Test Naturalness sum rule (maximal symmetry)?

Jing Shu

ITP-CAS

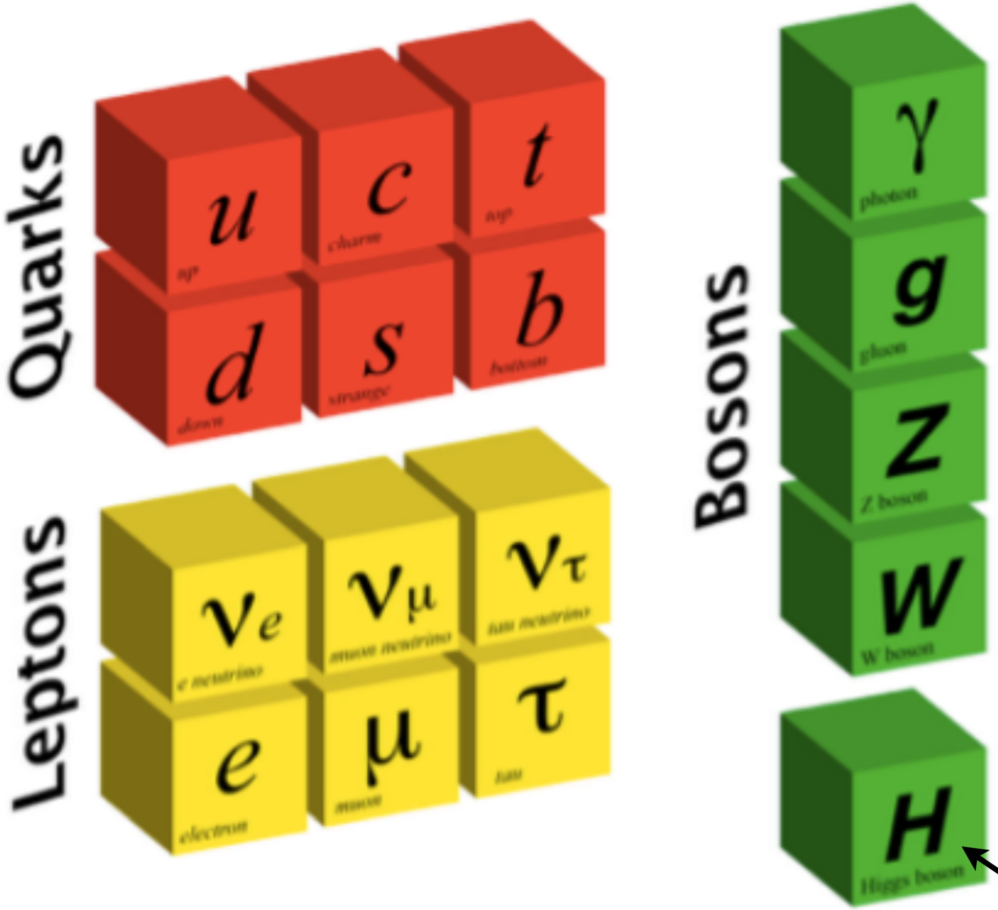
C. Csaki, F. Ferreira De Freitas, L. Huang, T. Ma, M. Perelstein, J. Shu., arxiv: 1811.01961

简介

- 电弱对称性破缺? 自然性问题?
- Non-SUSY情况的自然性sum rule (可以推广到SUSY)。
- 如何在未来对撞机上探测相关的问题。
- 展望

Naturalness

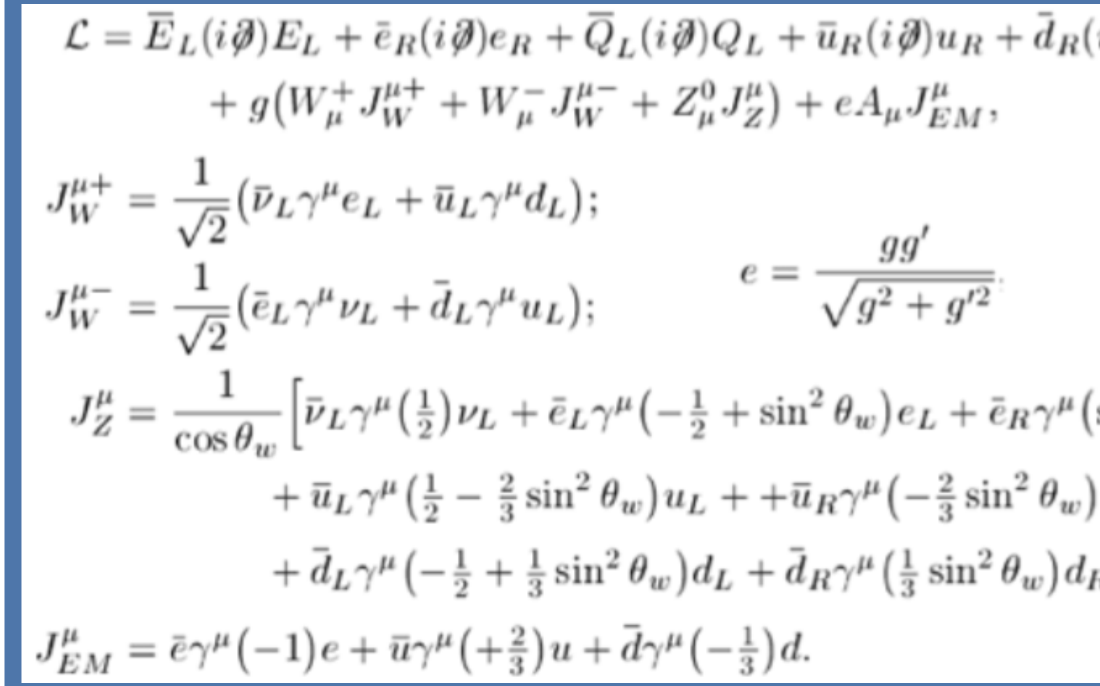
我们已知的“旧”物理



基本粒子图谱

The chosen one!

The Weinberg-Salam Model



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

$$+ g(W_\mu^+ J_W^{\mu+} + W_\mu^- J_W^{\mu-} + Z_\mu^0 J_Z^\mu) + eA_\mu J_{EM}^\mu,$$

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

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

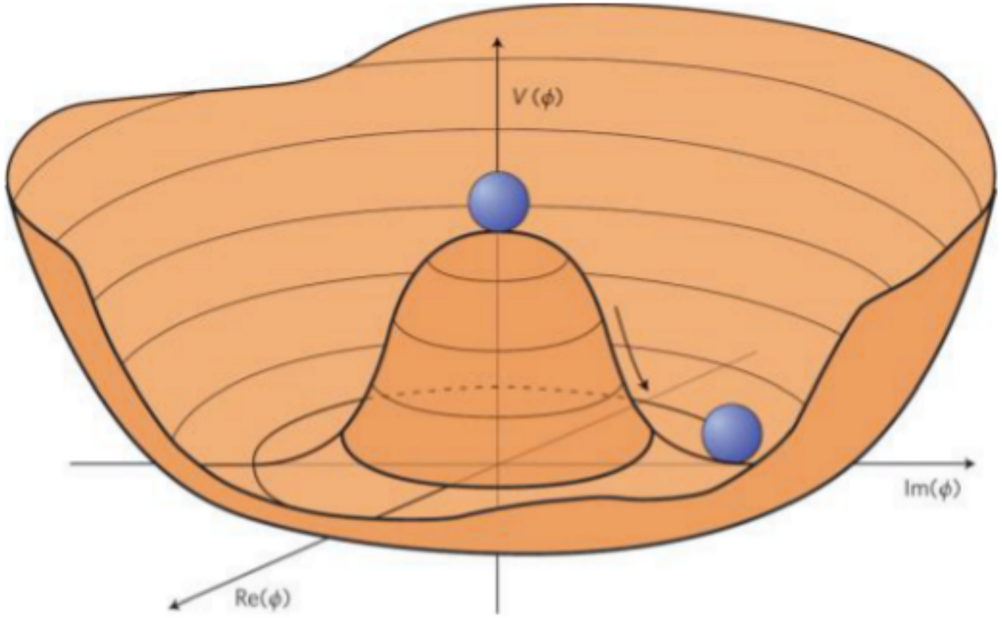
$$J_Z^\mu = \frac{1}{\cos\theta_w}\Big[\bar{\nu}_L\gamma^\mu(\tfrac{1}{2})\nu_L + \bar{e}_L\gamma^\mu(-\tfrac{1}{2}+\sin^2\theta_w)e_L + \bar{e}_R\gamma^\mu($$

