Physics at Belle II

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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

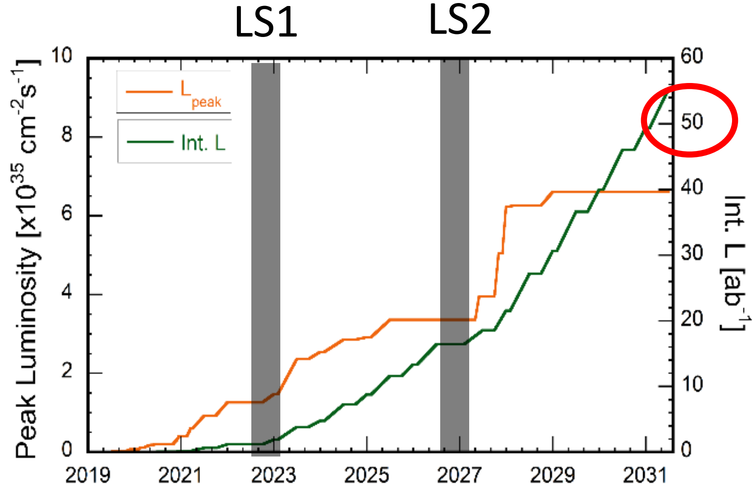
E. Kou[75,*,§,†], P. Urquijo[145,‡,†], W. Altmannshofer[135,§], F. Beaujean[79,§], G. Bell[122,§], M. Beneke[114,§], I. I. Bigi[148,§], F. Bishara[150,16,§], M. Blanke[49,51,§], C. Bobeth[113,114,§], M. Bona[152,§], N. Brambilla[114,§], V. M. Braun[50,§], J. Brod[112,135,§], A. J. Buras[115,§], H. Y. 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

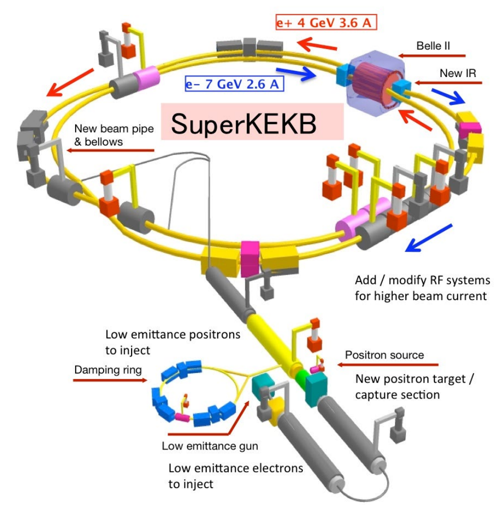
Joint effort of theorists and experimentalists.
Some of you contributed to the book. Thank you!

Belle II @ SuperKEKB

- Highest luminosity collider experiment
  - $L=6.5\times10^{35}\ cm^{-2}s^{-1}$
  - E_{CM}=10.58GeV on Υ(4S)
    - Just above the BB threshold to produce B meson pairs efficiently
    - Can go higher, Υ(5S) and above
  - Energy-asymmetric collisions
    - 7.0GeV x 4.0GeV
    - To boost B mesons to measure time dependent CPV
  - $50ab^{-1}$ will be accumulated around 2031
    - Containing 1×10^{11} B mesons, 1.5×10^{11} charm hadrons, and 0.9×10^{11} τ
    - Processes with cross sections of O(1)ab are reachable
- Physics
  - Flavor physics : B, D and τ
    - Including HVP with radiative return for muon g-2
  - Light dark matter search
  - And more

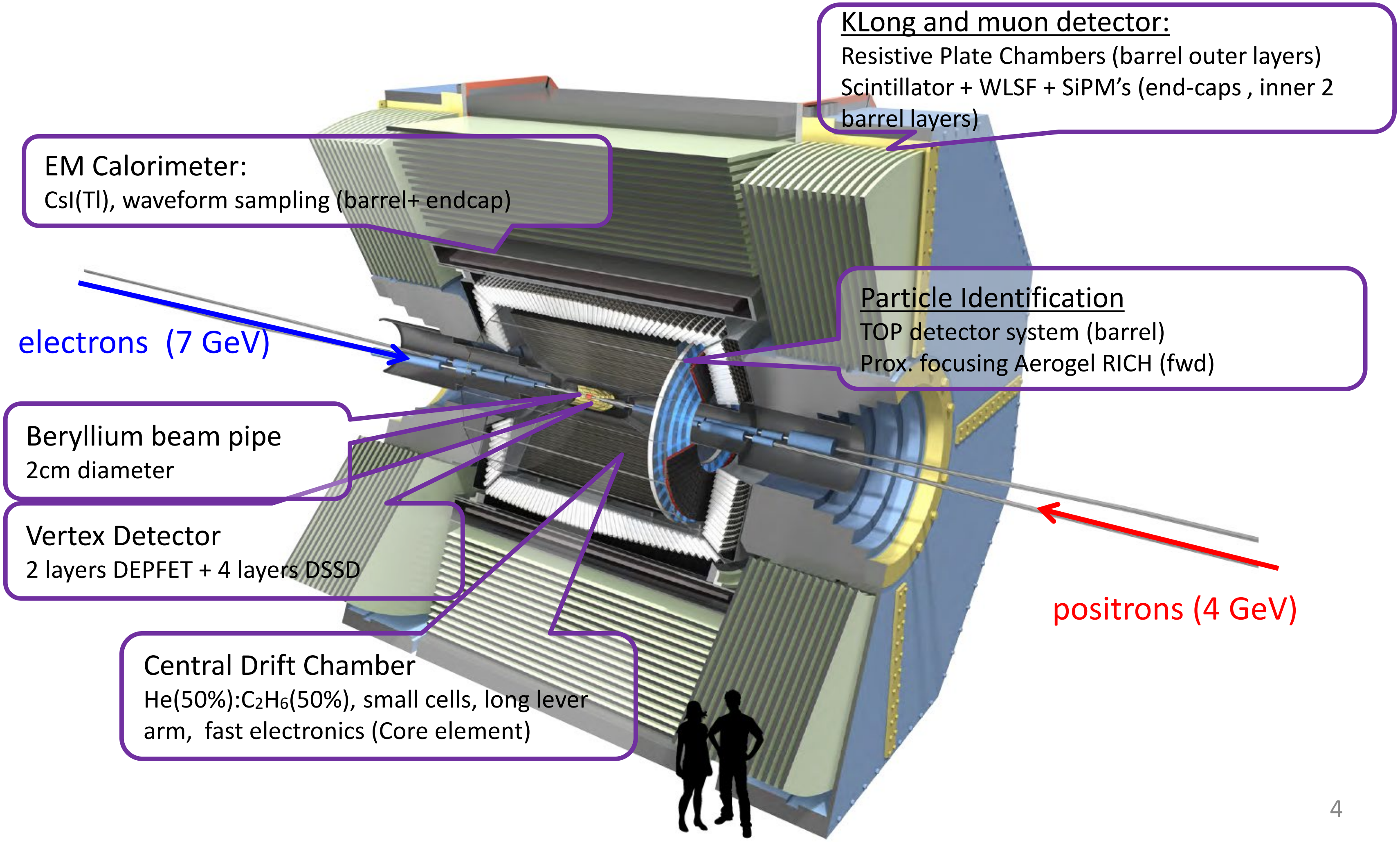
Luminosity Projection





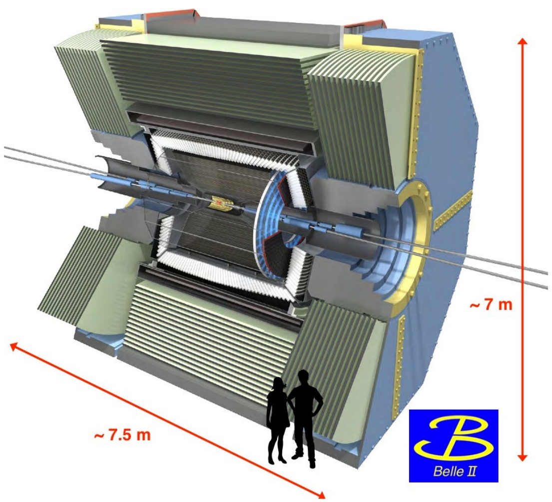
Belle II Detector

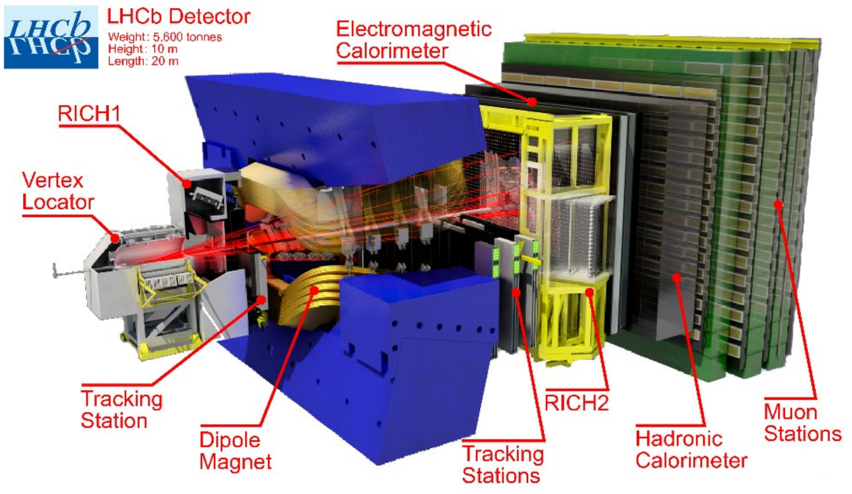
- Significant detector improvements
  - Better and Larger VXD ➔ Time dependent CPV, especially with long lived Ks.
  - Trigger improvement ➔ single photon final state etc.



Belle II Cons and Pros (VS LHCb)

- Cons.
  - Statistics of b hadrons!! (1nb VS 144μb)
    - We will only have 10^{11} B mesons with $50ab^{-1}$ on Y(4S) and $5x10^8$ B_s with $5ab^{-1}$ on Y(5S)
  - No large samples of b baryon and B_c
    - Production of these hadrons are not yet established around Y(nS).
  - Proper time resolution is worse and B meson is not so boosted.
    - Background suppression with B vertex is not so easy
    - Bs mixing (Δm_s) can not be measured (while $\Delta\Gamma_s$ can be measured).





Belle II Cons and Pros (VS LHCb)

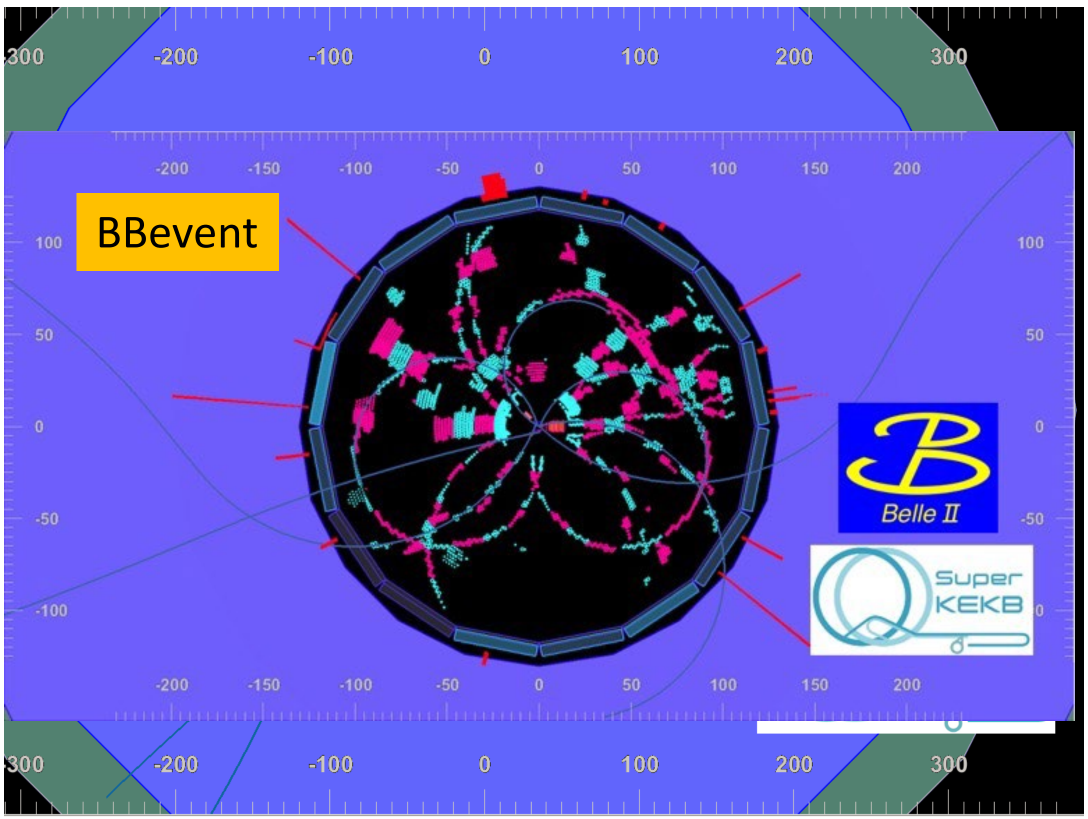
- Pros.
  - Smaller background cross section (O(1)nb VS O(10)mb)
    - ~3.4nb for ee→qq, ~1nb for ee→Y(4S)→BB
  - Almost 100% trigger efficiency for BB events.
    - Main trigger : 3-track-trigger || ECL energy sum trigger >1GeV || ECL nCluster >=4
    - Absolute BF measurement possible.
  - High hermeticity 4π x 94%
    - High reconstruction efficiency of O(1)~O(10)%.
    - Full reconstruction possible (Reconstruction of the other B meson)
    - More than one missing neutrino modes ➔ $B\to D(*)\tau\nu$, $B\to\tau\nu$, $B\to K^{(*)}\nu\nu$, $B\to K\tau\tau$, $B\to\nu\nu$
  - Detection of electron
    - Detection efficiency of electron is almost the same as that of muon ➔ test of LFU
    - Easy to recover bremsstrahlung photon
  - Detection of neutrals
    - γ, π^0 and Ks can be reconstructed efficiently ➔ sum-of-exclusive approach $B\to Xsl^+l^-$, $B\to\pi^0\pi^0$, $B_{(s)}\to\gamma\gamma$
    - Better energy resolution of hard γ ➔ $B\to\rho\gamma$ with good PID devise to suppress $B\to K^*\gamma$

