`` Energy Frontier in Particle Physics: LHC and Future Colliders", Sept. 2017, NTU

TESTING NATURALNESS

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Based on

[C. Chen, J. Hajer, TL, I. Low and H. Zhang, arXiv: 1705.07743]

What is the Naturalness Problem?

A discrepancy between two energy scales strongly correlated

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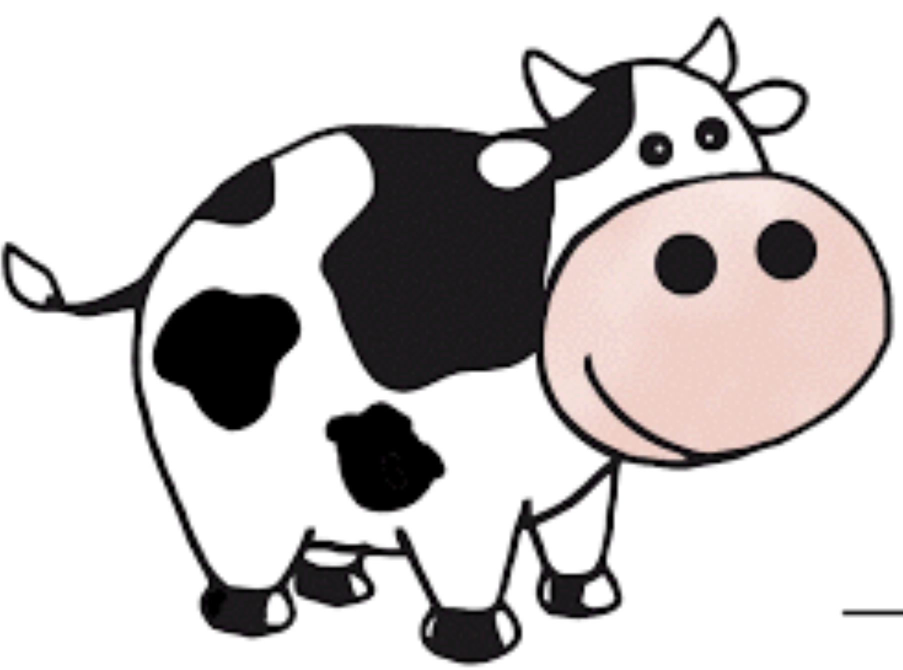
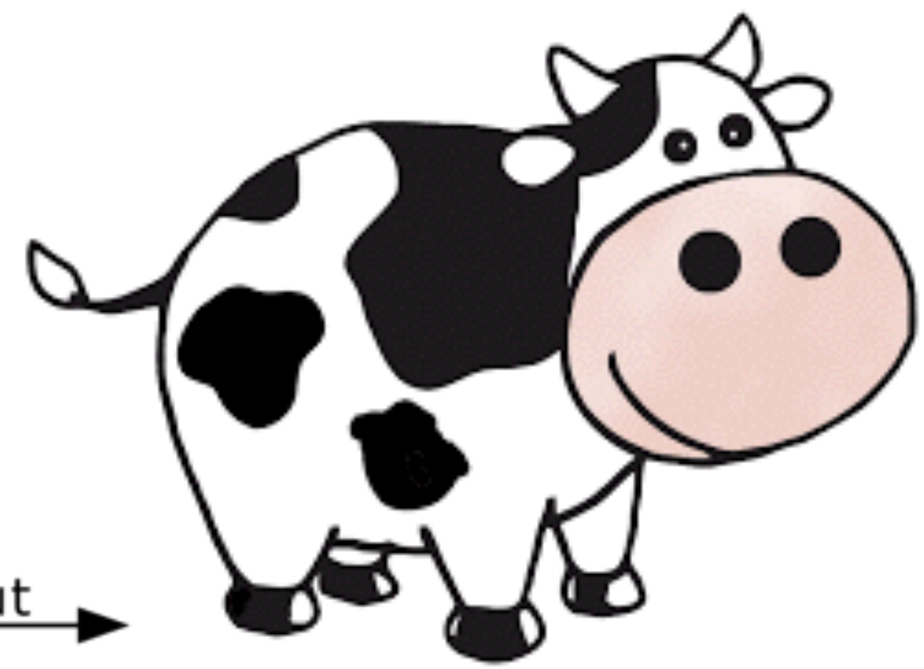
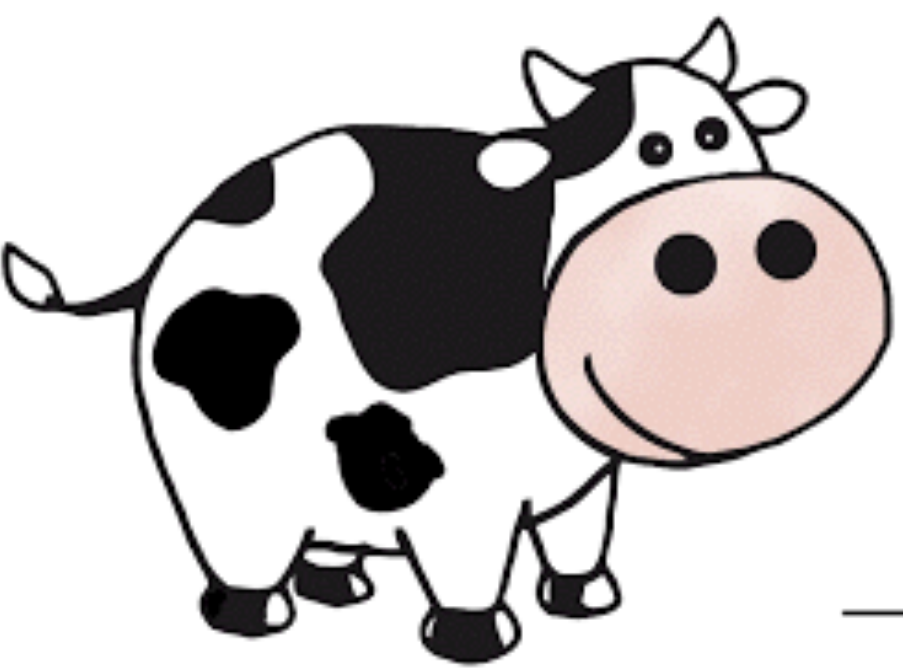


Natural!

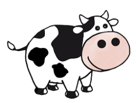


What is the Naturalness Problem?

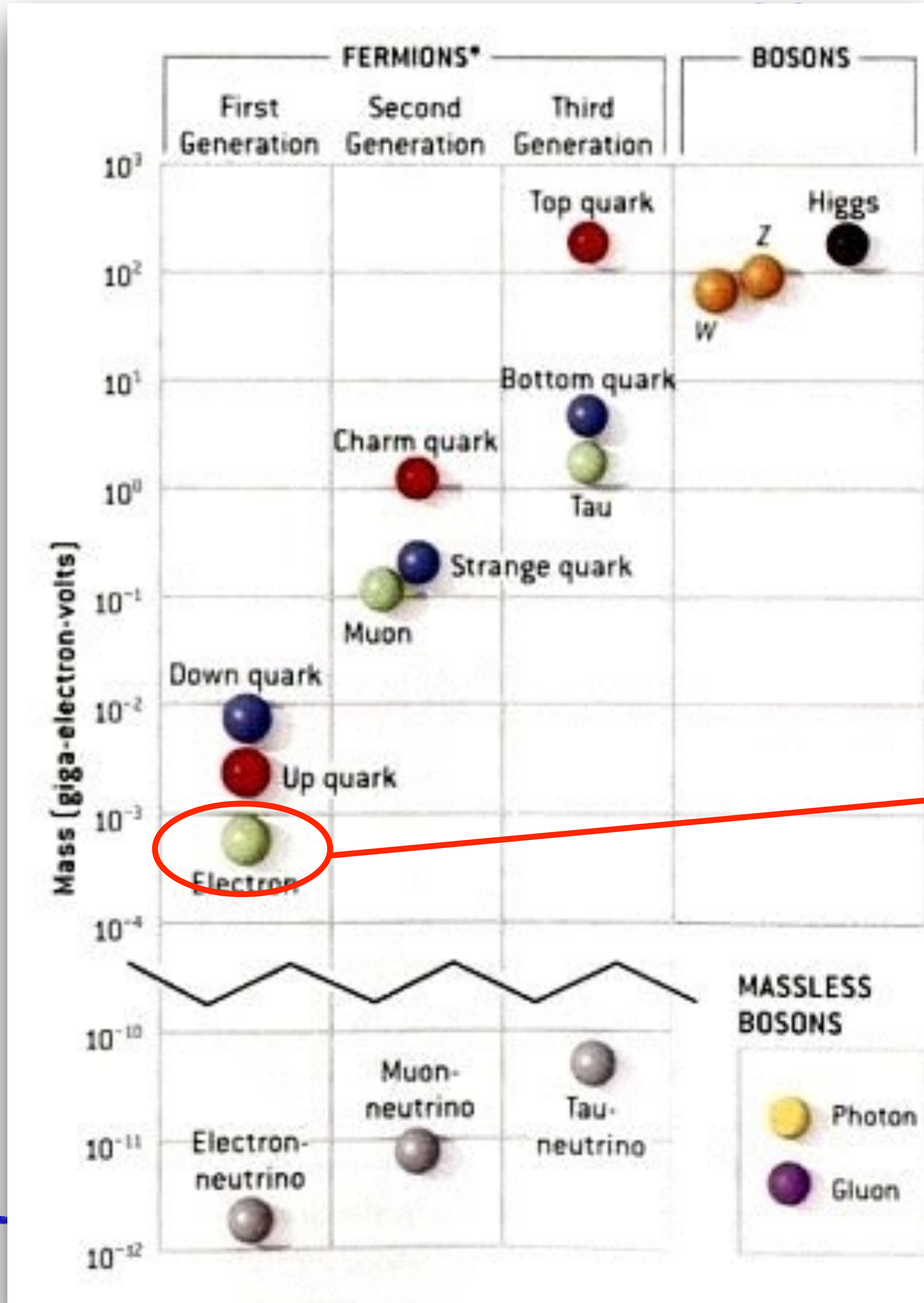
A discrepancy between two energy scales strongly correlated



Unnatural!



Naturalness Problem in Particle Physics



EW scale ~ 100 GeV

Why electron mass orders smaller than the EW scale? Unnatural!

