Collider signals of a composite Higgs in the SM4

or: Heavy Higgs phenomenology with a "3-prong composite solution" to the SM4

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Based on: arXiv:1001.0569 [hep-ph, 2010], Gad Eilam, Amarjit Soni & SBS

Outline

- **The "3-prong composite solution" to the SM4**
- **Heavy (SM4) Higgs phenomenology@LHC in a nutshell**
- **Decays of a composite Higgs to a single 4th-gen fermion:**
  - **Flavor conserving channels**

$$H \to \bar{t}' t'^{\star} \to \bar{t}' b W^+ + h.c.$$
$$H \to \bar{b}' b'^{\star} \to \bar{b}' t W^- + h.c.$$

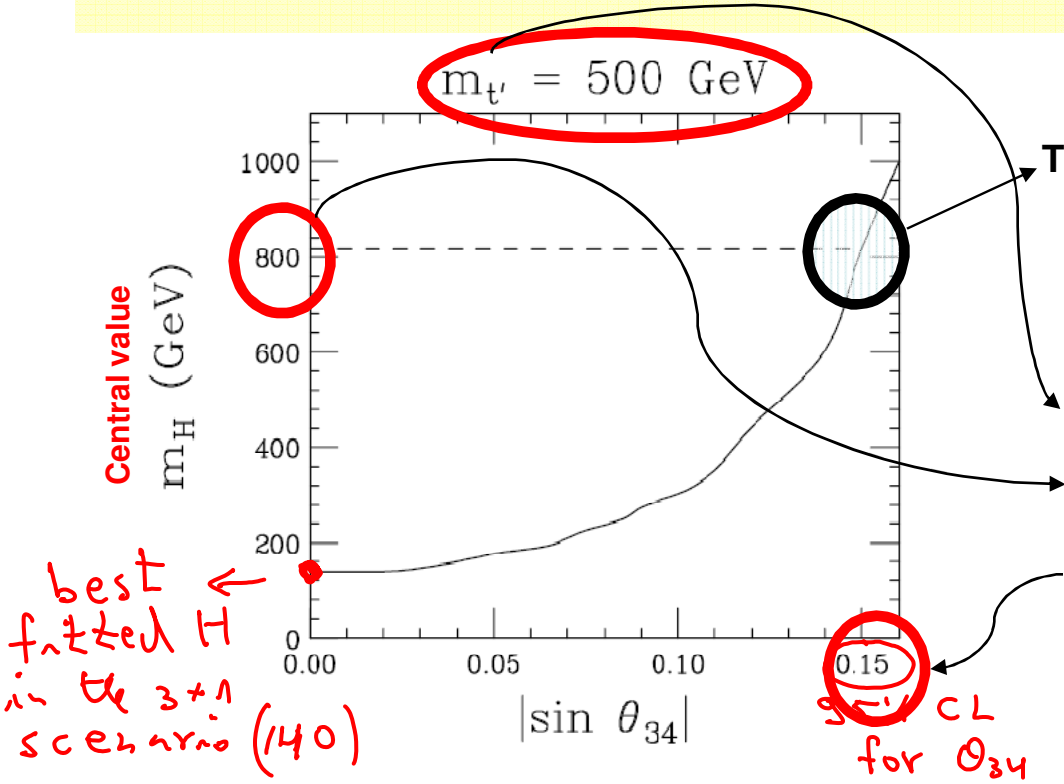
  - **Flavor violating channels**

$$H \to t' \bar{t} + h.c.$$
$$H \to b' \bar{b} + h.c.$$

- **Summary & concluding remarks**

The "3-prong composite solution" to the SM4

(figure taken from: Chanowitz, Phys.Rev.D79:113008,2009)



The compositeness SM4 "spot"?

