Physics Beyond the SM
Under The Higgs Lamppost

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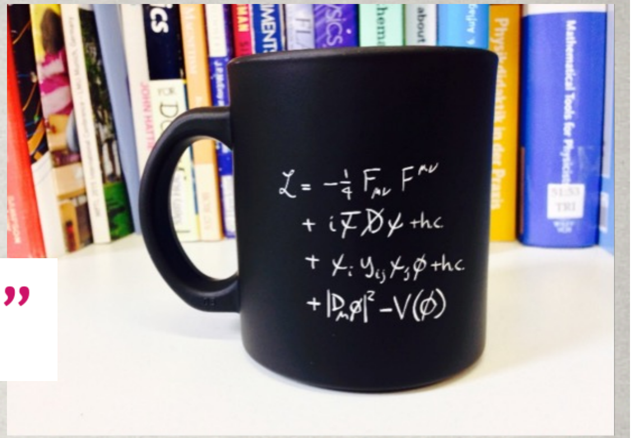
In summary: SM solidly established

$$\mathcal{L} \propto \mu^2 H^2 - \lambda H^4 + \sum_i c_i \mathcal{O}_i(\mathrm{BSM})$$



"Higgs isn't everything. It's the only thing."

M. E. Peskin Lepton-Photon 2025

Questions that we need the answers

1. Nature of EW Superconductivity: BCS?
2. Large hierarchy problem: the next scale?
3. Nature of EW phase transition?
4. Flavor physics: fermion mixing/neutrino mass*
5. Dark matter*: WIMP & Higgs portal?
6. Matter – antimatter asymmetry*: baryogenesis
7. … …

All demands new physics BSM!

1. The Quest for the SM & Beyond
2. A Strongly-coupled EW Sector
3. A Weakly-coupled Extension
4. Flavors of Matter Fields

A Lesson from QCD

QCD coupling runs logarithmically between vastly separated scales:

$$\alpha_s(\Lambda^2) \approx \frac{\pi}{2\ln(\Lambda^2/\Lambda^2_{QCD})} \quad e.g. \quad \Lambda_{QCD} \approx \Lambda\, e^{-\frac{\pi}{4\alpha_s(\Lambda^2)}}$$

Barbieri-Giudice fine-tune measure rather high:

$$\frac{\partial \ln(\Lambda_{QCD}/M_{Pl})}{\partial \ln \alpha_s} \approx \ln(M_{Pl}/\Lambda_{QCD}) \approx 100!$$ 1%-level fine tune!

but we understand it: dimensional transmutation.

Below Λ_{QCD}, QCD becomes strongly interacting and forms condensate: $\langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \sim f_\pi^3$

LR chiral symmetry is spontaneously broken to iso-spin:

$$-\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a - \sum_{u,d} (\bar{q}_L \gamma^\mu D_\mu q_L + \bar{q}_R \gamma^\mu D_\mu q_R)$$

$$SU(2)_L \otimes SU(2)_R \Rightarrow SU(2)_V, \text{thus } U_L = U_R.$$

→ 3 Nambu-Goldstone bosons: π^+, π^-, π^0 (u, d bound states)

In the non-linear realization of the Chiral symmetry, the Lagrangian for the Goldstone bosons $\pi^{+,-,0}$

\

$$\phi = \frac{f_\pi}{\sqrt{2}} \exp(i\vec{\tau}\cdot\vec{\pi}/f_\pi) \equiv \frac{f_\pi}{\sqrt{2}} U, \quad \mathcal{L} = \frac{f_\pi^2}{4} Tr(\partial^\mu U \partial_\mu U)$$

- Derivative coupling → **shift symmetry** $\pi \to \pi$+const.
- Pseudo Nambu-Goldstone bosons π^+, π^-, π^0 acquire their masses from explicit symmetry breaking: QED, $m_{u,d}$
- There is a rich hadronic spectrum with dynamical mass

  $m \sim 4\pi f_\pi \sim 1$ GeV, typically $\Gamma \geq 20\%$ m :

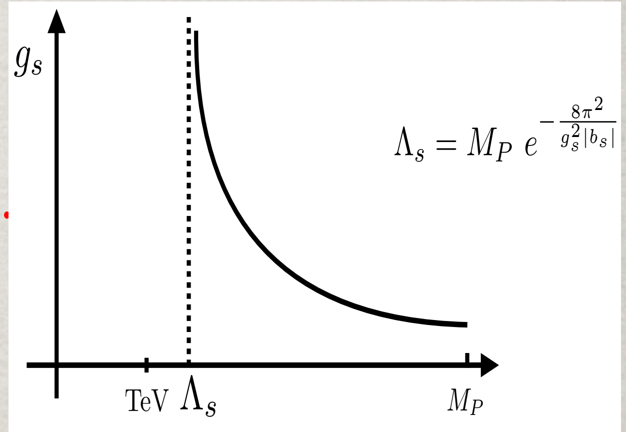
  $m(f_0) \sim 0.4$ -1.2 GeV, $\Gamma \sim 0.6$ - 1.0 GeV !

  $m(\rho^{\pm,0}) \sim 0.77$ GeV, $\Gamma \sim 0.15$ GeV … …
- After confinement by QCD dynamics, the composite states (hadrons) may be described perturbatively, e.g., by the chiral perturbation theory.

From QCD to Technicolor

QCD strong dynamics breaks the chiral symmetry as well as the $SU(2)_L$ gauge symmetry, therefore:

$M_{(W,Z)} \sim O(g\, f_\pi)$ Weinberg, Susskind, '80



Technicolor: A lesson from QCD

$SU(N_{TC})$ gauge theory, TC fermions $Q = U, D, ...$

EWSB by TC-fermion condendation at Λ_{TC}:

$$v \sim \langle \overline{Q_L} Q_R \rangle^{1/3} \sim 246 \text{ GeV}.$$

3 Nambu-Goldstone bosons in the non-linear realization of the gauge symmetry:

$$U = \exp\{i\omega^i \tau^i / v\}, \quad D_\mu U = \partial_\mu U + i g W_\mu^i \frac{\tau^i}{2} U - i g' U B_\mu \frac{\tau^3}{2}$$

$$\mathcal{L} = \frac{v^2}{2}[D^\mu U^\dagger D_\mu U] \to \frac{v^2}{4}(\sum_i g^2 W_i^2 + g'^2 B^2)$$

$M_{(W,Z)} = g\, v/2$, plus some TC hadrons $M \sim 4\, \pi\, v$

Extended Technicolor for fermions masses

Gauge boson masses are easy to generate (EWSB),

But fermion masses are header.

G_{ETC} gauge theory, ETC fermions: $U, D, ...,\quad u, d...$

TC-fermion condensate,SM fermion mass generated:

$$m_f \sim \langle \overline{Q_L} Q_R \rangle / \Lambda_{ETC}^2 \sim \Lambda_{TC}^3 / \Lambda_{ETC}^2.$$

Flavor is the show-stopper:

On the one hand: small FCNC: $\frac{1}{\Lambda_{ETC}} < \frac{1}{10^3\ \text{TeV}}$.

On the other hand, heavy quark $m_c \sim 1$ GeV $\Rightarrow \Lambda_{ETC} < 30 \times \frac{\Lambda_{TC}}{1\ \text{TeV}}$

$\Longrightarrow$ Non-QCD like: Walking TC

TC gauge coupling running very slowly.

$\langle \overline{Q_L} Q_R \rangle$ almost constant over $\Lambda_{TC} - \Lambda_{ETC}$.

$\langle \overline{Q_L} Q_R \rangle_{ETC}$ enhanced by 100$-$1000.

Overall on TC / Extended TC:

√ theory natural: Λ_{TC} dynamical. $\Lambda_{TC} \approx \Lambda \ \exp(-\frac{1}{2\alpha_{TC}}) \approx 4\pi v.$

√ predicts new strong dynamics at the TeV scale: $\pi_T, \ \eta_T, \ \rho_T, \ \omega_T \ldots$

x Tension with EW precision measurements

x Tension with LHC direct searches

x Difficult to generate fermion mass hierarchy (ETC)

x AND, hard to have the Higgs boson light

The existence of a light, weakly coupled Higgs boson carries important message (!) for our understanding & theoretical formulation

for & beyond the SM.

"Why I would be very sad if a Higgs boson were discovered"

by Howard Georgi, 1993

(Perspectives on Higgs physics, p.337-342)

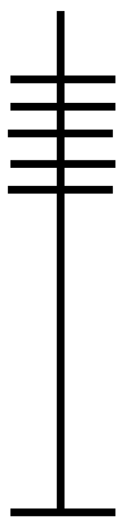
THE COMPOSITE HIGGS

§ H. Georgi and David B Kaplan, 1984.

The Higgs boson may be a **Nambu-Goldstone boson:**

Like $W^{\pm}_L$, Z_L; unlike dynamical states f_0, $\rho^{\pm,0}_{TC}$, ω_{TC} etc.

Global symmetry, G *spontaneously* broken to subgroup, H at scale, f



$\rho^{(n)} \gtrsim \text{TeV}$

Resonance mass: $m_\rho \sim g_\rho f \qquad 1 \lesssim g_\rho \lesssim 4\pi$

coset $G/H \supset h + W_L, Z_L$ } Higgs doublet

$e.g.\ SO(5)/SO(4)$

h

Higgs mass protected by shift symmetry
-- like pions in QCD !

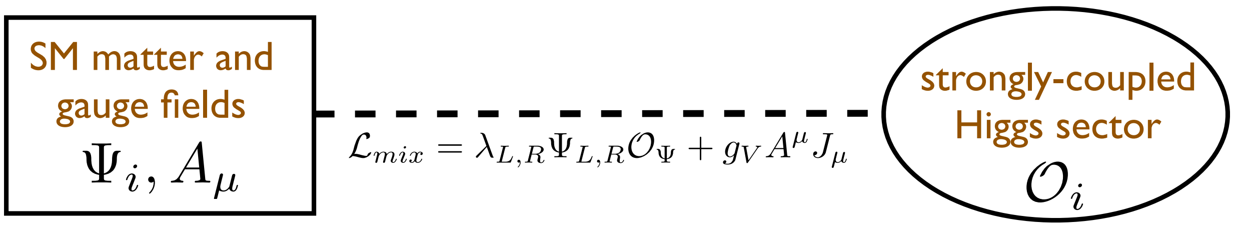
$h \to h + \text{const.}$

Nambu-Goldstone bosons remain massless,
and thus "naturally light".

