If not SUSY, what?

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Fayet Fest

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SUSY or not SUSY?

- On pure aesthetic and theoretic grounds
  a very compelling symmetry of nature

- Unambiguous discovery signal: find the superpartners
  (gauge coupling unification not enough)

- Since SUSY broken, the key question is:
  Where are the superpartners?

  1. SUSY may intervene to address the "hierarchy" problem

$$\delta m_h^2 \sim \frac{3y_t^2}{4\pi^2}\Lambda^2 \sim m_h^2(\frac{\Lambda}{400\ GeV})^2$$

  2. SUSY may provide a stable weakly-interaction
     neutral particle as Dark Matter (See tomorrow afternoon)

Where are the superpartners?

$$\frac{m_h^2}{2} \approx -|\mu|^2 + m_{H_u}^2 \qquad m_{\tilde{h}}$$

$$\delta m_{H_u}^2 \approx -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2)\log M/m_{\tilde{t}}$$

Define an "inverse fine-tuning" measure

$$\Delta = \frac{\delta m_h^2}{m_h^2}, \quad Max_{a_i}\frac{dm_h^2/m_h^2}{da_i/a_i}, \ldots$$

G. Ross (sept 2016)

low energy

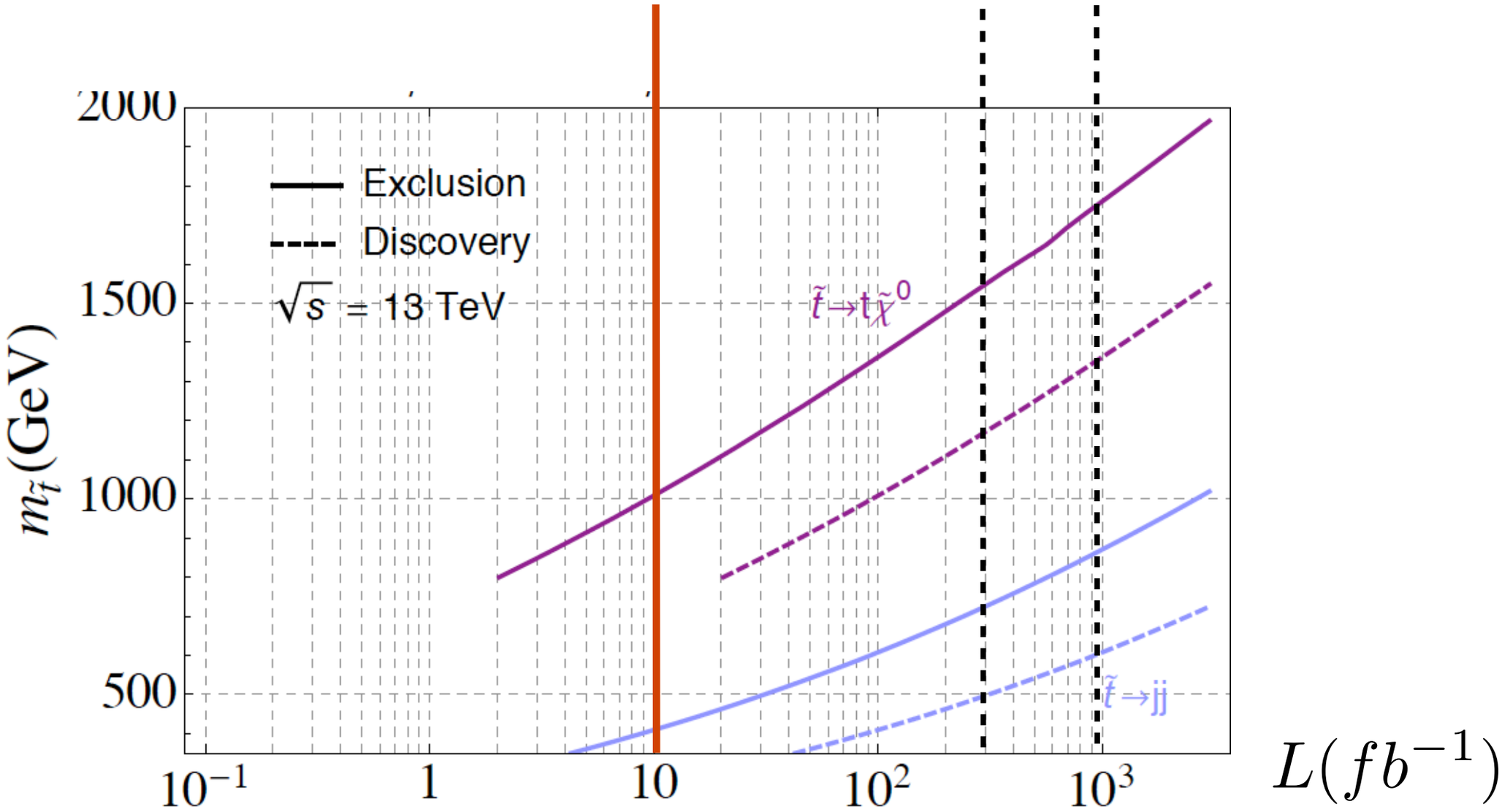
Is Λ SUSY alive ?

$\Delta^{CMSSM} > 350$ ✗ $\quad \Delta^{(C)MSSM} > 40\,(200)^{SUSY\ DM}$

$\Delta^{CGMSSM} > 60$ ✗ $\quad \Delta^{(C)GNMMS} > 20$ ✔8TEV 13TEV?

$\Delta^{(C)MSSM+\mu'} > 20\,(40)^{SUSY DM}$

Shall the s-top be found (or any other s-partner)?



Yes, even though one needs a bit of s-faith (J. Ellis, Sept 2016) to be sure that it will happen at LHC (or even in a future collider?) with current information

The (historical) Mirror World

$$\mathcal{L}_{\rm MW} = \mathcal{L}_{321}(g_i, y_f, \lambda, m_H) + \mathcal{L}'_{3'2'1'}(g_{i'}, y_{f'}, \lambda', m_{H'})$$

$$\lambda' = \lambda, \qquad m_{H'} = m_H, \qquad g_{i'} = g_i, \qquad y_{t'} = y_t$$

3 motivations:

1. Restore space parity

Lee, Yang 1956

Kobzarev, Okun, Pomeranchuk 1966

2. Mirror baryons, as DM, may explain comparable Ω_B and Ω_{DM}
(unlike in any other discussed Baryogenesis picture)

Blinnikov, Khlopov 1982

3. Make the Higgs a (quasi) Goldstone boson: Twin Higgs

Chacko, Goh, Harnik 2005

Twin Higgs

$$\mathcal{L}_{\rm TH} = \mathcal{L}_{321}(g_i, y_f, \lambda, m_H) + \mathcal{L}'_{3'2'1'}(g_{i'}, y_{f'}, \lambda', m_{H'}) + 2\lambda'' H^\dagger H H'^\dagger H'$$

and take $\lambda = \lambda' = \lambda''$ so that

$V(H, H') \to V(\mathcal{H}), \quad |\mathcal{H}|^2 = |H|^2 + |H'|^2$ is $SO(8)$-symmetric

$$\Downarrow$$

$$V(\mathcal{H}) : SO(8) \to SO(7) \Rightarrow 7\ PGBs,\ SU(2)' \times U(1)' \to U(1)'_{em}$$

+ $SU(2) \times U(1)$ unbroken and 1 massless Higgs doublet

3 problems

1. Where is the Dark/Mirror radiation?

$$\gamma',\ \nu' \Rightarrow \Delta N_{eff}$$ (bounded by Planck)

2. $\Omega_{DM} \approx 5\ \Omega_B$, so not $\Omega_{DM}(=\Omega_{B'}) = \Omega_B$

3. Some breaking of the mirror symmetry needed
to get $< H > \equiv v$ < $< H' > \equiv v'$, where

$h = cos\theta H + sin\theta H'$ the observed Higgs boson

$h' = -sin\theta H + cos\theta H'$ a heavier Higgs boson

$tan\theta \approx \frac{v}{v'}$ (hence bounded from above)