Naturalness Problem in Particle Physics

Observation: (1) zero mass limit => chiral symmetry, and (2) chiral symmetry breaking => logarithmically divergent in m_e

$$m_e \sim m^0_e\,[1 + 3\alpha/4\pi\ 1n(\Lambda/m_e)]$$

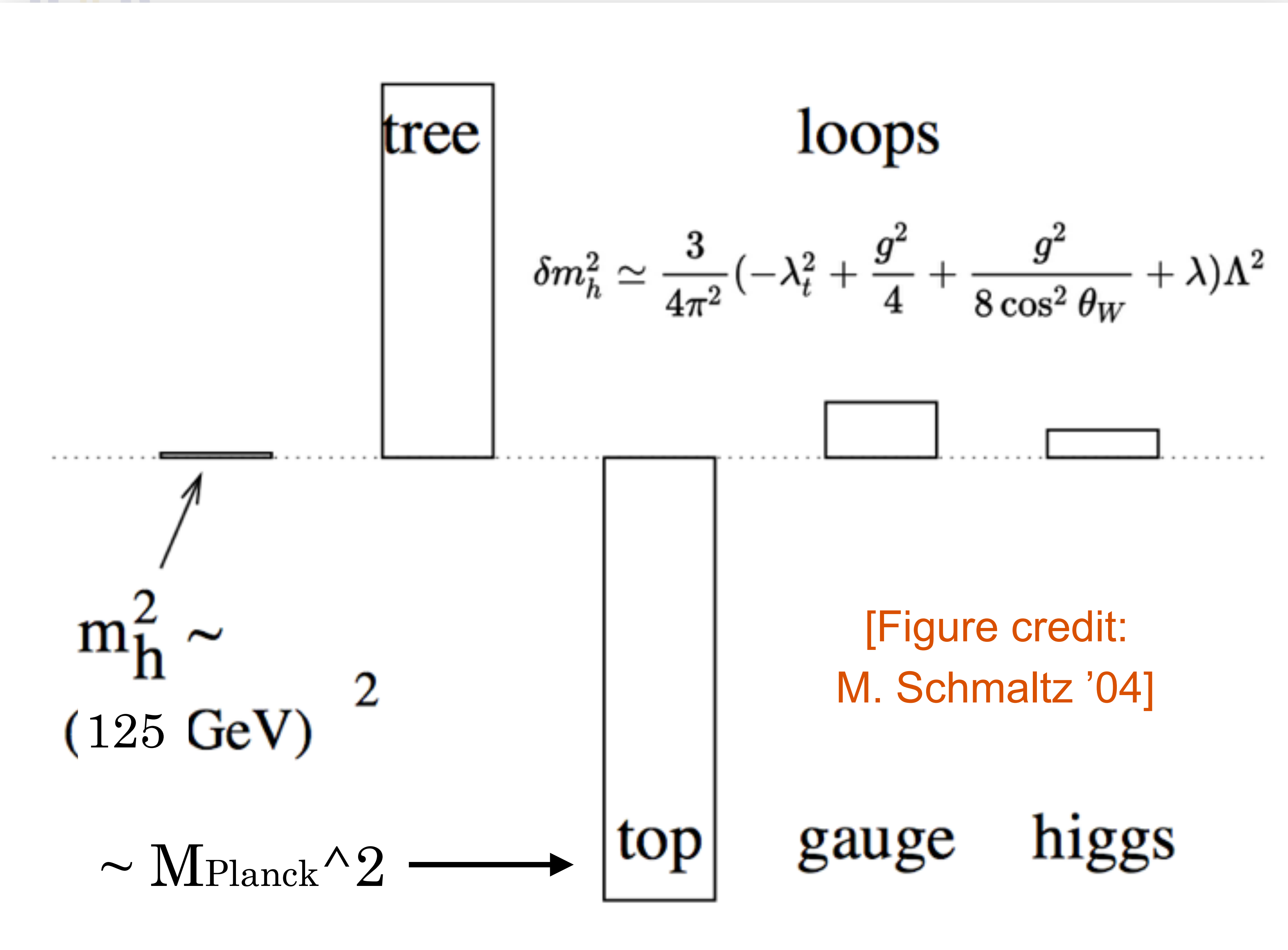
t'Hooft statement for "technical naturalness"

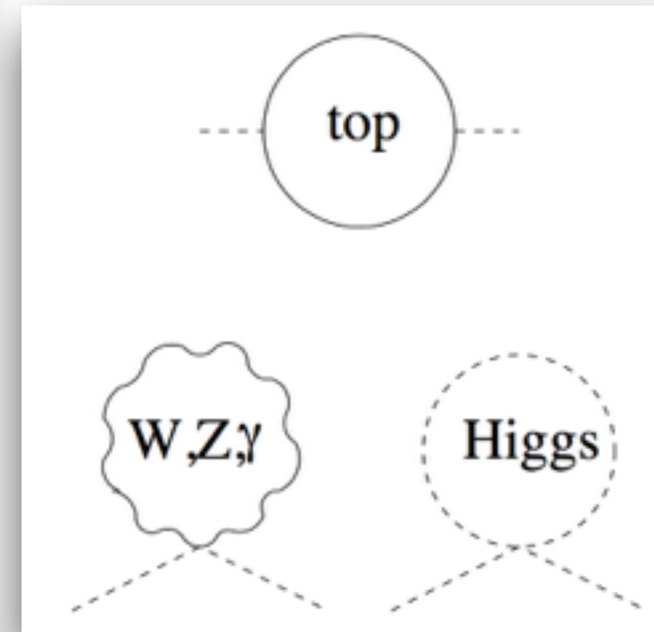
If the turning off of an ``unnatural" parameter results in an enhanced symmetry, then this parameter is ``technically" natural.

=> The smallness of m_e: not natural, but technically natural !

However, not all particle masses are technically natural in the SM

Naturalness Problem in Particle Physics

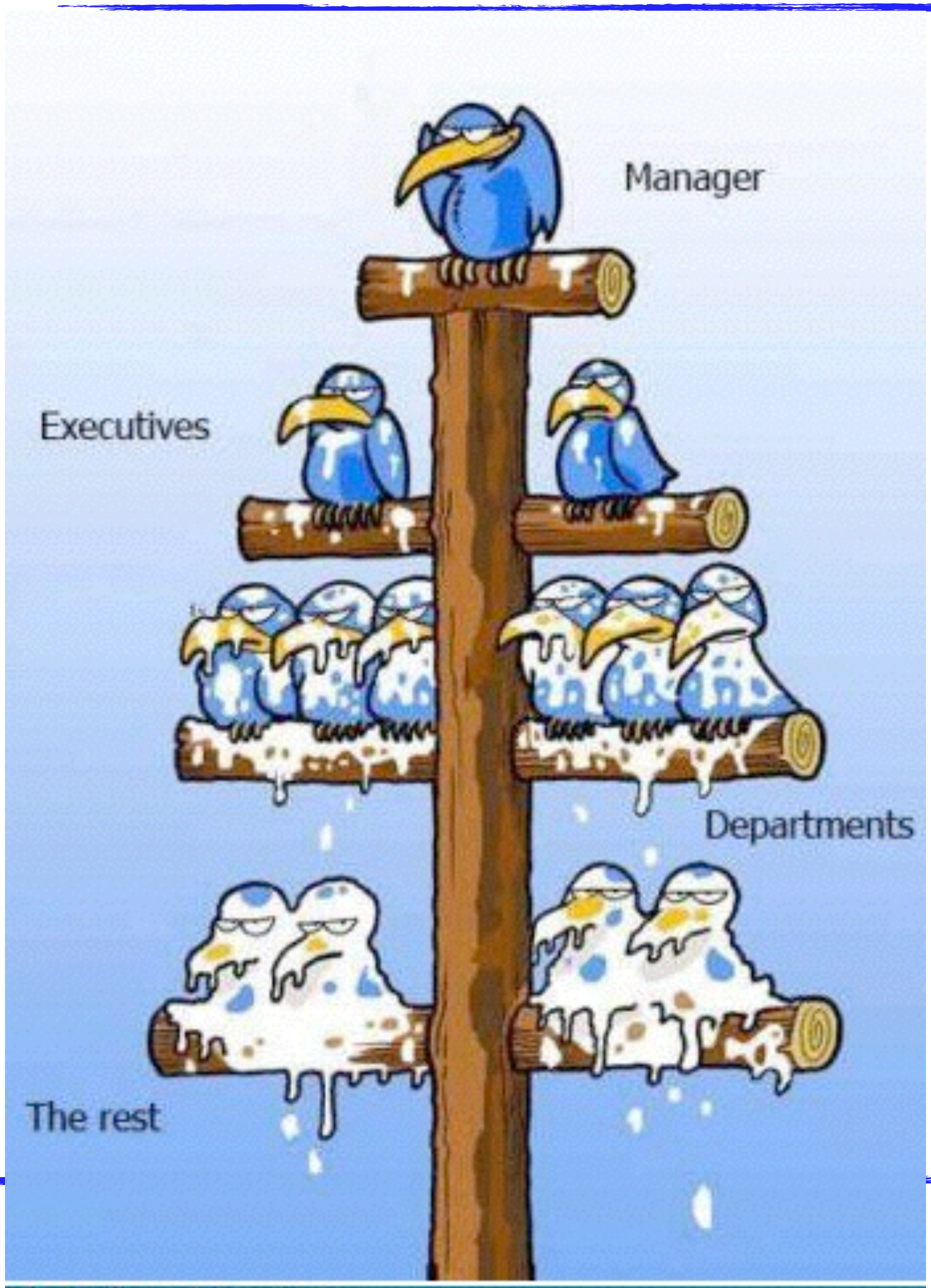




A hierarchy of 30 orders!

- Unnatural!

