Short recap

Last lecture (on Tuesday) we have learned that:

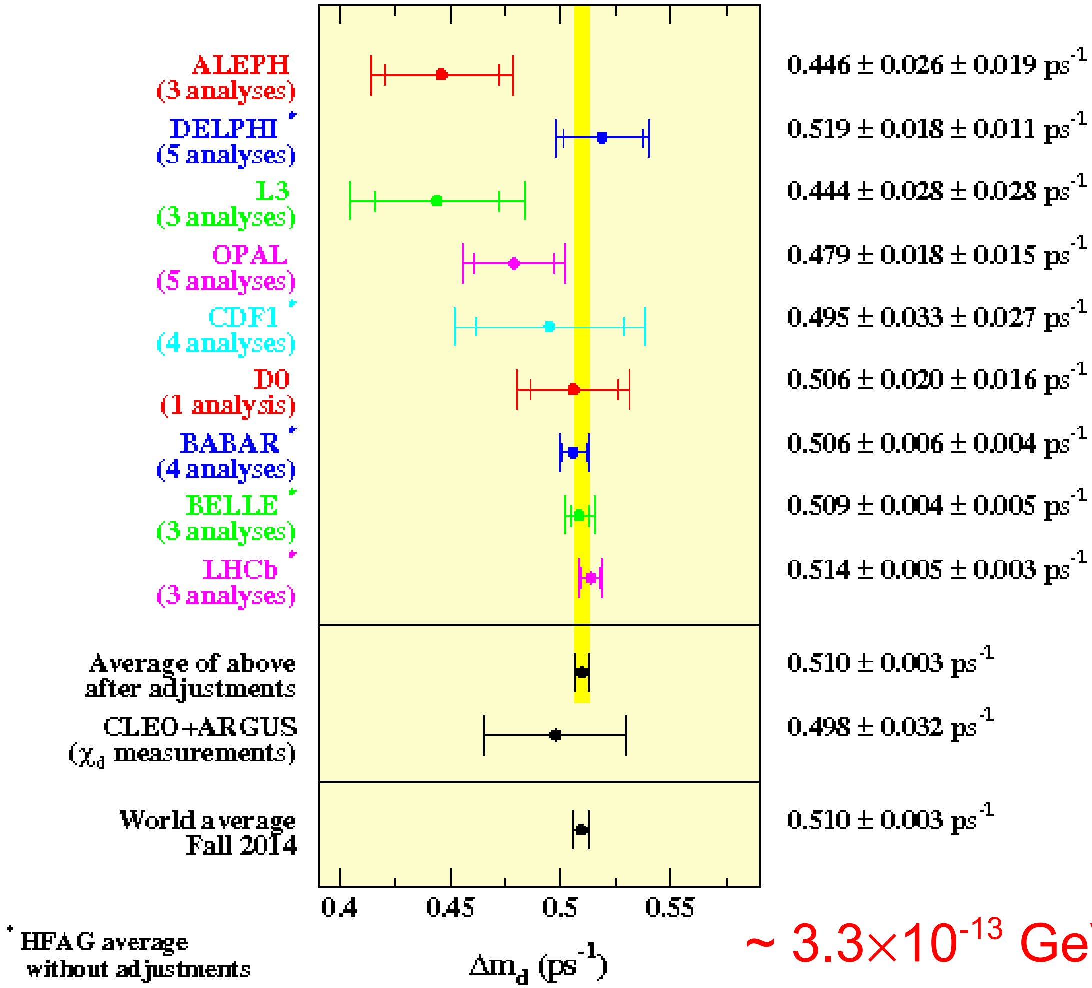
The SM:

- Has a gauge sector with a large flavor global symmetry. Which one?
- Predicts very suppressed flavor changing neutral interactions (GIM mechanism).
- Does not explain the origin of the large hierarchies in between quark (lepton) masses and CKM elements (SM flavor problem).
- Have one source of CP violation: the phase of the CKM matrix.
- Leads to three different types of CP violation in the meson systems: CP violation in the mixing; in the decay; in the interference.

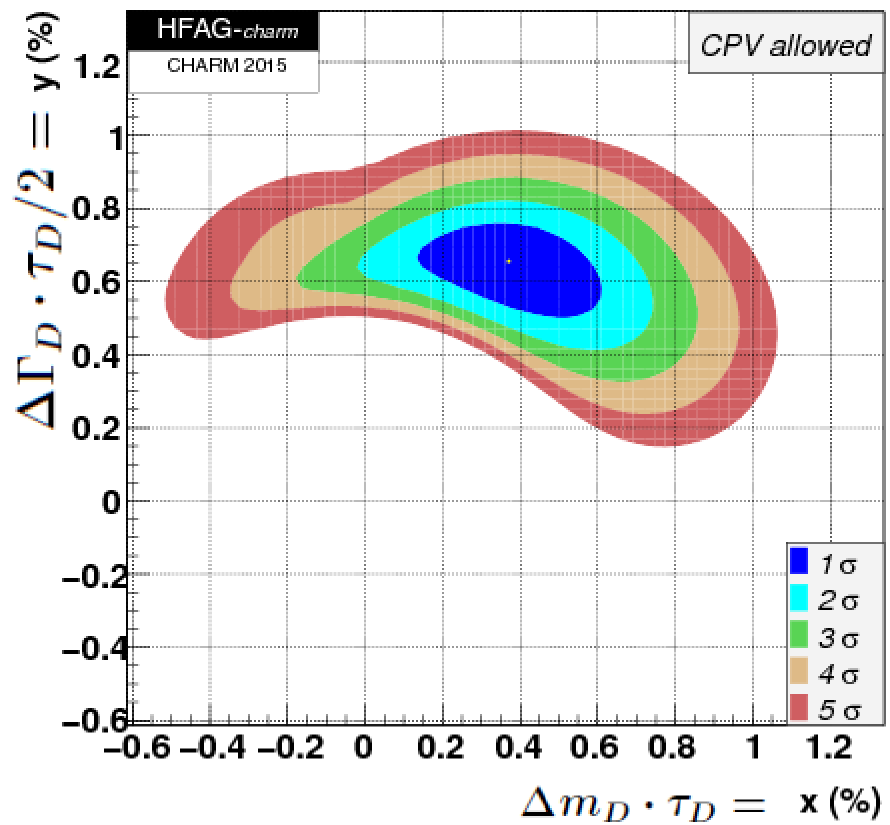
This lecture:

- Brief discussion about measurements of the meson-antimeson systems.
- Going beyond the SM: Effective theories and Minimal Flavor Violation.

