
LIFE IN
TECHNICOLOR ii
(life in technicolor ii)

Minimal Conformal Technicolor

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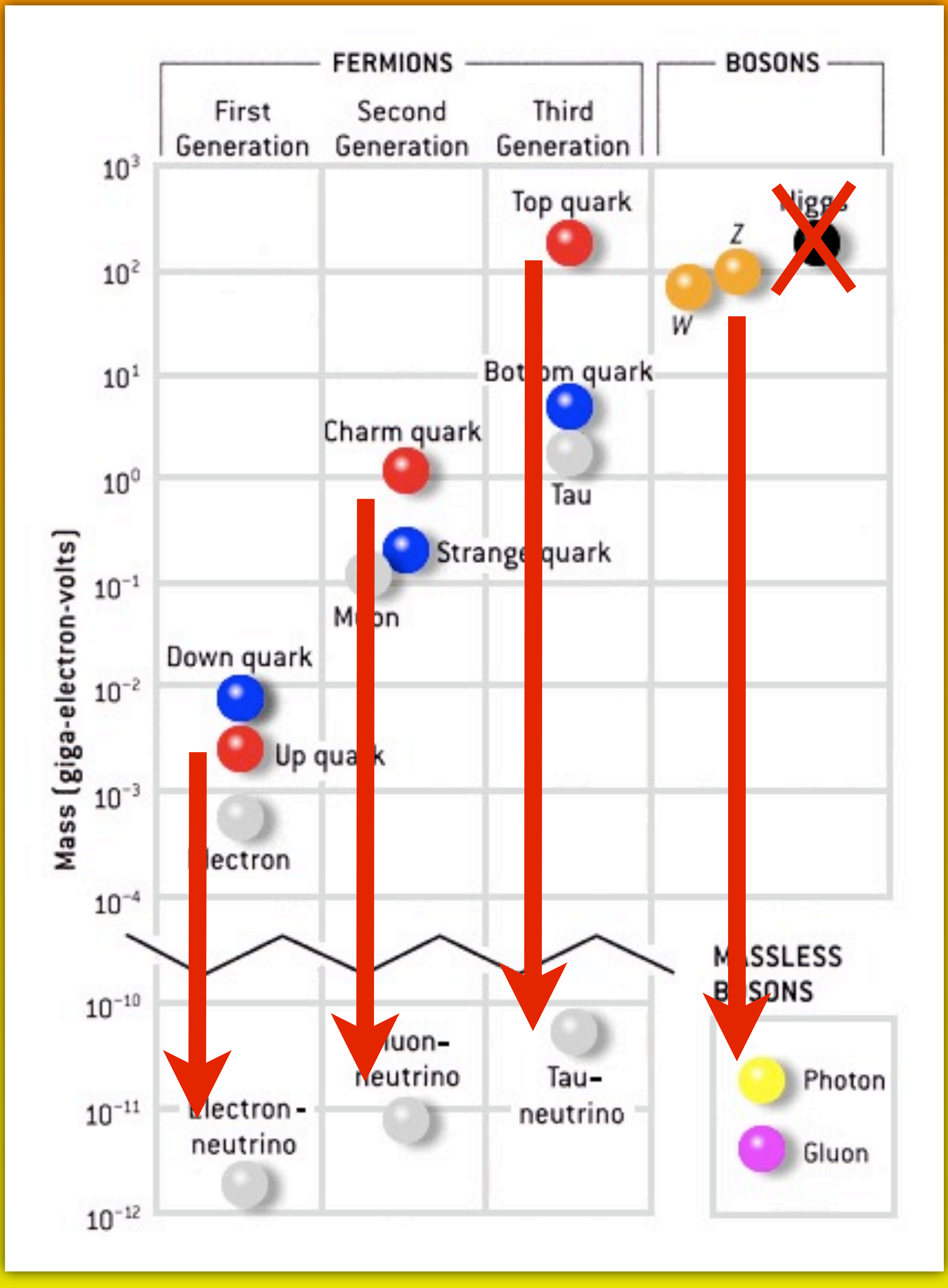
hep-ph/1001.1361 with J. Evans, J. Galloway, M. Luty
University of California, Davis

Minimal Conformal Technicolor

Higgs vs Technicolor

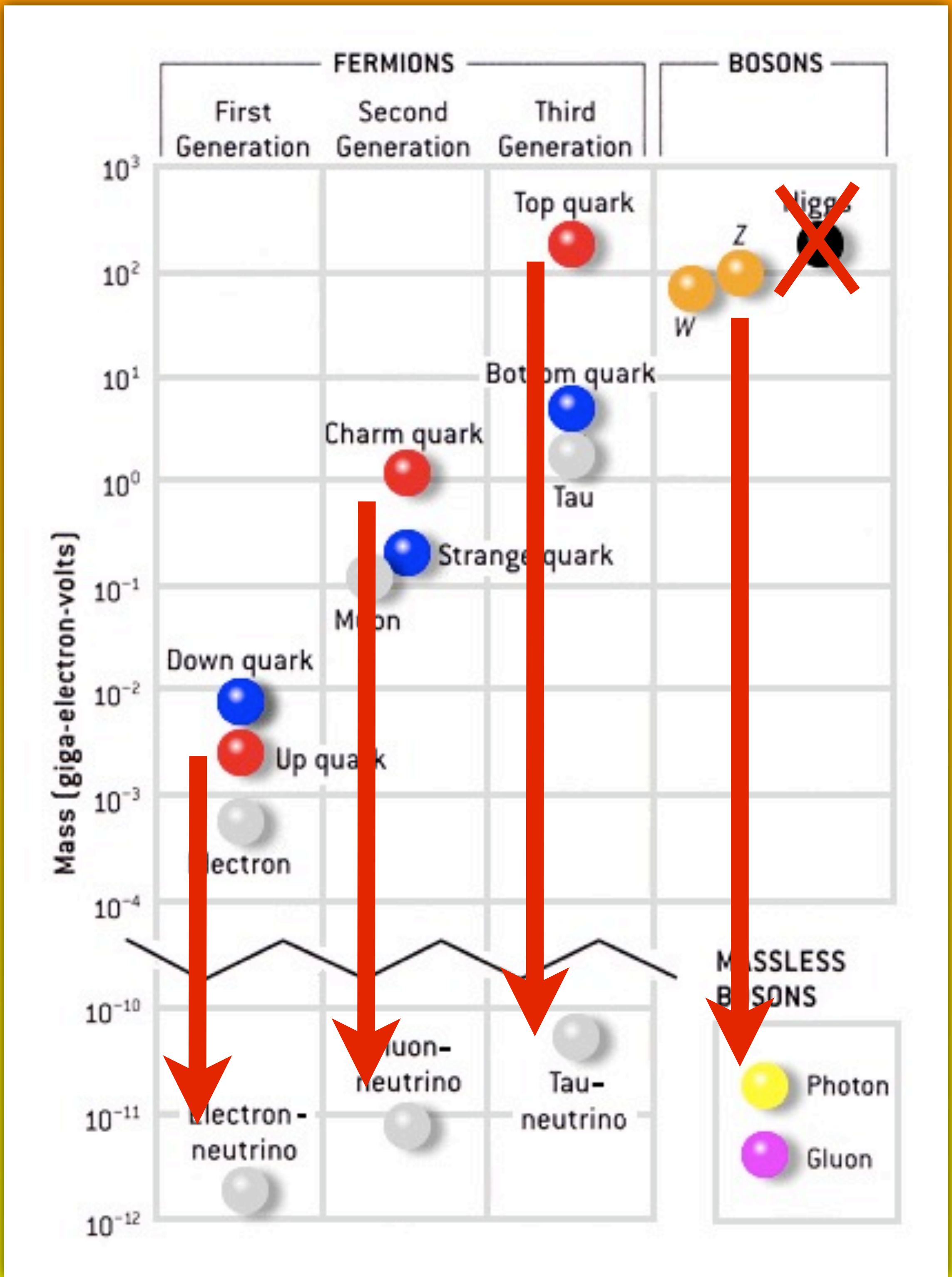


- Standard Model
- Mass origin?
- Higgs? ... (maybe)
- Higgsless SM, disaster?

?

Minimal Conformal Technicolor

Higgs vs Technicolor



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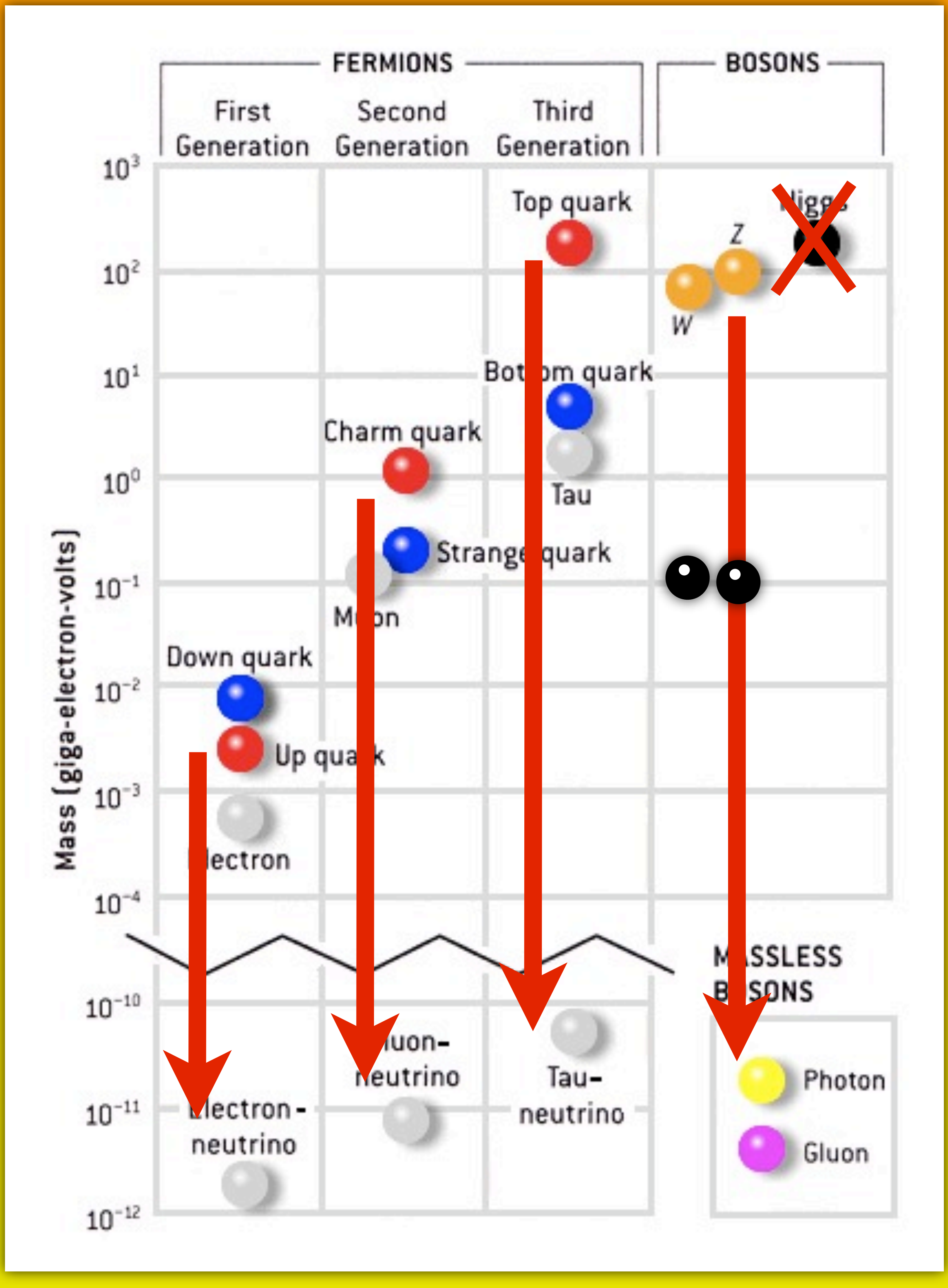

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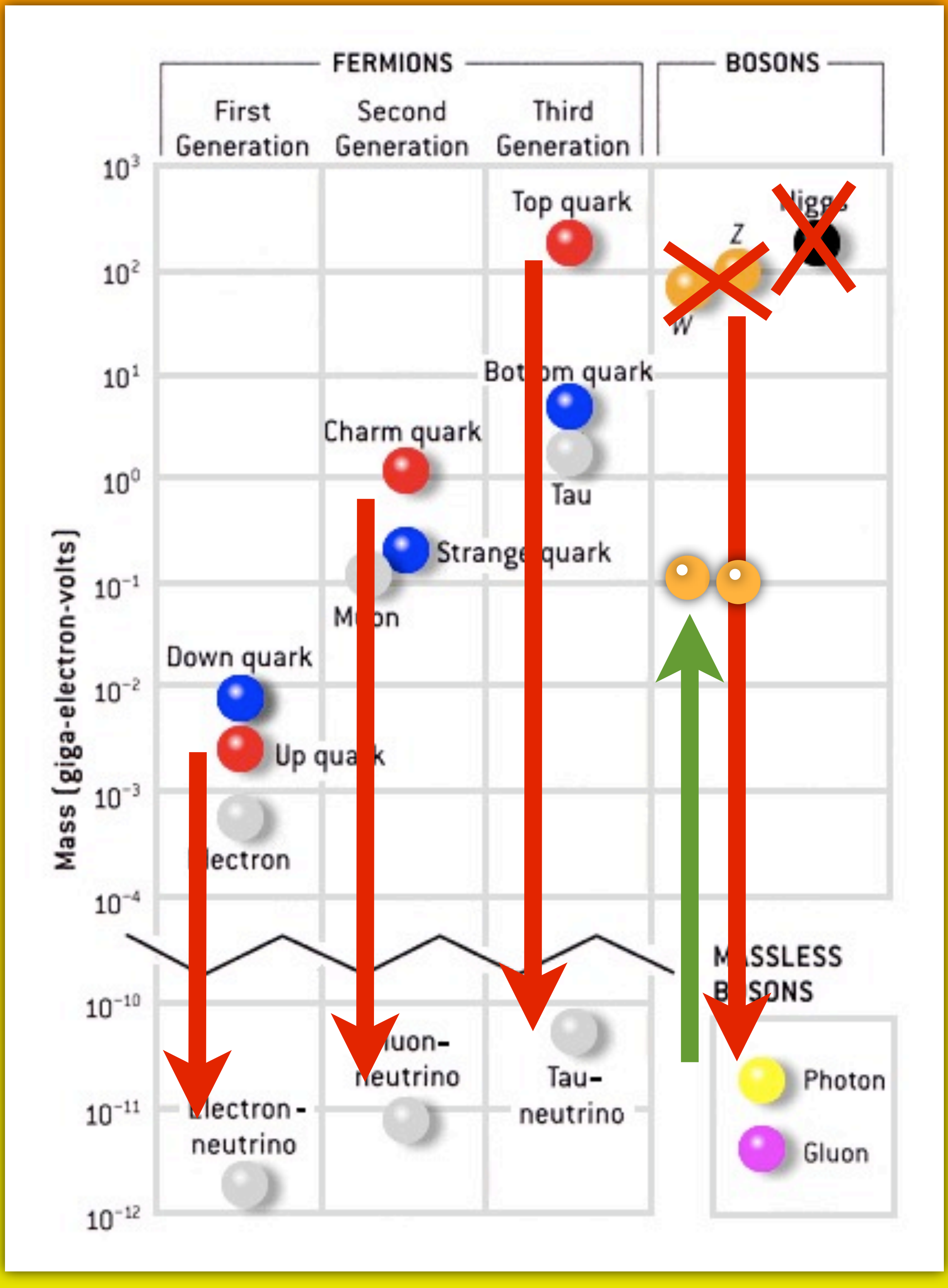

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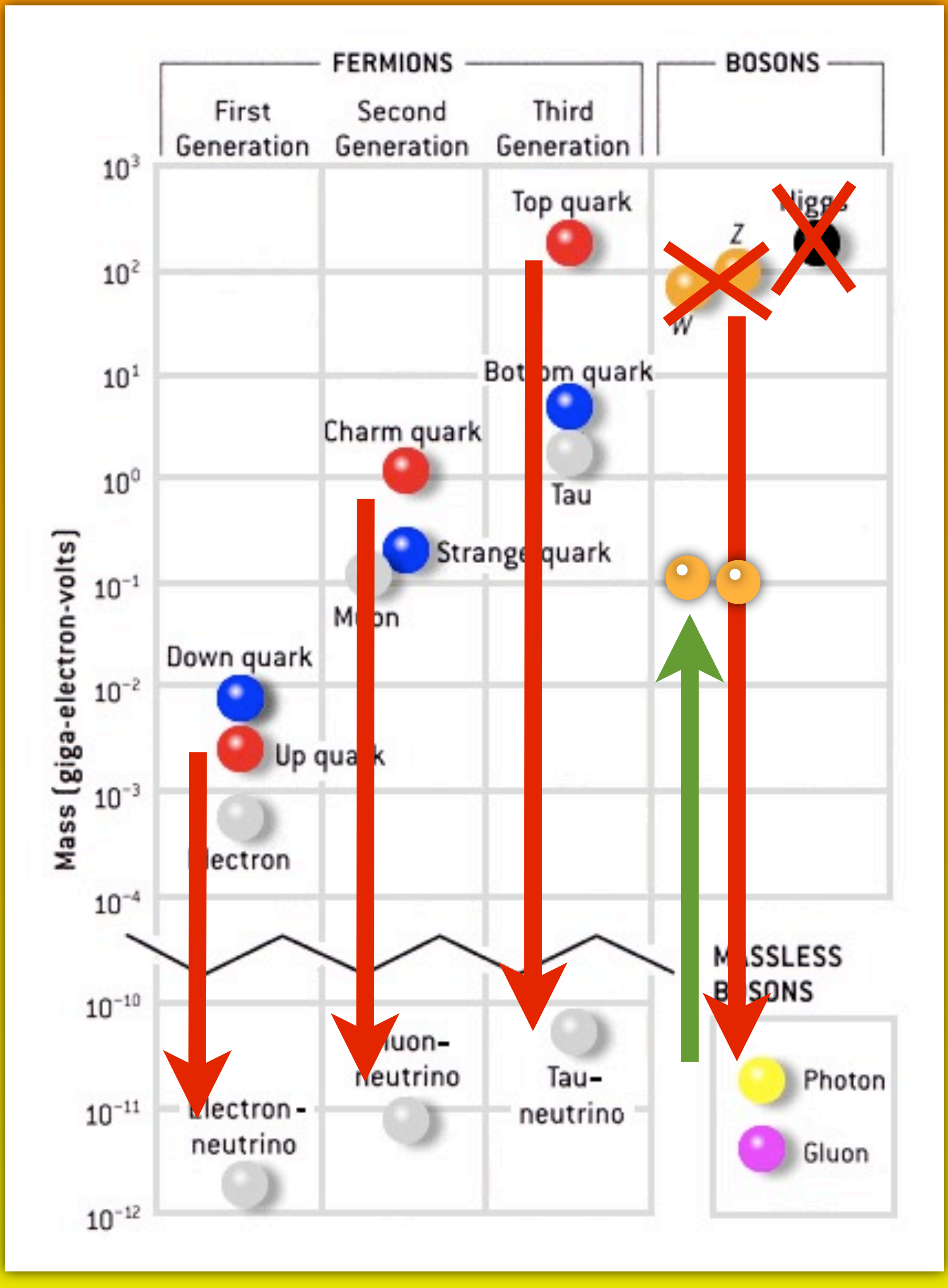

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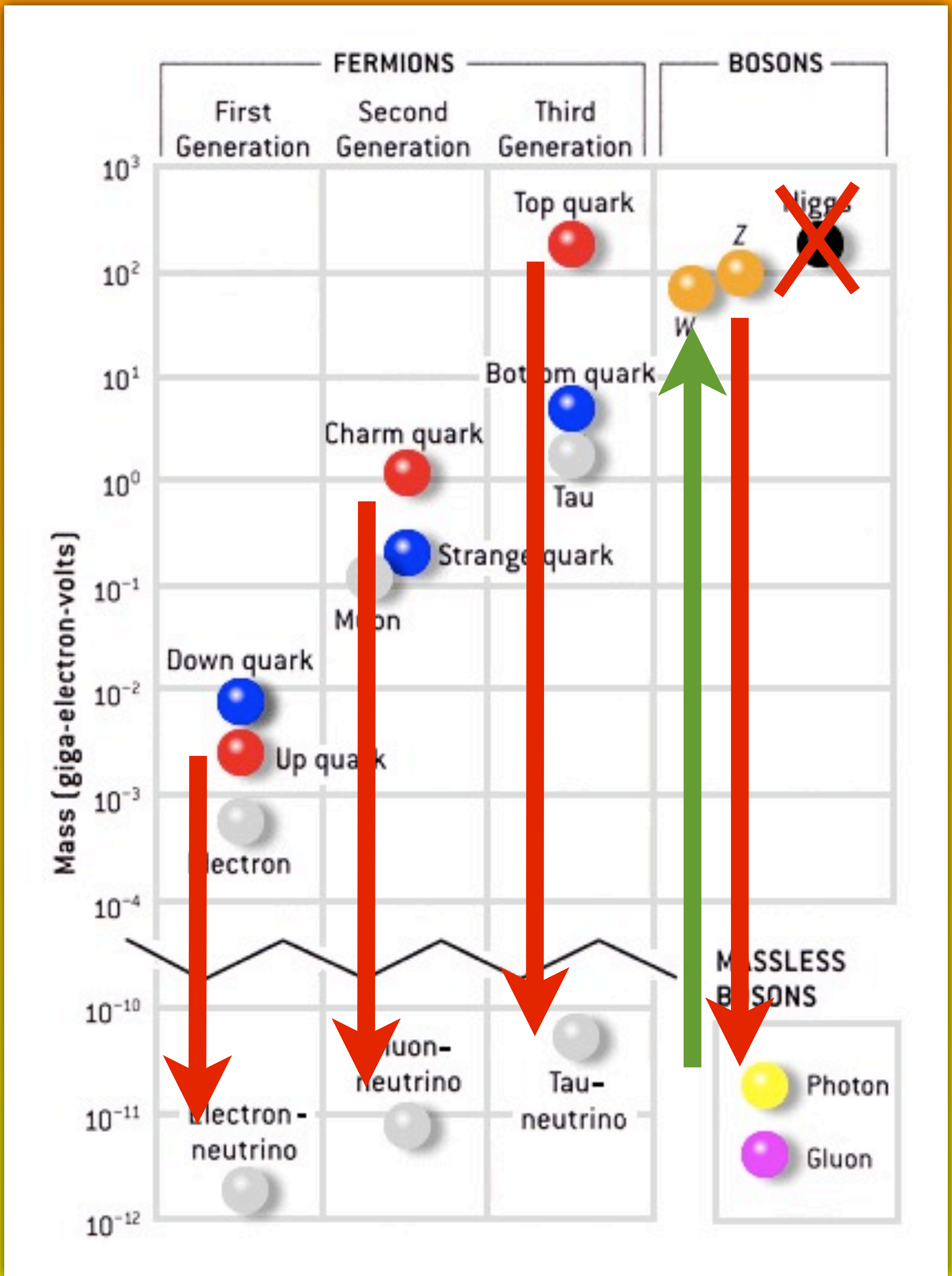

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- QCD-like sector: TC
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- Fermion mass origin?

