Karlsruher Institut für Technologie

Particle Physics Phenomenology after the Higgs Discovery

Project C3b: “New Physics models for flavour observables”

Robert Ziegler (KIT)

Annual meeting of the SFB TRR 257, Siegen 2020

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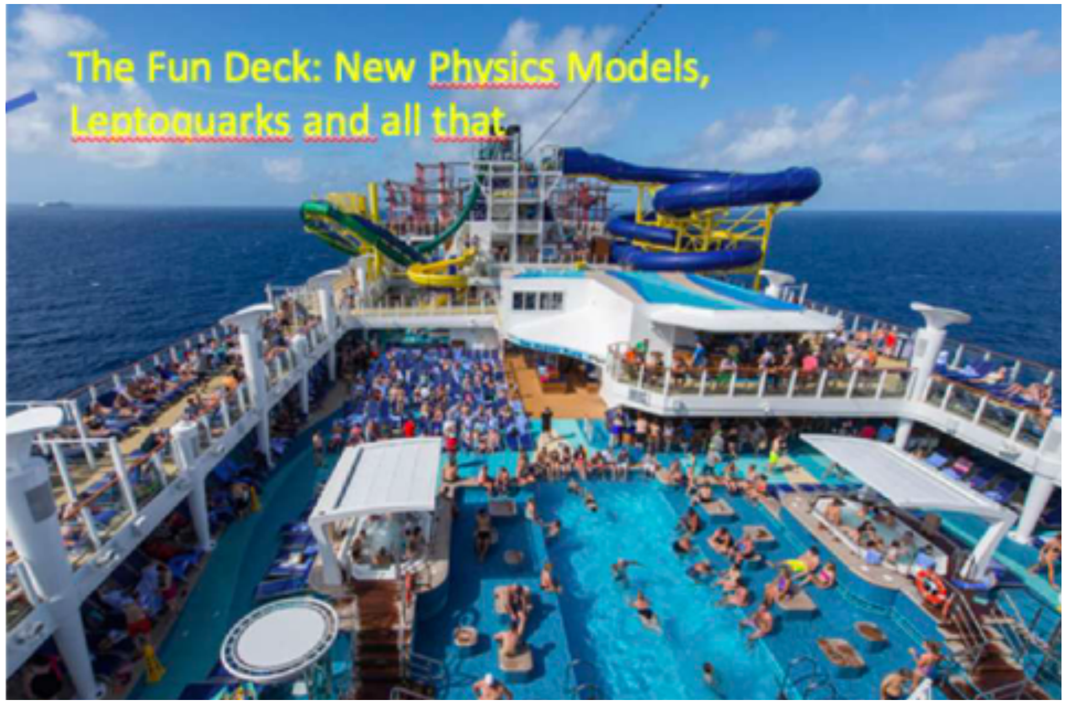
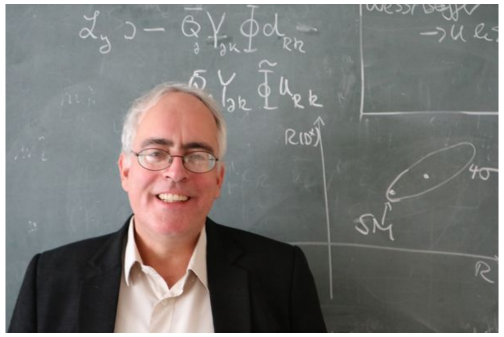


