Heavy Flavor Physics Experiments

Akimasa Ishikawa
(KEK)

LHC and Beyond @Matsue, Japan

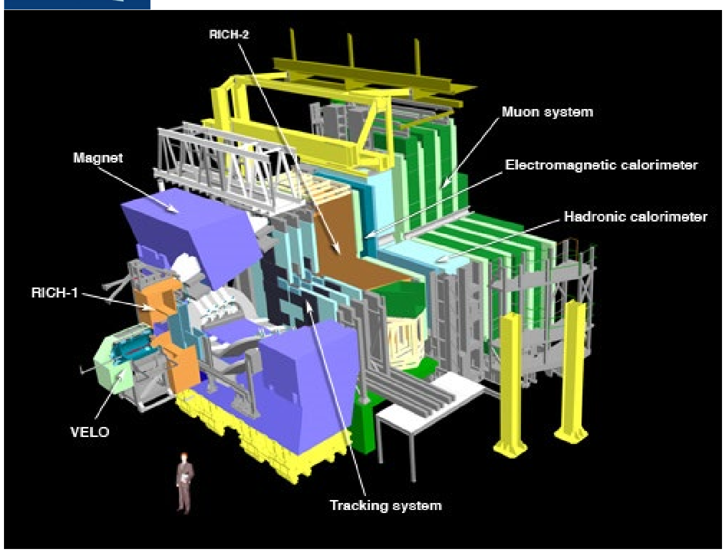
https://unseki.co.jp/blog/archives/2009/06/09235903.php

https://www.sanin-chuo.co.jp/articles/-/4693

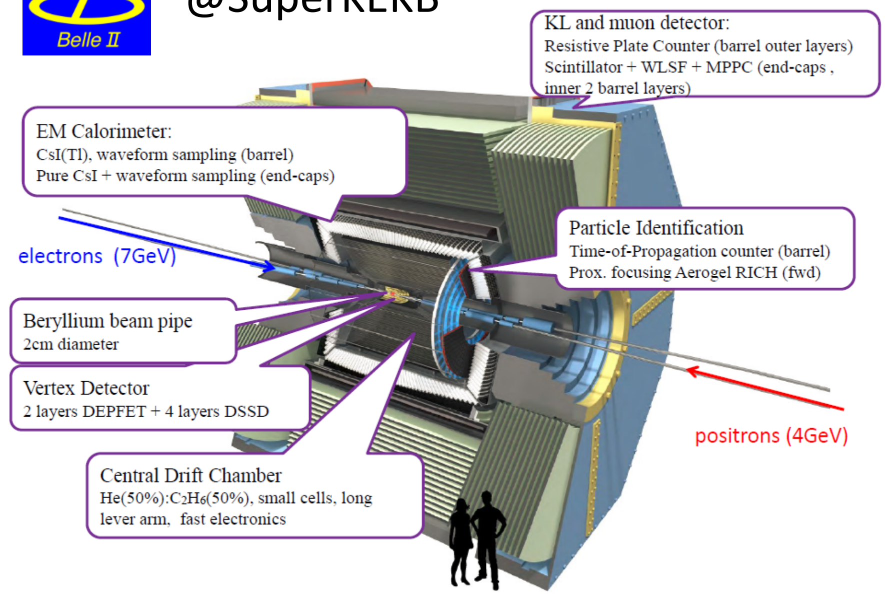
LHC and Beyond

- SuperKEKB is the first collider after LHC
- Hope something beyond the SM will be observed at LHC and SuperKEKB

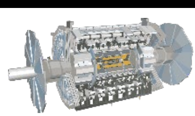
@LHC

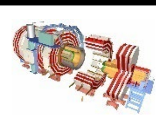


@SuperKEKB



ATLAS





CMS

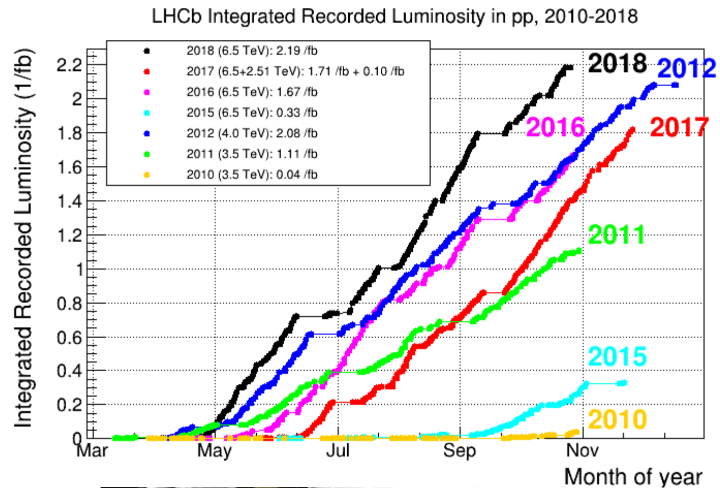
Comparison of LHCb and Belle II

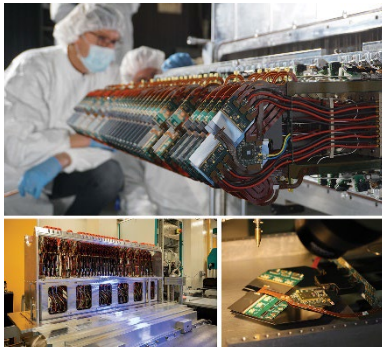
- LHCb and Belle II are competitive and complementary

	LHCb	Belle II
Detector	Forward Spectrometer $2<\eta<5$	4π detector
physics	Focusing on b and c	Focusing on b, c and tau
Signal σ	$\sigma(pp \to bX) \sim 144\mu b$ at 13TeV	$\sigma(ee \to BB) \sim 1.08nb$ at 10.58GeV
BG σ	$\sigma(pp \to X) \sim O(10)mb$	$\sigma(ee \to qq) \sim 3.5nb$
Luminosity	$50fb^{-1}$ by 2029	$50ab^{-1}$ around 2031 (50 x Belle1)
b hadrons	B^0, B^+, Bs, Bc, and B Baryon	B^0 and B^+ (some Bs at Y(5S))
Event	B hadrons associated with many particles	Only two B mesons almost at rest in CM frame while boosted forward in lab frame
Discriminator	Vertex separation (B mesons travel several mm)	4momentum conservation (E_{CM} known) Event shape (spherical BB, isotropic qq)
Efficiency	Lower	Higher : O(1)-O(10)%
Good at	all charged final states	Electron and neutrals : π^0, γ, K_S, K_L, ν, and DM

Status

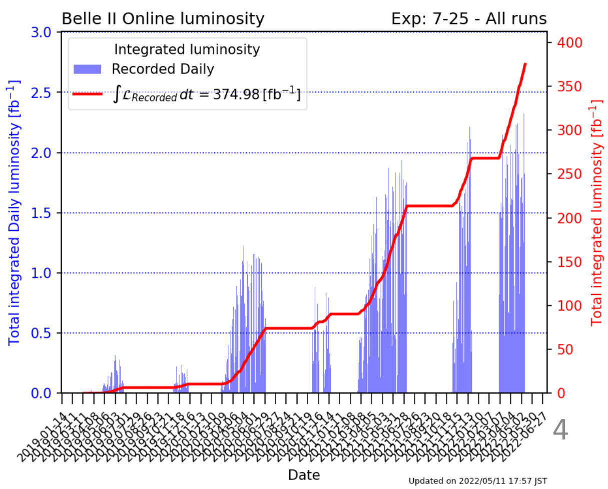
- LHCb
  - Accumulated 9 fb^{-1} so far
  - New VELO detector installed in LS2
  - Resumed the operation in Apr 2022





https://cerncourier.com/a/velos-voyage-into-the-unknown/

- Belle II
  - Accumulated 0.375ab^{-1} so far
  - LS1 from July 2022
    - To install second layer of PXD detector
  - Resume the operation in 2023



Contents

- B Physics
  - Beyond the SM Physics in loop
    - B^0-B^0 mixing and Unitarity Triangle (LHCb, Belle II)
    - $B \rightarrow X_s\gamma$ (Belle II)
  - Beyond the SM Physics Physics in tree
    - $B^+ \rightarrow \tau\nu$, $\mu\nu$ (Belle II)
  - Hint of Beyond the SM Physics in Lepton Flavor Universality??
    - $b \rightarrow c\tau\nu$ (LHCb, Belle II)
    - $b \rightarrow sll$ (LHCb, Belle II)
- τ Physics
  - Beyond the SM Physics in forbidden processes
    - Lepton Flavor Violating τ decays (Belle II)

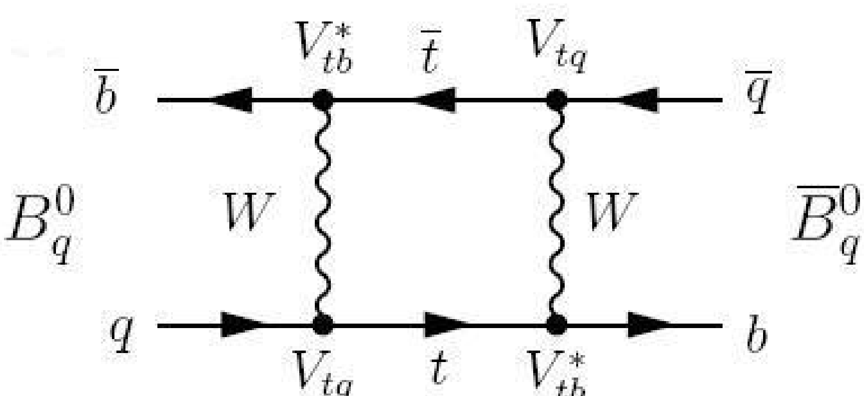
B^0-$\overline{B}^0$ Mixing

- B^0-$\overline{B}^0$ mixing proceeds via loop diagrams with V_{td} and V_{tb} in the SM.
- New particles, such as SUSY particles (gluino-sbottom-sdown) or charged Higgs, can enter in the loop

