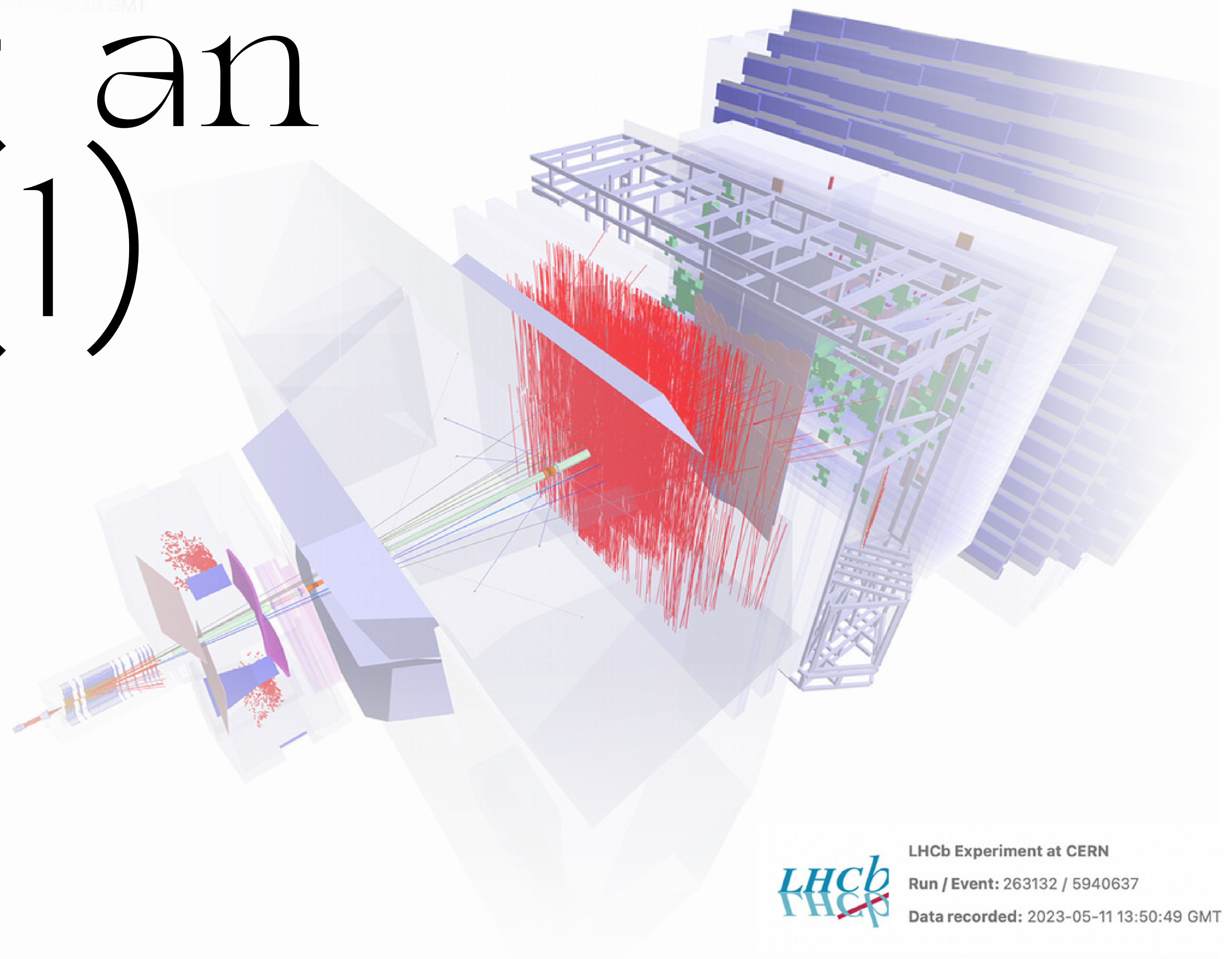
Search for an optimal U'(1)

Anna Mullin
University of Cambridge
arXiv:2306.08669

GATES Cambridge

UNIVERSITY OF CAMBRIDGE



YOUNG THEORISTS FORUM

DECEMBER 2023

New U(1)

Gauged U(1) extensions of the SM answer many phenomenological + philosophical questions

Consider the SM as a low-energy EFT; fermions may have a family-dependent charge under new gauge group

Z’ heavy gauge boson of the broken symmetry

EFT is embedded into a renormalisable UV completion

New U(1) group spontaneously broken

Contents

Shopping list for a U(1) extension:

1. Answer **pertinent questions**
2. Assign **realistic U(1) charges** for fermionic fields
3. Produce pheno that is an **optimal fit** to relevant measurements
4. **Optimal example** $U(1)_{3B_3-L_e-2L_\mu}$

