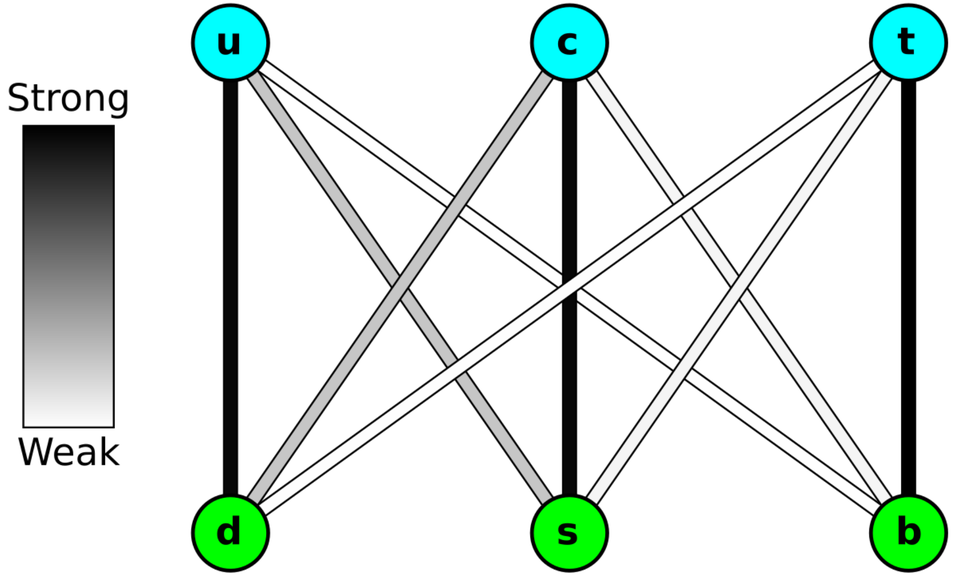


クォークセクターのフレーバー物理

北原鉄平（千葉大学）

Flavor Physics Workshop 2026

於　富山呉羽ハイツ

2026年 11月18日

Chiba Particle Physics

フレーバー物理：新物理を間接的に探る

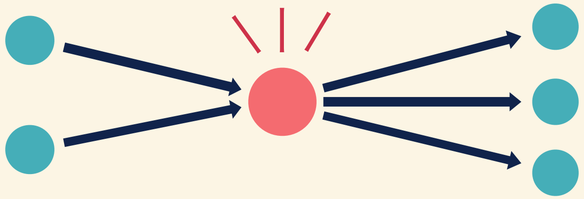
標準模型に残る謎　　物質・反物質の非対称性 ／ クォーク・レプトンの質量の階層性、など

未知の粒子や相互作用がある？

加速器での直接探索

高エネルギー ($\sqrt{s} >$ TeV) で

新粒子を直接つくる



新粒子の生成・崩壊を探す

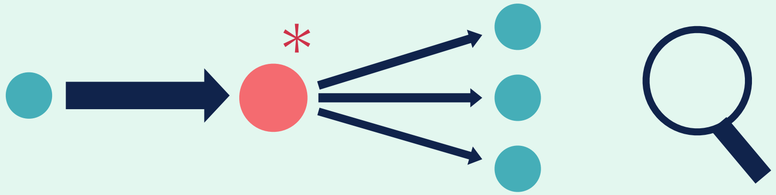
ATLAS・CMS

相補的

フレーバー物理での間接探索

低エネルギー ($\sqrt{s} \sim$ GeV) で

粒子の崩壊・特性を精密に測る



崩壊頻度やCP非対称性のずれを探す

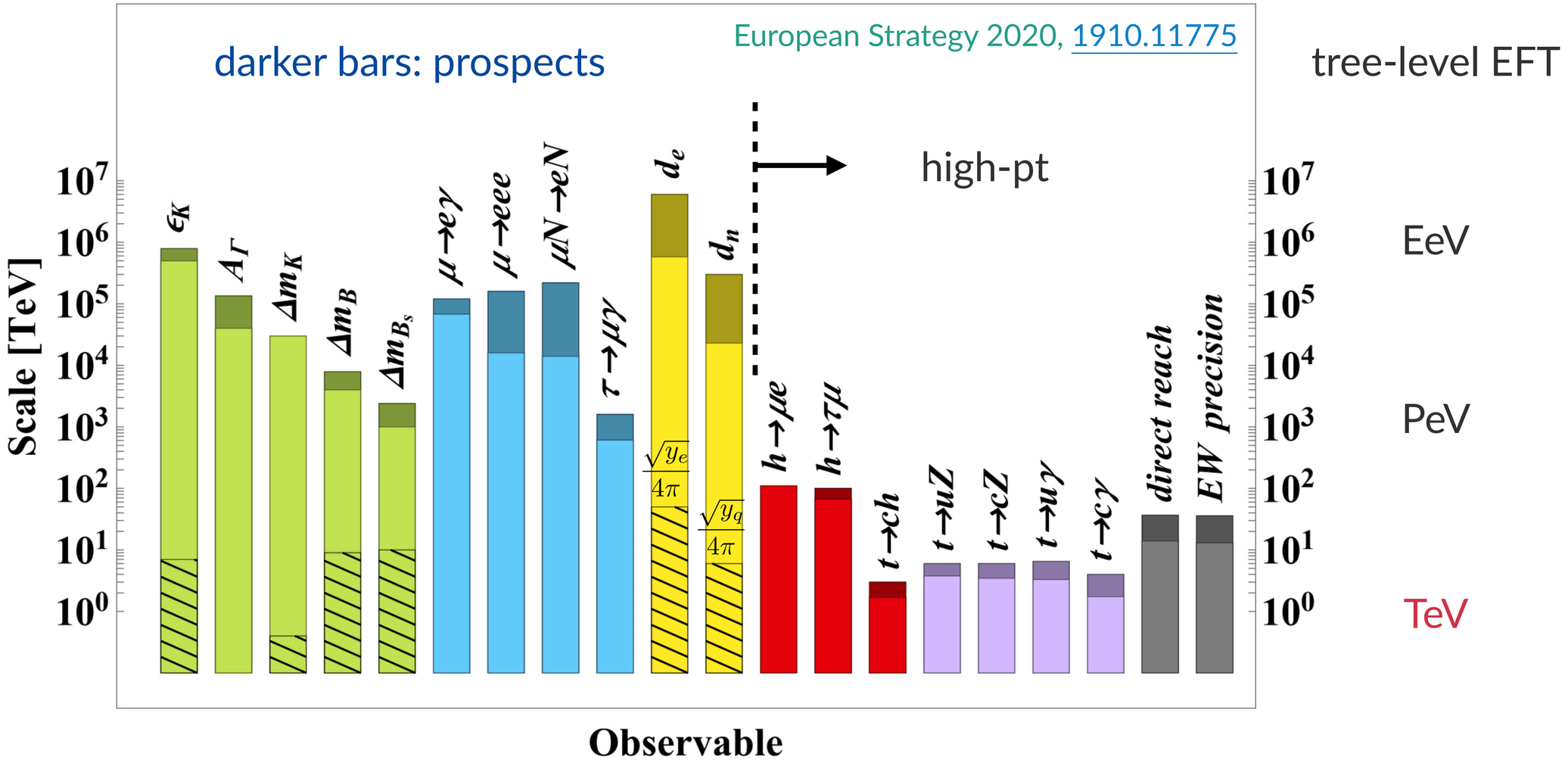
Belle II・LHCb・KOTO・BESIII・…

鍵：精密測定 ＋ 精密な理論予測

直接つくれない重い新粒子の影響にも迫る

フレーバー物理 vs 新物理

ナイーブには、
コライダー実験
をはるかに凌ぐ
新物理感度

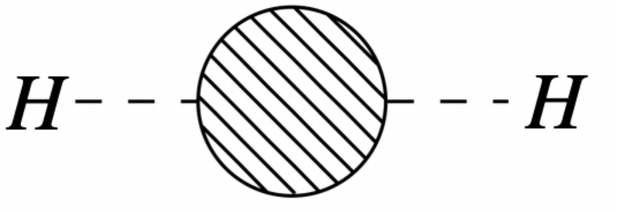


MFV sensitivity



フレーバーにとっての階層性の問題

階層性問題



$$m_\phi^2 = m_{\phi,\mathrm{bare}}^2 + \frac{1}{16\pi^2} M_{\mathrm{UV}}^2$$

125GeV

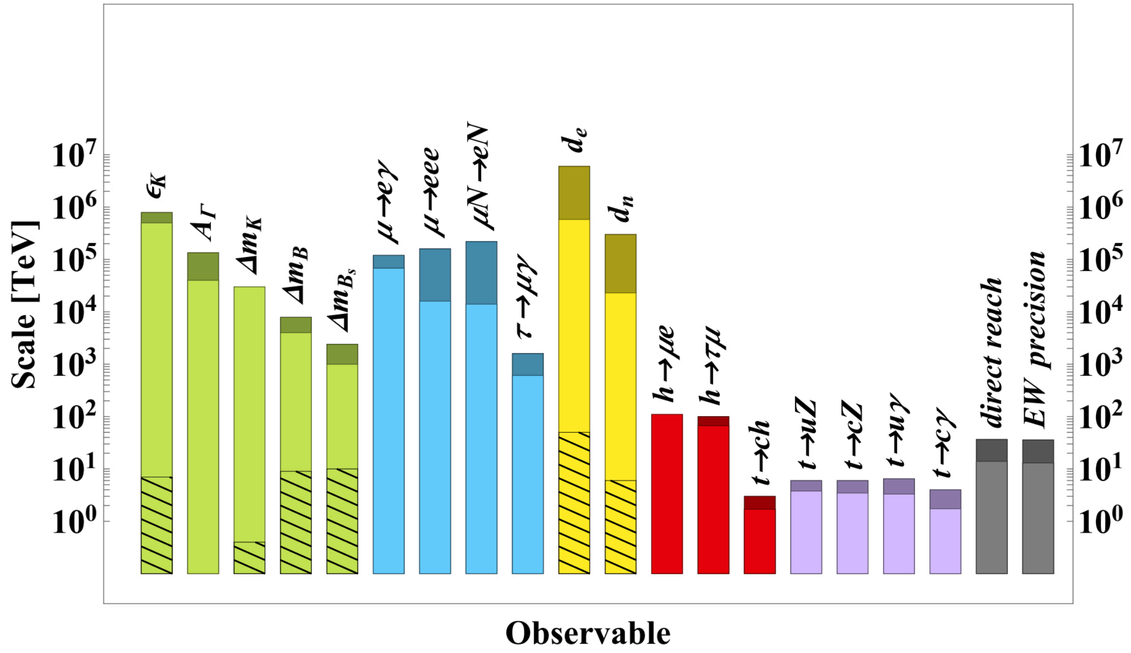
スカラー粒子はUV scaleに感度がある閾値 (輻射) 補正を受ける

M_{UV} ~ **TeV scale** (or above)

so-called Naturalness

puzzle?

フレーバー測定



新物理 scale $> 10^6$ **TeV scale**

解決案？: Minimal Flavor violation, $U(2)^5$ symmetry, … [2311.09288]

フレーバー物理の概観

謎

フレーバー構造・階層性、
バリオン数非対称性、etc

フレーバー対称性

別の実験で同じ量を測る

異なる観測量による探索

q^2, 偏極, CPの破れ, …

- **有効場の理論**
- **具体的な模型**

異なるフレーバー過程

B・D・K中間子

bバリオン崩壊

EDM探索

理論計算の改善

lattice QCD計算, QED補正, 量子補正の理論誤差の理解・改善

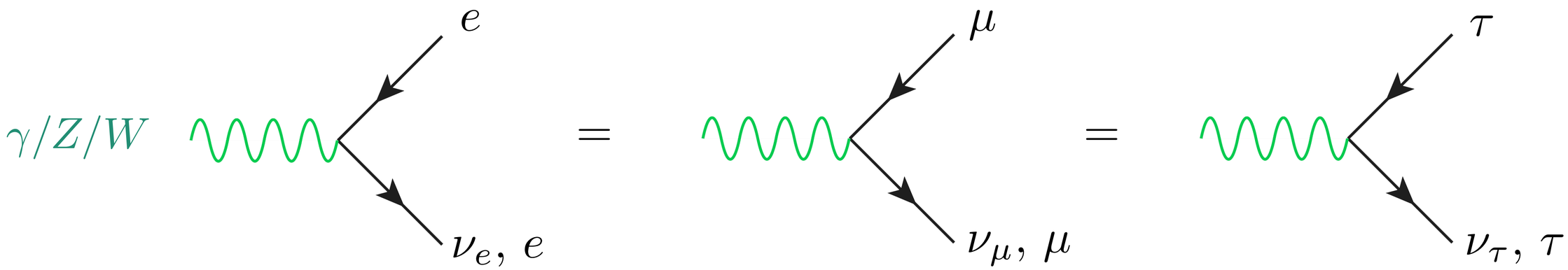
三位一体が重要

(理論と実験の協創・協奏・競走)

フレーバーアノマリー

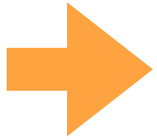
レプトン普遍性

- ゲージ対称性はレプトン普遍性を（当然）予言する



- レプトンの質量 (+QED 量子補正) によって実際の物理量の普遍性は破れる

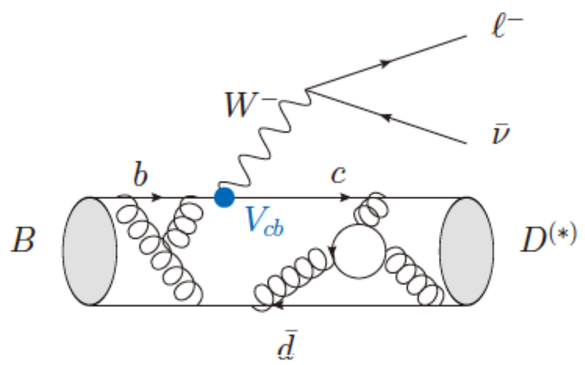
$$m_e = 0.5\,\text{MeV} \quad \ll \quad m_\mu = 105\,\text{MeV} \quad \ll \quad m_\tau = 1776\,\text{MeV}$$



different phase space

$b \to c\tau\nu$ におけるレプトン普遍性の破れ (1/2)

