Recent hot topics in B physics

-- Flavor Anomalies

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高能物理实验的任务是

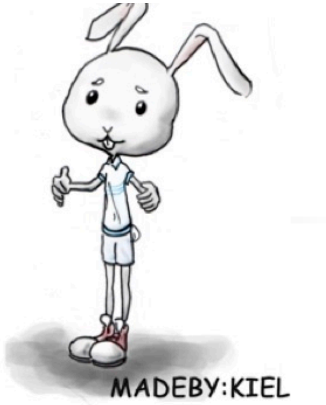
探索新粒子和新现象...

- 可以通过两种方式: 直接或间接
- 我们有两个高能物理实验前沿: 高能量和高精度 ...

我听说过好多挺低能量的...

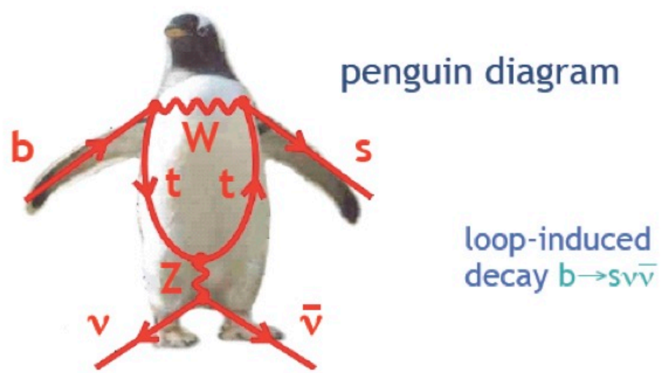
- 北京正负电子对撞机(BEPC)
- 大亚湾中微子实验
- B-工厂，好像还有两个?
- LHCb
- 还有人要造超级B-工厂 （Belle II）

味物理：研究不同“味”直接的转换



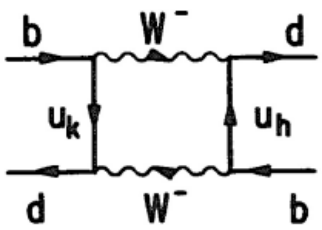
- 强相互作用和电磁作用过程味是守恒的
- 新物理的效会比较弱，比弱作用还弱...
- 理论上对弱相互作用的理解比较清楚

研究味转换过程中对理论的微小偏离，探索新物理！

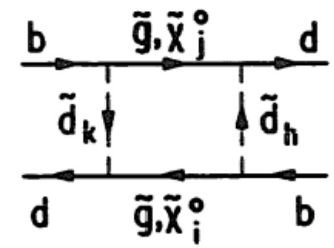


New Physics in FCNC processes

- Mixing

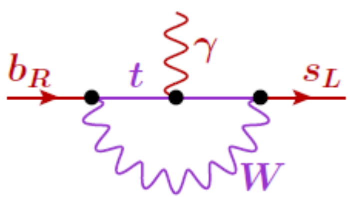


~~OR~~ $\Rightarrow$ AND?

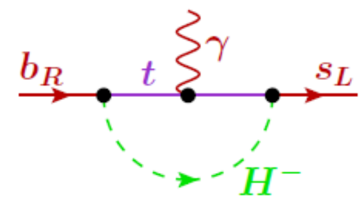


Simple parameterization for each neutral meson: $M_{12} = M_{12}^{\rm SM}\,(1 + h e^{2i\sigma})$

- Penguin decays



~~OR~~ $\Rightarrow$ AND?



Many operators for $b \to s$ transitions — no simple parameterization of NP

- $V_{td,\,ts}$ only measurable in loops; likely also subleading couplings of new particles

- Isolating modest NP contributions requires many measurements
  Compare NP-independent (tree) with NP-dependent (loop) processes

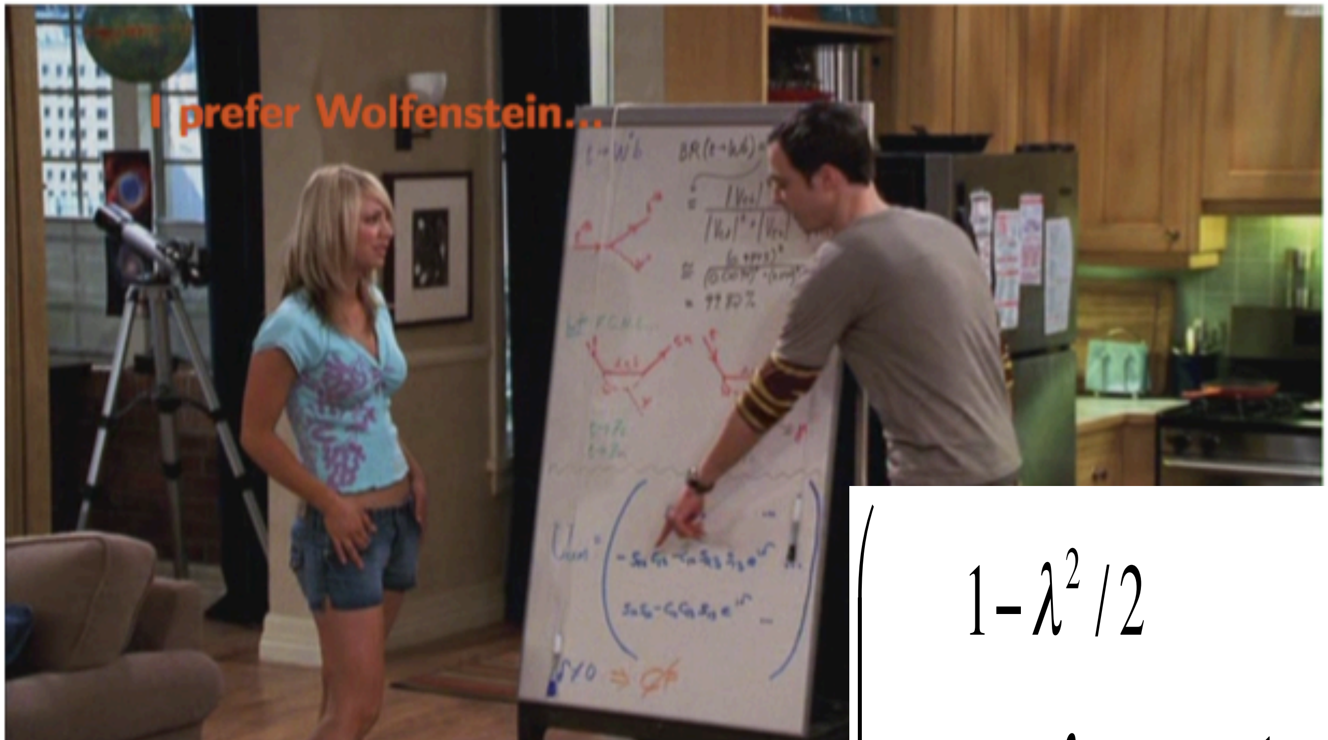
近年来，重味物理一直是粒子物理的最重要研究方向之一

- 顶夸克的质量非常接近电弱能标破缺尺度，有希望找到新物理

  但是顶夸克在现有实验产额太低
- 同为第三代夸克的**b**夸克便担负起了寻找新物理信号的重任。

The CKM (Cabibbo·Kobayashi·Maskawa) matrix

Another possible parametrisations (Chau and Keung parametrisation, adopted by PDG):



$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

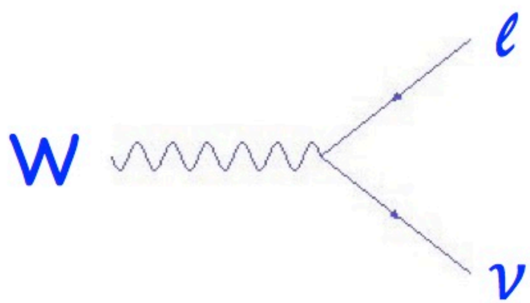
Current Flavor Anomalies

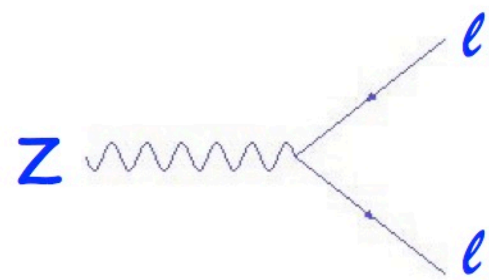
$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly	
$\sim 3.5\sigma$	non-standard like-sign dimuon charge asymmetry	
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates	$R_{D^{(*)}}$
$\sim 3.5\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$	
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\|V_{ub}\|$	
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\|V_{cb}\|$	
$2-3\sigma$	anomaly in $B \to K^*\mu^+\mu^-$ angular distributions	P_5'
$2-3\sigma$	SM prediction for ϵ'/ϵ below experimental result	
$\sim 2.5\sigma$	lepton flavor non-universality in $B \to K\mu^+\mu^-$ vs. $B \to Ke^+e^-$	R_K
$\sim 2.5\sigma$	non-zero $h \to \tau\mu$	

