Flavor Physics in the New Era

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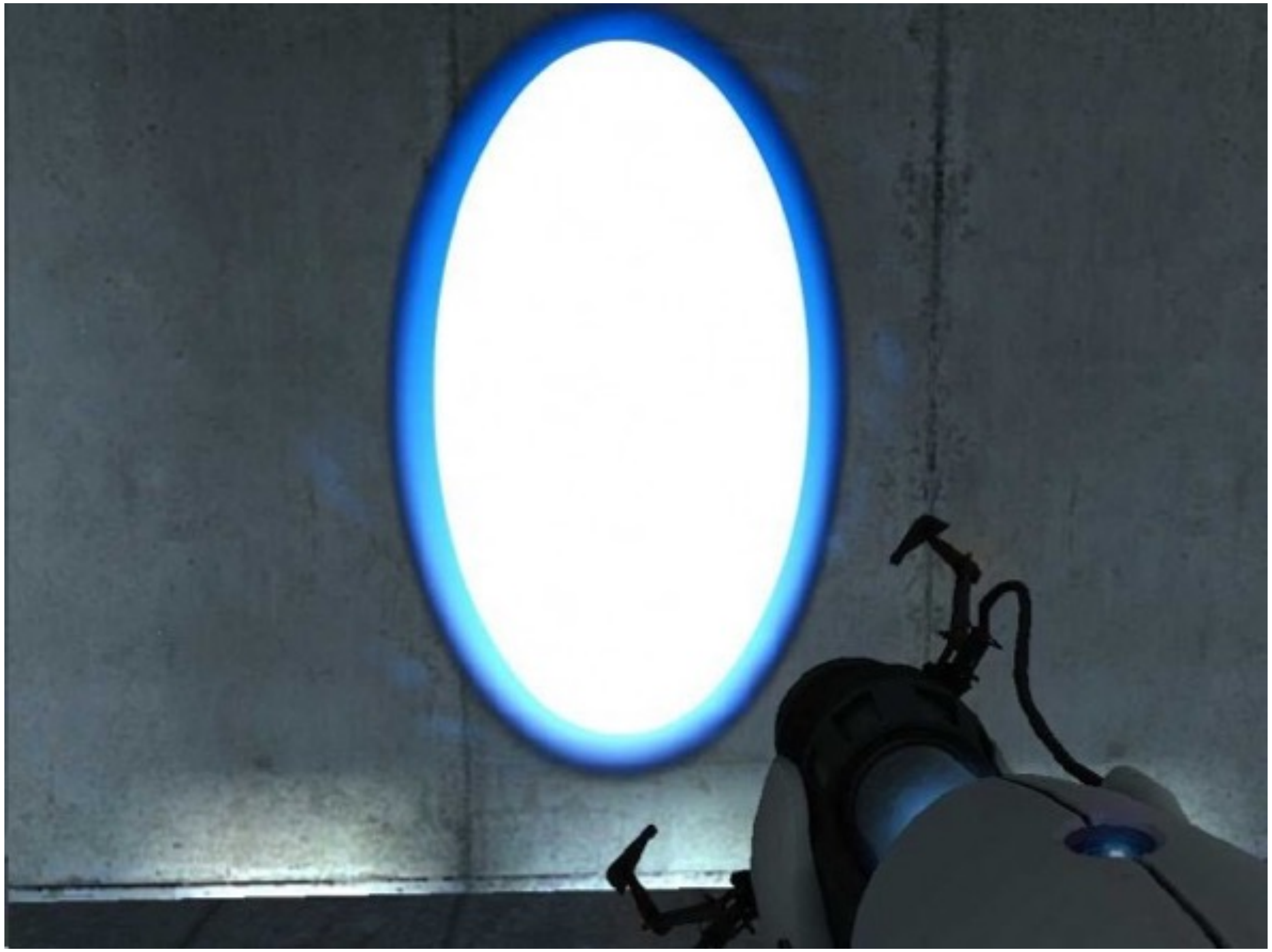
Disclaimer

- It is impossible for me to cover all aspects of flavor physics in this talk. I will emphasize on the heavy flavor physics-B physics.

- More topics will be missed
  - Charm physics
  - Tau physics
  - Exotic states
  - K Physics

- Apologies for many missing references.

- Many of us thought that the "scalar particle" found at CERN was going to be ALSO $\Rightarrow$ the **PORTAL** for NEW PHYSICS.



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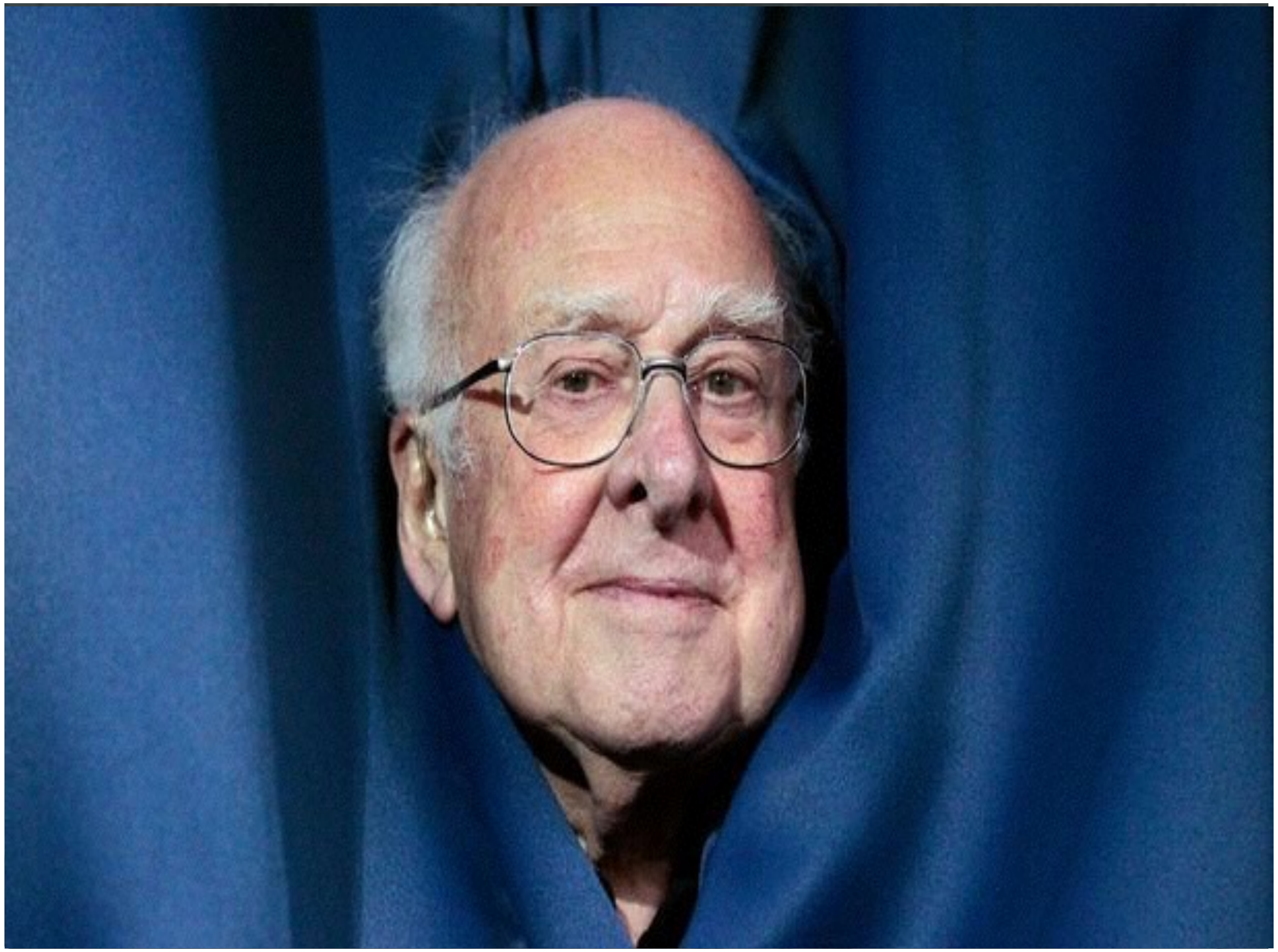

- BUT the "scalar particle" found resembles very much the SM Higgs particle, with SM-like couplings up to the present precision.

- ⇒ it will be a long term task...

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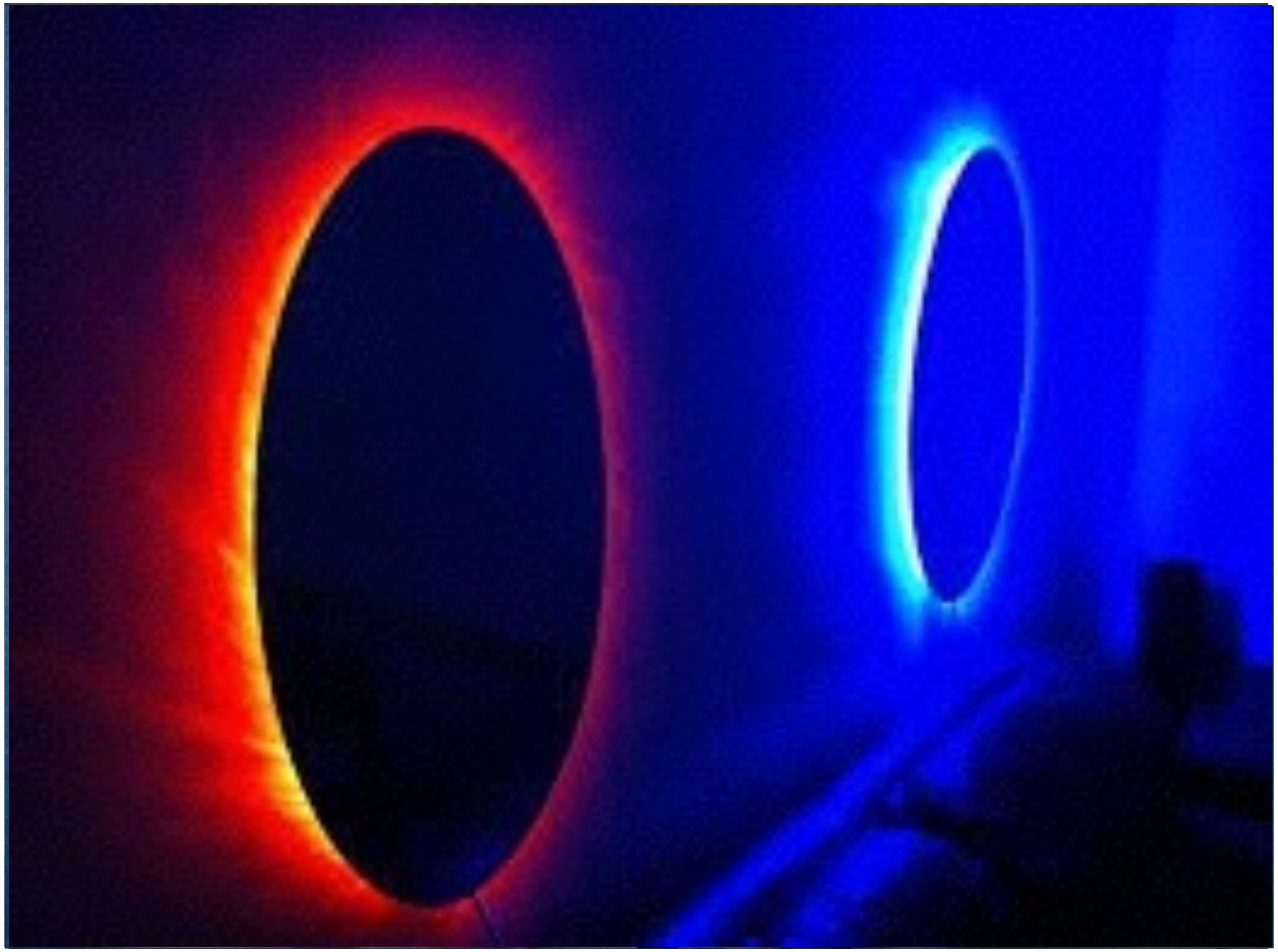


- HOWEVER, there are OTHER PORTALS: RARE B DECAYS (FCNC)
- New Physics same footing as SM
- They allow you to explore higher scales Λ

- BUT the "scalar particle" found resembles very much the SM Higgs particle, with SM-like couplings up to the present precision.
- $\Rightarrow$ it will be a long term task...

Outline

- Why do we study flavor physics?
- Where do we study flavor physics?
- Recent anomalies in flavor physics.
- Possible explanations to these anomalies.
- Flavor physics at CepC.
- Summary and outlook

Why do we study flavor physics?

- SM flavor problem: hierarchy of masses and mixing angles; why ν's are different

- Empirical evidence that SM is incomplete: dark matter, baryon asymmetry, neutrino mass — at least two related to flavor

- NP flavor problem: TeV scale ≪ flavor & CPV scale

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

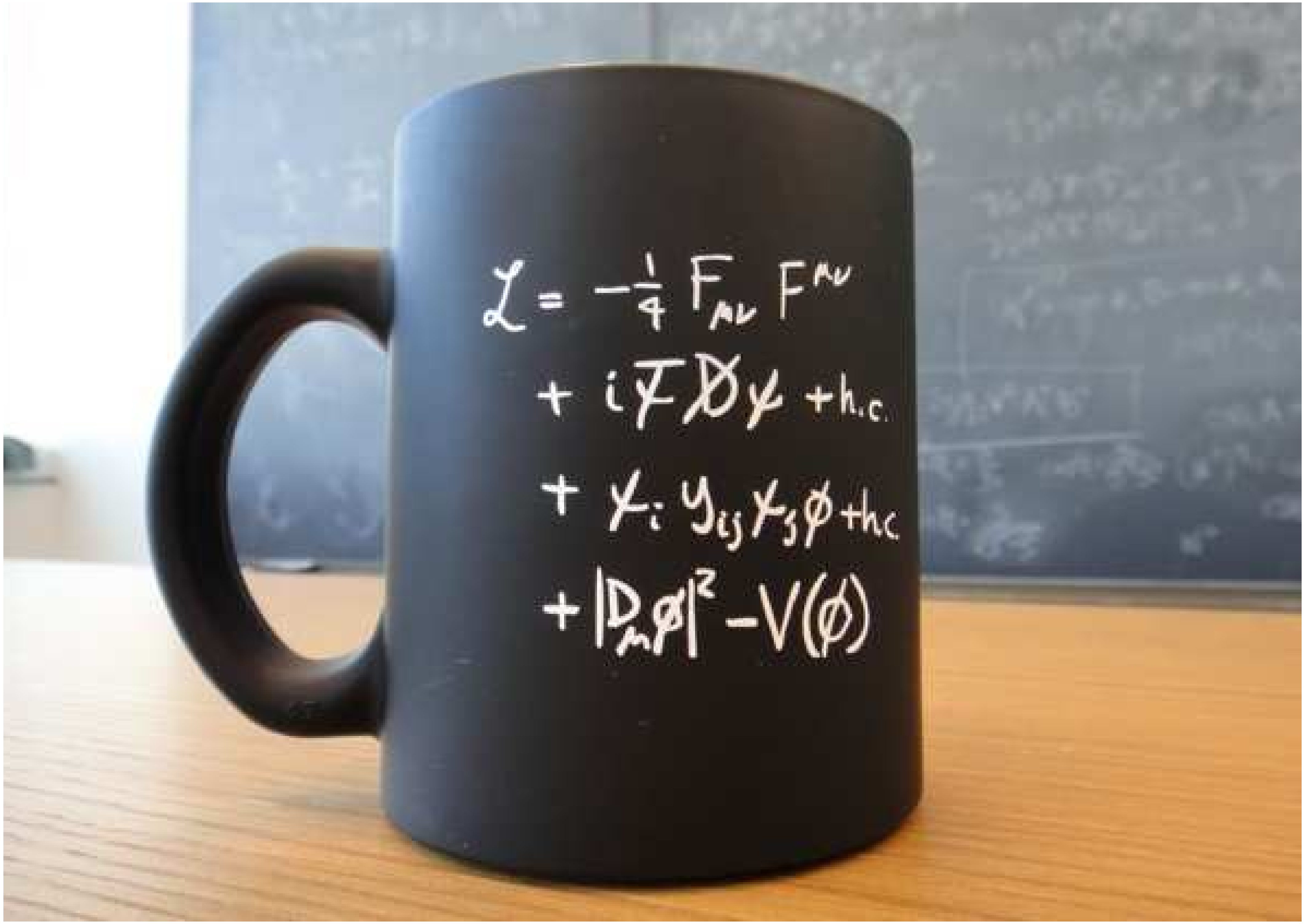
- Many extensions of the SM have new sources of CP and flavor violation, the observed baryon asymmetry of the Universe requires CPV beyond the SM.

- Flavor sector can be tested a lot better, many NP models should have observable effects

Why do we study flavor physics?

- Searching for new physics via virtual effects has been extremely successful
- Flavor physics was crucial to figure out $\mathcal{L}_{\mathrm{SM}}$:
  - Absence of $K_L \to \mu\mu$ predicted charm (Glashow, Iliopoulos, Maiani)
  - ϵ_K predicted 3rd generation (Kobayashi & Maskawa)
  - Δm_K predicted m_c (Gaillard & Lee; Vainshtein & Khriplovich)
  - Δm_B predicted large m_t
- Likely to be important to figure out $\mathcal{L}_{\mathrm{BSM}}$ as well
- If new physics discovered, want to probe it in as many different ways as possible

Why do we study flavor physics?

