An Overview of Flavor Physics (I)

J. Martin Camalich

XLVIII International Meeting on Fundamental Physics In Benasque

September 7th 2021

Outline of the talks

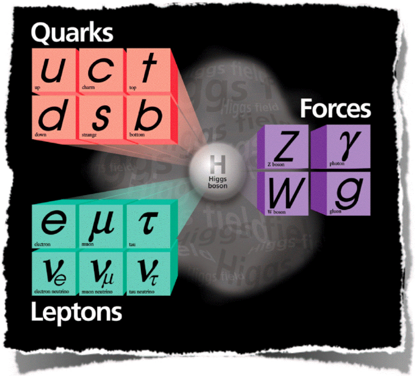
1. **1st talk: September 7th**
   - Introduction to flavor and “Why to investigate on Flavor Physics in the XXI c.?”
   - Quick status CKM metrology and Cabibbo-angle Anomaly
   - The R_K lepton-flavor universality anomalies
2. **2nd talk: September 8th**
   - The R_D lepton universality anomalies
   - The LHC flavor-physics program
   - A view on dark-flavor sectors

What is Flavor Physics?

"Just as ice-cream has both ***colour*** *and* ***flavour so do quarks."***

H. Fritzsch & M. Gell-Mann, 1971

- **Standard Model of Particle Physics**



- **3 *almost identical* families of "Matter"**
  - "Up quarks": "*up*", "*charm*", "*top*"
  - "Down quarks": "*down*", "*strange*", "*bottom*"
  - "Neutral leptons": Neutrinos
  - "Charged leptons": *e*, μ and τ
- **"Identical":** Same gauge forces (e.g. electric)
- **"*Almost*":** Different masses!

Flavor Physics in the Standard Model

Yukawa sector of the Standard Model

$$-\mathcal{L}_Y = \bar{q}_L Y_D d_R H + \bar{q}_L Y_U u_R \tilde{H} + \bar{\ell}_L Y_e e_R H + \text{h.c.}$$

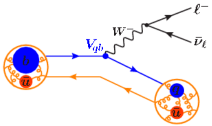
- **Fermion mass generation:** $H \to \text{vev} + h^0$
  - Yukawa matrices diagonalizable

$$M_{U(D)} \equiv \begin{pmatrix} m_{u(d)} & 0 & 0 \\ 0 & m_{c(s)} & 0 \\ 0 & 0 & m_{t(b)} \end{pmatrix} = \text{vev} \times L^{\dagger}_{u(d)}\, Y_{U(D)} R_{u(d)}$$

- **Cabibbo-Kobayashi-Maskawa mixing matrix**
  - Flavor violation in $W^{\pm}$ (charged current) weak couplings

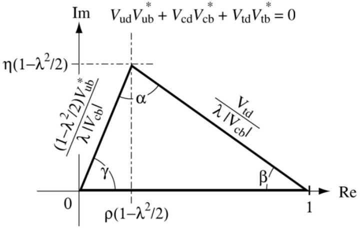
$$V_{\rm CKM} = L_u^{\dagger} L_d \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

  - **Heavy-flavored matter is unstable!**



The CKM unitary triangle

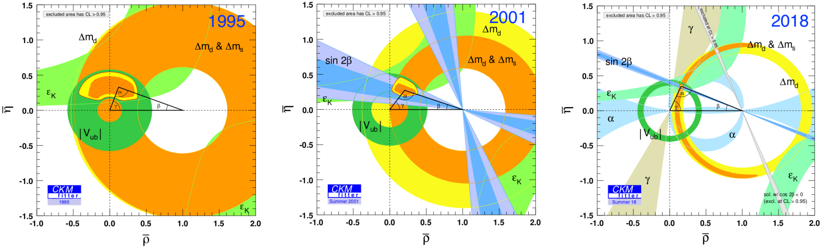
- Complex and Unitary matrix $\Longrightarrow$ Parametrized by **3 angles** and **1 *CP* phase**



Unitary Triangle

- **Unitary relations:** Triangles in complex plane
- **Few parameters** compared to **thousands** of processes they describe – **PDG**

- **Flavor Physics** has become a very mature field



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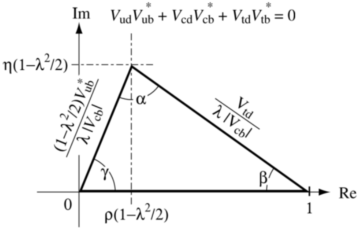

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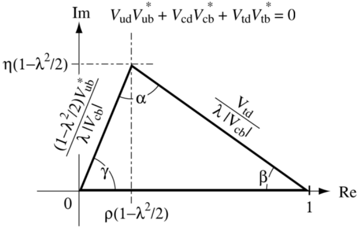
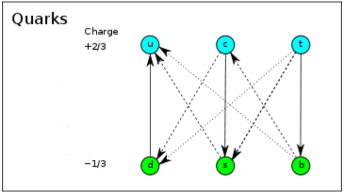


Unitary Triangle

- **Unitary relations:** Triangles in complex plane
- **Few parameters** compared to **thousands** of processes they describe – **PDG**

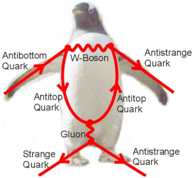
- **CKM matrix is almost diagonal**
  - ΔF suppressed by $\lambda \approx 0.225$



$$|V_{\rm CKM}| = \begin{pmatrix} \mathbf{0.97434(12)} & 0.22506(50) & 0.00357(15) \\ 0.22492(50) & \mathbf{0.97351(13)} & 0.0411(13) \\ 0.00875 & 0.0403(13) & \mathbf{0.99915(5)} \end{pmatrix}$$

