Prospettive nella fisica dei sapori (adronici e leptonici)

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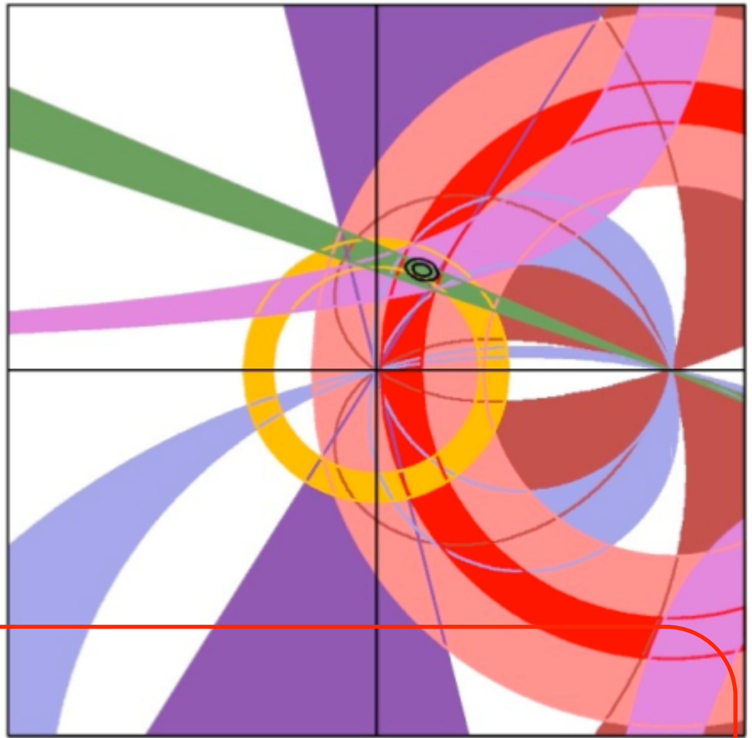
This is a very hard task since:

It is difficult to make predictions, especially about the future

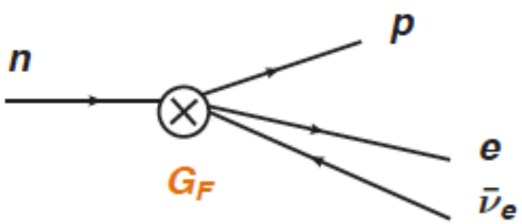
N. Bohr

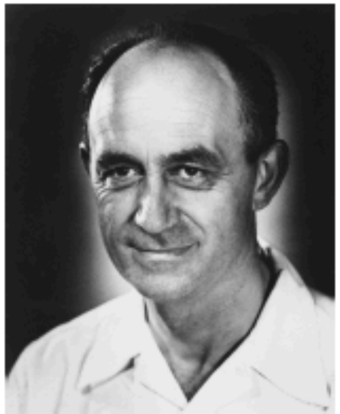


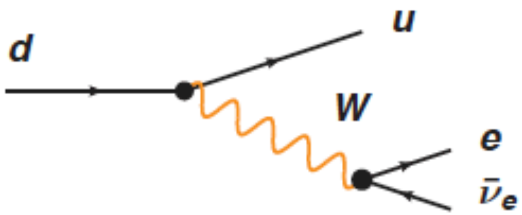
however, to foresee the future, we must at least know the past and:

In the past Flavor Physics was a portal to predict the existence Of new interactions or new particles before we could have enough energy to produce them

Historic Example: Beta Decay







effective low energy description
of nuclear beta decay by a
4 fermion contact interaction

the interaction strength is given by
the Fermi constant

$$G_F \simeq 1.17 \times 10^{-5}\ \text{GeV}^{-2}$$

this defines an energy scale

$$\Lambda = (G_F\sqrt{2})^{-1/2} \simeq 246\ \text{GeV}$$

in the Standard Model
we understand beta decay
as consequence of
the exchange of virtual
weak gauge bosons

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8m_W^2}$$

$$m_W^2 = \frac{g_2^2 v^2}{4}$$

$$m_W \simeq 80\ \text{GeV}$$

Discoveries from Flavor Physics

CP Violation !!

- the tiny branching ratio of the decay $K_L \to \mu^+\mu^-$ led to the prediction of the charm quark to suppress FCNCs
(Glashow, Iliopoulos, Maiani 1970)

- the measurement of the frequency of kaon anti-kaon oscillations allowed a successful prediction of the charm quark mass
(Gaillard, Lee 1974)

(direct discovery of the charm quark in 1974 at SLAC and BNL)

- the observation of CP violation in kaon anti-kaon oscillations led to the prediction of the 3rd generation of quarks
(Kobayashi, Maskawa 1973)

- the measurement of the frequency of B - $\bar{B}$ oscillations allowed to predict the large top quark mass
(various authors in the late 80's)

(direct discovery of the bottom quark in 1977 at Fermilab)
(direct discovery of the top quark in 1995 at Fermilab)

The fundamental issue for the future is
to find signatures of new physics
see Standard Mantra (SM)

and to unravel the underlying theoretical structure

Since New Physics particles
have not been discovered (yet)

Precision Flavor physics is a key tool,
complementary to the high
energy searches @ the LHC

Precision is not important in itself
It is important to explore high energy scales/small couplings

If the LHC discovers new elementary particles BSM, then precision flavor physics will be necessary to constrain the underlying framework;

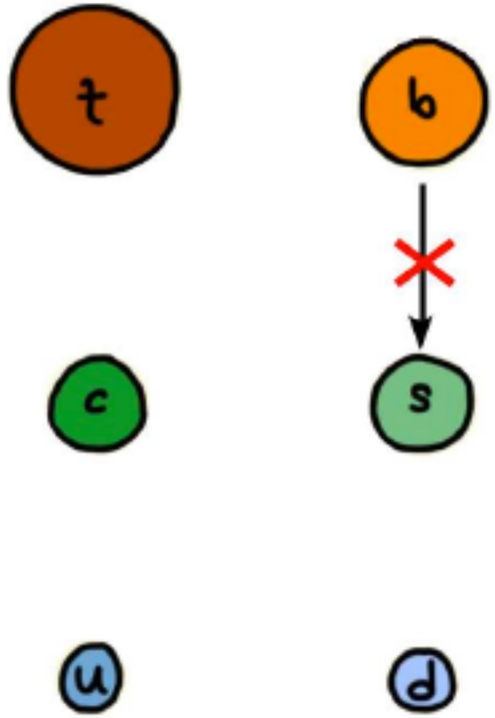
The discovery potential of precision flavor physics however should not be underestimated.

Absence of FCNC at tree level (& GIM suppression of FCNC @loop level)

Almost no CP violation at tree level

Flavour Physics is extremely sensitive to New Physics (NP)

In competition with Electroweak Precision Measurements



WHY RARE DECAYS ?

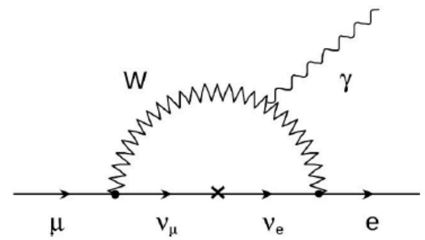
Rare decays are a manifestation of broken (accidental) symmetries e.g. of physics beyond the Standard Model

Proton decay — **baryon and lepton number conservation**

$\mu \to e + \gamma$

lepton flavor number

$\nu_i \to \nu_k$ **found !**



$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

RARE DECAYS WHICH ARE ALLOWED IN THE STANDARD MODEL

FCNC:

$q_i \;\; -> \;\; q_k \; + \;\; \nu \; \bar{\nu}$

$q_i \;\; -> \;\; q_k \; + \;\; l^+ \; l^-$

$q_i \;\; -> \;\; q_k \; + \;\; \gamma$

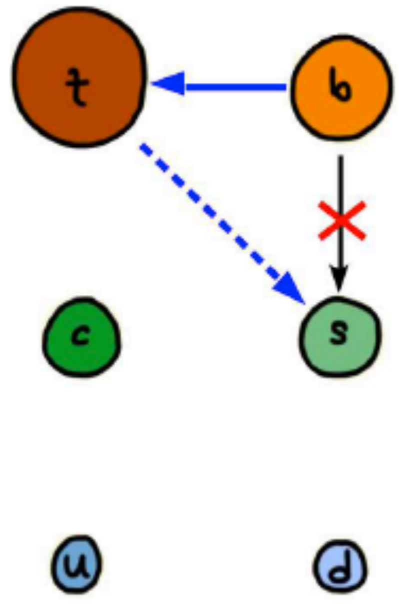
these decays occur only via loops because of GIM and are suppressed by CKM

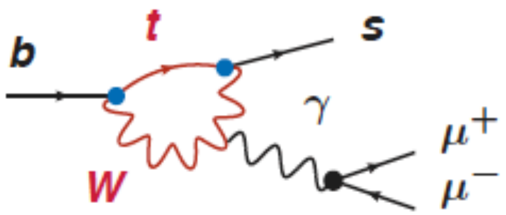
THUS THEY ARE SENSITIVE TO NEW PHYSICS

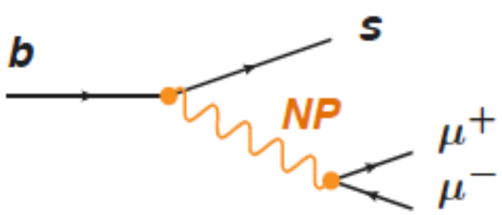
Flavor Changing Neutral Currents in the SM

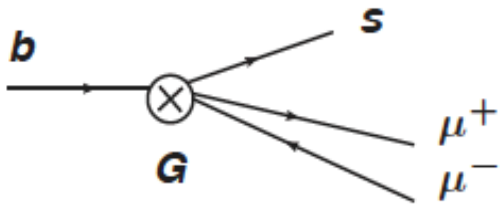
In the SM, flavor changing neutral currents (FCNCs) are absent at the tree level

FCNCs can arise at the loop level
they are suppressed by loop factors
and small CKM elements









$$G \sim \frac{1}{16\pi^2}\frac{g^4}{m_W^2}\frac{m_t^2}{m_W^2}V_{tb}V_{ts}^* + \frac{C_{NP}}{\Lambda_{NP}^2}$$

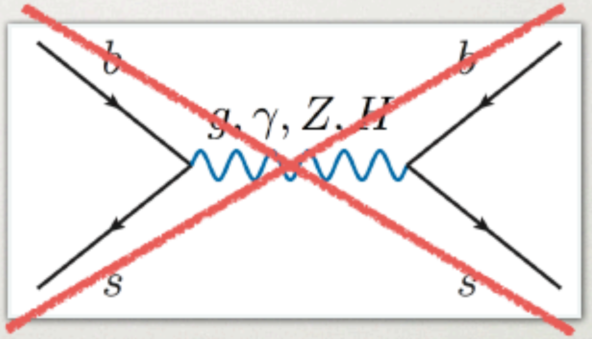
$\rightarrow$ measuring low energy flavor observables gives information on new physics flavor couplings and the new physics mass scale

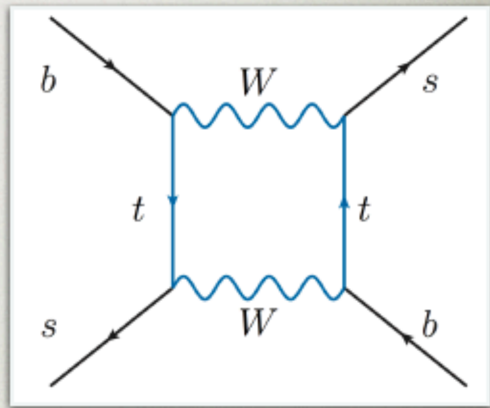
SENSITIVITY TO NEW PHYSICS

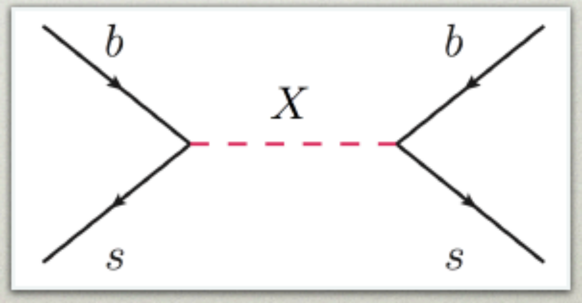
- SM@tree level: no Flavor Changing Neutral Currents
    - all FCNC processes loop suppressed
    - e.g., meson mixing
- can be modified by NP
- NP contribs. scale as

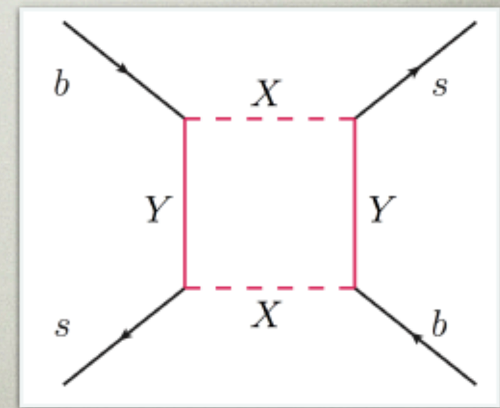
$$\boxed{\delta C^{\mathrm{NP}} \propto \frac{\sin\theta_i \sin\theta_j}{M_{\mathrm{NP}}^2}}$$

- depends on mix. angles and NP masses





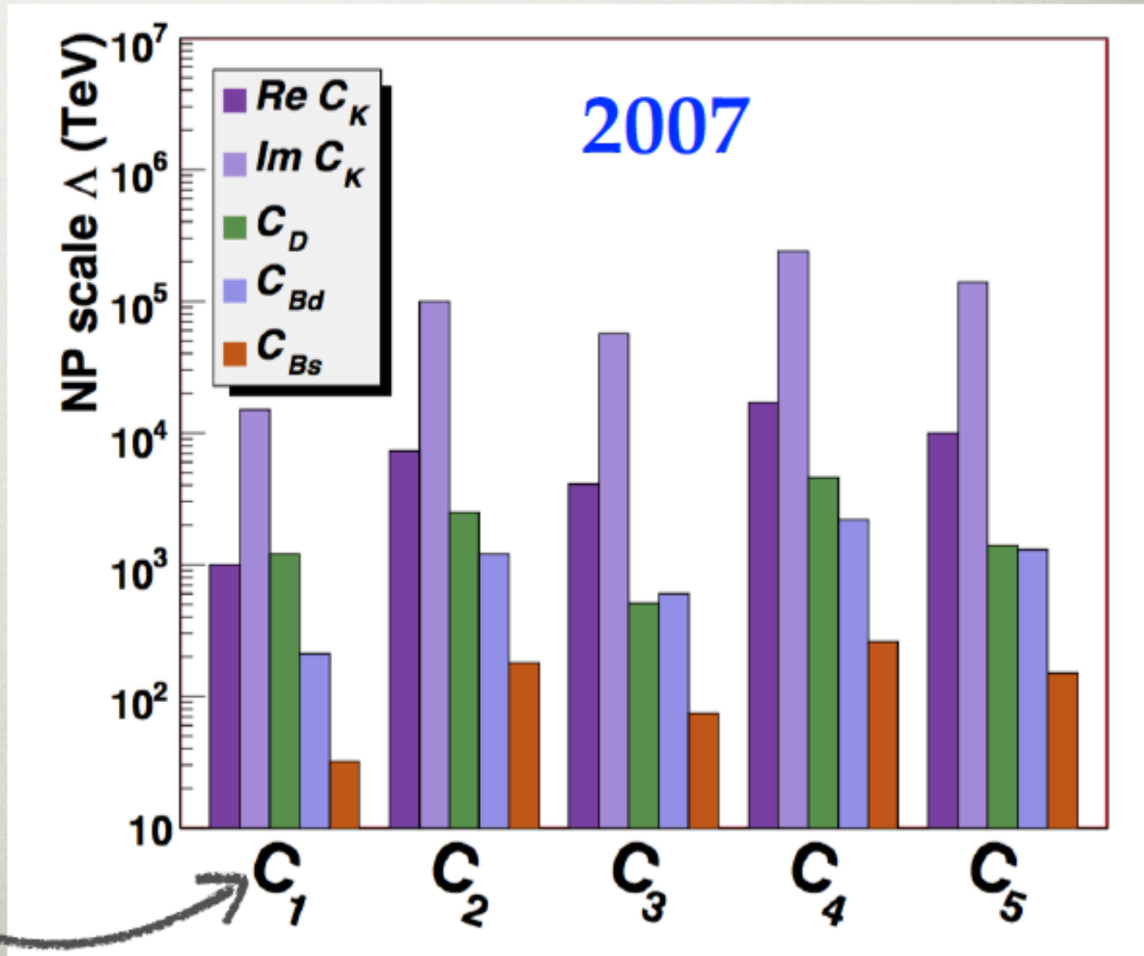




K0-K0bar Mixing continues to provide the best constraints on New Physics up to very large energy scales

- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing
- also from ε_K

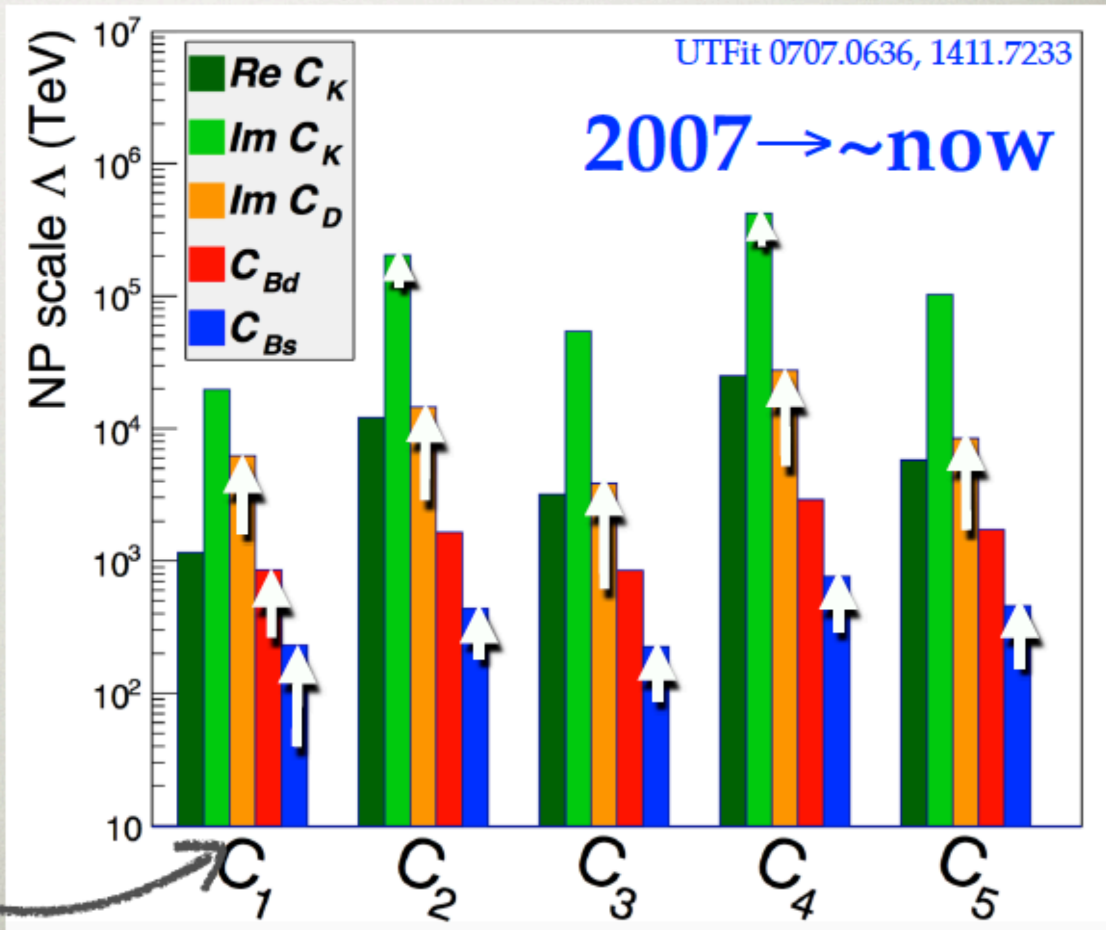
$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$



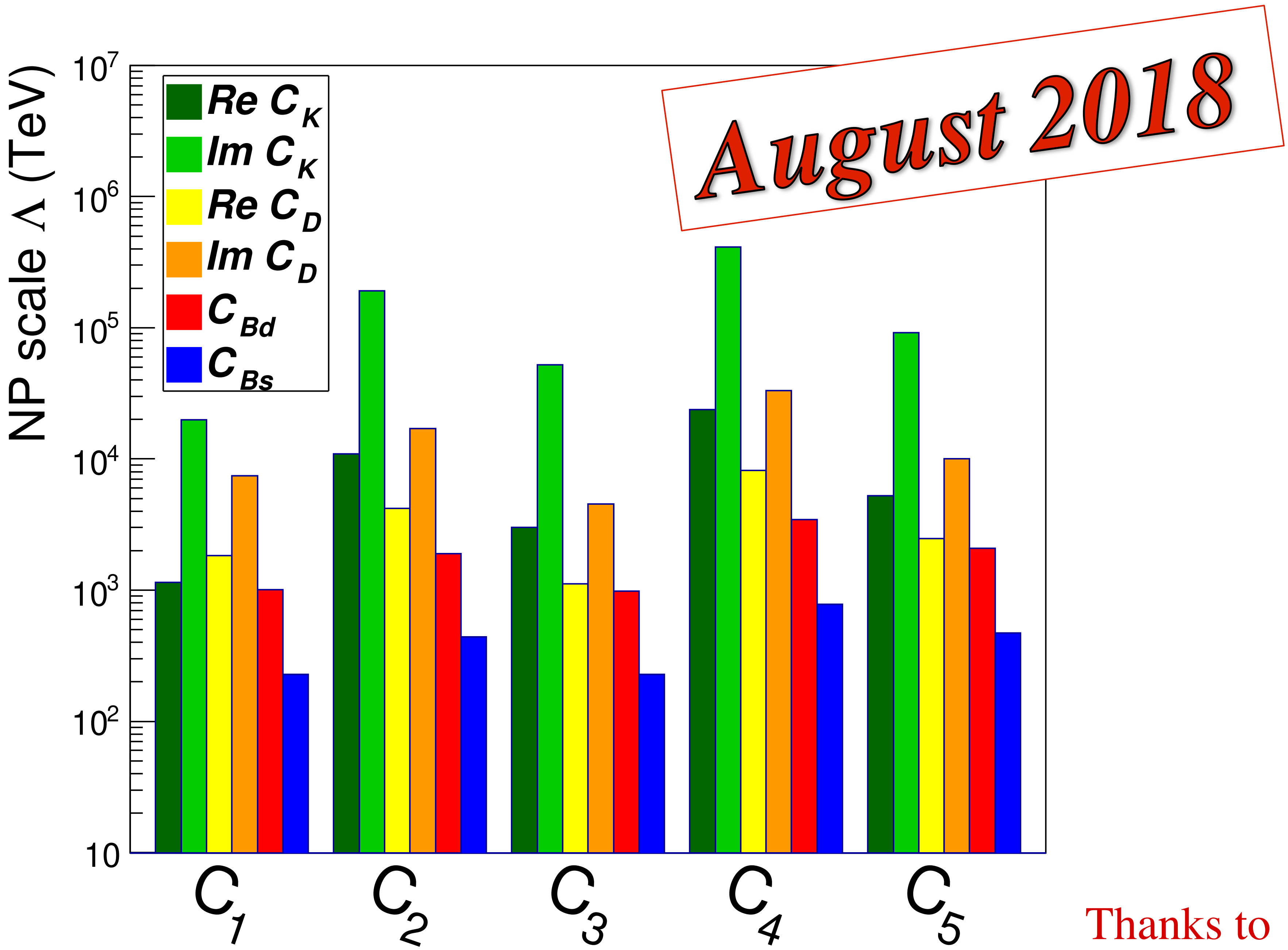
LOW ENERGY PRECISION BOUNDS

UTFit 0707.0636, 1411.7233
for latest charm see also Bazavov et al, 1706.04622

- an impressive progress on flavor bounds in last 10 years
- in D, B_s mixing
- also from ε_K

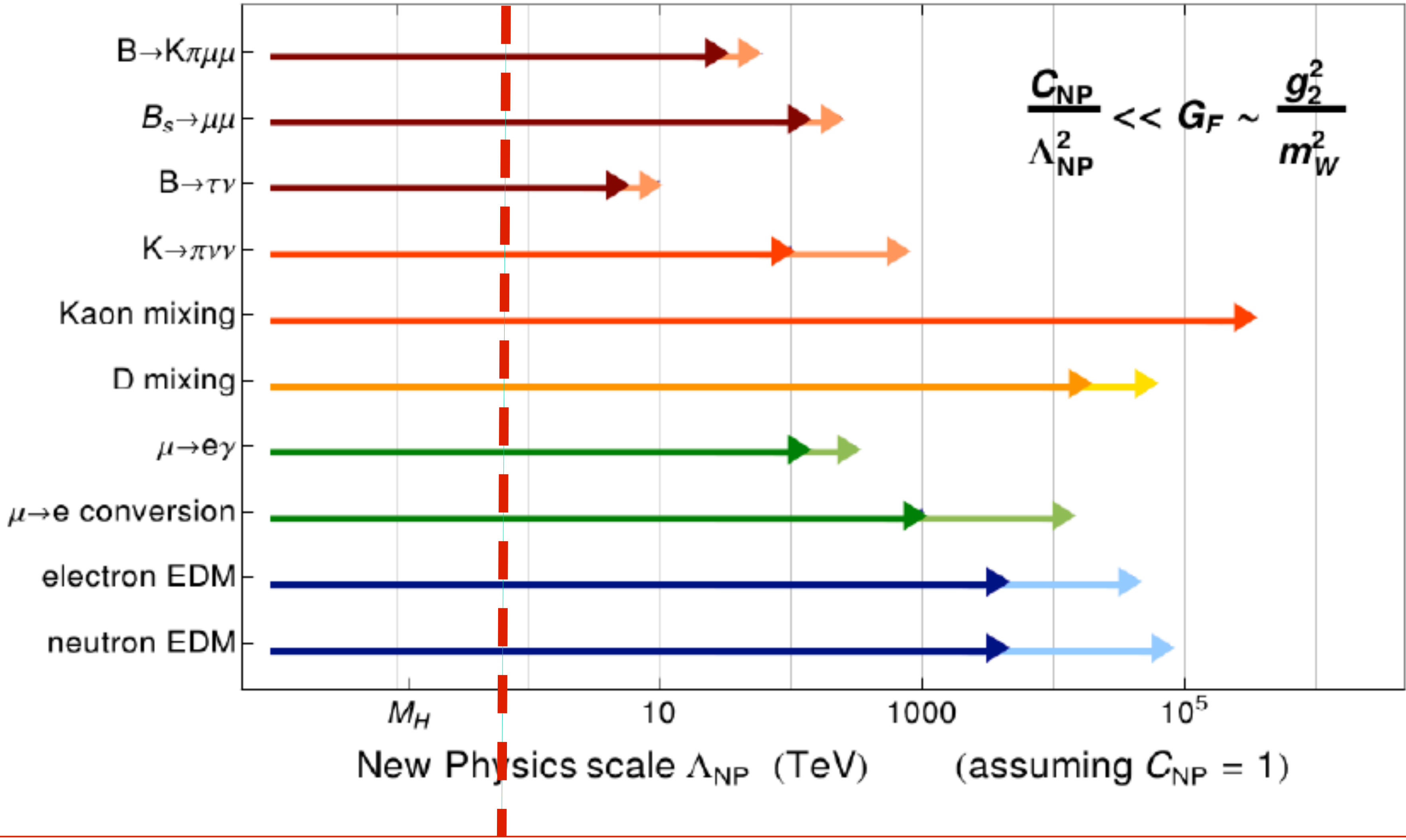


$$\frac{1}{\Lambda^2}(\bar{b}_L\gamma^\mu d_L)(\bar{b}_L\gamma_\mu d_L)$$



Thanks to
L. Silvestrini

Sensitivity to New Physics from Flavor



Approximate LHC direct reach

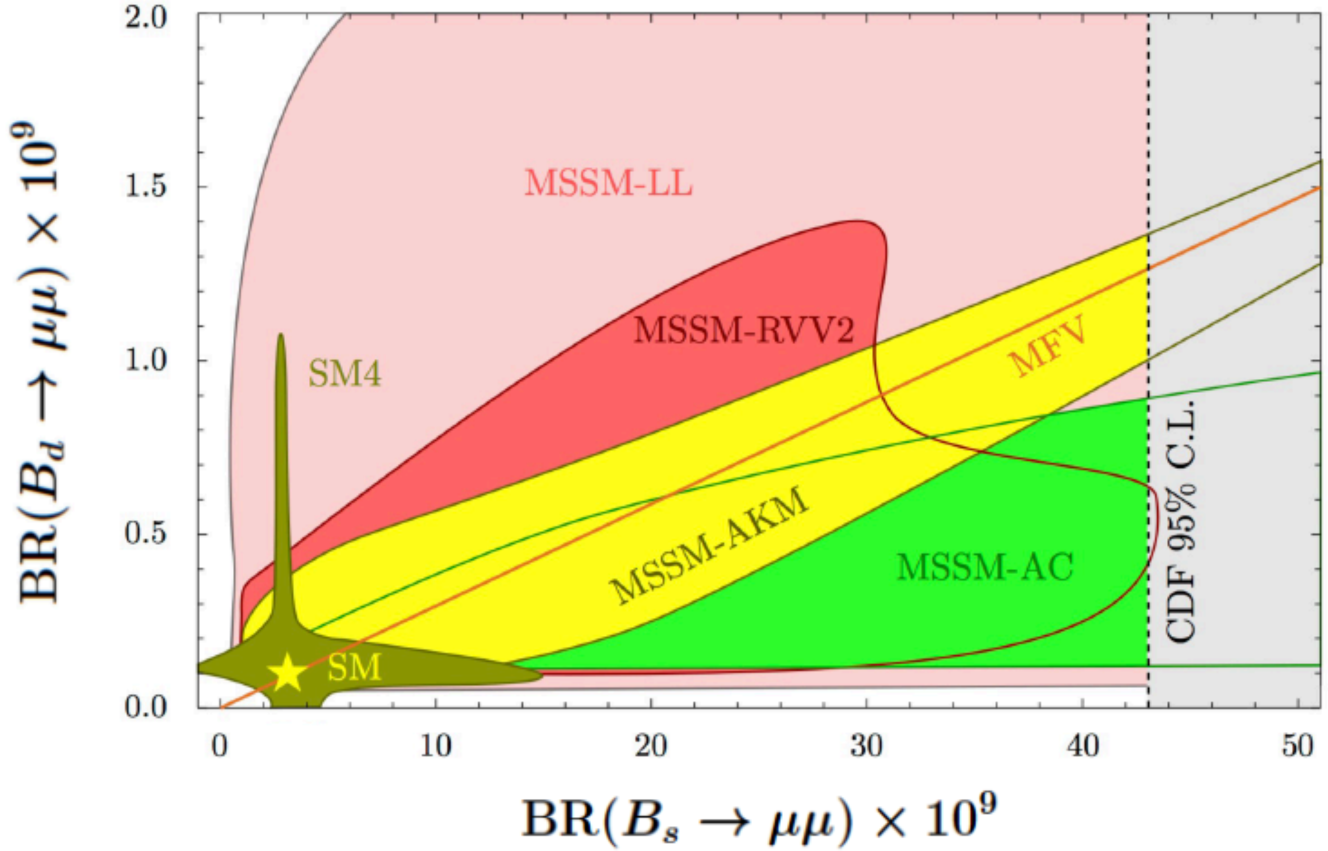
Bs→μμ in NP theories

Generically, sizable NP effects are expected in Beyond the SM theories:

(cancelation of the helicity suppression, m_μ/m_{Bs})

b → s

Pre-LHC, 2011



Straub, 1107.0266

Bs→μμ in NP theories

Generically, sizable NP effects are expected in Beyond the SM theories:

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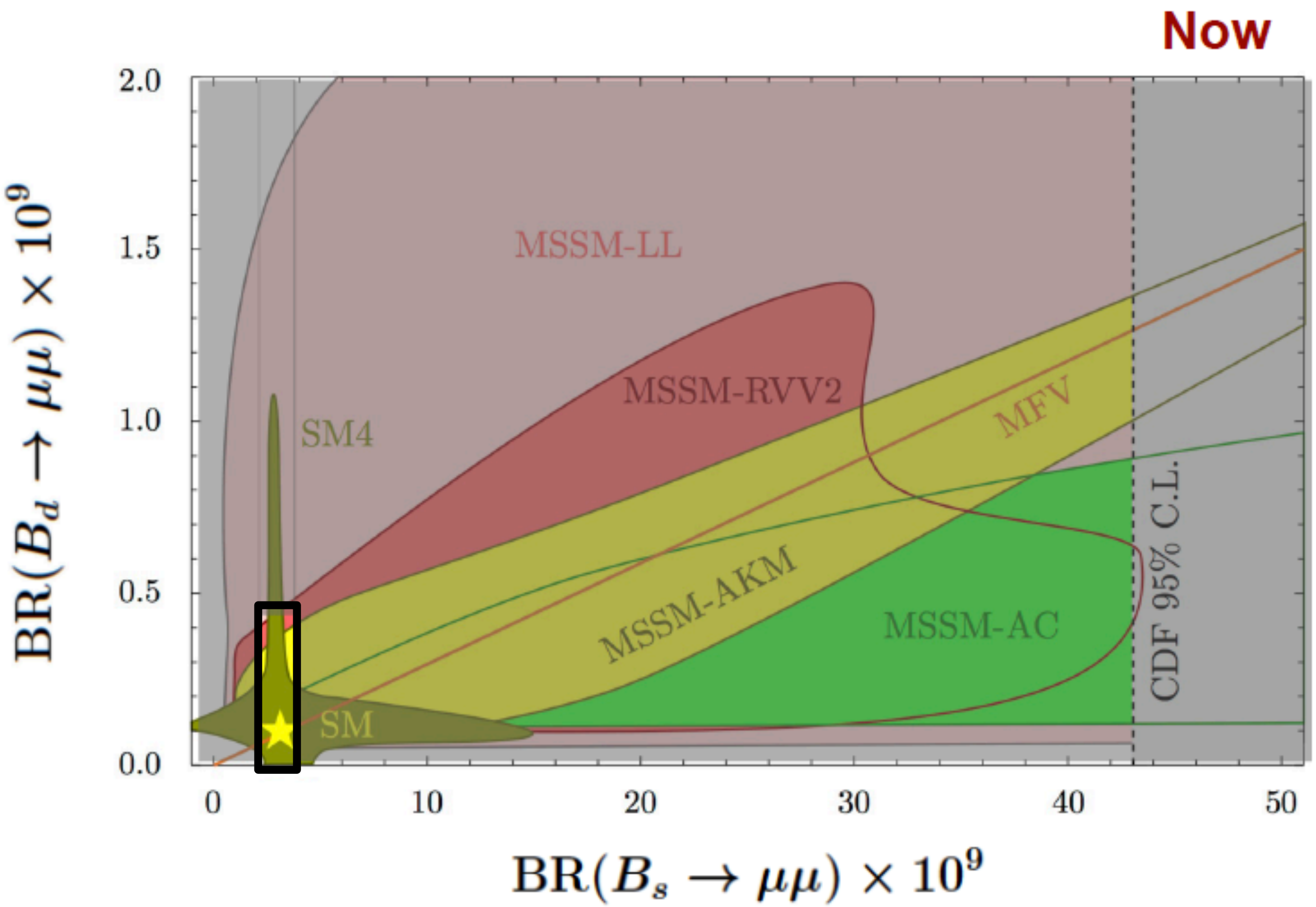
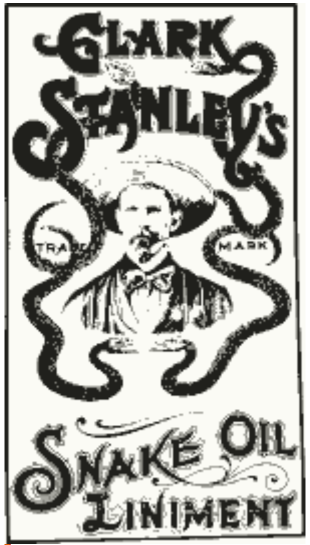


After LHCb

Straub, 1107.0266

Updates from UTfit

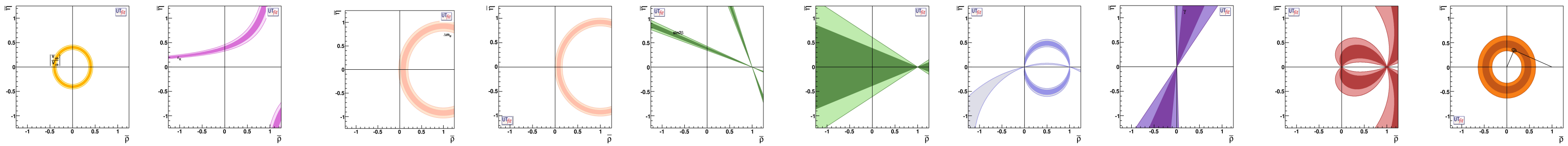


UTfit

www.utfit.org

C. Alpigiani, A. Bevan, M.B., M. Ciuchini,
D. Derkach, E. Franco, V. Lubicz, G. Martinelli,
F. Parodi, M. Pierini, C. Schiavi, L. Silvestrini,
A. Stocchi, V. Sordini, C. Tarantino and V. Vagnoni

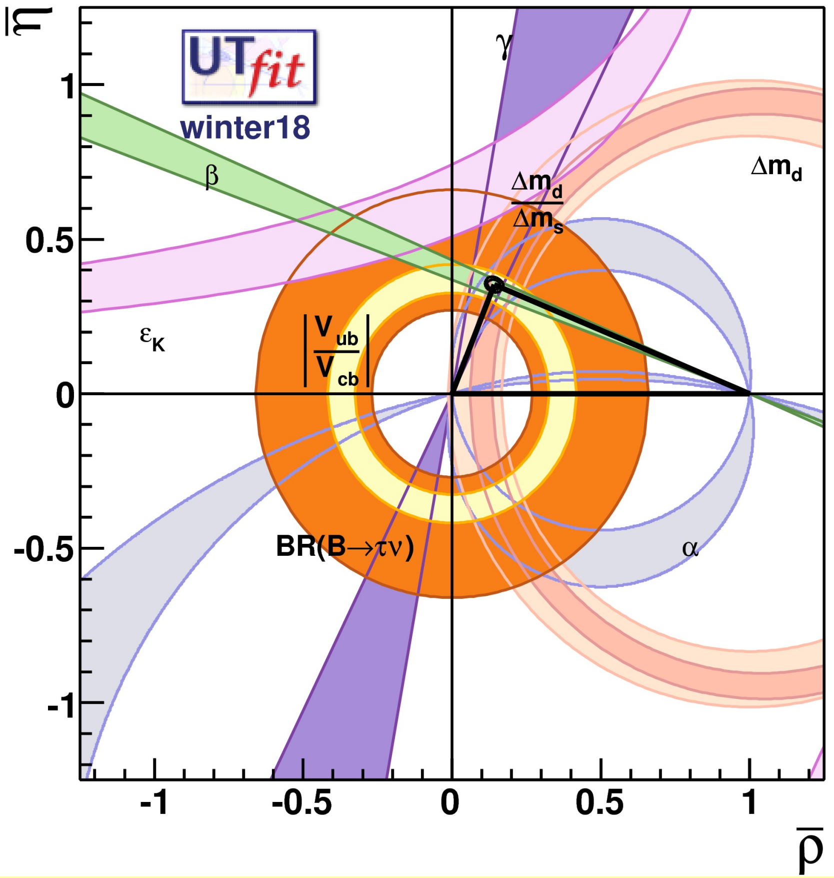
Other UT analyses exist, by:
CKMfitter (http://ckmfitter.in2p3.fr/),
Laiho&Lunghi&Van de Water (http://latticeaverages.org/)
Lunghi&Soni (1010.6069)



Winter 2018 results

$\overline{\rho} = 0.145 \pm 0.014$ $\overline{\eta} = 0.349 \pm 0.010$

In the hadronic sector, the SM CKM pattern represents the principal part of the flavor structure and of CP violation



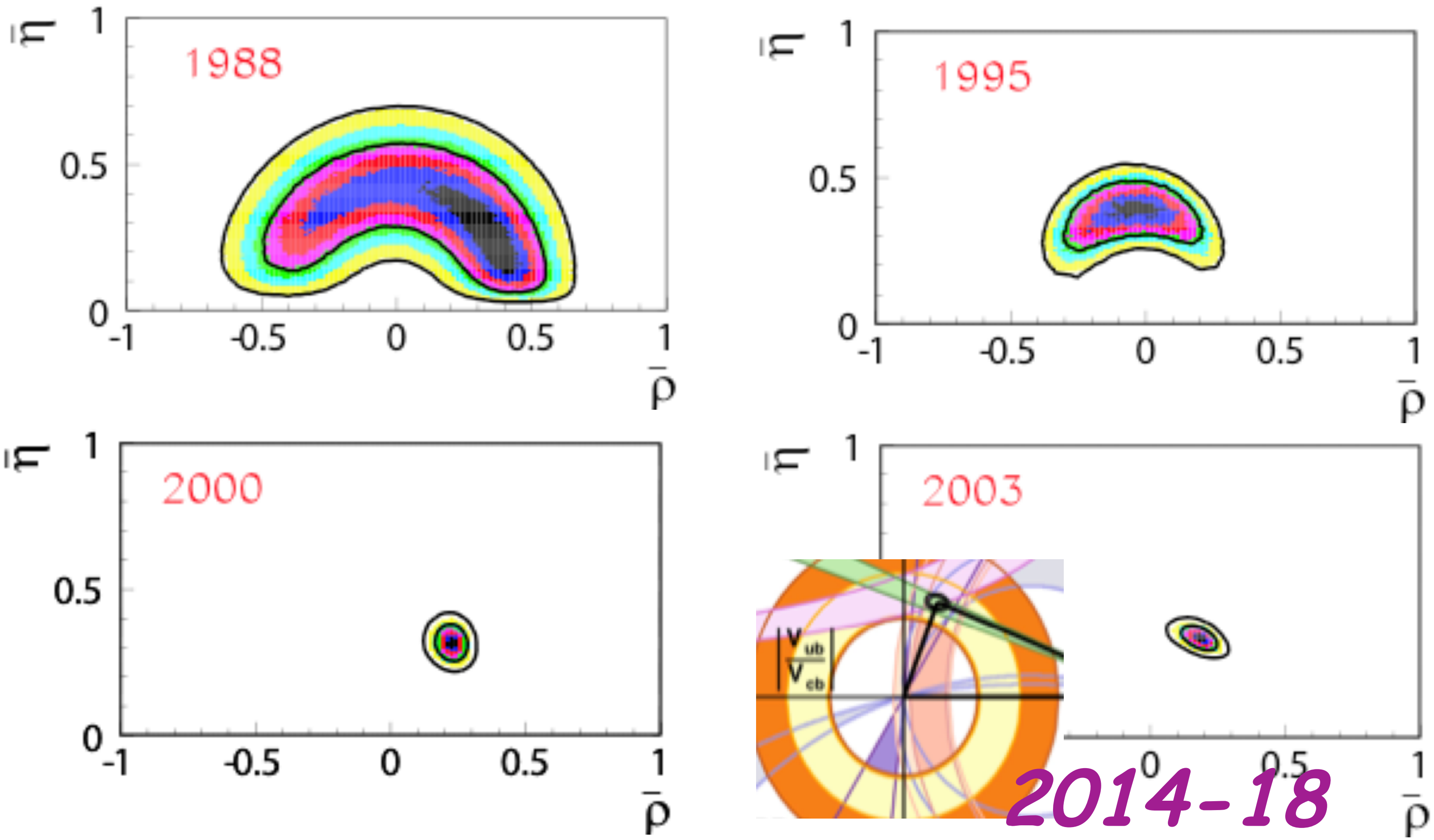
$\alpha = (88.2 \pm 0.1)^0$
$\sin 2\beta = 0.699 \pm 0.068$
$\beta = (22.3 \pm 0.66)^0$
$\gamma = (65.8 \pm 2.2)^0$
$A = 0.825 \pm 0.012$
$\lambda = 0.22502 \pm 0.00053$

