Focus Workshop on Particle Physics and Cosmology
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TESTING NATURALNESS

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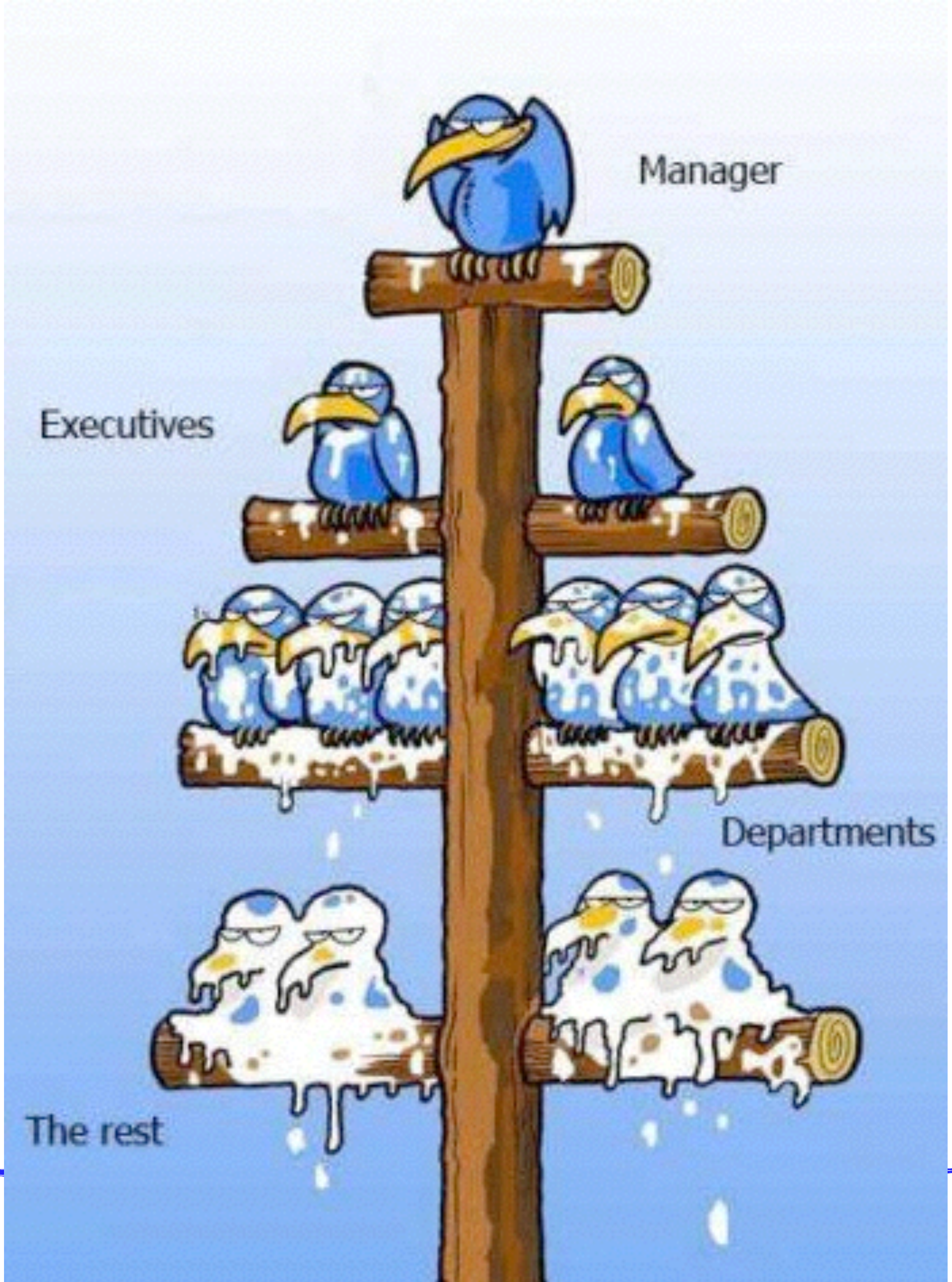
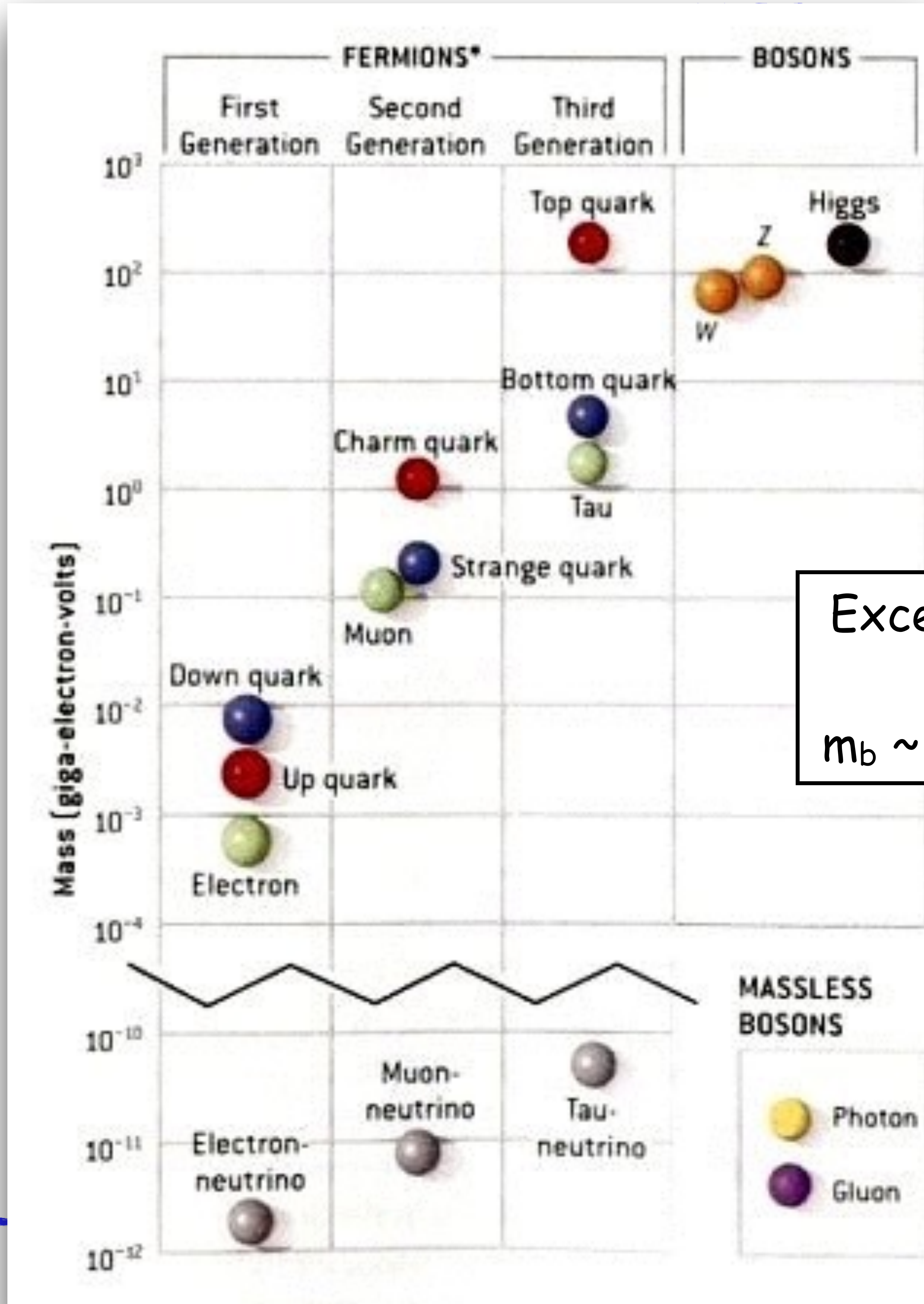
[C. Chen, J. Hajer, TL, I. Low and H. Zhang, arXiv: 1612.0xxxx]

Naturalness Problem



Naturalness Problem



Except M_W, M_Z, M_H, $m_t \sim g\,v$, all others are unnaturally light:
$m_b \sim 5$ GeV, $m_e \sim 0.5$ MeV, $m_\nu < 0.2$ eV ...