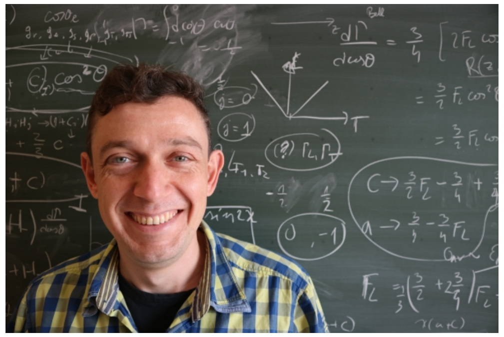
Mannel/Lenz

Annual meeting of the SFB TRR 257, Siegen 2020

People

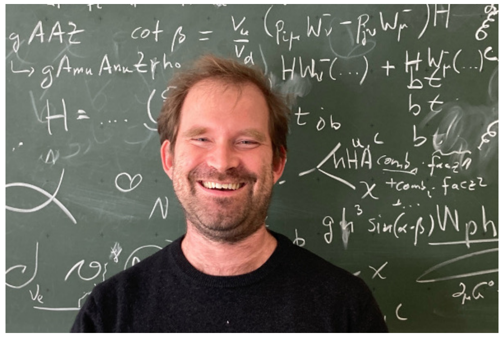


Ulrich Nierste (PI)

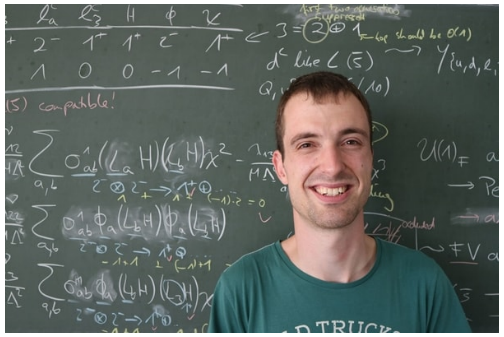


Wolfgang Hollik

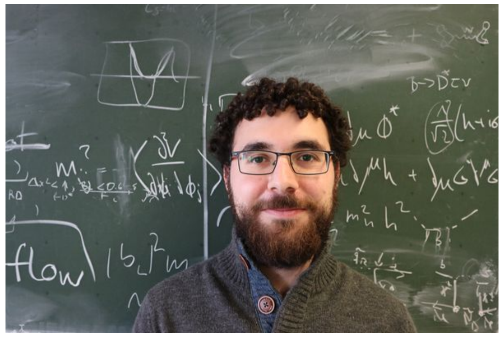
Ivan Nišandžić



Robert Ziegler

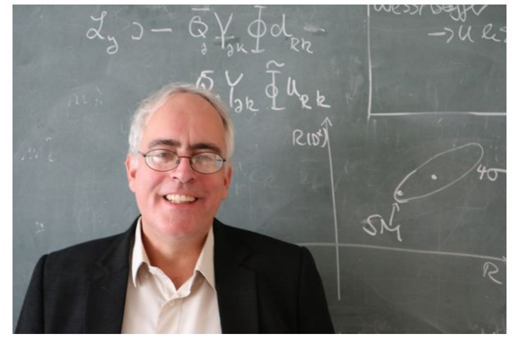


Matthias Linster



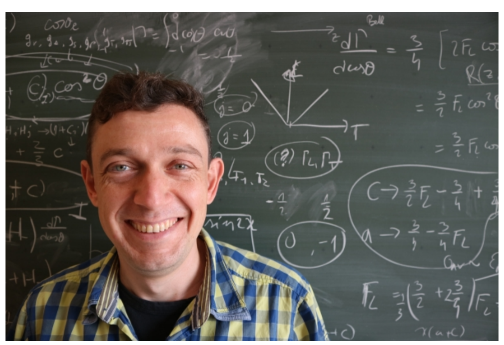
Mustafa Tabet

People



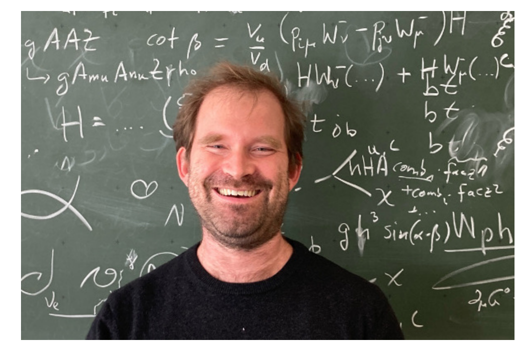
Ulrich Nierste (PI)

Zagreb U.