A (the only) common solution

Minimal Mirror Twin Higgs

B, Hall, Gregoire 2006
B, Hall, Harigaya 2016

$$y_t = y_{t'} \approx 1$$

$$y_{f' \neq t'} \text{ > (>>) } y_{f \neq t}$$

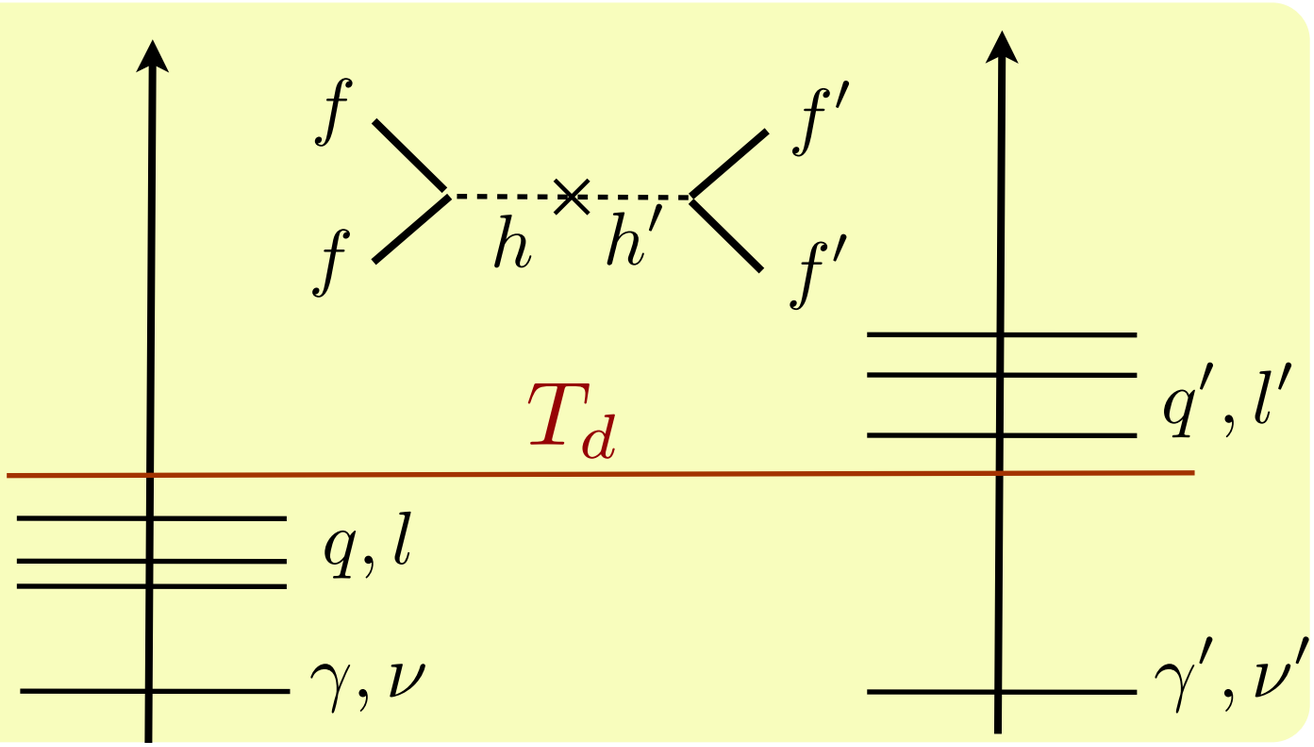
as in a Froggatt-Nielsen picture of flavour

