Naturalness sum rules at future colliders

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ITP-CAS

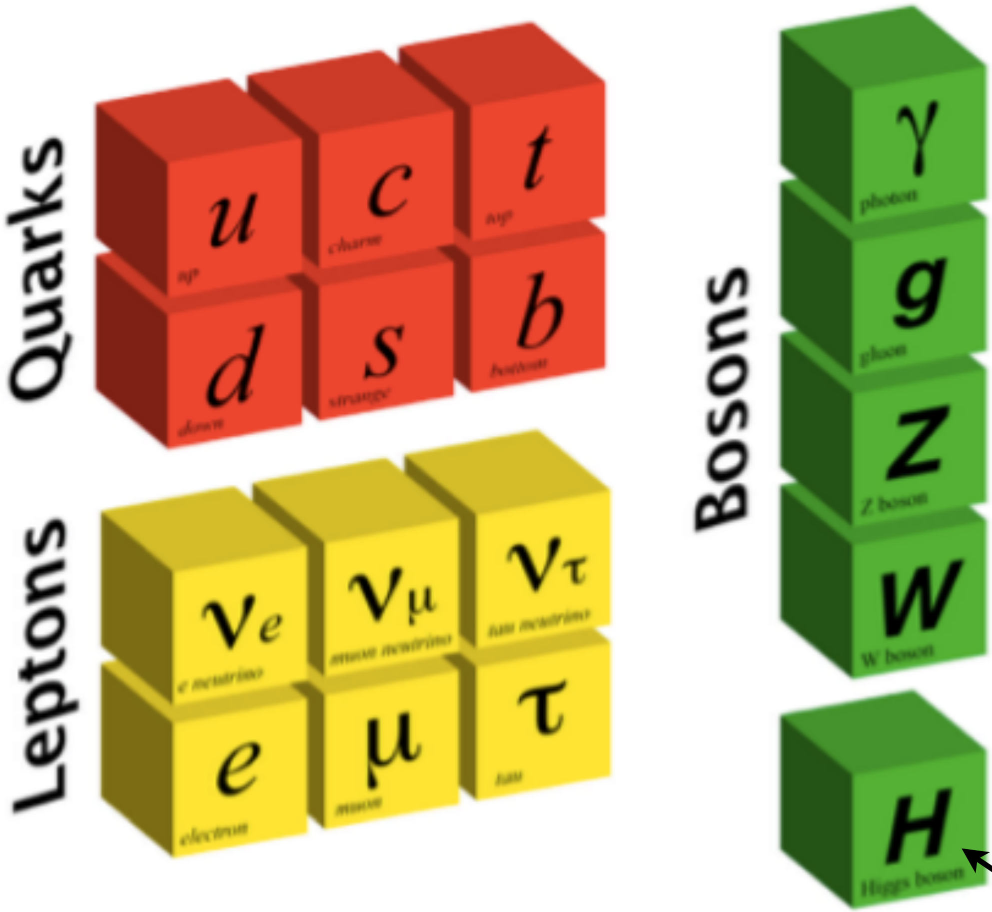
C. Csaki, F. Ferreira De Freitas, L. Huang, T. Ma, M. Perelstein, J. Shu., arxiv: 1811.01961

Outline

- Electroweak symmetry breaking? Naturelness?
- Natureless sum rule in the non-SUSY and SUSY case.
- How to test naturalness at the 100TeV colldier?
- Outlook

Naturalness

The known "old" physics



The Weinberg-Salam Model

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

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

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

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

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

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

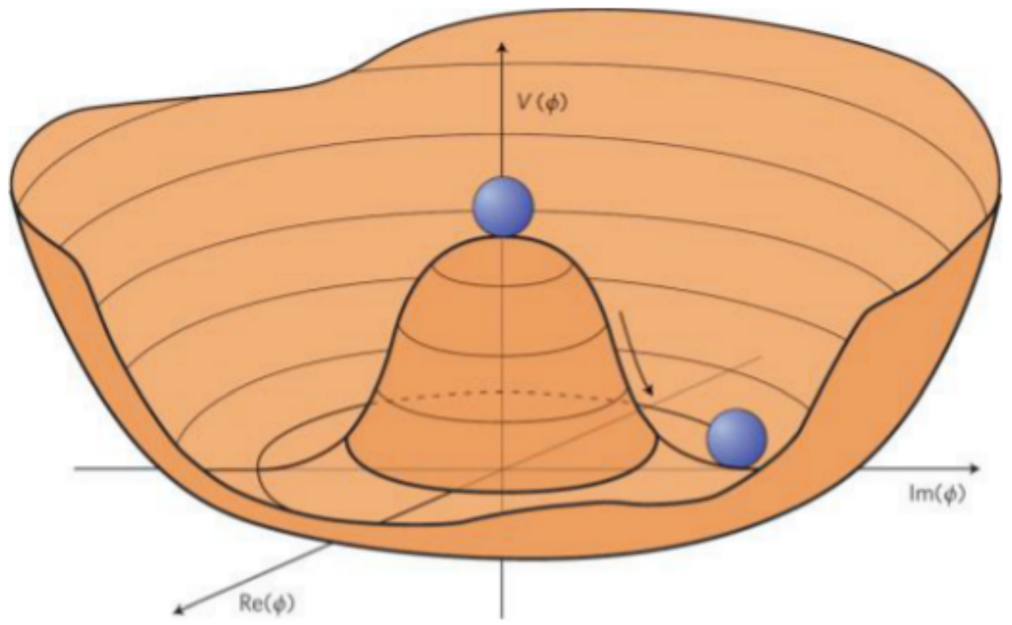
$$+ \bar{d}_L\gamma^\mu(-\tfrac{1}{2}+\tfrac{1}{3}\sin^2\theta_w)d_L + \bar{d}_R\gamma^\mu(\tfrac{1}{3}\sin^2\theta_w)d_R$$

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

elementary particles

The chosen one!

Why God's particle?



Higgs potential

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

EWSB
(Higgs mechanism)

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

Gives all particles mass

The origin of the mass

Natureless

As a scalar, Higgs has large quantum corrections

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

If no NP particles cancel the quadratic divergence, there are quadratic quantum corrections up to the new physics scale.

Big tuning if \lambda is large

Symmetries could forbid such a quantum correction, by introducing new particles

Linear divergence of electron mass

chiral symmetry positron

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

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

Natureless

BSM guidance "old days"

SUSY

	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		

Non-SUSY

top	top partner, t'
W, Z	rho meson (W', Z'), etc

In the LHC era, we first search for something new, if there is something, we better check the principle!

Is the new particle cancel the Higgs UV divergence from SM particles?