Lepton universality

Lepton couplings to gauge bosons in the standard model are all the same

Very well tested, PDG averages:





$$\frac{B(W^+ \to \mu^+\nu)}{B(W^+ \to e^+\nu)} = 0.991 \pm 0.018$$

$$\frac{B(W^+ \to \tau^+\nu)}{B(W^+ \to e^+\nu)} = 1.043 \pm 0.024$$

$$\frac{B(W^+ \to \tau^+\nu)}{B(W^+ \to \mu^+\nu)} = 1.070 \pm 0.026$$

$$\frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

$$\frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

.9977 (SM)

Current new physics signal in B physics

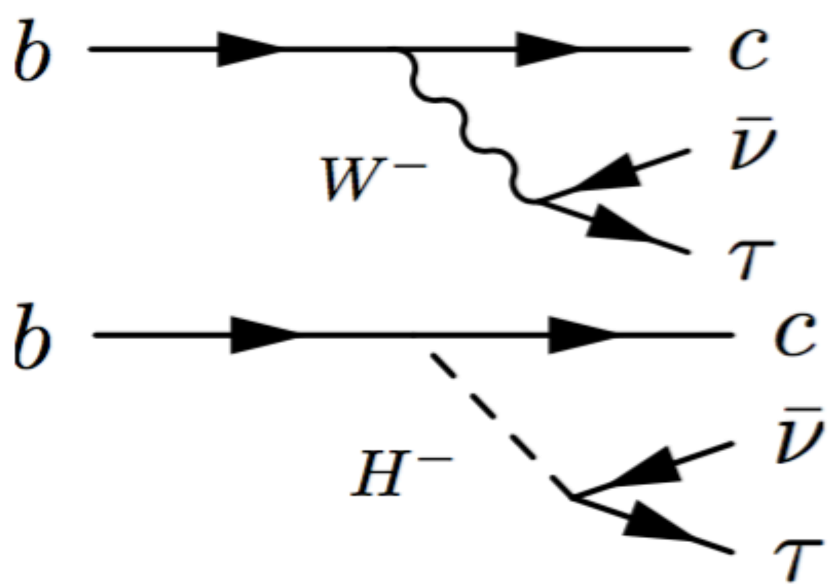
$\bar{B} \to D^{(*)}\tau\bar{\nu}$ Br ~ 0.7+1.3 % in the SM

Not rare, but two or more missing neutrinos

Data available since 2007 (Belle, BABAR, LHCb)

Theoretical motivation

W.S. Hou and B. Grzadkowski (1992)



SM: gauge coupling

lepton universality

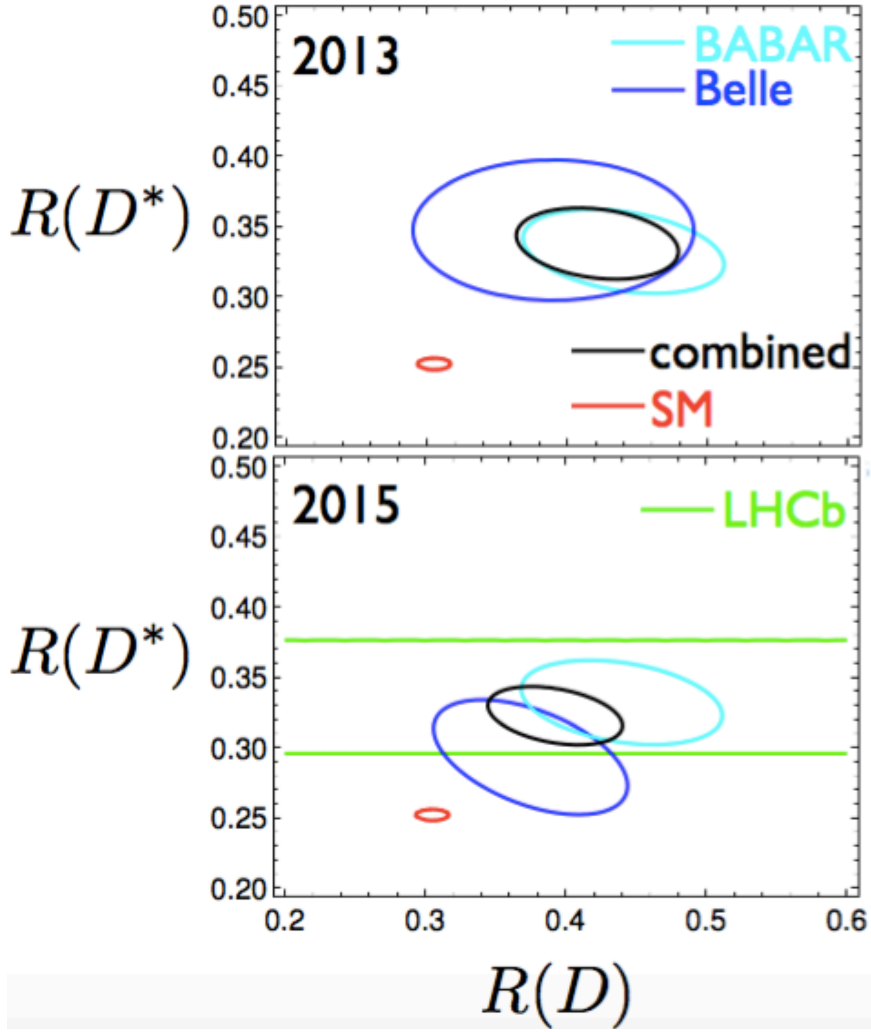
Type-II 2HDM (SUSY)

Yukawa coupling

$\propto m_b m_\tau \tan^2\beta$

$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X(e/\mu)\bar{\nu})}$$

Experiments



$$R(D) = 0.421 \pm 0.058$$
$$R(D^*) = 0.337 \pm 0.025$$

~3.5σ

Y. Sakaki, MT, A. Tayduganov, R. Watanabe

$$R(D) = 0.391 \pm 0.041 \pm 0.028$$
$$R(D^*) = 0.322 \pm 0.018 \pm 0.012$$

~3.9σ HFAG

Standard model predictions

Theoretical uncertainty: form factors

data from $\bar{B} \to D^{(*)}\ell\bar{\nu}$ $(\ell = e, \mu)$

\+ HQET or pQCD

\+ lattice QCD

$R(D) = 0.296 \pm 0.016$ (Fajfer, Kamenik, Nisandzic)

0.302 ± 0.015 (Sakaki, MT, Tayduganov, Watanabe)

0.299 ± 0.011 (Bailey et al.)

$0.337^{+0.038}_{-0.037}$ (Fan, Xiao, Wang, Li)

$0.391 \pm 0.041 \pm 0.028$ (Exp. HFAG)

