Heavy Flavour Physics at the LHC

Ying Li

Yantai University

Talk given in The 5th China LHC Physics Workshop)

Topics in Heavy Flavour Physics

Neutral heavy meson mixings

CP Violation

Rare decays

Heavy mesons production

Heavy baryon production and decays

Heavy hadron Spectroscopy

Tau physics

Outline

- CKM Matrix and CPV
  - 2-body decays
  - 3-body decays
- Flavour Anomalies
  - $R(D)$ and $R(D^*)$
  - $R(K)$ and $R(K^*)$
- CPV in D meson Decays
- Summary

New Physics, where are you?

Despite many convincing motivations for NP at the TeV scale, we are still lacking a discovery!

Too heavy to be probed by direct searches

too weakly coupled to leave a visible imprint

Needed: indirect probes of new particles and interactions that are sensitive even to very small NP effects

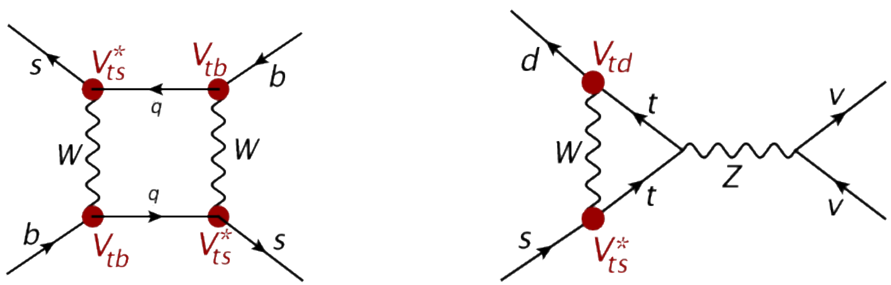
FLAVOUR PHYSICS

Flavour changing neutral current processes

FCNCs are strongly suppressed in the SM

- Loop factor
- Chiral structure of weak interactions
- CKM hierarchy
- GIM mechanism (CKM unitarity)

⇒ unique sensitivity to NP contributions – probing scales far beyond the TeV range



Crucial:

high precision in
- ➤ measurements of flavour violating decays
- ➤ predictions of the SM contribution

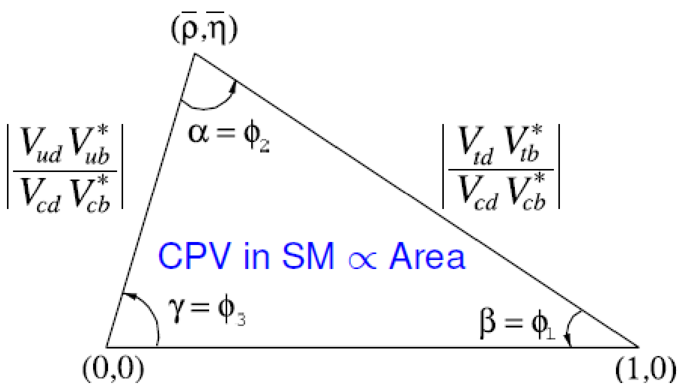
Precision determination of CKM elements

- The $(u, c, t)W^{\pm}(d, s, b)$ couplings:

$$V_{\rm CKM} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{\text{CKM matrix}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \ldots$$

  - 9 complex couplings depend on 4 real parameters ⇒ many testable relations
  - One complex phase in VCKM: only source of CP violation in quark mixing

- Unitarity triangle: visualize SM constraints and compare measurements

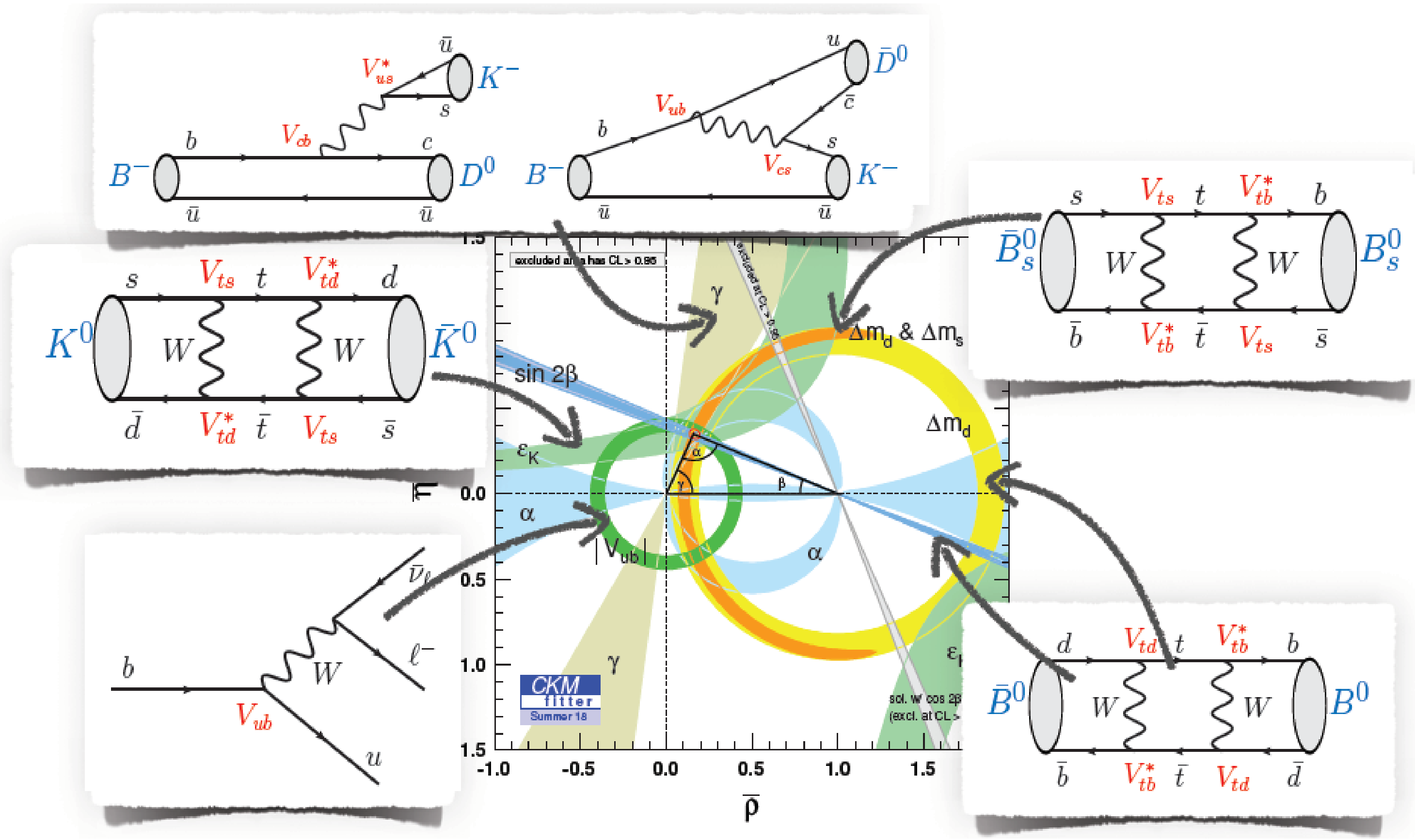


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Sides and angles measurable in many ways

Goal: overconstrain by many measurements sensitive to different short distance physics