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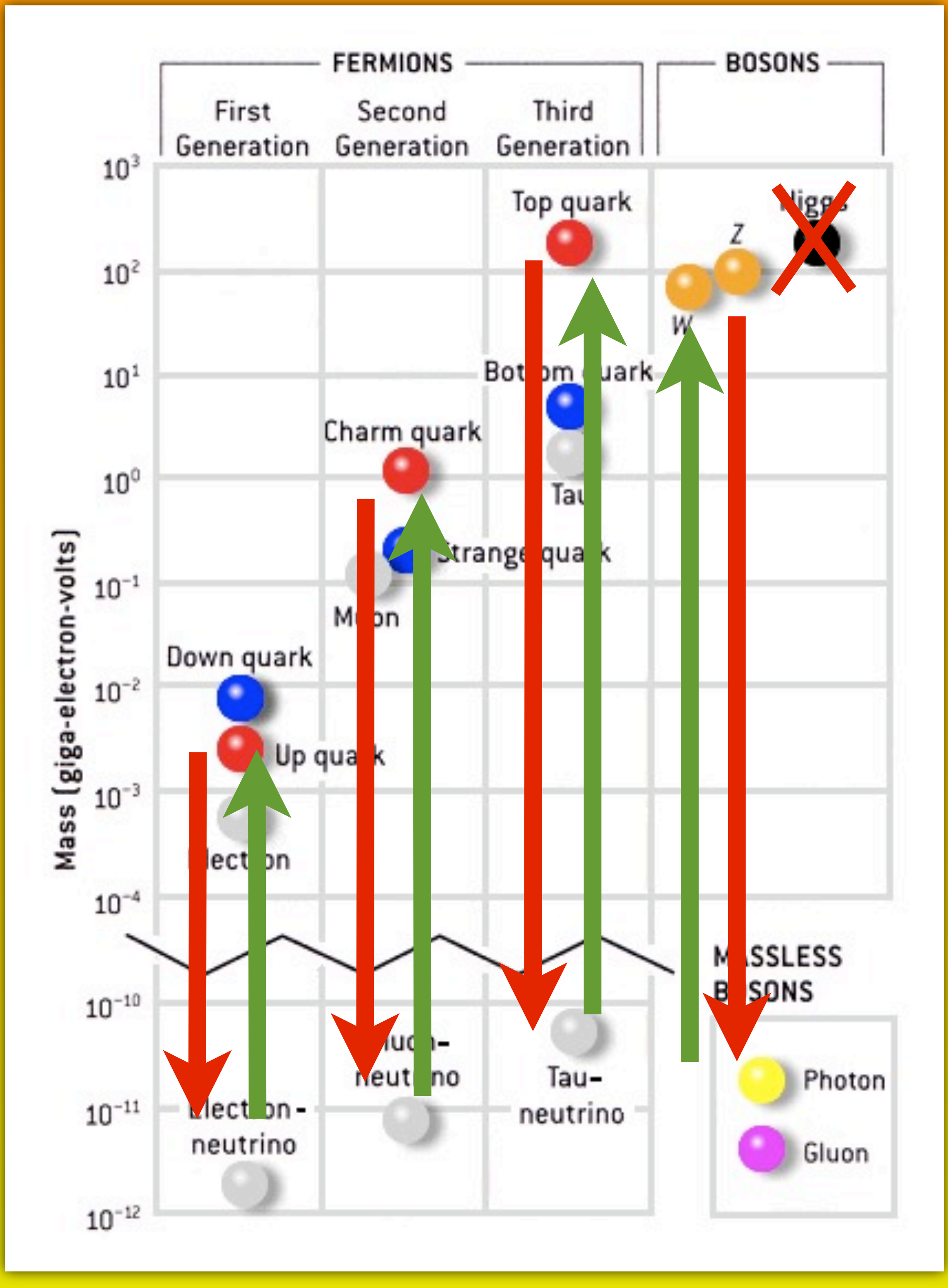

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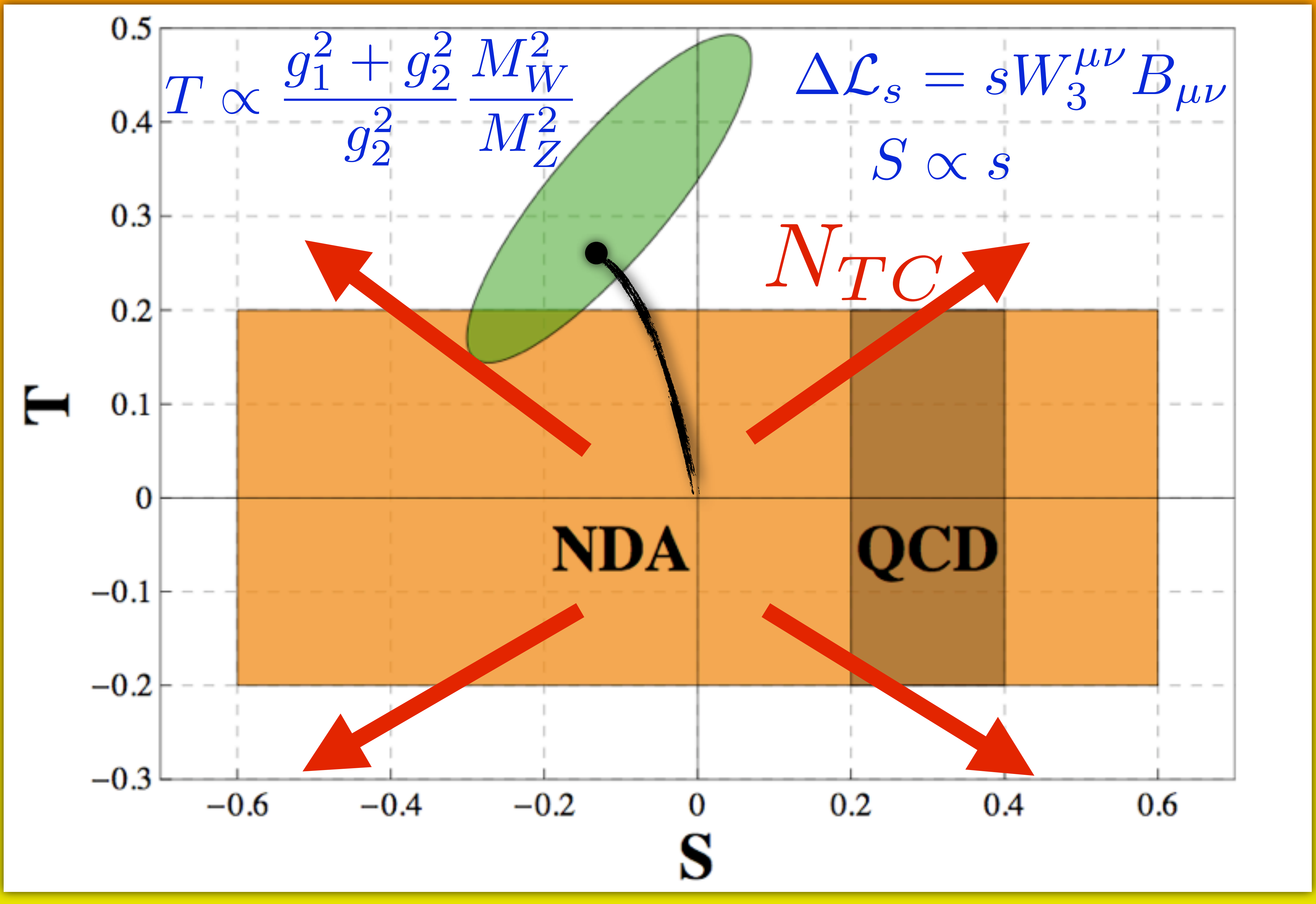
- QCD-like sector: TC
- Technifermions
- Fermion mass origin?
- f f ⟷ Tf Tf
- Extended TC
- Seem good... happy?
- Not quite yet...

Minimal Conformal Technicolor

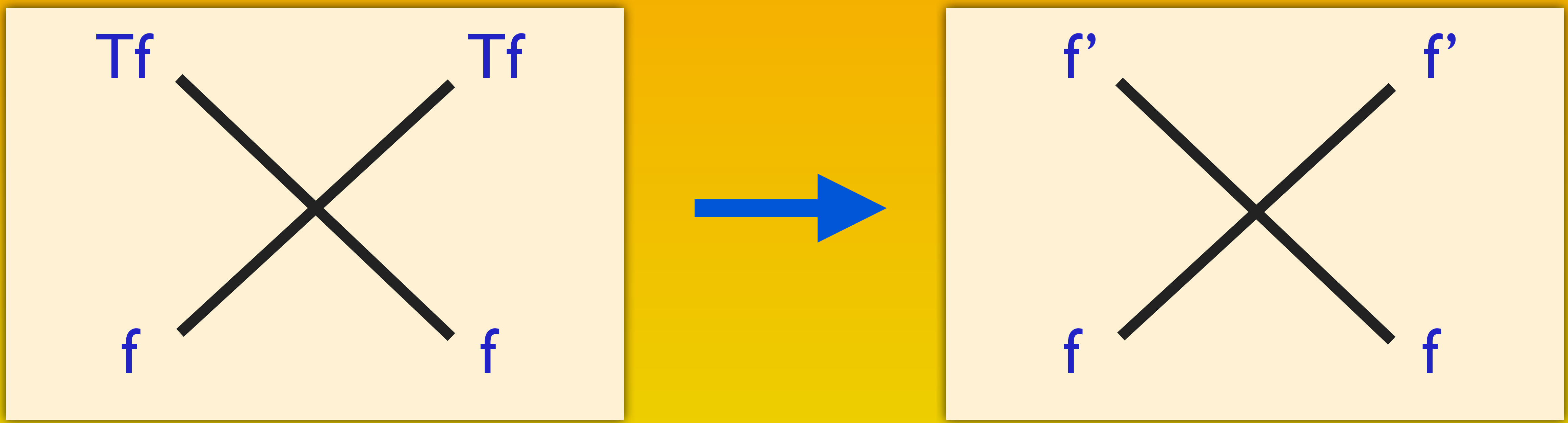
- TC models have to deal with EWPT



Minimal Conformal Technicolor

- TC models have to deal with the flavor problem

Remember... fermion mass problem in TC
ETC: four fermion interactions



$$\Delta\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{f} f)(\bar{\psi}\psi)$$

$$\Delta\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{f} f)(\bar{f}' f')$$

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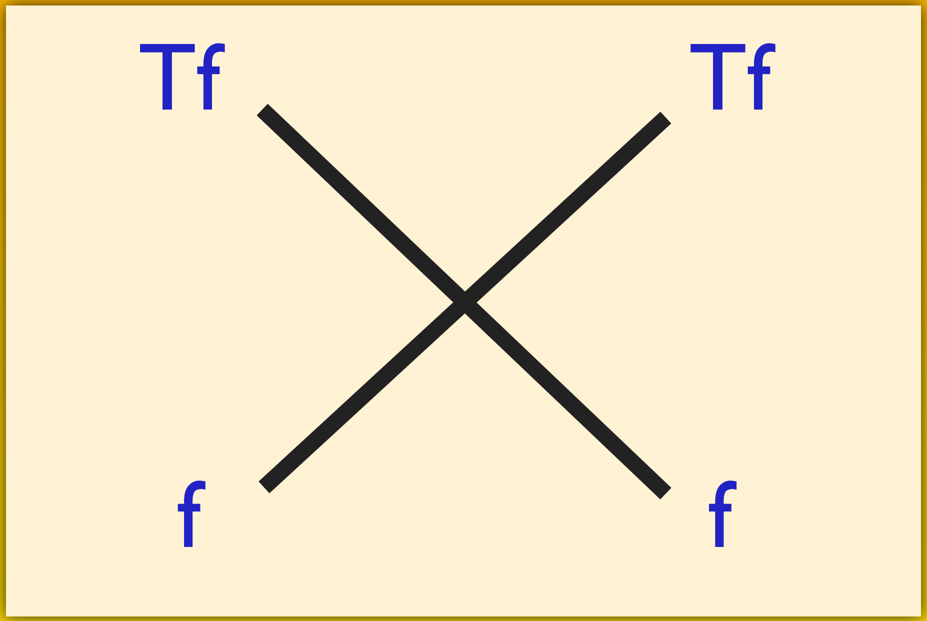

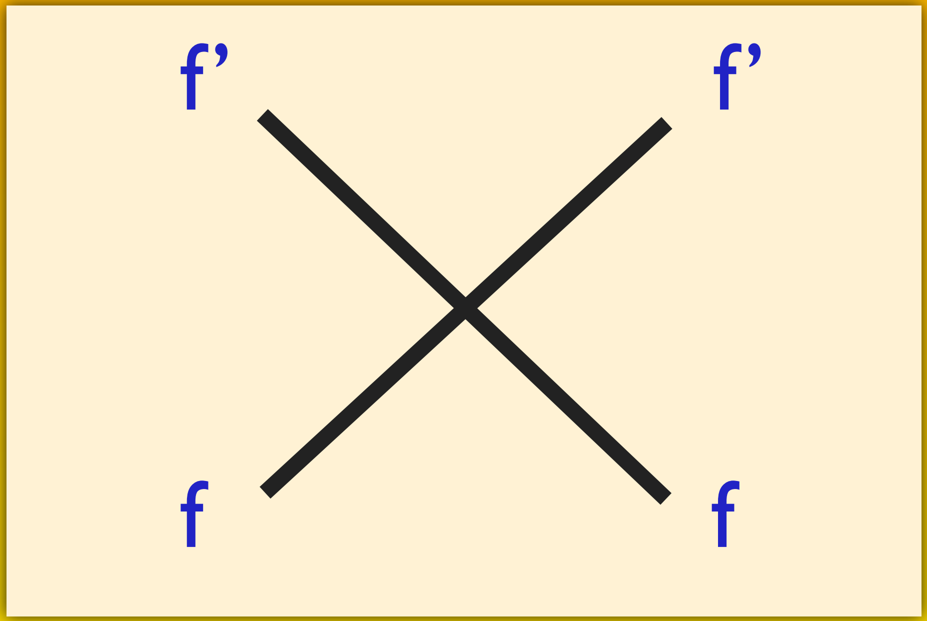

$$\Delta\mathcal{L} = y_f(\bar{f}_L f_R)\mathcal{H}$$

FCNCs at the EWSB scale...

Minimal Conformal Technicolor

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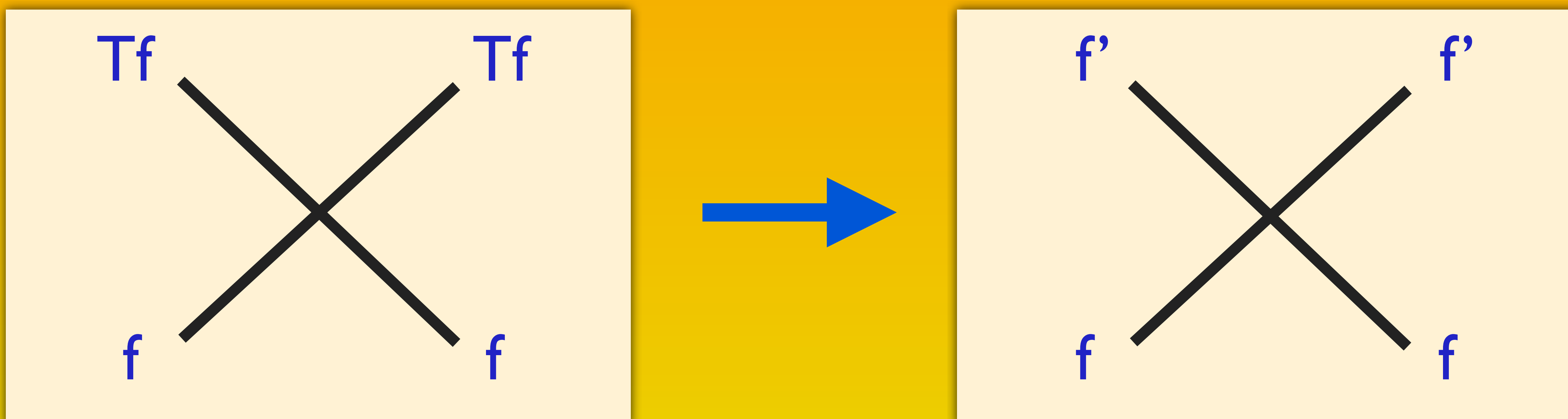

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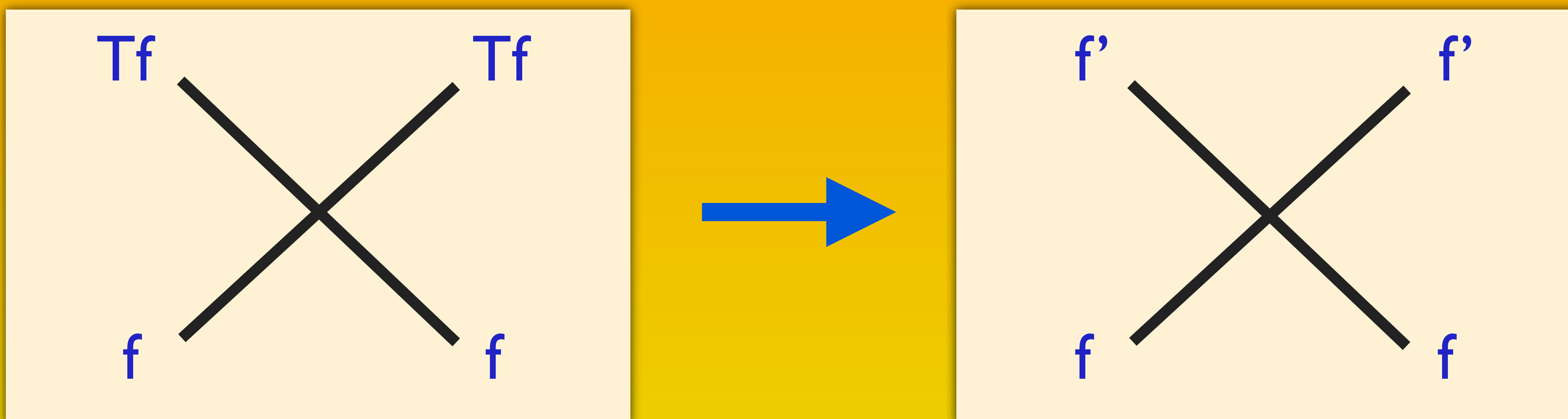


$$\mathcal{H} \to \mathcal{H}^\dagger \mathcal{H}$$

$$\Delta\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{f}f)(\bar{f}'f')$$

Minimal Conformal Technicolor

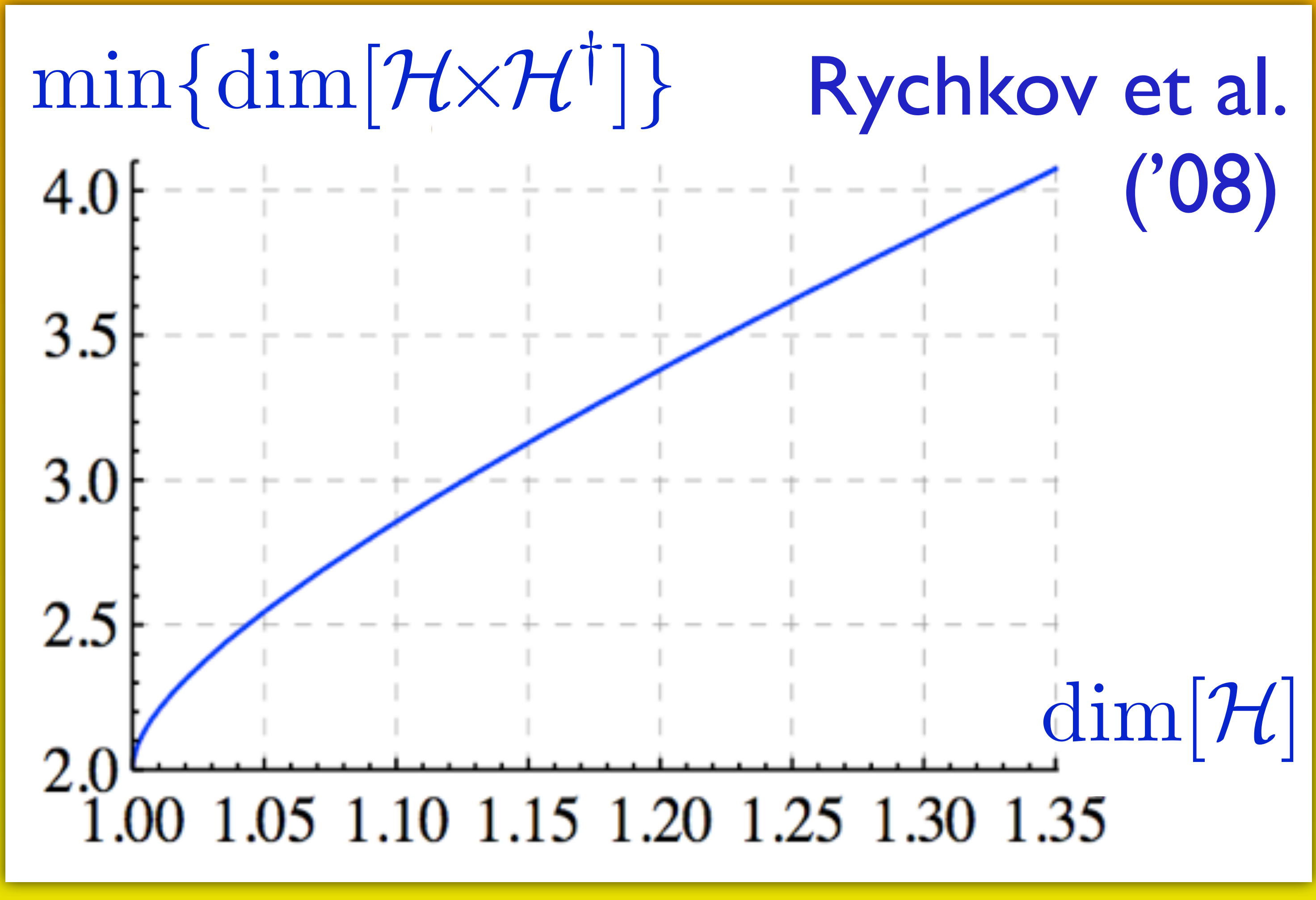
- TC models have to deal with the flavor problem

One possibility to explore:
Conformal Technicolor (Luty, Okui '04)

