Search for new physics signals in precision B physics

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Elementary particles

Complete?

费米子为什么有三代?

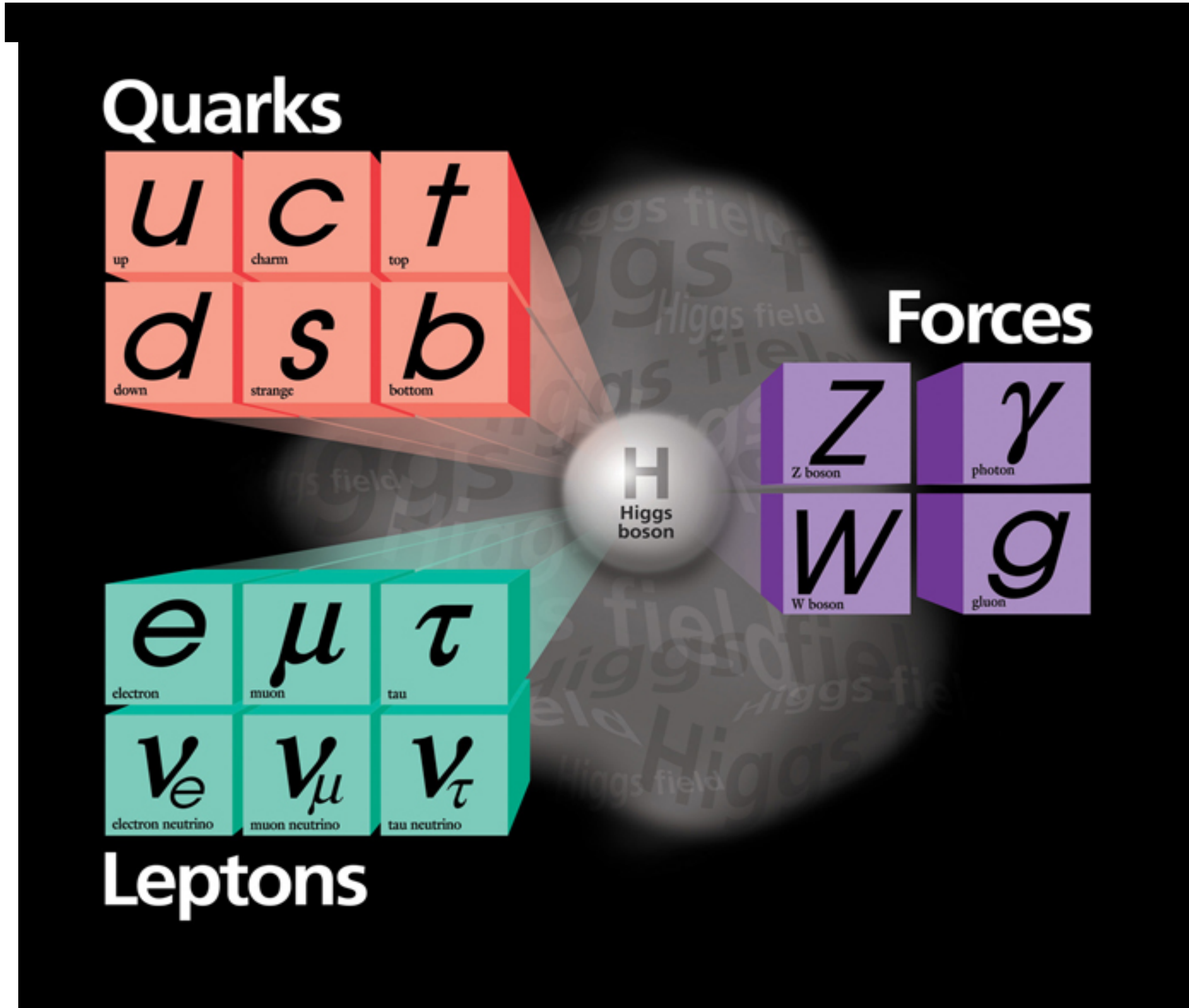
质量的起源?

中微子振荡

反物质、暗物质的疑问

CP起源?

Higgs势稳定性。。。



Search for new particle or new phenomena is our major task in particle physics

- There are two ways to achieve that: direct search or indirect search
- Accordingly we have two directions in high energy physics experiments: high energy and high intensity ...

There are many high intensity experiments:

- Beijing electron position collider (BEPC)
- Daya Bay neutrino experiment (Jiangmen)etc.
- B-factories (two machines)
- There is even a super B-factory（Belle II）

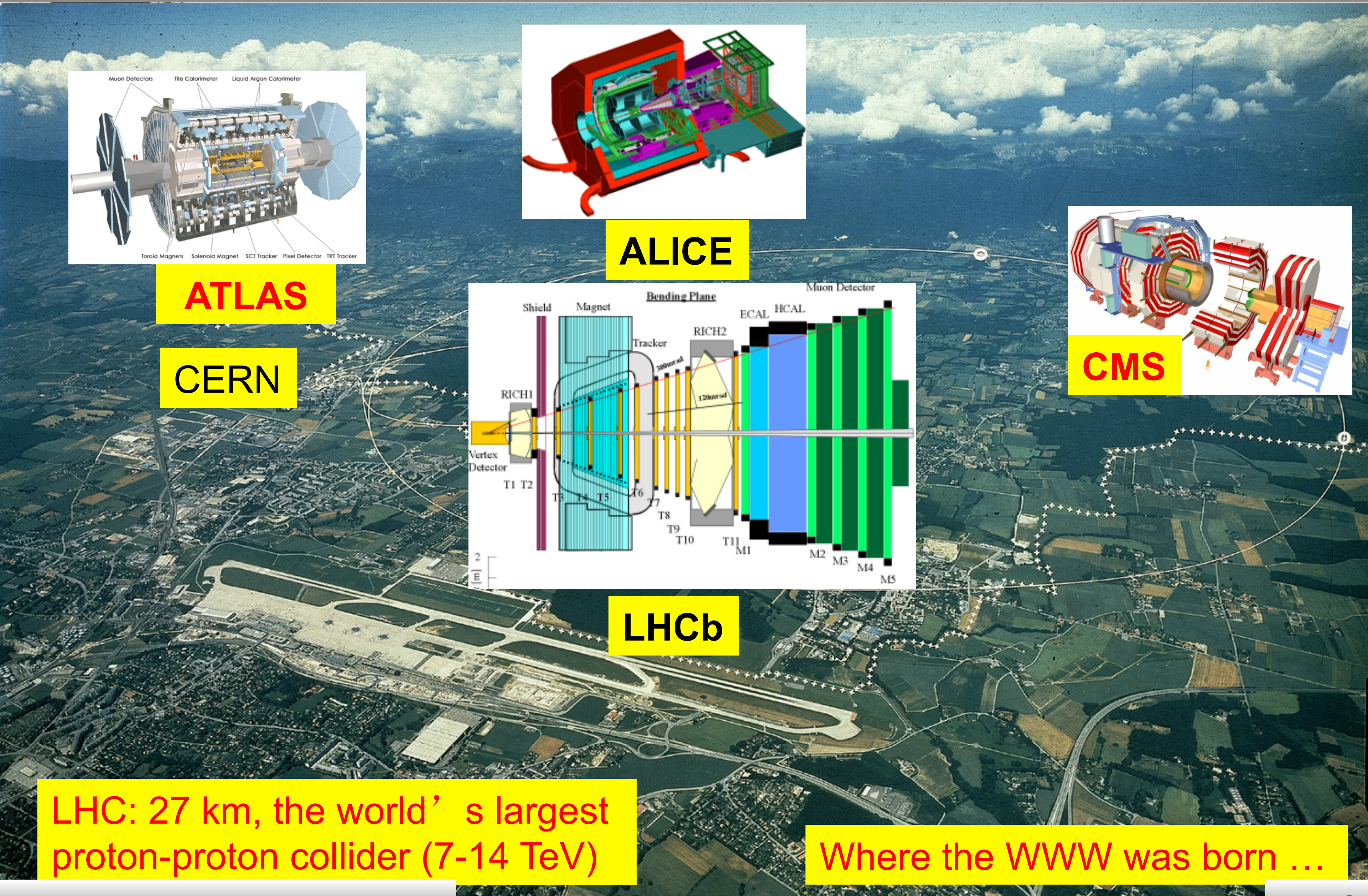
B factory


Mt. Tsukuba
KEKB ring (HER+LER)
3km circumference
Belle detector
Linac
KEK Tsukuba site
CDLu

Super B factory
Belle II

The discovery of direct CP violation leads to 2008 Nobel Prize

大型强子对撞机(LHC)



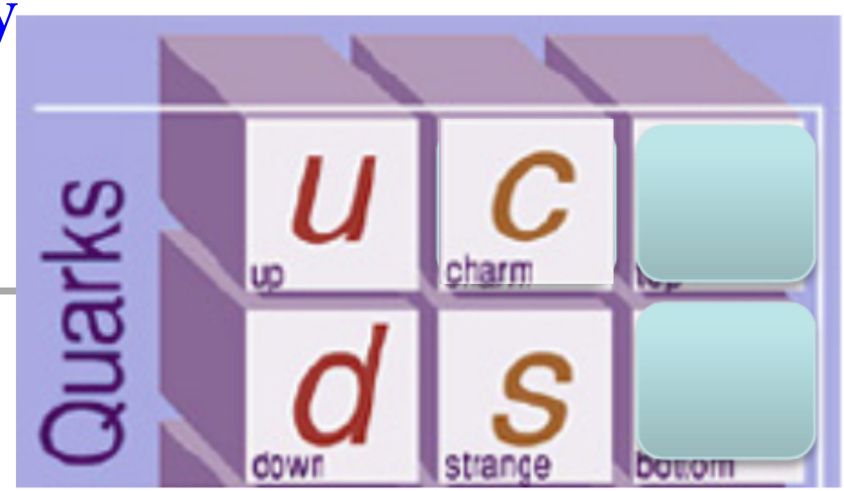
LHC: 27 km, the world’s largest proton-proton collider (7-14 TeV)

Where the WWW was born …

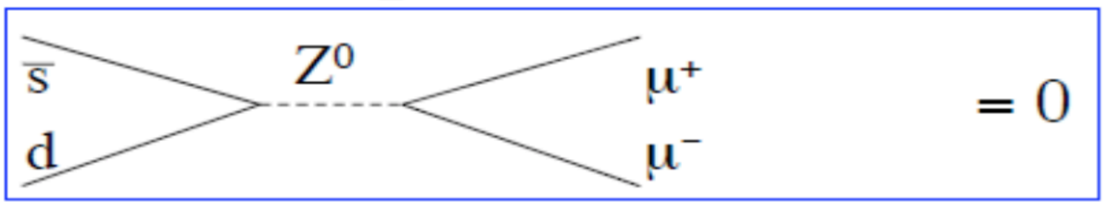
Example in the history

Long time ago, we had only 3 flavors of quarks: u,d,s.

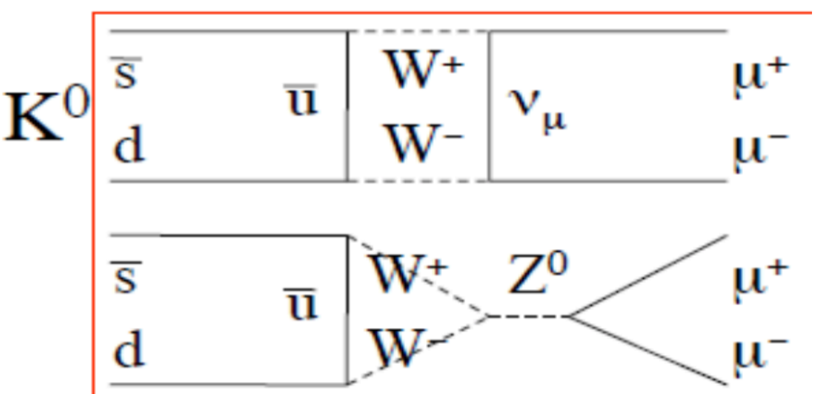
Experimentally we found that



$$K^0 \not\to \mu^+\mu^-$$



$\begin{pmatrix}u\\d\end{pmatrix}\begin{pmatrix}c\\s\end{pmatrix}$ **GIM**



Divergent

$V_{us}\,V_{ud} \sim \sin\theta_c$

θ_c Cabibbo angle

GIM 2x2

PHYSICAL REVIEW D VOLUME 2, NUMBER 7 1 OCTOBER 1970

Weak Interactions with Lepton-Hadron Symmetry*

S. L. GLASHOW, J. ILIOPOULOS, AND L. MAIANI†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

theless, suitable redefinitions of the relative phases of the quarks may be performed in order to make U real and orthogonal, so without loss of generality we write

$$U=\begin{bmatrix} -\sin\theta & \cos\theta \\ \cos\theta & \sin\theta \end{bmatrix}. \qquad (5)$$

$$\begin{pmatrix} u \\ d' \end{pmatrix} \qquad \begin{pmatrix} c \\ s' \end{pmatrix}$$

We begin by introducing four quark fields.[10] The three quarks $\mathcal{P}$, $\mathfrak{N}$, and λ form an $SU(3)$ triplet, and the fourth, $\mathcal{P}'$, has the same electric charge as $\mathcal{P}$ but differs from the triplet by one unit of a new quantum number $\mathcal{C}$ for charm. The strong-interaction Lagrangian

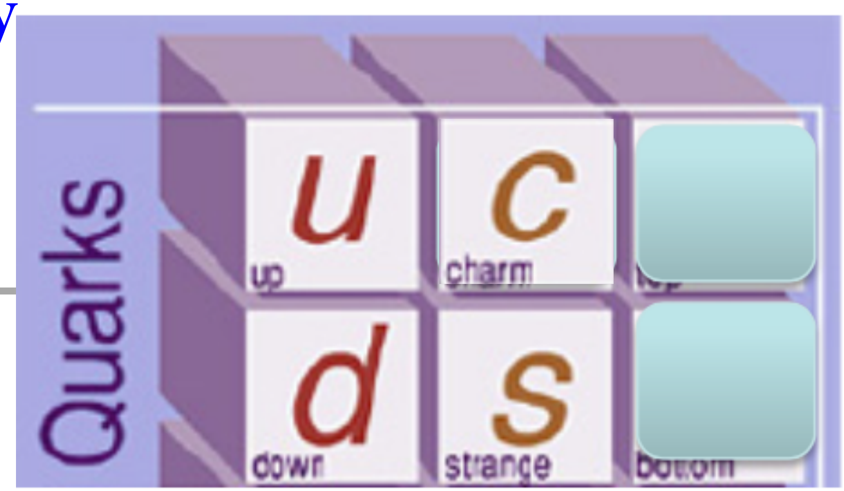
55

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix}$$

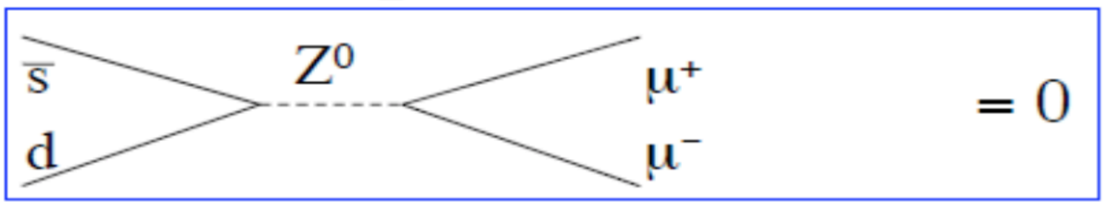
Example in the history

Long time ago, we had only 3 flavors of quarks: u,d,s.

