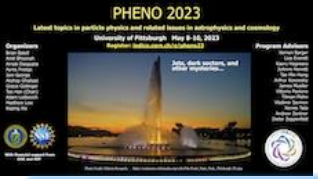
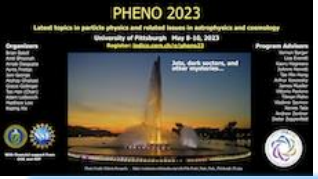


Perspective on Flavor Physics

George W.S. Hou (侯維恕)
National Taiwan University

May 9, 2023, PHENO @ U. Pittsburgh

National Taiwan University



Outline

0. Backdrop — "charge" & quotes

I. A Cry in the Wilderness

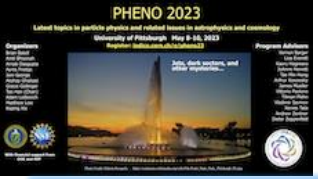
Caution on B-anomalies @ 2018 Rencontres du Vietnam

II. Response(s) to $R_{K^{(*)}}$ Disappearance — some fun

& Zip thru "my view for BSM"

III. Rehab of H^+ for $R_{D^{(*)}}$ in G2HDM (w/o Z_2) — not necessary

IV. G2HDM as *Next New Physics*?



0. Backdrop

"the Charge"

"Seeing the K/D anomalies come and go, that has caused a lot of excitement as well as some confusion. Would you be willing to offer your perspectives on the current stand of flavor physics, of course in connection with your view for BSM."

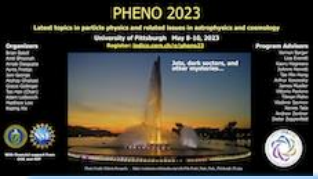
12/20 *Nature News* (LHCb Seminar @ CERN)

Although the latest result had been rumoured for months, its confirmation comes as a surprise, says Gino Isidori, a theoretical physicist at the University of Zurich who was at the CERN talk, because a coherent picture seemed to be emerging from related anomalies. This could have pointed to the existence of previously unseen elementary particles that affect the decay of *B* mesons. Isidori gives the LHCb collaboration credit for being "honest" in admitting that its previous analyses had problems, but he regrets that it took so long for the collaboration to find the issues.

"Just, please try to engage a broader audience."

M. Mangano ("the diplomat"), 12/20 *CERN Courier*

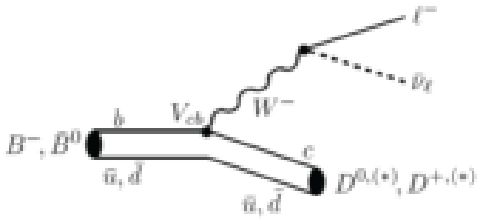
"That such anomalies could have been real shows how little we know about the deep origin of flavour symmetries and their relation with the Higgs, and highlights the key role of experimental guidance. ... The latest LHCb findings take nothing away from our mission to push further the boundary of our knowledge, and the search for anomalies goes on!"

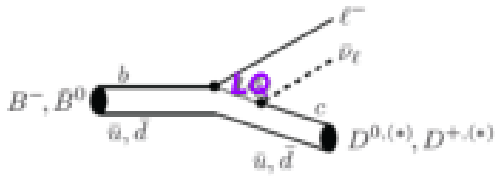


I. A Cry in the Wilderness

*** Flavor, where Anomalies/hoopla are !**

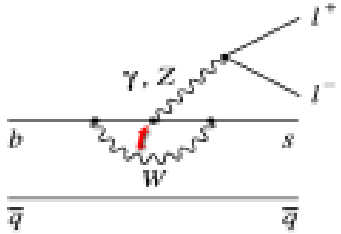
$$R(D^*)=\frac{BF(B\to D^*\tau\nu)}{BF(B\to D^*\mu\nu)}$$





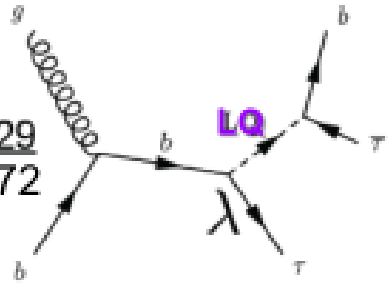
Hiller & Krüger 2004

$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\,dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\,dq^2}$$



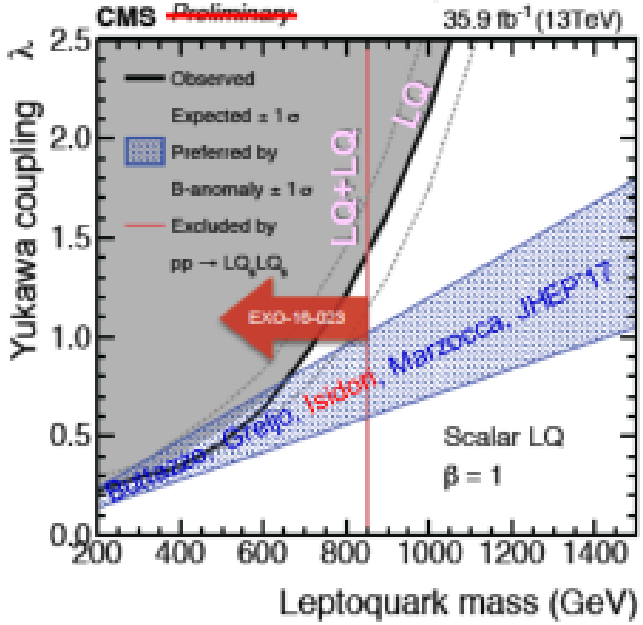
High p_T took Notice !

Rahatlou@ ICHEP2018



EXO-17-029
1806.03472

JHEP07(2018)



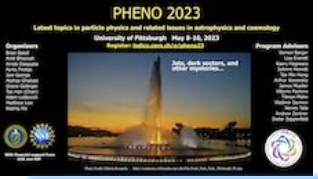
My (Th) Bias: LQ's *Now !?*

see Isidori talk for "PS^3"

Rencontres du Vietnam, 2018

"Pati-Salam^3"

LeptoQuark



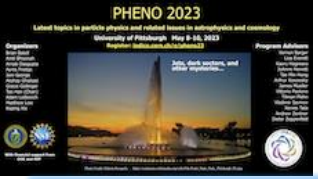
A Cry in the Wilderness

*** Flavor, where Anomalies/hoopla are !**

Experimental Caution/Reminder on Flavor Anomalies

[inasmuch as it is our current Best Hope

... advice from an "Experimentheorist"
George W.S. Hou (NTU)

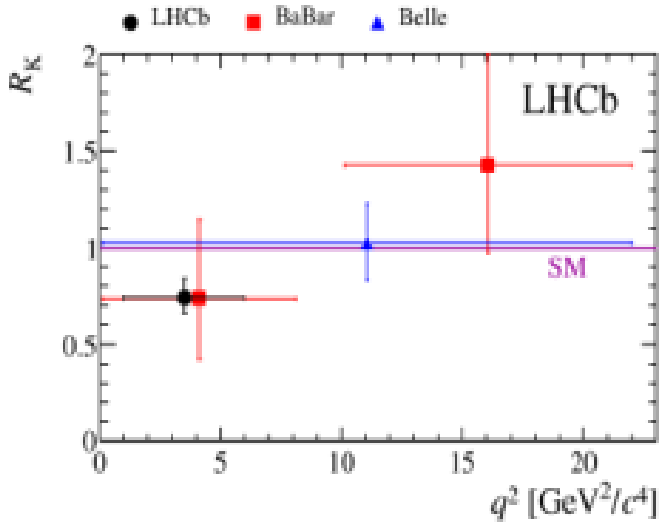


A Cry in the Wilderness

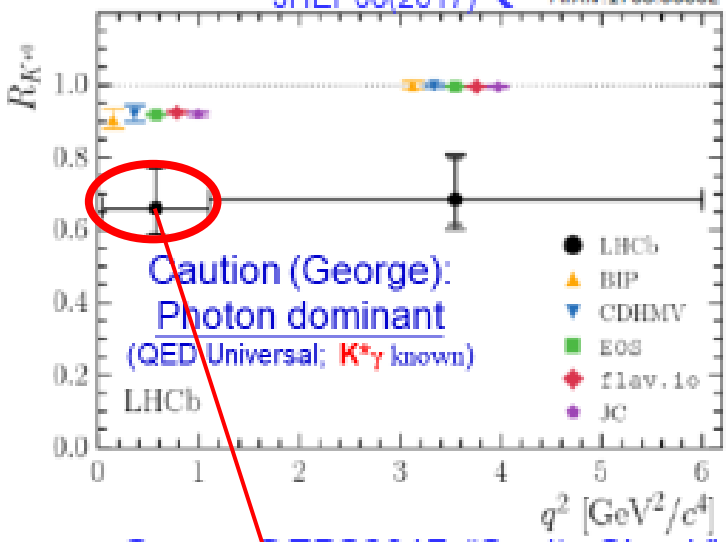
LUV: R_K & R_{K^*} Anomaly

$$R_H = \frac{\int \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}\,dq^2}{\int \frac{d\Gamma(B\to He^+e^-)}{dq^2}\,dq^2}$$

Phys. Rev. Lett. 113 (2014) 151601



JHEP08(2017) ← ArXiv:1705.05802



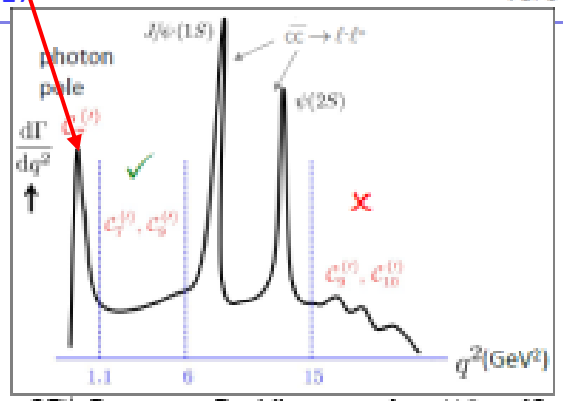
George@EPS2017: "Sanity Check"

11 July 2017 Ulrik Egede @ EPS-HEP 2017 15/31

George @ EPS2017, Venezia

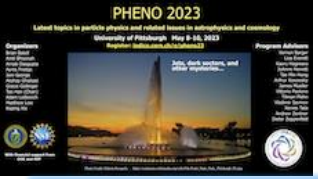
"I'll betcha the plan was to demonstrate Universal behavior for low bin, making high bin, together with R_K, convincing!"