Experimental status (CP conserving)



~ 3.3×10^{-13} GeV



D mixing

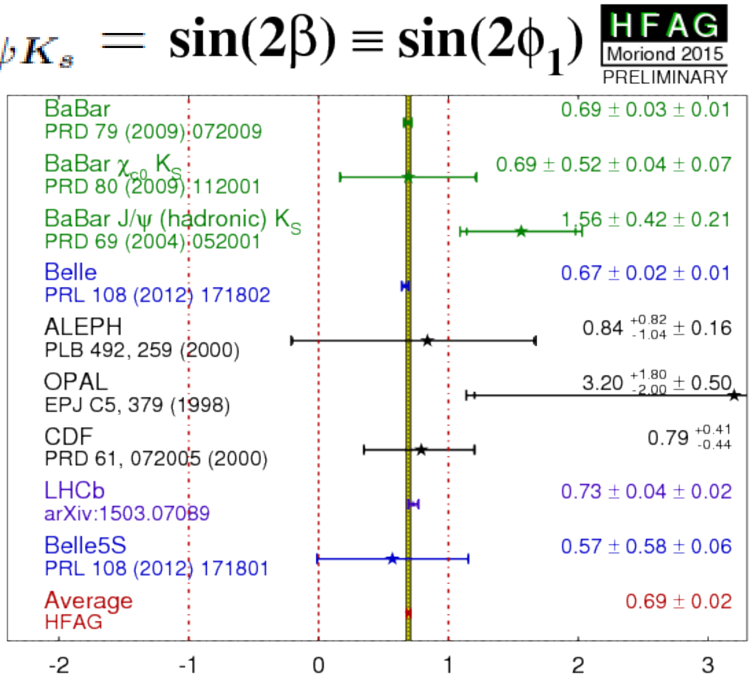
B_d mixing

~ 6.5×10^{-15} GeV

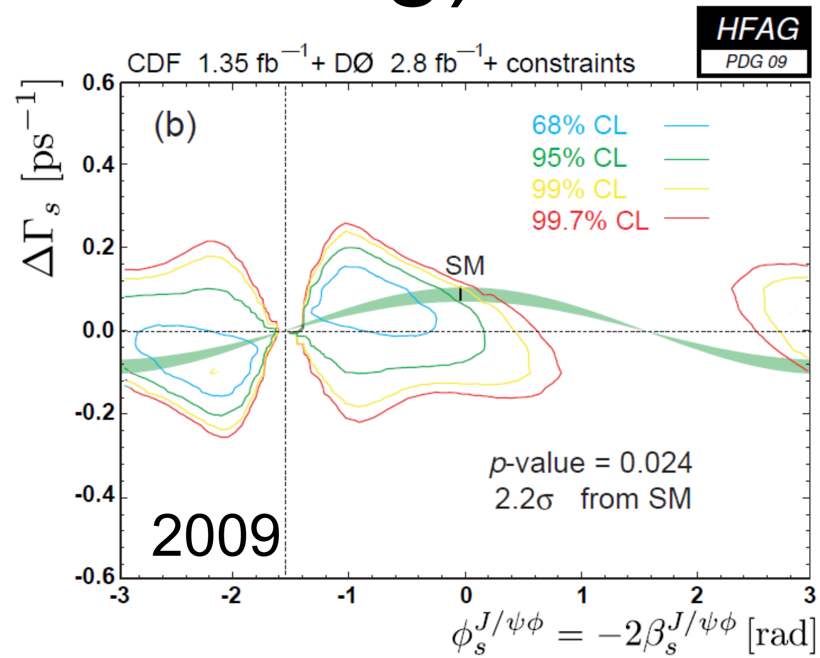
For a complete list of observables:
http://www.slac.stanford.edu/xorg/hfag/
http://pdg.lbl.gov/

Experimental status (CP violating)

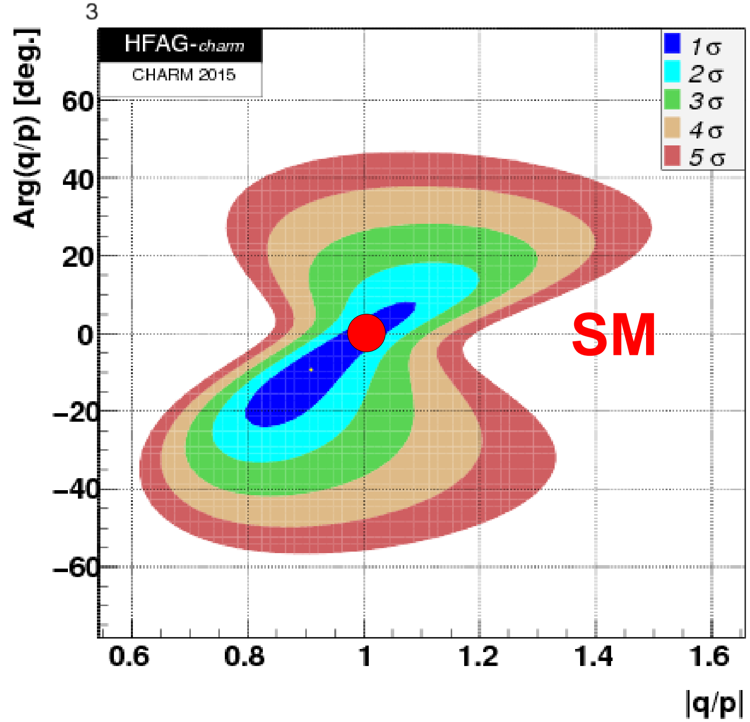
$S_{\psi K_s} = \sin(2\beta) \equiv \sin(2\phi_1)$