Precision determination of CKM elements



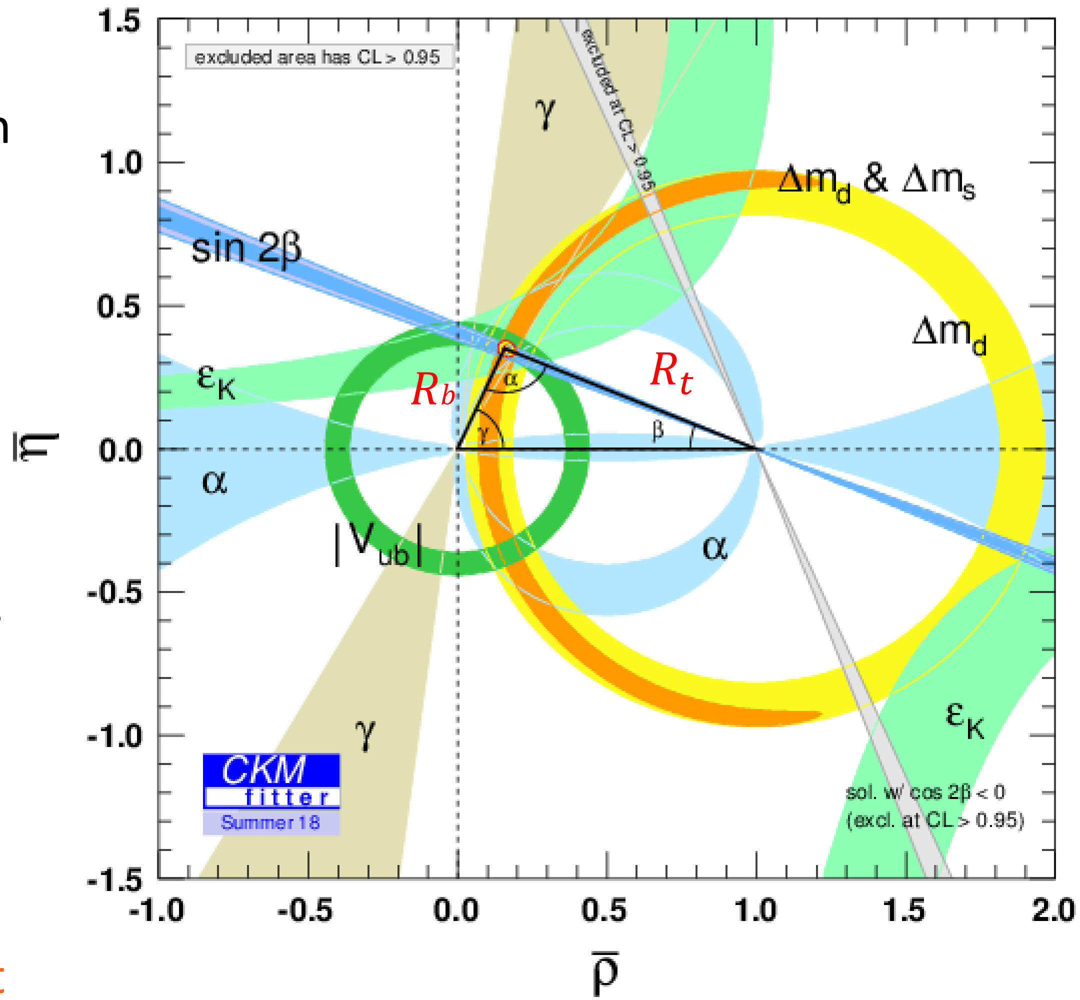
- ➢ model-independent determination of CKM matrix as a standard candle of the SM

Learned a lot, plenty of room for new physics

- Ideally determined solely through tree-level measurements:

  $|V_{ub}|, |V_{us}|, |V_{cb}|$ and γ

- $Rb \sim |Vub|/|Vcb|$ not well known due to persisting |Vub| problem
- Successful explanation of flavour physics up to now! Hundreds of observables (including dozens of CPV) are explained by this single matrix
- O(20%) NP contributions to most loop-level processes (FCNC) are still allowed



Searching New Physics via CPV

- Interference of Tree and Penguin diagrams induce CPV observable.

$$
\begin{aligned}
A(\overline{B}^0 \to \overline{f}) &= A_1 e^{+i\theta_1} e^{+i\delta_1} + A_2 e^{+i\theta_2} e^{+i\delta_2} \\
A(B^0 \to f) &= A_1 e^{-i\theta_1} e^{+i\delta_1} + A_2 e^{-i\theta_2} e^{+i\delta_2}
\end{aligned}
$$

$\theta_{1,2}$: CP the violating phase, $\delta_{1,2}$: the CP conserving phase.

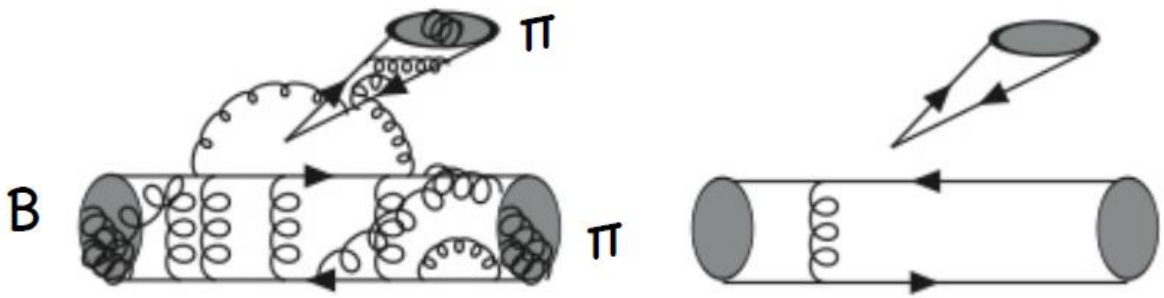
$$
\frac{\Gamma(\overline{B}^0 \to \overline{f}) - \Gamma(B^0 \to f)}{\Gamma(\overline{B}^0 \to \overline{f}) + \Gamma(B^0 \to f)} = \frac{2(A_2/A_1)\sin(\theta_1 - \theta_2)\sin(\delta_1 - \delta_2)}{1 + 2(A_2/A_1)\cos(\theta_1 - \theta_2)\cos(\delta_1 - \delta_2)}
$$

- We can measure CPV only through an interference of two amplitudes with different CP conserving and CP violating phases.

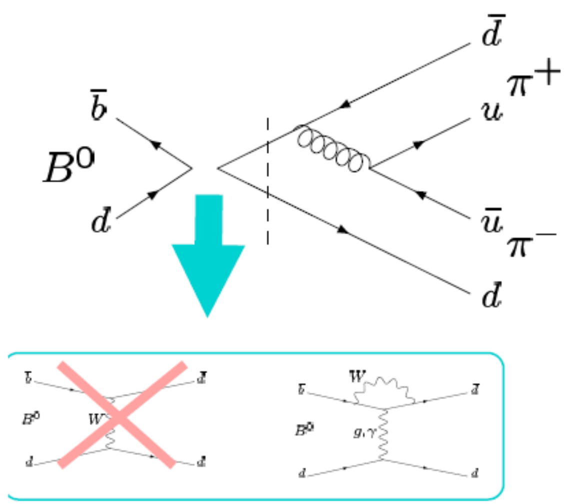
- Tree/Penguin contributions provide two sources of weak phases. Big challenge is to theoretically/ experimentally obtain the strong phase difference.

Searching New Physics via CPV

2-Body decays, the most challenge is how to calculate the hadronic matrix elements.



QCDF,
PQCD,
SCET,
FA+SU(3),
LCQCDSR



- ✓ Theoretical development in QCD higher order and high power corrections, Lattice QCD etc, allow to reduce the theoretical uncertainties.