But …



Seemingly Impressive

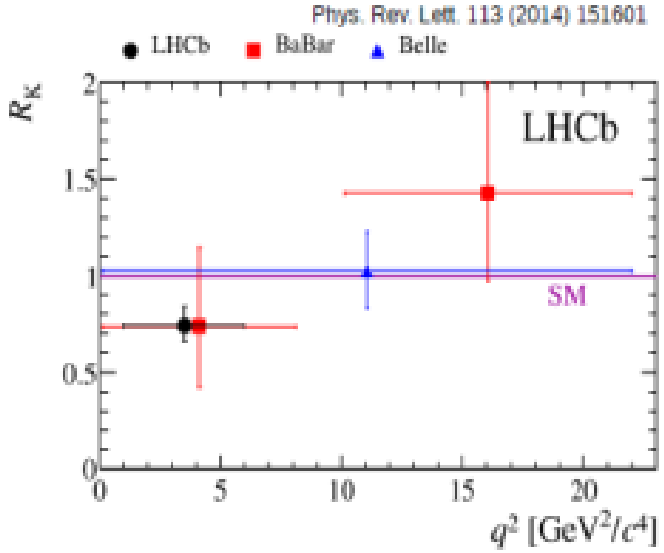
HEP Outlook George W.S. Hou (NTU) 25th Rencont. Du Vietnam, Aug '18 42

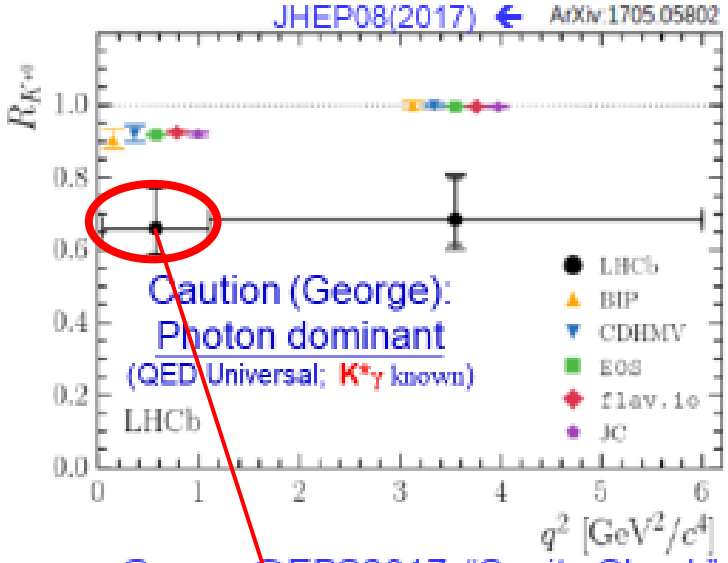


A Cry in the Wilderness

LUV: R_K & R_{K^*} Anomaly

real?





George@EPS2017: "Sanity Check"

11 July 2017 Ulrik Egede @ EPS-HEP 2017 15/31

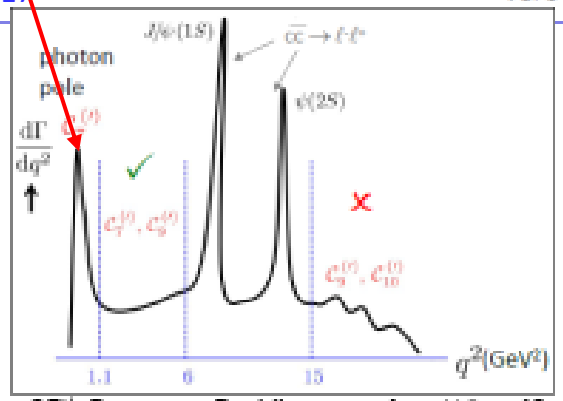
Occam's razor

$R_K \sim 0.745$ @ -2.6σ, 1.0 – 6.0 GeV^2

$R_{K^*} \sim 0.66$ @ -2.2σ, 0.045 – 1.1 GeV^2

$R_{K^*} \sim 0.69$ @ -2.4σ, 1.1 – 6.0 GeV^2

A Simpler, Common Cause !?

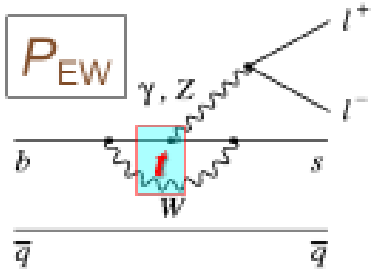


"Systematic effect?"

HEP Outlook George W.S. Hou (NTU) 25th Rencont. Du Vietnam, Aug '18 42

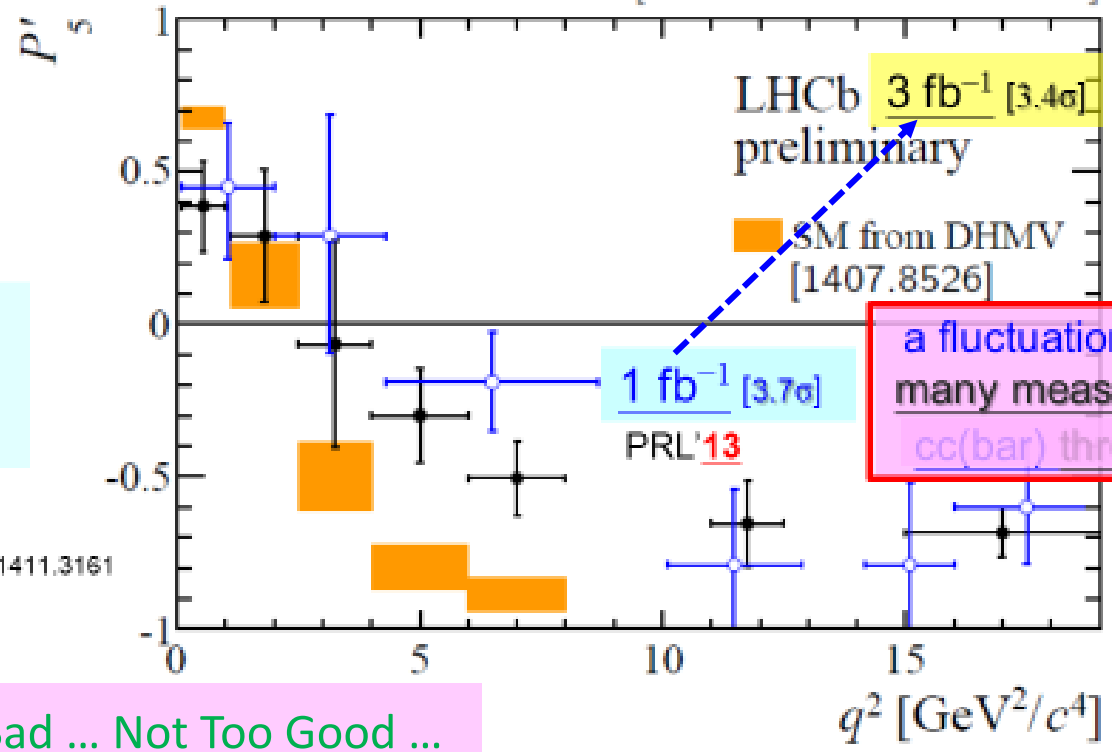
A Cry in the Wilderness

Flavour Anomaly #1 @ LHCb



P'_5 B → K*μμ angular analasis

JHEP02(2016) ← [LHCb-CONF-2015-002]



NP? $\Delta C_9 \sim -1$: heavy Z' (tree) [gives R_K, too]

e.g. 1307.5683; 1308.1501; 1310.2478; 1310.3877; 1310.1082; 1311.6729 ... 1411.3161

a fluctuation among many measurables ?

cc(bar) threshold ?

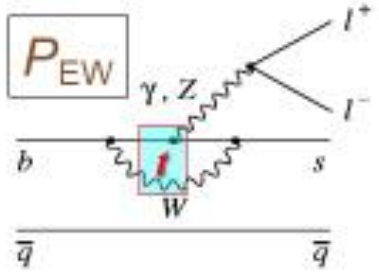
Not Good, Not Bad ... Not Too Good ...

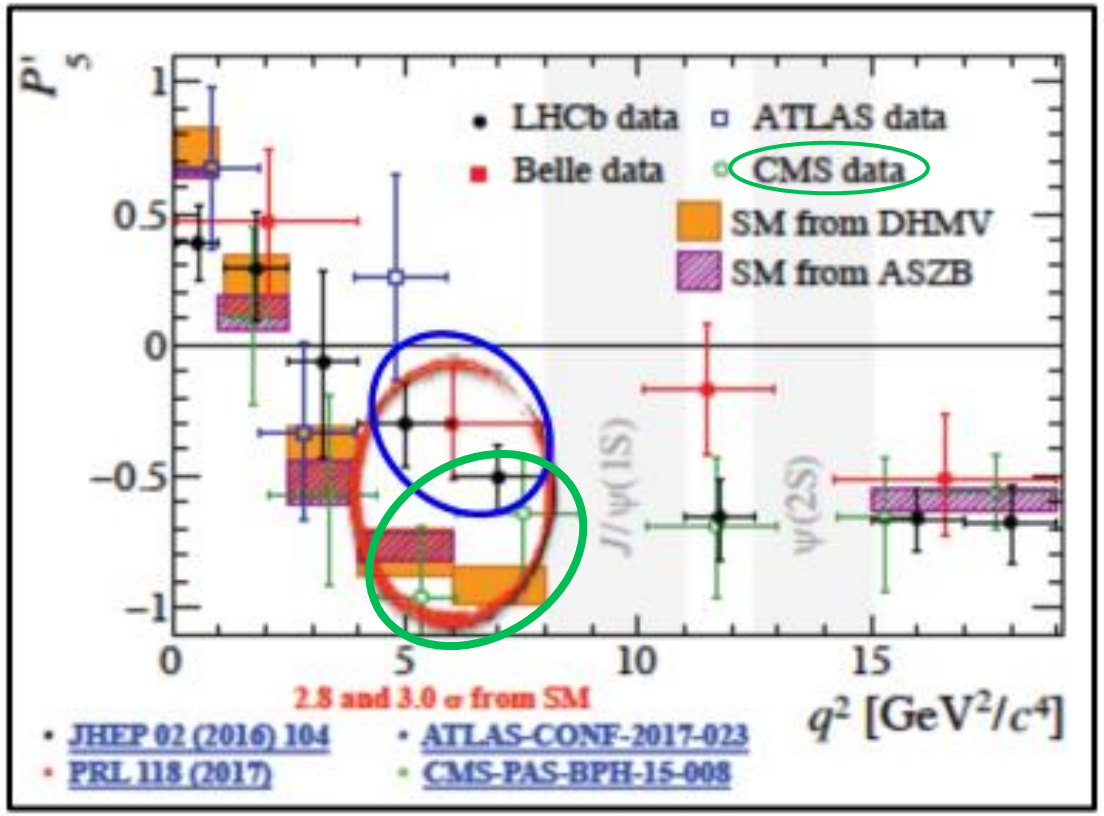
Significance did not improve. [3.7σ → 3.4σ]

Will see ...