Consistence on an over constrained fit of the CKM parameters

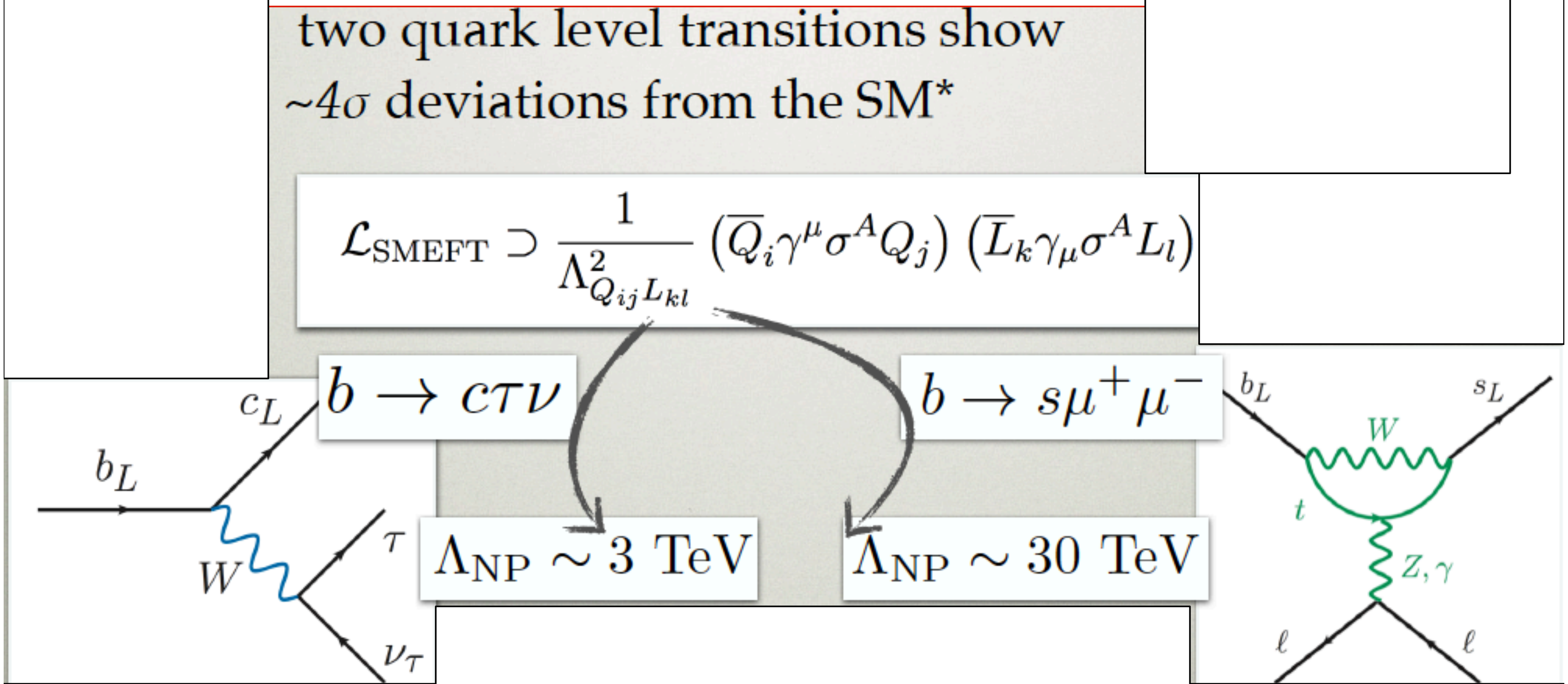
CKM matrix is the dominant source of flavour mixing and CP violation

PROGRESS SINCE 1988

Experimental progress so impressive that we can fit the hadronic matrix elements (in the SM)

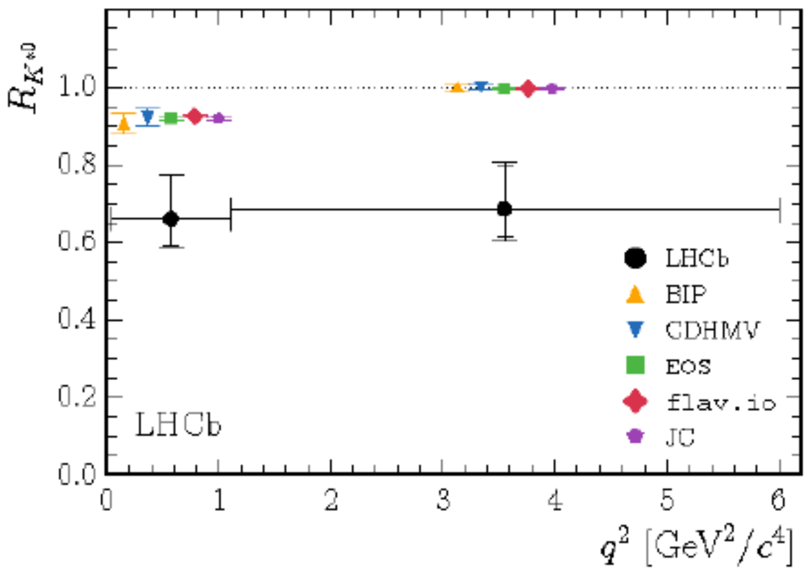


ANOMALIES and the expected naive energy scales LFUV



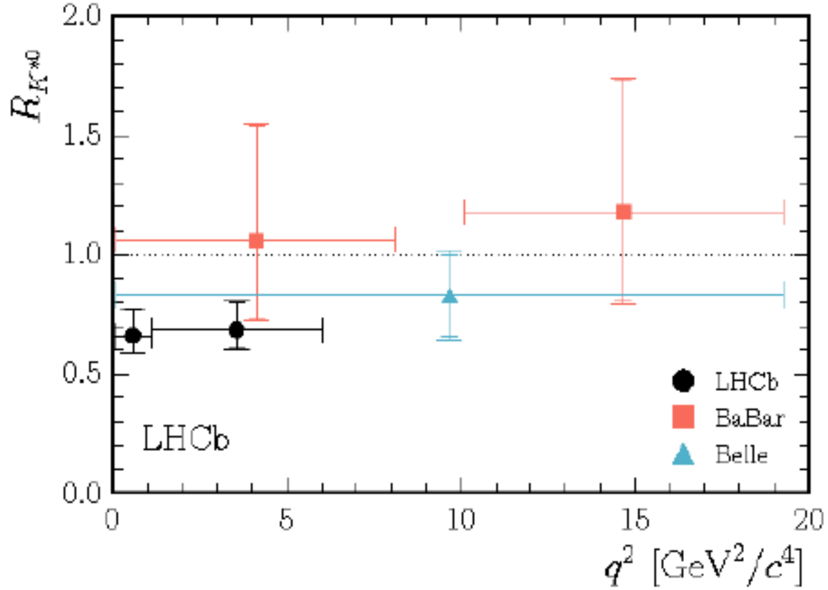
Results

Comparison with SM predictions



BIP: arXiv:1605.07633
CDHMV: arXiv:1510.04239, 1605.03156, 1701.08672
EOS: arXiv:1610.08761, https://eos.github.io
flav.io: arXiv:1503.05534, 1703.09189, flav-io/flavio
JC: arXiv:1412.3183

Comparison with BaBar & Belle



BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

LHCb: arXiv:1705.05802
Submitted to JHEP

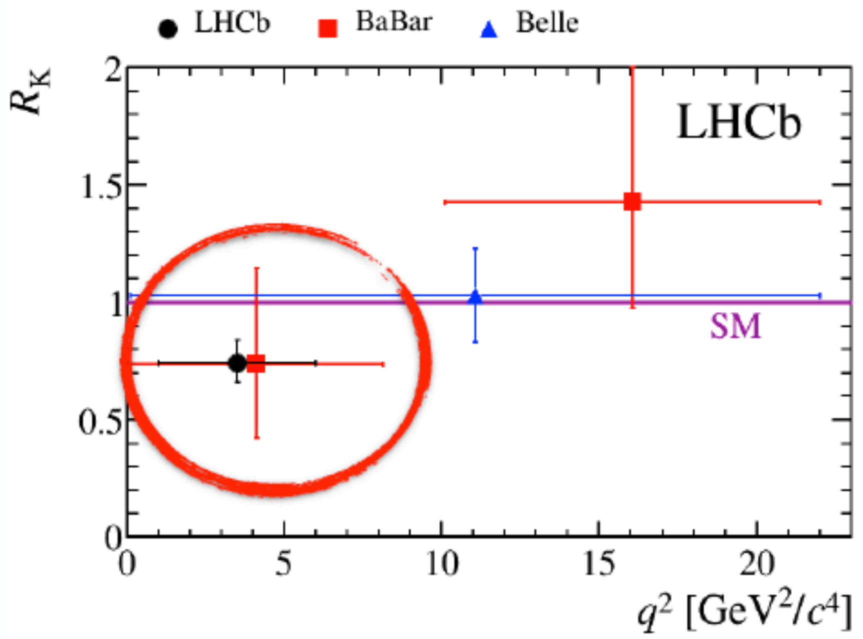
$$R_{K^*} = \begin{cases} 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst}) & \text{for } 0.045 < q^2 < 1.1\,\text{GeV}^2 \\ 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst}) & \text{for } 1.1 < q^2 < 6.0\,\text{GeV}^2 \end{cases}$$

2.1 - 2.3 σ
2.4 - 2.5 σ

R_K

- LHCb published an analysis of R_K based on Run 1 data:

$$R_K\left[q^2_{\rm min}, q^2_{\rm max}\right] = \frac{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B^+\to K^+\mu^+\mu^-)}{{\rm d}q^2}}{\int_{q^2_{\rm min}}^{q^2_{\rm max}} {\rm d}q^2 \frac{{\rm d}\Gamma(B^+\to K^+e^+e^-)}{{\rm d}q^2}}, \quad 1 < q^2 < 6\,{\rm GeV}^2$$



$$R_K = 0.745^{+0.090}_{-0.074}\,({\rm stat}) \pm 0.036\,({\rm syst})$$

LHCb: PRL 113 (2014) 151601

BaBar: PRD 86 (2012) 032012
Belle: PRL 103 (2009) 171801

- Compatible with SM at 2.6 σ

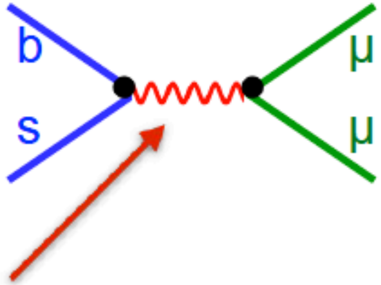
A EFT description

$b \longrightarrow s$

A relatively sizable New Physics effect...

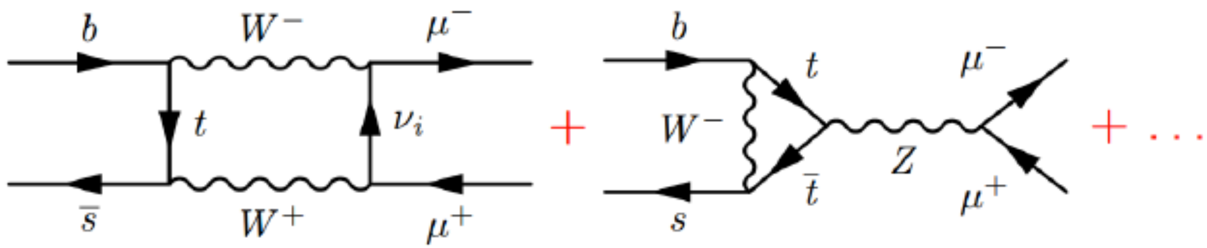
~30% of the Standard Model contribution (arising at one loop)

...hinting towards a relatively low New Physics scale:



generic tree	$\frac{1}{\Lambda_{\rm NP}^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 35\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV tree	$\frac{1}{\Lambda_{\rm NP}^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 7\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
generic loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 3\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$
MFV loop	$\frac{1}{\Lambda_{\rm NP}^2}\frac{1}{16\pi^2}\, V_{tb}V_{ts}^*\, (\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$	$\Lambda_{\rm NP} \simeq 0.6\text{ TeV} \times (C_9^{\rm NP})^{-1/2}$

EFT approach



If the LFUV takes place at scales well above EWSB, then use OPE:

$$\mathcal{H}_{\text{eff}} = -\frac{G_F \alpha}{\pi\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,8,9,10,P,S,\ldots} \left(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \right) \right]$$

- Operators relevant to $b \to s\ell\ell$ are

$$\boldsymbol{\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)}, \qquad \boldsymbol{\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu\gamma^5 \ell)},$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell), \qquad \mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell),$$

$$\mathcal{O}_7^{(\prime)} = m_b(\bar{s}\sigma_{\mu\nu} P_{R(L)} b)F^{\mu\nu} \qquad \ldots$$

Dipoles do not break LFU *Scalar operators strongly constrained by $B_s \to \mu\mu$*

$$\mathcal{B}(B_s \to \mu^+\mu^-) \propto |V_{tb}V_{ts}^*|^2 f_{B_s}^2 m_\mu^2 \left[\left| C_{10} - C_{10}' + \frac{m_{B_s}^2 (C_P - C_P')}{2m_\mu(m_b + m_s)} \right|^2 + |C_S - C_S'|^2 \frac{m_{B_s}^2 (m_{B_s}^2 - 4m_\mu^2)}{4m_\mu^2 (m_b + m_s)^2} \right]$$

right-handed quark currents result in an anti-correlation of R_K and R_{K^*}

left-handed quark currents result in a correlation of R_K and R_{K^*}

Let us assume that these anomalies are due to New Physics and try to estimate the NP scale

$$|V_{tb}V_{ts}|\frac{\alpha_{em}}{4\pi v^2}C_{NP} \sim \frac{C_{NP}}{(35\text{TeV})^2}$$

- Tree level effects
- Loop effects

$\rightarrow$ model building is very challenging

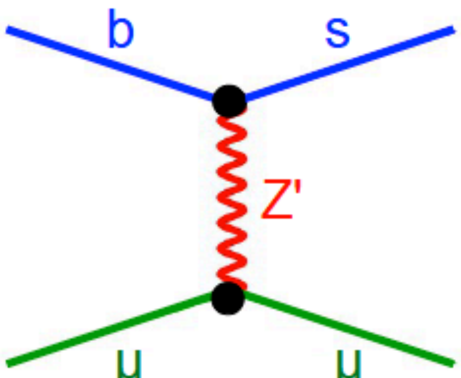
lepto-quarks? RPV SUSY? W' bosons?

