(\Pi_0^q(p) + \Pi_1^q(p)\Sigma')\Psi_{Q_L} \\ & + \bar{\Psi}_{t_R} \not{p}(\Pi_0^t(p) + \Pi_1^t(p)\Sigma')\Psi_{t_R} \\ & + \bar{\Psi}_{Q_L} M_1^t(p)\Sigma'\Psi_{t_R} + h.c. \end{aligned}$$

Higgs势能项来源于

top圈图贡献

根据对称性写出的有效场(任何模型),不同形状因子的来源

# Higgs势能项

- $\Pi_{0,1}^{q;t}$ 为0的话　左右手top分别有 $G_L \times G_R$ 对称性

只有质量项破缺了这个对称性到 $G_{V'}$

$$g_L \Sigma' g_R^\dagger = \Sigma'.$$

NGB矩阵在这个对称性下不变

$$V(h) = -2N_c \int \frac{d^4p}{2\pi^4} \log\left[1 + \frac{(M_1^t)^2 |\mathrm{Tr}[\Sigma'.P_{lr}^1]|^2}{p^2 \mathrm{Tr}[\Pi_0^q P_l^{11}] \mathrm{Tr}[\Pi_0^t P_r]}\right]$$

Coleman-Weinberg势

top质量是左右手top分别和top伴随子混合产生的话　No UV Divergence

$$M_1^t \sim \lambda_L \lambda_R f^2 (M_Q - M_S)/p^2 \qquad V(h) \sim \lambda_L^2 \lambda_R^2 f^4 (M_Q - M_S)^2/\Lambda^2$$

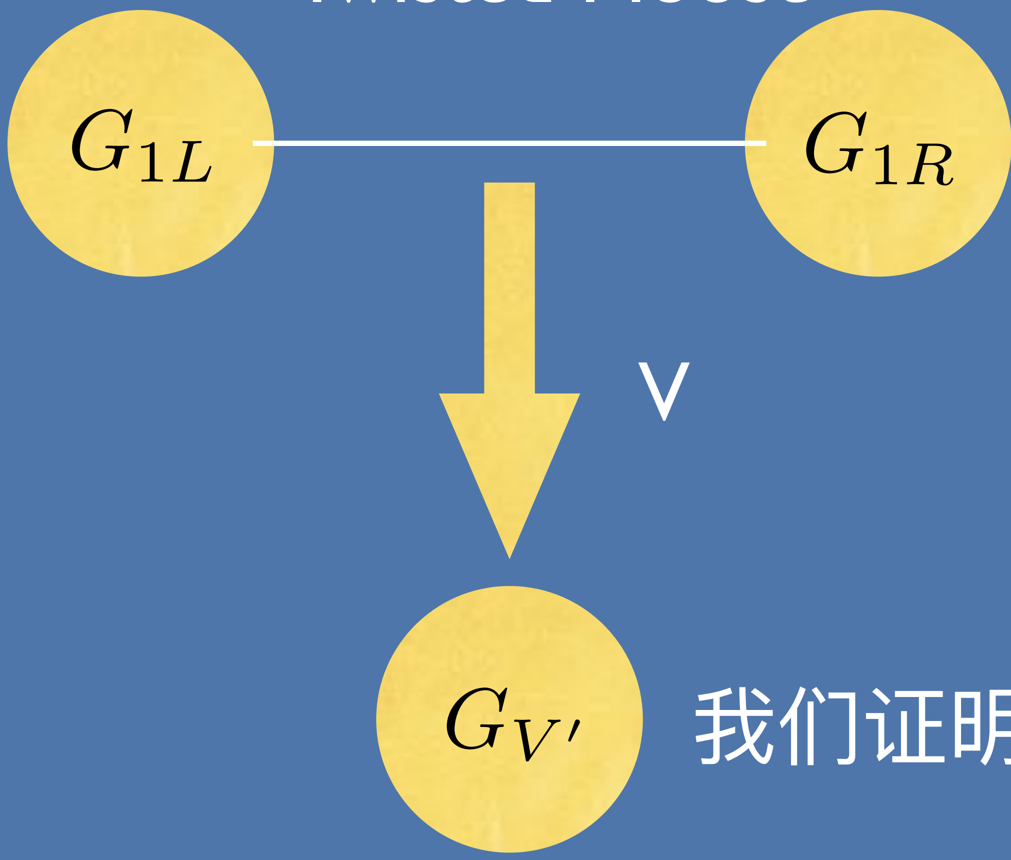
Higgs的势能项对Higgs场的依赖就是top质量依赖关系的平方！

$$m_t \sim \sin_{2h}$$

Higgs势能项 $(\sin_{2h})^2 = s_h^2 - s_h^4.$

# 什么是Maximal Symmetry

## Twisted Moose




我们证明

SO(5)/SO(4)

$$V = \begin{pmatrix} \mathbf{1}_{4\times 4} & 0 \\ 0 & -1 \end{pmatrix}$$

$H_V$

$(G/H)_A$

# 集体化对称性破缺

Collective Symmetry Breaking, "Little Higgs"

$$\sim \int d^4p\,\Pi_1^{q,t}$$

$$\Pi_1^{q,t} \propto p^{-2N}$$

G/H → G/H, G/H, G/H

最少需要3个全同的对称性结构和3套类SM粒子

不依赖于高能的Higgs势能代价是最少6次方压低

Higgs势能的倾向于得到偏大的v/f

Higgs势能的倾向于得到500GeV左右的Higgs

精细条件参数

Nima Arkani-hamed

IAS

"That is how I get tenured in Harvard"

# 具体实现

费米子质量和相互作用通过带有pNGB矩阵的线性混合产生

$$\mathcal{L}_{mix} = \lambda \bar{q}_i \mathcal{O}_i$$

$$\mathcal{O}_i \sim U\Psi_i$$

$$\mathcal{L} = \lambda_L \bar{q}_L^{\alpha} \Lambda^L_{\alpha I} \mathcal{O}^I_R + \lambda_R \bar{t}_R \Lambda^R_{\alpha I} \mathcal{O}^I_L + h.c$$

$$\begin{aligned}\mathcal{L}_f = &\bar{\Psi}_Q(i\not{\nabla} - M_Q)\Psi_Q + \bar{\Psi}_S(i\not{\nabla} - M_S)\Psi_S \\ &+ \frac{\lambda_R f}{\sqrt{2}}\bar{\Psi}_{t_R} P_L(\epsilon_{tS}U\Psi_S + \epsilon_{tQ}U\Psi_Q) \\ &+ \lambda_L f \bar{\Psi}_{q_L} P_R(\epsilon_{qS}U\Psi_S + \epsilon_{qQ}U\Psi_Q) + h.c,\end{aligned}$$

5=4+1 新的复合的top伴随子

$$\Psi_Q = \frac{1}{\sqrt{2}}\begin{pmatrix} iB - iX_{5/3} \\ B + X_{5/3} \\ iT + iX_{2/3} \\ -T + X_{2/3} \\ 0 \end{pmatrix} \quad \Psi_S = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ T_1 \end{pmatrix}$$

G/H如果是对称性培集空间

$$\Psi_+ = V\Psi_- \quad V = \begin{pmatrix} \mathbb{1}_{4\times4} & 0 \\ 0 & -1 \end{pmatrix}$$

$$\Psi_+ = \frac{1}{\sqrt{2}}(\Psi_2 + \Psi_1) \quad \Psi_- = \frac{1}{\sqrt{2}}(\Psi_2 - \Psi_1)$$

# 形状因子的形式

如果把新的复合的 top伴随子积掉，我们能得到低能线性表示的有效理论

$$
\begin{aligned}
\frac{\Pi_0^{q,t}}{\lambda_{L,R}^2 f^2} &= 1 + \frac{(c_{-L,R}^2 + c_{+L,R}^2)(M_Q^2 + M_S^2 - 2p^2)}{2(p^2 - M_S^2)(M_Q^2 - p^2)} \\
&+ \frac{c_{-L,R}c_{+L,R}(M_S + M_Q)(M_S - M_Q)}{(p^2 - M_S^2)(M_Q^2 - p^2)} \\
\frac{\Pi_1^{q,t}}{\lambda_{L,R}^2 f^2} &= \frac{c_{+L,R}c_{-L,R}(M_Q^2 + M_S^2 - 2p^2)}{(p^2 - M_S^2)(M_Q^2 - p^2)} \\
&+ \frac{(c_{+L,R}^2 + c_{-L,R}^2)(M_S - M_Q)(M_S + M_Q)}{2(p^2 - M_S^2)(M_Q^2 - p^2)} \\
\frac{M_1^t}{\lambda_L \lambda_R f^2} &= \frac{M_Q^2 M_S(c_{-L} - c_{+L})(c_{-R} - c_{+R})}{2(p^2 - M_Q^2)(p^2 - M_S^2)} \\
&- \frac{M_S^2 M_Q(c_{-L} + c_{+L})(c_{-R} + c_{+R})}{2(p^2 - M_Q^2)(p^2 - M_S^2)} \\
&+ \frac{M_Q(c_{-L} + c_{+L})(c_{-R} + c_{+R})p^2}{2(p^2 - M_Q^2)(p^2 - M_S^2)} \\
&- \frac{M_S(c_{-L} - c_{+L})(c_{-R} - c_{+R})p^2}{2(p^2 - M_Q^2)(p^2 - M_S^2)}, \qquad (54)
\end{aligned}
$$