A Cry in the Wilderness

Is P'_5 Anomaly Real? Enter CMS





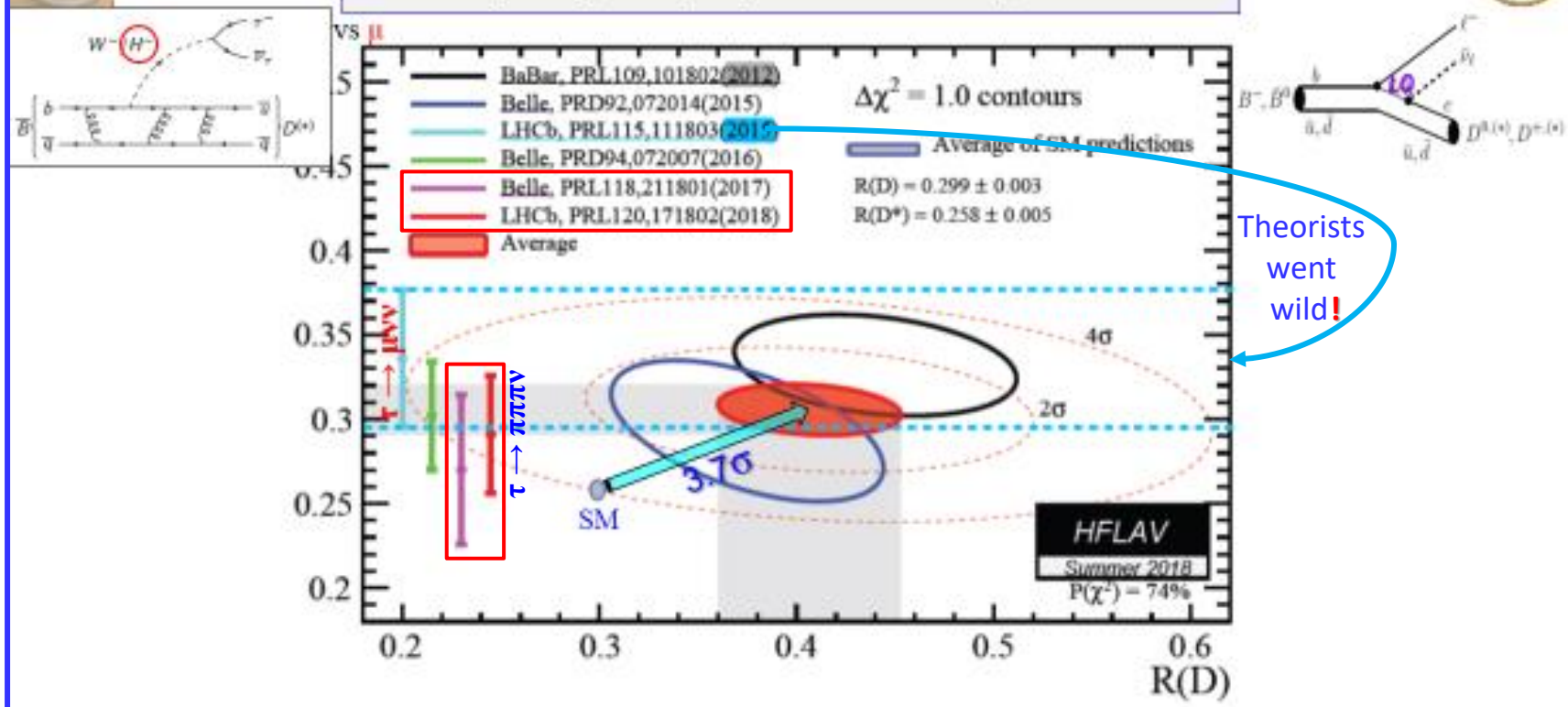
1710.02846 (PLB'18)

NP? $\Delta C_9 \sim -1$:
heavy Z' (tree)
[gives R_K, too]

Consistent w/ SM!

A Cry in the Wilderness

Is R(D*), R(D) Anomaly Real?



Theorists went wild!

- Two elipses are R_D - R_{D^*} measurements of BaBar'12 and Belle'15
- R_{D^*} measurement of LHCb'15 (concur with BaBar) caused sensation
- Sobering: R_{D^*} measurement of LHCb'18 consistent w/ SM (via $\tau \to$ 3-prong)
  R_{D^*} – and $\tau_{pol.}$ – measurement by Belle'18 ~ SM

A Cry in the Wilderness

Rencontres du Vietnam, 2018

On Flavour Anomalies

Anomalies come and go, and they mostly go ...

Flavour Anomalies have been more persistent.

But now they all source to (fabulous) **LHCb** ...

Until 12/20 talk by Renato Quagliani at CERN

Butler

... and CMS 2018 Trig./DAQ

Per physics tradition, need **Belle II** for Confirmation, If not Competition!

The World After (in 2023)

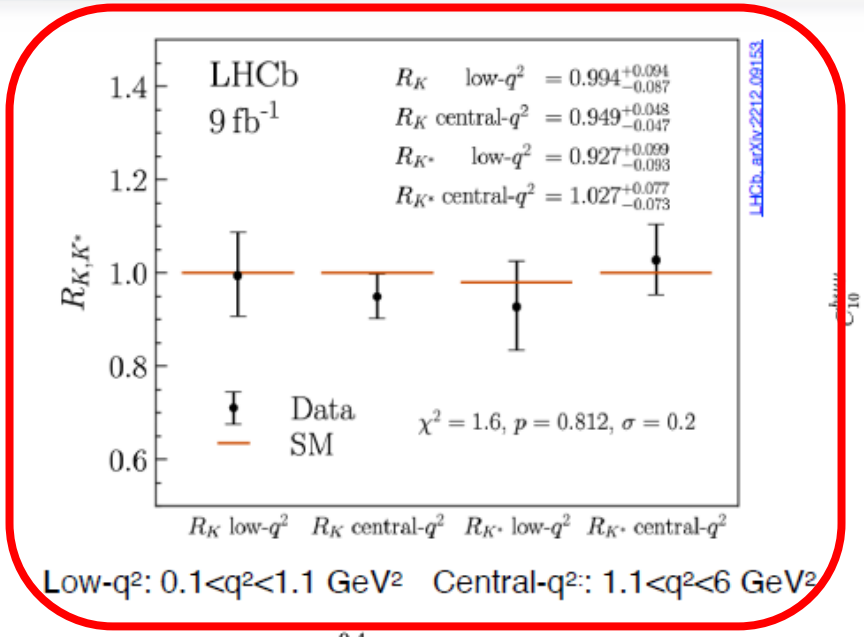
- Update of LHCb $R(K^{(*)})$:
  - Simultaneous $R(K)$, $R(K^*)$ measurement with full stat.
  - Increased signal purity and significance.
  - Better background modelling.

    Redefinition of q^2 regions.

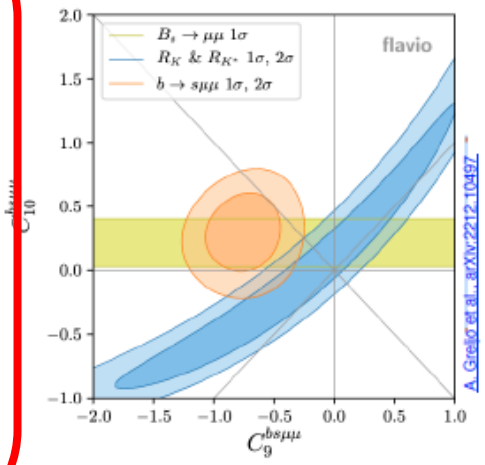
    Treatment of e bremsstrahlung, stricter particle-id.

    Misidentified hadronic background in e mode.
  - Overall 0.2σ agreement with SM. Still stat limited.

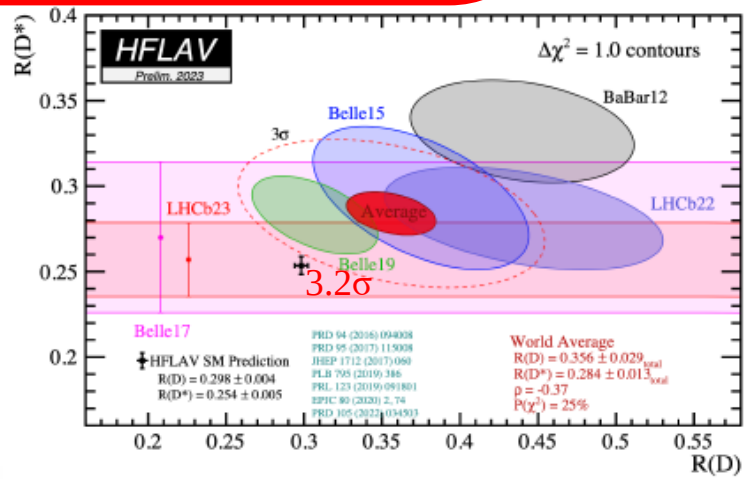
    R_K, R_{K^*} Evaporated



Low-q^2: $0.1<q^2<1.1$ GeV^2 Central-q^2: $1.1<q^2<6$ GeV^2



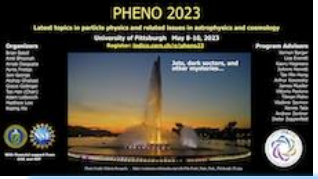
- New recent $b \to c\, l\, \nu$ LHCb measurements:
  - $R(\Lambda_b)$ with $\Lambda_b \to \Lambda_c \tau \nu$. (LHCb, Phys.Rev.Lett. 128 (2022))
  - $R(D^{(*)})$ with $\tau \to \mu$ (LHCb, arXiv:2302.02886) and hadronic τ (LHCb-PAPER-2022-052 in preparation).
  - Move toward SM prediction. But Not Gone.



Isidori:
"Not all is lost."

- Discrepancies in other $b \to s\, l^+ l^-$ results remain:
  - B.R., angular distributions.
  - But less theoretically clean than ratios.

