Beyond the Standard Model: a mini-review

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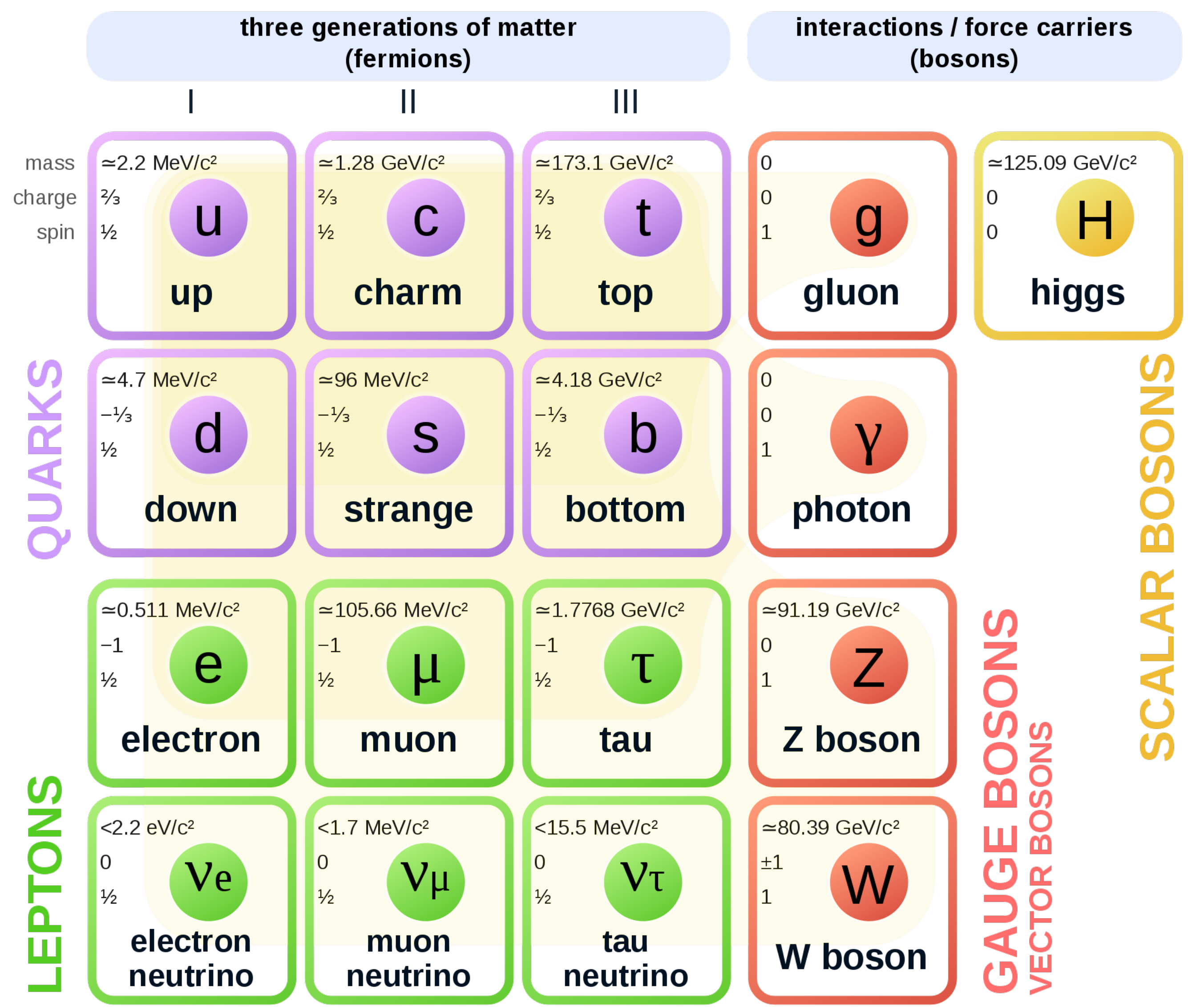
Sun Yat-sen University(中山大学)

The 8th China LHC Physics Workshop(CLHCP2022)
Nanjing Normal university
2022.11.23-2022.11.27

Standard Model of Elementary Particles



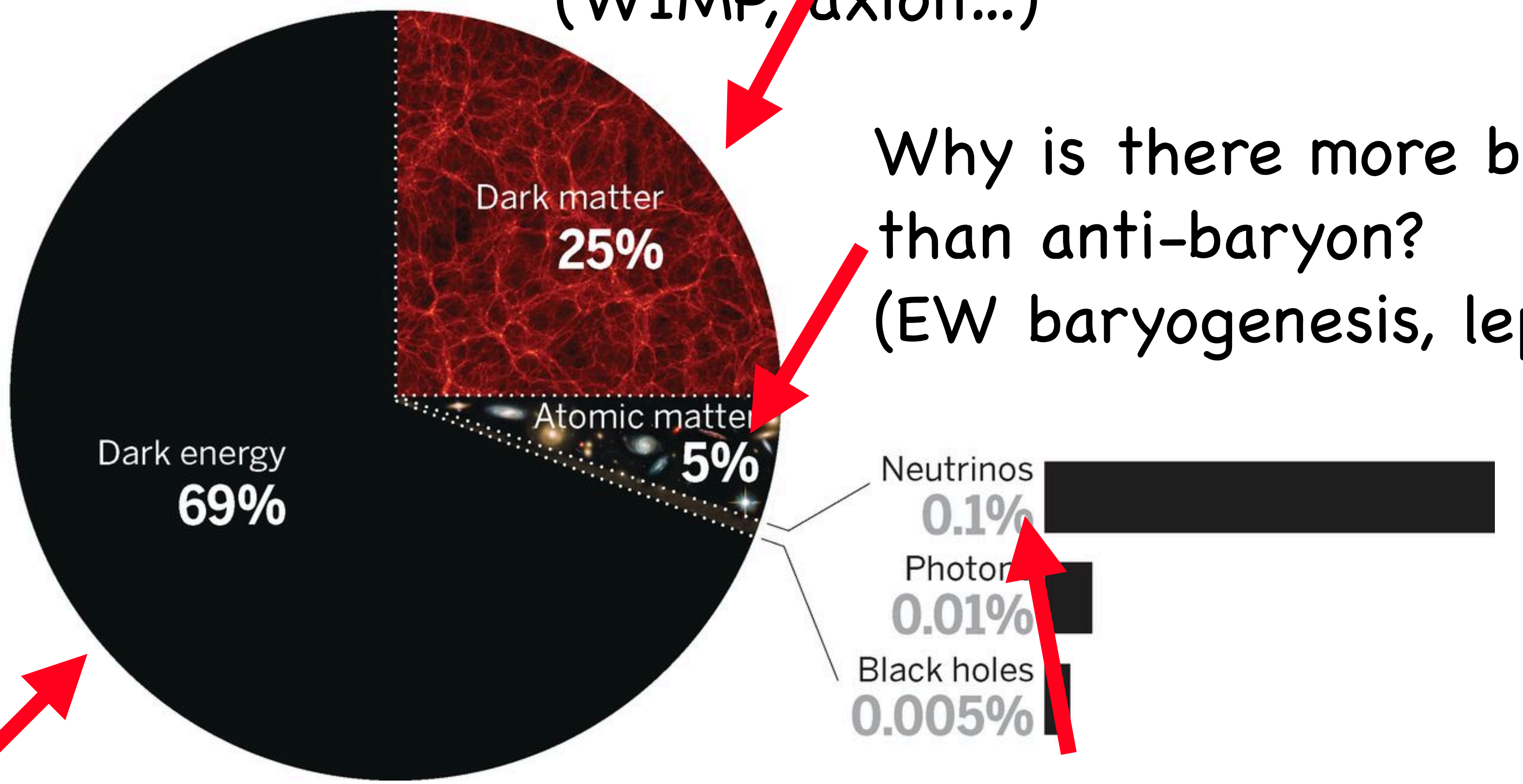
Very successful describing low energy scale physics

Why do we need new physics beyond SM?

Look at the constituents of our universe

What is the dark matter?
(WIMP, axion…)

Why is there more baryon
than anti-baryon?
(EW baryogenesis, leptogenesi



What is the dark energy?
(cc, quintessence…)

What is the origin of
the neutrino masses?
(type I,II,III seesaw…)

We (almost) know nothing about the origin of our universe!

Why do we need new physics beyond SM?

Theoretical motivated

- Naturalness problem
- Vacuum stability
- Strong CP problem
- Why three generation fermions
- Grand unification
- Quantum gravity

Why do we need new physics beyond SM?

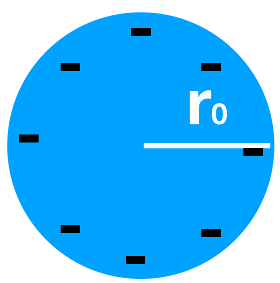
Experimental data request

- Muon g-2
- W mass
- LFU
- ...

Naturalness problem for the electron

Classical description of electron

Borrowed from Hitoshi Murayama, hep-ph/0002232



electron

electrostatic self-energy

Physical mass   Bare mass

$$m_e = m_0 + \delta m, \;\; \delta m = \frac{q^2}{4\pi r_0}$$

No structure of electron: $r_0 < 10^{-19}\mathrm{m}$

$m_p \sim 1 \text{ GeV} \sim 10^{-16}\mathrm{m}$

0.5 = -9999.5 + 10000.   MeV

Large cancellation is needed, unnatural in the classical electromagnetism

Solution to naturalness problem of the electron

Problem solved by Dirac

Particles get doubled

Quantum Electrodynamics(QED) ⟶ Existence of the positron

The correction:

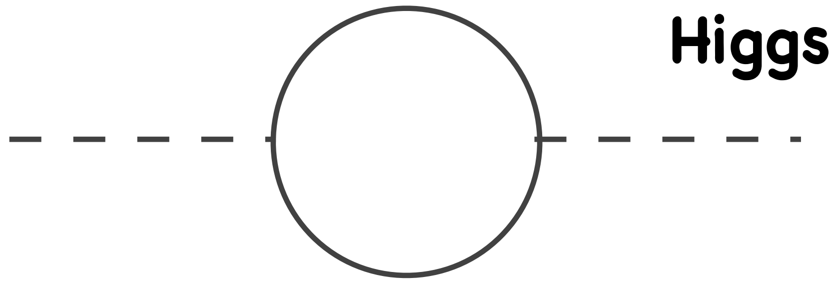
Physical mass　Bare mass　self-energy

$$m_e = m_0 + \delta m,\ \ \delta m = \frac{3q^2}{4\pi} m_0 \log \frac{1}{m_0 r_0}$$

log dependence

Even if $r_0 = l_{pl} = 10^{-34} m$, the correction is only few percent

Naturalness problem for the Higgs



See Lian-tao Wang's talk

$$m_h^2 = m_0^2 + \delta m^2$$

$(125\ \mathrm{GeV})^2$

$$\delta m^2 \sim M_{pl}^2 = (10^{18}\ \mathrm{GeV})^2$$

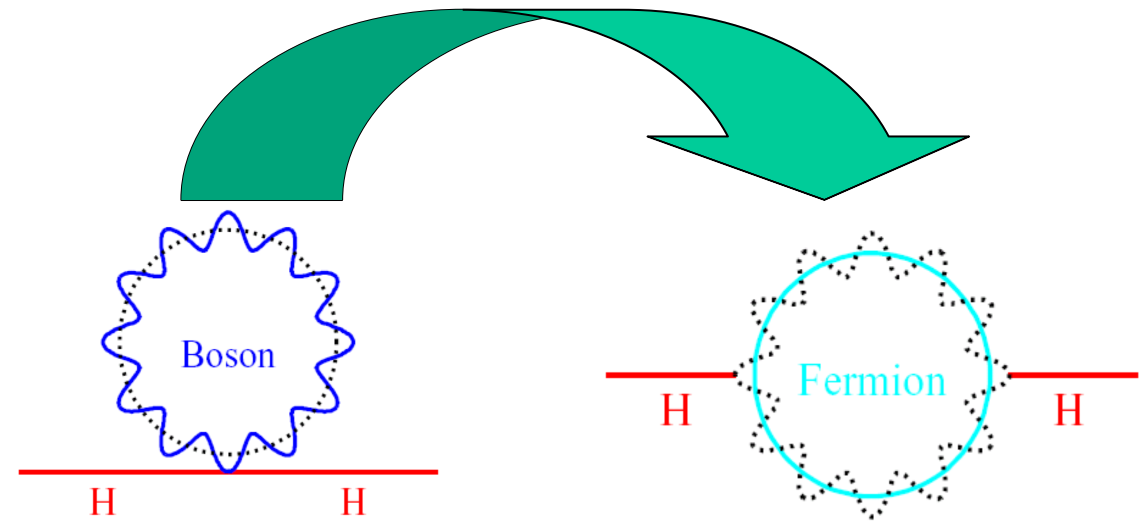
Much larger cancelation is needed, not natural

Solutions to naturalness problem

Supersymmetry

Quadratic divergence becomes log

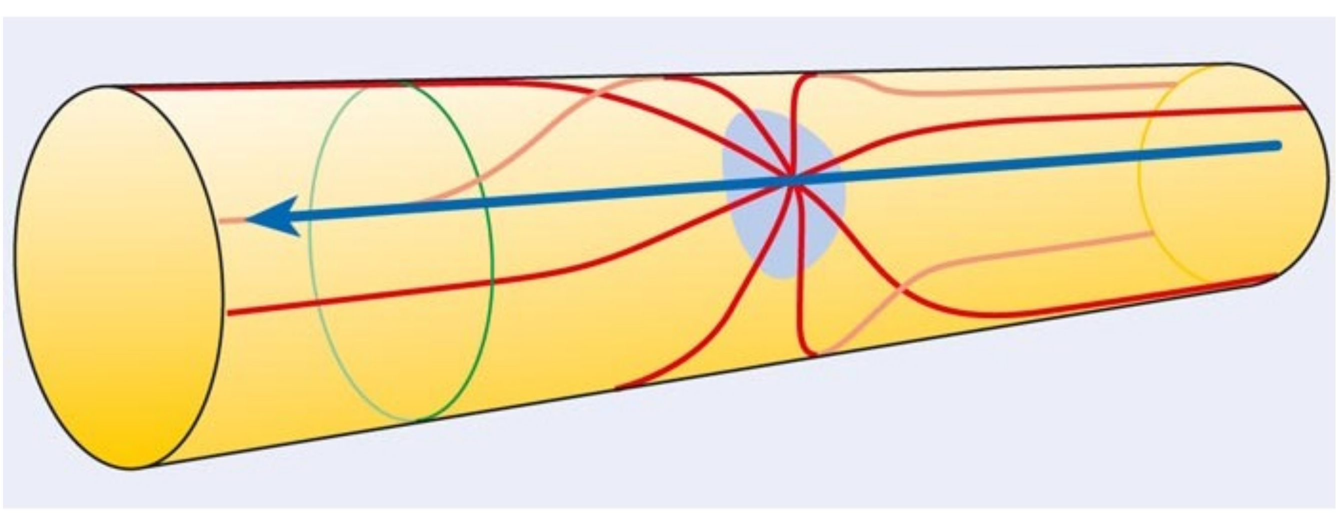
Particle number get doubled



$$\delta m^2 = M_{pl}^2 \to M_{SUSY}^2 \log M_{pl}/M_{SUSY}$$

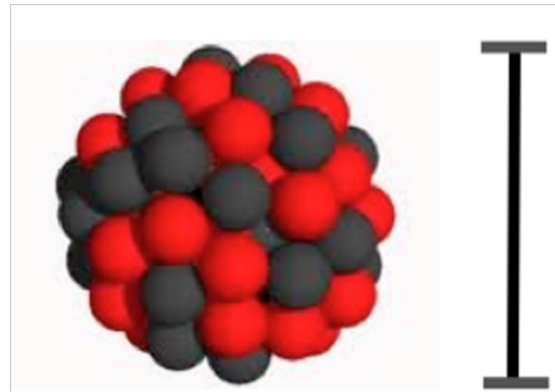
All predict new particles at around TeV scale!

