Flavors of future surprises?

(Embrace unpredictability)

Zoltan Ligeti and Clara Murgui

New Physics from Precision at High Energies

March 8 – May 21, 2021

April 13, 2021

Preliminaries...

- Asked to give "a general overview of upcoming prospects at LHCb and Belle II, ... anomalies but we're more interested in general prospects"

- Many reviews of key measurements, sensitivities, discovery and exclusion limits:

  – "Physics case for an LHCb Upgrade II" [1808.08865]
  – "EoI for Phase-II LHCb Upgrade," LHCC-2017-003

  – B2TIP workshop report (Belle II Physics Book) [arXiv:1808.10567]
  – "Impact of Belle II on flavor physics," BELLE2-NOTE-0021

- If you like impressive large tables of sensitivity projections, this talk will disappoint

  (Very significant improvements shown in the links above!)

- Experiments have the potential to discover unpredictable things; manifestations of NP may be unexpected, with more imagination we may find signals soon

Outline

- ZL:

  Some past surprises

  Future improvements, some extrapolations, possible directions

  Many areas connected to flavor, left for discussions: higgs, charm, top, EDMs

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- Clara Murgui:

  Two exciting avenues

  Bottom-up: EFT perspective on $b \to c$ anomaly, prospects & implications

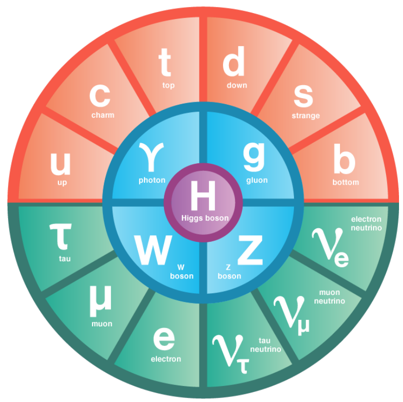
  Top-down: Observable predictions from quark-lepton unification

- Please interrupt with any questions or comments. I mean it! (Can't see raised hands)

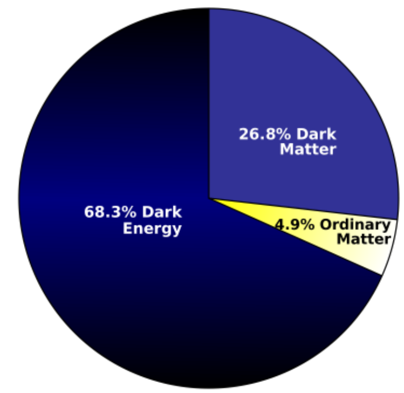
What is particle physics?

- What are the elementary interactions and degrees of freedom?

- Standard Model of particle physics:



Standard Model of cosmology:



- Inconsistent: Two very successful theories, but this cannot be the full story
  - Dark matter
  - Baryon asymmetry
  - Neutrino mass

- Michelson 1894: "... it seems probable that most of the grand underlying principles have been firmly established ..."

  Before 2012, 30-year "anomaly": certainty that LHC would say something about electroweak symmetry breaking

Why is CP violation interesting?

- SM cannot explain baryon asymmetry
  - Electroweak baryogenesis? (testable at LHC?)
  - Leptogenesis? (connection to neutrinos?)
  - Something else? E.g., B-mesogenesis? [1810.00880, 2101.02706]
- SM: one CP violating parameter in quark sector

  (Neglecting strong CP phase, negligible in flavor changing processes)
  - Many predictions, correlations, zeros
  - Stringent tests of the standard model
- NP: many sources of CP violation (CPV) possible
  - Higgs, neutral currents, new sectors

CP violation involving known particles: 2, 3, 5?

- Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$ — param's (CPV)

  8 gluons $\quad W^\pm$, Z^0, γ — $3\ (+\theta_{\rm QCD})$

- Particle content: 3 generations of quarks and leptons

  $Q_L(3,2)_{1/6},\ u_R(3,1)_{2/3},\ d_R(3,1)_{-1/3}$ — $10\ (1)$

  $L_L(1,2)_{-1/2},\ \ell_R(1,1)_{-1}$ — $12\ (3)$ or $10\ (1)$

  quarks: $\begin{pmatrix} u & c & t \\ d & s & b \end{pmatrix}$ leptons: $\begin{pmatrix} \nu_1 & \nu_2 & \nu_3 \\ e & \mu & \tau \end{pmatrix}$

- Symmetry breaking: $SU(2)_L \times U(1)_Y \ \to\ U(1)_{\rm EM}$

  $\phi(1,2)_{1/2}$ Higgs, with vev: $\langle\phi\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$ — $2\ (0)$

Not known: $\mathcal{L}_Y = -Y_e^{ij}\, \overline{L^I_{Li}}\, \phi\, e^I_{Rj} - \begin{cases} \frac{Y_\nu^{ij}}{\Lambda}\, L^I_{Li} L^I_{Lj}\, \phi\, \phi & \text{violates lepton number} \\ Y_\nu^{ij}\, \overline{L^I_{Li}}\, \tilde\phi\, \nu^I_{Rj} & \text{requires } \nu_R \text{ fields} \end{cases}$

- We do not know what is the Lagrangian that describes the observed particles!

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Brief history of CP violation

- 1964 – 1999: CP violation discovered in K decay, "ϵ" [fitted w/ CKM phase, not a test]
- 1999: second CP violation measured in kaons, "ϵ'/ϵ" [notoriously hard to calculate]
- 1999 – 2010:
  e^+e^- B-factories, BABAR and Belle, measured dozens of CPV observables
- 2009 – 2019:
  LHCb: improvements + CP violation in B_s decays with comparable precision
- 2019:
  LHCb: discovery of CP violation in D meson decay $(A_{K^+K^-} - A_{\pi^+\pi^-})$
- One CP violating parameter (KM phase) can account for it all so far
- CP violation in itself is no longer automatically interesting, only if sensitive to NP

1964: CP violation was a surprise

- History can differ from what may seem “obvious” later:

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

- Must be a new interaction:

VIOLATION OF CP INVARIANCE AND THE POSSIBILITY OF VERY WEAK INTERACTIONS*

L. Wolfenstein
Carnegie Institute of Technology, Pittsburgh, Pennsylvania
(Received 31 August 1964)

- After 8 years:

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

The experimental proposal

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

⇒ Cronin & Fitch, Nobel Prize, 1980

⇒ 3 generations, Kobayashi & Maskawa, Nobel Prize, 2008

A near miss: factor-of-2 improvements matter

ANNALS OF PHYSICS: 5, 156–181 (1958)

Long-lived Neutral K Mesons*

M. Bardon, K. Lande, and L. M. Lederman

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

and

William Chinowsky

Brookhaven National Laboratories, Upton, New York

set an upper limit $<0.6\,\%$ on the reactions

$$K_2^0 \to \begin{cases} \mu^{\pm} + e^{\mp} \\ e^{+} + e^{-} \\ \mu^{+} + \mu^{-} \end{cases}$$

and on $K_2^0 \to \pi^+ + \pi^-$.

Volume 6, Number 10 PHYSICAL REVIEW LETTERS May 15, 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov

Joint Institute of Nuclear Research, Moscow, U.S.S.R.

(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3 % for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our

"At that stage the search was terminated by administration of the Lab."

[Okun, hep-ph/0112031]

Volume 13, Number 4 PHYSICAL REVIEW LETTERS 27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§

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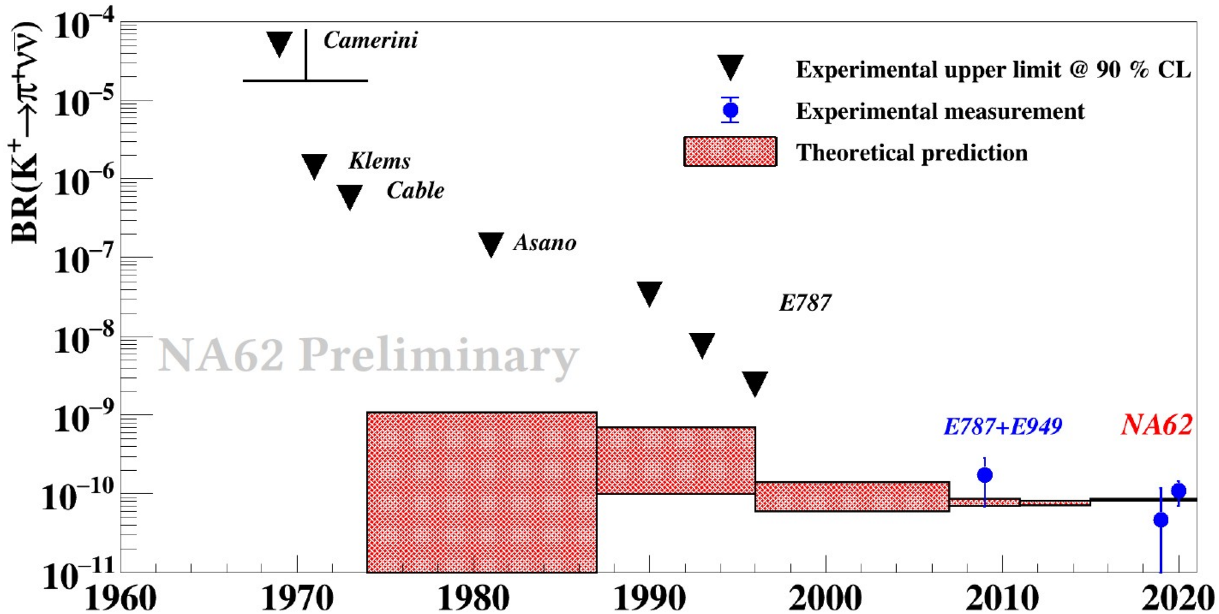
We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \to \pi^+ + \pi^-)/(K_2^0 \to \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As empha-

The quest for $K \to \pi\nu\bar{\nu}$

- Theoretically clean: $K_L \to \pi^0\nu\bar{\nu}$ is CP violating, $K^+ \to \pi^+\nu\bar{\nu}$ is dominantly so

  50 years of searches, sensitivity $\mathcal{O}(100\,\text{TeV})$ ("waiting longer than for Higgs" — Mary K Gaillard)



- NA62: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.6} \pm 0.9) \times 10^{-11}$ — at SM level [2103.15389]
- KOTO: 4 $K_L \to \pi^0\nu\bar{\nu}$ events in 2019; then $4 \to 3$, w/ 1.22 ± 0.26 BG [2012.07571]
- Exciting prospects, plenty of room for new physics

Past surprises exploring b quarks

- 1977: Υ discovery — after $6\,\mathrm{GeV}$ "Oops-Leon" in 1976 [Lederman et al. @ Fermilab]

- 1983: Long B meson lifetime $\Rightarrow |V_{cb}|$ is small [MAC & Mark II @ SLAC]

  If $|V_{cb}| \sim |V_{us}|$, no time dependent measurements, no B factories...

- 1987: $B^0 - \overline{B}^0$ mixing discovered, ARGUS [PLB 192 (1987) 245]

  $$r = 0.21 \pm 0.08 = \text{(decay, after mixing)}\big/\text{(decay, no mixing)}$$

  Few months earlier, CLEO: $r < 0.24\ \ (90\%\,\mathrm{CL})$ [PRL 58 (1987) 183]

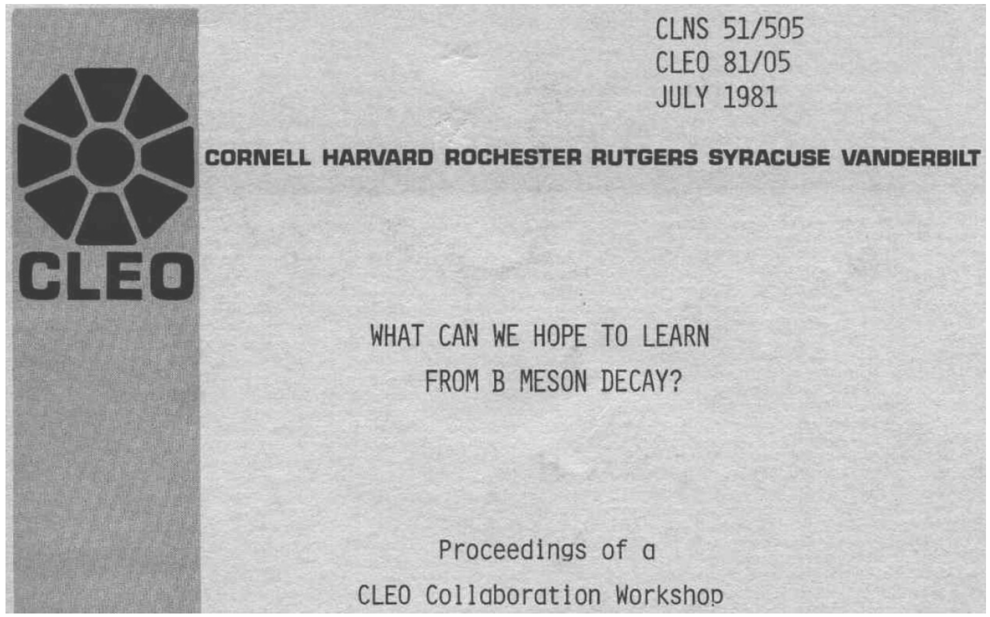
  (Then 2 more years to confirm ARGUS — can be rather different to set limits vs. observe signals)

  Implied: $m_t > m_W$ (bound was $23\,\mathrm{GeV}$) $\Rightarrow$ no top hadrons, maximal B_s mixing

  $\Rightarrow$ SM predicts large CP violation, and large FCNC B decay rates

- All above required to be able to test KM mechanism of CP violation at B factories

Prospects in 1981



CLNS 51/505
CLEO 81/05
JULY 1981

CLEO

CORNELL HARVARD ROCHESTER RUTGERS SYRACUSE VANDERBILT

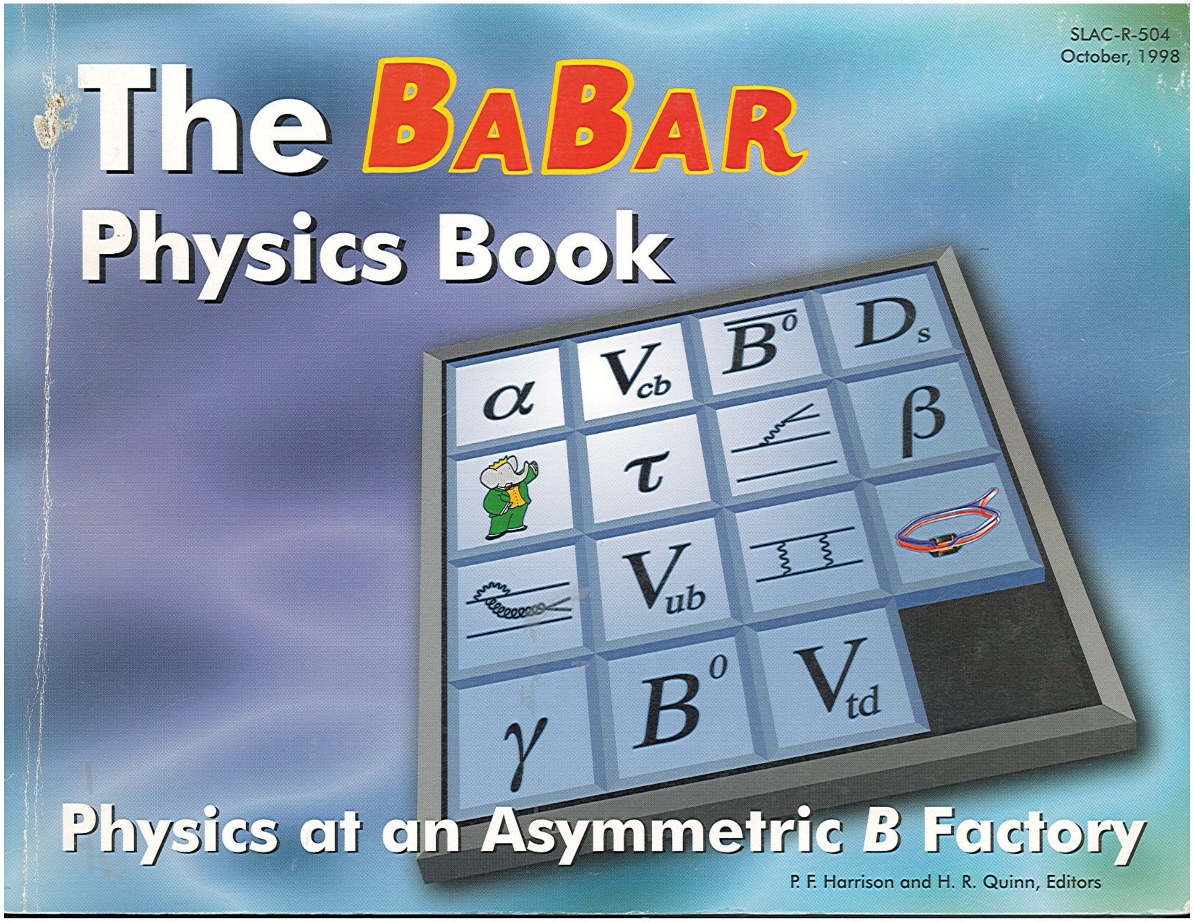
WHAT CAN WE HOPE TO LEARN
FROM B MESON DECAY?

Proceedings of a
CLEO Collaboration Workshop

"... the nature of CP violation. This violation, observed so far only in K^0 decays, must show up some other place. Our theoretical advice is that the size of the effects expected in B decays is very small, unobservably small."

"Where are the Higgs'? Nobody knows. If they are in the 5–10 GeV range, there will be observable effects in B decay."

BaBar and Belle: testing CP violation



- No executive summary, no list of killer apps, no gold-plated measurements...

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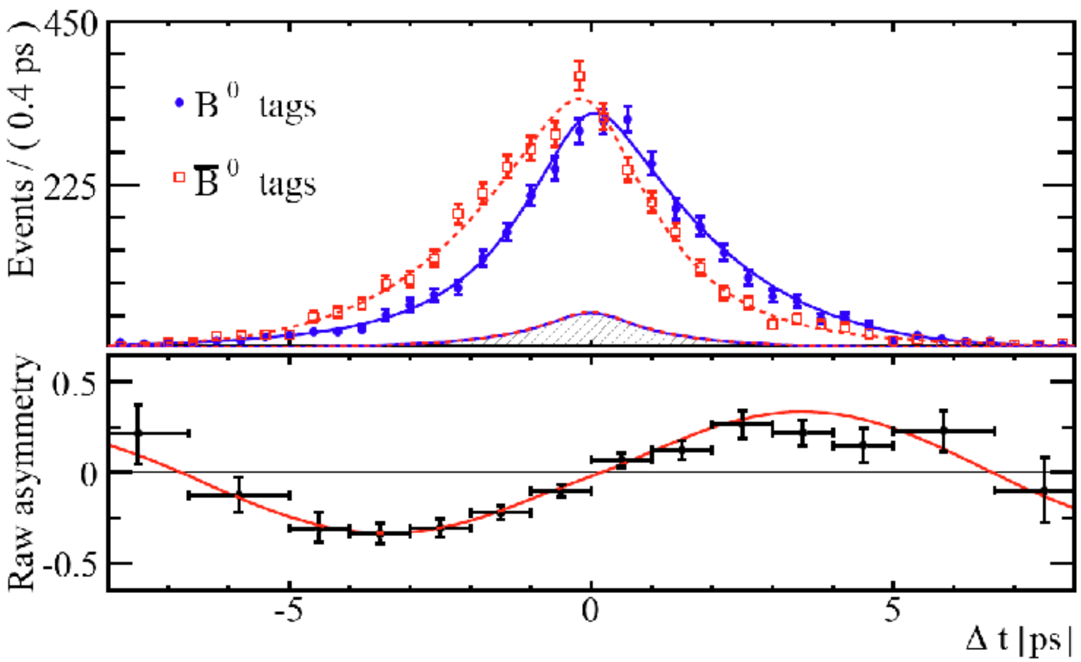
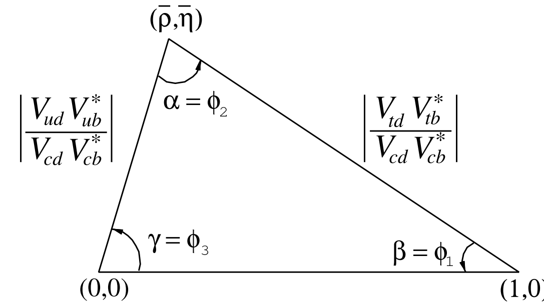
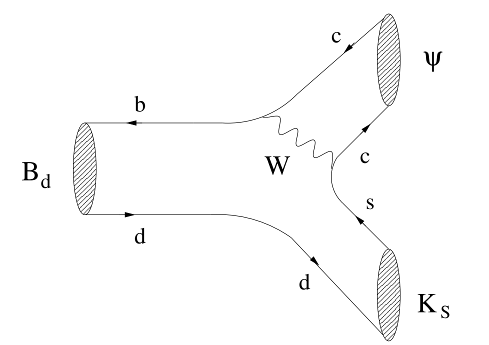
CP violation in $B \to \psi K_S$ by the naked eye

- CP violation is an $\mathcal{O}(1)$ effect: $\sin 2\beta = 0.699 \pm 0.017$

$$a_{f_{CP}} = \frac{\Gamma[\overline{B}^0(t) \to \psi K] - \Gamma[B^0(t) \to \psi K]}{\Gamma[\overline{B}^0(t) \to \psi K] + \Gamma[B^0(t) \to \psi K]} = \sin 2\beta \, \sin(\Delta m \, t)$$



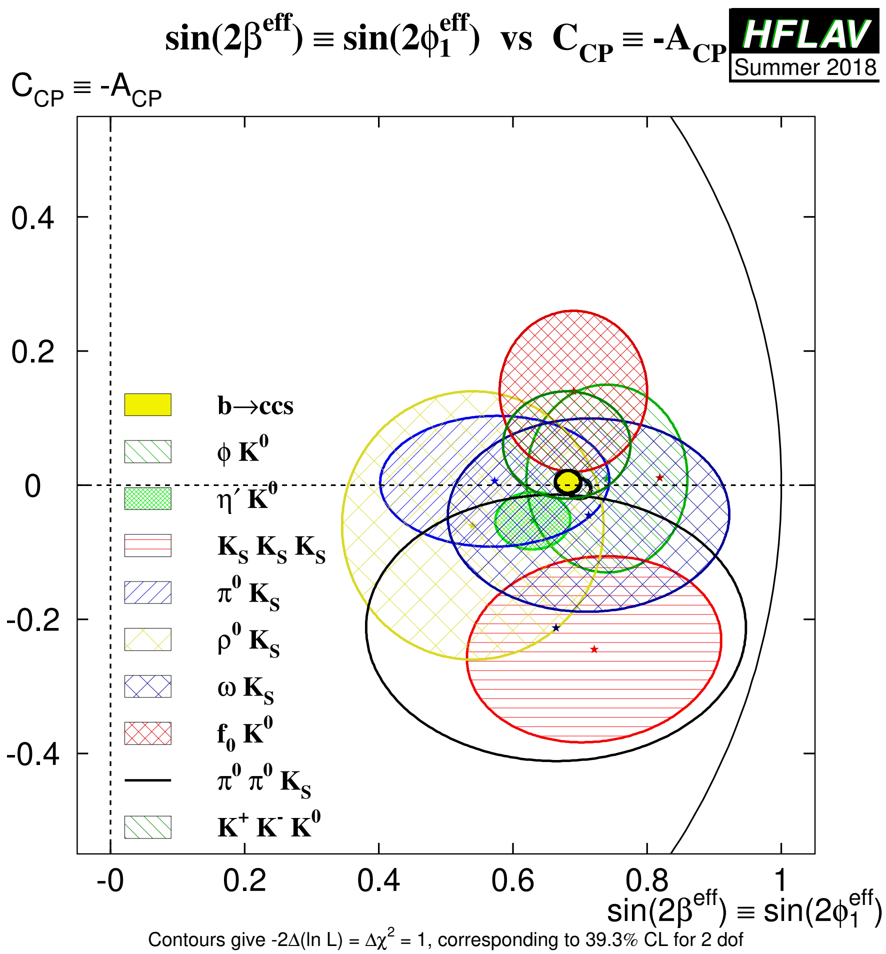




- CP violation in K decays is small because of small CKM elements, not because CP violation is generically small — it is $\mathcal{O}(1)$ in numerous B decays

CPV in $b \to s\bar{s}s$ "penguin" decays

- Many modes, close to $S_{\psi K}$ in SM; recall earlier $(2-4)\sigma$ tensions, e.g., $S_{\phi K}$, $S_{\eta' K}$



Probe NP in decays dominated by 1-loop amplitudes

B factories were also responsible for proliferation of blind analyses

- Some of these uncertainties will be reduced by nearly an order of magnitude

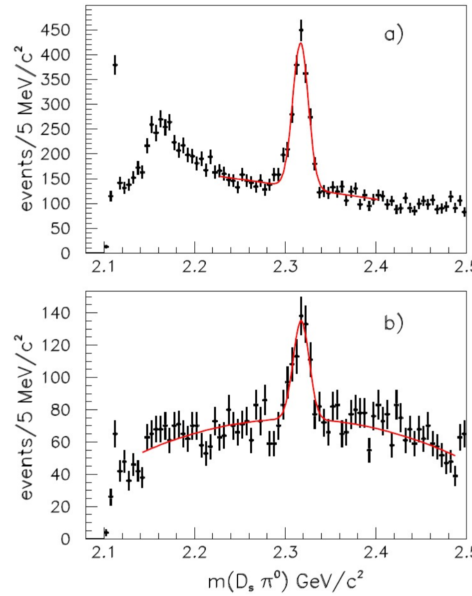
2003: $D^*_{s0}(2317)$ and $X(3872)$ discovery

- BaBar's 2nd most cited, hep-ex/0304021 (Apr 12), 91/fb, 903 cites (detector papers aside, citations on this page: 3/31/2021)

  Quark model predicted above DK, isospin viol. decay to $D_s\pi$

  CLEO could have discovered it years before hep-ex/0305100 (May 28), 13.5/fb, 632 cites