# 对称性

$$\mathcal{L}_f = \bar{\Psi}_+ i\not{D}\Psi_+ + \bar{\Psi}_+ i\not{D}\Psi_+ \\ + \lambda_R f(c_{-R}\bar{\Psi}_{t_R} P_L U V \Psi_+ + c_{+R}\bar{\Psi}_{t_R} P_L U \Psi_+) \\ + \lambda_L f(c_{-L}\bar{\Psi}_{q_L} P_R U V \Psi_+ + c_{+L}\bar{\Psi}_{q_L} P_R U \Psi_+) \\ - (M_Q + M_S)\bar{\Psi}_{+L}\Psi_{+R} - (M_Q - M_S)\bar{\Psi}'_{+L} V \Psi_{+R} \\ + h.c. \tag{21}$$

$$c_{\pm R} = \frac{\epsilon_{tQ} \pm \epsilon_{tS}}{2},\ c_{\pm L} = \frac{\epsilon_{qQ} \pm \epsilon_{qS}}{\sqrt{2}}.$$

$$c_{-L} = c_{-R} = 0.$$

$$\mathcal{L}_f = \bar{\Psi}_+ i\not{D}\Psi_+ + \bar{\Psi}_- i\not{D}\Psi_- + \lambda_R f c_{+R}\bar{\Psi}_{t_R} P_L U \Psi_+ \\ + \lambda_L f c_{+L}\bar{\Psi}_{q_L} P_R U \Psi_+ - (M_Q + M_S)\bar{\Psi}_{+L}\Psi_{+R} \\ - (M_Q - M_S)\bar{\Psi}_{+L} V \Psi_{+R} + h.c. \tag{22}$$

$$SO(5)_L \times SO(5)_R$$

$$M_Q - M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R / SO(5)_V \\ M_Q + M_S = 0 \Rightarrow SO(5)_L \times SO(5)_R / SO(5)_{V'} \\ |M_Q| \neq |M_S| \Rightarrow SO(5)_L \times SO(5)_R / SO(4)_V \tag{23}$$

质量项破坏对称性

# 对称性决定势能的形式

$SO(4)_V$

Log 发散

- If $c_{+L}=0$, it is obvious that the Lagrangian has the Higgs goldstone symmetry $L=U^\dagger \in SO(5)_L$ and $R=U^\dagger \in SO(5)_R$ for $M_1=M_2$ and $R=(UV)^\dagger \in SO(5)_R$ for $M_1=-M_2$. Therefore, for the real Higgs potential, we have

$$V_{L\xi} \sim |\lambda_L|^2 c_{+L}^2 f^2 (M_1+M_2)(M_1-M_2)\log\Lambda^2 \quad (24)$$

- $c_{-L}=c_{-R}=0$ and $M_1+M_2=0$. In this case, if $c_{+L}=0$, the Higgs Goldstone symmetry is $L=U^\dagger \in SO(5)_L$ for $\Psi_{+L}$ and $R=(UV)^\dagger \in SO(5)_R$ for $\Psi_{+R}$. Similarly, for $c_{+R}=0$, the Higgs Goldstone symmetry is $R=U^\dagger \in SO(5)_R$ and $L=(UV)^\dagger \in SO(5)_L$. Therefore, the potential must be

$$|\lambda_L\lambda_R|^2 c_{+L}^2 c_{+R}^2 f^4 (M_1-M_2)^2/\Lambda^2. \qquad (26)$$

$SO(5)_{V'}$

有限项

# Higgs势能结构

$$V_f(h) \simeq -\gamma_f s_h^2 + \beta_f s_h^4,$$

$$\xi = \frac{\gamma_f}{2\beta_f}$$

To obtain $\xi \ll 1$

$\gamma_{\rm div}$ much smaller than $\beta_{\rm div}$

$$\begin{aligned}V_{\rm div} = &\frac{N_c M_f^4}{16\pi^2 g_f^2}[(\frac{c_L}{2}\epsilon_L^2 - c_R\epsilon_R^2 + c_{LL}\frac{\epsilon_L^4}{g_f^2} + c_{RR}\frac{\epsilon_R^4}{g_f^2})s_h^2 \\ &+ (c'_{LL}\frac{\epsilon_L^4}{g_f^2} + c'_{RR}\frac{\epsilon_R^4}{g_f^2})s_h^4] \\ &\equiv -\gamma_{\rm div}s_h^2 + \beta_{\rm div}s_h^4 \qquad (34)\end{aligned}$$

quadratic divergent parts

$\mathcal{O}(\epsilon_L^2)$ and $\mathcal{O}(\epsilon_R^2)$

$c_L \sim c_R \sim \Lambda^2$

$$\Delta^{5+5} \simeq \frac{\max(|\frac{c_L}{2}|, |c_R|)}{\gamma_{\rm div}} \simeq \frac{1}{\xi}\frac{g_f^2}{\epsilon^2}\frac{\Lambda^2}{M_f^2 \log\frac{\Lambda^2}{M_f^2}}$$

Tuning

log divergent

$\mathcal{O}(\epsilon_L^4)$ and $\mathcal{O}(\epsilon_R^4)$.

$c_{LL} \sim c'_{LL} \sim c_{RR} \sim c'_{RR} \sim \log\Lambda$

# 电弱对称性破缺Tunning

$$
\begin{aligned}
V_h &= c_{LR}\frac{N_c M_f^4}{16\pi^2}\left(\frac{\epsilon_L^2\epsilon_R^2}{g_f^4}\right)[-s_h^2+s_h^4]+\mathcal{O}(\frac{\epsilon_L^4\epsilon_R^4}{g_f^8}) \\
&\simeq c_{LR}\frac{N_c M_f^4}{16\pi^2}\left(\frac{y_t}{g_f}\right)^2[-s_h^2+s_h^4]+\mathcal{O}(\frac{y_t^4}{g_f^4}) \\
&\equiv -\gamma_f s_h^2+\beta_f s_h^4 \qquad (39)
\end{aligned}
$$

Maximally symmetric case

$$\xi = \frac{\gamma_f}{2\beta_f} = 0.5$$

$$\gamma_g = -\frac{9 f^2 g^2 m_\rho^2 \log 2}{64\pi^2}$$

$\xi \ll 1$, we require $\gamma_f \simeq -\gamma_g$.

$$\Delta^{(5+5)} = \frac{\max(|\gamma_f|,|\gamma_g|)}{|\gamma_f+\gamma_g|} \simeq \max(\frac{1}{2\xi},\frac{1}{2\xi}-1) = \frac{1}{2\xi} \quad (44)$$

20% tuning

# 得到Higgs质量

$$m_t \sim \sin\theta_L \sin\theta_R\, |M_Q - M_S| s_h$$

我们一般的困难是top太重，很难得到一个轻的Higgs

$\theta_L$ and $\theta_R$ 最小 $M_Q = -M_S$

$$\min\{M_T, M_{T_1}\} = \min\{\frac{M_S}{\cos\theta_L}, \frac{M_Q}{\cos\theta_R}\}$$ 最小

$$m_H \propto \min\{M_T, M_{T_1}\} m_t / f$$

能最容易的得到轻的Higgs质量

# 矢量波色子

## SO(5)/SO(4)

$$\mathcal{L}^v = -\frac{1}{4}\,\mathrm{Tr}[\rho_{\mu\nu}\rho^{\mu\nu}] + \frac{f_\rho^2}{2}\mathrm{Tr}[(g_\rho\rho_\mu - E_\mu)^2]$$

$$\mathcal{L}^a = -\frac{1}{4}\,\mathrm{Tr}[a_{\mu\nu}a^{\mu\nu}] + \frac{f_a^2}{2\Delta^2}\mathrm{Tr}[(g_a a_\mu - \Delta d_\mu)^2]$$

$$\mathcal{L}_{\rm kin} = \frac{f^2}{4}\mathrm{Tr}[d_\mu d^\mu] \qquad (3)$$

$$\rho_\mu \equiv \mathbf{6} \qquad a_\mu \equiv \mathbf{4}$$

$$\rho_\mu \to h\rho_\mu h^\dagger + \frac{i}{g_\rho}h\partial_\mu h^\dagger \qquad a_\mu \to h a_\mu h^\dagger$$

