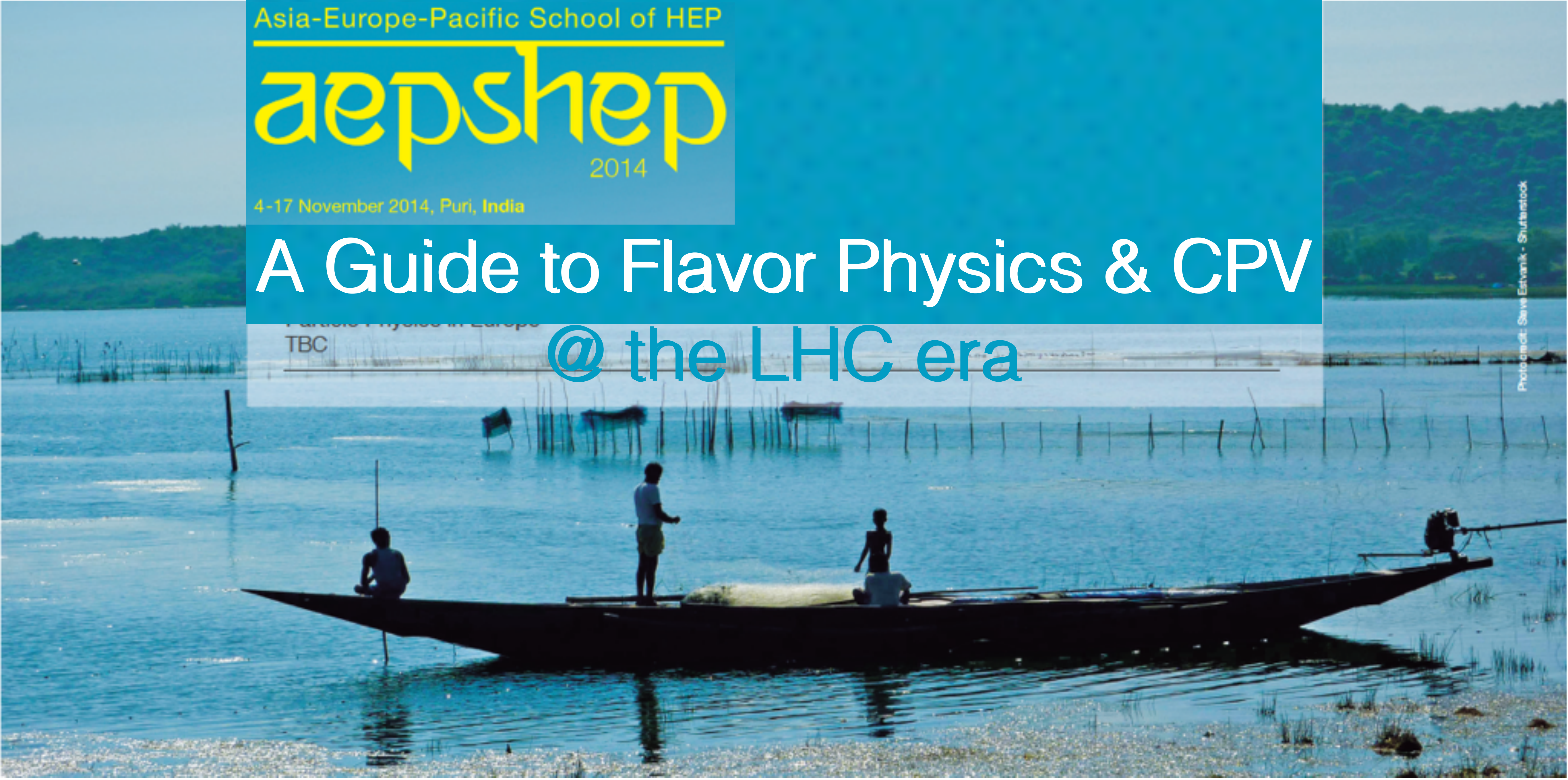

A Guide to Flavor Physics & CPV @ the LHC era

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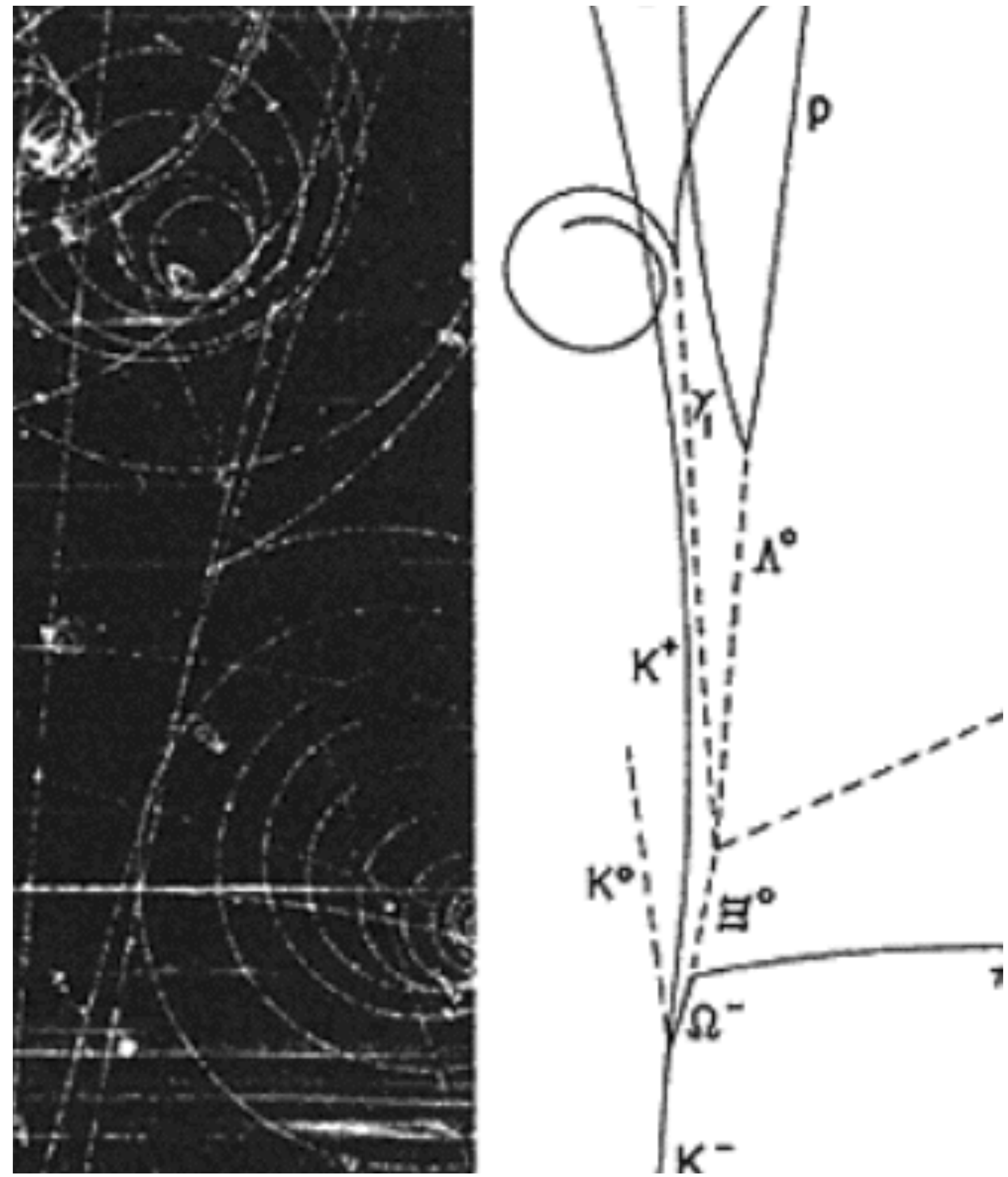
Lecture 4

Outline

- Lecture I: Motivation, and Basic Introduction to Flavor Physics
- Lecture 2: Flavor and CP Violation in the meson mixings and decays
- Lecture 3: OPE, Effective Theories for heavy flavors.
- Lecture 4: New Physics Puzzle & Implication on BSM flavor structure. Flavor Physics at the LHC era



references: Y. Nir, hep-ph/0510413
D'Ambrosio et al, arXiv:hep-ph/0207036
A. Buras, hep-ph/9806471
G. Perez arXiv:1005.3106
Y. Grossman, arXiv:1006.3534

Lecture IV

- New physics flavor puzzle
- Minimal flavor violation
- Partial compositeness
- New Phyics in the B-physics

Flavor Physics (current issues)

- Flavor physics can predicted New Physics before it's directly observed
- Flavor physics (CP Violation) predicts that there should be New Physics beyond the SM
- SM flavor problem: hierarchy of masses and mixing angles; why neutrinos are different
- NP flavor problem: TeV scale (hierarchy problem) << flavor & CPV scale

$$\epsilon_K\colon \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}, \quad \Delta m_B\colon \frac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\mathrm{TeV}, \quad \Delta m_{B_s}\colon \frac{(b\bar{s})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2\,\mathrm{TeV}$$

– Many extensions of the SM have new sources of CP and flavor violation

Clues for the subtle structure of the NP?