$m_H \sim O(1)$ TeV $< 2m_{t'b'}$

$\theta_{34} \sim O(0.1)$ — $m_{t',b'} \sim O(500)$ GeV

Figure 2: Higgs boson mass as a function of $|\sin\theta_{34}|$ for the global fit to the four family with $m_{t'} = 500$ GeV. The horizontal line indicates the 95% confidence interval for $|\sin$

$$m_{t'} - m_{b'} \approx \left(1 + \frac{\ln \frac{m_H}{115\ \text{GeV}}}{5}\right) \times 50\ \text{GeV}$$

Further hints from:

- compositeness
- Flavor data
- Direct searches

Hints from compositeness

★**The original idea using the top quark as the agent for EWSB ($t\bar{t}$ condensate) led to the prediction of a too large m_t**

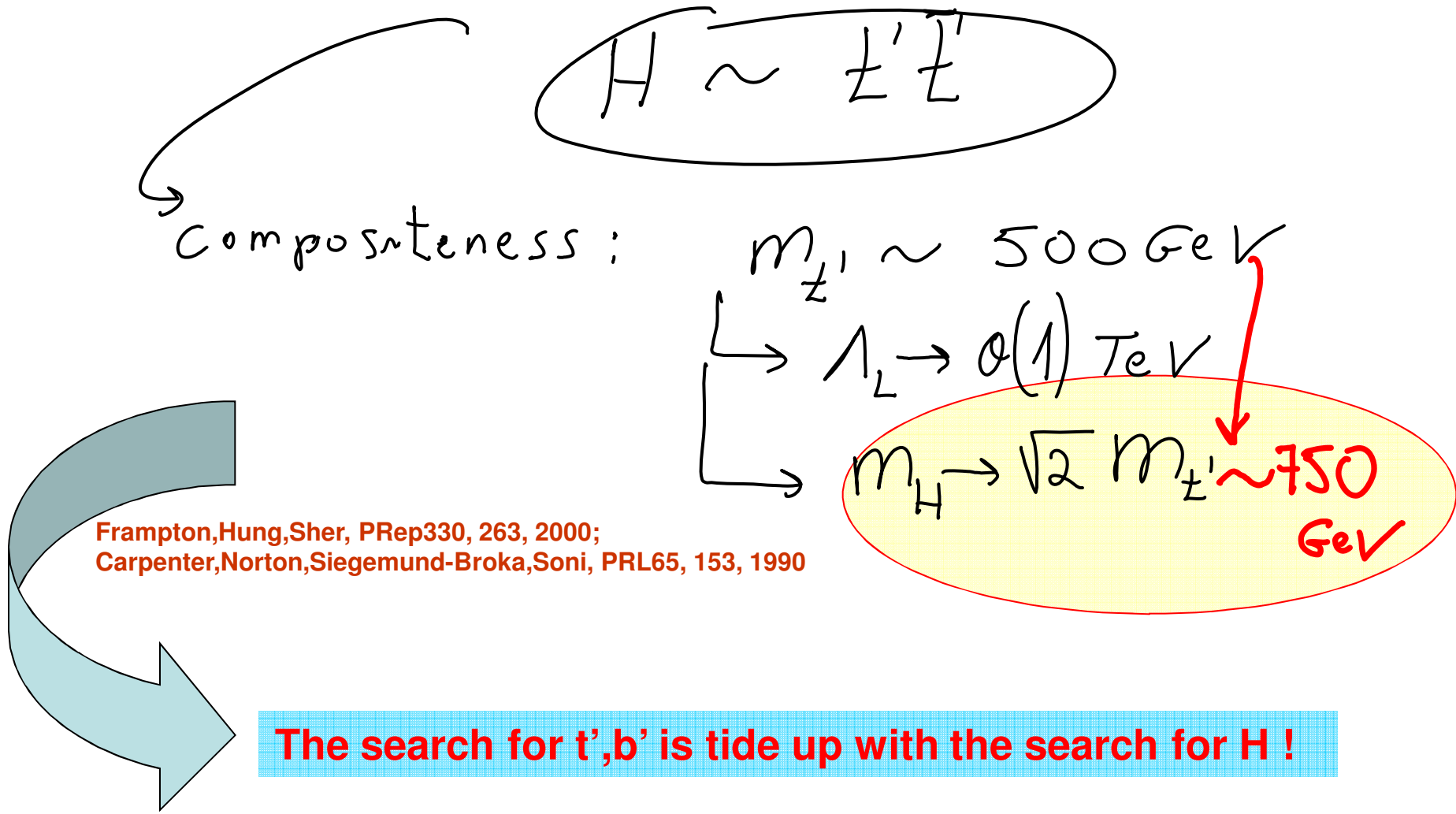
Bardeen,Hill,Lindner, PRD41,1647,1990

★**was that a prediction of the (t',b') ?**

Compositeness from a 4th Q' & L' condensates …

Holdom, PRL57, 2496, 1986 & JHEP,0608,076,2006;
Hill,Luty,Paschos,PRD43,3011, 1991;
Hung, Isidori,PLB402,122,1997;
Burdman,Da Rold, JHEP,0712,086,2007;
Hung,Xiong,arXiv:0911.3890 & arXiv:0911.3892;
Hashimoto,Miransky, arXiv:0912.4453