Indirect information

One-loop \beta function: (also for gluon)

$$\mathcal{L}_{\gamma\gamma} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \sum_i \frac{b_i e^2}{16\pi^2} \log \frac{\Lambda^2}{m_i^2} + \cdots ,$$

I. Low, R. Rattazzi, A. Vichi, arxiv: 0907.5413

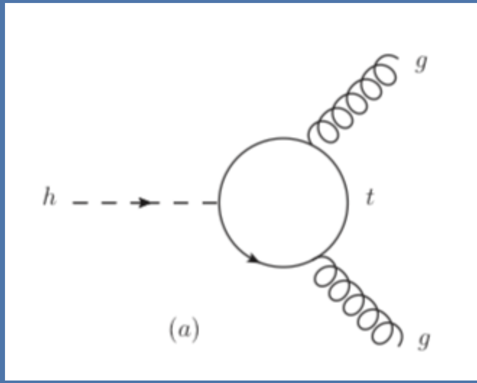
$h \to h + v$

I. Low, A. Vichi, arxiv: 1010.2753

$$\mathcal{L}_{h\gamma\gamma} = \frac{\alpha}{16\pi} \frac{h}{v} \left[\sum_i 2b_i \frac{\partial}{\partial \log v} \log m_i(v) \right] F_{\mu\nu} F^{\mu\nu} .$$

Non-SUSY

h is really H H^\dag



More natural

suppressed hgg

SUSY

enhanced hgg

R. Dermisek, I. Low, arxiv: hep-ph/0701235

also for strongly 1st EWPT

has to attach external gauge fields, not know how precise is the cancellation

Resonance discovery

Direct test of naturalness would be the discovery of new resonances

Previous, all those resonances searches are in the gauge basis, model dependent, have to know (at least) rough the model and check the complicated mass matrix.

We better test naturalness in the mass basis

Naturalness sum rule in the mass eigenstate

Fermion sum rule

$$a_T = -|\lambda_t|^2 + \mathcal{O}\left(\frac{v^2}{m_T^2}\right)$$

LH model, no quadratic div

C.-R. Chen, J. Hajer, T. Liu, I. Low, and H. Zhang, *Testing naturalness at 100 TeV*, *JHEP* **09** (2017) 129, [arXiv:1705.0774].

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

No quadratic div

$$\mathrm{Tr}[Y_m M_D^3] \;=\; 0 + \mathcal{O}(v^2/M_f^2)$$

No log div

C. Csaki, T. Ma, J. Shu., Phys.Rev.Lett. 119 (2017) no13, 131803

Fermion sum rule

Top sector mass matrix

$$M_F = M_{F0} + f\,U(\frac{H}{f}),$$

QD in 1-loop CW potential

$$V(H) \sim \mathrm{Tr}[M_F.M_F^\dagger]\Lambda^2,$$

$$\frac{\partial^2}{\partial H^2}\mathrm{Tr}[M_F.M_F^\dagger]|_{H=0} = 0$$

No quadratic potential in the mass term

$$H = v + h.$$

$$\begin{aligned}
&\frac{\partial \mathrm{Tr}[M_F.M_F^\dagger]}{\partial h}|_{h=0} \quad \text{Tadpoles} \\
&= (\frac{\partial(H/f)}{\partial h}|_{h=0}\frac{\partial \mathrm{Tr}[M_F.M_F^\dagger]}{\partial(H/f)}|_{H=0} + \frac{\partial(H/f)^2}{\partial h}|_{h=0}\frac{\partial^2 \mathrm{Tr}[M_F.M_F^\dagger]}{2\partial^2(H/f)}|_{H=0} + \mathcal{O}\left(v^2/f^2\right)) \\
&= \frac{\partial(H/f)^2}{\partial h}|_{h=0}\frac{\partial^2 \mathrm{Tr}[M_F.M_F^\dagger]}{2\partial^2(H/f)}|_{H=0} + \mathcal{O}\left(v^2/f^2\right) \qquad (2.5)
\end{aligned}$$

No quadratic divergence

$$\frac{\partial \mathrm{Tr}[M_F.M_F^\dagger]}{\partial h}|_{h=0} = 0 + \mathcal{O}(v^2/f^2).$$

mass basis

$$L^\dagger M_F|_{h=0} R = M_D \quad L^\dagger(\frac{\partial}{\partial h} M_F)|_{h=0} R = Y_M,$$

$$\frac{\partial \mathrm{Tr}[M_F.M_F^\dagger]}{\partial h}|_{h=0} = \mathrm{Tr}[Y_M.M_D^\dagger + M_D.Y_M] = 0 + \mathcal{O}(v^2/f^2).$$

CP conservation

$$\mathrm{Tr}[Y_D.M_D^\dagger] = 0 + \mathcal{O}(v^2/f^2).$$

No log divergence

Log divergence

$$\mathrm{Tr}\left[(M_F.M_F^\dagger)^2\right]\log\Lambda^2$$

Ignore high order terms beyond 1/f^2

$$\frac{\partial^2}{\partial H^2}\mathrm{Tr}[(M_F.M_F^\dagger)^2]|_{H=0} = 0$$

$$\begin{aligned}
&\frac{\partial}{\partial h}\mathrm{Tr}[(M_F.M_F^\dagger)^2]|_{h=0} \\
&= \left(\frac{\partial(H/f)}{\partial h}|_{h=0}\frac{\partial \mathrm{Tr}[(M_F.M_F^\dagger)^2]}{\partial(H/f)}|_{H=0} + \frac{\partial(H/f)^2}{\partial h}|_{h=0}\frac{\partial^2\mathrm{Tr}[(M_F.M_F^\dagger)^2]}{2\partial^2(H/f)}|_{H=0} + \mathcal{O}\left(v^2/f^2\right)\right) \\
&= \frac{\partial(H/f)^2}{\partial h}|_{h=0}\frac{\partial^2\mathrm{Tr}[(M_F.M_F^\dagger)^2]}{2\partial^2(H/f)}|_{H=0} + \mathcal{O}\left(v^2/f^2\right) \\
&= 0 + \mathcal{O}\left(v^2/f^2\right) \qquad (2.12)
\end{aligned}$$

$$\frac{\partial}{\partial h}\mathrm{Tr}[(M_F.M_F^\dagger)^2]|_{h=0} = 2\mathrm{Tr}[Y_M M_D^\dagger M_D M_D^\dagger + Y_M^\dagger M_D.M_D^\dagger.M_D] = 0 + \mathcal{O}(v^2/f^2)$$

CP conservation

$$\mathrm{Tr}[Y_M M_D^3] = 0 + \mathcal{O}(v^2/f^2).$$

Gauge sum rule

No quadratic divergence

$$\mathrm{Tr}[g_{VVh}] = 0 + \mathcal{O}(v^2/f^2).$$

No log divergence

$$\mathrm{Tr}[g_{VVh} M_V^2] = 0 + \mathcal{O}(v^2/f^2),$$

SUSY Case

$$\mathrm{Tr}[g_{SSh}] - 2\mathrm{Tr}[Y_M M_D^\dagger + M_D Y_M^\dagger] + 3\mathrm{Tr}[g_{VVh}] = 0,$$

$$\mathrm{Tr}[g_{SSh}] - 4\mathrm{Tr}[Y_M M_D] + 3\mathrm{Tr}[g_{VVh}] = 0.$$

Quadratic divergence

Top sector/stop sector

$$\sum_i g_{\tilde{t}_i \tilde{t}_i h} - 4 y_t m_t = 0,$$

Gauge/gaugino/Higgs/Higgsino sector

$$4\sum_i (y_{C_i^+ C_i^- h} m_{C_i} + y_{N_i N_i h} m_{N_i}) - 3(g_{W^+W^-h} + g_{ZZh})$$
$$-\sum_i (g_{H_i^0 H_i^0 h} + g_{H_i^+ H_i^- h}) - g_{hhh} = 0$$

