March 17th 2021
International Workshop on Future Linear Colliders

Top quark mass and physics beyond the Standard Model from Higgs Parity

Keisuke Harigaya
(Institute for Advanced Study)

Standard Model parameters at linear colliders

* Top quark mass

$\Delta m_t = O(10)$ MeV

Seidel et al. (2013), Horiguchi et al. (2013), Kiyo et al. (2015), Beneke et al. (2015)

* Strong coupling constant

$\Delta \alpha_s(m_Z) = 0.0001$

TLEP Design Study Working Group report

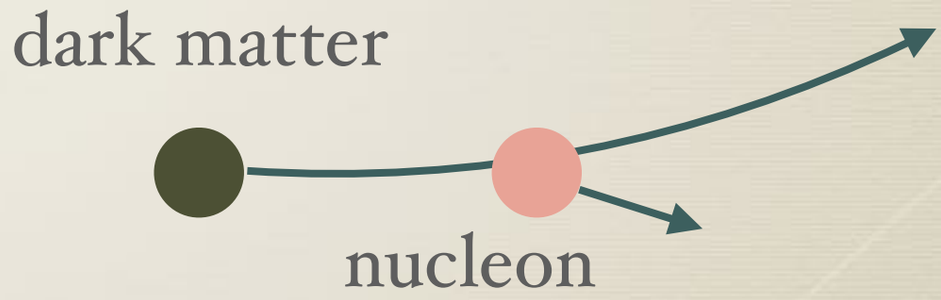
Can we learn something about Beyond the Standard Model ?

Standard Model parameters and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

Top quark mass
Strong coupling constant

Higgs Parity



Experimental signatures of new physics

Dark matter detection, proton decay, gravitational waves, dark radiation, warm dark matter, ...

Outline

* Introduction
* Higgs Parity
* Dark matter detection rate
* Summary and outlook

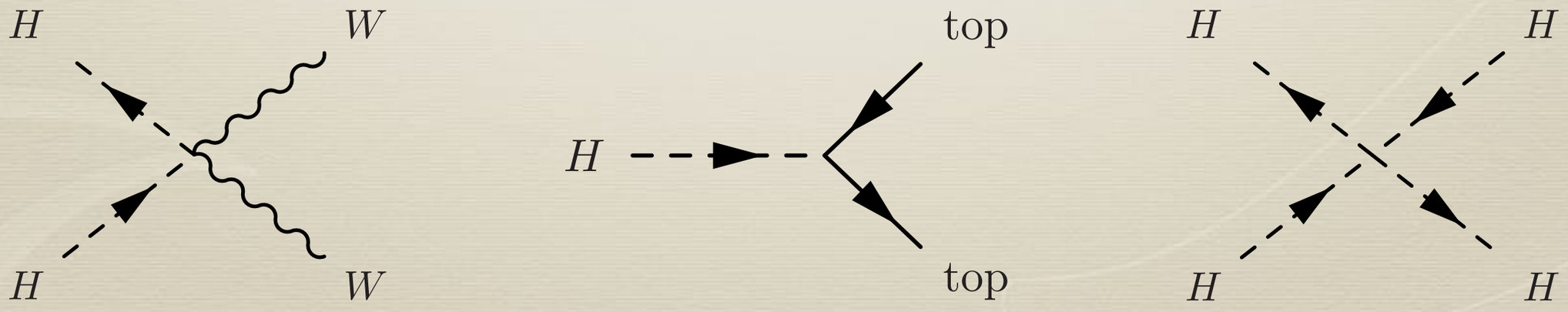
Introduction

Higgs quartic

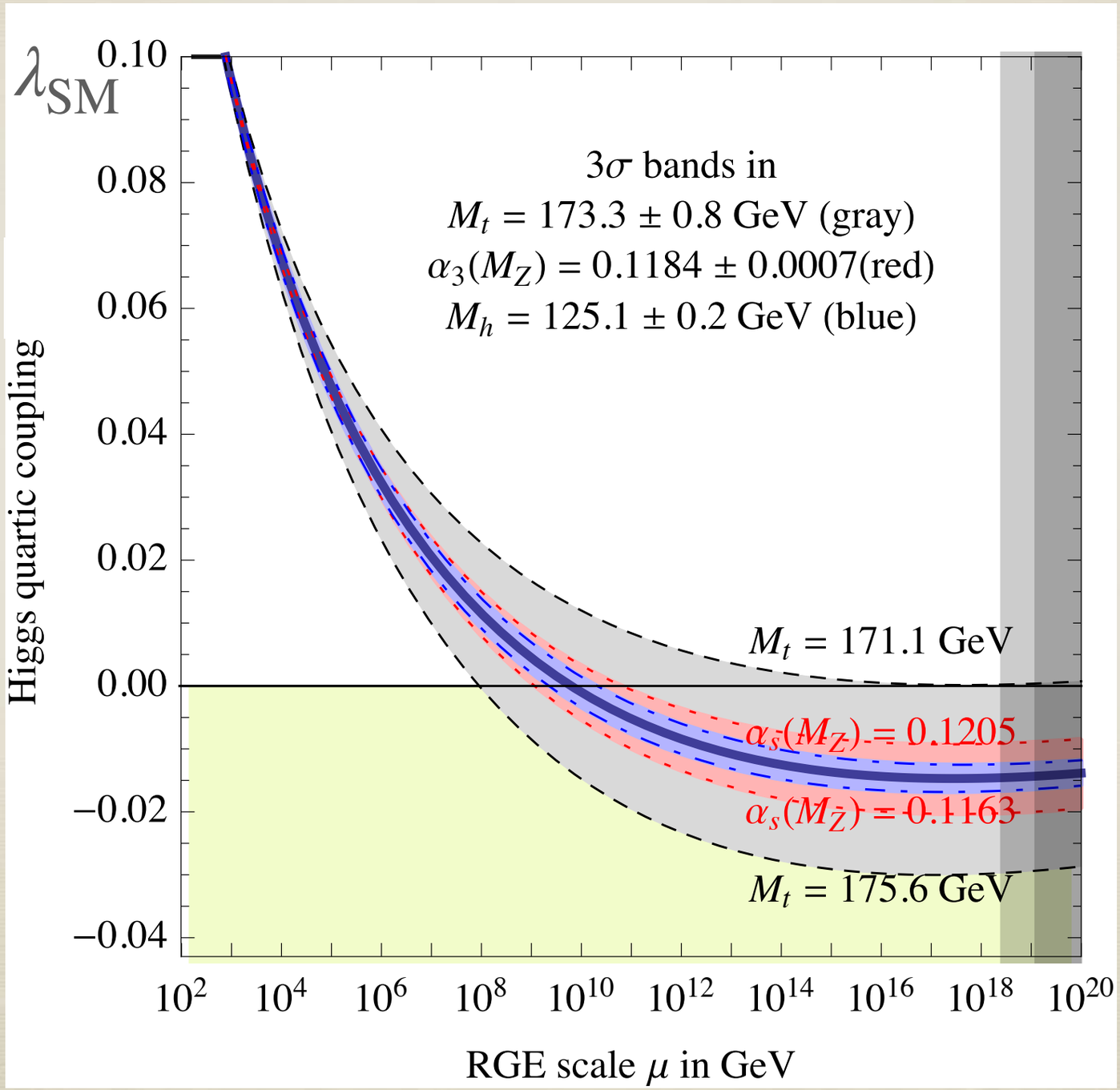
$$V(H) = \lambda_{\rm SM} \left(|H|^2 - v^2 \right)^2$$

$$m_h^2/(4v^2) \simeq 0.13$$

Let us examine the evolution of the quartic coupling
by quantum corrections,
assuming that the standard model is valid up to high energy scales

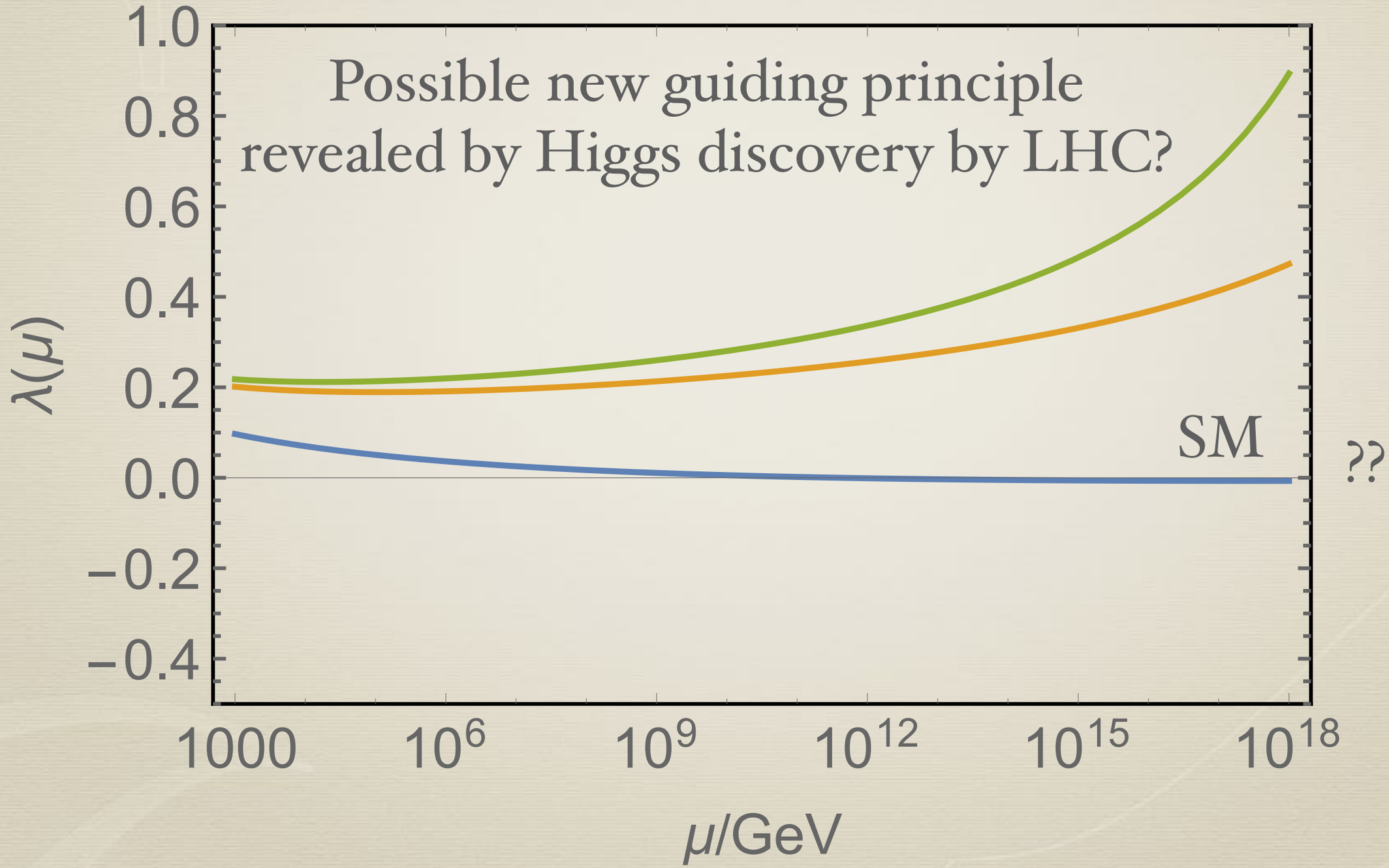


Small quartic coupling



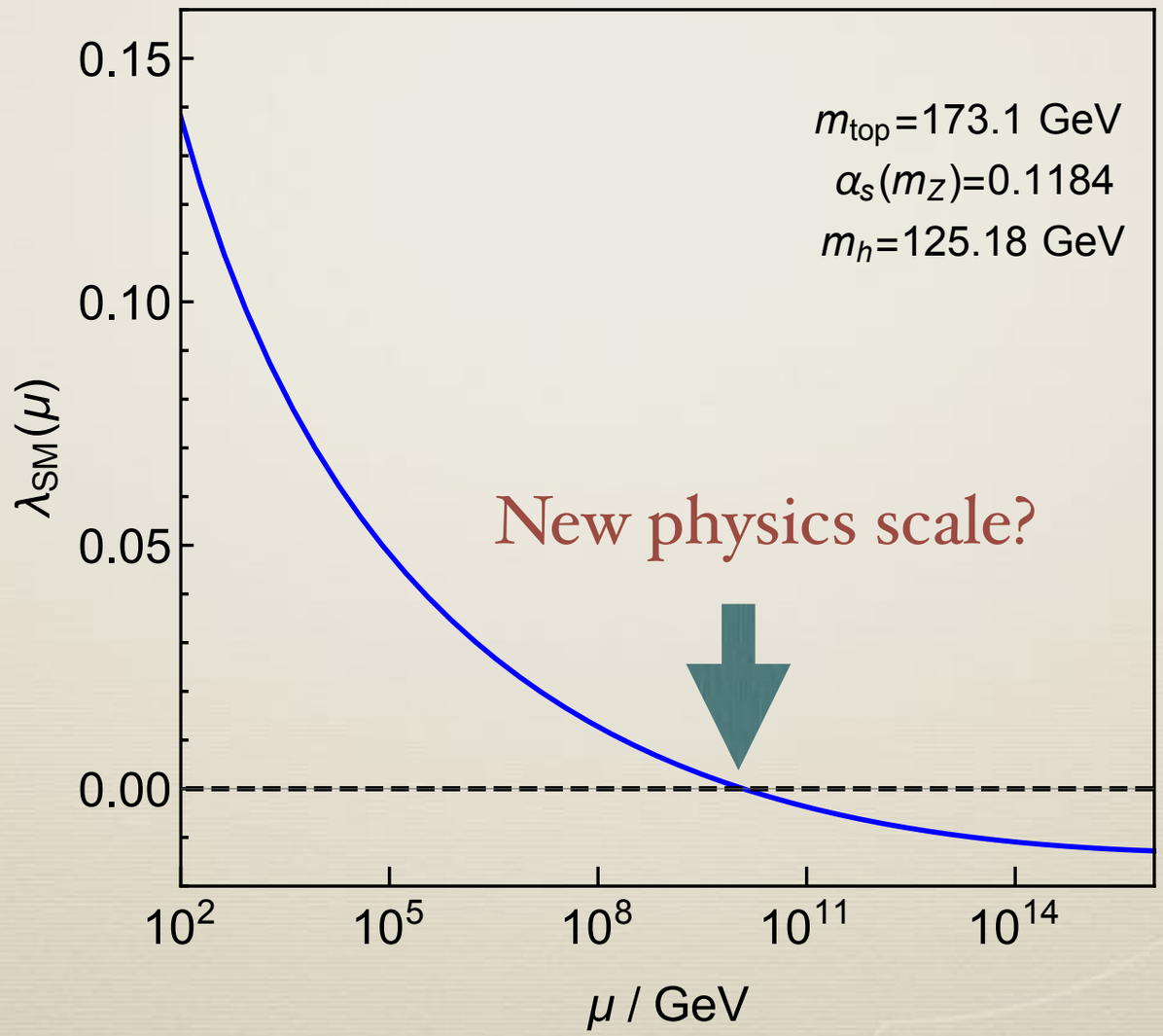
Buttazzo et.al (2013)

Small quartic coupling



New physics?

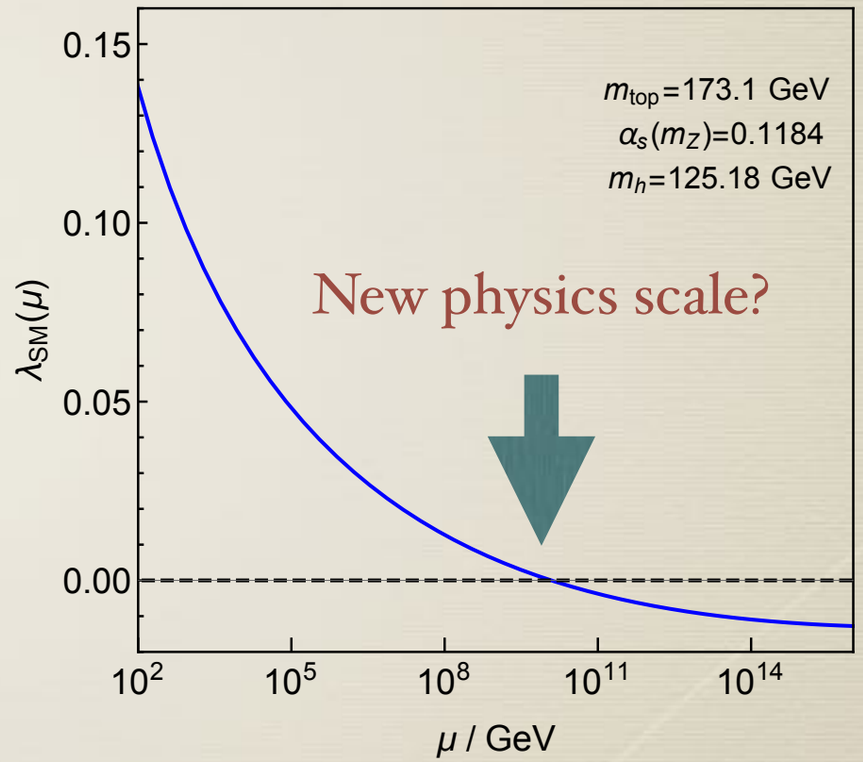
Conjecture : some new physics which couples to Higgs sets $\lambda_{SM} \simeq 0$ at a high energy scale



Standard Model parameters and new physics?

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

Top quark mass
Strong coupling constant



Scale of the new physics ⟷ Experimental signatures?

Snowmass2021 - Letter of Interest

Probing High Scale Physics via Standard Model Parameters

David Dunsky[1,2], Lawrence J. Hall[1,2], and Keisuke Harigaya[3]

[1] *Department of Physics, University of California, Berkeley, California 94720, USA*

[2] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

[3] *School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*

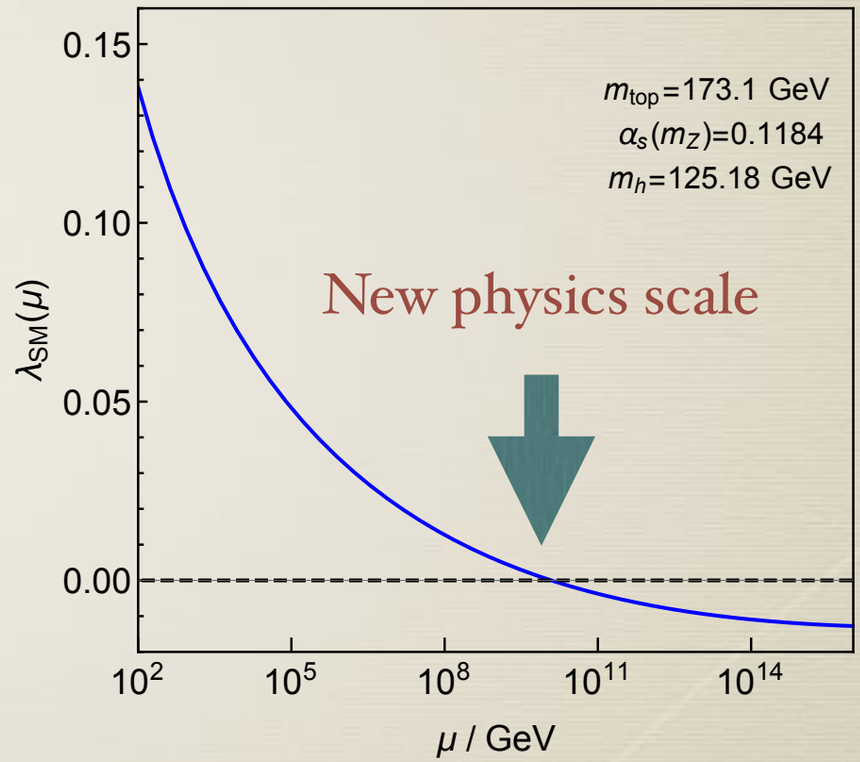
https://www.snowmass21.org/docs/files/summaries/TF/SNOWMASS21-TF8_TF5-EF3_EF5-NF3_NF0-RF4_RF0-CF1_CF3-012.pdf

PQ symmetry?
Redi and Strumia (2012)
Supersymmetry?
Hall and Nomura (2009, 2013),
Dunsky, Hall and KH (2020)
Extra dimension?
Gogoladze, Okada and Shafi (2007)

Standard Model parameters and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

Top quark mass
Strong coupling constant



New symmetry
(Higgs Parity)
breaking scale

Experimental signatures

Outline

* Introduction
* Higgs Parity
* Dark matter detection rate
* Summary and outlook

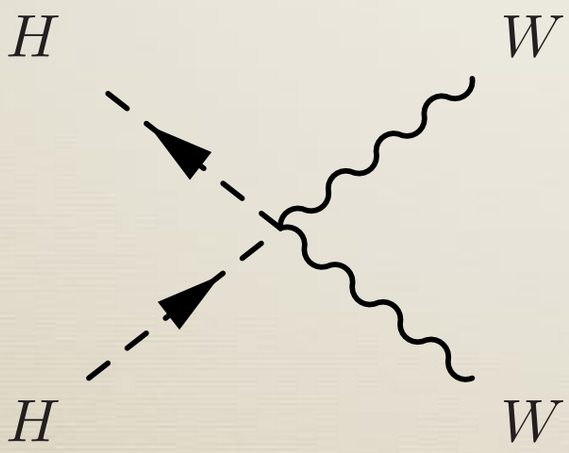
Z_2 symmetry

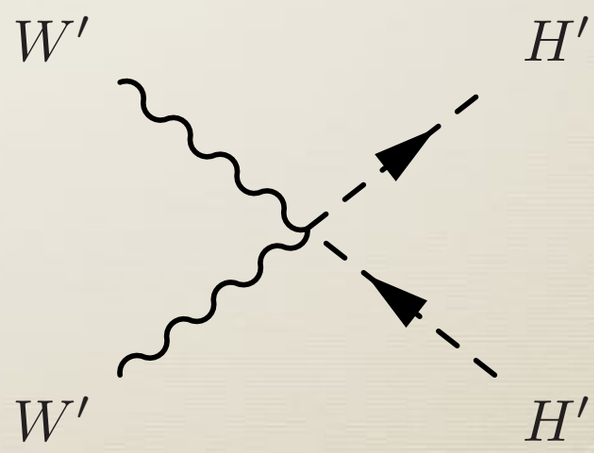
Higgs
H

Higgs'
H'

Weak gauge boson
W
$SU(2)$

Weak gauge boson'
W'
$SU(2)'$





Z_2 symmetry

Higgs
H

Higgs'
H'

Weak gauge boson
W
$SU(2)$

Weak gauge boson'
W'
$SU(2)'$

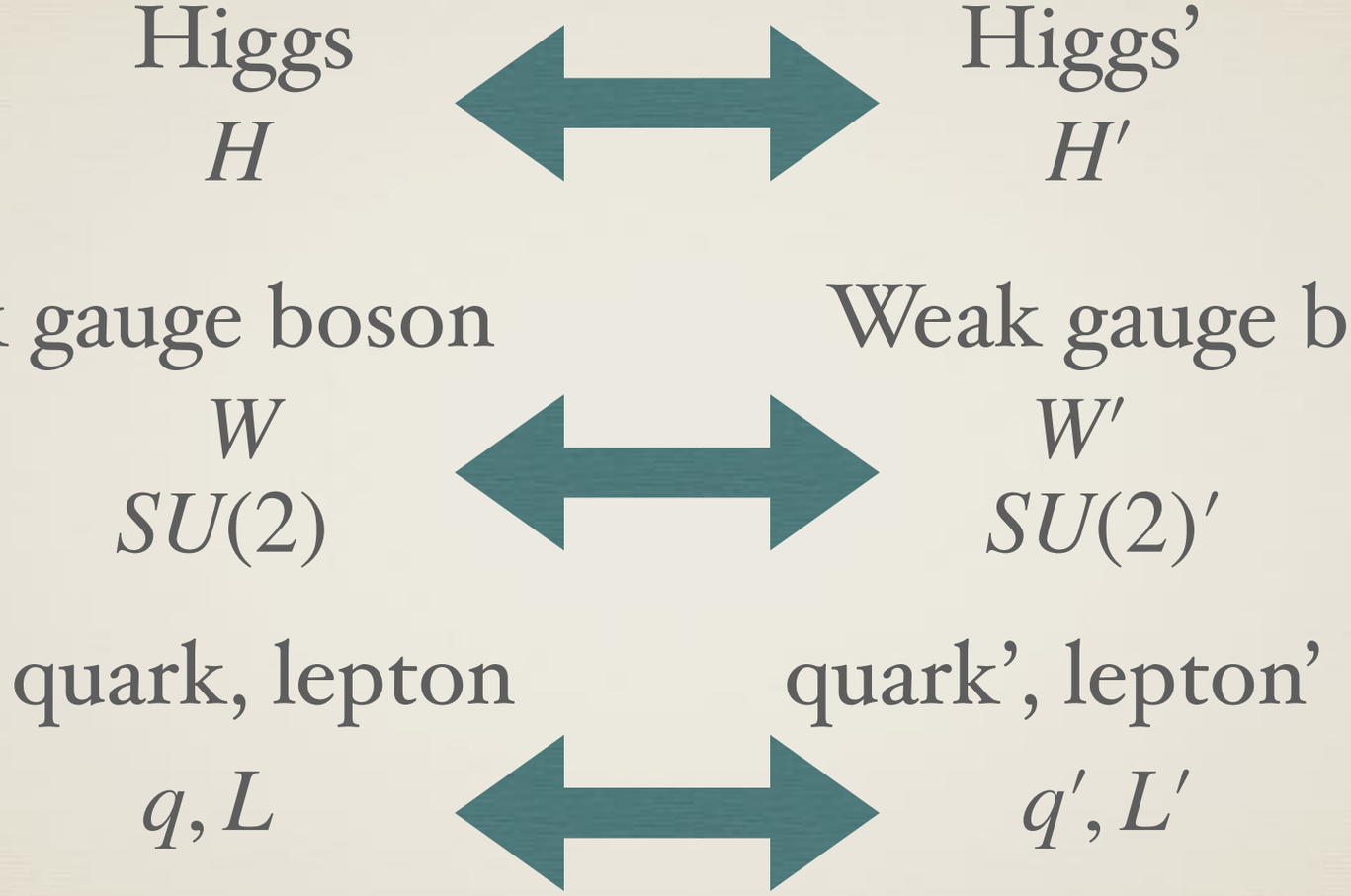
quark, lepton
q, L

quark', lepton'
q', L'

