Theory Developments in Heavy Flavor

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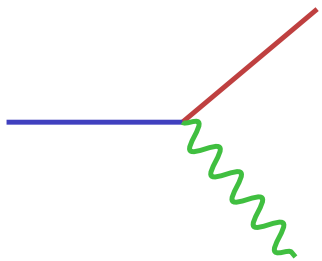
SM Flavor

Nutshell: How do we describe quark/lepton interactions?

SM EW Lagrangian:

$$\mathcal{L}_{\text{EW}} = \frac{g_2}{\sqrt{2}} \begin{pmatrix} u & c & t \end{pmatrix} \not{W} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$



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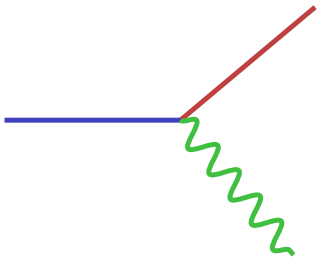


CKM matrix

3×3 unitary $\sim$

$$\begin{pmatrix} 1 & 0.2 & 4\,10^{-3} \\ 0.2 & 1 & 4\,10^{-2} \\ 4\,10^{-3} & 4\,10^{-2} & 1 \end{pmatrix}$$

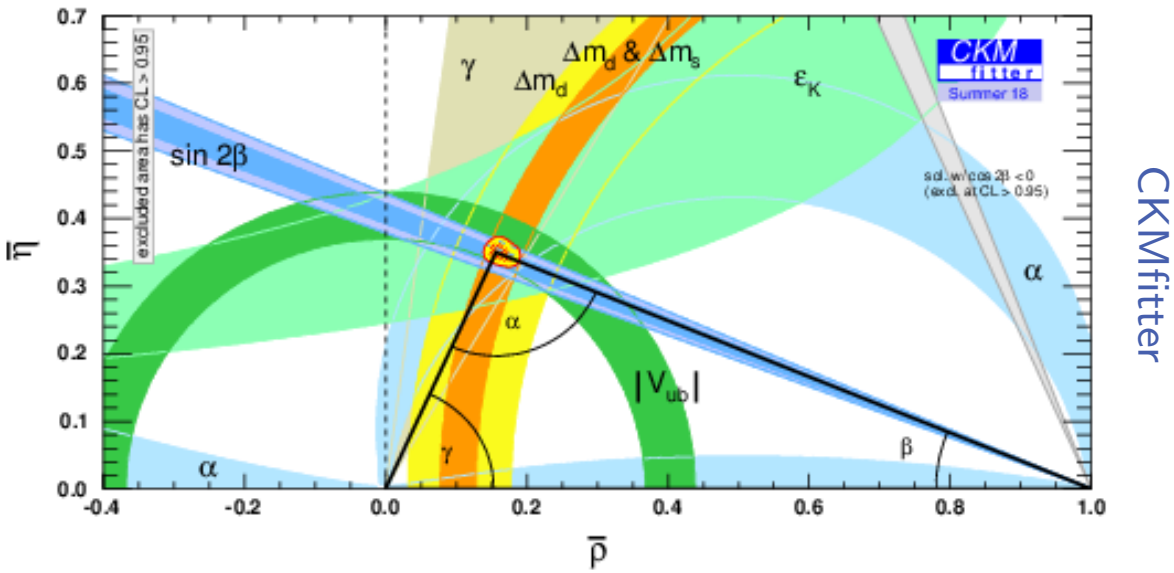
In the SM:

- Flavor changing processes through electroweak charged currents (CC)
- No tree-level flavor changing neutral currents (FCNC)
- Similar story for charged leptons with ν masses

Flavor Data

Can test SM flavor structure with CKM unitarity triangles, e.g.

$$V_{tb}^* V_{td} + V_{cb}^* V_{cd} + V_{ub}^* V_{ud} = 0$$



- Huge multitude of physical observables projected onto CKM parameter plane (from decays, (in)direct CP violation, mass splittings $\Delta m \ldots$) (see S. Stone's talk for more details)
- SM $\Longrightarrow$ all allowed regions should intersect. Lesson: Good agreement with SM flavor structure
- Leads to powerful constraints and powerful discovery potential

New Physics (NP) Constraints

History:

- $n \to pe\nu$: Energy scale $\sim$ MeV, probes EW current at $\sim 100\,\text{GeV}$!
- $\Delta m_K / m_K \simeq 7 \times 10^{-15}$ predicted charm, $m_c \sim 1$–2GeV

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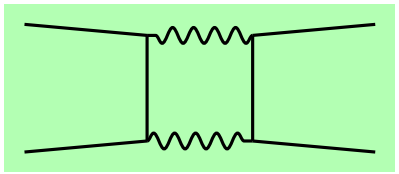
Constraints on 4-Fermi FCNC operators from e.g. meson mixing

$$\frac{(\bar{q}\Gamma q')(\bar{q}'\Gamma' q)}{\Lambda^2}$$ via:



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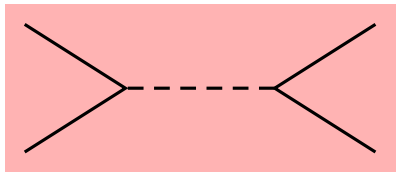

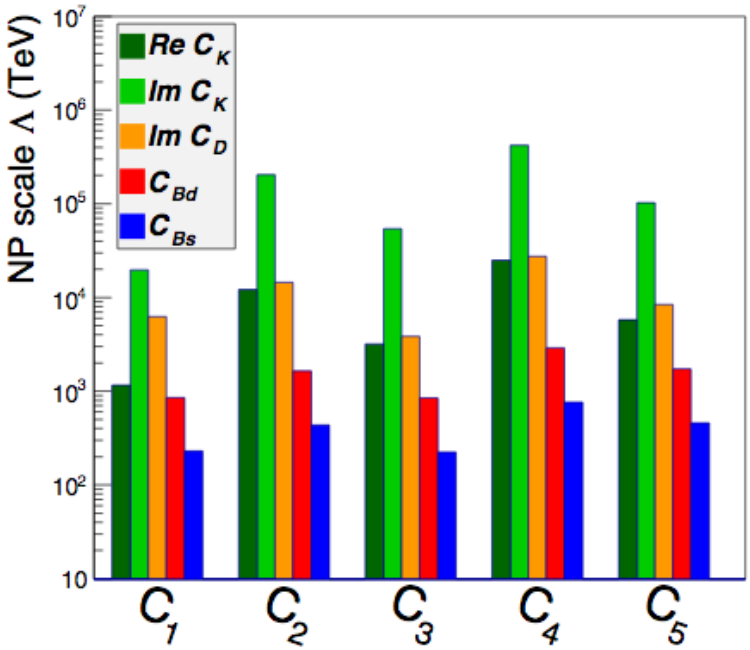

UTfit 1411.7233

Indirect access to scales
$\sim 10^4$ TeV far above
LHC direct production!

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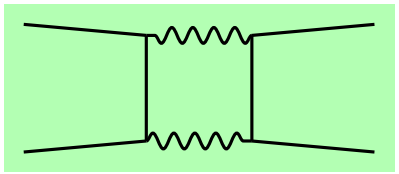
Constraints on 4-Fermi FCNC operators from e.g. meson mixing

$$\frac{V_{td} V_{ts}}{16\pi^2} \frac{(\bar{q}\Gamma q')(\bar{q}'\Gamma' q)}{\Lambda^2}$$

via:



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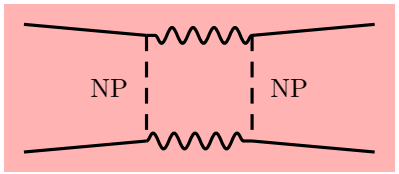

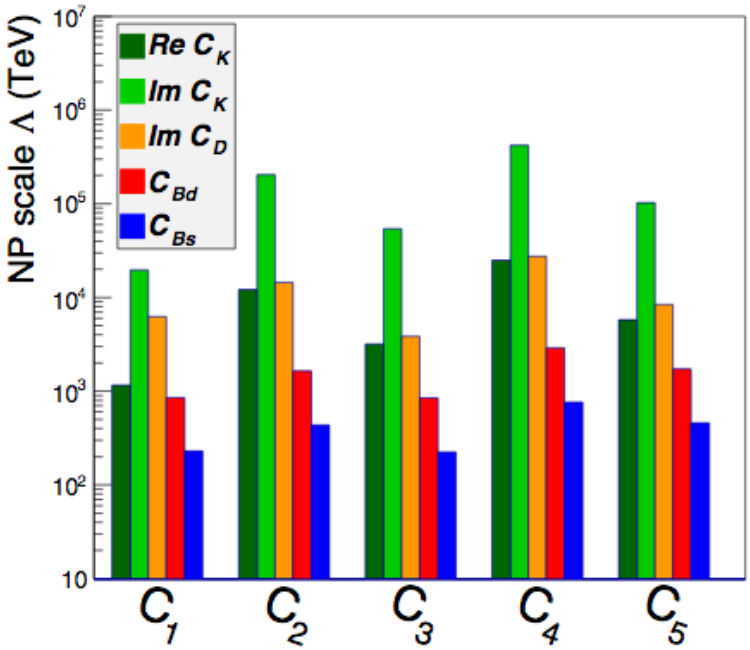

UTfit 1411.7233

Indirect access to scales $\sim 10^4$ TeV far above LHC direct production!

But, with loop + CKM suppression: NP/SM $\sim$ 20% in FCNC still compatible!

(Incomplete) Perspectives on Flavor

Precision Th.
Control

NP

Tensions:
Measurements vs predictions

- $|V_{cb}|$, $|V_{ub}|$
- $(g-2)_\mu$ (see J. Crnkovic's talk)
- ΔA_{CP} in charm
- $b \to s\mu\mu$
- ...

Smoking Guns

Enhancement of
rare/forbidden SM

Flavor symmetry violation

- $K \to \pi\nu\nu$
- $\mu \to e$
- $b \to c\ell\nu$: τ vs e,μ
- $b \to s\ell\ell$: e vs μ
- ...