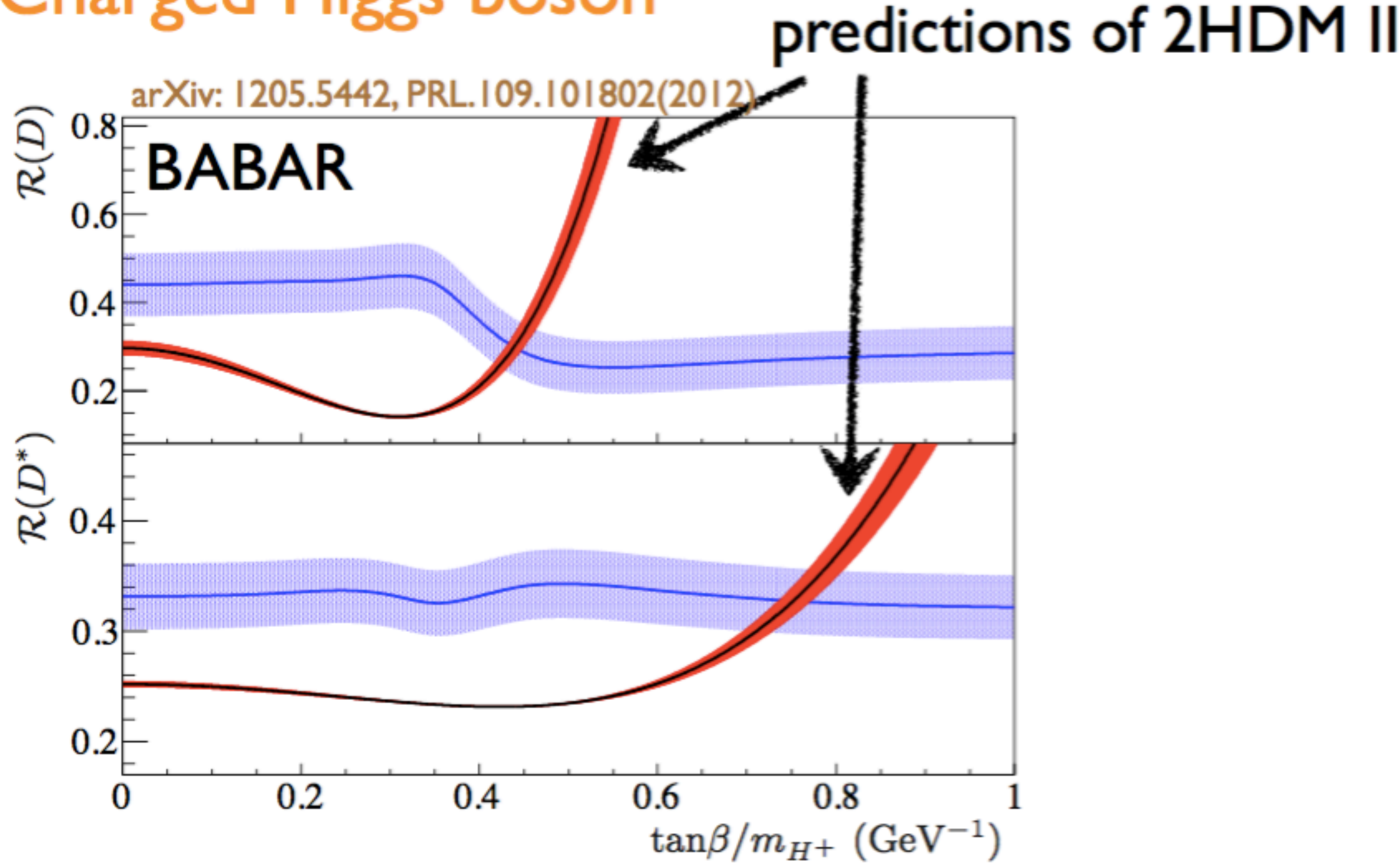
$R(D^*) = 0.252 \pm 0.003$ (Fajfer, Kamenik, Nisandzic)

0.252 ± 0.004 (Sakaki, MT, Tayduganov, Watanabe)

$0.269^{+0.021}_{-0.020}$ (Fan, Xiao, Wang, Li)

$0.322 \pm 0.018 \pm 0.012$ (Exp. HFAG)

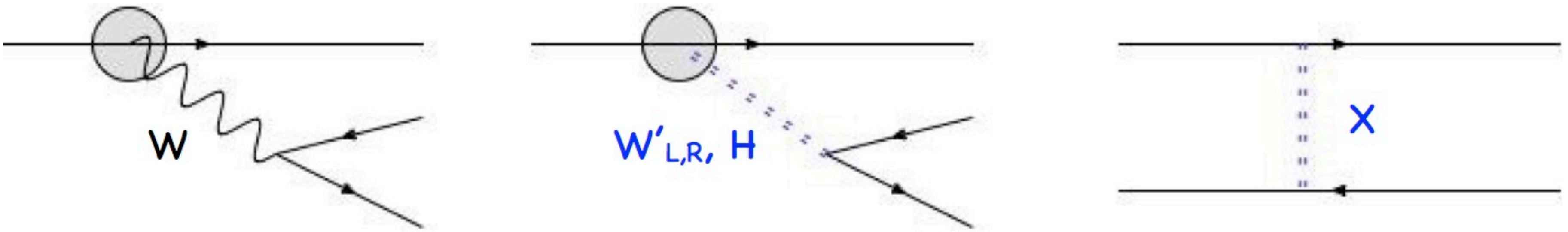
Charged Higgs boson



Charged Higgs *excluded* at 99.8% CL

first surprise in $b \to c \tau \nu$

- apparently the τ has a stronger coupling
- at tree level, several possible other couplings



- new W gauge boson with non-universal couplings (our model W_R)
- leptoquark - need very specific flavour structure
- charged Higgs, seems a natural explanation but the simple models do not work

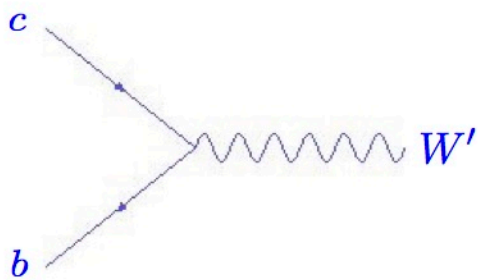
Nothing seen in other meson decay

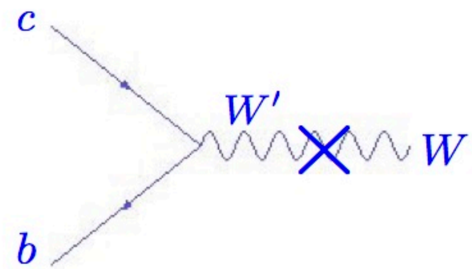
	Exp. (PDB)	SM
$\frac{B(K^+ \to \pi^0 \mu^+ \nu)}{B(K^+ \to \pi^0 e^+ \nu)}$	0.6608±0.0029	0.6631±0.0042 (Cirigliano et al)
$\frac{B(K^+ \to e^+ \nu)}{B(K^+ \to \mu^+ \nu)}$	2.488±0.009(10^{-5})	2.477±0.001 (10^{-5}) (Cirigliano et al)
$\frac{B(\pi^+ \to e^+ \nu(\gamma))}{B(\pi^+ \to \mu^+ \nu(\gamma))}$	1.2327±0.0023(10^{-4})	1.2352±0.0005(10^{-4}) (Marciano, Sirlin)

- no simple models
- need to arrange the flavour structure to single out this family: b, τ

W´and semileptonic B decay to tau

quark sector





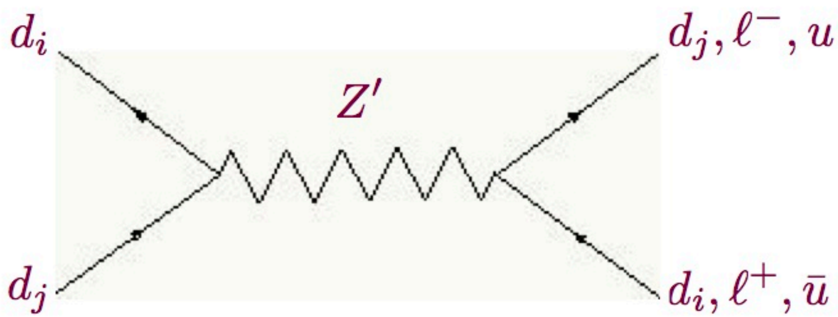
$$
\begin{aligned}
\mathcal{L}_W \;=\; & -\frac{g_L}{\sqrt{2}}\bar{U}_L\gamma^\mu V_{KM} D_L(\cos\xi_W W_\mu^+ - \sin\xi_W W_\mu^{'+}) \\
& -\frac{g_R}{\sqrt{2}}\bar{U}_R\gamma^\mu V_R D_R(\sin\xi_W W_\mu^+ + \cos\xi_W W_\mu^{'+}) \;+\; \text{h. c.},
\end{aligned}
$$

- two (sets) of parameters come into play
- mixing between W and W'
- right handed analog of CKM matrix

previously worked out constraints

*HFAG-2012

*From $b \to s\,\gamma$ = $(3.55\pm0.25) \times 10^{-4}$ $\quad -0.0013 \leq \frac{g_R}{g_L}\xi_W \leq 0.0027$



strongest constraints from meson mixing

FCNC constraints can be summarised by $V^d_{Rbi} \sim \delta_{bi}$

with $V_L^{u,d} = V_R^{u,d},\ V_L^{u\dagger} V_L^d = V_{CKM}$ this allows us to predict

