01/13/2020

Brookhaven National Laboratory

Experimental Probe of Higgs Parity

Keisuke Harigaya
(Institute for Advanced Study)

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
(of particle physics)

* Three generations of quarks and leptons
* Electromagnetic, strong, and weak interactions by gauge bosons
* Higgs field gives masses to quarks, leptons and gauge bosons

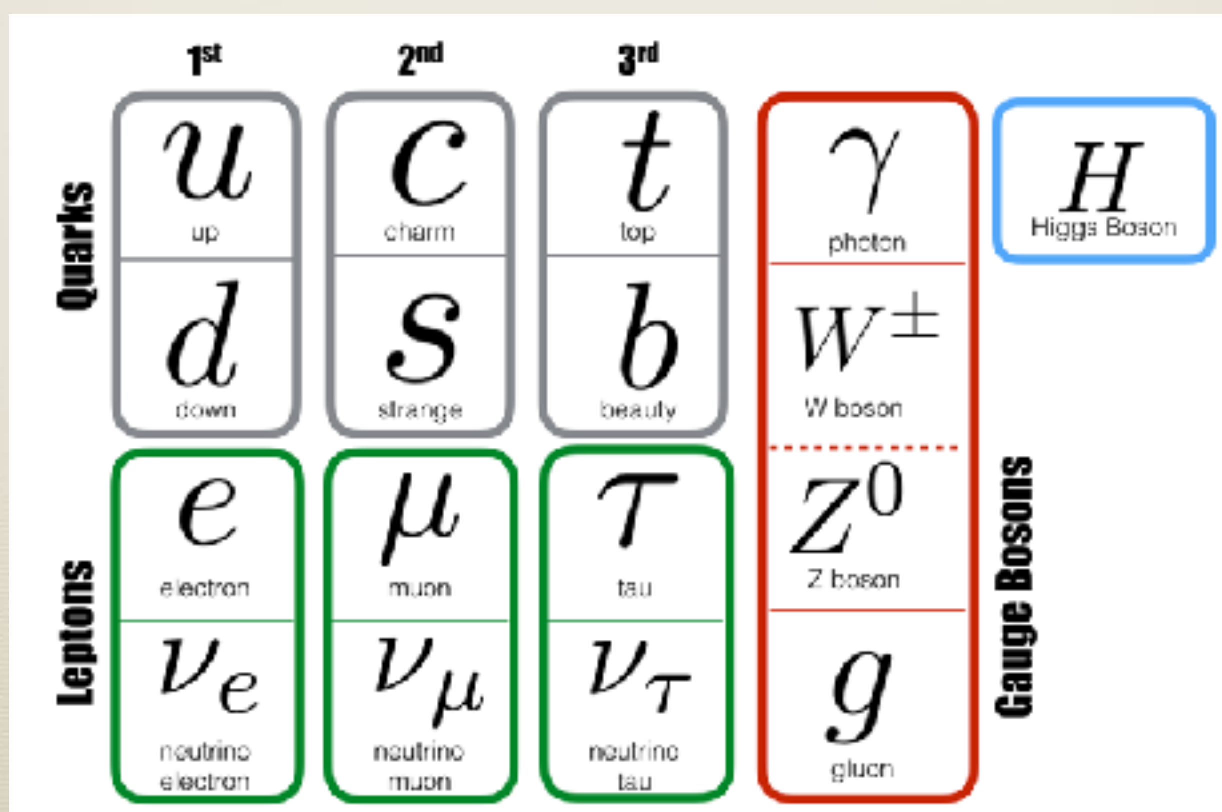


figure from www.physik.uzh.ch

Standard Model

- Three generations of quarks and leptons
- Electromagnetic, strong, and weak interactions by gauge bosons
- Higgs field gives masses to quarks, leptons and gauge bosons

proton

neutron

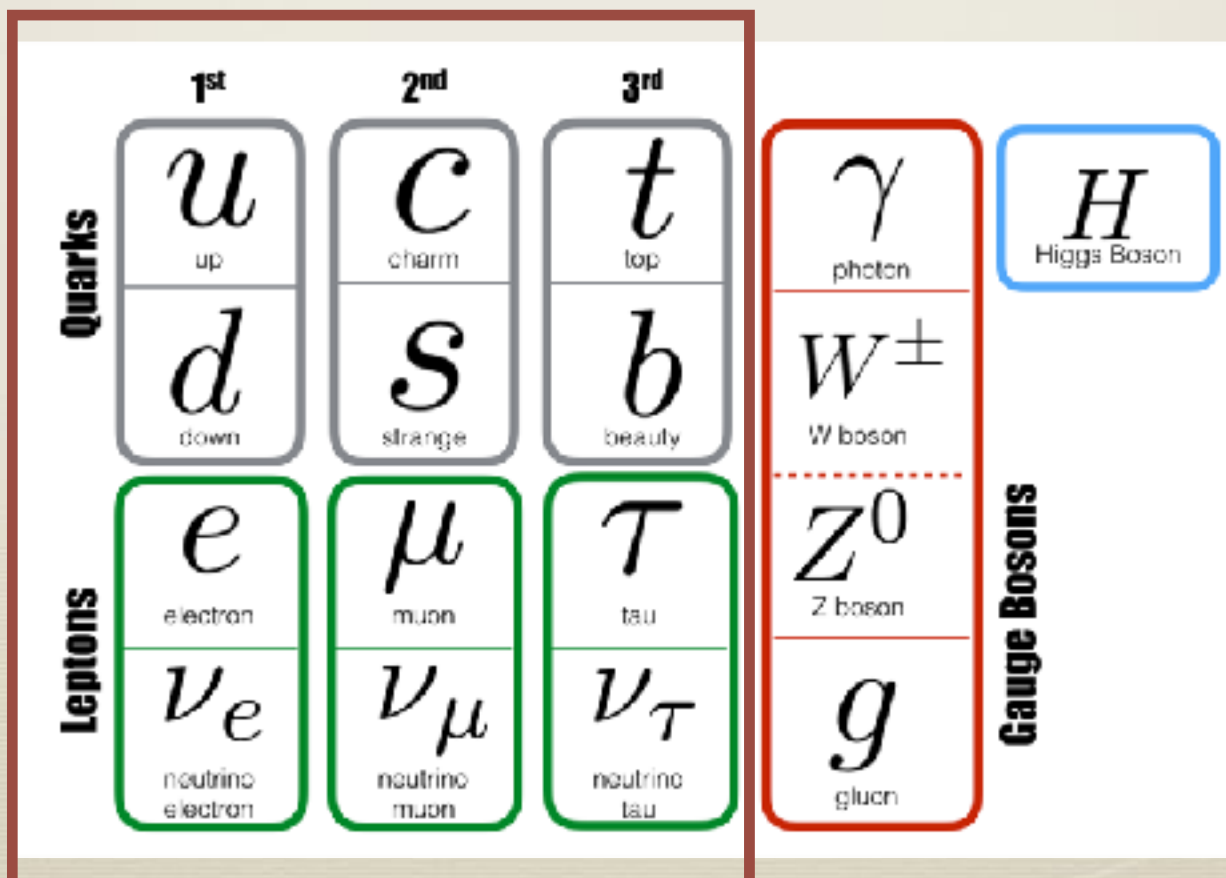


figure from www.physik.uzh.ch

Standard Model

- Three generations of quarks and leptons
- Electromagnetic, strong, and weak interactions by gauge bosons
- Higgs field gives masses to quarks, leptons and gauge bosons

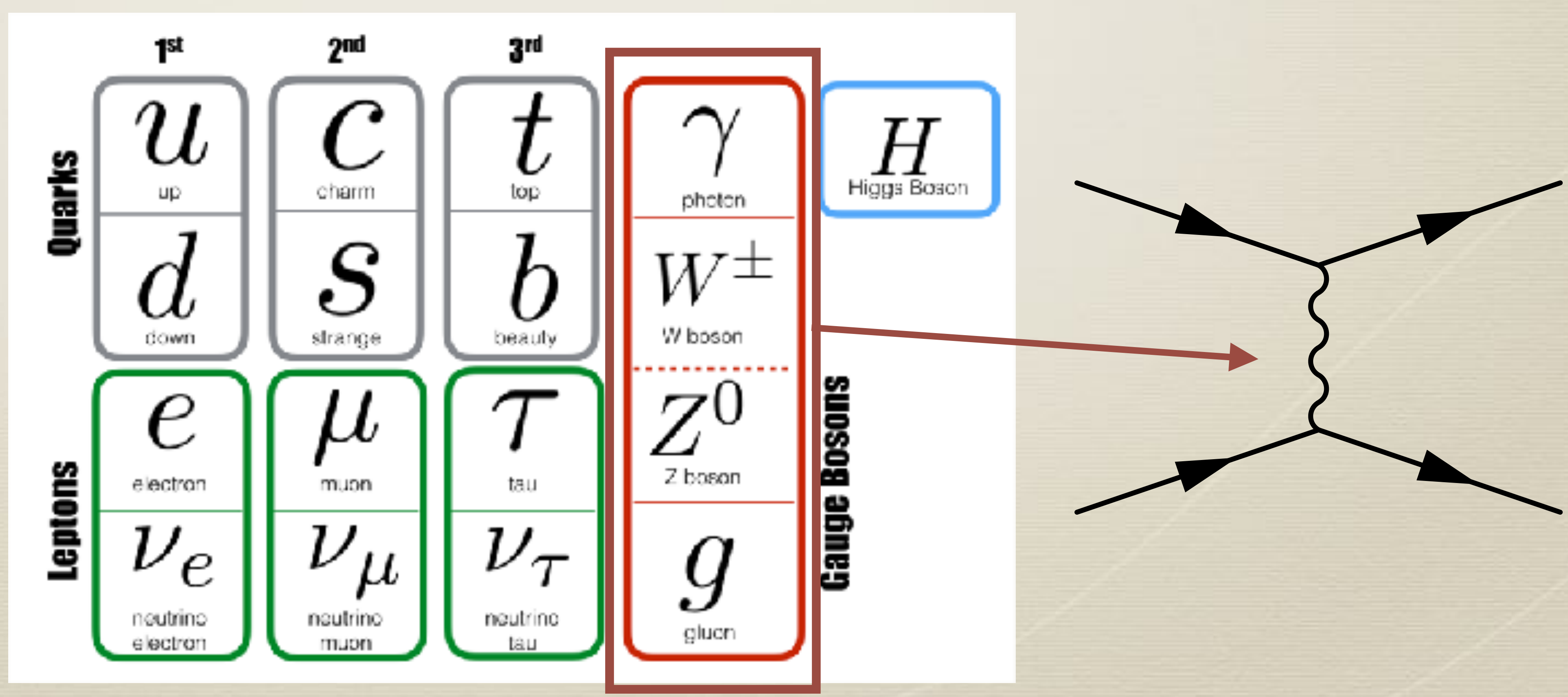
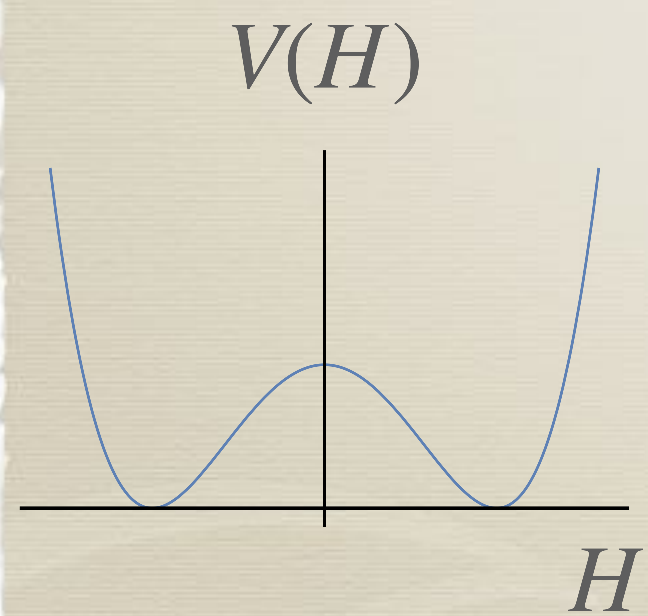
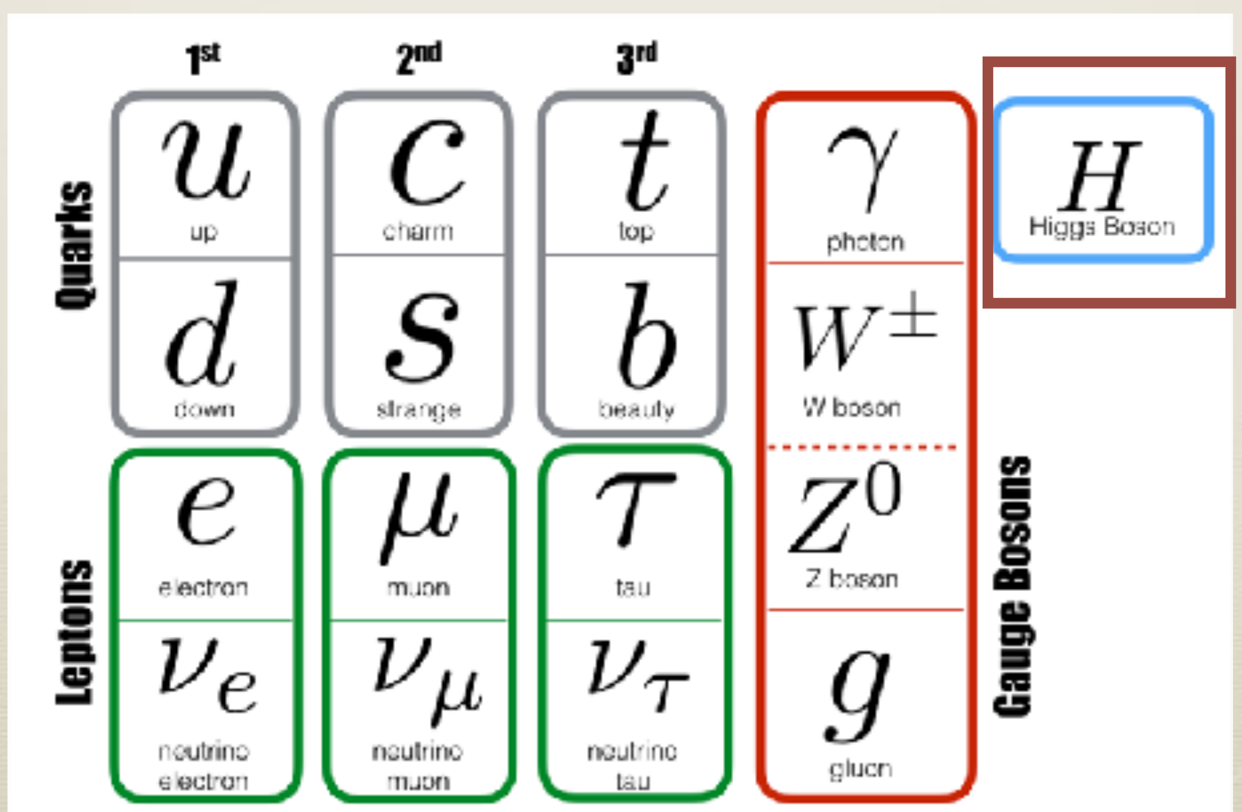


figure from www.physik.uzh.ch

Standard Model

* Three generations of quarks and leptons
* Electromagnetic, strong, and weak interactions by gauge bosons
* Higgs field gives masses to quarks, leptons and gauge bosons





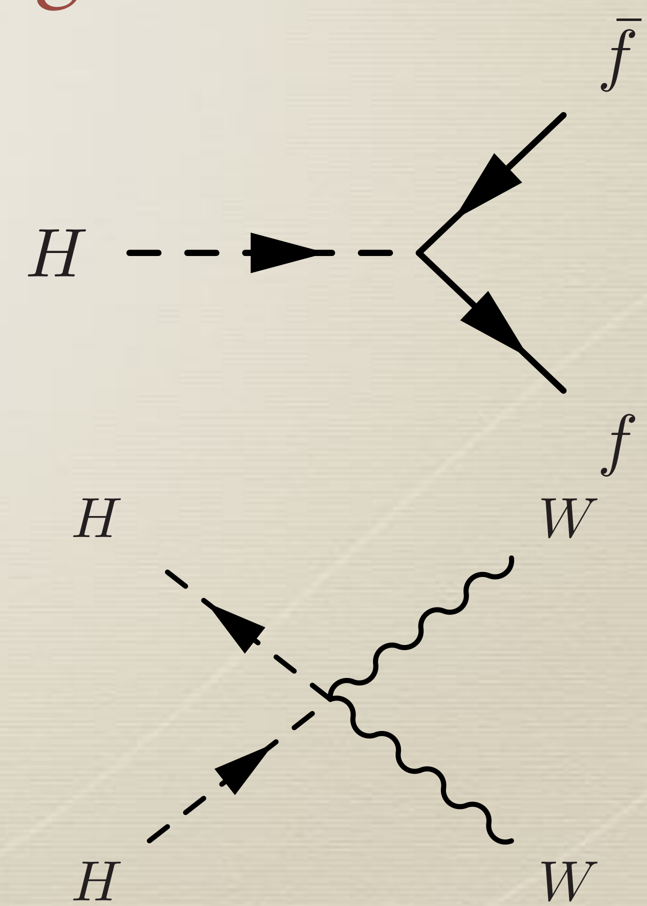


figure from www.physik.uzh.ch

All particles have been discovered

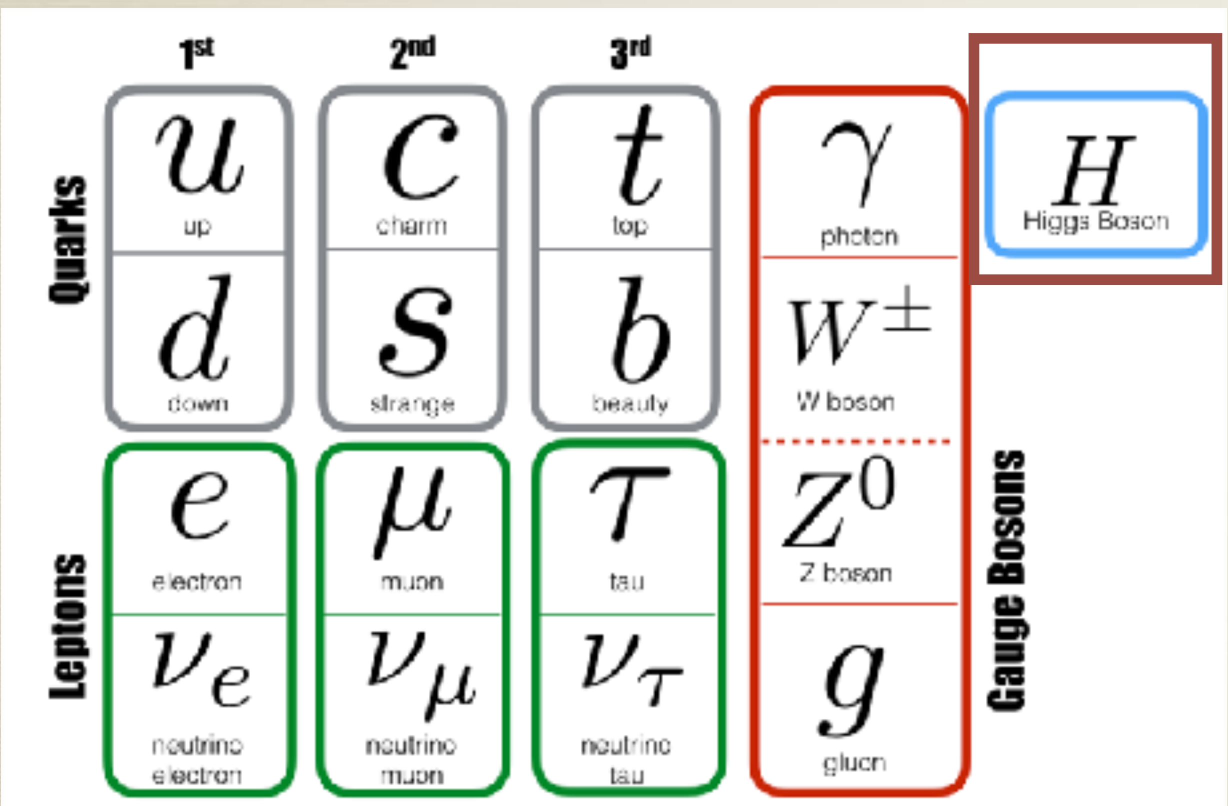
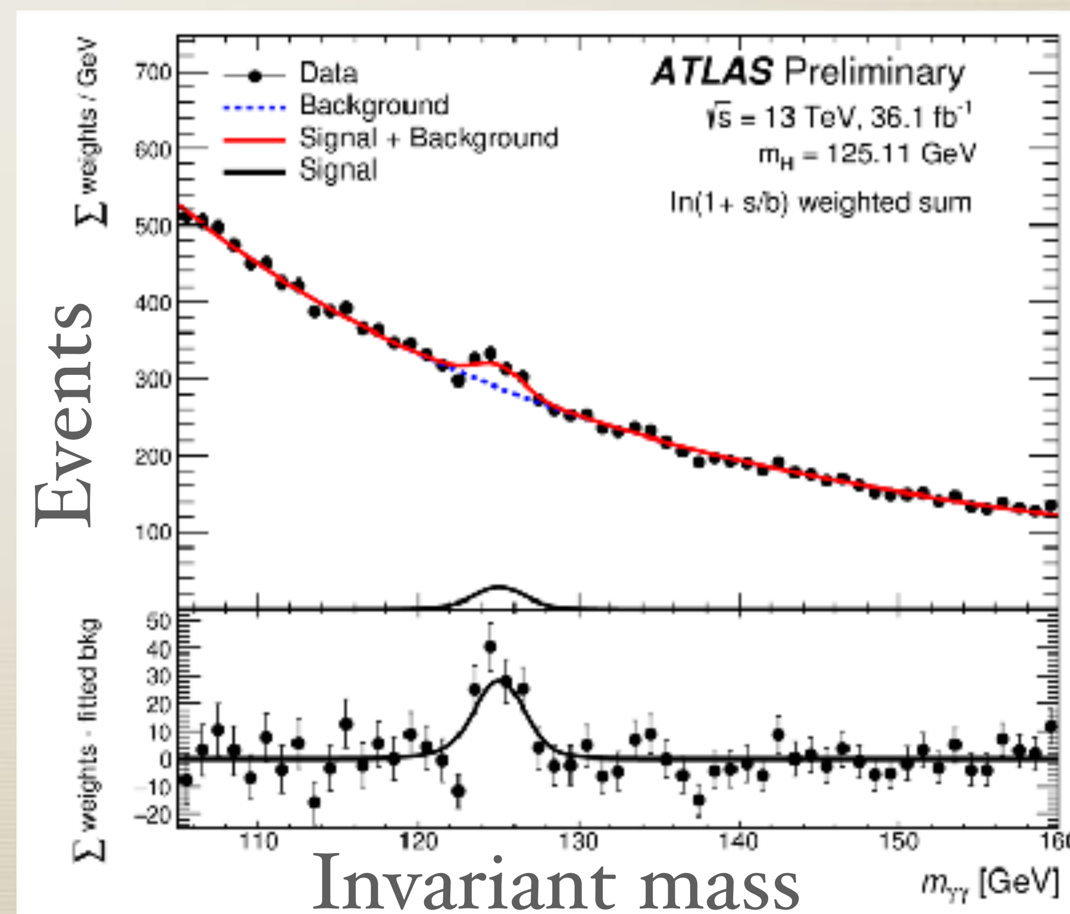


figure from www.physik.uzh.ch



Precise measurements

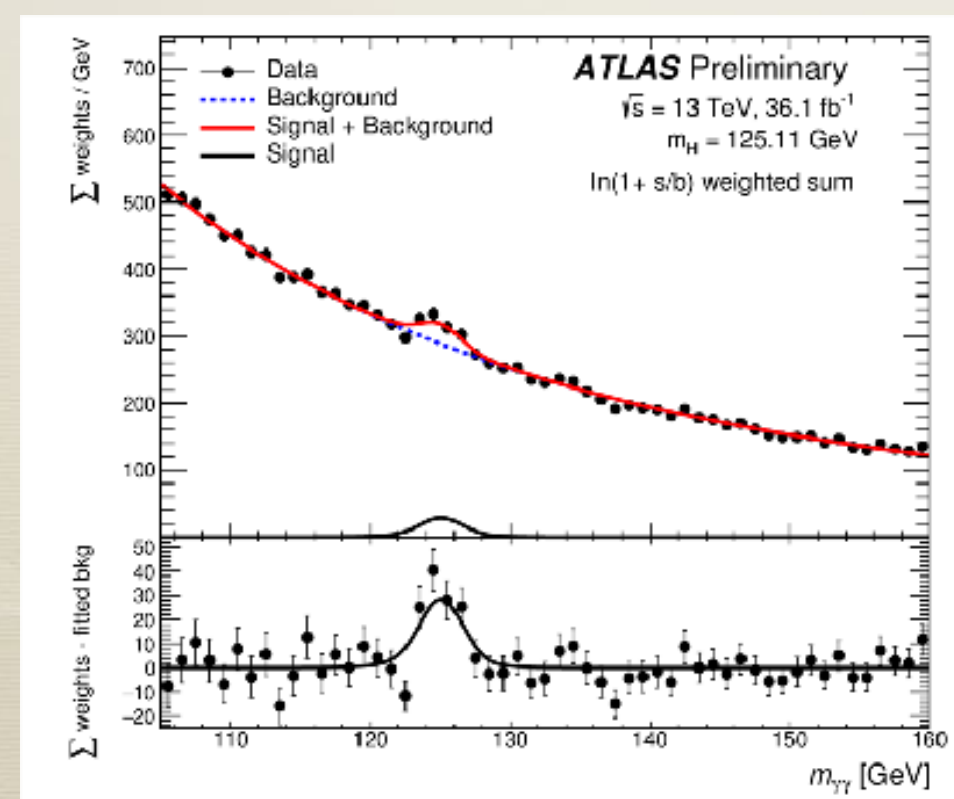
- Higgs mass $m_h = 125.18 \pm 0.16$ GeV

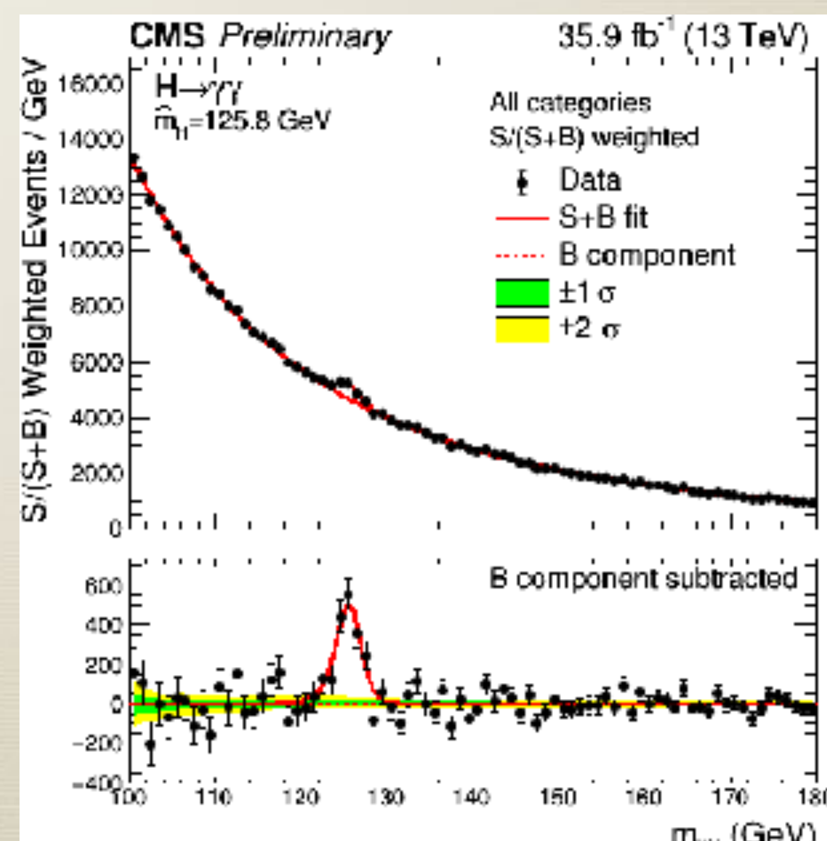
  (world average by PDG)

- Top quark mass

- Strong coupling constant

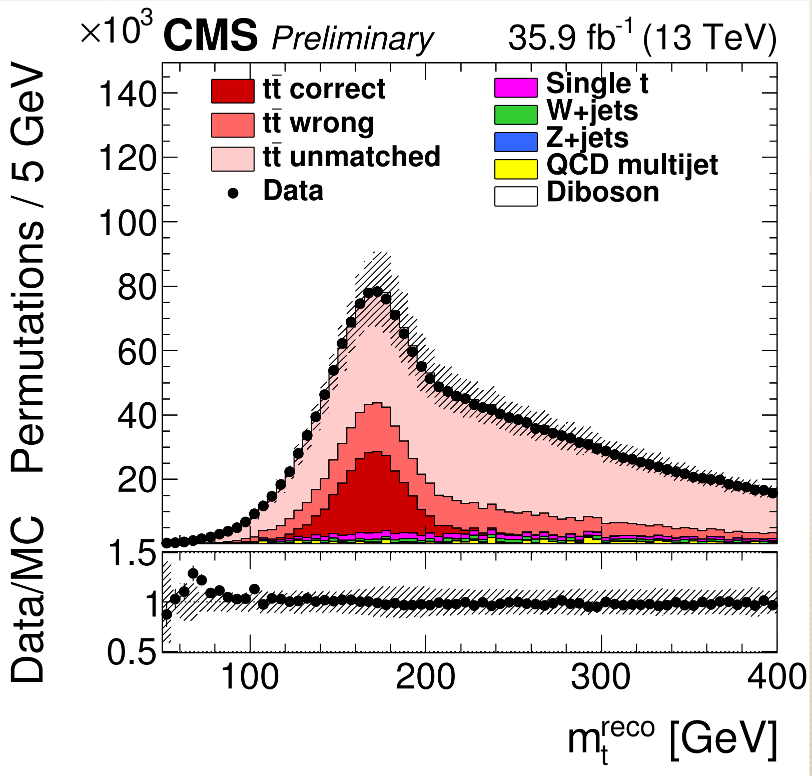
- ...

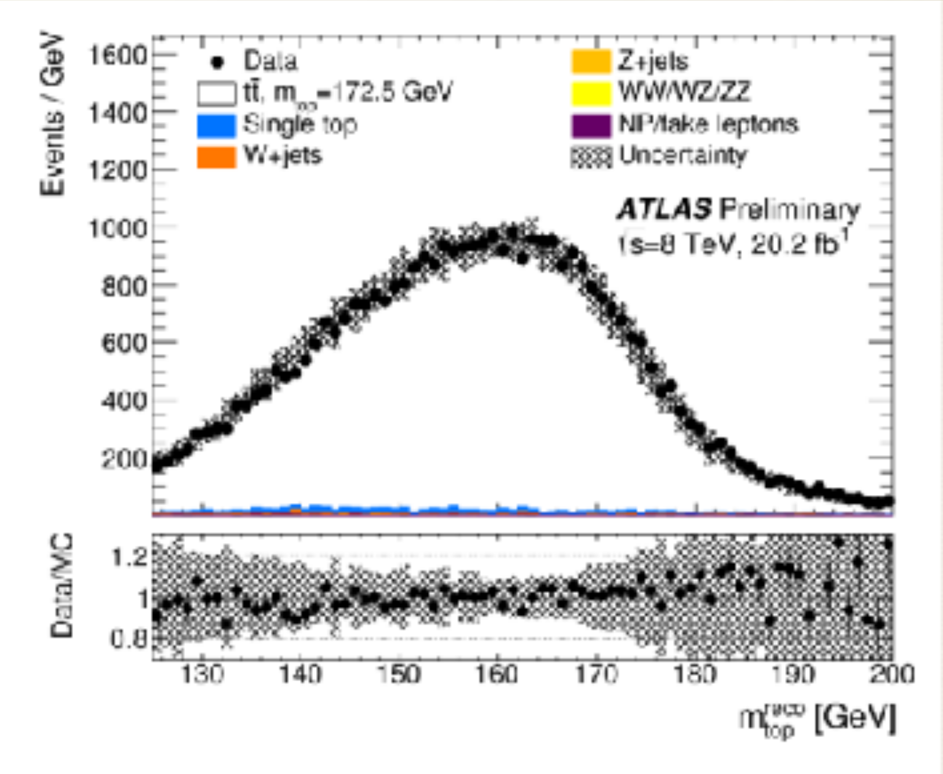




Precise measurements

* Higgs mass
* Top quark mass $m_t = 173.1 \pm 0.4$ GeV
  (world average by PDG)
* Strong coupling constant
* ...





Precise measurements

* Higgs mass
* Top quark mass
* Strong coupling constant $\alpha_s(m_Z) = 0.1184 \pm 0.0011$

(world average by PDG)

* ...

Lattice QCD,
decay of tau leptons,
deep inelastic scattering,
jet productions

Precise measurements

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

Can we learn something beyond the Standard Model ?

Precise measurement and new physics

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

New symmetry
(Higgs Parity)

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

Precise measurement and new physics

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

top quark yukawa
Higgs mass
strong coupling constant

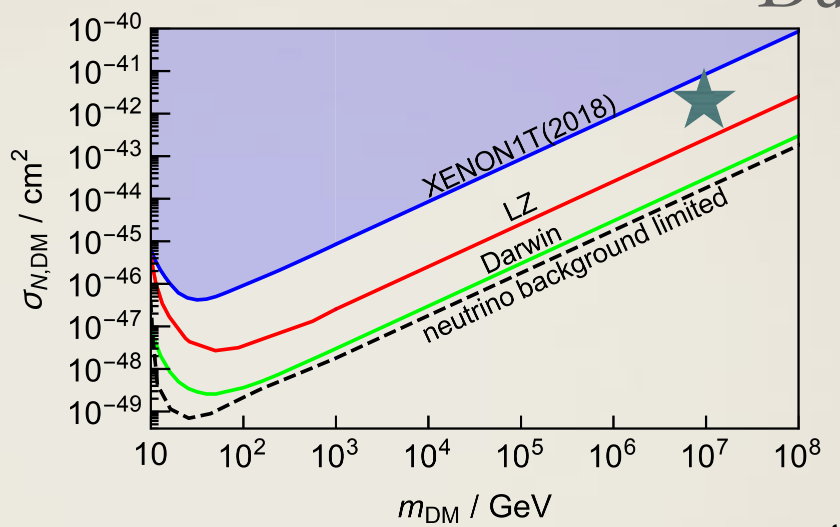
↕

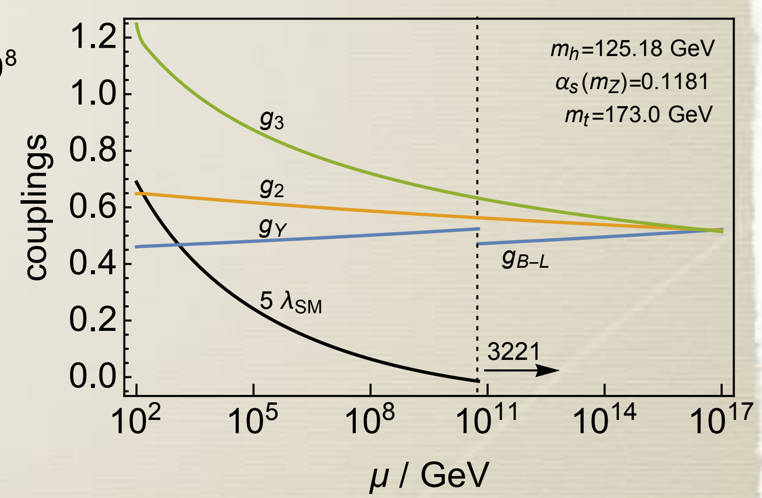
Higgs Parity
symmetry
breaking scale

Precise measurement and new physics

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

top quark yukawa
Higgs mass
strong coupling constant





Higgs Parity
symmetry
breaking scale

Experimental signatures

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

Outline

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

Introduction

Standard Model

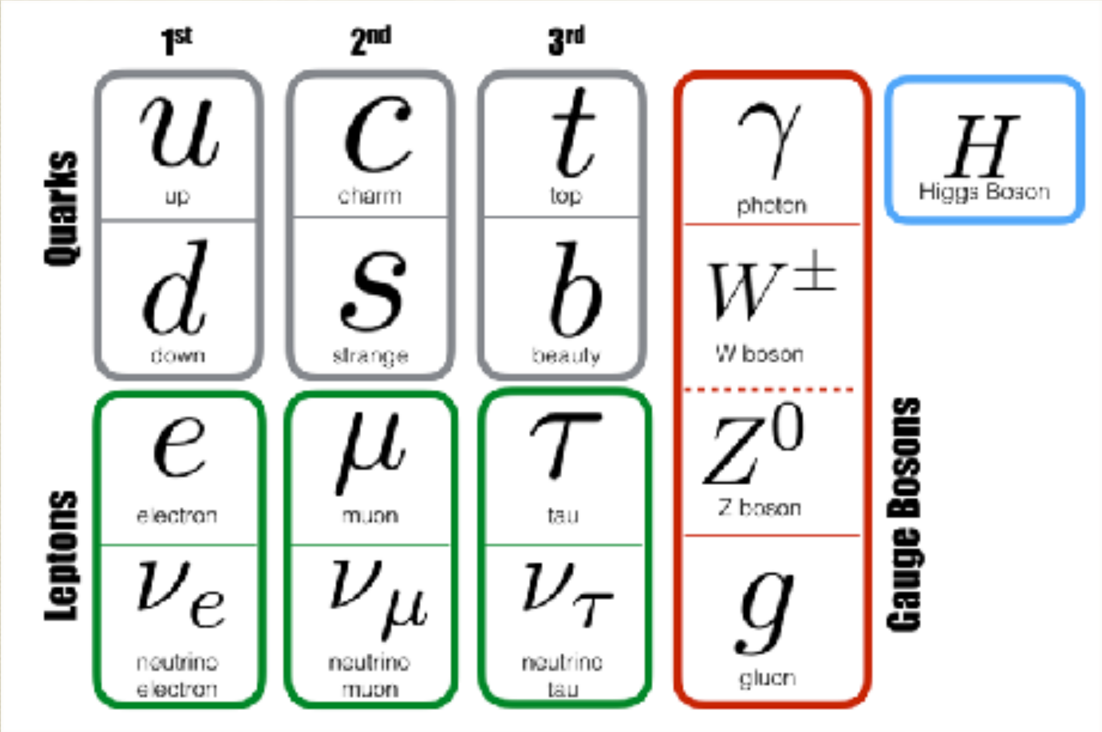
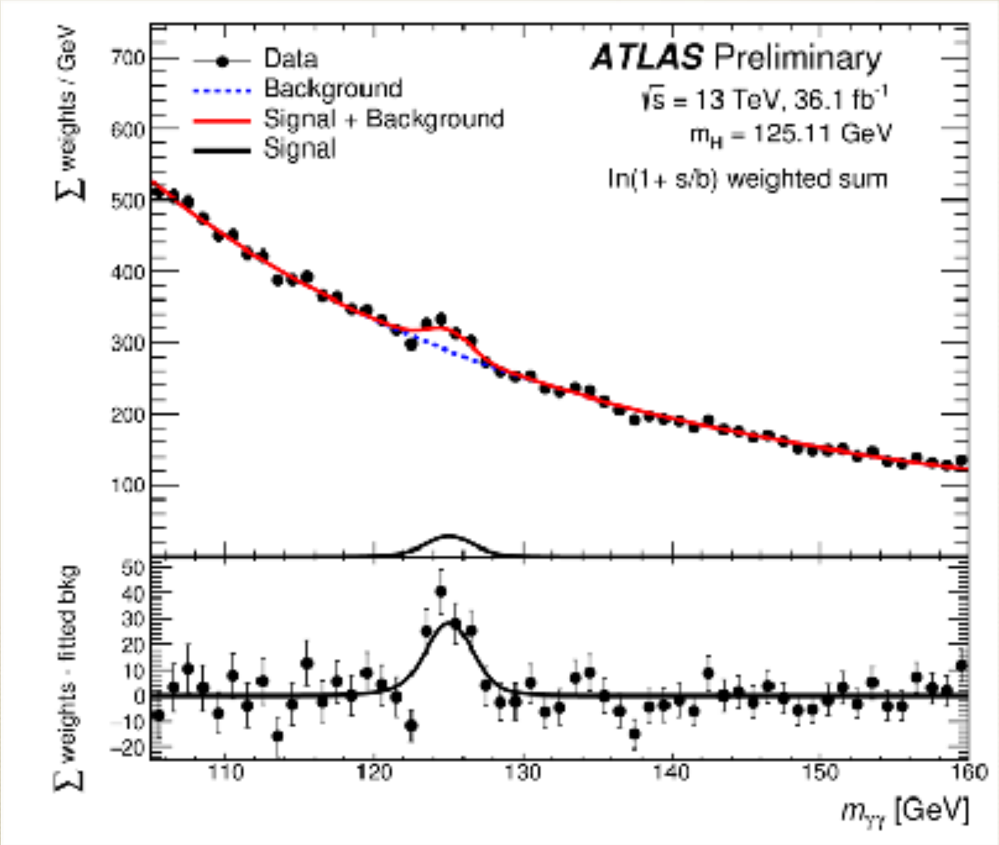


figure from www.physik.uzh.ch



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?

We are far away from the goal

* What is dark matter?
  Barbieri, Hall and KH (2016, 2017), KH, Lin and Lou (2016),
  Badziak, Cortona and KH (2019), ...
* How did cosmic inflation occur?
  KH, Ibe, Schmitz and Yanagida (2015),
  KH and Schmitz (2017), ...
* How was the baryon asymmetry of the universe created?
  KH, Kamada, Kawasaki, Mukaida and Yamada (2019),
  KH (2019), ...
* Why does QCD preserve CP symmetry?
  Co, Hall and KH (2017,2019), KH and Leedom (2017,2019), ...
* What sets the Higgs potential parameters?
  KH, Matsumoto, Nojiri and Tobioka (2011), Badziak and KH (2017), ...

KH and Yamada (2019)

Co and KH (2019)

We are far away from the goal

* What is dark matter?

  Barbieri, Hall and KH (2016, 2017), KH, Lin and Lou (2016), Badziak, Cortona and KH (2019), ...

* How did cosmic inflation occur?

  KH, Ibe, Schmitz and Yanagida (2015), KH and Schmitz (2017), ...

* How was the baryon asymmetry of the universe created?

  KH, Kamada, Kawasaki, Mukaida and Yamada (2019), KH (2019), ...

* Why does QCD preserve CP symmetry?

  Co, Hall and KH (2017,2019), KH and Leedom (2017,2019), ...

* What sets the Higgs potential parameters?

  KH, Matsumoto, Nojiri and Tobioka (2011), Badziak and KH (2017), ...

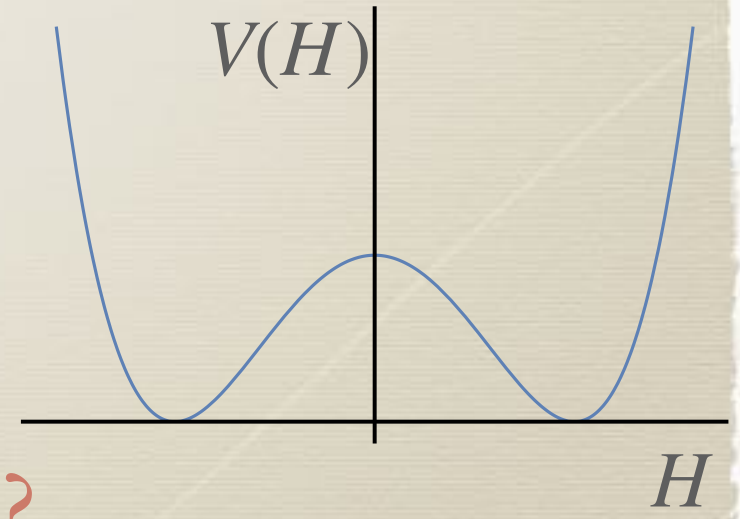
KH and Yamada (2019)

Co and KH (2019)

baryon asymmetry from QCD axion

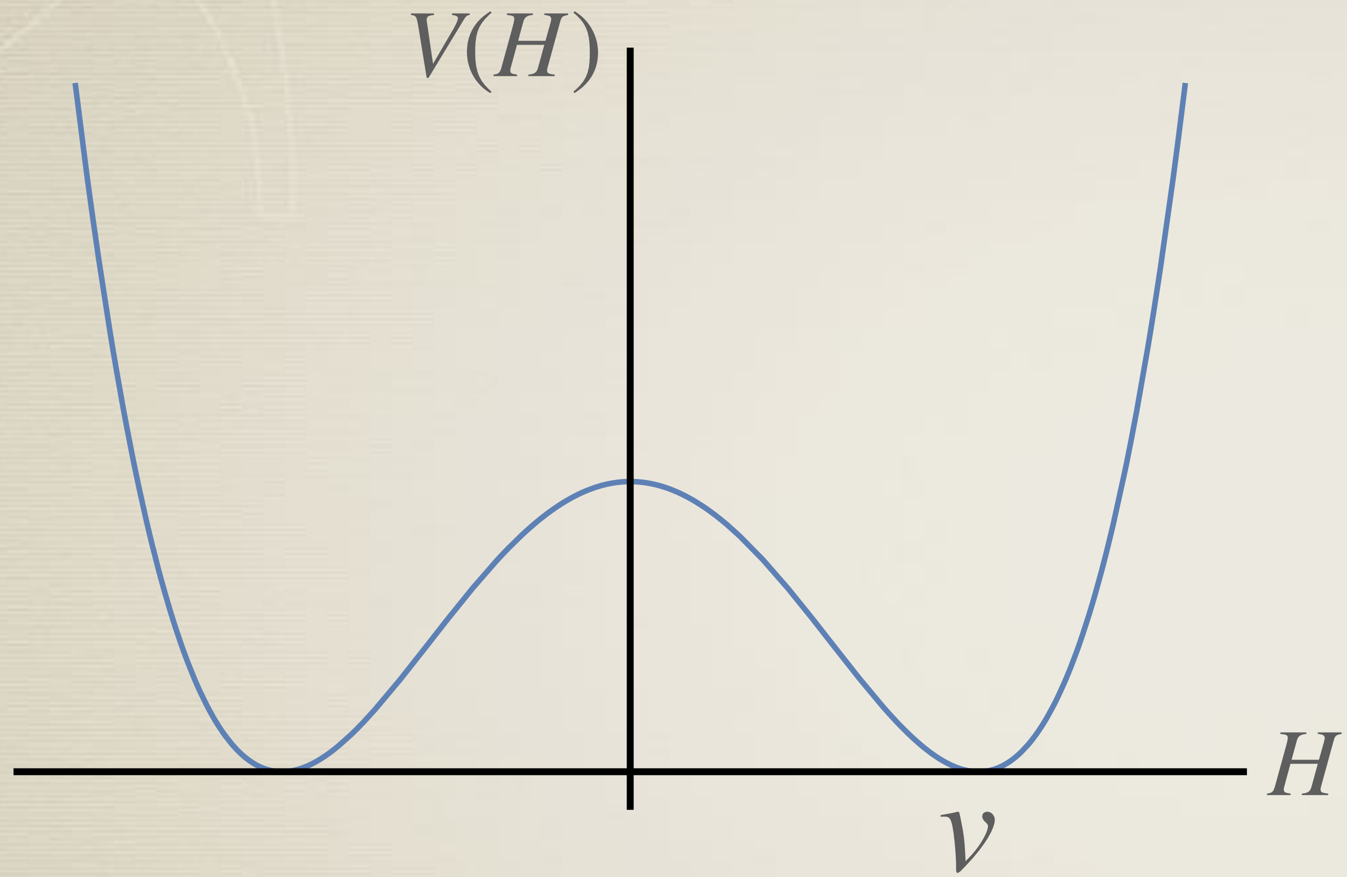
We are far away from the goal

* 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?



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

Higgs potential



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

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?