``Hierarchy'' Problem



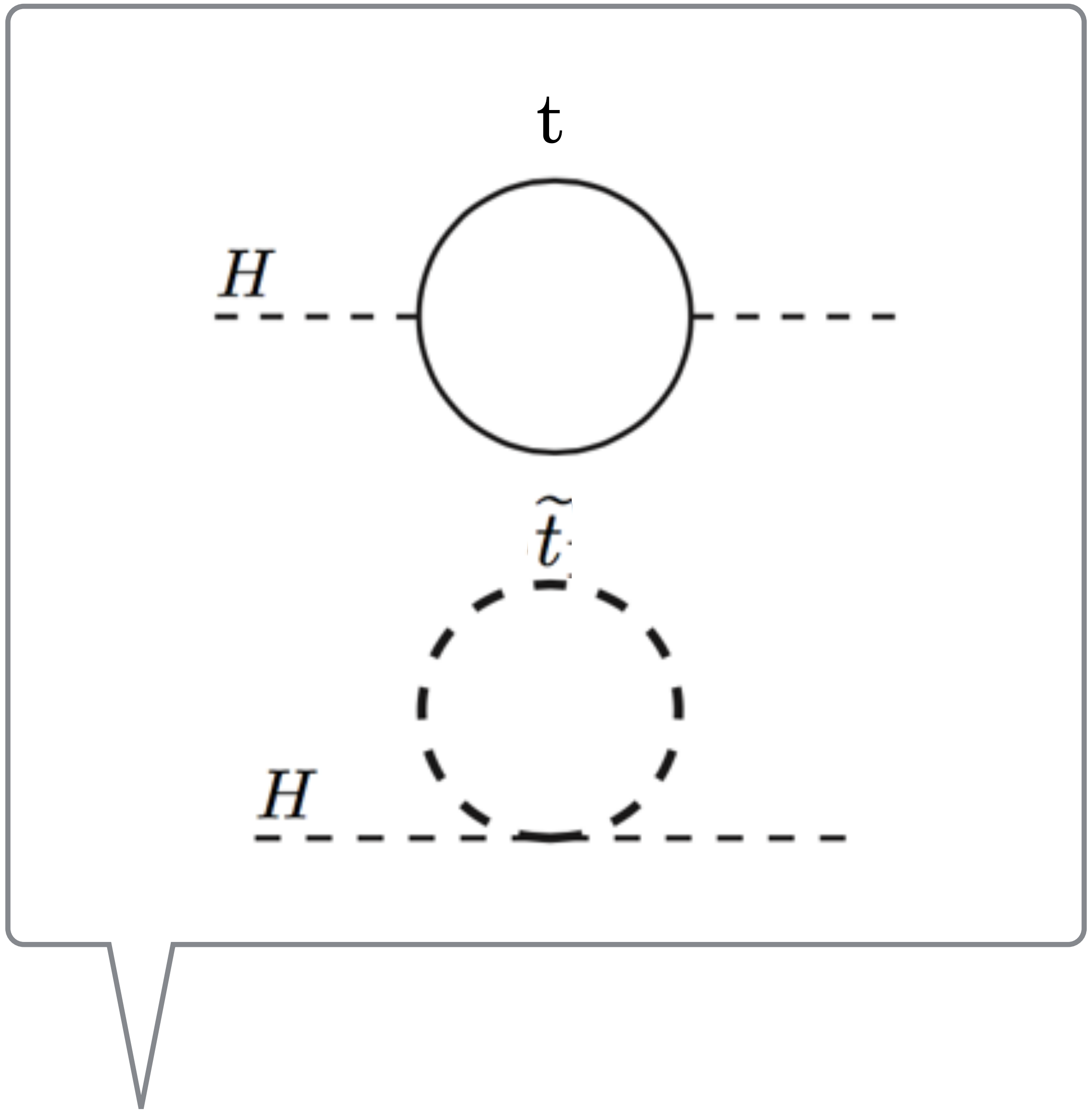
Picture credit: www

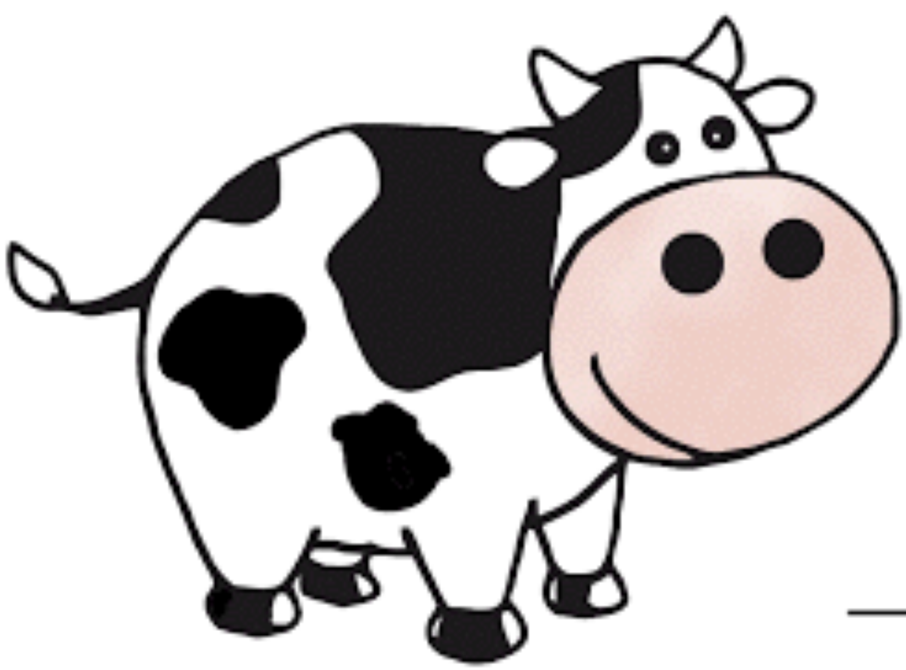
Planck scale

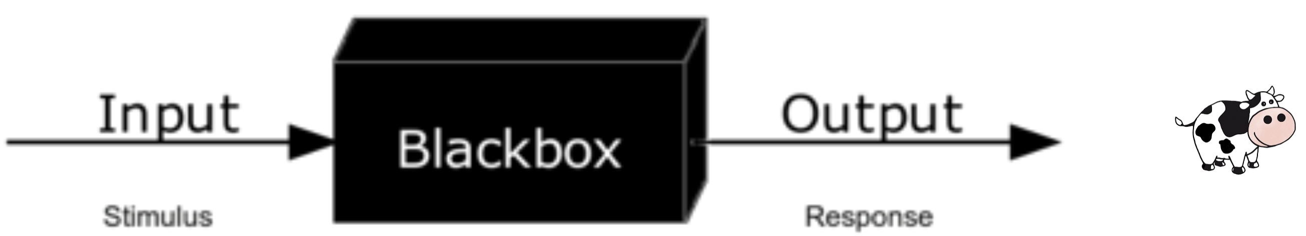
Is there a ``technically natural'' solution?

EW scale

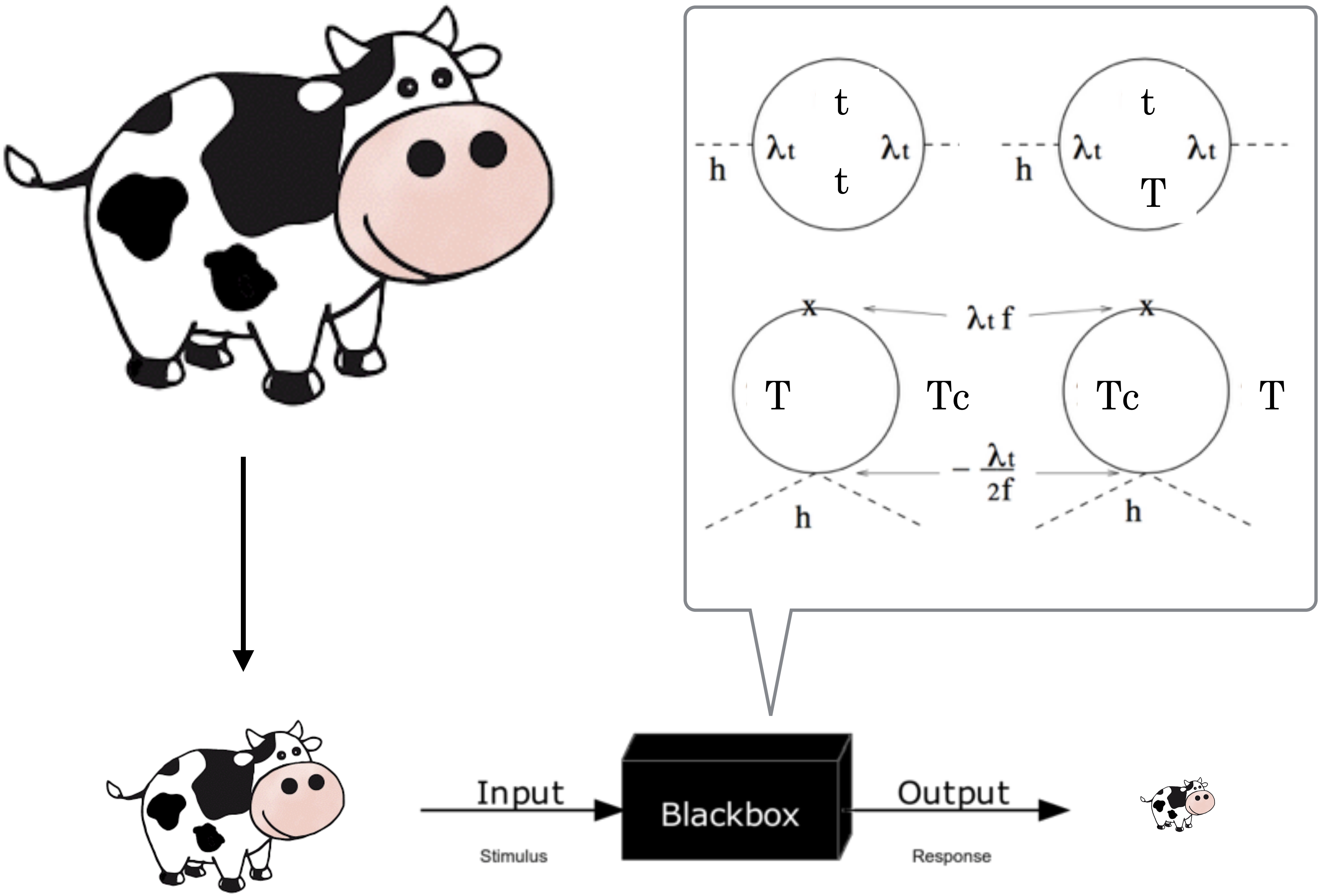
Solution I - Fermionic Symmetry (Supersymmetry)







Solution II - Bosonic Symmetry (Little/Twin Higgs)



Some Wisdoms

The underlying symmetry =>

(1) a spectrum of ``partner" particles

(2) a sum rule for canceling quadratic divergence in mh^2

Motivated a vast amount of searches for ``partner" particles at, e.g., LEP, Tevatron, LHC, for decades

A must-be-done task post the discovery of any partner-like particle:

Measuring the sum rule

One might ask:

why worry about step 2) when we have seen no empirical sign of a top partner??

The answer:

We live in a unique juncture in history!

As part of the planning for a new generation of particle accelerators, we would like to know the ability of a new hadron machine to unambiguously establish the Naturalness principle, should a top partner-like particle be discovered.