Examples

Simplest little Higgs SU3/SU2

$$\mathcal{L}_t = -\lambda_1 f \bar{\Psi}_q \mathcal{H} u_{3R} - \lambda_2 f \bar{\tilde{T}}_L \tilde{T}_R + h.c.,$$

$$M_F = -f \begin{pmatrix} \lambda_1 \sin(\frac{H}{\sqrt{2}f}) & 0 \\ \lambda_1 \cos(\frac{H}{\sqrt{2}f}) & \lambda_2 \end{pmatrix}.$$

$$\mathrm{Tr}[M_F.M_F^\dagger]\Lambda^2 = f^2(\lambda_1^2 + \lambda_2^2)\Lambda^2$$

first sum rule

After EWSB

$$m_t = \frac{\lambda_1 \lambda_2 v}{\sqrt{\lambda_1^2 + \lambda_2^2}} + \mathcal{O}(\frac{v^2}{f^2}) \quad m_T = -f\sqrt{\lambda_1^2 + \lambda_2^2} + \mathcal{O}(\frac{v^2}{f^2}).$$

$$y_t = -\frac{m_t}{v} + \mathcal{O}(\frac{v^2}{f^2}) \quad y_T = \frac{y_t^2 v}{m_T}.$$

$$y_t m_t + y_T m_T = 0 + \mathcal{O}(\frac{v^2}{f^2}).$$

Examples

Maximally symmetric composite Higgs SO5/SO4

$$\mathcal{L}_f = \bar{q}_L i \not{D} q_L + \bar{t}_R i \not{D} t_R + \bar{\Psi}_Q i \not{\nabla} \Psi_Q + \bar{\Psi}_S i \not{\nabla} \Psi_S - \frac{1}{\sqrt{2}} \epsilon_t \bar{\Psi}_{t_R} U \Psi_{+L} - \epsilon_q \bar{\Psi}_{q_L} U \Psi_{+R} - M \bar{\Psi}_{+L} V \Psi_{+R} + h.c,$$

Before EWSB

$$M_F = \begin{pmatrix} 0 & \epsilon_q \cos^2\left(\frac{H}{2f}\right) & \epsilon_q \sin^2\left(\frac{H}{2f}\right) & -\frac{\epsilon_q \sin\left(\frac{H}{f}\right)}{\sqrt{2}} \\ \frac{1}{2}\epsilon_t \sin\left(\frac{H}{f}\right) & M & 0 & 0 \\ -\frac{1}{2}\epsilon_t \sin\left(\frac{H}{f}\right) & 0 & M & 0 \\ \frac{\epsilon_t \cos\left(\frac{H}{f}\right)}{\sqrt{2}} & 0 & 0 & -M \end{pmatrix}.$$

$$\mathrm{Tr}[M_F.M_F^\dagger]\Lambda^2 = (3M^2 + \epsilon_q^2 + \frac{\epsilon_t^2}{2})\Lambda^2$$

$$\mathrm{Tr}[(M_F.M_F^\dagger)^2]\log\Lambda^2 = (3M^4 + \epsilon_q^4 + \frac{\epsilon_t^4}{4} + (2\epsilon_q^2 + \epsilon_t^2)M^2)\log\Lambda^2.$$

Examples

Maximally symmetric composite Higgs SO5/SO4

After EWSB

$$Y = (\frac{\partial}{\partial H} M_F)|_{H=v} = \begin{pmatrix} 0 & -\frac{\epsilon_q \sin\left(\frac{v}{f}\right)}{2f} & \frac{\epsilon_q \sin\left(\frac{v}{f}\right)}{2f} & -\frac{\epsilon_q \cos\left(\frac{v}{f}\right)}{\sqrt{2}} \\ \frac{\epsilon_t \cos\left(\frac{v}{f}\right)}{2f} & 0 & 0 & 0 \\ -\frac{\epsilon_t \cos\left(\frac{v}{f}\right)}{2f} & 0 & 0 & 0 \\ -\frac{\epsilon_t \sin\left(\frac{v}{f}\right)}{\sqrt{2}f} & 0 & 0 & 0 \end{pmatrix}$$

$$\mathrm{Tr}[Y_D.M_D^\dagger] = \mathrm{Tr}[Y.(M_F^\dagger)|_{H=v}] = 0$$

$$\mathrm{Tr}[Y_D.M_D^3] = \mathrm{Tr}[Y.(M_F^\dagger.M_F.M_F^\dagger)|_{H=v}] = 0$$

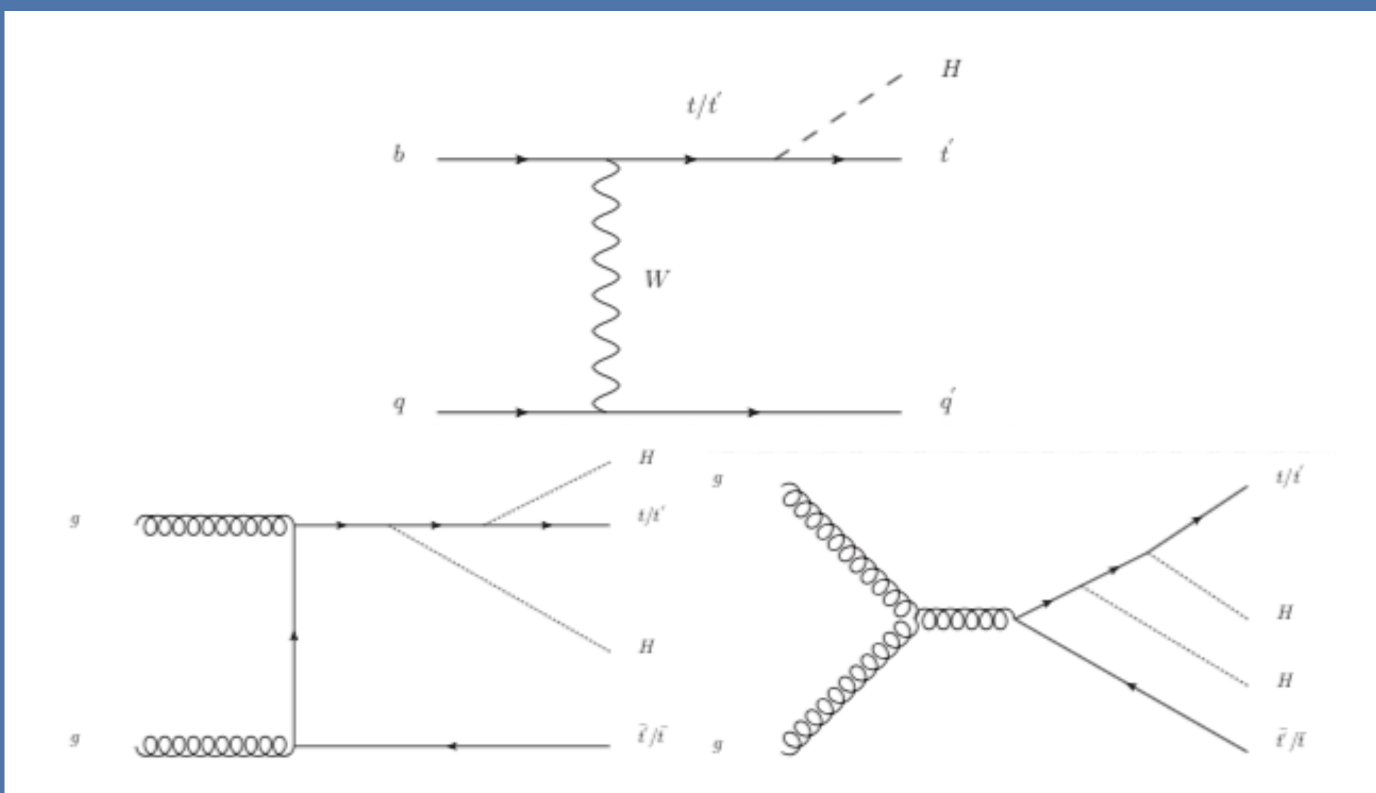
100TeV Collider Test

Collider Test

C.-R. Chen, J. Hajer, T. Liu, I. Low, and H. Zhang, *Testing naturalness at 100 TeV*, *JHEP* **09** (2017) 129, [arXiv:1705.0774].