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

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

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

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）

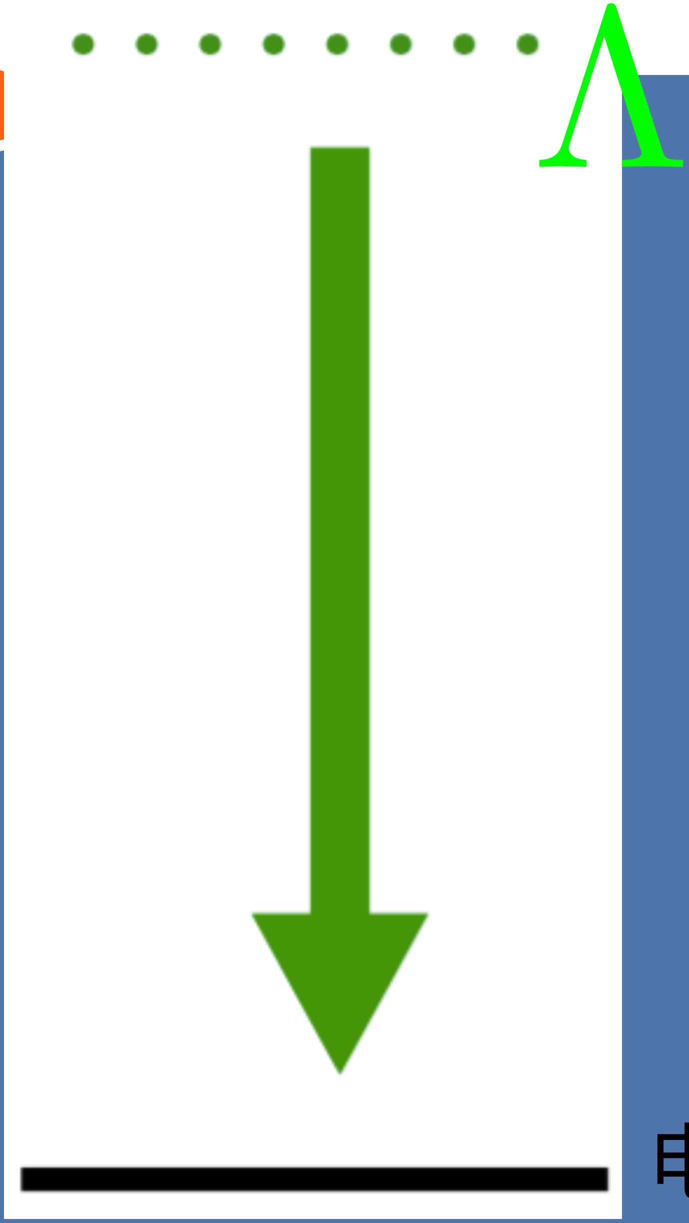
规范对称性自发破缺

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

发现Higgs让我们对质量起源了解更多

Higgs机制给予所有基本粒子质量

为什么这是一个问题?



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

- 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

我们先看看具体情况：

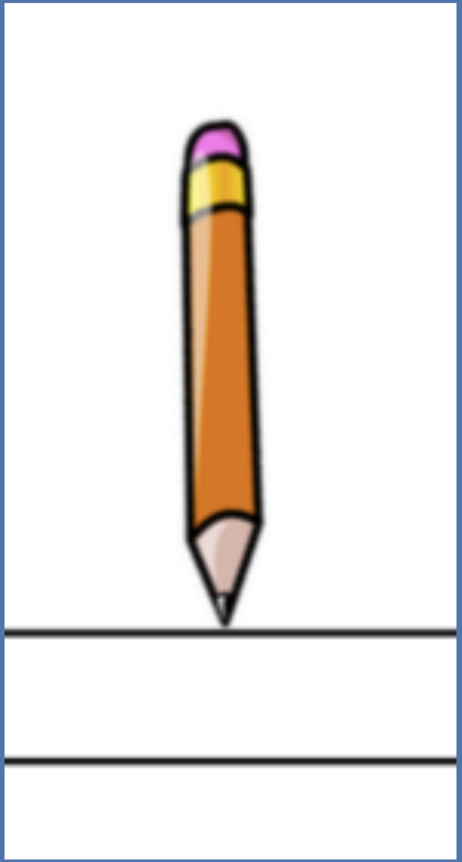
$$m_{phys}^2 = m_0^2 + c\Lambda^2 + \ldots$$

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）

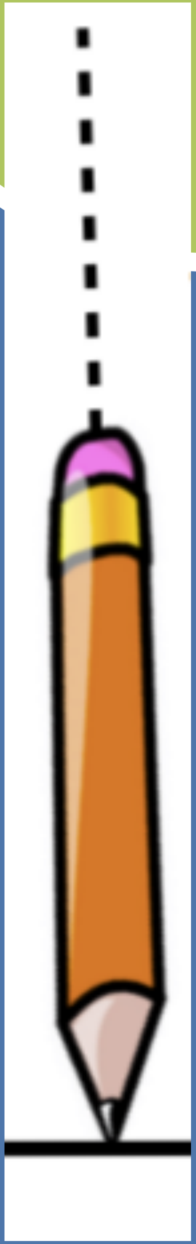
事实上对称性能够保证（Higgs势能）
对于量子辐射修正的稳定性

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

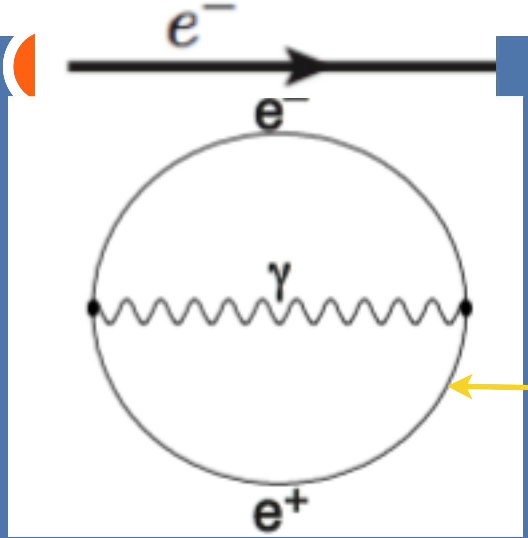
$$\delta m_e = \int_{r=\Lambda^{-1}} d^3r\,\vec{E}^2 \simeq \alpha\Lambda$$

$$(m_ec^2)_{obs} = (m_ec^2)_{bare} + \Delta E_{\mathrm{Coulomb}}.$$

电子质量项
线性发散



电子质量的启示

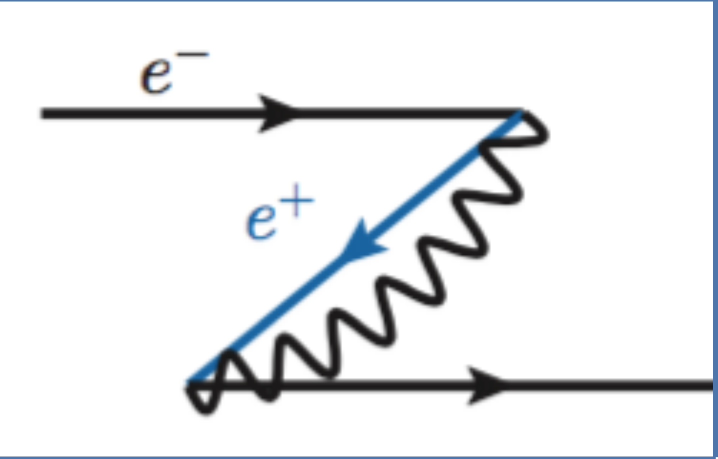


$$\Delta E_{\text{pair}} = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_e}.$$