The First Collisions observed by Belle II

- 26th Apr 2018

People excited by the first collisions

Event Display : e+e- →BB

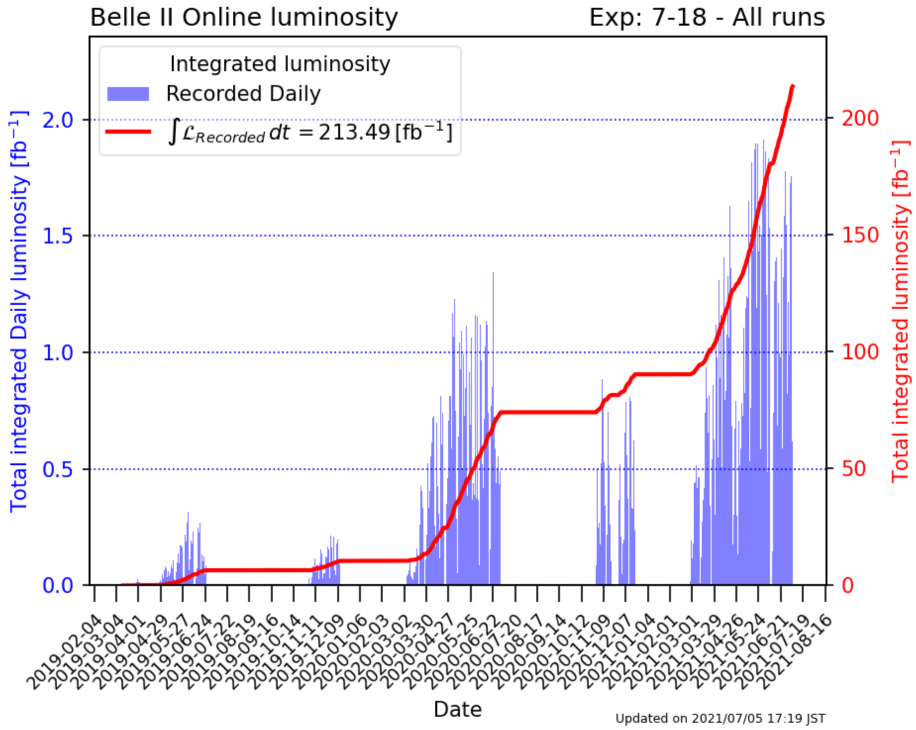


SuperKEKB control room

Belle II control room

Belle II 2021

- Physics run since 2019
- World records
  - $L = 3.12 \times 10^{34}\ cm^{-2}\ s^{-1}$ ($31.2\ nb^{-1}/s$)
  - $L_{int} = 1.96\ fb^{-1}/day$
  - $L_{int} = 12.1\ fb^{-1}/week$
- $213 fb^{-1}$ has been accumulated so far (Belle $1040 fb^{-1}$).



Contents

- $\Delta B=2$ loop process : B^0-$\overline{B}^0$ mixing
- $\Delta B=1$ loop processes : Penguin B decays
  - 3rd paper on $B \rightarrow K\nu\nu$
- Lepton Flavor Universality violation in B decays
- Lepton Flavor Violating τ decays
- HVP in radiative return events for muon g-2
- Light new particle searches
  - 1st and 2nd papers on Z' in $L\mu$-$L\tau$ and ALPs

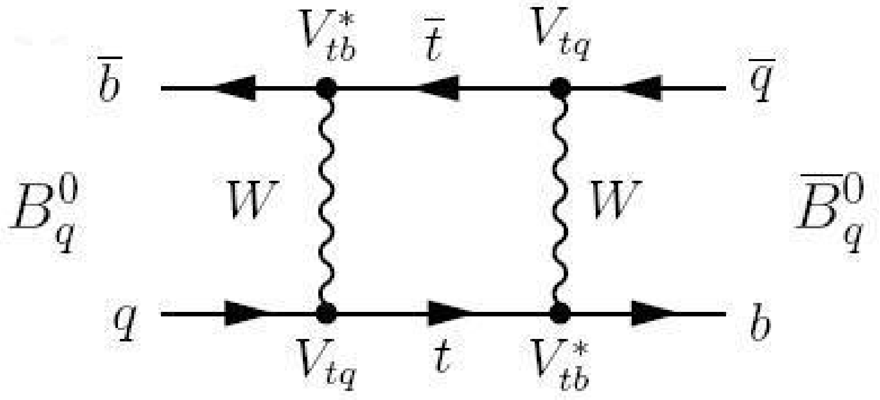
Sorry if I miss your favorites

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

- B^0-$\overline{B}^0$ mixing is proceed via loop diagrams in the SM.
  - The loop is dominated by top quark and W
- New particles, such as SUSY particles 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)

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

T. Goto et al, Phys.Rev. D53 (1996) 6662-6665



Unitarity Triangle

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

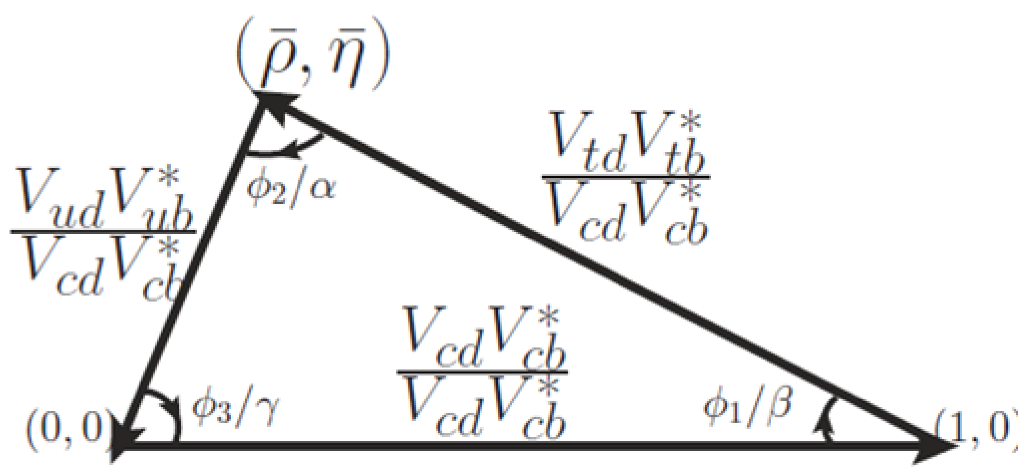
by Wolfenstein parameterization

Irreducible complex phase cause CP Violation!

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

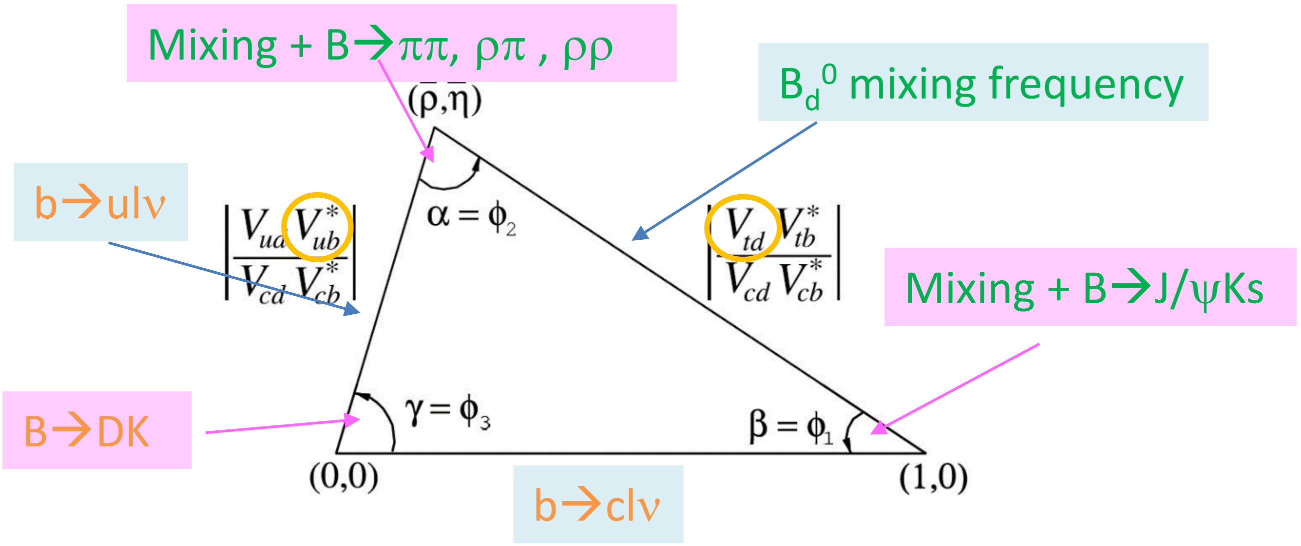
Comprehensive test;
measure all the angles and sides.

B system : very good place,
all the angle are O(0.1)!



Unitarity Triangles : Tree VS Loop

- We can measure six observables; three angles and three sides.
  - Can make two triangles from the measurements
- If UT drawn with tree measurements is not consistent with the one with mixing measurements, it is clear NP signal



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

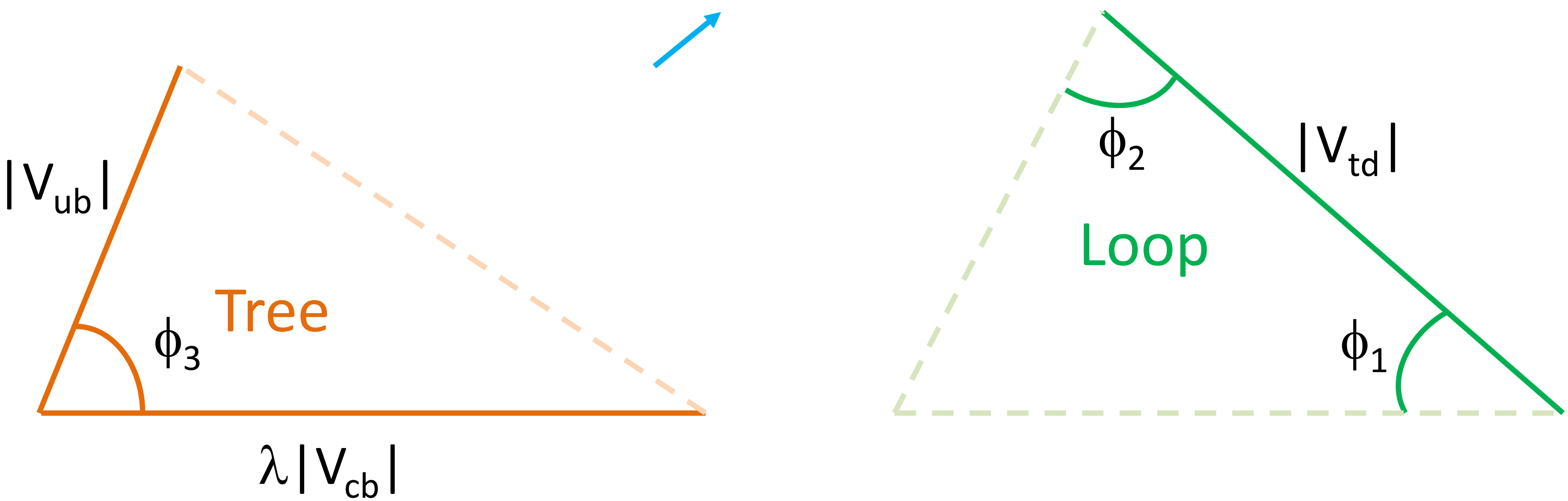
Tree Loop side angle

phase

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

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

Including theory and LQCD uncertainties

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\lvert V_{cb}\rvert$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\lvert V_{cb}\rvert$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\text{ex.}} \pm 1.4\%_{\text{th.}})$	1.8%	1.4%
$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$	3.4%	3.0%
$\lvert V_{ub}\rvert$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\text{ex.}} \pm 3.0\%_{\text{th.}})$	2.4%	1.2%
$\sin 2\phi_1(B \to J/\psi K^0)$	$0.667 \pm 0.023 \pm 0.012$	0.012	0.005
ϕ_2 [°]	85 ± 4 (Belle+BaBar)	2	0.6
ϕ_3 GGSZ	68 ± 13	4.7	1.5

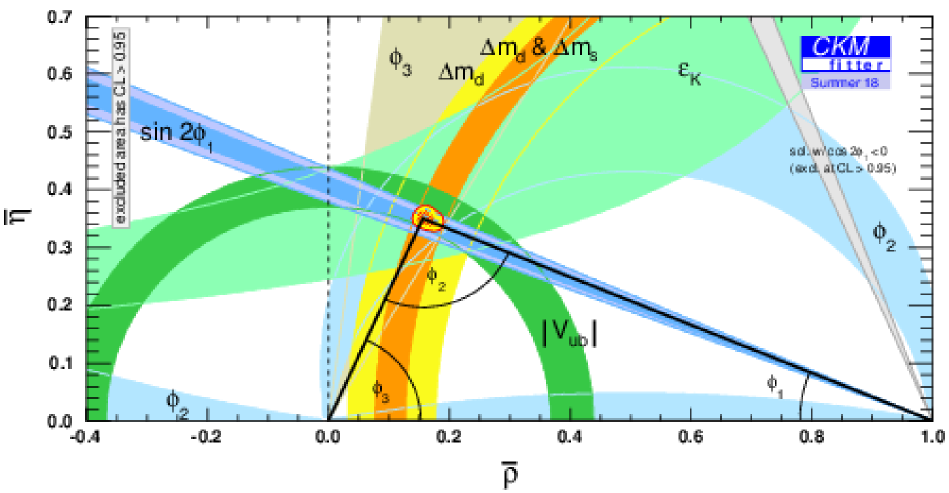
Theory uncertainties not included for ϕ_1 and ϕ_2

UT Before/After Belle II

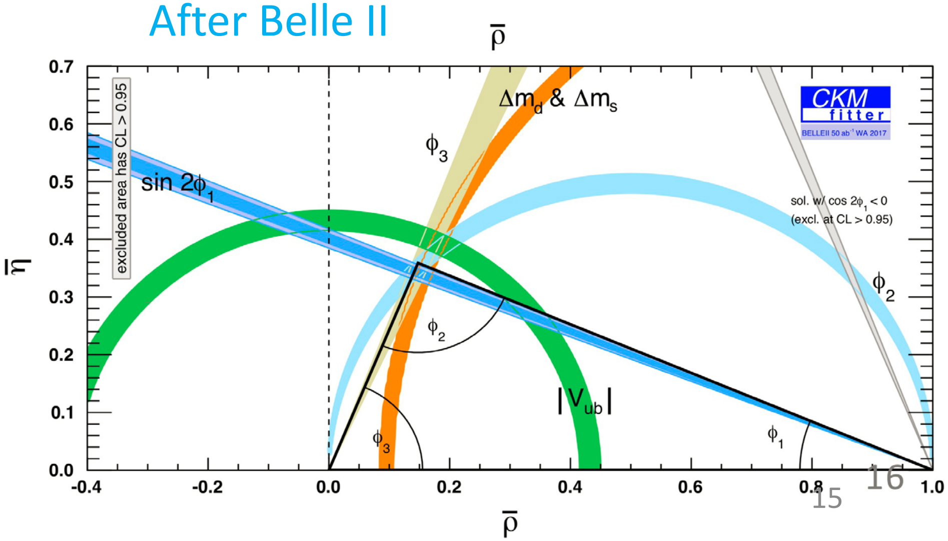
- Still uncertainties are large to conclude