Extra dimension



Mpl is low (TeV) in extra dimension

Composite Higgs



$$\sim \frac{1}{\text{TeV}} = 10^{-18}\,\text{m}$$

Higgs is not fundamental

Alternatives: cosmological selection of the electroweak scale

Selected for a Viewpoint in *Physics*
PRL **115,** 221801 (2015) PHYSICAL REVIEW LETTERS week ending 27 NOVEMBER 2015

Relaxion

Cosmological Relaxation of the Electroweak Scale

Peter W. Graham,[1] David E. Kaplan,[1,2,3,4] and Surjeet Rajendran[3]

PRL **117,** 251801 (2016) PHYSICAL REVIEW LETTERS week ending 16 DECEMBER 2016

Nnaturalness

Solving the Hierarchy Problem at Reheating with a Large Number of Degrees of Freedom

Nima Arkani-Hamed,[1] Timothy Cohen,[2] Raffaele Tito D'Agnolo,[1] Anson Hook,[3] Hyung Do Kim,[4] and David Pinner[5]

New degree of freedom(s)!

Self-Organised Localisation **arXiv:2105.08617(104 Pages)**

Gian F. Giudice,[a] **Matthew McCullough,**[a,b*] **Tevong You**[a,b,c]

[a] *CERN, Theoretical Physics Department, Geneva, Switzerland*

PHYSICAL REVIEW LETTERS **128,** 021803 (2022)

Featured in Physics

Sliding naturalness

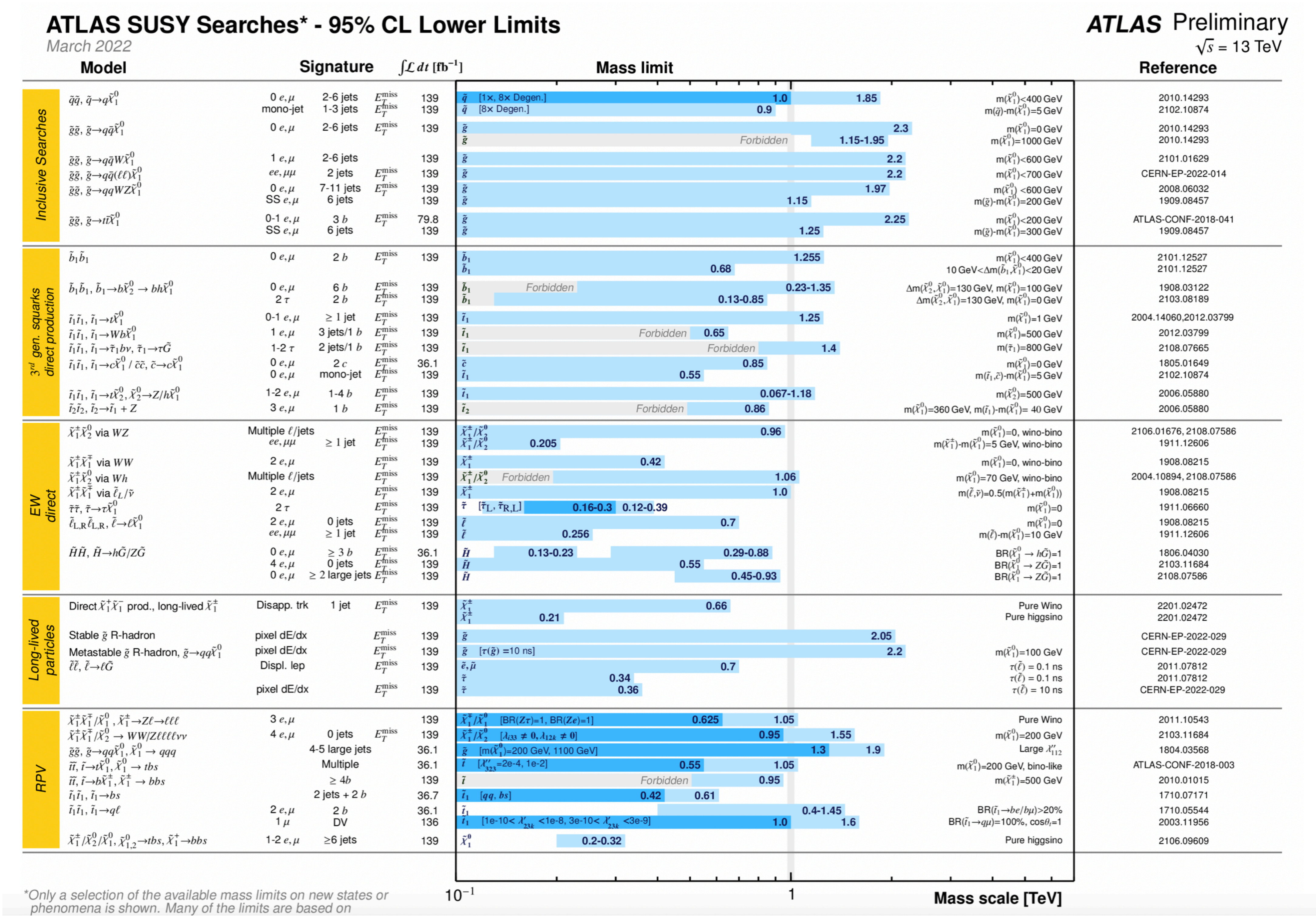
Sliding Naturalness: New Solution to the Strong-*CP* and Electroweak-Hierarchy Problems

Raffaele Tito D'Agnolo[1] and Daniele Teresi[2]
[1] *Institut de Physique Théorique, Université Paris Saclay, CEA, F-91191 Gif-sur-Yvette, France*
[2] *CERN, Theoretical Physics Department, 1211 Geneva 23, Switzerland*

Supersymmetry

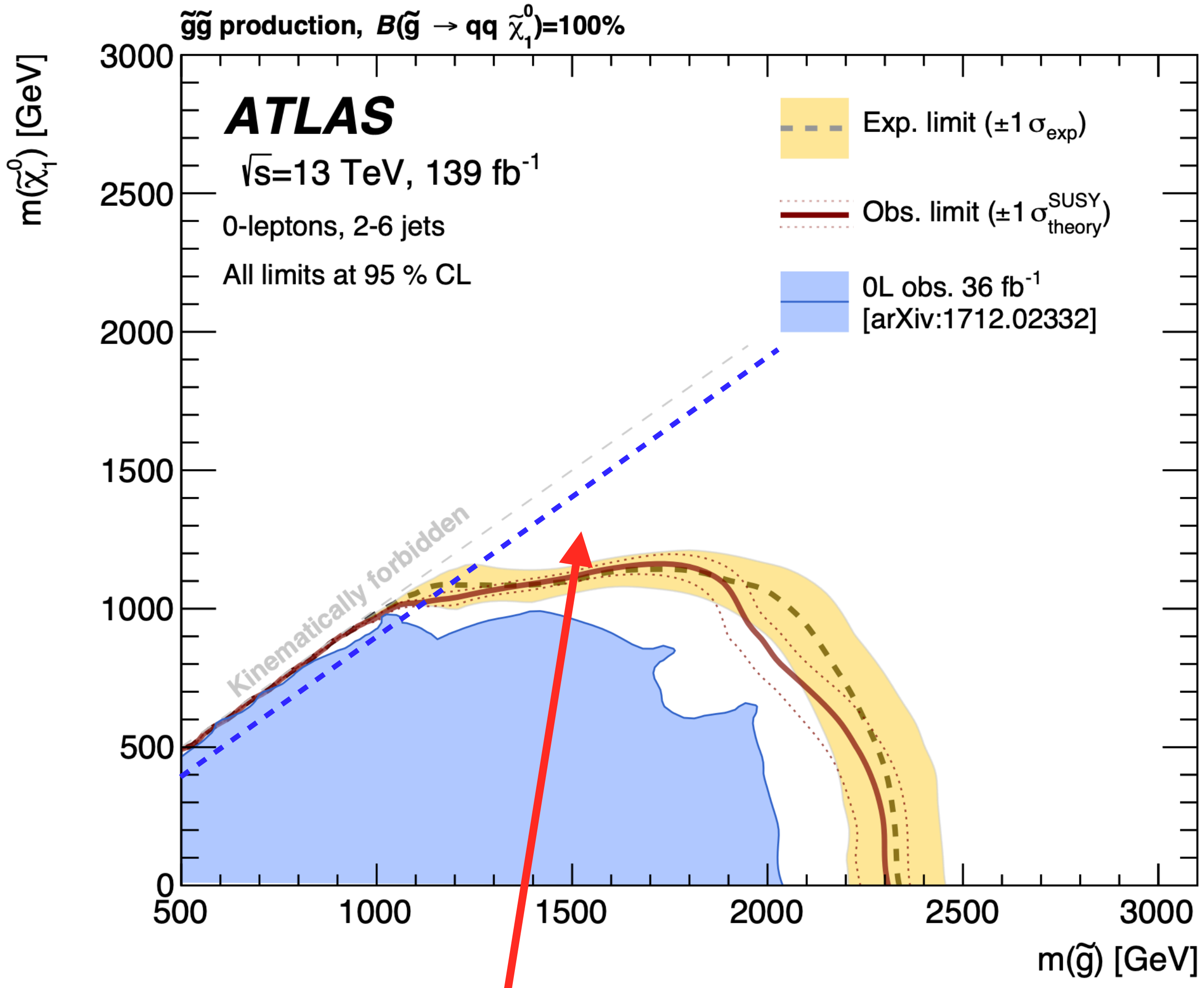
- Naturalness problem
- Unification of forces
- Dark matter
- Baryogenesis
- …

