09/02/2020

Progress of Particle Physics

Physics beyond the standard model from Higgs Parity

Keisuke Harigaya

(Institute for Advanced Study)

Hall and KH :1803.08119, 1905.12722

Dunsky, Hall and KH :1902.07726, 1908.02756

Particle physics

is trying to answer questions such as

* What are the fundamental laws of physics?

  Particles, interactions among them, ...

* How did our universe begin and evolve?

  Inflation, cosmic perturbations,
  baryon asymmetry, dark matter, ...

Standard Model

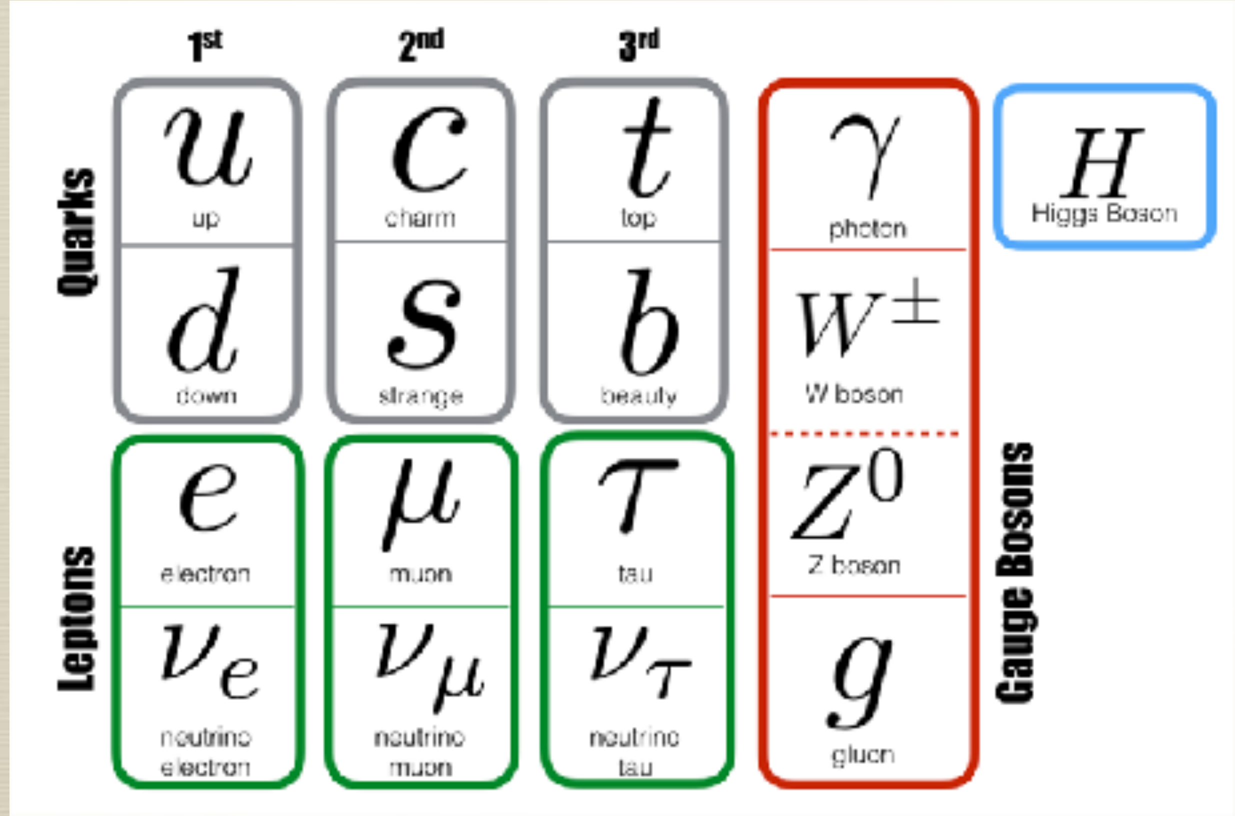
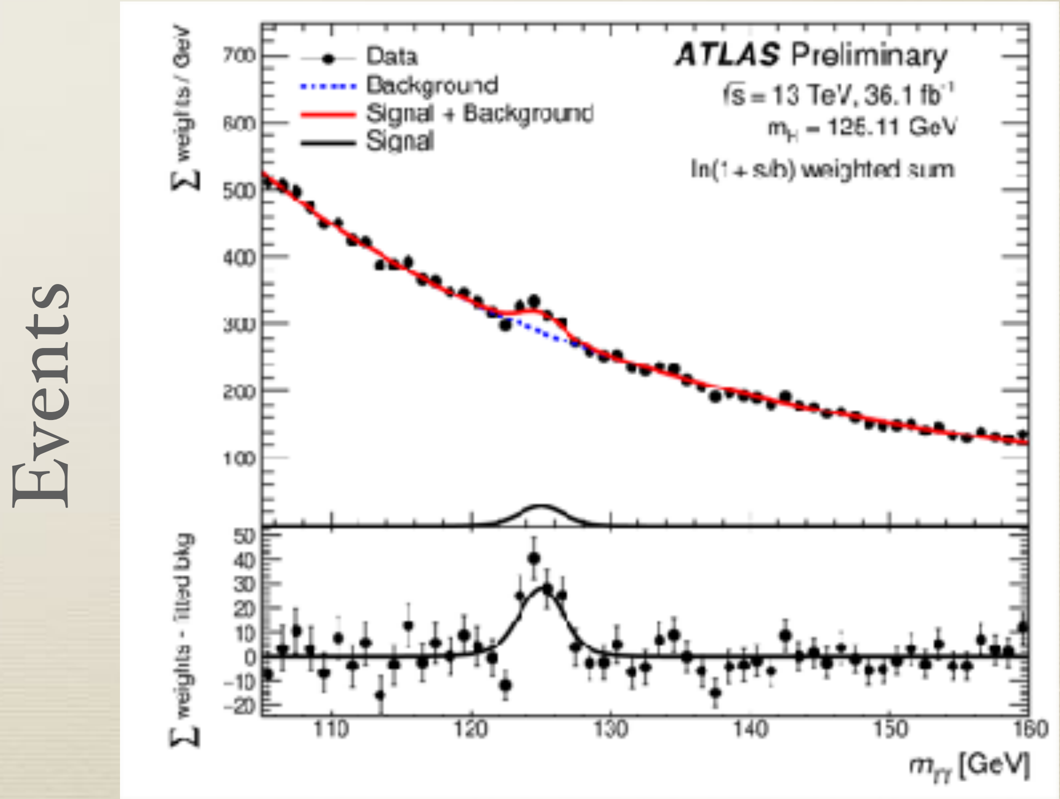


figure from www.physik.uzh.ch



Invariant mass

Precise measurements

- Higgs mass $m_h = 125.18 \pm 0.16\ \mathrm{GeV}$
- Top quark mass $m_t = 173.1 \pm 0.4\ \mathrm{GeV}$
- Strong coupling constant $\alpha_s(m_Z) = 0.1184 \pm 0.0011$
- ...

Can we learn something beyond the Standard Model ?

nature of dark matter, mass of new particles, rare decays, etc.

Precise measurement and new physics

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

New symmetry
Higgs Parity

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

Precise measurement and new physics

Hall and KH (2018, 2019)
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top quark mass
Higgs mass
strong coupling constant

Higgs Parity
symmetry
breaking scale

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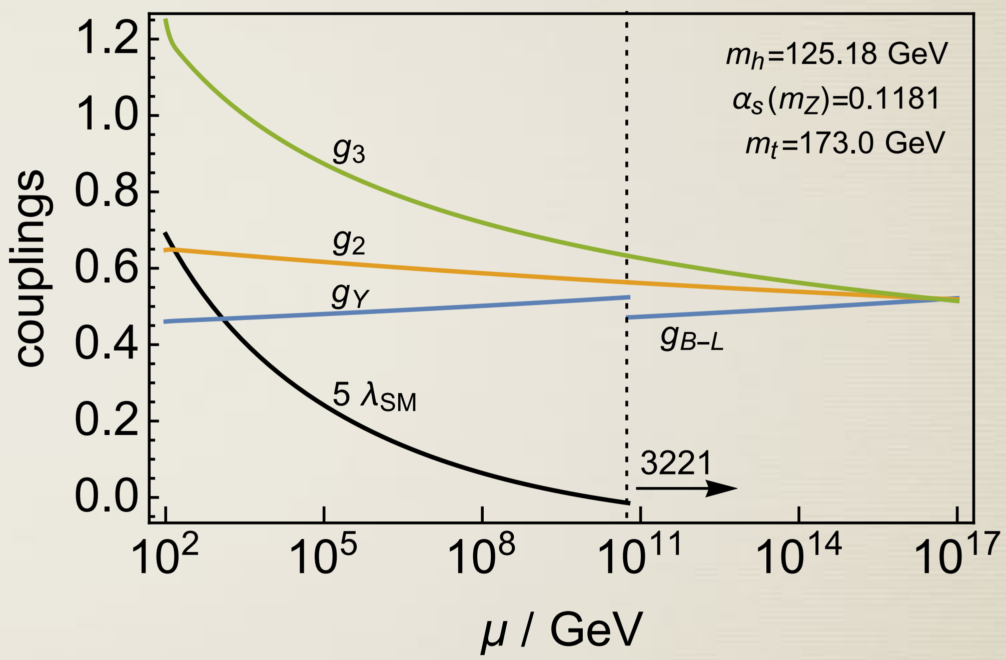


Higgs Parity
symmetry
breaking scale

UV physics,
experimental signatures

Grand unification, proton decay

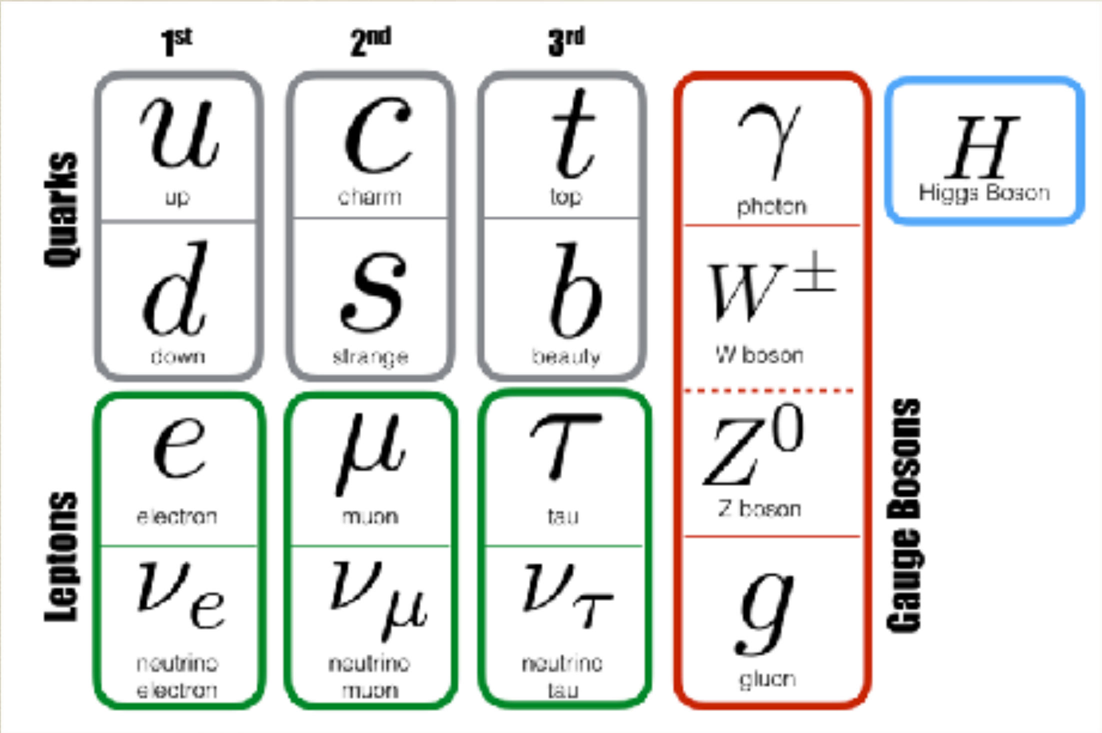
Dark matter detection rate, neutron EDM,
gravitational waves, dark radiation, warm dark matter, ...

Outline

* Introduction (continued)
* Higgs Parity
* Grand unification and proton decay
* Summary and outlook

Introduction

Standard Model



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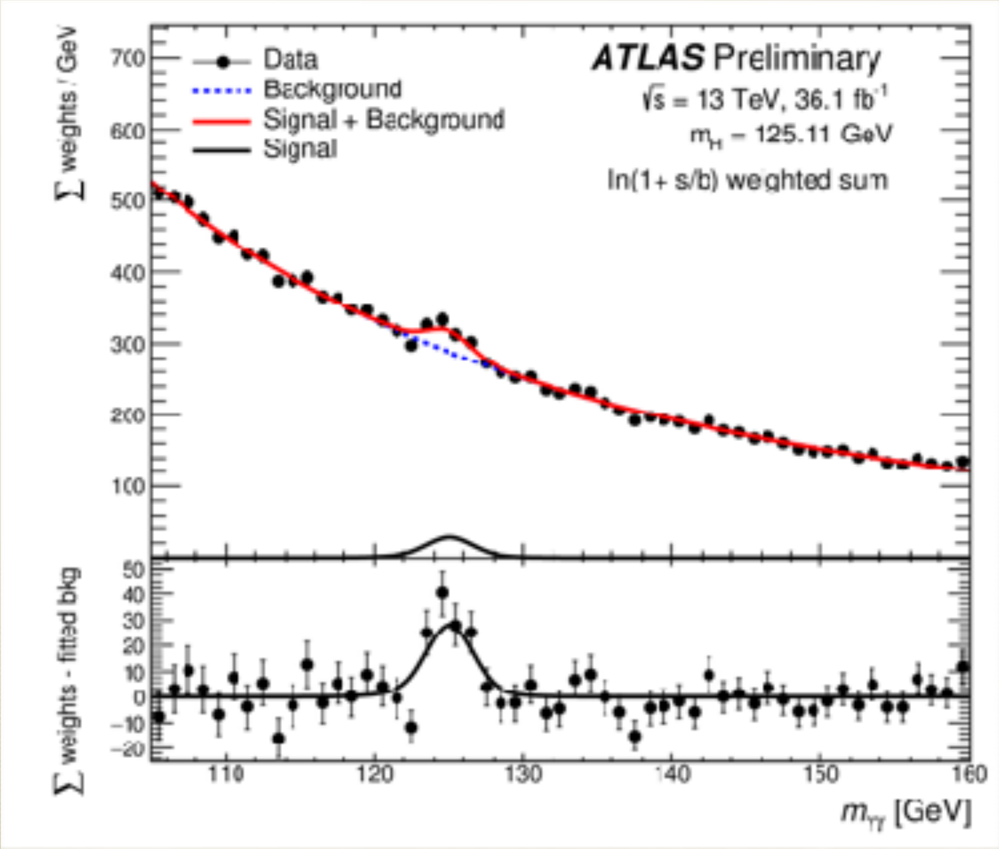

CERN, 2013

Picture from Recondito.org

CERN, 2013

Picture from Recondito.org

We are far away from the goal

* What is dark matter?
* How did cosmic inflation occur?
* How was the baryon asymmetry of the universe created?
* Why does QCD preserve CP symmetry?
* What sets the Higgs potential parameters?

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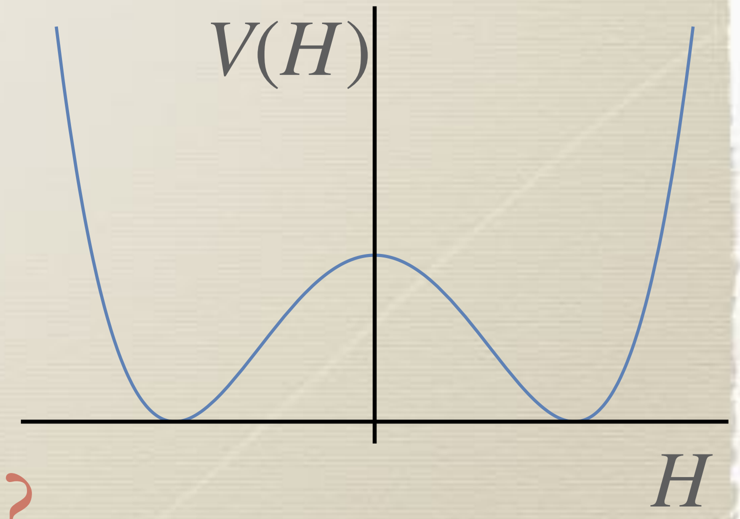
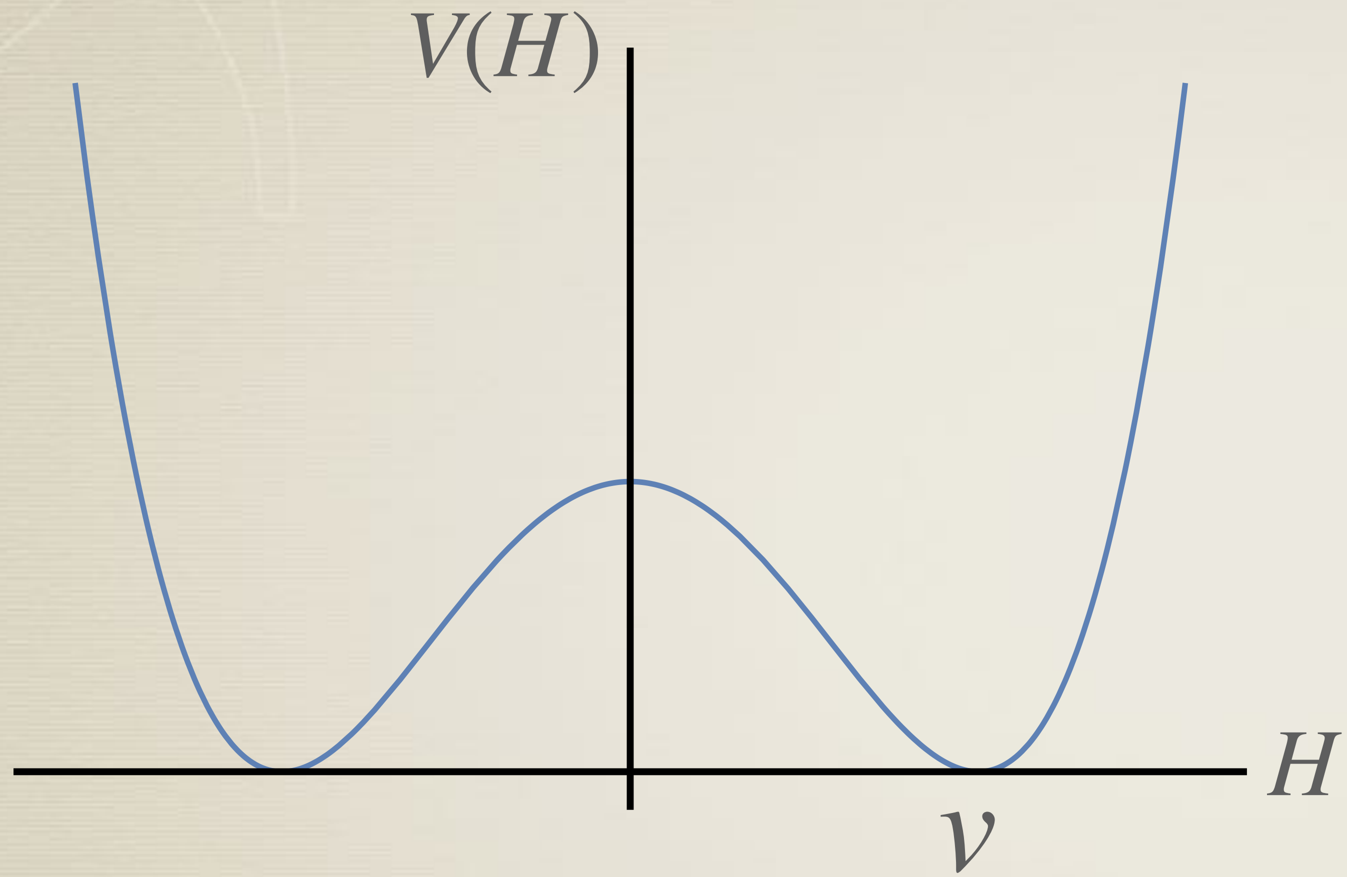


$$V(H) = \lambda_{\rm SM}\left(|H|^2 - v^2\right)^2$$

Higgs potential



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

A question of few decades:
What sets the mass scale of Higgs?

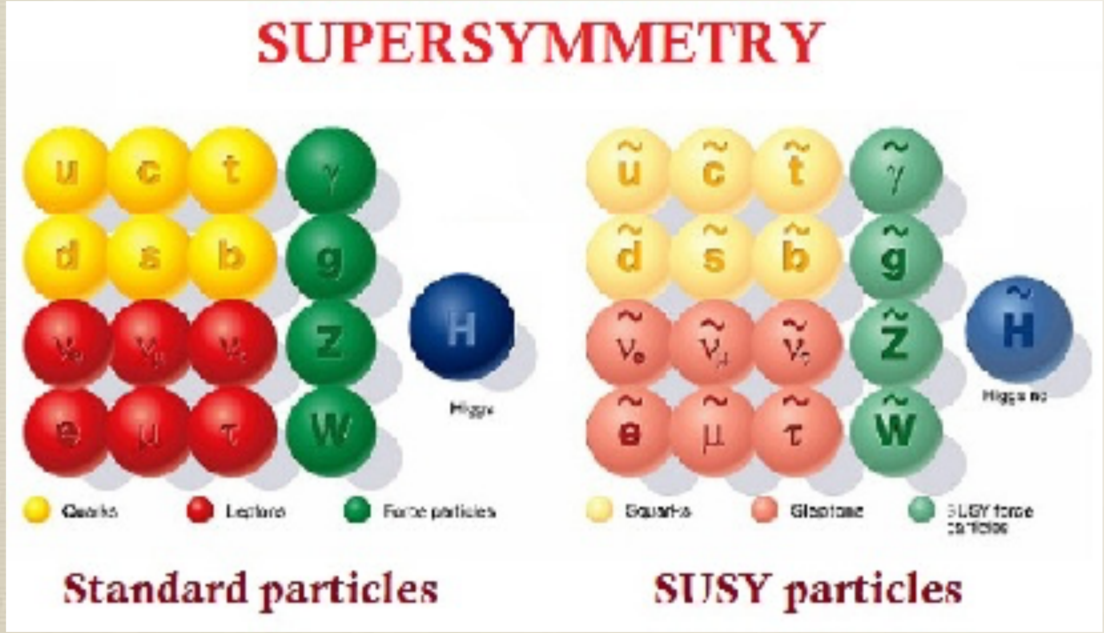
$v = 173$ GeV $\ll$ (Planck scale, GUT scale)

Hierarchy problem

Higgs potential

What sets the small mass scale of Higgs?

Ex. Supersymmetry, composite Higgs



CERN & IES de SAR

Higgs mass scale is naturally much smaller than the Planck scale

Maiani (1979), Veltman (1979), Witten (1981), Kaul (1982), Kaplan and Georgi (1984) Kaplan, Georgi and Dimopoulos (1984)

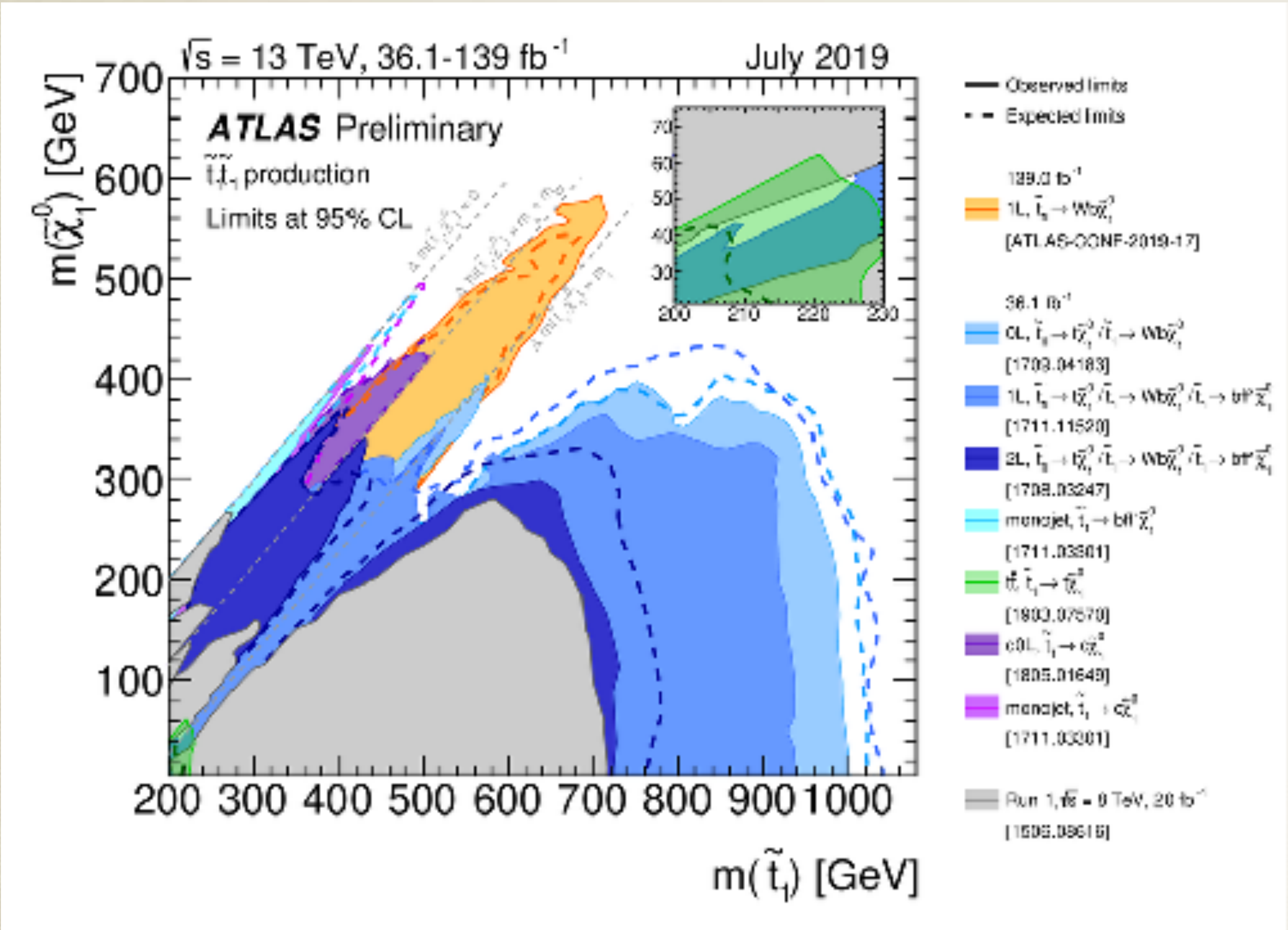
$$m_{\rm SUSY}, m_{\rm composite} \propto \exp\left(-\frac{8\pi^2}{g^2}\right)$$

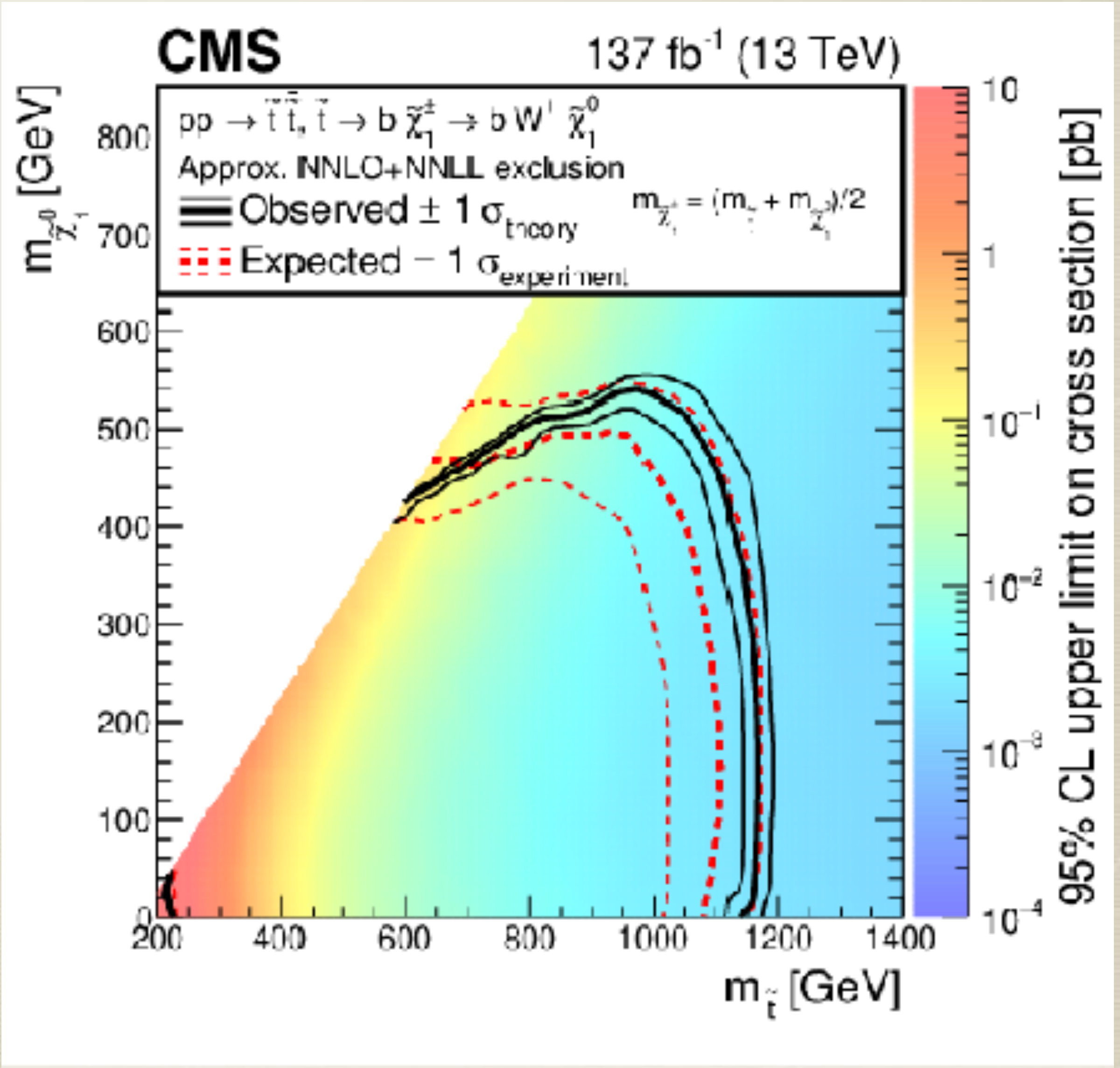
predict new particles with masses around 100 GeV

100 GeV scale new physics

New particles have not been found so far

Ex. Constraints on stop and neutralino masses in MSSM





Fine-tuned Higgs mass?

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

We are not sure if the small Higgs mass is a guiding principle to look for new physics

The small Higgs mass may be explained by theoretical ideas which are difficult to probe experimentally

Ex. Multiverse and anthropic selection

Weinberg (1987), Susskind (2003), Agrawal, Barr, Donoghue and Seckel (1998), Clavelli and White (2006), Hall, Pinner and Ruderman (2014), D'Amico, Strumia, Urbano and Xue (2019), ...

Fine-tuned Higgs mass?

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

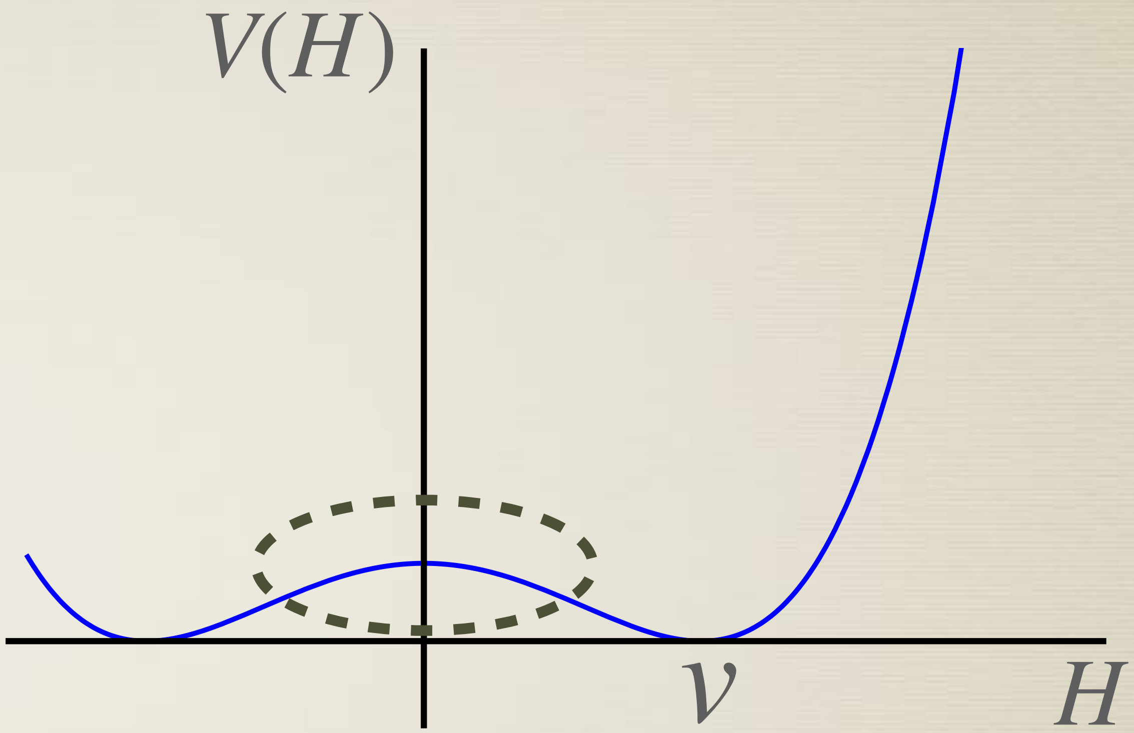
We are not sure if the small Higgs mass is
a guiding principle to look for new physics

I will postulate fine-tuned Higgs mass and look for another clue

Higgs mass

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

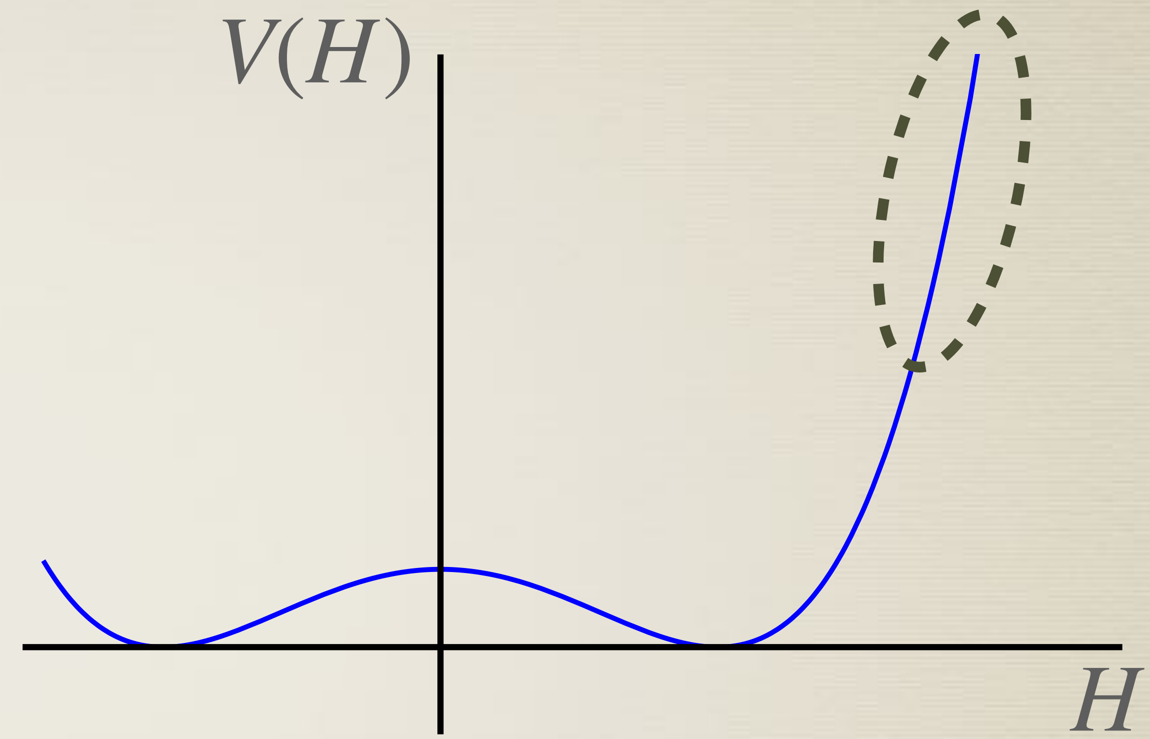
$(173\mathrm{GeV})^2$



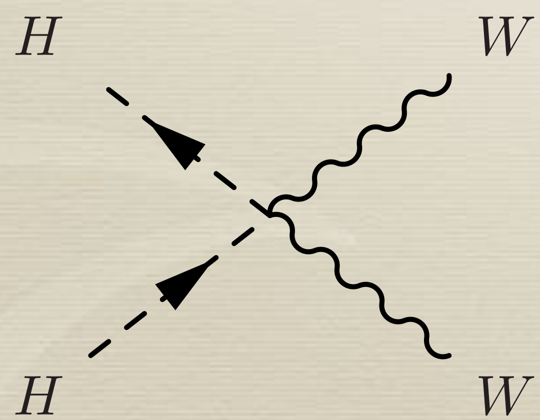
Higgs self-interaction?

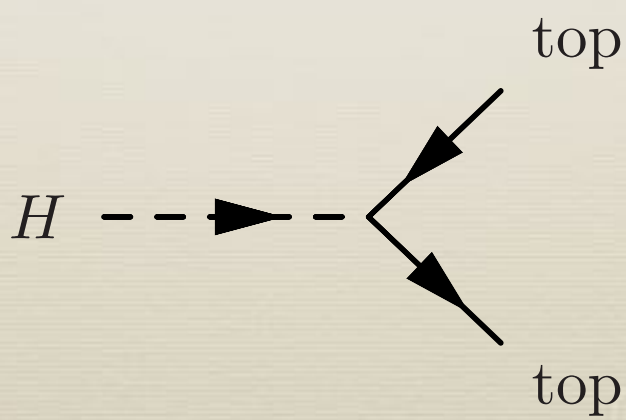
$$V(H) = \lambda_{\rm SM}\left(|H|^2 - v^2\right)^2$$

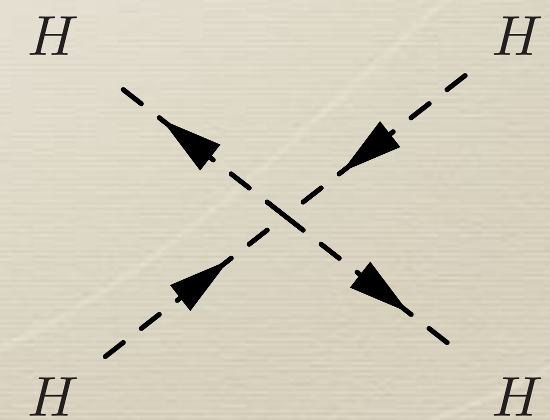
$$m_h^2/(4v^2) \simeq 0.13$$



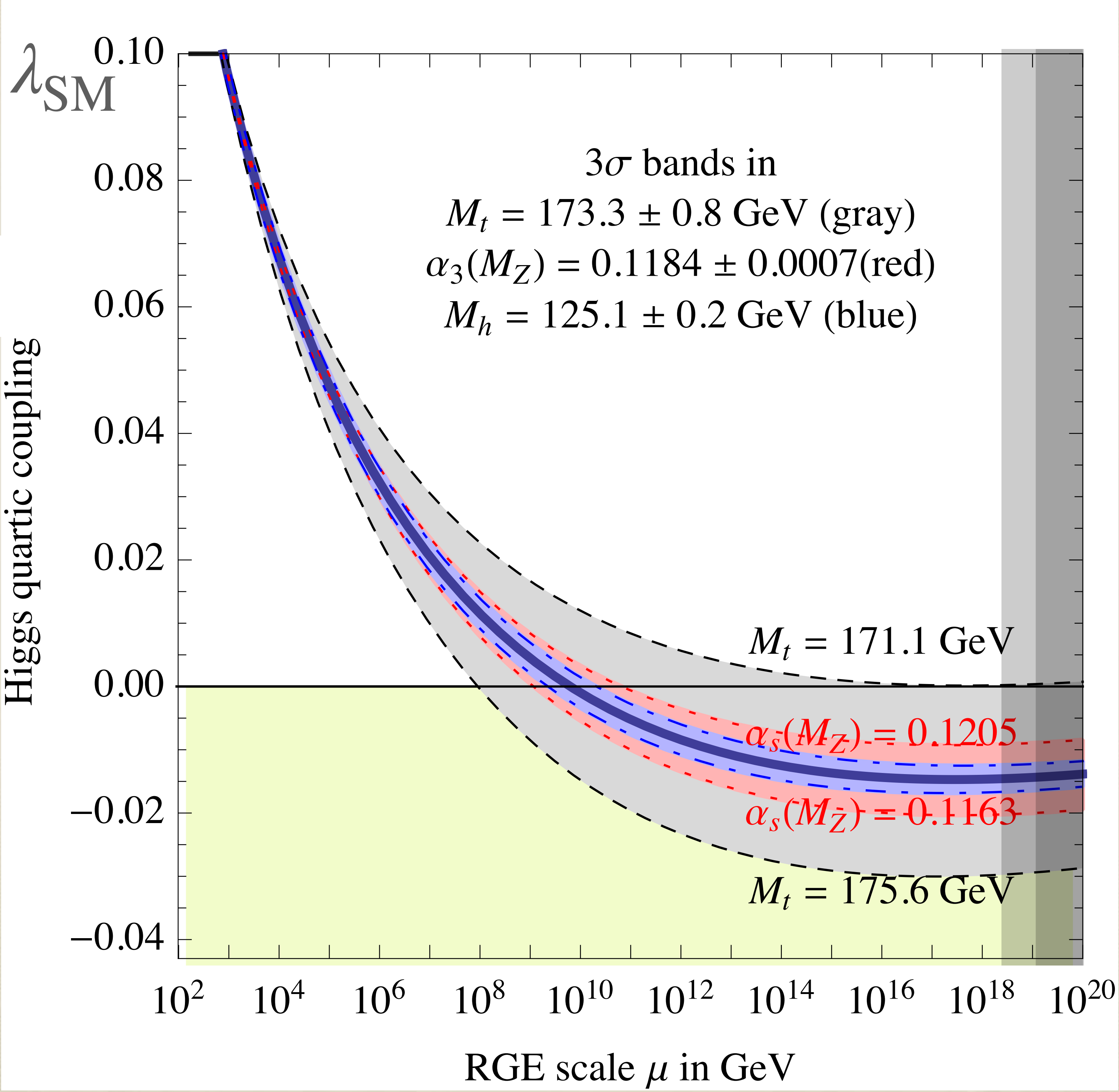
Let us examine the quartic coupling,
assuming that the standard model is valid up to high energy scales,
including quantum corrections





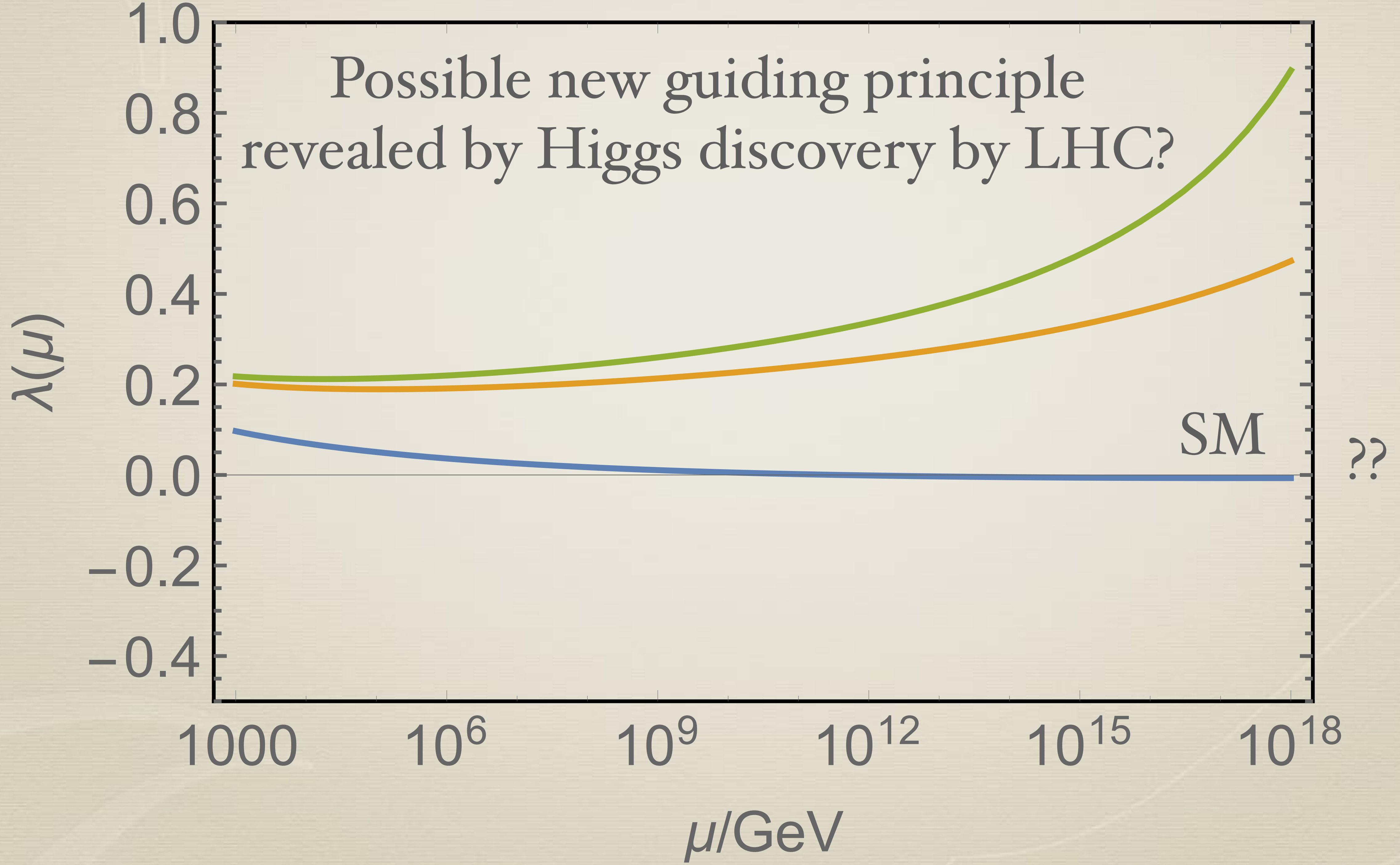


Small quartic coupling



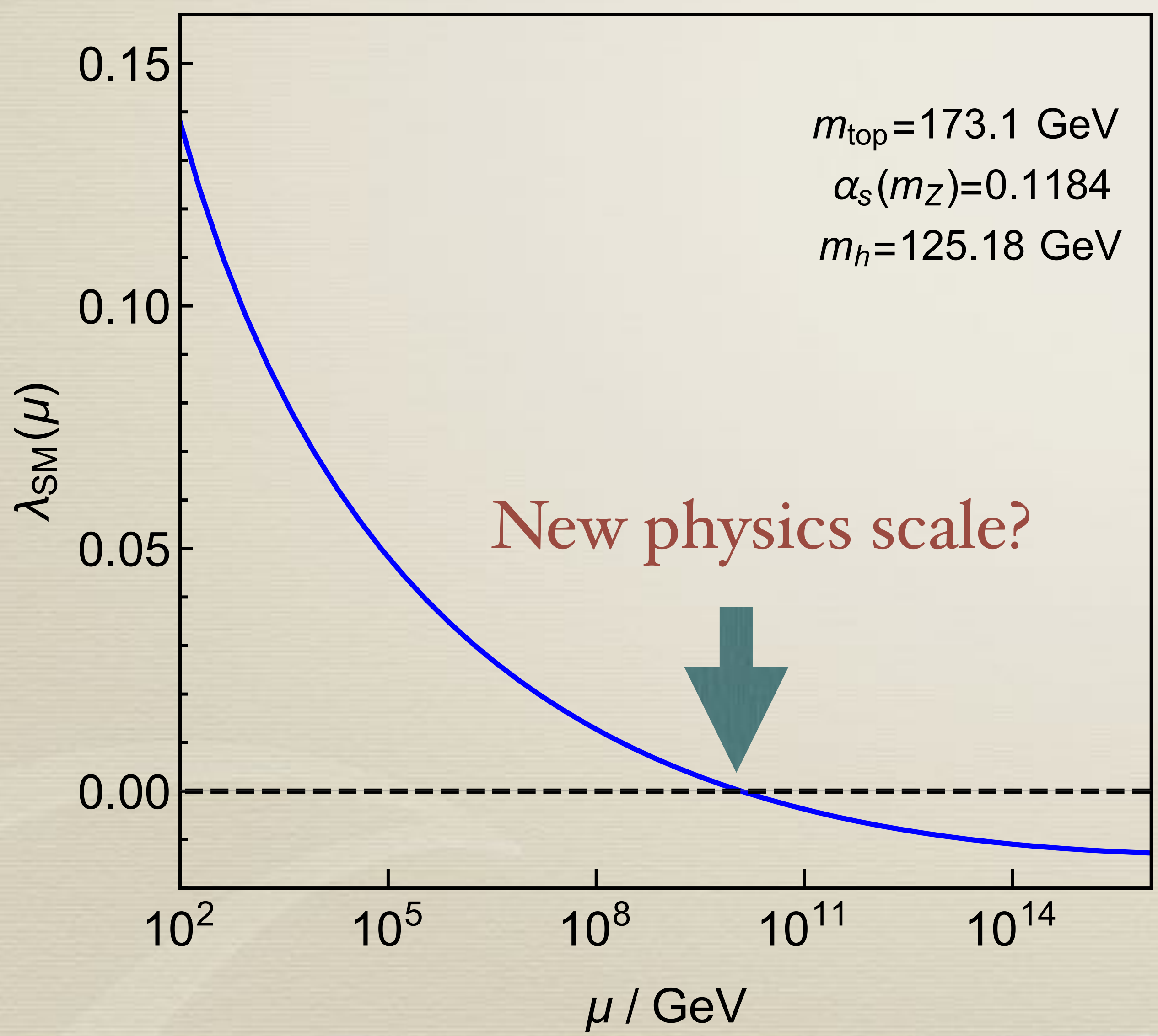
Buttazzo et.al (2013)

Small quartic coupling



New physics?