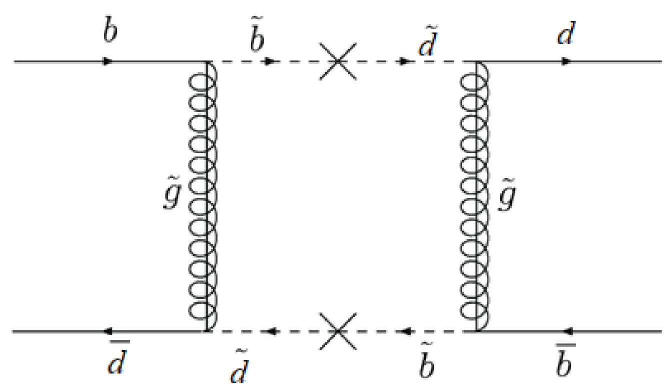
- Two approaches to search for NP in B^0-$\overline{B}^0$ mixing (assuming no NP in tree level processes)
  - Unitarity Triangle
  - NP amplitude and phase (h and σ)

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

Goto, Kitazawa, Okada, and Tanaka, Phys.Rev. D53 (1996) 6662-6665



SM



SUSY

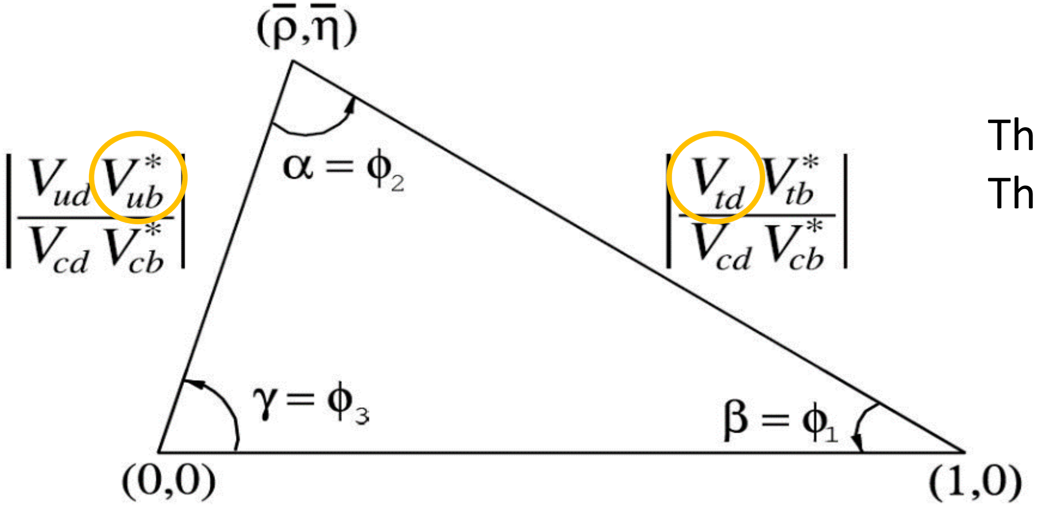
CKM matrix and Unitarity Triangle

λ=0.22

$$V_{\mathrm{CKM}} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Wolfenstein parameterization

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

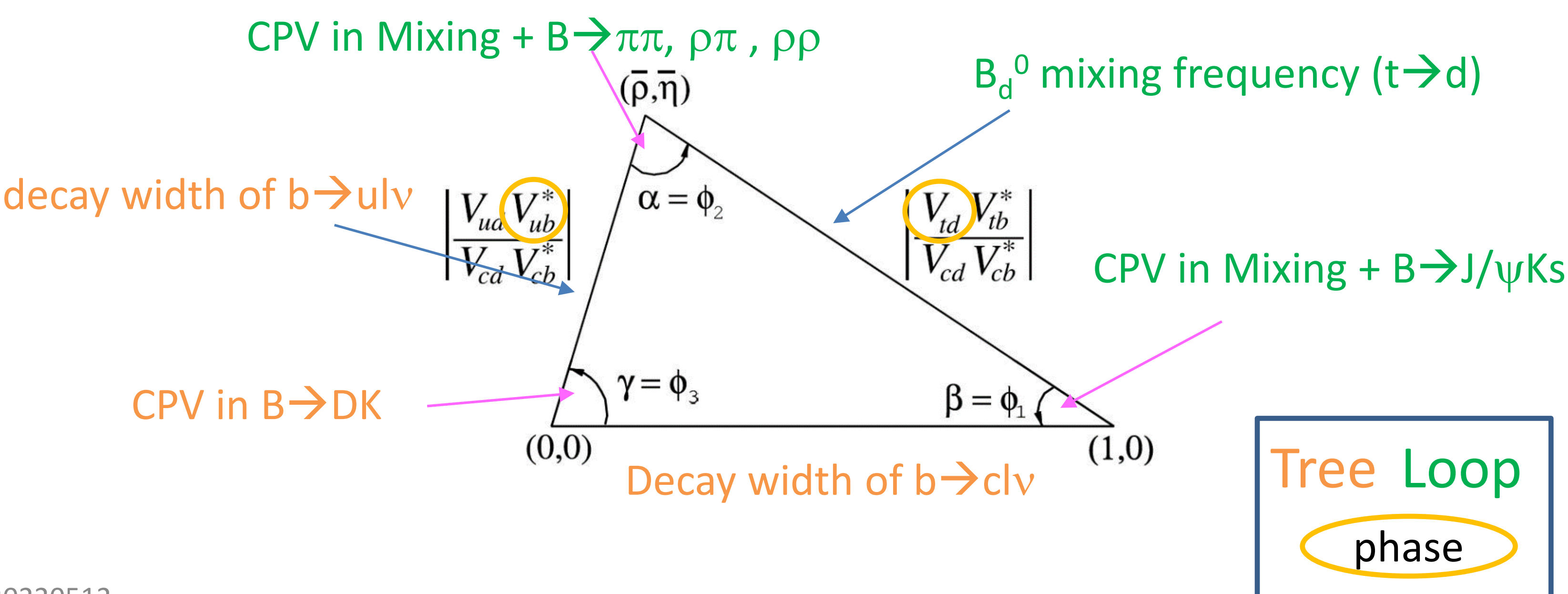


Three angles are O(1)rad

Three sides are O(λ^3)

Unitarity Triangles : Tree VS Loop

- We can measure six observables
  - three angles (CPV) and three sides (|amplitude|).
- Can make two triangles from the measurements
  - tree measurements ($|V_{cb}|$, $|V_{ub}|$, ϕ_3)
  - mixing measurements ($|V_{td}|$, ϕ_1, ϕ_2)
- If not consistent, it is **clear NP signal !**

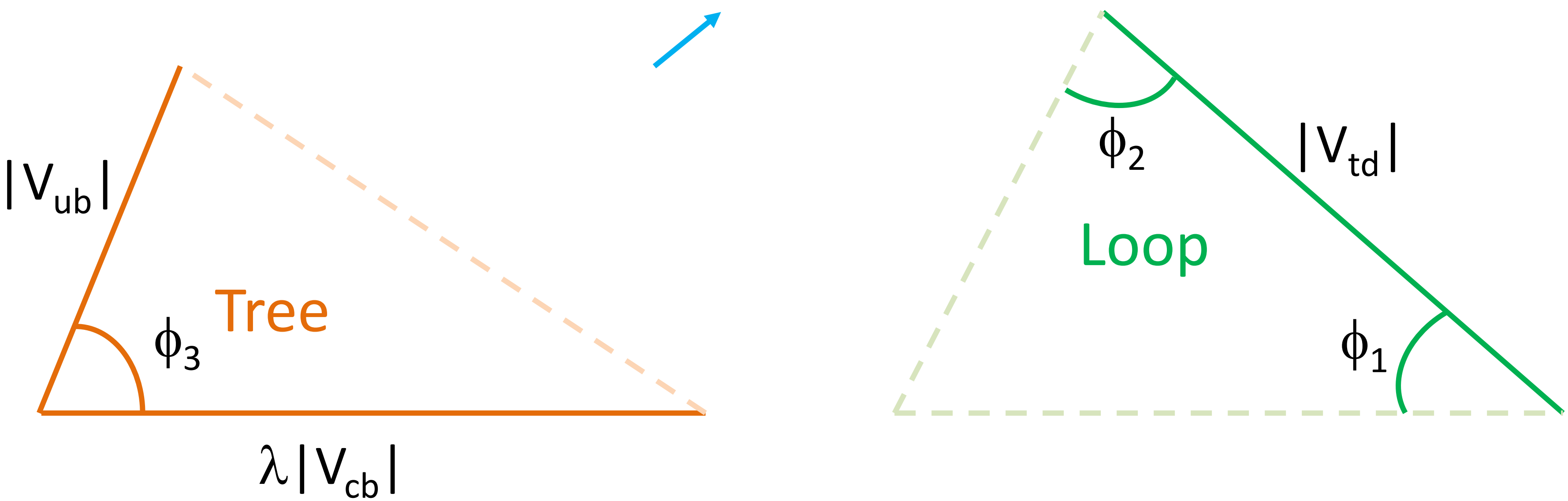


$$\overline{\rho} = \rho(1 - \lambda^2/2), \quad \overline{\eta} = \eta(1 - \lambda^2/2)$$