New Physics Flavor Problem (Puzzle)

- NP flavor problem: TeV scale (hierarchy problem) << flavor & CPV scale

$$\epsilon_K\colon \frac{(s\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^4\,\mathrm{TeV}, \quad \Delta m_B\colon \frac{(b\bar{d})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^3\,\mathrm{TeV}, \quad \Delta m_{B_s}\colon \frac{(b\bar{s})^2}{\Lambda^2} \Rightarrow \Lambda \gtrsim 10^2\,\mathrm{TeV}$$

  – Many extensions of the SM have new sources of CP and flavor violation

What kind of new physics can survive?

$$\Delta\mathcal{L}^{\Delta F=2} = \sum_{i\neq j} \frac{c_{ij}}{\Lambda^2}(\overline{Q}_{Li}\gamma^\mu Q_{Lj})^2$$

Operator	Bounds on Λ in TeV ($c_{ij}=1$)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_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}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_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}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{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}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.1×10^2		7.6×10^{-5}		Δm_{B_s}
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	3.7×10^2		1.3×10^{-5}		Δm_{B_s}
$(\bar{t}_L\gamma^\mu u_L)^2$					same sign t's

New Physics Flavor Problem (Puzzle)

- For a TeV scale NP (hierarchy problem) to be compatible with precision measurements, we need a special flavor structure to make all the dimensionless coefficients small

- Effective theory approach: SM as an effective theory

$$\mathcal{L} = \mathcal{L}_{kin} + \mathcal{L}_{Higgs} + \mathcal{L}_{Yukawa} + \sum_{n(d \geq 5)} \frac{c_n}{\Lambda^{(d)}} O_n^{(d)}(\psi_i, A_a, h)$$

higher dimensional operators consisting of SM fields only, still respecting gauge symmetries

M

Λ

NP appear at Λ~TeV but c_n is not O(1), but is very small - highly tuned

E

New Physics Flavor Problem (Puzzle)

* For a TeV scale NP (hierarchy problem) to be compatible with precision measurements, we need a special flavor structure to make all the dimensionless coefficients small

* One popular way to do it: Minimal Flavor Violation (MFV)
  - No new Operators beyond those present in the SM
  - All flavour changing transitions are governed by CKM. i.e. No new complex phases beyond those present in the SM

$$A(\text{Decay}) \propto V^i_{CKM} \underbrace{\left(F^i_{\text{SM}} + F^i_{\text{NP}}\right)}_{\text{real}}$$

MFV

- MFV is not a model It's a simple framework for flavour structure of NP from EFT point of view
  - Observation: CKM (only source of FV in SM) is approximately an unit matrix such that CKM-induced flavor change is guaranteed to be small (and no tree level FCNC)
  - If the new physics is flavor-diagonal such that all of the flavour-violation goes through the CKM then we're guaranteed to have small effects.
  - So, just like in SM, Yukawa couplings is the only sources of flavour symmetry breaking in physics beyond the SM

⇒ CKM and GIM suppressions similar to SM; allows EFT-like analyses

with TeV scale, expect few % deviations from SM in B,D,K

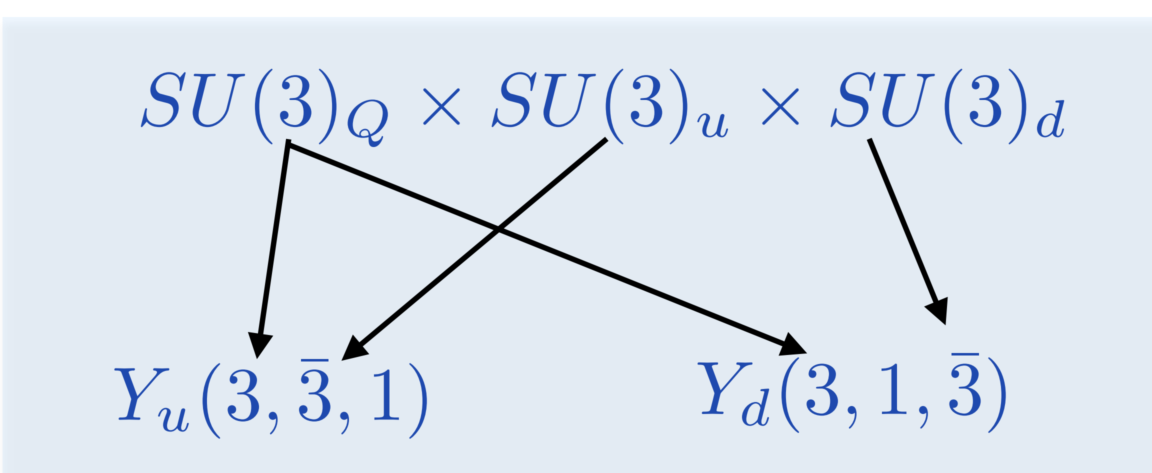
MFV

- Recall that in the vanishing Yukawa coupling limit, SM has global symmetries:

$$\mathcal{G}_{\rm global}(Y^{u,d,l}=0) = U(3)^5 \supset SU(3)_Q \times SU(3)_u \times SU(3)_d \times \ldots$$

  - In the SM, Yukawa interactions break this symmetry group

  - We can formally restore flavour symmetry by promoting Yukawa matrices to be spurions (appropriate dimensionless auxiliary fields), which transforms under the flavor group.



$$Q_L(3,1,1), u_R(1,3,1), d_R(1,1,3)$$

Using $SU(3)_q{}^3 \otimes SU(3)_\ell{}^2$ symmetry, we can rotate the background values of the auxiliary field Y:

$$Y_d = \lambda_d,\;\; Y_u = V^\dagger_{\rm CKM}\,\lambda_u,\;\; Y_L = \lambda_l$$

MFV

- For an effective theory to be MFV theory, all its higher dimensional operators, constructed from SM and Y fields, should be invariant under CP and (formally) under the flavour group.
  - MFV requires that the dynamics of flavour violation is completely determined by the structure of the ordinary Yukawa couplings. In particular, all CP violation originates from the CKM phase.
  - From the hierarchical structure of Yukawa matrix (only top Yukawa is large),

$$(\lambda_{\rm FC})_{ij} = \begin{cases} \left(Y_U Y_U^\dagger\right)_{ij} \approx \lambda_t^2 V_{3i}^* V_{3j} & i \neq j \\ 0 & i = j \end{cases}$$

$$(Y_U Y_U^+)_{ij} \approx y_t^2 V_{3i}^* V_{3j} \quad \Rightarrow \quad \begin{aligned} &V^+ \times \mathrm{diag}(y_u^2, y_c^2, y_t^2) \times V \\ &\approx V^+ \times \mathrm{diag}(0, 0, y_t^2) \times V \end{aligned}$$

MFV

- Basic building blocks of FCNC operators:

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

- Expanding in powers of off-diagonal CKM matrix elements and in powers of small Yukawa couplings

$$\bar{Q}_L \lambda_{\rm FC} Q_L \quad \text{and} \quad \bar{D}_R \lambda_d \lambda_{\rm FC} Q_L \qquad (\lambda_{\rm FC})_{ij} = \begin{cases} \left(Y_U Y_U^\dagger\right)_{ij} \approx \lambda_t^2 V_{3i}^* V_{3j} & i \neq j \\ 0 & i = j \end{cases}$$

Minimally flavour violating dimension six operator	main observables	Λ [TeV] −	Λ [TeV] +
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)^2$	ϵ_K, Δm_{B_d}	6.4	5.0
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{\rm FC} \sigma_{\mu\nu} T^a Q_L\right) G_{\mu\nu}^a$	$B \to X_s \gamma$	2.6	3.5
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{\rm FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi$, $\epsilon'/\epsilon, \ldots$	~ 1	

MFV

$$A(\text{Decay}) \propto V^i_{CKM} \underbrace{\left(F^i_{\text{SM}} + F^i_{\text{NP}}\right)}_{\text{real}}$$

- MFV framework is general, and can be implemented for a given BSM scenario (e.g. SUSY and composite Higgs models)
- The bound for Flavor cutoff scale is reduced from O(1000)TeV to O(1)TeV
- MFV is very predictive: compared to SM prediction, only the flavour-independent magnitude of the transition amplitudes can be modified. Possible to be identified by experiments