Ian Low, 2017 CERN-KCK workshop

Simplified Model

SM + one pair of vector-like (weak isospin singlet) top partners

$$\mathcal{L}_U = u_3^c \left(c_0 f U + c_1 H q_3 + \frac{c_2}{f} H^2 U + \dots \right) + U^c \left(\hat{c}_0 f U + \hat{c}_1 H q_3 + \frac{\hat{c}_2}{f} H^2 U + \dots \right) + \text{h.c.}\ .$$

Simplified Model

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Model	Coset		SU(2)	c_0	c_1	c_2	$\hat{c}_0$	$\hat{c}_1$	$\hat{c}_2$
Toy model	$\frac{SU(3)}{SU(2)}$	[22]	**1**	λ_1	$-\lambda_1$	$-\lambda_1$	λ_2	0	0
Simplest	$\left(\frac{SU(3)}{SU(2)}\right)^2$	[23]	**1**	λ	$-\lambda$	$-\lambda$	λ	λ	$-\lambda$
Littlest Higgs	$\frac{SU(5)}{SO(5)}$	[14]	**1**	λ_1	$-\sqrt{2}i\lambda_1$	$-2\lambda_1$	λ_2	0	0
Custodial	$\frac{SO(9)}{SO(5)\,SO(4)}$	[20]	**2**	y_1	$\frac{i}{\sqrt{2}}y_1$	$-\frac{1}{2}y_1$	y_2	0	0
T-parity invariant	$\frac{SU(3)}{SU(2)}$	[19]	**1**	λ	$-\lambda$	$-\lambda$	$-\lambda$	$-\lambda$	λ
T-parity invariant	$\frac{SU(5)}{SO(5)}$	[19]	**1**	λ	$-\sqrt{2}i\lambda$	-2λ	$-\lambda$	$-\sqrt{2}i\lambda$	2λ
Mirror twin Higgs	$\frac{SU(4)\,U(1)}{SU(3)\,U(1)}$	[24]	**1**	0	$i\lambda_t$	0	λ_t	0	$-\lambda_t$

Naturalness Sum Rule - Mass Basis Before EWSB

$$\mathcal{L}_{T'} = m_{T'} T'^c T' + \lambda_{t'} H t'^c t' + \lambda_{T'} H T'^c t' + \frac{\alpha_{t'}}{2m_{T'}} H^2 t'^c T' + \frac{\alpha_{T'}}{2m_{T'}} H^2 T'^c T' + \frac{\beta_{t'}}{6m_{T'}^2} H^3 t'^c t' + \frac{\beta_{T'}}{6m_{T'}^2} H^3 T'^c t' + \mathcal{O}\left(H^4\right) + \text{h.c.}$$

The contribution of the top sector to the C-W potential can be calculated, with the quadratically divergent contribution given by

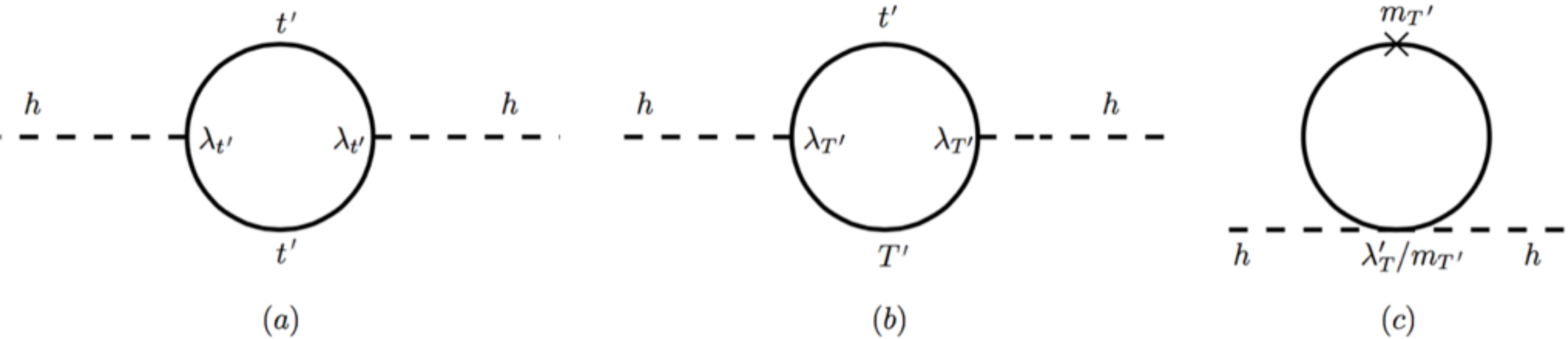
$$\frac{1}{16\pi^2} \Lambda^2 \operatorname{tr} \mathcal{M}(H)^\dagger \mathcal{M}(H)$$

The requirement of a vanishing coefficient in H^2 =>

$$\boxed{\alpha_{T'} = -\left|\lambda_{T'}\right|^2 - \left|\lambda_{t'}\right|^2}$$

Testing the Sum Rule -Traditional Wisdom

$$\mathcal{L}_{T'} = m_{T'} T'^c T' + \boxed{\lambda_{t'}} H t'^c t' + \boxed{\lambda_{T'}} H T'^c t' + \frac{\alpha_{t'}}{2m_{T'}} H^2 t'^c T' + \boxed{\frac{\alpha_{T'}}{2m_{T'}}} H^2 T'^c T'$$
$$+ \frac{\beta_{t'}}{6m_{T'}^2} H^3 t'^c t' + \frac{\beta_{T'}}{6m_{T'}^2} H^3 T'^c t' + \mathcal{O}\left(H^4\right) + \text{h.c.}$$



$$\boxed{\alpha_{T'} = -\left|\lambda_{T'}\right|^2 - \left|\lambda_{t'}\right|^2}$$

Testing the Sum Rule -Traditional Wisdom

Top quarks and electroweak symmetry breaking in little Higgs models

Maxim Perelstein, Michael E. Peskin, and Aaron Pierce
Phys. Rev. D **69**, 075002 – Published 8 April 2004

$$\alpha_{T'} = -|\lambda_{T'}|^2 - |\lambda_{t'}|^2$$

$$\alpha_{T'} = \lambda_{T'} \frac{m_T}{f}$$

Really difficult!

Testing the Sum Rule -Traditional Wisdom

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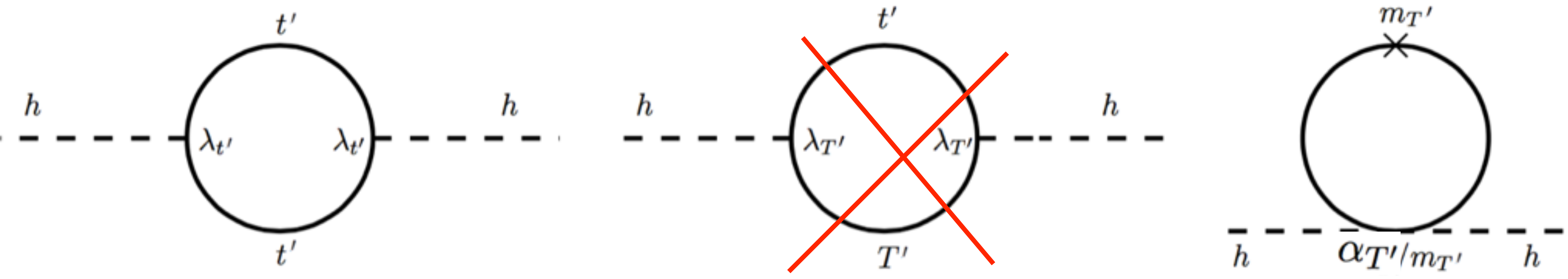


Not representative! E.g., little Higgs with T-parity

Naturalness Sum Rule - Mass Basis After EWSB

$$\mathcal{L}_T = m_T T^c T + \lambda_t v t^c t + \boxed{\frac{\lambda_t}{\sqrt{2}}} h t^c t + \frac{\lambda_T}{\sqrt{2}} h T^c t + \frac{a_t v}{\sqrt{2} m_T} h t^c T + \boxed{\frac{a_T v}{\sqrt{2} m_T}} h T^c T$$
$$+ \frac{\alpha_t}{4 m_T} h^2 t^c T + \frac{\alpha_T}{4 m_T} h^2 T^c T + \frac{b_t v}{4 m_T^2} h^2 t^c t + \frac{b_T v}{4 m_T^2} h^2 T^c t + \mathcal{O}\left(h^3, \frac{v^2}{m_T^2}\right) + \text{h.c.}$$

$$\boxed{\alpha_{T'} = -|\lambda_{T'}|^2 - |\lambda_{t'}|^2} \quad \Rightarrow \quad \boxed{a_T = -|\lambda_t|^2 + \mathcal{O}\left(\frac{v^2}{m_T^2}\right)}$$

- Surprising! Involves two parameters only
  - top Yukawa coupling
  - top partner Yukawa coupling

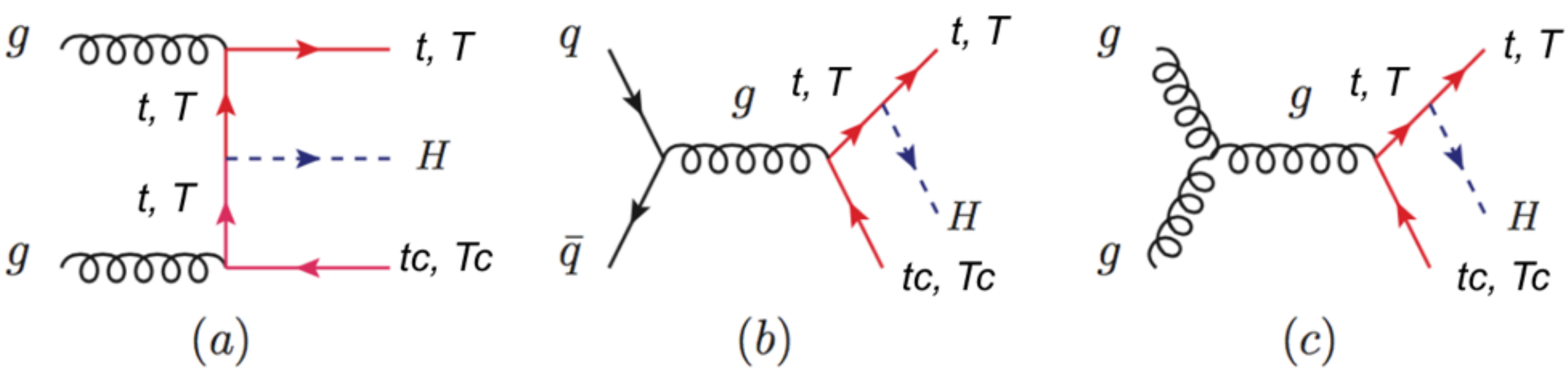
$$\boxed{a_T = \alpha_{T'} + |\lambda_{T'}|^2}$$