$$y_{f \neq t} = (\phi/M)^{q_f} \quad y_{f' \neq t'} = (\phi'/M)^{q_{f'}}$$

$$y_t \approx 1 \qquad y_{t'} \approx 1$$

with

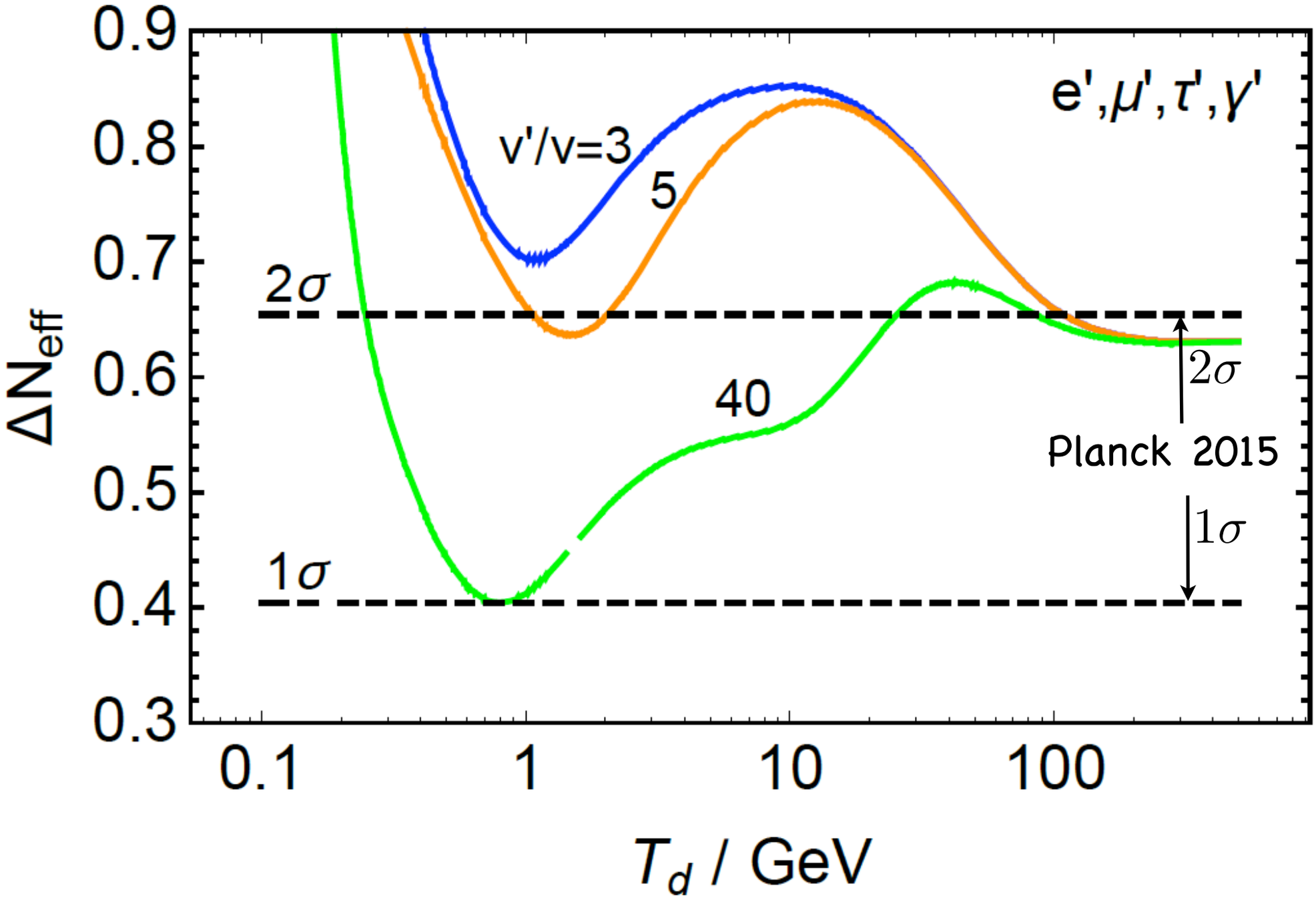
$$< \phi' > \gg < \phi >$$



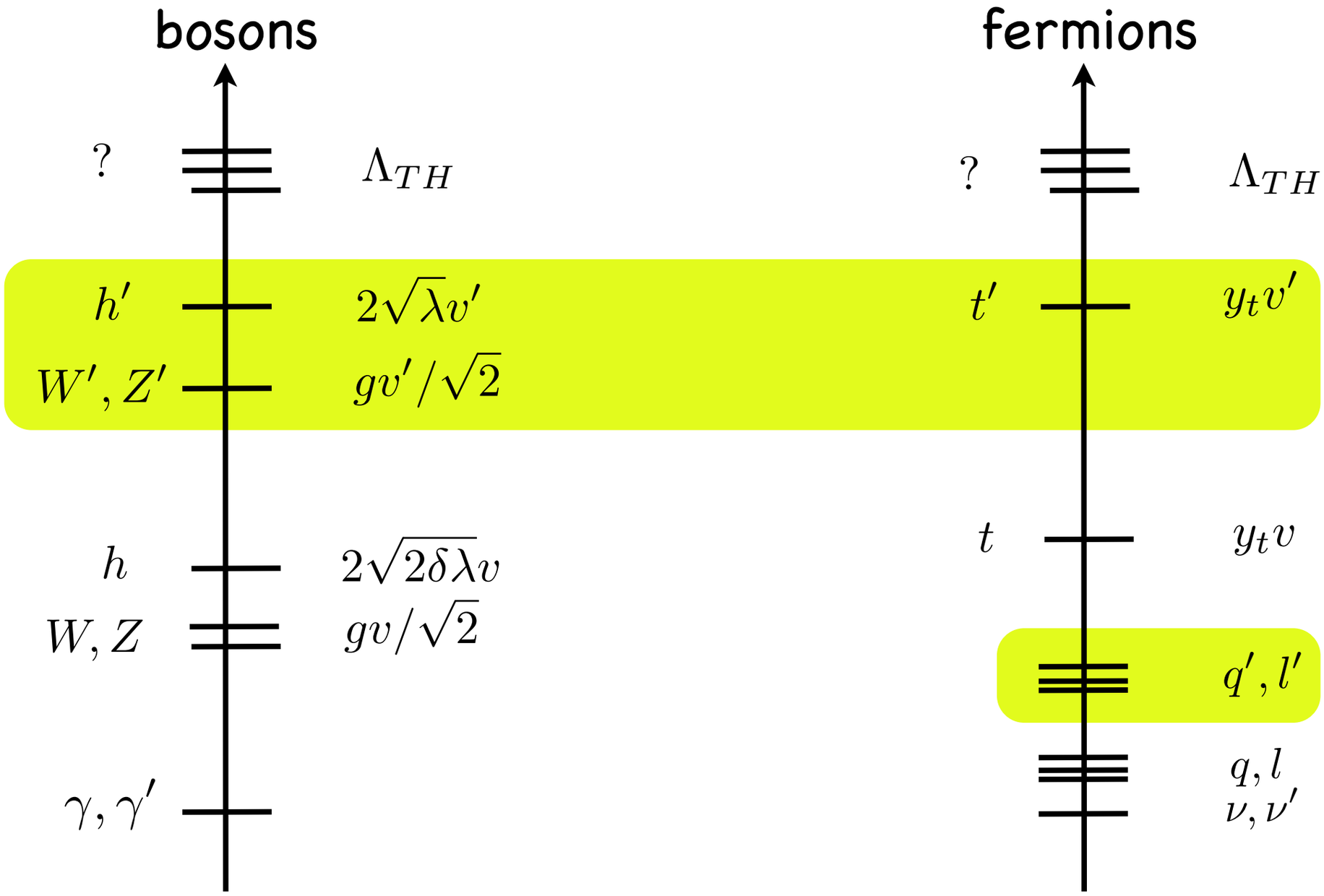
$$\Delta V = \Delta m^2 H^+ H$$

$$\Delta m^2 \simeq \sum_{f \neq t} \frac{N_{f'}}{8\pi^2} y_{f'}^2(\Lambda)\, \Lambda^2 \simeq \frac{1}{4} \frac{v'^2}{v^2} m_h^2$$

Consider only γ', e', μ', τ' with $m_{e',\mu',\tau'} = (v'/v) m_{e,\mu,\tau}$



The MTHW spectrum



Physics at Λ_{TH} (SUSY, composite, extra-dim.s, etc.?)
affects $m_{h'}$ (1 TeV?) but not m_h

Is this why nothing new has been seen so far at LHC?

Signals

1. h' production

2. Dark radiation ΔN_{eff}

3. Precision on Higgs decays

4. Dark matter detection

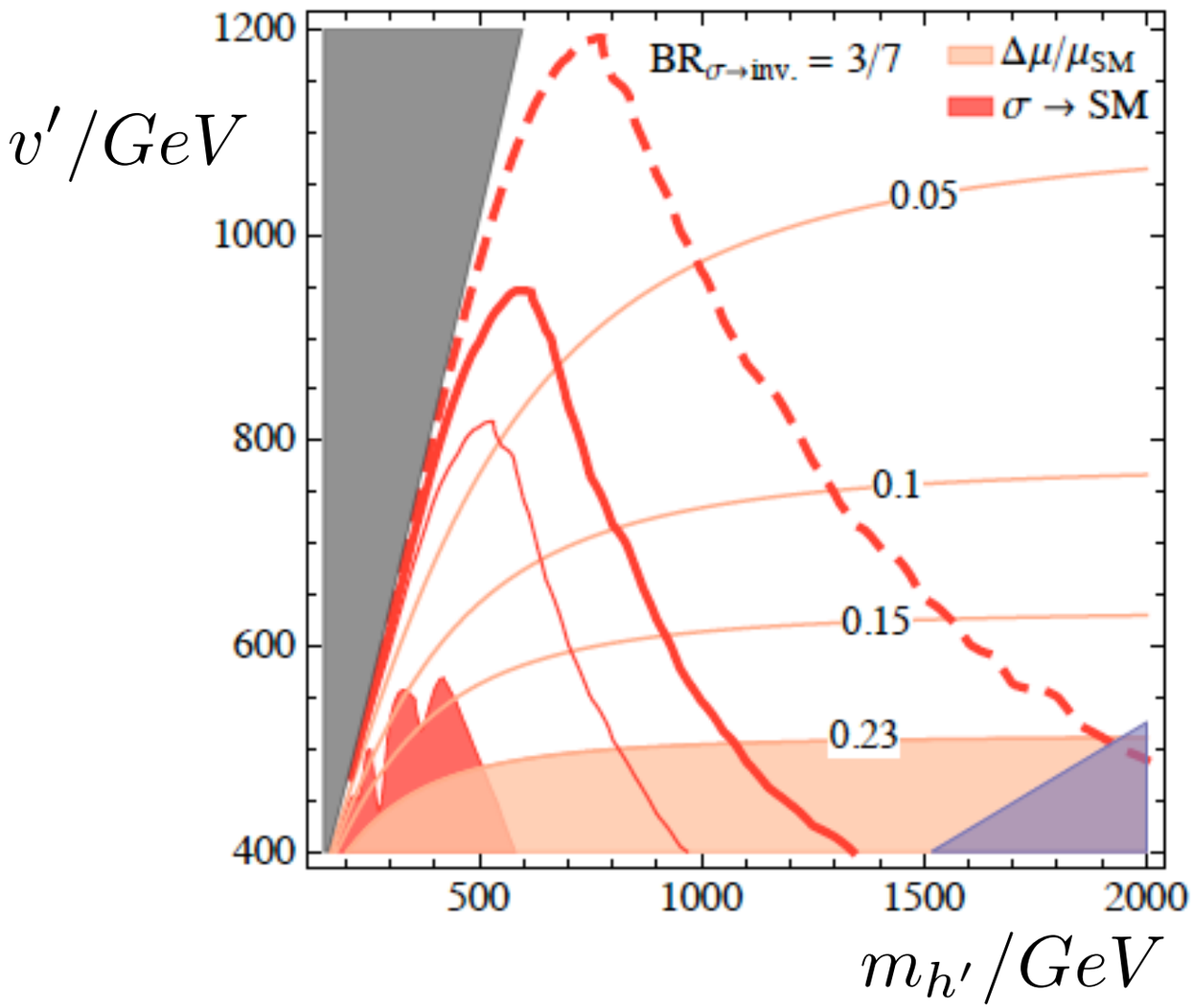
h' production and decays

B, Hall, Gregoire 2005

$$\sigma(pp \to \tilde{h}') \approx (\frac{v}{v'})^2 \sigma(pp \to h_{SM}(m = m_{h'}))$$ via a top loop