The idea:

$$\dim[\mathcal{H}] = 1 + \frac{1}{few}$$

$$\dim[\mathcal{H}^\dagger \mathcal{H}] > 4$$



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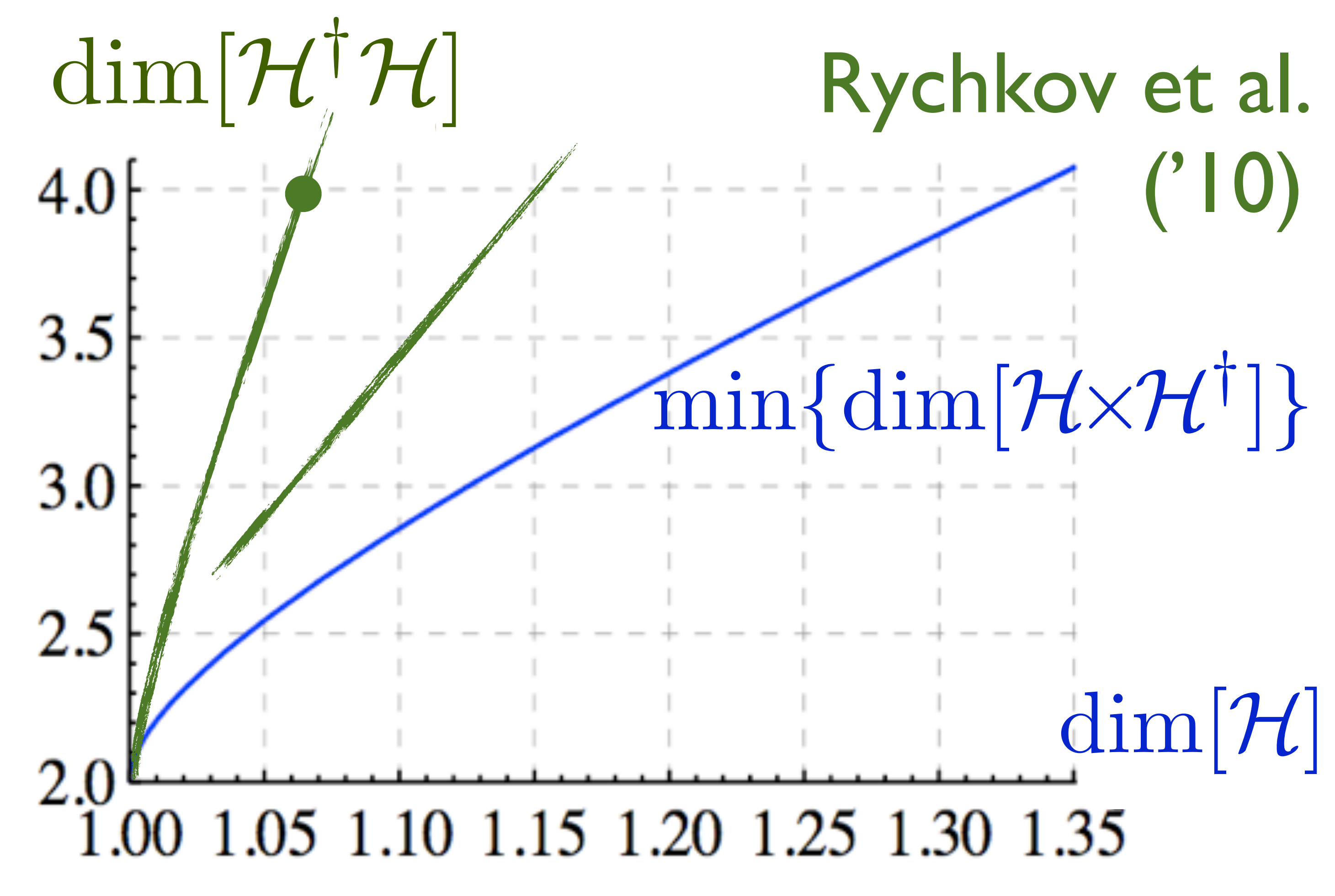
Conformal Technicolor
is a plausible scenario!



Minimal Conformal Technicolor

$$SU(N)_{TC} \times SU(2)_W \times U(1)_Y$$

- Strong SU(N) for TC-like EWSB
- SU(2)_L x SU(2)_R (custodial symmetry)
- Conformality to help the flavor problem
- Within EWPT constraints (small N)

We would like these properties in the "Minimal" setting...
How can we do that?

Minimal Conformal Technicolor

Ψ	$SU(2)_{TC}$	$SU(2)_W$	Y
ψ	$\square$	$\square$	0
$\tilde{\psi}_1$	$\square$	1	$-\frac{1}{2}$
$\tilde{\psi}_2$	$\square$	1	$\frac{1}{2}$

Strong SU(2)_TC to keep S and T small

Minimal Conformal Technicolor

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Global SU(4) (unbroken if EW is off)
Broken if a potential is present

$$\langle \Psi^A \Psi^B \rangle \neq 0$$

Minimal Conformal Technicolor

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$n \cdot \tilde{\chi}$	$\square$	1	0

Add some heavy SM sterile fields

Global SU(4+n)

Minimal Conformal Technicolor

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Conformal Symmetry breaks!

Global SU(4+n) ⟶ SU(4)

$$\Delta\mathcal{L} = -\kappa\psi\psi - \tilde{\kappa}\tilde{\psi}_1\tilde{\psi}_2 - K\chi\chi$$

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Conformal Symmetry breaks!

Global SU(4+n) ⟶ SU(4) ⟶ Sp(4)

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Minimal Conformal Technicolor

SU(4) → Sp(4) : Preskill, Peskin ('80)

10 unbroken generators + 5 broken generators
They find two solutions:

$$\Phi_{EW} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$\Phi_{TC} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

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$$\Phi_{TC} = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

We like them both and want to find a solution in between!
Can we do that?

$$\Phi_{MCTC} = \begin{pmatrix} 0 & \cos(\theta) & \sin(\theta) & 0 \\ -\cos(\theta) & 0 & 0 & \sin(\theta) \\ -\sin(\theta) & 0 & 0 & -\cos(\theta) \\ 0 & -\sin(\theta) & \cos(\theta) & 0 \end{pmatrix}$$

Minimal Conformal Technicolor

$$SU(2)_{TC} \times SU(2)_W \times U(1)_Y$$

- Condensate Sp(4) invariant $\langle \Psi\Psi \rangle \propto \Phi \neq 0$
- $\langle \Psi^A \Psi^B \rangle \propto \Phi^{AB} = -\Phi^{BA}$
- Pion fields transforming SU(4)-Sp(4) $\xi = e^{i\Pi}$
- SU(4) invariant $\xi \Phi \xi^T$

- Vacuum alignment
- EWSB (3 eaten goldstones)
- 2 uneaten PNGBs: a Higgs-like scalar and a pseudoscalar ‘A’

$$m_W^2 = \frac{g^2}{4} f^2 \sin^2(\theta)$$

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$$m_W^2 = \frac{g^2}{4} f^2 \sin^2(\theta) = v^2$$

Minimal Conformal Technicolor

Technicolor, Composite Higgs and the Standard Model Higgs

They all break the EW symmetry at the TeV

SM Higgs: $\mathcal{H}^\dagger = (\cancel{h^+} - i\cancel{H^+}, v + h - i\cancel{H})$

Old fashion TC model:

$f_\pi, \cancel{\pi_1}, \cancel{\pi_2}, \cancel{\pi_3}, (\sigma, \rho?)$

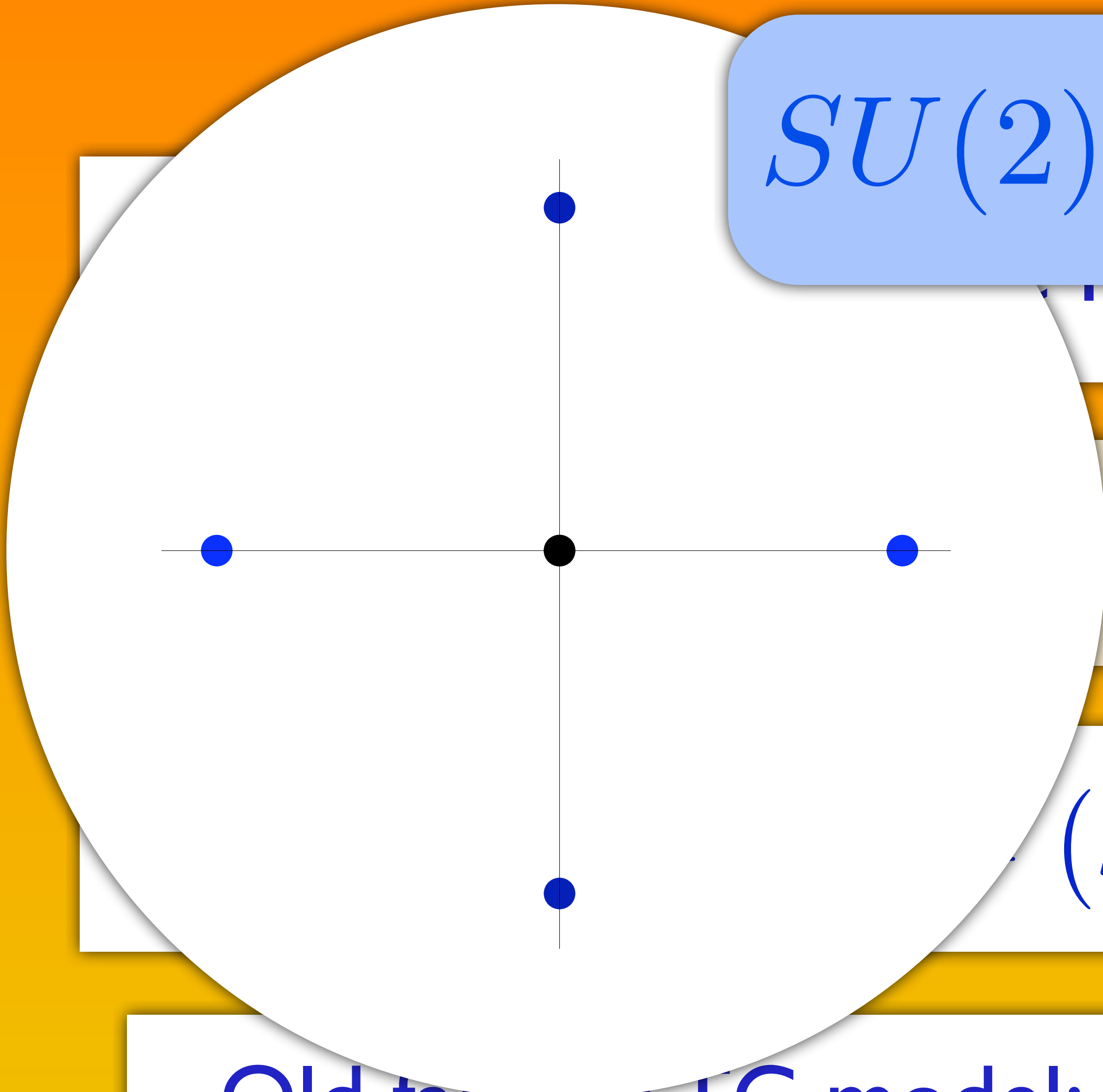
Composite Higgs models:

$f_\pi, \cancel{\pi_1}, \cancel{\pi_2}, \cancel{\pi_3}, \pi_4, \pi_5 \dots$

Composite Higgs models have a bigger symmetry!

nicolor

$SU(2) \times SU(2)$



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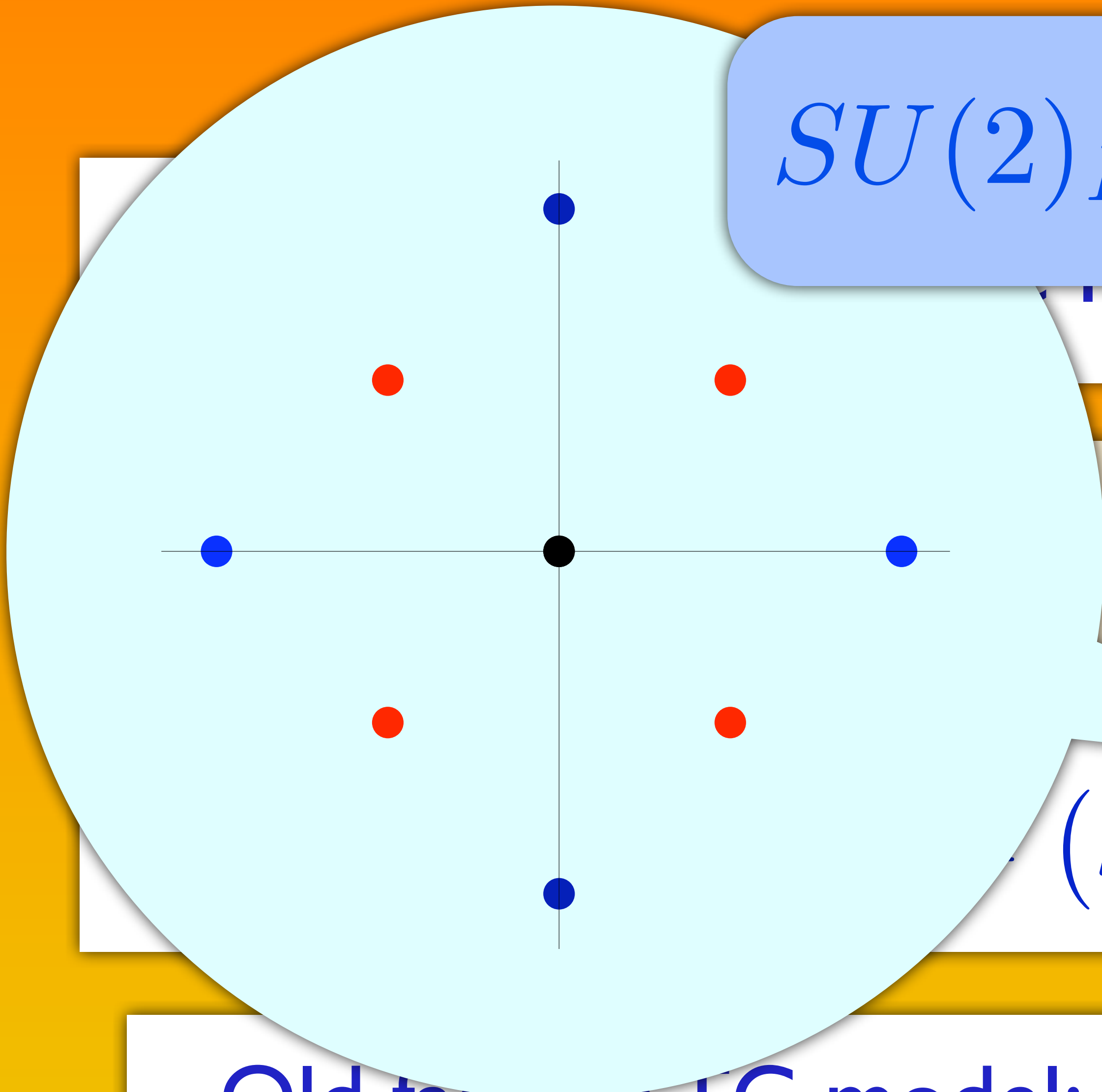

$SU(2)_L \times SU(2)_R$ with a $H:(2_L, 2_R)$

Higgs and the Standard Model Higgs

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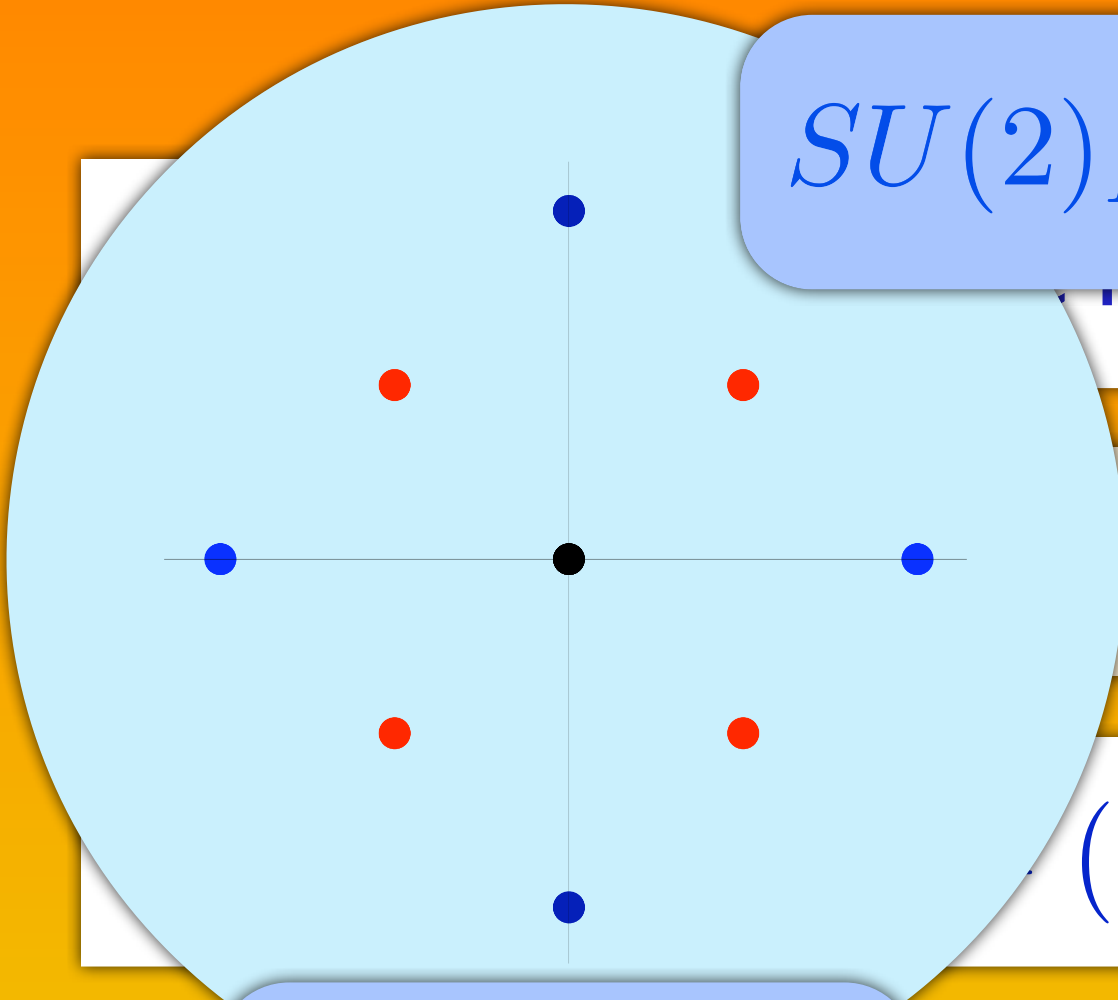

$SU(2)_L \times SU(2)_R$ with a $H:(2_L, 2_R)$

Higgs and the Standard Model Higgs

e EW symmetry at the TeV

$(h^+ - iH^+, v + h - iH)$

$SO(5)$

odel:

$f_\pi, \pi_1, \pi_2, \pi_3, (\sigma, \rho?)$

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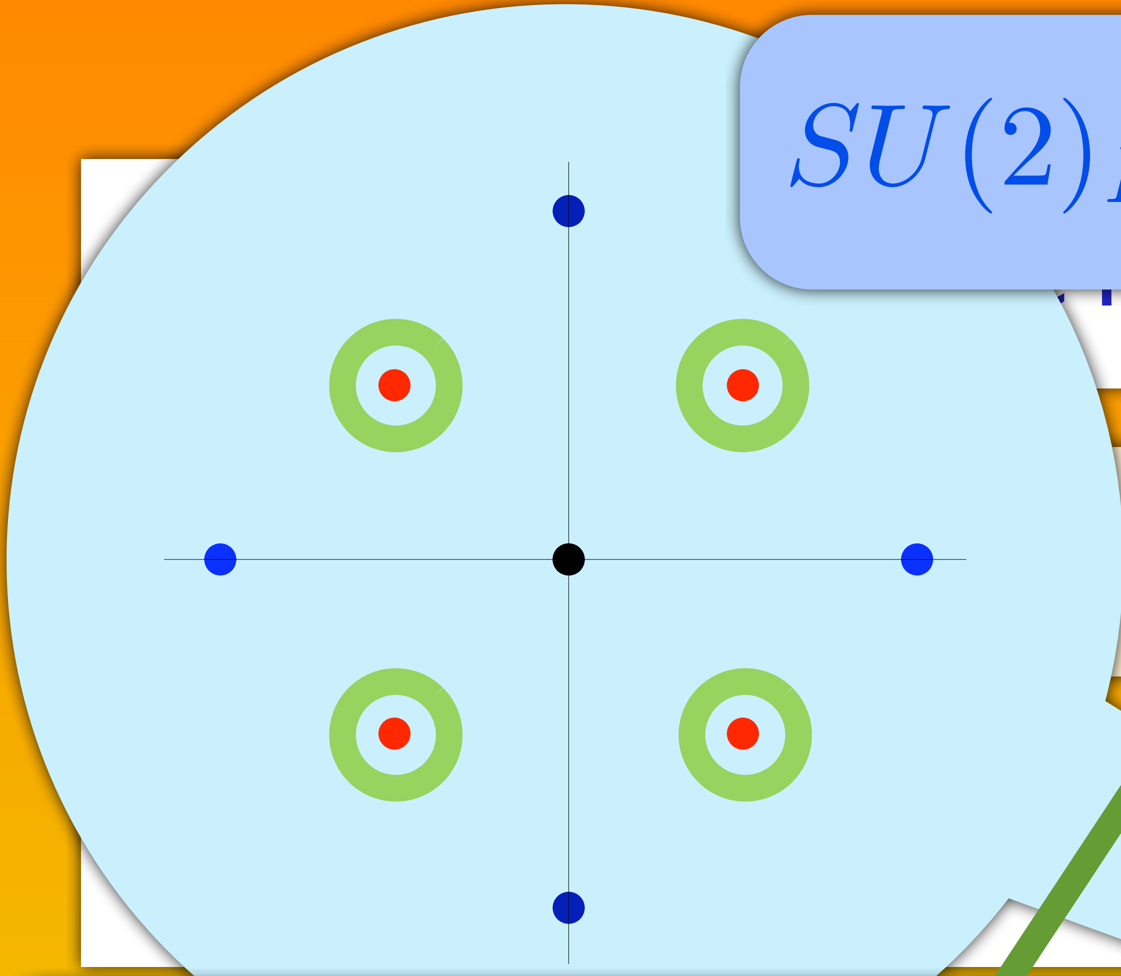

$SU(2)_L \times SU(2)_R$ with a H:$(2_L, 2_R)$

… Higgs an… the Standard Model Higgs

…e EW symmetry at the TeV

$\ldots i\not{H}^+, v + h - i\not{H})$

$SO(5) \to SO(4)$

$f_\pi, \not{\pi}_1, \not{\pi}_2, \not{\pi}_3, (\sigma, \rho?)$

Comp…ite Higgs models:

$f_\pi, \not{\pi}_1, \not{\pi}_2, \not{\pi}_3, \pi_4, \pi_5 \ldots$

Composite Higgs models have a bigger symmetry!