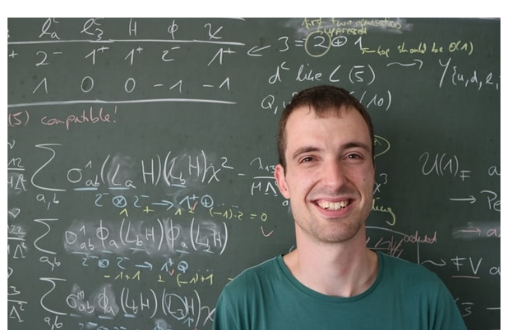


Wolfgang Hollik

Marco Fedele



Robert Ziegler



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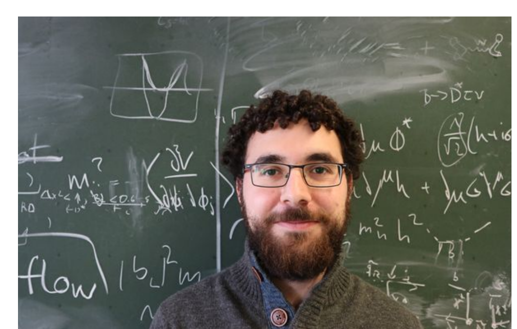


Mustafa Tabet

Papers

M. Blanke (KIT), A. Crivellin (PSI),
T. Kitahara (Technion), M. Moscati (KIT), U. Nierste (KIT)
Addendum to "Impact of polarization observables and $B_c \to \tau\nu$ on new physics explanations of the $b \to c\tau\nu$ anomaly"
arXiv:1905.08253

T. Deppisch, U. Nierste (KIT)
"Little hierarchies solve the little fine-tuning problem: a case study in supersymmetry with heavy guinos"
arXiv:1908.01222

U. Nierste, M. Tabet, R. Ziegler (KIT)
"Cornering Spontaneous CP Violation with Charged-Higgs Searches"
arXiv:1912.11501

W.G. Hollik, M. Linster, M. Tabet (KIT)
"A Study of New Physics Searches with Tritium and Similar Molecules"
arXiv:2004.11274

G. Barenboim (Valencia), U. Nierste (KIT)
"Modified majoron model for cosmological anomalies"
arXiv:2005.13280

M. Linster (KIT), J. Lopez-Pavon (Valencia), R. Ziegler (KIT)
"Neutrino Observables from a U(2) Flavor Symmetry"
arXiv:2009.10437

D. Bečirević (Orsay), M. Fedele (Barcelona),
I. Nišandžić (KIT), A. Tayduganov (Dortmund)
"Lepton Flavor Universality tests through angular observables of $\bar{B} \to D^{(*)}\ell\bar{\nu}$ decay modes"
arXiv:1907.02257

J. Albrecht, E. Stamou (Dortmund),
R. Ziegler (KIT), R. Zwicky (Edinburgh)
"Probing flavoured Axions in the Tail of Probing flavoured Axions in the Tail of $B_q \to \mu^+ \mu^-$"
arXiv:1911.05018

J. Martin Camalich (Tenerife), M. Pospelov (Minnesota),
H.Vuong (Grenoble), R. Ziegler (KIT), J. Zupan (Cincinnati)
"Quark Flavor Phenomenology of the QCD Axion"
arXiv:2002.04623

R. Ziegler (KIT), J. Zupan (Cincinnati),
R. Zwicky (Edinburgh)
"Three Exceptions to the Grossman-Nir Bound"
arXiv:2005.00451

L. Calibbi (Nankai), D. Redigolo (CERN),
R. Ziegler (KIT), J. Zupan (Cincinnati)
"Looking forward to Lepton-flavor-violating ALPs"
arXiv: 2006.04795

Outline

I will talk about two papers on

"Flavor phenomenology of extended scalar sectors"

Part I

(ultra-light pseudoscalar)

J. Martin Camalich, M. Pospelov, H. Vuong, RZ, J. Zupan

"Quark Flavor Phenomenology of the QCD Axion"

Phys.Rev.D 102 (2020) 1, 015023

Part II

(heavy charged Higgs)

U. Nierste, M. Tabet, RZ

"Cornering Spontaneous CP Violation with Charged-Higgs Searches"

Phys.Rev.Lett. 125 (2020) 3, 031801

Part I

J. Martin Camalich, M. Pospelov,
H. Vuong, RZ, J. Zupan

“Quark Flavor Phenomenology of the QCD Axion”