Belle II



II. Response(s) to $R_{K^{(*)}}$ Disappearance

(1) Hadronic Effect

PHYSICAL REVIEW D **107**, 055036 (2023)

Constraints on lepton universality violation from rare *B* decays

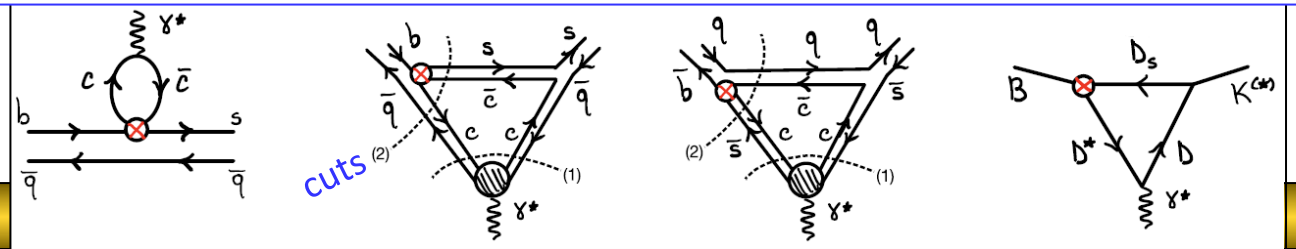
Marco Ciuchini,[1,*] Marco Fedele,[2,†] Enrico Franco,[3,‡] Ayan Paul,[4,§] Luca Silvestrini,[3,∥] and Mauro Valli[3,5,¶]

[1]*INFN Sezione di Roma Tre, Via della Vasca Navale 84, I-00146 Rome, Italy*
[2]*Institut für Theoretische Teilchenphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*
[3]*INFN Sezione di Roma, Piazzale Aldo Moro 2, I-00185 Rome, Italy*
[4]*Electrical and Computer Engineering, Northeastern University, Boston, Massachusetts 02115, USA*
[5]*C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, New York 11794, USA*

(Received 17 January 2023; accepted 10 March 2023; published 23 March 2023)

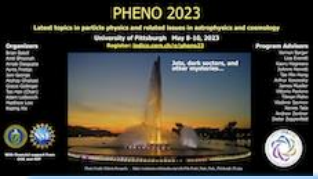
The LHCb Collaboration has recently released a new study of $B^+ \to K^+\ell^+\ell^-$ and $B \to K^{*0}\ell^+\ell^-$ ($\ell = e, \mu$) decays, testing lepton universality with unprecedented accuracy using the whole Run 1 and 2 dataset. In addition, the CMS Collaboration has reported an improved analysis of the branching ratios $B_{(d,s)} \to \mu^+\mu^-$. While these measurements offer, *per se*, a powerful probe of new physics, global analyses of $b \to s\ell^+\ell^-$ transitions also rely on the assumptions about nonperturbative contributions to the decay matrix elements. In this work, we perform a global Bayesian analysis of new physics in (semi)leptonic rare B decays, paying attention to the role of charming penguins which are difficult to evaluate from first principles. We find data to be consistent with the Standard Model once rescattering from intermediate hadronic states is included. Consequently, we derive stringent bounds on lepton universality violation in $|\Delta B| = |\Delta S| = 1$ (semi)leptonic processes.

been saying so for ages



hadronic rescattering

2212.10516 (12/20)



Response(s) to $R_{K^{(*)}}$ Disappearance

(2) "Die-Hard"

New Perspectives for Testing Electron-Muon Universality

Robert Fleischer [a,b], Eleftheria Malami [a,c], Anders Rehult [a], and K. Keri Vos [a,d]

Abstract

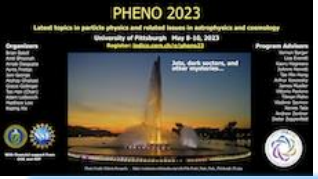
Intriguing results for tests of the universality of electrons and muons through measurements of rates of $B \to K\ell^+\ell^-$ and similar decays have been in the spotlight for years. The LHCb collaboration has recently reported new results which are in agreement with Lepton Flavour Universality, while the individual decay rates are found below their Standard Model predictions. In view of this new situation, we explore how much space is left for a violation of electron–muon universality. Considering new sources of CP violation and taking the new LHCb measurements into account, we show that significant differences between the short-distance coefficients for electronic and muonic final states are actually allowed by the current data. These patterns can be revealed through CP asymmetries in neutral and charged $B \to K\ell^+\ell^-$ decays. We obtain correlations between these observables and map them to the short-distance coefficients. This results in regions in New Physics parameter space with large differences between CP asymmetries of the decays with final-state electrons and muons, thereby leaving a lot of room for possible surprises in the future high-precision era.

Add CPV-LUV

Enlarged Space!

2303.08764

despite $R_{K^{(*)}} = 1$



Response(s) to $R_{K^{(*)}}$ Disappearance

(3) Defiant

The Rumble in the Meson: a leptoquark versus a Z' to fit $b \to s\mu^+\mu^-$ anomalies including 2022 LHCb $R_{K^{(*)}}$ measurements

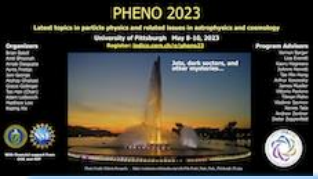
Ben Allanach[a,b] and Joe Davighi[c,1]

Also Greljo et al., 2212.10497 (12/20)

ABSTRACT: We juxtapose global fits of two bottom-up models (an S_3 scalar leptoquark model and a $B_3 - L_2$ Z' model) of $b \to s\mu^+\mu^-$ anomalies to flavour data in order to quantify statistical preference or lack thereof. The leptoquark model couples directly to left-handed di-muon pairs, whereas the Z' model couples to di-muon pairs with a vector-like coupling. $B_s - \overline{B_s}$ mixing is a focus because it is typically expected to disfavour Z' explanations. In two-parameter fits to 247 flavour observables, including $B_{s/d} \to \mu^+\mu^-$ branching ratios for which we provide an updated combination and LHCb $R_{K^{(*)}}$ measurements from December 2022, we show that each model provides a similar improvement in quality-of-fit of $\sqrt{\Delta\chi^2} = 3.6$ with respect to the Standard Model. The main effect of the $B_s - \overline{B_s}$ mixing constraint in the Z' model is to disfavour values of the $s_L - b_L$ mixing angle greater than about $5|V_{cb}|$.

2211.11766 **[v4]**

JHEP04(2023)033



Response(s) to $R_{K^{(*)}}$ Disappearance

(4) LUV gauge int.

But I'll follow a different path.

Non-universal gauge interactions addressing the inescapable link between Higgs and Flavour

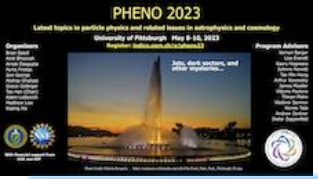
Joe Davighi and Gino Isidori

Gino means it.

UV completion

ABSTRACT: We systematically explore ultraviolet complete models where flavour hierarchies emerge, via approximate accidental symmetries, from an underlying flavour non-universal gauge structure. In order to avoid large quantum corrections to the Higgs mass, the first layer of non-universality, separating the third generation from the light ones, should appear at the TeV scale. A handful of models survive the combined criteria of naturalness in the Higgs sector, having a semi-simple embedding in the UV, and compatibility with experiments. They all feature quark-lepton unification in the third family and a non-universal electroweak sector. We study in more detail the interesting option of having colour and hypercharge non-universal at the TeV scale, while $SU(2)_L$ remains universal up to high scales: this gauge structure turns to be very efficient in secluding the Higgs from large quantum corrections and predicting flavour mixing consistent with data. In all cases, these models imply a rich TeV-scale phenomenology within the reach of near-future direct and indirect experimental searches.

2303.01520v3



Response(s) to $R_{K^{(*)}}$ Disappearance

(5) Everything
Everywhere
All at Once

Anomalies in Particle Physics

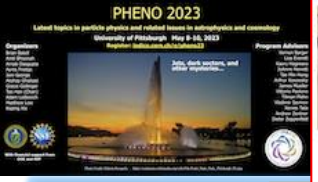
Andreas Crivellin[a,b]

Learn all the Anomalies here, if that's your creed.

I provide a (personal) review of the current hints for physics beyond the Standard Model, called "anomalies", obtained both at the intensity frontier (flavour and electroweak precision observables) and in direct LHC searches. This includes the deviations from the Standard Model predictions in semi-leptonic B decays, the anomalous magnetic moment of the muon, the Cabibbo Angle Anomaly, the W mass as well as non-resonant di-lepton searches, the hints for new scalar particles around ≈ 95 GeV, ≈ 151 GeV, ≈ 670 GeV and the (di-)di-jet excess at ≈ 1 TeV (≈ 3.6 TeV). Possible explanations in terms of new particles are briefly summarized and discussed.

8th Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE 2022)
7-11 November 2022
Baden-Baden, Germany

2304.01694



Whither Extra Yukawas?

Known CPV in CKM ➔ Yukawa's. Extra Yukawa's ?

my view for BSM

Jarlskog Invariant *way too small !*

Killed by Z_2 (Glashow-Weinberg 1977)

Natural Flavor Conservation (NFC)

Baryon
Asymmetry
of
Universe

2012⁺: *One Higgs* ➔ 2nd Higgs

Highly Plausible !

PLB'13

When the Higgs meets the top: Search for $t \to ch^0$ at the LHC

Kai-Feng Chen [a], Wei-Shu Hou [a,*], Chung Kao [a,b], Masaya Kohda [a]

PLB'92

[a] Department of Physics, National Taiwan University, Taipei 10617, Taiwan
[b] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK 73019, USA

1% Still Possible !!

Before Top Quark was Discovered. WSH, PLB'92 (PSI-PR-91-34)

$$\rho_{ct} \underbrace{\cos(\beta-\alpha)}_{c_\gamma} \bar{c} t h^0$$

c_γ

FCNH modulated by h–H mixing

→ **Alignment** overtakes Glashow-Weinberg NFC

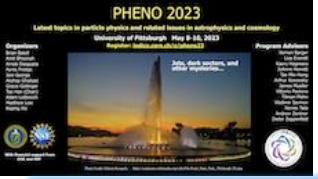
c_γ small

An Experimental Issue

$$\begin{pmatrix} \rho_{cc} & \rho_{ct} \\ \rho_{tc} & \rho_{tt} \end{pmatrix}$$

Extra Yukawas

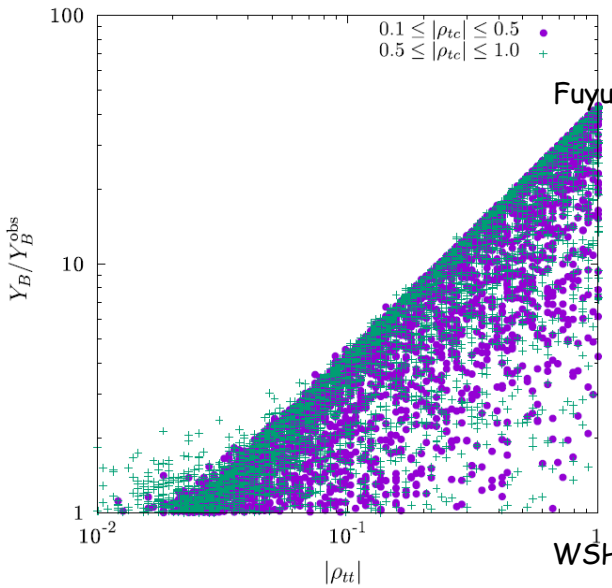
$$\begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$$



* top-Higgs? → "Flavored" Higgs → SM2 (?)

2HDM (w/o Z_2)

EW BaryoGenesis



- EWBG Remarkably Efficient w/

Fuyuto, wSH, Senaha, 5'17 (PLB'18)

$\mathcal{O}(1)$ { Higgs quartics η_i ; New Yukawa ρ_{tt} [and ρ_{tc} }

N.B. $\mathcal{O}(1)$ modulo flavor org. (of SM): much smaller Yuk. involving lower gen.