Naturalness Problem

But, these particles share a nice property: chiral symmetry is restored, in the zero mass limit. The quantum corrections are merely logarithmically divergent

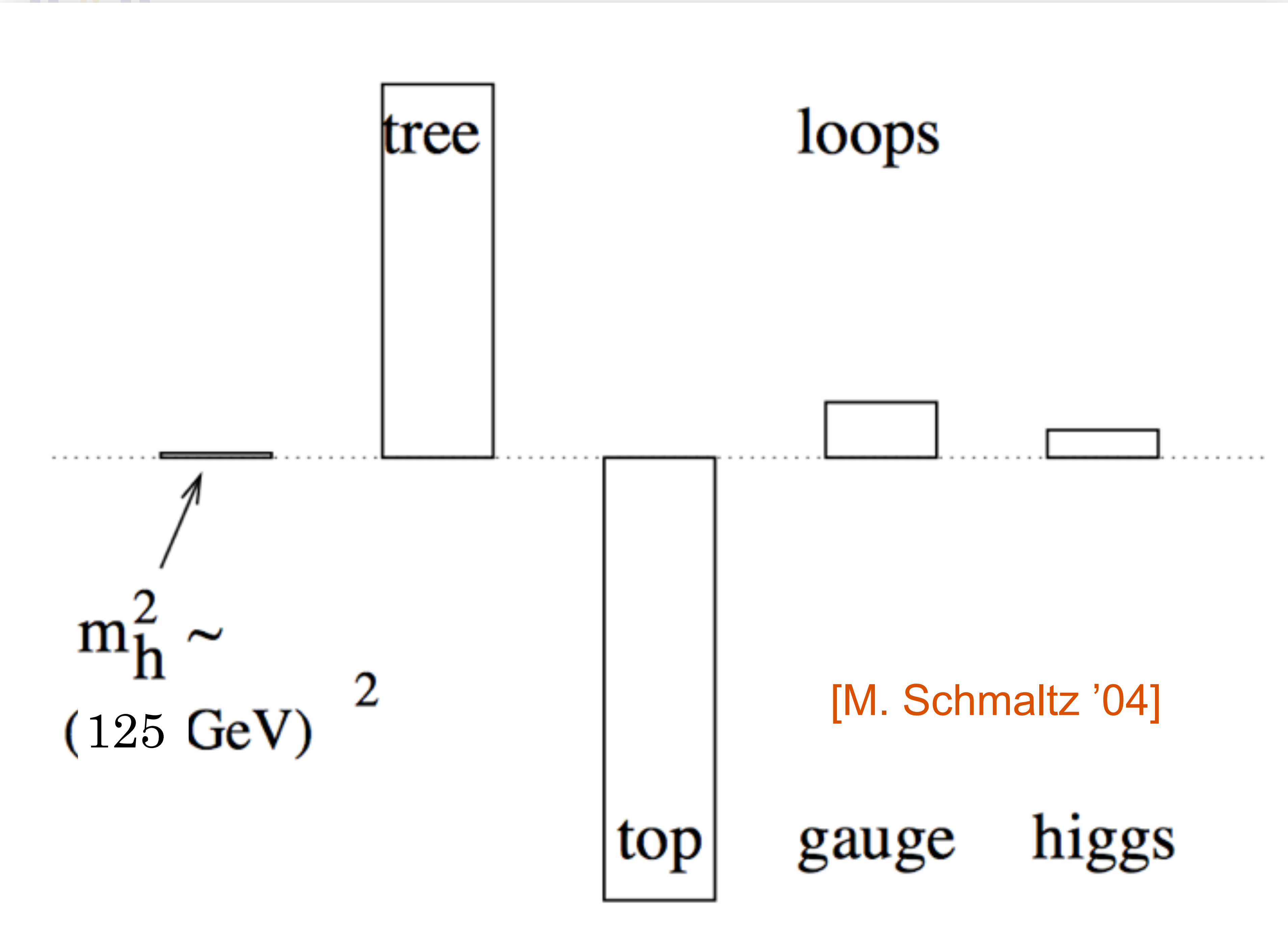
$$m_e \sim m^0_e \, [1 + 3\alpha/4\pi \, \ln(\Lambda/m_e)]$$

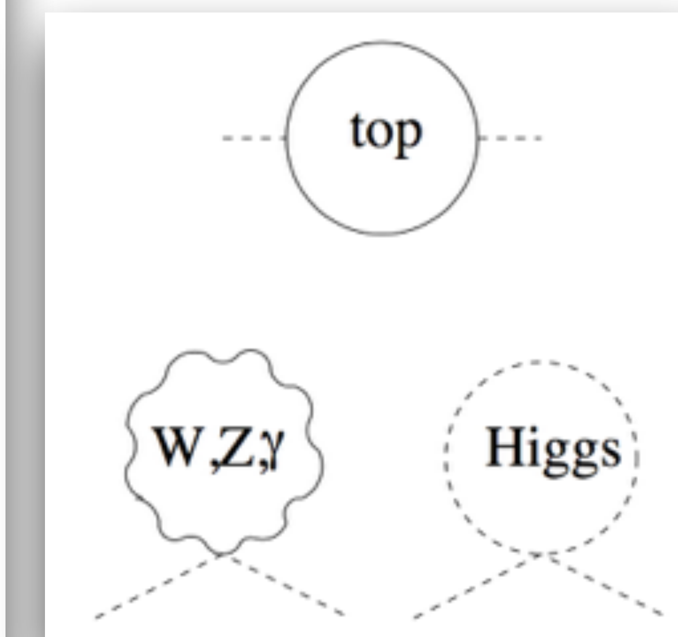
t'Hooft statement for "technical naturalness": If a parameter is turned off (set to 0), the system results in an enlarged symmetry, then this parameter must be technically natural.

=> The smallness of fermion (except top) mass is technically natural

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

Naturalness Problem





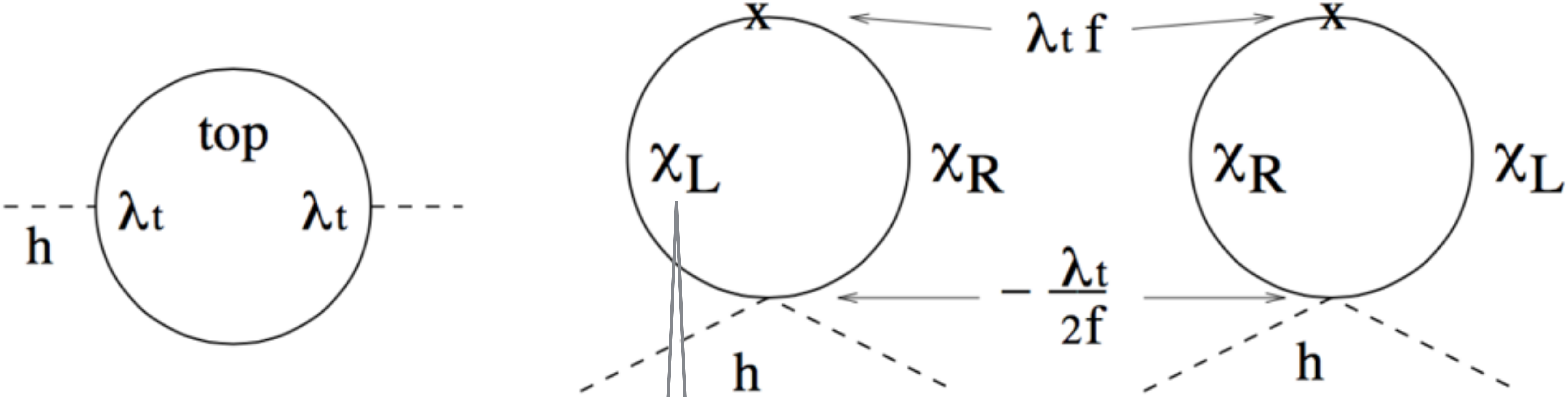
A Large Bulk of Ideas of Naturalness

Introduce partners to the SM fields which couple with the Higgs boson. These couplings contribute to the squared Higgs mass, yielding a cancellation of quadratic divergence ensured by the underlying symmetries which are broken softly or collectively.

- supersymmetric models
- Composite Higgs models/ little Higgs models
- Twin Higgs models
- … …

To test these ideas, we need to ensure that the newly found partner-like particle is not an impostor, but a particle with the right properties to cancel the quadratic divergence.

Focus - Fermionic Top Partners



Vector-like fermions
are requested

Simplified Model

SM + one pair of vector-like top partners

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

Model		c_0	c_1	c_2	$\widehat{c}_0$	$\widehat{c}_1$	$\widehat{c}_2$
$\left(\frac{SU(3)}{SU(2)}\right)^2$ simplest Higgs	[11]	λ	$-\lambda$	$-\lambda$	λ	λ	$-\lambda$
$\frac{SU(5)}{SO(5)}$ littlest Higgs	[7]	λ_1	$-\sqrt{2}i\lambda_1$	$-2\lambda_1$	λ_2	0	0
T-parity invariant $\frac{SU(3)}{SU(2)}$	[8]	λ	$-\lambda$	$-\lambda$	$-\lambda$	$-\lambda$	λ

