Minimal signatures of the Standard Model in cosmological collider physics

1907.10624 (JHEP), 1908.00019 (PRD)
with Anson Hook (Maryland), Junwu Huang (Perimeter)

Davide Racco
Perimeter Institute for Theoretical Physics

Université de Genève

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   - Higgs potential beyond the tree level
   - Implications of living in a false vacuum
   - Possible observational signatures
2. Cosmological Collider Physics
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   - Oscillatory features as a clue for heavy particles during inflation
   - Chemical potential for fermions
3. Signature of a SM vacuum at high energies
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   - Contribution of SM fermions to cosmological collider
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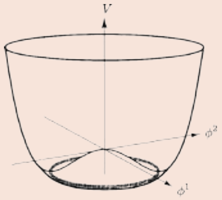
4. Signature of a dynamical Higgs minimum
   - A minimal signal from the SM
   - Contribution of fermion density to Higgs potential
   - Distinguishing feature of the signal

Higgs potential beyond the tree level

Tree level potential

$$V(h) = \frac{1}{4}\lambda\, h^4 - \frac{1}{2}\mu^2 h^2$$



RG improved potential

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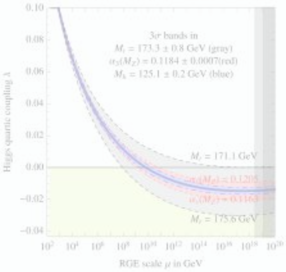

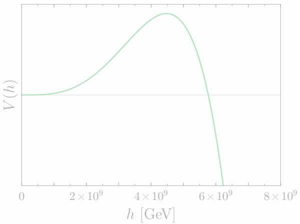

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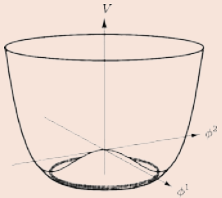

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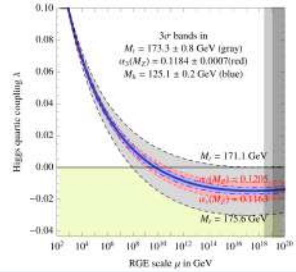
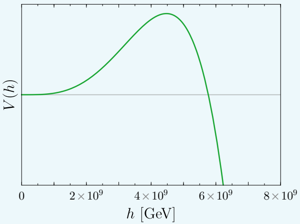


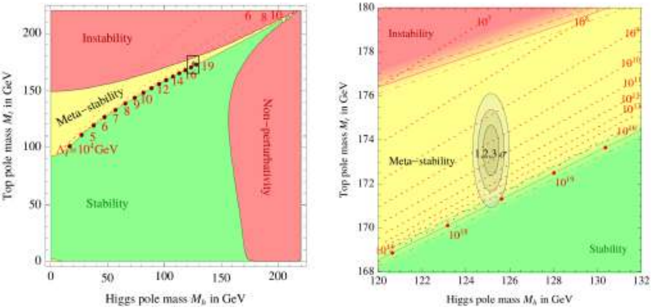


Implications of living in a false vacuum

['79 Cabibbo, Maiani, Parisi, Petronzio; Hung; '89 Sher; '94 Altarelli, Isidori; '96 Casas, Espinosa, Quirós; '07 Espinosa, Giudice, Riotto; '12 Degrassi, Di Vita, Elias-Miró, Espinosa, Giudice, Isidori, Strumia; . . .]

Tunnelling today

Negligible probability, today we are safe. We live in a metastable Universe.



[1307.3536 Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia]

Implications of living in a false vacuum

['07 Espinosa, Giudice, Riotto; '15 Espinosa, Giudice, Morgante, Riotto, Senatore, Strumia, Tetradis; '16 East, Kearney, Shakya, Yoo, Zurek; '16 Salvio, Strumia, Tetradis, Urbano; ...]

During inflation

- Power spectrum of a scalar field in de Sitter is $\left(\frac{H}{2\pi}\right)^2 \Longrightarrow$ quantum jumps of the background value of the Higgs field of order $\sim \pm\frac{H}{2\pi}$, on a time scale H^{-1}.
- Depending on the value of H, these fluctuations could lead the Higgs beyond the barrier, and make it roll towards the true vacuum.
- This vacuum has large negative energy $\Longrightarrow$ AdS bubble, which can expand at the speed of light. $\Longrightarrow$ $\boxed{\text{It didn't happen in our past lightcone.}}$

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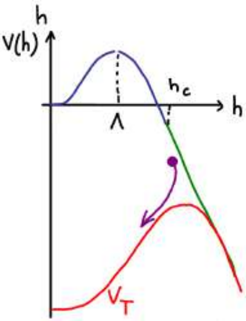
During reheating

- Higgs interacts with thermal bath of SM particles. Overall effect: stabilisation of the potential through a thermal contribution V_T,

$$V_0(h) + V_T(h) = \tfrac{1}{4}\lambda(h)h^4 + \tfrac{1}{2}m_T^2 h^2 \,,$$
$$m_T^2 = 0.12\, T^2 \exp\left(-\tfrac{h}{2\pi T}\right)$$

- If $T_{\rm RH}$ is high enough and h is not too far, thermal corrections can "rescue" the Higgs, bringing it back around 0.



Are there possible observational signatures of the Higgs instability?

Tunnelling today: not here, until this morning.

If this time is on the order of 10^9 yr, we have occasion for anxiety.

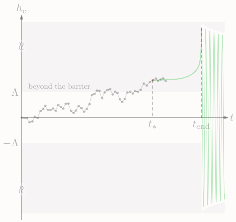
This would be the appropriate case to study if we were currently living in a false vacuum whose apocalyptic decay is yet to occur.

[Coleman]

What if the Higgs probed the unstable region at the end of inflation, and was rescued back in time by thermal corrections at reheating?