(photon and gluon : several options)

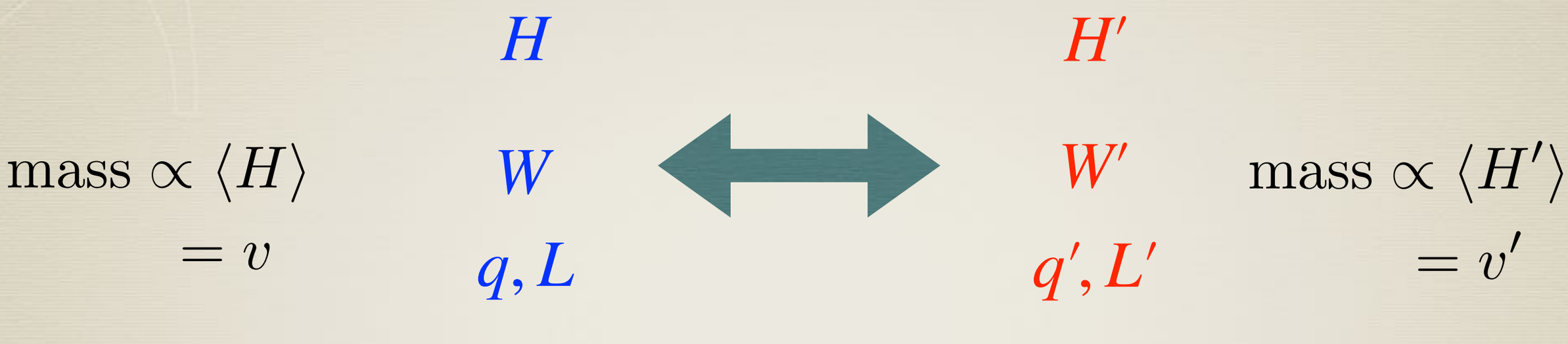
* gives a dark matter candidate
* solves the strong CP problem
* is part of a grand unified gauge symmetry

Z_2 symmetry



Higgs Parity (HP)

Spontaneously broken Higgs Parity



In well-motivated theories (explained later),
W', q', or L' interact with Standard Model particles with
$O(1)$ couplings

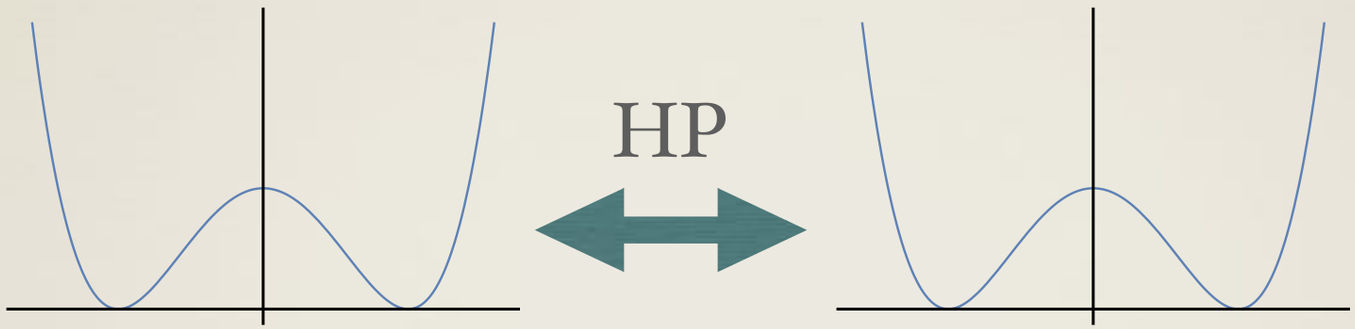
unbroken Z_2 $\langle H \rangle = \langle H' \rangle$ is experimentally excluded

symmetry breaking by $\langle H \rangle \ll \langle H' \rangle$ is required

Small quartic

Hall and KH (2018)

Higgs Parity strongly restricts the potential



$$V = \left(\lambda |H|^4 - m^2 |H|^2\right) + \left(\lambda |H'|^4 - m^2 |H'|^2\right) + \tilde{y} |H|^2 |H'|^2$$

Only three parameters. Maybe a prediction for Higgs?

$$\langle H \rangle \ll \langle H' \rangle \quad \Rightarrow \quad \lambda_{\rm SM}(\mu = v') \simeq 0$$

backup

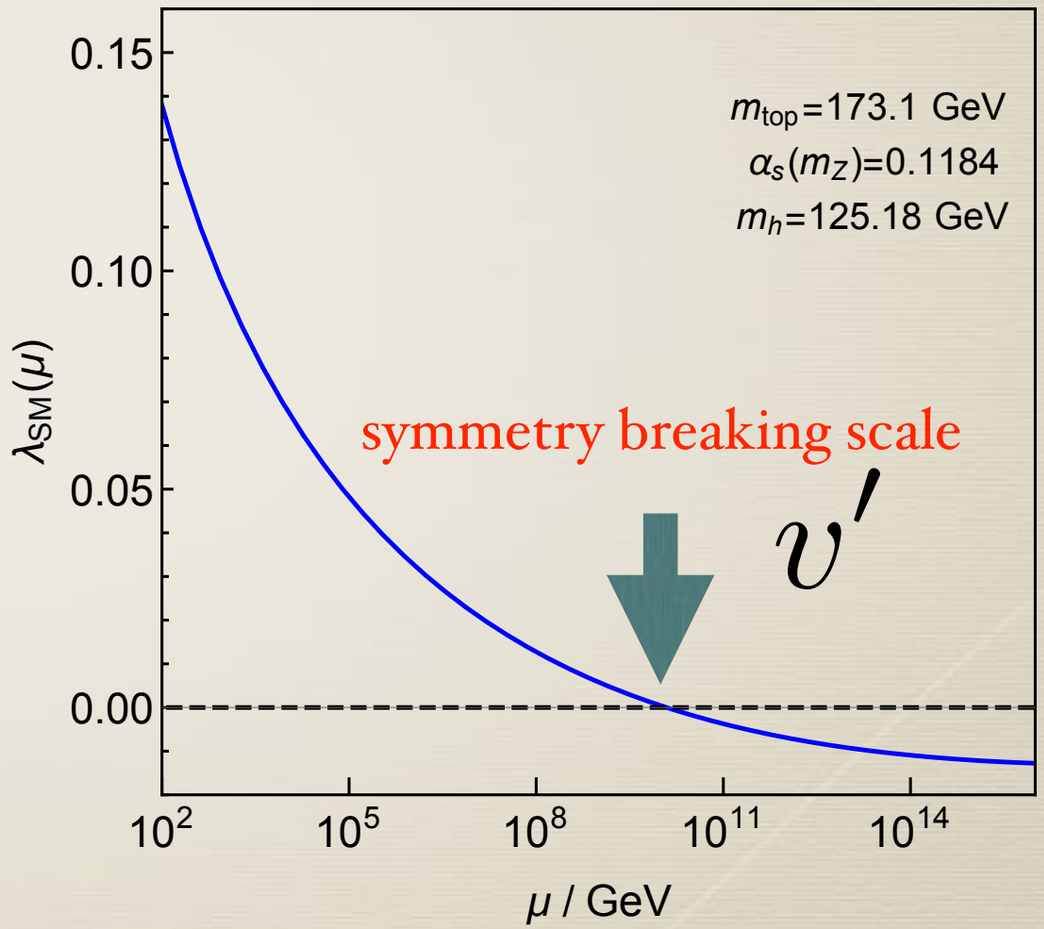
(This can be understood by accidental global symmetry for $\langle H \rangle \ll \langle H' \rangle$ and its spontaneous breaking, making H a Nambu-Goldstone boson)

Standard Model parameters and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

Top quark mass
Strong coupling constant

Higgs Parity (HP)
symmetry breaking scale



Standard Model parameters and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

Z_2 symmetry constraints the theory

Small number of parameters

Higgs Parity (HP)
symmetry breaking scale

Experimental signatures

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Mirrored electroweak theory

	SM particles		New particles
quark	q, u, d		q', u', d'
lepton	L, e		L', e'
Higgs	H	HP	H'
gauge bosons	W, Z γ	⟷	W', Z' γ'

Mirrored electroweak theory

	SM particles		New particles
	strong interaction $SU(3)_c$ g		
quark	q, u, d		q', u', d'
lepton	L, e		L', e'
Higgs	H	HP	H'
gauge bosons	W, Z γ	⟷	W', Z' γ'

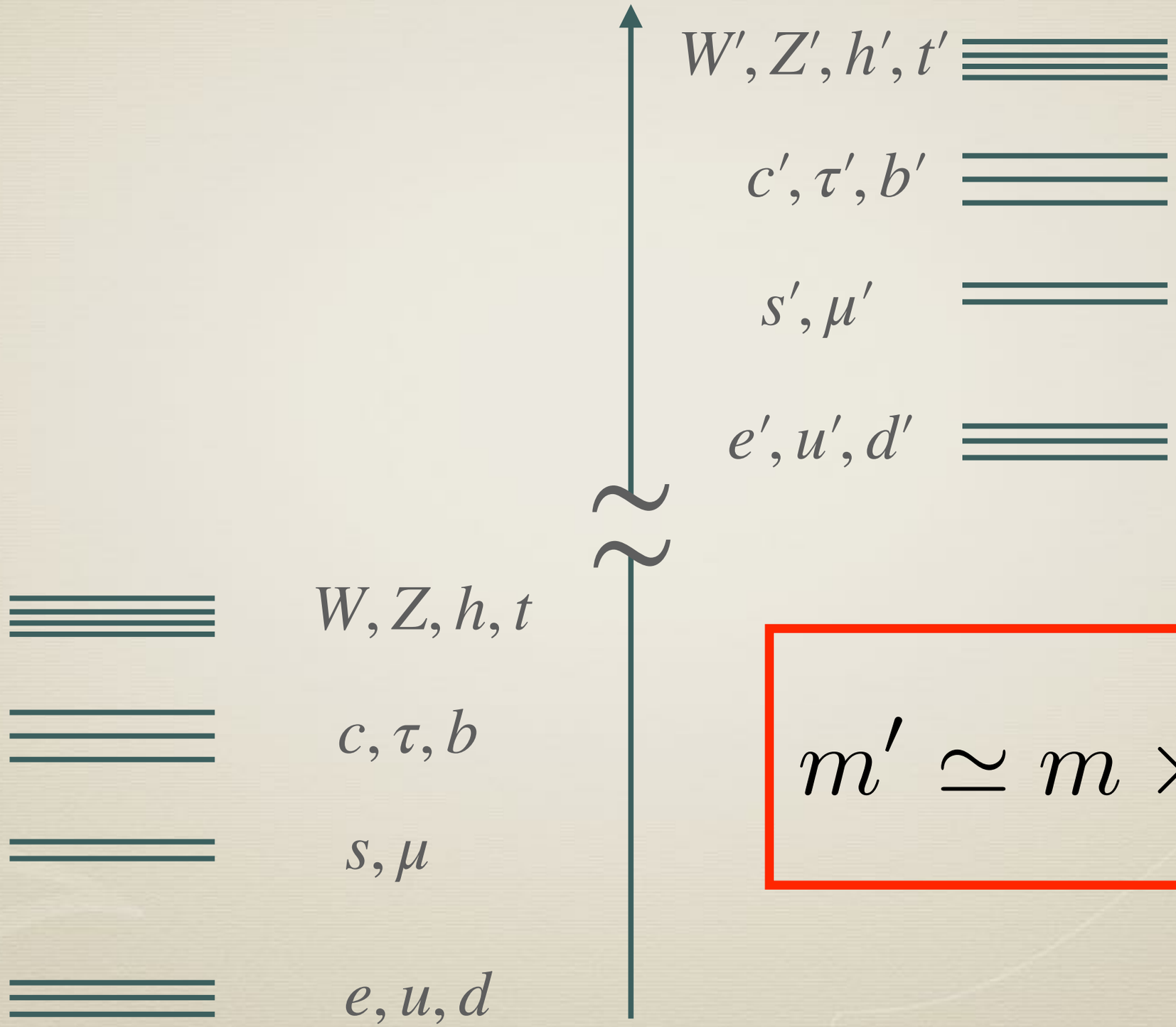
Combined with space-time parity,
the strong CP problem is solved

backup

Mohapatra and Senjanovic (1978), Beg and Tsao (1978),
Babu and Mohapatra (1989), Barr, Chang and Senjanovic (1991)
Dunsky, Hall and KH (2019)

(a quick explanation for experts: q and q' have masses with opposite phases)

Mass spectrum



$$m' \simeq m \times \frac{v'}{v}$$

Mirror dark matter

Dunsky, Hall, KH (2019)

electroweak'

$SU(2)'_L \times U(1)'_Y$ $\quad W', Z'$

$\downarrow$

$U(1)'_{\rm EM}$ $\quad \gamma'$

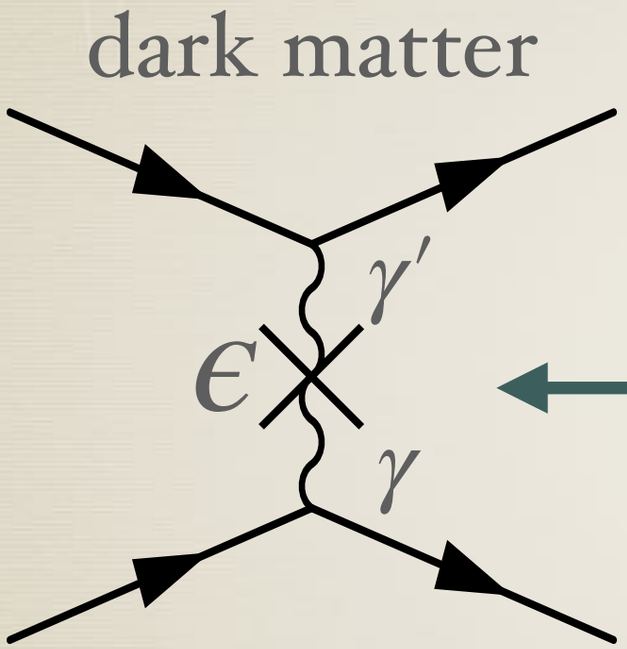
The mirror electron is absolutely stable

e'

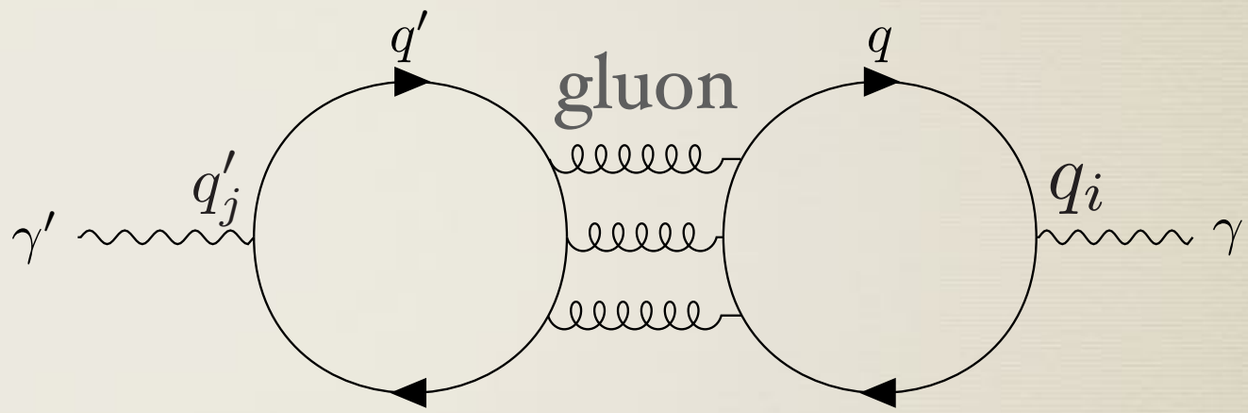
I assume that it comprises all of dark matter $\quad m_{\rm DM} \simeq m_e \times \dfrac{v'}{v}$

Dark matter-nucleon scattering

Dunsky, Hall, KH (2019)



photon-mirror photon mixing

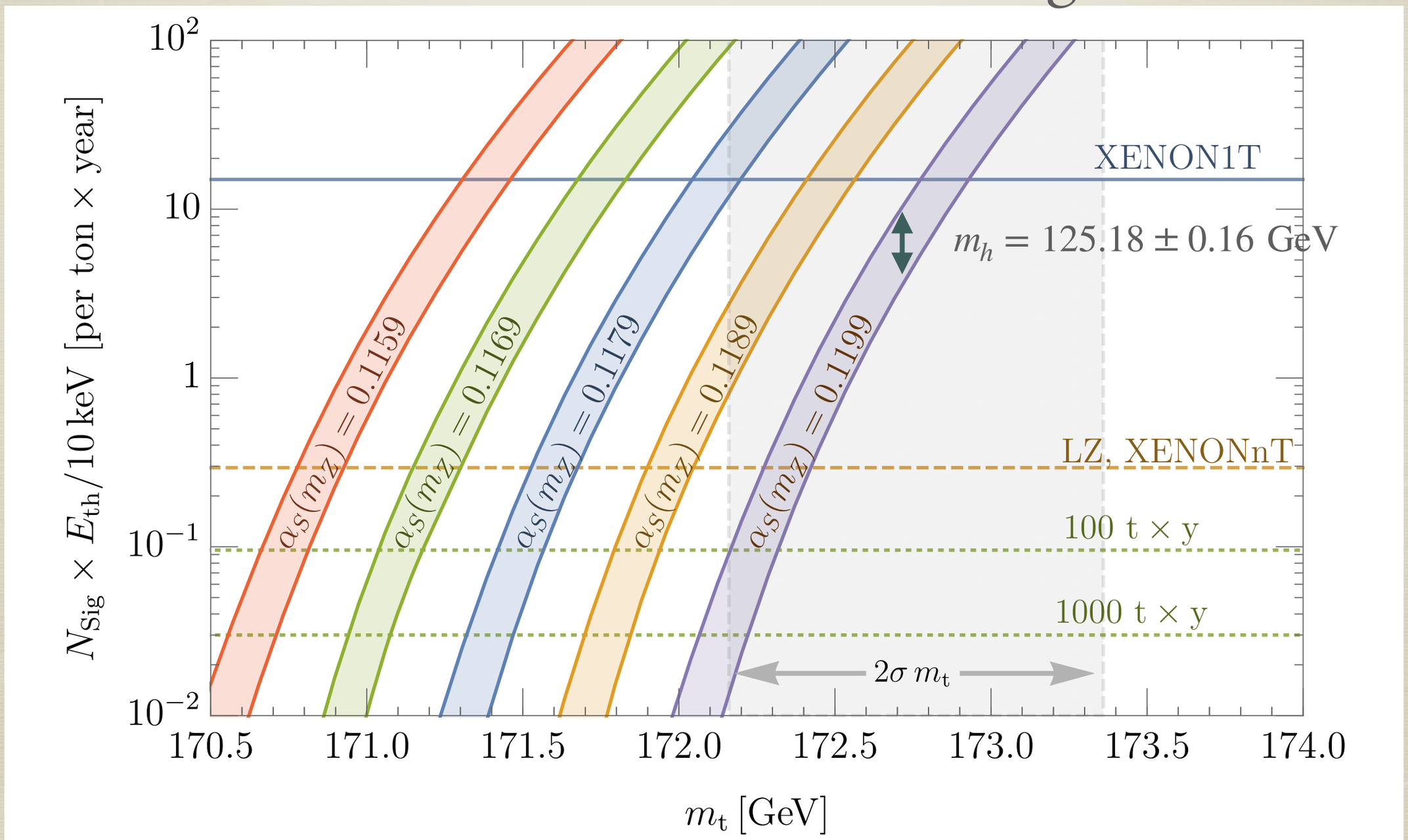


$$\epsilon \simeq 10^{-8}$$

SM parameters and DM

Dunsky, Hall, KH (2019)

Direct detection rate for Xe targets

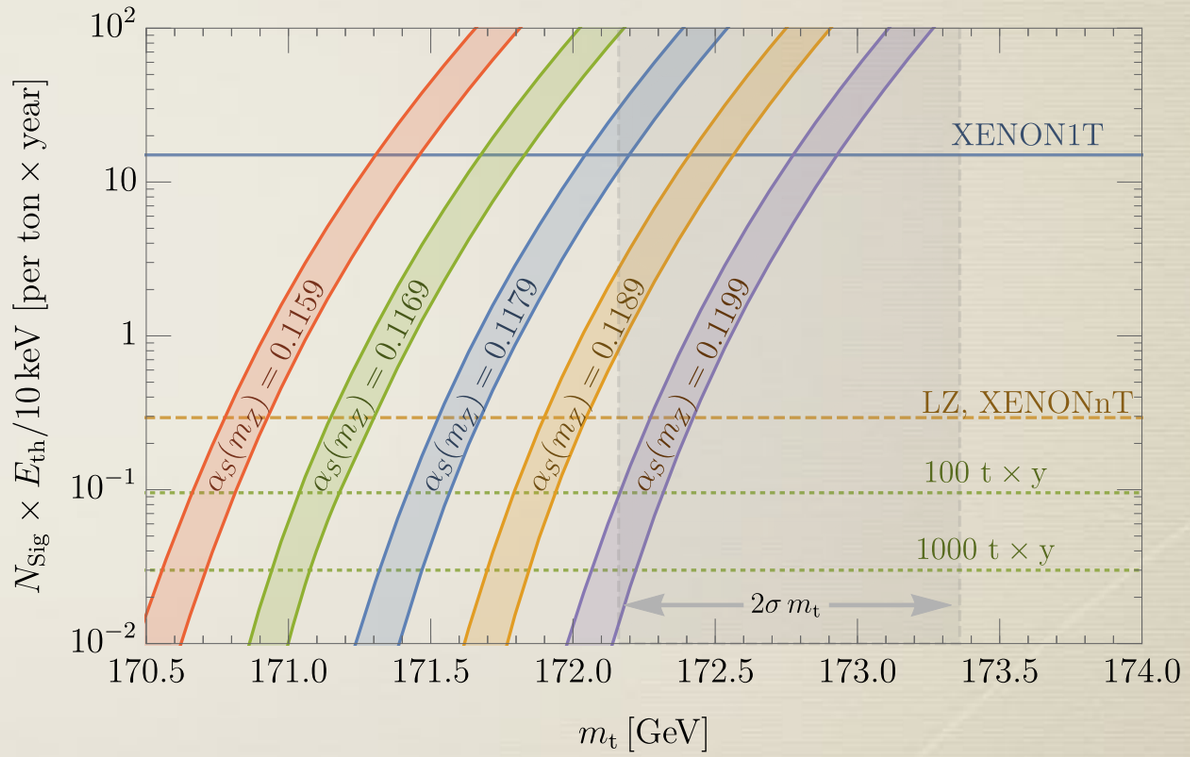


Summary and outlook

Standard Model parameters and new physics

Hall and KH (2018, 2019)
Dunsky, Hall and KH (2019)

Top quark mass
Strong coupling constant



Higgs Parity
breaking scale

Experimental signatures

Dark matter detection, proton decay, gravitational waves, dark radiation, warm dark matter, ...

backup

Future of colliders

We should maximize the impact of future colliders

* Searches for new particles
* Searches for deviation from the standard model predictions

$$N_{\text{events}} = N_{\text{SM prediction}} \ ?$$

* Precise measurement of the standard model parameters

top quark mass,
strong coupling constant

Any other new physics models
impacted by precise measurements?

Standard Model parameters and new physics

Hall and KH (2018, 2019)
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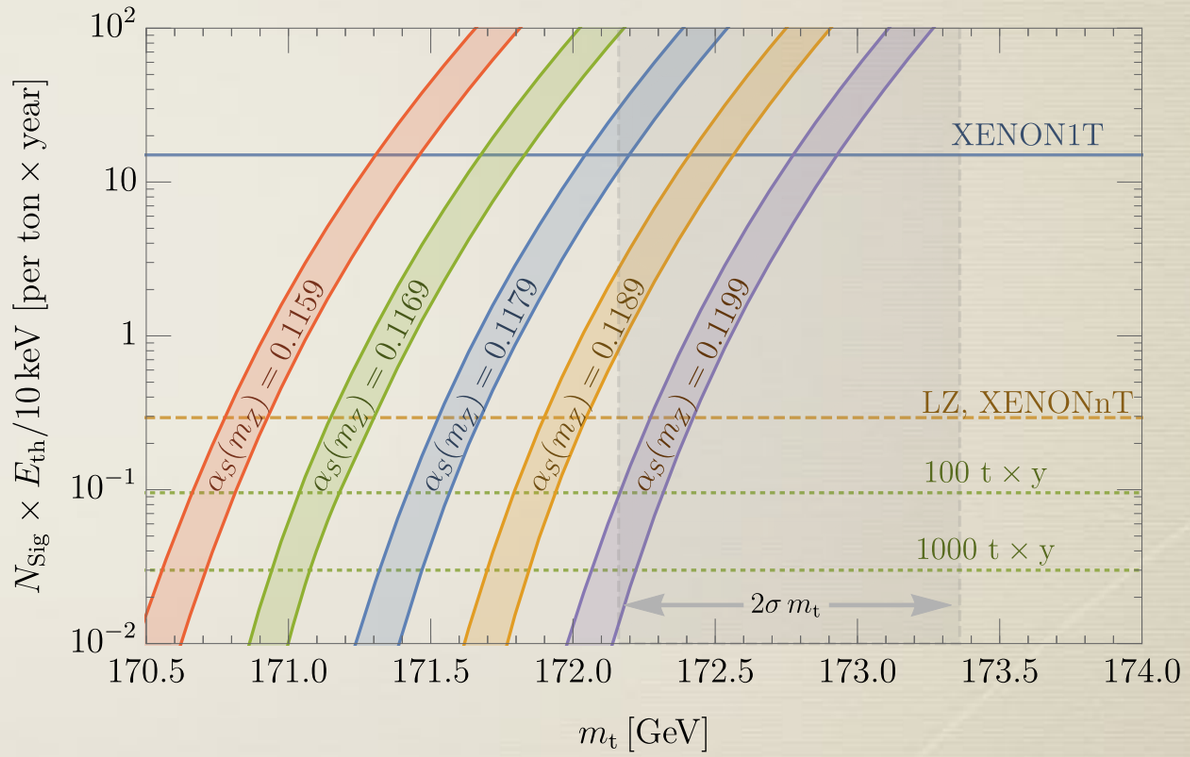
Top quark mass
Strong coupling constant



Higgs Parity
breaking scale

Experimental signatures

Dark matter detection, proton decay, gravitational waves, dark radiation, warm dark matter, ...