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



PQ symmetry?
  Redi and Strumia (2012)
Supersymmetry?
  Hall and Nomura (2013),
  Ibe, Matsumoto and Yanagida (2013)
Gauge-Higgs unification?
  Gogoladze, Okada and Shafi (2007)

New physics?

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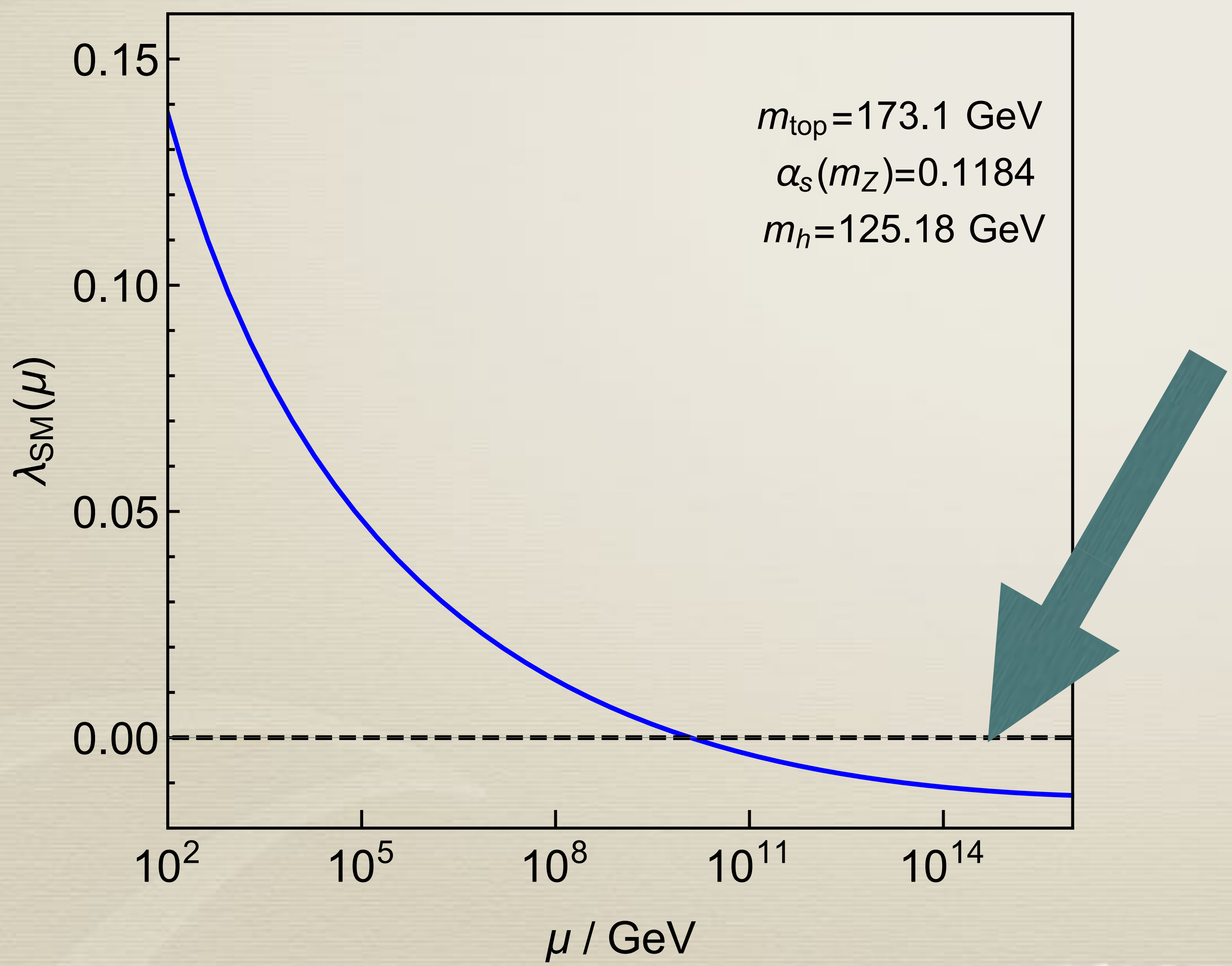
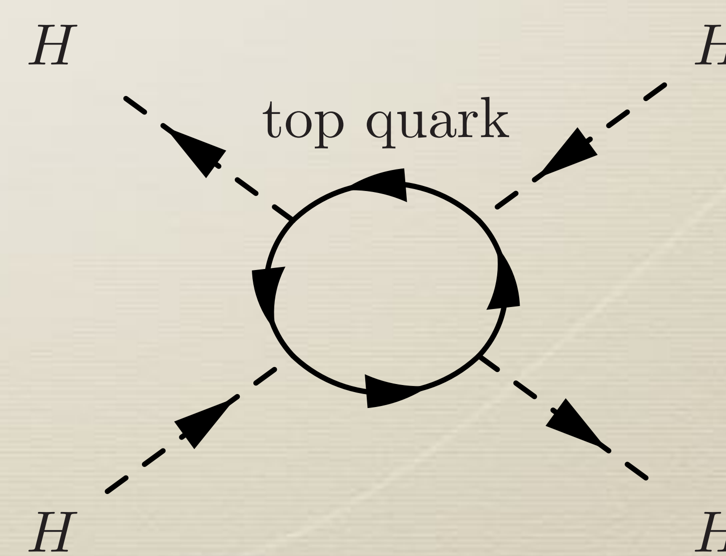
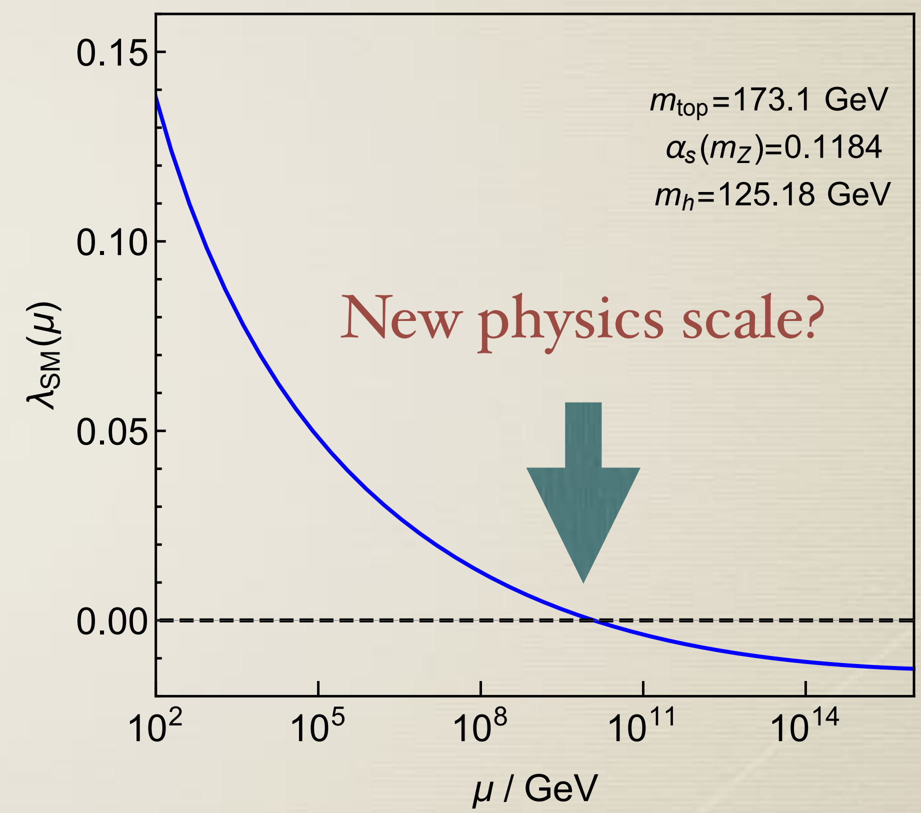


quartic coupling assuming Standard Model remains small due to small yukawa coupling at high energy



Precise measurement and new physics?

top quark mass
Higgs mass
strong coupling constant



scale of the new physics ⟷ further UV physics, experimental signals?

Precise measurement and new physics

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

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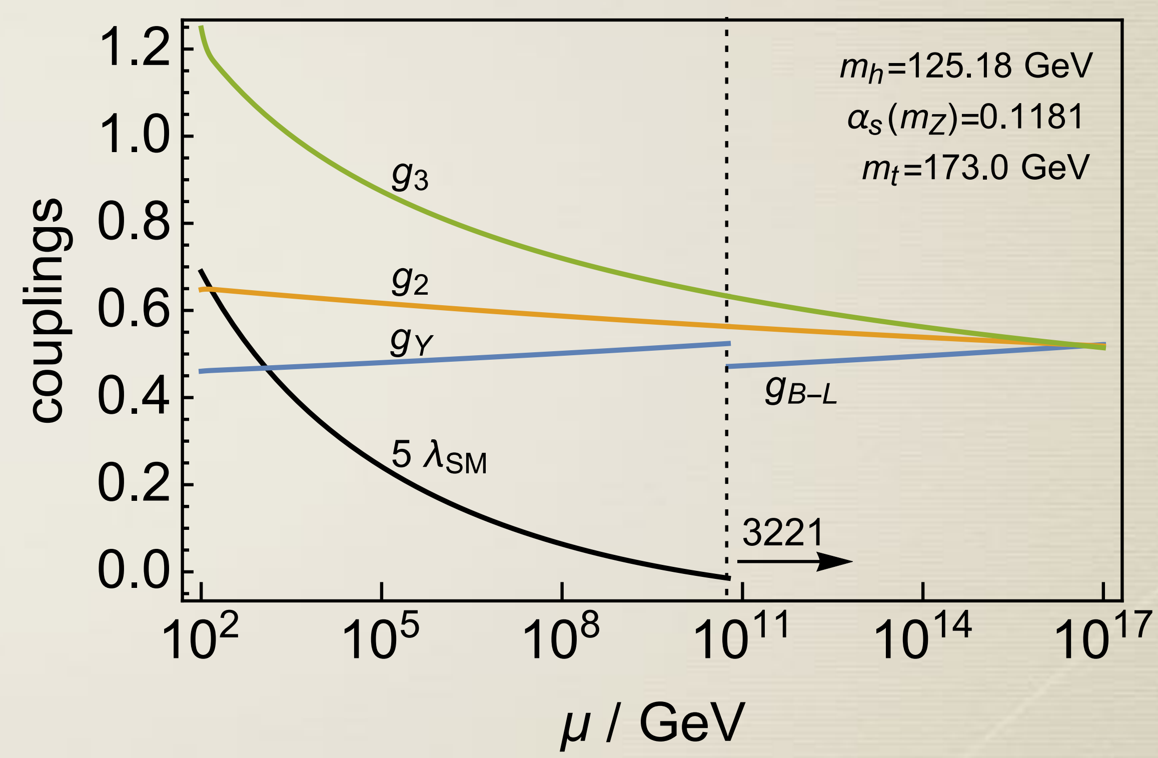


New symmetry
(Higgs Parity)
breaking scale

Grand unification
proton decay

Dark matter detection rate, neutron EDM, gravitational waves, dark radiation, warm dark matter, ...

Outline

* Introduction
* Higgs Parity
* Grand unification and proton decay
* Summary and outlook

Symmetry

Symmetry has been playing the central role in physics

Dictate relations among masses
and interaction rates of particles

Ex. Symmetry of hadrons

Explain why the proton mass is similar to the neutron mass

938.27 MeV 939.57 MeV

Z_2 symmetry

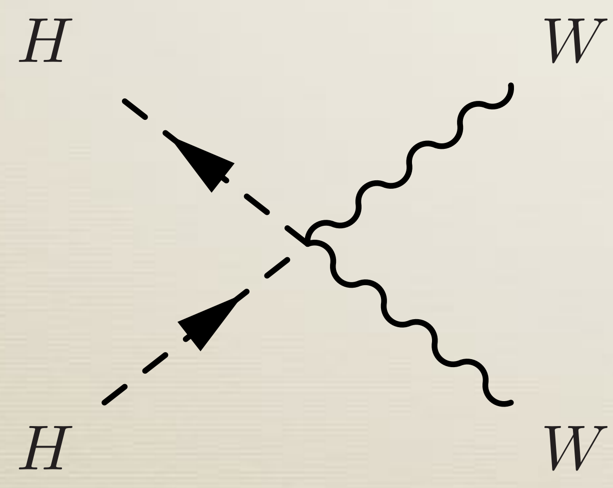
Higgs ⟷ Higgs'

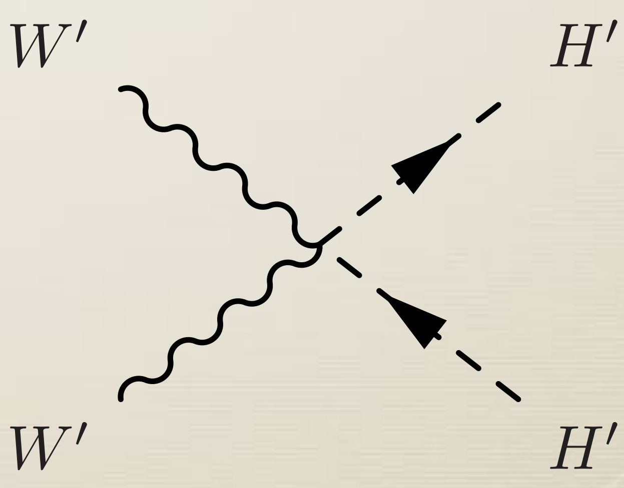
H ⟷ H'

Weak gauge boson ⟷ Weak gauge boson'

W ⟷ W'

$SU(2)$ ⟷ $SU(2)'$





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, gluon : several options)

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

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'

Higgs Parity (HP)

Spontaneously broken Higgs Parity

H $\quad\longleftrightarrow\quad$ H'

mass $\propto < H >$ $= v$ $\quad$ W $\quad\longleftrightarrow\quad$ W' $\quad$ mass $\propto < H' >$ $= v'$

q, L $\quad\longleftrightarrow\quad$ q', L'

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

unbroken Z2 $\langle H \rangle = \langle H' \rangle$ is experimentally excluded

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

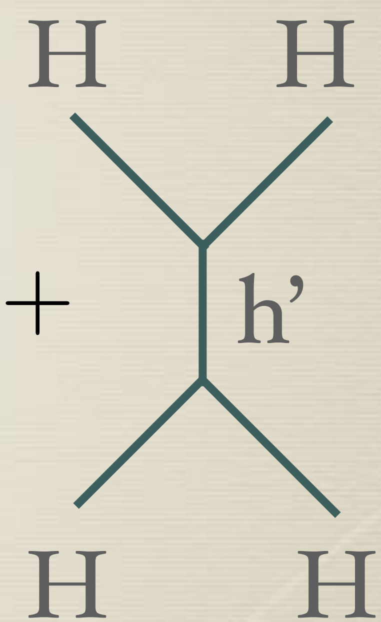
Small quartic

Hall, KH (2018)

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

$$\langle H' \rangle^2 = \frac{m^2}{2\lambda} \equiv v'^2$$

$\lambda|H|^4 +$



Integrate out heavy d.o.f.

$$V_{\text{eff}} \simeq \lambda' v'^2 |H|^2 - \lambda'(1 + \frac{\lambda'}{4\lambda})|H|^4$$

$|\lambda'| \ll 1$

$\lambda_{\text{SM}}(v') = 0$

Threshold correction: $\lambda_{\text{SM}}(v') \sim -\frac{y_t^4}{16\pi^2} \sim -10^{-3}$

pseudo-NGB Higgs

Hall, KH (2018)

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

Accidentally U(4) symmetric $\quad 4 = (H, H')$

U(4) -> U(3) by H'

$$16 - 9 = 7 = 4 + 3$$

W', Z'

SM Higgs is a pseudo Nambu-Goldstone boson

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

Prediction on symmetry breaking scale

Hall, KH (2018)

Higgs Parity

$$H \longleftrightarrow H'$$

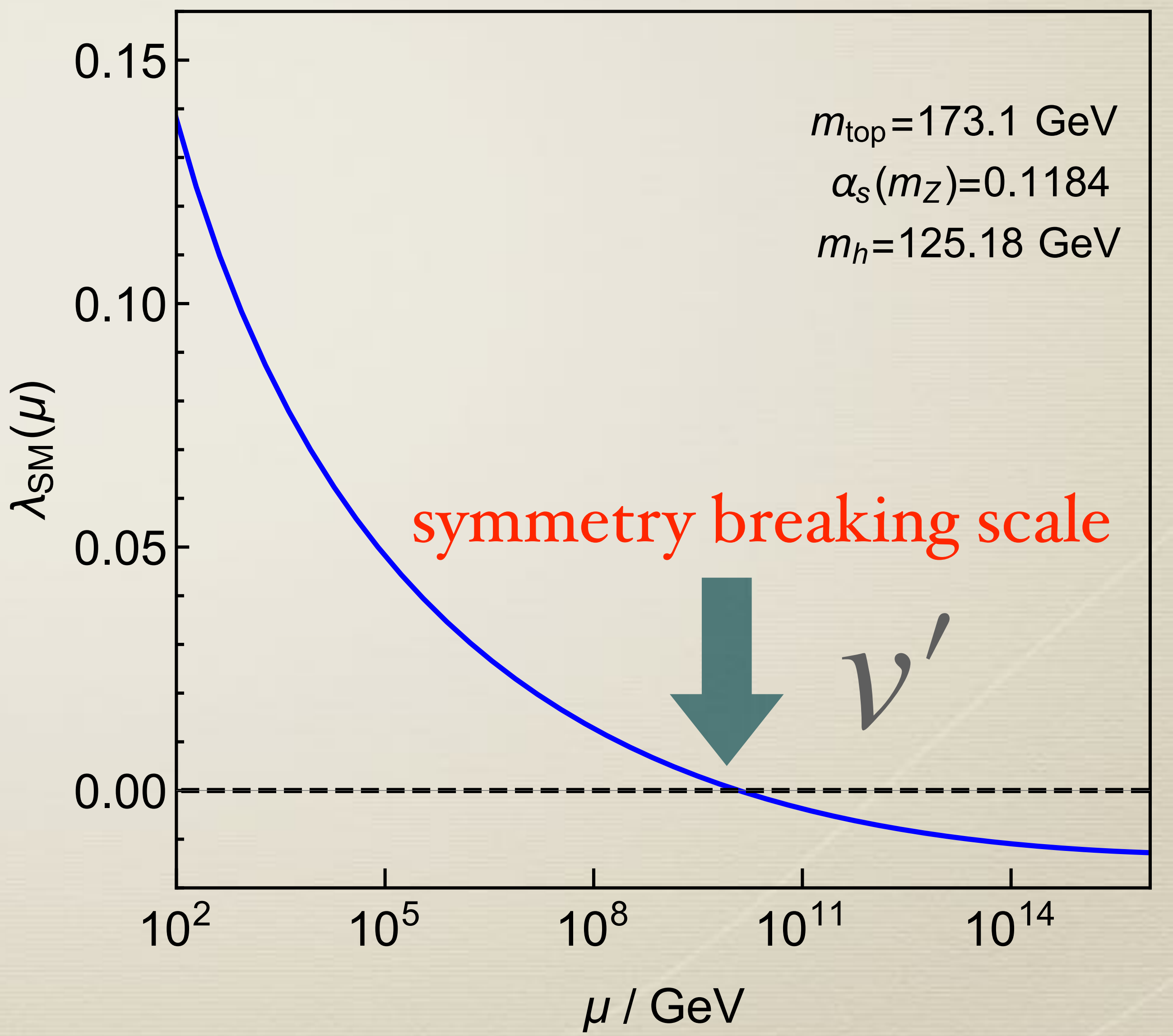
is broken by

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

$$v \ll v'$$

$$\Downarrow$$

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



Precise measurement and new physics

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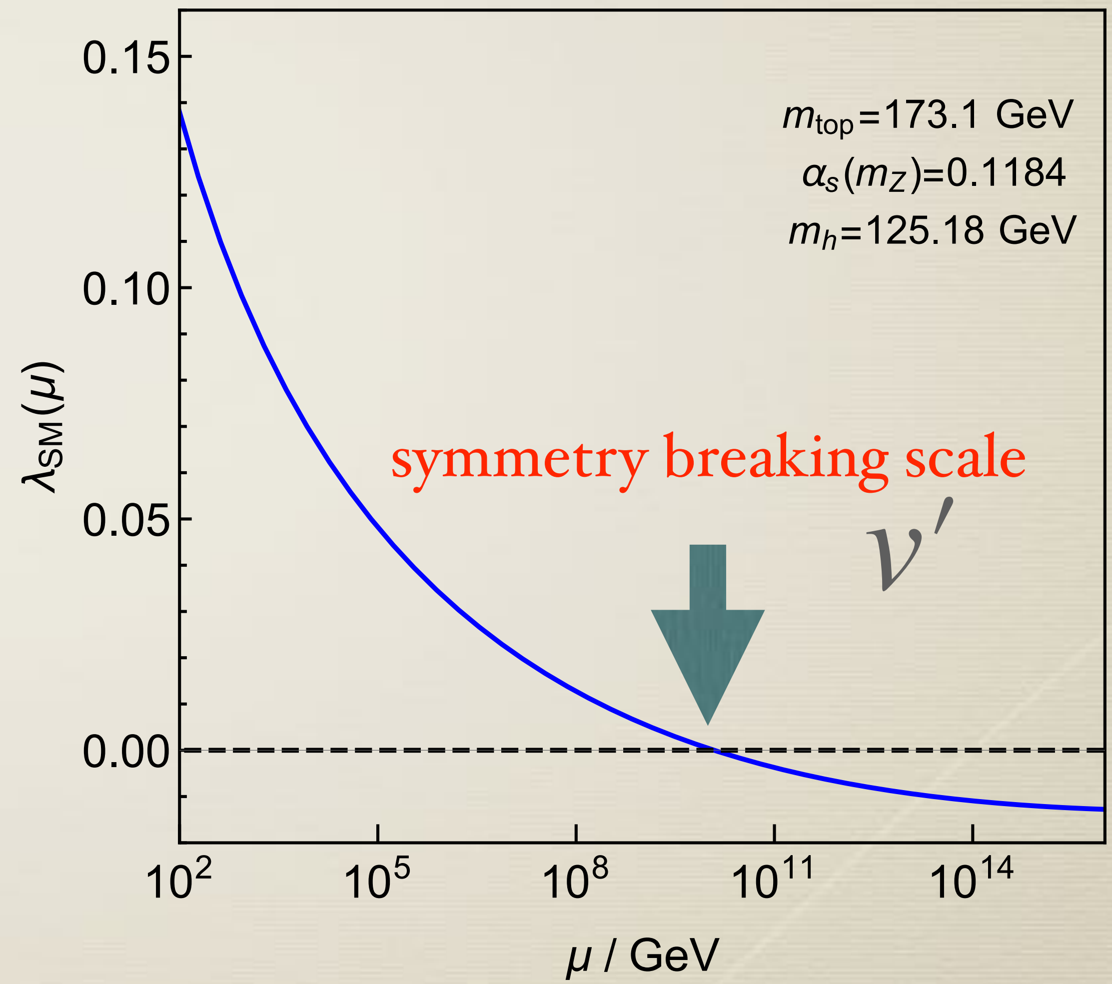


Higgs Parity (HP)
symmetry breaking scale

Experimental signatures

Fine-tuning

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

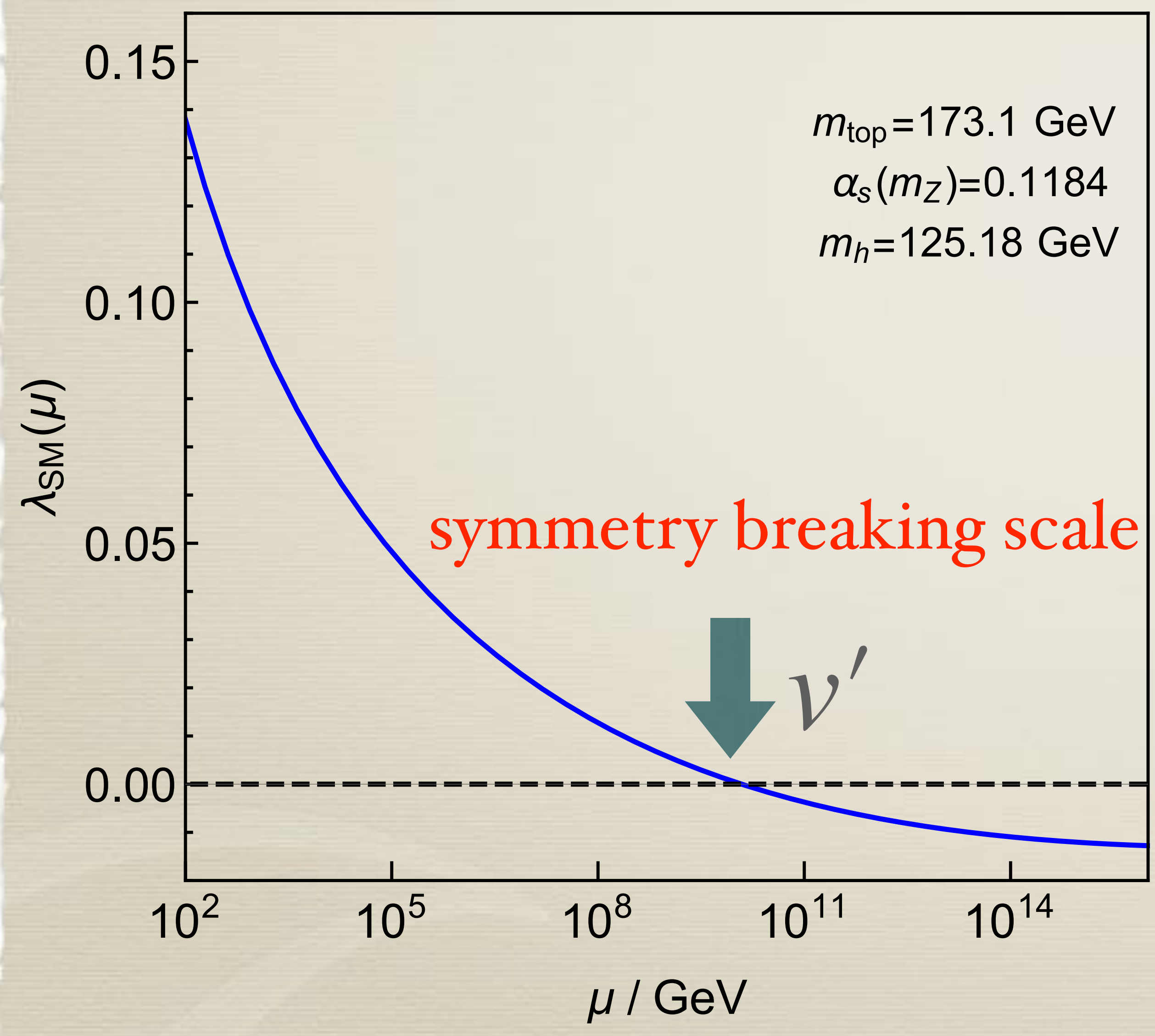
$$\frac{v^2}{v'^2} \times \frac{v'^2}{\Lambda_{\rm cut}^2} = \frac{v^2}{\Lambda_{\rm cut}^2}$$

Despite the intermediate scale v',

same as that of standard model

Quiz 1

If the Higgs mass is larger, v' is



A : Larger
B : Smaller

Hint: Higgs mass

$$m_h \propto \lambda_{SM}^{1/2}(\mu = \text{EW scale})$$

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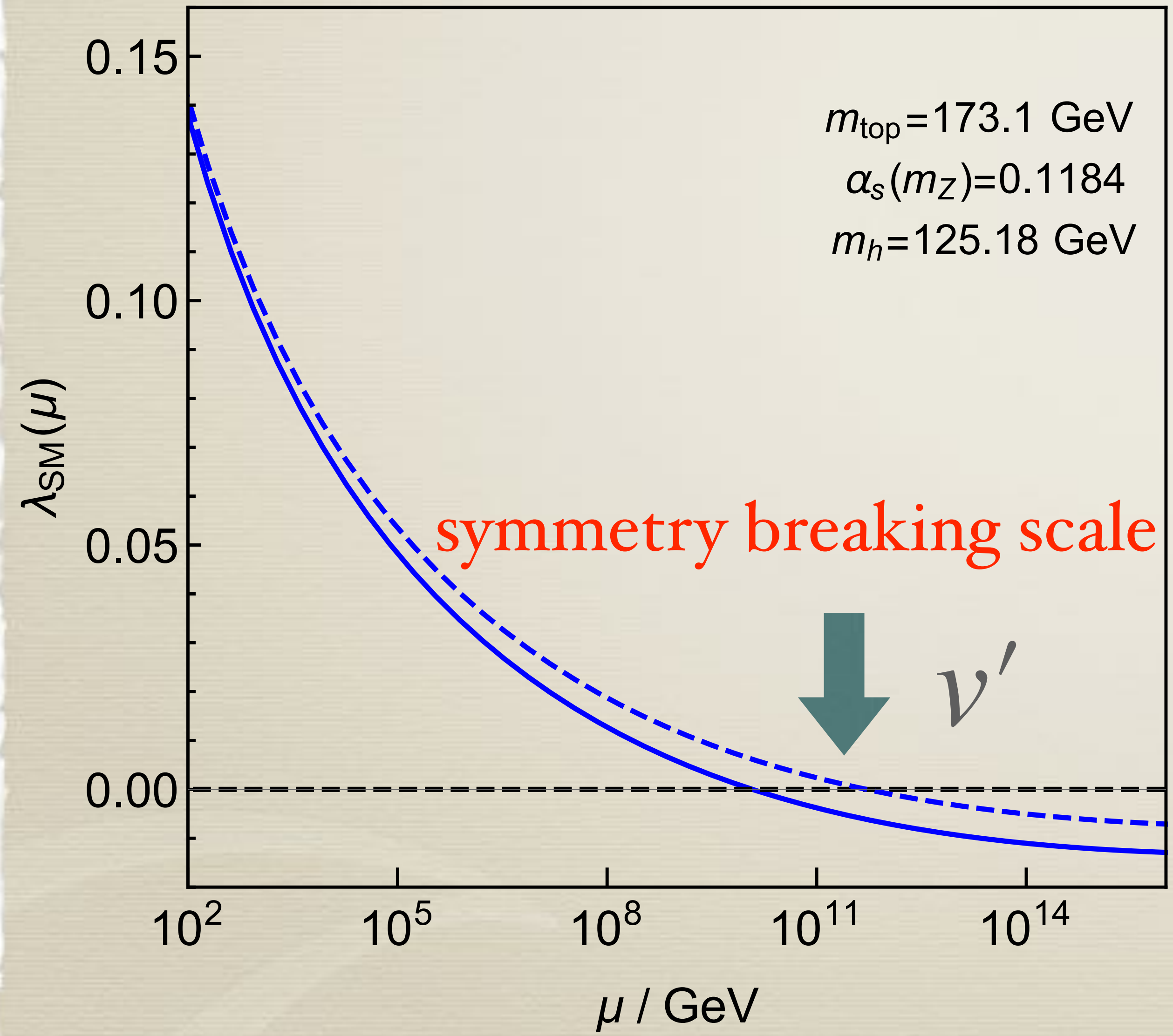

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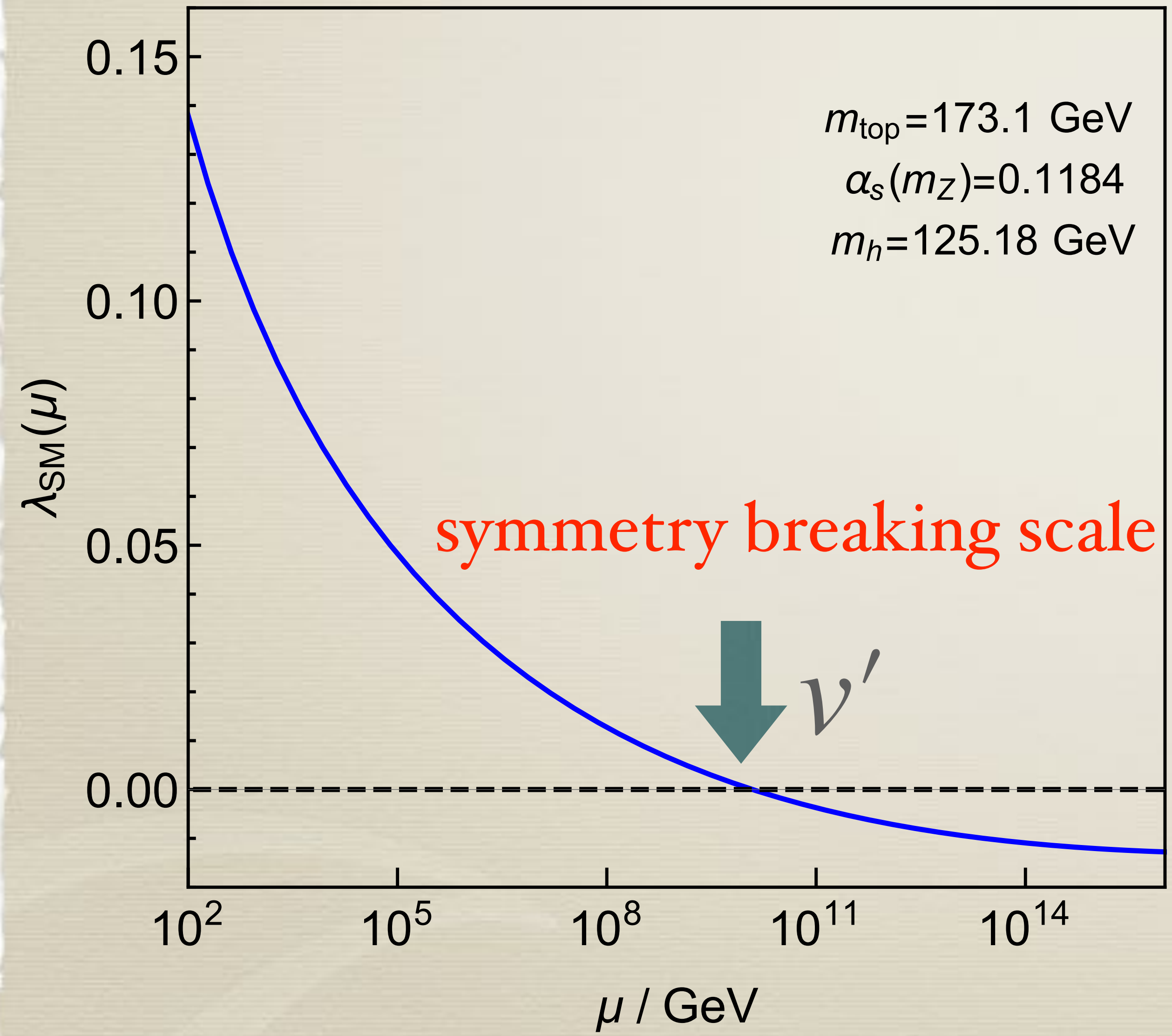
Quiz 2

If the top quark mass is larger, v' is



A : Larger
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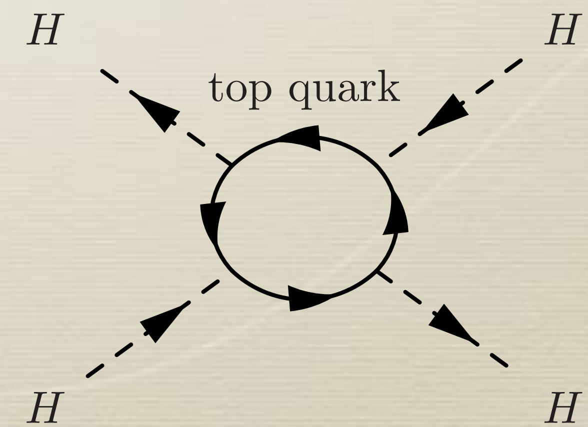
Hint: the quartic coupling becomes smaller because of the top quark yukawa



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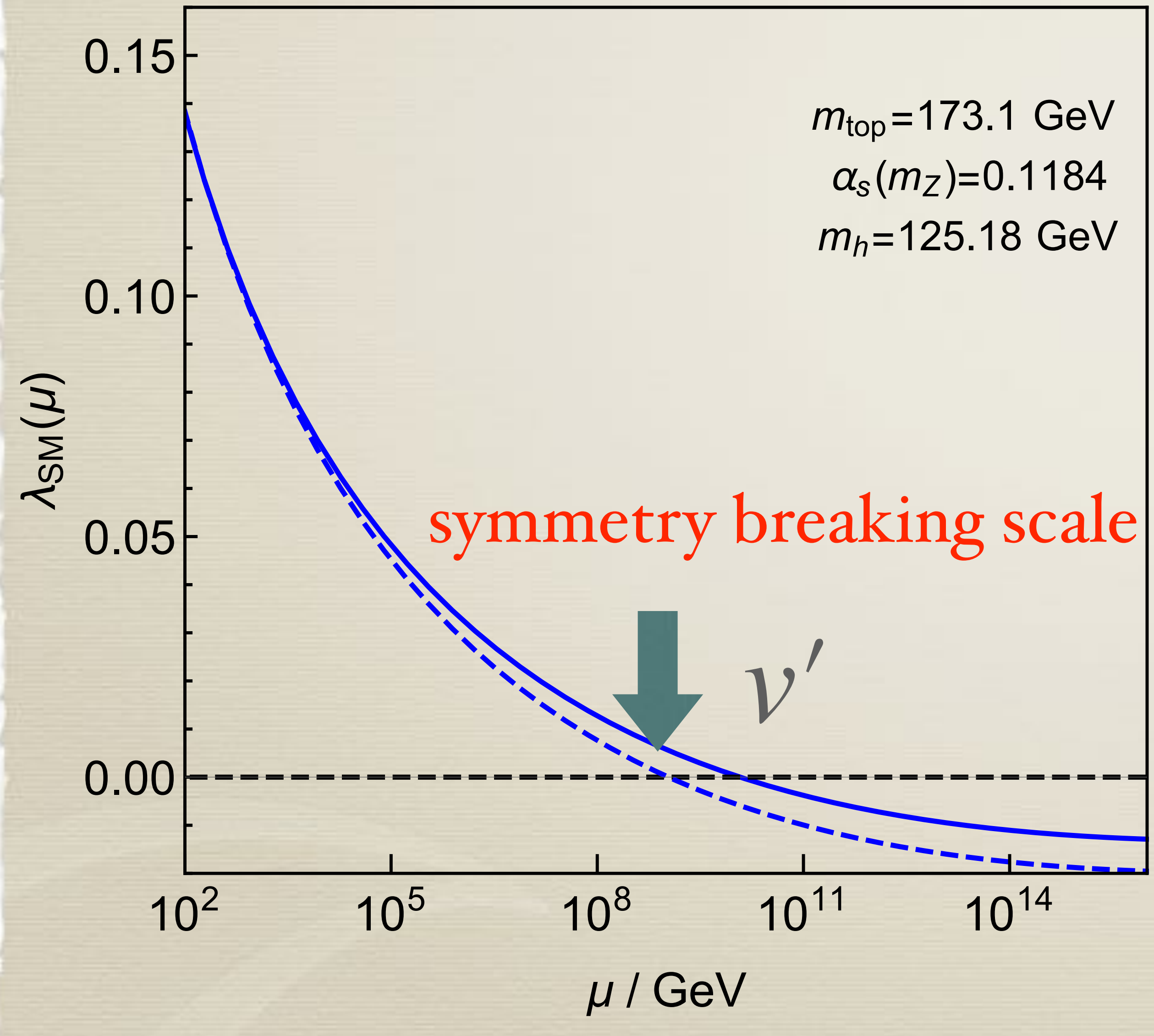

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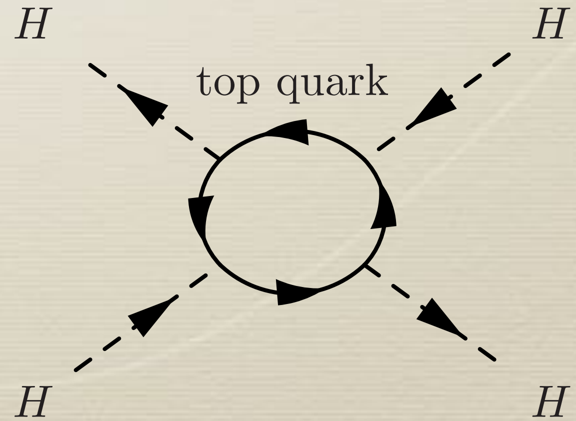

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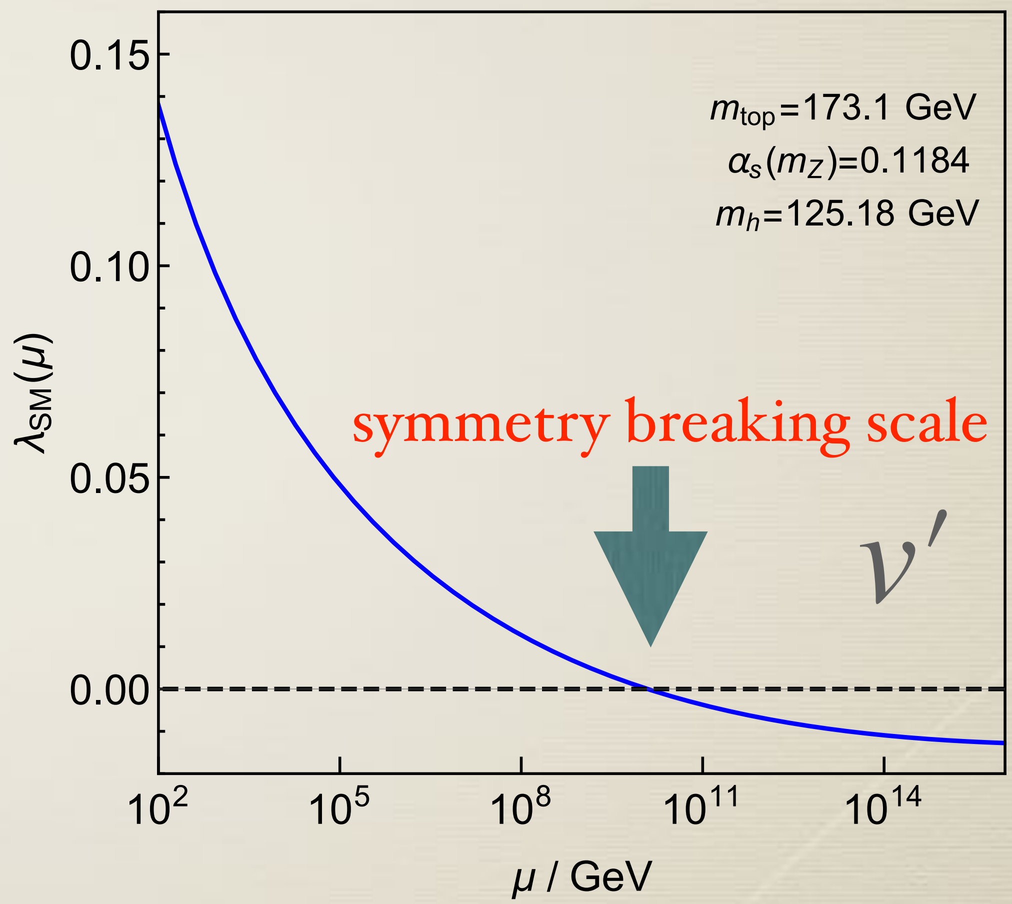