- Much New FPCP Pheno — most modulo c_γ — *a better substitute for NFC*

- Approx. Alignment for $\mathcal{O}(1)$ Higgs quartics ← w/o or w/ Z_2 !

WSH, Kikuchi, 6'17 (EPL'18)

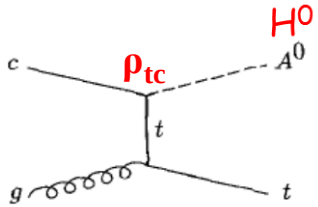
- mild tuning (1/4) ➔ Extreme Alignment
- mild Alignment ($c_\gamma = -0.2$) ➔ lower m_h by level repulsion
- sub-TeV H^0, A^0, H^+ preferred ➔ rethink LHC Search

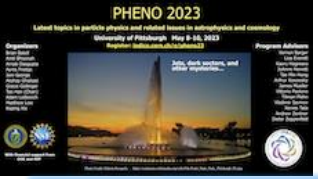
$$\begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$$

Kohda, Modak, WSH, 10'17 (PLB'18)

Discover @ LHC!? $cg \to tH^0/A^0 \to ttc(bar), ttt(bar)$

- NOT SUSY!
- Touch EWBG! [need CPV probe
- Another Energy Layer guaranteed! [by Landau pole



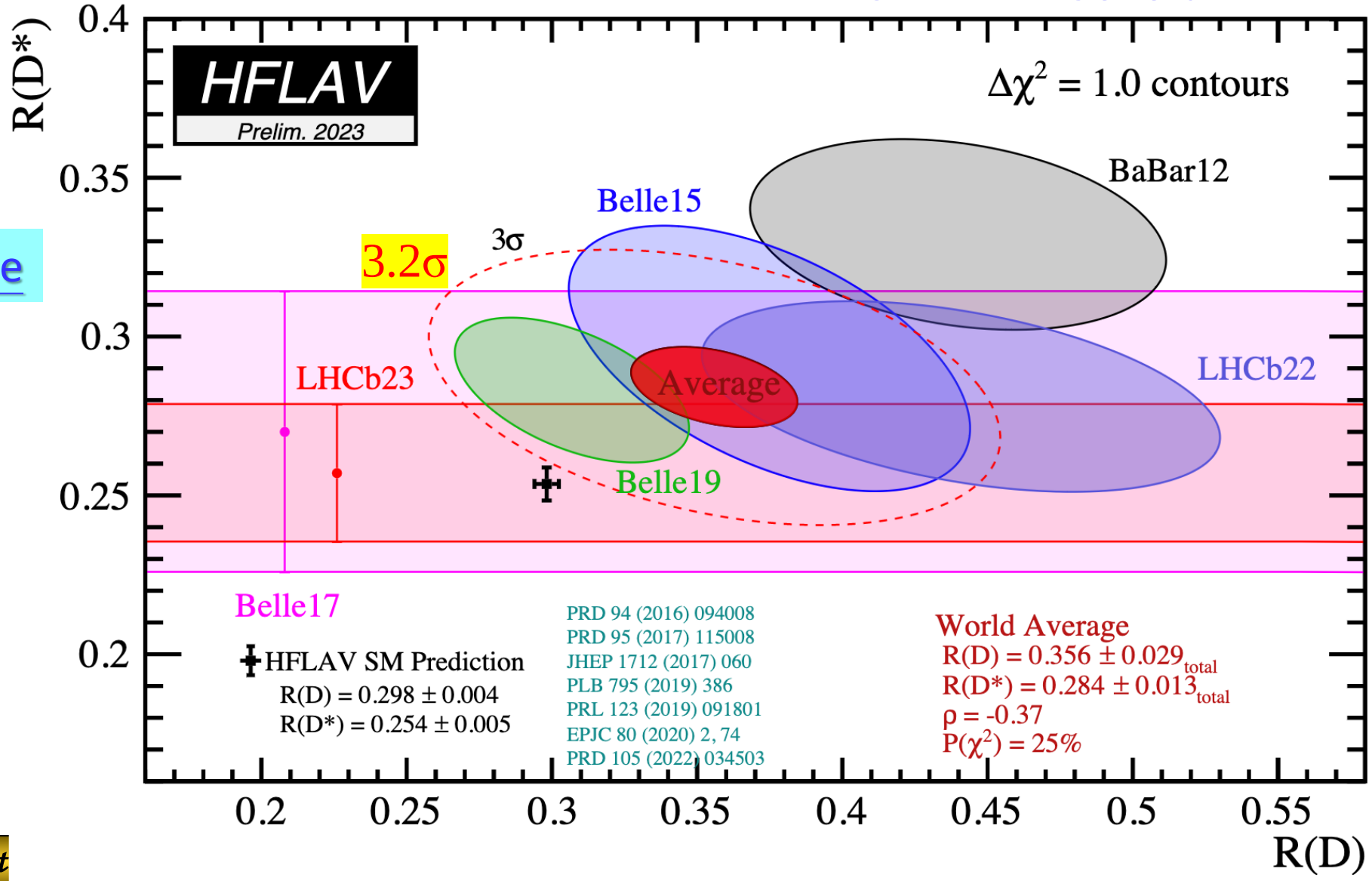


III. Rehab of H^+ for $R_{D^{(*)}}$ in G2HDM

G2HDM = General 2HDM = 2HDM w/o Z_2

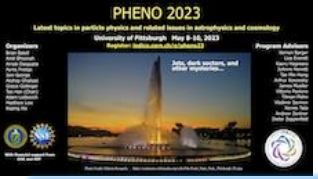
So has extra Yukawa

Not Gone



Isidori:

"Not all is lost."



Rehab of H^+ for $R_{D^{(*)}}$ in G2HDM

not necessary

"G2HDM" offered some earliest explanation:
e.g. Crivellin, Greub, Kokulu, PRD'12
Celis, Jung, Li & Pich, JHEP'13

but ruled out by B_c lifetime argument:
Alonso, Grinstein, Martin Camalich, PRL'17.

1612.06676 (PRL'17): $BR(B_c \to \tau\nu) < 30\%$

1708.04072 (PRD'17): $BR(B_c \to \tau\nu) < 10\%$

1811.09603 (PRD'19): $BR(B_c \to \tau\nu) < 60\%$
(Blanke et al.)

→ 1708. underestimate m_c uncertainty and $b \to B_c$ fragmentation;

2105.02988 (JHEP'21) affirm (63%).
(Aebischer-Grinstein)

G2HDM = General 2HDM = 2HDM w/o Z_2
So has extra Yukawa

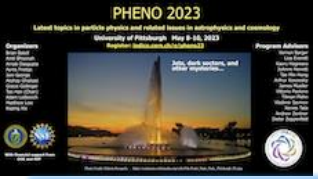
See e.g. also 2202.10468, 2302.08935

Revival of H^- interpretation of $R_{D^{(*)}}$ anomaly and closing low mass window
Syuhei Iguro* 2201.06565 (PRD'22)

Interplay of the charged Higgs boson effects in $R_{D^{(*)}}$, $b \to s\ell^+\ell^-$
Girish Kumar 2212.07233 (PRD'23)

These two papers use over-simplified, unrealistic extra Yukawa matrices, but illustrates G2HDM is Rehabilitated for $R_{D^{(*)}}$.
Exp't may further evolve.

N.B. Please let *Nature* decide on ρ_{ij} values.



IV. G2HDM (w/o Z_2) as *Next New Physics*?

"Just, please try to engage a broader audience."

- Glimpse from a TW Flagship Project
- Flavor, *Mass*, Higgs
- Heavens & Earth: EWBG & *e*EDM
- 2017 a Good Year
  → Fruition in 2023 …
- New Higgs/Flavor Era

Glimpse from a TW Flagship Project

Report at ASP Annual Meeting

Except h(125) discovered in 2012: *No New Physics!*

No SUSY, No Nothin'.
→ HEP Rudderless!

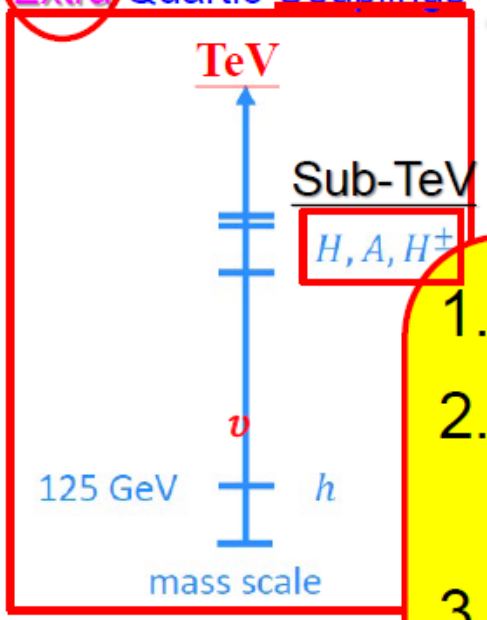
Hear all about it !

Extra Higgs Doublet w/
Extra Yukawa Couplings
& Extra Quartic Couplings

Quite ~~MOST~~ Likely *Next New Physics!* (our assessment)

Finite Chance. **Really**

Vision: CJP'22 (arXiv:2109.02557).
Chin.J.Phys.



1. CMS: **H**, **A**, **H**$^+$ search @ LHC
2. Belle II: $\tau \to \mu\gamma$; $B \to \mu\nu, \tau\nu$
   CMS/B II: $B_{s,d} \to \mu\mu, \tau\mu$
3. Lattice: Higgs Potential { 1st Order Ph.Tr. / Landau Pole }
4. "Steering": Pheno 粒子現象學