Neglecting phase space

f	ZZ	WW	hh	$W'W'$	$Z'Z'$
$\Gamma(\tilde{h}' \to f)$	1	2	1	2	1



$LHC13 - 100 fb^{-1}$

$LHC14 - 300 fb^{-1}$

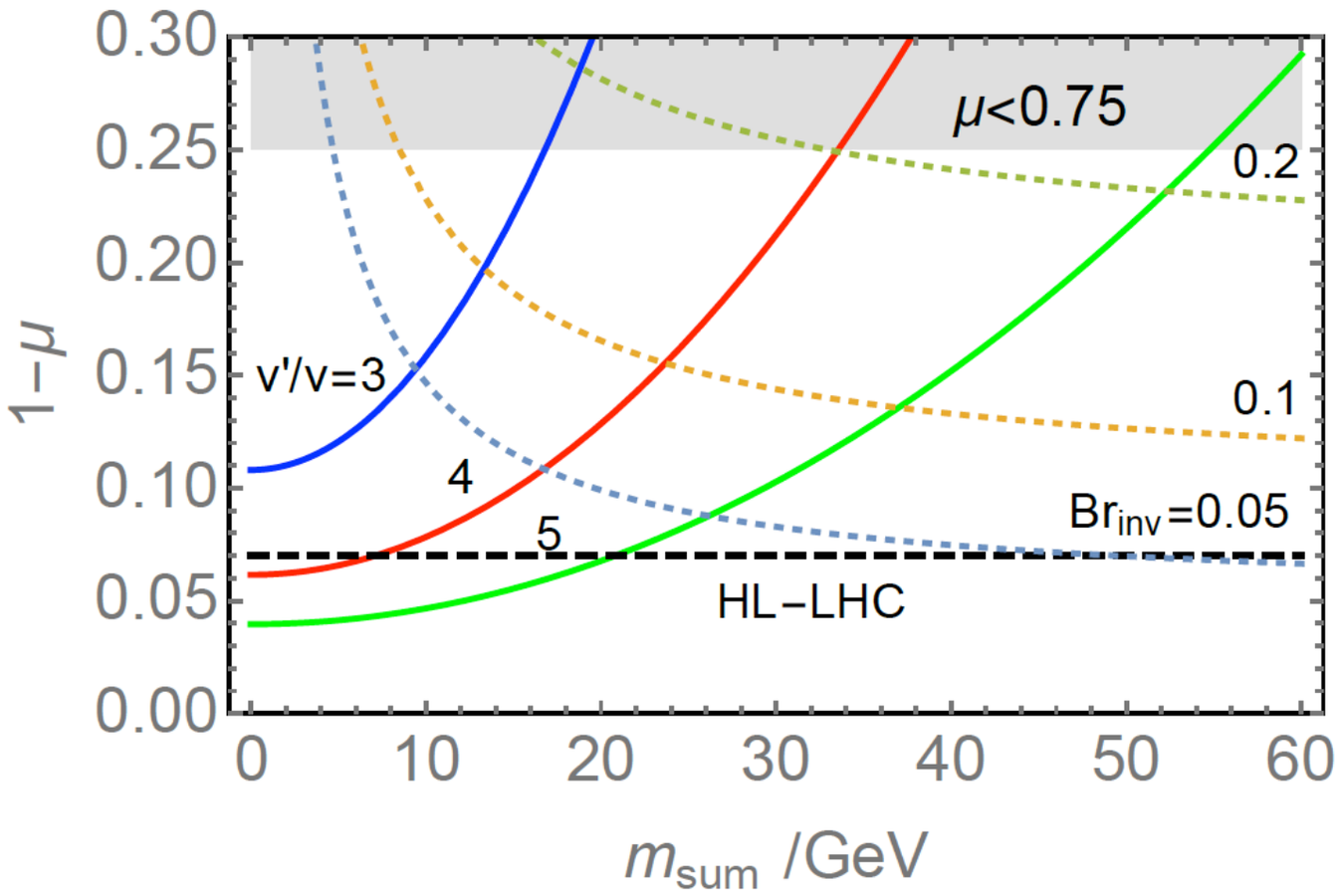
$HL - LHC - 3ab^{-1}$

Buttazzo, Sala, Tesi 2015

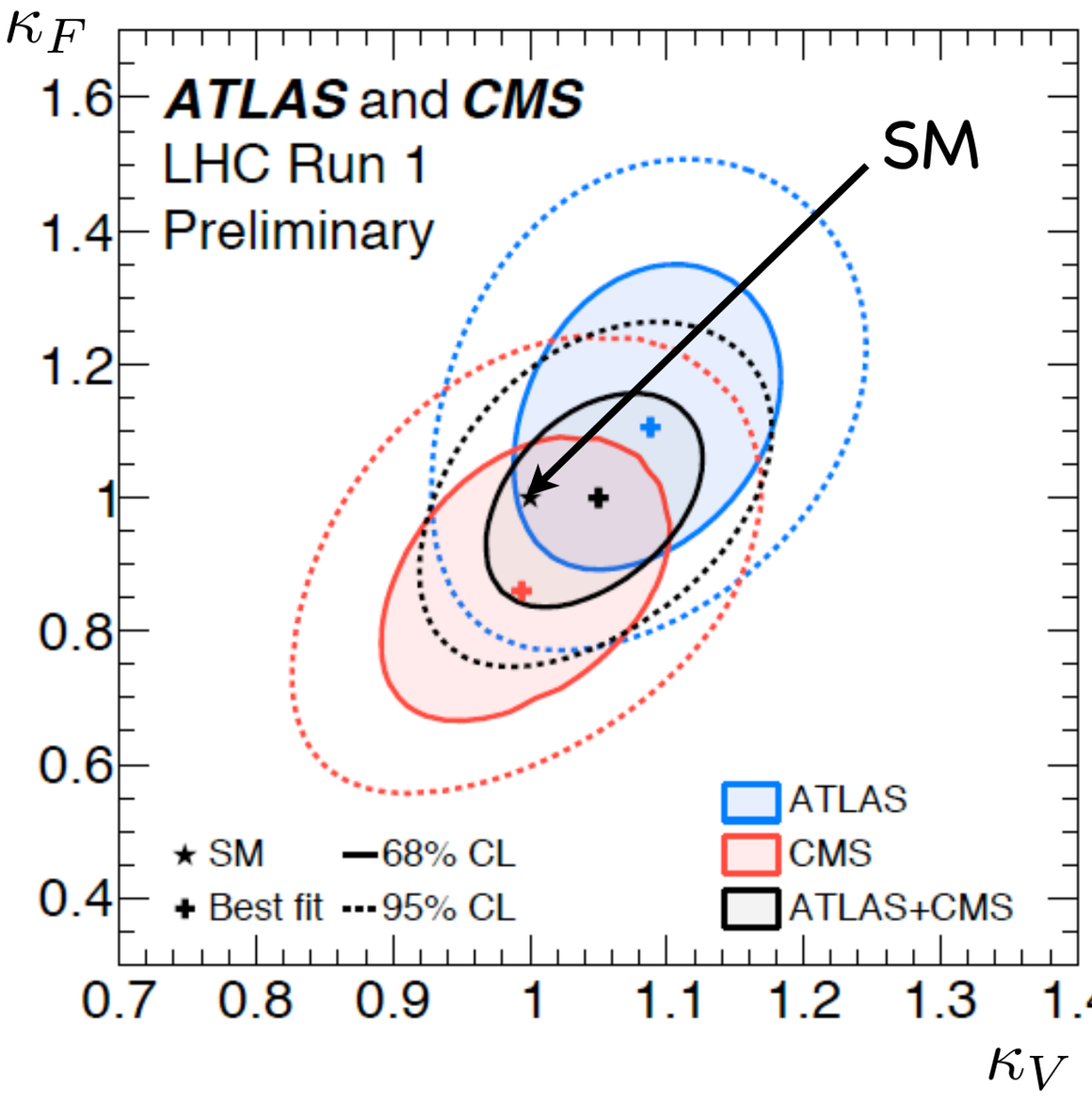
Precision on Higgs couplings

$$h = cos\theta H + sin\theta H' \qquad tan\theta \approx \frac{v}{v'} \qquad h \to i_{SM}, f'\bar{f}'$$

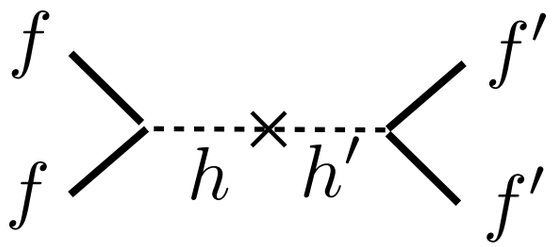
$$\mu(i_{SM}) \equiv \frac{\sigma^{TH}(pp \to i_{SM})}{\sigma^{SM}(pp \to i_{SM})} = \mu = cos^2\theta(1 - Br_{inv})$$