Flavor Changing Neutral Currents (FCNC)

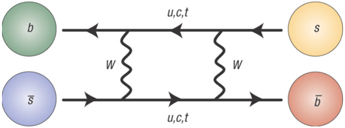
- **Theorem:** FCNC are "**Loop-Suppressed**" and "**Flavor-Suppressed**" in the SM!
  - **Penguin diagram**

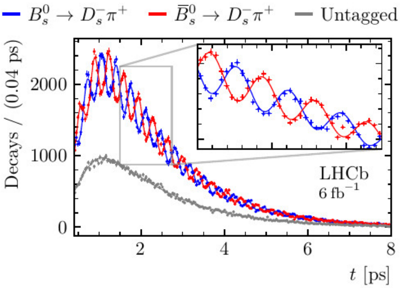


Glashow-Iliopoulos-Maiani mechanism

$$\mathcal{M}_{\rm SM} \sim \underbrace{\overbrace{G_F}^{\text{Weak}} \overbrace{\frac{y_t^2}{16\pi^2}}^{\text{Loop}} \overbrace{(V_{ts}^* V_{tb})^2}^{\text{Flavor}}}_{\text{GIM}}$$

- **Neutral-meson mixing**
  - **Box diagram**



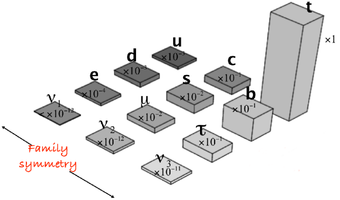


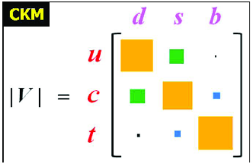
LHCb Collaboration, arXiv: 2104.04421

Why studying Flavor Physics in the 2020's?

(1) Fundamental Questions: The Flavor Puzzle

- CKM and mass matrices: **Parametrizations** of flavor phenomena in the SM





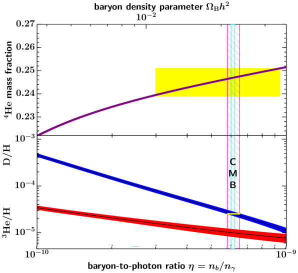
SM Flavor Puzzle: Where do hierarchies of masses and mixings come from?

- Horizontal-flavor symmetries Froggatt & Nielsen (1979)
- Warped extra dimensions Randall & Sundrum (1999)
- Clockwork mechanism Giudice & McCullough (2017), Alonso-Carmona-Dillon-Kamenik-JMC-Zupan (2019)
- Tree vs. loop **S. Weinberg** (2020) - arXiv: 2001.06582

- **However,** the solution might not be accessible at the energies at reach. . .

(1) Fundamental Questions: Baryogenesis

- **Baryogenesis** (*aka* “Where do we come from?”)



Sakharov conditions A. Sakharov 1967

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.105(55) \times 10^{-10}$$

PDG 2020

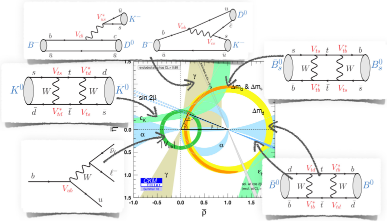
1. Baryon-number violation
2. No thermal equilibrium
3. Violation of C and CP symmetry

- **The Flavored Universe**
  - Is the CKM CP-violating phase large enough to generate η?
  - Does nature have 3 generations to trigger baryogenesis?
  - $\Omega_{\rm DM} h^2 \approx \Omega_b h^2$: Relic baryon and dark-matter production mechanisms related?

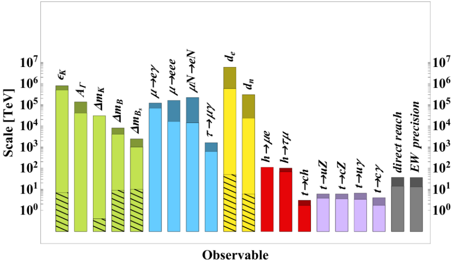
New physics needed for successful baryogenesis!

(2) Probe of New (Beyond the SM) Physics

- Several reasons for New Physics
  - Quantum Gravity, the Dark Universe, neutrino masses, the flavor puzzle, baryogenesis, the strong *CP* problem, the electroweak hierarchy problem ...
- Flavor processes are a powerful probe of New Physics
  - $\sim$1000's of flavor transitions described by **3 angles** and **1 *CP*-violating phase**