Simplified Model - Mass Basis Before EWSB

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

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

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

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

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

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

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

Naturalness Condition - Mass Basis Before EWSB

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

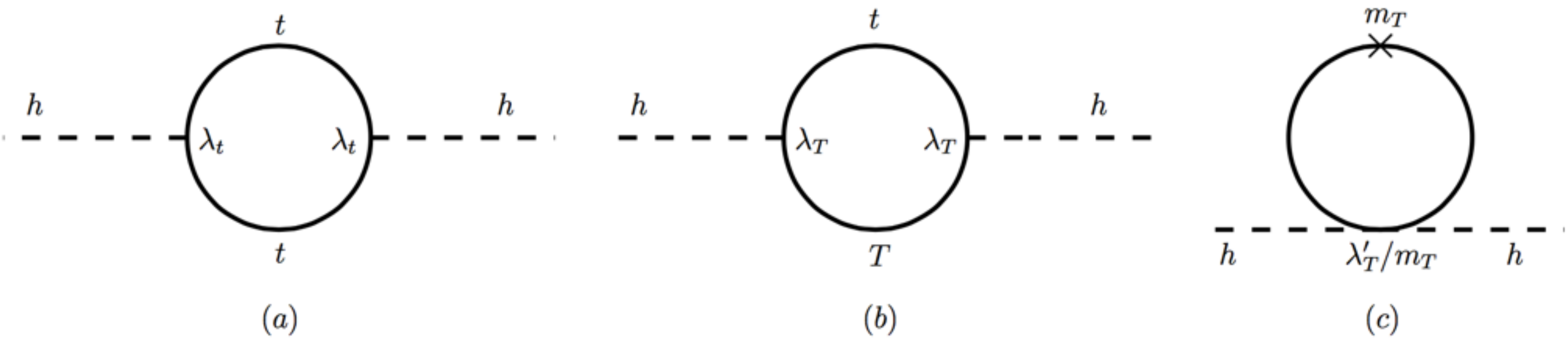
$$\frac{1}{16\pi^2}\Lambda^2 \,\mathrm{tr}\, \mathcal{M}(H)^\dagger \mathcal{M}(H)$$

$$\mathcal{M}(H) = \begin{pmatrix} 0 & 0 \\ 0 & m_{T'} \end{pmatrix} + \begin{pmatrix} \lambda_{t'} & 0 \\ \lambda_{T'} & 0 \end{pmatrix} H + \begin{pmatrix} 0 & \alpha_{t'} \\ 0 & \alpha_{T'} \end{pmatrix} \frac{H^2}{2m_{T'}} + \mathcal{O}\left(H^3\right)$$

The requirement for the coefficient of H^2 to vanish =>

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

Naturalness Condition - Familiar to Us?



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

Naturalness Condition - General Efforts

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

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

- Convert the measurement of alpha_T' as the measurements of lambda_T' and f

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

- Measure the total decay width => lanbda_T' $\Gamma_T = \frac{m_T \lambda_T^2}{16\pi}$
- Measure the vector boson sector => f $M_{Z_H} = \sqrt{\frac{g_L^2 + g_R^2}{2}} f = \frac{\sqrt{2} g}{\sin 2\psi} f.$

Simplified Model - Mass Basis After EWSB

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

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

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

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

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

Naturalness Condition - Mass Basis After EWSB

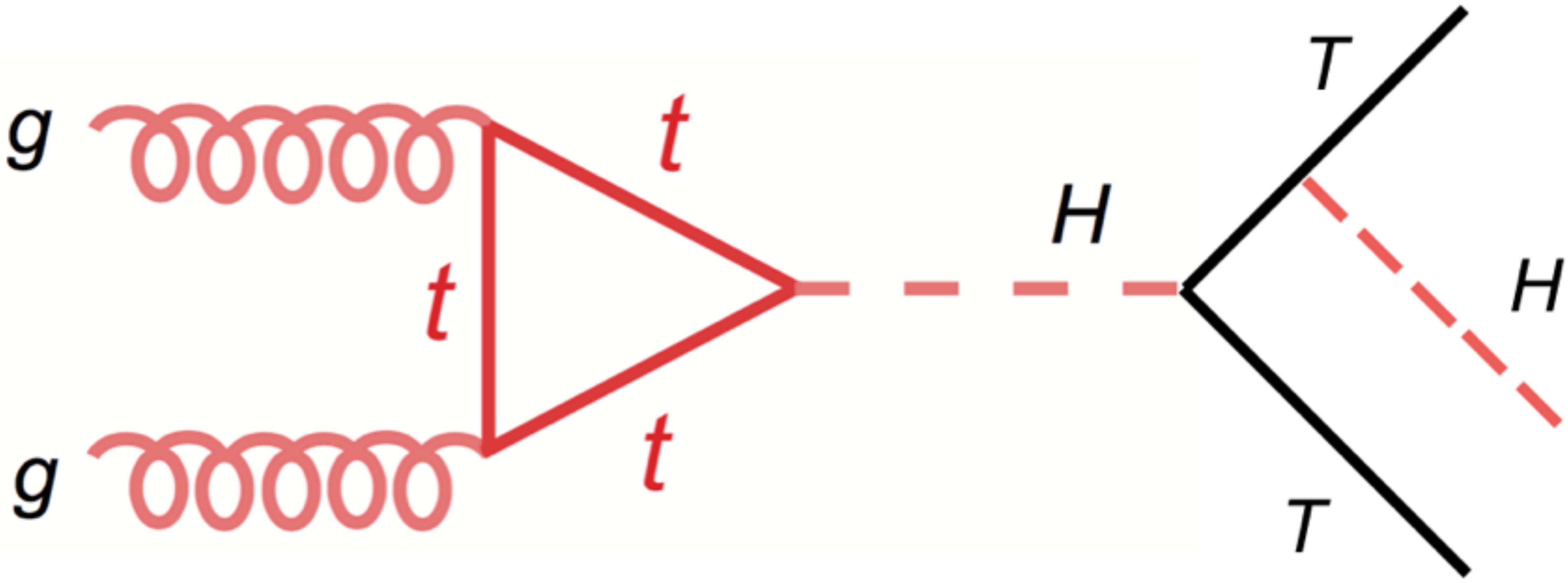
$$a_T = -|\lambda_t|^2 + \mathcal{O}\left(\frac{v^2}{m_T^2}\right)$$

This suggests：

To test the naturalness condition (up to the order of v^2 / mT^2), we only need to measure the Yukawa couplings of top quark pair and top partner pair

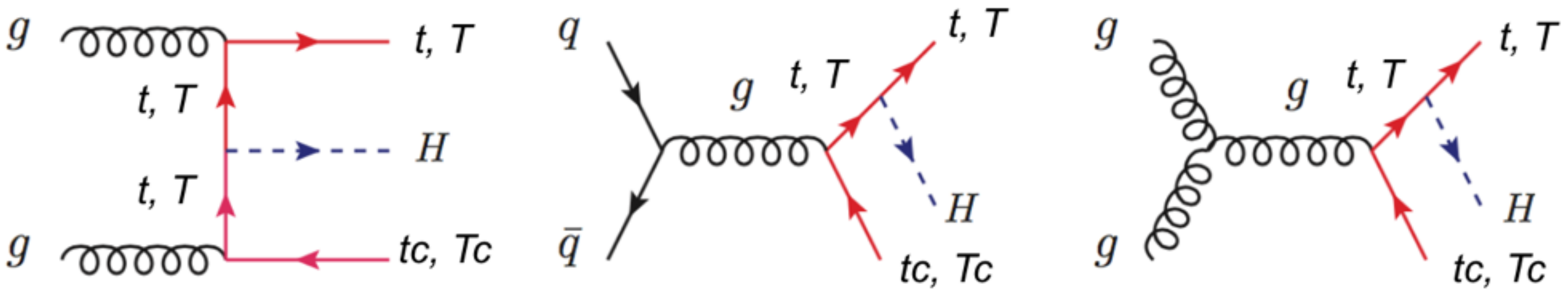
- More model-independent: with or without T-parity
- Irrelevant to the measurement of the decay constant

Collider Strategy - Colorless Top Partners



Maybe mono-Higgs search can help if T is stable

Collider Strategy - Colored Top Partners



(a) (b) (c)