Current SUSY searches

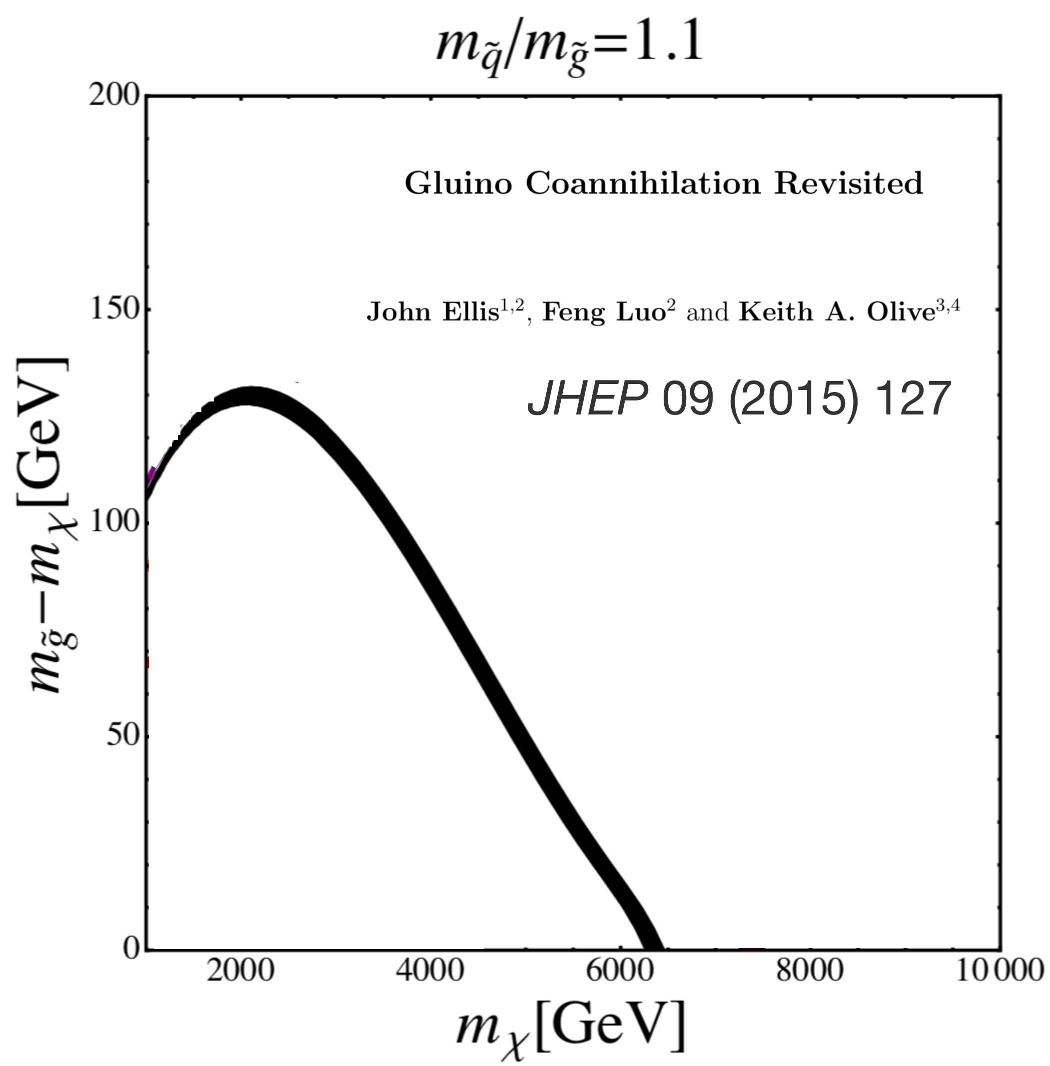


See Tong-guang Cheng's talk

Look at the data



Compressed region: SUSY particle is light, "hidden" in the backgrounds



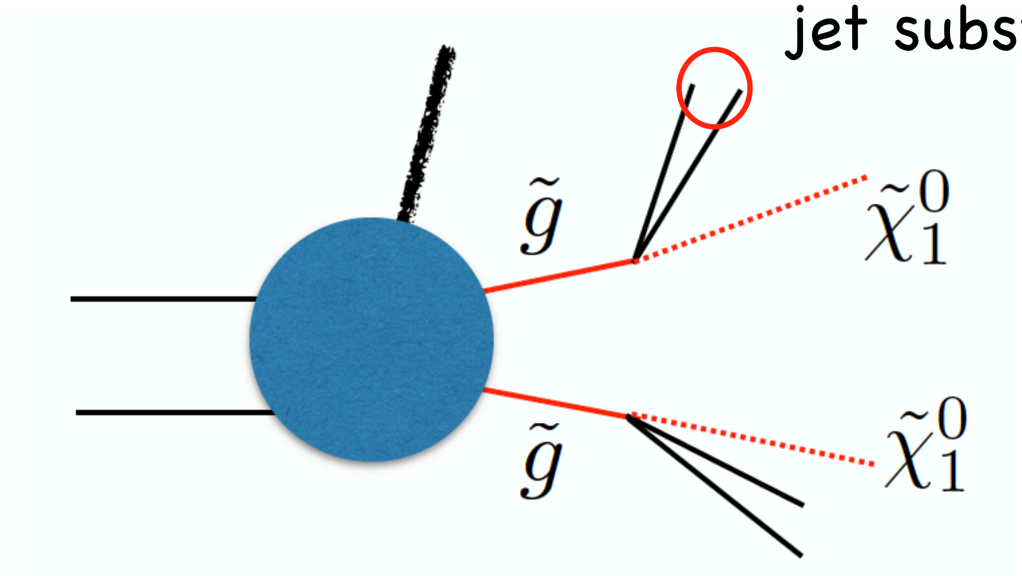
"Co-annihilation" DM prefers the compressed region

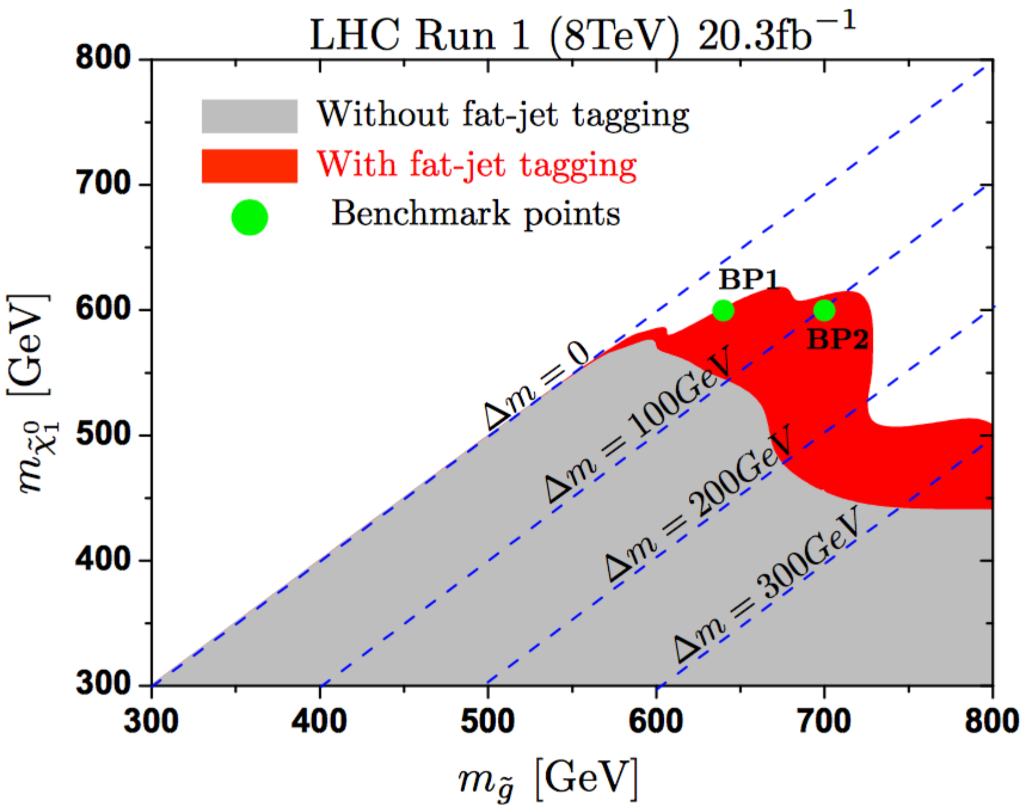
It is important to develop new methods to probe the compressed region

Jet substructure helps

"Revealing the jet substructure in a compressed spectrum"

CCH and M. Park, Phys. Rev. D 94, no. 1, 011502 (2016), Rapid Communication

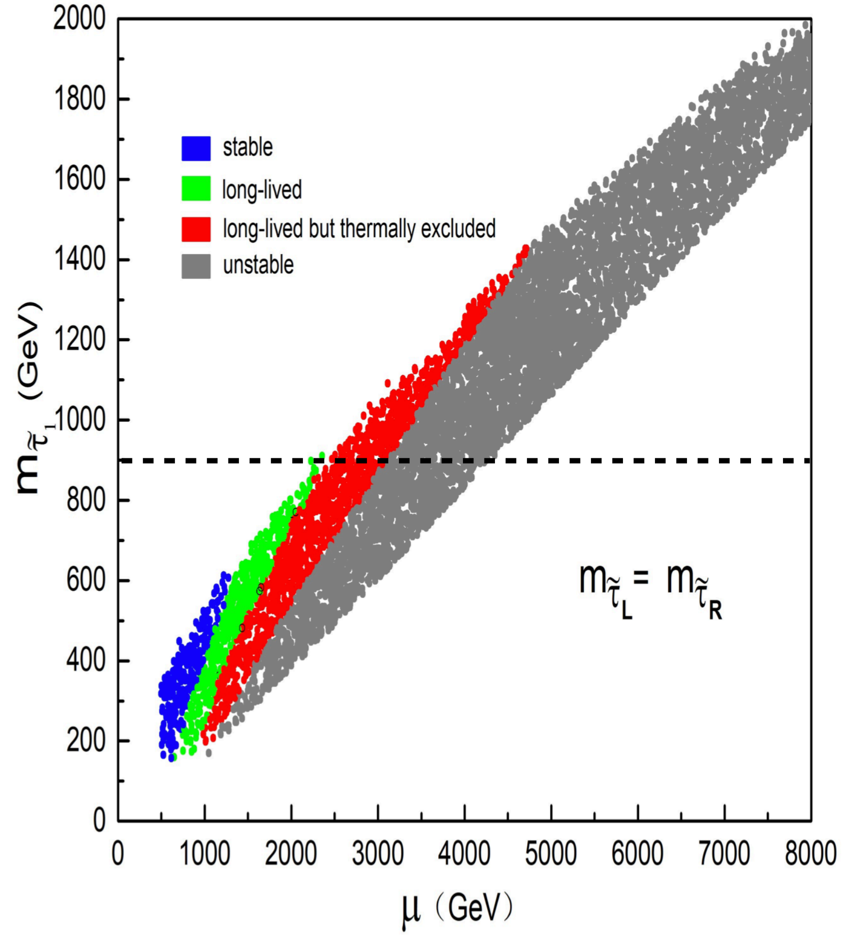




Jet substructure technique helps to probe the gluino co-annihilation region

DM from stau co-annihilation

G. H. Duan, **CCH**, B. Peng, L. Wu, J. M. Yang, Phys.Lett.B,788,475(2019)



Stau < 900 GeV

$\Delta M < 20$ GeV → Soft tau

PHYSICAL REVIEW LETTERS **124,** 041803 (2020)

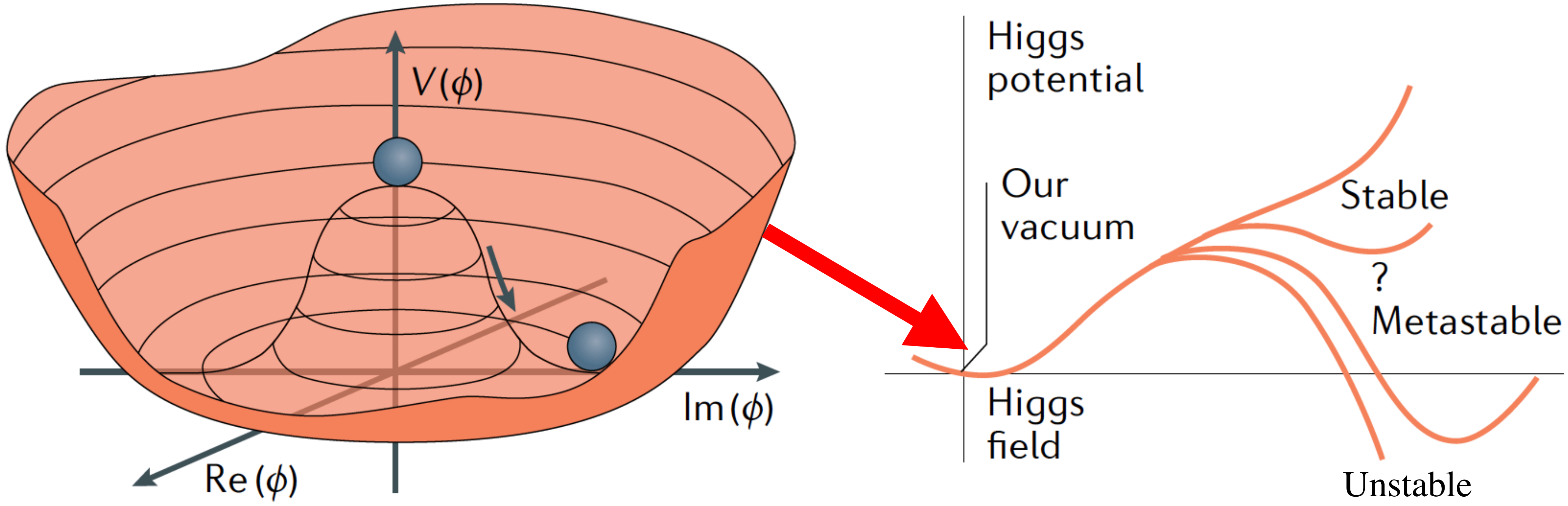
Search for Supersymmetry with a Compressed Mass Spectrum in Events with a Soft τ Lepton, a Highly Energetic Jet, and Large Missing Transverse Momentum in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. M. Sirunyan *et al.*[*]
(CMS Collaboration)

Vacuum stability of the Higgs

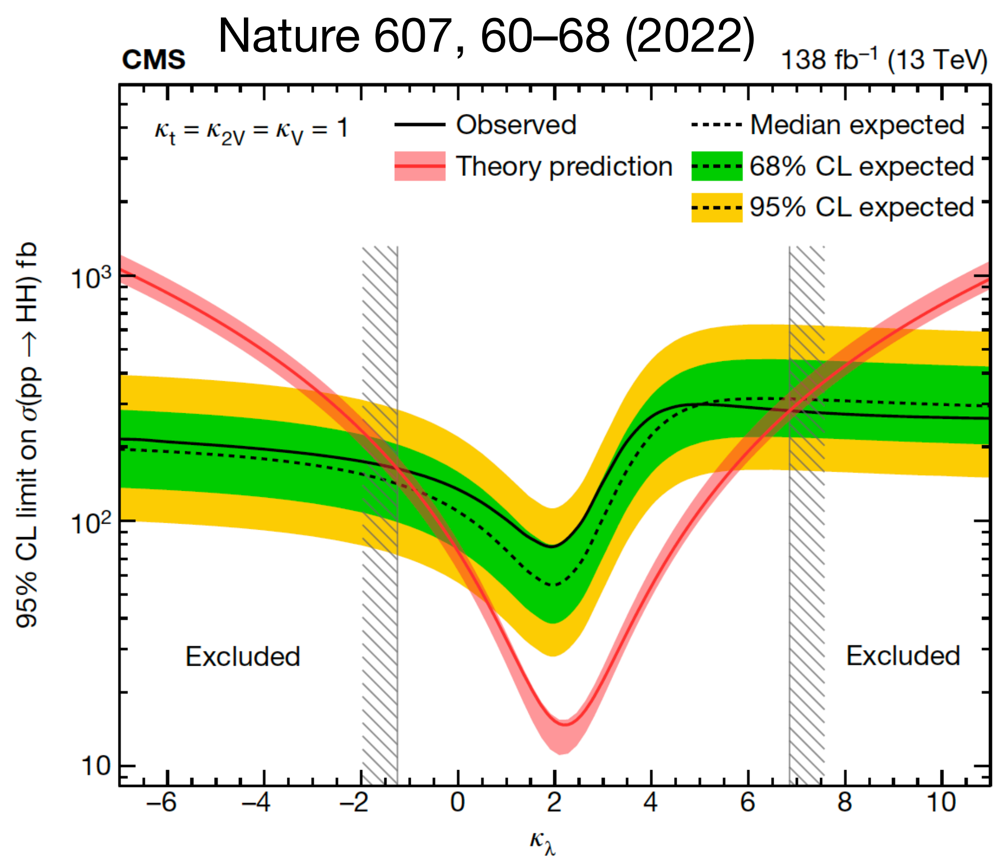
Let us forget about the naturalness problem(assuming Higgs mass is finetuned). Is there anything wrong if we extend SM up to a high(Mpl) scale?

