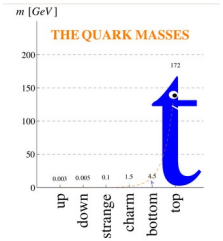
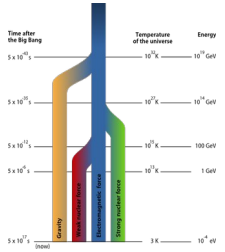
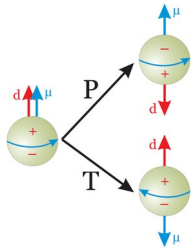
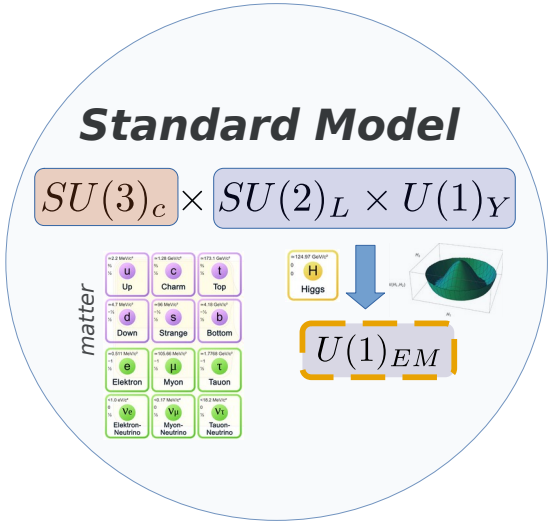






Of Hierarchies and Symmetries: Decoding the Pattern behind the Standard Model



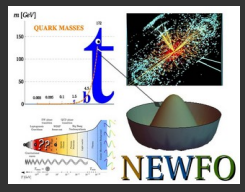
10 Years mitp :
Pushing the Limits
of Theoretical Physics

12.5.2023

Florian Goertz

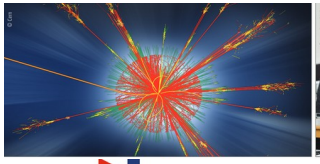
MPIK

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG



The first three years of the LHC

Mar 18 – 22, 2013
Mainz



Mainz Institute for Theoretical Physics

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Fabio Iocco ICTP-SAIFR & IFT-UNESP, São Paulo
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Effective Field Theories as Discovery Tools

Higgs Pair Production at Colliders

Daniel de Florian **Univ. Buenos Aires**, Christophe Grojean **CERN**,
Fabio Maltoni **Univ. Leuven**, Aleandro Nisati **INFN Rome**,
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Nathaniel Craig (UCSB), Nayara Fonseca (ICTP), Camila Machado (DESY),
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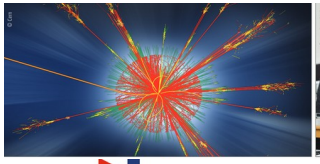

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July 11 – 22, 2022

Pulsar Timing Arrays: A Star-Way to New Physics

Simone Blasi **Vrije Univ. Brussel**, Vedran Brdar **Fermilab / Northwestern Univ.**, Wolfram Ratzinger **JGU Mainz**, Kai Schmitz **Univ. of Münster / CERN**, Pedro Schwaller **JGU Mainz**

August 14 – 18

2006/07

I was extremely lucky that Matthias came to Mainz, just when I was looking for a topic for my thesis!

Auf die W3-Professur in der Theoretischen Elementarteilchenphysik (ThEP) wurde Professor Dr. Matthias Neubert berufen.

Matthias Neubert, 1962 in Siegen geboren, studierte ab März 1984 Physik, Mathematik und Chemie an der Universität Siegen. Nachdem er bereits im August 1985 sein Vordiplom abgelegt hatte, wechselte Neubert an die Ruprecht-Karls-Universität Heidelberg, wo er im November 1990 seinen Ph.D. erhielt und sich schließlich 1993 mit einer Arbeit zum Thema „Heavy-quark symmetry" habilitierte. Im Oktober 1993 wechselte Neubert ans CERN, das größte Teilchenphysik-Forschungszentrum der Welt, in die Nähe von Genf, bevor er im Januar 1999 eine Gastprofessur am Stanford Linear Accelerator Center antrat. Neubert ist bereits seit 1998 Honorarprofessor an der Heidelberger Universität, und war von Juli 1999 bis zur jetzigen Berufung an die Universität Mainz Professor für Physik an der Cornell University, Ithaca, New York, seit September 2003 Direktor des Cornell Institute for High-Energy Phenomenology. Für seine Arbeiten zur Physik schwerer Quarks erhielt Neubert 2005 den Humboldt Forschungspreis und wurde 2006 zum Fellow der American Physical Society gewählt. Weiterhin ist er seit 1997 Herausgeber des Journal of High Energy Physics, und seit 1998 des European Physical Journal C. Neuberts besonderes Forschungsinteresse liegt im Gebiet der Theoretischen Teilchenphysik mit Schwerpunkt starke und schwache Wechselwirkungen. ■

23.02.2007 12:00

Teilen:

Konzepte für die Physik von morgen: Professor Matthias Neubert in Mainz

Petra Giegerich *Presse- und Öffentlichkeitsarbeit*
Johannes Gutenberg-Universität Mainz

International renommierter Physiker übernimmt Professur für Theoretische Elementarteilchenphysik an der Universität

(Mainz, 23. Februar 2007, lei) Mit einer exzellenten Neubesetzung am Institut für Physik hat die Johannes Gutenberg-Universität Mainz ihre Position im Forschungs- und Lehrbereich auf dem Gebiet der Teilchenphysik weiter verstärkt. Mit der Berufung von Univ.-Prof. Dr. Matthias Neubert auf die Professur für Theoretische Elementarteilchenphysik ist es der Universität gelungen, einen international hoch renommierten Wissenschaftler vom Physik-Department der Cornell University, die zu den US-Spitzenuniversitäten zählt, nach Mainz zu holen. Für den 44-jährigen Physiker ist es ein besonderer Anreiz, gerade zum jetzigen Zeitpunkt, kurz vor der weltweit mit Spannung erwarteten Fertigstellung eines neuen Teilchenbeschleunigers am Genfer CERN, zurück nach Deutschland zu kommen und hier eine neue Arbeitsgruppe aufzubauen. Im Bereich der Teilchenphysik spielt die Johannes Gutenberg-Universität mit experimentellen Arbeiten am CERN und am Neutrinoteleskop "Amanda", mit dem bestehenden Graduiertenkolleg "Eichtheorien", sowie mit dem Antrag für die Graduiertenschule "Femto" im Rahmen der Exzellenzinitiative des Bundes in der ersten Liga.

Nach seiner Promotion in Heidelberg war Matthias Neubert mit einem Stipendium der Studienstiftung des deutschen Volkes für zwei Jahre im kalifornischen Stanford und hat am dortigen Linearbeschleuniger wissenschaftlich gearbeitet. Es folgten ein sechsjähriger Aufenthalt am CERN und noch ein Forschungssemester in Stanford, bevor er 1999 als Leiter der Theoriegruppe und Direktor des Instituts für Hochenergie-Phänomenologie die Professur an der Cornell University, Bundesstaat New York, antrat. Er ist seit 1998 Honorarprofessor in Heidelberg und nun seit dem Wintersemester 2006/07 an der Johannes Gutenberg-Universität in Mainz tätig. "Wir sind in der Teilchenphysik über den ganzen Globus vernetzt, sodass meine Kontakte zu den USA bestehen bleiben", so Neubert, der seiner zweiten Heimat voraussichtlich als Adjunct Professor in Cornell verbunden bleiben wird.

Die Elementarteilchenphysik befasst sich mit der Erforschung der fundamentalen Bausteine der Materie sowie mit den Kräften, die zwischen diesen Bausteinen wirken. Insbesondere beschäftigen die Teilchenphysiker derzeit drei Fragen, die mit den Eigenschaften der Materie zu tun haben: Wie bekommen die Teilchen auf fundamentalem Niveau ihre Masse? Warum gibt es im Universum mehr Materie als Antimaterie? Und was genau ist die dunkle Materie, von der es weit mehr als von gewöhnlicher Materie im Universum zu geben scheint? Mit dem Large Hadron Collider (LHC) entsteht derzeit am CERN in Genf der weltweit größte Teilchenbeschleuniger, bei dem Protonen für den Zusammenprall auf bisher unerreicht hohe Energie beschleunigt werden. Die Fertigstellung ist für Herbst 2007 vorgesehen. "Wir erhoffen uns von der Inbetriebnahme des LHC, dass wir neue Teilchen wie das Higgs-Boson entdecken und vielleicht auch noch schwerere Teilchen finden, die als dunkle Materie identifiziert werden können", erläutert Neubert.

In der theoretischen Elementarteilchenphysik haben die Wissenschaftler mit den Experimenten meist nicht direkt zu tun, sondern befassen sich mit der Deutung der Ergebnisse und stellen theoretische Konzepte auf, die dann wiederum im Experiment überprüft werden. "Meine Arbeit hat sich dabei immer stark am Experiment orientiert und ist in engem Kontakt mit den experimentellen Zentren am Cornell Electron Storage Ring und dem Stanford Linear Accelerator Center erfolgt", erläutert der Physiker. Für die korrekte Interpretation der extrem aufwändigen Experimente sei diese Arbeit, so heißt es in der Laudatio zu Neuberts Berufung, von größtem Wert. Mit Blick auf die Nähe zu Genf sei es, so Neubert, ein guter Zeitpunkt, jetzt etwas Neues zu beginnen und den Umbruch in der theoretischen Physik hier in Deutschland mit zu gestalten. Ein Schwerpunkt seiner Arbeit ist auch in Mainz die Flavour-Physik, die sich mit den Eigenschaften von Elementarteilchen befasst sowie mit der theoretischen Erklärung, wie es zum Übergewicht der Materie in unserem Universum kommt. Für Arbeiten auf diesem Gebiet erhielt Neubert 2005 den Forschungspreis der Alexander von Humboldt-Stiftung und wurde 2006 zum Fellow der American Physical Society gewählt. In der Lehre will sich Neubert vor allem auch in der Doktorandenausbildung und der Veranstaltung von Sommerschulen engagieren. Er ist Herausgeber mehrerer Wissenschaftsjournale seines Fachgebiets.

Zu der Antrittsvorlesung von Prof. Neubert am 26. April 2007 ist die interessierte Öffentlichkeit herzlich eingeladen.

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23.02.2007 12:00

Konzepte für die Physik von morgen: Professor Matthias Neubert in Mainz

Teilen:

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Flavor Physik in Randall-Sundrum-Modellen

39. Herbstschule für Hochenergiephysik, Maria Laach, 04.-14.09. 2007

Florian Goertz
Institut für Physik, THEP
Johannes-Gutenberg-Universität Mainz

Download

Natürliche Erweiterung: SM im Bulk

Y. Grossman, M. Neubert, hep-ph/9912408
T. Gherghetta, A. Pomarol hep-ph/0003129

(Higgs auf IR-Brane)

- Betrachte Fermionen

$$S_{ferm} = \int d^4x \int dy \sqrt{-g}\,(e^M{}_m \frac{i}{2}\bar{\psi}\gamma^m(\partial_M - \overleftarrow{\partial_M})\psi - ck\,\mathrm{sgn}(y)\bar{\psi}\psi)$$

- effektive 4D Theorie: Kaluza-Klein-Zerlegung nach VONS:

$$\psi_{L,R}(x,y) = \frac{1}{\sqrt{2\pi r}} \sum_n \psi^{(n)}_{L,R}(x)\, f^{(n)}_{L,R}(y)$$

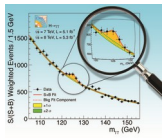
5D Dirac-Fermion $\psi \xrightarrow{eff.\ 4D} \psi^{(0)}_{L(R)} + \psi^{(n)} \quad (n \in \mathbb{N})$

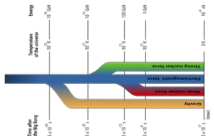
S_{ferm} gerade unter Z_2 $\Rightarrow$ $\psi_{L,R}$ gerade $\Leftrightarrow$ $\psi_{R,L}$ ungerade ($\psi^{(n)}_L + \psi^{(n)}_R$)

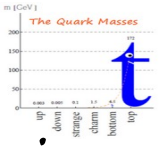
The SM is an EFT

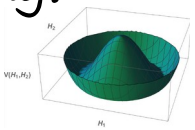
SM does not explain everything!

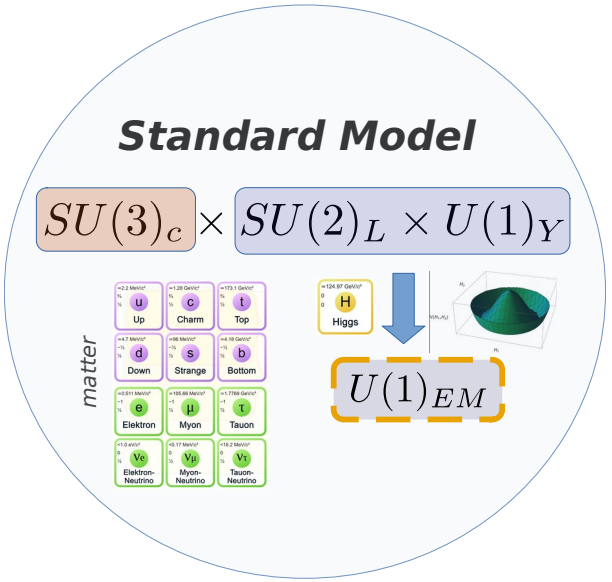
- Gravity $\notin$ SM
- Hierarchy Problem: $m_h \ll M_{PL}$
- Tiny Neutrino Masses
- Grand Unification of Forces?
- Hierarchical Flavor Structure
- Baryogenesis → Existence of Universe
- Dark Matter $\notin$ SM
- Trigger for Symmetry-Breaking?
- Strong CP Problem ...











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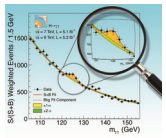

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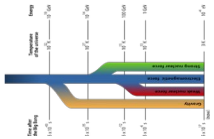
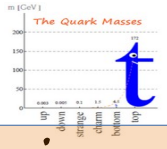


- Grand Unification of Forces?
- Hierarchical Flavor Structure



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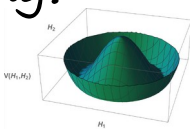

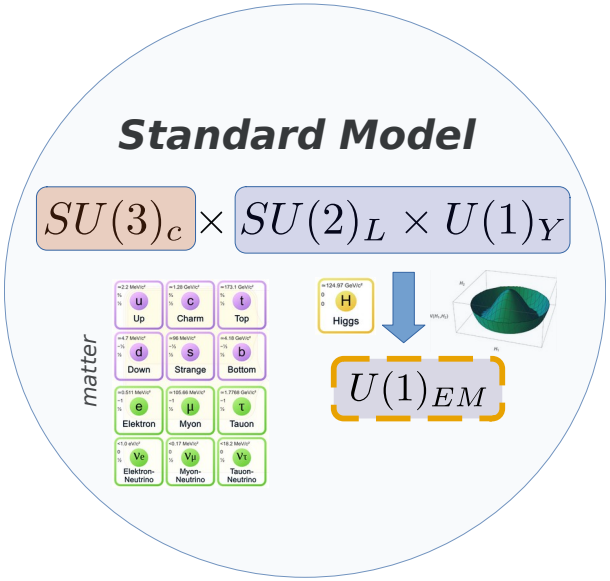

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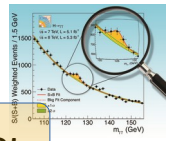

- Tiny Neutrino Masses

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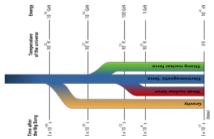
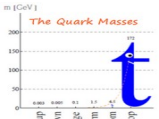


- Hierarchical Flavor Structure



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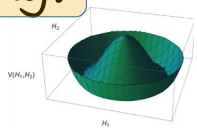
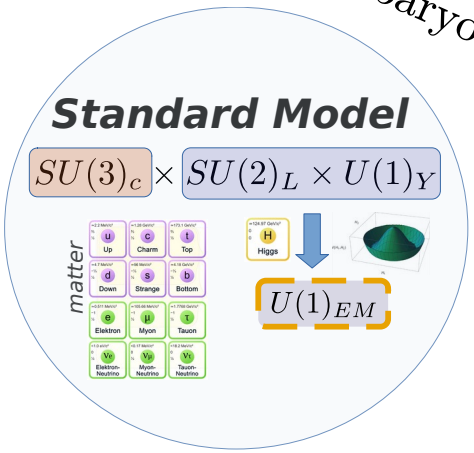


- Strong CP Problem ...

Great understanding of Symmetries in context of basic interactions, but still a puzzle how symmetries might address the hierarchies we see among interactions, particle masses (→ SM parameters), the baryon asymmetry, ...



Islands in Theory Space

Islands in Theory Space

Islands in Theory Space

Islands in Theory Space

+ consistency,...