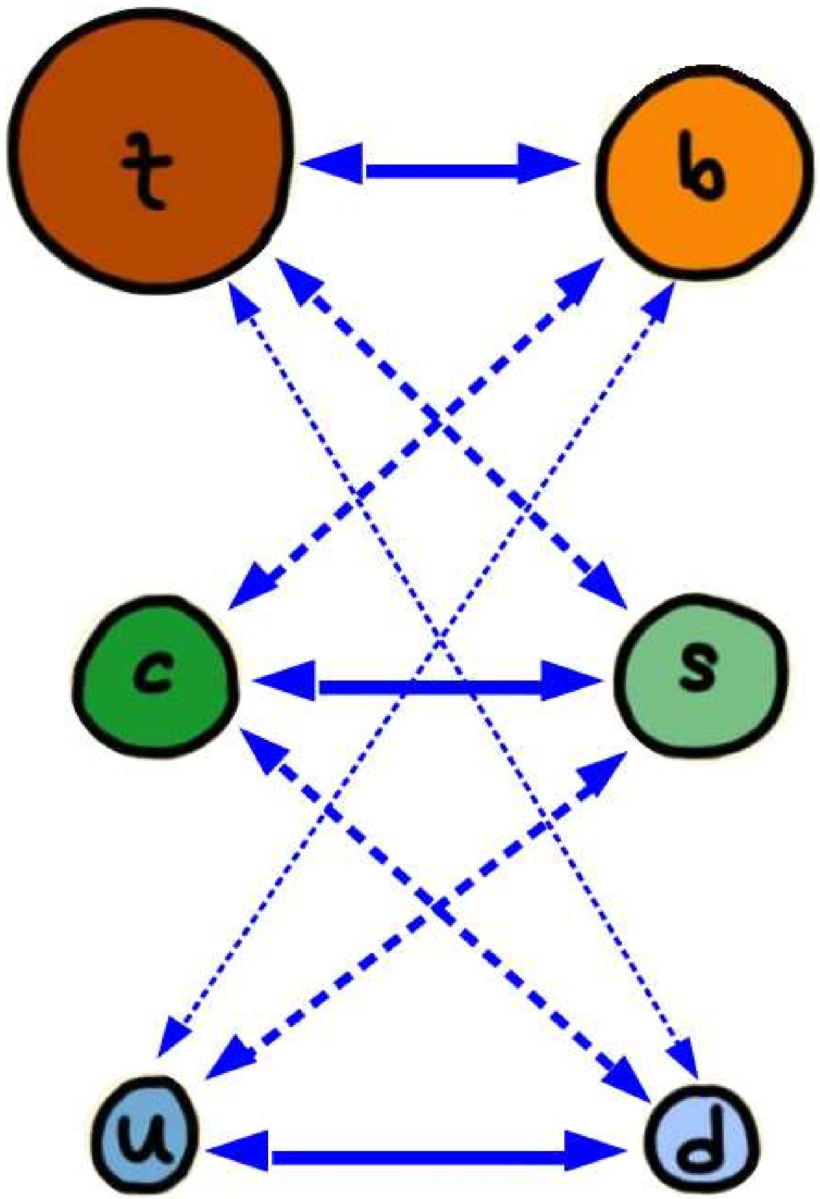


Why do we study flavor physics?

gauge sector	Higgs sector	flavor sector
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$	$+ \lvert D_\mu \phi \rvert^2 - V(\phi)$	$+ \psi_i y_{ij} \psi_j \phi + h.c.$
describes the gauge interactions of the quarks and leptons	breaks electro-weak symmetry and gives mass to the $W^\pm$ and Z bosons	leads to masses and mixings of the quarks and leptons
parametrized by 3 gauge couplings g_1, g_2, g_3	2 free parameters Higgs mass Higgs vev	22 free parameters to describe the masses and mixings of the quarks and leptons

the flavor sector is the most puzzling part of the Standard Model

Why do we study flavor physics?



in the Standard Model there are
no direct transitions
within up-type or down-type quarks

$\rightarrow$ GIM mechanism
(Glashow, Iliopoulos, Maiani)

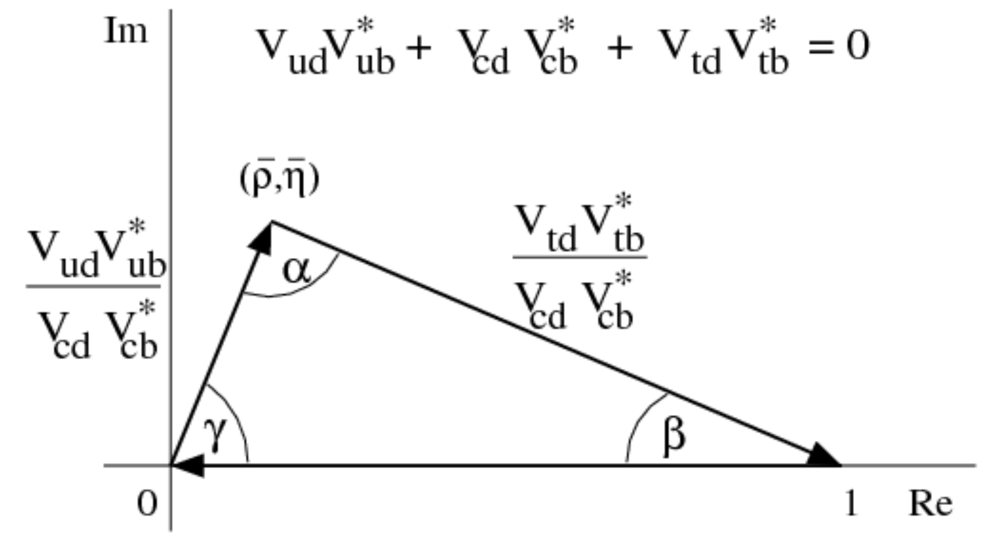
no flavor changing neutral currents
(FCNCs) at tree level

transitions among the generations
are mediated by the $W^{\pm}$ bosons
and their relative strength is
parametrized by the
Cabibbo-Kobayashi-Maskawa
(CKM) matrix

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

Why do we study flavor physics?

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

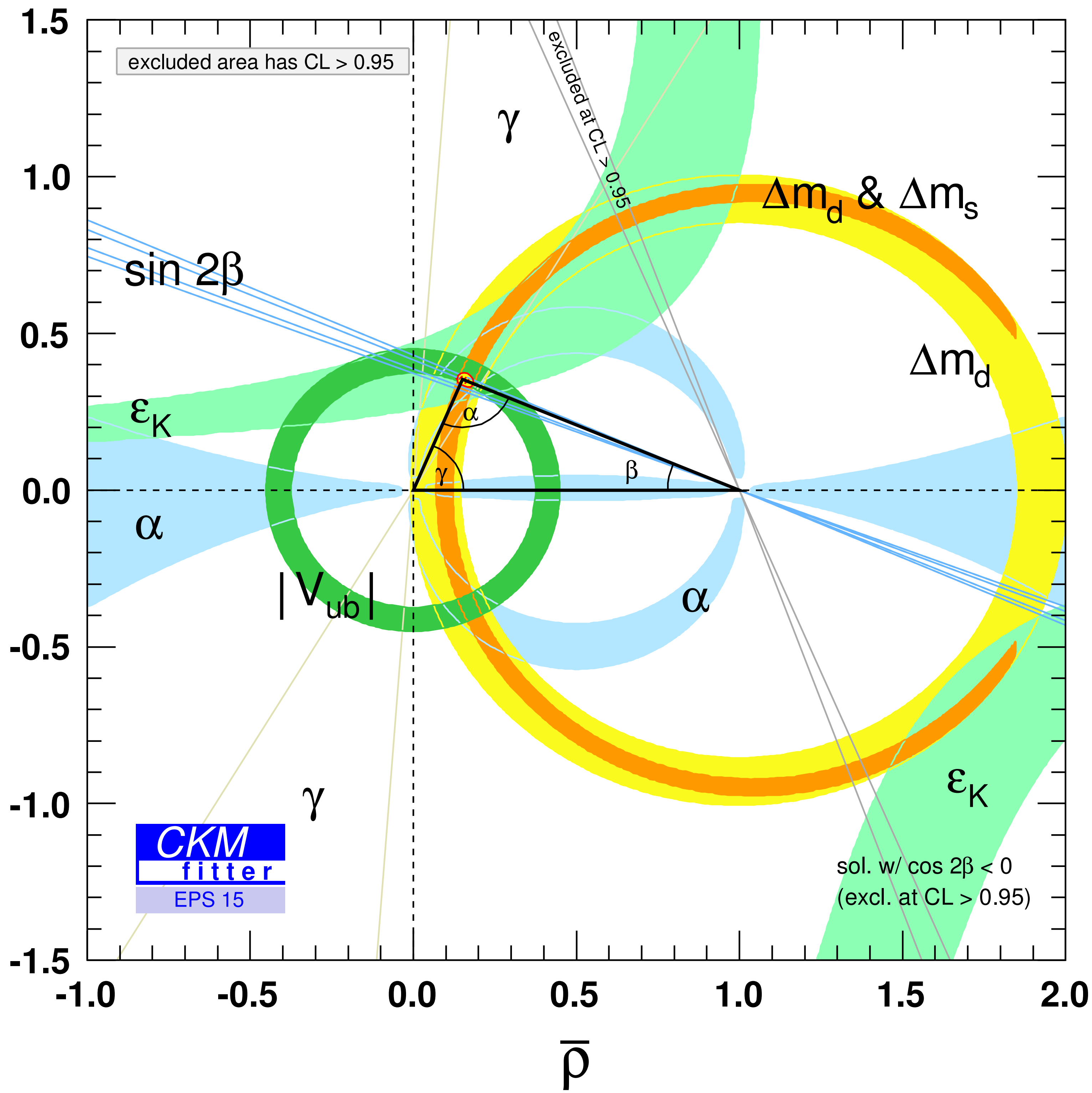


CKM	Process	Observables		Theoretical inputs
$\lvert V_{ud}\rvert$	$0^+ \to 0^+$ transitions	$\lvert V_{ud}\rvert_{\rm nucl} = 0.97425 \pm 0.00022$	[6]	Nuclear matrix elements
$\lvert V_{us}\rvert$	$K \to \pi\ell\nu$	$\lvert V_{us}\rvert_{\rm semi} f_+(0) = 0.2163 \pm 0.0005$	[7]	$f_+(0) = 0.9632 \pm 0.0028 \pm 0.0051$
	$K \to e\nu_e$	$\mathcal{B}(K \to e\nu_e) = (1.584 \pm 0.0020) \cdot 10^{-5}$	[8]	$f_K = 156.3 \pm 0.3 \pm 1.9$ MeV
	$K \to \mu\nu_\mu$	$\mathcal{B}(K \to \mu\nu_\mu) = 0.6347 \pm 0.0018$	[7]	
	$\tau \to K\nu_\tau$	$\mathcal{B}(\tau \to K\nu_\tau) = 0.00696 \pm 0.00023$	[8]	
$\lvert V_{us}\rvert/\lvert V_{ud}\rvert$	$K \to \mu\nu/\pi \to \mu\nu$	$\frac{\mathcal{B}(K \to \mu\nu_\mu)}{\mathcal{B}(\pi \to \mu\nu_\mu)} = (1.3344 \pm 0.0041) \cdot 10^{-2}$	[7]	$f_K/f_\pi = 1.205 \pm 0.001 \pm 0.010$
	$\tau \to K\nu/\tau \to \pi\nu$	$\frac{\mathcal{B}(\tau \to K\nu_\tau)}{\mathcal{B}(\tau \to \pi\nu_\tau)} = (6.33 \pm 0.092) \cdot 10^{-2}$	[9]	
$\lvert V_{cd}\rvert$	$D \to \mu\nu$	$\mathcal{B}(D \to \mu\nu) = (3.82 \pm 0.32 \pm 0.09) \cdot 10^{-4}$	[10]	$f_{D_s}/f_D = 1.186 \pm 0.005 \pm 0.010$
$\lvert V_{cs}\rvert$	$D_s \to \tau\nu$	$\mathcal{B}(D_s \to \tau\nu) = (5.29 \pm 0.28) \cdot 10^{-2}$	[11]	$f_{D_s} = 251.3 \pm 1.2 \pm 4.5$ MeV
	$D_s \to \mu\nu$	$\mathcal{B}(D_s \to \mu\nu_\mu) = (5.90 \pm 0.33) \cdot 10^{-3}$	[11]	
$\lvert V_{ub}\rvert$	semileptonic decays	$\lvert V_{ub}\rvert_{\rm semi} = (3.92 \pm 0.09 \pm 0.45) \cdot 10^{-3}$	[11]	form factors, shape functions
	$B \to \tau\nu$	$\mathcal{B}(B \to \tau\nu) = (1.68 \pm 0.31) \cdot 10^{-4}$	[4]	$f_{B_s} = 231 \pm 3 \pm 15$ MeV
				$f_{B_s}/f_B = 1.209 \pm 0.007 \pm 0.023$
$\lvert V_{cb}\rvert$	semileptonic decays	$\lvert V_{cb}\rvert_{\rm semi} = (40.89 \pm 0.38 \pm 0.59) \cdot 10^{-3}$	[11]	form factors, OPE matrix elts
α	$B \to \pi\pi,\ \rho\pi,\ \rho\rho$	branching ratios, CP asymmetries	[11]	isospin symmetry
β	$B \to (c\bar c)K$	$\sin(2\beta)_{[c\bar c]} = 0.678 \pm 0.020$	[11]	
γ	$B \to D^{(*)}K^{(*)}$	inputs for the 3 methods	[11]	GGSZ, GLW, ADS methods
$V_{tq}^* V_{tq'}$	Δm_d	$\Delta m_d = 0.507 \pm 0.005\ {\rm ps}^{-1}$	[11]	$\hat B_{B_s}/\hat B_{B_d} = 1.01 \pm 0.01 \pm 0.03$
	Δm_s	$\Delta m_s = 17.77 \pm 0.12\ {\rm ps}^{-1}$	[12]	$\hat B_{B_s} = 1.28 \pm 0.02 \pm 0.03$
$V_{tq}^* V_{tq'},\ V_{cq}^* V_{cq'}$	ϵ_K	$\lvert\epsilon_K\rvert = (2.229 \pm 0.010) \cdot 10^{-3}$	[8]	$\hat B_K = 0.730 \pm 0.004 \pm 0.036$
				$\kappa_\epsilon = 0.940 \pm 0.013 \pm 0.023$

[CKMfitter, arXiv:1106.4041]

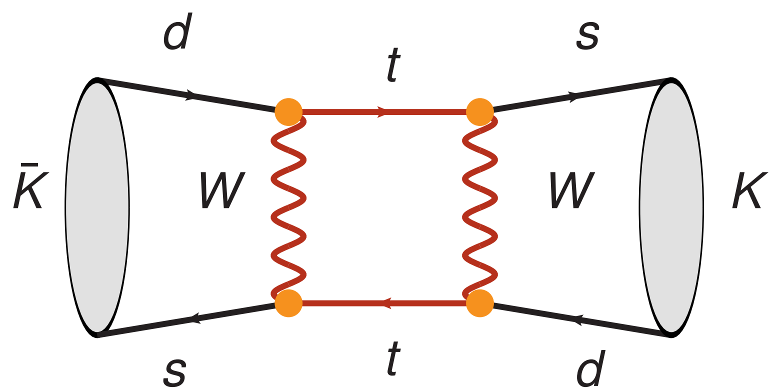
Why do we study flavor physics?

- ✦ The SM works well!
- ✦ The allowed region will become larger if the SM is not assumed.
- ✦ O(20%) NP contributions to the loop-level processes are still allowed.



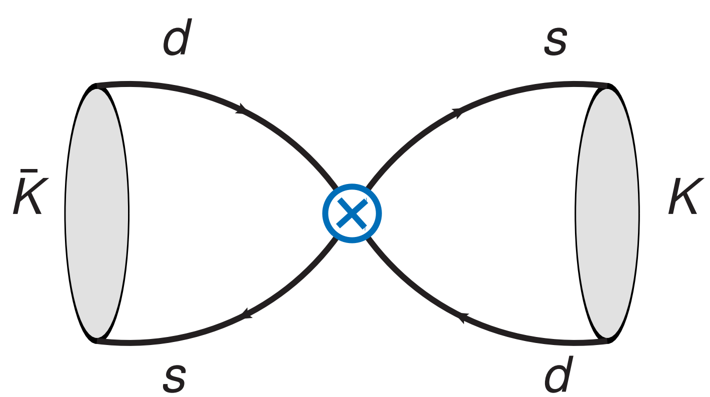
NP Scale?

- Standard Model amplitude is loop suppressed and CKM suppressed



$$\propto \frac{g^4}{16\pi^2} \frac{m_t^2}{M_W^4} (V_{td} V_{ts}^*)^2$$

- Generic New Physics amplitude only suppressed by New Physics scale

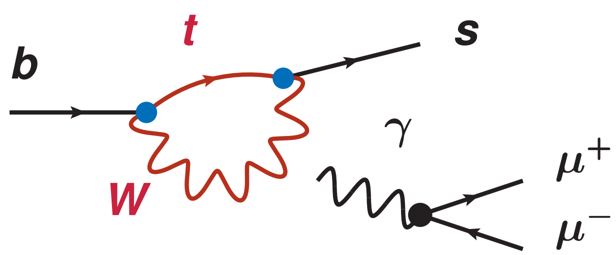


$$\propto \frac{1}{\Lambda_{\rm NP}^2}$$

- CP Violation in Kaon Mixing can probe extremely high scales

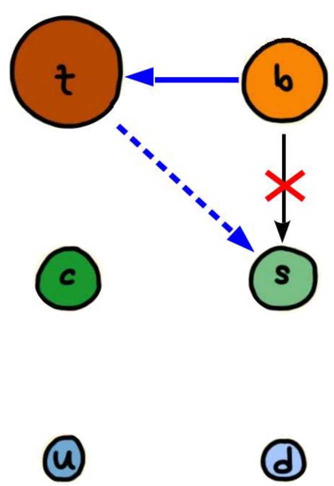
$$\Lambda_{\rm NP} \sim \frac{M_W^2}{m_t} \frac{4\pi}{g^2} \frac{1}{|V_{td} V_{ts}^*|} \sim 10^4 \text{ TeV}$$

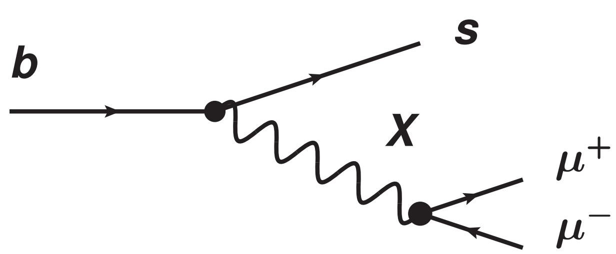
Why do we study flavor physics?



$$\sim \frac{g^4}{16\pi^2}\frac{1}{M_W^2} V_{ts}^* V_{tb}$$

SM amplitude is
loop suppressed and
CKM suppressed





$$\sim \frac{1}{\Lambda_{\rm NP}^2}$$

Generic NP
not necessarily
suppressed

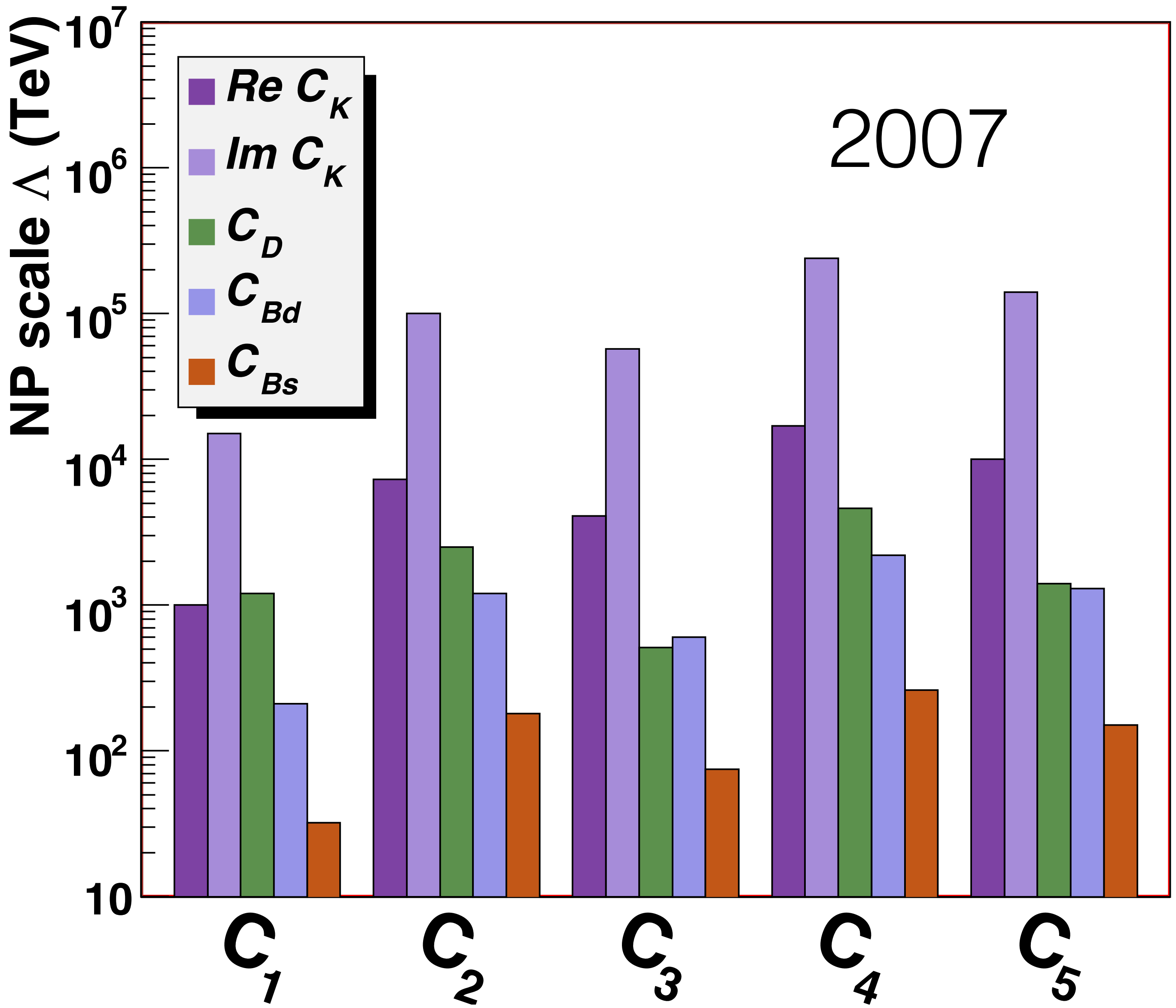
- ► O(1) non-standard effects in rare B decays correspond to new physics in reach of a 100 TeV collider

$$\Lambda_{\rm NP} \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{ts}^* V_{tb}|}} \sim 10\ \text{TeV}$$