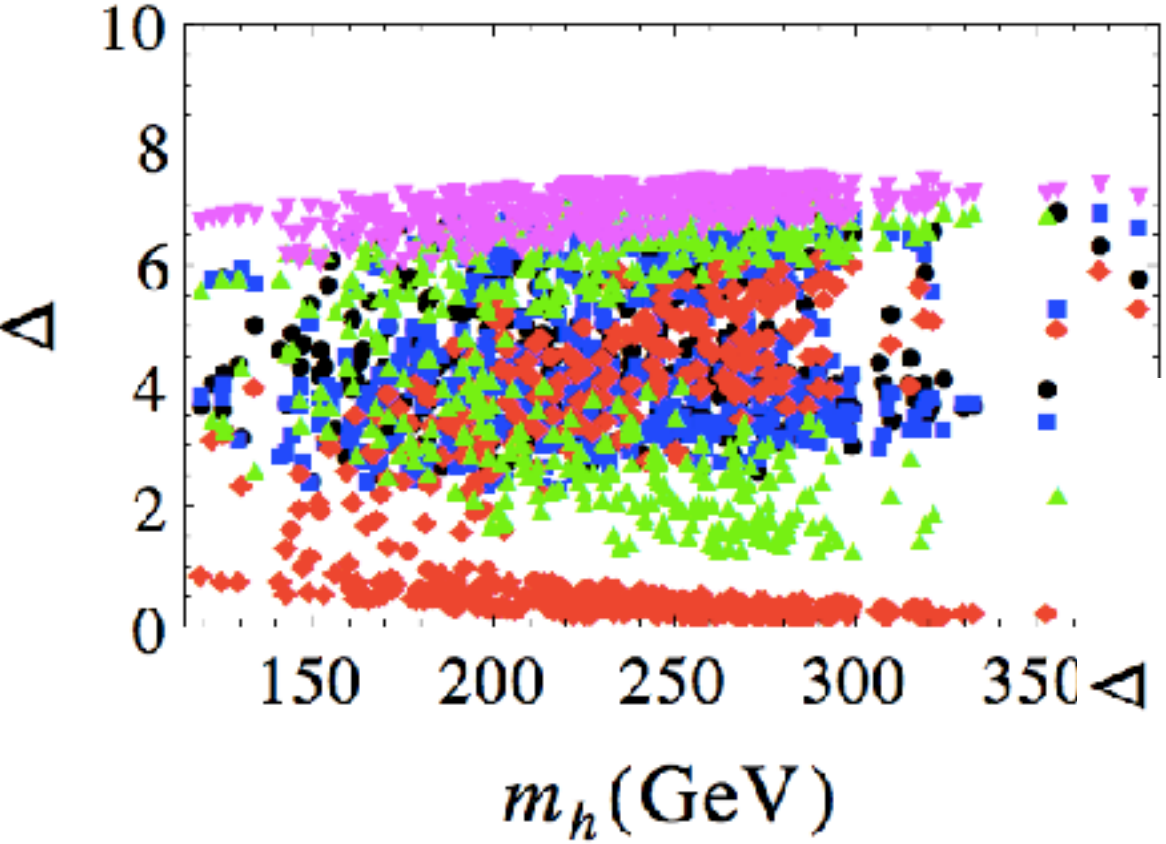
$$\begin{aligned}\mathcal{L} = {}& f_+^2\mathrm{Tr}[(d_\mu + E_\mu)^2] + f_-^2\mathrm{Tr}[V(E_\mu + d_\mu)V(E^\mu + d_\mu)]\\ & - m_+^2\,\mathrm{Tr}[(\rho_\mu + a_\mu)(d_\mu + E_\mu)] - m_-^2\,\mathrm{Tr}[V(\rho_\mu + a_\mu)V(d_\mu + E_\mu)]\\ & + \frac{m_\rho^2 + m_a^2}{4}\mathrm{Tr}[(\rho_\mu + a_\mu)(\rho_\mu + a_\mu)]\\ & + \frac{m_\rho^2 - m_a^2}{4}\mathrm{Tr}[V(\rho_\mu + a_\mu)V(\rho_\mu + a_\mu)] \qquad (8)\end{aligned}$$

$$m_+^2 = \frac{m_\rho f_\rho + m_a f_a}{2},\quad m_-^2 = \frac{m_\rho f_\rho - m_a f_a}{2} \qquad f_+^2 = \frac{f^2 + 2f_a^2 + 2f_\rho^2}{8},\quad f_-^2 = \frac{f^2 + 2f_a^2 - 2f_\rho^2}{8}$$