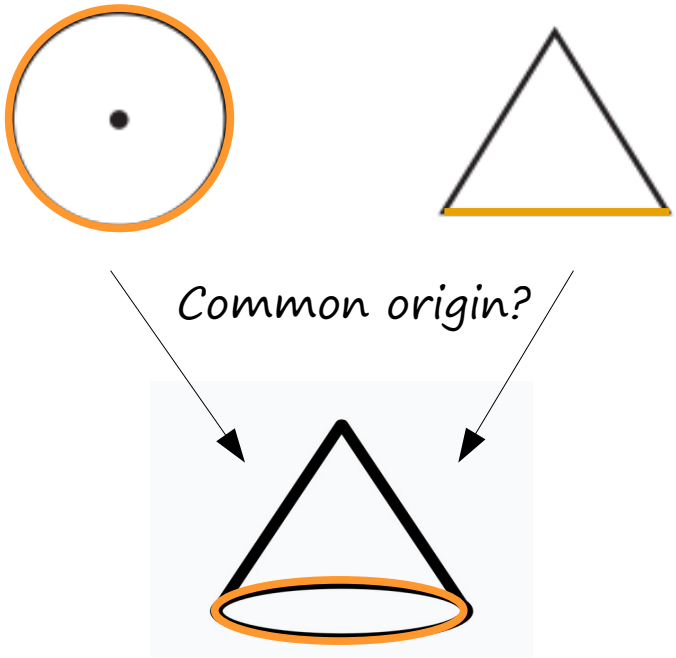
Islands in Theory Space

close targets

+ consistency,...

Unification and Symmetries

Unification and Symmetries

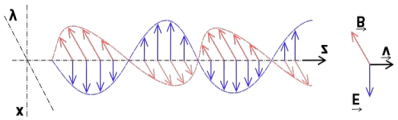
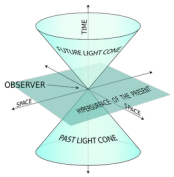
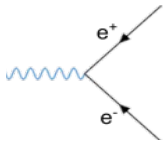
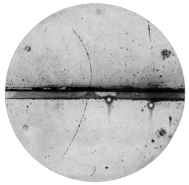
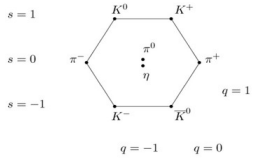
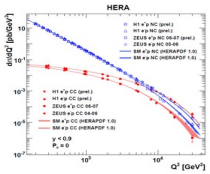
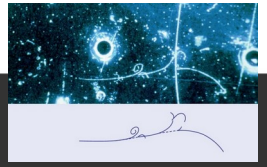
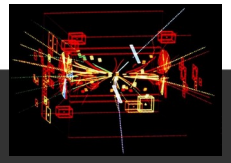


→ well defined question to nature that can try to answer....

- targets for searches, fewer parametrers → predictivity!
- sometimes understand hierarchies from unification/symmetries

Historic Examples

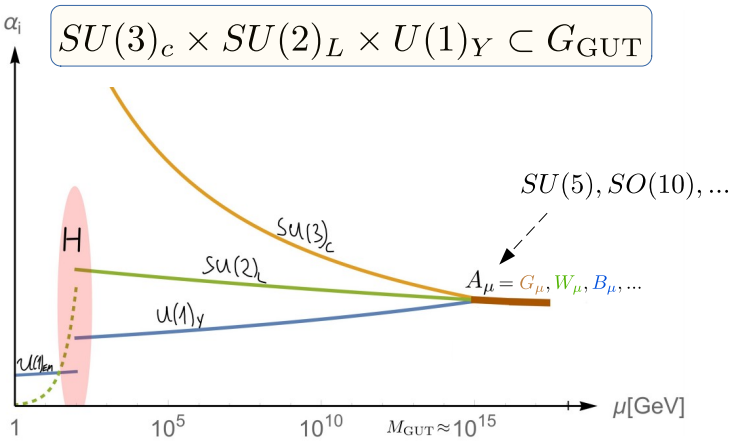
- Understanding the connection of different phenomena / theories frequently lead to crucial progress & discoveries

- Electricity ↔ Magnetism  → EM waves, … 
- Space ↔ Time  → $E=mc^2$, …
- QM & Relativity  → Positron, … 
- Eightfold Way  → Quarks 
- Electroweak Unification  → neutral currents, W&Z  

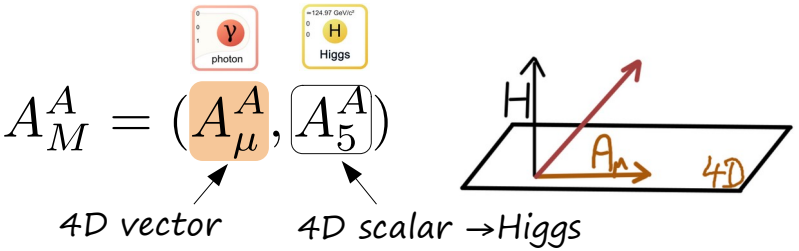
…

... Unification

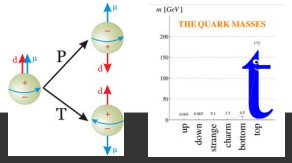
- Grand Unification



- Gauge-Higgs Unification
  (aka Composite Higgs)



- Axion-Flavon Unification $U(1)_{\rm PQ} = U(1)_{\rm FN}$ $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$



...

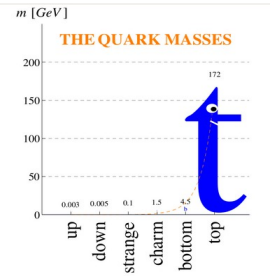
Hierarchies (in the SMEFT)

$$\mathcal{L}_H \supset m_H^2 |H|^2$$

$\sim 100\,\text{GeV}\ (\ll M_{Pl,GUT})$

$$\mathcal{L}_{\text{mass}} = -\bar{Q}_L \boldsymbol{m}_u u_R - \bar{Q}_L \boldsymbol{m}_d d_R - \bar{E}_L \boldsymbol{m}_e e_R + \text{h.c.}$$

$\text{diag}\,(m_u, m_c, m_t)\ , \ldots$



$$\mathcal{L}_{\text{ferm}} \supset \frac{g}{\sqrt{2}} \bar{u}_L \gamma^\mu W_\mu^+ V_{\text{CKM}}\, d_L$$

$$\begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim 0.23$$

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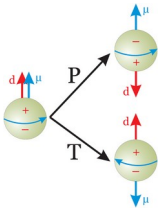
$\sim 100\,\text{GeV}\ (\ll M_{Pl,GUT})$

$$\mathcal{L}_{CP}^{\text{strong}} = \bar{\theta}\,\frac{\alpha_s}{8\pi} G_{a\mu\nu}\tilde{G}_a^{\mu\nu}$$

$\bar{\theta} \lesssim 10^{-10}$



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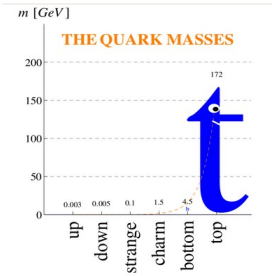

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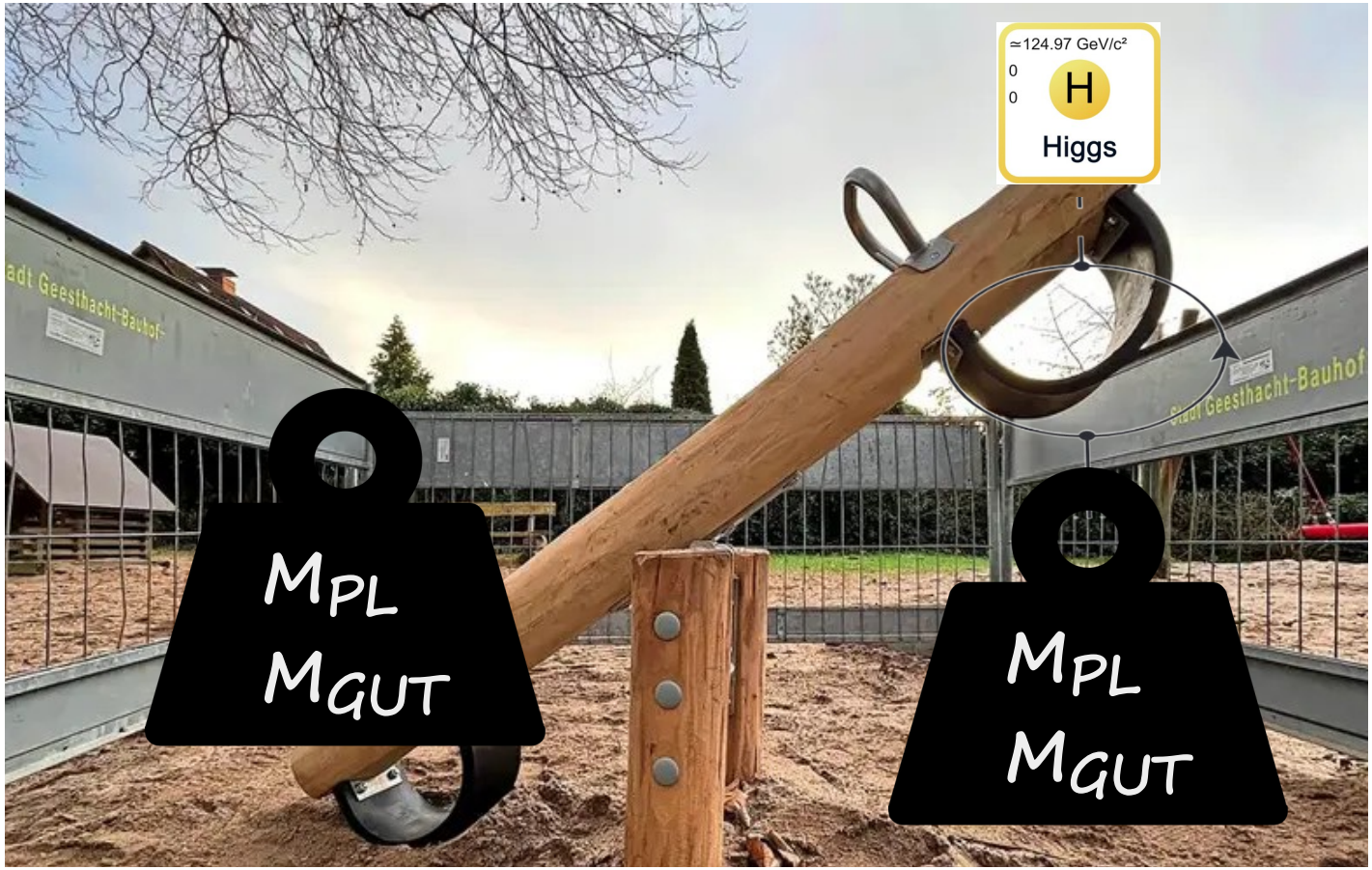
$\lambda \sim 0.23$

Hierarchies and Naturalness



©: Timo Jann

Hierarchies and Naturalness

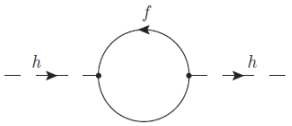
$$\mathcal{L}_H \supset m_H^2 |H|^2$$

$\sim 100\,\text{GeV}\ (\ll M_{Pl,GUT})$

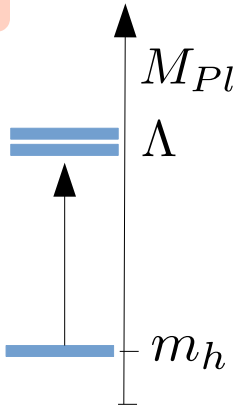
www.sport.de

$\Leftrightarrow g_{\text{grav}} \ll g_{\text{weak}}$

expect $m_H^2 \sim \Lambda^2 \gg 100\,\text{GeV}$



$\rightarrow \Delta m_h^2 \sim \Lambda^2$



$\Lambda^2 \sim M_{GUT}^2 \rightarrow$ Fine tuning 1 in 10^{26}

Hierarchies and Naturalness

$$\mathcal{L}_H \supset m_H^2 |H|^2$$

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www.sport.de

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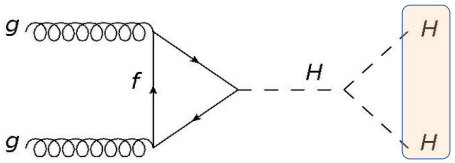
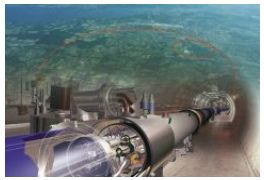


$\Rightarrow V(H)$

$\Downarrow$

HL-LHC



Historic Examples

- Puzzleing hierarchies/naturalness often understood via new physics
  → progress (calculability) & discoveries

$$m_e = (m_e)_0 \quad + \quad \Delta E_{\text{Coulomb}} \qquad \Delta E_{\text{Coulomb}} = \frac{1}{4\pi}\frac{e^2}{r_e}\,, \quad r_e \lesssim 10^{-17}\,\text{cm}$$

$$0.511\,\text{MeV} = -9999.498\,\text{MeV} + 10000.000\,\text{MeV}$$

Murayama, hep-ph/0002232

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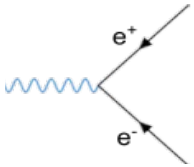
Murayama, hep-ph/0002232

cutoff: positron



$$r_\Lambda \gtrsim \frac{1}{2m_e} \sim 10^{-11}\,\text{cm}$$

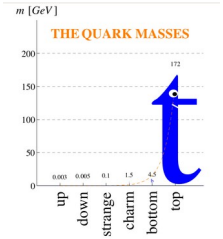
chiral sym.

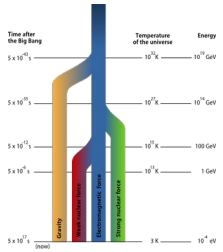
$$m_e = (m_e)_0 + \Delta E_{\text{Coulomb}} + \Delta E_{\text{pair}} = (m_e)_0 \left[1 + \frac{3\alpha}{4\pi}\log\frac{1}{(m_e)_0\, r}\right]$$

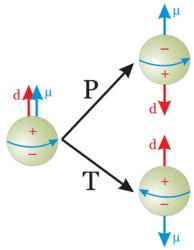
Weisskopf, Phys. Rev. 56, 72 (1939)

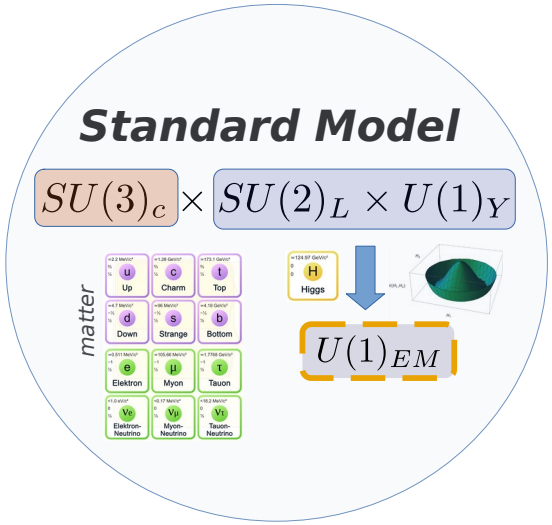
- More examples: pion mass splitting, K_L-K_S mass difference, ...