Back up

Dark Matter

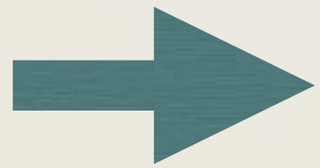
Composition of DM

e'

u'
$u'\ \ u'$

$m_{u'u'u'} \simeq 4m_{e'}$

$Q^2_{u'u'u'} = 2^2 = 4Q^2_{e'}$



Signal rates are independent of relative fractions

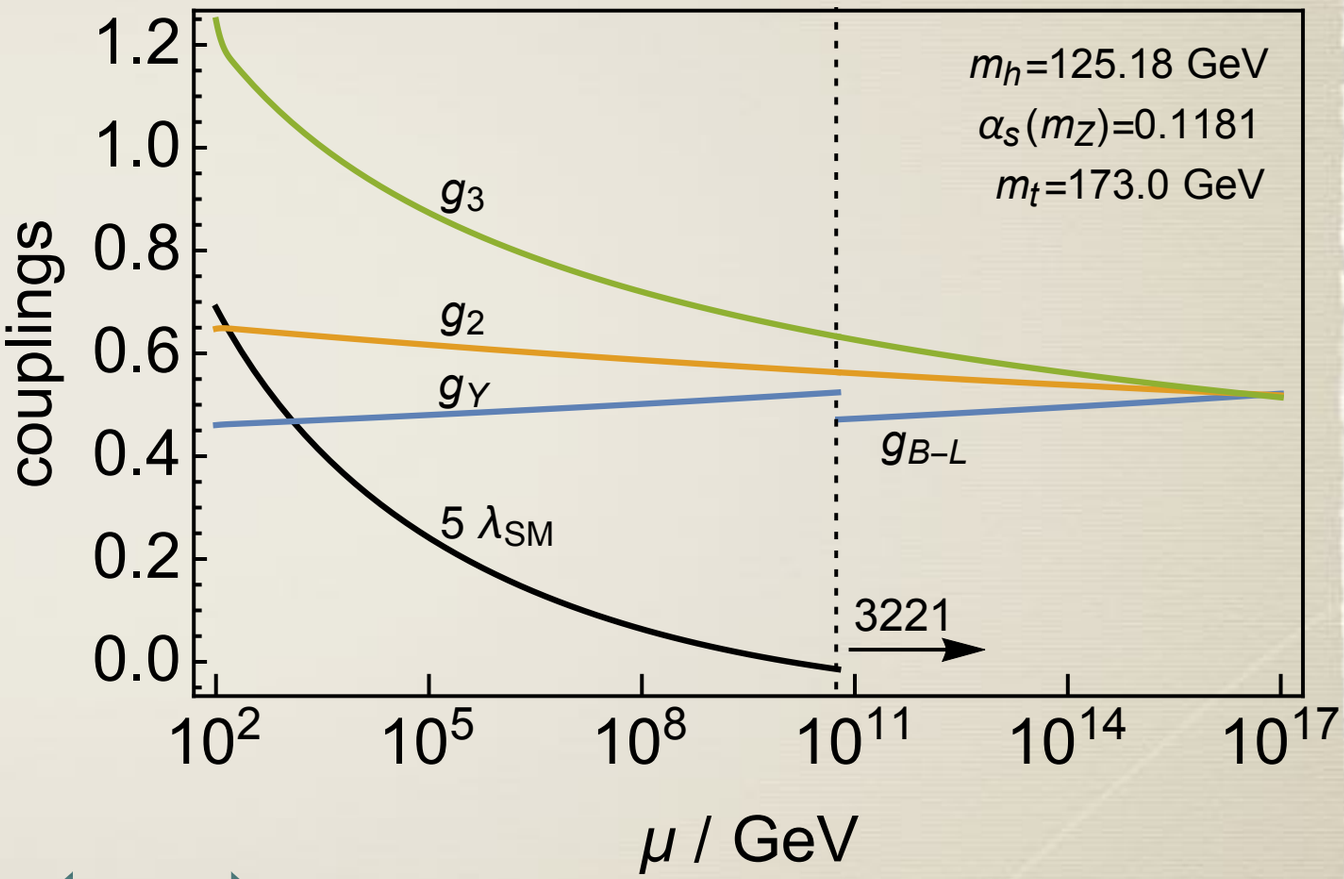
GUT

Precise measurement and Grand Unification

Hall and KH (2018, 2019)

top quark mass
Higgs mass
strong coupling constant

Higgs Parity
symmetry breaking scale



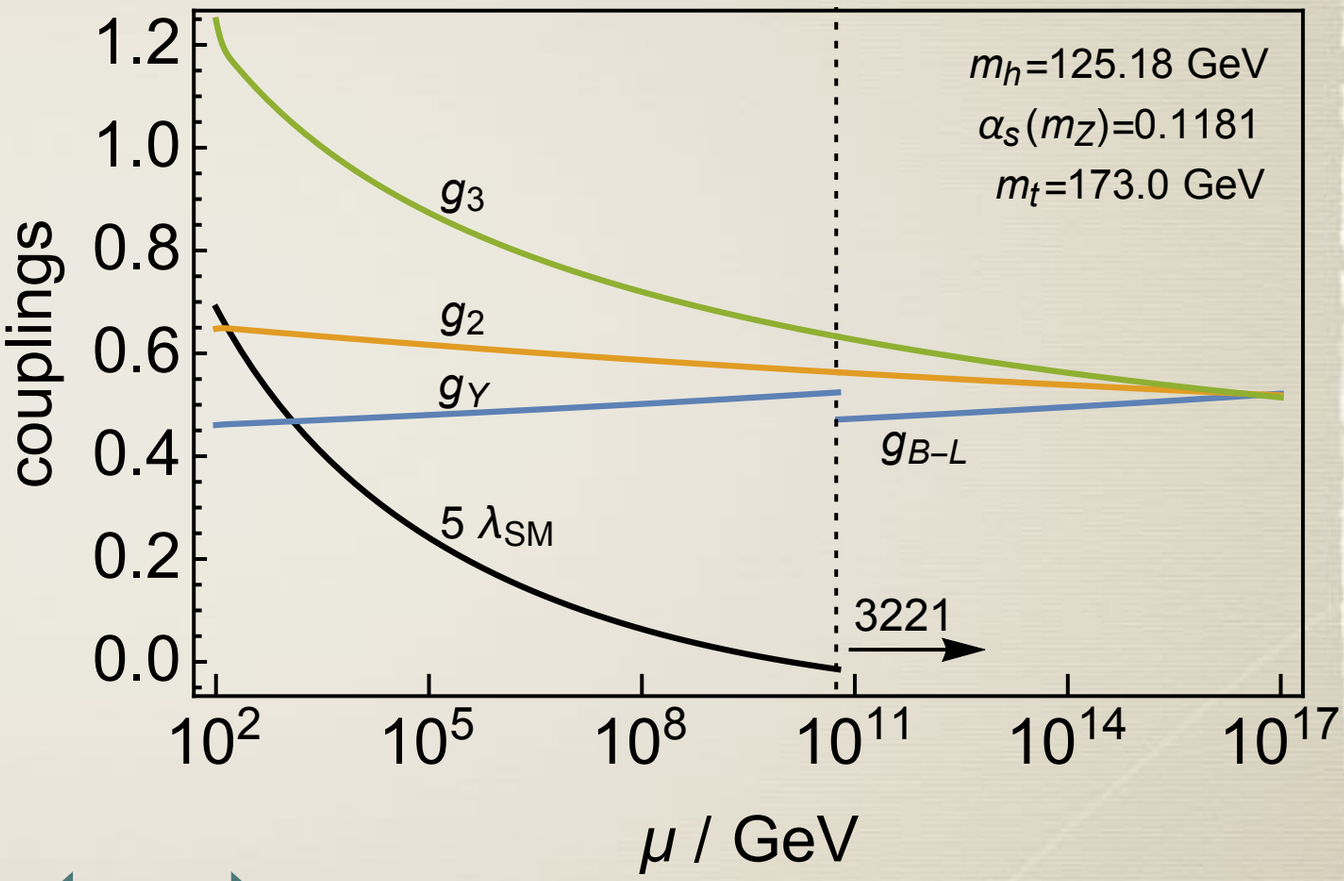
Proton decay from
Grand Unification

Precise measurement and Grand Unification

Hall and KH (2018, 2019)

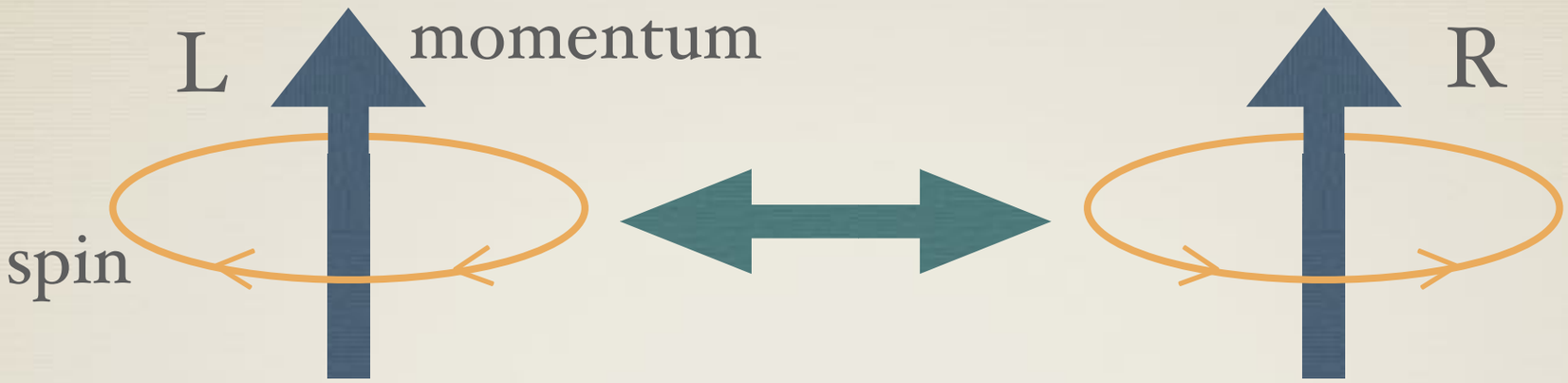
top quark mass
Higgs mass
strong coupling constant

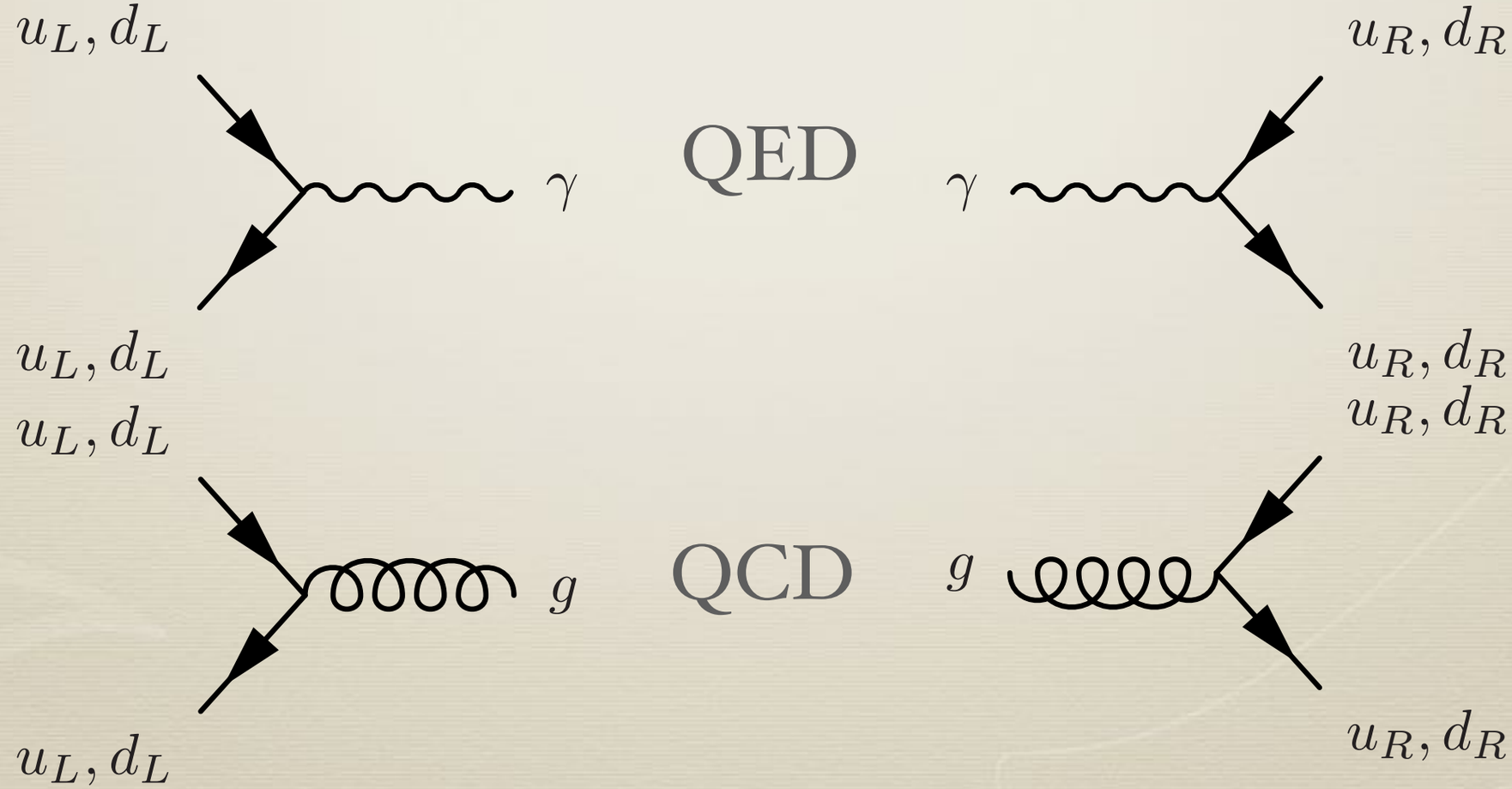
Left-Right
Higgs Parity
symmetry breaking scale



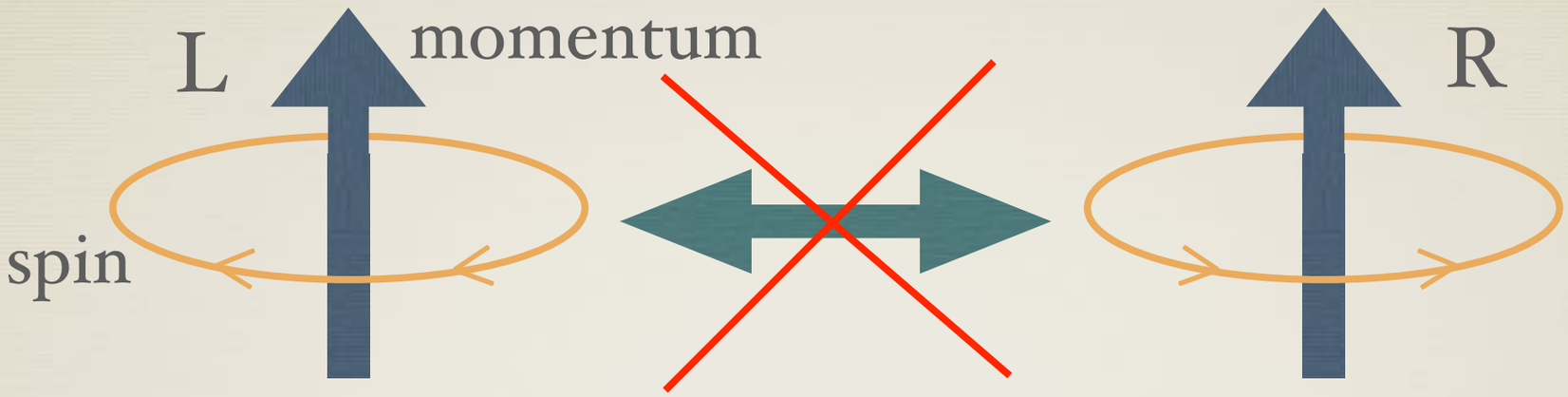
Proton decay from
Grand Unification

Left-Right symmetry

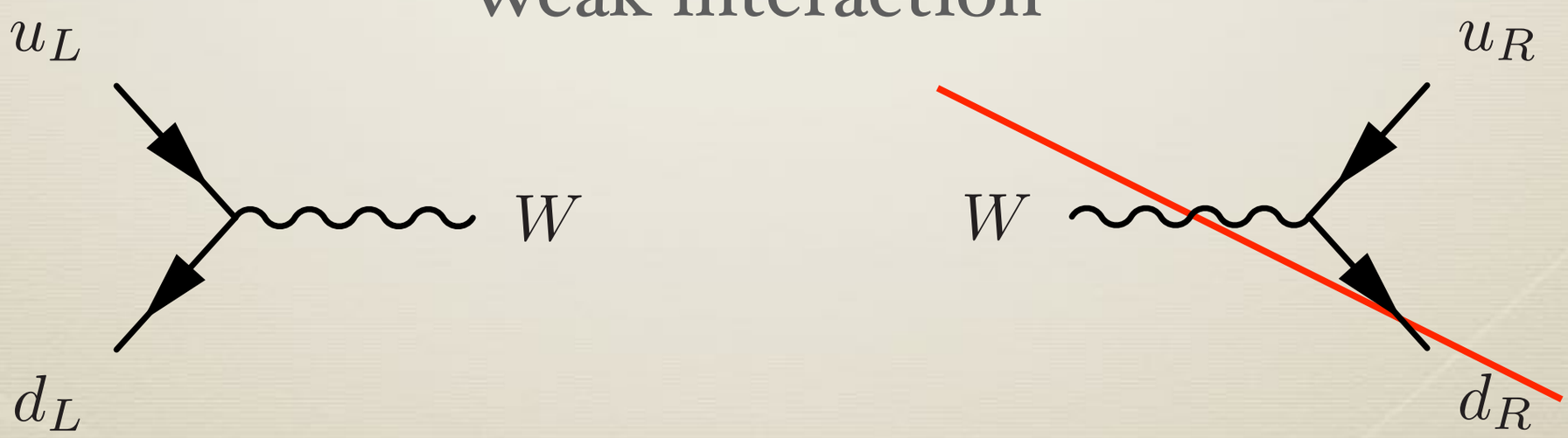




Left-Right symmetry

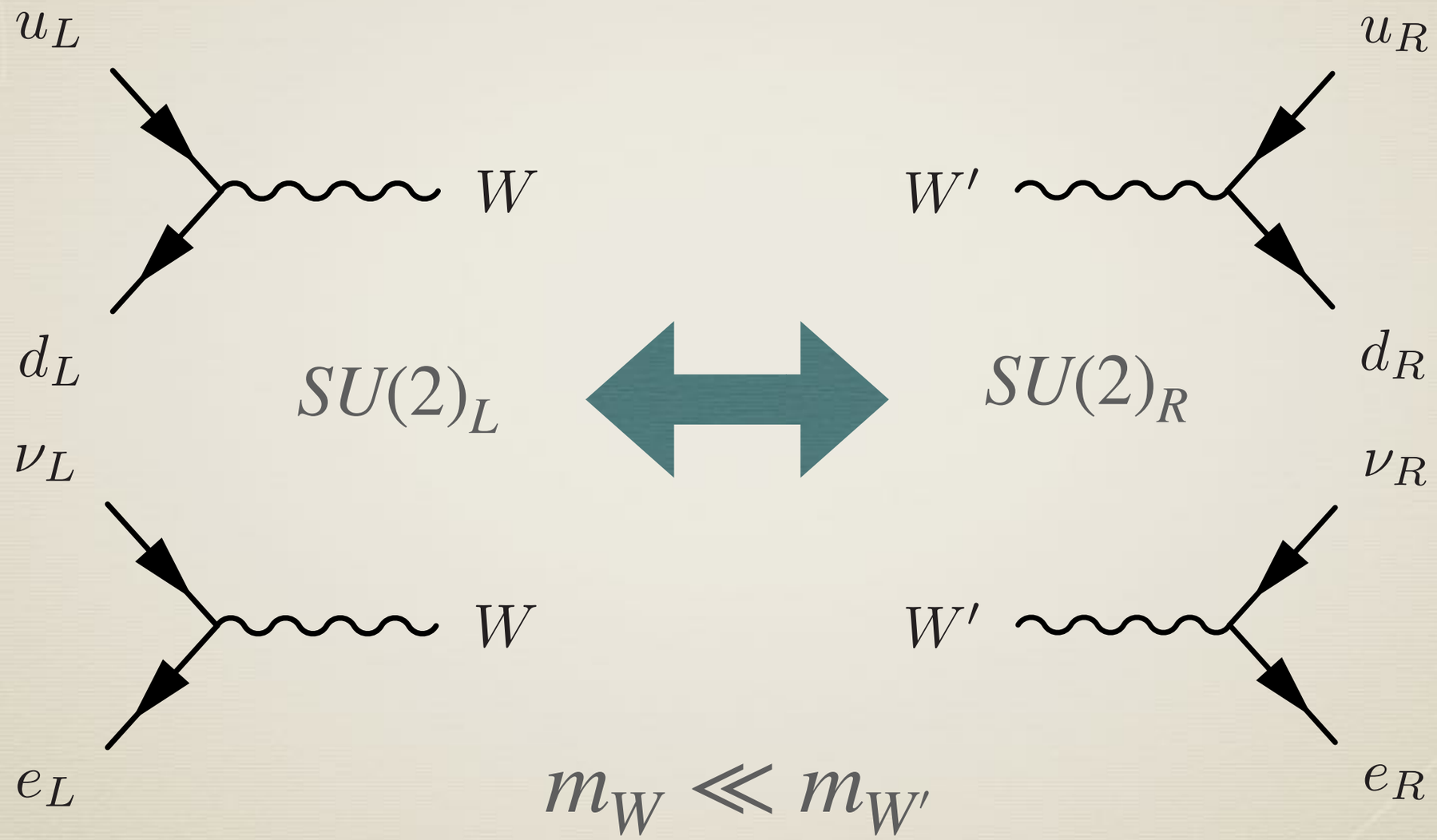


Weak interaction



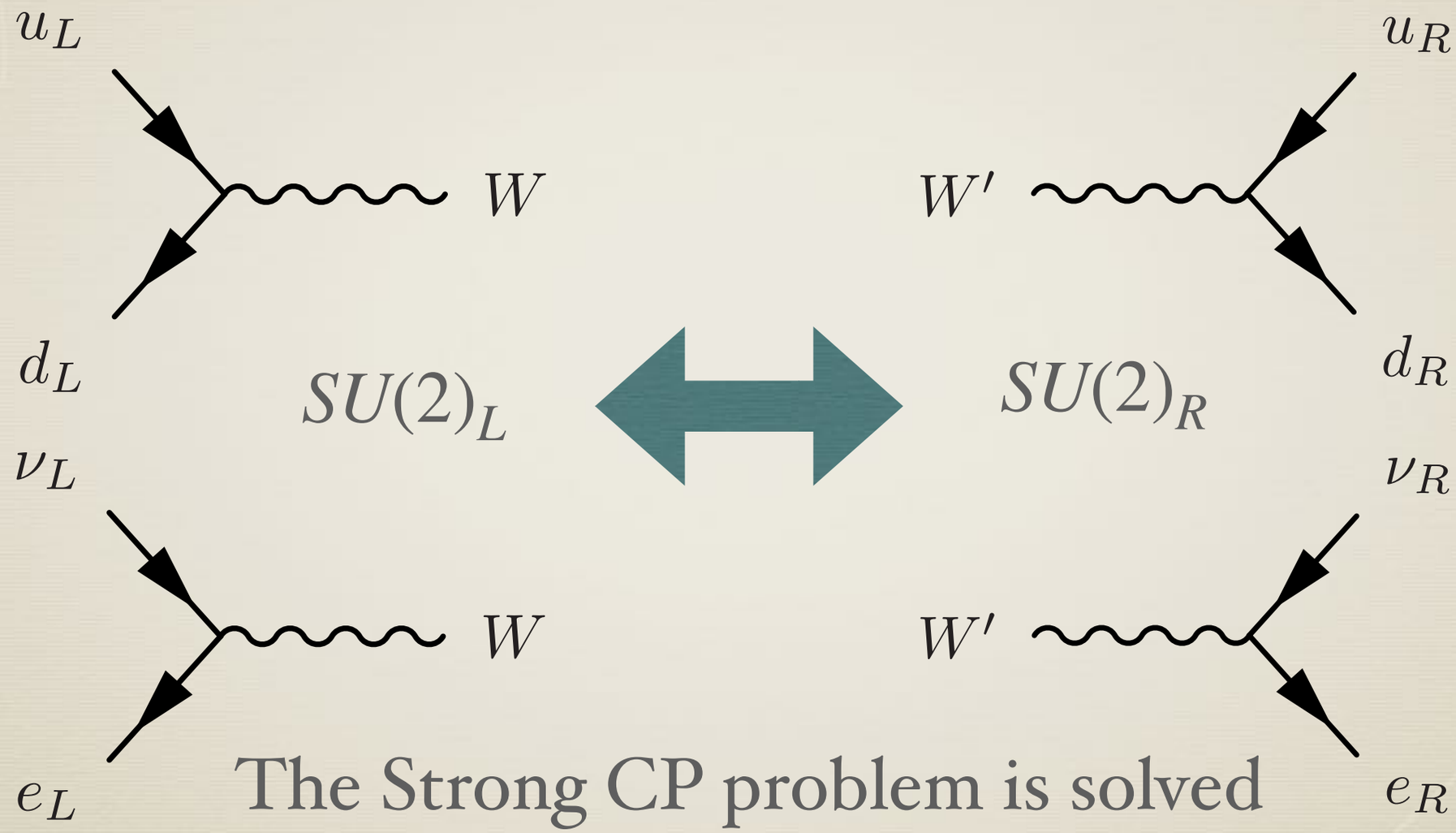
Lee and Yang (1956), Wu (1957)

Spontaneously broken Left-Right symmetry



Lee (1973), Pati and Salam (1975),
Moahapatra and Pati (1975), Senjanovic and Mohapatra (1975)