$$(\sin 2\beta)_{B\to\psi K_S} = (\sin 2\beta)_{K\to\pi\nu\bar{\nu}}$$

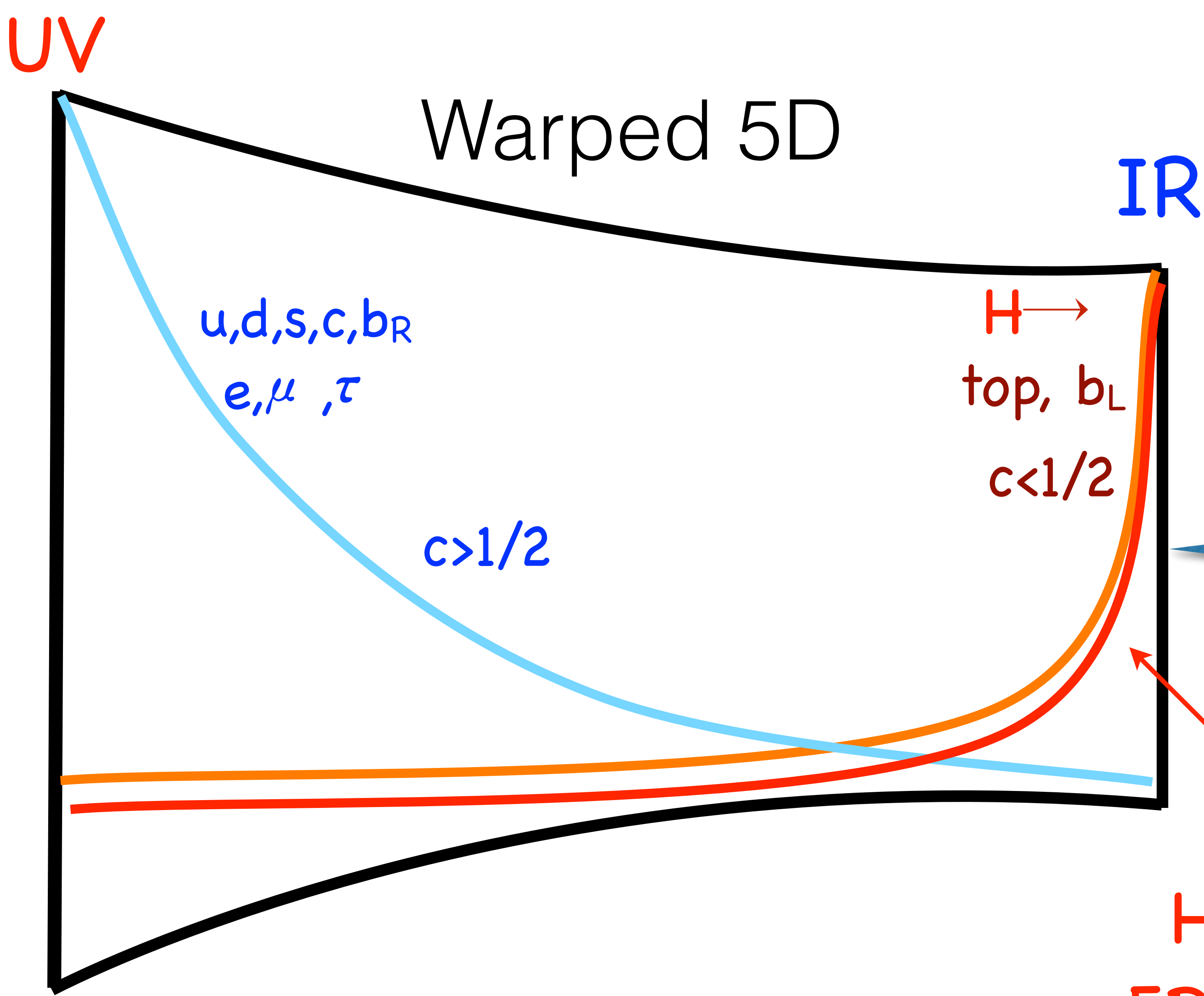
- Theoretical justification of MFV, for a given BSM model?

Partial Compositeness

* MFV is a very common principle, but there are other way to protect flavors
* example: beyond MFV SUSY: “split-family susy” (only 3rd generation sfermions light) + flavour symmetry acting only on 1st & 2nd generations
* Partial Compositeness is a completely different way of flavor protection mechanism
    - No new Operators beyond those present in the SM
    - All flavour changing transitions are governed by CKM. i.e. No new complex phases beyond those present in the SM

Partial Compositeness

- The flavor puzzle is solved due to exponential sensitivity of **wave function overlaps** on the 5D bulk masses, c_i



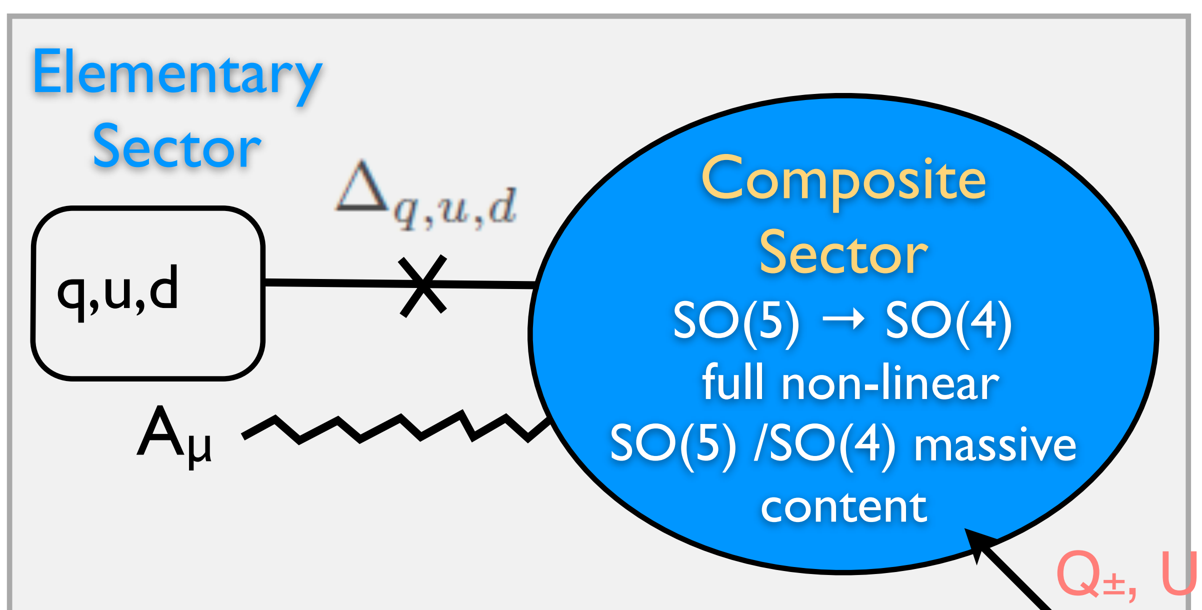
Anarchic model:
Localization (partial compositeness) address flavor hierarchy and also give protection against flavor & CPV

Higgs and KK resonances has a 5D profile localized near IR brane (light fields have highly suppressed coupling to them)

Partial Compositeness

- Elementary-composite states talk through linear couplings. $\mathcal{L}_{mix} = \Delta_q \bar{q}_{l_\mathcal{O}} \mathcal{O}^{l_\mathcal{O}} + \text{h.c.}$

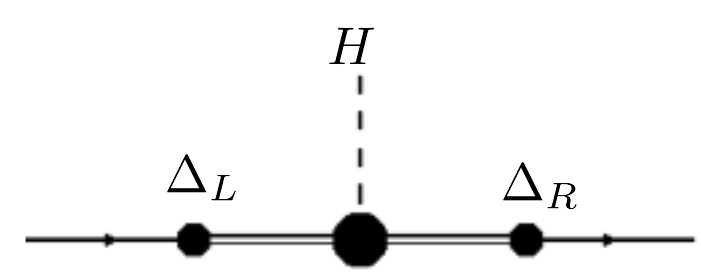
The flavor problem of theories with strong dynamics can be improved if the Yukawa couplings arise through mixings of elementary quarks with fermionic operators of the strong sector



Q±, U± + ... +EW + H

$m_\Psi \simeq g_\Psi f$

$y_{SM} = \frac{\Delta_L \Delta_R}{m_\Psi} \simeq \frac{y_L y_R}{g_\Psi}$



Typically (anarchy): $\Delta_i \ll \Delta_{q3,u3} \sim M$, i = 1, 2 .

$\Delta_i = y_i f$ (f ⇔ decay constant for the SO(5)/SO(4) breaking)

Partial Compositeness

* Partial compositeness provide (partial) solutions to both flavor hierarchy puzzle and NP flavor puzzle

* The constraints from ε and ε'/ε in the kaon system imply that this simple construction has to be improved with some sort of alignment, at least in the down sector. On the other hand, also in this model we can have a naturally sizable non-standard contribution to Δa_{CP}