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

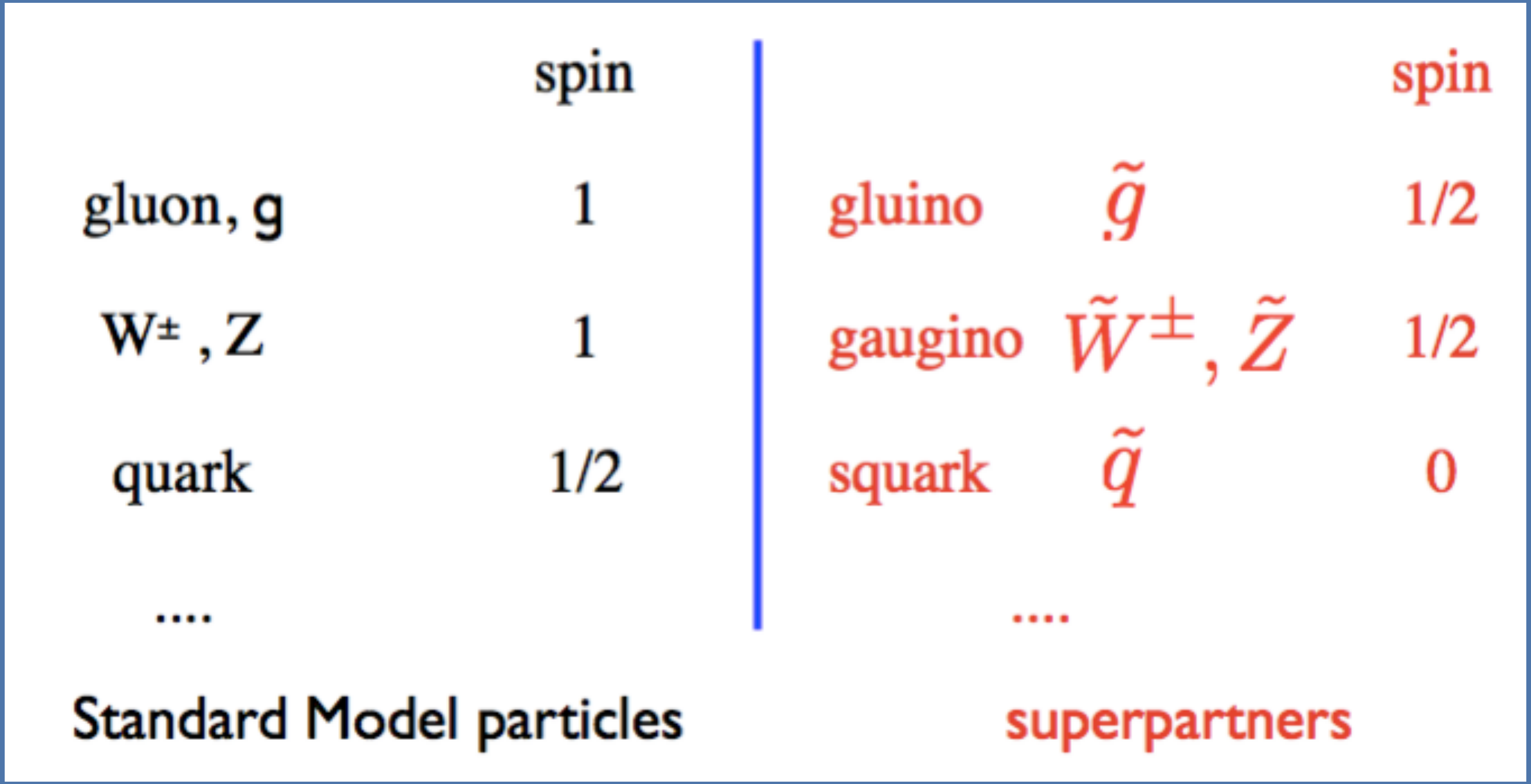
Chiral symmetry

Lambda取Plank质量，修正项只有10%

有关Higgs的对称性

手证对称性：　　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		

有关Higgs的对称性

Non-SUSY的情况

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

Test Naturalness问题

以前关于naturalness的test

主要是Little Higgs里面的t’ search

这些都是在gauge basis下的test，实际check
需要涉及的复杂的质量矩阵的测量

我们需要在mass basis下的test

Higgs as a pNGB

Fermion sum rule

Top sector质量矩阵

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

1-loop CW 势能

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

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

没有二次发散项的条件

$$H = v + h.$$

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

No quadratic divergence

不考虑1/f^2项高阶贡献

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

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守恒

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

No log divergence

Log divergence

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

不考虑1/f^2项高阶贡献

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

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

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

CP守恒

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

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

Gauge/gaugino/Higgs/Higgsino sector

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

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

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

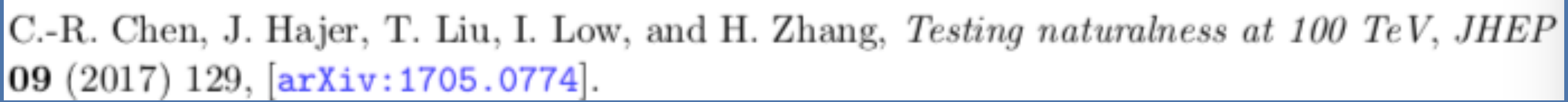
$$Y = (\frac{\partial}{\partial H} M_F)|_{H=v} = \begin{pmatrix} 0 & -\frac{\epsilon_q \sin\left(\frac{v}{f}\right)}{2f} & \frac{\epsilon_q \sin\left(\frac{v}{f}\right)}{2f} & -\frac{\epsilon_q \cos\left(\frac{v}{f}\right)}{\sqrt{2}} \\ \frac{\epsilon_t \cos\left(\frac{v}{f}\right)}{2f} & 0 & 0 & 0 \\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

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

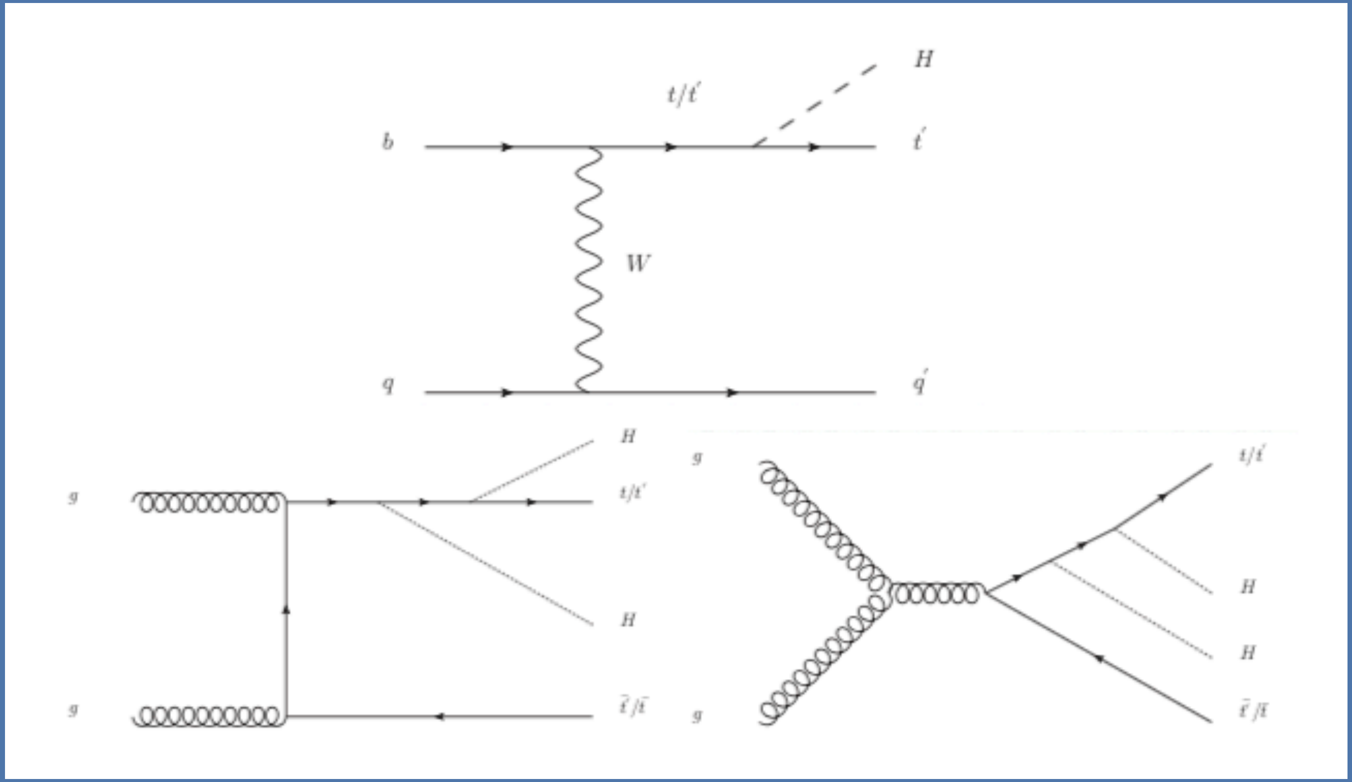
$$\mathrm{Tr}[Y_D . M_D^3] = \mathrm{Tr}[Y.(M_F^\dagger . M_F . M_F^\dagger)|_{H=v}] = 0$$

Collider Test

Double production： No sign of the couplings $pp \to t't'h,$



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



$pp \to qht'.$

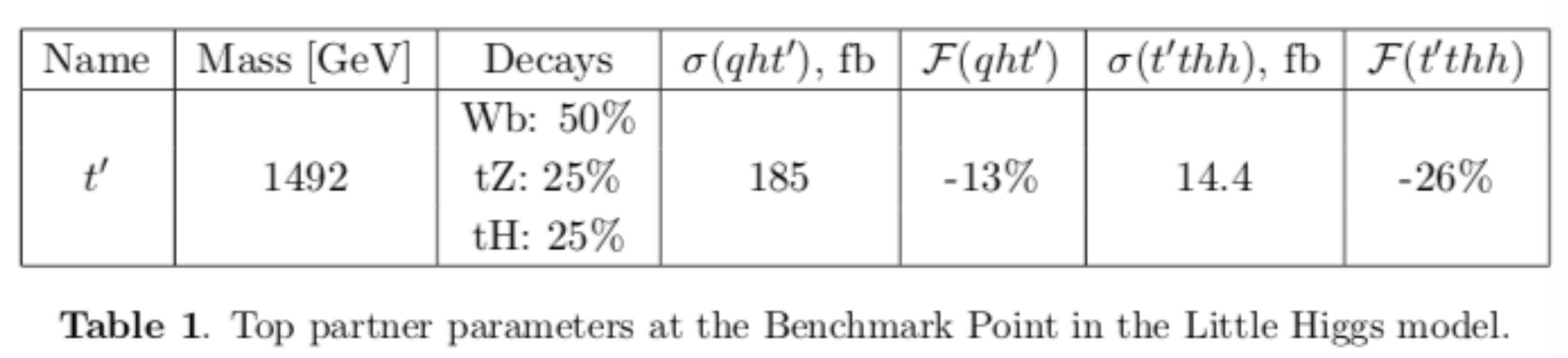
single production: interference

Benchmark-LH

Definition of flipped rate

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

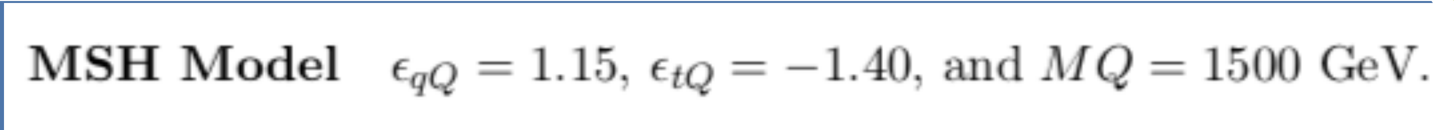
LH Model $\lambda_1 = 1.48$, $\lambda_2 = 1.11$ and $f = 811$ GeV.