B_d mixing



B_s mixing

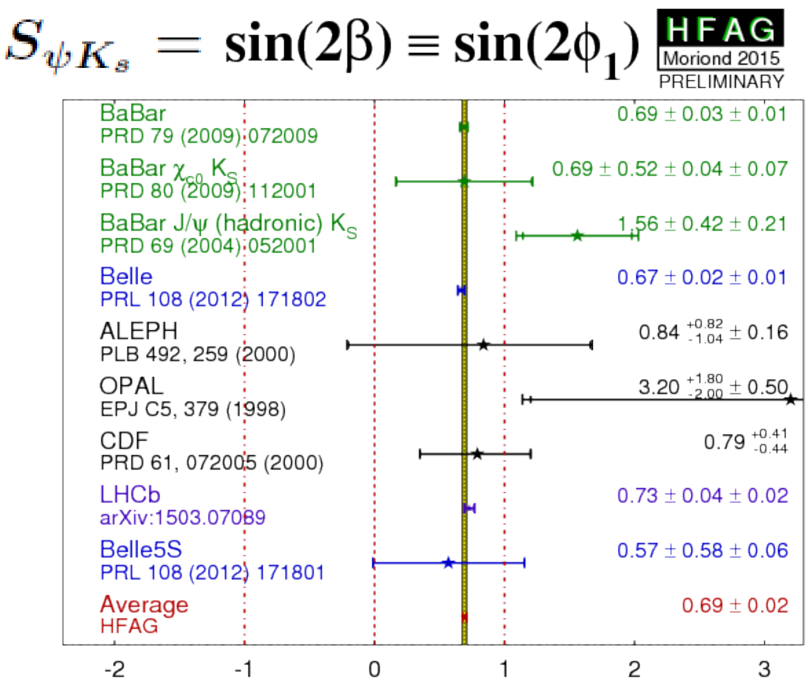


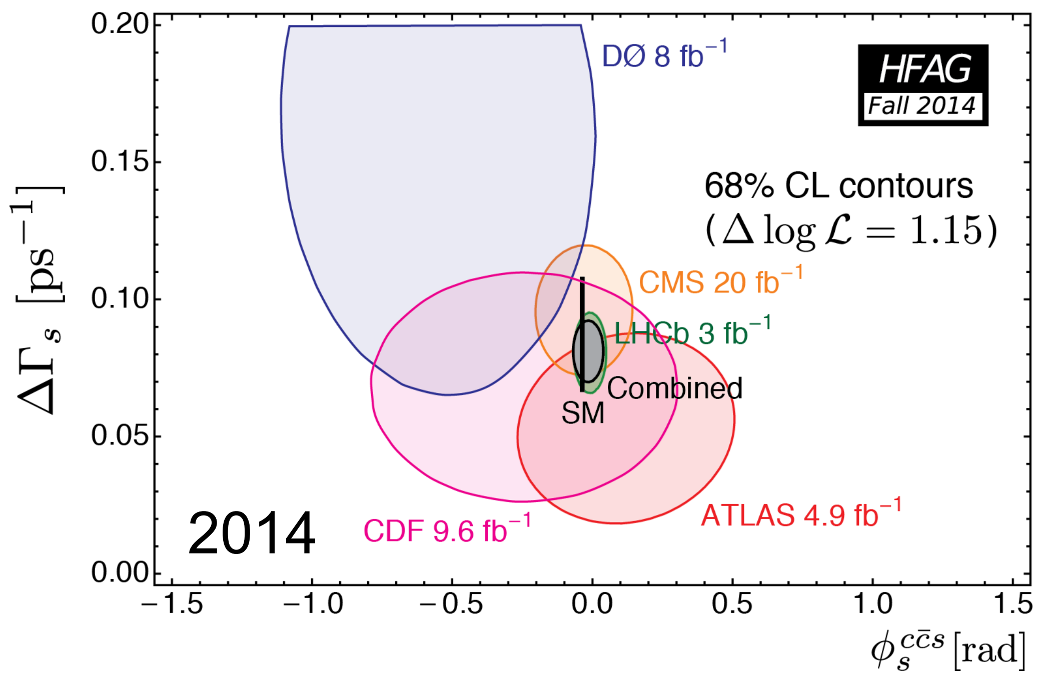
SM

D mixing

S.Gori

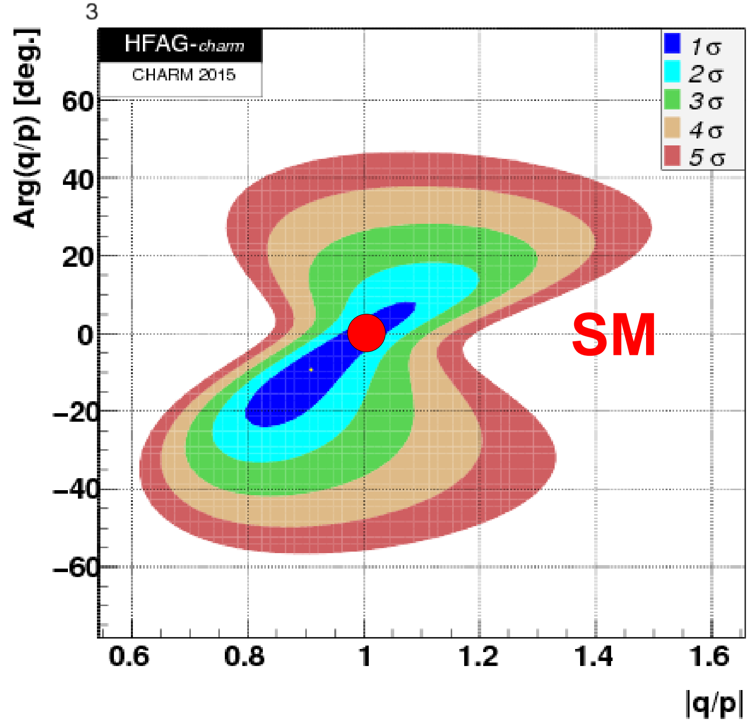
Experimental status (CP violating)





B_d mixing

B_s mixing



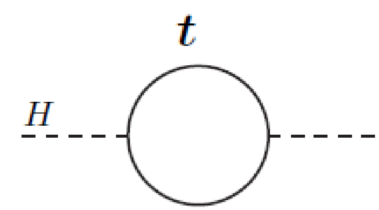
D mixing

S.Gori

Why to go beyond the Standard Model

The SM does not give an answer to

- Hierarchy problem: $m_h^2 \sim \mu^2 + c\,\Lambda^2$



- Dark matter:
  We know it exists and its abundance BUT we do not know:
  - What it is (quantum numbers, mass, interactions...)
  - If one or many components

- Baryon asymmetry of the Universe

- Neutrino mass:
  the SM Lagrangian does not give mass to the neutrinos

- Dark energy/cosmological constant

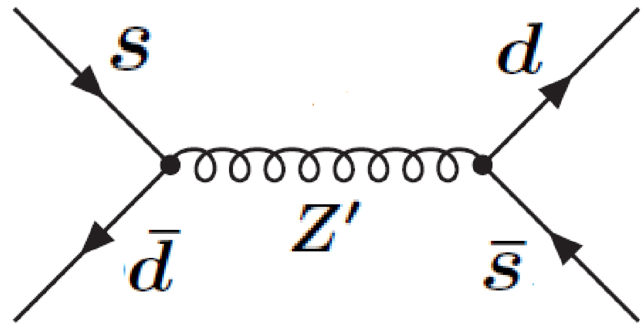
\+ We have already seen the SM flavor problem

TeV-scale New Physics?