- ✓ Improved measurements of "theoretical control channels" are very important to reduce the theoretical errors.

High Order/Power Corrections

□ Higher Order radiative corrections:

- QCDF at leading power and at NNLO in QCD established and almost complete.

  Xin-Qiang Li, Beneke, et.al.

- PQCD : NLO in QCD is being done

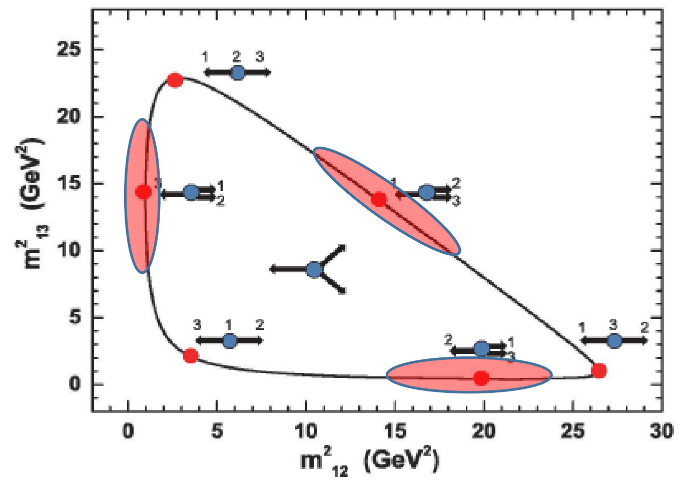
  H.N Li, Y.L. Shen, Y.M. Wang, Z.J. Xiao, S.Cheng, et.al

□ Higher Power Corrections

M.Beneke, Y.M. Wang, C.D.Lu, Y.L.Shen, Z.T.Zou,

Searching New Physics via CPV

3-Body decays



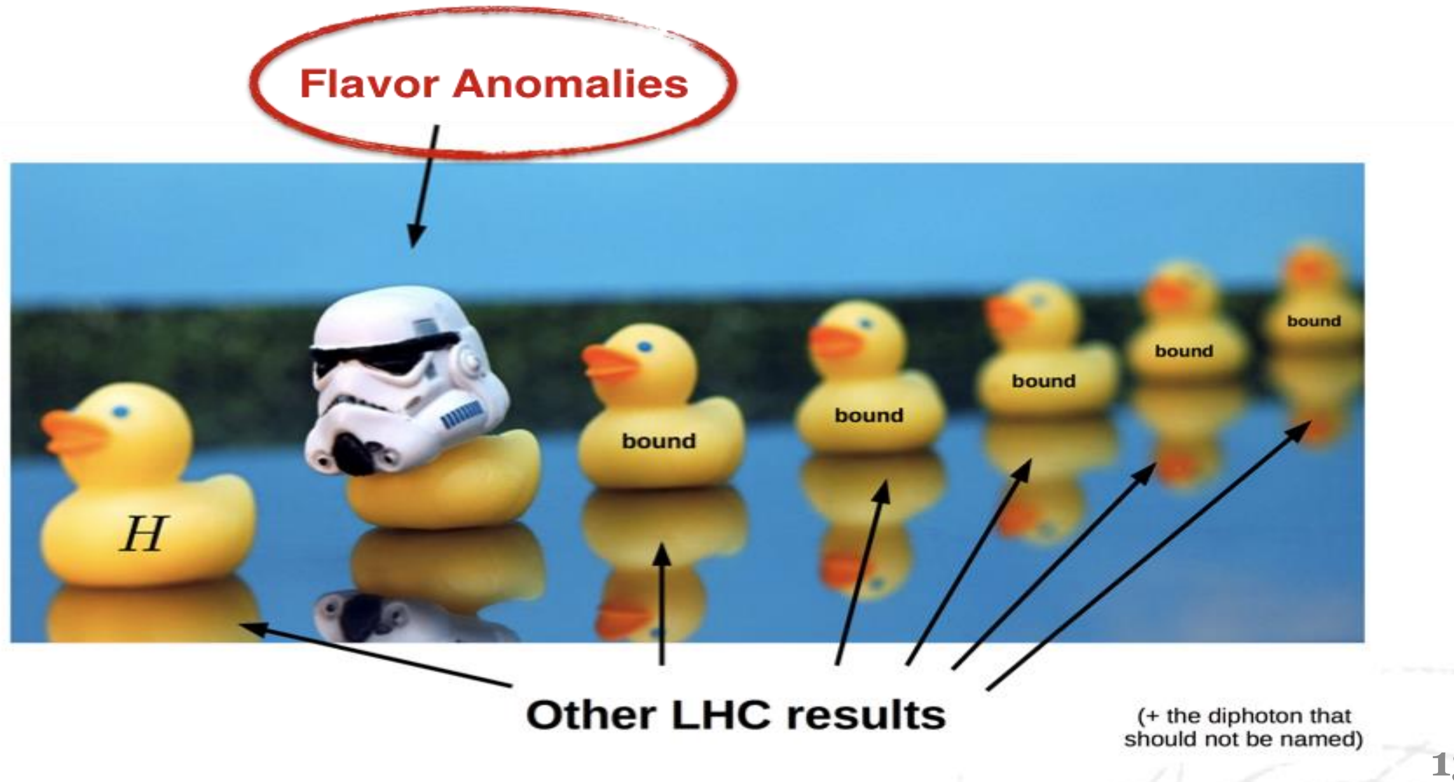
- A reliable theoretical approach to calculate 3-body hadronic B decays is needed .
- We need understand branching fractions and predict direct CP asymmetries in localized regions of phase space

Many attempts have been made to calculate 3-body decays:

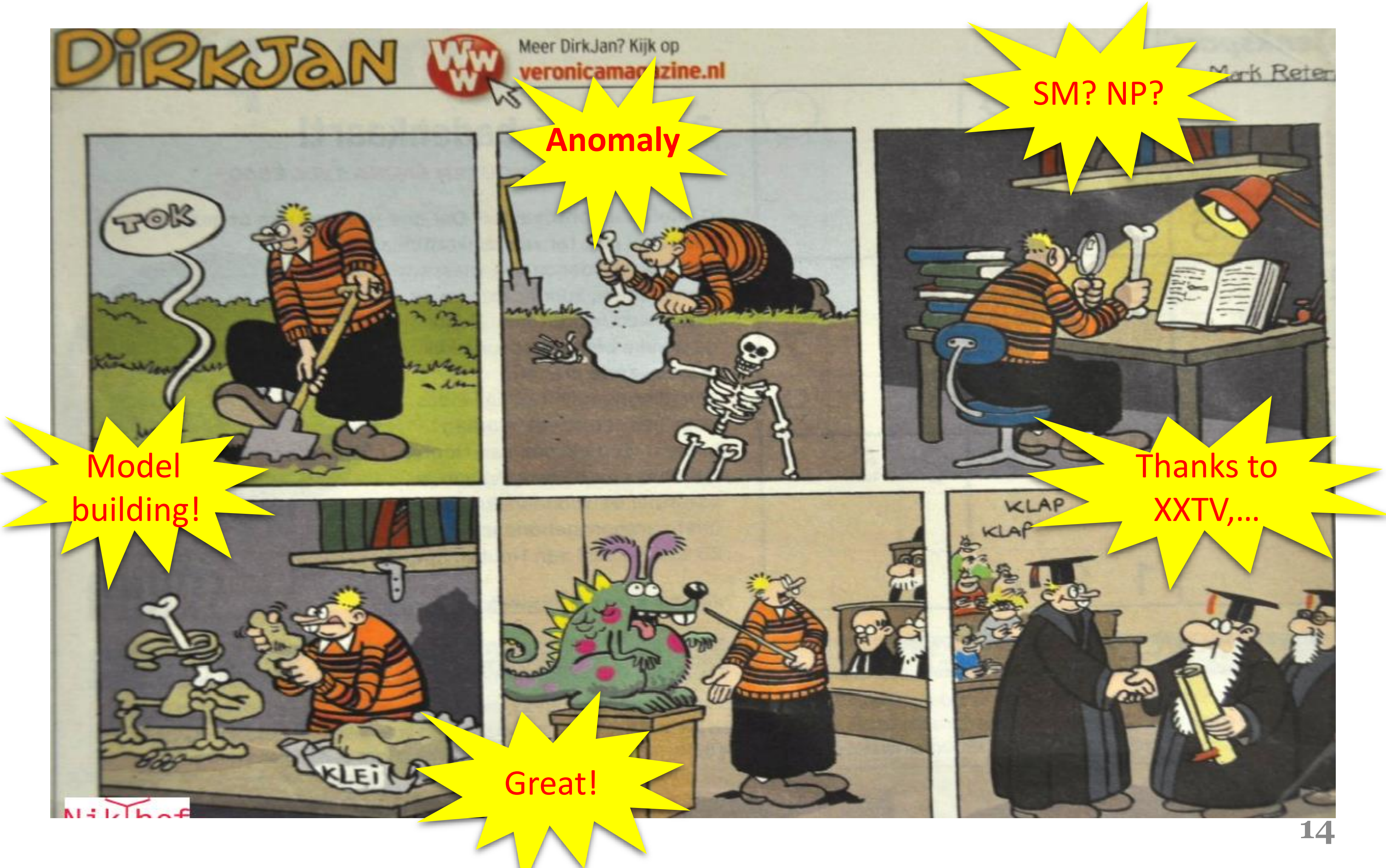
- **Factorization Approach** Cheng, Chua, S. Fajfer, YL,…
- **PQCD** Li, Chen, Wang, Wang, Lu, YL …
- **QCD Factorization** Krankl, Mannel,Virto,…
- **Diagrammatic Approach combined SU(3)** Gronau,London
- **QCD Sum Rules** Alexander Khodjamirian, S.Cheng…
- **Others** Feldman, Guo, He, Yang,…

Recent anomalies in LFU-violating B decays

- To search for NP, we build a big machine (LHC) with four detectors，
- Before the LHC started operating we all hoped for great discoveries...,
- So far, both ATLAS and CMS have not found any new particle,....



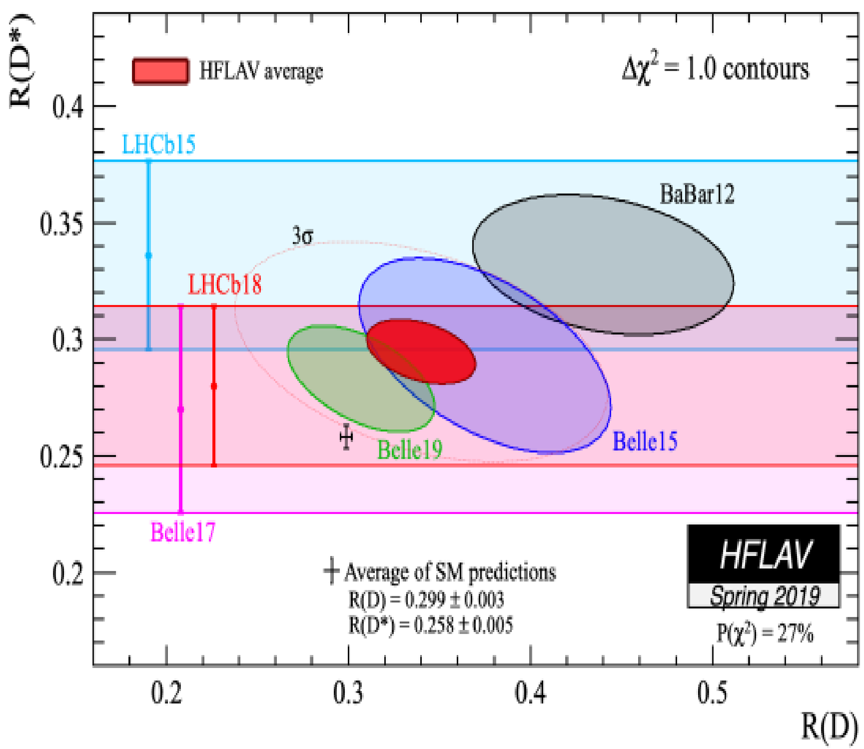
We love anomalies!



The R(D$^{(*)}$) anomaly

Test of lepton flavour universality in semi-tauonic *B* decays

$$\mathcal{R}(D^{(*)}) = \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)} \qquad (\ell = e, \mu)$$



- theoretically clean, as hadronic uncertainties largely cancel in ratio
- measurements by BaBar, Belle, LHCb (so far $R(D^*)$ only)
- recent Belle result (semi-leptonic tag) is in good agreement with SM prediction

➢ **3.1σ discrepancy with SM** **HFLAV (2019)**

Effective Hamiltonian for $b \to c\tau\nu$

New Physics above B meson scale is described model-independently by

$$\mathcal{H}_{\rm eff}^{\rm NP} = 2\sqrt{2}G_F V_{cb}\Big[(1+C_V^L)O_V^L + C_S^R O_S^R + C_S^L O_S^L + C_T O_T\Big]$$

$$O_V^L = (\bar{c}\gamma^\mu P_L b)\,(\bar{\tau}\gamma_\mu P_L \nu_\tau) \qquad O_S^R = (\bar{c}P_R b)\,(\bar{\tau}P_L\nu_\tau)$$

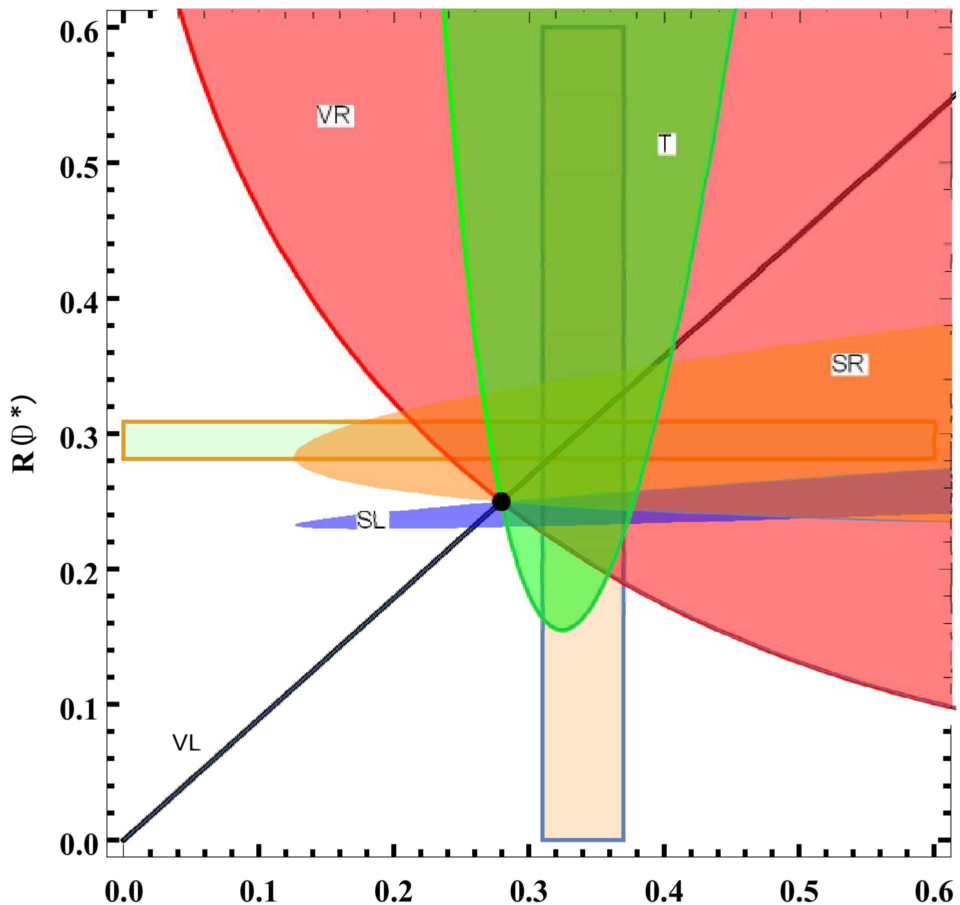
$$O_T = (\bar{c}\sigma^{\mu\nu}P_L b)\,(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau) \qquad O_S^L = (\bar{c}P_L b)\,(\bar{\tau}P_L\nu_\tau)$$