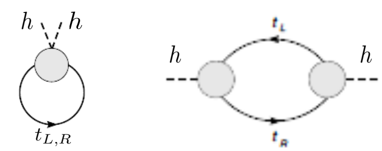
The global symmetry G must also be explicitly broken to generate the Higgs potential and thus m_h

Global symmetry broken by *mixing* with elementary sector

[Contino, Nomura, Pomarol `03; Agashe, Contino, Pomarol `04]



Higgs potential: $V(h) = -\mu_h^2|H|^2 + \lambda_h|H|^4$



where $\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2 \qquad \lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$ [g_{SM} = SM gauge or Yukawa coupling]

EWSB: $\left(\langle H \rangle = \frac{v}{\sqrt{2}}\right)$ $\quad v^2 = \frac{\mu_h^2}{\lambda_h}$ ⇒ $f \sim v$

Higgs mass: $m_h^2 = 2\lambda_h v^2 \simeq \frac{N_c}{\pi^2} m_t^2 g_T^2$ ⇒ $g_T \sim 1.3$

i.e. light top partners (= fermionic resonances) $\quad m_T \sim g_T f$

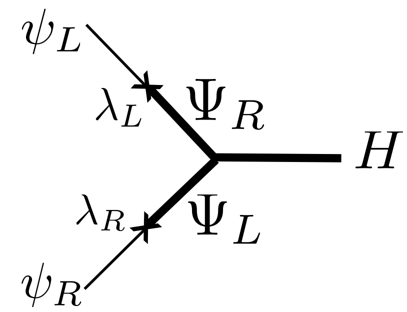
Bonus feature:

Partial compositeness $$\mathcal{L} = \lambda_L \psi_L \mathcal{O}_R + \lambda_R \psi_R \mathcal{O}_L$$

Explains the fermion mass hierarchy [Kaplan 91;TG, Pomarol 00]

$$m_f \sim \lambda_L \lambda_R v$$

where $$\lambda_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\dim\ \mathcal{O}_{L,R} - \frac{5}{2}}$$

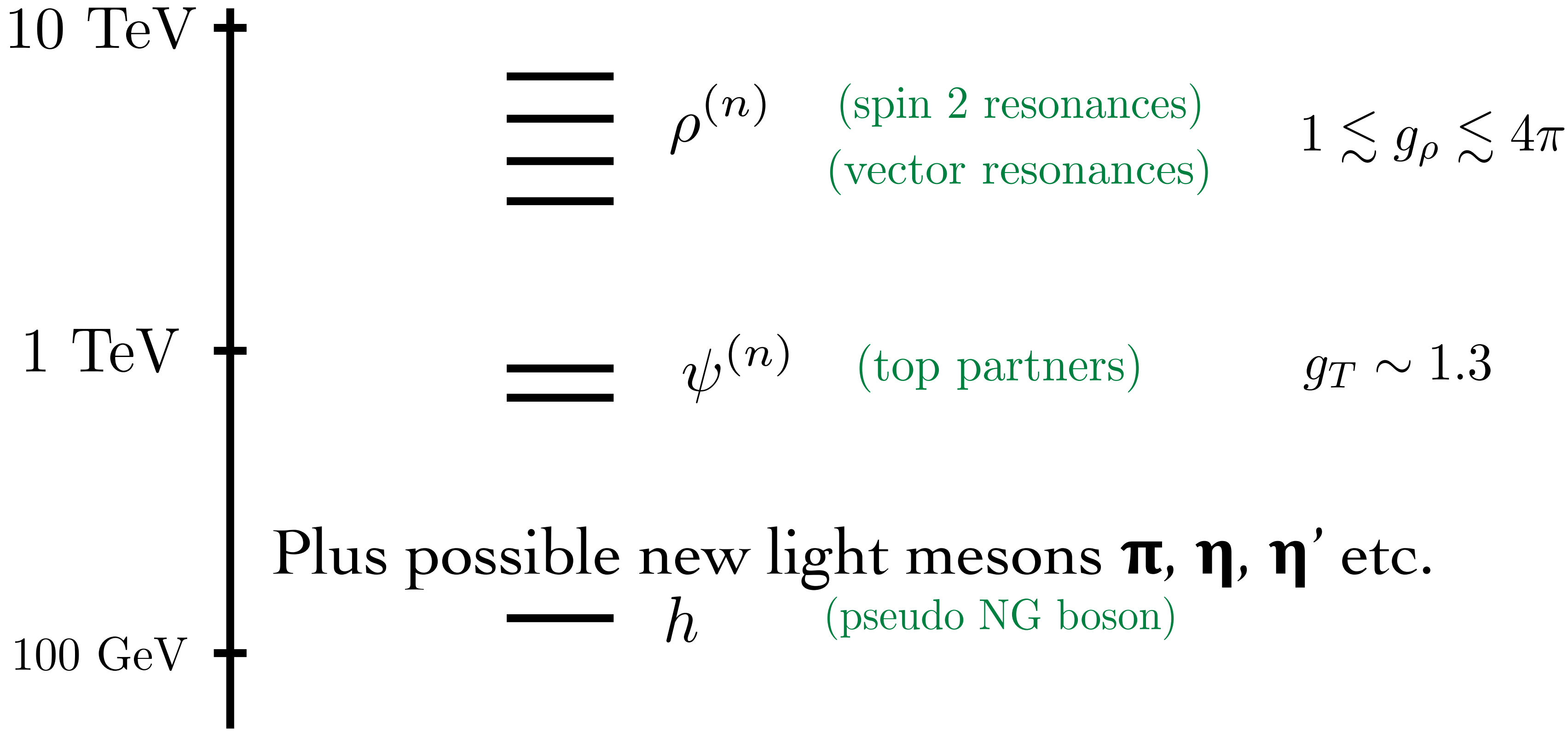


- Light fermions are mostly elementary ⇨ $\dim\ \mathcal{O}_{L.R} > \frac{5}{2}$

- Top quark is mostly composite! ⇨ $\dim\ \mathcal{O}_{L,R} \sim \frac{5}{2}$

A “Natural” Composite Higgs spectrum :

$$750\ \text{GeV} \lesssim f \lesssim 1\ \text{TeV}$$



Plus possible new light mesons **π, η, η’** etc.

The Littlest Higgs Model

*Arkani-Hamed, Cohen, Katz, Nelson, hep-ph/0206021.

A specific realization: $SU(5)$ Non-linear σ-model*

(Ann Nelson, 1958-2019)

The gauged non-linear σ-model:

$$\mathcal{L}_\Sigma = \frac{1}{2}\frac{f^2}{4}\mathrm{Tr}|\mathcal{D}_\mu\Sigma|^2, \qquad \Sigma = e^{2i\Pi/f}\Sigma_0,$$

where f is the condensate scale (the Goldstone-boson decay constant);

Σ, Σ_0, Π are 5×5 matrices.

A subgroup is gauged:

$$G_1 \otimes G_2 = [SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2$$

with the co-variant derivative

$$\mathcal{D}_\mu\Sigma = \partial_\mu\Sigma - i\sum_{j=1}^{2}\left[g_j W_j^a(Q_j^a\Sigma + \Sigma Q_j^{a\mathsf{T}}) + g'_j B_j(Y_j\Sigma + \Sigma Y_j^{\mathsf{T}})\right]$$

The spontaneous symmetry breaking by

$$<\Sigma> = \Sigma_0 = \begin{pmatrix} & & \mathbb{1} \\ & 1 & \\ \mathbb{1} & & \end{pmatrix}$$

Global: $SU(5) \Rightarrow SO(5)$, leading to 14 Goldstone bosons;

Gauged: $[SU(2) \otimes U(1)]_1 \otimes [SU(2) \otimes U(1)]_2 \Rightarrow SU(2)_L \otimes U(1)_Y$

The fate of the Goldstone bosons

$1_0 \oplus 3_0$	Longitudinal modes of $Z_H, W_H^{\pm}, A_H$
$2_{\pm\frac{1}{2}}$	h doublet
$3_{\pm 1}$	ϕ triplet

Introduce a vector-like pair of colored fermions

Basically, $\tilde{t}:\ (3_c, 1_L)_{Y_i}$ and $\tilde{t}'^c:\ (3_c, 1_L)_{-Y_i}$.

$$t_3 \to t_L,\ \tilde{t} \to T_L,\ u_3'^c \to t_R,\ \tilde{t}'^c \to T_R.$$

Quadratic divergences cancelled at one-loop level by new states:*

$$W, Z, B \leftrightarrow W_H, Z_H, B_H; \quad t \leftrightarrow T; \quad H \leftrightarrow \Phi.$$

(cancellation among same spin states!)