Higgs Parity (HP)
symmetry breaking scale

Precise measurement and new physics

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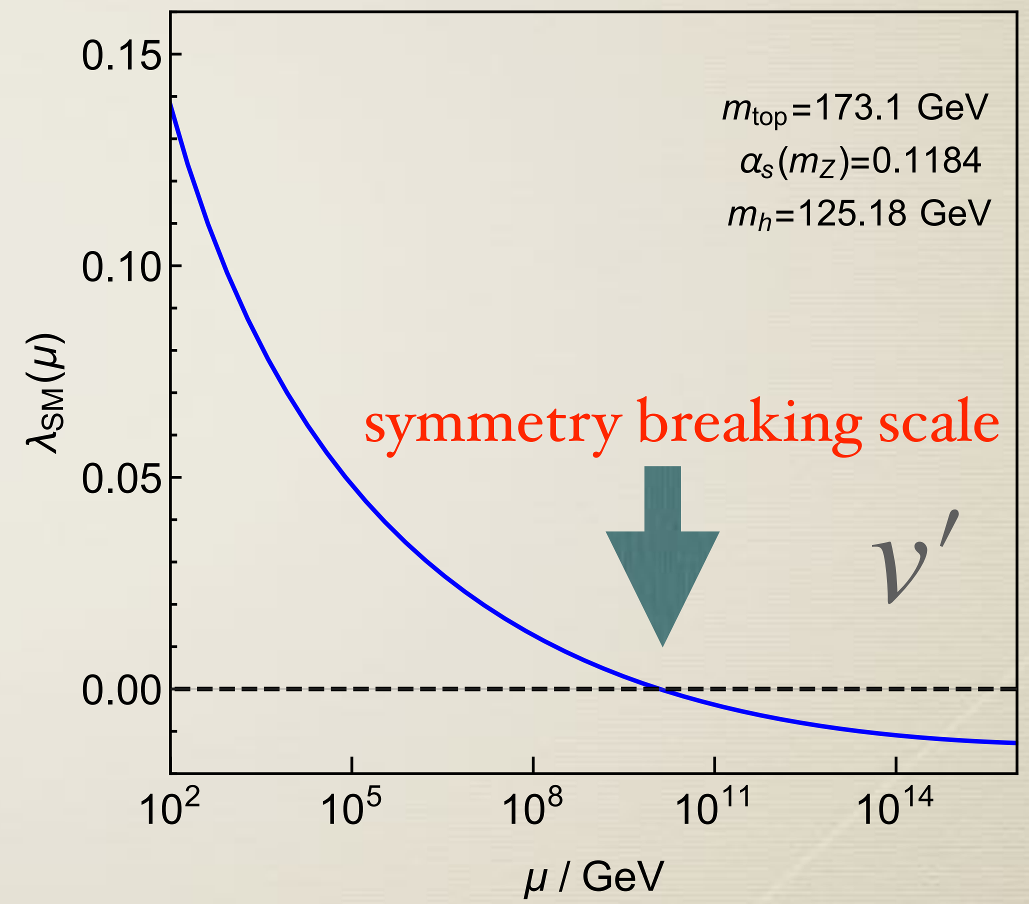

Higgs Parity (HP)
symmetry breaking scale

further UV physics,
experimental signatures

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Precise measurement and Grand Unification

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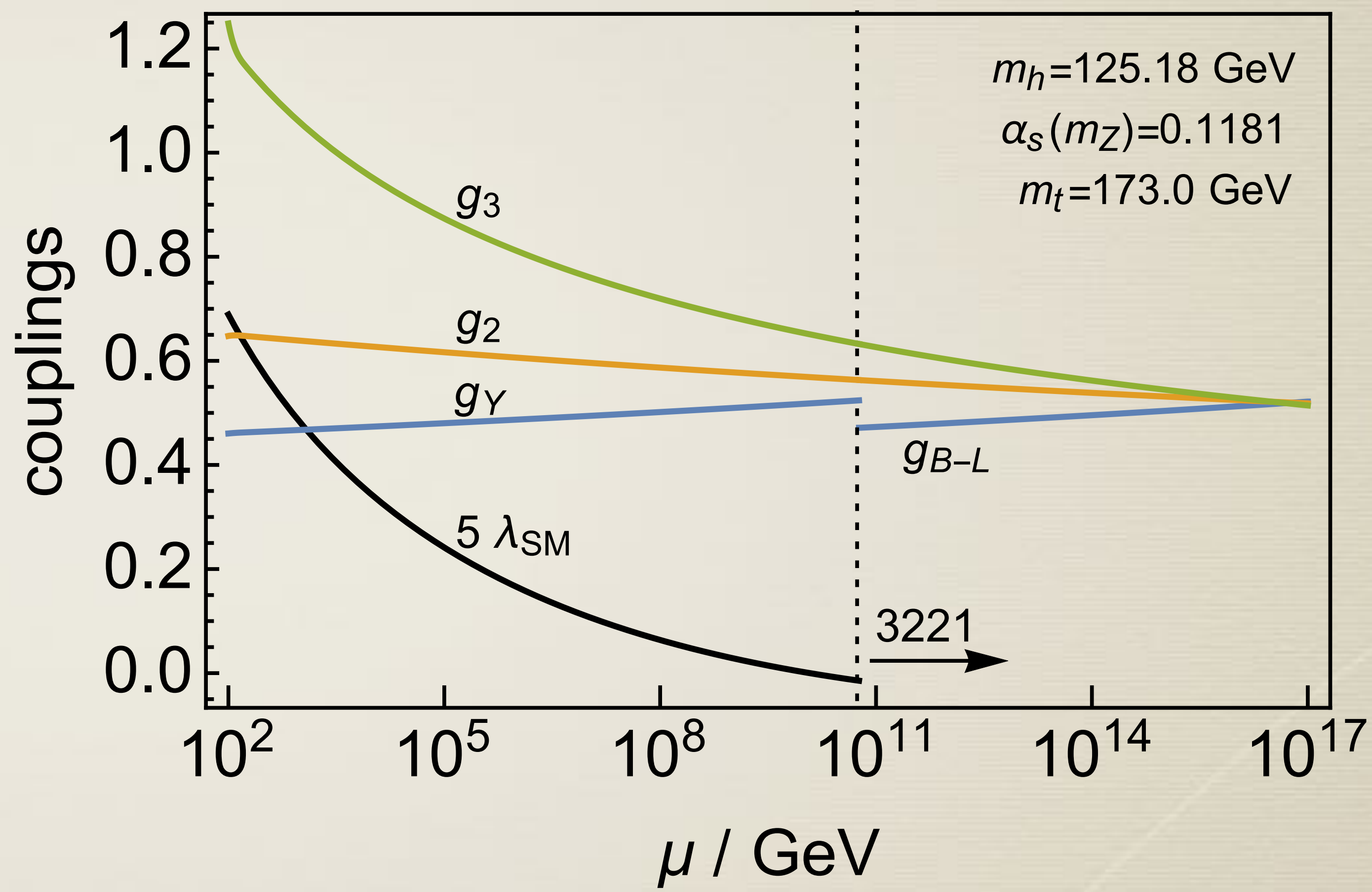

Higgs Parity
symmetry breaking scale

Grand Unification
Proton decay

Precise measurement and Grand Unification

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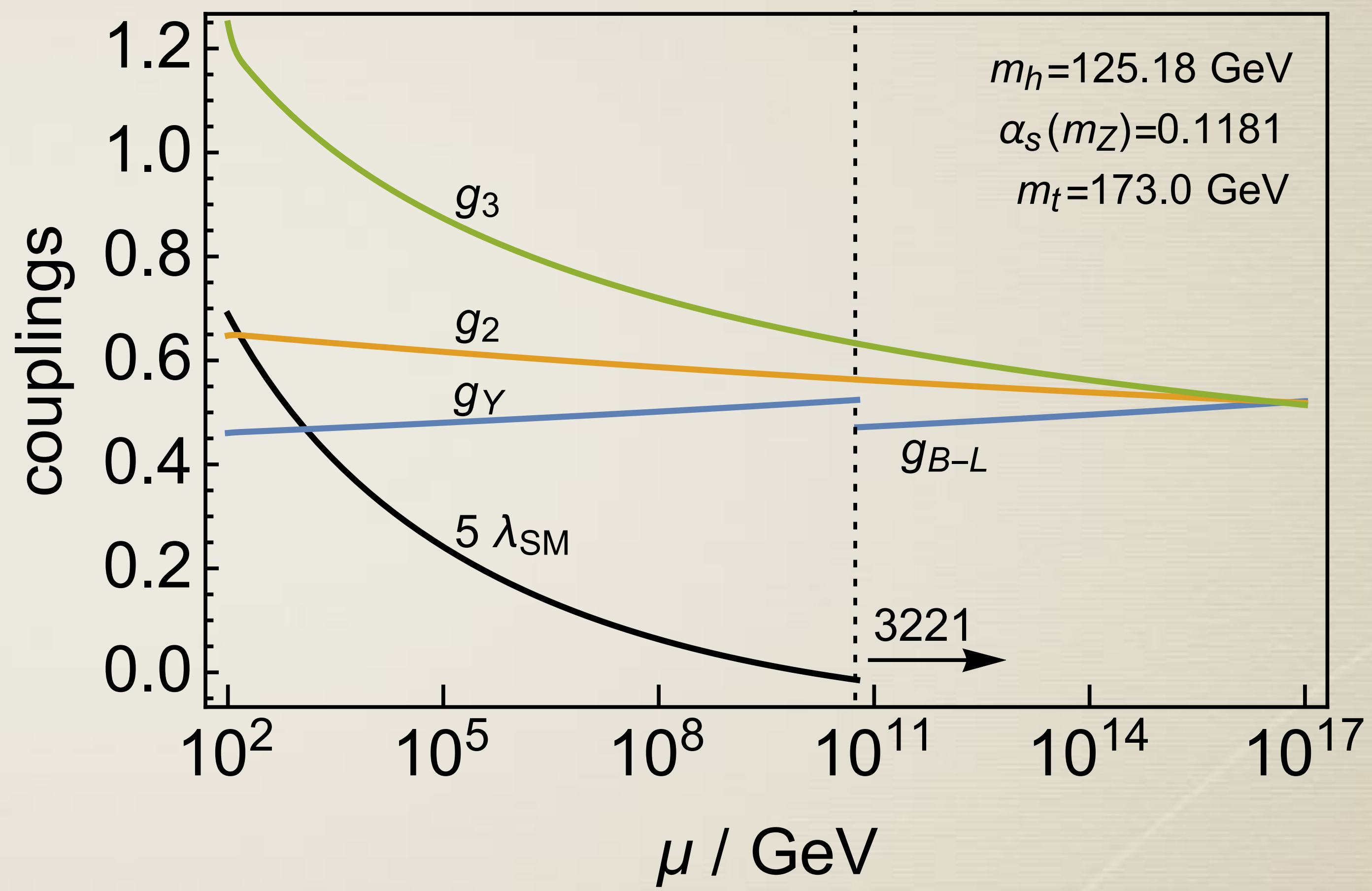
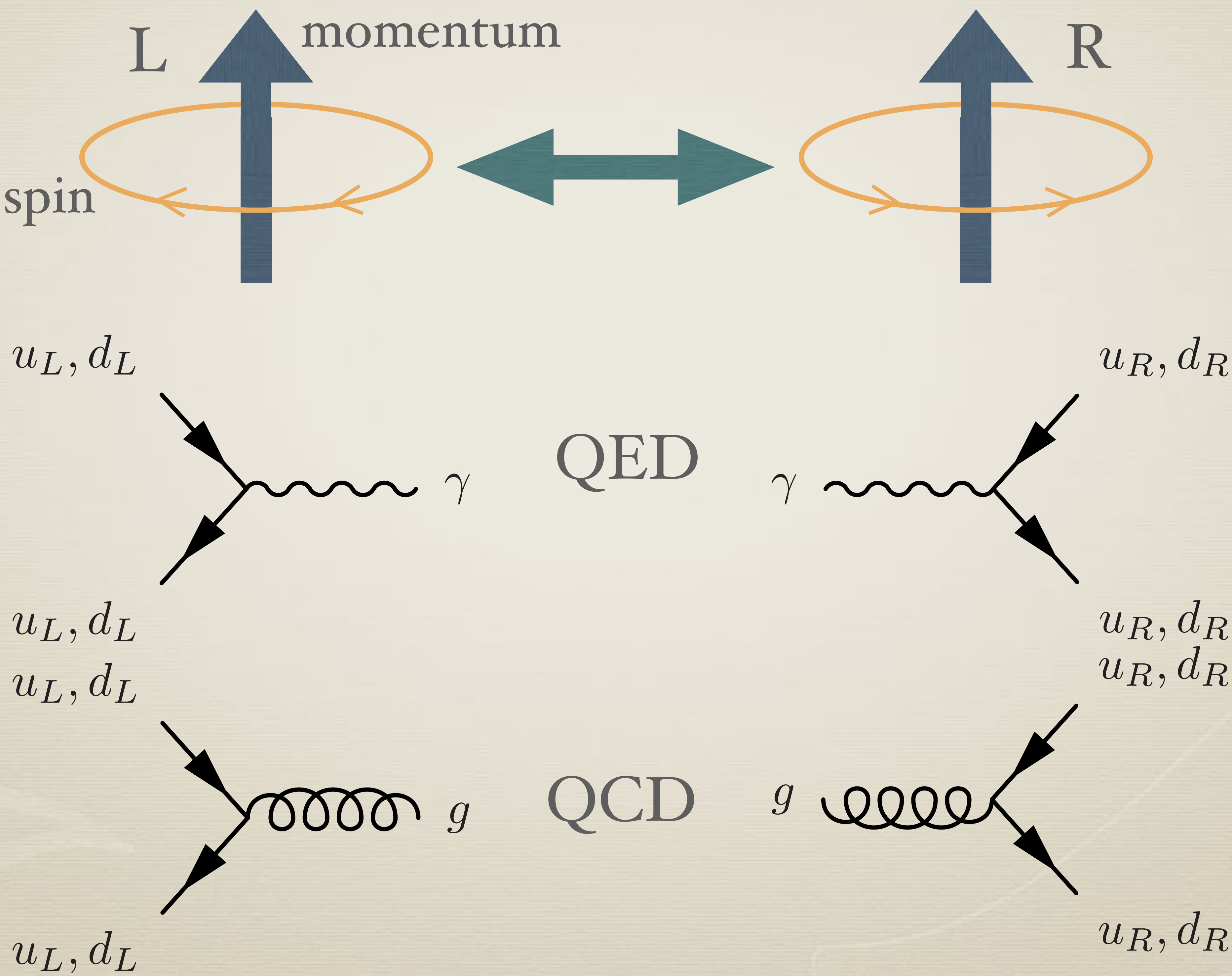


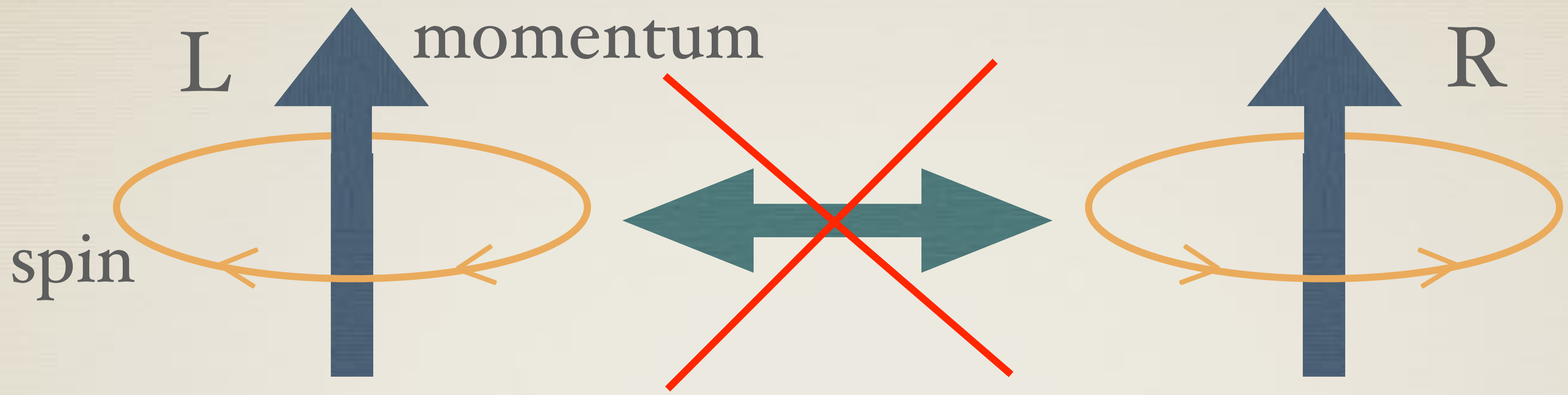
Left-Right
Higgs Parity
symmetry breaking scale

Grand Unification
Proton decay

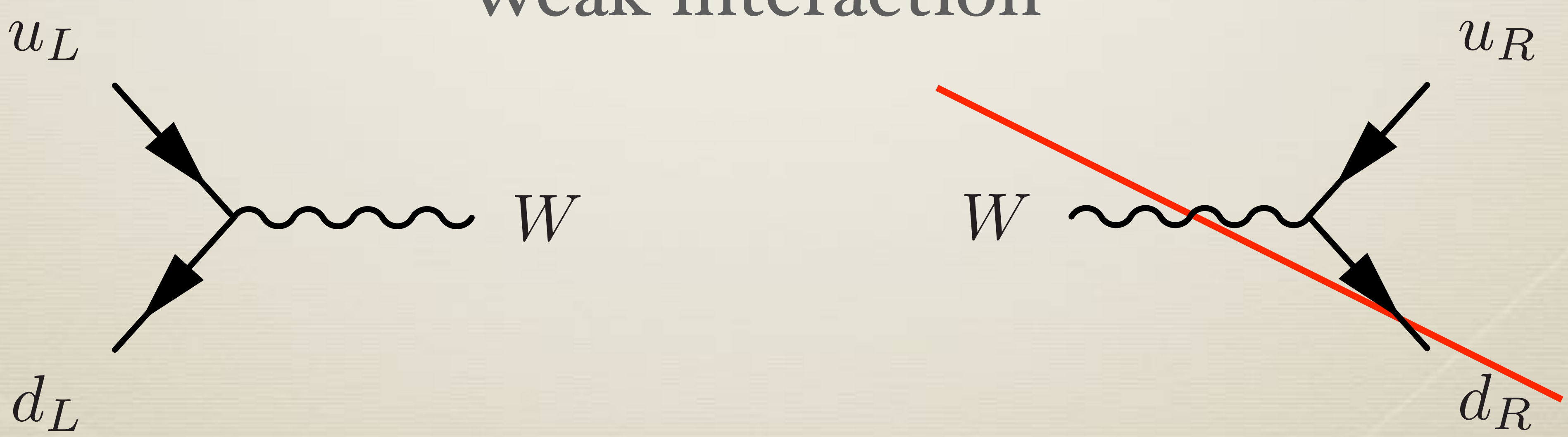
Left-Right symmetry



Left-Right symmetry

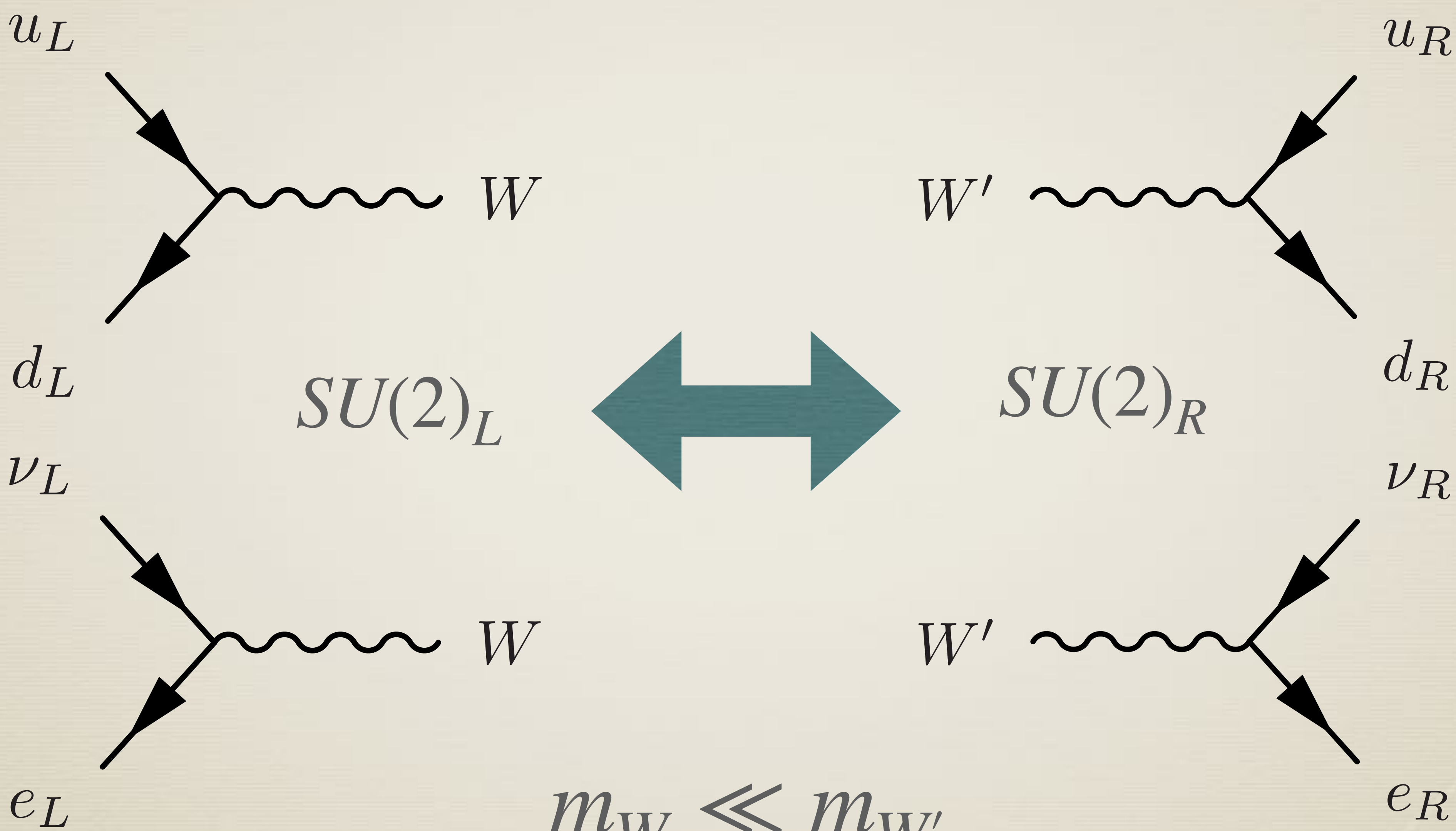


Weak interaction



Lee and Yang (1956), Wu (1957)

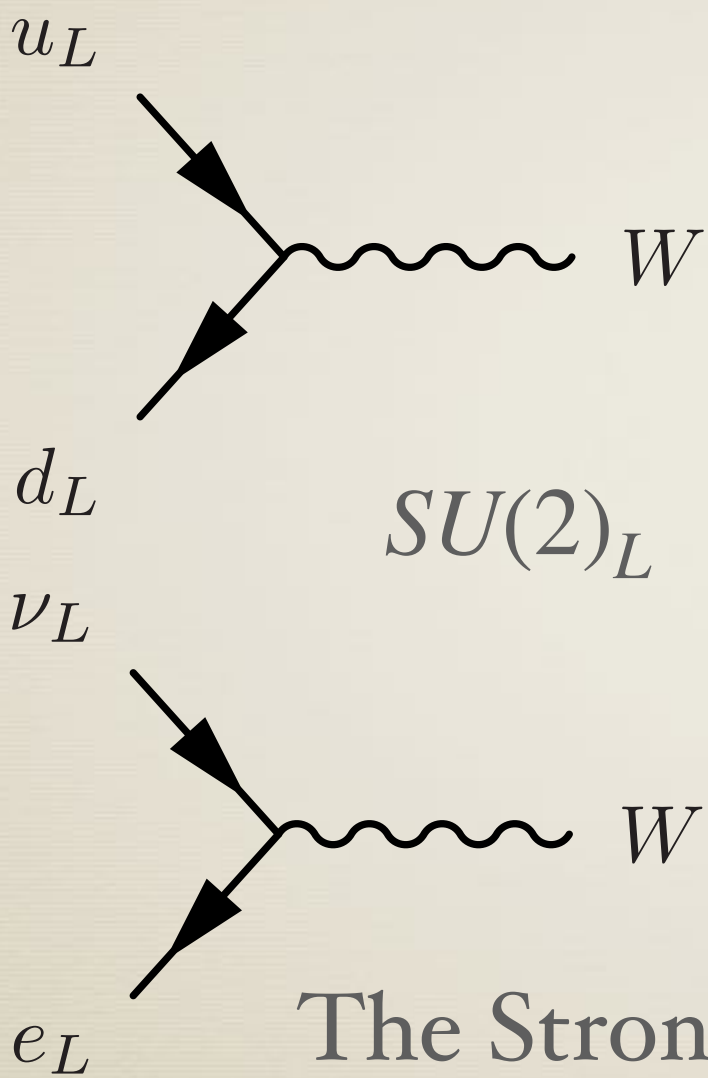
Spontaneously broken Left-Right symmetry



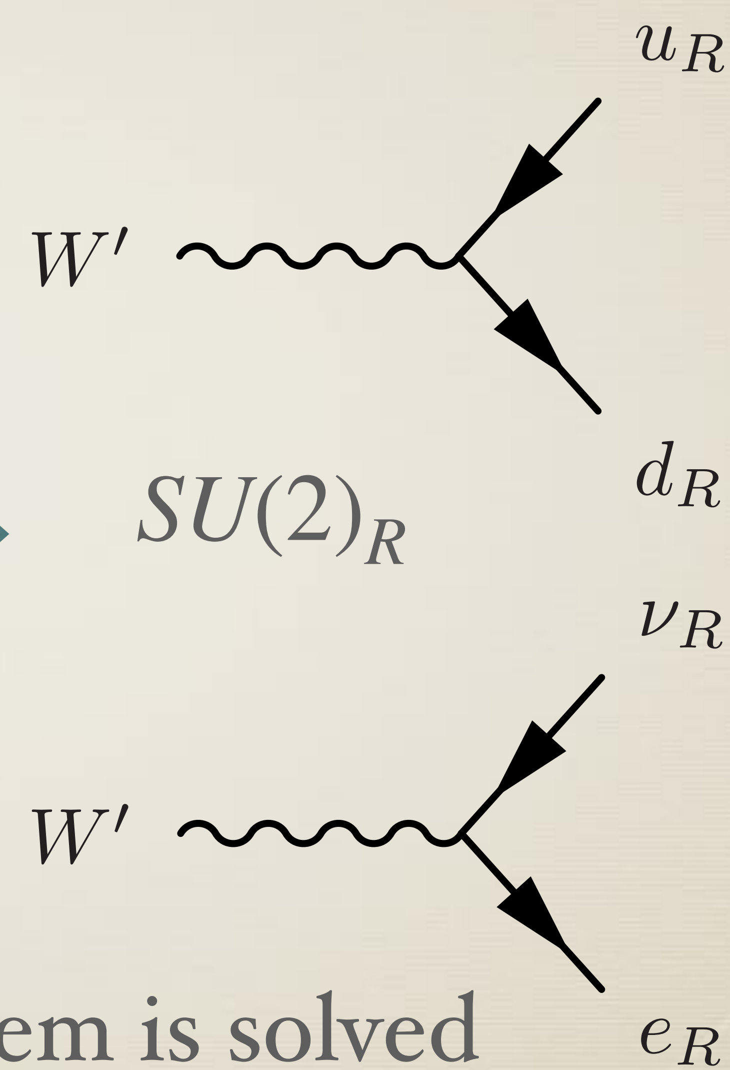
$$m_W \ll m_{W'}$$

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

Spontaneously broken Left-Right symmetry



$SU(2)_L$ ⟷ $SU(2)_R$



The Strong CP problem is solved via space-time parity

~~$H = d_n \vec{E} \cdot \vec{S}$~~

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

Left-Right Higgs Parity

Higgs ⟷ Higgs'

H ⟷ H'

Weak gauge boson ⟷ Weak gauge boson'

W ⟷ W'

$SU(2)_L$ ⟷ $SU(2)_R$

left-handed quark, lepton ⟷ right-handed quark, lepton

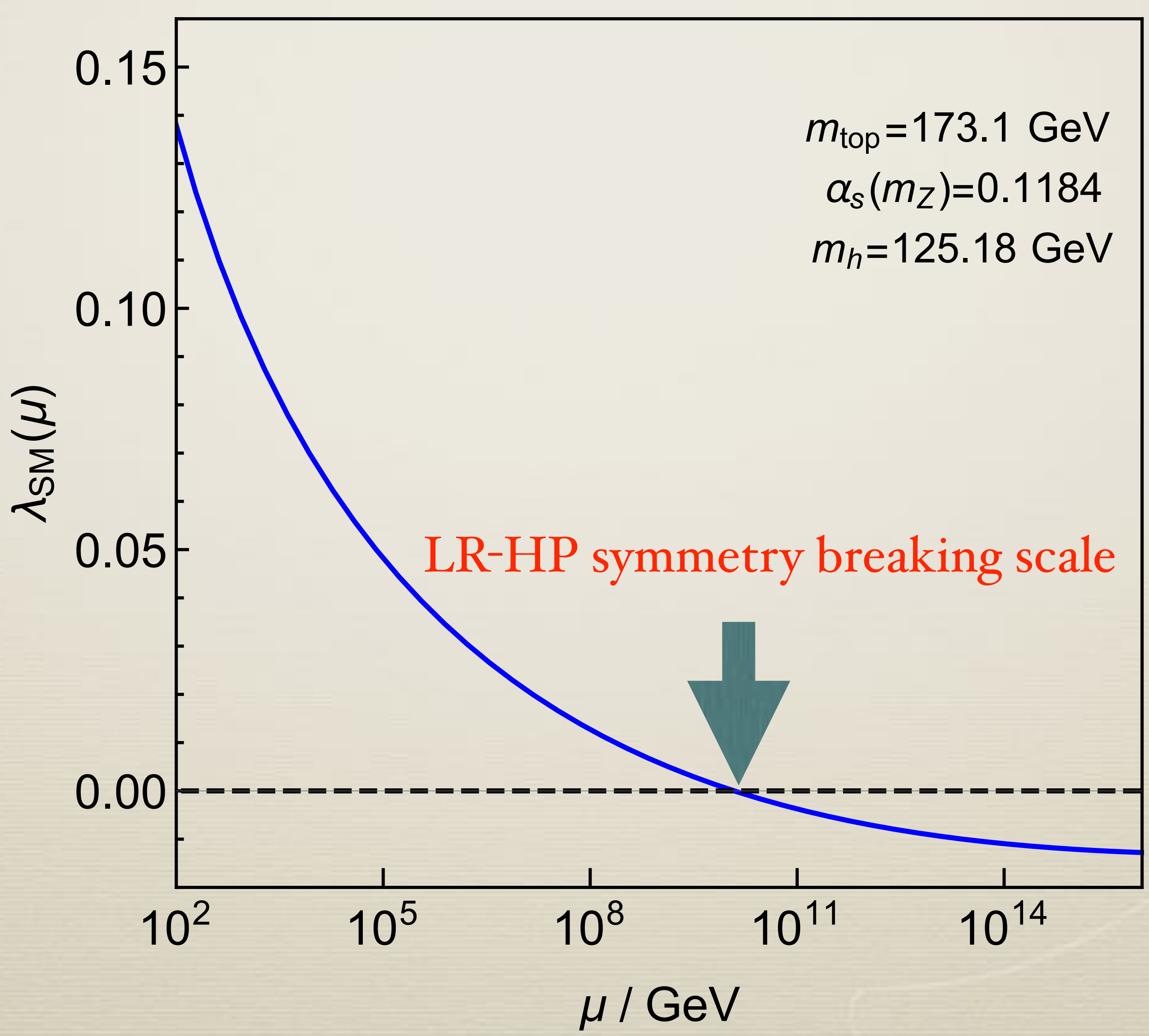
q_L, L_L ⟷ $q', L' = q_R, L_R$

$$SU(3)_c \times SU(2)_L \times \underbrace{SU(2)_R \times U(1)}_{\langle H' \rangle \;\downarrow\; U(1)_Y}$$

Left-Right Higgs Parity

Higgs
H

Higgs'
H'



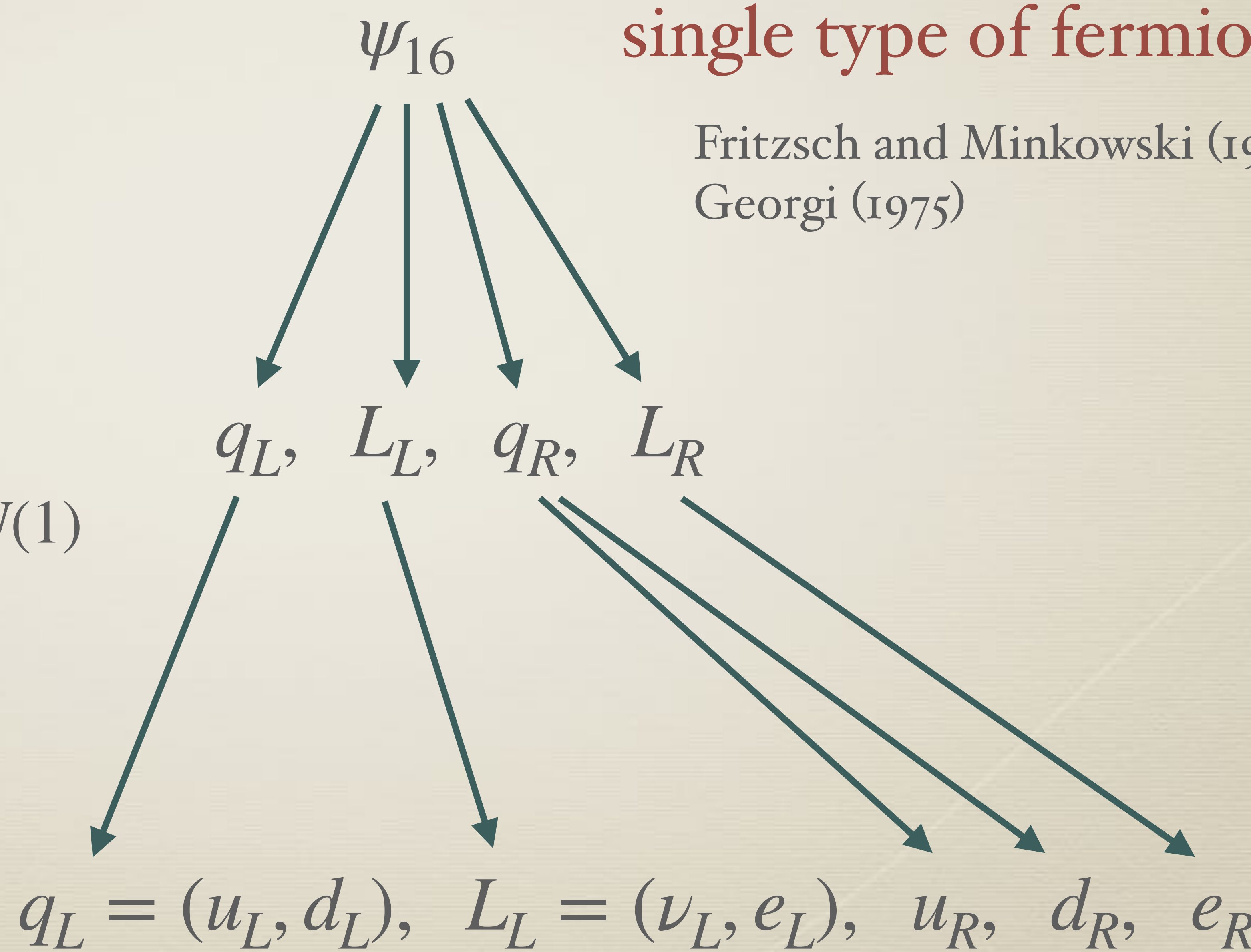
Left-Right symmetry and Grand Unified Theory

Grand Unification
$SO(10)$

$\langle H' \rangle \neq 0$

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

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



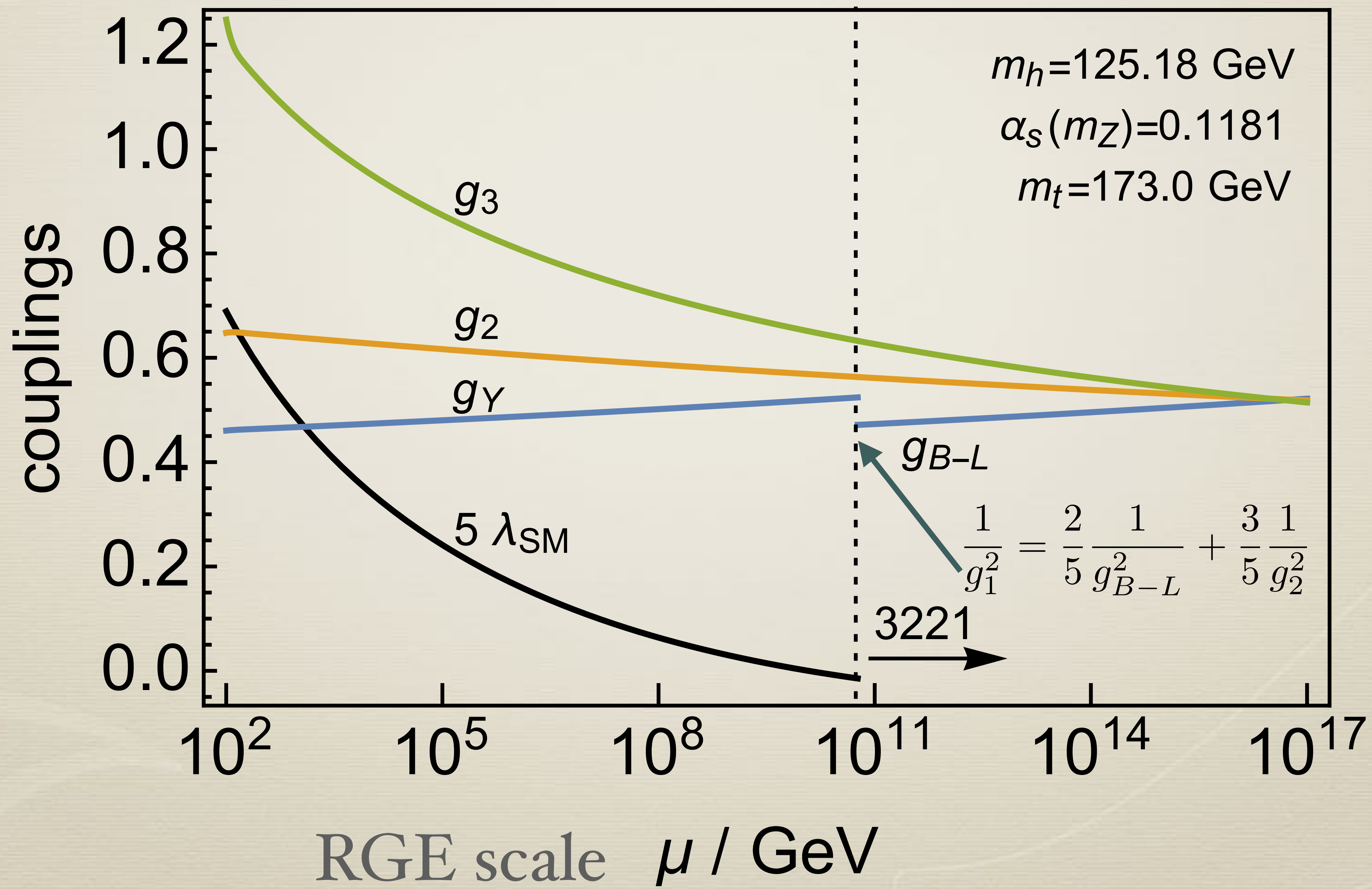
Single gauge group,
single type of fermions

Fritzsch and Minkowski (1975),
Georgi (1975)

Coupling unification

Hall, KH (2018, 2019)

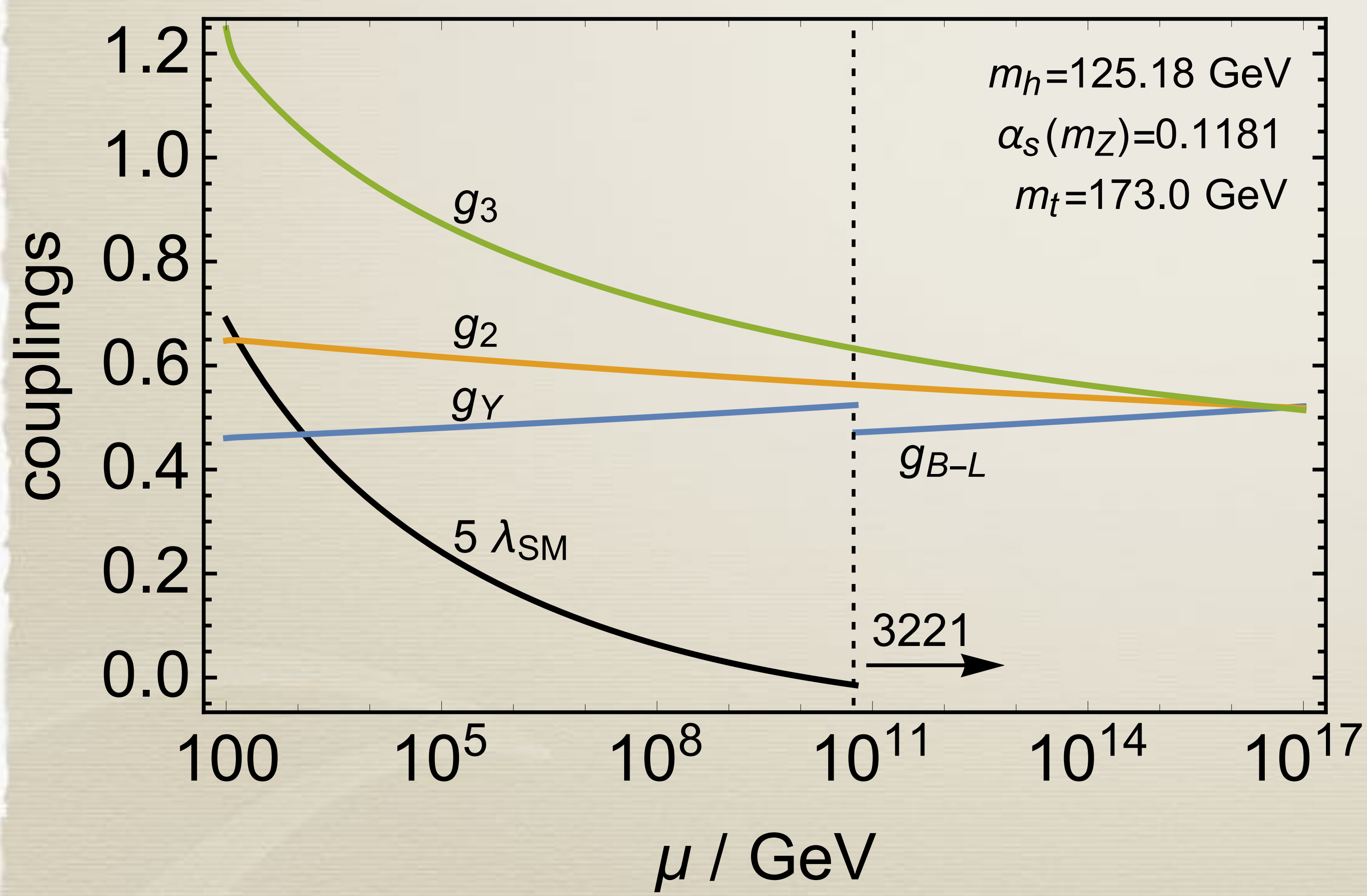
energy-dependent couplings



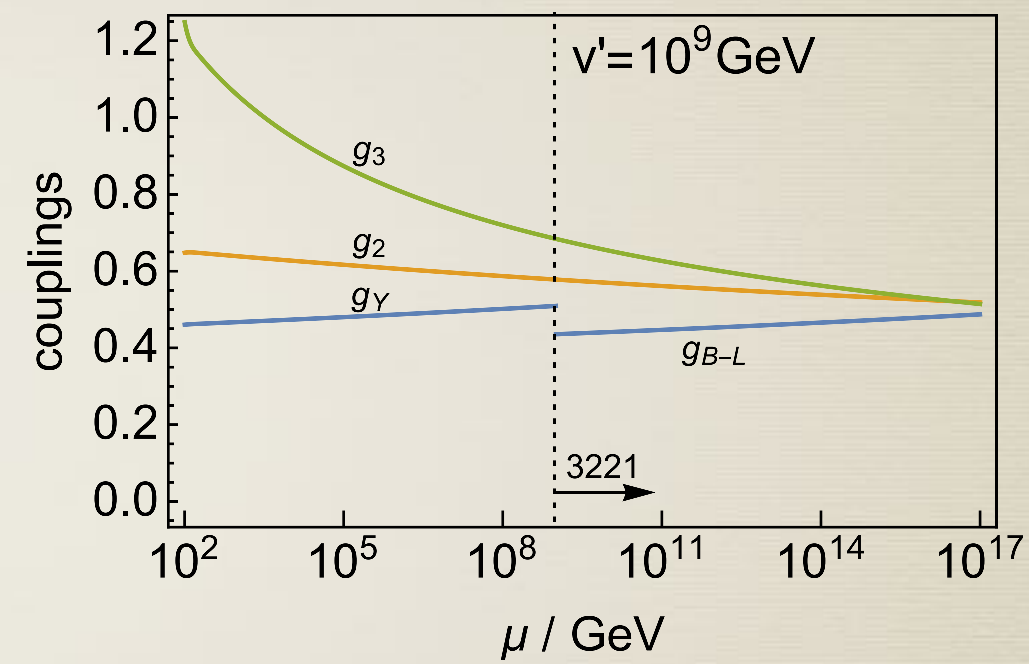
Coupling unification

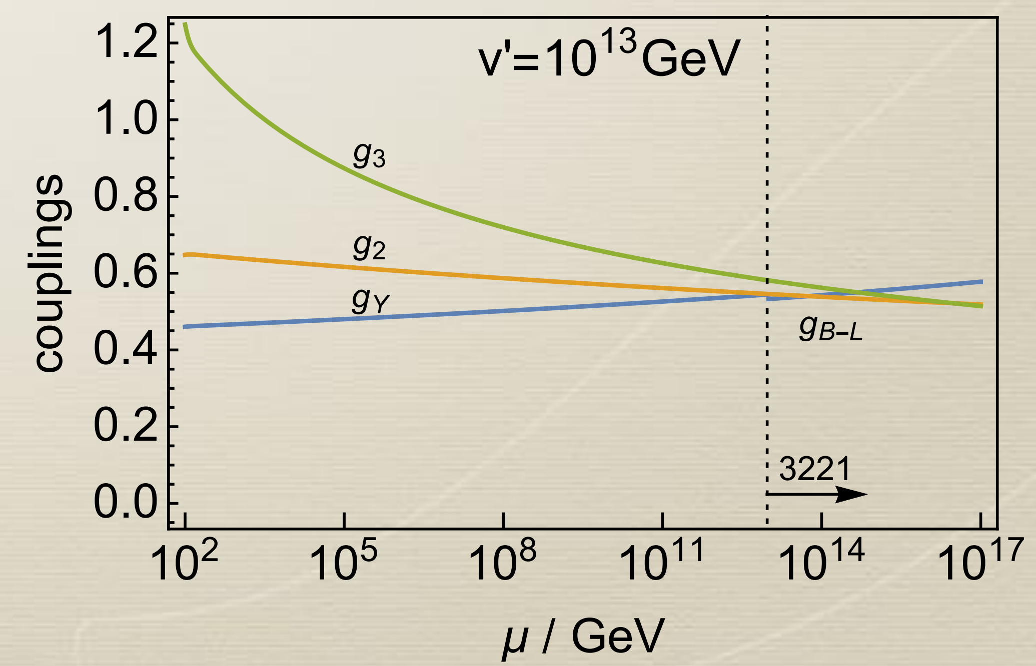
Hall, KH (2018, 2019)

v' determined by Higgs Parity



Other v'