Popular BSM scenarios:

- Charged Higgs $C_S^{L,R} \neq 0$ **Kalinowski (1990); Hou (1993) Crivellin, Kokulu, Greub (2013)…**
- Charged vector boson W' $C_V^L \neq 0$ **He,Valencia(2012); Greljo,Isidori, Marzocca(2015)…**
- Scalar or vector leptoquark various $C_j^{L,R} \neq 0$ $(depending\ on\ models)$

Tanaka, Watanabe (2012); Deshpande, Menon (2012); Kosnik (2012); Freytsis et al (2015) Alonso et al (2015); Calibbi et al (2015); Fajfer, Kosnik (2015); Becirevic et al (2016),(2018) ,XQ Li,,et.al (2015,2016)

Single particle scenarios



Mu,YL, et. al, 1909.10769

Mu,YL, et.al, 1909.10769
Monika, Crivellin, Kitahara, 1811.09603
Murgui et.al 1904.09311
Shi et al 1905.08498
....

Main results

- W' solution disfavoured by LHC direct searches Faroughy, Greljo, Kamenik (2016)
- Significant improvement possible with various leptoquark scenarios
- Charged Higgs scenario predicts very large

$$BR(B_c \to \tau\nu) \simeq 50\%$$

Alonso, Grinstein, Martin Camalich (2016)
Akeroyd, Chen (2017);
Blanke et al (2018)

More flavour observables to test NP in R(D$^{(*)}$)

☐ Direct probes of NP structure

- $B \to D^{(*)}\tau\nu$ differential distributions, angular and polarization observables

$$\text{EX}\ \ F_L(D^*) = 0.60 \pm 0.08 \pm 0.04$$

Belle，1901.06380

$$\text{SM}\ F_L(D^*) = 0.455 \pm 0.003$$

ZR Huang, YL, et.al, 1808.03565

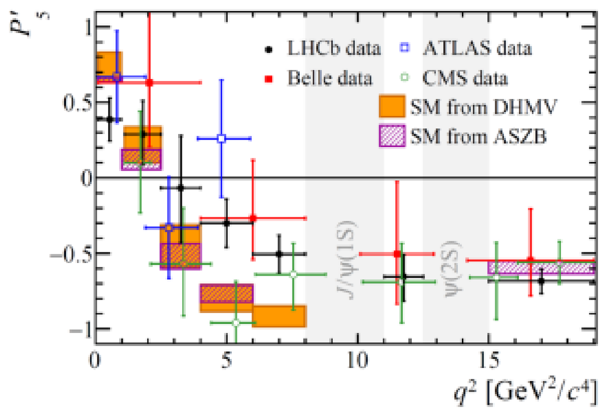
- $B_c \to J/\psi\tau\nu$ differential distributions, angular and polarization observables
- $\Lambda_b \to \Lambda_c\tau\nu$ differential distributions, FBA and polarization observables

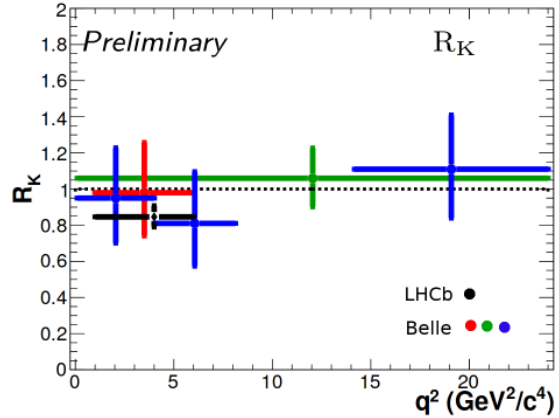
Mu,YL, et. al, 1909.10769

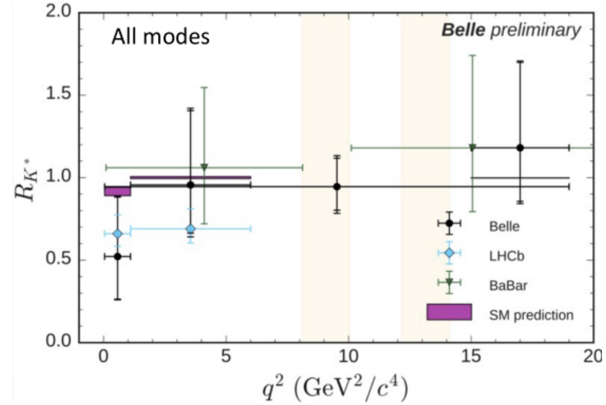
☐ Additionally: implied by SU(2)$_L$ symmetry

- large impact $B \to K^{(*)}\upsilon\bar{\upsilon}$, $B_s \to \tau^+\tau^-$, $B \to K\,\tau^+\tau^-$
- contributions to $\Upsilon \to \tau^+\tau^-$ and $\psi \to \tau^+\tau^-$

Anomalies in $b \to s l^+ l^-$ transitions



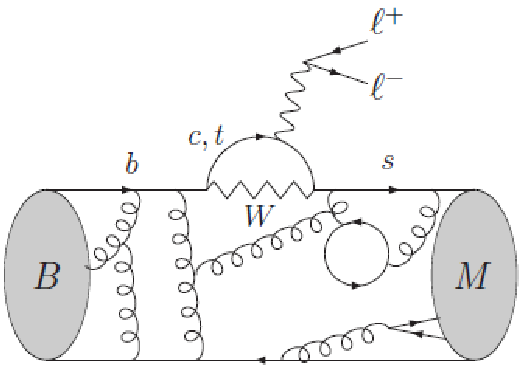




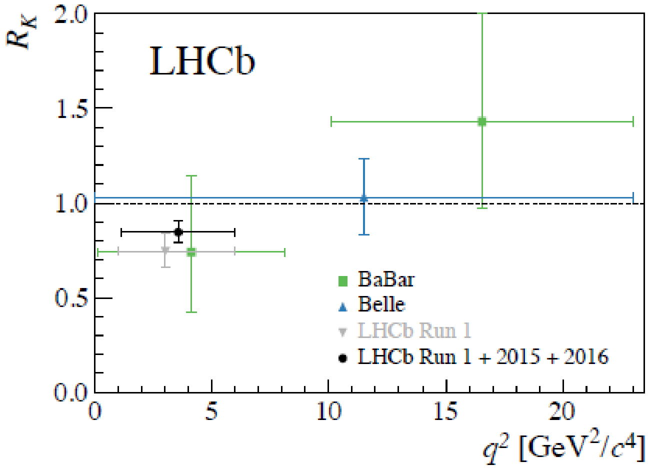
deviations from SM predictions seen in

- angular distribution of $B \to K^* \mu^+ \mu^-$ (mainly P_5')
- lepton flavour universality ratios $\mathcal{R}_{K^{(*)}} = \frac{\text{BR}(B \to K^{(*)} \mu^+ \mu^-)}{\text{BR}(B \to K^{(*)} e^+ e^-)}$
- less significant tensions in other observables, e. g. BR$(B_s \to \phi \mu^+ \mu^-)$, BR$(B_s \to \mu^+ \mu^-)$