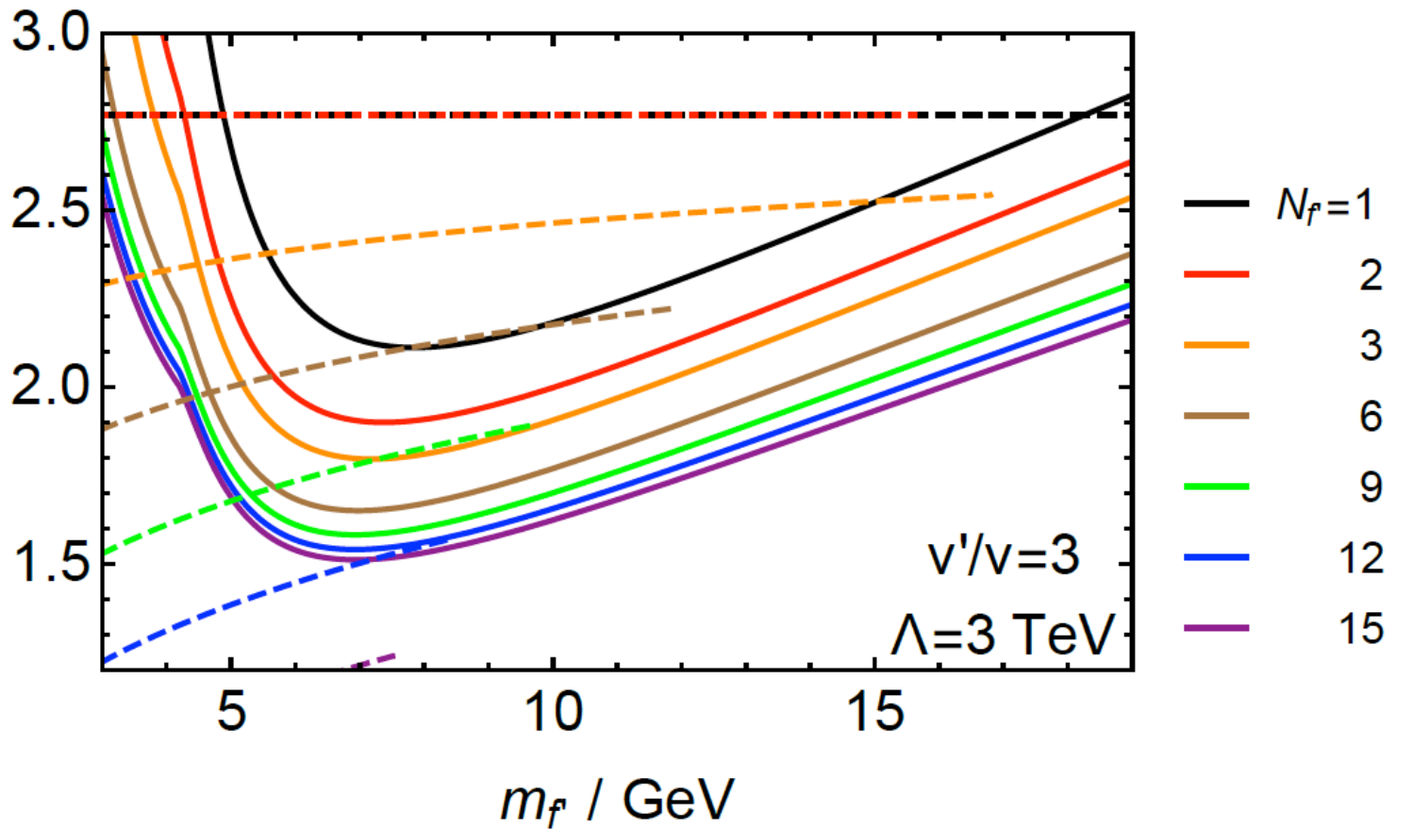
$$m^2_{\rm sum} \equiv \sum_{f',2m_{f'}<m_h} m^2_{f'} \frac{N_{f'}}{3} \left(\frac{1.3}{\delta_{f',m_h}}\right)^2$$



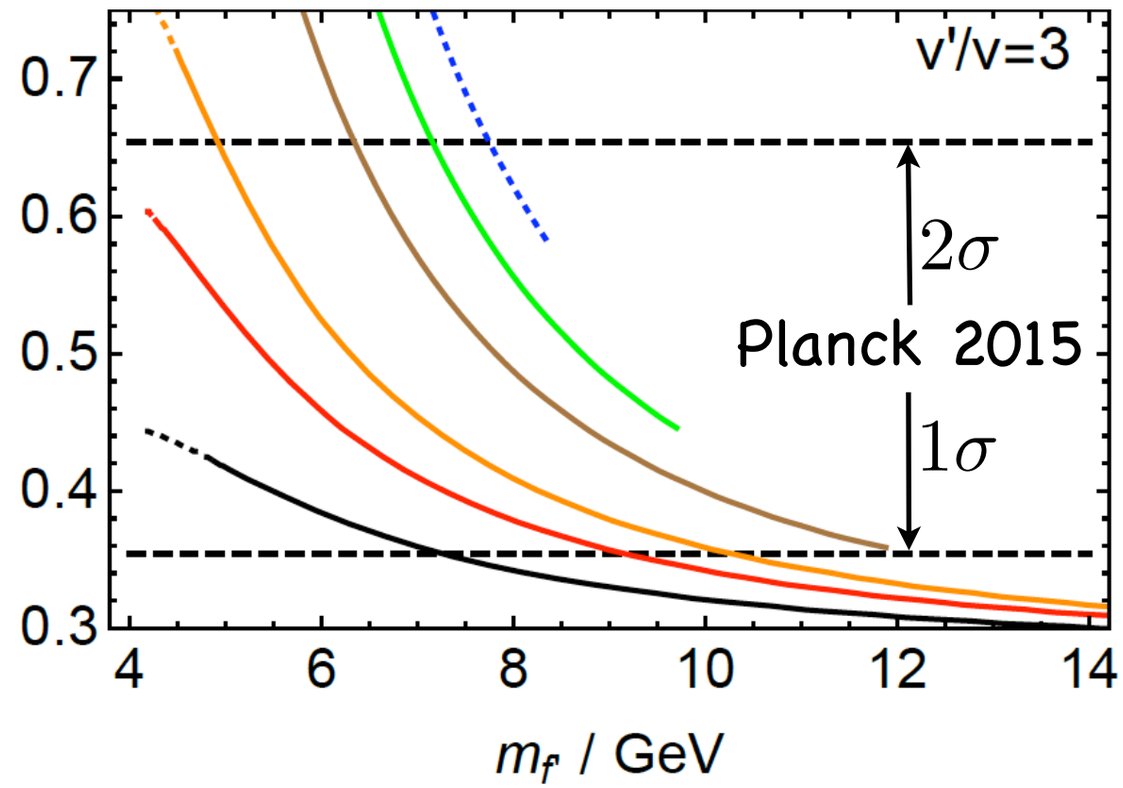
Dark Radiation $\Delta N_{eff} = \frac{\rho_{\gamma',\nu',f'}}{\rho_{1\nu}}|_{now}$



$T'_c \div T_d(GeV)$



ΔN_{eff}



N_f = number of f' with $2m_{f'} < m_h$ $(N_{l'} = 1, N_{q'} = 3)$

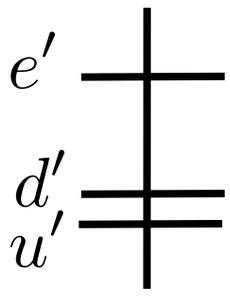
left, dotted lines: QCD' phase transition temperature T'_c

left, full lines: decoupling temperature of the mirror world T_d

What's needed to suppress ΔN_{eff} is $T'_c > T_d$

Dark Matter

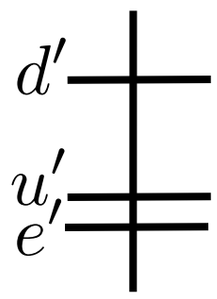
B′, Q′, L′ conserved - Mirror DM depends on the spectrum of the lightest mirror fermions



at $T < m_{e'}$ $\quad e' \to \bar{u}' d' \nu'$

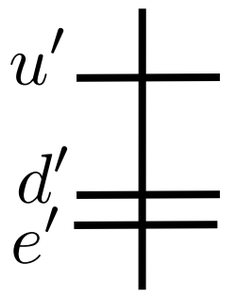
stable hadrons: $M'_{ud}, B'_{uuu}, B'_{uud}, B'_{udd}, B'_{ddd}$