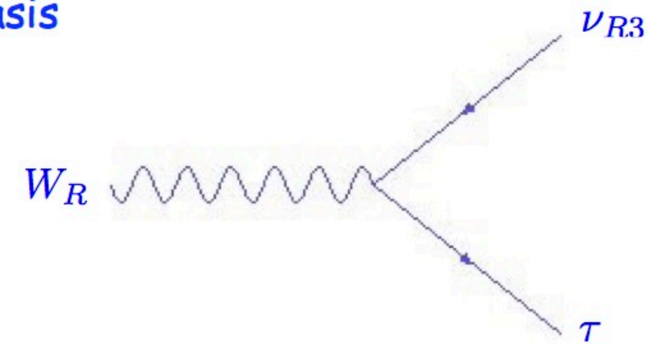
$$V_R = (V_{Rij}) = (V^{u*}_{Rti} V^d_{Rbj}) \qquad V_R \sim \begin{pmatrix} 0 & 0 & A\lambda^3 \\ 0 & 0 & A\lambda^2 \\ 0 & \lambda^4 & 1 \end{pmatrix}$$

$$V^u_{Rtc} \sim V_{cb}, V^u_{Rtu} \sim V_{ub}$$

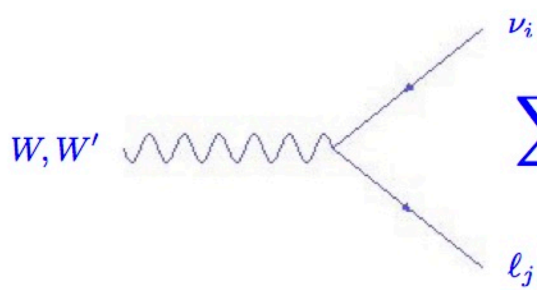
W′and semileptonic B decay to tau

weak eigenstate basis

lepton sector



- need the new right-handed neutrino to be light
- it is possible to have a scalar sector that gives an acceptable neutrino mass spectrum and mixing



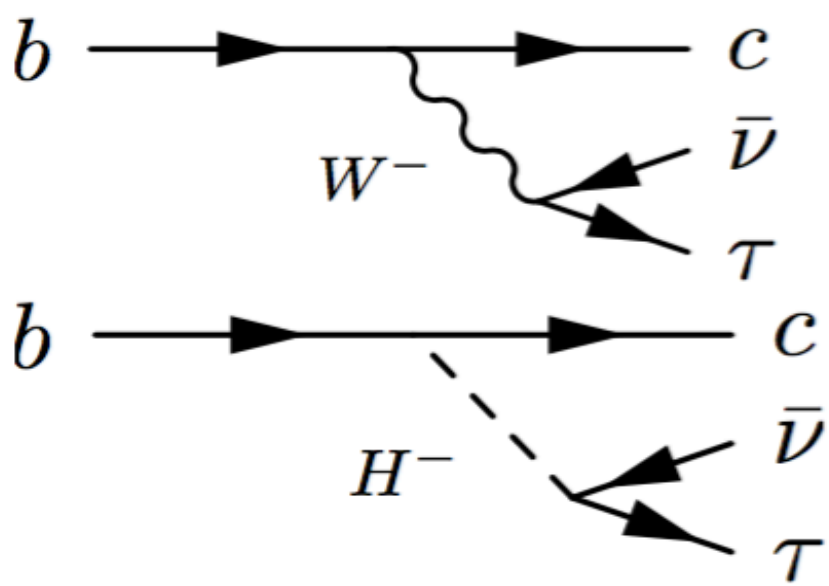
no interference if neutrino mass << charged lepton mass

$$\sum_i |M_{\rm lepton}|^2 \propto \begin{cases} 1 & \text{for } \ell_L \\ |V^\ell_{R3j}|^2 & \text{for } \ell_R. \end{cases} \quad \sim 1 \text{ for } j = \tau$$

rotates RH charged lepton to mass eigenstate

Very recent measurement of LHCb

$$R(J/\psi) = \frac{Br(B_c \to J/\psi \tau \nu)}{Br(B_c \to J/\psi \mu \nu)} = 0.71 \pm 0.17 \pm 0.18.$$



It is 2σ away from the SM predictions

$B \to \tau\,\nu$

CKMfitter

$$B(B^+ \to \tau^+\nu) = \begin{cases} \text{with meas.} & 0.851^{+0.035}_{-0.038} \times 10^{-4} \\ \text{without} & 0.821^{+0.034}_{-0.028} \times 10^{-4} \end{cases}$$

Heavy Flavor Averaging Group - October 2016

Compilation of B^+ and B^0 Leptonic Branching Fractions ($\times 10^{-6}$) - UL at 90% CL

In PDG2014 New since PDG2014 (preliminary) New since PDG2014 (published)

Mode	PDG2014 Avg.	BABAR	Belle
$e^+\nu$	< 0.98	< 1.9	< 0.98 †
$\mu^+\nu$	< 1.0	< 1.0	< 1.7 †
$\tau^+\nu$	114 ± 27	179 ± 48 ‡	$91 \pm 19 \pm 11$ ‡

$$\frac{\Gamma(B^- \to \tau^-\nu)}{\Gamma(B^- \to \tau^-\nu_\tau)_{SM}} = F^u_{W'} - 2\,F^u_{\text{Mix}} \quad \sim 1.3 \quad \text{with} \frac{V_{Rub}}{V_{ub}} \sim \frac{V_{Rcb}}{V_{cb}}$$

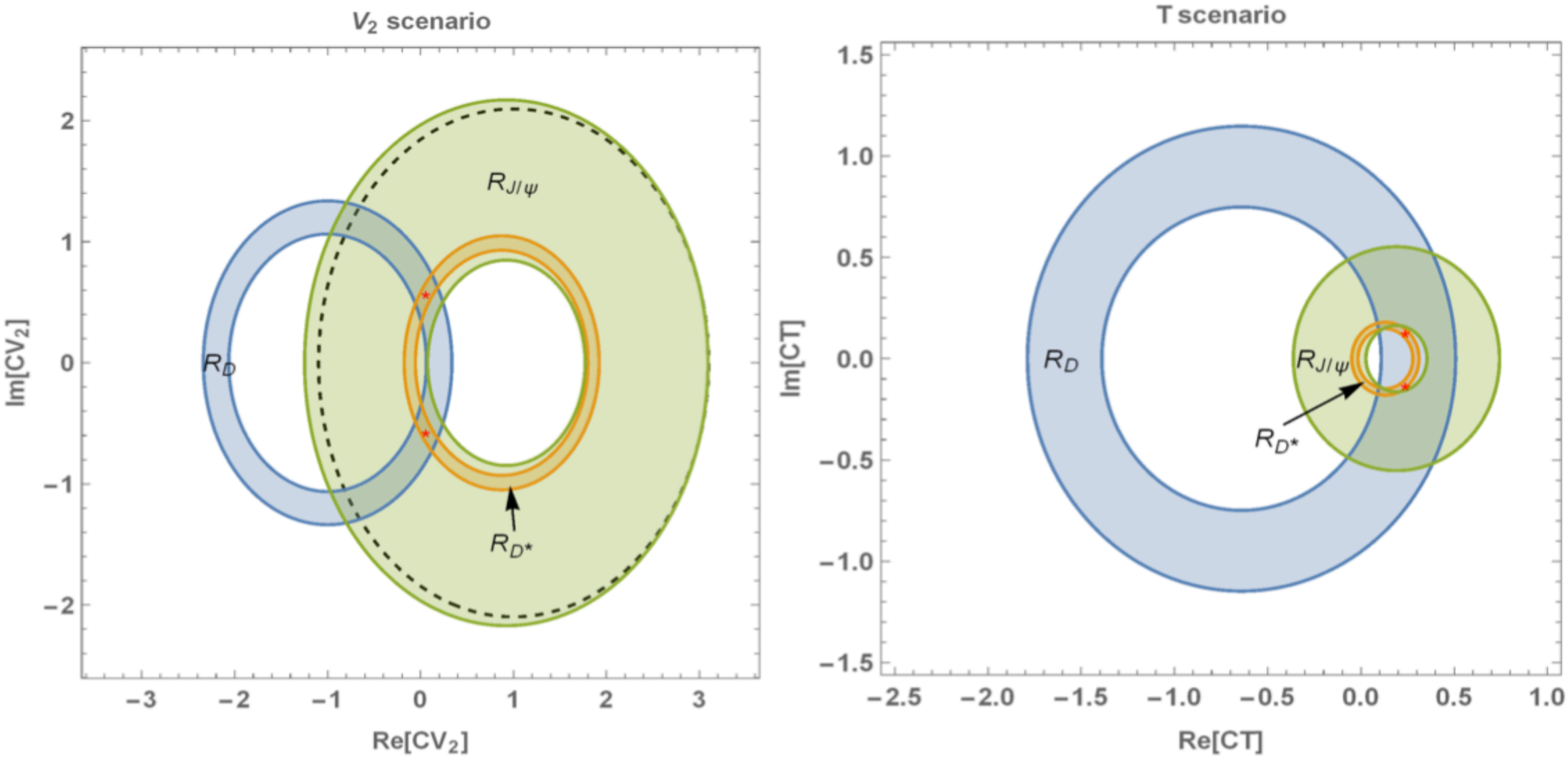
A combined model independent analysis of the $R(D)$, $R(D*)$ and $R(J/\psi)$ anomalies