Consistency btw Two Triangles

NP contribution in B^0 mixing can be measured (assuming no NP in tree).
Both real and imaginary parts (h and σ) can be determined

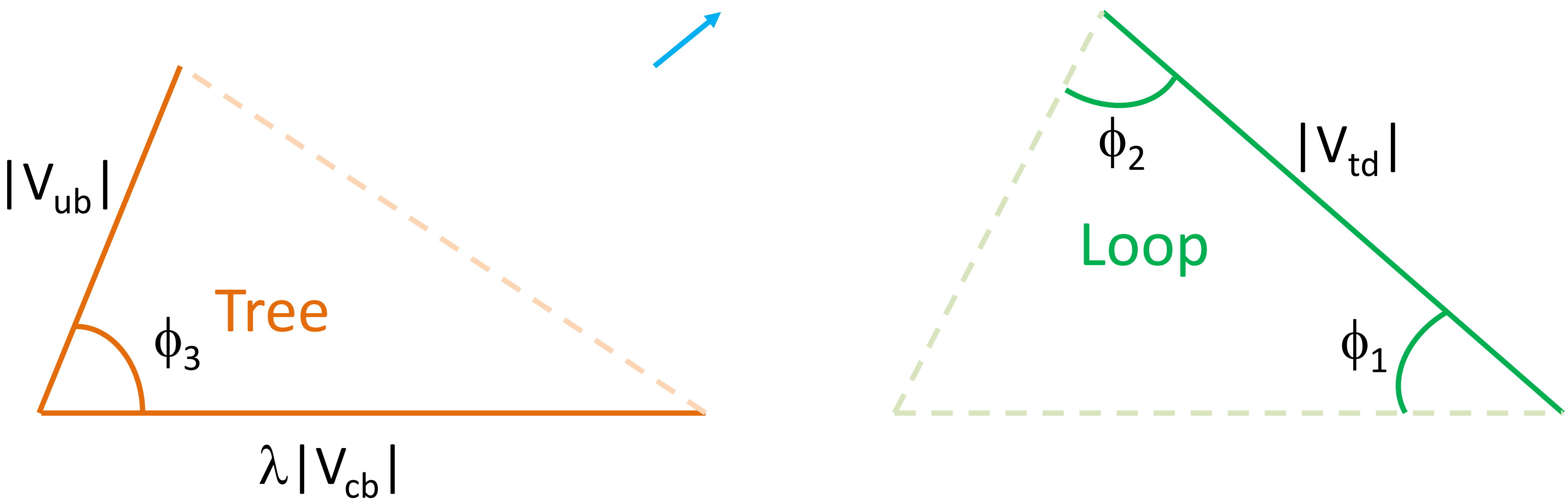
$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$



Consistency btw Two Triangles

NP contribution in B^0 mixing can be measured (assuming no NP in tree). Both real and imaginary parts (h and σ) can be determined

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$



Precisions of the Angles and Sides

- Ultimate precisions except for ϕ_3
- Precision will be limited by theory or lattice QCD except for ϕ_3
  - Uncertainties of the angles ~1deg
  - Uncertainties of the sides ~1%
  - We experimentalists should reduce QCD uncertainties together with theorists

Including theory and LQCD uncertainties

	Precisions	Belle 0.7ab^{-1}	LHCb 23fb^{-1} (2025)	Belle II 50ab^{-1} (2031)
angles	ϕ_1 [deg]	1.1	0.45	0.20
	ϕ_2 [deg]	5	---	0.6
	ϕ_3 [deg]	13	1.4	1.5
sides	$\|V_{cb}\|$ [%]	1.8	See below	1.2
	$\|V_{ub}\|$ [%]	3.9	3 (only ratio $\|V_{ub}\|/\|V_{cb}\|$)	1.2

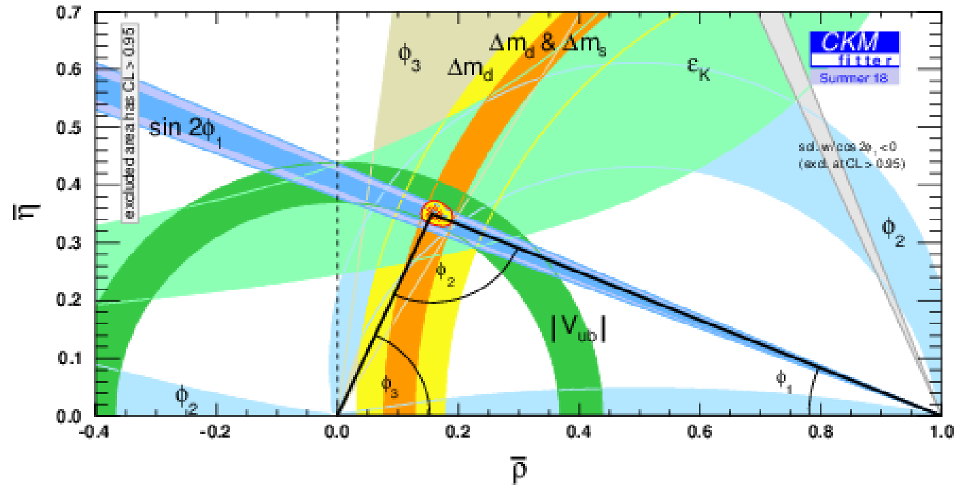
$|V_{td}|$ is already lattice QCD dominant

Theoretical uncertainties not included in ϕ_1 and ϕ_2

UT Before/After Belle II

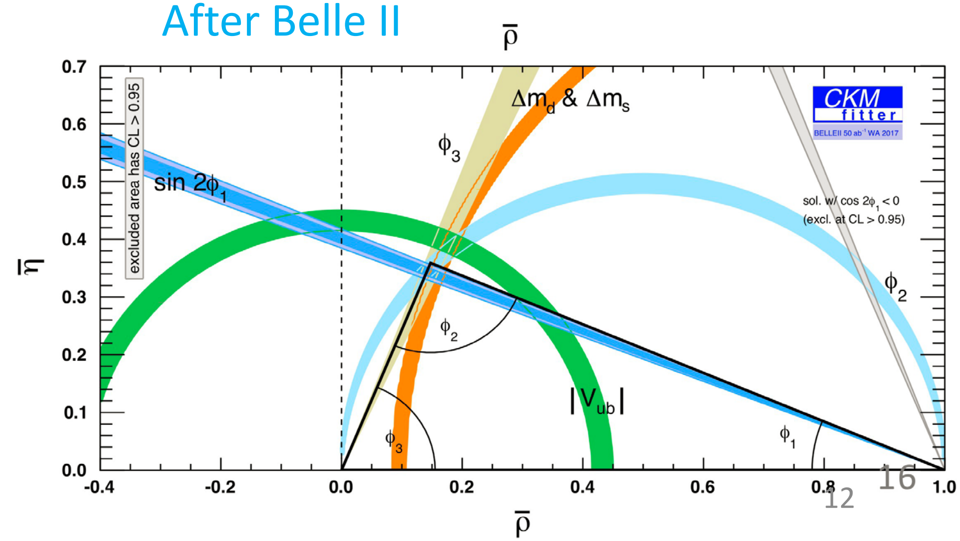
- Still uncertainties are large to conclude

Before Belle II



- Extrapolating 2013 WA values, we see clear deviation of some observables

After Belle II



NP Interpretations

- UT measurements → *h* and σ

$$M_{12}^{d,s} = (M_{12}^{d,s})_{\rm SM} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

- With an EFT analysis, 2000TeV (200TeV) NP scale in tree (loop) is accessible

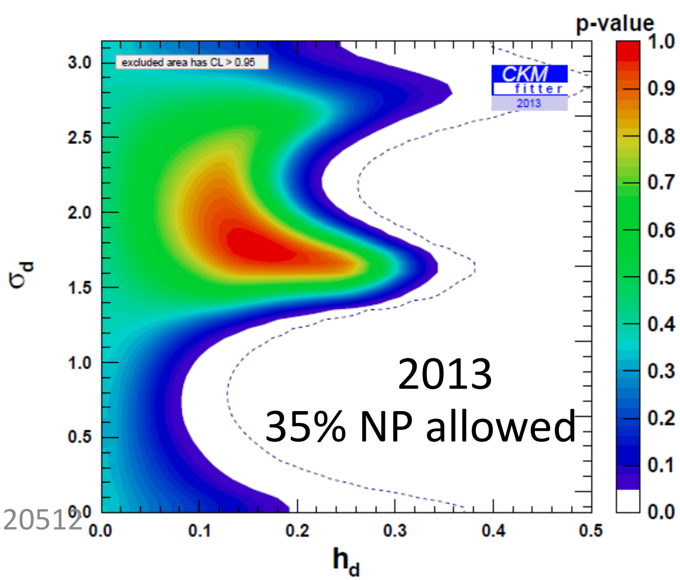
$$L = \frac{C_{ij}^2}{\Lambda^2} (\bar{q}_{i,L}\gamma^\mu q_{j,L})^2$$