The New Physics flavor problem

Let us take, for example, a new Z' gauge boson with couplings

$g' Z'_\mu (\bar{s}\gamma^\mu (1-\gamma_5) d)$ $\Rightarrow$



New contribution to Kaon mixing

If the Z' is heavy: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{g'^2}{m_{Z'}^2}(\bar{s}\gamma_\mu (1-\gamma_5) d)^2$

The mass difference of the two Kaons gets a new contribution:

$$\Delta m_K = \Delta m_{K_{\rm SM}} + \frac{8}{3} m_K F_K^2 B_K \frac{(g')^2}{m_{Z'}^2}$$

Let us do some estimation:

If $g' \sim 0.1,\ m_{Z'} \sim 1\,\mathrm{TeV}$ $\Rightarrow$ ~ 4 orders of magnitude larger than the SM contribution

Effective Lagrangians for meson mixings

Idea: the SM Lagrangian is only the low-energy limit of a more complete theory, or an effective field theory (EFT)

New degrees of freedom are expected at a scale Λ above the electroweak scale (Λ >> VEV)

Wilson coefficient

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \sum_{d\geq 5} \frac{c_n}{\Lambda^{d-4}} O_n^{(d)}(\mathrm{SM})$$

Renormalizable

Operators of dimension d ≥ 5 containing SM fields only and compatible with the SM gauge symmetry

This is the most general parameterization of the new degrees of freedom, (assuming Λ above the electroweak scale), as long as we perform low-energy experiments

Comment: the LHC (as well as all high energy experiments) takes a different point of view: direct production of new particles at the scale Λ

Effective Lagrangians for meson mixings

- We have already seen that the effective operator in the SM is $(\bar{s}\gamma_\mu(1-\gamma_5)d)^2$

- In all generality, at the lowest dimension (dimension 6) we can write the additional operators:

$$\left(P_{L,R} = \frac{1 \mp \gamma_5}{2}\right)$$

$$Q_1^{\mathrm{VLL}} = (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_L d)$$ (the one of the SM)

$$\begin{aligned} Q_1^{\mathrm{LR}} &= (\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_R d) \\ Q_2^{\mathrm{LR}} &= (\bar{s}P_L d)(\bar{s}P_R d) \end{aligned}$$

$$\begin{aligned} Q_1^{\mathrm{SLL}} &= (\bar{s}P_L d)(\bar{s}P_L d) \\ Q_2^{\mathrm{SLL}} &= (\bar{s}\sigma_{\mu\nu} P_L d)(\bar{s}\sigma^{\mu\nu} P_L d) \end{aligned}$$

$Q_1^{\mathrm{VRR}}, Q_1^{\mathrm{SRR}}, Q_2^{\mathrm{SRR}}$

with $P_L \to P_R$

- This leads to a NP contribution to the meson mass splitting:

$$\Delta m_K - \Delta m_{K_{\mathrm{SM}}} \sim \frac{1}{\Lambda^2} m_K F_K^2 B_i \times \mathrm{Re}(C_i)$$

Bounds on the New Physics scale

We have seen that the SM predictions
for meson mixing agree pretty well with the measurements...

Isidori, Nir, Perez,1002.0900

	Operator	Bounds on Λ [TeV] (C=1) Re	Im	Bounds on C (Λ=1 TeV) Re	Im	Observables
K	$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\epsilon_K$
	$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\epsilon_K$
D	$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\lvert q/p\rvert,\phi_D$
	$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\lvert q/p\rvert,\phi_D$
B_d	$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	$\Delta m_{B_d};S_{\psi K_S}$
	$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	$\Delta m_{B_d};S_{\psi K_S}$
B_s	$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2	2.2×10^2	7.6×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};S_{\psi\phi}$
	$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	7.4×10^2	1.3×10^{-5}	3.0×10^{-6}	$\Delta m_{B_s};S_{\psi\phi}$

Note: generically, the LHC aims to probe NP particles with mass ~ TeV

New Physics flavor problem

Ways out: either
- very heavy New Physics (Λ >> 1 TeV) or
- New Physics with a non-generic flavor structure (C<<1)

Breaking the SM flavor symmetry

Flavor symmetry: $U(3)^5 = SU(3)_Q \times SU(3)_U \times SU(3)_D \times \cdots$

(global symmetry of the SM gauge sector)

Symmetry-breaking terms: $\bar{Q}_L^i Y_D^{ij} d_R^j \Phi + \bar{Q}_L^i Y_U^{ij} u_R^j \tilde{\Phi}$

(quark Yukawa couplings)

This specific symmetry + symmetry-breaking pattern is responsible for all the successful SM predictions in the quark flavor sector

However, we can (formally) promote this symmetry to be an exact symmetry, assuming the Yukawa matrices are the vacuum expectation values of appropriate auxiliary fields: **spurions**

$Y_D \sim (3, 1, \bar{3}),\ Y_U \sim (3, \bar{3}, 1)$ (transformation under $SU(3)_Q \times SU(3)_U \times SU(3)_D$)

$$\underset{(\bar{3},1,1)}{\bar{Q}_L}\,\underset{(3,1,\bar{3})}{Y_D}\,\underset{(1,1,3)}{D_R}\,\Phi + \underset{(\bar{3},1,1)}{\bar{Q}_L}\,\underset{(3,\bar{3},1)}{Y_U}\,\underset{(1,3,1)}{U_R}\,\tilde{\Phi} \Longrightarrow (1, 1, 1)$$

The Minimal Flavor Violation ansatz

In all generality, New Physics theories with additional degrees of freedom can further break this flavor symmetry

Chivukula, Georgi '87

A natural mechanism to reproduce the SM successes in flavor physics -without fine tuning- is the MFV hypothesis:
The SM Yukawa couplings are the only sources of flavor violation in and beyond the Standard Model

Going back to the Z' example:
the $Z'_\mu(\bar{s}_L\gamma^\mu d_L)$ interaction with O(1) couplings is not allowed by this principle!

We will see that the MFV ansatz

- can address the NP flavor problem
- is stable under radiative corrections

- is not a theory of flavor.
  Why is NP so peculiar? What is the dynamic leading to this?
  Open question!