Two signatures: [Espinosa, DR, Riotto PRL '17; JCAP '18]

1. Primordial Black Holes as Dark Matter
2. Background of Gravitational Waves



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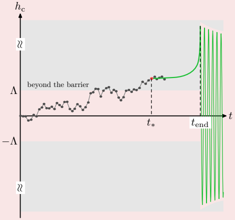

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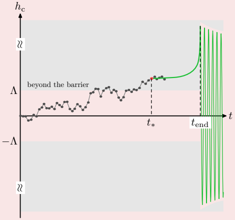

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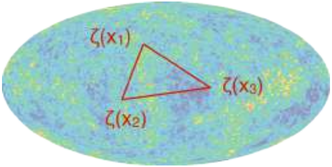
Density perturbations and inflationary Universe

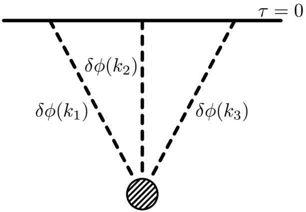


- In the inflationary paradigm, perturbations originate from quantum fluctuations of the inflaton ϕ.

curvature perturbation ζ $\longleftrightarrow$ inflaton fluctuations $\delta\phi$

- Correlation functions can shed light on inflaton interactions:

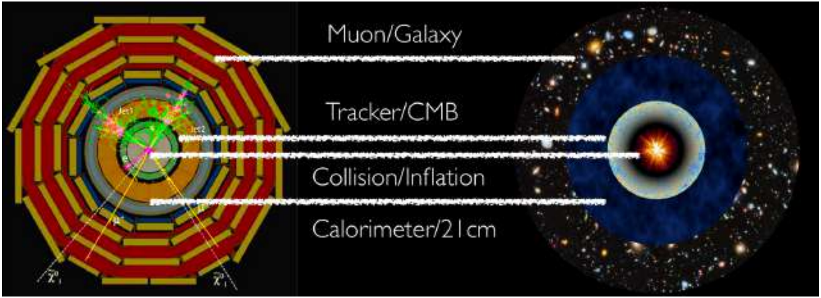
bispectrum $\langle\zeta(x_1)\zeta(x_2)\zeta(x_3)\rangle$ $\longleftrightarrow$ inflaton 3pt function $\langle\delta\phi(x_1)\delta\phi(x_2)\delta\phi(x_3)\rangle$



Cosmological collider physics

[Chen, Wang '09; Baumann, Green '11; Arkani-Hamed, Maldacena '15; Lee, Baumann, Pimentel '16; . . .]

- We can probe fundamental physics through primordial perturbations.
- Great potential with future surveys of intensity mapping (21cm emission).

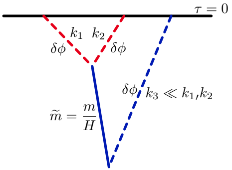


[Credit: Zhong-Zhi Xianyu, Junwu Huang]

Cosmological collider physics

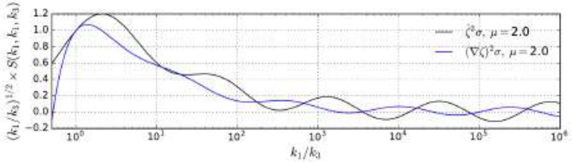
- Bispectrum defined through shape function S:

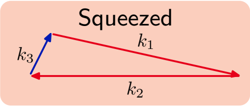
$$\langle\zeta(\vec{k}_1)\zeta(\vec{k}_2)\zeta(\vec{k}_3)\rangle = (2\pi)^3\,\delta(\vec{k}_1+\vec{k}_2+\vec{k}_3)\cdot \cdot\frac{(2\pi)^4\mathcal{P}_\zeta^2}{k_1^2k_2^2k_3^2}\,S(k_1,k_2,k_3)$$



- Distinctive signature of massive particles interacting with the inflaton: *oscillating* feature in the squeezed bispectrum.

$$S(k_1,k_2,k_3)\Big|_{k_3\ll k_1\sim k_2} \sim f_{\rm NL}^{(\text{clock})}\left(\frac{k_3}{k_1}\right)^{i\frac{m}{H}} \sim f_{\rm NL}^{(\text{clock})}\cos\left(\frac{m}{H}\ln\frac{k_3}{k_1}\right)$$





[Meerburg, Münchmeyer, Muñoz, Chen '16]

Oscillating pattern in the squeezed bispectrum

- Origin of the oscillating signal: the wavefunction of the massive particle evolves as

$$e^{im(t_3-t_1)} \overset{\tau\sim -e^{iHt}}{\sim} \left(\frac{\tau_3}{\tau_1}\right)^{i\frac{m}{H}}$$

- What are the most relevant times for particle production?
Early times ($|k\tau| \gg 1$): mode sees Minkowski space $\Rightarrow$ no production.
- Non-adiabatic particle production occurs when adiabatic regime fails. This goes as

$$P \sim e^{-\omega^2/\dot{\omega}} \sim e^{-m/H}\,,$$

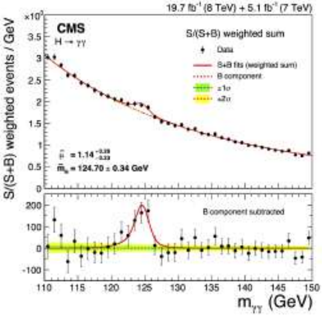
which occurs for $\omega \sim m$ when $|k\tau| \sim 1$.
$\Longrightarrow$ most efficient production for $|k\tau| \sim 1$, and

$$f_{\rm NL}^{\text{(clock)}} \sim \left(\frac{\tau_3}{\tau_1}\right)^{i\frac{m}{H}} \sim \left(\frac{k_3}{k_1}\right)^{-i\frac{m}{H}}$$

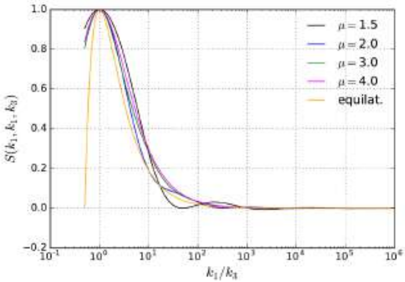
- Usually, the production is maximised for $m \sim H$.