New Physics Bound

An impressive progress on flavor bounds in last 10 years

UTFit 0707.0636, 1411.7233



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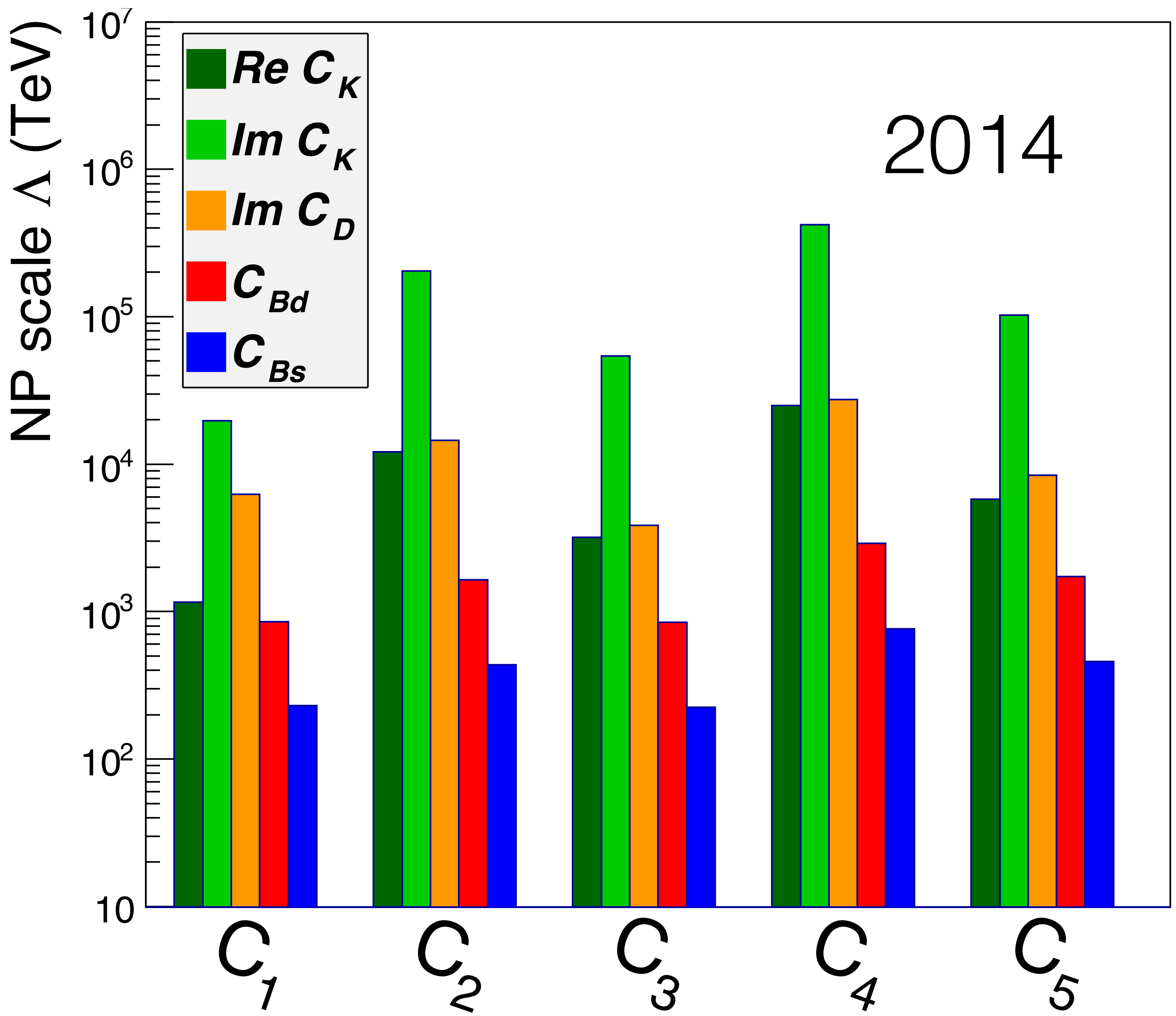

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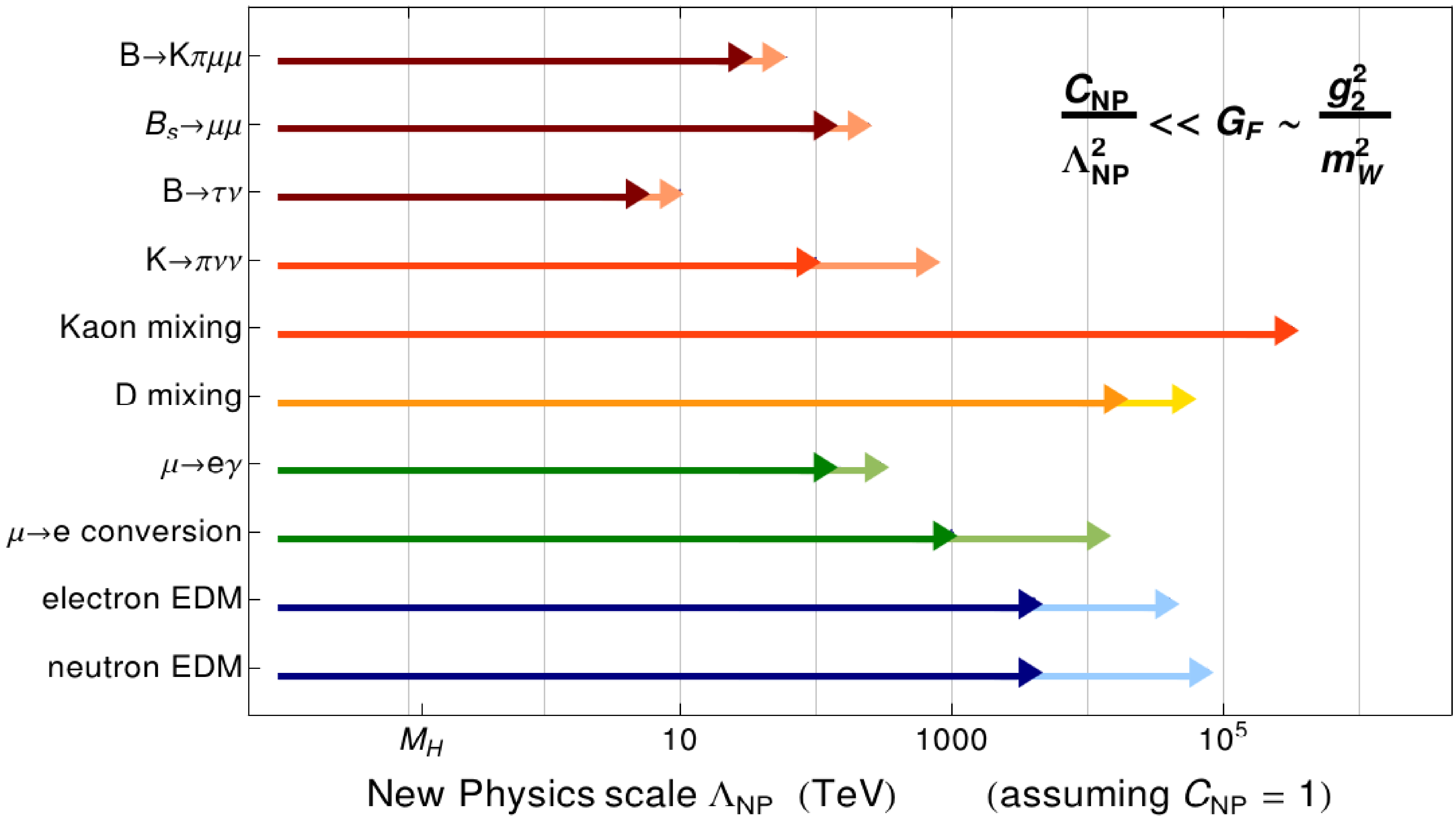
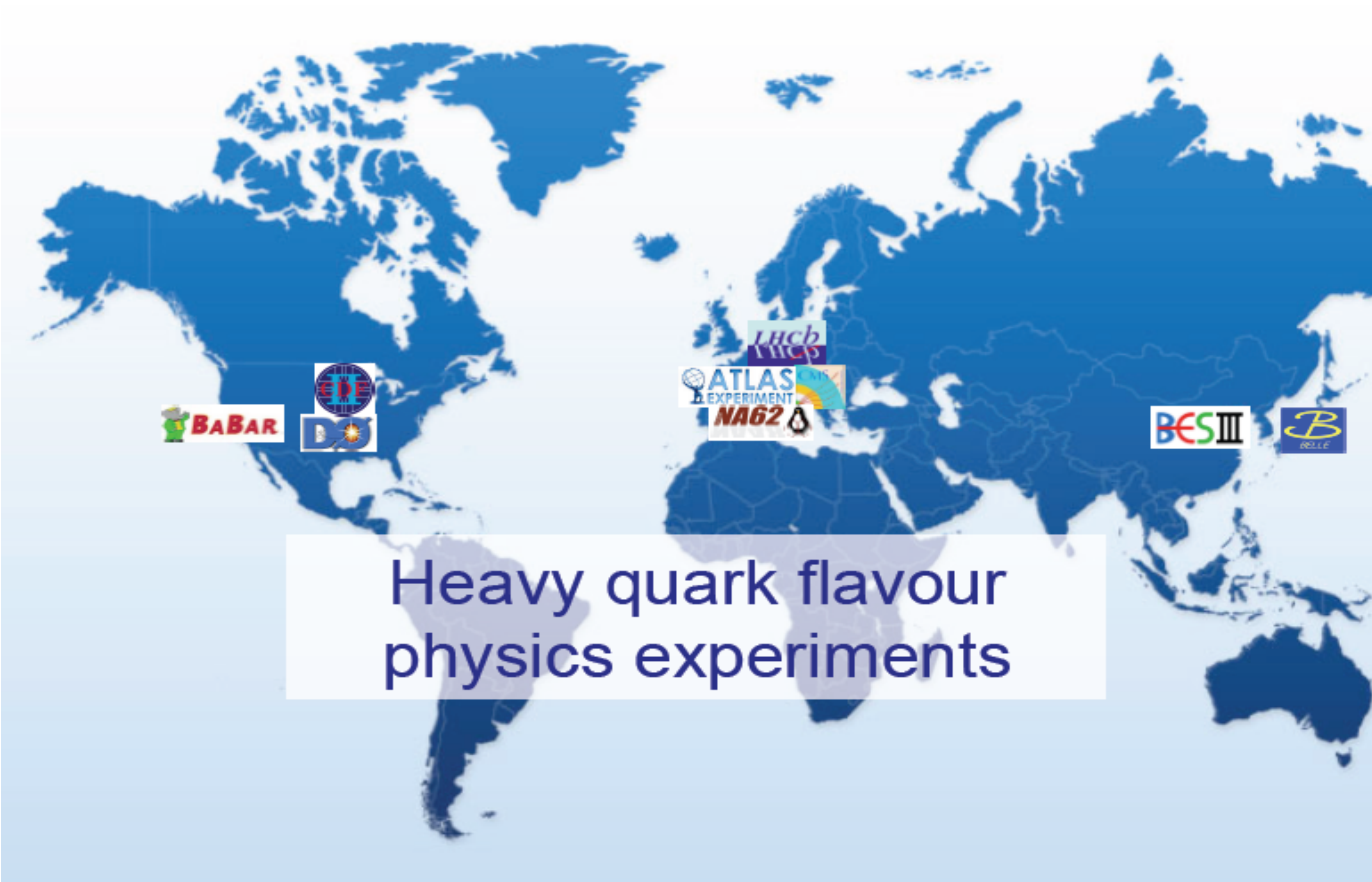
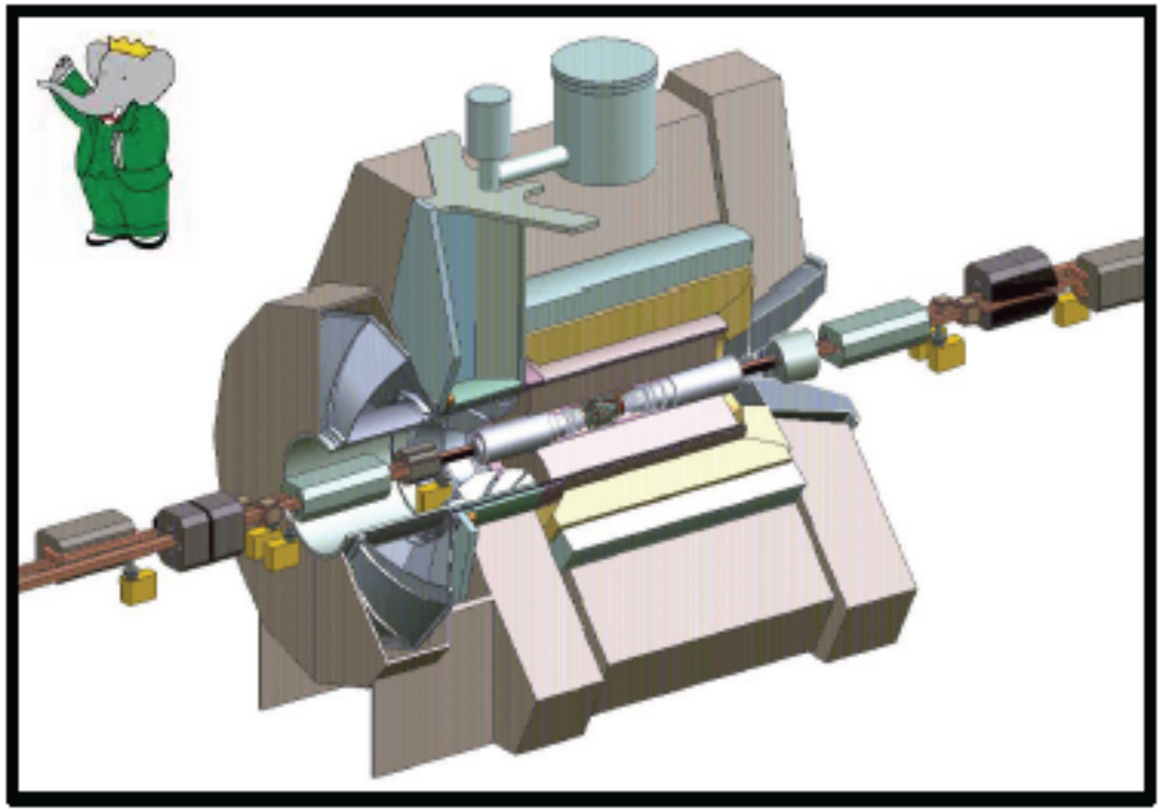
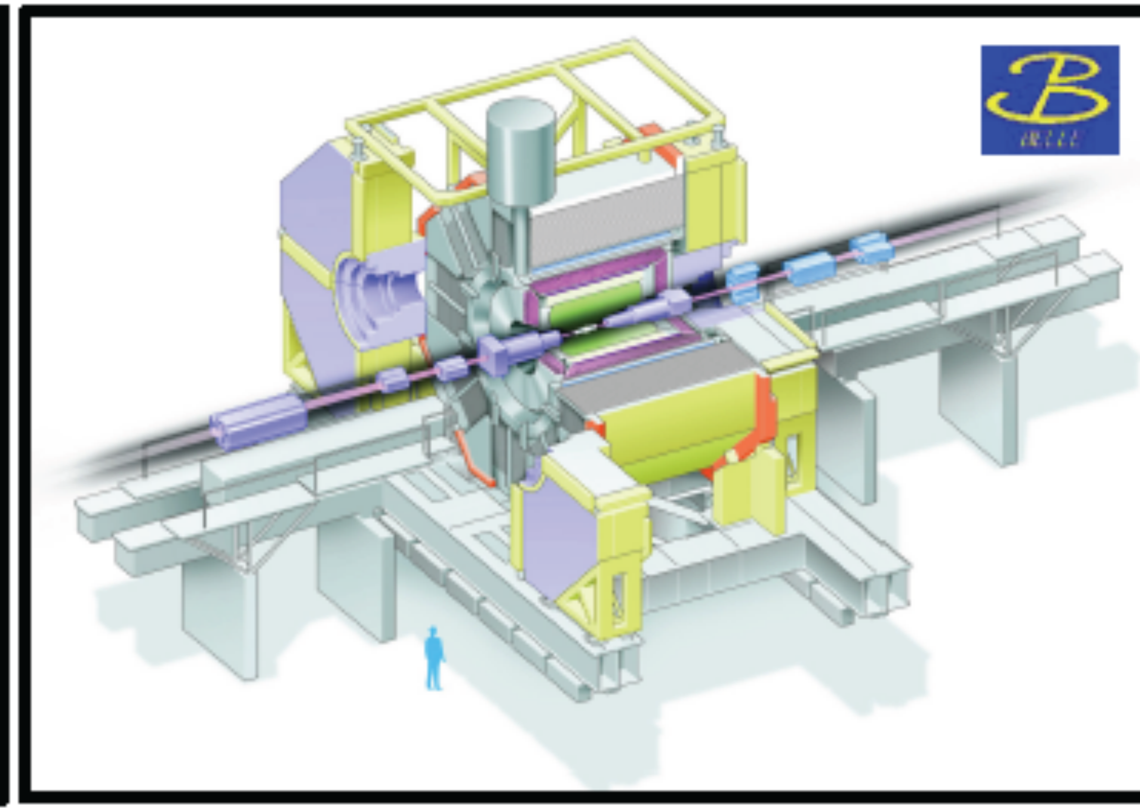