We may face the problem of Higgs instability

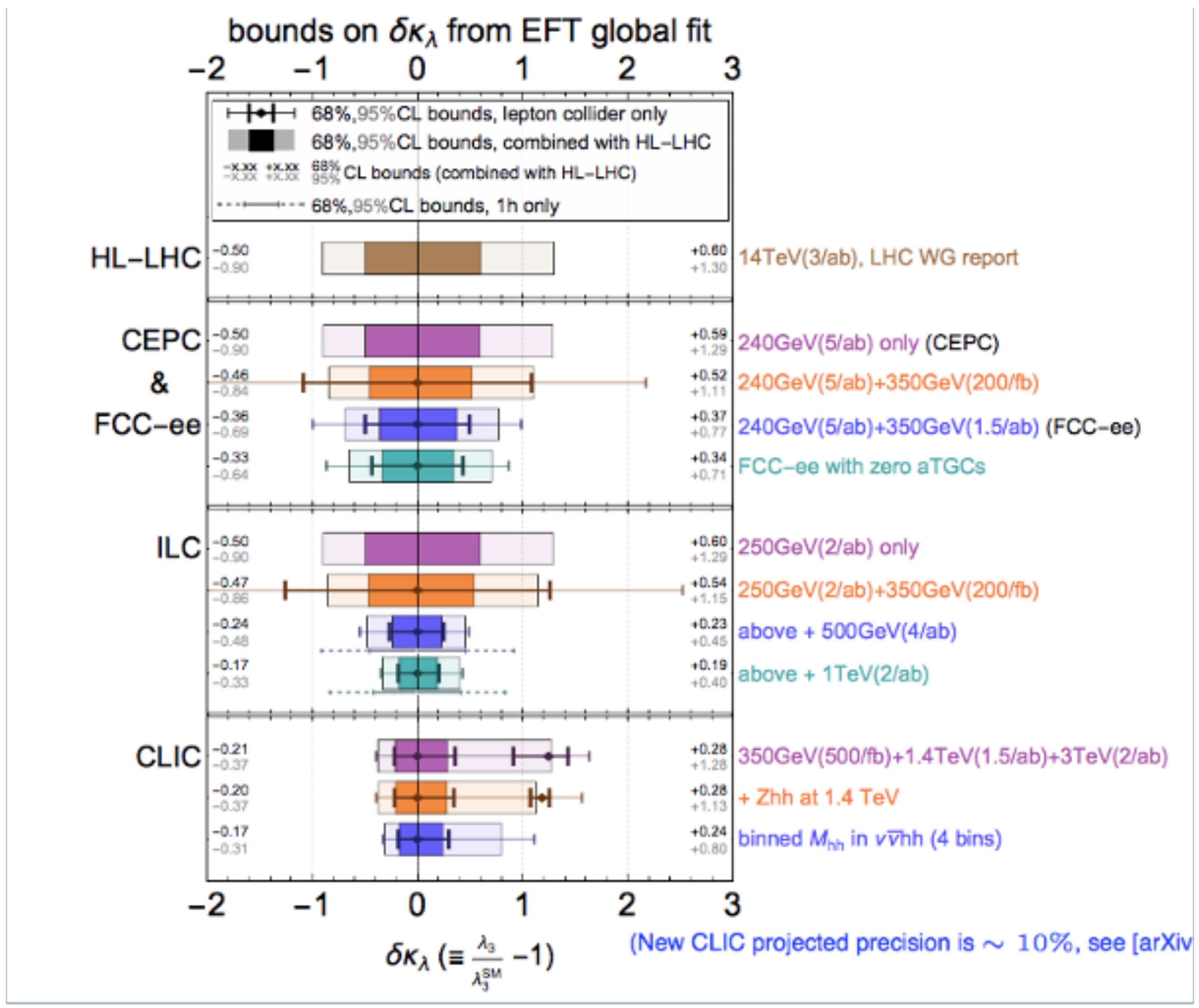


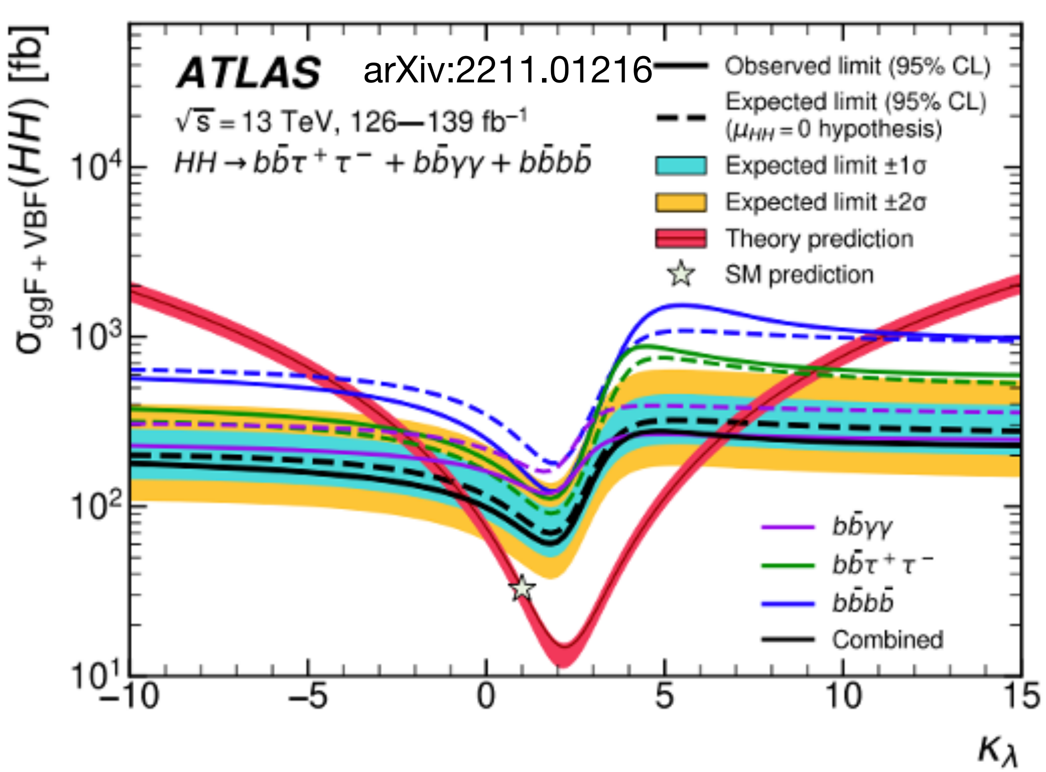
Higgs self-coupling measurement are important!

Higgs self-coupling measurement



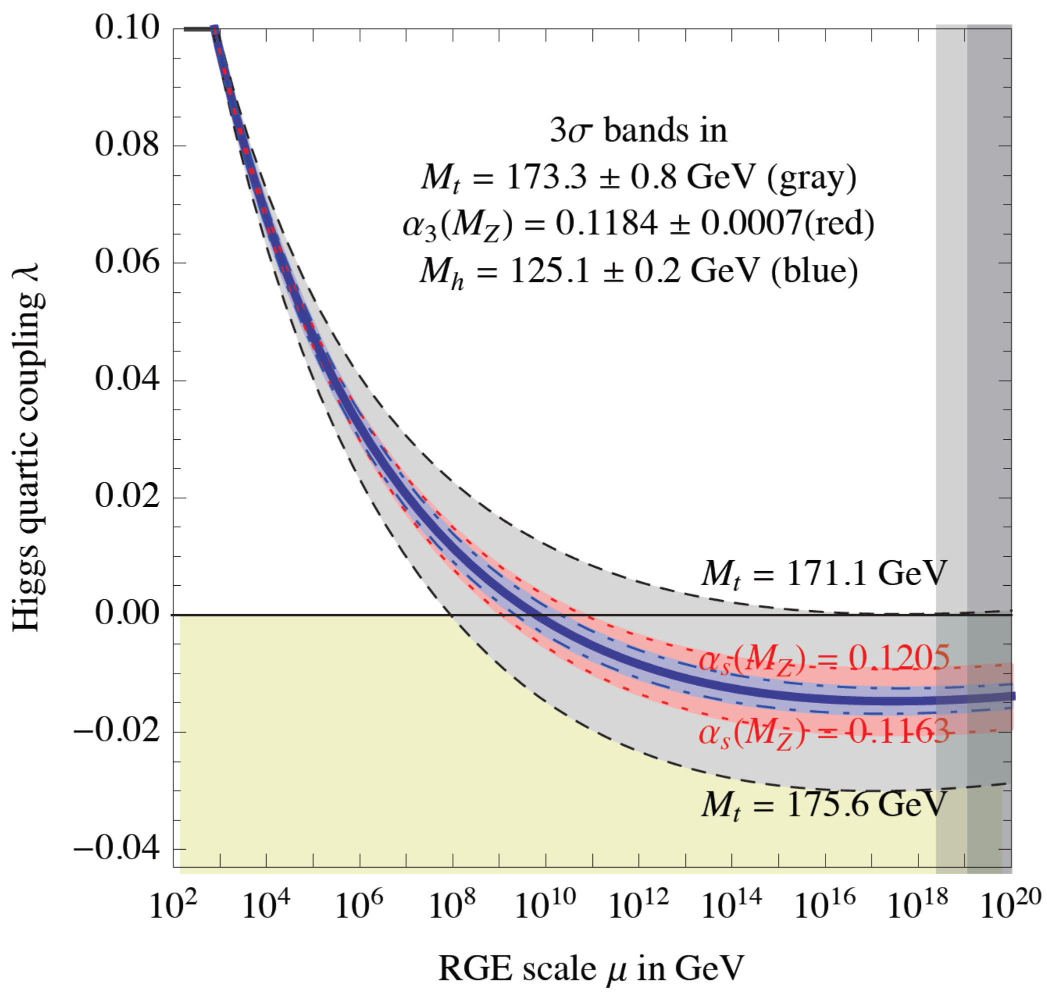
Sensitivity at future colliders, see Yaquan Fang' talk