Phys.Rev.D 102 (2020) 1, 015023

The QCD Axion

- ★ Motivated by **strong CP Problem** & Vanilla **Dark Matter** candidate

- ★ **Single scale** suppresses interactions $(\propto 1/f_a)$ and sets mass $(\propto m_\pi^2/f_a)$

- ★ Practically **massless and stable** (need $f_a > 10^7\mathrm{GeV} \Longleftrightarrow m_a < 1\mathrm{eV}$)

- ★ Can be searched for with

  - ✳ Astrophysics (star cooling via axion emission)

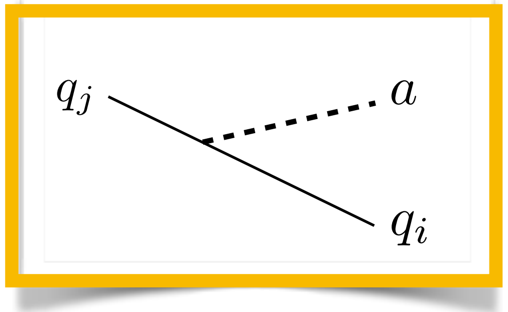
  - ✳ Microwave cavities (conversion to photons)

  - ✳ **Flavor physics (rare decays with missing energy)**

Flavor-violating Axion Couplings

- Most general axion couplings to fermions are flavor-violating

$$\mathcal{L}_{\rm eff} = \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C^V_{ij} + C^A_{ij}\gamma_5)\, f_j$$



- Present whenever axion sector has new sources of flavor violation

possibly connected to origin of SM flavor hierarchies, e.g. Wilczek '82

- Need to constrain **8 independent** flavor-violating quark couplings
  - ✦ 2-body meson decays $K \to \pi a, B \to K a, D \to \pi a, B \to K^* a, \ldots$
  - ✦ 2-body baryon decays $\Lambda \to n a, \Lambda_b \to n a, \ldots$
  - ✦ Neutral meson mixing — typically much less constraining than meson decays

- Same signature as SM decays with neutrino pair $K \to \pi \nu\bar{\nu}, B \to K \nu\bar{\nu}, \ldots$

Light vs. Heavy New Physics

Looking for 2-body decays gives **sensitivity to much higher NP scales** than looking for deviations from SM in 3-body decays

$B \to K a$	$B \to K \nu \overline{\nu}$
$\frac{\partial_\mu a}{f_a} \bar{b} \gamma^\mu s$	$\frac{1}{\Lambda^2} \left(\bar{b} \gamma^\mu s\right) \left(\overline{\nu} \gamma_\mu \nu\right)$
↓ $\Gamma \propto M_B^3 / f_a^2$	↓ $\Gamma \propto M_B^5 / \Lambda^4$
$f_a \gtrsim 3 \times 10^5\,\mathrm{TeV}$	$\Lambda \gtrsim 10\,\mathrm{TeV}$

(moreover heavy NP typically stronger constrained by mixing than decays)