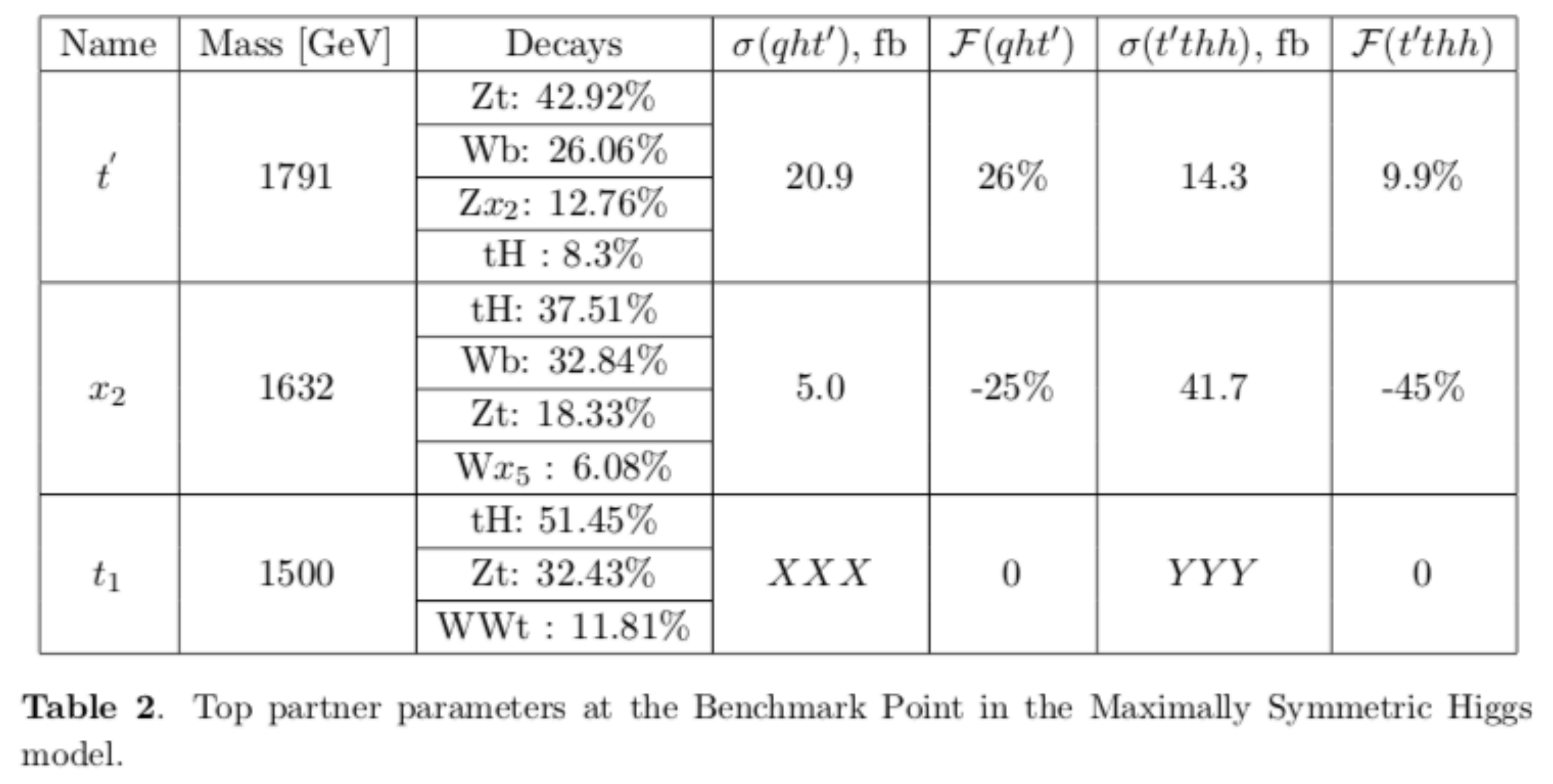
Name	Mass [GeV]	Decays	$\sigma(qht')$, fb	$\mathcal{F}(qht')$	$\sigma(t'thh)$, fb	$\mathcal{F}(t'thh)$
t'	1492	Wb: 50% tZ: 25% tH: 25%	185	-13%	14.4	-26%

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

Benchmark-MSCH



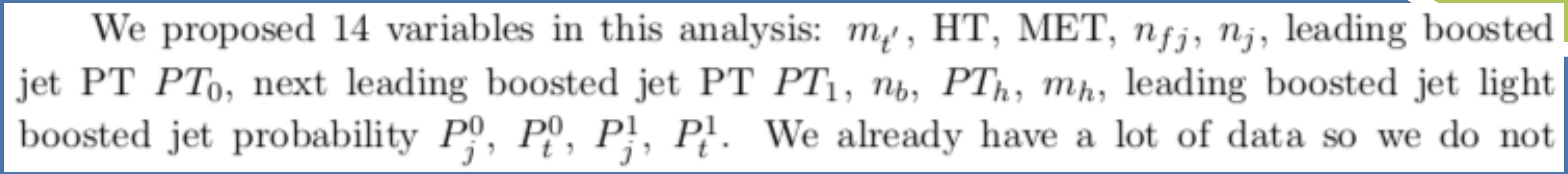
MSH Model $\epsilon_{qQ} = 1.15$, $\epsilon_{tQ} = -1.40$, and $MQ = 1500$ GeV.



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

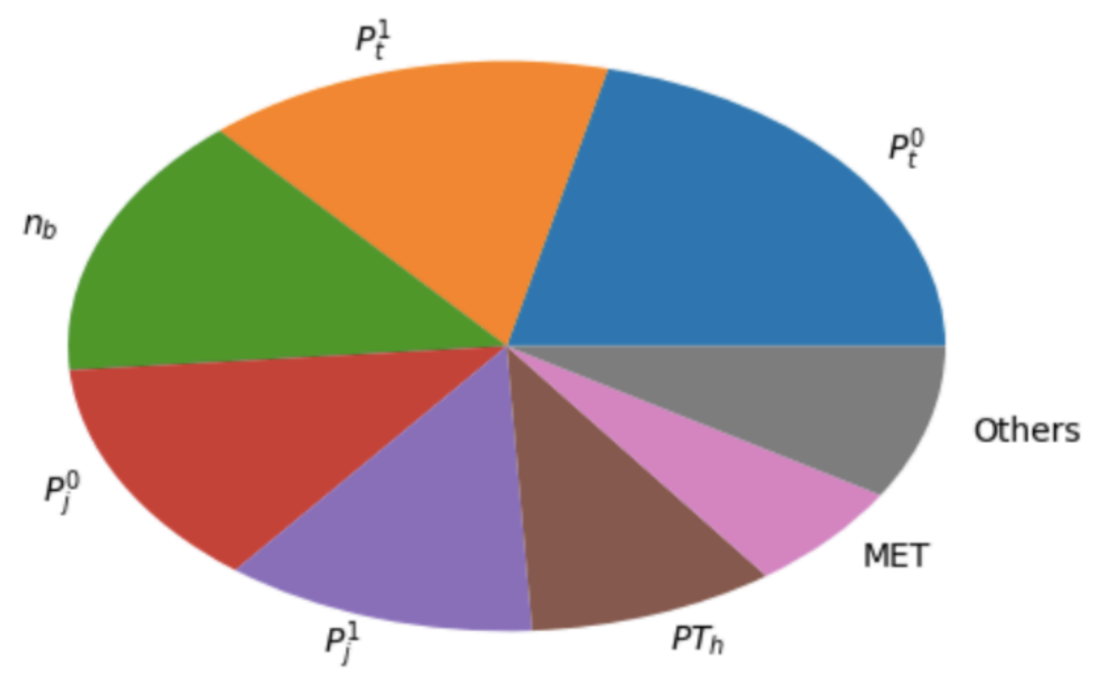
Table 2. Top partner parameters at the Benchmark Point in the Maximally Symmetric Higgs model.

Three channels

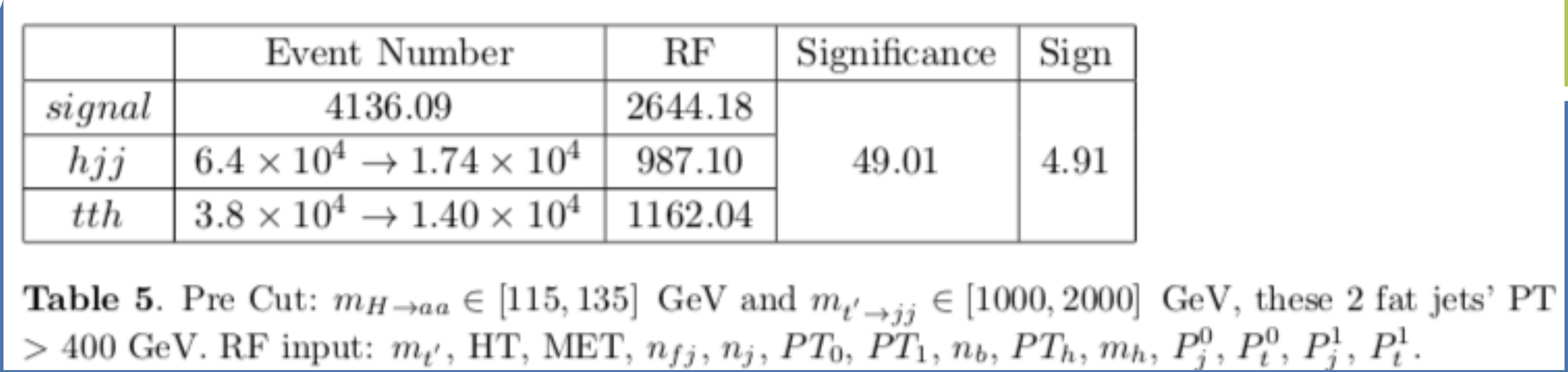


We proposed 14 variables in this analysis: $m_{t'}$, HT, MET, n_{fj}, n_j, leading boosted jet PT PT_0, next leading boosted jet PT PT_1, n_b, PT_h, m_h, leading boosted jet light boosted jet probability P_j^0, P_t^0, P_j^1, P_t^1. We already have a lot of data so we do not

RF: Random Forest methods

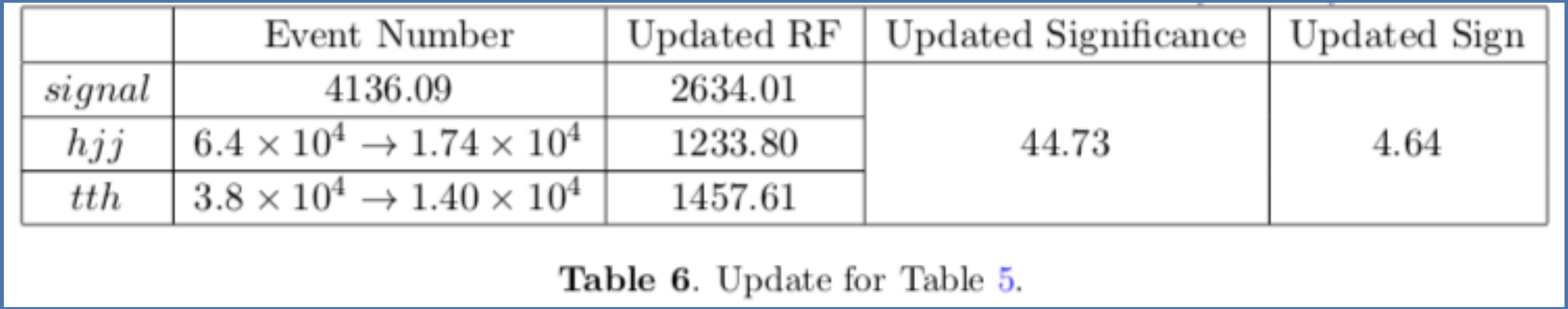


Three channels



	Event Number	RF	Significance	Sign
signal	4136.09	2644.18	49.01	4.91
hjj	$6.4 \times 10^4 \rightarrow 1.74 \times 10^4$	987.10		
tth	$3.8 \times 10^4 \rightarrow 1.40 \times 10^4$	1162.04		

Table 5. Pre Cut: $m_{H\rightarrow aa} \in [115, 135]$ GeV and $m_{t'\rightarrow jj} \in [1000, 2000]$ GeV, these 2 fat jets' PT > 400 GeV. RF input: $m_{t'}$, HT, MET, n_{fj}, n_j, PT_0, PT_1, n_b, PT_h, m_h, P_j^0, P_t^0, P_j^1, P_t^1.