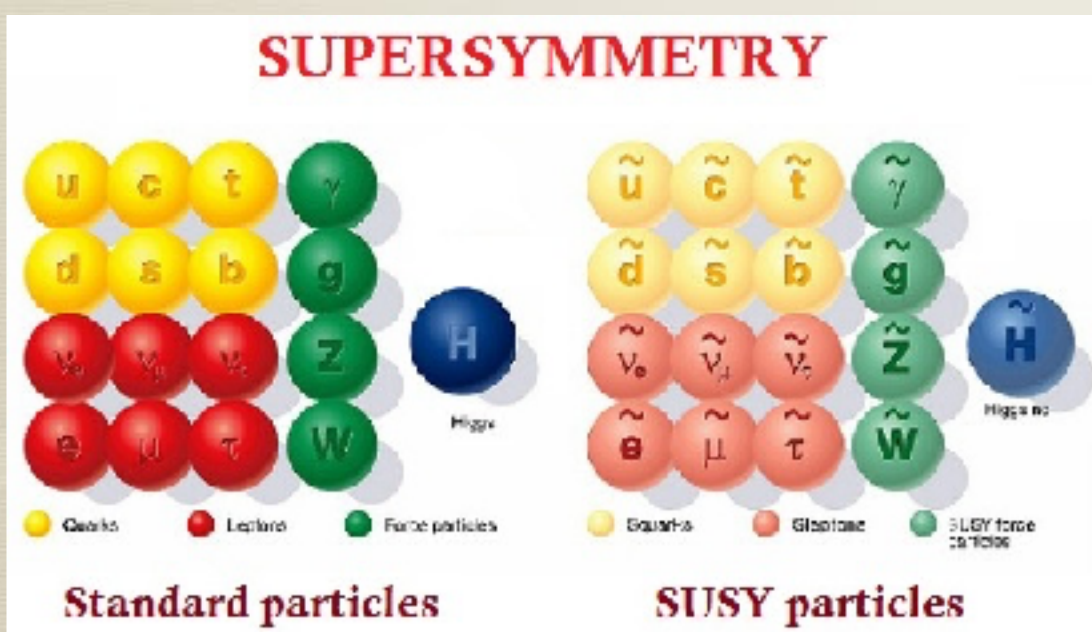
Ex. Supersymmetry and its breaking

Maiani (1979), Veltman (1979), Witten (1981)

$$m_H \sim m_{\mathrm{SUSY-breaking}}$$

$\propto$ new confining scale << Planck scale

$$\propto \exp\left(-\frac{8\pi^2}{g^2}\right)$$

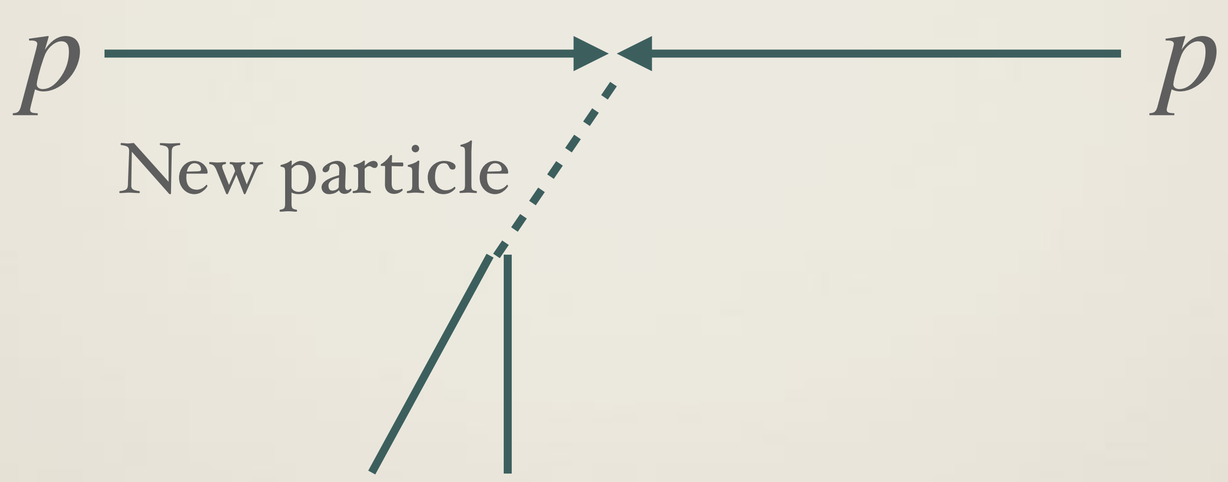


CERN & IES de SAR

predict new particles with masses around 100 GeV

100 GeV scale new physics

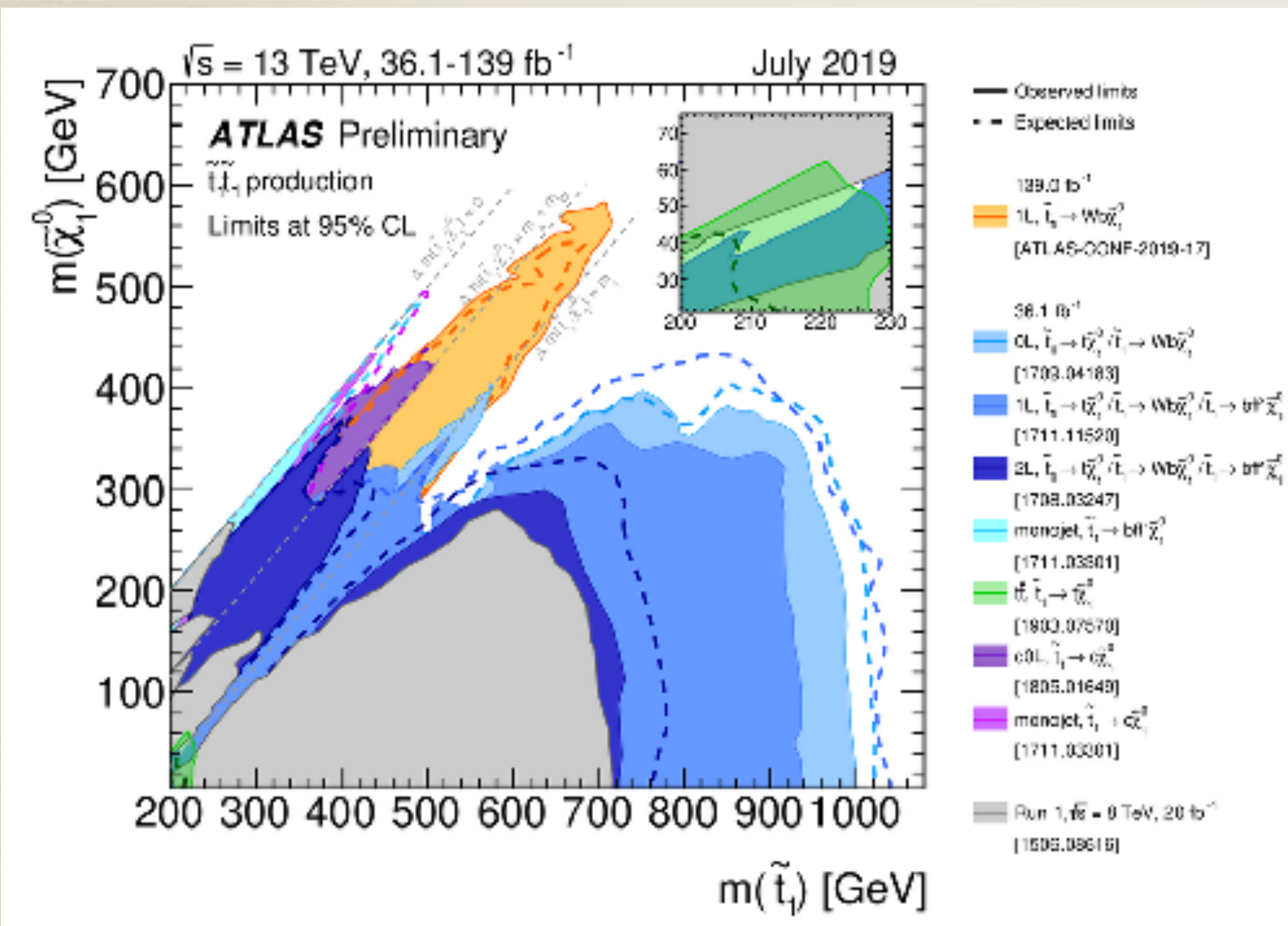
Searches for new particles at colliders

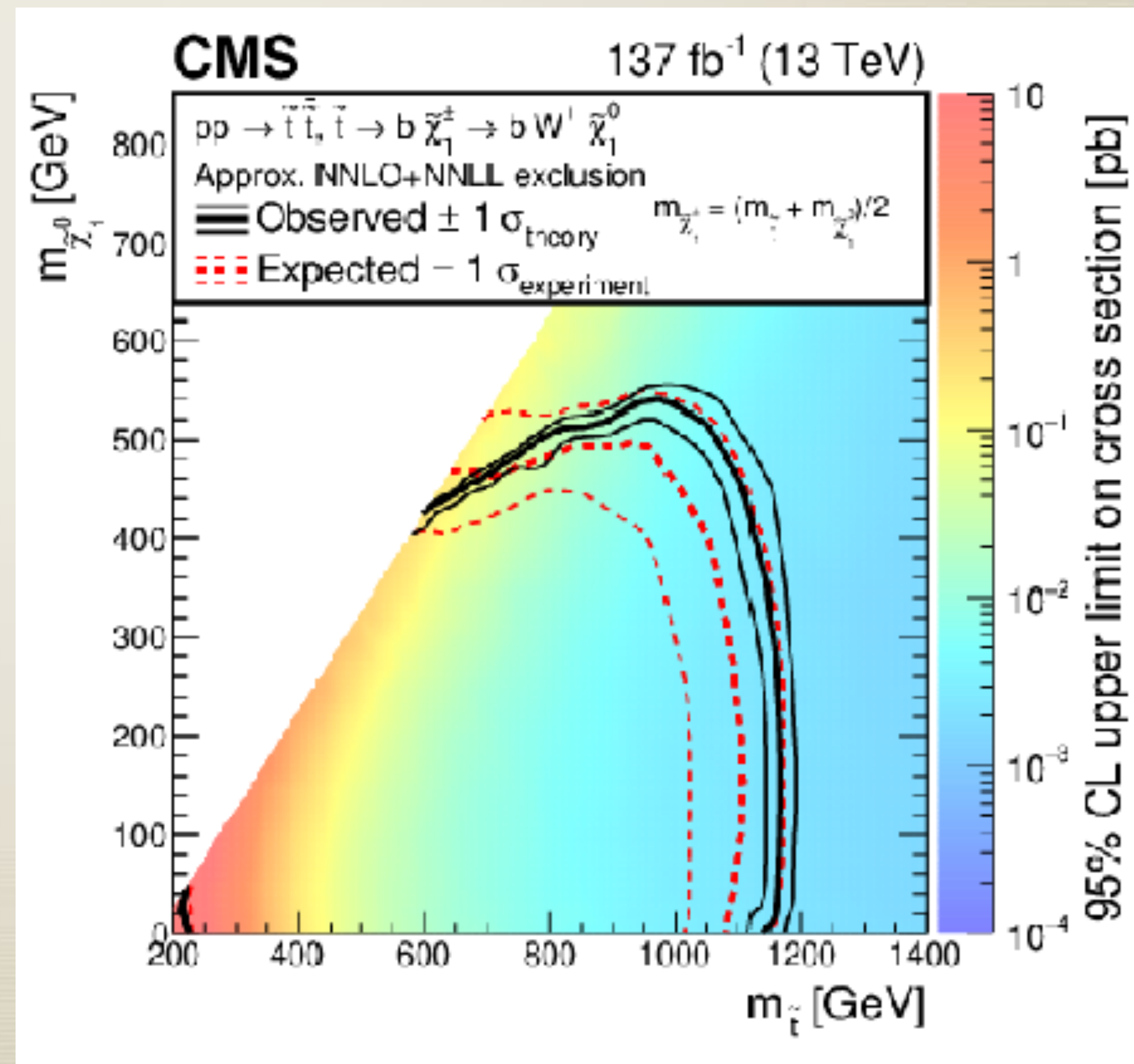


100 GeV scale new physics

New particles have not been found so far

Ex. Constraints on scalar top partner in supersymmetric theories





What to do?

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

We should keep trying to explain the small Higgs mass and seek signatures of the explanation.

* Non-minimal extensions, e.g. Twin Higgs

Chacko, Goh and Harnik (2006), Falkowski, Pokorski and Schmaltz (2006), Chang, Hall and Weiner (2006), Geller and Telem (2015), Barbieri, Greco, Rattazzi and Wulzer (2015), KH and Badziak (2017,2018), Barbieri, Hall and KH (2017,2018)

* Dynamical relaxation of the Higgs mass (Relaxion)

Graham, Kaplan and Rajendran (2015), Espinosa et.al. (2015), Hook and Marques-Tavares (2016), Evans, Gherghetta, Nagata and Thomas (2016), Ibe, Shoji and Suzuki (2019), ...

We should also pursue complementary directions

Fine-tuned Higgs mass?

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

The Higgs mass may not be a guiding principle
to look for new physics

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

Fine-tuned Higgs mass?

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

The Higgs mass may not be a guiding principle
to look for new physics

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

Ex. Dark matter and/or gauge coupling unification:

Arkani-Hamed and Dimopoulos (2004), Wells (2004), Hall and Nomura (2012),
Ibe and Yanagida (2012), Arvanitaki, Craig, Dimopoulos and Villadoro (2012),
Evans, Ibe, Olive and Yanagida (2013), Barnard, Gherghetta, Ray and Spray (2014)

Fine-tuned Higgs mass?

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

The Higgs mass may not be a guiding principle to look for new physics

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

Ex. Dark matter and/or gauge coupling unification:

Arkani-Hamed and Dimopoulos (2004), Wells (2004), Hall and Nomura (2012), Ibe and Yanagida (2012), Arvanitaki, Craig, Dimopoulos and Villadoro (2012), Evans, Ibe, Olive and Yanagida (2013), Barnard, Gherghetta, Ray and Spray (2014)

Ex. Multiverse and anthropic selection

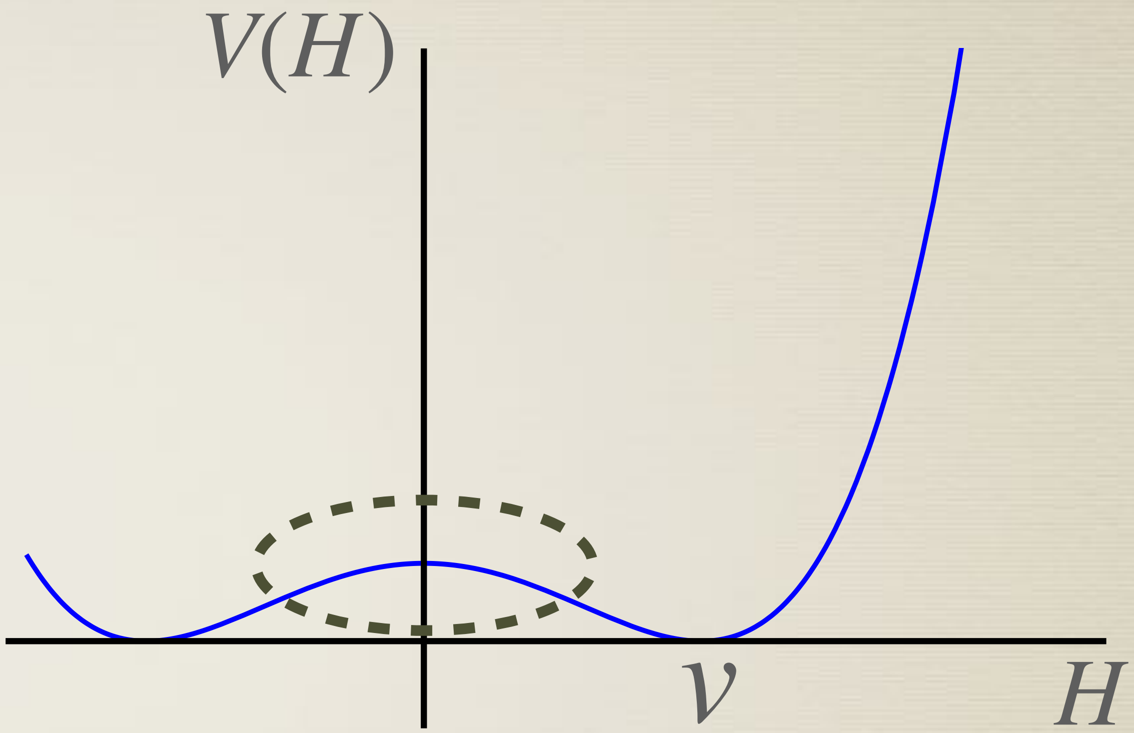
There may be multiple universes with different parameters. If the small Higgs mass is required to admit human beings, what we observe is a small Higgs mass

Weinberg (1987), Susskind (2003), Agrawal, Barr, Donoghue and Seckel (1998), Clavelli and White (2006), Hall, Pinner and Ruderman (2014), ...

Higgs mass

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

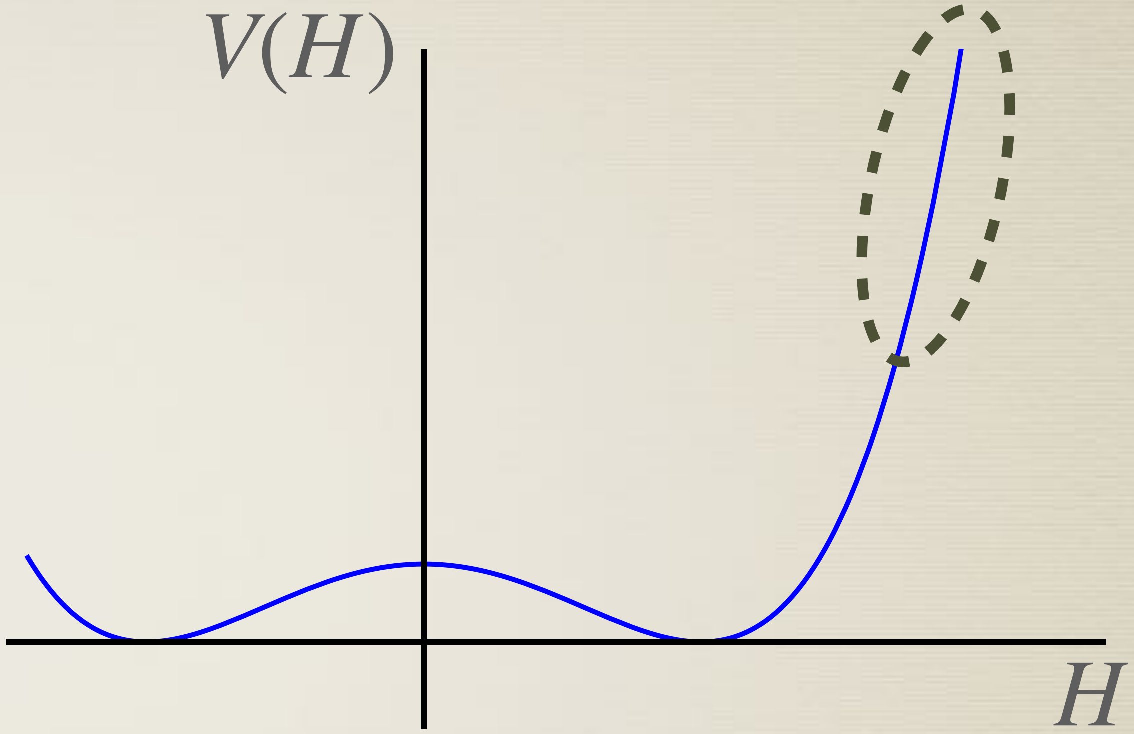
$(173\mathrm{GeV})^2$



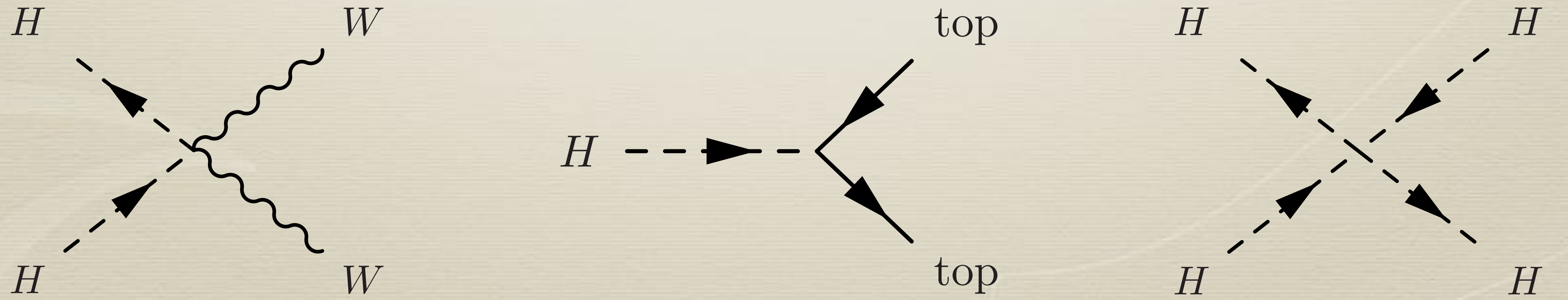
Higgs quartic coupling?

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

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



Let us take a closer look at the quartic coupling, assuming that the SM is valid up to high energy scales, including quantum corrections

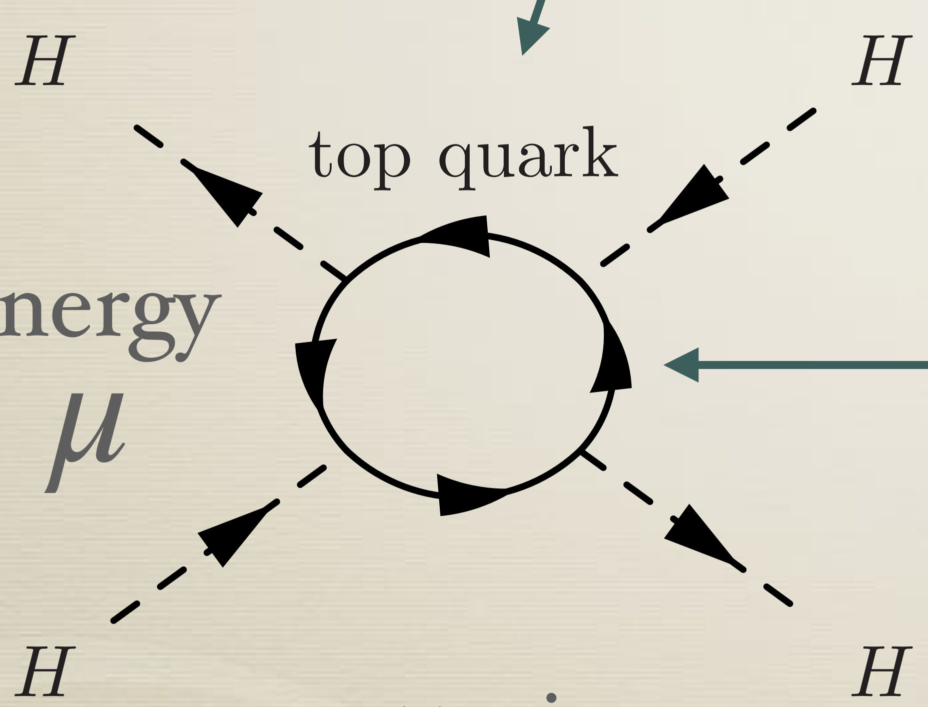


Energy-dependent quartic coupling

perturbation theory

$$\Delta\lambda_{\text{SM}} \sim \sum_i < HH | i > < i | HH >$$

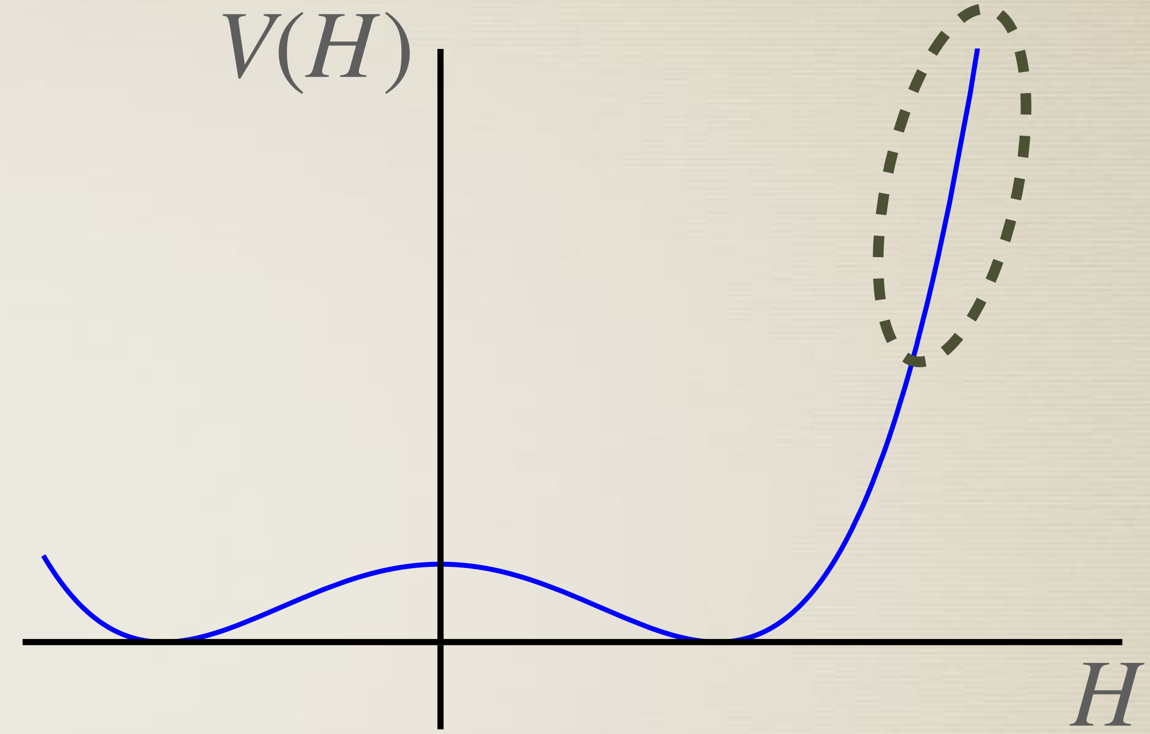
sum over intermediate states



energy

μ

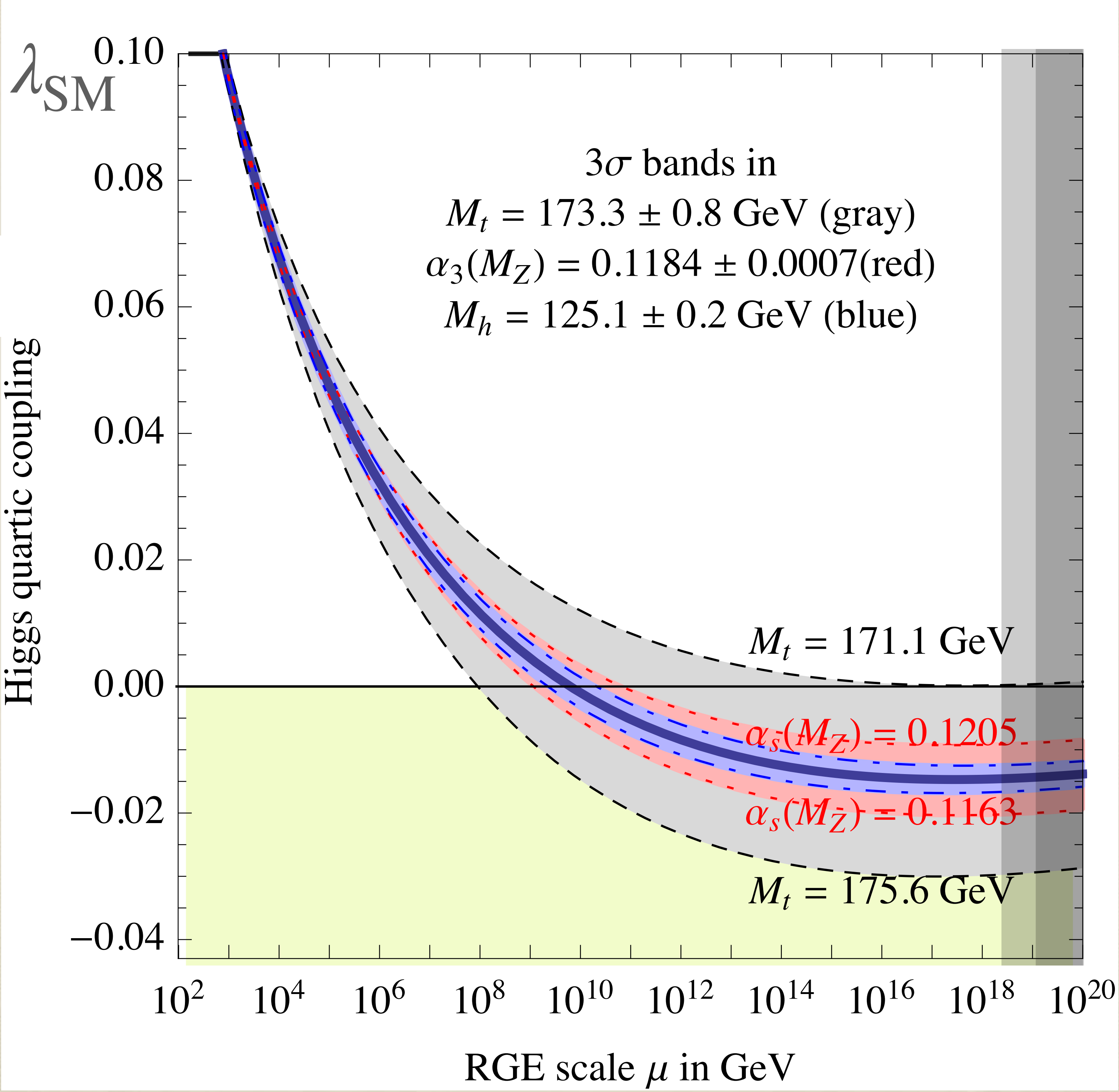
scattering



Intermediate states depend on energy μ

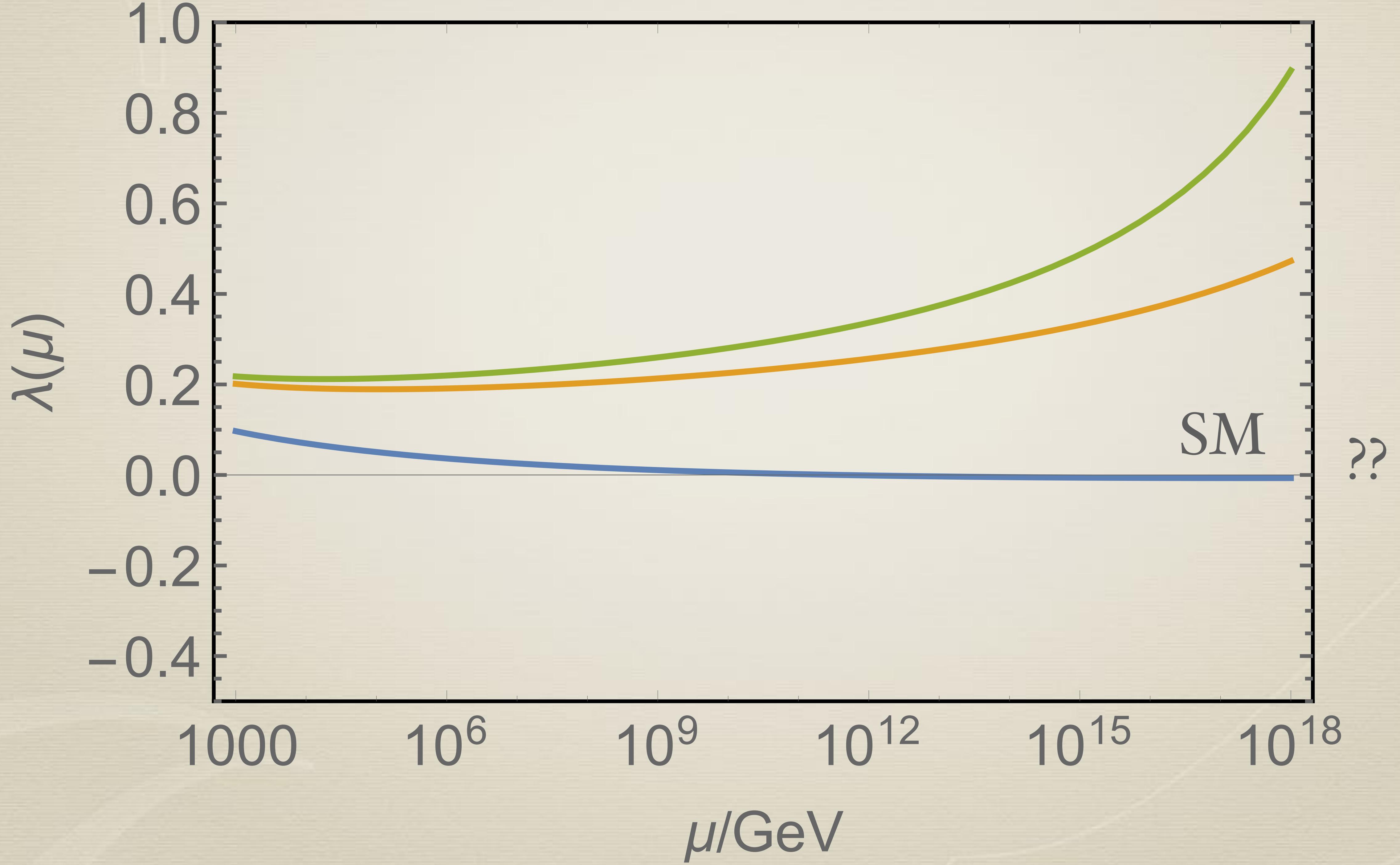
energy-dependent coupling

Small quartic coupling

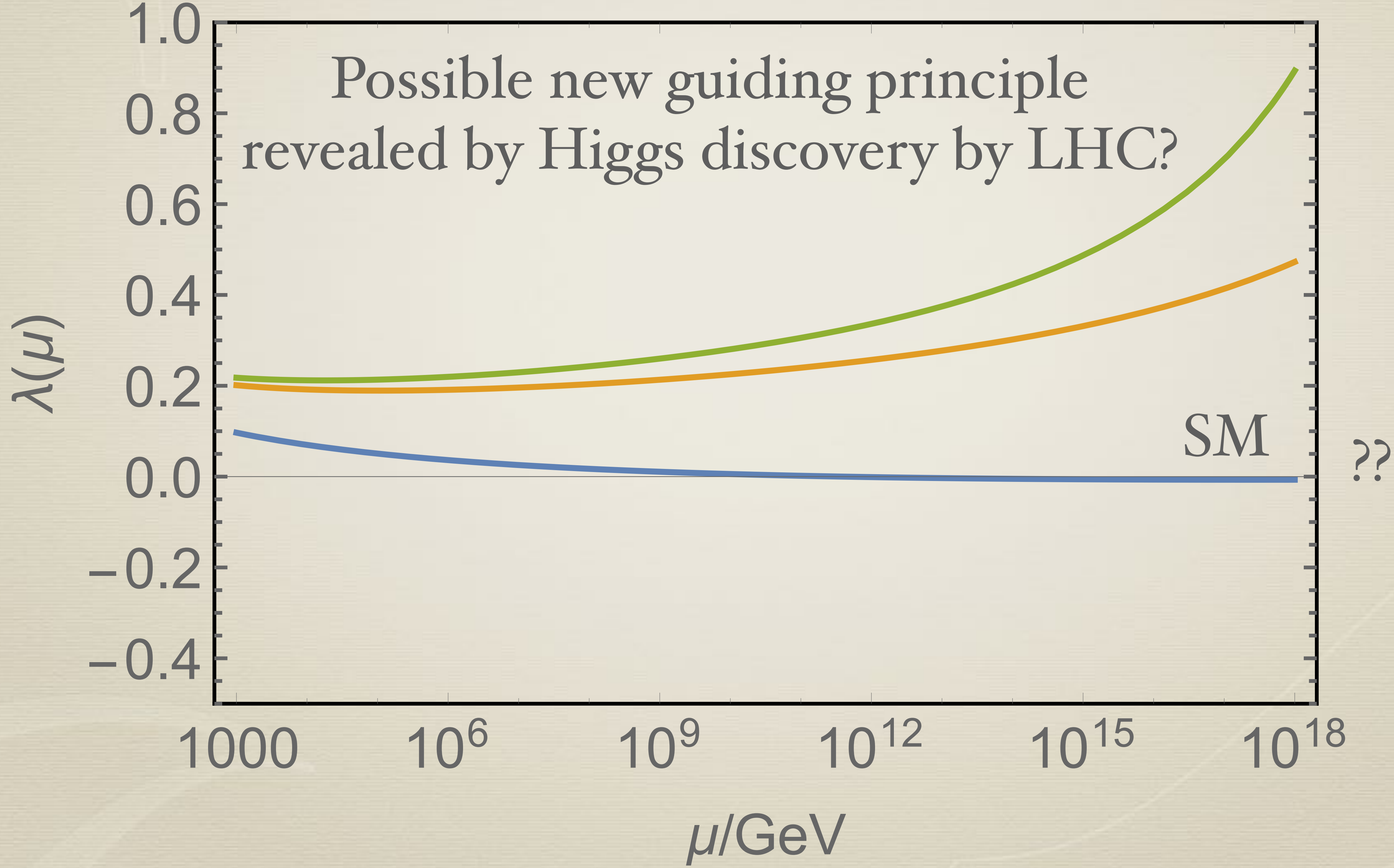


Buttazzo et.al (2013)

Small quartic coupling

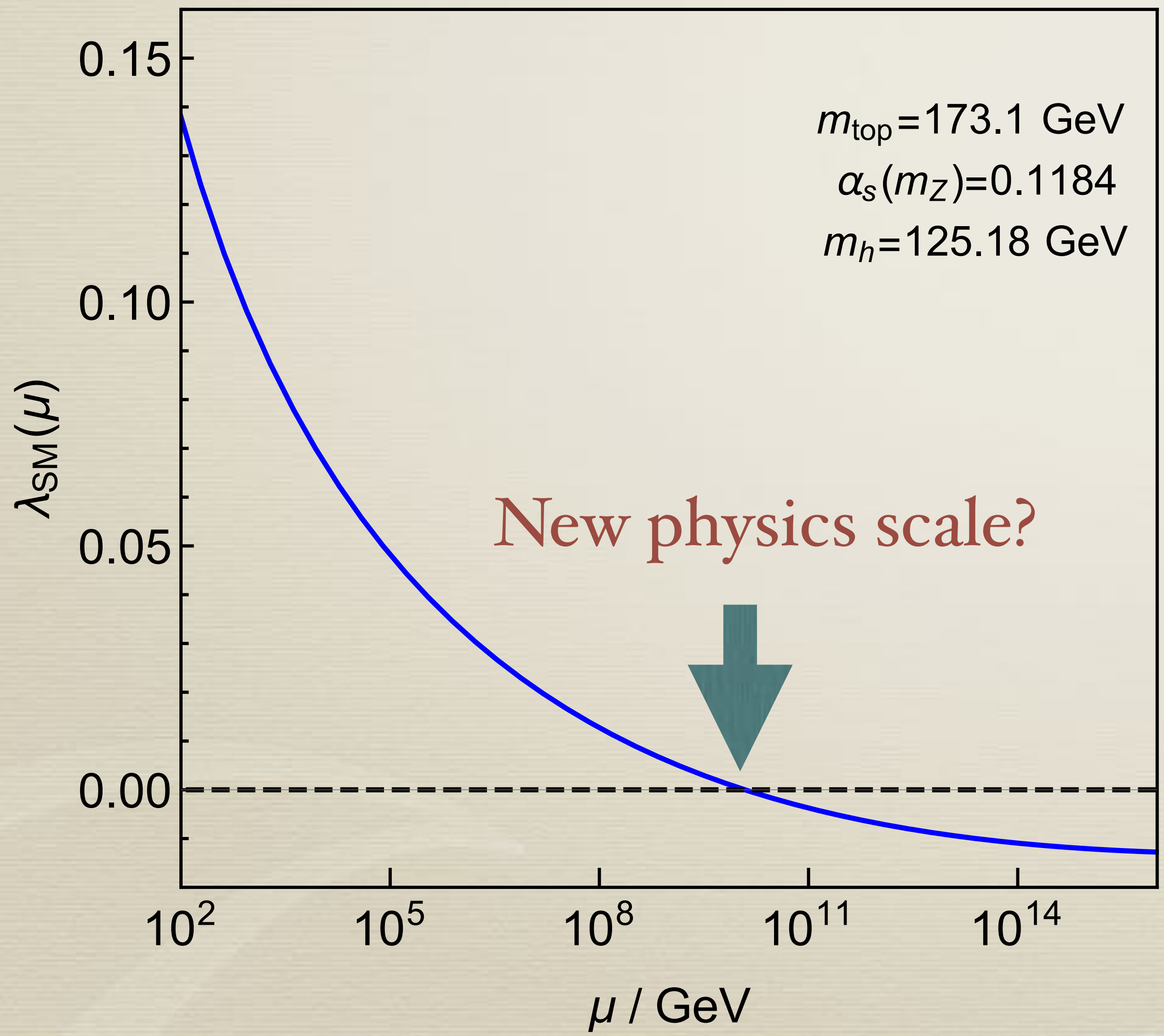


Small quartic coupling



New physics?

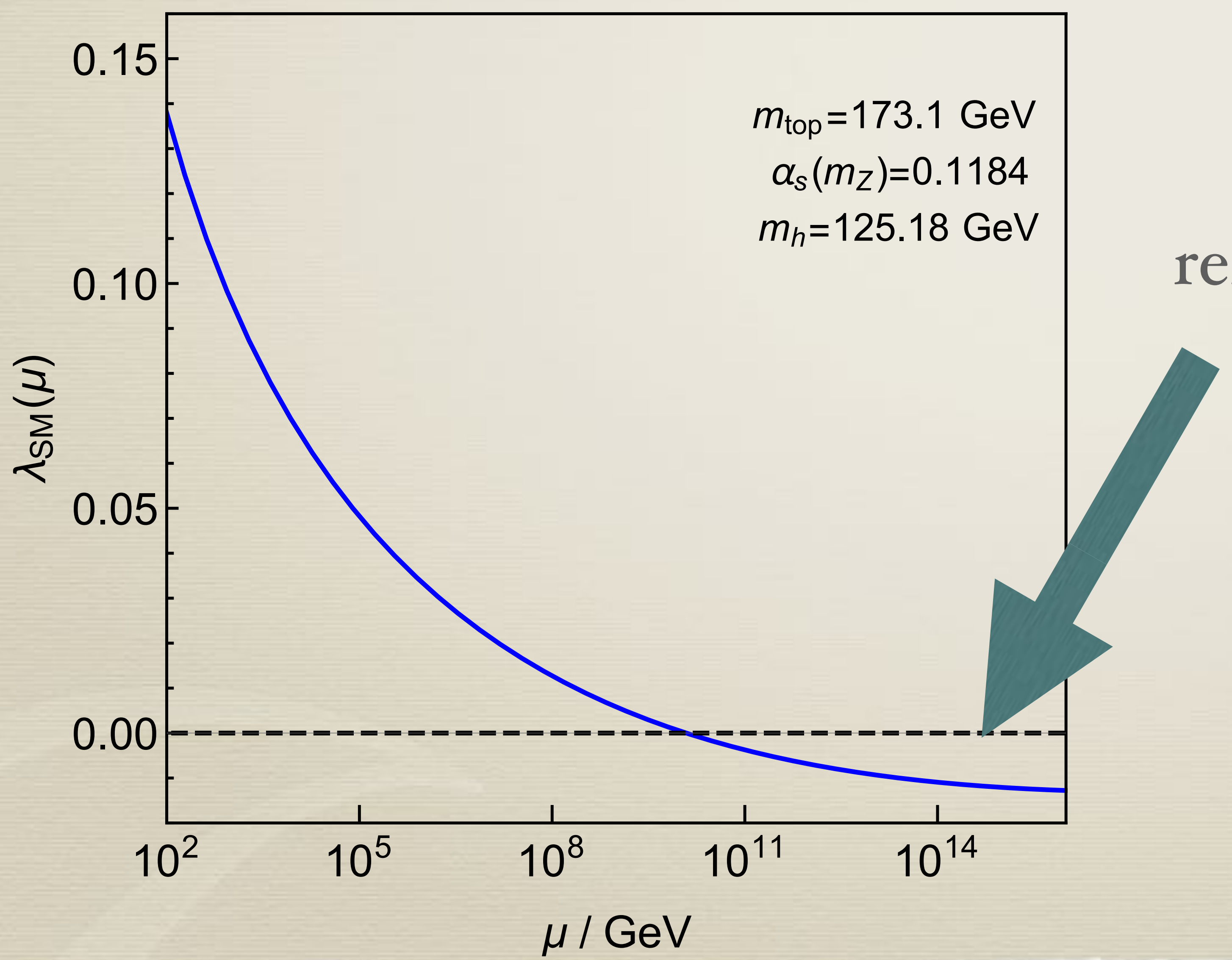
Conjecture : some new physics which couples to Higgs sets $\lambda_{\rm SM} \simeq 0$ at a high energy scale



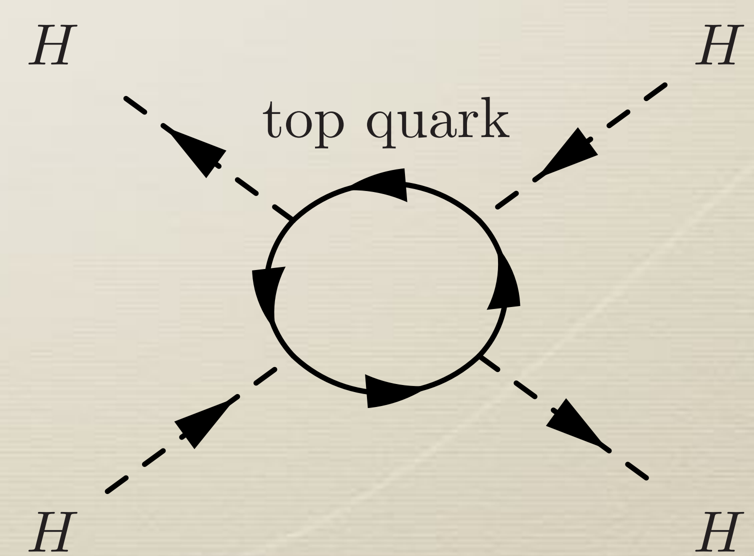
PQ symmetry? Redi and Strumia (2012)
Supersymmetry? Hall and Nomura (2013), Ibe, Matsumoto and Yanagida (2013)

New physics?

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



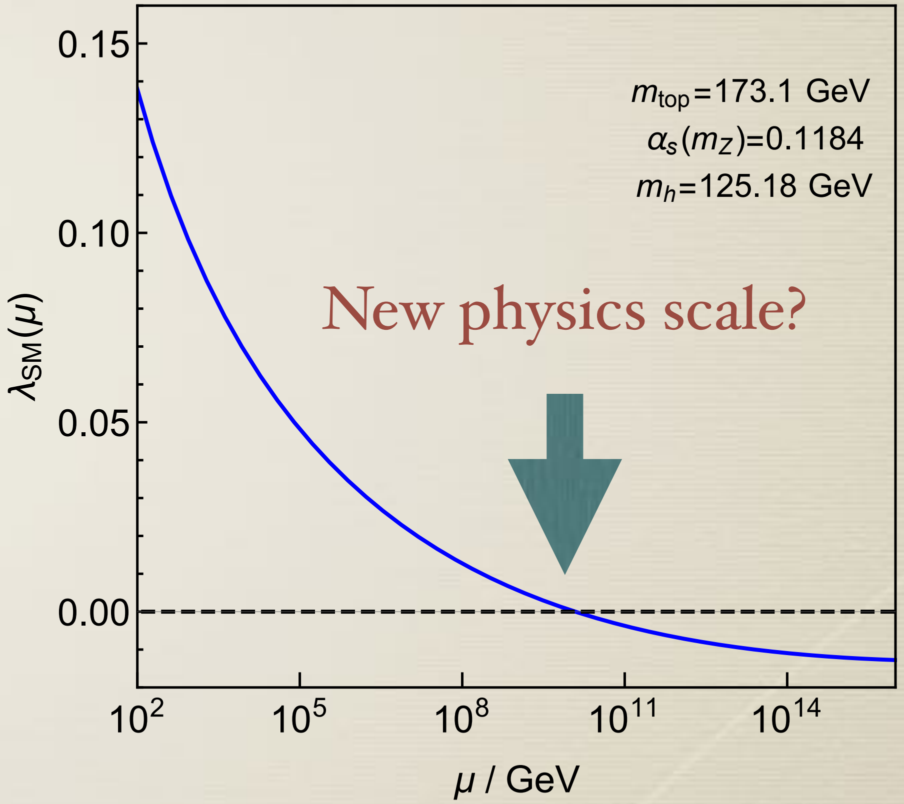
quartic coupling assuming SM remains small due to small yukawa coupling at high energy



Precise measurement and new physics?