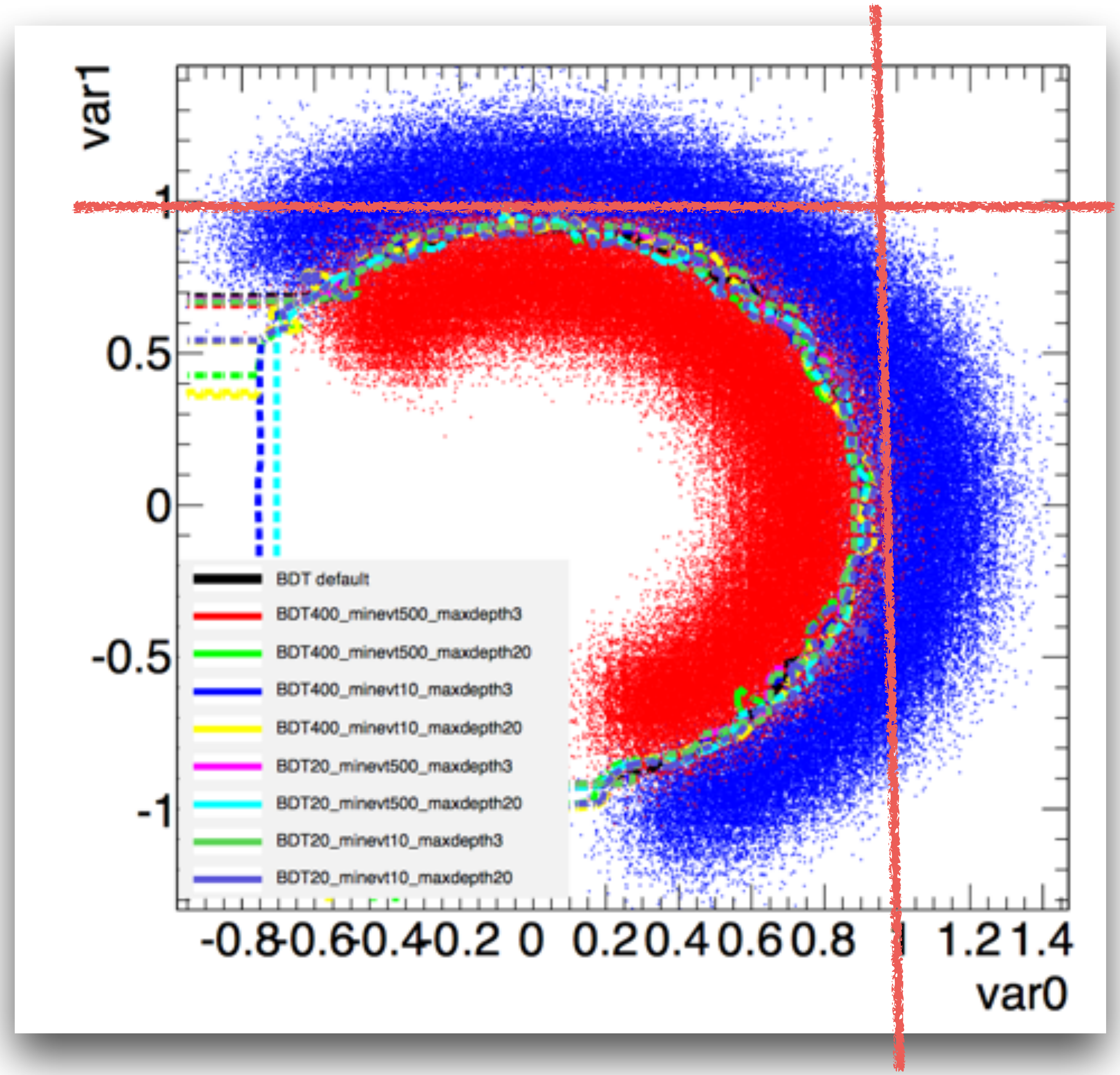
- TTh production at 100 TeV, with

$$\mathrm{BR}(T \to th) \simeq \mathrm{BR}(T \to tZ) \simeq \frac{1}{2}\mathrm{BR}(T \to Wb) \simeq 25\,\%$$

- For convenience of interpretation, introduce the naturalness parameter

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

The Tool - Boosted Decision Tree



(a) Circular correlation example

[Yann COADOU '13]

BDT: allow us to incorporate the correlation of variables to optimize the analysis. Particularly useful for suppressing combinatorial background

The Tool - BDT Top Tagger

JHEP

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Heavy Higgs bosons at 14 TeV and 100 TeV

Jan Hajer,[a,b] Ying-Ying Li,[a] Tao Liu[a] and John F.H. Shiu[a]

arXiv.org > hep-ph > arXiv:1605.08744

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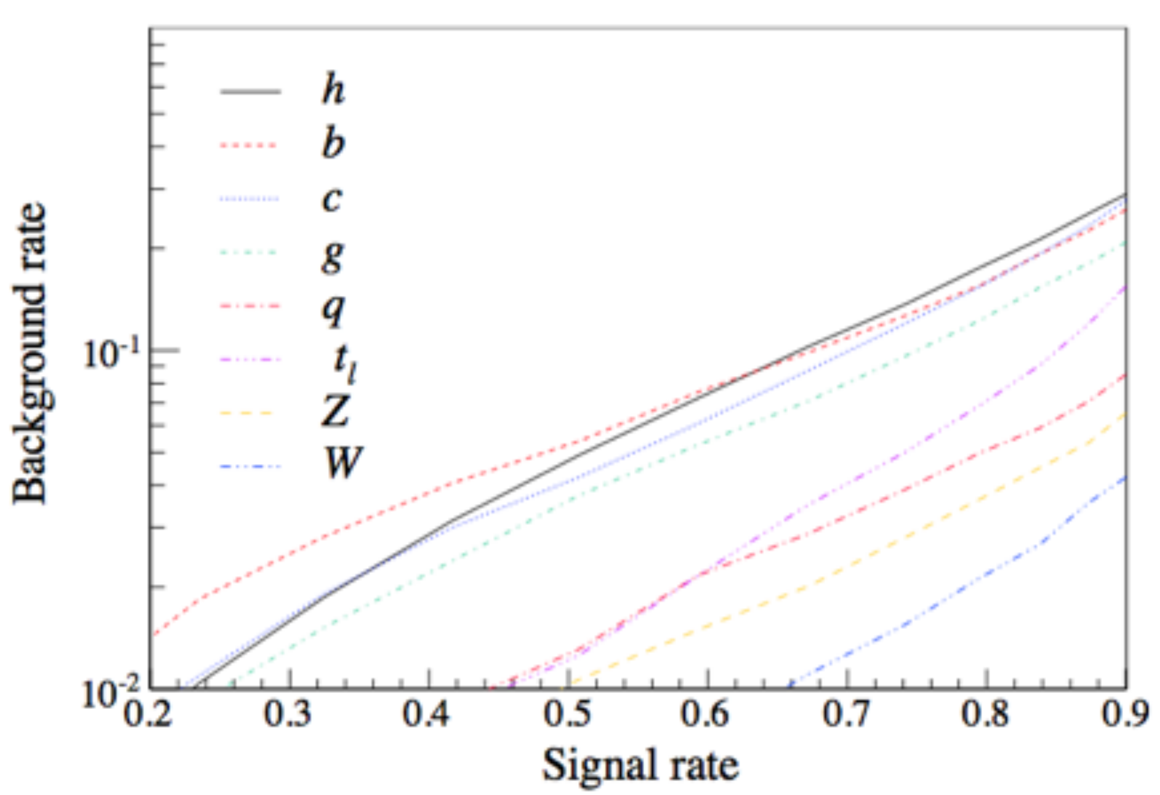
High Energy Physics – Phenomenology

Heavy Higgs Bosons at Low tan β: from the LHC to 100 TeV

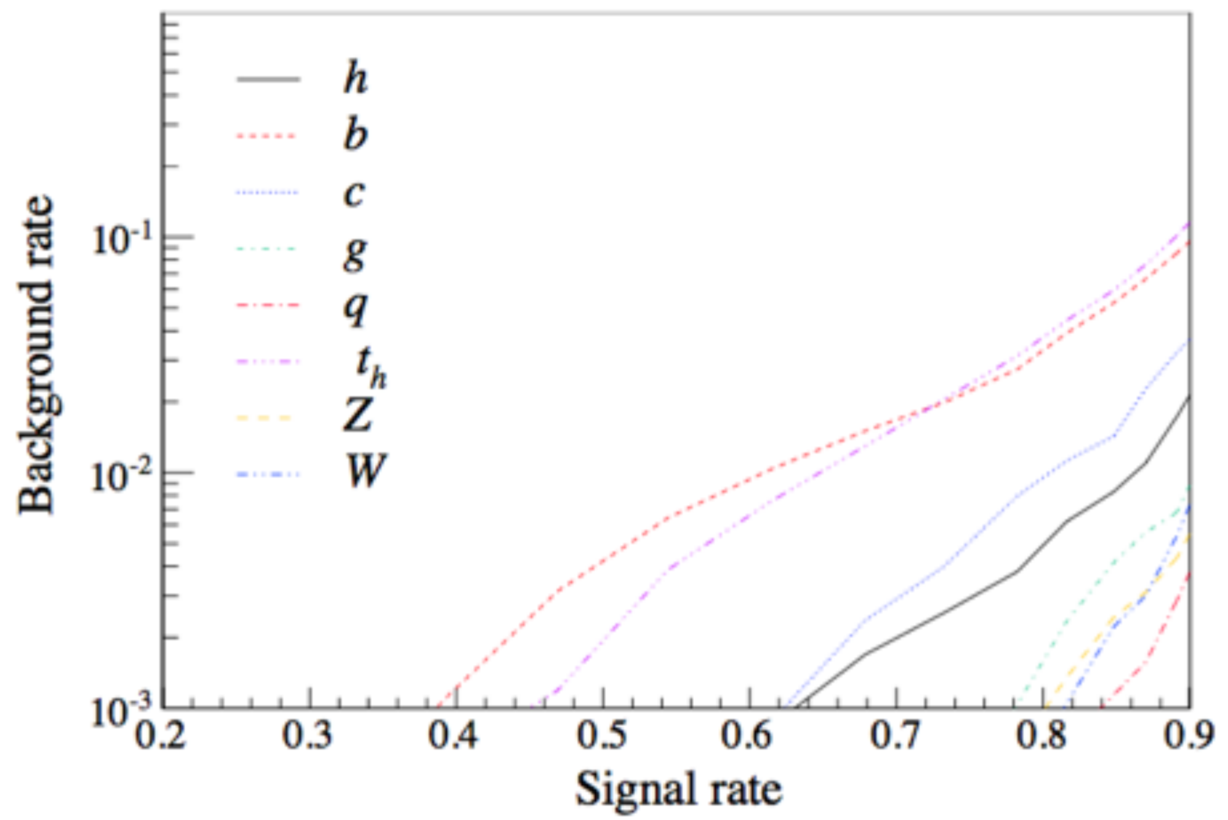
Nathaniel Craig, Jan Hajer, Ying-Ying Li, Tao Liu, Hao Zhang