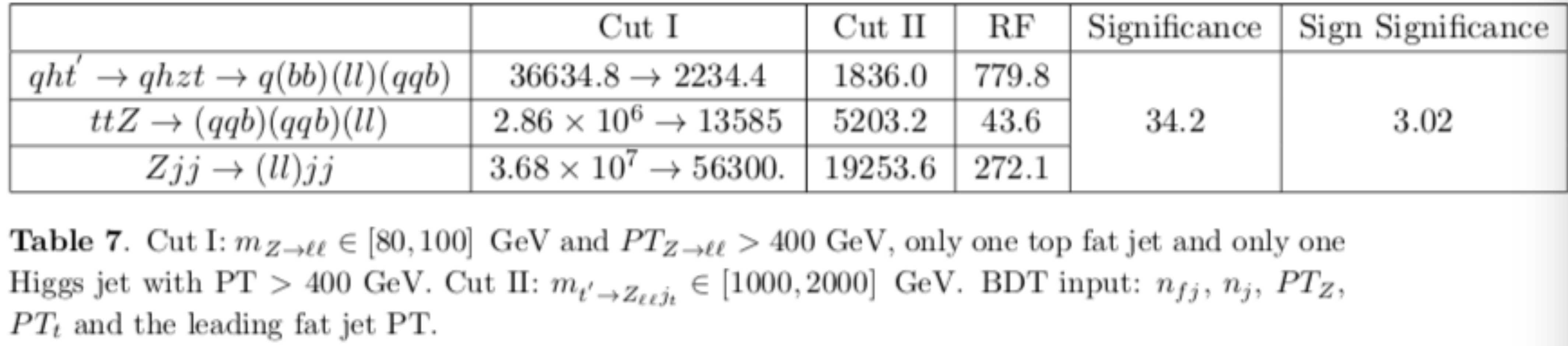


	Event Number	Updated RF	Updated Significance	Updated Sign
signal	4136.09	2634.01	44.73	4.64
hjj	$6.4 \times 10^4 \rightarrow 1.74 \times 10^4$	1233.80		
tth	$3.8 \times 10^4 \rightarrow 1.40 \times 10^4$	1457.61		

Table 6. Update for Table 5.

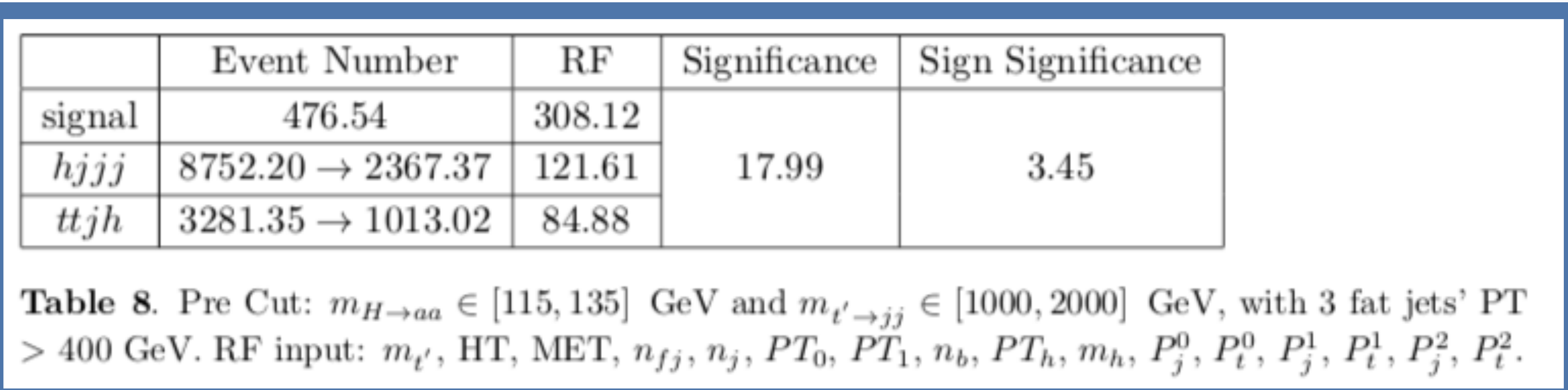
简化版的七个参数变化不大

Three channels



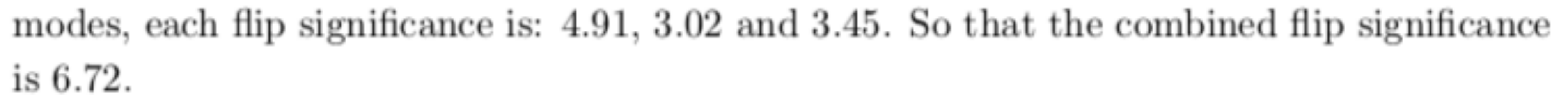
	Cut I	Cut II	RF	Significance	Sign Significance
$qht' \to qhzt \to q(bb)(ll)(qqb)$	$36634.8 \to 2234.4$	1836.0	779.8	34.2	3.02
$ttZ \to (qqb)(qqb)(ll)$	$2.86 \times 10^6 \to 13585$	5203.2	43.6		
$Zjj \to (ll)jj$	$3.68 \times 10^7 \to 56300.$	19253.6	272.1		

Table 7. Cut I: $m_{Z\to\ell\ell} \in [80,100]$ GeV and $PT_{Z\to\ell\ell} > 400$ GeV, only one top fat jet and only one Higgs jet with PT > 400 GeV. Cut II: $m_{t'\to Z_{\ell\ell}j_t} \in [1000,2000]$ GeV. BDT input: n_{fj}, n_j, PT_Z, PT_t and the leading fat jet PT.



	Event Number	RF	Significance	Sign Significance
signal	476.54	308.12	17.99	3.45
$hjjj$	$8752.20 \to 2367.37$	121.61		
$ttjh$	$3281.35 \to 1013.02$	84.88		

Table 8. Pre Cut: $m_{H\to aa} \in [115,135]$ GeV and $m_{t'\to jj} \in [1000,2000]$ GeV, with 3 fat jets' PT > 400 GeV. RF input: $m_{t'}$, HT, MET, n_{fj}, n_j, PT_0, PT_1, n_b, PT_h, m_h, P_j^0, P_t^0, P_j^1, P_t^1, P_j^2, P_t^2.



modes, each flip significance is: 4.91, 3.02 and 3.45. So that the combined flip significance is 6.72.

总结展望

- 100TeV，3000fb^-1可以测量并确定符号
- 方法推广到SUSY-stop里面的测量

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

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

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)　$M_Q + M_S = 0$

Backup
slice

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

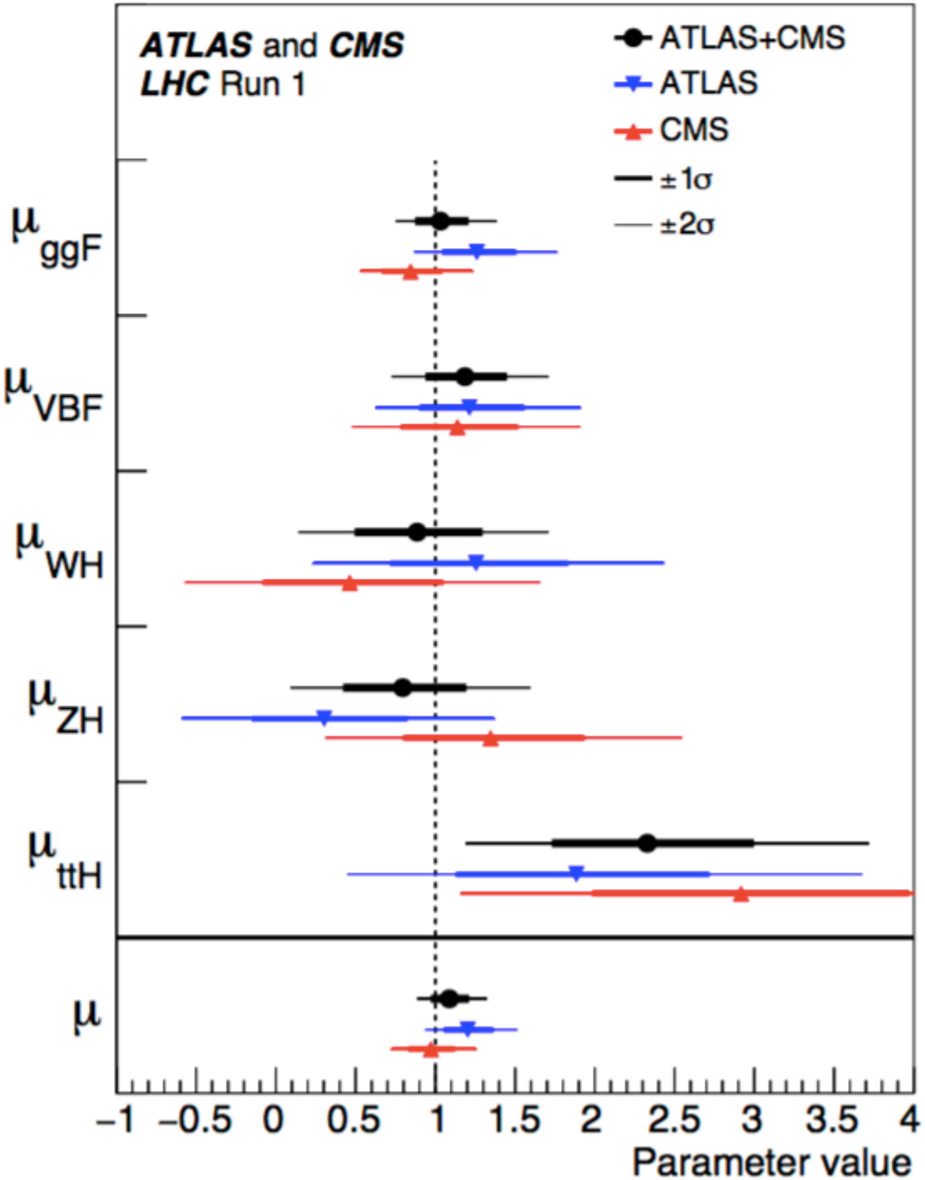
$\mathcal{O}_i \sim U \Psi_i$ Composite operators