Unification and Hierarchies

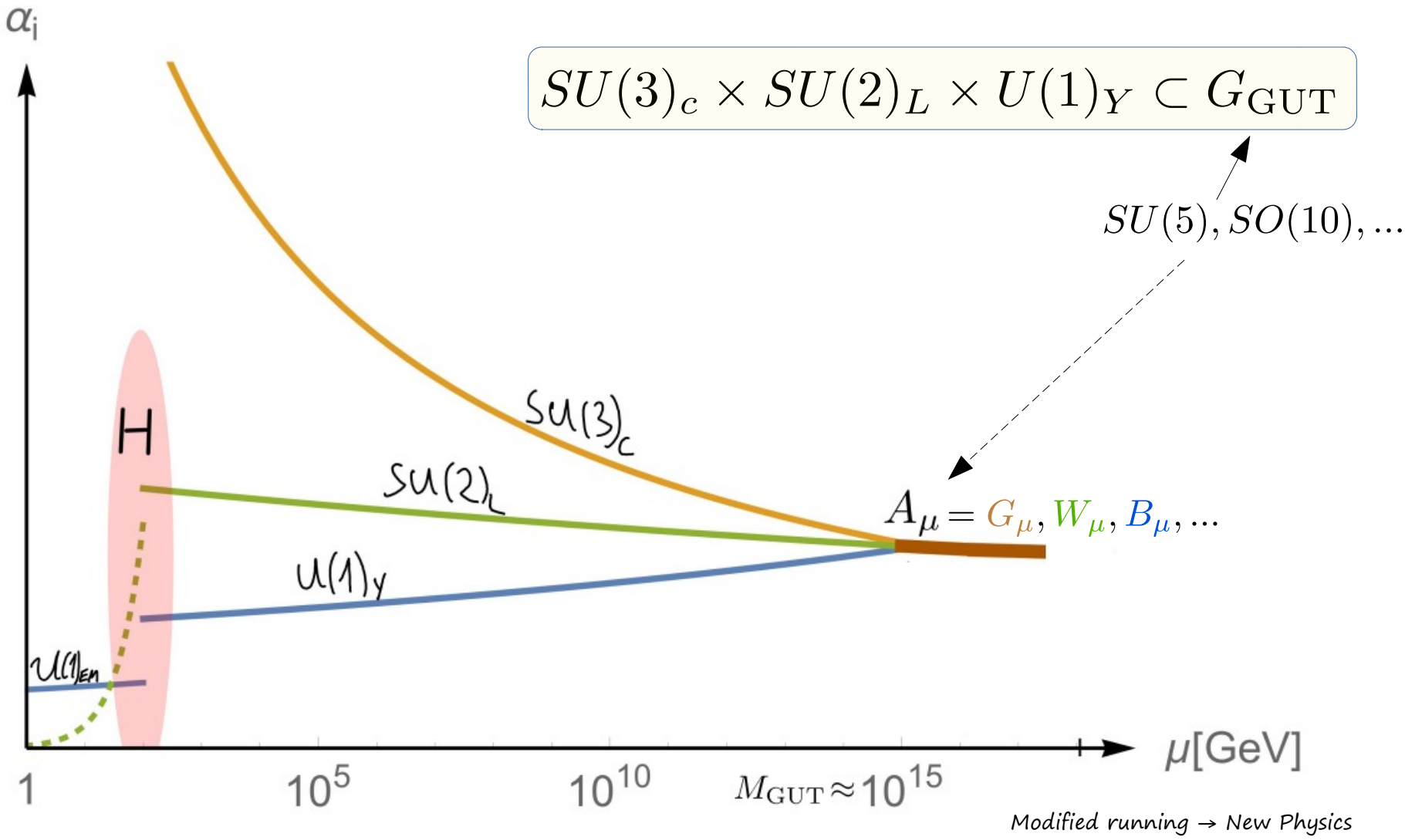




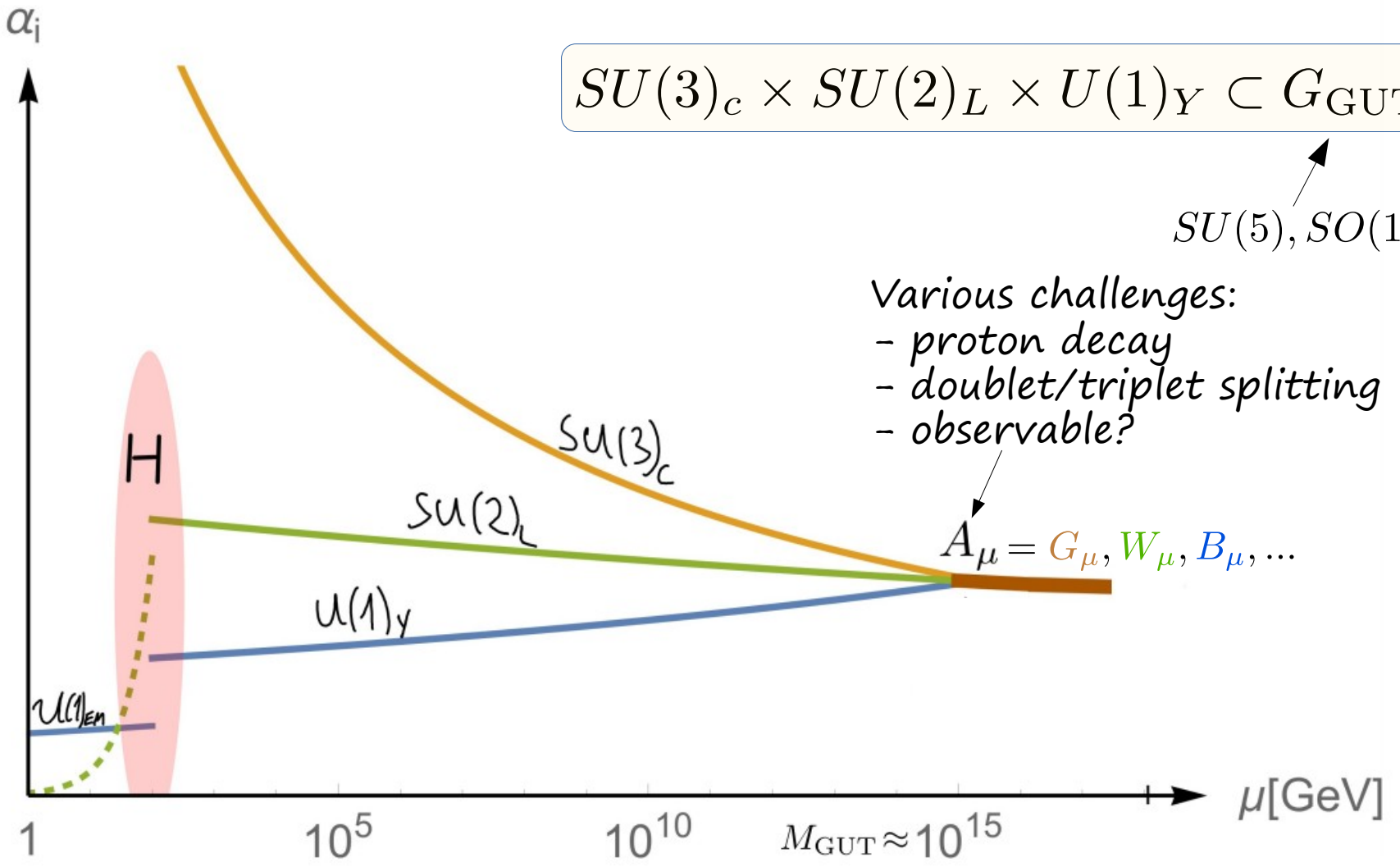




Grand Unification



Grand Unification



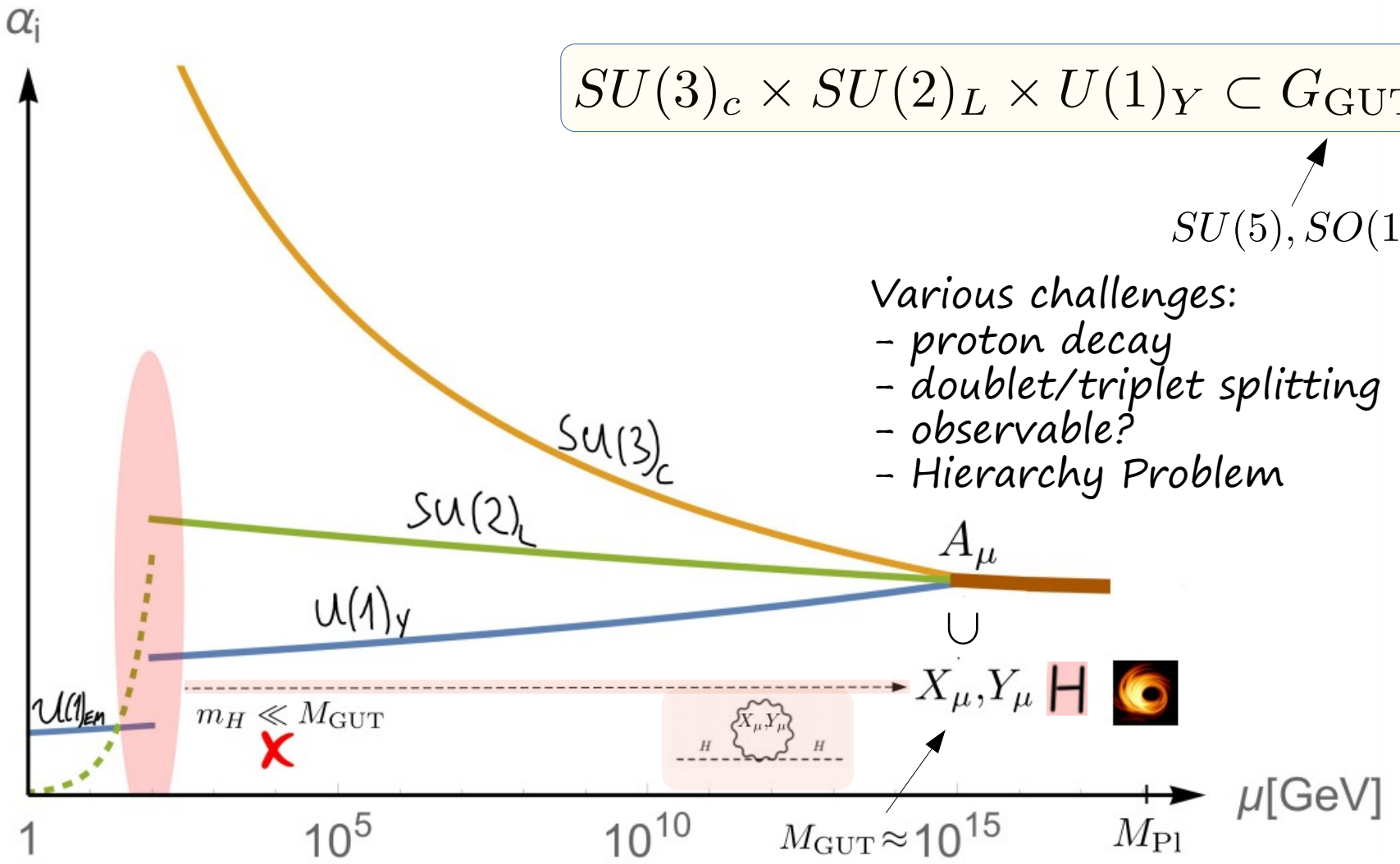
$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset G_{\rm GUT}$$

$SU(5), SO(10), \ldots$

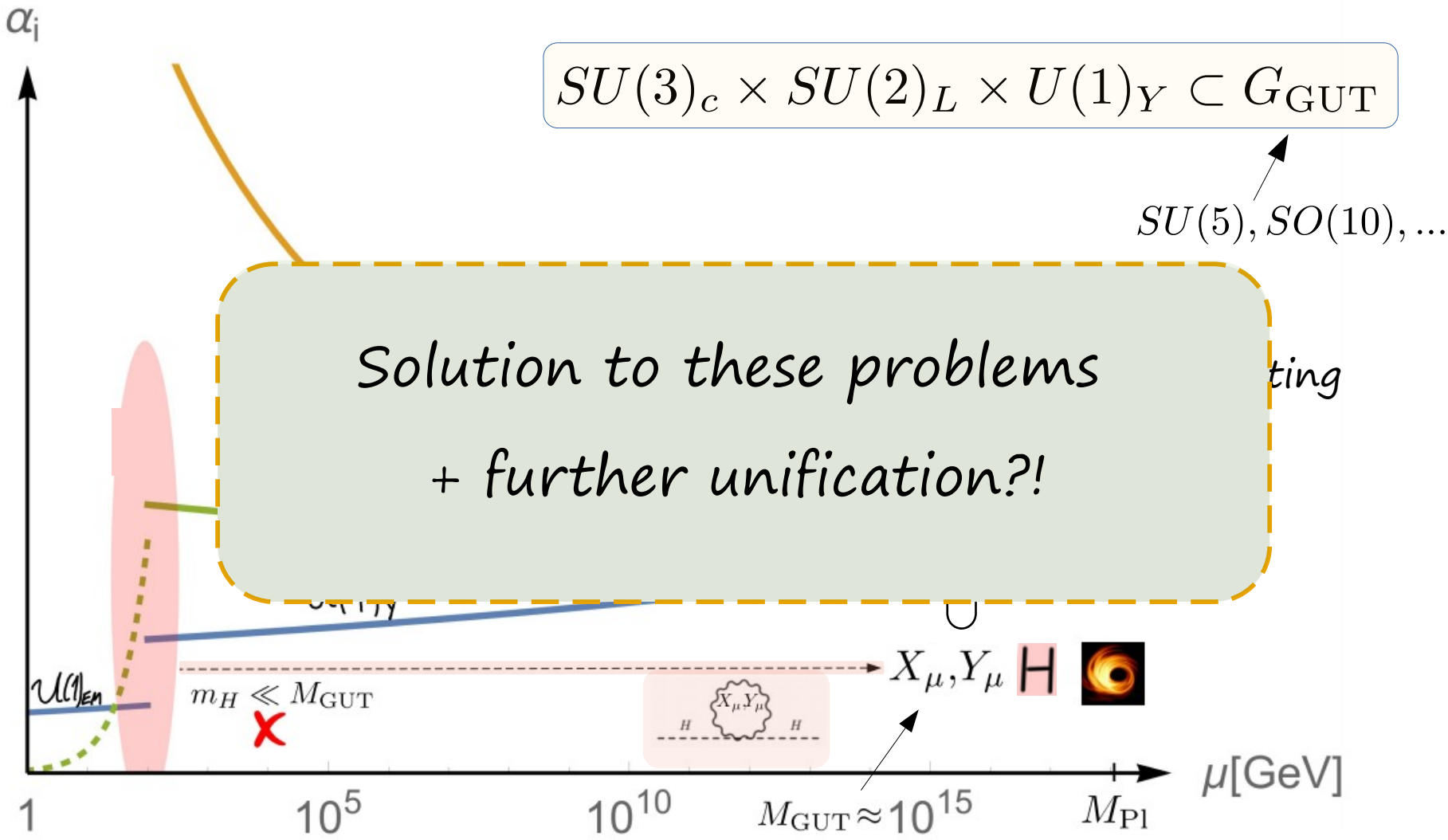
Various challenges:
- proton decay
- doublet/triplet splitting
- observable?

$A_\mu = G_\mu, W_\mu, B_\mu, \ldots$

+ GUT Hierarchy Problem

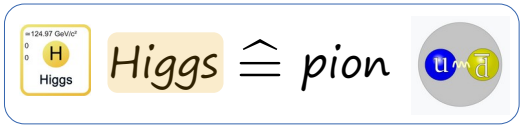


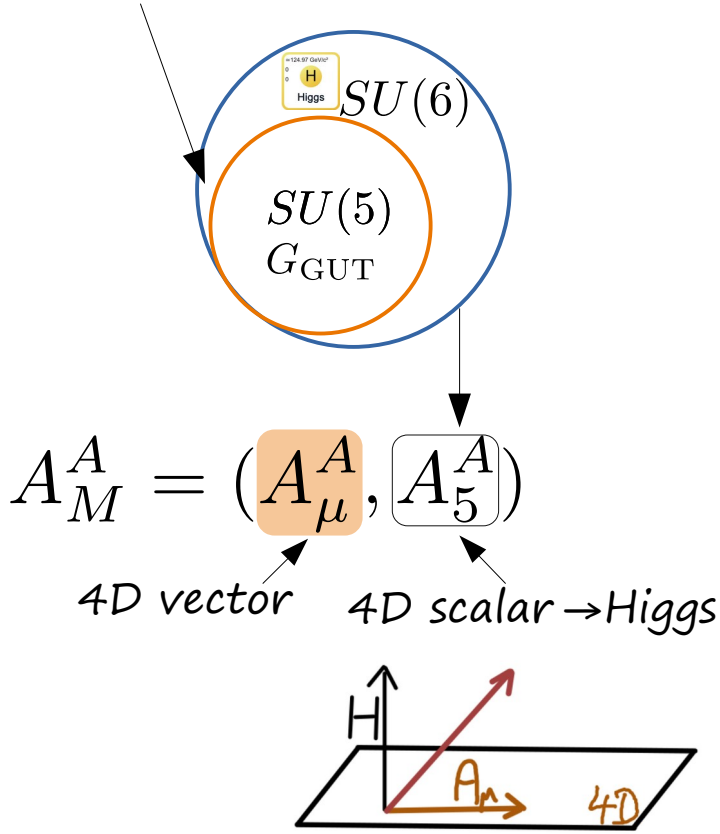
Grand Unification



Gauge-Higgs Grand Unification

- Embed GUT group in enhanced global symmetry of CH:
  Unification of all forces & EWSB (Higgs)!