  Belle, hep-ex/0307021 (Jul 9), 65/fb, 375 cites

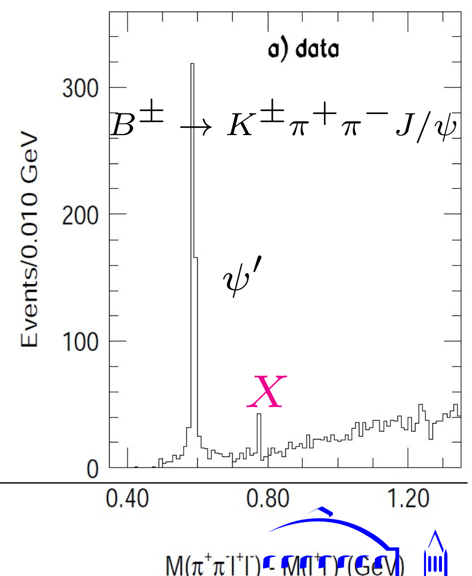


- Belle's most cited, hep-ex/0309032 (Sep 8), 1919 cites

  Narrow state above ψ', decays into $\pi^+\pi^- J/\psi$

  CDF confirmation 12σ, hep-ex/0312021 (Dec 5), 863 cites

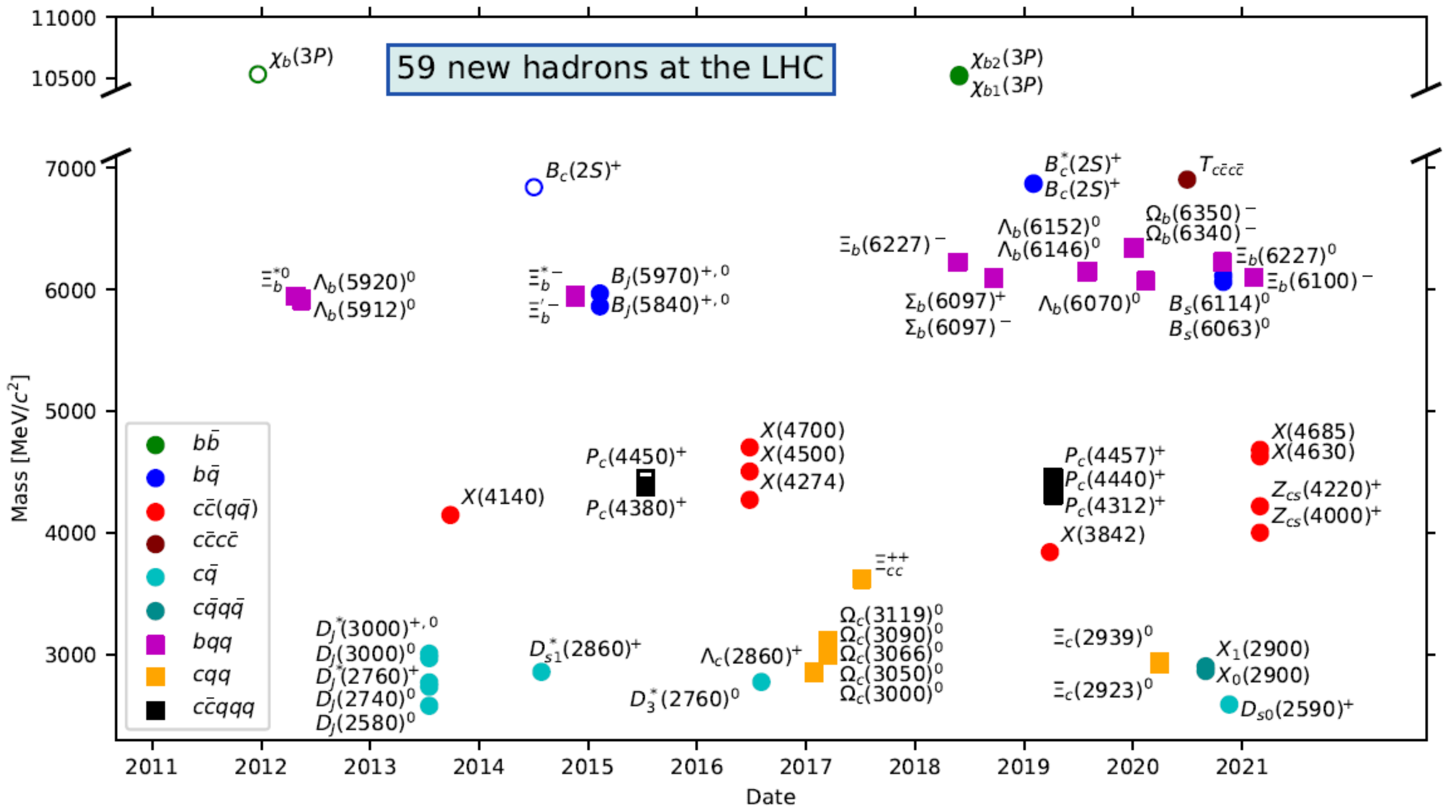
  BaBar hep-ex/0406022, 685 cite; bounds in hep-ex/0402025



Spectroscopy at the LHC

- LHCb's most cited paper: pentaquark 1507.03414, 1175 cites $(> R_K$ paper in 2014)
  Number of particles (width/mass $<$ you pick) discovered by LHC: hard to count

[plot credit]



- How complex the spectrum of strongly interacting theories can be...

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More surprises in 2003 – 2004: α and γ

- γ: $B^\pm \to D^0 K^\pm$ and $D^0 \to K_S \pi^+\pi^-$ [Bondar, 2002; Giri et al., hep-ph/0303187; Belle, hep-ex/0406067]
- α: $B \to \rho\rho$, large $\rho^+\rho^-$ & $\rho^\pm\rho^0$ rates, mostly longitudinal, $\rho^0\rho^0$ small [hep-ex/0404029]
- Critical for testing the SM by comparing tree- and loop-dominated processes

Neither of these methods were anticipated in the BaBar book, just 5 years earlier

Tons of data always stimulate new developments (both theory and experiment)

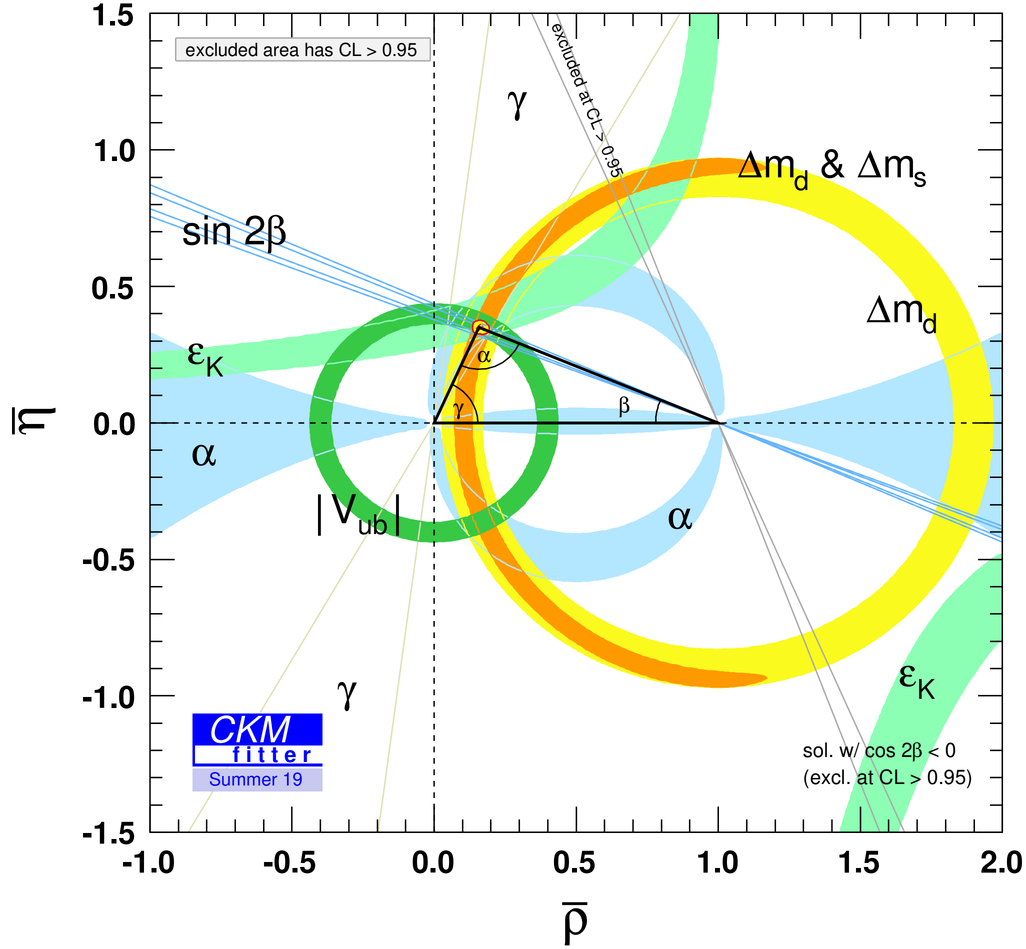
- The (to me most serious) $K\pi$ puzzle became significant:

$A_{K^+\pi^0} - A_{K^+\pi^-} = 0.124 \pm 0.022$ (tension with SCET / factorization)

Direct CPV can also be $\mathcal{O}(1)$ — many since

The B-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates CP violation & flavor changing processes
- The implications of the consistency of measurements are often overstated
- Larger allowed region if there is NP



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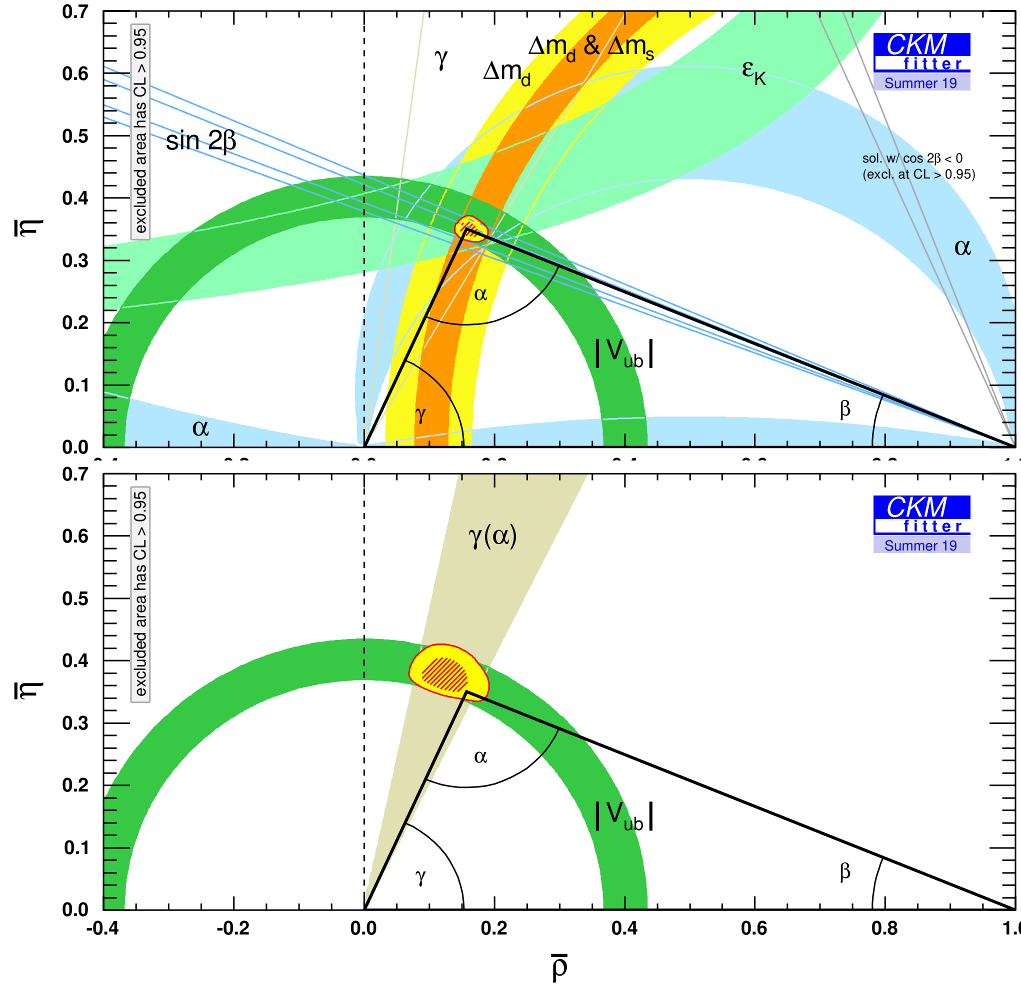
The B-factories money plot

- Spectacular progress in last 20 years
- The CKM mechanism dominates CP violation & flavor changing processes
- The implications of the consistency of measurements are often overstated
- Larger allowed region if there is NP
- Compare tree-level (lower plot) and loop-dominated measurements
- LHCb: constraints in the B_s sector (2nd–3rd gen.) caught up with B_d



- $\mathcal{O}(20\%)$ NP contributions to most loop-level processes (FCNC) are still allowed

Future

Reasons to seek higher precision

- Expected deviations from the SM, induced by TeV-scale NP?

  Generic flavor structures ruled out; can find any size deviations, detectable effects in many models

- Theoretical uncertainties?

  Highly process dependent, under control in many key measurements

- Expected experimental precision?

  Useful data sets will increase by $\sim 10^2$, and probe fairly generic BSM scenarios

- What will the measurements teach us if deviations from the SM are [not] seen?

  Complementary with LHC high-p_T LHC program; the synergy can teach us what the NP is [not]

> Summarizing, we have no guarantees that B decay will provide us with the answer to any of Nature's deep mysteries. However, we do have some reason for optimism.

[Same 1981 CLEO workshop]

LHCb — LHC

	LHC era			HL-LHC era	
	Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
ATLAS, CMS	25 fb^{-1}	150 fb^{-1}	300 fb^{-1}	$\longrightarrow$	3000 fb^{-1}
LHCb	3 fb^{-1}	9 fb^{-1}	23 fb^{-1}	50 fb^{-1}	*300 fb^{-1}

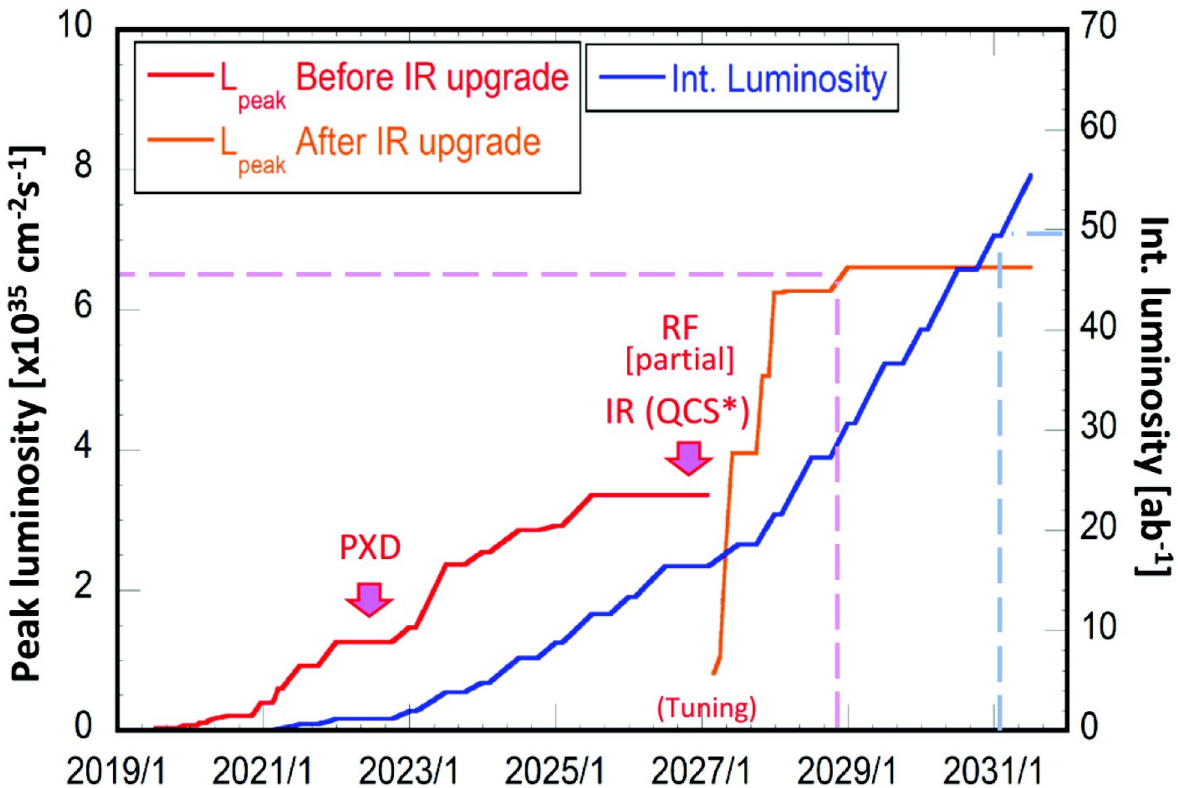
* assumes a future LHCb upgrade to raise the instantaneous luminosity to $2x10^{34}$ $cm^{-2}s^{-1}$

- Major LHCb upgrade in LS2 (raise instantaneous luminosity to $2 \times 10^{33}/\mathrm{cm}^2/\mathrm{s}$)
  Major ATLAS and CMS upgrades come in LS3 for HL-LHC

- LHCb plans to upgrade in LS4 to take data at $2 \times 10^{34}/\mathrm{cm}^2/\mathrm{s}$

  ATLAS & CMS will be competitive in some B physics measurements

Belle II — SuperKEKB



- First collisions 2018 (unfinished detector), with full detector starting spring 2019
  Goal: $50\times$ the Belle and nearly $100\times$ the $B\textsc{a}B\textsc{ar}$ data set

- Discussions started about physics case and feasibility of a factor ~ 5 upgrade, similar to LHCb Phase-II upgrade aiming 50/fb $\to$ 300/fb, after LHC LS4

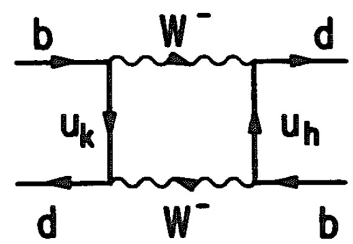
New physics in B mixing

- Assume: (i) 3×3 CKM matrix is unitary; (ii) tree-level decays dominated by SM

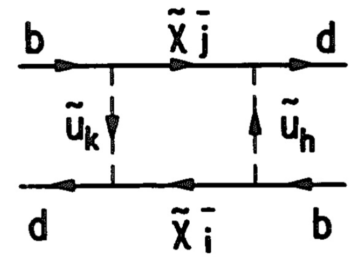
General parametrization of many models
by two real parameters (in addition to SM):

$$h\, e^{2i\sigma} = A_{\rm NP}(B^0 \to \overline{B}{}^0)/A_{\rm SM}(B^0 \to \overline{B}{}^0)$$

NP parameters



SM: $\dfrac{C_{\rm SM}}{m_W^2}$



NP: $\dfrac{C_{\rm NP}}{\Lambda^2}$

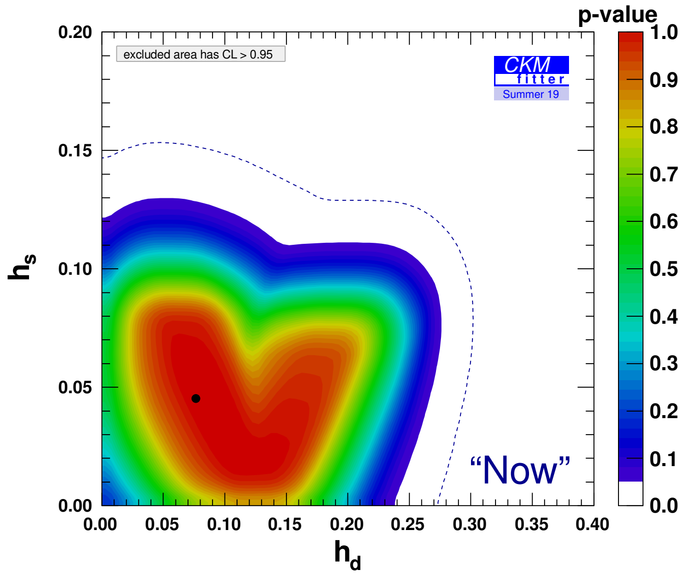
What is the scale Λ? How different is the $C_{\rm NP}$ coupling from $C_{\rm SM}$?

- Is $h = \mathcal{O}(1)$ allowed? If not, the CKM mechanism dominates

Redo CKM fit w/ NP param's: tree-dominated unchanged, loop-mediated modified

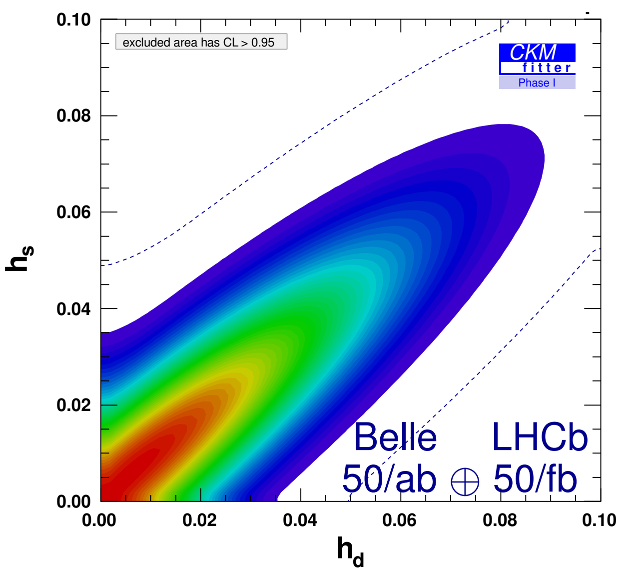
Importance known since 1970s ($\Delta m_K/m_K \sim 7 \times 10^{-15}$), conservative view of future progress

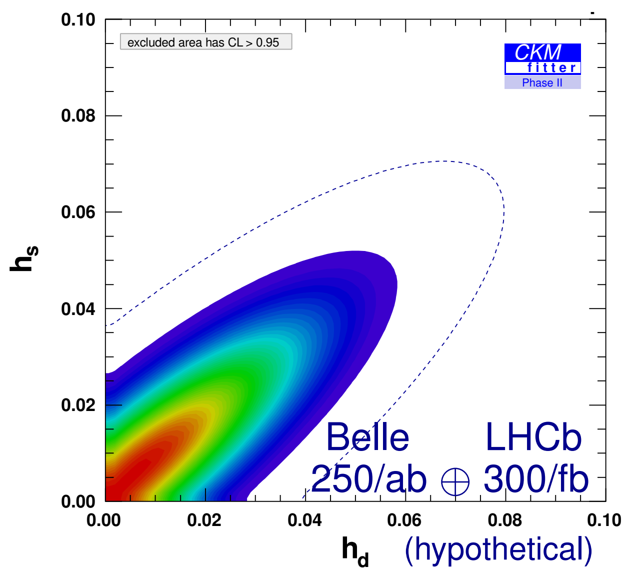
Future sensitivity to NP in B mixing



- What NP parameter space can be probed?
- $h_{d,s} \Leftrightarrow$ NP scale: $h \simeq \dfrac{|C_{ij}|^2}{|V_{ti}^* V_{tj}|^2} \left(\dfrac{4.5\ \text{TeV}}{\Lambda}\right)^2$ [2006.04824]

Couplings	NP loop order	Sensitivity for Summer 2019 [TeV]		Phase I Sensitivity [TeV]		Phase II Sensitivity [TeV]	
		B_d mixing	B_s mixing	B_d mixing	B_s mixing	B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$	tree level	9	13	17	18	20	21
(CKM-like)	one loop	0.7	1.0	1.3	1.4	1.6	1.7
$\lvert C_{ij}\rvert = 1$	tree level	1×10^3	3×10^2	2×10^3	4×10^2	2×10^3	5×10^2
(no hierarchy)	one loop	80	20	2×10^2	30	2×10^2	40





Big improvements in 2020s

Complementary to high-p_T searches

Then theory improves or progress slows

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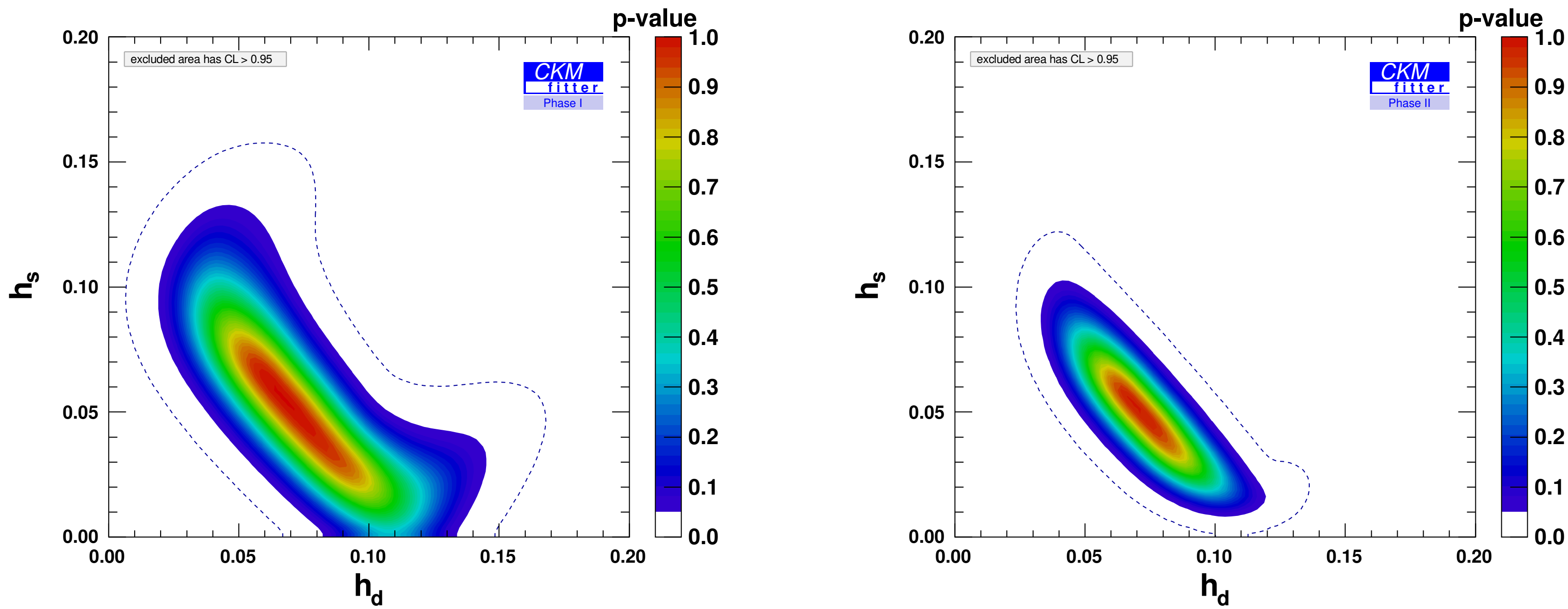
Example of discovery potential

- Discovery significance at Phase I and II, if central values remain as in current fit

(Assume future measurements have the central values corresponding to current best fit parameters)



- If new physics contributes to semileptonic decays, as hinted at by the $R(D^{(*)})$ anomaly, then things get more complicated, may still isolate sources

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2012, 2014: emerging hints of LUV

- 2012: BaBar, charged current
- 2014: LHCb, neutral current
- “Who ordered that?”