Cosmological collider physics

Particle colliders



Oscillating feature in squeezed bispectrum



amplitude, $\sqrt{s}$ ⟷ coupling to SM, mass

amplitude frequency ⟷ coupling in H units, m/H

Particle production in presence of a chemical potential

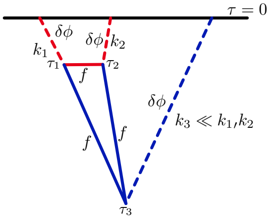
[Adshead, Pearce, Peloso, Roberts, Sorbo '18; Chen, Wang, Xianyu '18]

- Particle production is enhanced if the dispersion relation is modified with a time-dependent contribution.
- For fermions, the coupling

$$\frac{\partial_\mu \phi}{\Lambda_f}(\overline{f}\gamma^\mu\gamma_5 f) \xrightarrow{\text{inflation}} \frac{\dot{\phi}}{\Lambda_f}(\overline{f}\gamma^0\gamma_5 f)$$

during inflation (when $\dot{\phi} \neq 0$ violates Lorentz symmetry) modifies the dispersion relation into

$$\omega^2 = (|\vec{k}|\tau H \pm \lambda)^2 + m^2\,, \quad \lambda = \frac{\dot{\phi}}{\Lambda_f}$$

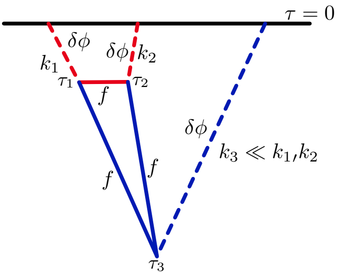


Particle production in presence of a chemical potential

Dispersion: $\omega^2 = (k\tau H \pm \lambda)^2 + m^2\,,\ \lambda = \frac{\dot\phi}{\Lambda_f},\quad H < m \ll \lambda$ (pert. $\Rightarrow \lambda \lesssim 60H$)

Non-adiabaticity: maximise $e^{-\omega^2/\dot\omega} \Rightarrow$

1. Production rate $\Gamma \sim \exp\left(-\frac{m^2}{\lambda H}\right)$
   Significant production also for $m > H$, as long as $\lambda \gg H$.
2. Enhancement for $k\tau H \sim \lambda$.
3. Fermion density: $n \sim k^2 \mathrm{d}k \sim \lambda^2 m\Big|_{m \ll H}$.



1. Two SM fermions get produced at τ_3
   $(\omega \sim m, k\tau \sim \lambda)$
   $\Rightarrow$ External soft inflaton $\delta\phi(k_3)$
2. Redshift: at later times τ_1, τ_2
   $(\omega \sim \lambda, k\tau \sim 0)$
   Oscillation frequency $(k_3/k_1)^{2i\lambda/H}$
3. Fermions pair annihilate into two inflatons
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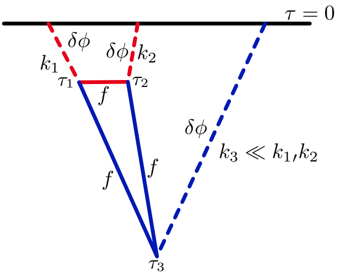

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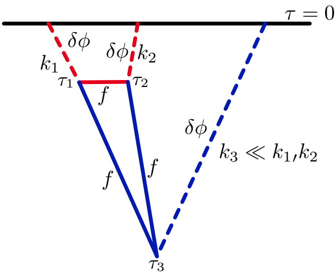

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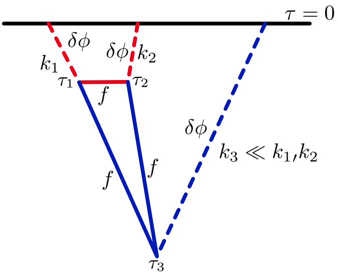

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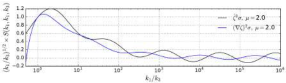
Summary: fermion production in presence of chemical potential

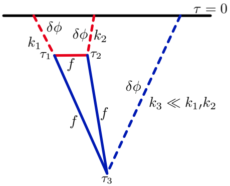
- The bispectrum of density perturbations can tell us of heavy particles interacting with the inflaton.
- The squeezed limit $(k_3 \ll k_1 \sim k_2)$ could display non-analytic contributions $(k_3/k_1)^{i\nu}$.
- These contributions can be large if they come from an interaction

$$\frac{\partial_\mu \phi}{\Lambda_f}(\overline{f}\gamma^\mu\gamma_5 f) \longrightarrow \lambda(\overline{f}\gamma^0\gamma_5 f)$$

  The signal is present for $\lambda \gg m > H$.
- Amplitude and frequency of the oscillations inform us of coupling and mass of the particle in Hubble units.

[Credit: Zhong-Zhi Xianyu]

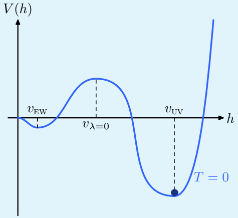




A new cosmological Higgstory

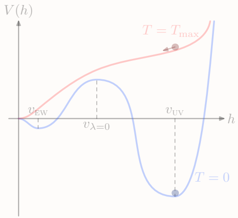
During inflation

- Existence of a new Higgs minimum at $v_{\rm UV} \gtrsim H$, generated by higher order operators (e. g. $|\mathcal{H}|^6/\Lambda_{\mathcal{H}}^2$).
- The Higgs field fluctuates beyond the barrier and rolls to the new minimum.
- SM fermions during inflation have a mass $yv_{\rm UV}$.



After inflation

- Contributions from the thermal bath to the Higgs potential lift the UV minimum if $T_{\rm max} > v_{\rm UV}$.
- The background field rolls back to the origin, and its amplitude quickly decreases due to interactions with the thermal bath.
- The Higgs field settles in the EW vacuum.



