The Standard Model
and (some of) its extensions

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III. Minimal Mirror Twin Higgs

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}

Blinnikov, Khlopov 1982

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

Chacko, Goh, Harnik 2005

Restoring space parity

Introduce:

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

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

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

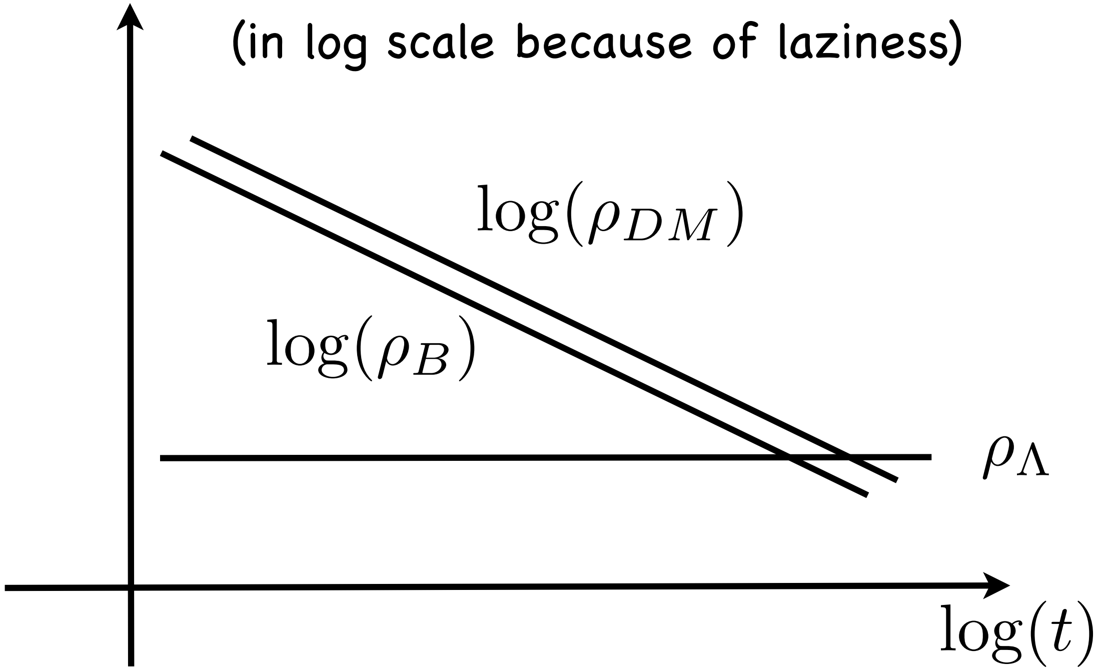
$$f_L \leftrightarrow \gamma_0 (f'_L)^c, \quad f_R \leftrightarrow \gamma_0 (f'_R)^c \qquad [f_L \leftrightarrow \gamma_0 f_R]$$

$$H \leftrightarrow H', \quad A_\mu^a \leftrightarrow A_{\tilde{\mu}}^{a\prime}$$

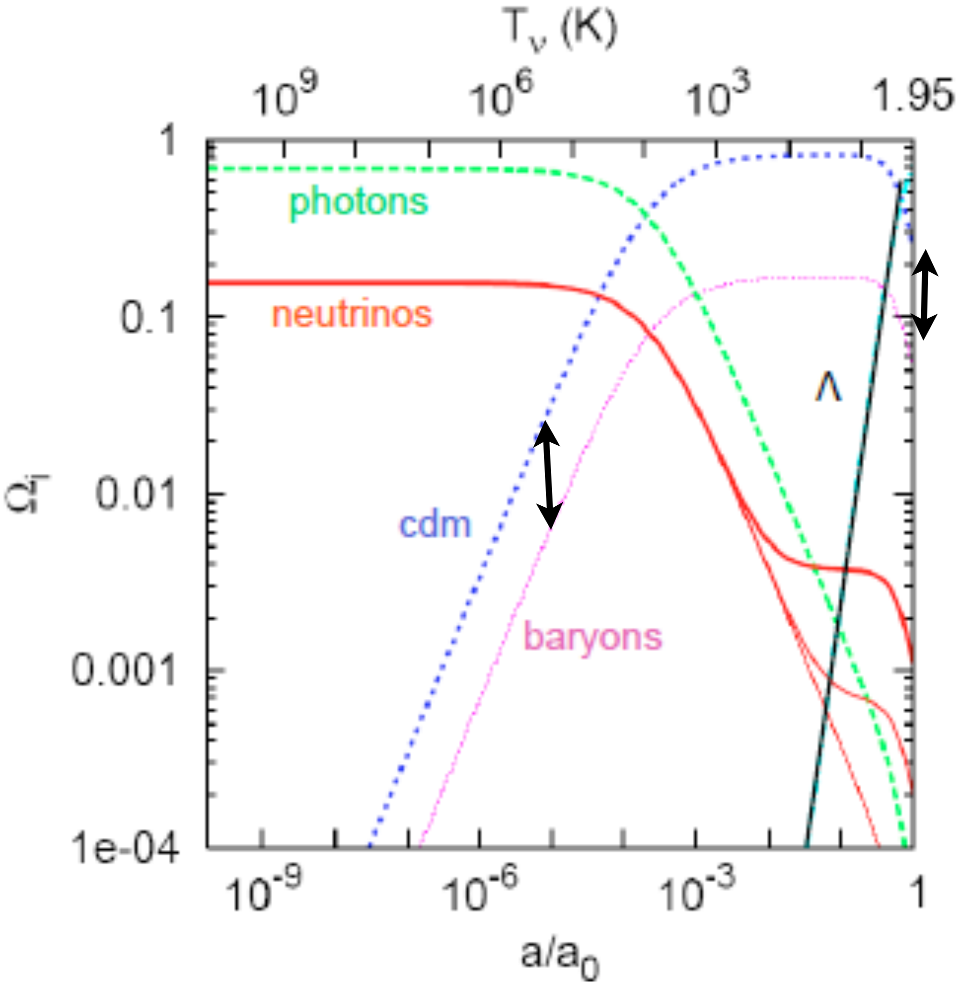
Need:

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

Comparable Ω_{DM} and Ω_B



(in log scale because of laziness)



$$\rho_{DM} = M_\chi n_\chi, \ \rho_B = M_N n_b$$

Why $n_b/n_\chi \sim M_\chi/M_N$ if they are all independent quantities?

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 $\Omega_{DM} (= \Omega_{B'}) = \Omega_B$
as expected in an exactly mirror world

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)

Minimizing the Higgs potential

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

$$V_{SO(8)-inv} = m^2|\mathcal{H}|^2 + \lambda|\mathcal{H}|^4$$

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

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

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

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

?

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

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

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'

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

Insist that $\Delta_{m_{h'}} \leq 1 \Rightarrow \Lambda_{TH} \lesssim 3.6\ m_{h'}$

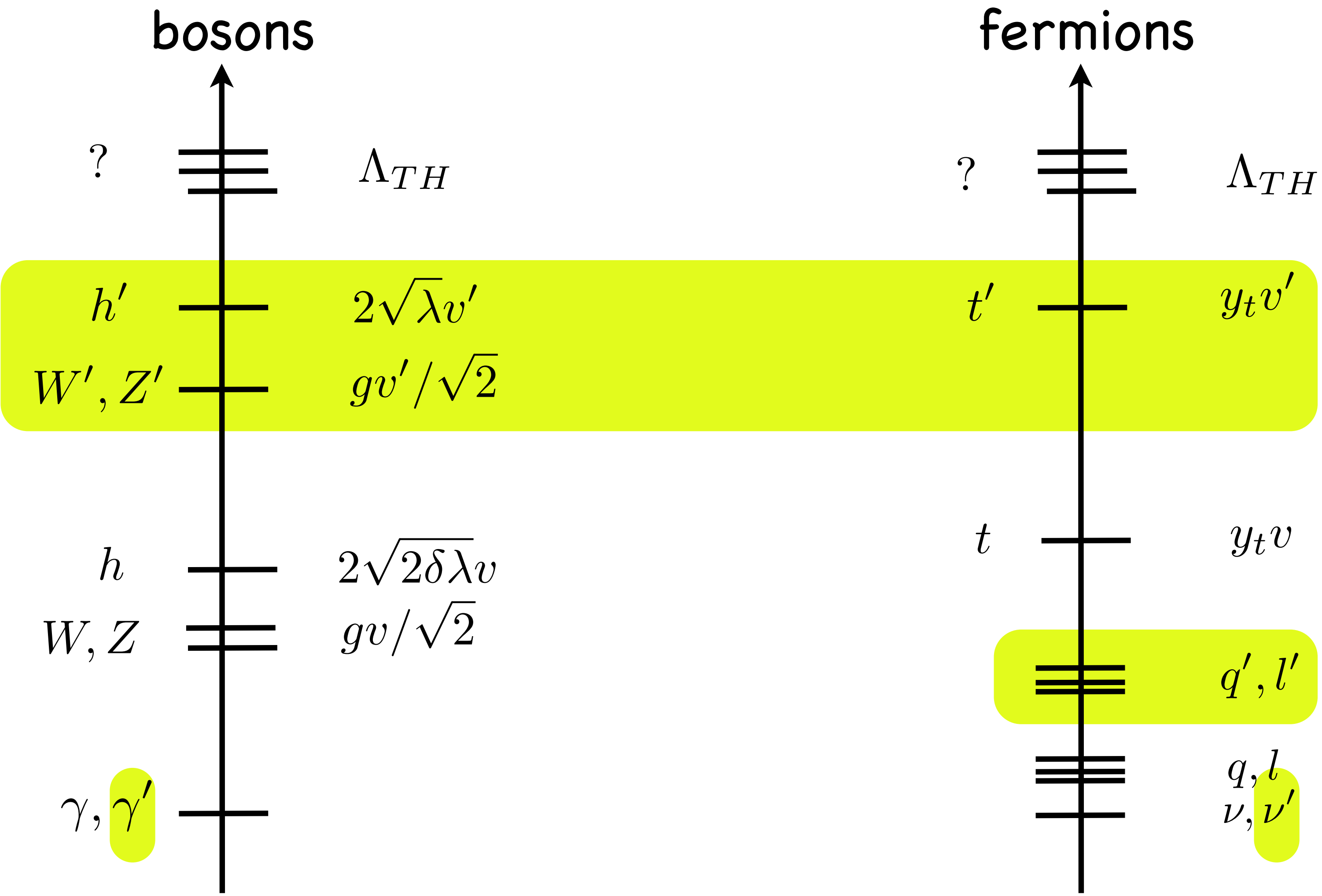
how does one compare it with the SM?