Spontaneously broken Left-Right symmetry



The Strong CP problem is solved via space-time parity

Mohapatra and Senjanovic (1978), Beg and Tsao (1978), Babu and Mohapatra (1989), Hall and KH (2018)

(a quick explanation for experts: quarks have Hermitian mass matrixes)

Left-Right Higgs Parity

Higgs
H

Higgs'
H'

Weak gauge boson
W
$SU(2)_L$

Weak gauge boson'
W'
$SU(2)_R$

left-handed quark, lepton
q_L, L_L

right-handed quark, lepton
$q', L' = q_R, L_R$

$$SU(3)_c \times SU(2)_L \times \underline{SU(2)_R \times U(1)}$$

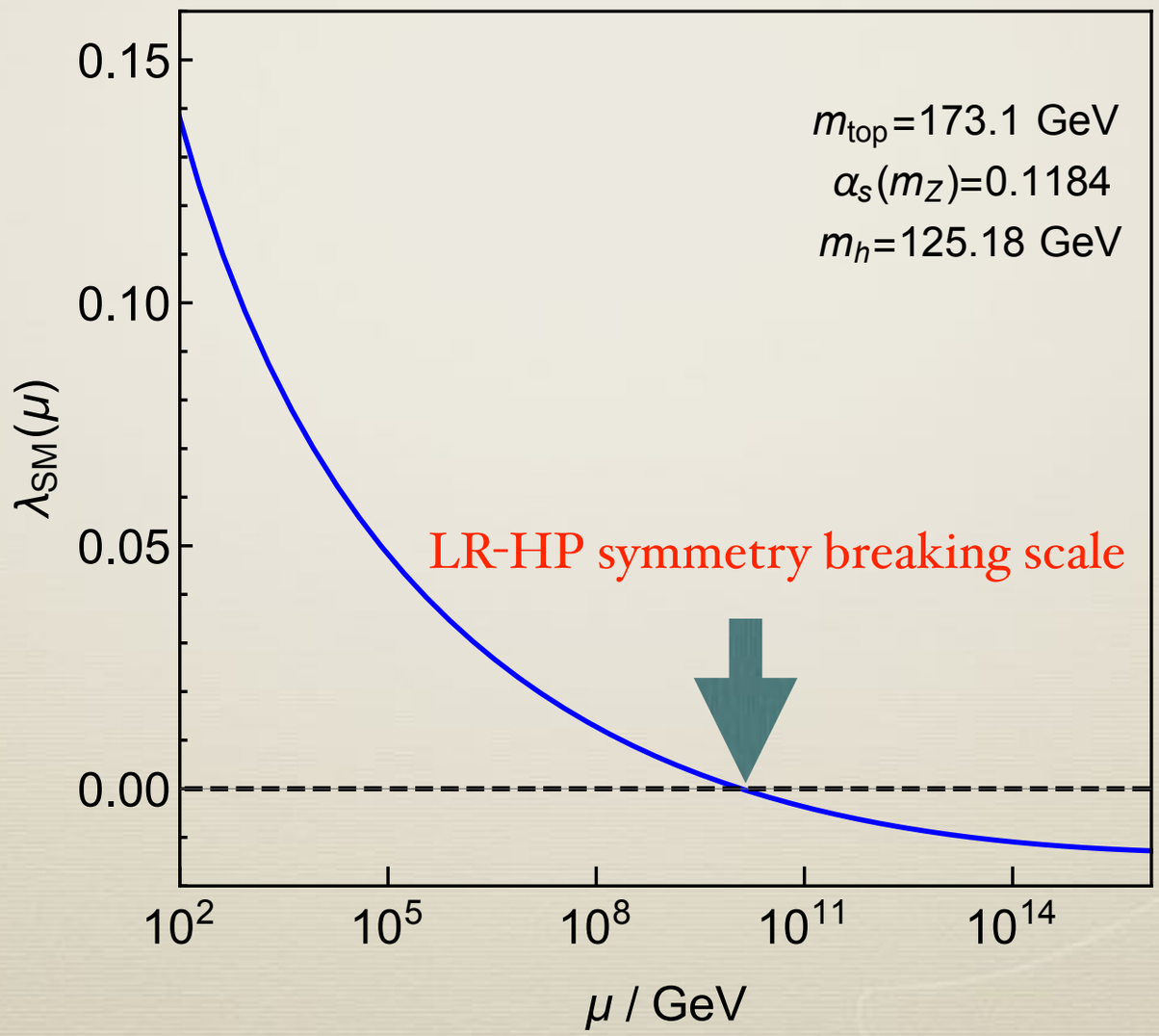
$\downarrow \langle H' \rangle$

$$U(1)_Y$$

Left-Right Higgs Parity

Higgs
H

Higgs'
H'



Left-Right symmetry and Grand Unified Theory

Grand Unification
$SO(10)$

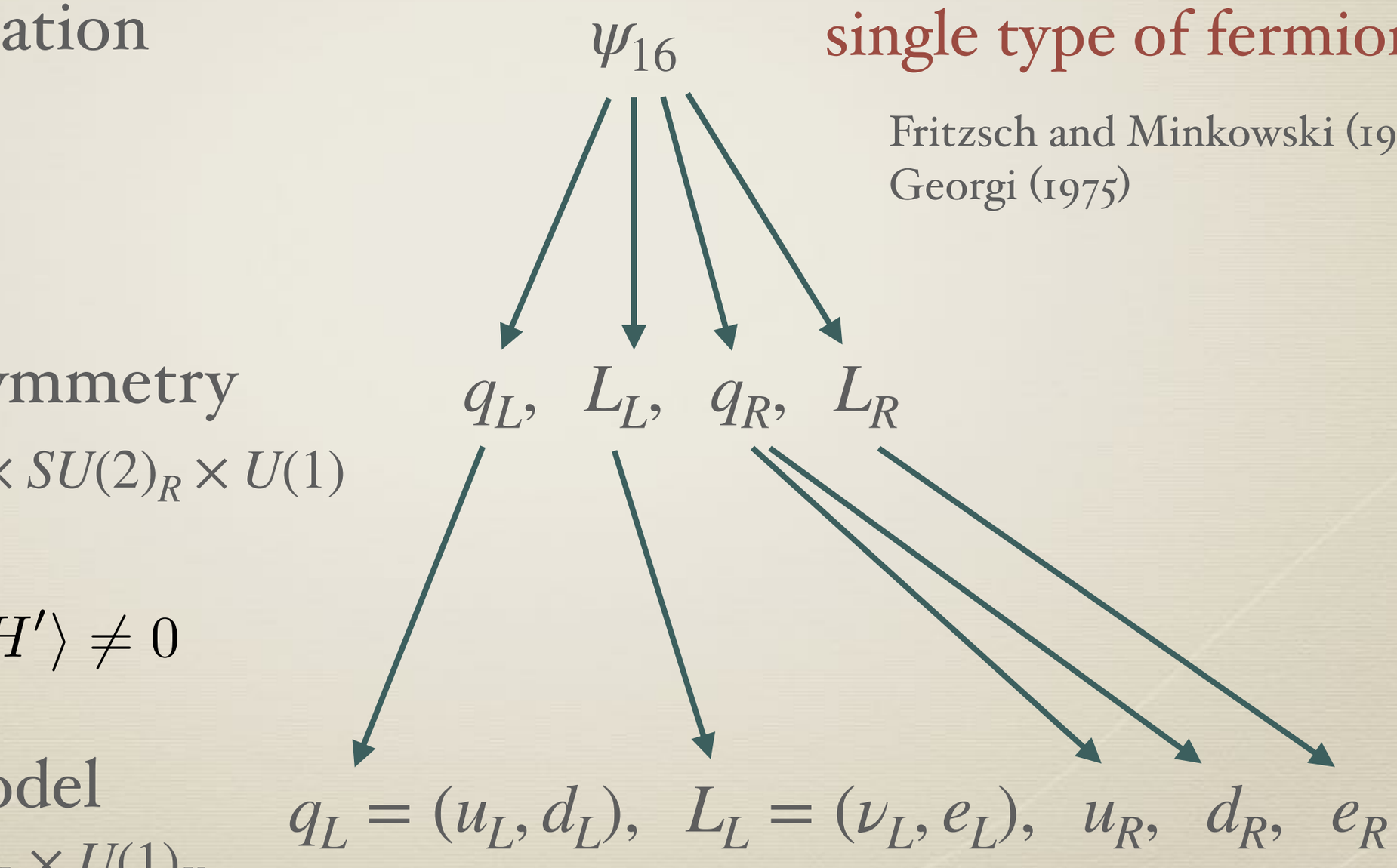
Left-Right Symmetry
$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$

$\langle H' \rangle \neq 0$

Standard Model
$SU(3)_c \times SU(2)_L \times U(1)_Y$

Single gauge group, single type of fermions

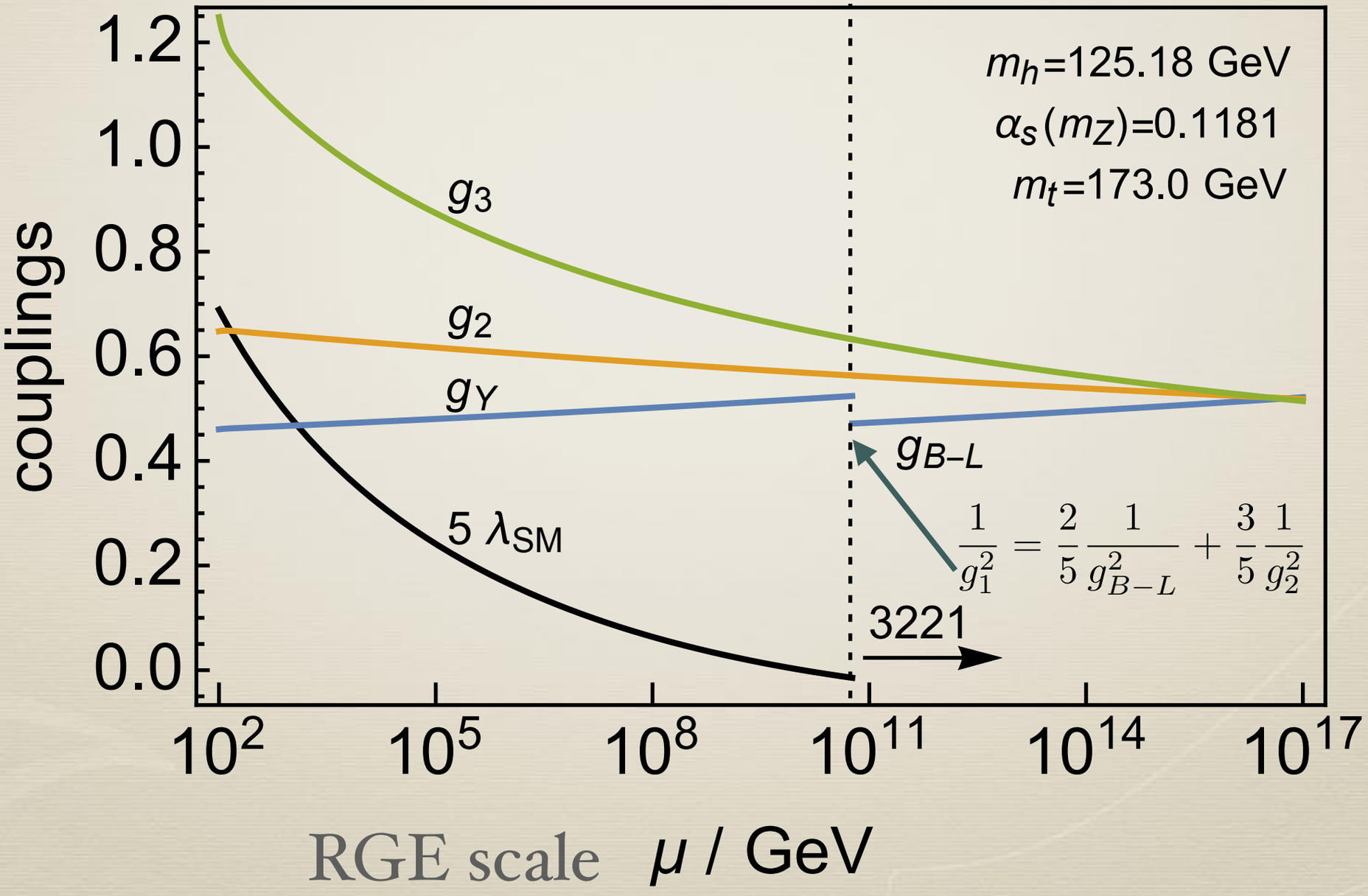
Fritzsch and Minkowski (1975), Georgi (1975)



Coupling unification

Hall, KH (2018, 2019)

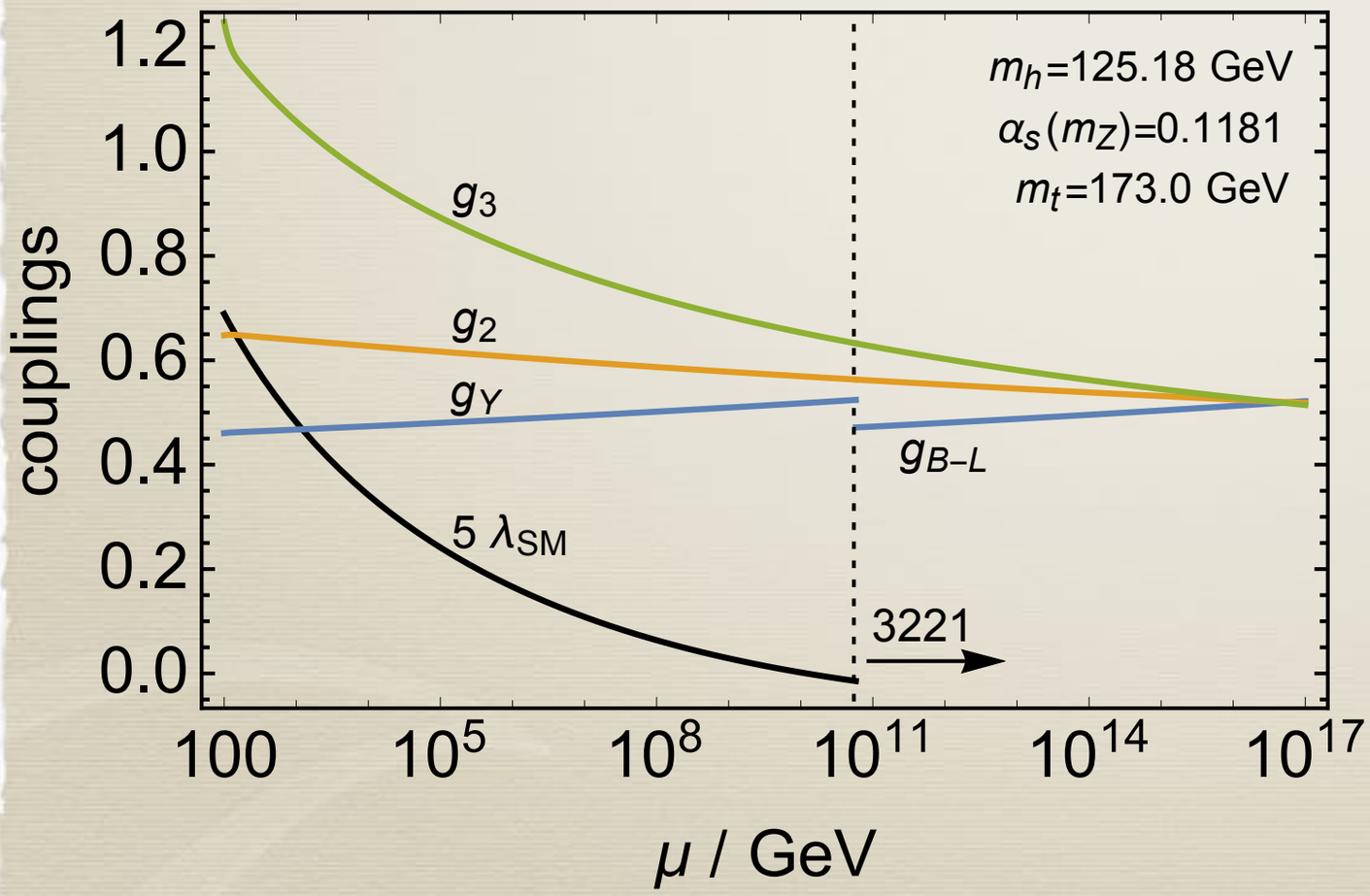
energy-dependent couplings



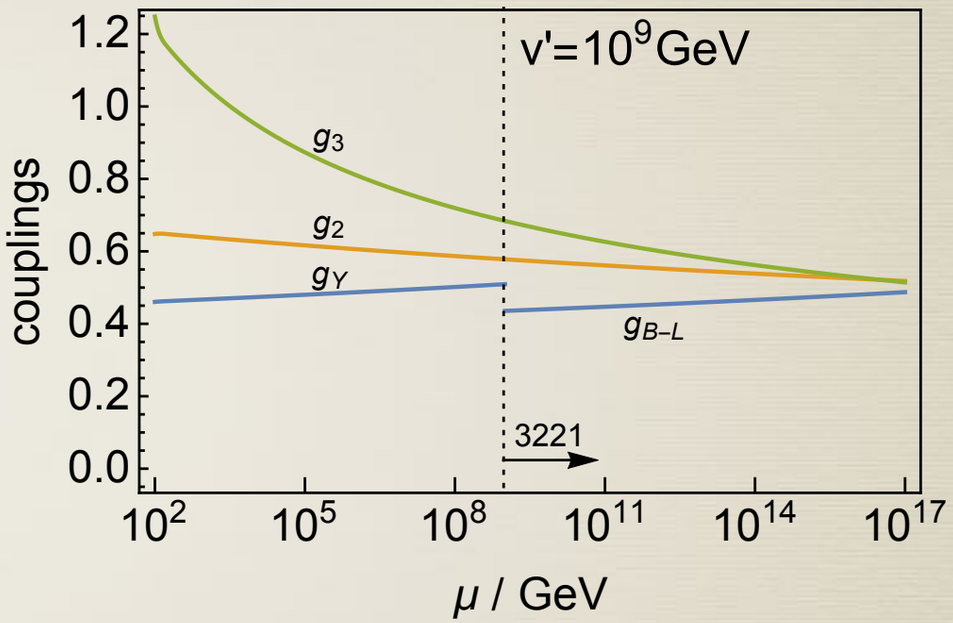
Coupling unification

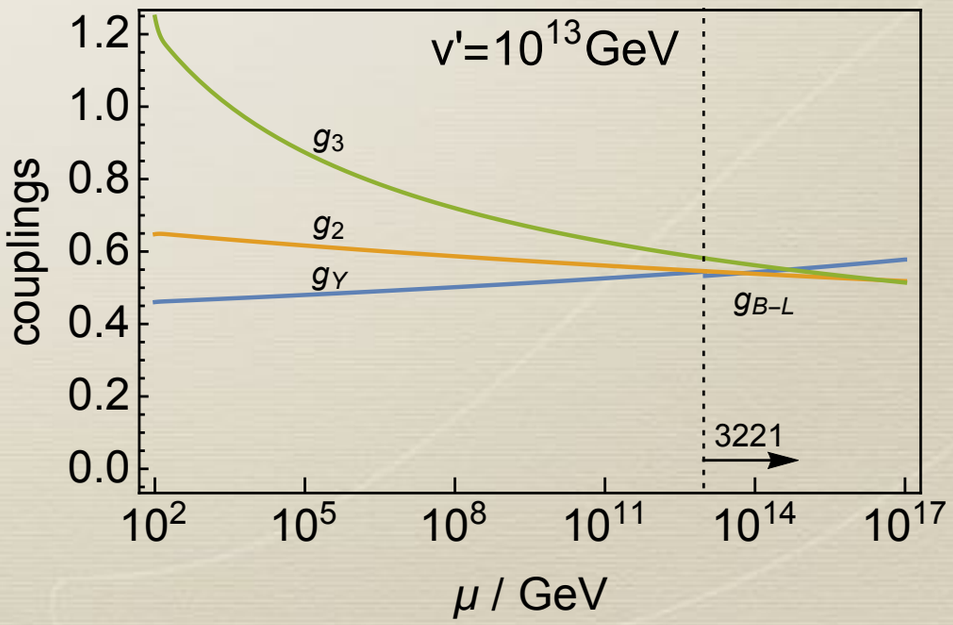
Hall, KH (2018, 2019)

v' determined by Higgs Parity



Other v'

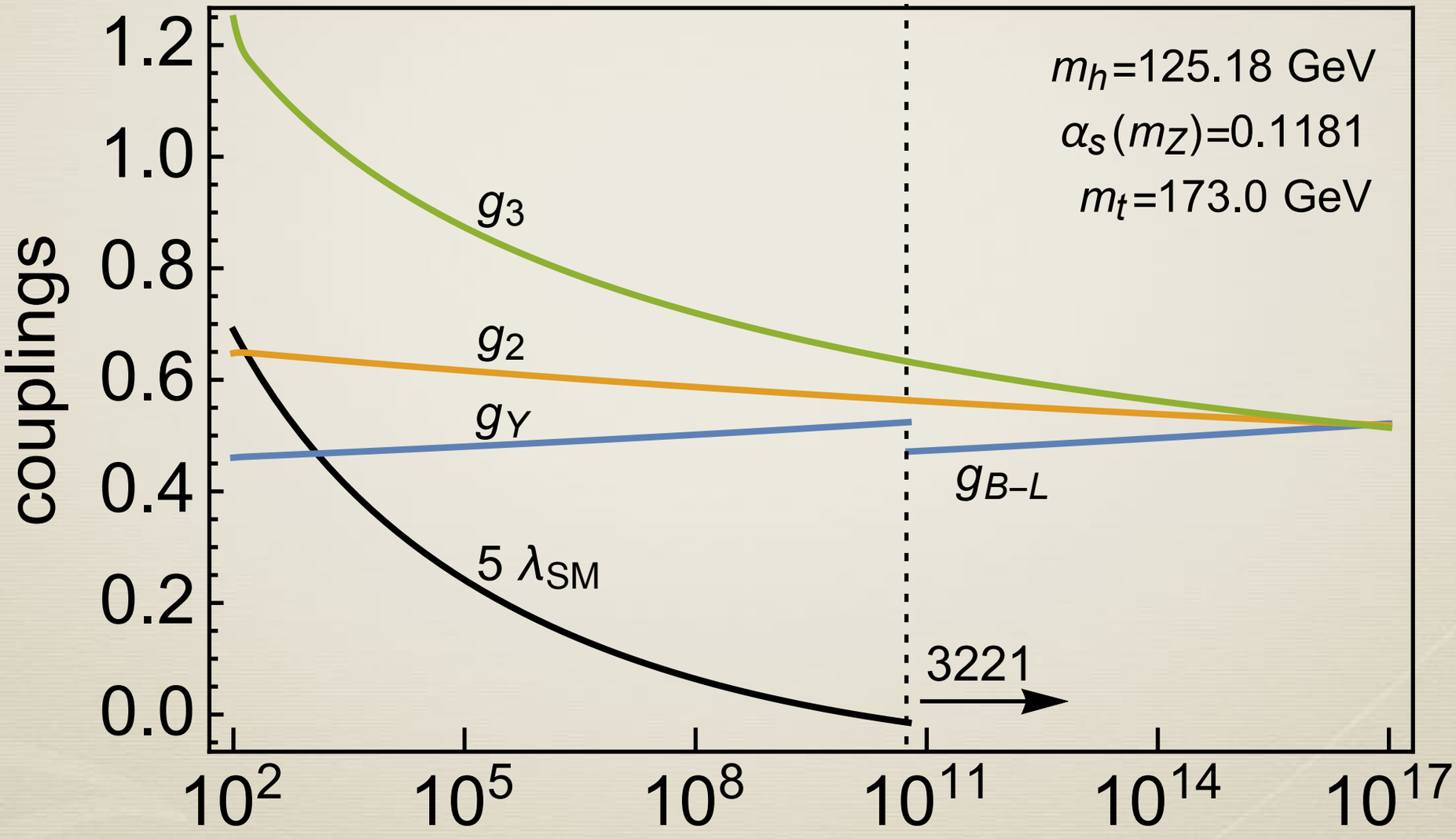




Higgs Parity GUT

Hall, KH (2018, 2019)

energy-dependent couplings



Higgs Parity GUT

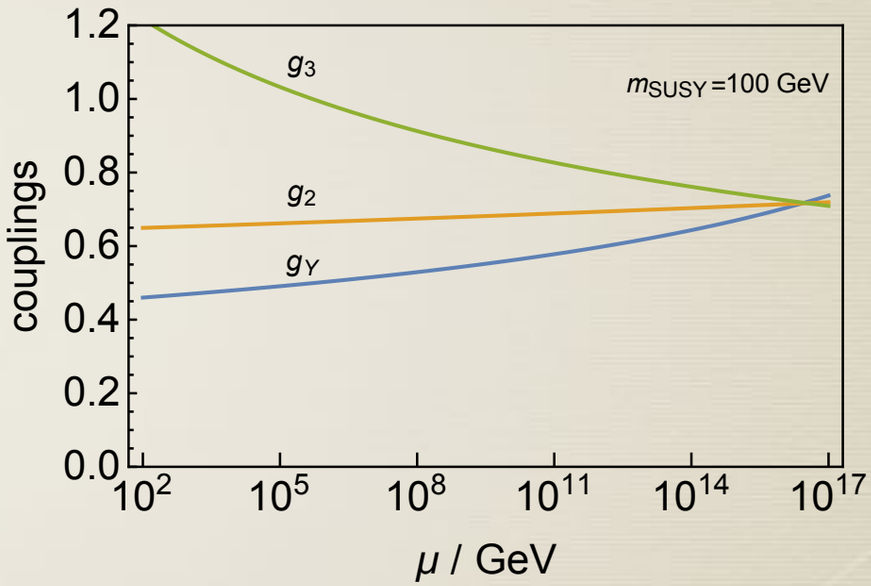
Hall, KH (2018, 2019)

weak scale 10^2 GeV

GUT scale 10^{16} GeV

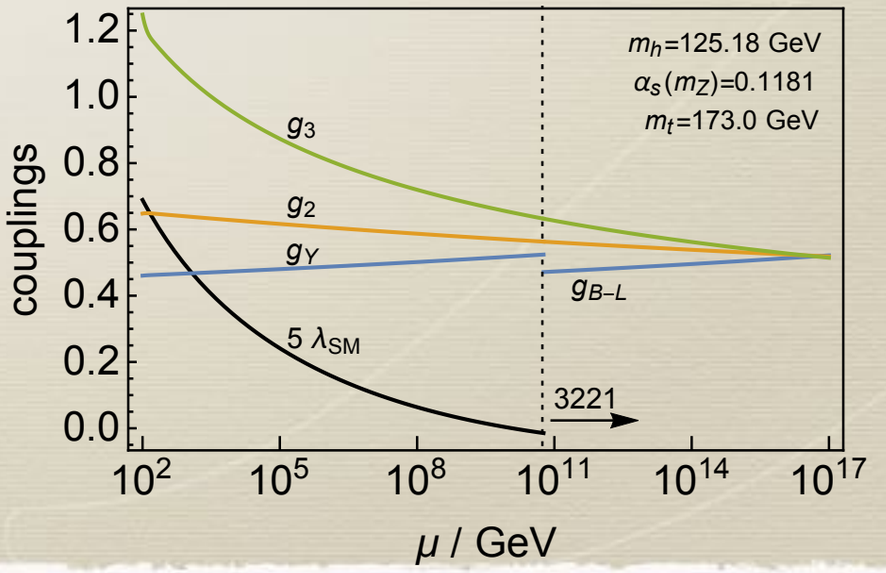
gauge coupling constants
(LEP, ...)