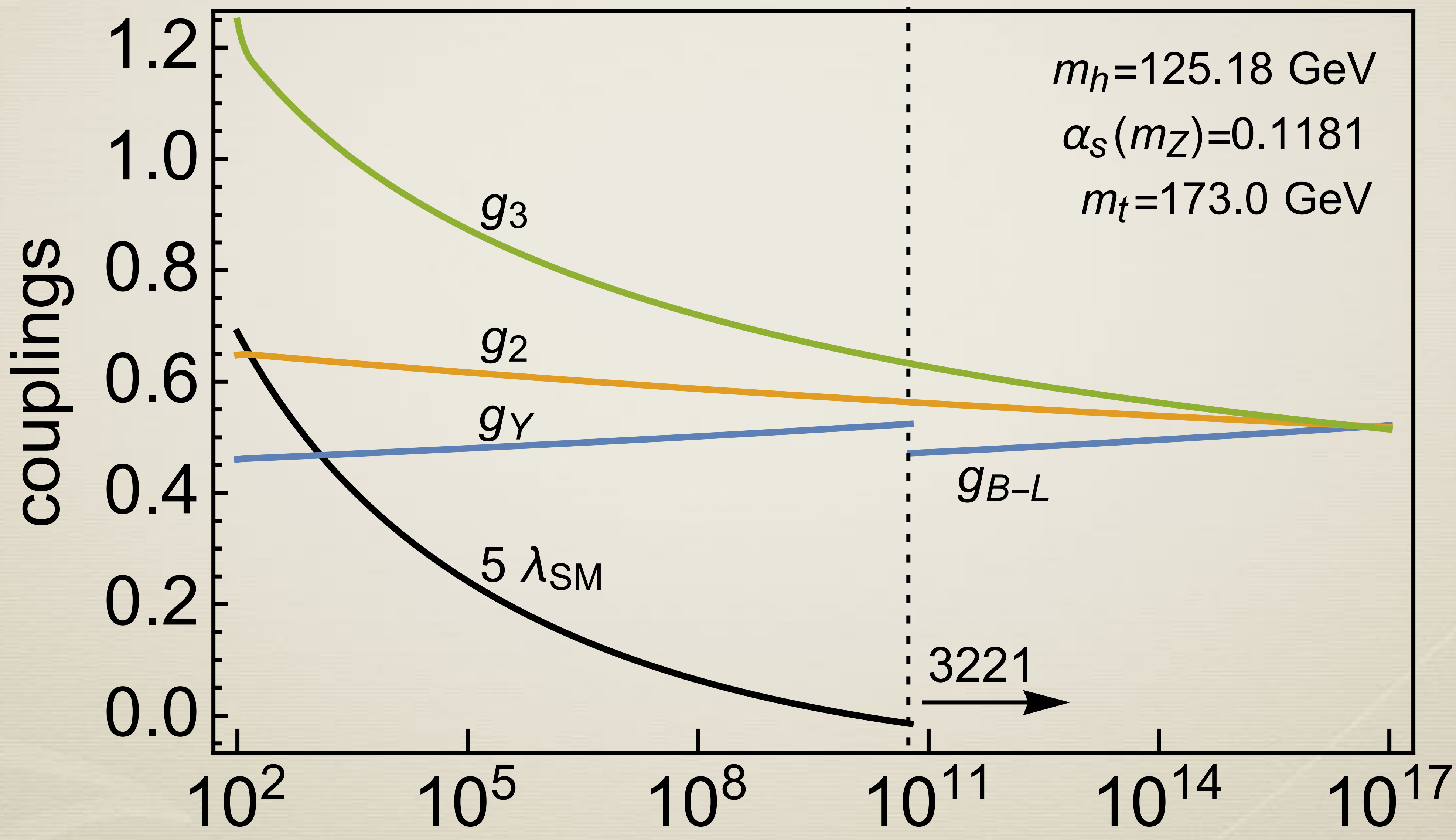




Higgs Parity GUT

Hall, KH (2018, 2019)

energy-dependent couplings



RGE scale μ / GeV

Higgs Parity GUT

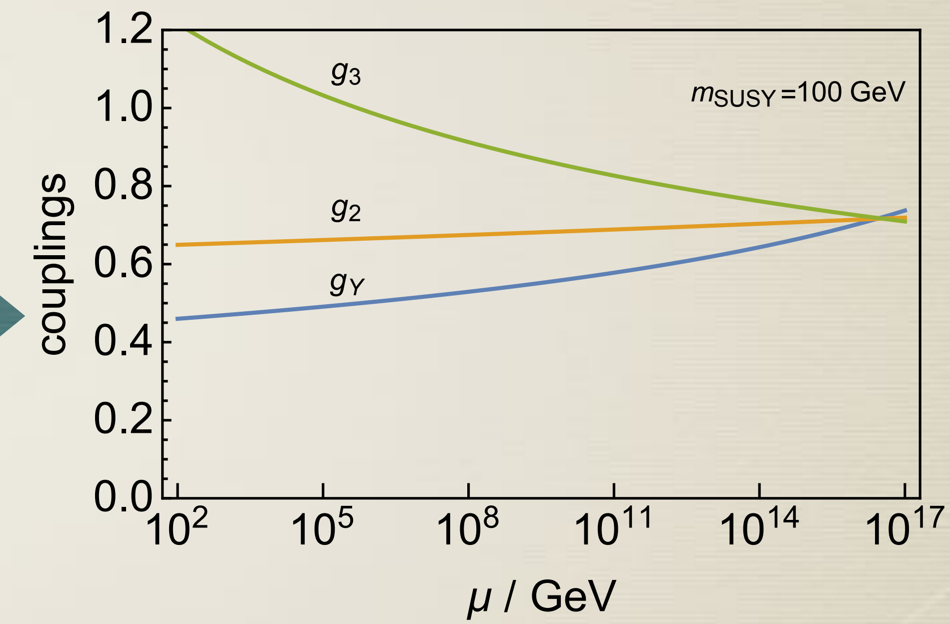
Hall, KH (2018, 2019)

weak scale 10^2 GeV

GUT scale 10^{16} GeV

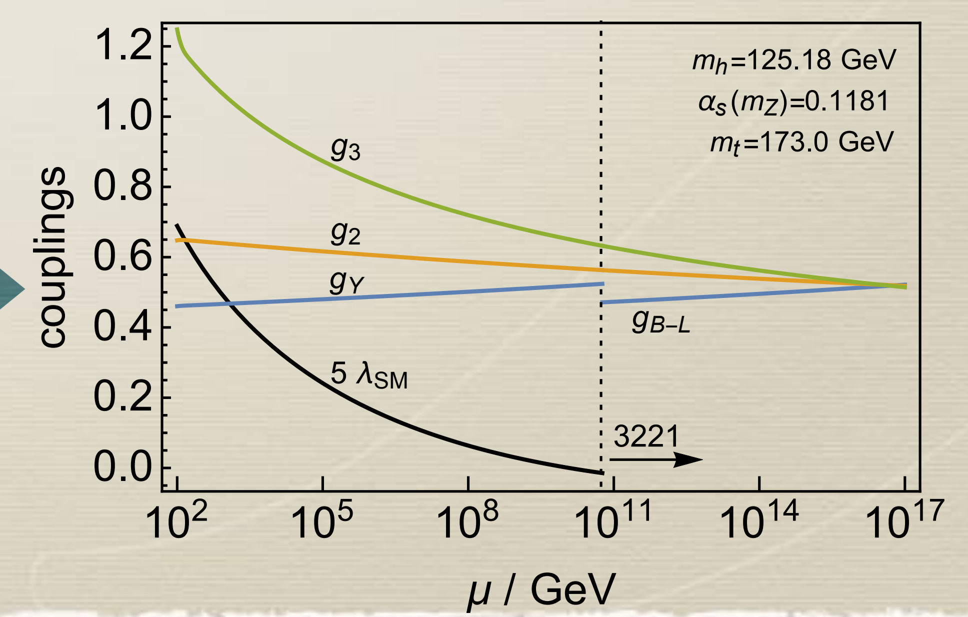
gauge coupling constants
(LEP, ...)

SUSY GUT

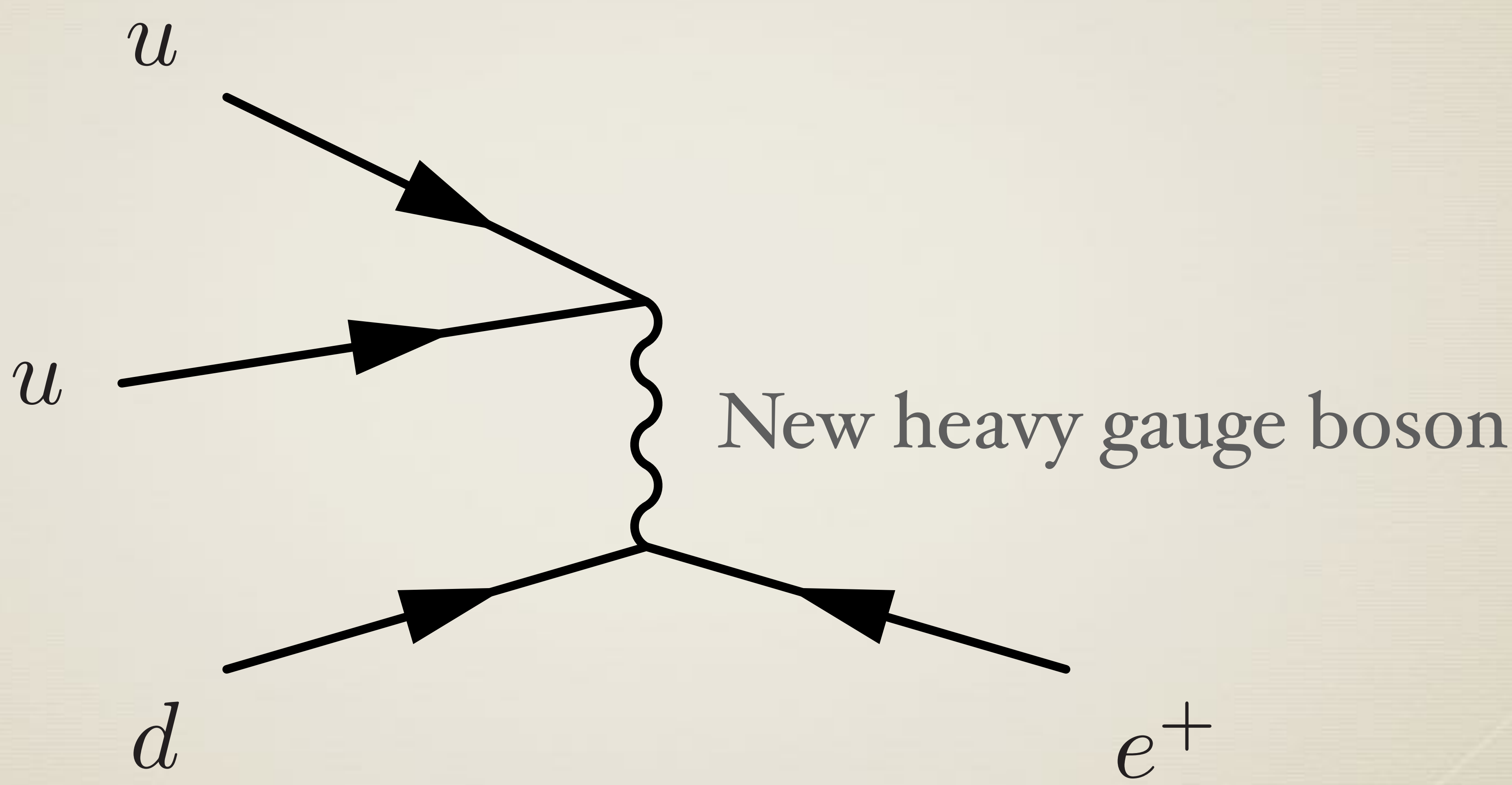


gauge coupling constants
top quark mass
Higgs mass
(LHC, lattice, future colliders, ...)

HP GUT



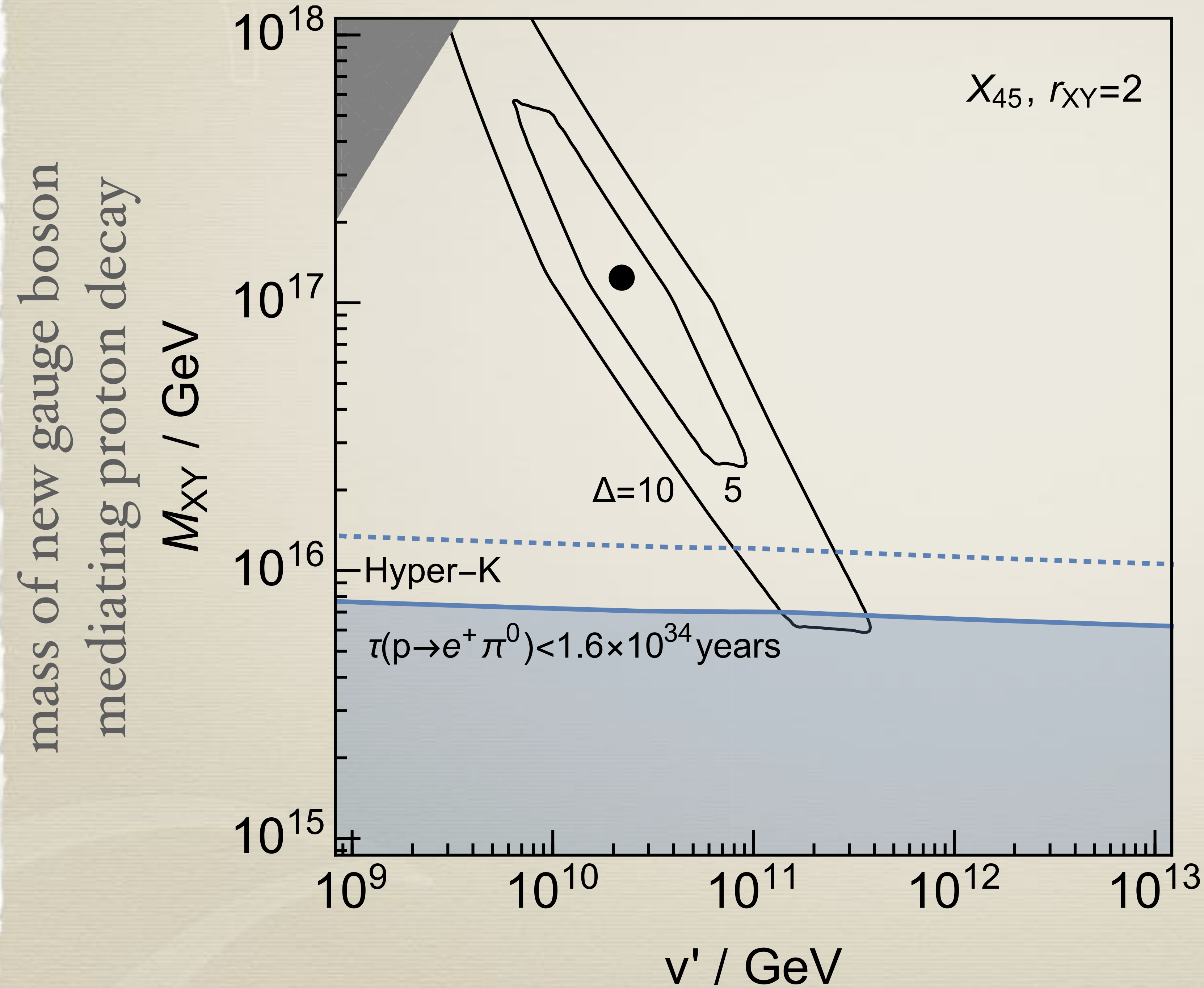
Proton decay



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

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

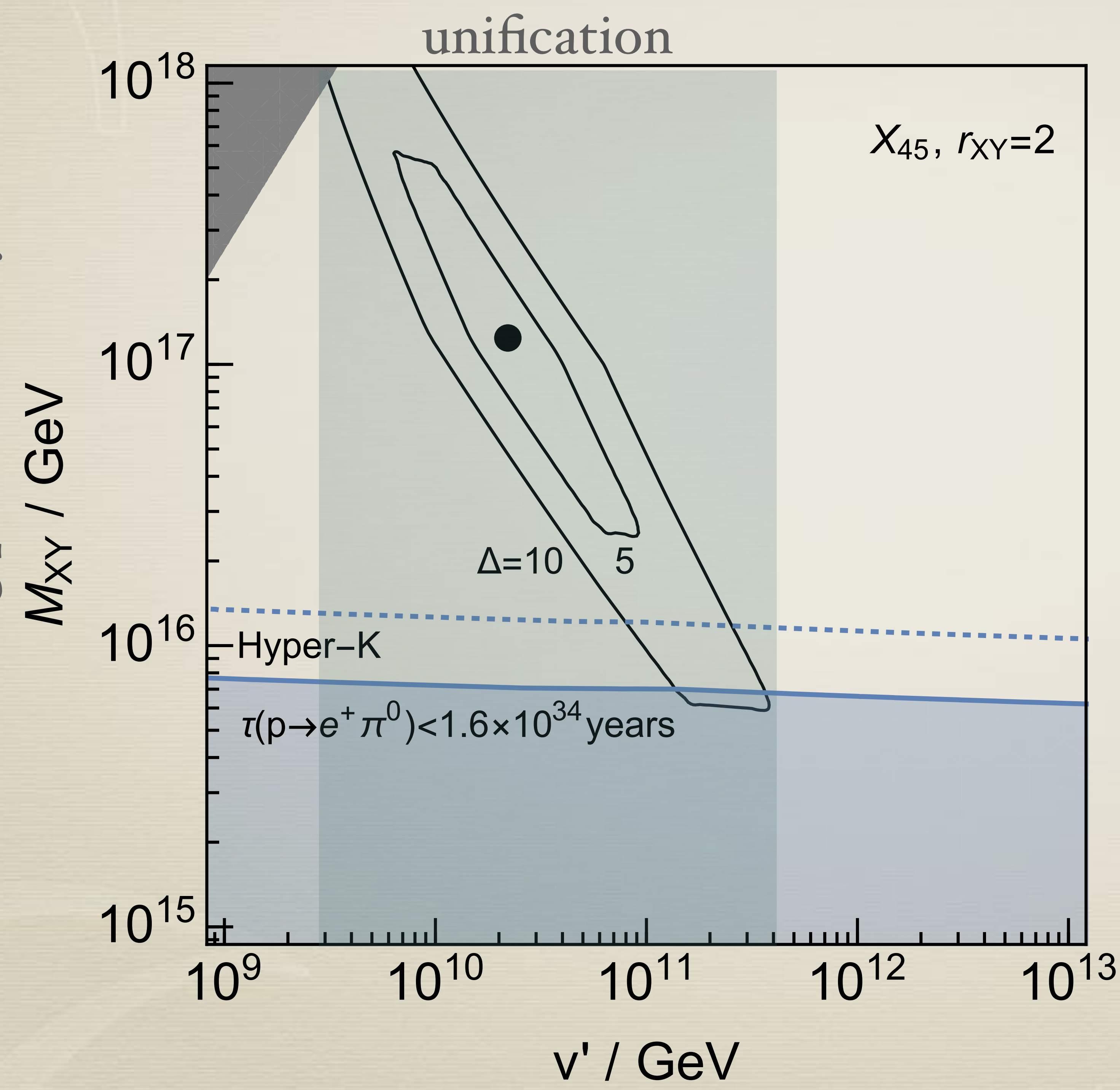
$$\Delta = \text{few} - 10$$

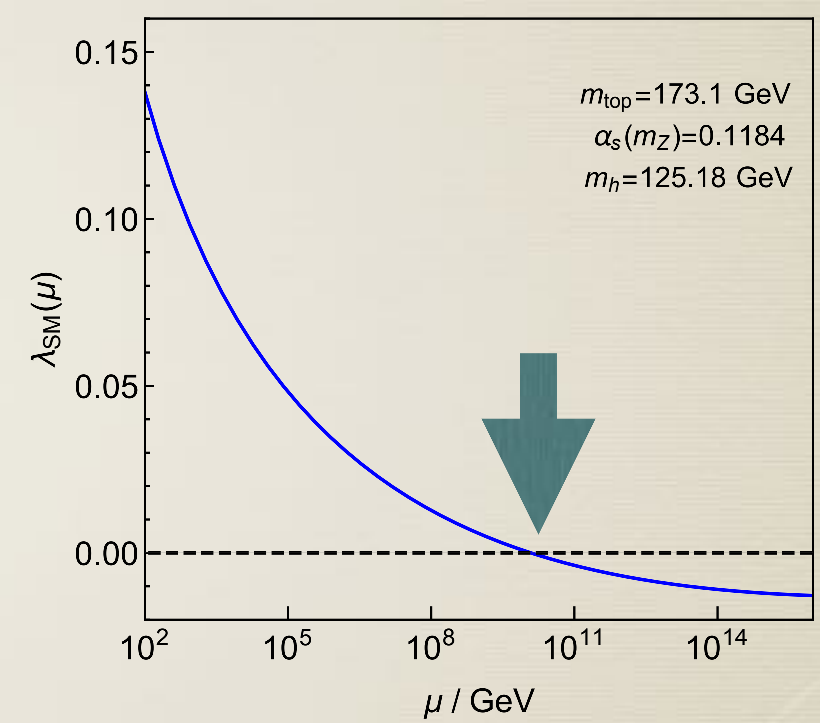
(smaller than SUSY GUT)

Quantify unification

Hall, KH (2019)

mass of new gauge boson
mediating proton decay





typically

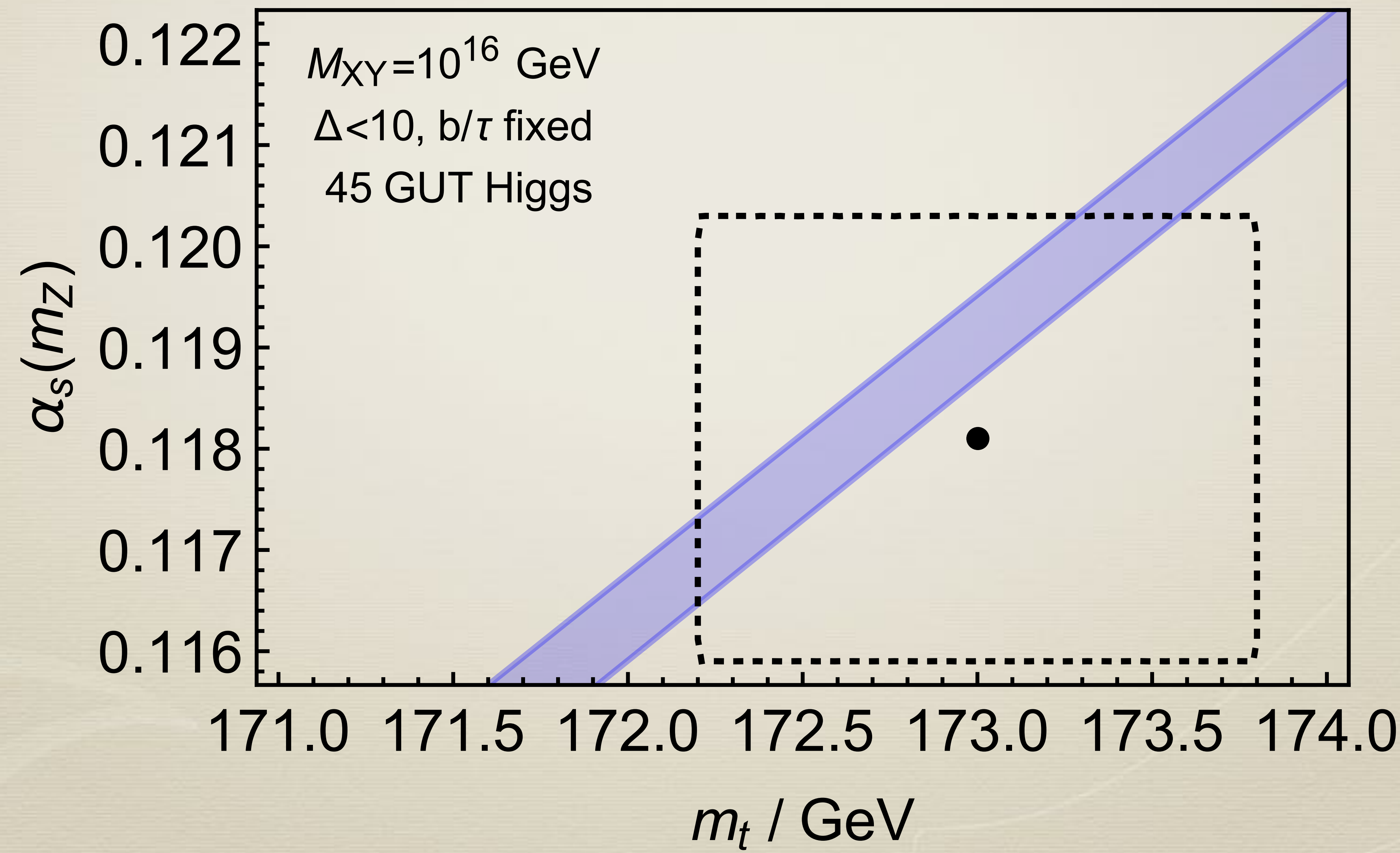
$$\Delta = \text{few} - 10$$

(smaller than SUSY GUT)

Proton decay

Hall, KH (2019)

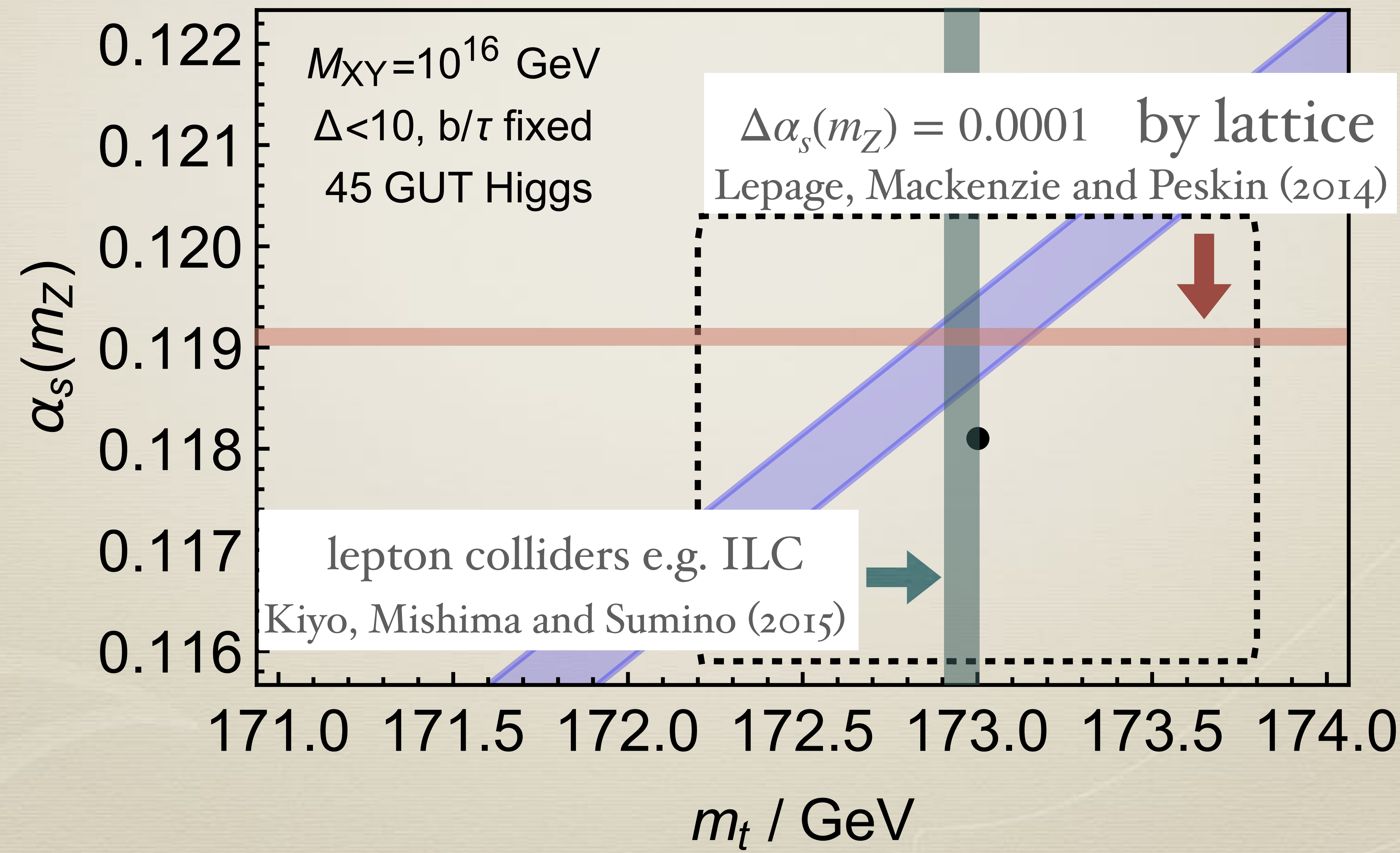
Suppose proton decay is observed at Hyper-K (2027-)



Proton decay

Hall, KH (2019)

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



Intermediate Pati-Salam

Grand Unification
$SO(10)$

↓

Pati-Salam group
$SU(4) \times SU(2)_L \times SU(2)_R$

↓ $\langle H' \rangle \neq 0$

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

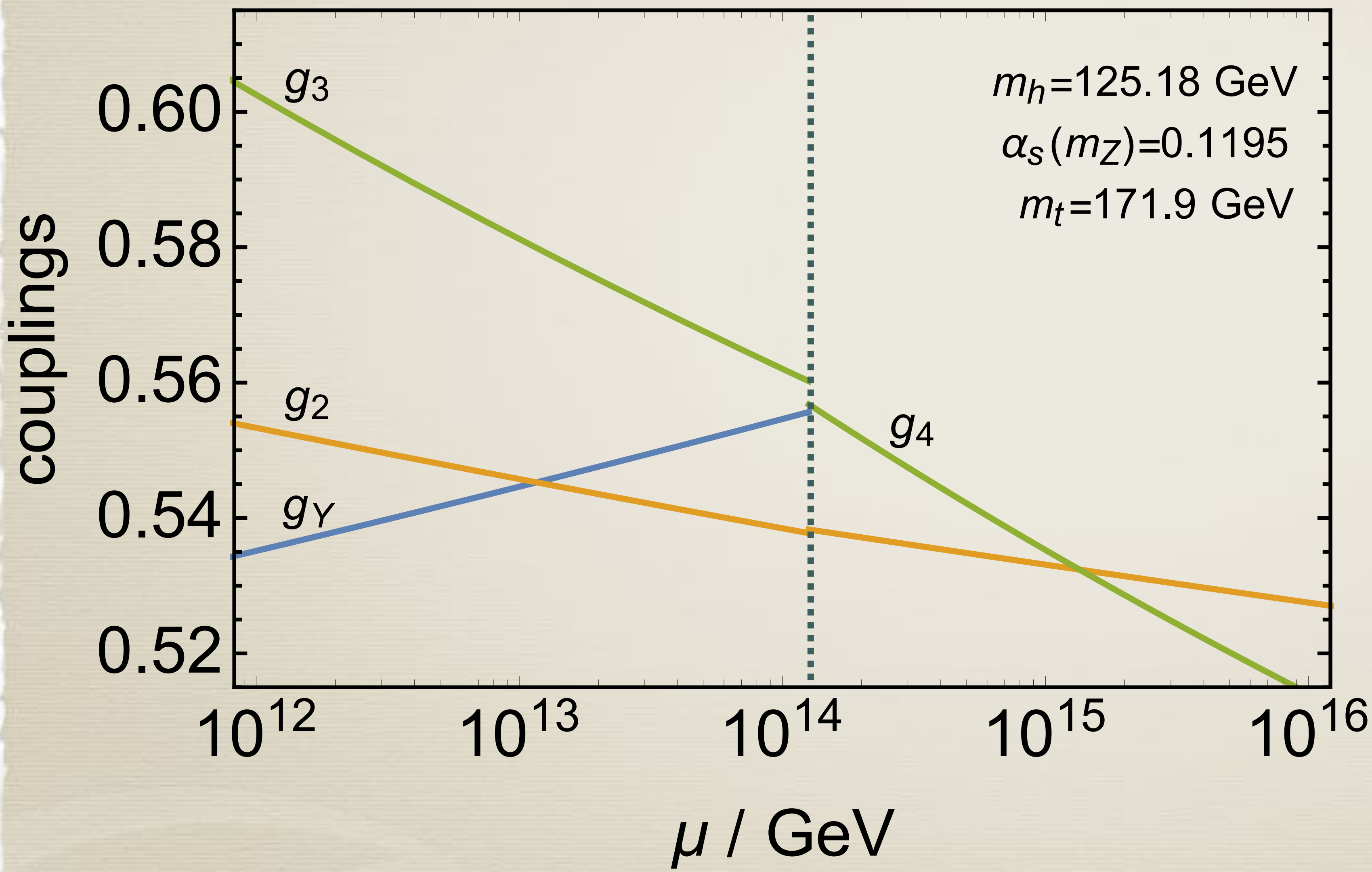
ψ_{16}

$(q_L,\ L_L),\ (q_R, L_R)$

$q_L = (u_L, d_L),\quad L_L = (\nu_L, e_L),\quad u_R,\quad d_R,\quad e_R$

Intermediate Pati-Salam

Hall, KH (2018, 2019)



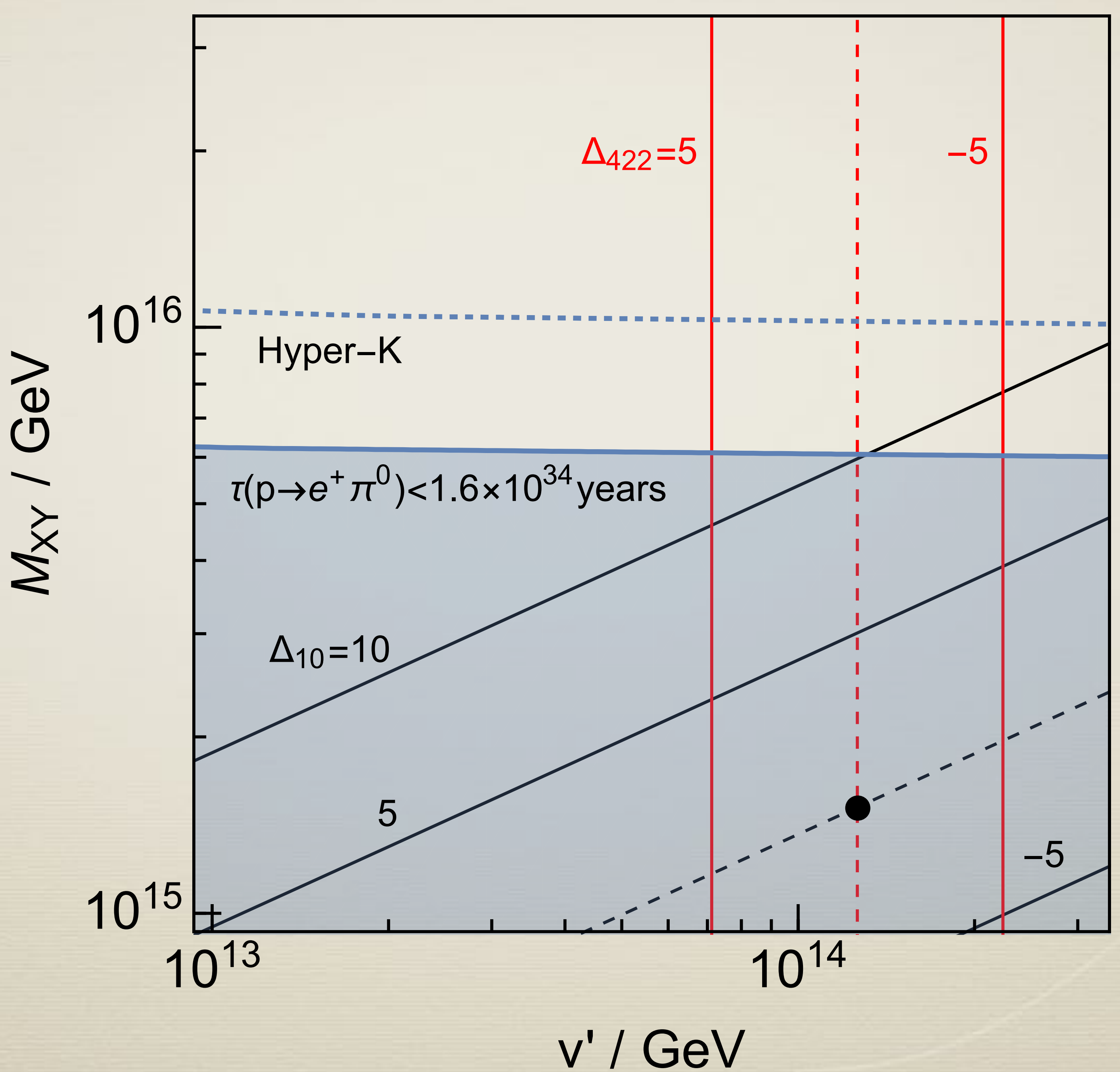
$SU(4) \times SU(2)_L \times SU(2)_R$

2 couplings

Pati-Salam scale is fixed by coupling unification

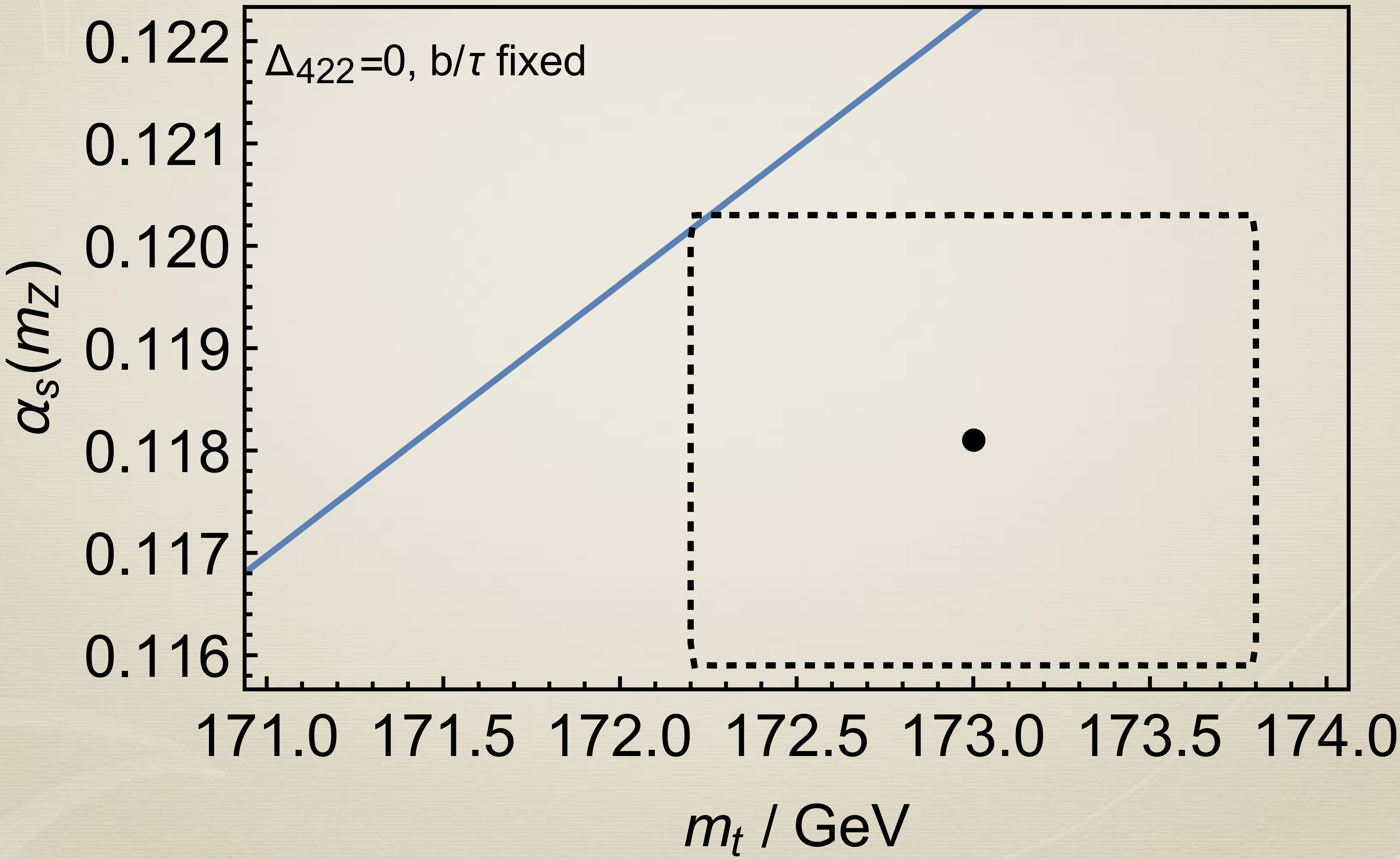
$$\frac{1}{g_1^2} \simeq \frac{2}{5}\frac{1}{g_4^2} + \frac{3}{5}\frac{1}{g_2^2}$$

Pati-Salam



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

Pati-Salam



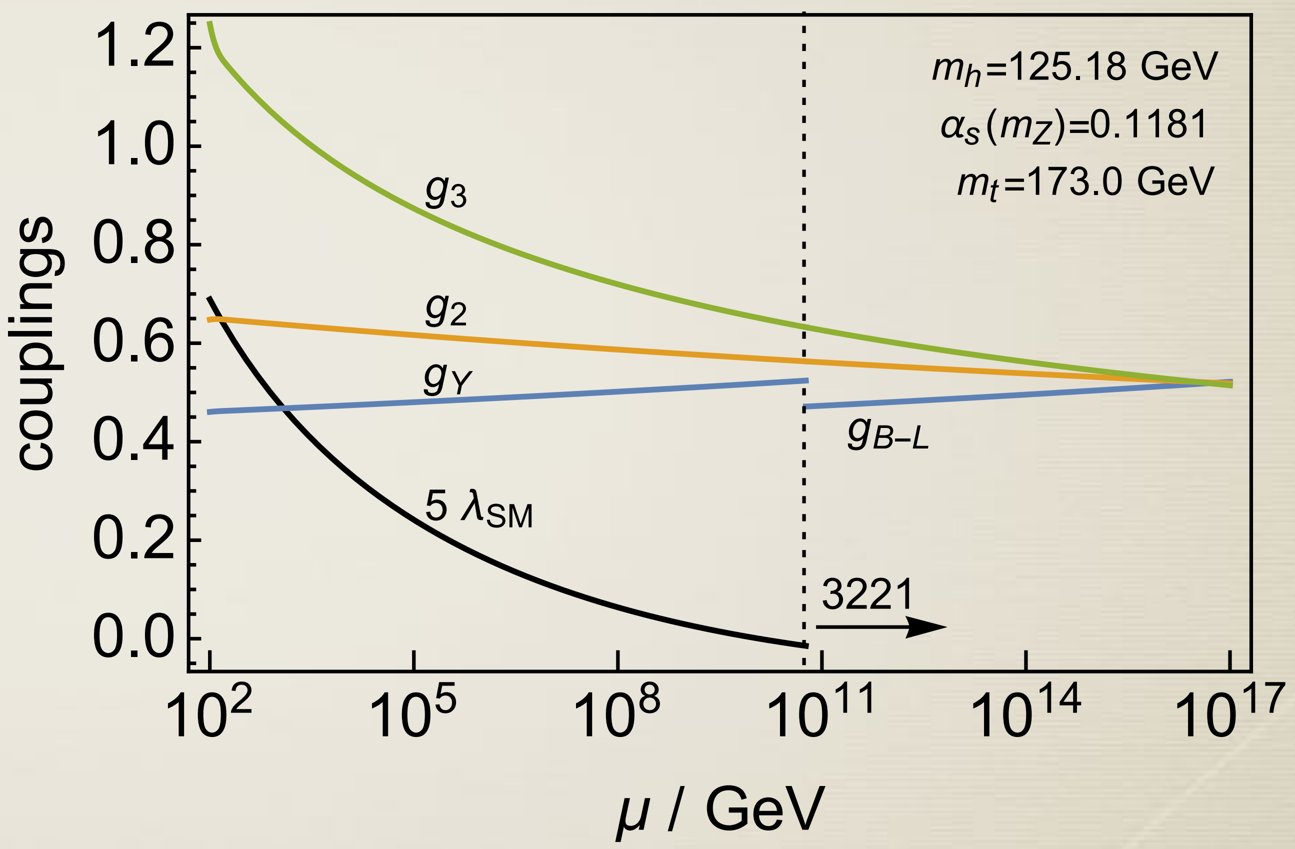
Δ422=0, b/τ fixed
0.122
0.121
0.120
0.119
0.118
0.117
0.116
αs(mZ)
171.0
171.5
172.0
172.5
173.0
173.5
174.0
mt / GeV

Summary and outlook

Higgs Parity

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

top quark mass
Higgs mass
strong coupling constant



Higgs Parity
symmetry breaking scale

Grand unification
proton decay

(dark matter detection, gravitational waves,
dark radiation, warm dark matter, neutron EDM, axion, ...)

Other models with Higgs Parity

* $SU(3)_c \times SU(2)_L \times SU(2)' \times U(1)_Y \times U(1)'_Y$

  Dunsky, Hall and KH, 1902.07726

  Dark matter direct detection rate is predicted from the SM parameters

  backup

* A model with a mirror copy of the SM

  Dunsky, Hall and KH, 1908.02756

  Dark radiation and gravitational wave abundance are predicted from SM parameters

  backup

* A model with a sterile neutrino DM and leptogenesis

  Dror, Dunsky, Hall and KH, 2004.09511
  Dunsky, Hall and KH, 2007.12711

  Strong CP problem is solved via parity. Possible range of sterile neutrino DM mass and warmness is predicted from SM parameters

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

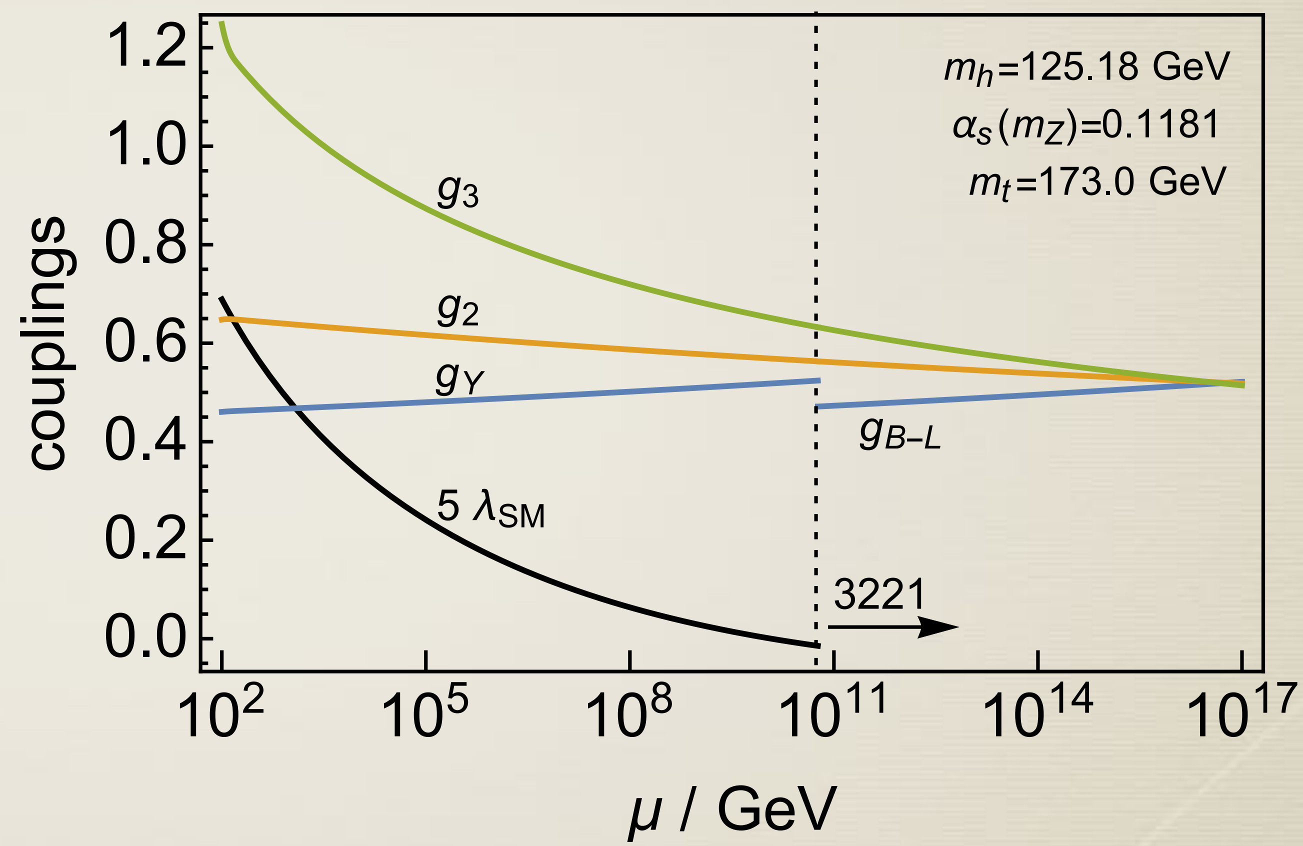
top quark mass,
strong coupling constant,
Higgs mass, etc.