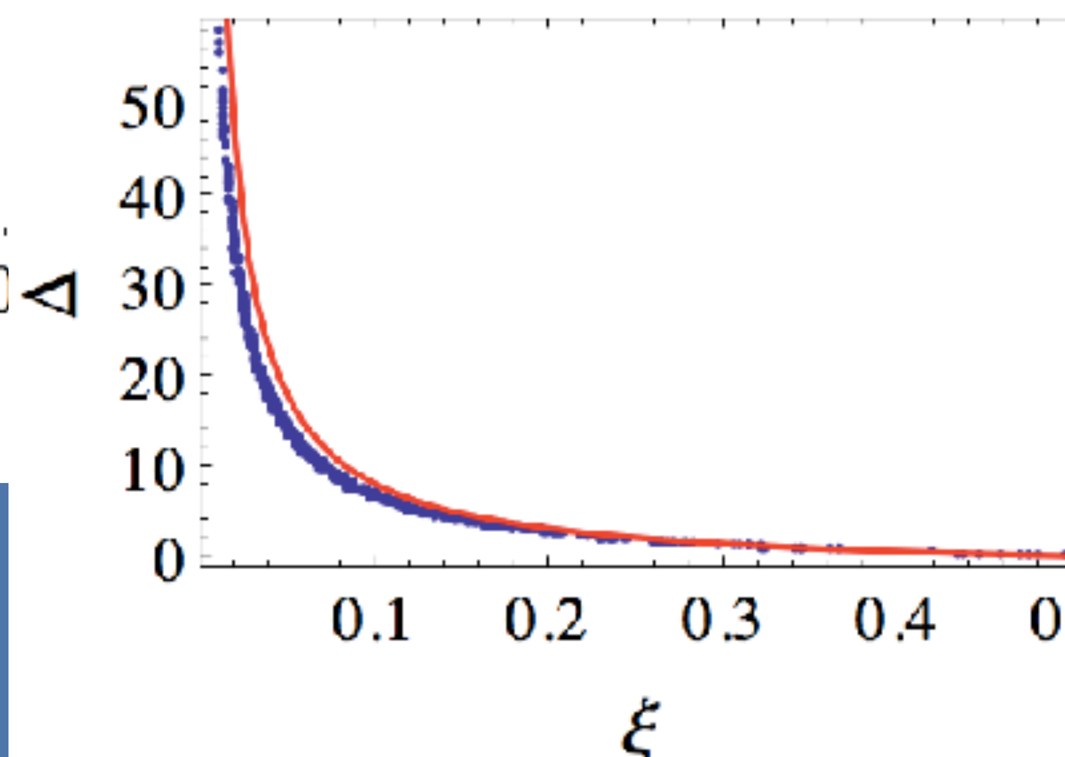
矢量波色子满足SO(5)对称性

自动推导出
Weinberg sum rule

# 参数精细调节

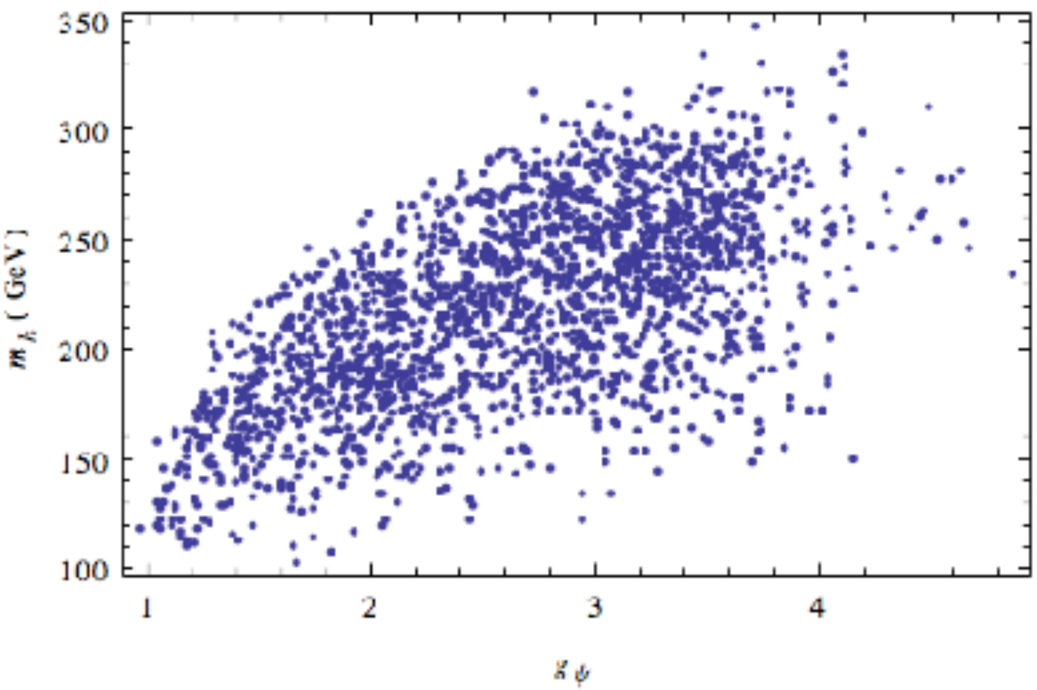


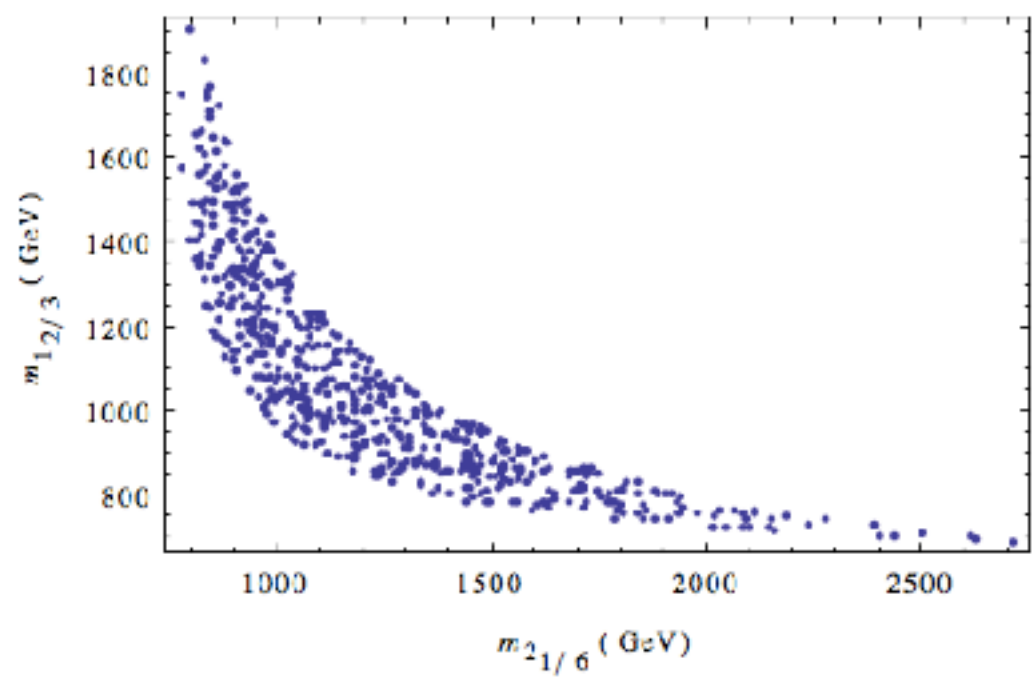

$$\Delta_m \simeq 2\gamma_g/|\gamma_f+\gamma_g| \simeq \frac{1}{\xi}-2$$




$$\Delta = \max\left|\frac{2x_i}{s_h}\frac{c_h^2}{f^2m_h^2}\frac{\partial^2 V}{\partial x_i \partial s_h}\right|$$

# 数值结果




| | $V(h)$ | $G/H$ | Tunig |
|---|---|---|---|
| $\mathrm{MCHM}_{10}$ | $\sim \lvert M_2^t\rvert^2 f^2 s_h^2 c_h^2$ | $\frac{SO(5)_L \times SO(5)_R}{SO(5)_{D'}}$ | $\frac{0.5}{\xi}$ |
| $\mathrm{MCHM}_{14}$ | $\sim f^2(6s_{2h}+5s_{4h})^2$ | $\frac{SO(5)_L \times SO(5)_R}{SO(4)_D}$ | $\frac{13-\sqrt{59}}{20\xi}$ |
| $\mathrm{MCHM}_{14}$ | $\sim f^2(6s_{2h}-3s_{4h})^2$ | $\frac{SO(5)_L \times SO(5)_R}{SO(4)_D}$ | $\frac{1+\sqrt{3}}{4\xi}$ |
| $\mathrm{MCHM}_{14}$ | $\sim \lvert M_2^t\rvert^2 f^2 s_{2h}^2 c_{2h}^2$ | $\frac{SO(5)_L \times SO(5)_R}{SO(5)_{D'}}$ | $\frac{2-\sqrt{2}}{4\xi}$ |

No tunning

# 物理意义和预言

物理 $\Pi_{0,1}^{q,t}$ 为0　　Top动能项：没有非线性修正

$$M_t(h) \sim \sin\left(\frac{2h}{f}\right)\left(1+\frac{1}{2}\sin^2(h/f)\left(\Pi_1^q(0)-\Pi_1^t(0)\right)\right)$$

通过测量mt, tth, tthh, etc可以确定 $\Pi_{0,1}^{q,t}$ 是否为0

发现类顶夸克态，测量它的性质

$$\mathrm{Tr}[Y_m M_D] = 0 + \mathcal{O}(v^2)$$

对角的Higgs Yukawa和质量

类顶夸克态最轻的是exotic charge (5/3)　$M_Q + M_S = 0$

# 未来可能的方向

- 方法推广到Twin Higgs和很多其他的模型 (unified description)
- Maximal Symmetry 新的 UV completion (Twisted Moose)
- 有效场论框架下新的collider search（Master formular）
- 方法推广到Inflation，同样解决自然性问题

# Models with Preons

# 电弱对称破缺机制二

Higgs 势能:　更基本的部分子+辐射修正

$$V(\theta) = 8C_Q f^3 m_Q \cos\theta + C_t f^4(\lambda_L^2 - 4\lambda_R^2)\cos^2\theta \, (37)$$

| | $\mathrm{Sp}(2\mathrm{N}_{TC})/\mathrm{SO}(\mathrm{N}_{TC})$ | $\mathrm{SU}(3)_c$ | $\mathrm{SU}(2)_L$ | $\mathrm{U}(1)_Y$ | $\mathrm{U}(1)_\sigma$ |
|---|---|---|---|---|---|
| $Q_1$ | $F/Spin$ | | | 0 | |
| $Q_2$ | $F/Spin$ | | **2** | 0 | |
| $Q_3$ | $F/Spin$ | **1** | | 1/2 | $q_Q$ |
| $Q_4$ | $F/Spin$ | | **1** | −1/2 | |
| $\chi_1$ | $A/F$ | | | | |
| $\chi_2$ | $A/F$ | **3** | **1** | 2/3 | $q_\chi$ |
| $\chi_3$ | $A/F$ | | | | |
| $\chi_4$ | $A/F$ | | | | |
| $\chi_5$ | $A/F$ | $\bar{\mathbf{3}}$ | **1** | -2/3 | $q_\chi$ |
| $\chi_6$ | $A/F$ | | | | |

D. Liu, Teng. Ma, J.S, 1608.XXXX

U(4)/Sp(4)

U(6)/SO(6)

$U(1)_\sigma$ 对称性

# Higgs as SU(4)/SP(4) pNGB

The electroweak part of CHM:

$$SU(4)\times U(1)_\sigma/Sp(4)$$

$$\Sigma_Q = e^{i\Pi}.\Sigma_{Q0} \quad \Pi = \cos\phi\frac{\sigma}{f_Q} + \frac{\pi^a T^a}{f}$$

$$\pi^a T^a = \frac{1}{2\sqrt{2}}\begin{pmatrix} \eta 1_{2\times 2} & ih1_{2\times 2} \\ -ih1_{2\times 2} & -\eta 1_{2\times 2}\end{pmatrix}$$

$$\tan\omega = -\frac{8}{3} \quad G_{TC} = SO(11),$$

$$\tan\omega = -\frac{16}{3} \quad G_{TC} = SO(13).$$

$$\tan\phi = \frac{f_X q_X}{f_Q q_Q}$$

$$f_Q = 2\sqrt{2}f,$$

$$\tan\omega \equiv q_X/q_Q = -2T_Q/3T_X,$$

Similar things happens in the QCD part of $SU(6)\times U(1)_\sigma/SO(6)$

# 部分子的Higgs势能贡献

来着于部分子的势能项

$$
\begin{aligned}
V_m &= -C_Q f^3 \mathrm{Tr}[\Sigma_{m_Q}.\Sigma_Q] - C_\chi f_6^3 \mathrm{Tr}\,[\Sigma_{m_\chi}.\Sigma_\chi] + h.c \\
&= -12 C_\chi m_\chi f_6^3 \cos[\frac{\sigma \sin\phi}{f_\chi}] \\
&\quad +8 C_Q m_Q f^3 \cos[\frac{\sigma\cos\phi}{f_Q}] \cos\frac{\pi}{2\sqrt{2} f} \\
&\quad -8 C_Q \Delta_{m_Q} f^3 \sin\frac{\sigma\cos\phi}{f_Q} \sin\frac{\pi}{2\sqrt{2} f}\frac{\eta}{\pi}
\end{aligned}
$$

$$
\Sigma_{m_Q} = \begin{pmatrix} i m_{Q1}\sigma_2 & 0 \\ 0 & i m_{Q2}\sigma_2 \end{pmatrix}
$$

$$
\Sigma_{m_\chi} = \begin{pmatrix} 0 & m_\chi 1_{3\times 3} \\ m_\chi 1_{3\times 3} & 0 \end{pmatrix}
$$

$$
m_Q = \frac{m_{Q1} - m_{Q2}}{2}, \quad \Delta_{m_Q} = \frac{m_{Q1} + m_{Q2}}{2}
$$

$$
\pi = \sqrt{h^2 + \eta^2}
$$

$$
f_\sigma = \sqrt{\frac{q_Q^2 f_Q^2 + q_\chi^2 f_\chi^2}{q_Q^2 + q_\chi^2}}
$$

$$
m_\sigma^2 = \frac{12 C_\chi m_\chi f_6^3 \sin^2\omega}{f_\sigma^2} - \frac{8 C_Q m_Q f^3 \cos^2\omega \cos\theta}{f_\sigma^2}
$$

$$
\theta = \langle \pi \rangle / 2\sqrt{2} f .
$$

# Top和伴随子的Higgs势能贡献

可能的Top伴随子

$$\psi_1 = \chi QQ \in (6,6) \quad \psi_2 = \chi\bar{Q}\bar{Q} \in (\bar{6},6)$$
$$\psi_3 = Q\bar{\chi}\bar{Q} \in (1,\bar{6}) \quad \psi_4 = Q\chi\bar{Q} \in (15,\bar{6})$$