Meson mixing & MFV

Going back to EFTs...

A low-energy EFT satisfies the criterion of MFV if all higher-dimensional operators, constructed from SM and Y fields, are (formally) invariant under the flavor group

For processes with external down-type quarks,
the relevant FCNC vertices:

$$\bar{Q}_L Y_U Y_U^\dagger Q_L,\ \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Q_L,\ \bar{D}_R Y_D^\dagger Y_U Y_U^\dagger Y_D D_R$$

Where, for convenience, we have chosen the basis for which

$$Y_D = \mathrm{diag}(y_d, y_s, y_b),\ Y_U = V^\dagger \mathrm{diag}(y_u, y_c, y_t)$$

If we expand, at the leading order in the quark masses and CKM elements:

$$\mathcal{O}_0 = y_t^4 \left(\bar{Q}_L^i V_{3i}^* V_{3j} \gamma_\mu Q_L^j \right)^2$$

C is not anymore O(1)!

S.Gori

TeV-scale NP is allowed!

D´Ambrosio, Giudice, Isidori, Strumia, 0207036

Minimal flavor violating dimension 6 operator	Main observables	Λ [TeV] $-$	$+$
$\mathcal{O}_0 = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	$\epsilon_K, \quad \Delta m_{B_d}$	9.1	7.1
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_{Rd} \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_{Rd} \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}, \quad K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi, \quad \epsilon'/\epsilon, \ldots$	~ 1	

$$(\lambda_{\rm FC})_{ij} = y_t^2 V_{3i}^* V_{3j}$$

Without MFV violation,
the bound was ~10^4 TeV!

The MFV ansatz leads to a very predictive framework...

TeV – scale NP with interesting flavor effects +
possibility to be discovered at the LHC?

B-rare decays

Beyond meson mixing, there are plenty of flavor transitions that have been/will be measured at B-factories & at the LHC

Rare decays of the B meson are a great ground to test NP

- The main decay modes are $D^{\pm} + X$
- Rare FCNC decays include

$$B \to e^+e^-,\ B \to \mu^+\mu^-,\ B \to \tau^+\tau^-,\ B \to K\mu^+\mu^-,\ B \to K\bar{\nu}\nu, \cdots$$

- Tiny SM predictions:

e^+e^-	$\mu^+\mu^-$	$\tau^+\tau^-$	
$(8.5 \pm 0.6) \times 10^{-14}$,	$(3.6 \pm 0.2) \times 10^{-9}$,	$(7.7 \pm 0.5) \times 10^{-7}$	B_s
$(2.5 \pm 0.2) \times 10^{-15}$,	$(1.1 \pm 0.1) \times 10^{-10}$,	$(2.2 \pm 0.2) \times 10^{-8}$	B_d

$(1.3 \pm 0.3) \times 10^{-7}$, $(4.0 \pm 0.5) \times 10^{-6}$

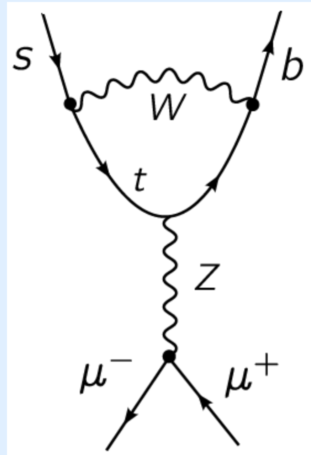
$B \longrightarrow K\mu^+\mu^-$ $\quad$ $B \longrightarrow K\nu\nu$

Since they are so rare, they can be easily affected by NP

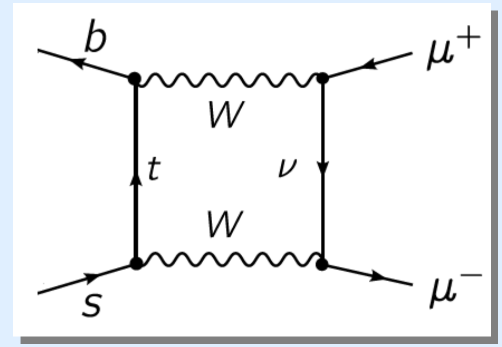
B-rare decays in the SM

$B \to \mu^+\mu^-$

Penguin diagrams



Box diagrams



$$\mathcal{H} = \frac{G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2\theta} V_{tb}^* V_{ts} Y(x_t) (\bar{b}\gamma_\mu (1-\gamma_5) s)(\bar{\mu}\gamma_\mu (1-\gamma_5)\mu)$$

Loop function

CKM element

Decay constants and CKM elements are the main source of theory uncertainty (even if small ~ 7%)