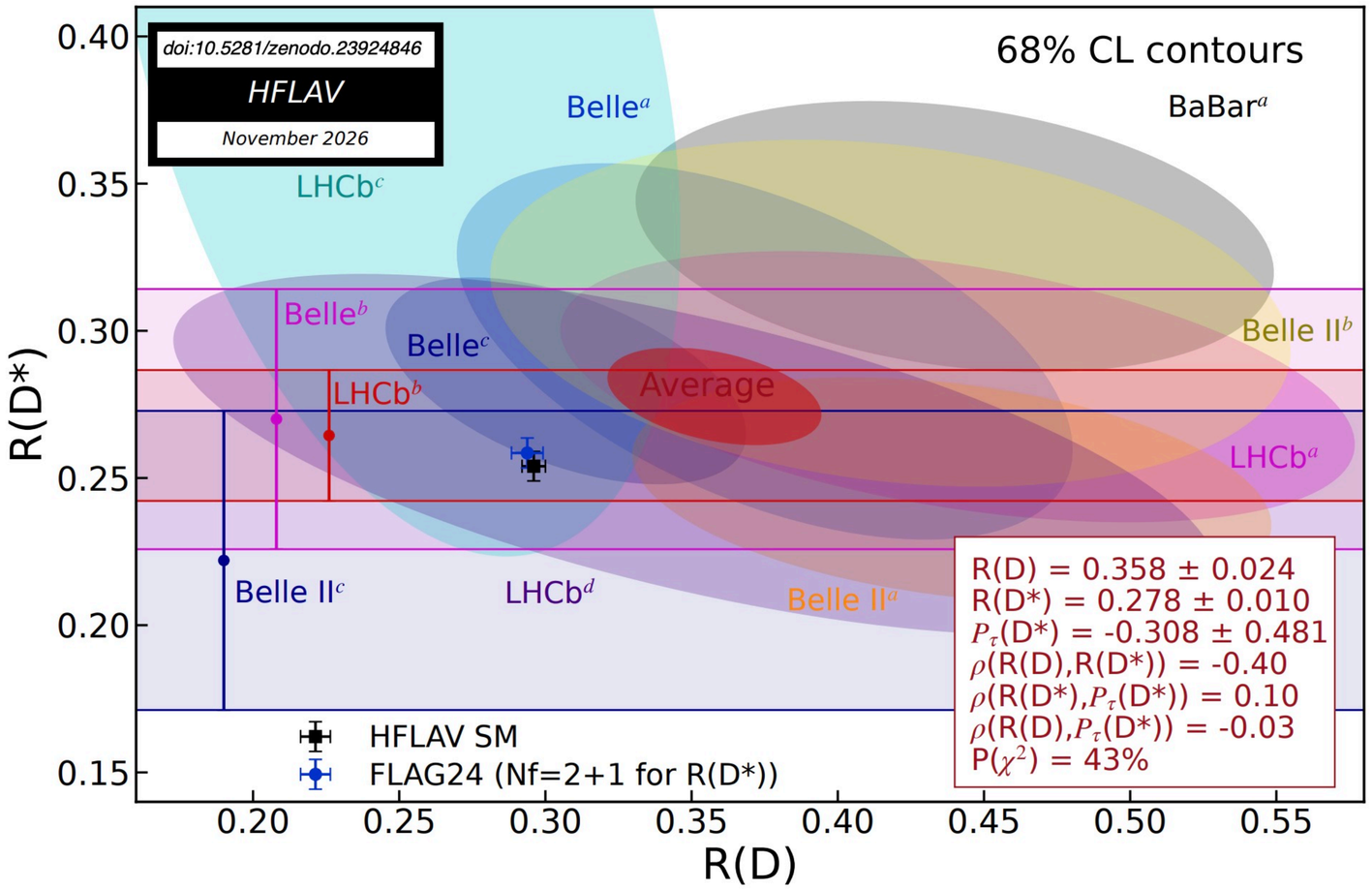
$$R(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\bar{\tau}\nu_\tau)}{\mathrm{BR}(B \to D^{(*)}\bar{\ell}\nu_\ell)} \quad (\ell = e, \mu)$$



11 independent data!

$b \to c\tau\nu$ アノマリー

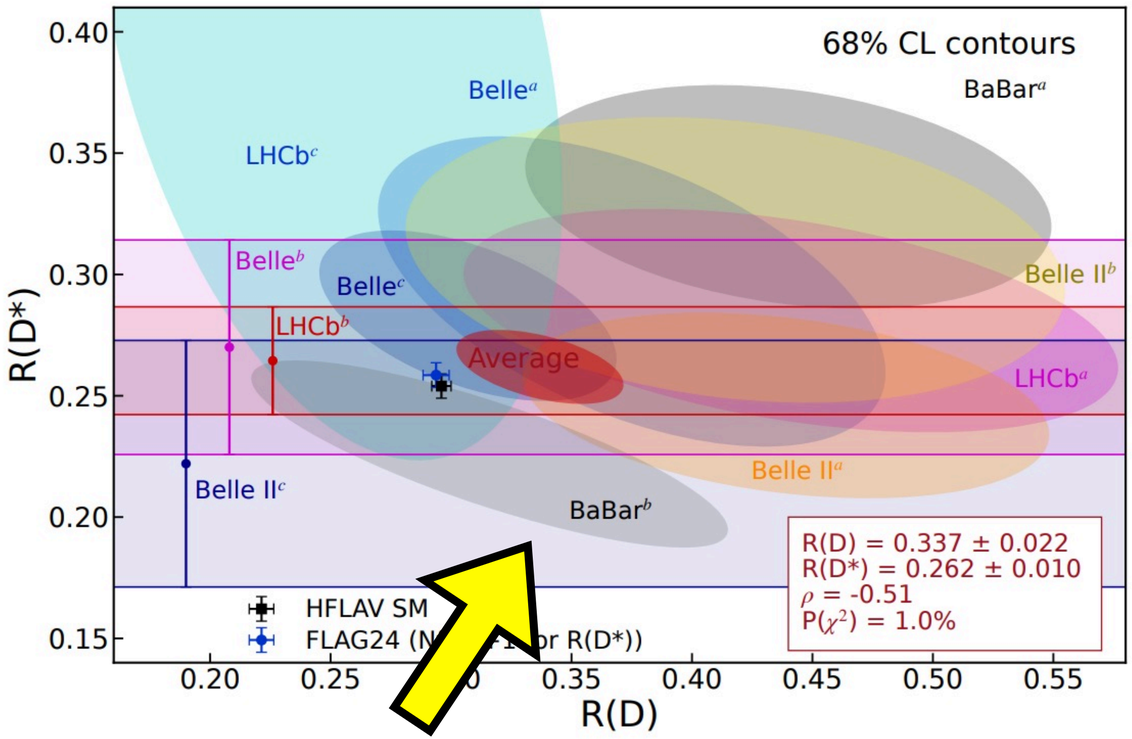
HFLAV 2026@November



3.4σ tension (HFLAV-TH), **4.1σ** (HQET-TH), **4.5σ** (BGL-TH)

$b \to c\tau\nu$ におけるレプトン普遍性の破れ (2/2)

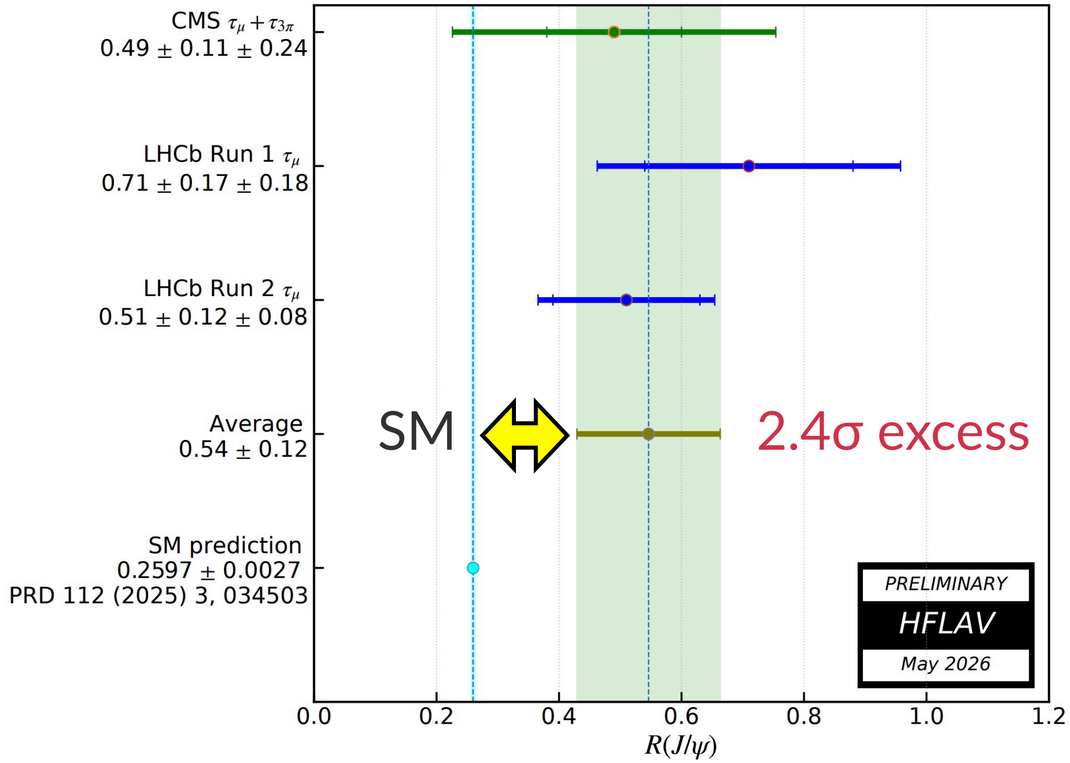
New BaBar analysis



!? (no paper yet)

3.4σ → 2.0σ

$$\mathrm{R}(\mathrm{J}/\psi) = \frac{\mathrm{BR}\,(\mathrm{B_c} \to \mathrm{J}/\psi\tau\nu)}{\mathrm{BR}\,(\mathrm{B_c} \to \mathrm{J}/\psi\mu\nu)}$$



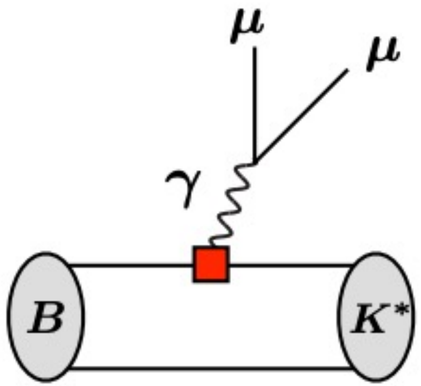
これも $b \to c\tau\nu$ に excess

$b \to s\ell^+\ell^-$ における異常

$B \to K^*\mu^+\mu^-$ のSM予言

$b \to s\gamma$ 演算子

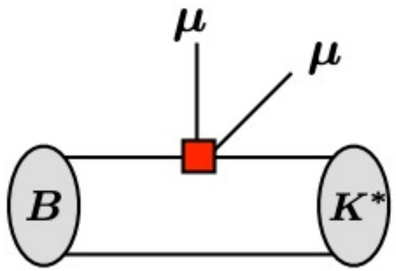
$$\mathcal{O}_7 \sim m_b\left(\bar{s}\sigma^{\mu\nu}P_R b\right)F_{\mu\nu}$$



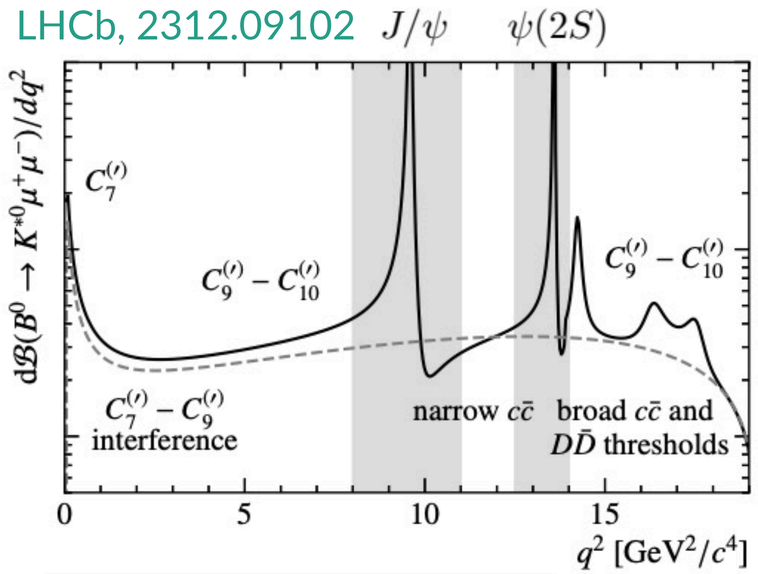
電弱ペンギン演算子

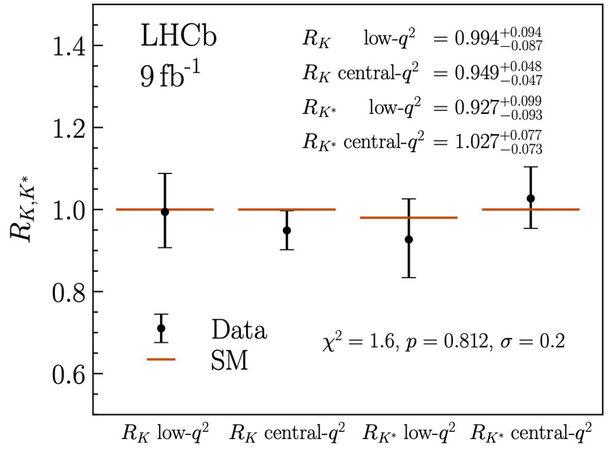
$$\mathcal{O}_9 \sim \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu \ell\right)$$

$$\mathcal{O}_{10} \sim \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu\gamma_5 \ell\right)$$



LHCb, 2312.09102





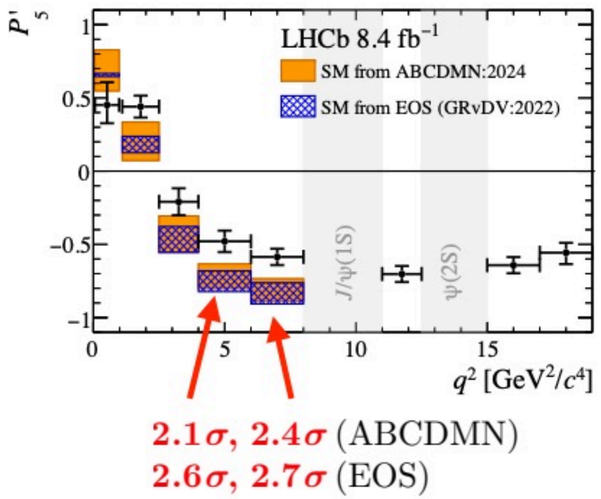
- R(K), R(K*) [$\mu^+\mu^-/e^+e^-$ の比] の観測量は標準模型と無矛盾。しかし…