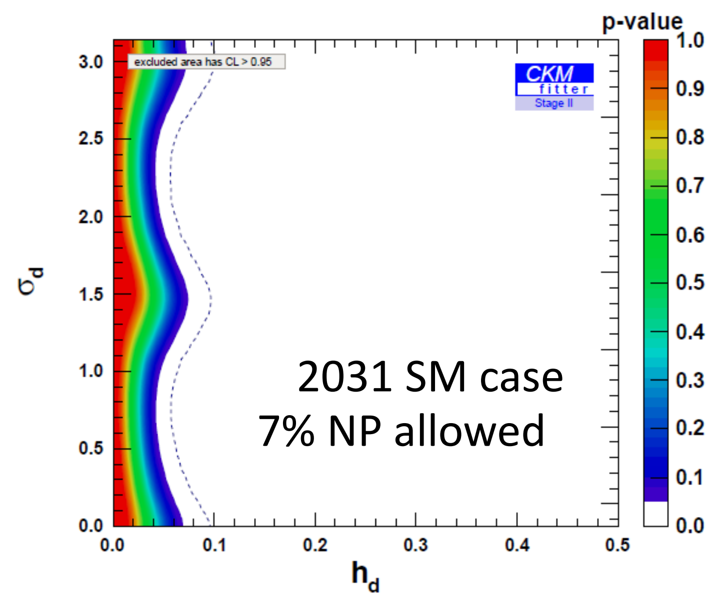
- With SUSY, ~10 TeV scale can be exploited

Tanimoto and Yamamoto 2014, 2015

arXiv:1309.2293

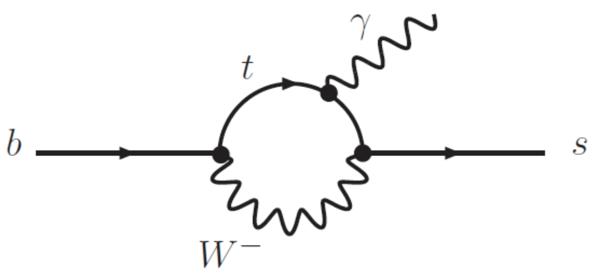
Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$ (CKM-like)	tree level	17	19
	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	2×10^3	5×10^2
	one loop	2×10^2	40



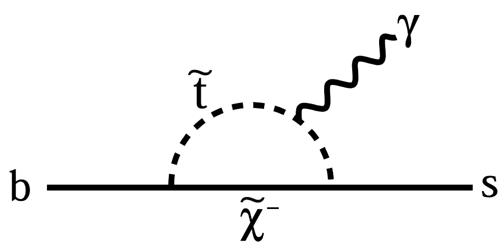


$B \rightarrow X_s \gamma$

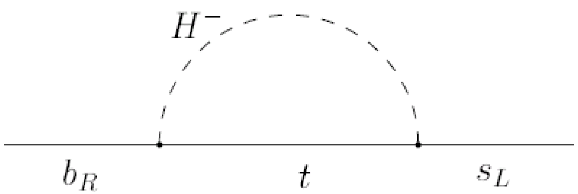
- At LHCb, exclusive $B \rightarrow K^*\gamma$ or $K\pi\pi\gamma$ decays can be reconstructed.
- At Belle II, both Inclusive and exclusive $b \rightarrow s\gamma$ can be measured.
- Inclusive $b \rightarrow s\gamma$ has smaller theoretical uncertainty



SM



SUSY

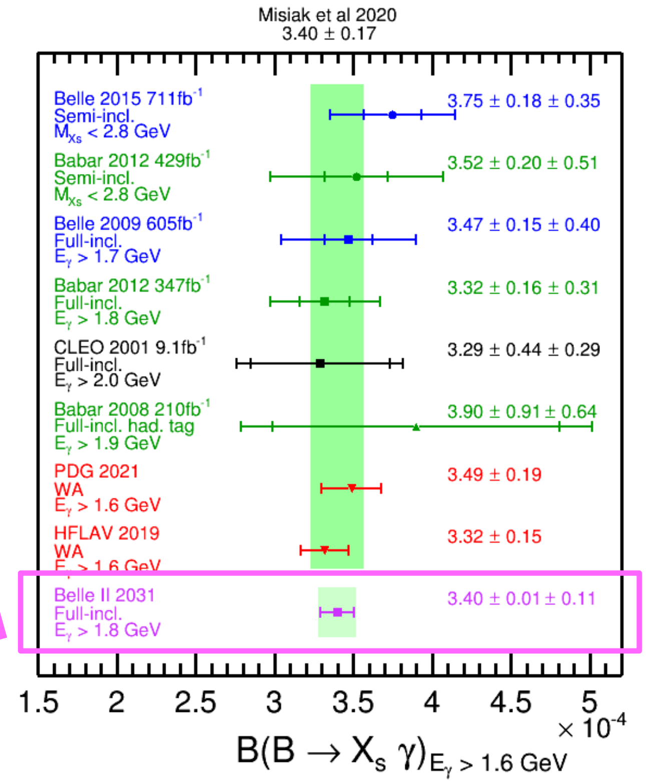


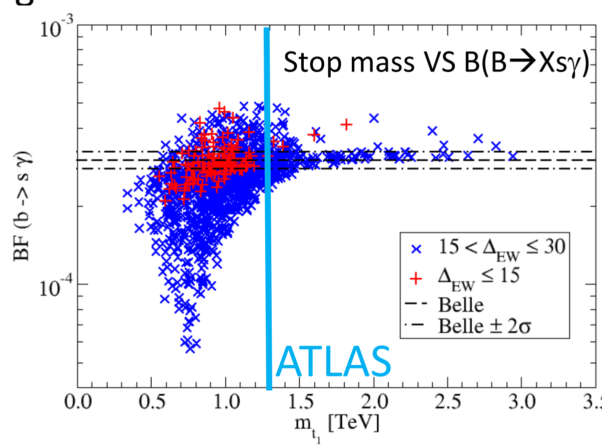
2HDM

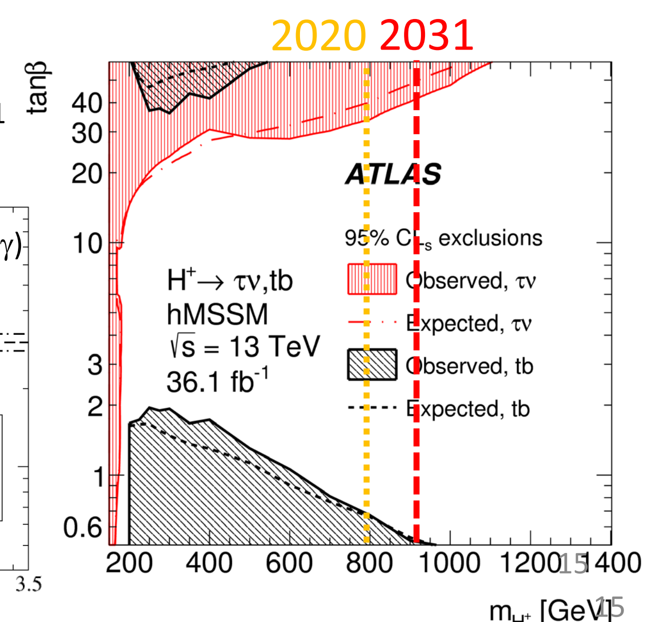
BF($B \to X_s\gamma$)

- Current situation M. Misiak et al, 2002.01548
  - Exp and thory in good agreement
  - Exp ~5% Thoery ~5%
- Belle II
  - With large data, can reduce the uncertainty to ~3%
- Theory
  - Uncertainty reducible to ~3.5% in 2025 Private communication with M.Misiak
- Constraints on NP
  - H^+ in 2HDM type-II : M_H >900GeV AI private estimation
  - Stop in Natural SUSY Baer, Bager, Nagata and Savoy 1611.08511
  - SUSY with large L-R mixing

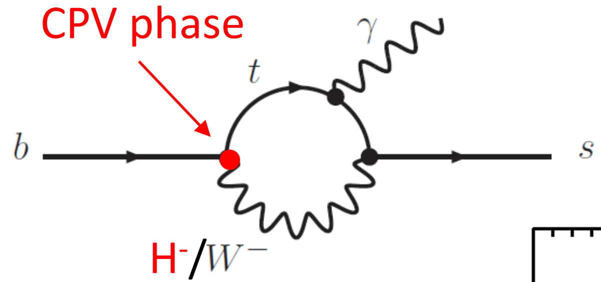
Eberl, Hidaka, Ginina, and AI 2106.15228

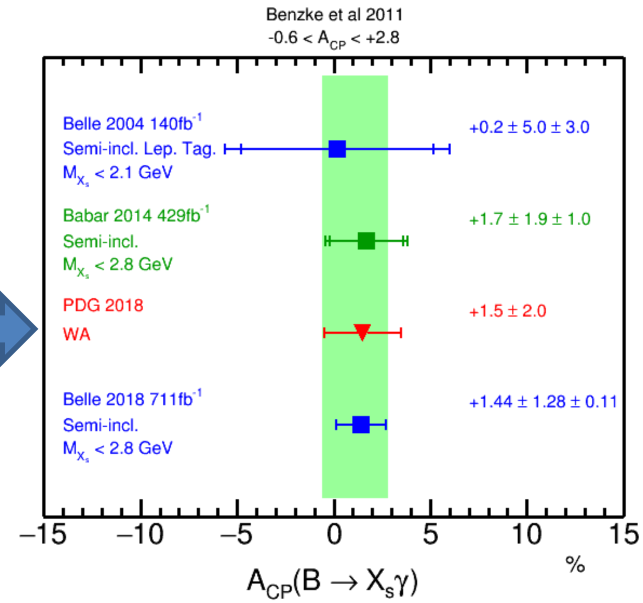






$\Delta A_{CP}(B \to X_s\gamma)$





- $A_{CP}(B \to X_s\gamma)$ is sensitive to CPV in NP but theoretical uncertainty already dominant

$$A_{CP} = \frac{\Gamma(\bar{B} \to \bar{X}_s\gamma) - \Gamma(B \to X_s\gamma)}{\Gamma(\bar{B} \to \bar{X}_s\gamma) + \Gamma(B \to X_s\gamma)}$$