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

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

The only fine tuning in $\Delta_{v/v'} = \dfrac{d\log v^2}{d\log \delta m^2} \approx \dfrac{1}{2}\dfrac{v'^2}{v^2}$

The MTHW spectrum

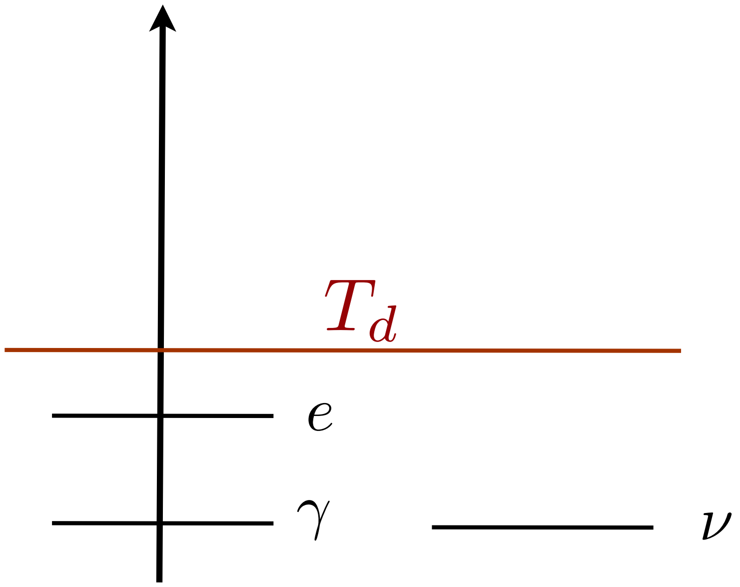


Physics at Λ_{TH} (SUSY, composite, extra-dim.s, etc.?) affects $m_{h'}$ (1 TeV?) but not m_h

Towards solving the Dark Radiation problem

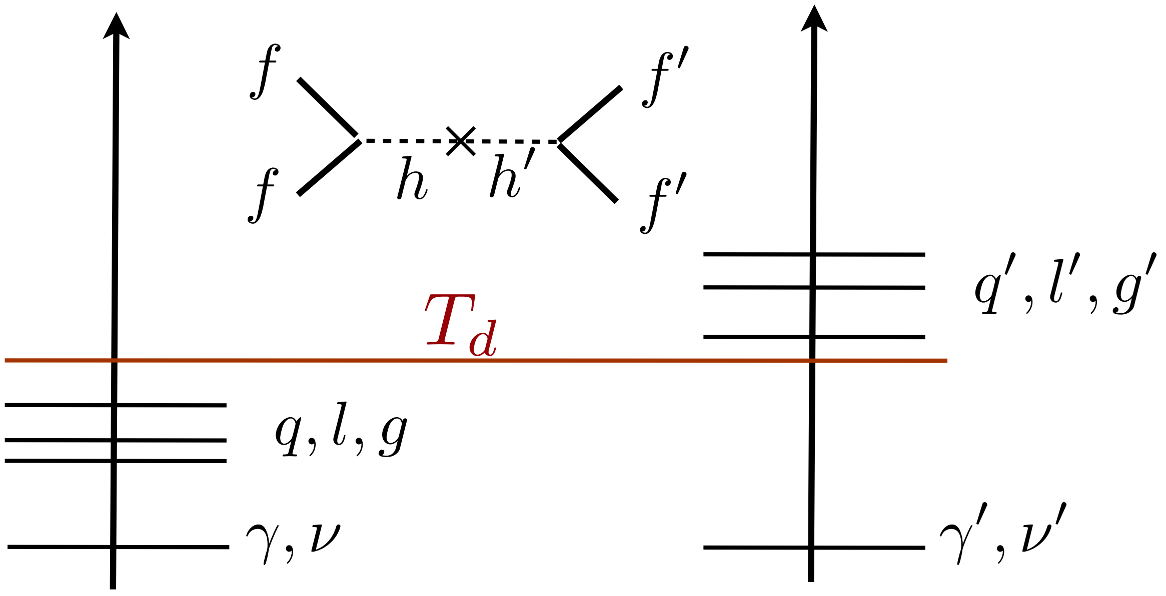
B, Hall, Gregoire 2005

Standard Big Bang



$$\frac{\rho_\nu}{\rho_\gamma} = \frac{3 \cdot 2 \cdot 7/8}{2} (\frac{T_\nu}{T_\gamma})^4 \sim 0.68$$

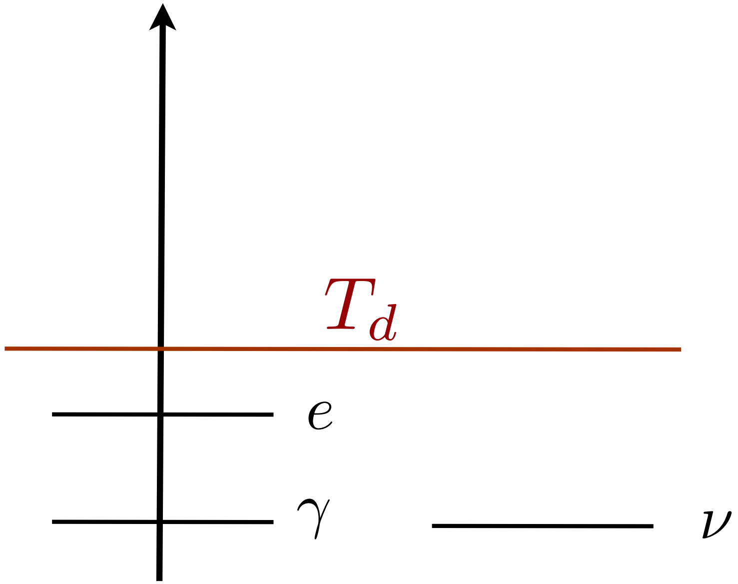
Mirror World



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

Towards solving the Dark Radiation problem

Standard Big Bang



1. At $T_d \approx 1\ MeV$ neutrinos decouple

$$\frac{\rho_\nu}{\rho_\gamma} = \frac{3 \cdot 2 \cdot 7/8}{2}$$

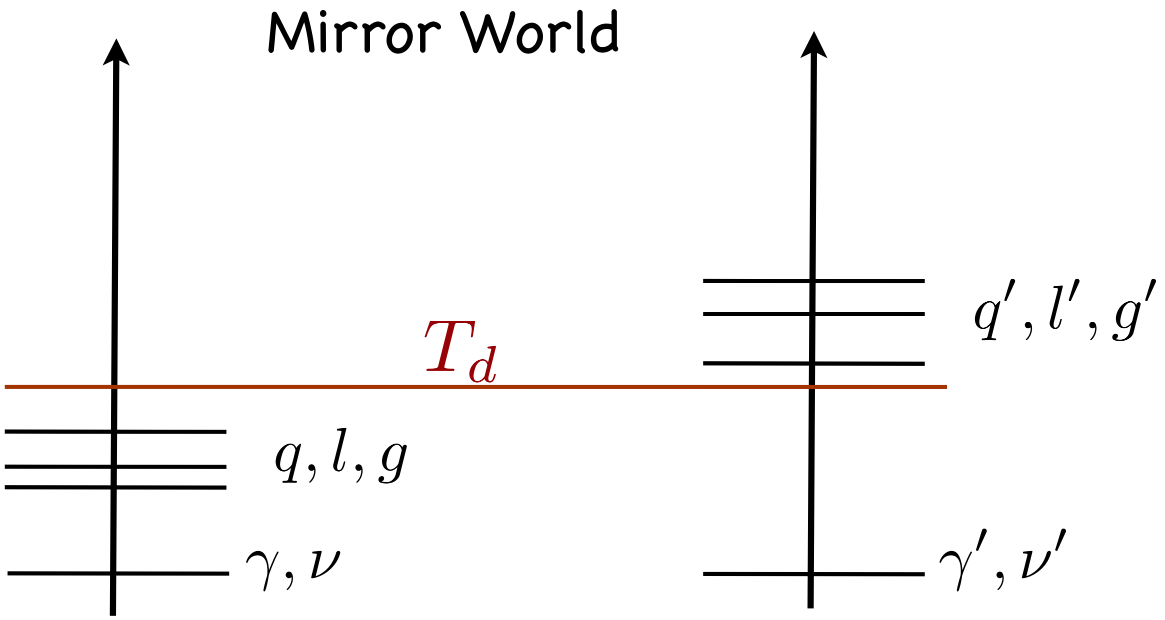
2. At $T \approx m_e$ electrons and positrons disappear while in equilibrium with photons only

3. From entropy conservation $T^3_{>m_e} g(> m_e) = T^3_{<m_e} g(< m_e)$

$$T_{>m_e} = T_\nu, \quad g(> m_e) = 2 + 7/2 \qquad T_{<m_e} = T_\gamma, \quad g(< m_e) = 2$$

$$\frac{T_\nu}{T_\gamma} = (\frac{g(< m_e)}{g(> m_e)})^{1/3} \qquad \frac{\rho_\nu}{\rho_\gamma} = \frac{3 \cdot 2 \cdot 7/8}{2}(\frac{g(< m_e)}{g(> m_e)})^{4/3} \sim 0.68$$

Towards solving the Dark Radiation problem



$$\Delta N_{eff} = \frac{\rho_{\gamma',\nu'}}{\rho_{1\nu}}\Big|_{now} = \frac{g'_r(g'(T_d)/g'_r)^{4/3}}{\frac{7}{8}2(g(T_d)/g(T_d^{\nu}))^{4/3}}$$

heating of mirror rad

heating of SM neutrinos

$g(T), g'(T)$ = effective d.o.f. of the SM and of the MW at T_d

g'_r = effective d.o.f. of the Mirror radiation now

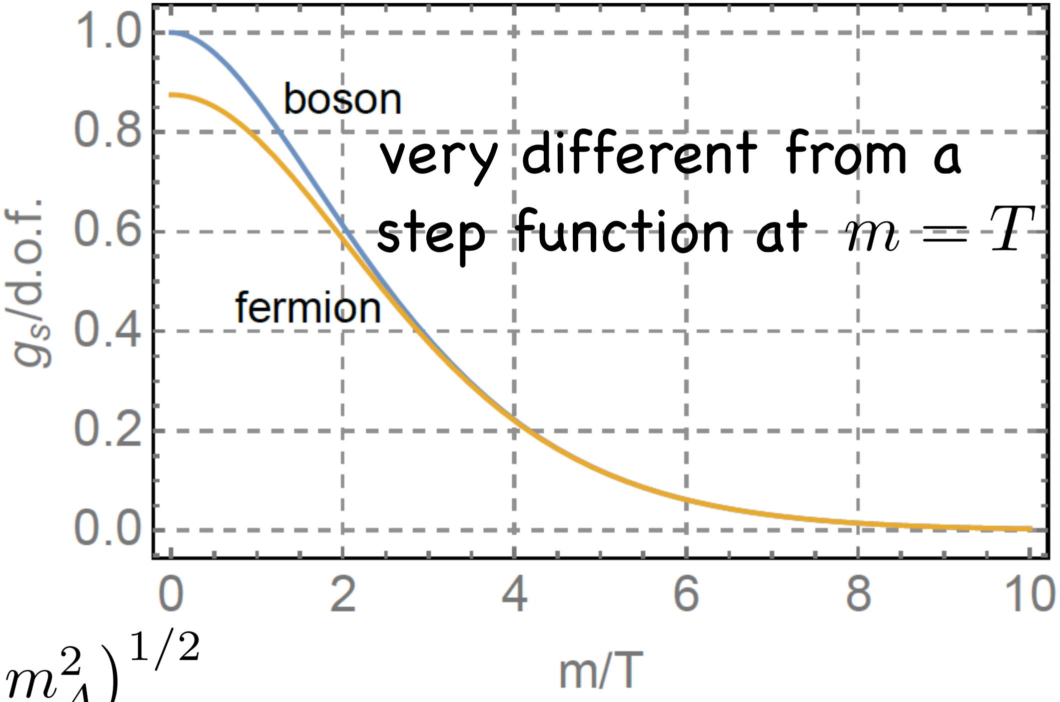
$$g(T_d^{\nu}) = 2|_{\gamma} + \frac{7}{8} \cdot 2 \cdot 3|_{\nu} + \frac{7}{8} \cdot 4|_{e^{\pm}} = 10.75$$