SUSY GUT



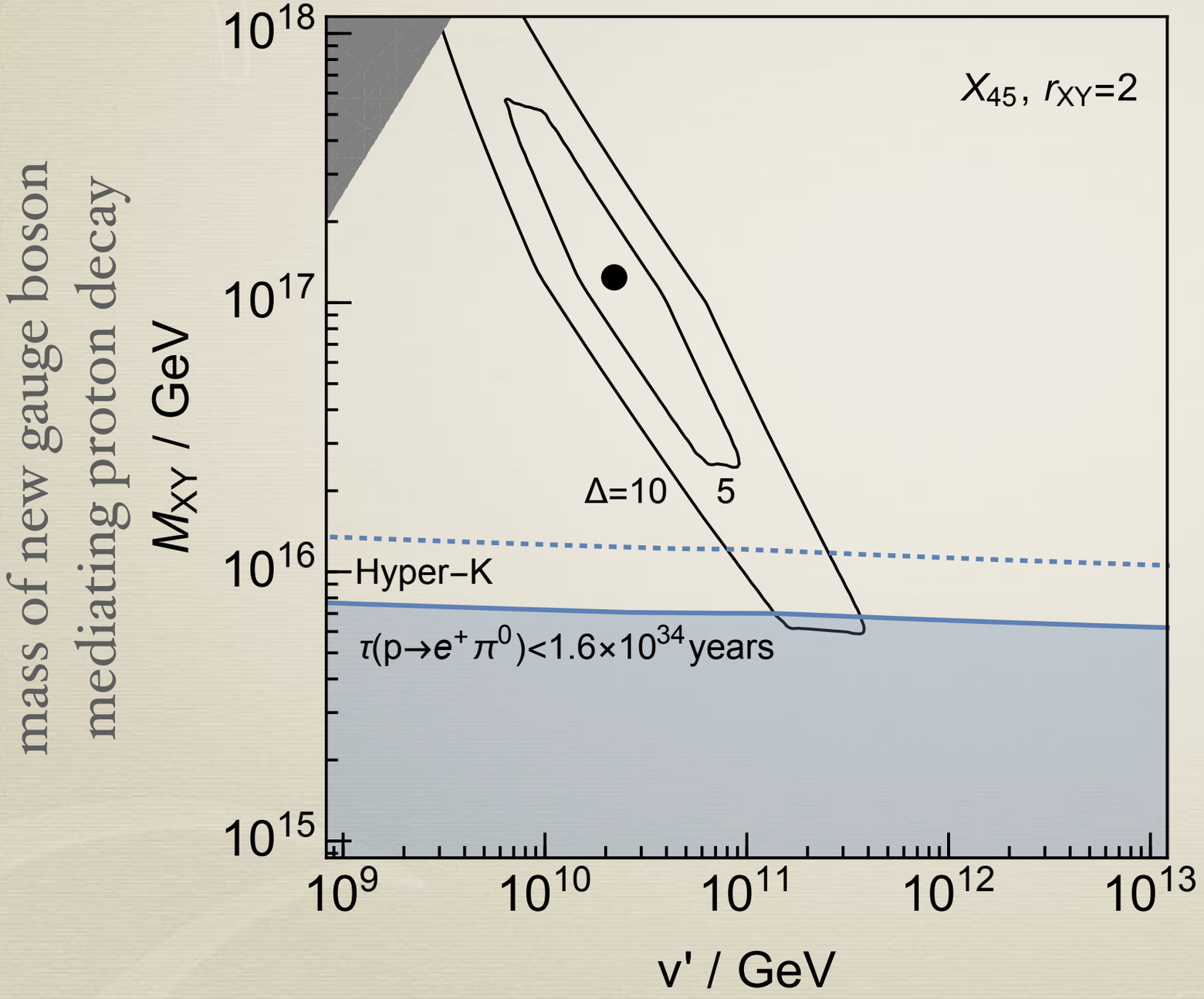
gauge coupling constants
top quark mass
Higgs mass
(LHC, lattice, future colliders, ...)

HP GUT



Quantify unification

Hall, KH (2019)



There can be quantum corrections from heavy particles around the GUT scale

$$\Delta = \max_{i,j} \left| \frac{8\pi^2}{g_i^2} - \frac{8\pi^2}{g_j^2} \right|$$

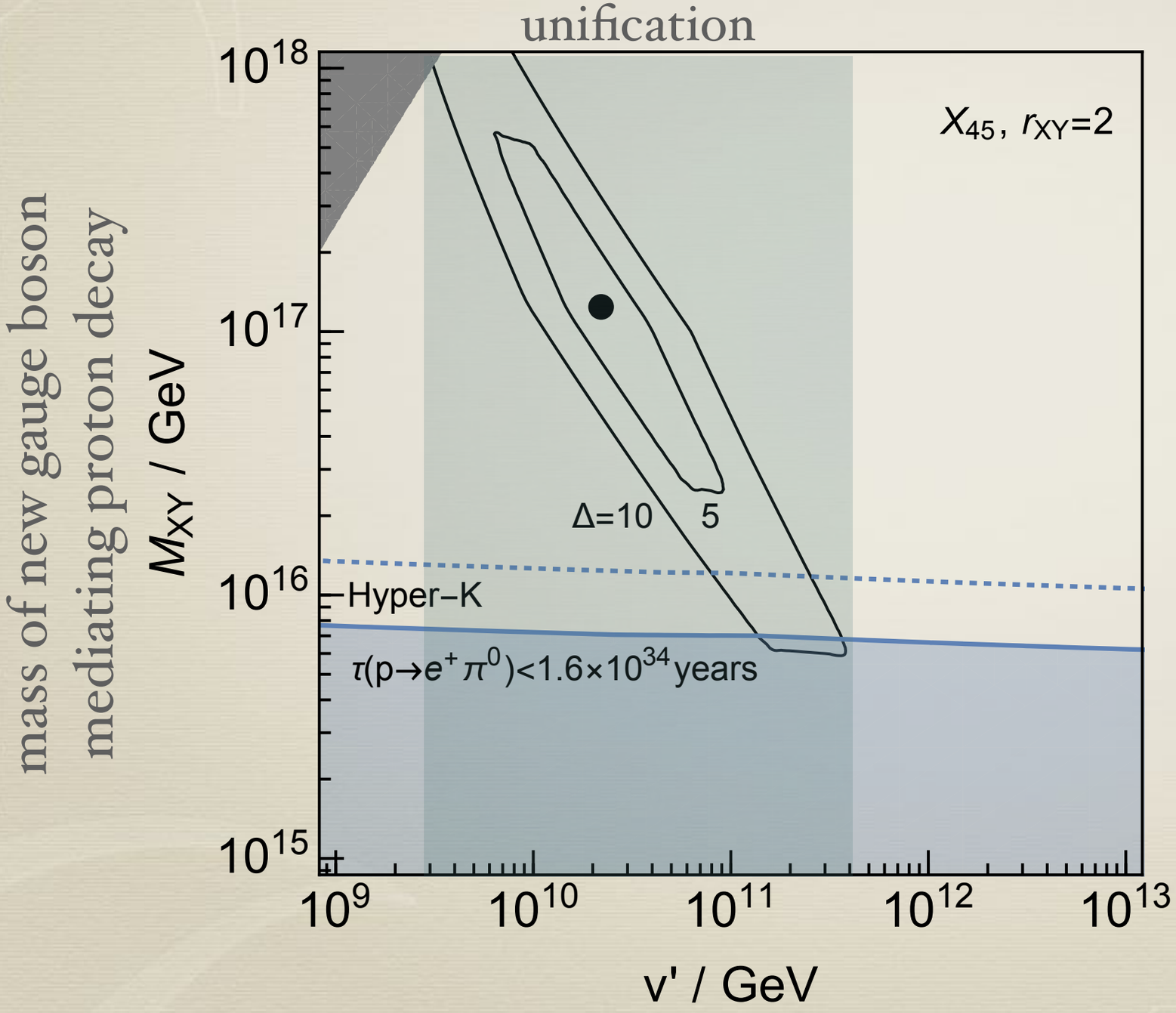
typically

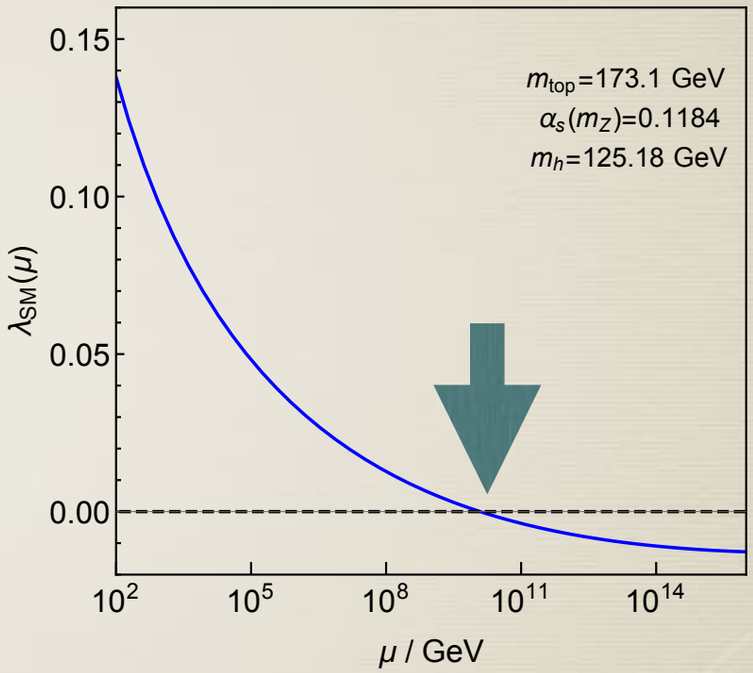
$$\Delta = \text{few} - 10$$

(smaller than SUSY GUT)

Quantify unification

Hall, KH (2019)



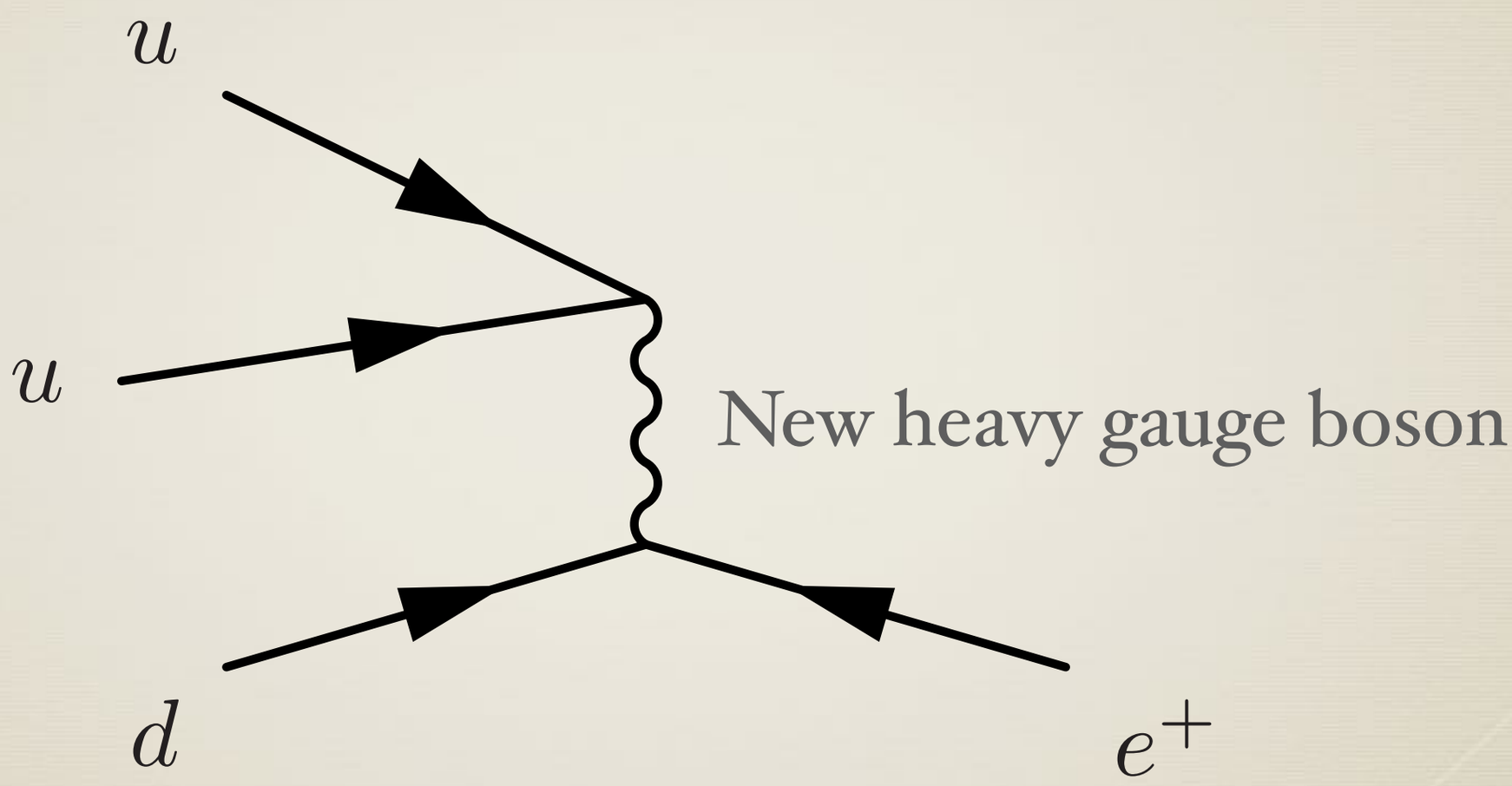


typically

$$\Delta = \text{few} - 10$$

(smaller than SUSY GUT)

Proton decay

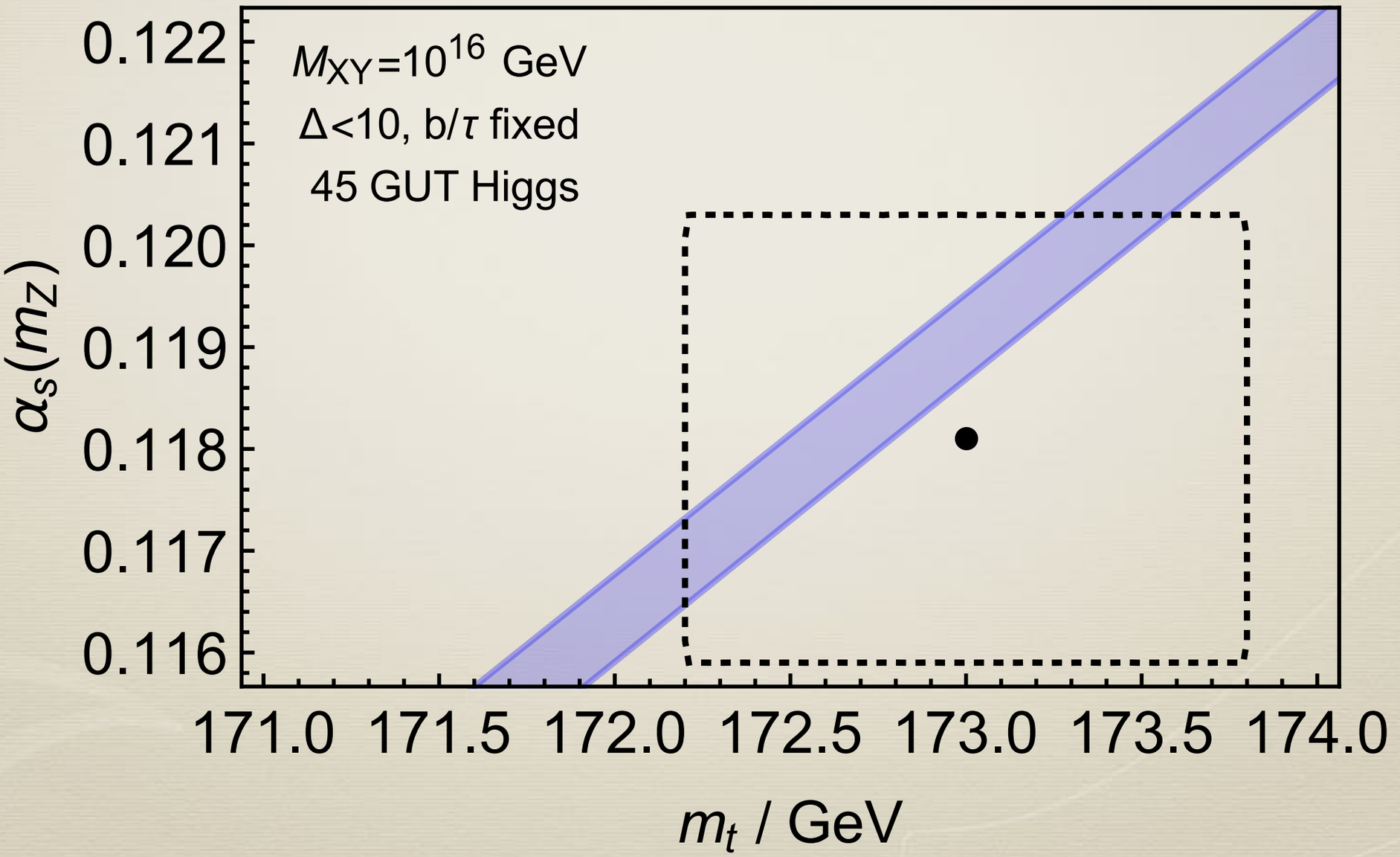


$$p \to e^+ \pi^0$$

Proton decay

Hall, KH (2019)

Suppose proton decay is observed at Hyper-K (2027-)



On fine-tuning

Fine-tuning

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

$$\frac{v'^2}{\Lambda_{\text{cut}}^2} \times \frac{v^2}{v'^2} = \frac{v^2}{\Lambda_{\text{cut}}^2}$$

Same as that of standard model

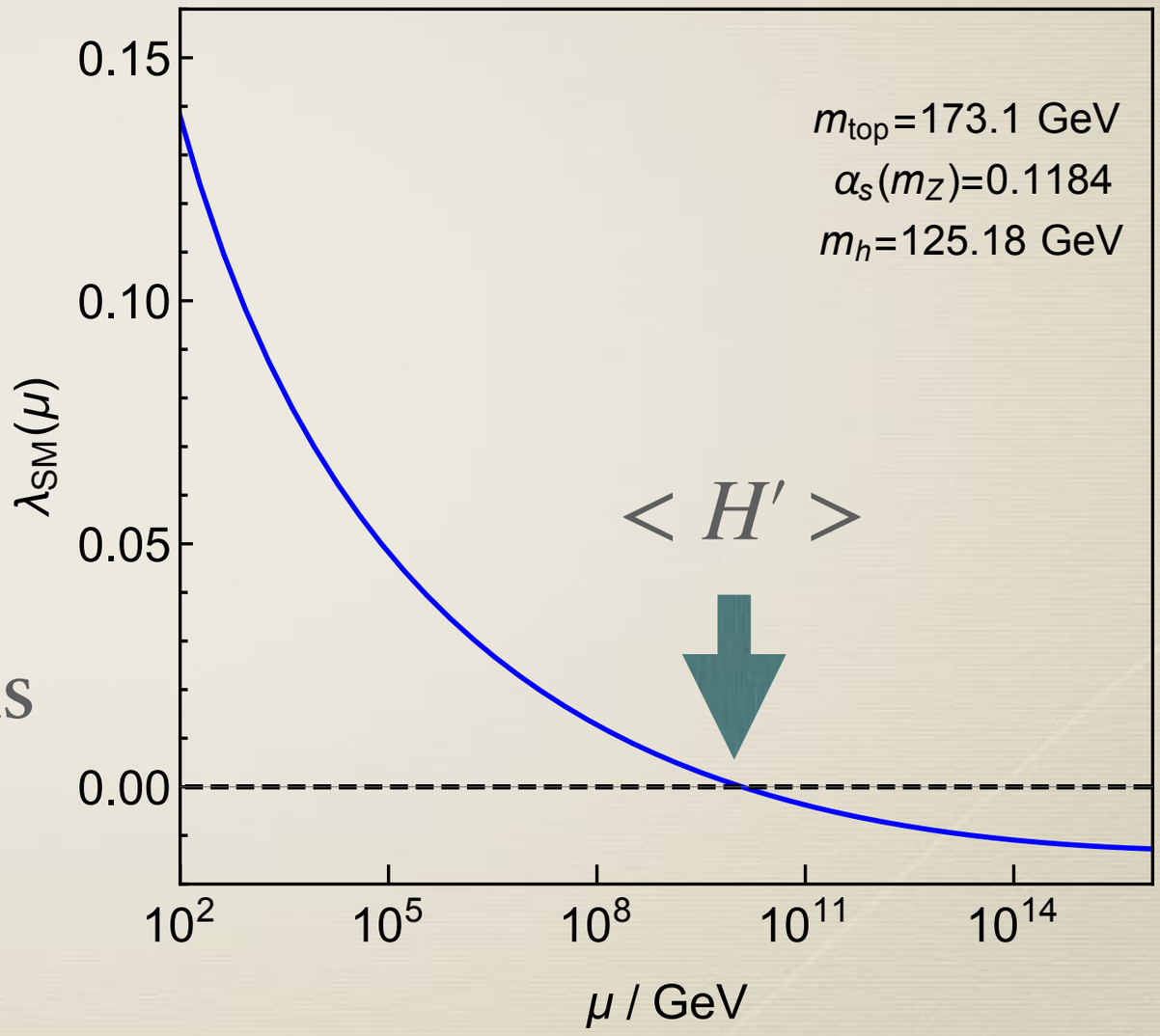
Small quartic

HP symmetry breaking scale

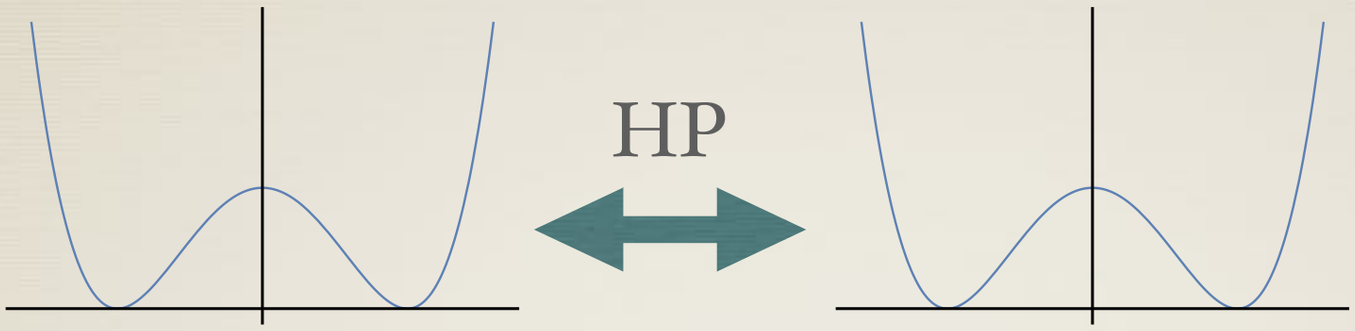
I will show that

$$\lambda_{\mathrm{SM}}(\,<H'>\,) \simeq 0$$

because Higgs Parity constrains the potential of H and H'