- New observable ΔA_{CP} is null in SM and sensitive to NP

$$\begin{aligned}\Delta A_{CP} &= A_{CP}(B^+ \to X_s^+\gamma) - A_{CP}(B^0 \to X_s^0\gamma) \\ &= 4\pi^2\alpha_s \frac{\tilde{\Lambda}_{78}}{m_b}\text{Im}\left(\frac{C_8}{C_7}\right), \\ &\approx 0.12\left(\frac{\tilde{\Lambda}_{78}}{100\text{ MeV}}\right)\text{Im}\left(\frac{C_8}{C_7}\right),\end{aligned}$$

c.f. $C_{7,8}$ are real in SM while NP has O(1) phase

M. Benzke, S. J. Lee, M. Neubert, G. Paz, JHEP 08 (2010) 099

  - Ex. SUSY with flavor violating trilinear couplings

M. Endo, T. Goto, T. Kitahara, S. Mishima, D. Ueda and K. Yamamoto, JHEP 04 (2018) 019.

- Belle measured the observable in 2018
  - Found dominant syst error can be reducible → Belle II further improve the measurement

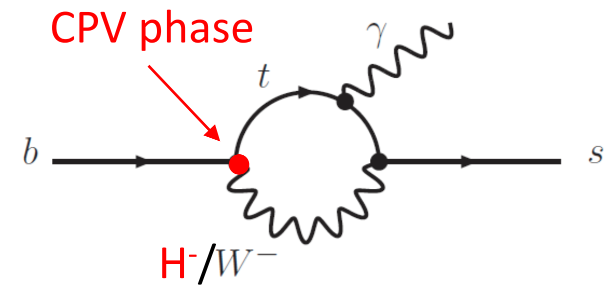
$$\Delta A_{CP} = [+3.69 \pm 2.65(\text{stat.}) \pm 0.76(\text{syst.})]\%$$

Watanuki, Ishikawa et al, PRD 99, 032012 (2019)

Observables	Belle $0.71\,\text{ab}^{-1}$	Belle II $5\,\text{ab}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$\Delta A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.7%	0.98%	0.30%

Belle II Physics book 1808.10567

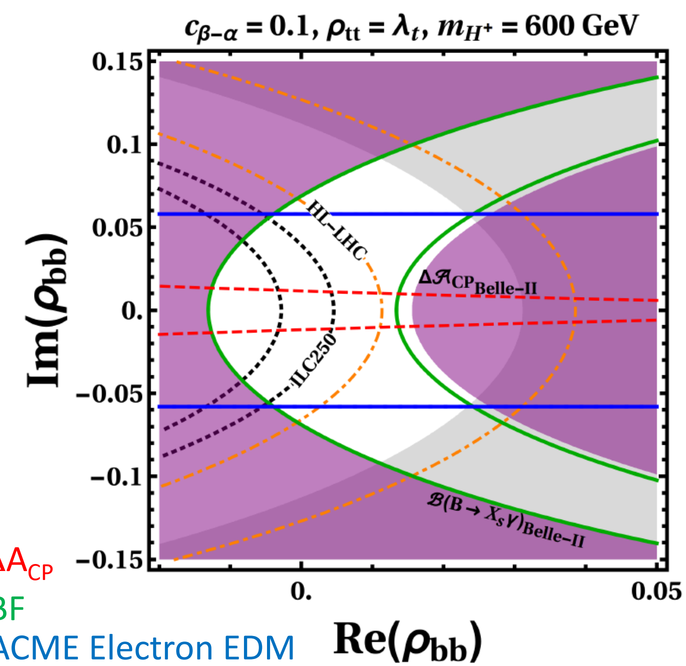
ΔA_{CP}(B→Xsγ) and EW Baryogensis



- Additional Yukawa coupling ρ appears in general 2HDM (no Z_2 symmetry)

$$y^f_{hij} = \frac{\lambda^f_i}{\sqrt{2}}\delta_{ij} s_{\beta-\alpha} + \frac{\rho^f_{ij}}{\sqrt{2}} c_{\beta-\alpha},$$
$$y^f_{Hij} = \frac{\lambda^f_i}{\sqrt{2}}\delta_{ij} c_{\beta-\alpha} - \frac{\rho^f_{ij}}{\sqrt{2}} s_{\beta-\alpha},$$
$$y^f_{Aij} = \mp\frac{i\rho^f_{ij}}{\sqrt{2}},$$

- If ρ has complex phase, this could generate CPV and thus EW Baryogensis is possible
- ΔA_{CP} is sensitive to phase in ρ
- Combining H→bb coupling measurements at HL-LHC/ILC, additional bottom Yukawa and phase can be searched
  - If found it→ Higgs self coupling measurments at ILC550



ΔA_{CP}
BF
ACME Electron EDM
HL-LHC H→bb coupling
ILC H→bb coupling

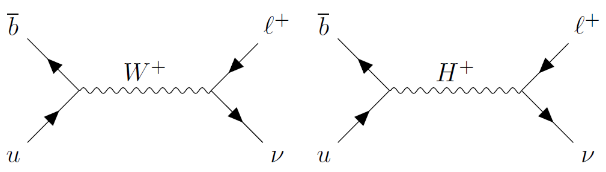
$B^+ \rightarrow \tau^+ \nu$

- Helicity suppressed decays

B→τν,μν in SM and 2HDM

- BF(B→τν) in SM
  - Helicity suppression : Amp ∝ m_τ

$$\mathcal{B}(B \to \ell\nu) = \frac{G_F^2 m_B}{8\pi} m_\ell^2 (1 - \frac{m_\ell^2}{m_B^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

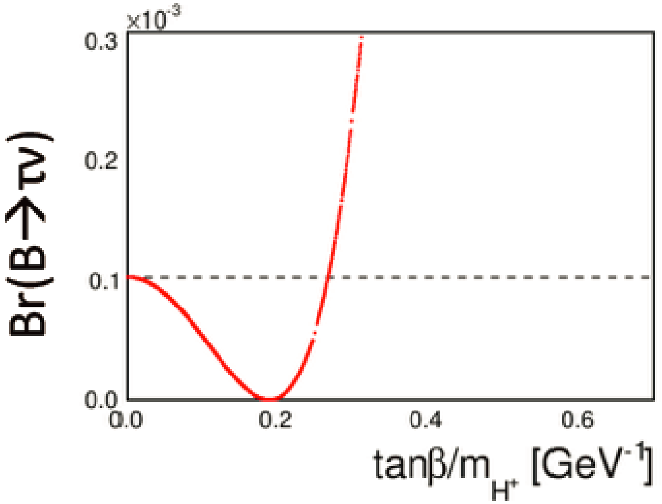


- BF(B→τν) in 2HDM type-II
  - No helicity suppression with Higgs exchange
  - Higgs coupling ∝ m_τ

$$\mathcal{B}(B \to \tau\nu) = \mathcal{B}(B \to \tau\nu)_{\text{SM}} \times r_H$$

$$r_H = (1 - \frac{m_B^2}{m_H^2} \tan^2\beta)^2$$

  - BF only dependent on r_H (function of $\tan\beta/m_H$)

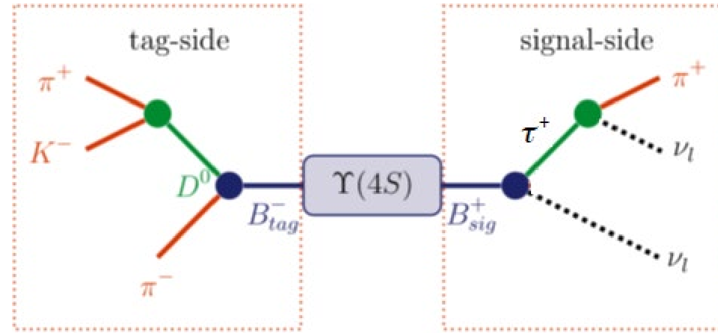


- The same can be applied to B→μν
  - LFU (or 2HDM type-II) can be tested with a ratio of BFs

$$R_{\text{pl}} = \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)}$$

$$= \frac{m_\tau^2}{m_\mu^2} \frac{(1 - m_\tau^2/m_B^2)^2}{(1 - m_\mu^2/m_B^2)^2} \left|1 + r_{\text{NP}}^\tau\right|^2 \simeq 222.37 \left|1 + r_{\text{NP}}^\tau\right|^2 .$$

BF(B→τν)



- Since two neutrinos are in the final states, the other B meson should be tagged.
- The tagging efficiency improved twice from Belle