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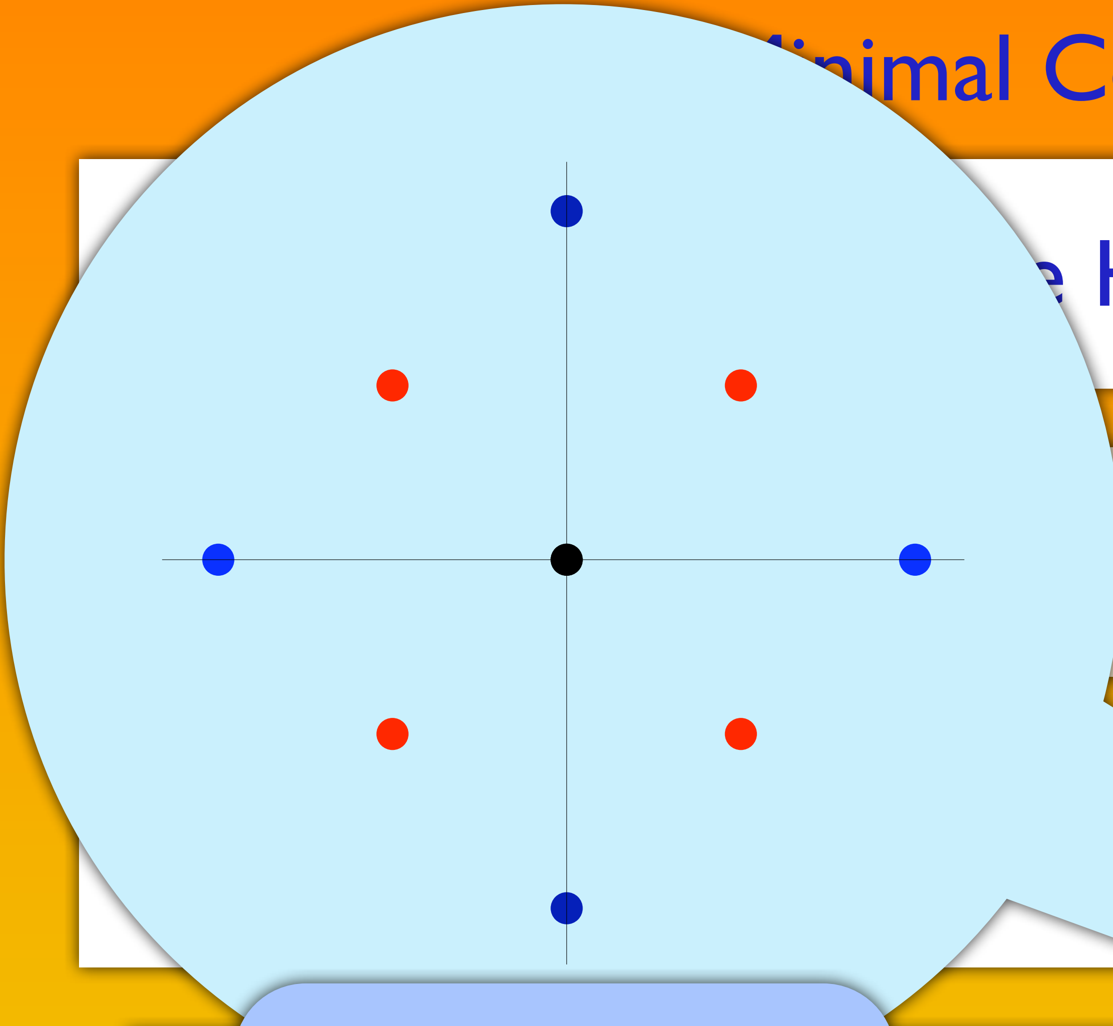

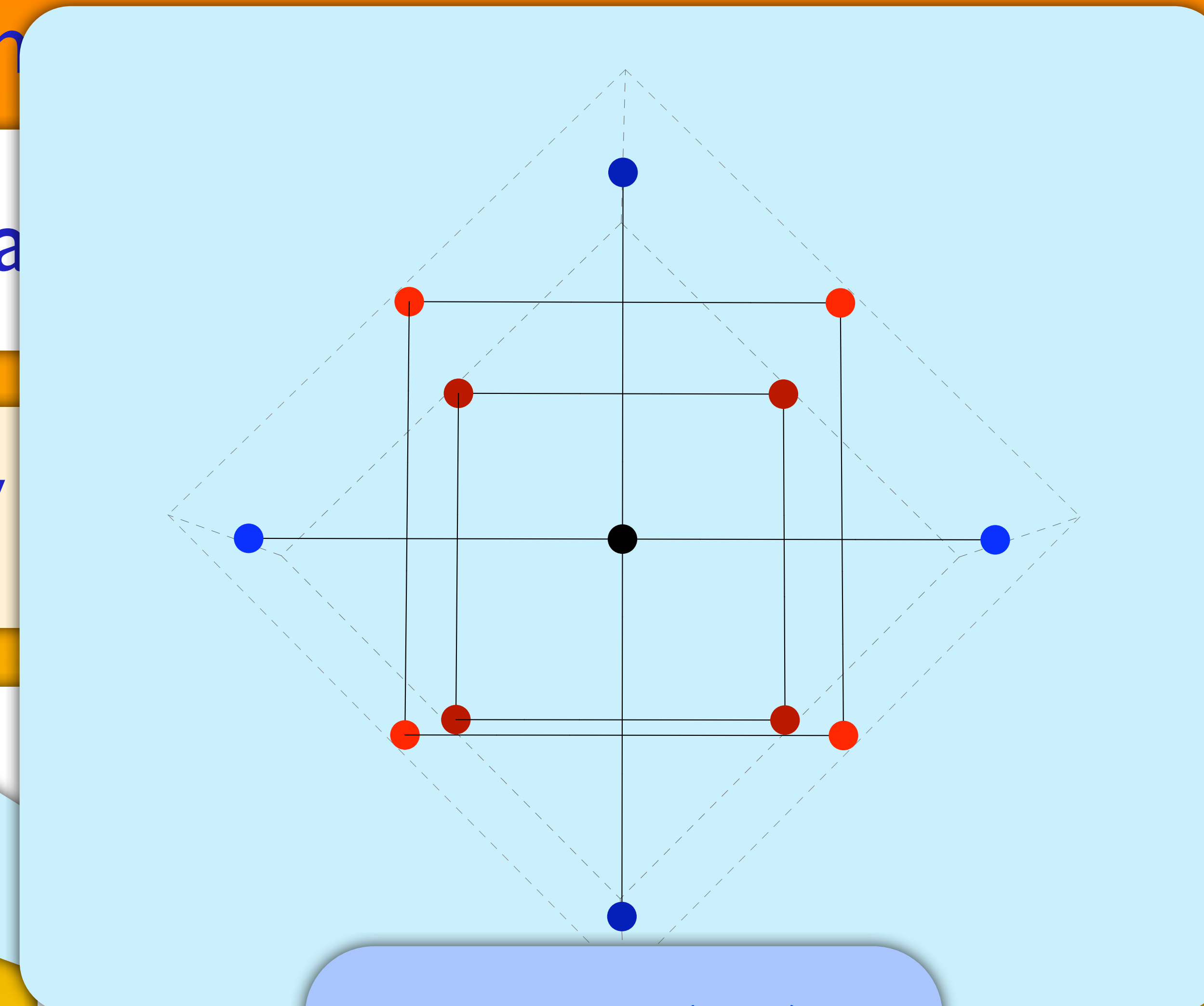

$SO(5)$

odel:

$f_\pi, \cancel{\pi_1}, \cancel{\pi_2}, \cancel{\pi_3}, (\sigma, \rho?)$

$SO(6)$

Comp els:

$f_\pi, \cancel{\pi_1}, \cancel{\pi_2}, \cancel{\pi_3}, \pi_4, \pi_5 \ldots$

Composite Higgs models have a bigger symmetry!

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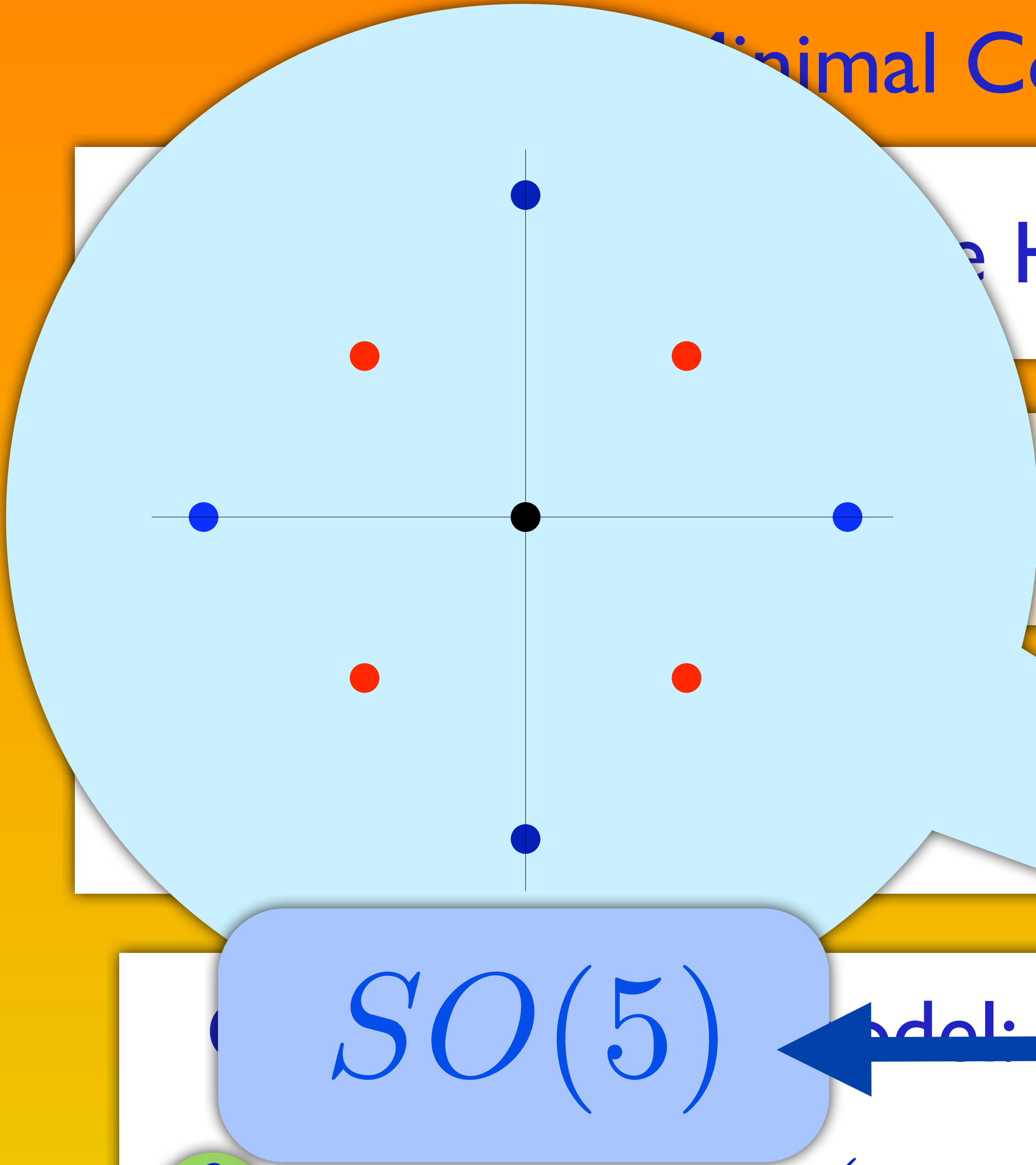

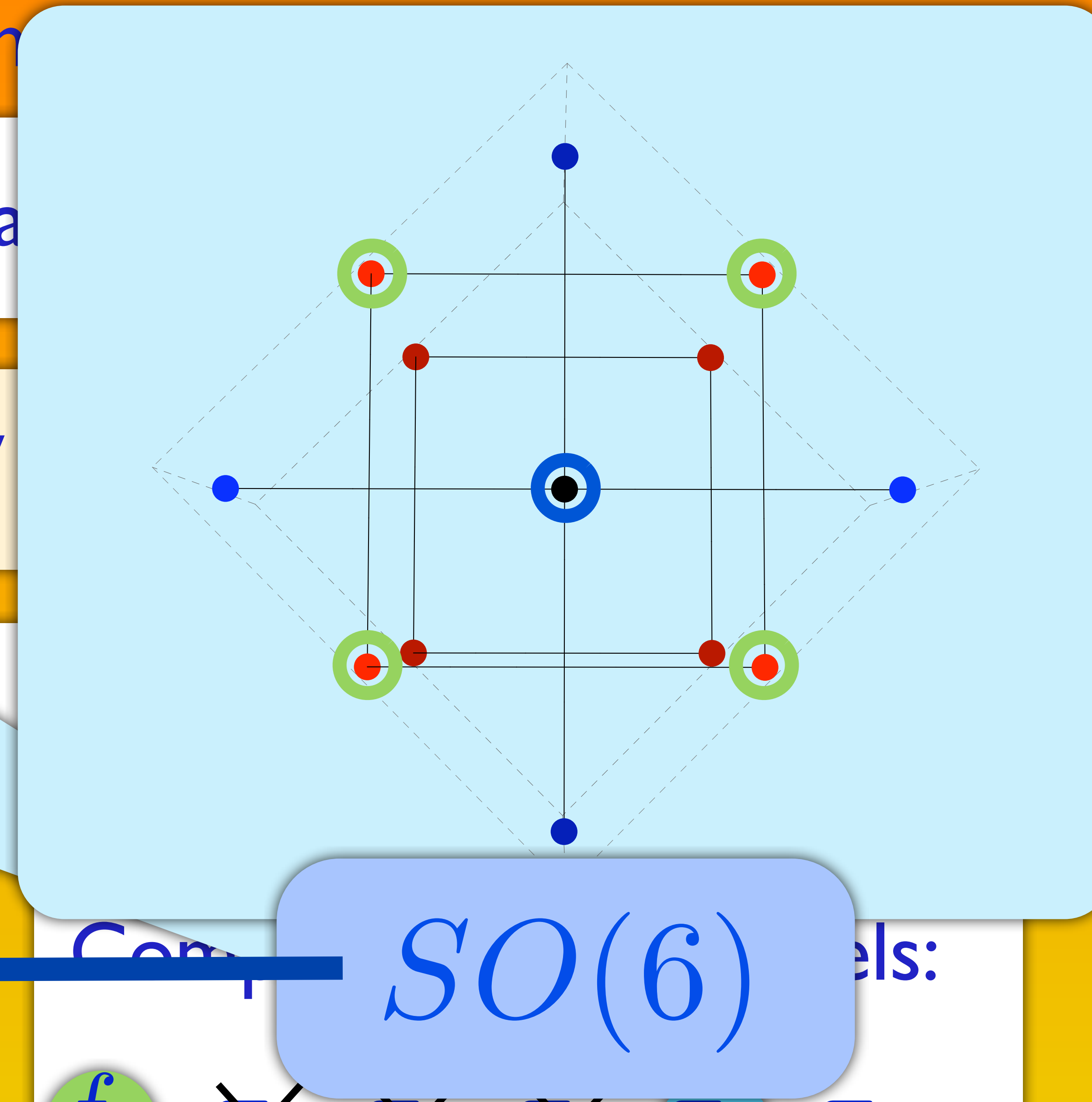

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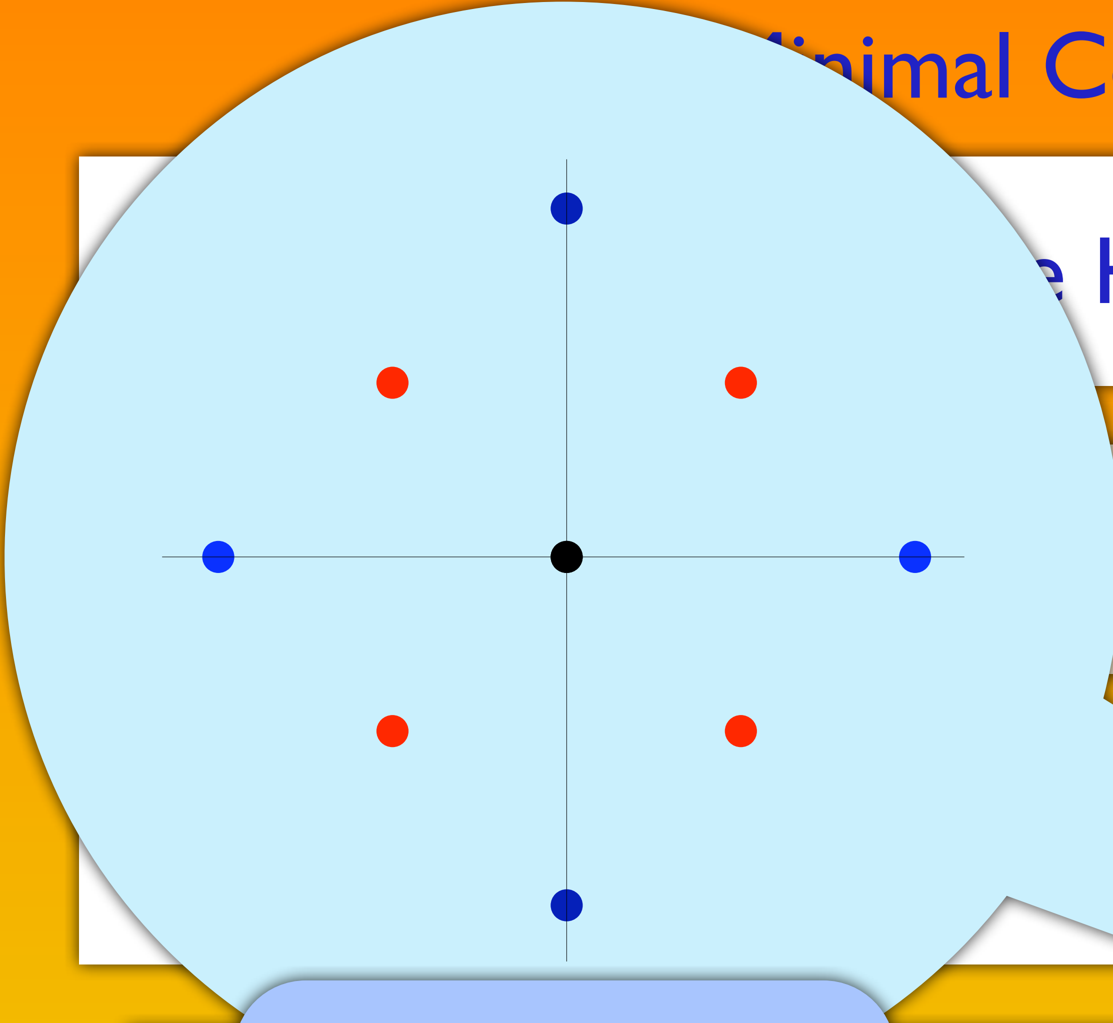

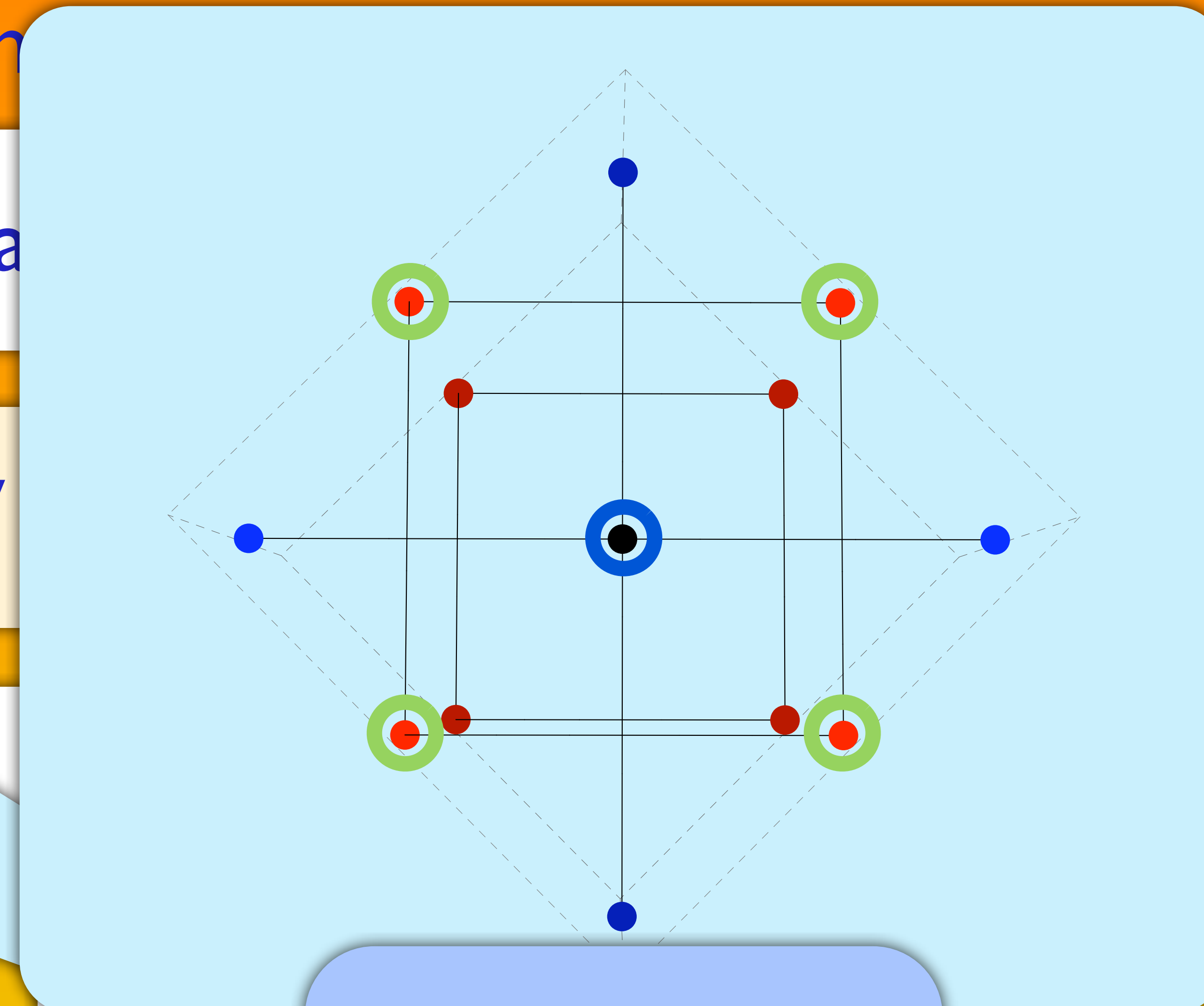

$Sp(4)$ ← $SU(4)$

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Composite Higgs models have a bigger symmetry!