Any other new physics models
impacted by precise measurements?

Higgs Parity

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

top quark mass
Higgs mass
strong coupling constant



Higgs Parity
symmetry breaking scale

Grand unification
proton decay

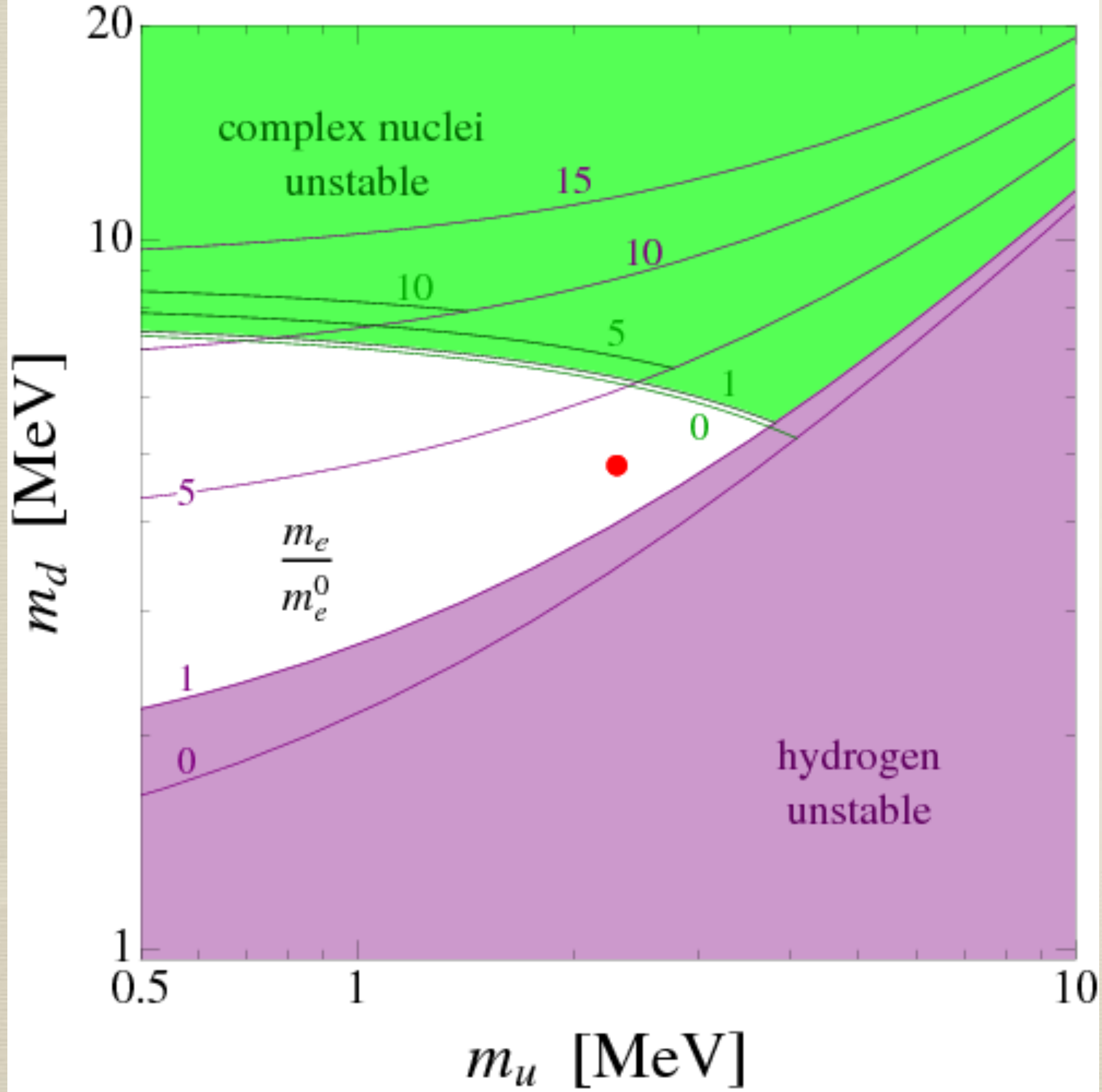
(dark matter detection, gravitational waves,
dark radiation, warm dark matter, neutron EDM, axion, ...)

Back up

On fine-tuning

Stability of nuclei

Plot from Hall, Pinner, Ruderman (2014)



We need smaller yukawa to compensate large v

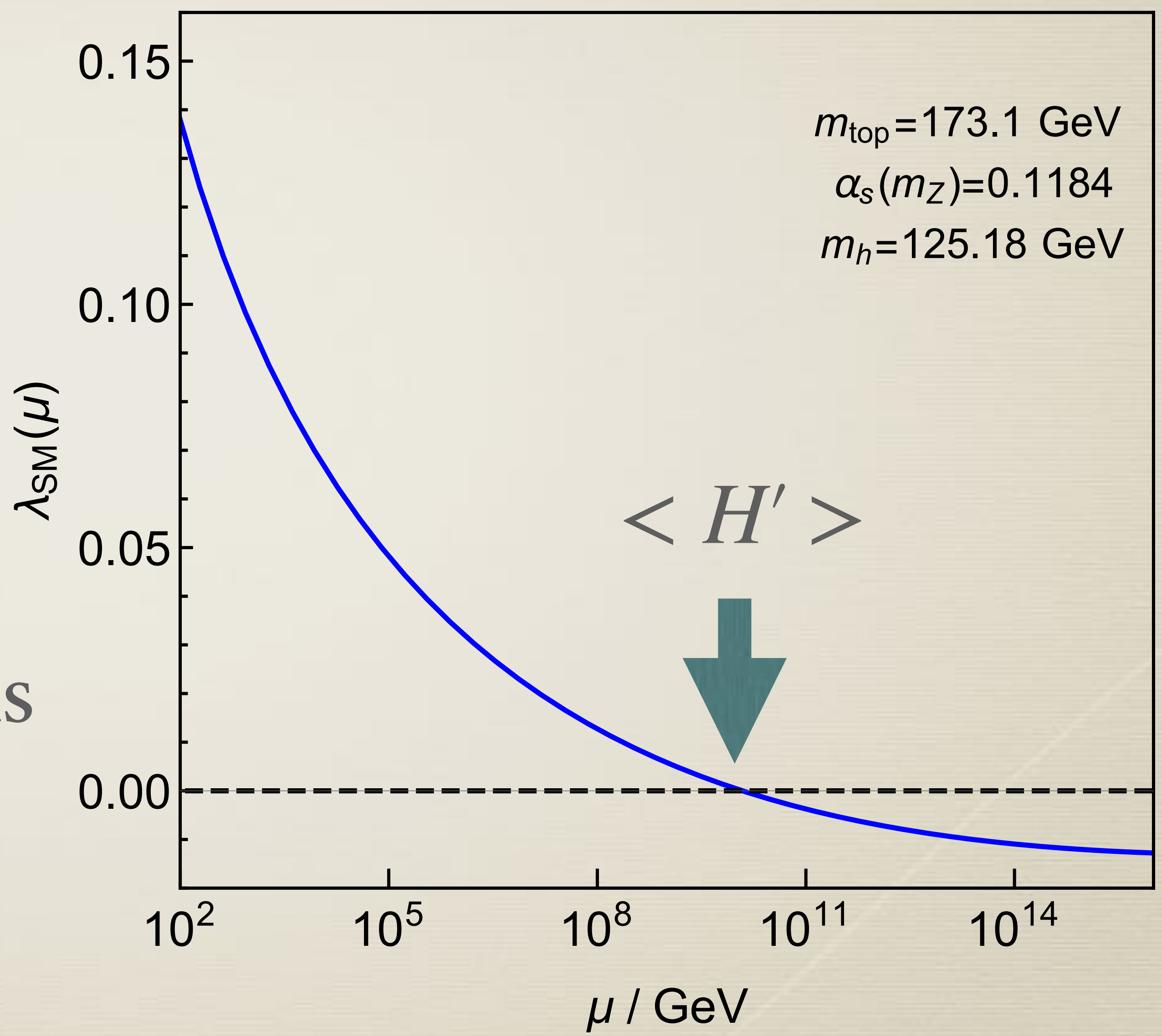
Detail about Small quartic

HP symmetry breaking scale

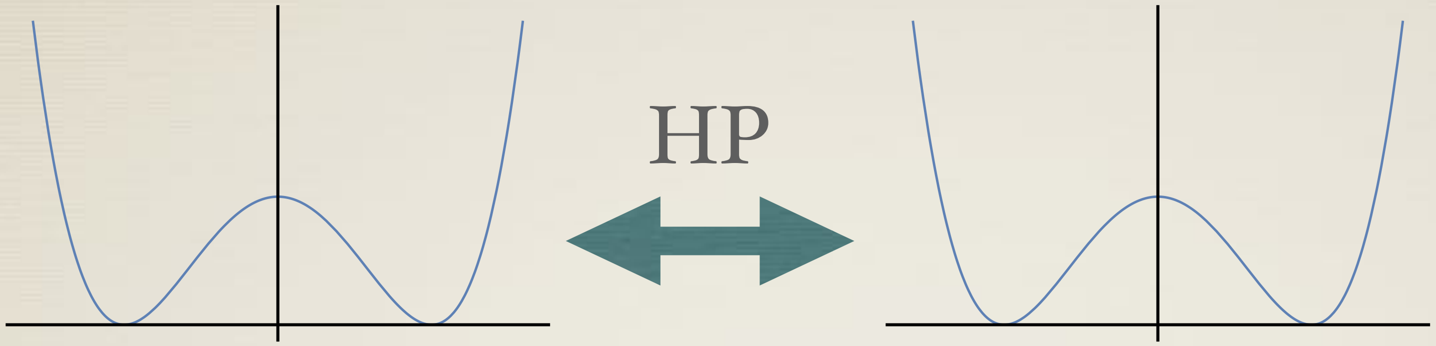
I will show that

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

because Higgs Parity constrains the potential of H and H'



Higgs potential

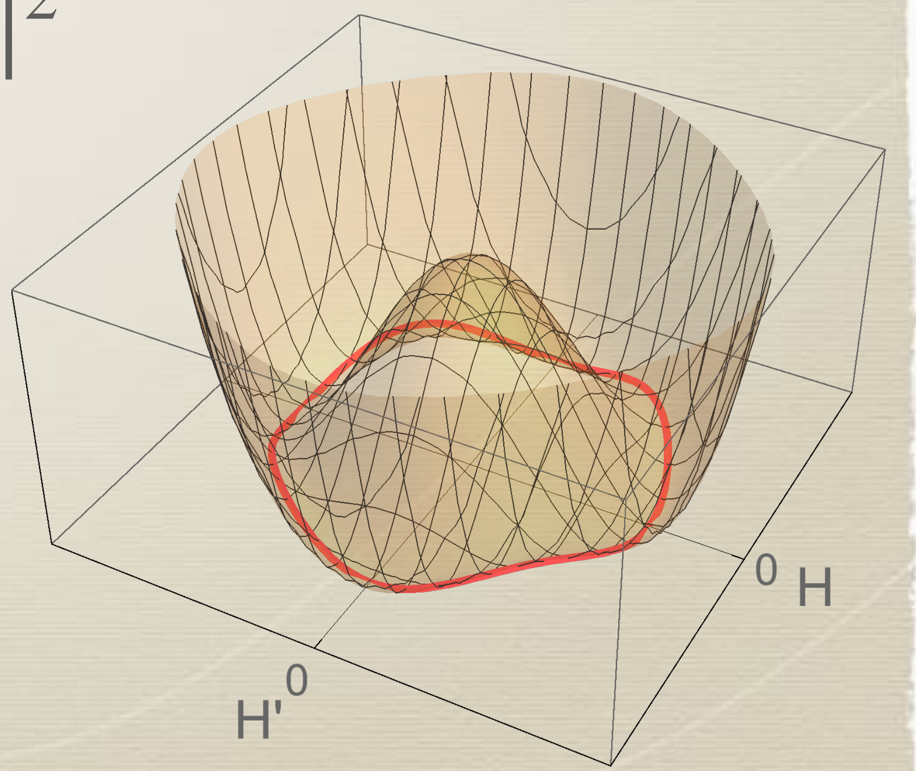


$$V = \left(\lambda |H|^4 - m^2 |H|^2\right) + \left(\lambda |H'|^4 - m^2 |H'|^2\right) + \tilde{y}\, |H|^2 |H'|^2$$

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

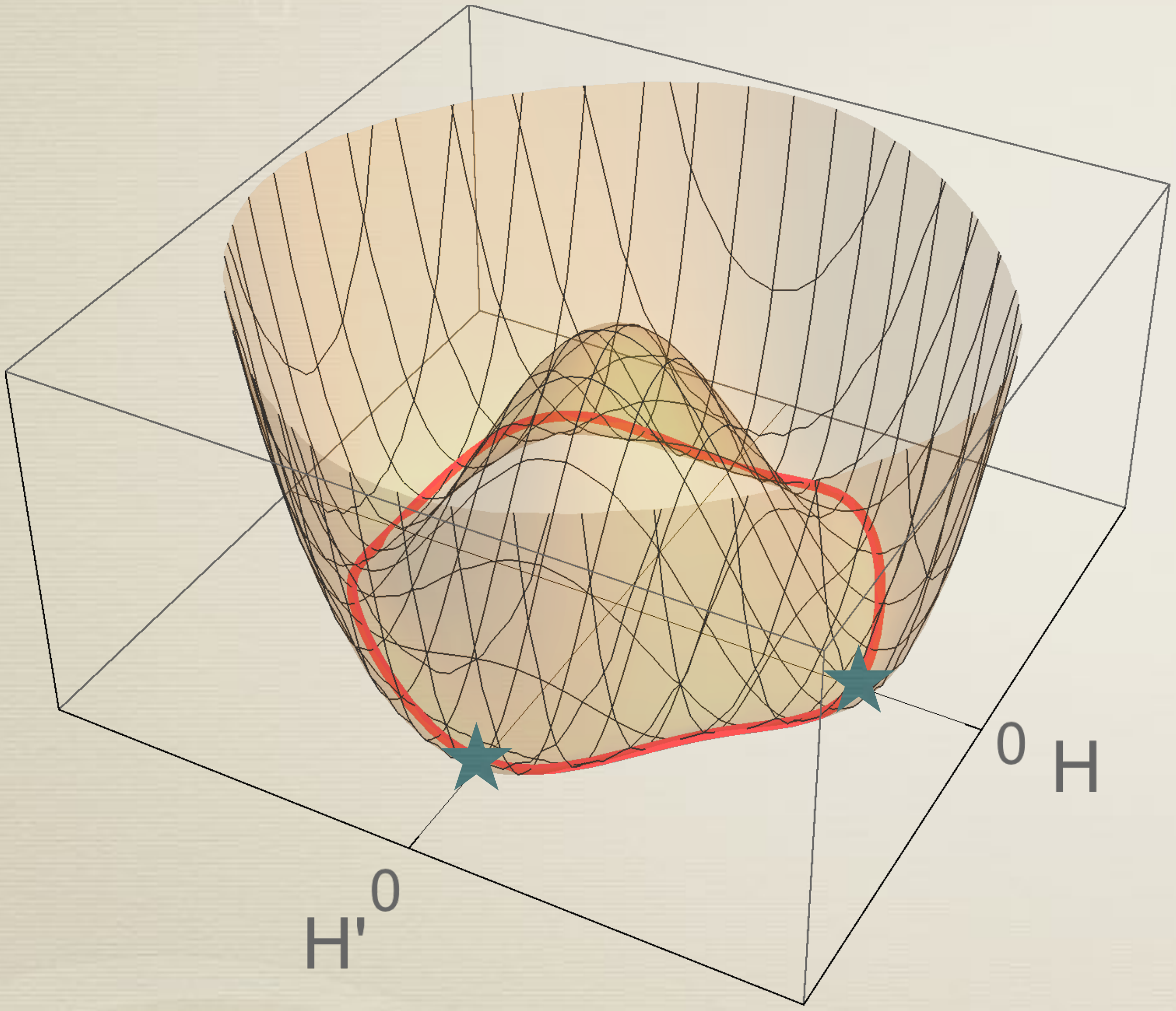
Can we find the minimum with

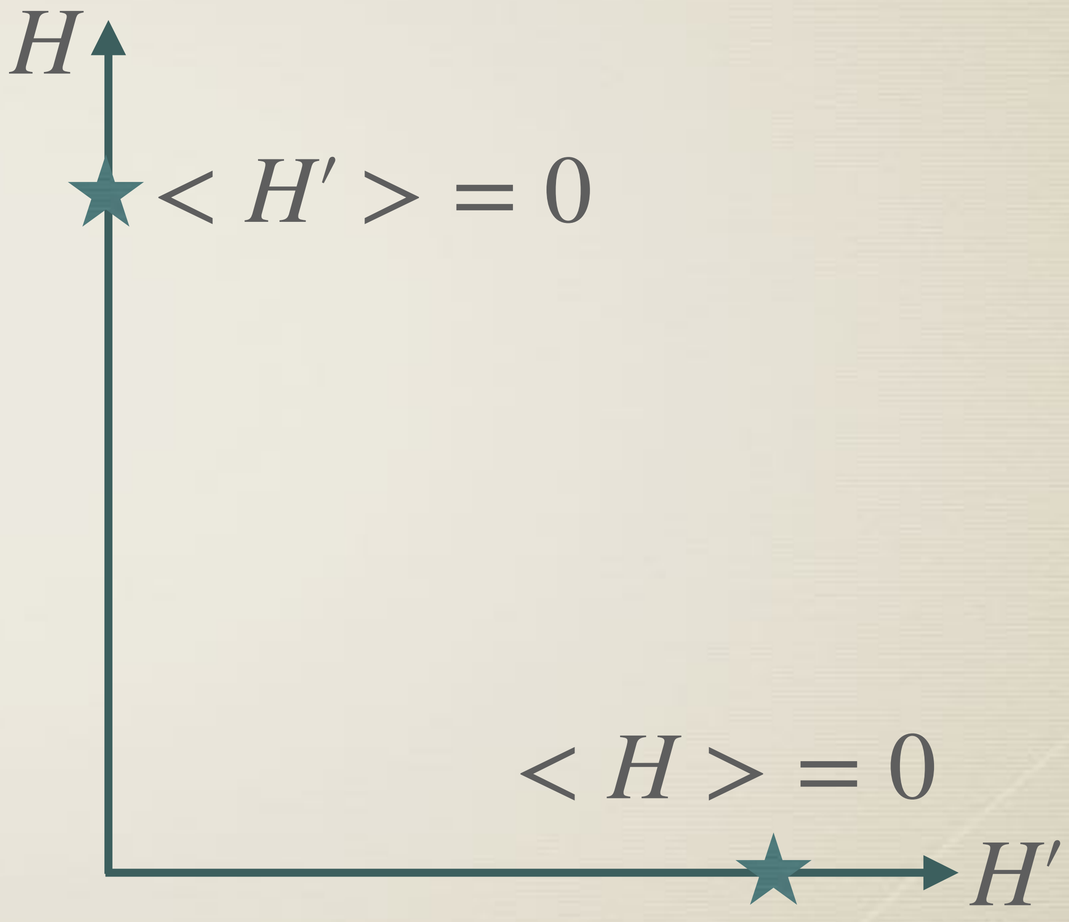
$$\langle H \rangle \ll \langle H' \rangle \; ?$$



$y > 0$

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

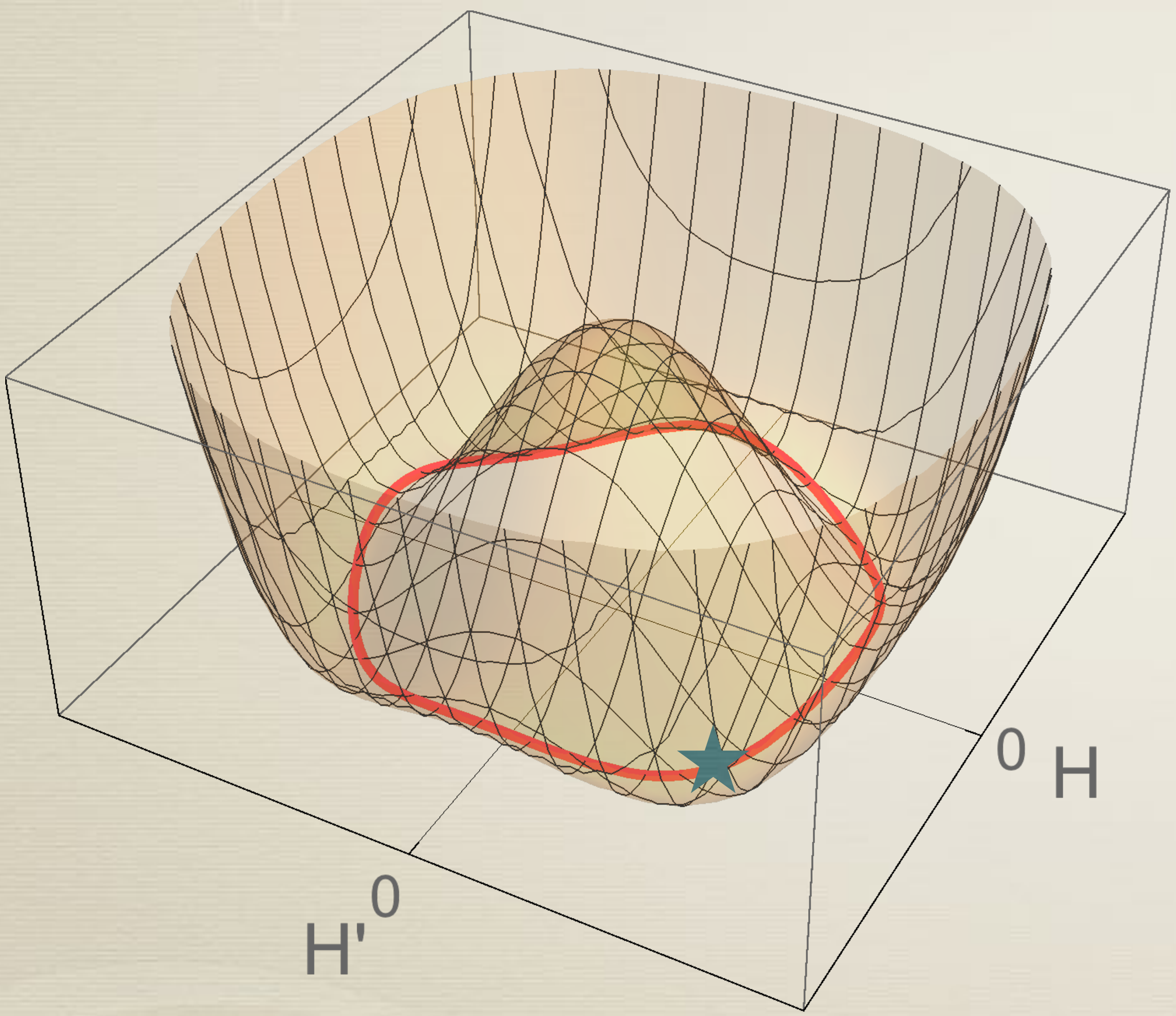


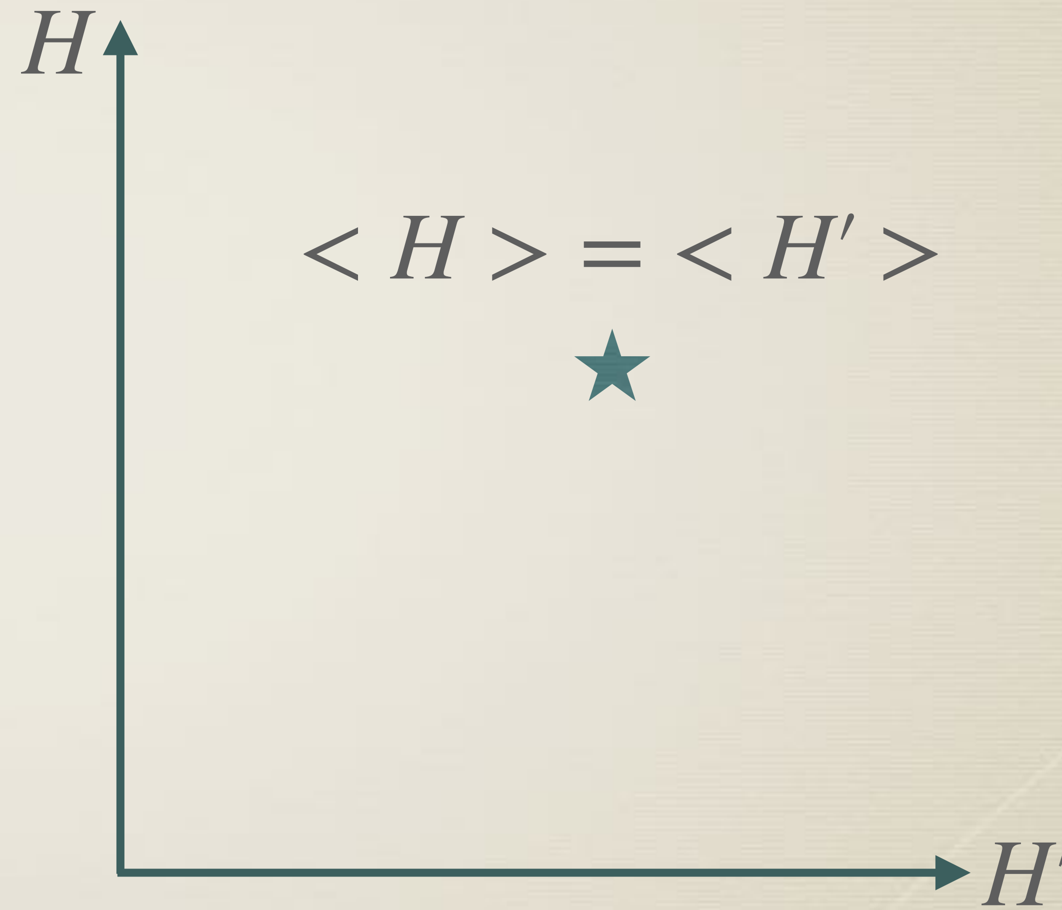


$$0 \neq \langle H \rangle \ll \langle H' \rangle$$

$y < 0$

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

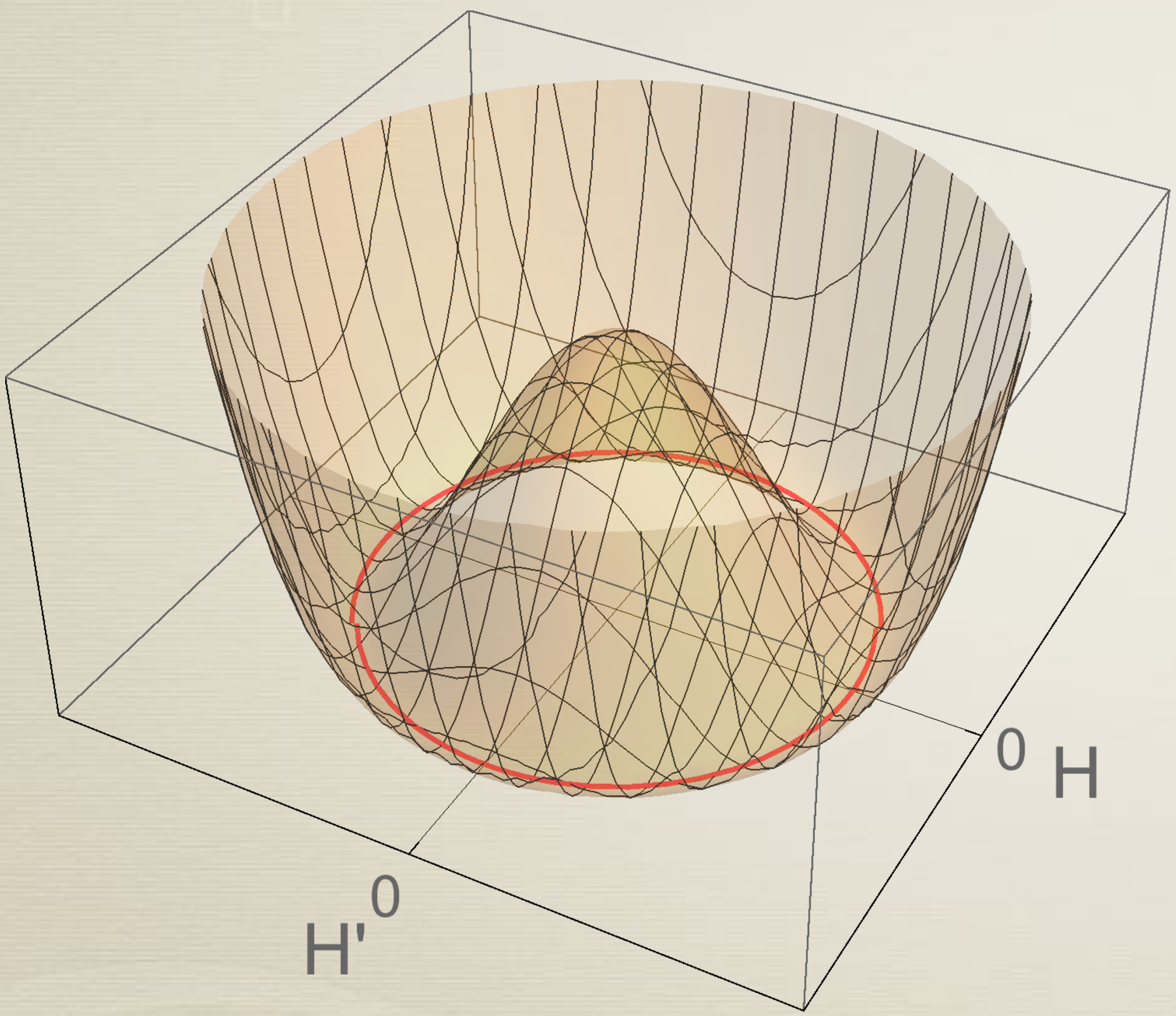


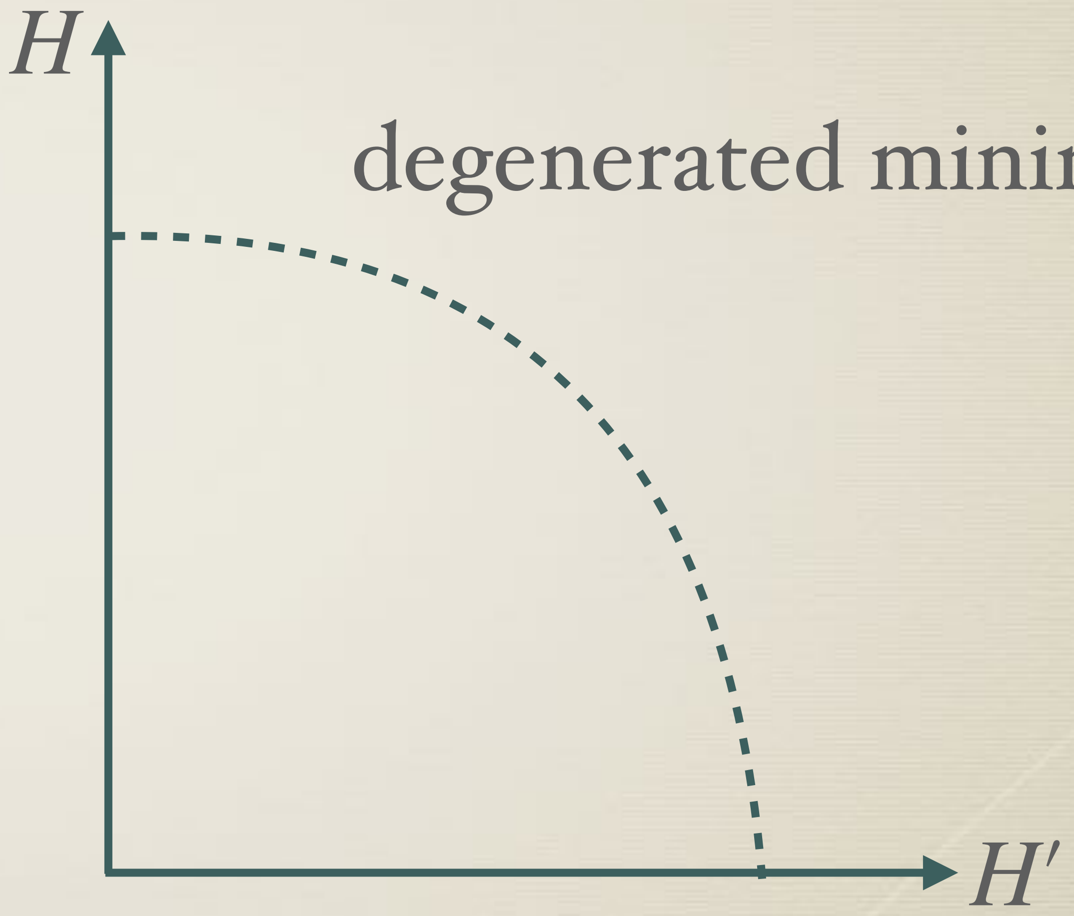


~~$\langle H \rangle \ll \langle H' \rangle$~~

$y \simeq 0$

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





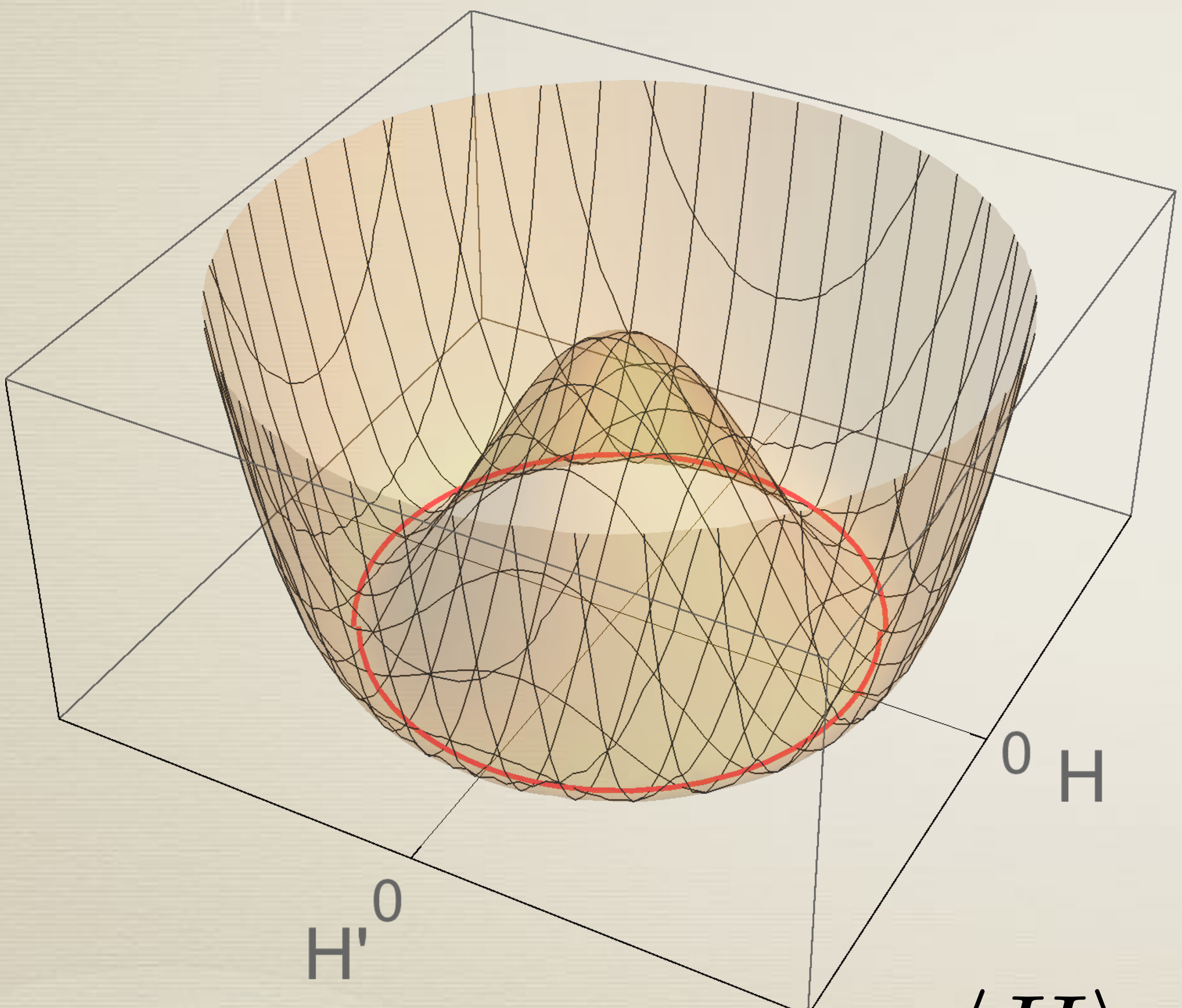
degenerated minima

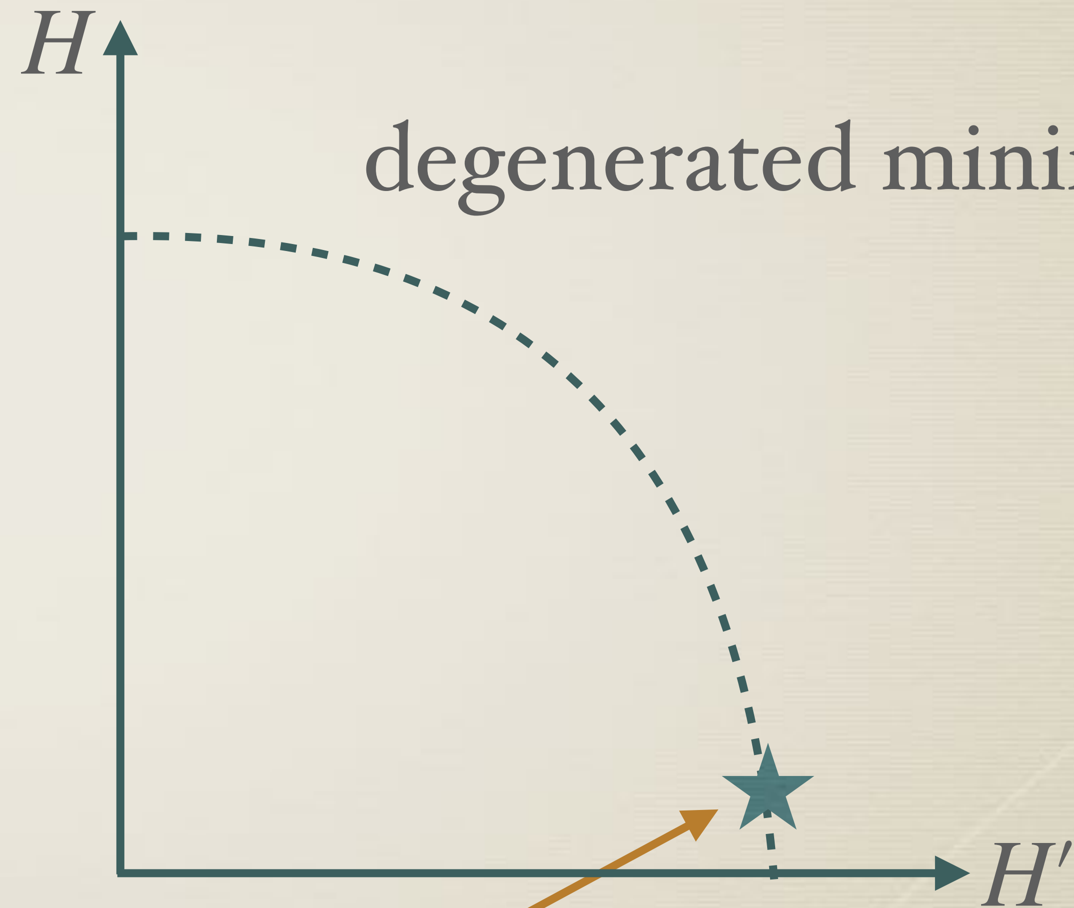
symmetry rotating the vector

(H, H')

$y \simeq 0$

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



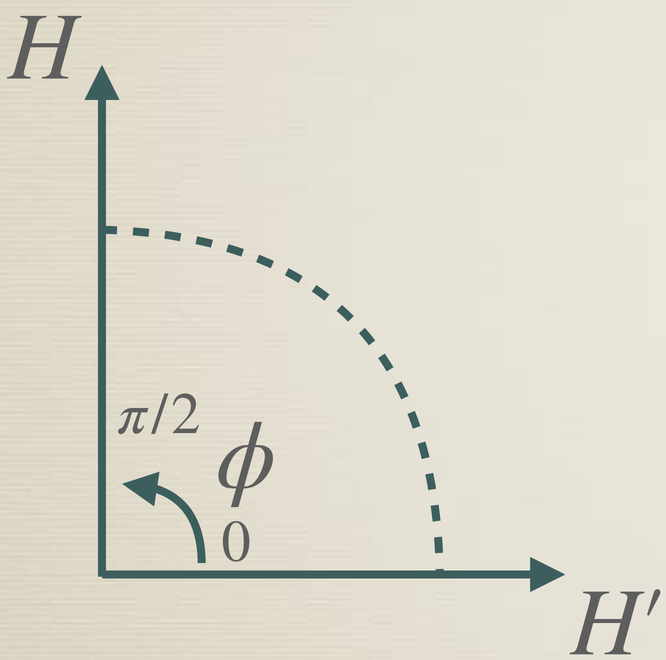


$\langle H \rangle \ll \langle H' \rangle$?