EWSB & the Higgs mass

The effective Higgs potential is written as

$$V = \lambda_{\phi^2} f^2 \mathrm{Tr}(\phi^\dagger \phi) + i\lambda_{h\phi h} f \left(h\phi^\dagger h^T - h^* \phi h^\dagger \right) - \mu^2 h h^\dagger + \lambda_{h^4} (h h^\dagger)^2$$

In terms of fundamental parameters:

$$\begin{aligned}
\lambda_{\phi^2} &= \frac{a}{2}\left[\frac{g^2}{s^2c^2} + \frac{g'^2}{s'^2c'^2}\right] + 8a'\lambda_1^2, \\
\lambda_{h\phi h} &= -\frac{a}{4}\left[g^2\frac{(c^2-s^2)}{s^2c^2} + g'^2\frac{(c'^2-s'^2)}{s'^2c'^2}\right] + 4a'\lambda_1^2, \\
\lambda_{h^4} &= \frac{a}{8}\left[\frac{g^2}{s^2c^2} + \frac{g'^2}{s'^2c'^2}\right] + 2a'\lambda_1^2 = \frac{1}{4}\lambda_{\phi^2}. \\
m_H^2 &= 2\mu^2 \sim v^2 \lesssim a_{1-\mathrm{loop}}\frac{f^2}{16\pi^2} + a_{2-\mathrm{loop}}\frac{f^2}{16\pi^2}
\end{aligned}$$

→ The quadratic divergence is then cancelled at one loop level, the logarithmically contribution to the Higgs mass square

$$m_h^2 \sim 6\frac{\lambda_t^2 m_T^2}{8\pi^2}\log\frac{\Lambda^2}{m_T^2}$$

m_h = 125 GeV → m_T < 1TeV

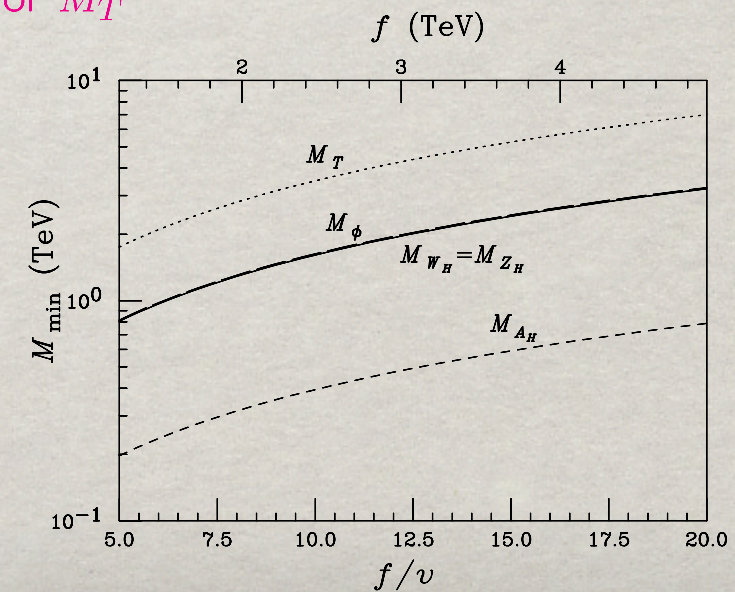
Independent model parameters

$\tan\theta = \frac{s}{c} = \frac{g_2}{g_1}$	New $SU(2)$ gauge coupling (or equivalently mixing angle θ)
$\tan\theta' = \frac{s'}{c'} = \frac{g'_2}{g'_1}$	New $U(1)$ gauge coupling (or equivalently mixing angle θ')
f	Symmetry breaking scale $\mathcal{O}$(TeV)
v'	Triplet ϕ vacuum expectation value, $v'/v \lesssim v/4f$
m_H	Regular SM Higgs mass
M_T	Heavy vector top mass, we trade λ_2 for M_T

Heavy particles	Mass
A_H	$m_z^2 s_W^2 \, \frac{f^2}{5s'^2c'^2v^2}$
Z_H	$m_W^2 \, \frac{f^2}{s^2c^2v^2}$
W_H	$m_W^2 \, \frac{f^2}{s^2c^2v^2}$
$\phi^{0,\ \pm,\ \pm\pm}$	$\frac{2m_H^2 f^2}{v^2} \, \frac{1}{1-(4v'f/v^2)^2}$
T	$\sqrt{\lambda_1^2+\lambda_2^2}\ f$

→ Leads to rich phenomenology:

- New particle searches
- Precision EW physics
- Flavor / neutrino physics



HOWEVER, precision electroweak, flavor constraints

EWPT: $\frac{s}{16\pi^2 v^2} H^\dagger \tau^a H B^{\mu\nu} W_{a\mu\nu}$ $\quad S = \frac{s}{2\pi} \sim \frac{m_W^2}{m_\rho^2}$ ⇒ $f \gtrsim \frac{2.5\ \mathrm{TeV}}{g_\rho}$

$\frac{-t}{16\pi^2 v^2}((D^\mu H)^\dagger H)(H^\dagger D_\mu H)$ $\quad T = \frac{t}{8\pi e^2} \sim \frac{v^2}{f^2}$ ⇒ $f \gtrsim 5.5\ \mathrm{TeV}$

e.g. FCNC $\epsilon_q^i \epsilon_q^j \epsilon_q^k \epsilon_q^l \frac{g_\rho^2}{m_\rho^2} \bar{q}^i q^j \bar{q}^k q^l$ $\quad \epsilon_q^i \sim \frac{g_i}{g_\rho}$ ⇒ $f \gtrsim 10\ \mathrm{TeV}$

[Bellazzini, Csaki, Serra 1401.2457]
[Panico, Wulzer 1506.01961]

⇒ $f \gg v$ *"Little" hierarchy*

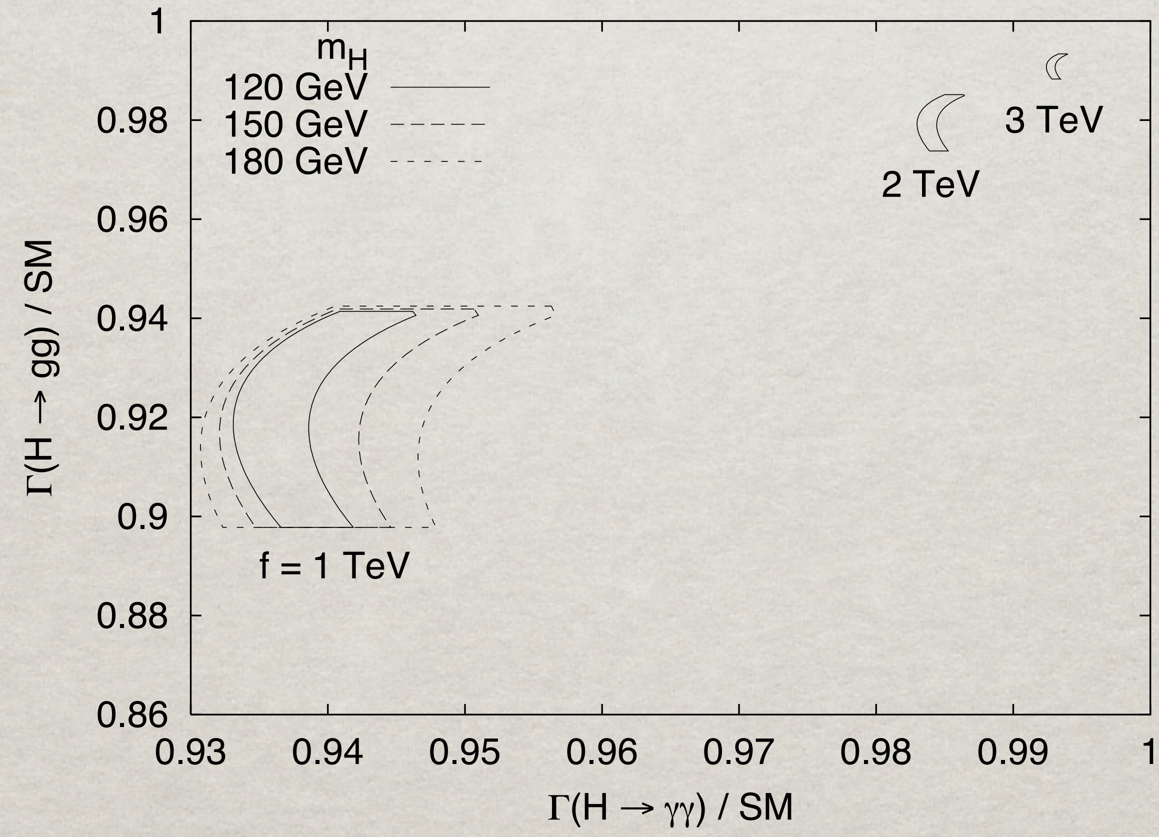
Tension partly alleviated by complicating minimal models

e.g. custodial symmetry, flavor, symmetry, twin parity….

Precision Higgs coupling constraints

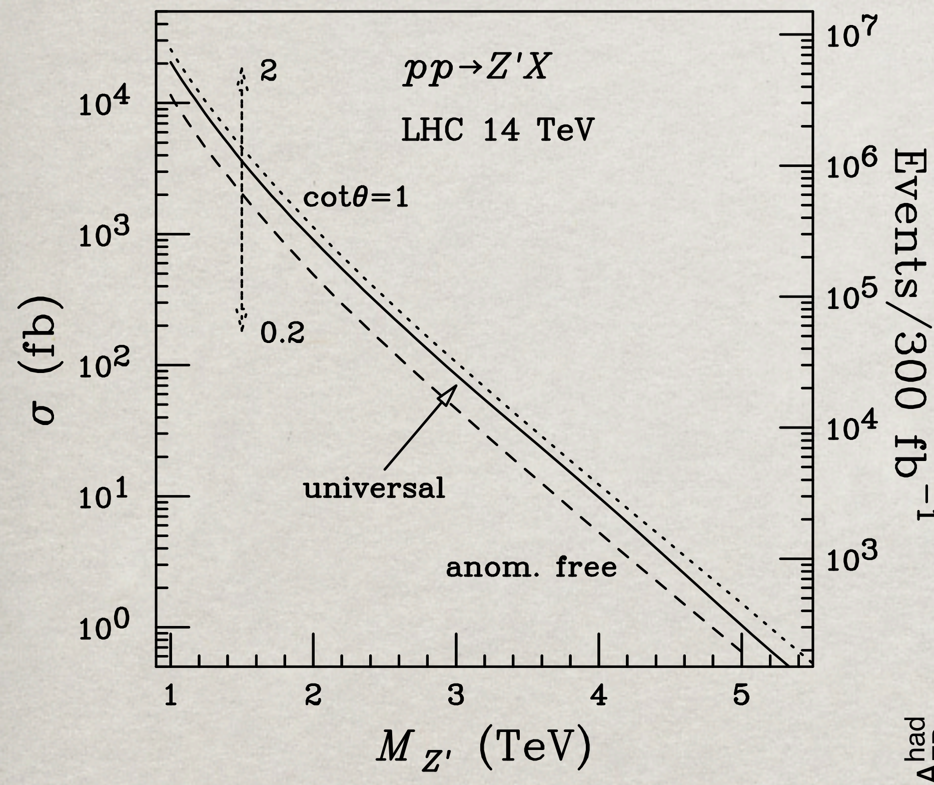
- T affects $H \to gg$
- $W_H^{\pm}$, T affect $H \to \gamma\gamma$