Higgs potential

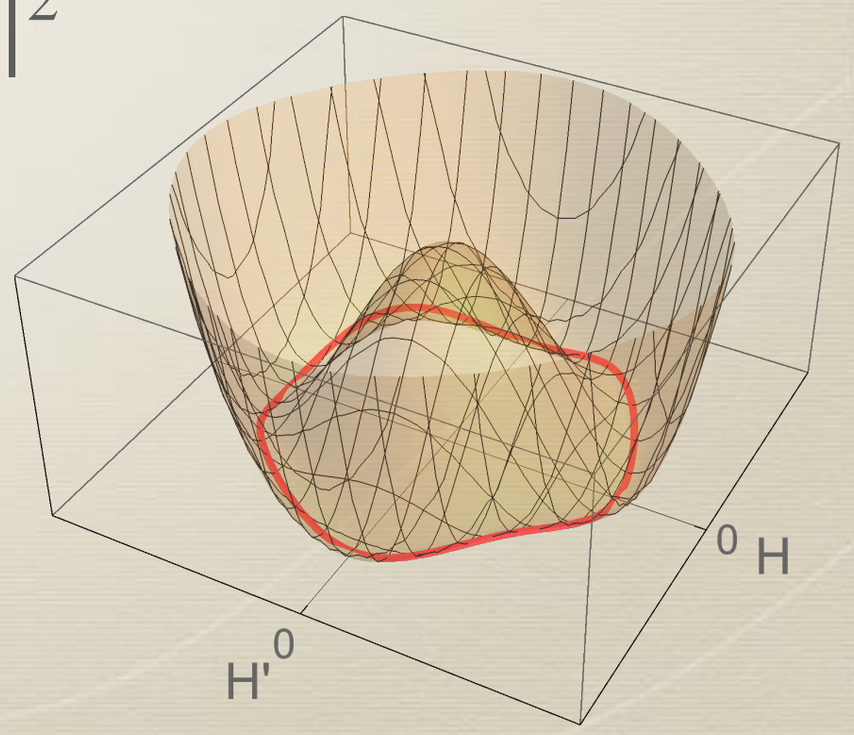


$$V = \left(\lambda |H|^4 - m^2 |H|^2\right) + \left(\lambda |H'|^4 - m^2 |H'|^2\right) + \tilde{y}\,|H|^2 |H'|^2$$

$$= \lambda \left(|H|^2 + |H'|^2 - v'^2 \right)^2 + y |H|^2 |H'|^2$$

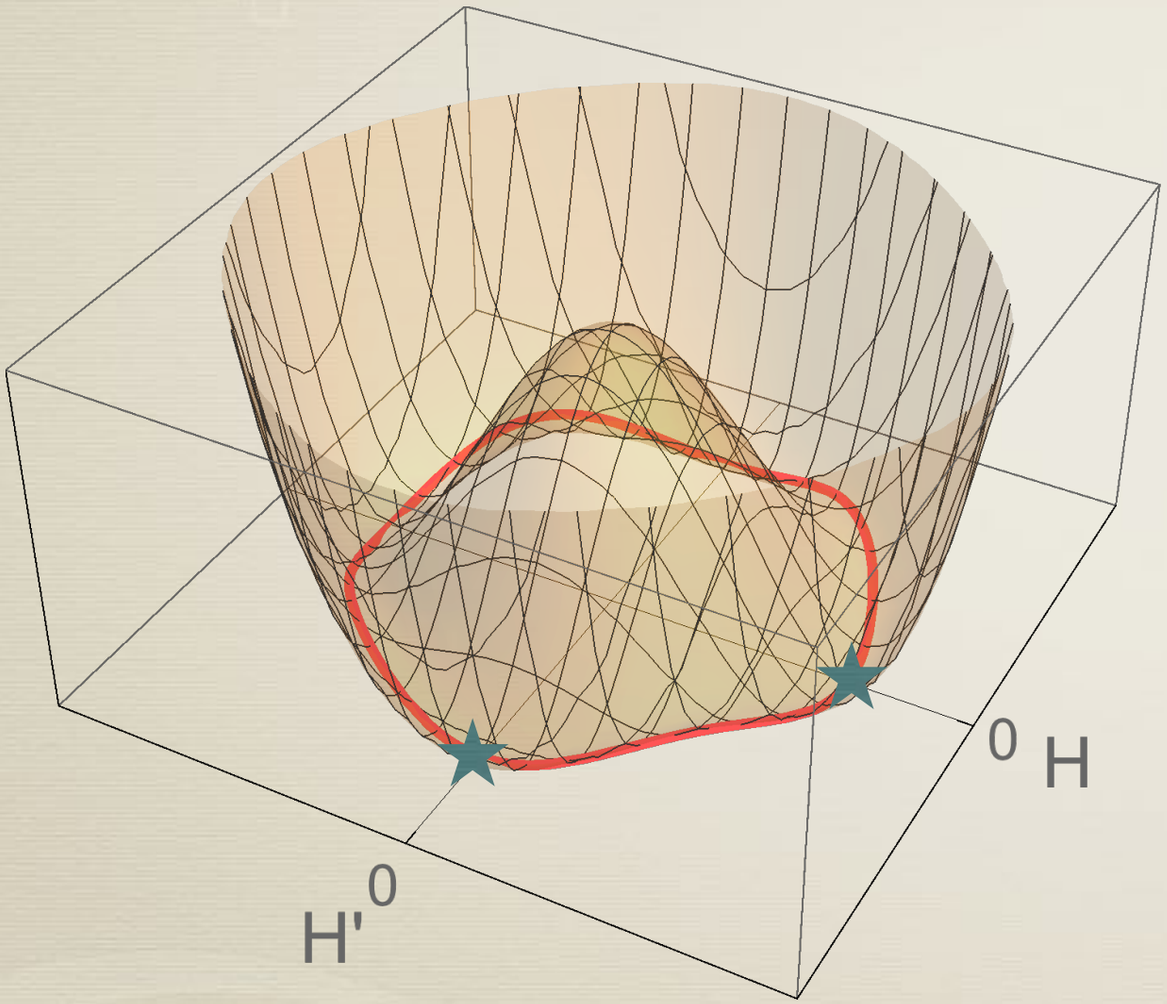
Can we find the minimum with

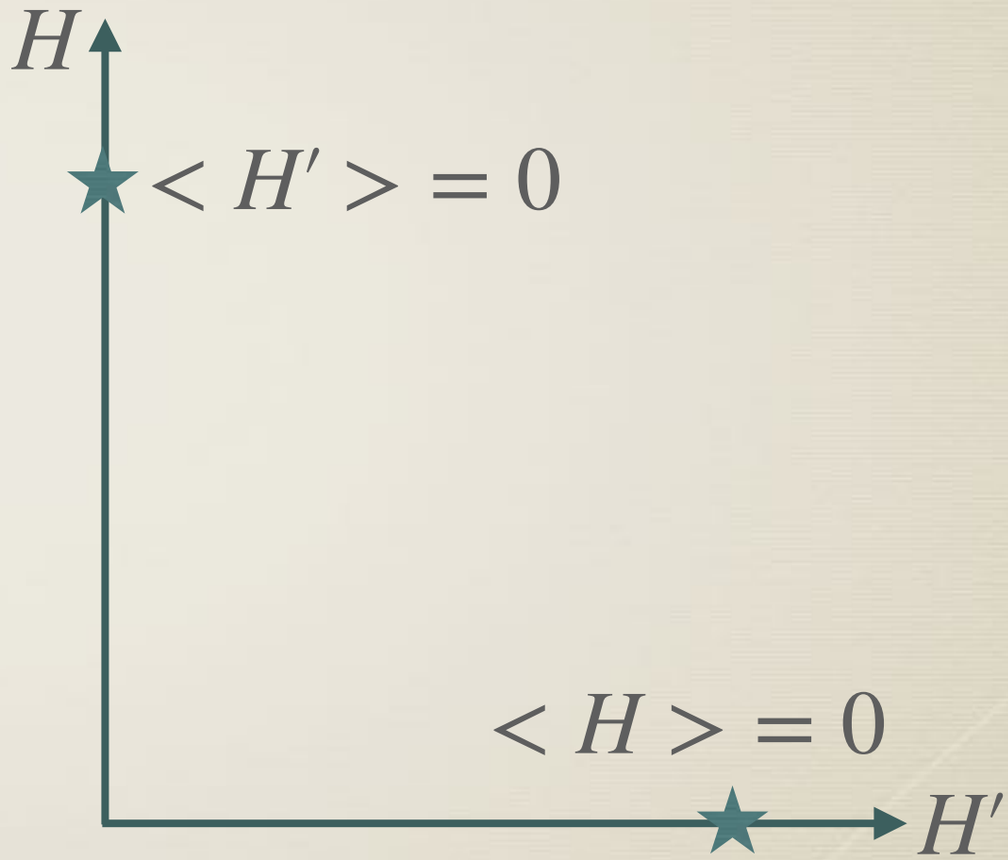
$$\langle H \rangle \ll \langle H' \rangle \; ?$$



$y > 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

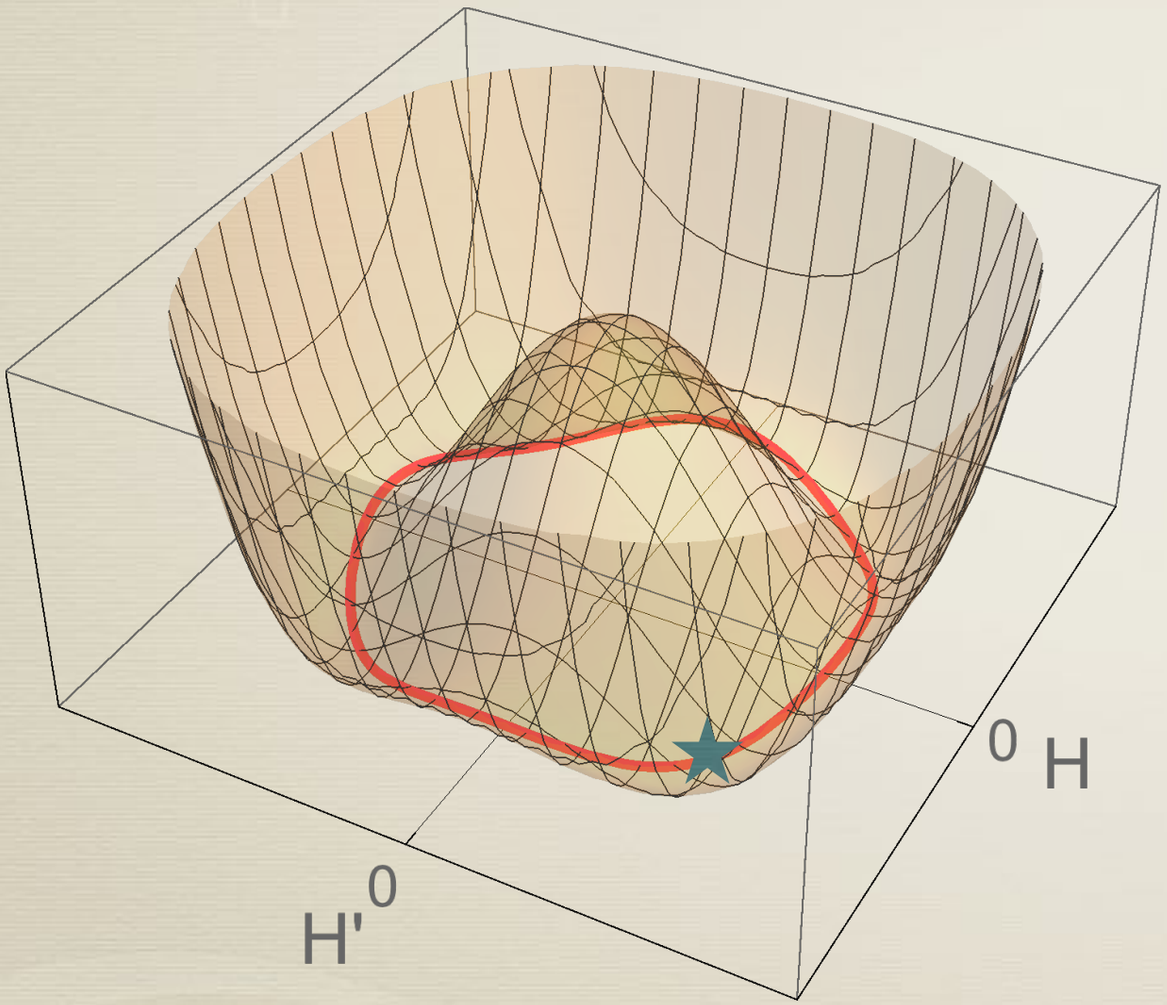


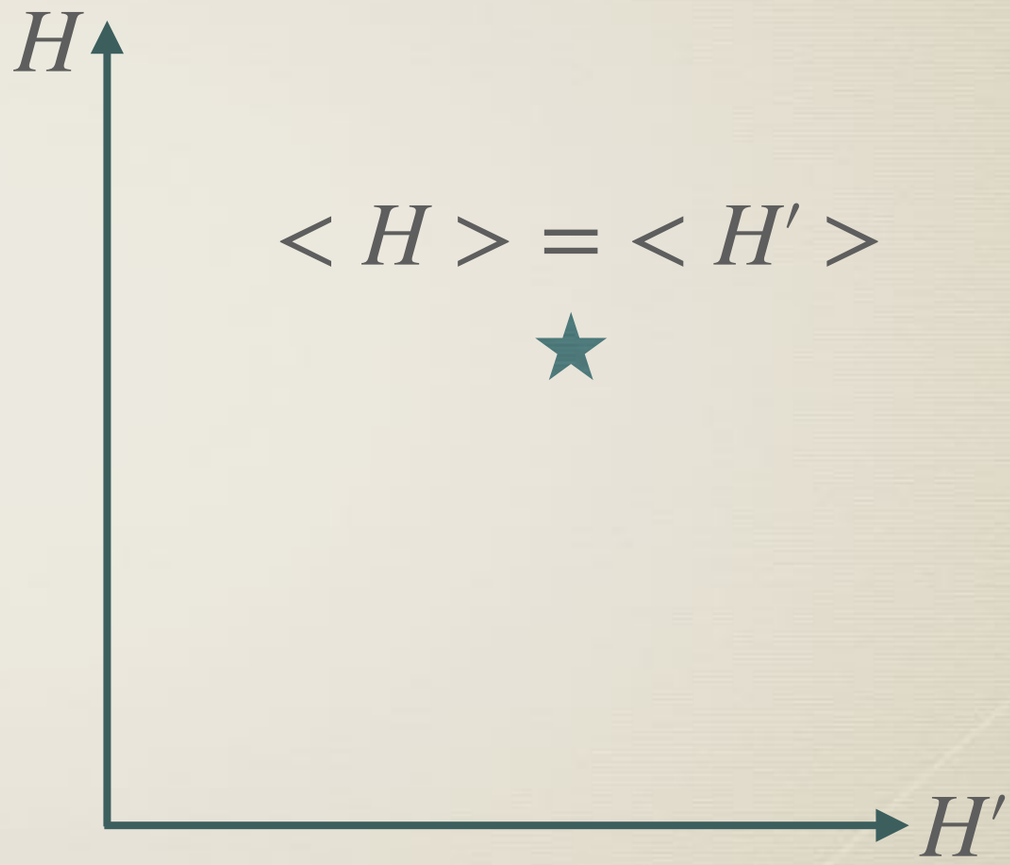


$$0 \neq \langle H \rangle \ll \langle H' \rangle$$

$y < 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

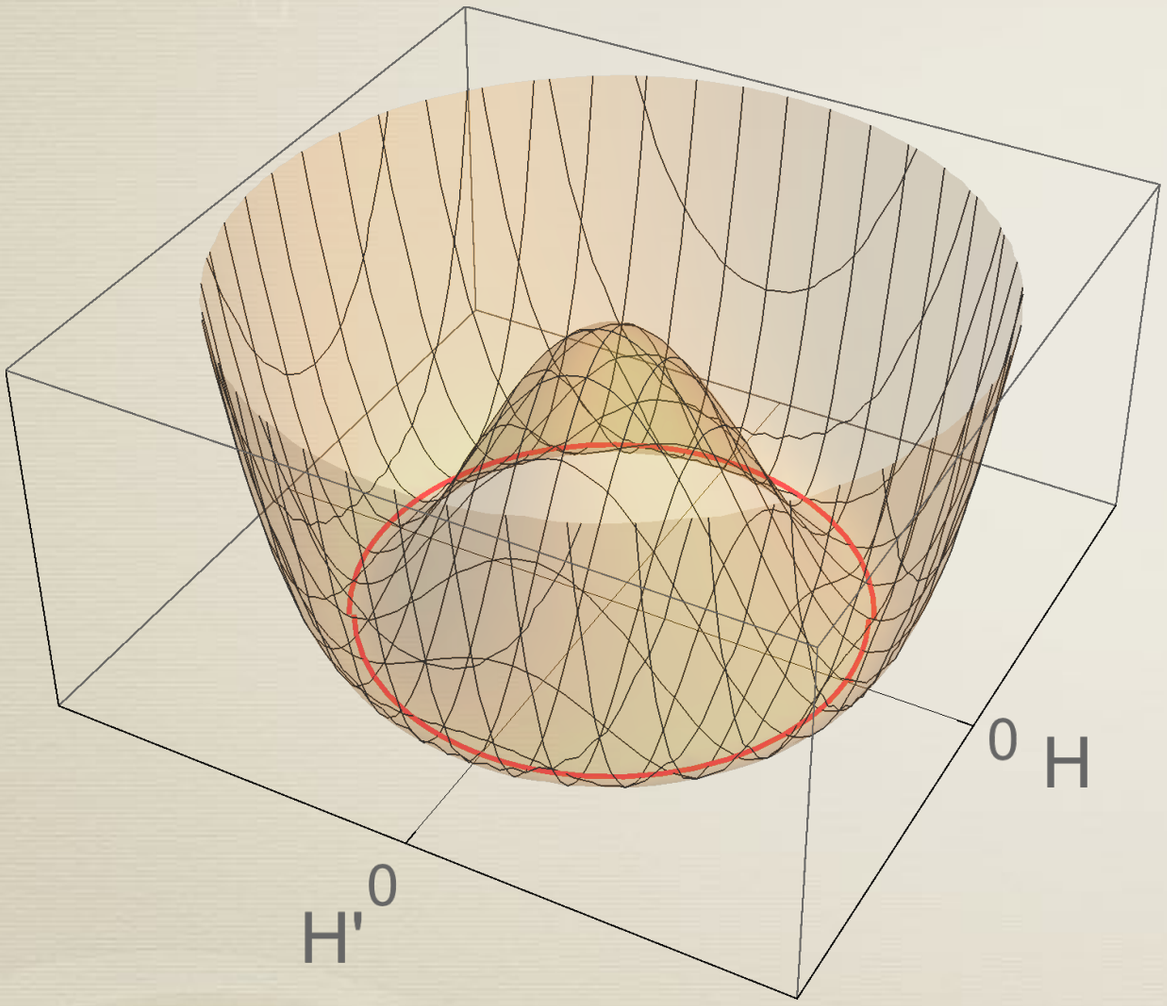


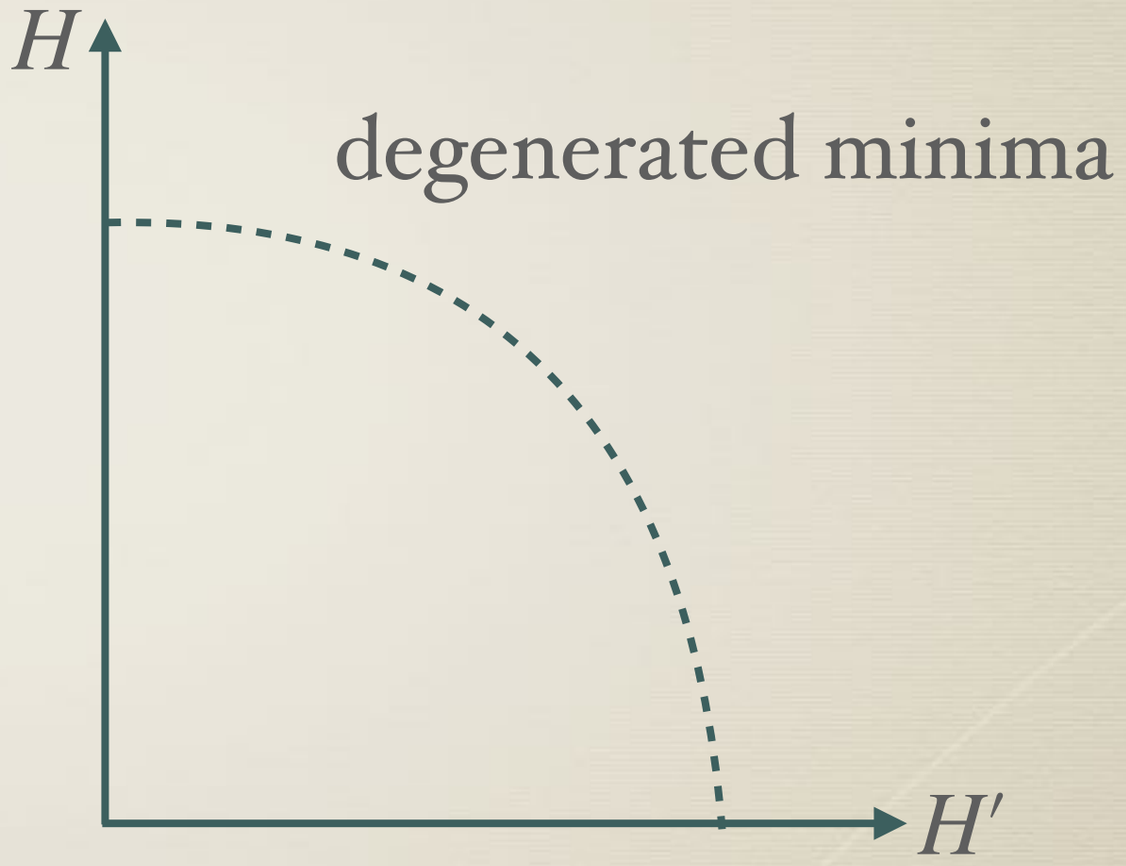


$$\langle H \rangle \ll \langle H' \rangle$$

$$y \simeq 0$$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + \cancel{y|H|^2|H'|^2}$$





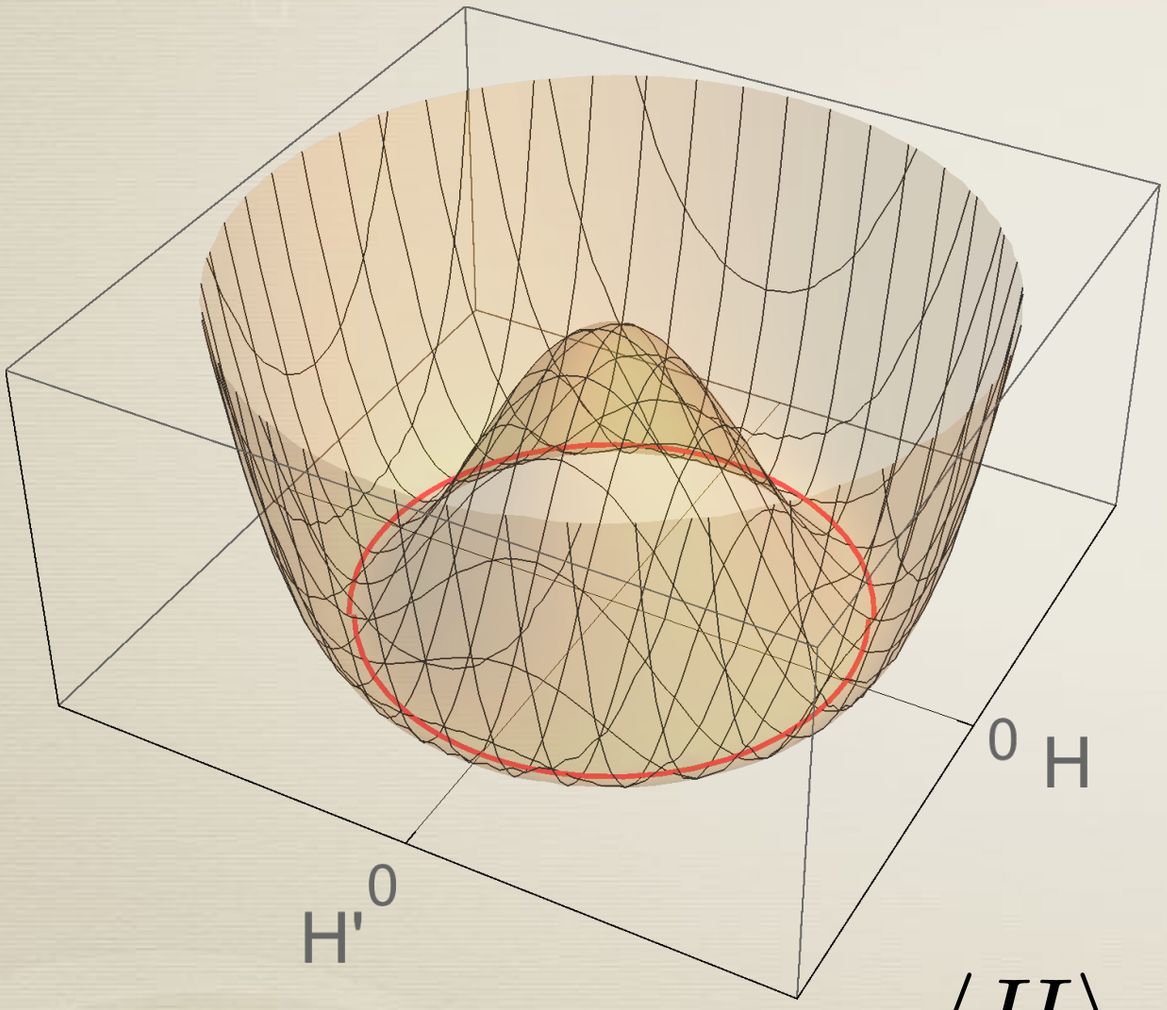
degenerated minima

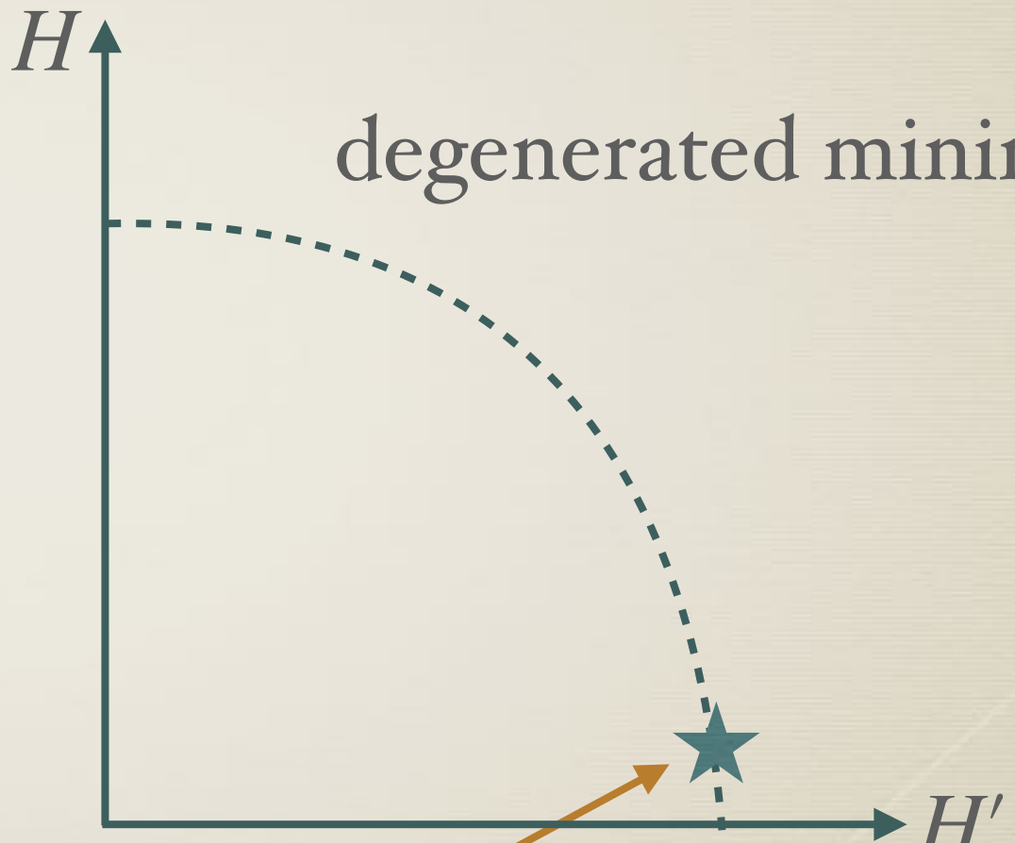
symmetry rotating the vector

(H, H')

$$y \simeq 0$$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + \cancel{y|H|^2|H'|^2}$$