Collider Strategy - Colored Top Partners

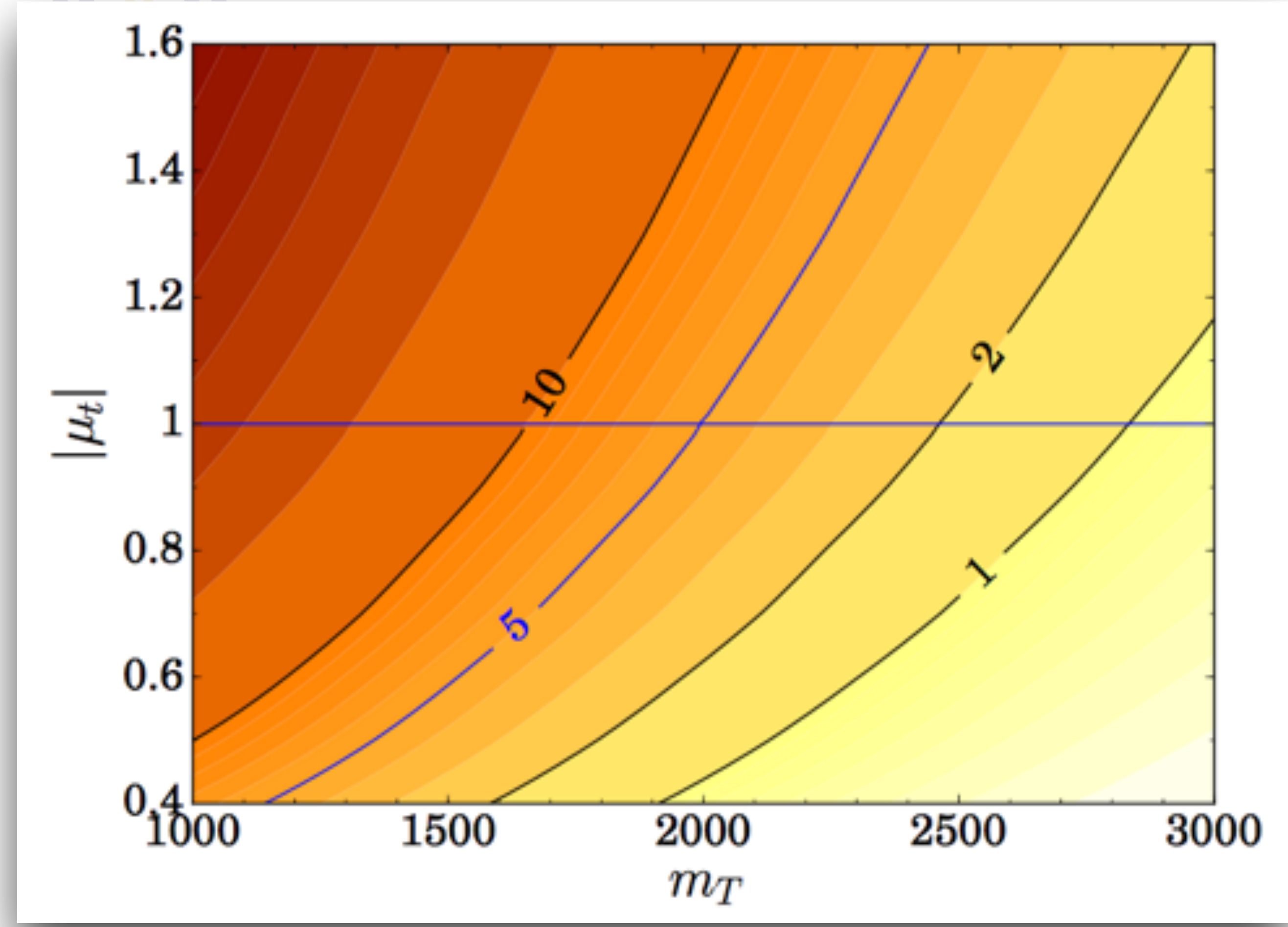
- For convenience, introduce a ``naturalness parameter''

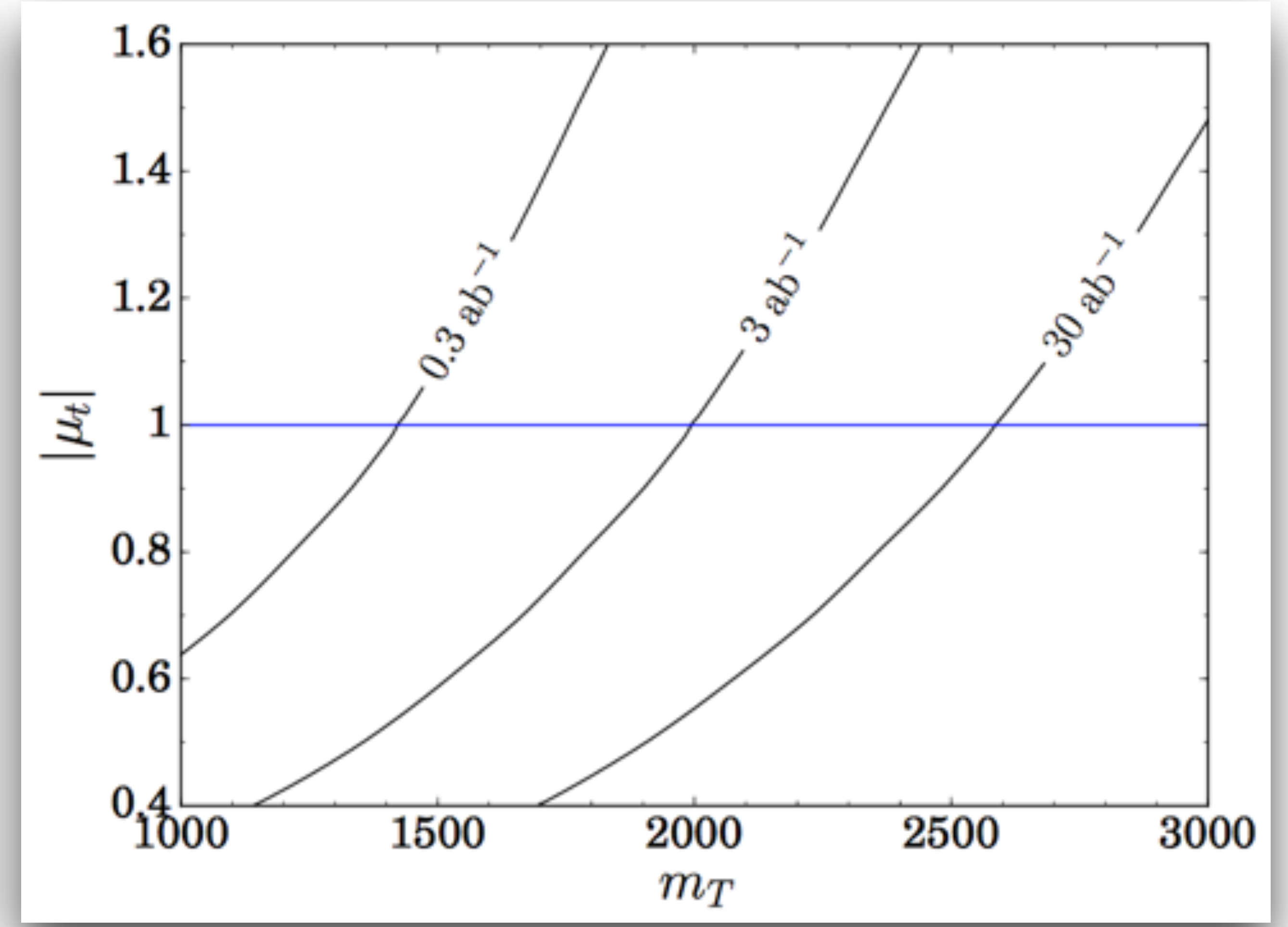
$$\mu = -\frac{\Delta m_H^2|_{\mathrm{NP}}}{\Delta m_H^2|_{\mathrm{SM}}} \quad \Rightarrow \quad \mu = -\frac{a_T}{\lambda_t^2} + \mathcal{O}\left(\frac{v^2}{m_T^2}\right) \qquad \mu|_{\mathrm{nat}} \equiv 1$$

- TTh production - insensitive to the sign of mu at leading order



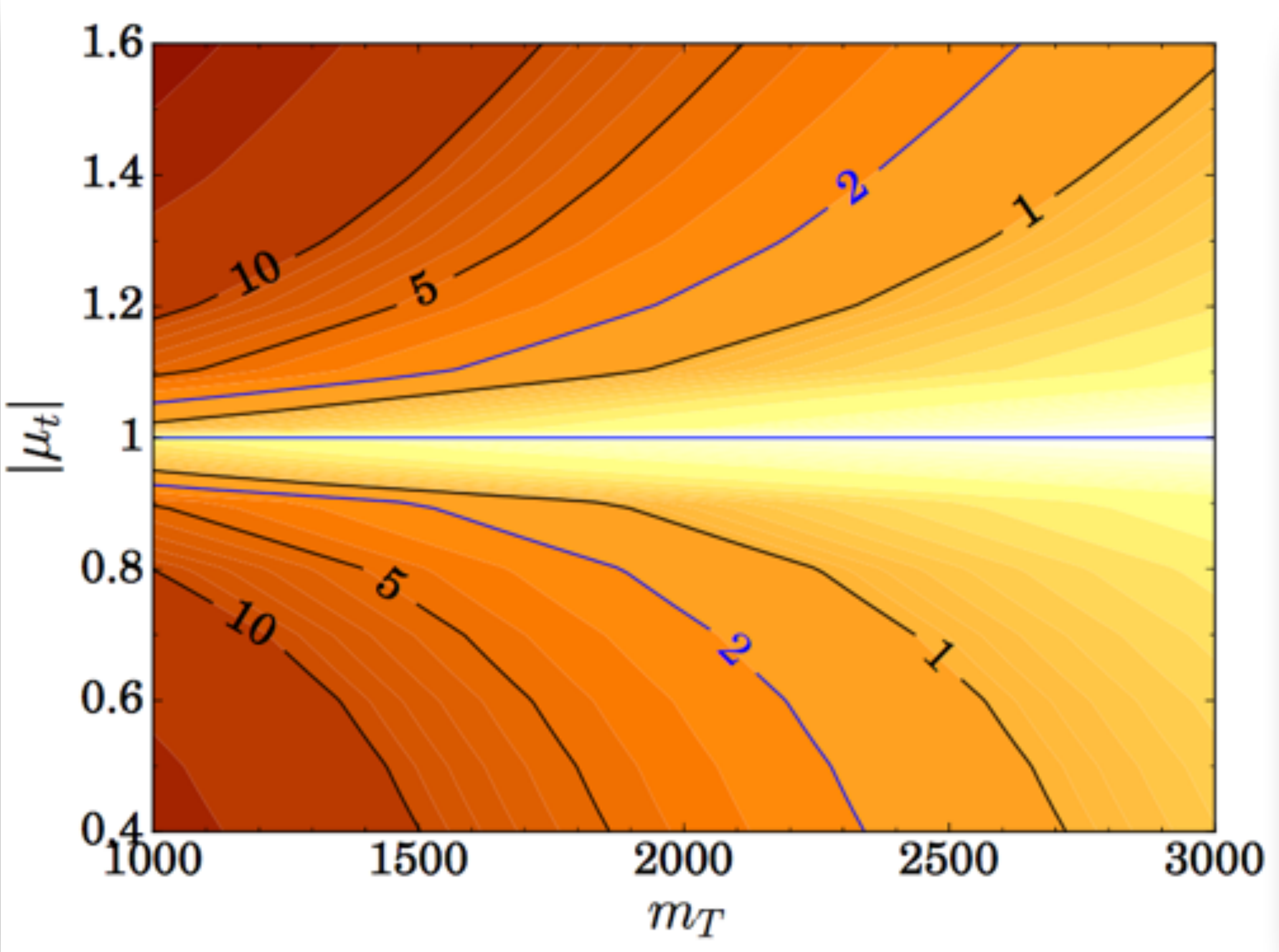
Discovery Potential of Top Partner at 100 TeV