Top伴随子的全表示 (6,6)

$$\begin{aligned}(6,6) &= (5,3,2/3) + (5,\bar{3},-2/3) + (1,3,2/3) + (1,\bar{3},-2/3) \\ &\equiv \Psi_5 + \Psi_5^c + \Psi_1 + \Psi_1^c\end{aligned} \tag{22}$$

$$\begin{aligned}\mathcal{L}_{mix} = &-\lambda_L f \left( \mathrm{Tr}[\Psi_q \xi \Psi_5^c \xi^T] + b_L \mathrm{Tr}[\Psi_q \xi \Psi_1^c \xi^T]\right) \\ &-\lambda_R f \left(a_R \mathrm{Tr}[\Psi_{t_R}^c \xi \Psi_5 \xi^T] + \mathrm{Tr}[\Psi_{t_R}^c \xi \Psi_1 \xi^T]\right) \\ &-M_5 \mathrm{Tr}[\Psi_5 \Sigma_{Q0} \Psi_5^c \Sigma_{Q0}] - M_1 \mathrm{Tr}[\Psi_1 \Sigma_{Q0} \Psi_1^c \Sigma_{Q0}] + h.c\end{aligned} \tag{28}$$

$$\xi = e^{i\left(\frac{\sigma}{2f_Q}\cos\phi + \frac{\pi^a T^a}{2f}\right)}$$

# Higgs势能的分析

$$V_{t6} = -C_t f^4 \left( \sum_{\alpha=1,2} |\mathrm{Tr}[\lambda_L \hat{P}_L^\alpha \Sigma_1]|^2 + |\ \mathrm{Tr}[\lambda_R \hat{P}_R \Sigma_1]|^2 \right)$$
$$= -C_t f^4 [\lambda_L^2 \sin^2 \frac{\pi}{2\sqrt{2}f} \frac{h^2}{\pi^2}$$
$$+4\lambda_R^2 (\cos^2 \frac{\pi}{2\sqrt{2}f} + \delta^2 \sin^2 \frac{\pi}{2\sqrt{2}f} \frac{\eta^2}{\pi^2})] \qquad (36)$$

$$m_t = \frac{f^2 \lambda_L \lambda_R |a_R M_1 + b_L M_5|}{2 M_T M_{T_1}} \sin\theta$$

$$m_h = \sqrt{C_t \left( \frac{1}{\lambda_R^2} - \frac{4}{\lambda_L^2} \right)} \frac{M_T M_{T_1}}{2fM} m_t$$
$$= \frac{\sqrt{N_c}}{4\pi} \frac{M_T M_{T_1}}{2\lambda f^2} m_t$$
$$= \frac{\sqrt{N_c}}{\pi} \frac{M_T M_{T_1}}{\lambda v_{SM}^2} m_t \sin^2\theta$$

$$V(\theta) = 8 C_Q f^3 m_Q \cos\theta + C_t f^4 (\lambda_L^2 - 4\lambda_R^2) \cos^2\theta \, (37)$$

No light higgs, light top partners!

和模型混合有关

Higgs势能项有了新的贡献, light Top伴随子可以很重。

# 单态决定部分子质量

$$m_\sigma^2 = \frac{12C_\chi m_\chi f_6^3 \sin^2\omega}{f_\sigma^2} - \frac{8C_Q m_Q f^3 \cos^2\omega\cos\theta}{f_\sigma^2}$$

$U(1)_\sigma$单态

$$\mathcal{L}_{WZW} = \frac{g_i^2\kappa_i}{32\pi^2 f_\sigma}\sigma\epsilon^{\mu\nu\alpha\beta}G^i_{\mu\nu}G^i_{\alpha\beta}$$

势能项只有部分子贡献

$$\Gamma(\sigma\to gg) = \frac{\alpha_s^2\kappa_g^2}{8\pi^3}\frac{m_\sigma^3}{f_\sigma^2}$$

$$\Gamma(\sigma\to W^+W^-) = \frac{\alpha_W^2\kappa_W^2}{32\pi^3}\frac{m_\sigma^3}{f_\sigma^2}\left(1-\frac{4m_W^2}{m_\sigma^2}\right)^{3/2}$$

$$\Gamma(\sigma\to\gamma\gamma) = \frac{\alpha^2}{64\pi^3}(\kappa_W+\kappa_B)^2\frac{m_\sigma^3}{f_\sigma^2}$$

$$\Gamma(\sigma\to ZZ) = \frac{\alpha^2}{64\pi^3 t_W^4}(\kappa_W+\kappa_B t_W^4)^2\frac{m_\sigma^3}{f_\sigma^2}\left(1-\frac{4m_Z^2}{m_\sigma^2}\right)^{3/2}$$

$$\Gamma(\sigma\to Z\gamma) = \frac{\alpha^2}{32\pi^3 t_W^2}(\kappa_W - t_W^2\kappa_B)^2\frac{m_\sigma^3}{f_\sigma^2}\left(1-\frac{m_Z^2}{m_\sigma^2}\right)^3 \tag{68}$$

通过反常和规范波色子相互作用

几百GeV到1~2TeV

可以用来解释750GeV共振峰

# More pheno

- Six top signals
- Colored pion constrains
- sigma —>ZZ (anomaly decay).

Even without a 750GeV jump, it is still interesting!

# Backup slice

# 电弱对称破缺机制

Higgs 势能:　　　辐射修正

$$V_f(h) \simeq -\gamma_f s_h^2 + \beta_f s_h^4,$$

$$\sin^2\langle H\rangle/f = \xi \ll 1$$

$$m_H^2 = 8\,\xi(1-\xi)\,\beta\,.$$

$$\gamma_g = -\frac{3}{8(4\pi)^2}\int_0^\infty dp_E^2\, p_E^2 \left(\frac{3}{\Pi_0} + \frac{c_X^2}{\Pi_B}\right)\Pi_1,$$

$$\beta_g = -\frac{3}{64(4\pi)^2}\int_{\mu_g^2}^\infty dp_E^2\, p_E^2 \left(\frac{2}{\Pi_0^2} + \left(\frac{1}{\Pi_0} + \frac{c_X^2}{\Pi_B}\right)^2\right)\Pi_1^2.$$

规范波色子贡献

$$\gamma_f = \frac{2N_c}{(4\pi)^2}\int_0^\infty dp_E^2\, p_E^2 \left(\frac{\Pi_{1Q}}{\Pi_Q} + \frac{\Pi_{1S}}{\Pi_S} + \frac{\Pi_{QS}^2}{p_E^2\Pi_Q\Pi_S}\right),$$

$$\beta_f = \frac{N_c}{(4\pi)^2}\int_{\mu_f^2}^\infty dp_E^2\, p_E^2 \left(\left(\frac{\Pi_{QS}^2}{p_E^2\Pi_Q\Pi_S} + \frac{\Pi_{1Q}}{\Pi_Q} + \frac{\Pi_{1S}}{\Pi_S}\right)^2 - \frac{2(p_E^2\Pi_{1Q}\Pi_{1S} - \Pi_{QS}^2)}{p_E^2\Pi_Q\Pi_S}\right).$$

费米子贡献

$$M_t^2(q^2,\langle h\rangle) = \frac{\left|\Pi_{t_L t_R}(q^2,\langle h\rangle)\right|}{\sqrt{\Pi_{t_L}(q^2,\langle h\rangle)\,\Pi_{t_R}(q^2,\langle h\rangle)}}.$$

Top 夸克质量

# Spin 1/2 Resonances

There are many ways to generate the fermion masses

Bilinear: $\mathcal{L} = \lambda \bar{q} q \langle \bar{\Psi} \Psi \rangle$ techicolor, conformal techicolor, etc

Here we only consider the "partial compositeness"