Experimentally we found that

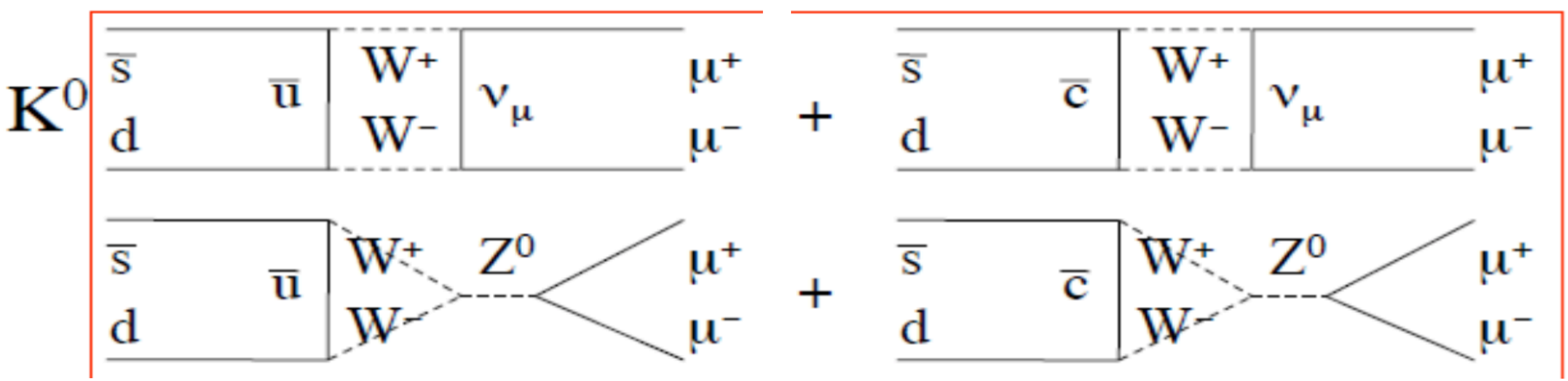


$$K^0 \not\rightarrow \mu^+\mu^-$$



$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}$$

GIM



Divergent cancel

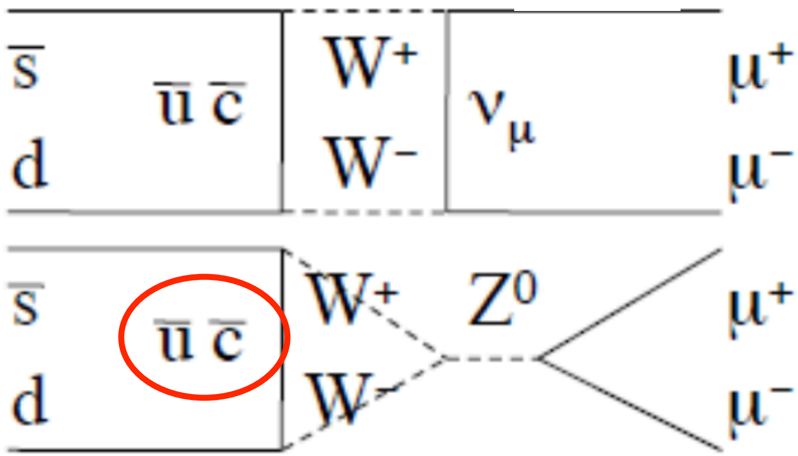
$\sin\theta_c[\, f(m_u) - f(m_c)\,] = 0$, if $m_u = m_c$

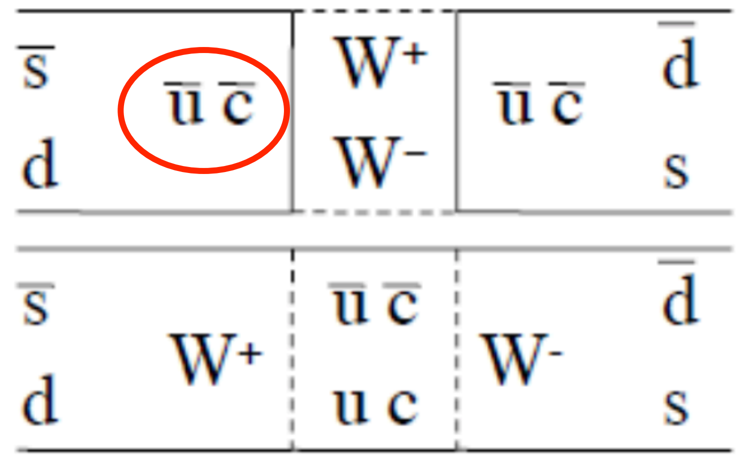
Later, more precise experiments found that

$J/\Psi(c\bar{c})$

$$Br(K^0 \to \mu^+\mu^-) \sim 10^{-9}$$

K-K 混合





$$Br(K^0 \to \mu^+\mu^-) = F(m_c, \ldots) \qquad \Delta m_K = G(m_c, \ldots)$$

$$\to m_c \approx 1.5\text{GeV}$$

Ting and Richter found that in 1974

Flavor physics is important

The origin of flavour is one of the big, unsolved mysteries of fundamental physics!

While the Standard Model (SM) ***describes*** flavour physics very accurately, it does not ***explain*** its mysteries:

- ✓ Why are there 3 generations in nature?
- ✓ What determines the extreme hierarchy of fermion masses?
- ✓ What determines the elements of the CKM matrix?
- ✓ What is the origin of the matter-antimatter asymmetry (CP violation)?

The SM CP-violation is insufficient to explain the matter/antimatter asymmetry
→ progress in flavour physics may help understand open questions in cosmology

History has shown that flavour physics often gives first evidence for new discoveries:

- ➢ Kaon mixing, BR($K^0_L \to \mu\mu$) & GIM → prediction of charm
- ➢ CP violation → prediction of third quark family
- ➢ B mixing → mass of top is very heavy
- ➢ rare B-decays → SUSY parameter space constrained

The universe comes from Big Bang

Where does the anti -matter go?

Necessary conditions: (A.Sakharov, 1967)

1) Baryon number violations: initial and final baryon numbers are different.
2) C and CP violation: partial decay widths are different.
3) Out of equilibrium: no reversing reaction installing the initial state.

Charge conjugate and Parity

Co^{60} experiment by Wu in 1957

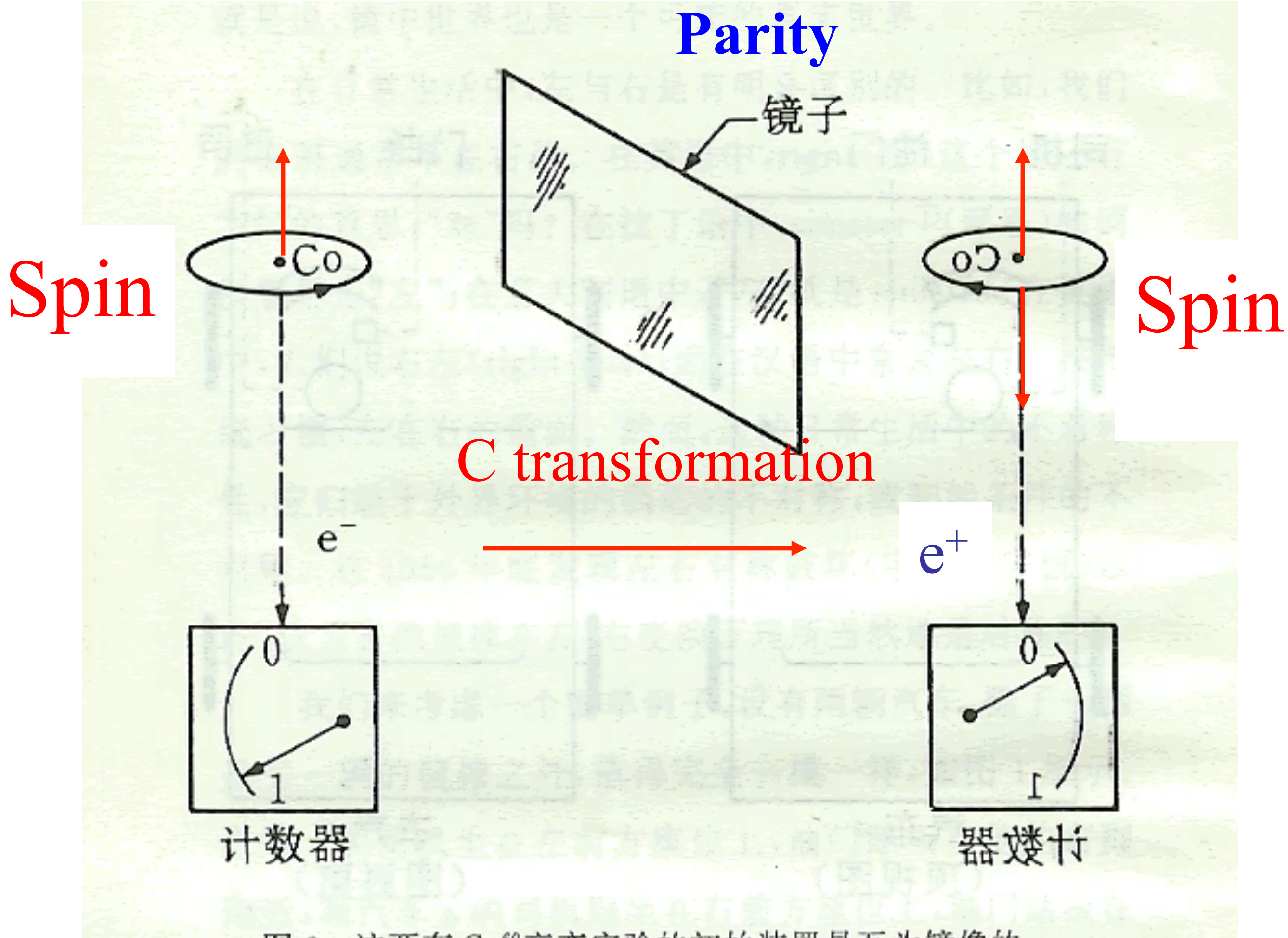


图 2 这两套 Co^{60} 衰变实验的初始装置是互为镜像的，

Parity violation by Lee and Yang in 1956

CP conserved

虽然C和P在弱作用下都不守恒
但是CP 联合变换是守恒的

- **CP conserved in most cases**
- 电磁流：矢量流 $A_\mu \bar{u}\gamma^\mu u$
- 弱作用拉氏量：左手流
- “上帝”是左撇子

$$W_\mu \bar{u}\gamma^\mu(1-\gamma^5)d'$$

$$= W_\mu \overline{u_L}\gamma^\mu d'_L$$

$$\Downarrow$$

$$\overline{\Psi_L} = \overline{\psi}P_R$$

左旋夸克，右旋反夸克

Experimental Discovery of CP Violation

VOLUME 13, NUMBER 4 PHYSICAL REVIEW LETTERS 27 JULY 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have served[1,2] to set an upper limit of 1/300 for the fraction of K_2^0's which decay into two charged pions. The present experiment, using spark chamber techniques, proposed to extend this limit.

In this measurement, K_2^0 mesons were produced at the Brookhaven AGS in an internal Be target bombarded by 30-BeV protons. A neutral beam was defined at 30 degrees relative to the circulating protons by a $1\frac{1}{2}$-in.$\times 1\frac{1}{2}$-in.$\times$48-in. collimator at an average distance of 14.5 ft. from

The analysis program computed the vector momentum of each charged particle observed in the decay and the invariant mass, m^*, assuming each charged particle had the mass of the charged pion. In this detector the K_{e3} decay leads to a distribution in m^* ranging from 280 MeV to ~536 MeV; the $K_{\mu 3}$, from 280 to ~516; and the $K_{\pi 3}$, from 280 to 363 MeV. We emphasize that m^* equal to the K^0 mass is not a preferred result when the three-body decays are analyzed in this way. In addition, the vector sum of the two momenta and the angle, θ, between it and the direction of the K_2^0 beam were determined. This

Fitch Turlay Cronin Christenson

Nobel prize ('80) for the discovery of violations of fundamental symmetry principles in the decay of neutral K-mesons

2×10^{-3} : *Too Small .... for Sakharov !*

CP violation in the K and B meson decays can be explained by the Standard Model.

$$\left.\frac{n_B}{n_\gamma}\right|_{SM} \approx 10^{-20}$$

CP violation in the universe can not be explained by the Standard Model.

$$\left.\frac{n_B}{n_\gamma}\right|_{WMAP} = (5.1^{+0.3}_{-0.2}) \times 10^{-10}$$

WMAP

New source for CP violation beyond the Standard Model in the particle world?

CP破坏的可能来源

- 在60年代的很多种理论探索中，超弱相互作用理论是最为多数人所接受的理论.
- 按照这个理论，CP破坏效应来自于与弱相互作用不同的超弱相互作用，并且CP破坏效应也将只能在中性K介子的衰变中被观察到(Wolfenstein)
- 当时的实验发现除中性K介子的衰变外其它的实验中也都没有观察到CP破坏现象

混合CP破坏

强作用本征态

- **CP本征态：**

$$K_+ = \frac{1}{\sqrt{2}}\left[K^0 + \overline{K}^0\right]$$

$$K_- = \frac{1}{\sqrt{2}}\left[K^0 - \overline{K}^0\right]$$

- 质量本征态

$$K_s = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left[K_+ - \varepsilon K_-\right] = \frac{1}{\sqrt{2(1+|\varepsilon|^2)}}\left[(1+\varepsilon)K^0 + (1-\varepsilon)\overline{K}^0\right]$$

$$K_L = \frac{1}{\sqrt{1+|\varepsilon|^2}}\left[K_- + \varepsilon K_+\right] = \frac{1}{\sqrt{2(1+|\varepsilon|^2)}}\left[(1+\varepsilon)K^0 - (1-\varepsilon)\overline{K}^0\right]$$

其中ε是一个小的复参量，描写CP不守恒成分所占比例

. ε=0时即CP守恒．这是**混合产生的*CP*破坏**

强CP破坏

- （1）按照量子色动力学，基本的拉格朗日量中可以存在一项

$$L_\theta = \theta\,[g^2/32\pi^2]\,F^{\mu\nu}\widetilde{F}_{\mu\nu}\,,$$

其中 θ 是一个无量纲的常量，$\theta \neq 0$ 时将导致强相互作用中有CP破坏出现，通常称为强CP破坏

$$\widetilde{F}_{\mu\nu} = i\varepsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$$

也可以用来解释暗物质

A lot of models have been proposed to explain the CP violation phenomena

In 1972, Kobayashi (b, 1944) & Maskawa (b, 1940) give a new explanition

Both received Ph.D. from Nagoya ('72 & '67) and both joined Kyoto as an assistant ('72 & '70).

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Nobel Prize of Physics in 2008

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

We accepted the Glashow-Weinberg-Salam theory of the weak interaction's extension to the hadron…, because the fourth quark already existed for us in a sense. Sometimes it is said that our *CP* paper was written before the discovery of charm. In this sense, however, our paper came after the charm.