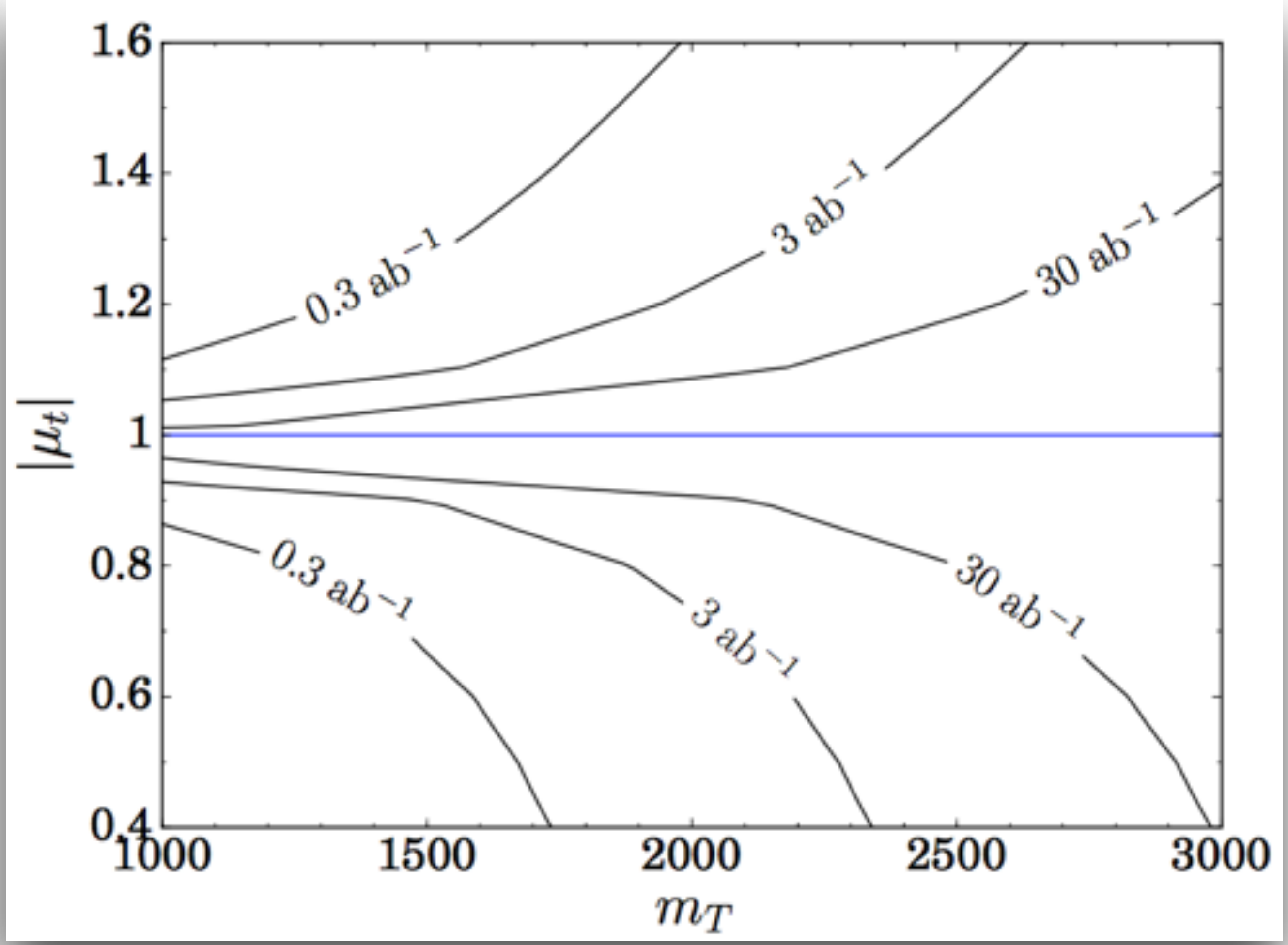




- Not the ``Gold" channel for top partner search, but to show the effectiveness of the analysis

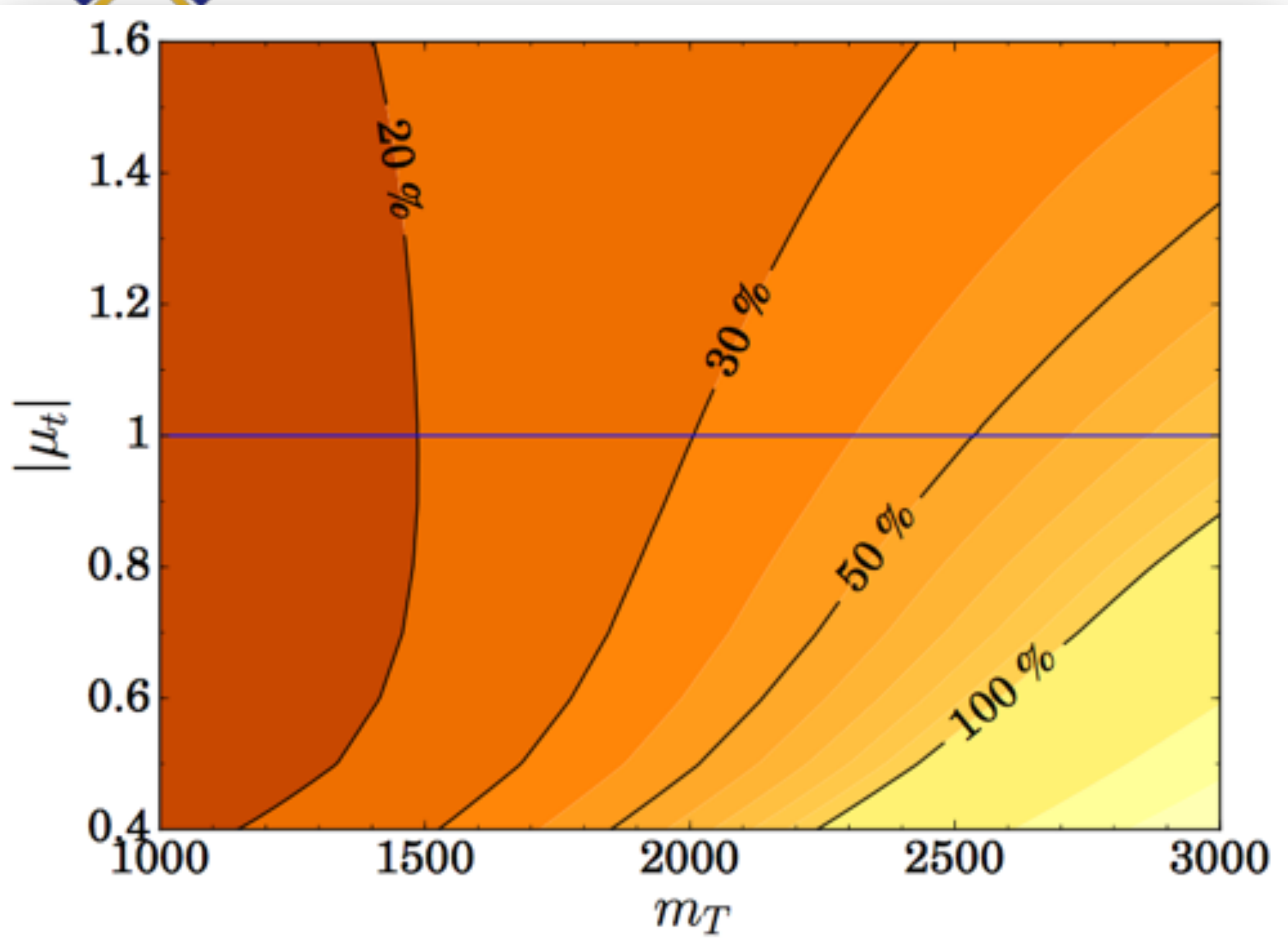
Exclusion of Unnatural Theories at 100 TeV



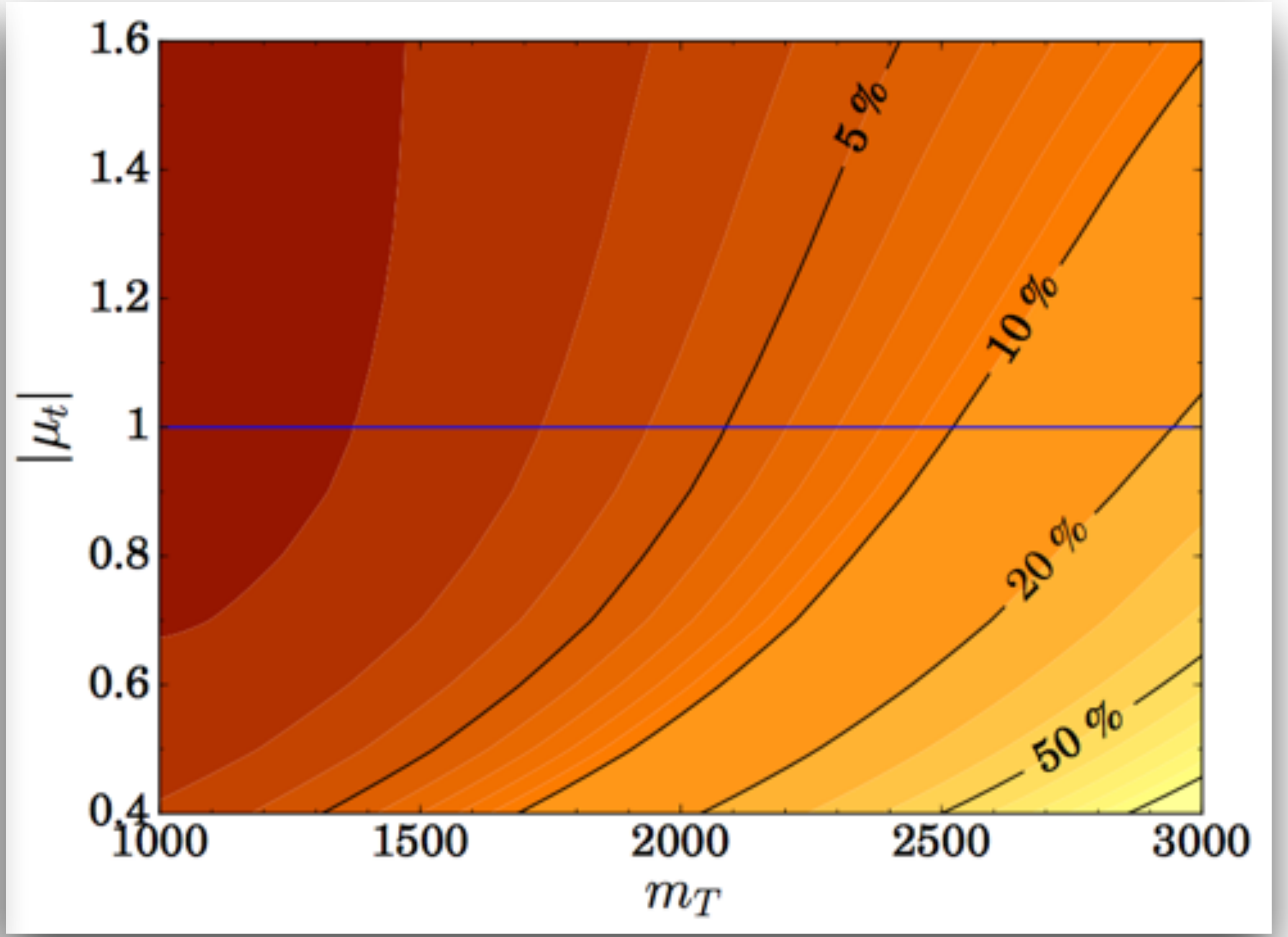


- ``unnatural theory" hypothesis: exclusion of ``unnatural theories" against a natural theory
- A deviation from the natural theory larger than 0.1 can be excluded up to ~ 2.2TeV