(Submitted on 27 May 2016)

The Tool - BDT Top Tagger



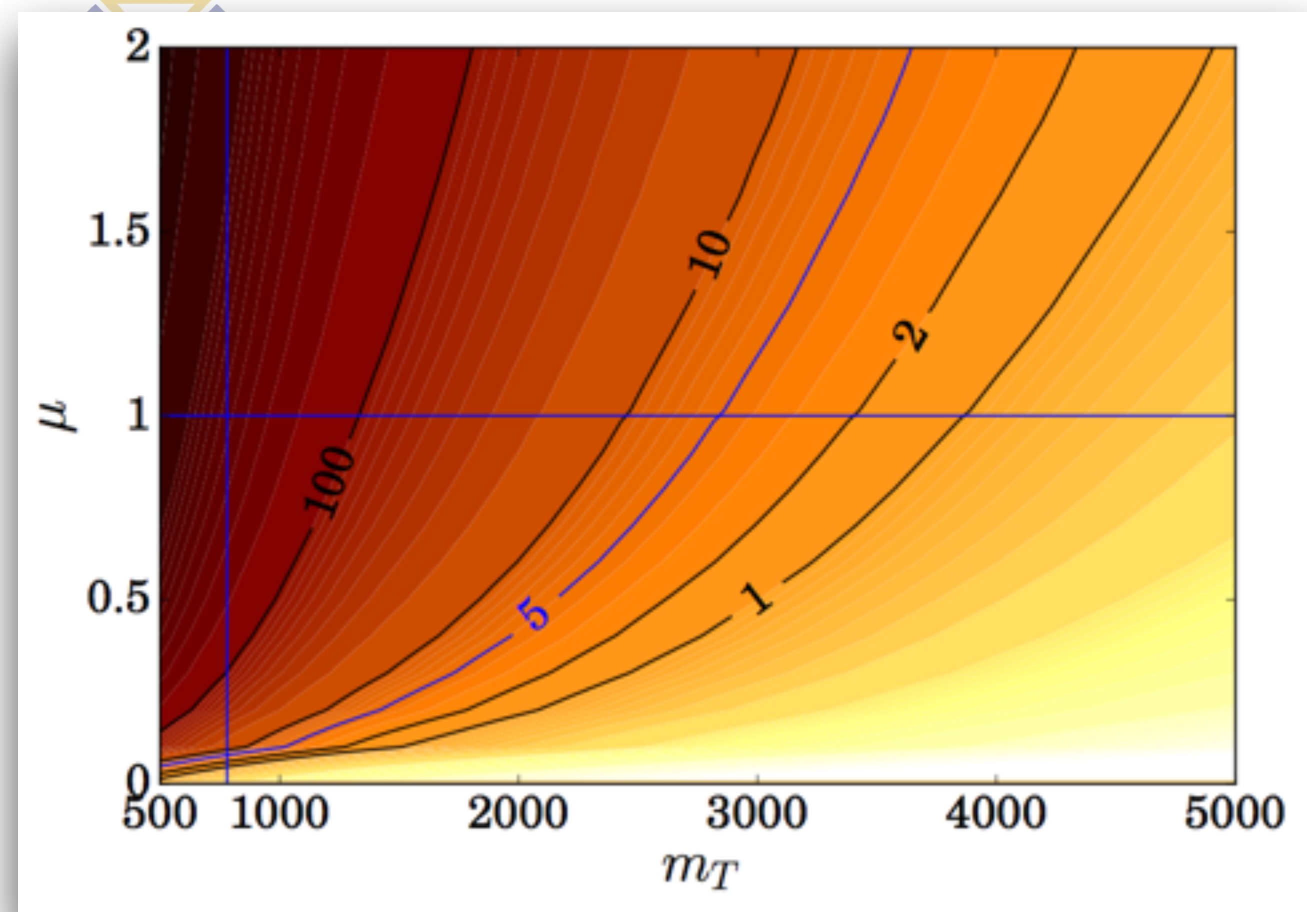
(b) $1000\,\text{GeV} < p_T^j(\text{hadronic}) < 1500\,\text{GeV}$

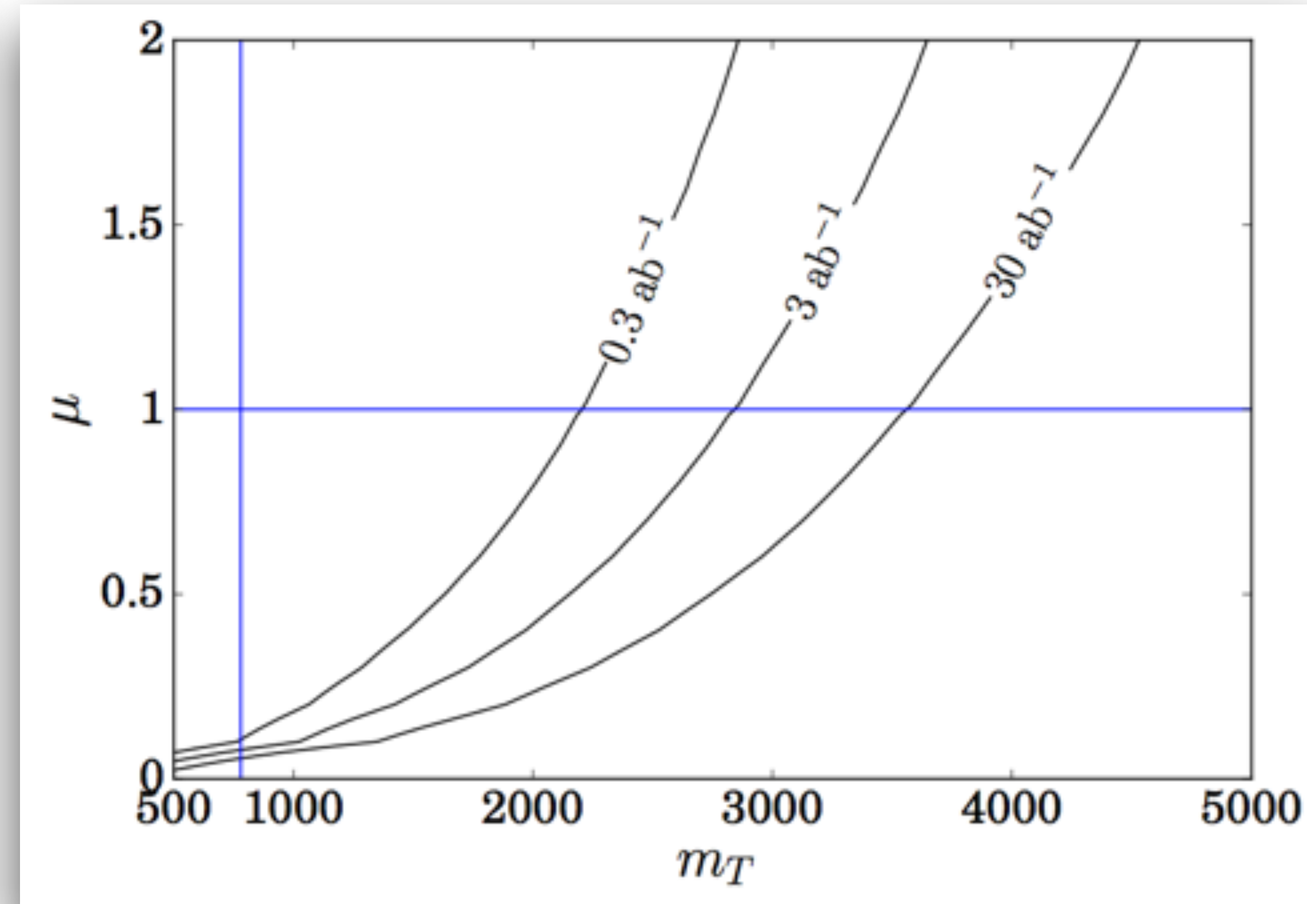


(d) $1000\,\text{GeV} < p_T^j(\text{leptonic}) < 1500\,\text{GeV}$

- Hadronic top tagger: b secondary vertex and jet mass information, veto hard lepton, etc.
- Leptonic top tagger: b secondary vertex and lepton information, jet mass requirement, etc.