-- Kobayashi (1992)

现在三代夸克

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

2008诺贝尔奖

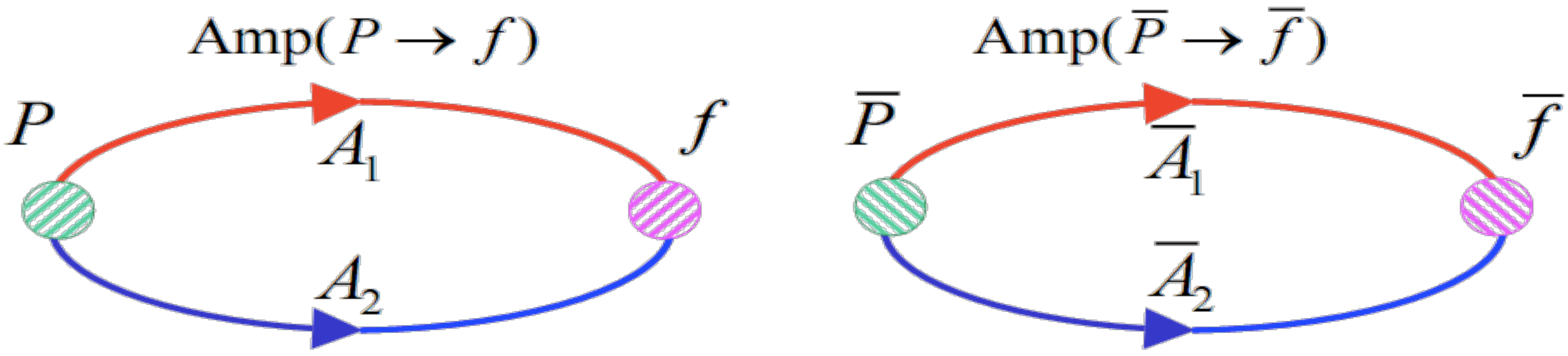
$[c_i = \cos\theta_i$ and $s_i = \sin\theta_i]$

$$\hat{V}_{\rm CKM} = \begin{pmatrix} c_1 & -s_1 c_3 & -s_1 s_3 \\ s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{i\delta} \\ s_1 s_2 & c_1 s_2 c_3 + c_2 s_3 e^{i\delta} & c_1 s_2 s_3 - c_2 c_3 e^{i\delta} \end{pmatrix}$$

KM矩阵, 小林和益川, M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49, 652 (1973)

$$\begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

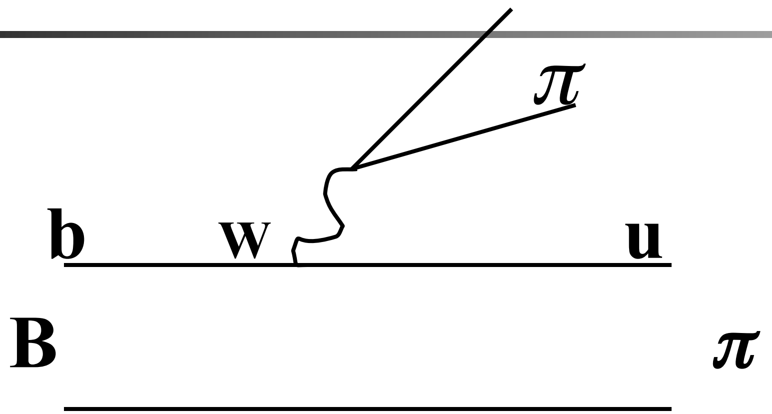
Direct CP violation



$$B^{+} = Te^{i(\delta_1+\phi_1)} + Pe^{i(\delta_2+\phi_2)} = Te^{i(\delta_1+\phi_1)}(1 + re^{i(\delta+\phi)})$$

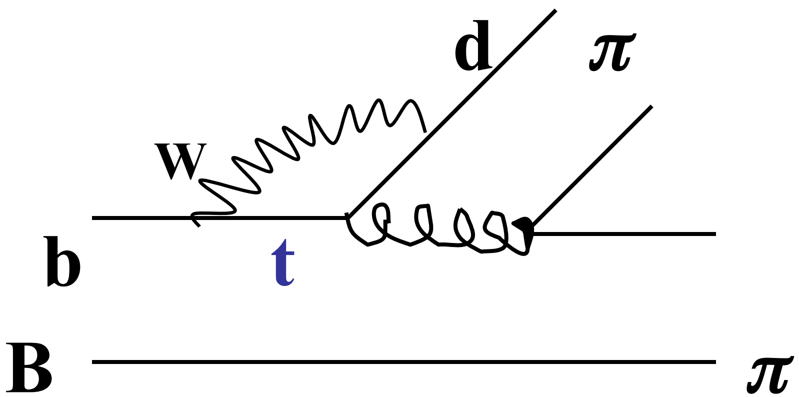
$$B^{-} = Te^{i(\delta_1-\phi_1)} + Pe^{i(\delta_2-\phi_2)} = Te^{i(\delta_1-\phi_1)}(1 + re^{i(\delta-\phi)})$$

$B \to \pi\pi$ Has Two Kinds of Diagrams with different weak phase



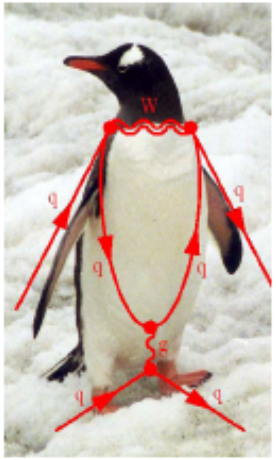
O_1, O_2

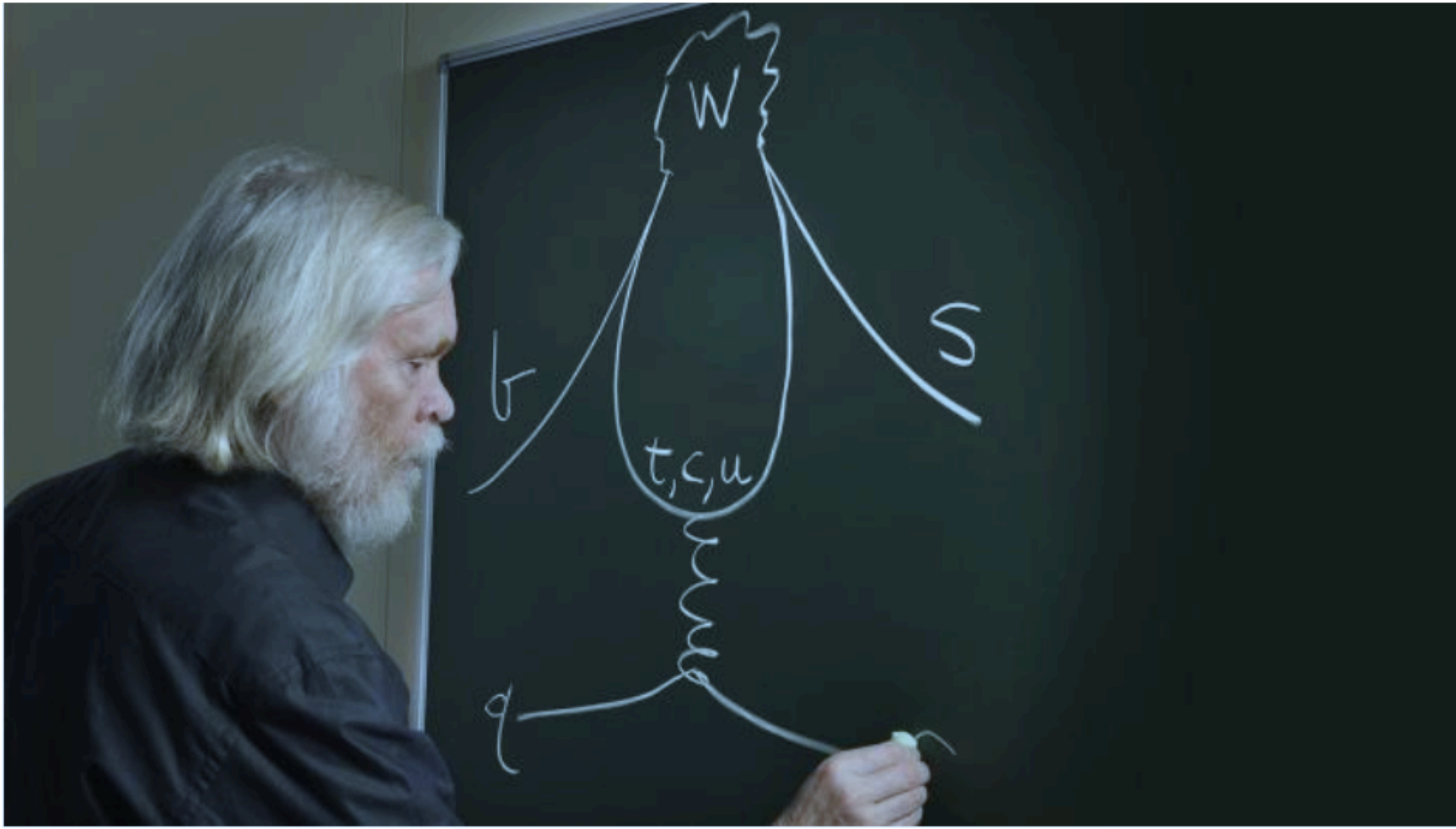
Tree $\propto V_{ub} V_{ud}^{*}$



O_3, O_4, O_5, O_6

Penguin $\propto V_{tb} V_{td}^{*}$





Prof. John Ellis @ SymmetryMagazine.org

CP Violation in $B \to \pi\pi(K)$ *(real prediction before exp.)*

CP(%)	FA	BBNS	PQCD (2001)	Exp (2004)
π^+K^-	+9±3	+5±9	–17±5	–11.5±1.8
π^0K^+	+8 ± 2	7 ±9	–13 ±4	+4 ± 4
π^+K^0	1. 7± 0. 1	1 ±1	–1. 0±0.5	–2 ±4
$\pi^+\pi^-$	–5±3	–6±12	+30±10	+37±10

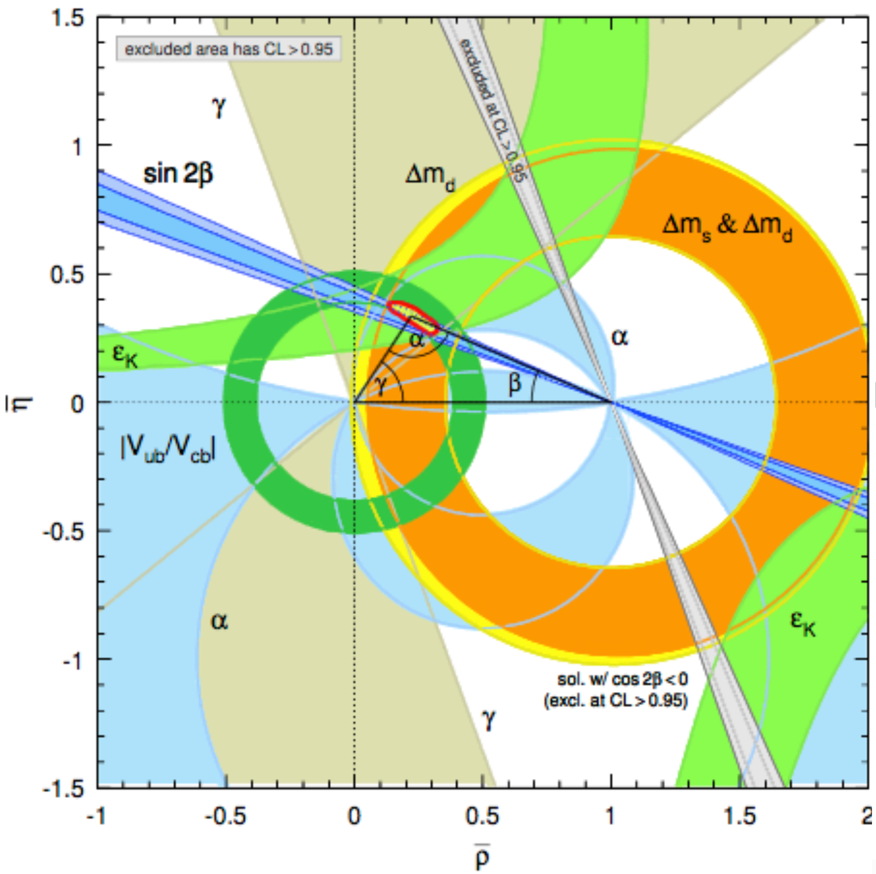
CP Violation in $B \to \pi\pi(K)$

Including large annihilation fixed from exp.

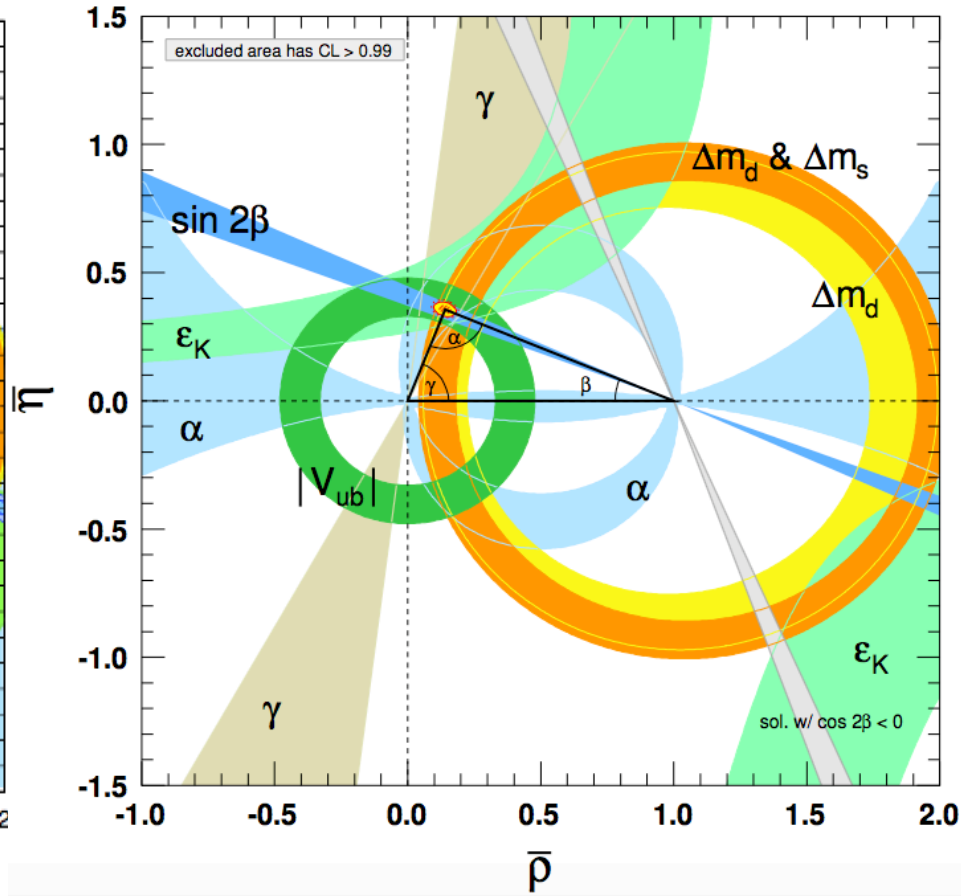
CP(%)	FA	Cheng,HY	PQCD (2001)	Exp
π^+K^-	+9±3	-7.4 ± 5.0	–17±5	–9.7±1.2
π^0K^+	+8 ± 2	0.28±0.10	–13 ±4	4. 7 ± 2.6
π^+K^0	1. 7± 0. 1	4.9 ± 5.9	–1. 0±0.5	0.9 ±2.5
$\pi^+\pi^-$	–5±3	17 ± 1.3	+30±10	+38±7