Where Do We Study Flavor Physics



Where Do We Study Flavor Physics





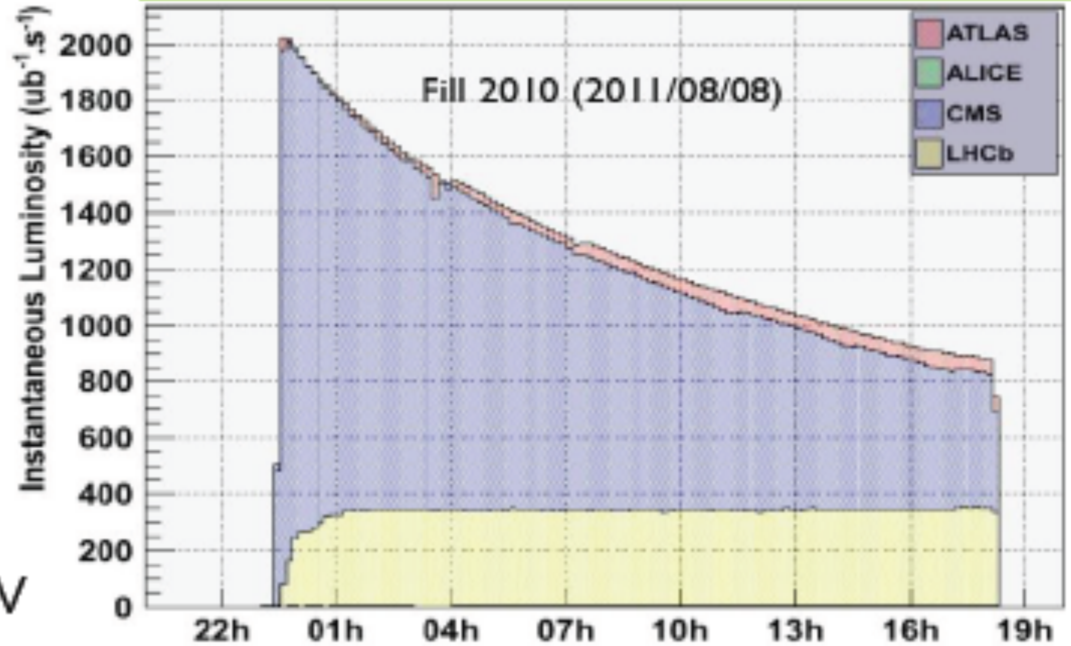
- BaBar/Belle: record asymmetric e^+e^- collisions at $\Upsilon(4S)$ resonance
  - Very clean sample of entangled BB pairs (dominantly B^0 and $B^\pm$)
  - Boost of B^0 allows time dependent measurements
  - Experimentally clean environment
- Data taking 1999- 2008 / 2010 (BaBar / Belle)
  - Total dataset at $\Upsilon(4S)$: 530fb^{-1} / 1000fb^{-1}

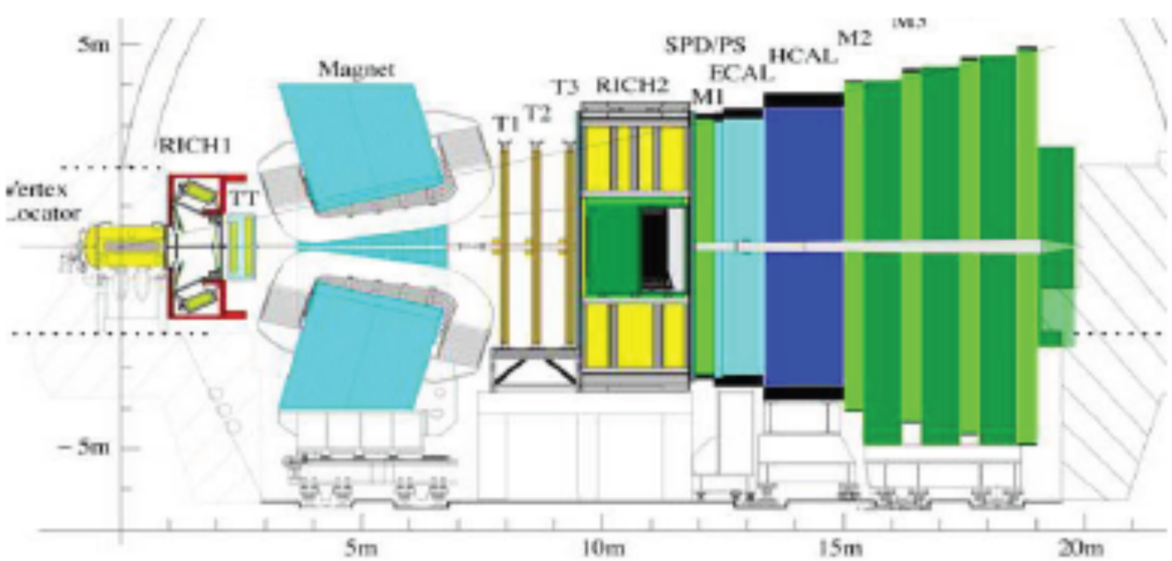
Where Do We Study Flavor Physics

- The LHC is a flavour factory
  - Large $b\bar{b}$ production rate: $\sigma_{bb} \sim 75\mu b$ for both ATLAS/CMS and LHCb

- ATLAS and CMS collect large samples of beauty events
  - Good trigger & PID for hard muons
  - No hadron PID
  - Total dataset: $5 fb^{-1}$ @7TeV and $25 fb^{-1}$@8TeV

LHC luminosity profile





- LHCb: the LHC flavour experiment
  - Very efficient and flexible trigger
  - Good muon & hadron PID
  - Luminosity leveling at 4×10^{32}
    → Constant luminosity for entire fill
  - Total dataset: $1 fb^{-1}$ @ 7TeV and $2.1 fb^{-1}$ @ 8TeV

LHCb 50/fb Summary

Type	Observable	LHC Run 1	LHCb 2018	LHCb upgrade	Theory
B_s^0 mixing	$\phi_s(B_s^0 \to J/\psi\,\phi)$ (rad)	0.049	0.025	**0.009**	~ 0.003
	$\phi_s(B_s^0 \to J/\psi\, f_0(980))$ (rad)	0.068	0.035	**0.012**	~ 0.01
	$A_{\rm sl}(B_s^0)$ (10^{-3})	2.8	1.4	**0.5**	0.03
Gluonic	$\phi_s^{\rm eff}(B_s^0 \to \phi\phi)$ (rad)	0.15	0.10	**0.018**	0.02
penguin	$\phi_s^{\rm eff}(B_s^0 \to K^{*0}\bar{K}^{*0})$ (rad)	0.19	0.13	**0.023**	< 0.02
	$2\beta^{\rm eff}(B^0 \to \phi K_S^0)$ (rad)	0.30	0.20	**0.036**	0.02
Right-handed	$\phi_s^{\rm eff}(B_s^0 \to \phi\gamma)$ (rad)	0.20	0.13	**0.025**	< 0.01
currents	$\tau^{\rm eff}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	5%	3.2%	**0.6%**	0.2 %
Electroweak	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.04	0.020	**0.007**	0.02
penguin	$q_0^2\, A_{\rm FB}(B^0 \to K^{*0}\mu^+\mu^-)$	10%	5%	**1.9%**	$\sim 7\%$
	$A_{\rm I}(K\mu^+\mu^-; 1 < q^2 < 6\,{\rm GeV}^2/c^4)$	0.09	0.05	**0.017**	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	14%	7%	**2.4%**	$\sim 10\%$
Higgs	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ (10^{-9})	1.0	0.5	**0.19**	0.3
penguin	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	220%	110%	**40%**	$\sim 5\,\%$
Unitarity	$\gamma(B \to D^{(*)}K^{(*)})$	7°	4°	**0.9°**	negligible
triangle	$\gamma(B_s^0 \to D_s^{\mp}K^{\pm})$	17°	11°	**2.0°**	negligible
angles	$\beta(B^0 \to J/\psi\, K_S^0)$	1.7°	0.8°	**0.31°**	negligible
Charm	$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**	–
CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**	–

- Many measurements with direct BSM sensitivity improve by a factor 5–10

Belle-II 50/ab Summary

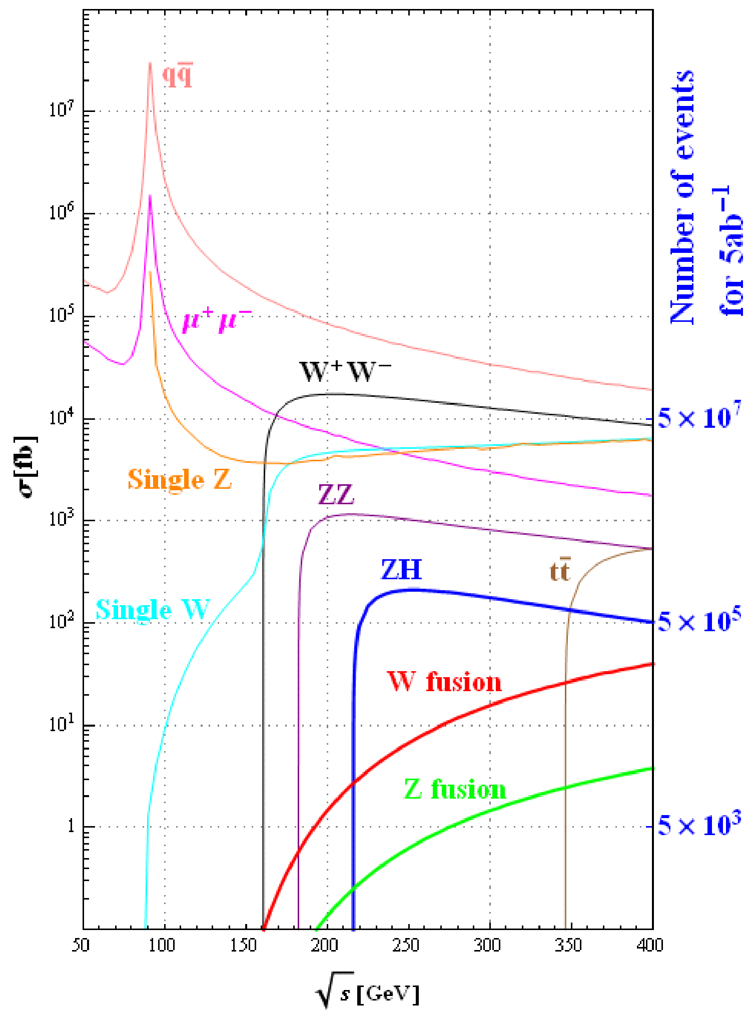
Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\sin 2\beta$	$0.667 \pm 0.023 \pm 0.012$	± 0.012	± 0.008	6
α		$\pm 2^\circ$	$\pm 1^\circ$	
γ	$\pm 14^\circ$	$\pm 6^\circ$	$\pm 1.5^\circ$	
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	± 0.053	± 0.018	>50
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	± 0.028	± 0.011	>50
$S(B \to K^0_S K^0_S K^0_S)$	$0.30 \pm 0.32 \pm 0.08$	± 0.100	± 0.033	44
$\lvert V_{cb}\rvert$ incl.	$\pm 2.4\%$	$\pm 1.0\%$		< 1
$\lvert V_{cb}\rvert$ excl.	$\pm 3.6\%$	$\pm 1.8\%$	$\pm 1.4\%$	< 1
$\lvert V_{ub}\rvert$ incl.	$\pm 6.5\%$	$\pm 3.4\%$	$\pm 3.0\%$	2
$\lvert V_{ub}\rvert$ excl. (had. tag.)	$\pm 10.8\%$	$\pm 4.7\%$	$\pm 2.4\%$	20
$\lvert V_{ub}\rvert$ excl. (untag.)	$\pm 9.4\%$	$\pm 4.2\%$	$\pm 2.2\%$	3
$\mathcal{B}(B \to \tau\nu)$ [10^{-6}]	96 ± 26	$\pm 10\%$	$\pm 5\%$	46
$\mathcal{B}(B \to \mu\nu)$ [10^{-6}]	< 1.7	5σ	$>> 5\sigma$	>50
$R(B \to D\tau\nu)$	$\pm 16.5\%$	$\pm 5.6\%$	$\pm 3.4\%$	4
$R(B \to D^*\tau\nu)$	$\pm 9.0\%$	$\pm 3.2\%$	$\pm 2.1\%$	3
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$ [10^{-6}]	< 40		$\pm 30\%$	>50
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$ [10^{-6}]	< 55		$\pm 30\%$	>50
$\mathcal{B}(B \to X_s\gamma)$ [10^{-6}]	$\pm 13\%$	$\pm 7\%$	$\pm 6\%$	< 1
$A_{CP}(B \to X_s\gamma)$		± 0.01	± 0.005	8
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	± 0.11	± 0.035	> 50
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	± 0.23	± 0.07	> 50
C_7/C_9 $(B \to X_s \ell\ell)$	$\sim 20\%$	10%	5%	
$\mathcal{B}(B_s \to \gamma\gamma)$ [10^{-6}]	< 8.7	± 0.3		
$\mathcal{B}(B_s \to \tau^+\tau^-)$ [10^{-3}]		< 2		

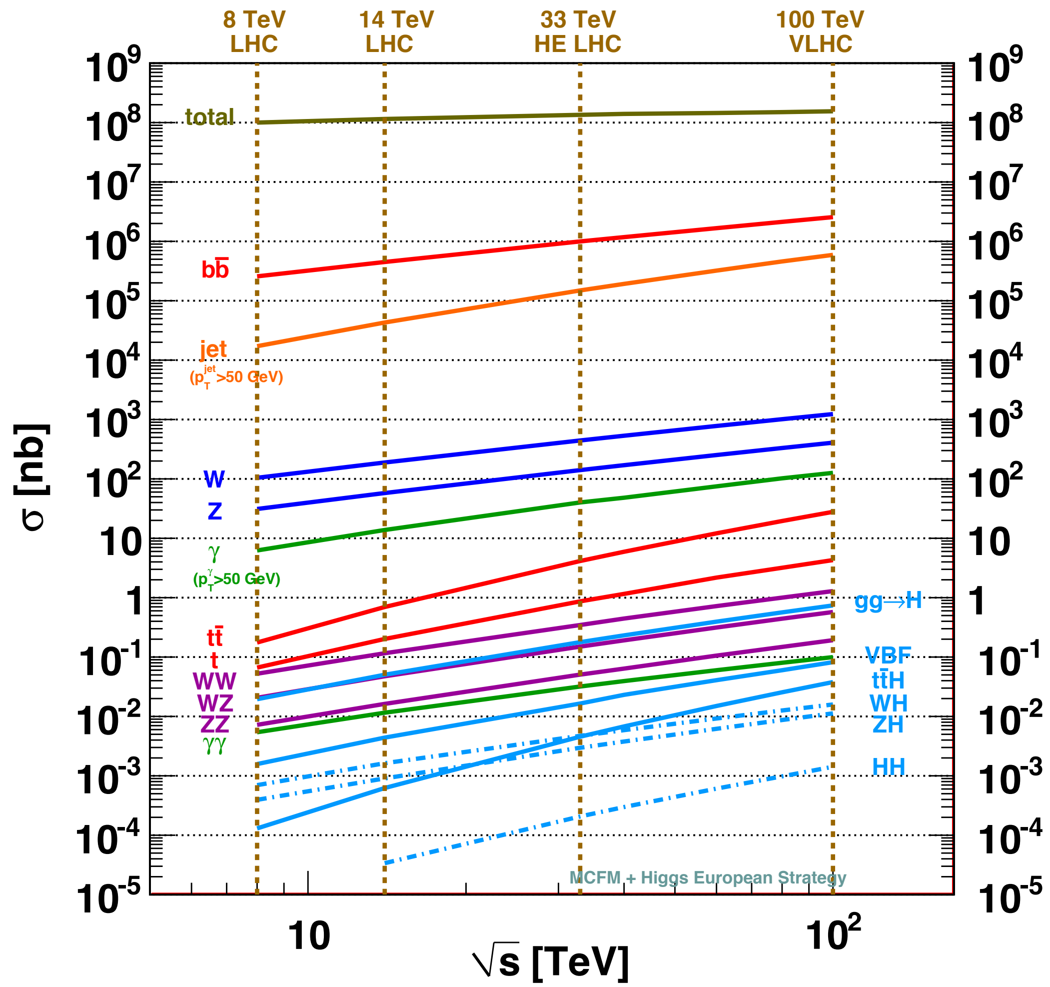
Observables	Belle (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	$\mathcal{L}_s$ [ab^{-1}]
$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \times 10^{-3}(1 \pm 0.053 \pm 0.038)$	$\pm 2.9\%$	$\pm(0.9\%$-$1.3\%)$	> 50
$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \times 10^{-3}(1 \pm 0.037 \pm 0.054)$	$\pm(3.5\%$-$4.3\%)$	$\pm(2.3\%$-$3.6\%)$	3-5
y_{CP} [10^{-2}]	$1.11 \pm 0.22 \pm 0.11$	$\pm(0.11$-$0.13)$	$\pm(0.05$-$0.08)$	5-8
A_Γ [10^{-2}]	$-0.03 \pm 0.20 \pm 0.08$	± 0.10	$\pm(0.03$-$0.05)$	7 - 9
$A_{CP}^{K^+K^-}$ [10^{-2}]	$-0.32 \pm 0.21 \pm 0.09$	± 0.11	± 0.06	15
$A_{CP}^{\pi^+\pi^-}$ [10^{-2}]	$0.55 \pm 0.36 \pm 0.09$	± 0.17	$\pm\ 0.06$	> 50
$A_{CP}^{\phi\gamma}$ [10^{-2}]	$\pm\ 5.6$	± 2.5	± 0.8	> 50
$x^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	± 0.14	± 0.11	3
$y^{K_S\pi^+\pi^-}$ [10^{-2}]	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	± 0.08	± 0.05	15
$\lvert q/p\rvert^{K_S\pi^+\pi^-}$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	± 0.10	± 0.07	5-6
$\phi^{K_S\pi^+\pi^-}$ [$^\circ$]	$-6 \pm 11 \pm {}^{4}_{5}$	± 6	± 4	10
$A_{CP}^{\pi^0\pi^0}$ [10^{-2}]	$-0.03 \pm 0.64 \pm 0.10$	± 0.29	± 0.09	> 50
$A_{CP}^{K^0_S\pi^0}$ [10^{-2}]	$-0.10 \pm 0.16 \pm 0.09$	± 0.08	± 0.03	> 50
$Br(D^0 \to \gamma\gamma)$ [10^{-6}]	< 1.5	$\pm 30\%$	$\pm 25\%$	2
	$\tau \to \mu\gamma$ [10^{-9}]	< 45	< 14.7	< 4.7
	$\tau \to e\gamma$ [10^{-9}]	< 120	< 39	< 12
	$\tau \to \mu\mu\mu$ [10^{-9}]	< 21.0	< 3.0	< 0.3

Clear physics cases

Broad program, large improvements

Flavor Physics @CepC &SppC





b-hadron species	Fraction in decays of $Z^0 \to b\bar{b}$	Number of b-hadron at Z^0 peak	Fraction in $\Upsilon(4S)/(5S)$ decays	Number of b-hadron at $\Upsilon(4S)/(5S)$
B^0	0.404 ± 0.009	22.0×10^{10}	0.486 ± 0.006 ($\Upsilon(4S)$)	4.9×10^{10}
B^+	0.404 ± 0.009	22.0×10^{10}	0.514 ± 0.006 ($\Upsilon(4S)$)	5.1×10^{10}
B_s	0.103 ± 0.009	5.4×10^{10}	0.201 ± 0.030 ($\Upsilon(5S)$)	0.6×10^{10}
b baryons	0.089 ± 0.015	4.8×10^{10}	—	—

CepC will be a big Z-Factory & a flavor factory!

Flavor physics: old/new players in particle physics

- Belle II is approaching
- In Feb: e^+ and e^- injected and circulated in SuperKEKB rings
- LHC is data-taking and will be ungraded.
- CEPC is being pushed.
- Flavor physics will be in the second golden time in the following 20 years.