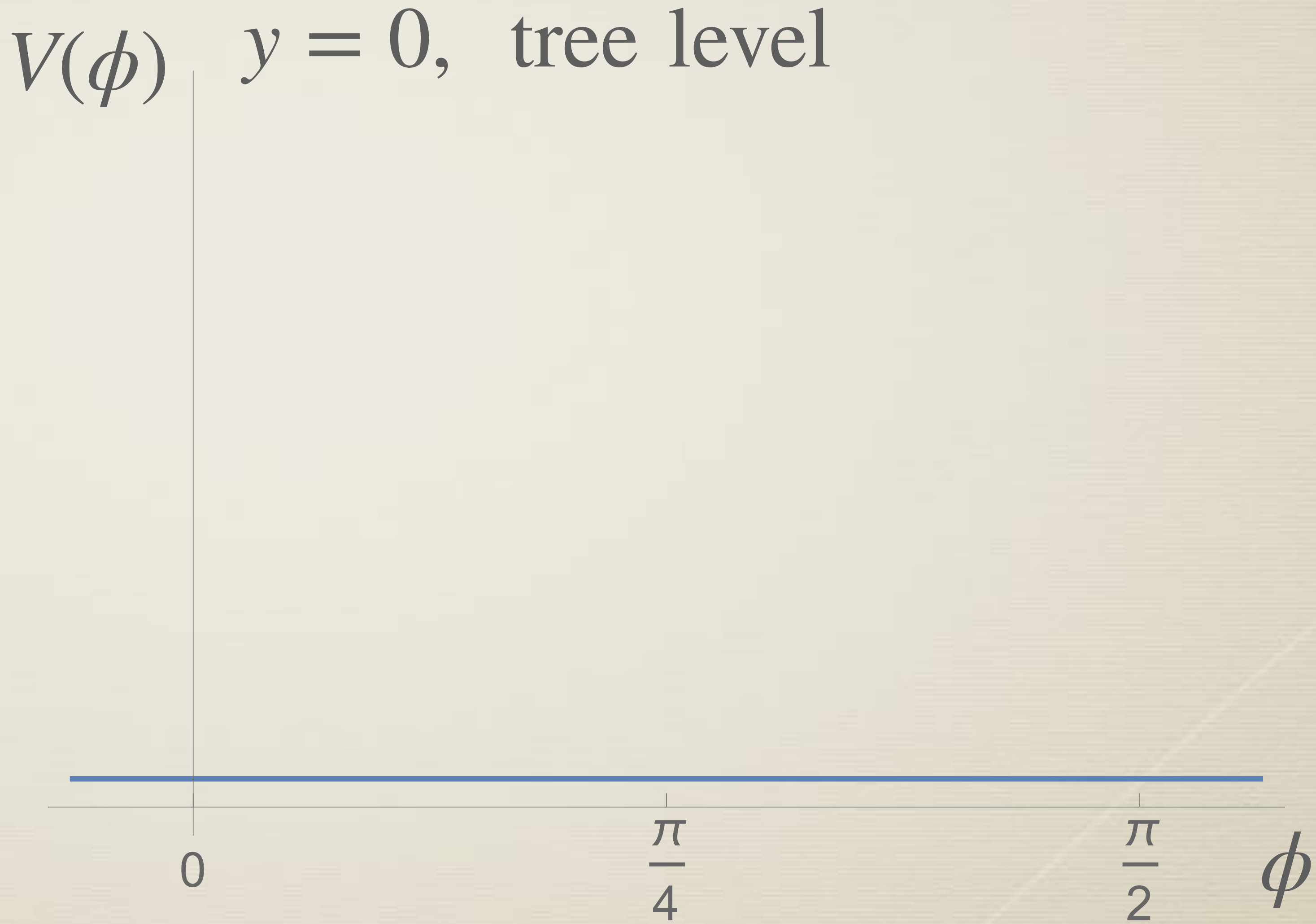
Degeneracy is resolved by quantum corrections

$y \simeq 0$

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



angular direction ϕ

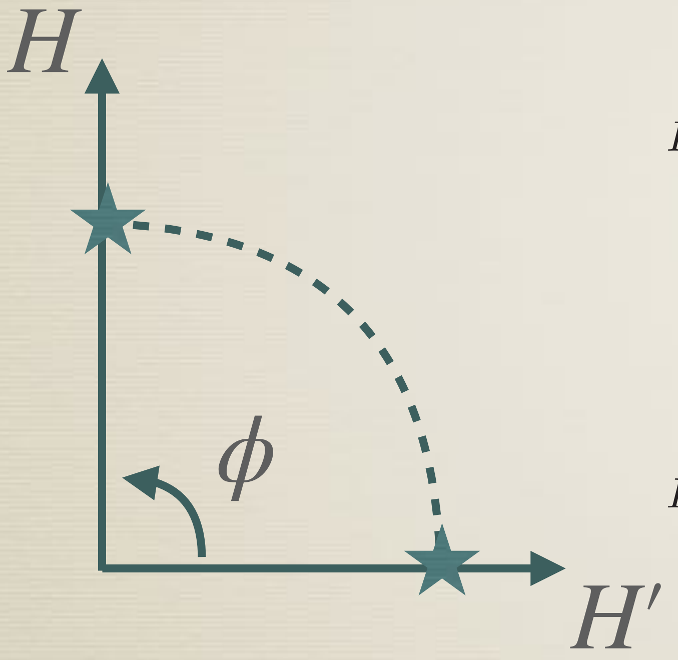


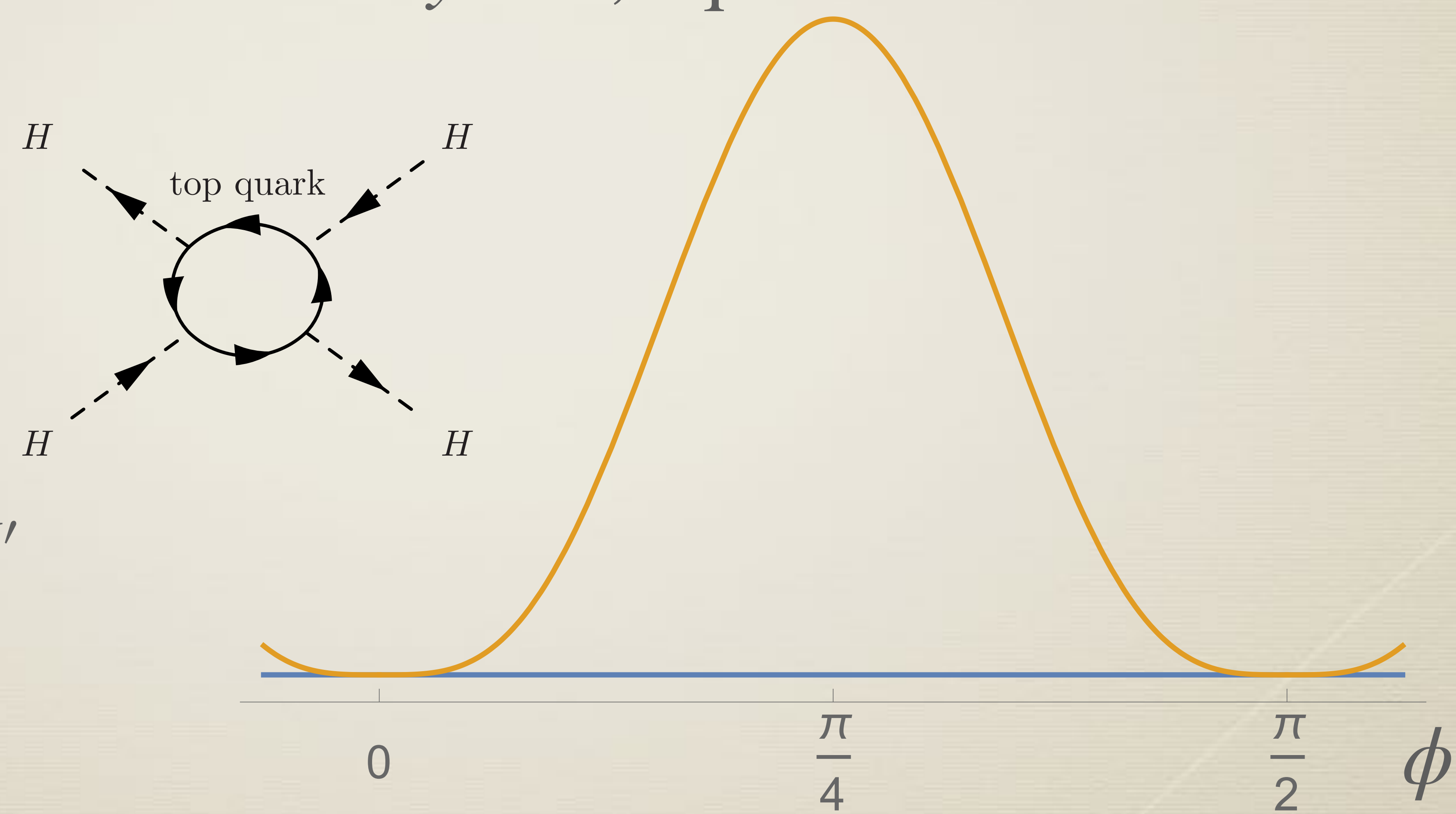
$$y \simeq 0$$

Colemann-Weinberg potential

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

$y = 0,$ quantum correction



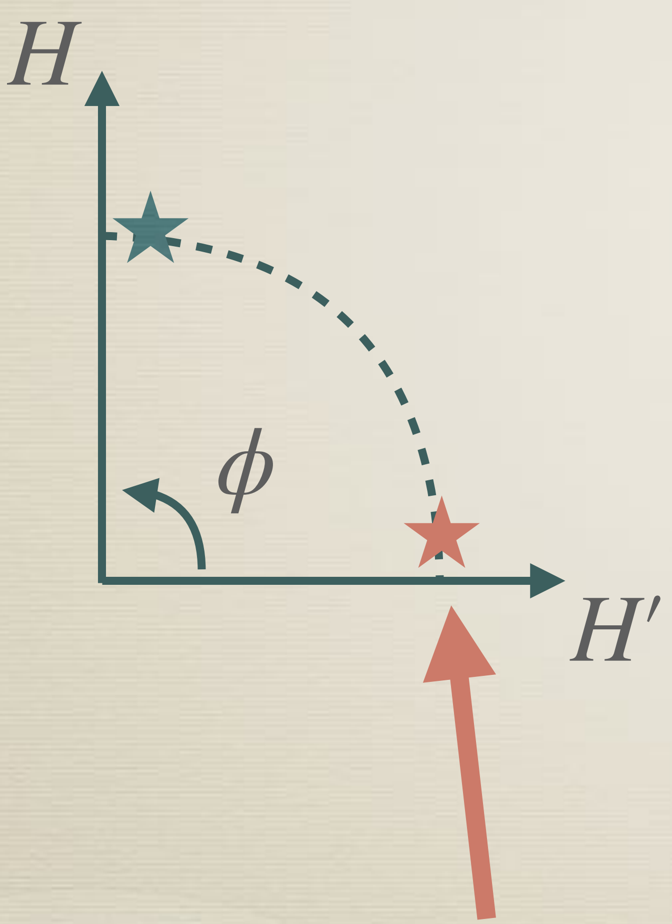


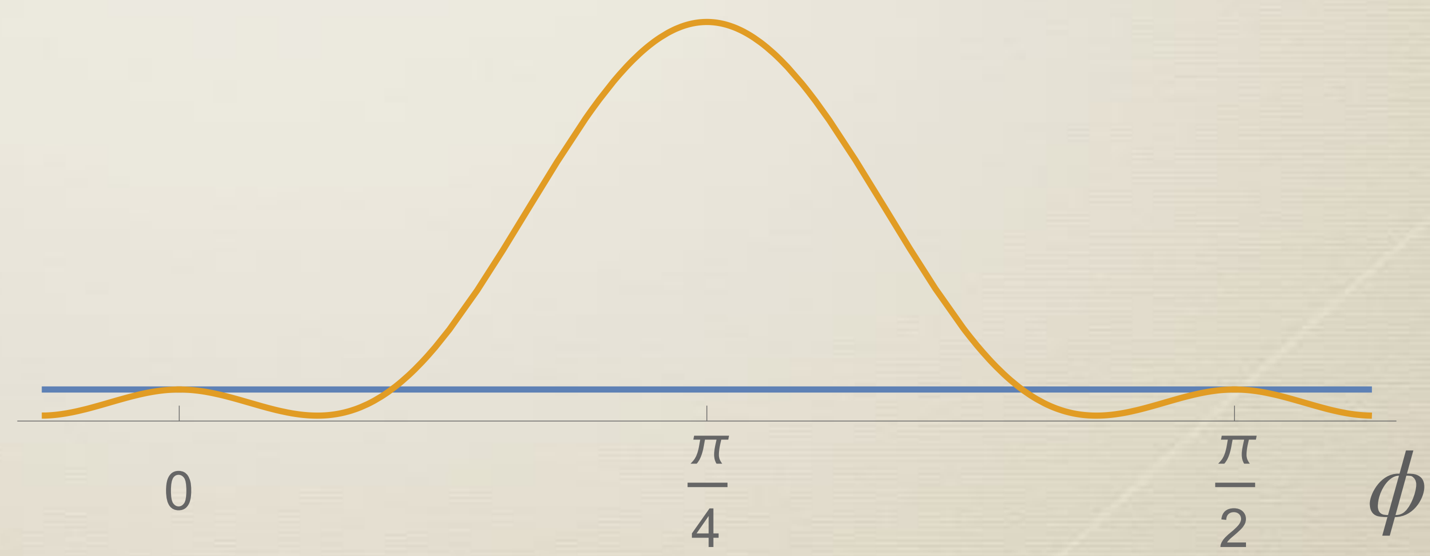
$y \simeq 0$

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

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

(fine-tuned Higgs mass)





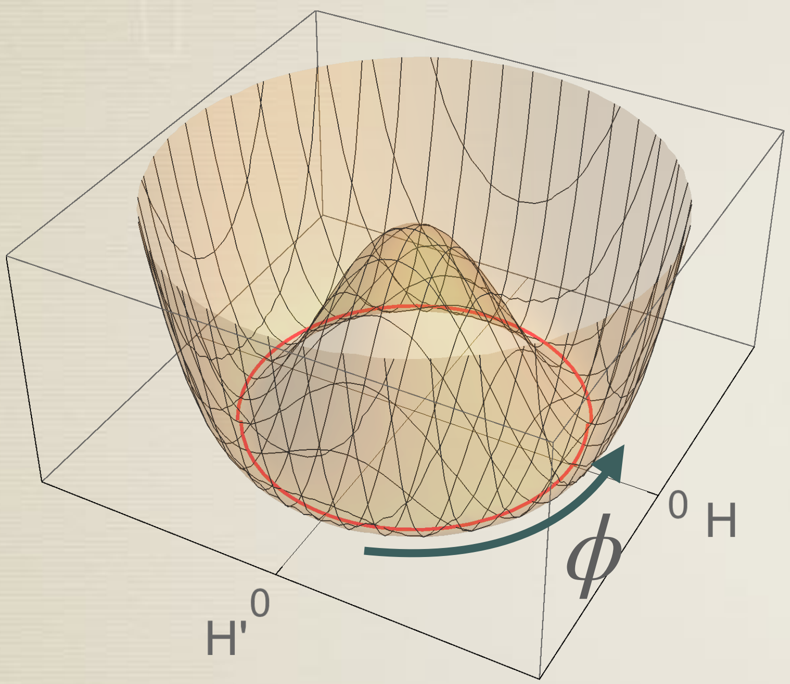
$\langle H \rangle \ll \langle H' \rangle$ is achieved !

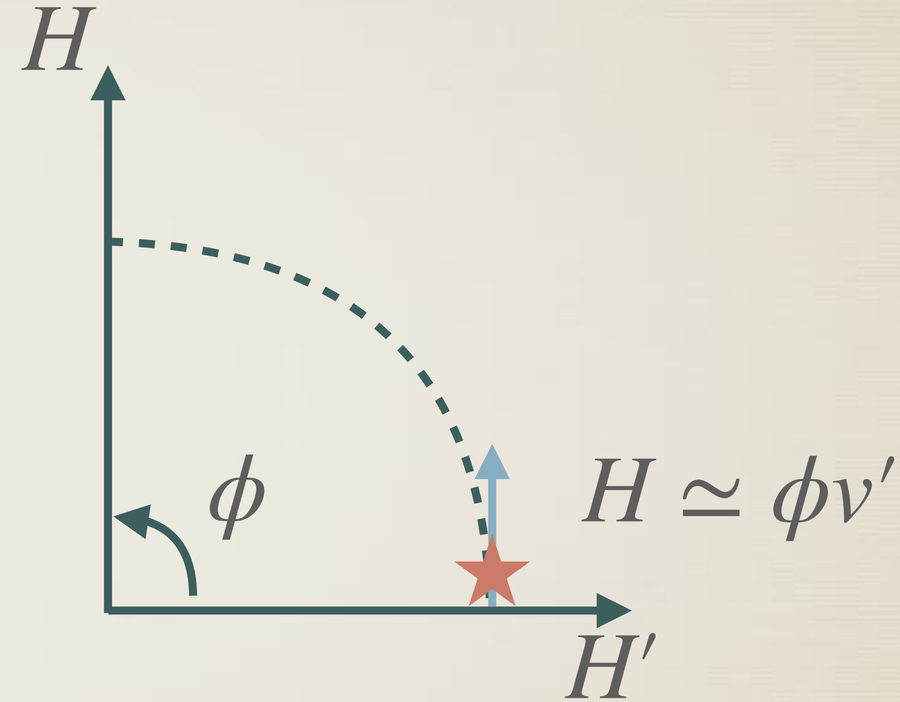
Hall, KH (2018)

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 $\langle H' \rangle = v'$

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

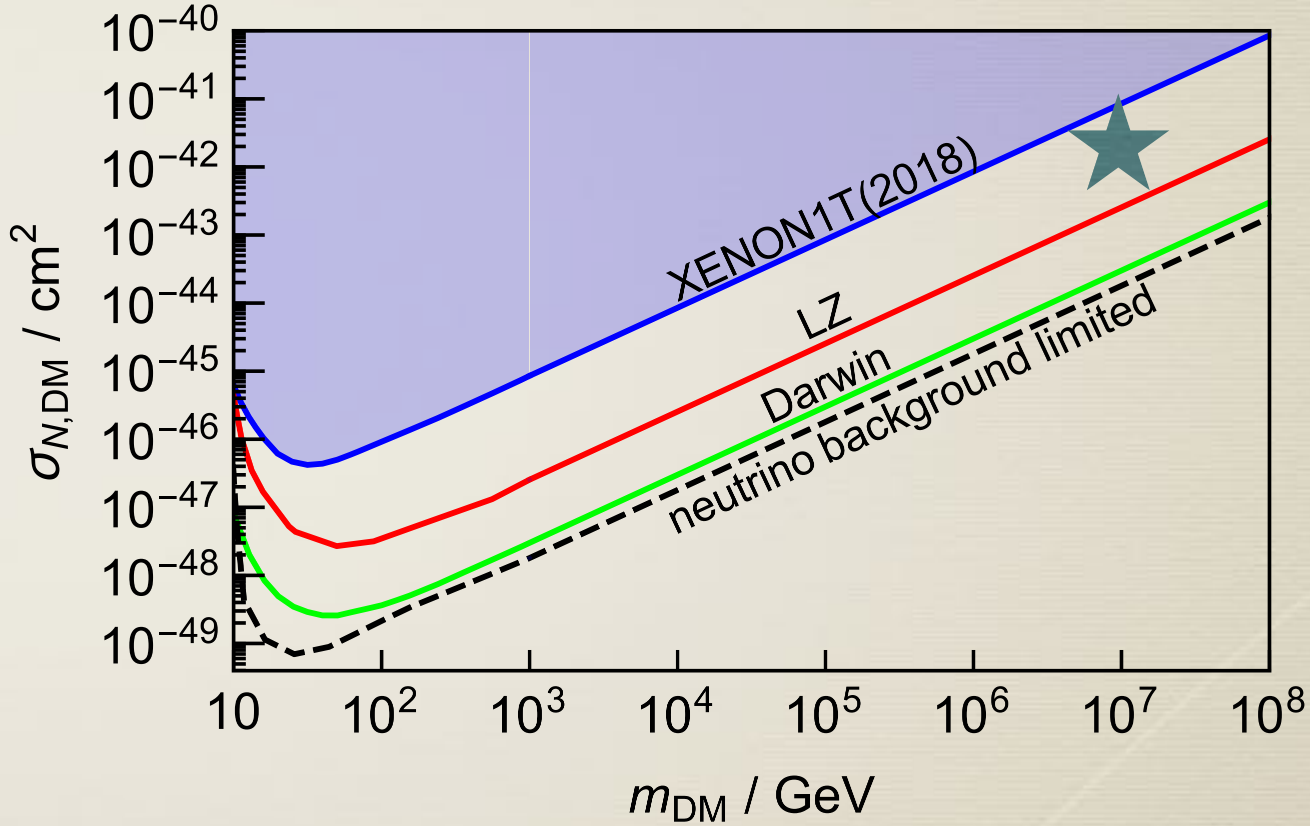
(up to calculable threshold correction)

Dark Matter

Precise measurement and dark matter

Dunsky, Hall and KH (2019)

top quark mass
Higgs mass
strong coupling constant



Higgs Parity
symmetry breaking scale

Dark matter direct
detection rate

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

Motivated from the Strong CP problem
in the Standard Model

Mirrored electroweak theory

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

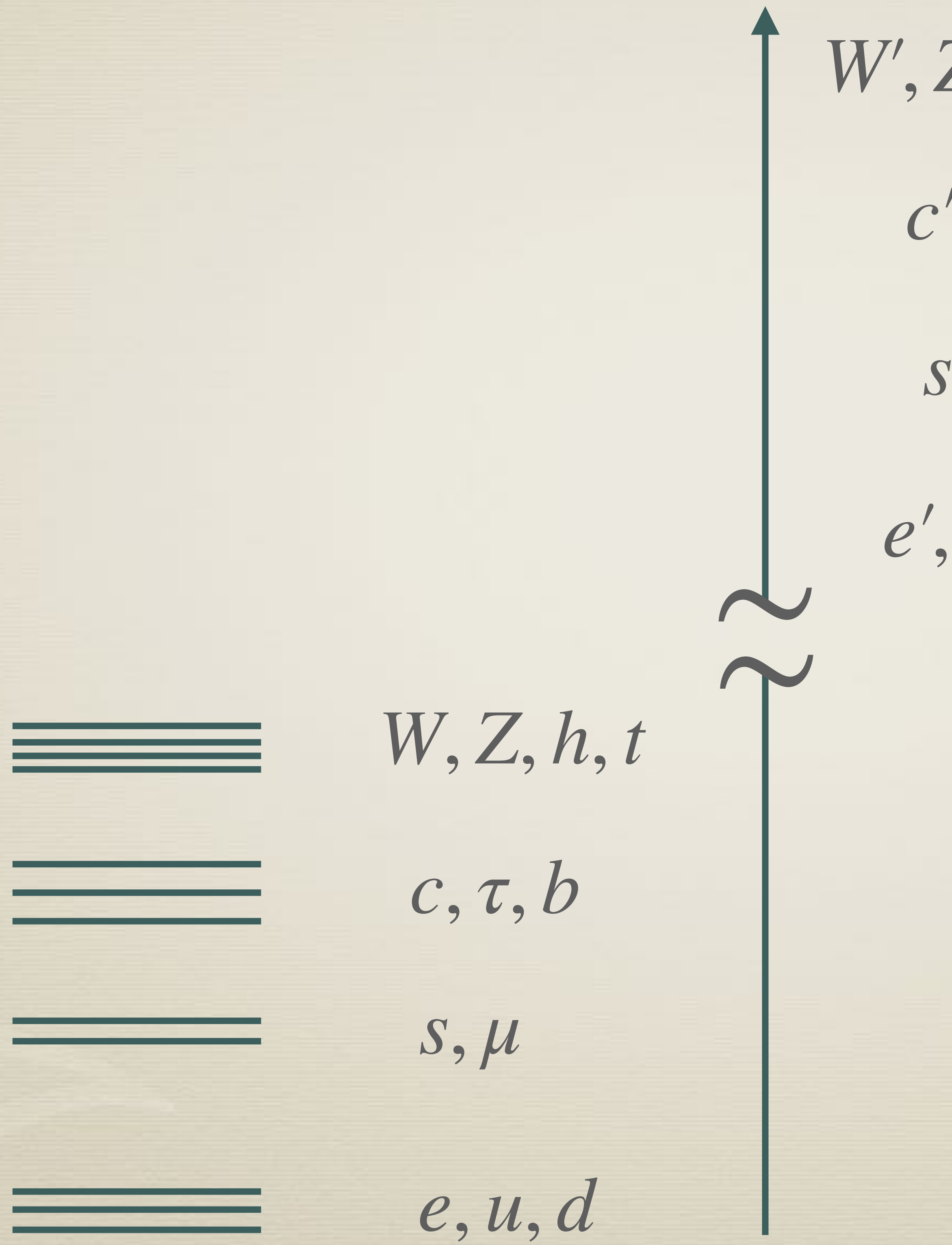
HP with space-time parity forbids the neutron EDM

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

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)

New particles

q', u', d'
L', e'
H'

electroweak'

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

$\downarrow$

$U(1)'_{\mathrm{EM}}$ γ'

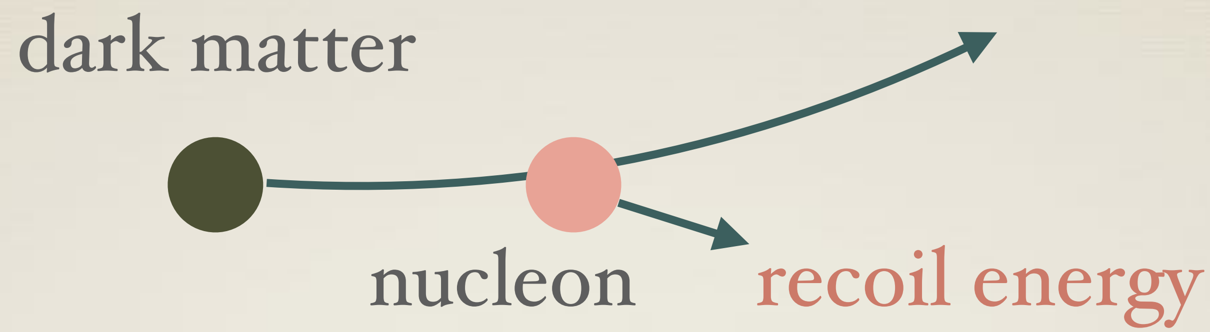
The mirror electron and the lightest mirror baryon are stable

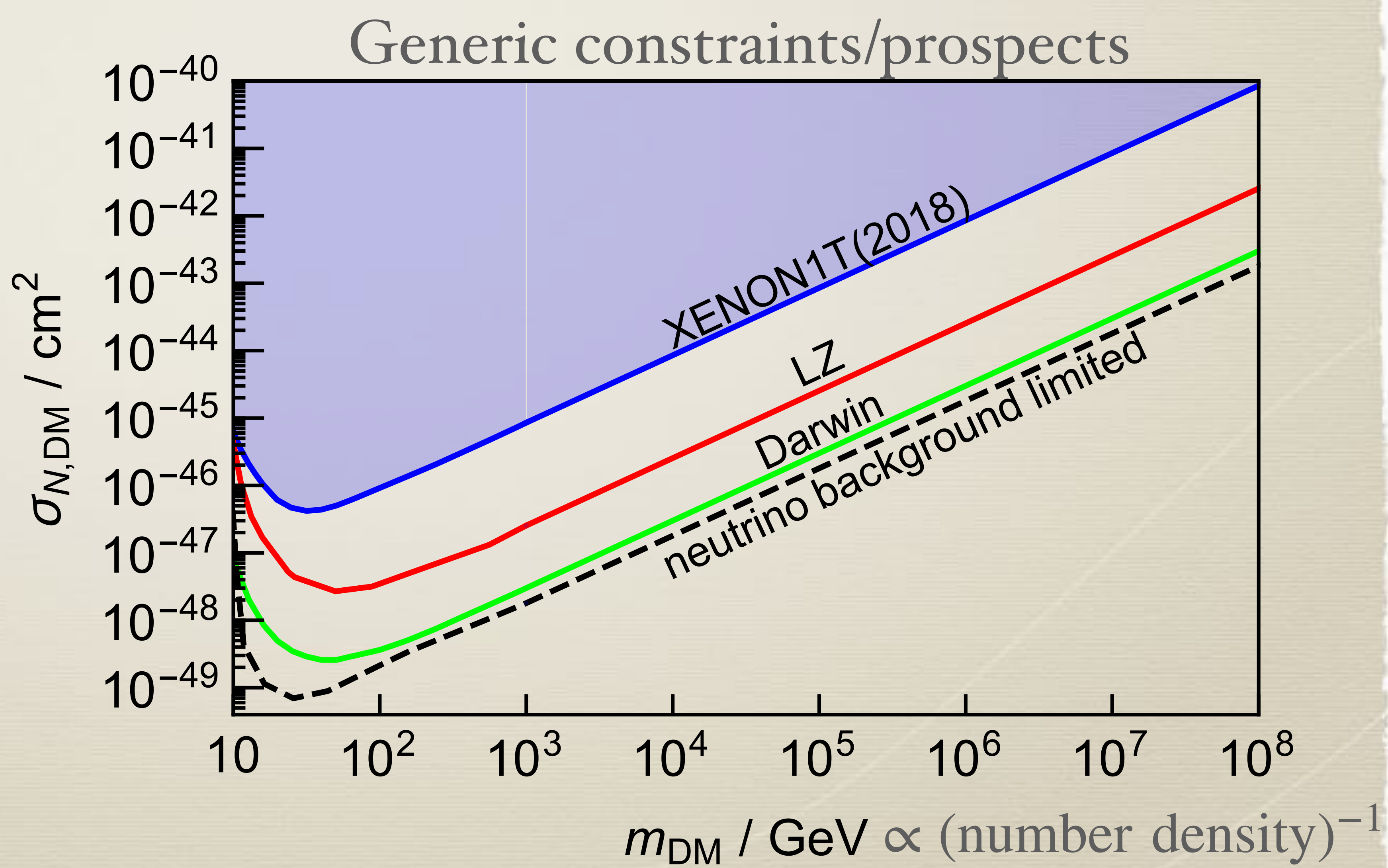
e'

u'
u' u'

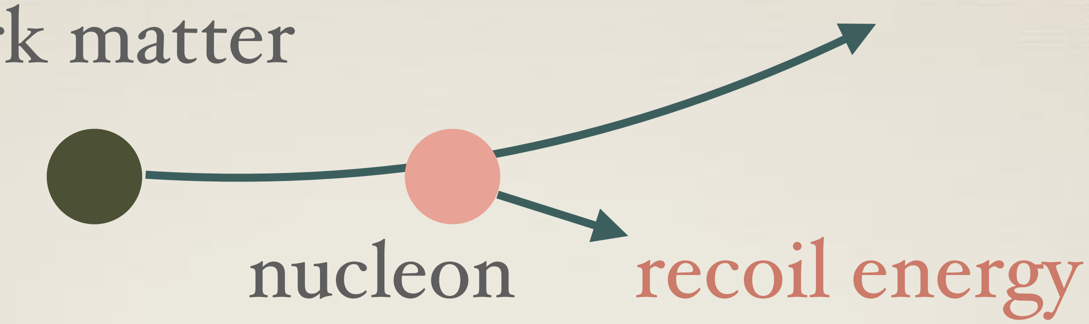
I assume that they comprise all of dark matter

Direct detection of dark matter



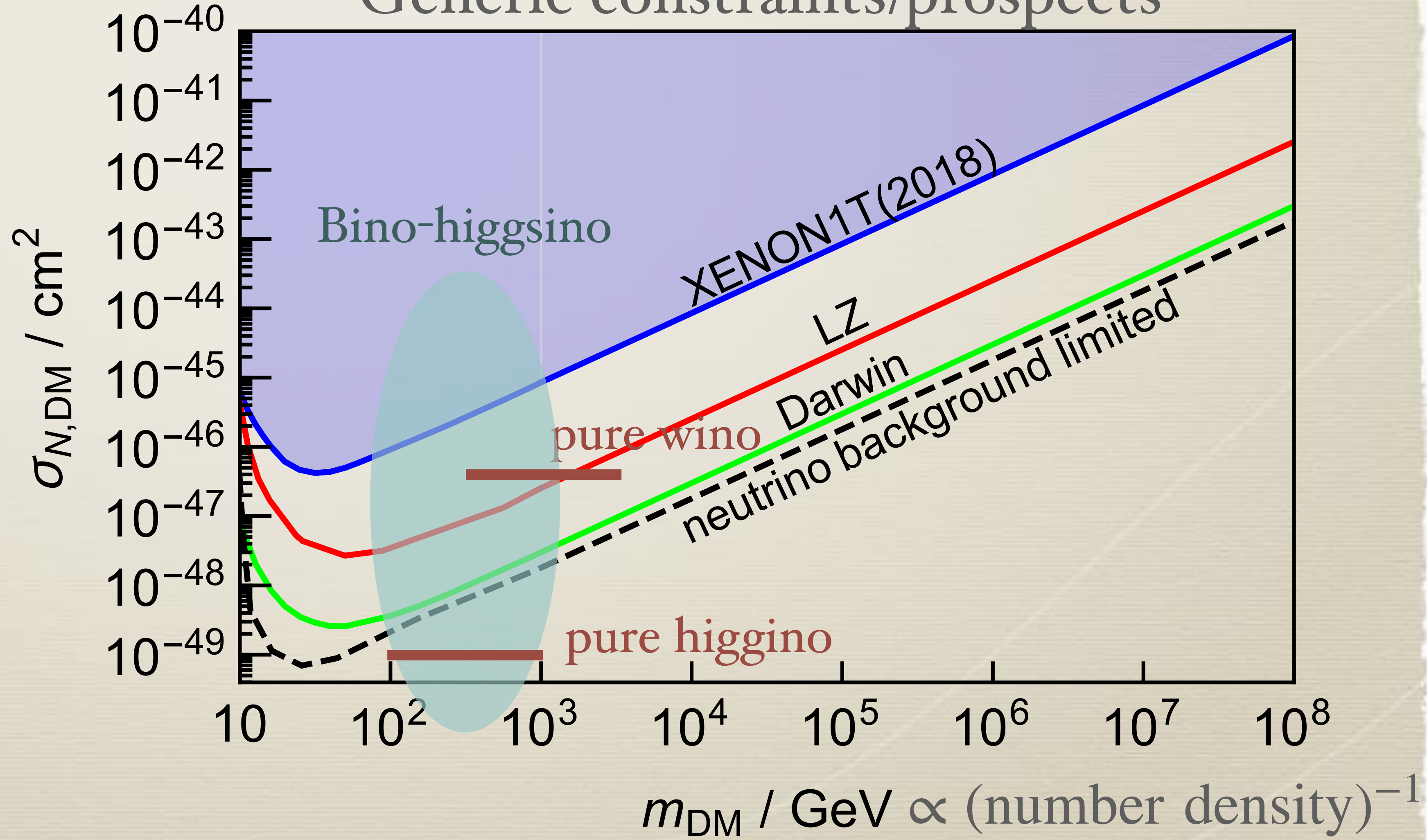


Direct detection of dark matter



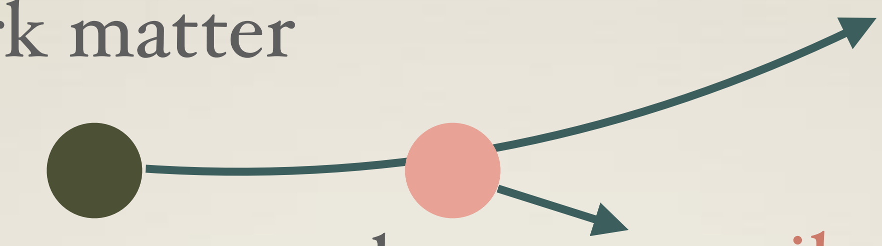
ex.
Dark matter in
supersymmetric
theories

Generic constraints/prospects



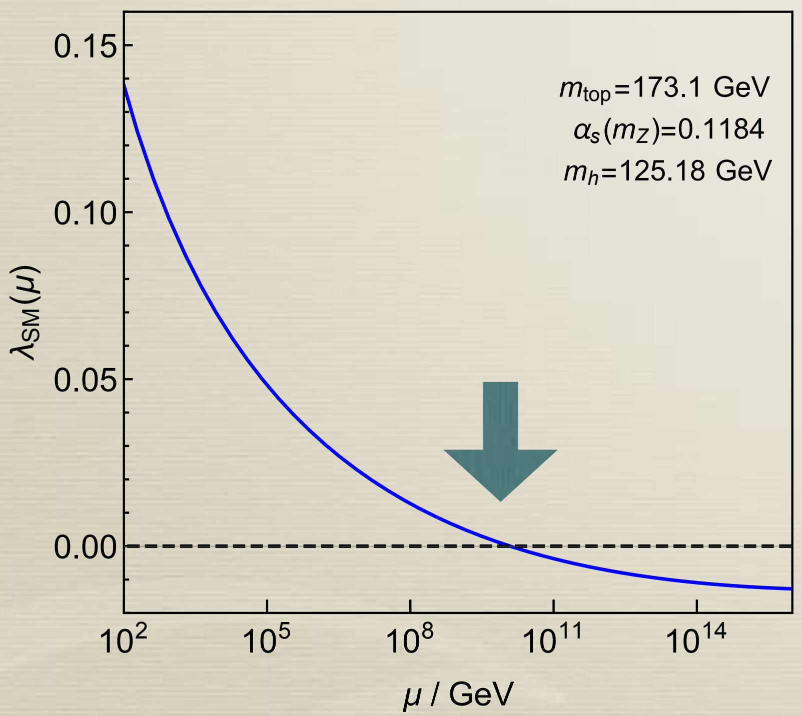
Direct detection of dark matter

Dunsky, Hall, KH (2019)



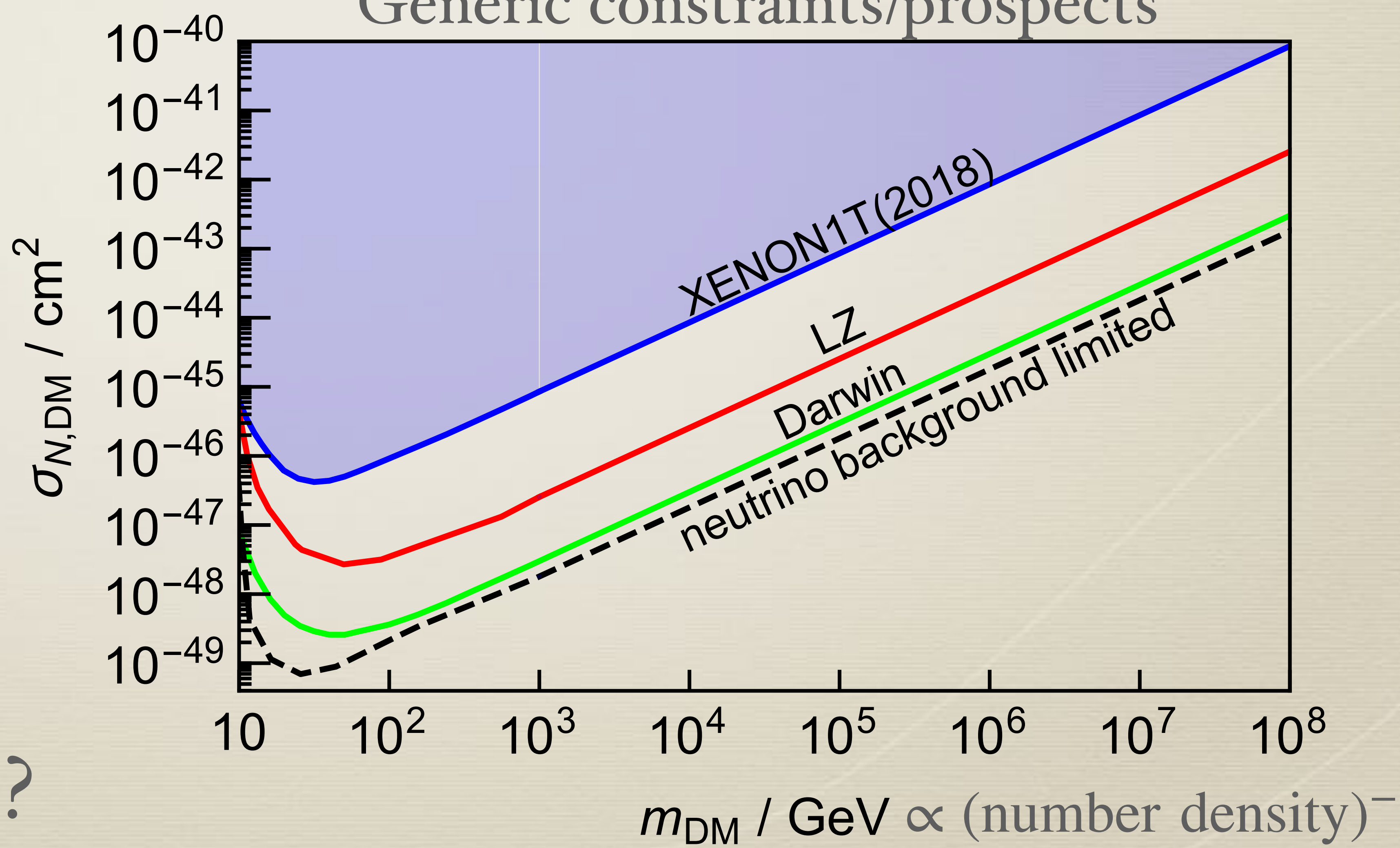
Higgs Parity

$$m_{e'} = y_e v'$$



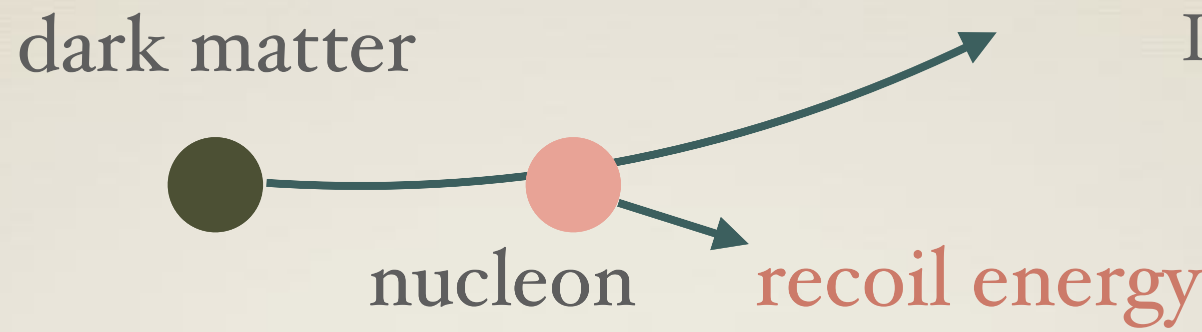
Interaction rate?

Generic constraints/prospects



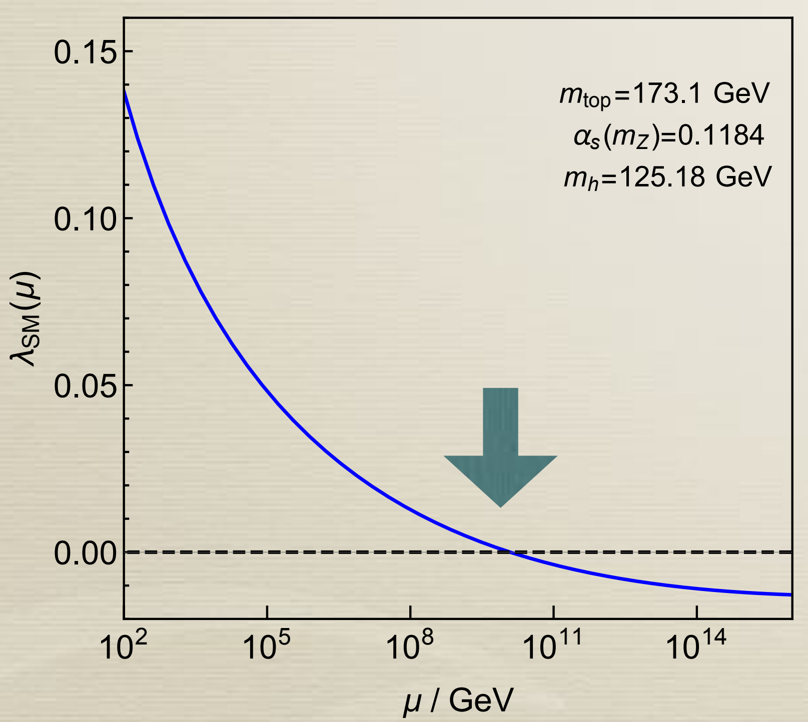
Direct detection of dark matter

Dunsky, Hall, KH (2019)



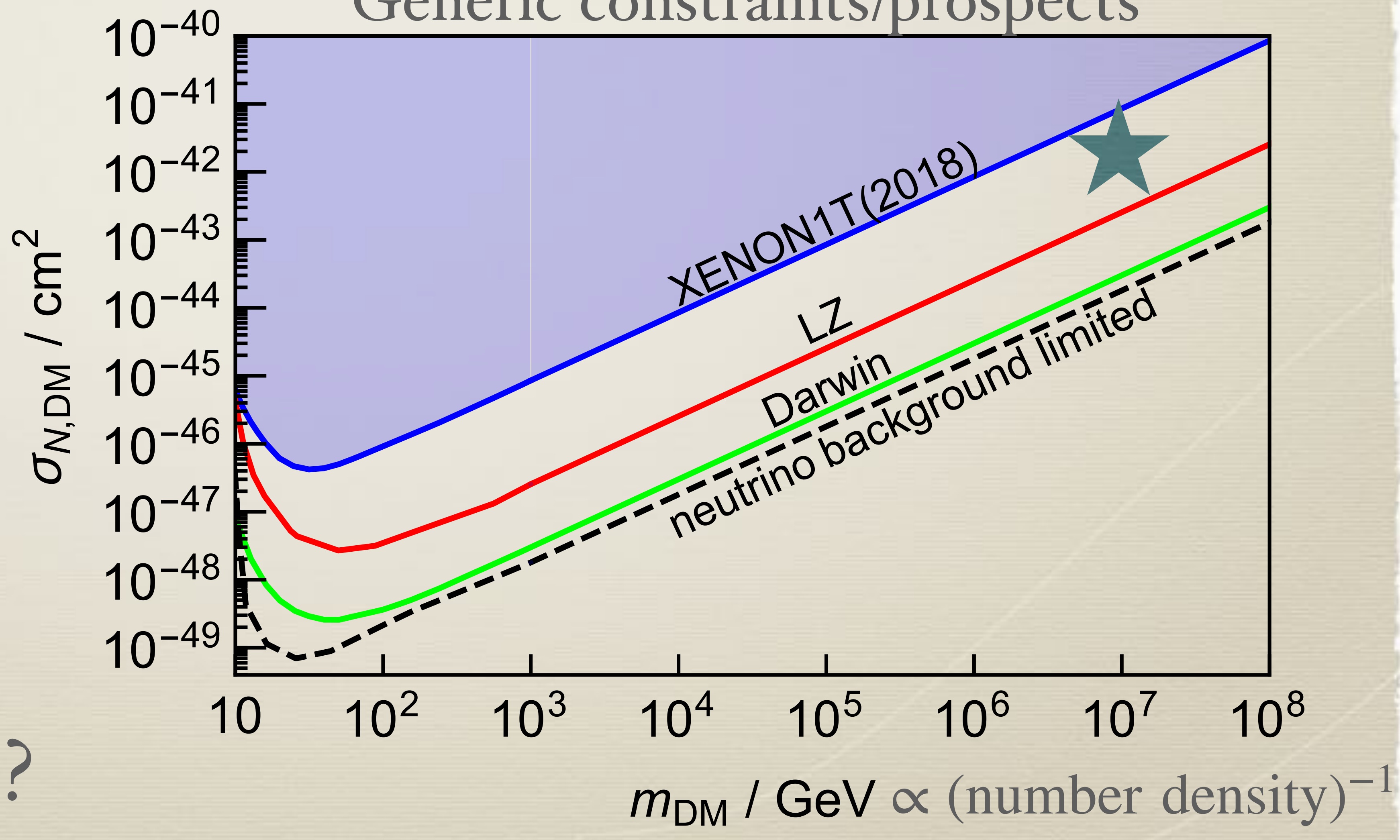
Higgs Parity

$m_{e'} = y_e v'$



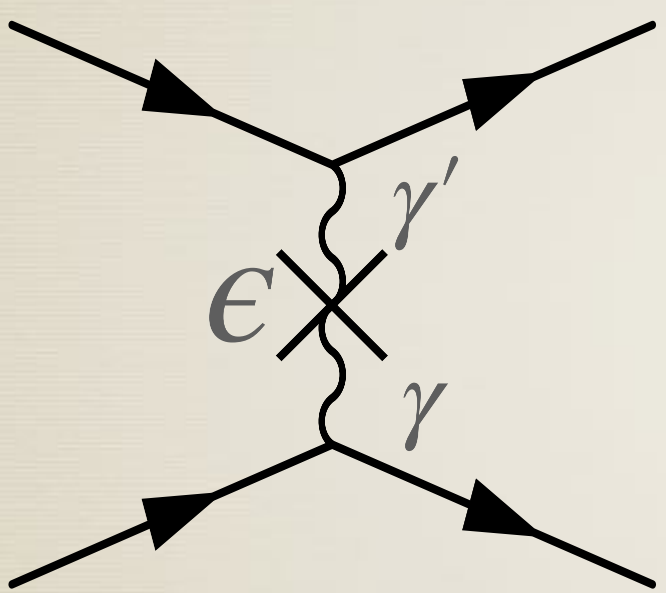
Interaction rate?