Jure Zupan, arXiv: 1903.05062

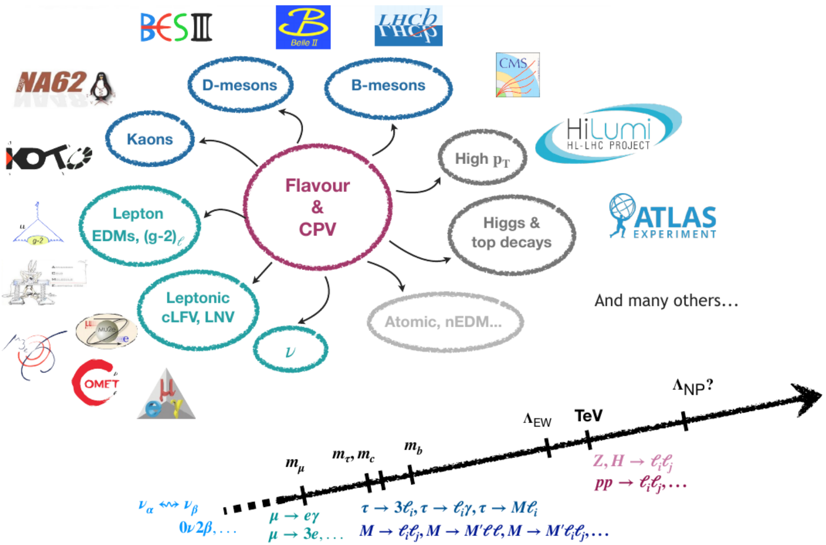


European Strategy for Particle Physics Update 2020, arXiv: 1910.11775

FCNCs indirectly sensitive to up to 10^7 TeV energy scales!

(2) Probe of New (Beyond the SM) Physics

- **Multi-energy scale experimental effort**

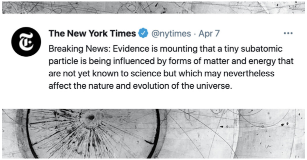


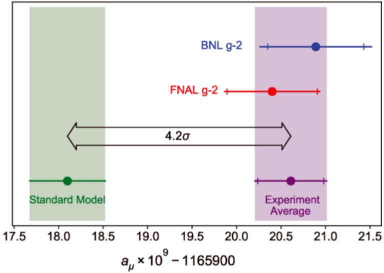
Plenary talk **Ana Teixeira** @ EPS-HEP 2021

(3) Flavor anomalies!

- **Anomalies in decays of *B*-mesons**

- **Muon's anomalous magnetic moment**





New fundamental forces sensitive to lepton flavor!

(3) Flavor anomalies!

Flavor physics was instrumental in **discovering** and **shaping** the SM

- **Nuclear β-decays:** Discovery **weak interactions** and **neutrino**
- **Rare Kaon-decays:** Discovery of the **charm quark**
- **Kaon decays:** Discovery of *CP* **violation** $\Longrightarrow$ Discovery of **3 generations**

- **Expect the unexpected**

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

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

(April 10, 1963)

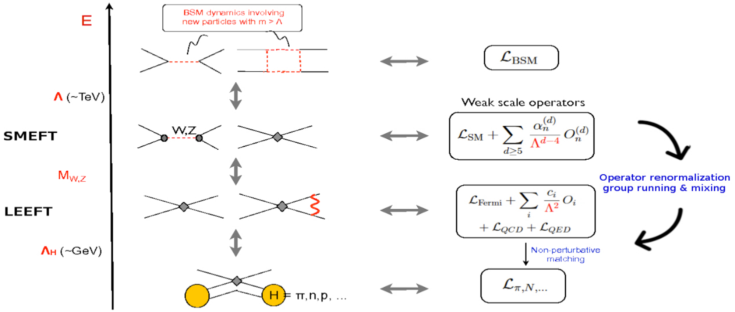
I. INTRODUCTION

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 $K^o_2 \rightarrow \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \rightarrow \mu^+ + \mu^-$.

Thanks to Zoltan Ligeti for sharing this

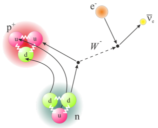
Testing (B)SM with Flavor Physics: Effective Field Theories

- Add all operators consistent with **symmetries** and **matter content**
- **Infinite terms? <u>NO</u>** if there is a **mass gap** $\Lambda_{\rm NewPhysics} \gg$ vev



Cirigliano and Mussolf Prog.Part.Nucl.Phys. 71 (2013) 2-20

- **The classic example: Fermi theory** for β decay!

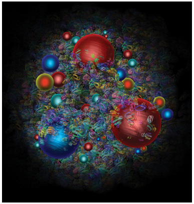


$$\mathcal{L}_{\rm Fermi} = \frac{G_F}{\sqrt{2}} V_{ud} (\bar{u}d)_{V-A} (\bar{e}\nu)_{V-A}$$

$$G_F = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2} \simeq \frac{1}{m_W^2}$$

Testing (B)SM with Flavor Physics: Hadronic Matrix Elements

- **Hadrons are the asymptotic states in QCD**



- E.g. neutron β decay

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} V_{ud} \langle p | (\bar{u}d)_{V-A} | n \rangle (\bar{e}\nu)_{V-A} + \mathcal{O}(\alpha_{\rm em})$$

$$\langle p | \bar{u}\gamma^\mu \gamma_5 d | n \rangle = \bar{u}_p \left[g_A \gamma^\mu + \frac{\tilde{g}_{T(A)}}{2m_n} \sigma^{\mu\nu} q_\nu + \frac{\tilde{g}_P}{2m_n} q^\mu \right] \gamma_5 u_n$$

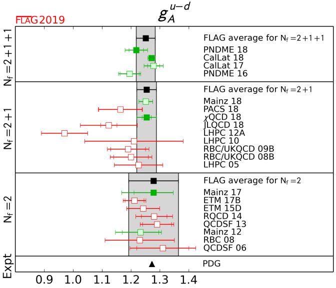
S. Weinberg, Phys. Rev.,112:1375 (1958)

- **Nonperturbative "form factors"** to learn about **short distances**!