  Nearly no discussion in the literature before the measurements

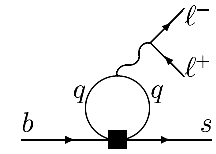
The simplest models to accommodate the data do not (trivially) connect to DM and the hierarchy puzzle

- Forced both theory and experiment to rethink program, discard some prejudices: broader searches, previously neglected measurements

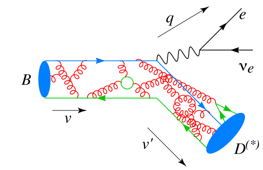
New directions: model building, high-p_T searches, lepton flavor violation searches

The current B "anomalies"

- Lepton non-universality would be clear evidence for NP



1) R_K and R_{K^*} $\quad (B \to X\mu^+\mu^-)/(B \to Xe^+e^-) \sim 20\%$ correction to SM loop



2) $R(D)$ and $R(D^*)$ $\quad (B \to X\tau\bar{\nu})/(B \to X(e,\mu)\bar{\nu}) \sim 20\%$ correction to SM tree

Scales: $R_{K^{(*)}} \lesssim$ few $\times\, 10^1\,\mathrm{TeV}$, $\quad R(D^{(*)}) \lesssim$ few $\times\, 10^0\,\mathrm{TeV}$ $\quad$ Would bound NP scale!

- Theor. less clean: 3) P_5' angular distribution $(B \to K^*\mu^+\mu^-)$
  4) $B_s \to \phi\mu^+\mu^-$ rate

Can fit 1), 3), 4) with one operator: $C_{9,\mu}^{(\mathrm{NP})}/C_{9,\mu}^{(\mathrm{SM})} \sim -0.2\,,\;\; O_{9,\mu} = (\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$

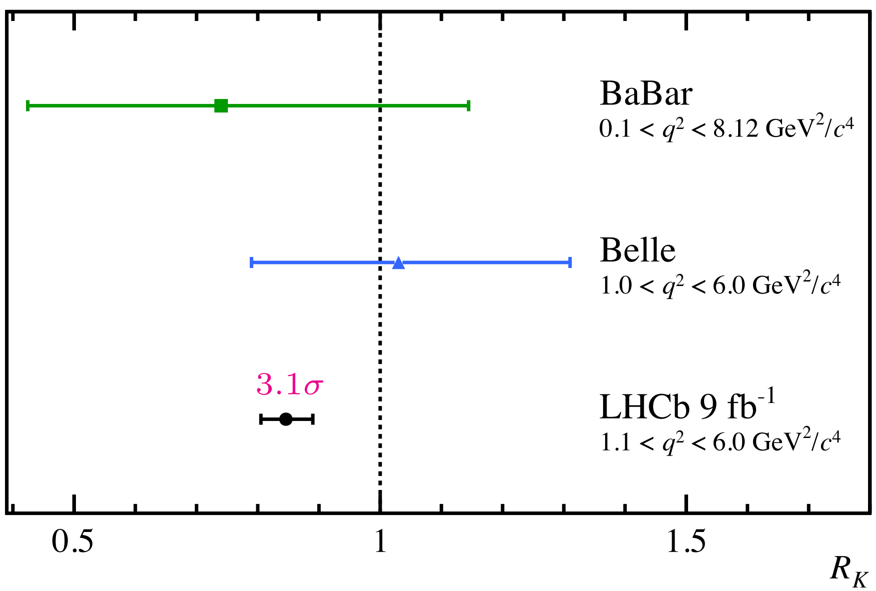
- Viable BSM models... leptoquarks? No clear connection to DM & hierarchy puzzle

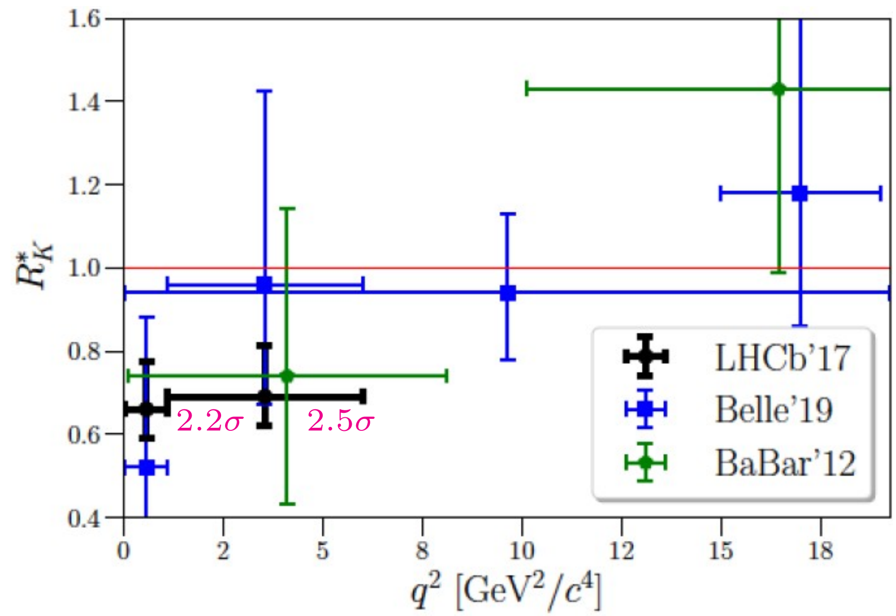
Attention to many BSM scenarios previously less explored

- What are smallest deviations from SM, which can be unambiguously established?

R_K and R_{K^*}: theoretically cleanest

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ both ratios $\sim 3\sigma$ from lepton universality





- Combined fits only by theorists (some include P_5' and/or $B_s \to \phi\mu^+\mu^-$)

- Modifying one Wilson coefficient in $\mathcal{H}_{\text{eff}}$ gives good fit: $\delta\, C_{9,\mu} \sim -1$ [See 3/29 discussion]

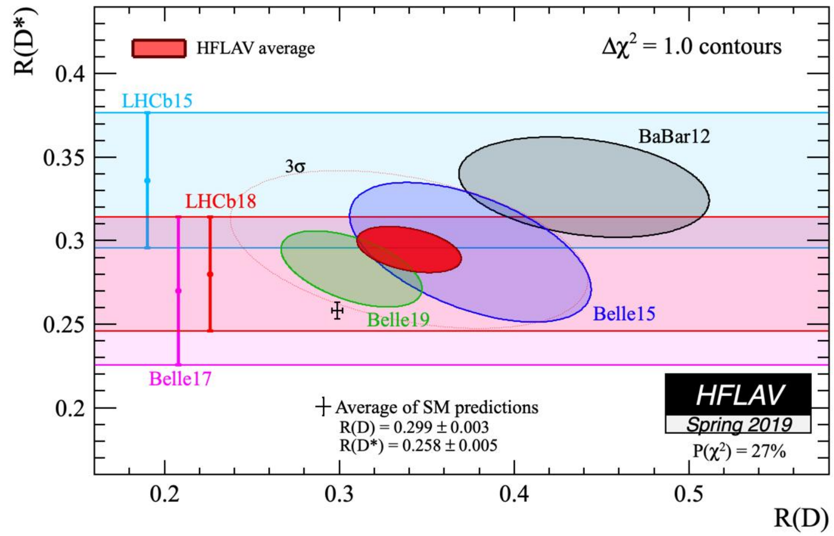
The $B \to D^{(*)}\tau\bar{\nu}$ decay rates

- BABAR, Belle, LHCb: $R(X) = \dfrac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$

  3.1σ from SM predictions — robust due to heavy quark symmetry + lattice QCD (only D so far)

  many channels: $R(D^*)$ with $\tau \to \nu 3\pi$ [1708.08856]

  $B_c \to J/\psi\, \tau\bar{\nu}$ [1711.05623]



- Imply NP at a fairly low scale (leptoquarks, W', etc.), likely visible at ATLAS / CMS

  Many models Fierz (mostly) to the SM operator: SM-like distributions and τ polarization

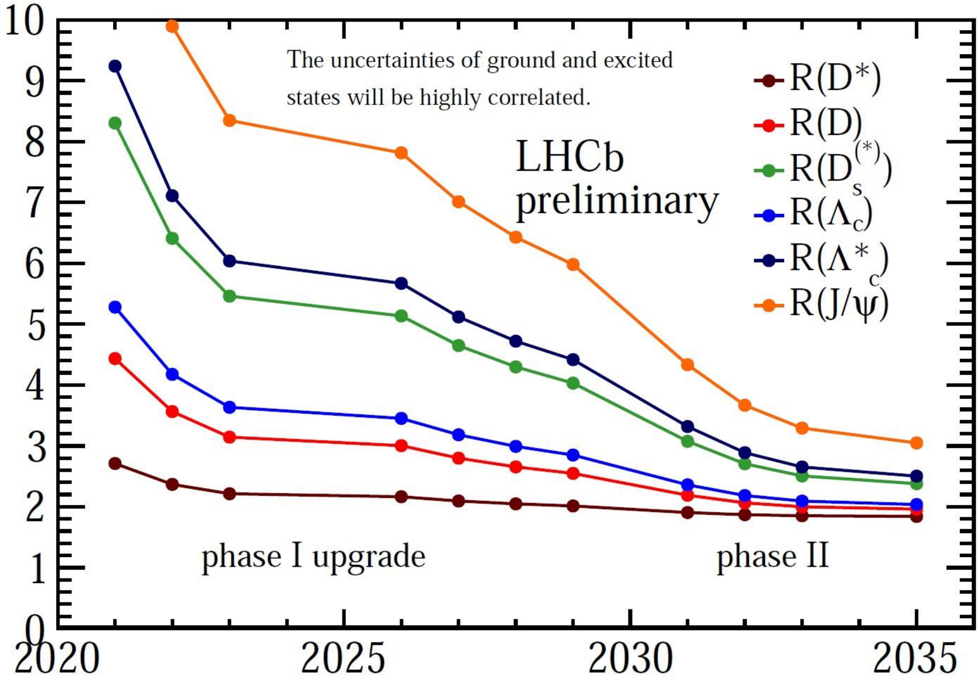
- Tree level: three ways to insert mediator: $(b\nu)(c\tau)$, $(b\tau)(c\nu)$, $(bc)(\tau\nu)$

  overlap with ATLAS & CMS searches for $\tilde{b}$, leptoquark, $H^{\pm}$

- Models built to fit these anomalies have impacted many ATLAS & CMS searches

Exciting future

- LHCb: $R_{K^{(*)}}$ sensitivity with existing Run 1–2 data can still improve a lot
- LHCb and Belle II: increase $pp \to b\bar{b}$ and $e^+e^- \to B\overline{B}$ data sets by factor ~ 50
- LHCb:



Belle II ($50/$ab, at SM level):

$\delta R(D) \sim 0.005\ (2\%)$

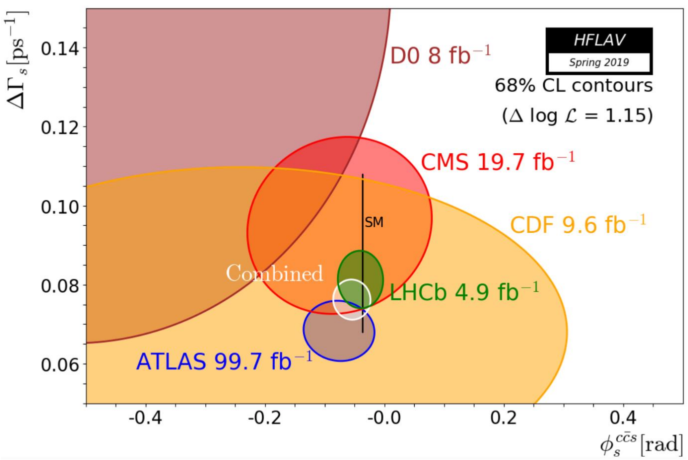
$\delta R(D^*) \sim 0.010\ (3\%)$

Measurements will improve a lot!

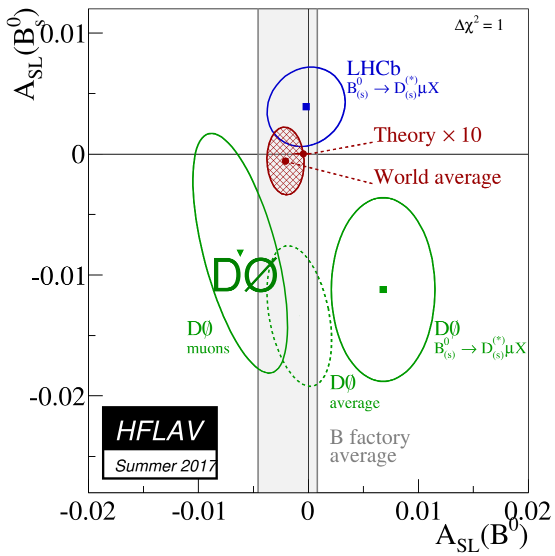
(Even if central values change, plenty of room for establishing deviations from SM)

- Competition, complementarity, cross-checks between LHCb and Belle II

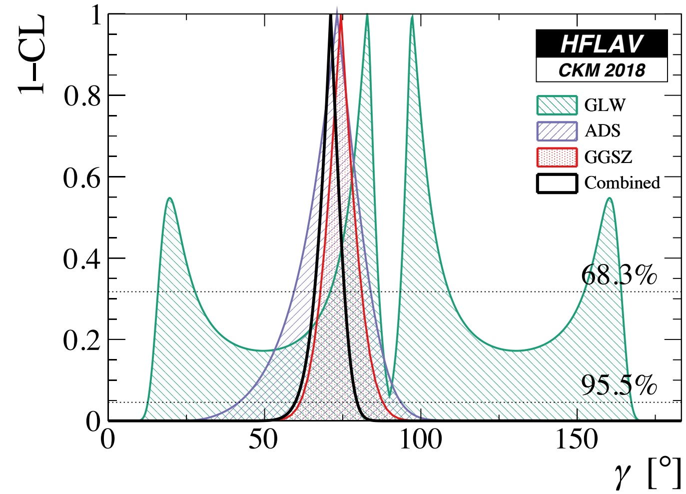
Some key measurements, done much better



CP violation in $B_s \to \psi\phi$ now consistent with SM



$A_{\rm SL}$: important, indep. of DØ anomaly



Measurements of γ crucial, LHCb is now most precise

- Breadth crucial, often the combination of many measurements is most useful

  ("The interesting messages are not simple, the simple messages are not interesting" [exceptions!])

- Uncertainty of predictions $\ll$ current experimental errors ($\Rightarrow$ seek lot more data)

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Another example: add one vector-like fermion

- Add one vector-like fermion: mass term w/o Higgs, hierarchy problem not worse

  11 models in which new particles can Yukawa couple to SM fermions and Higgs

  $\Rightarrow$ FCNC Z couplings to leptons or quarks [Ishiwata, ZL, Wise, 1506.03484; also 1609.04783, 2103.05549]

Upper (lower) rows are current (future, 50/fb LHCb & 50/ab Belle II) sensitivities

Model	Quantum numbers	Bounds on M/TeV and $\lambda_i\lambda_j$ for each ij pair					
		$ij=12$		$ij=13$		$ij=23$	
		$\Delta F=1$	$\Delta F=2$	$\Delta F=1$	$\Delta F=2$	$\Delta F=1$	$\Delta F=2$
V	$(3,1,-1/3)$	66^d $[100]^e$	$\{42, 670\}^f$	30^g	25^h	21^i	6.4^j
		280^d	$\{100, 1000\}^f$	60^l	61^h	39^k	14^j
VII	$(3,3,-1/3)$	47^d $[71]^e$	$\{47, 750\}^f$	21^g	28^h	15^i	7.2^j
		200^d	$\{110, 1100\}^f$	42^l	68^h	28^k	16^j
XI	$(3,2,-5/6)$	66^d $[100]^e$	$\{42, 670\}^f$	30^g	25^h	18^k	6.4^j
		280^d	$\{100, 1000\}^f$	60^l	61^h	39^k	14^j

Strongest bounds arise from many processes, nominally 1-2 generation most sensitive, large variation across models

- A 50-fold increase in data sets will raise mass scale sensitivity by $\sim 2.5 \sim \sqrt[4]{50}$

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$D-\overline{D}$ mixing and CP violation

- CP violation in D decays:

  LHCb, Nov. 2011: $\Delta A_{CP} \equiv A_{K^+K^-} - A_{\pi^+\pi^-} = -(8.2 \pm 2.4) \times 10^{-3}$

  LHCb, Mar. 2019: $\Delta A_{CP} = -(1.82 \pm 0.33) \times 10^{-3}$ (a stretch in the SM, imho)

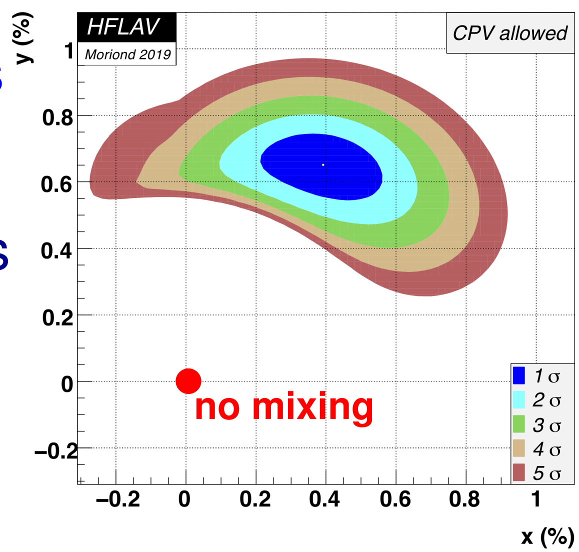
- I think we still don't know how big an effect could (not) be accommodated in SM

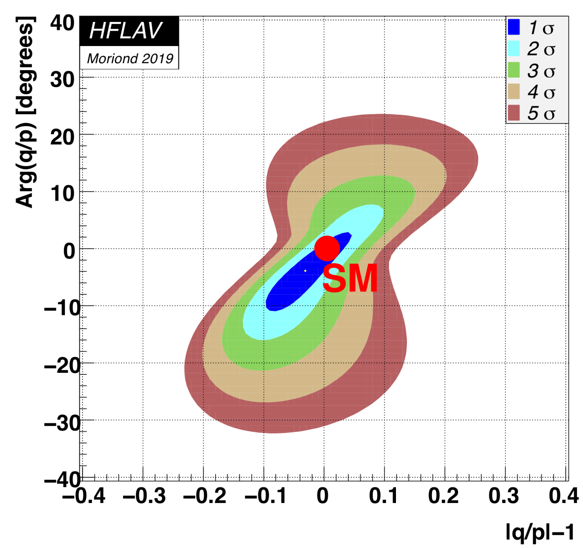
- Mixing generated by down quarks or in SUSY by up-type squarks

  Connections to FCNC top decays

- Value of Δm? Not even 3σ yet

- SM allowed range of $|q/p| - 1$?



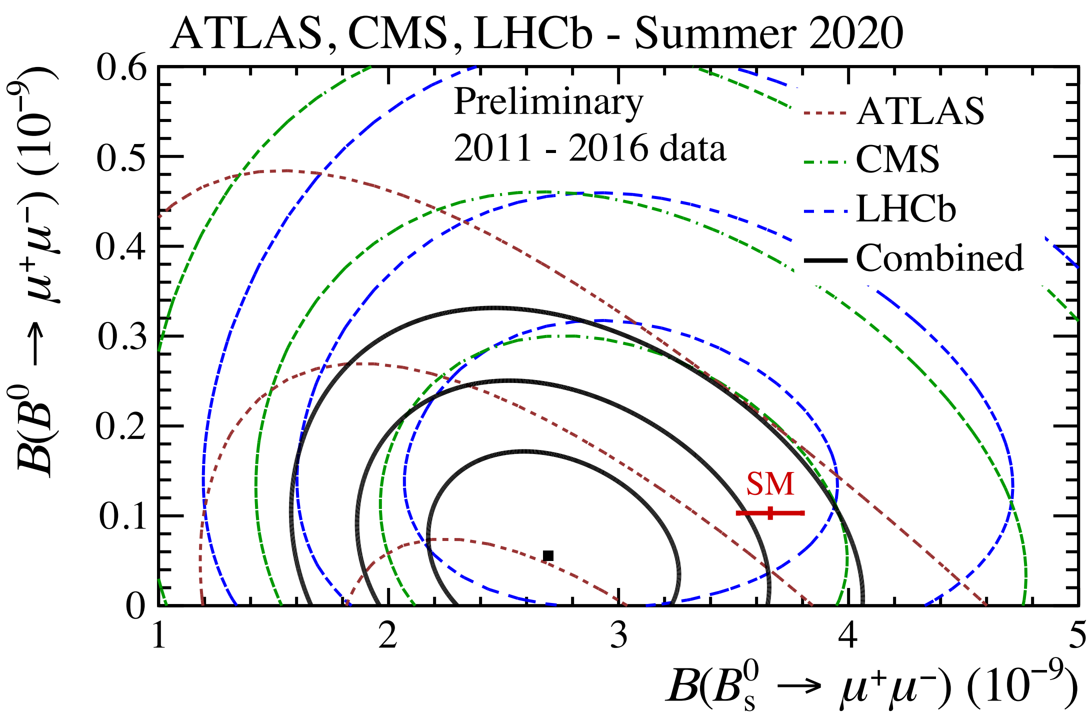


- SUSY: interplay of D & K bounds: alignment, universality, heavy squarks?

$B \to \mu^+\mu^-$: interesting well beyond HL-LHC

- $B_d \to \mu^+\mu^-$ in SM, 10^{-10} : LHCb expects 10% $(300/\text{fb})$, CMS expects 15% $(3/\text{ab})$

  SM uncertainty $\simeq (2\%) \oplus f_{B_q}^2 \oplus \text{CKM}$ [Bobeth, FPCP'15] and may be further reduced



- Theoretically cleanest $|V_{ub}|$ I know, use isospin: $\mathcal{B}(B_u \to \ell\bar\nu)/\mathcal{B}(B_d \to \mu^+\mu^-)$
- A decay with mass-scale sensitivity (dim.-6 operator) that competes w/ $K \to \pi\nu\bar\nu$

Many complementary CLFV processes

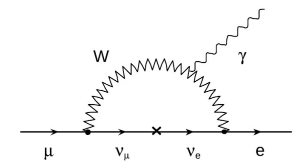
- SM w/ $m_\nu = 0 \Rightarrow$ lepton flavor conservation

  Given $m_\nu \neq 0$, no reason to impose it as a sym.