R(K)



$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$



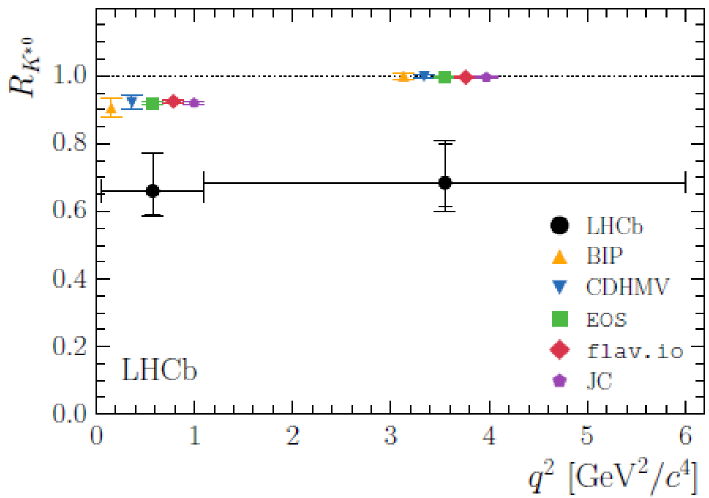
Adding 2015 and 2016 data, R_K becomes:

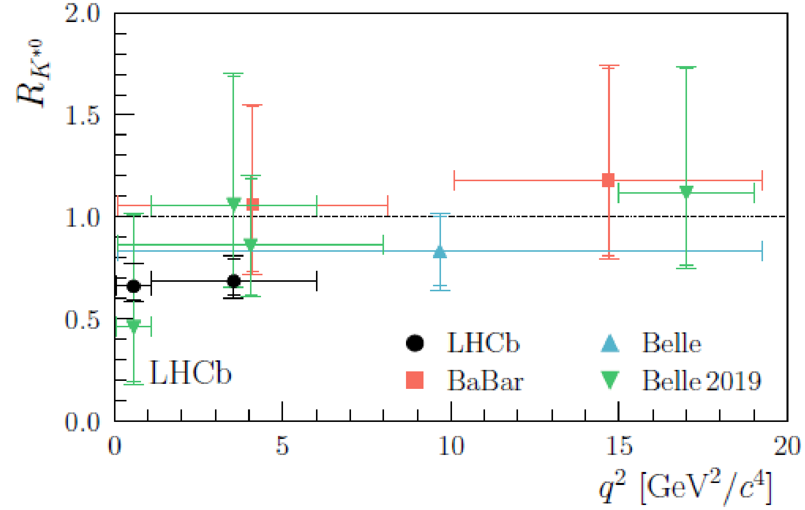
$$R_K = 0.846\ ^{+0.060}_{-0.054}\,(\text{stat.})\ ^{+0.016}_{-0.014}\,(\text{syst.})$$

$\sim 2.5\,\sigma$ from SM.

1903.09252

R(K*)



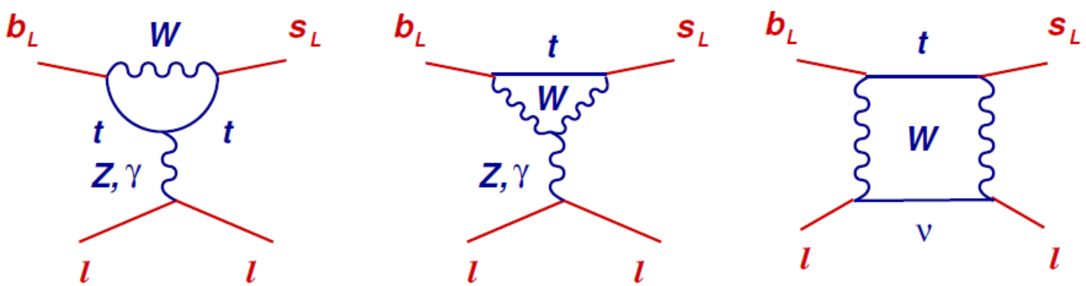


$$R_{K^*}^{\rm exp} = \begin{cases} 0.66\,^{+0.11}_{-0.07} \pm 0.03\,, & 0.045 \le q^2 \le 1.1\ {\rm GeV}^2\ (\text{low } q^2) \\ 0.69\,^{+0.11}_{-0.07} \pm 0.05\,, & 1.1 \le q^2 \le 6.0\ {\rm GeV}^2\ (\text{central } q^2) \end{cases}$$

- LHCb result is in tension with the SM at 2σ level
- New results from Belle are **in agreement with SM** and **previous** experimental results

What can we learn from this anomaly

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



$$\Rightarrow \quad G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \, \bar{s}_L \gamma^\mu b_L \, \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

- In SM, this is same for all lepton flavours: lepton univesality (LU)
- LUV could arise from new physics (NP): $\Lambda \gg m_W$

$$\frac{g^2}{\Lambda^2} \bar{s}_L \gamma^\mu b_L \, \bar{\ell} \gamma_\mu (\gamma_5) \ell$$

$$\frac{g^2}{\Lambda^2} \approx 0.25 \times G_F V_{tb} V_{ts}^* \frac{\alpha}{4\pi} C_{9(10)} \quad \Rightarrow \quad \frac{\Lambda}{g} \approx 28 \text{ TeV}$$

Scale of NP?

Good argument to build new colliders!

New Physics in $b \to sl^+l^-$

Effective $b \to sl^+l^-$ Hamiltonian

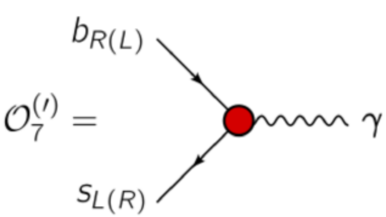
$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}^* V_{ts} \frac{e^2}{16\pi^2} \sum_i (C_i \mathcal{O}_i + C_i' \mathcal{O}_i') + h.c.$$

with the operators most sensitive to New Physics

$$O_7^{bs} = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \qquad O_7'^{bs} = \frac{m_b}{e} (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu},$$

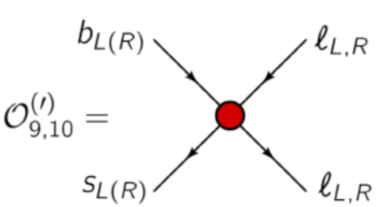
$$O_9^{bs\ell\ell} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad O_9'^{bs\ell\ell} = (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell),$$

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



electromagnetic dipole operators $O_7^{(\prime)}$

- govern inclusive and exclusive $b \to s\gamma$ transitions
- enhanced contribution to $B \to K^* \ell^+ \ell^-$ in low q^2 region