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[(1 + C_{V_1}) O_{V_1} + C_{V_2} O_{V_2} + C_{S_1} O_{S_1} + C_{S_2} O_{S_2} + C_T O_T \right]$$

All possible operators:

$$O_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_L), \quad O_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_L),$$
$$O_{V_1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L), \quad O_{V_2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L),$$
$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_L),$$

Huang, Li, Lu, Paracha, Wang, e-Print: **arXiv:1808.03565**



- It is found that none of the single operators can explain simultaneously the current experimental measurements of the ratios $R(D)$, $R(D*)$ and $R(J/\psi)$ at the confidence level of 1σ
- The obtained regions favor the vector operators O_{V1} and O_{V2} among all the NP operators

Using the fitted parameters, we can predict other observables for future test

- The polarization asymmetry of the τ lepton,

$$P_\tau = \frac{\Gamma(\lambda_\tau = 1/2) - \Gamma(\lambda_\tau = -1/2)}{\Gamma(\lambda_\tau = 1/2) + \Gamma(\lambda_\tau = -1/2)}$$

- longitudinal polarization of the final state vector meson

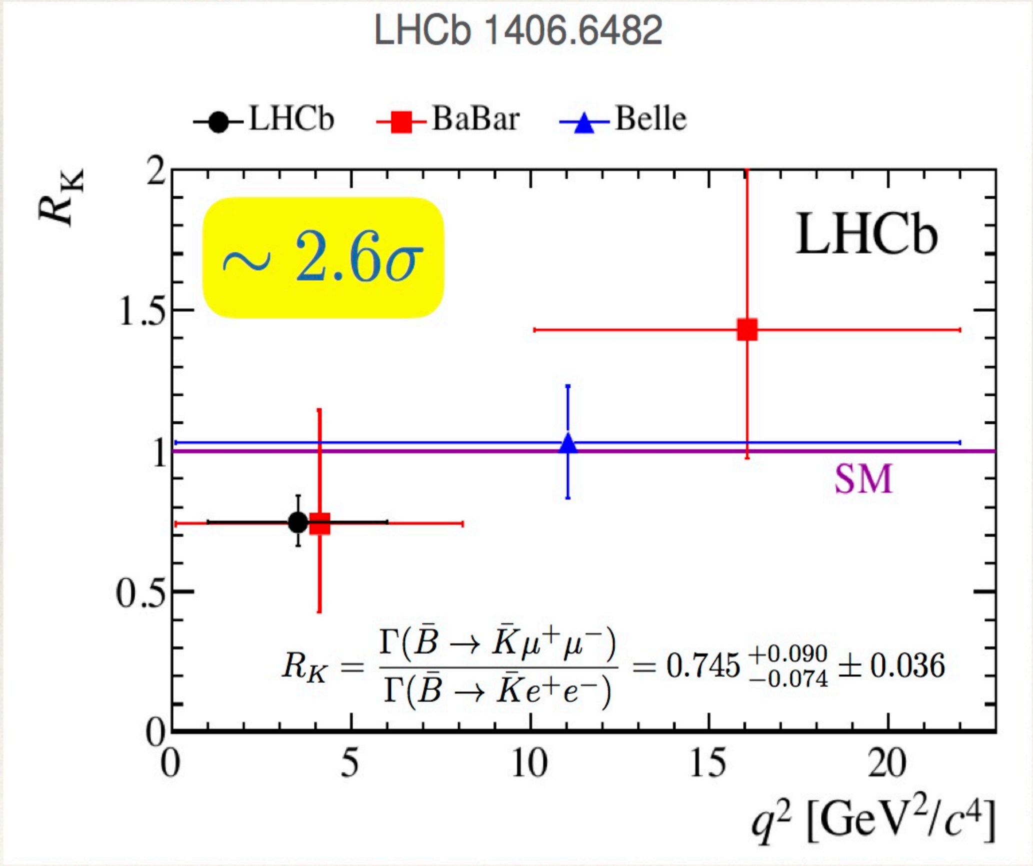
$$P_M = \frac{\Gamma(\lambda_M = 0)}{\Gamma(\lambda_M = 0) + \Gamma(\lambda_M = 1) + \Gamma(\lambda_M = -1)}$$

- the forward-backward asymmetry of the τ lepton

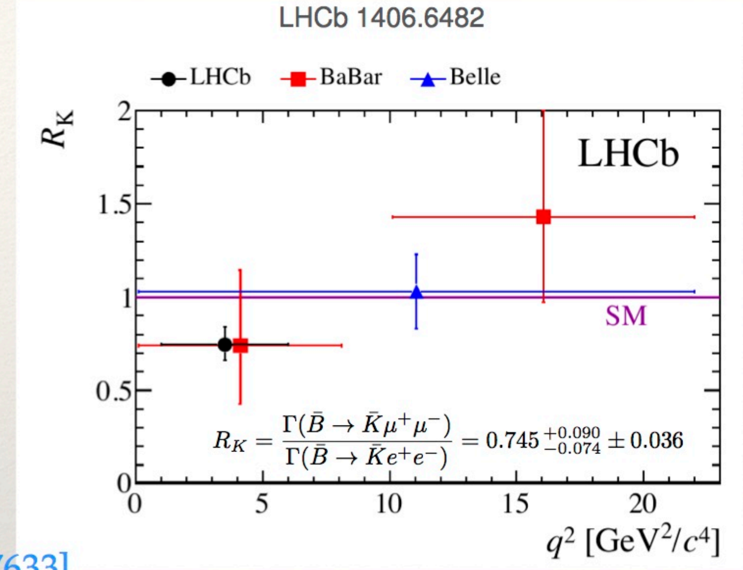
$$\mathcal{A}_{\rm FB} = \frac{\int_0^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta - \int_{-1}^0 \frac{d\Gamma}{d\cos\theta} d\cos\theta}{\int_{-1}^1 \frac{d\Gamma}{d\cos\theta} d\cos\theta}$$

Non-universal B→ K μμ / ee rates

- LHCb observation of a violation of lepton universality in the rare decays B→Kμμ vs. B→Kee — if confirmed — would be the most spectacular LHC discovery after the Higgs boson:

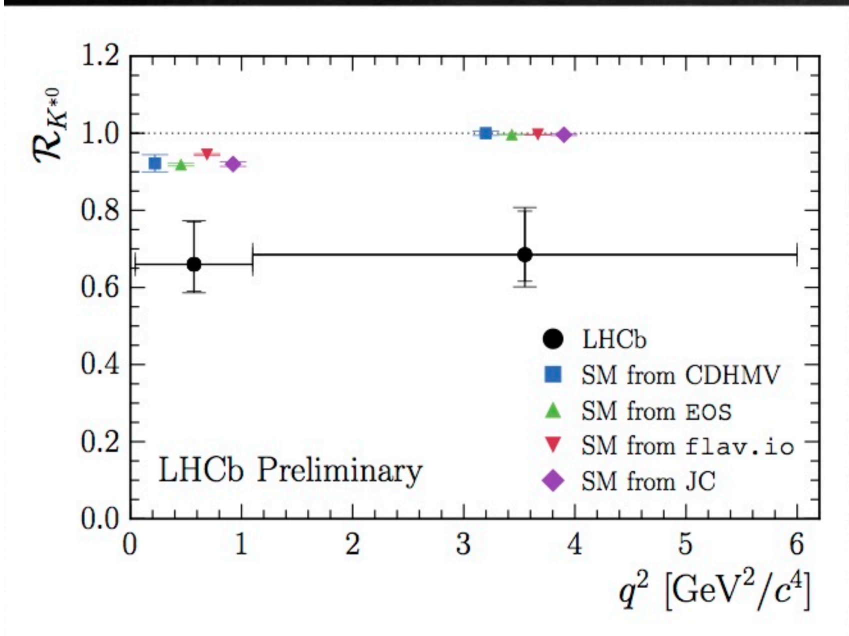


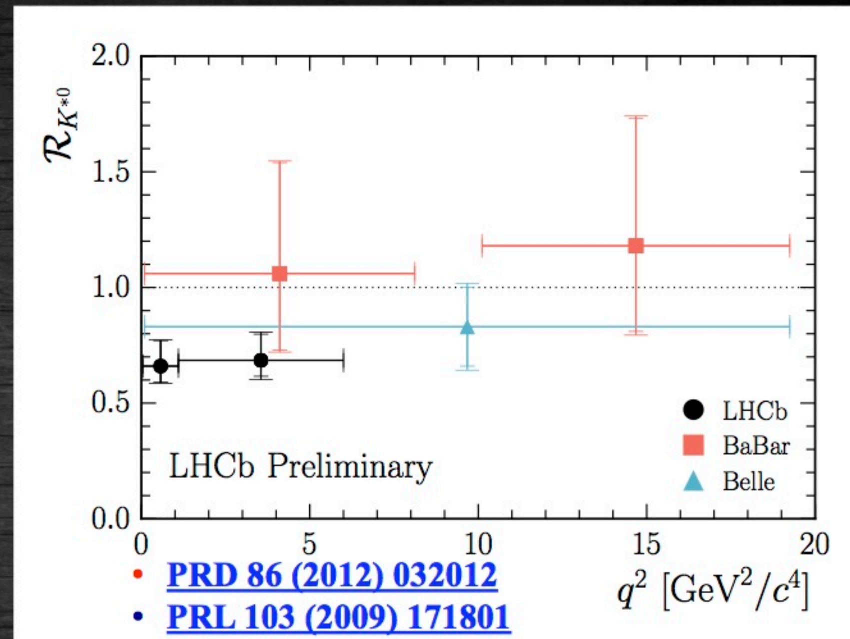
Non-universal B→ K μμ / ee rates



- In SM this ratio equals 1 to high accuracy
- Leading deviations arise from QED corrections, giving rise to large logarithms involving the ratio $m_B/m_{\mu,e}$
- The effects have been estimated and were found to be of O(1%) [Bordone, Isidori, Pattori: 1605.07633]
- SM prediction **very clean**!
- Eagerly awaiting an update from LHCb (electron reconstruction efficiency is rather different from that for muons)…
- Teaser on R_{K^*} People wait for that until two years later

Results – II

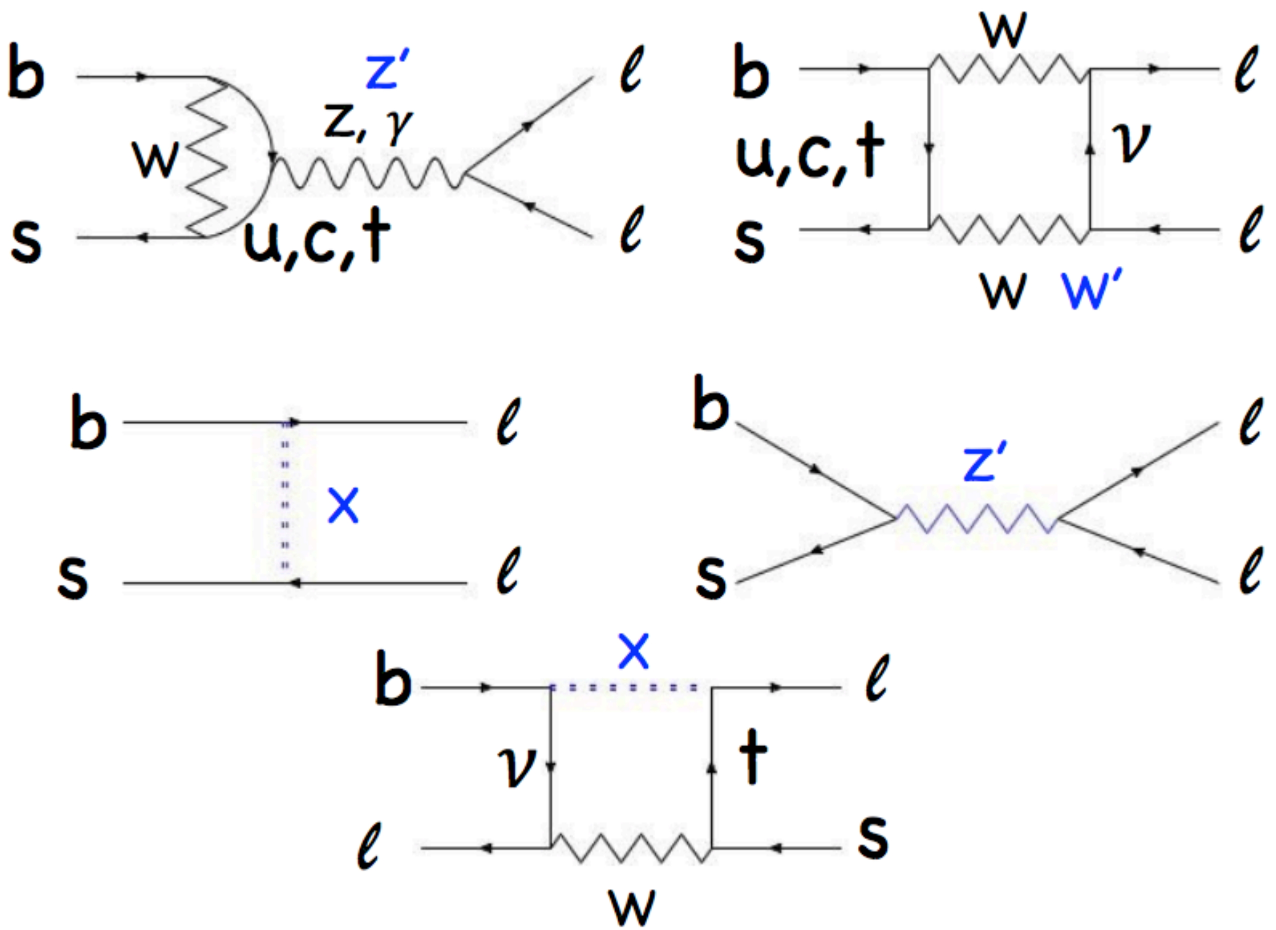




- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

Second surprise in b→ s *l*+*l*-

apparently the μ has a weaker coupling than the electron at tree and loop level, many possible other NP couplings



Violation of lepton flavor universality

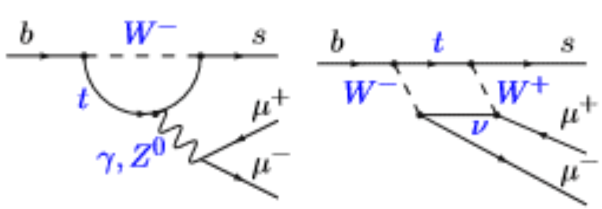
$$R(K) = \frac{BF(B \to K\mu^+\mu^-)}{BF(B \to Ke^+e^-)} \qquad R(K^*) = \frac{BF(B \to K^*\mu^+\mu^-)}{BF(B \to K^*e^+e^-)}$$

theoretically very clean!

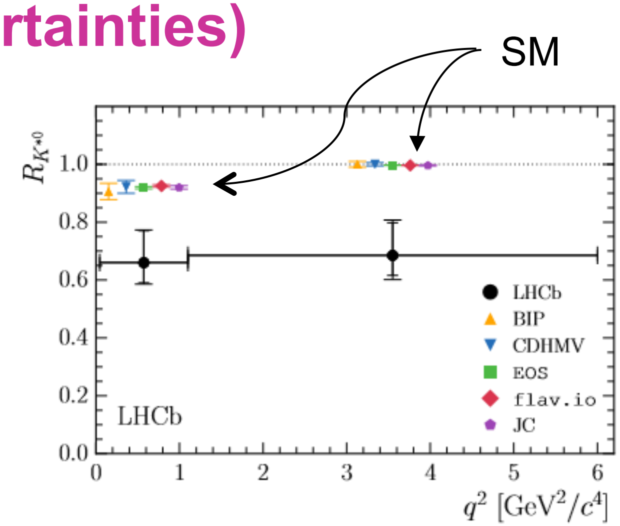
Observable	Expt (LHCb)	SM	σ
R(K), q^2=[1, 6] GeV^2	$0.745^{+0.090}_{-0.074}\pm0.036$	1.00±0.01	2.6
R(K^{*0}), q^2=[0.045, 1.1]	$0.66^{+0.11}_{-0.07}\pm0.03$	~ 0.920	2.1-2.3
R(K^{*0}), q^2=[1.1, 6]	$0.69^{+0.11}_{-0.07}\pm0.05$	~ 0.996	2.4-2.5

arXiv:1705.05802

For $q^2 < 6$ GeV^2, SM predictions for $b \to s\mu^+\mu^-$ consistently overshoot the data (also for $B_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$; both involve unknown hadronic uncertainties)



Loop, GIM, CKM suppressed



A lot of theoretical discussions

Capdevila et al [1704.05340]