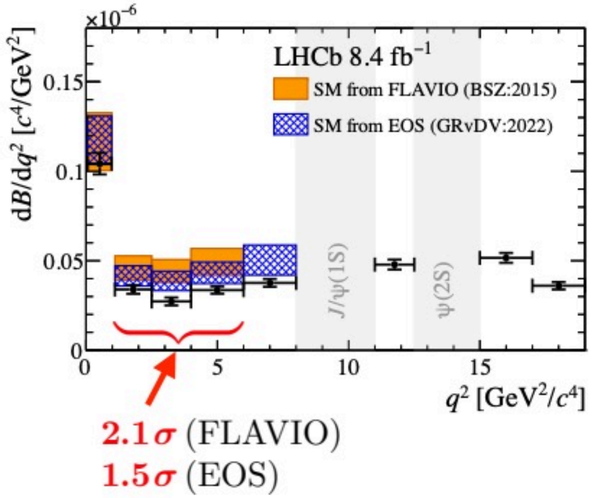
LHCb, 2212.09153

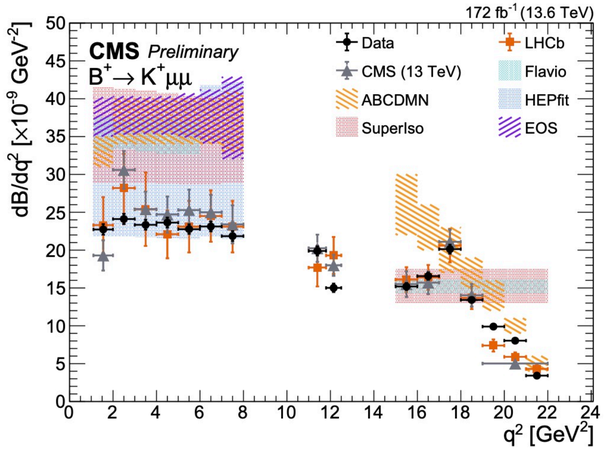
$b \to s\ell^+\ell^-$ における異常

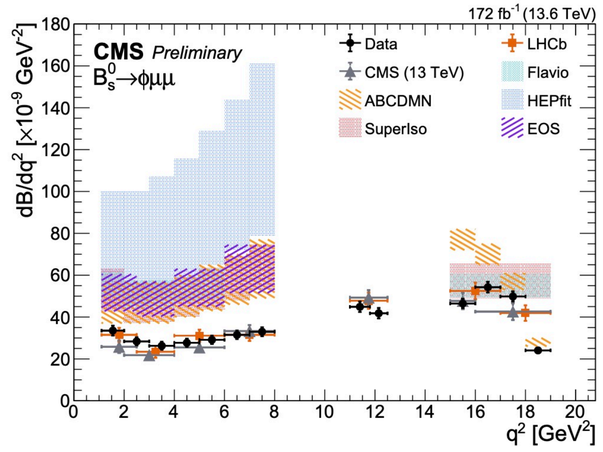
- **4つの観測量にて異常。**全てLHCbとCMS実験にてcross check 済み。

$$P_5'\left(B^0 \to K^{*0}\mu\mu\right) \qquad \frac{d\mathcal{B}\left(B^0 \to K^{*0}\mu\mu\right)}{dq^2} \qquad \frac{d\mathcal{B}\left(B^+ \to K^{+}\mu\mu\right)}{dq^2} \qquad \frac{d\mathcal{B}\left(B_s \to \phi\mu\mu\right)}{dq^2}$$







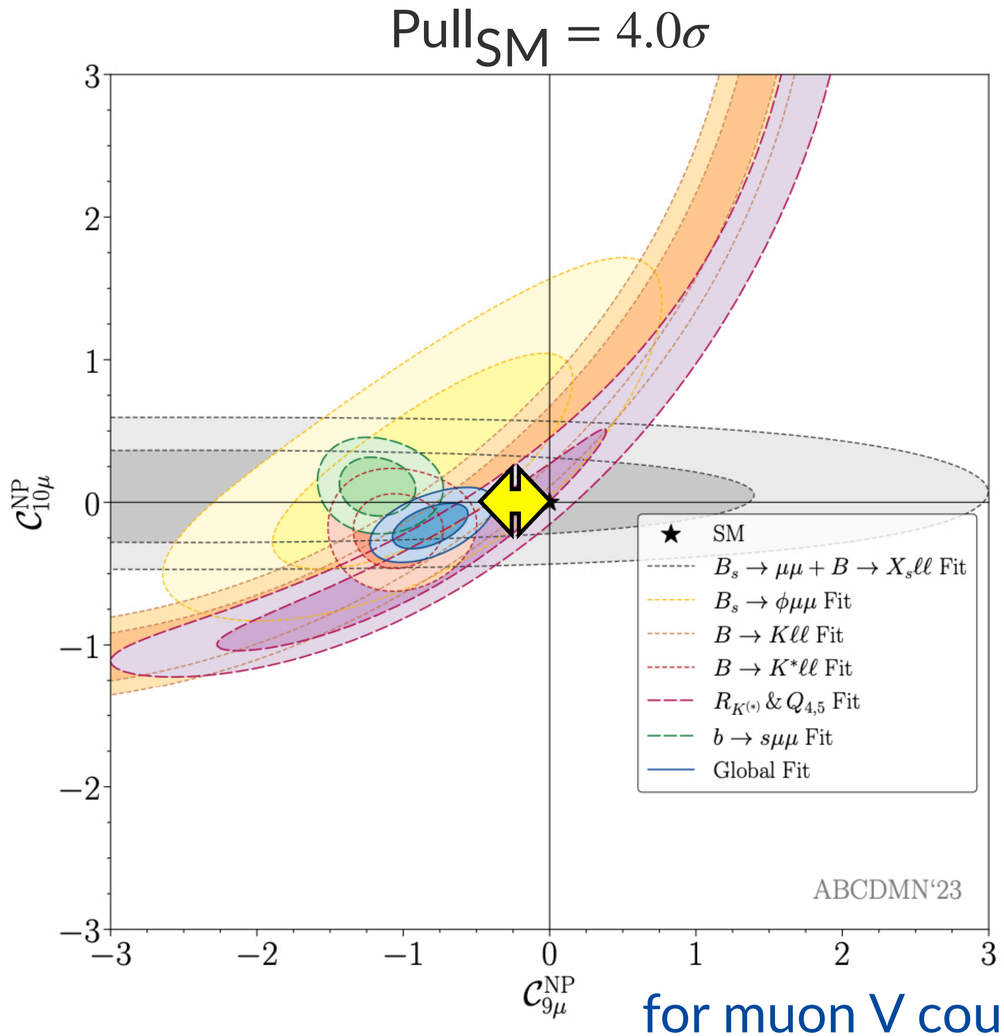


ちなみに、baryon mode ($\Lambda_b \to \Lambda\mu\mu$) でも異常が見えている　LHCb, 2512.18053; CMS, CMS-PAS-BPH-24-005

Global fit of $b \to s\ell^+\ell^-$ observables

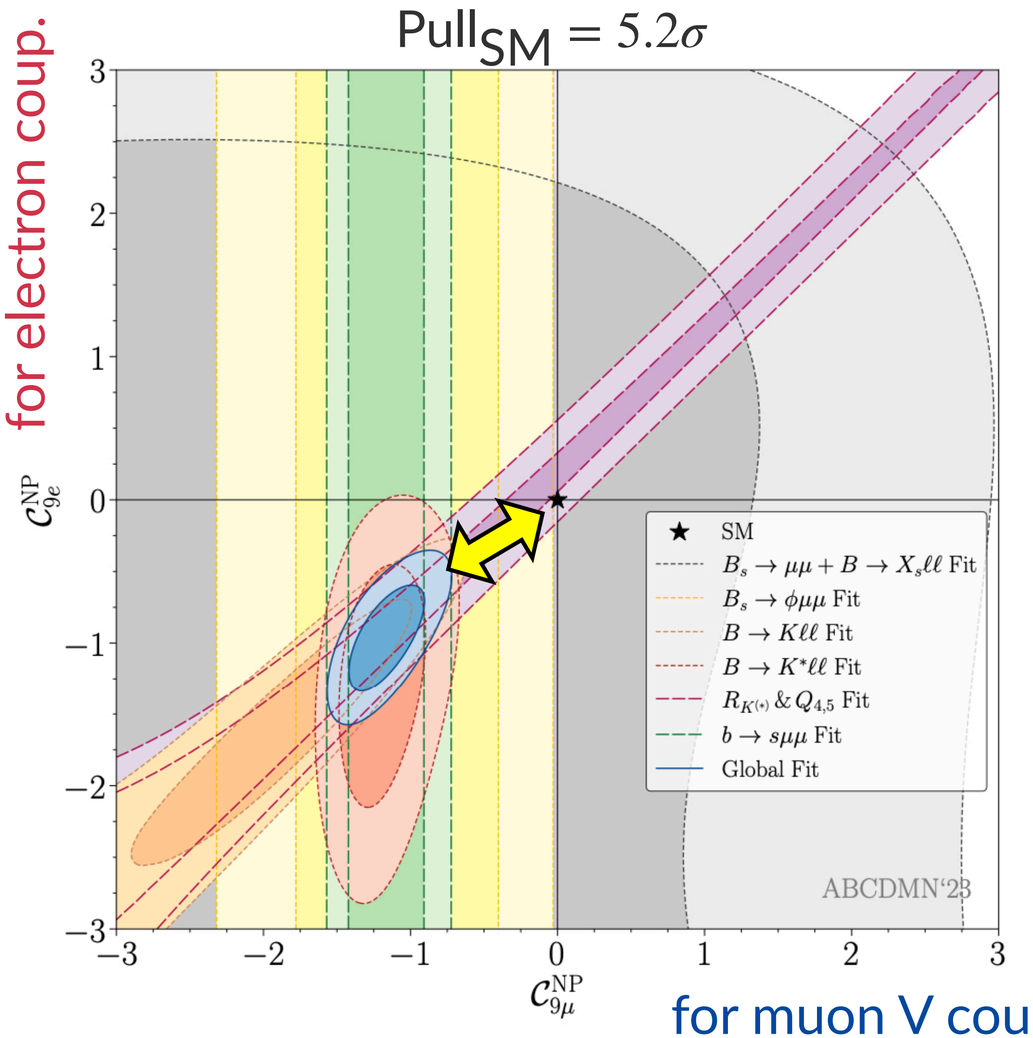
Algueró, et al, 2304.07330

for muon AV coup.



for muon V coup.

for electron coup.



for muon V coup.

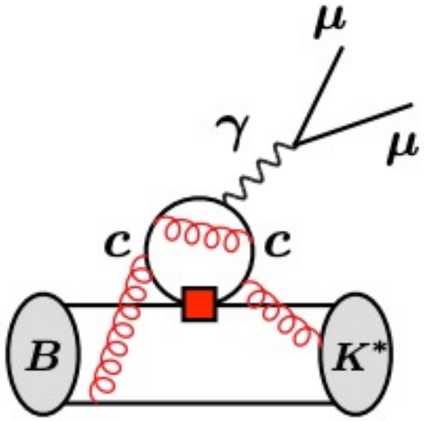
でもどうせQCDなんでしょ論: 非局所 charm ループ

- 非局所 (non-local) charm-quark ループ補正の寄与が存在する
- この寄与を含む lattice 計算はない
- q^2 によらない定数の寄与を与える = C_9 演算子をmimic
- soft-gluonの寄与が課題。suppression機構があるという発見もある

Gubernari , et al, 2011.09813

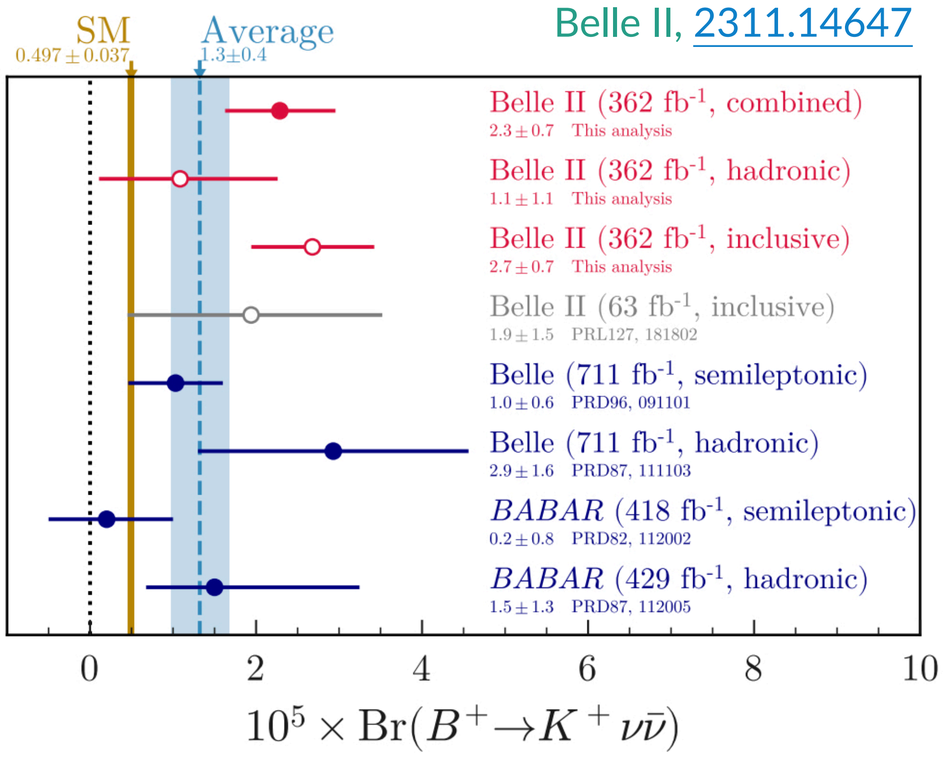
- 理論コミュニティ内ではまだ定まった見識はない
- inclusive モード ($B \to X_s \mu^+ \mu^-$) では精度良く計算可能 (Belle II の重要性)

光学定理を使用できる



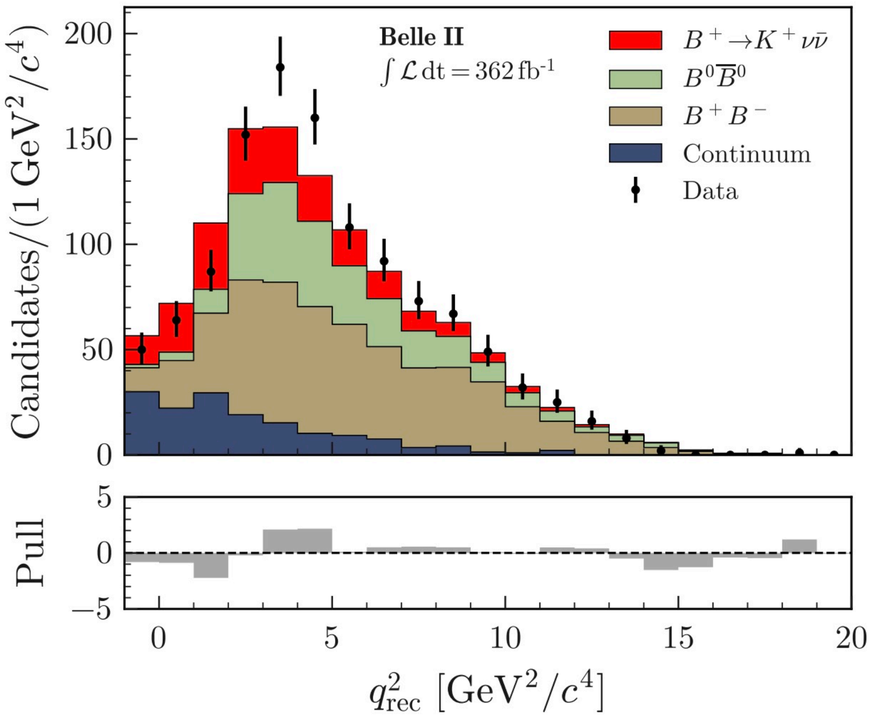
$b \to s\nu\bar{\nu}$ における異常

- $B^+ \to K^+\nu\bar{\nu}$: ≈ 2σ excess?　$\mu\left(B^+ \to K^+\nu\bar{\nu}\right) \equiv \dfrac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\mathrm{SM}}} = 2.75 \pm 0.86$



Belle II, 2311.14647

~2GeV に何かいる?