Two popular choices for NP effects @ tree level

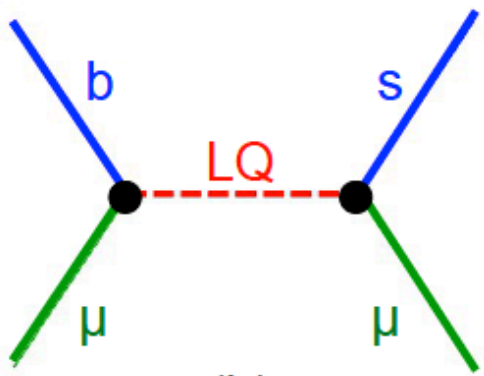
- Z' different $SU(2)_L$
- Leptoquark (LQ) spin 0,1

Two classes of models:

- Either tree-level or one-loop



(a)



(b)

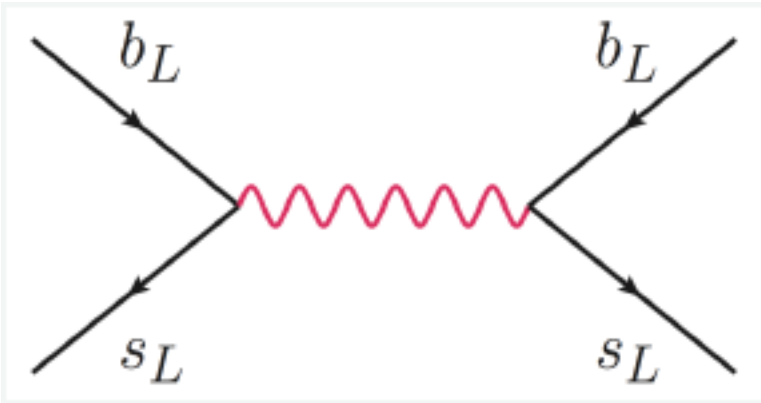
Constraints from B_s mixing can be accommodated

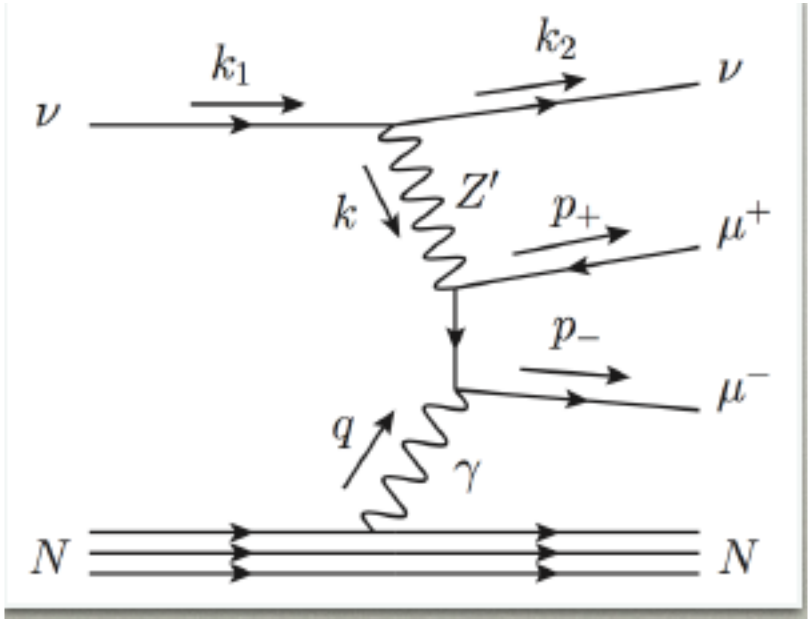
Altmannshofer,Straub 1308.1501,
Altmannshofee et al., 1403.1269,

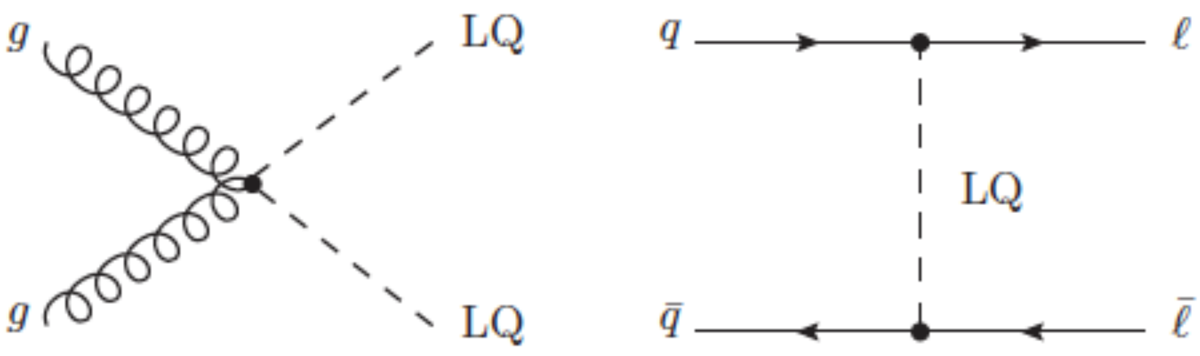
Greljo, Isidori,Marzocca, 1506.01705
etc.

Angelescu et al. 1808.08179 and refs therein
Hiller, Nisandric 1704.05444, Hiller et al., 1503.01084,
Hiller, Schmaltz 1411.4773
Gripaios, Nardecchia, Renner, 1412.1791
etc.

Constraints





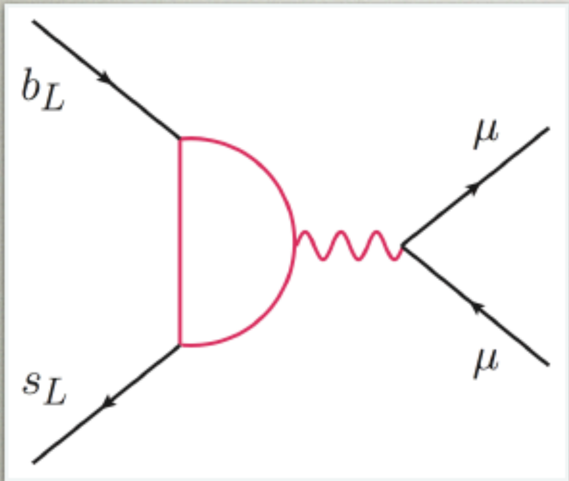


(a) (b)

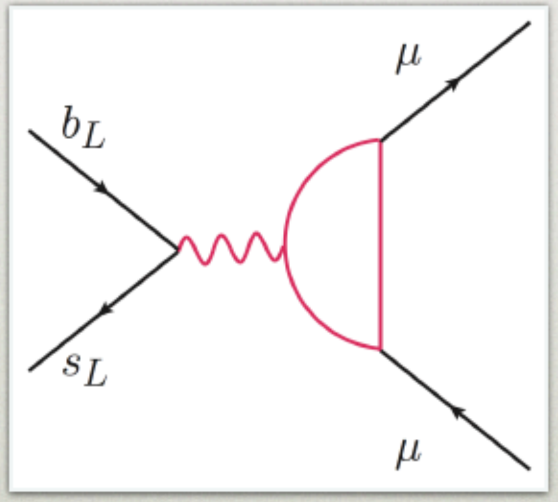
LOOP LEVEL

- three distinct options

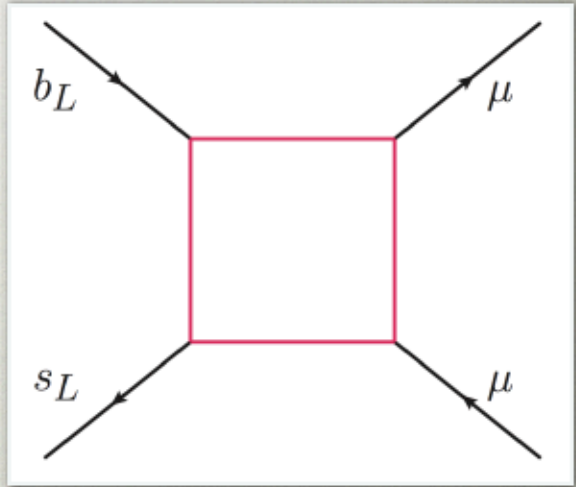
- Z' w/ loop to bs
- Z' w/ loop to $\mu\mu$
- box w/ NP fields



Kamenik, Soreq, JZ, 1704.06005



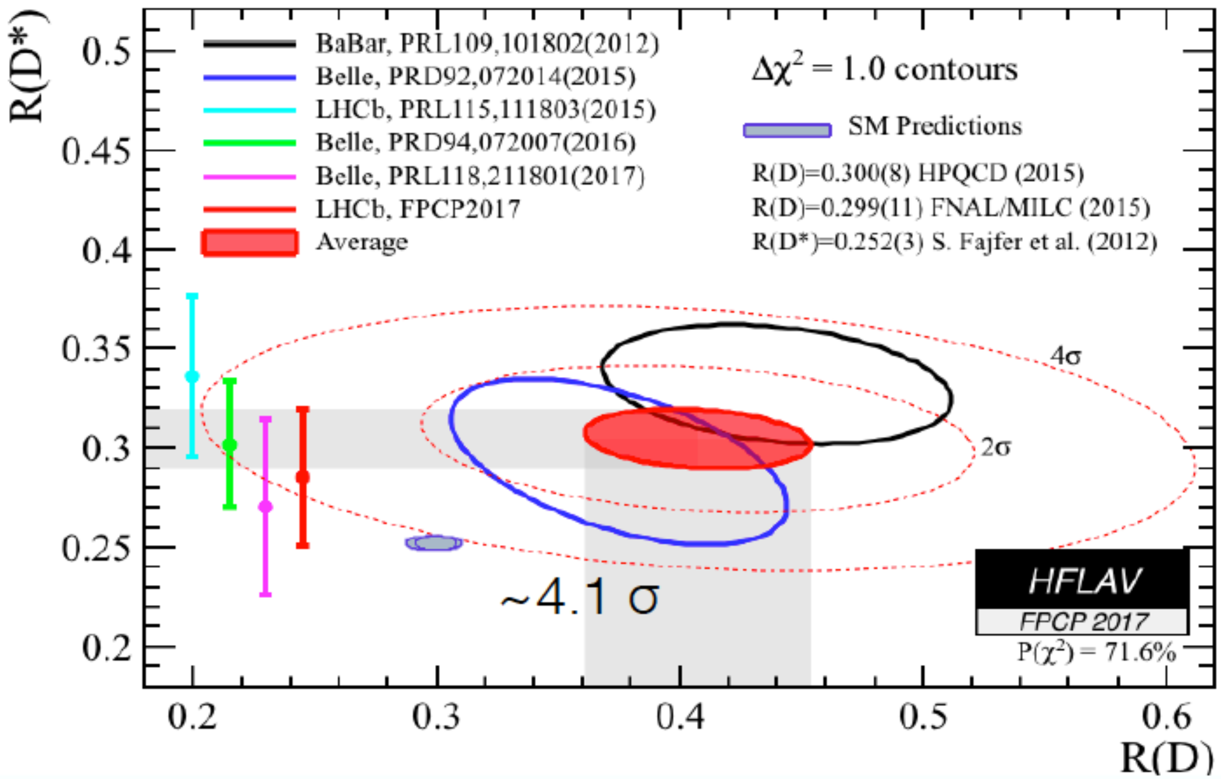
Bélanger, Delaunay, 1603.03333



Gripaios, Nardecchia, Renner, 1509.05020;
Bauer, Neubert, 1511.01900;
Becirevic, Sumensari, 1704.05835

$$R(D^{(*)}) = \frac{\Gamma(\bar{B} \to D^{(*)}\tau\bar{\nu})}{\Gamma(\bar{B} \to D^{(*)}\mu\bar{\nu})}$$

Tree level anomaly



Prospects

- LHCb: a whole programme of semi-tauonic measurements :

$$R(J/\psi) : B_c^+ \to J/\psi\,\tau^+\nu_\tau$$
$$R(D^-) : B^0 \to D^-\tau^+\nu_\tau$$
$$R(D^0) : B^+ \to D^0\tau^+\nu_\tau$$
$$R(D_s^{(*)}) : B_s^0 \to D_s^{(*)}\tau^+\nu_\tau$$
$$R(\Lambda_b) : \Lambda_b \to \Lambda_c^{(*)}\tau^+\nu_\tau$$

$R_D^{\text{exp}} = 0.407 \pm 0.039 \pm 0.024$, $\quad R_{D*}^{\text{exp}} = 0.304 \pm 0.013 \pm 0.007$

heavy quark expansion + $B \to D^{(*)}\ell\nu$ data + lattice input + QCD sum rule input

$R_D^{\text{SM}} = 0.298 \pm 0.003$, $\quad R_{D*}^{\text{SM}} = 0.261 \pm 0.004$

B -> D-D* *All SM predictions based on lattice calculations (same gauge fields configurations)*

	HPQCD	Fermilab/MILC	$\|V_{cb}\|$
B → D	Na et al, PRD92, 054510 (2015) • NRQCD b + HISQ c G(1) = 1.035(40)	Bailey et al, PRD92, 034506 (2015) • improved Wilson for heavy (c and b) G(1) = 1.054(4)(8)	HFLAV average (2016) + lattice ave 0.0398(10)(14)
B → D*	Harrison et al, PRD97, 054502 (2018) • NRQCD b + HISQ c F(1) = 0.895(10)(24)	Bailey et al, PRD89, 114504 (2014) • improved Wilson for heavy (c and b) F(1) = 0.906(4)(12)	HFLAV average (2016) + lattice ave 0.0391(5)(5)
inclusive	N/A		HFLAV (2016) 2.9 σ 0.0422(8)

In the case of D^* q^2-dependence and $A_0(q^2)$ never computed

HQET assumed in the calculation?

New Physics in $b \to c\ell\bar{\nu}_\ell$: model independent approach

"Model independent" includes following assumptions:

- No right-handed neutrino; charged lepton current remains left handed.
- Keep $V - A$ structure of the lepton current: $L^\mu = \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell$
- $b \to c\ell\bar{\nu}_\ell$ can then be described by a general effective Hamiltonian:

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}\big[(1+g_V)\bar{c}\gamma_\mu b + (-1+g_A)\bar{c}\gamma_\mu\gamma_5 b + g_S\, i\partial_\mu(\bar{c}b) + g_P\, i\partial_\mu(\bar{c}\gamma_5 b) + g_T\, i\partial_\nu(\bar{c}i\sigma_{\mu\nu}b)\big] \times L^\mu = \frac{G_F}{\sqrt{2}} V_{cb}\, H_\mu L^\mu$$

$$g_{V,A} \sim \mathcal{O}\left(\frac{v^2}{\Lambda^2_{\text{NP}}}\right), \quad g_{S,P,T,T5} \sim \frac{1}{v}\mathcal{O}\left(\frac{v^2}{\Lambda^2_{\text{NP}}}\right)$$

Full angular distribution can be made at Belle II to understand which/if-a NP operator matters.

Looking for a model

NP resolution of the R(D(*)) anomaly is challenging

Two classes of models

Scalar/pseudoscalar models

$$\boxed{C_{S_R} = -C_{S_L} \neq 0}$$

Strong constraints from

- B_c lifetime
- Measurements of the q^2 distribution of the $B \to D\tau\nu$ decay

Vector models

$$\boxed{C'_{V_L} \neq 0}$$

Constraints from

- Z branching ratios: $Z \to ll$
- Tau branching ratios: $\tau \to \mu\nu\nu$

In both cases, strong constraints from

- Direct searches of the new few-hundred GeV particles (ATLAS & CMS)
- Measurement of the branching ratio of $B^+ \to \tau^+\nu$ (Belle, Babar)
- $bb \to \tau\,\tau$ (ATLAS & CMS)
- $B_s \to \tau^+\tau^-,\ B \to K^{(*)}\nu\bar{\nu},\ B \to K\tau^+\tau^-, \cdots$ (LHCb, Belle, Babar)

generic tree $$\frac{1}{\Lambda_{\rm NP}^2}(\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$$ $\Lambda_{\rm NP} \simeq 2.4$ TeV

MFV tree $$\frac{1}{\Lambda_{\rm NP}^2}\, V_{cb}\, (\bar{c}\gamma_\nu P_L b)(\bar{\tau}\gamma^\nu P_L \nu)$$ $\Lambda_{\rm NP} \simeq 0.5$ TeV

- the $B_c \to \tau\nu$ rate and the total B_c life-time strongly constrain scalar explanations of R_D and R_{D^*}

  Li, Yang, Zhang 1605.09308; Alonso, Grinstein, Martin Camalich 1611.06676

- in many models strong constraints are obtained from $pp \to \tau\tau$ searches at the LHC

  Faroughy, Greljo, Kamenik 1609.07138

- in many models one finds strong constraints from Z couplings, W couplings, or tau decays, etc. that are modified at the loop level