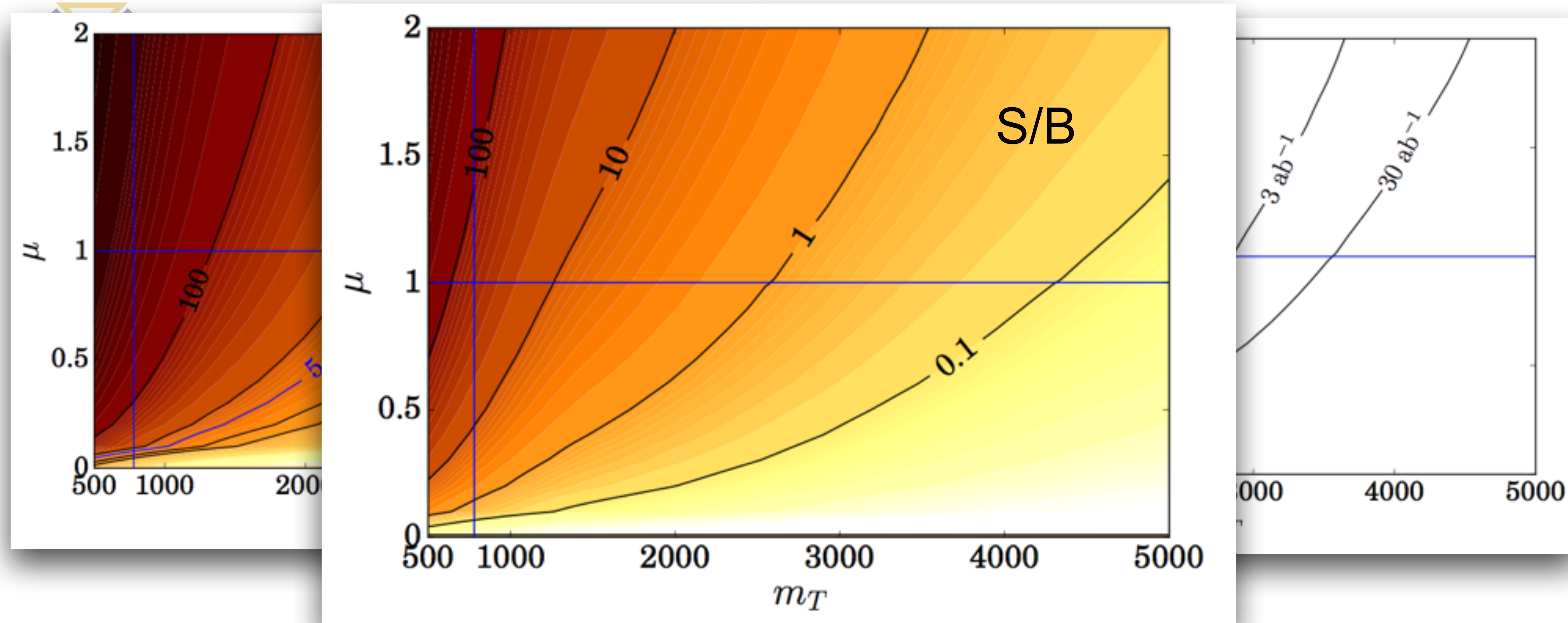
Discovery Potential of Top Partner





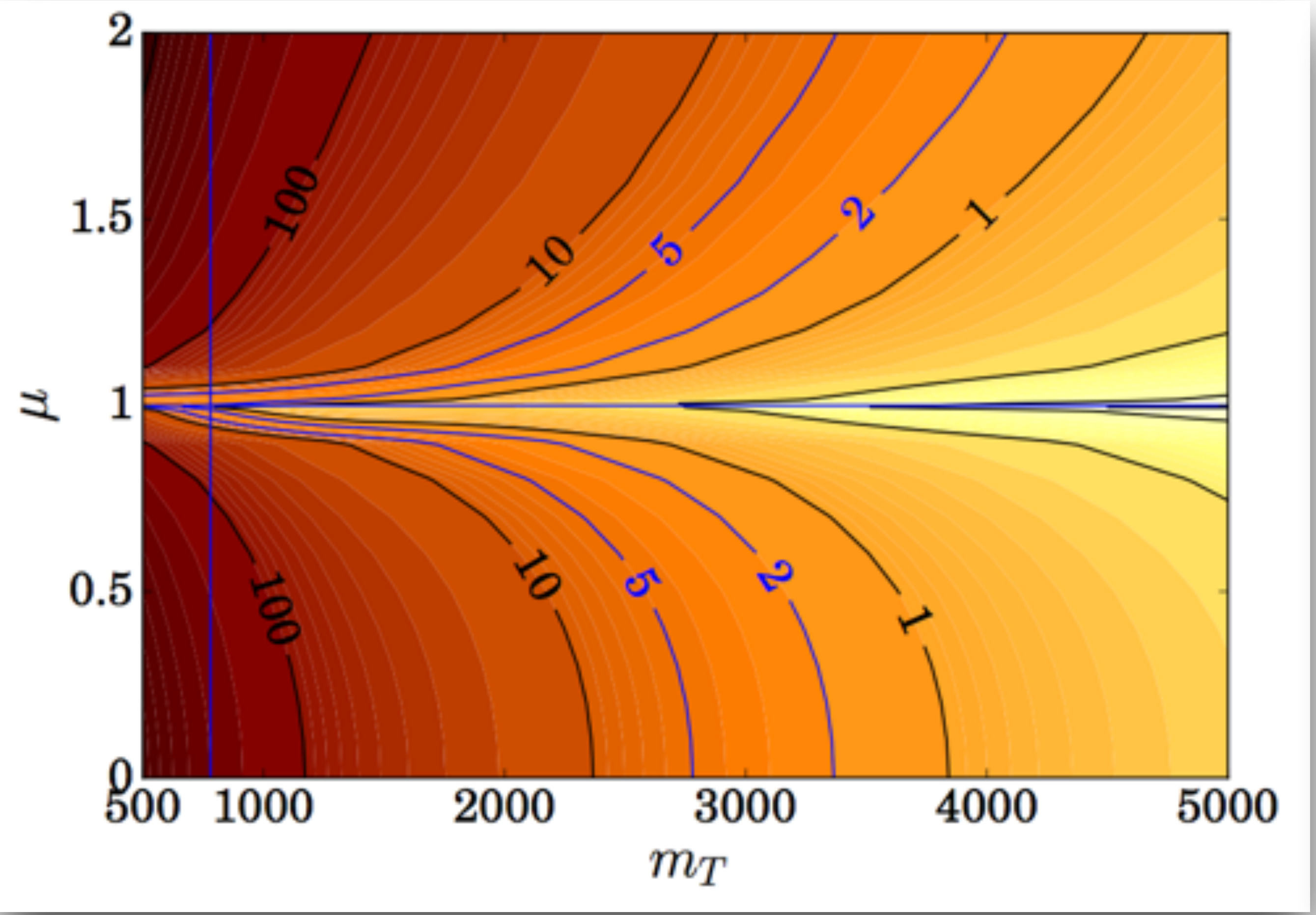
- May not be the most sensitive search channel for top partners
  - to show the effectiveness of the analysis