$M'_{u\bar{d}} + B'_{ddd} \to B'_{udd}\,(+\gamma') \quad B'_{uud} + B'_{ddd} \to 2B'_{udd}\,(+\gamma')$

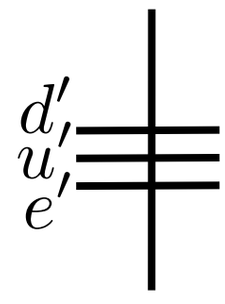


B'_{uuu} and e′ stable

and recombining into a mirror atom $B'_{uuu} + 2e'$



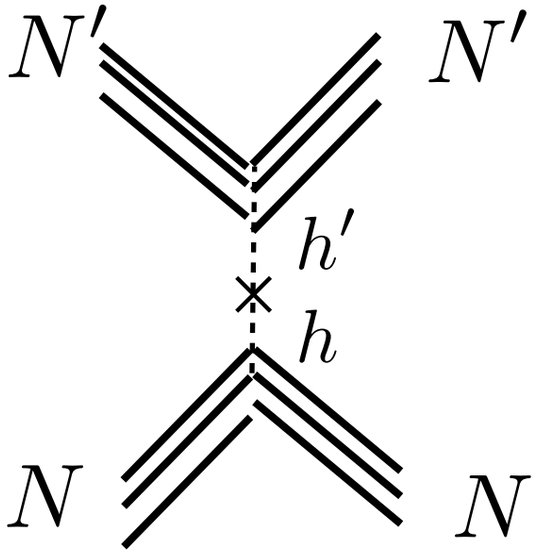
$B'_{ddd} + \bar{e}'$



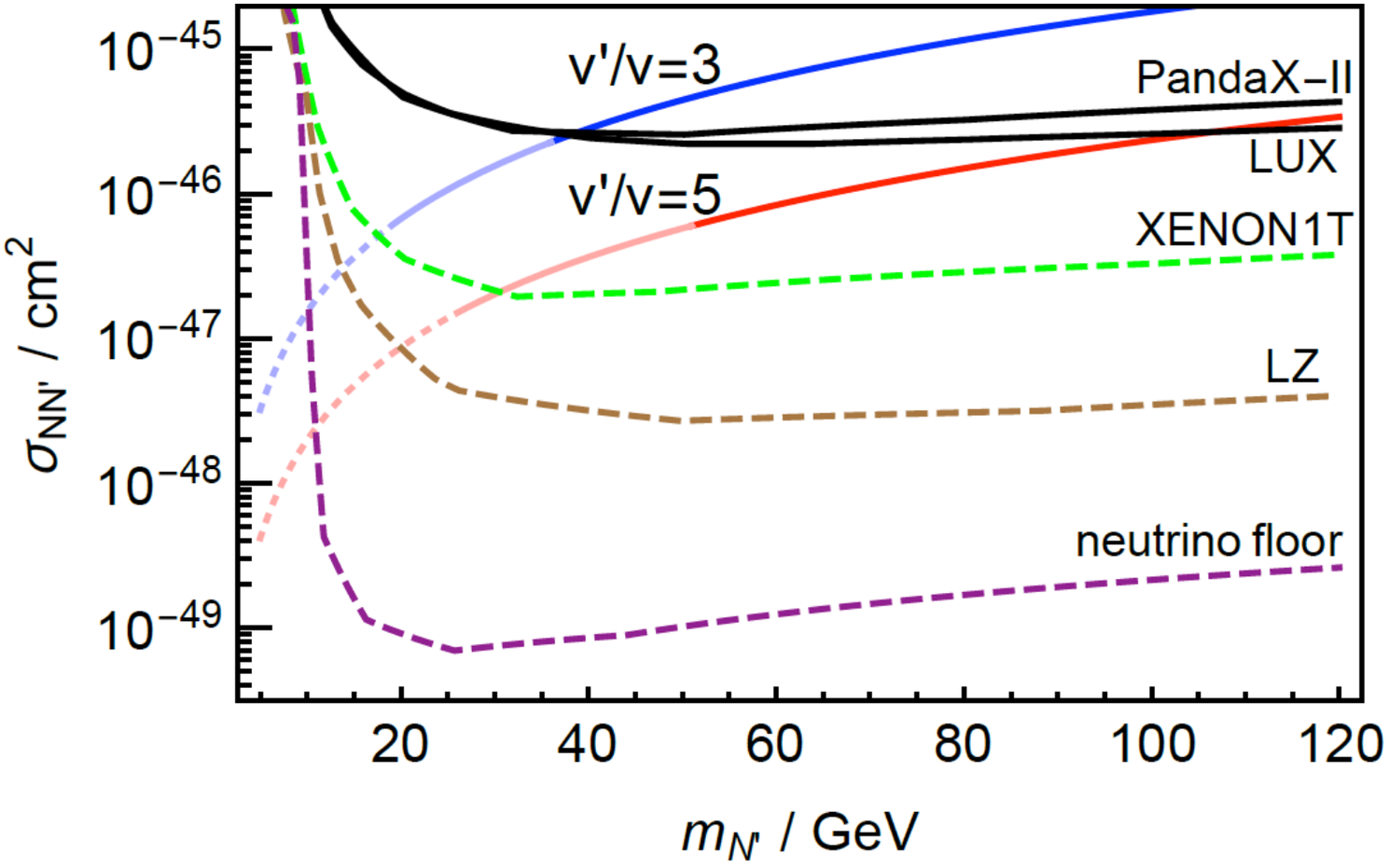
B'_{udd}

Note that, in any case, DM is self-interacting

Dark Matter direct detection



$$\sigma_{NN'} = \frac{0.028}{\pi} \frac{m_{N'}^2 m_N^2}{v'^4 m_h^4} \left(\frac{m_N m_{N'}}{m_N + m_{N'}} \right)^2$$



Conclusions

Had some superpartner shown up by now in some experiment, a day like this would have been glorious for Pierre Fayet and for the ENS in general

Perhaps the s-mirror world is the reason why this has not happened so far.

Or perhaps not.

In any case, in spite of the fact that I was convinced that SUSY would have shown up already at LEP, I keep s-faith that some signal will arise sooner or later.

Better sooner than later, though, given...

The Mirror World

Lee, Yang 1956

Kobzarev, Okun, Pomeranchuk 1966

Berezhiani 2006 and ref.s therein

Can one restore parity?

Introduce:

$$SU_{321} : (A^a_\mu, H, f_L, f_R) \qquad SU'_{321} : (A^{a\prime}_\mu, H', f'_L, f'_R)$$

and require that $\mathcal{L}_{SM} + \mathcal{L}'_{SM}$ be invariant under

$$(\vec{x}, t) \to (-\vec{x}, t)$$

$$f_L \leftrightarrow \gamma_0 (f'_L)^c, \quad f_R \leftrightarrow \gamma_0 (f'_R)^c \qquad [f_L \leftrightarrow \gamma_0 f_R]$$

$$H \leftrightarrow H', \quad A^a_\mu \leftrightarrow A^{a\prime}_{\tilde{\mu}}$$

Need:

$$m_H = m_{H'}, \quad \lambda = \lambda', \quad g_{3,2,1} = g'_{3,2,1}, \quad Y = Y'^*$$

The Mirror Twin Higgs World

The mirror world with a maximally symmetric Higgs system

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}'_{gauge} + \mathcal{L}_Y + \mathcal{L}'_Y + V(H, H')$$

$$V(H, H') = V_{SO(8)-inv} + V_{Z_2-inv} + V_{Z_2-broken}$$

$$V_{Z_2-inv} = \delta\lambda(|H|^4 + |H'|^4) \qquad V_{Z_2-broken} = \delta m^2 |H|^2$$

Minimizing the potential for $\delta\lambda << \lambda,\ \delta m^2 << m^2$

$$v'^2 =< H' >^2 = -\frac{m^2}{2\lambda} \qquad v^2 =< H >^2 = \frac{v'^2}{2}(1 - \frac{\delta m^2}{2\delta\lambda v'^2})$$

$$m^2_{\tilde{h}'} = 4\lambda v'^2 \qquad m^2_{\tilde{h}} = 8\delta\lambda v^2$$

$$\tilde{h}' = s_\theta h + c_\theta h' \qquad \tilde{h} = c_\theta h - s_\theta h'$$

$$\tan\theta = \frac{v}{v'}$$

what does one gain?