  Feruglio, Paradisi, Pattori 1606.00524 + 1705.00929

  Cornella, Feruglio, Paradisi 1803.00945

V_{cb} and V_{ub}

Smallisch Anomalies

updated for LHPC17

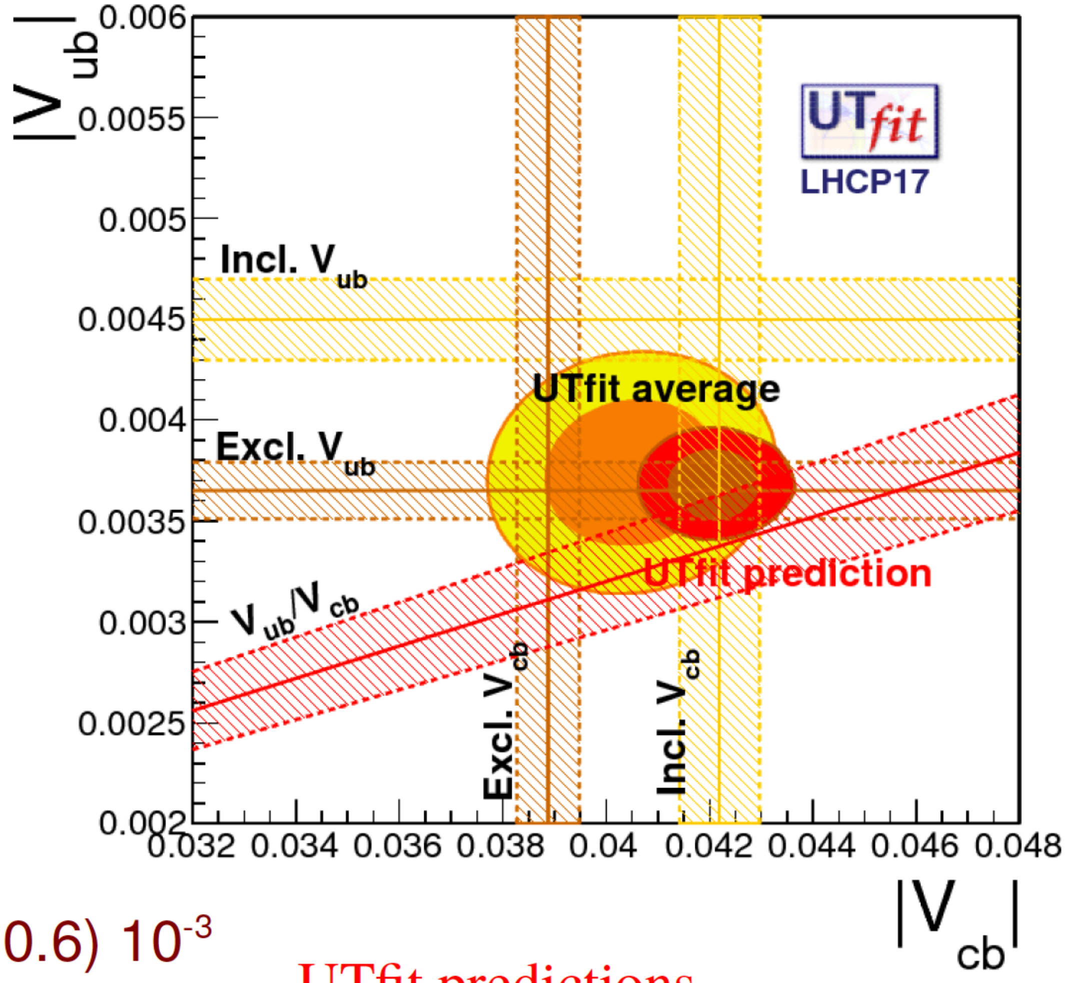
2D average inspired by D'Agostini skeptical procedure (hep-ex/9910036) with σ=1.
Very similar results obtained from a 2D a la PDG procedure.

$$|V_{cb}| = (40.5 \pm 1.1)\ 10^{-3}$$

uncertainty ~ 2.4%

$$|V_{ub}| = (3.74 \pm 0.23)\ 10^{-3}$$

uncertainty ~ 5.6%



Incl

Excl

$$|V_{cb}| = (42.1 \pm 0.6)\ 10^{-3}$$

$$|V_{ub}| = (3.68 \pm 0.11)\ 10^{-3}$$

UTfit predictions

Model-Independent Extraction of $|V_{cb}|$ from $\bar{B} \to D^* \ell \overline{\nu}$, cont'd

- New Belle analysis released: Abdesselam *et al* (Belle) 1702.01521
  - Unfolded data, full correlation matrix
  - Large dataset, energy and angular distributions
  - CLN: $|V_{cb}| = (37.4 \pm 1.3) \times 10^{-3}$

Exclusive

- Two independent analyses using BGL:
  - Very consistent fits:

$$|V_{cb}| = (41.7\ {}^{+2.0}_{-2.1}) \times 10^{-3}$$
Bigi, Gambino & Schacht, 1703.06124

$$|V_{cb}| = (41.9\ {}^{+2.0}_{-1.9}) \times 10^{-3}$$
BG & Kobach, 1703.08170

  - Robust: different numerical inputs
  - Likely culprit: independent form factors (no HQET symmetry)

$$\begin{aligned} \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu b|\bar{B}(p)\rangle &= ig\epsilon^{\mu\nu\alpha\beta}\varepsilon^*_\nu p_\alpha p'_\beta, \\ \langle D^*(\varepsilon, p')|\bar{c}\gamma^\mu\gamma^5 b|\bar{B}(p)\rangle &= f\varepsilon^{*\mu} + (\varepsilon^* \cdot p)[a_+(p+p')^\mu + a_-(p-p')^\mu], \end{aligned}$$

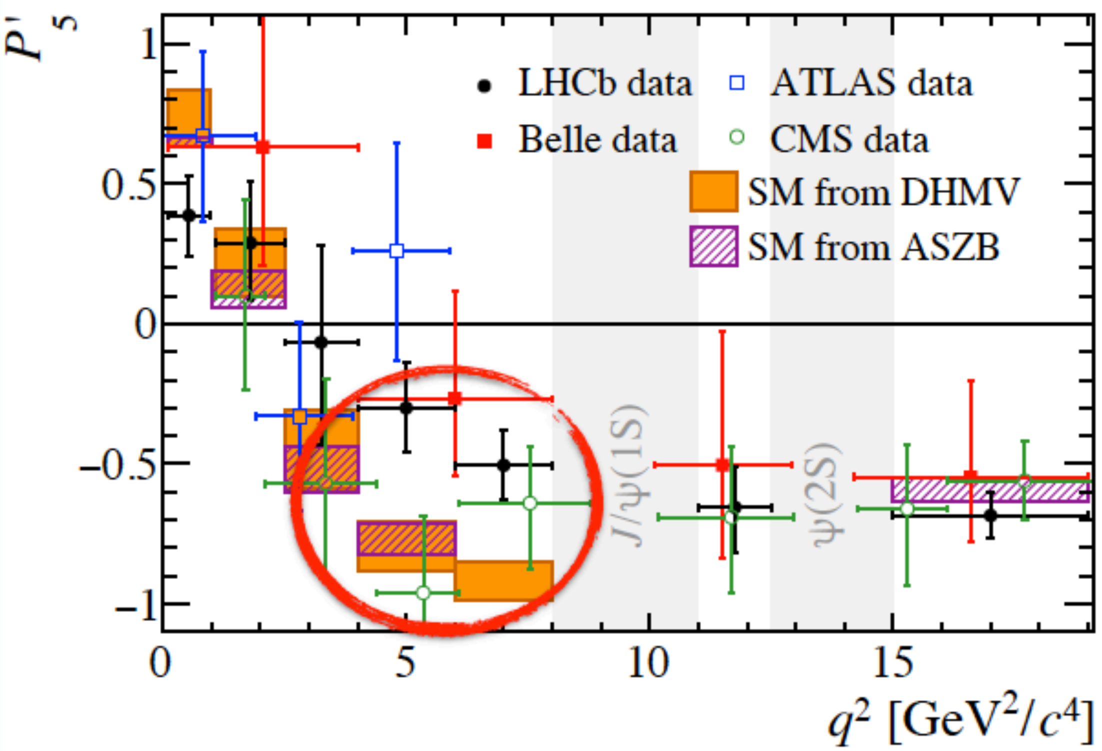
Recall: BGL introduced z-parametrization, eg,

$$g(z) = \frac{1}{P_g(z)\phi_g(z)} \sum_{n=0}^{N} a_n z^n \quad \text{with} \quad \sum_n a_n^2 \leq 1 \quad \text{and} \quad 0 \leq z \leq z_{\max} = 0.056$$

with calculable outer function ϕ and Blaschke factor P
  - CLN uses BGL technique, but imposes HQET conditions

P_5' anomaly

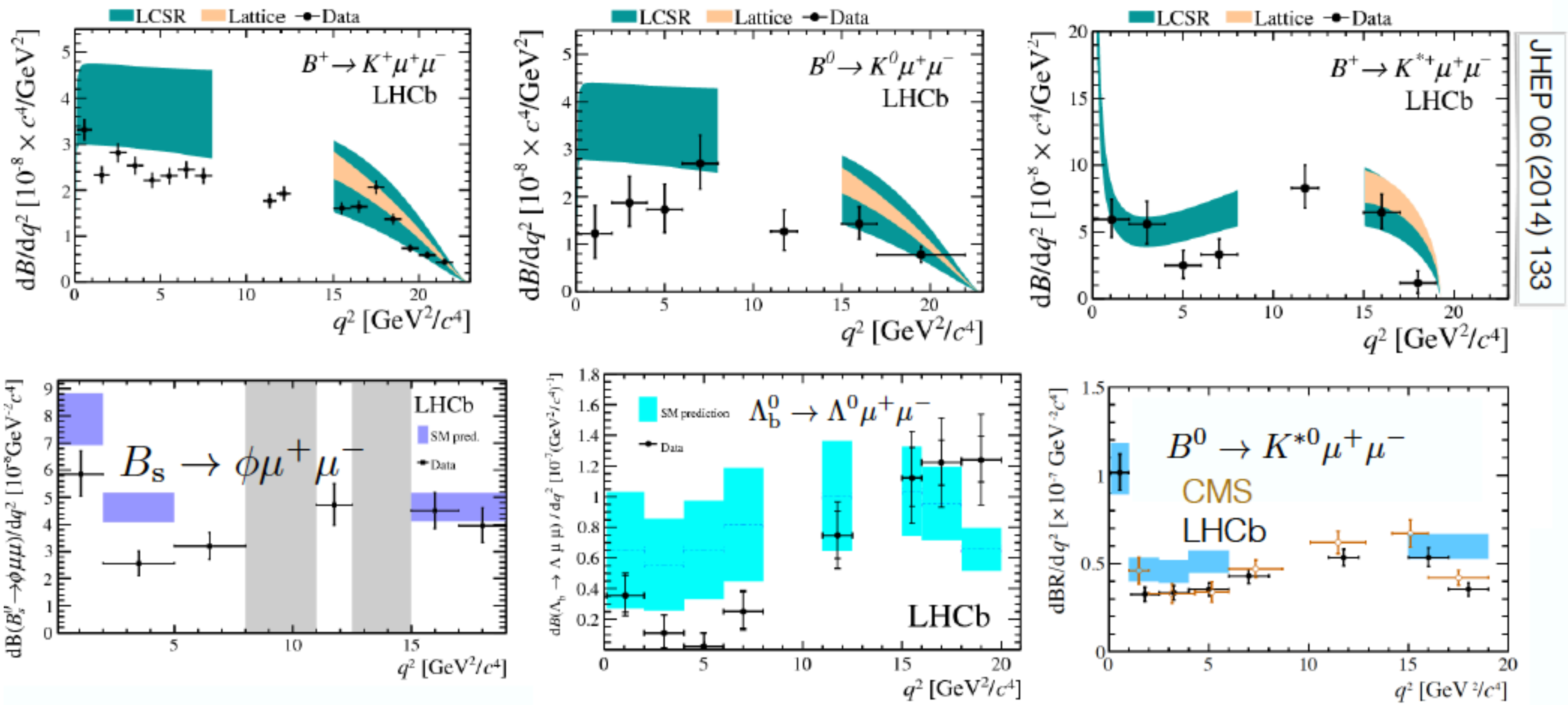
- One such observable is so-called P'_5 , not intuitive, but constructed from angular observables to be robust from 'form-factor uncertainties'



LHCb: JHEP 02 (2016) 104
Belle: PRL 118 (2017) 111801
ATLAS-CONF-2017-023
CMS-PAS-BPH-15-008

Only short distance local operators contributions are checked

Intriguing set of results in differential branching fractions for b→sμμ transitions