Minimal Conformal Technicolor

Effective Potential: Top loops and technifermion masses

$$\Delta\mathcal{L} = \frac{g_t^2}{\Lambda_t^{d-1}}(Qt^c)(\psi\tilde{\psi})$$

$$\Delta\mathcal{L} = -m\psi\psi - \tilde{m}\tilde{\psi}_1\tilde{\psi}_2$$

→

$$V_t \sim -\sin^2(\theta)$$

$$V_m \sim -(m-\tilde{m})\cos(\theta)$$

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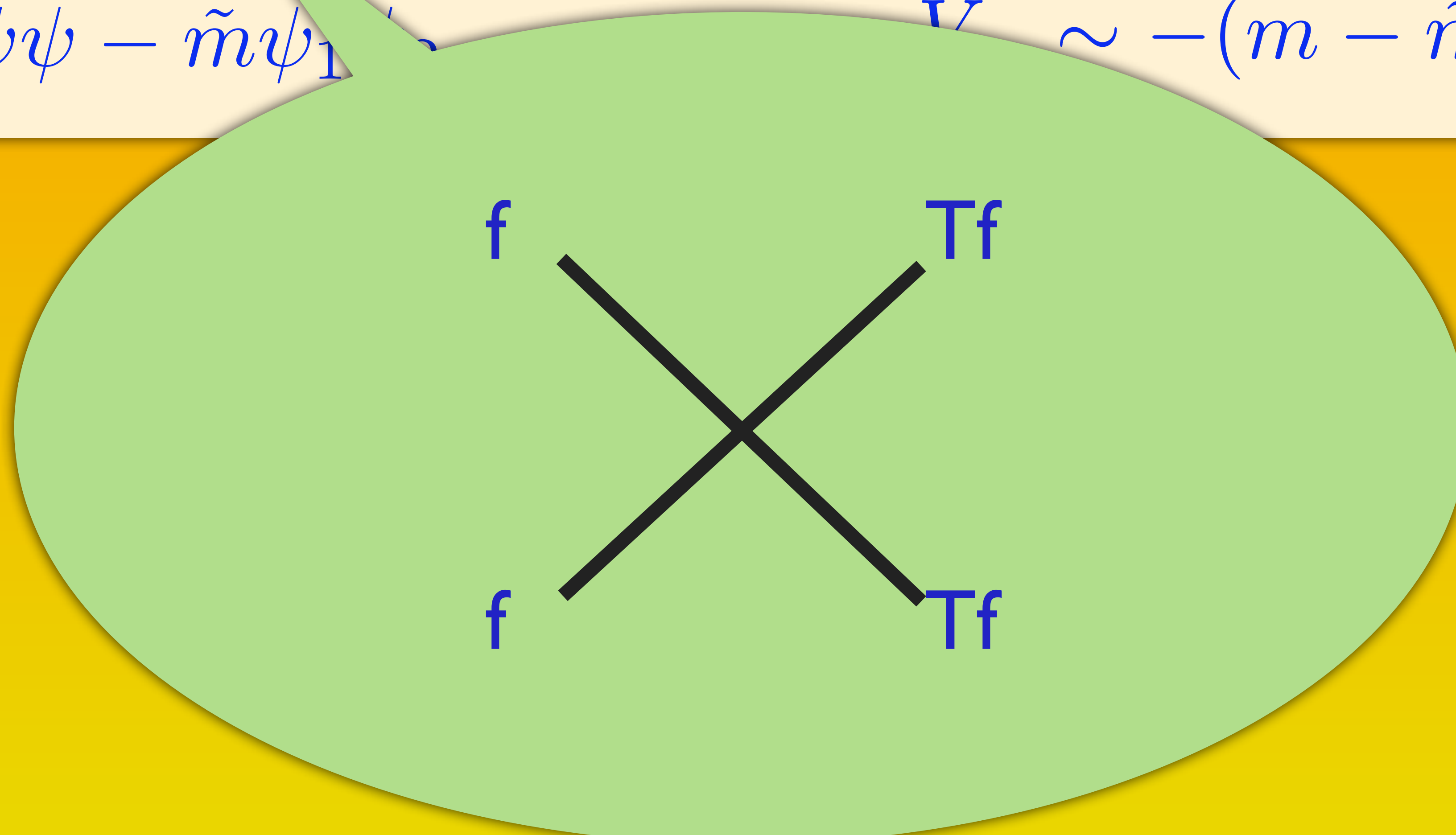

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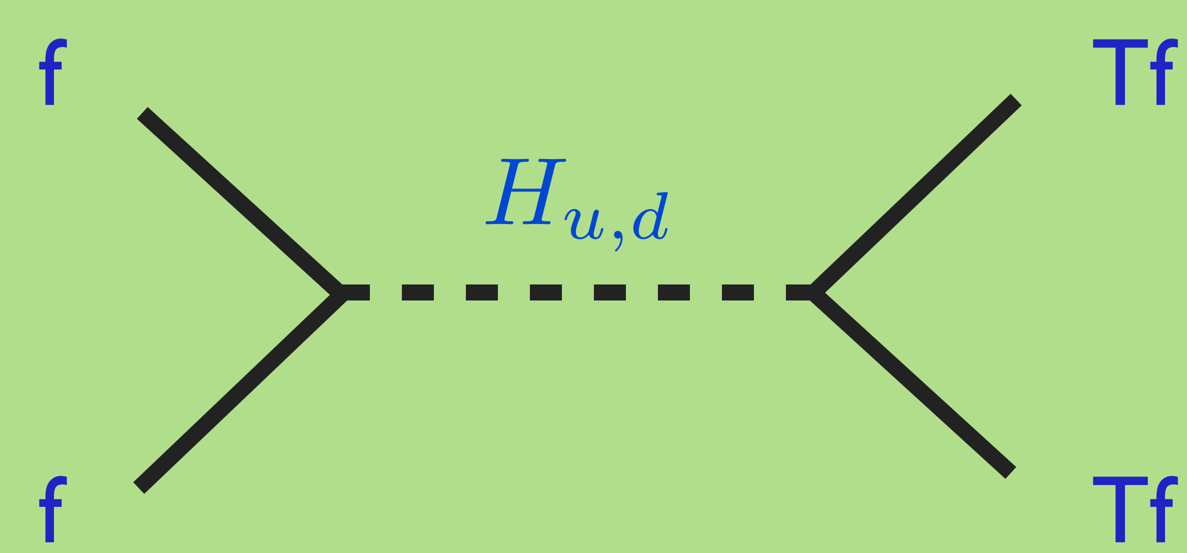
$$V_t \sim -\sin^2(\theta)$$

$$V \sim -(m-\tilde{m})\cos(\theta)$$



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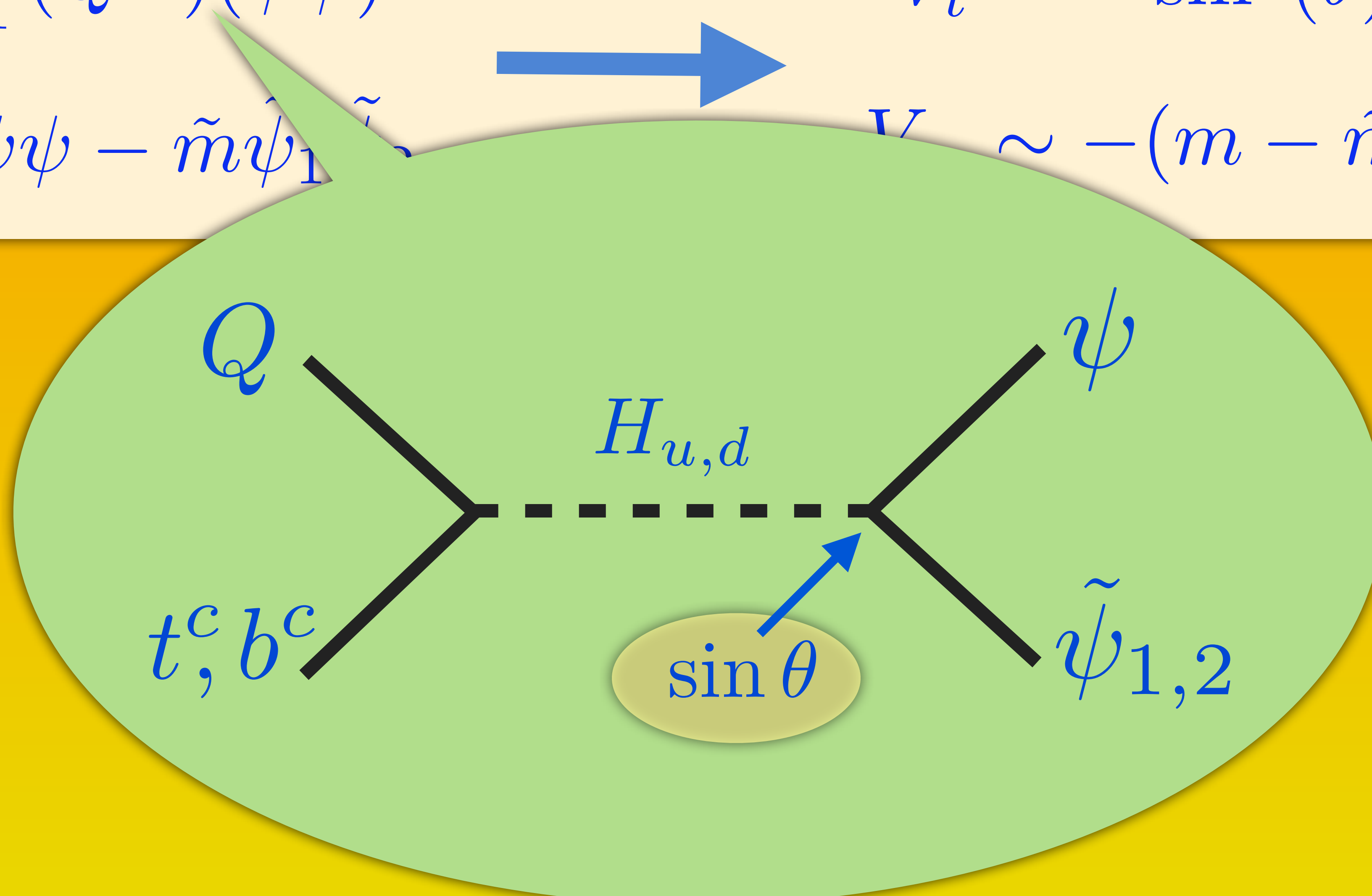

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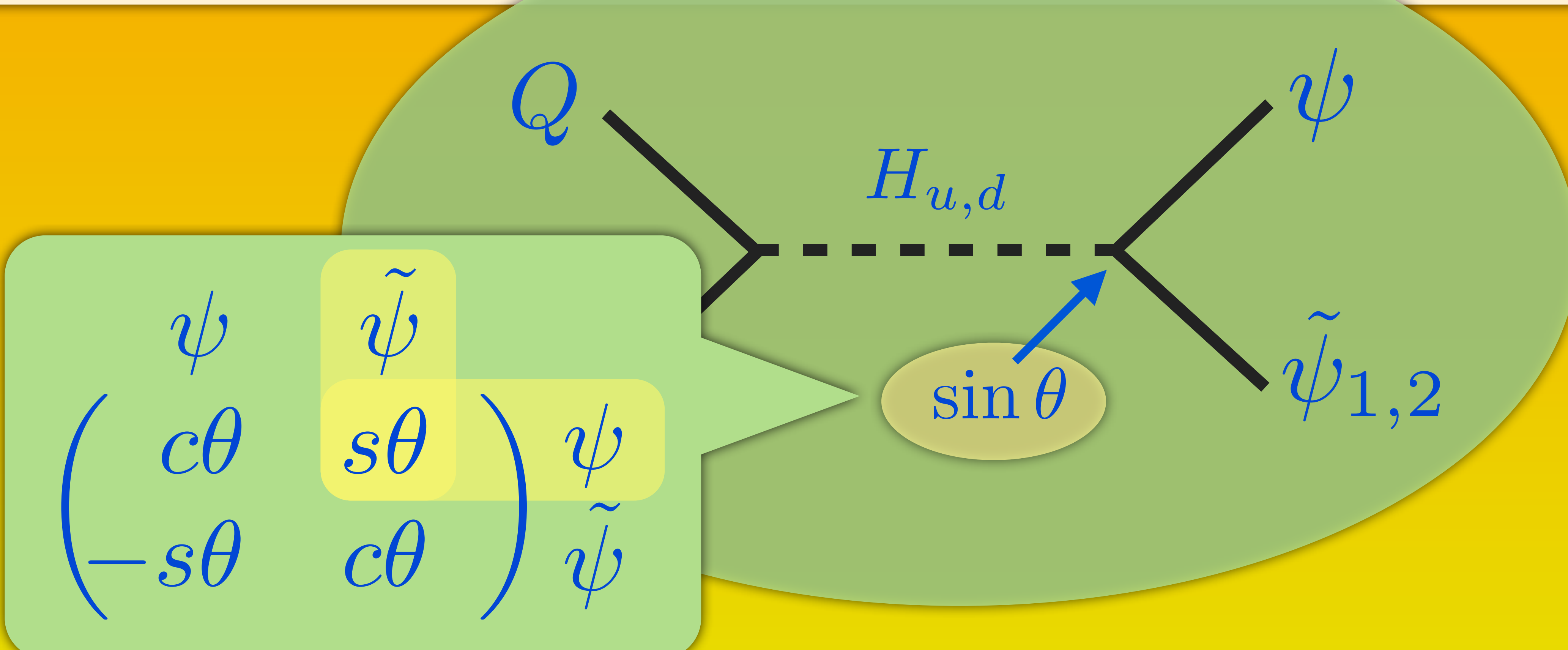

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Effective Potential: Top loops and technifermion masses

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$$\Delta\mathcal{L} = -m\psi\psi - \tilde{m}\tilde{\psi}_1\tilde{\psi}_2$$

$\longrightarrow$

$$V_t \sim -\sin^2(\theta)$$

$$V_m \sim -(m-\tilde{m})\cos(\theta)$$

$$\begin{array}{cc} \psi & \tilde{\psi} \end{array}$$

$$\begin{pmatrix} c\theta & s\theta \\ -s\theta & c\theta \end{pmatrix} \begin{array}{c} \psi \\ \tilde{\psi} \end{array}$$

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Effective Potential: Top loops and technifermion masses

$$\Delta\mathcal{L} = \frac{g_t^2}{\Lambda_t^{d-1}}(Qt^c)(\psi\tilde{\psi})$$

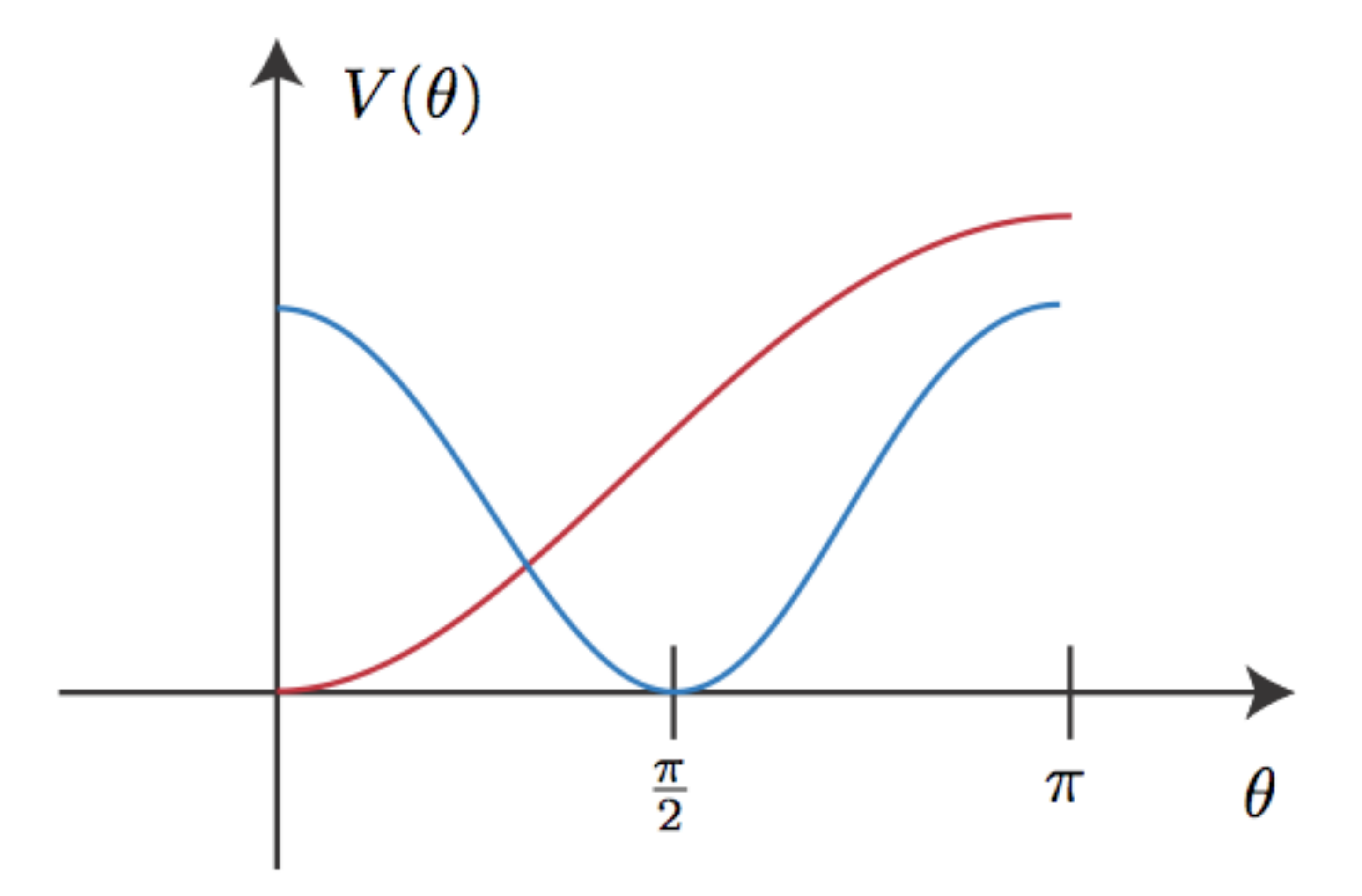
$$\Delta\mathcal{L} = -m\psi\psi - \tilde{m}\tilde{\psi}_1\tilde{\psi}_2$$

$$\longrightarrow$$

$$V_t \sim -\sin^2(\theta)$$

$$V_m \sim -(m-\tilde{m})\cos(\theta)$$

We can finally find a minimum between the technicolor vacuum and the EW preserving vacuum!



Effective Potential: Minimum and vacuum alignment

$$V = -C_m(m-\tilde{m})\cos(\theta) - C_t\sin^2(\theta)$$

$$V_{min} \rightarrow \cos(\theta) = \frac{C_m(m-\tilde{m})}{C_t}$$

Two important consequences!

$$m_h^2 = N_c c_t m_t^2$$

- Completely independent of θ!
- Calculable!

$$m_A^2 = \frac{m_h^2}{\sin^2(\theta)}$$

- Decouples for $\sin(\theta) \sim 0$

Minimal Conformal Technicolor

Standard Model (and not) couplings, A decay rate

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SM-phobic Higgs!
but maybe
hard to see

$$\Gamma_{AV_1V_2} = \frac{g^2_{AV_1V_2}}{32\pi}\left[m_A^2 - (m_{V_1}+m_{V_1})^2\right]^{\frac{3}{2}}$$
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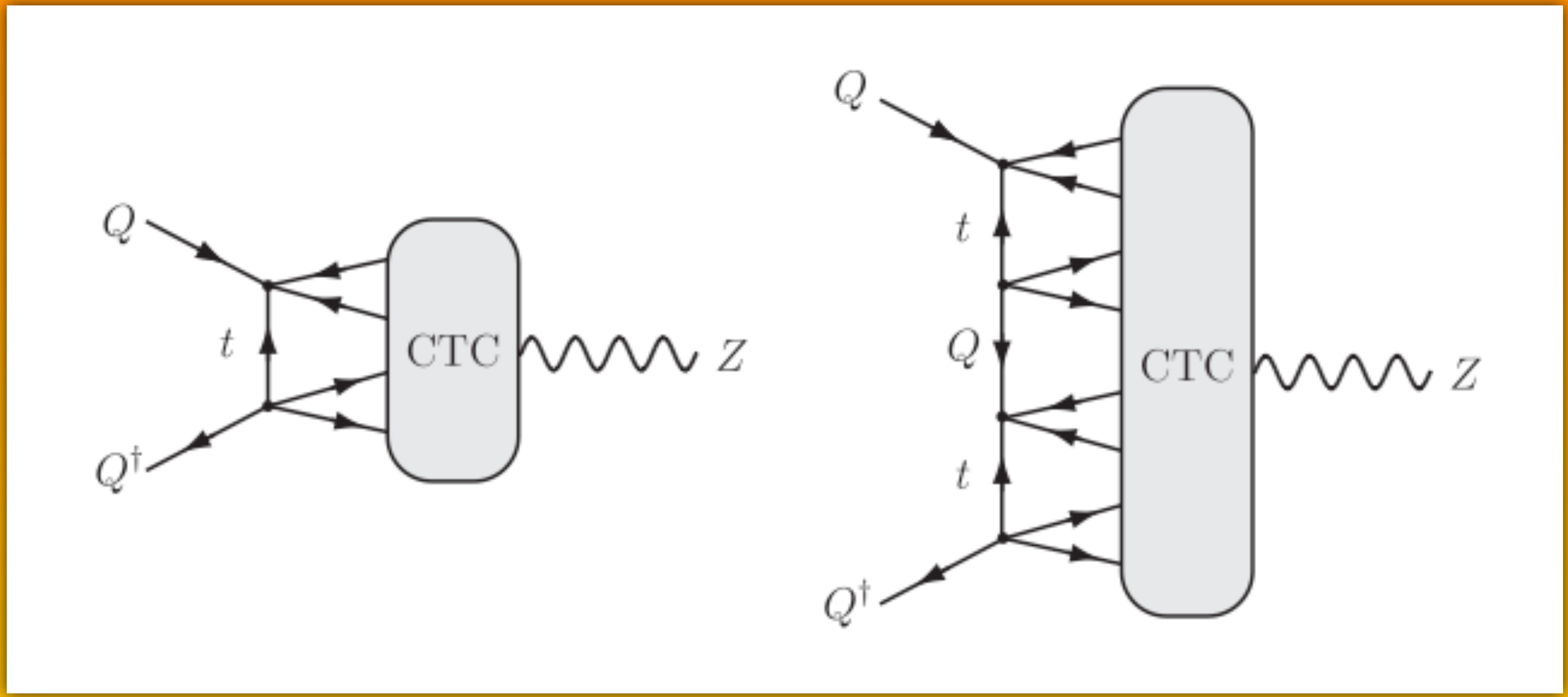
Minimal Conformal Technicolor

Electroweak precision tests:

$Z \longrightarrow b\bar{b}$



- The "first" order diagram vanishes
- The "second" order gives a contribution:

$$\frac{\Delta g_{Zb\bar{b}}}{g_{Zb\bar{b}}} \sim \left(\frac{m_t}{4\pi v}\right)^4 \sin^2\theta \sim 10^{-5}\sin^2\theta$$

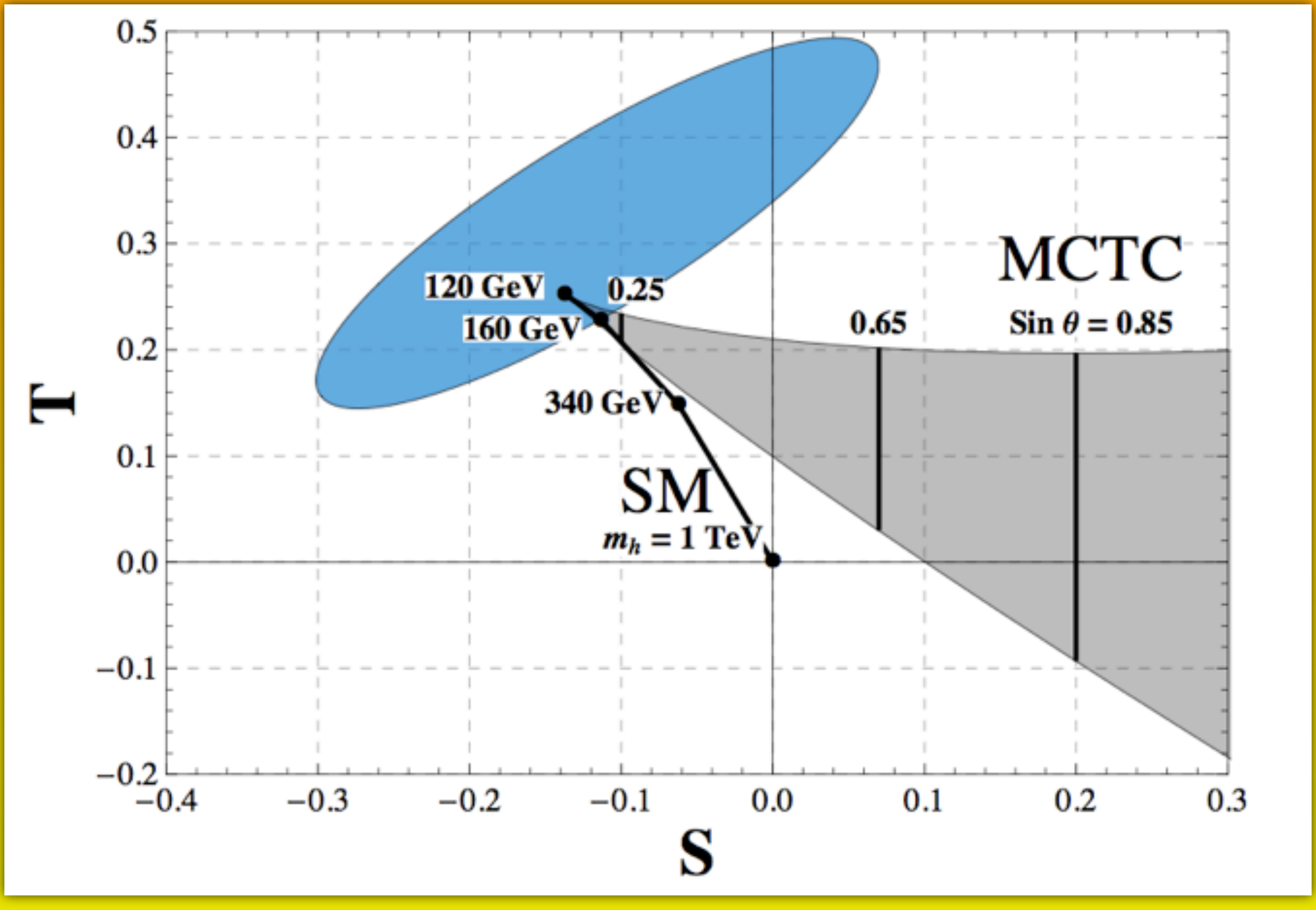
- No danger from Zbb!