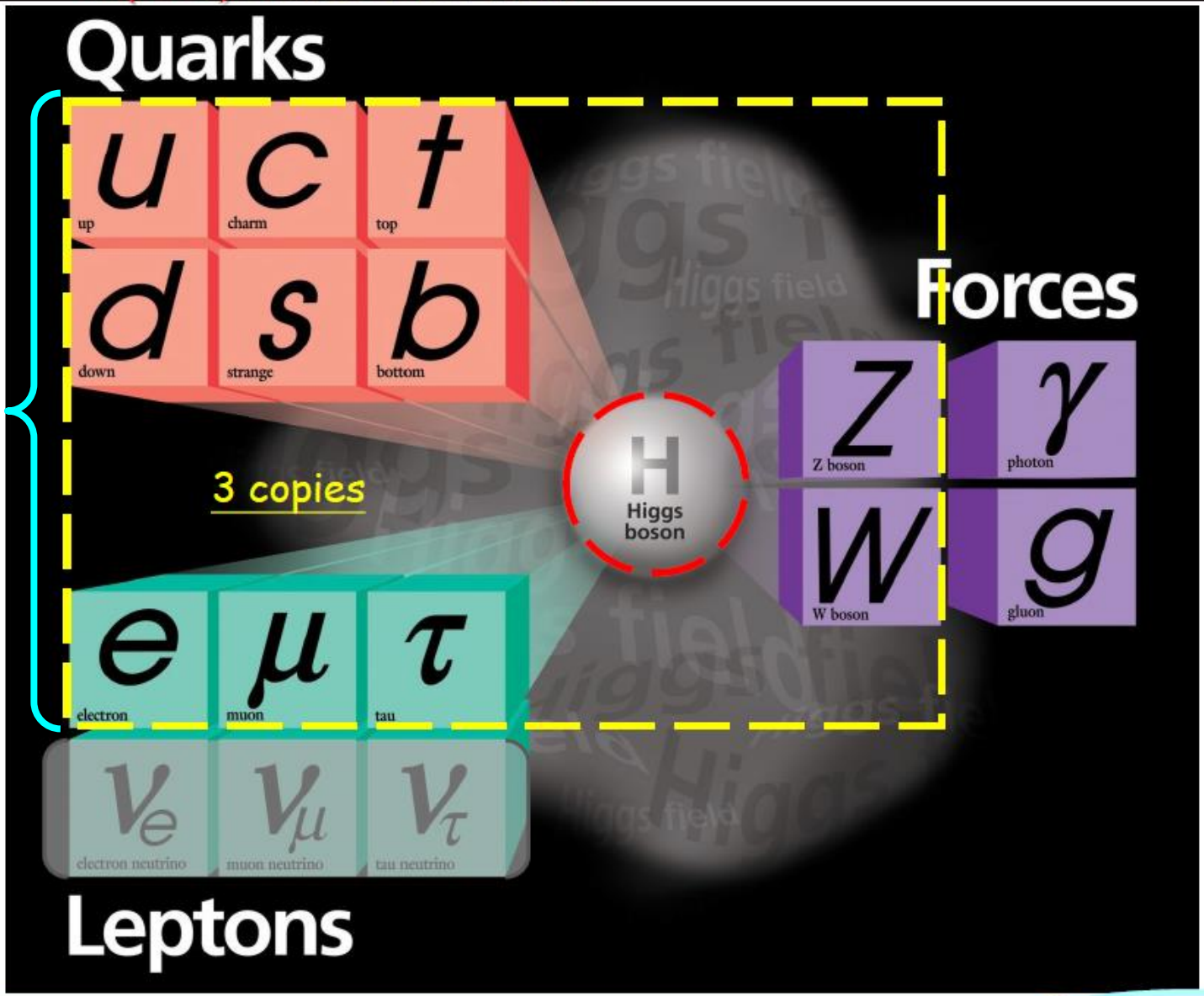
ASP = Academic Summit Project

The "God" Particle: the Origin of Mass

h(125): observed 7/4/2012

"Flavor"

m_e



The "God" Particle: the Origin of Mass

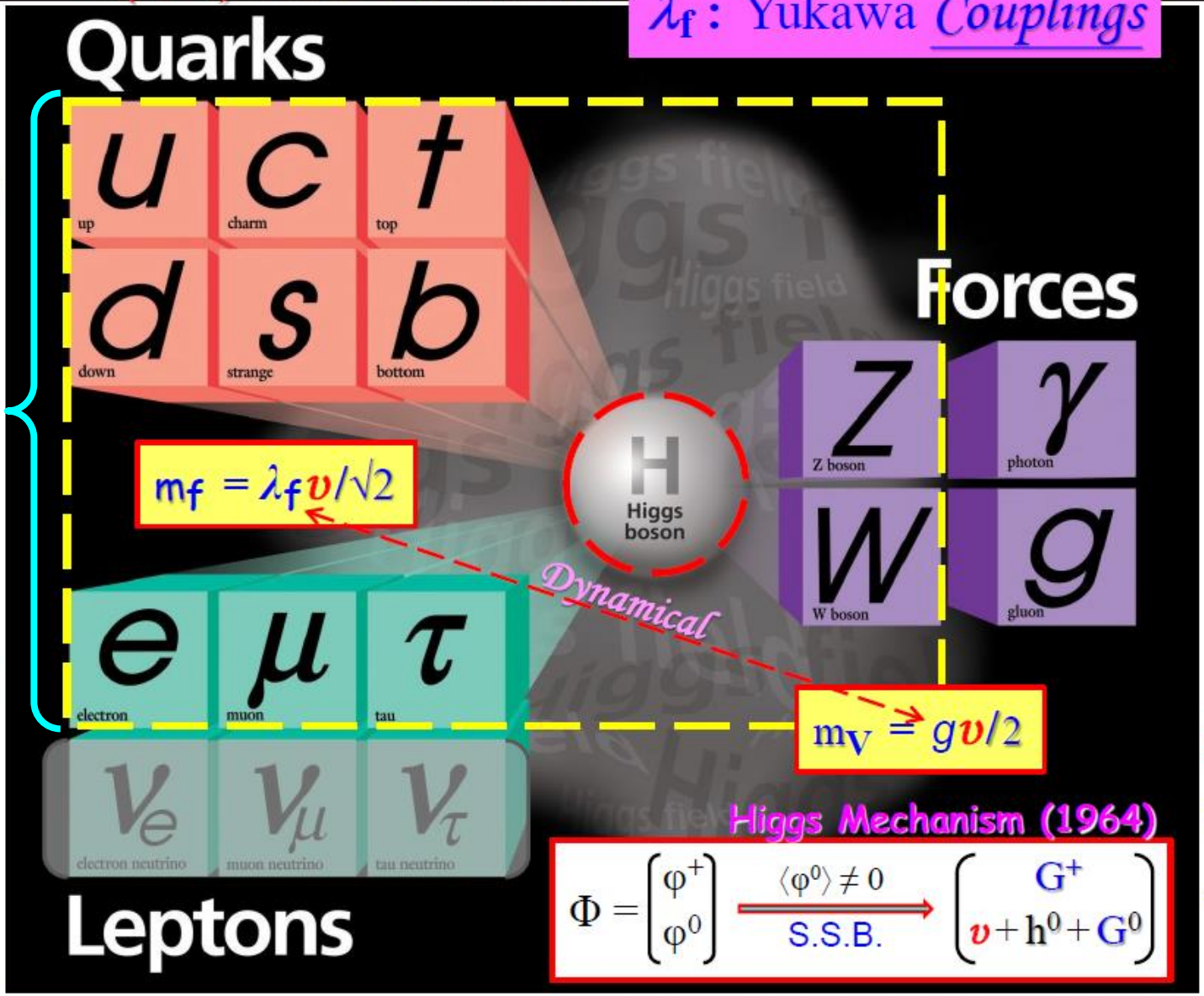
h(125): observed 7/4/2012

λ_f : Yukawa *Couplings*

to ~ 173 GeV

"*Flavor*"

m_e ~ from 0.5 MeV



$v \approx 246$ GeV

~ Meissner effect of superconductor (MagLev)

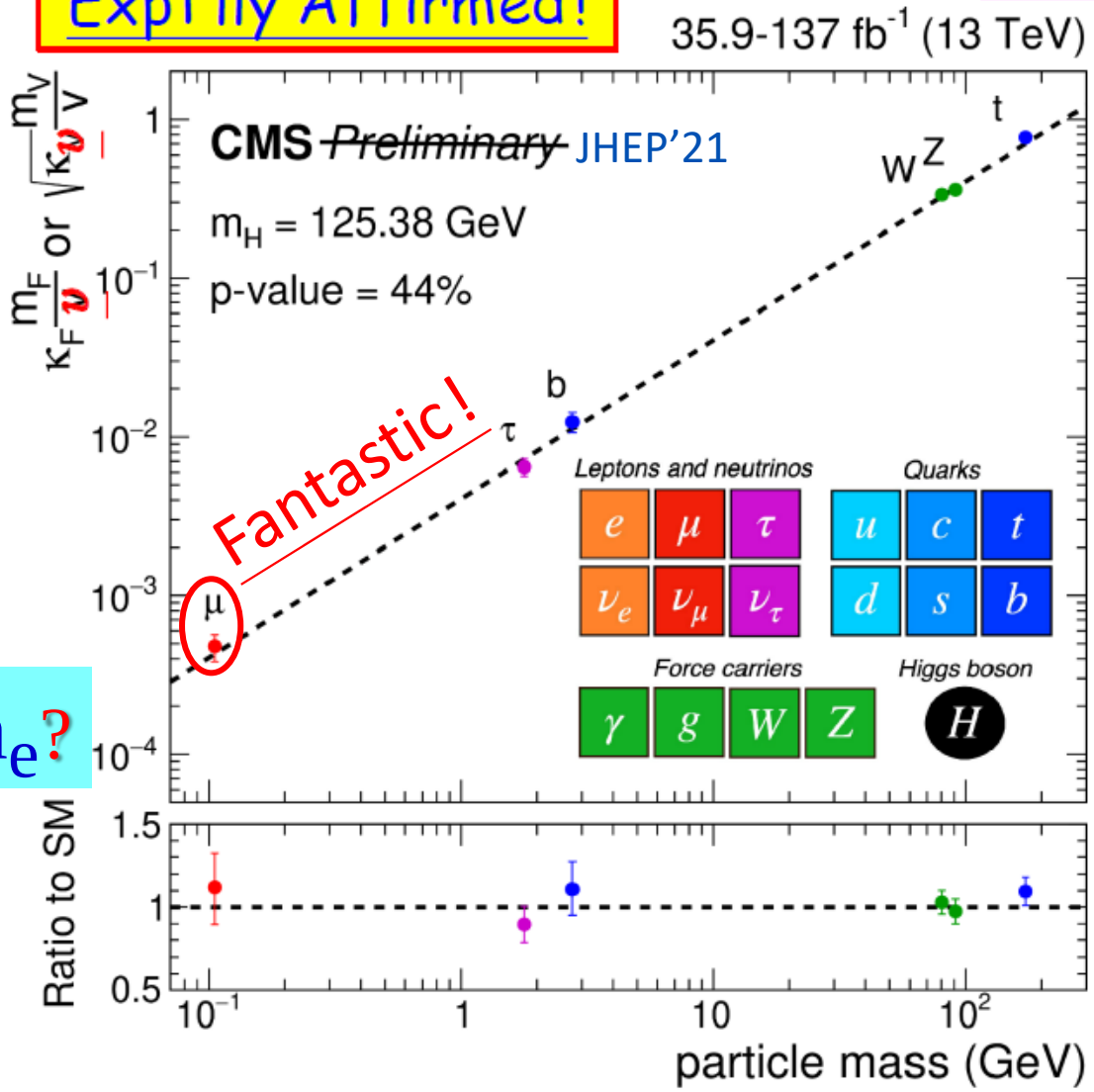
G
Goldstone Boson
("eaten")

The "God" Particle: the Origin of Mass ✓

h(125): observed 7/4/2012

λ_f : Yukawa *Couplings*

Expt'lly Affirmed!



m_e?