Hints from compositeness



Frampton,Hung,Sher, PRep330, 263, 2000;
Carpenter,Norton,Siegemund-Broka,Soni, PRL65, 153, 1990

The search for t',b' is tide up with the search for H !

Support from Flavor data

✓ **400 GeV < $m_{Q'}$ < 600 GeV** may help address **CP-asymmetries/anomalies in b-quark systems**

Hou,Nagashima,Raz,Soddu, JHEP,0609,012,2006;
Hou,Nagashima,Soddu, PRL95,141601,2005 & PRD76,016004,2007;
Soni,Aluk,Giri,Mohanta,Nandi,arXiv:0807.1971,2008

✓ Meson mixings (K,D,B) & b $\to$sγ allows a **Cabibbo angle** size for θ_{34} with **300 GeV < $m_{Q'}$ < 650 GeV**

Bobrowski,Lenz,Riedl,Rohrwild,PRD79,113006,2009;
Arhib,Hou,JHEP0609,9,2006;
Eilam,Melic,Trampetic,PRD80,116003,2009

Support from direct searches

- ✓ **Current CDF limit on the mass of a 4th generation heavy quark:**

  $m_{b'} > 340$ GeV

  T. Aaltonen et al. (CDF collaboration), arXiv:0912.1057 [hep-ex]

- ✓ **Higgs searches at the Tevatron via H → WW imply that**

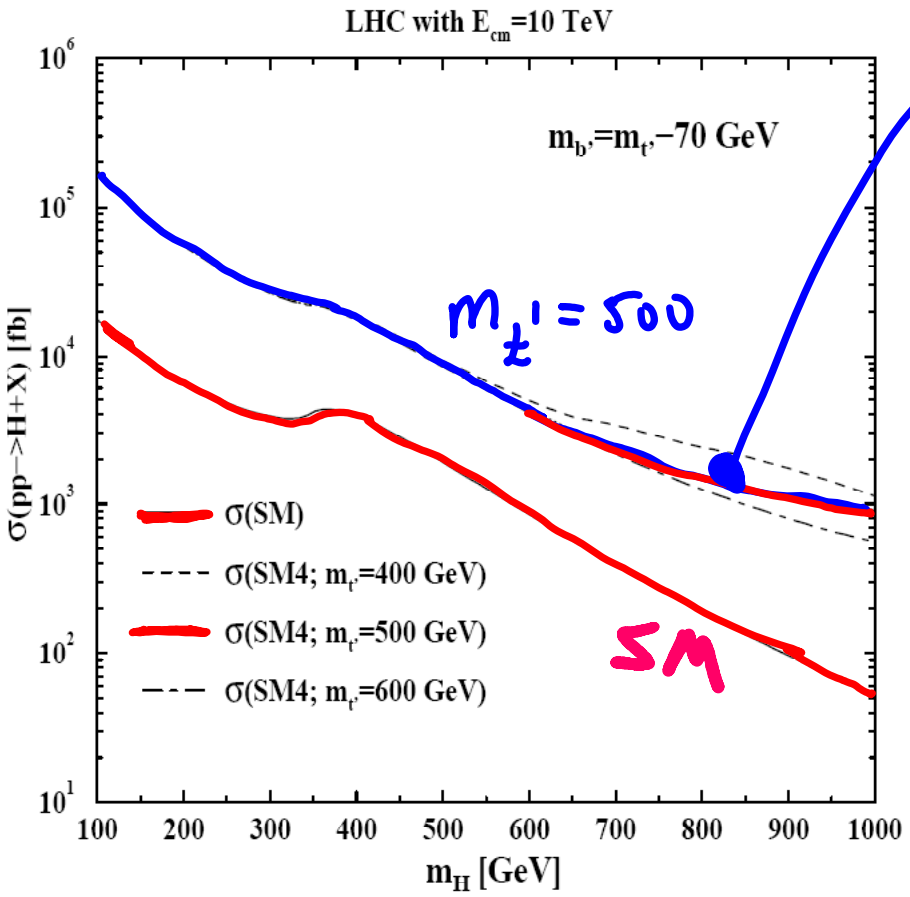
  m_H(SM4) is heavier than ~ 200 GeV

  (if not found within the window 115 – 140)

  www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H21

Heavy Higgs pheno@LHC in a nutshell

- With $m_{Q'} \sim 500$ GeV & $m_H < 2m_{Q'}$, heavy H decays still dominated by H->ZZ,WW,tt