Minimal Conformal Technicolor

Electroweak precision tests: S and T

$$S = \sin^2(\theta) S_0 + \cos^2(\theta) \frac{1}{6\pi} \log\left(\frac{m_h}{m_{h,ref}}\right)$$

$$T = \sin^2(\theta) T_0 - \cos^2(\theta) \frac{3}{8\pi c_w^2} \log\left(\frac{m_h}{m_{h,ref}}\right)$$



Good if $\theta \lesssim 0.25$!

Minimal Conformal Technicolor

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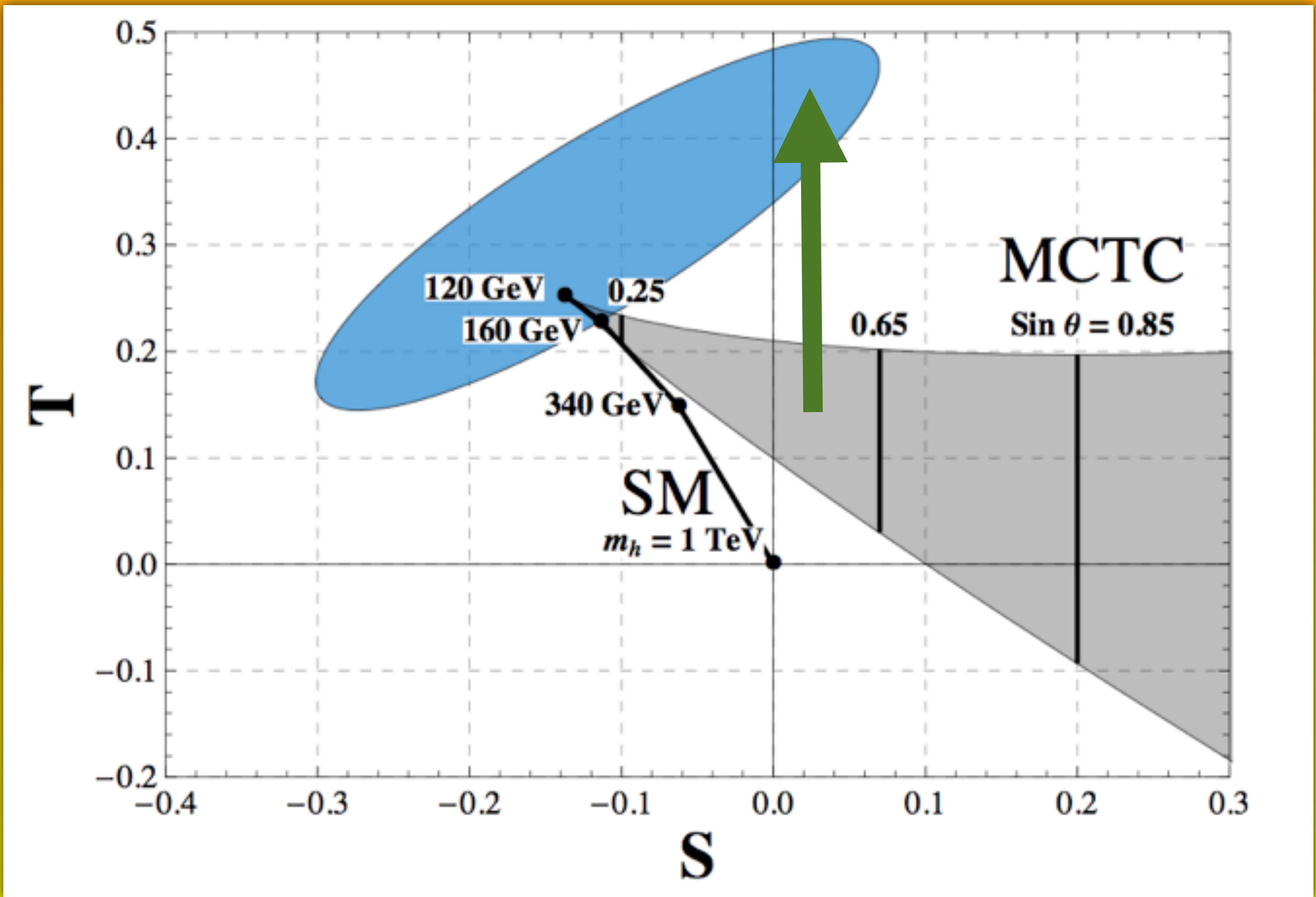


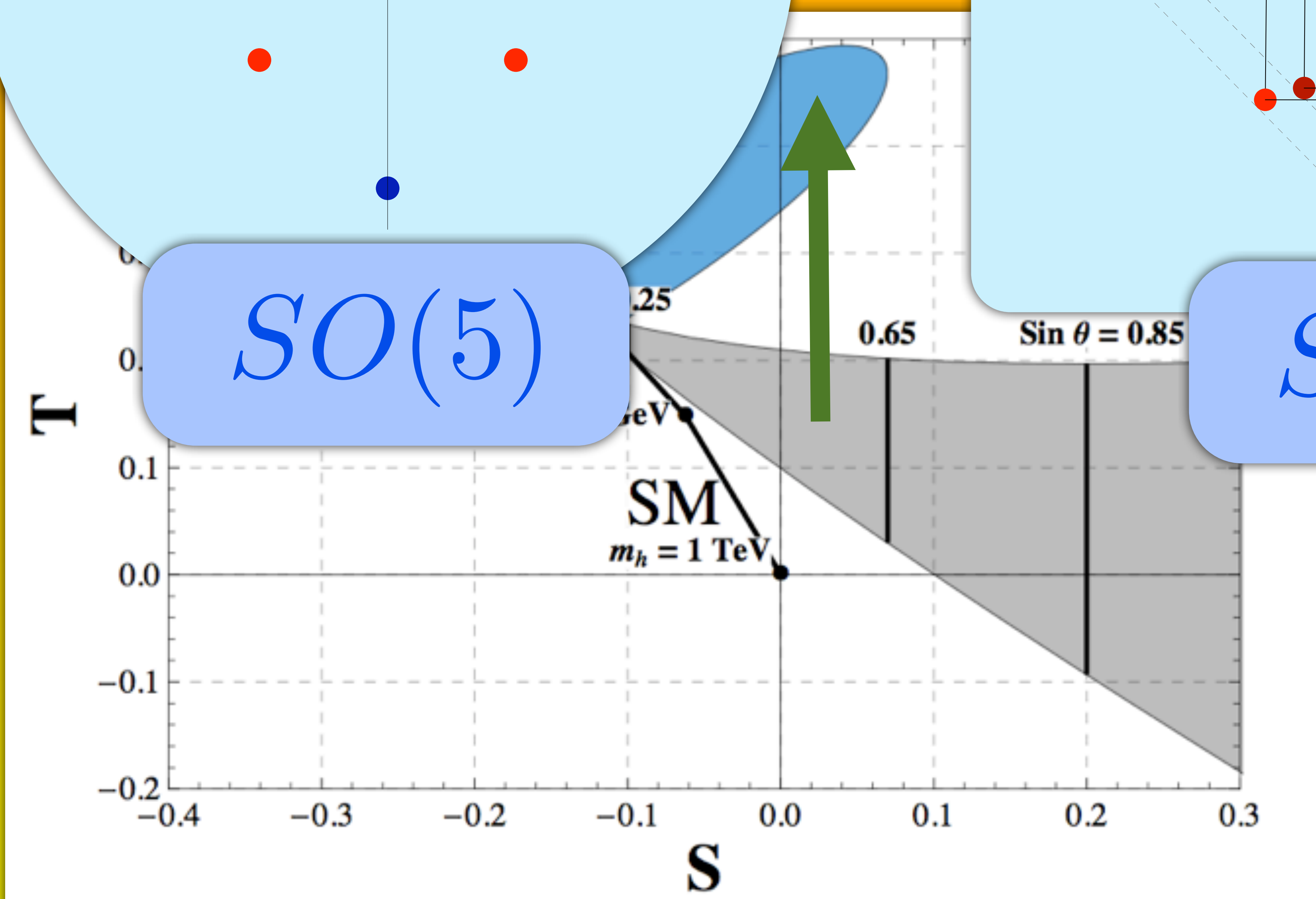
Good if $\theta \lesssim 0.25$!

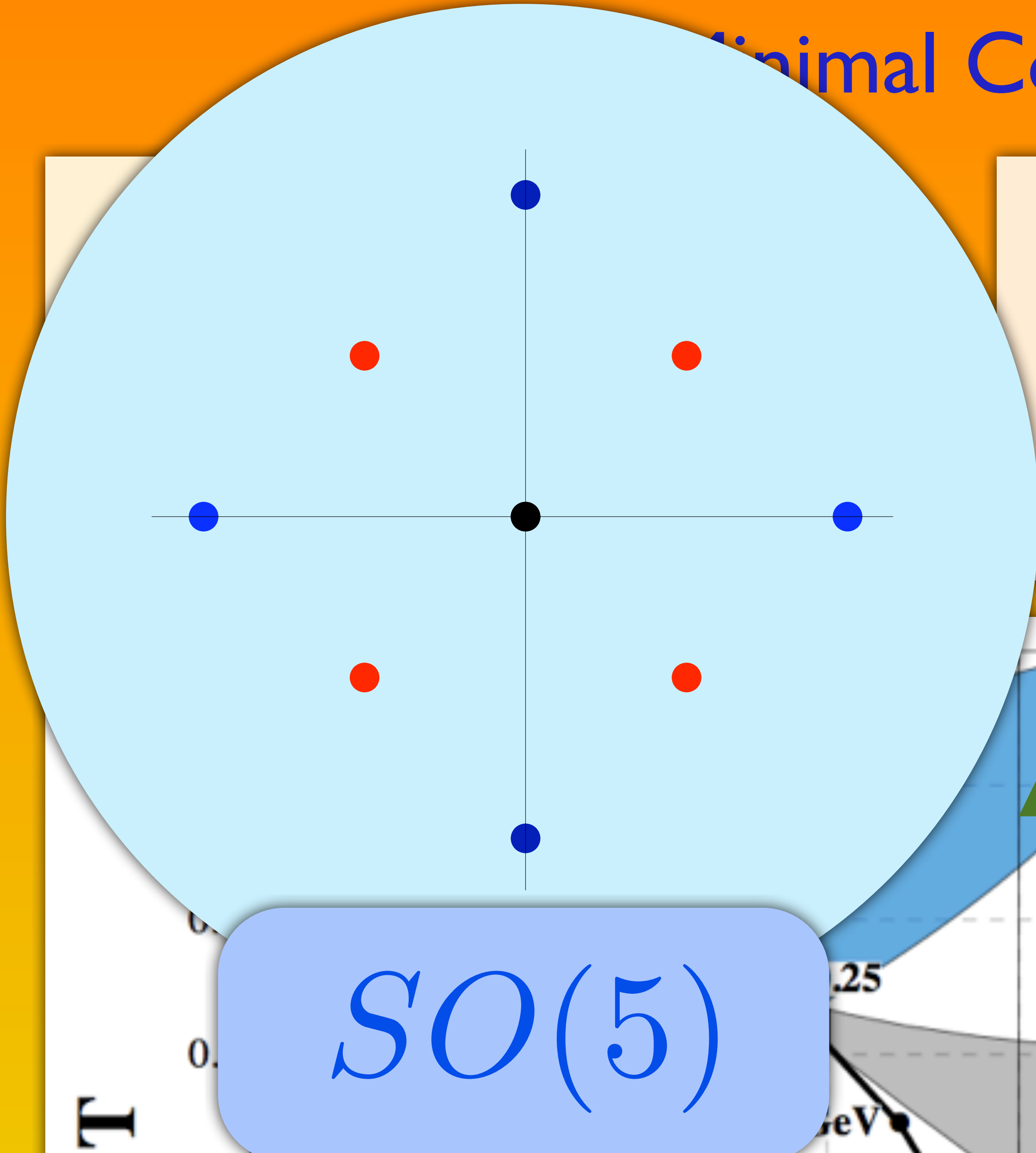
or even more if T is larger!

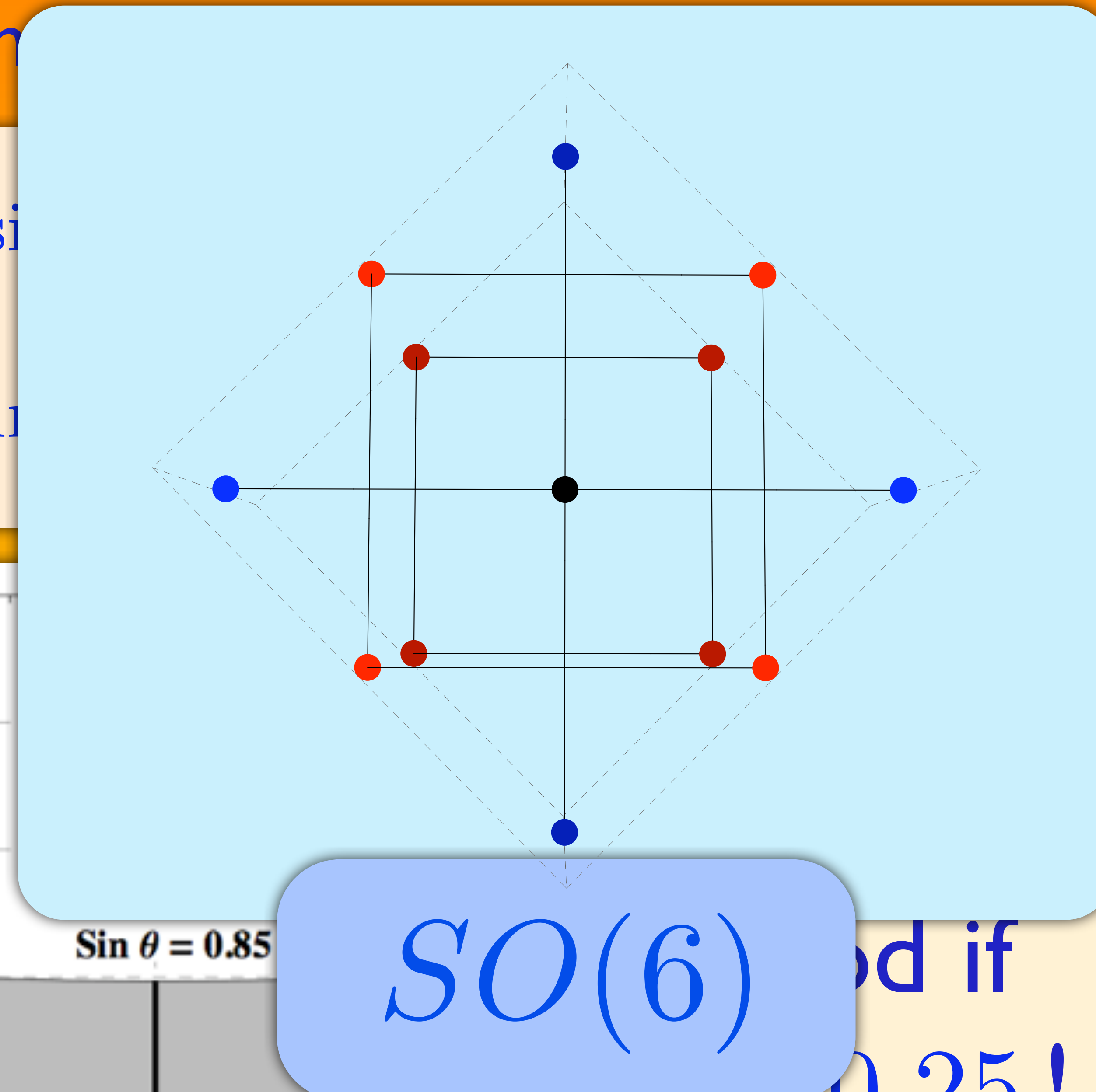
...inimal Conform...

$S = \mathrm{si}$...

$T = \mathrm{si}$...







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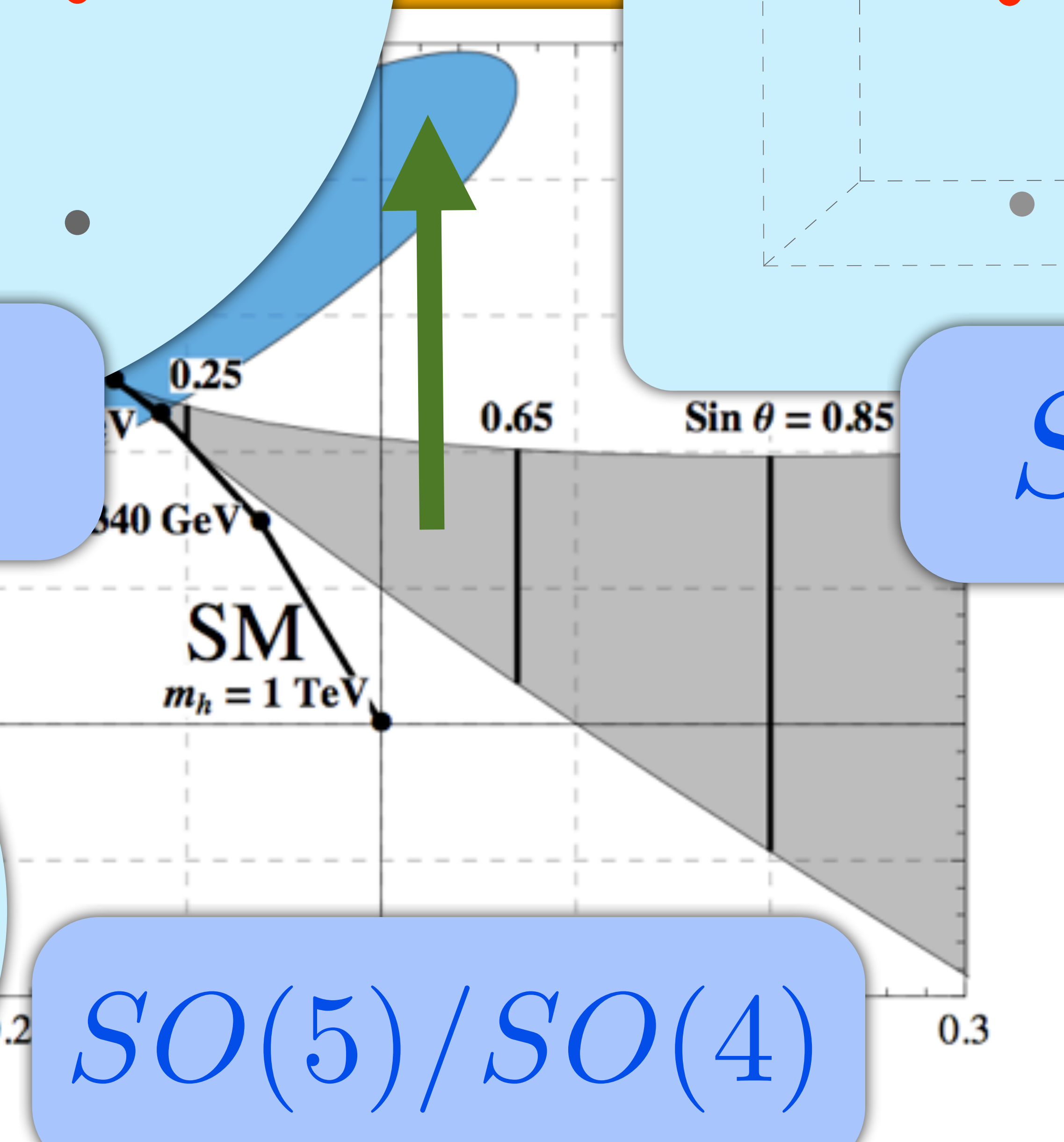