最も素朴な implication

- これらの異常は全て 2クォーク-2レプトンの4フェルミ演算子 であり、bottom quark を必ず含む。
- 一方で、kaonやpion の実験から、1-2 世代には厳しい新物理制限。
- 新物理は第三世代のクォークに強く結合しているというset upが良い (top からの制限はまだ弱い） （なぜ第三世代？対称性起源？量子情報的示唆？）
- （陽子崩壊を起こさない）**レプトクォーク**は素朴な良い例

Leptoquarks

- TeV leptoquarks (**LQ**) can accommodate all flavor anomalies (without collider bounds). Feynman diagrams are shown in next slide
- We consider two examples:
  - $S_1 + S_3$ **scalar** LQ $(\bar{\mathbf{3}}, \mathbf{1}, {}^1\!/_3)$ $(\bar{\mathbf{3}}, \mathbf{3}, {}^1\!/_3)$ (SU(3), SU(2), U(1)) UV model?

$$\mathcal{L}_{\mathrm{S_1+S_3}} = \left(\lambda^L_{ij}\overline{Q^C_i}\left(i\sigma^2\right)L_j + \lambda^R_{ij}\overline{u^C}_i e_j\right)S_1 + \kappa_{ij}\overline{Q^C_i}\left(i\sigma^2\right)\sigma^I L_j S^I_3 + \mathrm{h.c.}\,,$$

minimal set of the couplings

$$\lambda^L_{ij} = \lambda^L \begin{pmatrix} 0 & 0 & r^3 \\ 0 & 0 & r \\ 0 & 0 & 1 \end{pmatrix}, \quad \lambda^R_{ij} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \lambda^R_{23} \\ 0 & 0 & 0 \end{pmatrix},$$

$$\kappa_{ij} = (1-\epsilon)\lambda^L \begin{pmatrix} 0 & 0 & (1-\delta)r^3 \\ 0 & 0 & -r \\ 0 & 0 & 1 \end{pmatrix}.$$

  - U_1 **vector** LQ $(\mathbf{3}, \mathbf{1}, {}^2\!/_3)$ Several UV completions are proposed

$$\mathcal{L}_{U_1} = \left(\kappa^L_{ij}\overline{Q_i}\gamma_\mu L_j + \kappa^R_{ij}\overline{d_i}\gamma_\mu e_j\right)U^\mu_1 + \mathrm{h.c.}$$

minimal set

$$\kappa^L_{13}, \kappa^L_{23}, \kappa^L_{33}$$

偏極観測量

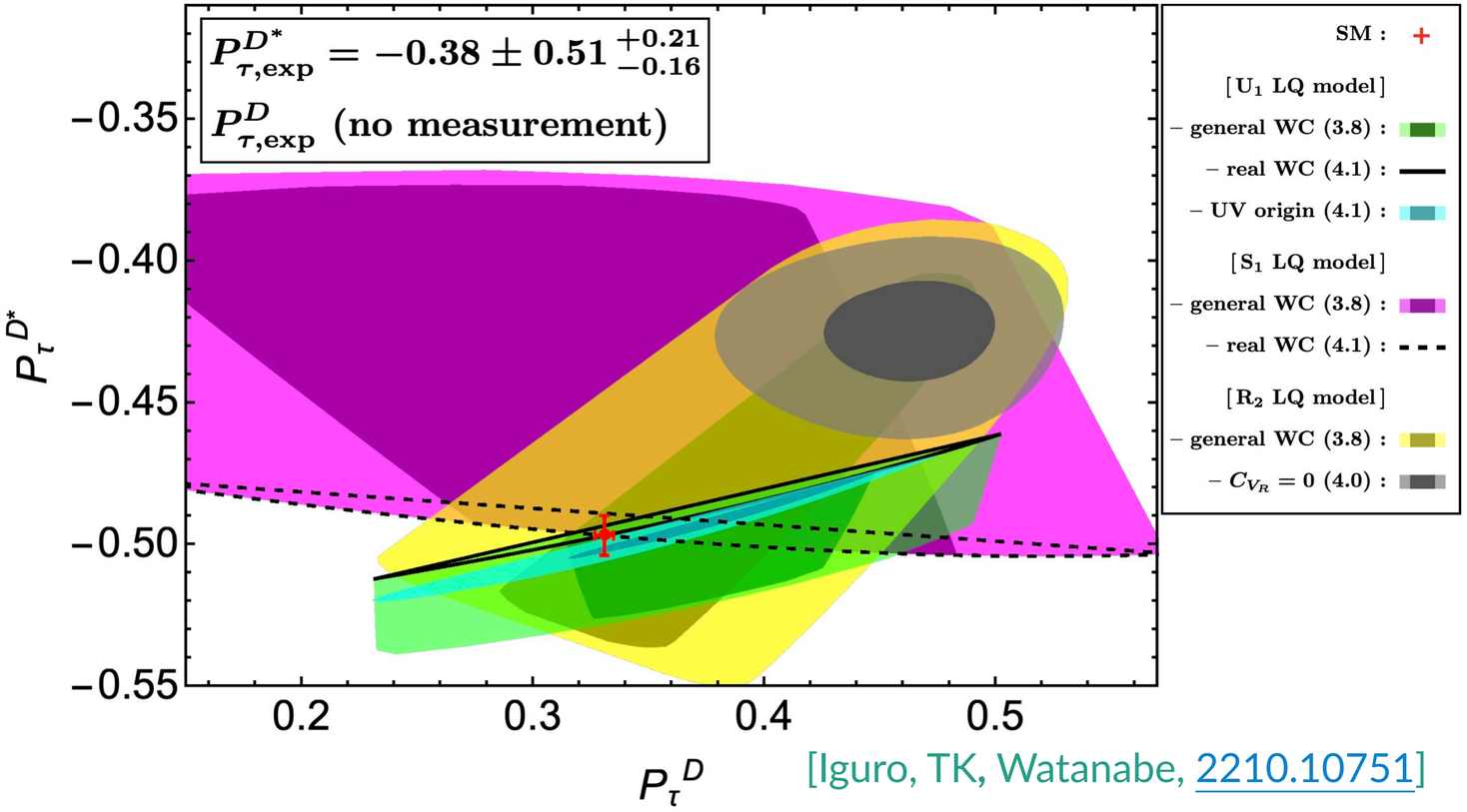
$$P_\tau(D^{(*)}) = \frac{\Gamma\left(B \to D^{(*)}\tau^{\lambda=+1/2}\nu\right) - \Gamma\left(B \to D^{(*)}\tau^{\lambda=-1/2}\nu\right)}{\Gamma\left(B \to D^{(*)}\tau\nu\right)}$$

- τ polarization asymmetry along the longitudinal directions of τ [$\tau \to \pi\nu,\ \rho\nu$]

  [Tanaka, hep-ph/9411405]

  Fit of an angle dependence: between π/ρ and $W^*(\to\tau\nu)$ in τ rest frame

- Belle II sensitivity is enough to distinguish NP models



[Iguro, TK, Watanabe, 2210.10751]

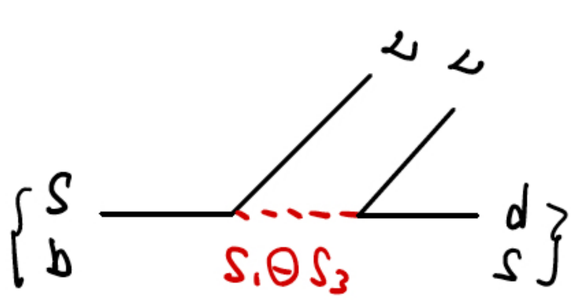
Leptoquark contributions

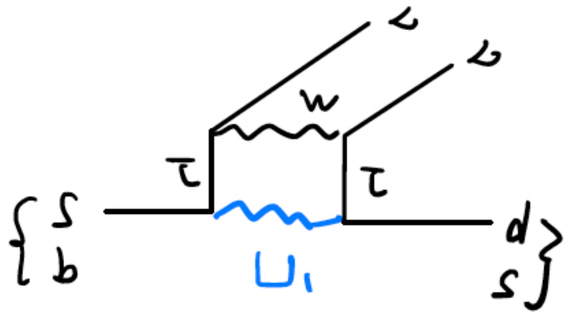
S1 + S3 **scalar** LQ

U1 **vector** LQ

$K \to \pi\nu\bar{\nu}$

$B \to K\nu\bar{\nu}$

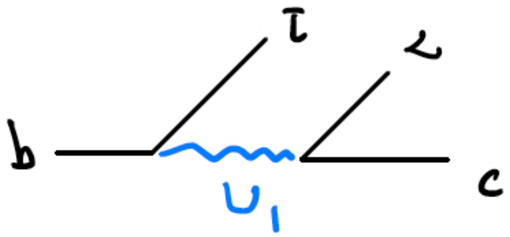




$S_1 - S_3$ cancelation must be satisfied

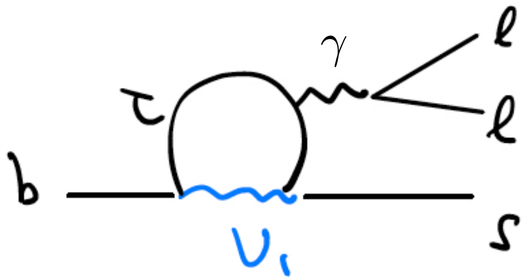
$B \to D\tau\bar{\nu}$





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



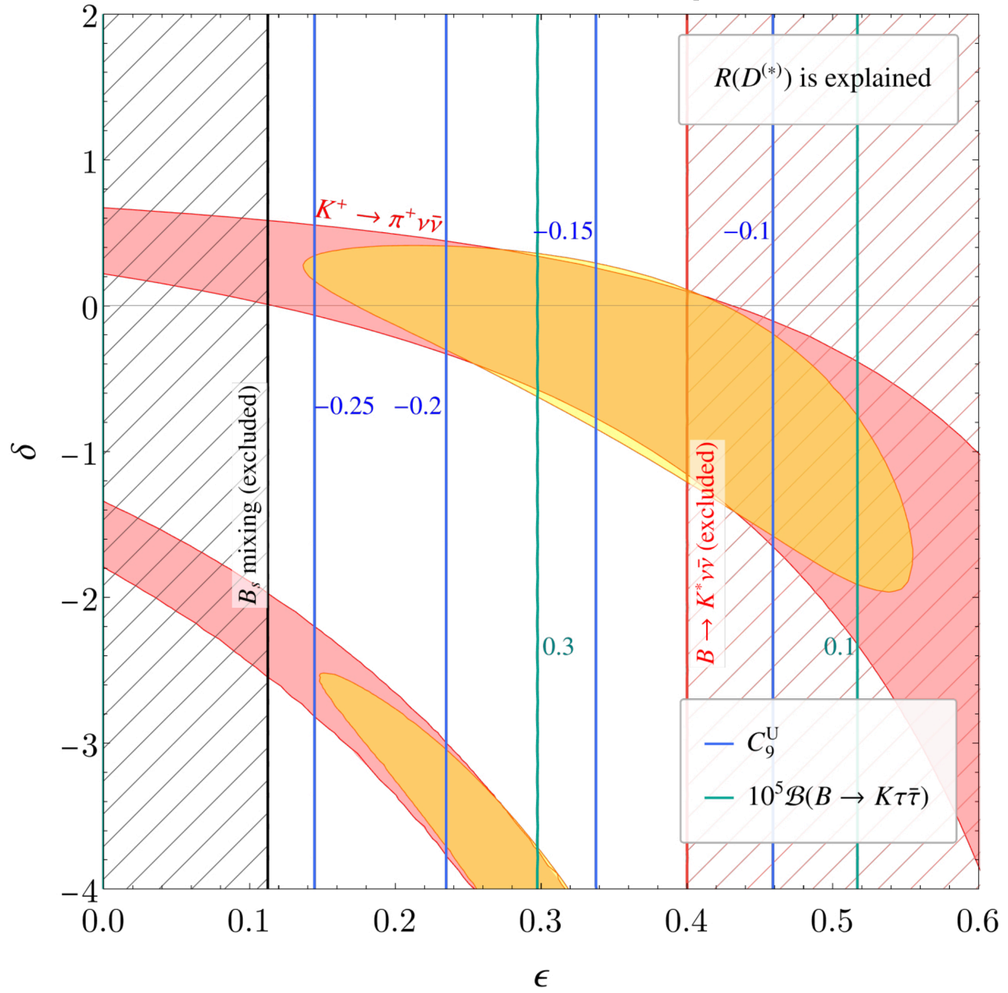


loop-induced lepton-universal contributions

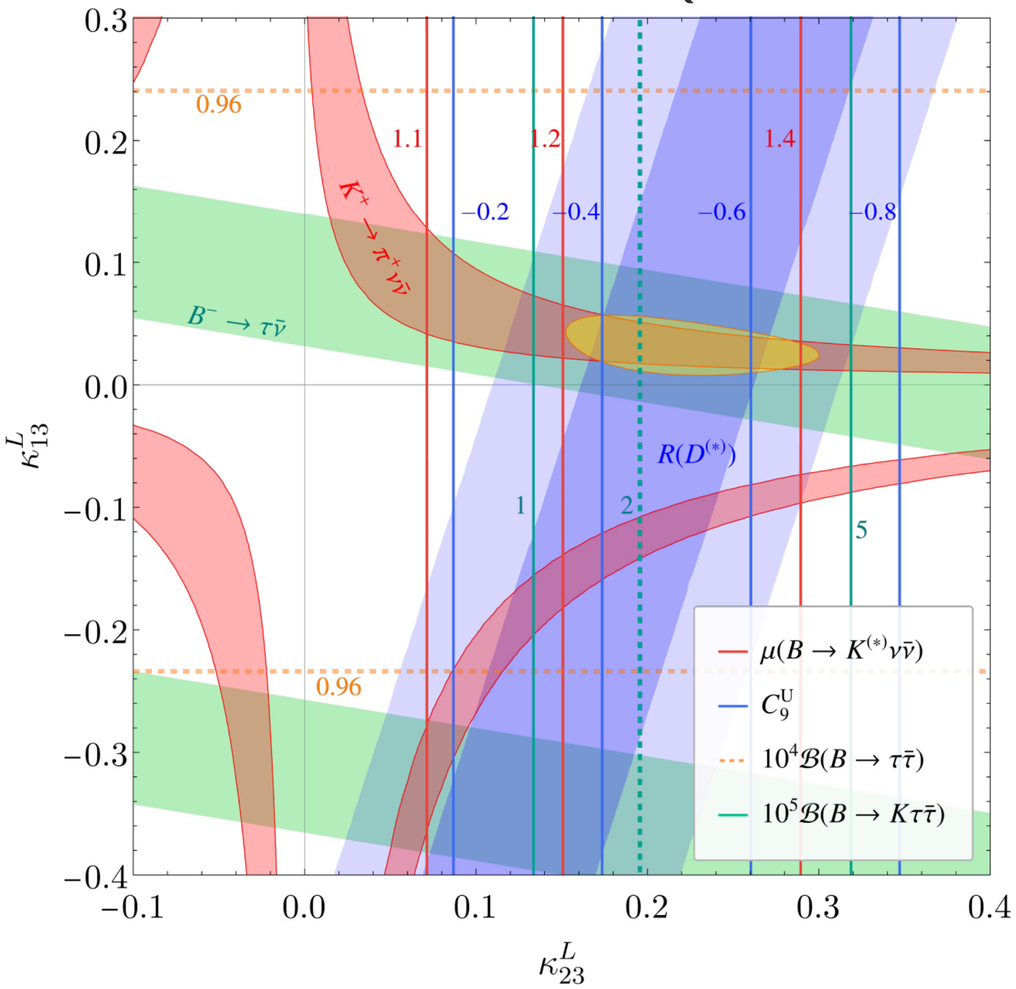
LQ vs flavor anomalies

Crivellin, Iguro, TK, 2505.05552

S1 + S3 scalar LQ



U1 vector LQ



$b \to c$ セミレプトニック和則

- バリオンにけるレプトン普遍性： $\mathcal{R}(\Lambda_c) = \dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar{\nu}_\ell)}$