Improvement of Algorithm

Improvement of Detector and Increase of Background effects

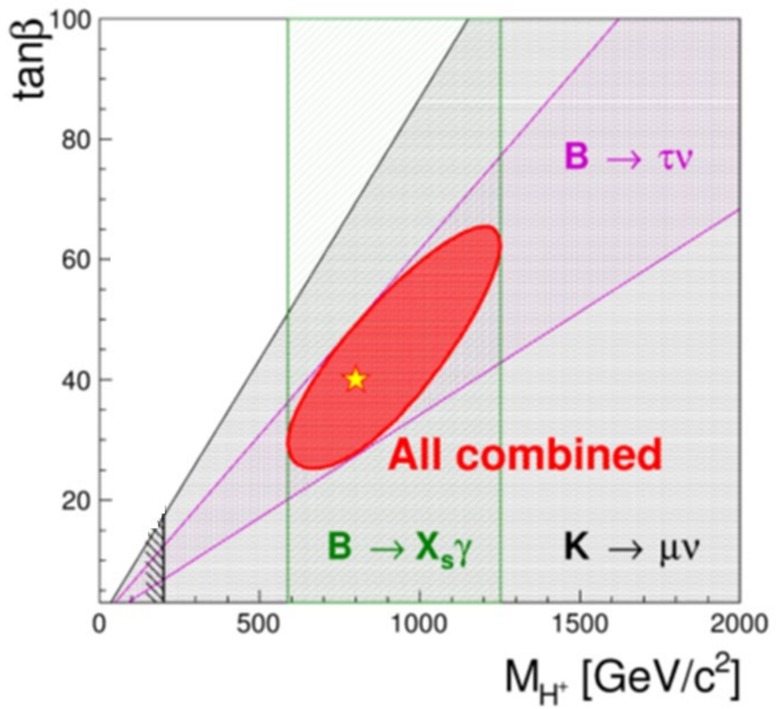
Tag	FR[4] @ Belle	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %

- Precision of BF(B→τν) at Belle II

	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29	13	4
	systematic uncertainty (%)	13	7	5
	total uncertainty (%)	32	15	6
semileptonic tag	statistical uncertainty (%)	19	8	3
	systematic uncertainty (%)	18	9	5
	total uncertainty (%)	26	12	5

A Scenario of Evidence for Charged Higgs

- $B \rightarrow X_s\gamma$: $\tan\beta$ independent
- $B \rightarrow \tau\nu$: $\tan\beta/m_H$ = const.
- With 50/ab, M_{H+}=800GeV and $\tan\beta$=40 can be found.

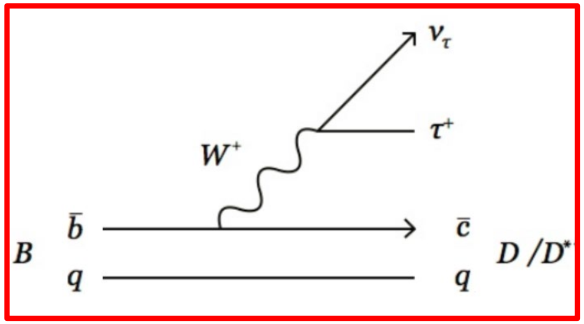


Belle II Physics book 1808.10567

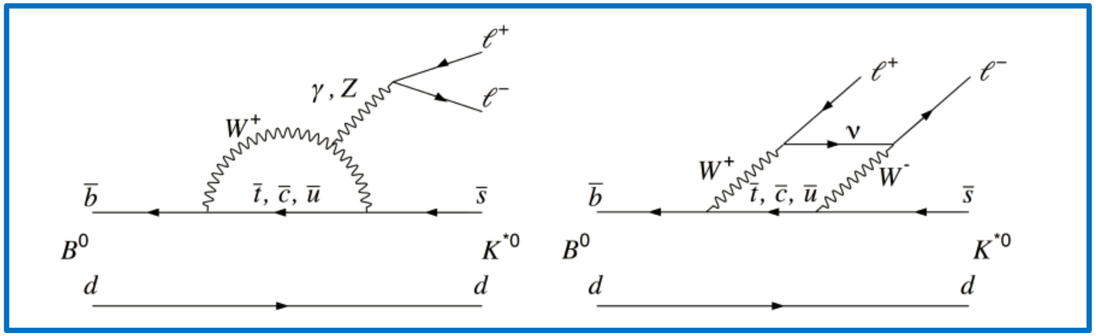
Lepton Flavor Universality in B decays

- Recently, two hints of LFU Violation are found in $b \rightarrow c\tau\nu$ and $b \rightarrow sl^+l^-$
  - Anomaly in $b \rightarrow c\tau\nu$ by LHCb, Babar and Belle.
  - Anomaly in $b \rightarrow sl^+l^-$ by LHCb

$b \rightarrow c\tau\nu$



$b \rightarrow sl^+l^-$



Tree
BF~O(10^{-2})

Loop
BF~O(10^{-6})

LFUV in B decays

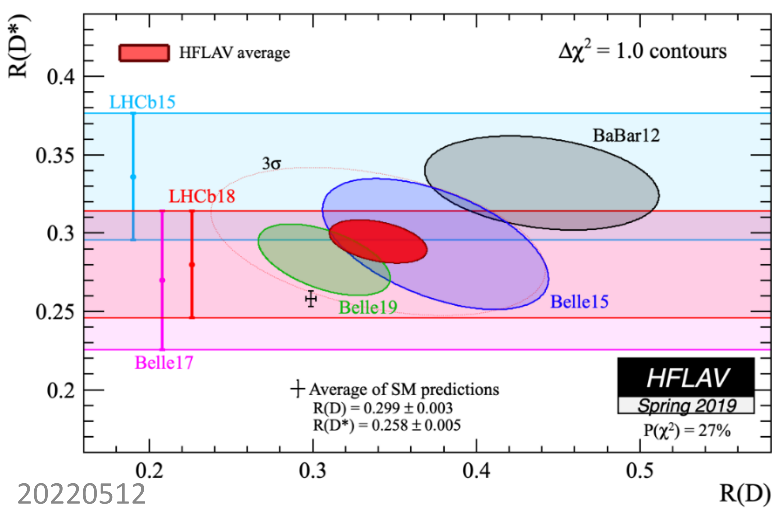
- Recently, two hints of LFU Violation are found in $b \to c\tau\nu$ and $b \to s l^+ l^-$
  - Anomaly in $b \to c\tau\nu$ by LHCb, Babar and Belle. ~4σ
  - Anomaly in $b \to s l^+ l^-$ by LHCb　　Naïve combination of R_K and R_{K*} ~4.5σ

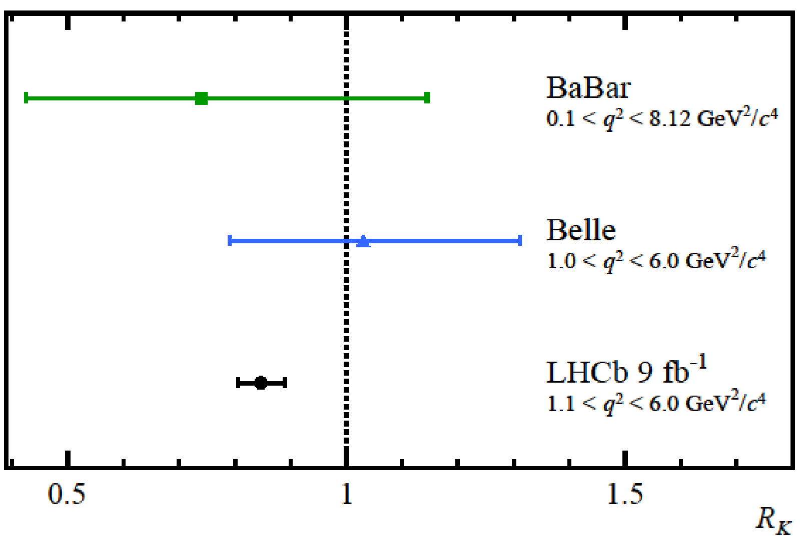
$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}_{l=e,\mu}$$

$$R_H = \frac{\mathcal{B}(B \to H\mu^+\mu^-)}{\mathcal{B}(B \to He^+e^-)}$$

$$H = K, K^*, X_s, \ldots$$

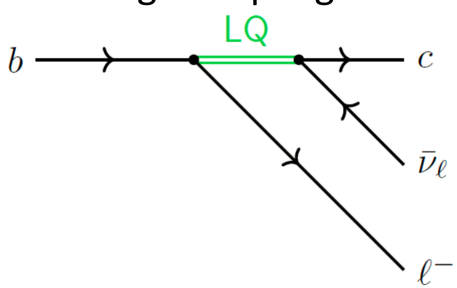
~15% deviations!