Linear mixing: $\mathcal{L}_{mix} = \lambda \bar{q}_i \mathcal{O}_i$

Good for flavor physics

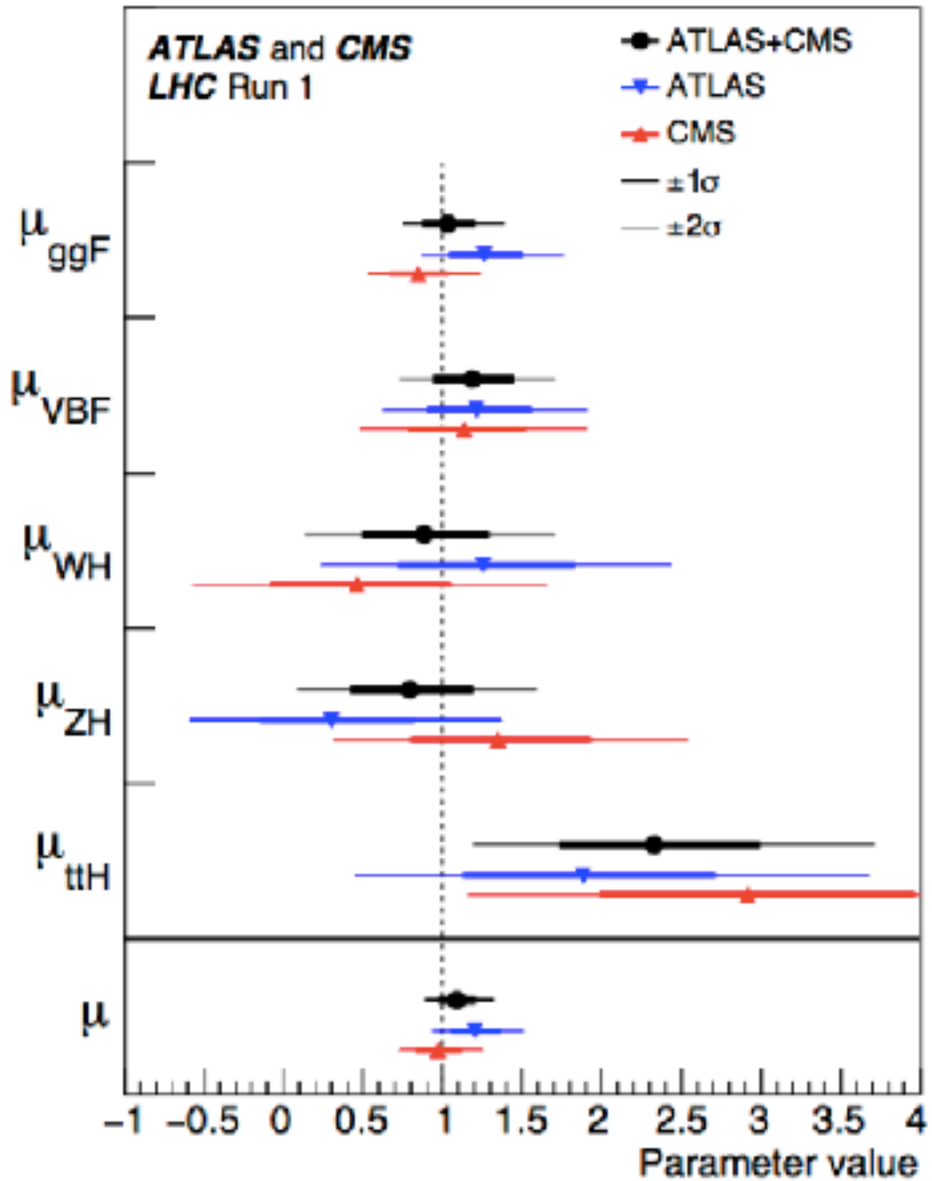
$\mathcal{O}_i \sim U \Psi_i$ Composite operators

$\Psi_i$ Composite fermions sit in the representation of SO(4)

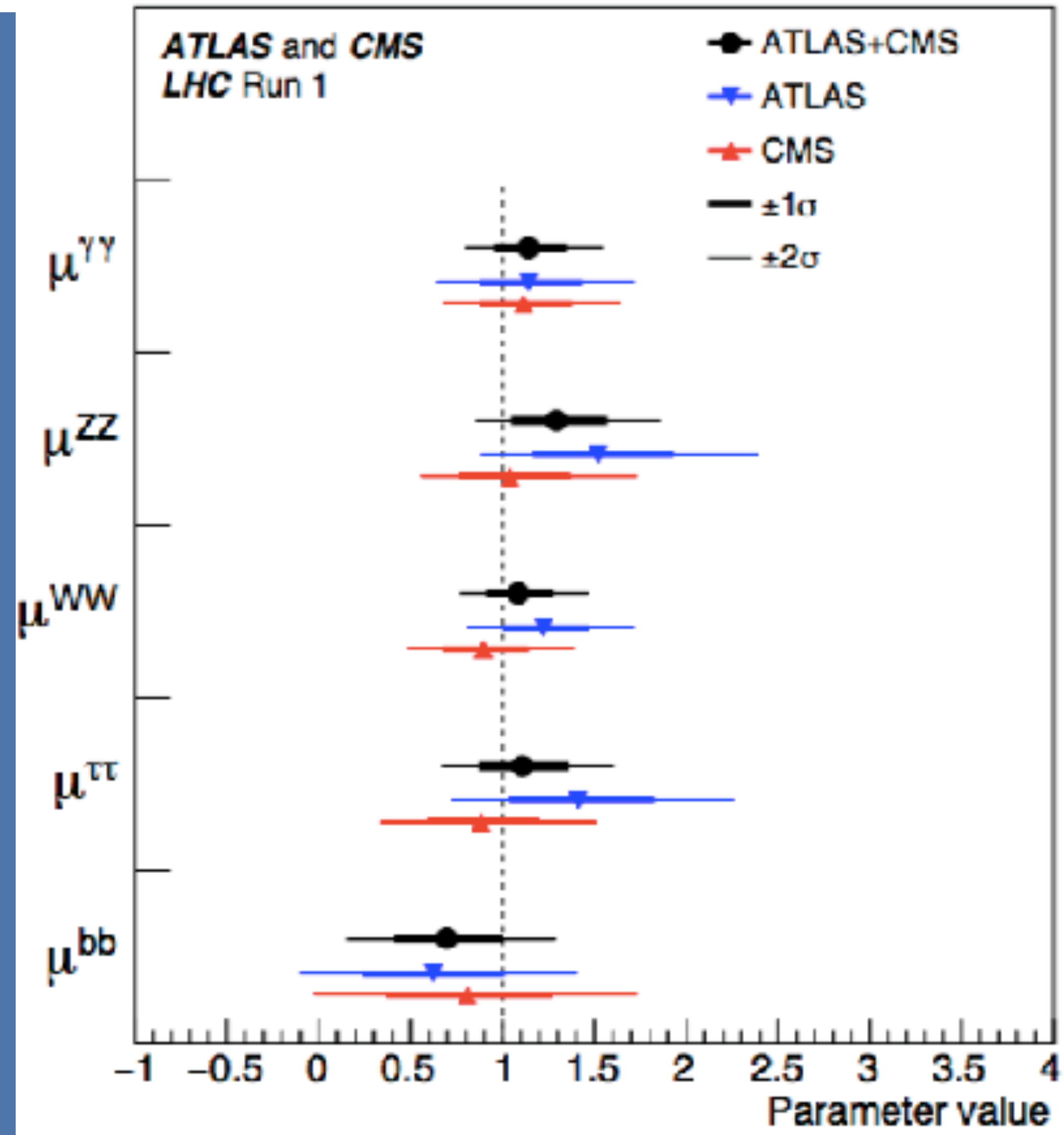
Maximally suppressed the FCNC by the small fermion mass