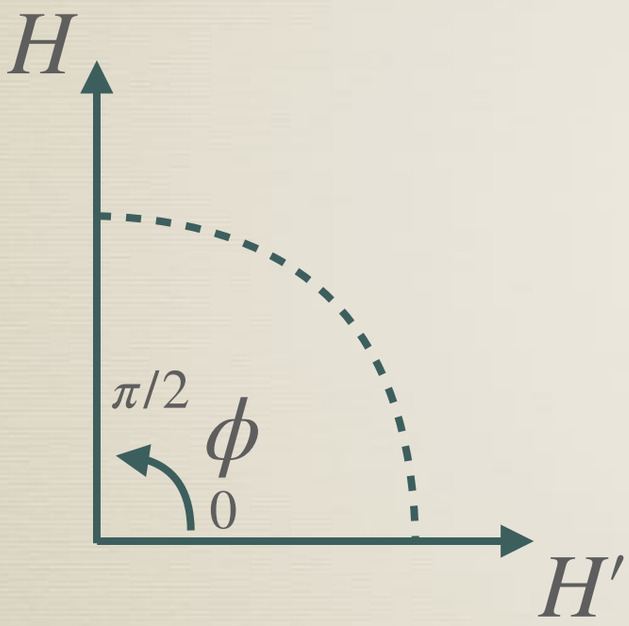
degenerated minima

$$\langle H \rangle \ll \langle H' \rangle \, ?$$

Degeneracy is resolved by quantum corrections

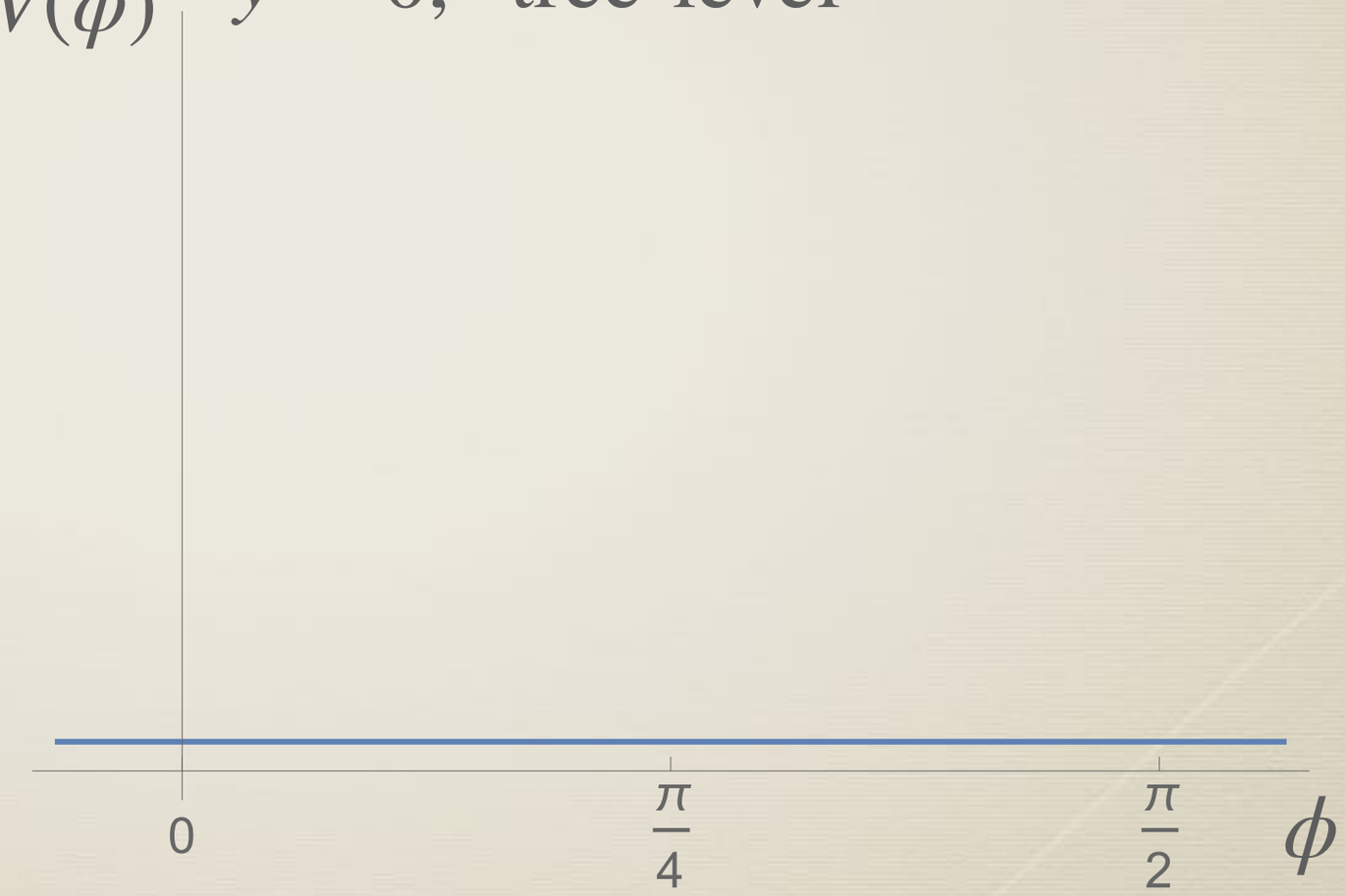
$y \simeq 0$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2$$



angular direction ϕ

$V(\phi)$ $y = 0$, tree level

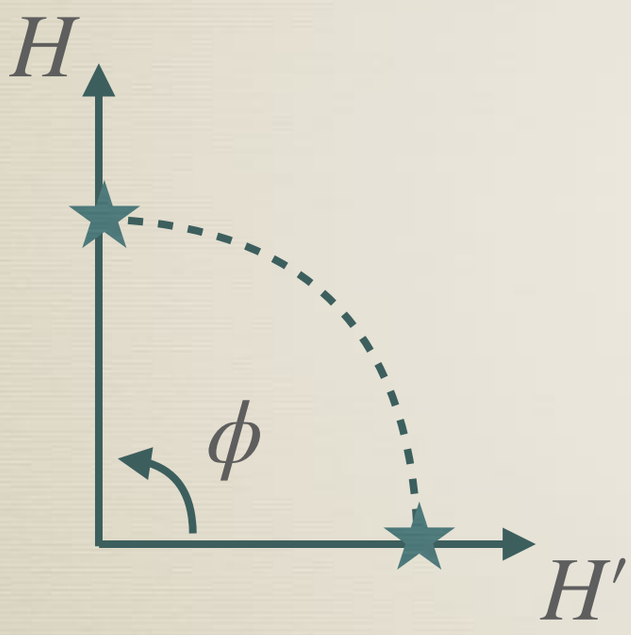


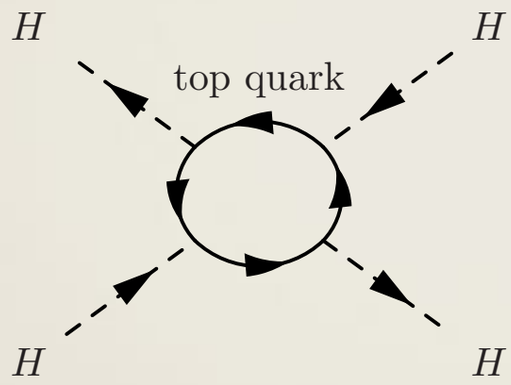
$$y \simeq 0$$

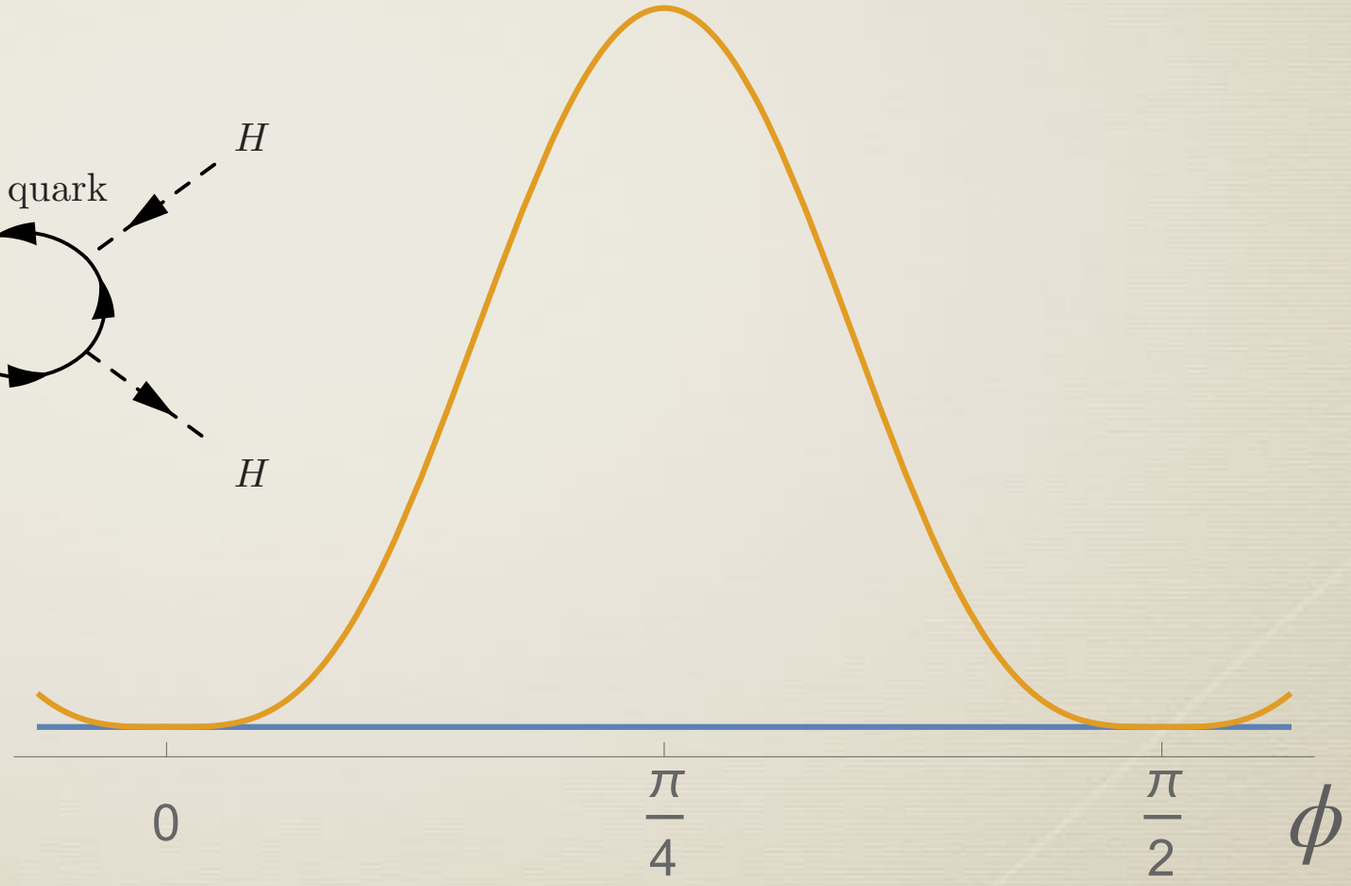
Colemann-Weinberg potential

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + V_{\text{quantum}}(H, H')$$

$y = 0$, quantum correction





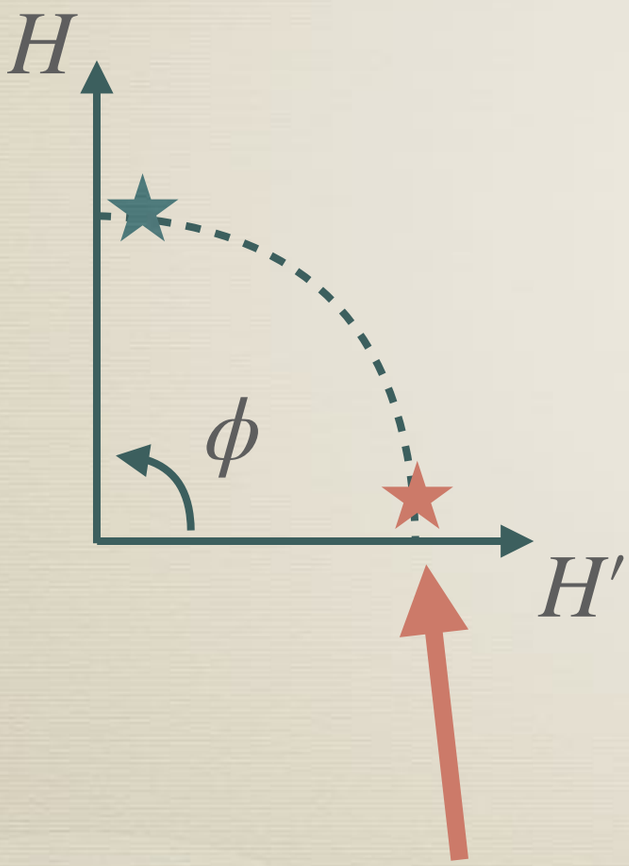


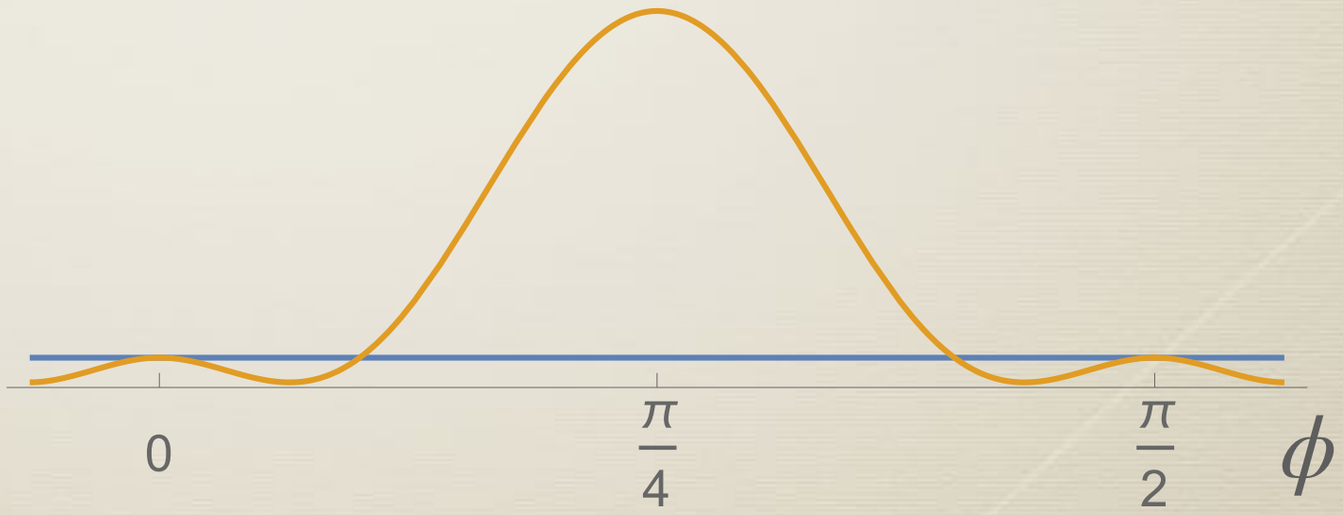
$$y \simeq 0$$

$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + V_{\text{quantum}}(H, H') + y|H|^2|H'|^2$$

$$y \simeq -\frac{v^2}{v'^2}, \quad \text{quantum correction}$$

(fine-tuned Higgs mass)





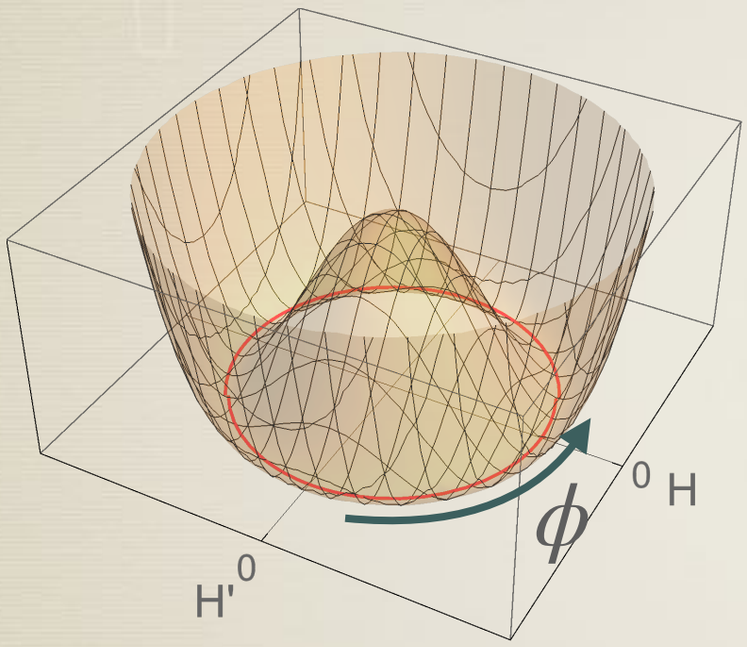
$\langle H \rangle \ll \langle H' \rangle$ is achieved !

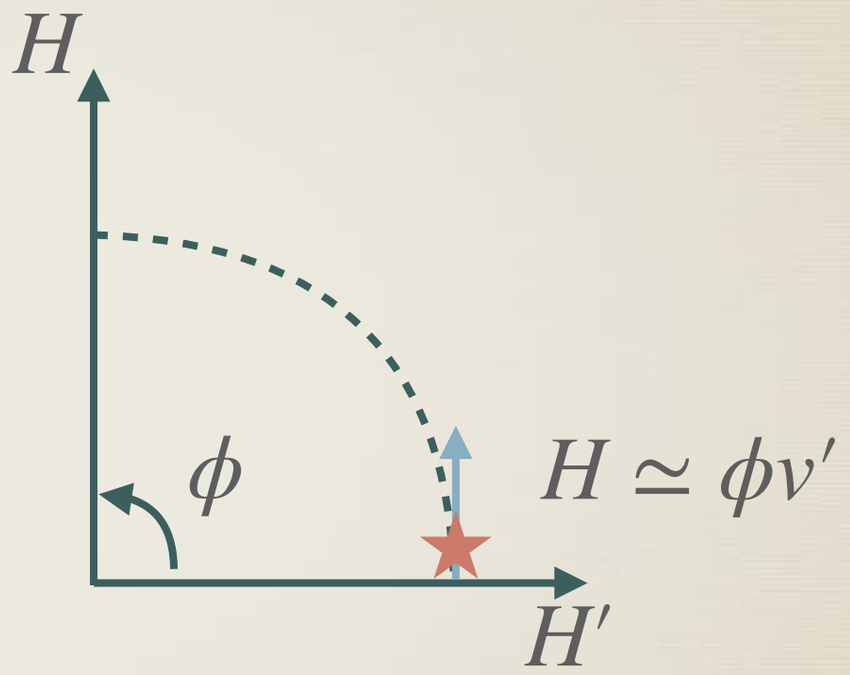
Hall, KH (2018)

Prediction on the quartic coupling

Hall, KH (2018)

$V \simeq \lambda(|H|^2 + |H'|^2 - v'^2)^2$ + small corrections





symmetry rotating the vector (H, H')

Standard Model Higgs is a (pseudo) Nambu-Goldstone boson associated with symmetry breaking by $\langle H' \rangle = v'$

$$\lambda_{\rm SM}(v') \simeq 0$$

(up to calculable threshold correction)

Strong CP problem

Mirrored electroweak theory

SM particles

New particles

q	strong interaction	q’
u	$SU(3)_c$	u’
d		d'
L	HP	L’
e		e’
H		H’

electroweak

W, Z $SU(2)_L \times U(1)_Y$ γ

$\downarrow$

$U(1)_{\mathrm{EM}}$

electroweak’

$SU(2)'_L \times U(1)'_Y$ W', Z'

$\downarrow$

$U(1)'_{\mathrm{EM}}$ γ'

Strong CP problem solved

Barr, Chang and Senjanovic (1991)

HP

$$\mathscr{L} = yq\bar{u}H^{\dagger} + yq'^{\dagger}\bar{u}'^{\dagger}H' + y^{*}q^{\dagger}\bar{u}^{\dagger}H + y^{*}q'\bar{u}'H'^{\dagger}$$

HP

$$+\frac{\theta}{32\pi^2}G\tilde{G}$$

$\Delta\theta_q$

$\Delta\theta_{q'} = -\Delta\theta_q$

$\theta_{\mathrm{CPV}} = \Delta\theta_q + (-\Delta\theta_q) = 0$ cancel with each other

Dark Matter

u'u'u' DM?

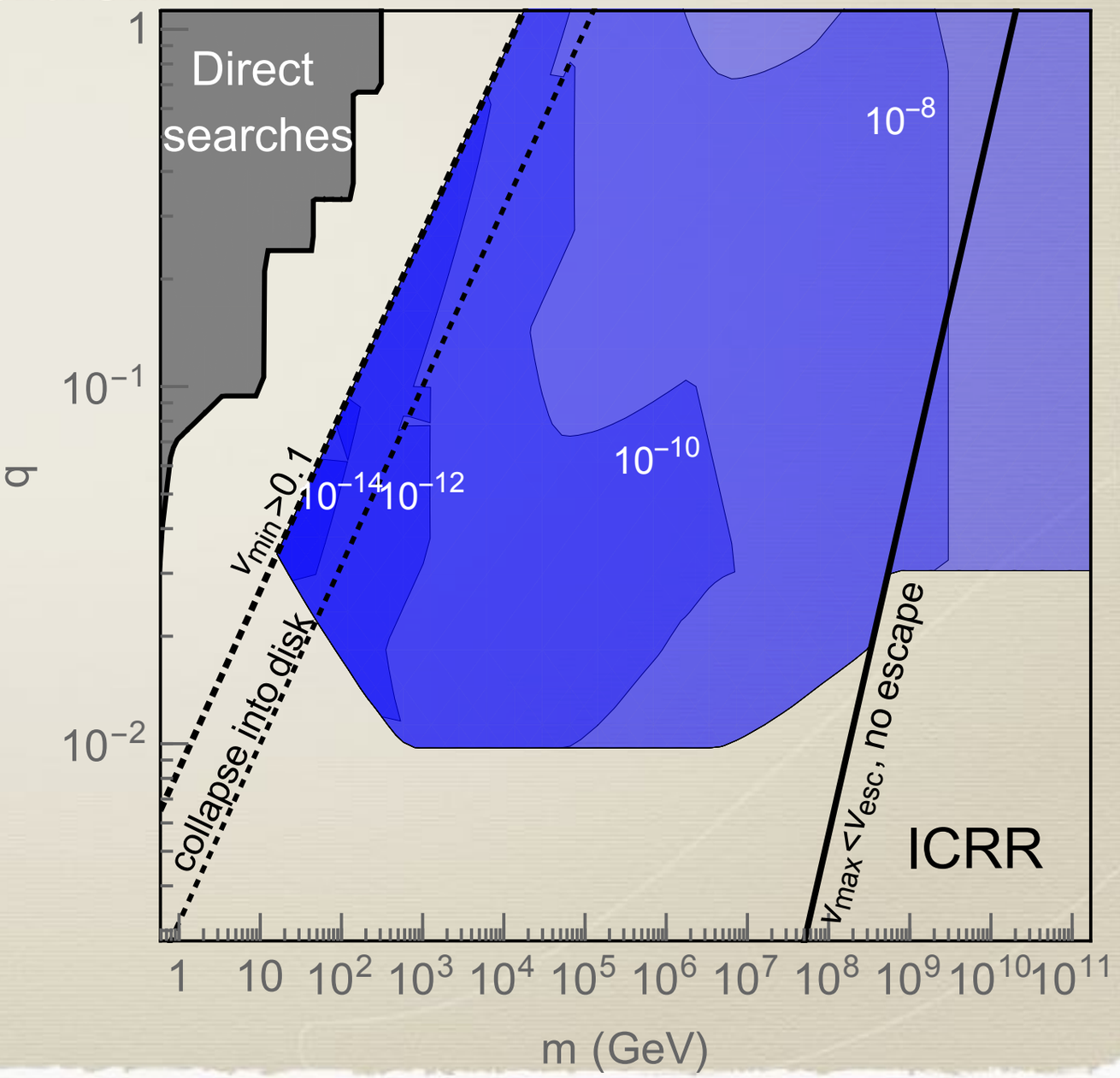
u'qq, u'qbar are necessarily produced after the QCD phase transition

Dunsky, Hall, KH (2018)

Upper bound on

$$\frac{\Omega_{u'\bar{u}}}{\Omega_{\rm DM}}$$

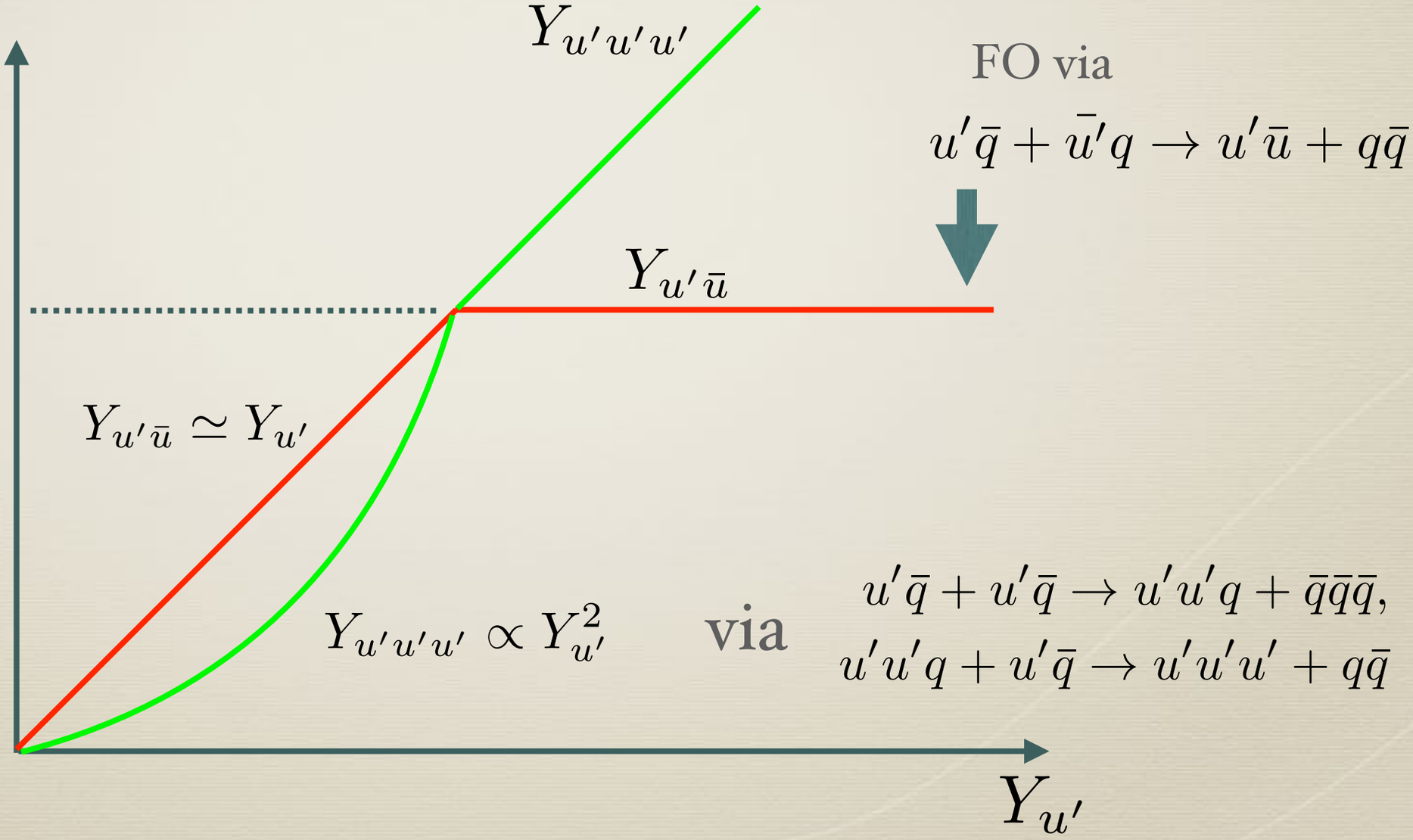
by ionizing particle searches



u'u'u' DM?