Precision of Measuring Naturalness Parameter at 100 TeV



delta_lambda_t ~10% (HL-LHC)
+ delta_aT (3/ab, 100TeV)



delta_lambda_t ~1% (100TeV)
+ delta_aT (30/ab, 100TeV)

- A precision of 10% in measuring mu could be achieved up to ~ 2.5TeV

$$\delta\mu = \sqrt{\left(-\frac{1}{\lambda_t^2}\delta a_T\right)^2 + \left(2\frac{a_T}{\lambda_t^3}\delta\lambda_t\right)^2}$$

Summary

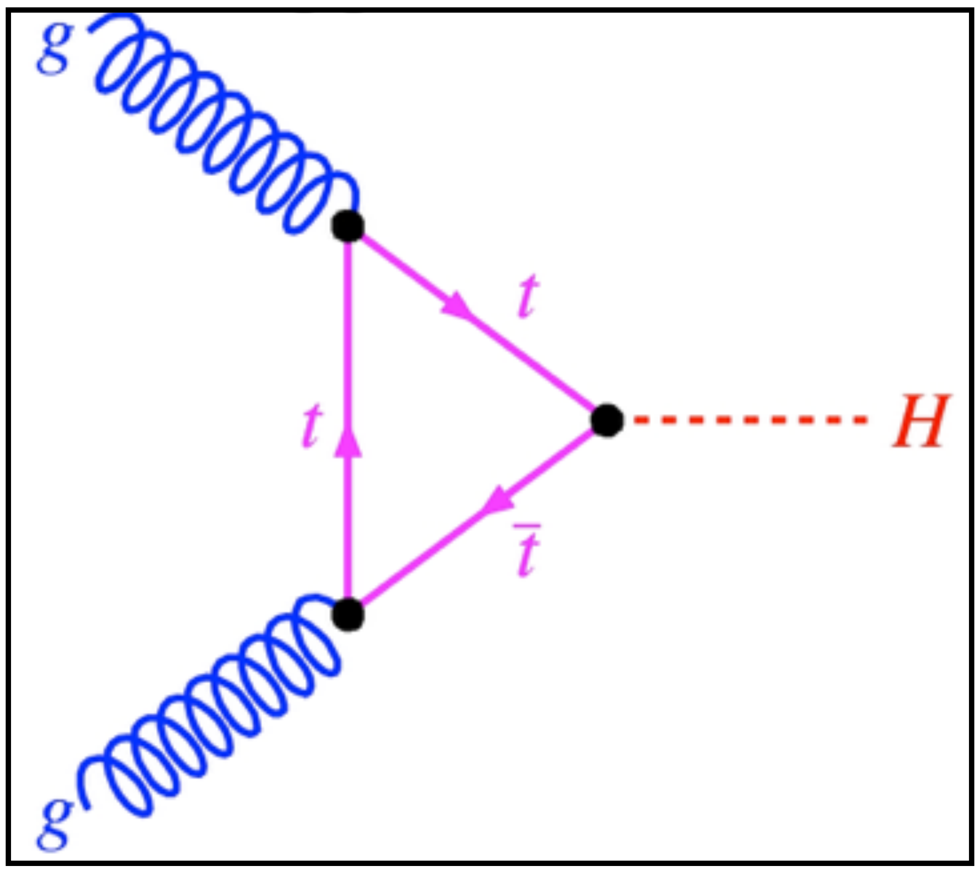
- The naturalness problem has driven particle physics for decades
- To test the theories of naturalness, it is crucial to measure the naturalness sum rule, post the discovery of any partner-like particle
- For a top sector with fermionic top partners, the naturalness sum rule only depends on flavor-diagonal Yukawa couplings, up to an order O(v^2/mT^2)

$$a_T = -|\lambda_t|^2 + \mathcal{O}\left(\frac{v^2}{m_T^2}\right)$$

- At 100 TeV with 30/ab, a precision of 10% for the measurement of the naturalness parameter could be achieved for top partners up to ~2.5TeV

Outlook I

How to break the degeneracy of the sign in the mu parameter?



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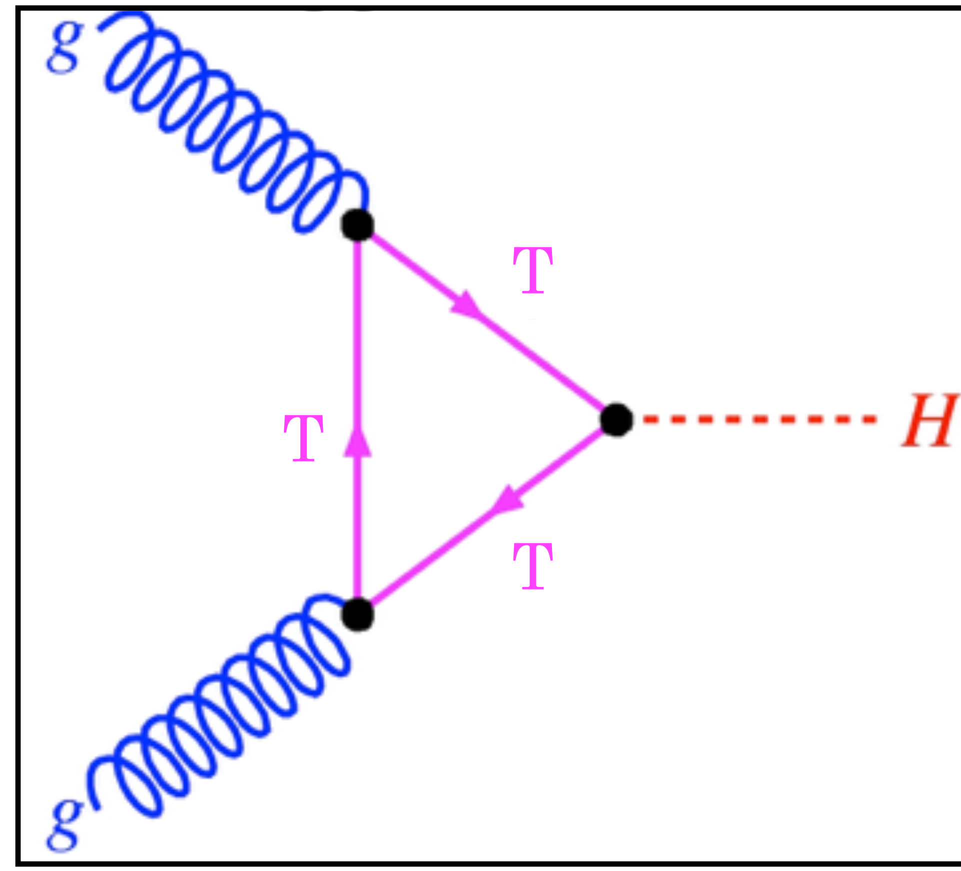
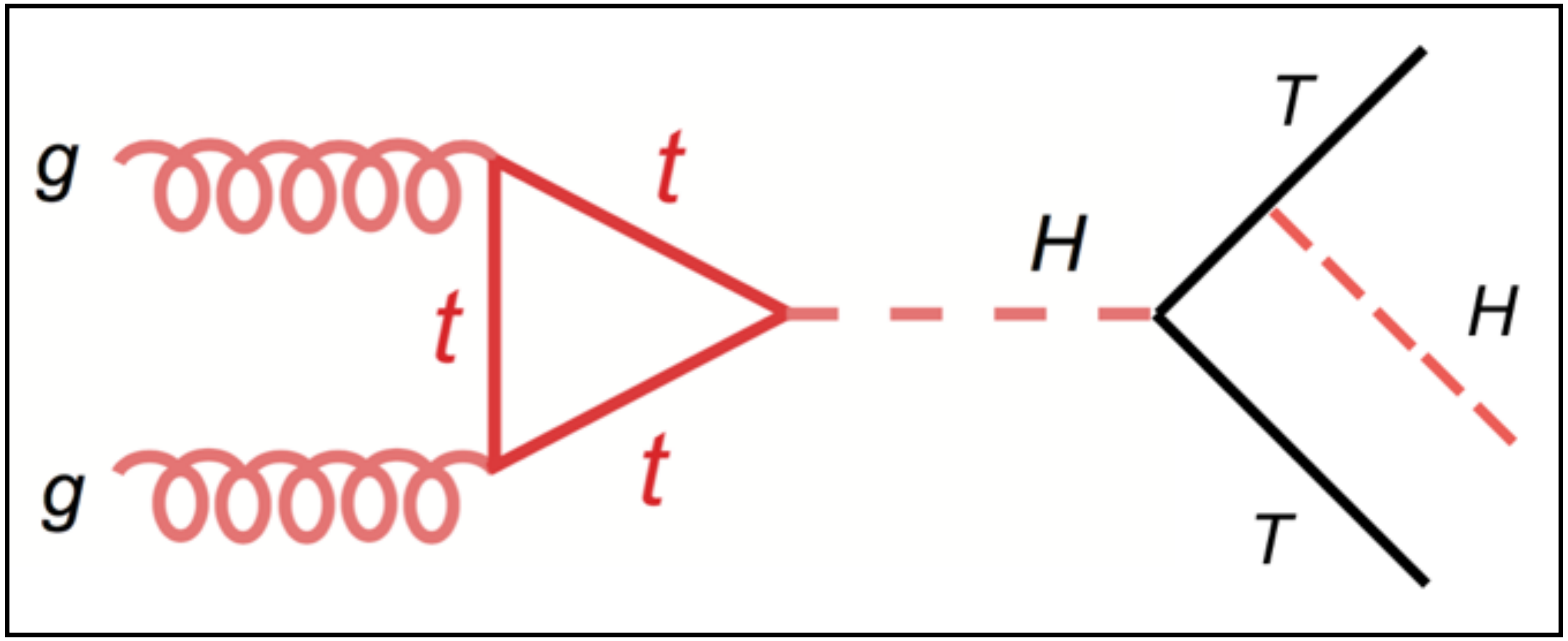


$$C_g \equiv 1 + \Delta C_g \equiv \sqrt{\frac{\Gamma(h \to gg)^{\mathrm{BSM}}}{\Gamma(h \to gg)^{\mathrm{SM}}}} = \left| \frac{C_{htt}\left(\frac{v}{m_t}\mathcal{A}_{1/2}(\tau_t) - \tilde{\mu} C_{htt}\frac{v^2}{M_T^2}\mathcal{A}_{1/2}(\tau_T)\right)}{\mathcal{A}_{1/2}(\tau_t)} \right|$$

Outlook II

For twin Higgs model, how to test the naturalness sum rule at collider level?