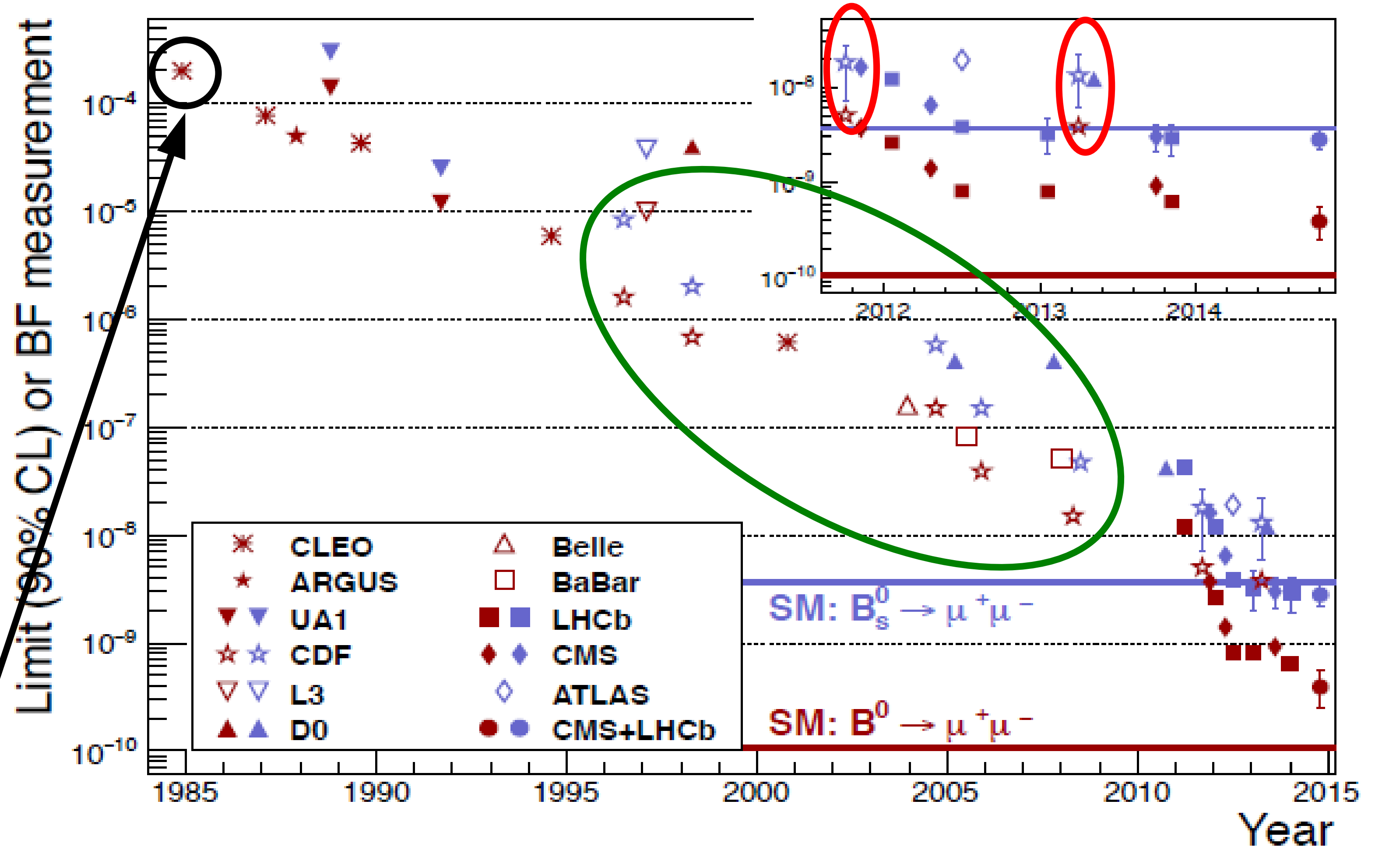
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{G_F^2}{\pi} \left(\frac{\alpha}{4\pi \sin^2\theta}\right)^2 |V_{tb}^* V_{ts}|^2 Y(x_t)^2 m_\mu^2 m_{B_s} \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} F_{B_s}^2 \tau_{B_s}$$

"Helicity suppression"

Searches for B-rare decays

Maybe larger than the SM?
Or maybe not...

LHCb and CMS coll., Nature, 522 (2015) 68



CLEO, 1985

1997-2010: Tevatron era. Best limits in 2010:

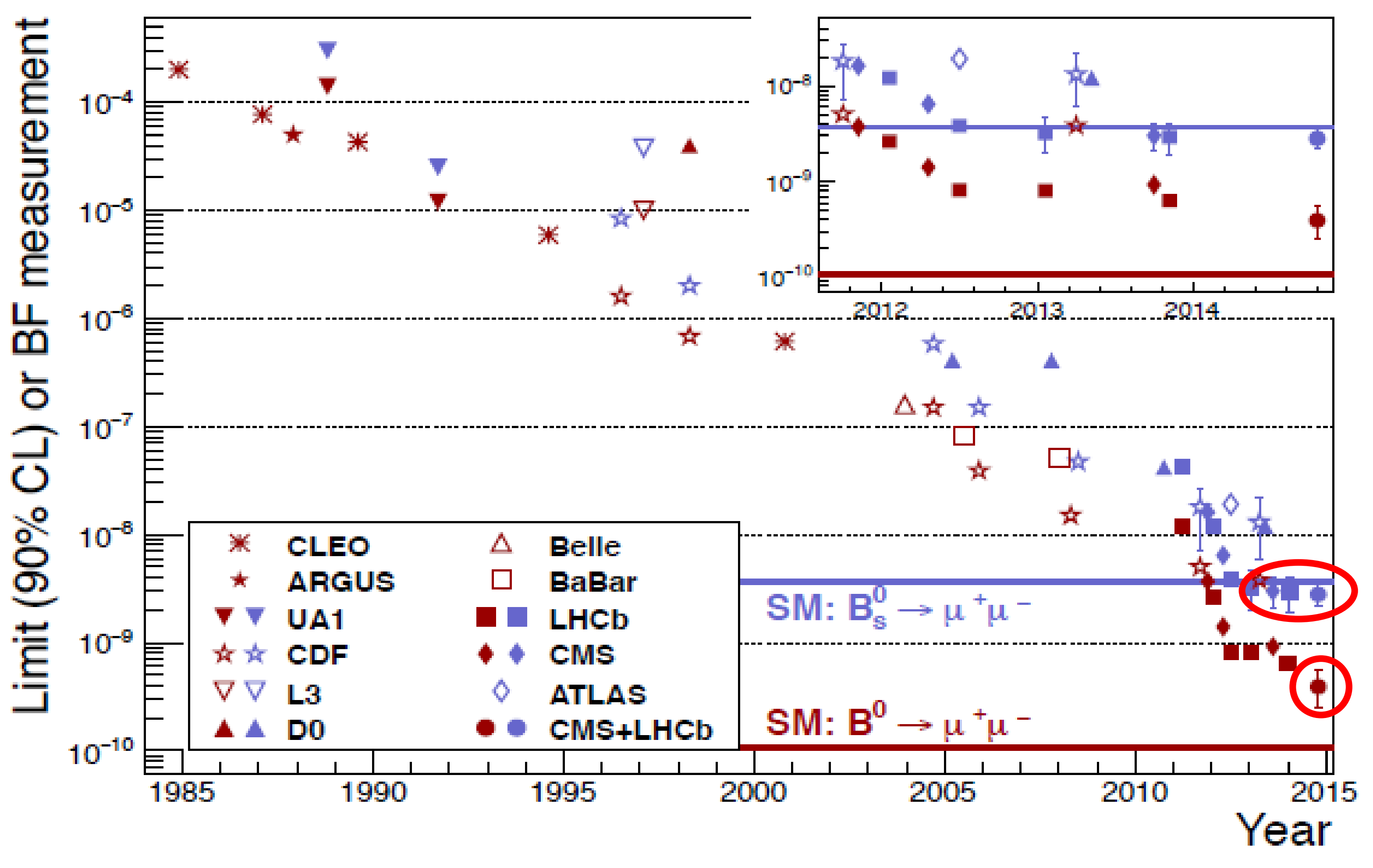
CDF (~3.7 fb^{-1}) $BR(B_s \to \mu\mu) <$ **36×10^{-9}**