$g \simeq 2m_V/v$ ca. 2015

$\lambda_f \simeq \sqrt{2}m_f/v$ t/b/τ: 2018

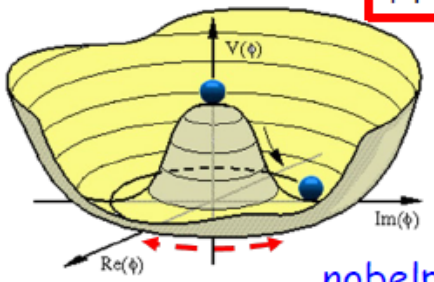
μ: 2020

Higgs "potential": Simplest!!

$$V(\Phi) \sim -|\mu|^2|\Phi|^2 + \lambda|\Phi|^4$$

$$\Rightarrow \quad |\varphi^0|^2 = v^2 \sim \mu^2/\lambda$$

$v \approx 246$ GeV



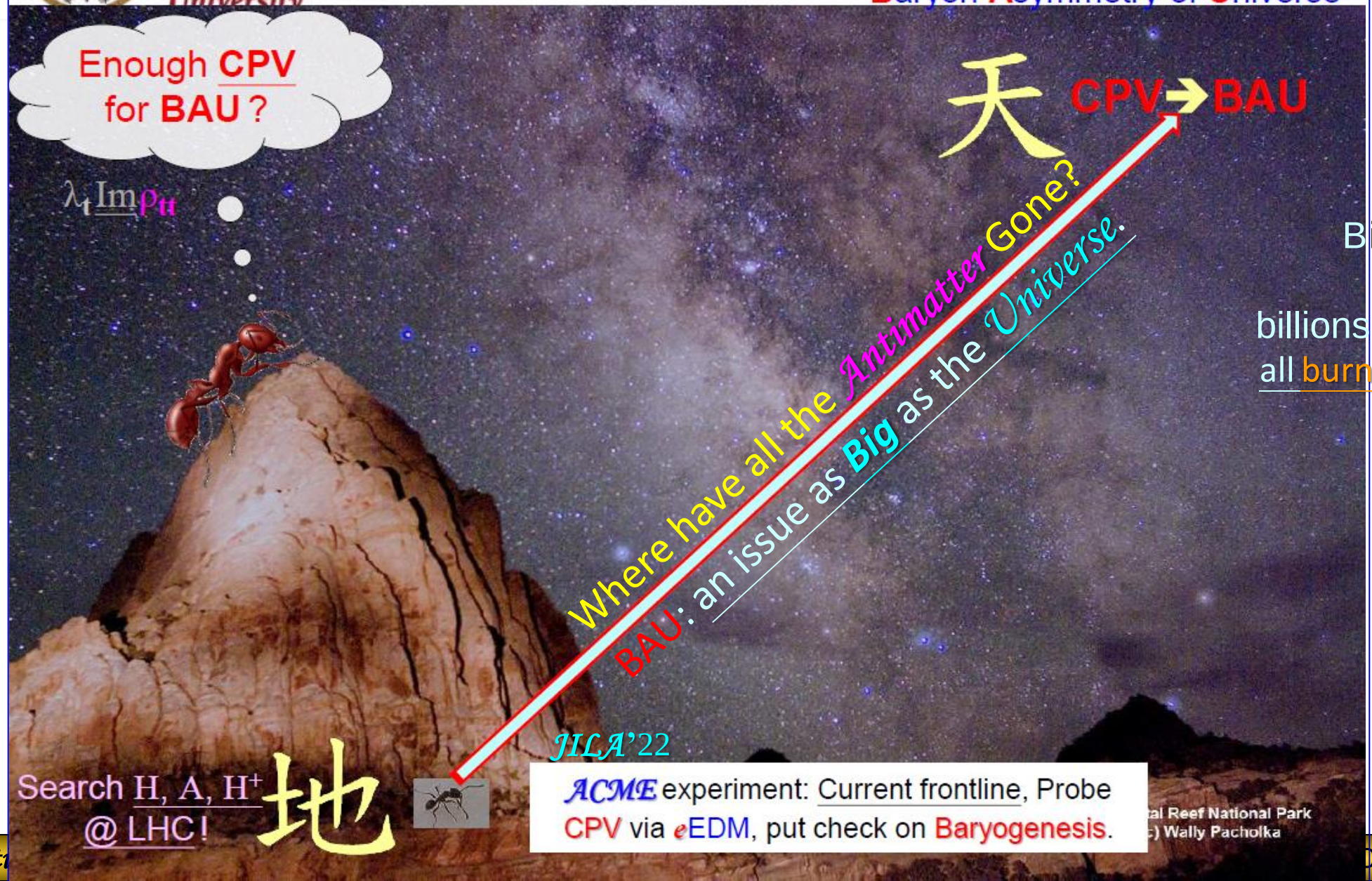
nobelprize.org (2013)

le Raison d'être

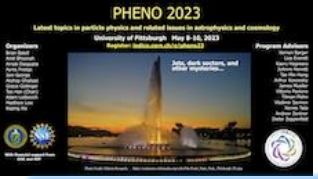
國立臺灣大學 National Taiwan University

Soaring to the Starry Heavens

Baryon Asymmetry of Universe



Billions
&
billions of stars …
all burning protons



Our *Life* & Times

h(125) ✓ *New Physics* ✗

EWBG ought to be pursued while LHC is still running!

No SUSY, No Nothin'!

Beyond CKM CPV

EW BaryoGenesis (EWBG)

- more testable -

tension

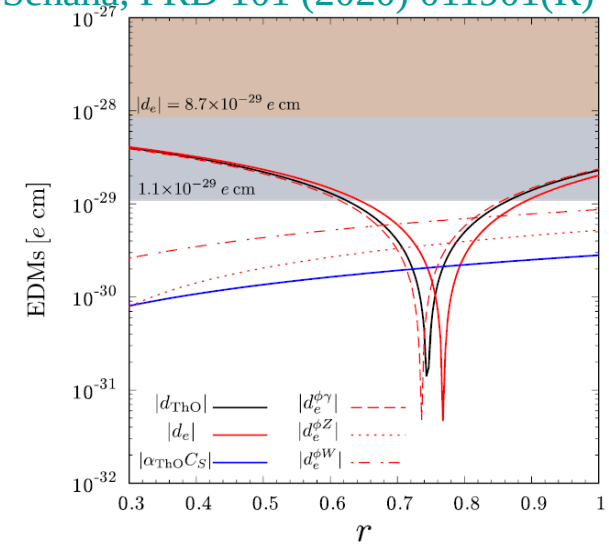
LHC

- *N*o *N*ew *P*hysics -

tension

competition

Fuyuto, WSH, Senaha, PRD 101 (2020) 011901(R)



JILA'22

*e*EDM: ACME14 → ~~ACME18~~

- L.E. Precision Frontier -

0.41

$|d_e| < \cancel{1.1} \times 10^{-29}\ e$ cm

A *Natural* Cancellation Mechanism!

Zooming in . . .

國立臺灣大學 National Taiwan University

Gell-Mann (1969 sole Laureate)

"Everything not forbidden is compulsory." (Wiki)

Vision: CJP'22 (arXiv:2109.02557).

∃ Weak Higgs Doublet $v \approx 246$ GeV

$$\Phi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \xrightarrow[\text{S.S.B.}]{\langle \varphi^0 \rangle \neq 0} \begin{pmatrix} G^+ \\ v + h^0 + G^0 \end{pmatrix}$$

Observed.

Higgs Mechanism (Meissner effect)

$h(125)$ ✓

No Reason to forbid
a Second Higgs,
so ∃ Second Higgs Doublet

$$\Phi' = \begin{pmatrix} \varphi'^+ \\ \varphi'^0 \end{pmatrix} \xrightarrow{\langle \varphi'^0 \rangle = 0} \begin{pmatrix} H^+ \\ H^0 + iA \end{pmatrix}$$

(1979 Laureates)

Glashow-Weinberg '77 sought to **forbid Second Set of Yukawa's**, refuted by my PLB'92 & EPL'18 (next page).

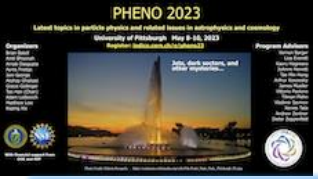
ad hoc

- Still Minority View -

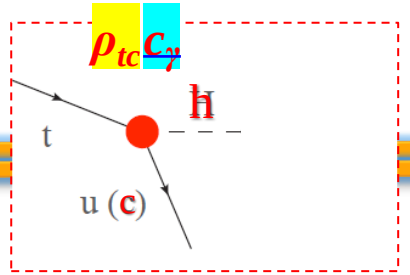
forward looking NSTC! *Thanks.*

so, the ρ_{ij}s
G2HDM

TW Funding Agency



First Fruit



"alignment"
c_γ small
emergent

c_γ: h-H mixing

Extra Higgs Doublet w/
Extra Yukawa Couplings
Extra Quartic Couplings

General 2HDM

H^+
$H + iA$

Before Top Quark was Discovered: WSH, PLB'92 (PSI-PR-91-34)

Correction on formulation with "SM"-like Higgs h: Chen, WSH, Kao, Kohda, PLB'13

PHYSICAL REVIEW LETTERS **129,** 032001 (2022)

Search for Flavor-Changing Neutral Current Interactions of the Top Quark and Higgs Boson in Final States with Two Photons in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Tumasyan *et al.*[*]
(CMS Collaboration)

(Received 3 November 2021; accepted 13 June 2022; published 13 July 2022)

Proton-proton interactions resulting in final states with two photons are studied in a search for the signature of flavor-changing neutral current interactions of top quarks (t) and Higgs bosons (H). The analysis is based on data collected at a center-of-mass energy of 13 TeV with the CMS detector at the LHC, corresponding to an integrated luminosity of 137 fb^{-1}. No significant excess above the background prediction is observed. Upper limits on the branching fractions ($\mathcal{B}$) of the top quark decaying to a Higgs boson and an up (u) or charm (c) quark are derived through a binned fit to the diphoton invariant mass spectrum. The observed (expected) 95% confidence level upper limits are found to be 0.019% (0.031%) for $\mathcal{B}(t \to Hu)$ and 0.073% (0.051%) for $\mathcal{B}(t \to Hc)$. These are the strictest upper limits yet determined.

NTUCMS Group

World Best Bound:
$t \to ch < 0.00073$

So, How "Steered"?

2017 was "a Good Year".

Explaining **BAU**

1705.05034 — Physics Letters B 776 (2018) 402–406

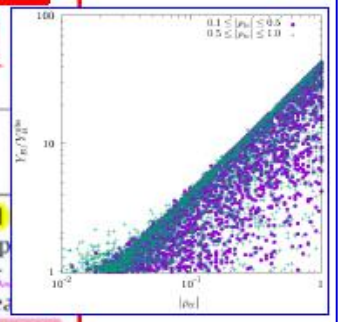
Electroweak baryogenesis driven by extra top Yukawa couplings

Kaori Fuyuto[a,*], Wei-Shu Hou[b], Eibun Senaha[c]

[a] Amherst Center for Fundamental Interactions, Department of Physics, University of Massachusetts Amherst, MA 01003, USA
[b] Department of Physics, National Taiwan University, Taipei 10617, Taiwan
[c] Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon 34051, Republic of Korea

EWBG Driven by $\lambda_t \mathrm{Im}\rho_{tt}$

Grand Motivation!