- With current (in 2013) WA values, we see clear deviation of some observables

Before Belle II



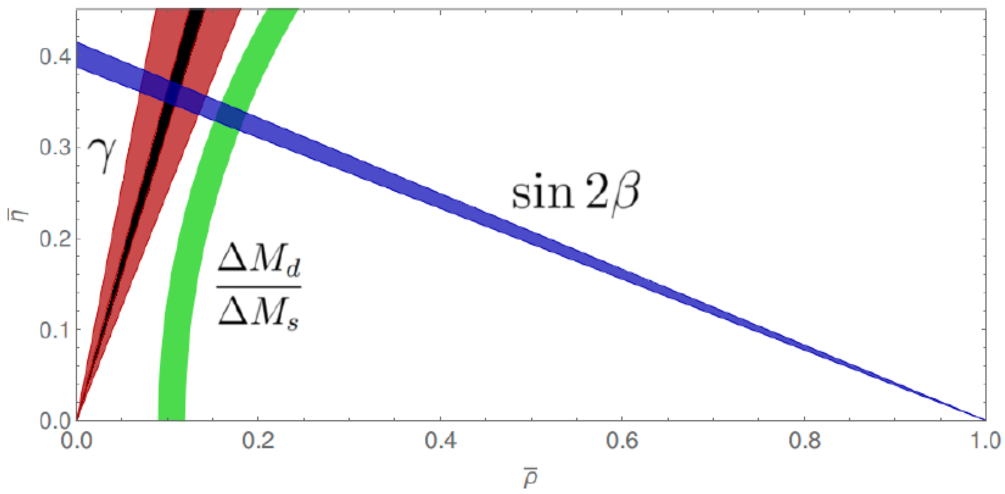
After Belle II



M. Blanke and A. J. Buras, Eur. Phys. J. C 79 (2019) 159

Current Situation

- See deviation?
- Hint for NP in mixing?



NP Interpretations

arXiv:1309.2293

- 200TeV NP scale can be accessible with EFT analysis

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

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

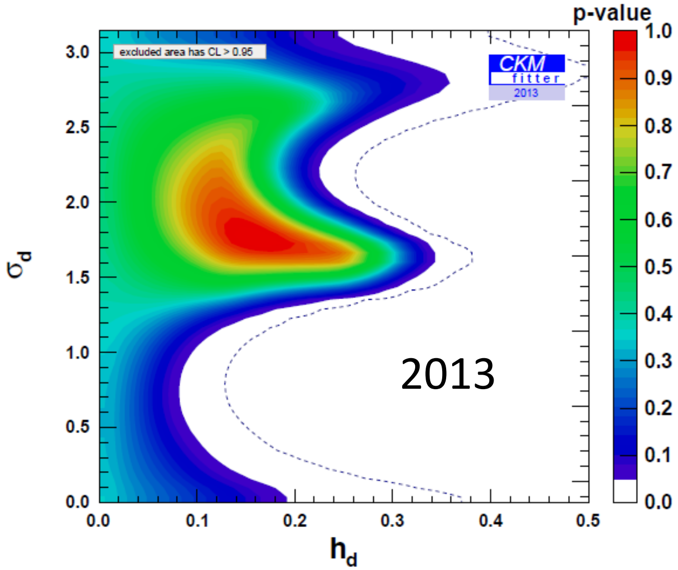
- 10(?) TeV in SUSY
  - Can see the deviations in loop (ϕ_1 and Δm_d)

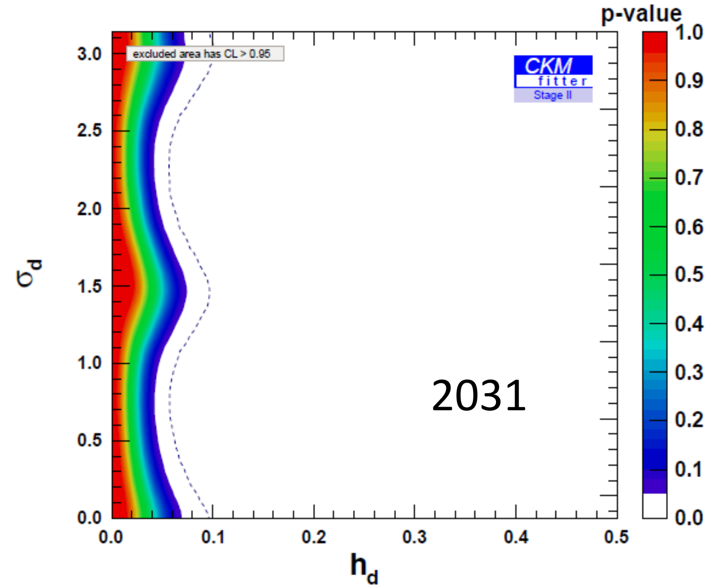
Tanimoto and Yamamoto 2014, 2015

$$\lambda_{ij}^t = V_{ti}^* V_{tj}$$

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\ \text{TeV}}{\Lambda}\right), \quad \sigma = \arg(C_{ij}\lambda_{ij}^{t*}),$$

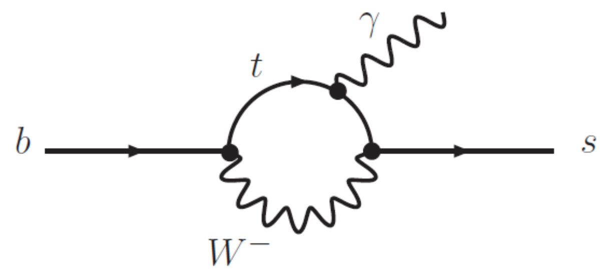
Couplings	NP loop order	Scales (in TeV) probed by B_d mixing	Scales (in TeV) probed by B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V_{tj}^*\rvert$	tree level	17	19
(CKM-like)	one loop	1.4	1.5
$\lvert C_{ij}\rvert = 1$	tree level	2×10^3	5×10^2
(no hierarchy)	one loop	2×10^2	40



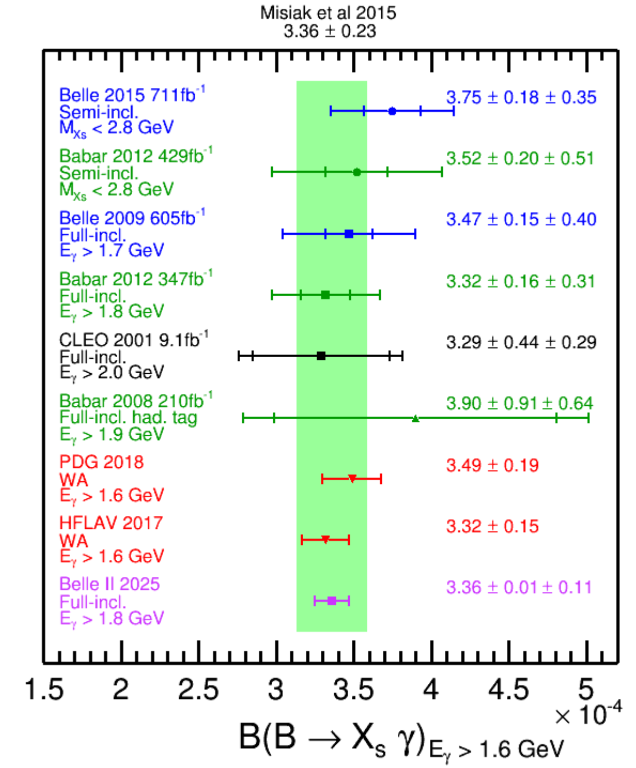


ΔB=1 loop processes : Penguin Decays

- EW penguin
- 3rd paper on B→K ν ν



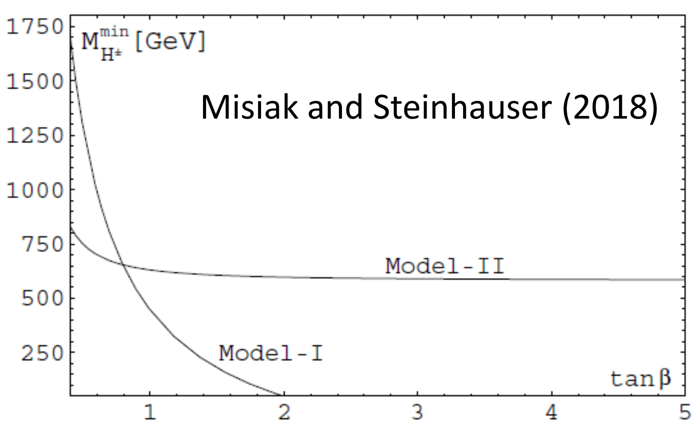
BF($B \to X_s\gamma$)



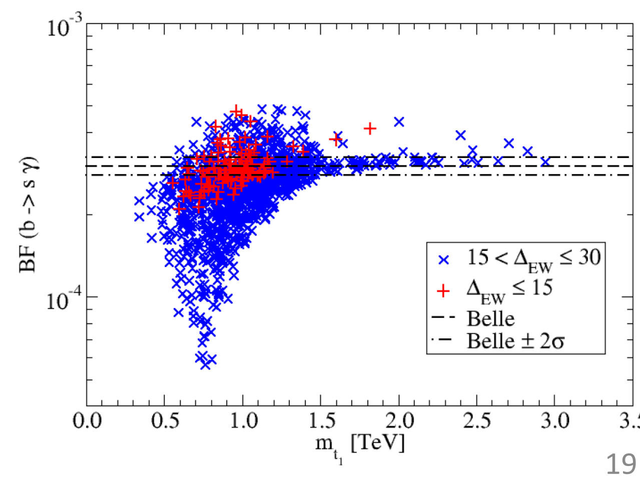
- Exp and theory are in good agreement
  - Exp ~5% (systematic dominant)
  - Thoery ~5%

M. Misiak et al, 2002.01548

- Constraints
  - H+ in 2HDM type-II : M_H >600GeV
  - Stop in Natural SUSY



Baer, Bager and Nagata (2017)



BF($B \to X_s\gamma$) in 2031

- Exp : Already systematic dominant
  - But large Belle II data can reduce the uncertainty to ~3%

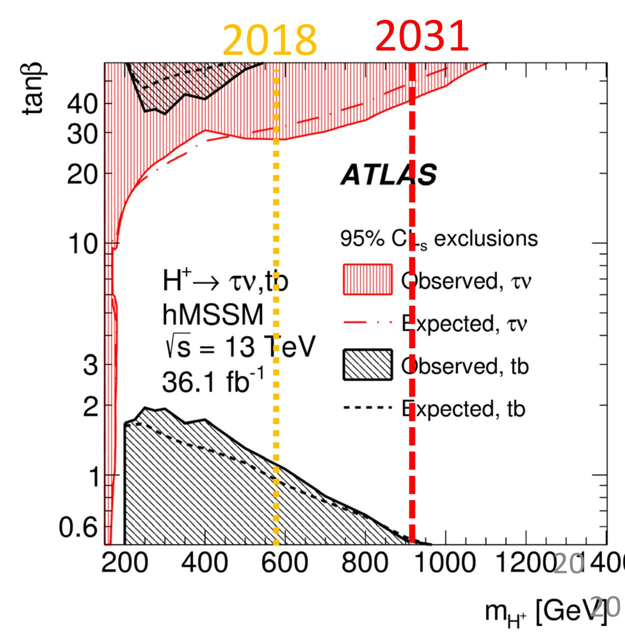
Ishikawa's private estimation

- Theory
  - Part of Non-perturbative can be reduced by data driven way
  - Other uncertainties also reducible
  - 3.5% in 2025

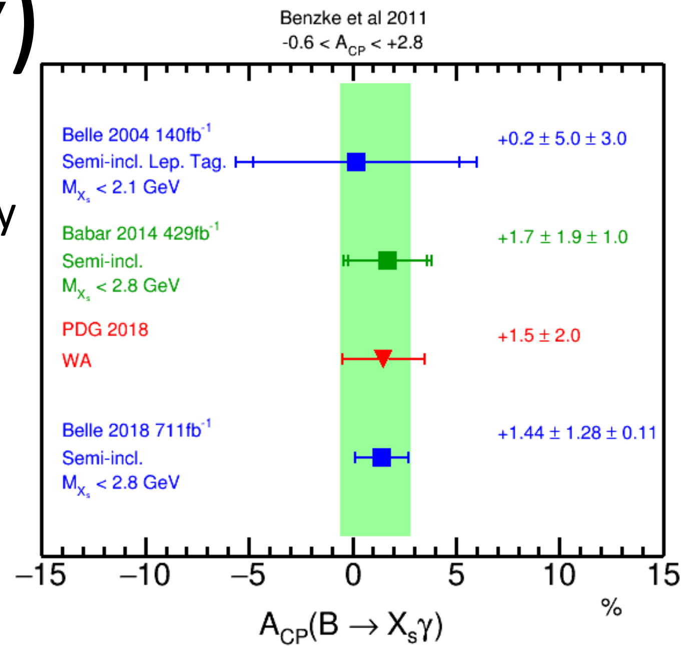
Private communication with M.Misiak

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\text{Br}(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$\text{Br}(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$\text{Br}(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.4%	0.94%	0.69%
$\Delta_{0+}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	2.6%	0.85%

Belle II Physics book 1808.10567



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



- $A_{CP}(B \to X_s\gamma)$ is sensitive to CPV in NP but theory 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