A careful definition of $g(T)$

For any particle A (m_A, n_A^{dof}) in equilibrium

$$g_A(T) = \frac{45}{2\pi^2}\frac{\rho_A(T)+p_A(T)}{T^4}$$

$$g(T) = \sum_A g_A(T)$$

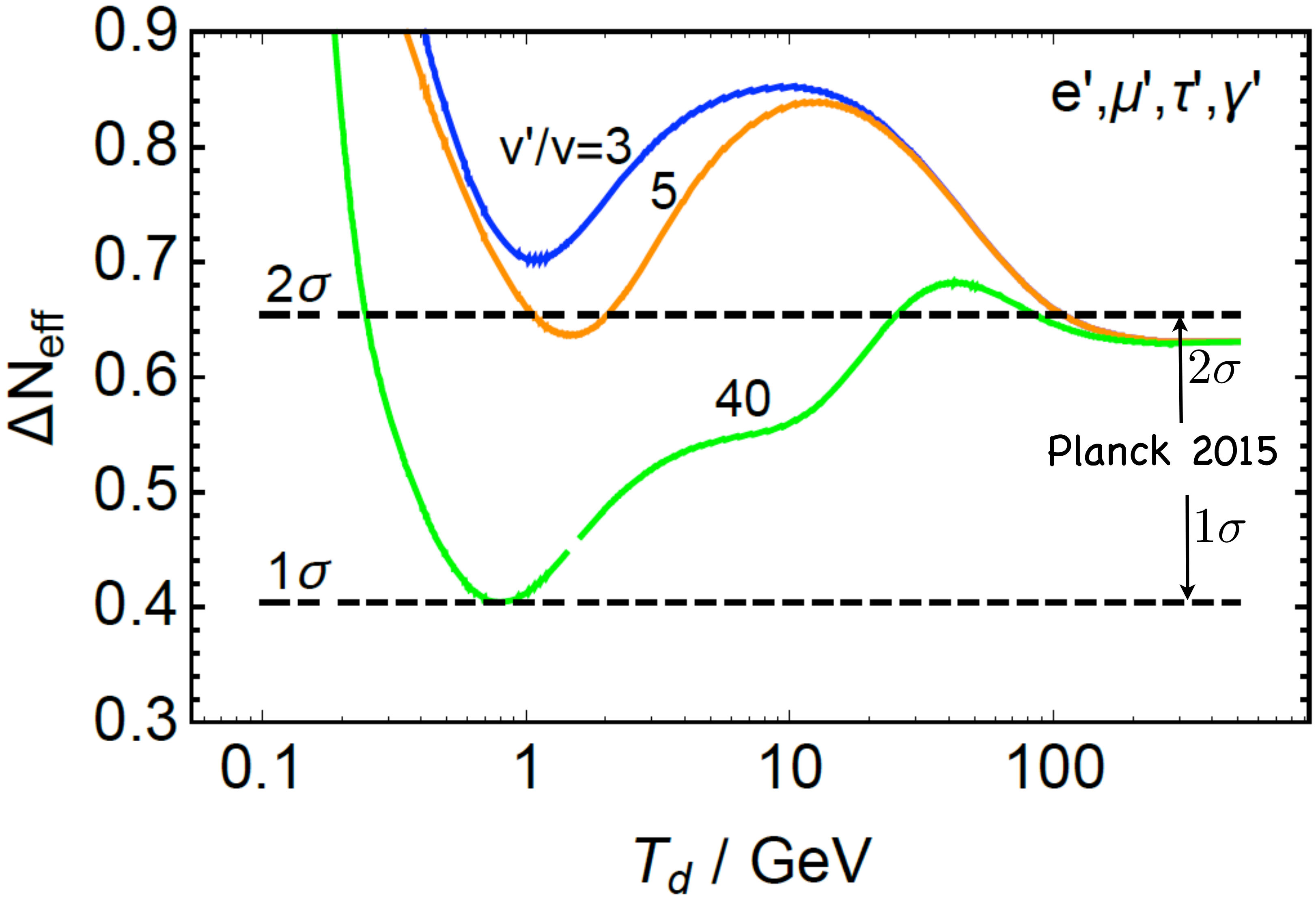


very different from a step function at $m = T$

$$\rho_A(T) = \frac{n_A^{dof}}{2\pi^2}\int_{m_A}^{\infty} E^2 dE \frac{\left(E^2 - m_A^2\right)^{1/2}}{\exp(E/T) \pm 1}$$

$$p_A(T) = \frac{n_A^{dof}}{6\pi^2}\int_{m_A}^{\infty} dE \frac{\left(E^2 - m_A^2\right)^{3/2}}{\exp(E/T) \pm 1}$$

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



can reach the 1σ bound only at $v'/v \geq 40$!

Need to push up $m_{f'} = y_{f'} v'$ by Yukawa couplings as well

A (the only) common solution

Minimal Mirror Twin Higgs

B, Hall, Gregoire 2005
B, Hall, Harigaya 2016

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

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

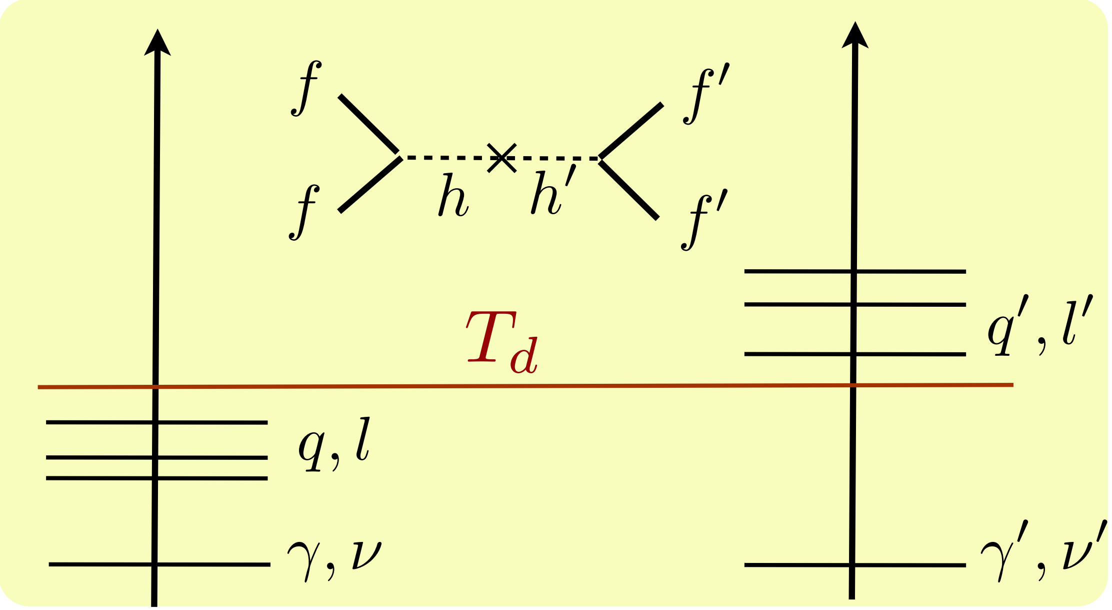
as in a Froggatt-Nielsen picture of flavour

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

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

with

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



from the same source of Z_2 -breaking

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

Constraints on $y_{f'}$ of the light f'

1. Require that $\Delta m^2|_{\mathrm{Yuk}} \simeq \sum_{f\neq t} \frac{N_{f'}}{8\pi^2}\, y^2_{f'}(\Lambda)\,\Lambda^2 \simeq \frac{1}{4}(\frac{v'}{v})^2 m_h^2$

$$\sum_{f'}\left(\frac{N_{f'}}{3\,\delta^2_{f',\Lambda}}\right) m^2_{f'} \;\simeq\; (100\ \mathrm{GeV})^2\left(\frac{v'/v}{3}\right)^4\left(\frac{5\ \mathrm{TeV}}{\Lambda}\right)^2$$