Altmannshofer, Steangl, Straub [1704.05435]

D'Amico et al [1704.05438]

Hiller, Nisandzic [1704.05444]

Geng et al [1704.05446]

Ciuchini et al [1704.05447]

Celis et al [1704.05672]

Becirevic, Sumensari [1704.05835]

Cai et al [1704.05849]

Kamenik, Soreq, Zupan [1704.06005]

Sala, Straub [1704.06188]

Di Chiara et al [1704.06200]

Ghosh [1704.06240]

Alok, D. Kumar, J. Kumar, Sharma [1704.07347]

Alok et al [1704.07397]

Wang, Zhao [1704.08168]

Bonilla, Modak, Srivastava, Valle [1705.00915]

Bishara, Haisch, Monni [1705.03465]

Megias, Panico, Pujolas Quiros [1705.04822]

Tang, Wu [1705.05643]

Hurth, Mahmoudi, Santos, Neshatpour [1705.06274]

Poh, Raby [1705.07007]

Datta, Kumar, Liao, Marfatia [1705.08423]

Das, Hati, Kumar, Mahajan [1705.09188]

Bardhan, Byakti, Ghosh [1705.09305]

Matsuzaki, Nishiwaki, Watanabe [1706.01463]

Luzio, Nardecchia [1706.01868]

Chiang, He, Tandean, Yuan [1706.02696]

Chauhan, Kindr, Narang [1706.04598]

King [1706.06100]

Chivukula, Isaacson, Mohan et al [1706.06575]

Khalil [1706.07337]

He, Valencia [1706.07570]

Doršner, Fajfer, Faroughy, Košnik [1706.07779]

Buttazzo, Greljo, Isidori, Marzocca [1706.07808]

Choudhury, Kundu, Mandal, Sinha [1706.08437]

Cline, Camalich [1706.08510]

Crivellin, Mueller, Signer, Ulrich [1706.08511]

Guo, Han, Li, Liao, Ma [1707.00522]

Chen, Nomura [1707.03249]

Baek [1707.04573]

Bian, Choi, Kang, Lee [1707.04811]

$$H_{eff} \propto \frac{\alpha}{4\pi} V_{tb} V_{ts}^{*} (C_9 O_9 + C_{10} O_{10} + C'_9 O'_9 + C'_{10} O'_{10})$$

$$O_9 = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad O'_9 = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \qquad O'_{10} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

SM $\Rightarrow$ $C_9^{SM} \approx -C_{10}^{SM} \approx 4.2$, $C'^{SM}_9 = C'^{SM}_{10} = 0$

- **Best fit to R(K) & R(K*) in one individual WC $\Rightarrow$ NP in** C_9^μ, C_9^e, C_{10}^μ, C_{10}^e. **NP in primed operators do not play a role**

Altmannshofer et al.; Hiller et al. & many others

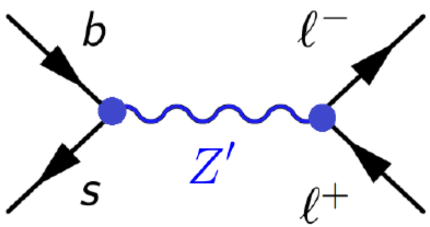
$$C_{9,\mu}^{NP} \approx -C_{10,\mu}^{NP} \approx -1.3, \quad C_{9,e}^{NP} \approx -C_{10,e}^{NP} \approx -1.3$$

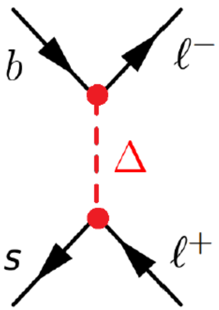
- **Global fit to angular observables of** $B \to K^* \mu^+ \mu^-$ **and BF of** $B_s \to \phi \mu^+ \mu^-$ $\Rightarrow$ **NP in** C_9^μ **favored, in** C_9^e **not favored.**

NP models capable of generating $C_{9,10}^{NP}$:

- **Tree level:**
  - Z’, $SU(2)_L$ singlet or triplet
  - leptoquark, spin 0 or 1
  - SUSY with R-parity violating interactions

- **Loop level:**
  - Z’ penguin
  - new heavy scalars/vectors





Flavour anomalies and New Physics

If confirmed by future analyses, what does this point to?

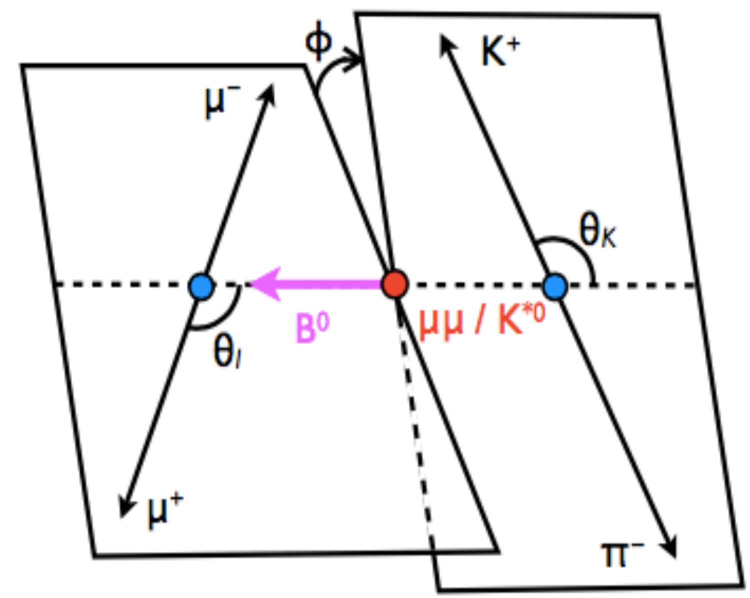
$$R_{D^{(*)}} \quad \Leftrightarrow \quad \tau \neq e, \mu \qquad\qquad R_K \quad \Leftrightarrow \quad \mu \neq e$$

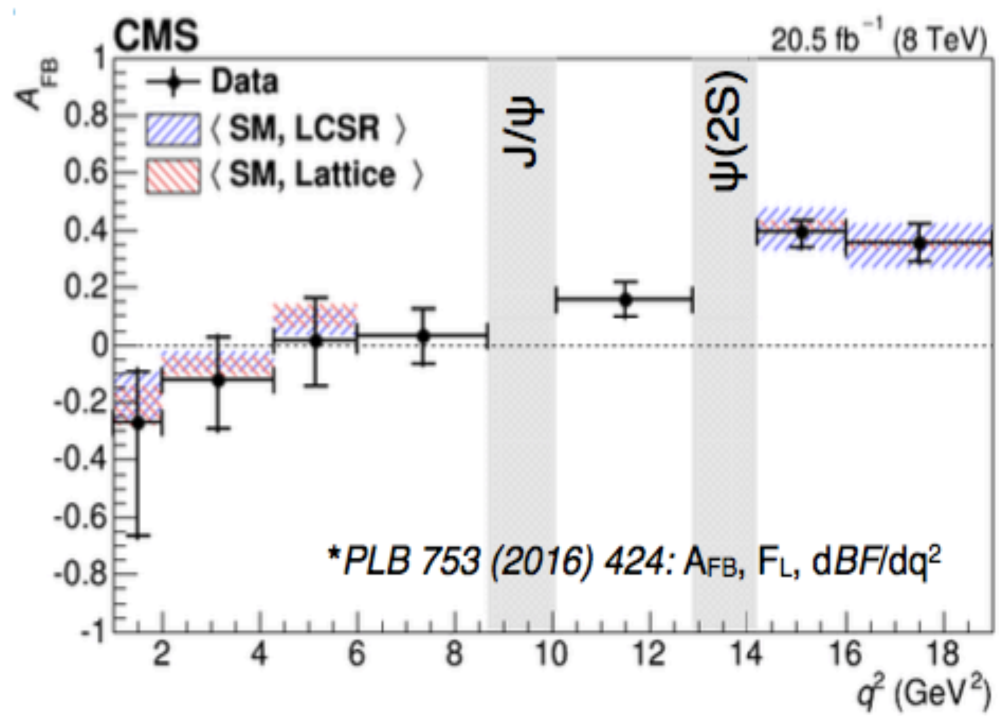
SM gauge interactions do not distinguish between different leptons, and Higgs exchange is irrelevant; hence need new particles beyond the SM with new types of interactions

- $U(1)_{\tau-\mu} \rightarrow$ new Z' boson coupling with opposite sign to μ/τ
- New particles with Yukawa-like interactions, leptoquarks (better: lepto-quark-bosons)