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

top quark yukawa
Higgs mass
strong coupling constant

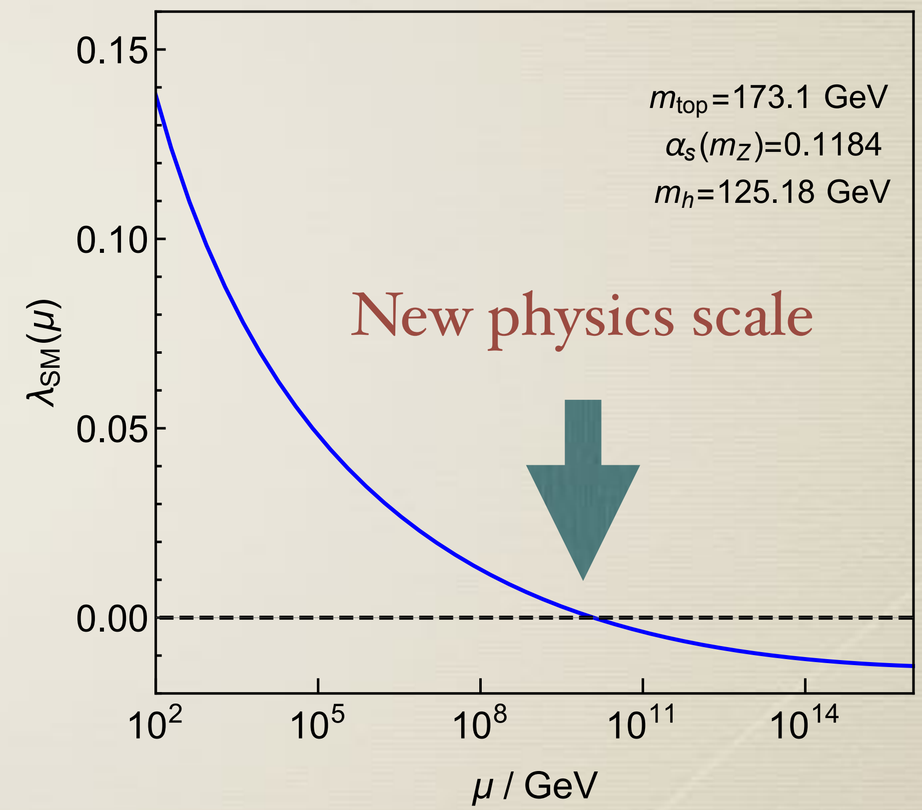


scale of the new physics ⟷ Experimental signatures?

Precise measurement and new physics

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

top quark yukawa
Higgs mass
strong coupling constant



New symmetry
(Higgs Parity)
breaking scale

Experimental signatures

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

Outline

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

Z_2 symmetry

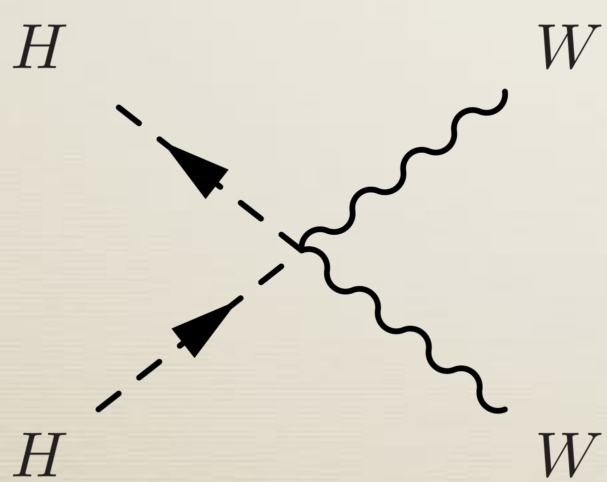
Higgs ⟷ Higgs'

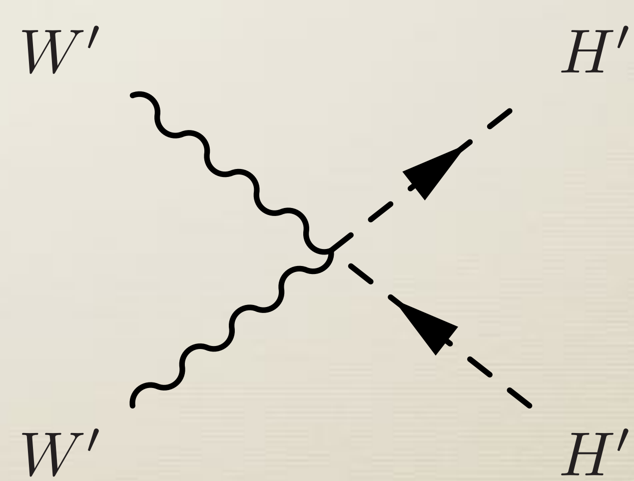
H ⟷ H'

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'

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

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

$H \leftrightarrow H'$

$W \leftrightarrow W'$

mass $\propto\ < H >$ $\quad q, L \leftrightarrow q', L'$ $\quad$ mass $\propto\ < H' >$

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

unbroken Z2 is experimentally excluded

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

HP symmetry breaking scale

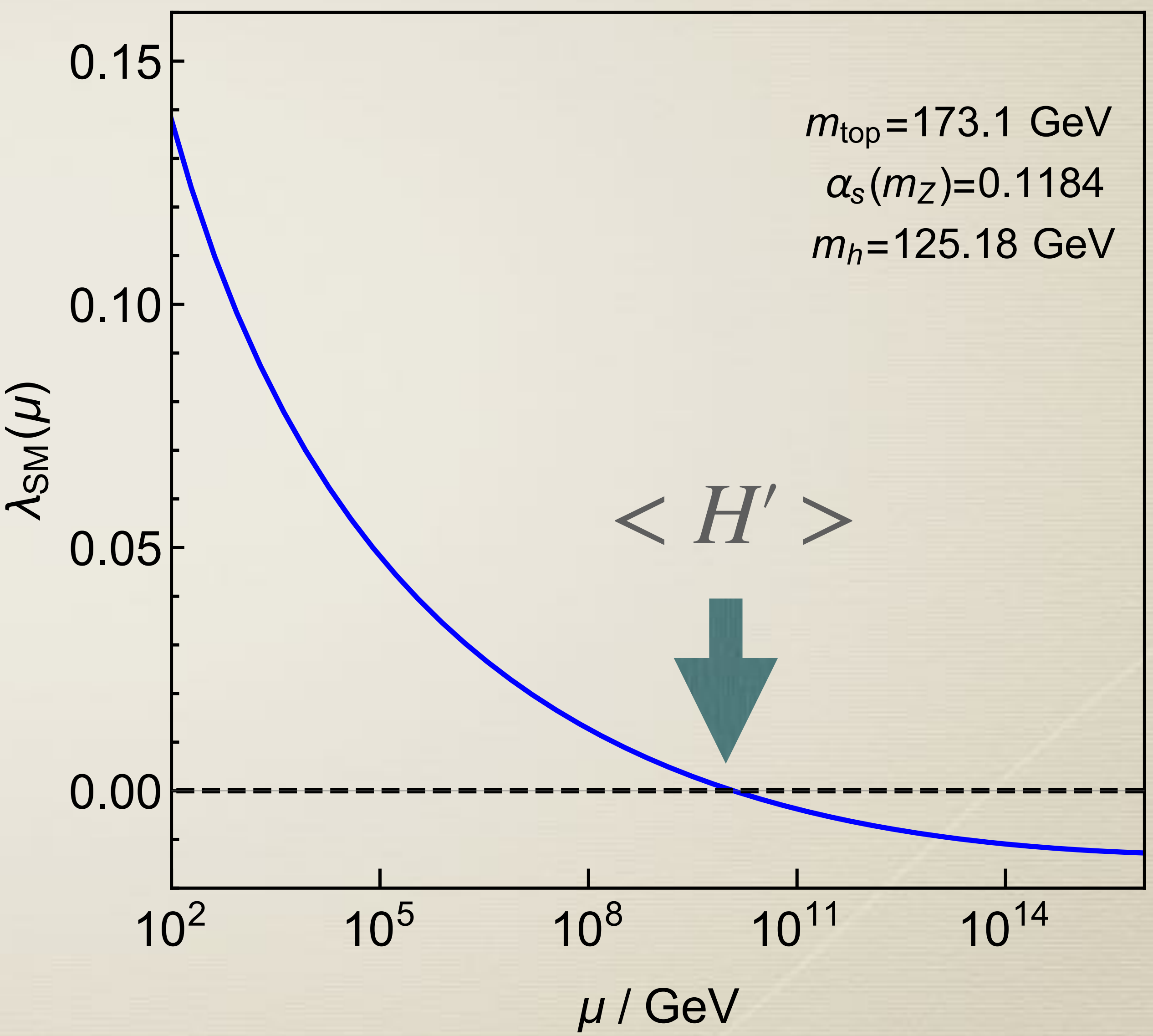
I will show that

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

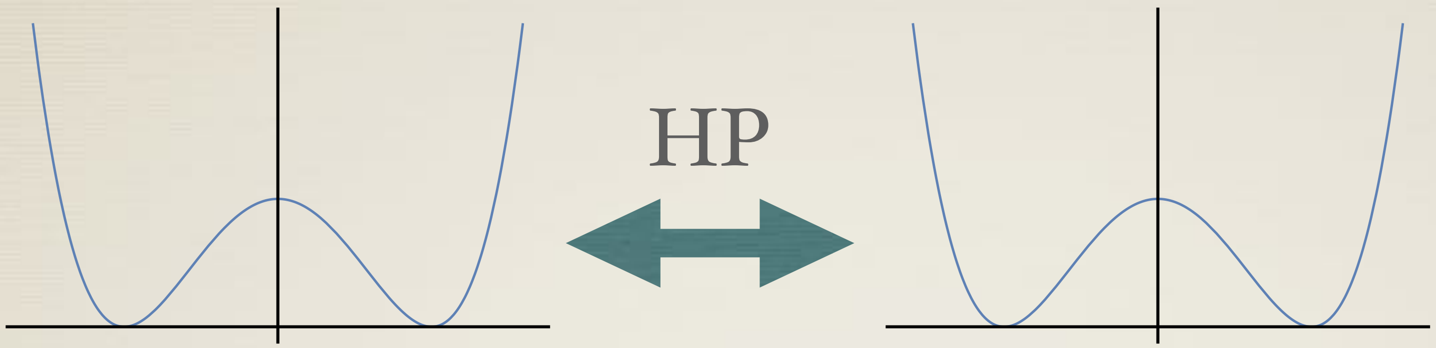
SM parameters

prediction

Higgs Parity
symmetry breaking scale



Higgs potential

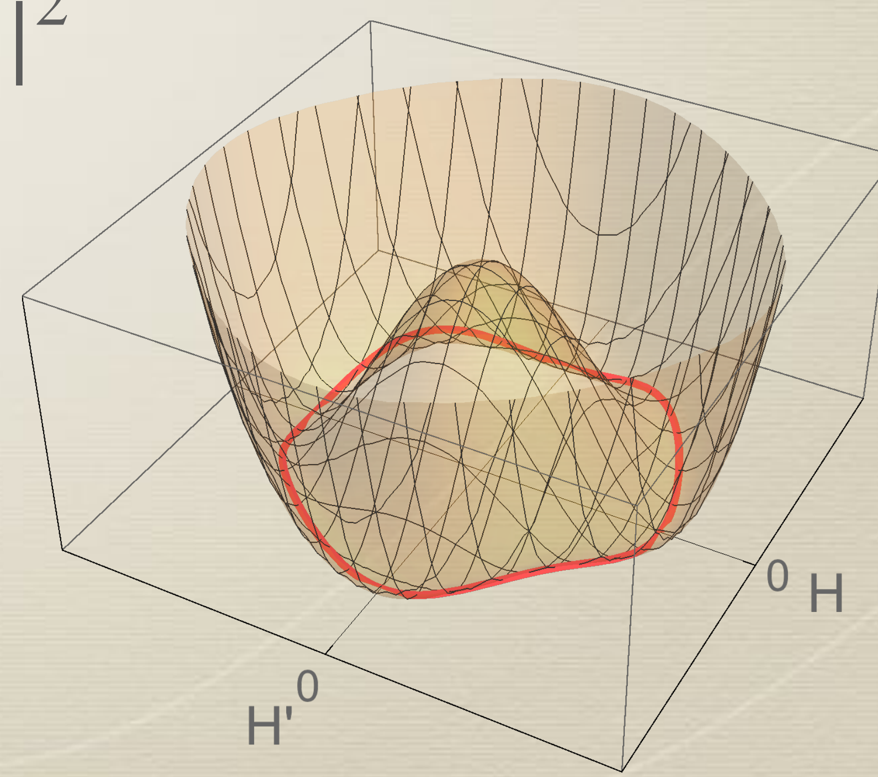


$$V = \left(\lambda |H|^4 - m^2 |H|^2\right) + \left(\lambda |H'|^4 - m^2 |H'|^2\right) + \tilde{y}\, |H|^2 |H'|^2$$

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

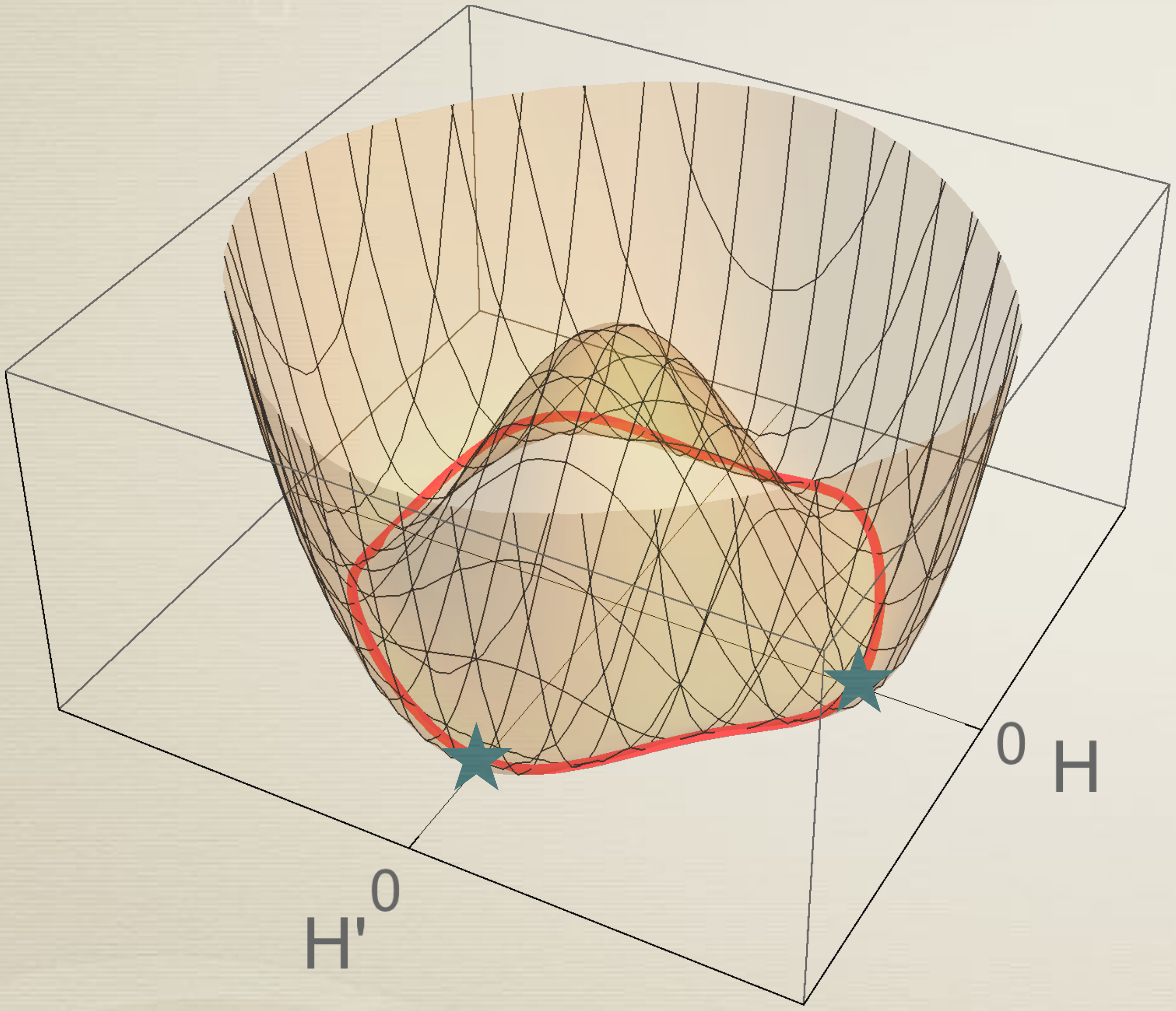
Can we find the minimum with

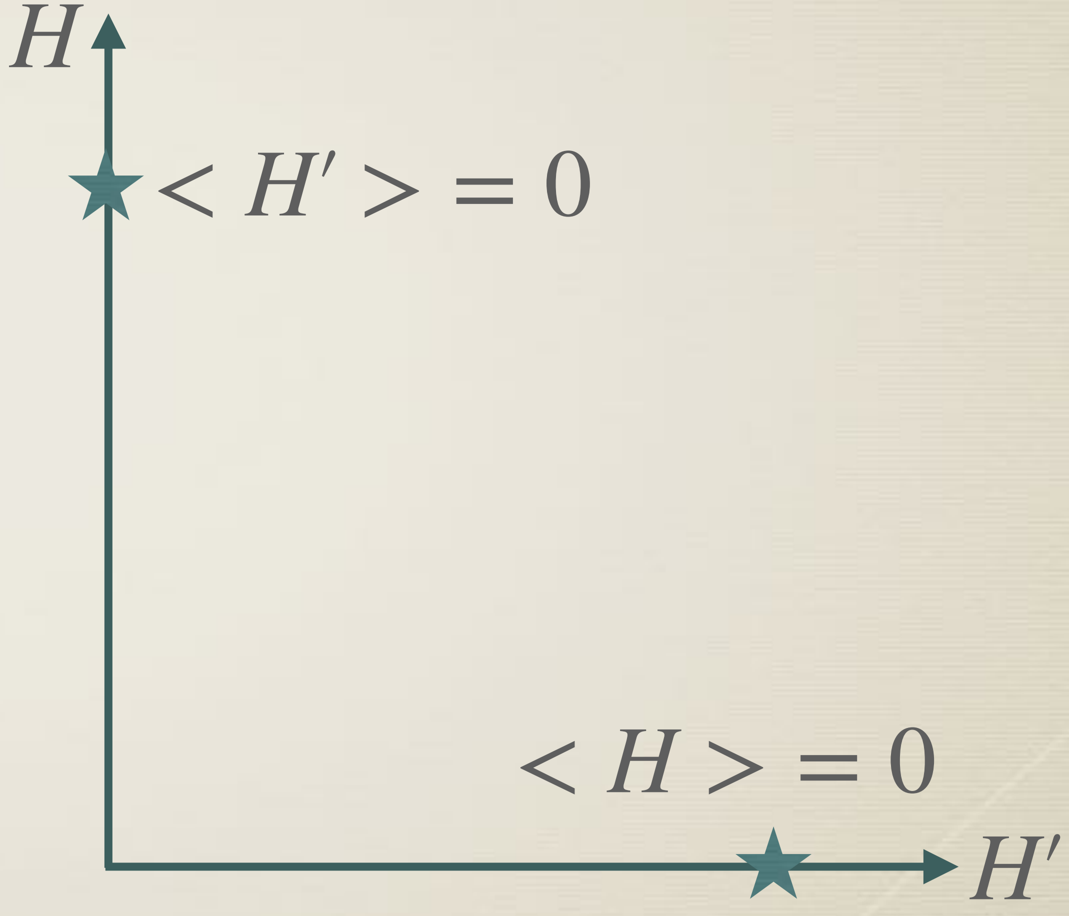
$$\langle H \rangle \ll \langle H' \rangle \ ?$$



$y > 0$

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

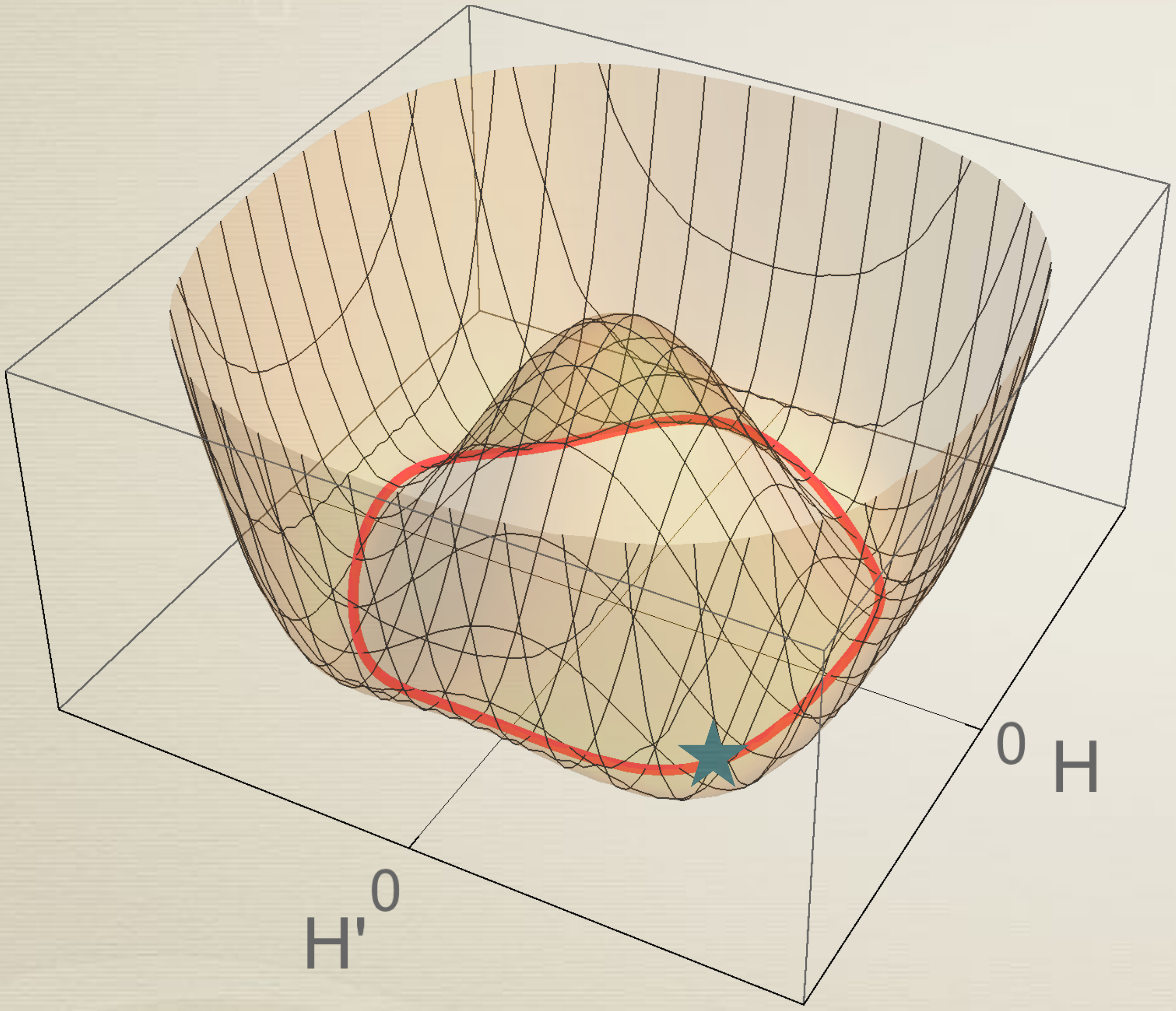


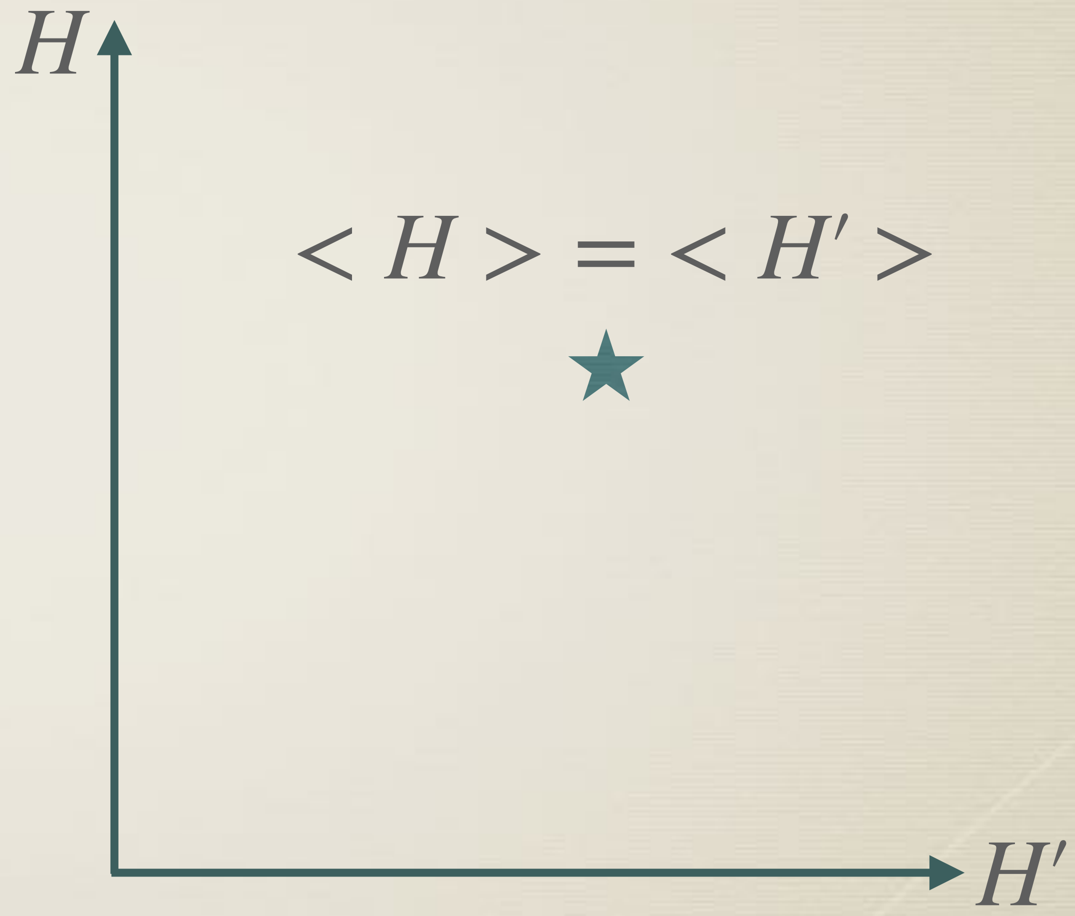


$$0 \neq \langle H \rangle \ll \langle H' \rangle$$

$y < 0$

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



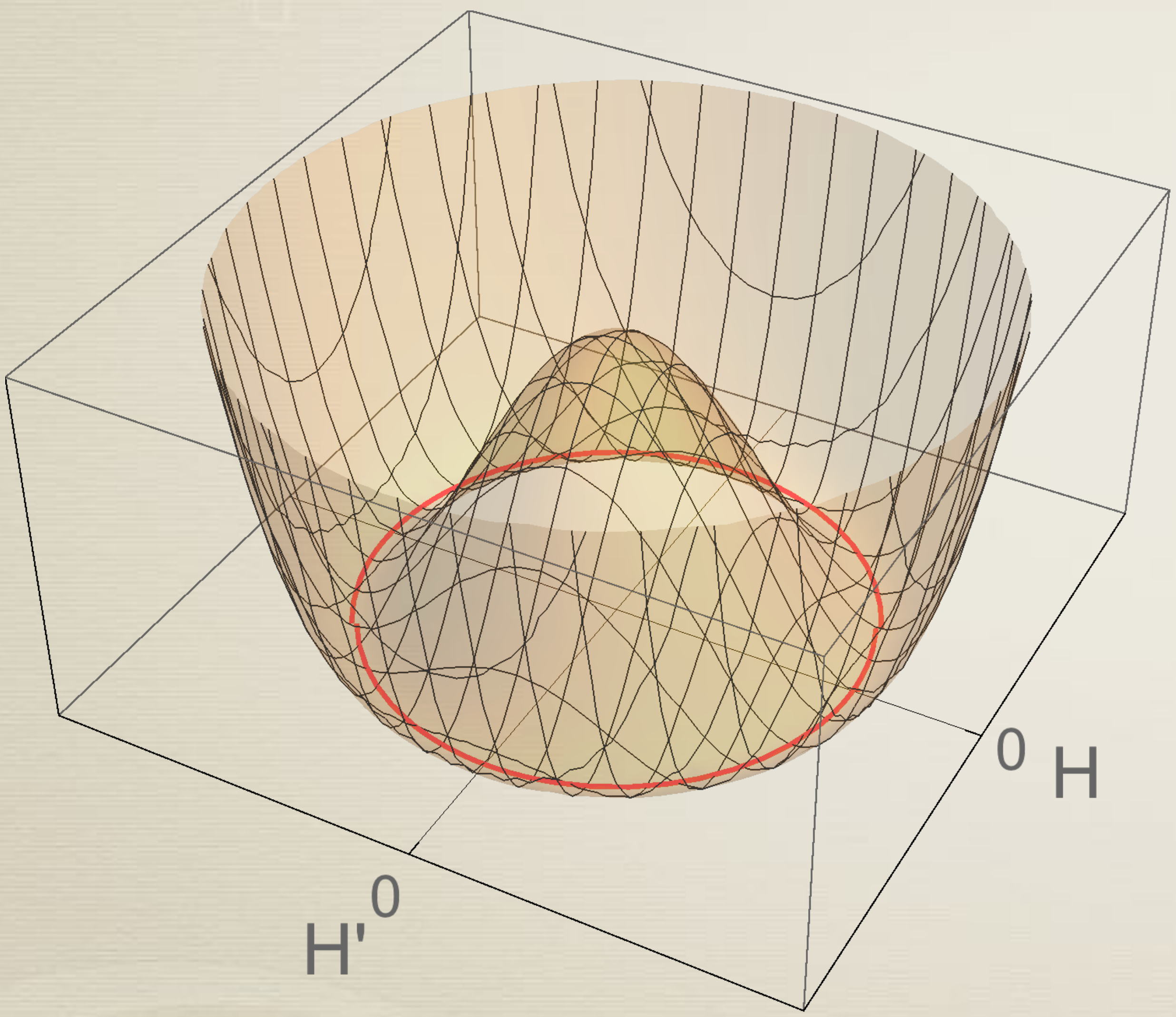


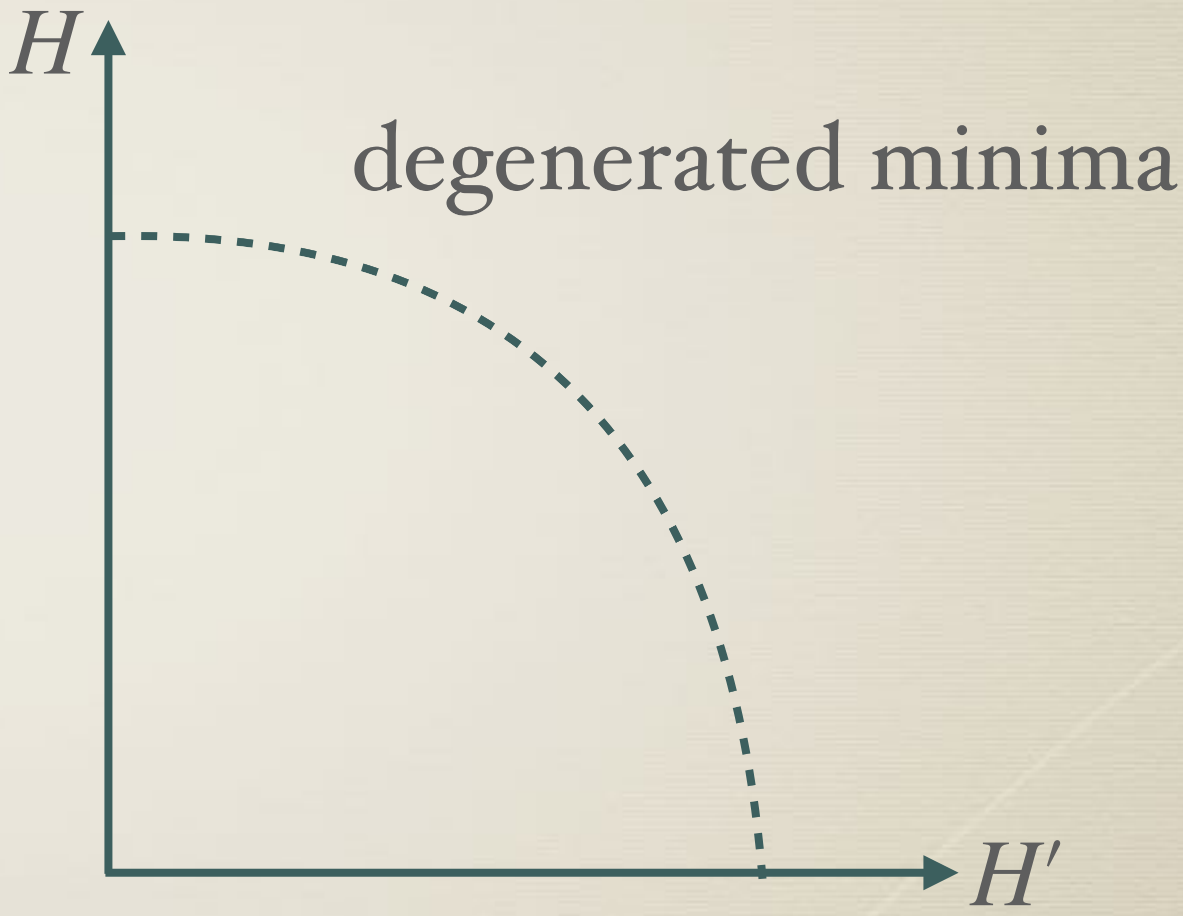
$< H > = < H' >$

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

$$y \simeq 0$$

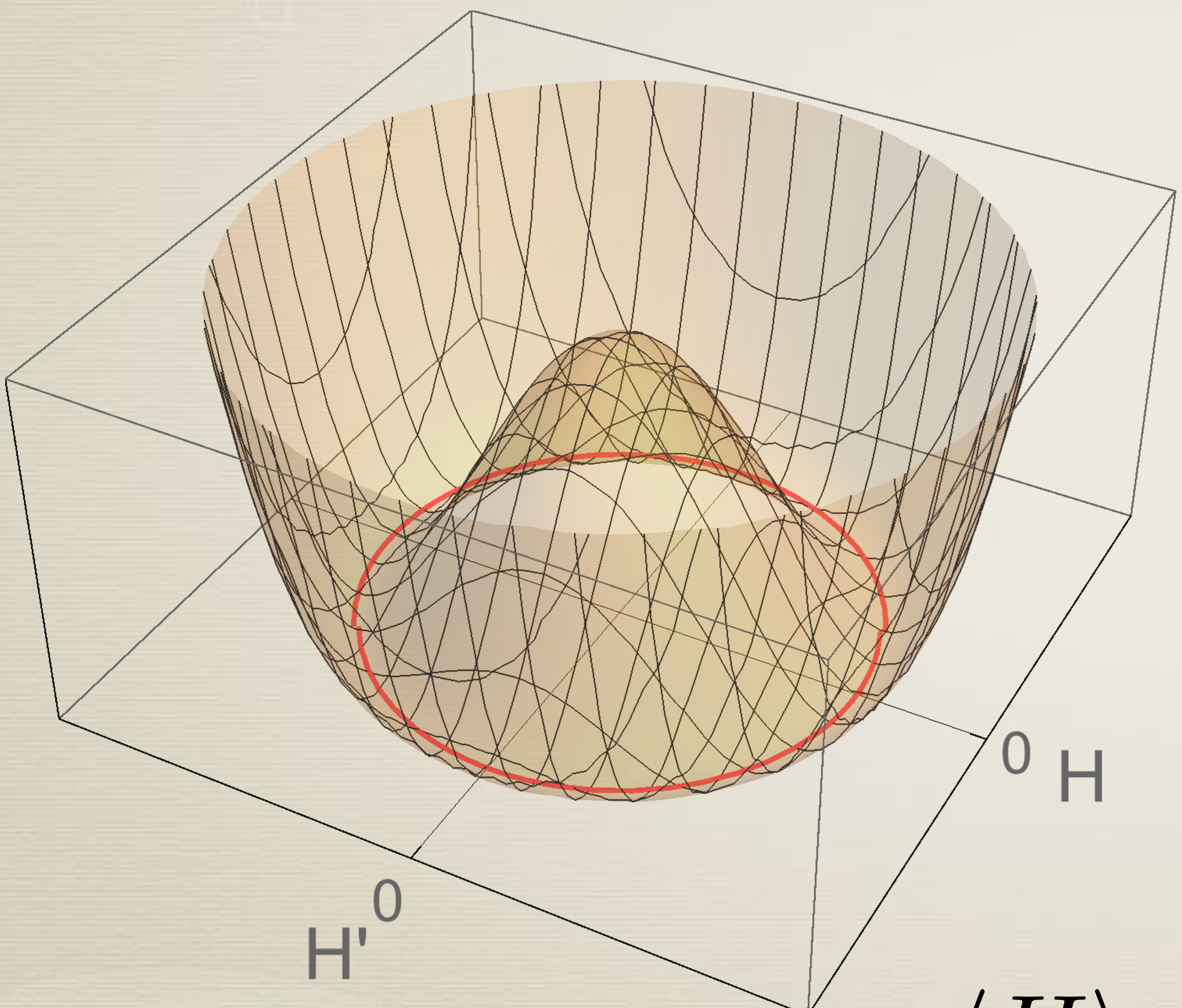
$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

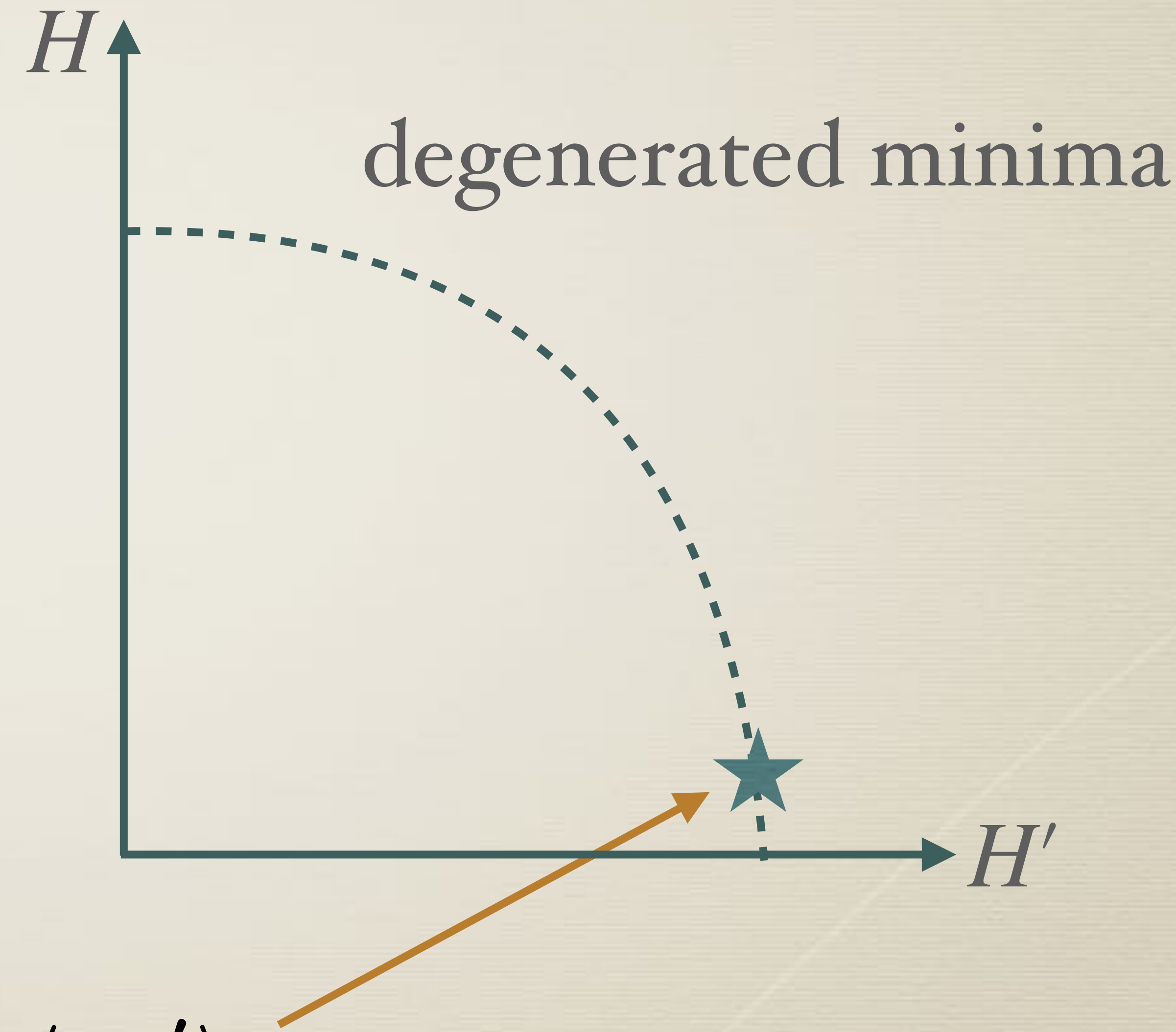




$y \simeq 0$

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



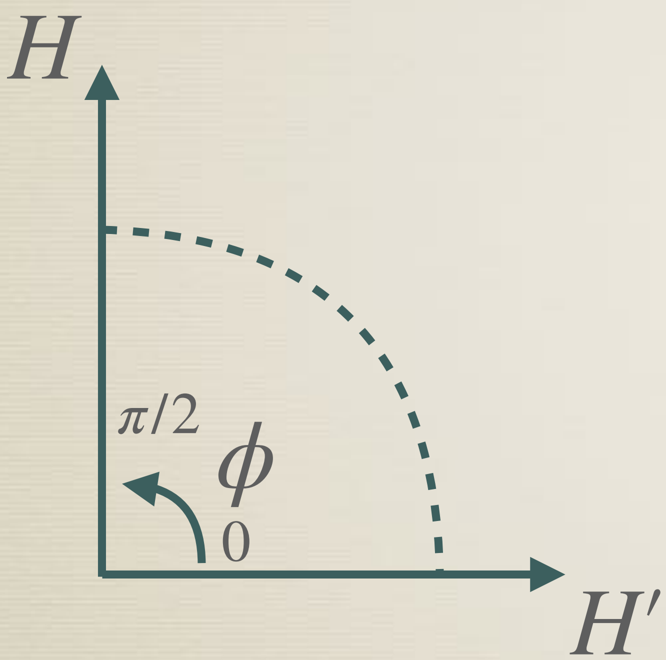


$$\langle H \rangle \ll \langle H' \rangle \,?$$

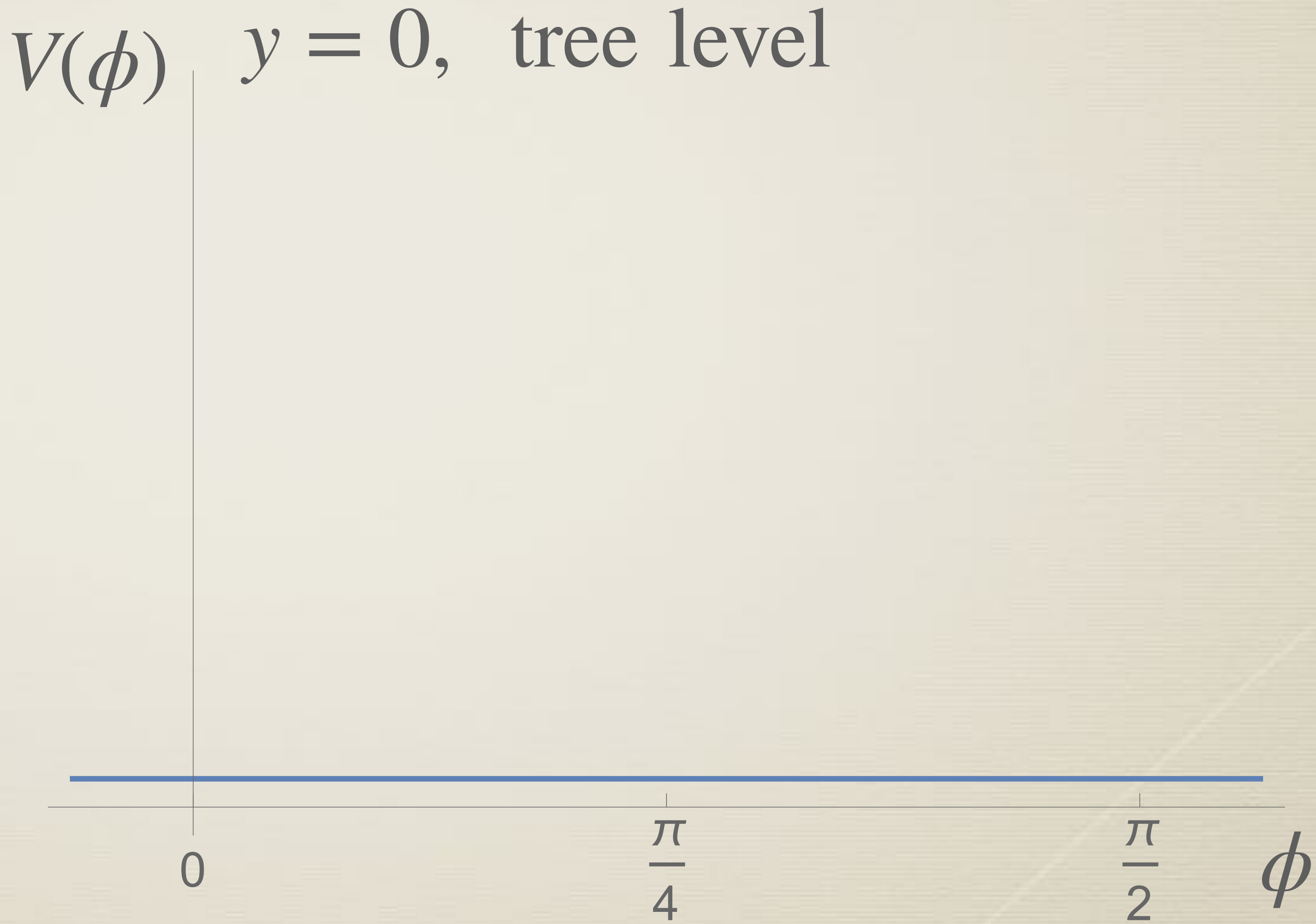
Degeneracy is resolved by quantum corrections