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

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

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

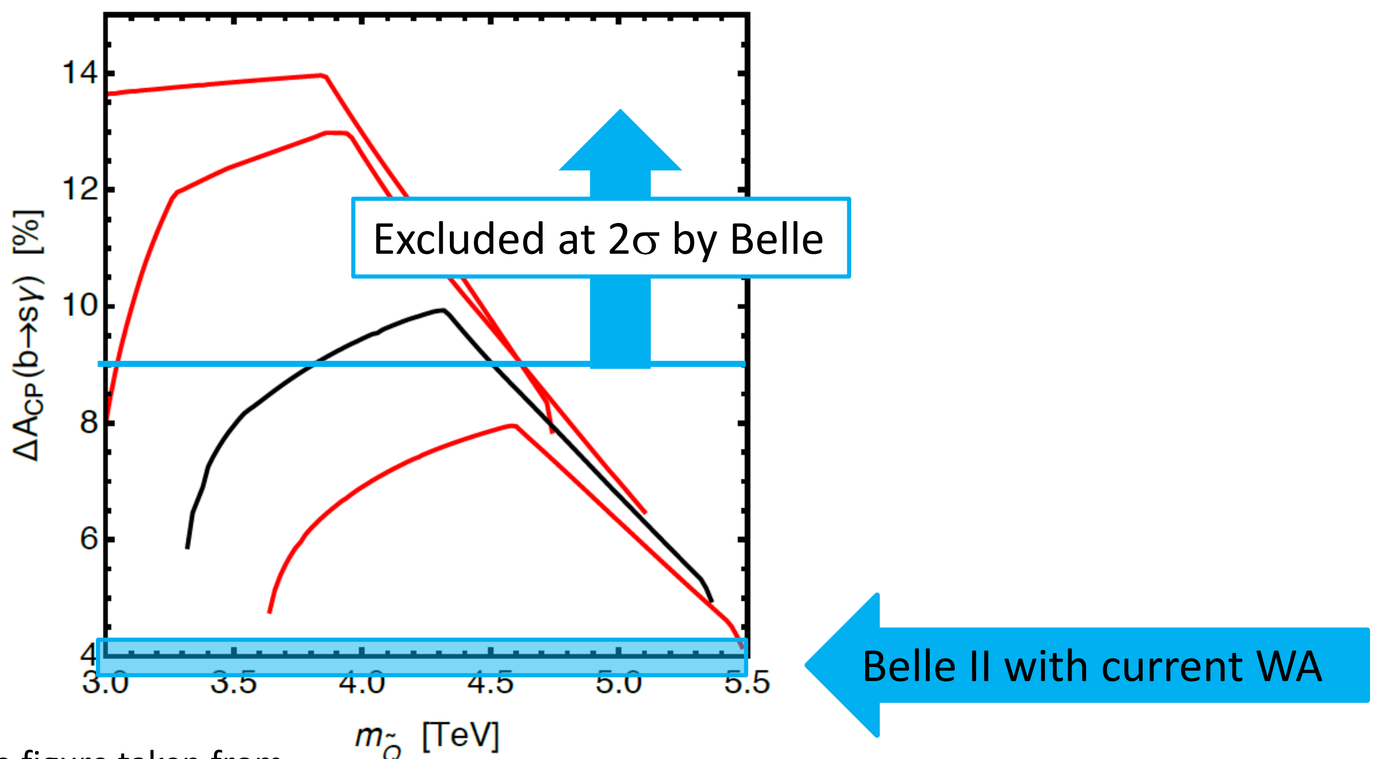
Watanuki, Ishikawa et al, PRD 99, 032012 (2019)

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

Belle II Physics book 1808.10567

$\Delta A_{CP}(B \rightarrow X_s\gamma)$ and Constraint on SUSY

- Set a limit on parameter space in SUSY
  - Gluino mediated EWP which explains ε'/ε from CPV trilinear couplings



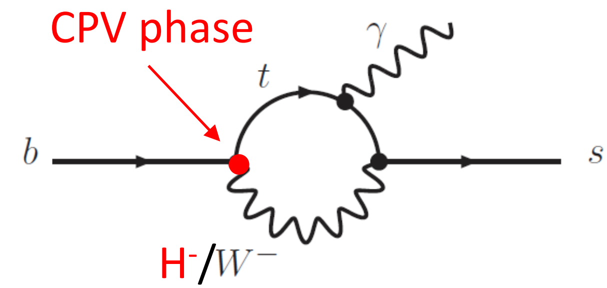
Lines overlaid onto the figure taken from
M. Endo, T. Goto, T. Kitahara, S. Mishima, D. Ueda and K. Yamamoto, JHEP 04 (2018) 019.

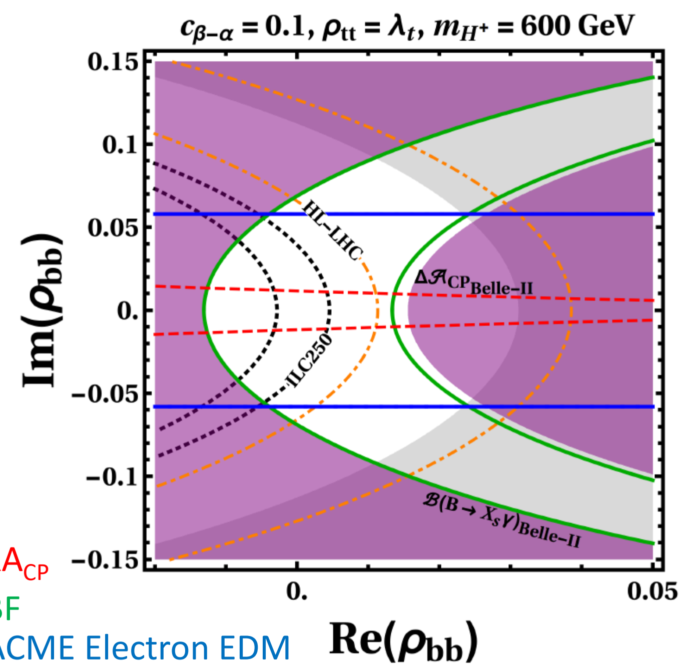
ΔA_{CP}(B→Xsγ) and EW Baryogensis

- 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 ILC500



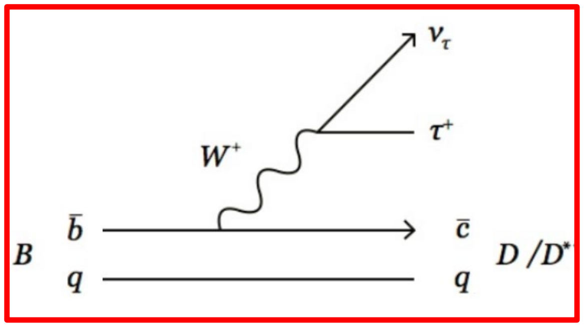


ΔA_{CP}
BF
ACME Electron EDM
HL-LHC H→bb coupling
ILC H→bb coupling

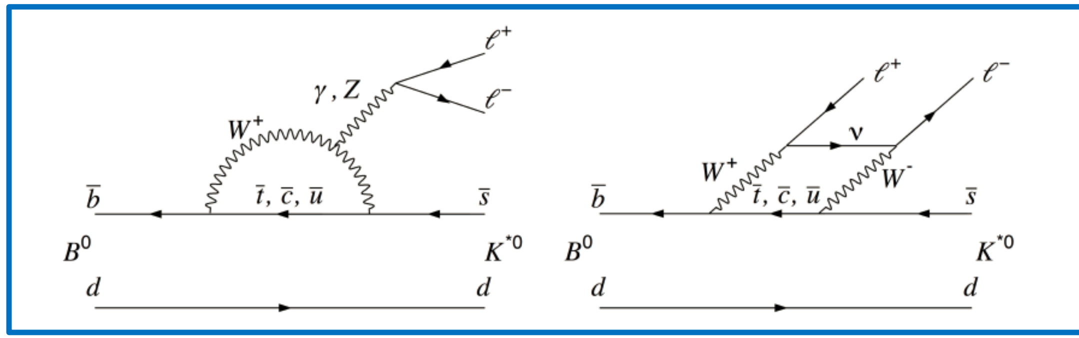
LFU violation in B decays

- Recently, two hints of LFUV are found in b→cτν and b→sl⁺l⁻
  - Anomaly in b→cτν driven by LHCb, Babar and Belle.
  - Anomaly in b→sl⁺l⁻ Driven by LHCb

b→cτν



b→sl⁺l⁻



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

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

LFUV in B decays

- Recently, two hints of LFUV are found in $b \to c\tau\nu$ and $b \to s l^+ l^-$
  - Anomaly in $b \to c\tau\nu$ driven by LHCb, Babar and Belle. ~4σ
  - Anomaly in $b \to s l^+ l^-$ Driven by LHCb   Naïve combination of R_K and R_{K^*} ~4σ
- Leptoquark and flavorful W'/Z' models can explain the deviation

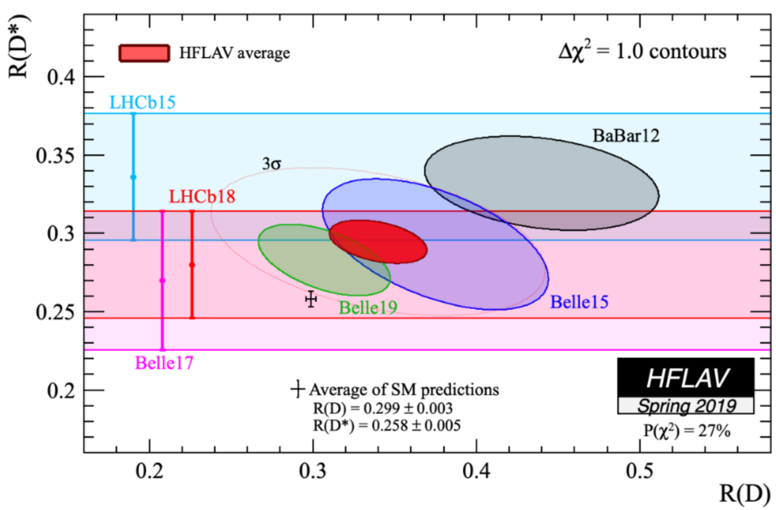
$$R(D^{(*)}) = \frac{BF(B \to D^{(*)} \tau \nu_\tau)}{BF(B \to D^{(*)} l \nu_l)}$$

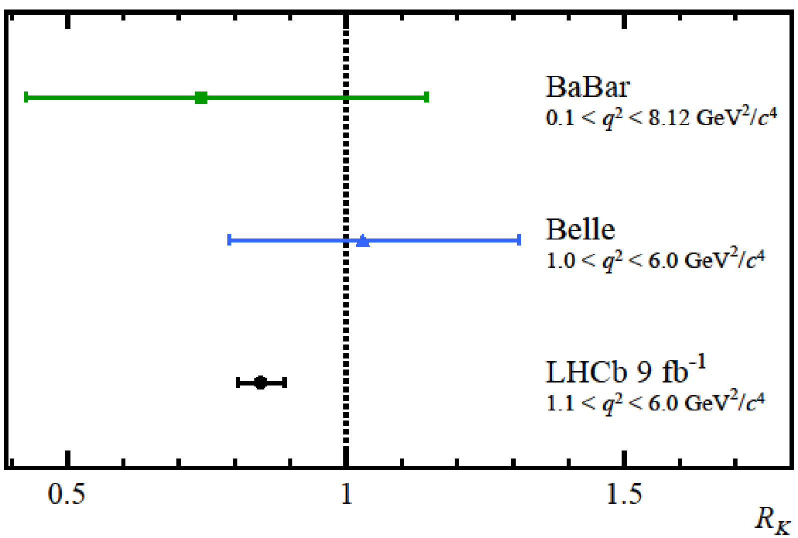
l=e,μ

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

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

~15% deviation!

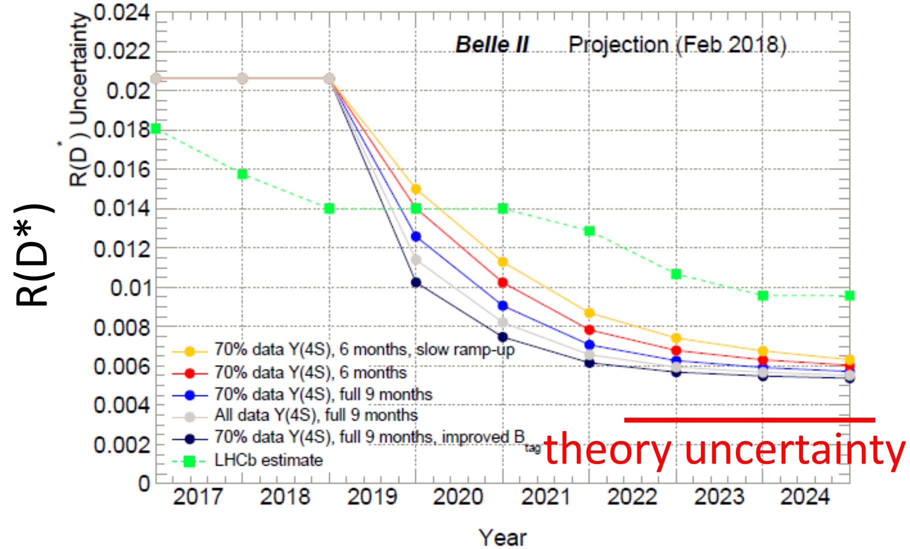




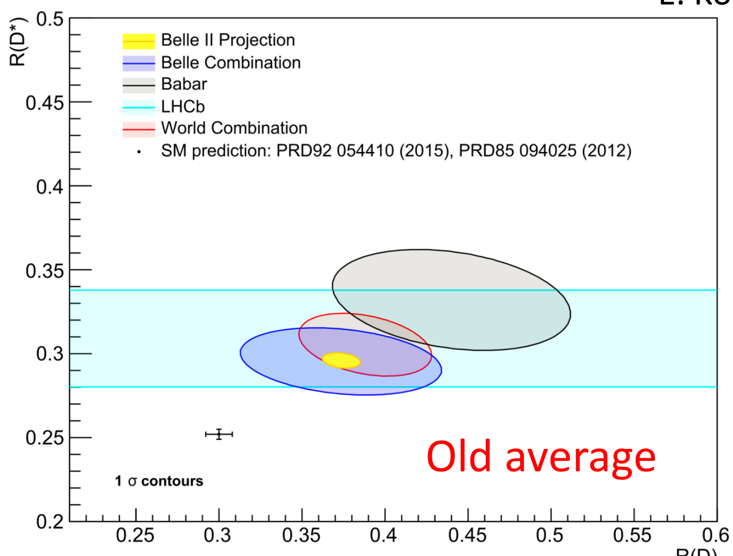
Future Prospects on R($D^{(*)}$) at Belle II