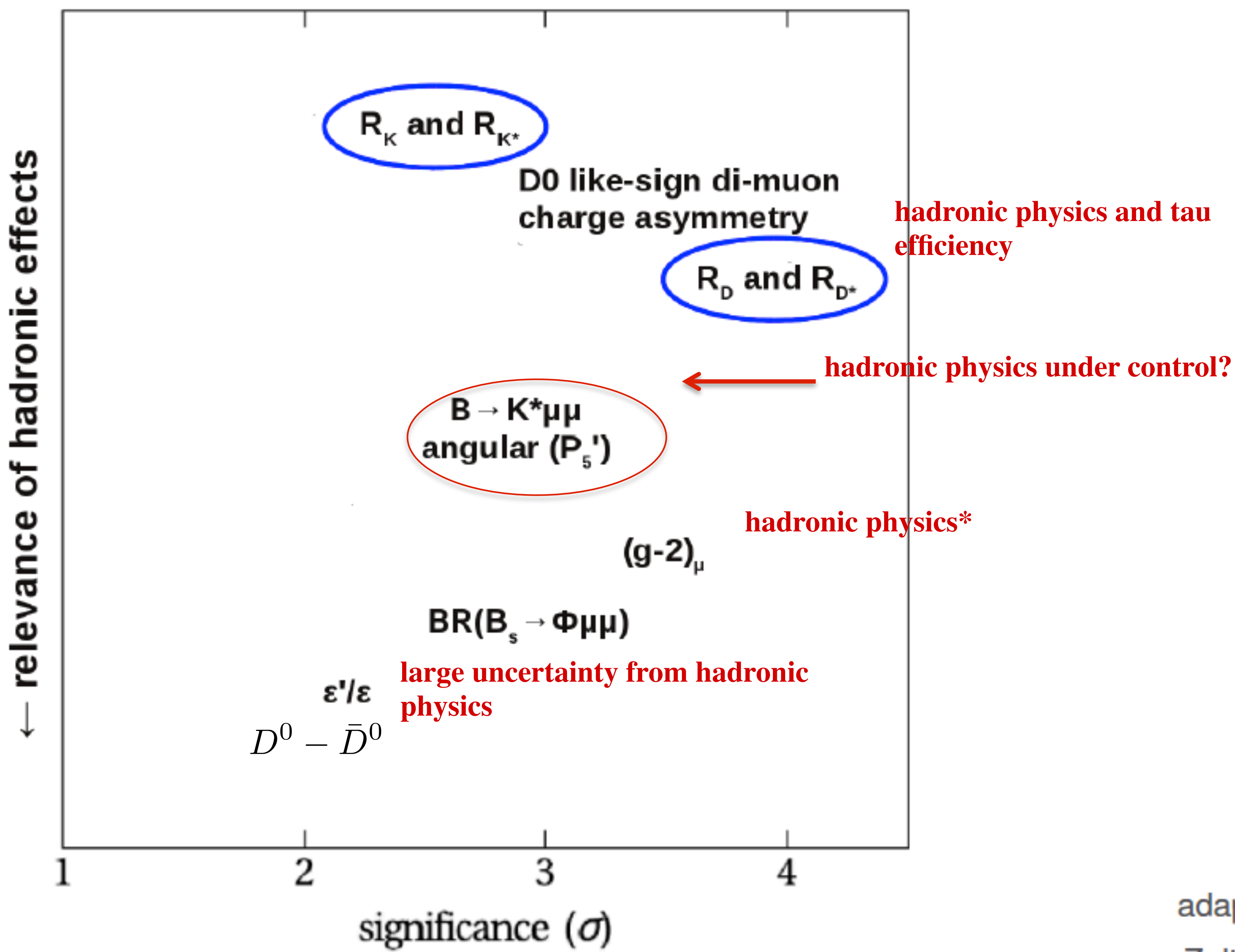


JHEP 09 (2015) 179

JHEP 06 (2015) 115

LHCb: JHEP 11 (2016) 047, JHEP 04 (2017) 142
CMS: PLB 753 (2016) 424

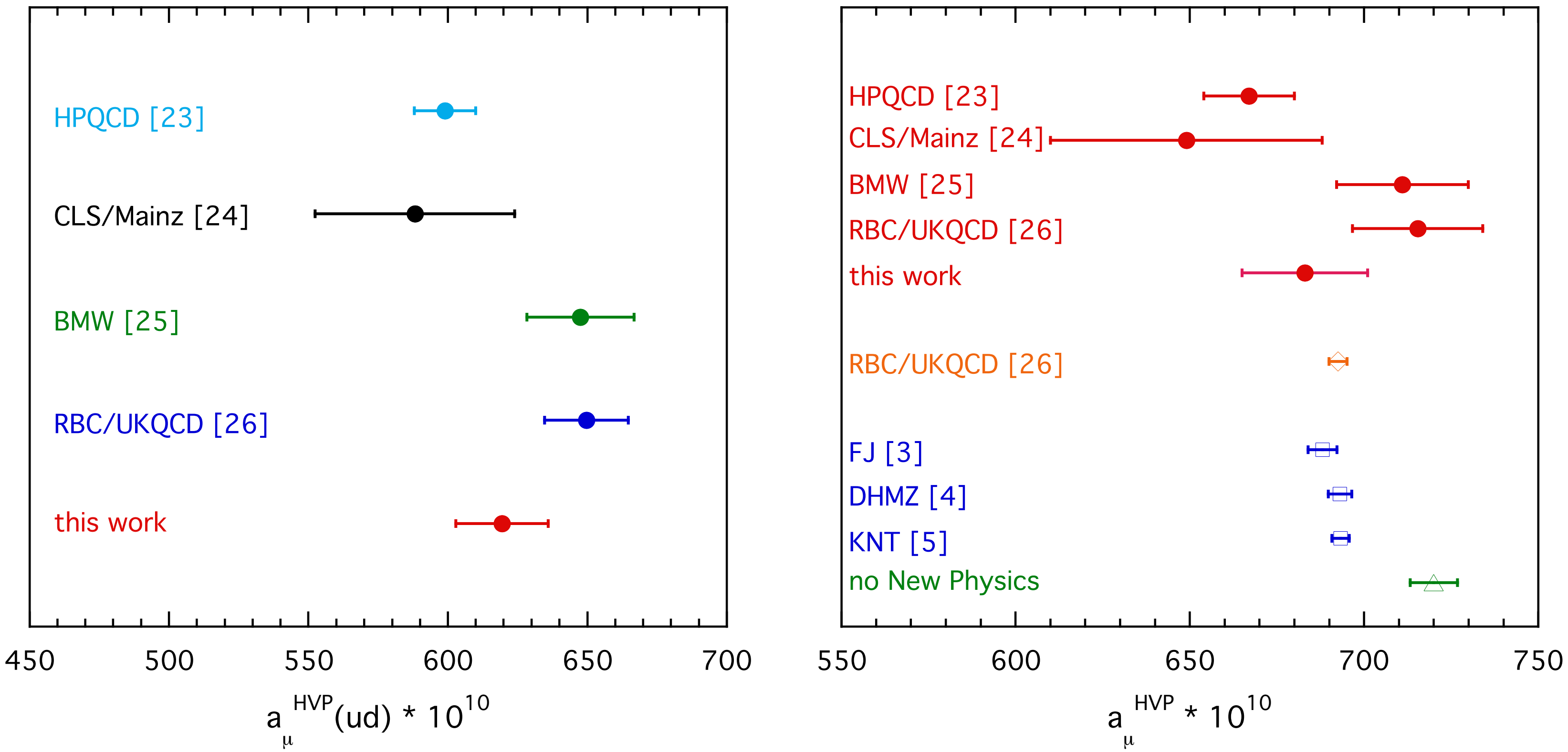
- In general, data tend to be lower than theory predictions



adapted from

Zoltan Ligeti

g-2
HVP from Lattice QCD



Giusti, Sanfilippo, Simula 1808.00887

Long Distance Effects in Neutral Meson Mixing

- The general formula can be written: N.H.Christ, G.Martinelli & CTS, arXiv:1401.1362
  N.H.Christ, X.Feng, G.Martinelli & CTS, arXiv:1504.01170

$$\Delta m_K = \Delta m_K^{\rm FV} - 2\pi \; {}_V\langle \bar{K}^0 \,|\, H \,|\, n_0 \rangle_V \; {}_V\langle n_0 \,|\, H \,|\, K^0 \rangle_V \left[\cot \pi h \, \frac{dh}{dE} \right]_{m_K} ,$$

where $h(E,L)\pi \equiv \phi(q) + \delta(k)$.

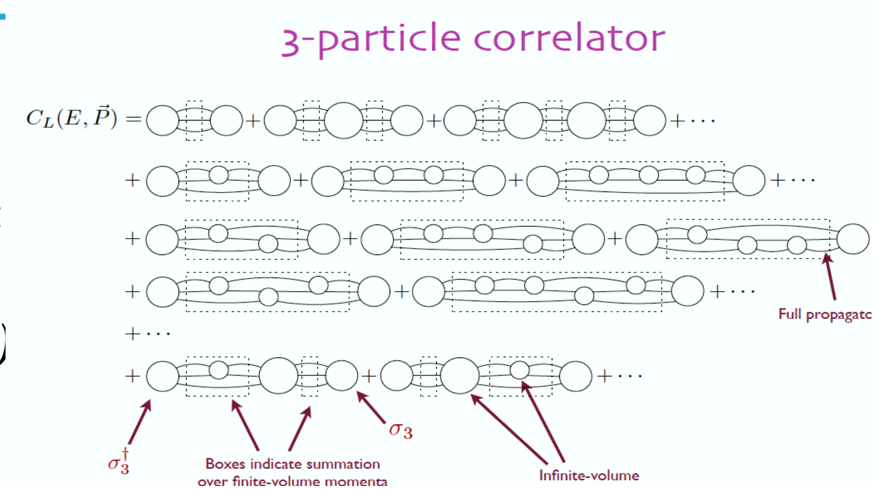
- This formula reproduces the result for the special case when the volume is such that there is a two-pion state with energy $= m_K$. N.H.Christ, arXiv:1012.6034
- Increasing the volumes keeping $h = n/2$ and thus avoiding the power corrections is an intriguing possibility.

Within reasonable approximations can be extended to D meson mixing

M. Ciuchini,V. Lubicz, L. Silvestrini, S. Simula

(progresses made by M. T. Hansen & S. Sharpe,1204.0826v4,1409.7012v,1504.04248v1)

Also CPV in D -> ππ or KK



D MIXING

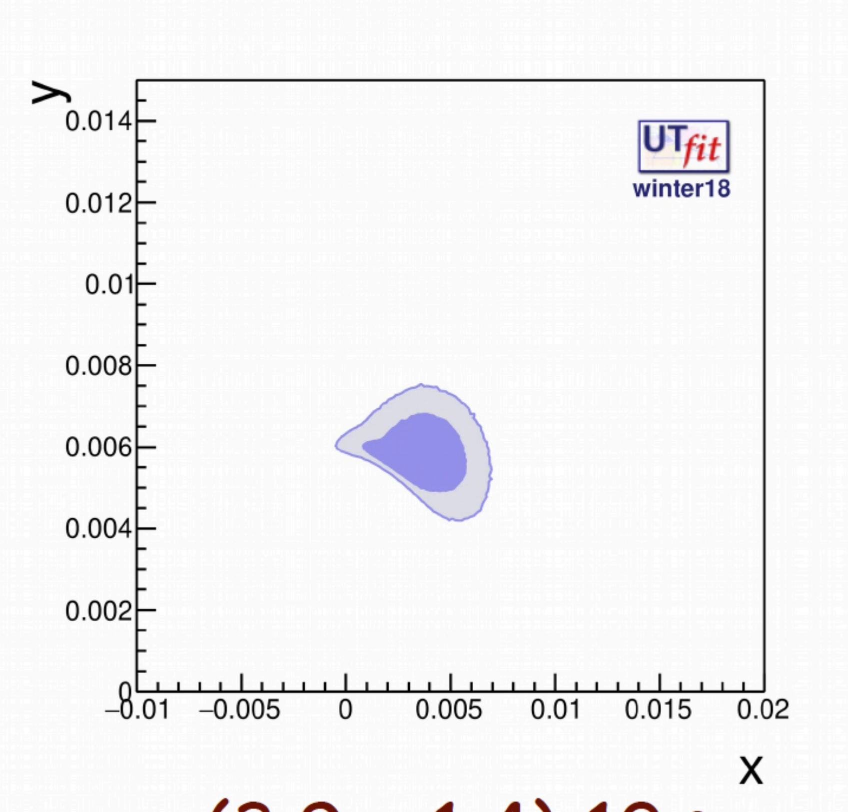
- D mixing is described by:
  - Dispersive $D \to \bar{D}$ amplitude M_{12}
    - SM: long-distance dominated, not calculable
    - NP: short distance, calculable w. lattice
  - Absorptive $D \to \bar{D}$ amplitude Γ_{12}
    - SM: long-distance, not calculable
    - NP: negligible
  - Observables: $|M_{12}|$, $|\Gamma_{12}|$, $\Phi_{12}=\arg(\Gamma_{12}/M_{12})$

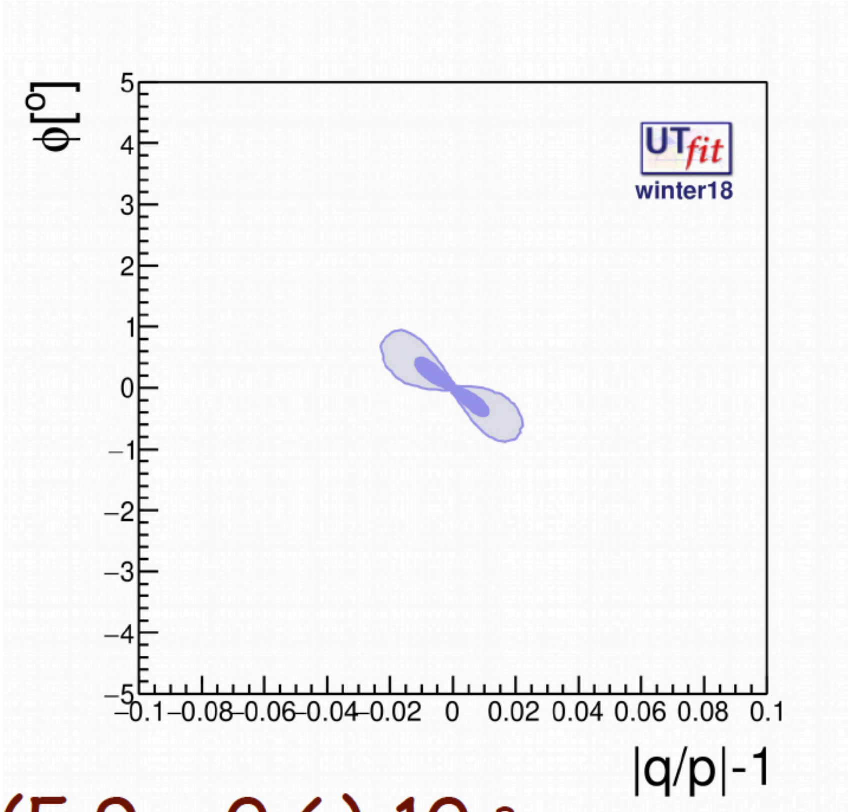
Let us assume that the Standard Model contributions to M_{12} and Γ_{12} are real

"REAL SM" APPROXIMATION

- Define $|D_{S,L}| = p|D^0| \pm q|\bar{D}^0|$ and $\delta = (1-|q/p|^2)/(1+|q/p|^2)$. All observables can be written in terms of $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$ and δ
- Introduce $\phi = \arg(q/p) = \arg(y + i\delta x)$
- $|q/p| \neq 1 \Leftrightarrow \phi \neq 0$ clear signals of NP
- Combine all available data with the assumption of real decay amplitudes and real Γ_{12}
- Preliminary winter18 combination

D mixing fit results





$x = (3.9 \pm 1.4)\ 10^{-3}$, $y = (5.9 \pm 0.6)\ 10^{-3}$,

$\phi = (0.02 \pm 0.32)°$, $|q/p|-1 = (0 \pm 9)\ 10^{-3}$

STRONG CP VIOLATION

$$\mathcal{L}_\theta = \theta\, \tilde{G}^{\mu\nu a} G^a_{\mu\nu} \qquad \tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\rho\sigma} G^a_{\rho\sigma}$$

$$\mathcal{L}_\theta \sim \theta\, \vec{E}^a \cdot \vec{B}^a$$

This term violates CP and gives a contribution to the electric dipole moment of the neutron

$$e_n < 3\ 10^{-26}\ \mathrm{e\ cm}$$

$\theta < 10^{-10}$ which is quite unnatural !!