- I find it interesting to think about:

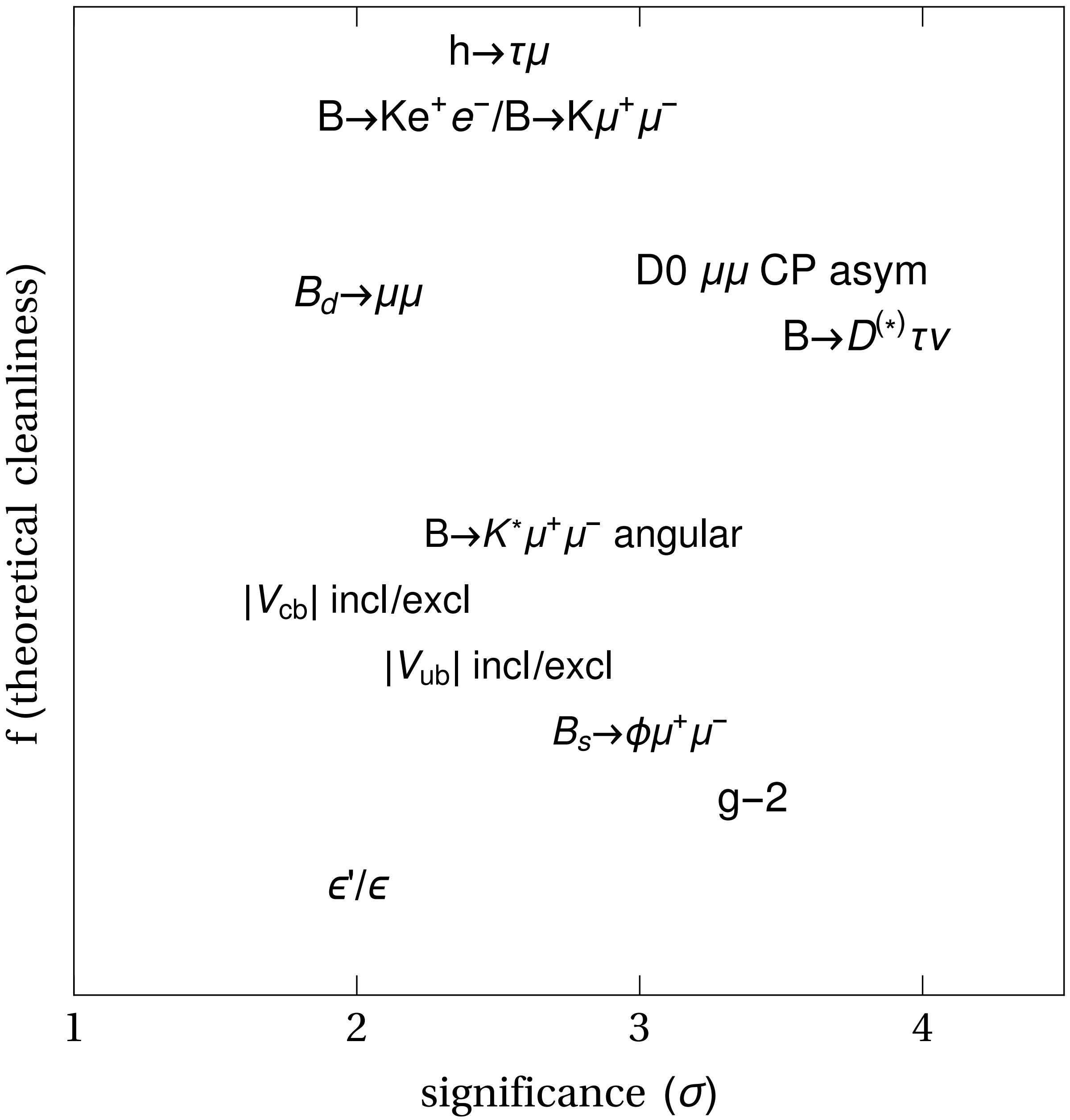
– What can be done with 10 -100 times more data, that has not been done?

– What important/useful theoretical predictions have not been made?

– New ideas? Room for major developments?

– What will be left for CepC and SppC after Belle-II and LHCb in flavor physics?

Status of Flavor Anomalies



✔ Some would be unambiguous NP signals

✔Except for theoretically cleanest modes, cross-checks needed to build robust case

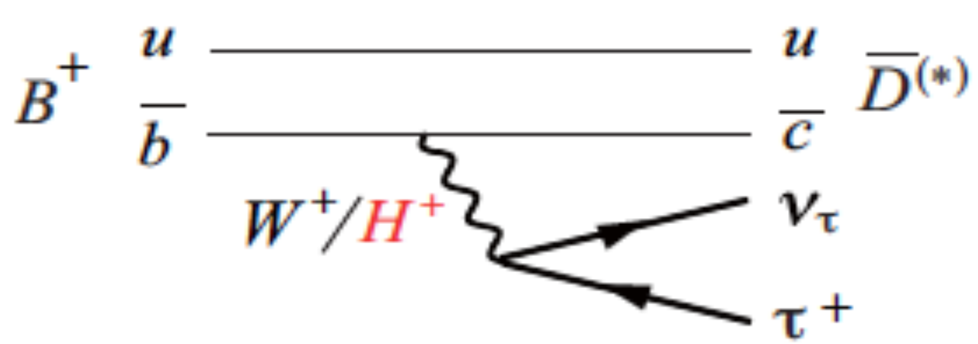
– measurements of related observables

– independent theory / lattice calc.

✔ Few of these are where NP was expected to show up, even just 5–10 years ago

✔ Each could be an hour talk...

The B → $D^{(*)}\tau\bar{\nu}$ Anomaly



Z. Phys, C46, 93 (1990)

- S.L. decays involving a $\tau^\pm$ have an additional helicity amplitude (for $D^*\tau\nu$)

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cb}|^2 \left|\mathbf{p}^*_{D^{(*)}}\right| q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[\left(|H_+|^2+|H_-|^2+|H_0|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3m_\tau^2}{2q^2}|H_s|^2\right]$$

For $D\tau\nu$, H_+ and H_- do not contribute!

- A charged Higgs (2HDM type II) of spin 0 coupling to the τ will only affect H_s

$$\boxed{H_s^{2HDM} = H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m_H^2}\frac{q^2}{1 \mp \frac{m_c}{m_b}}\right)}$$

\- for $D\tau\nu$
\+ for $D^*\tau\nu$

PRD 78, 015006 (2008)
PhD 85, 094025 (2012)

This could enhance or decrease the BF, depending on $\tan\beta/m_H$

The B → $D^{(*)}\tau\bar{\nu}$ Anomaly

A charged Higgs(2HDM type II)of spin0 coupling to the τ will only affect H_s

$$\boxed{H_s^{2HDM} = H_s^{SM} \times \left(1 - \frac{\tan^2\beta}{m_H^2}\frac{q^2}{1 \mp \frac{m_c}{m_b}}\right)}$$

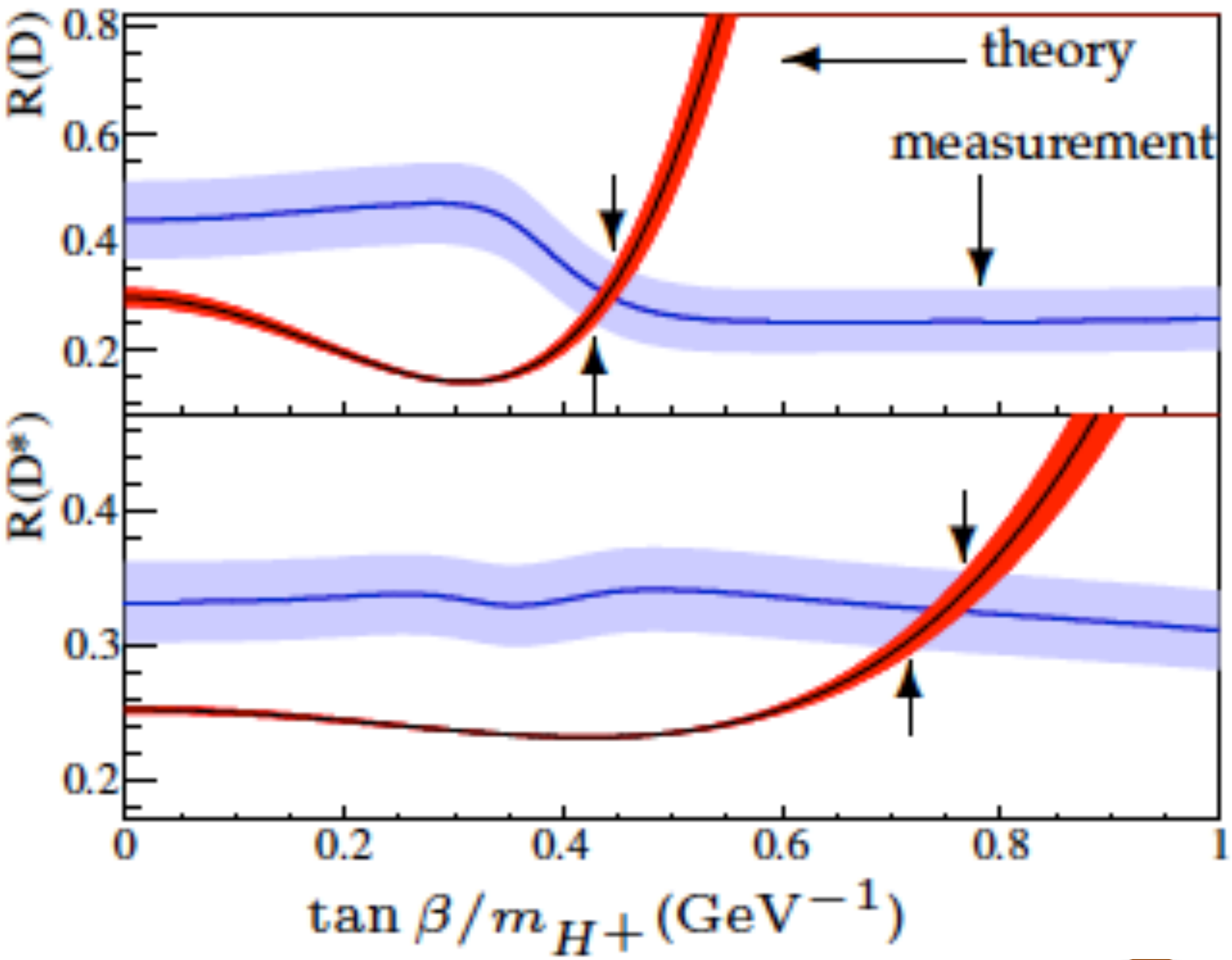
$$R(X) = \frac{\Gamma(B \to X\tau\bar{\nu})}{\Gamma(B \to X\ell\bar{\nu})}$$

We estimate the effect of 2HDM, accounting for difference in signal yield and efficiency.

The data match 2HDM Type II contribution at

$\tan\beta/m_H = 0.44 \pm 0.02$ for R(D)

$\tan\beta/m_H = 0.75 \pm 0.04$ for R(D*)

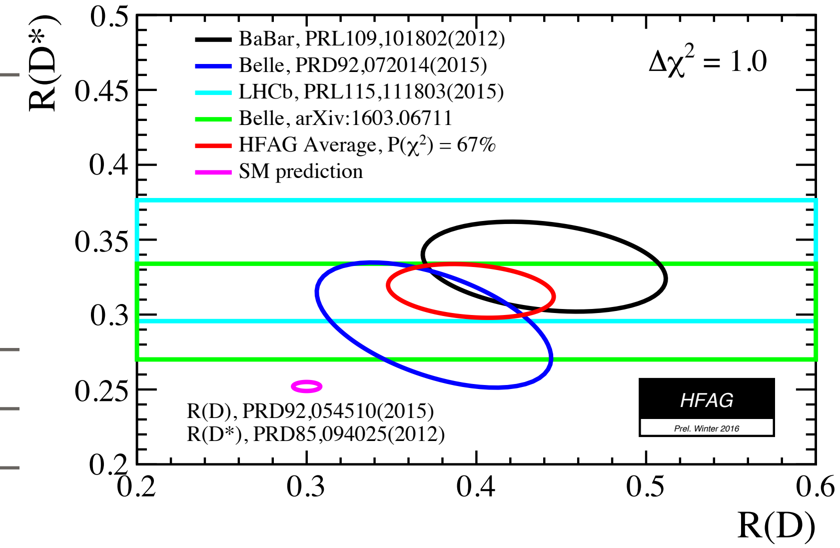


In other words, found NP but *killed* the 2HDM NP model.

The B → D$^{(*)}$τ ν̄ Anomaly

- deviation first seen at BaBar, later results from Belle and LHCb
  BaBar/Belle full datasets $\tau \to \ell\nu\bar{\nu}$ to minimize lepton reco systematics

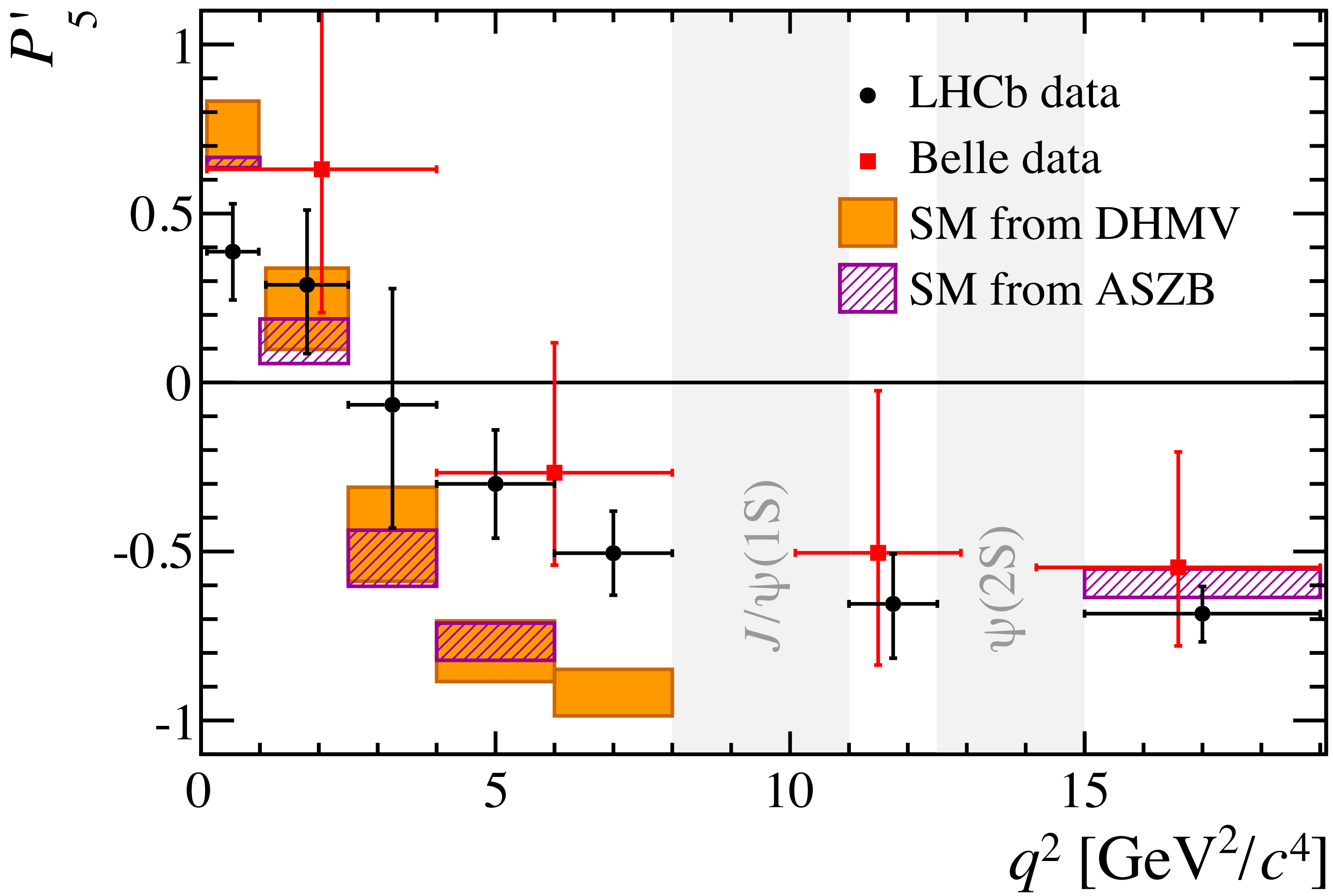
	$R(D)$	$R(D^*)$
BaBar	$0.440 \pm 0.058 \pm 0.042$	$0.332 \pm 0.024 \pm 0.018$
Belle ($B_{\text{tag}}^{(\text{had})}$)	$0.375 \pm 0.064 \pm 0.026$	$0.293 \pm 0.038 \pm 0.015$
Belle ($B_{\text{tag}}^{(\ell)}$)		$0.302 \pm 0.030 \pm 0.011$
LHCb		$0.336 \pm 0.027 \pm 0.030$
Exp. average	$0.397 \pm 0.040 \pm 0.028$	$0.316 \pm 0.016 \pm 0.010$
SM expectation	0.300 ± 0.010	0.252 ± 0.005
Belle II, 50/ab	± 0.010	± 0.005



  - clean SM observables: heavy quark symmetry relates FFs
    Caprini, Lellouch, Neubert, hep-ph/9712417
    cancellation of hadronic uncertainties, $|V_{cb}|$ in ratios
    lattice QCD for $R(D)$ only [MILC, 1503.07237; HPQCD, 1505.03925]
  - $R(D)$ — 1.9σ, $R(D^*)$ — 3.3σ
    total significance — 4.0σ largest deviation from SM right now!

- similar ratios before Belle II: LHCb: $R(D)$? $\Lambda_b \to \Lambda_c^{(*)}\tau\bar{\nu}$?
  BaBar/Belle: hadronic τ decays?

The B → $K^*\mu^+\mu^-$ Anomaly

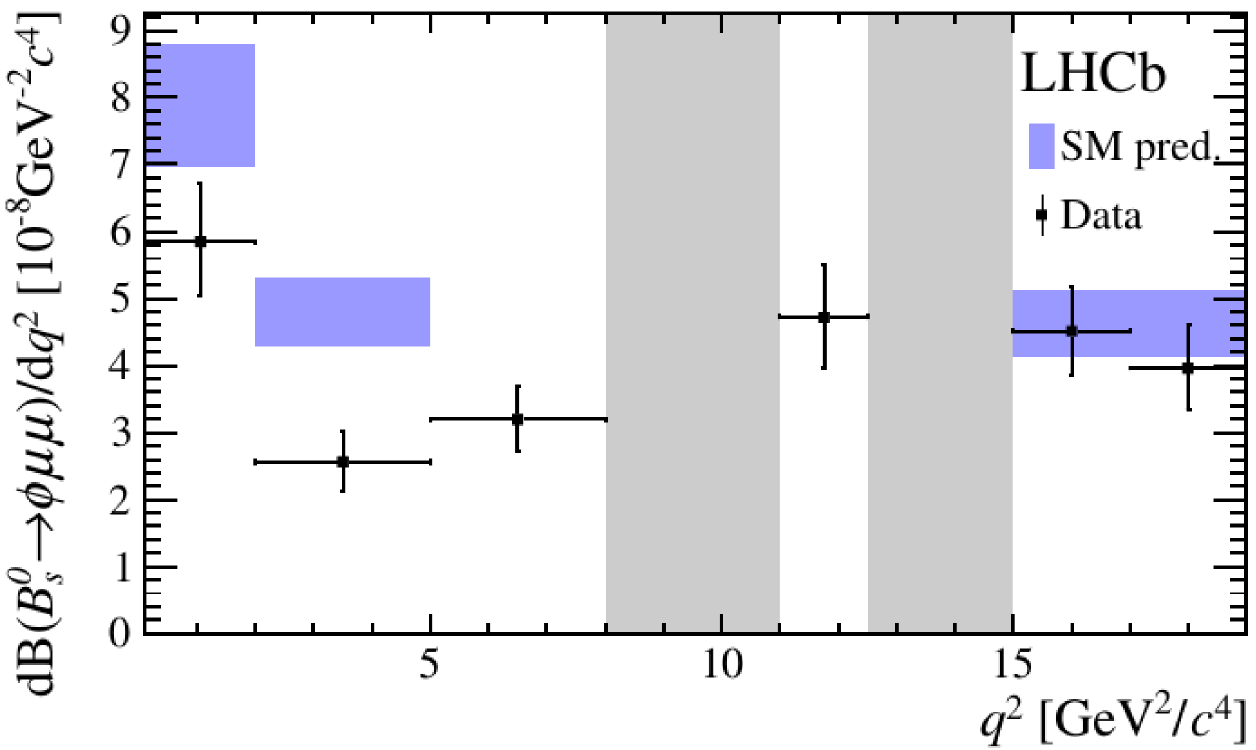


- Statistical fluctuation
- Underestimated SM uncertainties?
  (Khodjamirian, Jager, Martin, Camalich, Lyon, Zwicky, Descotes-Genon, Wolfgang Altmannshofer, YL, ...)
- New Physics?