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Editor: M. Trodden

ABSTRACT

We study electroweak baryogenesis driven by the top quark in a general two Higgs doublet model flavor-changing Yukawa couplings, keeping the Higgs potential CP invariant. With Higgs sector coup and the additional top Yukawa coupling ρ_{tt} all of $\mathcal{O}(1)$, one naturally has sizable CP violation that the cosmic baryon asymmetry. Even if ρ_{tt} vanishes, the favor-changing coupling ρ_{tc} can still lea successful baryogenesis. Phenomenological consequences such as $t \to ch$, $\tau \to \mu\gamma$ electron electric dipole moment, $h \to \gamma\gamma$, and hhh coupling are discussed.

$\begin{pmatrix} H^+ \\ H + iA \end{pmatrix}$

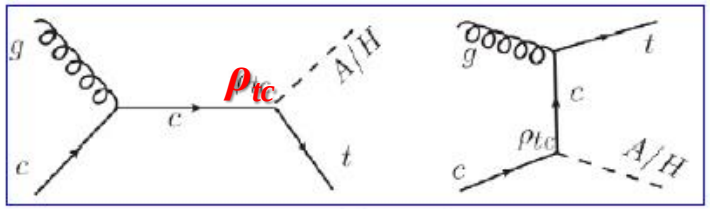
Fit for LHC

1706.07694 — Sub-TeV H, A, H^+ @ LHC; G2HDM well-hidden so far. — EPL 123 (2018) 11001

Production Processes

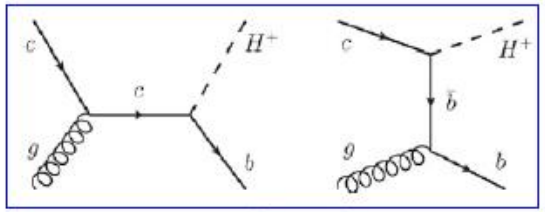
1710.07260

$cg \to tA/H \to tt\bar{c}, t\bar{t}\bar{t}$



PLB 776 (2018) 379-384

$cg \to bH^+ \to bt\bar{b}$



PRL 125 (2020) 221801

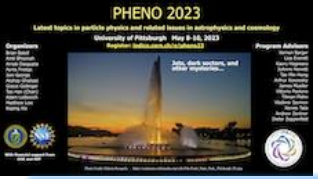
unsuppressed by alignment

ATLAS-CONF-2022-039 (ICHEP)

Search Started 2/2020.

Fruition 2023!

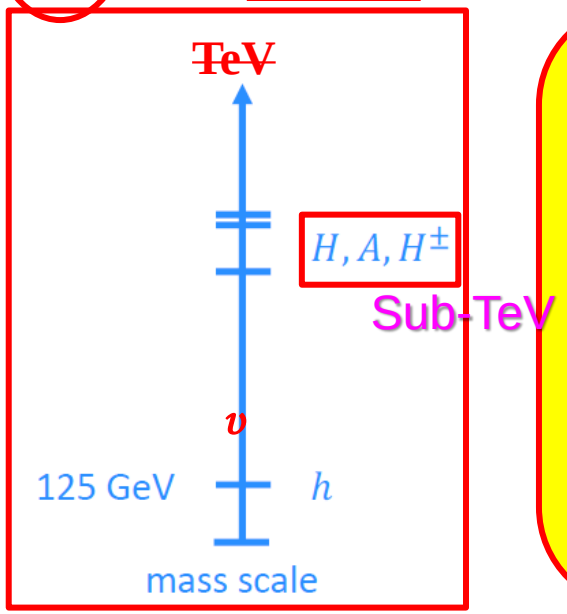
Can't tell you…



2nd ASP 8/2021 – 7/2026

Finite Chance for Discovery!

Extra Higgs Doublet w/
Extra Yukawa Couplings
& Extra Quartic Couplings

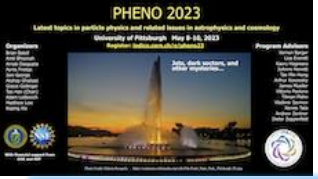


Decadal Mission of New Higgs/Flavor Era

54 extra flavor param.
& 7 add'l Higgs param.

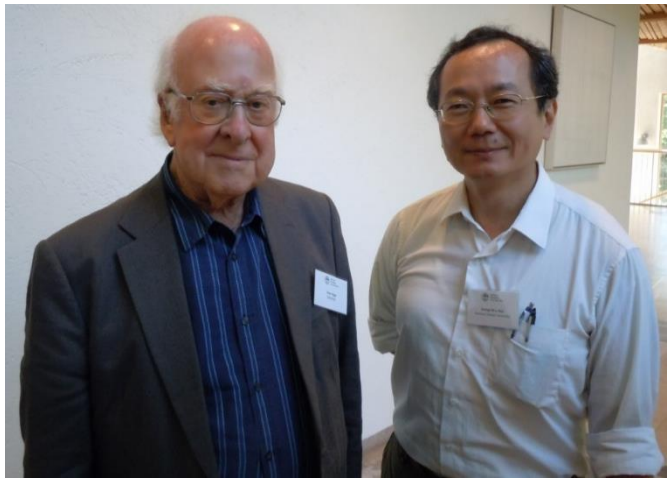
1. CMS: H, A, H^+ search @ LHC — Kai-Feng (Jack) Chen
2. Belle II: $\tau \to \mu\gamma$; $B \to \mu\nu, \tau\nu$; $\tau\tau, \tau\mu$ — Paoti Chang
   CMS: $B_{s,d} \to \mu\mu$
3. Lattice: Higgs Potential { 1st EWPT, Landau Pole } — David C.J. Lin (NYCU)
4. Steering: Pheno 粒子現象學

Wish us Luck!



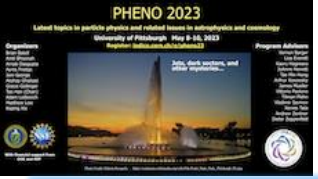
Up to *Nature* whether our "Wish for *Discovery*" is Granted … or Not …

Thank You!



a Higgs, and a 2nd Higgs …

Glimpse of coming New *Flavor* Era in G2HDM

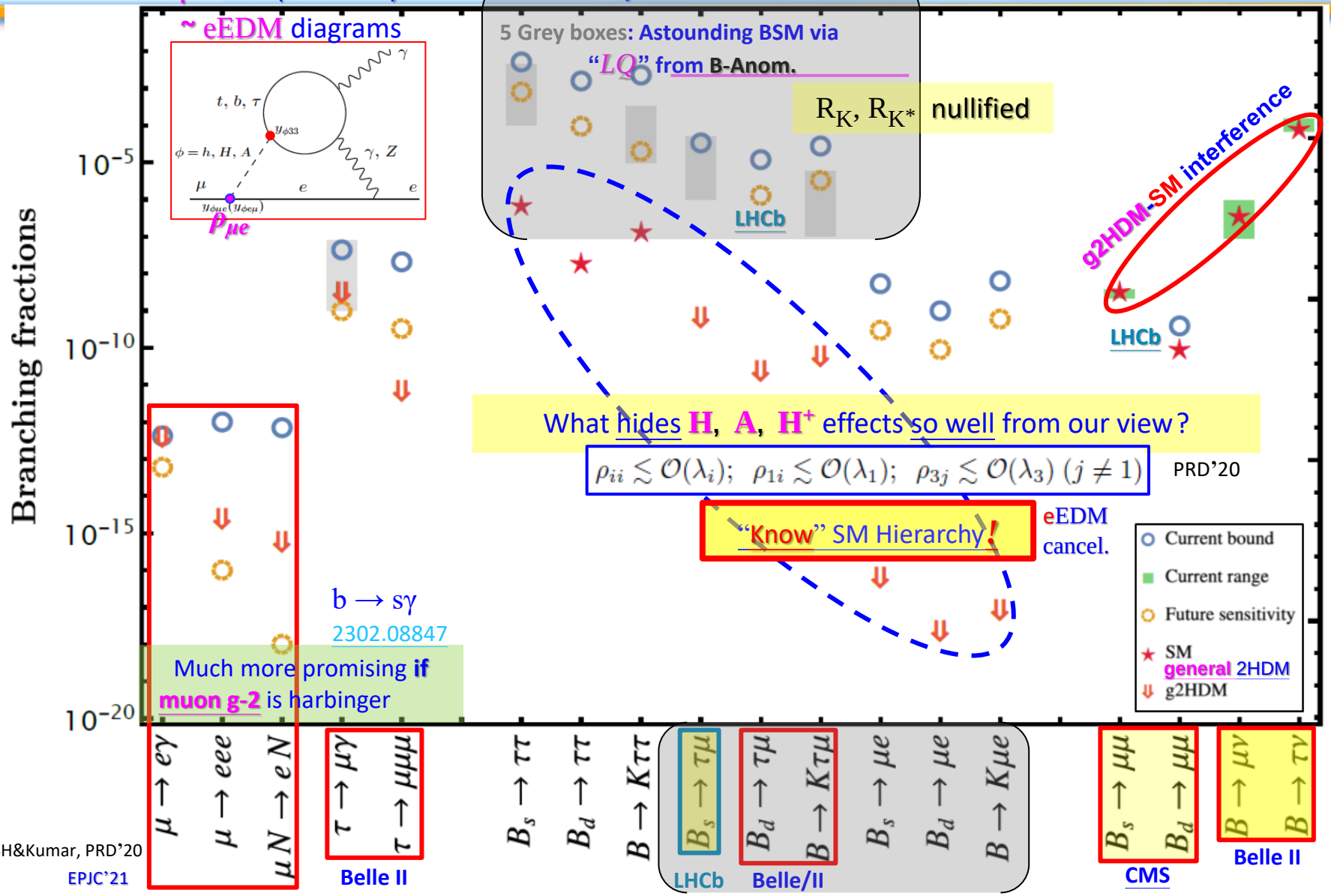


μ & τFV (Flav.Viol.)
~ eEDM diagrams

in B decay

5 Grey boxes: Astounding BSM via "*LQ*" from B-Anom.

R_K, R_{K^*} nullified



What hides **H**, **A**, **H⁺** effects so well from our view?

$$\rho_{ii} \lesssim \mathcal{O}(\lambda_i); \quad \rho_{1i} \lesssim \mathcal{O}(\lambda_1); \quad \rho_{3j} \lesssim \mathcal{O}(\lambda_3) \ (j \neq 1)$$

PRD'20

"Know" SM Hierarchy!

eEDM cancel.

$b \to s\gamma$
2302.08847

Much more promising **if** muon g-2 is harbinger

WSH&Kumar, PRD'20
EPJC'21