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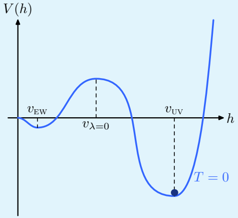

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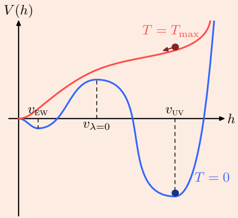
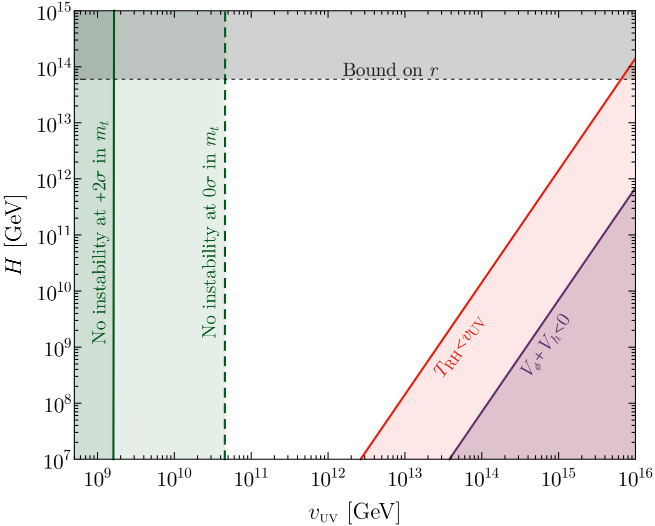
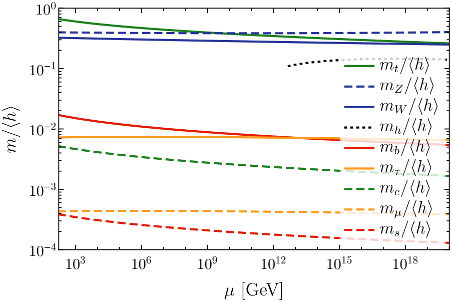
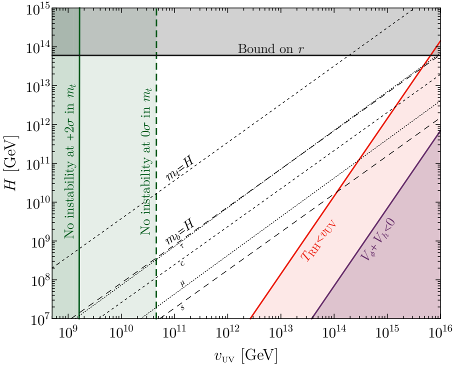


Available parameter space for $(v_{\rm UV}, H)$



SM fermions span many orders of magnitude in mass





We easily have one or two SM fermions with mass close to Hubble.

Coupling between SM fermions and inflaton

- The lowest order coupling of SM fermions to a shift-symmetric inflaton contains

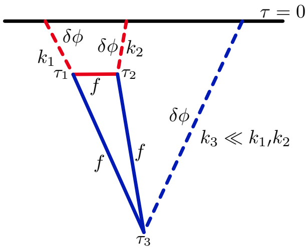
$$c_{f_i} \frac{\partial_\mu \phi}{\Lambda_f} (\overline{f}_i \gamma^\mu \gamma_5 f_i)$$

- This term is a chemical potential for SM fermions.
- The result for the contribution to the squeezed bispectrum is [Chen, Wang, Xianyu '18; Hook, Huang, DR '19]

$$(\mu \equiv \sqrt{\lambda^2 + m^2},\ \widetilde{x} \equiv x/H)$$

$$S(k_1, k_2, k_3) \overset{k_3 \ll k_1 \sim k_2}{\underset{\lambda \gg m}{\simeq}} f_{\rm NL}^{(\rm clock)} \left(\frac{k_3}{k_1}\right)^{2-2i\tilde{\mu}} + \cdots$$

$$f_{\rm NL}^{(\rm clock)} \approx \frac{N_c}{6\pi} \mathcal{P}_\zeta^{-1/2} \left(\frac{m}{\Lambda_f}\right)^3 \widetilde{\lambda}^2 \frac{e^{\pi\widetilde{\lambda}} \widetilde{\mu} \Gamma(-i\widetilde{\mu})^2 \Gamma(2i\widetilde{\mu})^3}{2\pi\Gamma(i(\widetilde{\lambda}+\widetilde{\mu}))^3 \Gamma(i(\widetilde{\mu}-\widetilde{\lambda})+1)}$$



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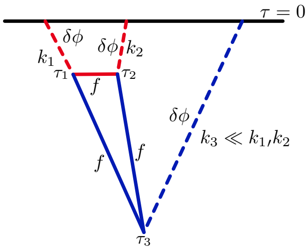