D0 (~6.1 fb^{-1}) $BR(B_s \to \mu\mu) <$ **42×10^{-9}**

~11 times the SM

Searches for B-rare decays

LHCb and CMS coll., Nature, 522 (2015) 68



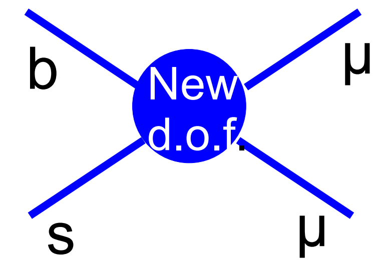
$\mathrm{BR}(B^0_s) = (2.8^{+0.7}_{-0.60}) \times 10^{-9}$ 6.2σ observed

$\mathrm{BR}(B^0) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}$ 3.0σ observed

Effective Lagrangians for B-rare decays

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i C_i Q_i$$

Semileptonic operators



In the Wilson coefficient
a new flavor structure can appear

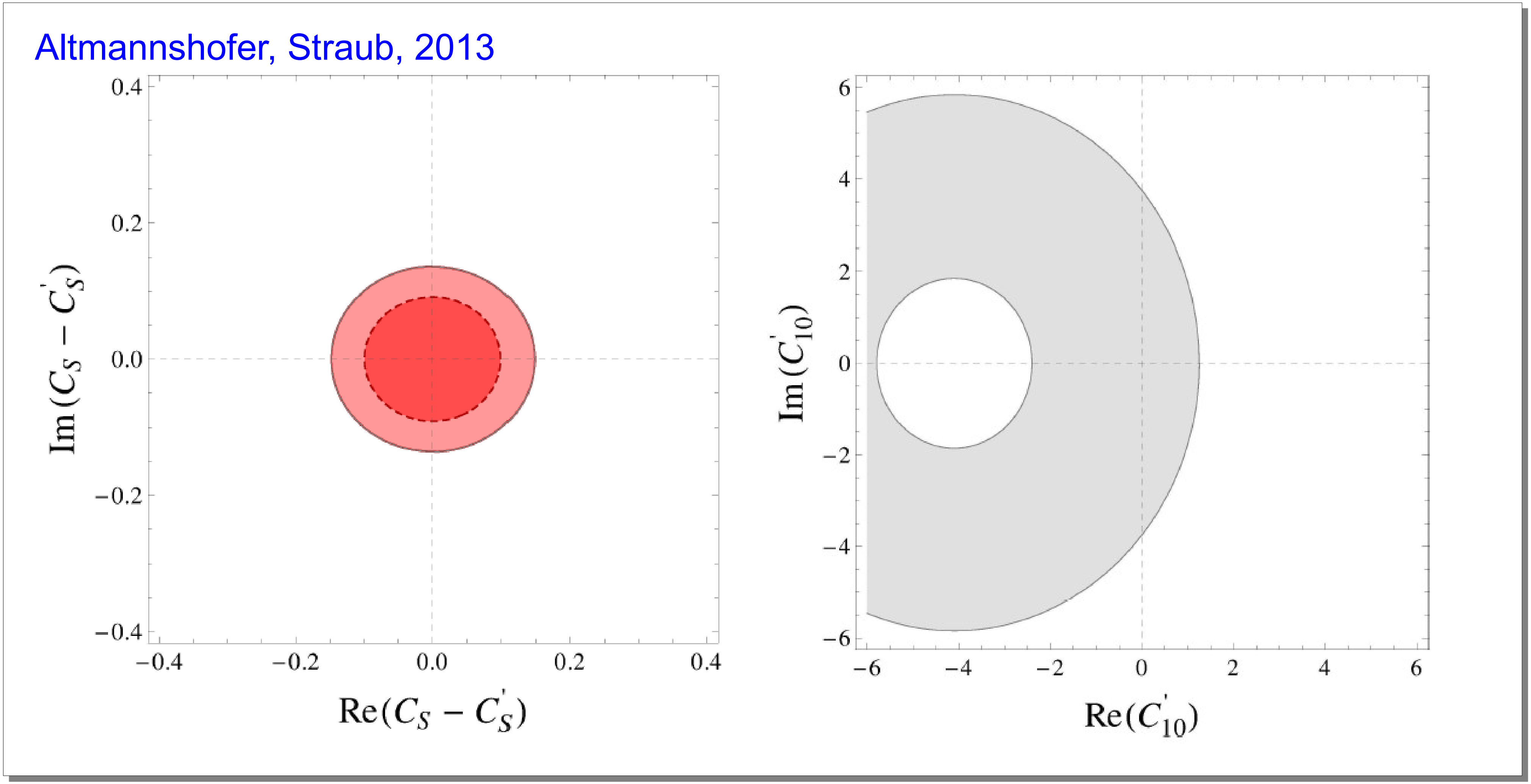
d.o.f = degree of freedom

$$\begin{aligned}
\mathcal{O}_{10} &= (\bar{b}\gamma_\mu P_L s)(\bar{\mu}\gamma_\mu\gamma_5\mu) \quad \text{(the one of the SM)}\\
\mathcal{O}'_{10} &= (\bar{b}\gamma_\mu P_R s)(\bar{\mu}\gamma_\mu\gamma_5\mu)\\
\mathcal{O}_S &= (\bar{b}P_L s)(\bar{\mu}\mu)\\
\mathcal{O}'_S &= (\bar{b}P_R s)(\bar{\mu}\mu) \qquad \left(P_{L,R} = \frac{1 \mp \gamma_5}{2}\right)\\
\mathcal{O}_P &= (\bar{b}P_L s)(\bar{\mu}\gamma_5\mu)\\
\mathcal{O}'_P &= (\bar{b}P_R s)(\bar{\mu}\gamma_5\mu)
\end{aligned}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) \propto m_\mu^2 \left(\left| (C_{10}^{\mathrm{SM}} + C_{10}^{\mathrm{NP}} - C'_{10}) + \frac{m_{B_s}}{2m_\mu}(C_P - C'_P) \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(C_S - C'_S) \right|^2 \right)$$

The helicity suppression can be eliminated
thanks to the scalar/pseudoscalar operators

Bounds on DF=1 operators



$$\mathrm{BR}(B_s \to \mu^+\mu^-) \propto m_\mu^2 \left(\left| (C_{10}^{\mathrm{SM}} + C_{10}^{\mathrm{NP}} - C_{10}') + \frac{m_{B_s}}{2m_\mu}(C_P - C_P') \right|^2 + \left| \frac{m_{B_s}}{2m_\mu}(C_S - C_S') \right|^2 \right)$$