$Q_j$ bi-doublet $S_i$ Singlet

# Higgs产生和衰变

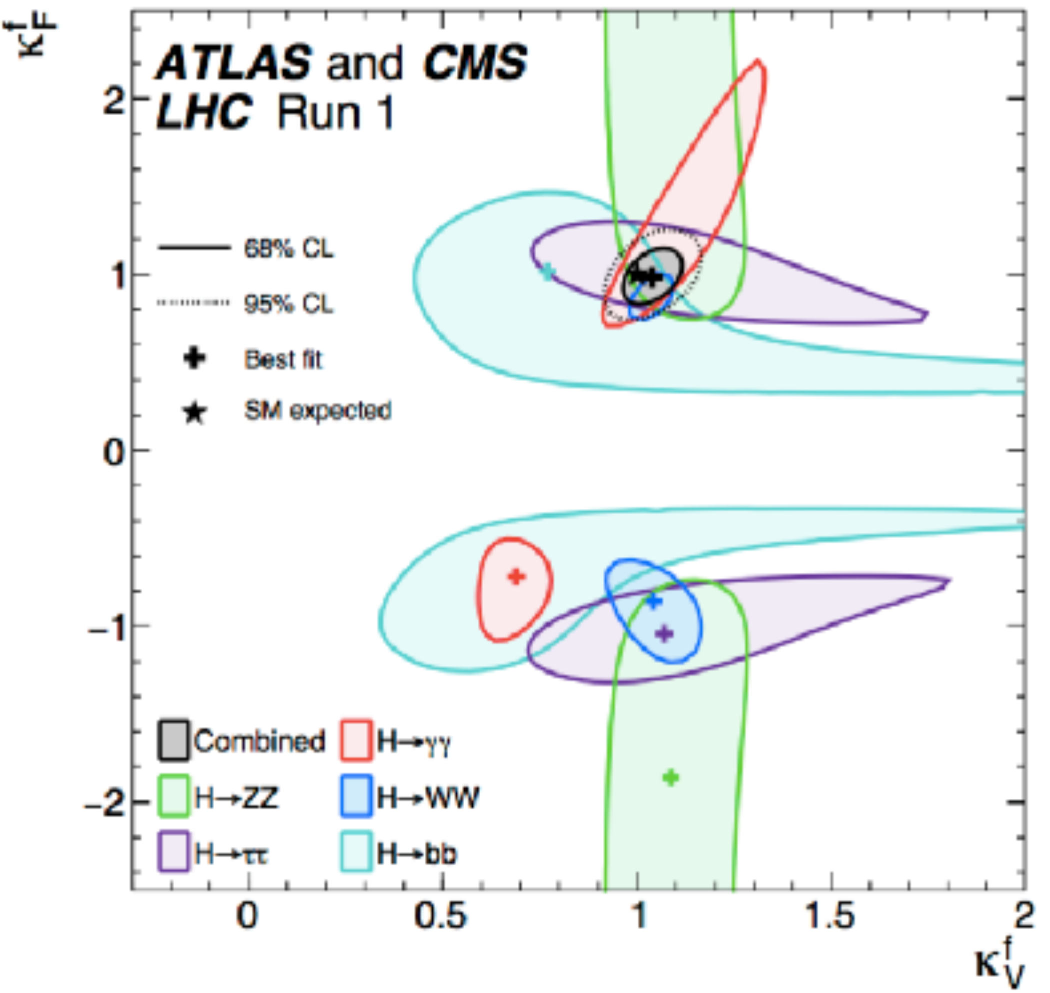


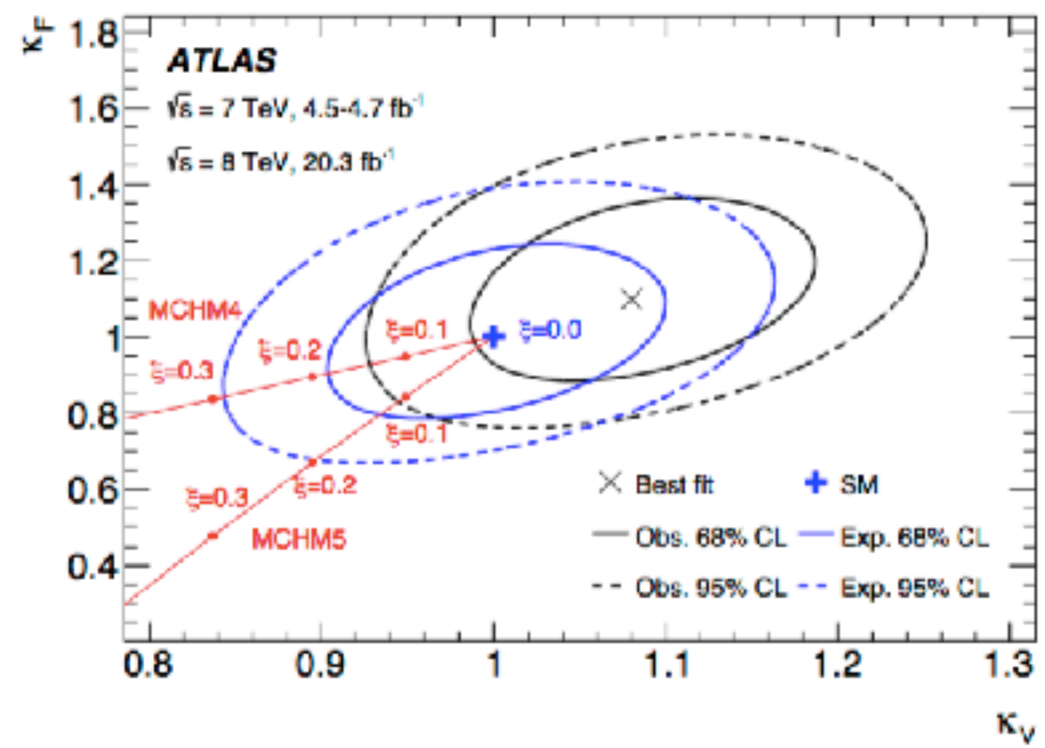
ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
μggF
μVBF
μWH
μZH
μttH
μ
−1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
μγγ
μZZ
μWW
μττ
μbb
−1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