Correlation between $H \to gg$ and $H \to \gamma\gamma$:



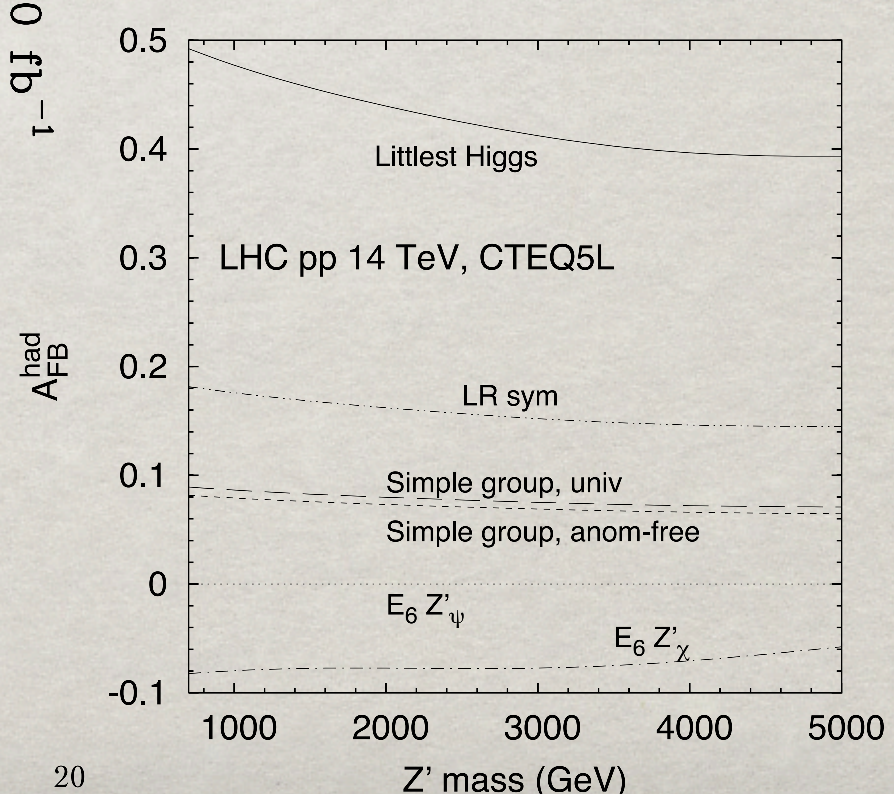
New gauge bosons: easiest signals

- Z_H versus Z'



Significant differences for FB asymmetry among Z's:

$$A_{FB}^{i,f} = \frac{3}{4} A_i A_f, \quad A_i = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}.$$

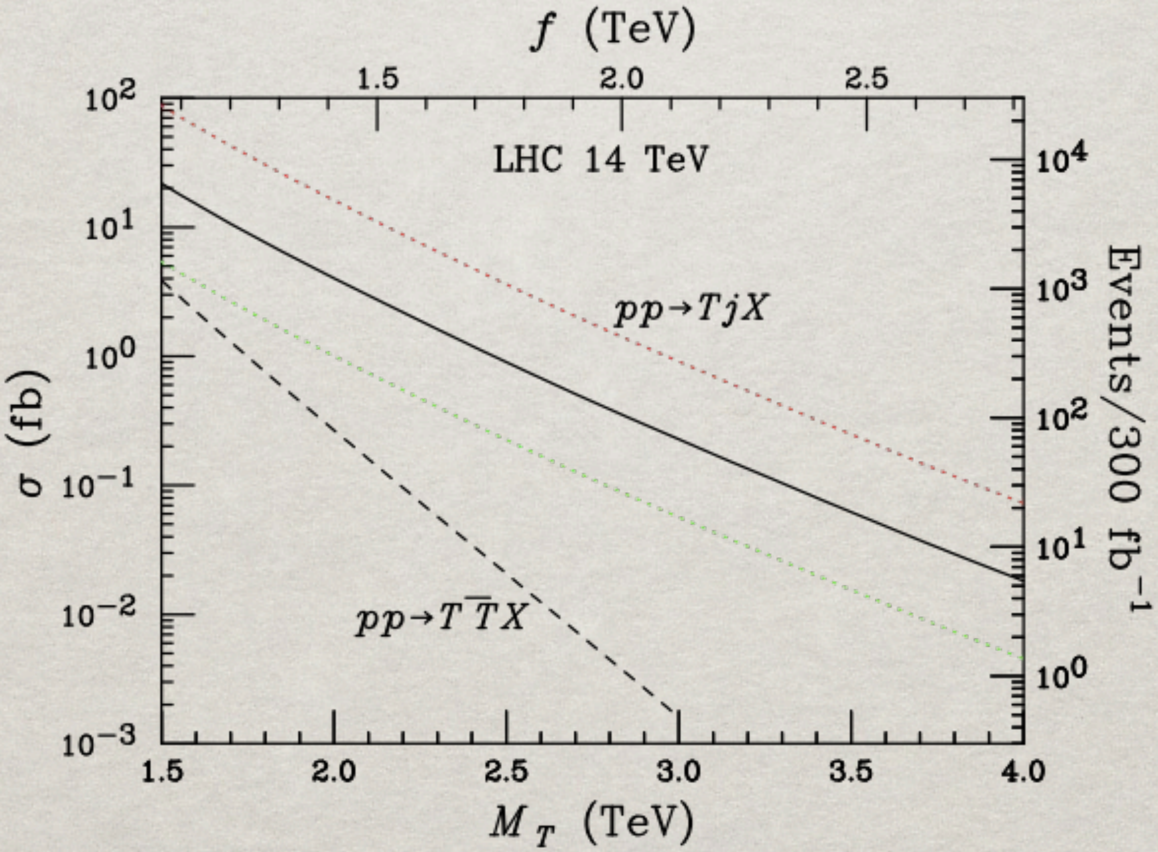


Most wanted: T production:

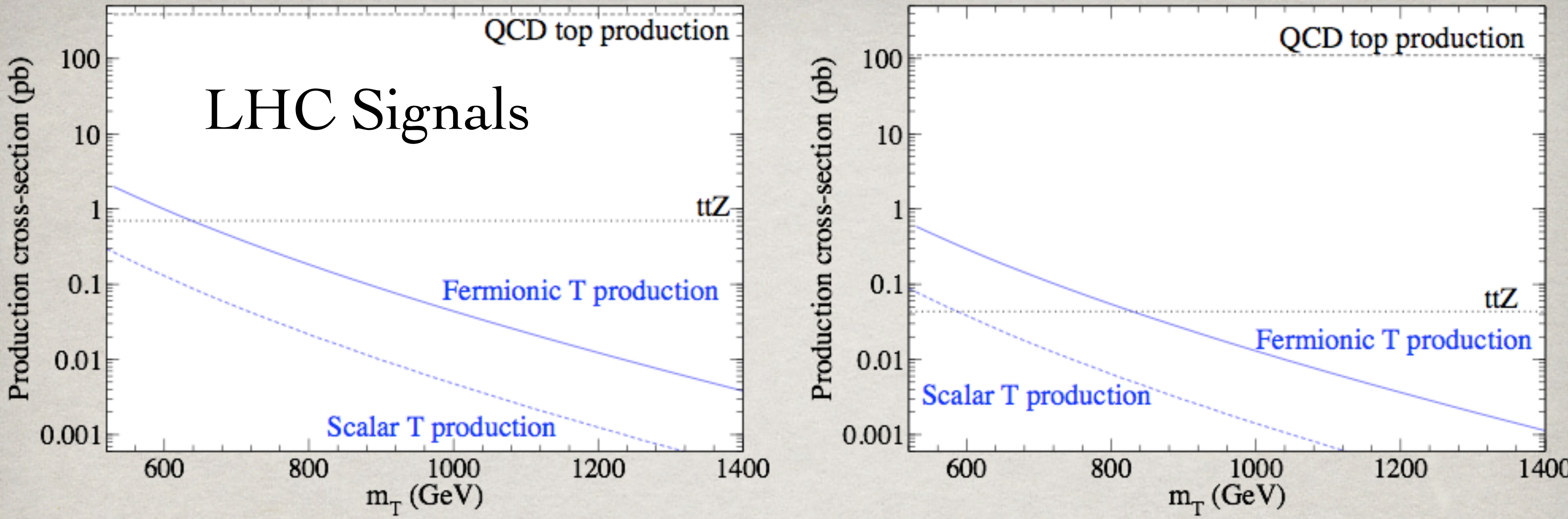
$gg \to T\bar{T}$ phase-space suppression;

$qb \to q'T$ via t-channel $W_L b \to T$.