Manton, Hosotani, Fairlie,
Hatanaka, Inami, Lim...
Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

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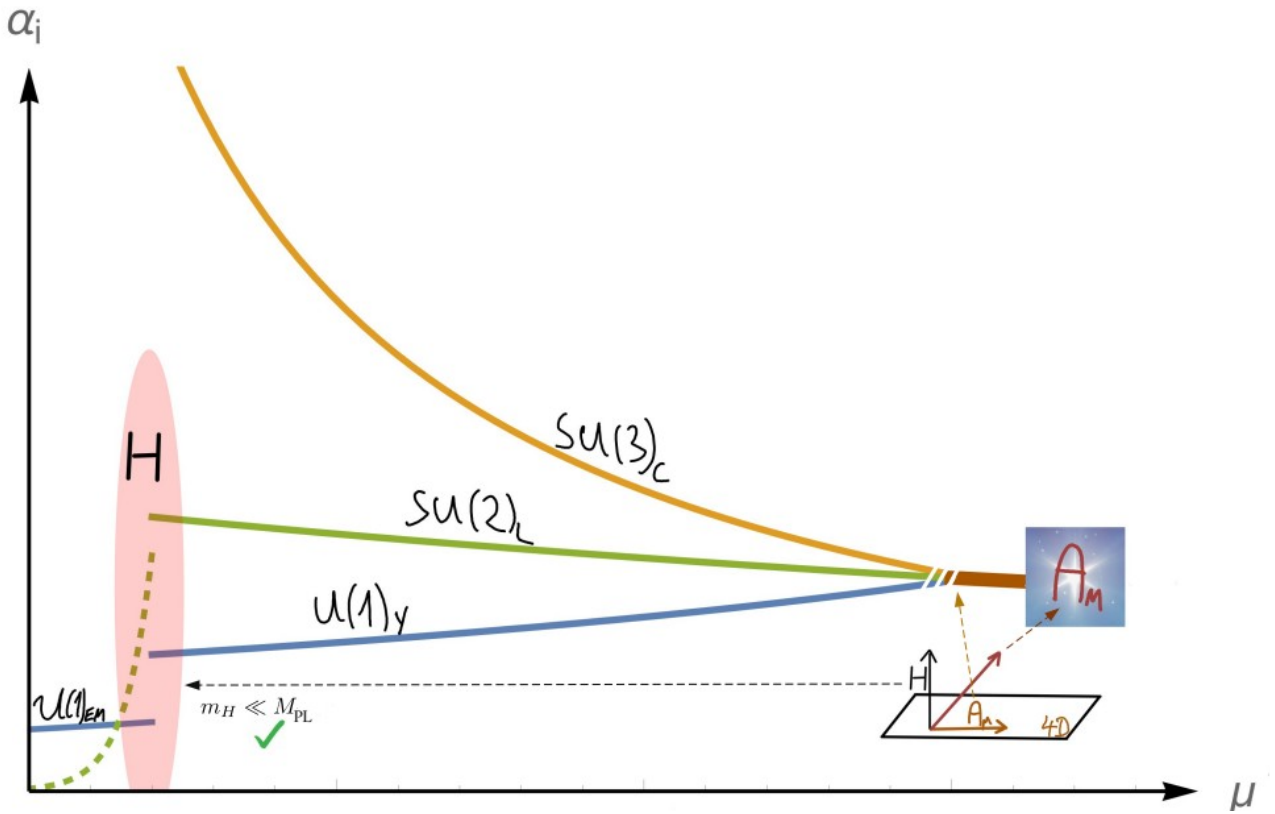
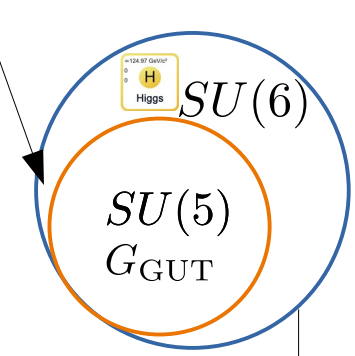
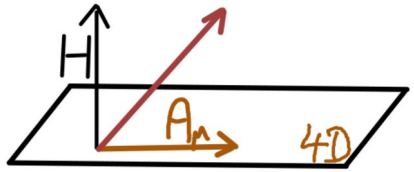




$$A_M^A = (A_\mu^A, A_5^A)$$

4D vector — 4D scalar → Higgs



Gauge-Higgs Grand Unification

Manton, Hosotani, Fairlie,
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Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

light pNGB: ✓

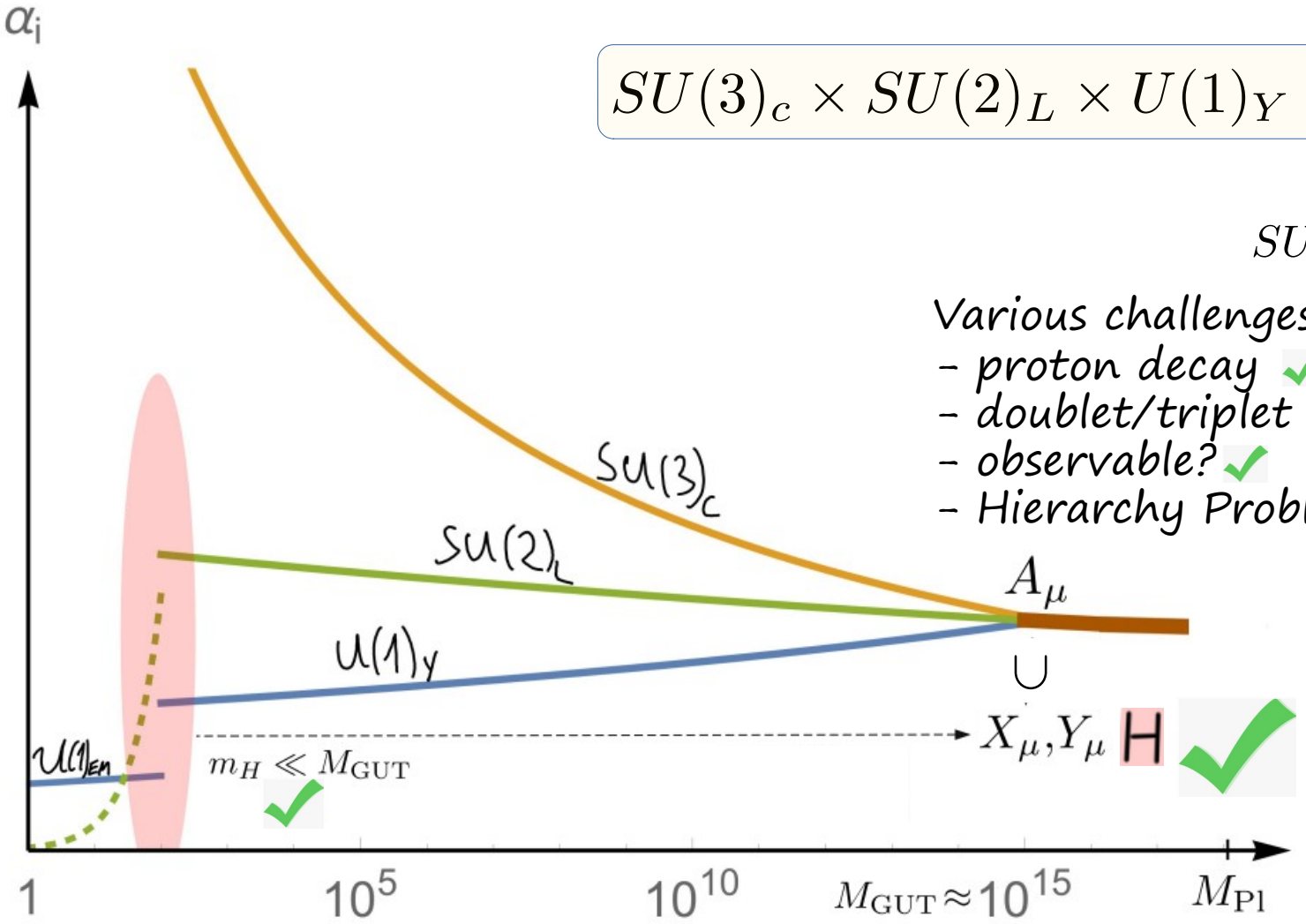
4D shift sym. ↔ 5D gauge sym.

Gauge-Higgs Grand Unification

$$SU(3)_c \times SU(2)_L \times U(1)_Y \subset G_{\rm GUT}$$

$SU(5), SO(10), \ldots$

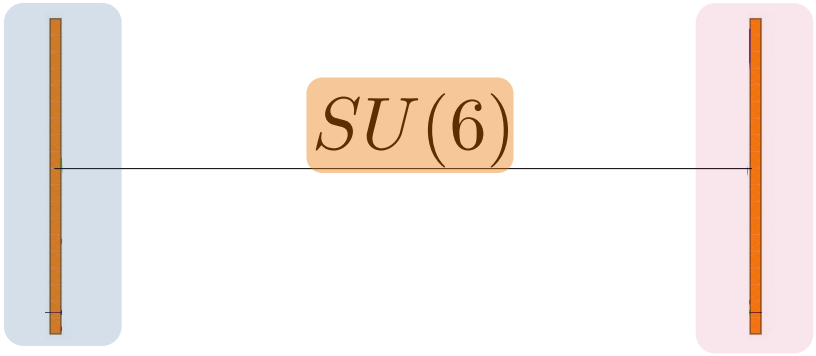
Various challenges:
- proton decay ✓
- doublet/triplet splitting ✓
- observable? ✓
- Hierarchy Problem ✓



Novel Breaking Pattern

Former Proposals

$SU(5)$ $\quad$ $SU(2)_L \times SU(4) \times U(1)_A$



SM at low energies? ✗

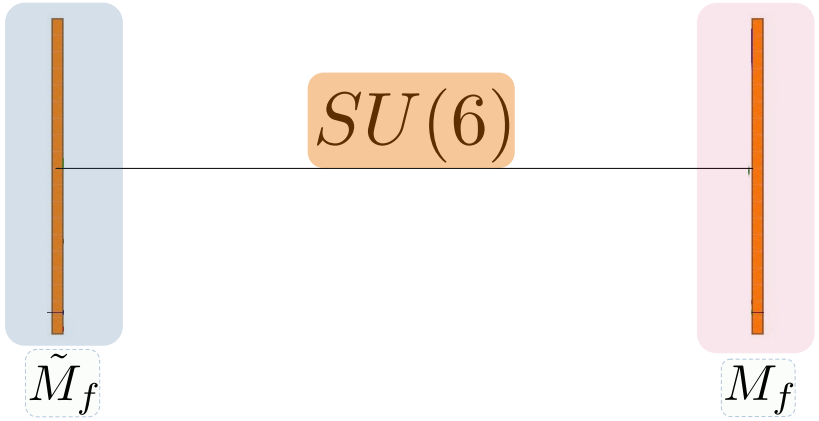
$m_e(=m_u) = 0$ $\quad$ $\tilde{e}_R(\mathbf{1},\mathbf{1})_1$

$m_h \not\approx 125\,\mathrm{GeV}$

New Pattern

$G_{\rm SM}$

$SU(5)$ $\quad$ $SU(2)_L \times SU(3)_c \times U(1)_Y$



Reproduces SM at low energies!
(incl. EWSB, m_H, ...)

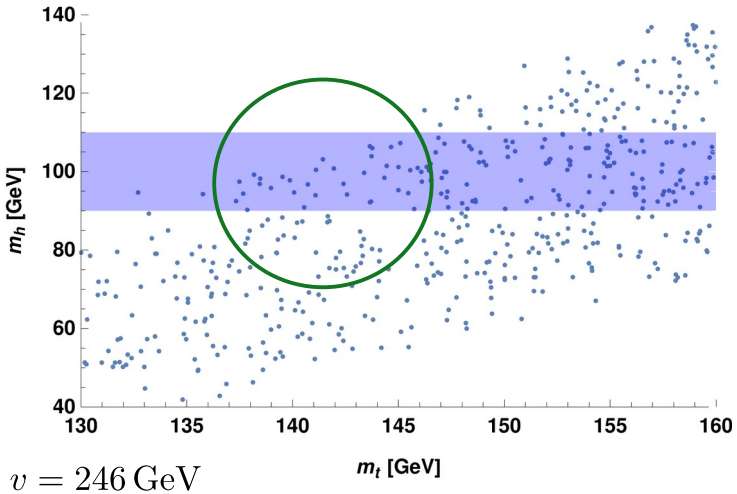
Angelescu, Bally, Blasi, FG [PRD] (2104.07366)
Angelescu, Bally, FG, Weber [JHEP] (2208.13782)

$\mathrm{Higgs} + \mathrm{singlet} + (\mathbf{3},\mathbf{1})_{-1/3}\,\mathrm{LQ}$

Phenomenology

Angelescu, Bally, Blasi, FG [PRD] (2104.07366)

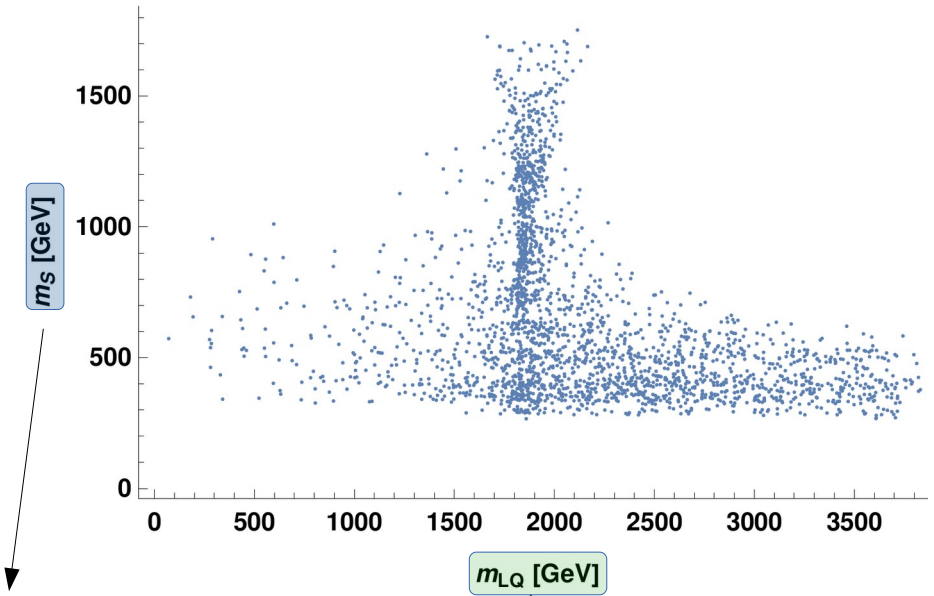
Higgs + singlet + $(\mathbf{3},\mathbf{1})_{-1/3}$ LQ



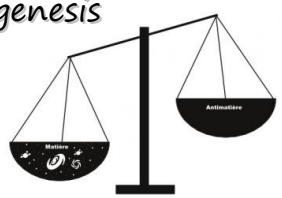
$v = 246\,\text{GeV}$

→ Correct quartic/m_H predicted!

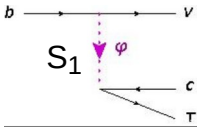
Calculable!



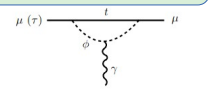
Potentially induce strong 1st order Phase transition (PhT) → Baryogenesis



Address (CC) B anomalies?

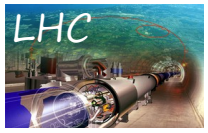


Muon (g-2)?



$\cup$

X_μ, Y_μ Excitations at TeV!



New territory → **searches** at LHC, Future Collider, ...

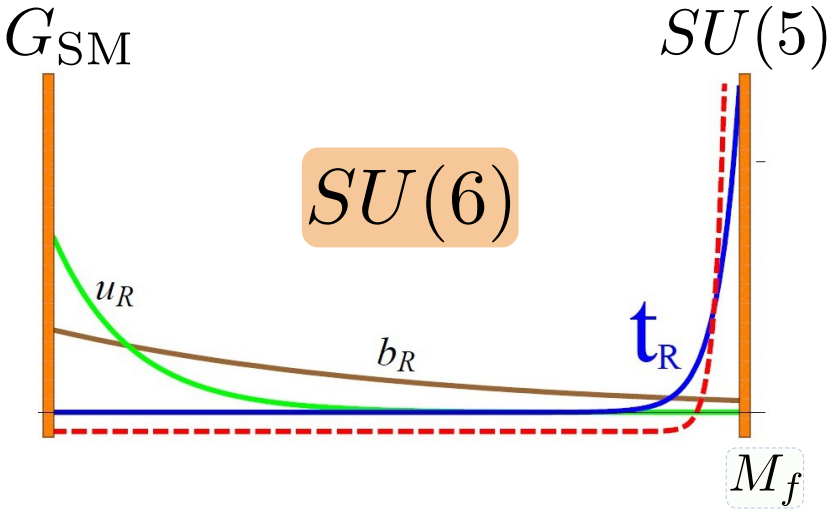
Bauer, Neubert, 1511.01900

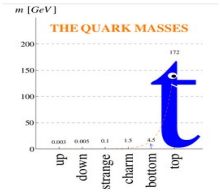
Angelescu, Becirevic, Faroughy, Jaffredo, Sumensari, 2103.12504

Phenomenology

Angelescu, Bally, FG, Weber [JHEP] (2208.13782)

- Flavor Hierarchies





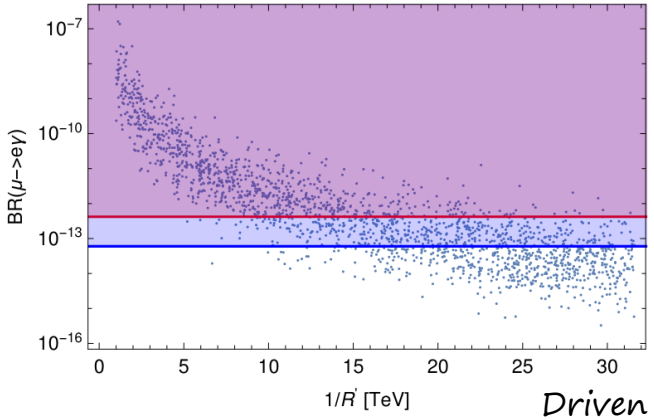
5D generation of masses + GUT nature

→ down-type hierarchies *predicted* correctly from PMNS anarchy and CKM hierarchies!

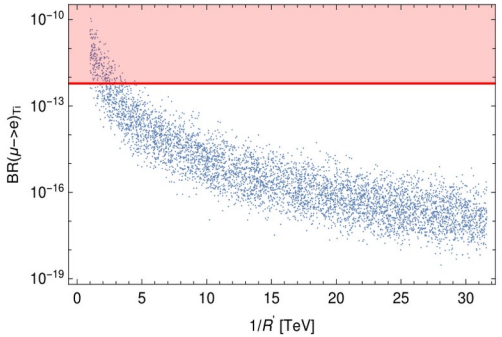
$$m_b/m_s/m_d \sim 1/\lambda_{\rm CKM}^2/\lambda_{\rm CKM}^3$$

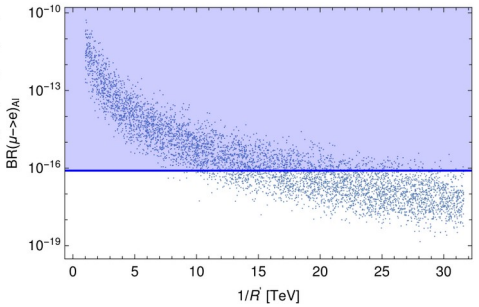
$$\lambda_{\rm CKM} \approx 0.23$$

- Interesting Tests



Driven by LQ!