Double production： No sign of the couplings

$pp \to t't'h,$



$pp \to qht'.$

single production: interference

$pp \to t'thh.$

Benchmark-LH

Definition of flipped rate

$$\mathcal{F} = 2\frac{\sigma(Y_{tt'h}) - \sigma(-Y_{tt'h})}{\sigma(Y_{tt'h}) + \sigma(-Y_{tt'h})}.$$

LH Model $\lambda_1 = 1.48$, $\lambda_2 = 1.11$ and $f = 811$ GeV.

Name	Mass [GeV]	Decays	$\sigma(qht')$, fb	$\mathcal{F}(qht')$	$\sigma(t'thh)$, fb	$\mathcal{F}(t'thh)$
t'	1492	Wb: 50% tZ: 25% tH: 25%	185	-13%	14.4	-26%

Table 1. Top partner parameters at the Benchmark Point in the Little Higgs model.

Benchmark-MSCHM

MSH Model $\epsilon_{qQ} = 1.15$, $\epsilon_{tQ} = -1.40$, and $MQ = 1500$ GeV.

Name	Mass [GeV]	Decays	$\sigma(qht')$, fb	$\mathcal{F}(qht')$	$\sigma(t'thh)$, fb	$\mathcal{F}(t'thh)$
t'	1791	Zt: 42.92%	20.9	26%	14.3	9.9%
		Wb: 26.06%				
		Zx_2: 12.76%				
		tH : 8.3%				
x_2	1632	tH: 37.51%	5.0	-25%	41.7	-45%
		Wb: 32.84%				
		Zt: 18.33%				
		Wx_5 : 6.08%				
t_1	1500	tH: 51.45%	XXX	0	YYY	0
		Zt: 32.43%				
		WWt : 11.81%				

Another way of proving MS at colliders

Table 2. Top partner parameters at the Benchmark Point in the Maximally Symmetric Higgs model.

Top partner mass and Br

Measure precision in percent!

Name	Mass $m_{t'}$	$\mathrm{Br}(t' \to Zt)$	$\mathrm{Br}(t' \to th)$	$\mathrm{Br}(t' \to Wb)$	$g_{bt'W}$	$g_{tt'h}$	$Y_{t't'h}$
T (LHT)	1.2	2.4	2.3	2.4	1.2	2.1	2.9
t'_2 (MSCH)	0.7	4.4	3.9	8.6	3.2	5.7	6.9
t'_3 (MSCH)	0.8	0.8	3.9	1.3	1.9	2.8	7.0

Mass reconstruction: $T \to Zt$, both Z's decays leptonically.

hadronic boosted top tagging

$$\frac{\delta \mathrm{Br}(tZ)}{\mathrm{Br}(tZ)} = \frac{1}{2}\left(\frac{\delta N}{N} \oplus \frac{\partial \log \sigma}{\partial \log M_T}\frac{\delta M_T}{M_T}\right).$$

$\mathrm{Br}(T \to th)$ $thth$ events. one of the Higgs bosons decays to $\gamma\gamma$, the other Higgs decays to $b\bar{b}$.

$\mathrm{Br}(T \to Wb)$

both W bosons decay leptonically, resulting in a final state $\ell^+\ell^- + 2b + \not{E}_T$.

Preliminary

Before the measurements of diagonal t' Higgs Yukawa couplings, one have to pin down other unknown particles, details see the paper

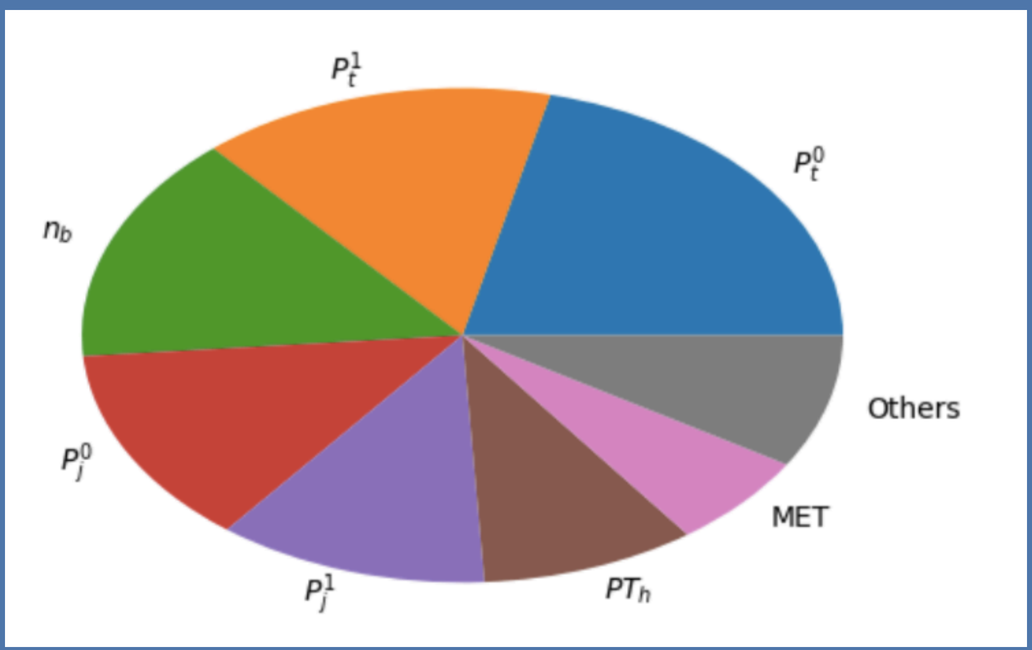
Preselection:

Channel	Selection Cuts	Results
$(\gamma\gamma)+2j+X$	$p_T(j^k)\geq 400$ GeV, $k=1,2$; $p_T(\gamma^1)\geq 100$ GeV; $p_T(\gamma^2)\geq 50$ GeV $m_{\gamma\gamma}\in[120,130]$ GeV; $m_{jj}\in[1.0,2.0]$ TeV	Table 5
$(\ell^+\ell^-)+2j+X$	**Pre-cuts:** $p_T(j^k)\geq 400$ GeV, $k=1,2$; $m_{\ell^+\ell^-}\in[80,100]$ GeV; $p_T(Z)\geq 400$ GeV; 1 top-tag, 1 Higgs-tag **Cut I:** $m(j_t\ell^+\ell^-)\in[1.0,2.0]$ TeV	Table 6
$(\gamma\gamma)+3j+X$	$p_T(j^k)\geq 400$ GeV, $k=1\ldots3$; $m_{\gamma\gamma}\in[115,135]$ GeV; $\exists i,k\in\{1,2,3\}:m(j_ij_k)\in[1.0,2.0]$ TeV	Table 7

Table 4. Summary of selection cuts used for each of the three channels analyzed in this section. See text for more details.