π K puzzle

PDG2006 & 2020 Unitarity Triangle Comparison



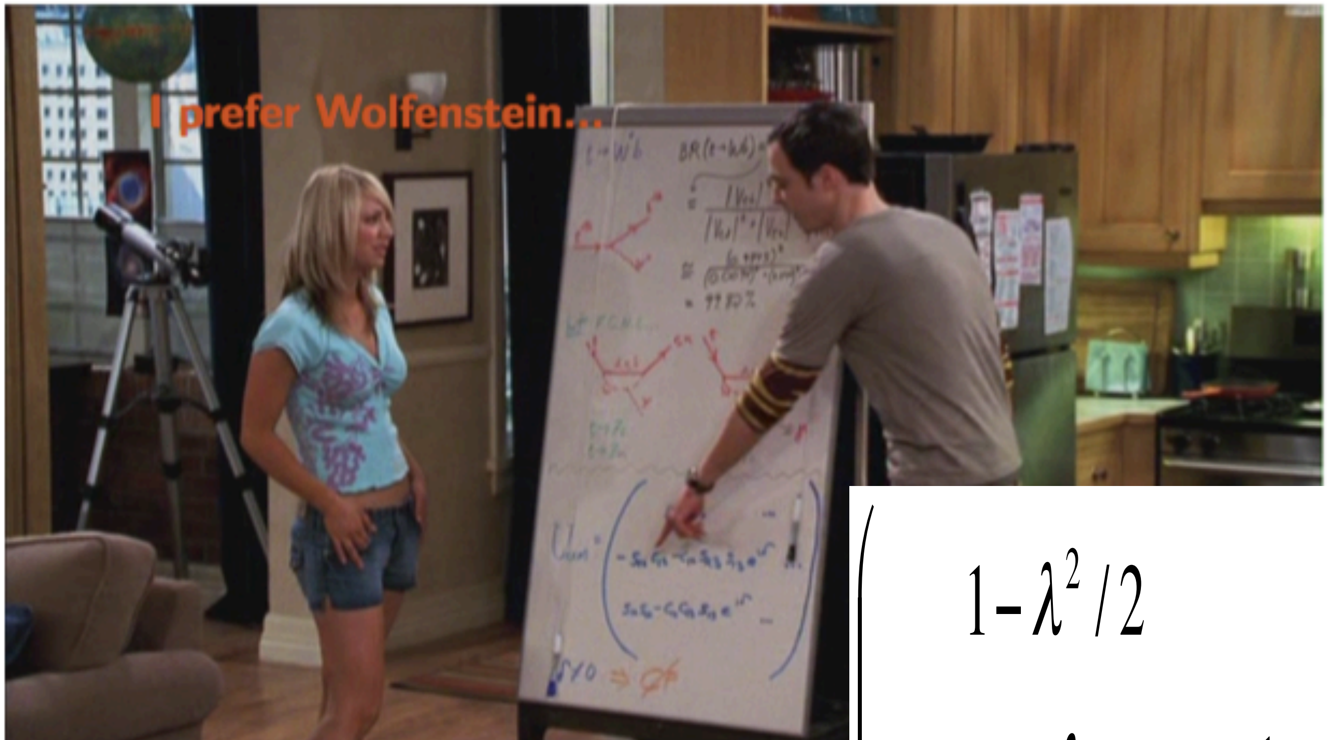
2006



2020

The CKM (Cabibbo·Kobayashi·Maskawa) matrix

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



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

CDLu

The key point of CP violation

- **If we found another world of civilization, we have to make sure whether they are made of anti-matter, before we travel to them**
- **This is very important (Annihilation)**
- **Since the definition of matter/anti-matter, left/right is arbitrary, unless we have CP violation:**

$$\frac{\Gamma(K_L \to \pi^- \mu^+ \nu) - \Gamma(K_L \to \pi^+ \mu^- \overline{\nu})}{\Gamma(K_L \to \pi^- \mu^+ \nu) + \Gamma(K_L \to \pi^+ \mu^- \overline{\nu})} = (0.64 \pm 0.08)\%$$

Heavy flavor physics is a very important hot topic in particle physics recently

- People expect the new physics signal from the heaviest top quark, since it is very close to the electroweak breaking scale
- But there are too few data of top quark production
- Therefore beauty quark is our best chance for new physics signals, since they both belong to the third family

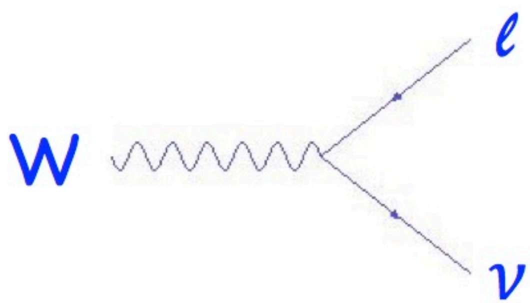
Current Flavor Anomalies

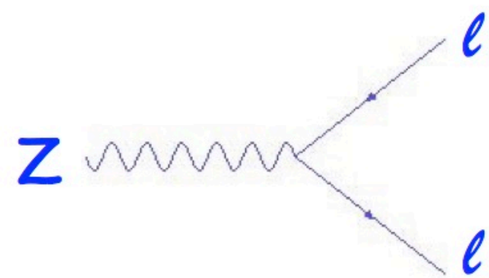
$\sim 3.5\sigma$	$(g-2)_\mu$ anomaly **4.2 σ**	
$\sim 3.5\sigma$	non-standard like-sign dimuon charge asymmetry	
$\sim 3.5\sigma$	enhanced $B \to D^{(*)}\tau\nu$ rates	$R_{D^{(*)}}$
$\sim 3.5\sigma$	suppressed branching ratio of $B_s \to \phi\mu^+\mu^-$	
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{ub}\rvert$	
$\sim 3\sigma$	tension between inclusive and exclusive determination of $\lvert V_{cb}\rvert$	
$2-3\sigma$	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:





$$\frac{B(W^+\to\mu^+\nu)}{B(W^+\to e^+\nu)} = 0.991\pm0.018$$

$$\frac{B(W^+\to\tau^+\nu)}{B(W^+\to e^+\nu)} = 1.043\pm0.024$$

$$\frac{B(W^+\to\tau^+\nu)}{B(W^+\to \mu^+\nu)} = 1.070\pm0.026$$

$$\frac{B(Z\to\mu^+\mu^-)}{B(Z\to e^+e^-)} = 1.0009\pm0.0028$$

$$\frac{B(Z\to\tau^+\tau^-)}{B(Z\to e^+e^-)} = 1.0019\pm0.0032$$

.9977 (SM)

Introduction to $R(D^{(*)})$

$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \quad \text{with } \ell = \mu, e$$

SM predictions (2012):

$R(D) = 0.297 \pm 0.017$

$R(D^*) = 0.252 \pm 0.003$

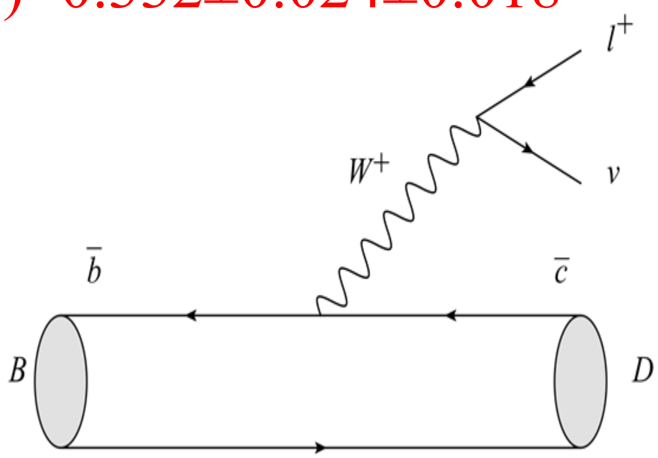
3.4σ

BABAR (2012):

$R(D) = 0.440 \pm 0.058 \pm 0.042$

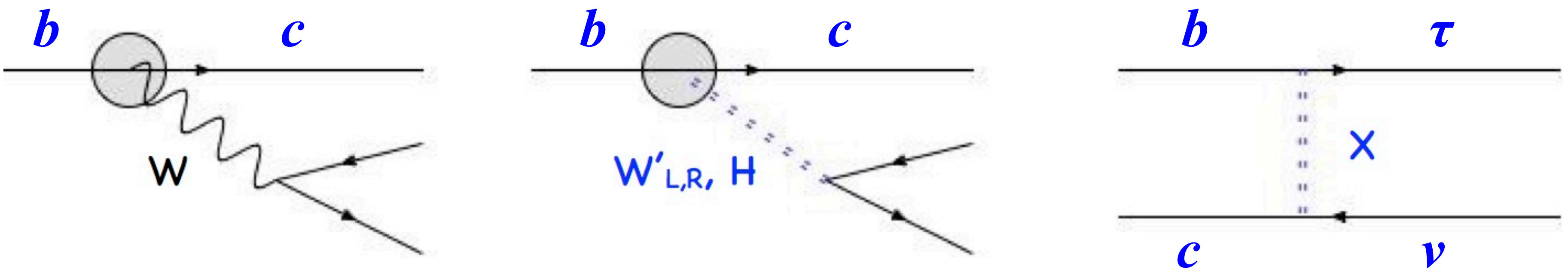
$R(D^*) = 0.332 \pm 0.024 \pm 0.018$

- Type II 2HDM is said to be ruled out



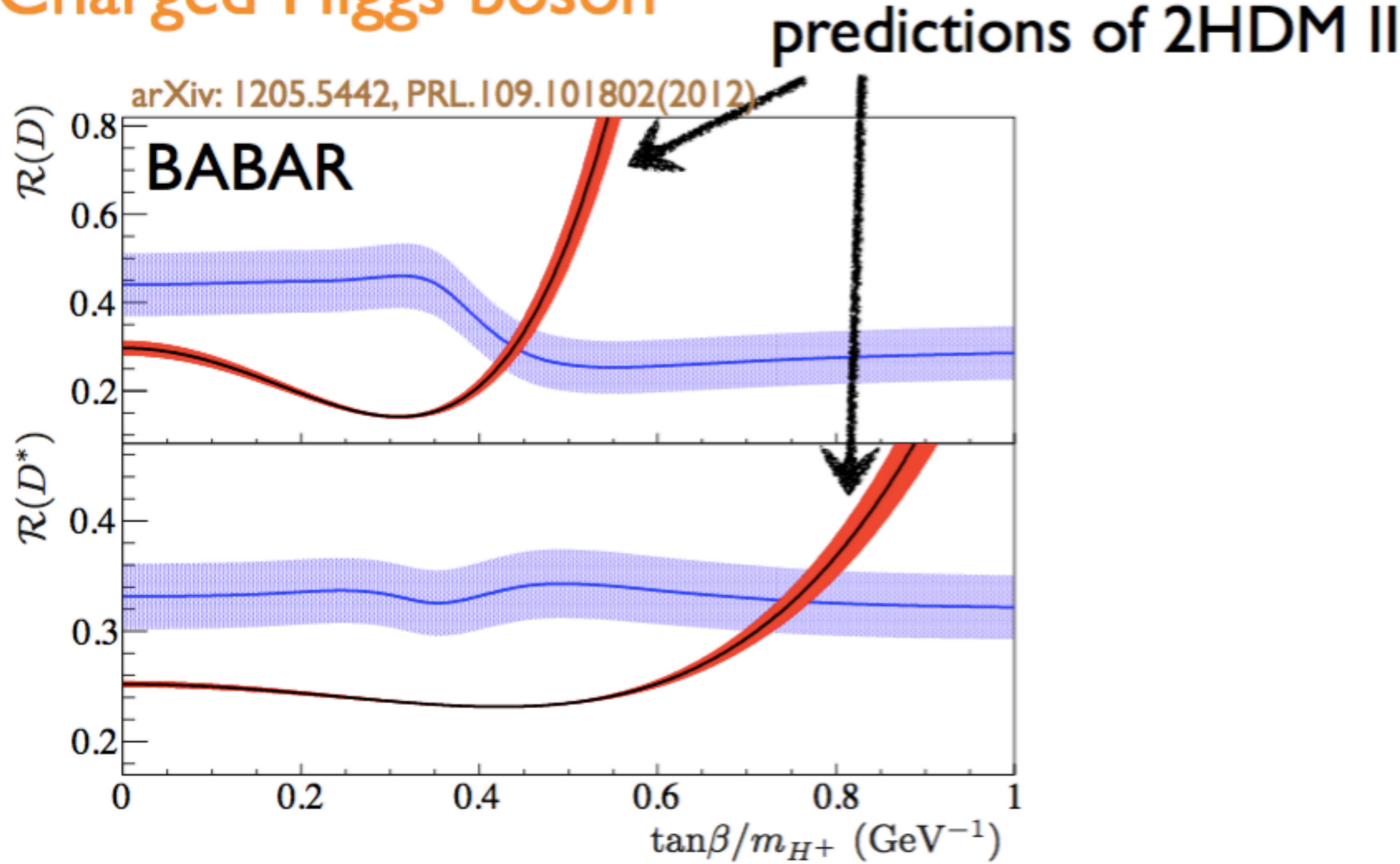
first surprise in b → c τ ν

- 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

Charged Higgs boson



Charged Higgs *excluded* at 99.8% CL

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)

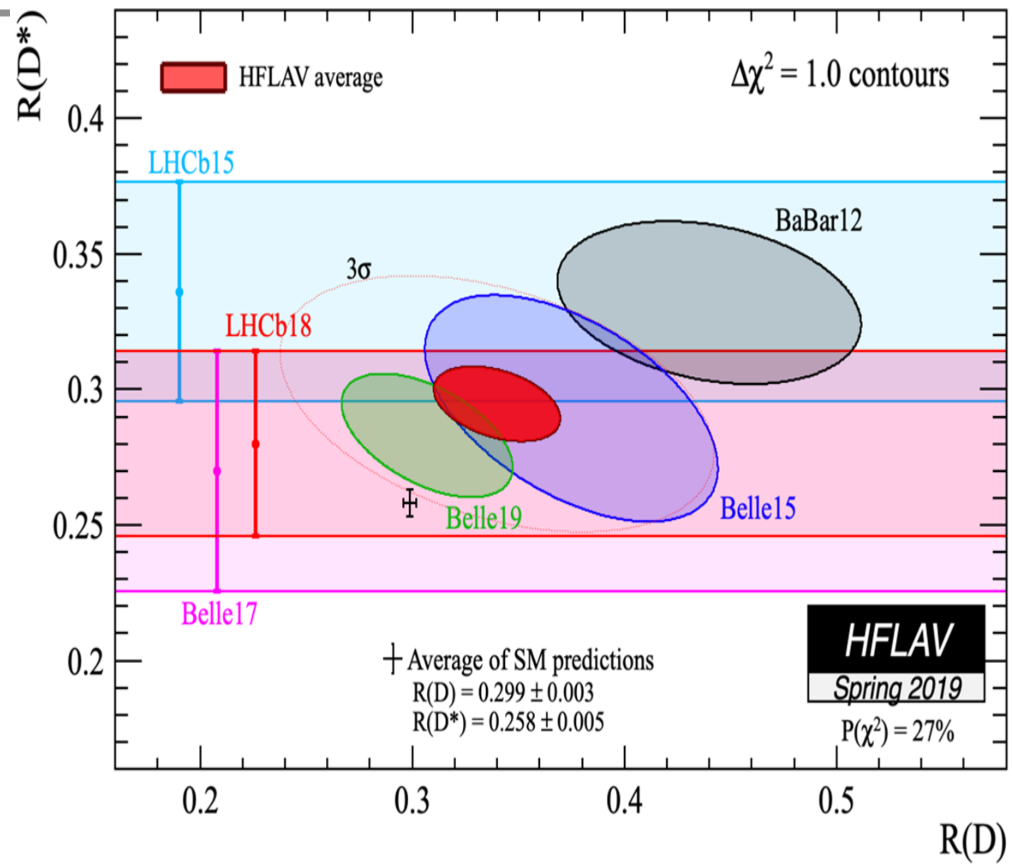
$0.322 \pm 0.018 \pm 0.012$ (Exp. HFAG)

Current Experimental Status

- The combined results of $R(D^{(*)})$ indicate about 3σ deviation from the SM predictions

$R(D)$=0.340±0.027±0.013

$R(D^*)$=0.295±0.011±0.008



- LHCb reported

$$R(J/\psi) = \frac{\mathcal{B}(B_c \to J/\psi\tau\nu)}{\mathcal{B}(B_c \to J/\psi\mu\nu)}$$

$= 0.71 \pm 0.17 \pm 0.18$,

which deviate 2σ away from the SM prediction

$\mathcal{B}(B_c \to \tau\nu) < 10\%$ from LEP

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

Calculation of Form factors

All form factors are functions of q^2

- Small recoil (Near Max point of q^2):

  HQET, Lattice QCD

- Large recoil (Near $q^2 = 0$):

  Light Cone Sum Rule, Perturbative QCD

- Other point of q^2 need Extrapolation :

  Pole model $\oplus$ z expansion

  HQET Specific Parameterization:

  Boyd-Grinstein-Lebed (BGL)

  Bourrelly-Caprini-Lellouch (BCL)

  Caprini-Lellouch-Neubert (CLN)

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: **Lorentz Invariant**

$$O_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R \nu_L)\,, \quad O_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R \nu_L)\,,$$