Phenomenology

Angelescu, Bally, FG, Weber [JHEP] (2208.13782)

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Accepted: October 8, 2008
Published: October 24, 2008

Redoing

Flavor physics in the Randall-Sundrum model
I. Theoretical setup and electroweak precision tests

S. Casagrande, F. Goertz, U. Haisch, M. Neubert and T. Pfoh

Institut für Physik (THEP), Johannes Gutenberg-Universität, Staudingerweg 7, D-55128 Mainz, Germany
E-mail: casagrande@thep.physik.uni-mainz.de, goertz@thep.physik.uni-mainz.de, uhaisch@thep.physik.uni-mainz.de, neubertm@uni-mainz.de, pfoh@thep.physik.uni-mainz.de

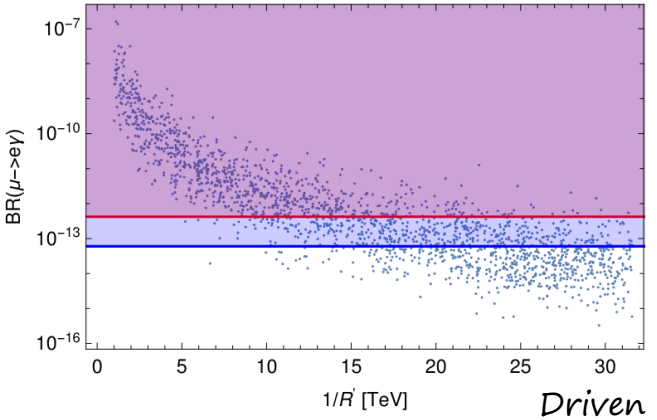
5D generation of masses + GUT nature

→ down-type hierarchies predicted correctly from PMNS anarchy and CKM hierarchies!

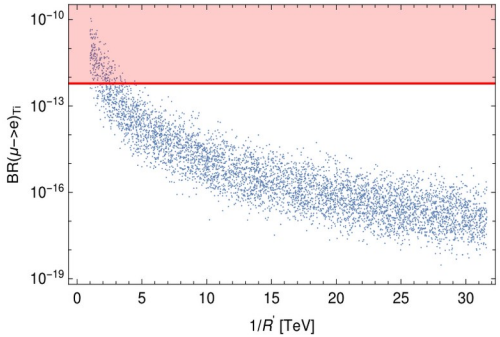
$$m_b/m_s/m_d \sim 1/\lambda_{\rm CKM}^2/\lambda_{\rm CKM}^3$$

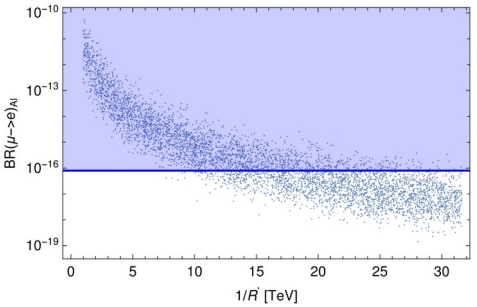
$$\lambda_{\rm CKM} \approx 0.23$$

- Interesting Tests



Driven by LQ!





Phenomenology

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Flavor physics in the Ranc
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Institut für Physik (THEP), Johannes Gute
Staudingerweg 7, D-55128 Mainz, Germany
E-mail: casagrande@thep.physik.uni-ma
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neubertm@uni-mainz.de, pfoh@thep.phys

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Published: September 6, 2010

The custodial Randall-Sundrum model: from precision tests to Higgs physics

S. Casagrande,[a] F. Goertz,[b] U. Haisch,[b] M. Neubert[b,c] and T. Pfoh[b]
[a] *Excellence Cluster Universe, Technische D-85748 Garching, Germany*
[b] *Institut für Physik (THEP), Johannes G D-55099 Mainz, Germany*
[c] *Institut für Theoretische Physik, Ruprecl Philosophenweg 16, D-69120 Heidelberg,*

Physics Letters B 713 (2012) 23–28
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www.elsevier.com/locate/physletb

Bounds on warped extra dimensions from a Standard Model-like Higgs boson

Florian Goertz [a,*], Ulrich Haisch [b], Matthias Neubert [c]

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Higgs production in a warped extra dimension

Marcela Carena,[a,b] Sandro Casagrande,[c] Florian Goertz,[d] Ulrich Haisch[e] and Matthias Neubert[f]

Phenomenology

JHEP

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Received: *August 4, 2008*
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S. Casagrande, F. Goertz, U. Haisch, M. Neubert and T. Pfoh

Institut für Physik (THEP), Johannes Gutenberg-Universität, Staudingerweg 7, D-55128 Mainz, Germany
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ELSEVIER

Physics Letters B

Volume 474, Issues 3–4, 17 February 2000, Pages 361-371

Neutrino masses and mixings in non-factorizable geometry

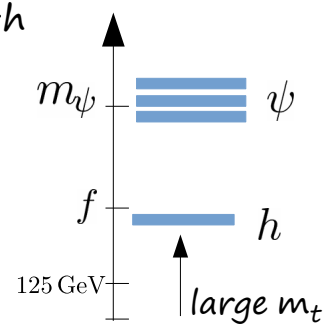
Yuval Grossman a [1] [1], Matthias Neubert b [2] [2]

973 citations

Light Top Partners

- Large top yukawa → large m_h

$$m_h \sim y_t^2\, v \sim m_t\, m_T/f$$

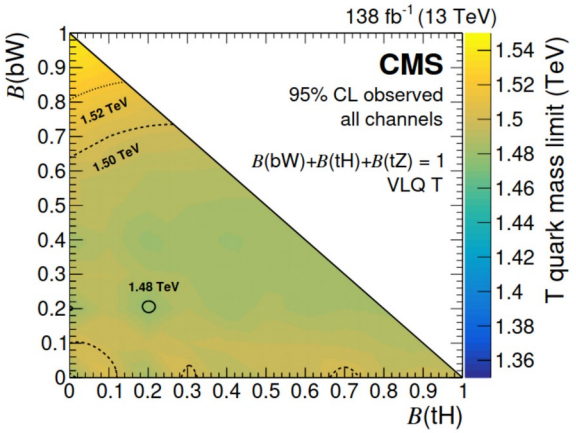


=> light top partners:

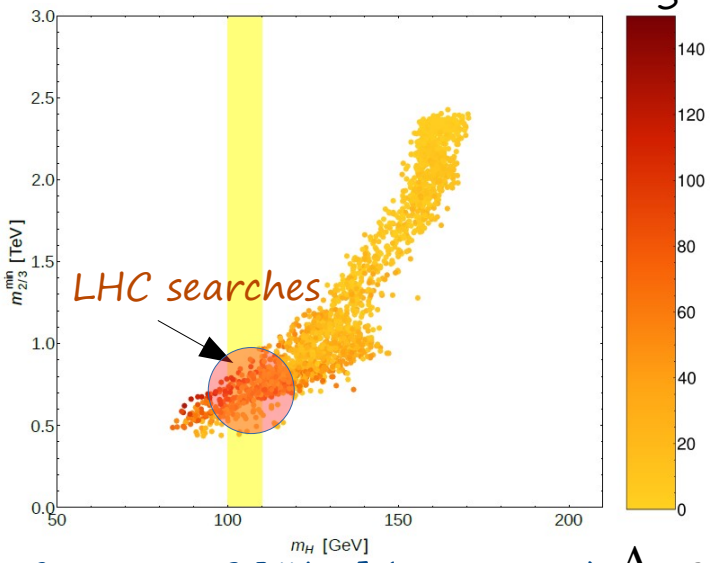
$$m_T \sim f \sim 800\,\text{GeV}$$

$$\rightarrow m_T \gtrsim 1500\,\text{GeV}$$

latest limit



MCHM$_5$



Carmona, FG [JHEP] (1410.8555)

$f = 800\,\text{GeV}$

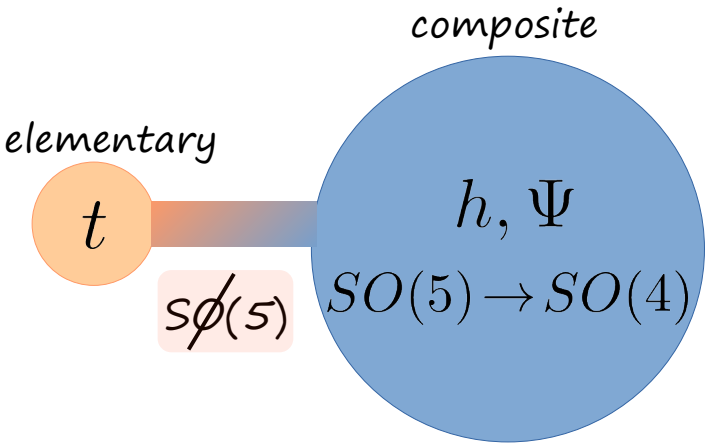
currently strongest constraints on CH

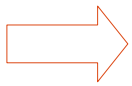
Matsedonskyi, Panico, Wulzer, 1204.6333;
Contino, Da Rold, Pomarol, ph/0612048; Csaki, Falkowski, Weiler, 0804.1954;
De Curtis, Redi, Tesi, 1110.1613; Pomarol, Riva, 1205.6434; Carmona, FG, 1410.8555

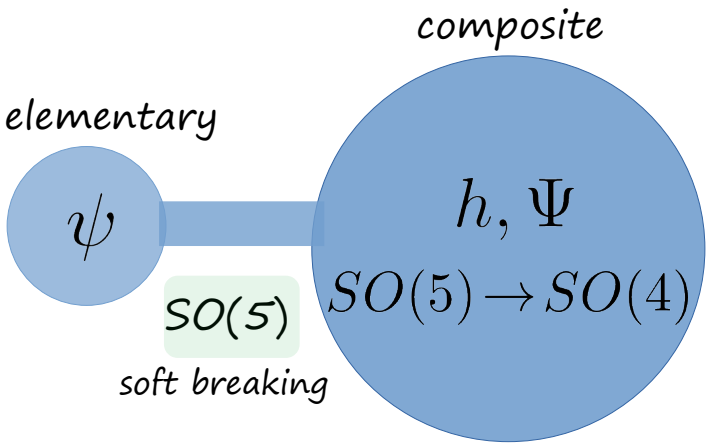
Avoiding Light Top Partners I

Change the nature of explicit Goldstone-symmetry breaking

Blasi, FG [PRL] (1903.06146); Blasi, Csaki, FG [SciPost] (2004.06120); Blasi, Bollig, FG (2212.11007)

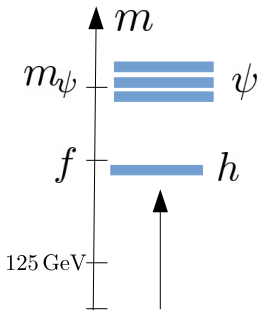






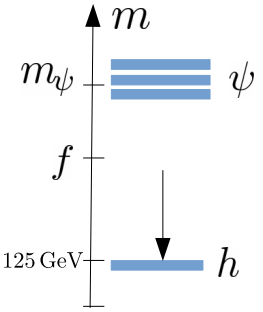
$\bar{q}_L \cdot \Psi_R^T$

$\mathbf{5}$ of $SO(5)$



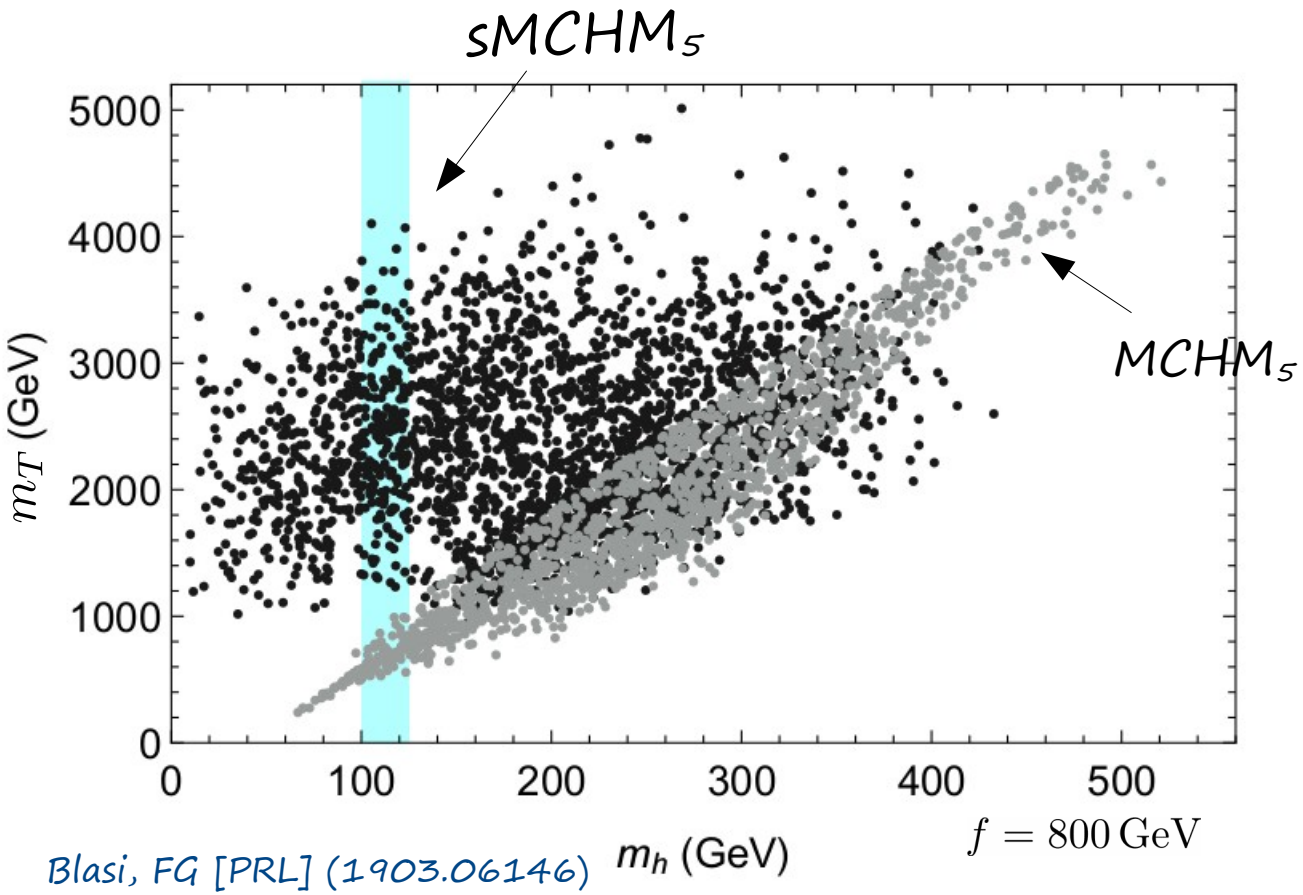
$\bar{\psi}_L \cdot \Psi_R^T$

$$\begin{pmatrix} b_L - w_L^1 \\ -ib_L - iw_L^1 \\ t_L + w_L^2 \\ it_L - iw_L^2 \\ i\sqrt{2}\, s_L \end{pmatrix}$$

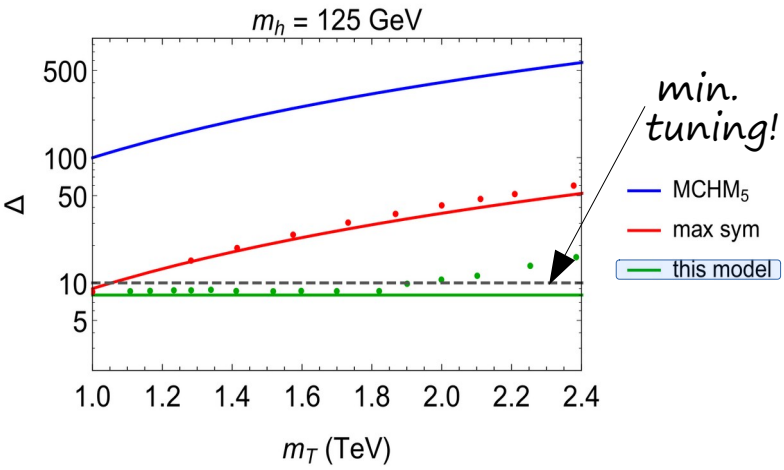


Symmetry restored → unification

Avoiding Light Top Partners I



Blasi, FG [PRL] (1903.06146)
Blasi, Bollig, FG (2212.11007)



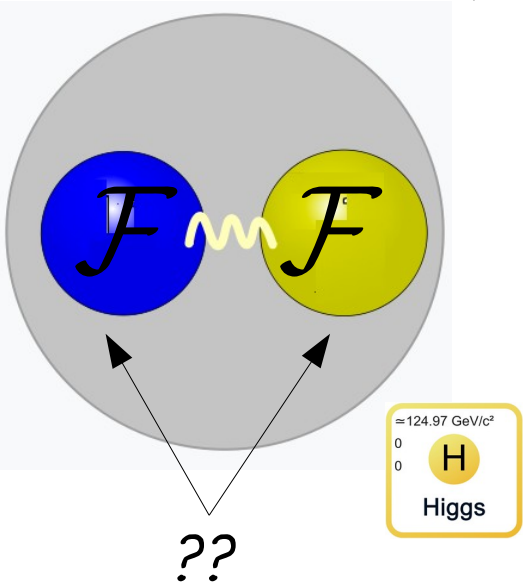
Blasi, Csaki, FG [SciPost] (2004.06120)

New Signatures!