Precision Flavor

Constrain high NP scales
(no obs $\gg$ SM prediction)

- $B_s \to \mu\mu$
- $\Delta M_{s,d}$
- $b \to s\nu\nu$
- ...

Flavor Models

Explain SM hierarchies:
Quark/lepton mass and mixing
Can imply NP signals

Theoretically
Clean

SM

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We'll look at theory developments in understanding heavy flavor anomalies

els

hies:
d mixing

Can imply NP signals

SM

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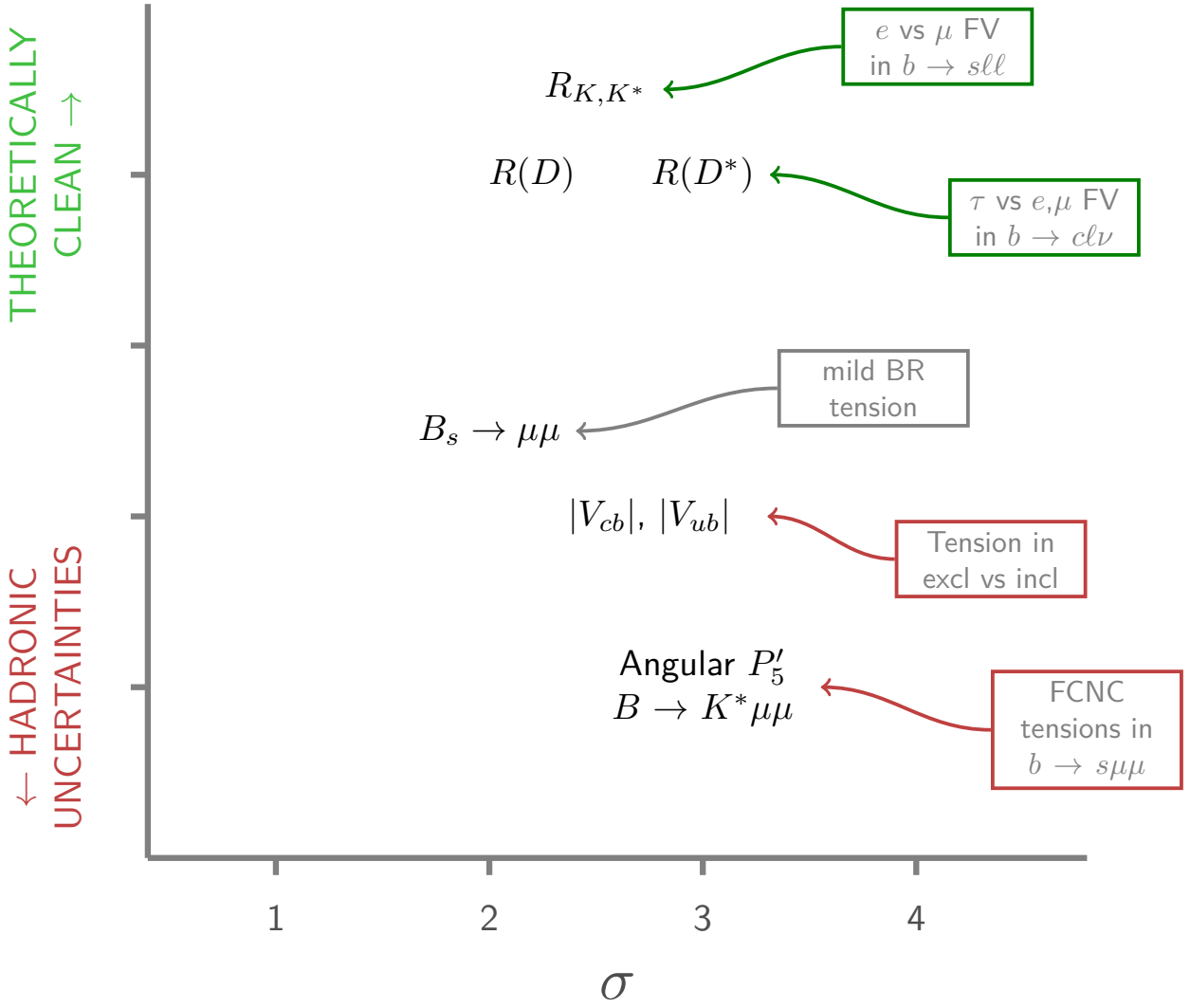
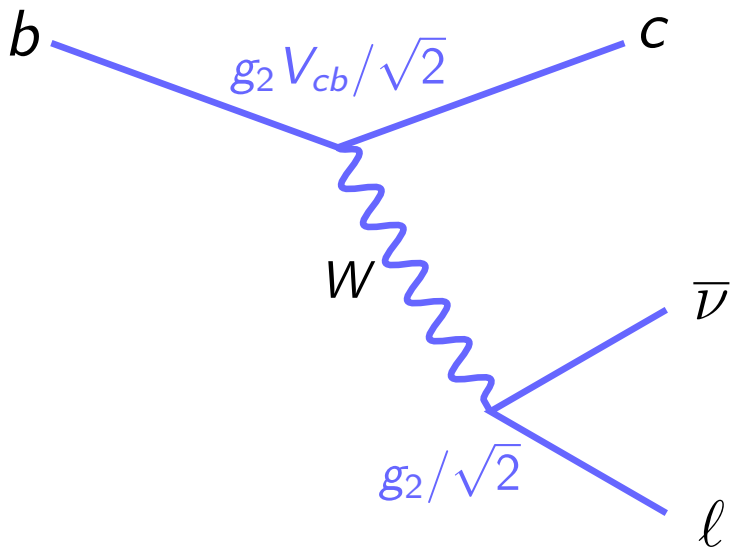
Space of Heavy Flavor Anomalies

Involving $B_q = (bq)$ mesons



Adapted from Z Ligeti and W Altmannshofer

Semileptonic Decays: $b \to c\ell\nu$



- Tree-level W exchange (in the SM)
- Approx. 25% of all B decays: huge statistics!

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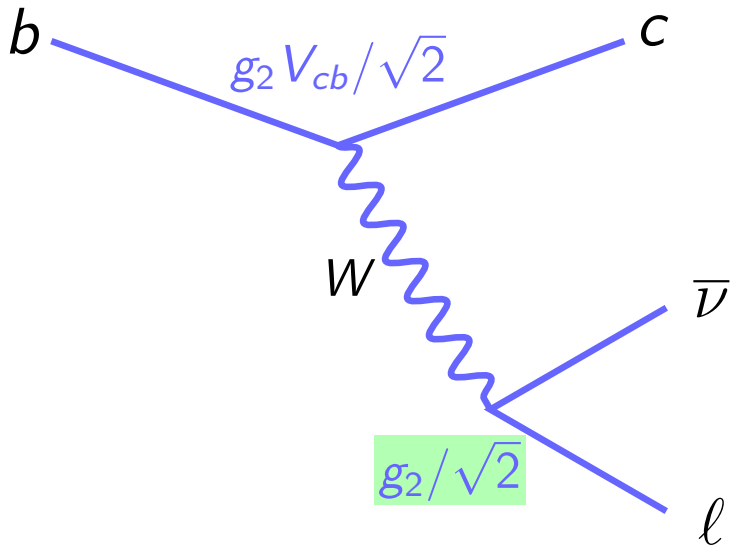

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- Theoretically clean:

Probe of lepton flavor universality

g_2 ($\ell = e, \mu, \tau$) up to masses:

$m_\tau \simeq 1777$MeV vs $m_\mu = 105$MeV;

PS and hadronic effects

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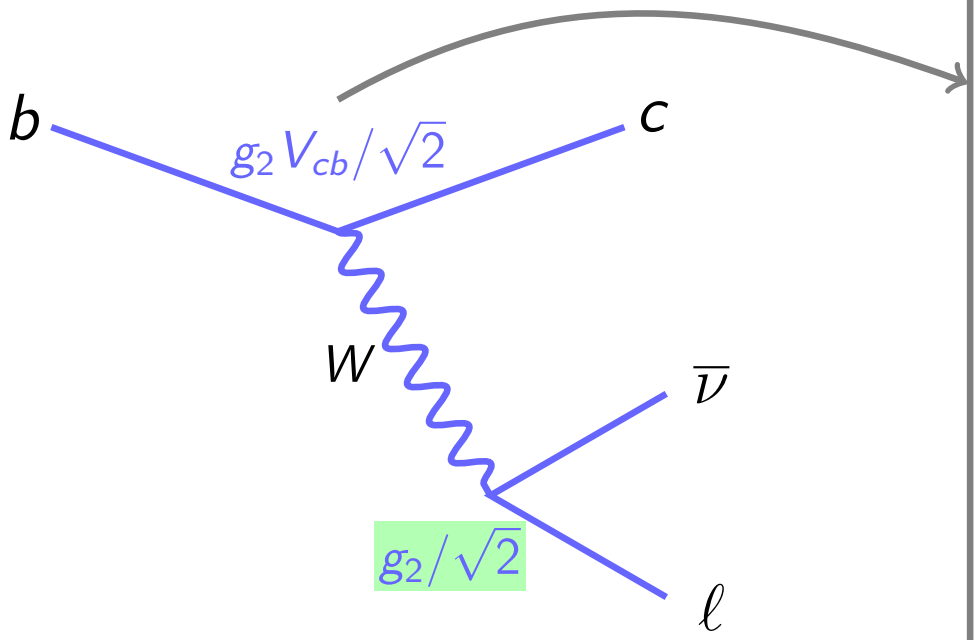

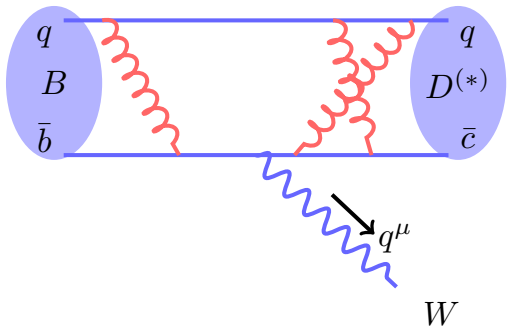

NB: Hadronic decays:

$B \to D^{(*)}$ (spin 0, 1)

$\Lambda_b \to \Lambda_c$ (spin 1/2)

...