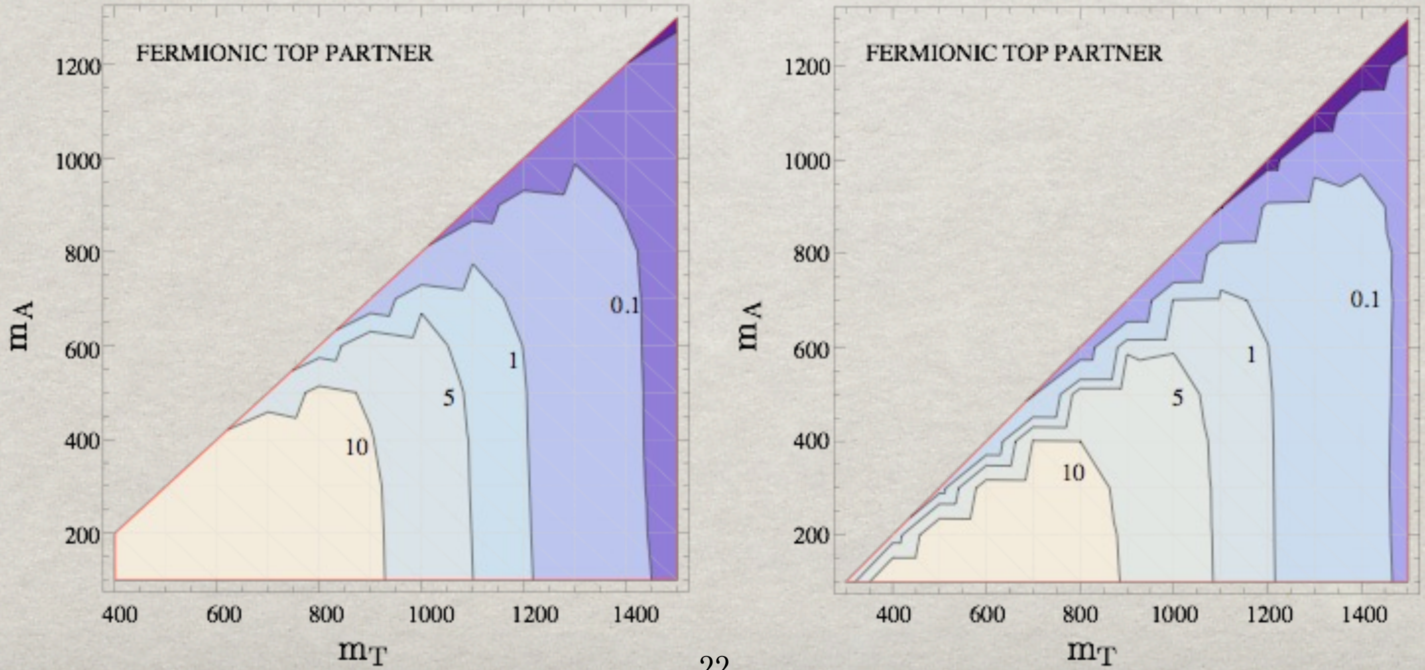
$$J^{+\mu} = \frac{1}{\sqrt{2}} \left[c_L \bar{t}_L \gamma^\mu b_L + s_L \bar{T}_L \gamma^\mu b_L \right] \qquad s_L \simeq \frac{\lambda_1}{\lambda_2} \frac{m_t}{M_T}.$$



LHC Signals

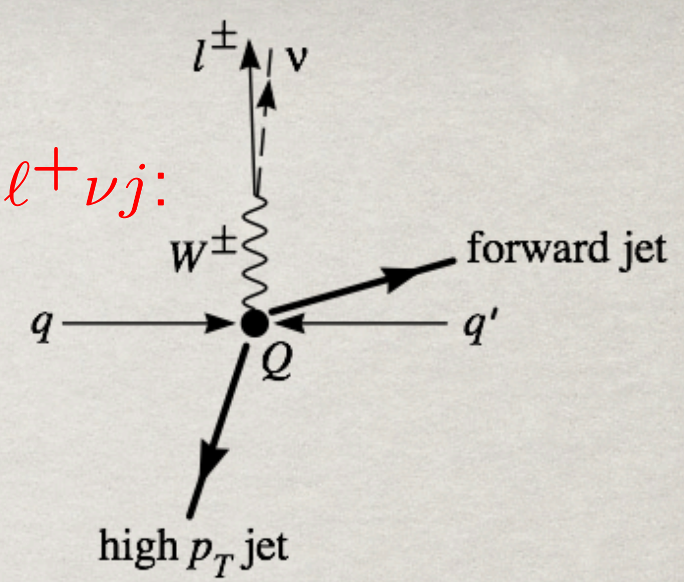


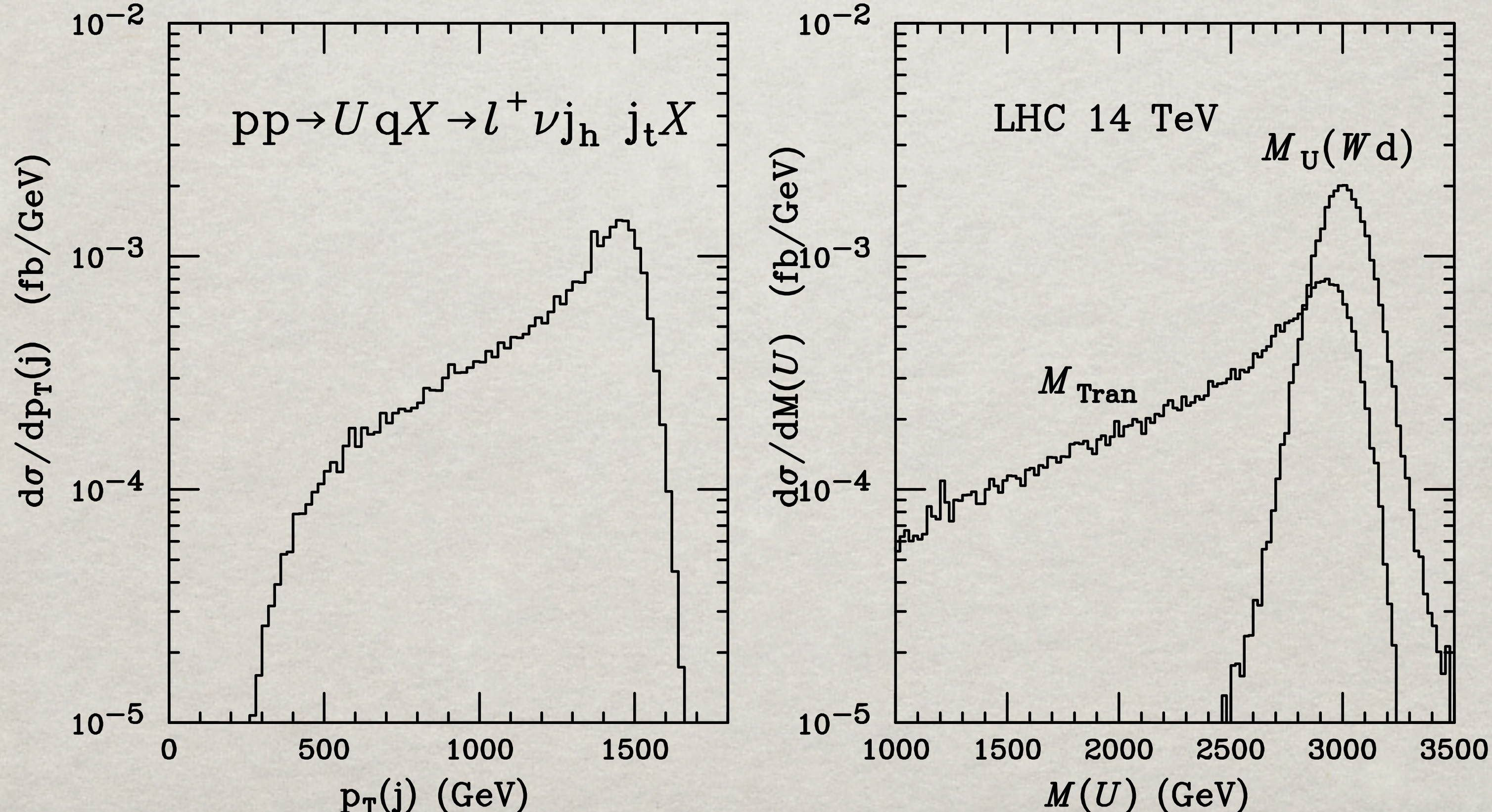
$$q\bar{q},\ gg \to T\bar{T} \to t\bar{t}\ A^0 A^0 X \to b j_1 j_2\ \bar{b}\ \ell^- \bar{\nu}\ A^0 A^0\ X + c.c.$$



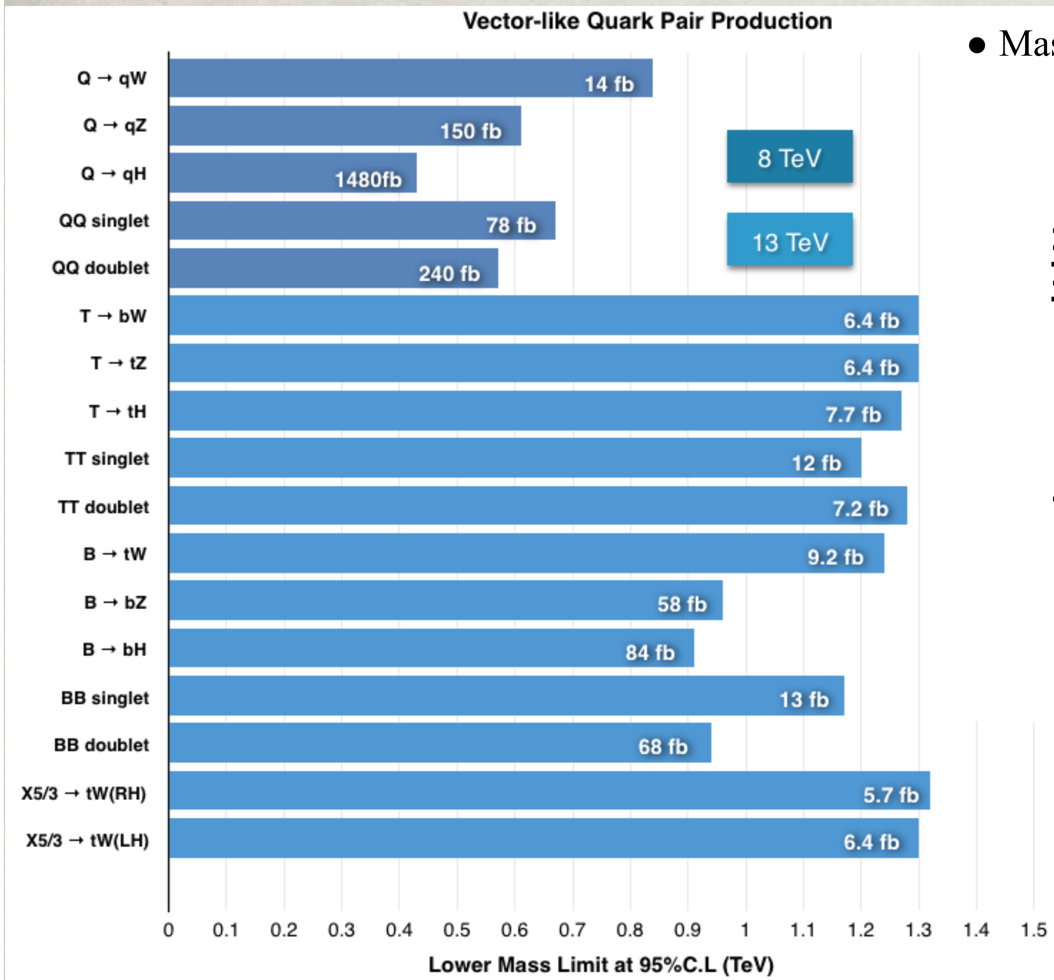
Single T production:

Kinematical features: $W^+ d \to U \to \ell^+ \nu j$:

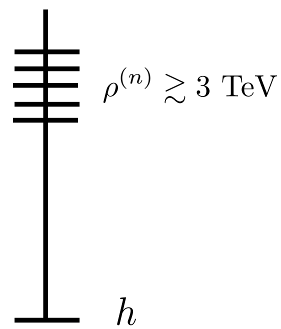


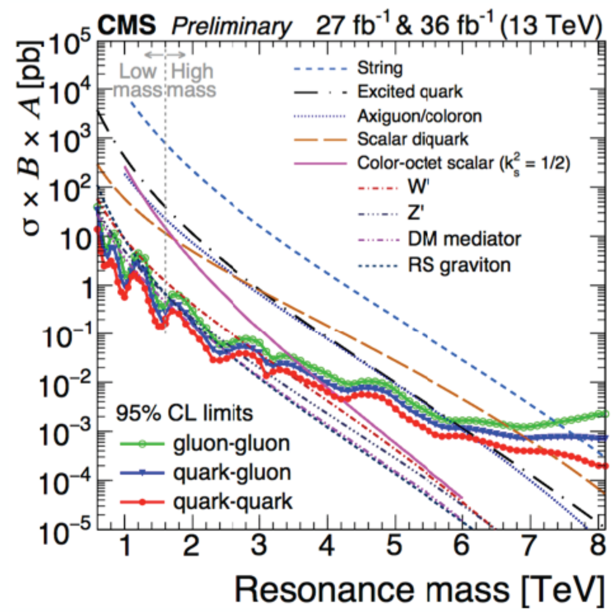


LHC bound update:
Vector-Like-Quark & Di-jet resonances



- Massive spin-1, spin-2 resonances





Testing the Higgs "compositeness"

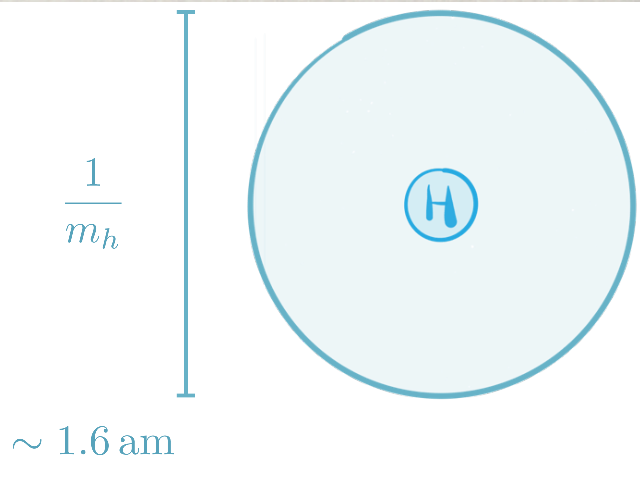
Historically,

- Rutherford (1919) discovered & named the "proton": "the 1st (in Greek)" → the most elementary element.
- Otto Stern (1933) discovered the "anomalous" magnetic moment $\boldsymbol{\mu}_p \sim 2.8\ \boldsymbol{\mu}_N$ → not Dirac-like
- Robert Hofstadter (1960) discovered the proton form factor → spatial charge distribution.
- DIS at SLAC (1969) … that's all history

Lesson:

If the composite scale is not accessible,

- Look for "anomalous coupling" $\sim E^2$
- Probe the form factor at high Q^2

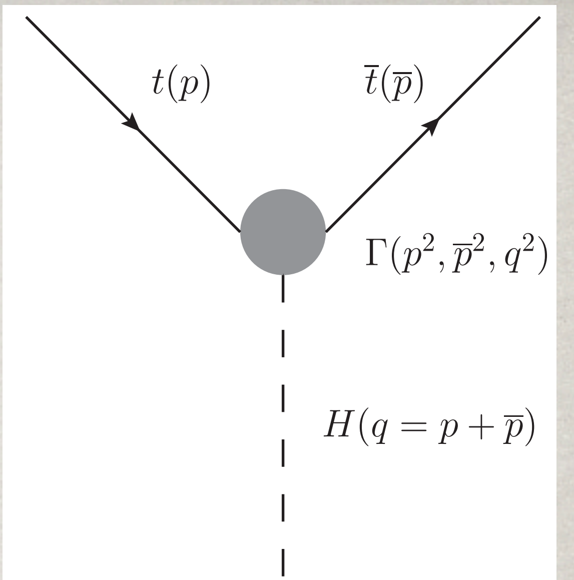


Higgs Boson Form Factor at top:

$$V_{ttH}(p^\mu, \bar{p}^\mu) = \frac{\sqrt{2}m_t}{v}\Gamma\left(p^2/\Lambda_c^2, \bar{p}^2/\Lambda_c^2, q^2/\Lambda_c^2\right)$$

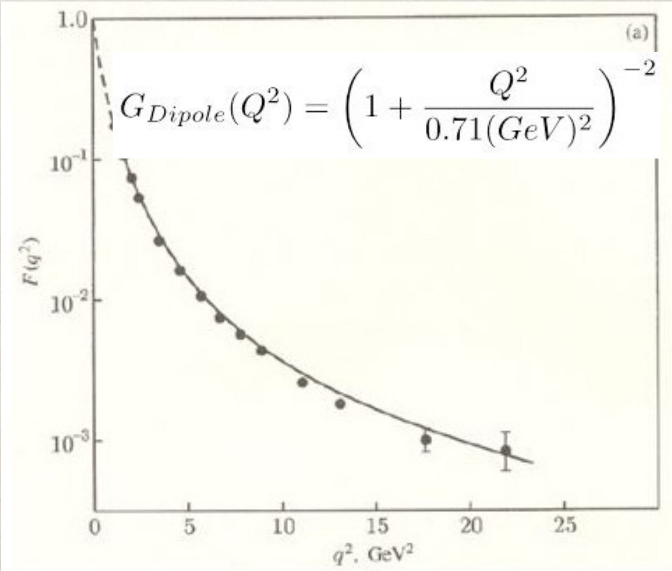
Current 95%CL bound from the LHC Higgs signal:

$$|\Gamma\left(m_h^2/\Lambda^2\right)^2 - 1| < 0.1$$



Nucleon form factor:

$$\Gamma\left(q^2/\Lambda_c^2\right) = \frac{1}{(1 + q^2/\Lambda_c^2\ )^n}$$



n=2 → "Dipole FF"

Leading to a suppressed ttH

But enhanced gg→ZZ signal!

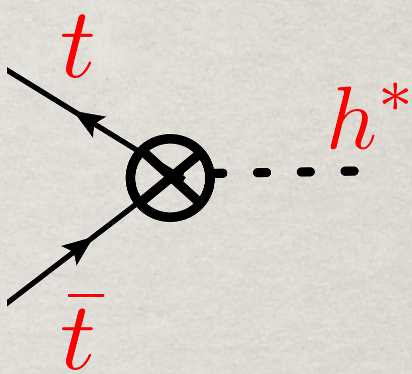
HL-LHC: Λ_c ~0.8 TeV @ 2σ

HE-LHC: Λ_c ~3.3 TeV @ 2σ; 2.1 TeV @ 5σ.

Other tests at high scales

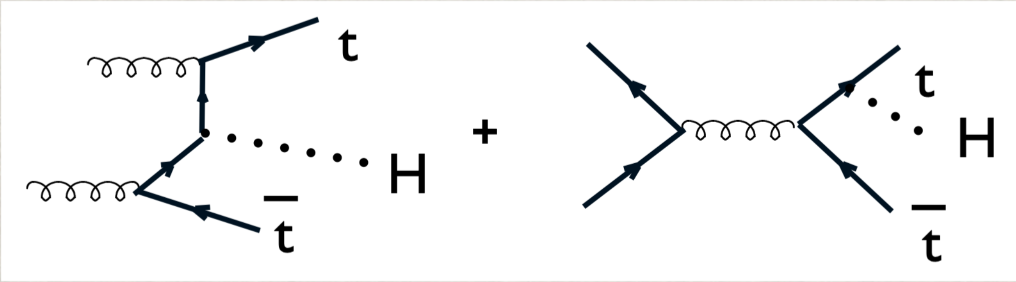
At far off-shell

$$\sigma_{\text{on}} \propto \frac{g_i^2(m_h^2)g_f^2(m_h^2)}{m_h\Gamma_h} \text{ and } \sigma_{\text{off}} \propto \frac{g_i^2(Q^2)g_f^2(Q^2)}{Q^2}$$



include other decay modes, like ZZ, WW …

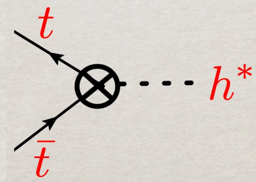
At high pT



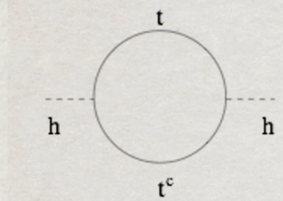
Event rate for gg→tth comparable to gg → h at high pT at high energy colliders

(1). Higgs coupling @ high scales:

Largest & most-wanted coupling: the "naturalness" & vacuum stability



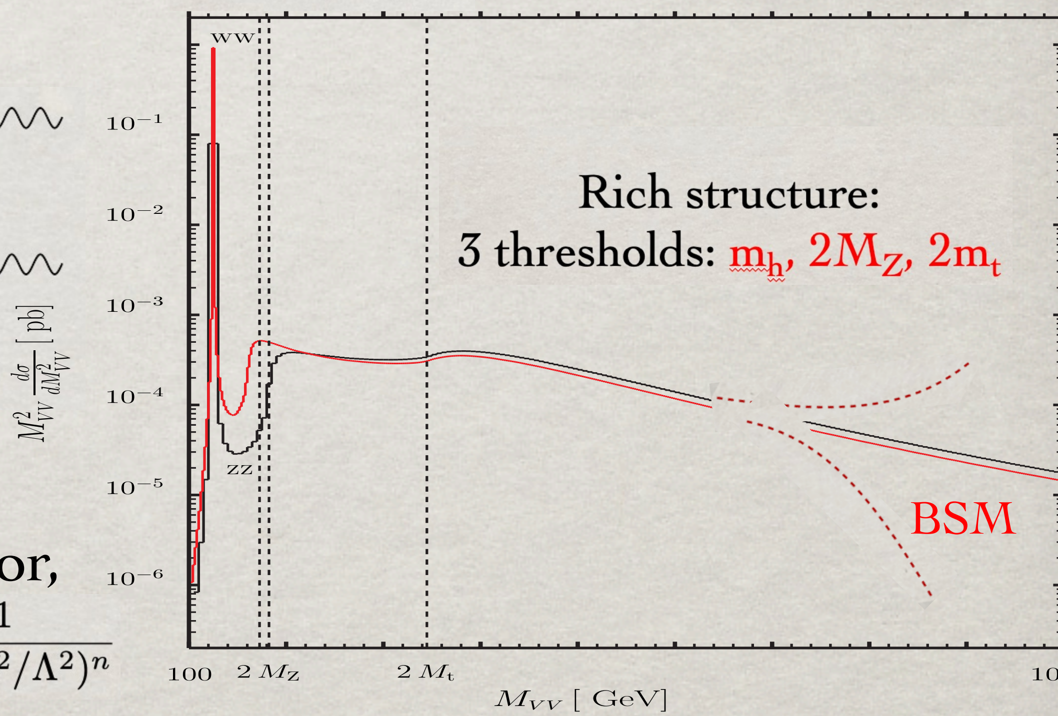
$y_t(q^2)$



$$m_H^2 = m_{H0}^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2$$

gg → h* → WW, ZZ

$$\sigma_{\rm on} \propto \frac{g_i^2(m_h^2) g_f^2(m_h^2)}{m_h \Gamma_h} \text{ and } \sigma_{\rm off} \propto \frac{g_i^2(Q^2) g_f^2(Q^2)}{Q^2}$$



Sensitive to:

- Γ_h, y_t, ZZh: a new mediator, SMEFT & Form Factor $\frac{1}{(1+q^2/\Lambda^2)^n}$

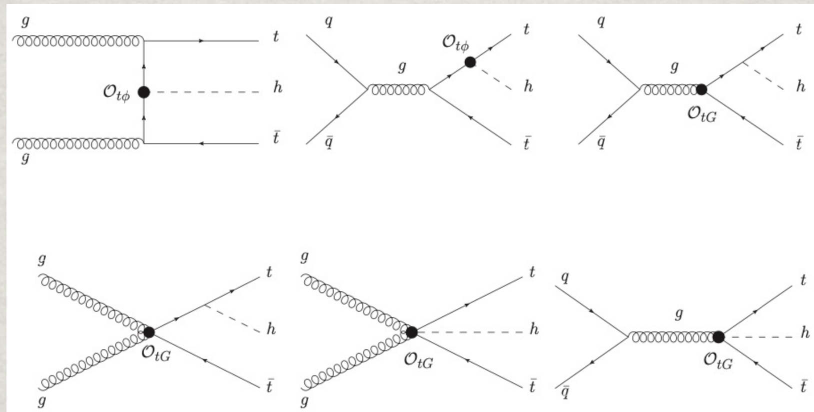
CMS/ATLAS: arXiv:2202.06923; 2304.01532

- $3.6\sigma/3.3\sigma$ observation for off-shell Higgs signal
- SM width bound: $3.2^{+2.4}_{-1.7}$ / $4.5^{+3.3}_{-2.5}$ MeV

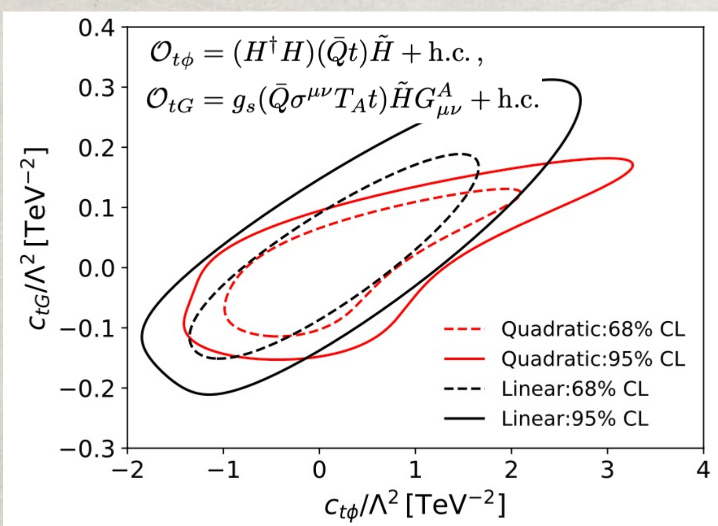
Frederic Deloit, Monday plenary
Jahid Hossain, Wed Higgs session 2

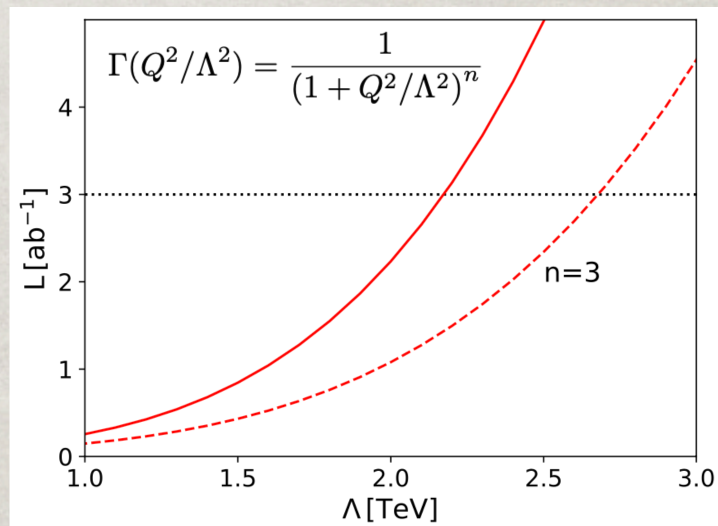
D. Goncalves, TH, S. Mukhopadhyay, arXiv:1710.02149 (PRL, 2017); arXiv:1803.09751; D. Goncalves, TH. I. Leung, H. Qin, arXiv:2012.05272; R. Abraham, D. Goncalves, TH, S.C.I. Leung, H. Qin, arXiv:2012.05272.

tth coupling @ high scales:
gg, qq → tth @ high $p_T(h)$



The current LHC sensitivity: $\kappa_t = 0.35^{+0.36}_{-0.34}$ (ATLAS)





HL-LHC @ 3 ab^{-1}

R. Abraham, D. Goncalves, TH, S.C.I. Leung, H. Qin, arXiv:2106.00018.

The Randall-Sundrum Model

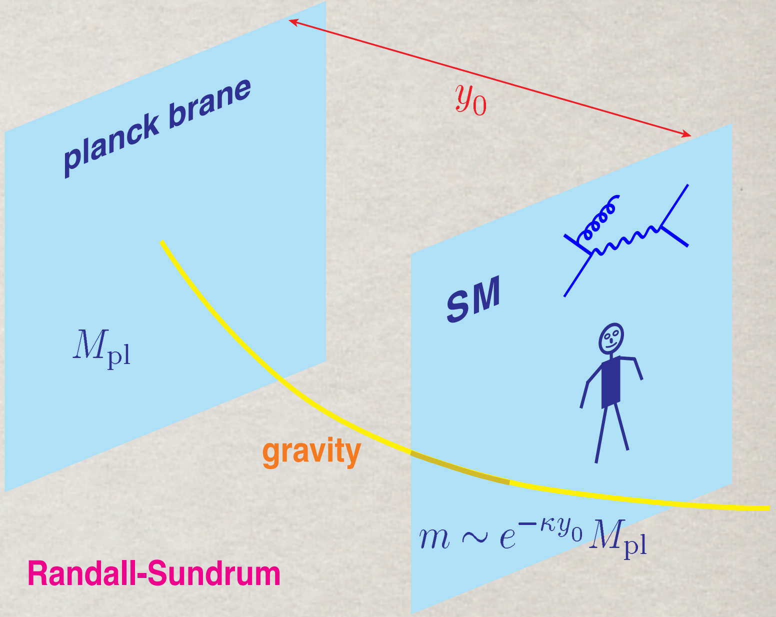
*L. Randall, R. Sundrum, hep-th/9905221.

Warped Extra Dimensions

$$ds^2 = e^{2A(y)}\ \eta_{\mu\nu}\ dx^\mu dx^\nu - dy^2,$$

where the "warp" factor $A(y) = -ky$,
with k the curvature scale in the 5^{th}-dim.

The extra dimension y is "warped".