1. Pertinent questions

Experiment tensions / Flavour puzzles / Neutrino mass

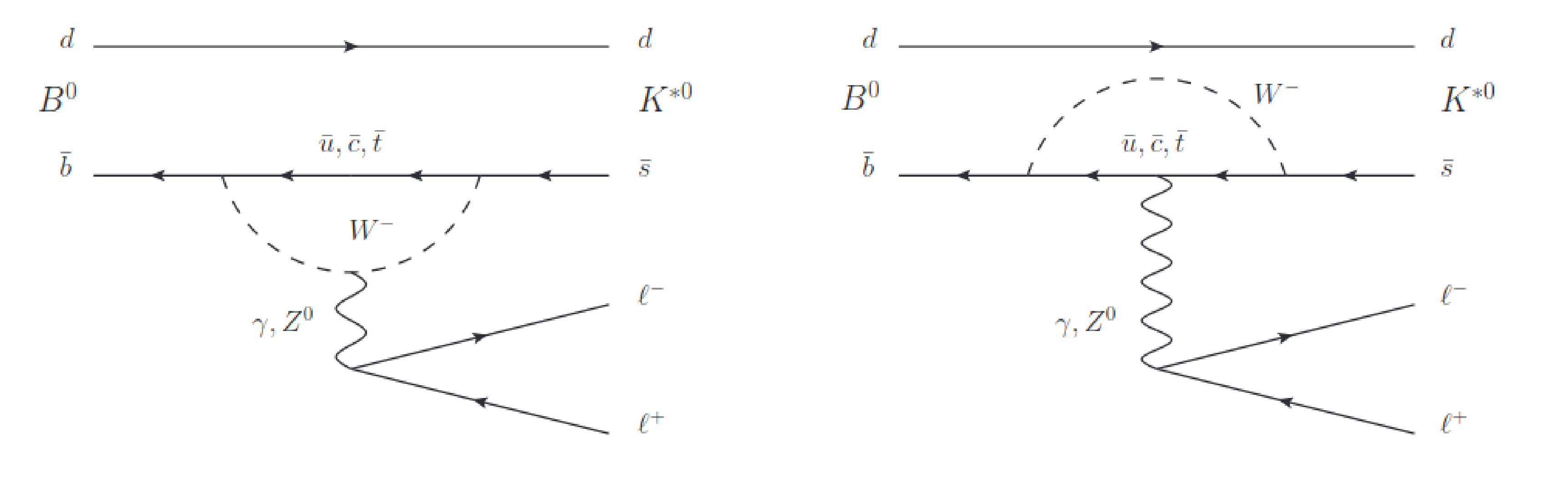
Tensions at B-factories

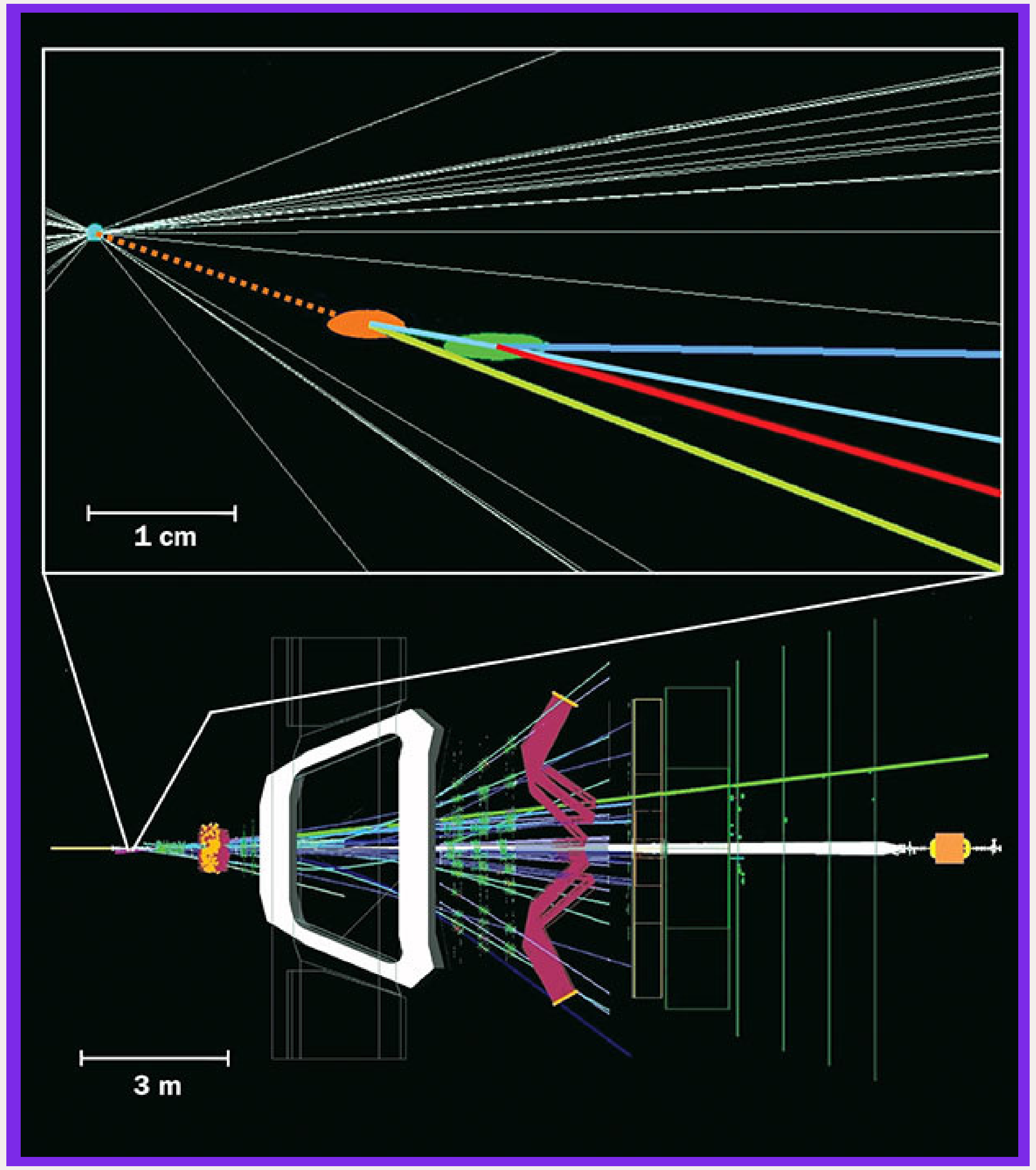
- BaBar, anomalous branching fractions for B --> D meson decays, 2012
- Belle, 2015

  ...
- LHCb, 2022

$R_D, R_{D^*}, R_K, R_{K^*}$

+ rare neutral current B-decays





LHCb side-view

Enlarged near interaction point

B meson decay event

CERN

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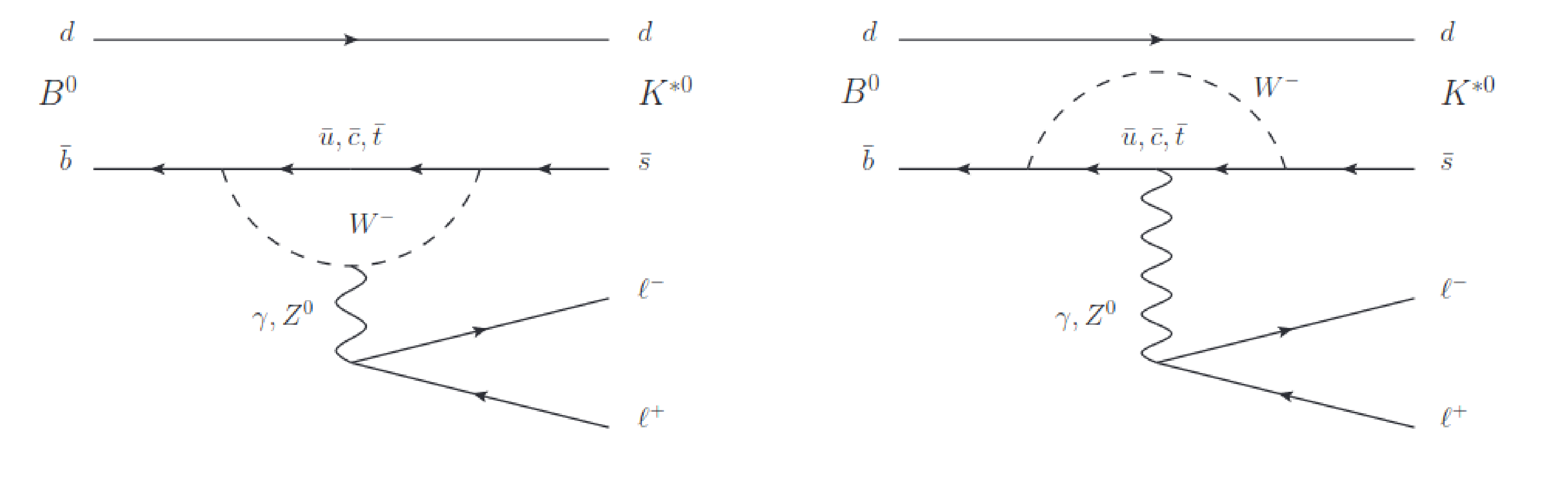
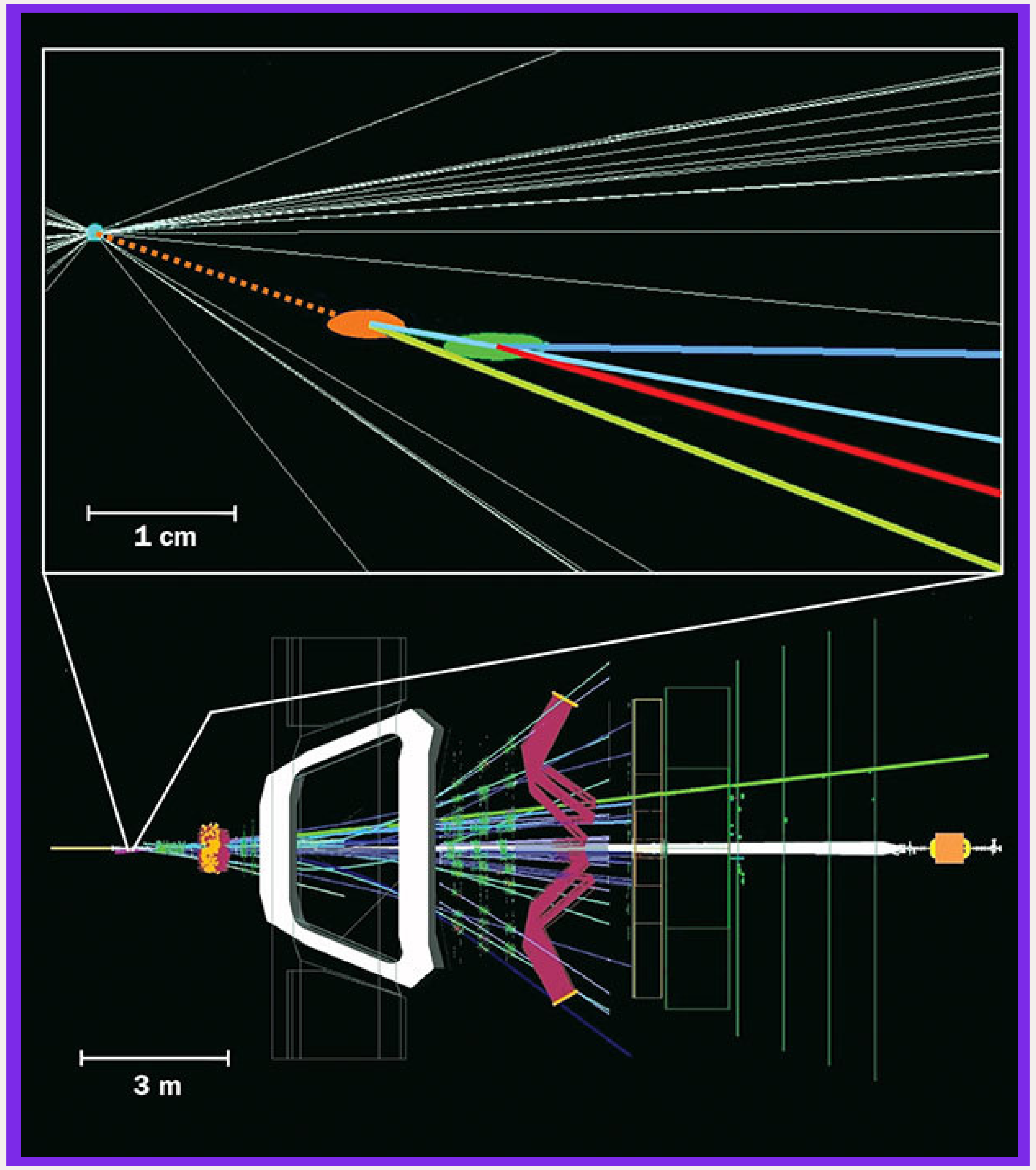