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- Approx. 25% of all B decays: huge statistics!
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Probe of lepton flavor universality

g_2 ($\ell = e, \mu, \tau$) up to masses:

$m_\tau \simeq 1777$MeV vs $m_\mu = 105$MeV;

PS and hadronic effects

Hadronic matrix elements $\Longrightarrow$ measure

$|V_{cb}|$ in exclusive $l = e, \mu$ modes

(more details in tomorrow's parallel session)

Two Anomalies/Puzzles

1. Inclusive $B \to X_c l \nu$ versus exclusive $B \to D^* l \nu$

   Measurement is done with $l = e, \mu$: The τ mode involves more ν's from τ decays and less statistics

$$|V_{cb}|_{X_c} \simeq (42.2 \pm 0.8) \times 10^{-3}$$
$$|V_{cb}|_{D^*} \simeq (38.7 \pm 0.7) \times 10^{-3}$$

   A 3σ tension?!?

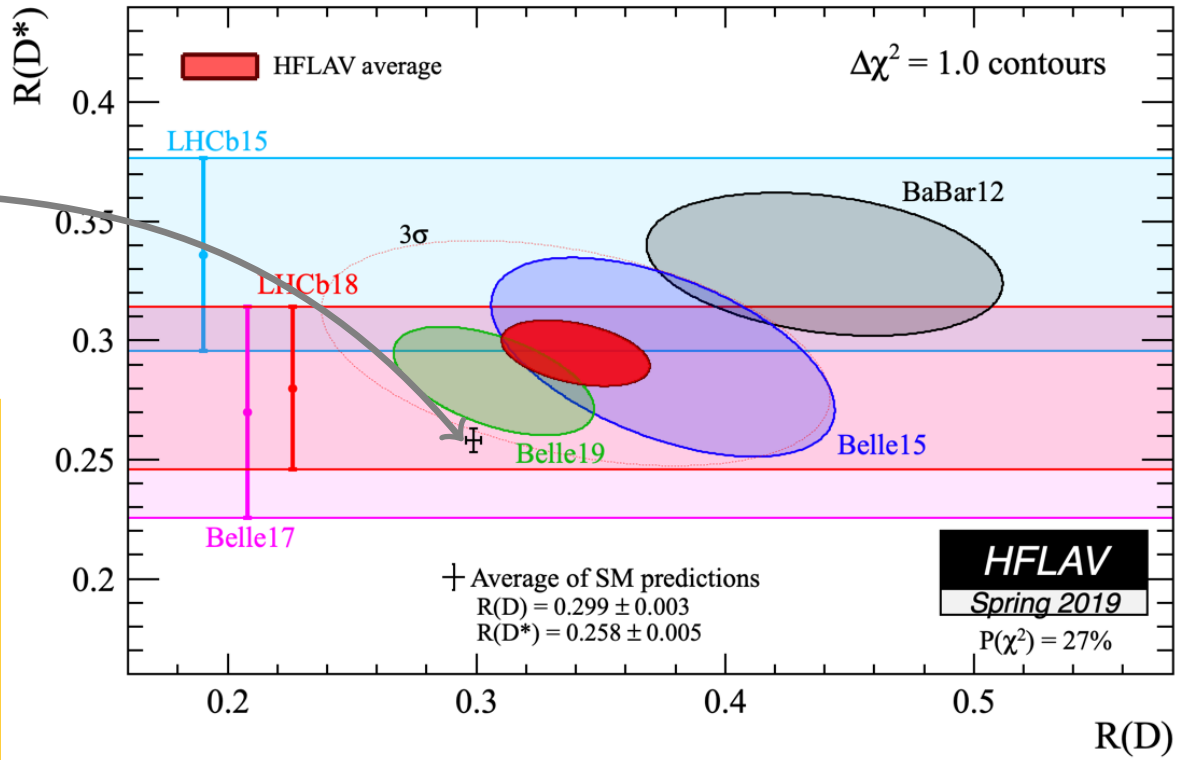
2. Can factor out $|V_{cb}|$, and measure the ratios

$$R(D^{(*)}) \equiv \frac{\Gamma[B \to D^{(*)} \tau \nu_\tau]}{\Gamma[B \to D^{(*)} l \nu]}, \qquad l = e, \mu .$$

$R(D^{(*)})$ anomaly

Persistent hints of lepton flavor universality violation for 7+ years

SM prediction
1703.05330 [Bernlochner, Ligeti, Papucci, & DR]
1707.09509 [Bigi, Gambino,Schacht]



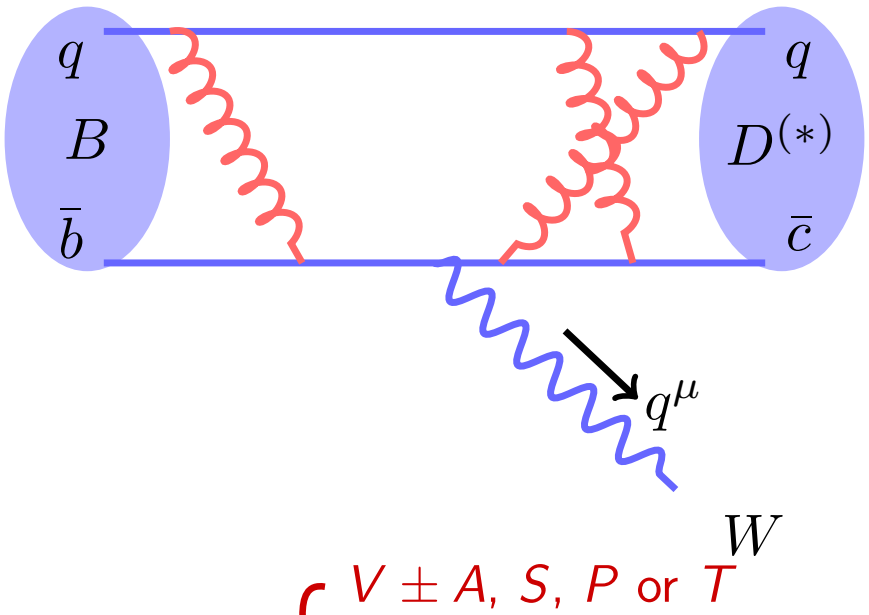
$\sim$ 20-30% tension at $\sim 3.1\sigma$ level with SM predictions
(was $4\sigma <$ March)

Also mild anomaly in $B_c \to J/\psi\tau\nu$, and (possibly) in $B \to X_c\tau\nu$.

- More measurements are coming! E.g. $R(D)$ or $R(\Lambda_b)$ from LHCb

Hadronic Matrix Elements

For exclusive processes: Main theory uncertainty is mapping partons $\rightarrow$ hadrons:



- Need predictions for $\left\langle D^{(*)} \middle| \bar{c}\,\Gamma\, b \middle| \bar{B} \right\rangle$ for any NP/SM current
- Use parametrizations of form factors

$$\left\langle D^* \middle| \bar{c}\Gamma^\mu b \middle| \bar{B} \right\rangle \sim FF_\varepsilon(q^2)\,\varepsilon^\mu + FF_B(q^2)\,p_B^\mu + FF_{D^*}(q^2)\,p_{D^*}^\mu$$

- Logic: Fit to $l = e$, μ SM measurements; predict SM or NP τ modes
- Ultimate: Lattice calculations! But only limited results currently available

$|V_{cb}|$ developments

- The Belle expt published an unfolded $B \to D^* l \nu$ dataset 1702.01521. Permits theorists to fit with different FF parametrization choices
- Using parametrization based on just analyticity and unitarity ('BGL'):

$\|V_{cb}\|_{\text{'CLN'}} = (38.2 \pm 1.5) \times 10^{-3}$,	1702.01521 [Belle]
$\|V_{cb}\|_{\text{'BGL'}} = (41.7^{+2.0}_{-2.1}) \times 10^{-3}$,	1703.06124, 1707.09509 [Bigi, Gambino, Schacht]
$\|V_{cb}\|_{\text{'BGL'}} = (41.9^{+2.0}_{-1.9}) \times 10^{-3}$,	1703.08170 [Grinstein, Kobach]

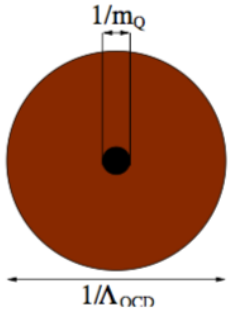
- Compare with $|V_{cb}|_{\text{incl}} = (42.2 \pm 0.8) \times 10^{-3}$
- Does this resolve $|V_{cb}|$ incl vs excl tension?