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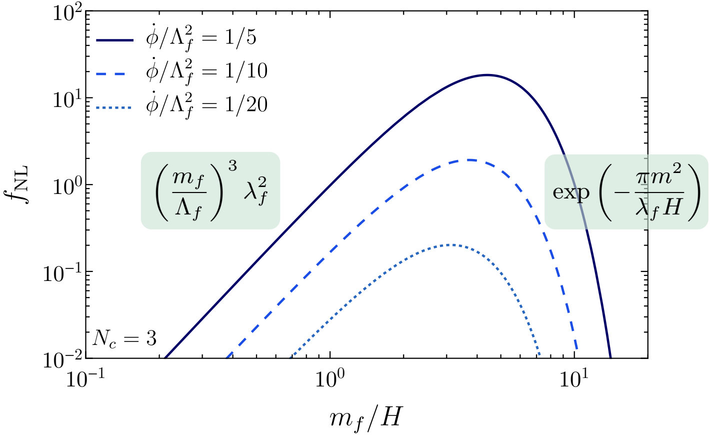
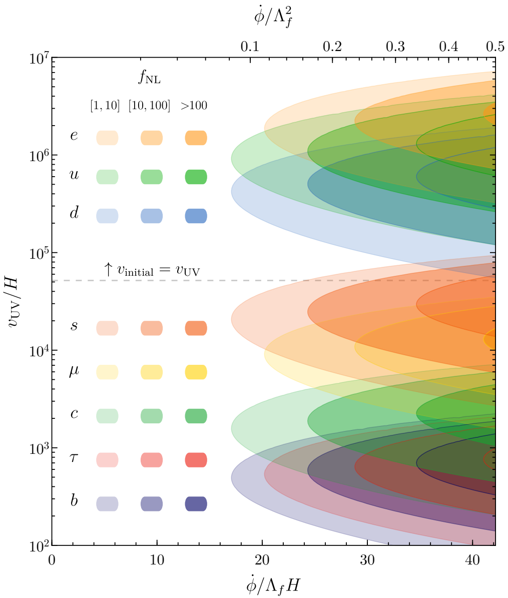
Signal strength as a function of m_f/H and λ_f



Signal strength as a function of λ_f and $v_{\rm UV}/H$

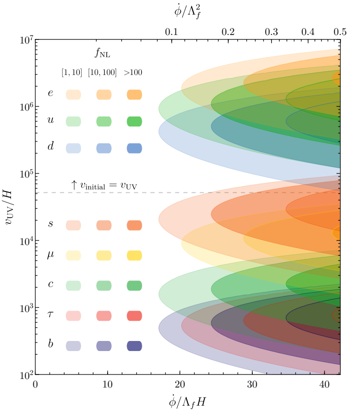


Implications of the detection of a signal

- Two SM fermions could simultaneously contribute to the signal!
- From the amplitudes and frequencies of the oscillations, we can get $(\widetilde{m}_i, \widetilde{\lambda}_i)$ and $(\widetilde{m}_j, \widetilde{\lambda}_j)$.
- The ratio

$$\frac{\widetilde{m}_i}{\widetilde{m}_j} = \frac{y_i}{y_j}$$

  can confirm the origin of the signal.
- Implication of a new Higgs minimum at high energies.
- Important implications for models addressing hierarchy problem.
- (At least) two vacua configurations: measure problem? Anthropics?



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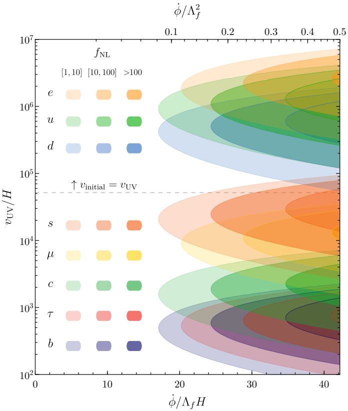
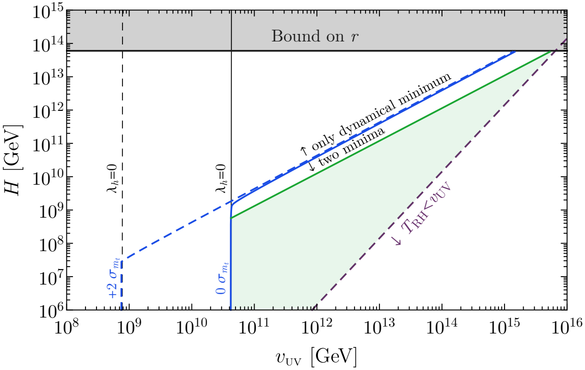
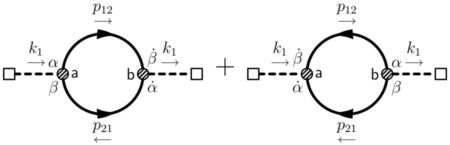


A fresh look at the parameter space



- Green region: SM fermions (lighter than top) are accessible.
  What about the rest of parameter space?
- What about the top, that would require $v_{\rm UV} \sim H$?
- What is the effect of the fermion density on the Higgs potential?

Contribution of the fermion density to the Higgs potential



- We expect a contribution

$$\delta V_h \sim -m_f n_f \sim -\lambda_f^2 m_f^2 \exp\left(-\frac{\pi m_f^2}{\lambda_f H}\right)$$

where the $-$ sign is expected for the contribution of a chemical potential [Benson, Bernstein, Dodelson '91; Linde '90].

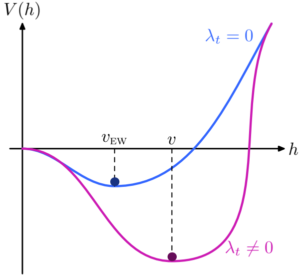
- Result:

$$V_h = -\mu_h^2 |\mathcal{H}|^2 + \lambda_h |\mathcal{H}|^4 - \frac{N_c y_f^2}{\pi^2} \lambda_f^2 |\mathcal{H}|^2 \exp\left[-\frac{\pi y_f^2 |\mathcal{H}|^2}{\lambda_f H}\right]$$

with a *dynamical negative mass* term during inflation.

Dynamical generation of a Higgs minimum

1. The effect of the fermion density is to enhance EW symmetry breaking.
2. The increased fermion mass amplifies their production.
3. When the fermion mass becomes too large, the exponential suppression kicks in.



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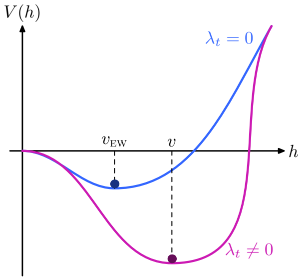

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- The dynamically induced mass can dominate the quartic term for $y_f \sim \mathcal{O}(1) \Longrightarrow$ **top quark** contribution.