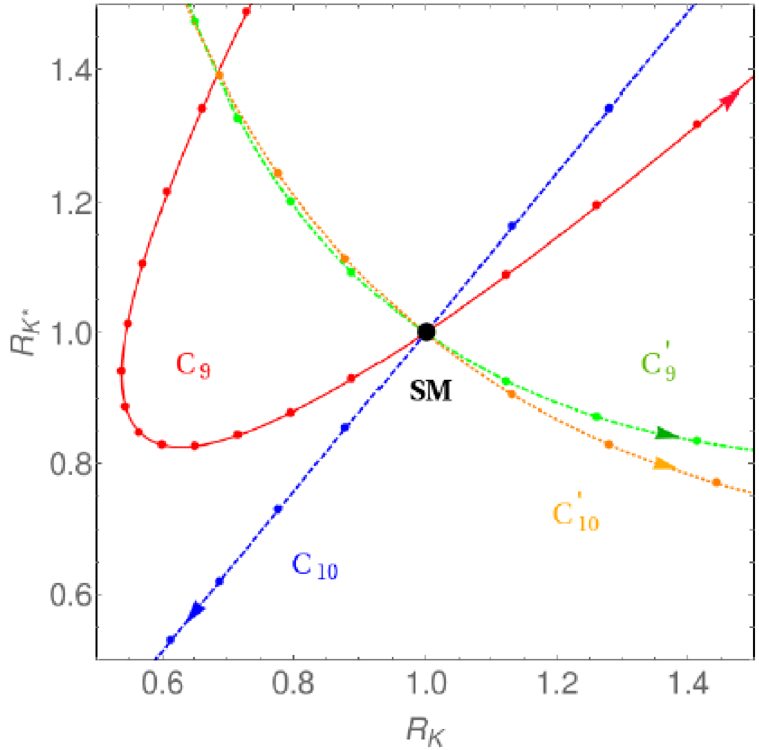


semileptonic four-fermion operators $O_9^{(\prime)}, O_{10}^{(\prime)}$

- loop-suppressed in the SM, but potentially tree level in the presence of NP

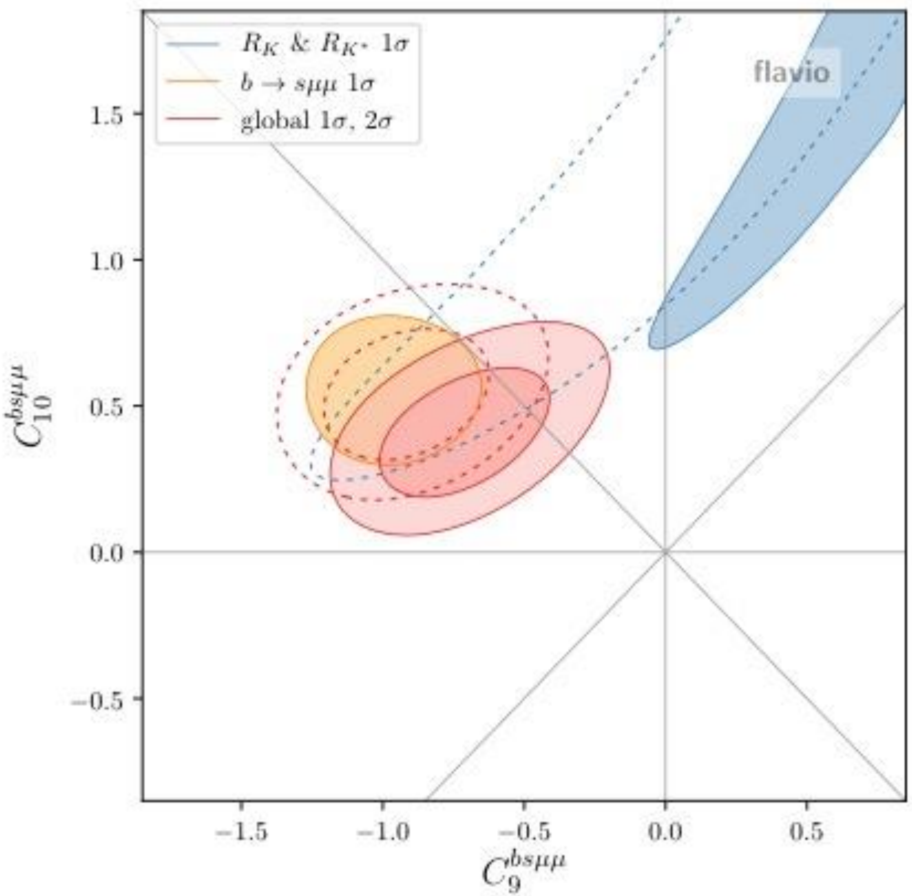
Status of global fits

Li-Sheng Geng,et.al, 1704.05446

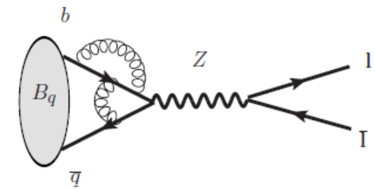


- Nodes indicate steps of $\Delta C^{\mu} = 0.5$
  - **Primed operators** $C'_{9,10}$: Monotonically decreasing dependence $R_{K}(R_{K})$!
- New physics in electrons mirror image of above

Status of global fits



Main results



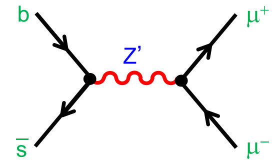
- Best 1D fit solution
  - C_9^μ=-0.95
  - C_9^μ=- C_{10}^μ= -0.73
- Nonzero C_{10}^μ preferred by deviation in BR($B_s \to \mu^+\mu^-$)
- Some tension between $b \to s\mu^+\mu^-$ data and LFU ratios R_{K^*}
  - Small flavor-universal contribution to C_9 possibility generated by RGE effects.

Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub (2019)
Alguero et al (2019); Arbey et al (2019); Kowalska et al (2019)

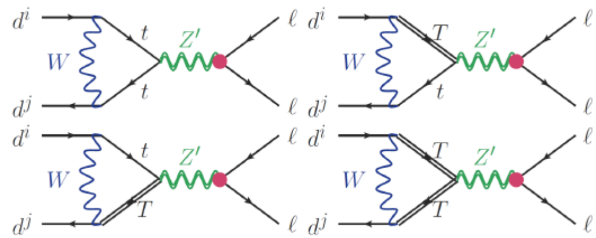
Opening up the black box

Variety of NP models on the market

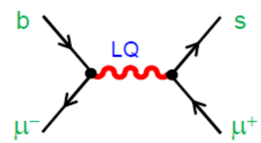
- tree-level flavour changing Z'

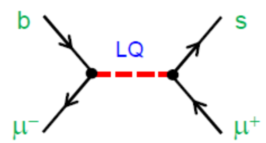


- loop-induced NP



- leptoquarks



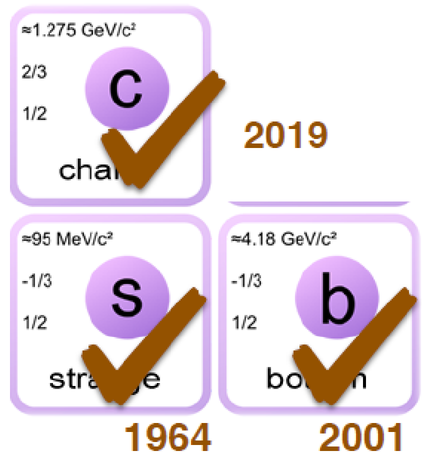


Most popular (subject to personal taste): $SU(2)_L$-singlet vector leptoquark U_1