2. Respect bounds on Higgs decays

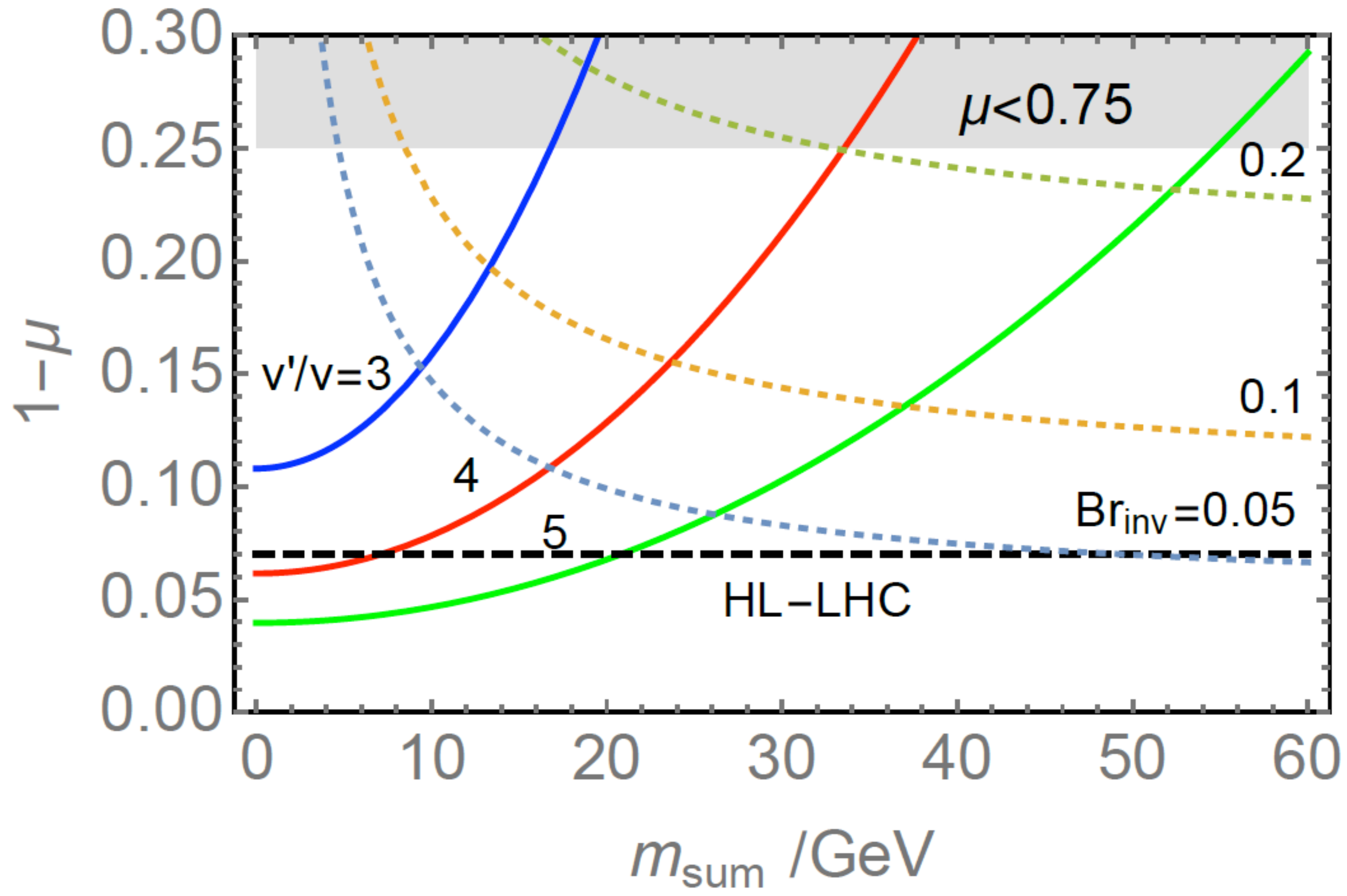
$$h = cos\theta H + sin\theta H' \qquad tan\theta \approx \frac{v}{v'} \qquad h \longrightarrow i_{SM}, f'\bar{f}'$$

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

?

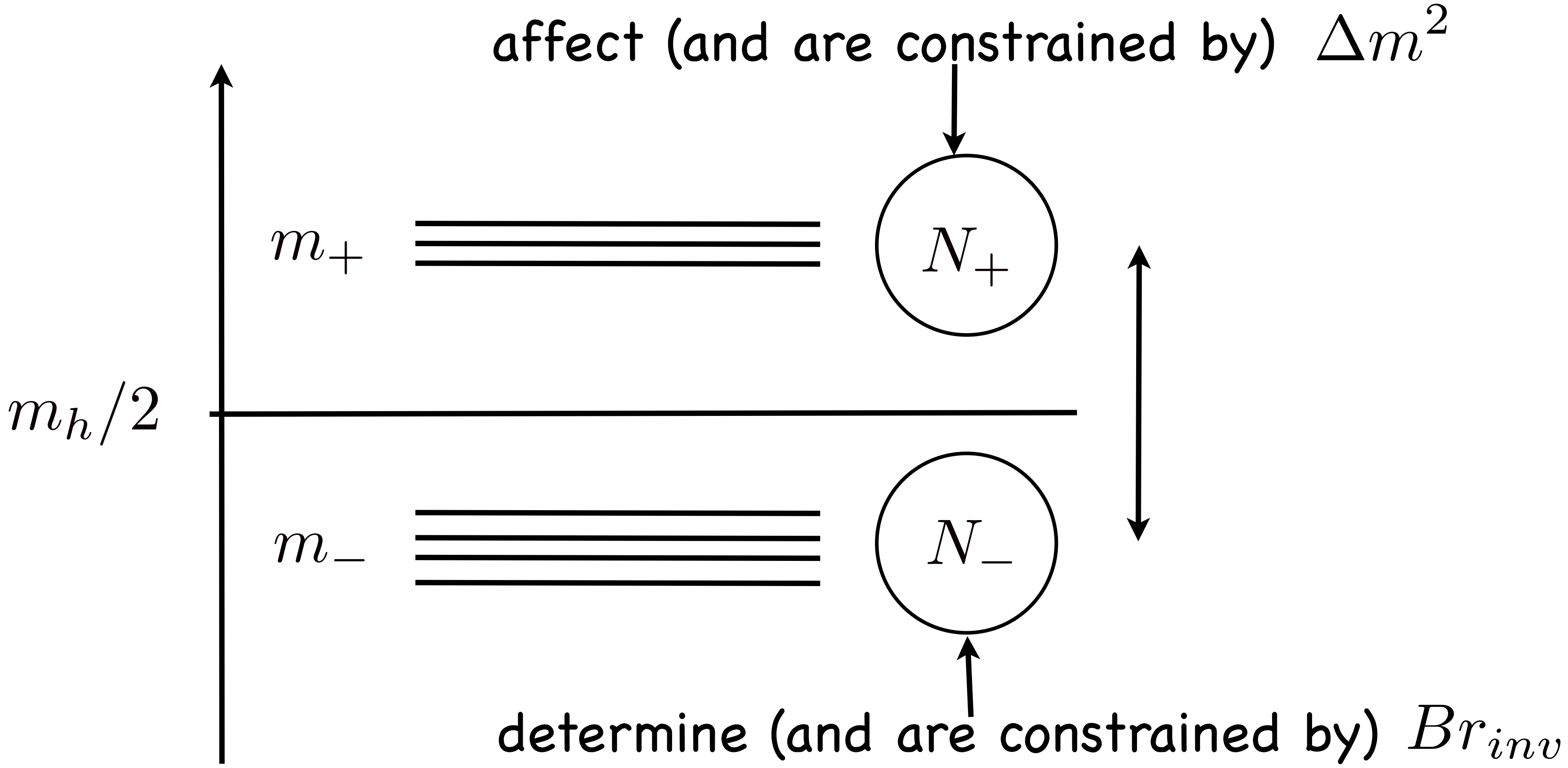
$$\mathrm{Br}_{\mathrm{inv}} = \mathrm{Br}(h \to f'\bar{f}') \simeq 0.1 \times \left(\frac{3}{v'/v}\right)^4 \sum_{f',2m_{f'}<m_h} \frac{N_{f'}}{3}(\frac{m_{f'}}{10\mathrm{GeV}})^2\delta^{-2}_{f',m_h}$$

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



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

To deal with the remaining freedom in the $m_{f'}$



affect (and are constrained by) Δm^2

determine (and are constrained by) Br_{inv}

Allow N_+ and N_- to move, while keeping the sum fixed

$$N_+ + N_- = 5 \cdot 3 + 3 = 18$$

Program

1. At various m_- and N_- calculate T_d and see if ΔN_{eff} can be made consistent with Planck

This needs to compare T_d with T_c'

In zero-flavour QCD $g'_{QCD}(T)$, starting from the perturbative value of 16, sharply drops near 0 at $T \approx T_c'$

$$\Delta N_{eff} = \frac{\rho_{\gamma',\nu'}}{\rho_{1\nu}}|_{now} = \frac{g_r'(g'(T_d)/g_r')^{4/3}}{\frac{7}{8}2(g(T_d)/g(T_d^\nu))^{4/3}}$$

hence require $T_d < T_c'$

2. If 1 passed, look at observable consequences

Towards computing T'_c : an example

Take $\quad m_{u'} = m_{d'} = m_{s'} = m_{c'} = m_{b'} \equiv M$

1. Start at a common scale $m_{t'} = y_t v'$ where $\alpha_S^0 = \alpha_{S'}^0 = \alpha_S(y_t v')$

$$\frac{1}{\alpha_S(m_Z)} = \frac{1}{\alpha_S^0} - b_6 \log(\frac{y_t v'}{m_t})^2 - b_5 \log(\frac{y_t v}{m_Z})^2$$

$$\frac{1}{\alpha_{S'}(q)} = \frac{1}{\alpha_S^0} - b_5 \log(\frac{y_t v'}{M})^2 - b_0 \log(\frac{M^2}{q^2})$$

2. Define $\frac{1}{\alpha_{S'}(q)} = b_0 \log(\frac{q^2}{\Lambda^2_{QCD'}})$ and eliminate α_S^0

$$\log(\frac{\Lambda_{QCD'}}{m_Z})^2 = -\frac{1}{b_0 \alpha_S(m_Z)} + \frac{b_6 - b_5}{b_0} \log \xi + \frac{b_0 - b_5}{b_0} \log(\frac{M}{m_Z})^2$$

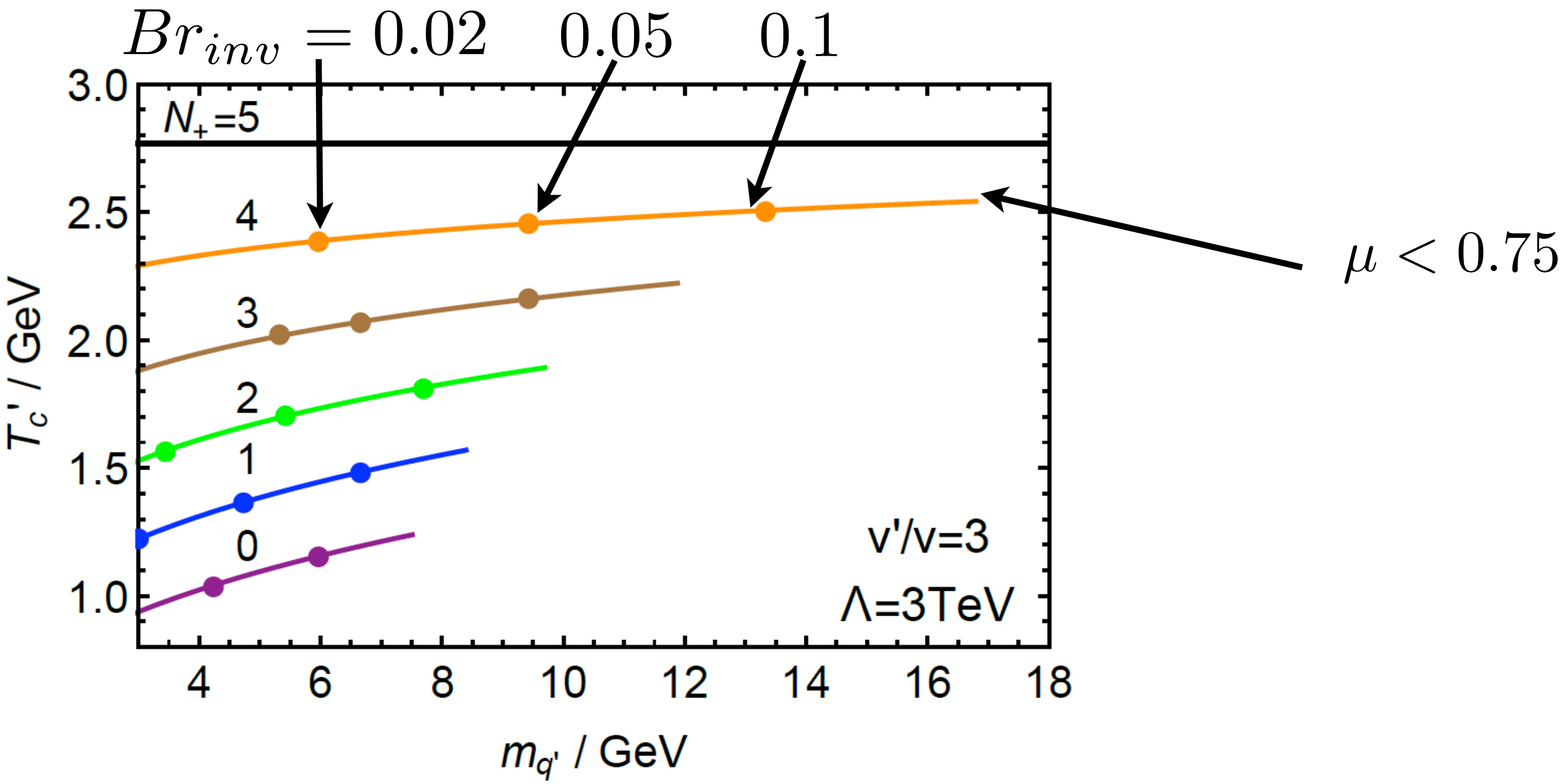
$$\Lambda_{QCD'} \approx 1 \; GeV \; (\frac{0.1}{\xi})^{1/33} (\frac{M}{m_Z})^{10/33}$$

?