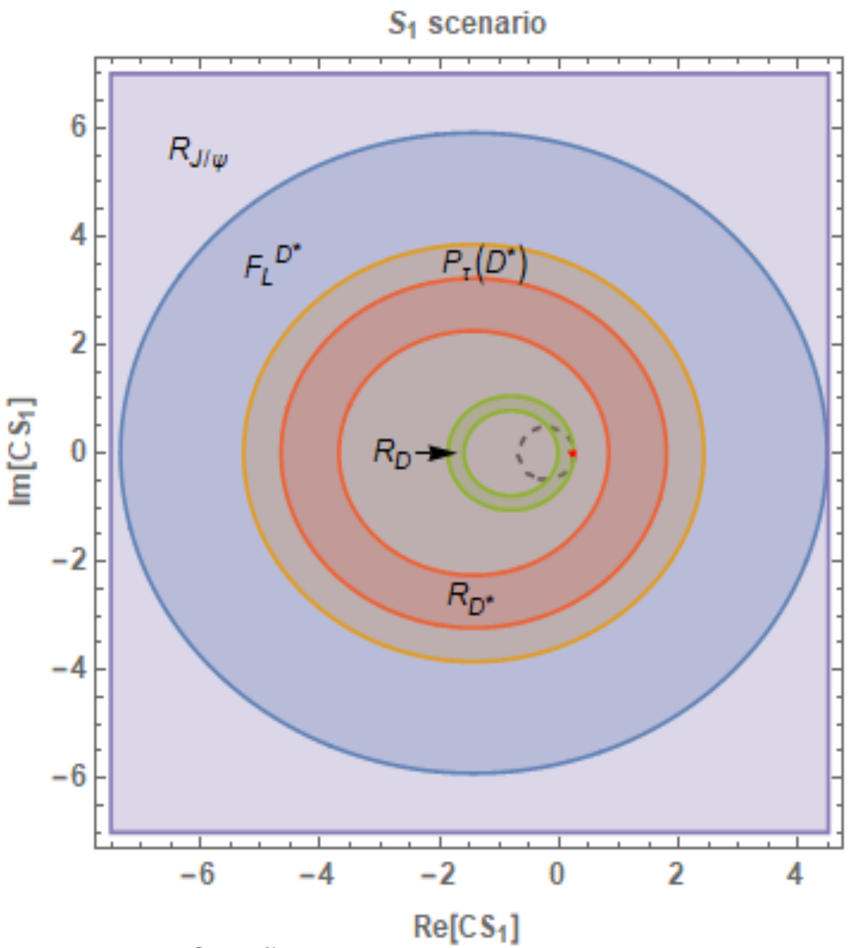
$$O_{V_1} = (\bar{c}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)\,, \quad O_{V_2} = (\bar{c}_R \gamma^\mu b_R)(\bar{\tau}_L \gamma_\mu \nu_L)\,,$$

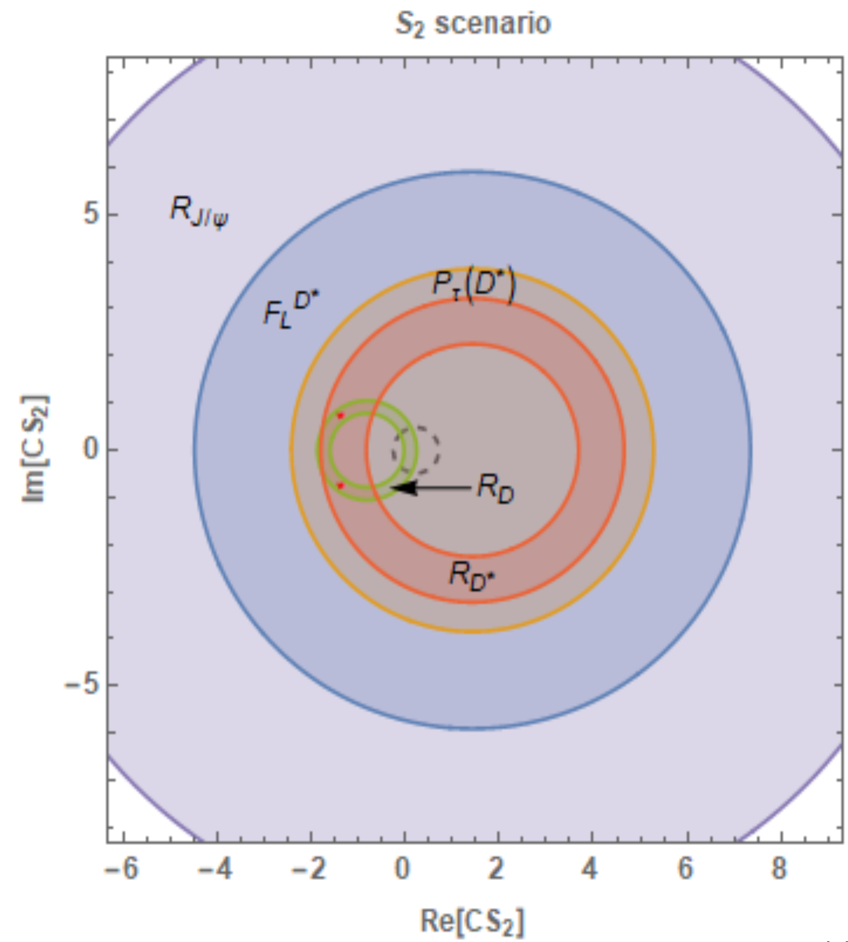
$$O_T = (\bar{c}_R \sigma^{\mu\nu} b_L)(\bar{\tau}_R \sigma_{\mu\nu} \nu_L)\,,$$

Huang, Li, Lu, Paracha, Wang, PRD98 (2018) no.9, 095018

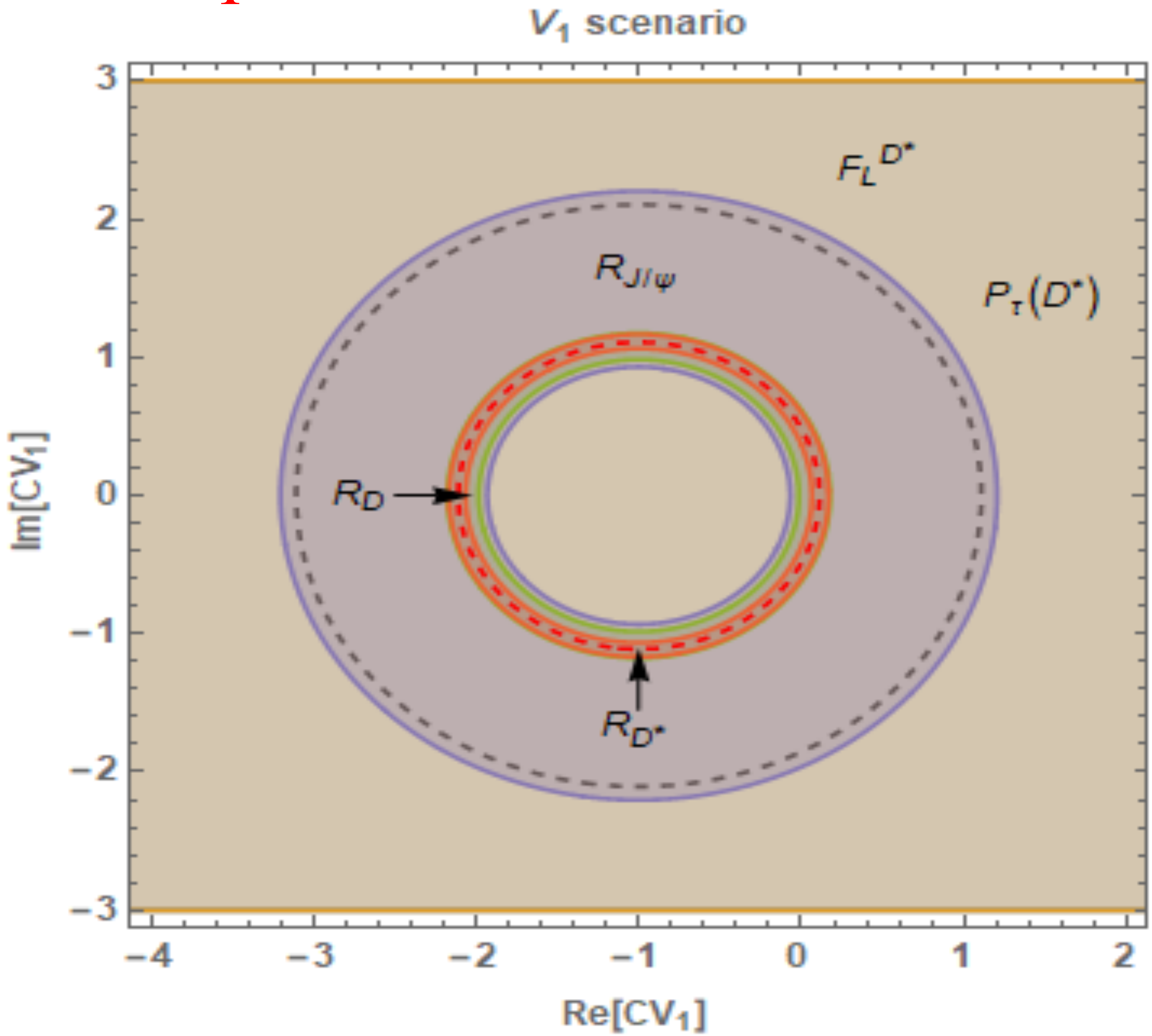
It is found that none of the single operators can explain simultaneously the current experimental measurements of the ratios $R(D)$, $R(D*)$ and $R(J/\psi)$ at the confidence level of 1σ

Even with 2σ Constraints, the NP scalar operators are also ruled out

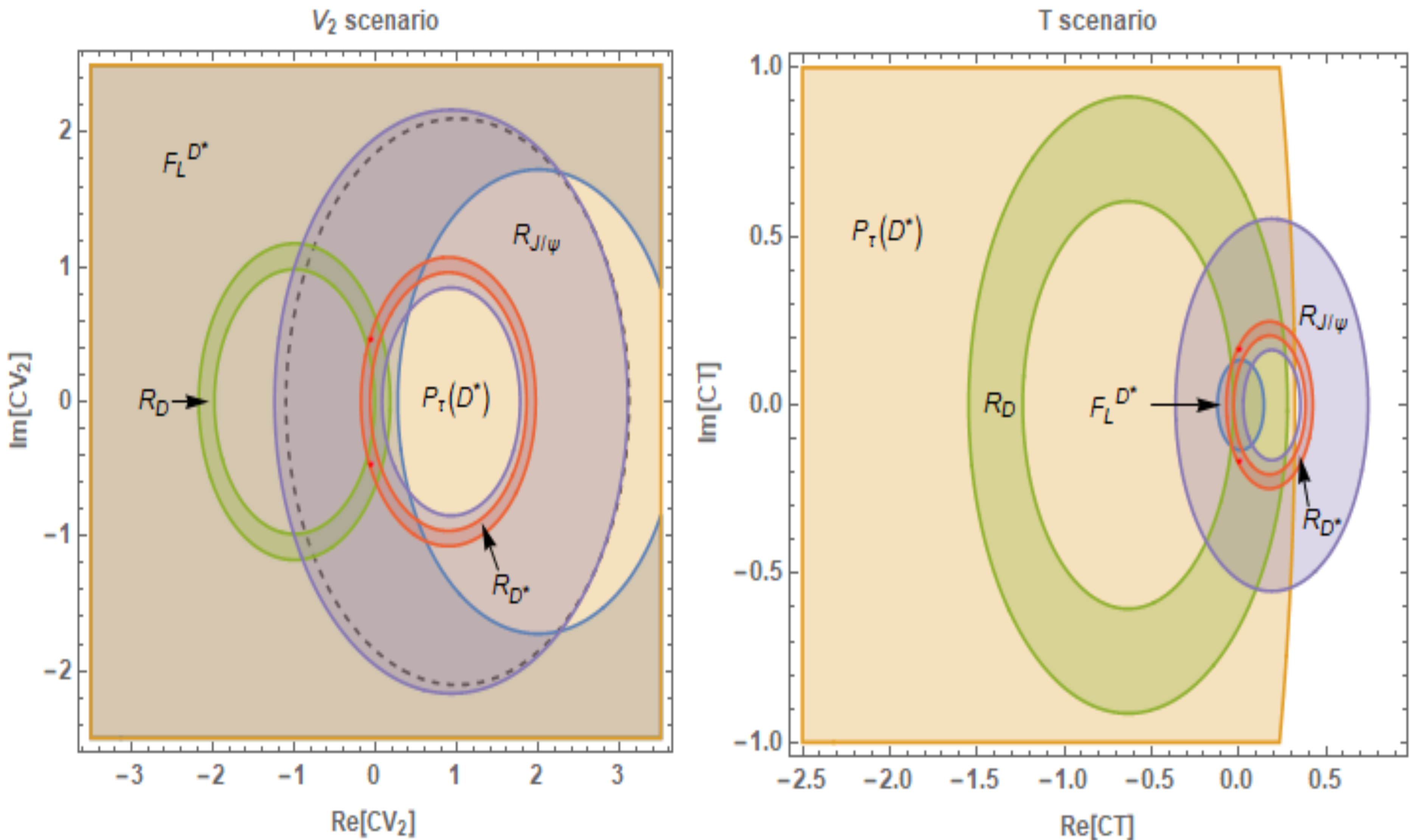




2σ Constraints on the left-handed vector operator

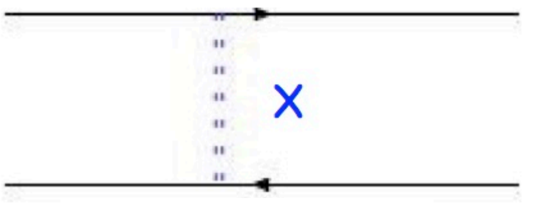


2σ Constraints on the right-handed vector operator and tensor operator



Leptoquark model

Cheung, Huang, Li, Lu, Mao Tang, arXiv:2002.07272 [hep-ph]