- 新物理によらず、任意のラグランジアンで以下の和則が $R(D)$, $R(D^*)$, $R(\Lambda_c)$

  の間に成立する (重クォーク対称性)

現象論的解析: Blanke, TK, et al, 1811.09603, Fedele, TK, et al, 2211.14172

理論的導出: Endo, Iguro, et al, 2501.09382, 2506.16027, 2508.06322, 2509.02006

分子には dim-6 SMEFT 演算子が入る →

$$\frac{R(\Lambda_c)}{R(\Lambda_c)_{\rm SM}} \simeq 0.28 \frac{R(D)}{R(D)_{\rm SM}} + 0.72 \frac{R(D^*)}{R(D^*)_{\rm SM}}$$

$R(\Lambda_c)$ を測定すれば、$R(D^{(*)})$ アノマリーを追試可能であることがわかった

R(D(*)) anomaly input →

$$R(\Lambda_c) = 0.377 \pm 0.011_{R_{D^{(*)}}} \pm 0.005_{R^{SM}_{\Lambda_c}} \quad \left(R(\Lambda_c)_{\rm SM} = 0.324 \pm 0.004 \right)$$

LHCb result

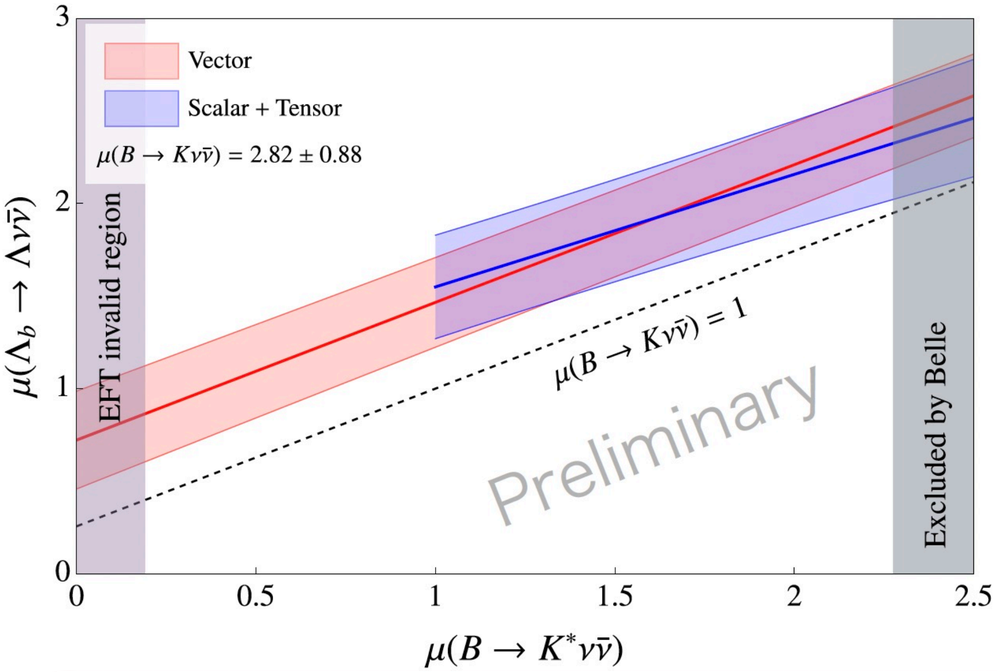
$R(\Lambda_c)_{\rm exp} = 0.242 \pm 0.075$ LHCb, 2201.03497

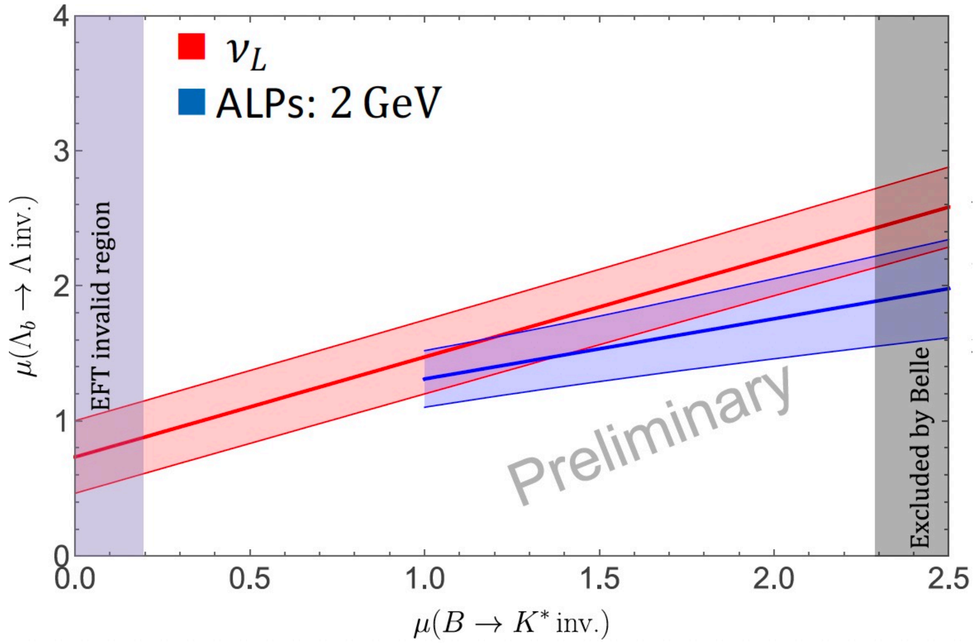
1.8σ tension from the sum-rule

$b \to s\nu\nu$ 和則 + 右巻きν + ALP

- 同様の和則を $b \to s\nu\nu$ 過程にも実行し、普遍性と模型識別性を予言可能

[TK, Mohapatra, Sasaki, 2604.20340] + WIP [Mohapatra, Sasaki] + WIP [Sasaki, Tomita]





$$\mu\left(\Lambda_b \to \Lambda\nu\bar{\nu}\right) = 0.26(5)\mu(B \to K\nu\bar{\nu}) + 0.74(5)\mu\left(B \to K^*\nu\bar{\nu}\right)$$

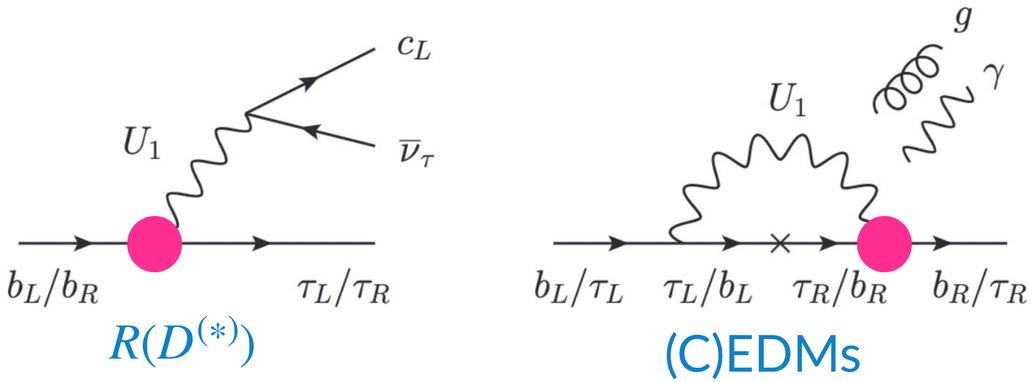
K*の偏極の測定が crucial

see → Sasaki-san, Tomita-san

Leptoquark induced EDM

- LQ models naturally contain the CPV phase in the Yukawa interactions

$$\mathcal{L} = \left(Y_L \bar{Q}_i \gamma_\mu P_L L_3 + Y_R \bar{b} \gamma_\mu P_R \tau \right) U_1^\mu$$

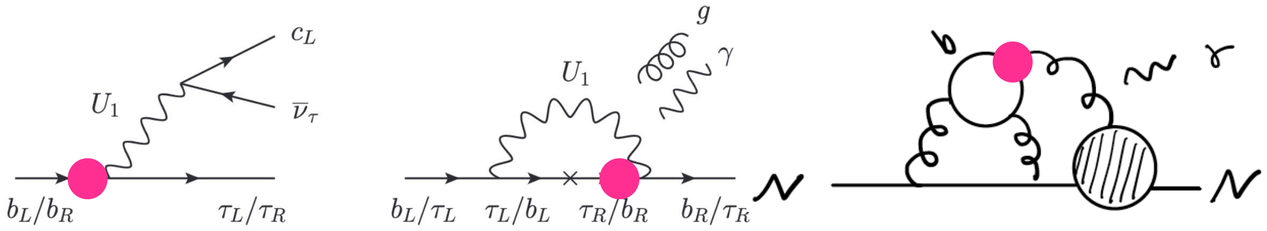


U_1 vector LQ induces bottom quark (C)EDM

R_2 scalar LQ induces charm quark (C)EDM

- At hadronic scale, the neutron and proton EDMs are radiatively induced from the heavy-quark EDM and chrome-EDM

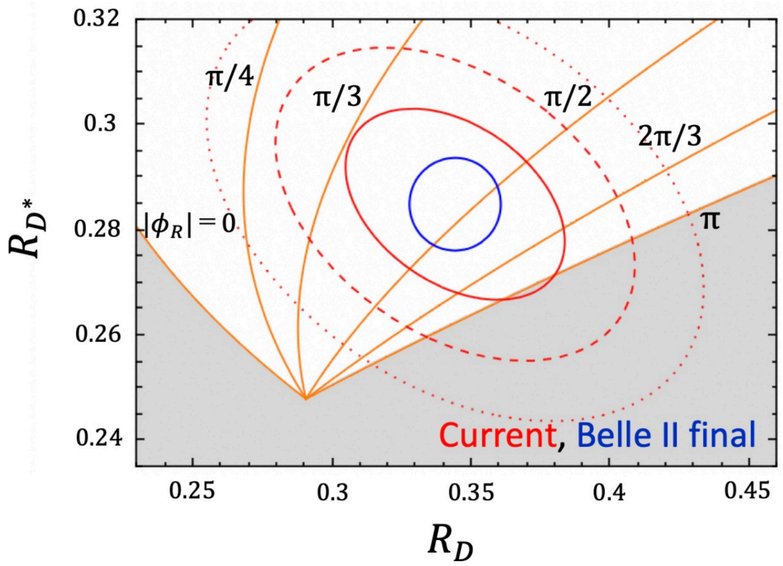
LQ vs EDM

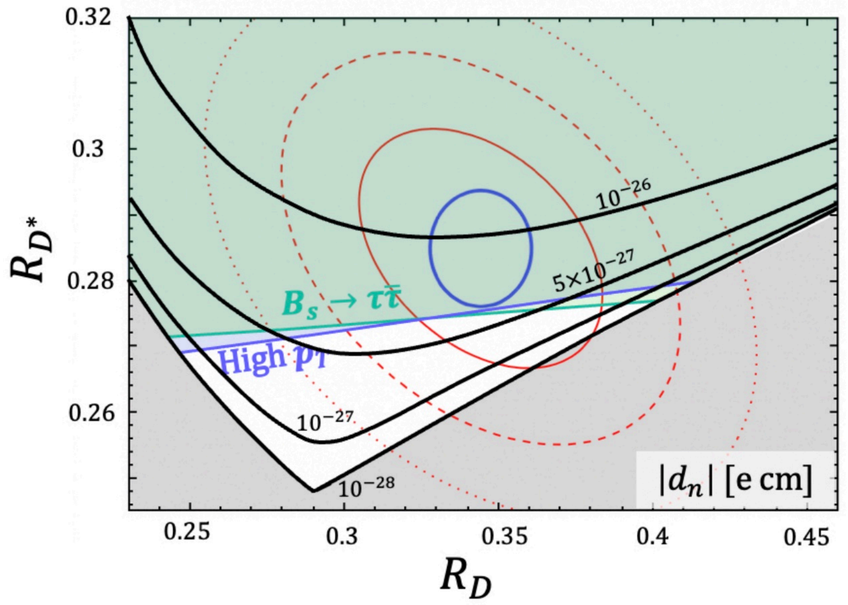


- CP-conserving Observables = SM^2 + SM-NP + NP^2
  $|C_{NP}|\cos\theta$ $|C_{NP}|^2$