fermions may have family-dependent U (1) charge



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Tensions at B-factories

Recent update: LFU test

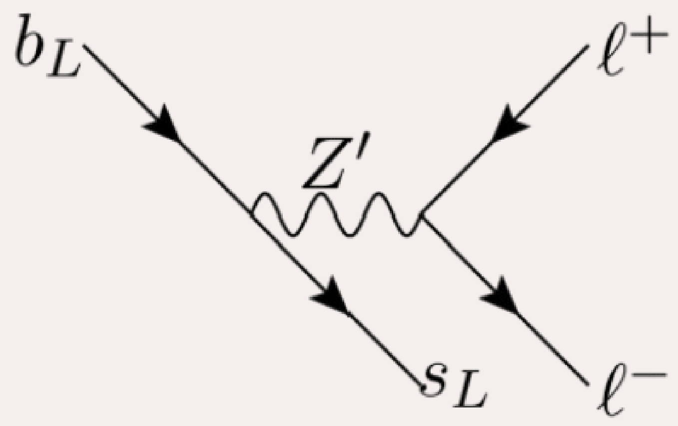
$$R_A(q^2_{\min},\ q^2_{\max}) := \frac{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 BR(B \to A\mu^+\mu^-(q^2))}{\int_{q^2_{\min}}^{q^2_{\max}} dq^2 BR(B \to Ae^+e^-(q^2))}$$

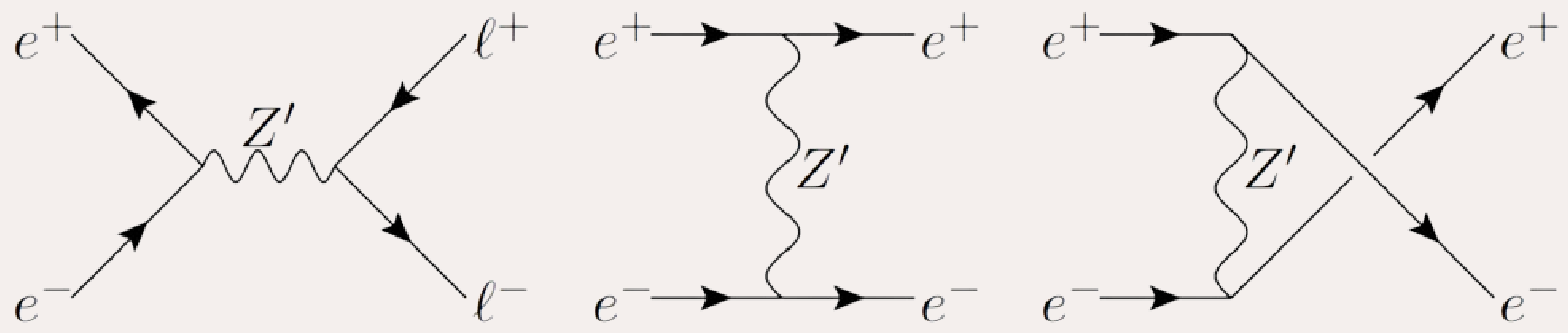
$$A \in \{K, K^*\}$$

Current tensions:

- 1.6σ for $B_s \to \mu^+\mu^-$
- Up to 4σ for $B_s \to \phi\mu^+\mu^-$ in some bins
- ~few σ for angular distributions in $B \to K^*\mu^+\mu^-$
- 3.3σ combined CC anomalies in $b \to c\ell\bar{\nu}$

If family-dependent U(1) charges:

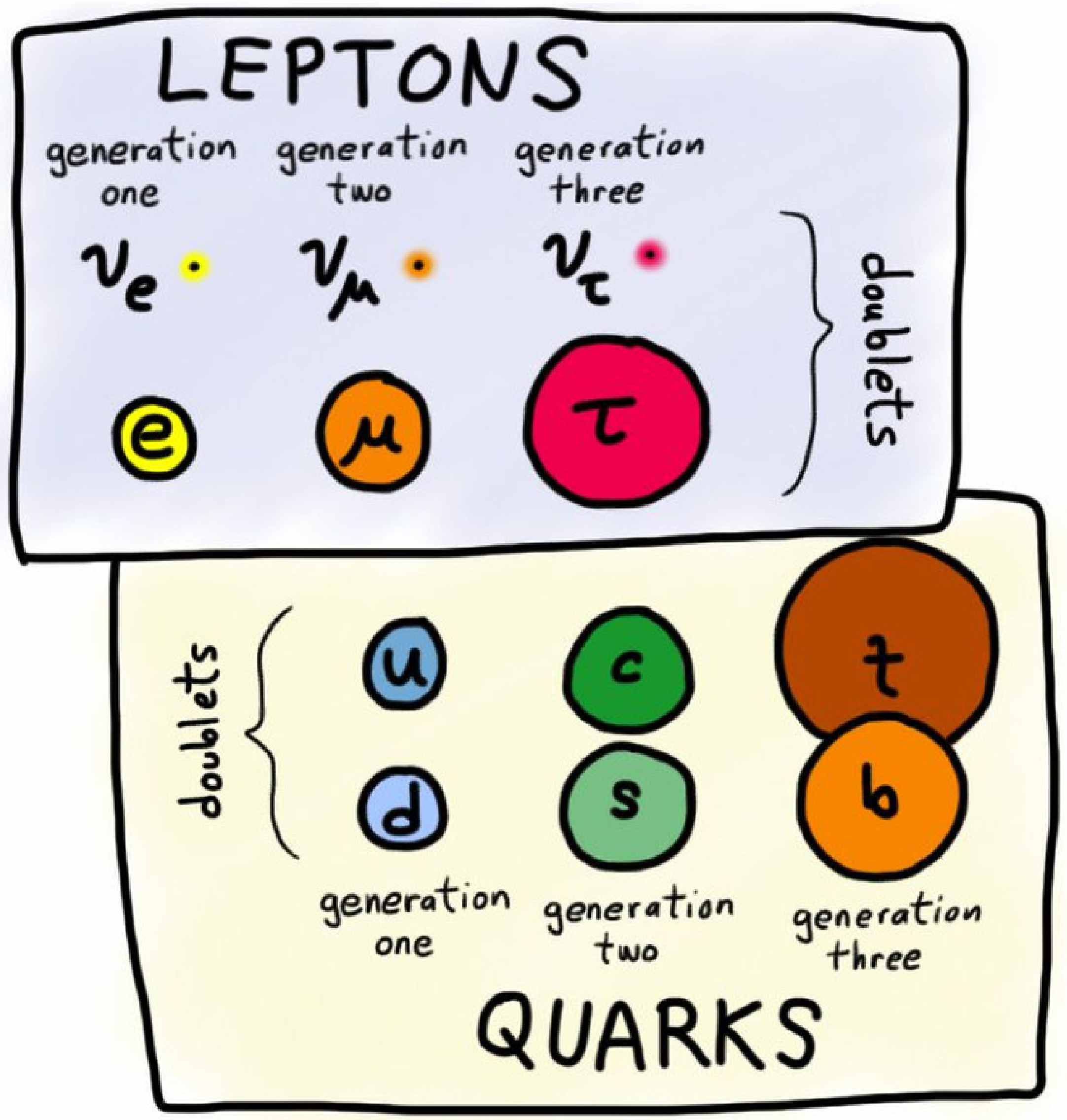




- Implies mediator of other processes -> constrains our **optimal fit**

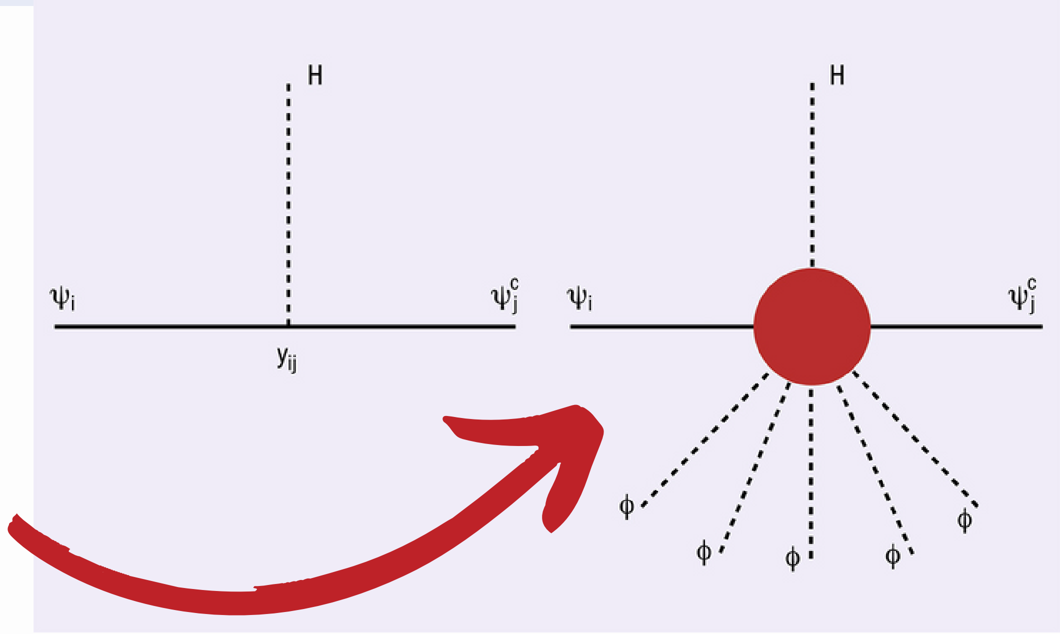
Flavour puzzles

- Bizarre hierarchy: at least **12 orders of magnitude** between largest+smallest fermion masses
- ~22 masses+mixings are unexplained



Explanations

Contact interactions with a new field ϕ (via 2.)?



1. Weinberg: Yukawa couplings forbidden at tree level **by a flavour symmetry, generated in loop diagrams** (1972)?

2. Froggatt and Nielsen: additional **U(1) flavour symmetry** -> different fermion charges + new fields (e.g. ϕ) (1979)?

Flavour puzzles

Froggatt & Nielsen: **new scalar field ϕ** -> acquires a VEV & **breaks the U(1) symmetry.**

A two-family example:

$$M_u = \begin{pmatrix} \epsilon^4 & \epsilon^2 \\ \epsilon^2 & 1 \end{pmatrix} v_u \,, \quad M_d = \begin{pmatrix} \epsilon^3 & \epsilon^3 \\ \epsilon & \epsilon \end{pmatrix} v_d$$

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↓

$$\frac{m_c}{m_t} \sim \epsilon^4 \,, \quad \frac{m_s}{m_b} \sim \epsilon^2 \,, \quad |V_{cb}| \sim \epsilon^2$$

correct if $\epsilon = \langle \phi \rangle / M^*$ is around 0.2

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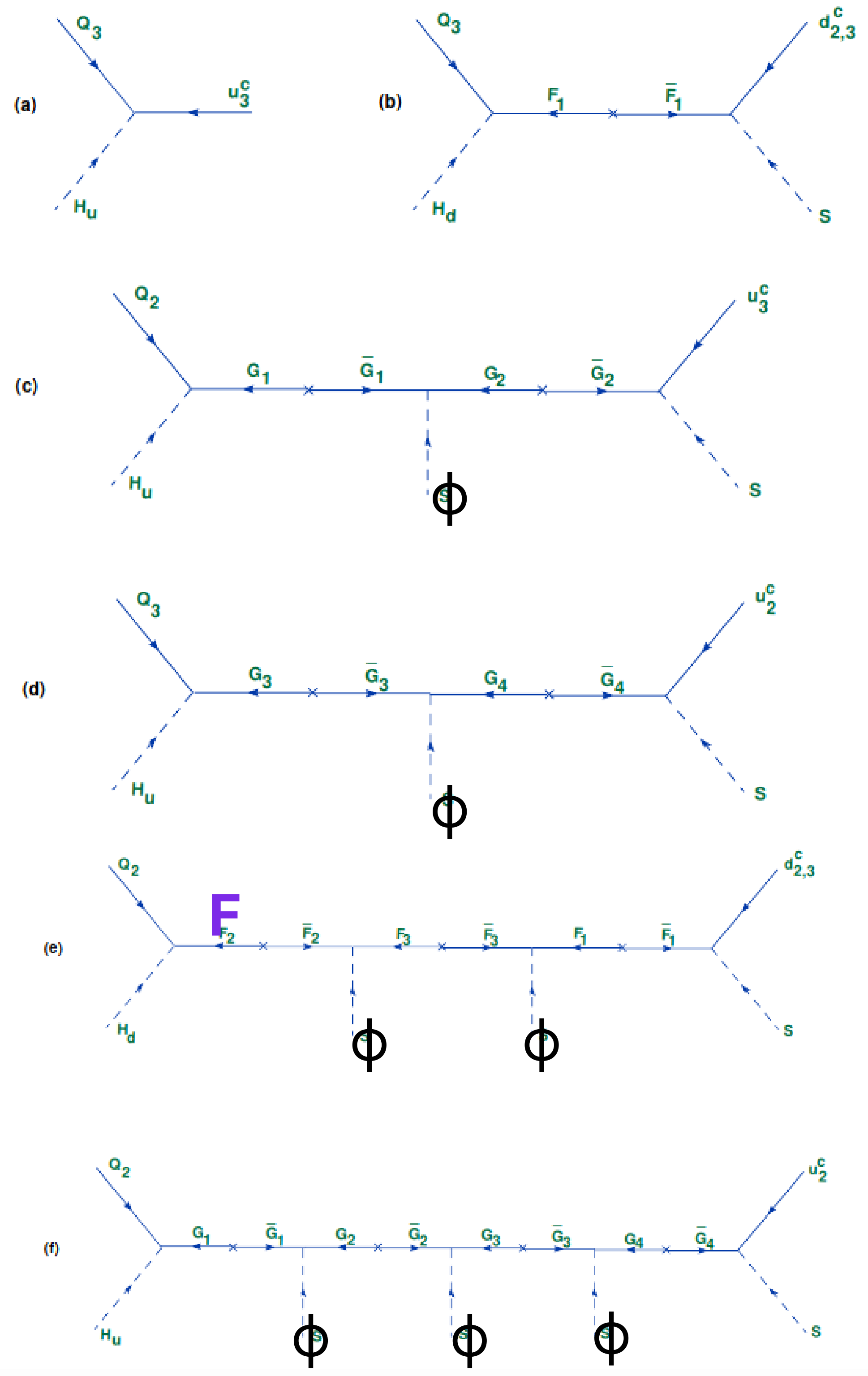
M^* mass scale of heavy new fields (integrated out) e.g. **F**



- Spaghetti diagrams

Flavour puzzles

Frog

b quark:

$$\mathcal{L}_b^{\rm eff} = Y_1 Y_2 \left(Q_3 d_3^c H_d\right) \; (<\phi>/M^*)$$

M* mass scale of heavy new fields (integrated out)