  TeV-scale loop-level NP may be observable

SM predictions incredibly small

rates $\propto \dfrac{m_\nu^4}{m_W^4} < 10^{-50}$



- Many interesting processes; NP-dependent which is most sensitive:

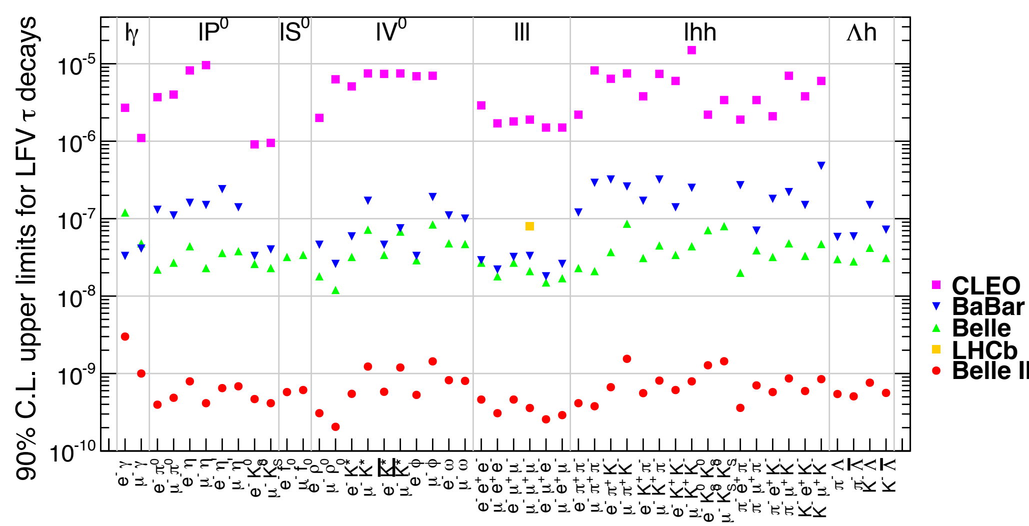
  $\mu \to e\gamma,\ \mu \to eee,\ \mu + N \to e + N^{(\prime)},\ \mu^- pp \to e^+ nn, \tau \to \mu\gamma,\ \tau \to e\gamma,\ \tau \to \mu\mu\mu,$
  $\tau \to eee,\ \tau \to \mu\mu e, \tau \to \mu ee, \tau \to \mu\pi,\ \tau \to e\pi,\ \tau \to \mu K_S,\ eN \to \tau N$

- τ decays: $\mu \to e\gamma, eee$ vs. $\tau \to \mu\gamma, \mu\mu\mu$

  Either can "win", huge NP model dependence: $\mathcal{B}(\tau \to \mu\gamma)/\mathcal{B}(\mu \to e\gamma) \sim 10^{4\pm3}$

- Belle II: improve 2 orders of magnitude

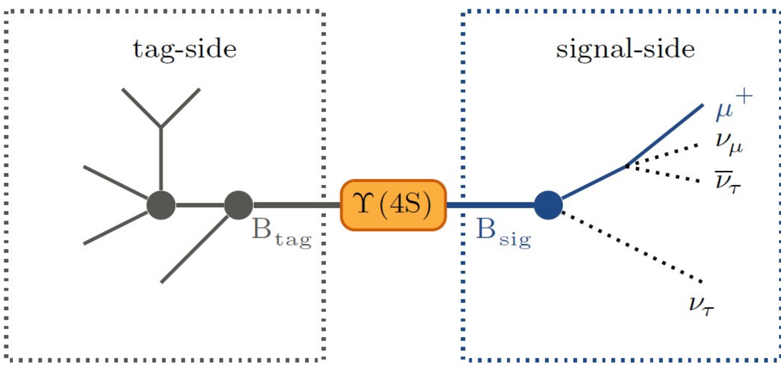
- Any discovery $\Rightarrow$ broad program to map out the detailed structure

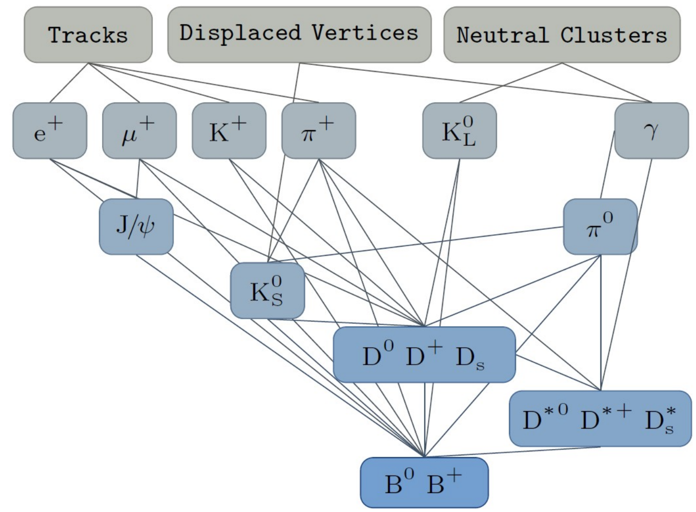


Aside: many innovative uses of ML

- Machine learning tools are also heavily used by B-physics experiments

E.g., “full event interpretation” (FEI) at Belle II [1807.08680]





Improve on boosted decision trees using deep learning

Optimize tagging in purity / efficiency, the full reconstruction (B-beam) technique

Ongoing work on many directions, e.g., graph neural networks

Final remarks

Many "exotic" searches at LHCb and Belle II

- Better tests of (exact or approximate) conservation laws
- Exhaustive list of dark / hidden sector searches
- LFV meson decays, e.g., $M^0 \to \mu^- e^+$, $B^+ \to h^+ \mu^- e^+$, etc.
- Invisible modes, even baryonic, $B \to N + \text{invis.}\ [+\text{mesons}]$ [1708.01259, 1810.00880, 2101.02706]
- Hidden valley inspired scenarios, e.g., multiple displaced vertices, even with $\ell^+\ell^-$
- Exotic Higgs decays, e.g., high multiplicity, displaced vertices ($H \to XX \to abab$)
- Search for "quirks" (non-straight "tracks") at LHCb using many velo layers
- Hot topics 10 years from now are probably not what we have thought about yet

  (Whether or not NP is discovered by then)

What are the largest useful data sets?

- No one has seriously explored it! (Recall, Sanda, 2003: the question is not 10^{35} or 10^{36}...)
- Which measurements will remain far from being limited by theory uncertainties?
  - For $\gamma \equiv \phi_3$, theory uncertainty only from higher order EW
  - $B_{s,d} \to \mu\mu$, $B \to \mu\nu$ and other leptonic decays (lattice QCD, [double] ratios)
  - $A_{\rm SL}^{d,s}$ — can it keep scaling with statistics?
  - Lepton flavor violation & lepton universality violation searches
  - Possibly CP violation in D mixing (firm up theory)
- Very broad program
- In some decay modes, even in 2030s we'll have: (exp. bound)/SM $\gtrsim 10^3$

  E.g., $B_{d,s} \to e^+e^-$, $\tau^+\tau^-$, etc. — can build models... (Please prove me wrong!)
- Sensitivity to NP would improve with data $\gg$ LHCb & Belle II

FCC-ee would have huge flavor program

- Very large and clean samples of B decays ($\sim 10^6 \times$ LEP)
- Production yields at tera-Z compared to Belle II (from CERN-ACC-2018-0056)

Particle production (10^9)	$B^0 + \overline{B}^0$	$B^\pm$	$B_s^0 + \overline{B}_s^0$	$\Lambda_b + \bar{\Lambda}_b$	$c\bar{c}$	$\tau^+\tau^-$
Belle II (50 ab^{-1})	27.5	27.5	—	—	65	45
FCC-ee (5×10^{12} Z)	400	400	100	100	550	170

Most often this is the sole focus of flavor @ FCC

- WW threshold: $W \to b\bar{c}$ can give a qualitatively new determination of $|V_{cb}|$
  Estimate 0.3% uncertainty using 10^8 WW, independent of B measurements

[See: Schune, 3rd FCC Physics and Experiments Workshop, Jan 2020, Azzurri, 4th FCC Physics and Experiments Workshop, Nov 2020]

- $t\bar{t}$ threshold: improvements in FCNC top decay searches, $t \to \{H, Z, \gamma\}\, q$

Some conclusions

- Flavor physics probes scales $\gg 1\,\mathrm{TeV}$; sensitivity limited by statistics, not theory

  $\Rightarrow$ New physics could show up any time measurements improve

- In FCNCs, NP/SM $\gtrsim 20\%$ still allowed; any discovery $\Rightarrow$ upper bound on NP scale

- Precision tests of SM will improve in the next decade by $10-10^4$

- Few tensions with SM; some of these (or others) could soon become decisive

- Discovering lepton universality violation would focus even more attention on LFV

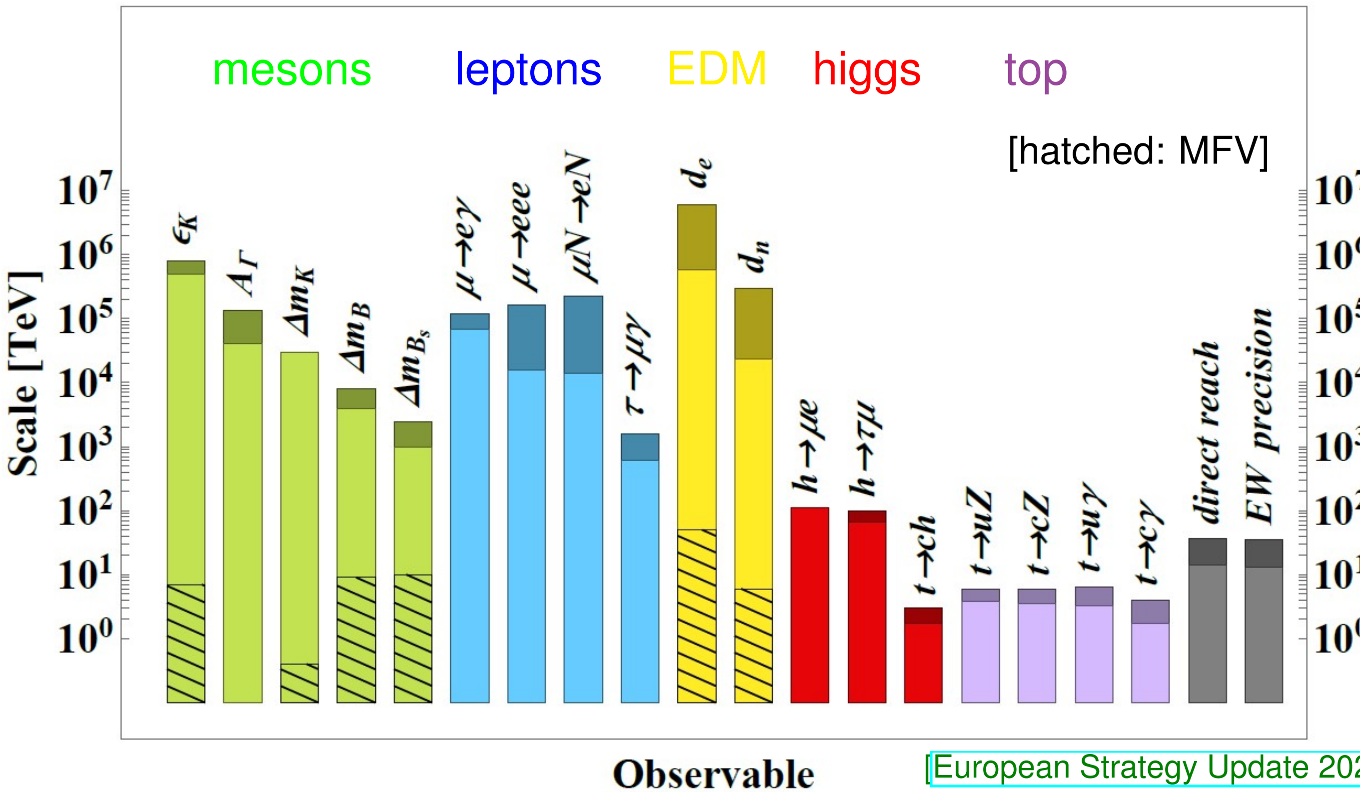
- Many interesting theoretical questions relevant for optimal experimental sensitivity

- I cannot imagine a scenario in which there is no complementarity between flavor and LHC searches of new physics, and hopefully understanding it

Extra slides

Anticipated increases in sensitivity

- Scales of dim-6 operators probed — various mechanisms devised to let TeV-scale NP obey these bounds (Pattern and orders of magnitudes matter more than precise values)



[European Strategy Update 2020, arXiv:1910.11775]

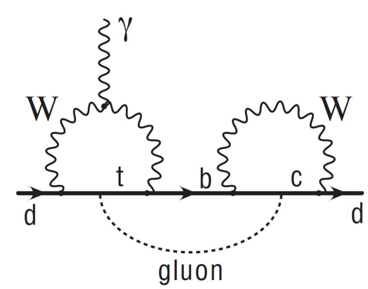
- $\mu N \to eN$ may be the largest increase in mass-scale sensitivity in next 10–15 yrs

Electric dipole moments

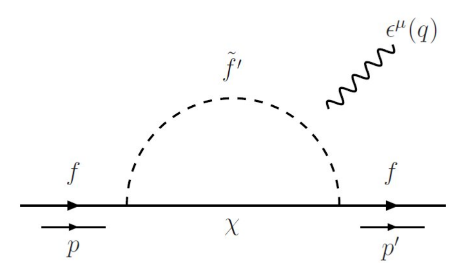
- SM $+\, m_\nu$: CPV can occur in: (i) quark mixing; (ii) lepton mixing; and (iii) $\theta_{\rm QCD}$
  Only observed $\delta_{\rm KM} \neq 0$, baryogenesis implies there must be more

- Neutron EDM bound: "the strong CP problem", $\theta_{\rm QCD} < 10^{-10}$ — axion?
  $\theta_{\rm QCD}$ is negligible for CPV in flavor-changing processes

- EDMs from CKM: vanish at one- and two-loop
  large suppression at three-loop level



- E.g., SUSY: quark and lepton EDMs can be generated at one-loop
  Generic prediction ($\rm TeV$-scale, no small param's) above current bounds; if $m_{\rm SUSY} \sim \mathcal{O}(10\,{\rm TeV})$, may still discover EDMs



- Expected 10^2–10^3 improvements: complementary to LHC
  Discovery would give (rough) upper bound on NP scale

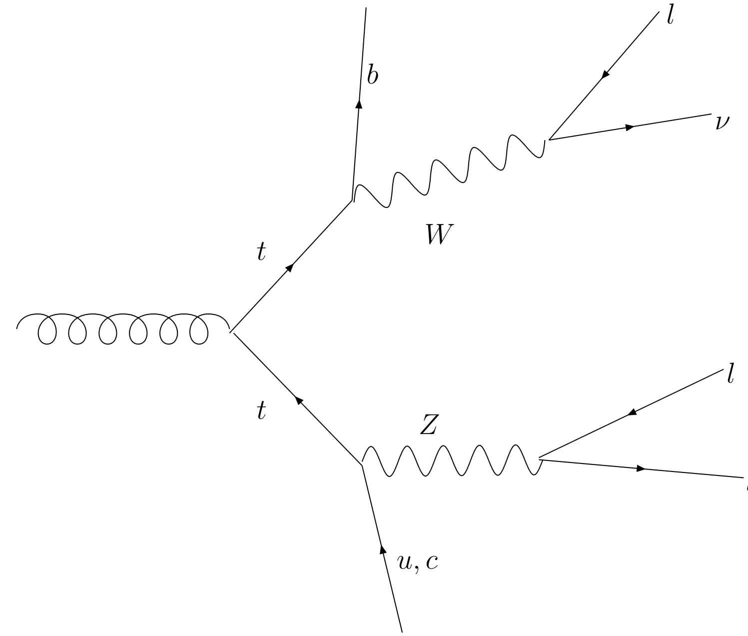
The LHC is a top factory: top flavor physics

- FCNC top decays not yet strongly constrained

$$t \to cZ,\ c\gamma,\ cH,\ \ uZ,\ u\gamma,\ uH$$

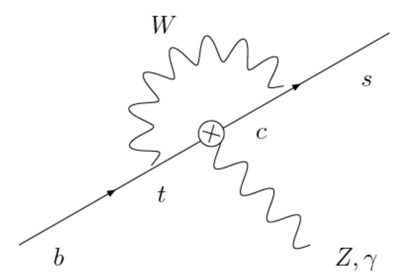
SM predictions: $< 10^{-12}$

Best current bound: $\lesssim$ few $\times\, 10^{-4}$ [ATLAS, CMS]



- Sensitivity will improve ~ 2 orders of magnitude

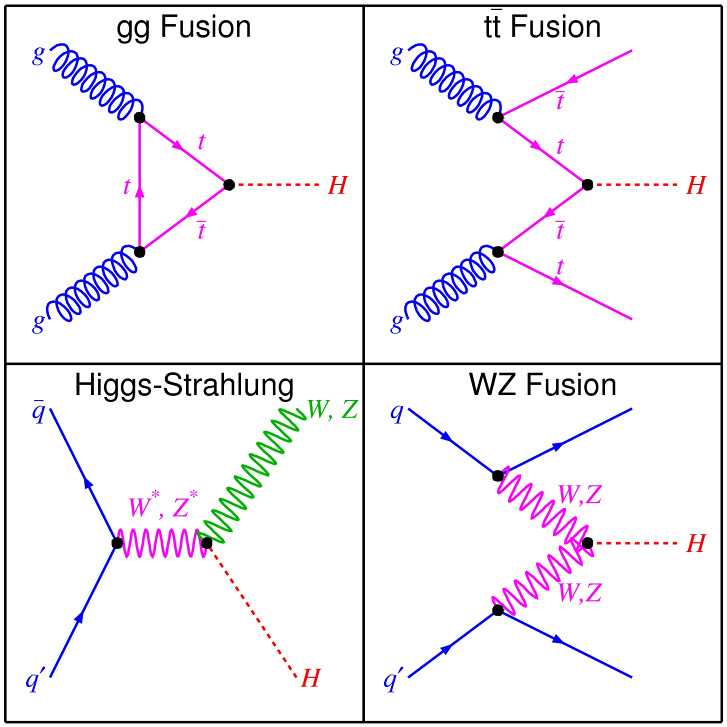
- Indirect constraints: $t_L \leftrightarrow b_L \Rightarrow$ tight bounds from B decays
  - Strong bounds on operators with left-handed fields
  - Right-handed operators could give rise to LHC signals

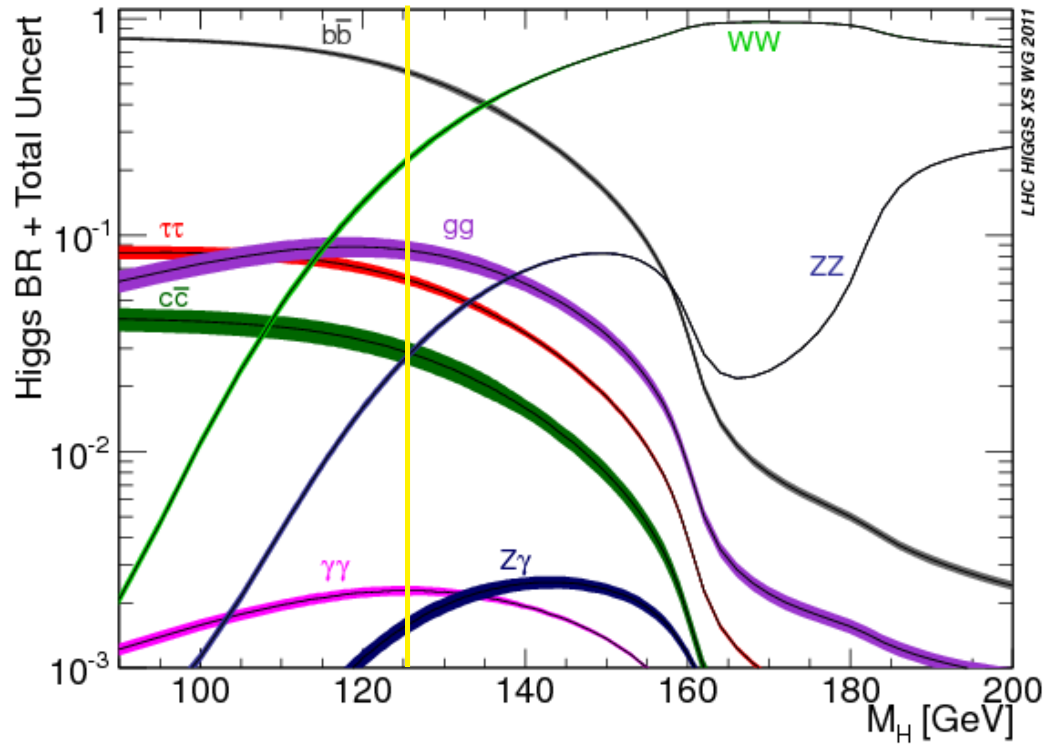


- If top FCNC is seen, LHC & B factories will both probe the NP responsible for it

The LHC is a Higgs factory

- Rich physics: many production and decay channels (fermion couplings crucial)

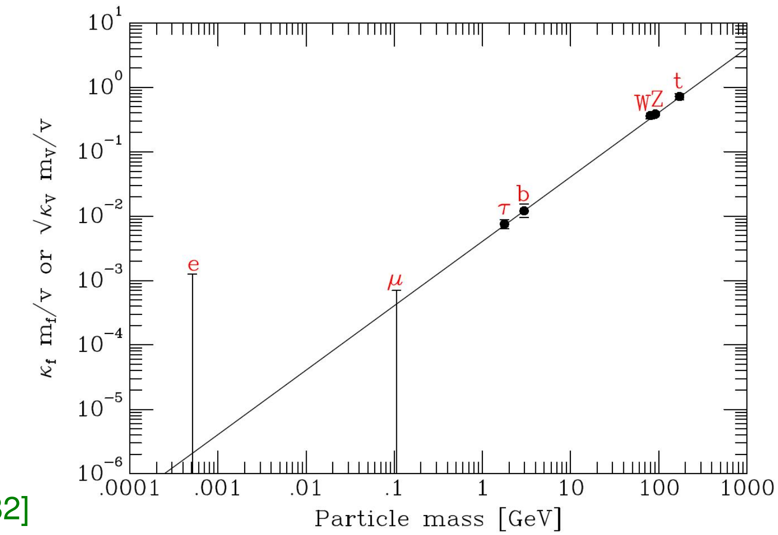




- Higgs flavor param's: 3rd gen: κ_t, κ_b, κ_τ; 2nd gen: κ_c, κ_μ; do $\kappa_{t,c}$, $\kappa_{\tau\mu}$ vanish?
- Thoroughly test Higgs paradigm $\Rightarrow$ seek much higher precision

Higgs flavor prospects

- Higgs couplings to gauge bosons, τ, t, (b) have been constrained with some precision, $\mathcal{O}(10\%)$
- ICHEP 2020: Evidence for $H \to \mu^+\mu^-$
- Reducing uncertainties is a key long-term goal



Future precision of flavor-diagonal couplings [Heinemann & Nir, 1905.00382]

Observable	Current range	HL-LHC	ILC250	ILC250+500	CLIC380	CLIC3000	CEPC	FCC240	FCC365	LHeC
		$\delta y/y$ (%)								
y_t/y_t^{SM}	$1.02^{+0.19}_{-0.15}$ [35] $1.05^{+0.14}_{-0.13}$ [36]	3.4	–	6.3	–	2.9	–	–	–	–
y_b/y_b^{SM}	$0.91^{+0.17}_{-0.16}$ [35] $0.85^{+0.13}_{-0.14}$ [36]	3.7	1.0	0.60	1.3	0.2	1.0	1.4	0.67	1.1
$y_\tau/y_\tau^{\mathrm{SM}}$	0.93 ± 0.13 [35] 0.95 ± 0.13 [36]	1.9	1.2	0.77	2.7	0.9	1.2	1.4	0.78	1.3
y_c/y_c^{SM}	< 6.2 [40, 41]	< 220	1.8	1.2	4.1	1.3	1.9	1.8	1.2	3.6
$y_\mu/y_\mu^{\mathrm{SM}}$	$0.72^{+0.50}_{-0.72}$ [35] < 1.63 [36]	4.3	4.0	3.8	–	5.6	5.0	9.6	3.4	–
y_e/y_e^{SM}	< 611 [42]	–	–		–	–	–	–	$< 1.6^{(+)}$	–

Theory challenges / opportunities

- New methods & ideas: recall that the best α and γ measurements are in modes proposed in light of Belle & BaBar data (i.e., not in the BaBar Physics Book)
  - Better SM upper bounds on $S_{\eta' K_S} - S_{\psi K_S}$, $S_{\phi K_S} - S_{\psi K_S}$, and $S_{\pi^0 K_S} - S_{\psi K_S}$ And similarly in B_s decays, and for $\sin 2\beta_{(s)}$ itself
  - How big can CP violation be in $D^0 - \overline{D}^0$ mixing (and in D decays) in the SM?
  - Better understanding of semileptonic form factors; bound on $S_{K_S \pi^0 \gamma}$ in SM?
  - Many lattice QCD calculations (operators within and beyond SM)
  - Inclusive & exclusive semileptonic decays
  - Factorization at subleading order (different approaches), charm loops
  - Can direct CP asymmetries in nonleptonic modes be understood enough to make them "discovery modes"? [$SU(3)$, the heavy quark limit, etc.]
- We know how to make progress on some $+$ discover new frameworks / methods?

Roadmap: 1981

Fig. 3. A Program to Understand B Decay

1. Search for exotic B decays.

   If found, explore details;

   -otherwise-

   $\Rightarrow$ dark sector searches, violation of symmetries

2. Search for flavor changing neutral currents.

   If found, measure $(b \to dZ^0)/(b \to sZ^0)$;

   -otherwise-

   $\Rightarrow$ important part of current/future program

3. Measure semileptonic decay branching ratio.

   $\Rightarrow$ important part of current/future program

4. Measure ratio $(b \to uW^-)/(b \to cW^-)$.

   $\Rightarrow$ $|V_{ub}/V_{cb}|$: essential to constrain NP

5. Measure $e\nu:\mu\nu:\tau\nu$ ratio in semileptonic decay.

   $\Rightarrow$ Only possible recently: prophecy of $R(D^{(*)})$?

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Non-b-Decay Features of B Decay

6. Look for lifetime difference between $B^\pm$ and B^0.

   $\Rightarrow$ Seems less important now

7. Look for B^0-$\bar{B}^0$ mixing.

   $\Rightarrow$ Was the first item discovered

[8. CP violation?]

   $\Rightarrow$ Became a central focus of the field

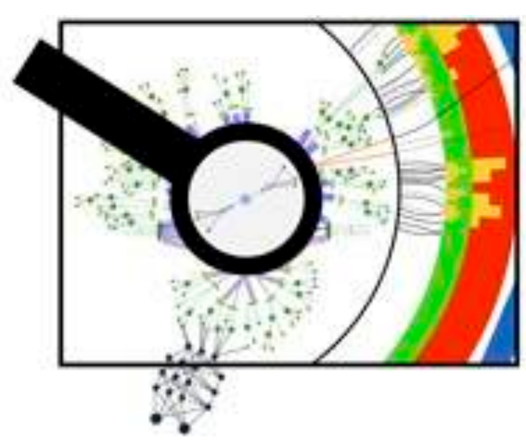
Caltech

Flavors of future surprises?

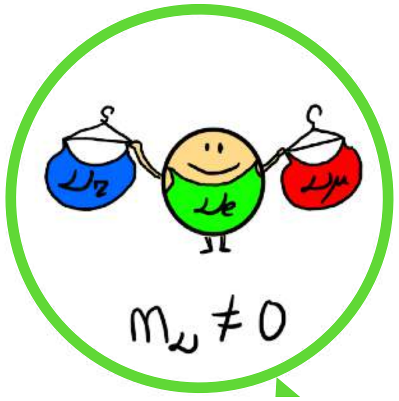
Zoltan Ligeti and Clara Murgui

13th April 2021

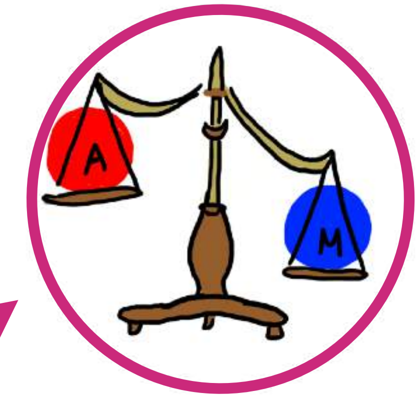
Kavli Institute for Theoretical Physics



Neutrino mass generation



Baryogenesis

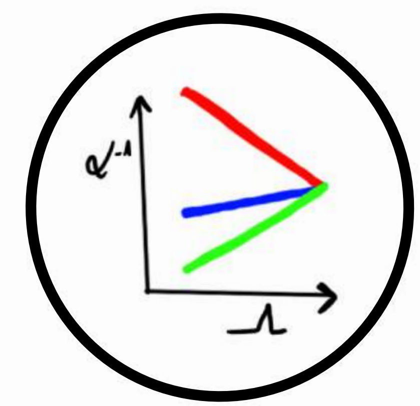


Flavors of future surprises?