$y \simeq 0$

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



angular direction ϕ

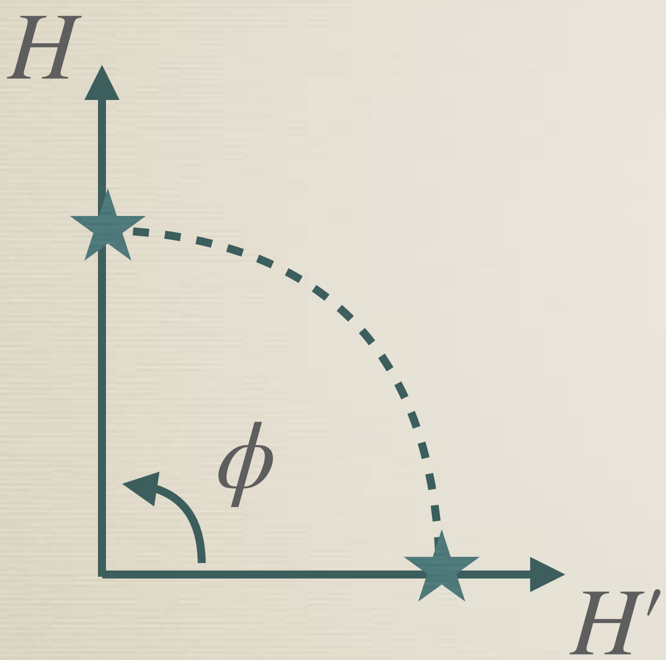


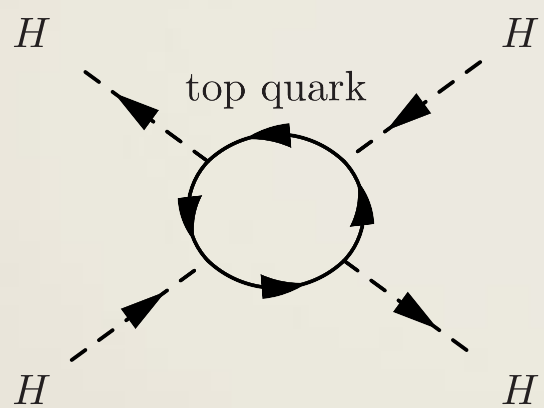
$$y \simeq 0$$

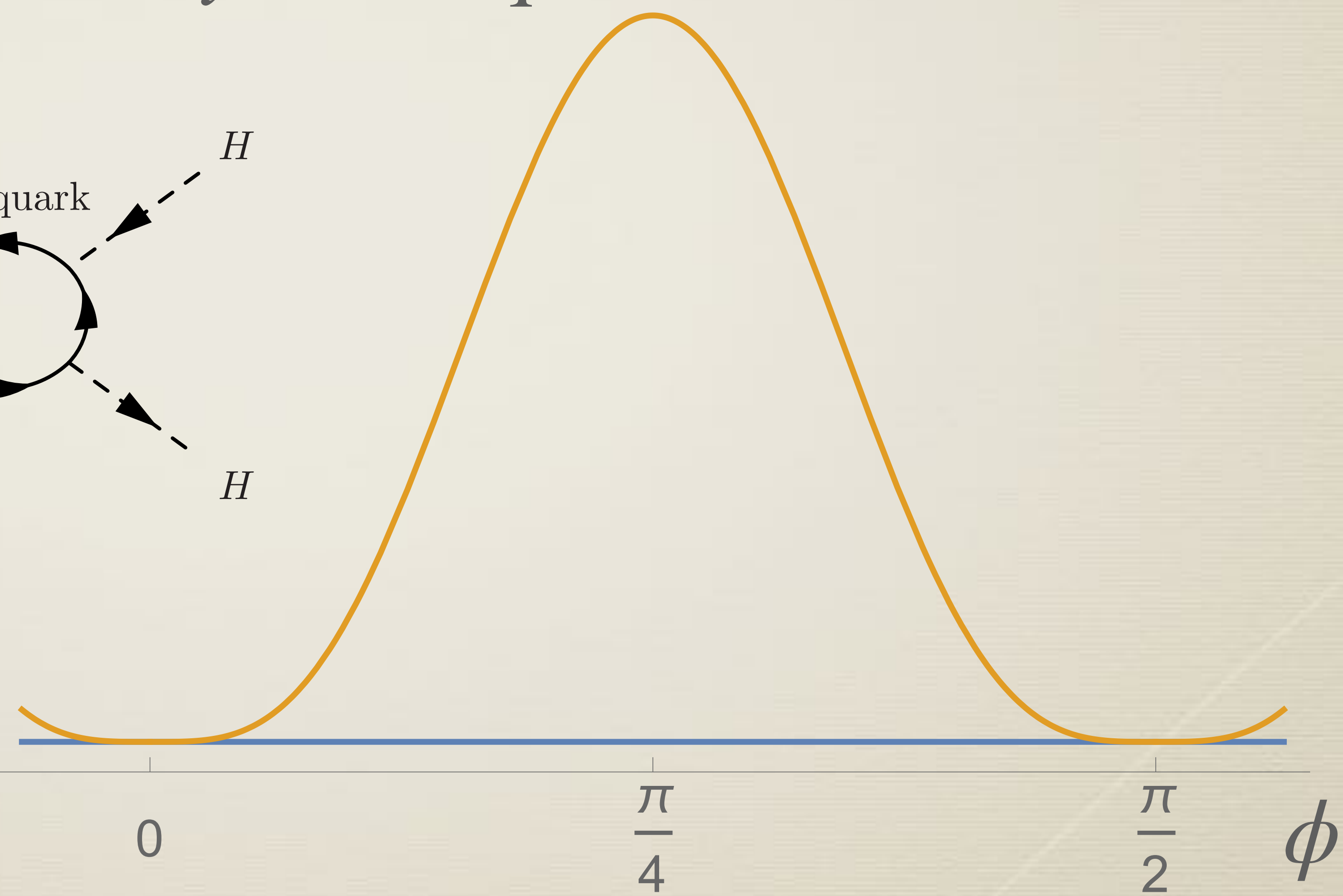
Colemann-Weinberg potential

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

$y = 0$, quantum correction





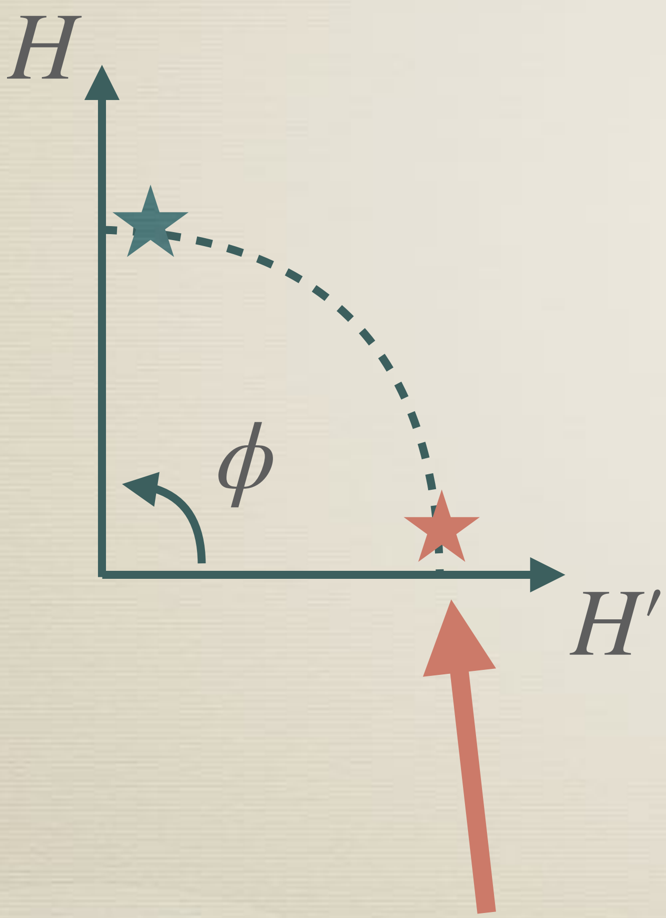


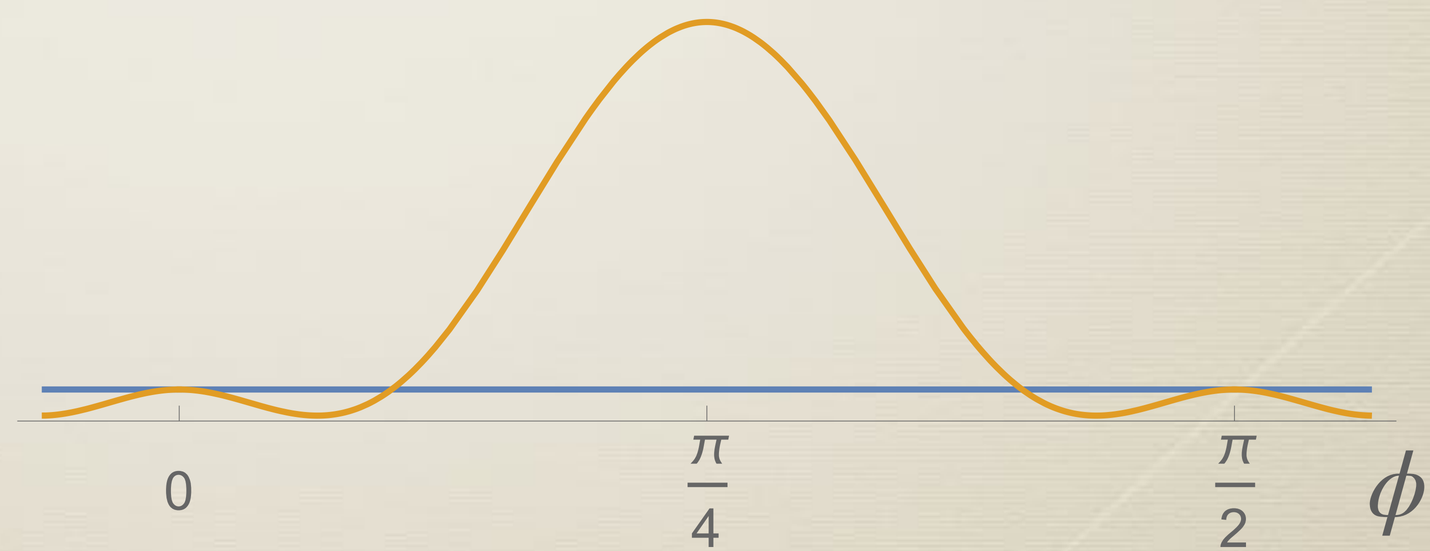
$$y \simeq 0$$

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

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

(fine-tuned Higgs mass)





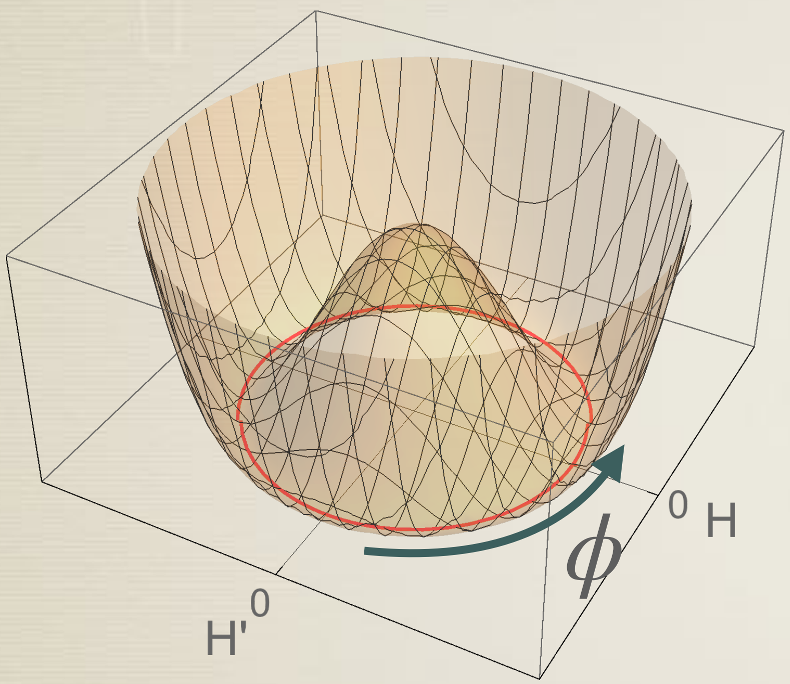
$\langle H \rangle \ll \langle H' \rangle$ is achieved !

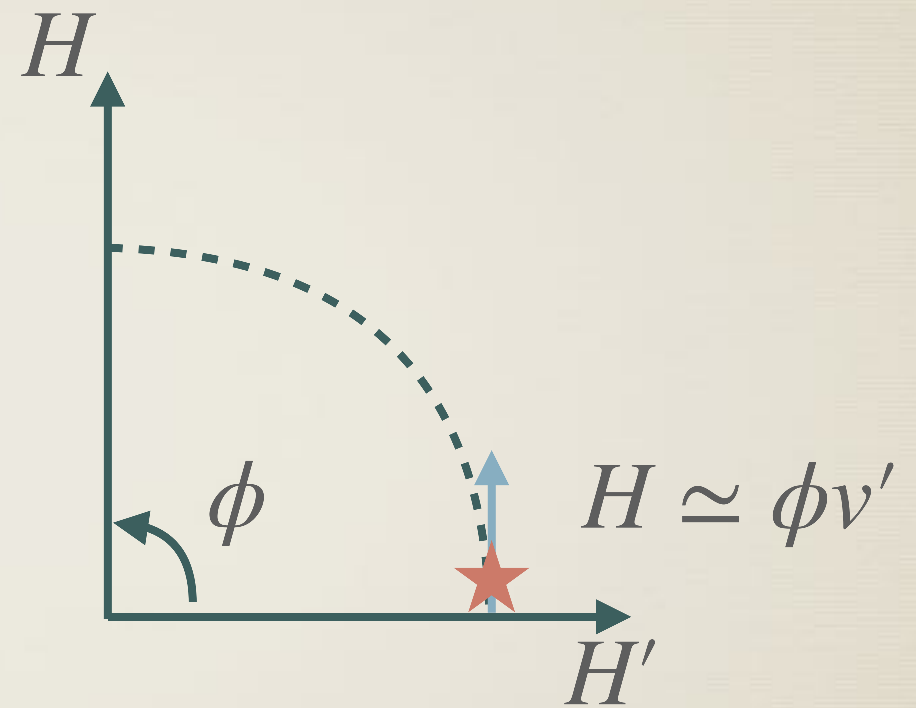
Hall, KH (2018)

Prediction on the quartic coupling

Hall, KH (2018)

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





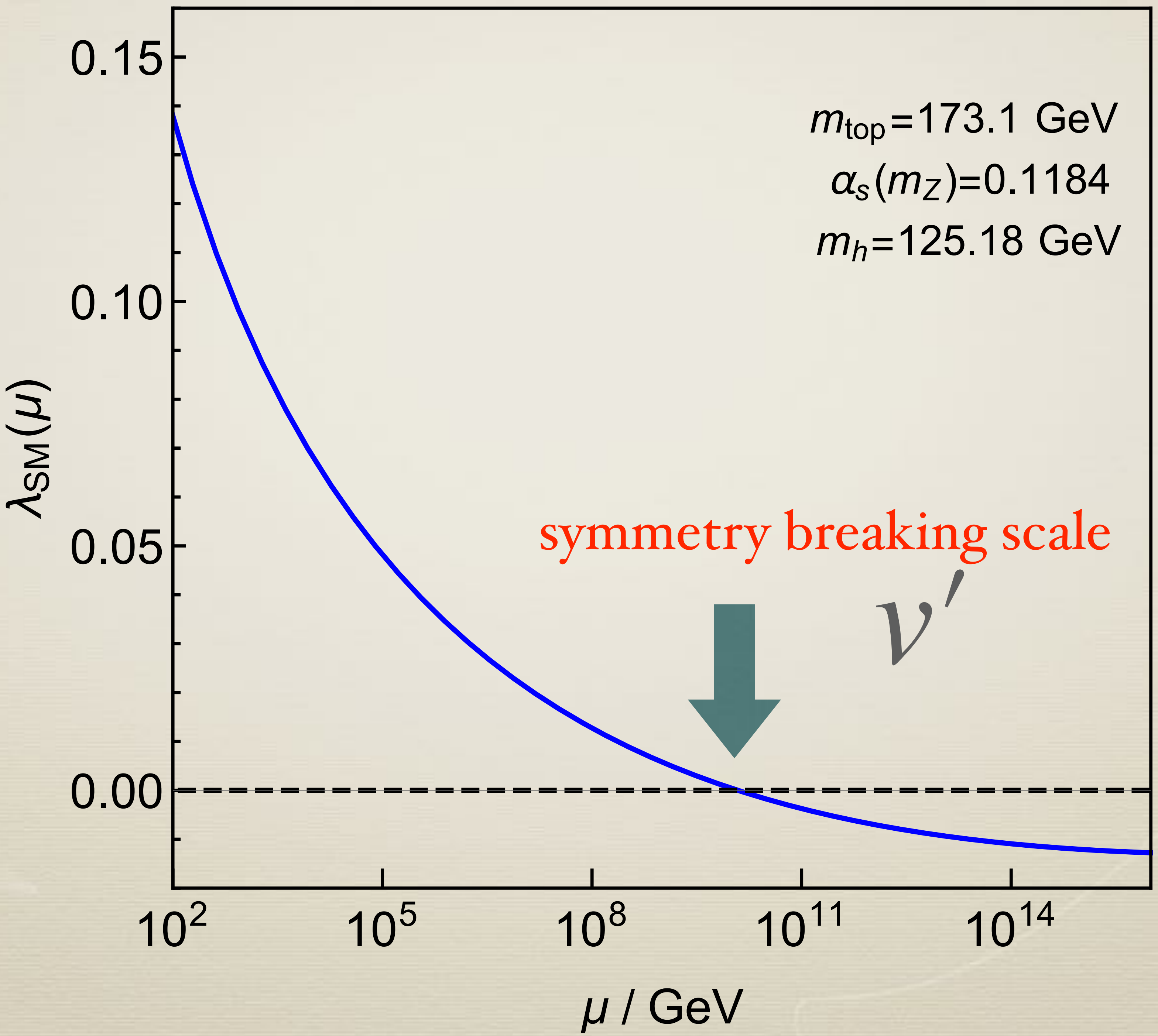
SM Higgs is a Nambu-Goldstone boson associated with symmetry breaking by $\langle H' \rangle = v'$

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

(up to calculable threshold correction)

Prediction on symmetry breaking scale

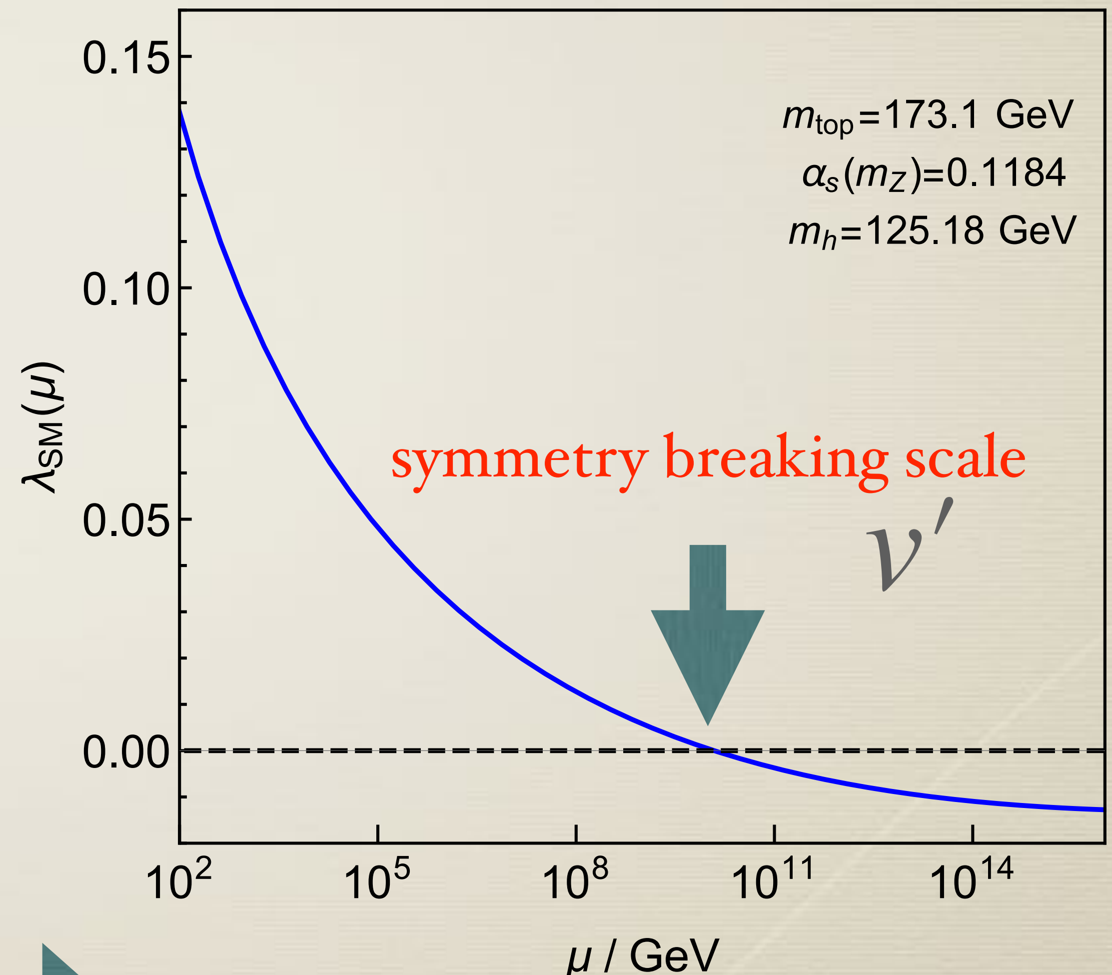
Hall, KH (2018)



Precise measurement and new physics

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

top quark yukawa
Higgs mass
strong coupling constant



Higgs Parity (HP)
symmetry breaking scale

Experimental signatures

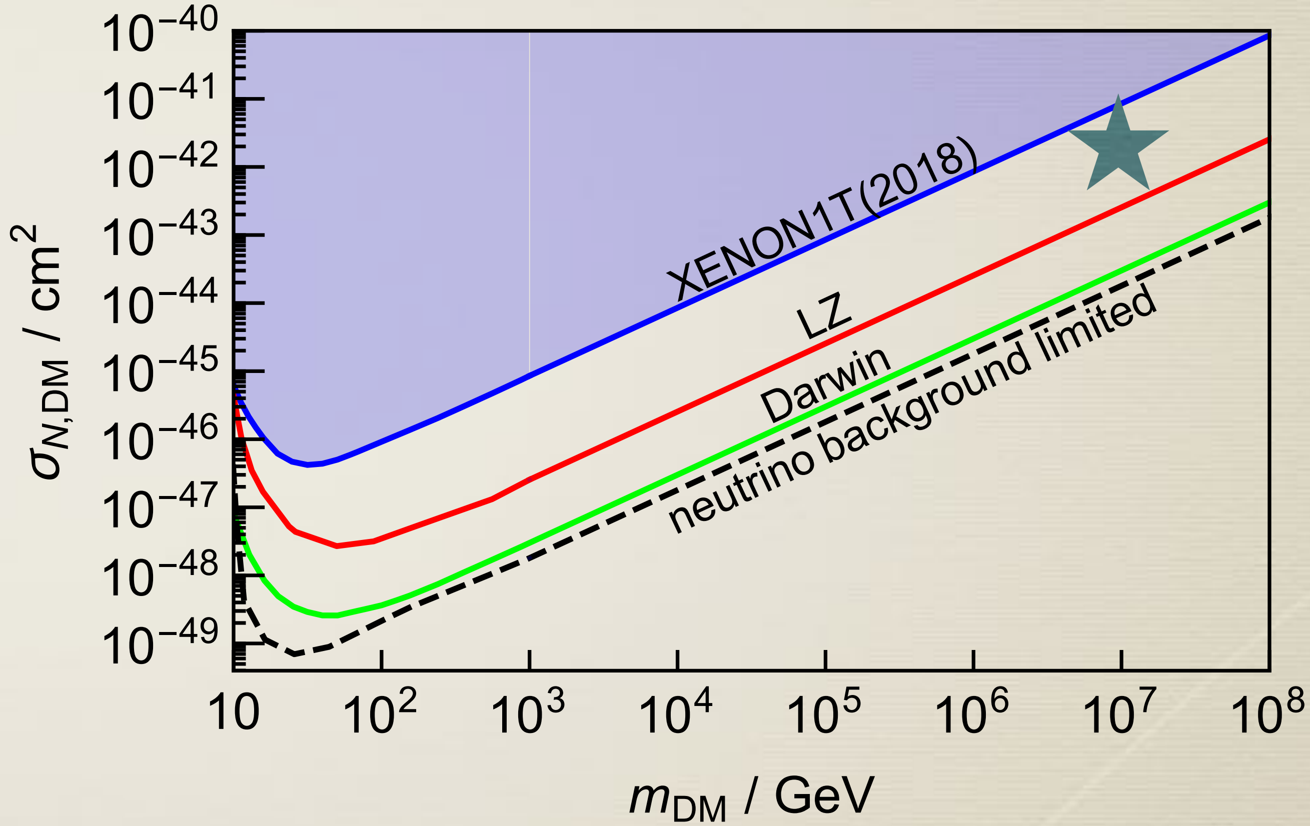
Outline

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

Precise measurement and dark matter

Dunsky, Hall and KH (2019)

top quark yukawa
Higgs mass
strong coupling constant



Higgs Parity
symmetry breaking scale

Dark matter direct
detection rate

Mirrored electroweak theory

	SM particles	HP	New particles
	q		q’
quark	u		u’
	d		d'
	L		L’
lepton	e		e’
Higgs	H	⟷	H’

electroweak	electroweak’
W, Z $\quad SU(2)_L \times U(1)_Y$	$SU(2)'_L \times U(1)'_Y$ $\quad W', Z'$
$\downarrow < H >$	$< H' > \quad \downarrow$
γ $\quad U(1)_{\text{EM}}$	$U(1)'_{\text{EM}}$ $\quad \gamma'$

Mirrored electroweak theory

SM particles | New particles

strong interaction

$SU(3)_c$

	SM particles		New particles
quark	q		q’
	u		u’
	d		d'
lepton	L		L’
	e	HP	e’
Higgs	H		H’

electroweak

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

$\downarrow < H >$

γ $U(1)_{\rm EM}$

electroweak’

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

$< H' > \downarrow$

$U(1)'_{\rm EM}$ γ'

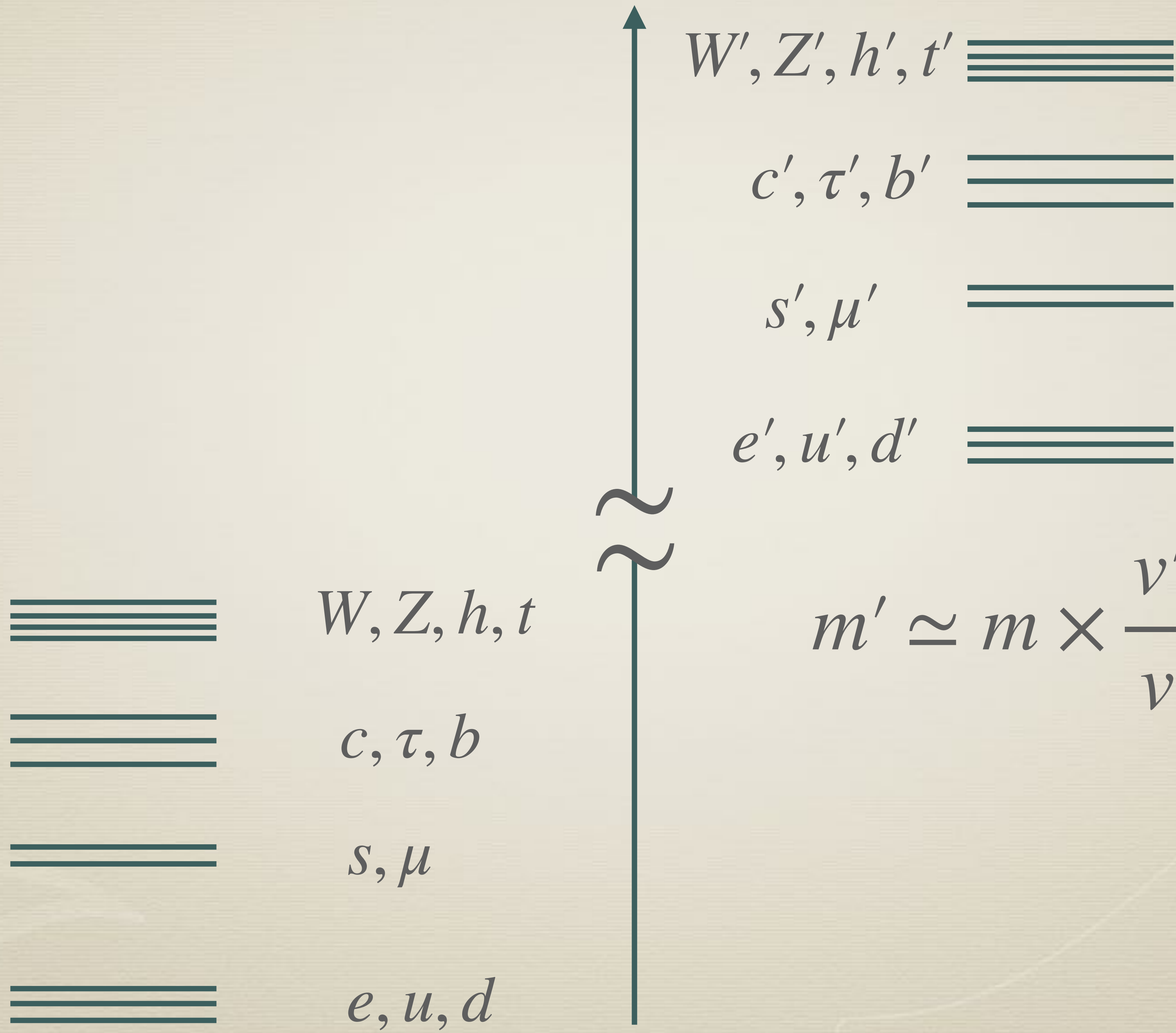
Mirrored electroweak theory

	SM particles		New particles
quark	q	strong interaction	q'
	u	$SU(3)_c$	u'
	d		d'
lepton	L	HP	L'
	e		e'
Higgs	H		H'

The Strong CP problem is solved
via space-time parity

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

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'

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

$$\downarrow$$

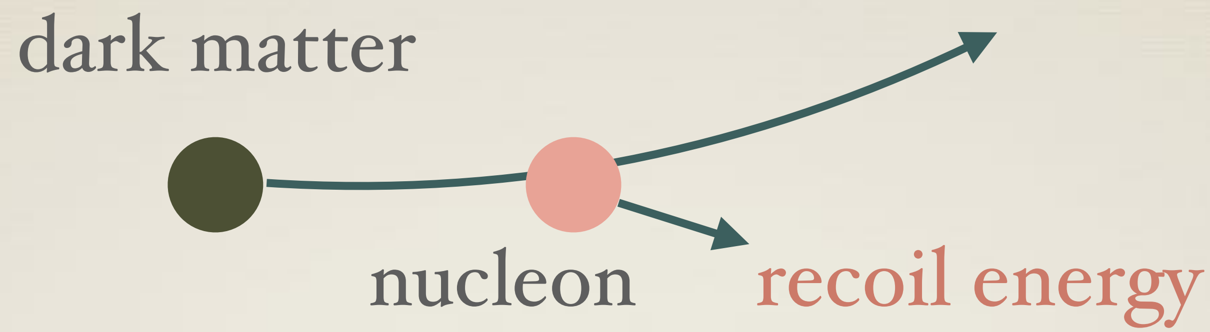
$$U(1)'_{\mathrm{EM}} \quad \gamma'$$

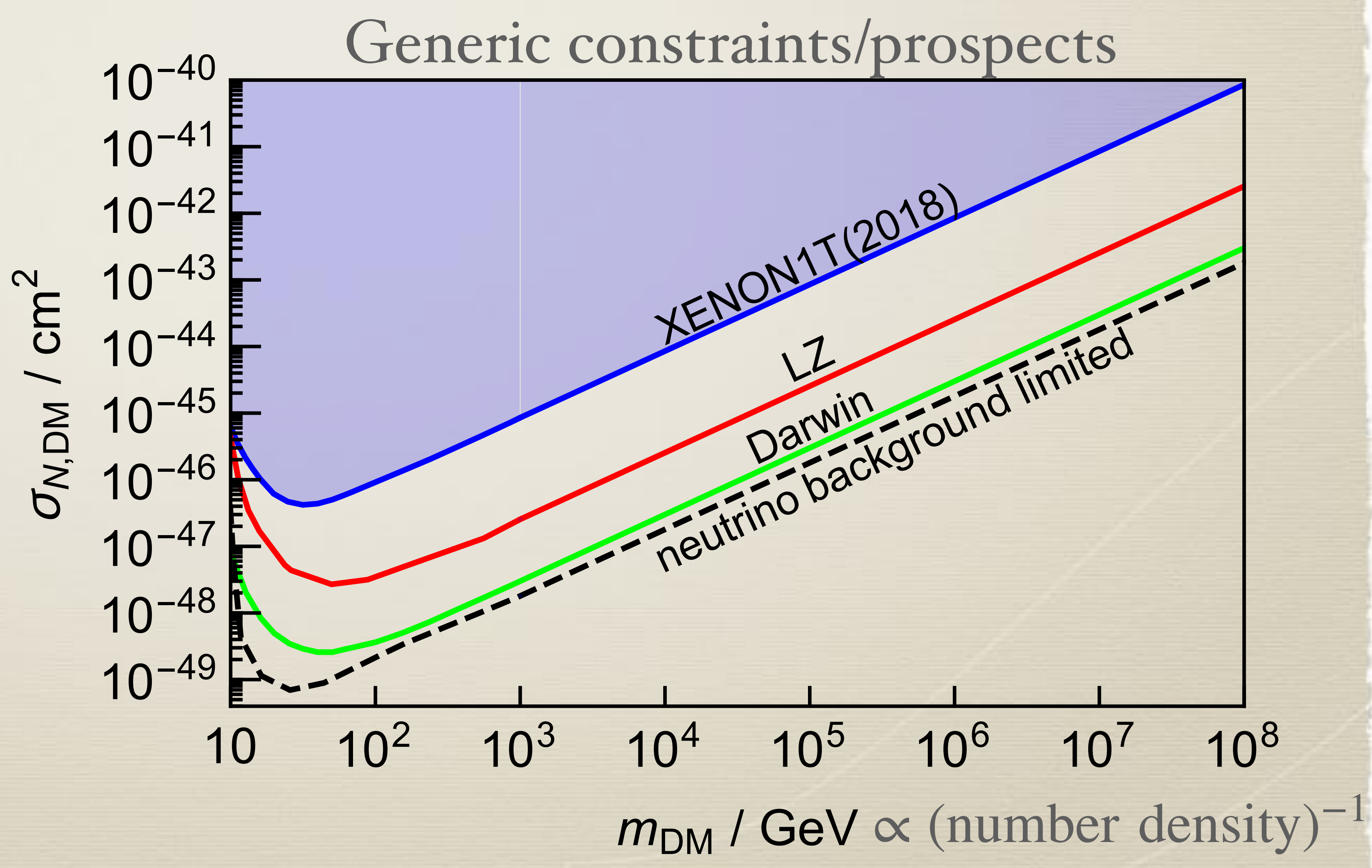
Mirror electron and the lightest mirror baryon are stable

e'

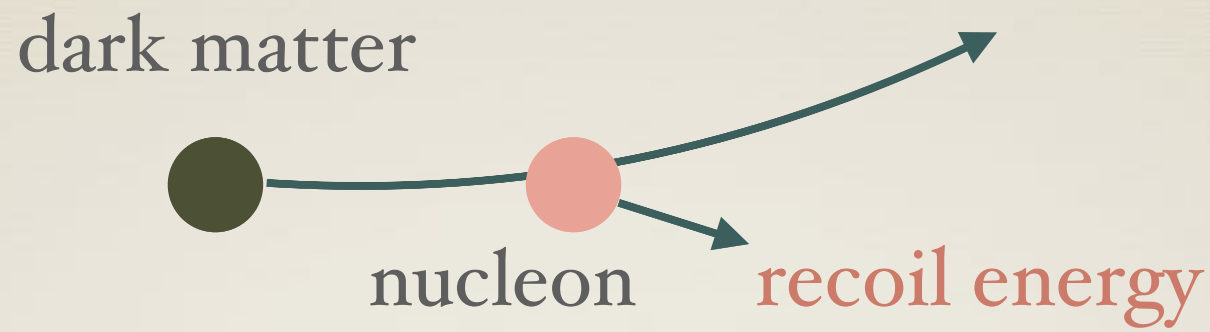
u'
$u' \; u'$

Direct detection of dark matter

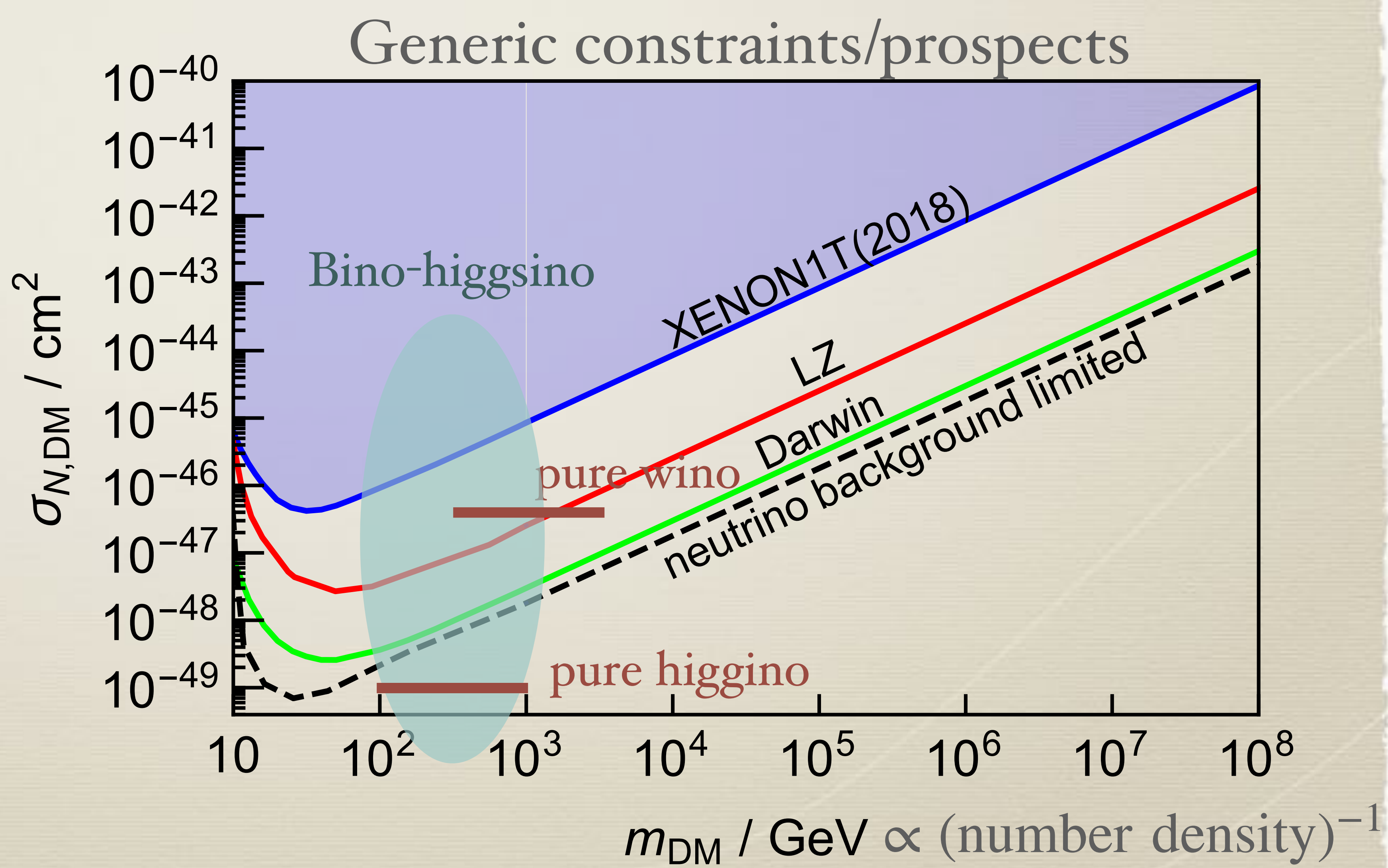




Direct detection of dark matter

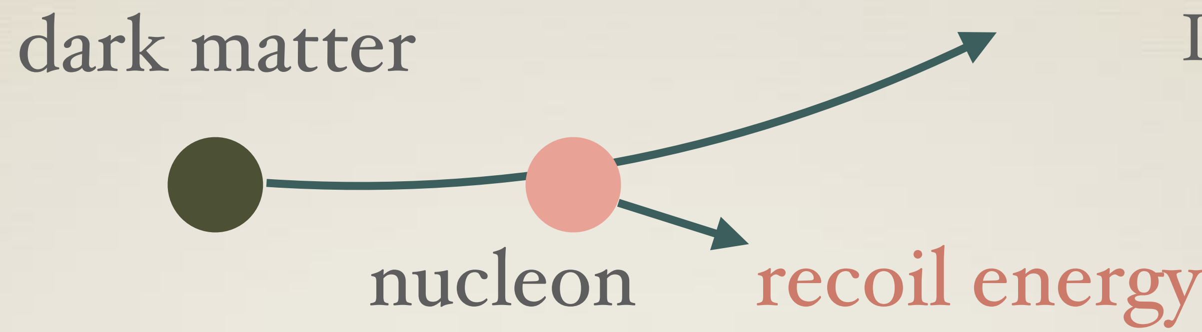


ex.
Dark matter in supersymmetric theories



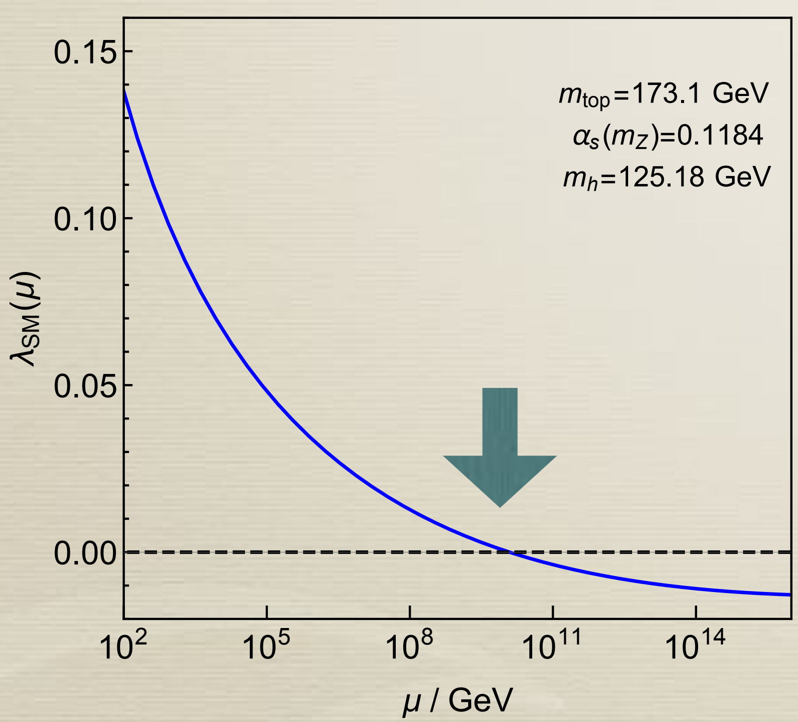
Direct detection of dark matter

Dunsky, Hall, KH (2019)



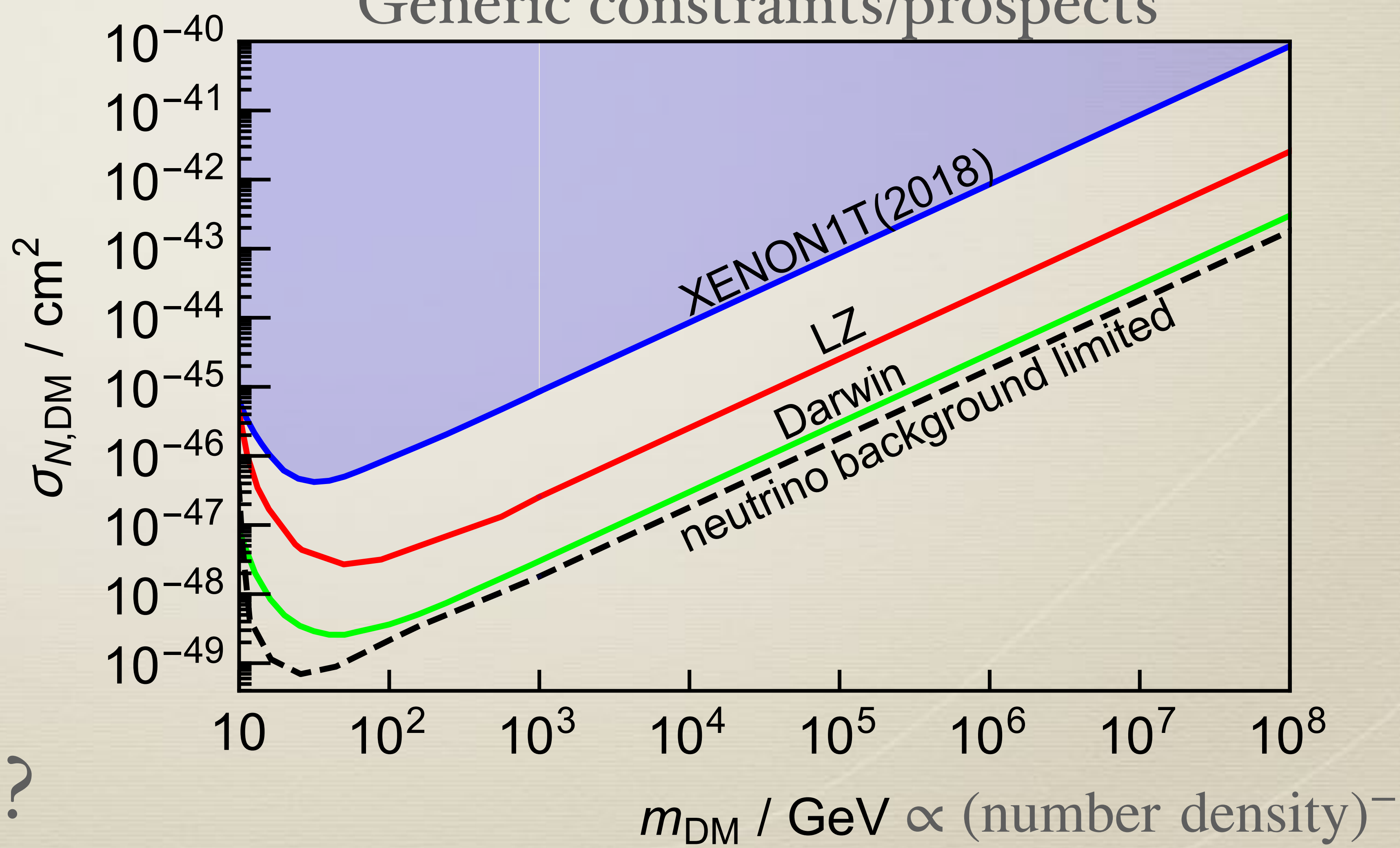
Higgs Parity

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



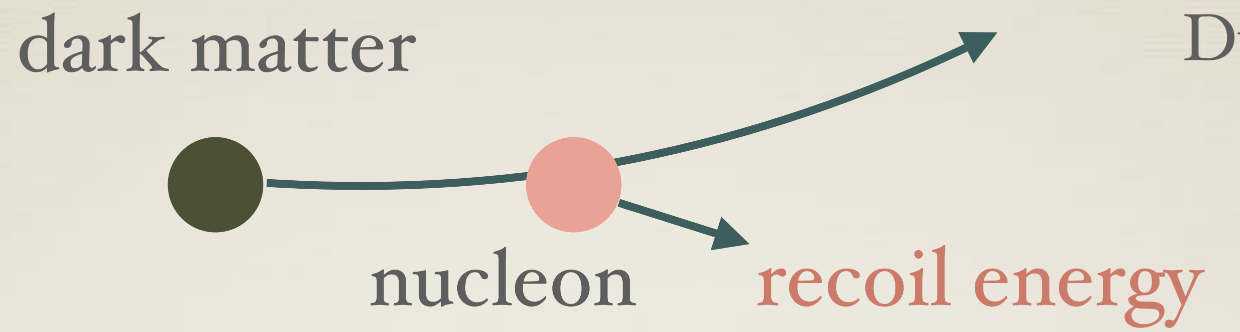
Interaction rate?