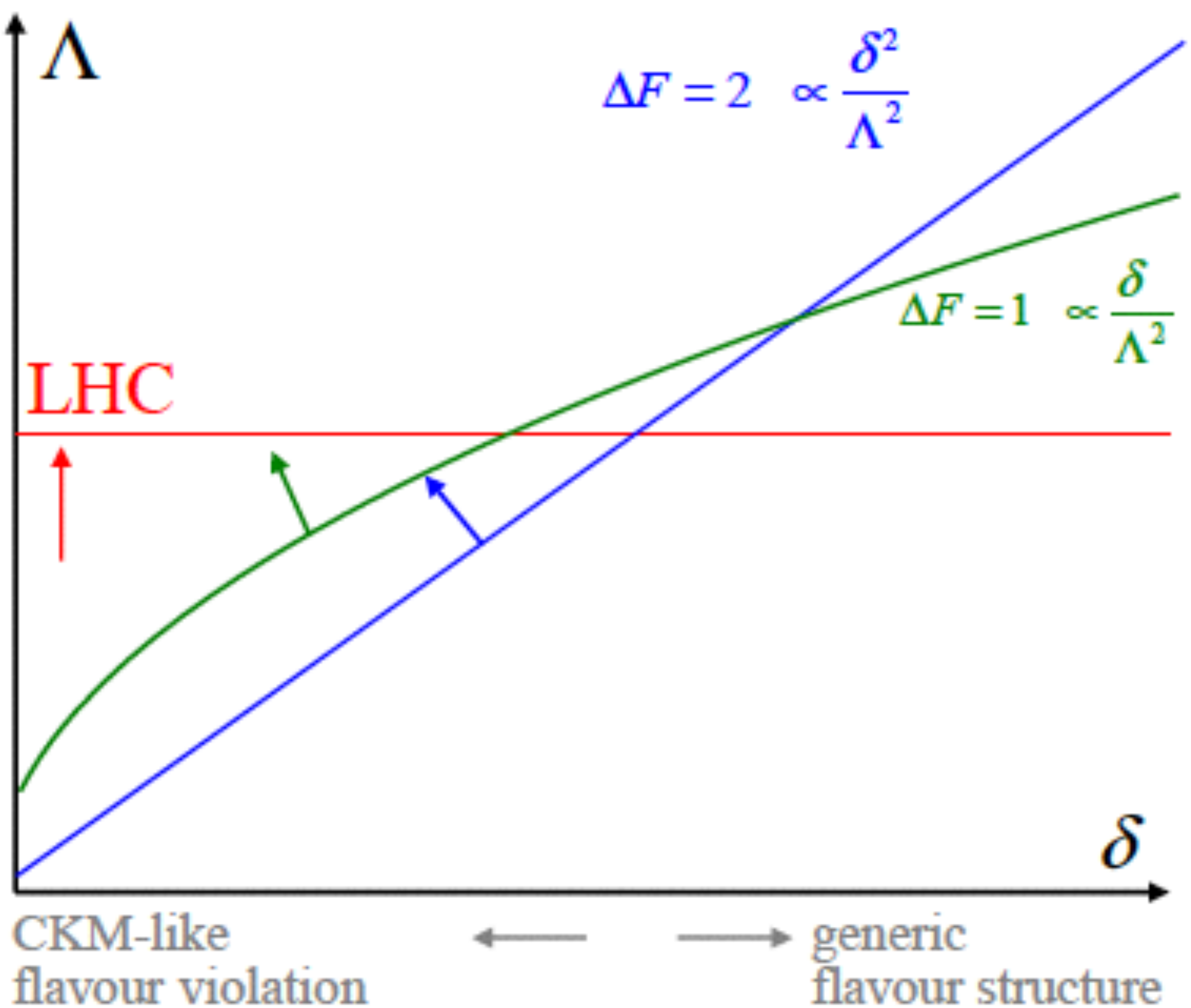
* MFV is not the only solution for the NP flavor problem:

Flavor Physics in the LHC era

Flavour & collider searches are complementary

- Sketch of the bounds on new physics with scale and flavour changing parameter

David Straub



Meson-antimeson mixing can probe the highest scales if flavour-violation is generic (large)

Route for find NP through Flavor Physics

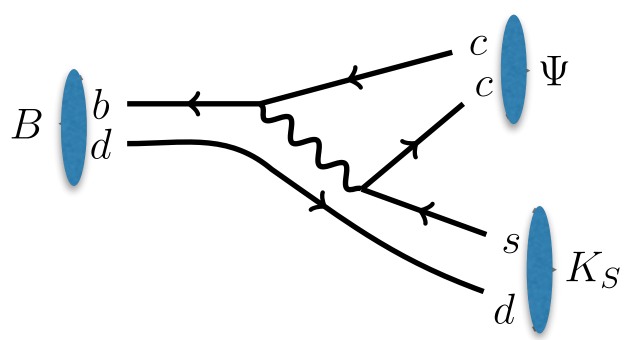
* We need many precision measurements of many observables as well as precise theory predictions

* Study patterns on flavour violation in various New Physics models (correlations between many flavour observables).

* Important to exploit correlations between low energy flavour observables and collider physics

New Physics in the B system

* Time-dependent CP asymmetry in B → ψK_S



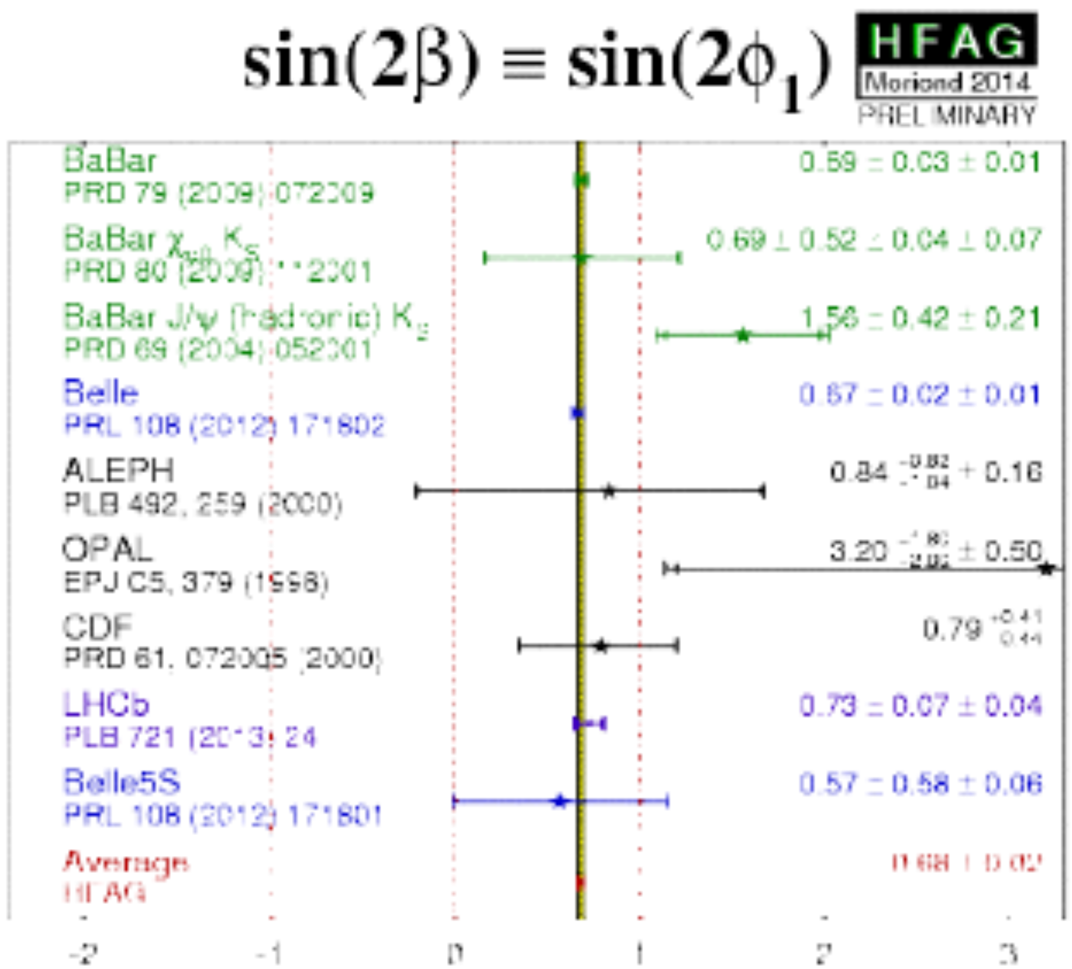
$$A_{\rm CP}(t, J/\psi K_S) = \frac{\Gamma(B^0(t) \to J/\psi K_S) - \Gamma(\bar{B}^0(t) \to J/\psi K_S)}{\Gamma(B^0(t) \to J/\psi K_S) + \Gamma(\bar{B}^0(t) \to J/\psi K_S)} \simeq C_{\psi K_S} \cos(\Delta M t) - S_{\psi K_S} \sin(\Delta M t)$$