- Cross checks: different regions of phase space, also study in B_s and Λ_b decays?

The Bs $\to \Phi\mu^+\mu^-$ Anomaly

LHCb 1506.08777



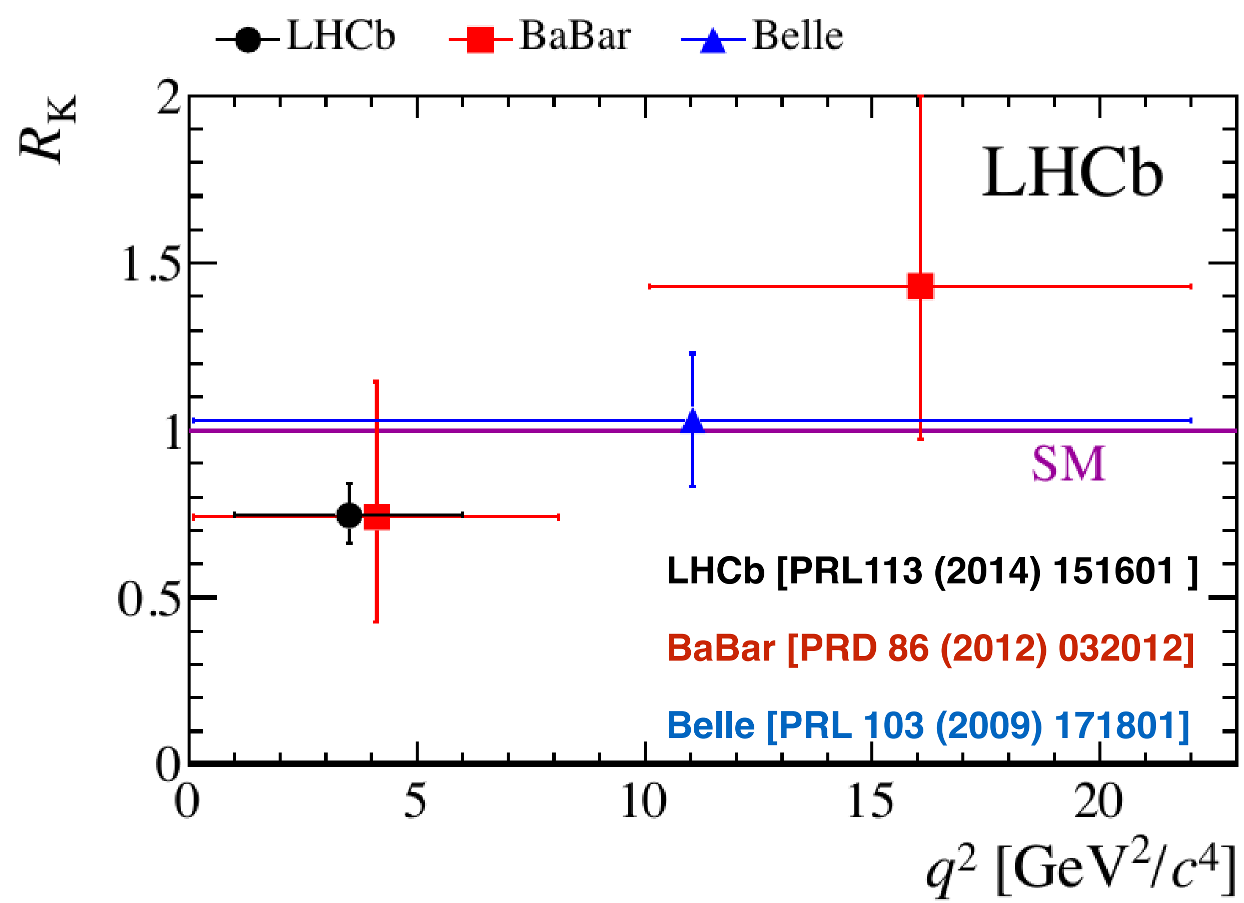
branching ratio is 3.5σ below SM prediction for $1\,\text{GeV}^2 < q^2 < 6\,\text{GeV}^2$

$10^7 \times BR(B_s \to \phi\mu^+\mu^-)$	Prediction	Experiment
$[0.1, 2.]$	1.71 ± 0.34	1.11 ± 0.16
$[2., 5.]$	1.58 ± 0.25	0.77 ± 0.14
$[5., 8.]$	1.81 ± 0.32	0.96 ± 0.15
$[15, 18.8]$	1.74 ± 0.13	1.62 ± 0.20

Descotes-Genon, Matias, Virto arXiv:1510.04239

The R_K Anomaly

LHCb 1406.6482



2.6σ hint for violation of lepton flavor universality (LFU)

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to Ke^+e^-)_{[1,6]}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

More Tensions

A number of rare decay observables deviate from SM expectations. 1411.3161

Decay	obs.	q^2 bin	SM pred.	measurement	
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7 \frac{d\mathrm{BR}}{dq^2}$	$[2, 4.3]$	0.44 ± 0.07	0.29 ± 0.05	LHCb
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	$10^7 \frac{d\mathrm{BR}}{dq^2}$	$[16, 19.25]$	0.47 ± 0.06	0.31 ± 0.07	CDF
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{d\mathrm{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{d\mathrm{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{d\mathrm{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{d\mathrm{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb
$B \to X_s e^+e^-$	10^6 BR	$[14.2, 25]$	0.21 ± 0.07	0.57 ± 0.19	BaBar

Significances depend on treatment of several nonperturbative effects.

Descotes-Genon, Altmannshofer, Straub Hurth, Mahmoudi, Martin Camlich, Lu, Wang, **YL**,….

What Could They Be ?

	branching ratios	angular observables	LFU ratios
statistical fluctuations?	✓	✓	✓
parametric uncertainties?	✓	✗	✗
underestimated hadronic effects?	✓	✓	✗
New Physics?	✓	✓	✓

What Could They Be ?

BSM detectives

SUSY
Leptoquarks
Extended Higgs Sector
Little Higgs Models
Z'
331 models
…

SM magistrats

HQET/SCET
Lattice QCD
OPE
Pert QCD
SCET
Sum Rules
…

NP Models

Possible New Physics to explain these anomalies

- Z' Models

  U. Haisch, W. Altmannshofer A. Cvrivellin, X-Q,Li, X-G He, Y.LI…

- Extended Higgs Sector

  J. Heeck, A. Greljo, A. Crivellin,…

- Leptoquarks

  M. Bauer, M. Neubert, L. Calibbi, ….

- More complete models:

  2HDM with gauged $L\tau$ -Lμ

  2HDM-X: one higgs couples to quarks, one to leptons

-Model independence analysis

Consider redundant set of operators

Freytsis,et.al, 1506.08896

		Operator	Fierz identity	Allowed Current	$\delta\mathcal{L}_{\rm int}$
SM	$\mathcal{O}_{V_L}$	$(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu)$		$(1,3)_0$	$(g_q \bar{q}_L \boldsymbol{\tau}\gamma^\mu q_L + g_\ell \bar{\ell}_L \boldsymbol{\tau}\gamma^\mu \ell_L)W'_\mu$
	$\mathcal{O}_{V_R}$	$(\bar{c}\gamma_\mu P_R b)\,(\bar{\tau}\gamma^\mu P_L \nu)$			
	$\mathcal{O}_{S_R}$	$(\bar{c}P_R b)\,(\bar{\tau}P_L \nu)$			
	$\mathcal{O}_{S_L}$	$(\bar{c}P_L b)\,(\bar{\tau}P_L \nu)$		$(1,2)_{1/2}$	$(\lambda_d \bar{q}_L d_R \phi + \lambda_u \bar{q}_L u_R i\tau_2 \phi^\dagger + \lambda_\ell \bar{\ell}_L e_R \phi)$
	$\mathcal{O}_T$	$(\bar{c}\sigma^{\mu\nu} P_L b)\,(\bar{\tau}\sigma_{\mu\nu} P_L \nu)$			
	$\mathcal{O}'_{V_L}$	$(\bar{\tau}\gamma_\mu P_L b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad \mathcal{O}_{V_L}$	$(3,3)_{2/3}$	$\lambda\, \bar{q}_L \boldsymbol{\tau}\gamma_\mu \ell_L \boldsymbol{U}^\mu$
				$(3,1)_{2/3}$	$(\lambda\, \bar{q}_L \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{d}_R \gamma_\mu e_R)U^\mu$
	$\mathcal{O}'_{V_R}$	$(\bar{\tau}\gamma_\mu P_R b)\,(\bar{c}\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$		
	$\mathcal{O}'_{S_R}$	$(\bar{\tau}P_R b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{V_R}$		
	$\mathcal{O}'_{S_L}$	$(\bar{\tau}P_L b)\,(\bar{c}P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} - \frac{1}{8}\mathcal{O}_T$	$(3,2)_{7/6}$	$(\lambda\, \bar{u}_R \ell_L + \tilde{\lambda}\, \bar{q}_L i\tau_2 e_R)R$
	$\mathcal{O}'_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L b)\,(\bar{c}\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} + \frac{1}{2}\mathcal{O}_T$		
	$\mathcal{O}''_{V_L}$	$(\bar{\tau}\gamma_\mu P_L c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -\mathcal{O}_{V_R}$		
	$\mathcal{O}''_{V_R}$	$(\bar{\tau}\gamma_\mu P_R c^c)\,(\bar{b}^c\gamma^\mu P_L \nu)$	$\longleftrightarrow \quad -2\mathcal{O}_{S_R}$	$(\bar{3},2)_{5/3}$	$(\lambda\, \bar{d}^c_R \gamma_\mu \ell_L + \tilde{\lambda}\, \bar{q}^c_L \gamma_\mu e_R)V^\mu$
				$(\bar{3},3)_{1/3}$	$\lambda\, \bar{q}^c_L i\tau_2 \boldsymbol{\tau} \ell_L \boldsymbol{S}$
	$\mathcal{O}''_{S_R}$	$(\bar{\tau}P_R c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad \frac{1}{2}\mathcal{O}_{V_L}$		
				$(\bar{3},1)_{1/3}$	$(\lambda\, \bar{q}^c_L i\tau_2 \ell_L + \tilde{\lambda}\, \bar{u}^c_R e_R)S$
	$\mathcal{O}''_{S_L}$	$(\bar{\tau}P_L c^c)\,(\bar{b}^c P_L \nu)$	$\longleftrightarrow \quad -\frac{1}{2}\mathcal{O}_{S_L} + \frac{1}{8}\mathcal{O}_T$		
	$\mathcal{O}''_T$	$(\bar{\tau}\sigma^{\mu\nu} P_L c^c)\,(\bar{b}^c\sigma_{\mu\nu} P_L \nu)$	$\longleftrightarrow \quad -6\mathcal{O}_{S_L} - \frac{1}{2}\mathcal{O}_T$		

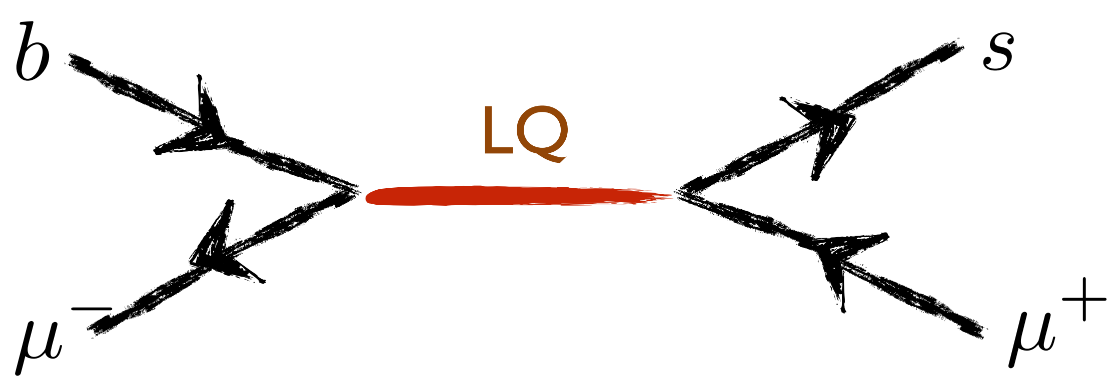
Data → Operator Analysis → Model Building → Model Verify

Possible Models

- Good fits for several mediators: scalar, "Higgs-like" $(1,2)_{1/2}$
  vector, "W'-like" $(1,3)_0$
  "scalar leptoquark" $(\bar{3},1)_{1/3}$ or $(\bar{3},3)_{1/3}$
  "vector leptoquark" $(3,1)_{2/3}$ or $(3,3)_{2/3}$

- Which BSM scenarios can be MFV? [1506.08896]
  Not scalars, nor vectors, possibly viable LQ: scalar $S(\mathbf{1},\mathbf{1},\bar{\mathbf{3}})$ or vector $U_\mu(\mathbf{1},\mathbf{1},\mathbf{3})$

  Bounds: $b \to s\nu\bar{\nu}$, D^0 & K^0 mixing, $Z \to \tau^+\tau^-$, LHC contact int., $pp \to \tau^+\tau^-$, etc.



Many signals, tests, consequences

- LHCb, maybe soon: measure $R(D)$? use hadronic τ? measure $\Lambda_b \to \Lambda_c^{(*)} \tau\nu$?

  Ratios of c/u besides τ/μ? e.g.: $\Lambda_b \to \Lambda\tau\bar{\nu}$, $B \to \pi\tau\bar{\nu}$, $B \to \rho\tau\bar{\nu}$?

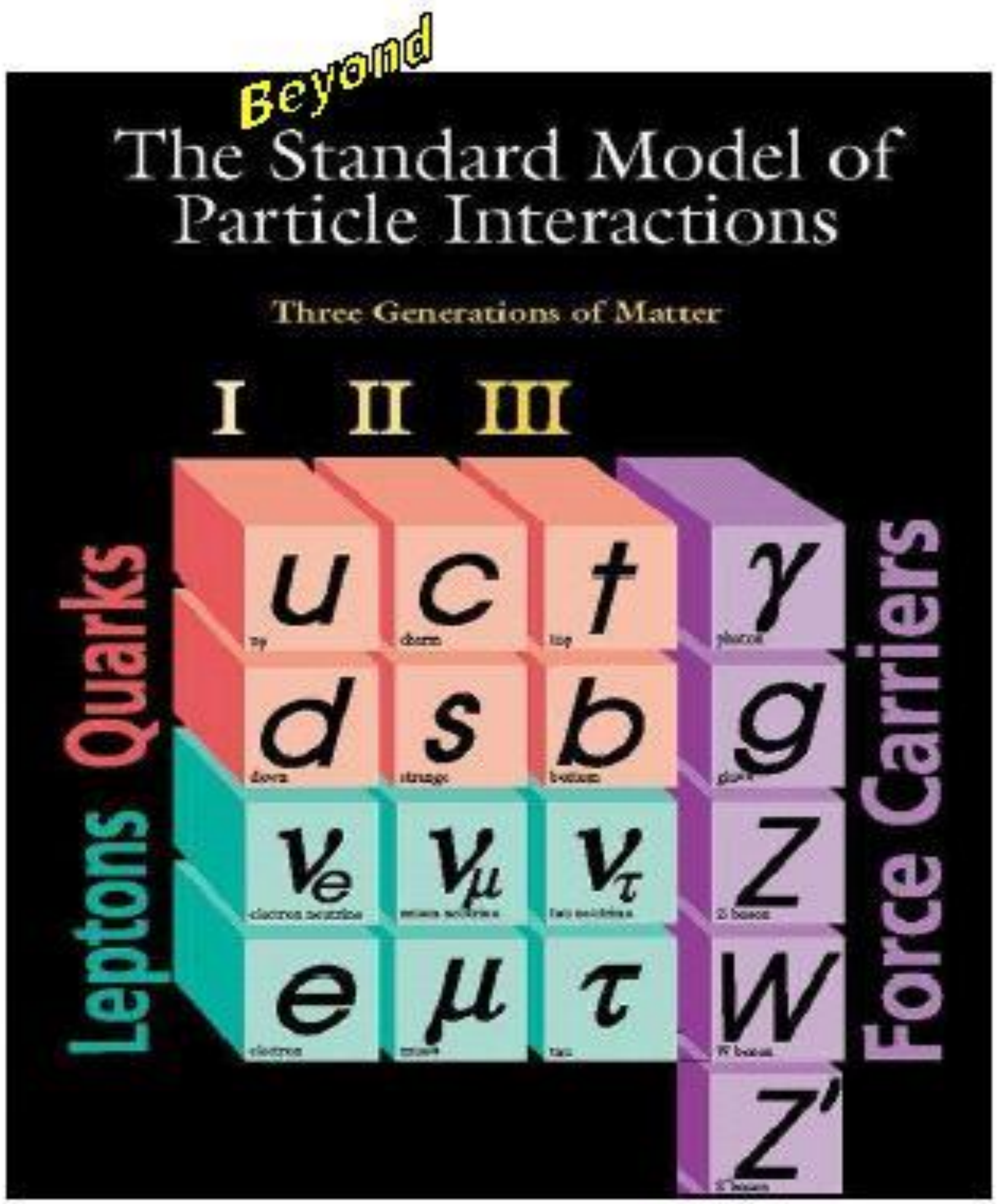
- longer term: refine $R(D^{(*)})$ and spectra; attempt inclusive (Belle II?)
  - Smaller theor. error in $[\mathrm{d}\Gamma(B \to D^{(*)}\tau\bar{\nu})/\mathrm{d}q^2]/[\mathrm{d}\Gamma(B \to D^{(*)}l\bar{\nu})/\mathrm{d}q^2]$ at same q^2
  - Improve bounds on $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$; $\mathcal{B}(B_s \to \tau^+\tau^-) \sim 10^{-3}$ possible?
  - $\mathcal{B}(D \to \pi\nu\bar{\nu}) \sim 10^{-5}$ possible, maybe BES III; enhanced $\mathcal{B}(D \to \mu^+\mu^-)$

Example-1: Models with Flavor Changing Z' Boson

- SUSY
- String Models
- E_6 Models
- U Boson Model
- Grand Unitary Theory

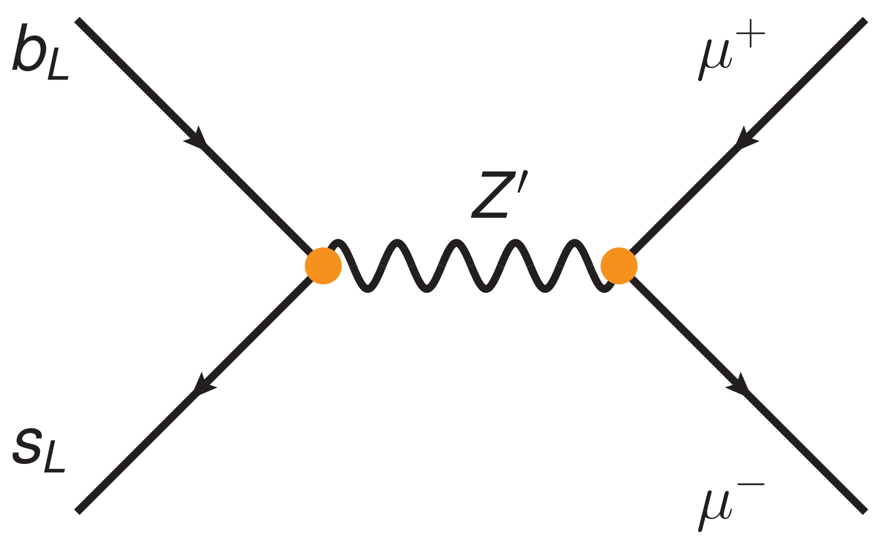
The effect of Z' on flavor physics have been discussed for many years.