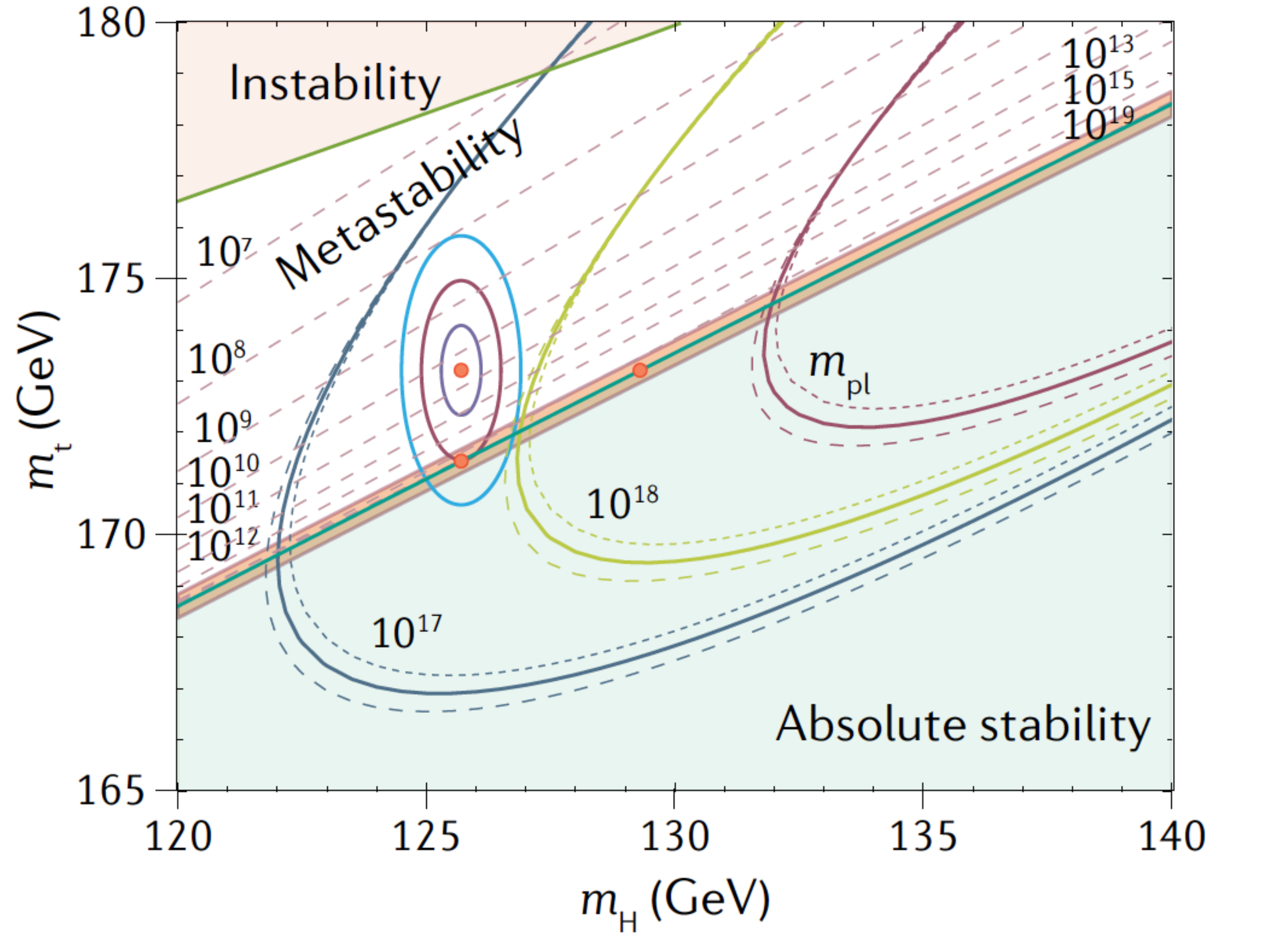


Vacuum stability of the Higgs in SM

D. Buttazzo, et al arXiv:1307.3536



S. D. Bass, A. D. Roeck, M. Kado, Nature Reviews Physics(2021)



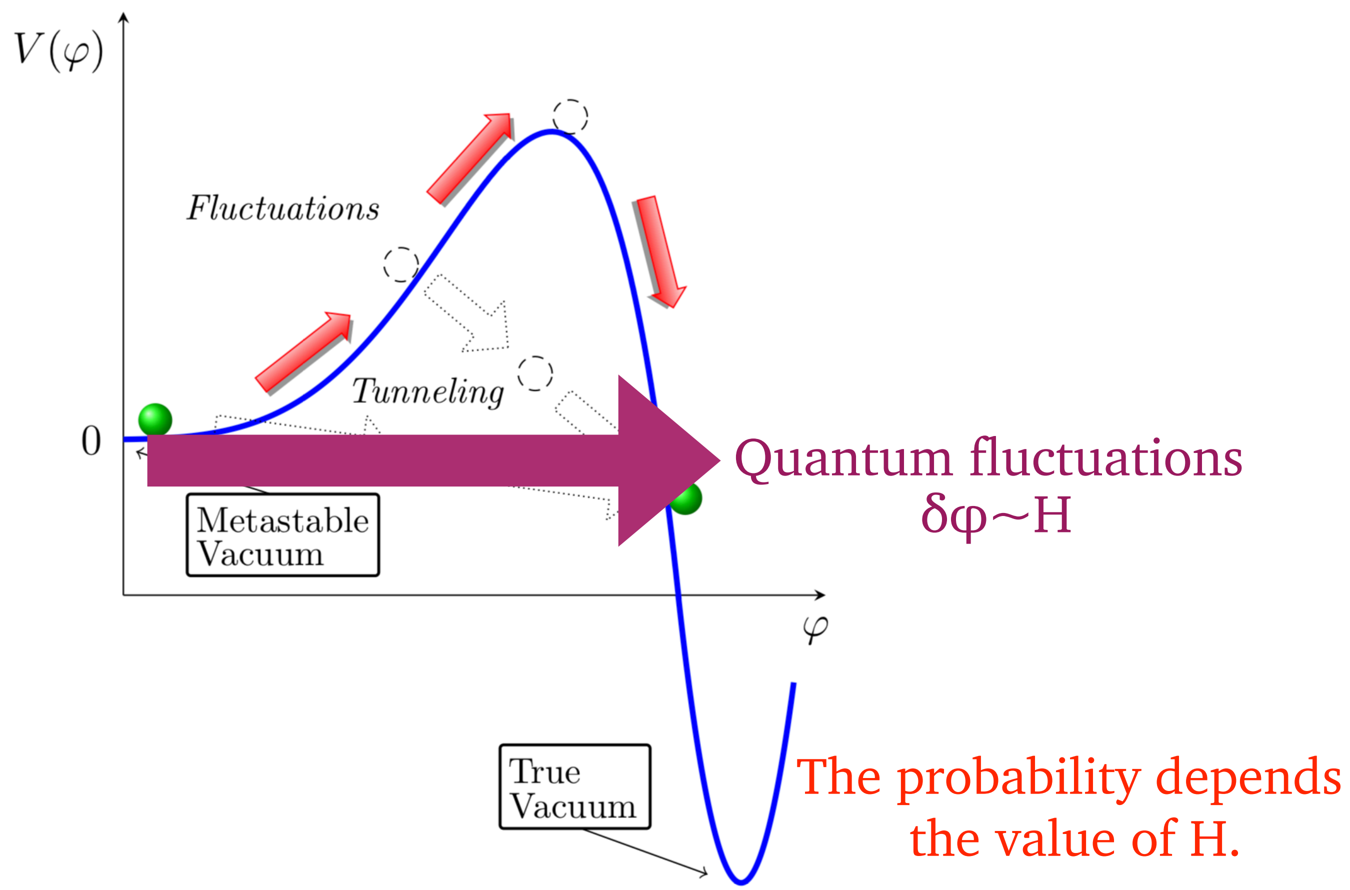
Our vacuum is not at the minimum

Our vacuum is metastable(not stable but decay lifetime is longer than the age of the universe), so far so good!

The cosmological Higgstory of the vacuum instability

1505.04825(231 citations)

José R. Espinosa[a,b], Gian F. Giudice[c],
Enrico Morgante[d], Antonio Riotto[d], Leonardo Senatore[e],
Alessandro Strumia[f,g], Nikolaos Tetradis[h]



Decay rate becomes very high in the very early universe

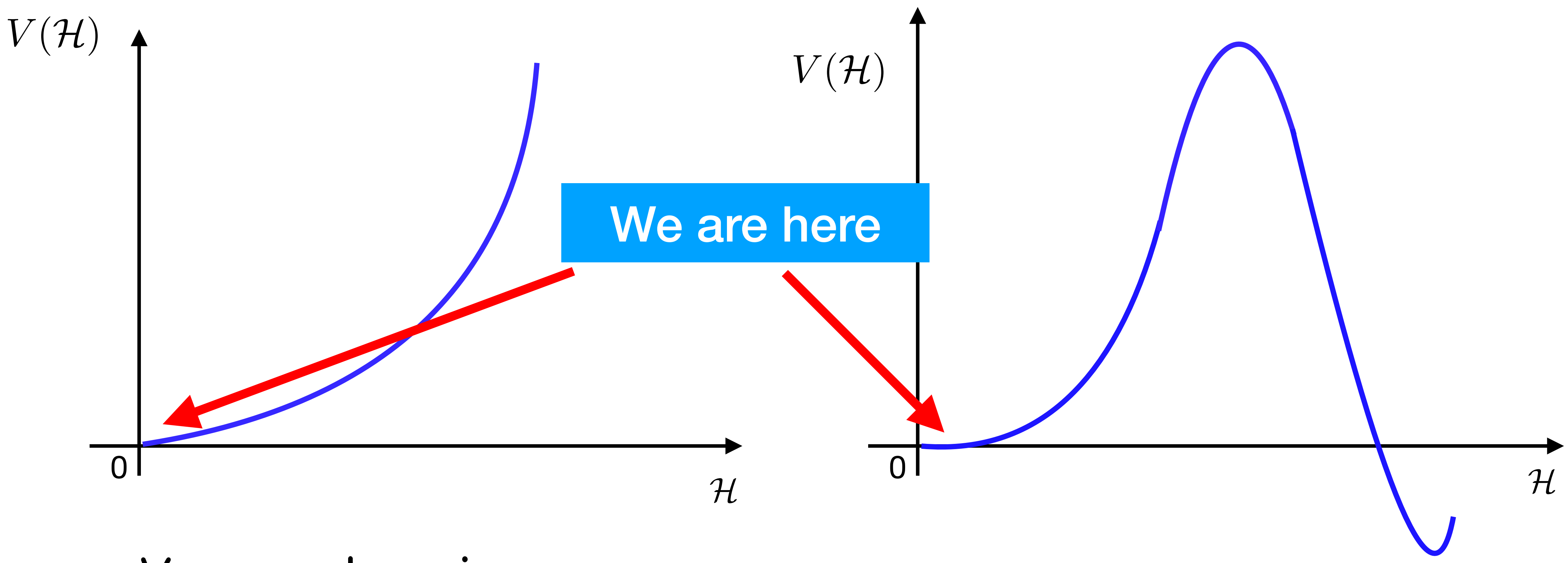
Solving the Higgs instability problem becomes urgent!

Quintessence Saves Higgs Instability

CCH, Shi Pi and Misao Sasaki, Phys.Lett.B 791 (2019) 314-318

$$V(\phi, \mathcal{H}) = e^{-\xi\phi}\left(\lambda\left(|\mathcal{H}|^2 - v^2\right)^2 + \Lambda\right) \quad (\xi > 0)$$

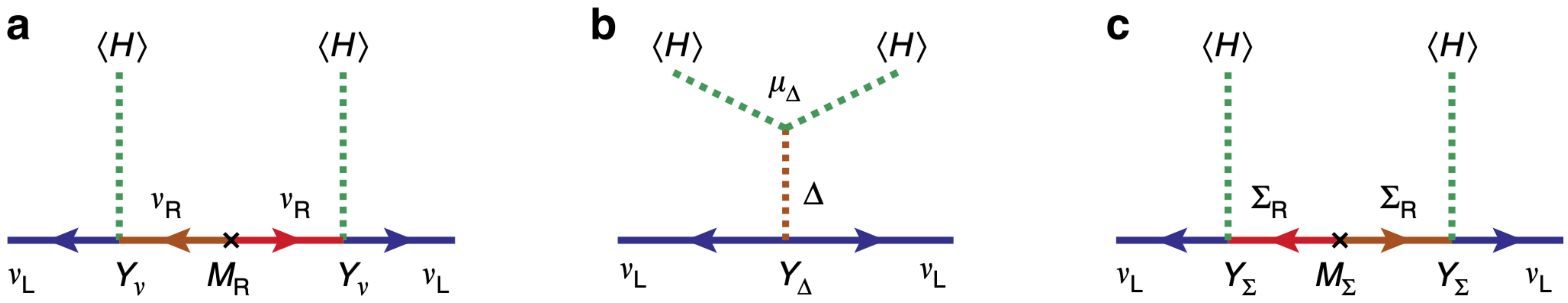
Higgs potential   Higgs potential



Very early universe   Late universe

Three types of seesaw models(tree level)