What's Inside?

with Alvaro Pastor Gutierrez and Jan M. Pawlowski

- 4D UV Completion



$$\langle \mathcal{F}^a \epsilon_{\rm TC}\, \mathcal{F}^b \rangle = \Lambda_c f^2 \Sigma_\theta^{ab} \xrightarrow{\text{minimal}} SO(6) \to SO(5)$$

→ 5 Goldstones: Higgs + EW Singlet

see Cacciapaglia, Pica, Sannino, 2002.04914 for Review

$G_{\rm TC} = Sp(N)_{\rm TC}$, with $N_F = 4$ Weyl fermions

Barnard, Gherghetta, Ray 1311.6562,
Ferretti, Karateev, 1312.5330
Cacciapaglia, Sannino 1402.0233,
Vecchi, 1506.00623, Ma, Cacciapaglia, 1508.07014
Cacciapaglia, Pica, Sannino, 2002.04914

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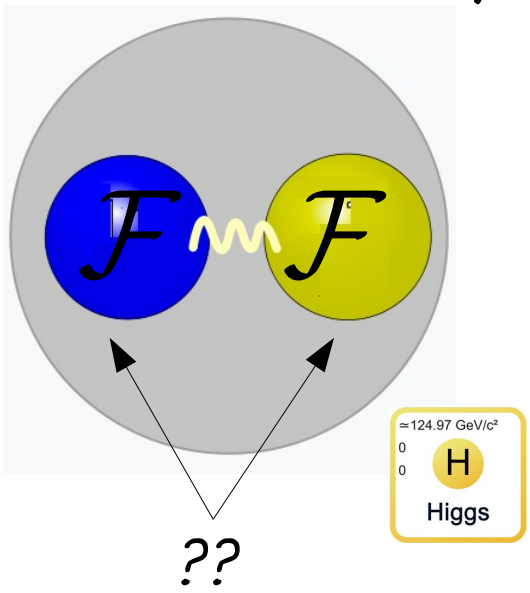

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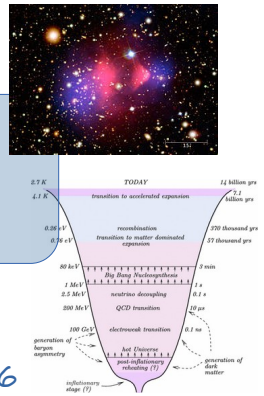
→ 5 Goldstones: Higgs + EW Singlet

- Dark Matter
- Baryogenesis



Frigerio, Pomarol, Riva, Urbano, 1204.2808

Espinosa, Gripaios, Konstandin, Riva, 1110.2876

see Cacciapaglia, Pica, Sannino, 2002.04914 for Review

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Barnard, Gherghetta, Ray 1311.6562,
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Cacciapaglia, Sannino 1402.0233,
Vecchi, 1506.00623, Ma, Cacciapaglia, 1508.07014
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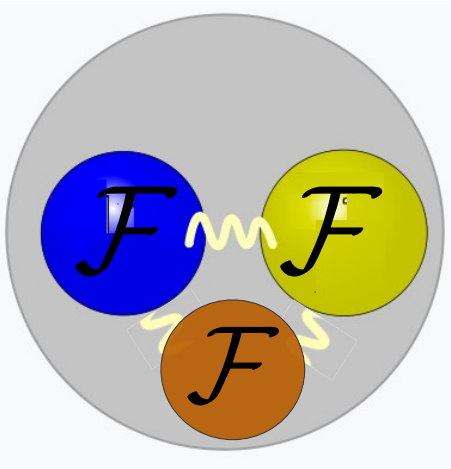
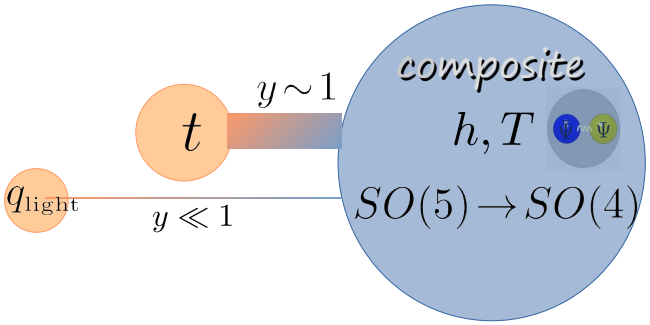
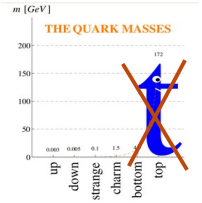






$$\mathcal{L} = y\,\bar{q}\,\mathcal{O}_\Psi + \text{h.c.}$$

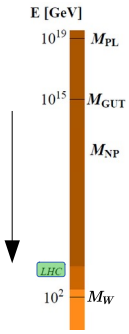
Fermionic resonances Ψ ?

$$\mathcal{O}_\Psi \sim \mathcal{F}\mathcal{F}\mathcal{F}$$

$$\gamma = [\mathcal{O}_\Psi] - 5/2$$

Lattice: $0 \ll \gamma \lesssim 2$

$$y \sim (\Lambda/\Lambda_{UV})^\gamma \ll 1$$



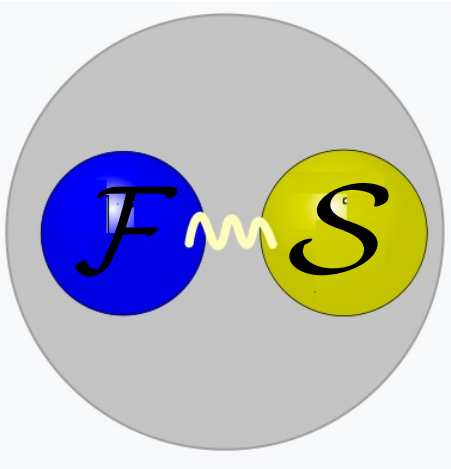
DeGrand, Shamir, 1508.02581
Pica, Sannino, 1604.02572
Ayyar, DeGrand, Hackett, Jay, Neil, Shamir, Svetitsky, 1812.02727

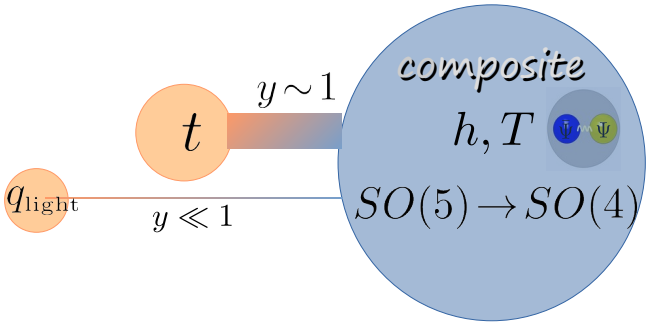
'anarchic approach'

What's Inside?

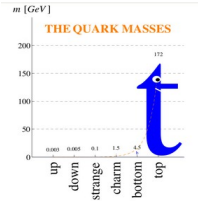
with Alvaro Pastor Gutierrez and Jan M. Pawlowski

- 4D UV Completion





$$\mathcal{L} = y\,\bar{q}\,\mathcal{O}_\Psi + \text{h.c.}$$

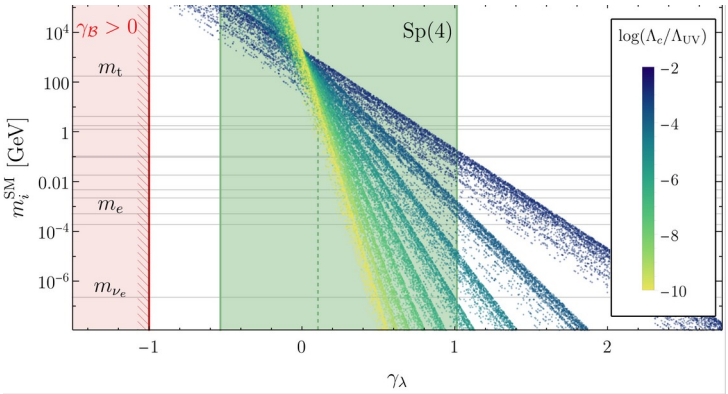


Fermionic resonances Ψ?

$$\mathcal{O}_\Psi \sim \mathcal{F}\mathcal{S}$$

$$\gamma = [\mathcal{O}_\Psi] - 5/2$$

FRG:



PRELIMINARY result

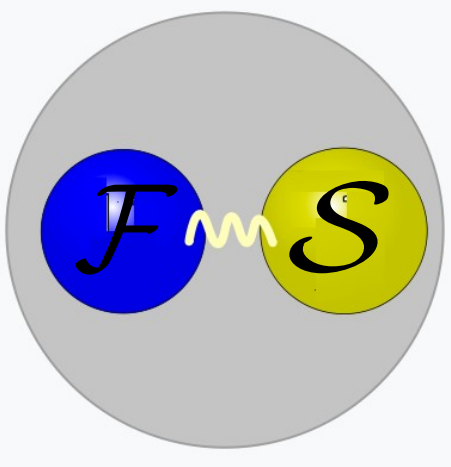
$$y \sim (\Lambda/\Lambda_{UV})^\gamma \ll 1$$

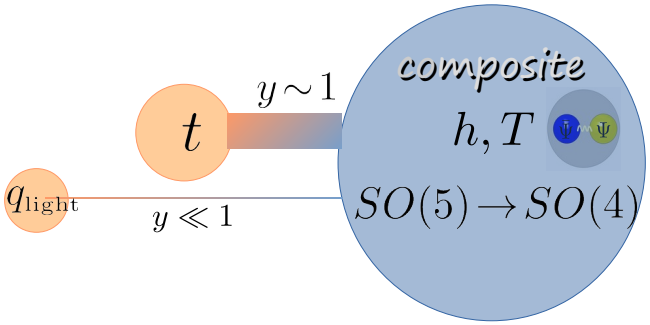
Cacciapaglia, Gertov, Sannino, Thomsen, 1704.07845
Sannino, Strumia, Tesi, Vigiani, 1607.01659

What's Inside?

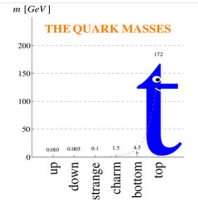
with Alvaro Pastor Gutierrez and Jan M. Pawlowski

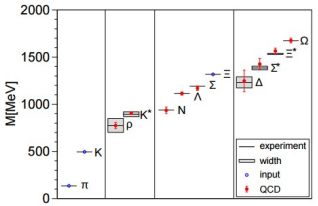
- 4D UV Completion





$$\mathcal{L} = y\,\bar{q}\,\mathcal{O}_\Psi + \text{h.c.}$$





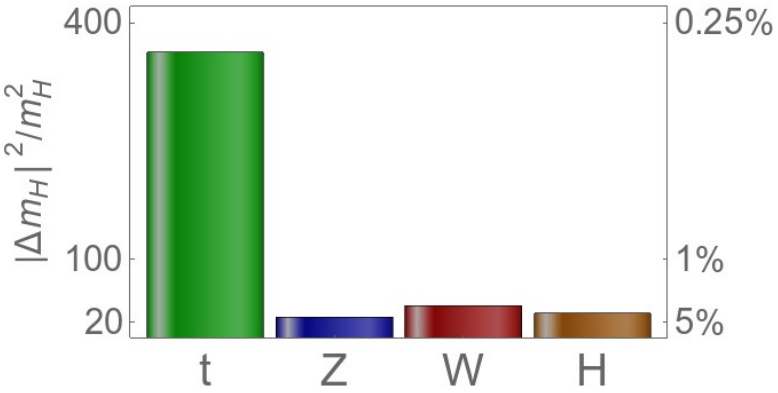
- Further Targets: resonance spectrum, ...
- New way to explore strongly coupled BSM
  [control transition region]

Light Top Partners: Alternative Solution

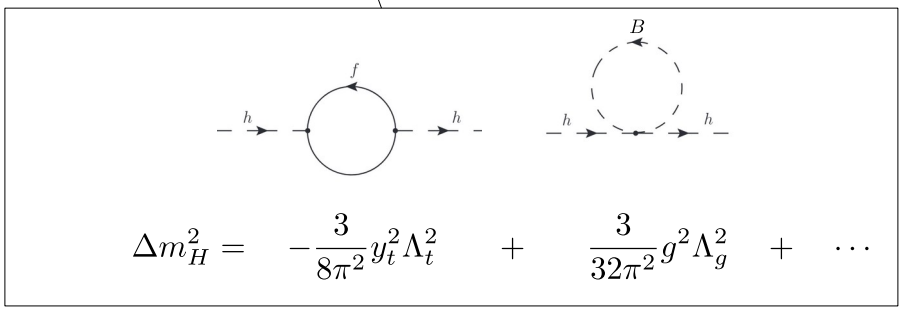
Bally, Chung, FG, 2211.17254

$$\rightarrow \Delta m_H^2 \sim \Lambda_{\rm NP}^2$$

$\Lambda_{\rm NP} = 10\,\text{TeV}$



$$\Delta_{\rm FT} \equiv m_H^2/|\Delta m_H^2|$$



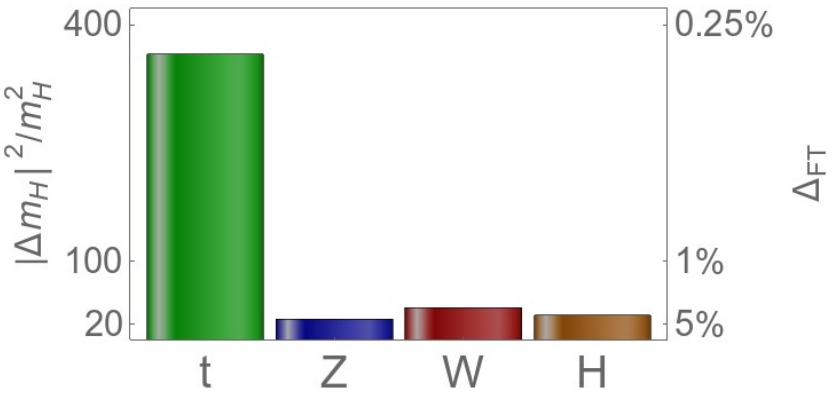
$$\Delta m_H^2 = -\frac{3}{8\pi^2} y_t^2 \Lambda_t^2 + \frac{3}{32\pi^2} g^2 \Lambda_g^2 + \cdots$$

Light Top Partners: Alternative Solution

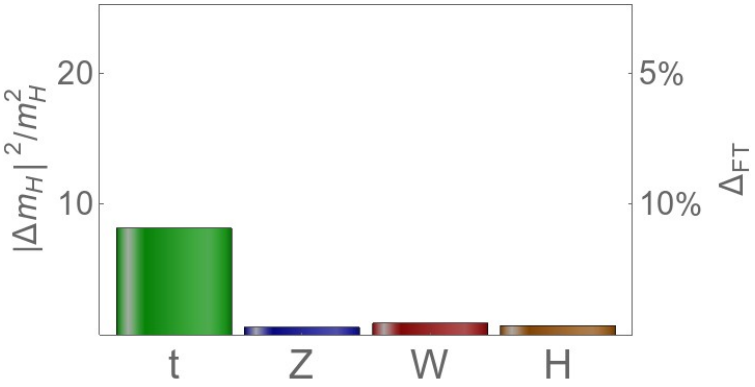
Bally, Chung, FG, 2211.17254

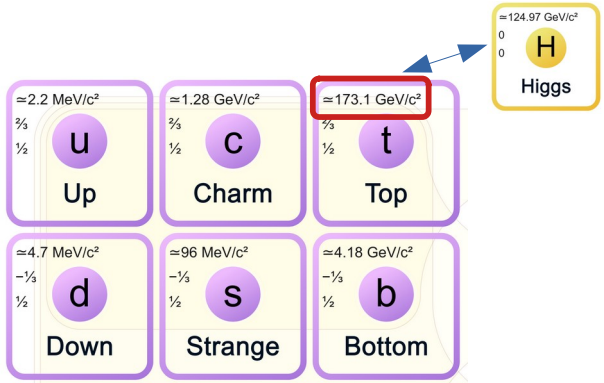
$$\rightarrow \Delta m_H^2 \sim \Lambda_{\rm NP}^2$$

$\Lambda_{\rm NP} = 10\,\text{TeV}$



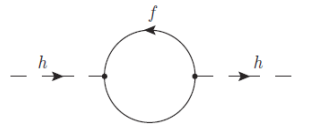
$\rightarrow \Lambda_{\rm NP} \approx (1-2)\,\text{TeV}$





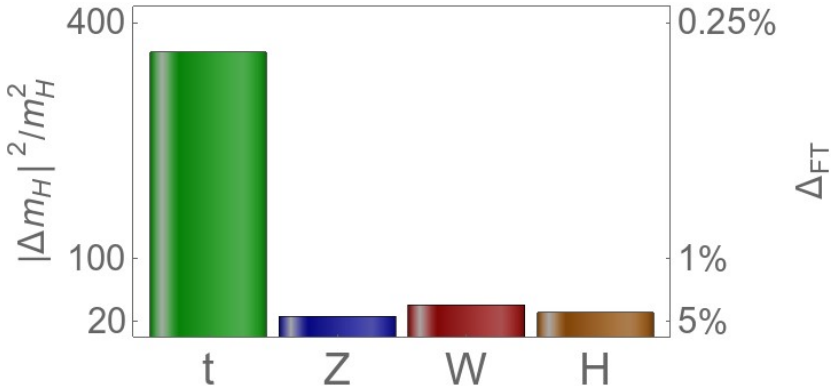
Light Top Partners: Alternative Solution