$\sigma(pp \to H+X) \sim \mathcal{O}(1000)$ fb at $m_H = 800$ GeV

Factor of 10 enhancement

⇒ handy for a TeV scale H

"Golden mode" H->ZZ->4μ remains a useful Higgs discovery channel "all the way"

Decays of a composite Higgs to a single 4th-gen fermion

(the leading probes of the HQ'Q' Yukawa couplings)

- **Flavor conserving channels:**

$$H \to \bar{t}' t'^{\star} \to \bar{t}' b W^+ + h.c. \quad \& \quad H \to \bar{b}' b'^{\star} \to \bar{b}' t W^- + h.c.$$

- **Flavor violating channels:**

$$H \to t'\bar{t} + h.c. \quad \& \quad H \to b'\bar{b} + h.c.$$

Assume: $V_{tb} = V_{t'b'} = 1$ & $\theta_{34} \equiv V_{tb'} = V_{t'b} >> V_{t'd},\ V_{t's},\ V_{ub'},\ V_{cb'}$.

↳ BR(t'→bW), BR(b'→tW) ~ 1

Flavor conserving channels

"Naively" (with $m_H < 2m_{t'}, 2m_{b'}$) the 3-body flavor conserving decays lead to:

$$\left.\begin{aligned} BR(H \to t'\bar{t}'^{\star}) &\sim BR\left(H \to t'\bar{b}W^- \to (bW^+)_{t'}\bar{b}W^-\right) \\ BR(H \to b'\bar{b}'^{\star}) &\sim BR\left(H \to b'\bar{t}W^+ \to (tW^-)_{b'}\bar{t}W^+\right) \end{aligned}\right\} \sim 10^{-6} - 10^{-5}$$

BUT:

dramatically enhanced due to finite (large) width effects of the heavy Higgs …

e.g., in resonance Higgs production through gg-fusion

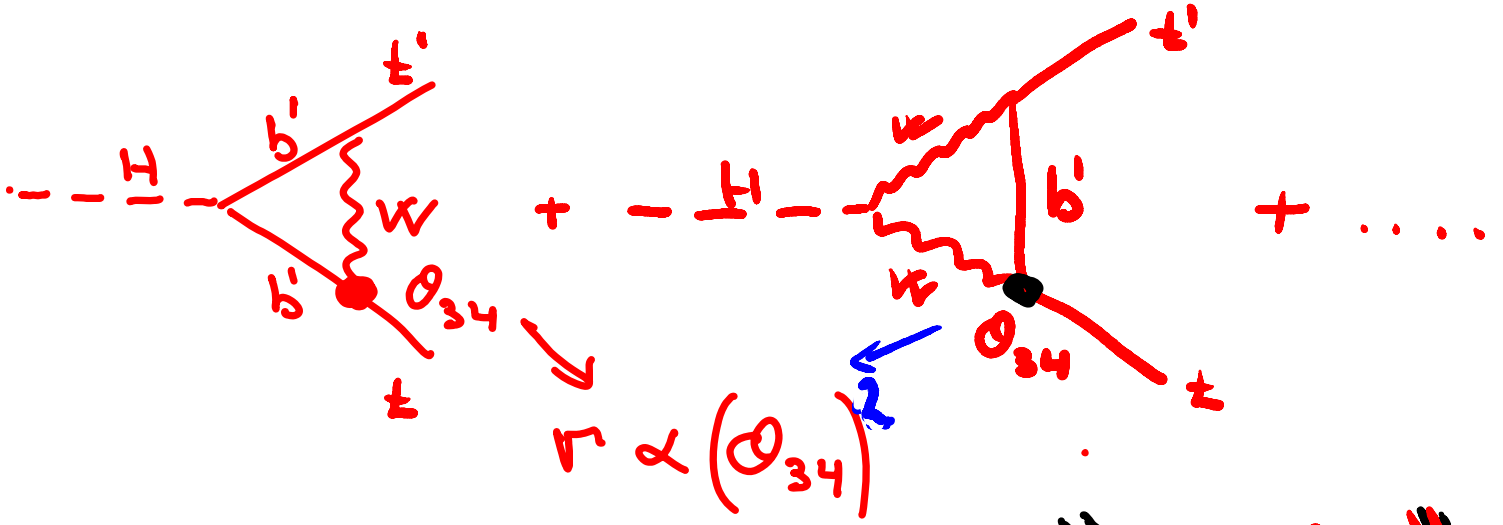
$$gg \to H \to \bar{t}'t'^{\star} \to \bar{t}'bW^+ + h.c.$$