The helicity suppression can be eliminated thanks to the scalar/pseudoscalar operators

The prediction of MFV models

- To satisfy the MFV condition:

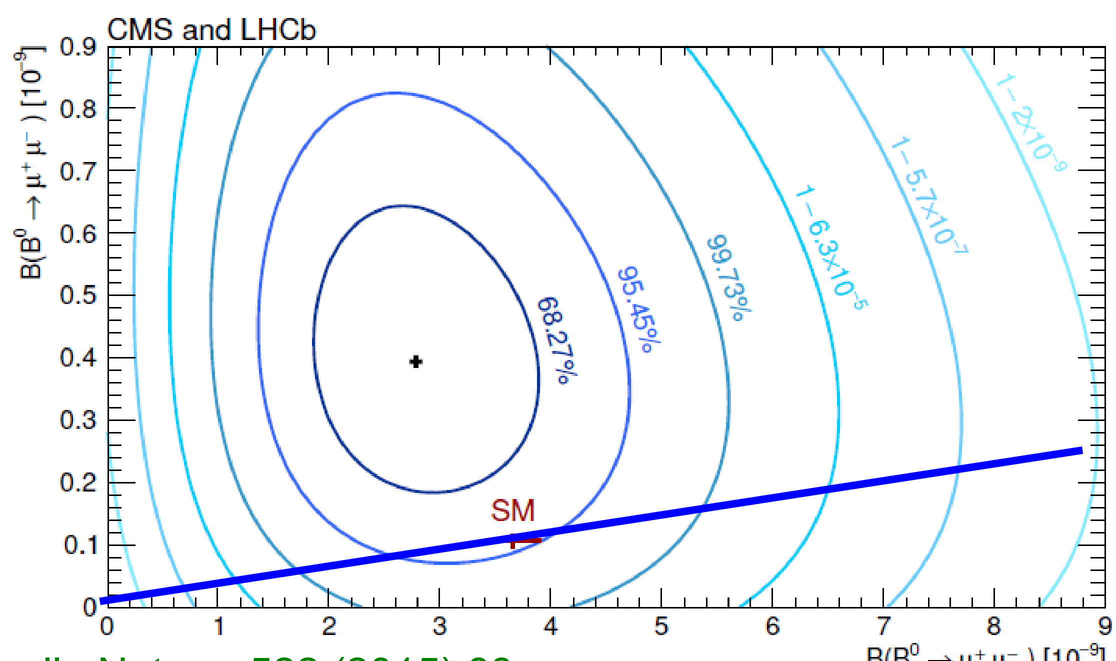
$$C_i \sim V_{tb}^* V_{ts} \qquad \text{(B}_s\text{ decay)}$$
$$C_i \sim V_{tb}^* V_{td} \qquad \text{(B}_d\text{ decay)}$$

Reminder:
MFV ansatz: The SM Yukawa couplings are the only sources of flavor violation in and beyond the Standard Model

- Therefore, in MFV theories we always get

$$\frac{\mathrm{BR}(B_s \to \mu^+\mu^-)}{\mathrm{BR}(B_d \to \mu^+\mu^-)} \sim \left|\frac{V_{ts}}{V_{td}}\right|^2$$

Large part of the theory uncertainty (top mass, decay constant, …) is cancelled in the ratio



Theory uncertainty ~5%

LHCb and CMS coll., Nature, 522 (2015) 68

Take home messages (for EFTs)

- New Physics at around the TeV scale cannot have a generic flavor structure (NP flavor problem)

- The Minimal Flavor Violation ansatz
  - is an "effective" way to address the NP flavor problem
  - leads to precise predictions (example with B rare decays)

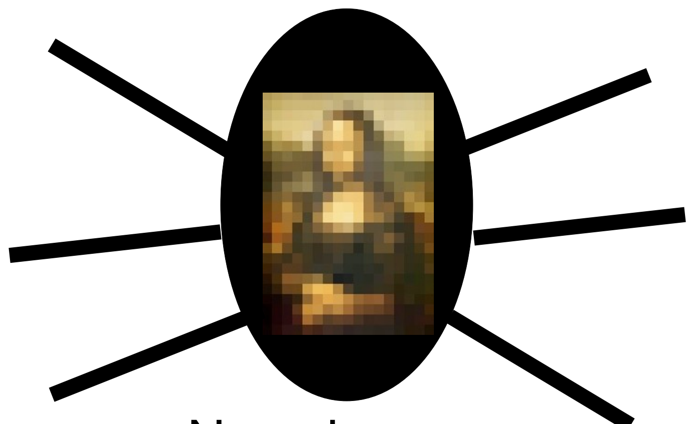
- We do not know why (and if) the MFV ansatz is realized in nature

Minimal Flavor Violation or Beyond Minimal Flavor Violation?

Beyond effective theories. A 2HDM

- Up to now, we have considered effective theories arising from more complete theories beyond the SM, with new heavy degrees of freedom that they can be integrated out

Effective operator:



SM fields

New degrees of freedom (d.o.f.)

- What is the complete BSM theory?
  What are the new degrees of freedom?

Next: models with additional Higgs bosons, SUSY models, ...

How to discover a new d.o.f.

High energy vs. high precision experiments

Synergy

Producing new particles on shell at high energy experiments

Collision of protons/electrons at high energy producing directly new particles and observe their decay products

Most recent examples from the past

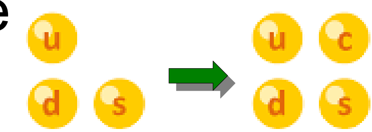
- Tevatron at Fermilab
(center of mass energy 1.96 TeV)
discovery of the top quark 1995
- Large Hadron Collider at CERN
(center of mass energy 8 TeV)
discovery of the Higgs boson 2012

What is next?

Testing new particles through flavor and CP transitions

Some examples from the past

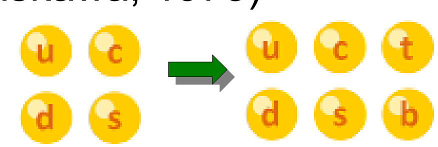
- Measurement of the tiny branching ratio of the decay $K_L \to \mu^+\mu^-$



⇨ prediction of the charm quark
(Glashow, Iliopoulos, Maiani, 1970)

- Observation of CP violation in kaon anti-kaon oscillations

⇨ prediction of the 3rd generation
(Kobayashi, Maskawa, 1973)



What is next?