Zoltan Ligeti and Clara Murgui

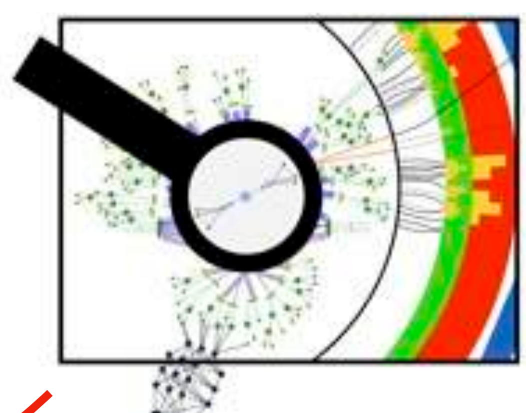
LR-Symmetry?

GUTs

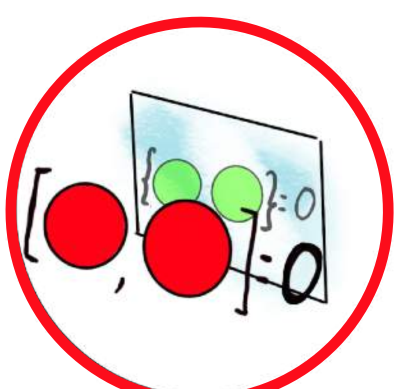


13th April 2021

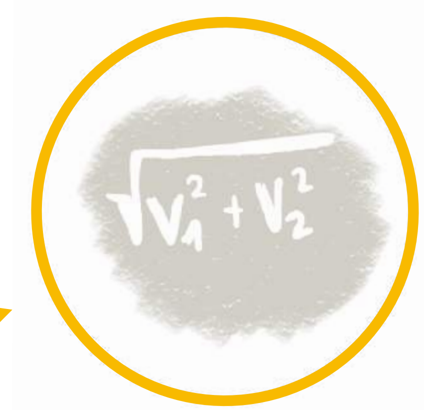
Kavli Institute for Theoretical Physics



SUSY



2HDM

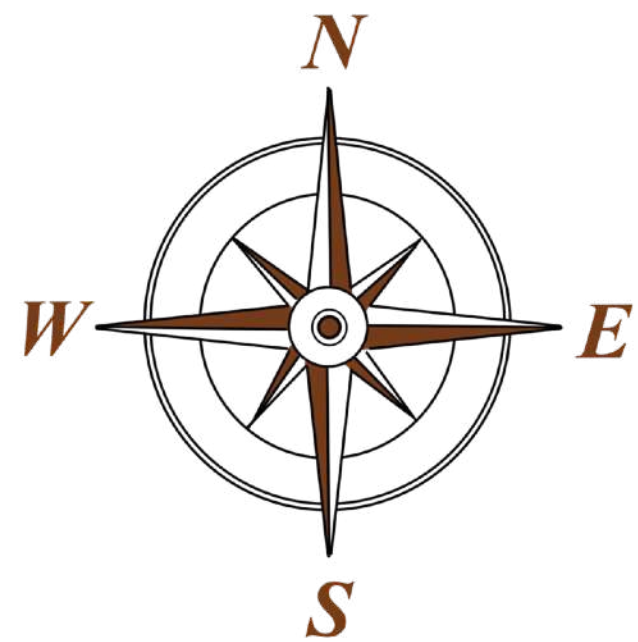


"You are perhaps indeed a searcher,
because, striving for your goal,
there are many things that you don't see,
which are directly in front of your eyes"

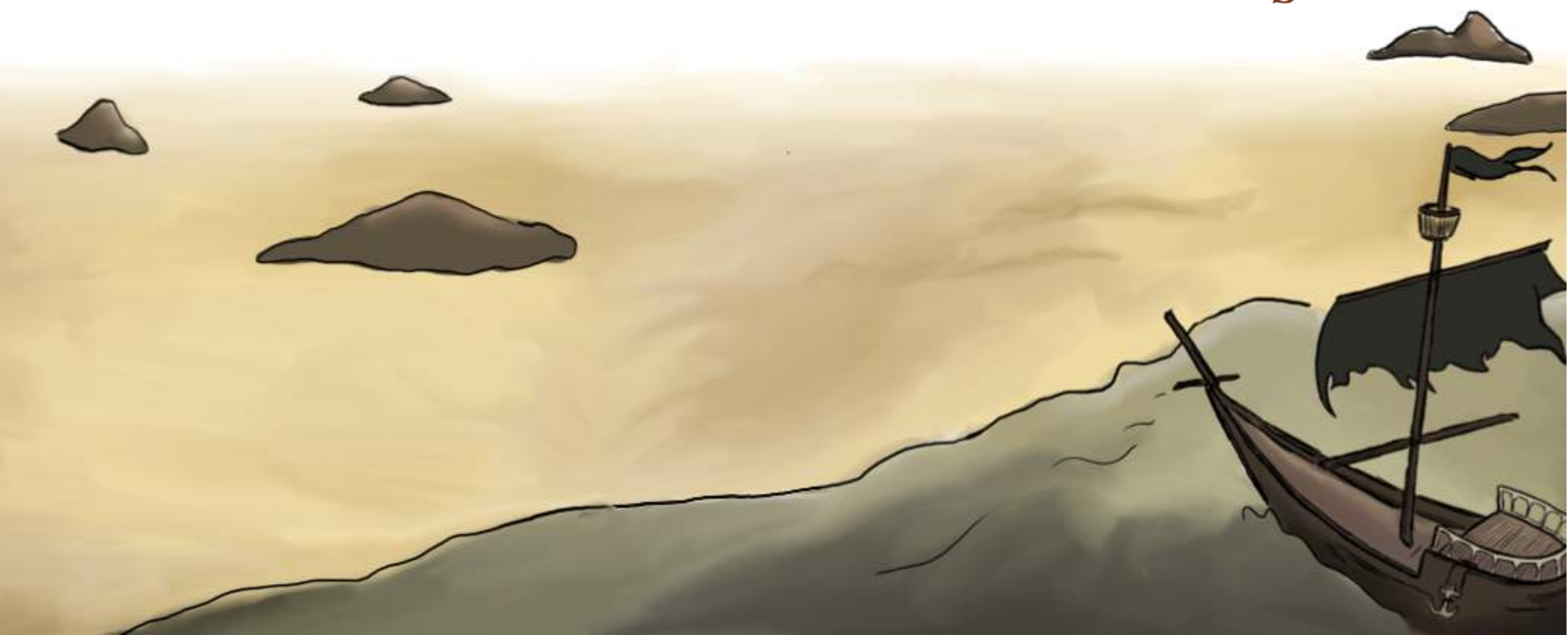
-*Siddhartha*. Hermann Hesse.

(Embrace unpredictability)

Bottom-up approach



[Based on Refs. **1904.09311** and **2004.06726**, in collaboration with **Martin Jung, Rusa Mandal, Ana Peñuelas and Antonio Pich.**]



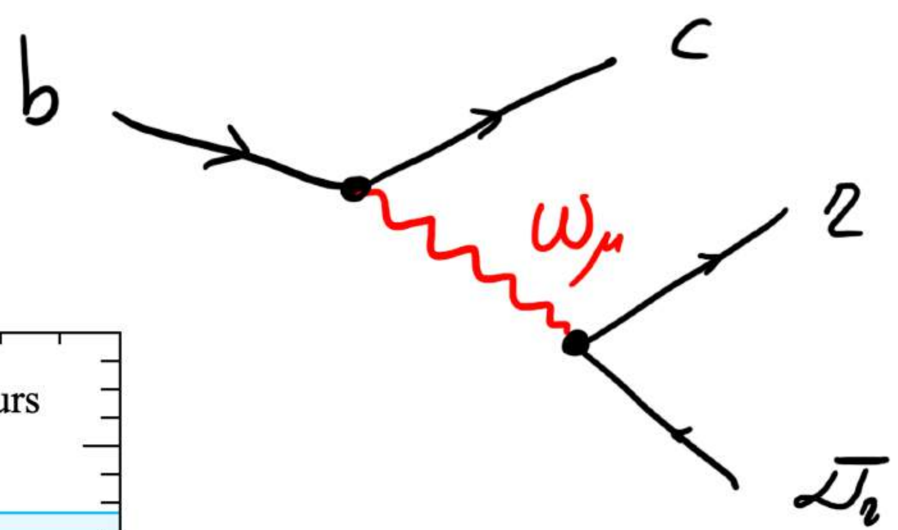
Anomalies in $b \to c$ transitions

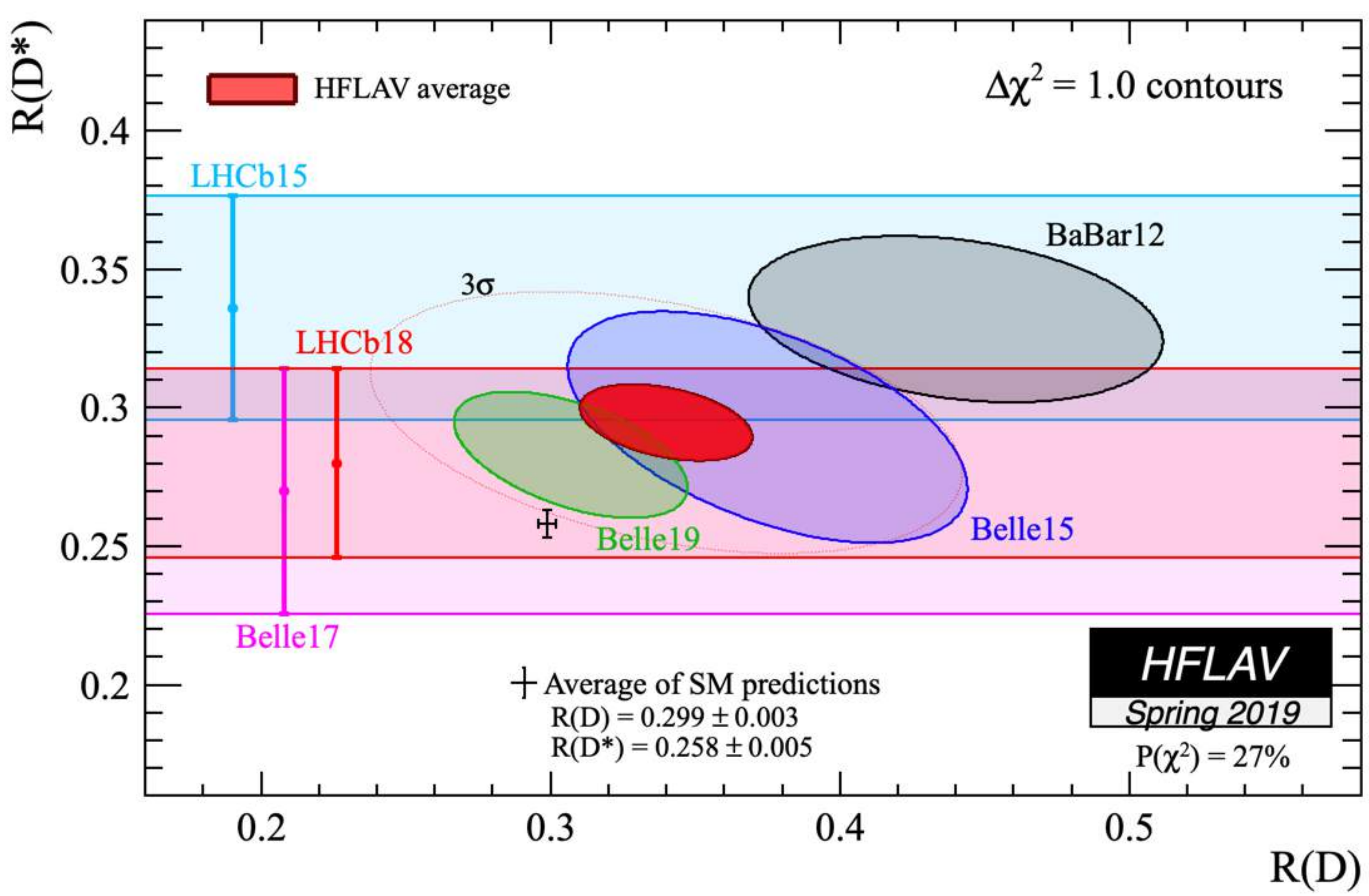
Pattern of deviations in B-meson decays involving b to c transitions pointing to "the same direction"

$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)}$$

3.1 σ

HFLAV, up to date





Anomalies in $b \to c$ transitions

Pattern of deviations in B-meson decays involving b to c transitions pointing to "the same direction"

- $\mathcal{R}_{D^{(*)}} \equiv \dfrac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu}_\ell)}$ **3.1 σ**

  HFLAV, up to date

- $\mathcal{R}_{J/\Psi} \equiv \dfrac{\mathcal{B}(B_c \to J/\Psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\Psi\mu\bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18$ **1.7 σ**

  LHCb, 2017

  $R_{J/\Psi\, SM} \sim 0.25 - 0.28$

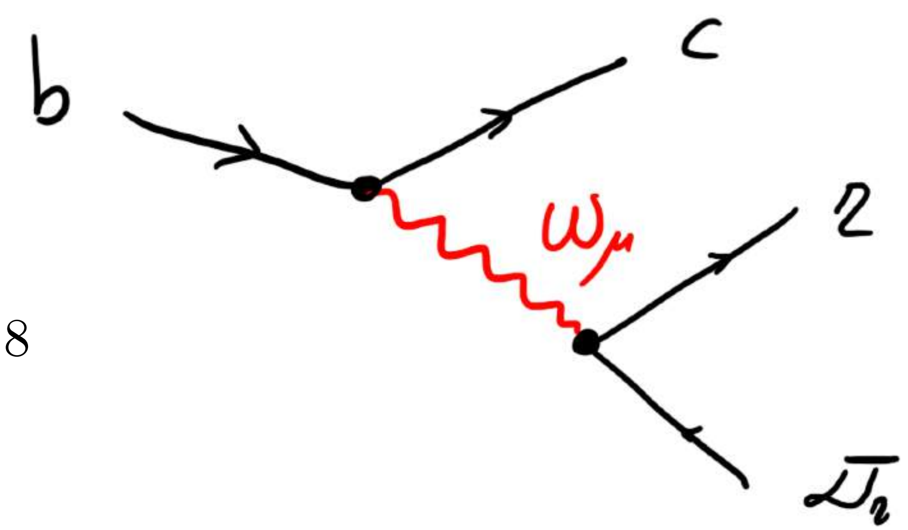
- $\bar{\mathcal{P}}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}$

  Belle, 2016

  $\mathcal{P}_\tau(D^*)_{SM} = -0.499 \pm 0.003$

- $\bar{F}_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$ **1.6 σ**

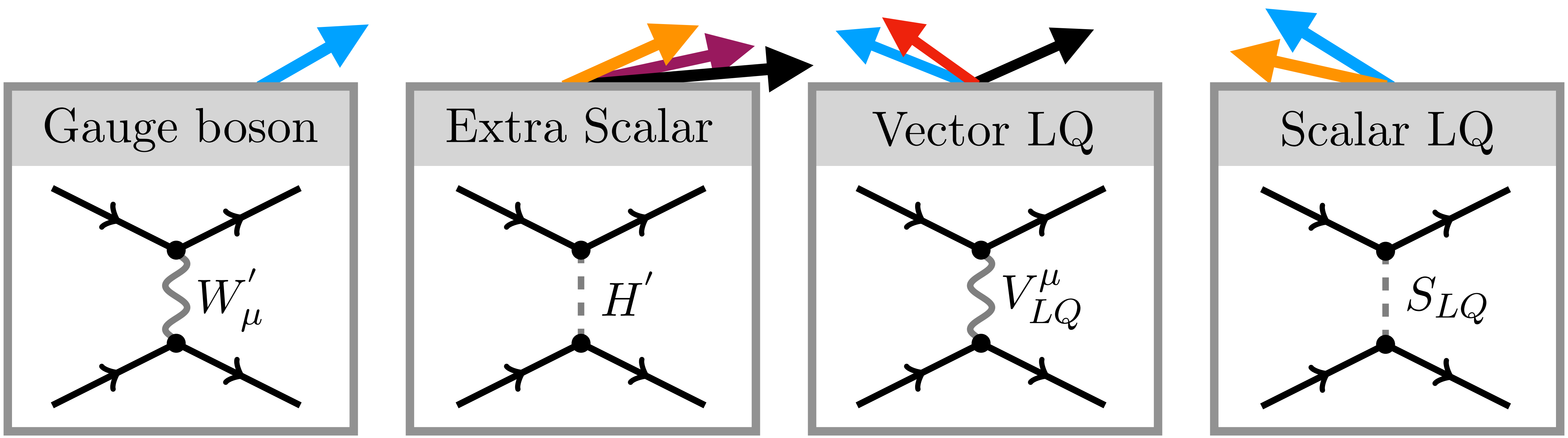
  Belle, 2019



Theoretical Framework

- Most general effective dim 6 Hamiltonian:

$$\mathcal{H}_{\rm eff}^{b\to c\ell\nu} = \frac{4\,G_F}{\sqrt{2}} V_{cb}[(1 + C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\,\mathcal{O}_{V_R} + C_{S_R}\,\mathcal{O}_{S_R} + C_{S_L}\,\mathcal{O}_{S_L} + C_T\,\mathcal{O}_T] + {\rm h.c.}$$



$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell),$$

$$\boxed{\mathcal{O}_{S_R}} = (\bar{c}\,P_R b)(\bar{\ell}\,P_L \nu_\ell), \qquad \boxed{\mathcal{O}_{S_L}} = (\bar{c}\,P_L b)(\bar{\ell}\,P_L \nu_\ell),$$

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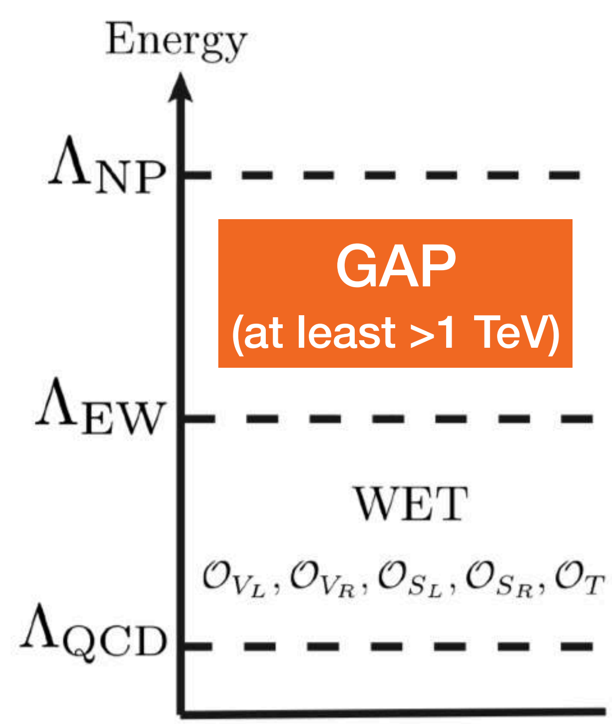
- Assumptions:

  EFT ✓



$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\ell}\,\gamma_\mu P_L \nu_\ell),$$

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- Assumptions:

  - EFT ✓
  - New physics only in the **third generation**

NP effects negligible in $b \to c(e,\mu)\bar{\nu}_{(e,\mu)}$ analysis [Jung, Straub, 1801.01112]

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^{\mu} P_L b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^{\mu} P_R b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}),$$

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Theoretical Framework

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$$\mathcal{H}_{\text{eff}}^{b\to c\ell\nu} = \frac{4\,G_F}{\sqrt{2}} V_{cb}[(1 + C_{V_L})\mathcal{O}_{V_L} + \cancel{C_{V_R}}\mathcal{O}_{V_R} + C_{S_R}\,\mathcal{O}_{S_R} + C_{S_L}\,\mathcal{O}_{S_L} + C_T\,\mathcal{O}_T] + \text{h.c.}$$

- Assumptions:

  - EFT ✓
  - New physics only in the **third generation,**
  - C_{V_R} lepton flavour universal $\Rightarrow C_{V_R}^{\tau} \sim 0$

$$C_{V_R}^{\ell} \equiv C_{V_R} + \mathcal{O}\left(\frac{v^4}{\Lambda_{\text{NP}}^4}\right)$$

Assuming SMEFT and no significant effect from NP in $b \to c(e,\mu)\bar{\nu}_{(e,\mu)}$ [Jung, Straub, 1801.01112]

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^{\mu}P_L b)(\bar{\tau}\,\gamma_{\mu}P_L\nu_{\tau}), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^{\mu}P_R b)(\bar{\tau}\,\gamma_{\mu}P_L\nu_{\tau}),$$

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- Assumptions:
  - EFT
  - New physics only in the **third generation,**
  - C_{V_R} lepton flavour universal $\Rightarrow C_{V_R}^{\tau} \sim 0$
  - CP conserving W.C.

    Fitted complex W.C. without significant improvement

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^\mu P_L b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^\mu P_R b)(\bar{\tau}\,\gamma_\mu P_L \nu_\tau),$$

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- Assumptions:

$$\left.\begin{array}{l}\Rightarrow \text{EFT} \; ✓\\ \Rightarrow \text{New physics only in the \textbf{third generation,}}\\ \Rightarrow C_{V_R} \text{ lepton flavour universal} \;\; \Rightarrow C_{V_R}^{\tau} \sim 0\\ \Rightarrow \text{CP conserving W.C.}\end{array}\right\} \boxed{\text{4 d.o.f.}}$$

$$\boxed{\mathcal{O}_{V_L}} = (\bar{c}\,\gamma^{\mu} P_L b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}), \qquad \boxed{\mathcal{O}_{V_R}} = (\bar{c}\,\gamma^{\mu} P_R b)(\bar{\tau}\,\gamma_{\mu} P_L \nu_{\tau}),$$

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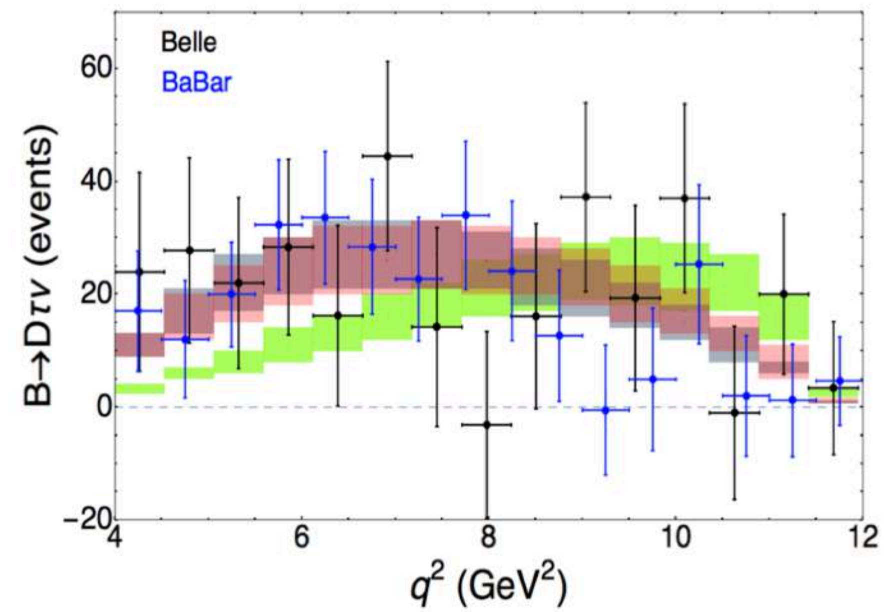
- Inputs:

  - $\mathcal{R}_D$
  - $\mathcal{R}_{D^*}$
  - $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$

$$\tilde{\Gamma}(B \to D^{(*)}\tau\bar{\nu}_\tau) = \frac{\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)_{\text{bin}}}{\sum_{\text{all bins}}\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)_{\text{bin}}}$$

[Belle, 1507.03233]



[BaBar, 1303.0571]

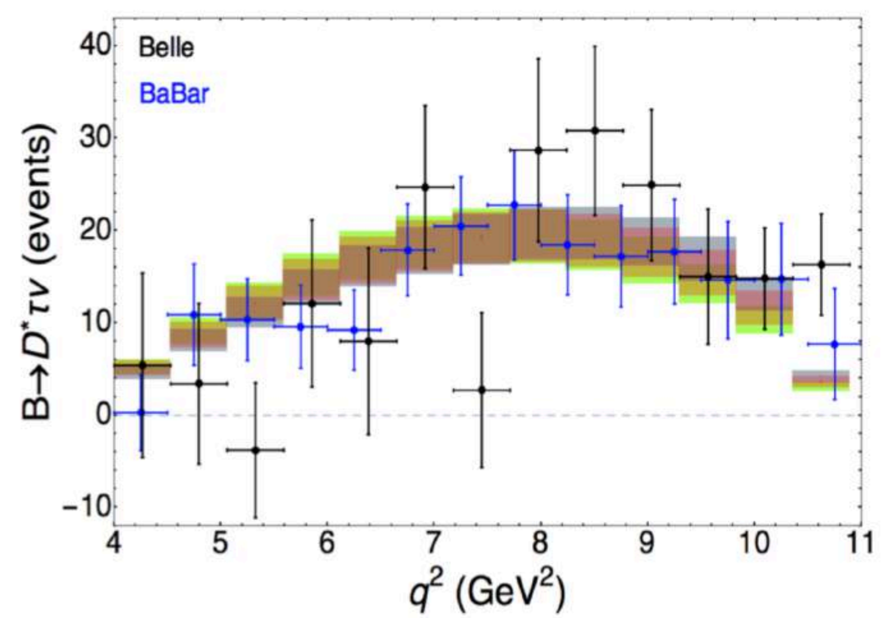


Image borrowed from [Celis et al., 2016]