- **Many theoretical methods - Only few from first principles (QCD)!**

  - Lattice QCD
  - Flavor symmetries and EFTs - ChPT, HQET, SCET, . . .
  - QCD sum rules
  - Quark and hadronic models

Much progress in lattice QCD in the last decade

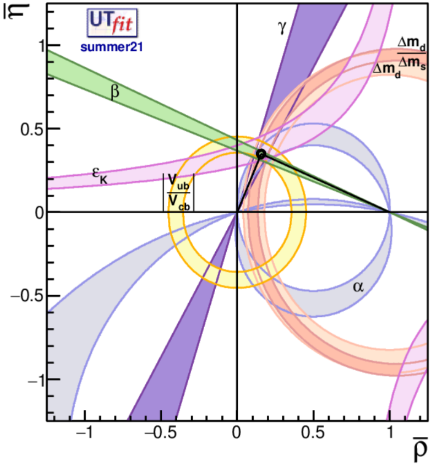


Personal selection of flavor topics

CKM metrology and Cabibbo-angle anomaly

Status of Flavor Metrology: The unitary triangle

- **Excellent consistency of the constraints ...**



levels @
95% Prob

~8%

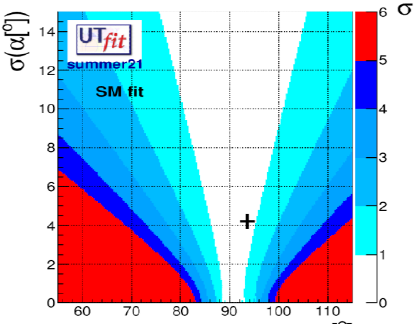
$\bar\rho = 0.157 \pm 0.012$
$\bar\eta = 0.350 \pm 0.010$

~3%

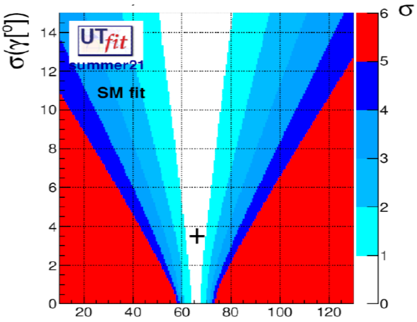
M. Bona @ EPS-HEP 2021

Status of Flavor Metrology: The unitary triangle

- **Excellent consistency of the constraints ...**
  - Good agreement between direct and indirect determinations of CKM angles



$\alpha_{exp} = (93.6 \pm 4.2)^\circ$
$\alpha_{UTfit} = (90.5 \pm 2.1)^\circ$

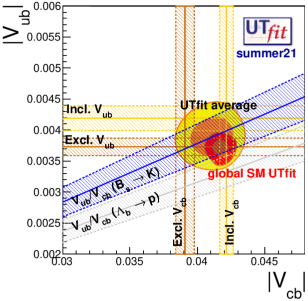


$\gamma_{exp} = (66.1 \pm 3.5)^\circ$
$\gamma_{UTfit} = (66.1 \pm 2.1)^\circ$

M. Bona @ EPS-HEP 2021

Status of Flavor Metrology: The unitary triangle

- **Except for a long-standing discrepancy**



$$\mathcal{L}_{\rm SM} \supset \frac{G_F}{\sqrt{2}} V_{cb} (\bar{c}b)_{V-A} (\bar{e}\nu)_{V-A}$$

★ **Exclusive decays:** Definite final state
E.g. $B \to D^{(*)}\ell\nu$, $|\mathbf{V}_{\mathbf{cb}}^{\rm exc}| = \mathbf{39.09(68)} \times \mathbf{10^{-3}}$ FLAG 2019

★ **Inclusive decays:** Sum rate over all charmed final states
$B \to X_c\ell\nu$, $|\mathbf{V}_{\mathbf{cb}}^{\rm inc}| = \mathbf{42.16(50)} \times \mathbf{10^{-3}}$

Bordone *et al.*, arXiv: 2107.00604

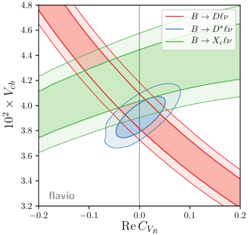
- **Discrepancy at** 2.8σ

- **The V_{ub} and V_{cb} puzzle: No (effective) BSM scenario can solve the discrepancy**

Crivellin & Pokorski, PRL114(2015)1,011802, Straub & Jung JHEP 01 (2019) 009

★ E.g. effective BSM right-handed interaction

$$\mathcal{L}_{\rm BSM} \supset \frac{G_F}{\sqrt{2}} V_{cb} C_{V_R} (\bar{c}b)_{\mathbf{V+A}} (\bar{e}\nu)_{V-A}$$



★ **Experimental systematic effects?** Bordone *et al.*, arXiv: 2107.00604

Status of Flavor Metrology: The Cabibbo-angle anomaly

In the SM: First-row unitarity relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- $|V_{us}| \approx \sin\theta_C = \lambda \simeq 0.225$
- $|V_{ud}| \approx \cos\theta_C \approx 1 - \lambda^2/2$

- **Most precise experimental and theoretical inputs in quark-flavor sector!**

- **Super-allowed nuclear β decays**

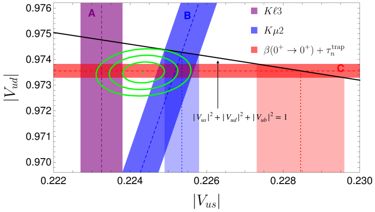
  $$|V_{ud}| = 0.97370(14)$$ SGPR, PRL121(2018)24,241804