ML based multi-variables

We proposed 14 variables in this analysis: $m_{t'}$, HT, MET, n_{fj}, n_j, leading boosted jet PT PT_0, next leading boosted jet PT PT_1, n_b, PT_h, m_h, leading boosted jet light boosted jet probability P_j^0, P_t^0, P_j^1, P_t^1. We already have a lot of data so we do not



Single channel:

Sign determinations

RF: Random Forest methods

Simplified seven parameters: no much difference

Three channels

Process	Pre-cuts	RF I	RF II	σ	Sign σ
LH: $qhT \to (\gamma\gamma) + 2j + ...$	2.8×10^3	1540	744	42	4.5
hjj	1.2×10^4	550	1766		
tth	6.3×10^3	507	1273		
$\gamma\gamma jj$	4.8×10^4	344	2069		

Table 5. First three columns: Signal and background event numbers in the $\gamma\gamma + 2j + X$ channel in

Process	Pre-cuts	Cut I	RF I	RF II	σ	Sign σ
LH: $qhT \to qh_{bb}Z_{\ell\ell}t_q$	2234	1836	1232	366	52	4.2
$t_q t_q Z_{\ell\ell}$	1.4×10^4	5203	64	431		
$Z_{\ell\ell}jj$	5.6×10^4	1.9×10^4	211	1431		
MSCH: $qht'_3 \to qh_{bb}Z_{\ell\ell}t_q$	586	440	263/70, 86/429		23	3.8

Table 6. First four columns: Signal and background event numbers in the $(\ell\ell) + 2j + X$ channel

Three channels

Process	Pre-cuts	RF	σ	Sign σ
LH: $Tthh \to (\gamma\gamma) + jjj + ...$	148	126	14	2.4
$ttjh$	183	48		
$ttVh$	5.6	1.6		
MSCH: $t_2'thh \to (\gamma\gamma) + jjj + ...$	487	467/83	34	8.5

Table 7. First two columns: Signal and background event numbers in the $(\gamma\gamma) + 3j + X$ channel

LH: Yukawa 3% level

Sign significances are all good

MSCHM:

t_2', the best channel is $t_2'thh \to (\gamma\gamma) + 3j + X$, see Table 7;

t_3', the best channel is $qht_3' \to qhZt$, see Table 6.

top partner Yukawa is about 7% for both t_2' and t_3'.

Systematic errors may decrease those a few percent

Outlook

- There is a very nice model independent naturalness sum rule in mass eigenstate
- Can be tested in 100TeV, 30ab^-1 with signs in LH & MSCHM
- Can extend to SUSY and other cases

Backup slice

物理意义和预言

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

$$M_t(h) \sim \sin\left(\frac{2h}{f}\right)\left(1+\frac{1}{2}\sin^2(h/f)\left(\Pi^q_1(0)-\Pi^t_1(0)\right)\right)$$

通过测量mt, tth, tthh, etc可以确定 $\Pi^{q,t}_{0,1}$ 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)

$$M_Q + M_S = 0$$

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

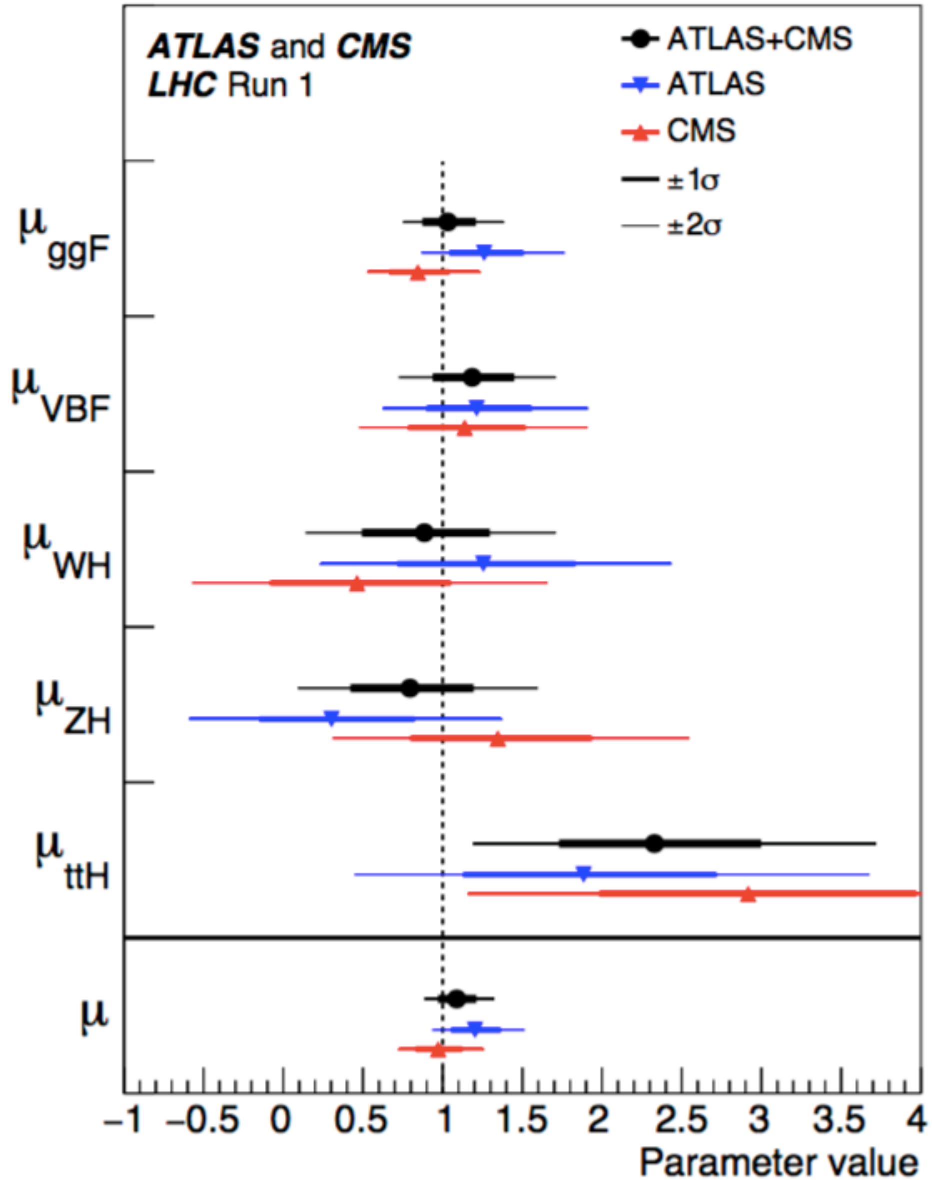
$\mathcal{O}_i \sim U \Psi_i$ Composite operators