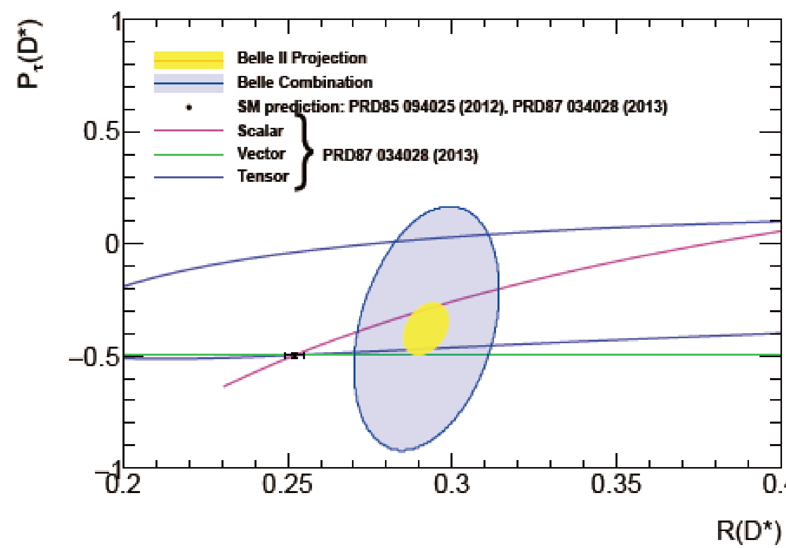
- Tagging effciency improved about factor 2
- We could observe 5σ deviation of R(D) VS R(D*) in 2025 with $10ab^{-1}$ or so if central value unchanged
  - Sensitivity of R(D*) is 0.006 in 2027.
- Then, model discrimination (Lorentz structure) with Polarization measurements
  - $P_\tau(D^*)$, $P_\tau(D)$, P_{D^*}

2year delay, Blue one is nominal scenario



E. Kou et al. 1808.10567

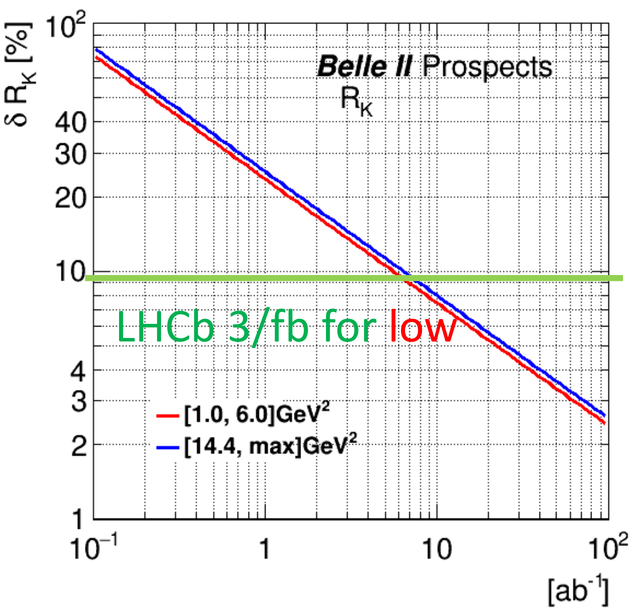


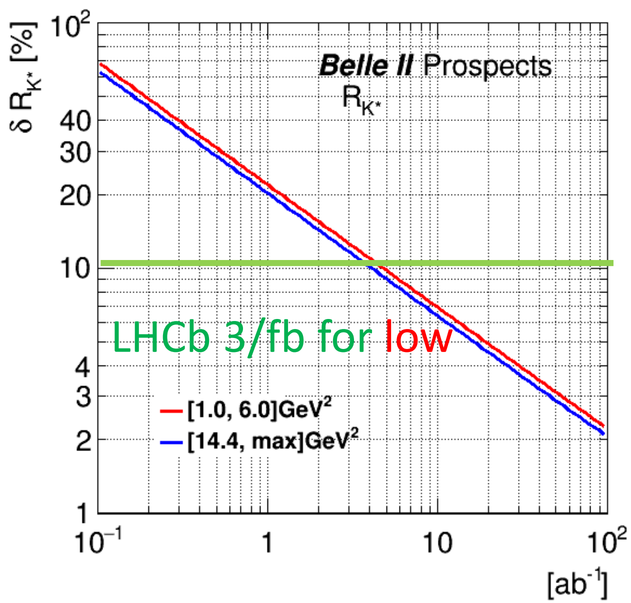


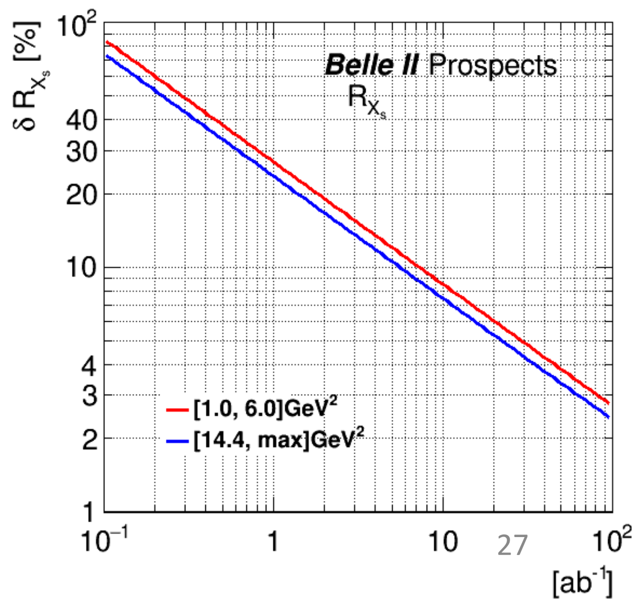
Prospects on R_K, R_{K*} and R_{Xs} at Belle II

- Ideal place to measure R_H
  - bremsstrahlung photon can be recovered easily, is problematic at LHCb
  - Both high and low q^2 accessible
  - Dominant systematics due to lepton ID ~0.4% is smaller than stat one even with $50ab^{-1}$
- We can observe NP using R_K and R_{K*} with ~$20ab^{-1}$ data in 2028
  - if central values unchanged
- About 3% uncertainty for both high and low q^2 with 50/ab
  - Assuming SM predictions for R_X

Low $1<q^2<6GeV^2$
High $q^2>14.4GeV^2$





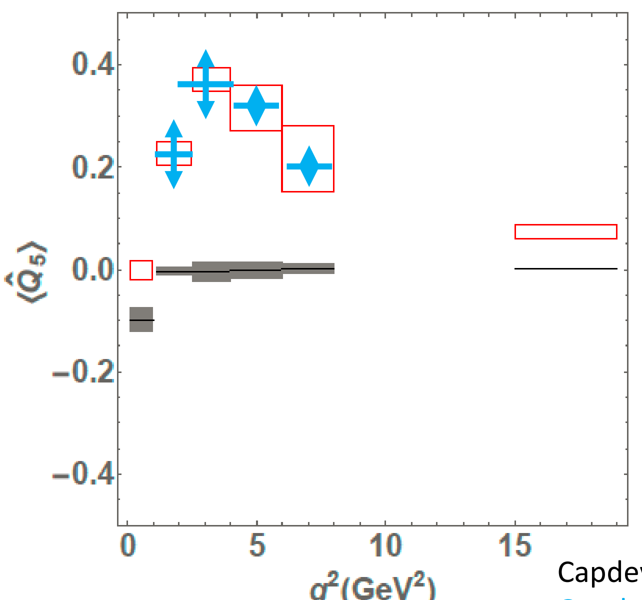


Q

- 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.
  - 5.3% for q^2=[1,6]GeV^2 with 50/ab

https://arxiv.org/abs/1612.05014

- This will be important discriminator for NP in P_5' at

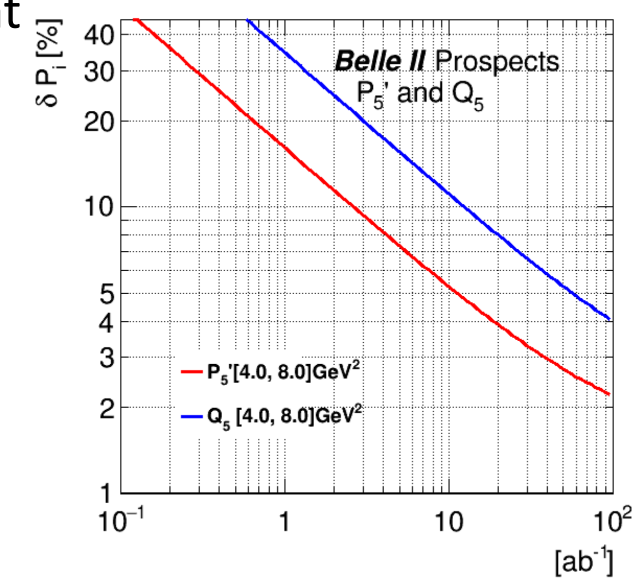


Belle II 50ab^{-1}

SM : gray

NP : red

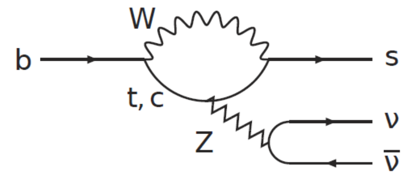
$$C_{9\mu}^{\mathrm{NP}} = -1.11$$



Capdevila, Descotes-Genon, Matias and Virto 1605.03156

Overlaid Belle II sensitivity

Result on $B^+ \to K\nu\nu$ with $63 fb^{-1}$

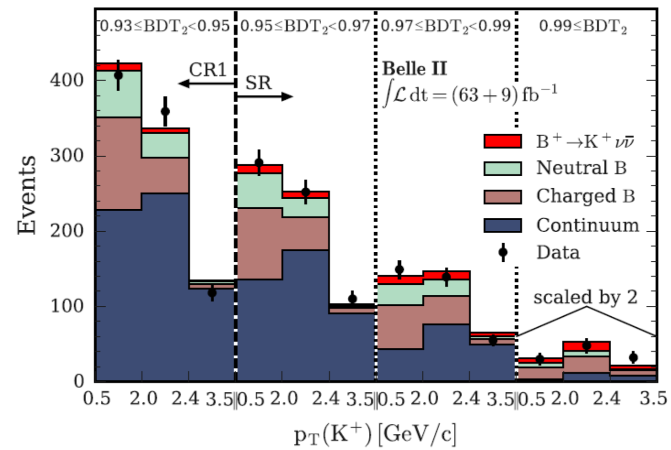


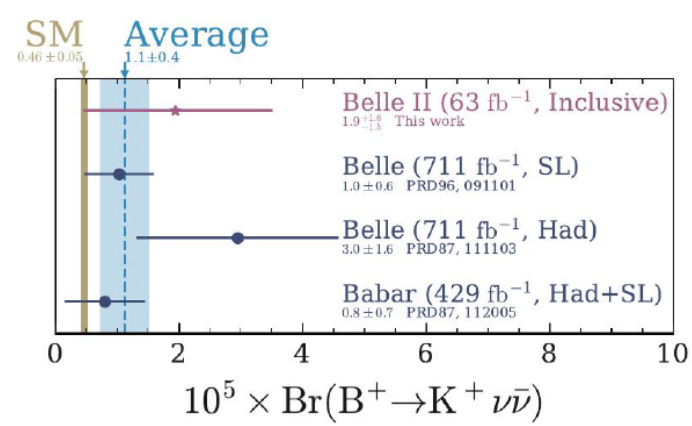
- Theoretically cleaner than B→K*l+l-
- Related to
  - LFU anomaly
  - DM if ν is replaced with χ
  - DM if νν are replaced with ϕ
- Efficiency of the other B meson tagging is low.
- We tried to inclusive tagging.
  - O(0.1)% → 4%
- The background is huge.
  - Use BDT with 51 variables
- Almost the same sensitivity as Hadronic tagging

$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = \left(1.9 \pm 1.3(\text{stat.})^{+0.8}_{-0.7}(\text{syst.})\right) \times 10^{-5}$$

$$< (4.1 \pm 0.5) \times 10^{-5} \text{ (90\% C.L.)}$$

- This technique can be used for other analysis



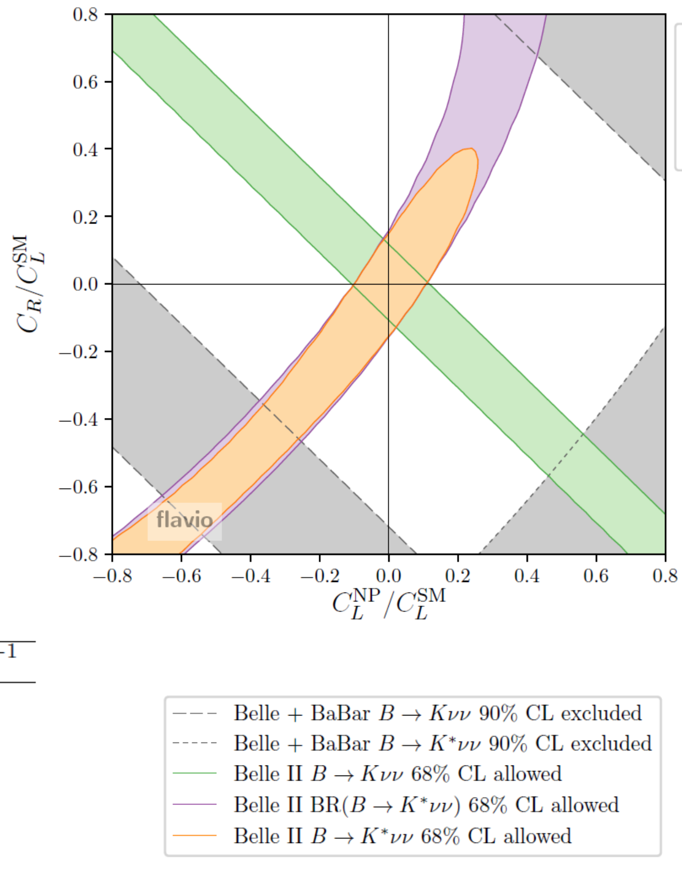


Measurements of B→K$^{(*)}\nu\nu$

- We can observe the B→K$^{(*)}\nu\nu$ at early stage (several ab^{-1}) of Belle II, and the sensitivity of the BF is 10% level with 50ab^{-1}.
- We can measure the $F_L(K^*)$, which is less sensitive to form factor uncertainty than BF, with 20% precision

$$\mathcal{O}_L = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

$$\mathcal{O}_R = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu(1-\gamma_5)\nu)$$

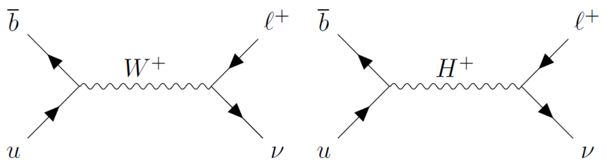


Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\nu\bar{\nu})$	$< 450\%$	30%	11%
$\mathrm{Br}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 180\%$	26%	9.6%
$\mathrm{Br}(B^+ \to K^{*+}\nu\bar{\nu})$	$< 420\%$	25%	9.3%
$F_L(B^0 \to K^{*0}\nu\bar{\nu})$	–	–	0.079
$F_L(B^+ \to K^{*+}\nu\bar{\nu})$	–	–	0.077
$\mathrm{Br}(B^0 \to \nu\bar{\nu}) \times 10^6$	< 14	< 5.0	< 1.5
$\mathrm{Br}(B_s \to \nu\bar{\nu}) \times 10^5$	< 9.7	< 1.1	–