  ★ Recent re-evaluation of $\alpha_{\rm em}$ corrections

- **(Semi)leptonic kaon decays**
  $|V_{us}| = 0.2238(5)$ with $K \to \pi\ell\nu$
  $|V_{us}| = 0.2253(5)$ $K \to \ell\nu/\pi \to \ell\nu$ and unitarity

- **Clean and precise lattice inputs for form factors**

FLAG Collaboration



$$|V_{ud}|^2 + |V_{us}|^2 = 0.9984(5)$$

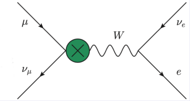
Claudio Manzari's @ EPS-HEP 2021

- **Cabibbo angle anomaly ($\sim 4\sigma$)**

Cabibbo anomaly and new physics

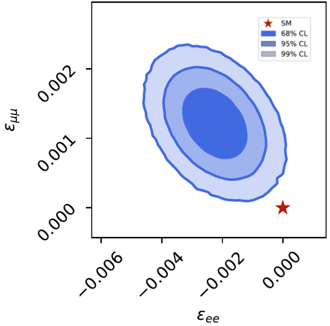
- **It can be easily fixed with NP!** Gonzalez-Alonso & JMC, JHEP12(2016)052, Grossman *et al.* JHEP 07(2020)068
  - E.g. **BSM couplings of $W^\pm$ and Z to neutrinos!**

$$\mathcal{L}_{\rm SMEFT} \supset \frac{\varepsilon_{ij}}{v^2}(H^\dagger D^l_\mu H)(\bar{L}_i\gamma_\mu L_j)$$



  - ★ Muonic G_F polluted by NP!
    $G_F^\mu = G_F^0\left(1 + \frac{1}{2}\varepsilon_{ee} + \frac{1}{2}\varepsilon_{\mu\mu}\right)$
  - ★ Cancellations in β- and kaon decay
    $|V_{us}^{K/\pi}| = |V_{us}^0| = 0.2253(5)$
    $|V_{us}^{K_{\mu 3}}| = |V_{us}^0|\left(1 - \frac{1}{2}\varepsilon_{ee}\right)$
    $|V_{us}^\beta|^2 = 1 - |V_{us}^0|^2\left(1 - \varepsilon_{\mu\mu}\right)$

  - **Fit to flavor and EWPO**



Coutinho *et al.* PRL125(2020)7,071802

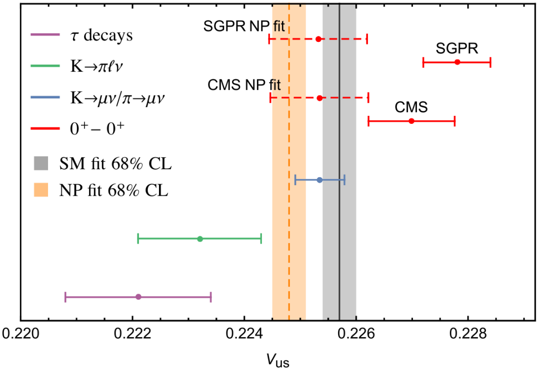
  - **NP hypothesis $> 4\sigma$ than SM**

- **Hint of lepton-universality violation?** (*cf.* $\varepsilon_{\mu\mu} \neq \varepsilon_{ee}$)

See Claudio Manzari's @ EPS-HEP 2021 for more BSM scenarios and UV completions

Cabibbo anomaly and new physics

- **Beautiful BSM path to solve the Cabibbo-angle anomaly**



Could there be a **less exotic** explanation?

- SM predictions with hadronic inputs at **subpercent (subpermille!)** precision
- **Hard problem:** Need accurate radiative (and isospin-breaking) corrections

See UMass Workshop on "Beta Decay as a Probe of New Physics"

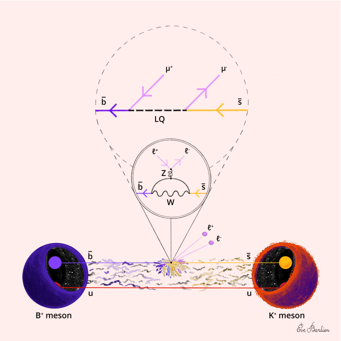
$b \to s\ell\ell$ and lepton universality violation

Effective field theory approach to $b \to s\ell\ell$ decays

- **FCNCs sensitive to very high-energy scales $\Rightarrow$ Less precision "required"**

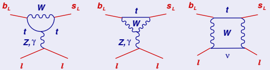
$$\mathcal{L}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{3j} V_{3i}^* \Big[\sum_{\substack{k=7,9,\\10,S,P}} \Big(C_k(\mu)\,\mathcal{O}_k(\mu) + C_k'(\mu)\,\mathcal{O}_k'(\mu) \Big) + C_T(\mu)\,\mathcal{O}_T(\mu) + C_{T_5}(\mu)\,\mathcal{O}_{T_5}(\mu) \Big]$$

★ *B* decays from $b \to s\ell\ell$



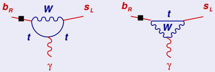
The $b \to s\ell\ell$ transition in the SM

★ **Semileptonic operators**: $\mathcal{O}_9$ $(L+V)$, $\mathcal{O}_{10}$ $(L+A)$



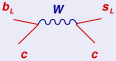
$$\frac{\alpha}{4\pi}\, C_{9(10)}\; \bar{s}_L \gamma^\mu b_L\; \bar{\ell}\gamma_\mu(\gamma_5)\ell$$