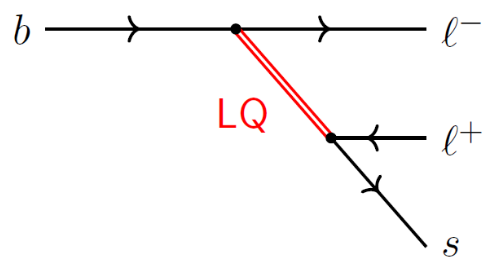


LFUV in B decays

- Recently, two hints of LFU Violation are found in $b \to c\tau\nu$ and $b \to s l^+ l^-$
  - Anomaly in $b \to c\tau\nu$ by LHCb, Babar and Belle. $\sim 4\sigma$
  - Anomaly in $b \to s l^+ l^-$ by LHCb Naïve combination of R_K and R_{K^*} $\sim 4.5\sigma$
- Leptoquark and flavorful W'/Z' models can explain the deviation
  - TeV scale LQ
  - Gauge coupling unification possible with two leptoquarks



NP in vector current



NP in V or (V-A) currents
C_9 or $(C_9$-$C_{10})$

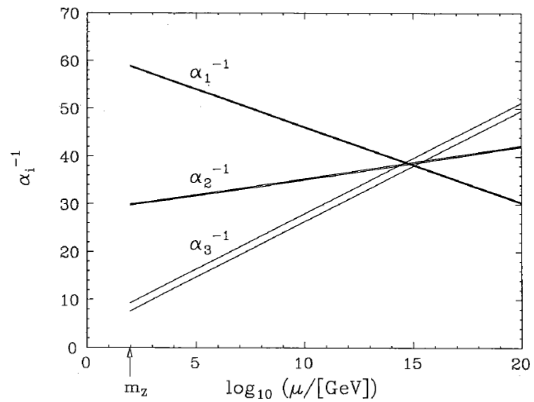


Fig. 1

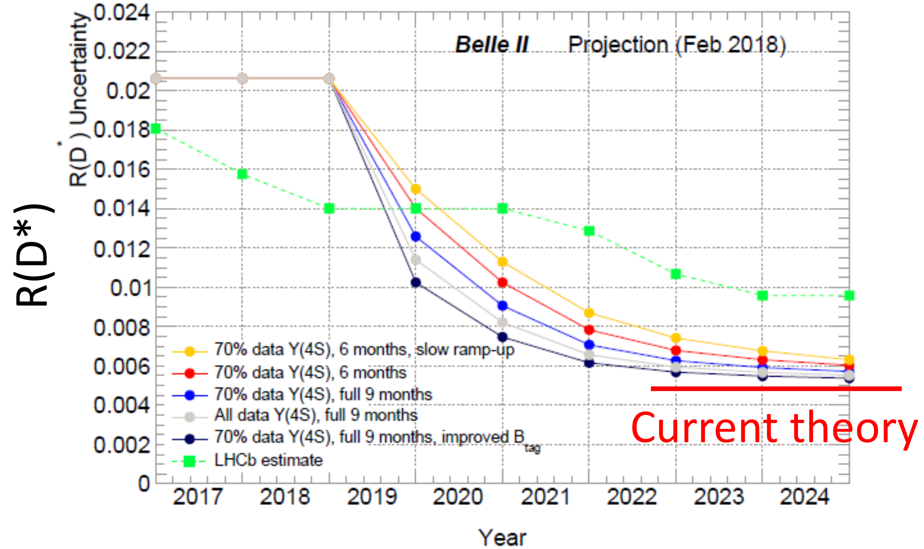
H. Murayama and T. Yanagida, Mod.Phys.Lett.A 7 (1992) 147-152.
9109149.pdf

- Belle II has better sensitivities to R(D), R(D*) and the polarizations
  - LHCb can test the LFU with B_c and Λ_b
- LHCb has better sensitivities to R_K and R_{K^*}
  - Belle II can test the LFU with the inclusive B→Xsl+l- and angular observables

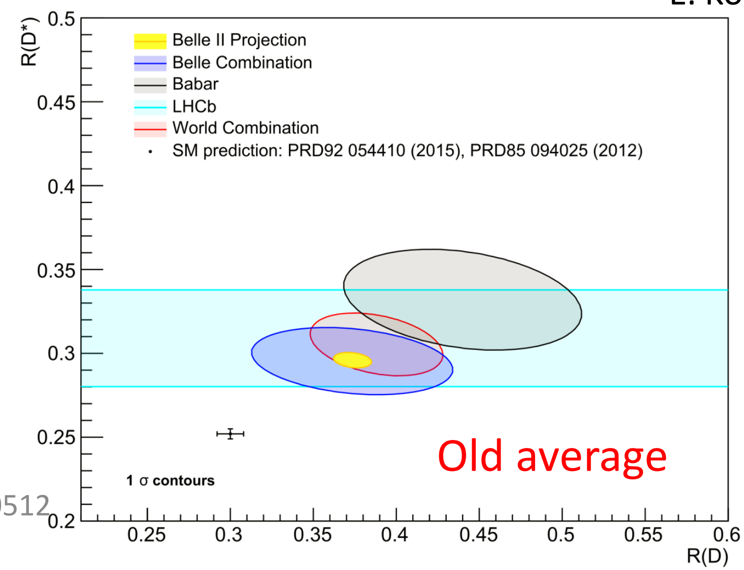
Future Prospects on $R(D^{(*)})$ at Belle II

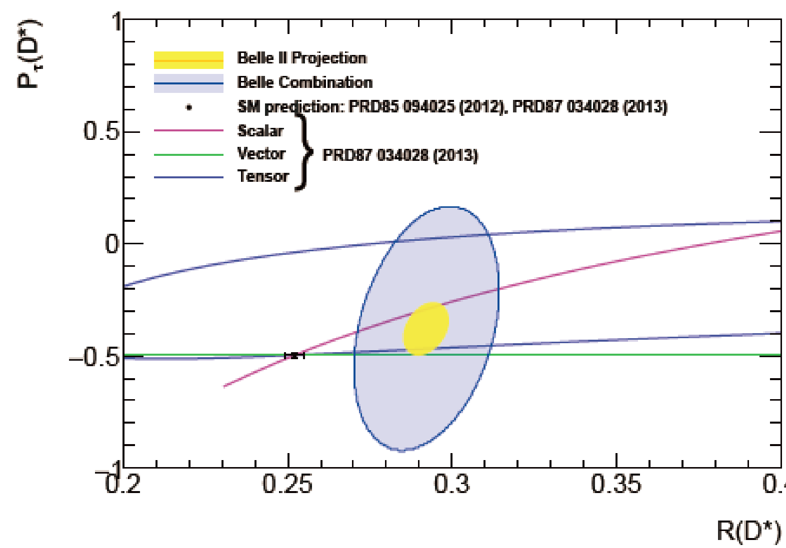
- At least two neutrinos in the final states
  - → tagging needed
- Tagging efficiency improved by factor 2
- We could observe 5σ deviation of R(D) VS R(D*) with 5ab^{-1} in 2026 if central value unchanged
  - After that LHCb will confirm with R(D*)
- Then, model discrimination with polarization measurements

2year delay, Blue one is nominal scenario



E. Kou et al. 1808.10567





Prospects of R_K and R_{K*} at LHCb

- Current LHCb measurements

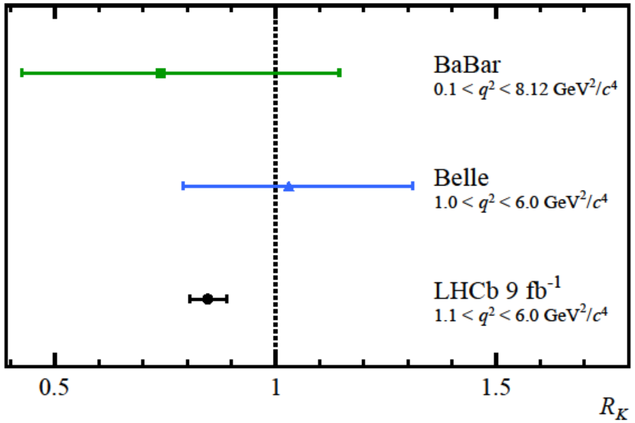
$$R_{K^*}(0.045 < q^2 < 1.1\,\mathrm{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$$ at low q^2: $2.1\text{-}2.3\,\sigma$

$$R_{K^*}(1.1 < q^2 < 6.0\,\mathrm{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$$ at central q^2: $2.4\text{-}2.5\,\sigma$

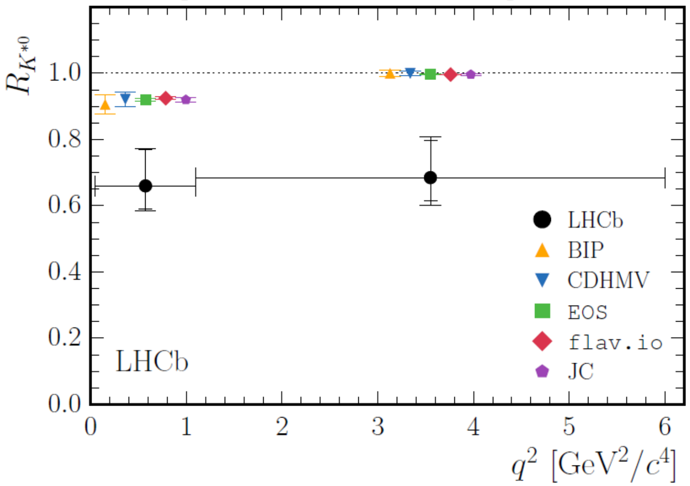
$$R_K(1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4) = 0.846\,^{+0.042}_{-0.039}\,^{+0.013}_{-0.012}$$ at central q^2: $3.1\,\sigma$

- Assuming above values, LHCb will observe 5σ deviation of
  - R_{K*} with 13fb^{-1} in 2023
  - R_K with 23fb^{-1} in 2025
- Then Belle II will confirm
  - R_{K*} with 20ab^{-1} in 2028
  - R_{Xs} with 30ab^{-1} in 2029
  - R_K with 50ab^{-1} in 2031
- And then LFU in angular observables