Tensions

Fits that lift $|V_{cb}|$ lead to Heavy Quark Effective Theory (HQET) tensions Bernlochner, Ligeti, Papucci, DR [1708.07134, 1902.09553]

HQ is a static color source

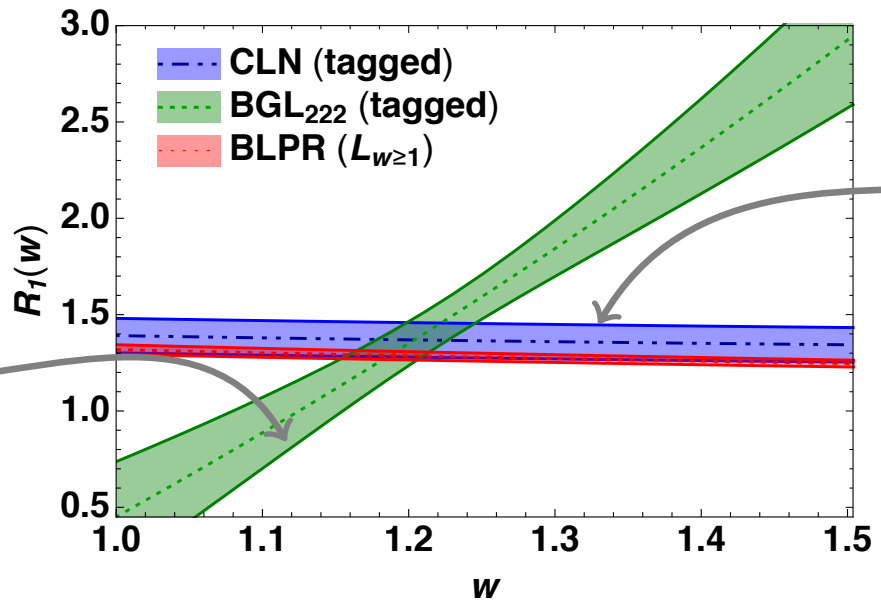
Like atomic physics: electronic states insensitive at LO to nuclear spin/flavor



- EFT of light dofs dressing a heavy quark Q ($m_Q \gg \Lambda_{\rm QCD}$)
- Implies relations between SM, NP FFs
- Corrections to HQ limit $\sim 20\%$; FF ratios

$$R = 1(0) + \mathcal{O}(\Lambda_{\rm QCD}/m_Q, \alpha_s) + \ldots$$

New choice: radical departure from HQET



Usual exp choice: consistent with HQET $R_1 \sim 1 + \ldots$

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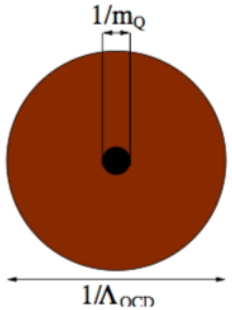

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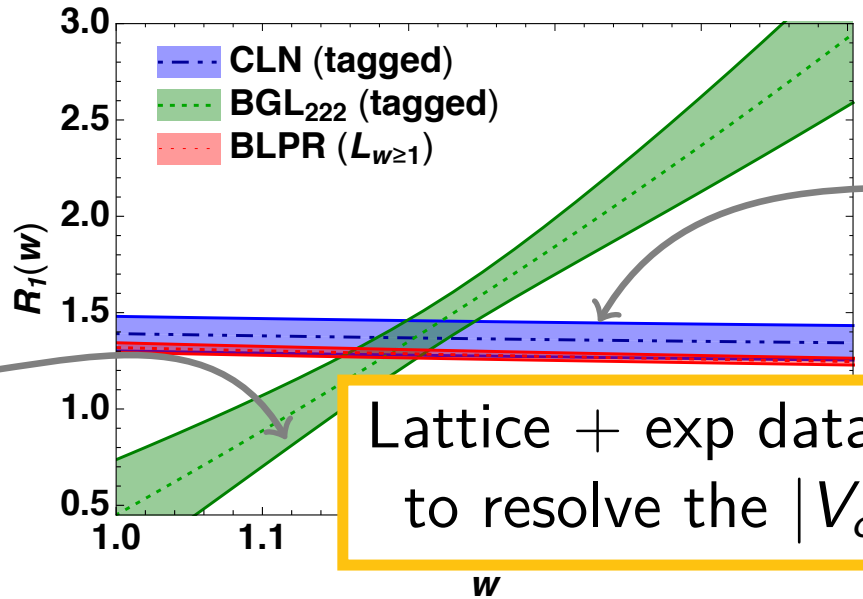

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Lattice + exp data is needed to resolve the $|V_{cb}|$ puzzle

1902.09553 [Bernlochner, Ligeti, DR]

NP Explanations: General 4-Fermi basis

At dimension-6

$$\mathcal{O}_6 \sim \frac{C}{\Lambda^2}\left(\bar{c}\Gamma b\right)\left(\bar{\tau}\Gamma'\nu\right) \qquad C \in \mathbb{C}(\Rightarrow \text{CPV})$$

Wilson coefficients:

LH (RH) $\nu_{L(R)}$

Vector: $C^V_{LL(LR)}$, $C^V_{RL(RR)}$,

Scalar: $C^S_{LL(LR)}$, $C^S_{RL(RR)}$,

Tensor: $C^T_{LL(RR)}$,

Simplified models:

EW scalars	C^S
W'	C^V
Scalar/Vector LQ	C^V, $C^{S\pm T}$

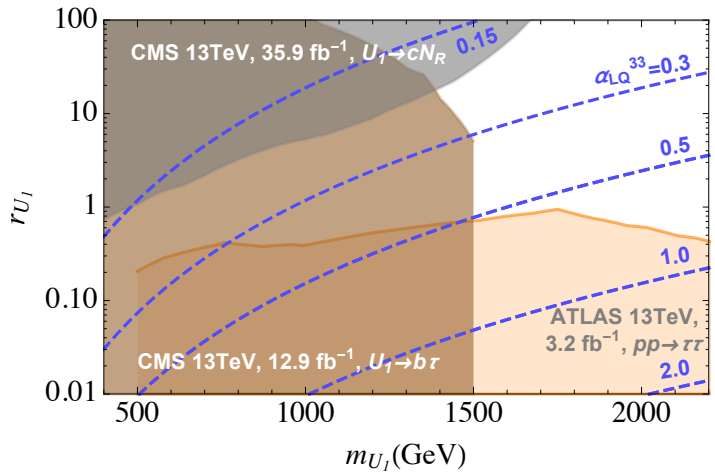
Normalized against SM: $\Lambda \sim (2\sqrt{2}G_F V_{cb})^{-1/2} \sim 870\,\text{GeV}$.
For 20–30% enhancement, expect TeV scale NP

- No* NP in $B \to D^{(*)}l\nu$: $|V_{cb}|$ constraints
- Huge literature for NP model building for $R(D^{(*)})$
- Simplified model mediators: EW charged scalars, W''s or leptoquarks ($\widetilde{R}_2$, S_1, U_1, ...)

NP Status

- Tensions on W' and leptoquark C_V and $C_{S\pm T}$ type models
  - LHC: $pp \to \tau\tau/\tau\nu$
  - LHC: single or pair production + bc, $b\tau$, $c\tau$ final states
  - Flavor: b–s bounds (If there is a quark doublet involved)
- Pure C_S (Φ, $\widetilde{R}_2$) leptoquark models face $B_c \to \tau\nu$ tensions

Eg. LHC exclusions/allowed regions for a vector leptoquark ($U_1 \sim (3,1)_{2/3}$)



1807.04753 [DR, Shakya, Zupan]

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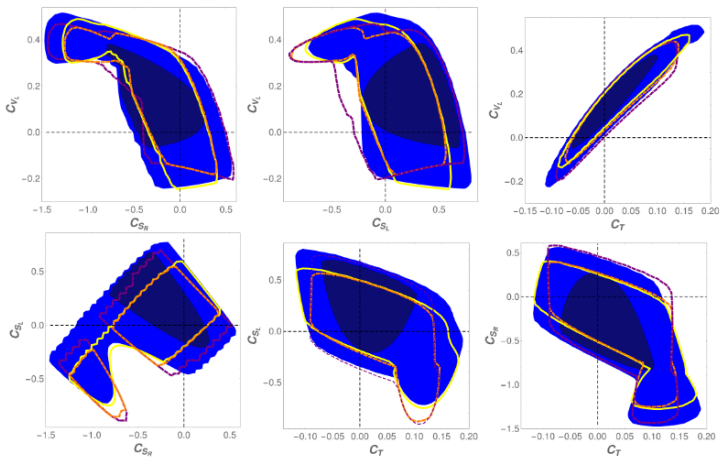
Latest (post-Moriond) global fits to $R(D^{(*)})$, plus other obs.

1904.09311, 1904.10432



1904.09311 [Murgui, Penuelas, Jung, Pich]

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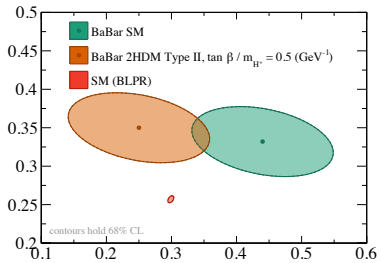
Latest (pos

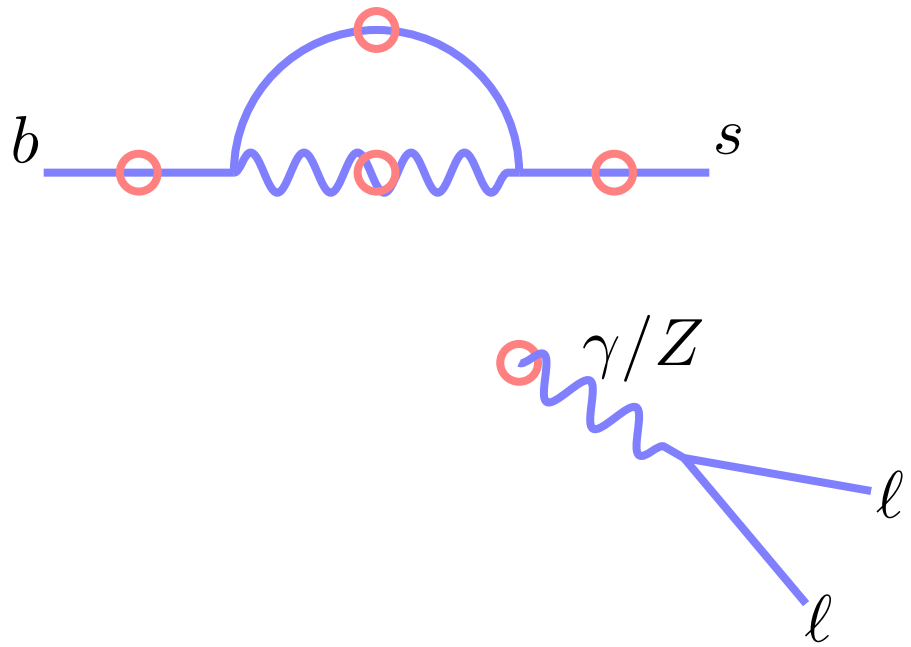
1904.09311, 19

Caveat: Measurement is a simultaneous BG + signal fit

- Naive global fits miss large SM/NP model template dependence
- Can't take fit exclusions/allowed regions too seriously
- Extensive program to correct this: expt reweighting software tool for direct WC fits Hammer [Bernlochner, Duell, Ligeti, Papucci, DR] hammer.physics.lbl.gov