- least constrained by complementary data (e. g. B_s mixing, direct searches)
- potential common origin of $b \to s\mu\mu$ and $b \to c\tau\nu$ anomalies
- naturally contained in the Pati-Salam gauge group $SU(4) \times SU(2)_L \times SU(2)_R$

Plenty of model-building effort for UV-complete model

CPV in D meson decay



$$\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$$

$$= (-1.54 \pm 0.29) \times 10^{-3}$$

LHCb, PRL122, 211803 (2019)

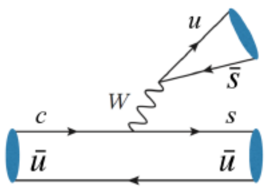
Charm CPV of order 10^{-3}

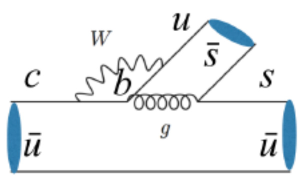
Precision of order 10^{-4}

➢ 5σ **, first observation of CPV in charm**

CPV in D meson decay

tree v.s. penguin





$V_{cd}V_{ud}/V_{cs}V_{us}$ $\qquad$ $V_{cb}V_{ub}$

λ $\qquad$ $\lambda^5 + i\lambda^5$

$$\mathcal{A}(D^0 \to K^+K^-) = \lambda_s \mathcal{T}^{KK} + \lambda_b \mathcal{P}^{KK},$$

$$\mathcal{A}(D^0 \to \pi^+\pi^-) = \lambda_d \mathcal{T}^{\pi\pi} + \lambda_b \mathcal{P}^{\pi\pi},$$

$$r = |\lambda_b/\lambda_{d,s}|$$

$$\Delta A_{CP} = -2r\sin\gamma\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right)$$

$$2r\sin\gamma = 1.5\times 10^{-3}$$

$$\Delta A_{CP} = (-1.54 \pm 0.29)\times 10^{-3}$$

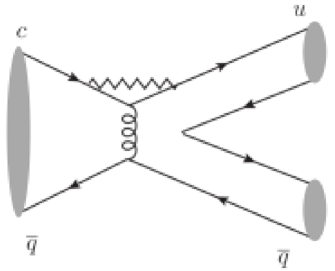
→ $\left(\frac{|\mathcal{P}^{KK}|}{|\mathcal{T}^{KK}|}\sin\delta^{KK} + \frac{|\mathcal{P}^{\pi\pi}|}{|\mathcal{T}^{\pi\pi}|}\sin\delta^{\pi\pi}\right) \approx 1$

→ $\frac{|\mathcal{P}|}{|\mathcal{T}|}\sin\delta \sim 1/2$

How to understand large penguin?

CPV in D meson decay

- **Where is large penguin from?**
  - Non-factorizable emission diagrams
  - Annihilation diagrams
  - New Physics



- **ΔACP(K+K-, π+π-) predicted from 10^{-4} to 10^{-2}**
  - *Ignoring annihilation diagrams： 10^{-4}*
  - *Adding annihilation diagrams from B decays： 10^{-2}*
  - *Fitting annihilation diagrams to data: 10^{-3}*
  - *Possible solutions: ignoring annihilation+chromomagnetic dipole*

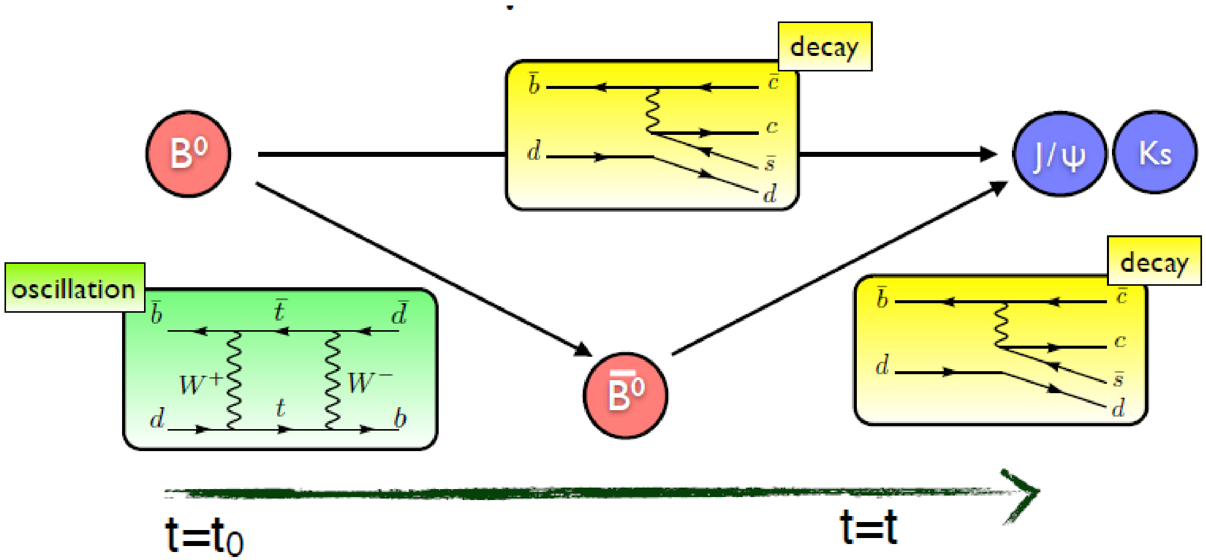
Grossman, Kagan, Nir, '07; Bigi, Paul, '11; Isidori, Kamenik, Ligeti, Perez, '11;
Brod, Grossmann,Kagan, Zupan, '11, '12; Feldmann, Nandi, Soni, '12;
Bhattarcharya, Gronau, Rosner, '12; **Cheng,Chiang, '12; Li, Lu,Yu, '12;**
Franco, Mishima, Silvestrini, '12; Hiller, Jung, Schacht, '12， Khodjamirian, Petrov, 17.

Summary

- Flavour structure and CP violation are major pending questions
- Flavour anomalies are sensitive to New Physics.
- Both experimental data and theoretical calculations in high precision are needed.
- Flavour anomalies offer great opportunities for model builders! (DM, g-2. neutrino,…)

Thank you for your attention!

CPV in time-dependent measurement



$$|B(t)\rangle = f_+(t)|B\rangle + \frac{q}{p} f_-(t)|\overline{B}\rangle$$

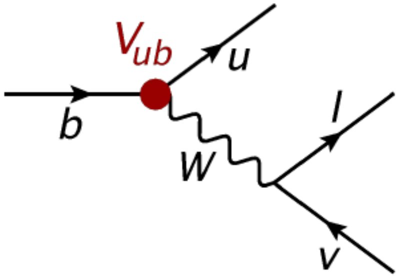
where

$$f_\pm = \frac{1}{2} e^{-iM_1 t} e^{-\frac{1}{2}\Gamma_1 t} \left[1 \pm e^{-i\Delta M t} e^{\frac{1}{2}\Delta\Gamma t} \right]$$

- The time-evolution gives the CP conserving phase and the $B - \bar{B}$ mixing gives the CP violating phase.

Precision determination of CKM elements

Tree level decays: flavour changing charged current interactions



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

- direct sensitivity to relevant CKM element
- small impact of NP contributions expected
- four independent measurements needed to fully determine CKM matrix

➢ model-independent determination of CKM matrix as a standard candle of the SM