Constraints on Meson Decays

- Experimental bounds often old/non-existent

  e.g. no bound in literature on $D^+ \to \pi^+ a, B \to K^* a, B \to \rho a$

- Need to recast available data for SM decays pairs in 2-body region

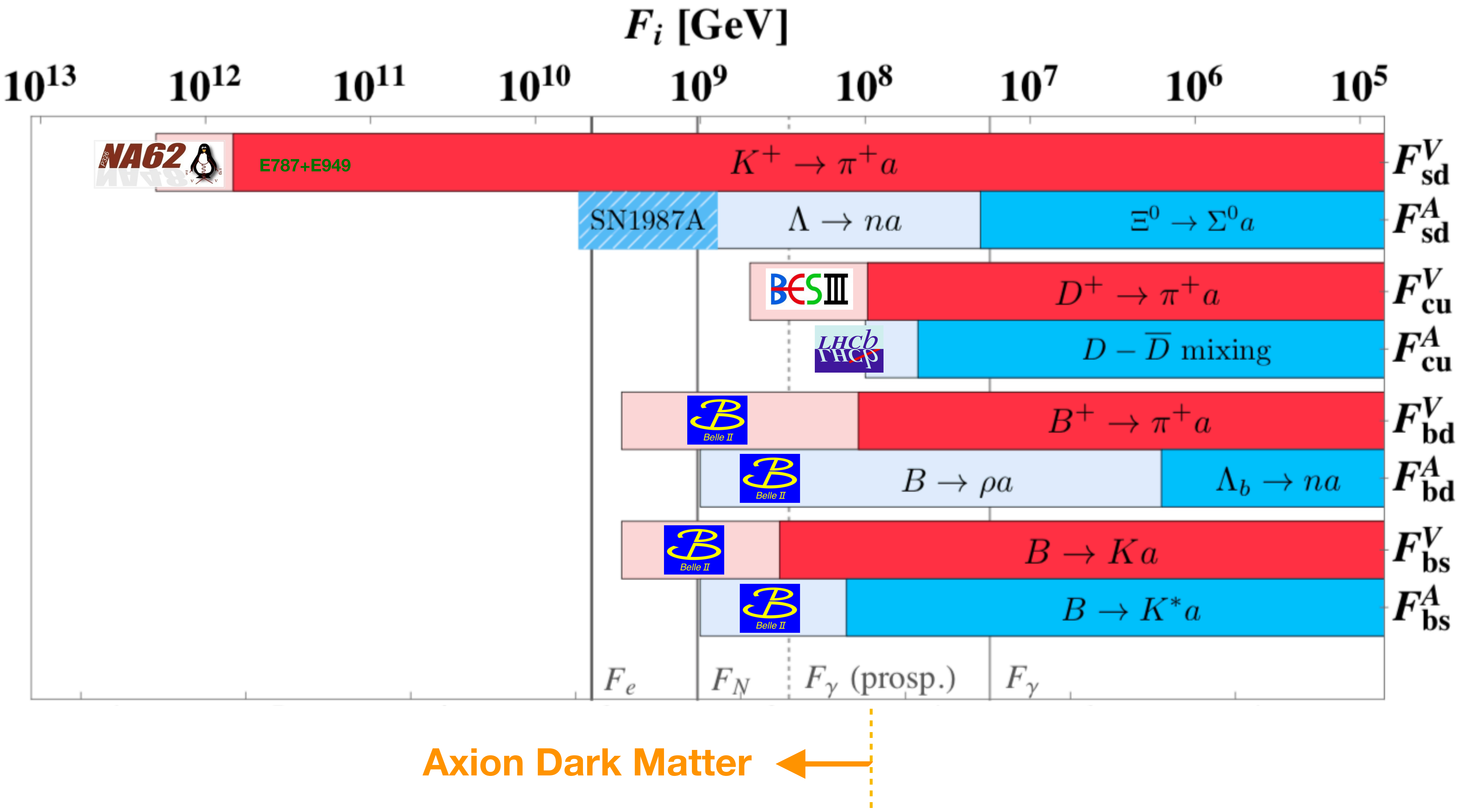
		$K^+ \to \pi^+ a$	$D^+ \to \pi^+ a$	$B^+ \to \pi^+ a$	$B^+ \to K^+ a$	
	Decay	sd	cu	bd	bs	
$\propto C^V_{ij}$	$\text{BR}(P_1 \to P_2 + a)$	7.3×10^{-11} [85] BNL	no analysis	4.9×10^{-5} [86]	4.9×10^{-5} [86]	CLEO
	$\text{BR}(P_1 \to P_2 + a)_{\text{recast}}$	no need	8.0×10^{-6} [87]	2.3×10^{-5} [88]	7.1×10^{-6} [89]	BaBar
	$\text{BR}(P_1 \to P_2 + \nu\bar{\nu})$	$1.47^{+1.30}_{-0.89} \times 10^{-10}$ [85]	no analysis	0.8×10^{-5} [90]	1.6×10^{-5} [90]	Belle
$\propto C^A_{ij}$	$\text{BR}(P_1 \to V_2 + a)$	[redacted]		no analysis	no analysis	
	$\text{BR}(P_1 \to V_2 + a)_{\text{recast}}$			no data	5.3×10^{-5} [89]	BaBar
	$\text{BR}(P_1 \to V_2 + \nu\bar{\nu})$			2.8×10^{-5} [90]	2.7×10^{-5} [90]	Belle
				$B \to \rho a$	$B \to K^* a$	