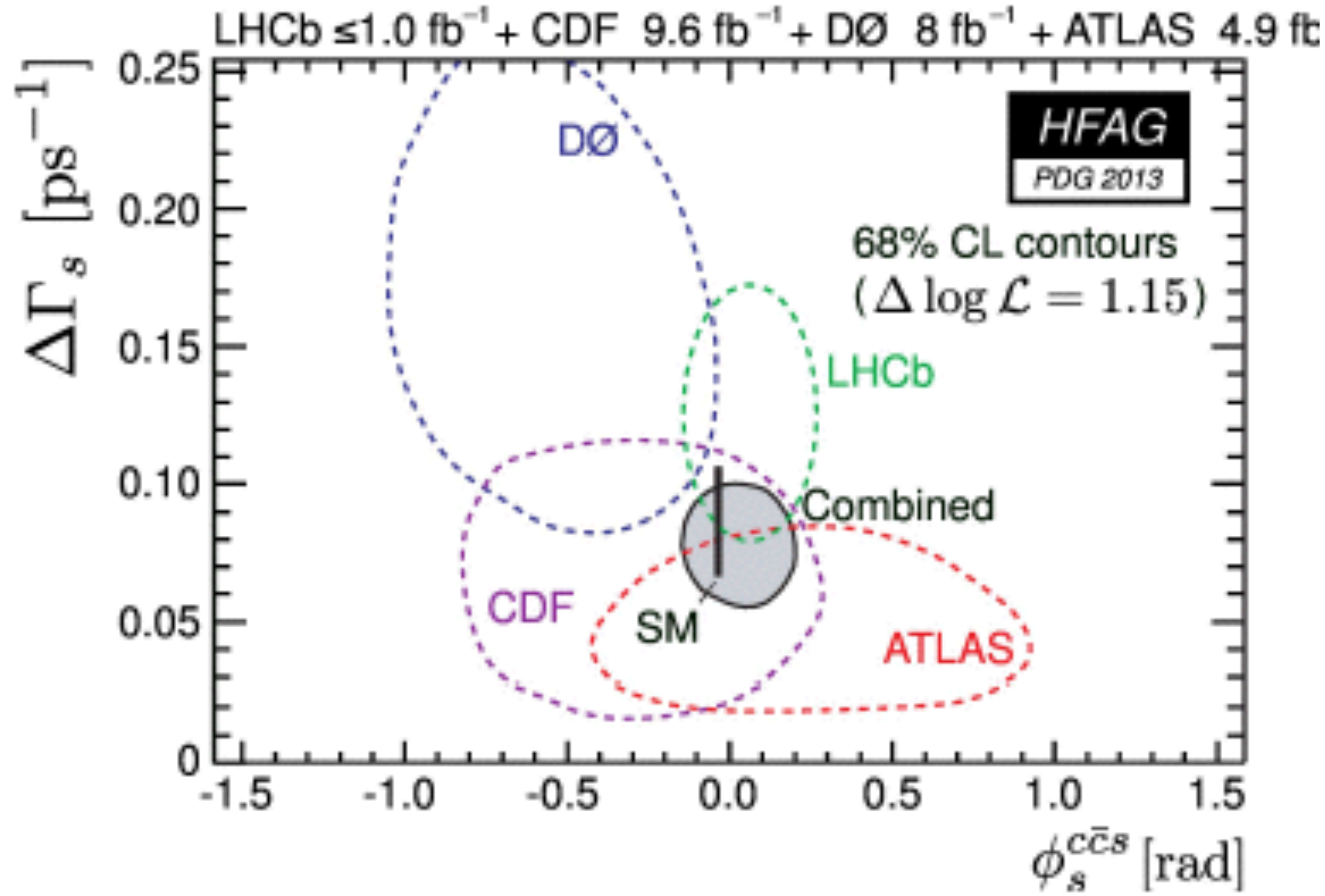
$$S_{\psi K_S} \simeq \sin(\phi_d^{c\bar{c}s}) = \sin(2\beta + \phi_d^\Delta)$$

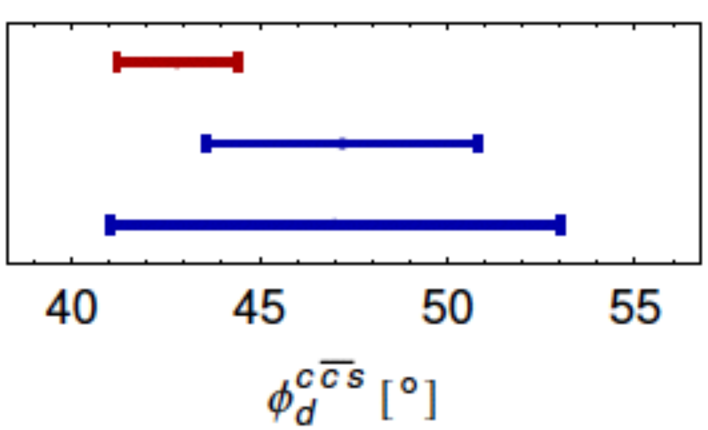
- $S_{\psi K_S}$:interference between CP violation in mixing and decay
- Hadronic uncertainties mostly cancel

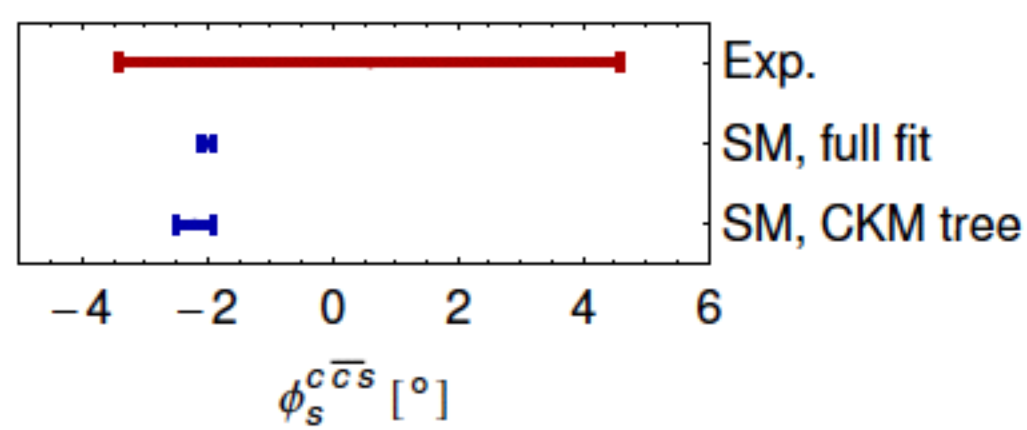
* Also Bs → J/ψ ϕ $\quad S_{\psi\phi} \simeq -\sin(\phi_s^{c\bar{c}s}) = \sin(2|\beta_s| - \phi_s^\Delta)$

New Physics in the B system



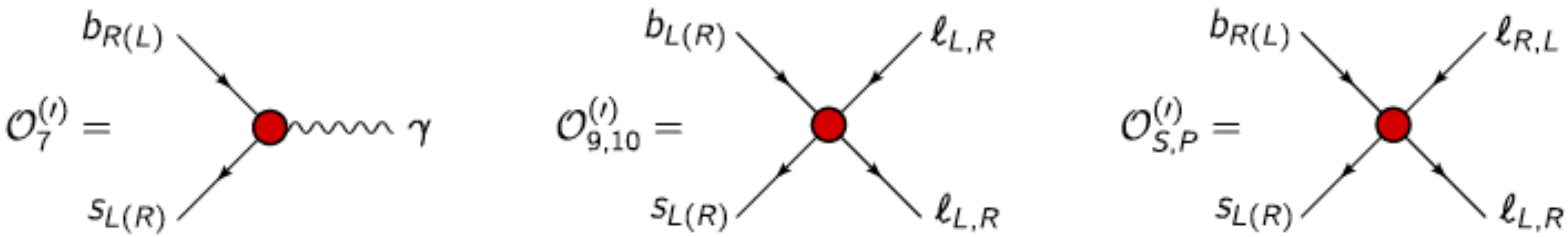






Model independent NP searches in B system

* Non-renormalizable operators might be generated by NP

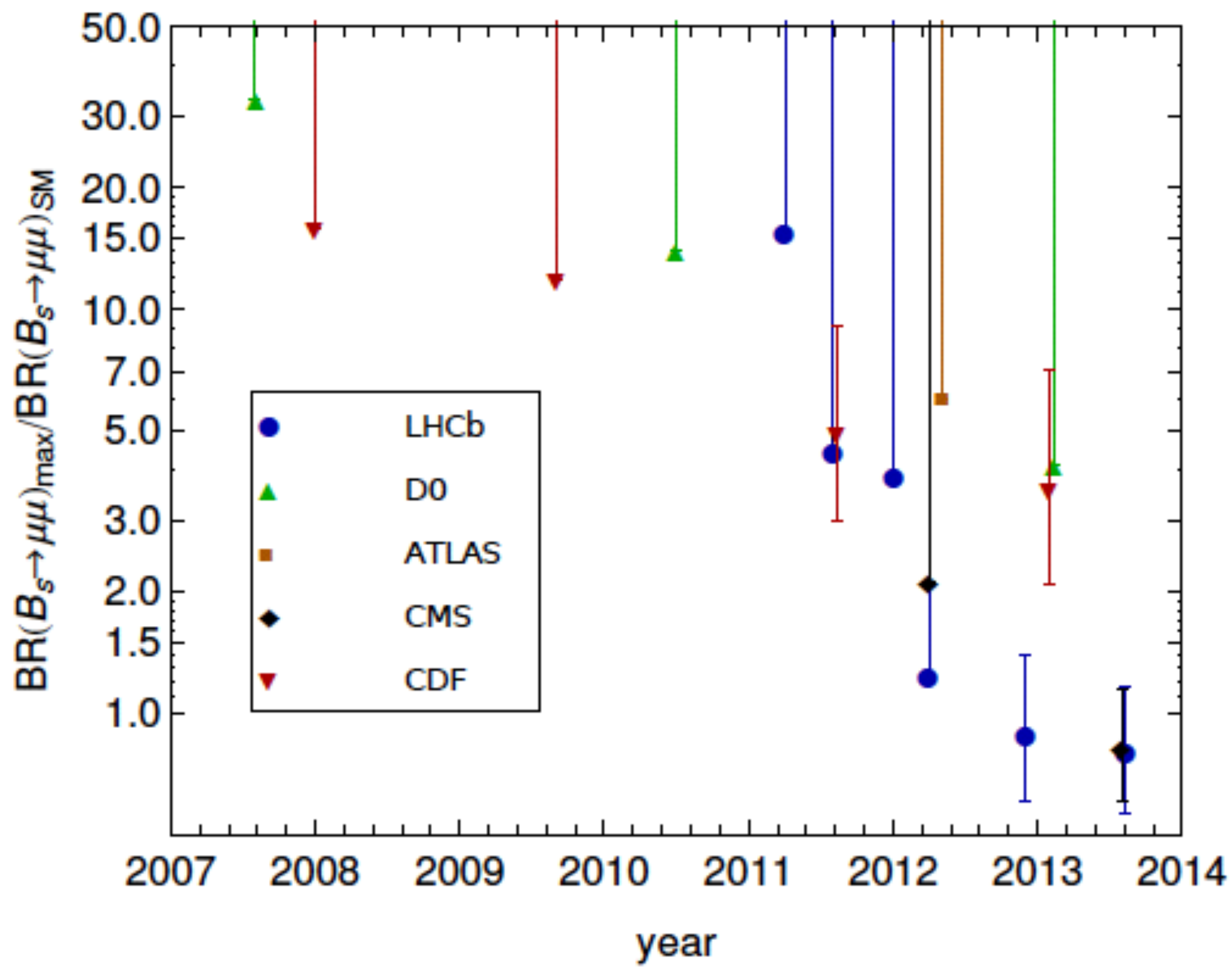


$$\mathcal{O}_7^{(\prime)} \propto \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu} \quad \mathcal{O}_9^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu \ell) \quad \mathcal{O}_{10}^{(\prime)} \propto (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