B→τν,μν in SM and 2HDM

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

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

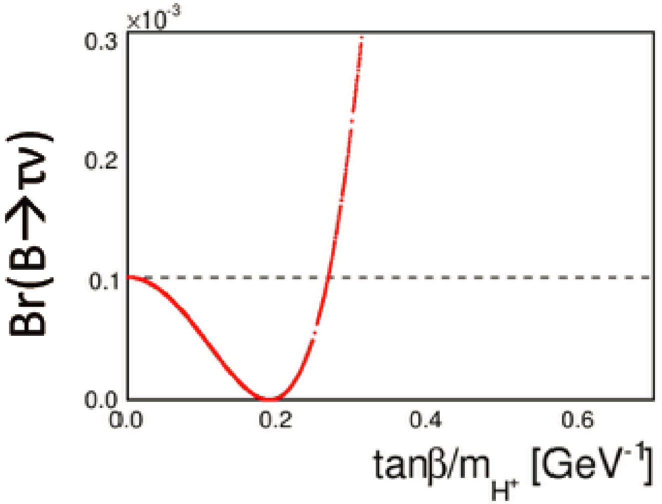


- BF(B→τν) in 2HDM type-II
  - No helicity suppression with Higgs exchange
  - Higgs coupling ∝ m_τ

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

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

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



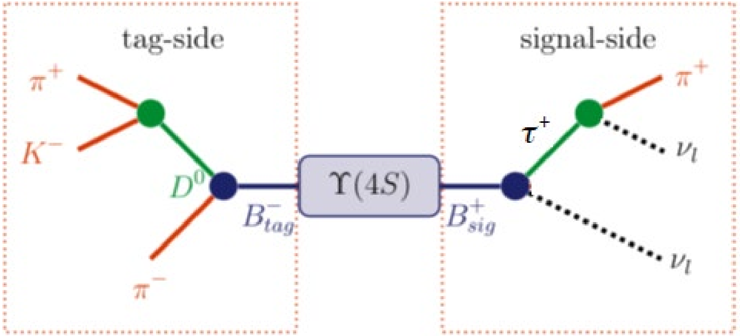
- The same can be applied to B→μν
  - LFU (or 2HDM type-II) can be tested with a ratio of BFs

$$R_{\text{pl}} = \frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)} = \frac{m_\tau^2}{m_\mu^2} \frac{(1 - m_\tau^2/m_B^2)^2}{(1 - m_\mu^2/m_B^2)^2} \left|1 + r_{\text{NP}}^\tau\right|^2 \simeq 222.37 \left|1 + r_{\text{NP}}^\tau\right|^2 .$$

BF($B \to \tau\nu$) and R_{pl}

- Precision of BF($B \to \tau\nu$) at Belle II
  - 2x better tagging efficiency (the other B recon)

	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



  - → charged Higgs search in next page
- The ratio R_{pl}
  - 35% with 5ab^{-1}
  - 13% with 50ab^{-1}

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

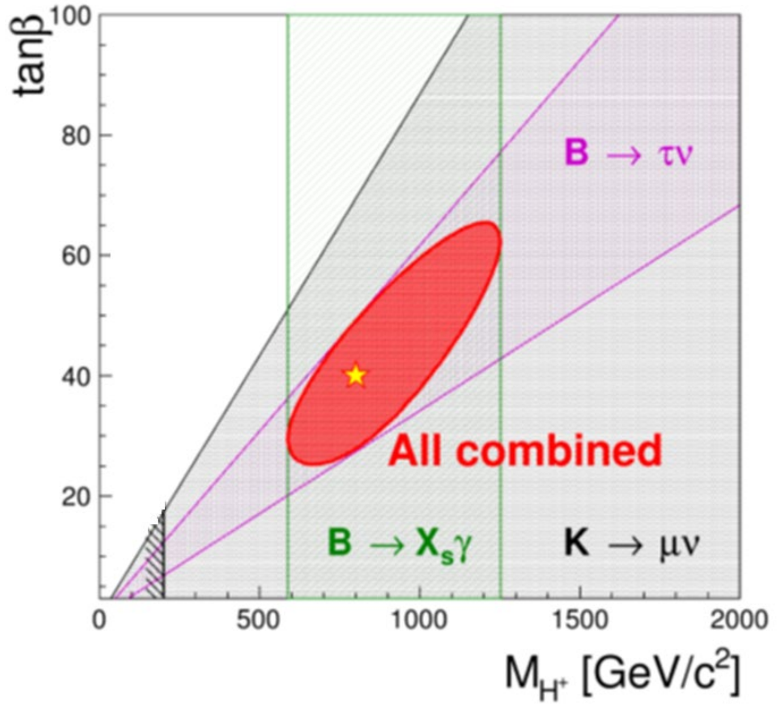
$$R_{\rm pl}^{5\,{\rm ab}^{-1}} = 222 \pm 76\,, \qquad R_{\rm pl}^{50\,{\rm ab}^{-1}} = 222 \pm 26\,.$$

- Interval on r_{NP}^τ

Luminosity	$R_{\rm ps}$	$R_{\rm pl}$
$5\,{\rm ab}^{-1}$	$[-0.22, 0.20]$	$[-0.42, 0.29]$
$50\,{\rm ab}^{-1}$	$[-0.11, 0.12]$	$[-0.12, 0.11]$

A Scenario of Evidence for Charged Higgs

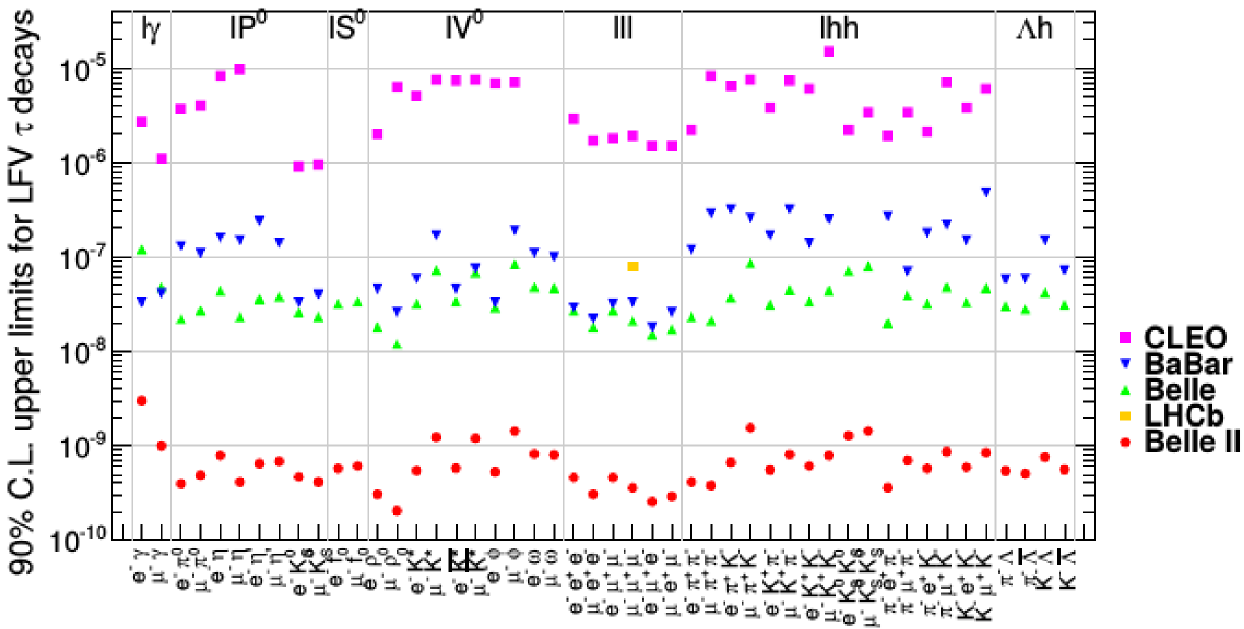
- $B \to X_s\gamma$: $\tan\beta$ independent
- $B \to \tau\nu$: $\tan\beta/m_H$ = const.
- With 50/ab, M_{H+}=800GeV and $\tan\beta$=40 can be found.



Belle II Physics book 1808.10567

Lepton Flavor 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, these are clear NP signals
- Unique at Belle II.
  - LHC can only search for $\tau \rightarrow 3\mu$ and $\tau \rightarrow p\mu\mu$ but worse than Belle II.
  - Muon case, three experiments search for $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, and μ-e conv. while Belle II can do the three for τ case, $\tau \rightarrow \mu\gamma$, $\tau \rightarrow \mu l^+l^-$, and $\tau \rightarrow \mu hh$.
- Upper limits of $O(10^{-9})$ or less are possible



Single Photon Trigger

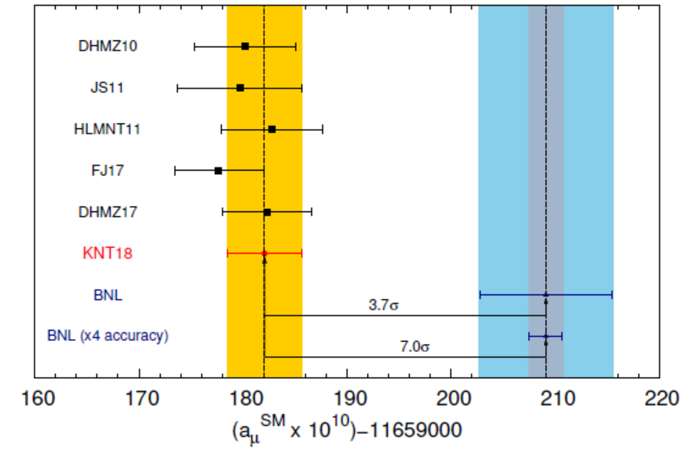
- At Belle, single photon trigger was not implemented
  - Large trigger rate due to large background events
  - So $e^+e^- \rightarrow \pi^+\pi^-\gamma$ and $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow$ invisible could not be studied

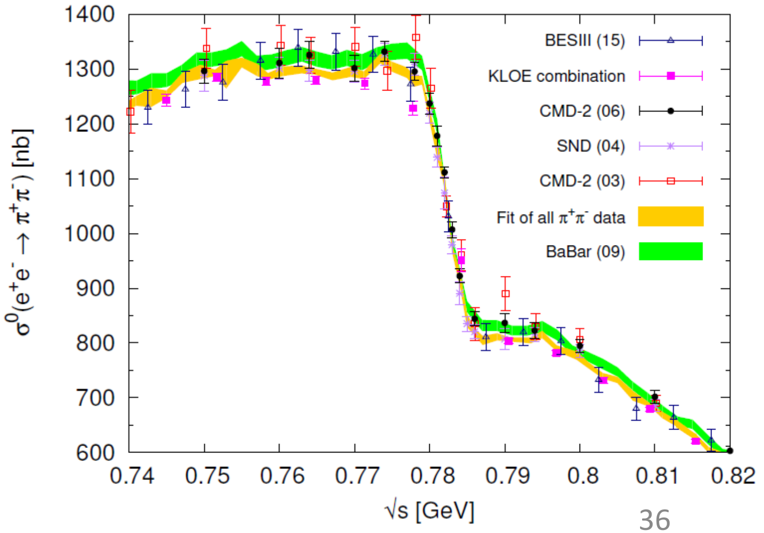
- At Belle II, trigger and DAQ system has been upgraded and the trigger was implemented
  - Radiative return measurement and Dark Sector search are possible!

Radiative Return : $\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)$

- If current muon g-2 anomaly is true, this suggests NP in EW scale.
  - Need to improve both exp and theory
- Radiative return is important for SM calculation for muon g-2
- There is a tension between KLOE and Babar around ρ peak
- We can measure $\sigma(e^+e^- \rightarrow \pi^+\pi^-\gamma)$ at least with a similar sensitivity as Babar (which is already systematic dominant).
  - Larger data set might allow to reduce the systematic uncertainties
  - Dominant ones
    - Luminosity 0.34%
    - Pion-ID 0.24%
  - It takes a few years to reach such small systematics

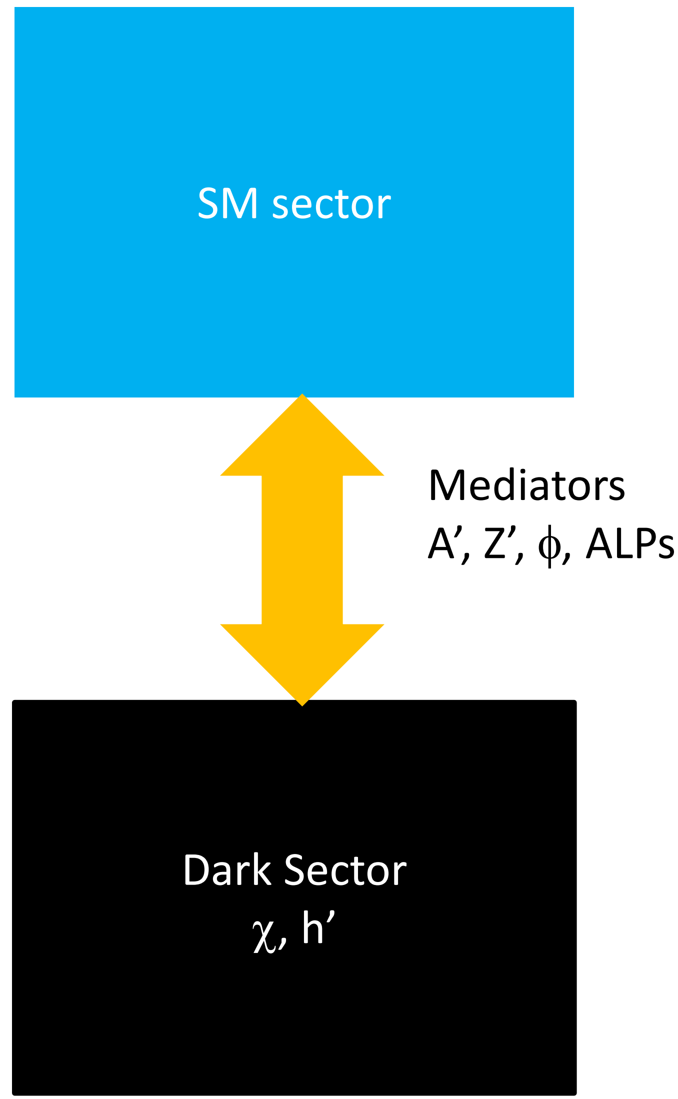
A. Keshavarzi, D. Nomura, T. Teubner 1802.02995