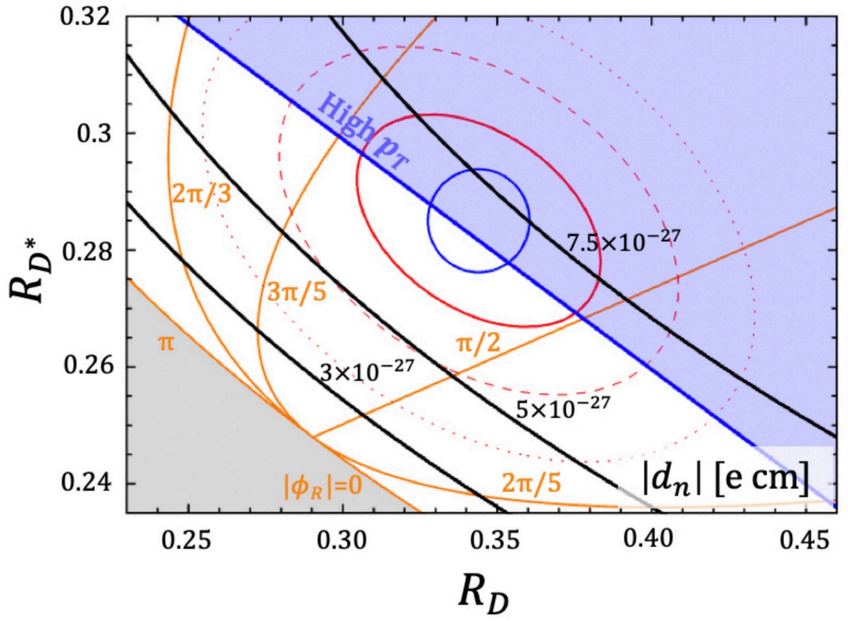
Fuyuto, et al, 1804.01137
Iguro, TK, 2307.11751

CPV phase in a vector LQ U_1





CPV phase in a scalar LQ R_2



4-loop level LQ-induced nucleon EDM can be probed with future sensitivity

The CKM matrix

Cabibbo-Kobayashi-Maskawa matrix

- The precision determinations of the CKM/PMNS elements are crucial to understanding the origin of quark/lepton flavor
- Each component can be measured independently without imposing the unitarity
- One can test the CKM unitarity conditions from data:

β decays

K meson decays

B meson decays

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

D meson decays

K and B mesons mixing

SM prediction

$$V^\dagger V = V V^\dagger = 1$$

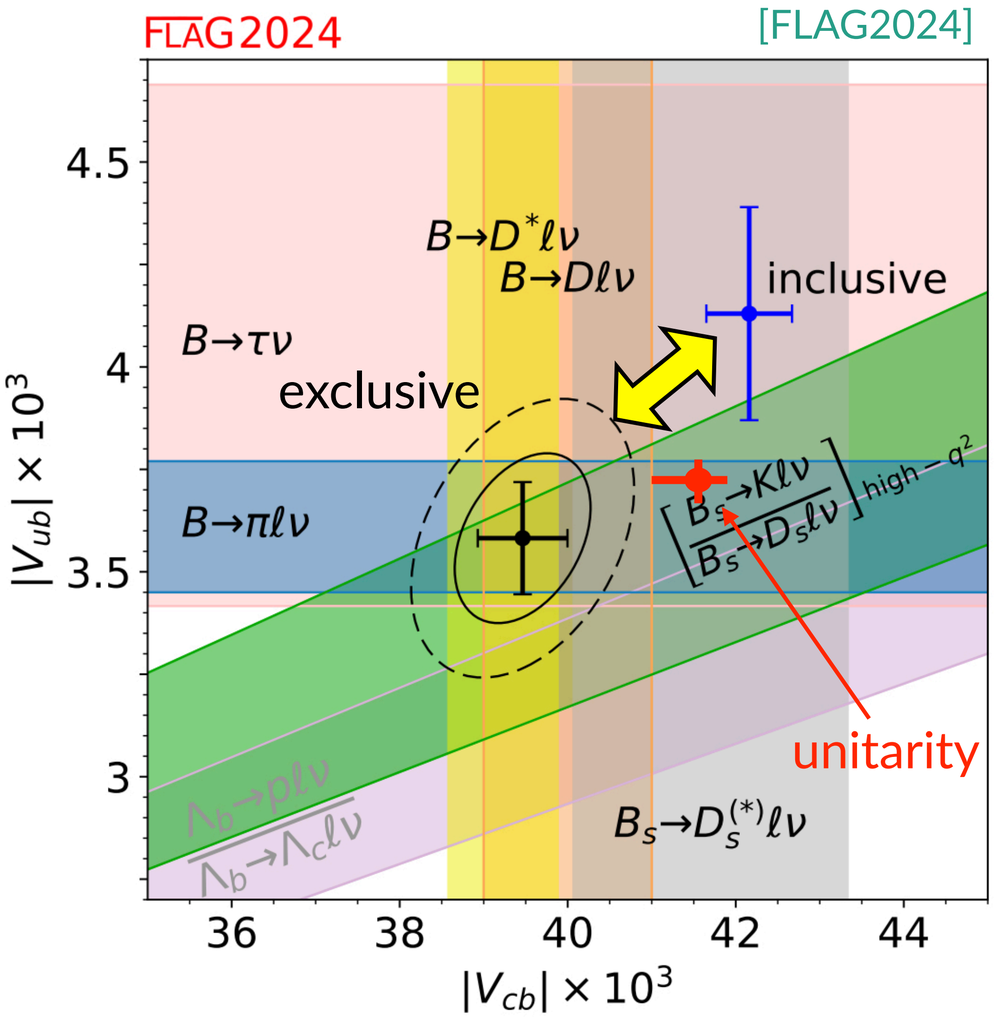
$$V^\dagger V \neq V V^\dagger \neq 1$$ ⇒ NP!

$|V_{cb}|$ – $|V_{ub}|$ plane

- The exclusive decays (black contour) provides lower values of both $|V_{cb}|$ and $|V_{ub}|$
- Inclusive one gives higher values
- Long standing **~3σ tension** between the exclusive and inclusive ones
- CKM Unitarity condition is also deviated

  CKMfitter2023
- Kaon sector (CP violation: ε_K) significantly prefers the inclusive $|V_{cb}|$ value

  SWME collaboration, 2312.02986



1st-row Unitarity test

- Thanks to the improvement of lattice QCD, the 1st-row unitarity test is currently excited

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Unitarity condition

$$VV^\dagger = \mathbb{I}_3$$

1st-row unitarity condition

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

10^{-5}

Sum of the absolute values must become exactly 1 within the SM

$VV^\dagger = \mathbb{I}_3$ or $\neq \mathbb{I}_3$?

SM NP?



Global fit of $|V_{ud}|$ and $|V_{us}|$

[Crivellin, Kirk, TK, Mescia, 2212.06862]

$K_{\ell 3}$

$K^0_{L,S} \to \pi^+ \ell \bar{\nu}$

$K^- \to \pi^0 \ell \bar{\nu}$

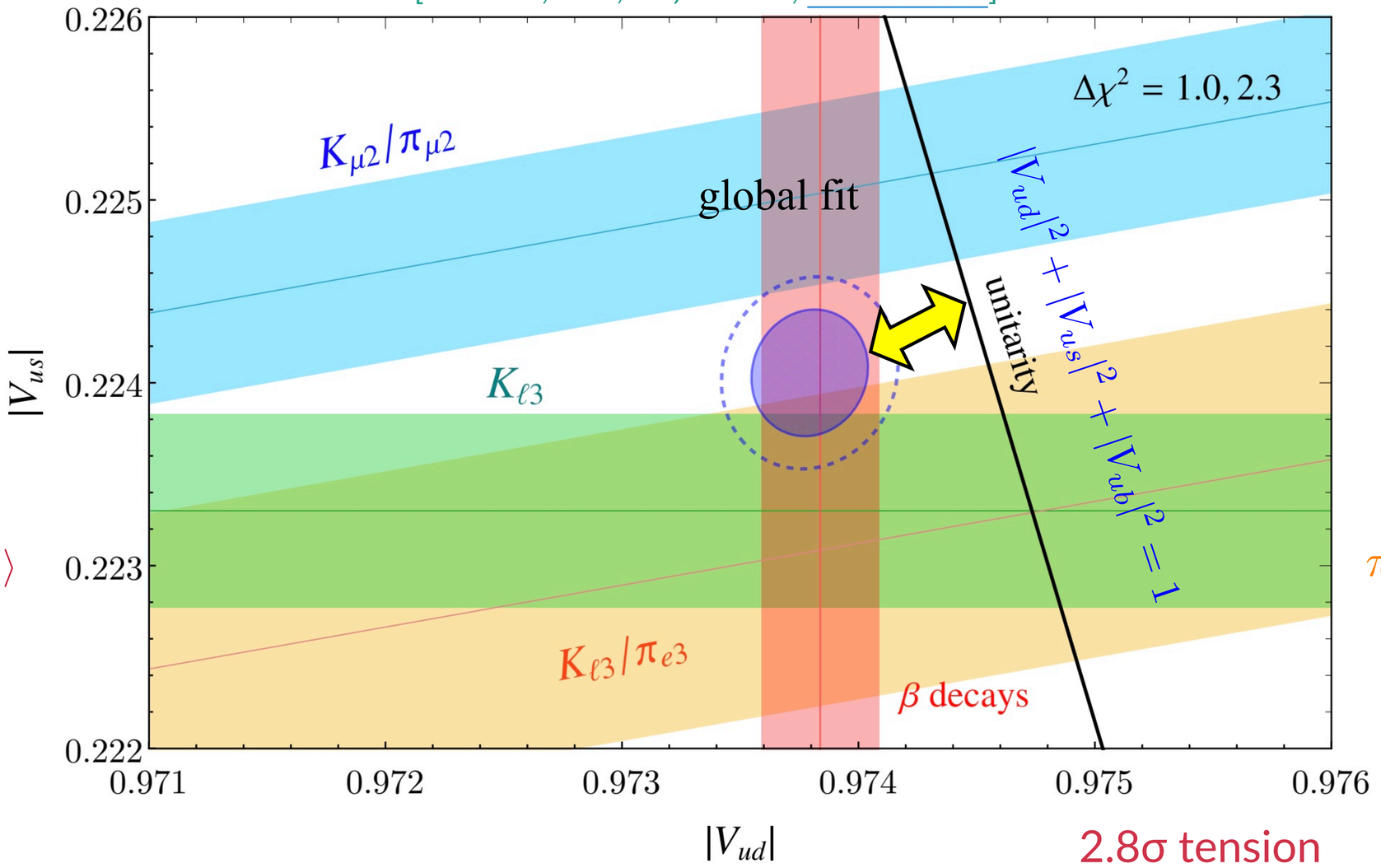
$(\ell = e,\ \mu)$

Error budgets:

LO: data, FFs

$\langle \pi\,(p')\,|\bar{s}\gamma_\mu u|\,K(p)\rangle$

NLO: Isospin breaking correction



$K_{\mu 2}/\pi_{\mu 2}$

$\dfrac{K^- \to \mu\bar{\nu}}{\pi^- \to \mu\bar{\nu}}$

Error budgets:

LO: FFs

$\langle 0\,|\bar{s}\gamma_\mu\gamma_5 u|\,K(p)\rangle$

NLO: data, radiative correction

$\pi_{e3} : \pi^+ \to \pi^0 e^+ \nu$

Error budgets:

LO: data

Uncertainty from $|V_{ub}|$ is negligible

2.8σ tension

SMEFT

- In general new physics scenario, if the NP scale is much higher than the EW scale, one can consider the dimension-six **Standard Model Effective Field Theory (SMEFT)**, where $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge symmetry is conserved below cutoff scale Λ

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i C_i Q_i$$ [Grzadkowski, et al., 1008.4884]

independent dimension-six operator contributing to CKM non-unitarity

$$Q_{Hq}^{(1)ij} = (H^\dagger i\overset{\leftrightarrow}{D}_\mu H)(\bar{q}_i \gamma^\mu P_L q_j)\,, \qquad Q_{Hq}^{(3)ij} = (H^\dagger i\overset{\leftrightarrow}{D}{}^I_\mu H)(\bar{q}_i \tau^I \gamma^\mu P_L q_j)\,,$$
$$Q_{Hu}^{ij} = (H^\dagger i\overset{\leftrightarrow}{D}_\mu H)(\bar{u}_i \gamma^\mu P_R u_j)\,, \qquad Q_{Hd}^{ij} = (H^\dagger i\overset{\leftrightarrow}{D}_\mu H)(\bar{d}_i \gamma^\mu P_R d_j)\,,$$
$$Q_{Hud}^{ij} = i(\tilde{H}^\dagger D_\mu H)(\bar{u}_i \gamma^\mu P_R d_j)\,.$$

Modified W and Z couplings

- After the spontaneous electroweak symmetry breaking $\langle H^0 \rangle = v/\sqrt{2}$ with $v = 246\,\text{GeV}$,

  W and *Z* quark currents are modified

SM terms

Observed V_{CKM} matrix (non-unitarity)

$$\mathcal{L}_{W,Z} = -\frac{g_2}{\sqrt{2}} W^+_\mu \bar{u}_i \gamma^\mu \left(\left[V \cdot \left(1 + v^2 C^{(3)}_{Hq} \right) \right]_{ij} P_L + \frac{v^2}{2} \left[C_{Hud} \right]_{ij} P_R \right) d_j + \text{ h.c.}$$

$$- \frac{g_2}{6 c_W} Z_\mu \bar{u}_i \gamma^\mu \left(\left[\left(3 - 4 s^2_W \right) + 3 v^2 V \cdot \left\{ C^{(3)}_{Hq} - C^{(1)}_{Hq} \right\} \cdot V^\dagger \right]_{ij} P_L - \left[4 s^2_W + 3 v^2 C_{Hu} \right]_{ij} P_R \right) u_j$$

$$- \frac{g_2}{6 c_W} Z_\mu \bar{d}_i \gamma^\mu \left(\left[\left(2 s^2_W - 3 \right) - 3 v^2 \left\{ C^{(3)}_{Hq} + C^{(1)}_{Hq} \right\} \right]_{ij} P_L + \left[2 s^2_W - 3 v^2 C_{Hd} \right]_{ij} P_R \right) d_j$$

- Non-unitary V_{CKM} provides non-trivial effects to *Z* currents including FCNCs

SMEFT fitting for CAA

[Grossman, Passemar, Schacht, 1911.07821]
[Crivellin, Kirk, TK, Mescia, 2212.06862]

- SMEFT global fit implies right-handed W-u-d and W-u-s currents C_{Hud} are preferred