Rare decays: $b \to s\ell\ell$



- Loop (penguin) process

$$\mathcal{M} \sim \frac{1}{16\pi^2} \frac{g^4}{m_W^2} V_{ts} V_{tb} \frac{m_t^2}{m_W^2}$$

- Experimentally clean signal: $B \to K^{(*)}\ell\ell$

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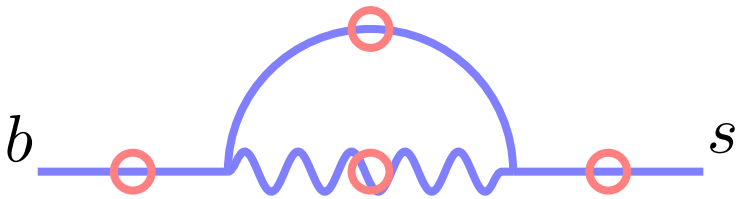

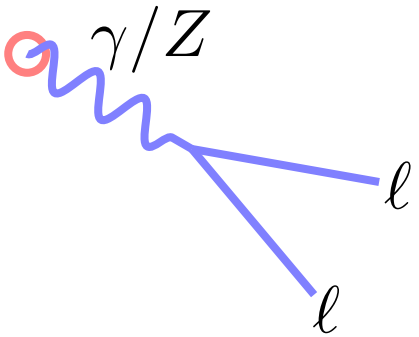

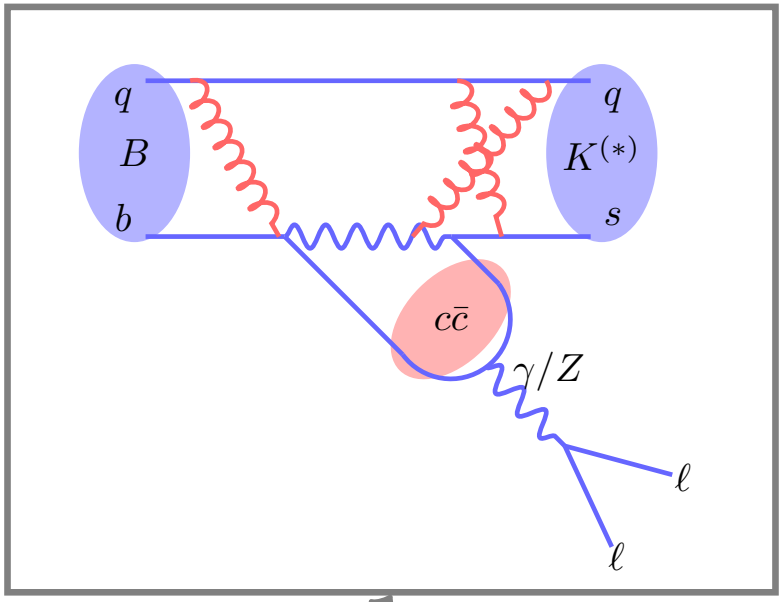

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- Experimentally clean signal: $B \to K^{(*)}\ell\ell$
- But hadronic uncertainties less clear (long distance $c\bar{c}$)

Lepton Universality Tests

Factor out hadronic uncertainties: Consider ratio (see S. Sandilya's talk!)

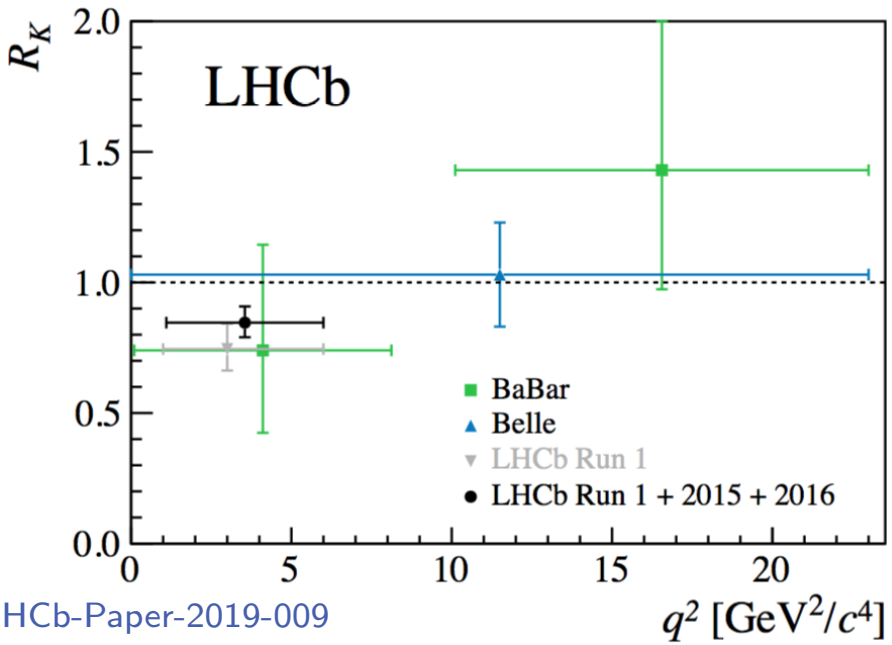
$$R_{K^{(*)}} = \frac{B \to K^{(*)} ee}{B \to K^{(*)} \mu\mu} \qquad \text{(in various } q^2 \text{ binnings)}$$

Should be 1.00 ± 0.01 in SM!

Bordone, Isidori, Pattori [1605.07633]

$R_{K^+} = 0.846^{+0.060+0.016}_{-0.054-0.014}$

$R_{K^{*0}} = 0.69^{+0.11}_{-0.07} \pm 0.05\,,$



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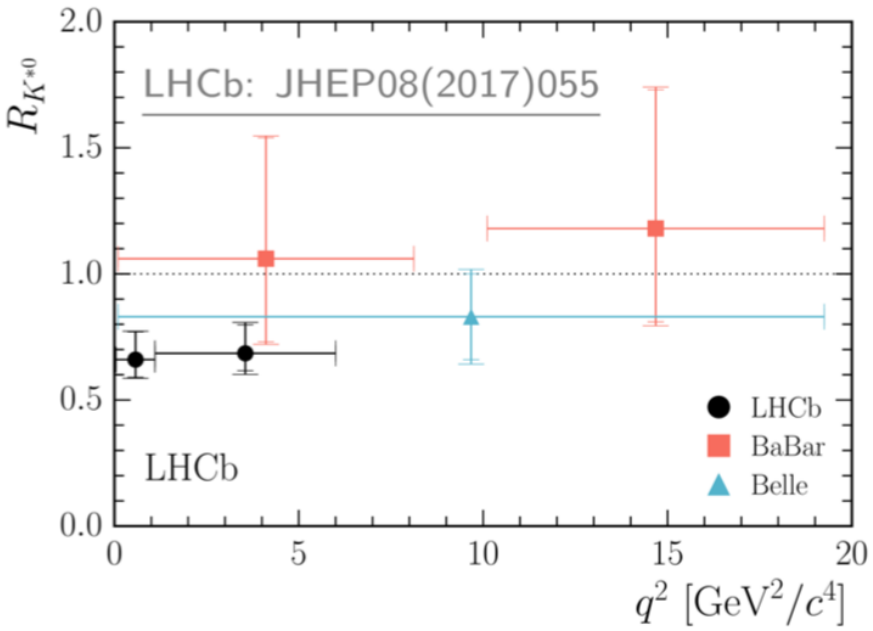

Deviations of about 2.5σ in each mode/q^2 bin

Lepton Universality Tests

Factor out hadronic uncertainties: Consider ratio (see S. Sandilya's talk!)

$$R_{K^{(*)}} = \frac{B \to K^{(*)} ee}{B \to K^{(*)} \mu\mu} \qquad \text{(in various } q^2 \text{ binnings)}$$

Should be 1.00 ± 0.01 in SM!

Bordone, Isidori, Pattori [1605.07633]