★ **Electromagnetic penguin**: $\mathcal{O}_7$



$$\frac{e}{4\pi^2}\, m_b\, C_7\; \bar{s}_L \sigma_{\mu\nu} b_R\, F^{\mu\nu}$$

★ **CC @ 1 loop**



$$C_2\; \bar{c}_L \gamma^\mu b_L\; \bar{s}_L \gamma_\mu c_L$$

- **New-Physics:** in C_i or e.g. $\mathcal{O}_i'$ obtained $P_L \to P_R$ in $\bar{s}_L b$

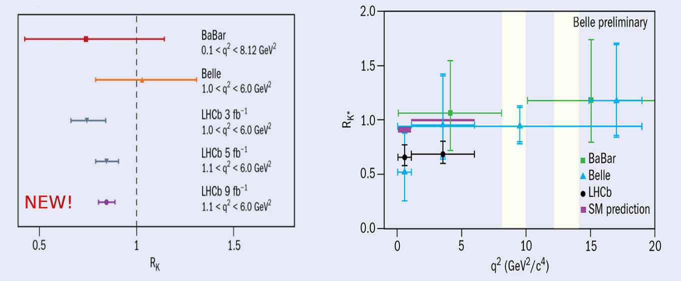
The lepton flavor universality violation anomalies: $b \to s\ell^+\ell^-$

The SM is (almost) Lepton-Flavor Universal!*
*Same couplings to e, μ, τ

- The gauge bosons **couple universaly** to leptons
- Broken by **Yukawa couplings** (negligible) and **masses** (kinematic effects)

Test of Lepton Universality: $R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B}\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(\bar{B}\to K^{(*)}e^+e^-)} \overset{\text{SM}}{\simeq} 1$

- Deficits on $R_{K^{(*)}}$ measured by **LHCb**



Signal of μ-to-e LFUV at 2-4σ

The lepton flavor universality violation anomalies: $b \to s\ell^+\ell^-$

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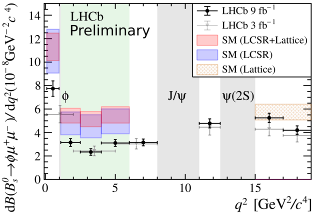
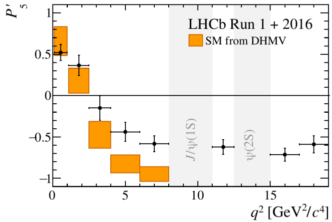
- Other anomalies in **branching ratios** and **angular observables**

[LHCB-PAPER-2021-014, in preparation]

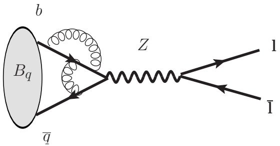


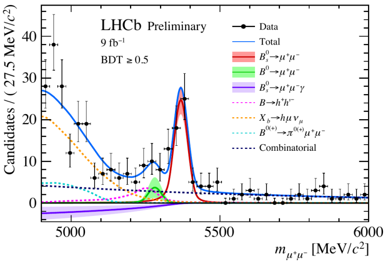


Claims of $> 5\sigma$ signal of NP in global fit to ca. 100+ observables

The beautiful example: $B_q^0 \to \ell\ell$

Marco Santimaria @ CERN, March 23rd 2021





$$\mathcal{B}_{s\ell} \propto G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2 m_\ell^2 f_{B_s}^2 |C_{10} - C'_{10}|^2$$

- $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$ (10.8σ)

- Also measured by **ATLAS** and **CMS**

- Semileptonic decay **constants** f_{B_q} can be calculated in LQCD FLAG averages
- Include **radiative corrections**: $\overline{\mathcal{B}}_{s\mu}^{\rm SM} = 3.66(14) \times 10^{-9}$ Beneke *et al.* JHEP10(2019)232

$\sim 2-3\sigma$ deficit with respect to SM predictions!

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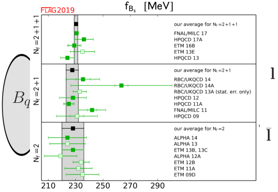
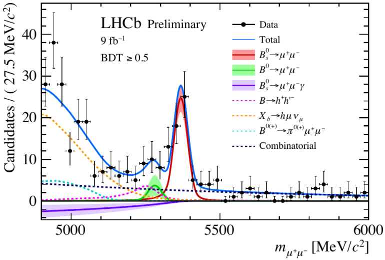


Marco Santimaria @ CERN, March 23rd 2021



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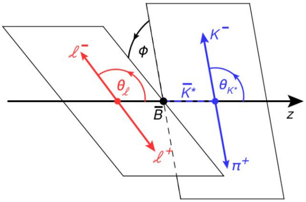
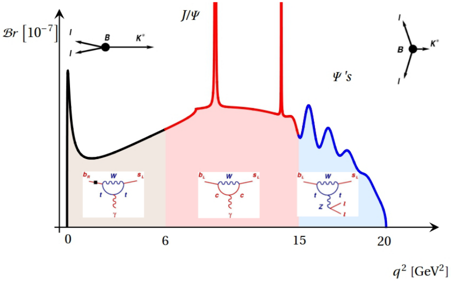
The complex (and rich) case: $B^0 \to K^{(*)}\ell\ell$