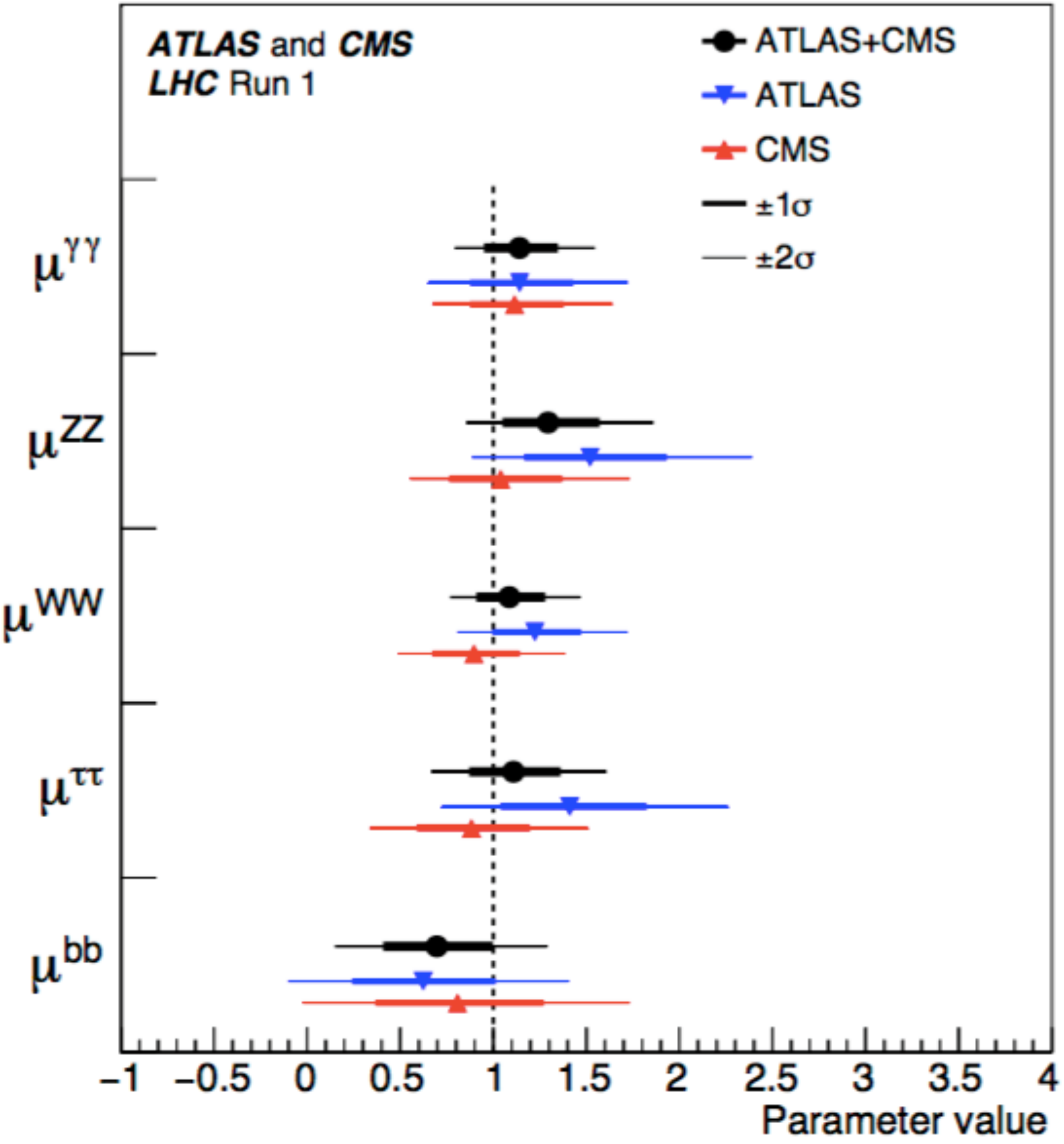
Ψ_i Composite fermions sit in the representation of SO(4)