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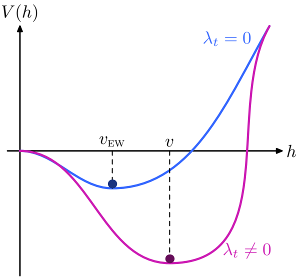


$$V_h = -\mu_h^2|\mathcal{H}|^2 + \lambda_h|\mathcal{H}|^4 - \frac{N_c y_f^2}{\pi^2}\lambda_f^2|\mathcal{H}|^2 \exp\left[-\frac{\pi y_f^2|\mathcal{H}|^2}{\lambda_f H}\right]$$

- The Higgs vev is set by the exponential:

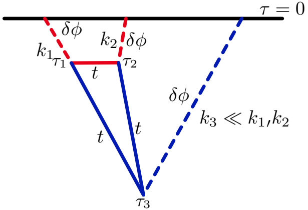
$$v \simeq \sqrt{\frac{2\widetilde{\lambda}_t}{\pi y_t^2}} H\,, \quad \frac{m_t}{H} \sim \sqrt{\frac{\widetilde{\lambda}_t}{\pi}}$$

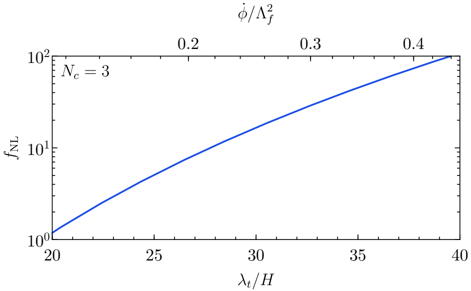
The signal: a unique relation between frequency and amplitude

- The coupling $\widetilde{\lambda}_t = \lambda_t/H$ sets both the mass and the coupling of the top quark for the cosmological collider:

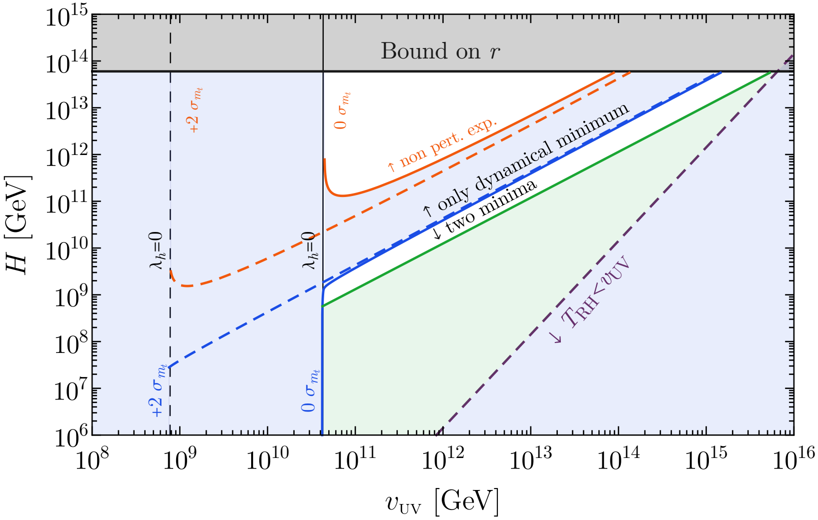
$$S(k_1,k_2,k_3) \overset{k_3 \ll k_1 \sim k_2}{\simeq} f_{\rm NL}^{(\rm clock)} \left(\frac{k_3}{k_1}\right)^{2-2i\widetilde{\lambda}_t},$$

$$f_{\rm NL}^{(\rm clock)} \approx \frac{4\sqrt{2} N_c \mathcal{P}_\zeta}{3e} \widetilde{\lambda}_t^{13/2}$$





The full parameter space



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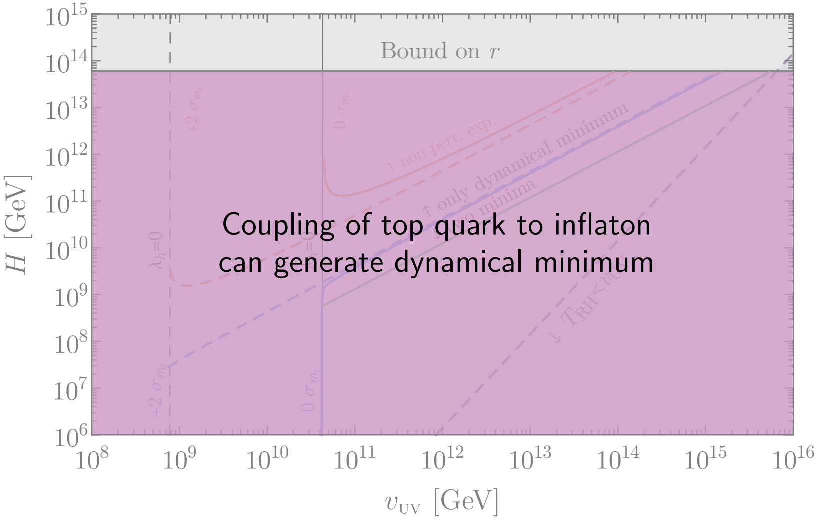
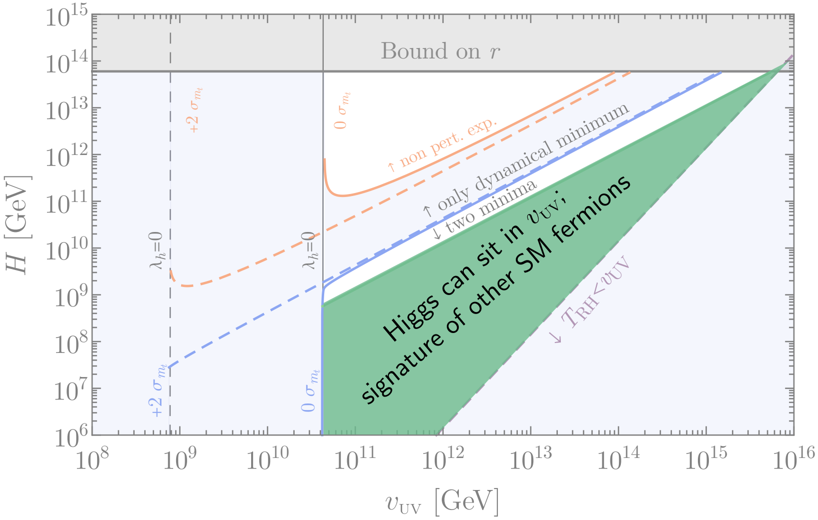