Angular analysis of B→ K* μμ decays

Rare B→K*μμ decays offer a rich laboratory for new-physics searches via differential angular distributions as a functions of lepton invariant mass:





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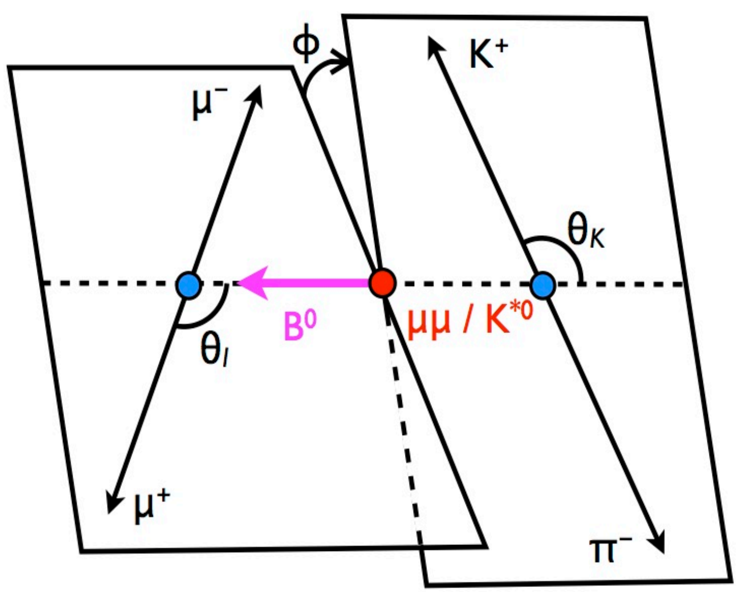


$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi}$$

S-wave and S&P-wave interference

$$= \frac{9}{8\pi}\Big\{\frac{2}{3}\Big[(F_S + A_S\cos\theta_K)(1-\cos^2\theta_l) + A_S^5\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\Big] + (1-F_S)\Big[2F_L\cos^2\theta_K(1-\cos^2\theta_l) + \frac{1}{2}(1-F_L)(1-\cos^2\theta_K)(1+\cos^2\theta_l) + \frac{1}{2}P_1(1-F_L)(1-\cos^2\theta_K)(1-\cos^2\theta_l)\cos 2\phi + 2P_5'\cos\theta_K\sqrt{F_L(1-F_L)}\sqrt{1-\cos^2\theta_K}\sqrt{1-\cos^2\theta_l}\cos\phi\Big]\Big\}$$

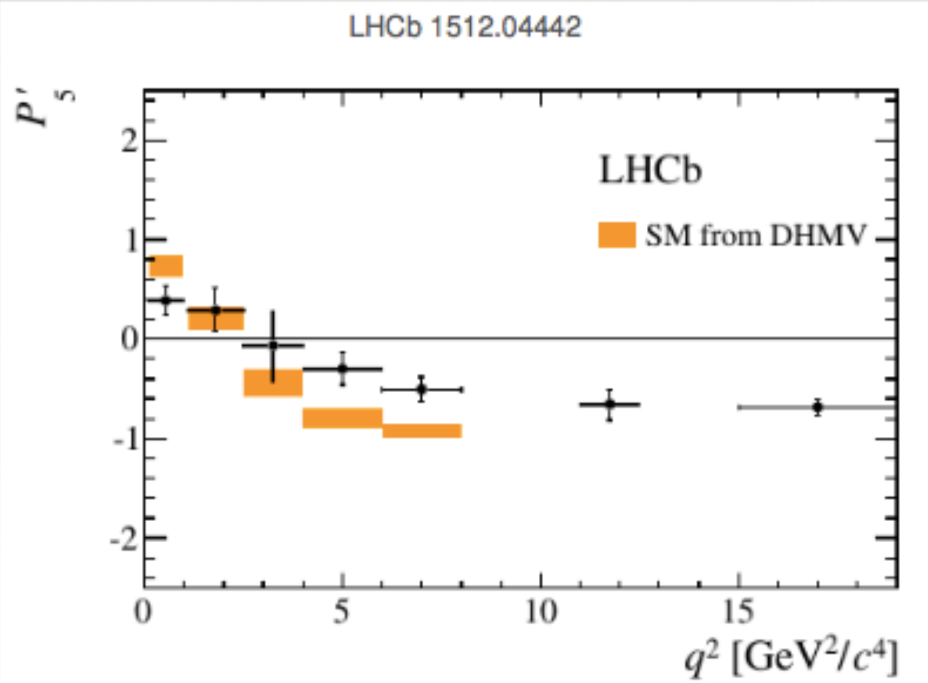
P-wave

Angular analysis of B→ K^* μμ decays

It is useful to construct observables which are less sensitive for hadronic uncertainties related to form factors

[Descotes-Genon, Matias, Ramon, Virto: 1207.2753]

One particular such observable — called P_5' — shows a large discrepancy with the SM prediction in a particular q^2 range:



2.8σ deviation in q^2 bin between [4, 6] GeV^2
(3.0σ in bin [6, 8] GeV^2)

Global fits

- from J. Matias, Moriond EW 2017:

Global analysis of $b \to s\mu\mu$ anomalies

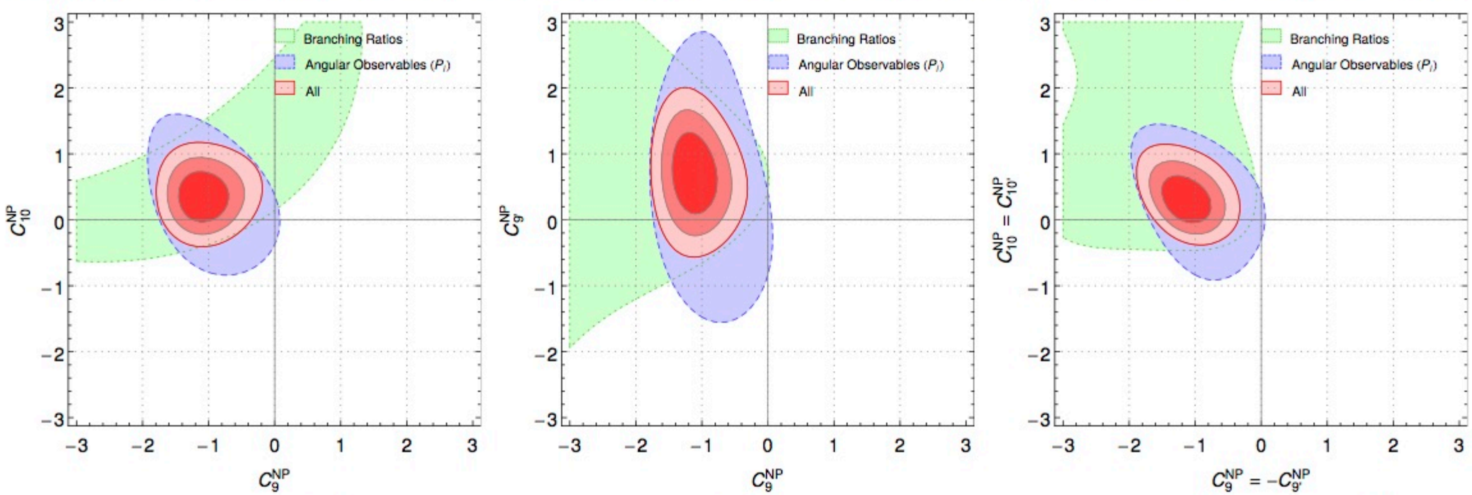
[Descotes, Hofer, JM, Virto]

96 observables in total (LHCb for exclusive, no CP-violating obs)

- $B \to K^*\mu\mu$ ($P_{1,2}$, $P'_{4,5,6,8}$, F_L in 5 large-recoil bins + 1 low-recoil bin)+available electronic observables.
- $B_s \to \phi\mu\mu$ (P_1, $P'_{4,6}$, F_L in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (BR) ($\ell = e, \mu$)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR), $B \to K^*\gamma$ (A_I and $S_{K^*\gamma}$)

Beyond 1D several favoured scenarios

Allowing for more than one Wilson coefficient to vary different scenarios with pull-SM beyond 4σ pop-up:



(C_9, C_{10}) (C_9, C_9') $(C_9 = -C_9'$ & $C_{10} = C_{10}')$

- BR and angular observables both favour $C_9^{\rm NP} \simeq -1$ in all 'good scenarios'.

Summary

- Some flavor anomalies have been discussed
- The tension between SM and experiments at the level of 3σ **level**
- **Flavor sector has only been tested at the 10% level and can be done much better**
- **We are still waiting for a clear New physics signal in the heavy flavor sector**

Thanks !