At $\quad q = O(GeV) << M \quad$ QCD′ is pure gluonic

Mirror QCD phase transition temperature

From 2 loop running and pure SU(3) Yang-Mills on the lattice

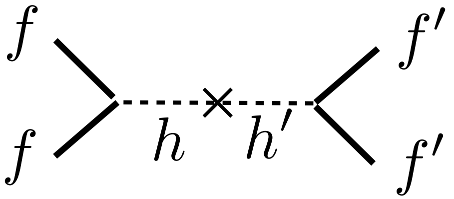


N_+ = number of degenerate q' with mass above $m_h/2$
and determined from Δm_H^2

$m_{q'}$ = mass of degenerate $(5 - N_+)\ q'$
and consistent with $\mu \gtrsim 0.75$

Calculating the decoupling temperature

the main mechanism that maintains coupling between SM and MW



($ff' \to ff'$ less important)

assume dynamics of f' in thermal bath as free fermions
(a posteriori, considering f' inside quarkonia', gives similar results)

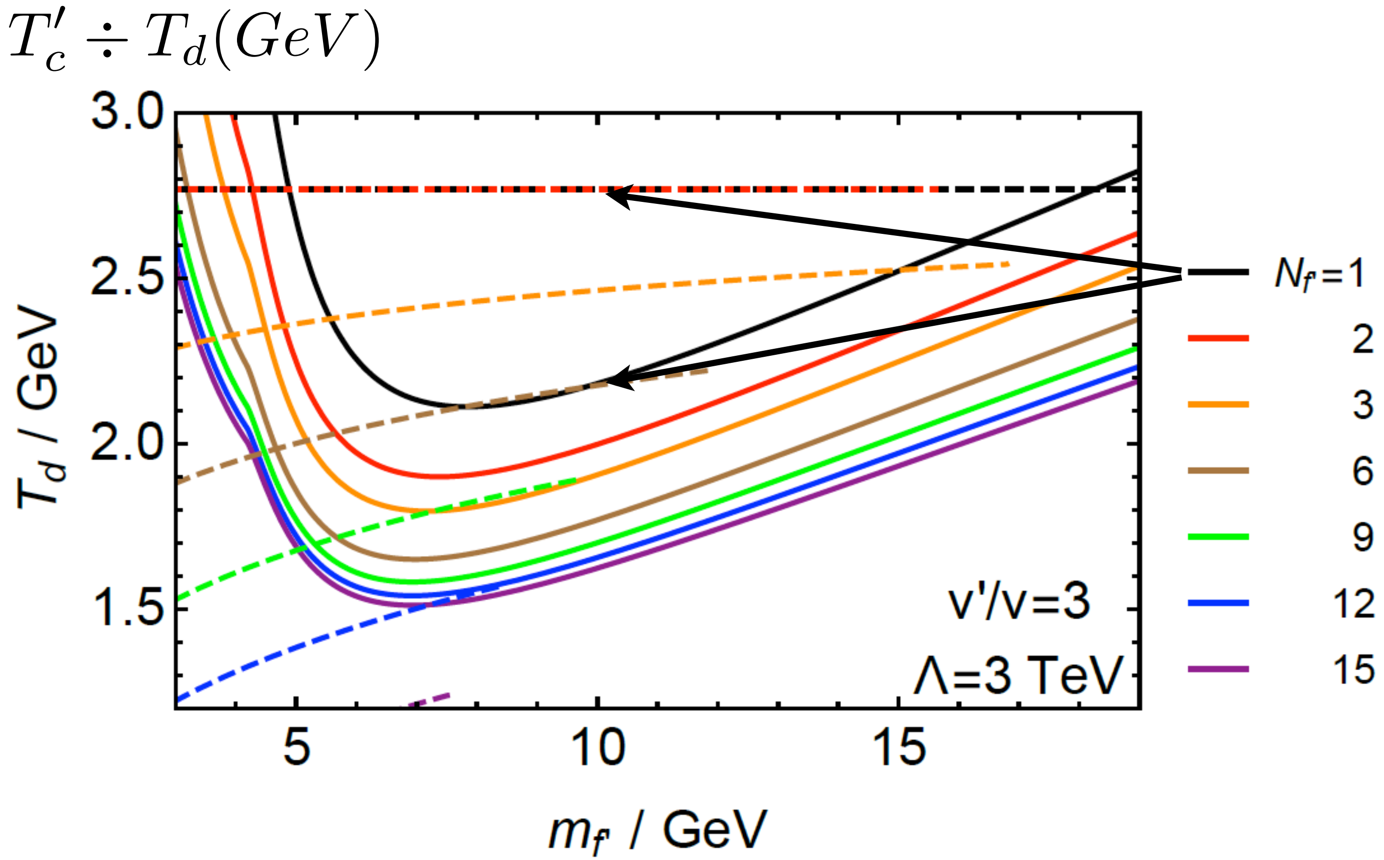
$$\frac{d}{dt}\rho' \approx \sum_f N_{f'} n_F(m_{f'},T)^2 \sigma v(f'\bar{f}' \to f\bar{f}) \times 2m_{f'}$$

?

$$\sigma(f'\bar{f}' \to f\bar{f})v = \frac{N_f}{4\pi}\left(\frac{m_f}{v}\right)^2\left(\frac{v m_{f'}}{v'^2}\right)^2 \frac{(m_{f'}^2 - m_f^2)^{3/2}}{m_{f'}^3 m_h^4} p_{f'}^2 \qquad p_{f'}^2 \simeq 3m_{f'}T/2$$

Define T_d from $(d\rho'/dt)/\rho'|_{T_d} \approx H(T_d)$ at varying $N_{f'}$ and $m_{f'}$

Decoupling temperature



full lines: decoupling temperature T_d

dotted lines: QCD′ phase transition temperature T'_c

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

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

$m_{f'} \sim (5 \div 20) \; GeV$

Signals

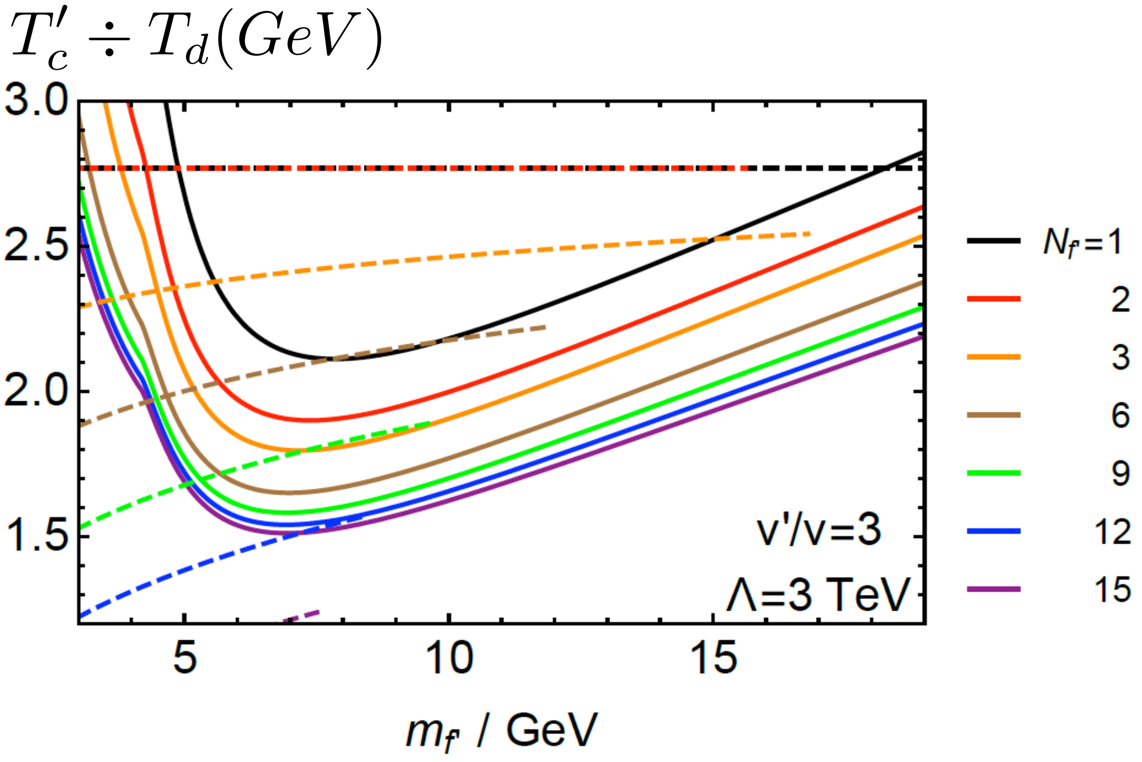
1. Dark radiation ΔN_{eff}
2. h' production
3. Precision on Higgs decays
4. Dark matter detection