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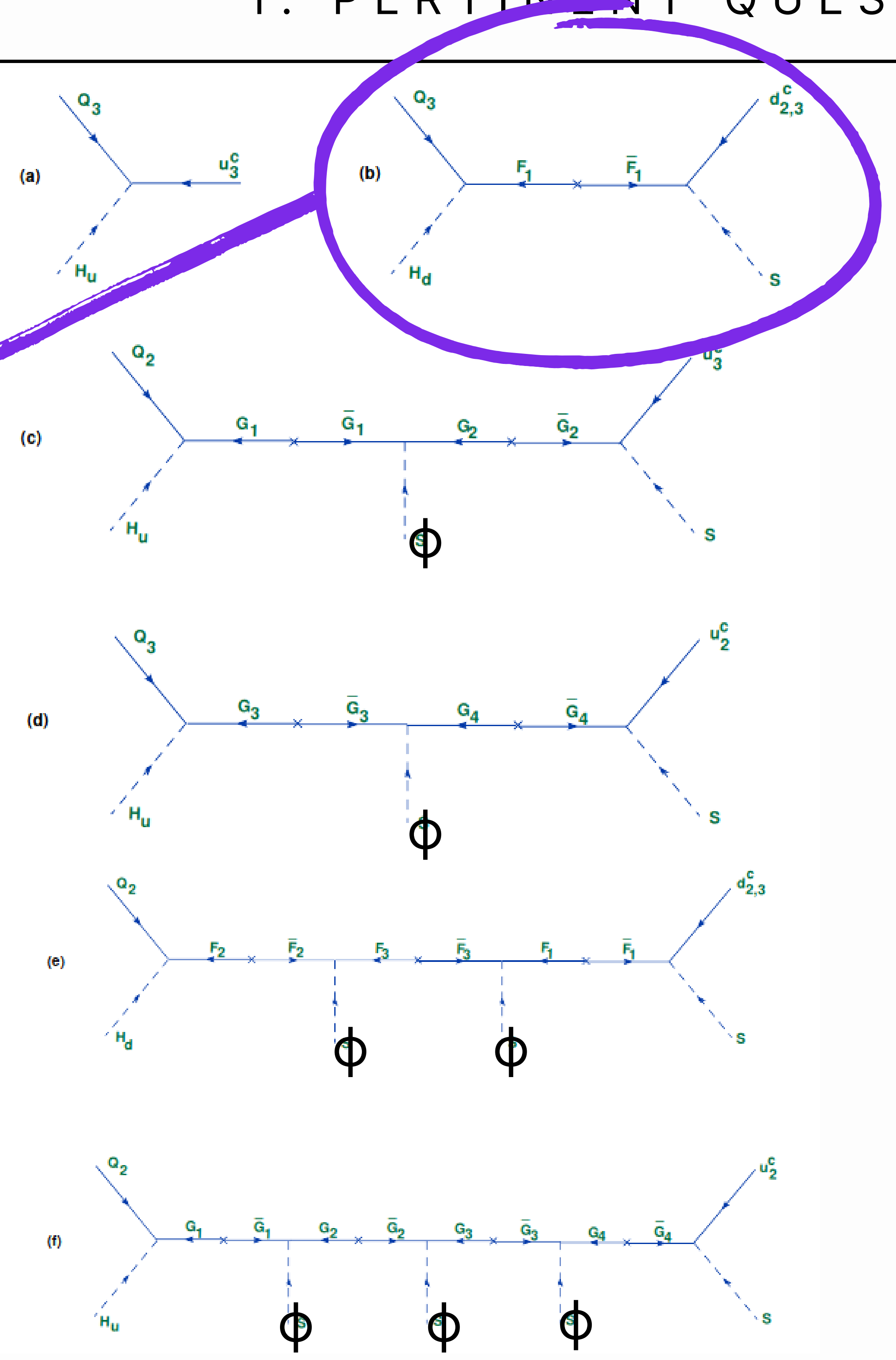
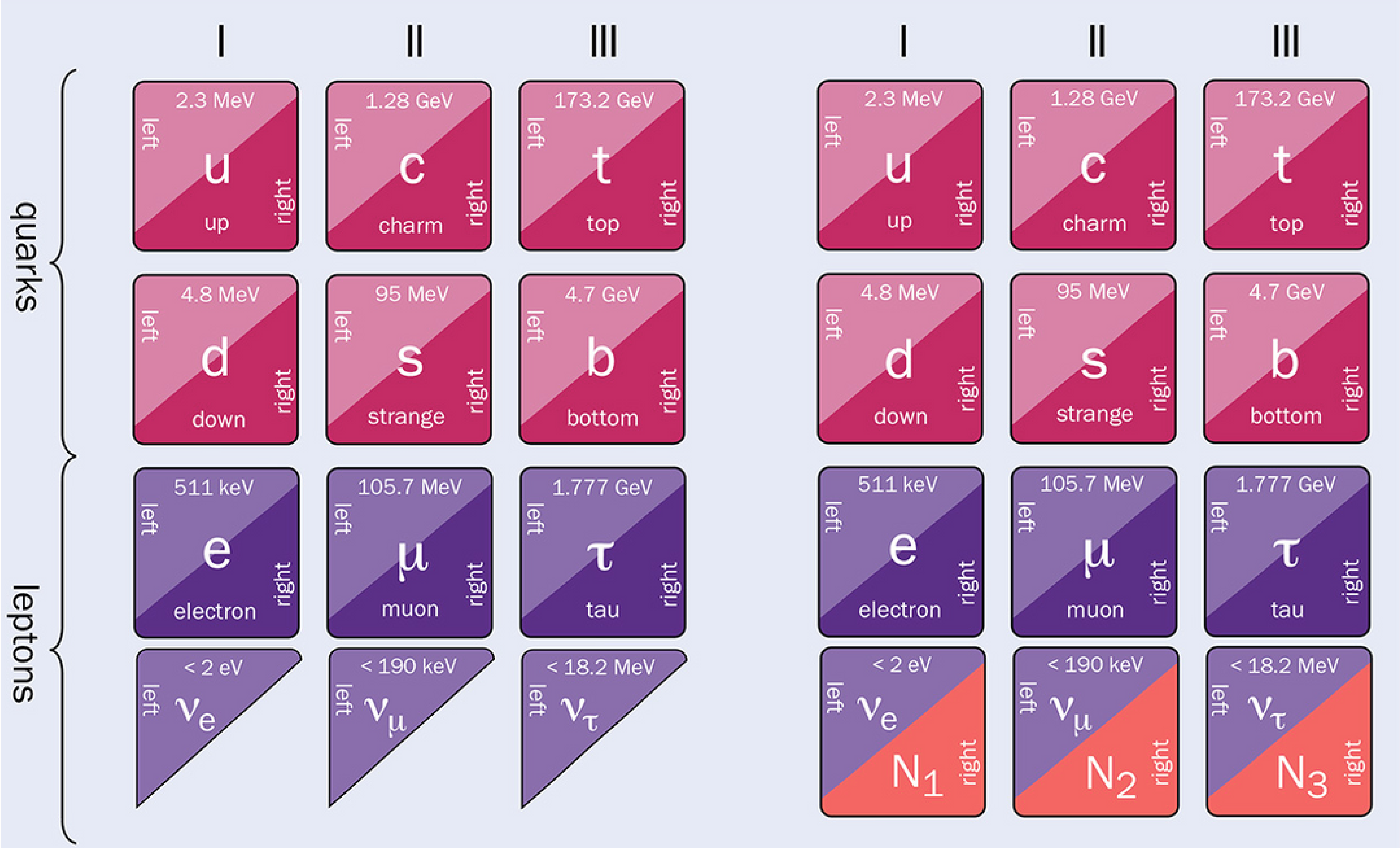


- Spaghetti diagrams

Right-handed neutrinos

- Explain: neutrino masses + dark matter + matter-antimatter asymmetry

- Example:
  a. Try new U(1) with B-L gauge symmetry in a UV completion of the SM,
     i. Because B-L appears to be an accidental global SM symmetry.
  b. Assign charge -1 to 3 RH neutrinos
     i. Introducing the scalar field with B-L charge 2 that generates Majorana masses of the RH neutrinos.
  c. Obtain the type-I seesaw mechanism.



RH neutrino masses often $10^{11} - 10^{13}$ GeV to explain the smallness of neutrino masses

Source

2. Realistic charges

Anomaly-free / Other requirements

Fermion charges

Assign new U(1) charges (Q, L, u etc.) based on:

1. **anomalies**
2. **phenomenology**

Field	$(SU(3), SU(2), U(1)_Y, U(1)_X)$
Q_i	$(3, 2, 1, Q_i)$
L_i	$(1, 2, 3, L_i)$
u_i	$(3, 1, 4, u_i)$
d_i	$(3, 1, -2, d_i)$
e_i	$(1, 1, -6, e_i)$
ν_i	$(1, 1, 0, \nu_i)$

Chiral fermion field content and its representations under SMxU(1)

Anomalies

- U(1) charges constrained by QFT anomalies spoiling renormalisability & gauge symmetry:
  - U(1) & "gauge-gravity" anomalies

Solved **anomaly cancellation equations** for integer charges between 10 and -10

$$\sum_i (2Q_i - u_i - d_i) = 0,$$

$$\sum_i (L_i + 3Q_i) = 0,$$

$$\sum_i (Q_i + 3L_i - 8u_i - 2d_i - 6e_i) = 0,$$

$$\sum_i (6Q_i + 2L_i - 3u_i - 3d_i - e_i - \nu_i) = 0,$$

$$\sum_i (Q_i^2 - L_i^2 - 2u_i^2 + d_i^2 + e_i^2) = 0$$

Cancellation conditions Paper

Other requirements

- We require Z′ coupling to left-handed $\bar{b}s$ pairs to **relate with $b \to s\mu^+\mu^-$ phenomenology**
  - choose non-zero Q3 so Z′ couples to left-handed $\bar{b}b$ pairs
  - assume Z′ coupling to $\bar{b}s$ is provided by a small b – s mixing from spontaneous breaking of U(1) symmetry
- Seek **looser bounds from LHC data**
  - choose Z′ coupling to 3rd family quarks only (so Z′ production at LHC is suppressed)
- **RH neutrinos assumed heavy** compared to TeV scale
  - irrelevant to $b \to s\mu^+\mu^-$

3. Optimal fits

Measurements / EFT coefficients / LFU violation

Measurements

Constraints from 3 categories of measurements

- **'LFU'**: 23 observables such as RK and RK$\ast$, which test lepton flavour universality (Belle, LHCb, BaBar)
- **'LEP'**: the 148 $e^+e^- \rightarrow l^+l^-$ measurements
- **'Quarks'**: contains 224 other $b \rightarrow s\mu^+\mu^-$ measurements (ATLAS, CMS, Belle, BaBar, LHCb)