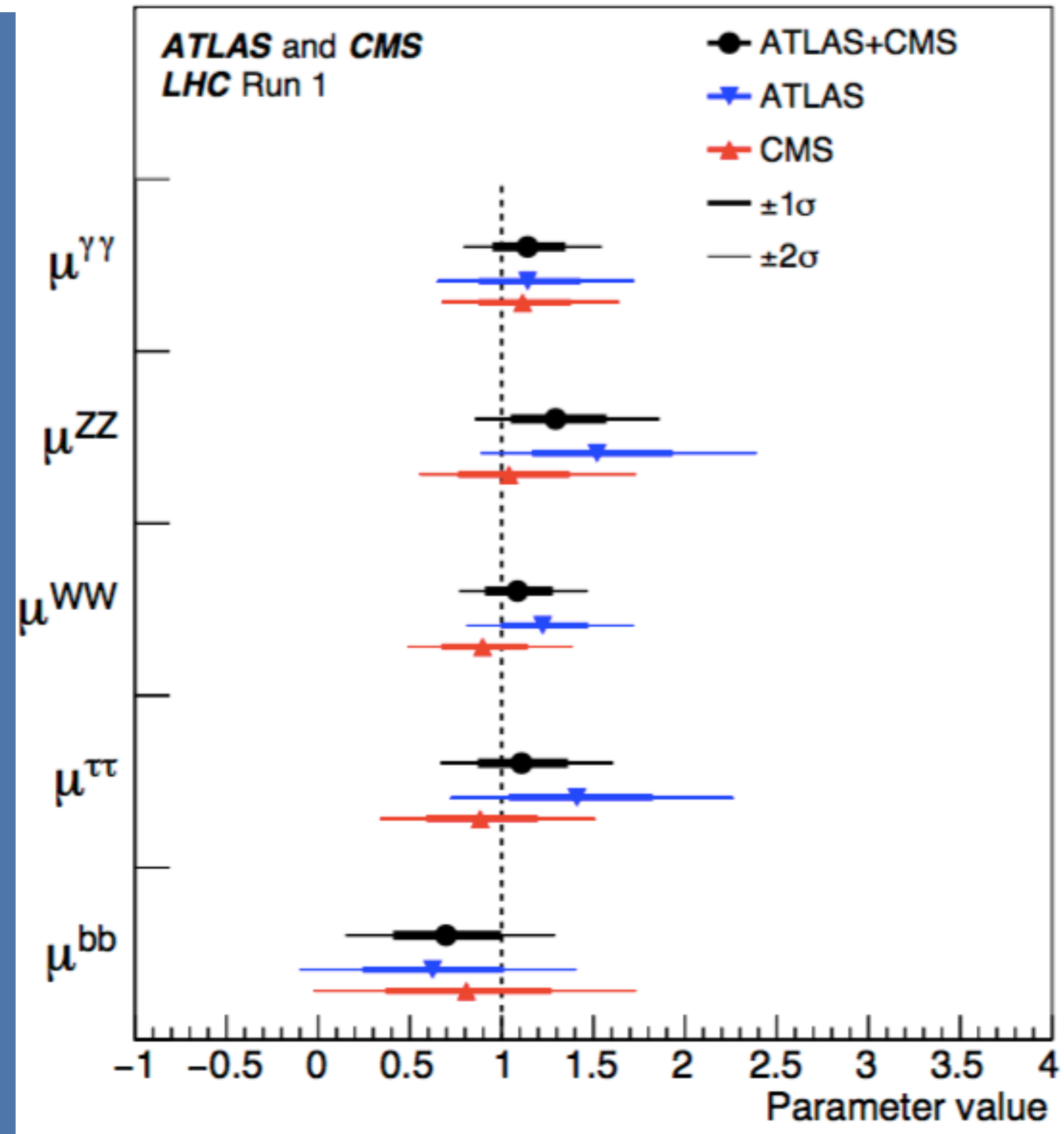
Ψ_i Composite fermions sit in the representation of SO(4)

Q_j bi-doublet S_i Singlet

Maximally suppressed the FCNC by the small fermion mass

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
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CMS
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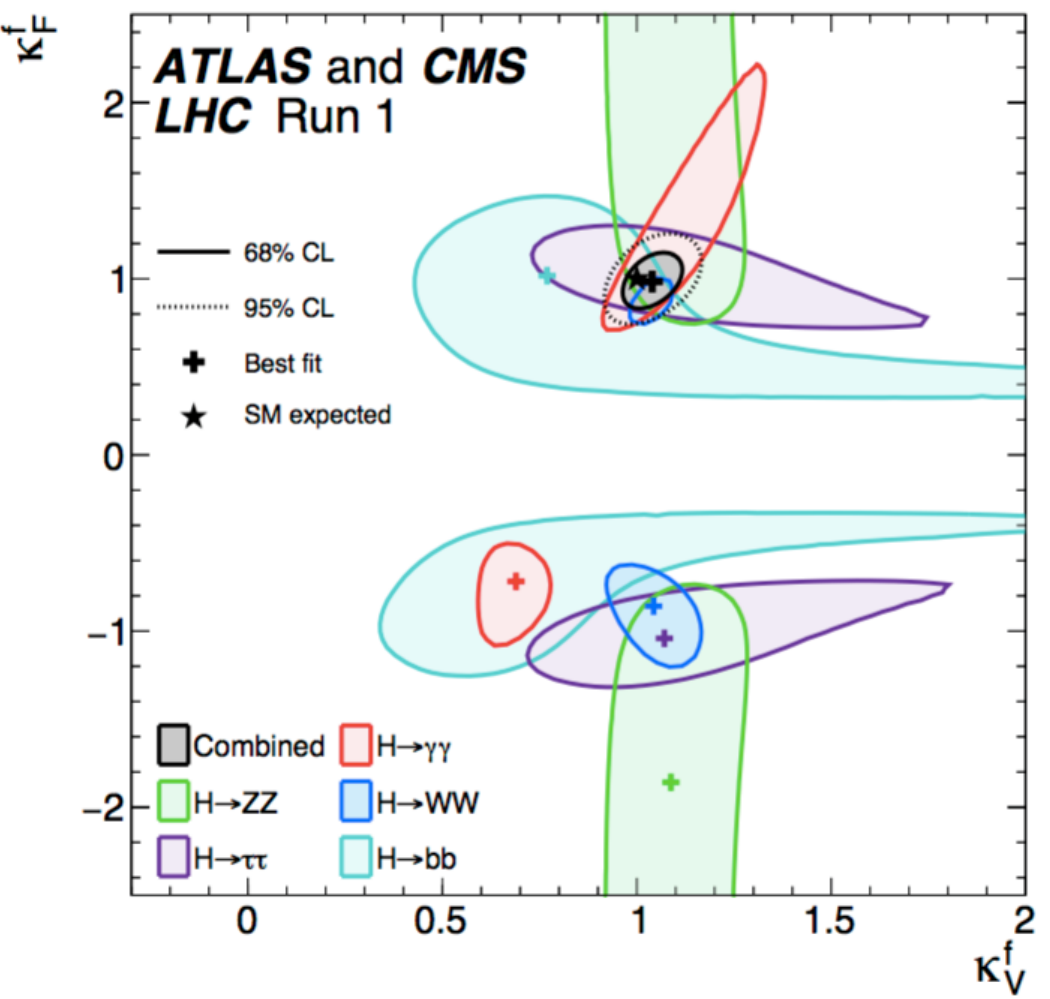
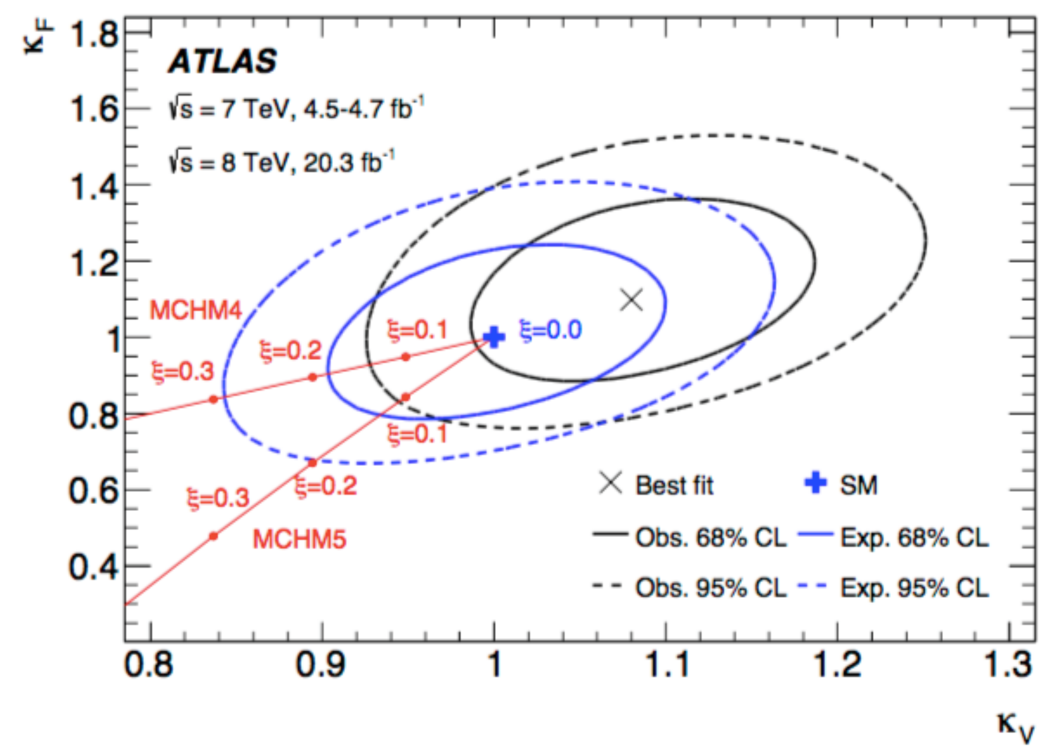
Parameter value