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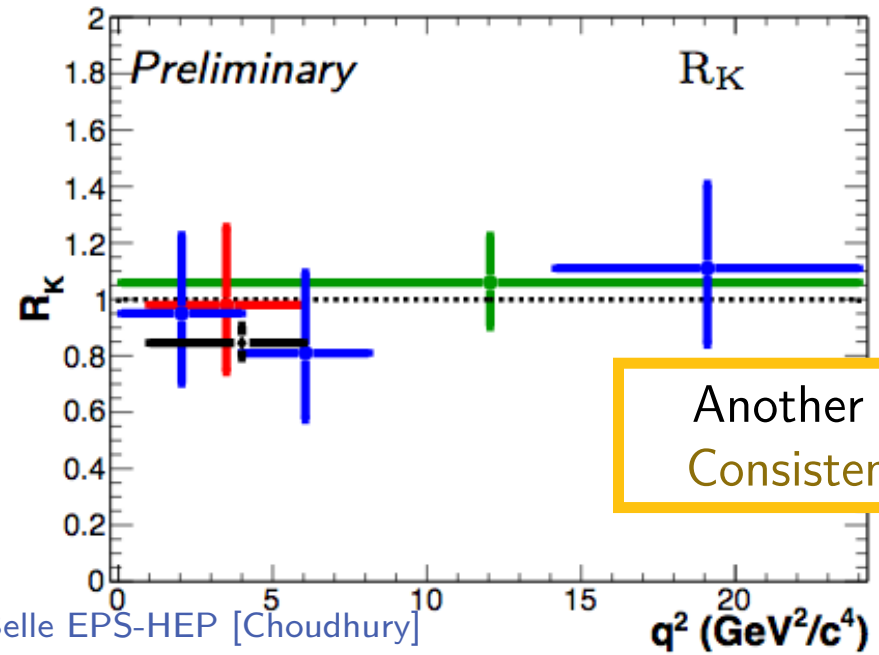
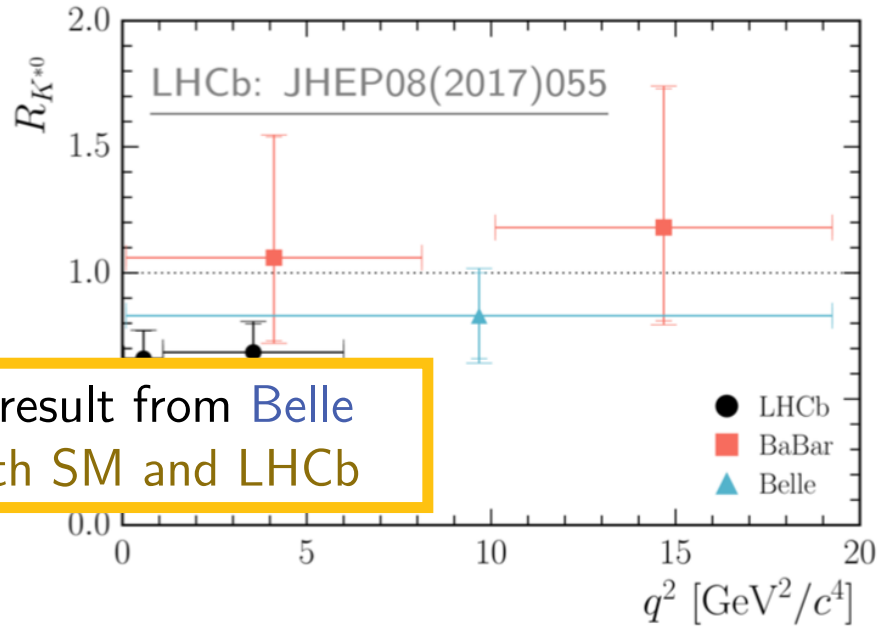


Belle EPS-HEP [Choudhury]



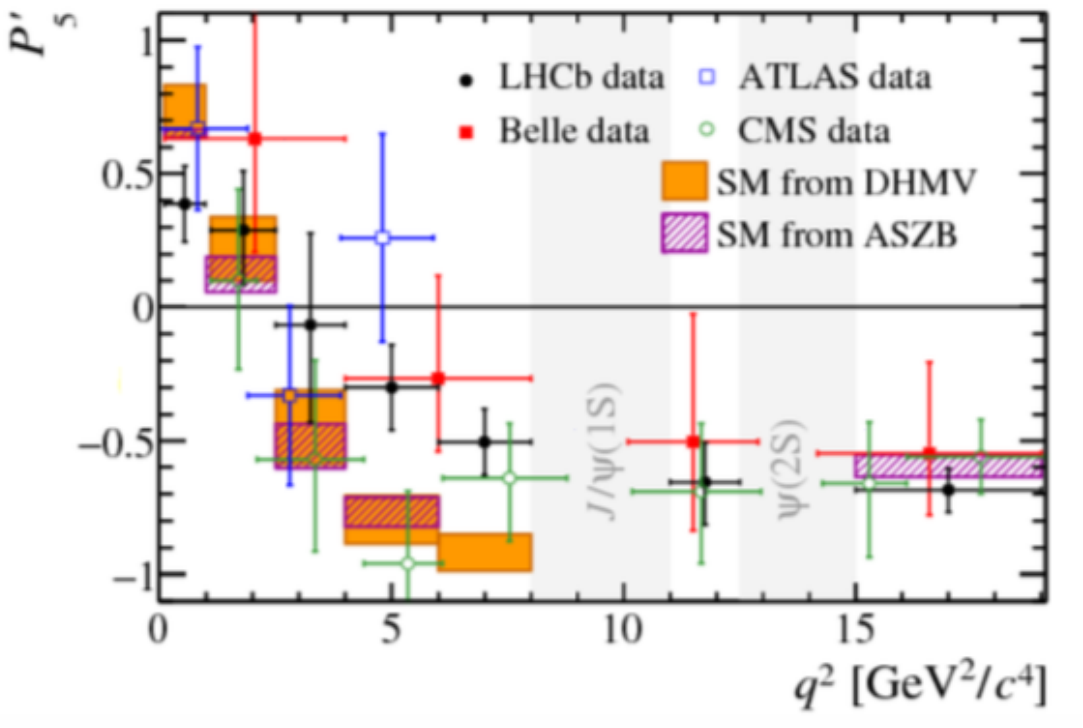
Another new result from Belle
Consistent with SM and LHCb

Deviations of about 2.5σ in each mode/q^2 bin

Puzzle: Precision moments

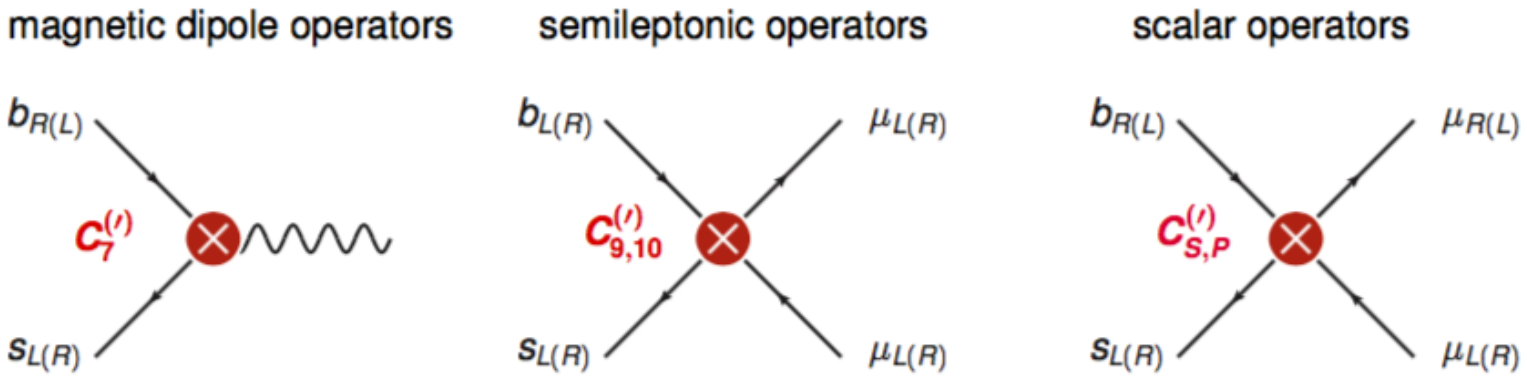
Measure angular distributions in

$$B \to K^*(\to K\pi)\mu\mu$$



Deviations of about 2.5σ in several q^2 bins, but SM predictions are hard.

NP Explanations



Courtesy W Altmannshofer

SM-like SL operators at dimension-6:

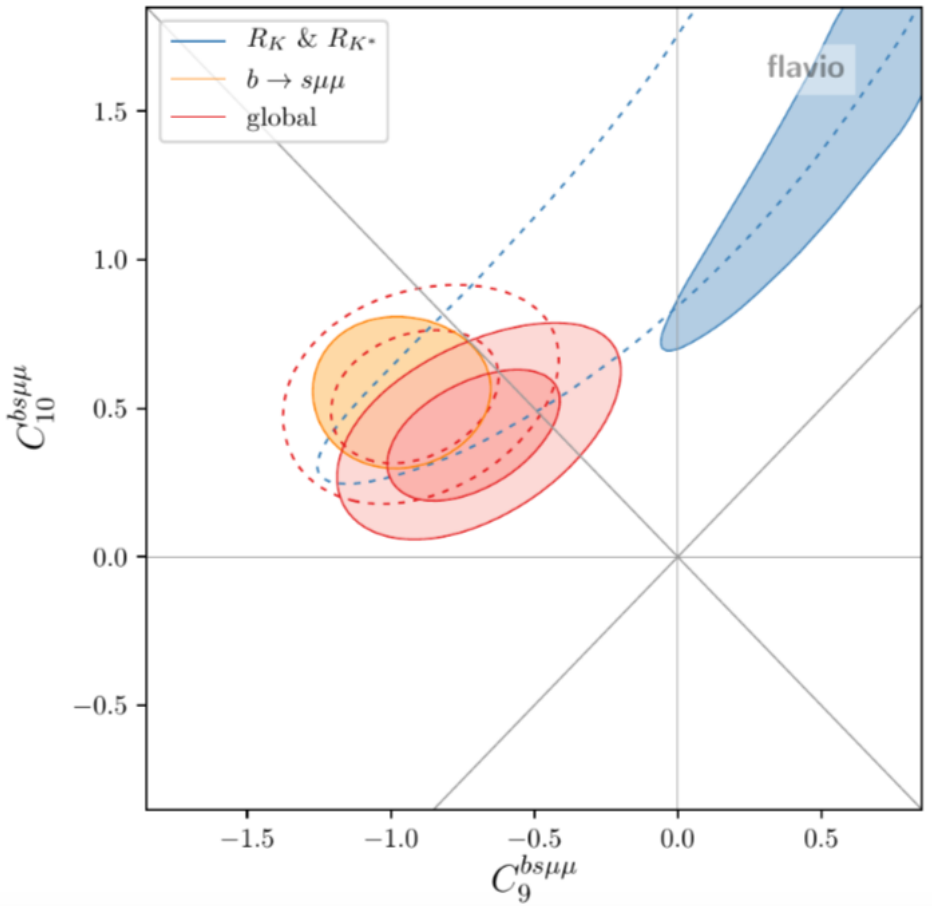
$$\frac{C_9^{(\prime)}}{\Lambda^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\mu\gamma^\mu\mu) + \frac{C_{10}^{(\prime)}}{\Lambda^2}(\bar{s}\gamma_\mu P_{L(R)} b)(\mu\gamma^\mu\gamma^5\mu)$$

Normalized against loop SM: $\Lambda \sim 4\pi v/\sqrt{V_{tb}V_{ts}} \sim 10\,\text{TeV}$.
Expect 10 TeV scale NP

- Large amount of NP model building
- Typically leptoquarks or Z' models (e.g. gauged $L_\mu - L_\tau$)
- Some attempts to relate to $R(D^{(*)})$.