EFT Scenario	Best fit point	$-\Delta\chi^2$	Pull
$[C_{Hq}^{(3)}]_{11}$ [unit of $(10^{-3}v^{-2})$]	-0.50	3.3	$1.8\,\sigma$
$[C_{Hq}^{(3)}]_{11} = [C_{Hq}^{(3)}]_{22}$	-0.27	1.1	$1.1\,\sigma$
$[C_{Hq}^{(3)}]_{11} = [C_{Hq}^{(1)}]_{11}$	-0.55	3.7	$1.9\,\sigma$
$[C_{Hud}]_{11}$	-1.0	3.1	$1.8\,\sigma$
$[C_{Hud}]_{12}$	-2.0	7.4	$2.7\,\sigma$
$([C_{Hud}]_{11}, [C_{Hud}]_{12})$	$(-1.4, -2.1)$	13	$3.2\,\sigma$
$([C_{Hq}^{(3)}]_{11}, [C_{Hud}]_{12})$	$(-0.43, -2.0)$	11	$2.8\,\sigma$
$([C_{Hq}^{(3)}]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12})$	$(0.27, -1.9, -2.4)$	16	$2.9\,\sigma$
$([C_{Hq}^{(3)}]_{11}, [C_{Hq}^{(3)}]_{22}, [C_{Hud}]_{11}, [C_{Hud}]_{12})$	$(0.59, 0.76, -2.6, -2.5)$	17	$2.9\,\sigma$
$([C_{Hq}^{(3)}]_{11}, [C_{Hq}^{(1)}]_{11}, [C_{Hud}]_{11}, [C_{Hud}]_{12})$	$(0.29, 0.11, -2.0, -2.4)$	13	$2.6\,\sigma$

no contribution to $D - \bar{D}$ mixing

Best pull

2nd-Column unitarity test

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

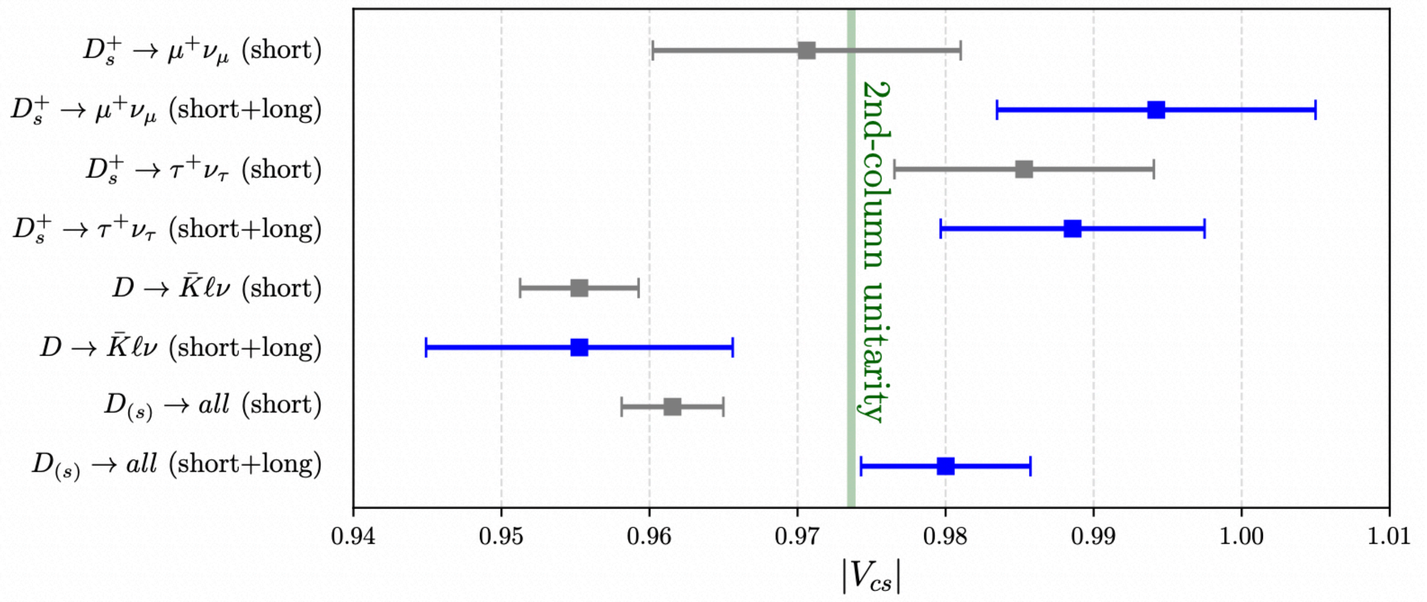
Unitarity condition

$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 - 1 = \begin{cases} -0.032 \pm 0.006 \ [-5.2\sigma] \\ -0.021 \pm 0.010 \ [-2.0\sigma] \end{cases}$$

[Bolognani, et al, 2407.06145]

with scale factor

[TK, Miyamoto, Sasaki, 2511.22383]



with **complete one-loop QED corrections** to $D_s^+ \to \ell^+\nu$

[TK, Miyamoto, Sasaki, 2511.22383]

$$= 0.012 \pm 0.011 \quad [+1.1\sigma]$$

Large positive shift is found due to the radiative corrections

Kaon ultra-rare decays

$|V_{us}|$ vs CKM unitarity

$K \to \pi \ell \bar{\nu}$
$K^- \to \mu \bar{\nu}$

tree-level CPC

ε_K and ε'

$K_L \to \pi\pi$

Correlation

B anomalies

FCNC and CPV

$K^0 \to \mu^+ \mu^-$

$K \to \pi \nu \bar{\nu}$

Sensitive to CPV when $K_L^0 - K_S^0$ interference considered!

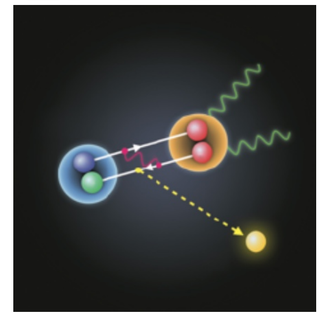
New idea in 2017

[D'Ambrosio, TK, PRL, 1707.06999]

kaon unitarity triangle

[Dery, 2504.12386]

$K \to \pi X?$

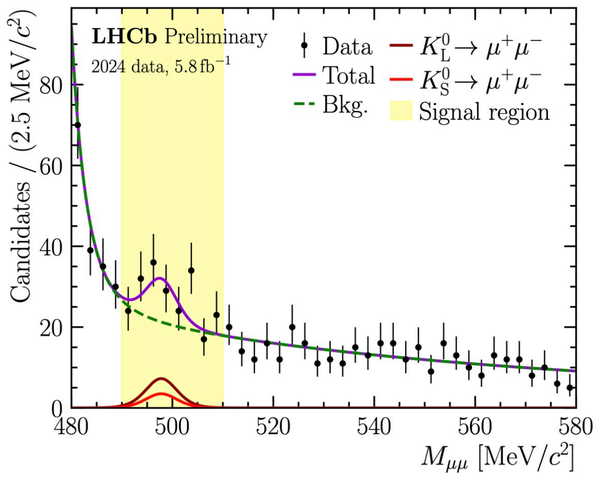


Very recent result from LHCb

Fit results

Result to be published as **LHCb-PAPER-2026-052**

- Significance for $K^0 \to \mu^+\mu^-$ of 4.5 σ with respect to background only hypothesis
- $(11 \pm 5)\, K_S^0 \to \mu^+\mu^-$ events
- $(24 \pm 5)\, K_L^0 \to \mu^+\mu^-$ events
- $K_S^0 \to \mu^+\mu^-$ has contribution of 1.1 σ significance



Combination with Run 1+2

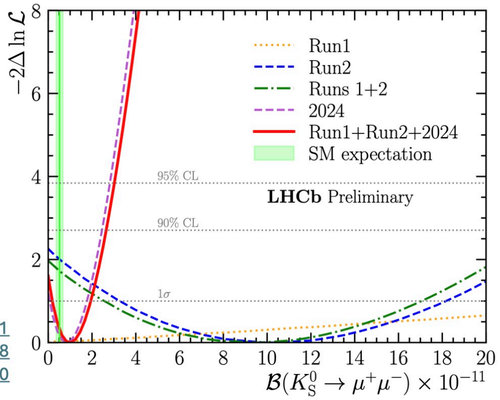
Result to be published as **LHCb-PAPER-2026-052**

- **Combining with Run 1+2:**

$\mathcal{B}(K_S^0 \to \mu^+\mu^-) < 2.7(3.0) \times 10^{-11}$ **at 90(95)% C.L.**

- Log likelihood interval with Run 1+2:

$\mathcal{B}(K_S^0 \to \mu^+\mu^-) = \left(9.1^{+6.5}_{-7.8}\right) \times 10^{-12}$



Phys. Rev. Lett. 125 (2020) 231801
Eur. Phys. J. C 77 (2017) 678
JHEP 01 (2013) 090

$$\mathcal{B}(K_S^0 \to \mu^+\mu^-)_{\rm SM} = 5.18(1.50) \times 10^{-12}$$

[D'Ambrosio, TK, 1707.06999]

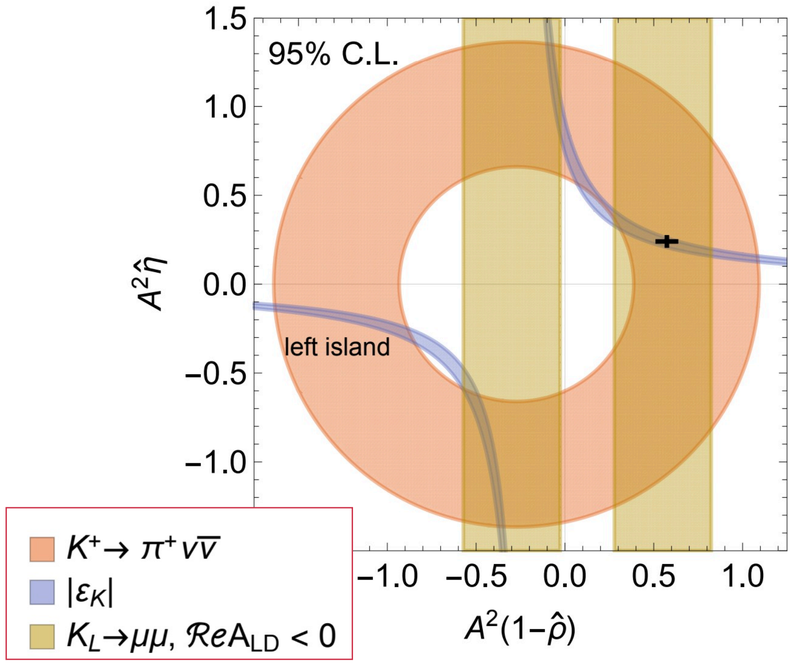
Kaon unitarity triangle

[Buras, Venturini, 2109.11032;
Lunghi, Soni, 2408.11190;
Dery, 2504.12386]

- New idea: large uncertainty from $|V_{cb}|$ can be dropped, when one considers the unitarity triangle in not $(\bar{\rho}, \bar{\eta})$, but in $(A^2(1-\hat{\rho}), A^2\hat{\eta})$ plane

with $A^2\lambda^4(1-\hat{\rho}+i\hat{\eta}) \equiv -\frac{V_{td}V_{ts}^*}{V_{cd}V_{cs}^*}$

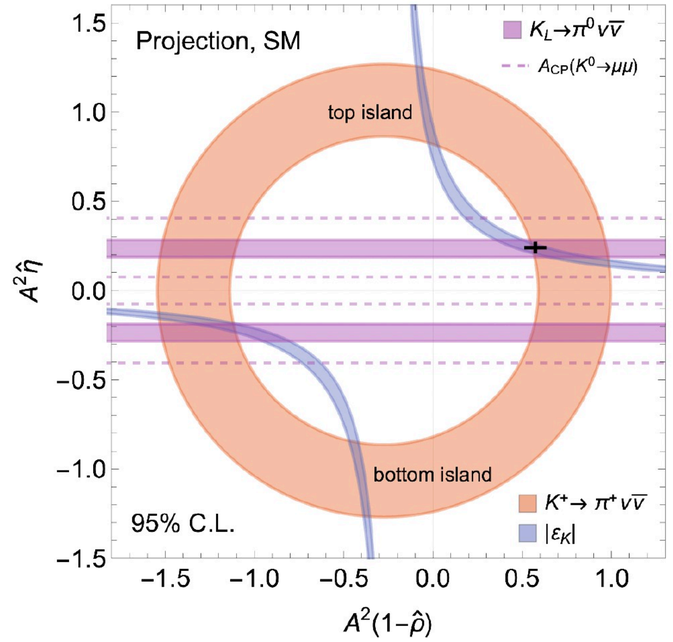
[Dery, 2504.12386]



current best-fit point

NB: The end of the base is $(\lambda^{-4}, 0)$

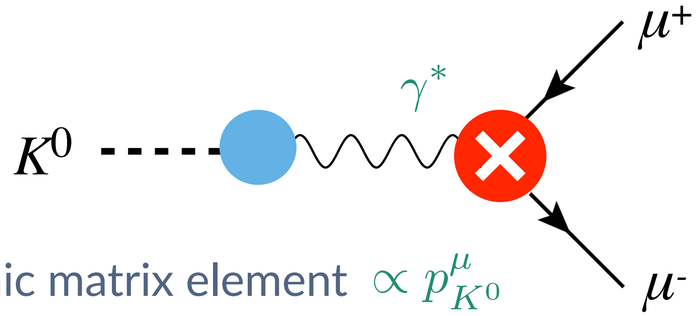
near future ≈ 2040



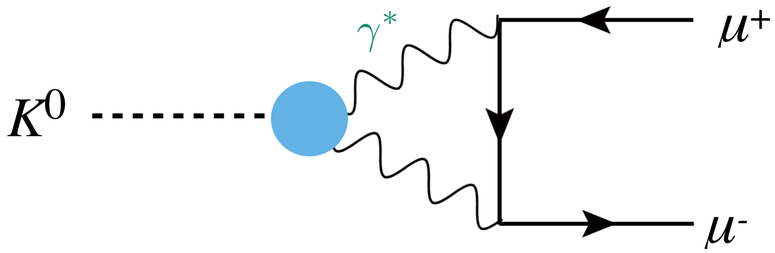
[Dery, KAON2025]

Introduction to $K^0_{L/S} \to \mu^+\mu^-$

- Double-photon exchange is the leading contribution in $K^0 \to \mu^+\mu^-$



Hadronic matrix element $\propto p^{\mu}_{K^0}$



Leading

- Both CP-conserving and CP-violating contributions exist

$J = 0$

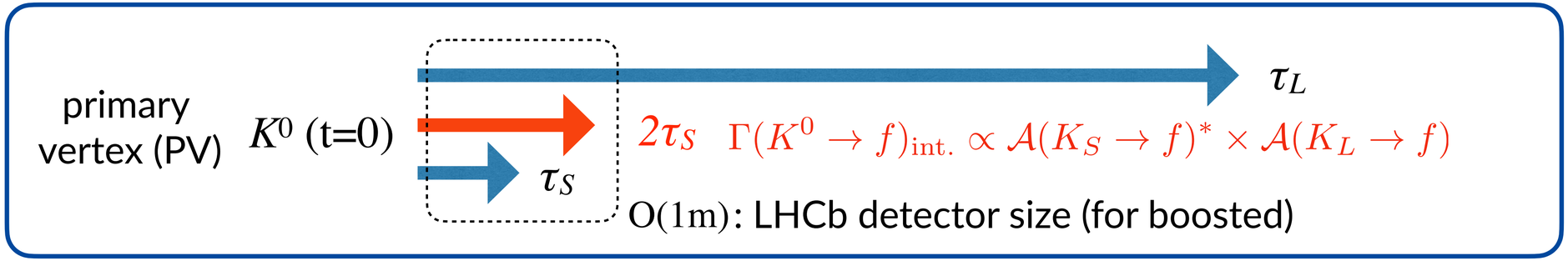
S-wave (L=0, S=0)