$$gg \to H \to \bar{b}'b'^{\star} \to \bar{b}'tW^- + h.c.$$

Flavor changing channels

Note: 1. the case H→b'b @ m_H < 100 GeV mentioned in **Haeri,Soni,Eilam,PRL62,719,1989**

2. the cases t'→ tH & b' → bH (**i.e., $m_{t',b'} > m_H$**) extensively studied



* dominated by b' exchange → "GIM free"

* Similarly for H→b'b (t'-exchange dominates...)

Motivation

An estimate of the FC 1-loop H → Uu width in the limit that only the heaviest d-type quark (D) runs in the loop

(multiply by the appropriate GIM-suppression factor):

$$\Gamma(H \to U\bar{u}) \sim \left(\frac{|V_{UD}^{\star} V_{uD}|}{16\pi^2}\right)^2 \left(\frac{g^2}{4\pi}\right)^3 \left(\frac{m_D}{m_W}\right)^4 m_H$$

$\longrightarrow 10^9$!

$m_{b'} \sim 500$ GeV

$V_{t'b'} \sim 1$, $\theta_{34} \sim 0.15$

$\Rightarrow BR_{SM4}(H \to t't) \sim 10^9 \cdot BR_{SM}(H \to tc) \sim 10^{-4}$!

Note:

not “good enough” for $\Gamma_{SM4}(H \to tc)$

$$BR_{SM4}(H \to tc) \sim V_{cb'}^2 \cdot 10^9 \cdot BR_{SM}(H \to tc) \xrightarrow[V_{cb'} \sim 0.03-0.04]{\text{at best}} 10^{-7}$$