Global Fits

$C_{S,P}$ operators bounded by $B_s \to \mu\mu$; C_7 from $b \to s\gamma$; $C'_{9,10}$ highly disrupt angular fits: focus on $C_{9,10}$



- Non-trivial: Mild coincidence for $R_{K^{(*)}}$ and P'_5 explanations

Aebischer et al [1903.10434]

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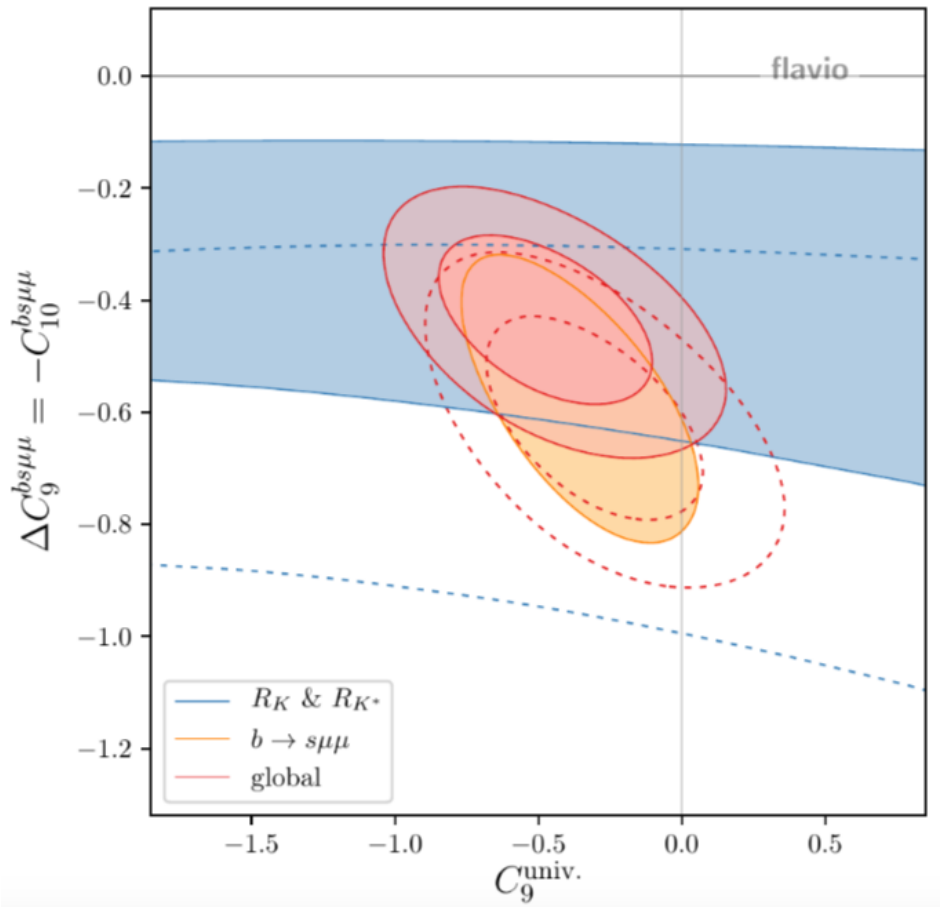

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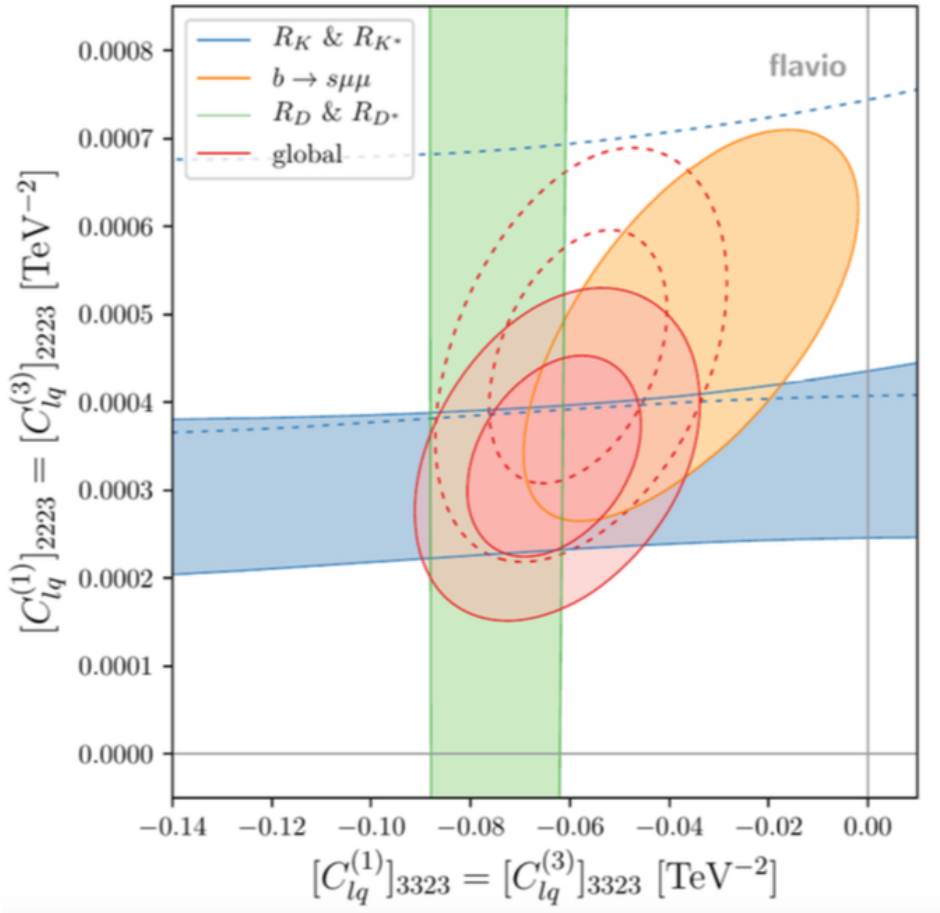

Aebischer et al [1903.10434]

- Non-trivial: Mild coincidence for $R_{K^{(*)}}$ and P'_5 explanations
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Naive global combination with $R(D^{(*)})$ $\implies$ vector leptoquark $U_1 \sim (3,1)_{2/3}$

But same cautions apply for $R(D^{(*)})$ data

Global Fits

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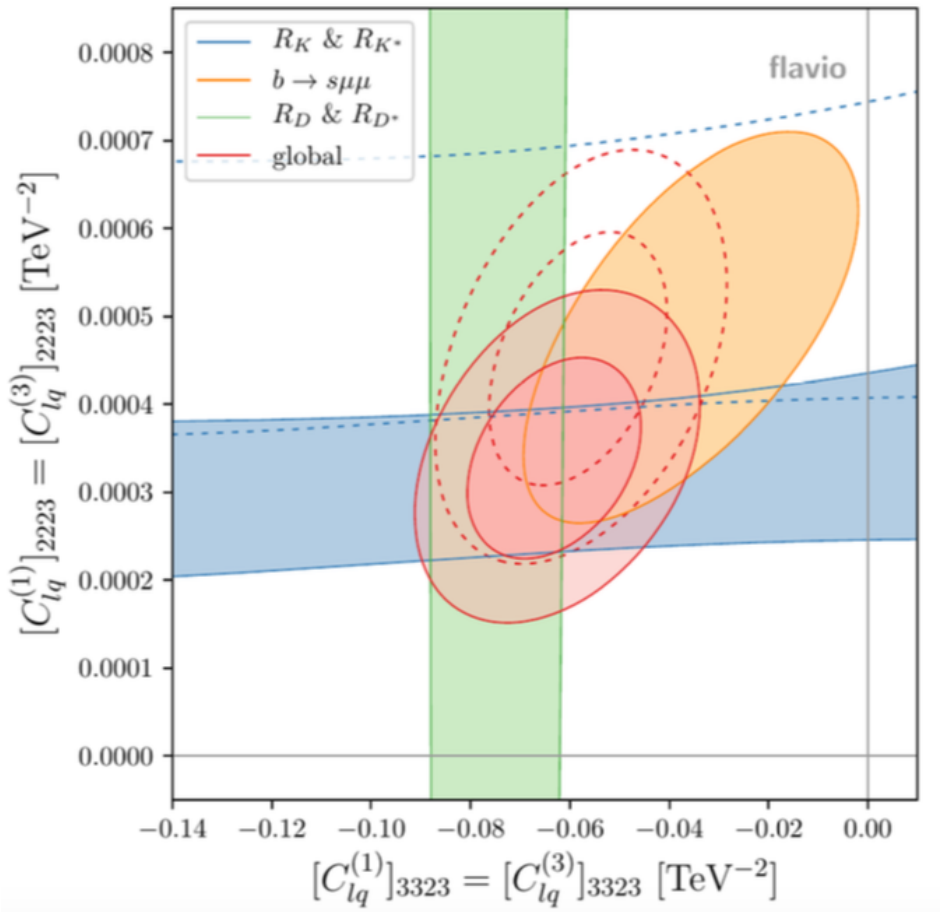

Aebischer et al [1903.10434]

- plus

But maybe some things aren't meant to be combined?

Bonus: Long-lived Particles (LLPs)

Emerging hot topic for future LHC searches:
Look for displaced decays-in-flight of exotic LLPs
E.g. in the SM: K_L, π^+, n, μ

- Occur generically in beyond SM extensions with small couplings or scale (or loop) hierarchies or phase space suppression: SUSY, Composite Higgs, Hidden Valleys, (inelastic) DM, neutrino masses

broken sym
weak mixing/ marginal operator
technically natural

$$\Gamma \sim \varepsilon^2 \left(\frac{m}{M}\right)^n \mathrm{PS}$$

$m \ll M$, typically $n \geq 4$
loop factors

squeezed spectra
approx sym
multibody decays

- If SM backgrounds are controlled: clean signature of NP

Beyond LHC: A large number of proposals
SHiP, MATHUSLA, FASER, CODEX-b, ...