Coupling of top quark to inflaton
can generate dynamical minimum

The full parameter space



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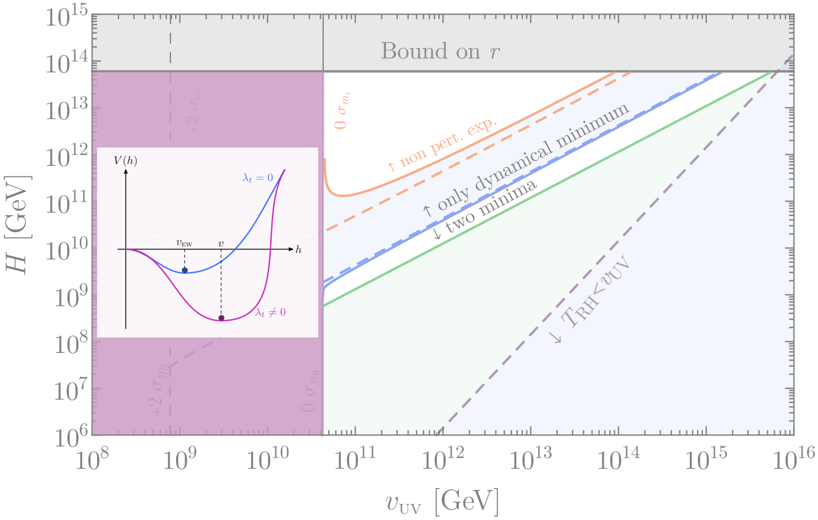

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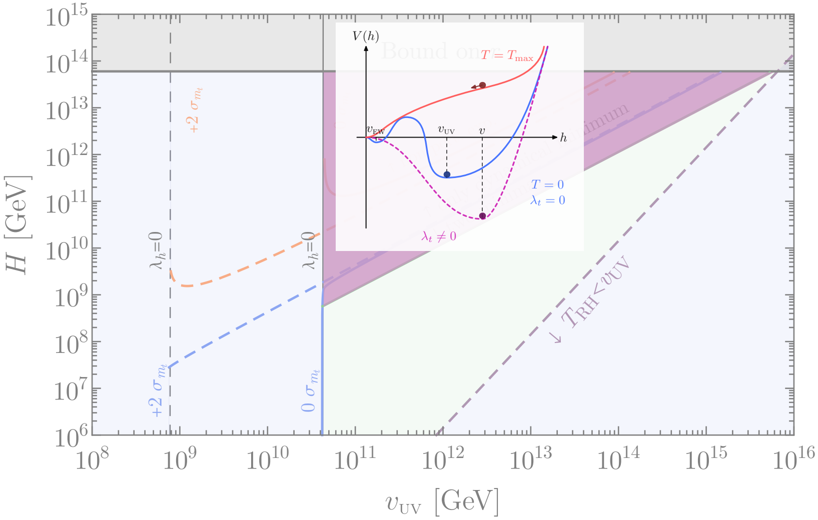

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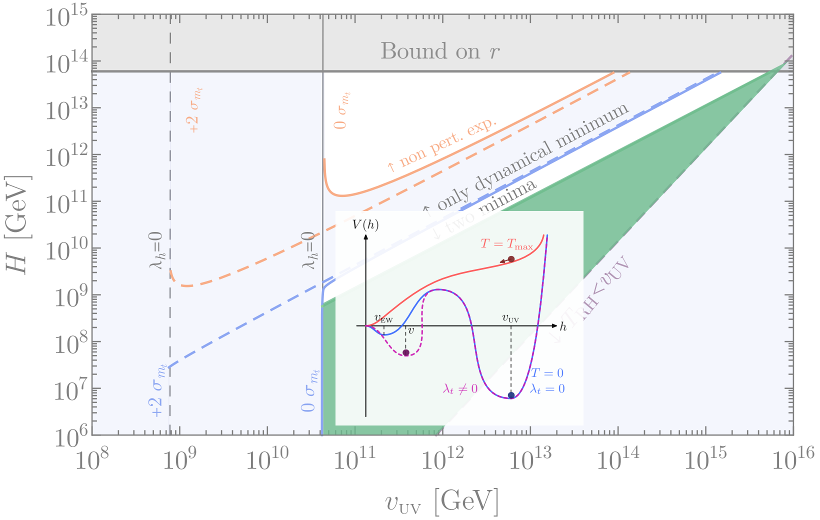