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Convert into constraints on EFT in chosen basis

WET

EFT coefficients

- Weak effective theory is valid below the W boson mass, therefore written in the spontaneously broken phase of the electroweak gauge symmetry

$$\mathcal{L} = \ldots + N\left(C_9^{(e)}(\bar{b}\gamma^\alpha P_L s)(\bar{e}\gamma_\alpha e) + C_{10}^{(e)}(\bar{b}\gamma^\alpha P_L s)(\bar{e}\gamma_\alpha\gamma_5 e) + H.c.\right)$$

$$\ldots + N\left(C_9^{(\mu)}(\bar{b}\gamma^\alpha P_L s)(\bar{\mu}\gamma_\alpha \mu) + C_{10}^{(\mu)}(\bar{b}\gamma^\alpha P_L s)(\bar{\mu}\gamma_\alpha\gamma_5 \mu) + H.c.\right)$$

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$$\ldots + N\Big(C_9^{(\mu)}(\bar{b}\gamma^\alpha P_L s)(\bar{\mu}\gamma_\alpha \mu) + C_{10}^{(\mu)}(\bar{b}\gamma^\alpha P_L s)(\bar{\mu}\gamma_\alpha\gamma_5 \mu) + H.c.\Big)$$

SMEFT

- Convert WCs in WET into SMEFT
- SMEFT involves complete representations of the unbroken SM gauge group (e.g. SU(2) doublets)

$$O_{qe}^{(l)2322} = (\bar{Q}_2\gamma_\alpha Q_3)(\bar{e}_2\gamma^\alpha e_2), \quad C_{qe}^{(l)2322} = N(C_9^{(\mu)} + C_{10}^{(\mu)})$$

$$O_{lq}^{(l)2223} = (\bar{L}_2\gamma_\alpha L_2)(\bar{Q}_2\gamma^\alpha Q_3) \quad C_{lq}^{(l)2223} = N(C_9^{(\mu)} - C_{10}^{(\mu)})$$

Computation

smelli

global likelihood function in space of dimension-6 Wilson coefficients in SMEFT

flavio

compute observables

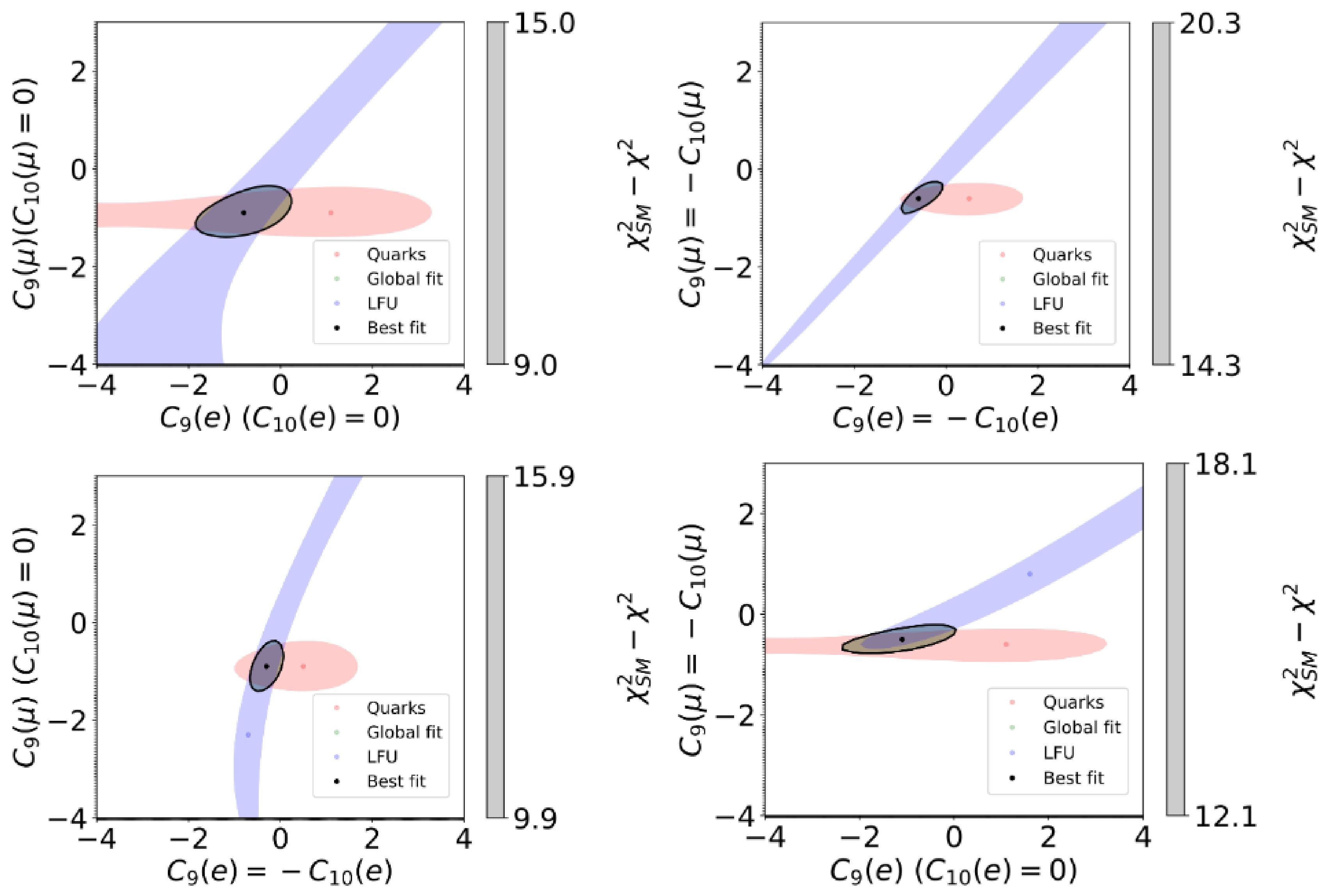
wilson

running, matching, translating Wilson coefficients beyond the SM above + below the EW scale

- Include a total of 247 observables
- Account for theory uncertainties
- Alter couplings at high energy scales (“running”)