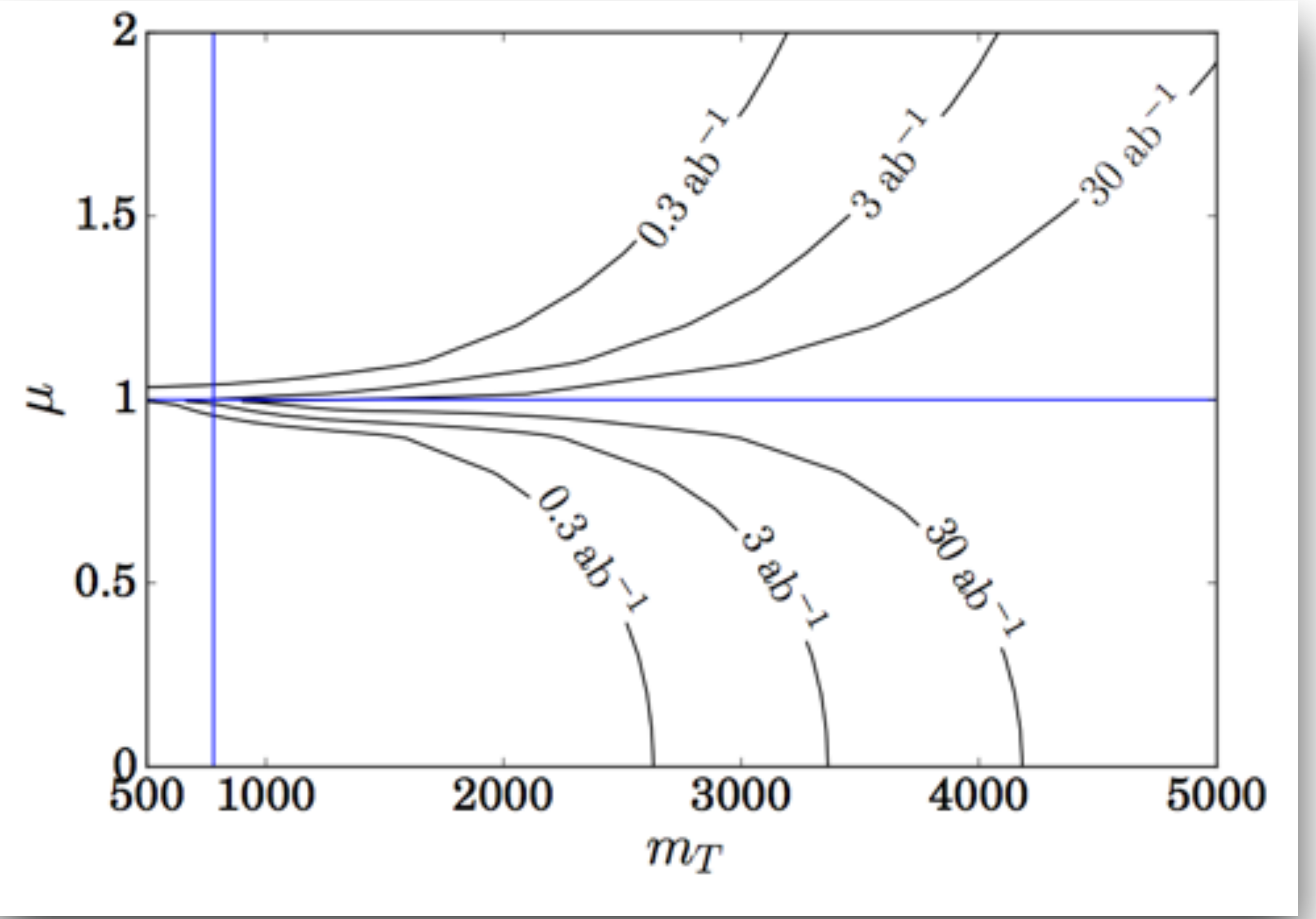
Discovery Potential of Top Partner



- May not be the most sensitive search channel for top partners
  - to show the effectiveness of the analysis
- Sys error is not included. relatively large S/B indicates that it is not out of control

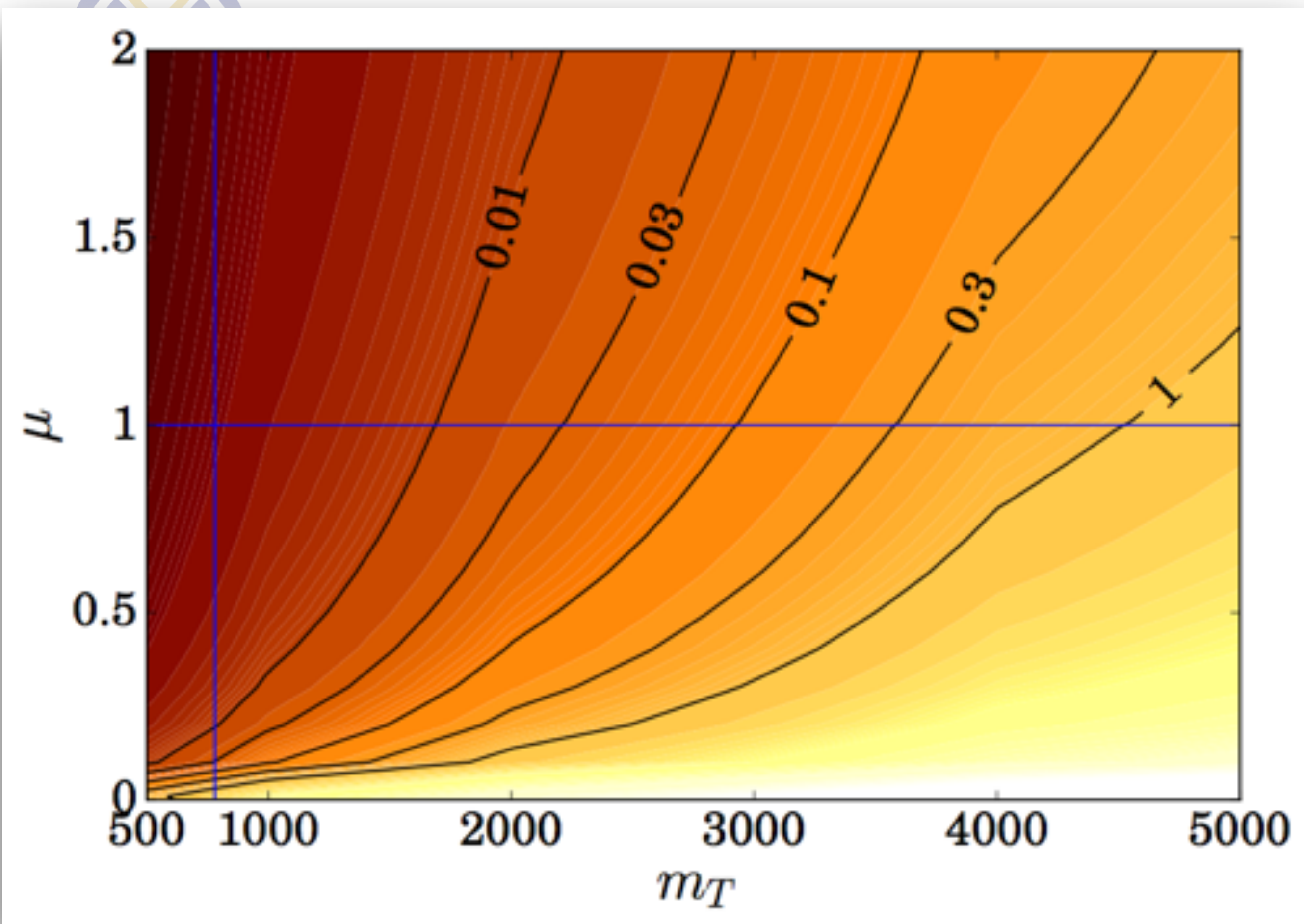
Exclusion of Unnatural Theories

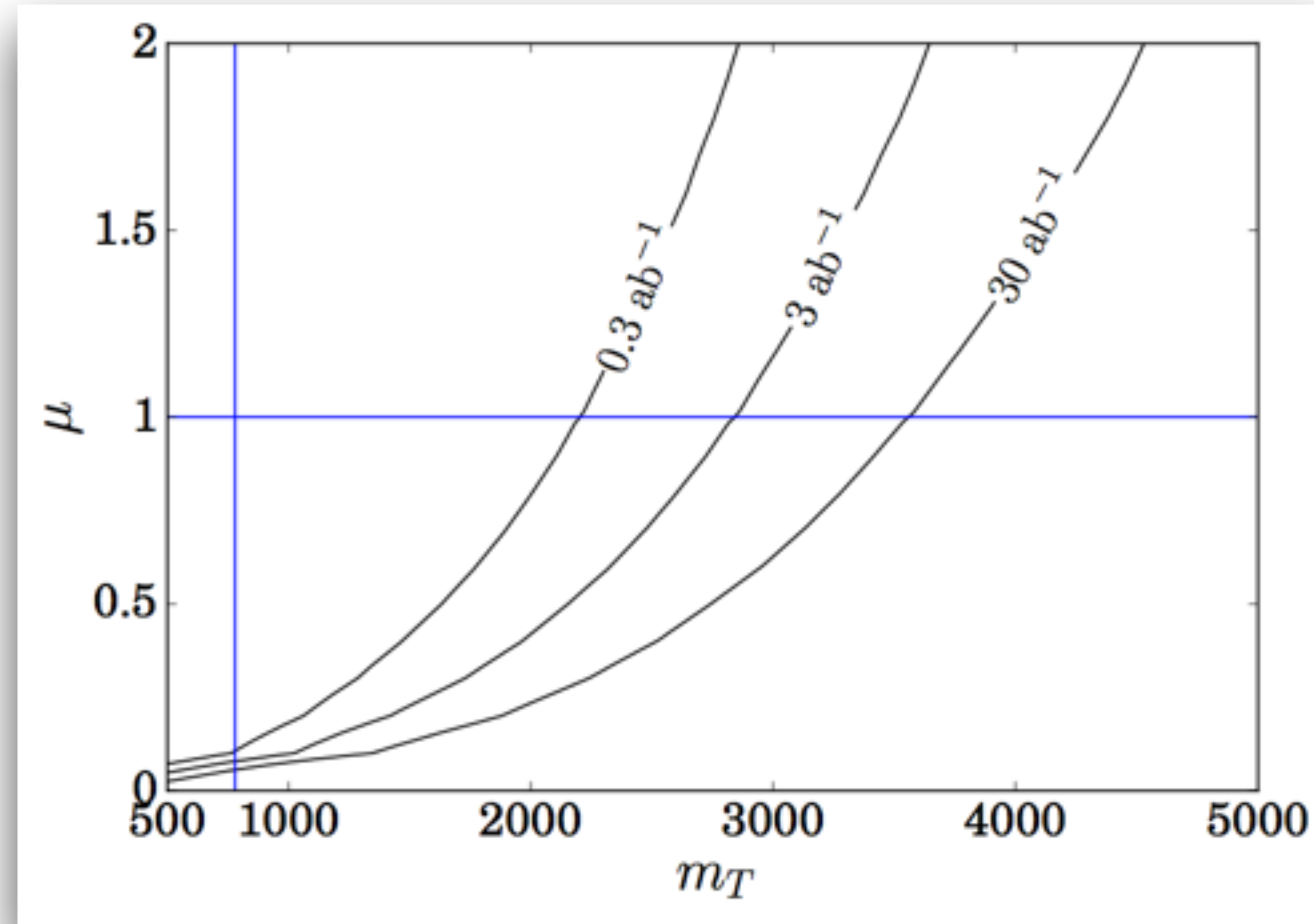




- ``Unnatural theory'' hypothesis - defined wrt the natural theory
- A deviation from the natural theory larger than 0.1 can be excluded up to ~ 3TeV