- Lagrangian of Leptoquark

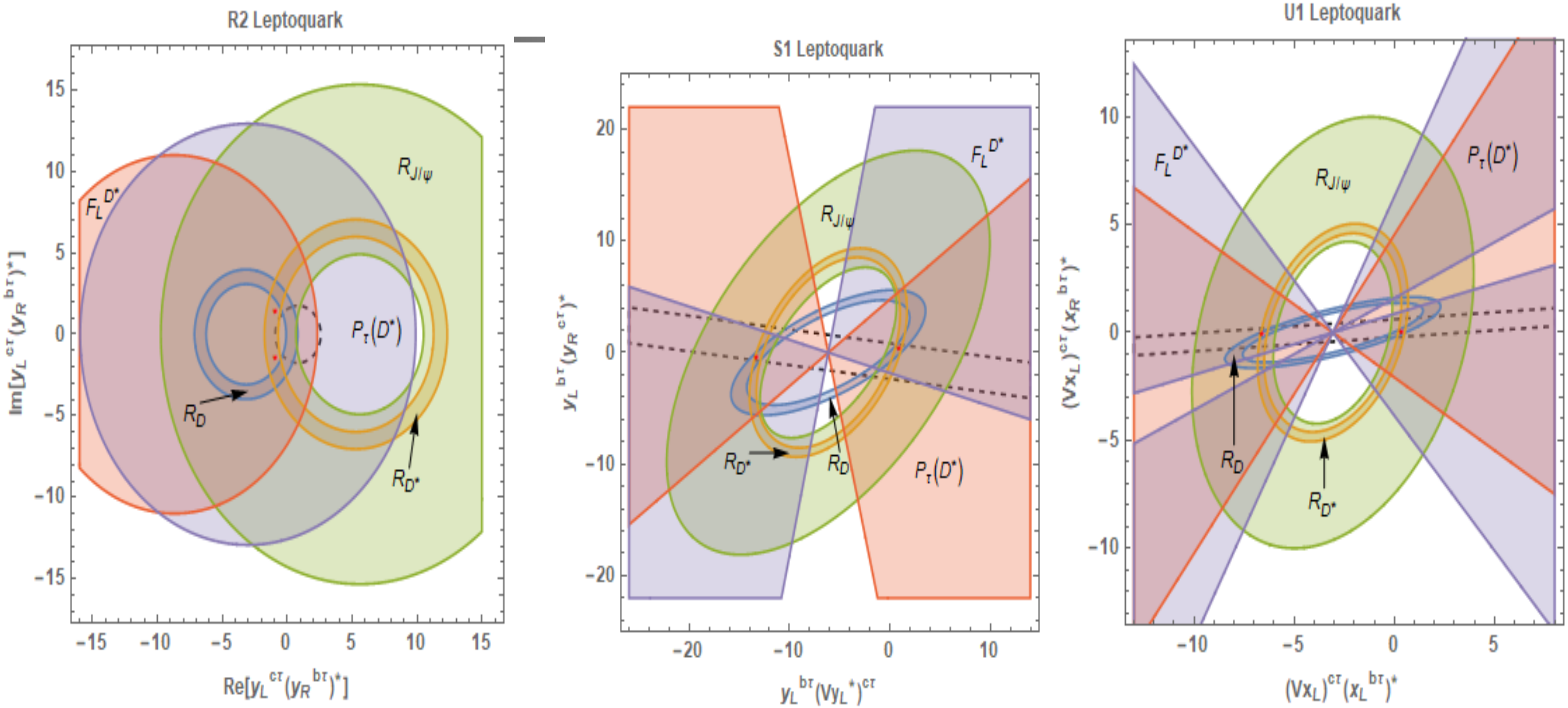
$$\mathcal{L}_{R_2} = \left(y_R^{b\tau}\bar{b}_L\tau_R + y_L^{c\tau}\bar{c}_R\nu_L\right)Y_{2/3} + \text{H.c.}$$

$$\mathcal{L}_{S_1} = \left((V^*_{\text{CKM}}y_L)^{c\tau}\bar{c}^c_L\tau_L - y_L^{b\tau}\bar{b}^c_L\nu_L + y_R^{c\tau}\bar{c}^c_R\tau_R\right)Y_{1/3} + \text{H.c.}$$

$$\mathcal{L}_{U_1} = \left((V_{\text{CKM}}x_L)^{c\tau}\bar{c}_L\gamma_\mu\nu_L + x_L^{b\tau}\bar{b}_L\gamma_\mu\tau_L + x_R^{b\tau}\bar{b}_R\gamma_\mu\tau_R\right)X^\mu_{2/3} + \text{H.c.}$$

	SM quantum number [SU(3) × SU(2) × U(1)]	Spin	Fermions coupled to
R_2	$(3, 2, 7/6)$	0	$\bar{c}_R\nu_L, \bar{b}_L\tau_R$
S_1	$(\bar{3}, 1, 1/3)$	0	$\bar{b}^c_L\nu_L, \bar{c}^c_L\tau_L, \bar{c}^c_R\tau_R$
U_1	$(3, 1, 2/3)$	1	$\bar{c}_L\gamma_\mu\nu_L, \bar{b}_L\gamma_\mu\tau_L, \bar{b}_R\gamma_\mu\tau_R$

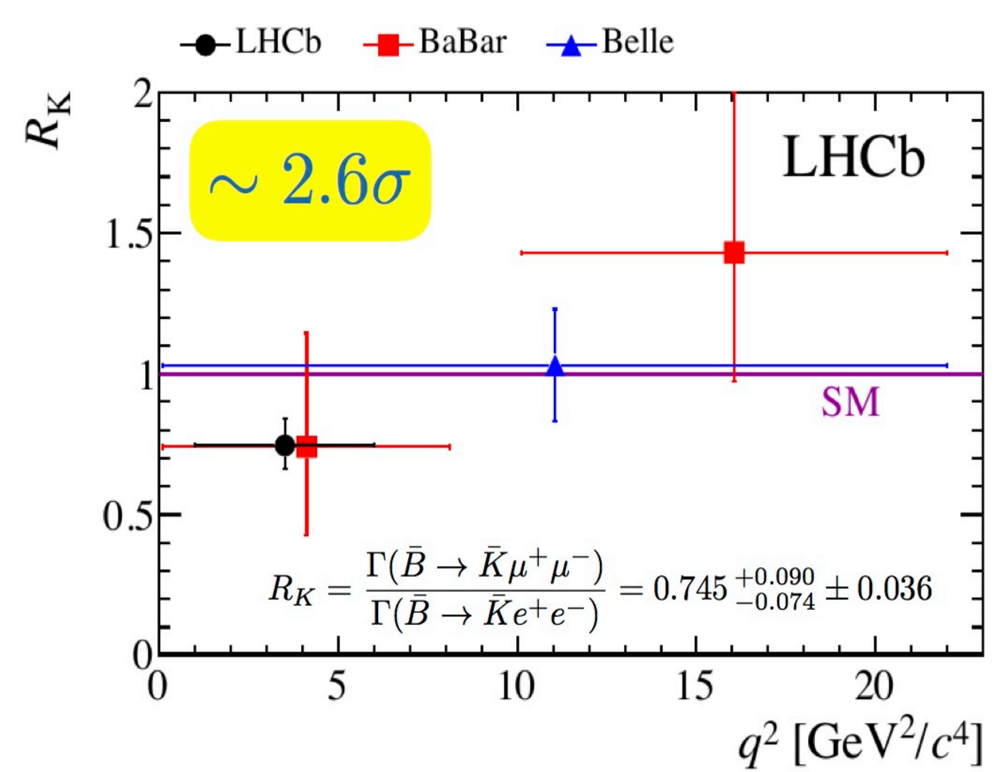
2σ Constraints on the Leptoquark couplings



Non-universal B→ K μμ / ee rates

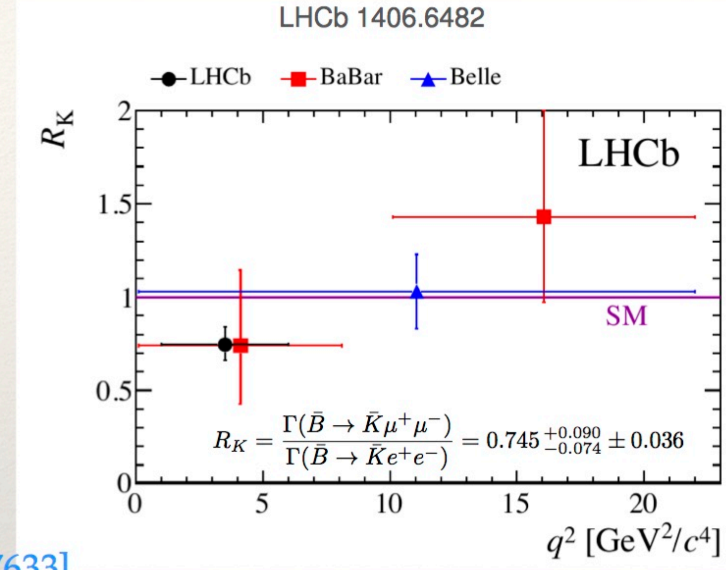
- LHCb observation of a violation of lepton universality in the rare decays B→Kμμ vs. B→Kee — if confirmed — would be the most spectacular LHC discovery after the Higgs boson:

LHCb 1406.6482

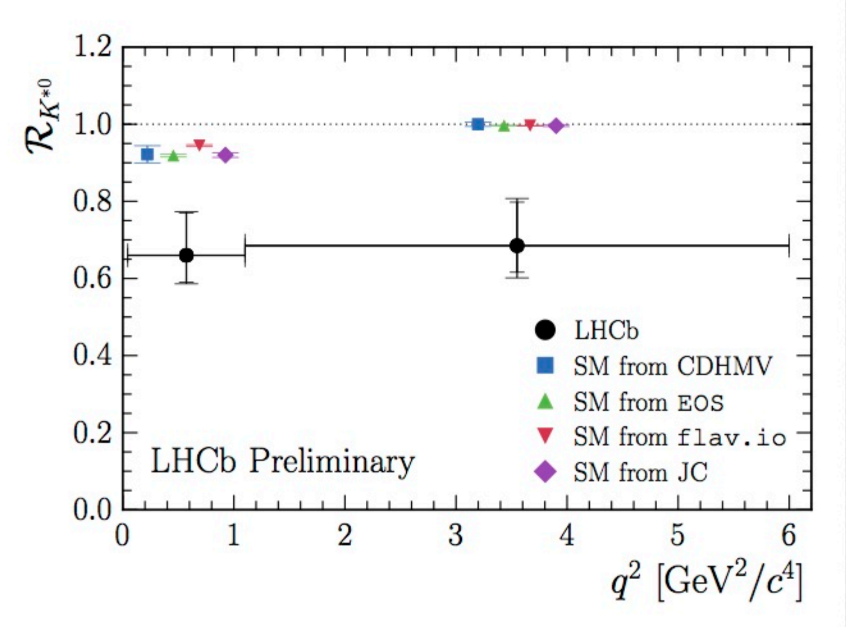


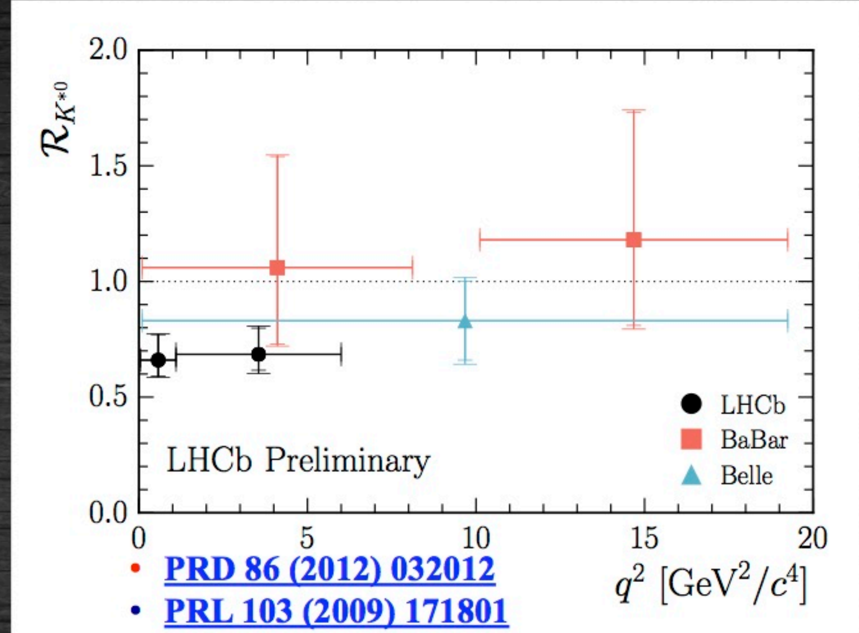
Non-universal B→ K μμ / ee rates

- 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

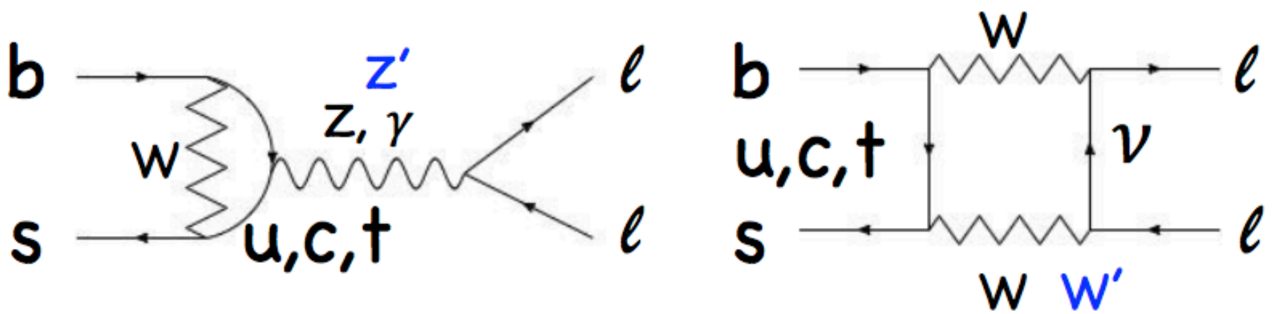




- The compatibility of the result in the **low-q^2** with respect to the SM prediction(s) is of **2.2-2.4** standard deviations
- The compatibility of the result in the **central-q^2** with respect to the SM prediction(s) is of **2.4-2.5** standard deviations

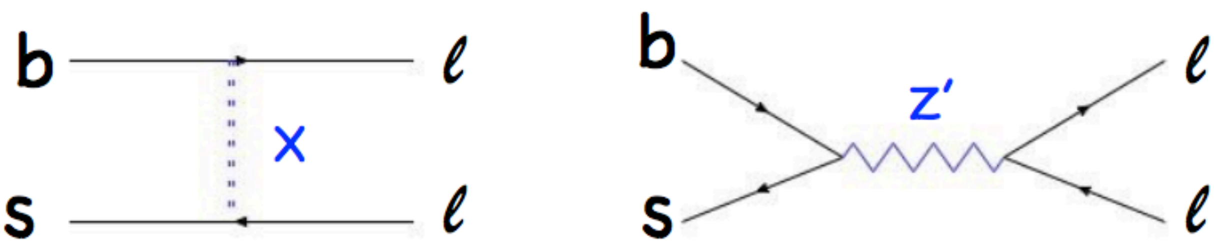
Second surprise in b→ s *l*+*l*-

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

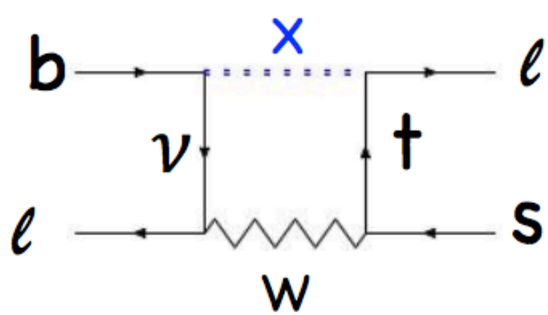


SM

Lepto-quark



supersymmetry



Violation of lepton flavor universality

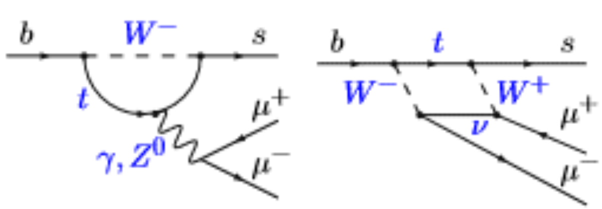
$$R(K) = \frac{BF(B \to K\mu^+\mu^-)}{BF(B \to Ke^+e^-)} \qquad R(K^*) = \frac{BF(B \to K^*\mu^+\mu^-)}{BF(B \to K^*e^+e^-)}$$

theoretically very clean!