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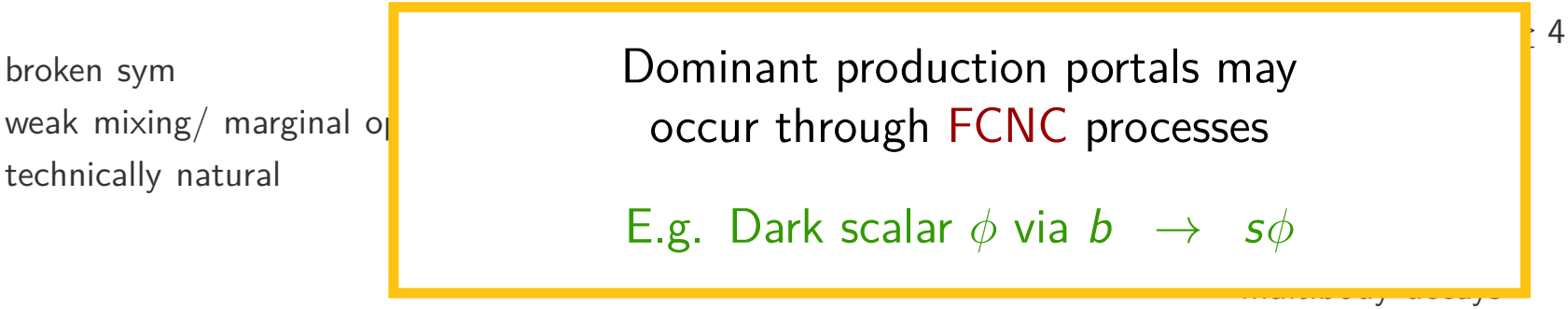

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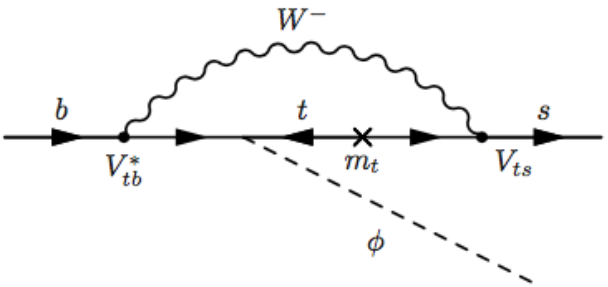
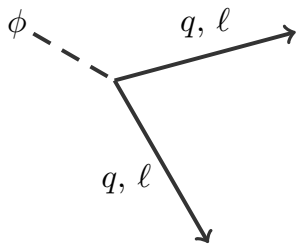
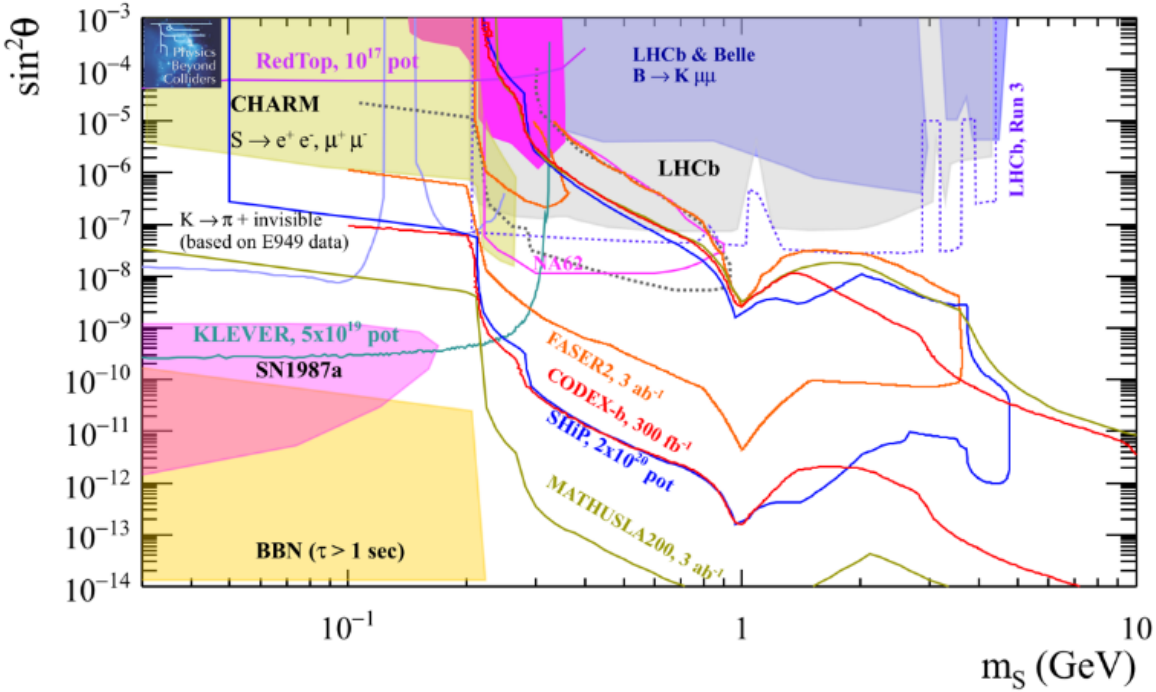
Beyond LHC: A large number of proposals
SHiP, MATHUSLA, FASER, CODEX-b, ...

E.g. Higgs-scalar mixing

- $\mathcal{L} \sim \phi H^\dagger H$
- Higgs-scalar mixing angle θ induces Yukawa $y_f \sin\theta \phi \bar{f} f$
- Production via $b \to s\phi$ and decay controlled by single parameter







1901.09966 [Physics Beyond Colliders: BSM WG]

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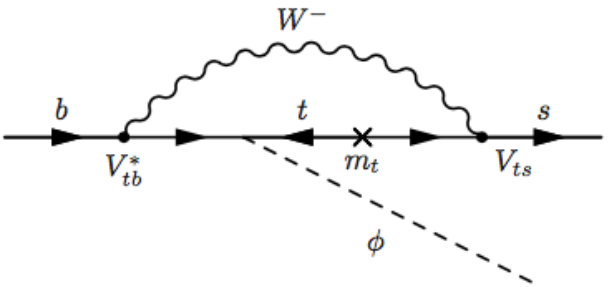

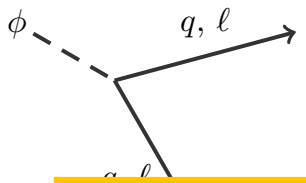

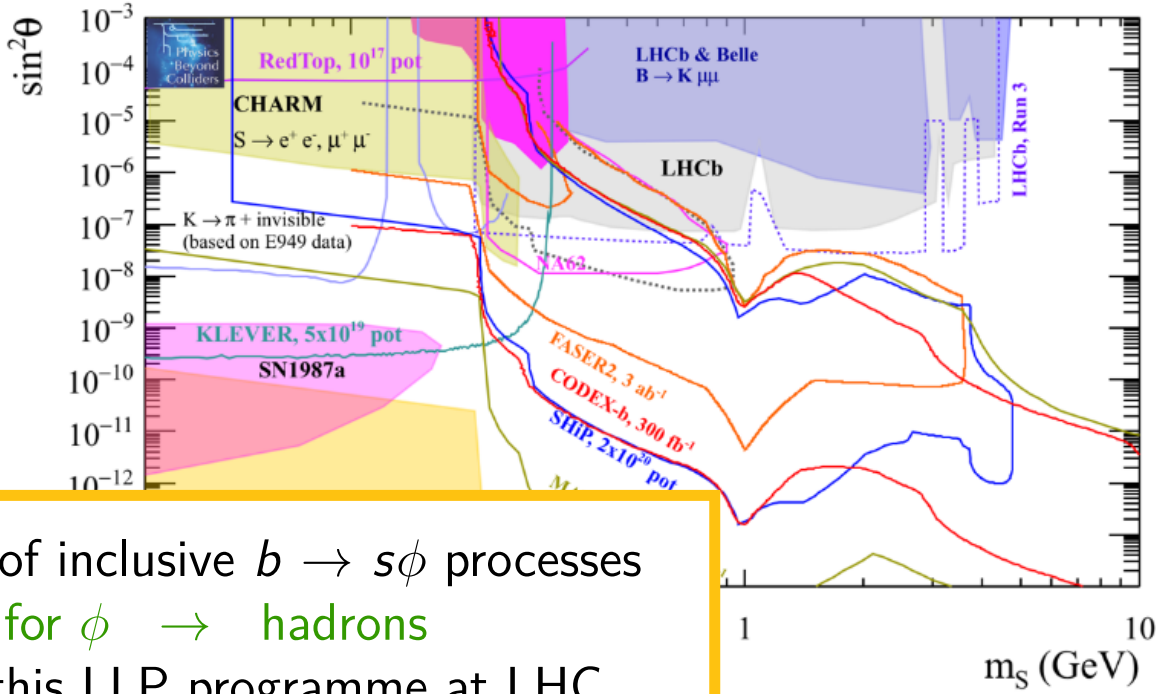

1901.09966 [Physics Beyond Colliders: BSM WG]

Theoretical control of inclusive $b \to s\phi$ processes
and rates for $\phi \to$ hadrons
will be crucial to this LLP programme at LHC

Similar: Heavy neutral lepton searches, ...

Summary

- Space of smoking guns and precision measurements: lots of heavy flavor mysteries to be understood!
- Precision tensions in $|V_{cb}|$, $b \to s\mu\mu$ will be established or resolved with more data
- Smoking gun anomalies suggest leptoquarks, but more careful, self-consistent study is needed (at least for $b \to c\tau\nu$, $R(D^{(*)})$ interpretations)
- Emerging and crucial role for flavor in development of the LLP program at LHC and beyond

Thanks!