Theoretical Framework

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- Inputs:

  - $\mathcal{R}_D$
  - $\mathcal{R}_{D^*}$
  - $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
  - $B_c \to \tau\bar{\nu}_\tau$

- Bc lifetime:

$\Rightarrow \text{Br}(B_c \to \tau\bar{\nu}_\tau) \leq 30 - 40\%$

[Alonso et al., 2016]

- Bound LEP Z peak:

[Akeroyd et al., 2017]

$\Rightarrow \text{Br}(B_c \to \tau\bar{\nu}_\tau) \leq 10\%$

$$\mathcal{B}(B_c \to \tau\bar{\nu}_\tau) = \#|V_{cb}|^2 \times \left|1 + C_{V_L} - C_{V_R} + \frac{m_{B_c}^2}{m_\tau(m_b + m_c)}(C_{S_R} - C_{S_L})\right|^2$$

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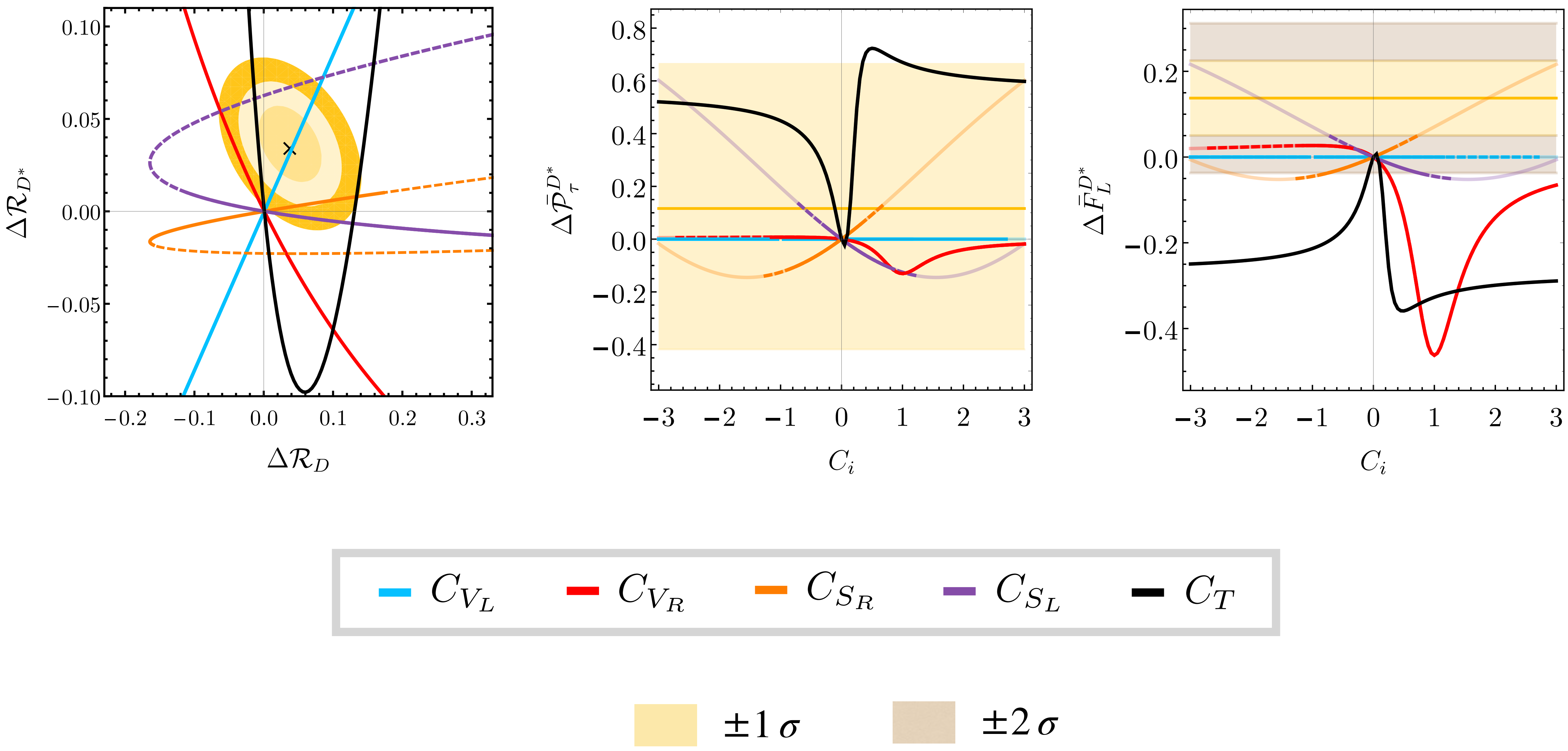
- Inputs:

  - $\mathcal{R}_D$
  - $\mathcal{R}_{D^*}$
  - $\Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
  - $B_c \to \tau\bar{\nu}_\tau$
  - $F_L^{D^*}$

▶ First measurement of D^* polarization in $B^0(\overline{B}^0) \to D^*\tau\nu$

$F_L^{D^*} = 0.60 \pm 0.08(stat.) \pm 0.035(syst.)$

Fit independent analysis



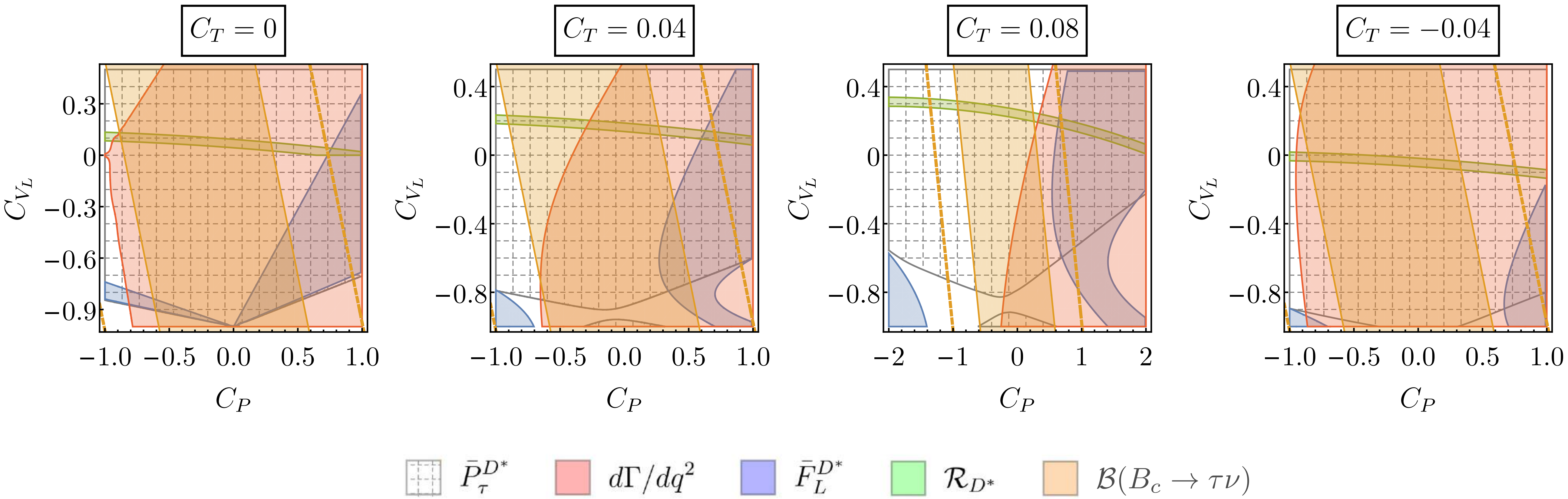
Fit independent analysis

$$\Rightarrow \mathcal{R}_{D^*} = \mathcal{R}_{D^*}[\underbrace{(1 + C_{V_L} - C_{V_R})}_{\text{axial}\equiv C_A},\ \underbrace{(C_{S_R} - C_{S_L})}_{\text{pseudo-scalar}\equiv C_P},C_T]$$

- Inputs:

  - $\Rightarrow \mathcal{R}_{D^*}$ (C_A) C_P C_T
  - $\Rightarrow \Gamma(B \to D^{(*)}\tau\bar{\nu}_\tau)$
  - $\Rightarrow B_c \to \tau\bar{\nu}_\tau$ C_A C_P
  - $\Rightarrow F_L^{D^*}$ C_A C_P C_T

Fit independent analysis



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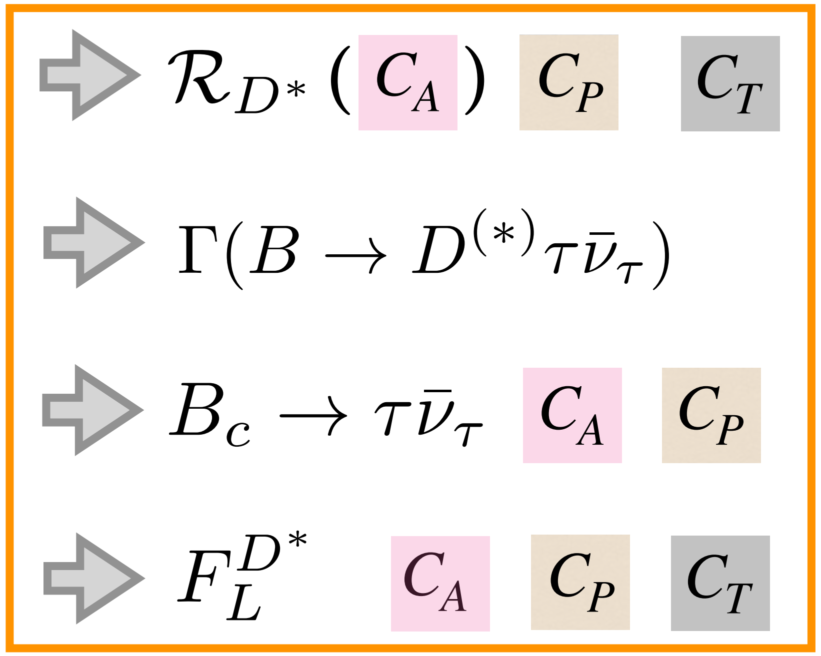
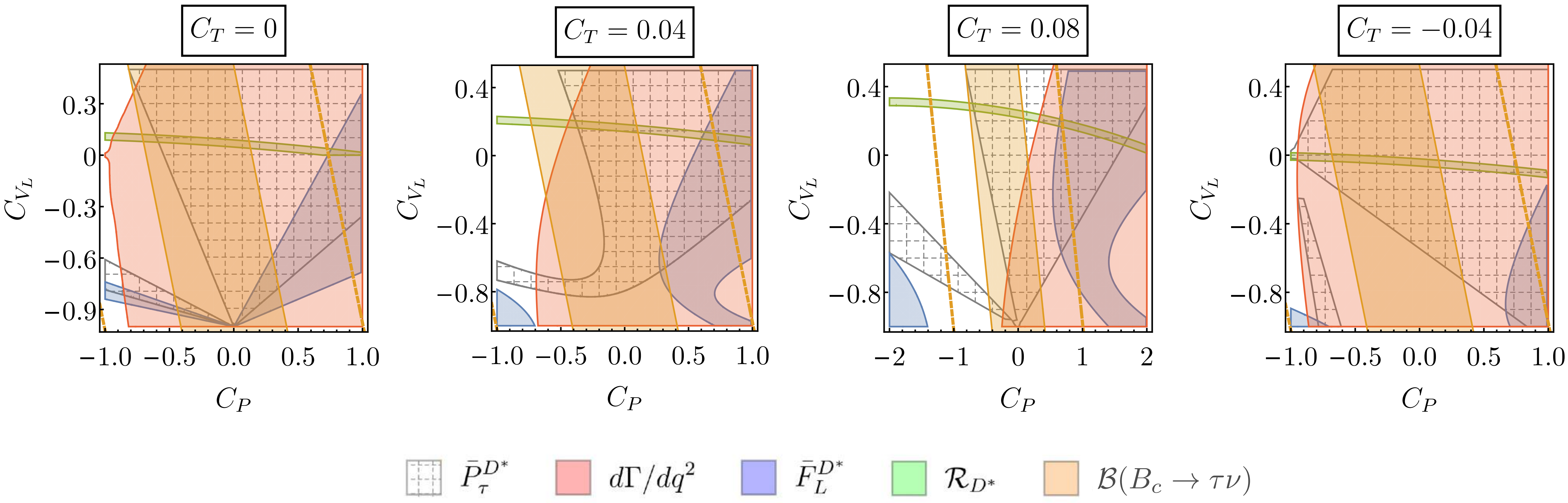


Implications of new measurements?



Belle-II	5 ab^{-1}	50 ab^{-1}
$\mathcal{R}_{D^*}$	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$
$\bar{P}_\tau^{D^*}$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

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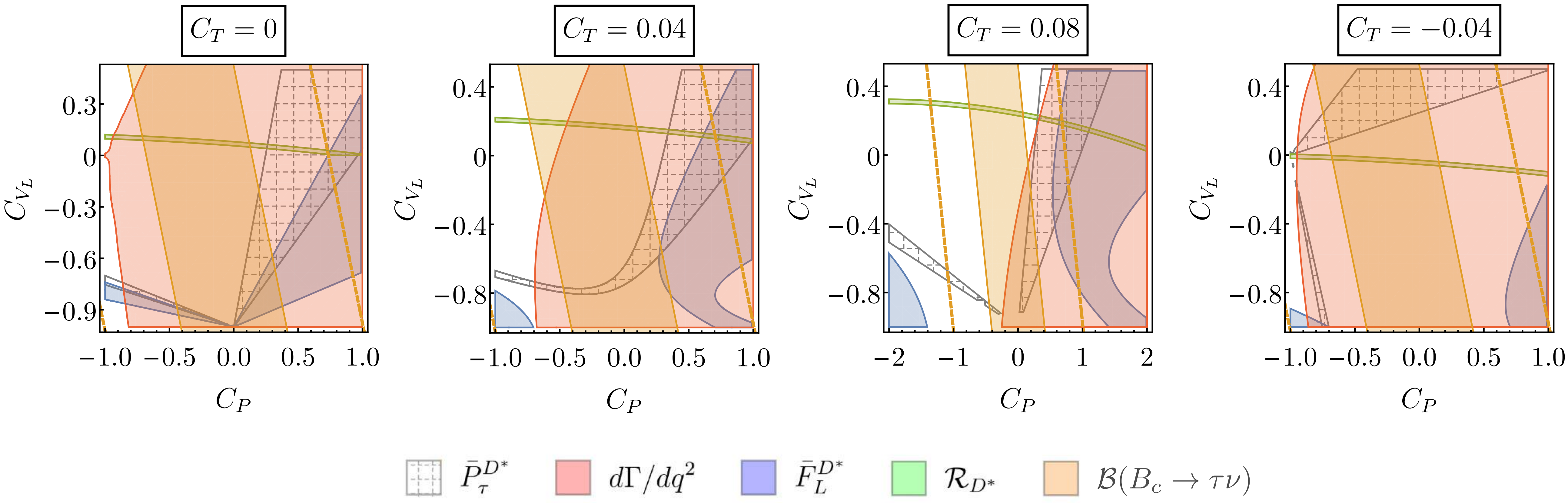

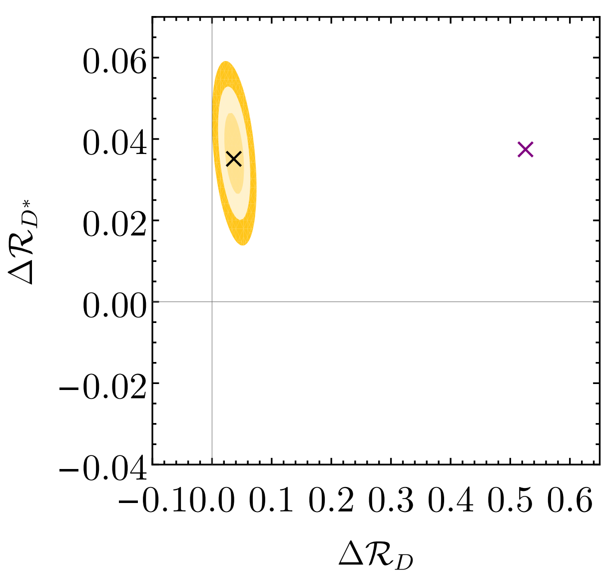

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▶ First measurement of D^* polarization in $B^0(\overline{B}^0) \to D^*\tau\nu$

$F_L^{D^*} = 0.60 \pm 0.08(\textit{stat.}) \pm 0.035(\textit{syst.})$

$$\chi^2 = \underbrace{\chi^2_{\rm exp}} + \underbrace{\chi^2_{FF}}$$

$\mathscr{R}_D, \mathscr{R}_{D^*}$ 2 d.o.f.

$\Gamma(B \to D^{(*)})$ 58 d.o.f.

$F_L^{D^*}$ 1 d.o.f.

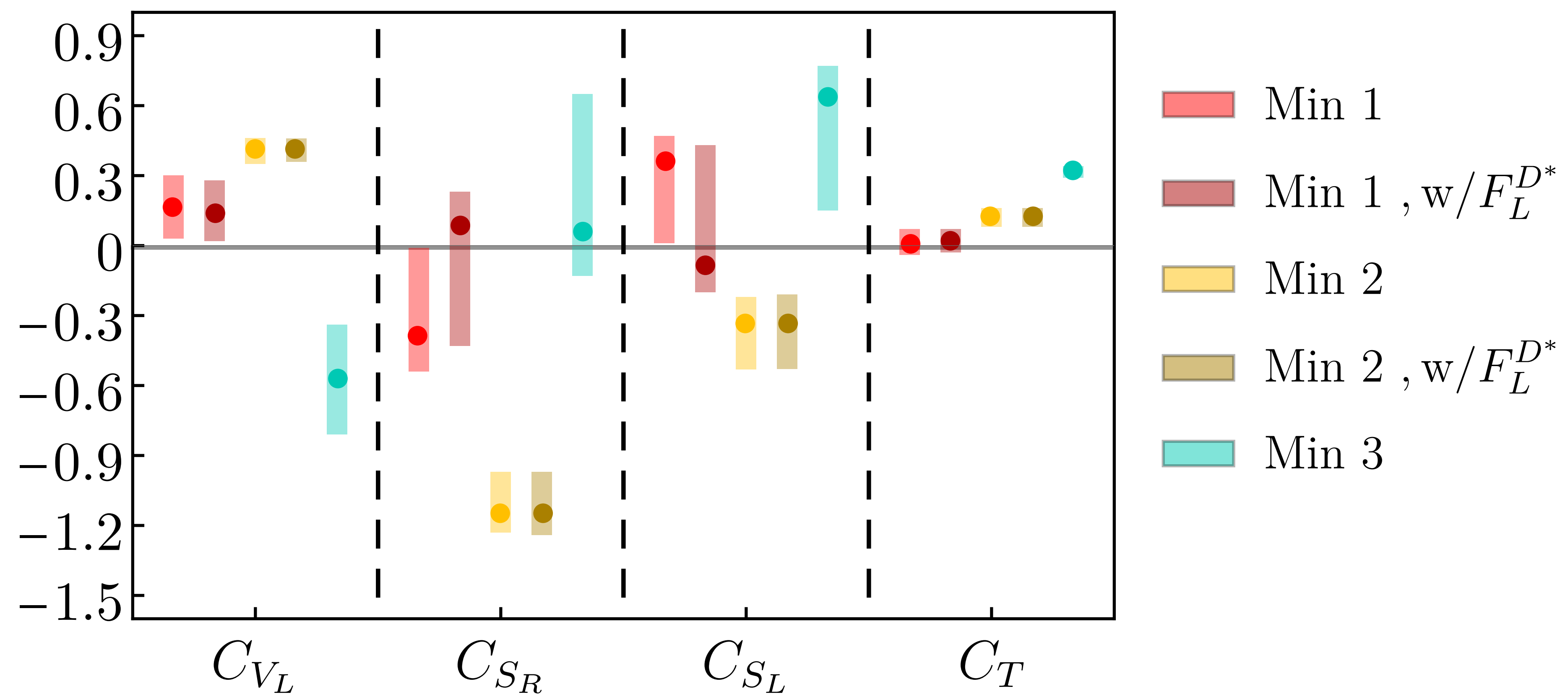
Global Fit

- SM: $\chi^2_{SM} = 65.5\,/\,57$ d.o.f.

- New Physics: $\chi^2_{min1} = 34.1\,/\,53$ d.o.f. $\quad \chi^2_{min2} = 37.5\,/\,53$ d.o.f. $\quad \cancel{\chi^2_{min3} = 58.6\,/\,53 \text{ d.o.f.}}$

$\chi^2_{min1b} = 37.4\,/\,54$ d.o.f. $\quad \chi^2_{min2b} = 40.1\,/\,54$ d.o.f.

10%



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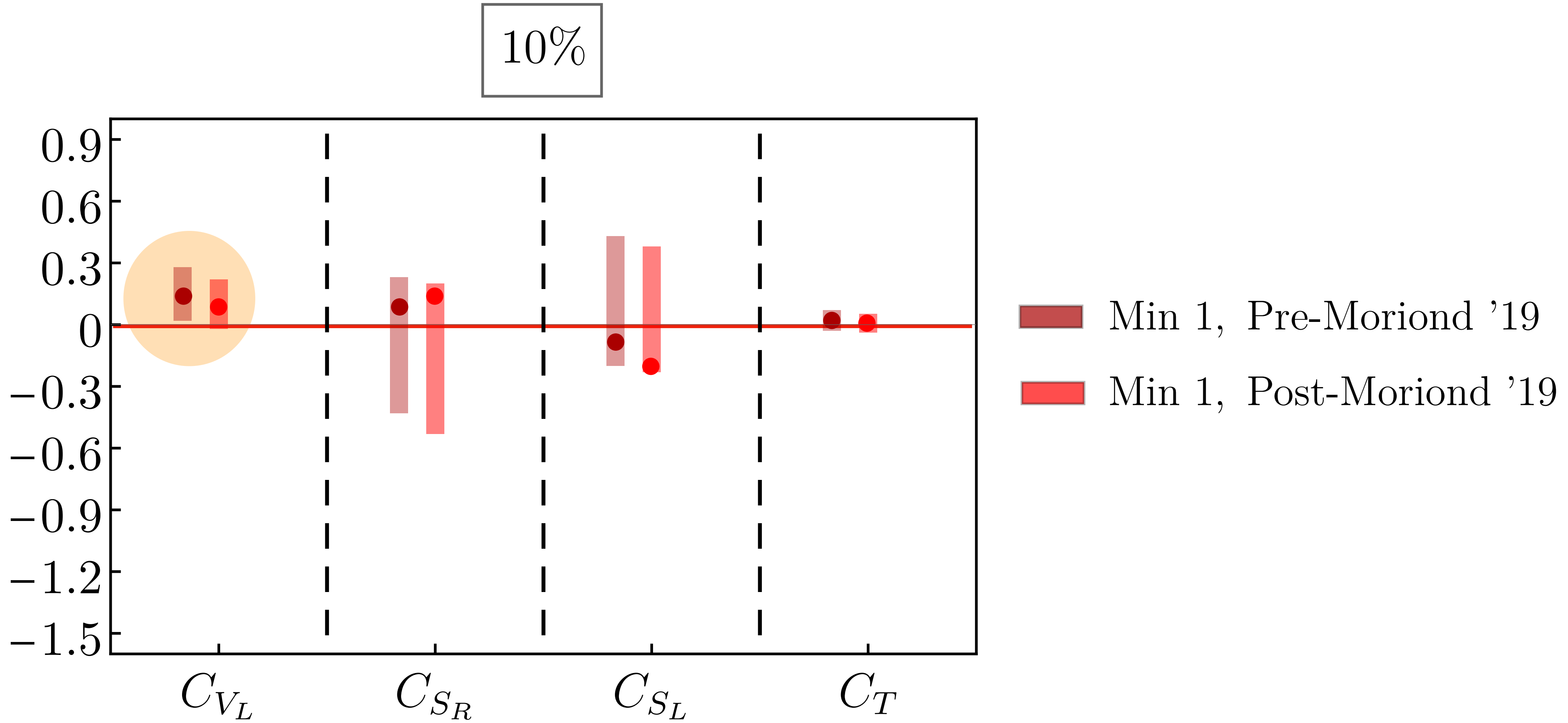
$$\boxed{\chi^2_{min1b} = 37.4\,/\,54 \text{ d.o.f.}}$$



What is going on?

- Theory assumptions:
  - EFT
  - New physics only in the third generation
  - C_{V_R} flavour universal
  - CP conserving W.C.
- Experimental measurements

  An unidentified or underestimated systematic uncertainty...

What is going on?

- Theory assumptions:
  - EFT
  - New physics only in the third generation of leptons
  - C_{V_R} flavour universal
  - CP conserving W.C.

No significant improvement of χ^2 by promoting the W.C. to be complex

- Experimental measurements

An unidentified or underestimated systematic uncertainty...

What is going on?

- Theory assumptions:

  ⇨ EFT

  ⇨ New physics only in the third generation of leptons

  ⇨ C_{V_R} ~~flavour universal~~

  EW breaking is non-linear?

  ⇨ CP conserving W.C.

- Experimental measurements

  An unidentified or underestimated systematic uncertainty...

What is going on?

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  - ~~EFT~~ New light d.o.f.

  - New physics only in the third generation of leptons

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What is going on?

- Theory assumptions:

  - EFT   New light d.o.f.