# Higgs物理

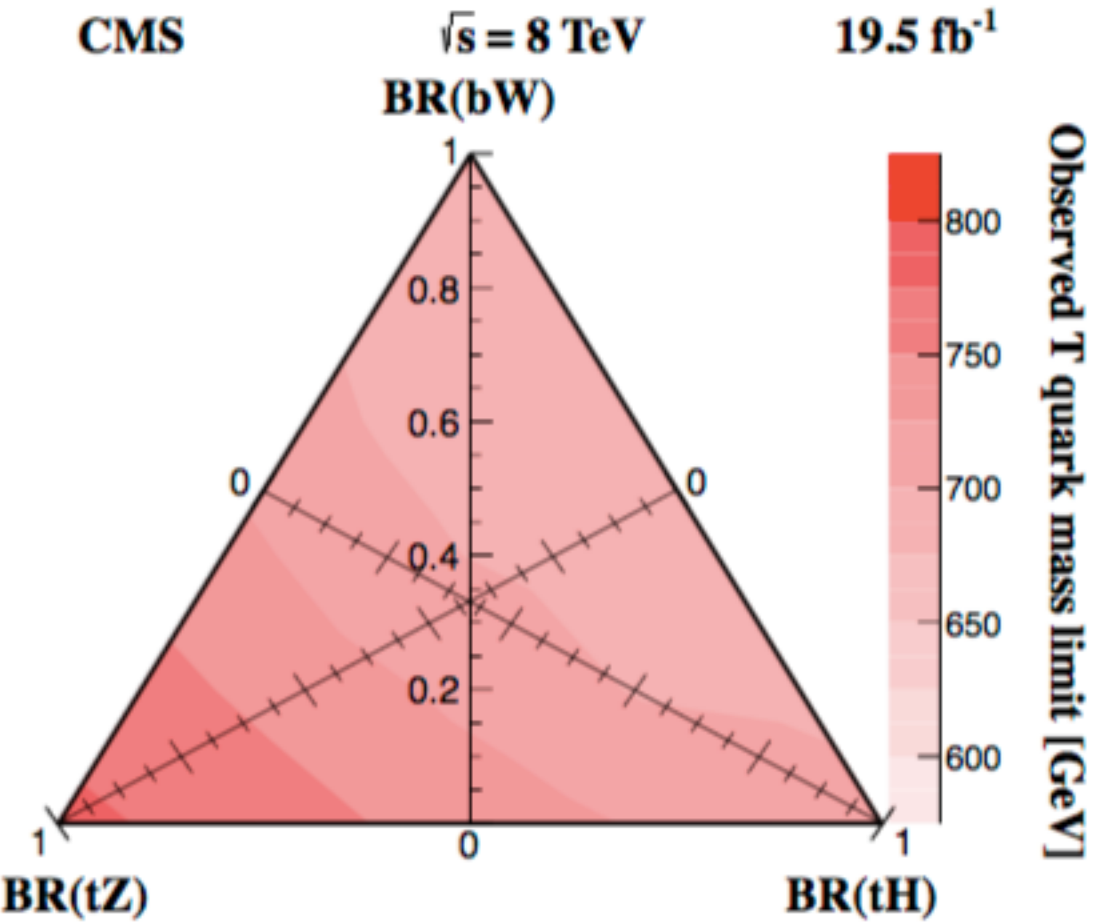


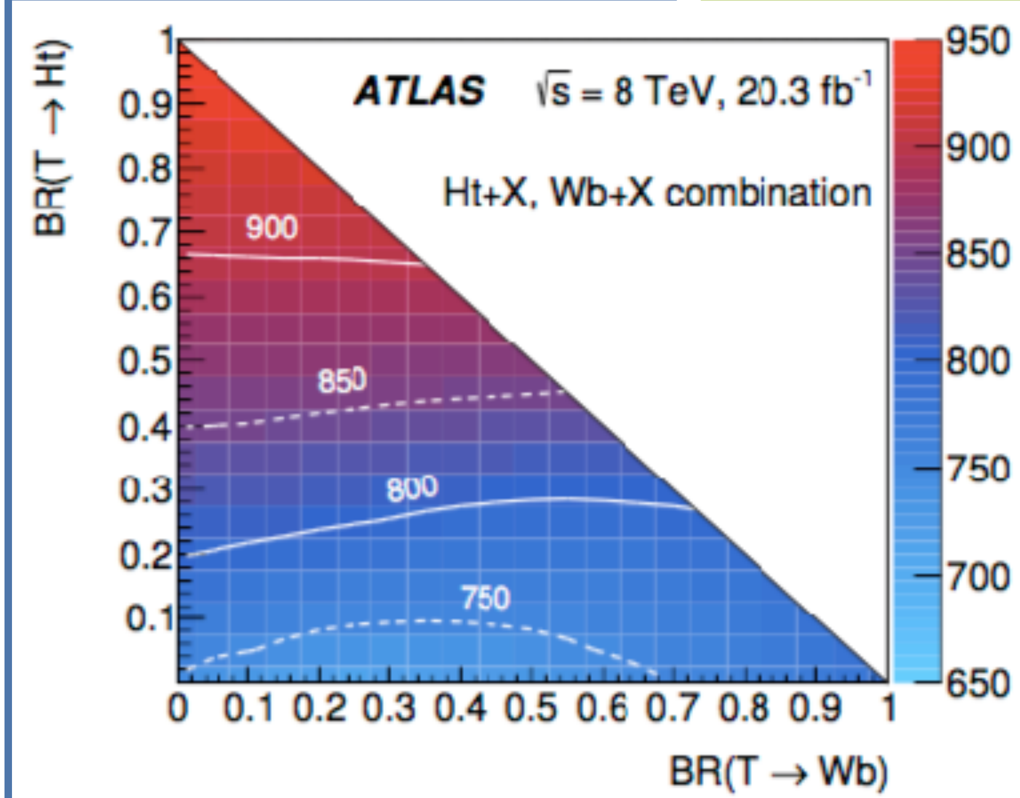




Top耦合为负的情况不再存在

Higgs 拟合 $\xi < 0.1$

# Top 伴随子的寻找

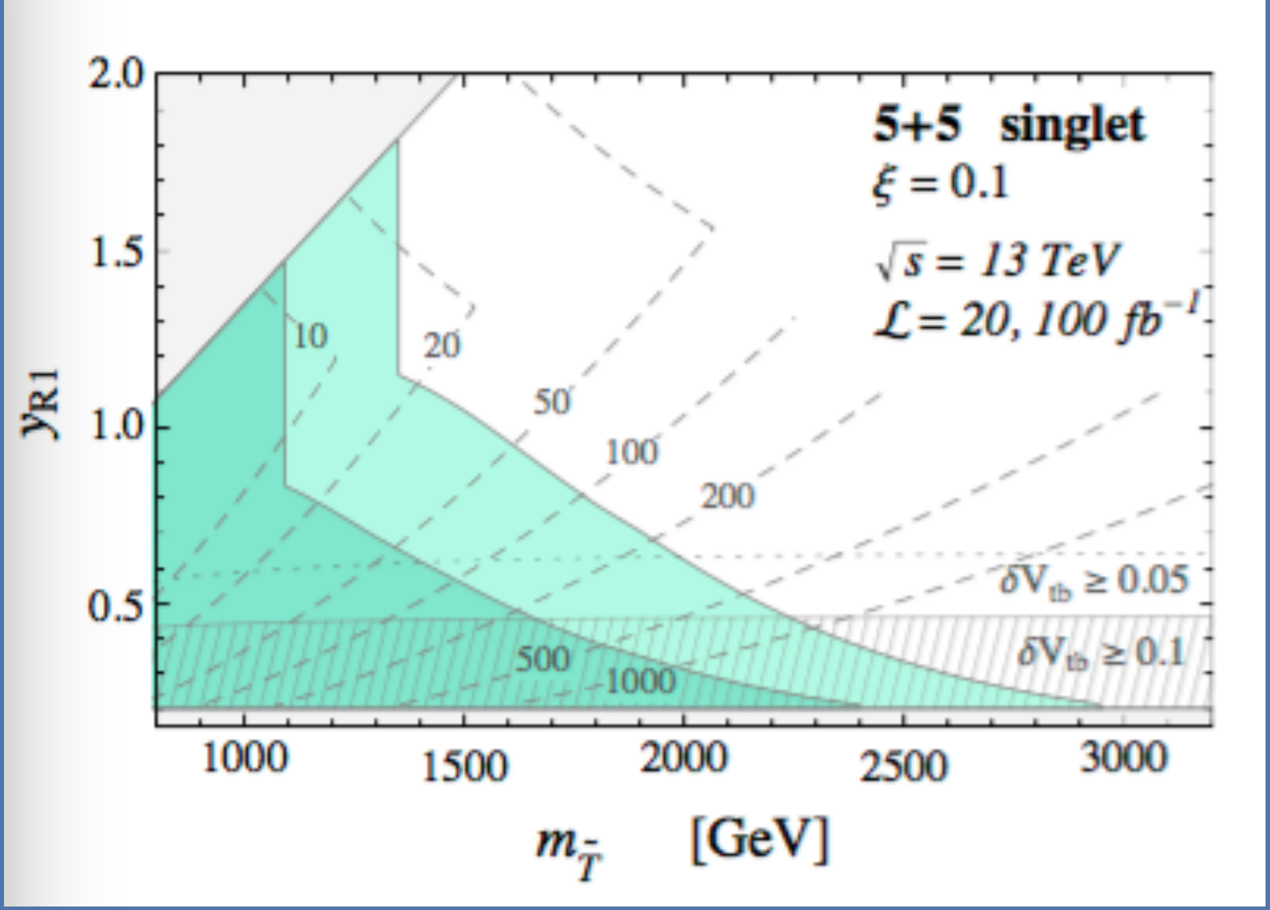



$$\mathrm{BR}(t' \to th) \approx \mathrm{BR}(t' \to tZ) \approx \mathrm{BR}(t' \to bW)/2 \approx 0.25$$

限制在700~900GeV

# Top 伴随子的寻找




D. Matsedonskyi, G. Panico, A. Wulzer, JHEP, 1604, (2016) 003.

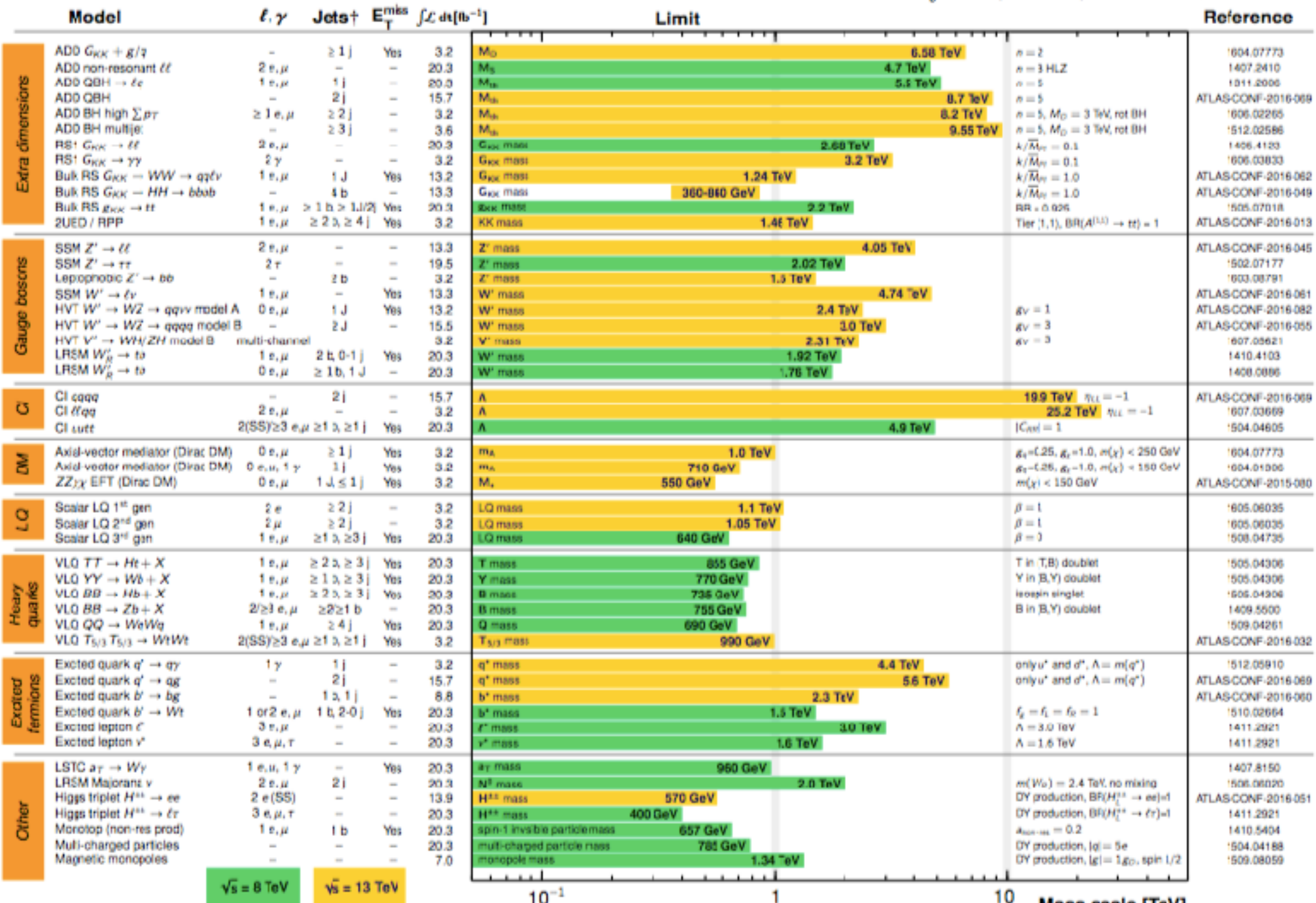
当前Top伴随子寻找正在检验原始的复合Higgs模型

# ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV




*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

# ttbar Higgs

- Summary of the $t\bar{t}H$ signal strength measurements (left) and upper limits (right).