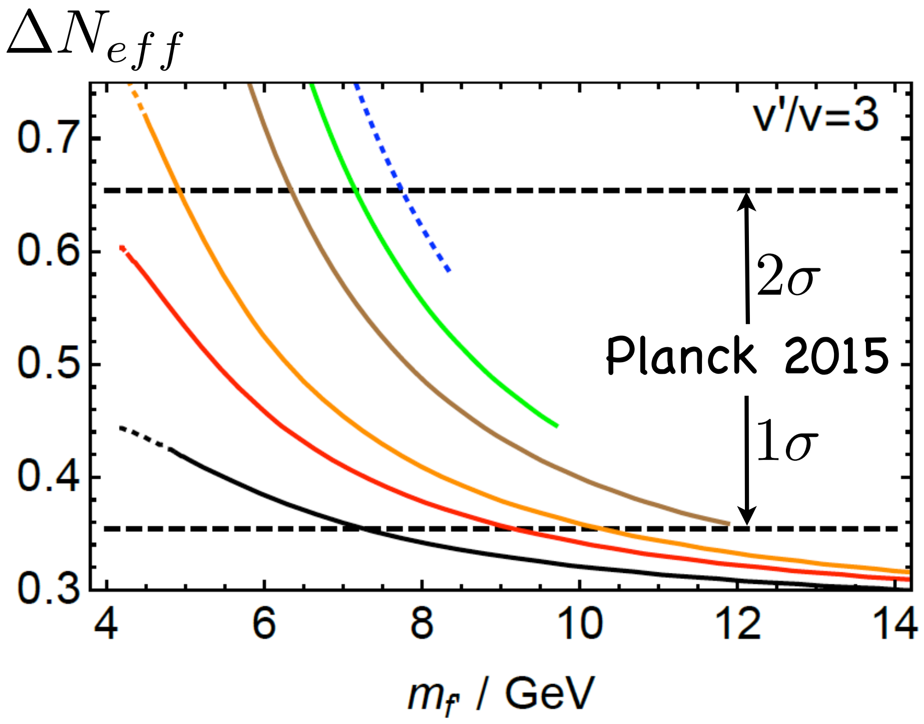
Dark Radiation $\Delta N_{eff} = \frac{\rho_{\gamma',\nu',f'}}{\rho_{1\nu}}|_{now}$

$$\Delta N_{\text{eff},\gamma'\nu'f'} = \frac{4}{7} g'_r \left(\frac{g'_r + g'_f(T_d)}{g'_r}\right)^{4/3} \left(\frac{10.75}{g(T_d)}\right)^{4/3}$$

$$= 0.29 \times \left(\frac{80}{g(T_d)}\right)^{4/3} \left(\frac{7.25 + g'_f(T_d)}{7.25}\right)^{4/3}$$

?





h' production and decays

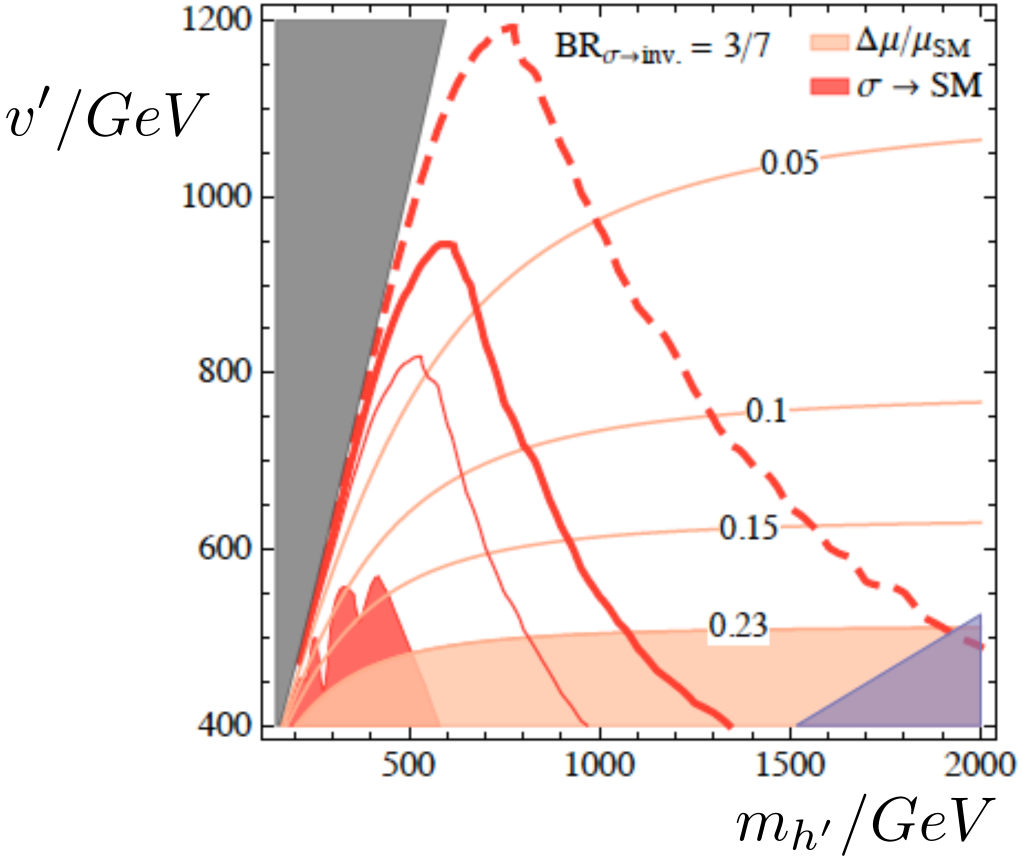
B, Hall, Gregoire 2005

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

Neglecting phase space $\frac{\Gamma_L}{\Gamma_L + \Gamma_T} \to 1$

?

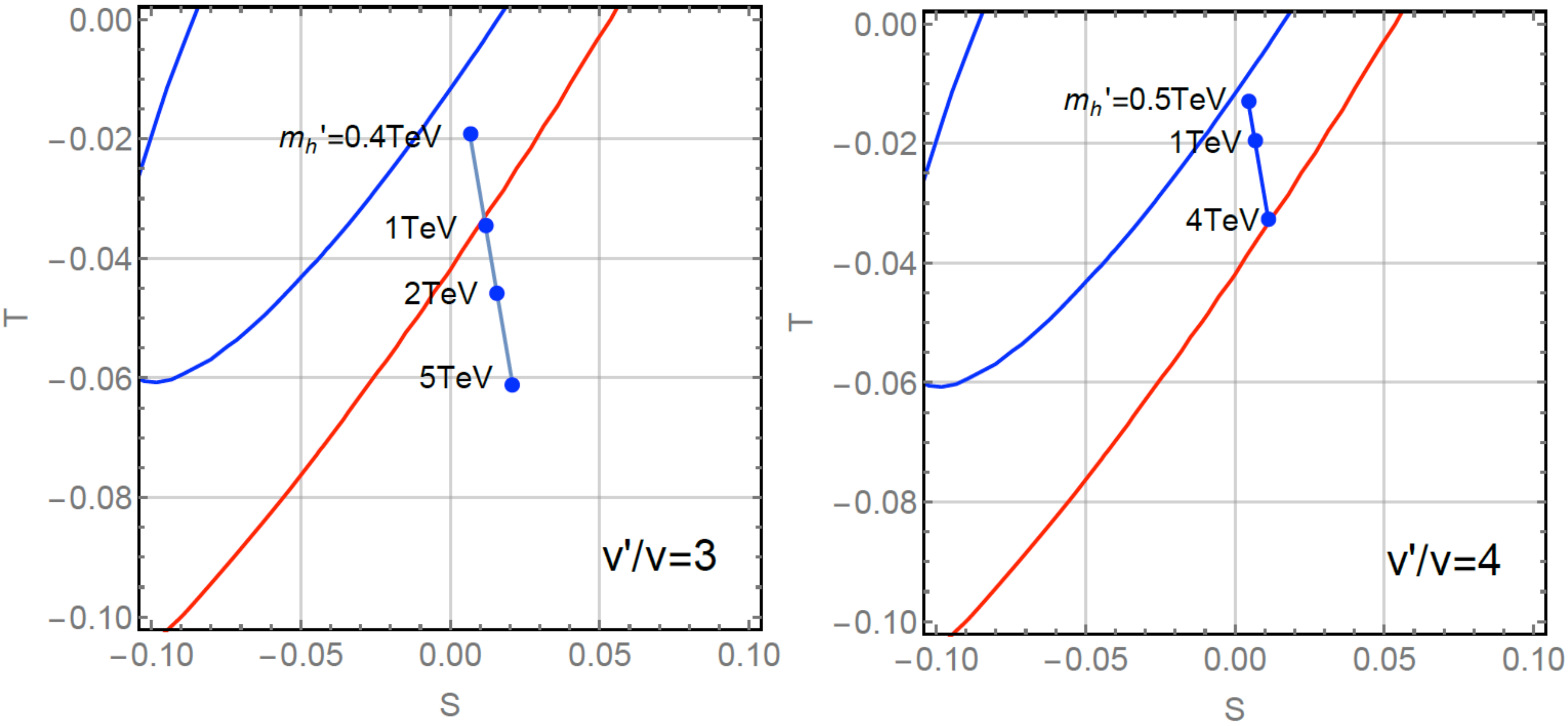
f	ZZ	WW	hh	$W'W'$	$Z'Z'$
$\Gamma(\tilde{h}' \to f)$	1	2	1	2	1



Buttazzo, Sala, Tesi 2015

Electroweak precision tests

(see lecture I)