Generic constraints/prospects



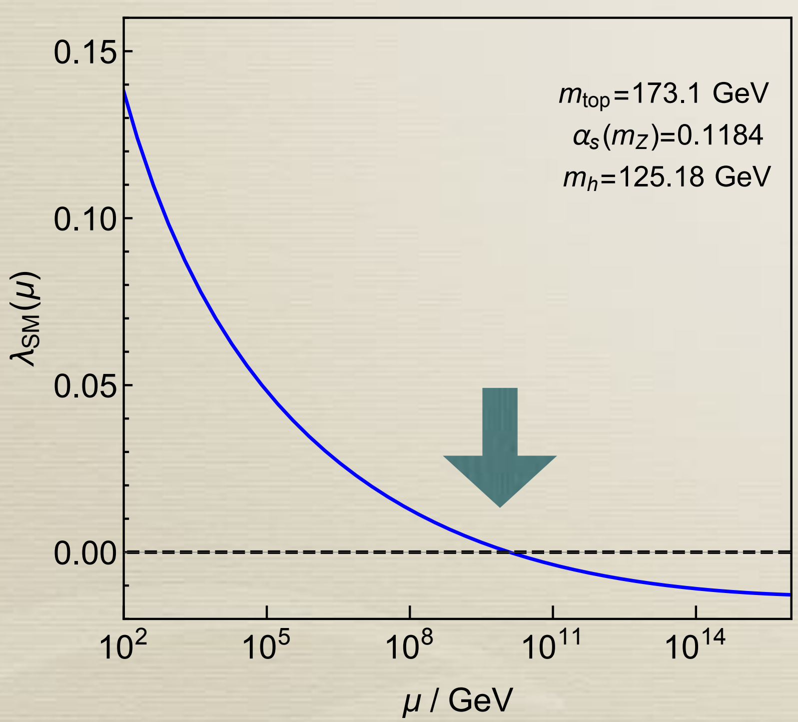
Direct detection of dark matter

Dunsky, Hall, KH (2019)



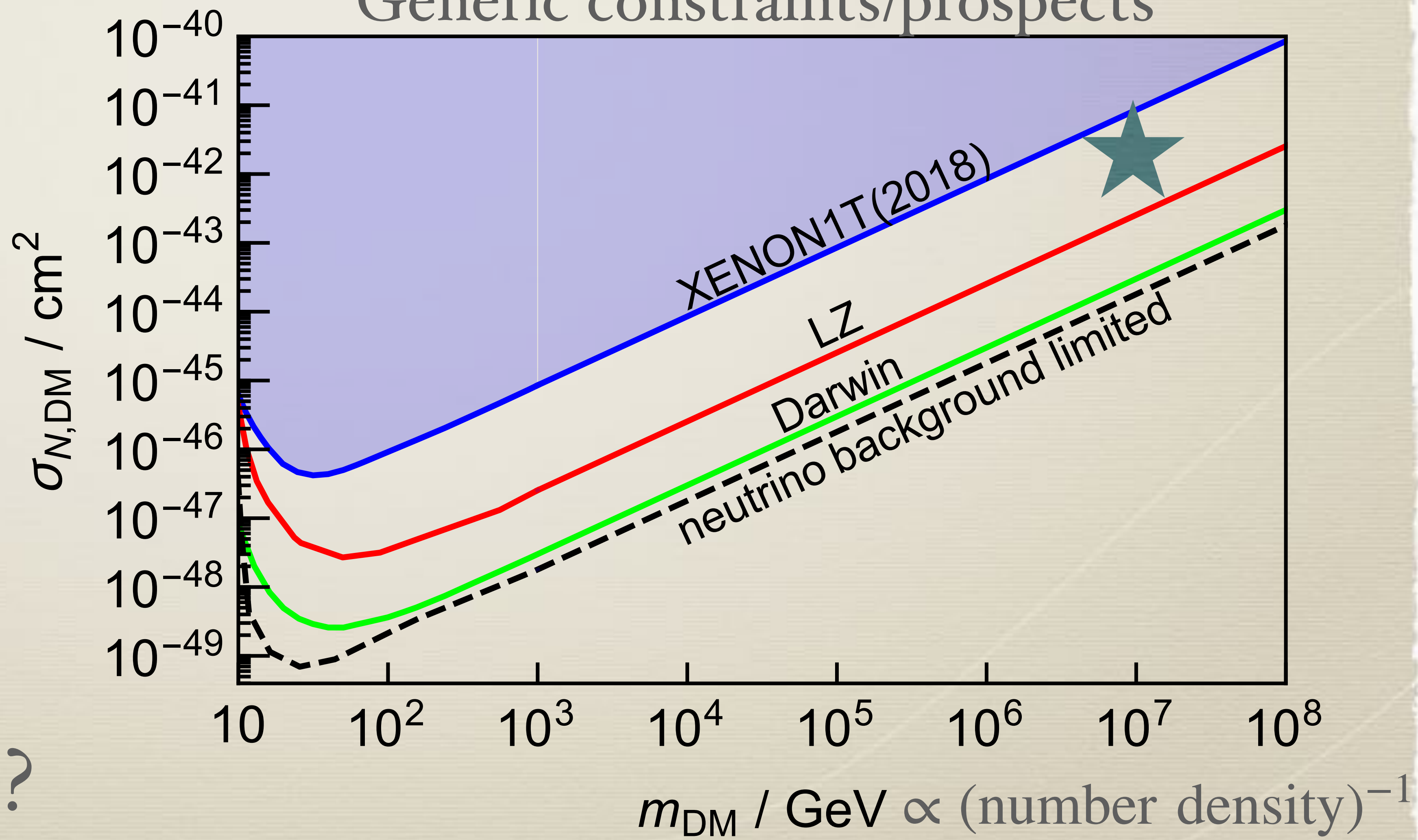
Higgs Parity

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



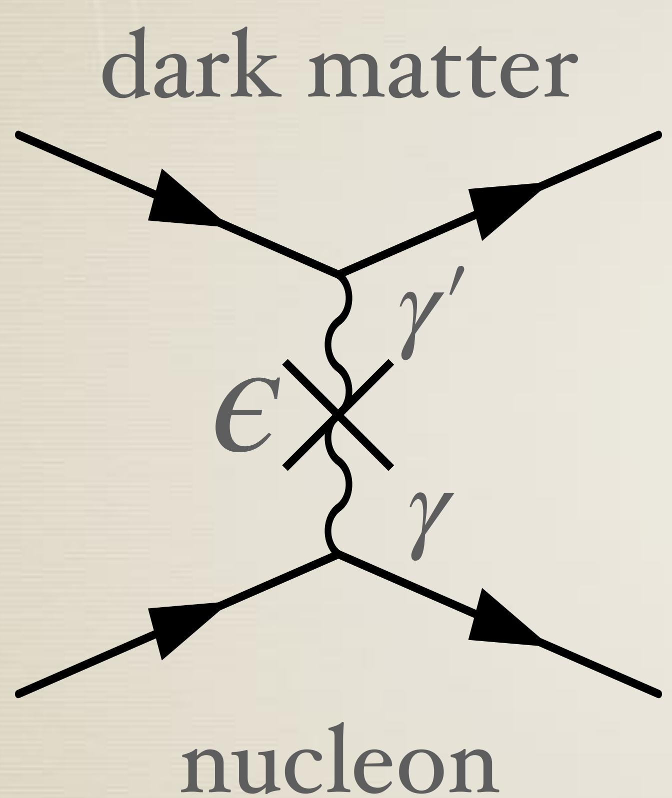
Interaction rate?

Generic constraints/prospects



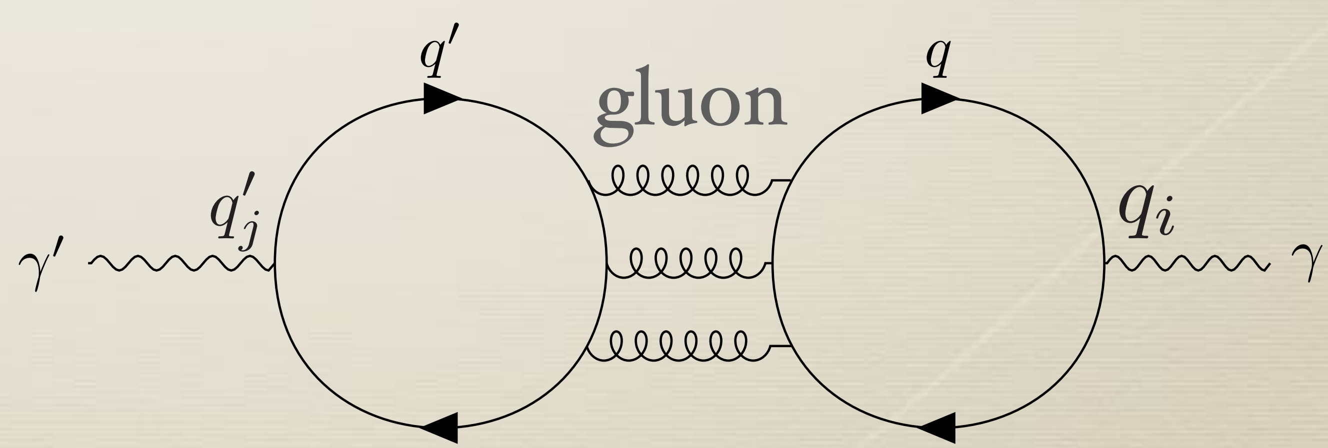
Prediction on interaction

Dunsky, Hall, KH (2019)

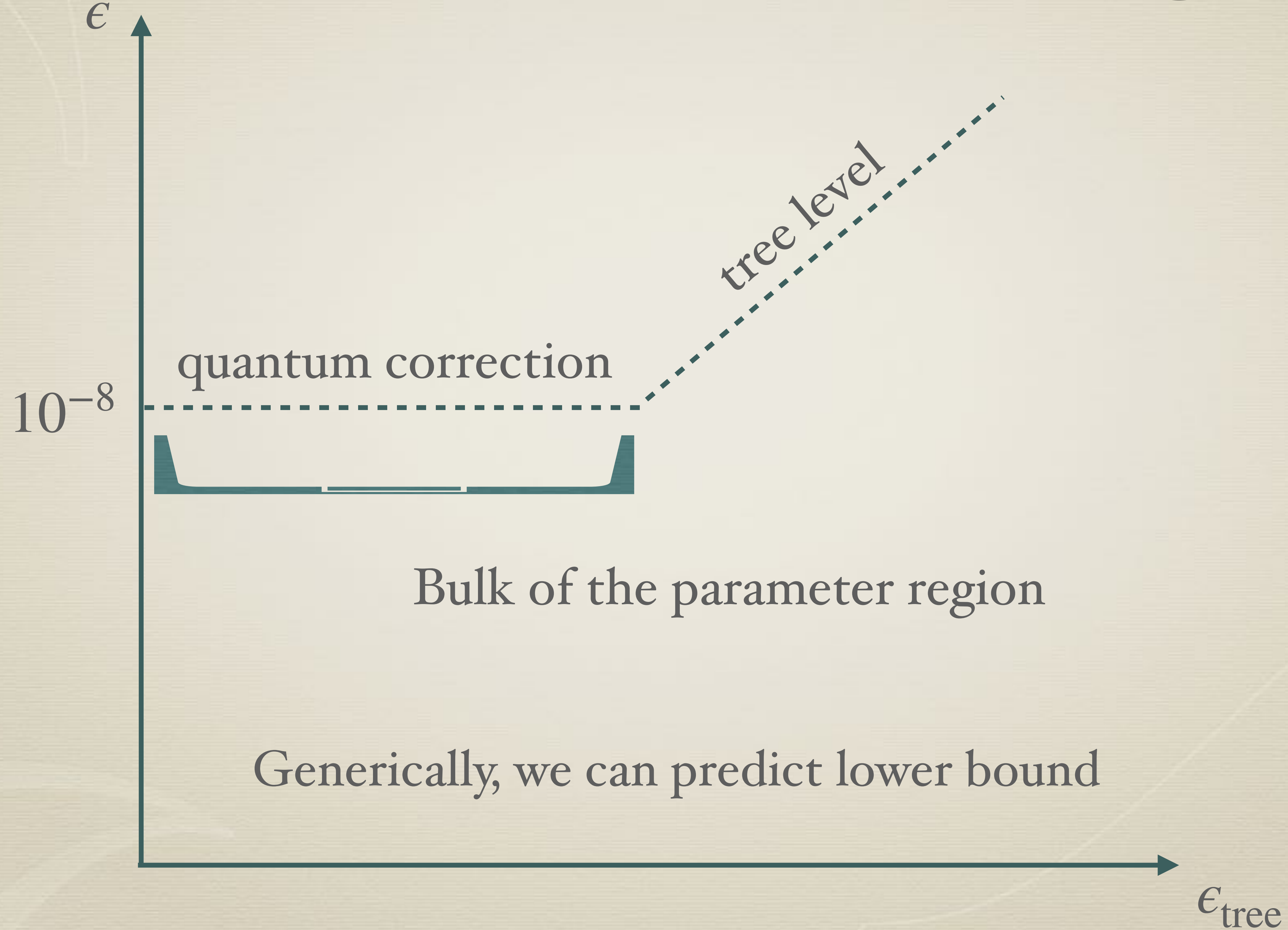


photon-mirror photon mixing

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



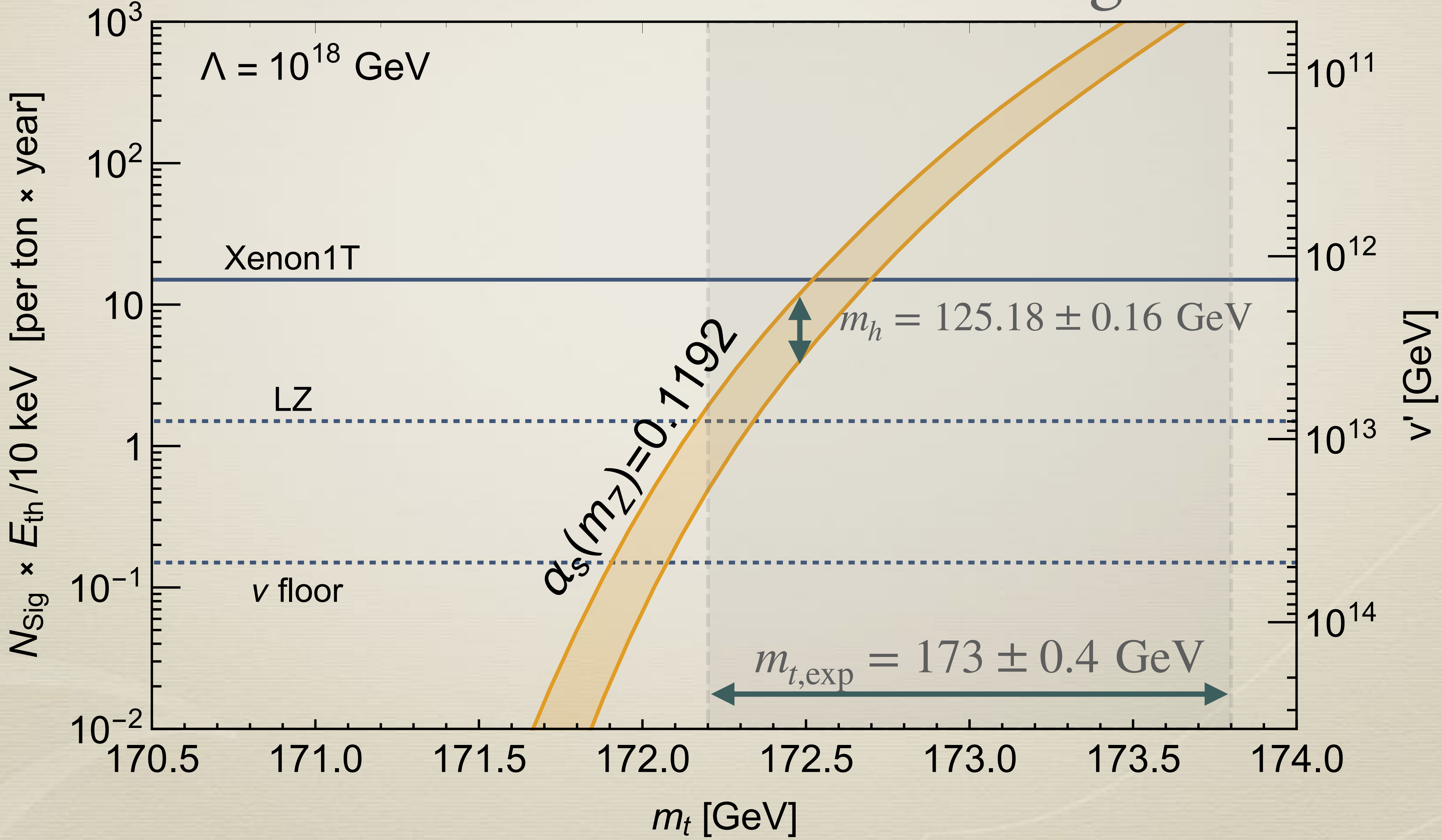
Prediction on mixing



SM parameters and DM

Dunsky, Hall, KH (2019)

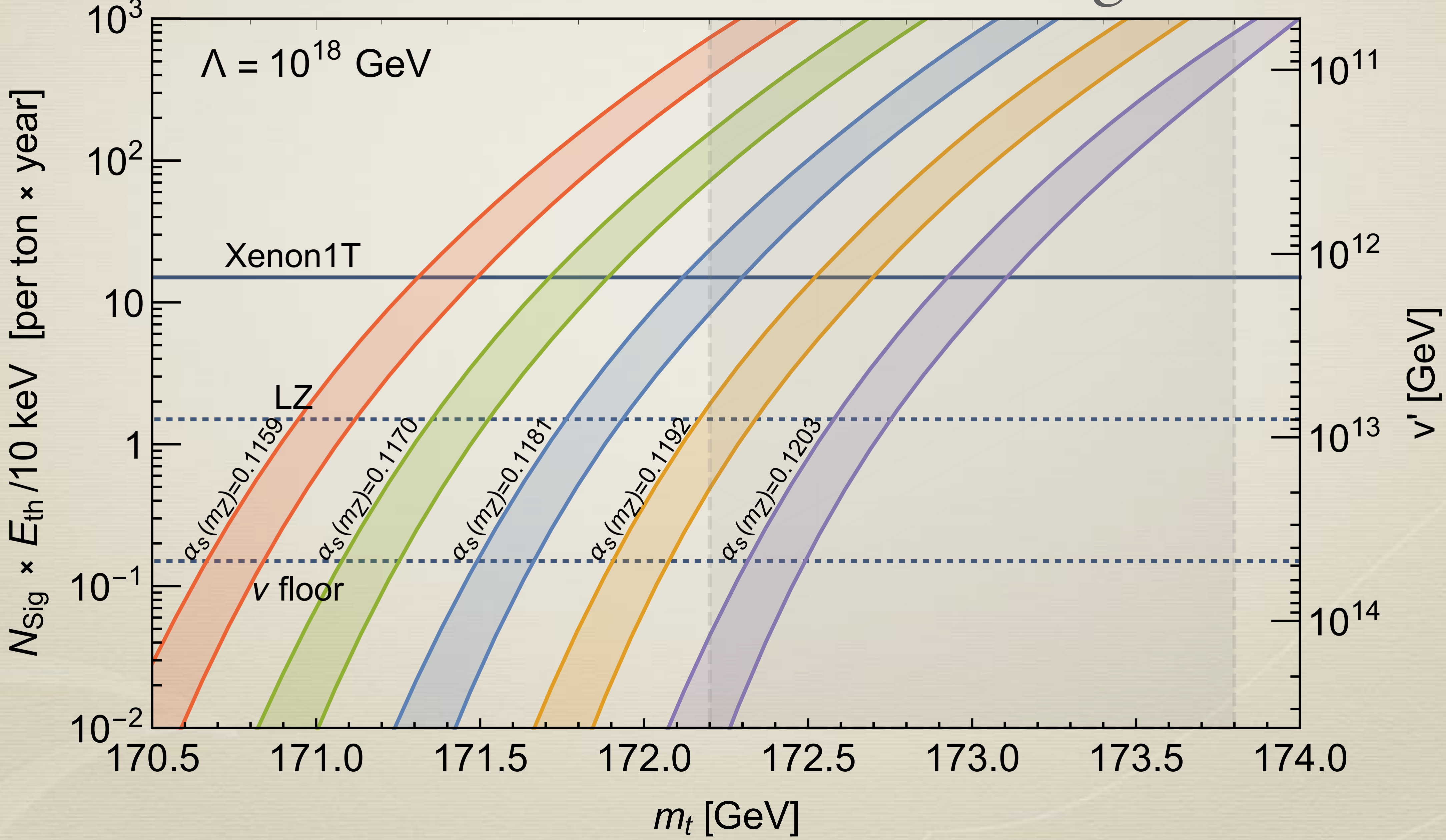
Direct detection rate for Xe targets



SM parameters and DM

Dunsky, Hall, KH (2019)

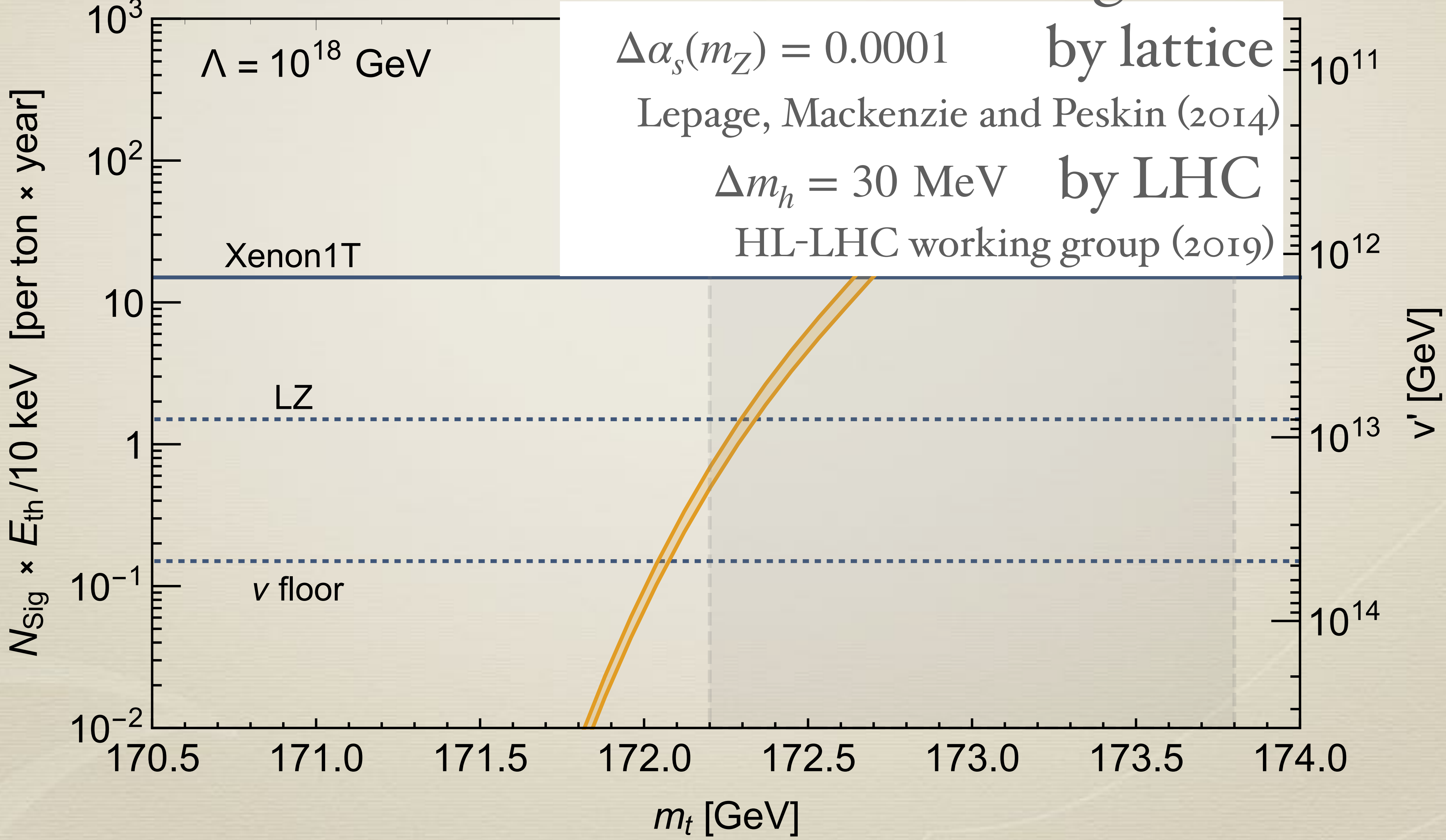
Direct detection rate for Xe targets



SM parameters and DM

Dunsky, Hall, KH (2019)

Direct detection rate for Xe targets



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

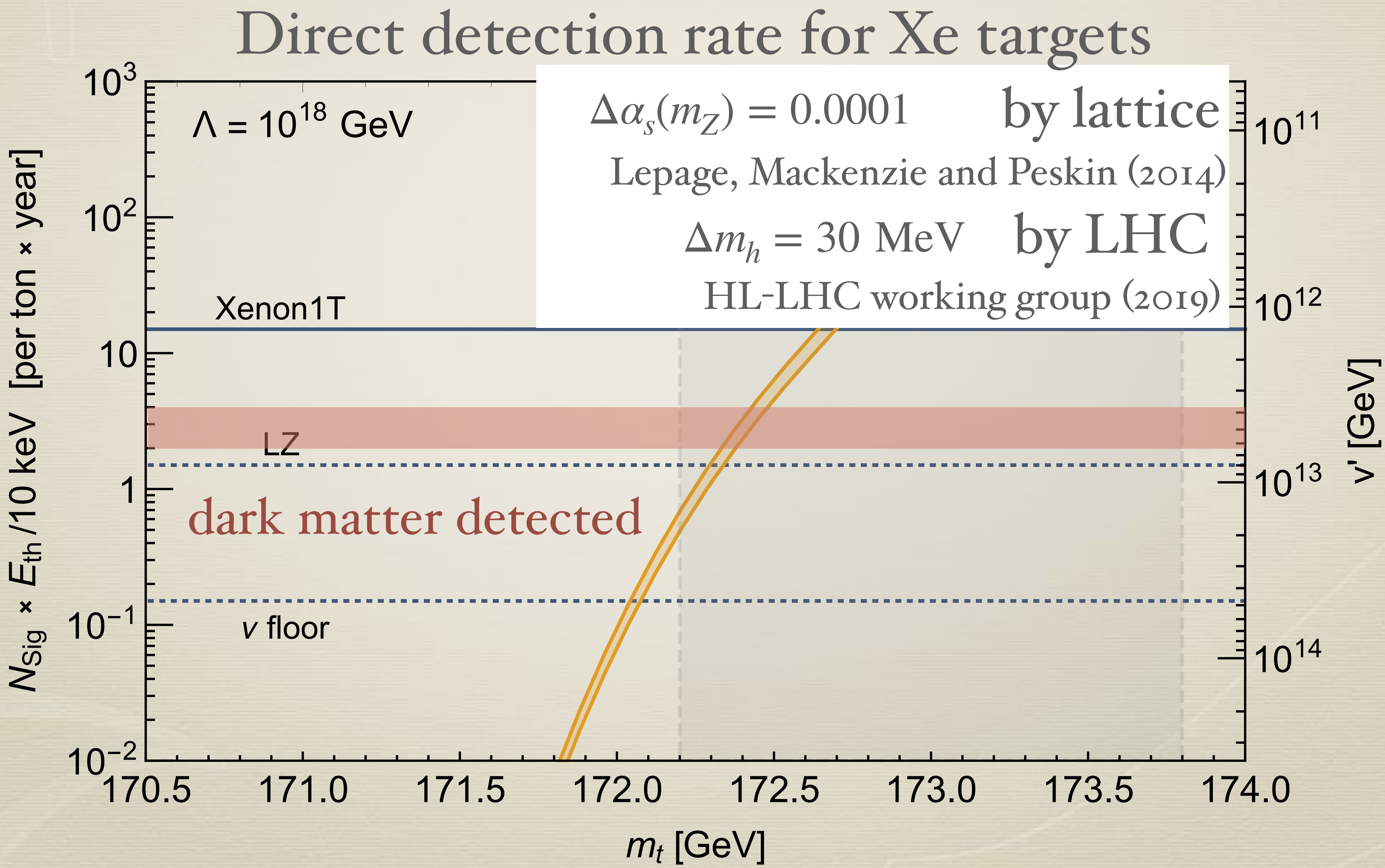
Lepage, Mackenzie and Peskin (2014)

$\Delta m_h = 30$ MeV by LHC

HL-LHC working group (2019)

SM parameters and DM

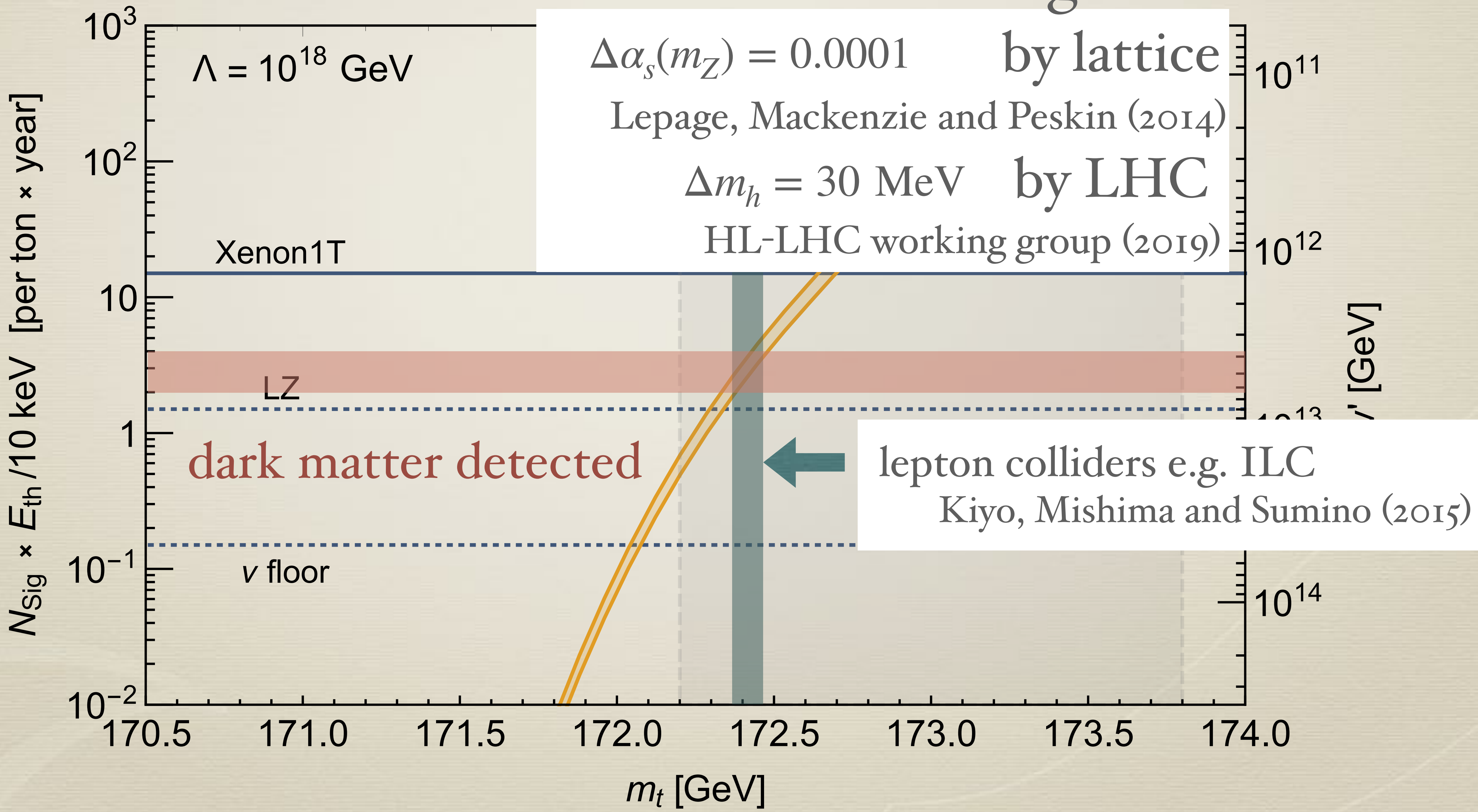
Dunsky, Hall, KH (2019)



SM parameters and DM

Dunsky, Hall, KH (2019)

Direct detection rate for Xe targets



Outline

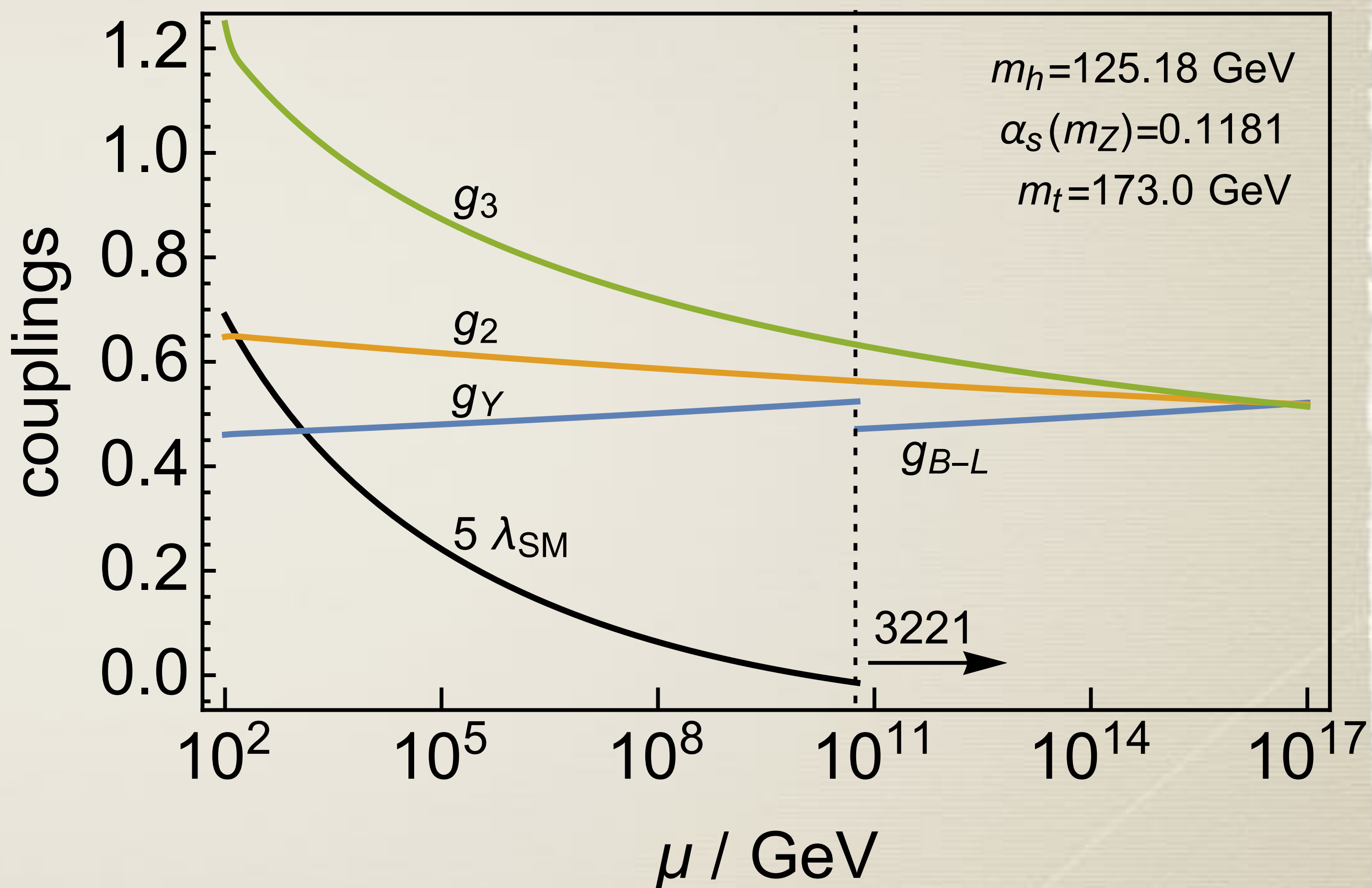
* Introduction
* Higgs Parity
* Dark matter
* Grand unification and proton decay
* Summary and outlook

different theories

Precise measurement and Grand Unification

Hall and KH (2018, 2019)

top quark yukawa
Higgs mass
strong coupling constant



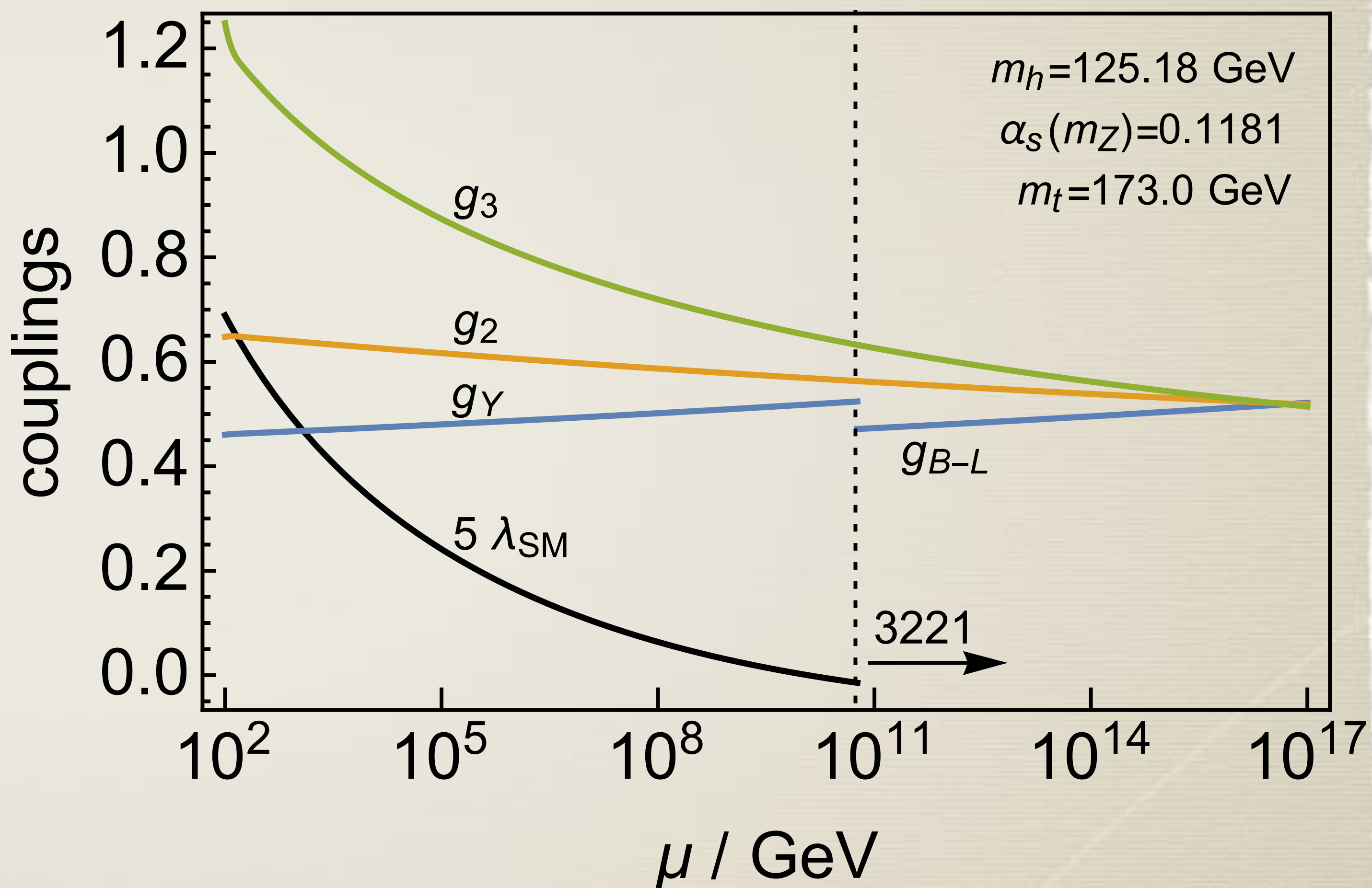
Higgs Parity
symmetry breaking scale

Proton decay from
Grand Unification

Precise measurement and Grand Unification

Hall and KH (2018, 2019)

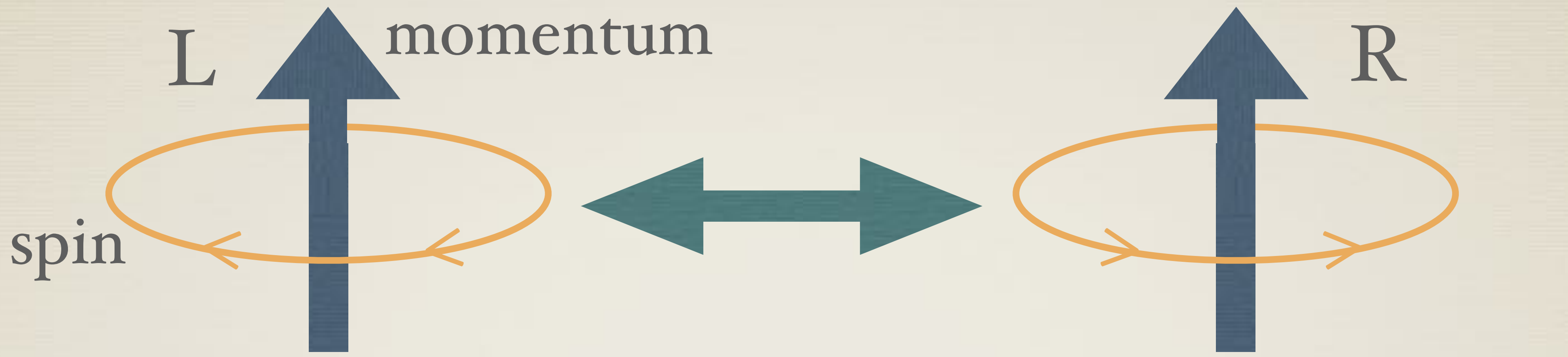
top quark yukawa
Higgs mass
strong coupling constant

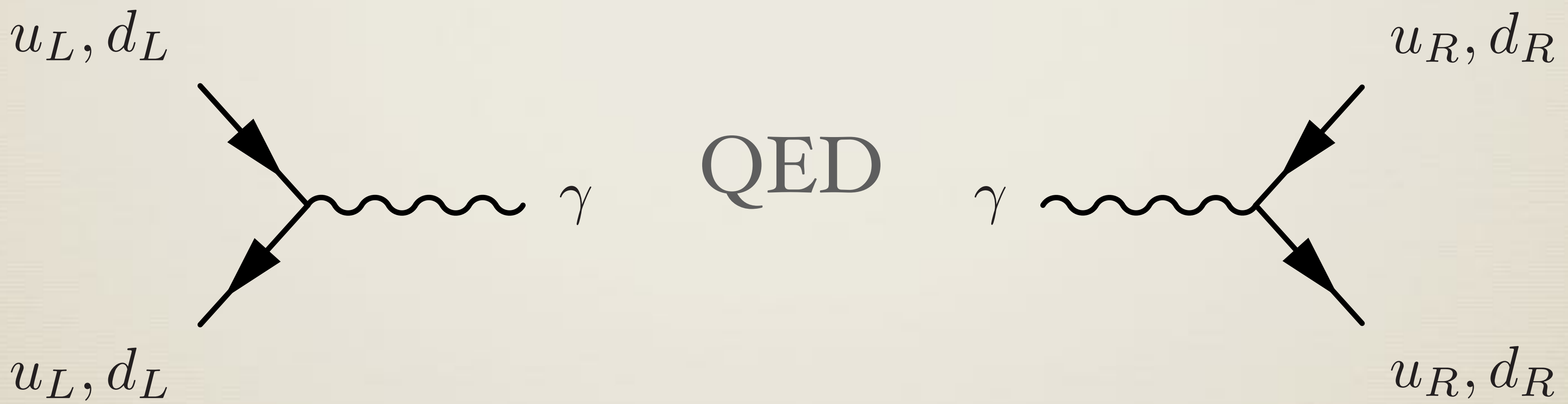


Left-Right
Higgs Parity
symmetry breaking scale

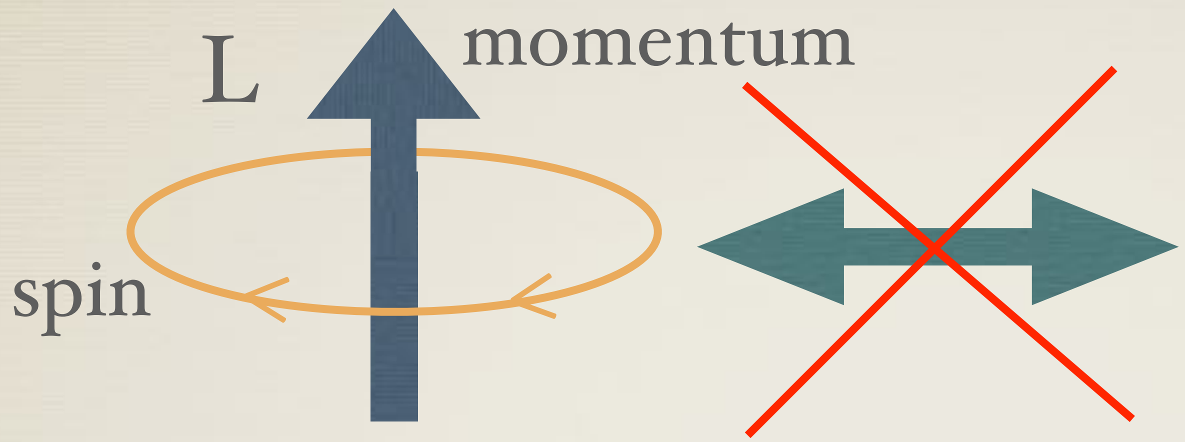
Proton decay from
Grand Unification

Left-Right symmetry

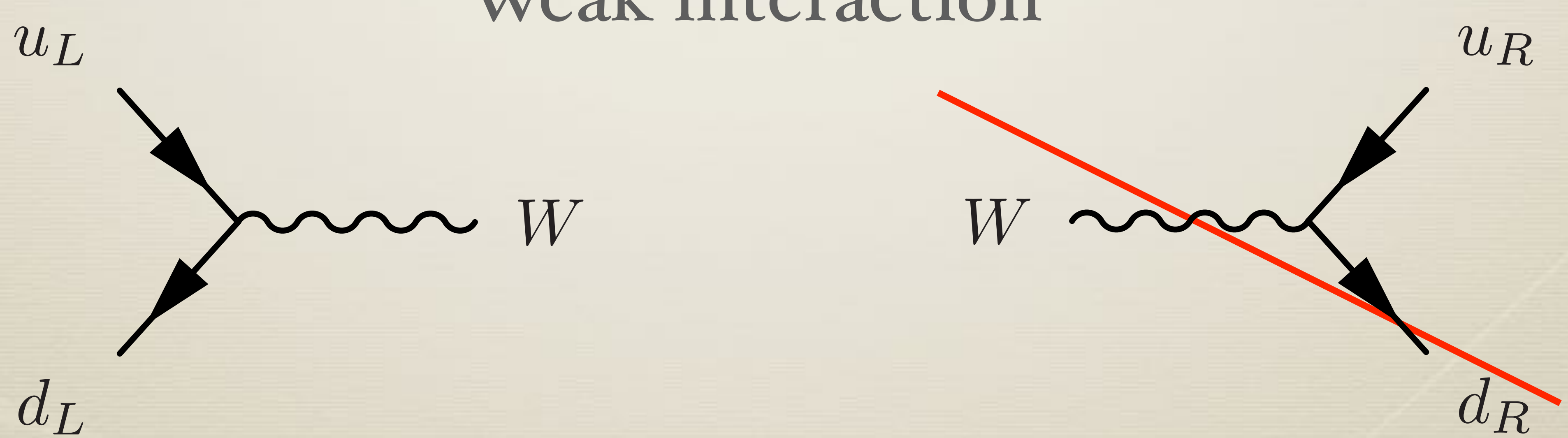




Left-Right symmetry

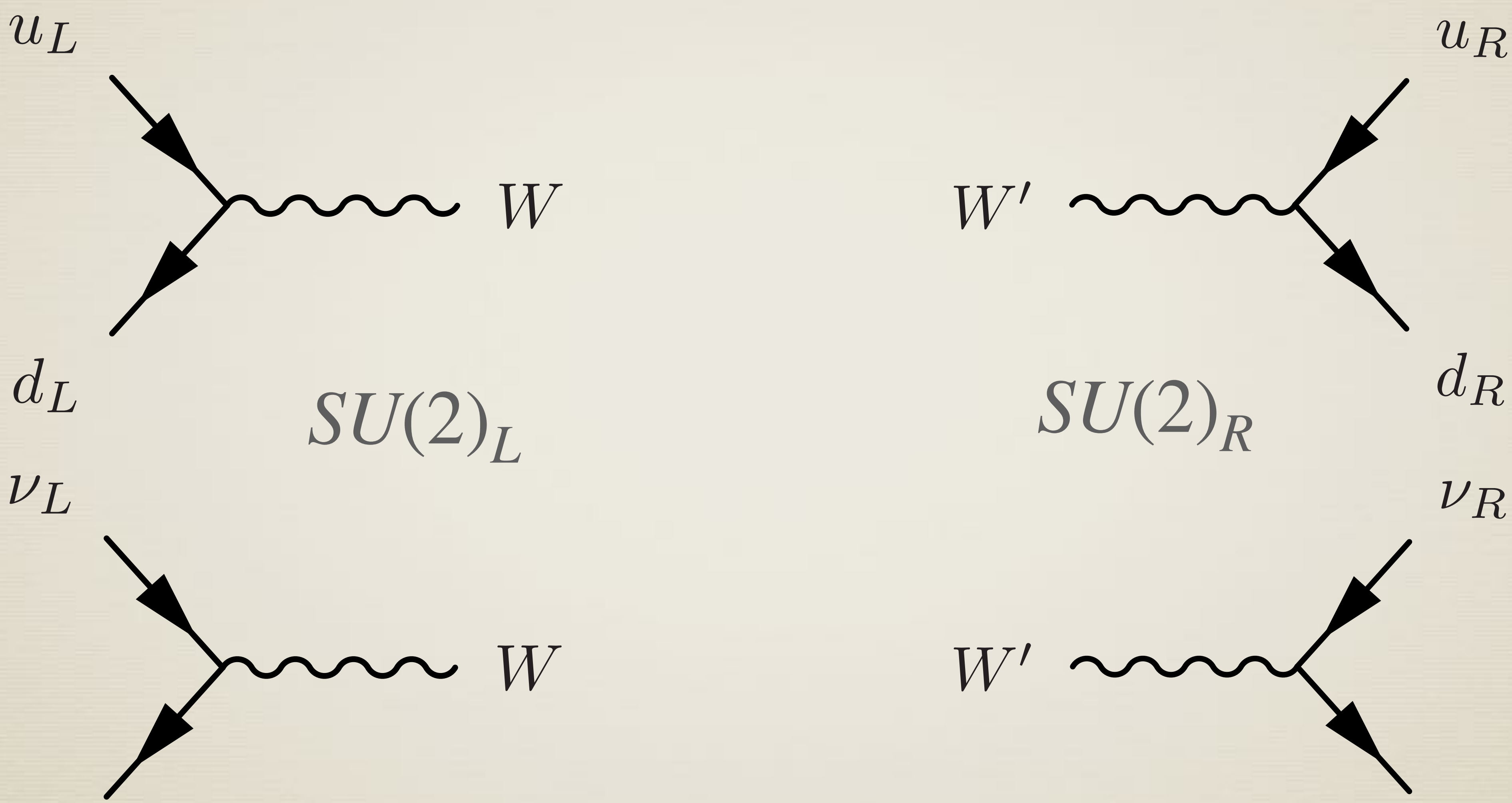


Weak interaction



Lee and Yang (1956), Wu (1957)