➡ The same effective vertices enter the processes $B \to K^*\mu^+\mu^-$, $B \to K\mu^+\mu^-$, $B \to X_s\ell^+\ell^-$, $B_s \to \mu^+\mu^-$, $B \to X_s\gamma$, $B \to K^*\gamma$

$B_{s,d} \to \mu^+\mu^-$

- Non-renormalizable operators might be generated by NP



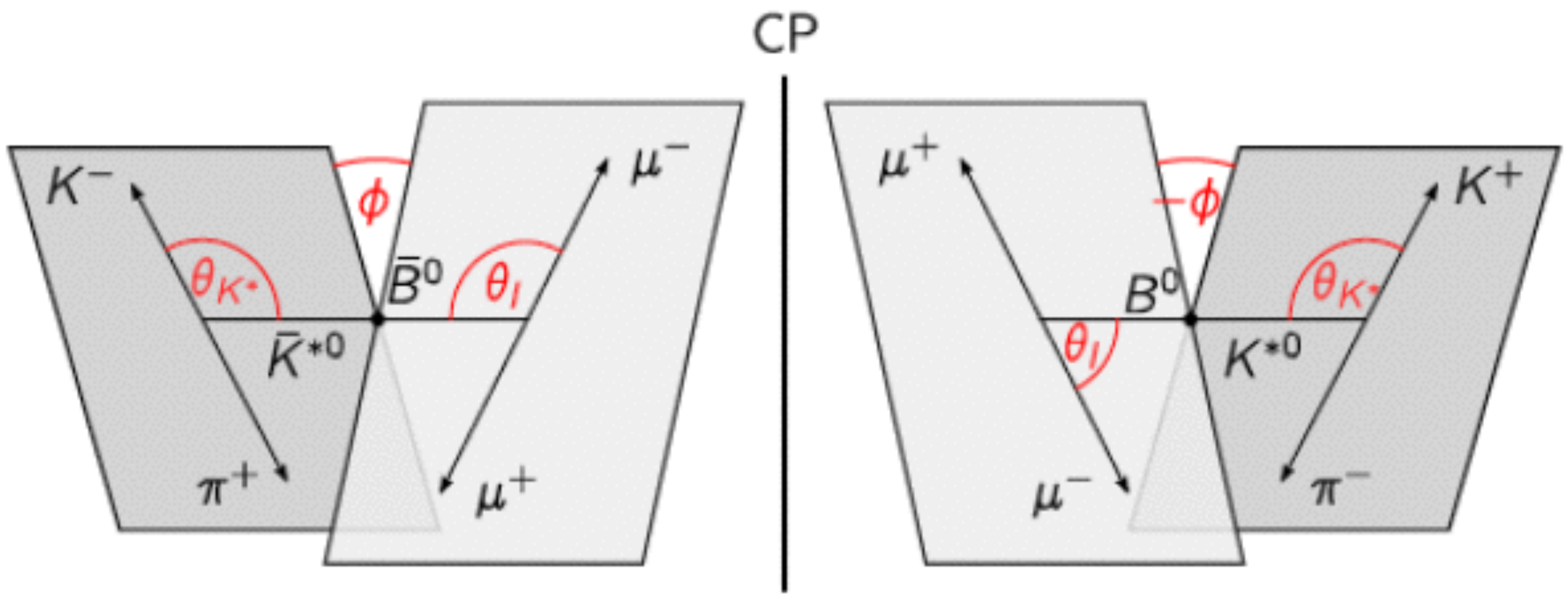
$$\frac{Br\left(B_d \to \mu^+\mu^-\right)}{Br\left(B_s \to \mu^+\mu^-\right)} \approx (4.3 \pm 1.8)\left[\frac{Br\left(B_d \to \mu^+\mu^-\right)}{Br\left(B_s \to \mu^+\mu^-\right)}\right]_{SM}$$

(LHCb, CMS)

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

Differential distribution

$B^0 \to K^{0*} (\to K^+\pi^-)\, \mu^+\mu^-$ $\bar{B}^0 \to \bar{K}^{0*} (\to K^-\pi^+)\, \mu^+\mu^-$

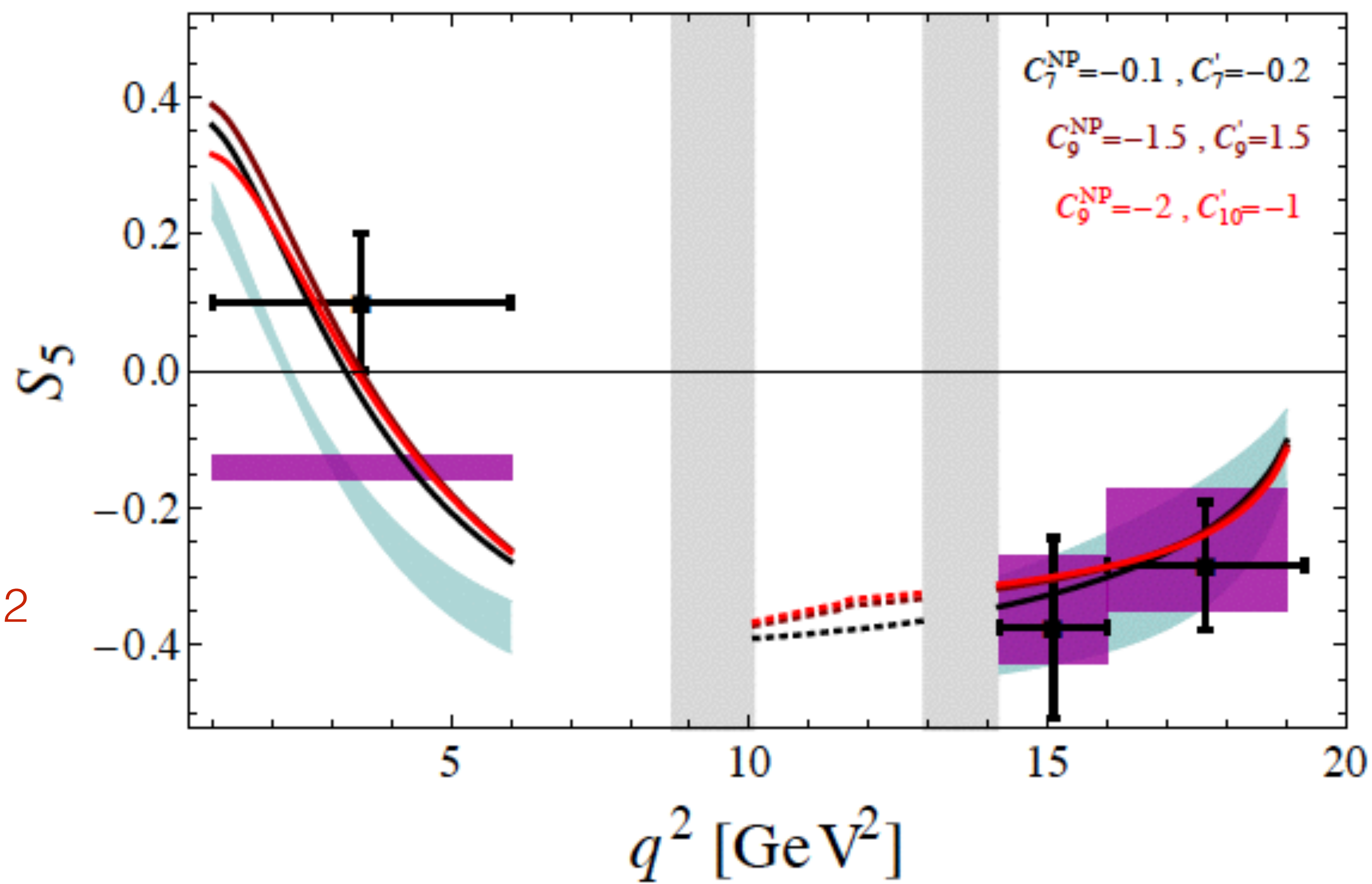


$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$
$$S_7\sin 2\theta_K\sin\theta_\ell\sin\phi +$$
$$S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\,\Big]$$

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

Differential distribution

$$\frac{1}{\Gamma}\frac{d^3(\Gamma+\bar{\Gamma})}{d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell +$$
$$S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi +$$
$$S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6^s\sin^2\theta_K\cos\theta_\ell +$$