Tommy Ohlsson, Shun Zhou, Nature Commun. 5 (2014) 5153



$M_\nu = -\langle H\rangle^2 Y_\nu M_R^{-1} Y_\nu^T$

$M_\nu = \langle H\rangle^2 Y_\Delta \mu_\Delta / M_\Delta^2$

$M_\nu = -\langle H\rangle^2 Y_\Sigma M_\Sigma^{-1} Y_\Sigma^T$

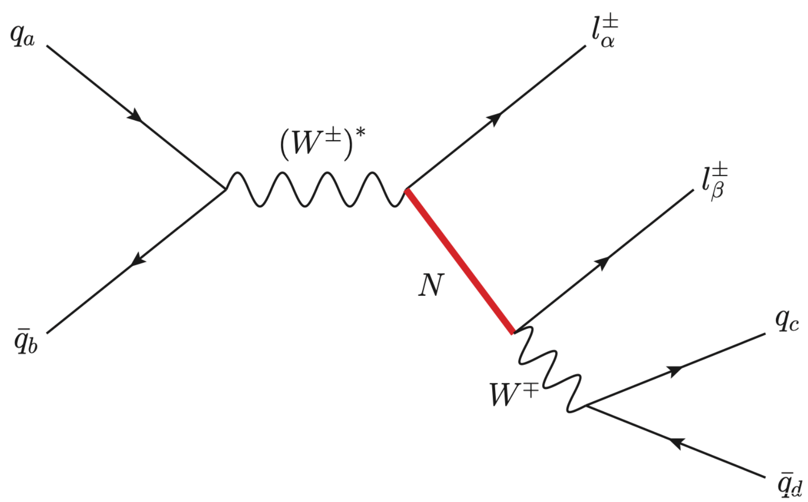
SM + 3 singlets fermions

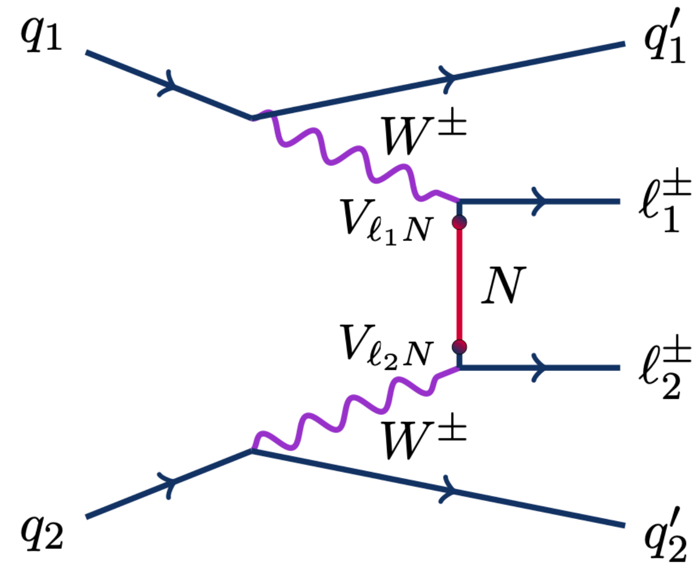
SM + 1 triplet Higgs

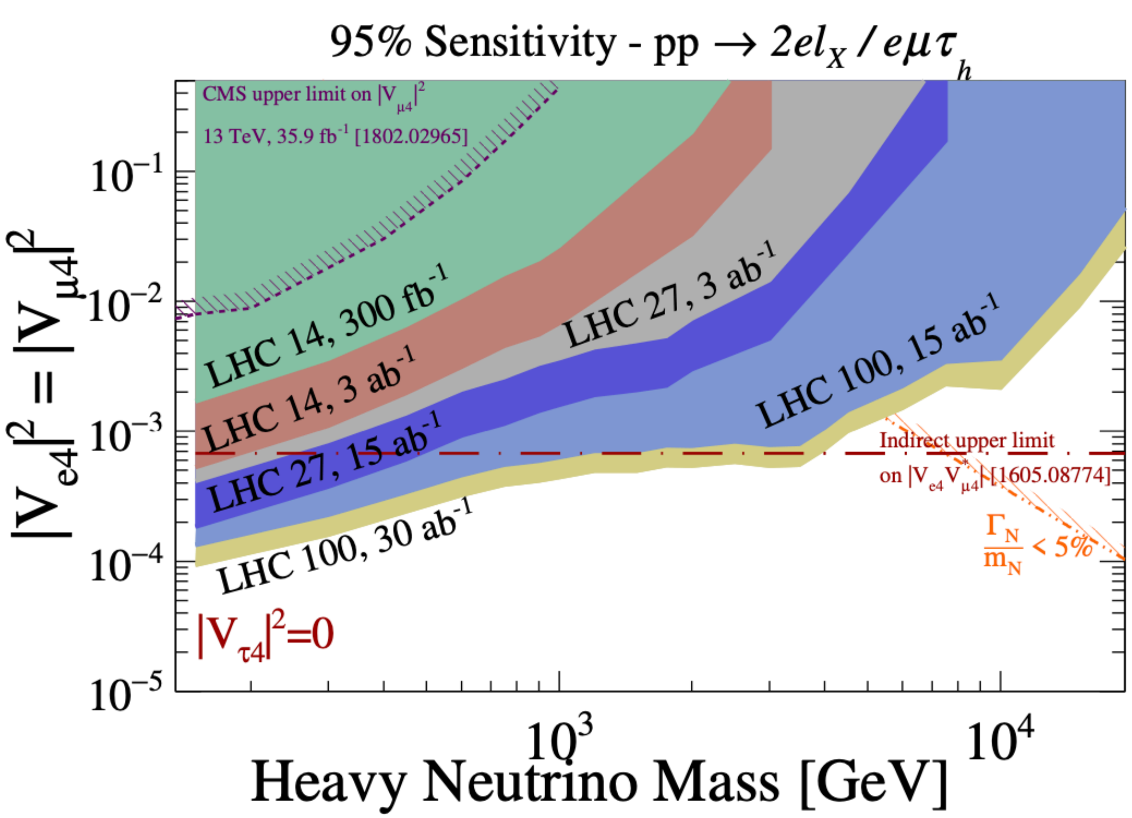
SM + 3 triplet fermions

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

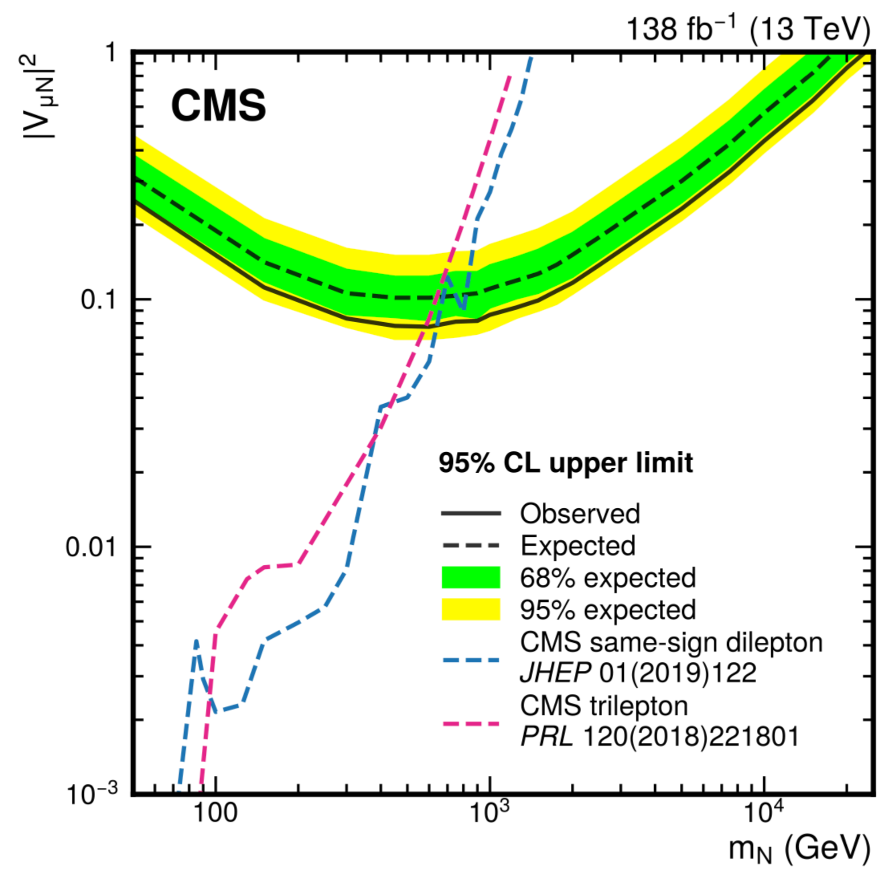
Collider searches for type I seesaw







T. Han, J. Liao, H. Liu, D. Marfatia, R. Ruiz, arXiv:2203.06131



CMS Collaboration, arXiv: 2206.08956

Collider searches for type II seesaw

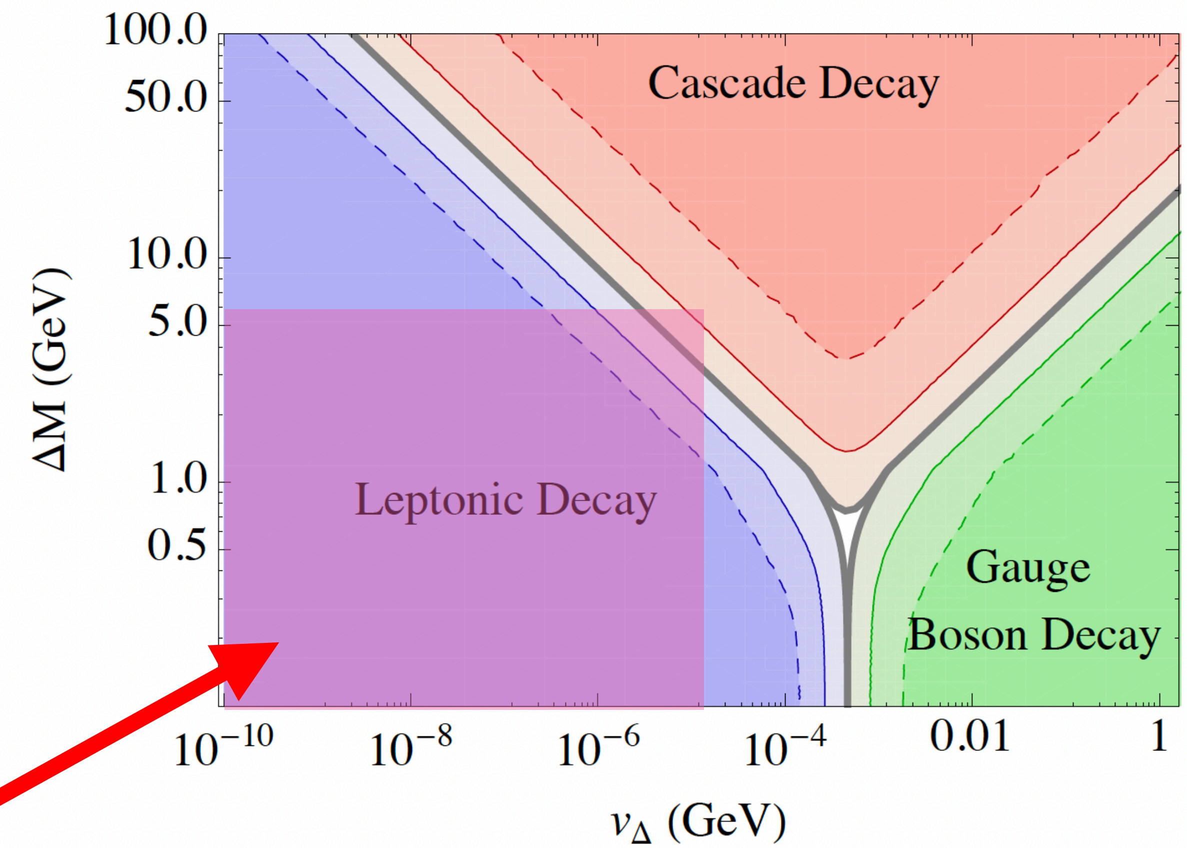
$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L} \supset \frac{1}{2} y_{ij} \Delta^0 \bar{\nu}^c \nu + h.c.$$

Neutrino masses from $\langle \Delta^0 \rangle = v_\Delta$

Decay of the doubly-charged Higgs

$\Delta M = m_{\Delta^{++}} - m_{\Delta^+}$



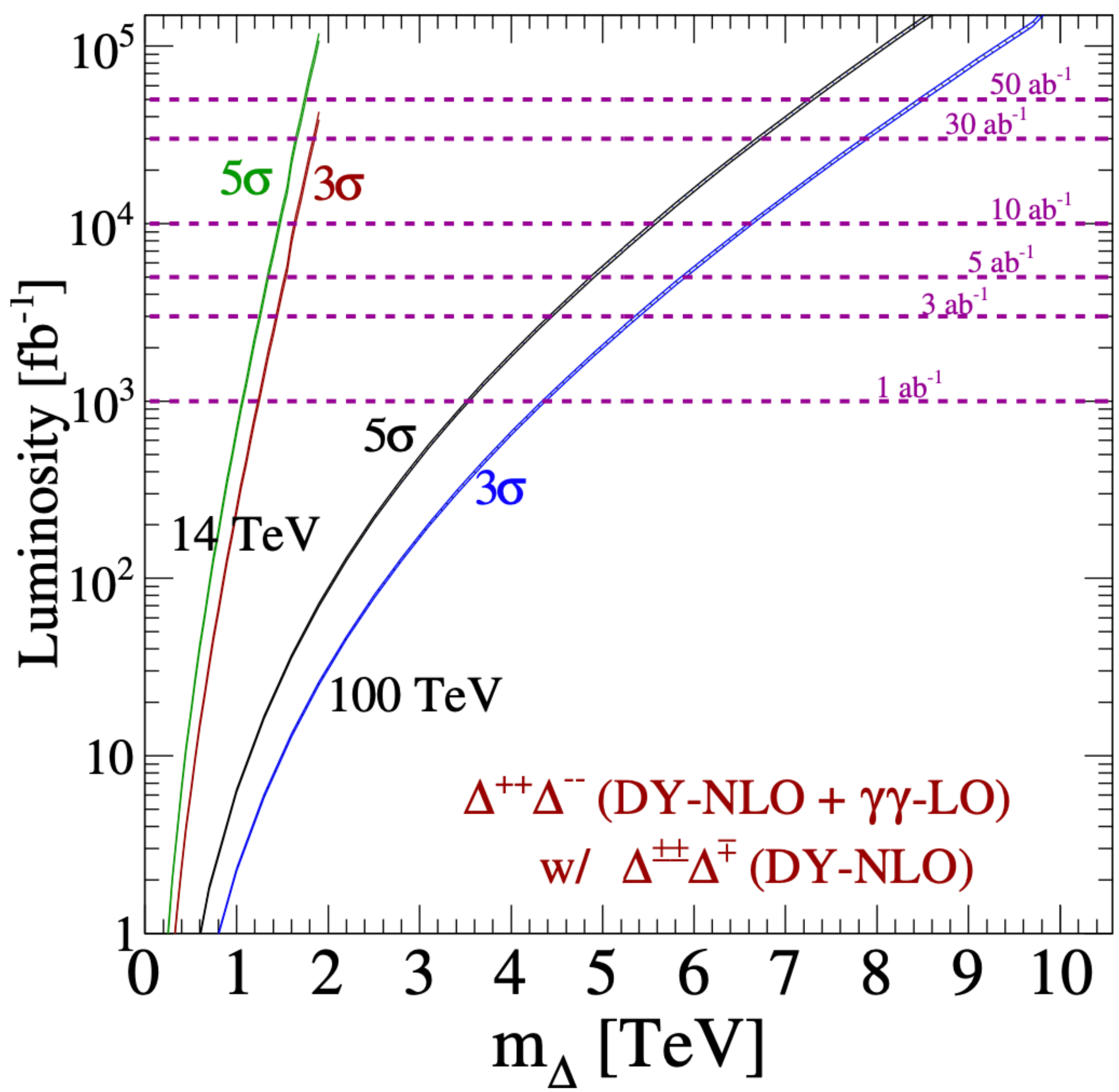
Consistent with baryogenesis from type II seesaw

N. D. Barrie, **CCH**, H. Murayama, Phys. Rev. Lett. 128, 141801

Testing the type II seesaw baryogenesis at colliders!

Collider searches for type II seesaw

T. Han, J. Liao, H. Liu, D. Marfatia, R. Ruiz, arXiv:2203.06131



Sensitivity of few TeV can be reached at future colliders

Strong CP problem

$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu} \qquad \bar{\theta} = \theta + \mathrm{Arg}\{\mathrm{Det}(M_u M_d)\}$$

Neutron eDM → $\bar{\theta} < 10^{-10}$

Solutions

- Pecci-Quinn symmetry → Axion, axion quality problem
- Nelson-Barr mechanism → Dangerous loop correction
- Massless u/d quark → Not favored by lattice result

SUSY Nelson-Barr

PHYSICAL REVIEW D **103,** L111701 (2021)

Letter

Complete solution to the strong *CP* problem: Supersymmetric extension of the Nelson-Barr model

Jason L. Evans,[1,*] Chengcheng Han,[2,3] Tsutomu T. Yanagida,[1,4] and Norimi Yokozaki[5]

- CP symmetry is spontaneously broken
- Avoid the higher loop correction
- Consistent with the leptogenesis

Axion dark matter solving the cosmic dipole problem

QCD axion dark matter and the cosmic dipole anomaly,
CCH, arXiv: 2211.06912

Recently a dipole problem appears in cosmology
reviewed by Noble Laureate, P. J. Peebles

> astro-ph > arXiv:2208.05018

Search...