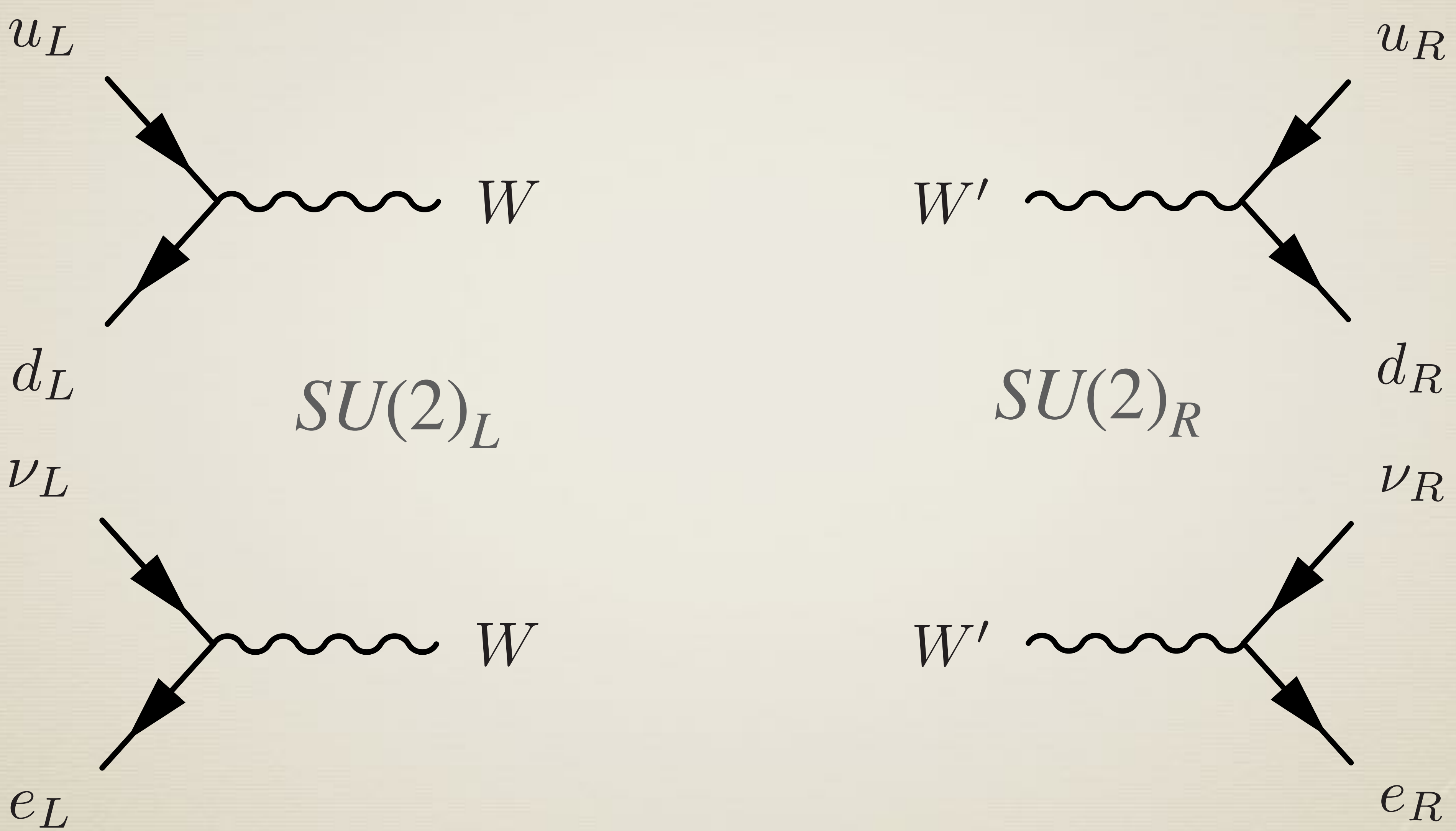
Spontaneously broken Left-Right symmetry



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

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

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

Left-Right symmetry and Grand Unified Theory

Standard Model $q_L = (u_L, d_L),\;\; L_L = (\nu_L, e_L),\;\; u_R,\;\; d_R,\;\; e_R$

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

Left-Right Symmetry $q_L,\;\; L_L,\;\; q_R,\;\; L_R$

$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Grand Unification ψ_{16}

$SO(10)$

Single gauge group, single type of fermions

Fritzsch and Minkowski (1975), Georgi (1975)

Left-Right Higgs Parity

Higgs ⟷ Higgs'

H ⟷ H'

Weak gauge boson ⟷ Weak gauge boson'

W ⟷ W'

$SU(2)$ ⟷ $SU(2)'$

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

q_L, L_L ⟷ $q', L' = q_R, L_R$

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

Left-Right Higgs Parity

Higgs H	⟷	Higgs' H'
Weak gauge boson W $SU(2)$	⟷	Weak gauge boson' W' $SU(2)'$
left-handed quark, lepton q_L, L_L	⟷	right-handed quark, lepton $q', L' = q_R, L_R$

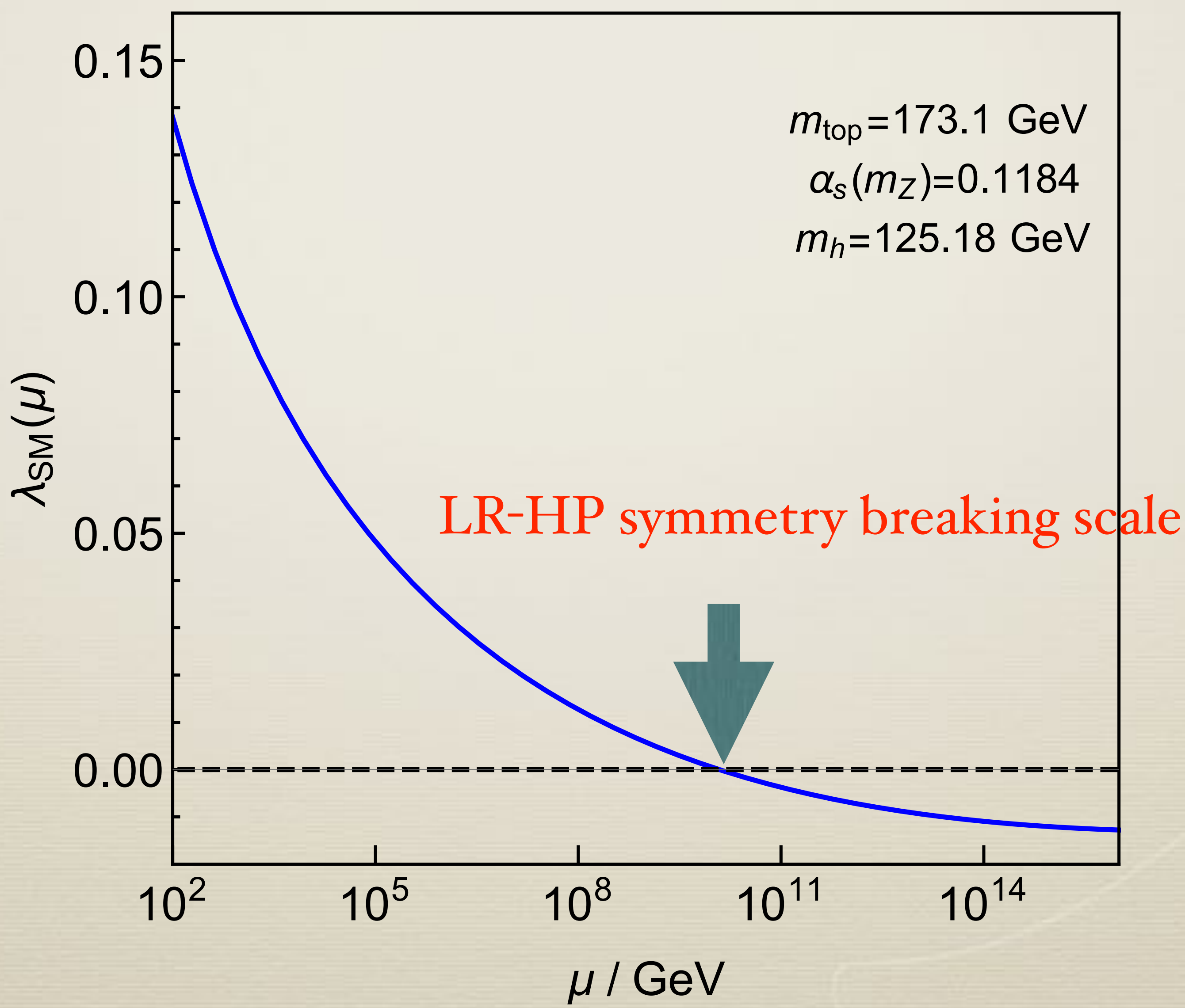
$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$\langle H' \rangle$ ↓

$$U(1)_Y \qquad Y = \frac{B-L}{2} \pm T_{3R}$$

Left-Right Higgs Parity

Higgs H ↔ Higgs' H'



Symmetry breaking

Hall, KH (2018)

Grand Unification $SO(10)$ $H, H' \subset 16$

quarks, leptons = 16

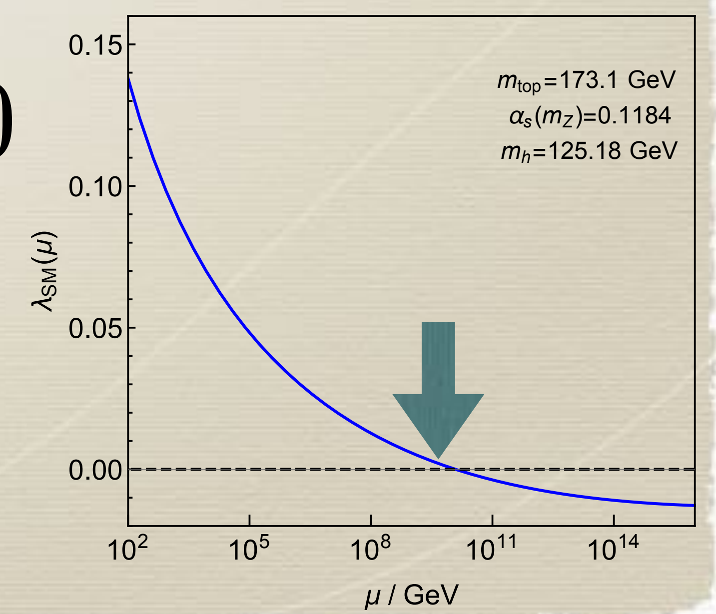
Left-Right HP

$$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

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

Standard Model

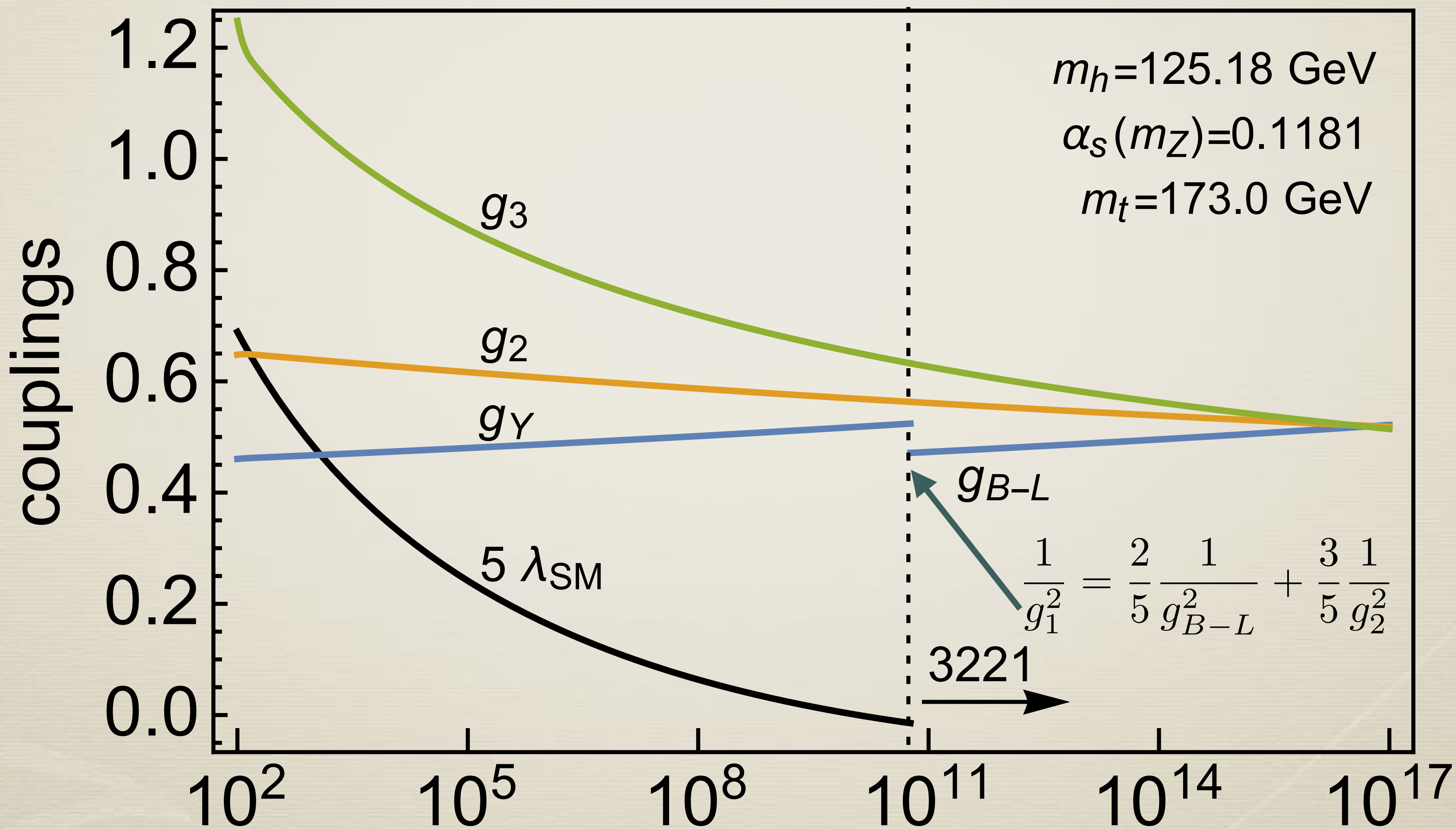
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$



Coupling unification

Hall, KH (2018, 2019)

energy-dependent couplings

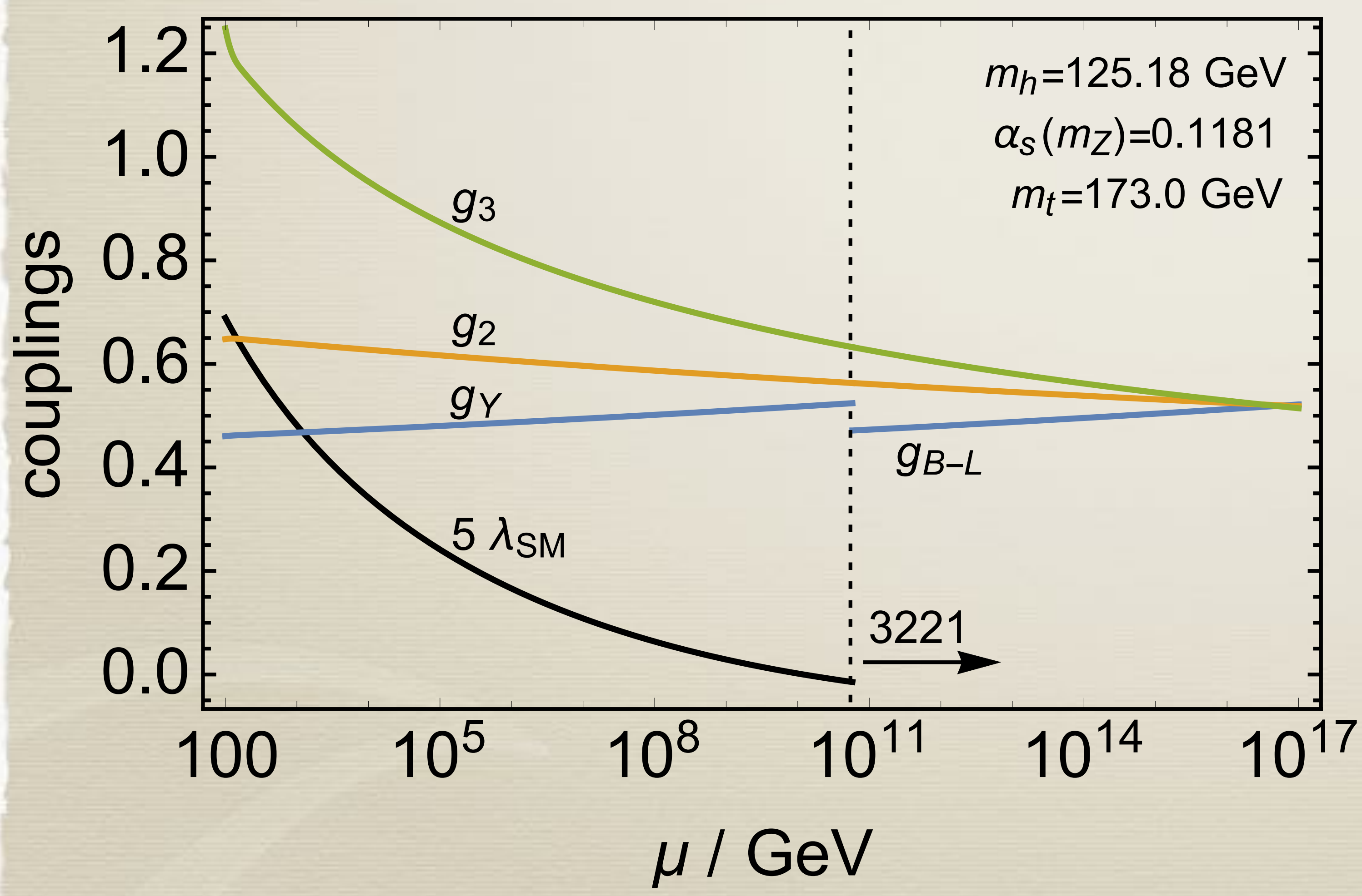


RGE scale μ / GeV

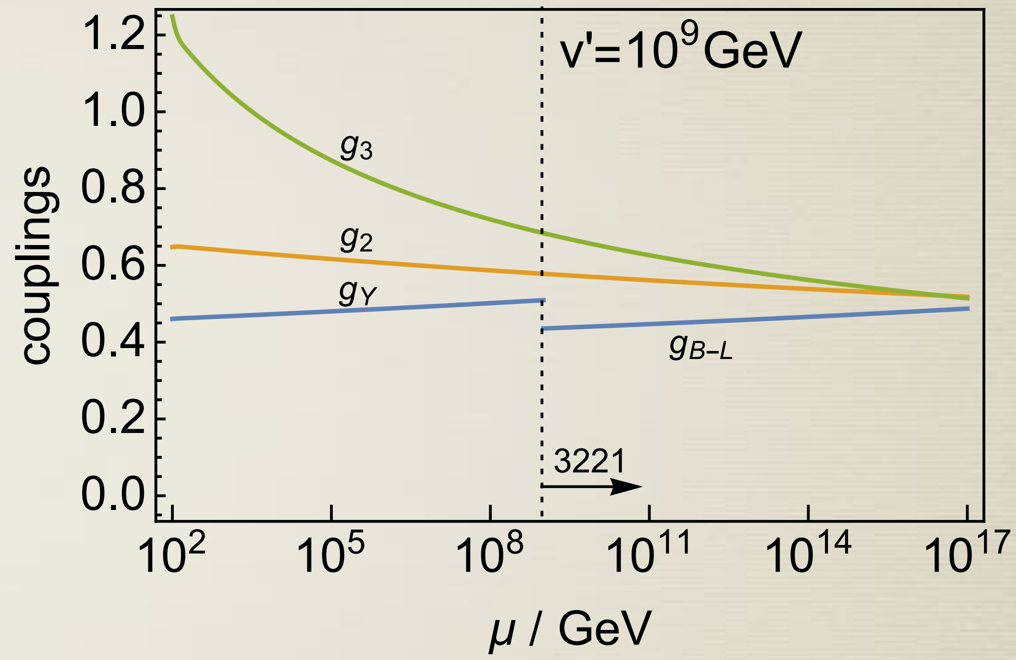
Coupling unification

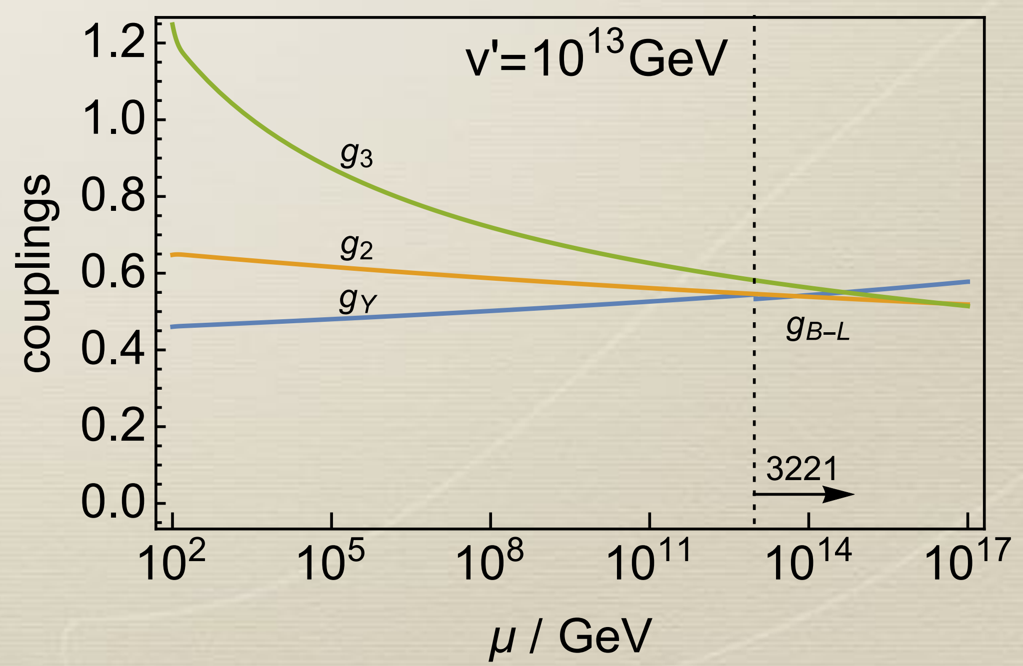
Hall, KH (2018, 2019)

v' determined by Higgs Parity



Other v'

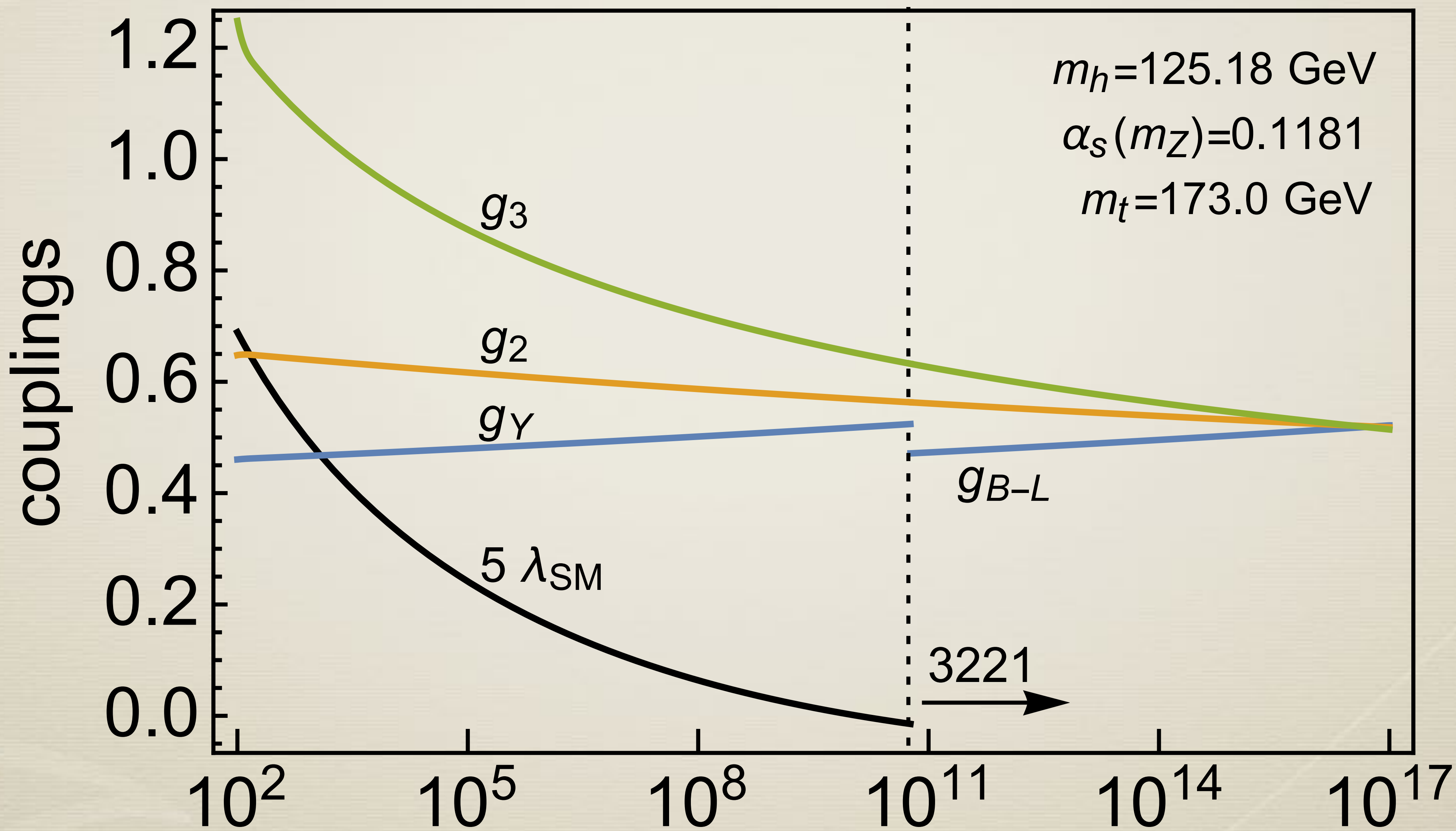




Higgs Parity GUT

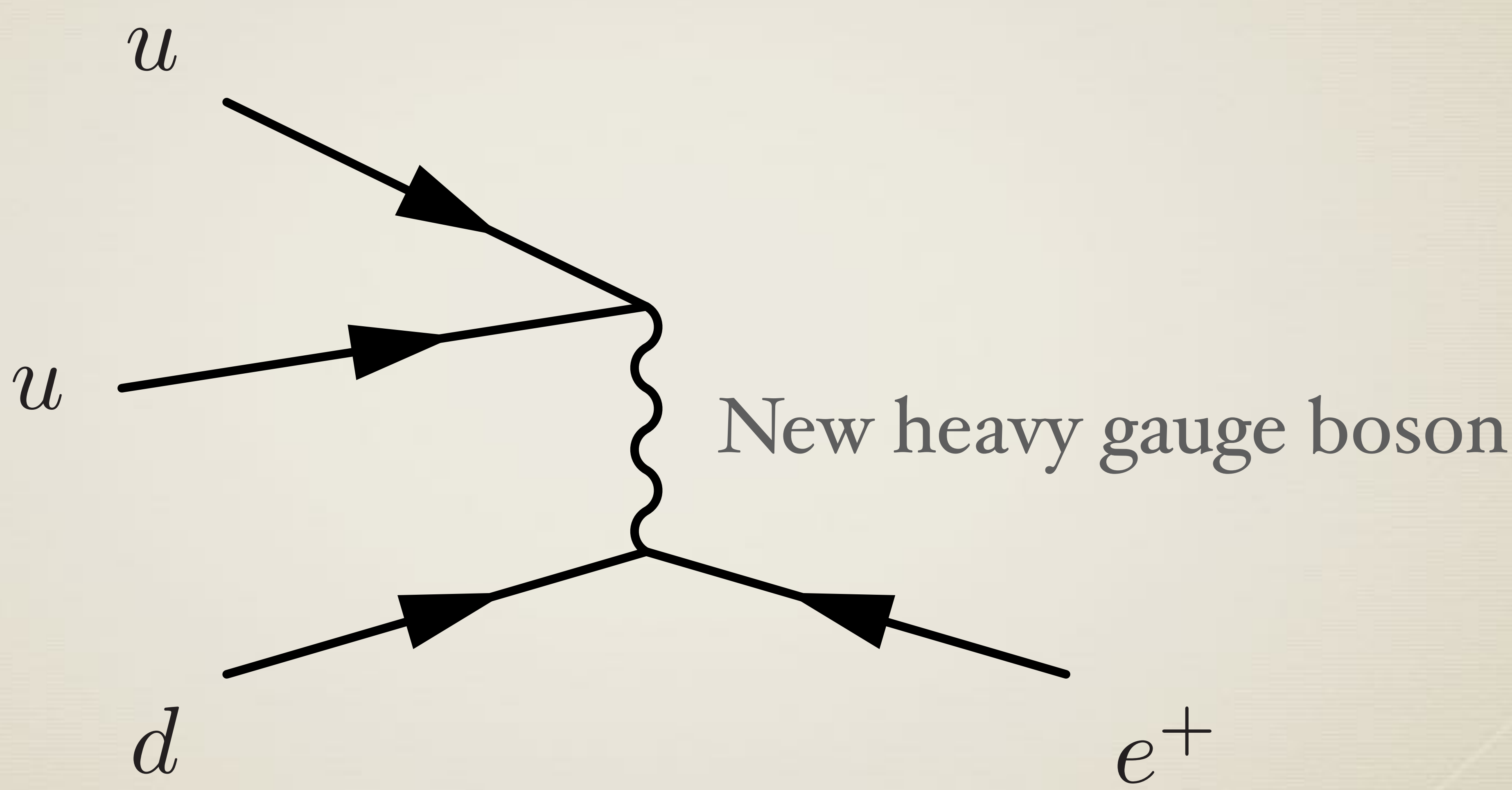
Hall, KH (2018, 2019)

energy-dependent couplings



RGE scale μ / GeV

Proton decay

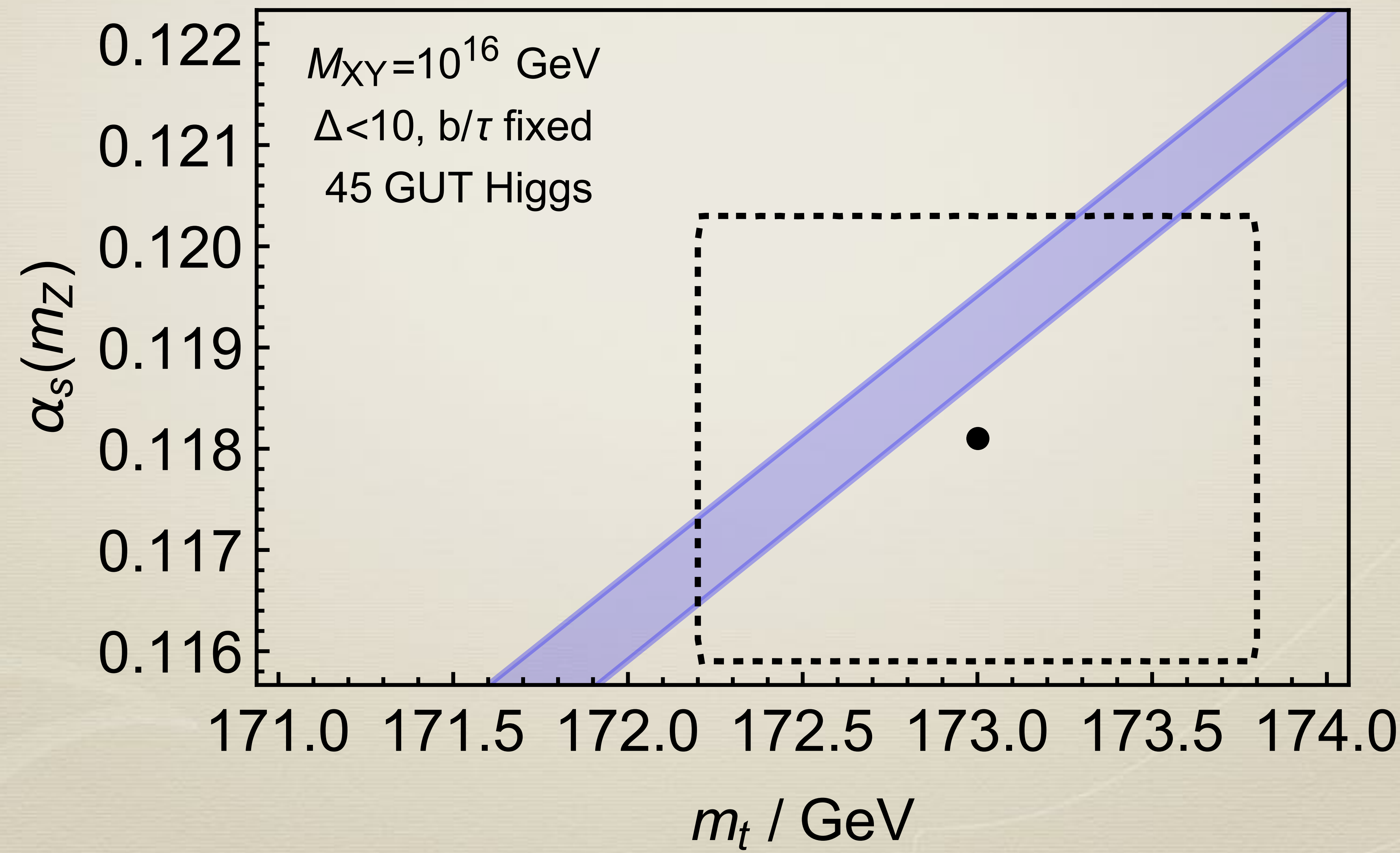


$$p \rightarrow e^+\pi^0$$

Proton decay

Hall, KH (2019)

Suppose proton decay is observed at Hyper-K

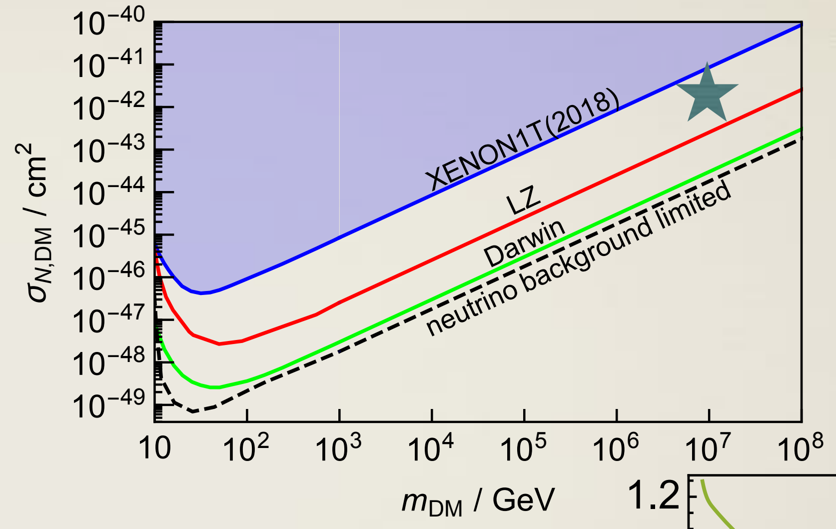


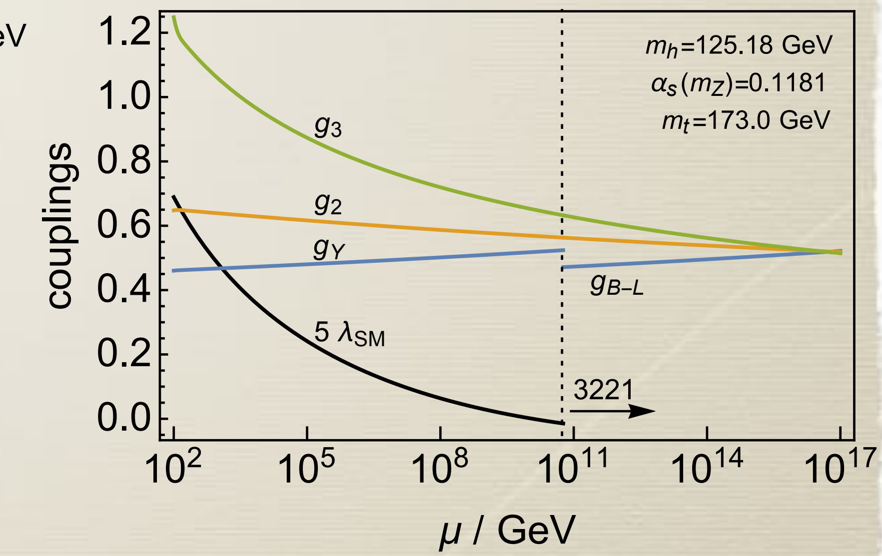
Summary and outlook

Higgs Parity

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

top quark yukawa
Higgs mass
strong coupling constant





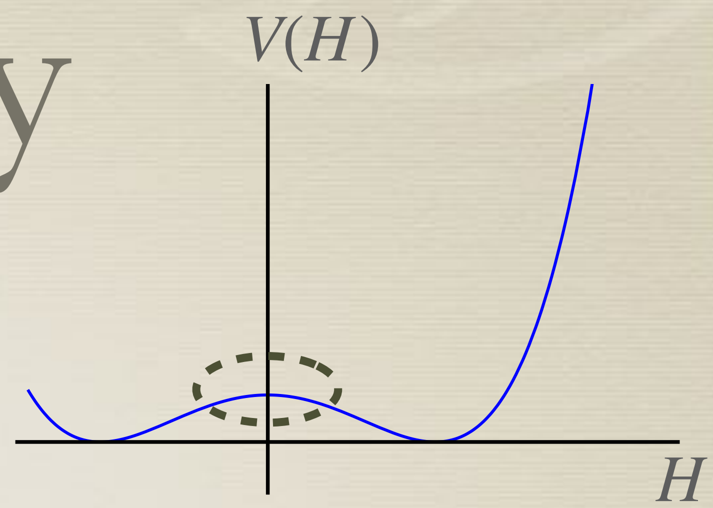
Higgs Parity
symmetry breaking scale

Dark matter direction,
proton decay

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

Supersymmetry

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



Dark matter

Witten (1981), Pagels and Primack (1982), Goldberg (1983), ...

Grand unification

Dimopoulos, Raby and Wilczek (1981), Dimopoulos and Georgi (1981), Sakai (1981) Ibanez and Ross (1981), Einhorn and Jones (1982), Marciano and Senjanovic (1982), ...

Inflation models

Ovrut and Steinhardt (1983), Holman, Ramond and Ross (1983), Goncharov and Linde (1984), ...

Baryon asymmetry

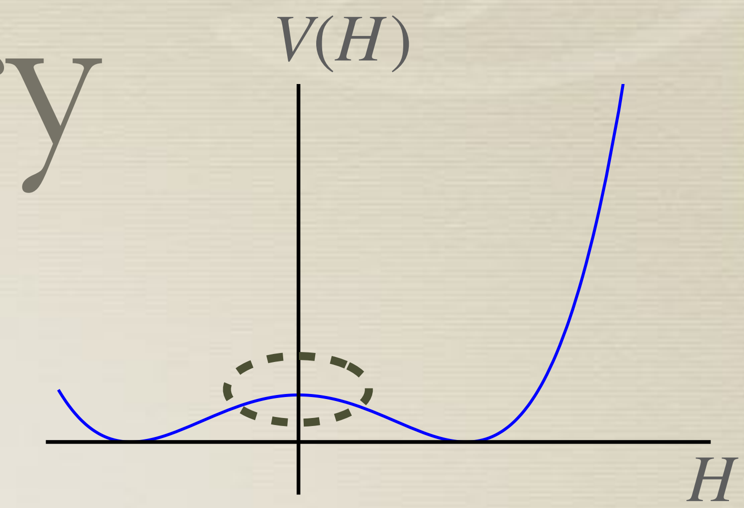
Affleck and Dine (1985), Cohen and Nelson (1992)

QCD axion

Kim (1984), Kim, Masiero and Nanopoulos (1984), ...

Supersymmetry

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



Dark matter

KH, Kaneta and Matsumoto (2015), ...

Grand unification

KH, Ibe and Suzuki (2015)

KH and Yamada (2019)

Co and KH (2019)

Inflation models

KH, Ibe, Schmitz and Yanagida (2015), ...

Baryon asymmetry

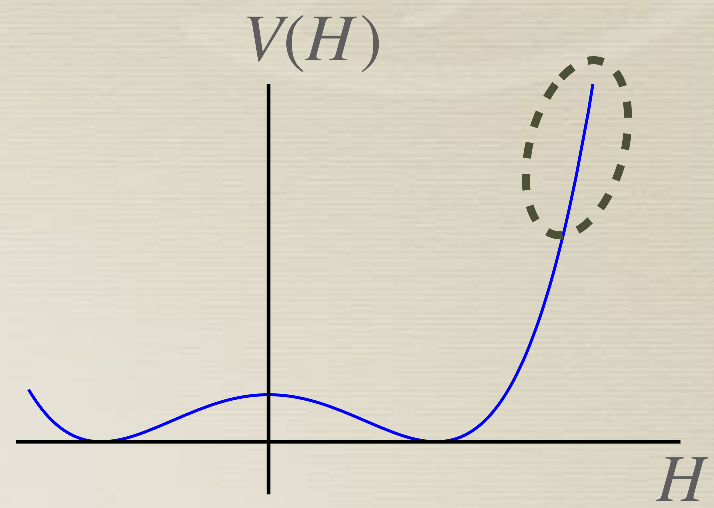
KH, Kamada, Kawasaki, Mukaida and Yamada (2019)

QCD axion

Co, Hall and KH (2017,2019), KH and Leedom (2017,2019), ...

Higgs Parity

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



Dark matter

Grand unification

Strong CP problem

Dunsky, Hall and KH (2019)

Hall and KH (2018,2019)

Dunsky, Hall and KH (2019)

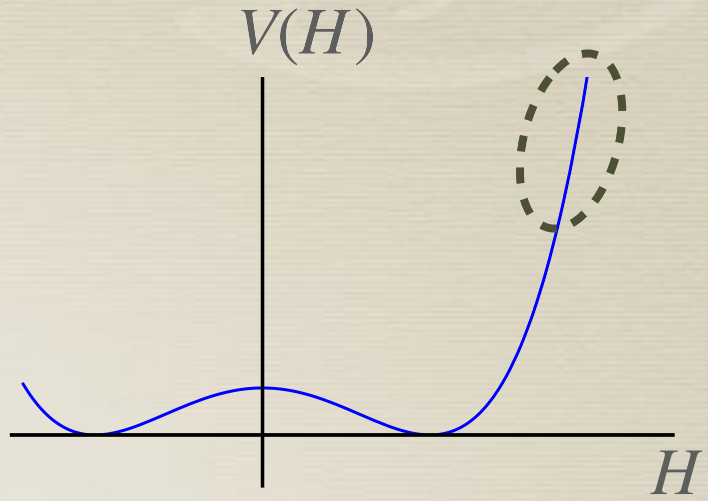
Dunsky, Dror, Hall
and KH (in progress)

Cosmology
Astrophysics

Baryon asymmetry

Higgs Parity

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



Dark matter

Grand unification

Strong CP problem

prediction on neutrinos from SO(10)?
hierarchy, masses, mixing, CP phase

Cosmology
Astrophysics

warm dark matter,
gravitational waves, ...