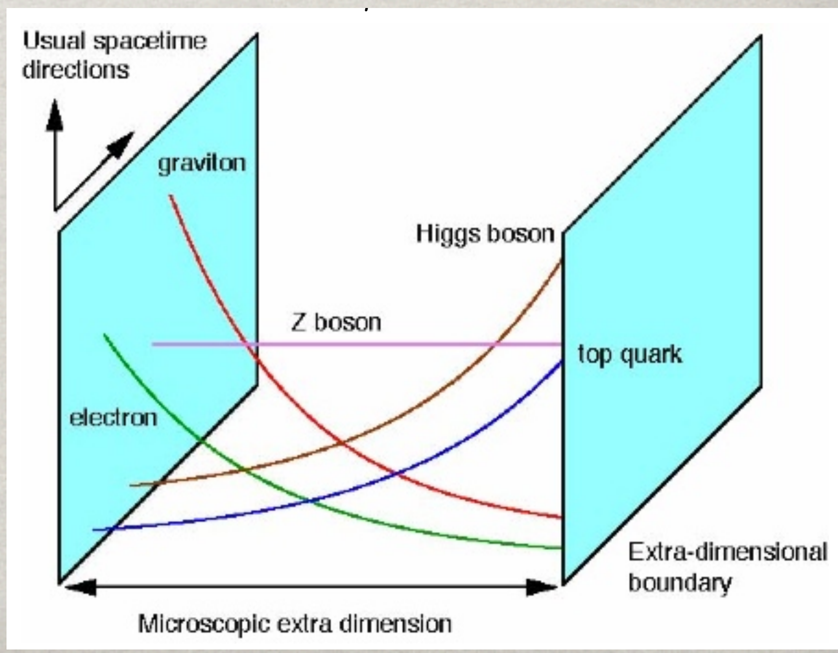


- Mass hierarchy M_{pl}/M_{EW} generated on the two branes:

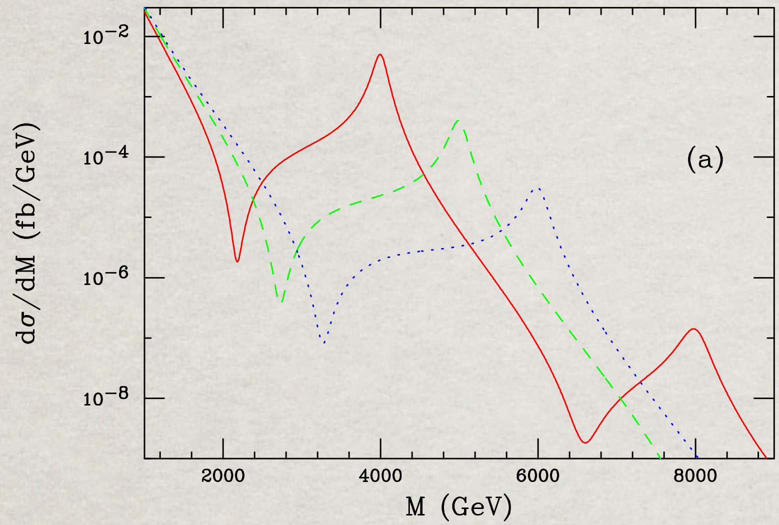
$$v = e^{-ky_0} M_{pl}.$$

To get $v \approx 246$ GeV, need $ky_0 \approx 40$.
the "size" of extra-dim: $y_0 \sim (10 - 100)\ l_{pl}$.

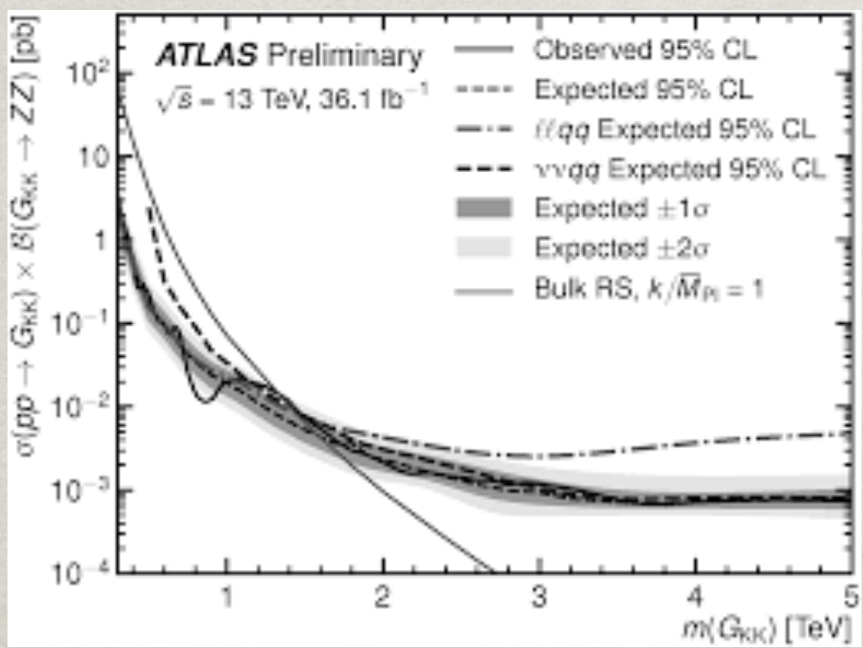
- TeV KK resonances: $M_{KK} \sim e^{-ky_0} M_{pl}$:[‡]
  $G_{KK},\ g_{KK},\ A_{KK}, ..., f_{KK} ...,$ with 1/TeV couplings.

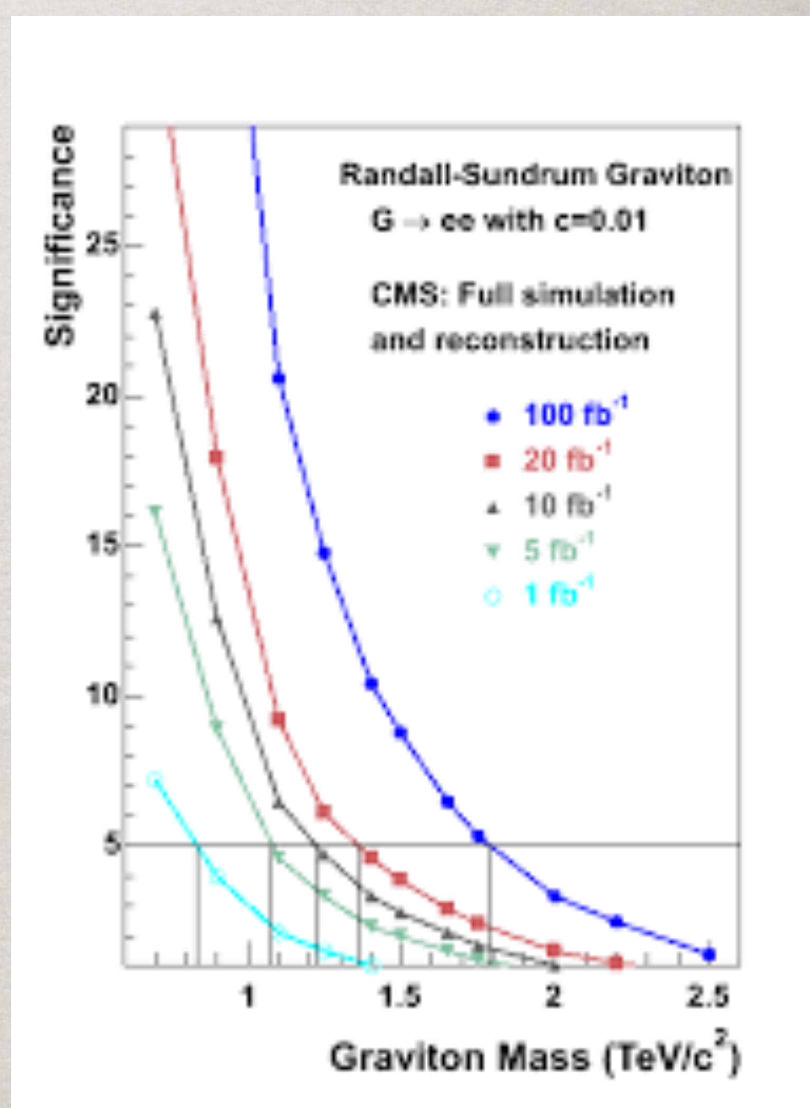


Resonant production at the LHC: Kaluza-Klein states



‡Davoudiasl, Hewett, Rizzo, hep-ph/9911262.

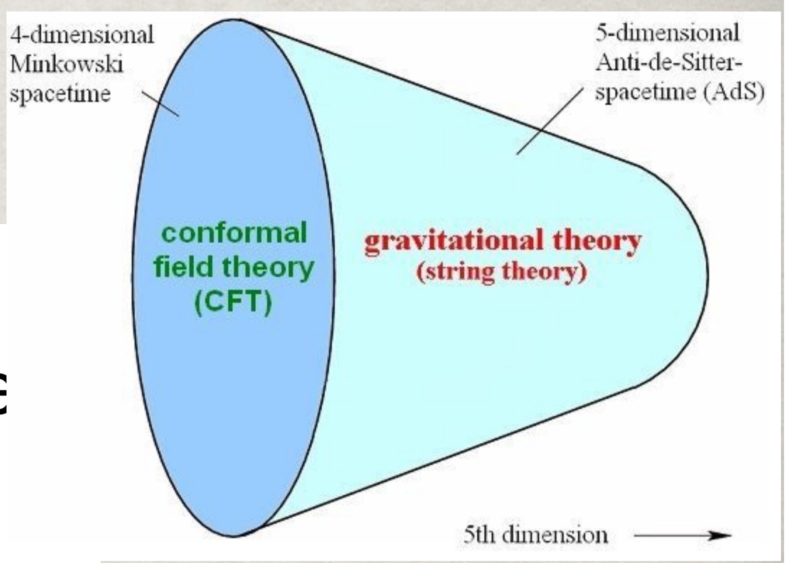




The AdS-CFT Correspondence

5d AdS theory $\Longleftrightarrow$ 4d strongly interacting walking TC!

$$S_{Full} = \int dx_4 dx_5 \, \mathcal{L}_{Full} \qquad \frac{1}{g_4^2} = \int dx_5 \, \mathcal{O}_5$$



Combined with the AdS/CFT conjecture, this is a very attractive idea, dual to TC.

Weakly coupled physics lives on UV brane. Strongly coupled physics lives on IR brane, model as CFT.

Expect composite nature of Higgs, top. No evidence so far.

Overall for strong EW scenarios:

- Strong gauge dynamics is "natural",
  solving the large hierarchy problem,
  owing to the dimensional transmutation (QCD-like)
- The Higgs boson can be "naturally light",
  as a pseudo-Goldstone boson: $m_H^2 \sim \frac{f^2}{(4\pi)^2} \sim \frac{m_t^2 M_T^2}{f^2}.$

- Predict rich physics near TeV: T, W_H, Z_H, H^{++}, $\boldsymbol{\rho}$, $\boldsymbol{\eta}$…
- The no-observation of those pushes f, M_T high,
  creating the "little hierarchy problem".

The Jury is still out …

1. The Quest for the SM & Beyond
2. A Strongly-coupled EW Sector
3. A Weakly-coupled Extension
4. Flavors of Matter Fields