✳ best data on B-decays from Belle, but do not allow for 2-body recast

e.g. in 1303.3719 2-body region cut out to reject bg from radiative decays

✳ took BaBar data to get bounds for $B \to (\pi/K/K^*)a$

Present Constraints & Prospects



Martin Camalich, Pospelov, RZ, Vuong, Zupan '20

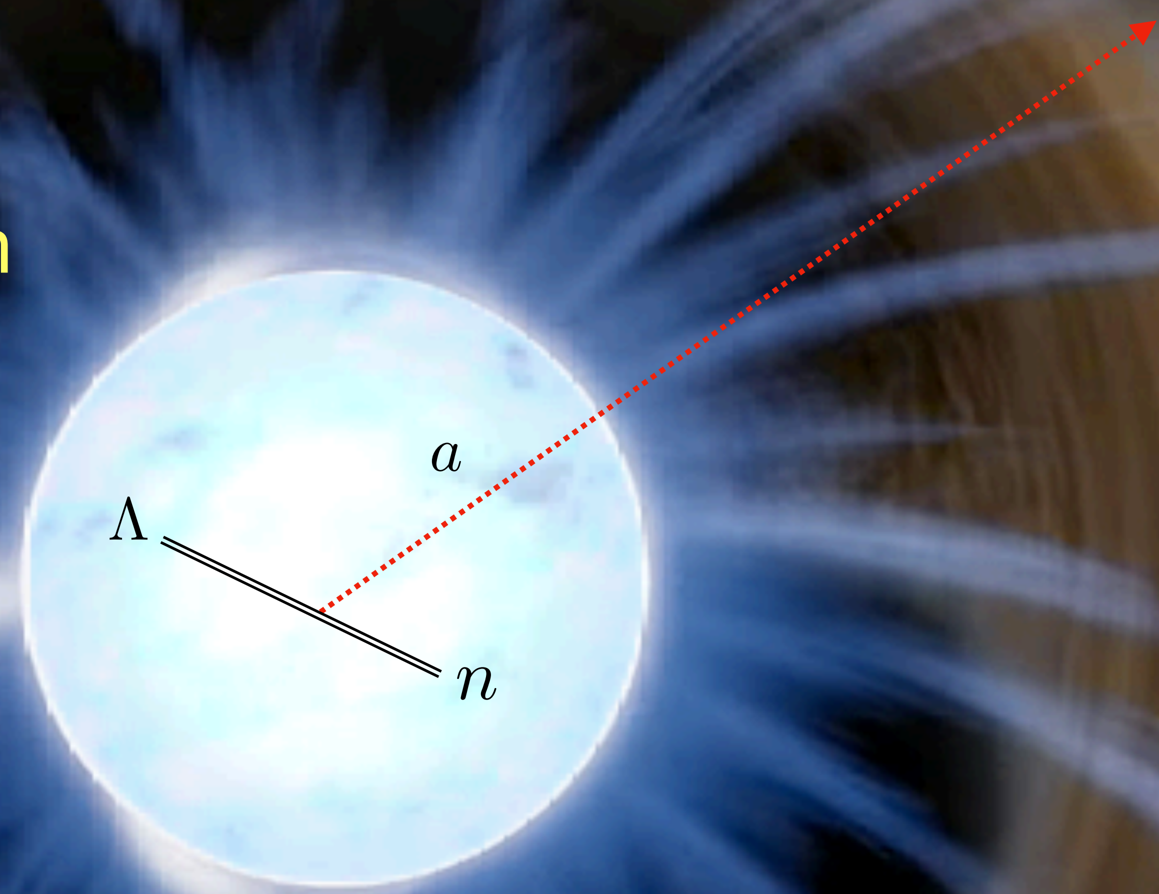
SN1987A constraints Hyperon Decays

Best handle on axial-vector coupling to s-d from hyperon decays

Many hyperons in hot neutron star formed few seconds after SN explosion [T ≈ 30 MeV]