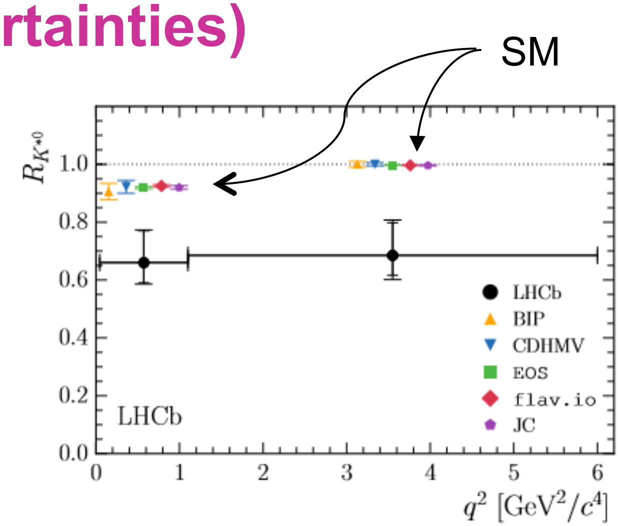
Observable	Expt (LHCb)	SM	σ
R(K), q^2=[1, 6] GeV^2	$0.745^{+0.090}_{-0.074}\pm0.036$	1.00±0.01	2.6
$R(K^{*0})$, q^2=[0.045, 1.1]	$0.66^{+0.11}_{-0.07}\pm0.03$	~ 0.920	2.1-2.3
$R(K^{*0})$, q^2=[1.1, 6]	$0.69^{+0.11}_{-0.07}\pm0.05$	~ 0.996	2.4-2.5

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]

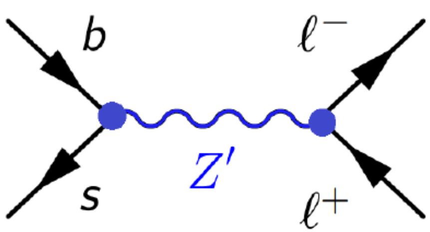
Chen, Nomura [1707.03249]

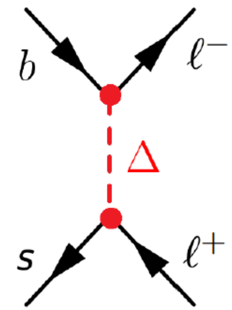
Baek [1707.04573]

Bian, Choi, Kang, Lee [1707.04811]

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?

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

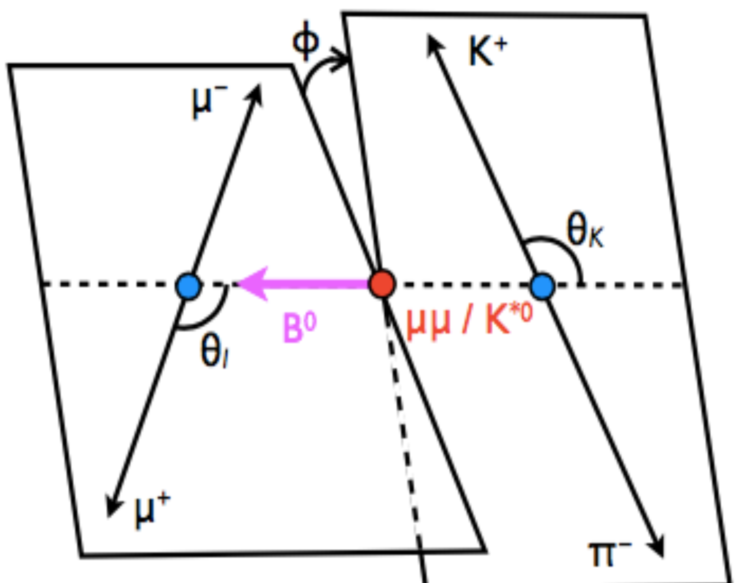
$$R_K \quad \Leftrightarrow \quad \mu \neq e$$

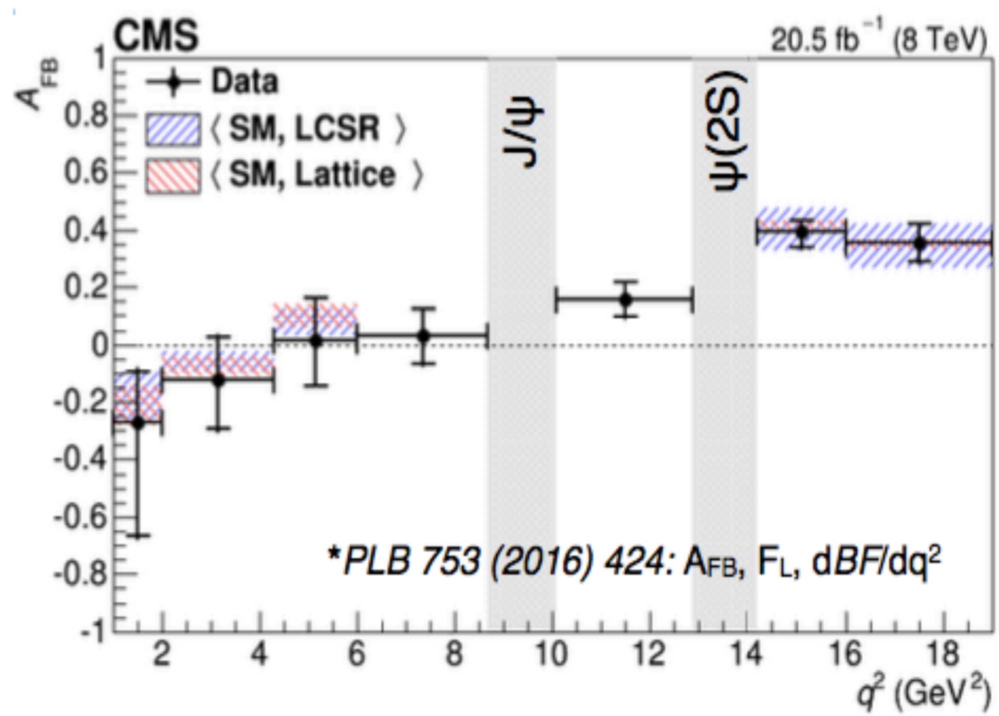
SM gauge interactions do not distinguish between different leptons, and Higgs exchange is irrelevant; hence need new particles beyond the SM with new types of interactions

- $U(1)_{\tau-\mu}$ → 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 $B \rightarrow K^* \mu\mu$ decays offer a rich laboratory for new-physics searches via differential angular distributions as a functions of lepton invariant mass:





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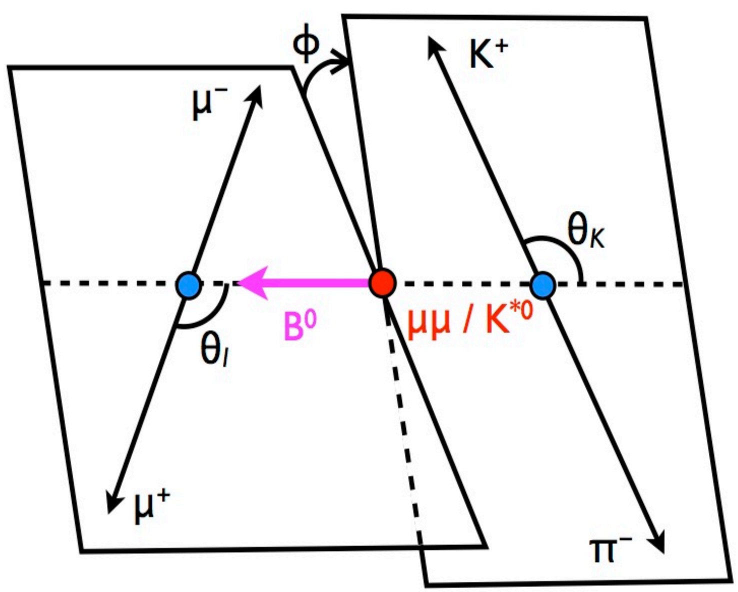


$$\frac{1}{d\Gamma/dq^2}\frac{d^4\Gamma}{dq^2\, d\cos\theta_l\, d\cos\theta_K\, d\phi}$$

S-wave and S&P-wave interference

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

P-wave

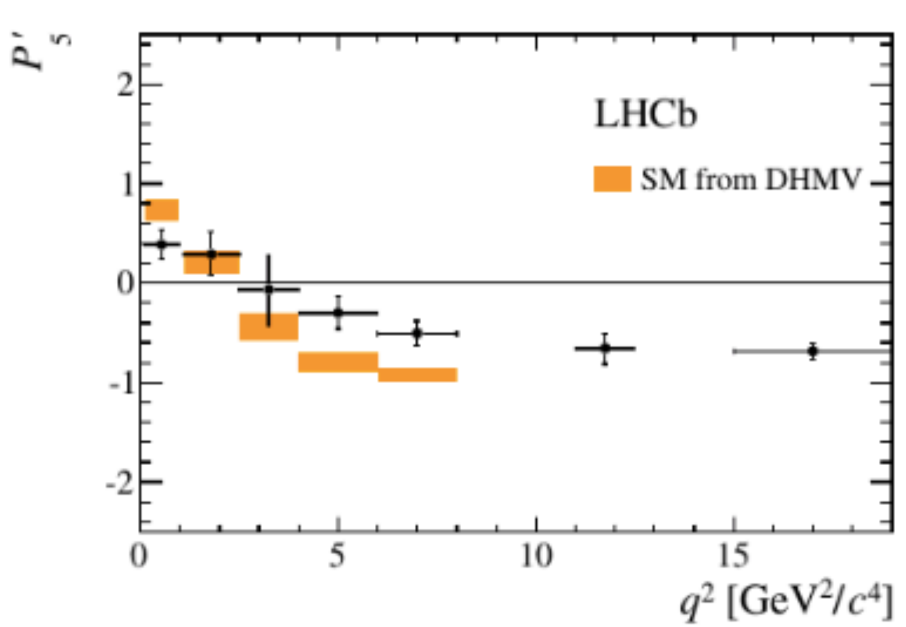
Angular analysis of $B \rightarrow K^* \mu\mu$ decays

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:

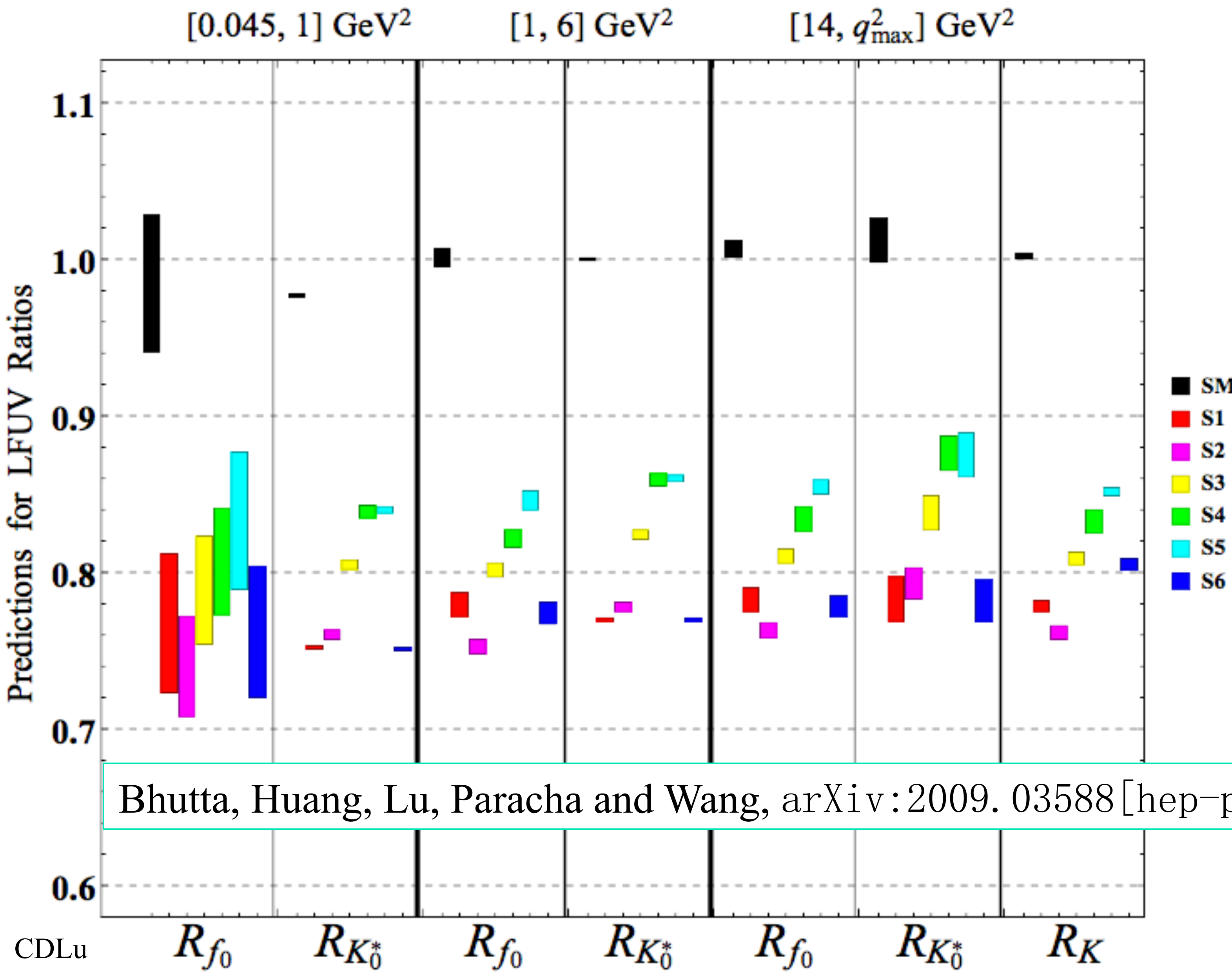
LHCb 1512.04442



2.8σ deviation in q^2 bin between [4, 6] GeV^2

(3.0σ in bin [6, 8] GeV^2)

Predictions for other similar channels



Bhutta, Huang, Lu, Paracha and Wang, arXiv:2009.03588[hep-ph]

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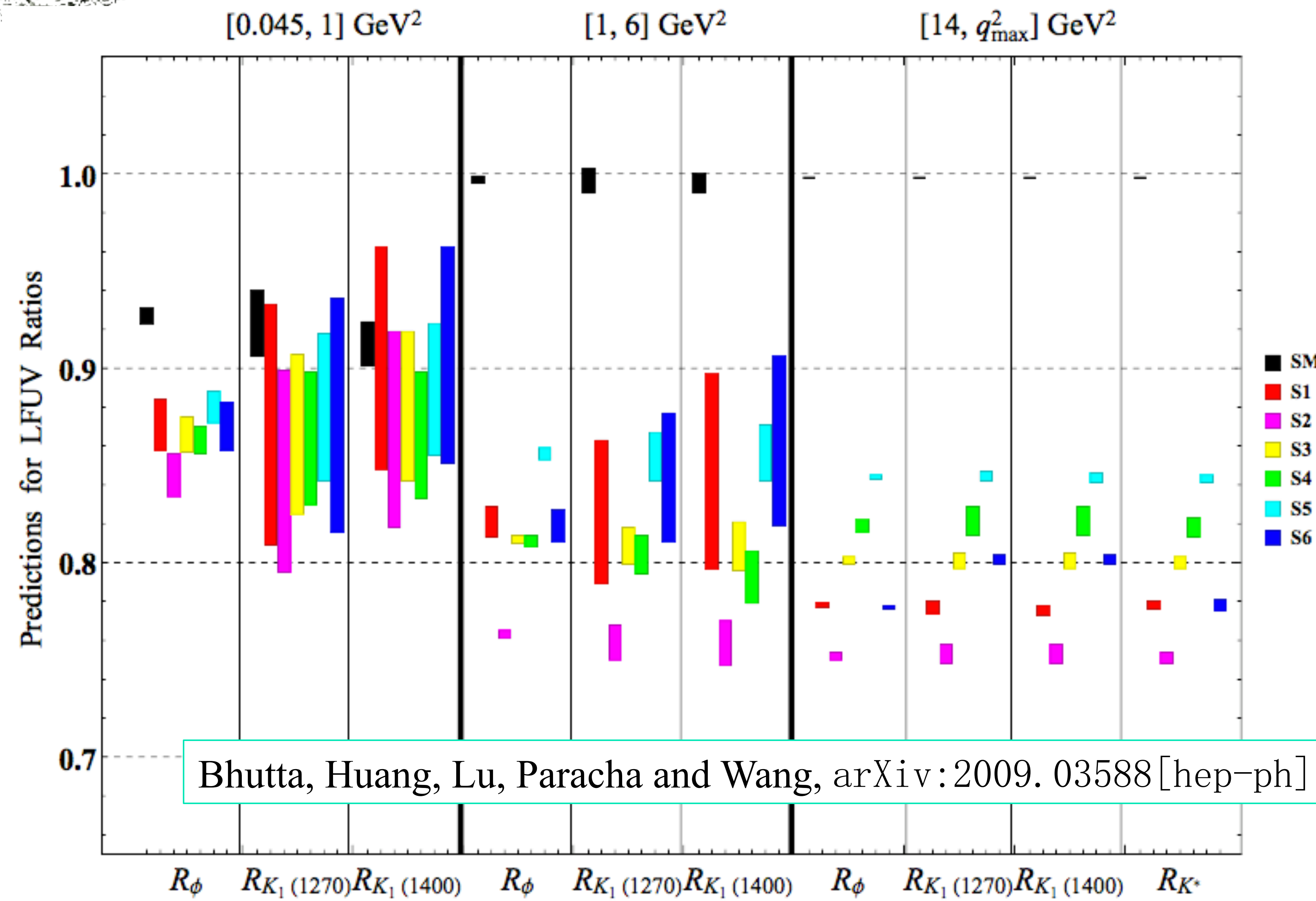
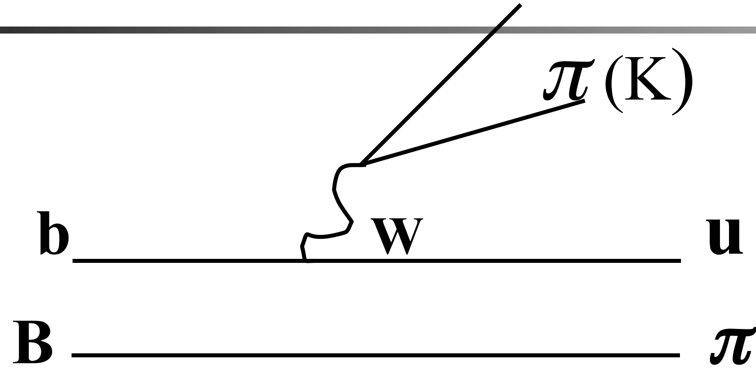