    [C. Bobeth et al., a week ago]

  - New physics only in the third generation of leptons   **??**

  - C_{V_R} flavour universal

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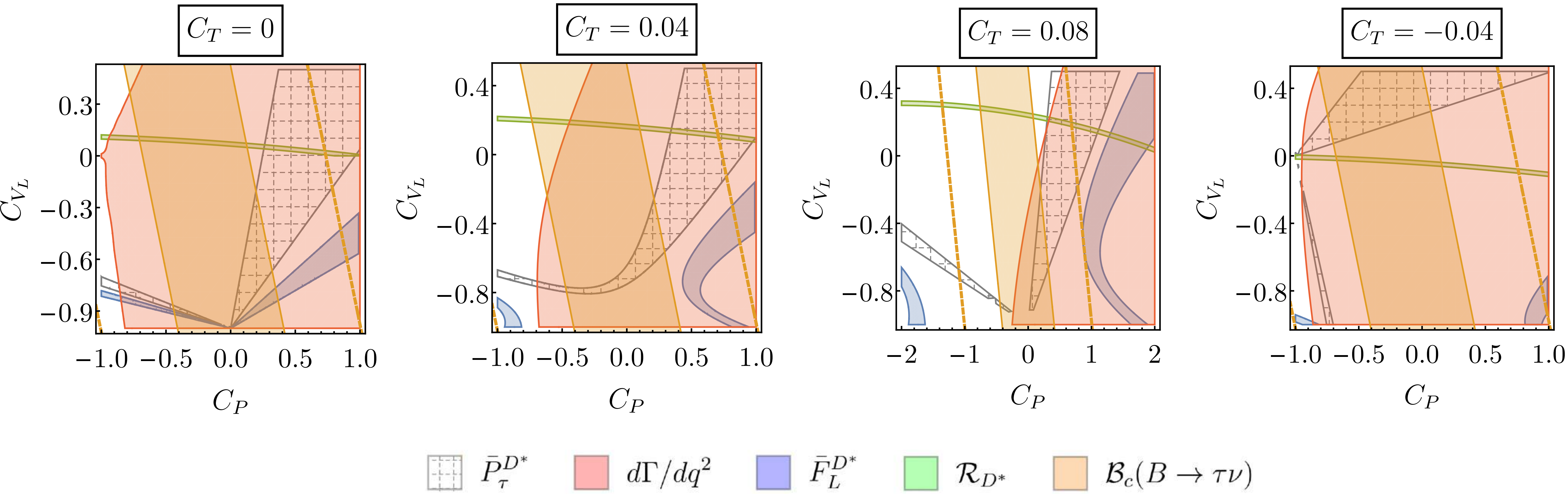
An unidentified or underestimated systematic uncertainty...

Implications of new measurements?

[Speculating...]



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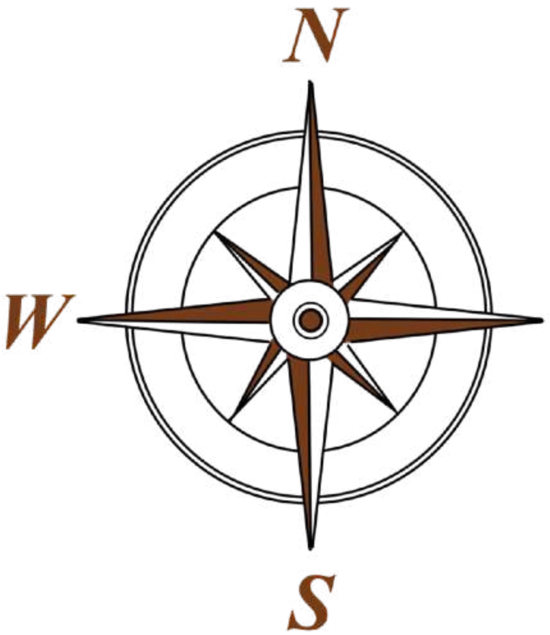
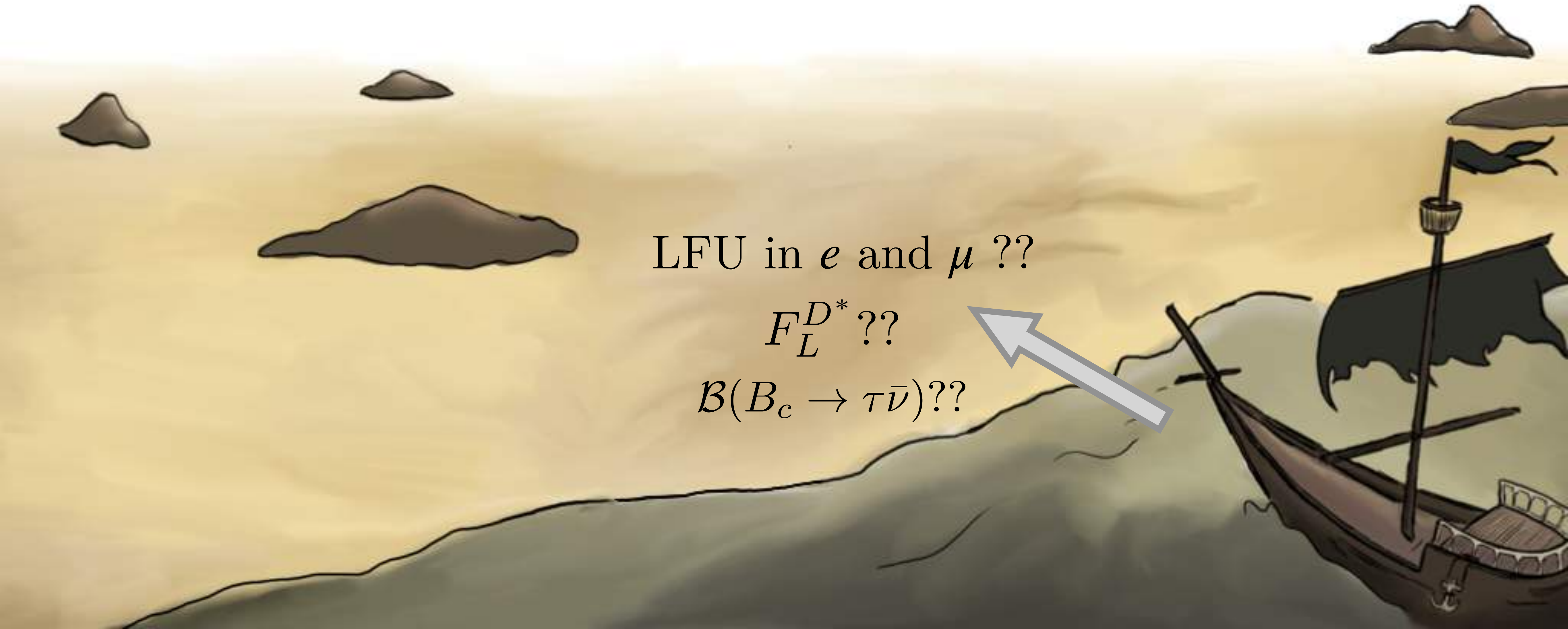
$\bar{P}_\tau^{D^*}$	$\pm 0.18 \pm 0.08$	$\pm 0.06 \pm 0.04$

My guess: $F_L^{D^*} \sim 15\%$ ⇨ 5%

Bottom-up approach



???



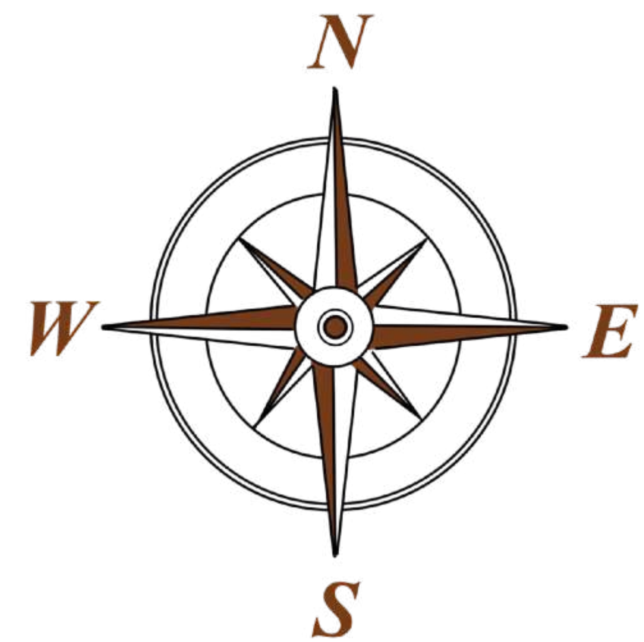
LFU in e and μ ??

$F_L^{D^*}$??

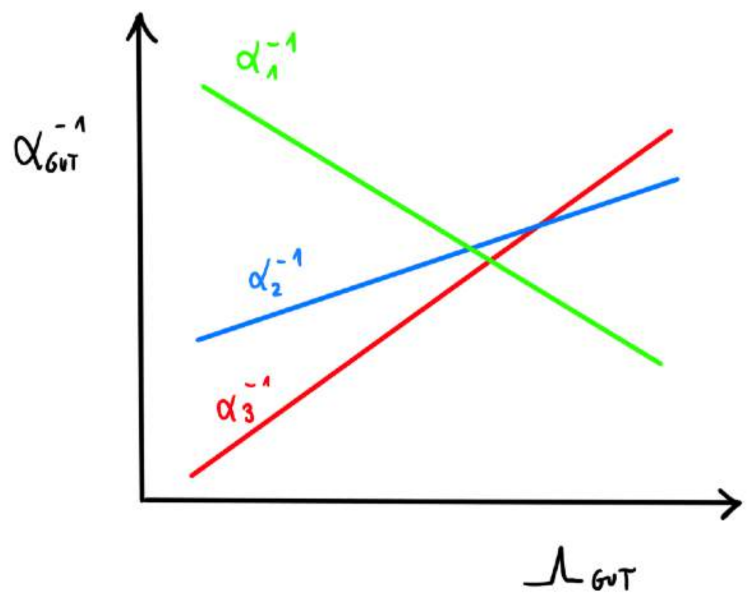
$\mathcal{B}(B_c \to \tau\bar{\nu})$??

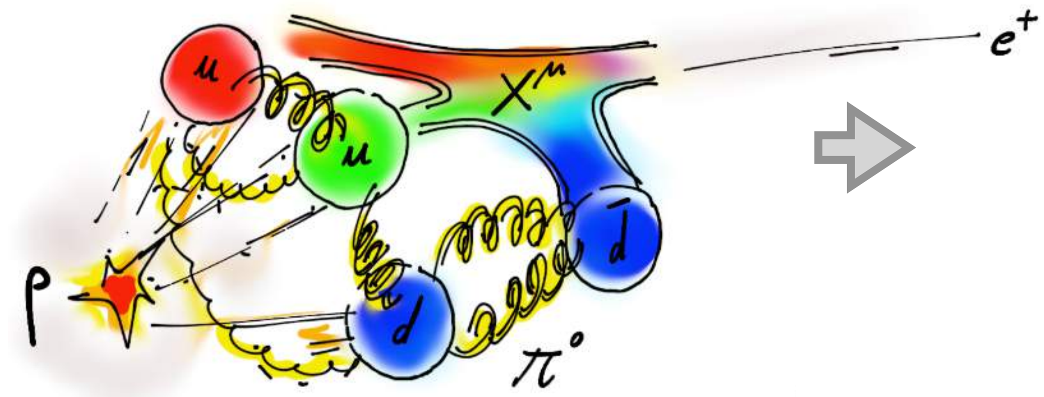
Top-down approach

[Ongoing work with **Pavel Fileviez Pérez** and **Alexis Plascencia**]



Unification of Matter





$\Lambda_{\mathrm{GUT}} \gtrsim 10^{15}$ GeV

$3 \times$

Q_L	Q_L	Q_L	ℓ_L
u_R	u_R	u_R	ν_L
d_R	d_R	d_R	e_R

$$\boxed{SU(3)_C} \otimes SU(2)_L \otimes U(1)_Y$$

Unification of Matter

$$F_{QL} \sim (4, 2, 0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L$$

$$F_u = \begin{pmatrix} u^c & \nu^c \end{pmatrix}_L \sim (\bar{4}, 1, -1/2)$$

$$F_d = \begin{pmatrix} d^c & e^c \end{pmatrix}_L \sim (\bar{4}, 1, 1/2)$$

$$3 \times \left\{ \begin{array}{ccc|c} Q_L & Q_L & Q_L & l_L \\ u_R & u_R & u_R & \nu_L \\ d_R & d_R & d_R & e_R \end{array} \right\}$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

[P. Fileviez Perez and M. Wise 2013]

Unification of Matter

$$\boxed{F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L}$$

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$$\mathcal{L}_Y = Y_1 \, F_{QL} F_u H + Y_3 \, H^\dagger F_{QL} F_d$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}}$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} \qquad M_e = Y_3 \frac{v_1}{\sqrt{2}}$$

$$H \sim (1, 2, 1/2)_{\mathrm{SM}}$$

$$\cancel{SU(4)}_c \otimes SU(2)_L \otimes \cancel{U(1)}_R \Rightarrow SU(3)_c \otimes \cancel{SU(2)}_L \otimes \cancel{U(1)}_Y \Rightarrow SU(3)_c \otimes U(1)_Q$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

[P. Fileviez Perez and M. Wise 2013]

Unification of Matter

$$\boxed{F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L}$$

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$$\mathcal{L}_Y = Y_1 \, F_{QL} F_u H + Y_3 \, H^\dagger F_{QL} F_d + Y_2 \, F_{QL} F_u \Phi + Y_4 \, \Phi^\dagger F_{QL} F_d + \text{h.c.}$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

$$M_\nu^D = Y_1 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_e = Y_3 \frac{v_1}{\sqrt{2}} - \frac{3}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}}.$$

$$\Phi \sim (15, 2, 1/2) = \begin{pmatrix} \Phi_{\text{MW}} & \Phi_3 \\ \Phi_4 & 0 \end{pmatrix} + T_4 H_2, \quad H \sim (1,2,1/2)_{\text{SM}}$$

$$\cancel{SU}(4)_c \otimes SU(2)_L \otimes U\cancel{(1)}_R \Rightarrow SU(3)_c \otimes \cancel{SU}(2)_L \otimes U\cancel{(}1)_Y \Rightarrow SU(3)_c \otimes U(1)_Q$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

[P. Fileviez Perez and M. Wise 2013]

Unification of Matter

$$\boxed{F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L}$$

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$$\boxed{F_d = \begin{pmatrix} d^c & e^c \end{pmatrix}_L \sim (\bar{4}, 1, 1/2)}$$

$$\mathcal{L}_K \supset \frac{g_4}{\sqrt{2}} U_1^\mu (\bar{Q}_L \gamma_\mu \ell_L + \bar{u}_R \gamma_\mu \nu_R + \bar{d}_R \gamma_\mu e_R) + \text{h.c.}$$

naive bound!

- Though constraint: $K_L \to \mu^\pm e^\mp \Rightarrow M_{U_1^\mu} \sim 10^3$ TeV

$$V_{15}^\mu \sim (15,1,0) = \begin{pmatrix} G^\mu & U_1^\mu/\sqrt{2} \\ (U_1^\mu)^*/\sqrt{2} & 0 \end{pmatrix} + T_4 B'^\mu$$

$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

[P. Fileviez Perez and M. Wise 2013]

Unification of Matter

$$\boxed{F_{QL} \sim (4,2,0) = \begin{pmatrix} u & \nu \\ d & e \end{pmatrix}_L}$$

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$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

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[P. Fileviez Perez and M. Wise 2013]

Unification of Matter

- The theory predicts scalar LQs:

$$\Phi_3 \sim (\bar{3}, 2, -1/6)_{\text{SM}} \qquad\qquad \Phi_4 \sim (3, 2, 7/6)_{\text{SM}}$$

$$-\mathcal{L}_Y \supset Y_2\, Q_L \Phi_3 (\nu^c)_L + Y_2\, \ell_L \Phi_4 (u^c)_L + Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

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[P. Fileviez Perez and M. Wise 2013]

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$$M_u = Y_1 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_2 \frac{v_2}{\sqrt{2}} \qquad M_d = Y_3 \frac{v_1}{\sqrt{2}} + \frac{1}{2\sqrt{6}} Y_4 \frac{v_2}{\sqrt{2}},$$

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$$SU(4)_C \otimes SU(2)_L \otimes U(1)_R$$

[P. Fileviez Perez and M. Wise 2013]

$b \to s\ell^+\ell^-$ transitions

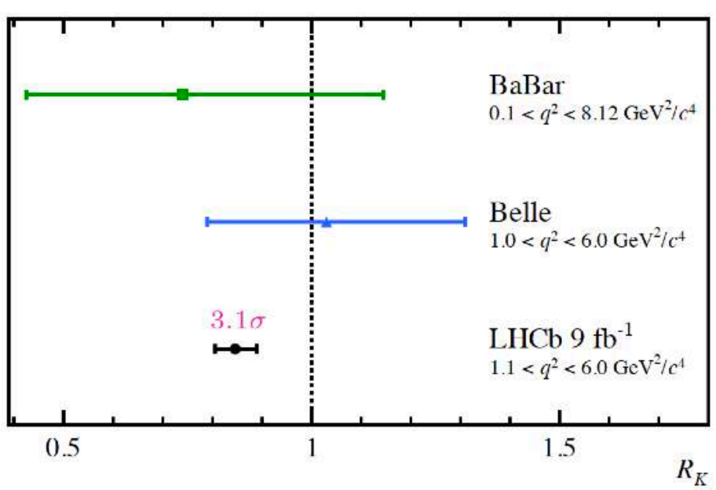
- Motivation: the theory allows us to understand the 3 σ in $\mathcal{R}_K$!

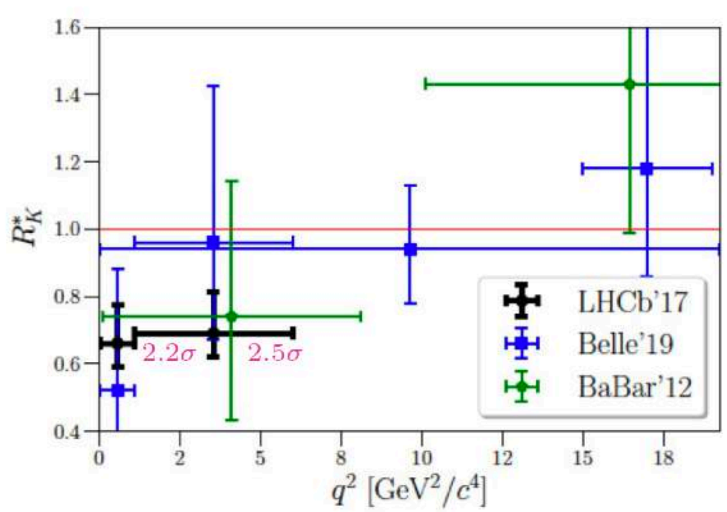
⇨ Will tell us about some parameters of the theory (mass LQs, Yukawa couplings)

stolen from Zoltan's talk

R_K and R_{K^*}: theoretically cleanest

- LHCb: $R_{K^{(*)}} = \dfrac{B \to K^{(*)}\mu^+\mu^-}{B \to K^{(*)}e^+e^-} < 1$ both ratios $\sim 2.5\sigma$ from lepton universality





- Combined fits only by theorists ~~(some include P_5'~~ and/or $B_s \to \phi\mu^+\mu^-$)
- Modifying one Wilson coefficient in $\mathcal{H}_{\text{eff}}$ gives good fit: $\delta C_{9,\mu} \sim -1$ (NP or QCD?)

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$b \to s\ell^+\ell^-$ transitions

- Motivation: the theory allows us to understand the 3 σ in $\mathcal{R}_K$!

  ⇨ Will tell us about some parameters of the theory (mass LQs, Yukawa couplings)

- Clean observables:

3.1σ $\mathcal{R}_K^{\text{exp}}(1.1 < q^2 < 6.0\ \text{GeV}^2/c^4) = 0.846^{+0.042\,+0.013}_{-0.039\,-0.012}$

2.1-2.5σ $$\mathcal{R}_{K^*}^{\text{exp}} = \begin{cases} 0.66^{+0.11}_{-0.07}\ (\text{stat}) \ \pm 0.03\ (\text{syst}) & \text{for } 0.045 < q^2 < 1.1\ \text{GeV}^2/c^4, \\ 0.69^{+0.11}_{-0.07}\ (\text{stat}) \ \pm 0.05\ (\text{syst}) & \text{for } 1.1 < q^2 < 6.0\ \text{GeV}^2/c^4. \end{cases}$$

2.1σ $\text{Br}(B_s \to \mu^+\mu^-)^{\text{exp}} = 2.69^{+0.37}_{-0.35} \times 10^{-9}$

$\text{Br}(B_s \to e^+e^-)^{\text{exp}} < 5.4 \times 10^{-5}$

Paper today by G. Isidori et al. ⇨ 3.9σ

Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions!

$$\mathcal{L}_{\text{eff}}^{\phi_3^{-2/3}} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \left[C'_{9\ell\ell} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell) + C'_{10\ell\ell} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma^5 \ell) \right]$$

$$\Rightarrow \quad C'_{10\ell\ell} = -C'_{9\ell\ell} = \left(\frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^* \alpha} \right) \frac{\tilde{Y}_4^{\ell 3} (\tilde{Y}_4^{\ell 2})^*}{4 M^2_{\phi_3^{-2/3}}}$$

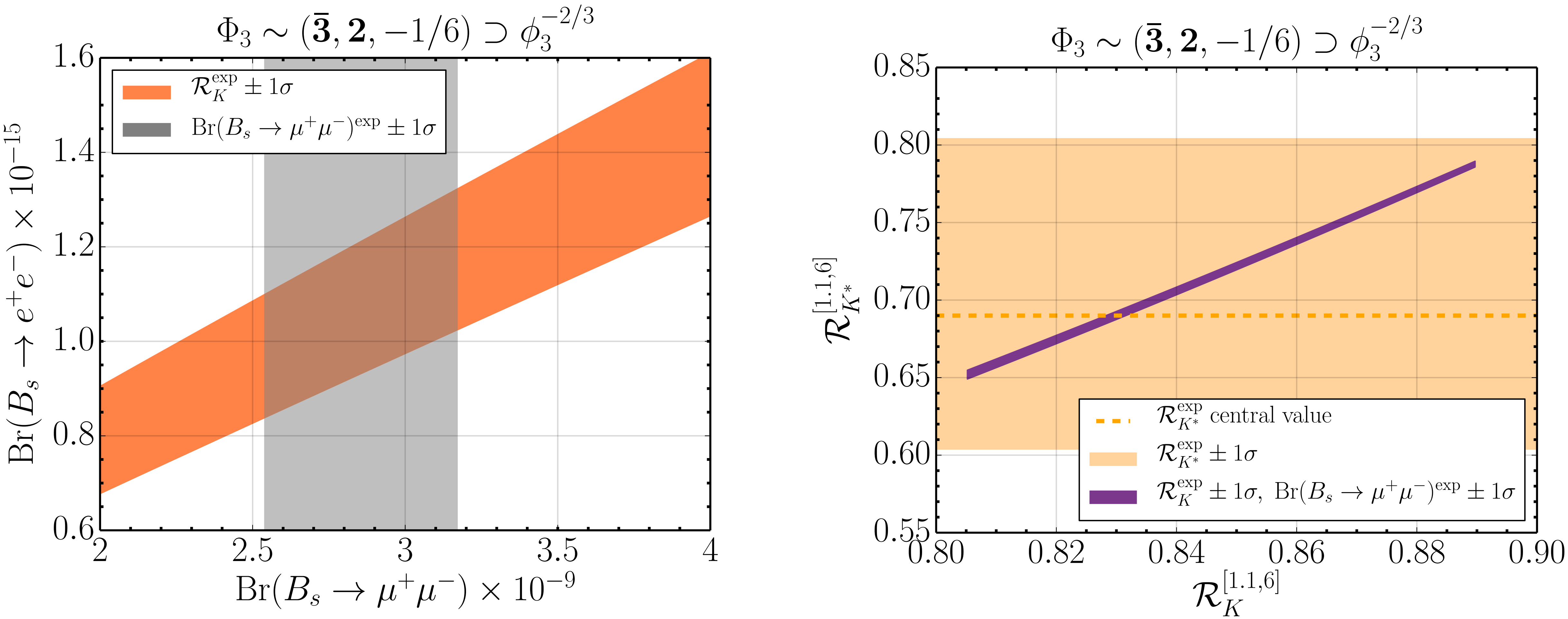
Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

$$C'_{10\ell\ell} = -C'_{9\ell\ell}$$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions!

$$\text{Br}(B_s \to \ell^+\ell^-) = f_2(C'_{10\ell\ell}) \qquad \mathcal{R}_{K^{(*)}} = \frac{f_2(C'_{10\mu\mu})}{f_2(C'_{10ee})}$$



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$$C'_{10\ell\ell} = -C'_{9\ell\ell}$$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)

$$\tilde{Y}_4 = \begin{pmatrix} Y_4^{11} & Y_4^{12} & Y_4^{13} \\ Y_4^{21} & Y_4^{22} & Y_4^{23} \\ Y_4^{31} & Y_4^{32} & Y_4^{33} \end{pmatrix}$$

Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

$$C'_{10\ell\ell} = -C'_{9\ell\ell}$$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)

$K_L \to \mu^{\pm} e^{\mp}$

$R_{K^{(*)}}$, $B_s \to \mu^+\mu^-$

$$\tilde{Y}_4 = \begin{pmatrix} Y_4^{ed} & Y_4^{es} & Y_4^{eb} \\ Y_4^{\mu d} & Y_4^{\mu s} & Y_4^{\mu b} \\ Y_4^{\tau d} & Y_4^{\tau s} & Y_4^{\tau b} \end{pmatrix}$$

$\tau \to \phi \mu$

$\tau \to K_s\, e/\mu$

Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

$$\Phi_3 = \begin{pmatrix} \phi_3^{1/3} \\ \phi_3^{-2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_3} = Y_4^{ab} \bar{d}_R^b (\phi_3^{1/3})^* \nu_L^a + \boxed{Y_4^{ab} \bar{d}_R^b (\phi_3^{-2/3})^* e_L^a} + \text{h.c.}$$

- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)

$$\tilde{Y}_4 = \begin{pmatrix} \cdot & \bigcirc & \bigcirc \\ \cdot & \bigcirc & \bigcirc \\ \cdot & \cdot & ? \end{pmatrix}$$

Scalar LQ: $\Phi_3 \sim (\bar{3}, 2, -1/6)$

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- $\phi_3^{-2/3}$ contributes to $b \to s$ transitions! (also to other processes...)