Generic constraints/prospects



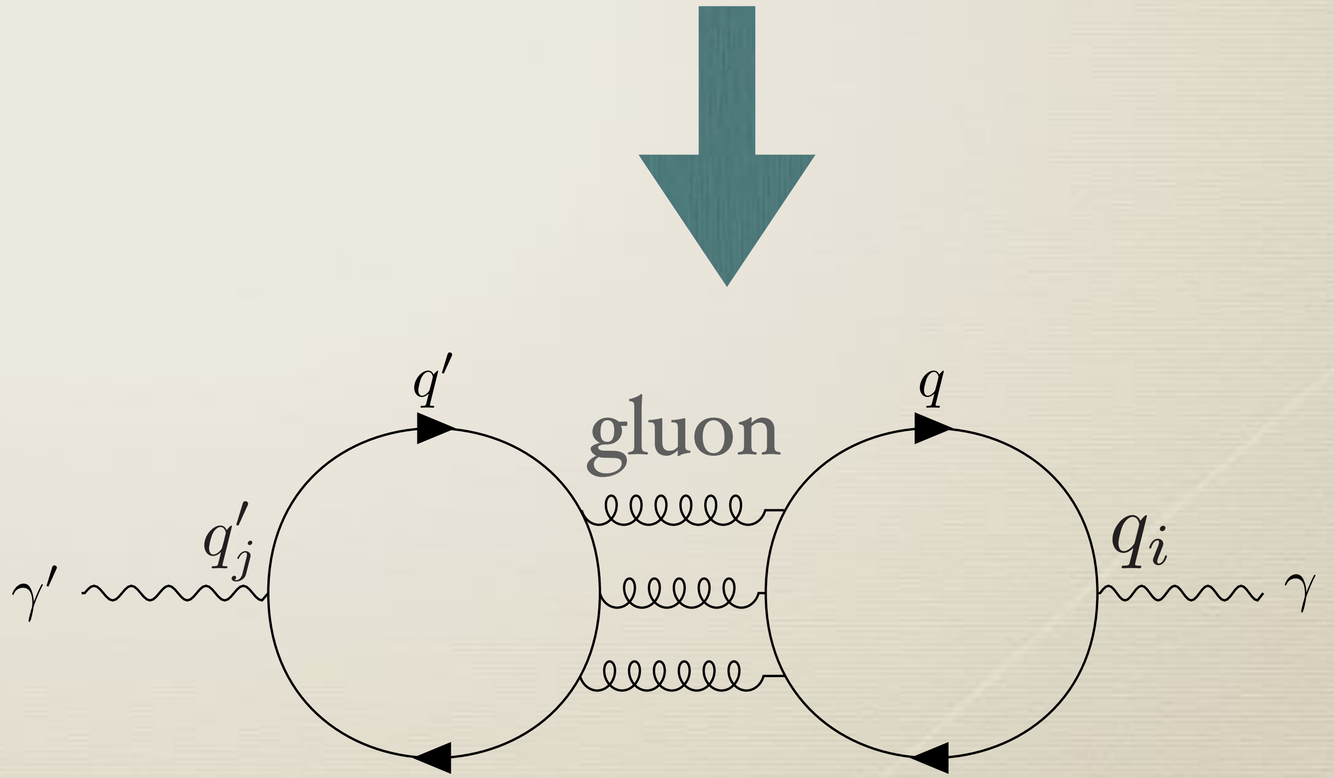
Prediction on interaction

Dunsky, Hall, KH (2019)

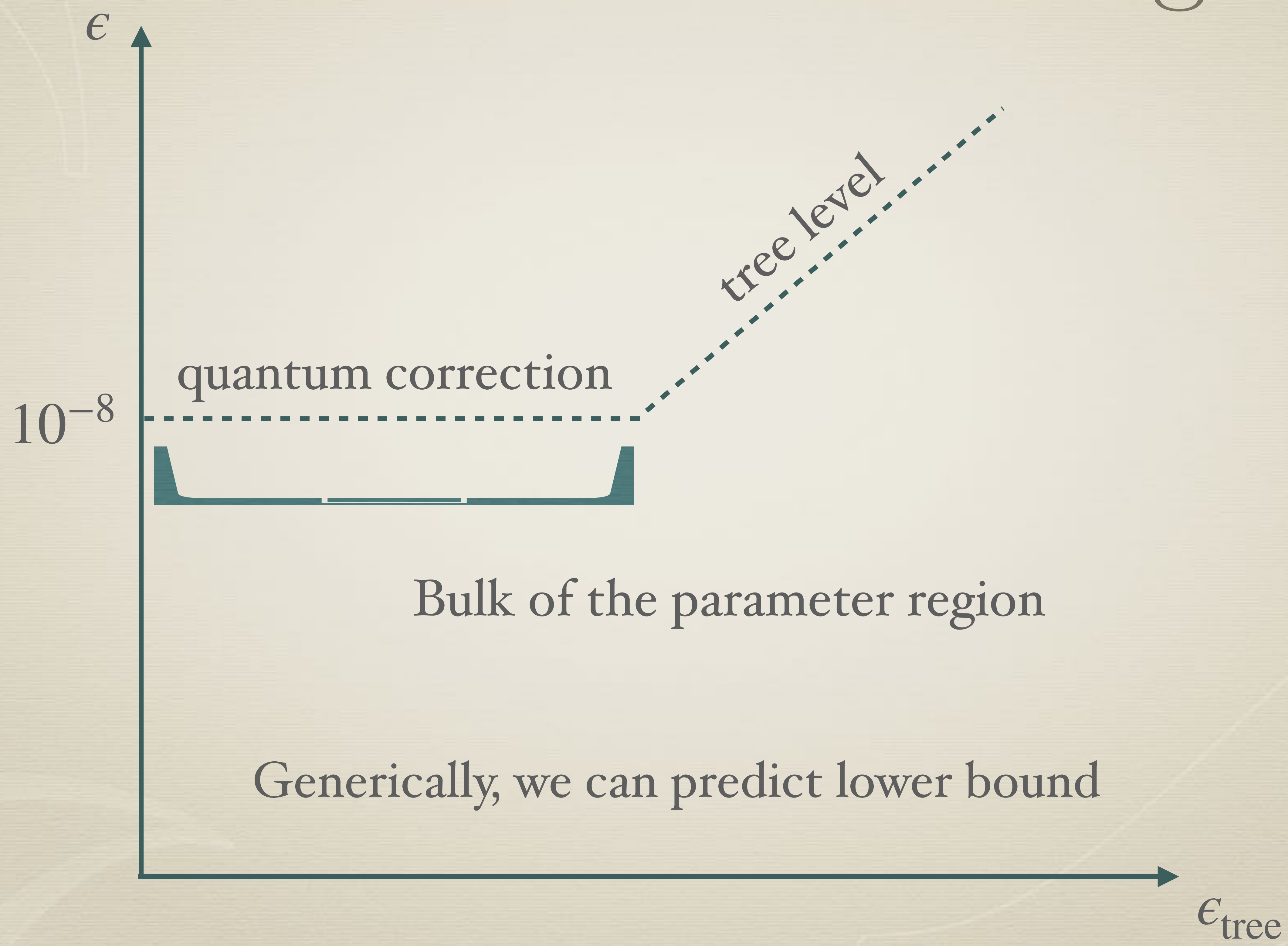


photon-mirror photon mixing

$$\epsilon = \epsilon_{\text{tree}} + \epsilon_{\text{quantum correction}}$$



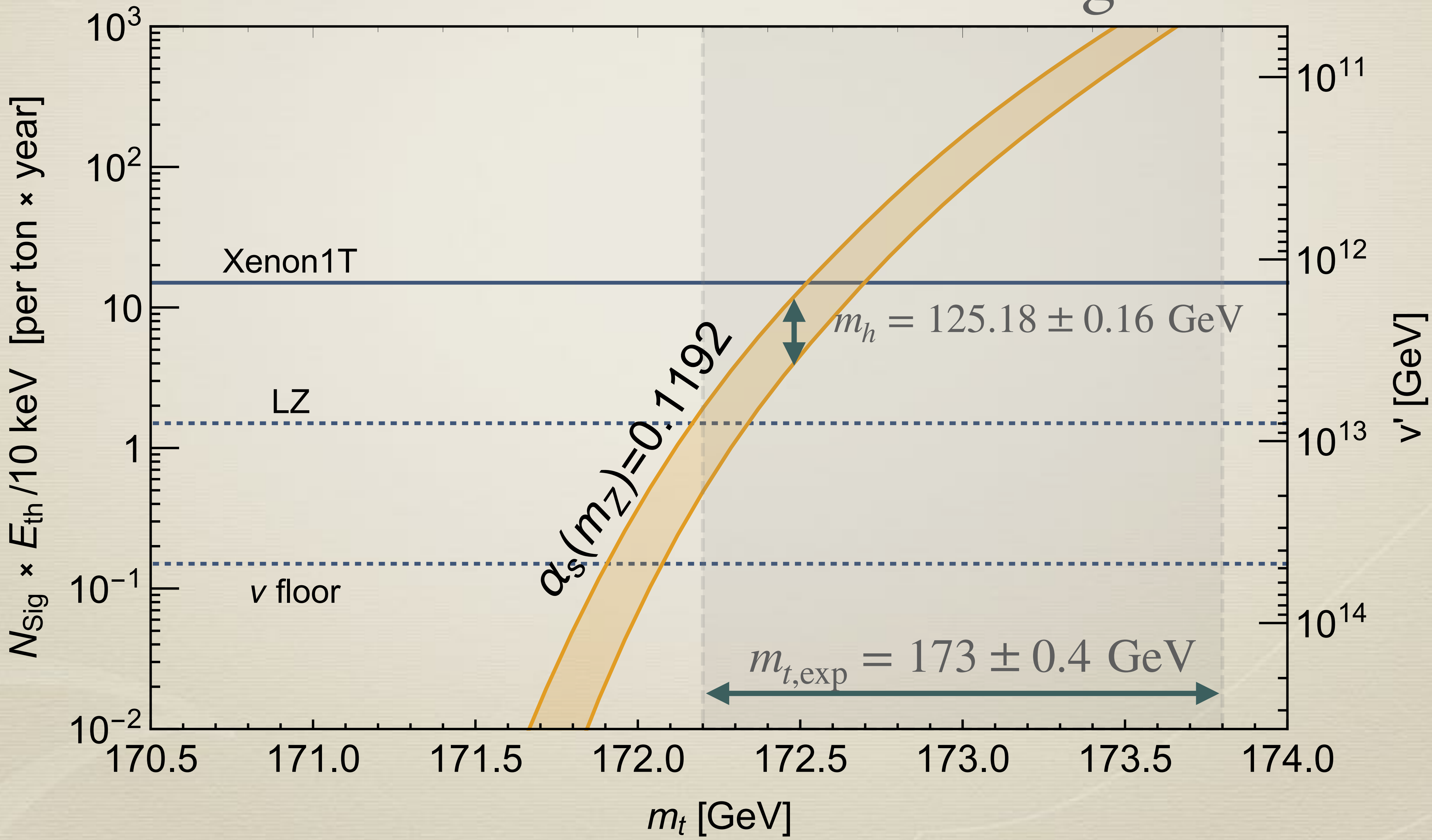
Prediction on mixing



SM parameters and DM

Dunsky, Hall, KH (2019)

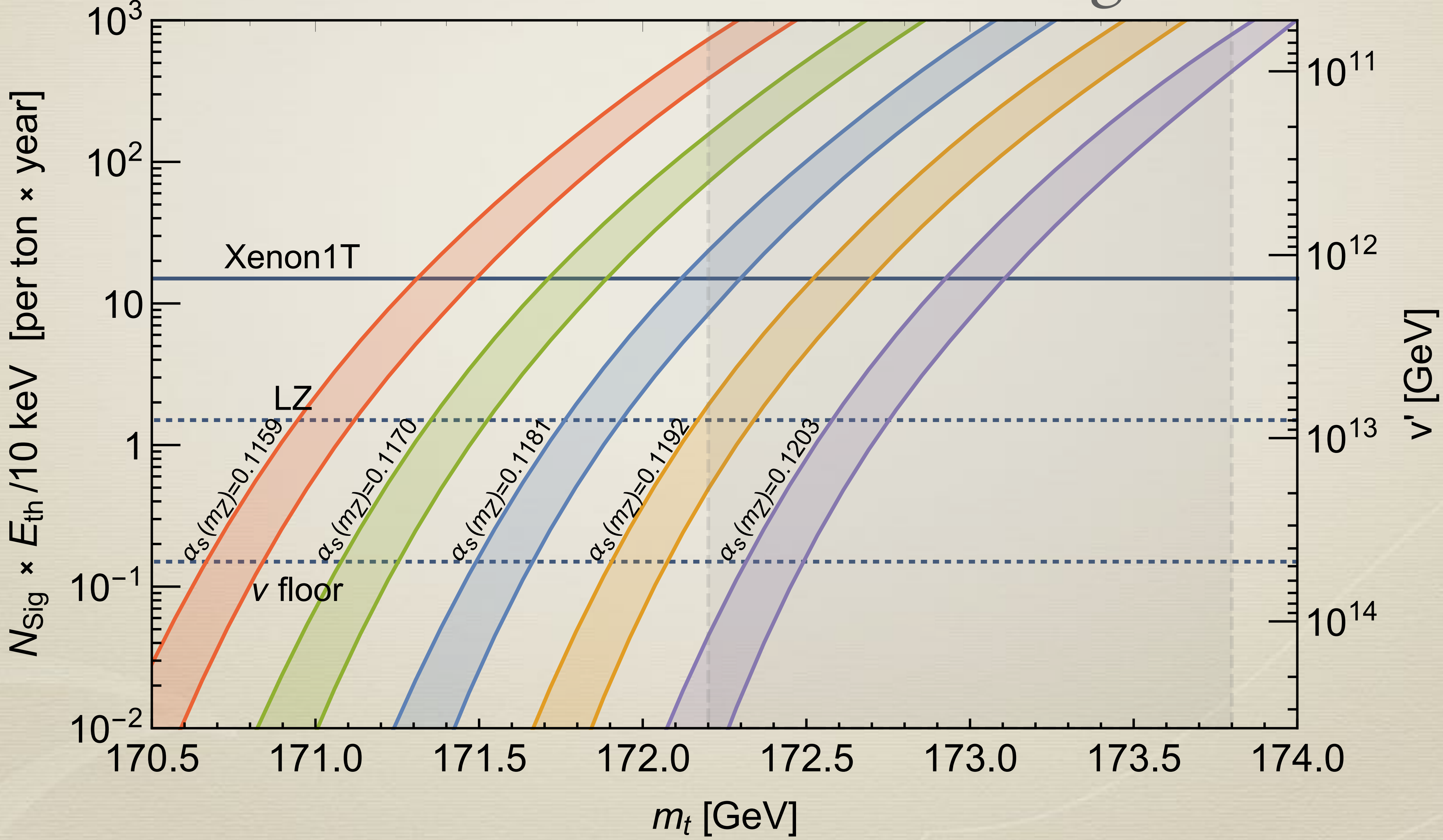
Direct detection rate for Xe targets



SM parameters and DM

Dunsky, Hall, KH (2019)

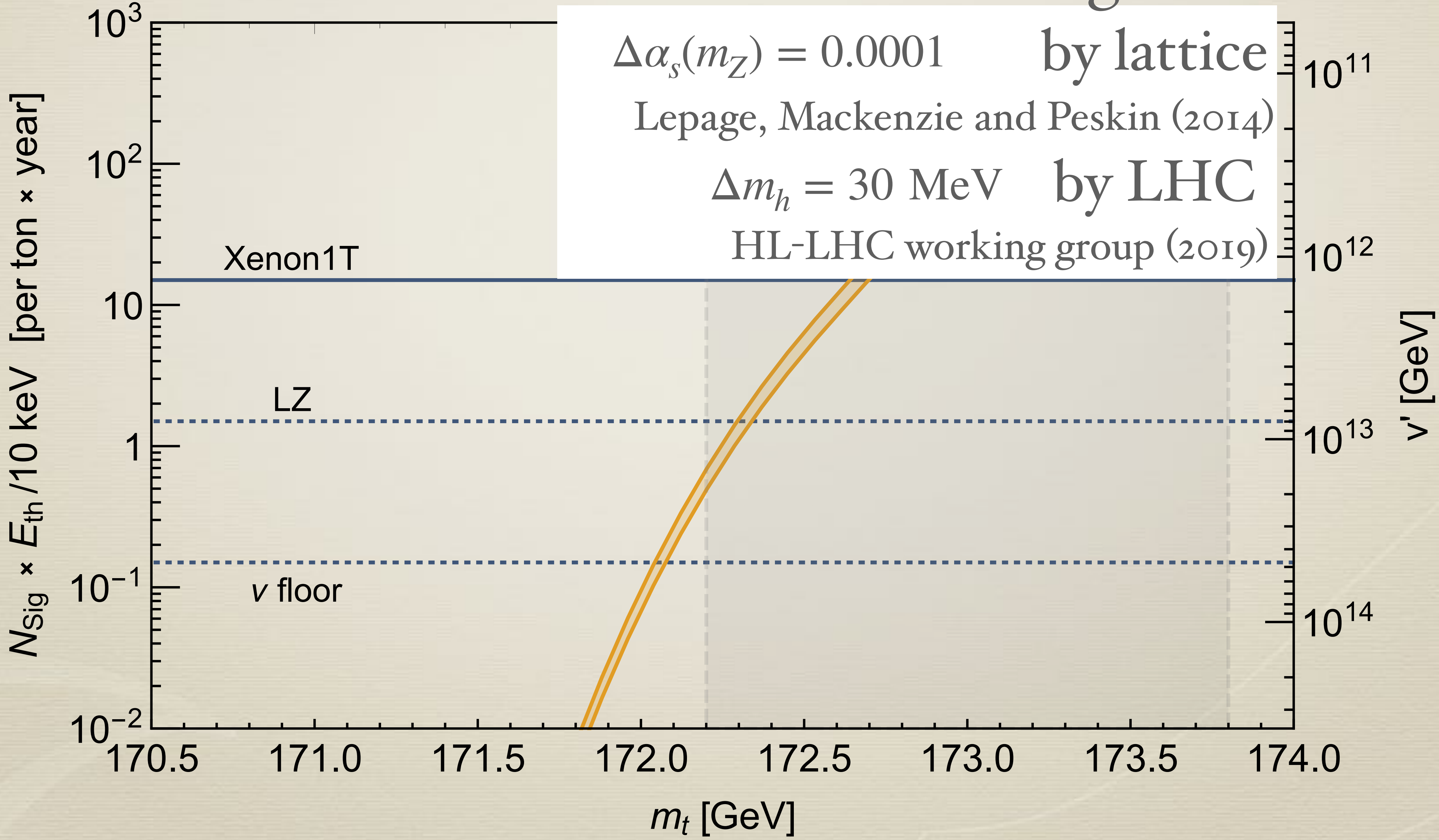
Direct detection rate for Xe targets



SM parameters and DM

Dunsky, Hall, KH (2019)

Direct detection rate for Xe targets



$\Delta\alpha_s(m_Z) = 0.0001$ by lattice

Lepage, Mackenzie and Peskin (2014)

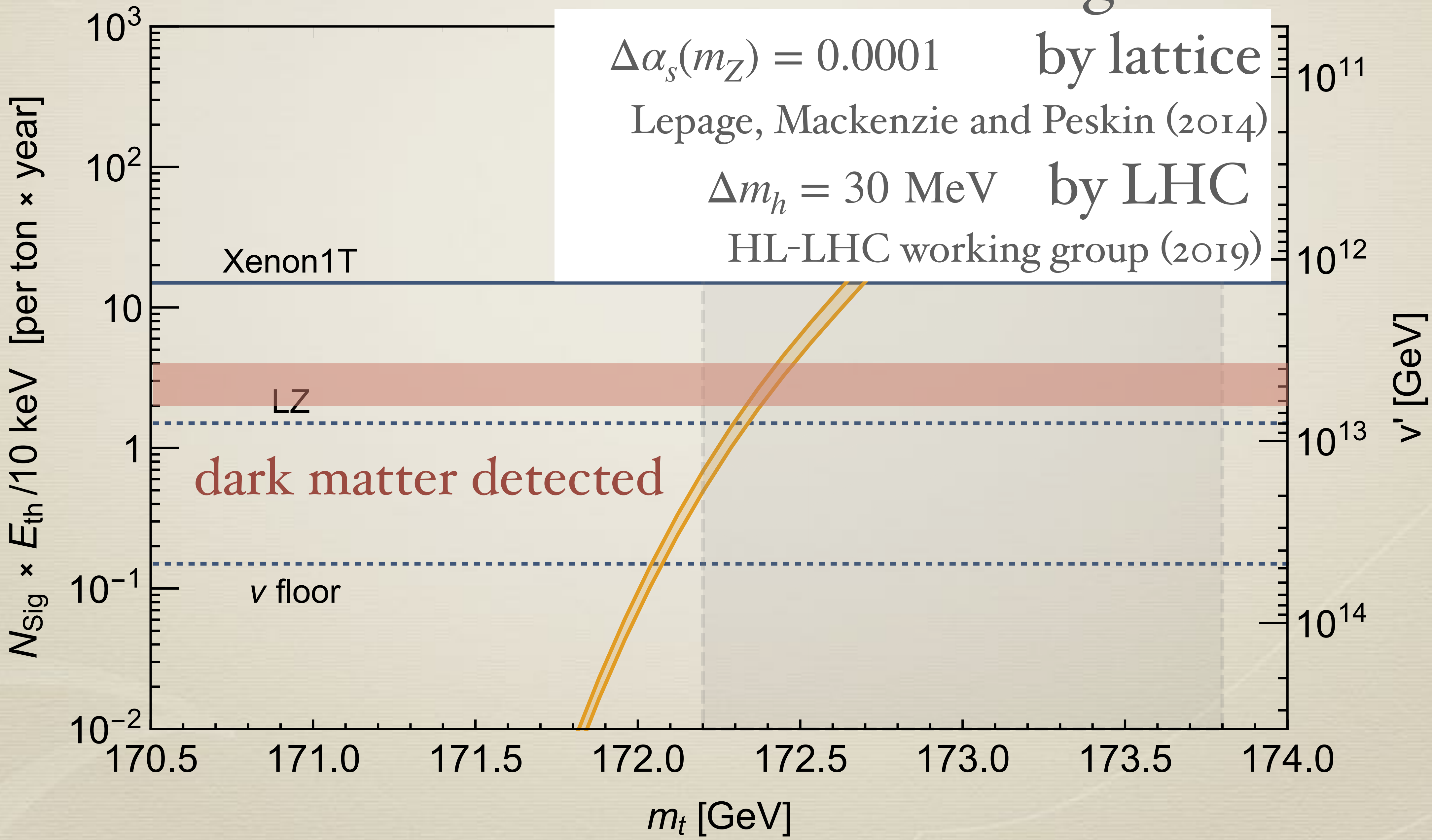
$\Delta m_h = 30$ MeV by LHC

HL-LHC working group (2019)

SM parameters and DM

Dunsky, Hall, KH (2019)

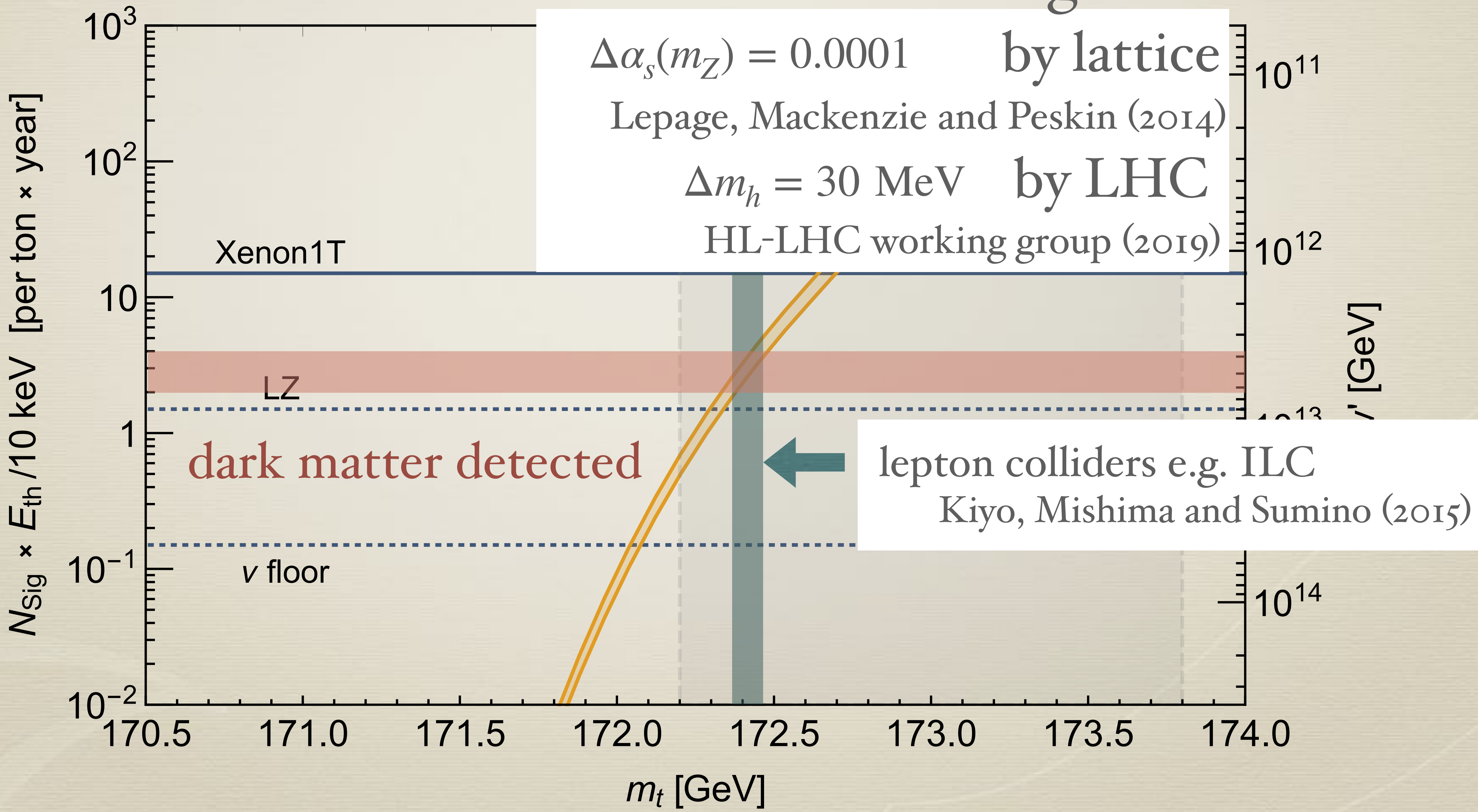
Direct detection rate for Xe targets



SM parameters and DM

Dunsky, Hall, KH (2019)

Direct detection rate for Xe targets



u'u'u' DM?

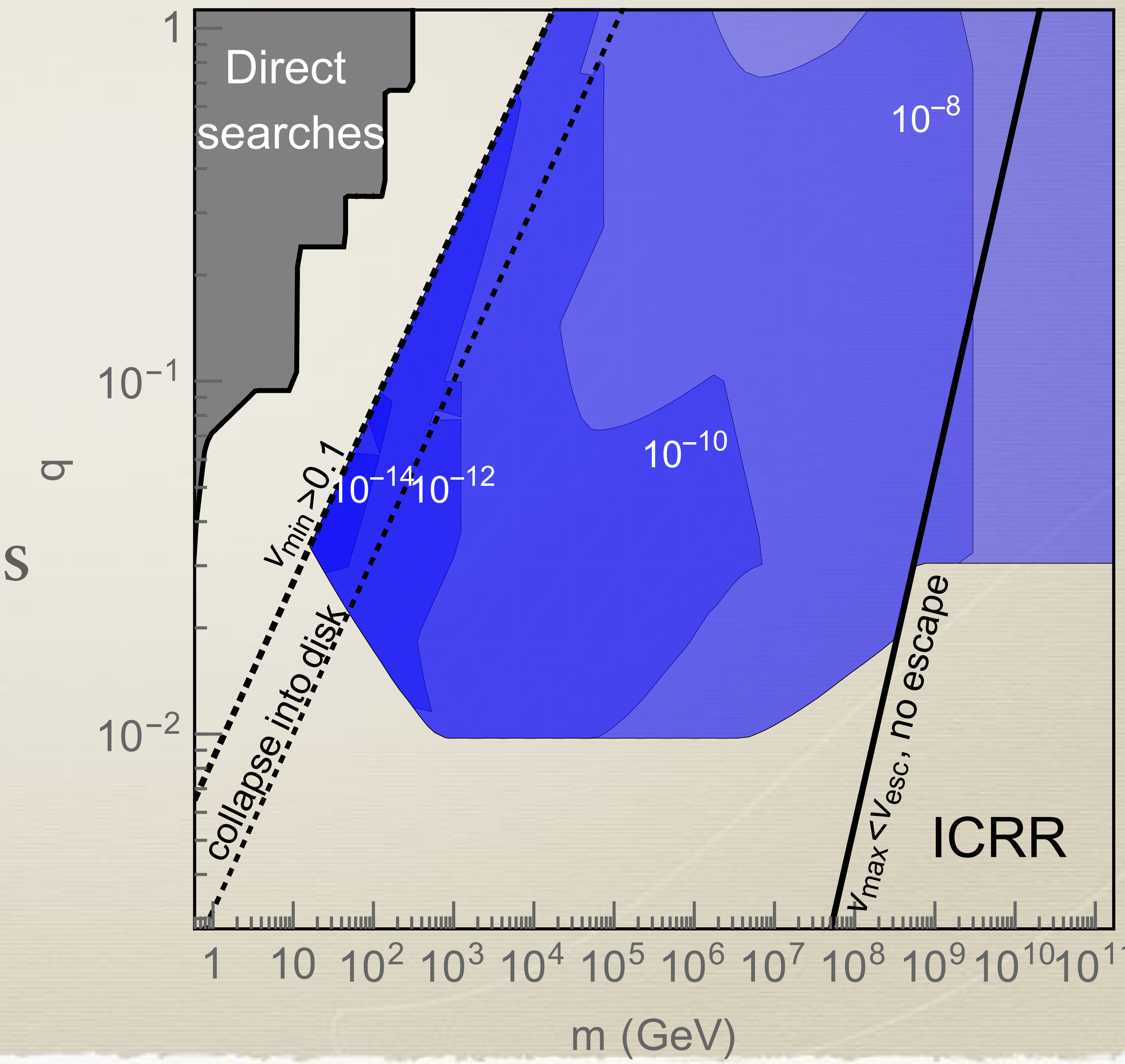
u'qq, u'qbar are necessarily produced after the QCD phase transition

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)

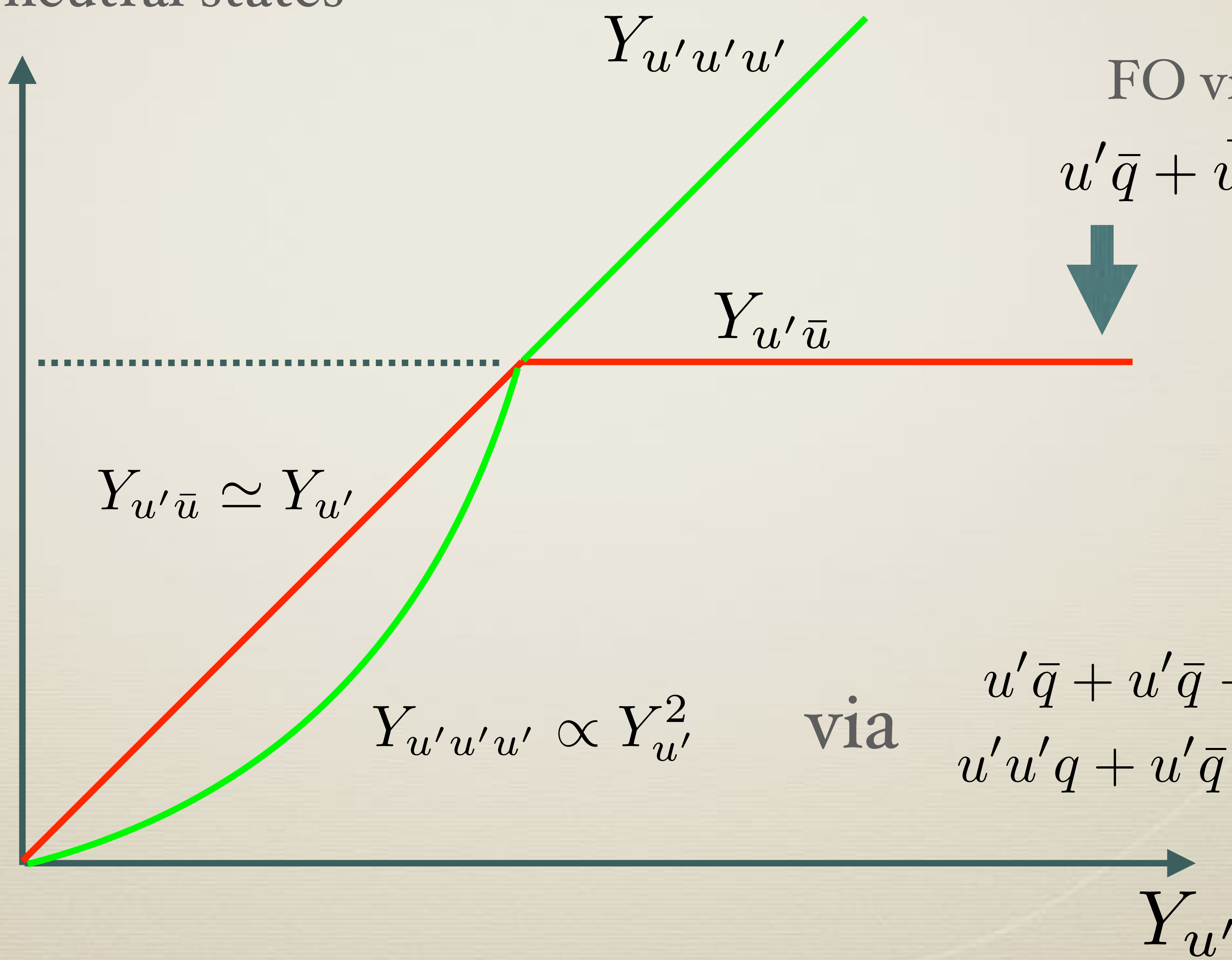
Y of colour neutral states

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)



FO via

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

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'

Dunsky, Hall, KH (2019)

$T \ll m_{u'}$ and

Inflaton → e'ebar', ~~u'ubar'~~

e.g. by

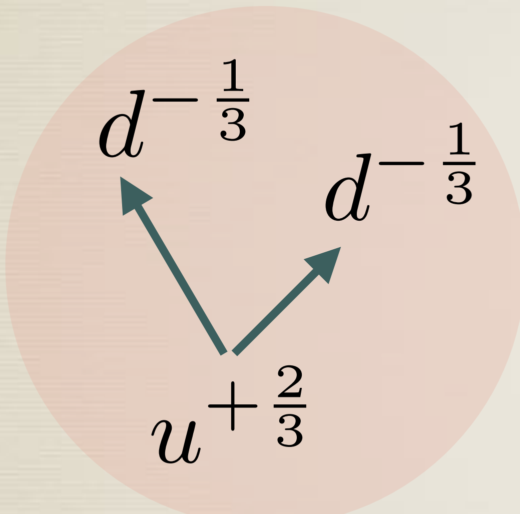
$2m_{e'} < \phi < 2m_{u'}$

Other possibilities?
Baryogenesis for low temperature?

Higgs Parity can solve Strong CP problem

QCD seems to preserve CP

Naively, neutrons will have electric dipole moments



$$d_n/e \sim 0.1 \text{ fm} \sim 10^{-14} \text{ cm ?}$$

$$H = d_n \vec{E} \cdot \vec{S}$$ Electric field-spin interaction

However,

$$d_n/e < 2.9 \times 10^{-26} \text{ cm}$$ Baker et.al (2006)

Suggests CP symmetry

$$d_n \vec{E} \cdot \vec{S} \overset{\text{CP=T}}{\Longrightarrow} -d_n \vec{E} \cdot \vec{S} \quad \Rightarrow \quad d_n = 0$$

CP is not preserved in SM

$$\mathscr{L} = y^u_{ij} H^\dagger q_i \bar{u}_j + y^d_{ij} H q_i \bar{d}_j + \frac{\theta_{\rm QCD}}{8\pi^2} \mathbf{E}^a \cdot \mathbf{B}^a$$

CP violation

observed $\theta_{\rm CKM} = O(1)$ ➡ $y^{u,d}$ must have complex phases

➡ CP is violated

$d_n/e \simeq 5 \times 10^{-16} \bar{\theta}$ cm   Crewther, Vecchia and Witten (1979)

$$\bar{\theta} = \arg\det(y^u y^d) + \theta_{\rm QCD} < 10^{-10}$$

The strong CP problem

Known Solutions

* QCD axion
* Spontaneously broken CP
* Spontaneously broken parity

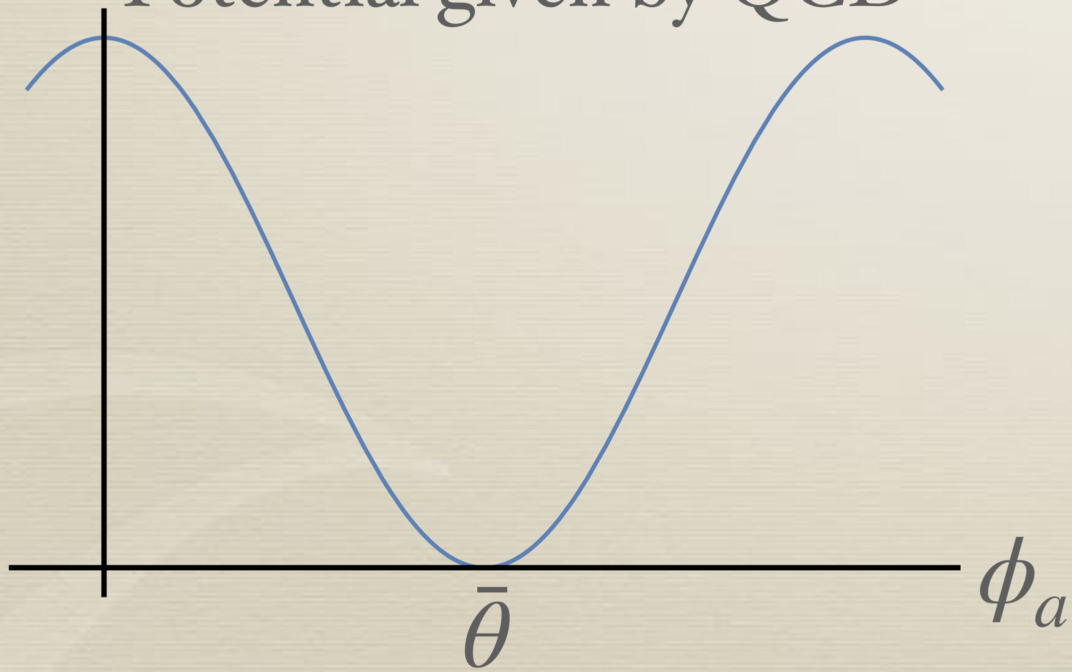
Known Solutions

Peccei and Quinn (1977)
Weinberg (1978), Wilczek (1978)

* QCD axion
* Spontaneously broken CP
* Spontaneously broken parity

$$\bar{\theta} \to \bar{\theta} - \phi_a(x)$$

Potential given by QCD



Axion is a dark matter candidate

Abbott and Sikivie (1983), Dine and Fischler (1983),
Preskill, Wise and Wilczek (1983), Davis (1986),
Co, Hall and KH (2017, 2019), KH and Leedom (2019)

can produce baryon asymmetry of the universe (axiogenesis)

Co and KH (2019)

Known Solutions

* QCD axion

* Spontaneously broken CP

* Spontaneously broken parity

$$\mathrm{CP} \rightarrow \bar{\theta} = 0,\ d_n = 0$$

CP symmetry is spontaneously broken ➡ complex yukawa $y^{u,d}$

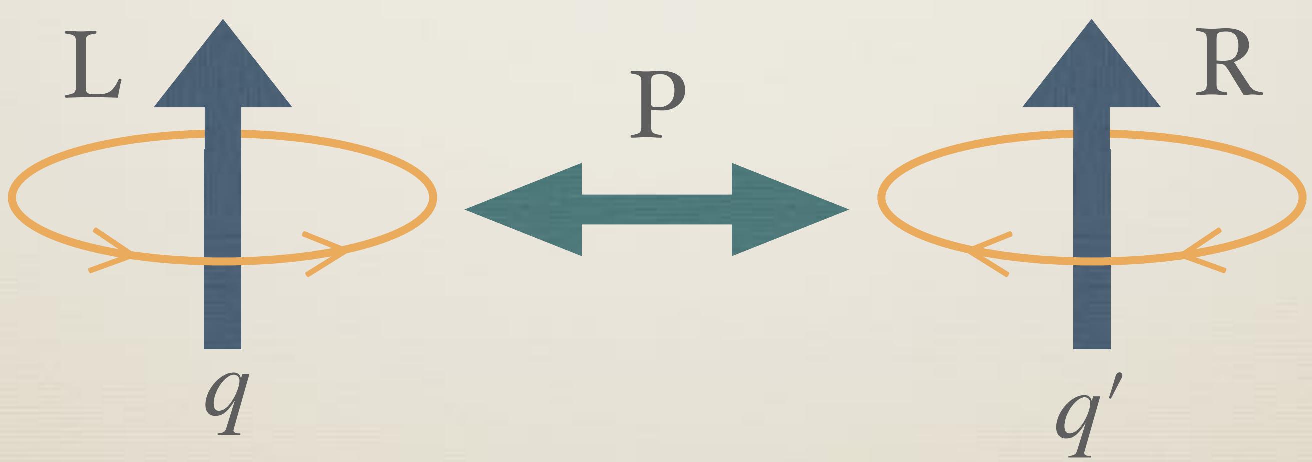
but in a sophisticated way so that $\bar{\theta}$ remains zero

Nelson (1984), Barr (1984)

Known Solutions

Mohapatra and Senjanovic (1978)
Beg and Tsao (1978)
Babu and Mohapatra (1989)
Barr, Chang and Senjanovic (1991)

- QCD axion
- Spontaneously broken CP
- Spontaneously broken parity



How the strong CP problem is solved depends on what q' is.

(q' = antiparticle of q : P is CP)

Mirrored electroweak theory

SM particles | New particles

strong interaction

$SU(3)_c$

SM particles		New particles
q		q'
u		u'
d		d'
L	HP	L'
e	⟷	e'
H		H'

electroweak | electroweak'

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

$\downarrow$ | $\downarrow$

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

Strong CP problem solved

Barr, Chang and Senjanovic (1991)

HP

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

HP

$$+\frac{\theta_{\rm QCD}}{8\pi^2}\mathbf{E}^a\cdot\mathbf{B}^a$$

$\Delta\bar{\theta}_q$

$\Delta\bar{\theta}_{q'} = -\Delta\bar{\theta}_q$

$\bar{\theta} = \Delta\bar{\theta}_q + (-\Delta\bar{\theta}_q) = 0$ cancel with each other

Neutron
electric dipole moment

Space-time parity and neutron EDM

The neutron EDM vanishes in the parity symmetric limit

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

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

We expect non-zero neutron EDM at some level

Non-zero CP violation

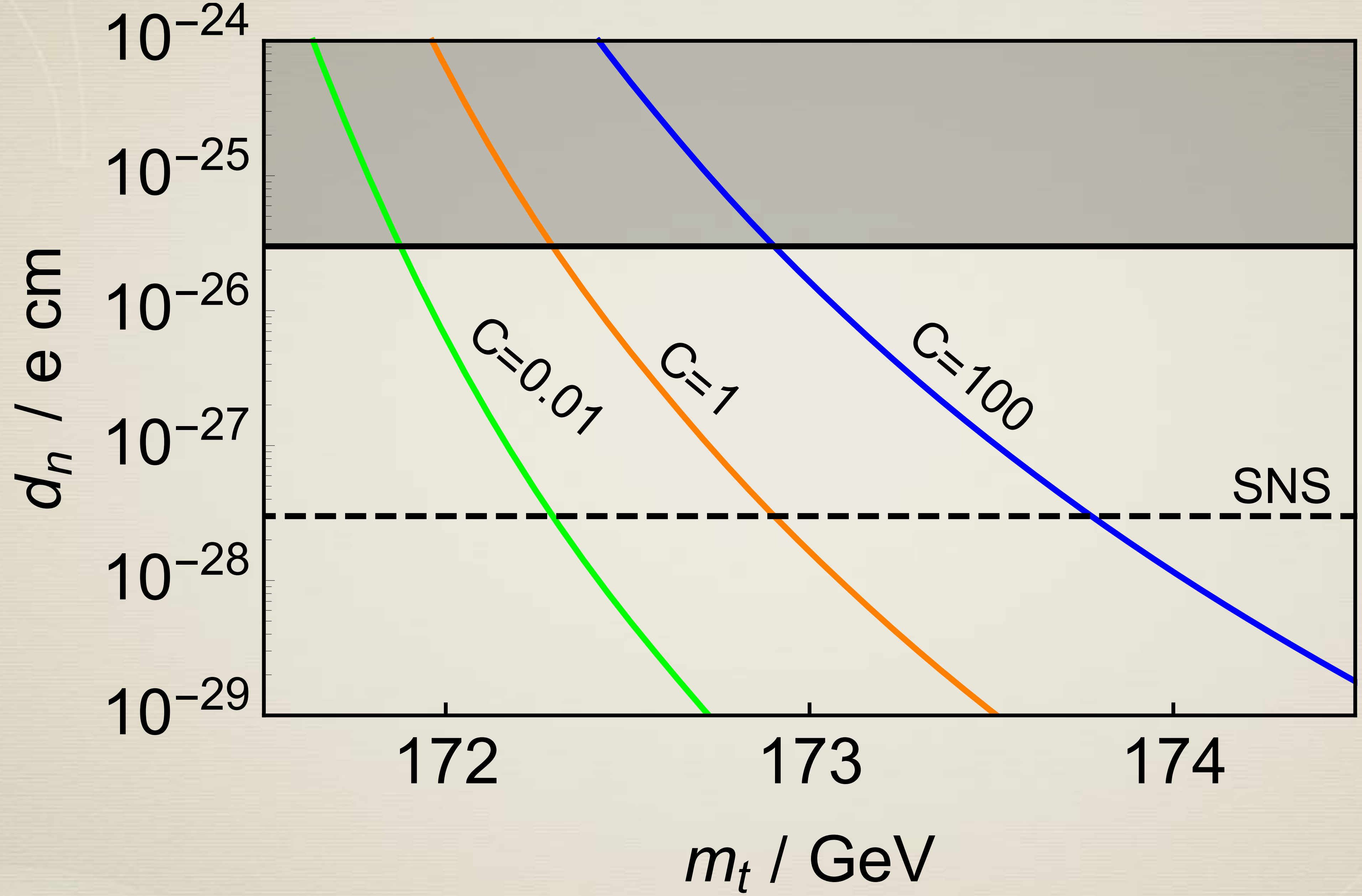
$$\frac{C}{M_{\rm pl}^2}\left(|H|^2 - |H'|^2\right)\mathbf{E}\cdot\mathbf{B}$$

Electric and magnetic fields of gluon

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

- Present limit $d_n < 2.9 \times 10^{-26} e$ cm Baker et.al (2006)
- PSI $d_n < 5 \times 10^{-27} e$ cm Baker et.al (2011)
- SNS $d_n < 3 \times 10^{-28} e$ cm Tsentalovich (2014)

Neutron EDM

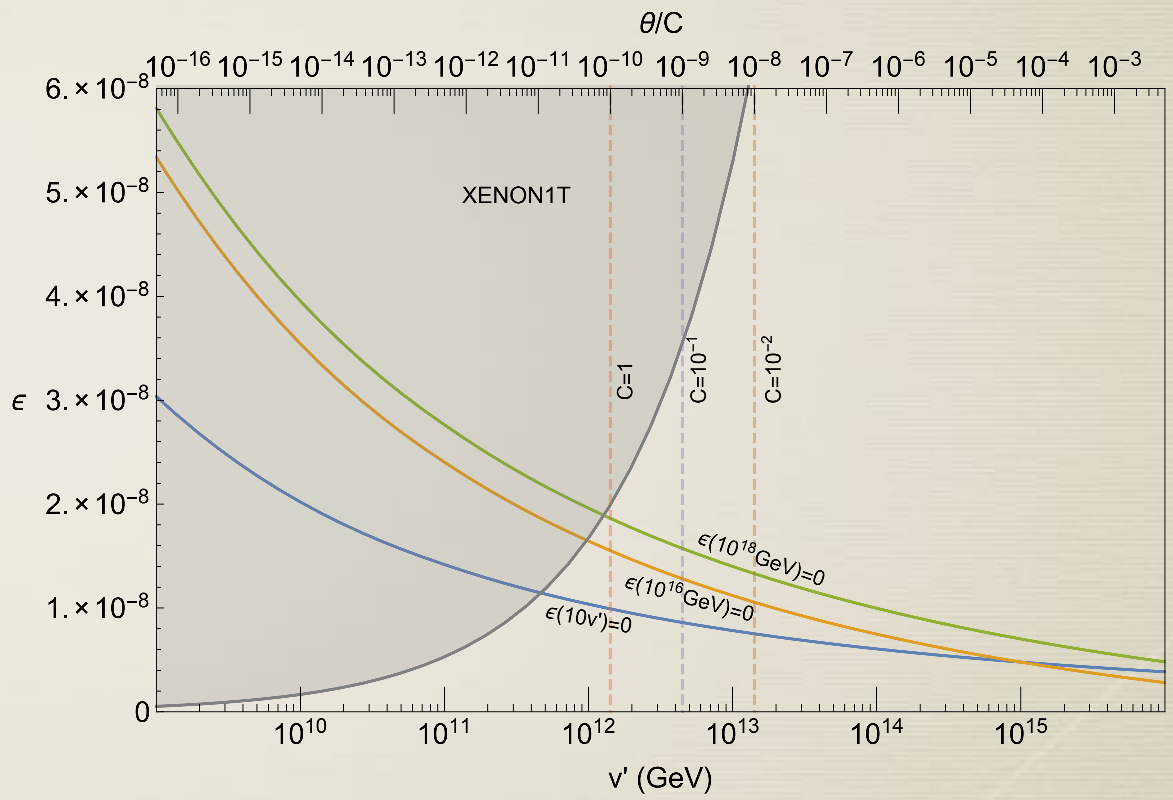


$$\frac{C}{M_{\rm pl}^2}\left(\left|H\right|^2-\left|H'\right|^2\right)\mathbf{E}\cdot\mathbf{B}$$

Experimental program

Dunsky, Hall and KH (2019)

Top quark yukawa
Higgs mass
Strong coupling constant



Higgs Parity
symmetry breaking scale

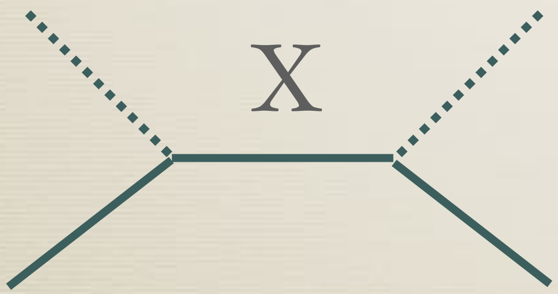
Dark matter detection
Neutron EDM

GUT

Yukawa interaction

No gauge invariant renormalizable coupling

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

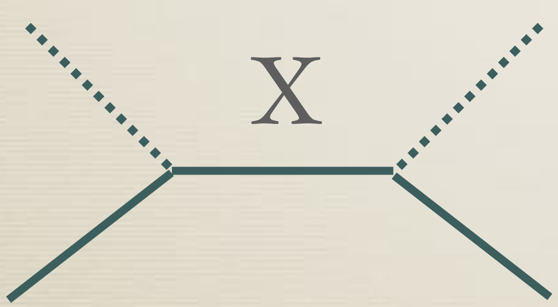


Strong CP problem solved

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

No gauge invariant renormalizable coupling

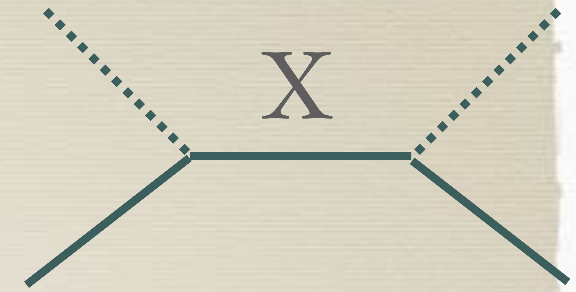
$$\frac{c_{ij}}{M} H H' q_L \bar{q}_R$$



$$q_L(t,x) \overset{\text{HP}}{\leftrightarrow} q_R(t,-x)$$

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

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	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$2/3$	$\mathbf{15}$	$\mathbf{45}$	$\bar{X} q H^\dagger + X q' H'^\dagger$
	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$	$-1/3$	$\mathbf{6}/\mathbf{10}$	$\mathbf{45}, \mathbf{54}, \mathbf{210}/\mathbf{210}$	$\bar{X} q H'^\dagger + X q' H^\dagger$
down	$\mathbf{3}$	$\mathbf{1}$	$\mathbf{1}$	$-1/3$	$\mathbf{6}/\mathbf{10}$	$\mathbf{10}, \mathbf{126}/\mathbf{120}$	$\bar{X} q H + X q' H'$
	$\mathbf{3}$	$\mathbf{2}$	$\mathbf{2}$	$2/3$	$\mathbf{15}$	$\mathbf{120}, \mathbf{126}$	$\bar{X} q H' + X q' H$
electron	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1	$\mathbf{10}$	$\mathbf{120}$	$\bar{X} \ell H + X \ell' H'$
	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	0	$\mathbf{1}/\mathbf{15}$	$\mathbf{10}, \mathbf{120}/\mathbf{120}, \mathbf{126}$	$X \ell H' + X \ell' H$
neutrino	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	0	$\mathbf{1}/\mathbf{15}$	$\mathbf{1}, \mathbf{54}, \mathbf{210}/\mathbf{45}, \mathbf{210}$	$X(\ell H^\dagger + \ell' H'^\dagger)$
	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	-1	$\mathbf{10}$	$\mathbf{210}$	$\bar{X} \ell H'^\dagger + X \ell' H^\dagger$
	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	0	$\mathbf{1}$	$\mathbf{45}$	$X \ell H^\dagger$
	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{3}$	0	$\mathbf{1}$	$\mathbf{45}$	$X \ell' H'^\dagger$

SO(10) embedding

Hall, KH (2018)

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

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

$q(t,x) \leftrightarrow \bar{q}'(t,x)$

C: Part of SO(10)

$q(t,x) \leftrightarrow i\sigma_2 q^*(t,-x)$

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

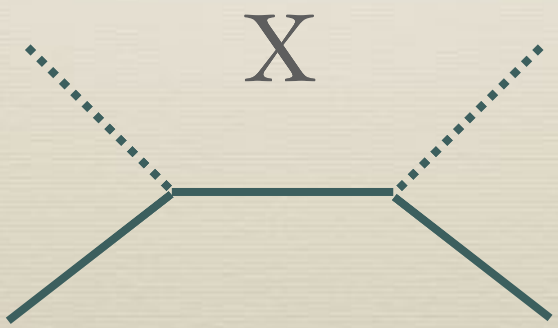
$$SO(10)\times CP \xrightarrow{\phi_{45}^{-}} SU(3)\times SU(2)_L\times SU(2)_R\times U(1)_{B-L}\times P_{LR}$$

Real yukawas, without CP symmetry breaking...