- **Rich kinematic distro**

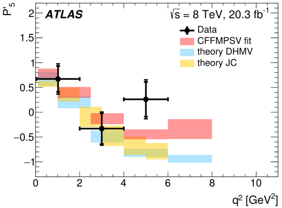


- **12 angular observables!**

- **Complex interplay of short- and long-distance physics**



- **Controversial interpretation of anomalies in angular distributions**



See also: LHCb, PRL125(2020)011802

- **Is it the effect of NP ...**

$$\delta C_9^\mu \simeq -1$$

Descotes-Genon *et al.* PRD88,074002

- **... Or of understimated hadronic contributions?**

Beneke *et al.* NPB592(2001)3, Jäeger and JMC JHEP1305(2013)043, PRD93(2016)1,014028, Bharucha *et al.*JHEP 1009 (2010) 090, Descotes-Genon *et al.* JHEP 1412 (2014) 125, Lyon *et al.* arXiv:1406.0566, Ciuchini *et al.* arXiv:1512.07157 + ...

The complex (and rich) case: $B^0 \to K^{(*)}\ell\ell$

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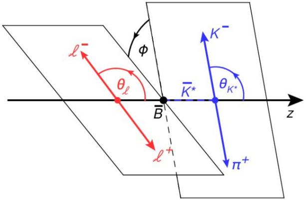

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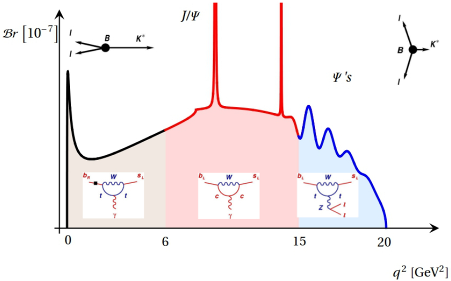


- **12 angular observables!**

- **Hadronic contributions**

- **7 form factors**

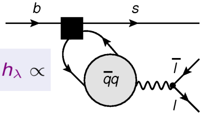
$$H_V(\lambda) = -iN\Big\{ \overbrace{\Big[C_9\,\tilde{V}_{L\lambda} + \frac{m_B^2}{q^2} h_\lambda \Big]}^{C_9^{\rm eff}} - \frac{\hat{m}_b m_B}{q^2} C_7\,\tilde{T}_{L\lambda} \Big\}$$

$$H_A(\lambda) = -iN C_{10}\,\tilde{V}_{L\lambda}$$

- **Very difficult in LQCD**

- **"Charm" contribution**

$h_\lambda \propto$



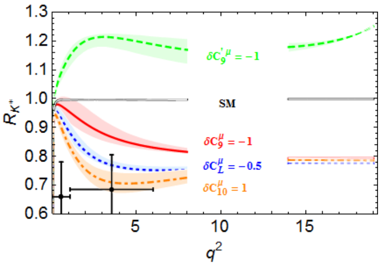
- **Only $C_9^{\rm eff}$ is observable!**

The lepton-universality ratios are clean observables

Leptons do not feel the strong force!

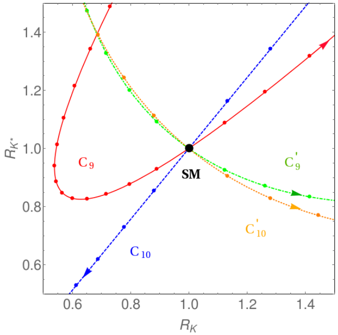
$$R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B}\to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(\bar{B}\to K^{(*)}e^+e^-)} \overset{\text{SM}}{\simeq} 1$$

- **Very clean null tests of the SM**



  - **Large ($\sim$ 20%) effects!**
  - **Th. uncertainties negligible!**

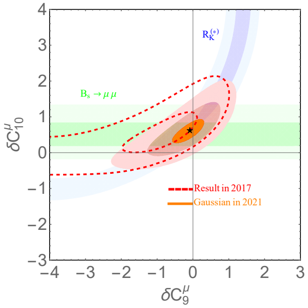
- **Sensitive to muonic LH currents!**



Geng, Grinstein, Jäger, JMC, Ren, Shi, PRD96(2017)093006

A theoretically-clean fit

- Define a χ^2 with "clean observables"
  - ★ $B_s \to \mu\mu$: **New LHCb + CMS + ATLAS**
  - ★ R_{K^*} and R_K from **LHCb**
- Fit **muon-philic** BSM contributions only

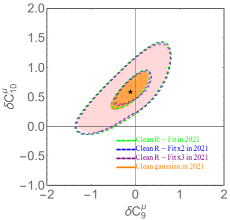


Geng *et al.* PRD104(2021)3,035029

Main results

- p-value (SM) = **7.6×10^{-5}**
  (4σ tension of SM with data)
- p-value (BSM) = **0.27**
  BSM better than SM by $\sim 4.9\sigma$**!**

- **Theoretically robust**



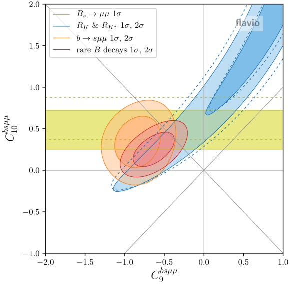
Impossible to understand within the SM

- Really New Physics?! ...
- Or statistical fluke?! (4σ)
- Or an experimental problem?!
  (seems very unlikely though!) See Arantxa's talk

The global fit

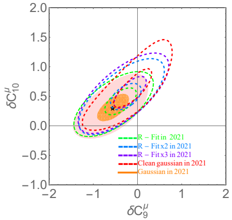
- **Add $\gtrsim$ 100 observables:** BRs, angular observables, low- and high-q^2 data ...