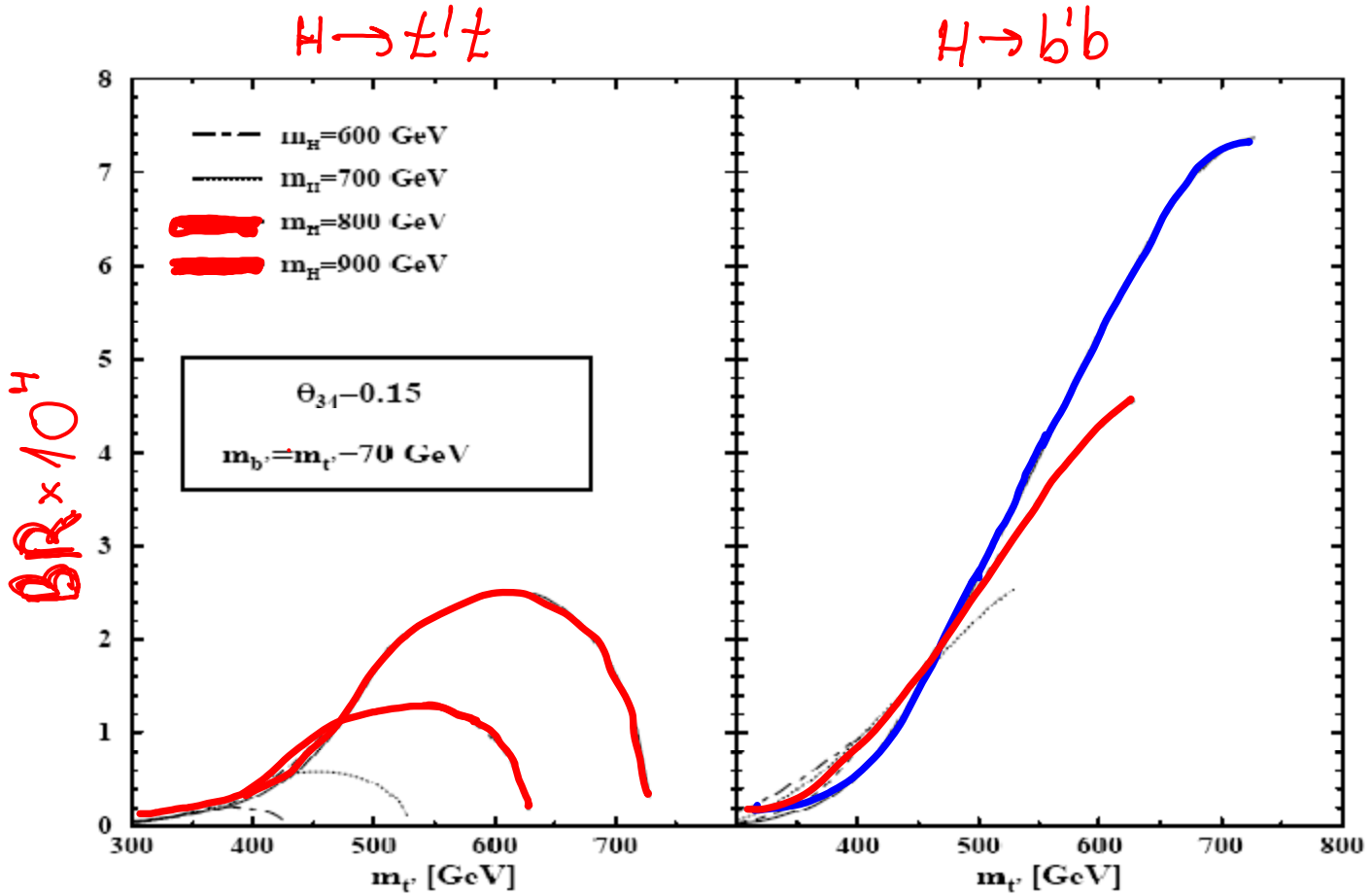
Eilam,Melic,Trampetic,PRD80,116003,2009

one typically finds:

$$10^{-4} < BR(t' \rightarrow tH) \, , \, BR(b' \rightarrow bH) < 10^{-2}$$

Haeri,Soni,Eilam,PRL62,719,1989; Hou,Stuart,PRL62,617,1989 & NPB320,277,1989 & PLB233,485,1989 & NPB349,91,1991 & PRD43,3669,1991; Sher,PRD61,057303,2000; Arhrib,Hou,PRD64,073016,2001; Arhib,Hou,JHEP0609,9,2006; Eilam,Melic,Trampetic,PRD80,116003,2009;

Typically, BR ~ 10^{-4} – 10^{-3} for $\theta_{34} = 0.15$



★ **Expecting tens such H→tt' & H→ bb' events @LHC which is able to produce 10^5 TeV-scale Higgs a year with *O*(100) fb^{-1}**

Estimate H-width effects in **gg → H → F** using the relativistic Breit-Wigner resonance formula:

$$\hat{\sigma}_H(\hat{s}) = \hat{\sigma}_{gg}(\hat{s}) \cdot \hat{s} \cdot \hat{BW}(\hat{s}) \cdot BR(H \to F)(\hat{s})$$

$$\hat{\sigma}_{gg}(\hat{s}) = \frac{\pi^2}{8m_H^3}\Gamma(H \to gg)$$

$$\hat{BW}(\hat{s}) = \frac{m_H\Gamma_H/\pi}{[(\hat{s}-m_H^2)^2 + m_H^2\Gamma_H^2]}$$

$$m_H\Gamma_H \to \sqrt{\hat{s}}\Gamma_H(\hat{s})$$

$$\Gamma_H(\hat{s}) = \sqrt{\hat{s}}\Gamma_H/m_H$$

$$\hat{\sigma}_H(\hat{s}) = \frac{\pi\,(\hat{s}/m_H^2)\,\Gamma(H \to gg)(\hat{s})\Gamma(H \to F)(\hat{s})}{8\left[(\hat{s}-m_H^2)^2 + (\hat{s}\Gamma_H/m_H)^2\right]}$$