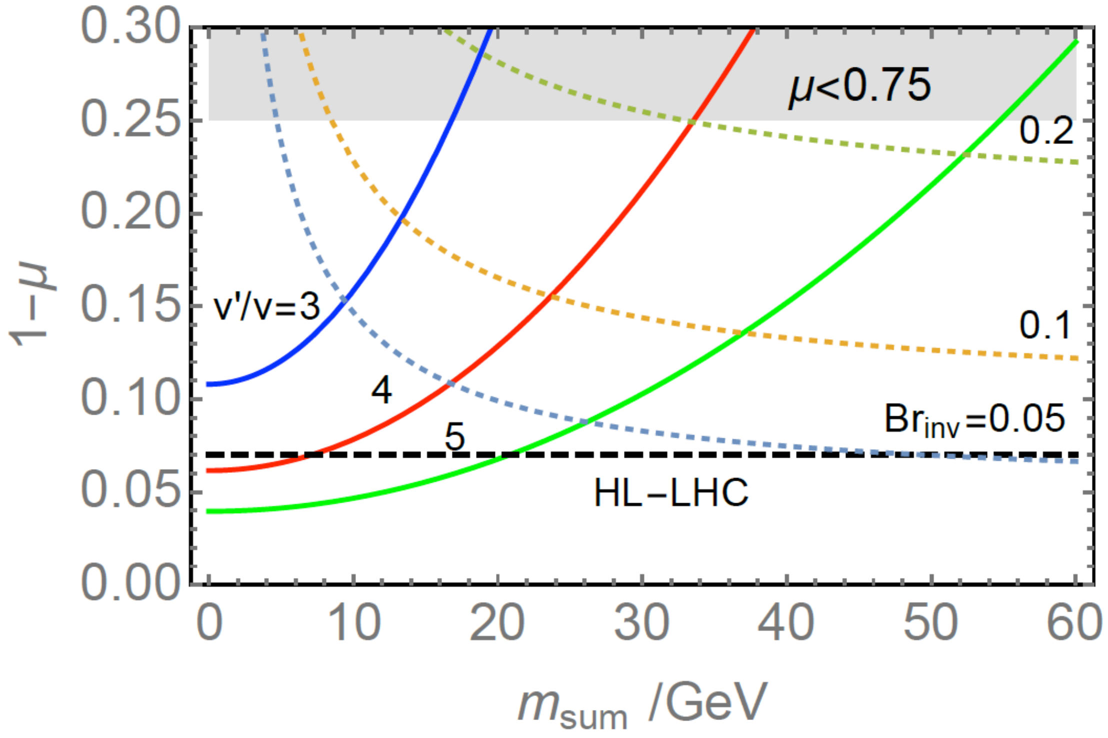


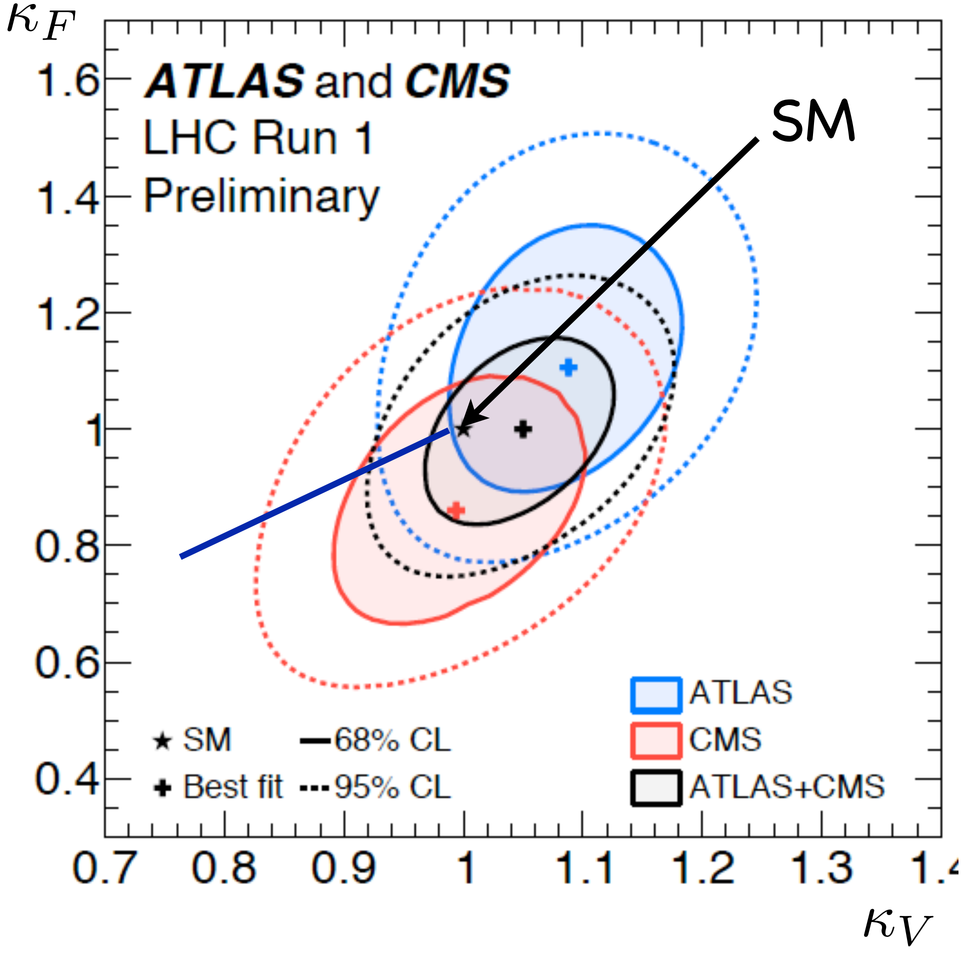
any other contribution?

Precision on Higgs couplings

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

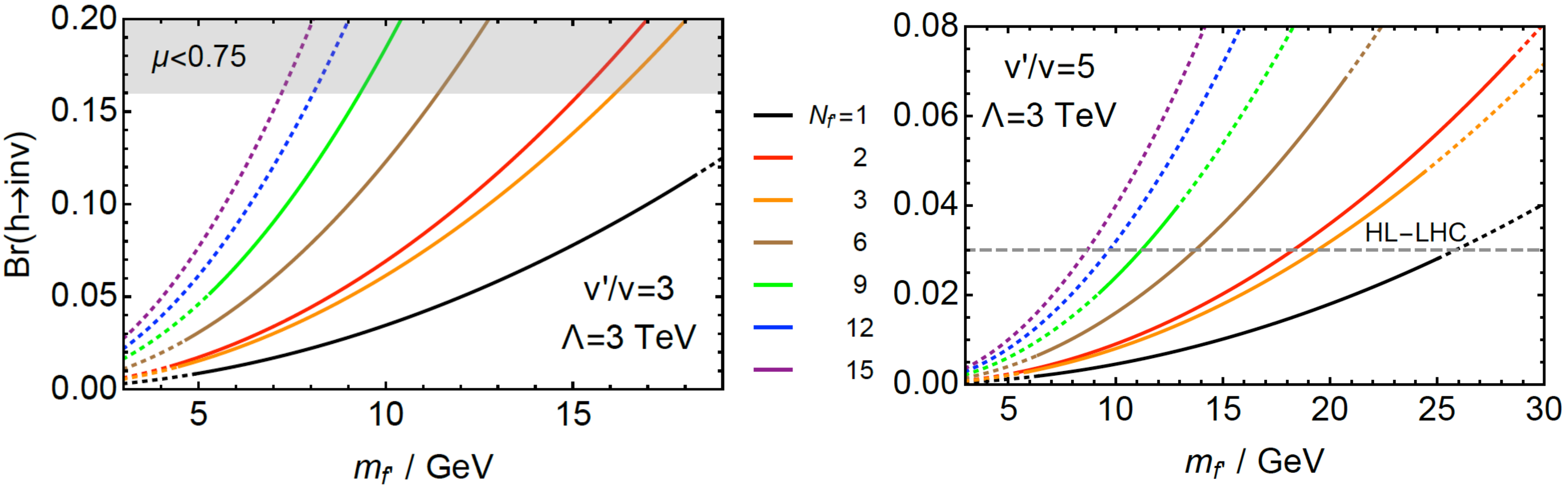
$$\mu(i_{SM}) \equiv \frac{\sigma^{TH}(pp \rightarrow i_{SM})}{\sigma^{SM}(pp \rightarrow i_{SM})} = \mu = cos^2\theta(1 - Br_{inv}) \approx 1 - (\sin^2\theta + Br_{inv})$$





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

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



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

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

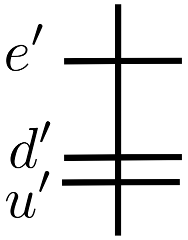
$ILC \qquad BR_{inv} < 0.9\%$

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

Dark Matter

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

Consider 1 configuration at a time



at $T < m_{e'}$ $e' \to \bar{u}'d'\nu'$ with u', d' stable

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

In the thermal bath

$$M'_{u\bar{d}} + B'_{ddd} \to B'_{udd}\ (+\gamma') \qquad (m(M'_{u\bar{d}}) + m(B'_{ddd}) \approx m(B'_{udd}) + 2m_{d'})$$

$$B'_{uud} + B'_{ddd} \to 2B'_{udd}\ (+\gamma') \qquad (m(B'_{uud} + m(B'_{ddd}) > 2m(B'_{udd}))$$

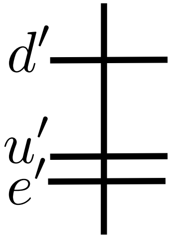
The mirror neutron B'_{udd} is the residual DM particle

with self-interacting cross section $= \mathcal{O}(m^{-2}_{B'_{udd}})$

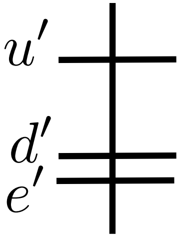
Dark Matter

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

other configurations:

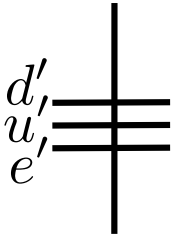


B'_{uuu} and e′ stable
and recombining into a mirror atom $B'_{uuu} + 2e'$



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

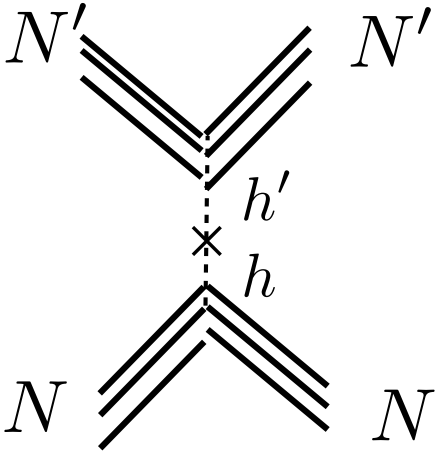
(the self-scattering of mirror atom
may be too strong)



d', u', e' all stable
e′ disappear by $e'u' \to \nu' d'$
scattering among B′ leaves only B'_{udd} due to mirror charge neutrality

Dark Matter direct detection

$$\mathcal{L} = \frac{h}{\sqrt{2}v}\left[-\left(\frac{v}{v'}\right)^2 \sum_{f'\in N'} m_{f'} f'\bar{f}' - \sum_{q=u,d,s} m_q q\bar{q} + 3.5\times\frac{\alpha_3}{12\pi} G^a_{\mu\nu}G^{a\mu\nu}\right]$$



need:

$$\sum_{f'\in N'} < N'|m_{f'} f'\bar{f}'|N' >= 2m^2_{N'}$$

$$< N|\left[-\sum_{q=u,d,s} m_q q\bar{q} + 3.5\times\frac{\alpha_3}{12\pi} G^a_{\mu\nu}G^{a\mu\nu}\right]|N >$$

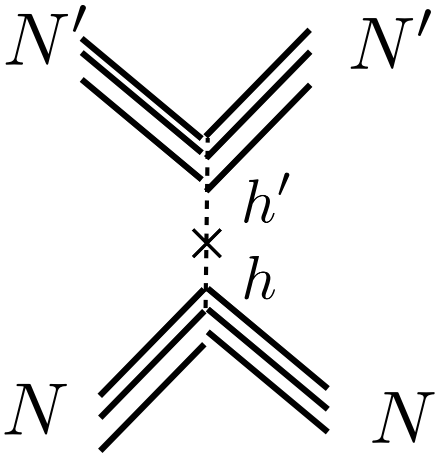
trace anomaly formula for the SM nucleon:

$$2m_N^2 =< N|T^\mu_\mu|N >= -\frac{9\alpha_3}{8\pi} < N|G^a_{\mu\nu}G^{a\mu\nu}|N > + \sum_{q=u,d,s} < N|m_q q\bar{q}|N >$$