$B_s \to \bar{\nu}\nu$ [missing energy]

$B \to K^{(*)} \bar{\nu}\nu$

$$\tilde{Y}_4 = \begin{pmatrix} \bullet & Y_4^{\nu_e s} & Y_4^{\nu_e b} \\ \bullet & Y_4^{\nu_\mu s} & Y_4^{\nu_\mu b} \\ \bullet & \bullet & ? \end{pmatrix}$$

Scalar LQ: $\Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions!

$$\mathcal{L}_{\text{eff}}^{\phi_4^{2/3}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{4\pi} \left[C_{9\ell\ell} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) + C_{10\ell\ell} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \right]$$

$$\Rightarrow \quad C_{10\ell\ell} = C_{9\ell\ell} = -\left(\frac{\pi\sqrt{2}}{G_F\, V_{tb} V_{ts}^*\, \alpha} \right) \frac{\tilde{Y}_4^{3\ell} (\tilde{Y}_4^{2\ell})^*}{4M^2_{\phi_4^{2/3}}}$$

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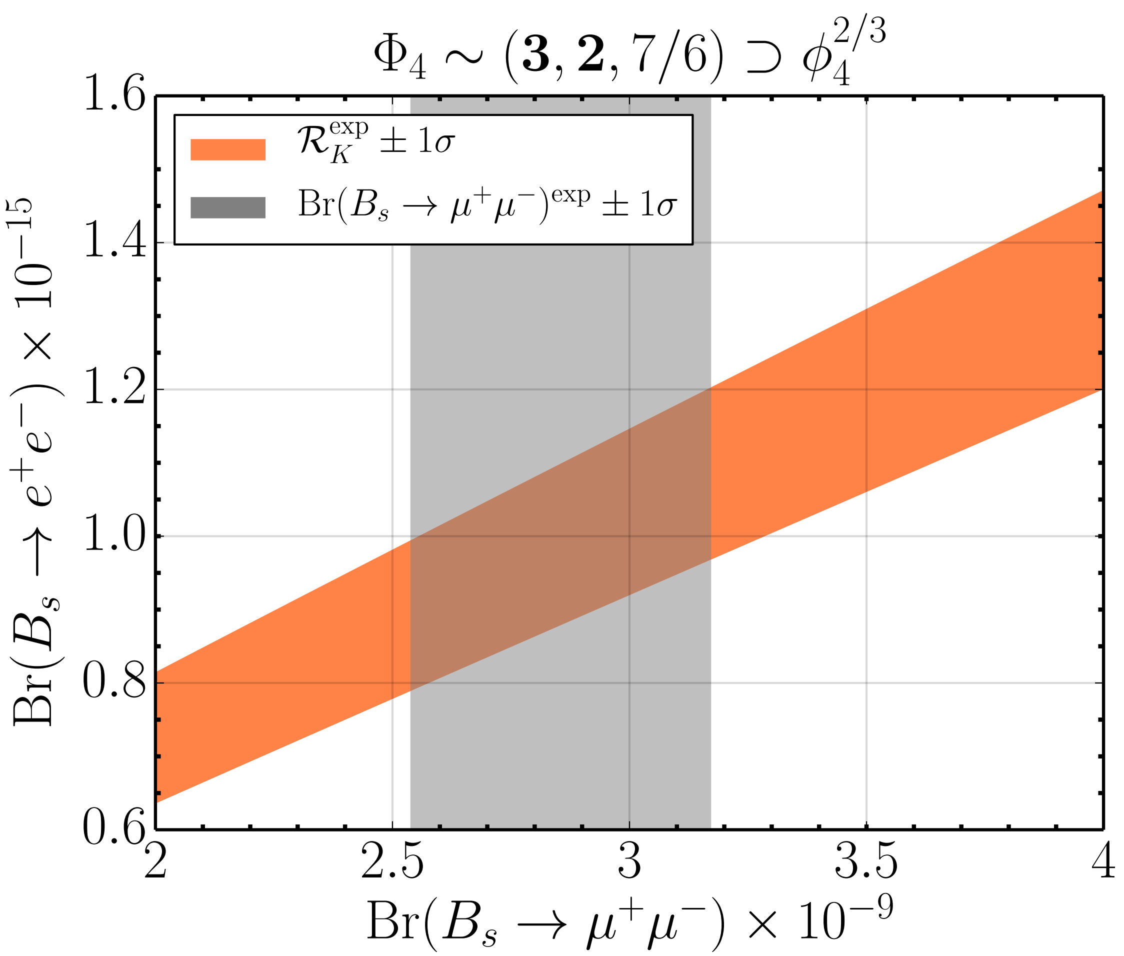
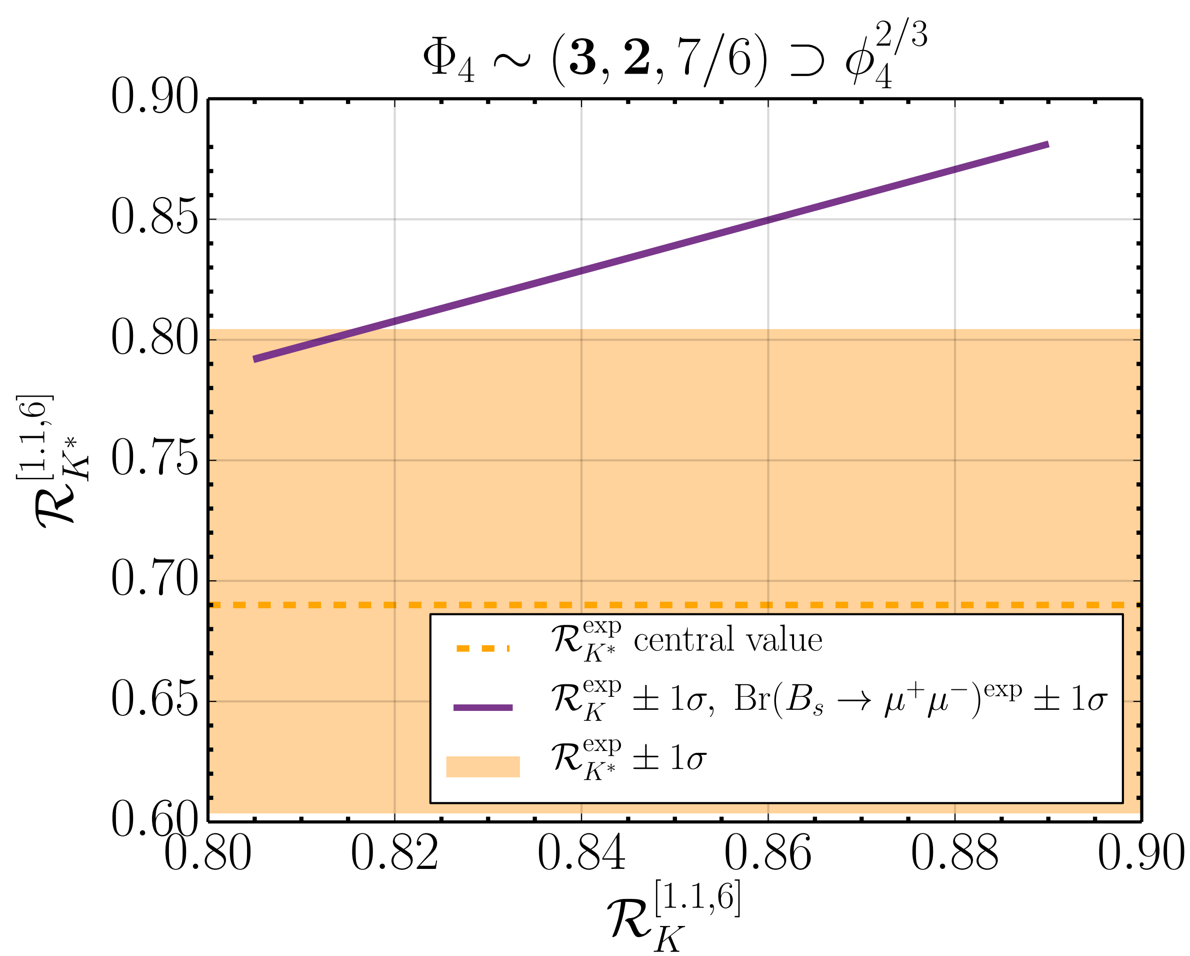
$$C_{10\ell\ell} = C_{9\ell\ell}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions!

$$\text{Br}(B_s \to \ell^+\ell^-) = f_2(C_{10\ell\ell}) \qquad \mathcal{R}_{K^{(*)}} = \frac{f_2(C_{10\mu\mu})}{f_2(C_{10ee})}$$





Scalar LQ: $\Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions! (and also to other processes...)

$K_L \to \mu^\pm e^\mp$

$\tau \to K_s\, \mu/e$

$\tau \to \eta'$

$$\tilde{Y}_4 = \begin{pmatrix} Y_4^{de} & Y_4^{d\mu} & Y_4^{d\tau} \\ Y_4^{se} & Y_4^{s\mu} & Y_4^{s\tau} \\ Y_4^{be} & Y_4^{b\mu} & Y_4^{b\tau} \end{pmatrix}$$

↳ $R_{K^{(*)}}$, $B_s \to \mu^+\mu^-$

Scalar LQ: $\Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a + \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a} + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions! (and also to other processes...)

$$\widetilde{Y}_4 = \begin{pmatrix} \cdot & \cdot & \cdot \\ \bullet & \bullet & \cdot \\ \bullet & \bullet & ? \end{pmatrix}$$

Scalar LQ: $\Phi_4 \sim (3, 2, 7/6)$

$$\Phi_4 = \begin{pmatrix} \phi_4^{5/3} \\ \phi_4^{2/3} \end{pmatrix} \qquad -\mathcal{L}_Y^{\Phi_4} \supset \boxed{Y_4^{ab}\, \bar{e}_R^b (\phi_4^{5/3})^* u_L^a} + Y_4^{ab}\, \bar{e}_R^b (\phi_4^{2/3})^* d_L^a + \text{h.c.}$$

- $\phi_4^{2/3}$ contributes to $b \to s$ transitions! (and also to other processes...)

$$\tilde{Y}_4 = \begin{pmatrix} \cdot & \cdot & \cdot \\ Y_4^{ce} & Y_4^{c\mu} & \cdot \\ Y_4^{te} & Y_4^{t\mu} & ? \end{pmatrix}$$

$\Rightarrow t \to c e \mu < 6.6 \times 10^{-6}$

What about $(g-2)_\mu$?

$$-\mathcal{L}_Y \supset Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$K_L \to \mu^\pm e^\mp$

$R_{K^{(*)}}$, $B_s \to \mu^+\mu^-$

$$Y_4 = \begin{pmatrix} Y_4^{ed} & Y_4^{es} & Y_4^{eb} \\ Y_4^{\mu d} & Y_4^{\mu s} & Y_4^{\mu b} \\ Y_4^{\tau d} & Y_4^{\tau s} & Y_4^{\tau b} \end{pmatrix}$$

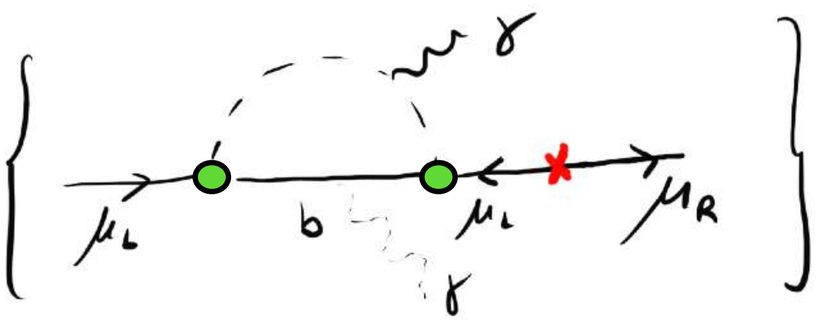
What about $(g-2)_\mu$?

$$-\mathcal{L}_Y \supset Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$K_L \to \mu^\pm e^\mp$

$R_{K^{(*)}},\ B_s \to \mu^+\mu^-$

$$Y_4 = \begin{pmatrix} Y_4^{ed} & Y_4^{es} & Y_4^{eb} \\ Y_4^{\mu d} & Y_4^{\mu s} & Y_4^{\mu b} \\ Y_4^{\tau d} & Y_4^{\tau s} & Y_4^{\tau b} \end{pmatrix}$$



$a_\mu \propto \dfrac{m_\mu}{M_{LQ}^2}\,\text{vev}\,(\mu_{L\leftrightarrow R}\text{ - flipping parameter})$

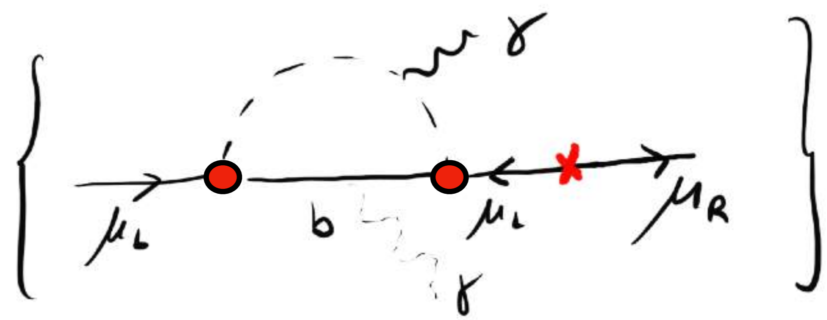
$\Gamma_{\mu\to e} \propto \dfrac{m_\mu^3\,\text{vev}}{M_{LQ}^4}(\mu_{L\leftrightarrow R}\text{ - flipping parameter})^2$

What about $(g-2)_\mu$?

$$-\mathcal{L}_Y \supset Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$$\tilde{Y}_4 = \begin{pmatrix} Y_4^{de} & Y_4^{d\mu} & Y_4^{d\tau} \\ Y_4^{se} & Y_4^{s\mu} & Y_4^{s\tau} \\ Y_4^{be} & Y_4^{b\mu} & Y_4^{b\tau} \end{pmatrix}$$

$\hookrightarrow R_{K^{(*)}}, B_s \to \mu^+\mu^-$



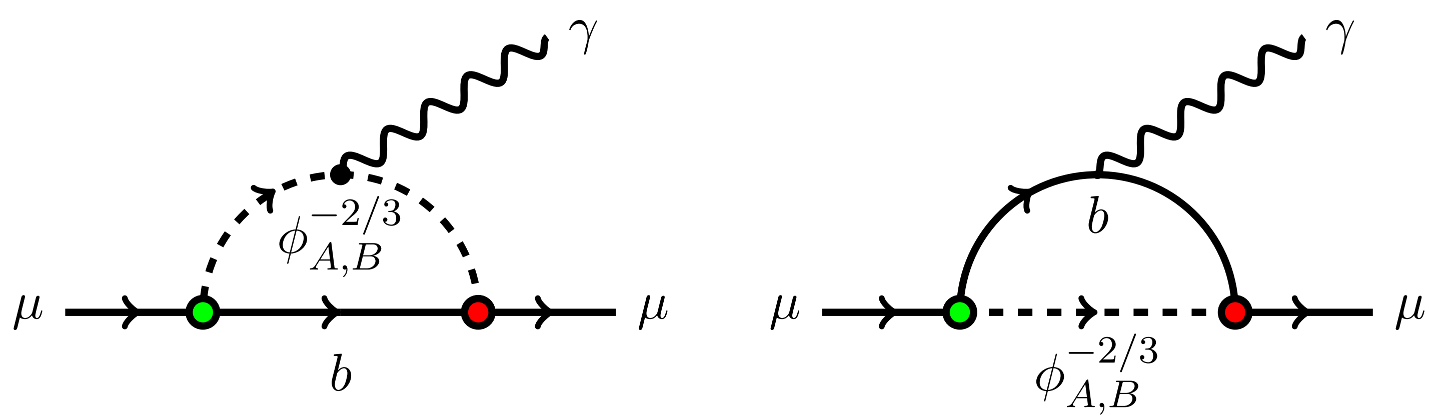
$$a_\mu \propto \frac{m_\mu}{M_{LQ}^2} \text{vev} \left(\mu_{L \leftrightarrow R} - \text{flipping parameter}\right)$$

$$\Gamma_{\mu \to e} \propto \frac{m_\mu^3}{M_{LQ}^4} \text{vev} \left(\mu_{L \leftrightarrow R} - \text{flipping parameter}\right)^2$$

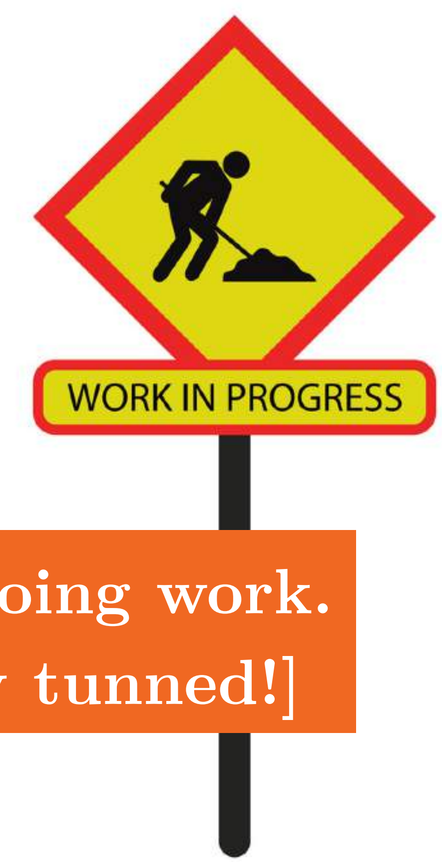
What about $(g-2)_\mu$?

$$-\mathcal{L}_Y \supset Y_4\, Q_L \Phi_4^\dagger (e^c)_L + Y_4\, \ell_L \Phi_3^\dagger (d^c)_L + \text{h.c.}$$

$$V \supset \mathrm{Tr}\{H^\dagger \Phi H^\dagger \Phi\} \xrightarrow{\langle H \rangle} \mu\, \phi_3^{-2/3} \phi_4^{2/3} \Rightarrow \phi_{A,B}^{-2/3} = f[\phi_3^{-2/3}, (\phi_4^{2/3})^*]$$

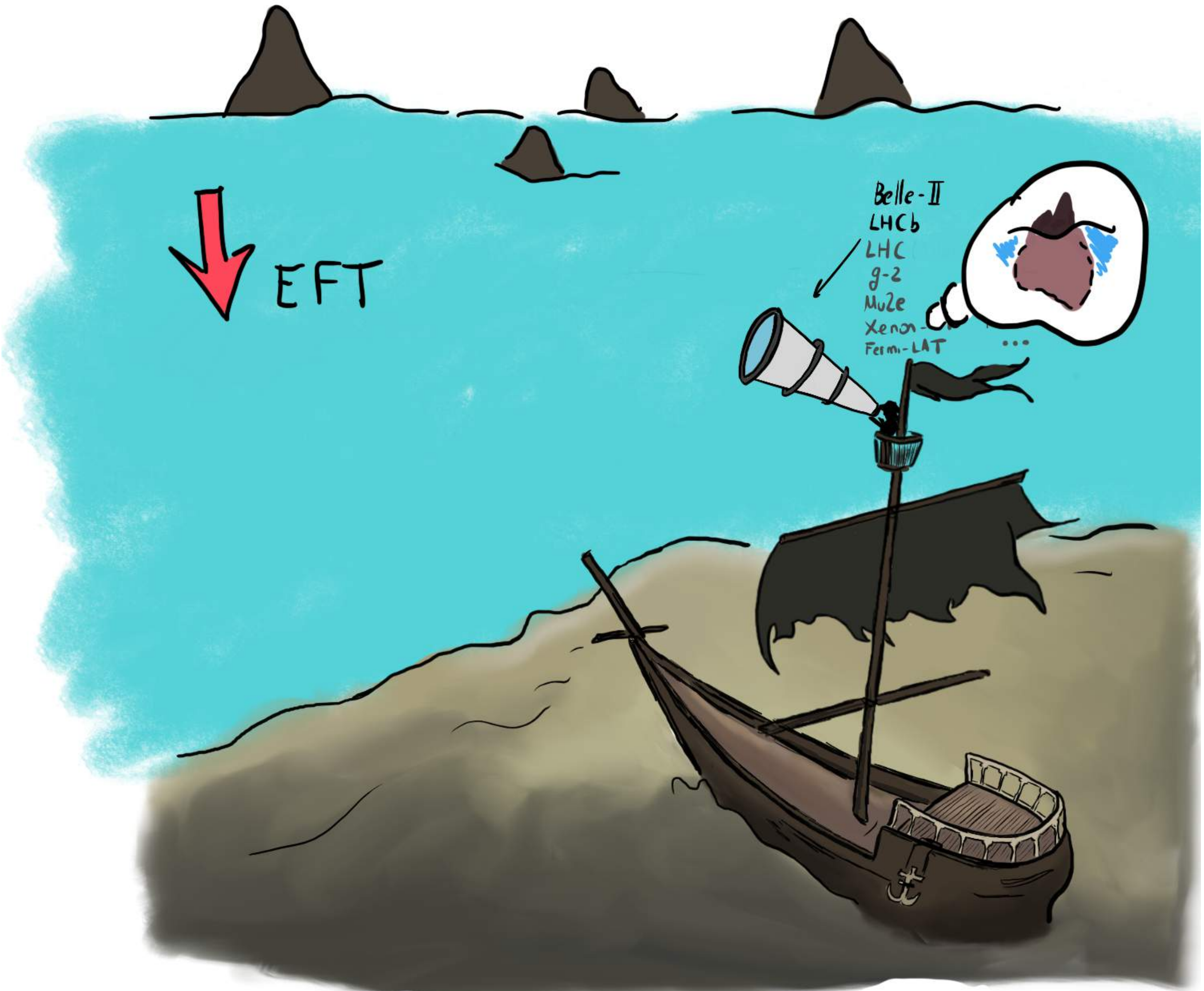


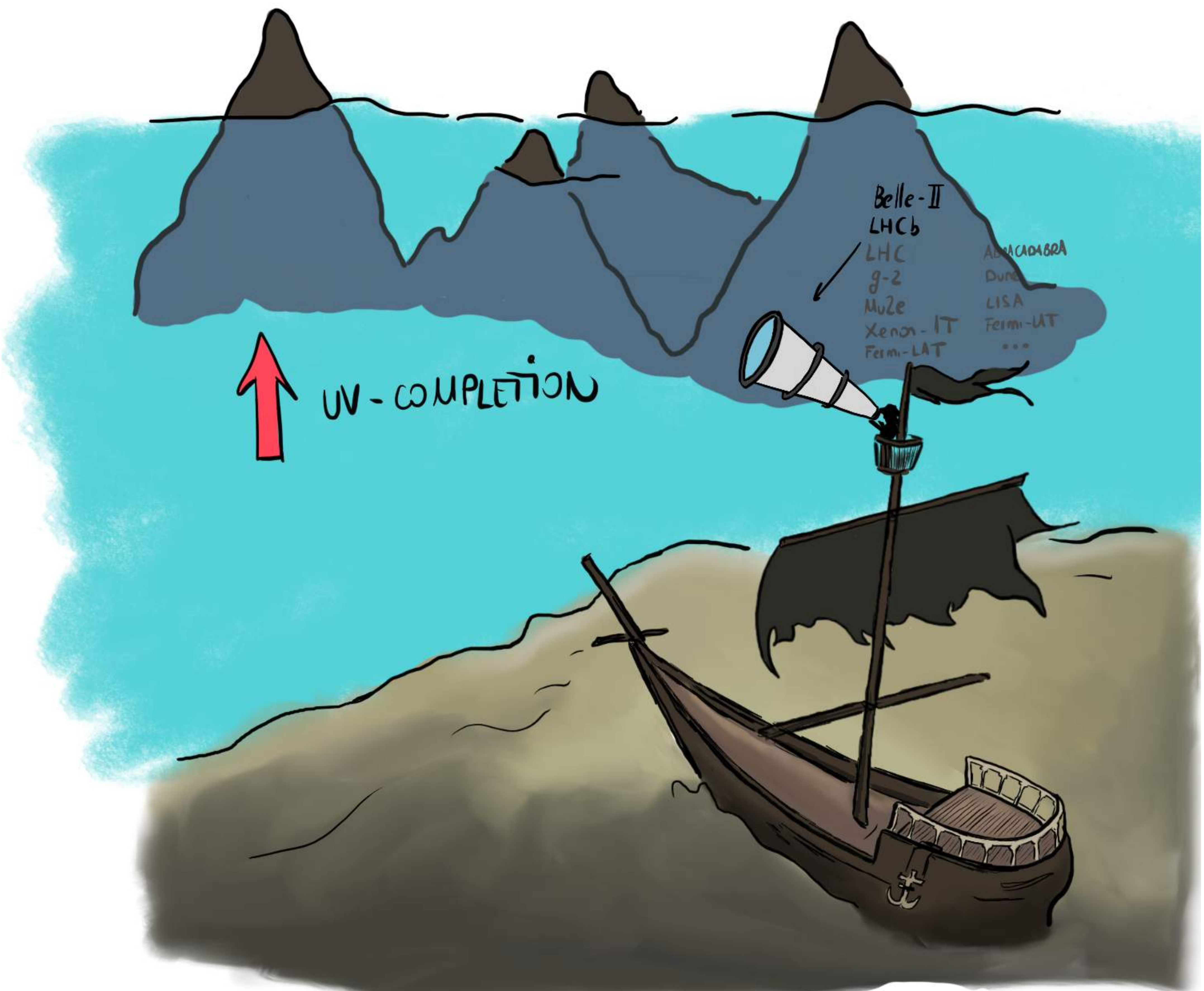
$$c_i = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_{22}^i & c_{23}^i \\ 0 & 0 & 0 \end{pmatrix}$$



[on-going work. Stay tunned!]


Belle-II
LHCb
LHC
g-2
MuZe
Xenon-1T
Fermi-LAT
ABRACADABRA
Dune
LISA
Fermi-LAT
...


EFT
Belle-II
LHCb
LHC
g-2
Mu2e
Xenon-
Fermi-LAT
...


Belle-II
LHCb
LHC
g-2
Mu2e
Xenon-IT
Fermi-LAT
LISA
Fermi-LAT
...
UV-COMPLETION

Thank you!