Fine tuning in the MTHW

$$v'^2 =< H' >^2 = -\frac{m^2}{2\lambda} \qquad v^2 =< H >^2 = \frac{v'^2}{2}(1 - \frac{\delta m^2}{2\delta\lambda v'^2})$$

need to fine tune v' (or $m_{h'}$) and v/v'

$$\Delta_{m_h^{TH}} = \Delta_{m'_h}\Delta_{v/v'}$$ (if both Δ's > 1)

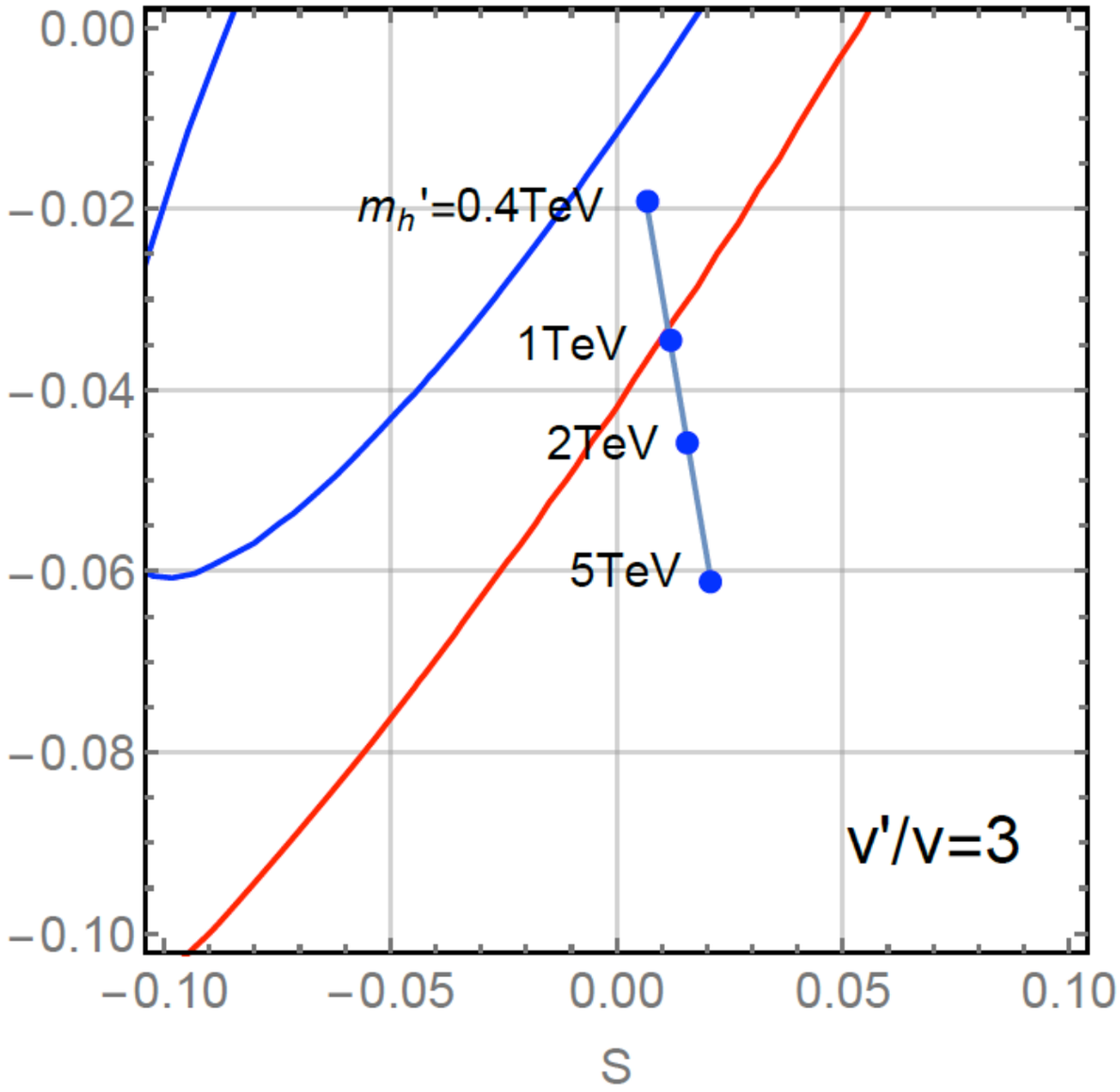
$$\Delta_{m_{h'}} = \frac{3}{4\pi^2}\frac{y_t^2\Lambda_{TH}^2}{m_{h'}^2} \qquad \Delta_{v/v'} = \frac{d\log v^2}{d\log\delta m^2} \approx \frac{1}{2}\frac{v'^2}{v^2}$$

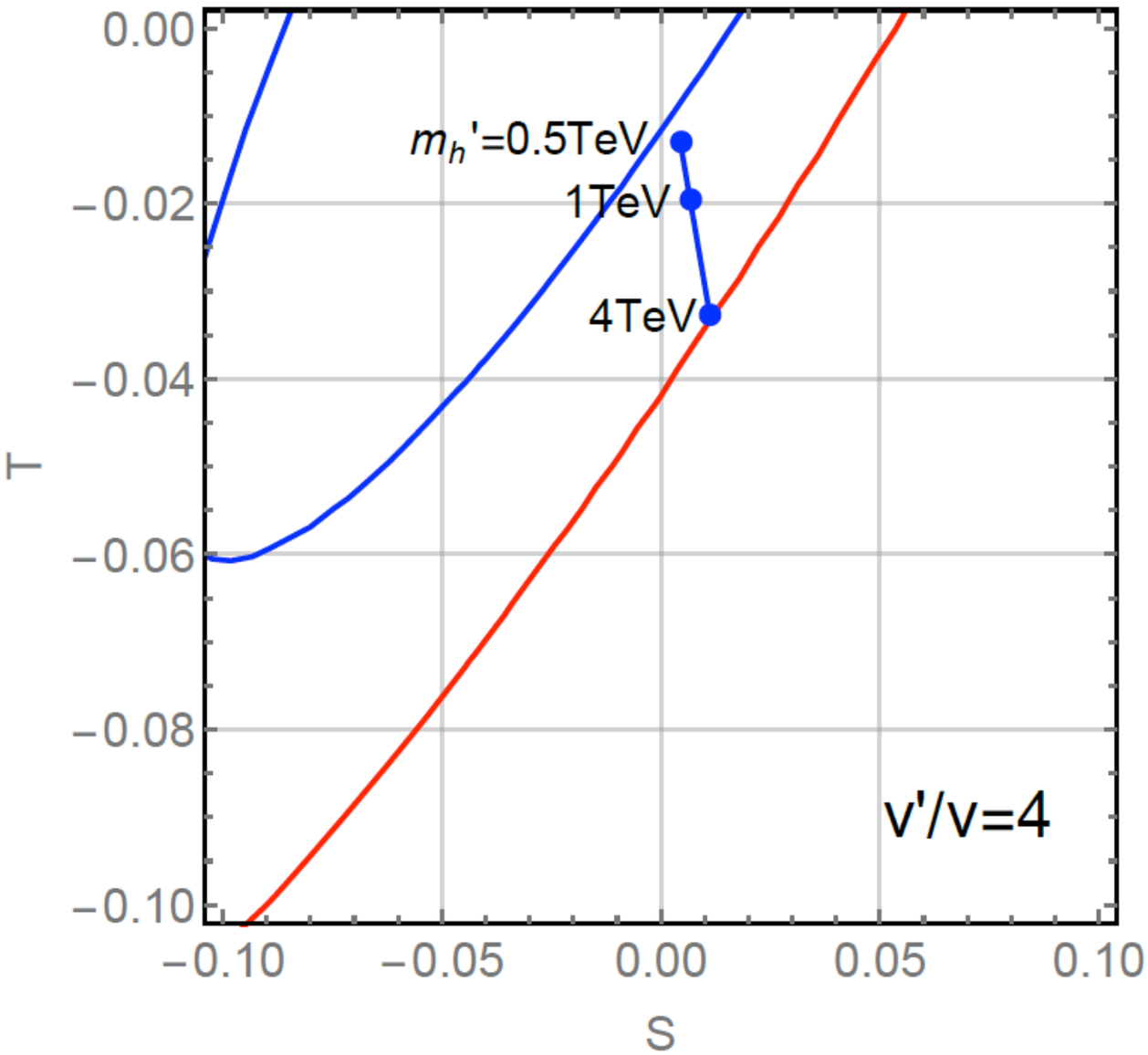
how does one compare it with the SM?