Maybe mono-Higgs search can help if T is stable



Outlook III

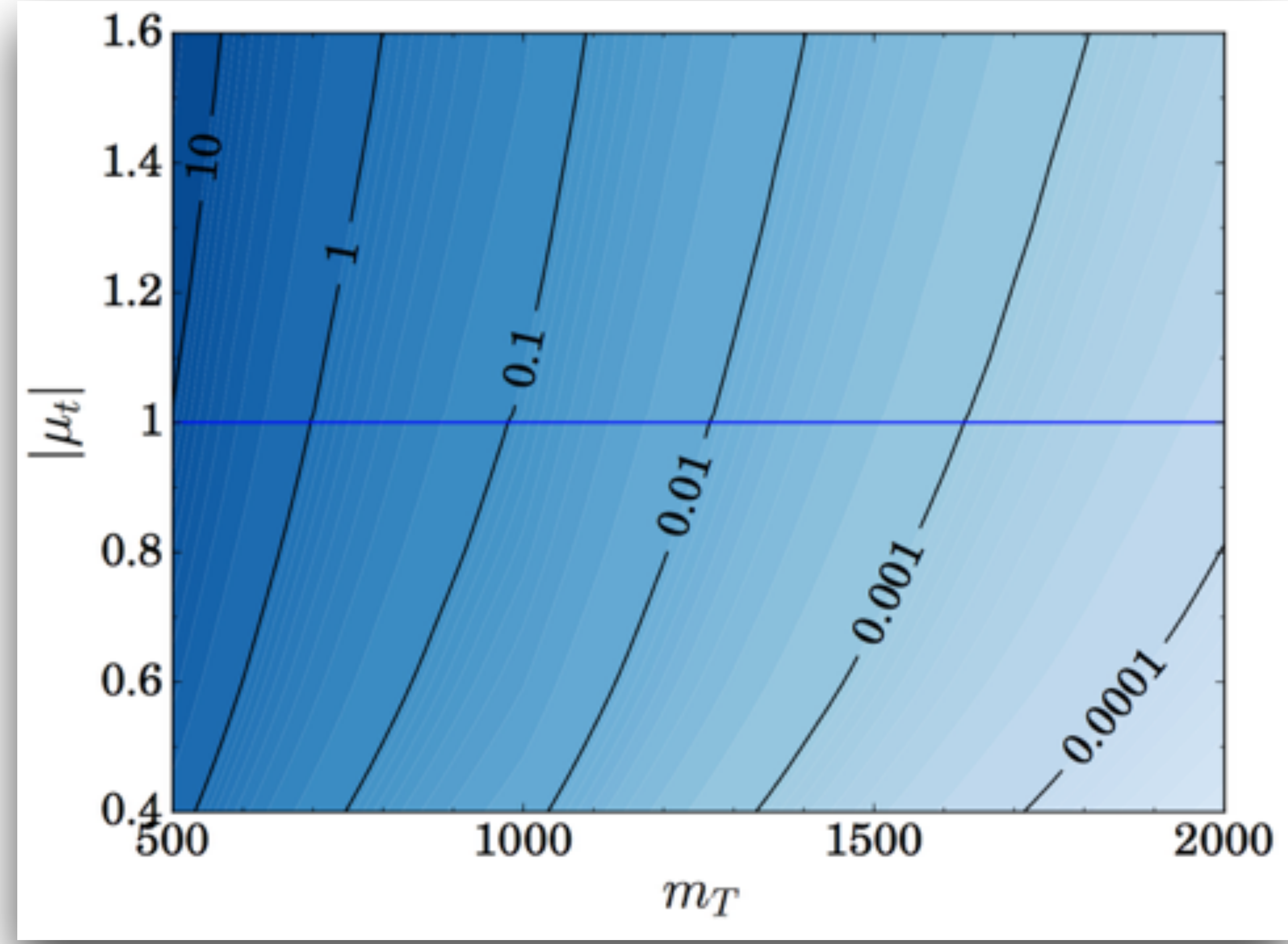
What is the naturalness sum rule in supersymmetry?

How to test the sum rule at colliders, post the discovery of any superparticle-like particle?

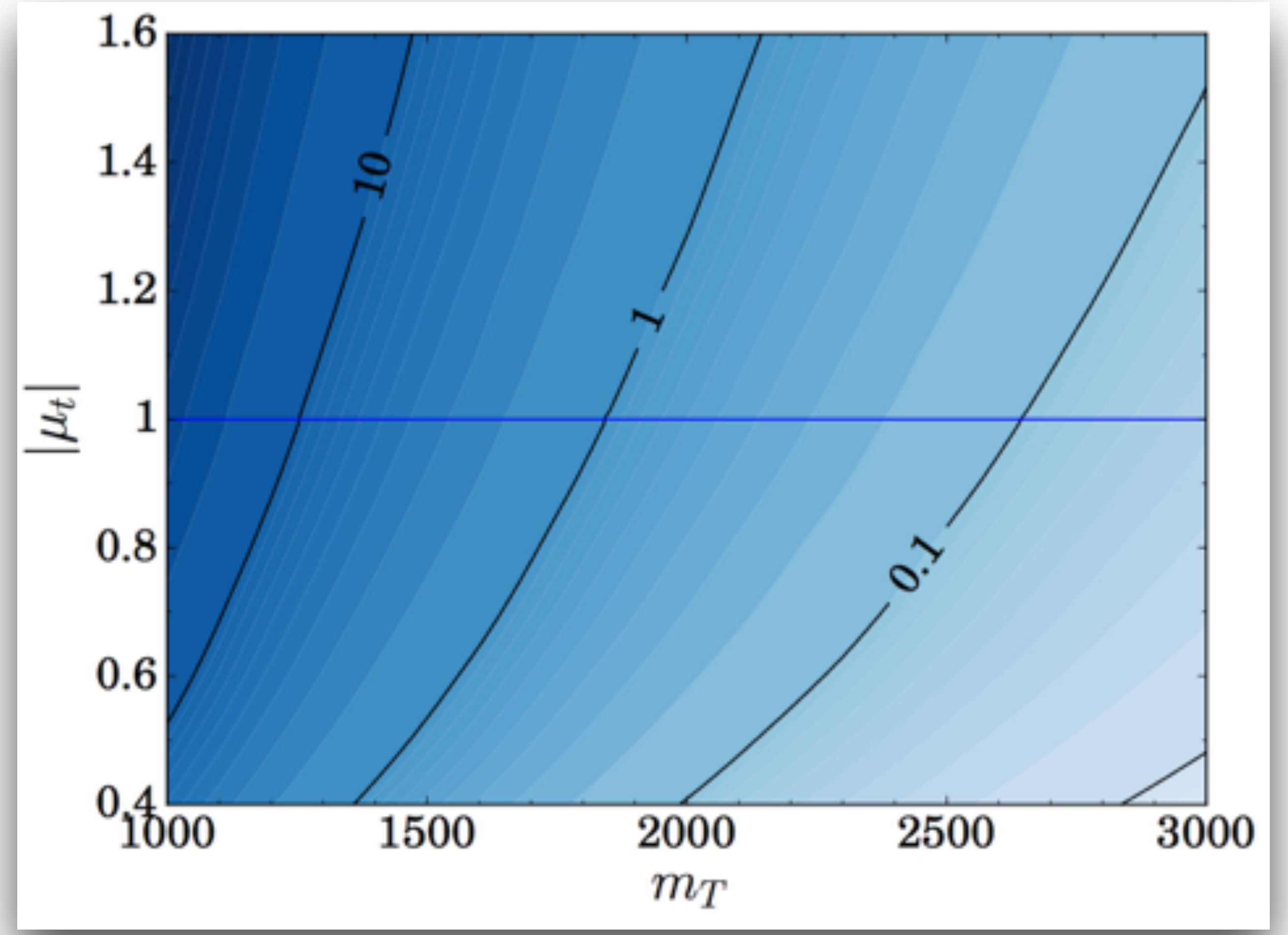
Long way to go, but exciting ……


Thank you!

Production Cross Section at LO



14 TeV



100 TeV

Simplified Model - Mass Basis Before EWSB

$$t'^c = \frac{\widehat{c}_0 u_3^c - c_0 U^c}{c} \qquad t' = q_3$$

$$T'^c = \frac{\widehat{c}_0 U^c + c_0 u_3^c}{c} \qquad T' = U$$

$$\mathcal{L}_{T'} = m_{T'} T'^c T' + \lambda_{t'} H t'^c t' + \lambda_{T'} H T'^c t' + \frac{\alpha_{t'}}{2m_{T'}} H^2 t'^c T' + \frac{\alpha_{T'}}{2m_{T'}} H^2 T'^c T' + \frac{\beta_{t'}}{6m_{T'}^2} H^3 t'^c t' + \frac{\beta_{T'}}{6m_{T'}^2} H^3 T'^c t' + \mathcal{O}\left(H^4\right) + \text{h.c.}$$

$$m_{T'} = fc\,, \qquad c = \sqrt{c_0^2 + \widehat{c}_0^2}$$

$$\lambda_{t'} = \frac{\widehat{c}_0 c_1 - c_0 \widehat{c}_1}{c}\,, \qquad \lambda_{T'} = \frac{c_0 c_1 + \widehat{c}_0 \widehat{c}_1}{c}\,,$$

$$\alpha_{t'} = \widehat{c}_0 c_2 - c_0 \widehat{c}_2\,, \qquad \alpha_{T'} = c_0 c_2 + \widehat{c}_0 \widehat{c}_2\,,$$

$$\beta_{t'} = \left(\widehat{c}_0 c_3 - c_0 \widehat{c}_3\right) c\,, \qquad \beta_{T'} = \left(c_0 c_3 + \widehat{c}_0 \widehat{c}_3\right) c$$

Simplified Model - Mass Basis After EWSB

$$t^c = t'^c + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right) \,, \qquad t = t' - T' \frac{v}{m_{T'}} \lambda_{T'}^* + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right)$$

$$T^c = T'^c + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right) \,, \qquad T = T' + t' \frac{v}{m_{T'}} \lambda_{T'} + \mathcal{O}\left(\frac{v^2}{m_{T'}^2}\right)$$

$$\mathcal{L}_T = m_T T^c T + \lambda_t v t^c t + \frac{\lambda_t}{\sqrt{2}} h t^c t + \frac{\lambda_T}{\sqrt{2}} h T^c t + \frac{a_t v}{\sqrt{2} m_T} h t^c T + \frac{a_T v}{\sqrt{2} m_T} h T^c T$$
$$+ \frac{\alpha_t}{4 m_T} h^2 t^c T + \frac{\alpha_T}{4 m_T} h^2 T^c T + \frac{b_t v}{4 m_T^2} h^2 t^c t + \frac{b_T v}{4 m_T^2} h^2 T^c t + \mathcal{O}\left(h^3, \frac{v^2}{m_T^2}\right) + \text{h.c.}$$

$$a_t = \alpha_{t'} + \lambda_{T'}^* \lambda_{t'} \,, \qquad a_T = \alpha_{T'} + |\lambda_{T'}|^2$$

$$b_t = \beta_{t'} - \alpha_{t'} \lambda_{T'} \,, \qquad b_T = \beta_{T'} - \alpha_{T'} \lambda_{T'}$$