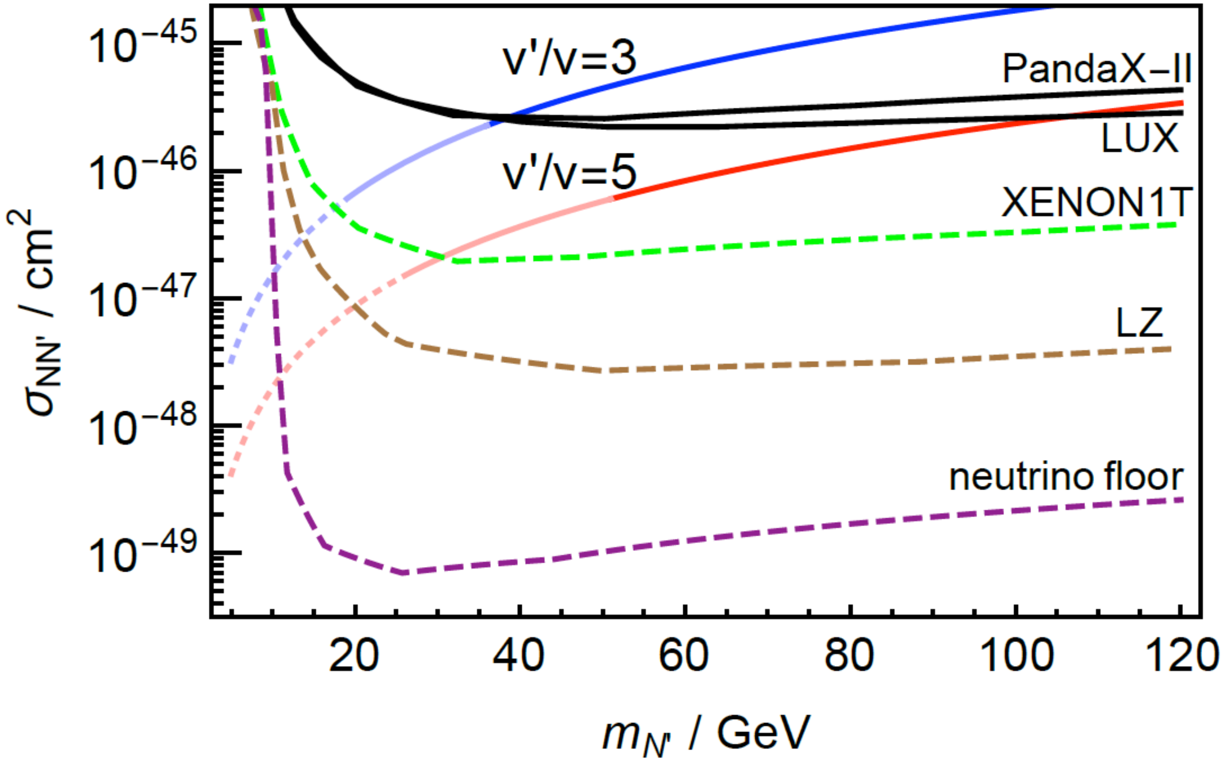
lattice calculations:

$$\sum_{q=u,d,s} < N|m_q q\bar{q}|N >\simeq 0.1\times 2m_N^2$$

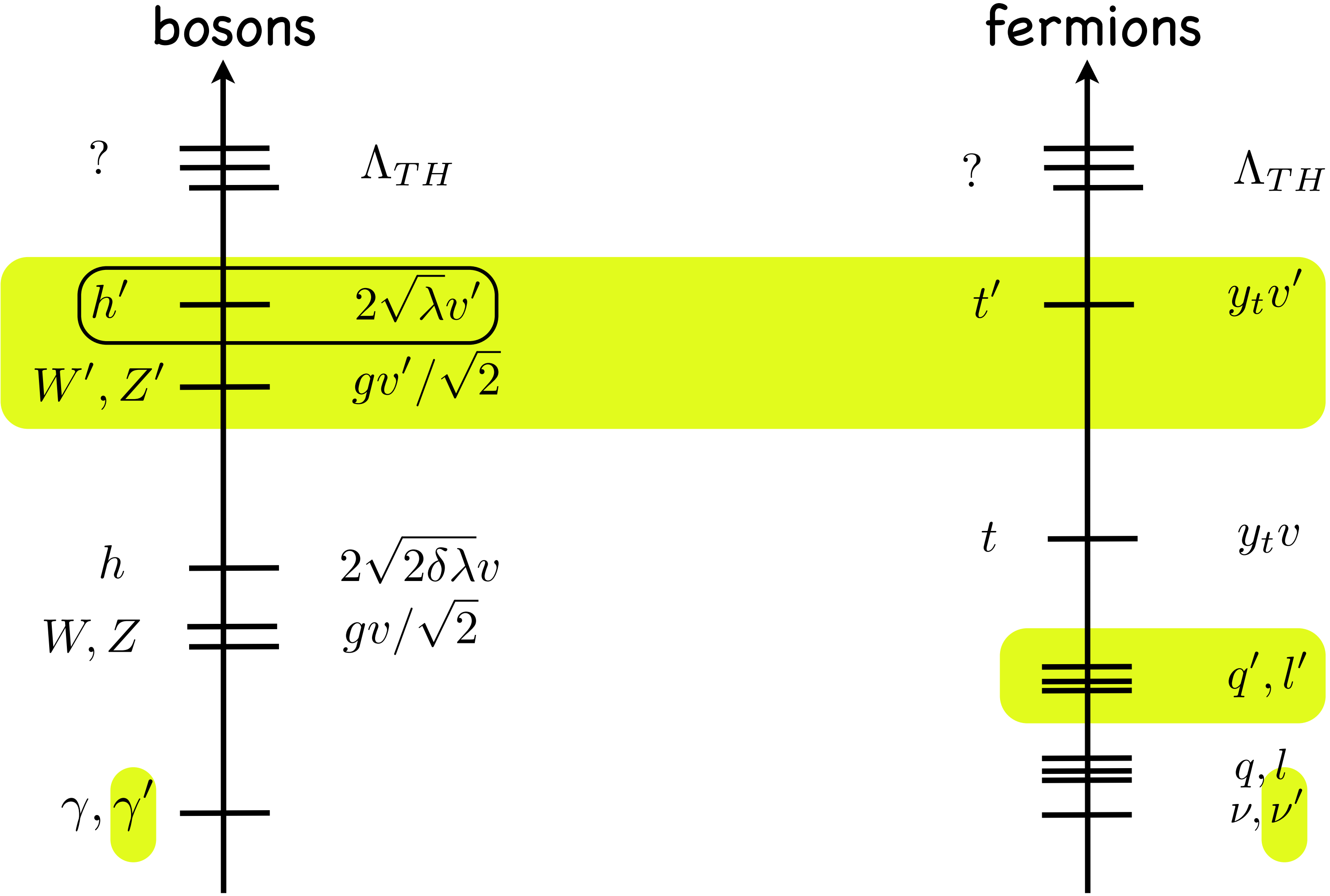
Dark Matter direct detection



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



The MTHW spectrum



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

Open problems

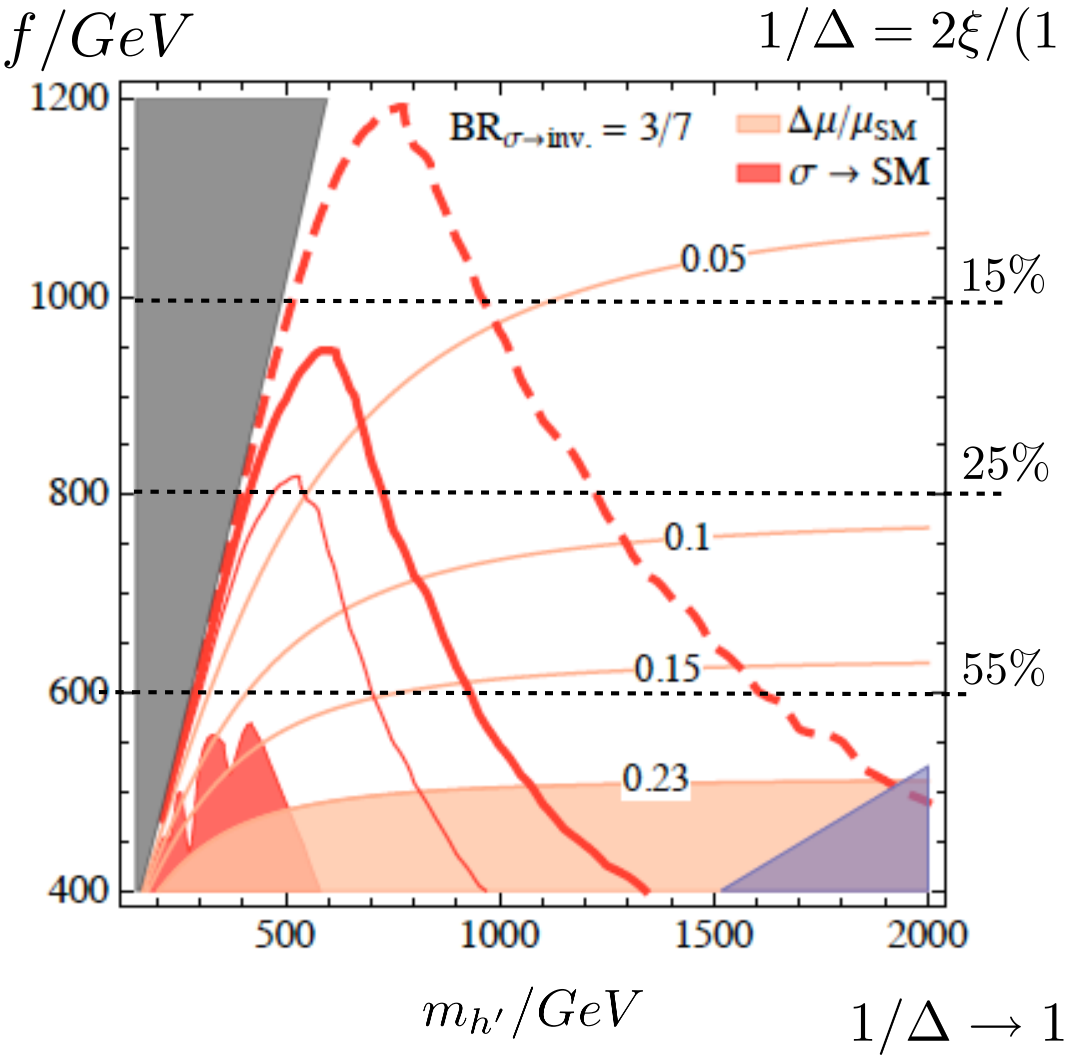
Improve on the ad hoc choice of the mirror masses
in explicit Froggatt Nielsen schemes

Refine the calculation of T_d
(hence of ΔN_{eff})

Properties and cosmological effects of different
DM candidates, all self-interacting

UV completions (?)

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	$4\text{-}8\times10^{-2}$
HE-LHC	–
FCC-hh	–
ILC	2×10^{-2}

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