Hyperon decays to axions provide effective cooling mechanism for SN1987A

$$Q \simeq n_n (m_\Lambda - m_n) \Gamma(\Lambda \to n a)\; e^{-\frac{m_\Lambda - m_n}{T}}$$



Gives strongest bound on invisible hyperon decays! $(\mathrm{BR} \lesssim 10^{-8}, \mathrm{BR}_{\mathrm{lab}} \lesssim 10^{-2})$

Part II

U. Nierste, M. Tabet, RZ

"Cornering Spontaneous CP Violation with Charged-Higgs Searches"

Phys.Rev.Lett. 125 (2020) 3, 031801

+ work in progress with N. Desai, U. Nierste & M. Tabet

Spontaneous CP Violation

- ★ In 1964 existence of CPV established by observing $K_L \to \pi\pi$
- ★ In 1973 two theoretical landmark papers:

M. Kobayashi & T. Maskawa:

can have **explicit CPV** with **3rd fermion** generation

T.D. Lee:

can have **spontaneous CPV** with **2nd scalar** doublet

- ★ Today we have discovered 3rd generation & established CKM mechanism, but origin of CPV still unclear! Complex fermion mass matrices could be due to real Yukawas + complex Higgs VEV
- ★ We studied this possibility in the most general 2HDM: SPCV implies **stringent upper bounds on new Higgs states with flavor-violating couplings**: nevertheless model is alive!

Setup: Higgs Sector

- General CP conserving 2HDM potential

$$
\begin{aligned}
V = {} & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - (m_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.}) \\
& + \frac{\lambda_1}{2} (\phi_1^\dagger \phi_1)^2 + \frac{\lambda_2}{2} (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \\
& + \left[\phi_1^\dagger \phi_2 \left(\frac{\lambda_5}{2} \phi_1^\dagger \phi_2 + \lambda_6 (\phi_1^\dagger \phi_1) + \lambda_7 (\phi_2^\dagger \phi_2) \right) + \text{h.c.} \right],
\end{aligned}
$$

…has for suitable choice of parameters global CPV minimum

$$
\langle \phi_1 \rangle = \begin{pmatrix} 0 \\ v c_\beta \end{pmatrix}, \qquad \langle \phi_2 \rangle = \begin{pmatrix} 0 \\ v s_\beta \mathrm{e}^{i\xi} \end{pmatrix}
$$

- 3 minimization equations: 3 mass scales fixed in terms of EW scale!

Perturbativity gives **stringent upper bounds on all Higgs masses**

$$
m_{H^\pm} \lesssim 435\,\mathrm{GeV}, \qquad m_{H_2} \lesssim 485\,\mathrm{GeV}, \qquad m_{H_3} \lesssim 545\,\mathrm{GeV}
$$

Setup: Yukawa Sector

- General CP conserving 2HDM Yukawa couplings

$$\mathcal{L}_{\rm yuk} = -\overline{Q}_L \left(Y_{u1}\tilde{\phi}_1 + Y_{u2}\tilde{\phi}_2\right) u_R - \overline{Q}_L \left(Y_{d1}\phi_1 + Y_{d2}\phi_2\right) d_R + \text{h.c.}$$

- Quark masses are only complex if phase from Higgs VEV is physical

$$\frac{M_u}{v} = Y_{u1} c_\beta + Y_{u2} e^{-i\xi} s_\beta \,, \quad \frac{M_d}{v} = Y_{d1} c_\beta + Y_{d2} e^{i\xi} s_\beta$$

…**necessarily implies flavor violation** (u and/or d) $Y_{q1} Y_{q2}^T - Y_{q2} Y_{q1}^T \neq 0$

- We want to study the most general, realistic scenario: a priori huge parameter space, but largely ruled out by FCNC constraints

- **Shortcut to viable region**: avoid d-sector FCNCs by setting $Y_{d2} = 0$

Phenomenology

★ Parameter space is still huge

- 3 heavy Higgs masses: $m_{H^\pm}, m_{H_2}, m_{H_3}$
- 3 neutral Higgs mixing angles
- 2 vacuum angles: β, ξ
- 3 angles + 6 phases parametrizing Higgs couplings

  [$M_u = V_{\rm CKM}^\dagger m_u^{\rm diag} V_R^\dagger \to Y_{u1}, Y_{u2}$ can be parametrized by unitary matrix]

★ Parameter space is strongly constrained by precision observables like EDMs, neutral meson mixing, $b \to s\gamma$, etc., but not sufficient to rule out scenario entirely!