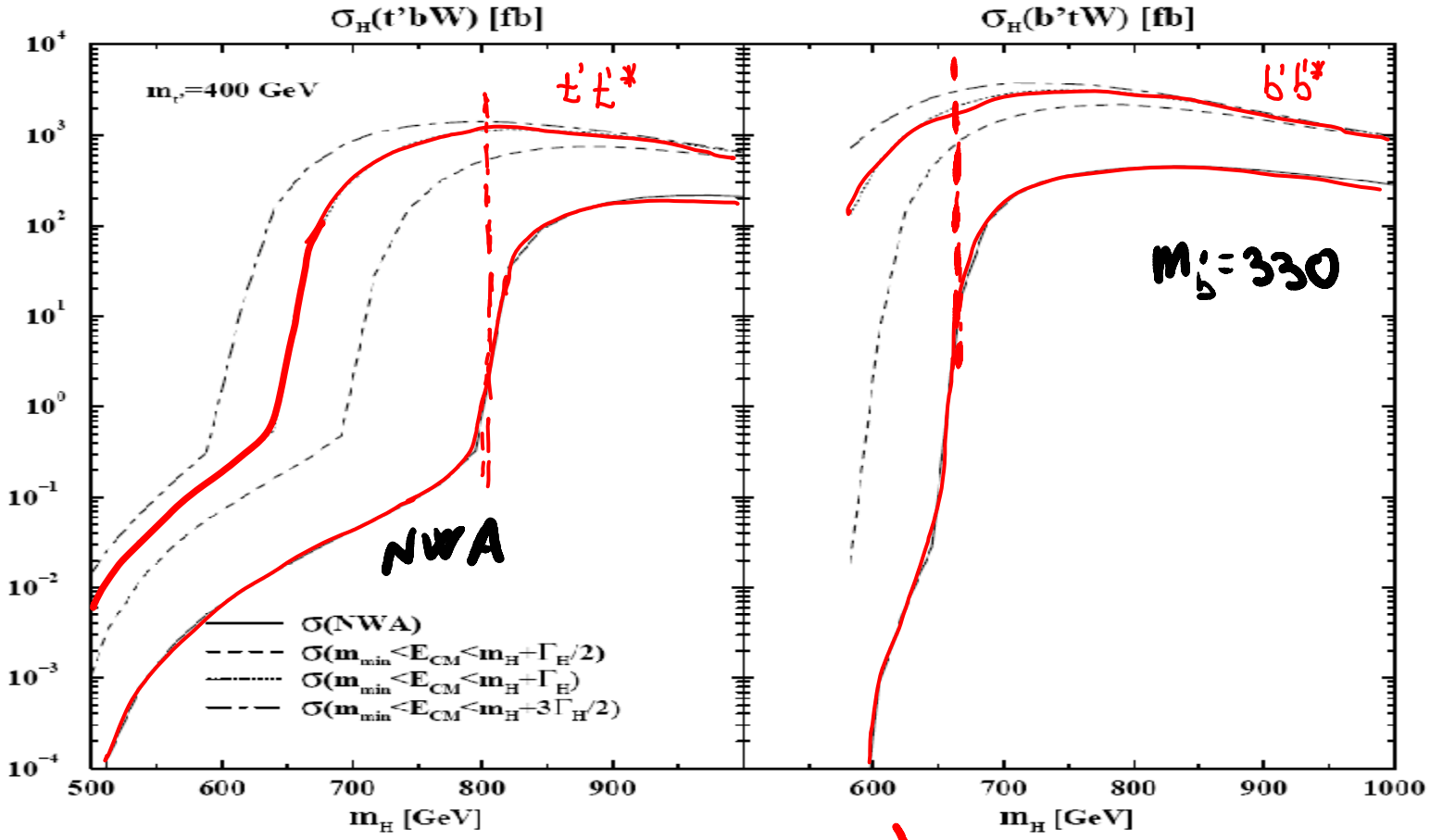
Estimate H-width effects by integrating $\hat{\sigma}_H(\hat{s})$
over some finite range around resonance
i.e., depending on the Higgs mass/width