Help | Adva

Astrophysics > Cosmology and Nongalactic Astrophysics

[Submitted on 9 Aug 2022]

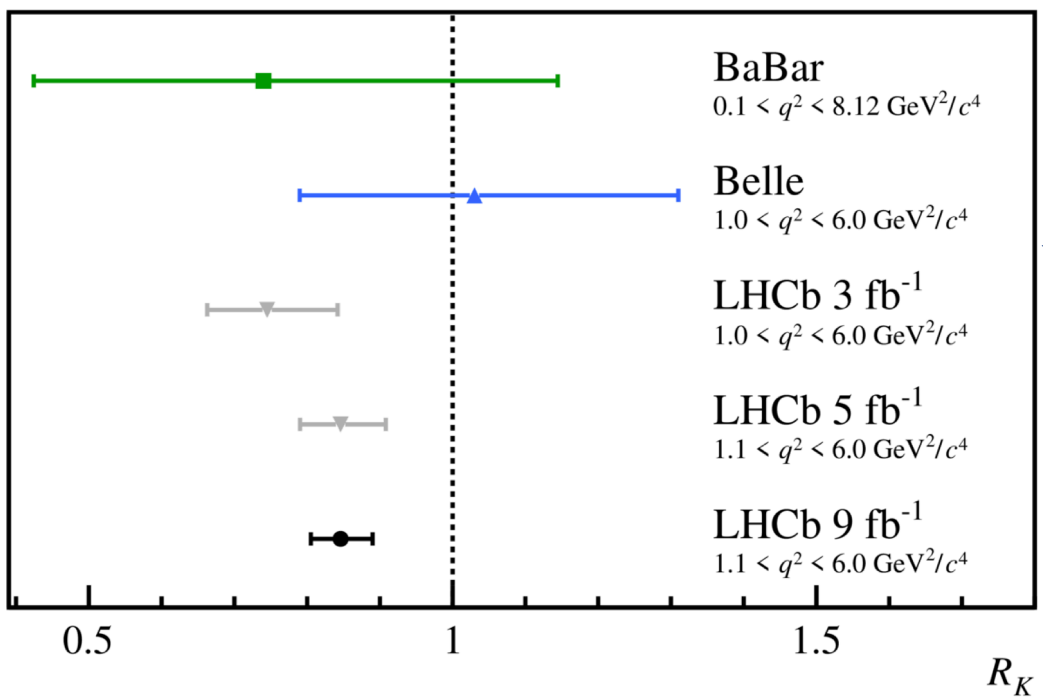
Anomalies in Physical Cosmology

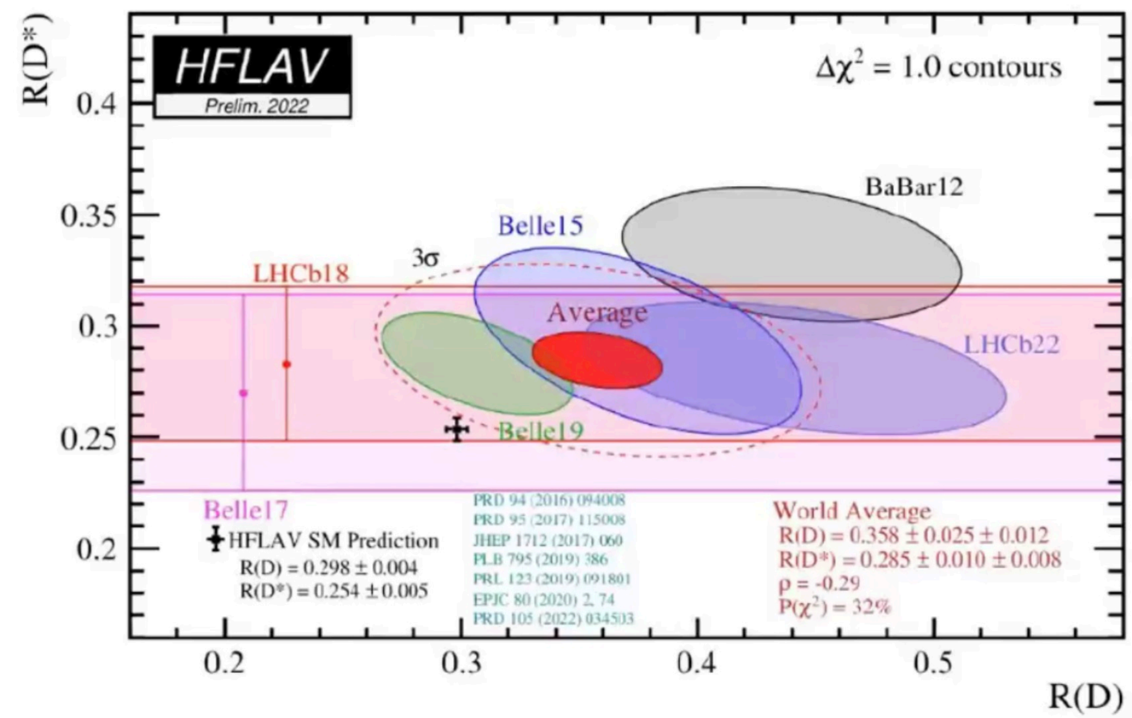
Phillip James E. Peebles

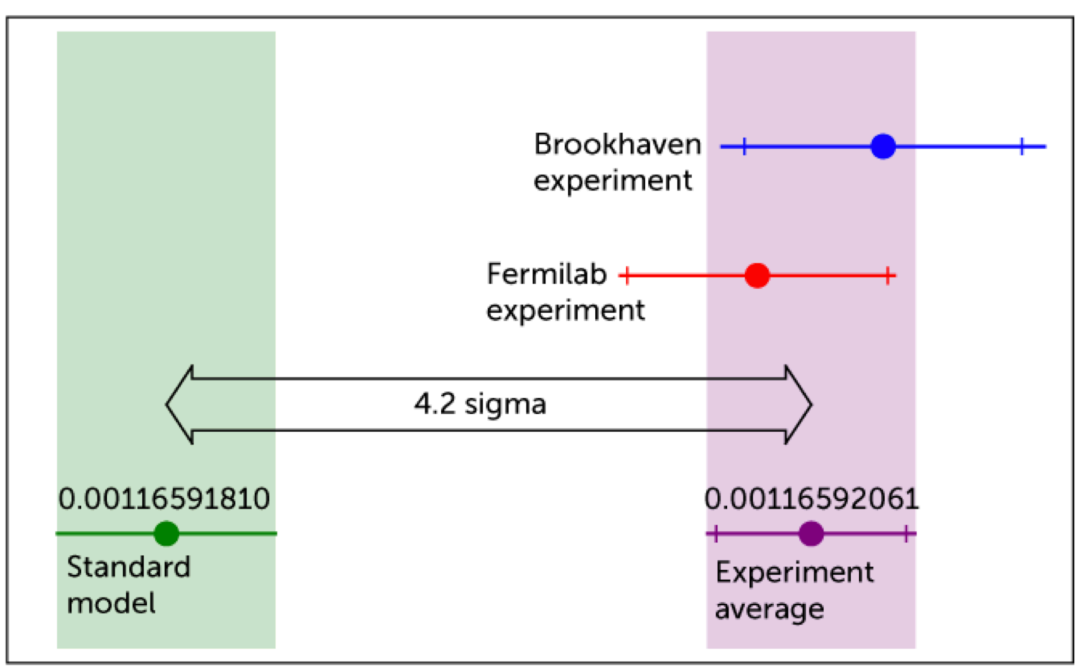
The ΛCDM cosmology passes demanding tests that establish it as a good approximation to reality. The theory is incomplete, of course, and open issues are being examined in active research programs. I offer a review of less widely discussed anomalies that might also point to hints to a still better cosmological theory if more closely examined.

This anomaly may be an evidence of the axion dark matter!

Flavor anomalies



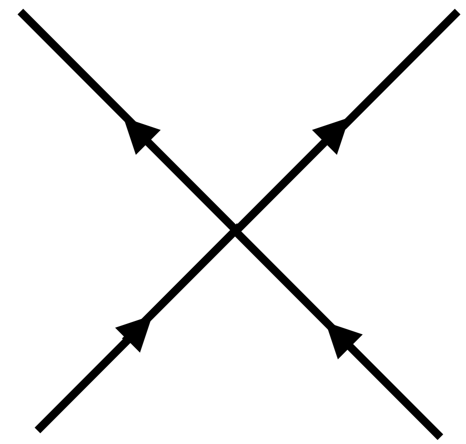


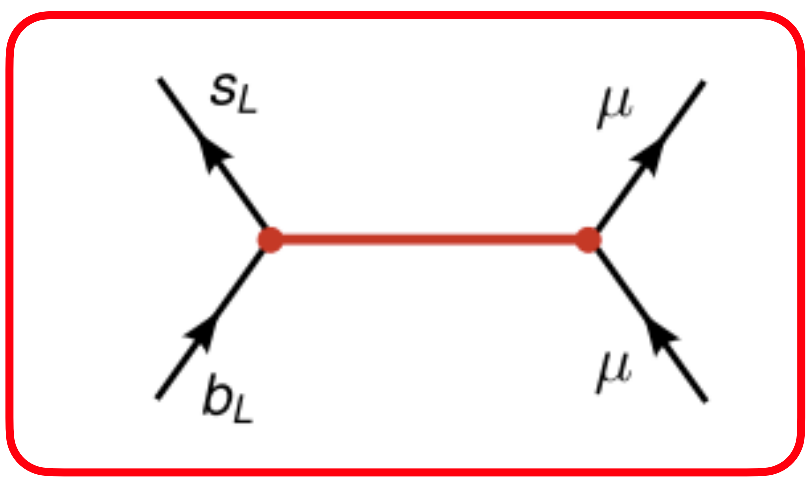


Muon magnetic anomaly

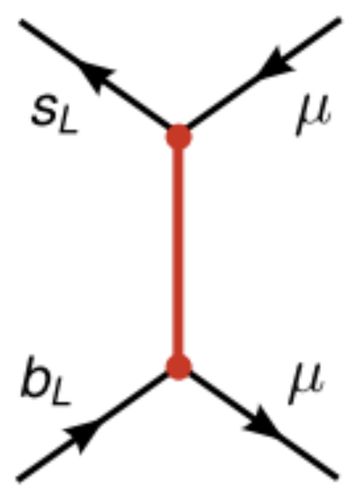
Z′, leptoquark, vector fermions, scalars …

Lepton flavor universality violation

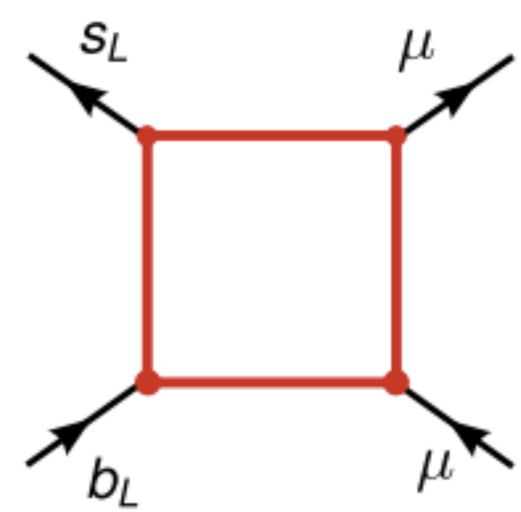
$\bar{s}\gamma_\rho b_L$  $\bar{\mu}\gamma^\rho \mu$



Z'



Lepto-quark



Loop

- New gauge symmetry should be anomaly-free
- Strong limit from LHC searches $pp \to Z' \to \mu\bar{\mu}$