G.Valencia, X.G He, C.W Chiang, T. Liu, C.S Kim, …..



Example-1: Models with Flavor Changing Z' Boson

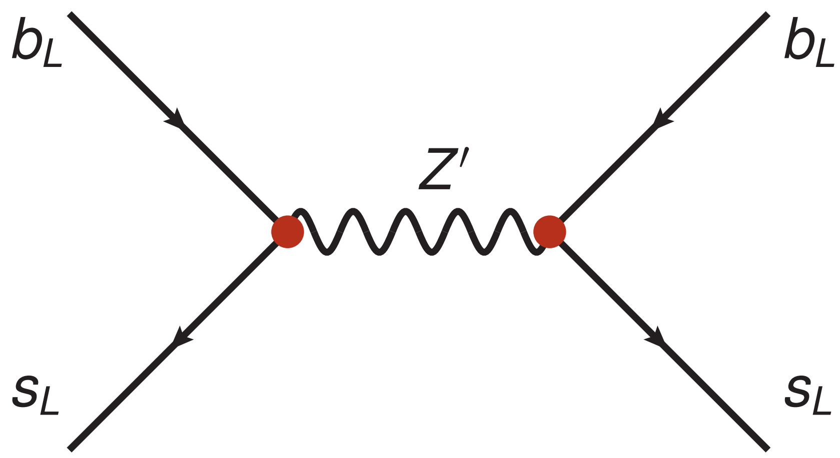
$$\mathcal{L} \supset \bar{f}_i \gamma^\mu \left[\Delta_L^{f_i f_j} P_L + \Delta_R^{f_i f_j} P_R \right] f_j Z'_\mu$$



want vectorial coupling to muons: $\Delta_L^{\mu\mu} = \Delta_R^{\mu\mu} = \frac{1}{2}\Delta_V^{\mu\mu}$

$$C_9^{\rm NP} = -\frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*} \frac{v^2}{M_{Z'}^2} \frac{4\pi^2}{e^2} \simeq -\frac{\Delta_L^{bs}\Delta_V^{\mu\mu}}{V_{tb}V_{ts}^*} \frac{(5\ \text{TeV})^2}{M_{Z'}^2}$$

Z'Boson in Bs-Mixing



- flavor changing Z' contributes also to B_s mixing at tree level

$$\frac{M_{12}}{M_{12}^{\text{SM}}} - 1 = \frac{v^2}{M_{Z'}^2} (\Delta_L^{bs})^2 \left(\frac{g_2^2}{16\pi^2} (V_{tb} V_{ts}^*)^2 S_0 \right)^{-1}$$

- constraint on the Z' mass and the flavor changing coupling (allowing for 10% NP in B_s mixing)

$$\frac{M_{Z'}}{|\Delta_L^{bs}|} \gtrsim 244 \text{ TeV} \simeq \frac{10 \text{ TeV}}{|V_{tb} V_{ts}^*|}$$

Example-2:A Model Based on Gauged $L_\mu - L_\tau$

W. Altmannshoher, et,al, 1403.1269
A. Crivellin, et.al, 1501.00993

New vector quark will be introduced

- the Z' model based on gauged $L_\mu - L_\tau$ predicts:

  1) opposite effects in the $\mu^+\mu^-$ and $\tau^+\tau^-$ final state
  2) no effect in the e^+e^- final state

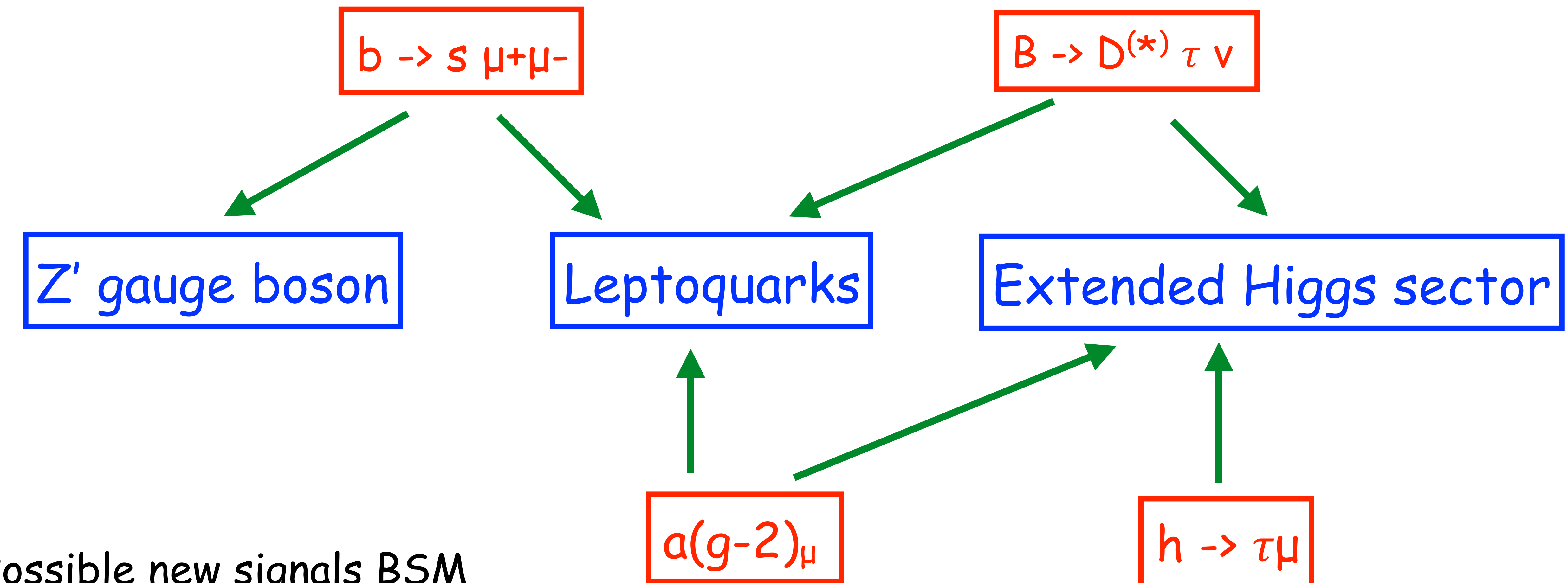
$\rightarrow$ prediction for LFU observables, e.g. ratios of branching ratios:

$$R_K = \frac{\mathrm{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\mathrm{BR}(B \to Ke^+e^-)_{[1,6]}} \simeq 0.82 \pm 0.11 \qquad (R_K^{\mathrm{SM}} \simeq 1)$$

model passed the first test (LHCb Collaboration arXiv:1406.6482)

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036$$

BSM Explanations

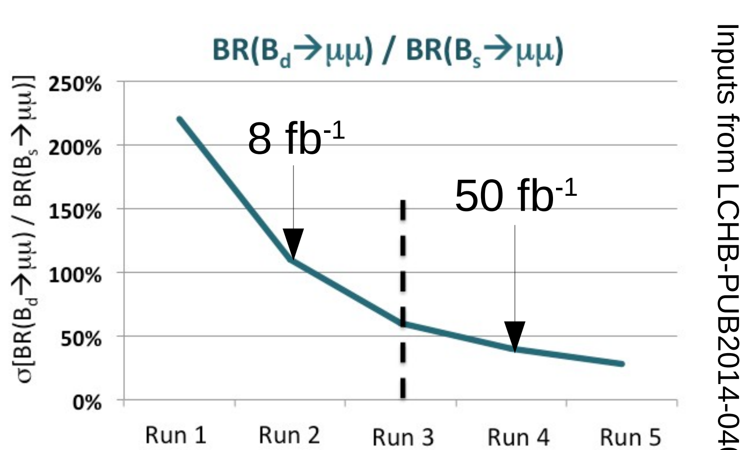


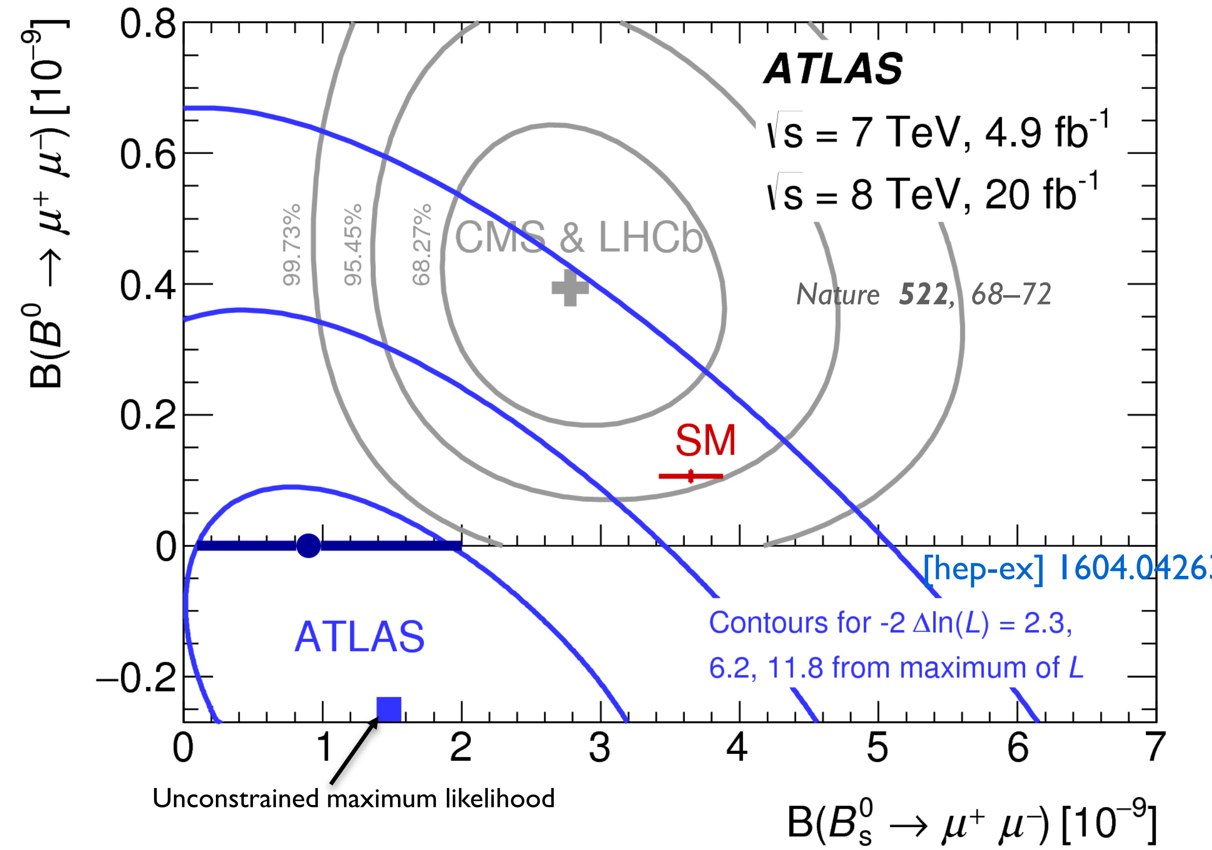
- Possible new signals BSM
  - $b \to s\,\mu^+\mu^- \oplus R(D^{(*)}) \Rightarrow$ Leptoquarks $\Rightarrow B_s \to \mu\mu,\ b \to s\,\tau\tau$
  - $a_\mu \oplus R(D^{(*)}) \Rightarrow$ 2HDM-X $\Rightarrow t \to Hc,\ B_s \to \mu\mu,\ \tau \to \mu\nu\nu$

Other recent highlights

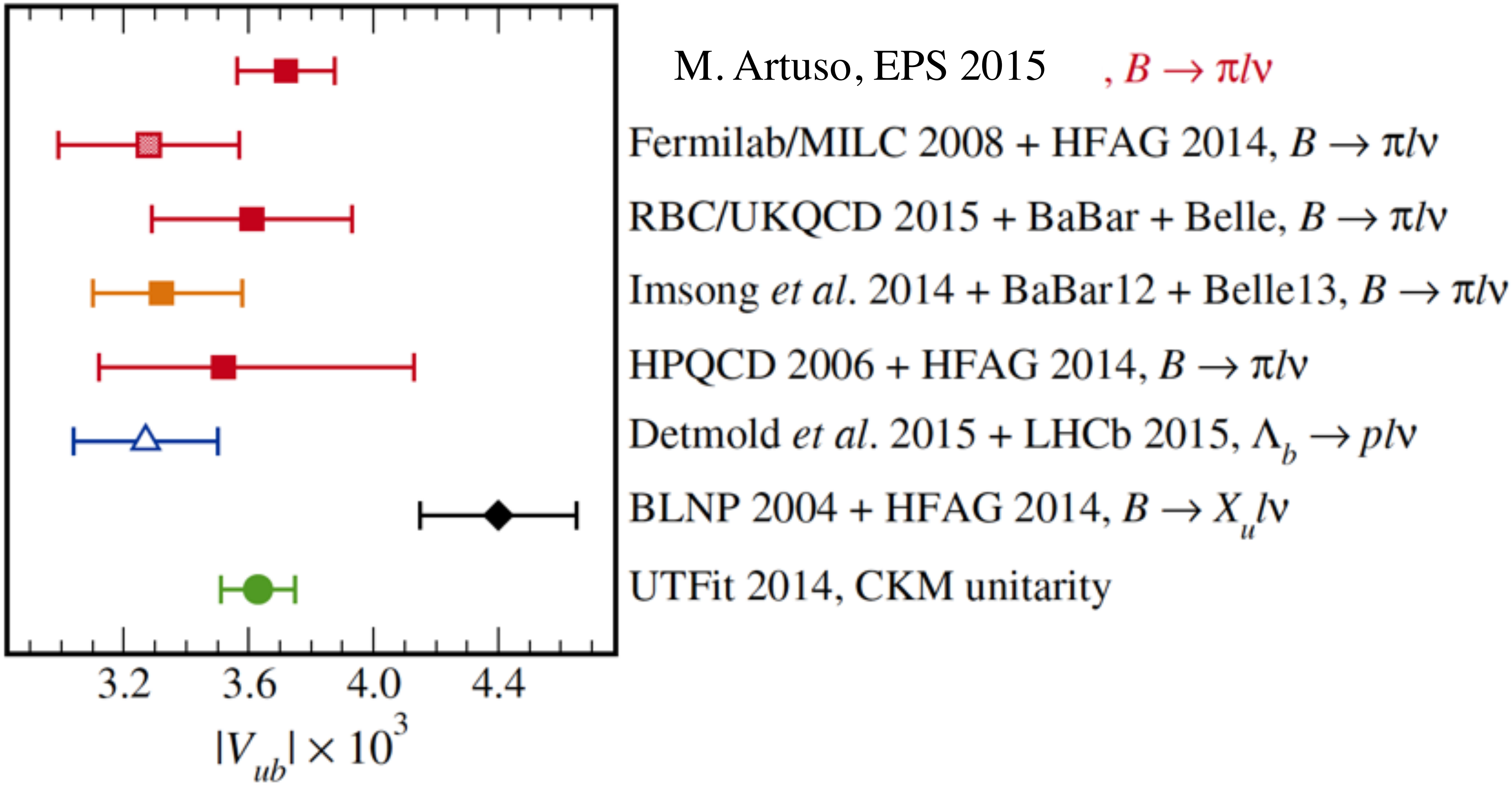
- Clean theoretically:
- BR($B_s \to \mu\mu$) = (3.65 + 0.23)x10^{-9}

  BR($B_d \to \mu\mu$) = (1.06 + 0.09) x10^{-10}
- With new Atlas results some tension with SM in B_s
- Await more data.
  - LHCb with 50 fb^{-1}
    - BR($B_s \to \mu\mu$) to 5%
    - BR($B_d \to \mu\mu$)/BR($B_s \to \mu\mu$) to 35%



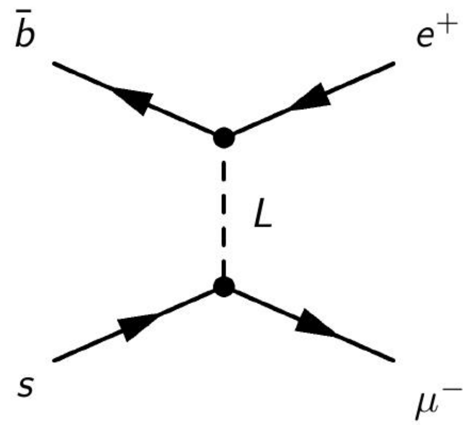


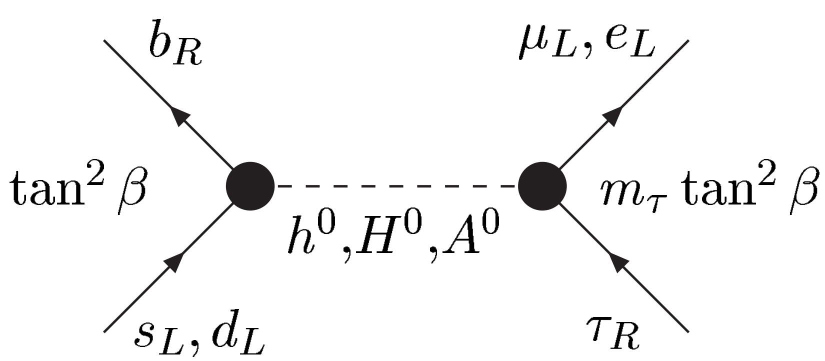
Puzzle of inclusive vs exclusive measures of CKM



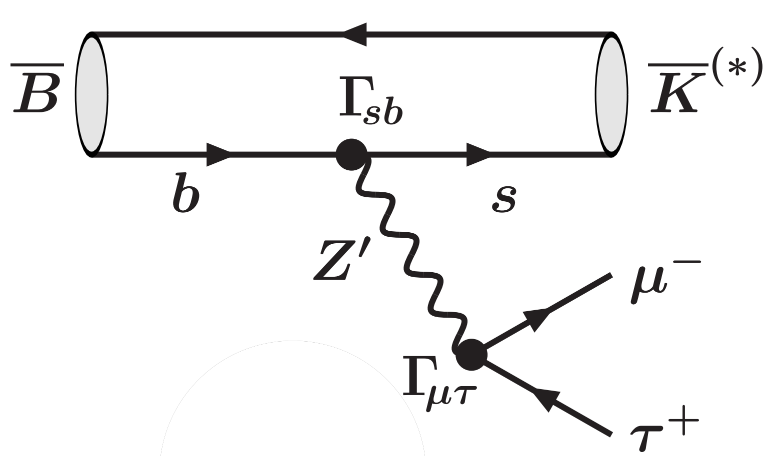
- Exclusive data consistent with each other and with indirect determination of $|V_{ub}|$.
- New physics in $|V_{ub}|$ from inclusive measurement?