Maximally suppressed the FCNC by the small fermion mass

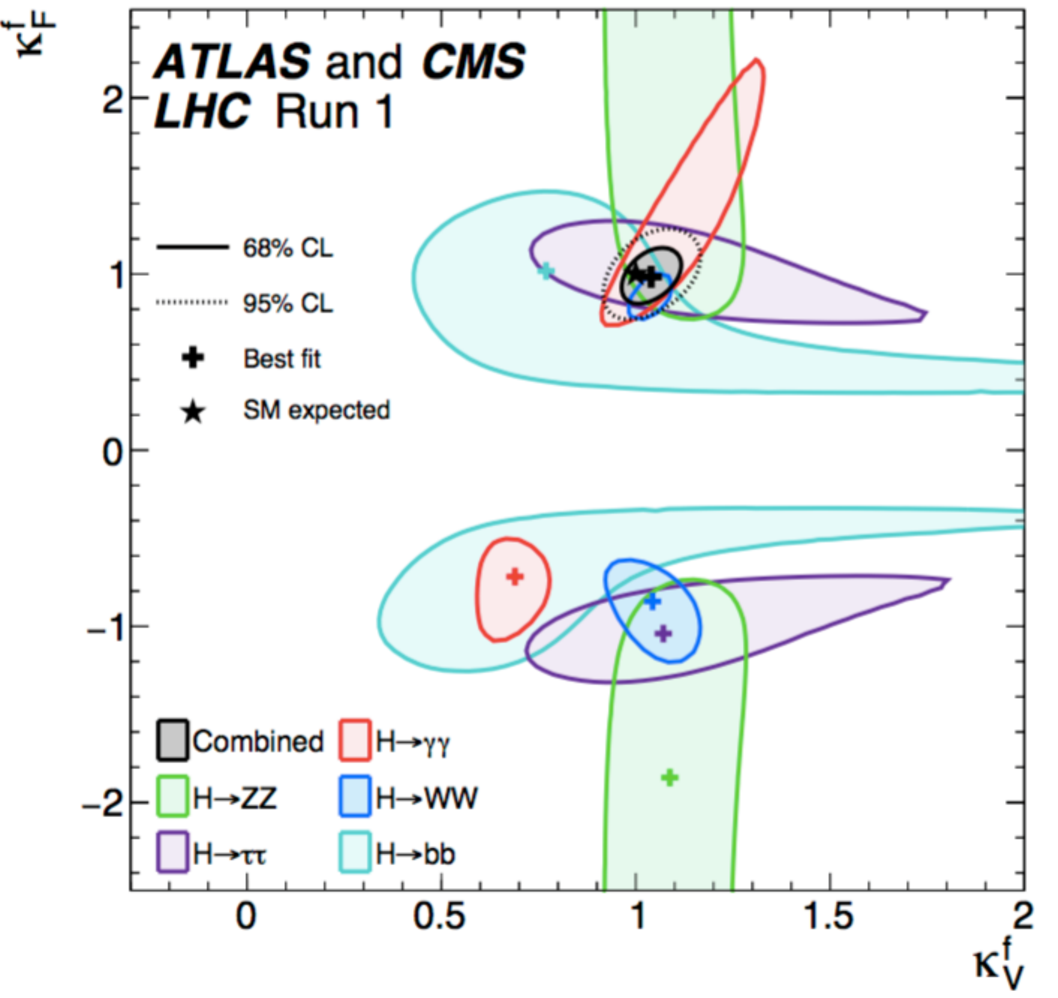
Q_j bi-doublet S_i Singlet

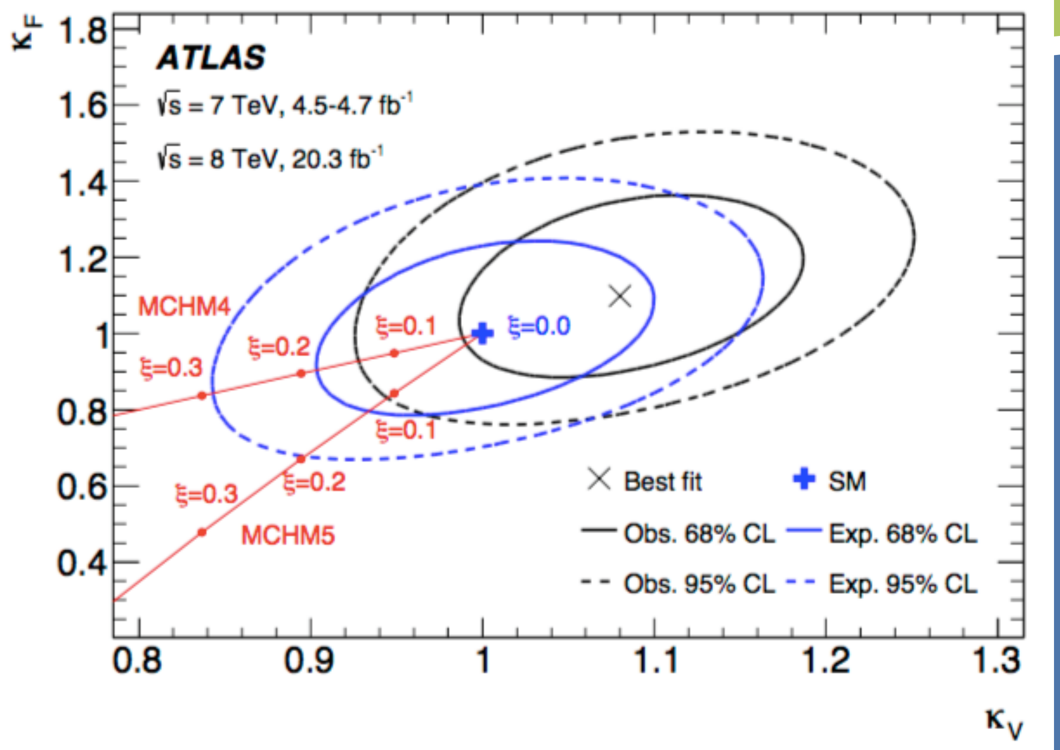
Higgs产生和衰变


ATLAS and CMS
LHC Run 1
ATLAS+CMS
ATLAS
CMS
±1σ
±2σ
μ_{ggF}
μ_{VBF}
μ_{WH}
μ_{ZH}
μ_{ttH}
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
$\mu^{\gamma\gamma}$
μ^{ZZ}
μ^{WW}
$\mu^{\tau\tau}$
μ^{bb}
−1 −0.5 0 0.5 1 1.5 2 2.5 3 3.5 4
Parameter value