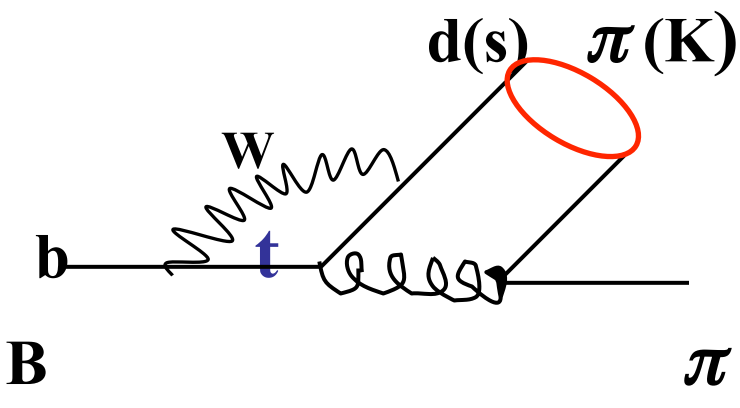
Bhutta, Huang, Lu, Paracha and Wang, arXiv:2009.03588[hep-ph]

Rich physics in hadronic B/D decays

CP violation, FCNC, sensitive to new physics contribution…



The standard model describes interactions amongst quarks and leptons



In experiments, we can only observe hadrons

pi K puzzle etc.

How can we test the standard model without solving QCD?

Perturbative calculations

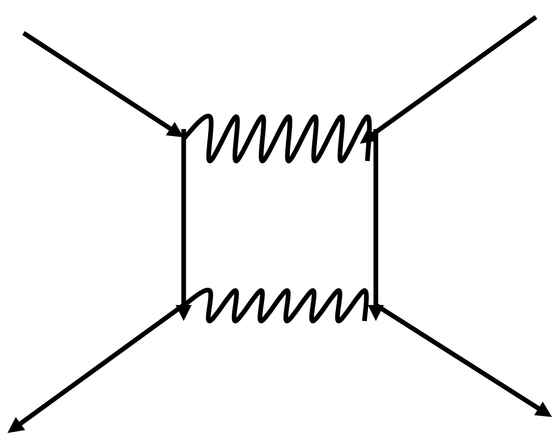
- In principle, all hadronic physics should be calculated by QCD
- In fact, you can always use QCD to calculate any process,

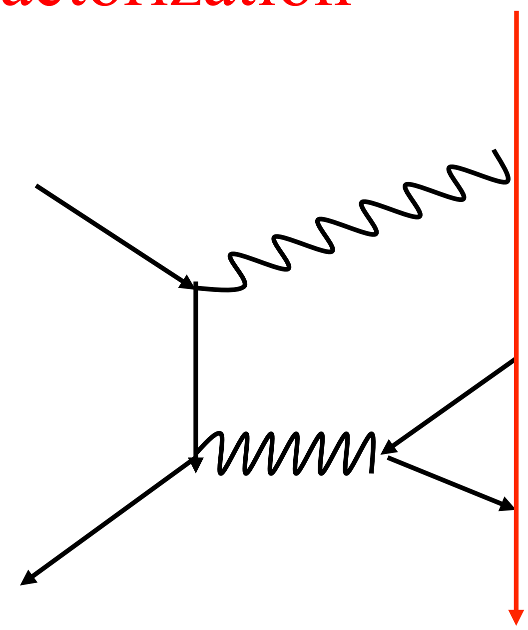
provided you can renormalize the infinities and do all order calculations.

- Perturbation calculation means order by order
- Involving loop diagrams
- Therefore divergences unavoidable

Divergences

- Ultraviolet divergences → renormalization
- Infrared divergences ? **Infrared divergence in virtual corrections should be canceled by real emission**
- In exclusive QCD processes → factorization





Divergences

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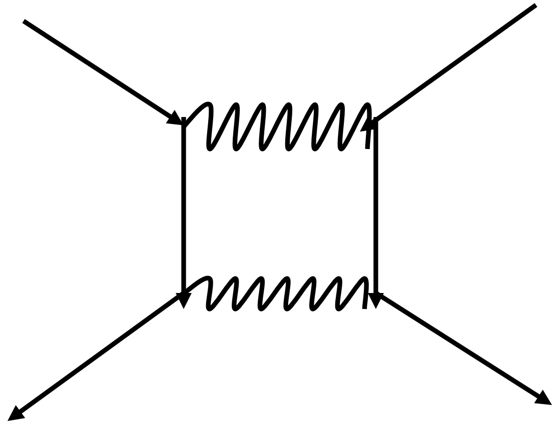
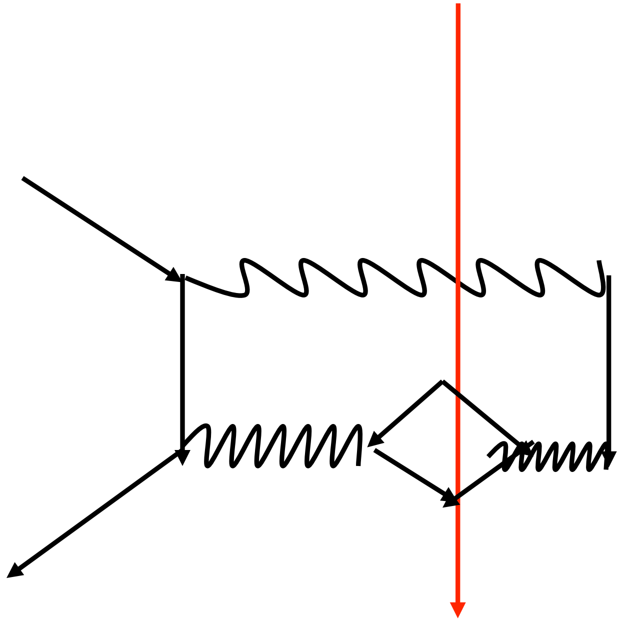




Factorization can only be proved in power expansion by operator product expansion. To achieve that, we need a hard scale Q

- In the certain order of 1/Q expansion, the hard dynamics characterized by Q factorize from the soft dynamics
- Hard dynamics is process-dependent, but calculable
- Soft dynamics are universal (process-independent) ⇨ predictive power of factorization theorem
- Factorization theorem holds up to all orders in α_s, but to certain power in 1/Q
- In B decays the hard scale Q is just the b quark mass

QCD-methods based on factorization work well for the leading power of $1/m_b$ expansion

collinear QCD Factorization approach
[Beneke, Buchalla, Neubert, Sachrajda, 99']

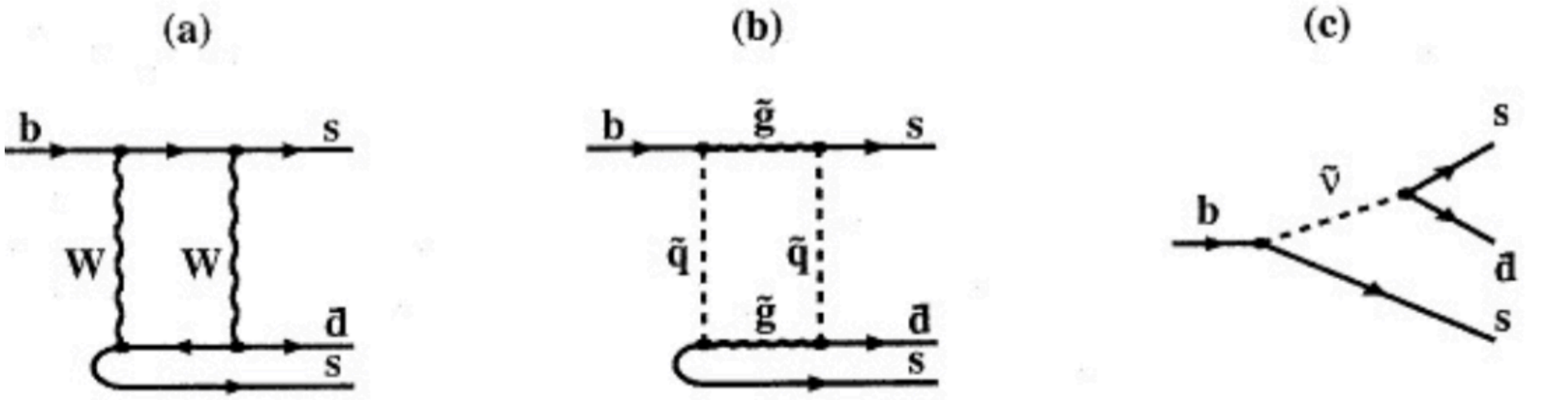
Perturbative QCD approach based on k_T factorization
[Keum, Li, Sanda, 00'; Lu, Ukai, Yang, 00']

Soft-Collinear Effective Theory
Bauer, Fleming, Pirjol, Stewart, Phys.Rev. D63 (2001) 114020

- Work well for most of charmless B decays, except for ππ, πK puzzle etc.

Search for new physics in hadronic B decays theoretically very complicated

K. Huitu, C.D. Lü, P. Singer D.X. Zhang, **Phys. Rev. Lett. 81, 4313 (1998), hep-ph/9809566.**



$b \to ss\bar{d}$ transition (a) SM, (b) MSSM, (c) MSSM with R-parity violating coupling

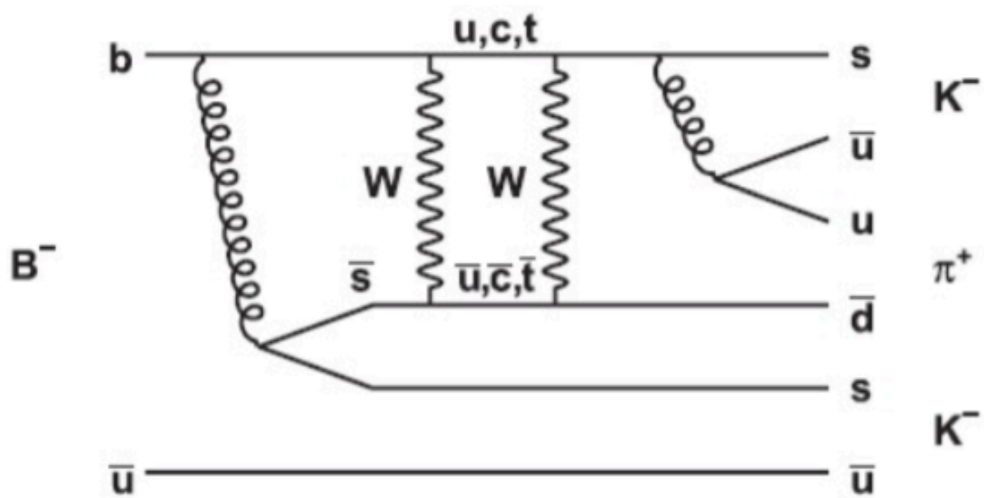
SM BRs: ~ 10^{-14},

Some New physics can reach 10^{-6}

Experimental search starting from OPAL @ LEP, phys. Lett. B 476 (2000) 233, later searched also by Belle/Babar

BABAR collaboration, Phys. Rev. D 78 (2008) 091102 [arXiv:0808.0900]

A search for the decay $B^- \to K^- K^- \pi^+$, Using a sample of $(467 \pm 5) \times 10^6$ $B\overline{B}$ pairs collected with the BABAR detector.



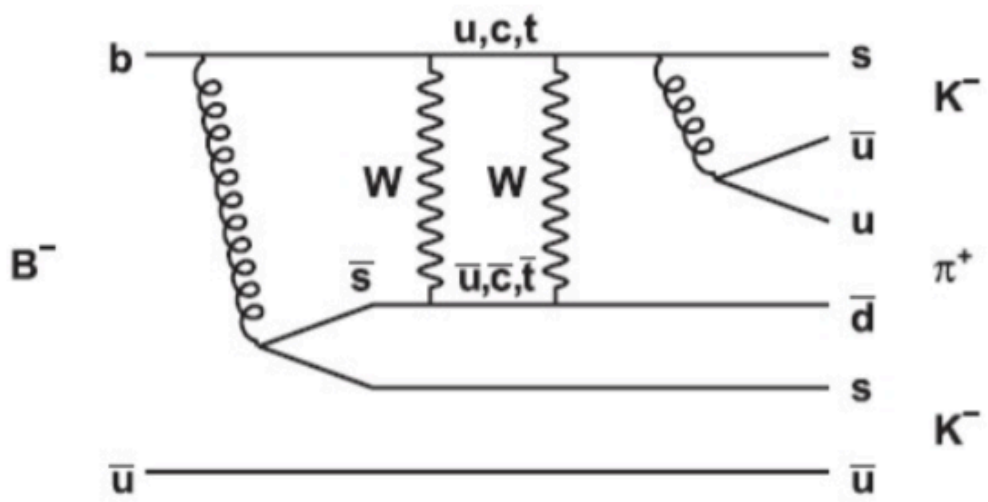
Result : No evidence for these decays was found and a upper limit was set as

$$\mathcal{B}(B^- \to K^- K^- \pi^+) < 1.6 \times 10^{-7}$$

Experimental search starting from OPAL @ LEP, phys. Lett. B 476 (2000) 233, later searched also by Belle/Babar

BABAR collaboration, Phys. Rev. D 78 (2008) 091102 [arXiv:0808.0900]

A search for the decay $B^- \to K^- K^- \pi^+$, Using a sample of $(467 \pm 5) \times 10^6$ $B\overline{B}$ pairs collected with the BABAR detector.



Similar channel $B^- \to \pi^- \pi^- K^+$

Result : No evidence for these decays was found and a upper limit was set as

$$\mathcal{B}(B^- \to K^- K^- \pi^+) < 1.6 \times 10^{-7}$$

Recent LHCb result:

Physics Letters B 765 (2017) 307–316

$$\mathcal{B}(B^+ \to K^+K^+\pi^-) < 1.1 \times 10^{-8}$$

$$\mathcal{B}(B^+ \to \pi^+\pi^+K^-) < 4.6 \times 10^{-8}.$$

Recent theoretical results in Randall-Sundrum model:

Chinese Physics C41 (2017) 053106

Br(b→ss d-bar) can reach to 10^{-10}

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 !