Higgs物理

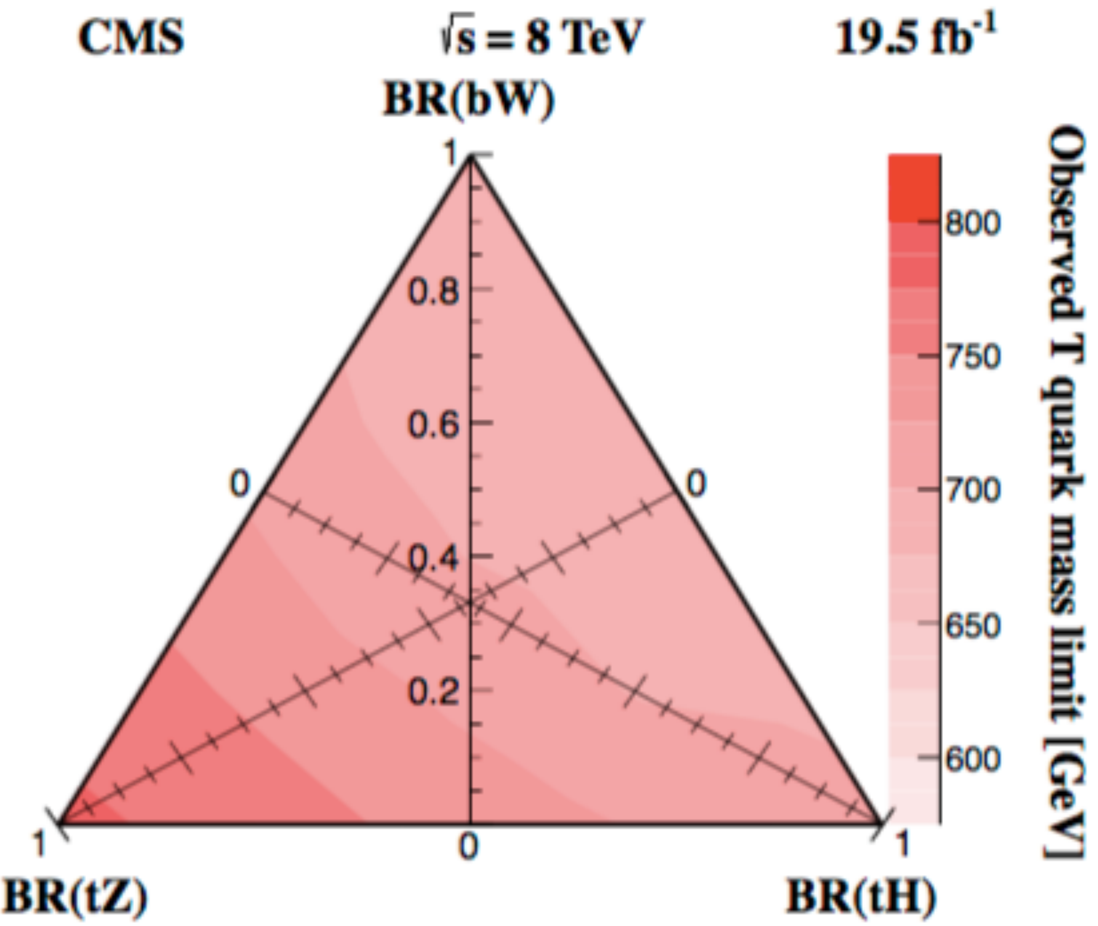


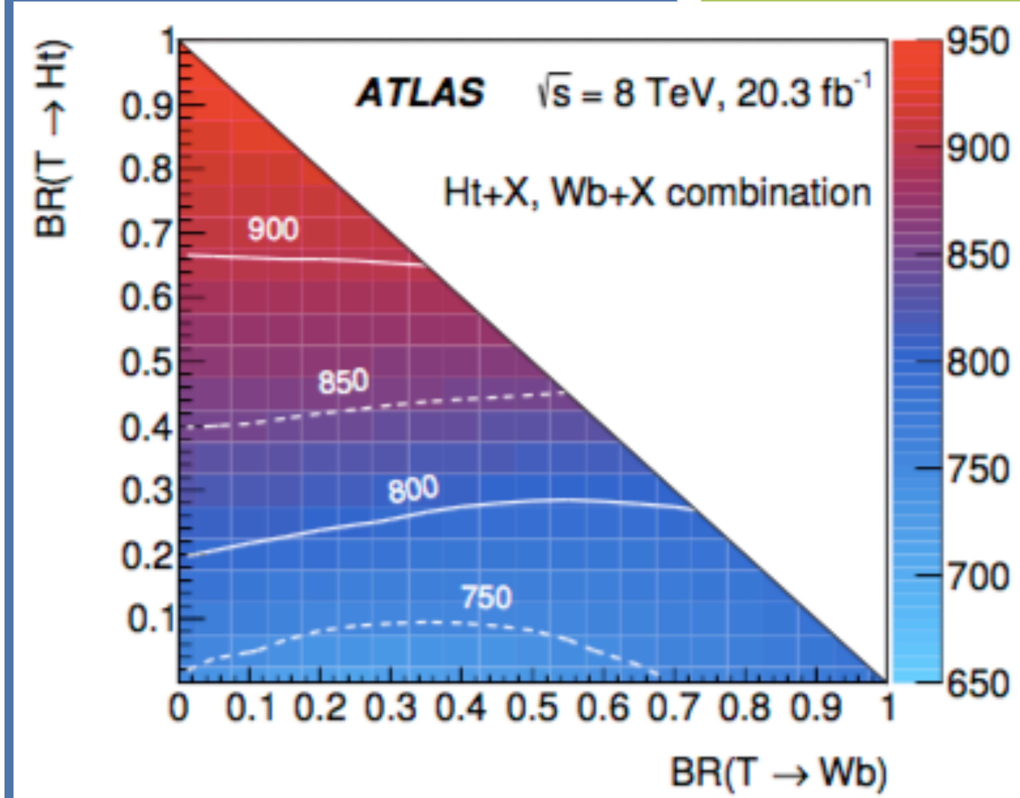


Top耦合为负的情况不再存在

Higgs 拟合 $\xi < 0.1$

Top 伴随子的寻找

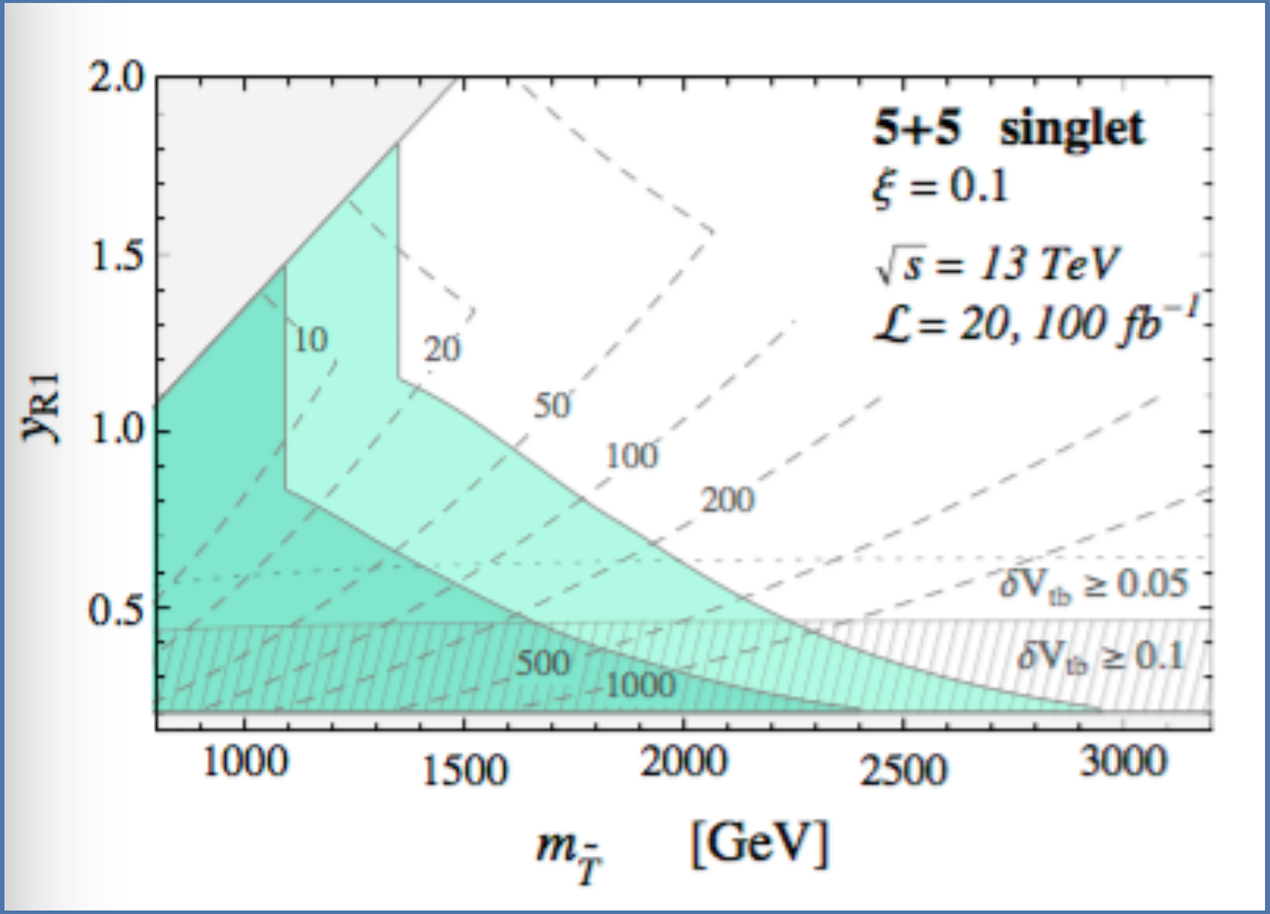




$$\mathrm{BR}(t' \to th) \approx \mathrm{BR}(t' \to tZ) \approx \mathrm{BR}(t' \to bW)/2 \approx 0.25$$

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

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

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit			Reference
Extra dimensions	ADO $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	M_D	6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	M_S	4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	M_{th}	5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	M_{th}	8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th}	8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th}	9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \rightarrow \ell\ell$	2 e, μ	–	–	20.3	G_{KK} mass	2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	–	–	3.2	G_{KK} mass	3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$	1 e, μ	1 J	Yes	13.2	G_{KK} mass	1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \rightarrow HH \rightarrow bbbb$	–	4 b	–	13.3	G_{KK} mass	360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \rightarrow tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	g_{KK} mass	2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	KK mass	1.46 TeV	Tier (1,1), BR($A^{(1,1)} \rightarrow tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	–	–	13.3	Z' mass	4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \rightarrow \tau\tau$	2 τ	–	–	19.5	Z' mass	2.02 TeV		1502.07177
	Leptophobic $Z' \rightarrow bb$	–	2 b	–	3.2	Z' mass	1.5 TeV		1603.08791
	SSM $W' \rightarrow \ell\nu$	1 e, μ	–	Yes	13.3	W' mass	4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	W' mass	2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \rightarrow WZ \rightarrow qqqq$ model B	–	2 J	–	15.5	W' mass	3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel			3.2	V' mass	2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \rightarrow tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass	1.92 TeV		1410.4103
	LRSM $W'_R \rightarrow tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass	1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	Λ	19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	Λ	25.2 TeV	$\eta_{LL} = -1$	1607.03669