Higgs物理

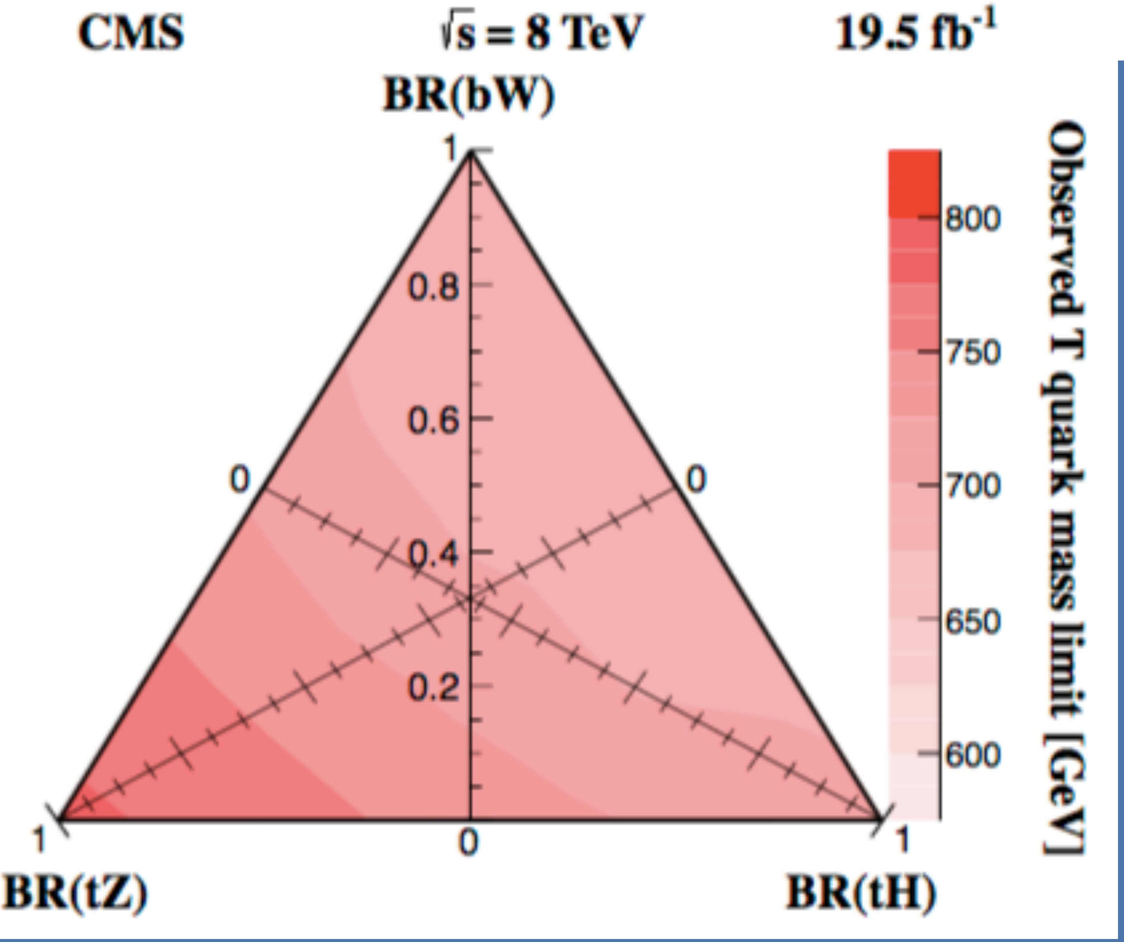


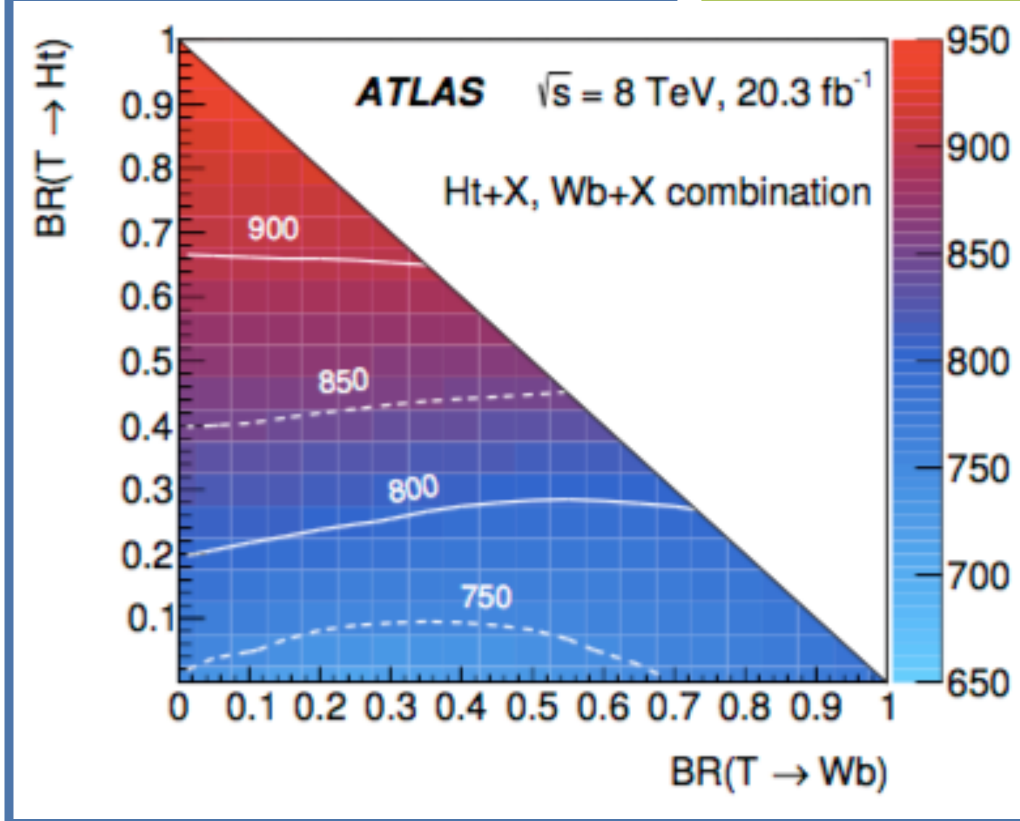


Top耦合为负的情况不再存在

Higgs 拟合 $\xi < 0.1$

Top 伴随子的寻找

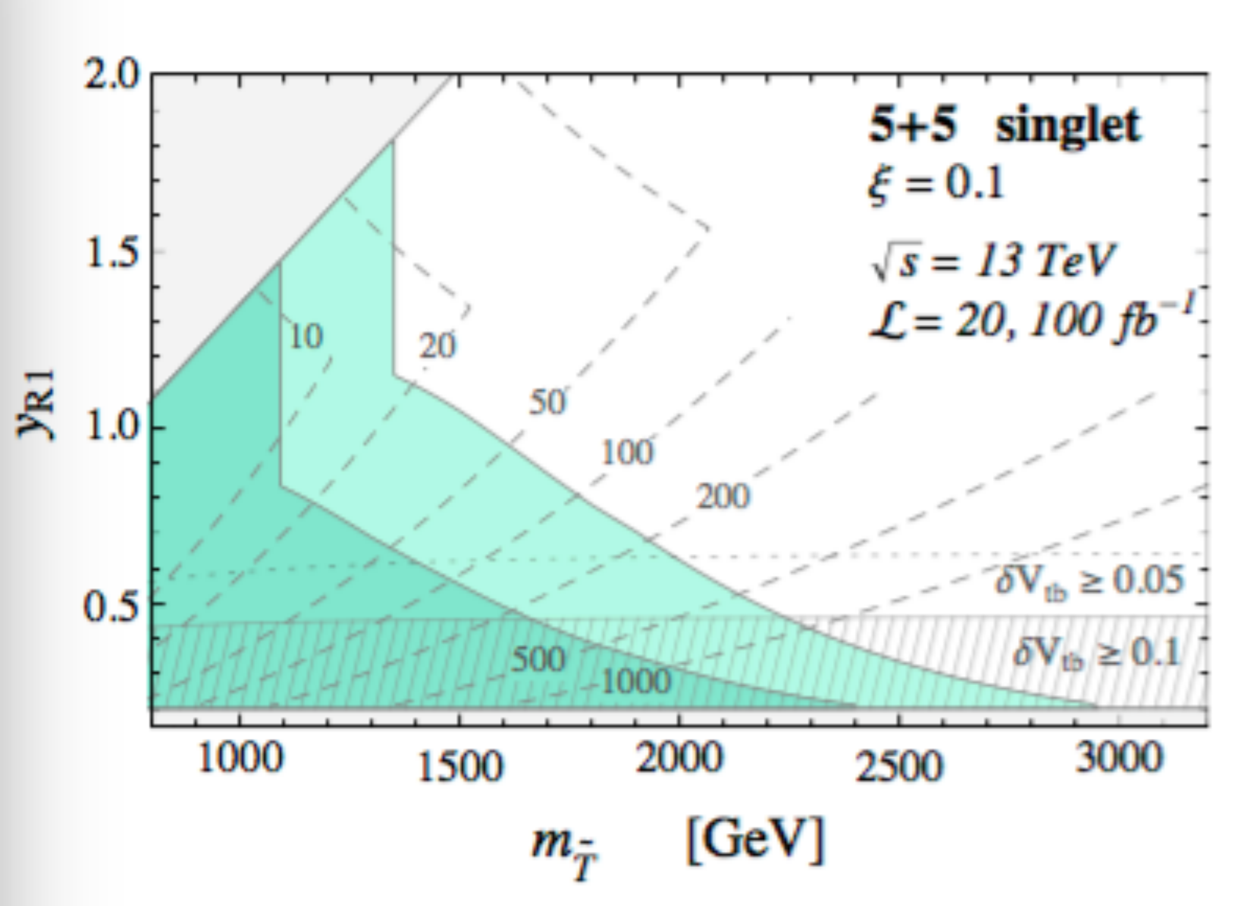




$\mathrm{BR}(t' \to th) \approx \mathrm{BR}(t' \to tZ) \approx \mathrm{BR}(t' \to bW)/2 \approx 0.25$

限制在700~900GeV

Top 伴随子的寻找



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

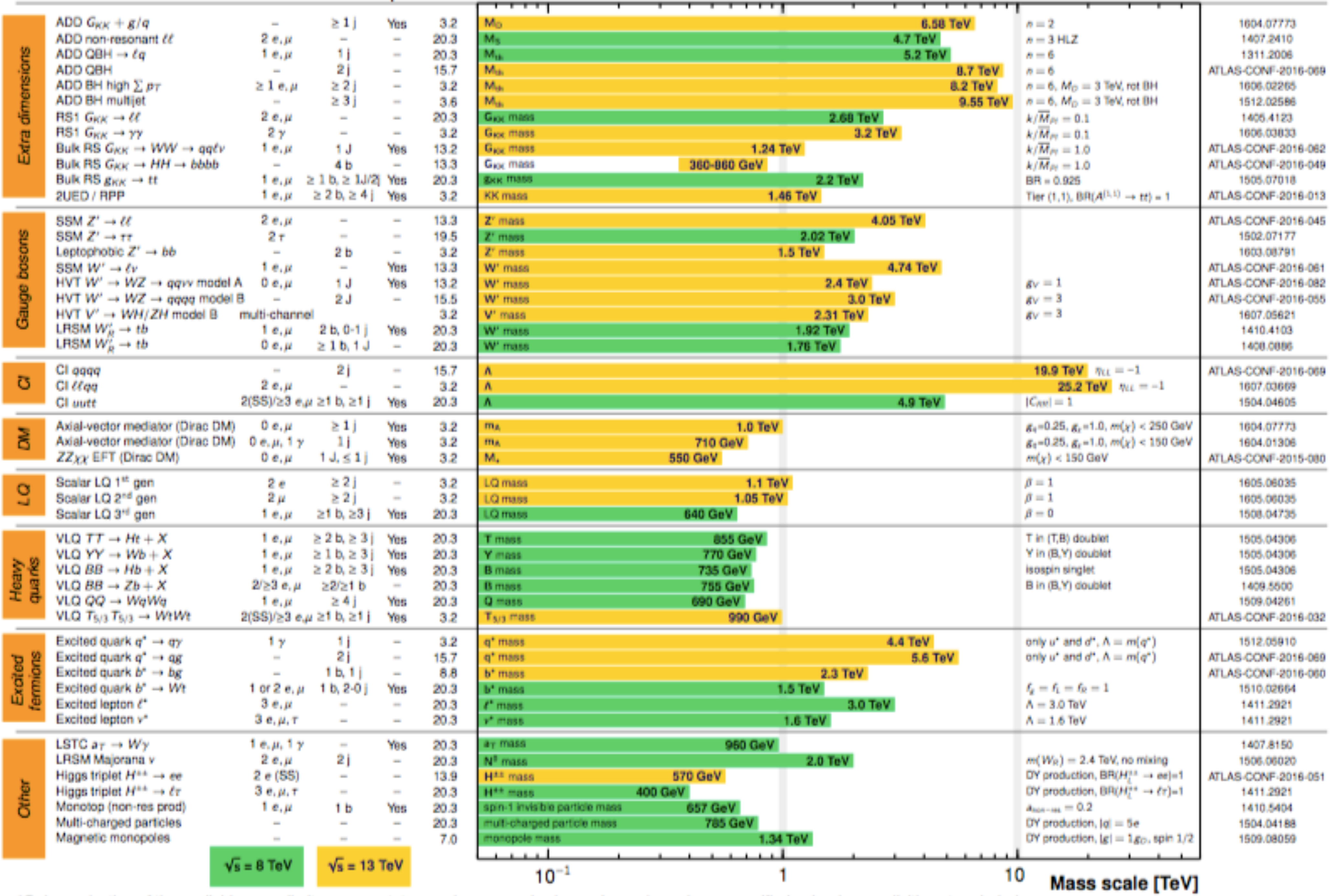
当前Top伴随子寻找正在检验原始的复合Higgs模型

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

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



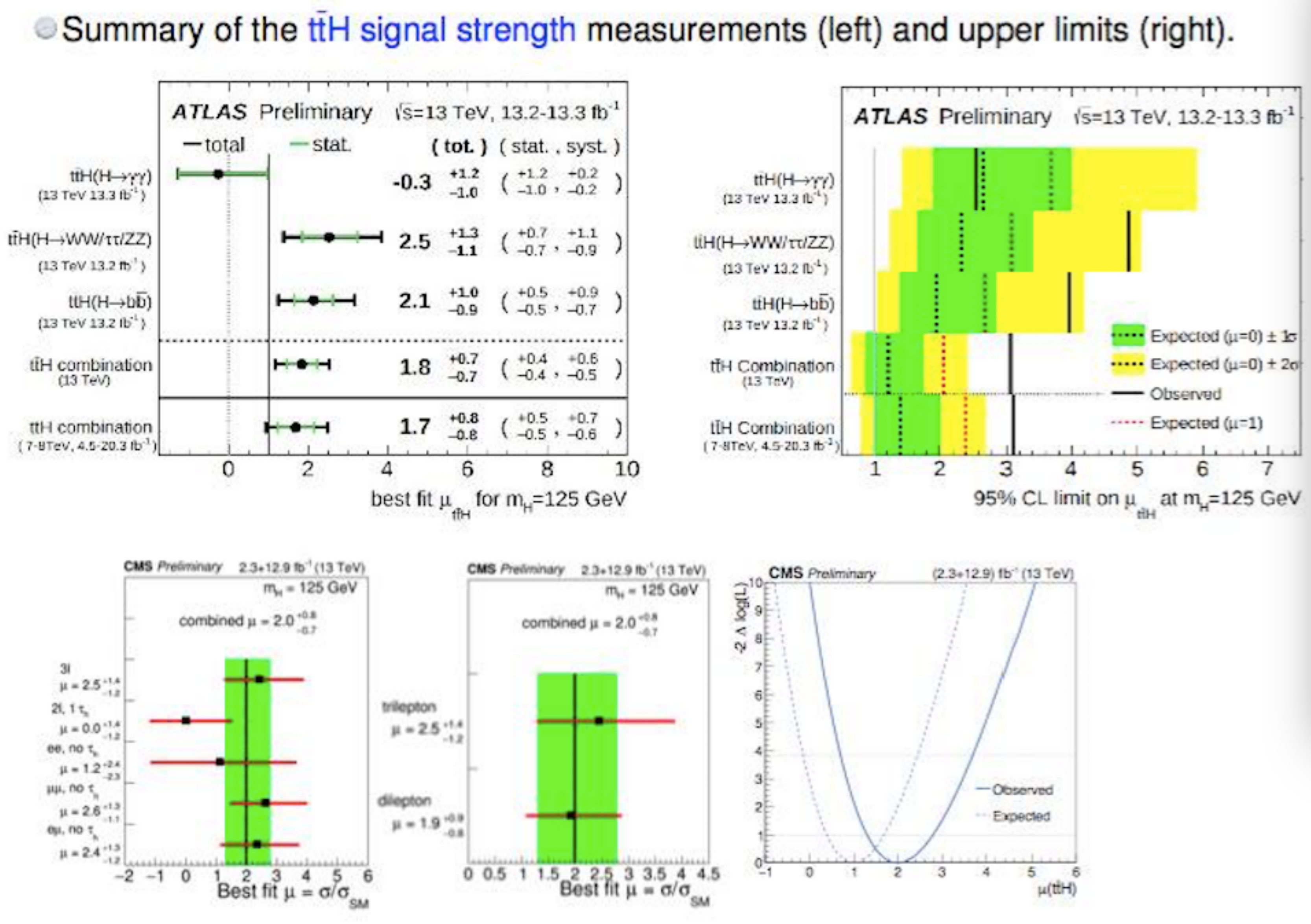
	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	🟩 M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\rightarrow \ell q$	1 e, μ	1 j	–	20.3	🟩 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

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

ttbar Higgs



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