Lepton flavour violating b hadron decays



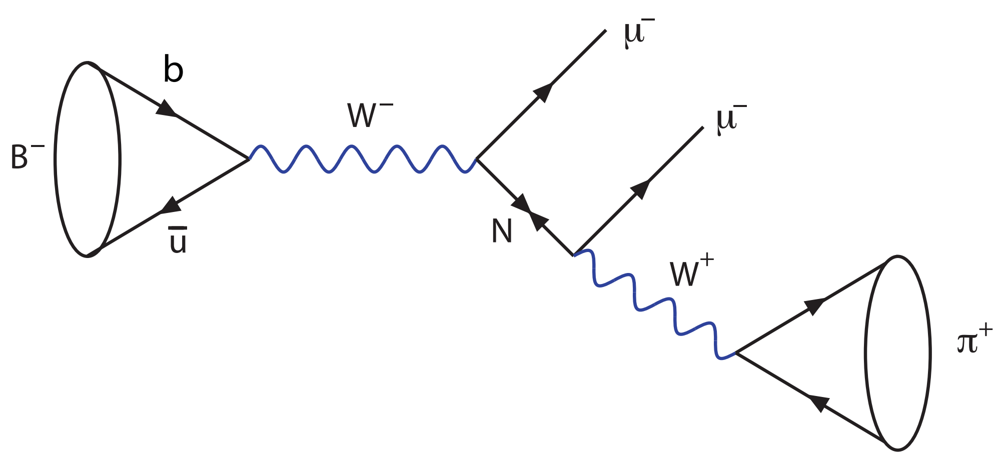


$$BR(B_s^0 \to \mu^\pm\tau^\mp) \simeq 3.6 \cdot 10^{-7} \left(\frac{\tan\beta}{60}\right)^8 \left(\frac{100 GeV}{M_A}\right)^4$$



Mode	BR upper limit
$B^0 \to \mu^\mp e^\pm$	$< 2.8 \times 10^{-9}$ at 90% CL
$B^0 \to \tau^\mp e^\pm$	$< 2.8 \times 10^{-5}$ at 90% CL
$B^0 \to \tau^\mp \mu^\pm$	$< 2.2 \times 10^{-5}$ at 90% CL
$B_s \to \mu^\mp e^\pm$	$< 1.1 \times 10^{-8}$ at 90% CL
$B^+ \to K^+\mu^\mp e^\pm$	$< 9.1 \times 10^{-8}$ at 90% CL
$B^+ \to K^{*+}\mu^\mp e^\pm$	$< 1.4 \times 10^{-6}$ at 90% CL
$B^+ \to K^+\tau^\mp e^\pm$	$< 3.0 \times 10^{-5}$ at 90% CL
$B^+ \to K^+\tau^\mp \mu^\pm$	$< 4.8 \times 10^{-5}$ at 90% CL
$B^+ \to \pi^+\mu^\mp e^\pm$	$< 1.7 \times 10^{-7}$ at 90% CL
$B^+ \to \pi^+\tau^\mp e^\pm$	$< 7.5 \times 10^{-5}$ at 90% CL
$B^+ \to \pi^+\tau^\mp \mu^\pm$	$< 7.2 \times 10^{-5}$ at 90% CL
$B^0 \to K^0\mu^\mp e^\pm$	$< 2.7 \times 10^{-7}$ at 90% CL
$B^0 \to \pi^0\mu^\mp e^\pm$	$< 1.4 \times 10^{-7}$ at 90% CL
$B^0 \to K^{*0}\mu^\mp e^\pm$	$< 5.8 \times 10^{-7}$ at 90% CL

Lepton number violating b hadron decays



Mode	BR upper limit
$B^+ \to \pi^- e^+ e^+$	$< 2.3 \times 10^{-8}$ at 90% CL
$B^+ \to K^- e^+ e^+$	$< 3.0 \times 10^{-8}$ at 90% CL
$B^+ \to \pi^- \mu^+ \mu^+$	$< 4.0 \times 10^{-9}$ at 95% CL
$B^+ \to K^- \mu^+ \mu^+$	$< 4.4 \times 10^{-8}$ at 90% CL
$B^+ \to D^- e^+ e^+$	$< 2.6 \times 10^{-6}$ at 90% CL
$B^+ \to D^- \mu^+ e^+$	$< 1.8 \times 10^{-6}$ at 90 % CL
$B^+ \to D^- \mu^+ \mu^+$	$< 6.9 \times 10^{-7}$ at 95% CL
$B^+ \to D^{*-} \mu^+ \mu^+$	$< 2.4 \times 10^{-6}$ at 95% CL
$B^+ \to D_s^- \mu^+ \mu^+$	$< 5.8 \times 10^{-7}$ at 95% CL

$$\boxed{\begin{aligned}\mathcal{B}(B^- \to \pi^+ \ell^- \ell^-) \quad = \quad & \frac{\tau_B G_F^4 f_B^2 f_\pi^2}{128\pi^2} |V_{ub} V_{ud}^*|^2 |V_{\ell N}|^4 \frac{m_B m_\tau^5}{2\Gamma_\tau} \\ & \times \left(1 - \frac{m_\pi^2}{m_N^2}\right)^2 \left(1 - \frac{m_N^2}{m_B^2}\right)^2 .\end{aligned}}$$

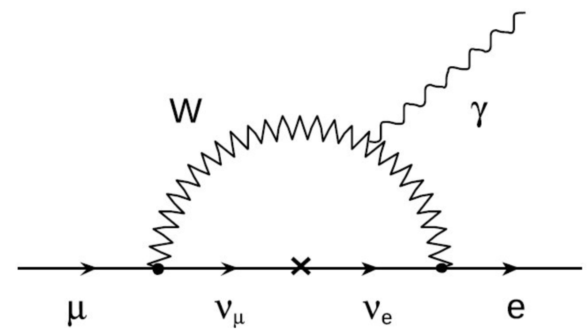
Wang,Si 1407.2468

$$\mathcal{B}(B^- \to \pi^+ \mu^- \mu^-) = 6.5 \times 10^{-10}.$$

Charged lepton flavor violation

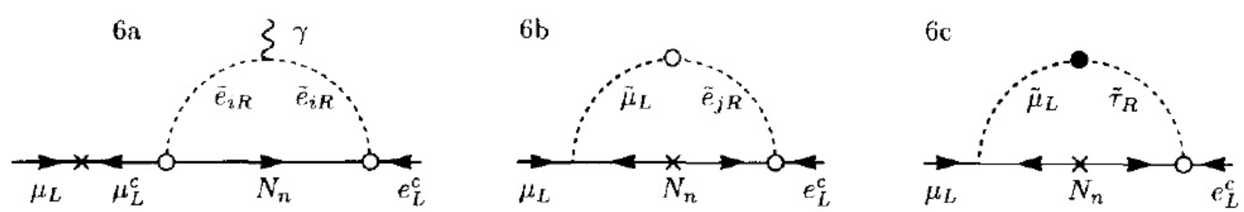
- SM predicted lepton flavor conservation with $m_\nu = 0$

  Given $m_\nu \neq 0$, no reason to impose it as a symmetry

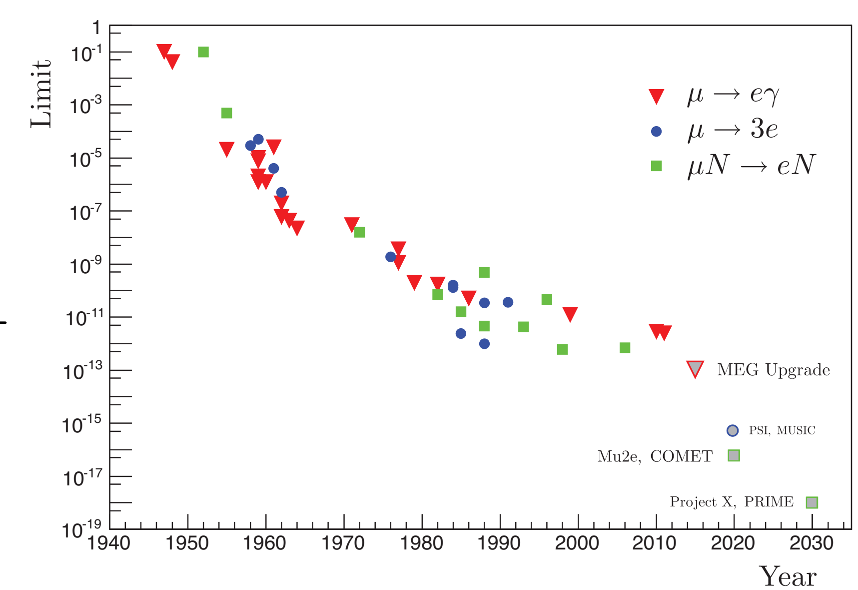


$$\mathcal{B}(\mu \to e\gamma) \sim \alpha \, \frac{m_\nu^4}{m_W^4} \sim 10^{-52}$$

- If new TeV-scale particles carry lepton number (e.g., sleptons), then they have their own mixing matrices $\Rightarrow$ charged lepton flavor violation [Passemar]



History of $\mu \to e\gamma$, $\mu N \to eN$, and $\mu \to 3e$



- Many interesting processes:

$$\mu \to e\gamma, \;\; \mu \to eee, \;\; \mu + N \to e + N^{(\prime)}, \;\; \mu^+ e^- \to \mu^- e^+$$
$$\tau \to \mu\gamma, \;\; \tau \to e\gamma, \;\; \tau \to \mu\mu\mu, \;\; \tau \to eee, \;\; \tau \to \mu\mu e$$
$$\tau \to \mu ee, \; \tau \to \mu\pi, \;\; \tau \to e\pi, \;\; \tau \to \mu K_S, \;\; eN \to \tau N$$

- Next 10–20 years: 10^2–10^5 improvement; any signal would trigger broad program

Charmless Decays

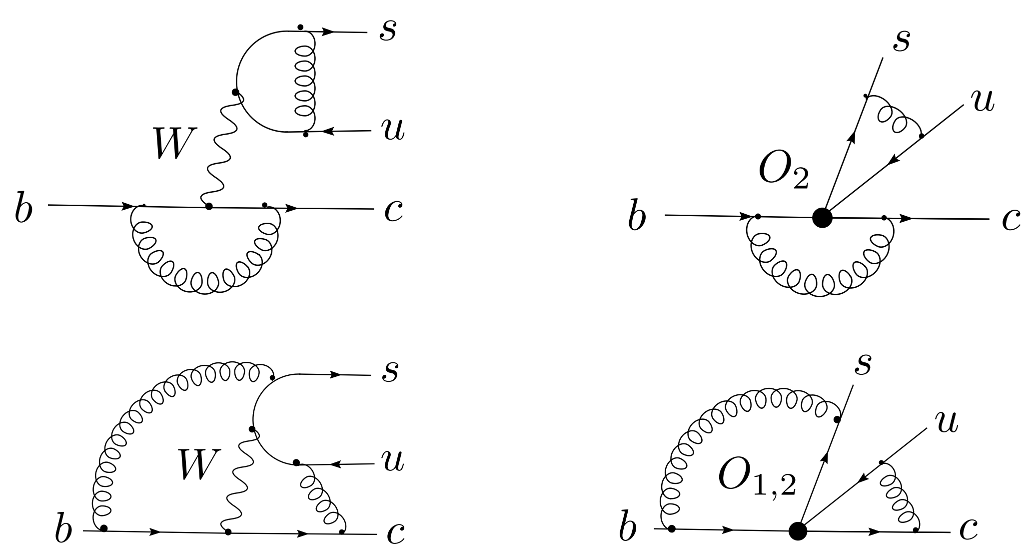
- Separation of short-distance from long-distance contributions (OPE):

$$\boxed{\langle \overline{f}|\mathcal{H}_{\rm eff}|\overline{B}\rangle = \frac{G_{\rm F}}{\sqrt{2}}\sum_j \lambda^j_{\rm CKM}\sum_k C_k(\mu)\,\langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle}$$

[$G_{\rm F}$: Fermi's constant, $\lambda^j_{\rm CKM}$: CKM factors, μ: renormalization scale]

- Short-distance physics: [Buras *et al.*; Martinelli *et al.* ('90s); ...]

$\rightarrow$ Wilson coefficients $C_k(\mu)$ $\rightarrow$ *perturbative* quantities $\rightarrow$ $\boxed{\text{known!}}$

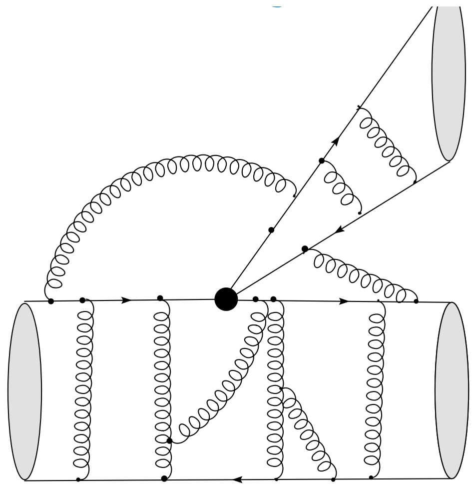


- Long-distance physics:

$\rightarrow$ matrix elements $\langle \overline{f}|Q^j_k(\mu)|\overline{B}\rangle$ $\rightarrow$ *non-perturbative* $\rightarrow$ $\boxed{\text{“unknown”!?}}$

Charmless Decays

$$|A_j|e^{i\delta_j} \propto \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \boxed{\langle \overline{f}|Q_k^j(\mu)|\overline{B}\rangle}$$



- QCD factorization (QCDF):

  Beneke, Buchalla, Neubert & Sachrajda (99–01); Beneke & Jäger (05); ... Bell, Bobeth, ...

- Perturbative Hard-Scattering (PQCD) Approach:

  Li & Yu ('95); Cheng, Li & Yang ('99); Keum, Li & Sanda ('00); ...

- Soft Collinear Effective Theory (SCET):

  Bauer, Pirjol & Stewart (2001); Bauer, Grinstein, Pirjol & Stewart (2003); ...

- QCD sum rules:

  Khodjamirian (2001); Khodjamirian, Mannel & Melic (2003); ...

$\Rightarrow$ $\boxed{\text{Lots of (technical) progress, still a theoretical challenge}}$

Theory Needs

- Form factors:

  - very reliant on light-cone sum rules. Need independent corroboration.

  - expect significant progress in lattice QCD (conceptual and numerical)

  - model-independent constraints from heavy quark expansion;

  - More data needed.

- New observables - to test lepton universality violation, but also to constrain hadronic inputs better from data

- Systematic exploitation of LHC/Belle2/CepC complementarity

- Better (correct?) models of BSM, if anomalies accumulate

CEPC

$$e^+e^- \to b\bar{b}$$

Table 4.1 The $b-$hadron fractions in Z decays are calculated by combining direct rate measurements performed at LEP from HFAG [1]. The B^+ and B^0 mesons are assumed to be produced in equal amount at Z^0 peak, and the sum of the fractions is constrained to unity. The expected numbers of $b-$hadrons are estimated by assuming an instantaneous luminosity of $8 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at Z^0 factory with two-year running at two collision points. For comparison, we also list the number of b-hadrons at the Belle-II with an integrated luminosity of about 50 ab^{-1} at $\Upsilon(4S)$ or $\Upsilon(5S)$ peak. B_c production is neglected; in future studies one includes the latter.

b-hadron species	Fraction in decays of $Z^0 \to b\bar{b}$	Number of b-hadron at Z^0 peak	Fraction in $\Upsilon(4S)/(5S)$ decays	Number of b-hadron at $\Upsilon(4S)/(5S)$
B^0	0.404 ± 0.009	22.0×10^{10}	0.486 ± 0.006 ($\Upsilon(4S)$)	4.9×10^{10}
B^+	0.404 ± 0.009	22.0×10^{10}	0.514 ± 0.006 ($\Upsilon(4S)$)	5.1×10^{10}
B_s	0.103 ± 0.009	5.4×10^{10}	0.201 ± 0.030 ($\Upsilon(5S)$)	0.6×10^{10}
b baryons	0.089 ± 0.015	4.8×10^{10}	–	–

CEPC

$$e^+e^- \to b\bar{b}$$

- At CepC, the produced b quark and anti-b quark are flying in the center of the mass. So, it is easy for us to measuring some time-dependent observables, for example, the time-dependence CP violation of hadronic decays.

- For LHCb, although it has large cross section, the uncertainties are large due to large background.

- In the Belle-II, the energy is not enough for studying the Bs decays.

- For Bc meson, although CDF、D0 and LHCb had collected some data, many results have large uncertainties because of the large background.

- If some new particles are detected , flavor physics @CEPC could help us to identify the characters of them

Conclusions and Outlook

- One of the most interesting puzzles in particle physics is that, on the one hand, new physics is expected in the TeV energy range to solve the hierarchy problem and stabiles the Higgs mass; but on the other hand, no sign of new physics has been detected through precision tests of the electroweak theory or through flavour-changing (or CP-violating) processes in strange, charm or beauty hadron decays.

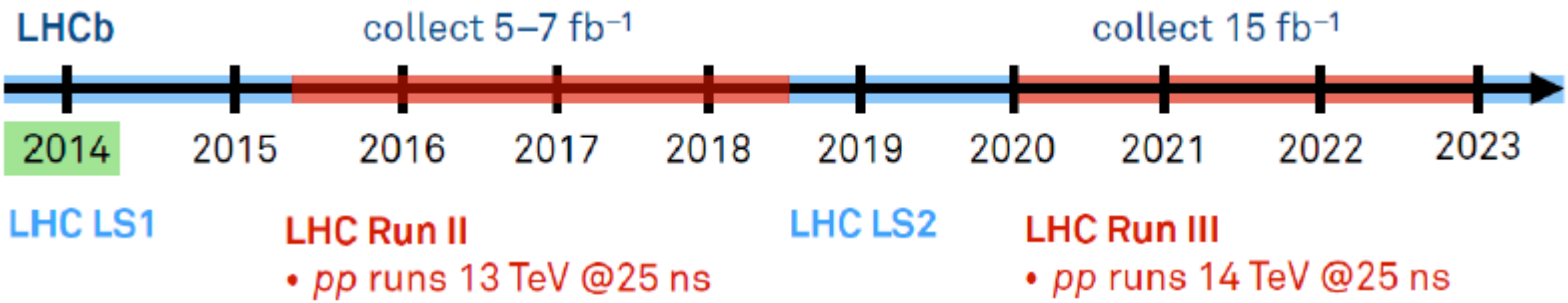
- In my view, flavor physics remains one of the most promising windows to & beyond the TeV scale.

- Many anomalies require better statistics and further measurements. The higher energy colliders (CepC&SppC) will be necessary and able to deliver these measurements, with important interplay/complementarity with Belle2/.

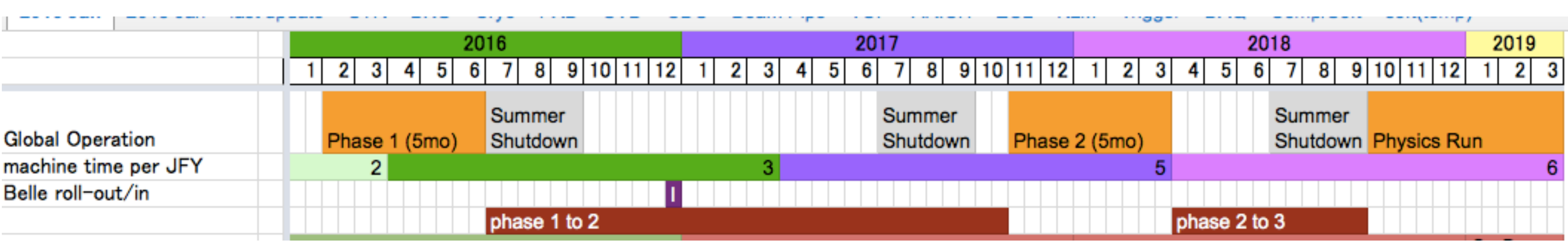
- Numerous models explaining and correlating (and in one case predicting) anomalies exist. Perhaps we are already holding clues to flavor dynamics at relatively low scale?

- Conversely, if nothing is found in LHC, the new colliders will significantly push up the effective scale of flavor violation (via Bs->mu mu, right-handed current probes, and other observables as theory control improves) .

LHCb upgrade timeline



Belle II Schedule (Zoom-in on operations)



Thanks