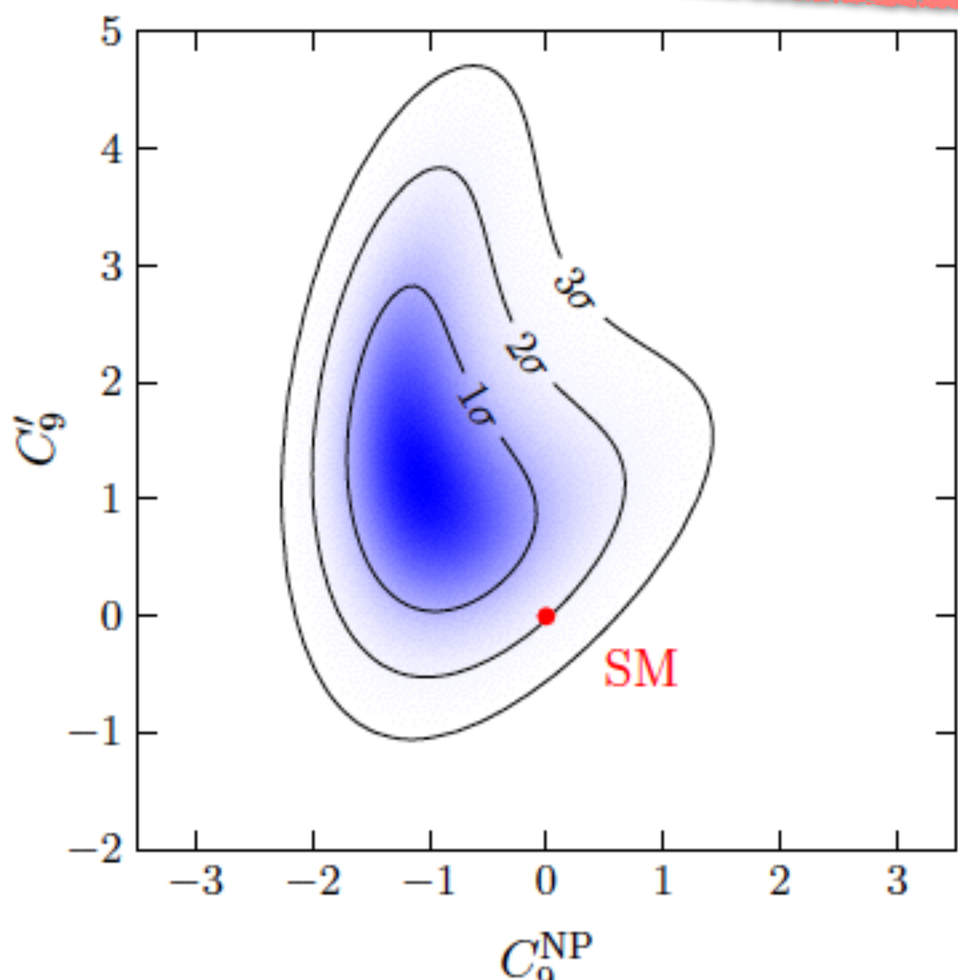


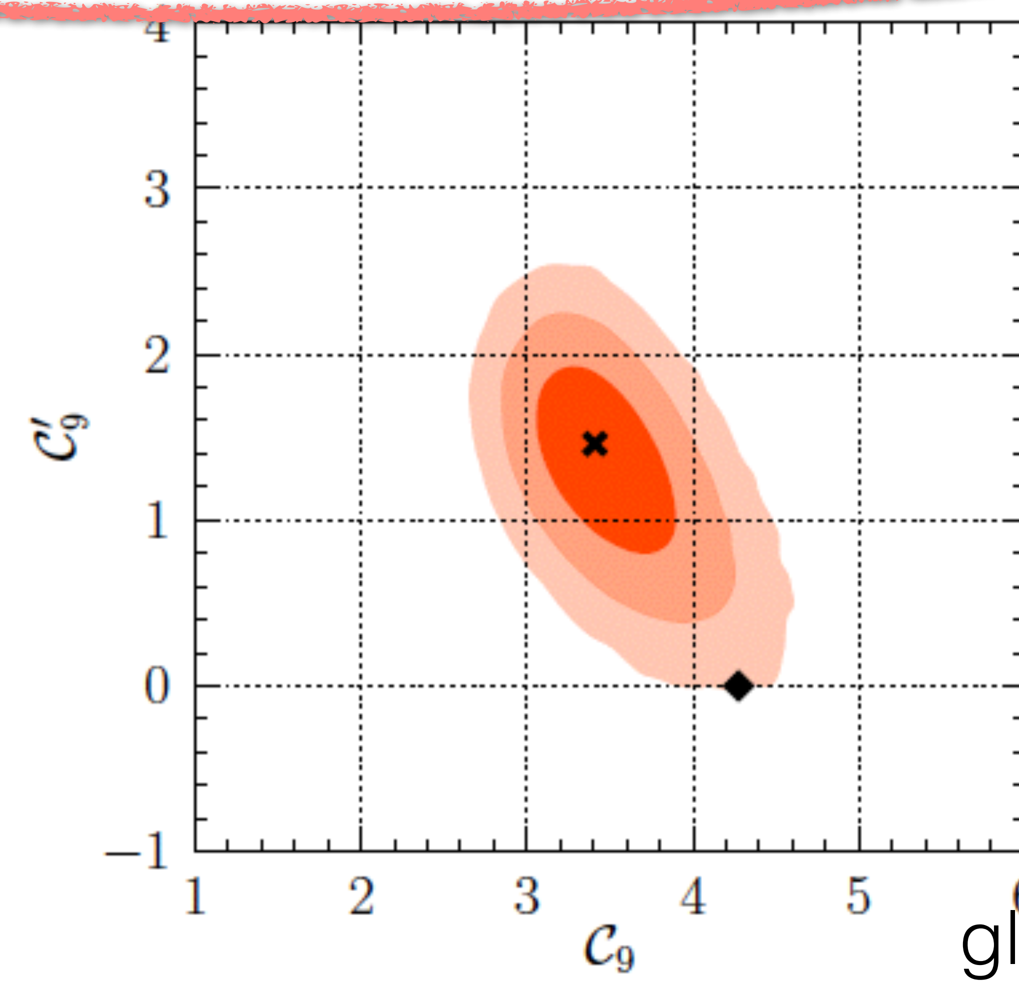
2.4σ tension at low q^2

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

- Lattice computation of form factors: SM BRs of B $\to K^* \mu+\mu-$ and B $\to \phi\, \mu+\mu-$ at high q² systematically above the data, explained equally well by $C_9^{NP} \simeq -1.5$ or $C_9^{NP} \simeq -C_9' \simeq -1$

$$-\frac{1}{\Lambda_{\rm ref}^2}\left[C_7\frac{m_b}{e}(\bar{s}_L\sigma^{\rho\nu}b_R)F_{\rho\nu} + C_9(\bar{s}_L\gamma^\rho b_L)(\bar{\mu}\gamma_\rho\mu) + C_{10}(\bar{s}_L\gamma^\rho b_L)(\bar{\mu}\gamma_\rho\gamma_5\mu)\right]$$
$$-\frac{1}{\Lambda_{\rm ref}^2}\left[C_7'\frac{m_b}{e}(\bar{s}_R\sigma^{\rho\nu}b_L)F_{\rho\nu} + C_9'(\bar{s}_R\gamma^\rho b_R)(\bar{\mu}\gamma_\rho\mu) + C_{10}'(\bar{s}_R\gamma^\rho b_R)(\bar{\mu}\gamma_\rho\gamma_5\mu)\right] + \text{h.c.}$$

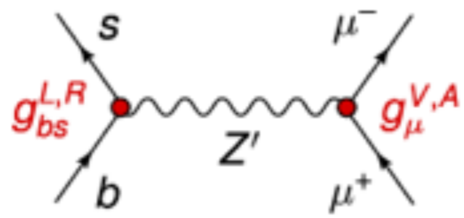


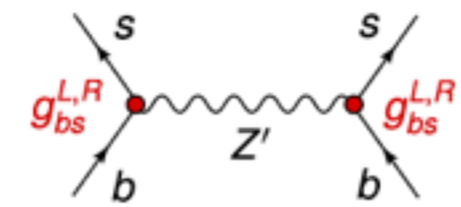


global fit

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

- Could it be from some peculiar BSM? $C_9^{NP} \simeq -1.5$ or $C_9^{NP} \simeq -C_9' \simeq -1$
  So far, some very wired Z' explanation….





$$\mathcal{L} \supset \frac{g_2}{2c_W}\left[\bar{s}\gamma^\mu(g_{bs}^L P_L + g_{bs}^R P_R)b + \bar{\mu}\gamma^\mu(g_\mu^V + \gamma_5 g_\mu^A)\mu\right]Z'_\mu$$

$$\left\{C_9^{NP}, C_9'\right\} \propto \frac{m_Z^2}{m_{Z'}^2}\left\{(g_{bs}^L)(g_\mu^V), (g_{bs}^R)(g_\mu^V)\right\}$$

$$\frac{\Delta M_s}{\Delta M_s^{SM}} - 1 \propto \frac{m_Z^2}{m_{Z'}^2}\left[(g_{bs}^L)^2 + (g_{bs}^R)^2 - 9.7(g_{bs}^L)(g_{bs}^R)\right]$$