Dark Sector Searches

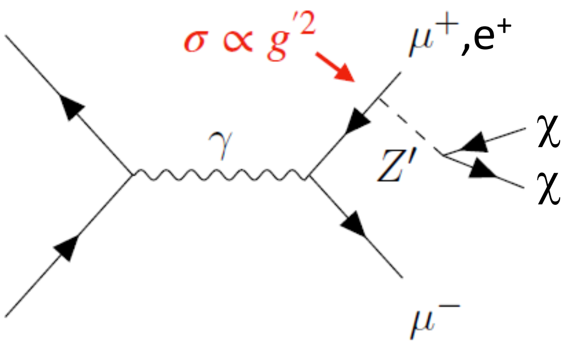
- Very Rich program
  - Unique E_{CM} ~ 10GeV
  - Highest Luminosity → low cross section
- Trigger is the key
  - We implemented single photon trigger!
- Many NP models
  - $L\mu$-$L\tau$ gauged Z' in ee→$\mu\mu\mu\mu$, $\mu\mu\nu\nu$
  - ALPs in ee→aγ (a→$\gamma\gamma$)
  - Extra U(1) Model
    - Dark photon A'
      - kinetic mixing with SM photon $\varepsilon^2=\alpha/\alpha_{EM}$
    - Dark Higgs h'
    - Inelastic dark matter χ_1 χ_2
  - dark scalar in Y(nS)→$\gamma\phi$ and B→Kϕ
    - Long lived also possible
  - And your models

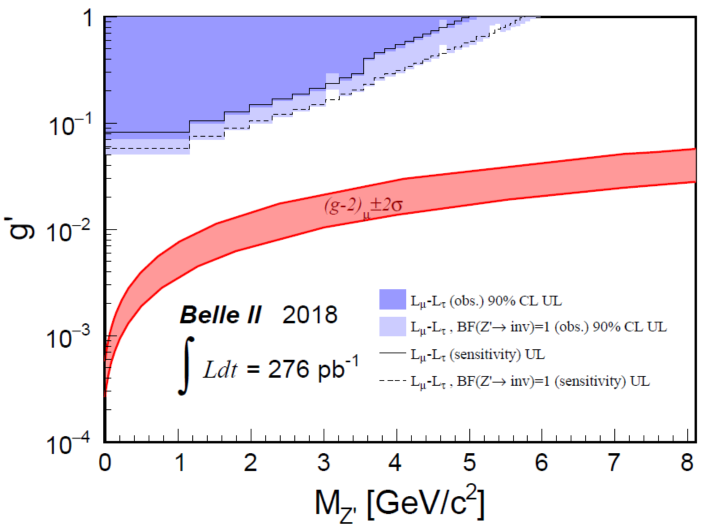


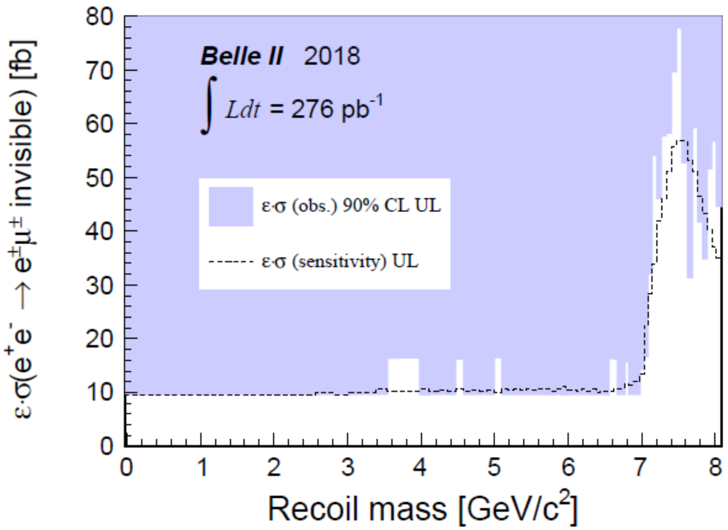
Phys. Rev. Lett. 124, 141801 (2020)
arXiv:1912.11276

The First Physics Paper

- Dark Z' search paper
  - $e^+e^- \rightarrow \mu\mu Z'$ or $e\mu Z'$, $Z' \rightarrow$ invisible
    - Z' in $L\mu$-$L\tau$ model
    - LFV Z'
    - Both are the first searches
  - With 276 pb^{-1}



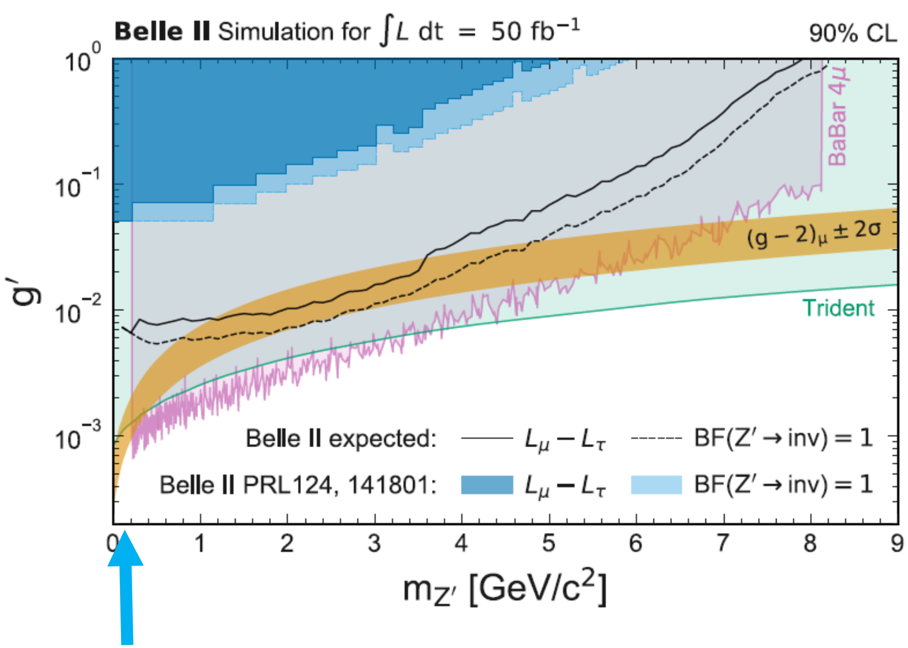




With 50fb^{-1}

We already have 213fb^{-1}

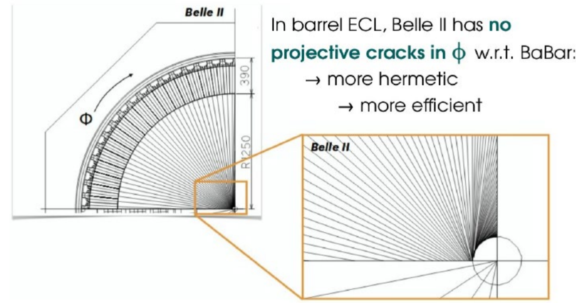
- $e^+e^- \rightarrow \mu\mu Z'$, $Z' \rightarrow$ invisible
  - $g' < 10^{-2}$ for $m_{Z'} < 2m_\mu$

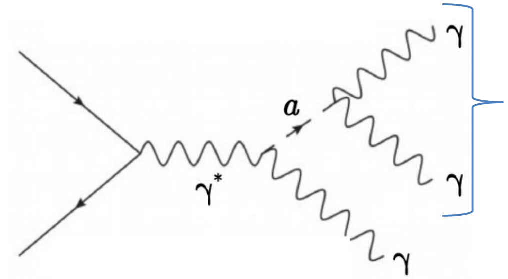


Invisible mode is accessible to $m_{Z'} < 2m_\mu$ region
to which is not possible with $Z' \rightarrow \mu\mu$

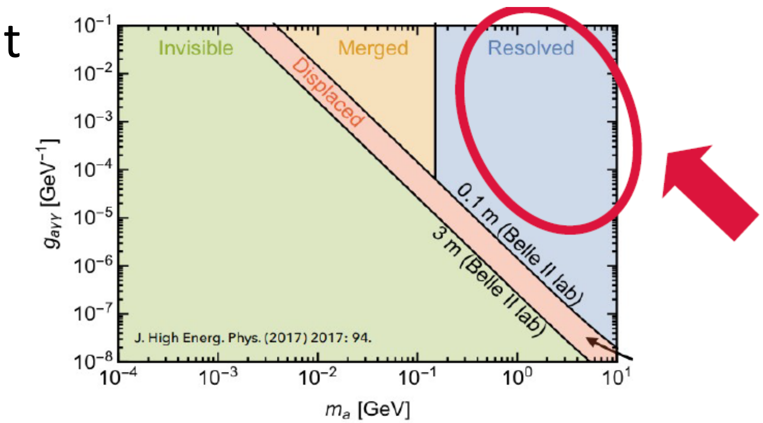
Phys. Rev. Lett. 125, 161806 (2020)
https://arxiv.org/abs/2007.13071

The Second Paper

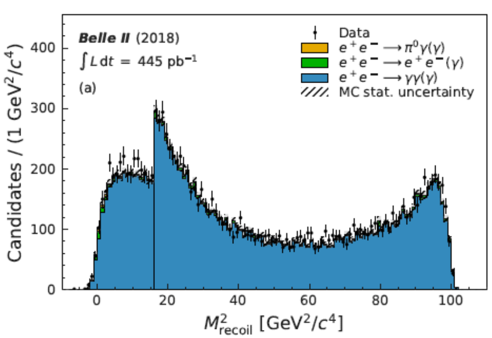




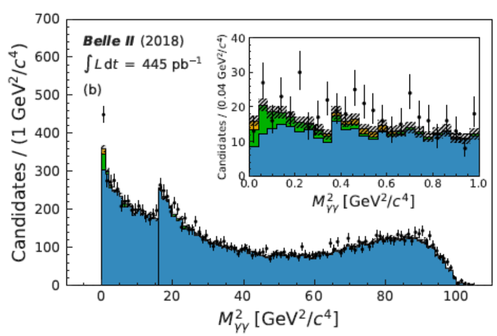
- ALPs : $e^+e^- \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$
  - With 445pb^{-1}
- No proximity ECL
- Two technique used in terms of mass resolut
  - Invariant mass for mA<16GeV
  - Recoil mass for mA>16GeV
- Best limits around 500MeV
- This region is only accessible with Belle II.

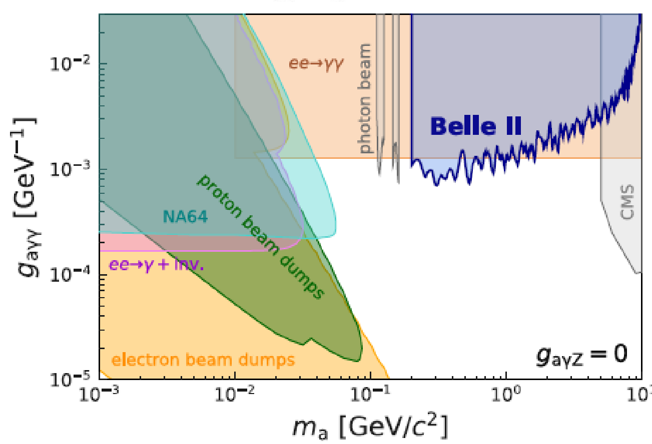


Recoil mass



Invariant mass

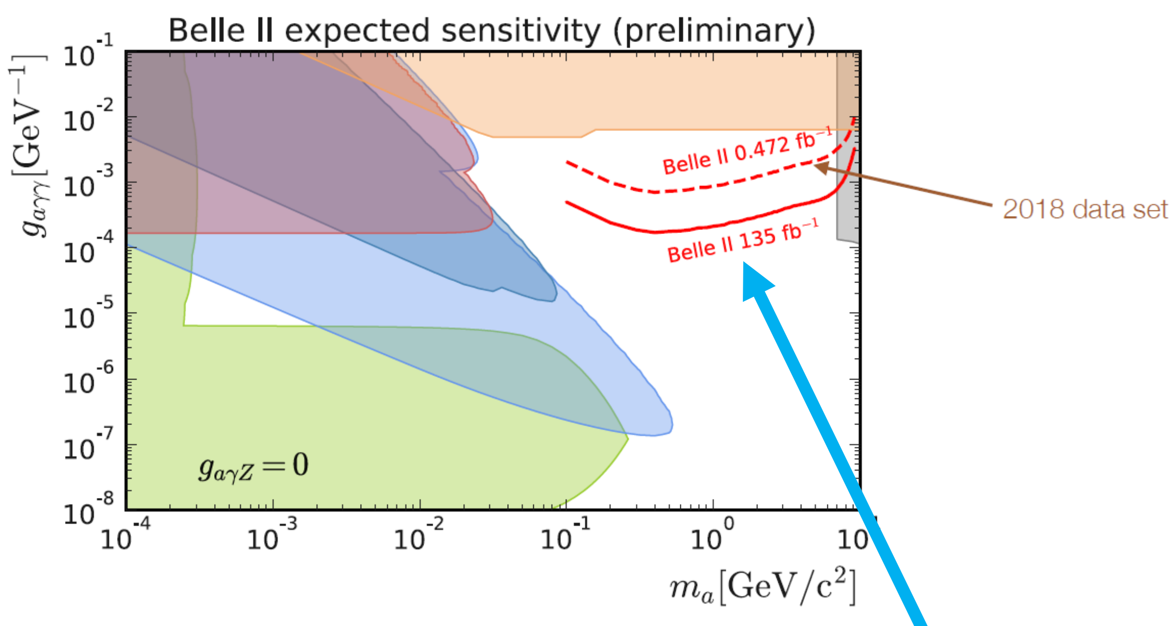




With 135fb^{-1}

We already have 213fb^{-1}

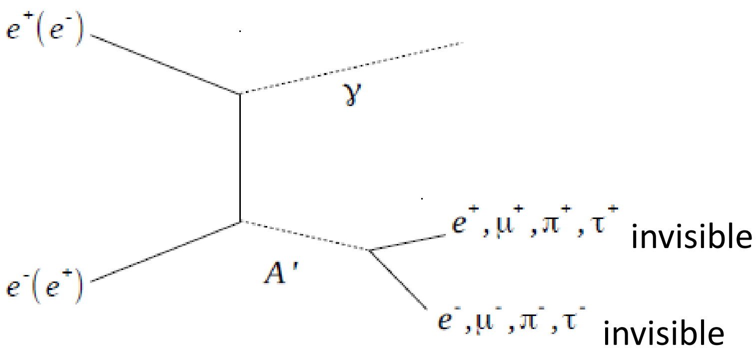
- ALPs : $e^+e^- \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$
  - $g_{a\gamma\gamma}$~10^{-4}



This region is only accessible with Belle II.