$$\sigma_H(t'bW) \equiv pp \to H + X \to t't'^{\star} + h.c. + X \to t'bW^+ + h.c. + X$$
$$\sigma_H(b'tW) \equiv pp \to H + X \to b'b'^{\star} + h.c. + X \to b'tW^- + h.c. + X$$

$$\frac{dL}{d\tau}(\hat{s} = \tau s) \equiv \int_\tau^1 \frac{dx}{x} g(x, \hat{s}) g(\frac{\tau}{x}, \hat{s})$$

$$\sigma_H = \int_{\tau_{min}}^{\tau_{max}} \frac{dL}{d\tau} \hat{\sigma}_H d\tau$$

huge effects near threshold crossover
independent of ϑ_{34} …



e.g. $\sigma_H(pp \to H \to t'bW) \sim 300$ fb at $m_H \sim 700$ GeV

(where $\sigma_H(NWA) \sim 0.03$ fb) $m_{t'} \sim 400$ GeV

Background from QCD (continuum) production under control:

e.g.,

m_H=800 GeV, $m_{t'}$=500 GeV, $m_{b'}$=430 GeV

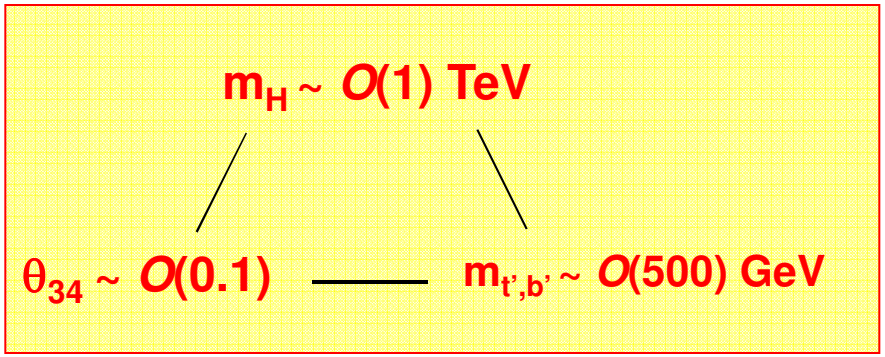
+ signal & backg. integrated over one width ($\Gamma_H \sim 300$ GeV)

$pp \to t'bW + h.c. + X$		$pp \to b'tW + h.c. + X$	
$\sigma_H(t'bW)$ [fb]	$\sigma_{QCD}(t'bW)$ [fb]	$\sigma_H(b'tW)$ [fb]	$\sigma_{QCD}(b'tW)$ [fb]
58	280	504	1716

$\frac{S}{\sqrt{B}} \sim \mathcal{O}(100)$ with $\mathcal{L} \sim \mathcal{O}(100)\ fb^{-1}$

Summary & concluding remarks

- **Precision EW data + flavor data may be telling us that compositeness & SM4 are linked in a "3-prong composite solution":**



  - **t' & b' (& perheps also t) are viewed as agents of EWSB**
  - **t' & b' strong Yukawa couplings are probed in H-decays to a single t' & b'**

- **Interesting phenomenological implications:**

  – **Effects of the large Higgs width dramatically enhance**

  $$H \to t't'^* \to t'bW \;\&\; H \to b'b'^* \to b'tW$$

  expecting up to 10^5 such events @LHC with O(100) fb^{-1} via the gluon-fusion channel

  $$gg \to H \to t'bW,\ b'tW$$

  – **This mechanism is particularly interesting for heavy *O*(500) GeV 4^{th}-gen. leptons, e.g.**

  enhanced $H \to \nu'\nu'^* \to \nu'\mu W \to 4\mu + \not{E}_T$ can compete with the "golden mode" $H \to ZZ \to 4\mu$

  – **Single t',b' production channels $gg \to H \to t'bW, b'tW$ may be rich in exhibiting various types of CP-asymmetries in analogy to CPV in single top production …**

– a large θ_{34} might lead to

BR(H→t't) & BR(H →b'b) ~ 10^{-4} – 10^{-3}

potentially observable @LHC with O(100) fb^{-1}

these are the only FC channels with potentially observable rates …

So don't be discouraged by the fact that m_H might be smaller than $2m_{Q'}$
i.e., no H → Q'Q'

**If m_H ~ O(1) TeV then one can still probe its decays to 4th generation fermions,
thanks to either its large width or to a large θ_{34}**