A simple renormalizable example to obtain CP phases

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

$$\frac{c_{ij}}{M} H H' q_i q_j'$$



Top-down perspective

SUSY GUT

3 parameters → 4 parameters

$g_{\mathrm{GUT}},\ M_{\mathrm{GUT}},\ m_{\mathrm{SUSY}}$ → $g_1,\ g_2,\ g_3,\ v_{\mathrm{EW}}$

(or more, e.g. Ω_{DM})

Similar structures

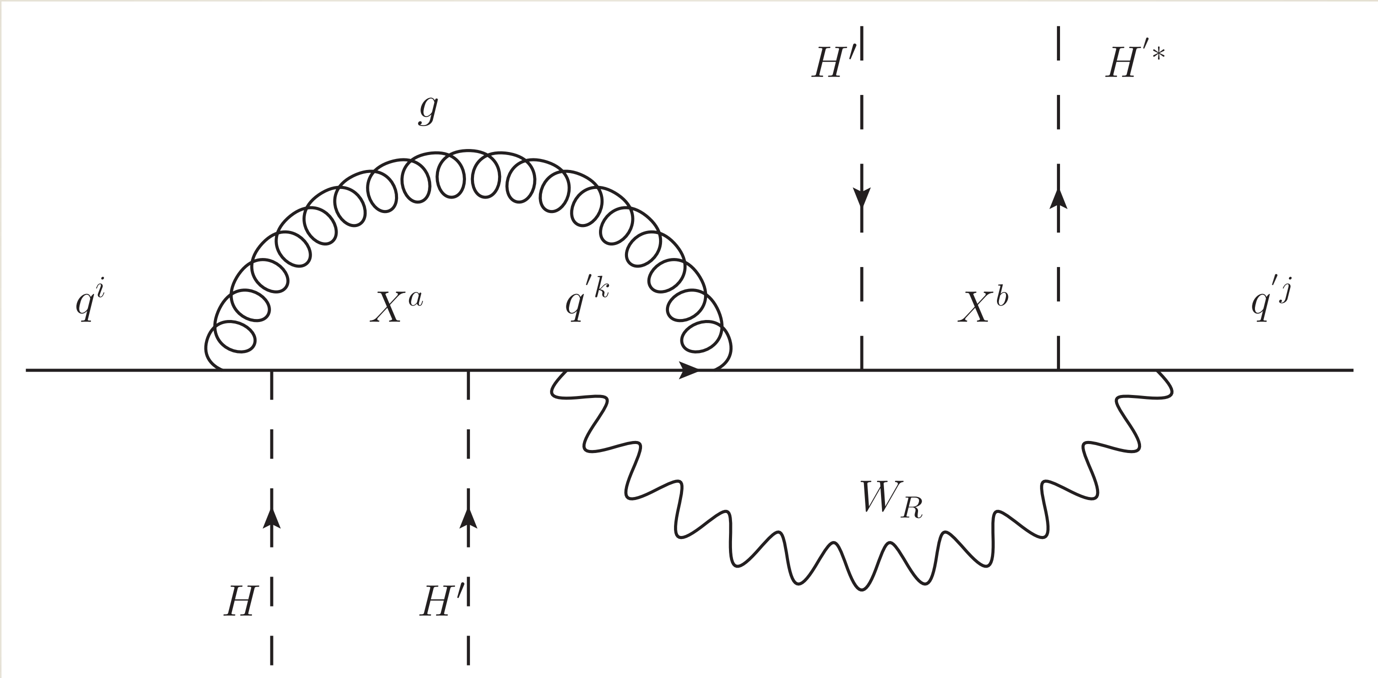
Parity GUT

4 parameters → 5 parameters

$g_{\mathrm{GUT}},\ M_{\mathrm{GUT}},\ v',\ y_t$ → $g_1,\ g_2,\ g_3,\ y_t,\ \lambda_{\mathrm{higgs}}$

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

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

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

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

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

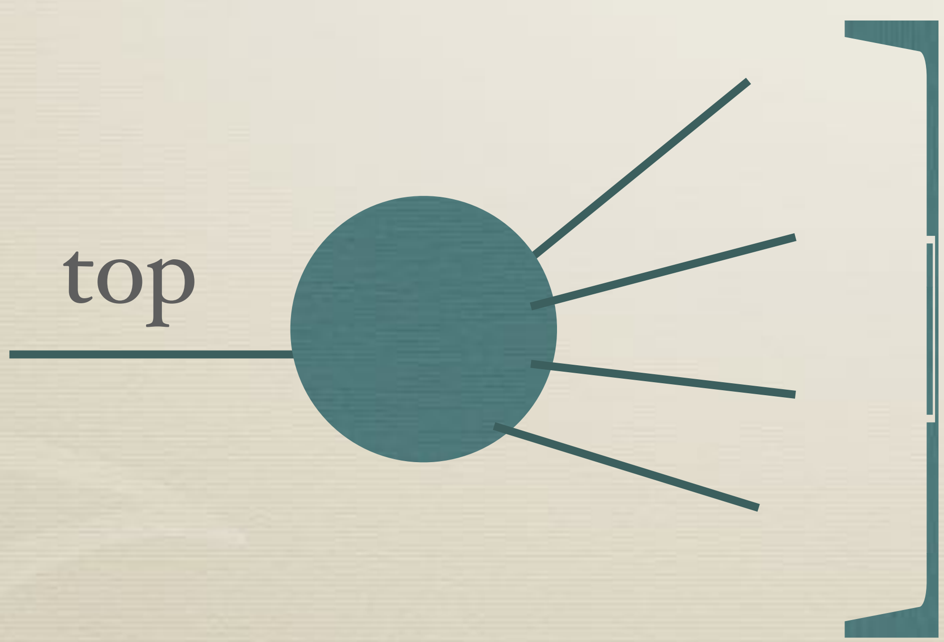
SM parameters

"top quark mass"

pole mass 172.9 ± 0.4 GeV

Particle Data Group

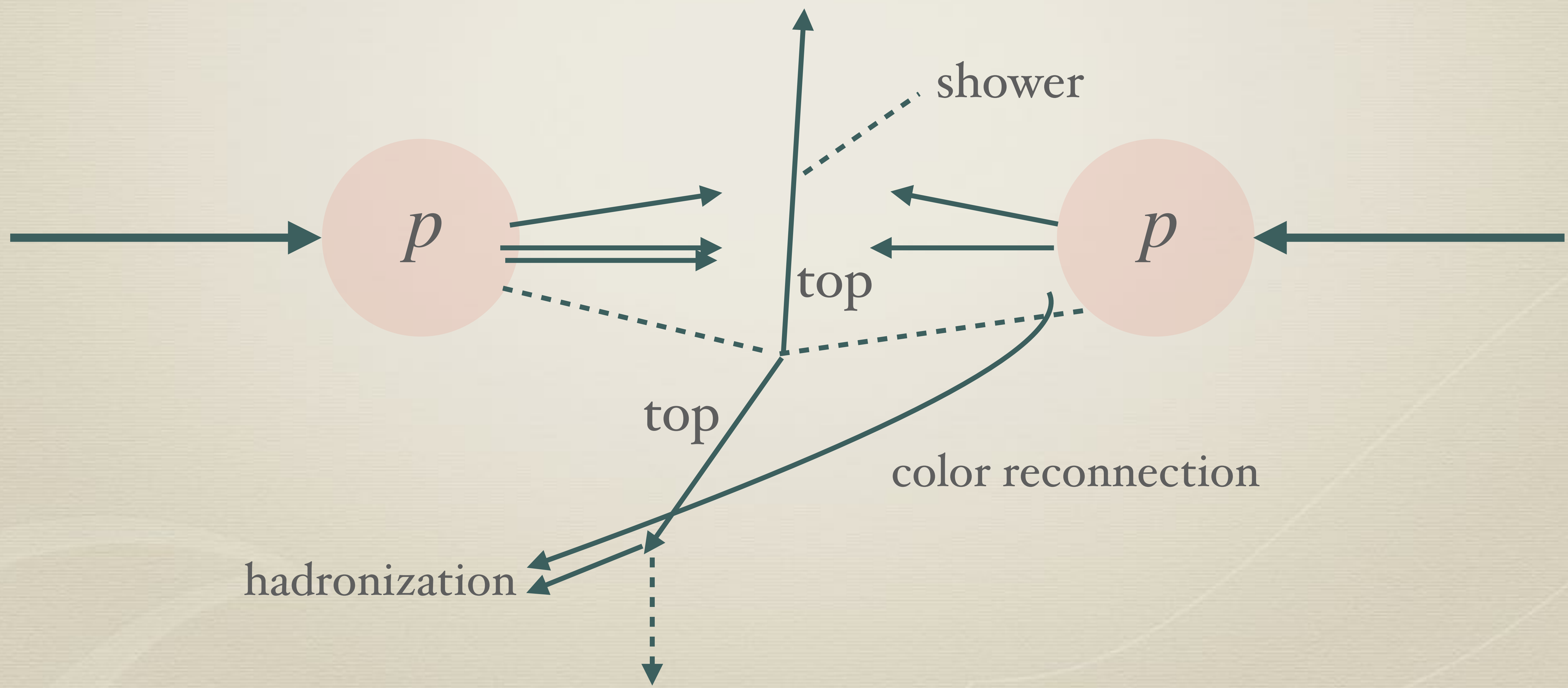
if top were colorless, isolated objects



measure momentum and energy,
take invariant mass

“top quark mass”

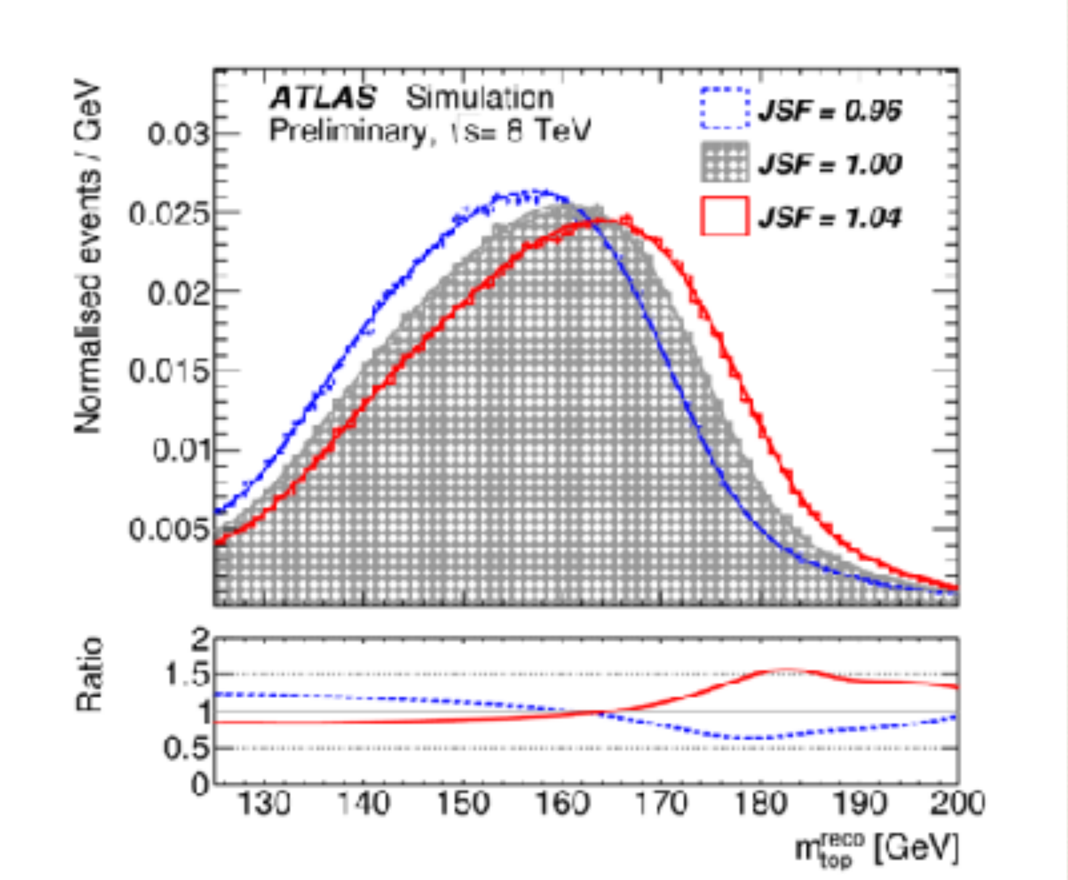
but of course top is colored and is not isolated



“top quark mass”

templates of distribution of kinematical observables

mass parameter → Monte-Carlo Simulation →



fitting the templates, combining results,

$$172.9 \pm 0.4 \text{ GeV}$$

Uncertainty from non-perturbative QCD $\Delta m_t \gtrsim \Lambda_{QCD}$

MSbar quantity

pole mass

$$y_{t,\overline{MS}}(m_t) = 0.93690 + 0.00556(\frac{m_t}{\text{GeV}} - 173.34) - 0.00042\frac{\alpha_s(m_Z) - 0.1184}{0.0007}$$

Buttazzo et.al. (2013)

* NNNLO QCD corrections included
* Uncertainty from non-perturbative nature of QCD

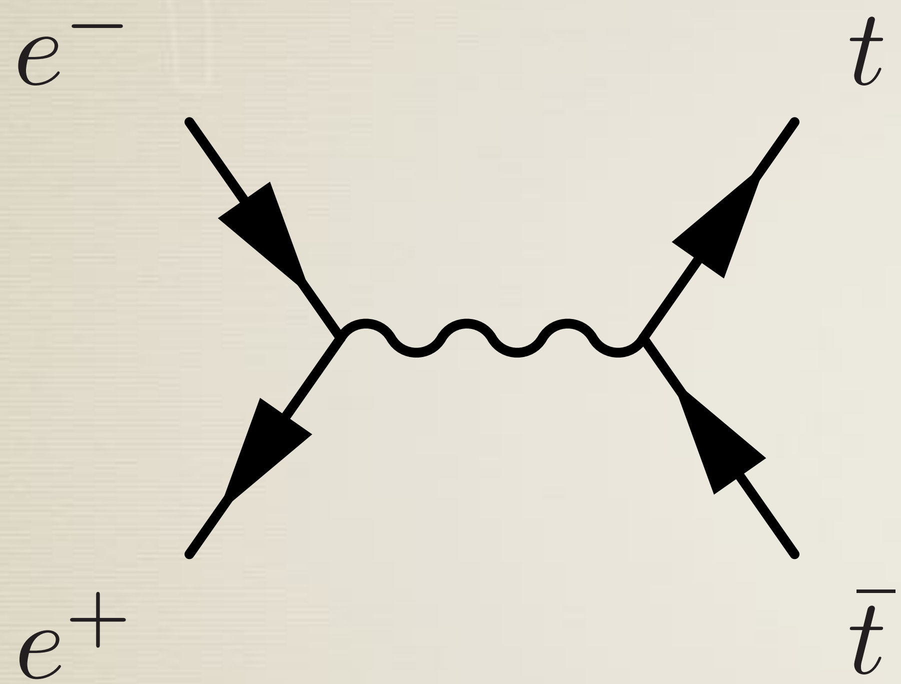
$$\Delta m_t \sim \Lambda_{\text{QCD}}$$

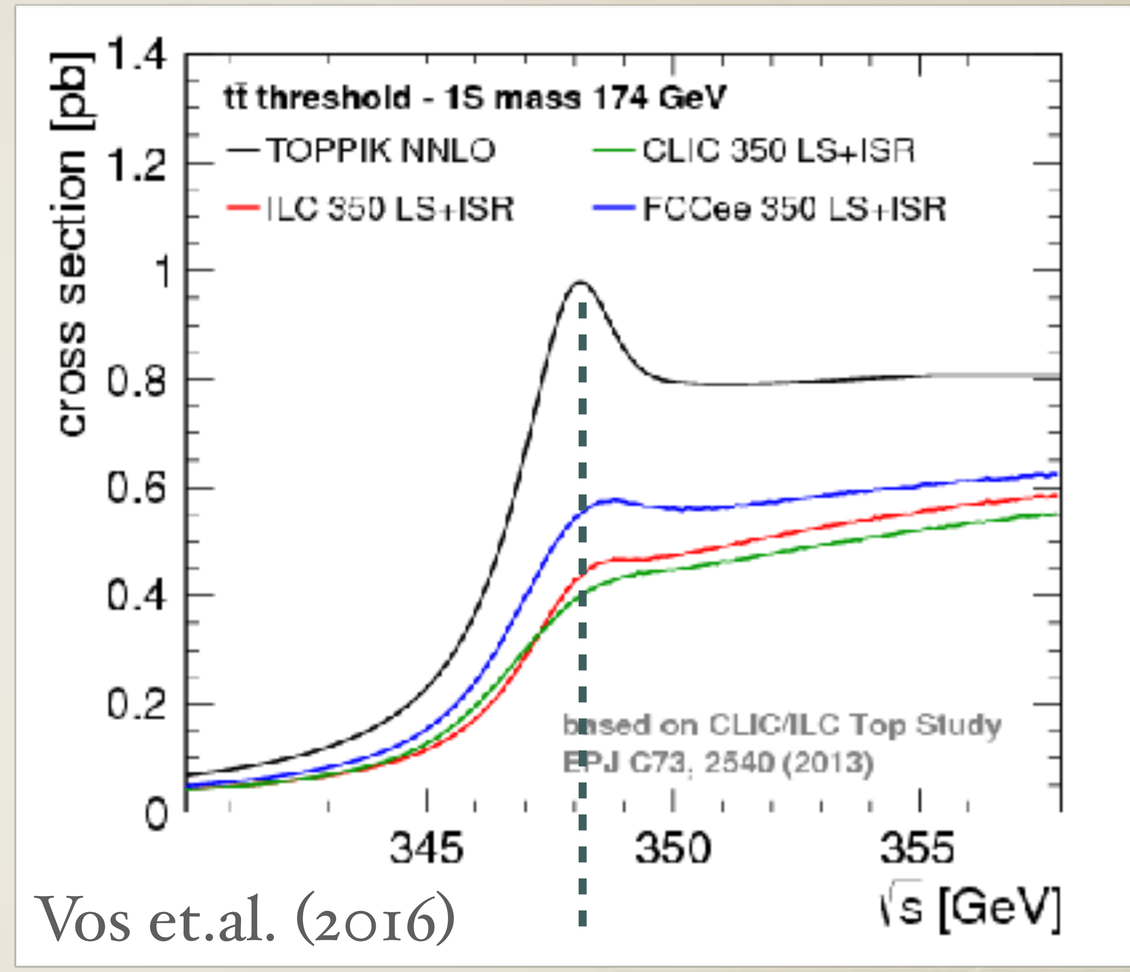
Bigi, Shifman, Uraltsev and Vainshtein (1994)
Benek and Braun (1994)

Eventually, we should directly determine MSbar quantity by

MSbar quantity $\longleftrightarrow$ observables

Lepton colliders





$M_{t\bar{t}}(1S)$

$$M_{t\bar{t}}(1S) = 2(165 + 7.20 + 1.20 + 0.216 + 0.0077 + \cdots)\ \text{GeV}$$

Kiyo, Mishima and Sumino (2015)

$$\Delta m_{t,\overline{MS}} \simeq \text{few tens MeV}$$

Strong coupling constant

e.g. HPQCD collaboration (2008)

tune

Lattice ← mass spectrum

↓

Physical quantity

↑

Perturbation theory $\alpha_s(\mu), m_{b,c}(\mu)$

Gravitational waves and dark radiation

Mirror Higgs Parity

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

$SU(3) \times SU(2) \times U(1)$ ⟷ $SU(3)' \times SU(2)' \times U(1)'$

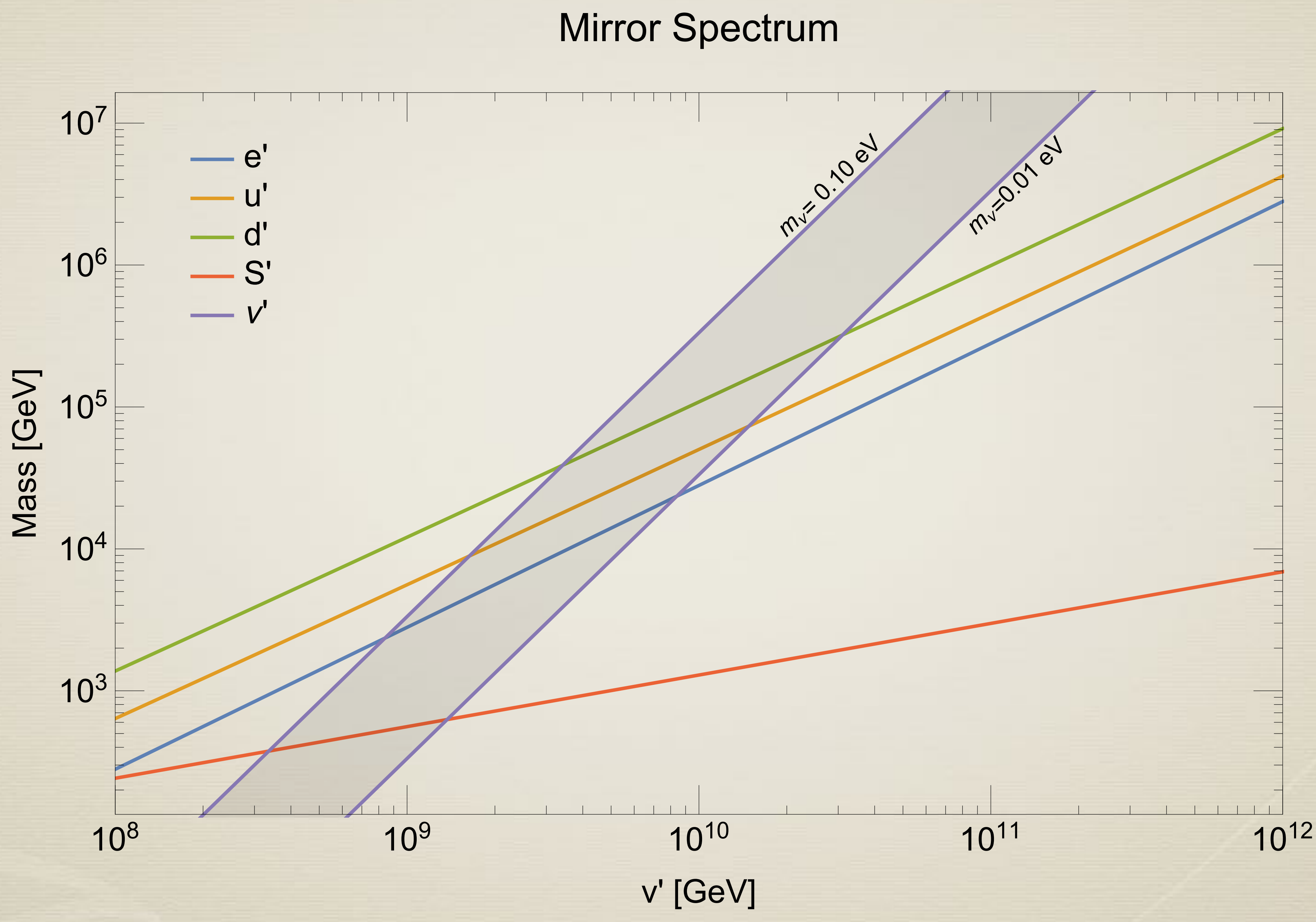
Mirror confinement

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

The confining occurs as a first order phase transition

Gravitational waves

Dilution

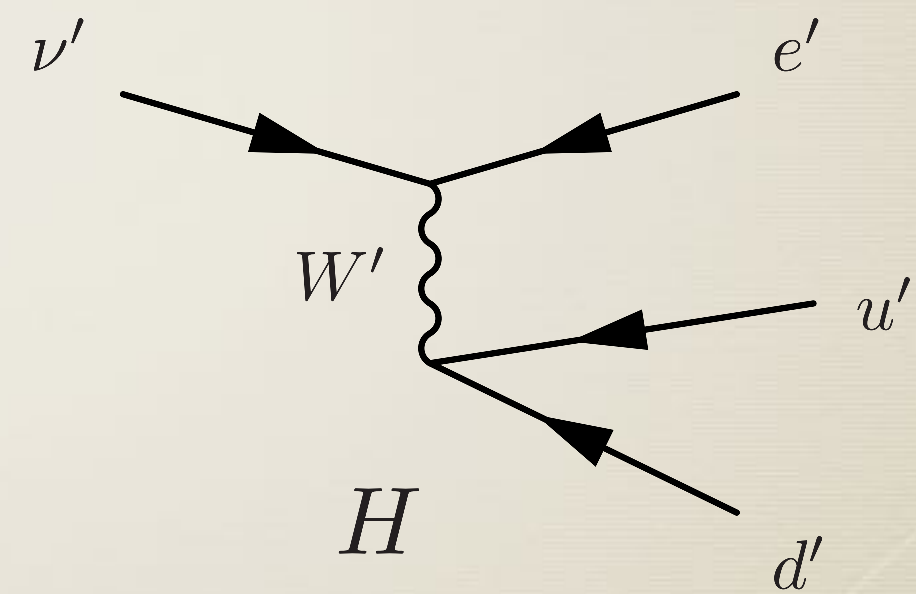


Mirror leptons and baryons overproduced, dilution required

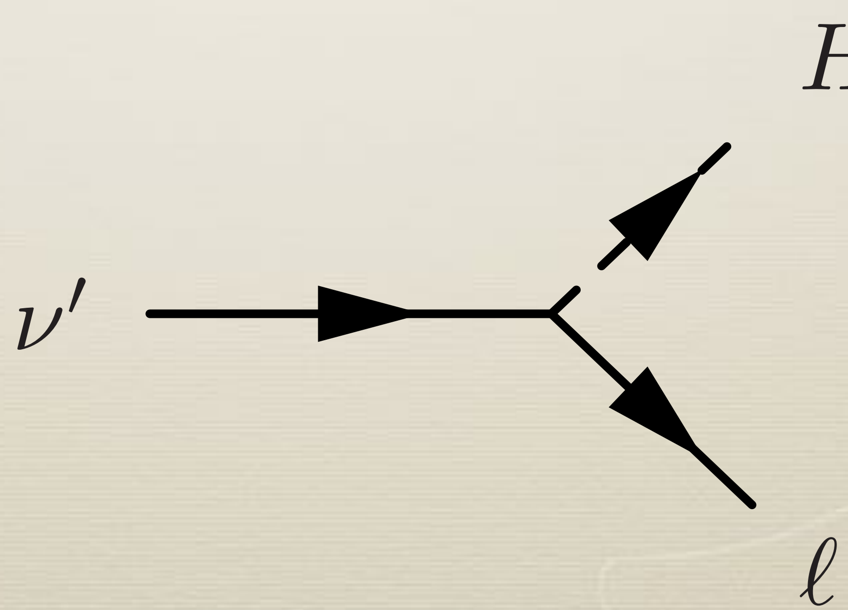
Dilution

Mirror neutrino can be long-lived

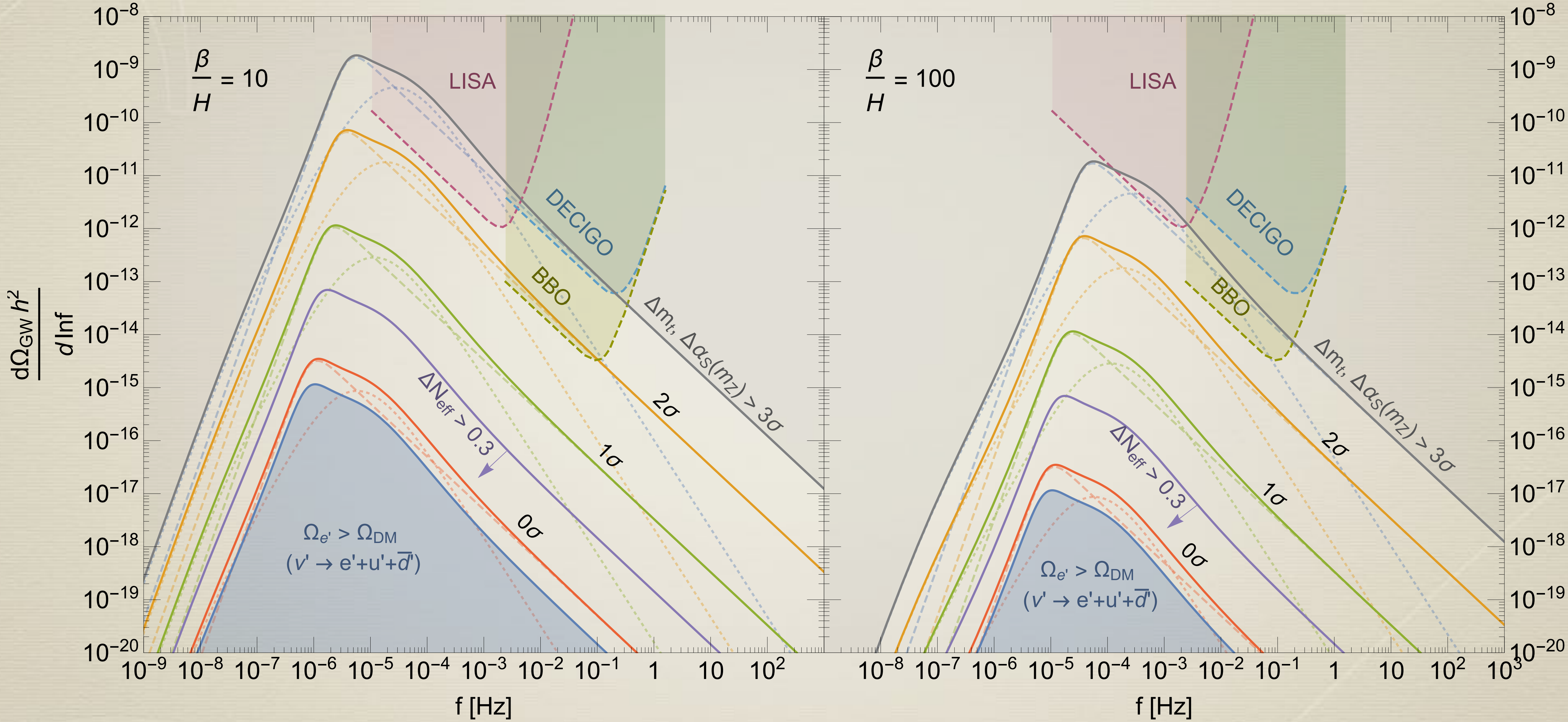
$$m'_\nu = m_\nu \left(\frac{v'}{v}\right)^2 < m'_e + m'_u + m'_d \propto v'$$



Dilution from

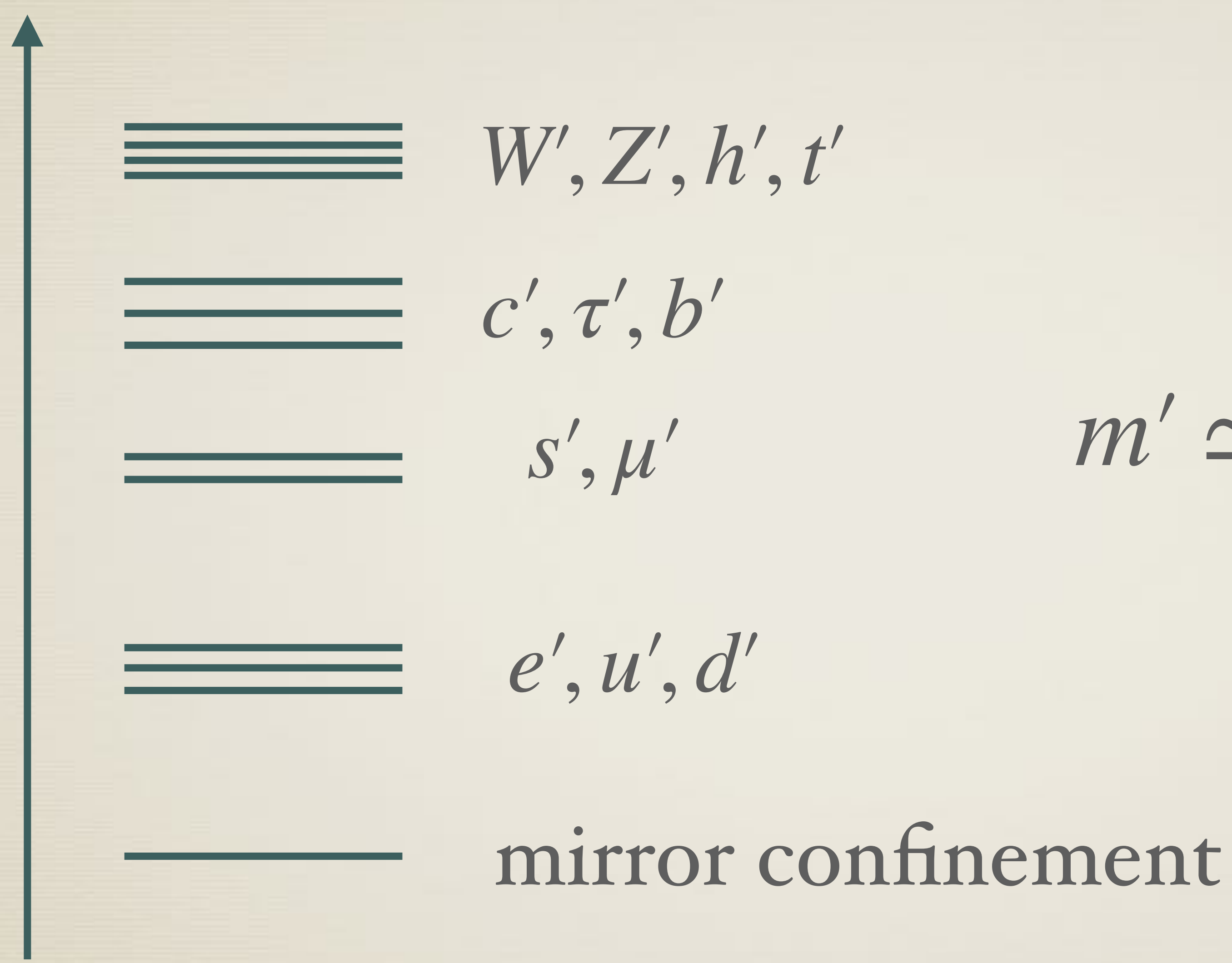


Gravitational waves



Nature of the phase transition needs to be better understood

Mirror glueball

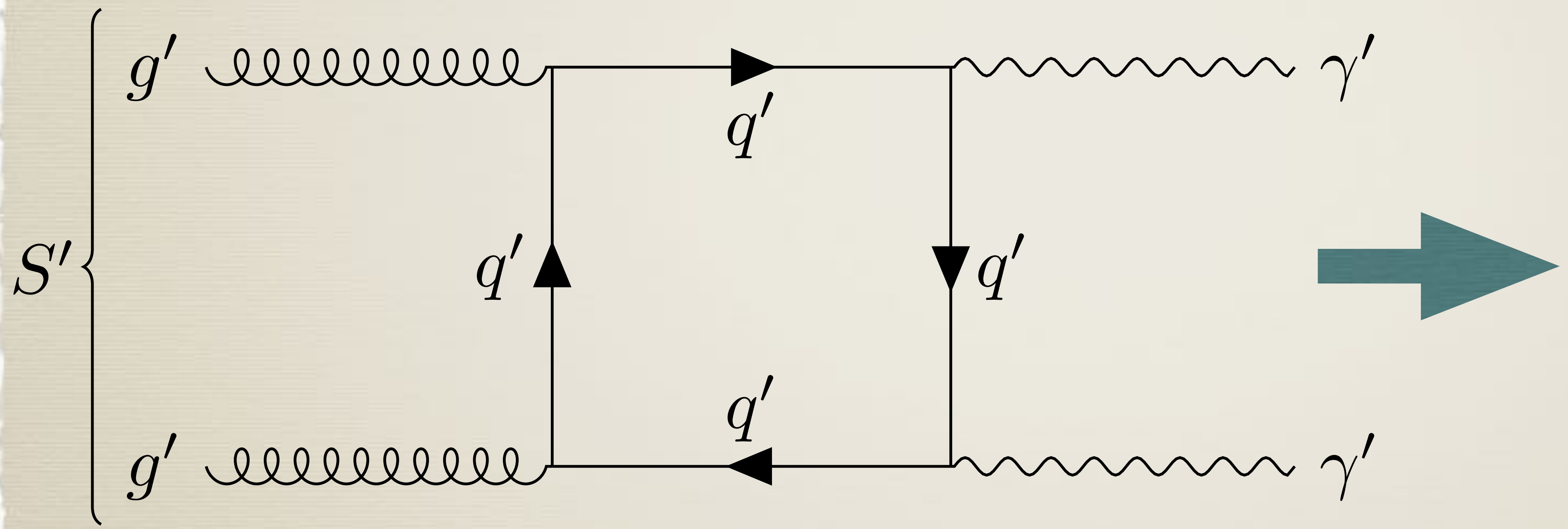


$$m' \simeq m \times \frac{v'}{v}$$

confined

Mirror gluons → Mirror glueballs

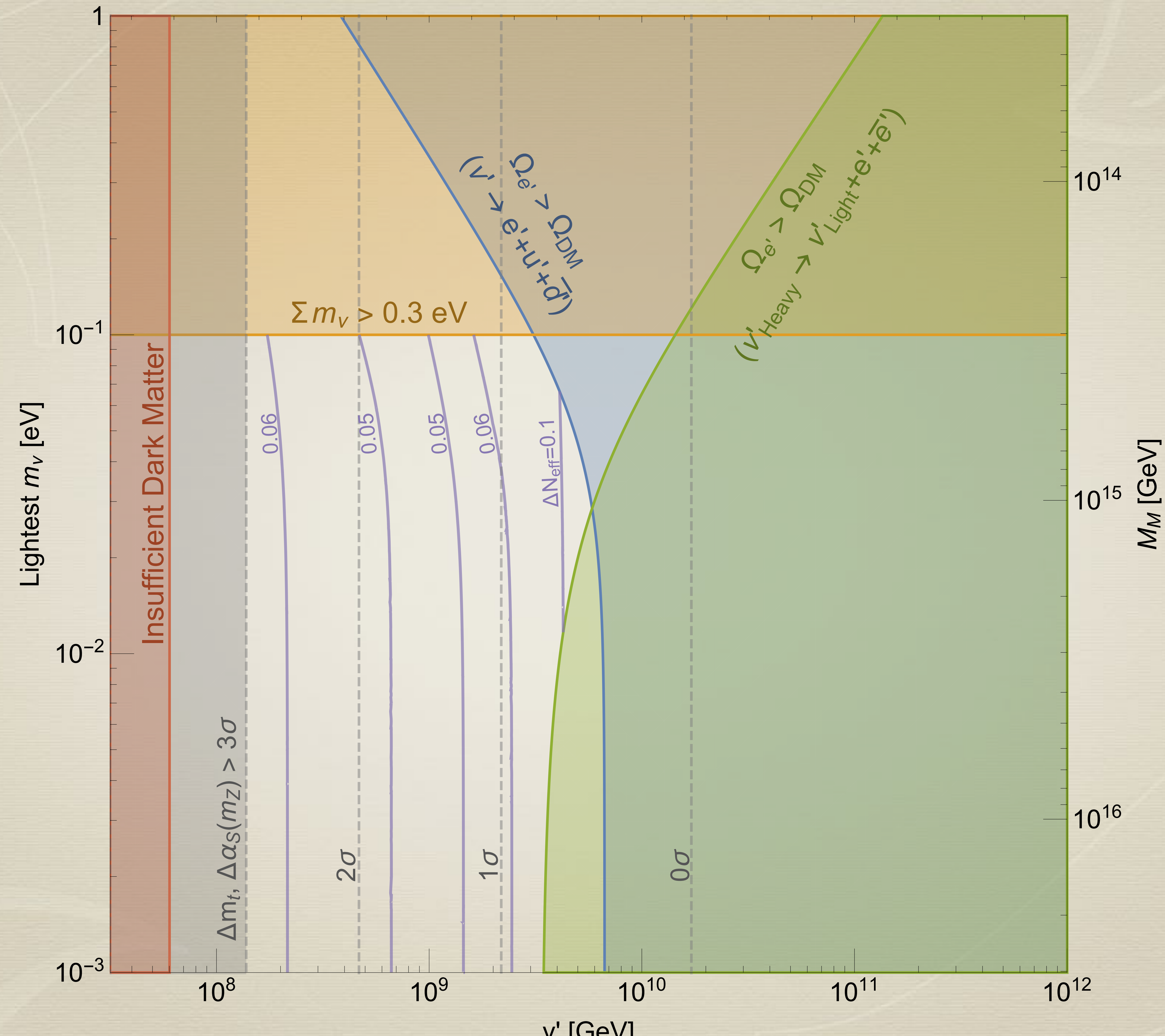
Long-lived mirror glueball



Extra radiation components

(Dark radiation)

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



Insufficient Dark Matter
Δm_t, $\Delta\alpha_S(m_Z) > 3\sigma$
$\Sigma m_\nu > 0.3$ eV
$\Omega_{e'} > \Omega_{DM}$
$(\nu' \to e' + \mu' + \bar{\mu}')$
$\Omega_{e'} > \Omega_{DM}$
$(\nu'_{Heavy} \to \nu'_{Light} + e' + \bar{e}')$
0.06
0.05
0.05
0.06
$\Delta N_{eff}=0.1$
2σ
1σ
0σ
Lightest m_ν [eV]
v' [GeV]
M_M [GeV]
1
10^{-1}
10^{-2}
10^{-3}
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{14}
10^{15}
10^{16}