Wilson coefficient	all rare B decays best fit	pull
$C_9^{bs\mu\mu}$	$-0.80^{+0.14}_{-0.14}$	5.7σ
$C_{10}^{bs\mu\mu}$	$+0.55^{+0.12}_{-0.12}$	4.8σ
$C_9^{\prime bs\mu\mu}$	$-0.14^{+0.13}_{-0.13}$	1.0σ
$C_{10}^{\prime bs\mu\mu}$	$+0.04^{+0.10}_{-0.10}$	0.4σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$-0.01^{+0.12}_{-0.12}$	0.1σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.41^{+0.07}_{-0.07}$	5.9σ



Altmannshofer & Stangl, arXiv: 2103.13370

- **Depends on size of hadronic corrections**



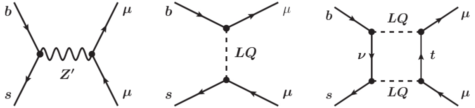
- **Independent observables:** Similar trend and size of NP!
- Interpretation blurred by hadronic effects. Global fit favors effects on C_9 (affected by charm)

Current-current interpretation!

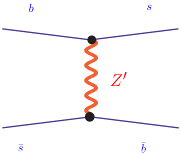
$$\mathcal{L}_{eff} \supset \frac{C_{9(10)}}{\Lambda^2_{\rm New-Physics}}(\bar{s}\gamma^\mu P_L b)(\bar{\mu}\gamma_\mu(\gamma_5)\mu)$$

$$\Lambda_{\rm New-Physics} \sim 30\ \text{TeV!!!}$$

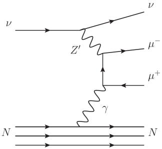
- UV completions: Z''s and **leptoquarks**



- **Extra bounds from low energy** e.g. Z'
  - B_s-$\bar{B}_s$ mixing



  - Neutrino trident production



  - Requires small $Z' bs$ coupling! (e.g **MFV**)
  - Controls $Z' \mu\mu$ coupling!

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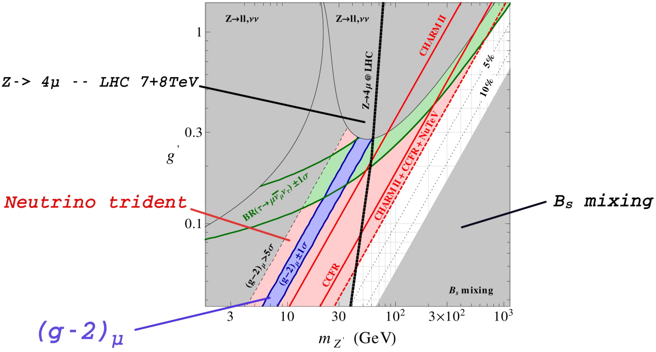
$$\Lambda_{\rm New-Physics} \sim 30 \text{ TeV!!!}$$

- "Colored" gauged $L_\mu - L_\tau$

  Altmannshofer *et al.* PRD89(2014)095033



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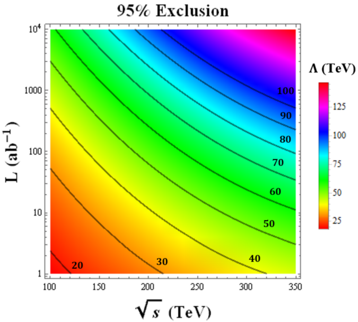
- "Agnostic" EFT: $pp \to \mu^-\mu^+ X$ LHC and beyond...

Bradley Garland's talk @ EPS-HEP 2021



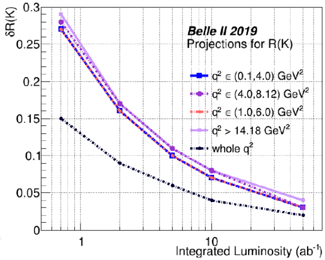
Could be far from production @ LHC (or even FCC!!)

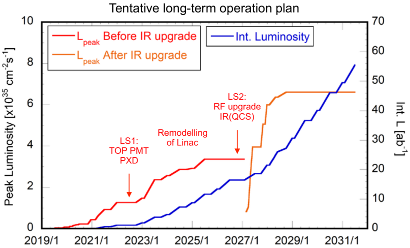
The $b \to s\ell\ell$ anomalies: What's next?

- Many ongoing analyses at **LHCb** See Arantxa's talk on Friday
  - R_{K^*}, R_ϕ, R_{Λ_b},...
  - Not only low q^2 but also high q^2
  - LFUV ratios or differences of angular observables!

LHCb may very soon exceed 5σ with clean observables!

- **Belle 2:** Necessary independent experimental confirmation





Carsten Niebhur @ EPS-HEP 2021

(At least) 2027 for same precision as current LHCb result

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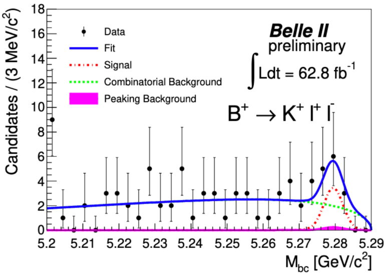
- **Belle 2:** Necessary independent experimental confirmation
  - **At least they are already seeing it!**



Simon Kurz @ EPS-HEP 2021