Dunsky, Hall, KH (2019)

Y of colour neutral states



FO via

$$u'\bar{q} + \bar{u}'q \to u'\bar{u} + q\bar{q}$$

At the smallest

$$\frac{\Lambda_{\rm QCD}}{M_{pl}} \sim 10^{-18}$$

Likely to be larger

Arvanitaki et.al (2005)
De Luca et.al (2018)

via

$$u'\bar{q} + u'\bar{q} \to u'u'q + \bar{q}\bar{q}\bar{q},$$
$$u'u'q + u'\bar{q} \to u'u'u' + q\bar{q}$$

e' without u'

$$T \ll m_{u'} \text{ and}$$

Dunsky, Hall, KH (2019)

Inflaton → e'ebar', ~~u'ubar'~~

e.g. by

$$2m_{e'} < \phi < 2m_{u'}$$

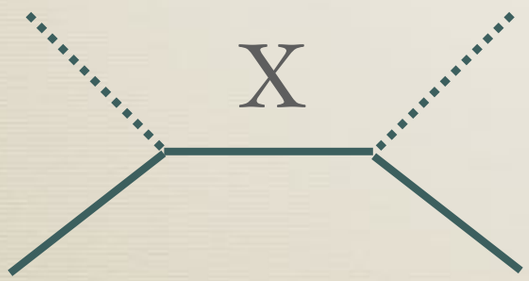
Other possibilities?
Baryogenesis for low temperature?

More on GUT

Yukawa interaction

No gauge invariant renormalizable coupling

$$\frac{c_{ij}}{M} H H' q_L \bar{q}_R$$

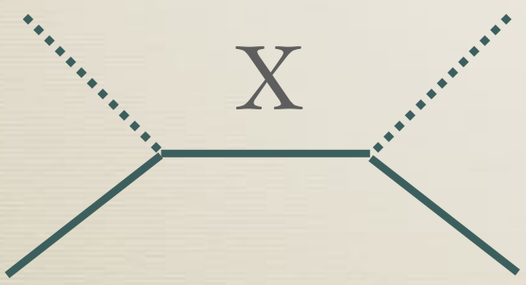


Strong CP problem solved

Babu and Mohapatra (1989)
Hall and KH (2018)

No gauge invariant renormalizable coupling

$$\frac{c_{ij}}{M} H H' q_L \bar{q}_R$$

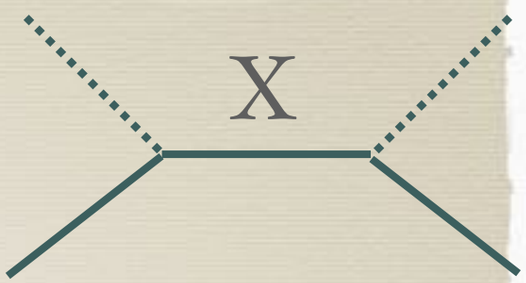


HP

$$q_L(t,x) \leftrightarrow q_R(t,-x)$$

$$c = c^\dagger, \arg(\det[c]) = 0$$

Yukawa couplings



Small enough not to blow up the gauge coupling

	$SU(3)_c$	$SU(2)_L$	$SU(2)_R$	$U(1)$	$SU(4)$	$SO(10)$	coupling
up	**3**	**1**	**1**	$2/3$	**15**	**45**	$\bar{X}qH^\dagger + Xq'H'^\dagger$
	3	**2**	**2**	$-1/3$	**6/10**	**45, 54, 210/210**	$\bar{X}qH'^\dagger + Xq'H^\dagger$
down	**3**	**1**	**1**	$-1/3$	**6/10**	**10, 126/120**	$\bar{X}qH + Xq'H'$
	3	**2**	**2**	$2/3$	**15**	**120, 126**	$\bar{X}qH' + Xq'H$
electron	**1**	**1**	**1**	-1	**10**	**120**	$\bar{X}\ell H + X\ell' H'$
	1	**2**	**2**	0	**1/15**	**10, 120/120, 126**	$X\ell H' + X\ell' H$
neutrino	**1**	**1**	**1**	0	**1/15**	**1, 54, 210/45, 210**	$X(\ell H^\dagger + \ell' H'^\dagger)$
	1	**2**	**2**	-1	**10**	**210**	$\bar{X}\ell H'^\dagger + X\ell' H^\dagger$
	1	**3**	**1**	0	**1**	**45**	$X\ell H^\dagger$
	1	**1**	**3**	0	**1**	**45**	$X\ell' H'^\dagger$

SO(10) embedding

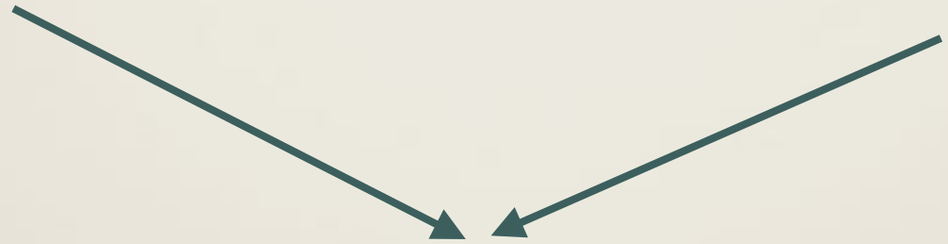
$$q, \ell, q', \ell' = 16$$

$$H, H' \subset 16_H$$

Hall, KH (2018)

$$q(t,x) \leftrightarrow \bar{q}'(t,x) \qquad q(t,x) \leftrightarrow i\sigma_2 q^*(t,-x)$$

C: Part of SO(10) CP



$$q(t,x) \leftrightarrow i\sigma_2 \bar{q}'^*(t,-x)$$

$$SO(10) \times CP \xrightarrow{\phi_{45}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

CKM phase

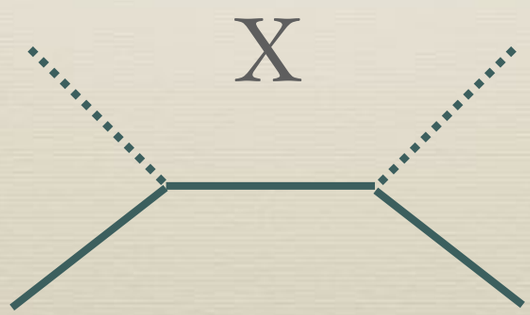
$$SO(10) \times CP \xrightarrow{\phi_{45}^{-}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

Real yukawas, without CP symmetry breaking...

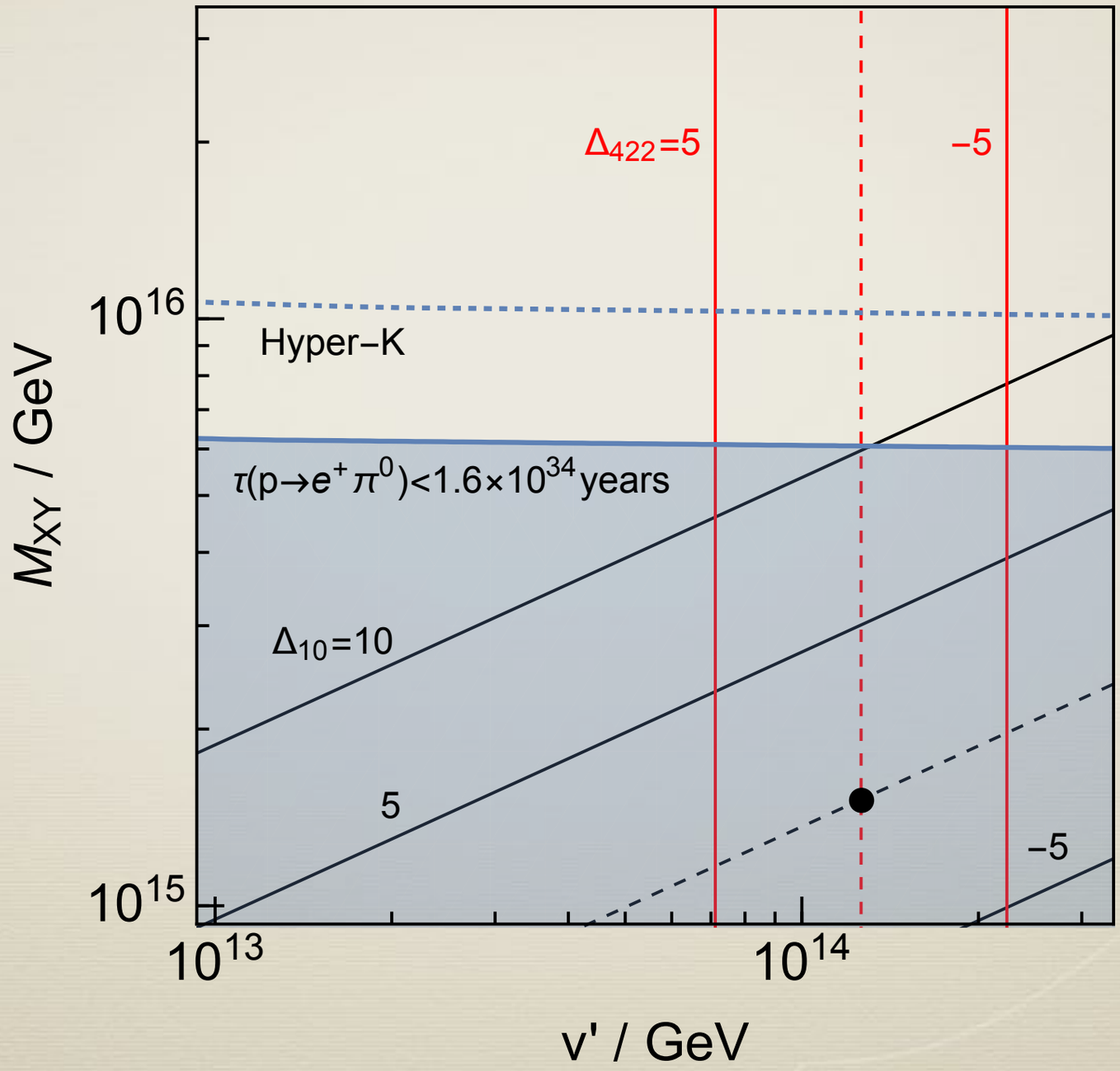
A simple renormalizable example to obtain CP phases

$$\mathcal{L} = \left(M^{ij} + i\lambda^{ij}\phi_{45}\right) X_{10,i} X_{10,j}$$

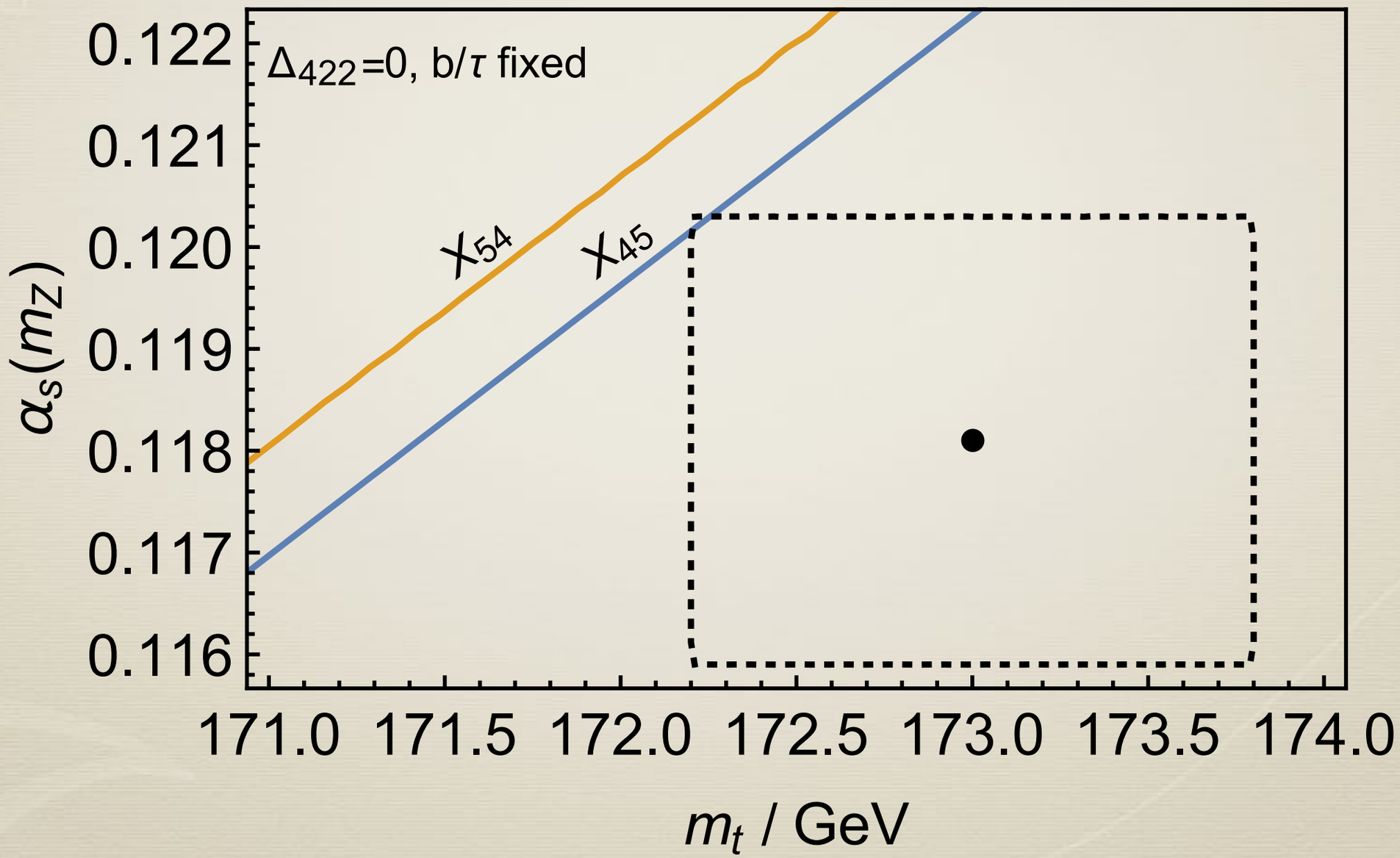
$$\frac{c_{ij}}{M} H H' q_i q'_j$$



Pati-Salam

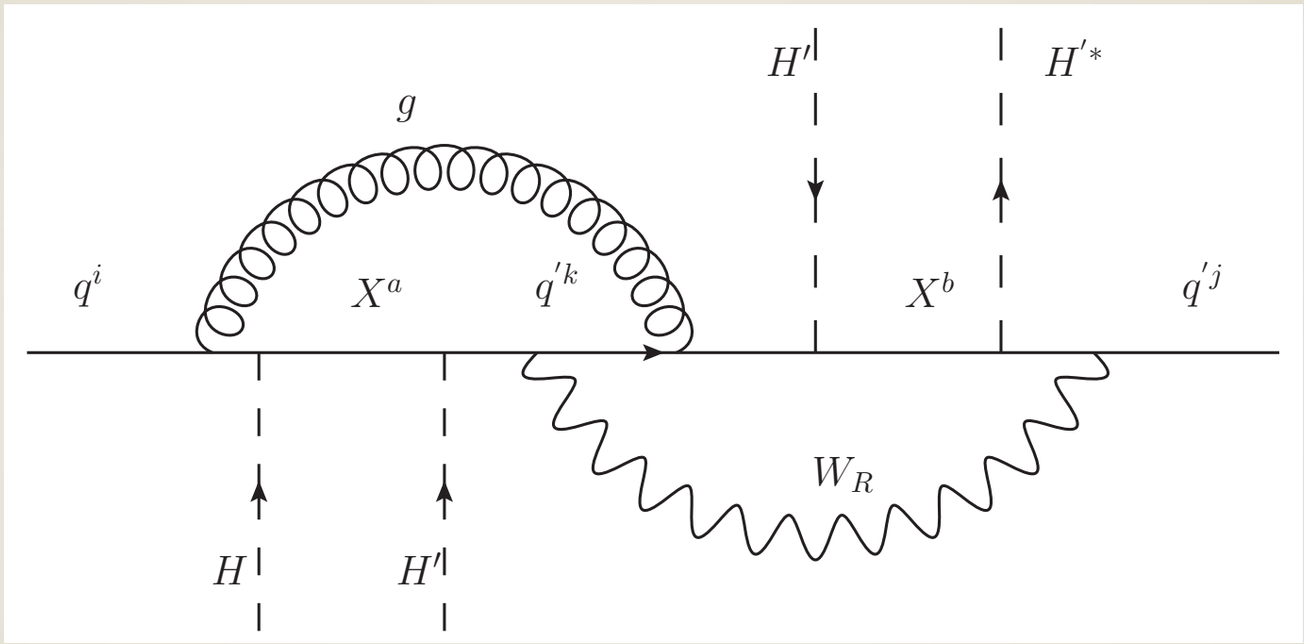

Δ_{422}=5
−5
10^{16}
Hyper−K
$\tau(p\to e^+\pi^0)<1.6\times10^{34}$years
M_{XY} / GeV
Δ_{10}=10
5
−5
10^{15}
10^{13}
10^{14}
v' / GeV

Pati-Salam


Δ_{422}=0, b/τ fixed
X_{54}
X_{45}
$\alpha_s(m_Z)$
0.122
0.121
0.120
0.119
0.118
0.117
0.116
171.0
171.5
172.0
172.5
173.0
173.5
174.0
m_t / GeV

Non-zero CPV

Hall, KH (2018)



$$\delta\theta \sim 10^{-11} \frac{\theta^u_{23}\theta^d_{23}}{V^2_{cb}}$$

Suppressed by loop factors, flavor mixing

Correction to the gauge coupling unification by high dimensional operator

$$SO(10) \xrightarrow{\phi_{210}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times C_{LR}$$

$$\frac{210^{abcd}}{M_*} F_{10}^{ab} F_{10}^{cd} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \lesssim 10$$

$$SO(10) \times CP \xrightarrow{\phi_{45}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

$$\frac{45^{ac}}{M_*} \frac{45^{bd}}{M_*} F_{10}^{ab} F_{10}^{cd} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \lesssim 1$$

Correction to the gauge coupling unification by high dimensional operator

$$SO(10) \xrightarrow{\phi_{54}} SU(4) \times SU(2)_L \times SU(2)_R \times C_{LR}$$

$$\frac{54^{ab}}{M_*} F_{10}^{ac} F_{10}^{bc} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \lesssim 1$$

$$SO(10) \times CP \xrightarrow{\phi_{210}} SU(4) \times SU(2)_L \times SU(2)_R \times P_{LR}$$

$$\frac{210}{M_*}\frac{210}{M_*} F_{10} F_{10} \qquad \Delta\left(\frac{2\pi}{\alpha}\right) \ll 1$$

Neutron electric dipole moment

Space-time parity and neutron EDM

The neutron EDM vanishes in the parity symmetric limit

$$\cancel{H = d_n E \cdot S}$$

$\langle H \rangle \ll \langle H' \rangle$ spontaneously breaks the parity

We expect non-zero neutron EDM at some level

Non-zero CP violation

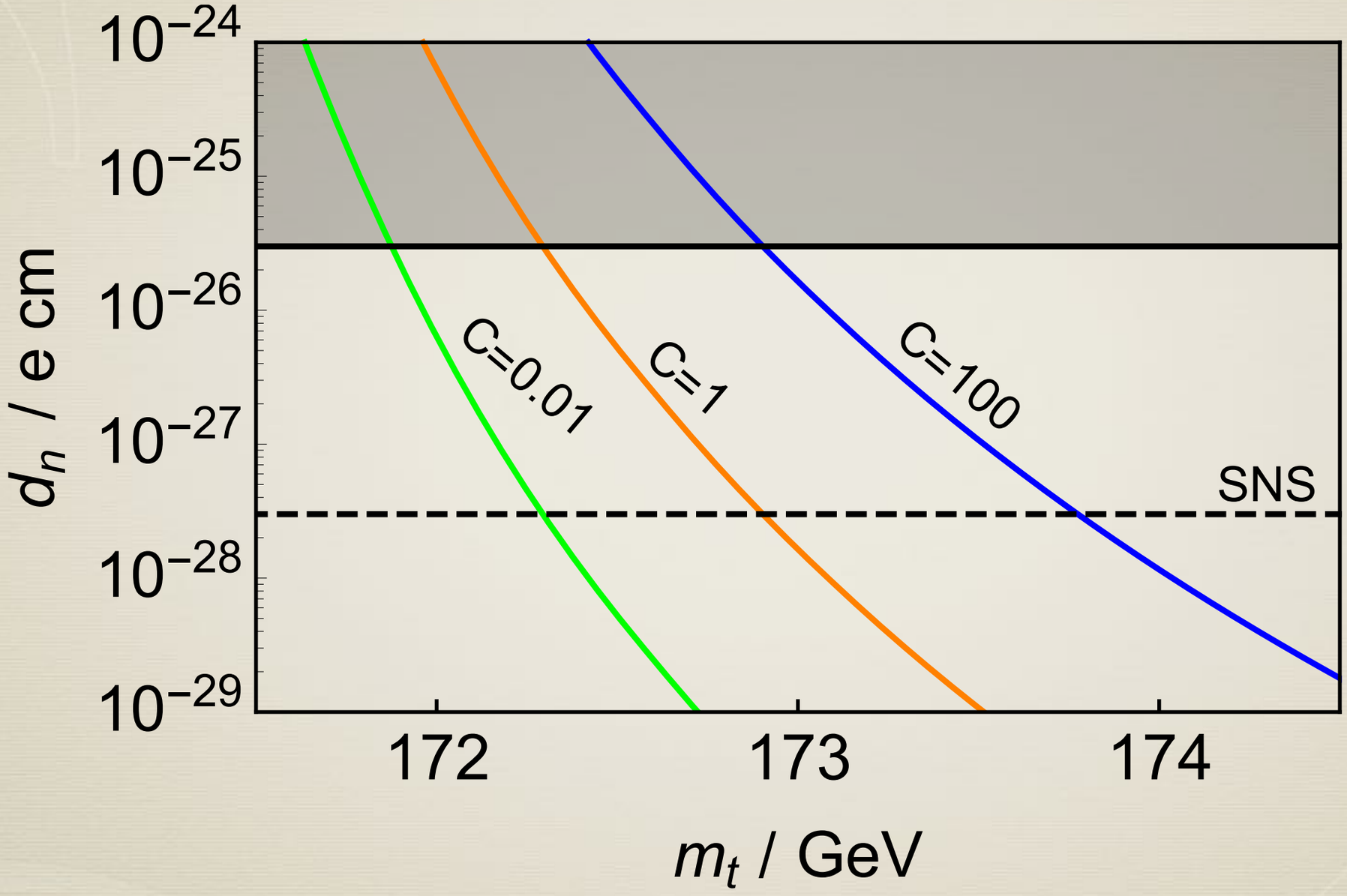
$$\frac{C}{M_{\rm pl}^2}\left(|H|^2-|H'|^2\right)\mathbf{E}\cdot\mathbf{B}$$

Electric and magnetic fields of gluon

$$d_n \simeq 10^{-26}\ e\ \text{cm} \times C\left(\frac{v'}{10^{12}\ \text{GeV}}\right)^2$$

* Present limit $d_n < 2.9\times10^{-26} e$ cm — Baker et.al (2006)
* PSI $d_n < 5\times10^{-27} e$ cm — Baker et.al (2011)
* SNS $d_n < 3\times10^{-28} e$ cm — Tsentalovich (2014)

Neutron EDM



$$\frac{C}{M_{\rm pl}^2}\left(|H|^2-|H'|^2\right)\mathbf{E}\cdot\mathbf{B}$$