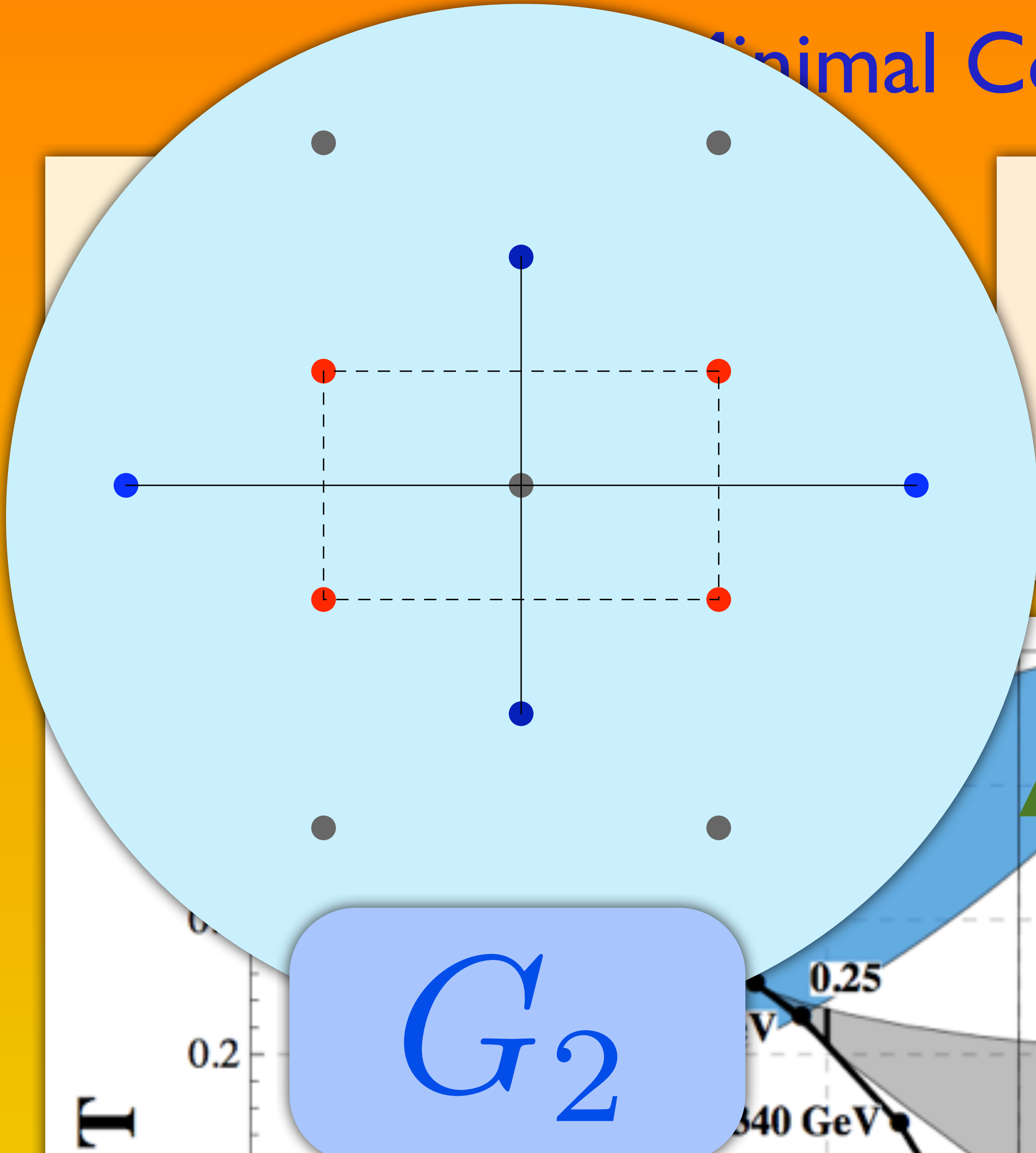

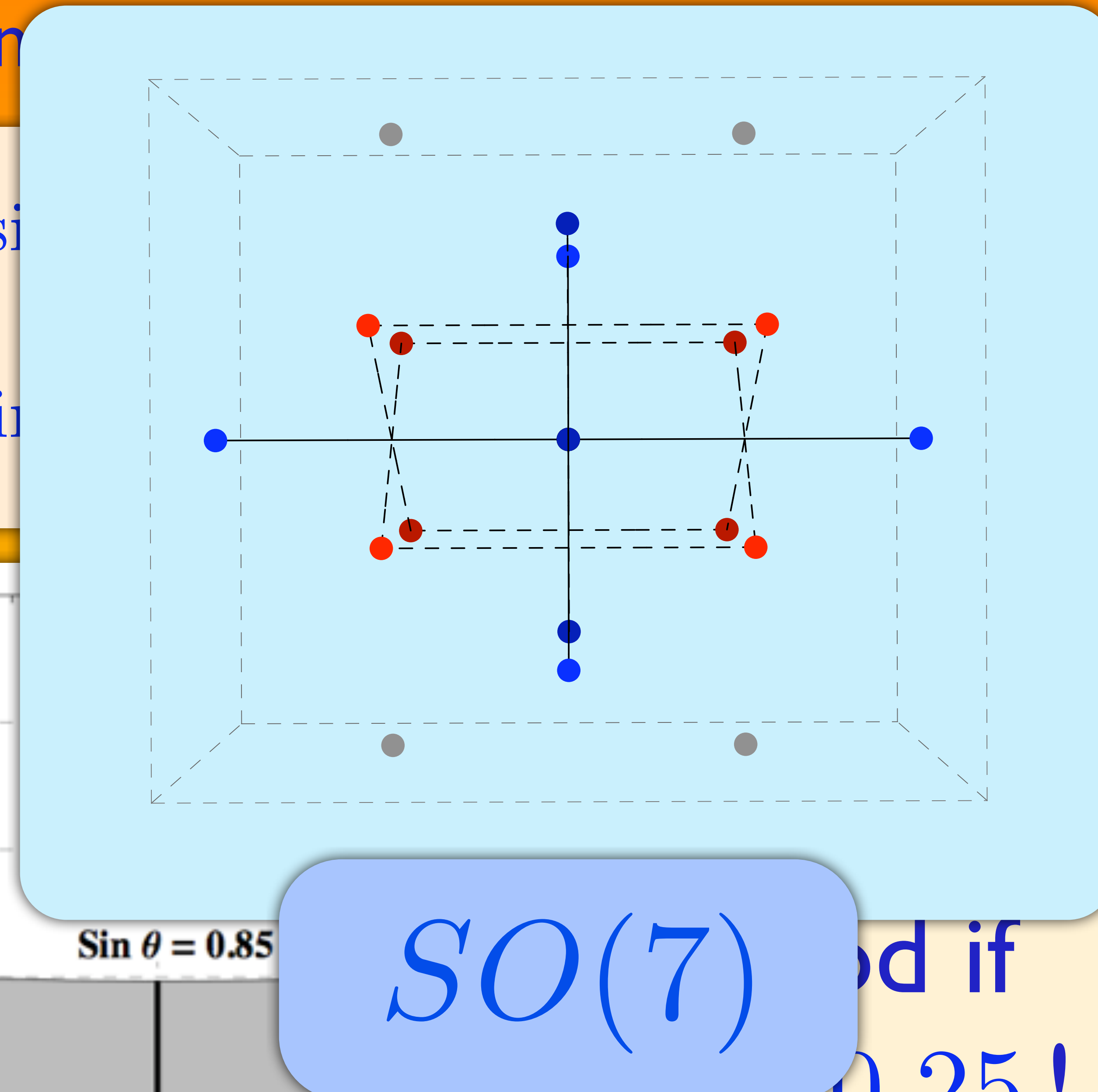

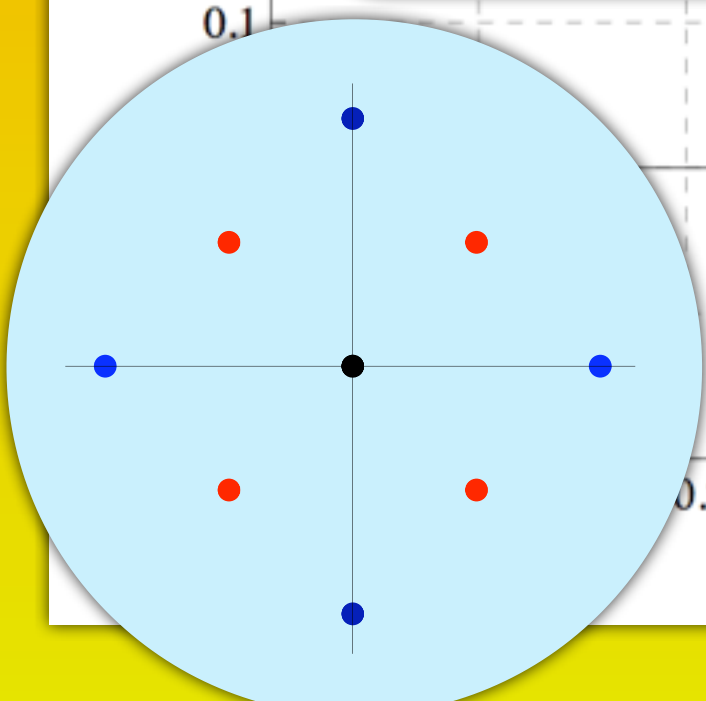

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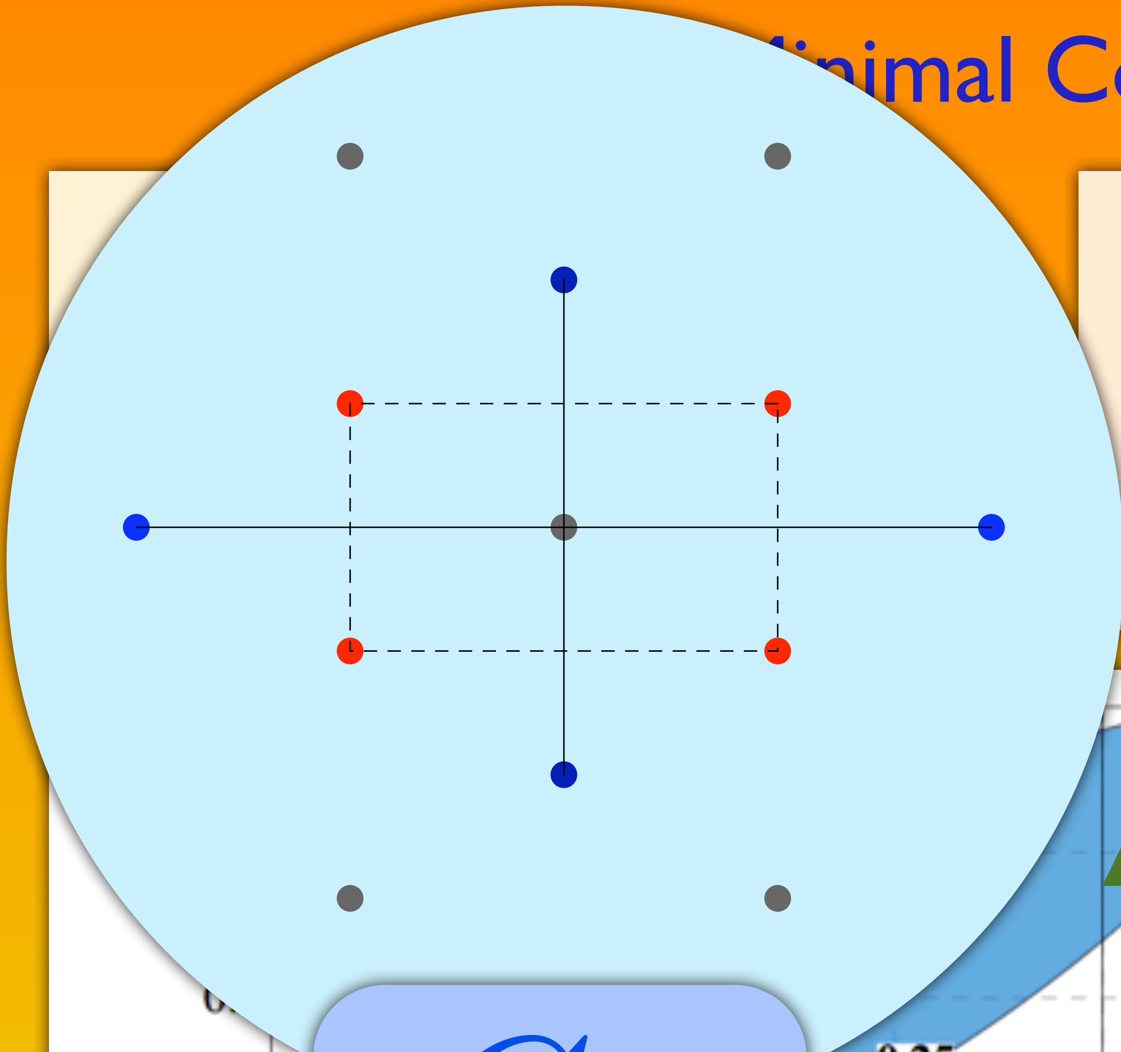

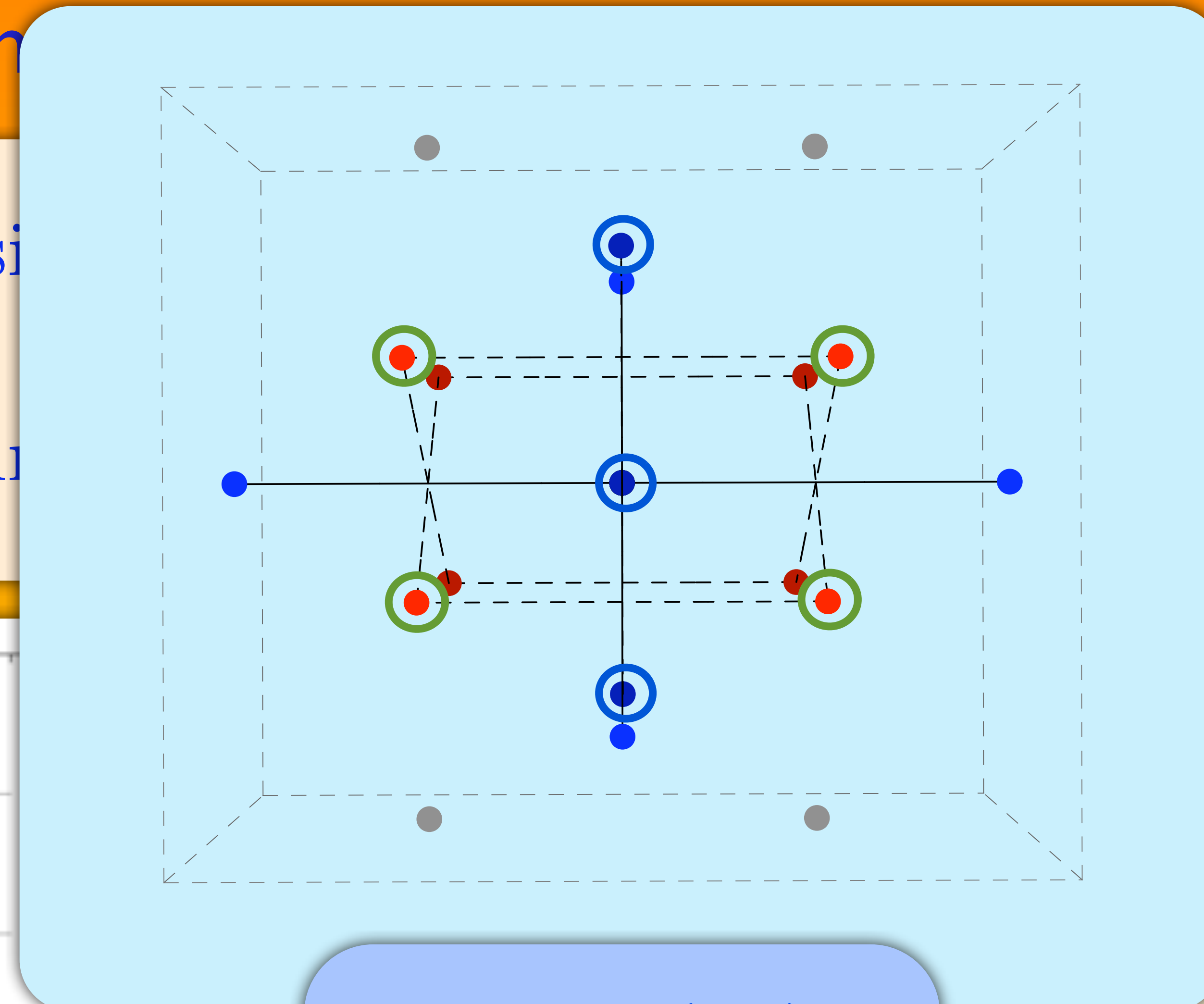

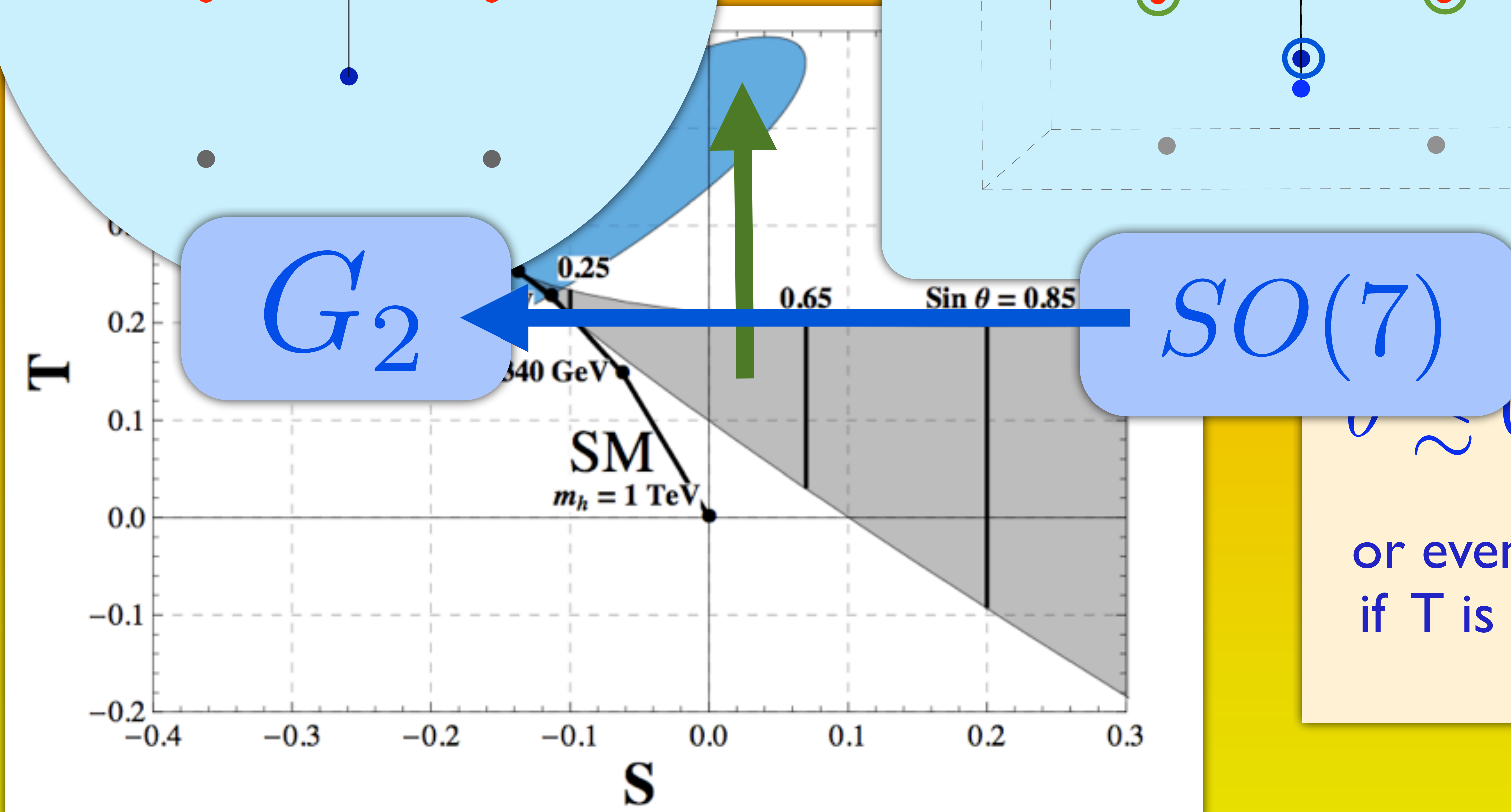

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Minimal Conformal Technicolor

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A little SM-phobic but hard to see

$$\cos\theta \gtrsim 0.95$$

$$\Gamma_{AV_1V_2} = \frac{g^2_{AV_1V_2}}{32\pi}\left[m_A^2 - (m_{V_1}+m_{V_1})^2\right]^{\frac{3}{2}}$$

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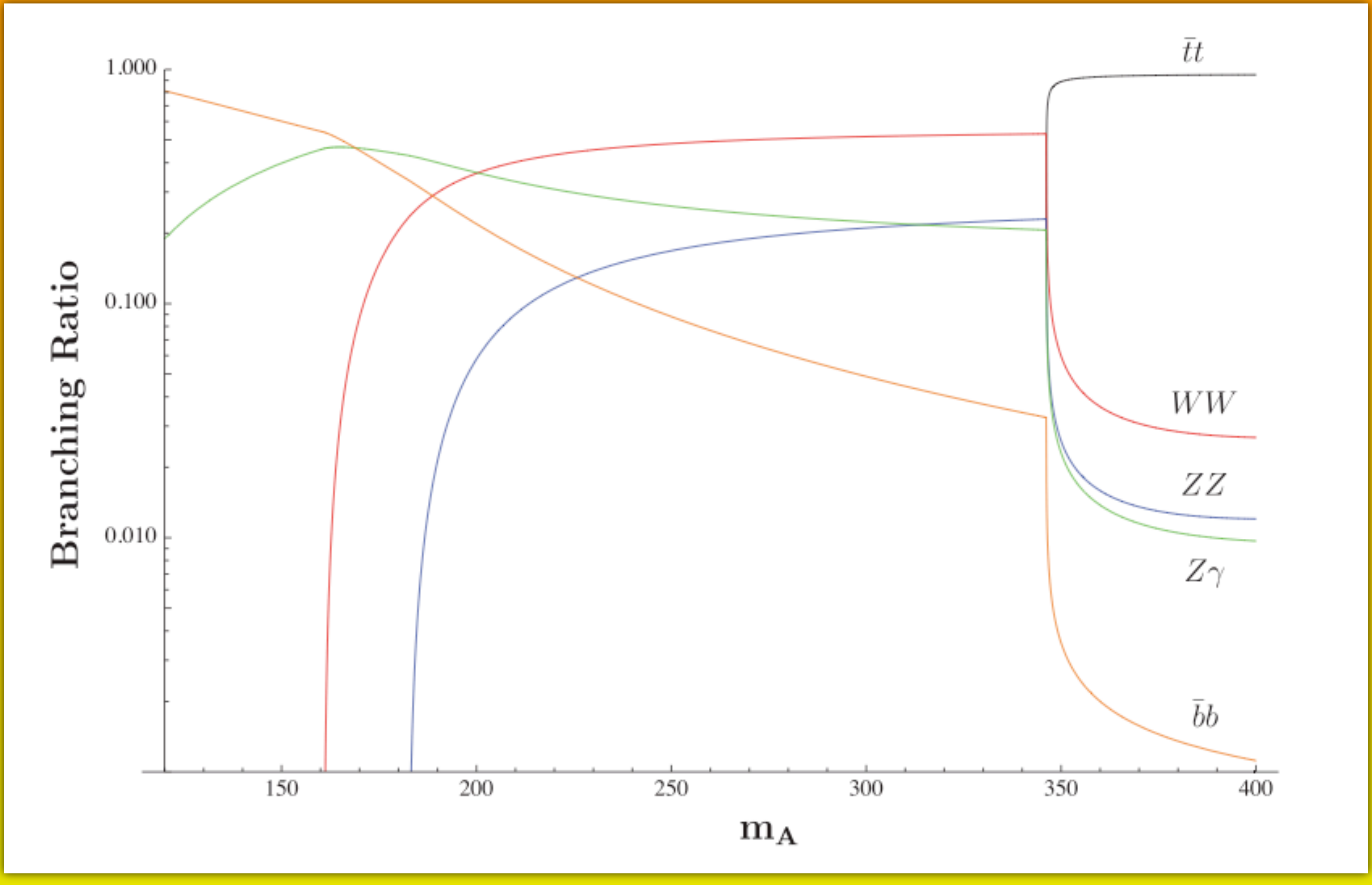
Minimal Conformal Technicolor