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	Λ	4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	m_A	1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	m_A	710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ_{\chi\chi}$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_*	550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass	1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass	1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥1 b, ≥3 j	Yes	20.3	LQ mass	640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \rightarrow Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	T mass	855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \rightarrow Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	Y mass	770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \rightarrow Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass	735 GeV	isospin singlet	1505.04306
	VLQ $BB \rightarrow Zb + X$	2/≥3 e, μ	≥2/≥1 b	–	20.3	B mass	755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \rightarrow WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass	690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \rightarrow WtWt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	3.2	$T_{5/3}$ mass	990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 j	–	3.2	q* mass	4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \rightarrow qg$	–	2 j	–	15.7	q* mass	5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \rightarrow bg$	–	1 b, 1 j	–	8.8	b* mass	2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \rightarrow Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b* mass	1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass	3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass	1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \rightarrow W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	a_T mass	960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass	2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \rightarrow ee$	2 e (SS)	–	–	13.9	$H^{\pm\pm}$ mass	570 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass	400 GeV	DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass	657 GeV	$a_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass	785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass	1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

$\sqrt{s} = 8$ TeV | $\sqrt{s} = 13$ TeV

Mass scale [TeV] (10^{-1}, 1, 10)

*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 tt̄H signal strength measurements (left) and upper limits (right).