$$\Delta_{m_h^{SM}} = \frac{3}{4\pi^2}\frac{y_t^2\Lambda_{SM}^2}{(m_h^{SM})^2} \qquad \frac{\Delta_{m_h^{TH}}}{\Delta_{m_h^{SM}}} = \frac{1}{2}\frac{\lambda_{SM}}{\lambda_{TH}}\frac{\Lambda_{TH}^2}{\Lambda_{SM}^2}$$

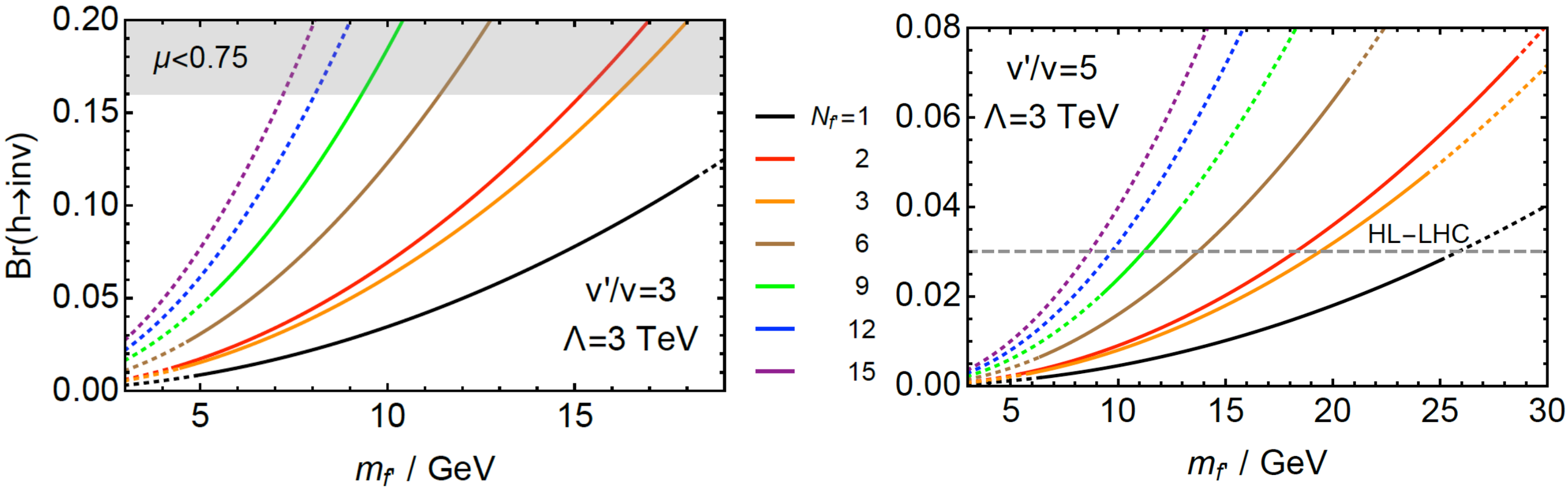
A considerable gain for $\lambda_{TH} \gtrsim 1 >> \lambda_{SM} \approx 0.1$

Electroweak precision tests





Higgs invisible decays $h \to f' \bar{f}'$



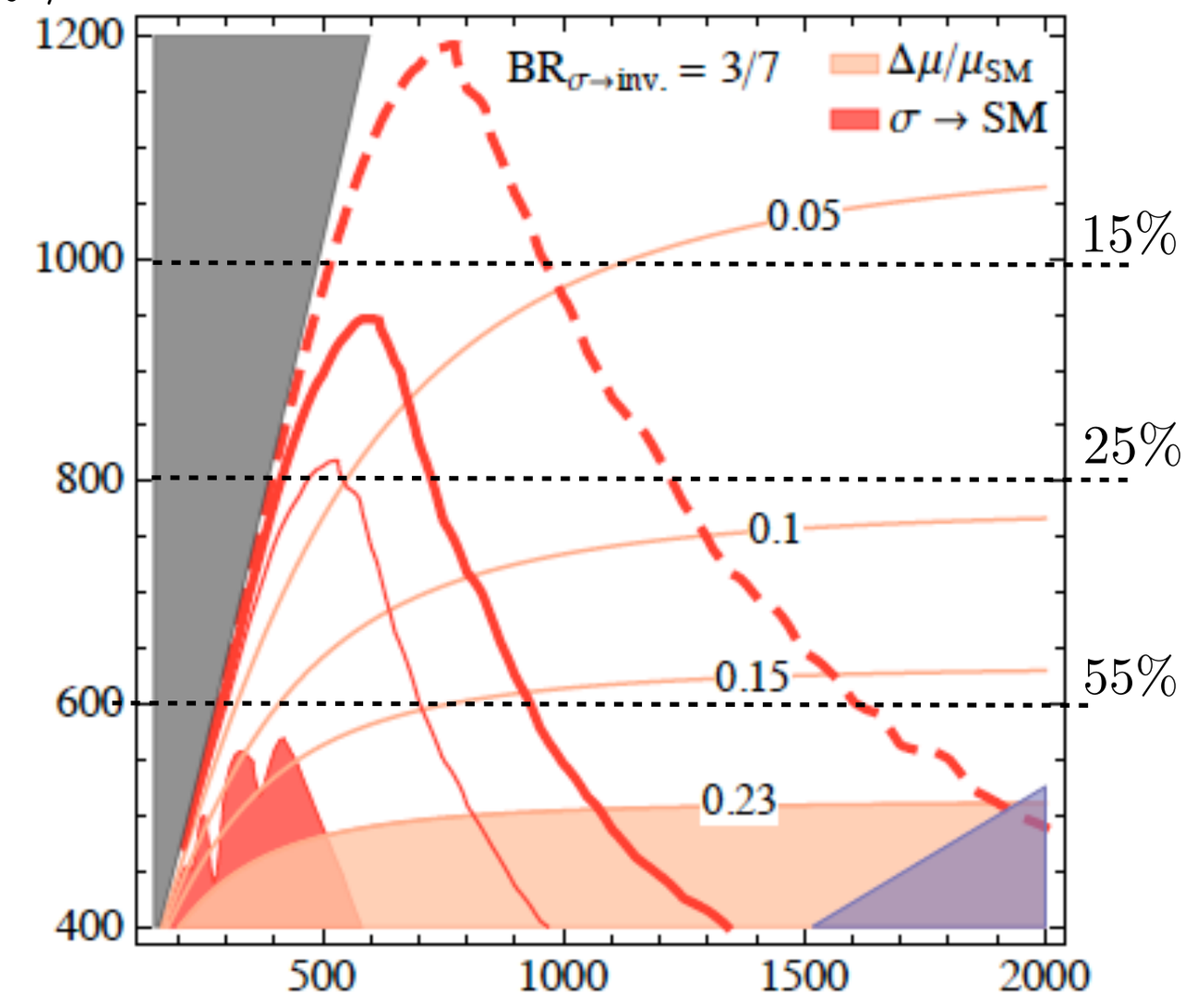
$300 \quad fb^{-1} \qquad BR_{inv} < 23 - 32\%(ATLAS) \quad 17 - 28\%(CMS)$

$3000 \quad fb^{-1} \qquad BR_{inv} < 8 - 16\%(ATLAS) \quad 6 - 17\%(CMS)$

$ILC \qquad BR_{inv} < 0.9\%$

$T - LEP \qquad BR_{inv} < 0.2\%$

Precision on Higgs couplings $\Delta\mu/\mu_{SM} = s_\gamma^2$
(and direct $h' \to SM$ searches)



$1/\Delta = 2\xi/(1-2\xi)$

$\xi = (v/f)^2 \approx s_\gamma^2, \quad v = 246\ GeV$

1σ reach in	s_γ^2
LHC8	0.2
LHC14	0.08-0.12
HL-LHC	4-8$\times 10^{-2}$
HE-LHC	–
FCC-hh	–
ILC	2×10^{-2}

$1/\Delta \to 1/\Delta \cdot min(1, (3.6 m_{h'}/\Lambda_{TH})^2)$