- K^0_{L} almost *CP*-odd → $\bar{\ell}\gamma_5\ell$ (spin singlet) = *CP*-odd
- ***CP* violation**
- K^0_{S} almost *CP*-even → $\bar{\ell}\ell$ (spin triplet) = *CP*-even

P-wave (L=1, S=1)

Interference between K_L^0 and K_S^0

- When the same final states exist in both K_L^0 and K_S^0 decays, the interference provides nonzero contributions:



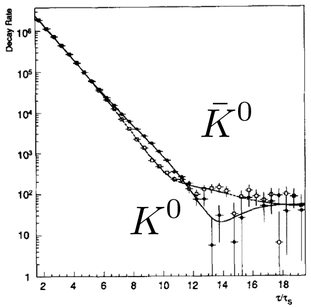
- Such an interference has been observed/utilized in many processes: e.g.,

$K^0 \to \pi\pi, K^0 \to 3\pi$ and $K^0 \to \pi^0 e^+ e^-$

cf. CPLEAR experiment@CERN) $\{K_S, K_L\} \to \pi^+\pi^-$

[CPLEAR collaboration '95] measured the interference between K_L and K_S

$$p\bar{p} \to \left[\begin{matrix} K^0 K^- \pi^+ \\ \bar{K}^0 K^+ \pi^- \end{matrix}\right.$$



Direct *CP* violation in $K^0_{L/S} \to \mu^+\mu^-$

- Important idea: interference corresponds to **genuine direct CP violation**

[D'Ambrosio, TK, 1707.06999; Dery, Ghosh, Grossman, Schacht, 2104.06427]



weak phase = 0;
CP-even phase = photon loop:
$K_L \to \gamma\gamma\,|\,\gamma\gamma \to \mu\mu$

weak phase = arg [$V^*_{ts}\, V_{td}$];
CP-even phase = 0

Both weak and "strong phase" differences exist

Two advantages:

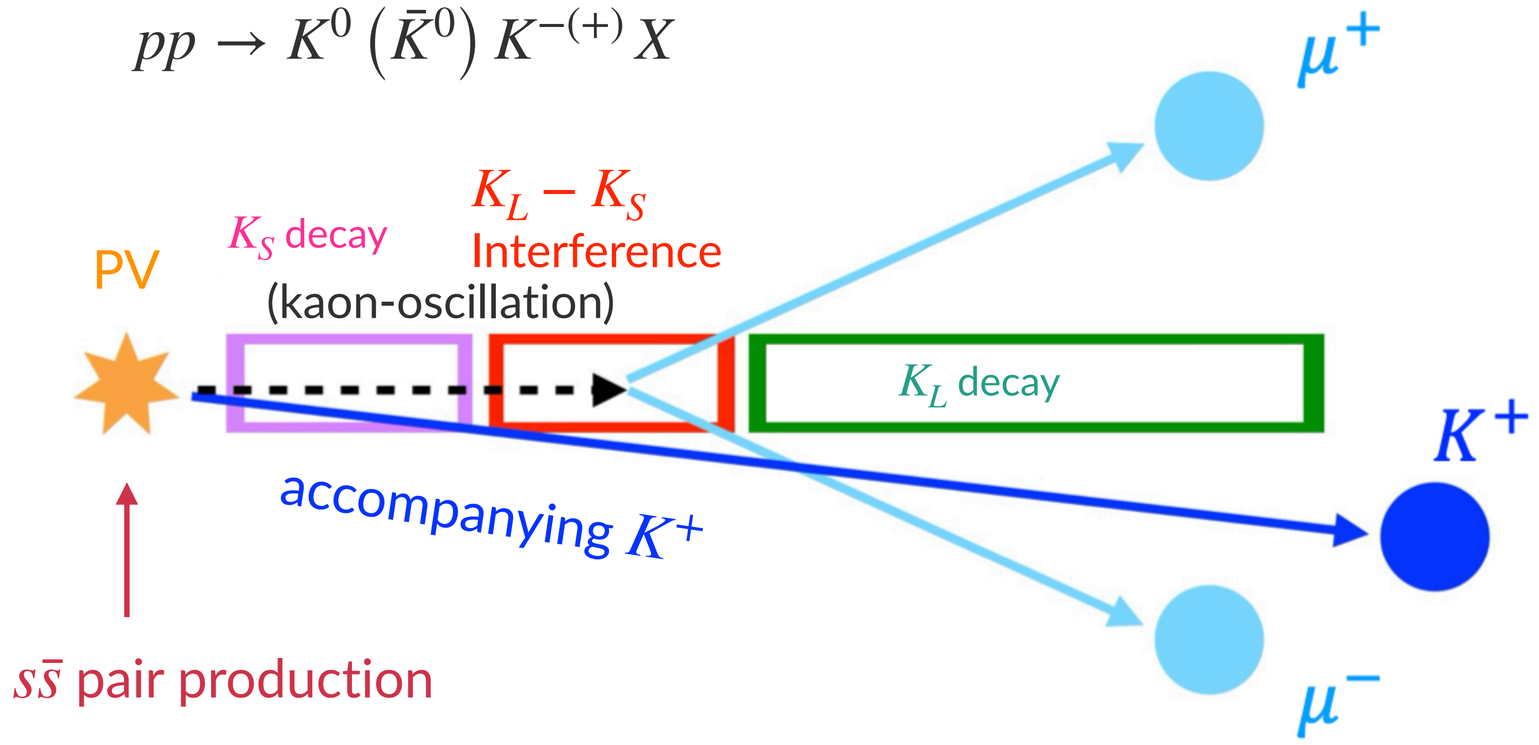
1. **Numerically enhanced** by the anomaly-driven (■) $K^0_L \to \gamma\gamma$, $\mathcal{O}(1/f_\pi)$
2. **Theoretically clean** due to the optical theorem in K^0_L amplitude

Flavor tagging method

- We simulate the following events within an LHCb-like setup:

[D'Ambrosio, TK, 1707.06999]

$$pp \to K^0 \left(\bar{K}^0\right) K^{-(+)} X$$

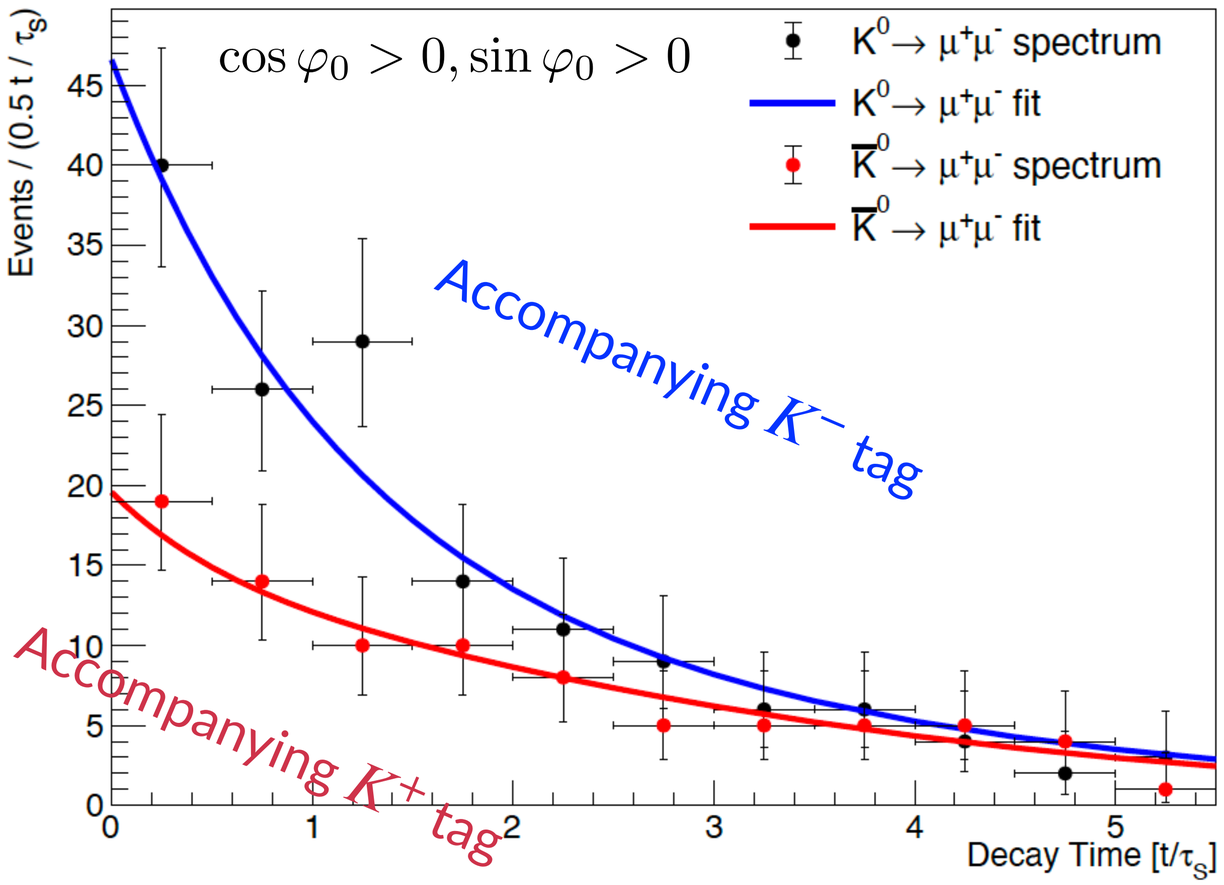


- Forward $s\bar{s}$ productions
- Two opposite sign muon generated from the interference region
- Single accompanying charged kaon to distinguish $K^0(t=0)$ or $\overline{K}^0(t=0)$

Decay-time analysis

- We simulate the decay-time distribution for the **LHCb Upgrade II setup**
- It is clearly shown that the CP violation between $K^0 \to \mu^+\mu^-$ and $\overline{K}^0 \to \mu^+\mu^-$ can be measured for small decay time region

[D'Ambrosio, Dery, Grossman, TK, Marchevski, Martinez Santos, Schacht, 2507.13445]



Sensitivity to the CP-violating parameter

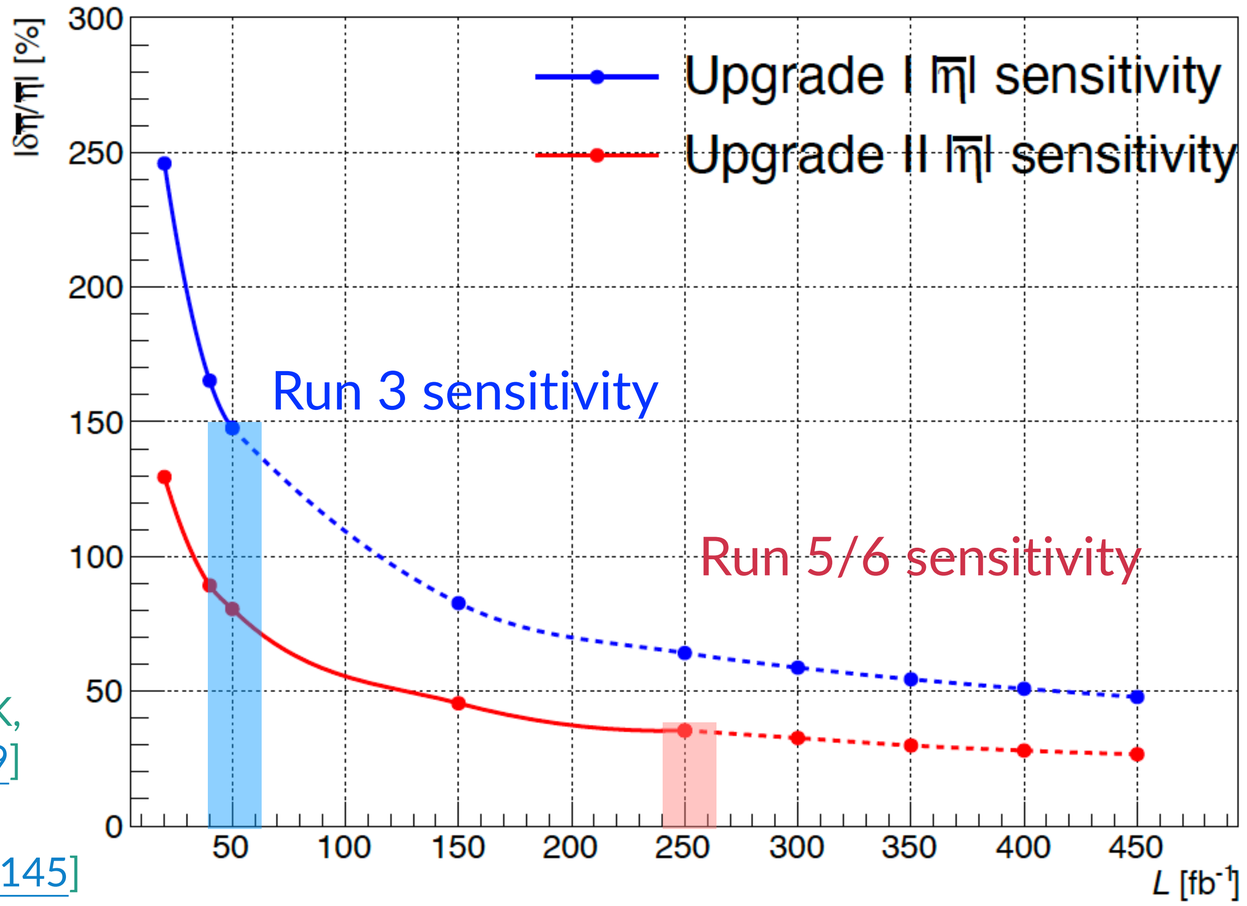
- In Upgrade II, a **factor 3 improvement** is expected using events by downstream track
- LHCb Upgrade I and II can measure $A^2\lambda^5|\bar{\eta}|$ with 150% and 35% accuracy, respectively
- Further improvements for flavor tagging are possible via

$$pp \to K^{*+}X \to K^0\pi^+X$$
$$pp \to K^0\Lambda(\to p\pi^-)X$$

[D'Ambrosio, TK, 1707.06999]

deep-learning method [Prouve, et al, 2404.14145]

[D'Ambrosio, Dery, Grossman, TK, Marchevski, Martinez Santos, Schacht, 2507.13445]



まとめ

- フレーバー物理において明確な新物理の証拠はまだ得られていないが、

  いくつかの tension は見えており、その**「解釈」**は定まっていない

  CKM 成分・ユニタリティ, $b \to c\tau\nu, b \to s\ell^+\ell^-, b \to s\nu\bar{\nu}, b \to c\bar{u}q, \ldots$

- **精密なSM予言**が、新物理を判断する基準を支える

  格子QCD計算, QED 量子補正, non-local charm 補正, …

- **多様な相関**から新物理を検証し、その **(フレーバー・ローレンツ) 構造**に迫る

  q^2 分布, 偏極, CPの破れ (with EDM), B・K 相関, バリオン・メソン和則, …