Bally, Chung, FG, 2211.17254

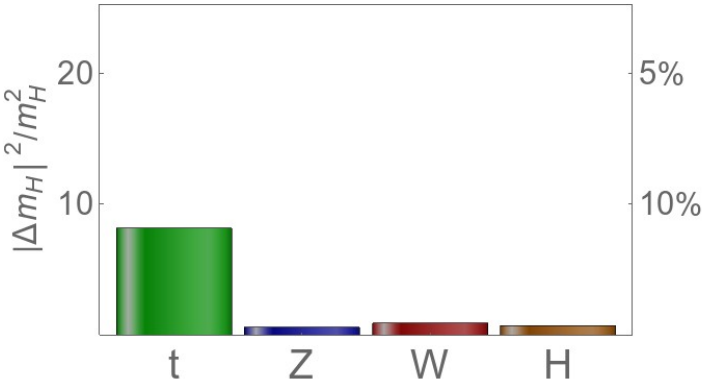


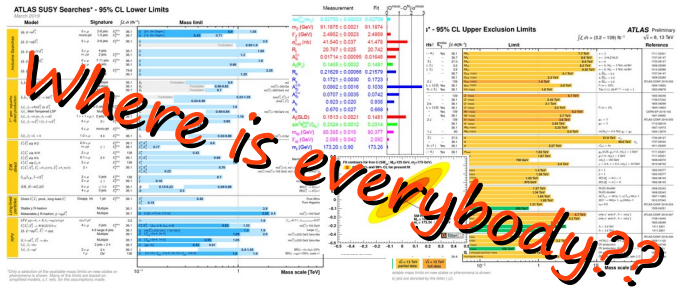
$$\rightarrow \Delta m_H^2 \sim \Lambda_{\rm NP}^2$$

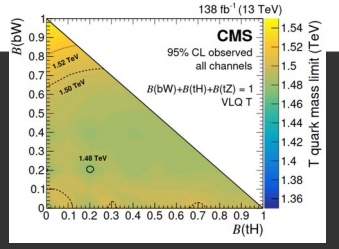
$$\Lambda_{\rm NP} = 10\,{\rm TeV}$$



$$\rightarrow \Lambda_{\rm NP} \approx (1-2)\,{\rm TeV}$$

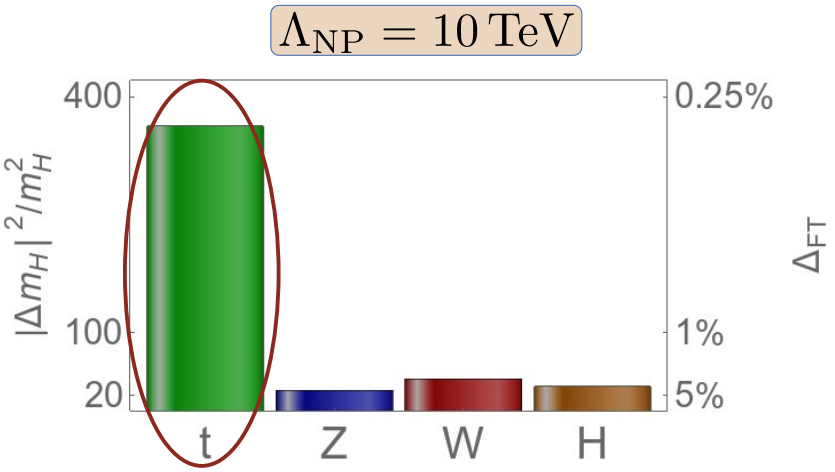






Light Top Partners: Alternative Solution

Bally, Chung, FG, 2211.17254



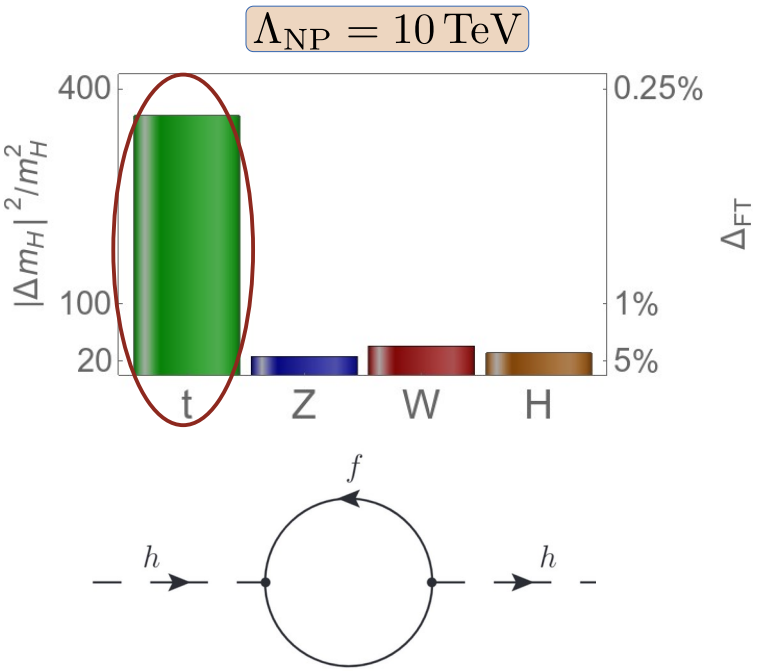
$$\mathcal{L} \supset y_t\, \bar{q}_l H t_R$$

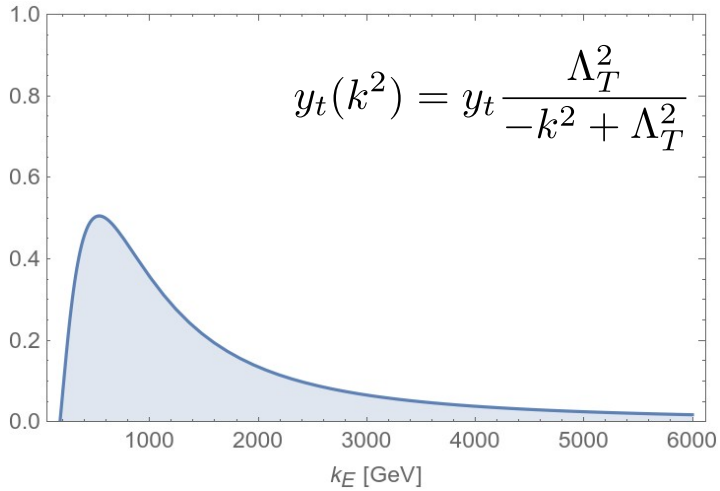
Biggest source of shift-symmetry breaking

$H \to H + a$

Alternative Solution: Non-Trivial Yukawa

Bally, Chung, FG, 2211.17254





$$\Delta m_H^2|_t \sim -i\,2N_c\,y_t^2 \int \frac{d^4k}{(2\pi)^4}\frac{k^2+m_t^2}{(k^2-m_t^2)^2}$$

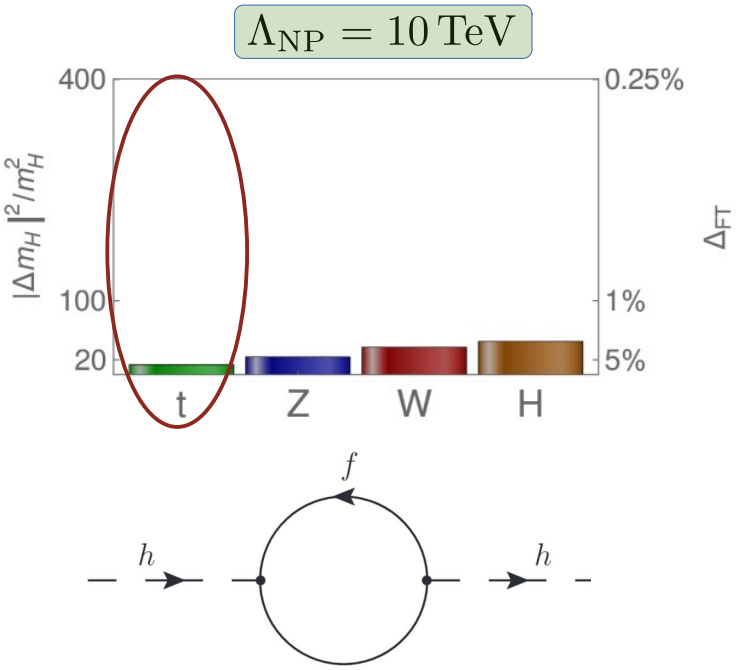
y_t drops above Λ_T

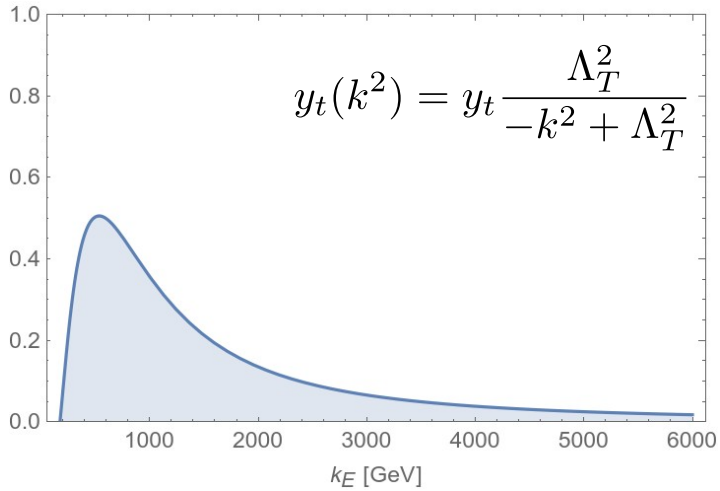
$$\longrightarrow \Delta m_H^2|_t \sim -i\,2N_c \int \frac{d^4k}{(2\pi)^4} y_t^2(k^2) \frac{k^2+m_t^2}{(k^2-m_t^2)^2} \sim -\frac{3}{8\pi^2} y_t^2 \Lambda_T^2 \sim m_H^2$$

$\Lambda_T \sim 500\,{\rm GeV} \ll 10\,{\rm TeV}$

Alternative Solution: Non-Trivial Yukawa

Bally, Chung, FG, 2211.17254





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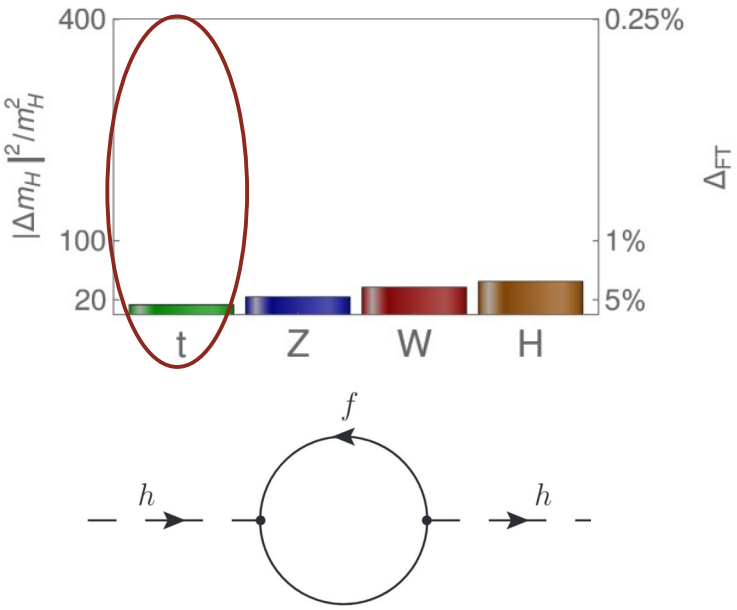
$\Lambda_T \sim 500\,{\rm GeV} \ll 10\,{\rm TeV}$

Pheno: Top-philic bosons

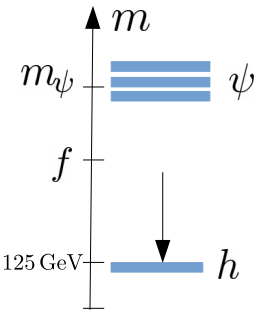
Alternative Solution: Non-Trivial Yukawa

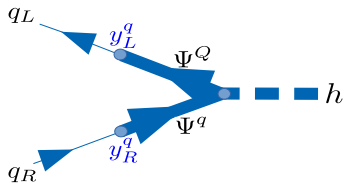
Bally, Chung, FG, 2211.17254

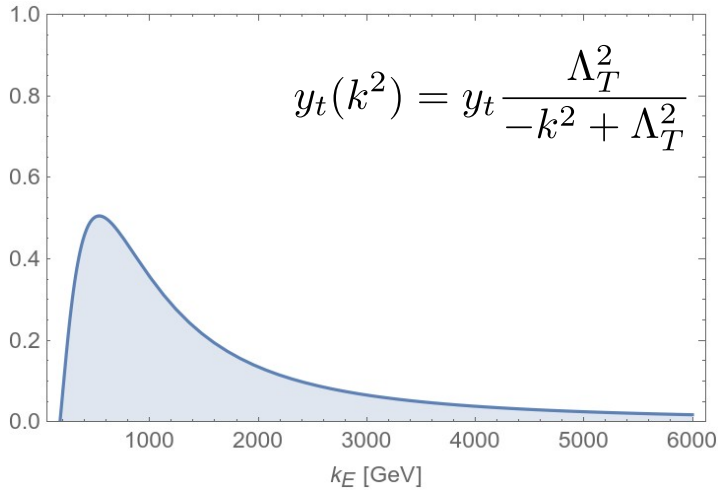
$\Lambda_{\rm NP} = 10\,\text{TeV}$



→ Apply to Partial Compositeness







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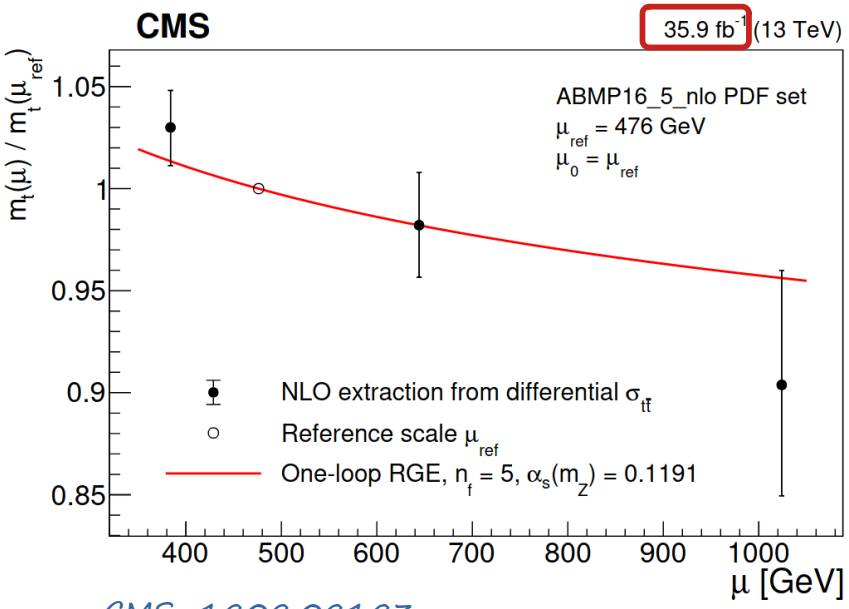
y_t drops above Λ_T

$$\longrightarrow \Delta m_H^2|_t \sim -i\,2N_c \int \frac{d^4k}{(2\pi)^4} y_t^2(k^2) \frac{k^2+m_t^2}{(k^2-m_t^2)^2} \sim -\frac{3}{8\pi^2} y_t^2 \Lambda_T^2 \sim m_H^2$$

$\Lambda_T \sim 500\,\text{GeV} \ll 10\,\text{TeV}$

Pheno: Top-philic bosons

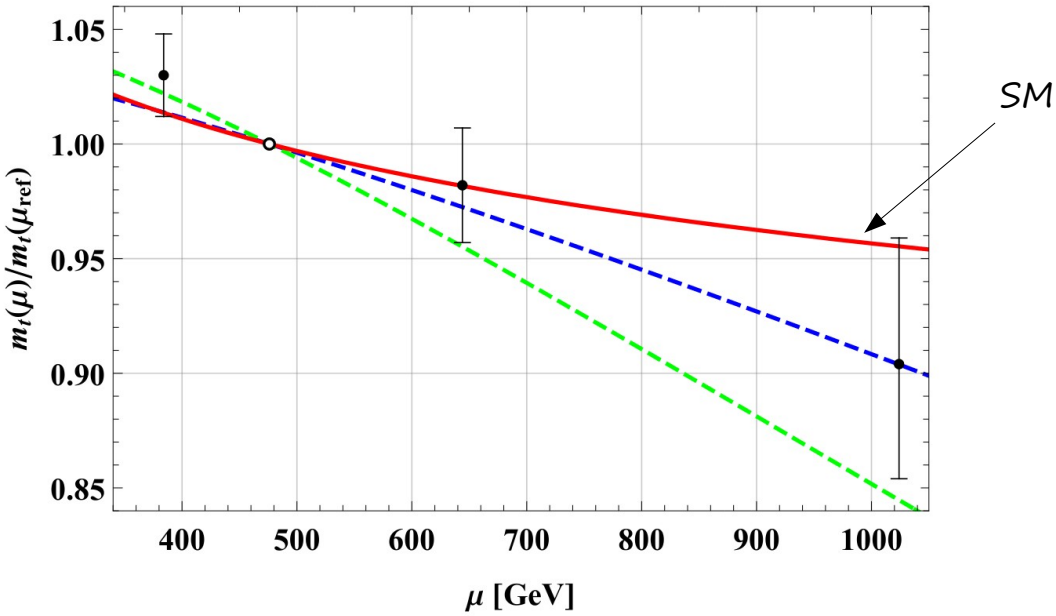
Running Top Mass



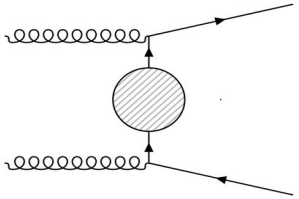
CMS, 1909.09193

$M_F = 1530$ GeV, $m_s = 0.4M_F$, $M_s = 0.9M_F$ (blue)

$M_F = 865$ GeV, $m_s = 0.5M_F$, $M_s = 1.5M_F$ (green)



Bally, Chung, FG, 2211.17254



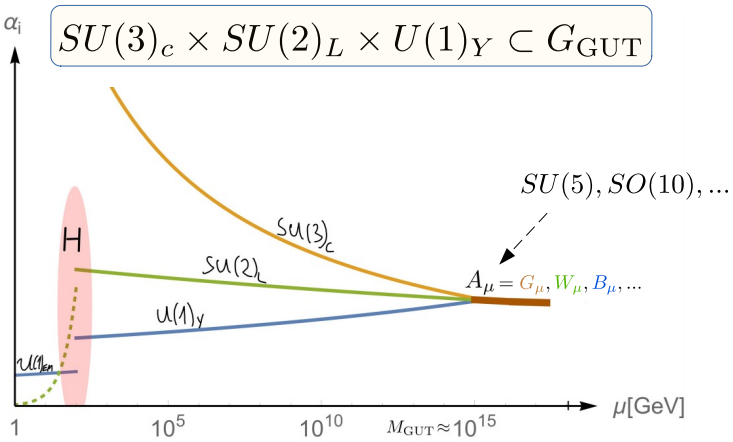
differential tt cross section

New direct test of Naturalness...