Fits to data

- **C9 = −C10** -> left-handed
- **C10 = 0** -> vector-like

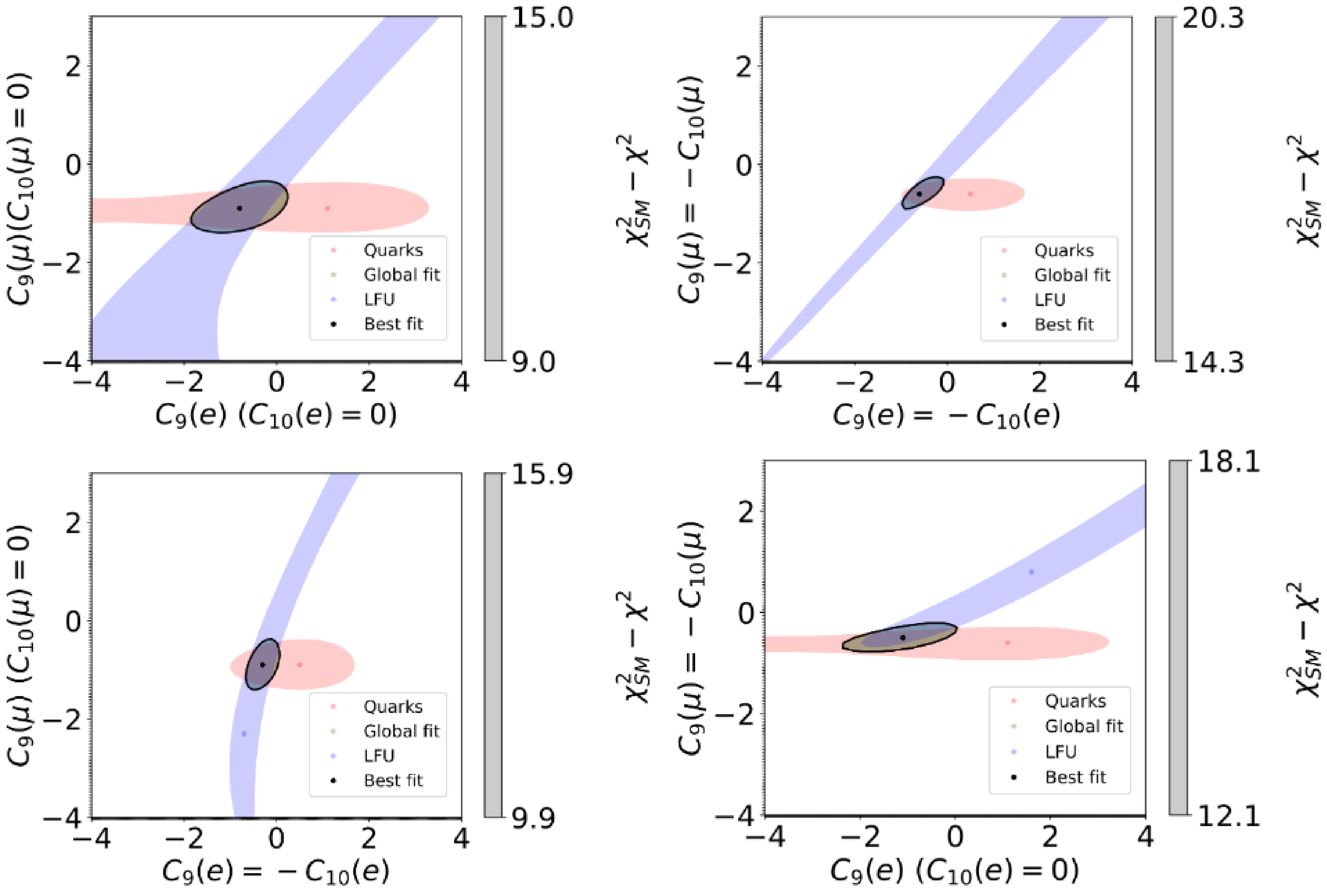


Fits to data

- **C9 = −C10** -> left-handed
- **C10 = 0** -> vector-like

=> best fit point is C9(e) ≈ C9(μ), values slightly negative, although C9(e)=0 may also fit

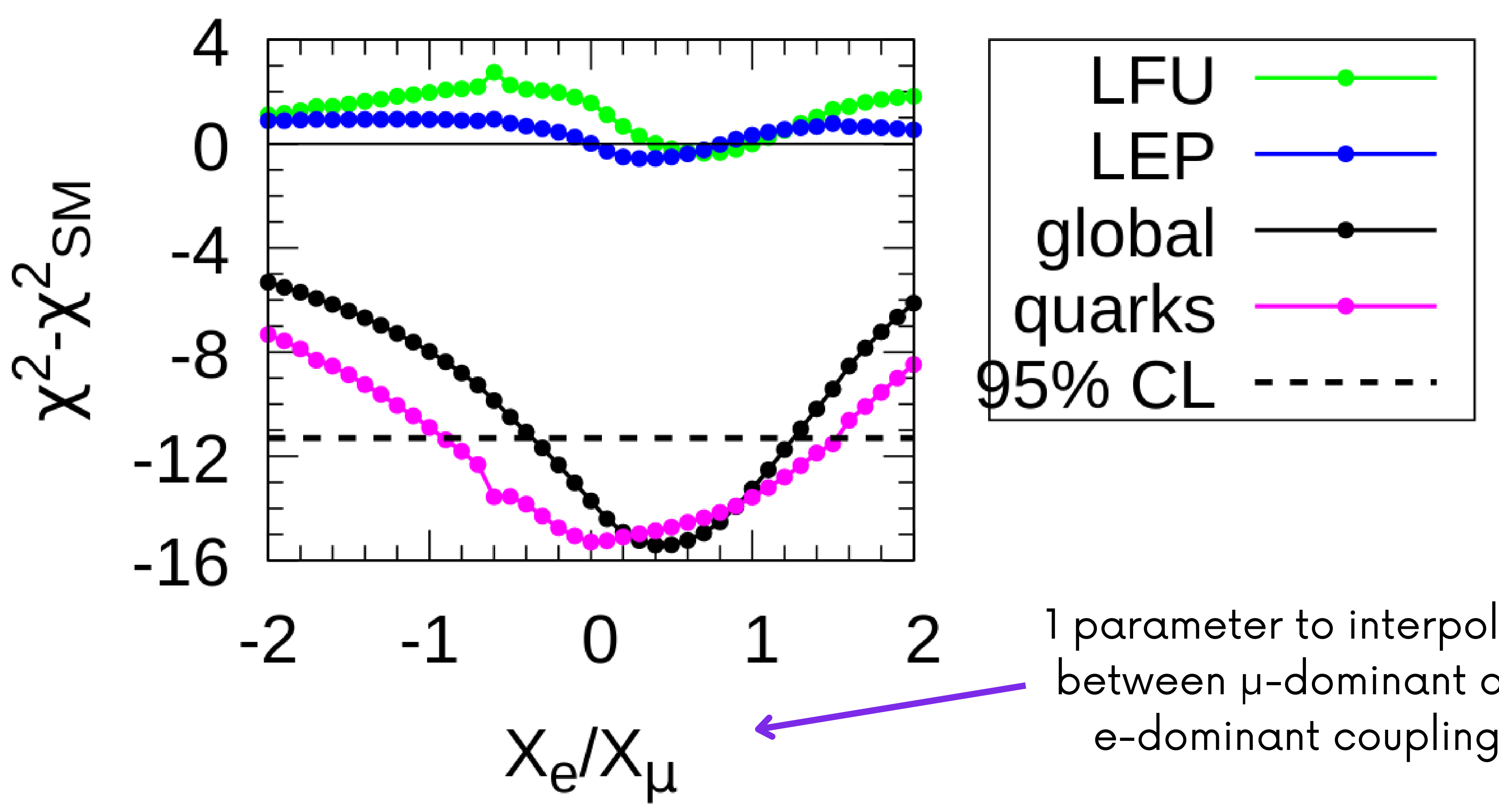
What models range these best fit lepton couplings?



LFU-violating charges

- Check how much U(1) improves fits to measurements compared with SM:
  - for a range of U(1) charges, **Xe** and **Xμ**

- Negative values of χ2 −χ2(SM) indicate improvement of fit



1 parameter to interpolate between μ-dominant and e-dominant couplings

4. Optimal example

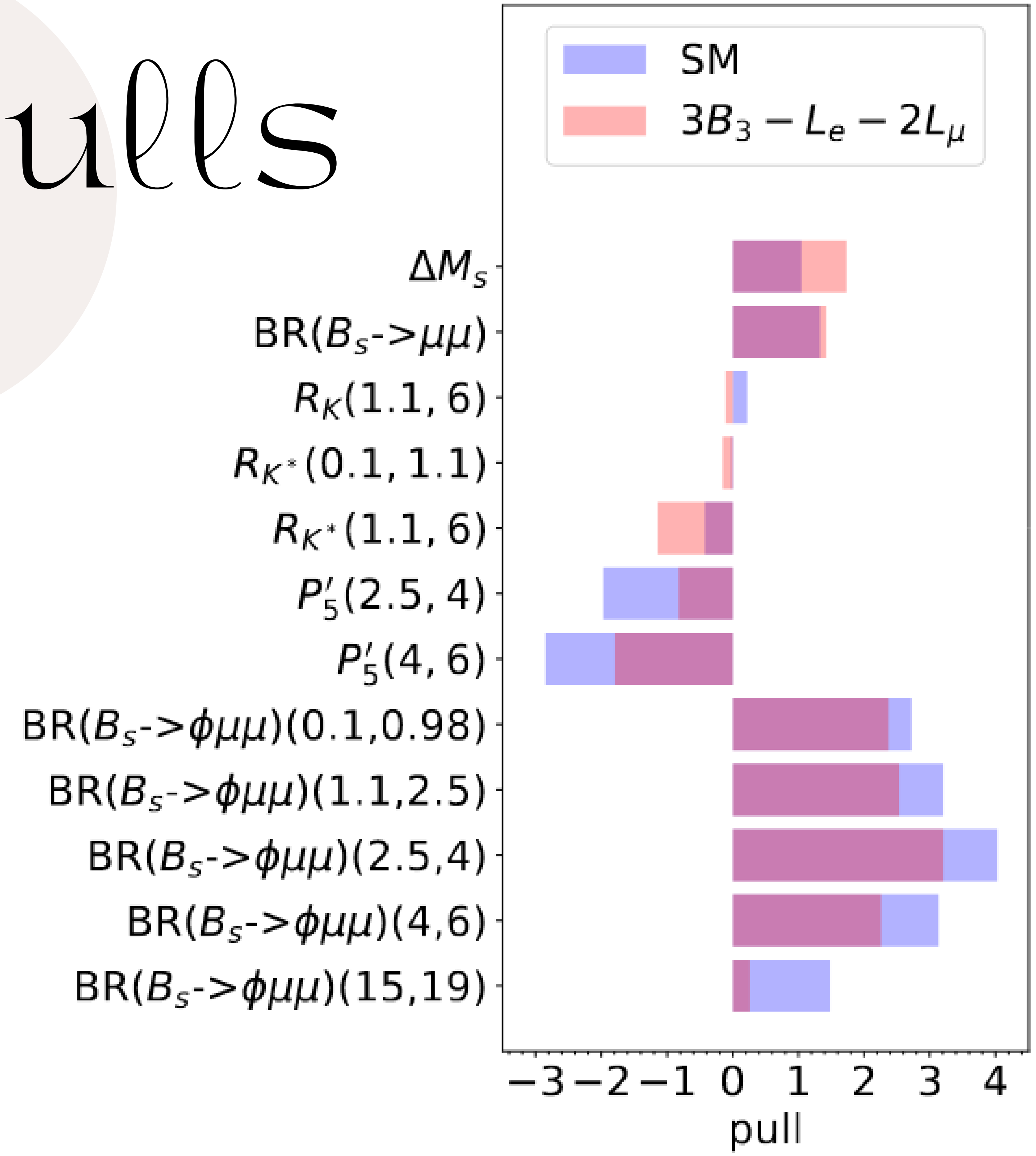
Model / Improved fits

U(1)$_{3B_3 - L_e - 2L_\mu}$

- Accounting for unexplained SM parameters instead of adding many new ones
- Relatively small fermion charges