Bs mixing has to be also taken into account

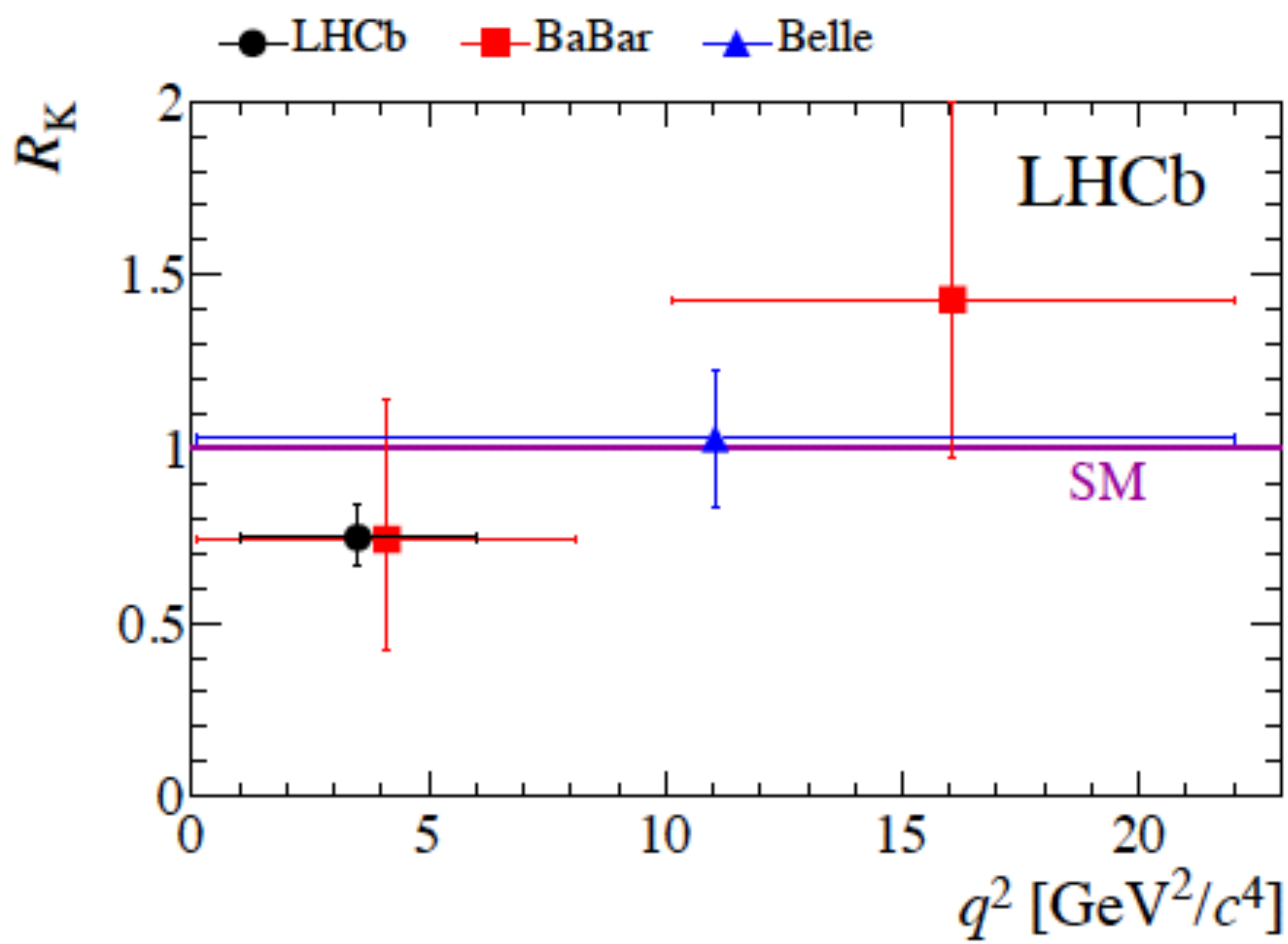
$$C_9^{NP} = -1,\ C_9' = 1 \qquad \Rightarrow M_{Z'} < g_\mu^V \times 0.9\ \text{TeV}$$

$$C_9^{NP} = -1.5 \qquad \Rightarrow M_{Z'} < g_\mu^V \times 2.0\ \text{TeV}$$

Lepton universality and R_K

- One of the clean observables (hadronic uncertainties cancels)

$$R_K = \mathrm{Br}(B^+ \to K^+\mu^+\mu^-)/\mathrm{Br}(B^+ \to K^+e^+e^-)$$



2.6σ tension at low q^2

these are just some examples….

Rare K, Bs, Bd Decays will play
crucial role in identifying New Physics

LHC era is also an era of
Flavour Precision
(Also KEK)

slide from A. Buras

Superstars and Stars of Quark Flavour Physics

Superstars

ε_K, ΔM_s, ΔM_d, $S_{\psi K_S}$	(TH)
$B_s \to \mu^+\mu^-$, $B_d \to \mu^+\mu^-$, $S_{\psi\varphi}(\varphi_s)$	(LHCb, CMS, ATLAS)
$B \to K\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$, $B \to X_s\nu\bar{\nu}$	(Belle II)
$K^+ \to \pi^+\nu\bar{\nu}$, $K_L \to \pi^0\nu\bar{\nu}$	(NA62, J-Parc)

Stars

$B \to K^*\mu^+\mu^-$ $\quad$ $B \to K\mu^+\mu^-$

$B \to D^*\tau\nu_\tau$ $\quad$ $B \to D\tau\nu_\tau$

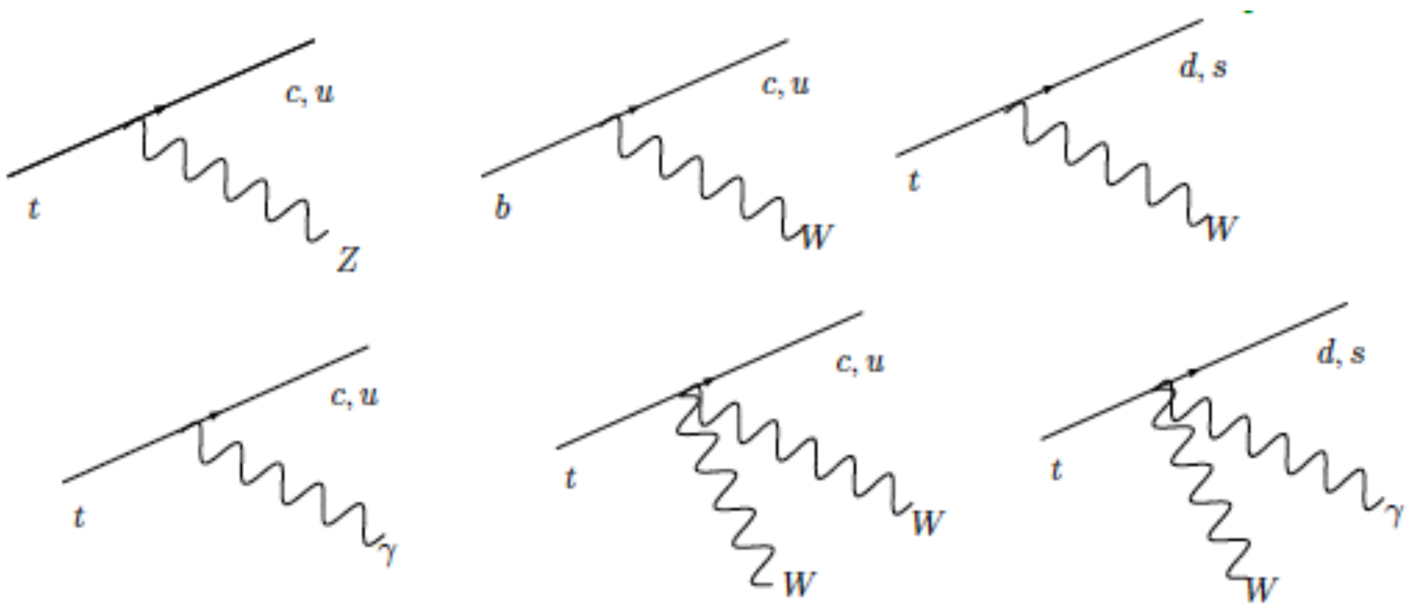
Old Superstar

ε'/ε will strike back provided B_6 (QCD Penguins) will be precisely known.

B_8 (EW Penguins) $\approx 0.65 \pm 0.05$ (UK-QCD)

Additionallly….

- LHC is a top factory: Improve bounds on FCNC top decays by more than several order of magnitude



- Flavor violation in Higgs decay

- LHC also provide an interesting flavor data: spectrum (degeneracies), information on some decay widths and production cross section

Summary

- The SM flavor sector has been tested with impressive & increasing precision
- Flavour structure of NP has to be special to be compatible with TeV scale NP (MFV?).
- If new particles discovered, their flavor properties can teach us about NP: masses (degeneracies), decay rates (flavour decomposition), cross sections
- Flavour physics provide important clues to model building in the LHC era
- LHC era is Flavor Precision era, and a lot of interesting measurements coming! (already seen some tensions with SM)