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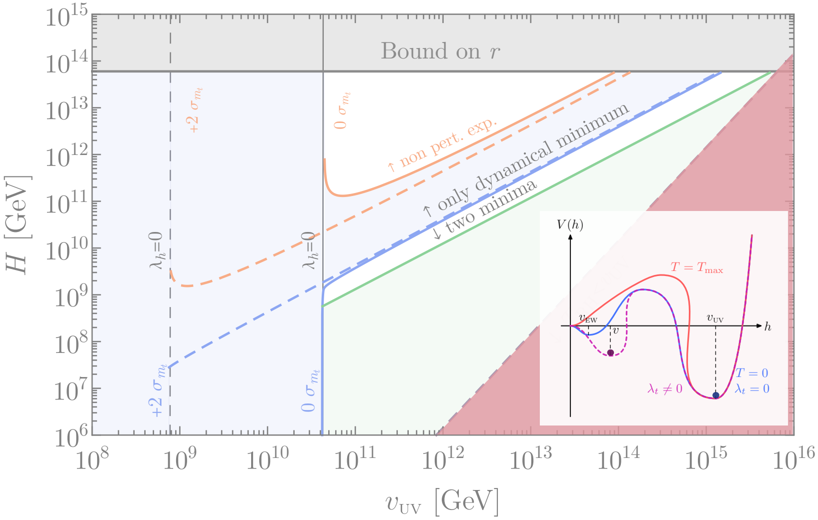
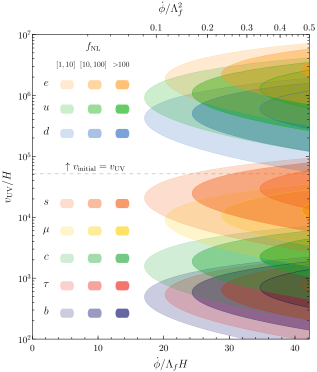
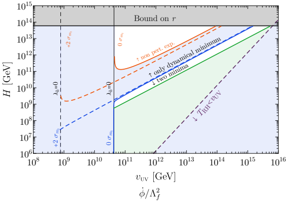
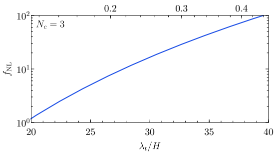


Conclusions

- Cosmological collider physics offers a tool for BSM physics.
- The coupling of SM fermions to the inflaton can lead to distinctive and minimal signatures from:
  1. a new Higgs minimum at high scales;
  2. a dynamical Higgs minimum during inflation.

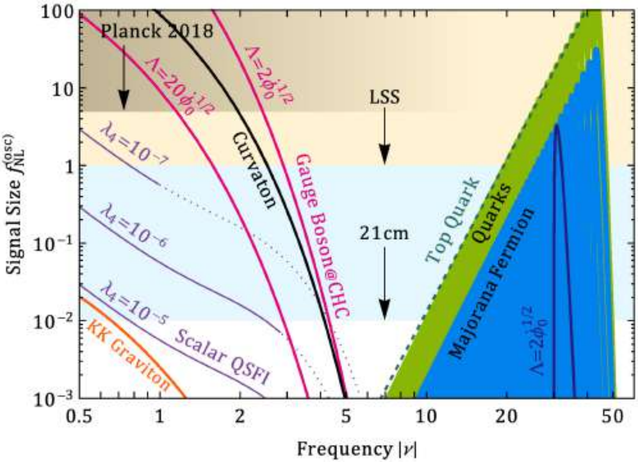






Thanks for your attention!

Prospects for detectability



[Wang, Xianyu '19]

Potential signals and effects of other operators

- $\boxed{c_2 \frac{(\partial_\mu \phi)^2}{\Lambda_{\mathcal{H}}^2} \mathcal{H}^\dagger \mathcal{H}}$ can lead to a sizeable contribution to the Higgs mass, but is hard to observe directly: large c_2 implies large Boltzmann suppression. [Kumar, Sundrum '17]

  For the case of dynamically generated minimum, its contribution is subleading to the fermion one if $c_2 \lesssim 0.1$ if $\Lambda_f \sim \Lambda_{\mathcal{H}}$.

- $\boxed{c_1 \frac{\partial_\mu \phi}{\Lambda_{\mathcal{H}}} \mathcal{H}^\dagger \mathcal{D}^\mu \mathcal{H}}$ induces a mixing between Higgs and time component of Z boson, and makes them acquire a mass of order $\widetilde{\lambda} H$ which exponentially reduces the signal. Suppression of $\mathcal{O}_1$, $\mathcal{O}_2$ ultimately related to hierarchy problem. [Kumar, Sundrum '17]

- $\boxed{c_G \frac{\phi}{\Lambda_G} G\widetilde{G}}$ (with G a generic SM gauge boson) is also a derivative coupling. If the fermion current coupling to ϕ is anomalous, we can expect a strength $\frac{\dot{\phi}}{\Lambda_G H} \sim \frac{\alpha}{4\pi} \frac{\dot{\phi}}{\Lambda_f H} \lesssim 1$. In absence of anomalies, it is more suppressed. Can lead to copious particle production [Anber, Sorbo '09; Barnaby, Pajer, Peloso '11]

UV motivation for assuming equal couplings $|c_{f_i}|$

The only flavour universal anomaly-free $U(1)'$ extension of the Standard Model is a linear combination of $U(1)_Y$ and $U(1)_{B-L}$.

	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-L}$	$U(1)'$
$Q = \begin{pmatrix} u \\ d \end{pmatrix}$	$\mathbf{3}$	$\mathbf{2}$	$\frac{1}{6}$	$+\frac{1}{3}$	$\frac{1}{6}\cos\theta + \frac{1}{3}\sin\theta$
u^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{2}{3}\cos\theta - \frac{1}{3}\sin\theta$
d^c	$\overline{\mathbf{3}}$	$\mathbf{1}$	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}\cos\theta - \frac{1}{3}\sin\theta$
$L = \begin{pmatrix} \nu \\ e \end{pmatrix}$	$\mathbf{1}$	$\mathbf{2}$	$-\frac{1}{2}$	-1	$-\frac{1}{2}\cos\theta - \sin\theta$
e^c	$\mathbf{1}$	$\mathbf{1}$	1	$+1$	$\cos\theta + \sin\theta$

The coefficients c_V and c_A are obtained via $c_V = \frac{c_L + c_R}{2}$, $c_A = \frac{-c_L + c_R}{2}$.

SM fermion f	Vector current	Axial current
up quarks	$\frac{5}{12}\cos\theta + \frac{1}{3}\sin\theta$	$\frac{1}{4}\cos\theta$
down quarks	$-\frac{1}{12}\cos\theta + \frac{1}{3}\sin\theta$	$-\frac{1}{4}\cos\theta$
leptons	$-\frac{3}{4}\cos\theta - \sin\theta$	$-\frac{1}{4}\cos\theta$