★ Similar for constraints from direct searches, but interesting future potential for charged Higgs searches

Charged Higgs Phenomenology

- Get sum rule for charged Higgs couplings to b-quarks

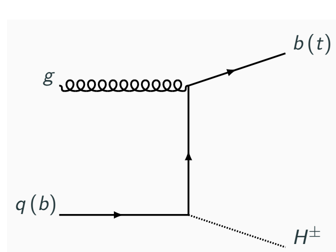
$$\mathcal{L} \supset H^+ \overline{u}_{iR} \Gamma^{RL}_{u_i b} b_L$$

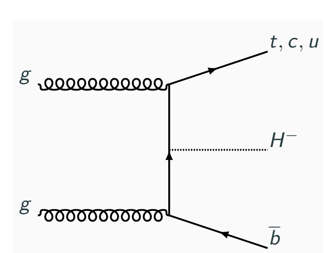
$$\sum_{i=u,c,t} |\Gamma^{RL}_{ib}|^2 = \frac{m_t^2}{v^2} + \frac{2m_t}{v s_{2\beta}} \left(c^2_{2\beta} \mathrm{Re}\Gamma^{RL}_{tb} - \frac{\mathrm{Im}\Gamma^{RL}_{tb}}{t_\xi} \right) + \mathcal{O}\left(|V_{cb}| \frac{m_c}{m_t} \right)$$

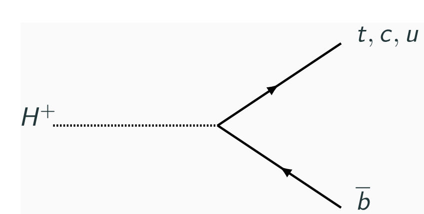
- Combination with perturbativity gives lower bound on charged Higgs couplings

$$\max\{|\Gamma^{RL}_{ub}|, |\Gamma^{RL}_{cb}|, |\Gamma^{RL}_{tb}|\} \geq 0.20$$

- Couplings to charged leptons are small: quark couplings dominate charged Higgs production and decay at LHC







Flavored Charged Higgs Phenomenolgy

Categorize phenomenology according to dominant channels: **qb-q'b**

production decay

- **tb-tb:** The standard search, ATLAS and CMS exclude signal strengths above O(1 pb) in relevant mass range; still can have viable BM point with charged Higgs mass = 180 GeV

- **cb-cb:** **"**Can only use low-mass dijet searches, not sensitive yet below charged Higgs masses < 450 GeV." Gori, Grojean, Juste, Paul '18

  Signal strengths as large as 1 nb are not excluded!?

- **cb-tb:** "Associated c- and b-jets typically too soft, can use only searches for tb resonances, but presently not available below 1TeV"

  Gori, Grojean, Juste, Paul '18

  "Discovery potential in signal region with 3b,1l,MET and optimized cuts for charged Higgs masses 300-500 GeV" Ghosh, Hou, Modak '19

work in progress…

Summary

- ★ The QCD axion can have large flavor-violating couplings and would contribute to 2-body meson decays with missing energy
- ★ Interesting exp. target because can probe much higher NP scales than deviations from SM 3-body decays (constraints from meson mixing much weaker)
- ★ Full data set of Belle II could provide bounds of order 10^9 GeV on effective axion coupling
- ★ Spontanous CPV in 2HDM is alive despite stringent upper bounds on heavy Higgs states with flavor-violating couplings
- ★ Surviving parameter space might be explored with new searches for charged Higgs with large ub/cb couplings