Precision of Measuring the Naturalness Parameter

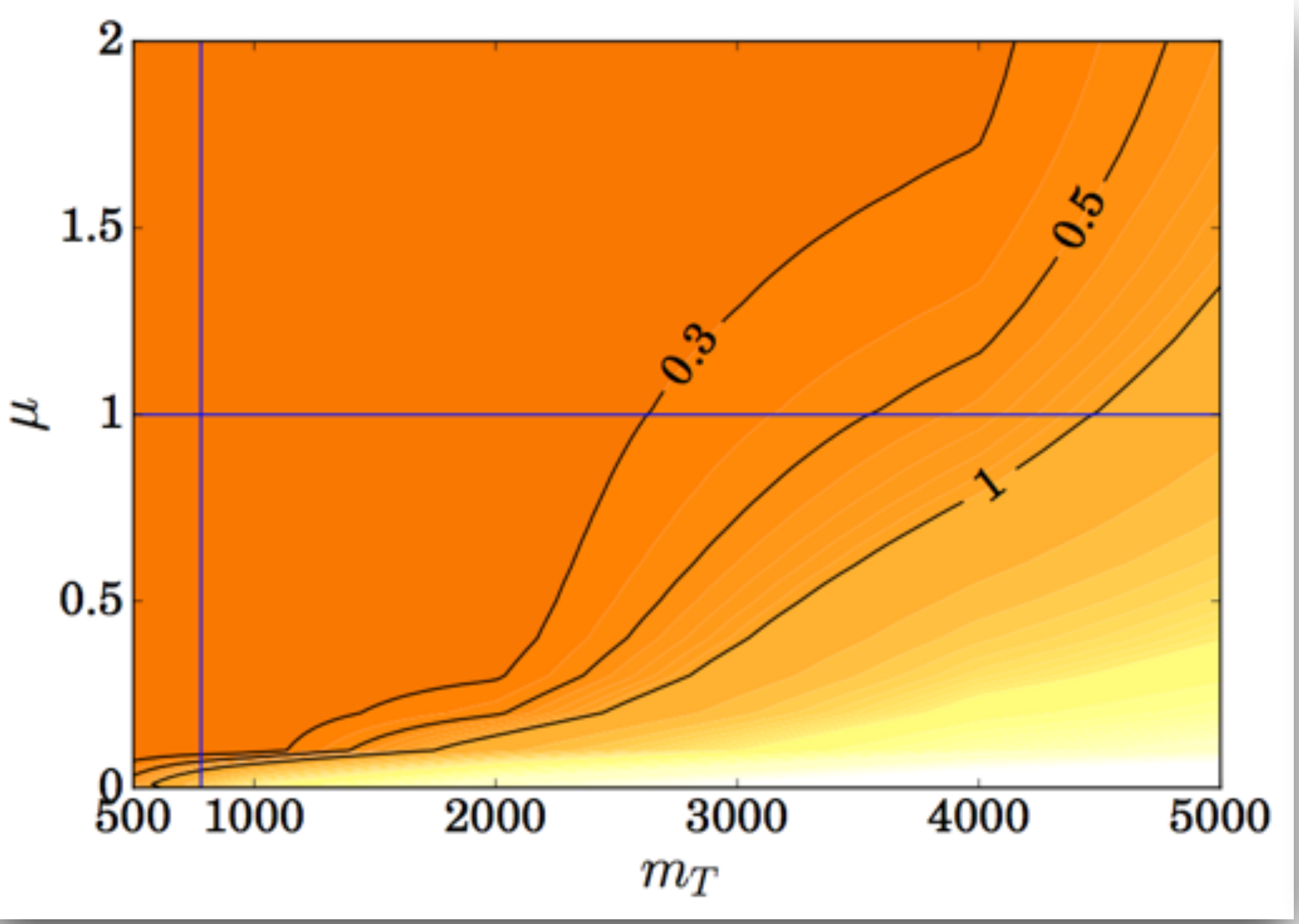




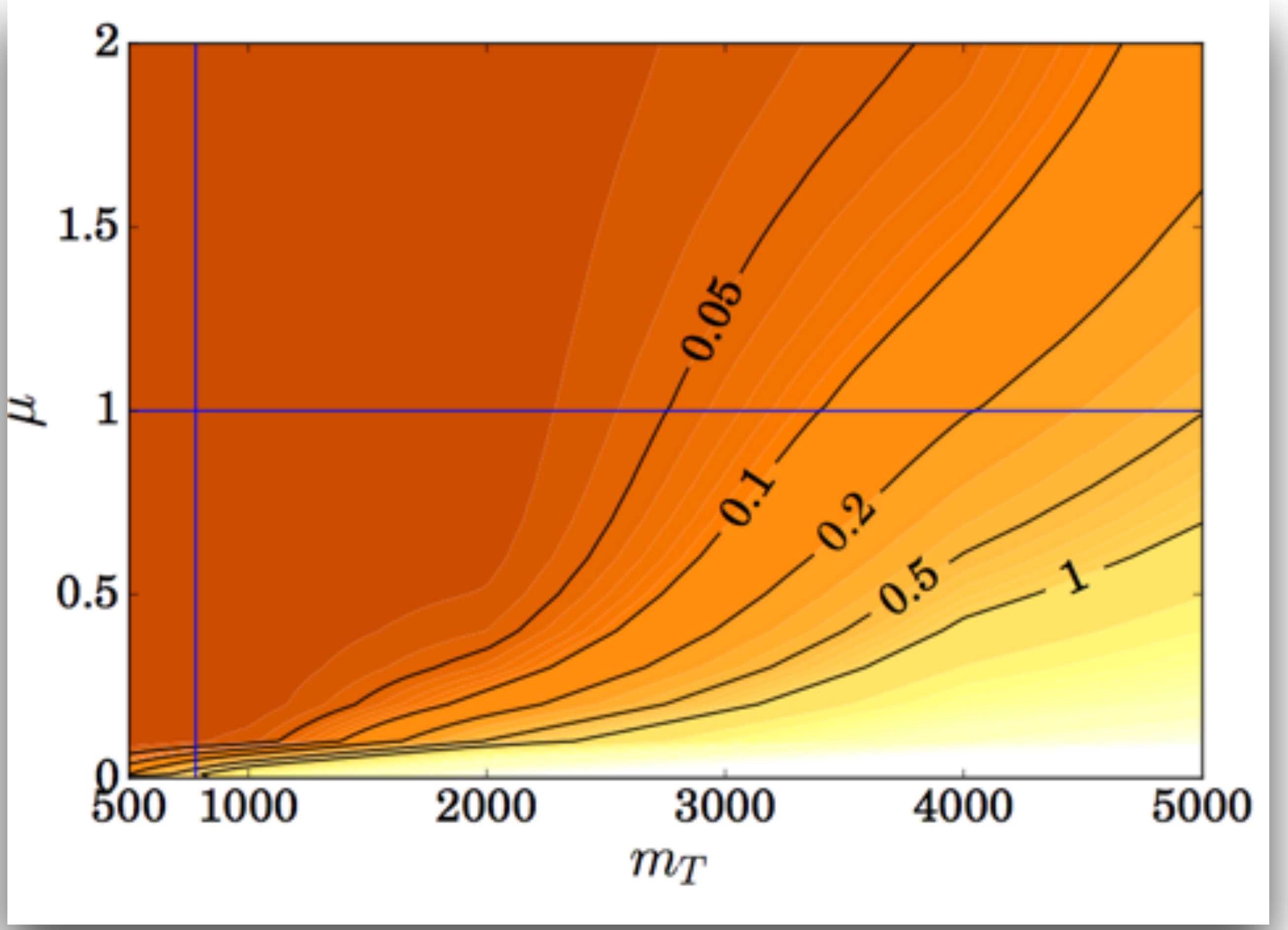
$$\delta\mu = \sqrt{\left(-\frac{1}{\lambda_t^2}\delta a_T\right)^2 + \left(2\frac{a_T}{\lambda_t^3}\delta\lambda_t\right)^2}$$

- If top Yukawa is perfectly measured, a precision of 10% could be pushed up to 3.5 TeV for a natural theory

Precision of Measuring Naturalness Parameter



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



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

- With a precision of 1% which might be achieved for the top Yukawa measurement at 100 TeV [M. Mangano et. al., '15], a precision of 10% could be still pushed up to >3 TeV for a natural theory.

Summary

- The naturalness problem drive particle physics for decades
- To test the theories of naturalness, it is extremely important to measure the naturalness condition
- The test of the naturalness condition for a top sector with fermionic top partners could be rather model-independent, without directly involving the measurement of the decay constant.
- 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 3 TeV
- Straightforward to generalize the discussions to the other sectors or the other theories of naturalness


Thank you!