2021 R_K w/ 9fb^{-1}

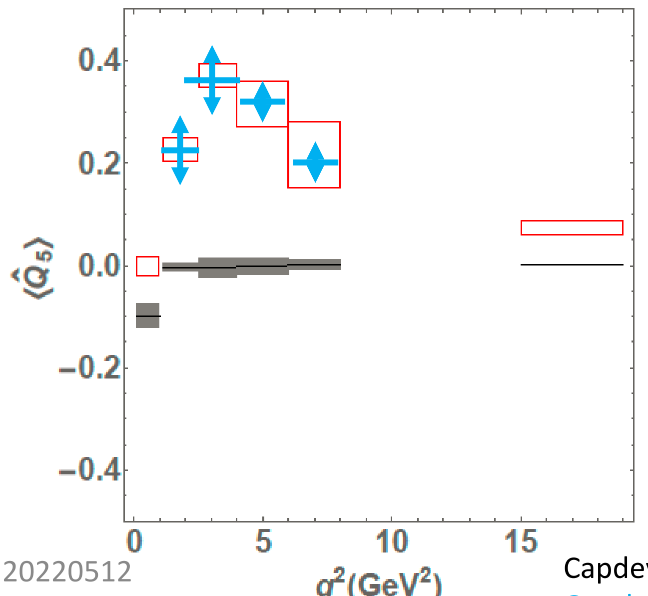


2017 R_{K*} w/ 3fb^{-1}



LFU in Angular Obs. $Q_5 = P_5'^e - P_5'^\mu$

- Angular observable P_5' in $B \rightarrow K^* \mu\mu$ is also deviated from theoretical prediction but this is dirty observable in terms of QCD uncertainty.
- $Q_5=P_5'^e-P_5'^\mu$ is also LFU observable and thus clean.
  - first measured by Belle. https://arxiv.org/abs/1612.05014
  - 5.3% for q^2=[1,6]GeV^2 with 50ab^{-1}
- This will be important discriminator for NP in P_5' at Belle II

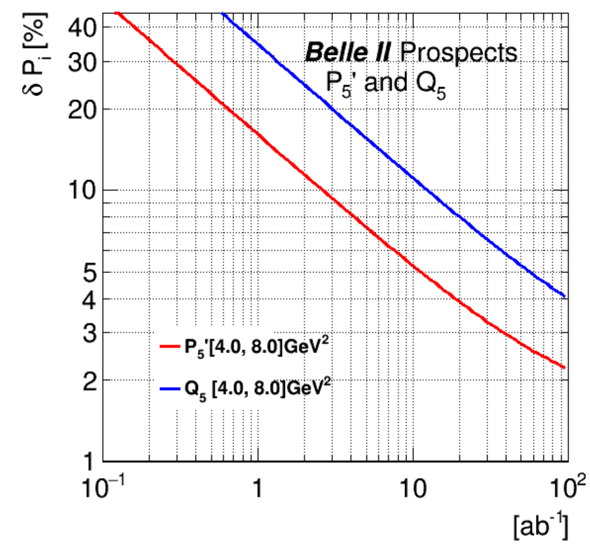


Belle II 50ab^{-1}

SM : gray

NP : red

$C_{9\mu}^{NP} = -1.11$

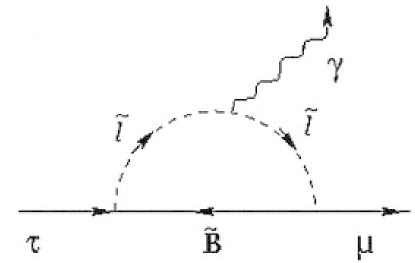


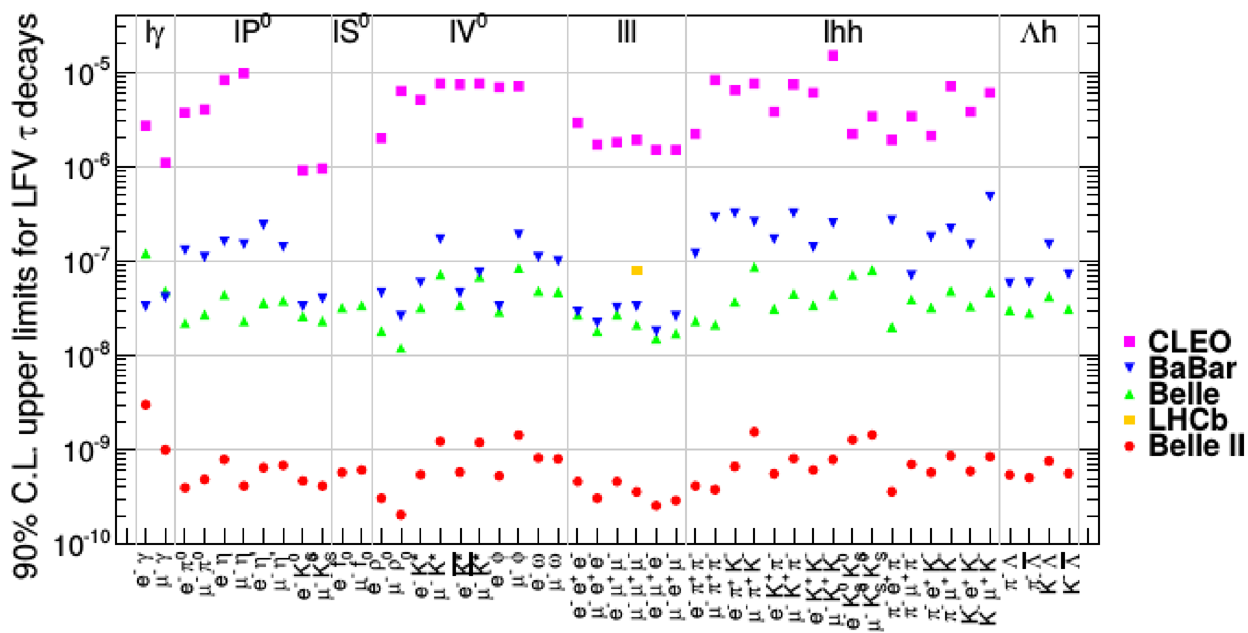
Capdevila, Descotes-Genon, Matias and Virto 1605.03156

Overlaid Belle II sensitivity

Lepton Flavor Violating τ Decays

- Forbidden in the SM
  - Even with neutrino oscillation, the BF is tiny <O(10^{-54})
  - If we find the decays at Belle II, it is clear NP signal
- Unique at Belle II.
  - Muon case, three experiments search for μ→eγ, μ→eee, and μ-e conv. while Belle II can do the three for τ case, τ→μγ, τ→μl+l-, and τ→μhh.
- Upper limits of O(10^{-9}) are possible





Summary

- Heavy Flavor Physics is sensitive to NP
  - B^0-B^0 Mixing
    - 2000TeV tree level BSM, 10TeV SUSY
  - $b \rightarrow s\gamma$
    - >1.7TeV stop with large flavor mixing, 900GeV charged Higgs
    - CPV → EW Baryogenesis together with HL-LHC and ILC
  - $B \rightarrow \tau\nu$
    - charged Higgs : a limit on $\tan\beta/m_H$
  - LFUV in $b \rightarrow c\tau\nu$ and $b \rightarrow sll$
    - TeV scale Leptoquark → LHC direct searches
    - → GUT
  - LFV τ decays
    - SUSY, Z', contact interaction
- 2020's is an exciting era for heavy flavor physics

backup

Light Flavors are also Interesting

- Electron EDM
  - ACME, Fr EDM@RIKEN
- Neutron EDM
  - n2EDM@PSI, TUCAN@TRIUMF, Cryogenic experiments
- Proton EDM
  - Storage Ring@CERN
- Muon

To be covered by Mibe-san

  - Muon g-2@Fermilab, muon g-2/EDM @ J-PARC, muon EDM@PSI
  - mu2e@Fermilab, COMET@J-PARC, DeeMe@J-PARC
  - MEG@PSI, mu3e@PSI
- Pion
  - pienu@TRIUMP
- Kaons
  - NA62@CERN, KOTO@J-PARC, KLEVER@CERN

Sorry if I missed your favorite experiments

Belle II Physics Book

- Published in Dec 2019
  - https://arxiv.org/abs/1808.10567
  - https://doi.org/10.1093/ptep/ptz106

PTEP

Prog. Theor. Exp. Phys. **2019**, 123C01 (654 pages)
DOI: 10.1093/ptep/ptz106

The Belle II Physics Book

E. Kou[75,∗,§,†], P. Urquijo[145,‡,†], W. Altmannshofer[135,§], F. Beaujean[79,§], G. Bell[122,§], M. Beneke[114,§], I. I. Bigi[148,§], F. Bishara[150,16,§], M. Blanke[49,51,§], C. Bobeth[113,114,§], M. Bona[152,§], N. Brambilla[114,§], V. M. Braun[50,§], J. Brod[112,135,§], A. J. Buras[115,§], H. Y. Cheng[43,§], C. W. Chiang[92,§], M. Ciuchini[59,§], G. Colangelo[128,§], A. Crivellin[102,§], H. Czyz[156,29,§], A. Datta[146,§], F. De Fazio[53,§], T. Deppisch[51,§], M. J. Dolan[145,§], J. Evans[135,§], S. Fajfer[109,141,§], T. Feldmann[122,§], S. Godfrey[7,§], M. Gronau[62,§], Y. Grossman[15,§], F. K. Guo[45,134,§], U. Haisch[150,11,§], C. Hanhart[21,§], S. Hashimoto[30,26,§], S. Hirose[89,§], J. Hisano[89,90,§], L. Hofer[127,§], M. Hoferichter[168,§], W. S. Hou[92,§], T. Huber[122,§], T. Hurth

Joint effort of theorists and experimentalists.
Some of you contributed to the book. Thank you!