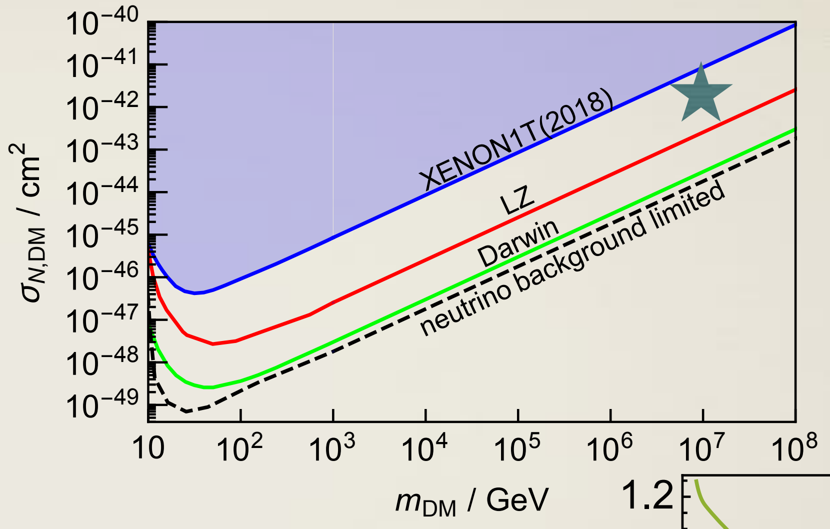
Baryon asymmetry

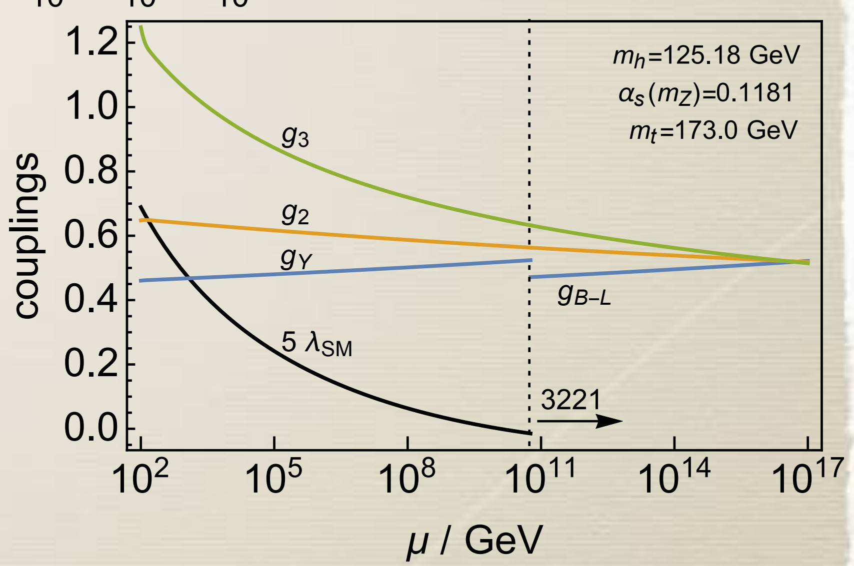
leptogenesis from ν'

Summary

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

top quark yukawa
Higgs mass
strong coupling constant





Higgs Parity
symmetry breaking scale

Dark matter direction,
Proton decay

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

Back up

On fine-tuning

Fine-tuning

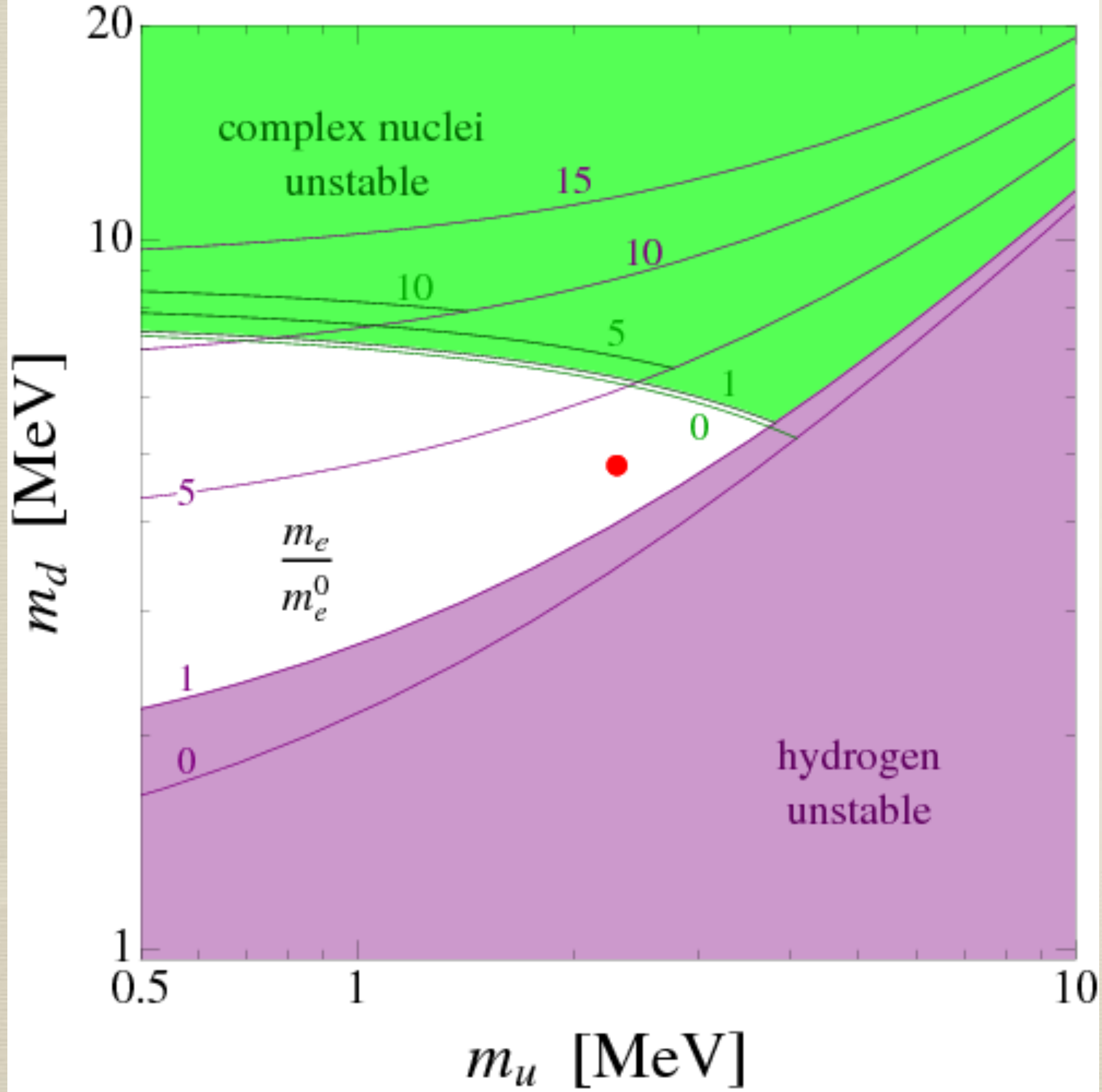
$$V = \lambda(|H|^2 + |H'|^2 - v'^2)^2 + y|H|^2|H'|^2$$

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

Same as that of standard model

Stability of nuclei

Plot from Hall, Pinner, Ruderman (2014)

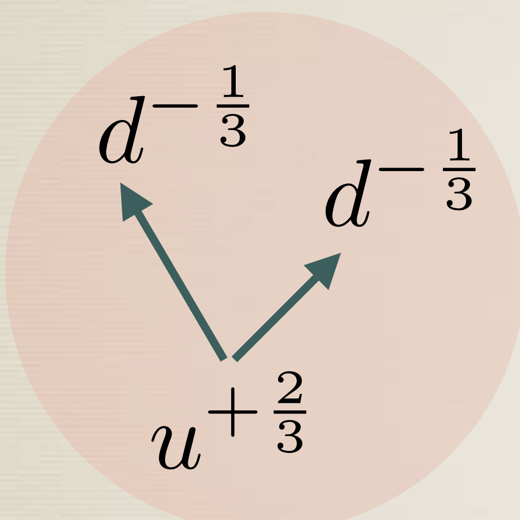


We need smaller yukawa to compensate large v

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

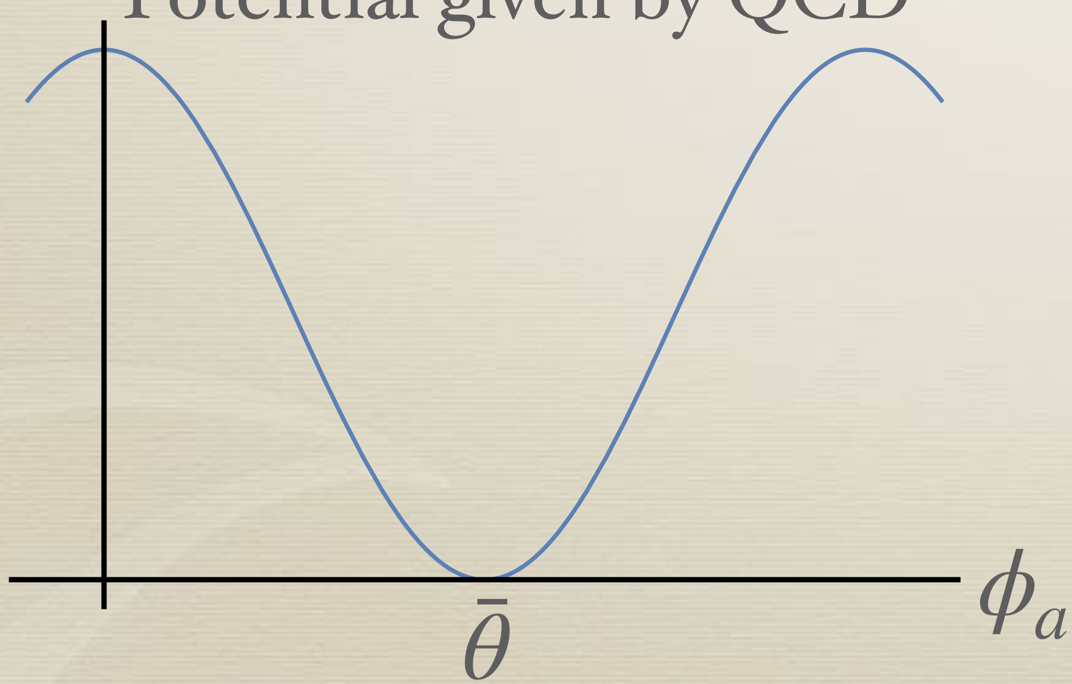
* QCD axion

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

* Spontaneously broken CP
* Spontaneously broken parity

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

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

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

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

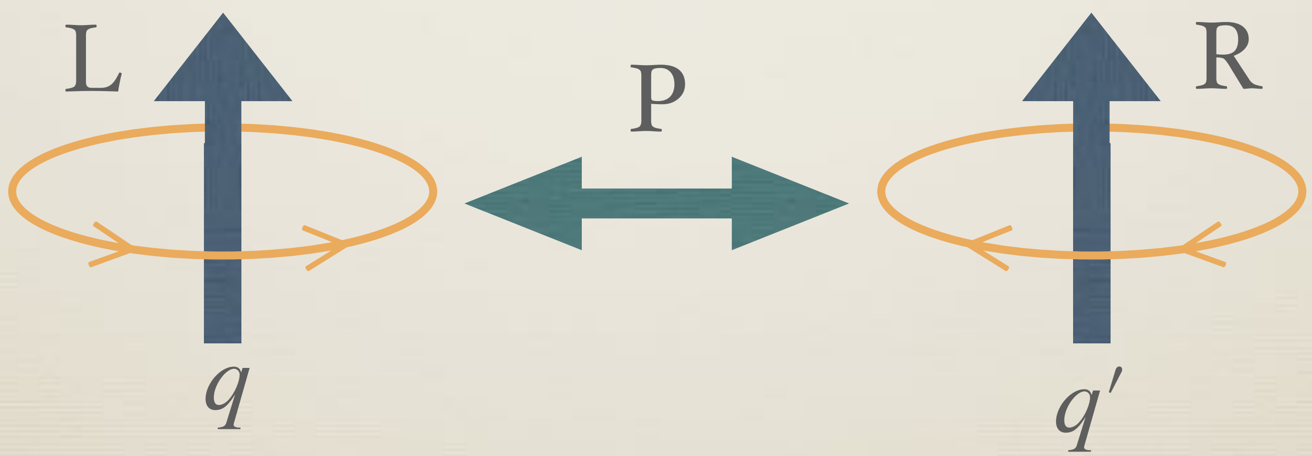
but in a sophisticated way so that $\bar{\theta}$ remains zero

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

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

$\downarrow$

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

electroweak’

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

$\downarrow$

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

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

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

$\Delta\bar{\theta}_q$

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

$\bar{\theta} = \Delta\bar{\theta}_q + (-\Delta\bar{\theta}_q) = 0$

cancel with each other

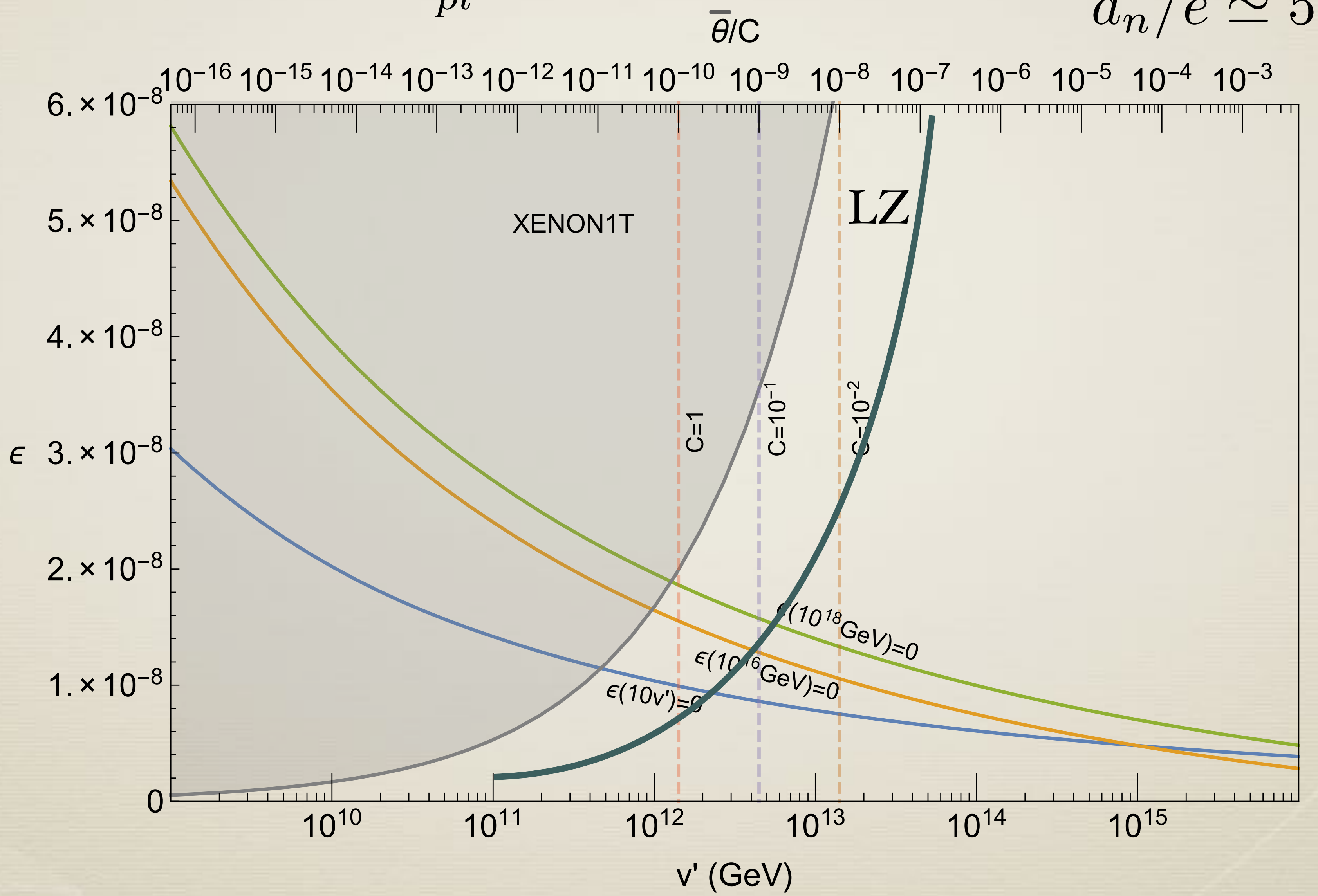
Non-zero CP violation

$$\frac{C}{M_{pl}^2}(|H|^2 - |H'|^2)G\tilde{G}$$

Dunsky, Hall, KH (2019)

$$d_n/e \simeq 5 \times 10^{-16}\bar{\theta}\ \text{cm}$$

$$\frac{\epsilon}{2}FF'$$



Large v' : neutron EDM

Small v' : DM direct detection

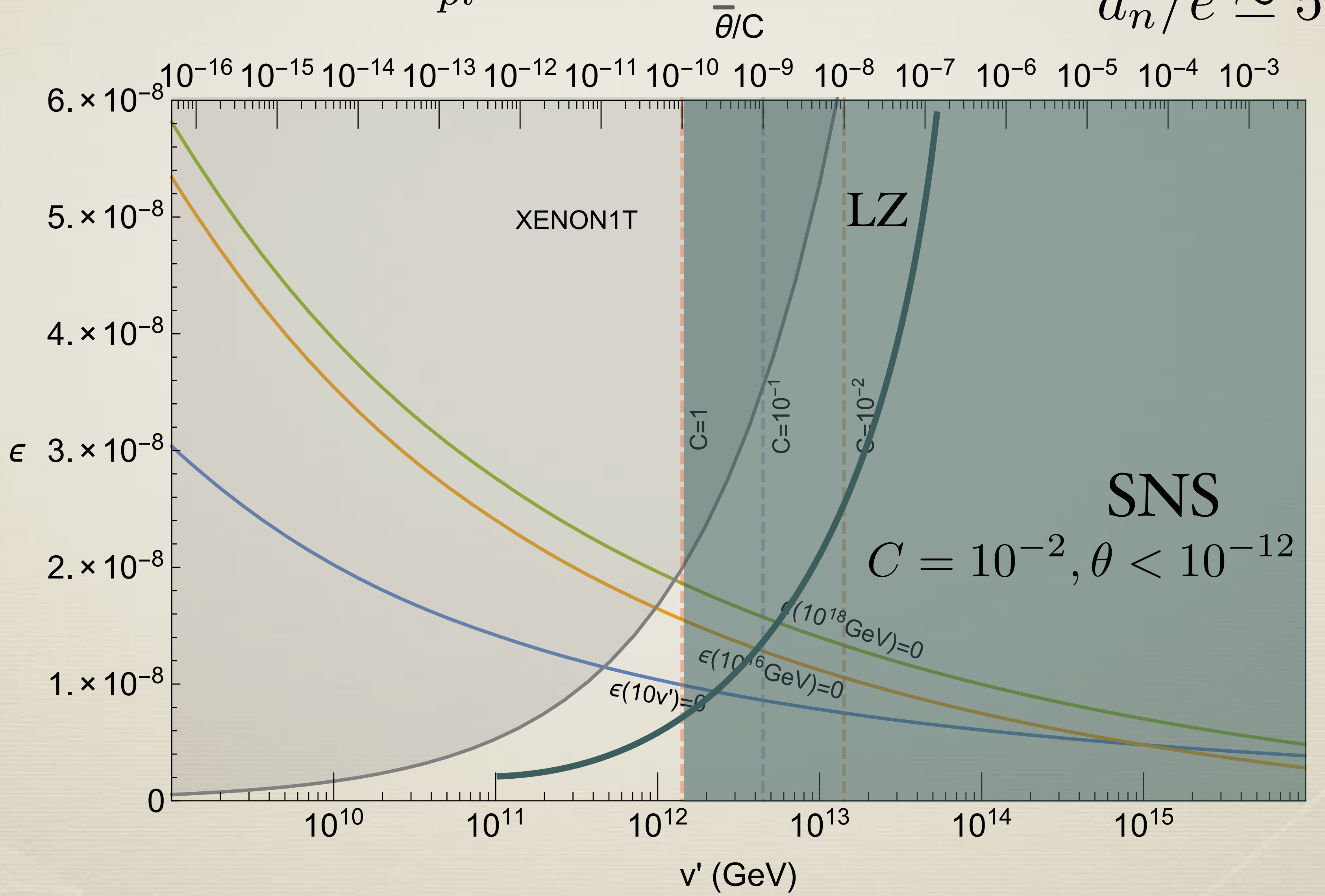
Non-zero CP violation

$$\frac{C}{M_{pl}^2}(|H|^2 - |H'|^2)G\tilde{G}$$

Dunsky, Hall, KH (2019)

$$d_n/e \simeq 5 \times 10^{-16}\bar{\theta}\ \mathrm{cm}$$

$$\frac{\epsilon}{2}FF'$$



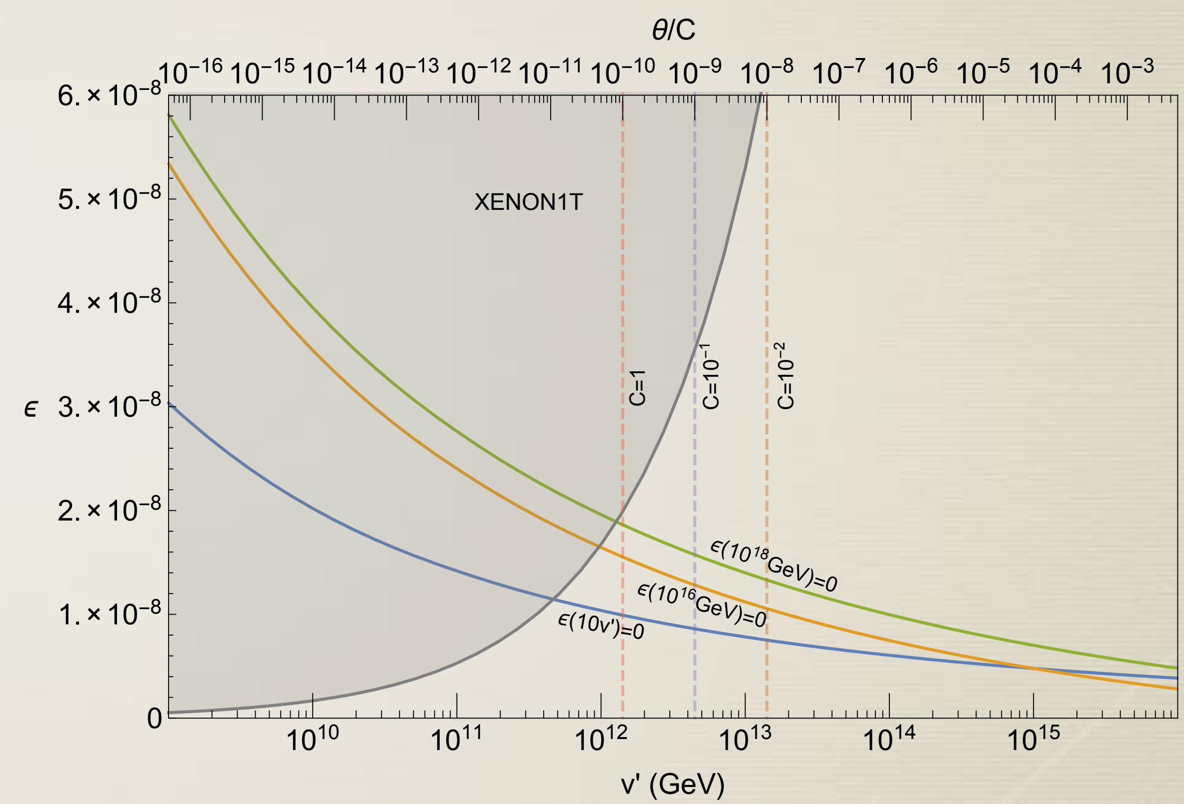
Large v’ : neutron EDM

Small v’ : DM direct detection

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

Neutron EDM

$$d_n \simeq 5 \times 10^{-16} \theta e \text{ cm}$$

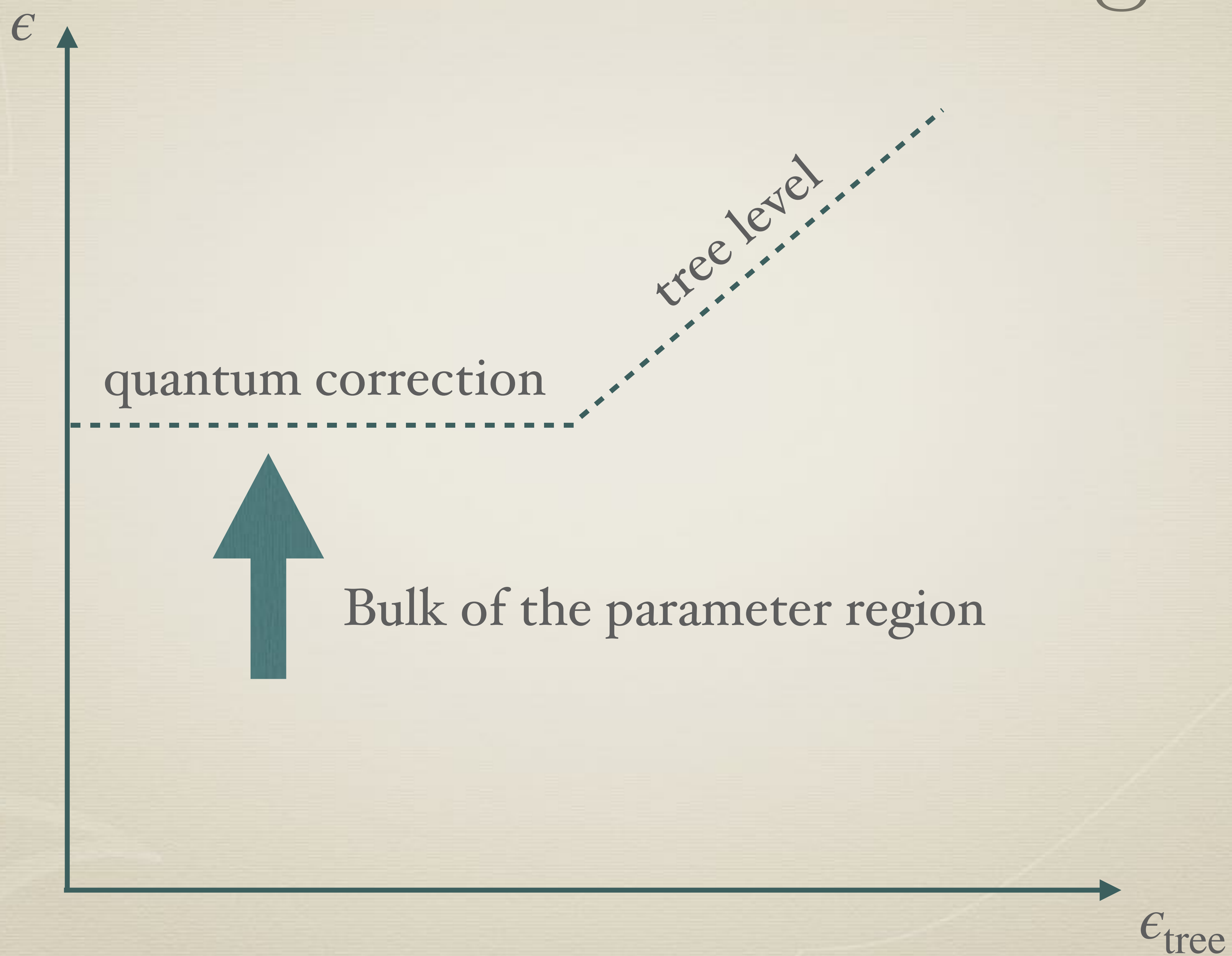
Crewther, Vecchia and Witten (1979)

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

$\theta < 10^{-12}$ in near future

Dark Matter

Prediction on mixing



u'u'u' DM?

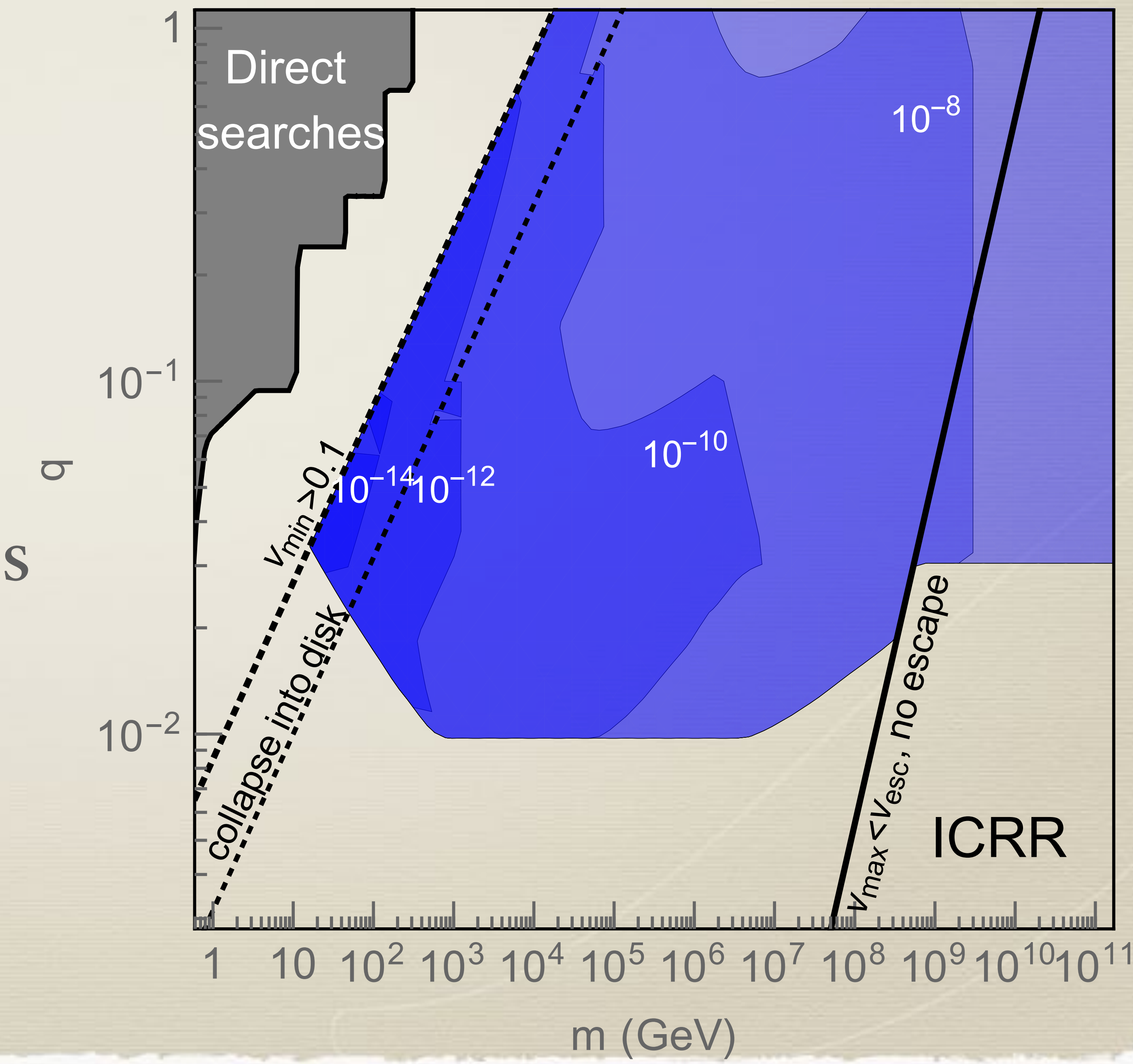
u'qq, u'qbar are necessarily produced after the QCD phase transition

Dunsky, Hall, KH (2018)

Upper bound on

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

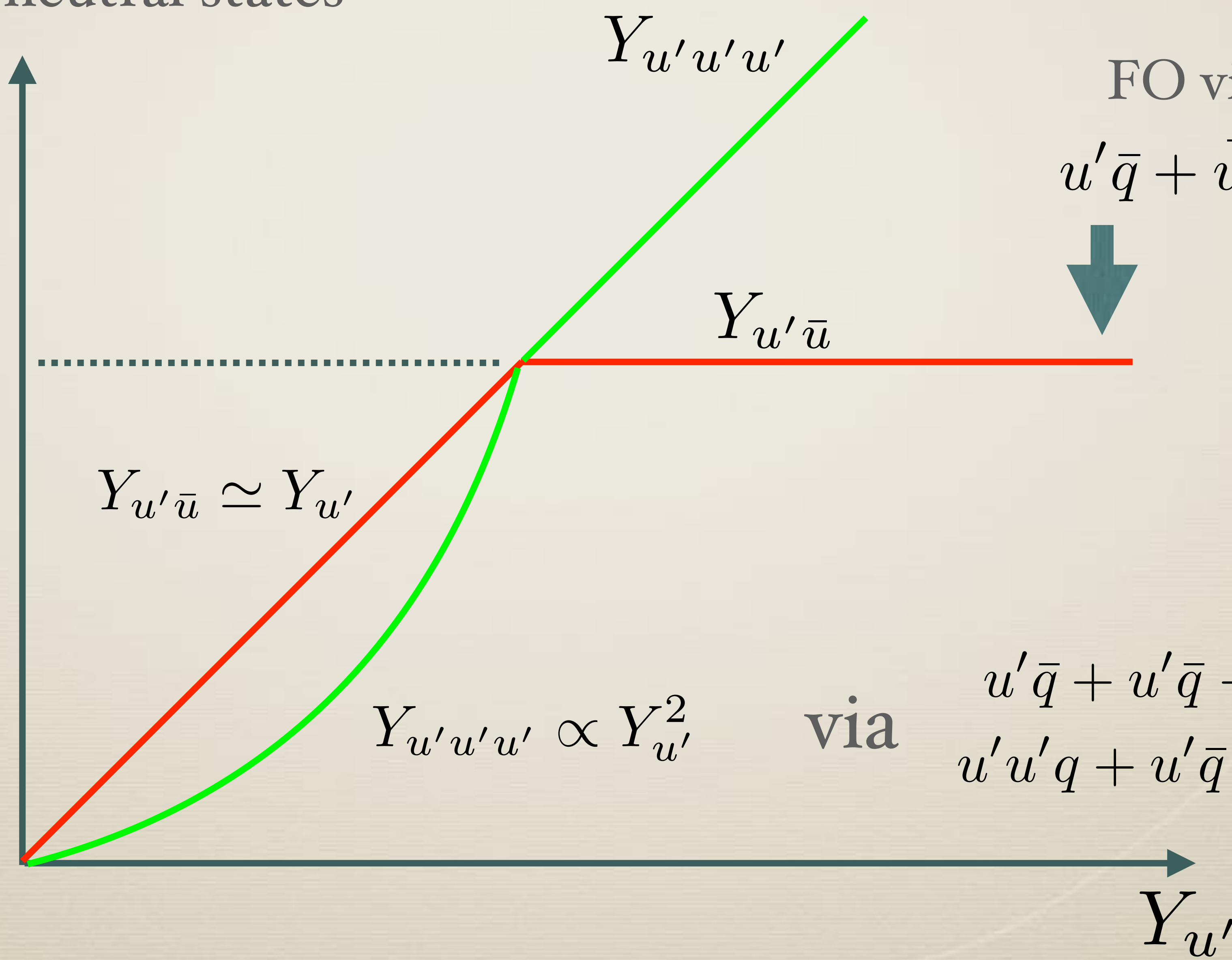
by ionizing particle searches



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

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

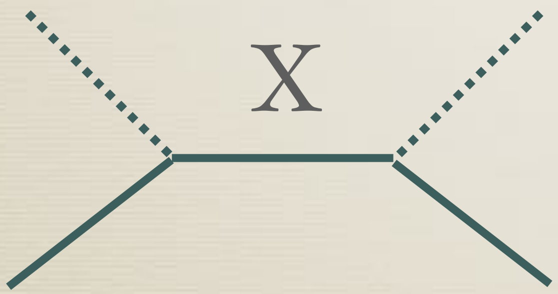
Other possibilities?
Baryogenesis for low temperature?

GUT

Yukawa interaction

No gauge invariant renormalizable coupling

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

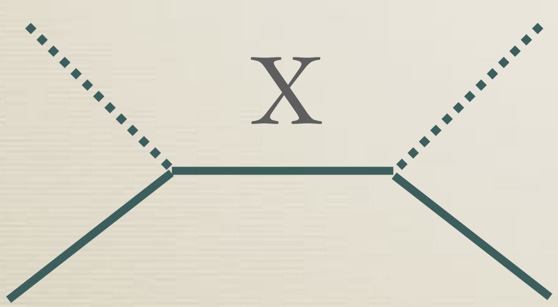


Strong CP problem solved

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

No gauge invariant renormalizable coupling

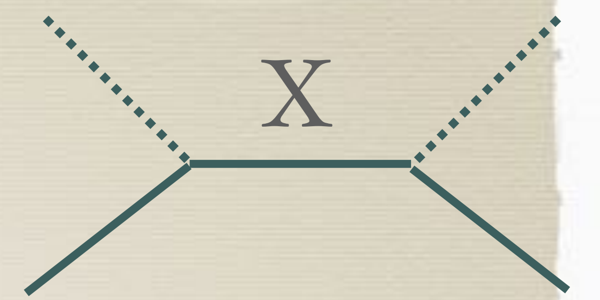
$$\frac{c_{ij}}{M} H H' q_L \bar{q}_R$$



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

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

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	**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

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

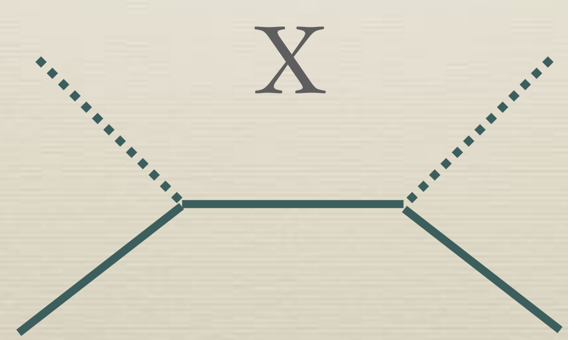
$$SO(10) \times CP \xrightarrow{\phi_{45}^{-}} SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times P_{LR}$$

Real yukawas, without CP symmetry breaking...

A simple renormalizable example to obtain CP phases

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

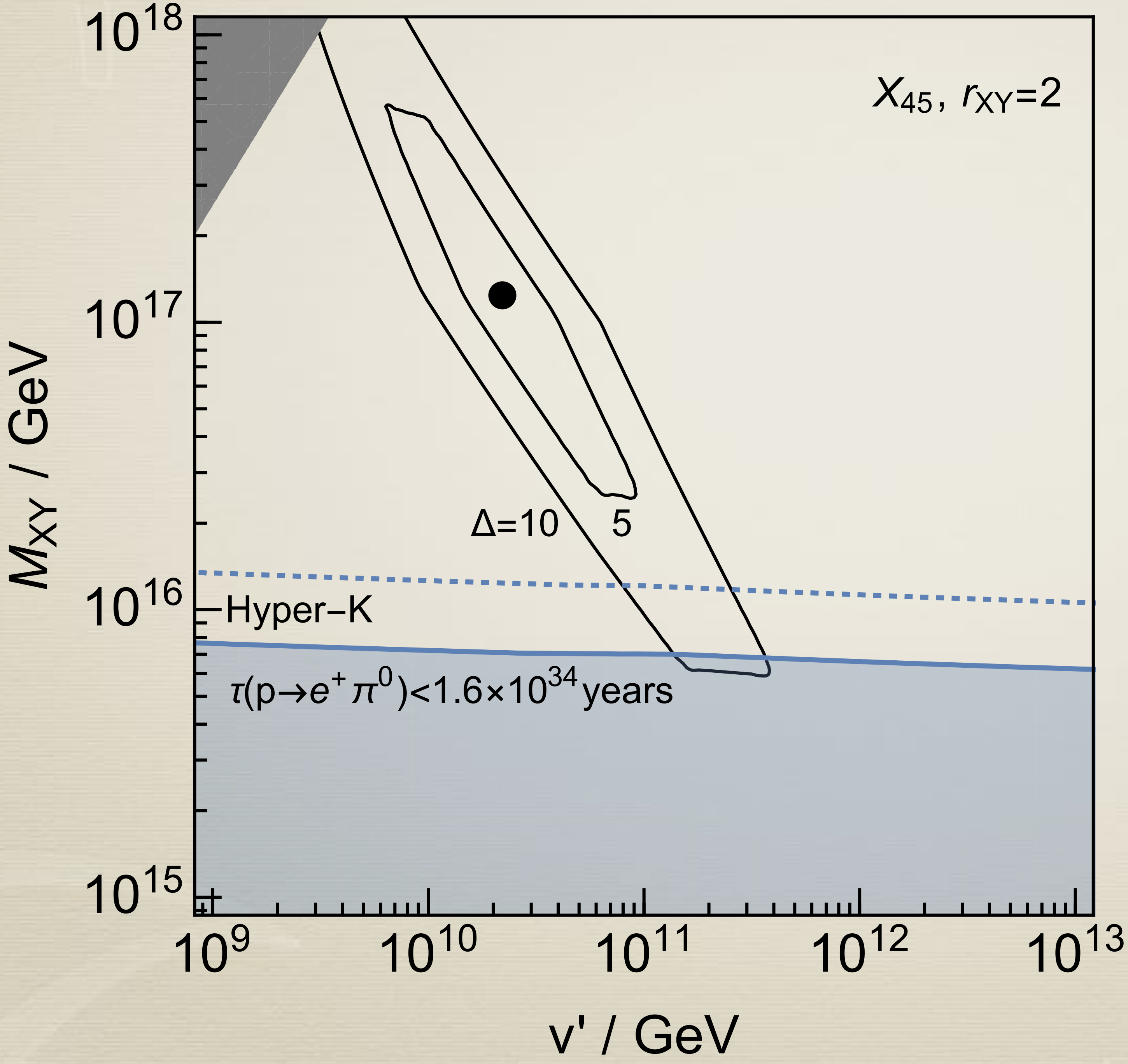
$$\frac{c_{ij}}{M} H H' q_i q'_j$$



Quantify unification

Hall, KH (2019)

mass of new gauge boson mediating proton decay



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

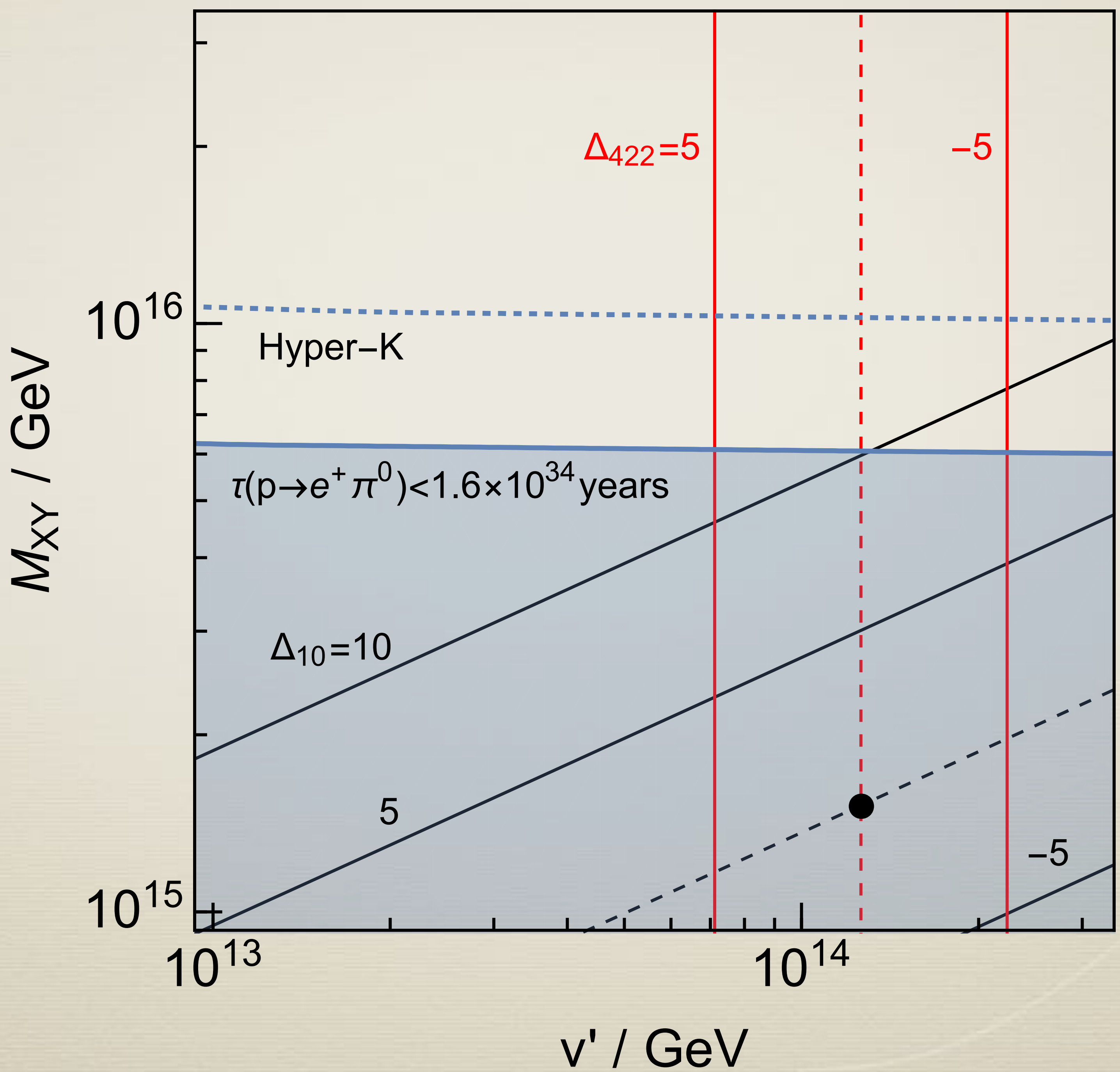
$$\Delta = \max_{i,j} \left| \frac{8\pi^2}{g_i^2} - \frac{8\pi^2}{g_j^2} \right|$$

typically

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

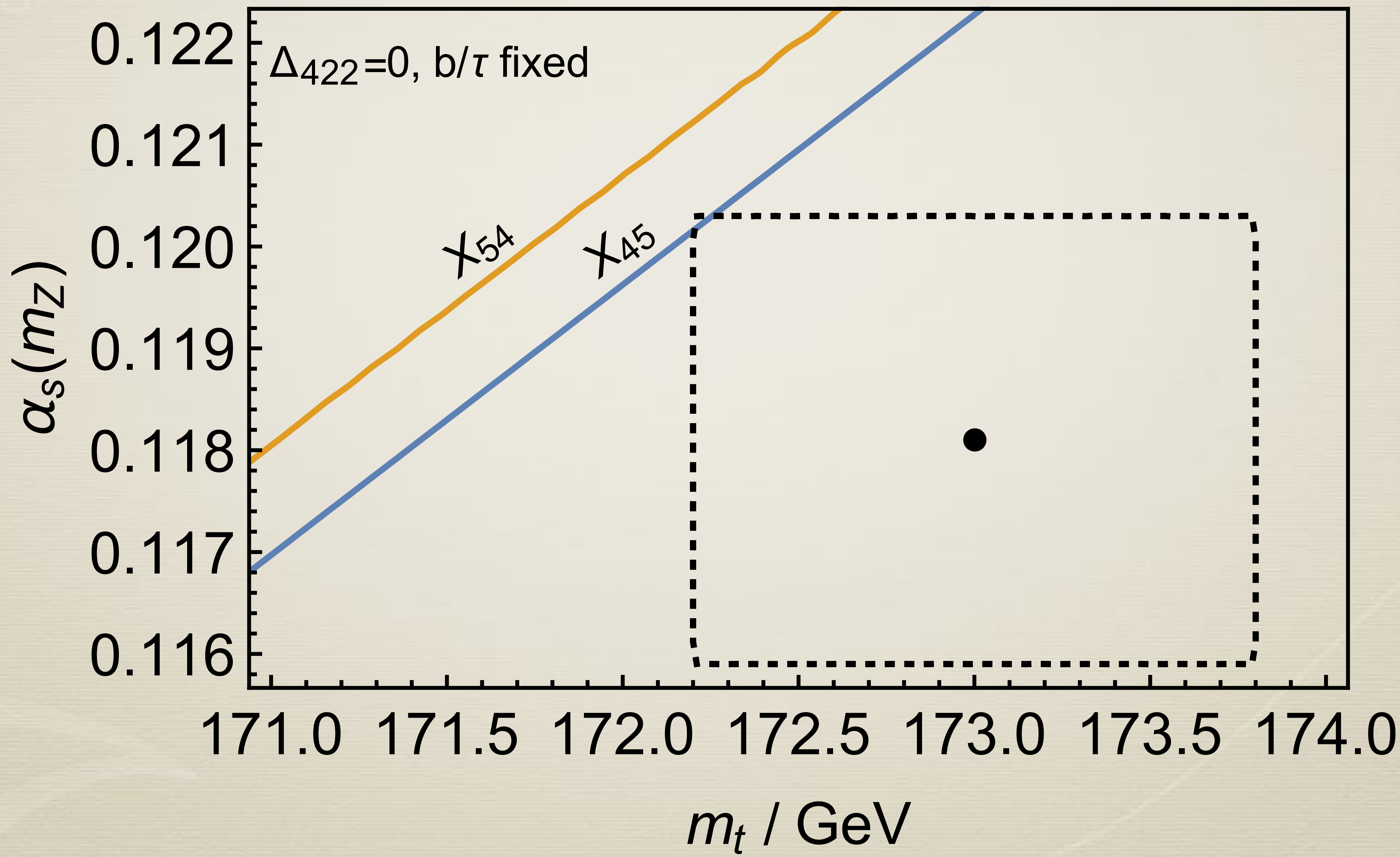
(smaller than SUSY GUT)

Pati-Salam



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

Pati-Salam



Δ422=0, b/τ fixed
X54
X45
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

Top-down perspective

SUSY GUT

3 parameters → 4 parameters

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

(or more, e.g. $\Omega_{\rm DM}$)

Similar structures

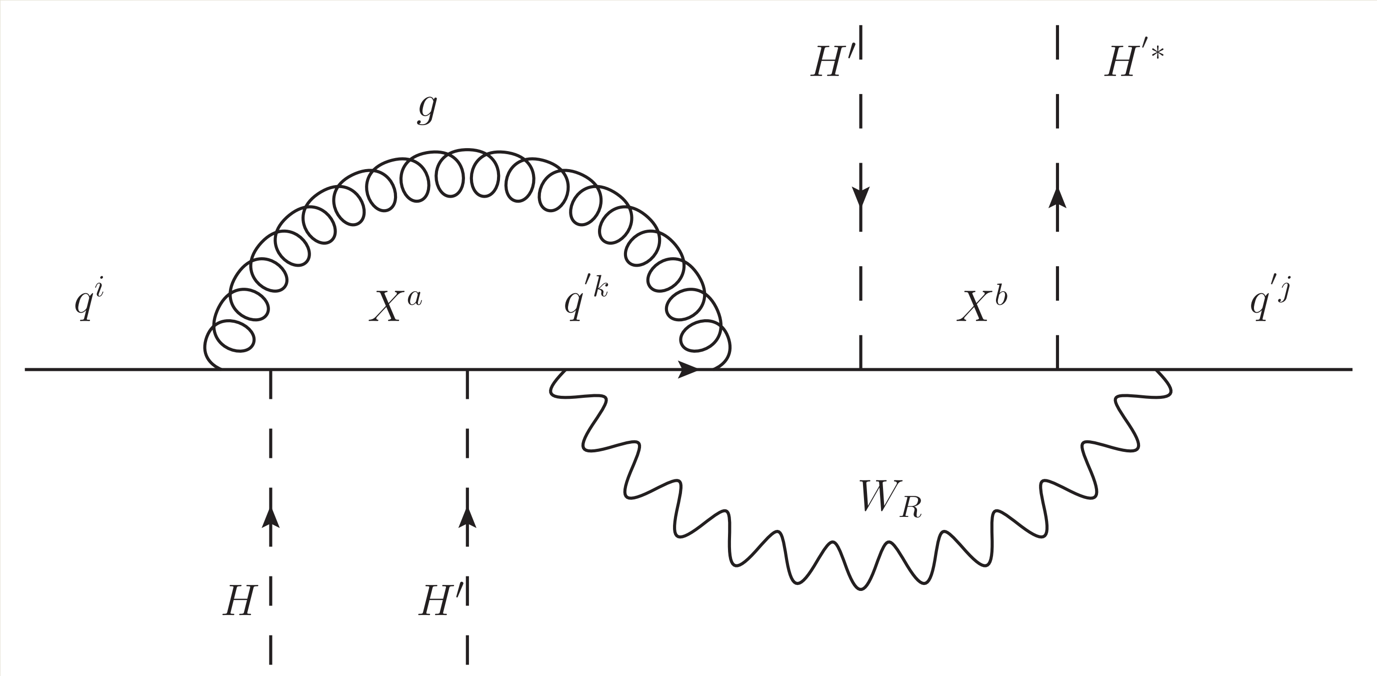
Parity GUT

4 parameters → 5 parameters

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

Non-zero CPV

Hall, KH (2018)



$$\delta\theta \sim 10^{-11}\frac{\theta_{23}^u\theta_{23}^d}{V_{cb}^2}$$

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

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

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

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

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

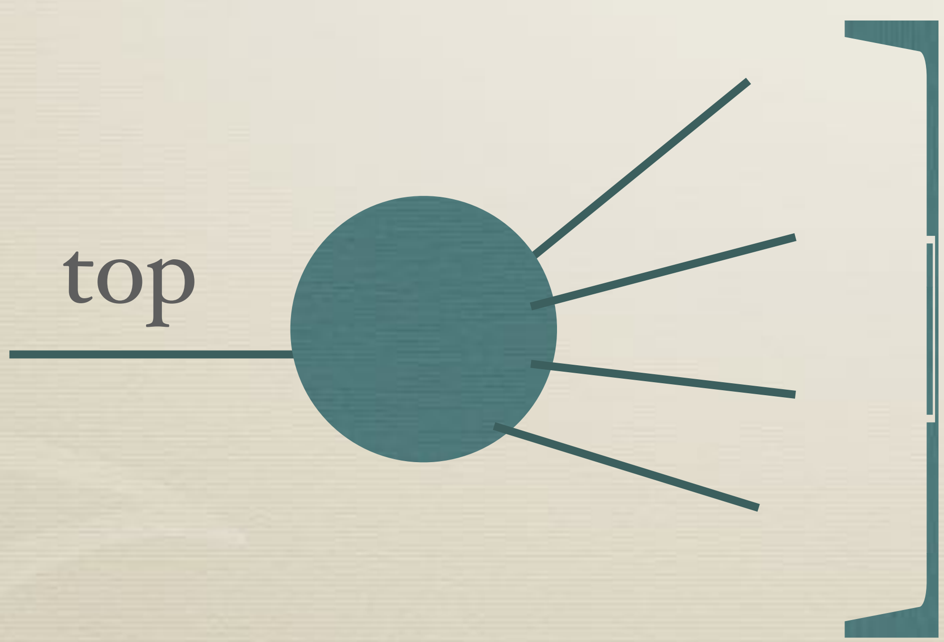
SM parameters

“top quark mass”

pole mass 172.9 ± 0.4 GeV

Particle Data Group

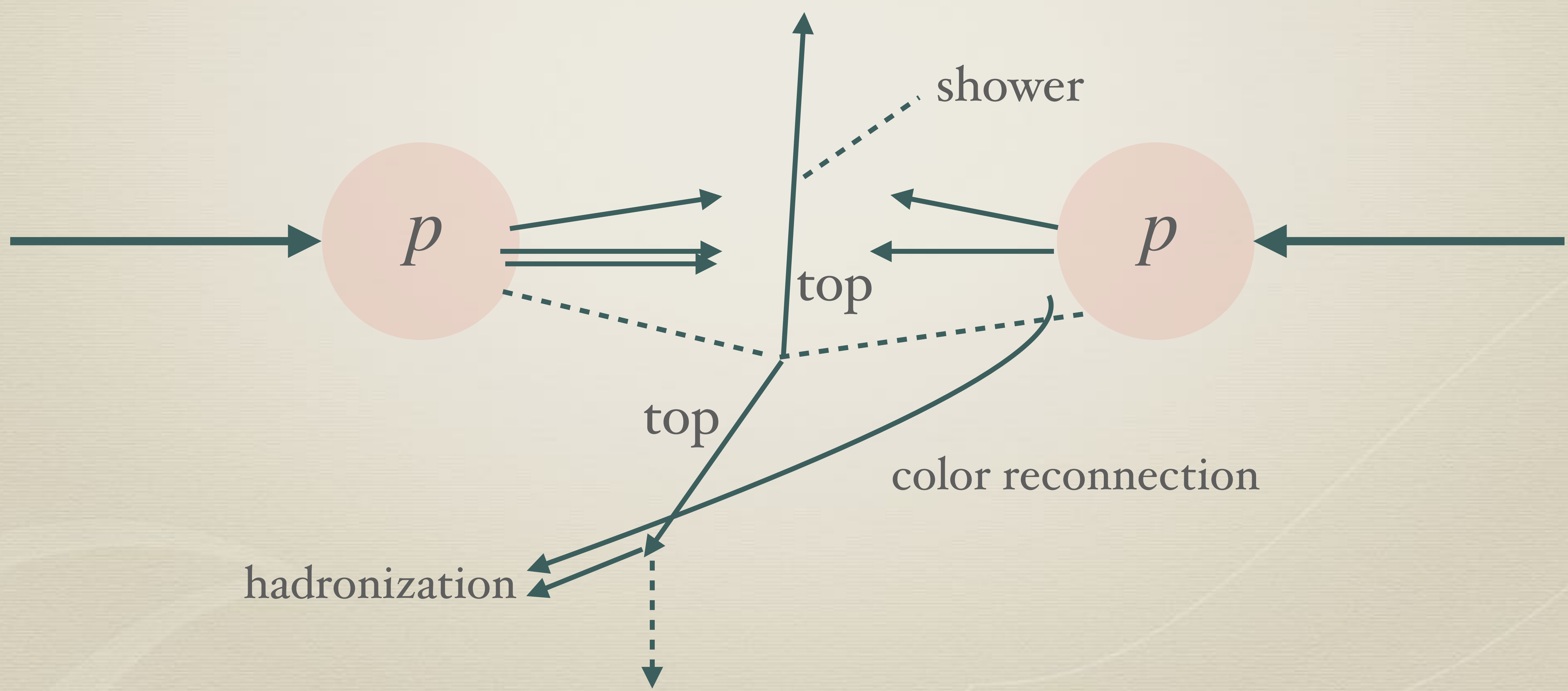
if top were colorless, isolated objects



measure momentum and energy,
take invariant mass

“top quark mass”