RADIATIVE/RARE KAON DECAYS

$$K \to \pi l^+ l^- \qquad\qquad K \to \pi \nu \bar{\nu}$$

- *G. Isidori, G. M., and P. Turchetti, Phys.Lett. B633, 75 (2006), arXiv:hep-lat/0506026*
- N.H. Christ X. Feng A. Portelli and C.T. Sachrajda *Phys.Rev. D92 (2015) no.9, 094512* 10.1103/PhysRevD.92.094512 *

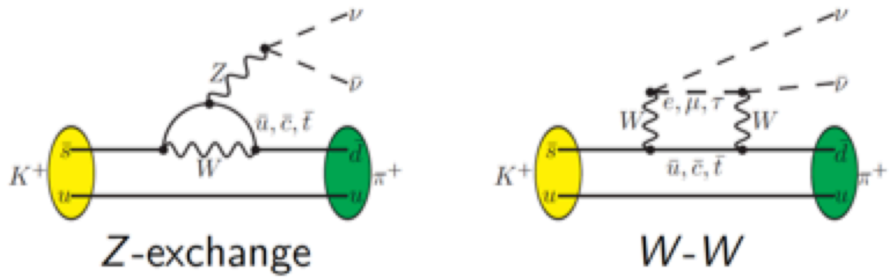
$K^+ \to \pi^+ \ell^+ \ell^-$ Long distance dominated easy experimentally*

$K^0_{L/S} \to \pi^0 \ell^+ \ell^-$ Long distance dominated CPV*

$K^+ \to \pi^+ \nu \bar{\nu}$ Mainly short distance (top quark) NA62*
Long distance charm effects

$K^0_{L/S} \to \pi^0 \nu \bar{\nu}$ Short distance (top quark) KOTO

* lattice calculations



$K^+ \to \pi^+ \nu\bar{\nu}$: largest contribution from top quark loop, thus theoretically clean

$$\mathcal{H}_{eff} \sim \frac{G_F}{\sqrt{2}} \cdot \underbrace{\frac{\alpha_{\rm EM}}{2\pi \sin^2\theta_W} \lambda_t X_t(x_t)}_{\mathcal{N} \sim 2\times 10^{-5}} \cdot (\bar{s}d)_{V-A} (\bar{\nu}\nu)_{V-A}$$

Probe the new physics at scales of $\mathcal{N}^{-\frac{1}{2}} M_W = O(10 \text{ TeV})$

Past experimental measurement is 2 times larger than SM prediction

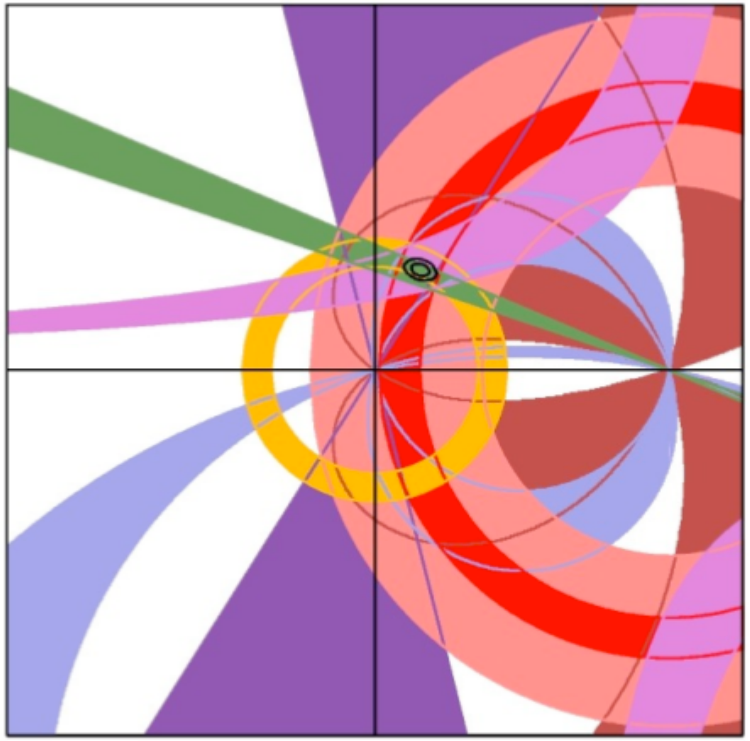
$$\text{Br}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{exp}} = 1.73^{+1.15}_{-1.05} \times 10^{-10} \qquad \text{[BNL E949, '08]}$$

$$\text{Br}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{SM}} = 9.11 \pm 0.72 \times 10^{-11} \qquad \text{[Buras et. al., '15]}$$

but still consistent with $> 60\%$ exp. error

$b \to c\tau\nu$ and $b \to s\mu\mu$

anomalies difficult to explain simultaneously



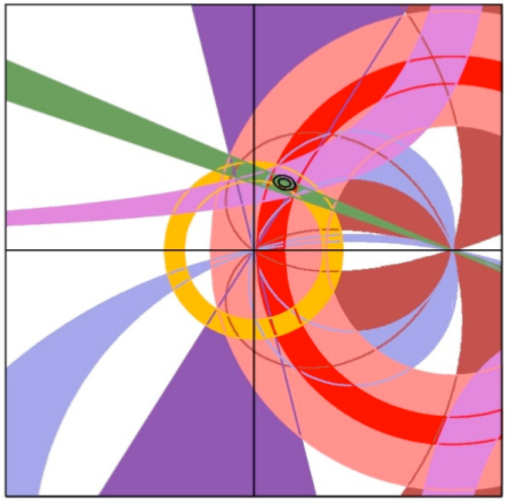
- *Need to clarify the theoretical side*

- *May imply new signals at high p_T (CMS and ATLAS)*

- *Effects also in g-2, Belle II, NA62, ..*

FUTURE

- Many related modes in $b \to c\tau\nu$ and $b \to s\mu\mu$
- $\Lambda_b \to \Lambda_c \tau\nu$, $B_c J/\psi\tau\nu$, $B_s \to D_s^* \tau\nu$, $B_s \to \phi\mu\mu$
  $B \to X_c \tau\nu$ and $B \to D^{**}\tau\nu$
- *LFU angular distributions*
  $B_s \to \phi\mu\mu \quad B^0 \to K^{0\,*}\mu\mu$
- $b \to s\ell\ell$ *inclusive;*
- $b \to s\nu\bar{\nu}$ *(radiative?) ideas*
- $B \to s\tau\bar{\tau}$
- $\dfrac{\delta f_B}{f_B} = 2\% \quad \left(\dfrac{\delta V_{ub}}{V_{ub}}\right)^{exc} = 4\% \quad \dfrac{\delta\Gamma[B \to \tau\nu]}{\Gamma[B \to \tau\nu]} = 20\%$



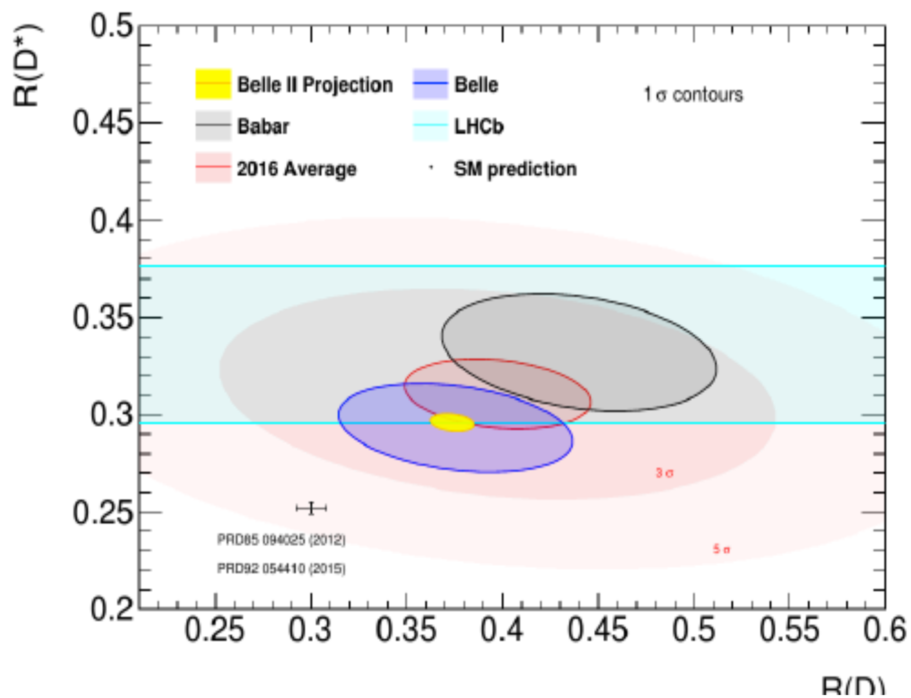
We need computer resources !!

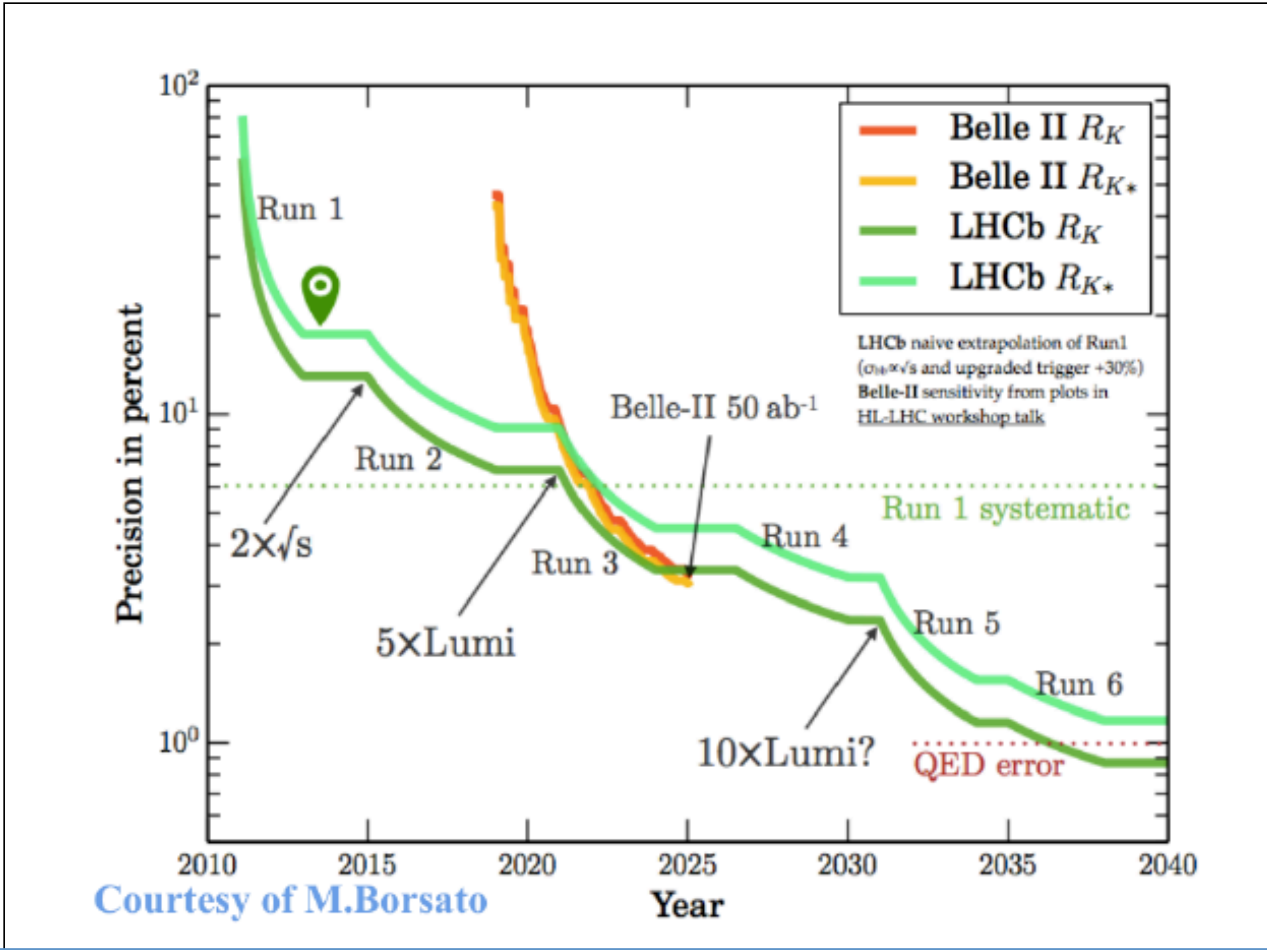
- R_D measurement from LHCb
- cross checks with other hadronic systems

$$R_{J/\psi} = \frac{BR(B_c \to J/\psi\tau\nu)}{BR(B_c \to J/\psi\mu\nu)} = 0.71 \pm 0.17 \pm 0.18 \quad \text{(LHCb 1711.05623)}$$

$$R_{\Lambda_c} = \frac{BR(\Lambda_b \to \Lambda_c\tau\nu)}{BR(\Lambda_b \to \Lambda_c\mu\nu)}$$

- Belle II can significantly improve current $R_{D^{(*)}}$ uncertainties
- precise measurements of q^2 spectra, angular distributions, tau polarization, ...



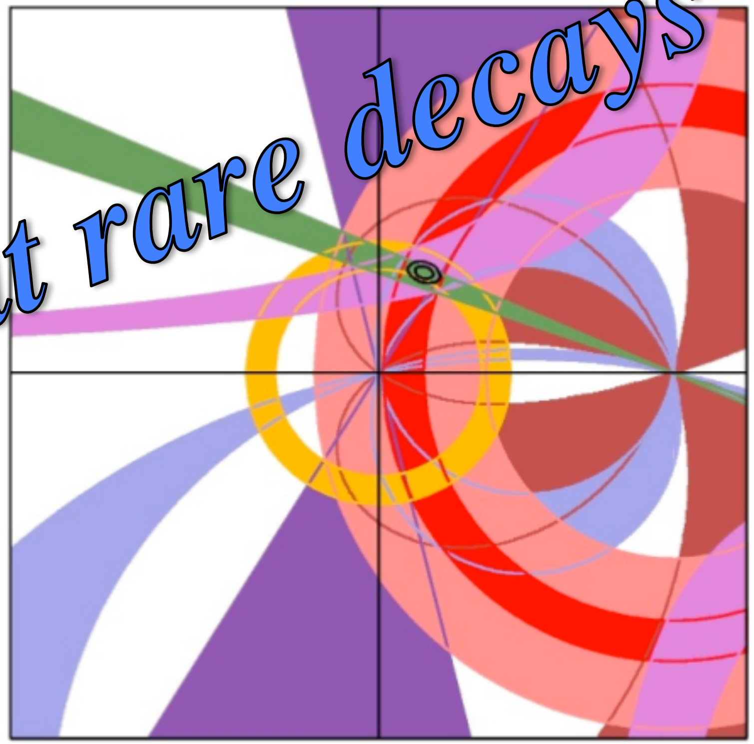


Improvement of theoretical accuracy also essential *and now:*

... the future (strategies)

LFU anomalies are very interesting but do not forget the fundamental questions (S Mantra):

- ***Baryon-Antibaryon asymmetry & CP violation***
- ***Strong CP problem***
- ***Dark matter and Dark Energy***
- ***Flavor origin***

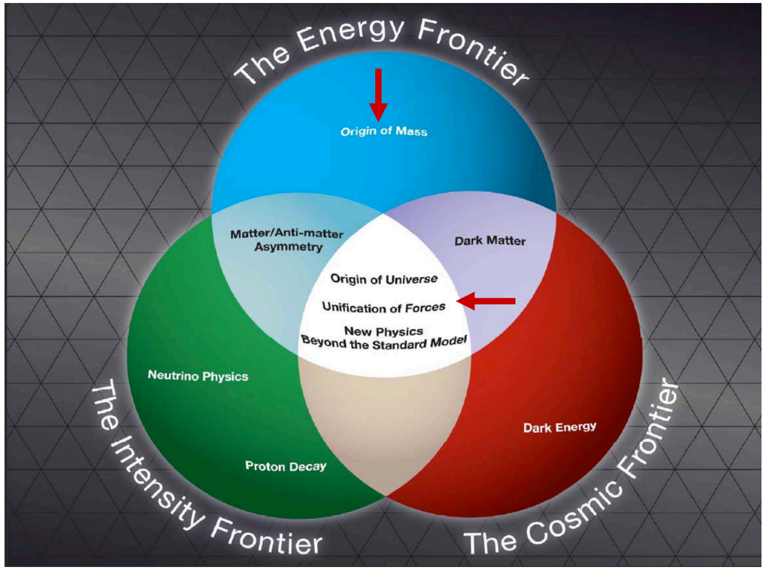


Look at rare decays

The Unknown

As we know,
There are known knowns.
There are things we know we know.
We also know
There are known unknowns.
That is to say
We know there are some things
We do not know.
But there are also unknown unknowns,
The ones we don't know
We don't know.

Donald Rumsfeld
—Feb. 12, 2002, Department of Defense news briefing



no (unespected) discoveries so far but ….

absence says more than presence

FRANK HERBERT

(Dune)

THANKS FOR YOUR ATTENTION