- B – L appears to be an accidental global symmetry in the SM, indicating that this might be a gauge symmetry in a UV completion of the theory
- B3: a single generation of quarks is charged under the additional U(1) gauge group (3rd family)

Pulls



$$\text{Pull} = \frac{\text{theory - experiment}}{\text{uncertainty}}$$

Improvement

Fits to some observables are better than the SM

Thanks!

Anna Mullin
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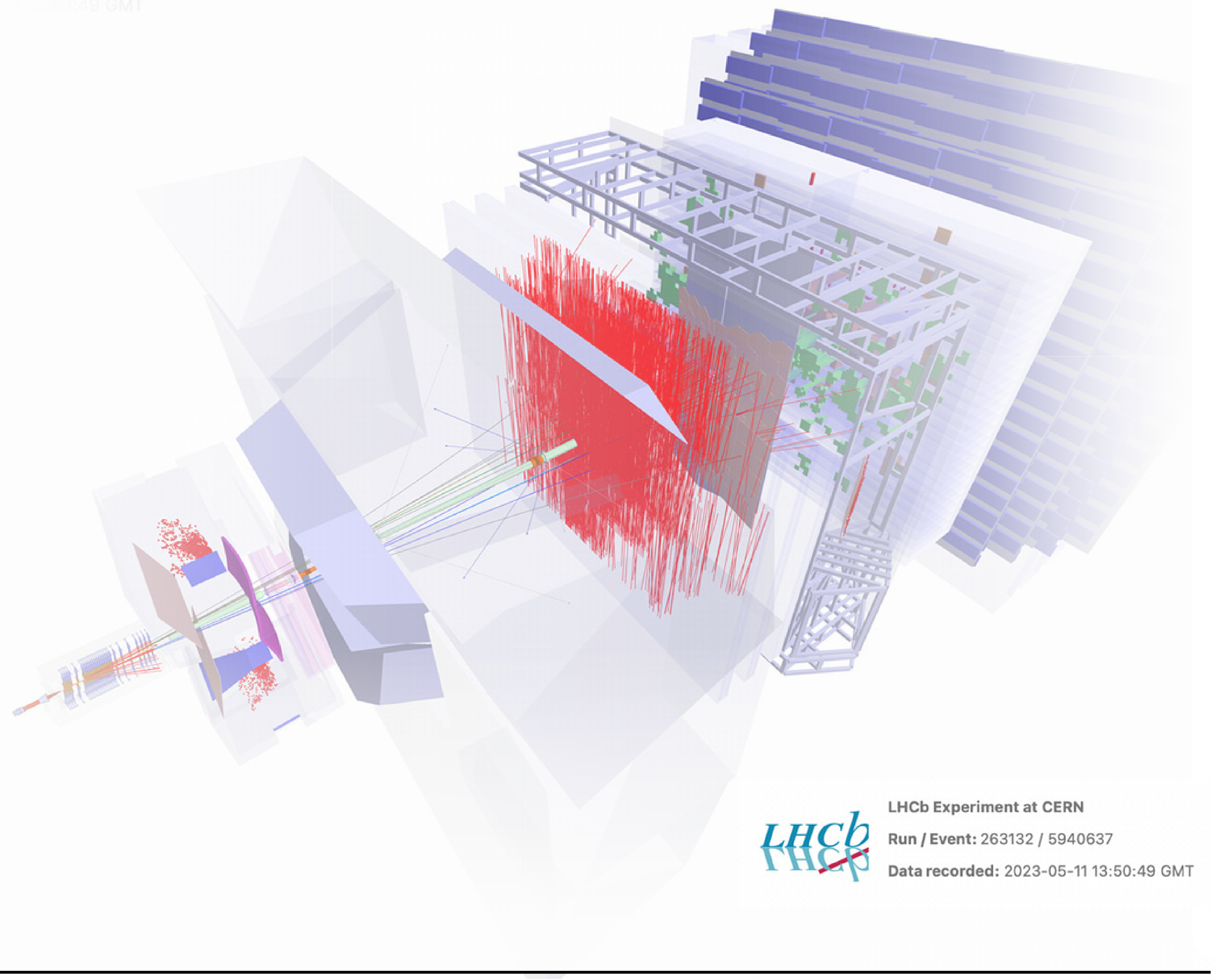


Backup

Fit to 88 b → sμ⁺μ⁻ observables

[Altmannshofer & Straub, 1503.06199]

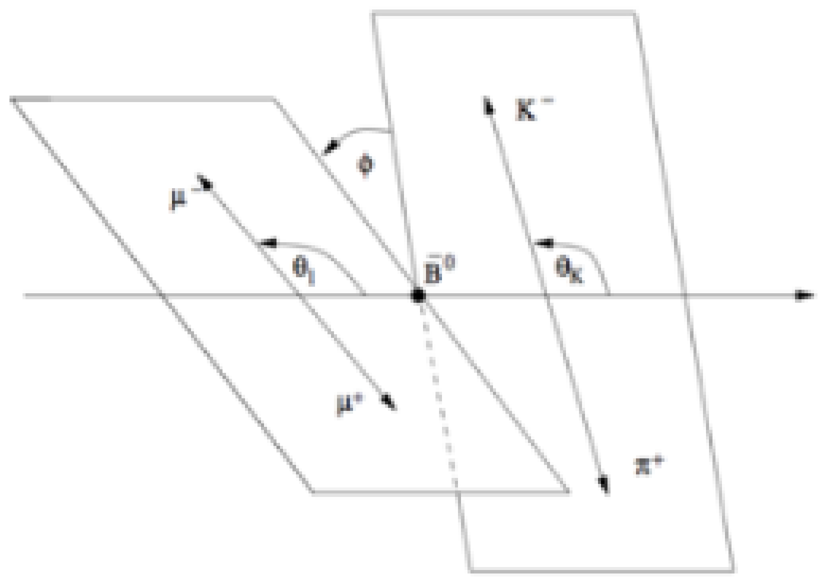
Coeff.	best fit	1σ	2σ	$\sqrt{\chi^2_{\text{b.f.}} - \chi^2_{\text{SM}}}$	p [%]
C_7^{NP}	-0.04	$[-0.07, -0.01]$	$[-0.10, 0.02]$	1.42	2.4
C_7'	0.01	$[-0.04, 0.07]$	$[-0.10, 0.12]$	0.24	1.8
C_9^{NP}	-1.07	$[-1.32, -0.81]$	$[-1.54, -0.53]$	3.70	11.3
C_9'	0.21	$[-0.04, 0.46]$	$[-0.29, 0.70]$	0.84	2.0
C_{10}^{NP}	0.50	$[0.24, 0.78]$	$[-0.01, 1.08]$	1.97	3.2
C_{10}'	-0.16	$[-0.34, 0.02]$	$[-0.52, 0.21]$	0.87	2.0
$C_9^{\text{NP}} = C_{10}^{\text{NP}}$	-0.22	$[-0.44, 0.03]$	$[-0.64, 0.33]$	0.89	2.0
$C_9^{\text{NP}} = -C_{10}^{\text{NP}}$	-0.53	$[-0.71, -0.35]$	$[-0.91, -0.18]$	3.13	7.1
$C_9' = C_{10}'$	-0.10	$[-0.36, 0.17]$	$[-0.64, 0.43]$	0.36	1.8
$C_9' = -C_{10}'$	0.11	$[-0.01, 0.22]$	$[-0.12, 0.33]$	0.93	2.0

- Since p-value of SM is 2.1%, no solution really nails it. Scenario with a -25% shift in C_9 (vector current) preferred

Source

What is P_5'?

- Integrated observables
- S are form factor dependent observables



$$\frac{1}{\mathrm{d}\Gamma/dq^2}\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \frac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$$

Source

Paper for definitions