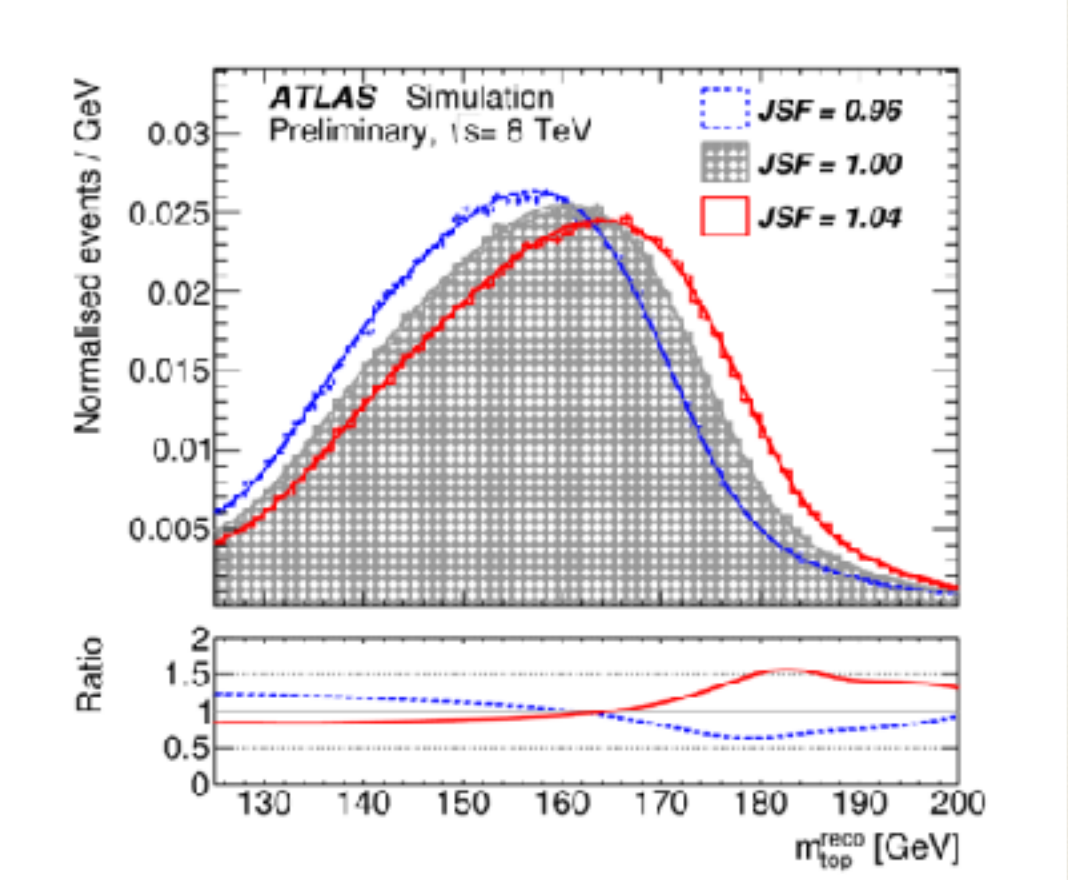
but of course top is colored and is not isolated



“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

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

Buttazzo et.al. (2013)

* NNNLO QCD corrections included

* Uncertainty from non-perturbative nature of QCD

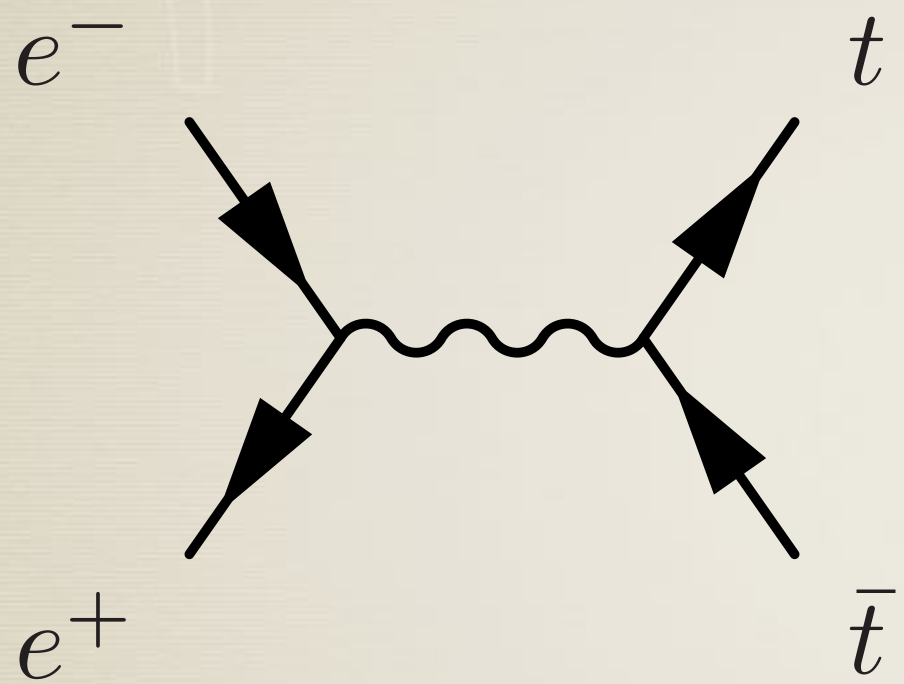
$\Delta m_t \sim \Lambda_{QCD}$

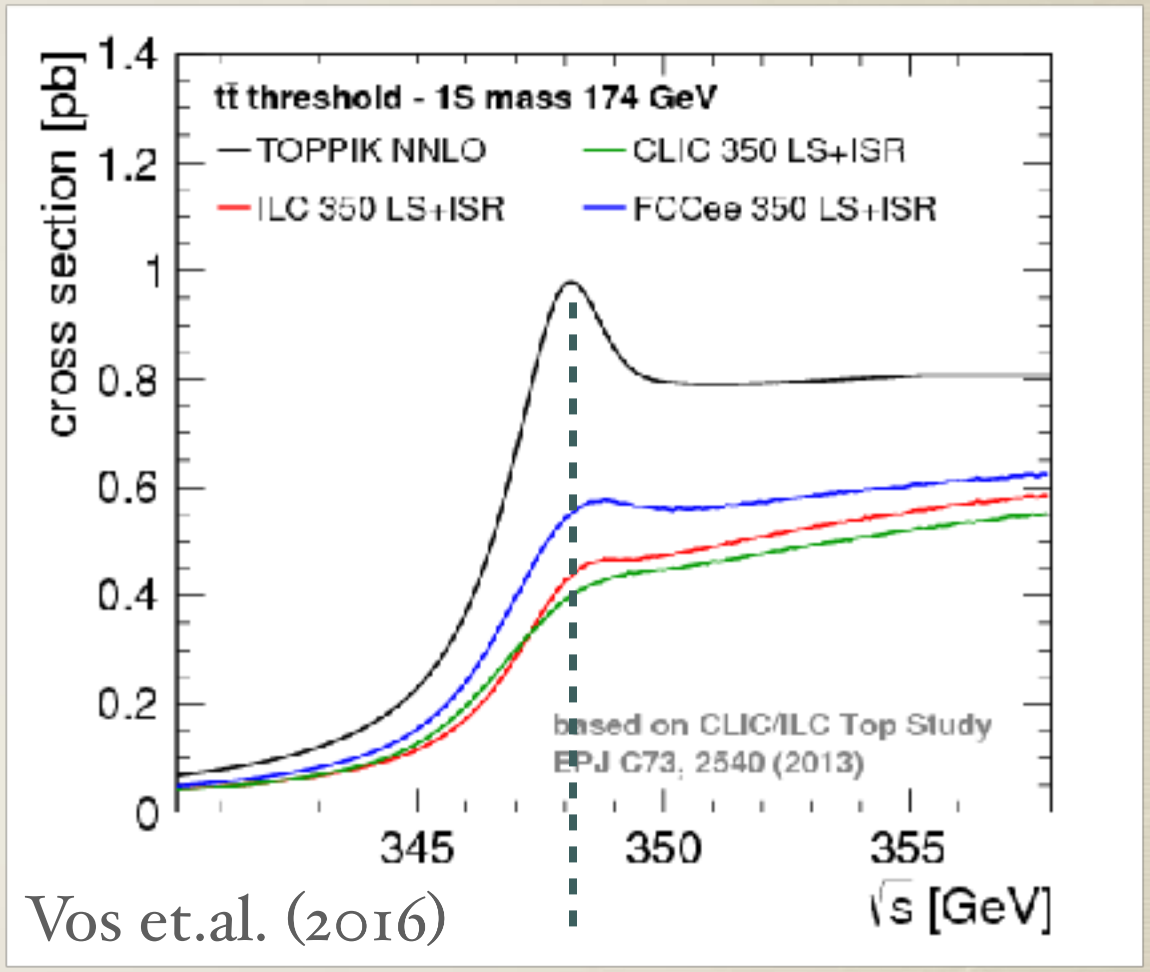
Bigi, Shifman, Uraltsev and Vainshtein (1994)
Benek and Braun (1994)

Eventually, we should directly determine MSbar quantity by

MSbar quantity ⟷ observables

Lepton colliders





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

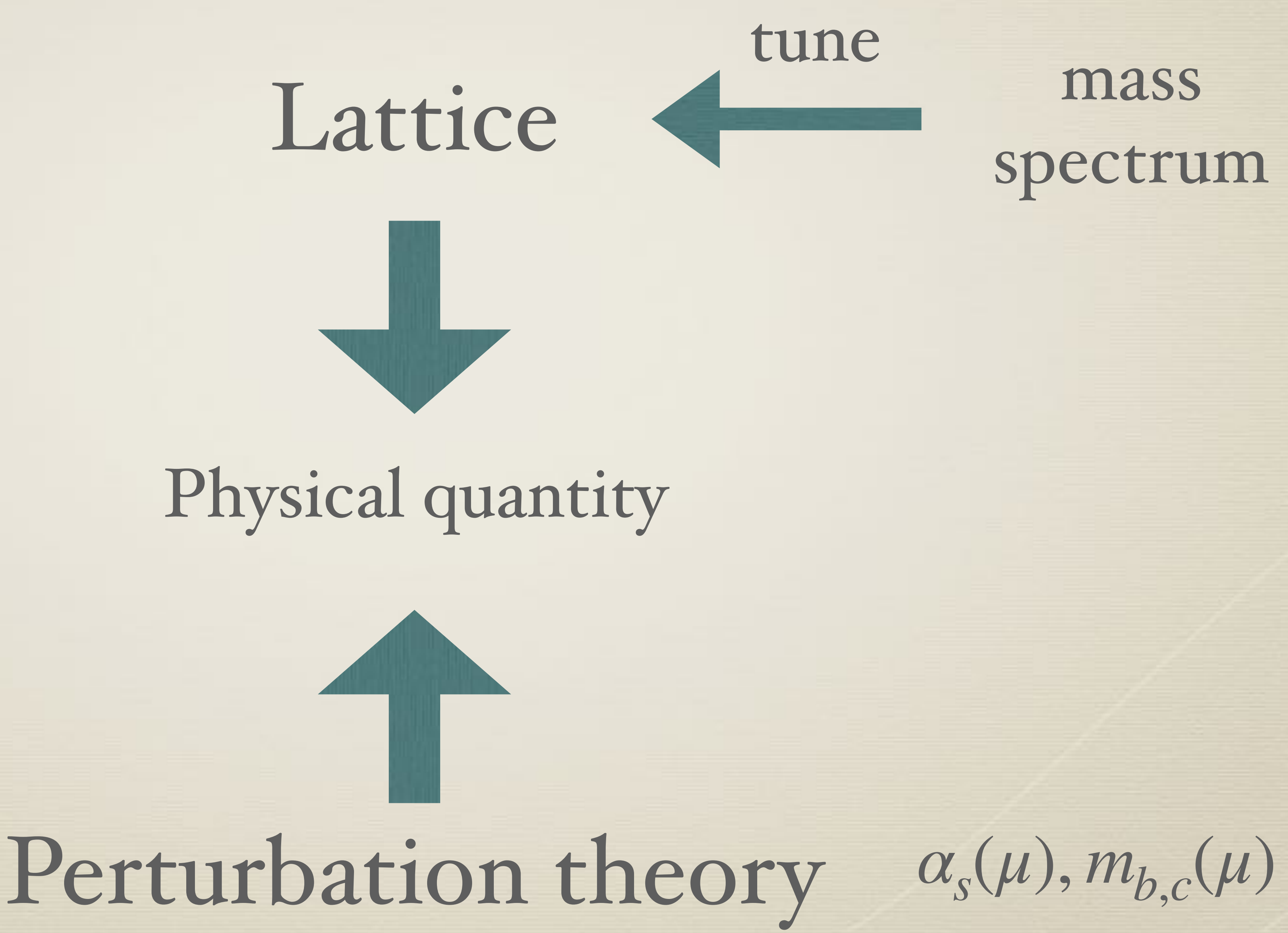
$$M_{t\bar{t}}(1S) = 2(165 + 7.20 + 1.20 + 0.216 + 0.0077 + \cdots)\ \text{GeV}$$

Kiyo, Mishima and Sumino (2015)

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

Strong coupling constant

e.g. HPQCD collaboration (2008)



Neutron electric dipole moment

Space-time parity and neutron EDM

The neutron EDM vanishes in the parity symmetric limit

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

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

We expect non-zero neutron EDM at some level

Non-zero CP violation

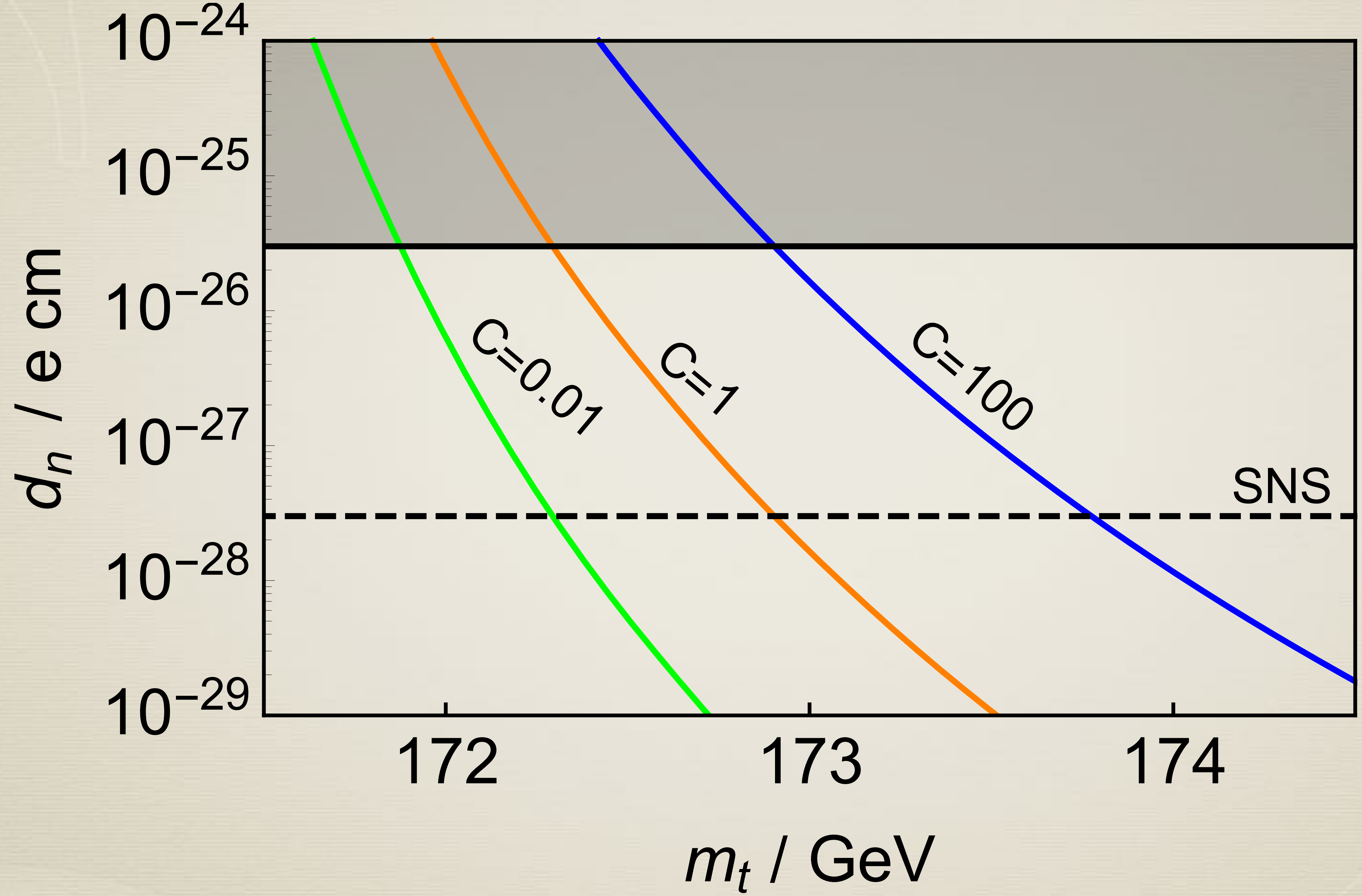
$$\frac{C}{M_{\rm pl}^2}\left(\left|H\right|^2-\left|H'\right|^2\right)\underline{\mathbf{E}\cdot\mathbf{B}}$$

Electric and magnetic fields of gluon

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

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

Neutron EDM



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

Gravitational waves

Mirror Higgs Parity

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

$SU(3) \times SU(2) \times U(1)$ $\quad\longleftrightarrow\quad$ $SU(3)' \times SU(2)' \times U(1)'$

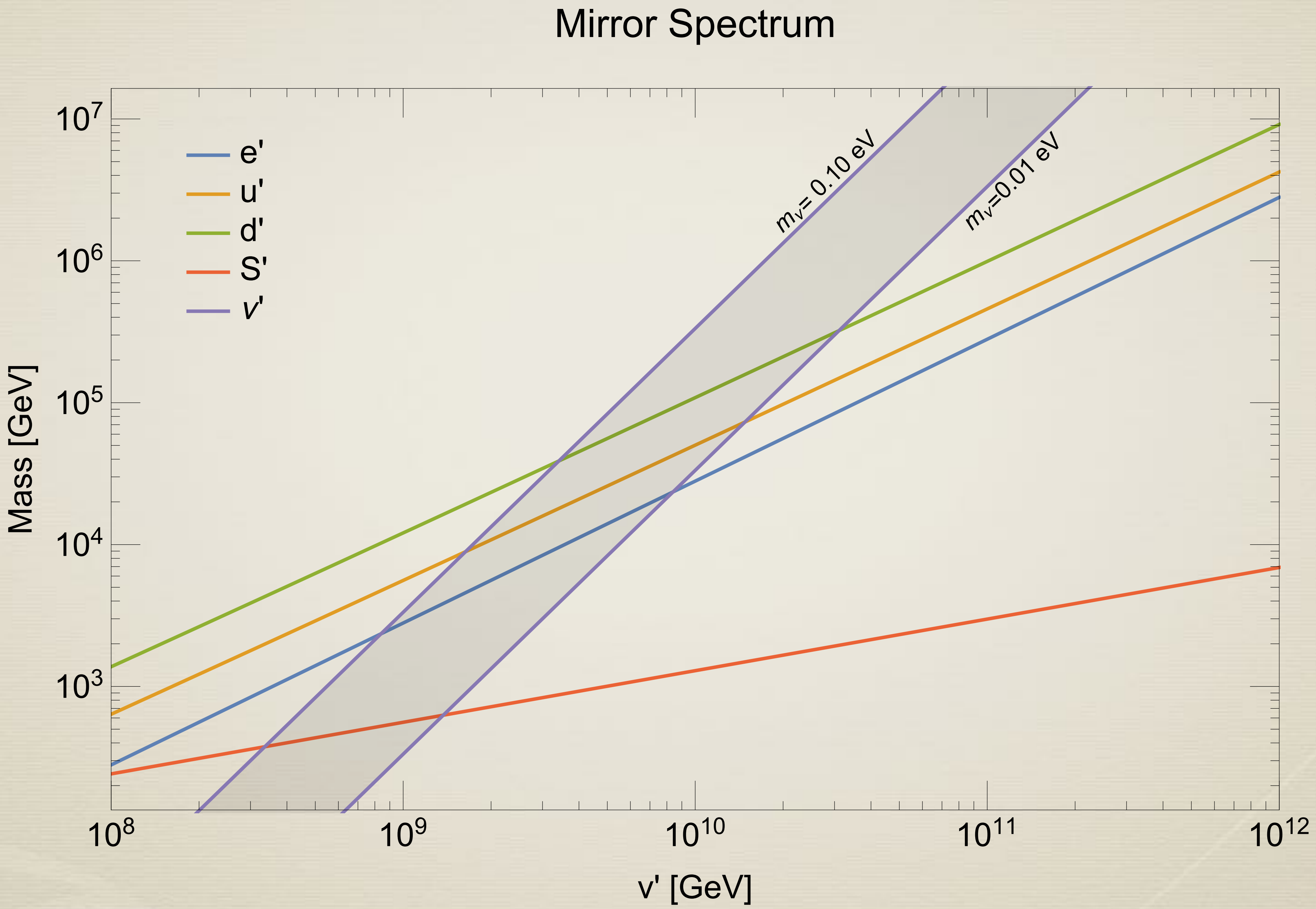
Mirror confinement

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

The confining occurs as a first order phase transition

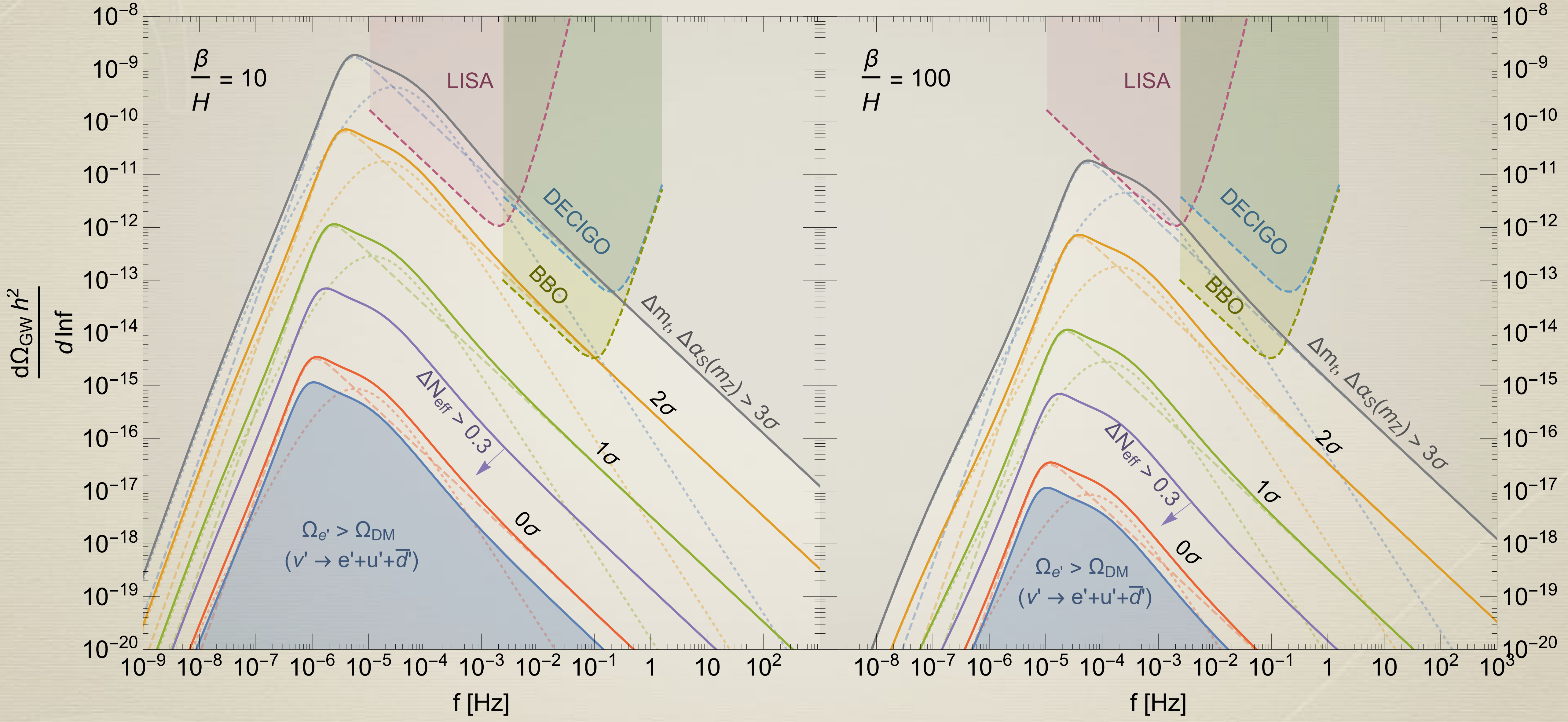
→ Gravitational waves

Dilution



Mirror leptons and baryons overproduced, dilution required

Gravitational waves



Nature of the phase transition needs to be better understood

Dark radiation

Mirror glueball

W', Z', h', t'

c', τ', b'

s', μ'

e', u', d'

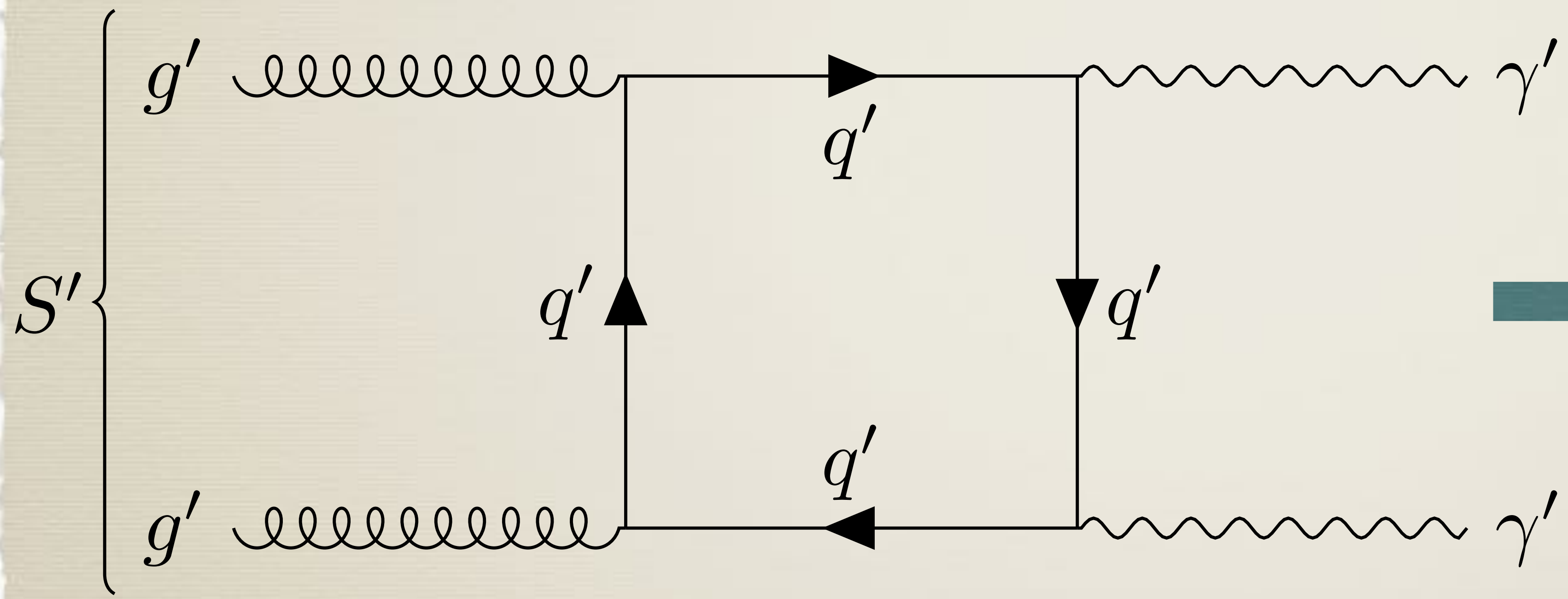
mirror confinement

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

confined

Mirror gluons → Mirror glueballs

Long-lived mirror glueball

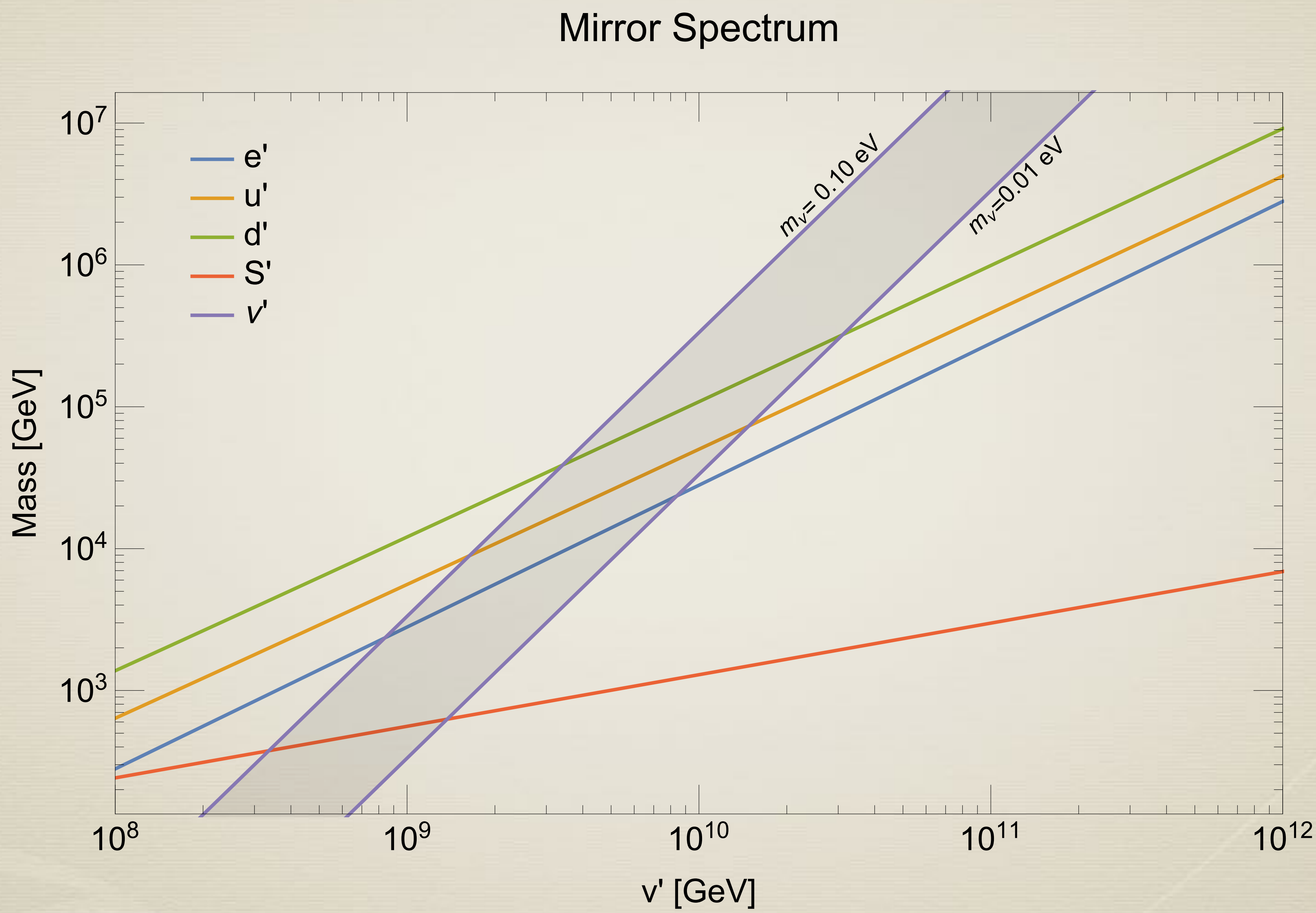


Extra radiation components

(Dark radiation)

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

Dilution

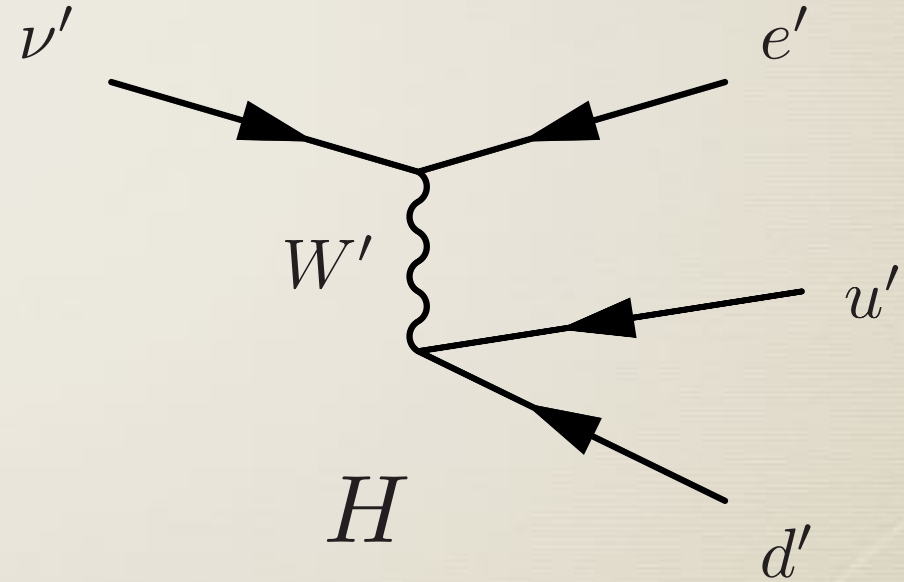


Mirror leptons and baryons overproduced, dilution required

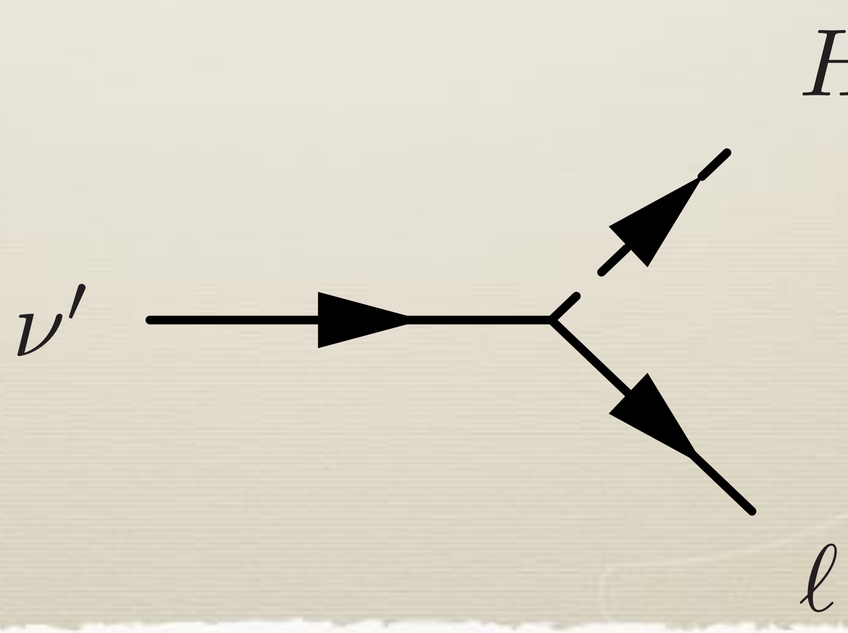
Dilution

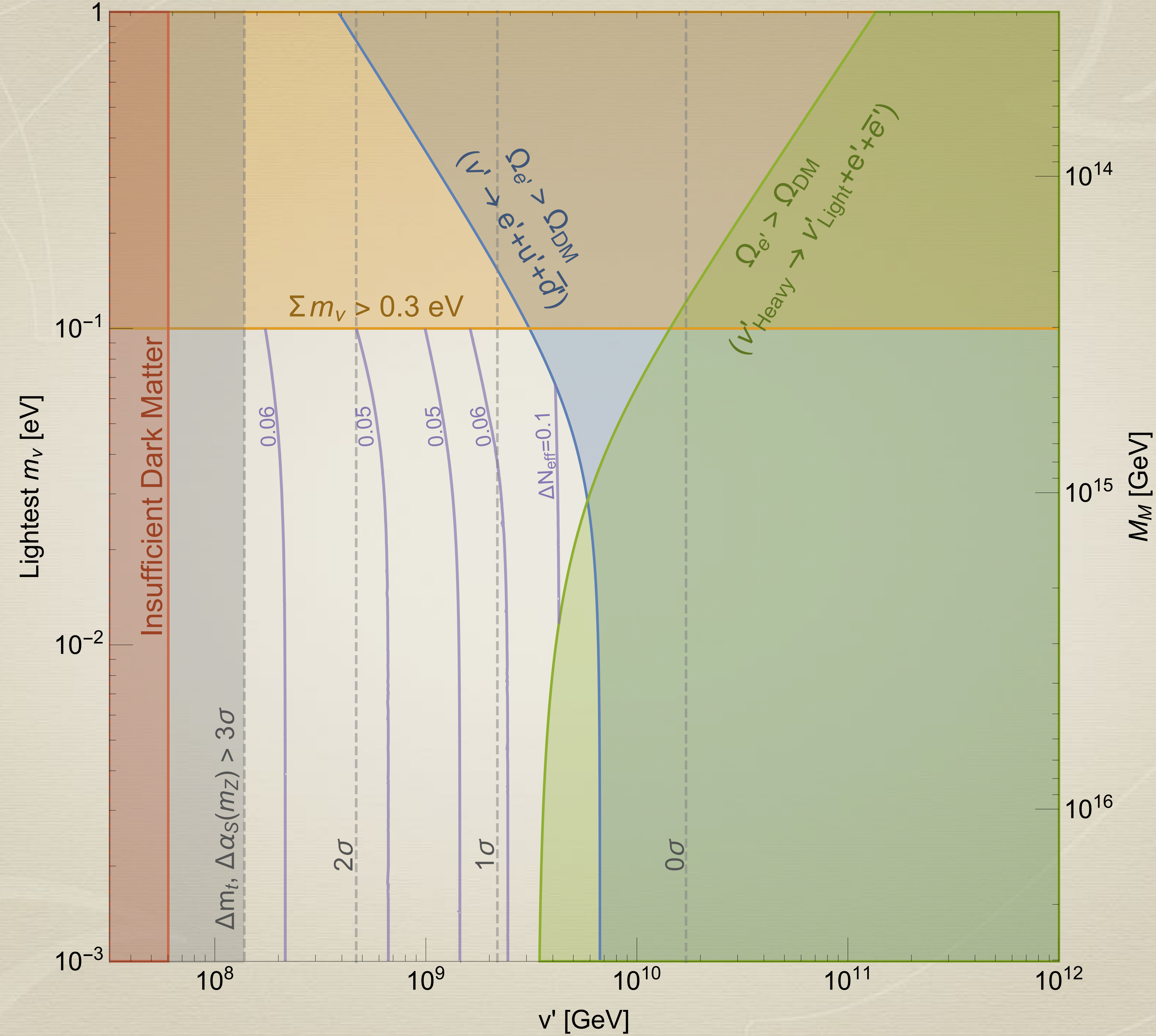
Mirror neutrino can be long-lived

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



Dilution from



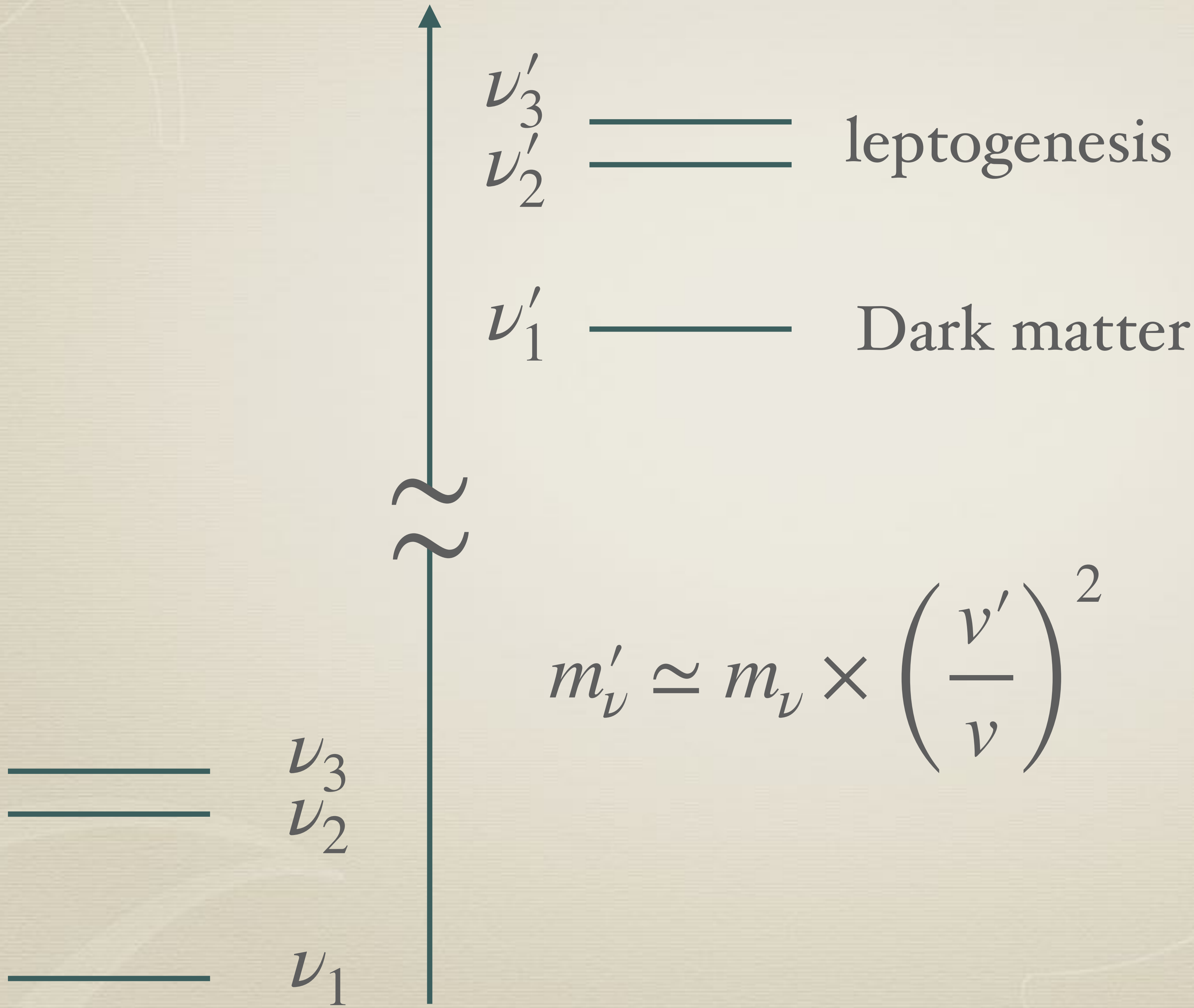


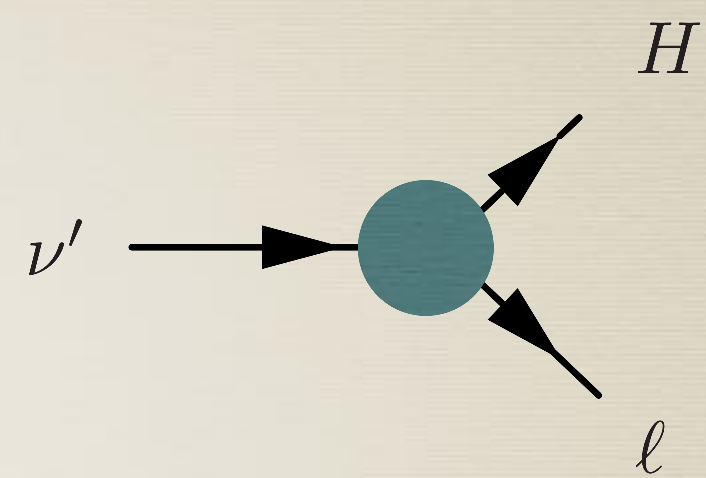
Lightest m_ν [eV]
v' [GeV]
M_M [GeV]
Insufficient Dark Matter
Δm_t, $\Delta\alpha_S(m_Z) > 3\sigma$
$\Sigma m_\nu > 0.3$ eV
$\Omega_{e'} > \Omega_{DM}$
$(\nu' \to e' + \mu' + \bar{\mu}')$
$\Omega_{e'} > \Omega_{DM}$
$(\nu'_{Heavy} \to \nu'_{Light} + e' + \bar{e}')$
0.06
0.05
0.05
0.06
$\Delta N_{eff}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

Warm dark matter

(Work in progress)

Neutrino partners





$$m_\nu' \simeq m_\nu \times \left(\frac{v'}{v}\right)^2$$

Dilution

Thermal dark matter is too abundant or hot

$$\frac{\rho_{\nu_1'}}{\rho_{\mathrm{DM}}} \simeq \frac{m'_{\nu_1}}{100\ \mathrm{eV}} \qquad \text{velocity} \propto \frac{1}{m'_{\nu_1}}$$

Dilution is required

The baryon asymmetry should not be diluted too much

→ m'_{ν_1} tends to be small, warm dark matter

Misc.

Nelson-Barr mechanism

Nelson (1984), Barr (1984)

$$\begin{pmatrix} Q & u \end{pmatrix} \begin{pmatrix} 0 & yH \\ M_1 & i\phi \end{pmatrix} \begin{pmatrix} \bar{u}_1 \\ \bar{u}_2 \end{pmatrix}$$