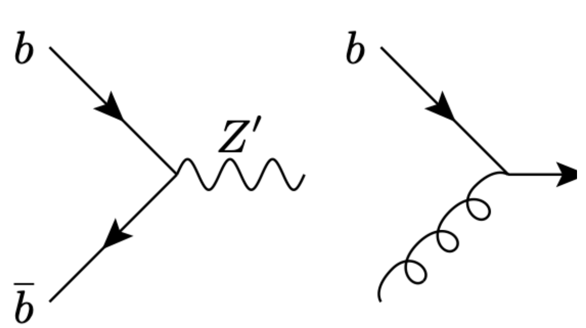
A simple Z' model

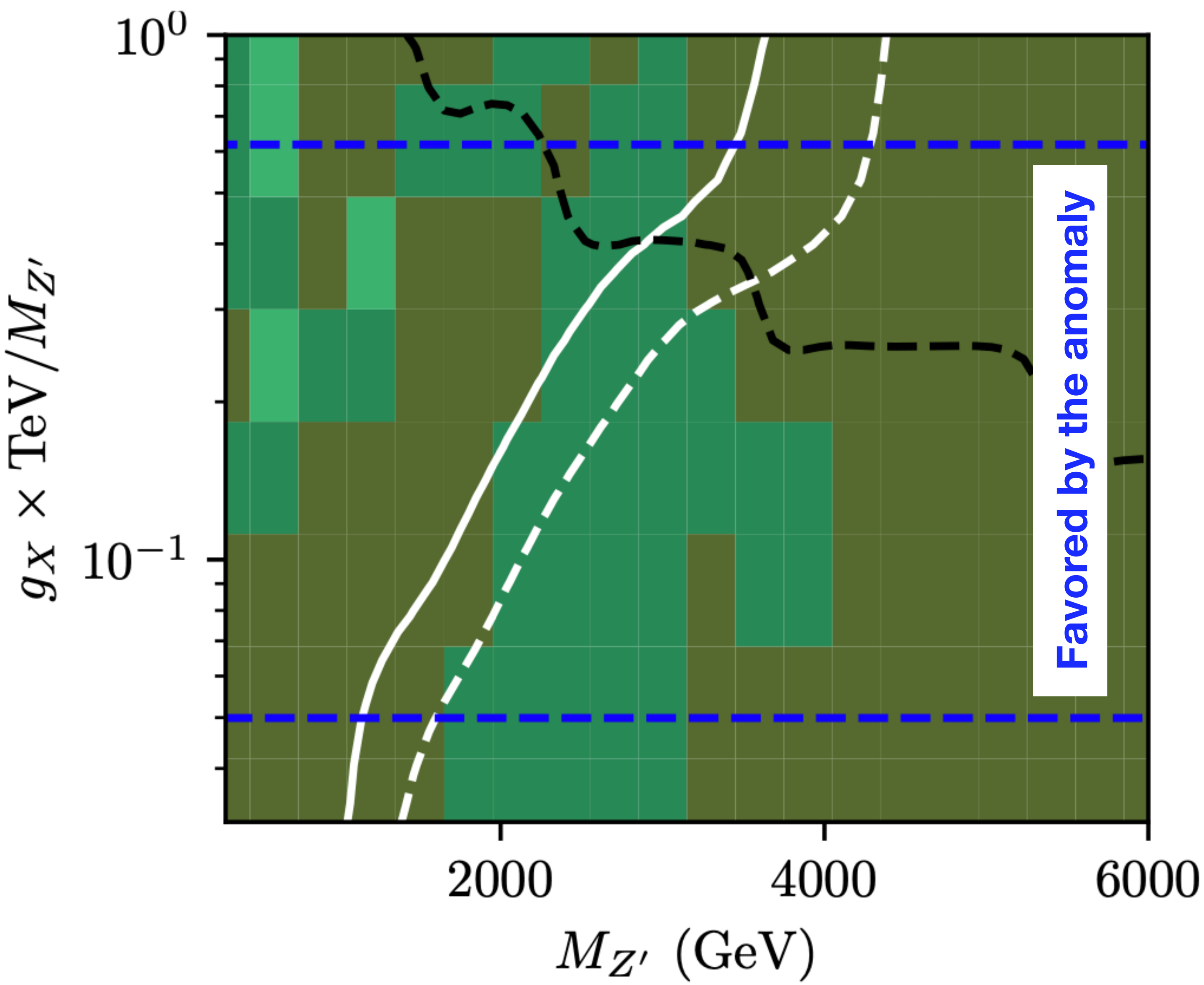
Flavored B-L $B_3 - L_2$

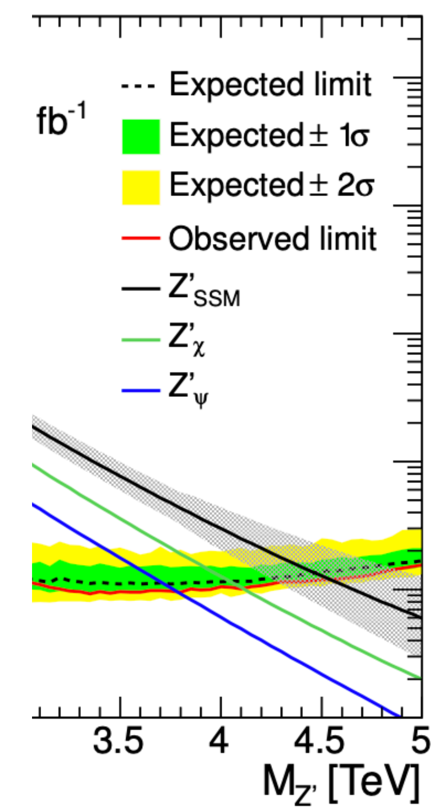
R. Alonso, P. Cox, **CCH**, T. T. Yanagida, Phys.Lett.B 774 (2017) 643-648

C. Bonilla, T. Modak, R. Srivastava and J. W. F. Valle, Phys. Rev. D 98 (2018), no. 9 095002

Strong interaction witl



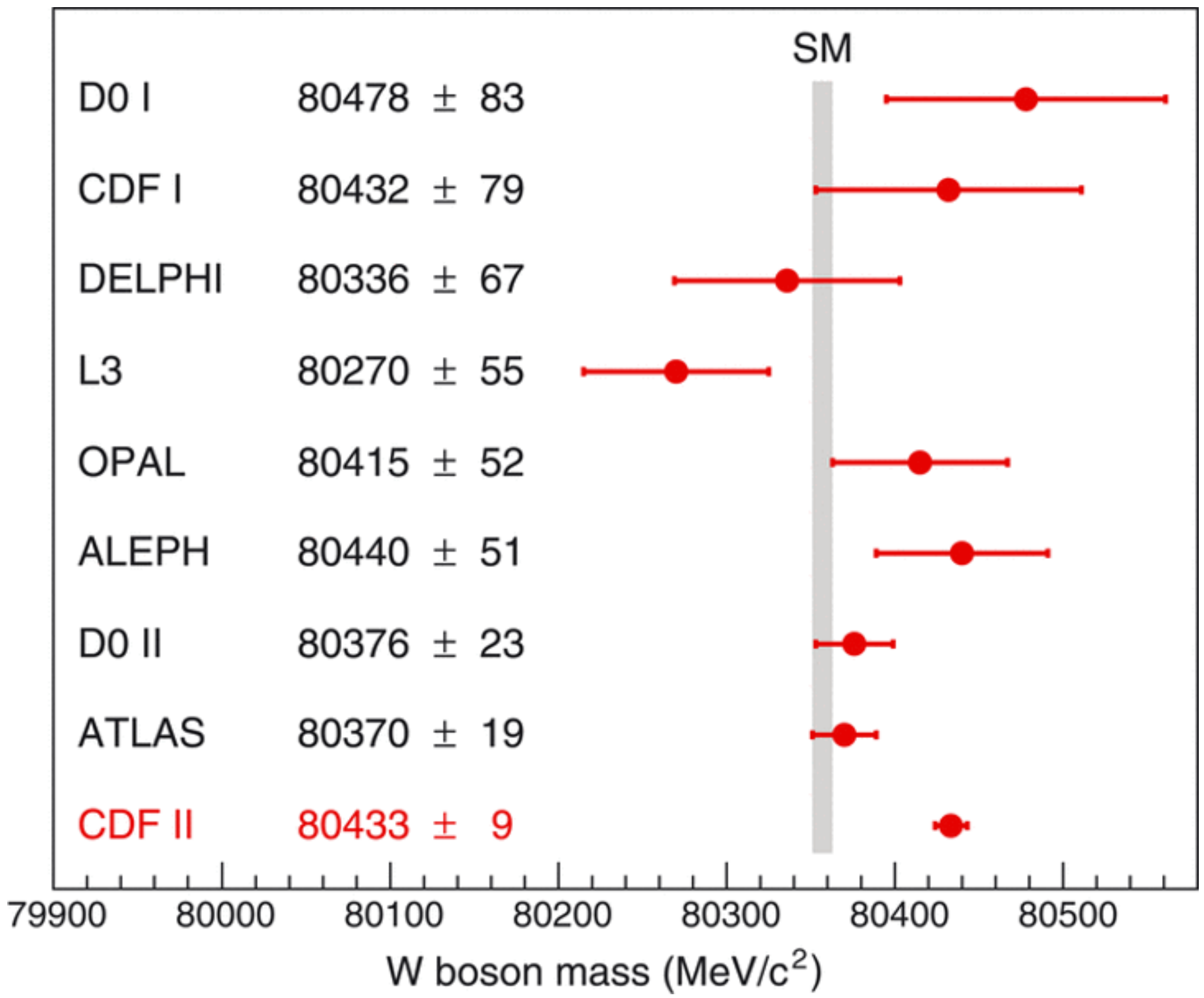




Large Hadron Collider Constraints on Some Simple Z′ Models for b→sμ+μ− Anomalies
B.C. Allanach, J. M. Butterworth, Tyler Corbett, *Eur.Phys.J.C* 81 (2021) 12, 1126

W mass problem

Science 376 (2022) 6589, 170-176



7 sigma away from SM prediction

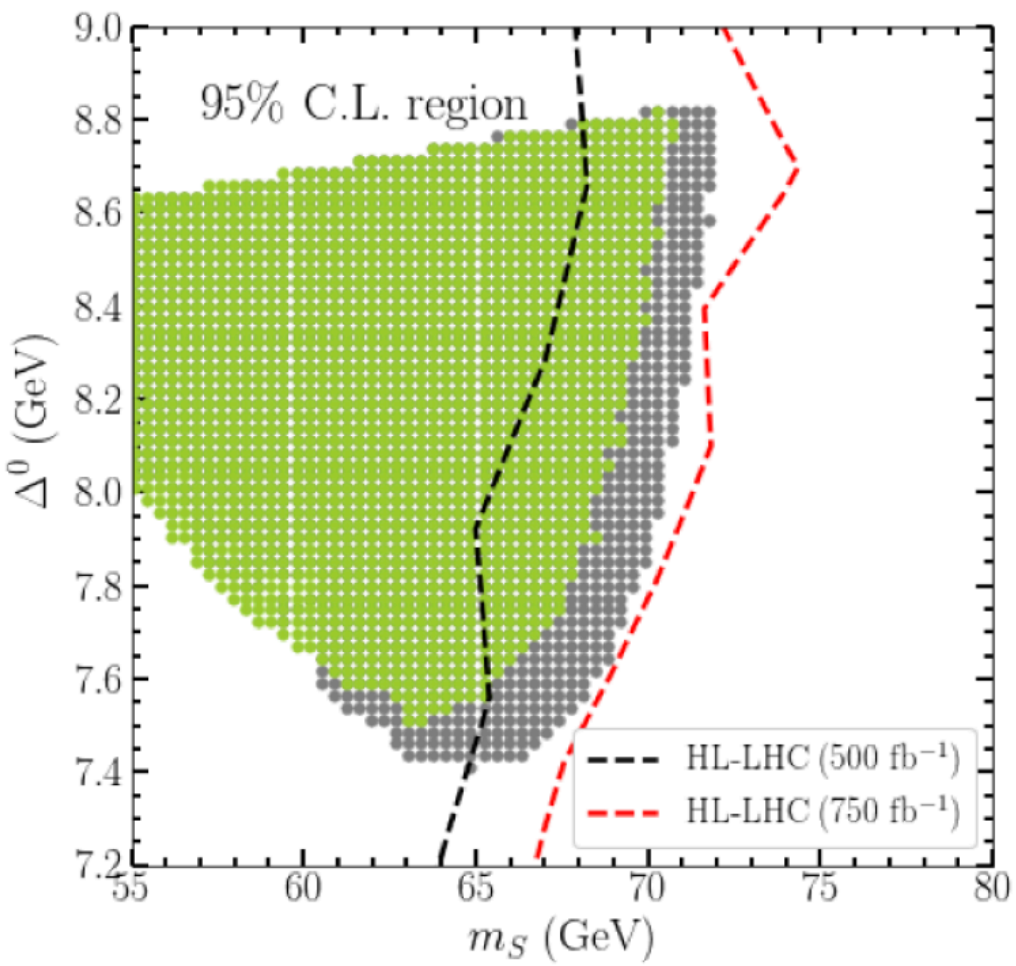
Many new physics models

Models to explain W mass problem

PHYSICAL REVIEW LETTERS **129,** 091802 (2022)

Inert Higgs Dark Matter for CDF II *W*-Boson Mass and Detection Prospects

Yi-Zhong Fan,[1,2,*] Tian-Peng Tang,[1,2,†] Yue-Lin Sming Tsai,[1,‡] and Lei Wu[3,‖]
[1]*Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210033, China*
[2]*School of Astronomy and Space Science, University of Science and Technology of China, Hefei, Anhui 230026, China*
[3]*Department of Physics and Institute of Theoretical Physics, Nanjing Normal University, Nanjing 210023, China*



- Provide dark matter candidate
- DM mass between 54-74 GeV
- Probed in near future

Models to explain W mass problem

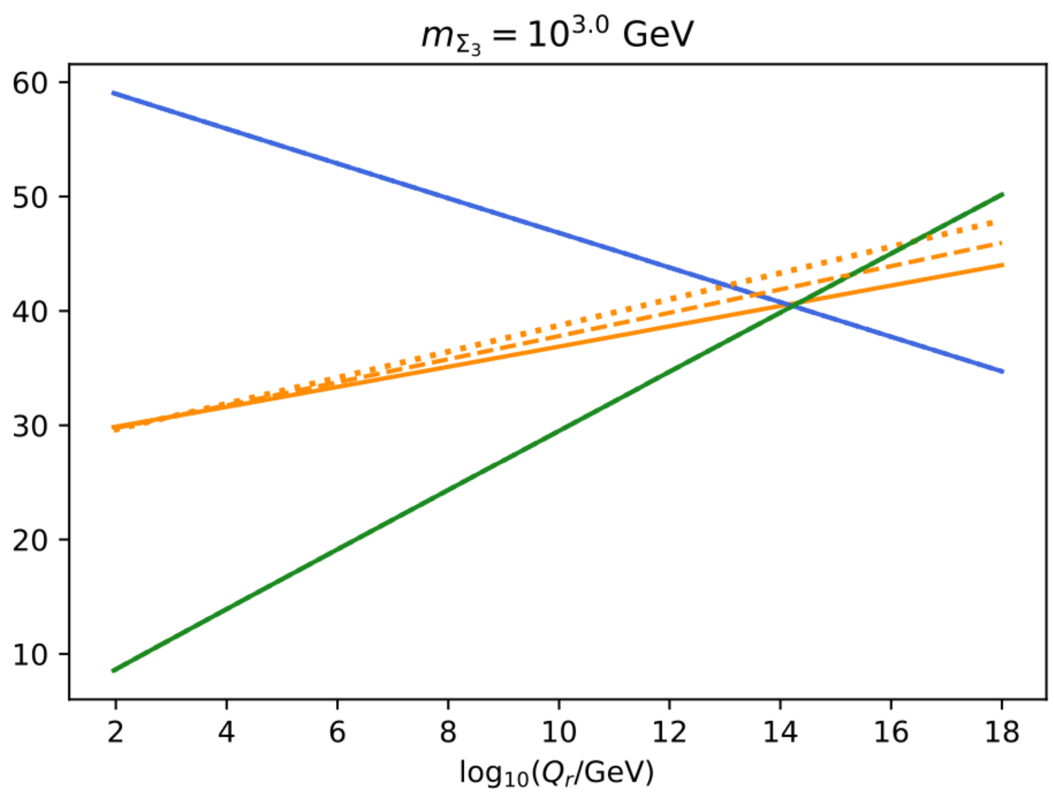
W boson mass anomaly and grand unification

Jason L. Evans[a], **Tsutomu T. Yanagida**[a,b], and **Norimi Yokozaki**[c]

[a] *Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai 200240, China*

[b] *Kavli IPMU (WPI), UTIAS, University of Tokyo, Kashiwa, Chiba 277-8583, Japan*

[c] *Zhejiang Institute of Modern Physics and Department of Physics, Zhejiang University, Hangzhou, Zhejiang 310027, China*



- SU(2) Triplet scalars around TeV
- Achieving gauge unification
- Easily probed at the LHC

Summary

- Many problems require new physics beyond SM
- Colliders are still one of the most powerful tools to probe new physics
- So many new physics models, we need experimental data to point out the direction

"The more I learn, the more I realize how much I don't know."

— **Albert Einstein**

The More We Learn, the Less We Know

Thanks!