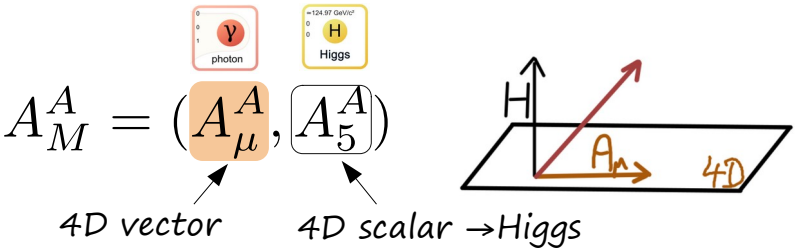
→ diagnose Hierarchy Problem (& Early Universe)

... Unification

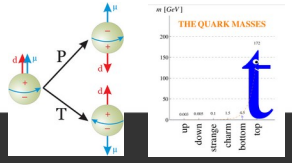
- Grand Unification



- Gauge-Higgs Unification
  (aka Composite Higgs)



- Axion-Flavon Unification $U(1)_{\rm PQ} = U(1)_{\rm FN}$ $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$



...

The Axiflavon

Calibbi, FG, Redigolo, Ziegler, Zupan [PRD] (1612.08040)

$$U(1)_{\rm FN} = U(1)_{\rm PQ}$$

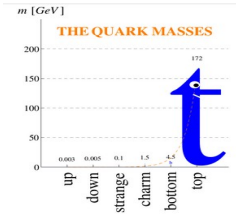
→ very predictive

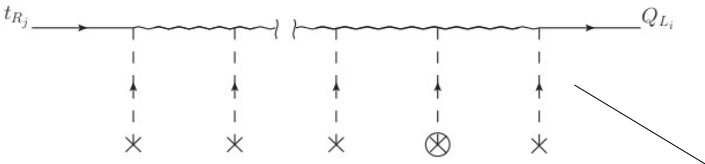
The Axiflavon

Calibbi, FG, Redigolo, Ziegler, Zupan [PRD] (1612.08040)

Why is the coefficient of the CP operator $\mathcal{L}_{\rm SM} \supset \bar{\theta}\,\frac{\alpha_s}{8\pi} G_{a\mu\nu}\tilde{G}_a^{\mu\nu}$ so tiny?

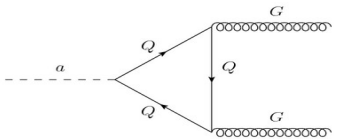
- **Flavor Puzzle**



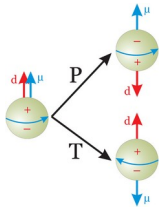


Froggatt, Nielsen, 1979

- **Strong CP Problem**



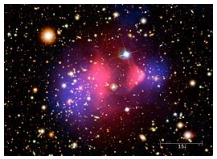
$\rightarrow aG\tilde{G}$



Wilczek 1978, Weinberg 1978, Kim 1979, ...

Axiflavon $\Phi = \frac{1}{\sqrt{2}}(v_\Phi + \phi)e^{ia/v_\Phi}$

- **Dark Matter**

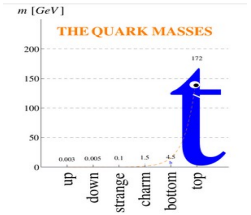


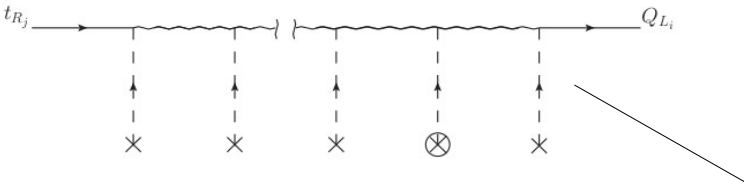
Strong CP ↔ Flavor ↔ Cosmology

The Axiflavon

Calibbi, FG, Redigolo, Ziegler, Zupan [PRD] (1612.08040)

- Flavor Puzzle





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Flavor physics in the Randall-Sundrum model
I. Theoretical setup and electroweak precision tests

S. Casagrande, F. Goertz, U. Haisch, M. Neubert and T. Pfoh

4.1 Warped-space Froggatt-Nielsen mechanism

Concentrating on the well-motivated case of anarchic 5D Yukawa couplings, i.e. , complex-valued matrices $\boldsymbol{Y}_q$ with random elements, it turns out that the up- and down-type quark mass hierarchies can be reproduced by assuming a hierarchical structure of the elements of the zero-mode profiles of the form[5]

$$|F(c_{A_1})| < |F(c_{A_2})| < |F(c_{A_3})|\,. \tag{4.10}$$

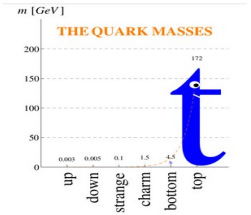
Strong CP ↔ Flavor ↔ Cosmology

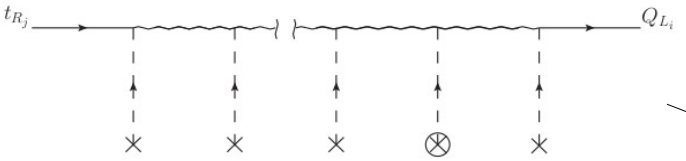
The Axiflavon-Higgs

Calibbi, FG, Redigolo, Ziegler, Zupan [PRD] (1612.08040)

Alanne, Blasi, FG [PRD] (1807.10156)

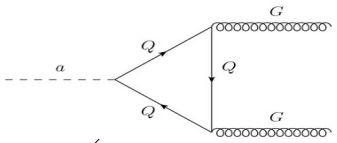
- Flavor Puzzle



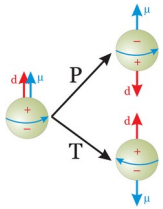


Froggatt, Nielsen, 1979

- Strong CP Problem

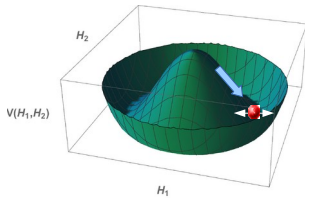


$\rightarrow a G\tilde{G}$



$$\Sigma = e^{i(\sqrt{2}h_{\hat{a}}\hat{T}^{\hat{a}} + a)/f} \begin{pmatrix} \tilde{H} \\ (f+\sigma)/\sqrt{2} \end{pmatrix}$$

- EW Symmetry Breaking



- Dark Matter

Strong CP ↔ Flavor ↔ Cosmology ↔ EWSB

The Axiflavon-Higgs

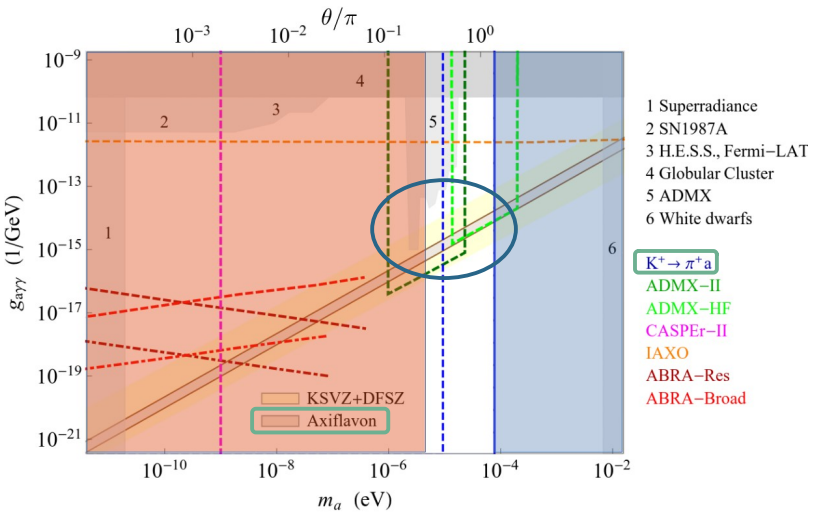
Calibbi, FG, Redigolo, Ziegler, Zupan [PRD] (1612.08040)

Alanne, Blasi, FG [PRD] (1807.10156)

$$\Sigma = e^{i(\sqrt{2}h_{\hat{a}}\hat{T}^{\hat{a}}+a)/f}\begin{pmatrix}\widetilde{H}\\(f+\sigma)/\sqrt{2}\end{pmatrix}$$

Successful Matching → $\lambda(\mu) \approx 0$ ➡ $10^7\,\text{GeV} \lesssim f_a \lesssim 10^{12}\,\text{GeV}$

Flat potential!!



NA62 → currently tested! + (future) axion searches + Belle II

NA62, 1807.10170, 2011.11329, 2103.15389

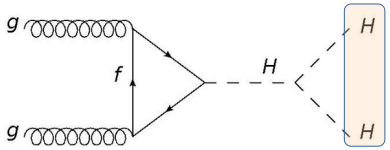
- Signal regions **R1**,**R2**: search for $K^+\to\pi^+X$ (X=invisible), $0 \le m_X \le 110$ MeV/c² and $154 \le m_X \le 260$ MeV/c².
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.

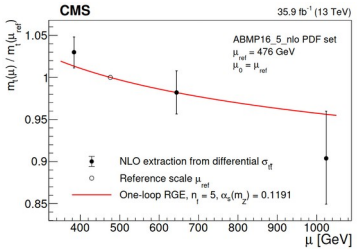
Strong CP ↔ Flavor ↔ Cosmology ↔ EWSB

high E ↔ low E

Thank you!

- We can still hope to understand better what is going on in the next decades, also from LHC





+ DM, Precision/Flavor, Axion, GW,...

Thank you!

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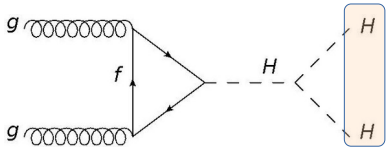
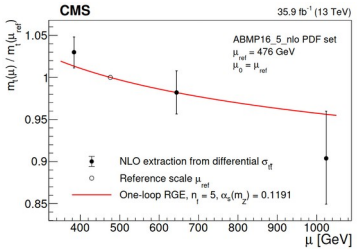


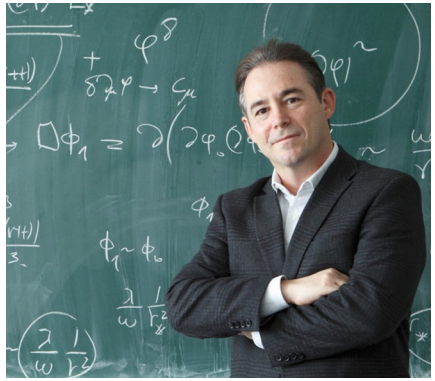


+ DM, Precision/Flavor, Axion, GW,...

Happy Birthday, Matthias!

celebrating the 10th anniversary of the mitp Mainz Institute for Theoretical Physics

MITP accumulates incredible expertise
→ shapes and pushes limits!



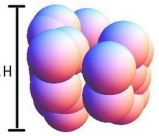
'Every' Problem is solvable!

Thank You!

Backup: Composite Higgs Models

Kaplan, Georgi, Dimopoulos, ...

- Higgs is composite at small distances l_H



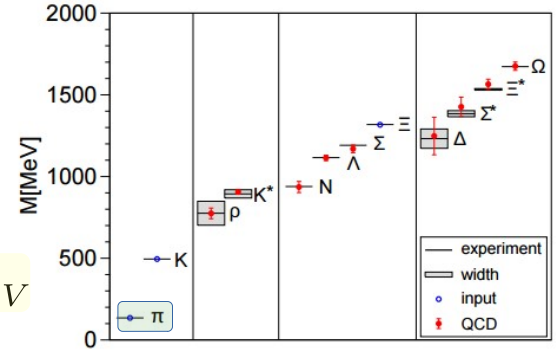
➡ Hierarchy Problem solved

- Higgs = (pseudo) Nambu-Goldstone Boson

➡ $m_H << m_\rho$

like pions

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q}q \rangle \neq 0} SU(2)_V$$



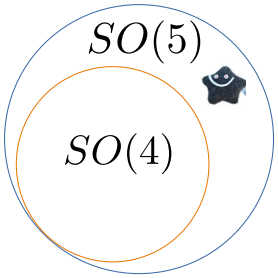
0906.3599

Nature chose this path already once...

- MCHM: SO(5) → SO(4)

$$\dim[SO(5)/SO(4)] = 4 \text{ GB}$$

$\rightarrow$  $h_{1,..,4}$



Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

Backup: Composite Higgs Models

Kaplan, Georgi, Dimopoulos, ...

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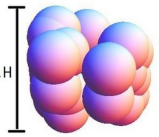
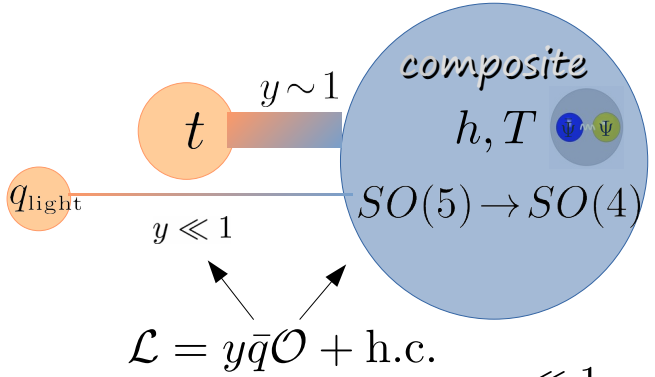


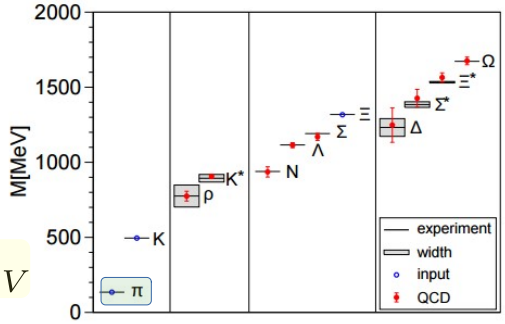
➡ Hierarchy Problem solved

+ Addresses the flavor puzzle:



- Higgs = (pseudo) Nambu-Goldstone Boson

➡ $m_H << m_\rho$



0906.3599

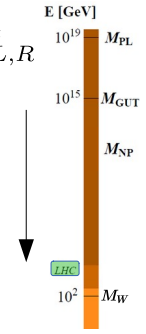
like pions

$$SU(2)_L \times SU(2)_R \xrightarrow{\langle \bar{q}q \rangle \neq 0} SU(2)_V$$

$$y^q_{L,R} \sim (\Lambda/\Lambda_{UV})^{\gamma_{L,R}} \ll 1$$

→ Hierarchies naturally from anom. dimensions

$$\gamma^u_{L,R} \gtrsim \gamma^c_{L,R} \gtrsim \gamma^t_{L,R}$$



- MCHM: SO(5) → SO(4)

Contino, Nomura, Pomarol, ph/0306259
Agashe, Contino, Pomarol, ph/0412089

$$\dim[SO(5)/SO(4)] = 4 \text{ GB}$$

$$\to \text{Higgs boson } h_{1,..,4}$$

custodially symmetric

'anarchic approach'

Backup: The Model is True! :)

Higgs + singlet + $(\mathbf{3},\mathbf{1})_{-1/3}$ LQ

- The mode is true....

  ... well, because 20+15+6+1 =  :) (irreps)