Branching ratio for A decays



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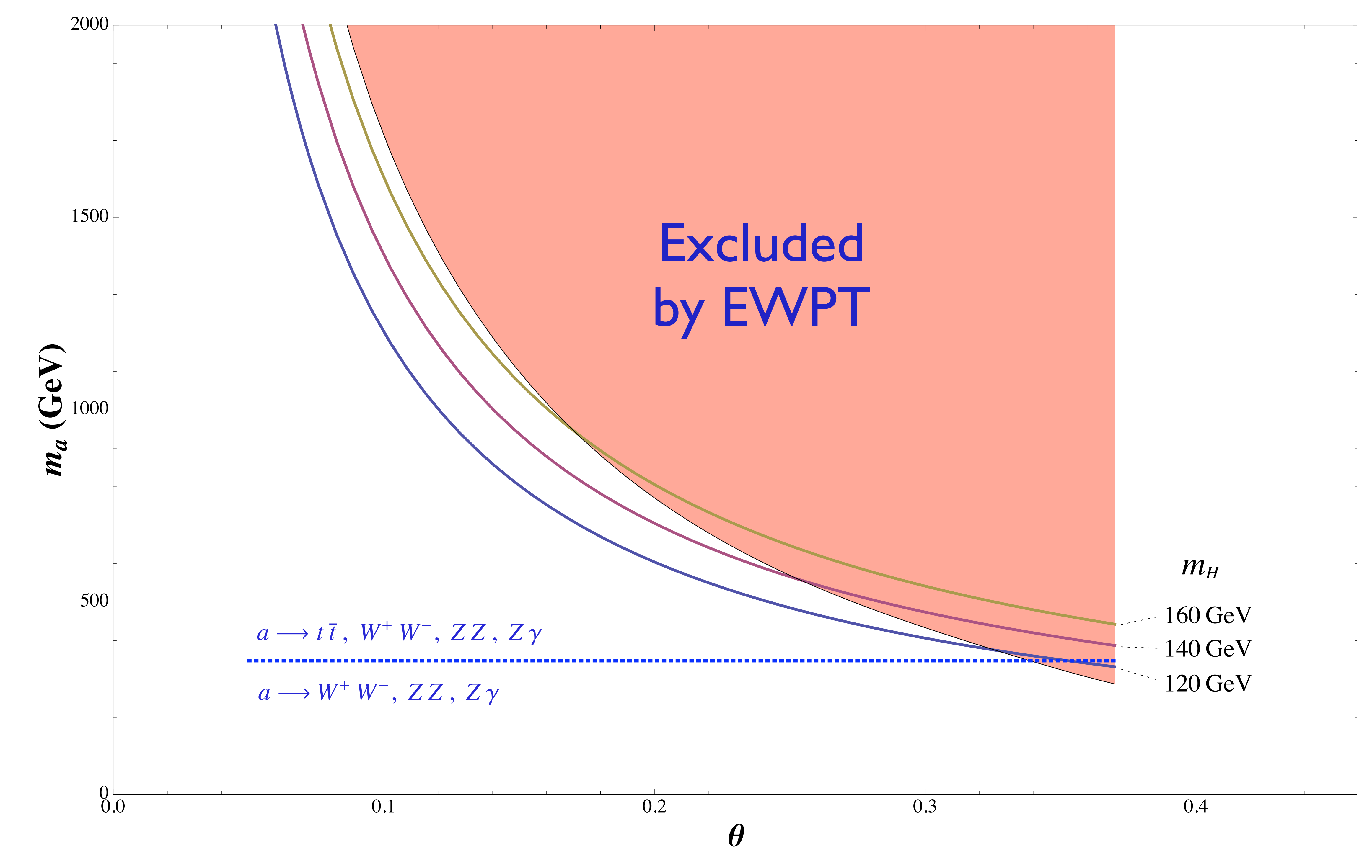
Constraints for the mass of A from EWPT



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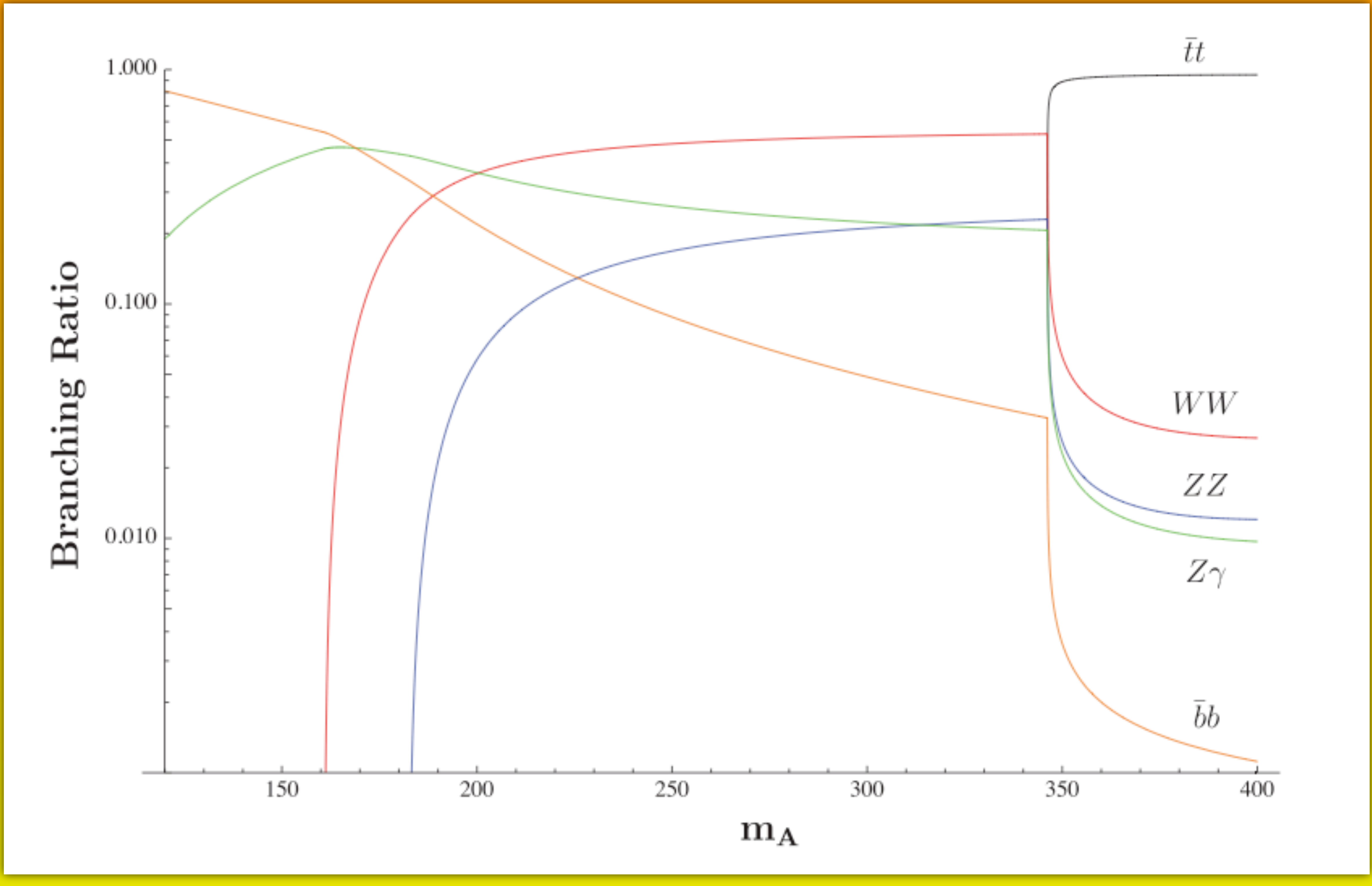

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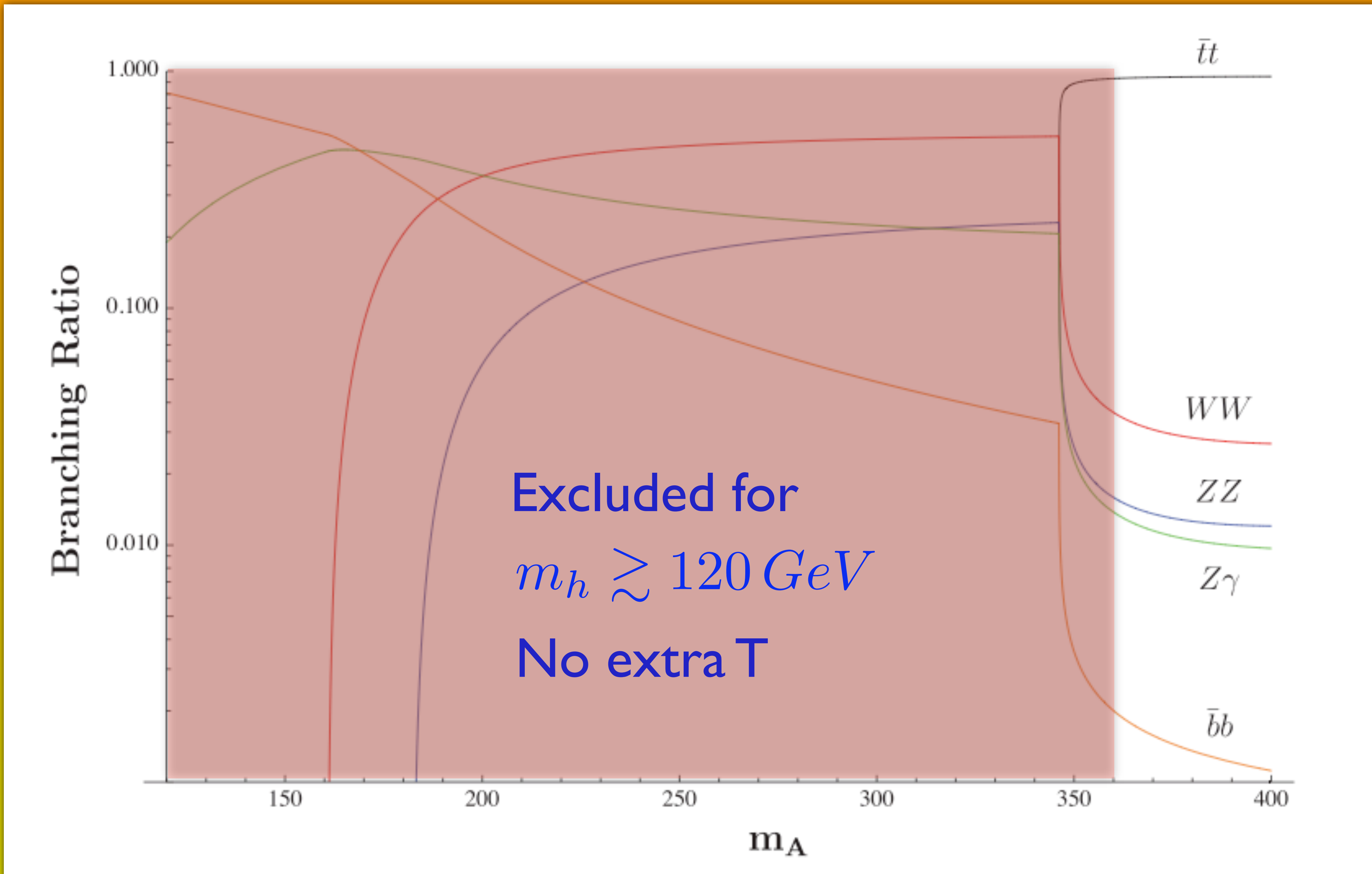
Branching ratio for A decays after EW constraints



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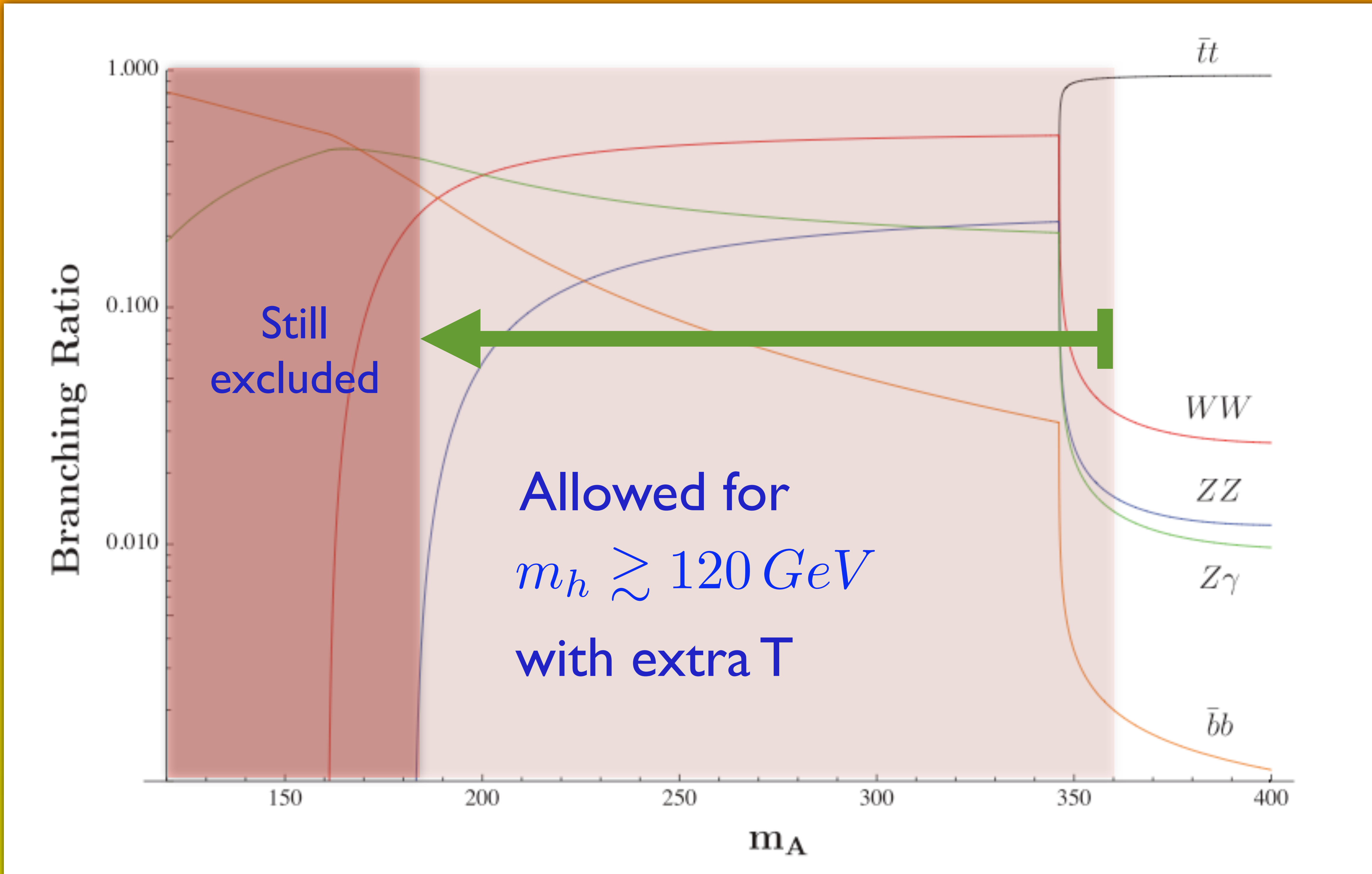

Minimal Conformal Technicolor

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More SM-phobic still hard

$$\cos\theta \geq 0.8$$

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Minimal Conformal Technicolor

Standard

$$\frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\left(1+2a\frac{h}{v}+b\frac{h^2}{v^2}+\ldots\right)$$

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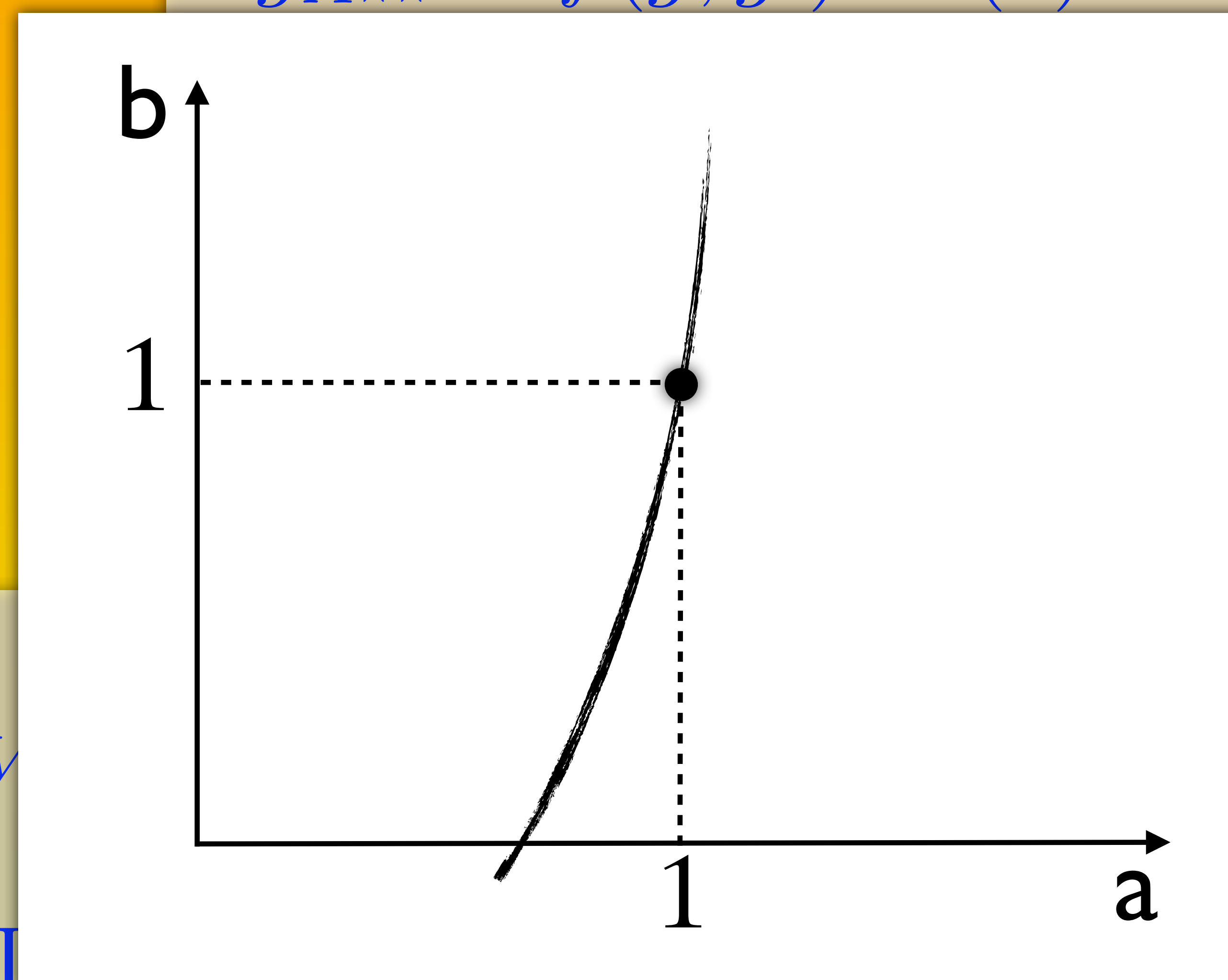

More SM-phobic still hard

$$\cos\theta \geq 0.8$$

Γ_{AV_1V} ... $)^2]^{\frac{3}{2}}$

Γ_{Aff} ... 8π

Conclusions

Results

- It's a 4D model
- It works! (EWPT...)
- It's a composite Higgs
- Has minimal fine tuning
- Strong dynamics is still viable
- There is a pseudoscalar A that might give a signal

Things to do

- A 5D model (here with an elementary top quark)
- More work on strong conformal theories with N~1
- More phenomenology of the model for LHC
- Supersymmetric extension

Minimal Conformal Technicolor

Supersymmetric extensions: WHY???

- need a stable scalar for the Bosonic TC interaction

- but in SUSY we need a big top Yukawa (strong)

$$m_t \sim 4\pi v \left(\frac{y_t}{4\pi}\right)\left(\frac{y_{\rm TC}}{4\pi}\right)\left(\frac{4\pi f}{M_{\rm SUSY}}\right)^{d-1}$$

- Problems: FCNCs ⟶ of course... very bad headaches!

Minimal Conformal Technicolor

Supersymmetric extension I: Topcolor-like

	$SU(3)_{tC}$	$SU(3)_{\tilde{C}}$	$SU(2)_W$	$U(1)_Y$
q_3	3	1	2	1/6
t^c	$\bar{3}$	1	1	-2/3
b^c	$\bar{3}$	1	1	1/3
q_i	1	3	2	1/6
u_i^c	1	$\bar{3}$	1	-2/3
d_i^c	1	$\bar{3}$	1	1/3
U	1	3	1	2/3
U^c	1	$\bar{3}$	1	-2/3
D	1	3	1	-1/3
D^c	1	$\bar{3}$	1	1/3
H_u	1	1	2	1/2
H_d	1	1	2	-1/2
Φ	3	$\bar{3}$	1	0
$\bar{\Phi}$	$\bar{3}$	3	1	0

- Good CKM fit
- Good FCNCs
- SUSY scale ~ 40 TeV
- Good SM masses
- MCTC at low energy

Minimal Conformal Technicolor

Supersymmetric extension II: Junk-QCD

$$SU(6) \times SU(3)_{C1} \times SU(3)_{C2}$$

- Automatic CKM fit
- Good FCNCs with a clear no-FCNC limit
- SUSY scale ~ 40 TeV
- Good SM masses
- MCTC at low energy

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LIFE IN TECHNICOLOR ii
(life in technicolor ii)