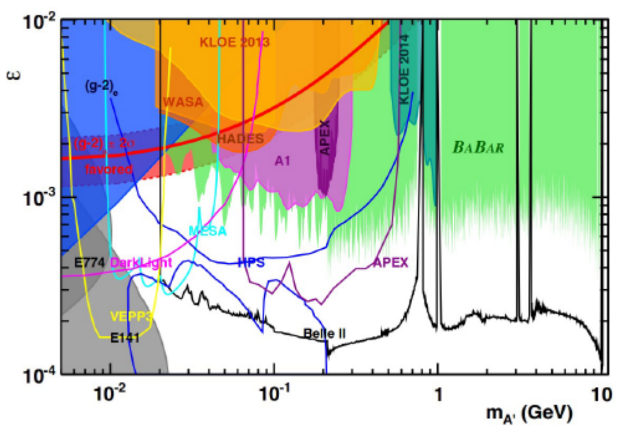
Dark Photon A’

- Extra U(1) model
  - Kinetic mixing with SM photon
  - Both visible and invisible decays

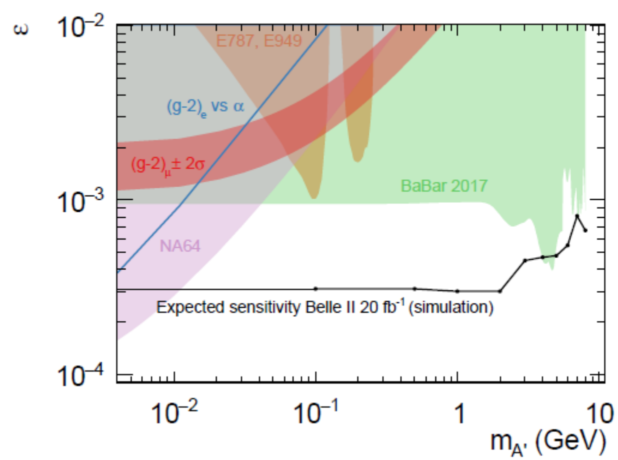


Visible decays with 50ab^{-1}

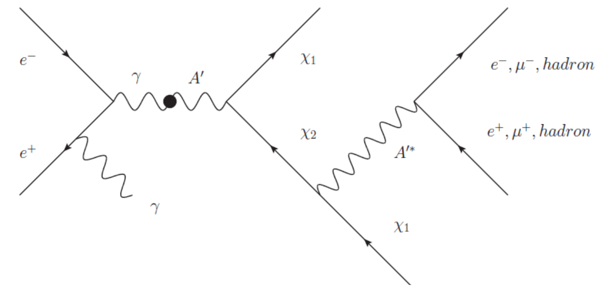
$e^+e^- \to \gamma A' \to \gamma e^+ e^-, \gamma \mu^+ \mu^-$, *prompt*



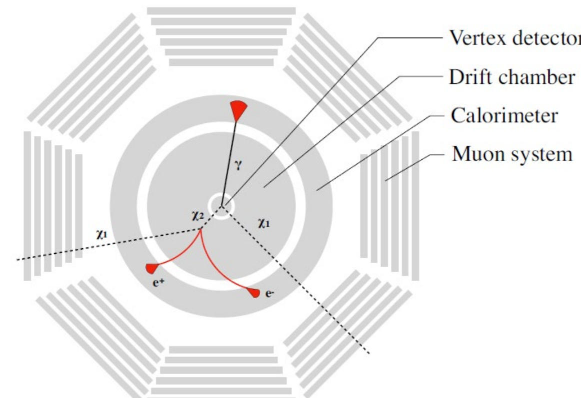
Invisible decays 20fb^{-1}



Inelastic Dark Matter

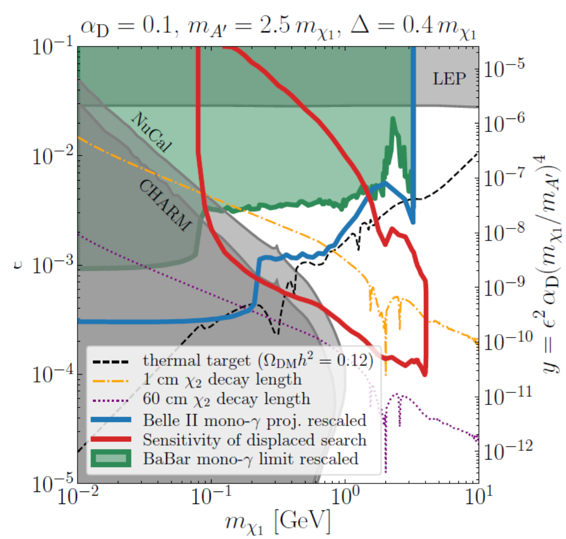


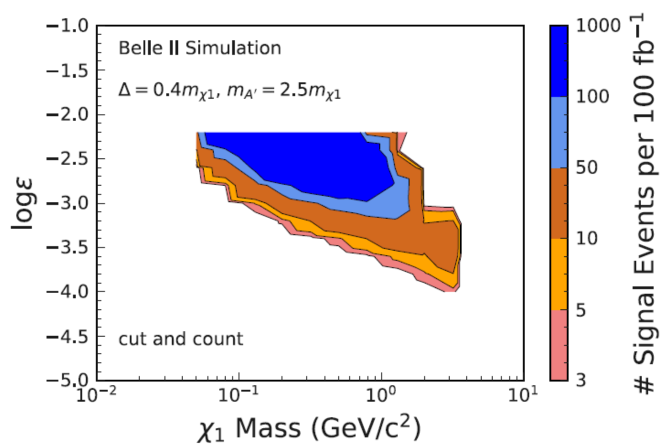
- Dark photon and two dark matter χ_1 and χ_2 with small mass splitting → can be long lived



5 parameter model:
$m_{A'}$ (fixed relative to $m_{\chi 1}$)
$m_{\chi 1}$ (scan)
mass difference $\Delta = m_{\chi 2} - m_{\chi 1}$ (categorical)
dark coupling α_D (fixed to benchmarks)
kinetic mixing parameter ε (limit)

- The event tagged with photon but we are developing the dedicated trigger for displaced tracks.





JHEP 02 (2020) 039

Summary

- Belle II started physics run in 2019 with almost full detector
- We have accumulated 213fb^{-1} so far
- Wide physics coverage
  - B physics
  - Charm physics
  - Tau physics
  - Radiative return
  - Dark sector searches
- The 1st and 2nd paper on dark sector published.
- The 3rd paper on $B \rightarrow K\nu\nu$ submitted to PRL.

https://confluence.desy.de/display/BI/Public+Belle+II+Publications

- We are resuming the operation from Oct 2021 aiming to accumulate ~700fb^{-1} by next summer.

- Stay tuned.

Flavor Physics Workshop 2021

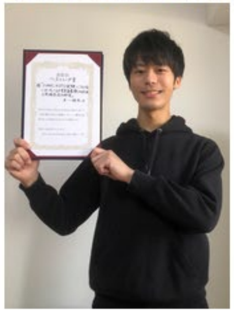
- 今年も FPWS を開催します。
- 学生の発表には Best Talk Awards の表彰もありますので、よろしければ参加して下さい。テーマは Flavor じゃなくても、皆が楽しければOKです。

ベストトーク賞

浅井 健人 (東京大)
"Search for U(1)_{mu-tau} charged Dark Matter with neutrino telescope"

鷲見 一路 (名古屋大)
"KEKテストビームライン建設に向けたビーム輸送シミュレーション"

乃一 雄也 (大阪大)
"J-PARC KOTO実験におけるハローKL→2γ背景事象数の評価と削減方法の研究"



小川 真治 (東京大)
"MEGII実験にむけた液体キセノンガンマ線検出器の開発"

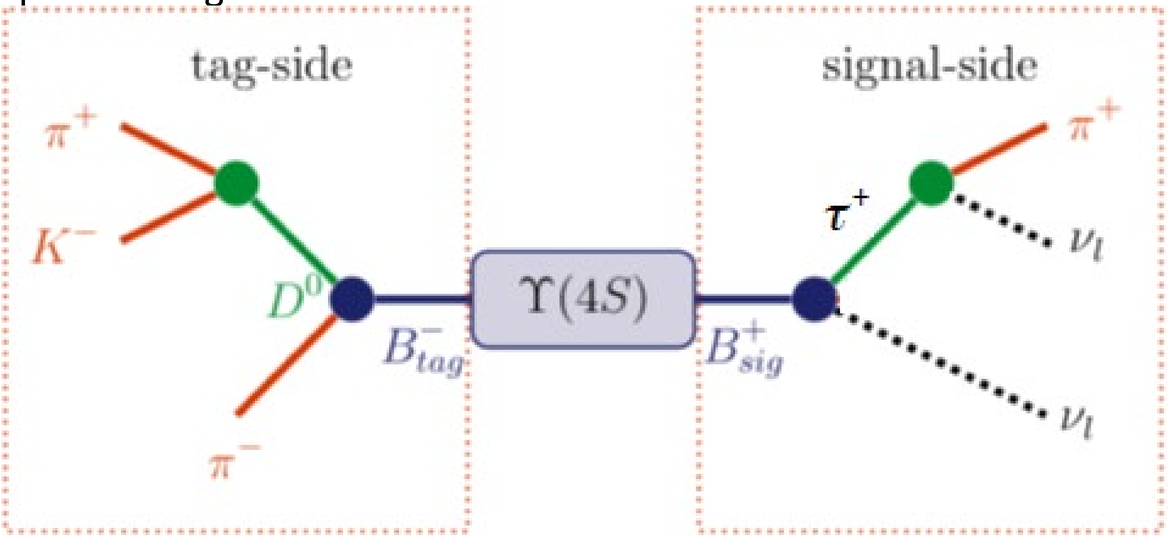
https://agenda.hepl.phys.nagoya-u.ac.jp/indico/conferenceDisplay.py?ovw=True&confId=1771

Thank you for your attention

backup

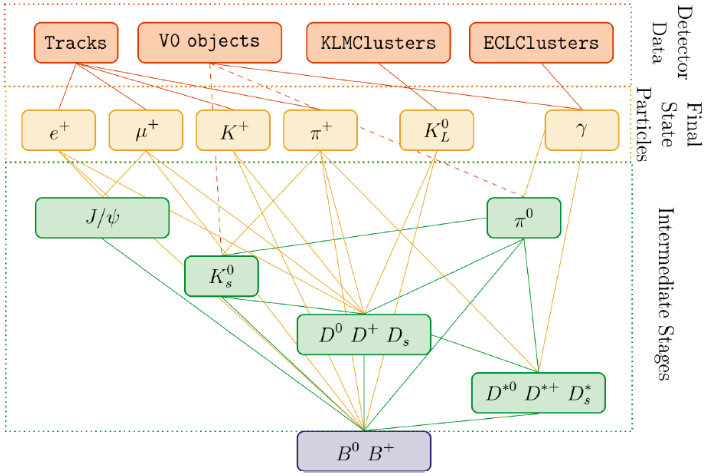
B Decays with Multiple ν

- We need to tag the other B meson which is not so easy at LHCb.
  - Can go to rest frame of the other B meson thanks to 4-momentum conservation
  - B→Dτν, B→τν, b→sνν , b→sττ
- Three tagging methods
  - Inclusive tag
  - Hadronic B tag
  - Semileptonic B tag



Improvement of Tagging

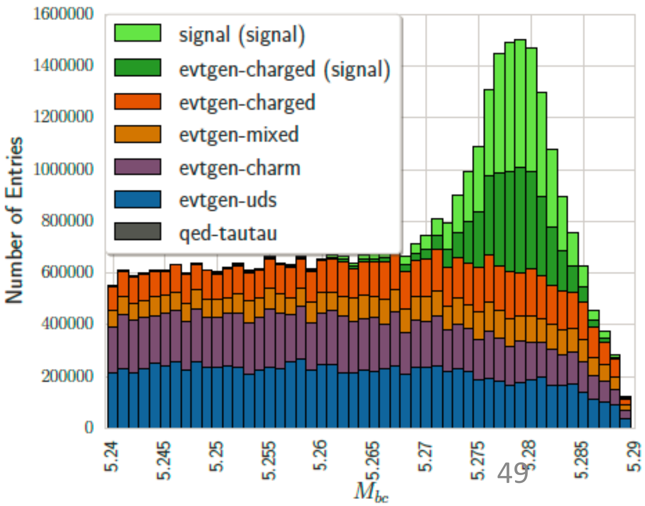
- Full Event Interpretation (FEI)
  - Tagging method using multivariate technique
    - Hierarchical reconstruction
  - More tagging modes than Belle 1
  - Both hadronic decays and semileptonic decays can be used
- About 2 times better tagging efficiency than Belle 1 (FR).



Improvement of Algorithm

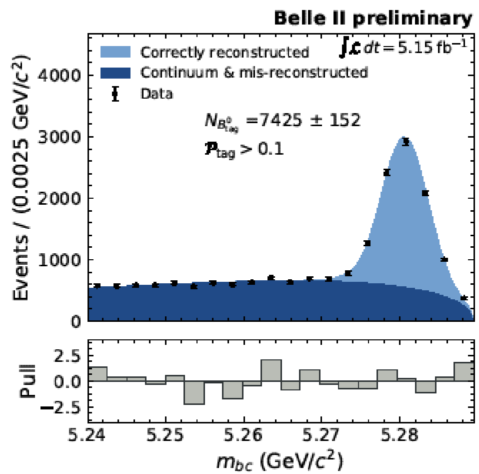
Improvement of Detector and Increase of Background effects

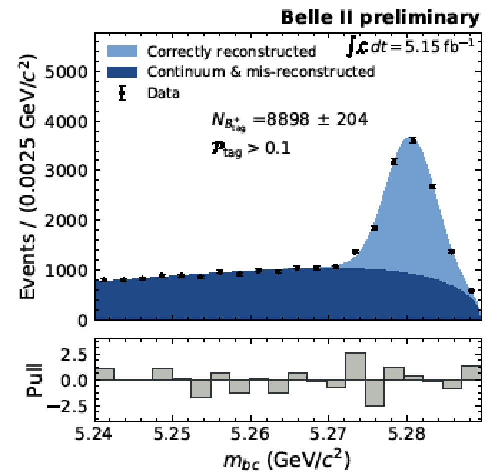
Tag	FR[4] @ Belle	FEI @ Belle MC	FEI @ Belle II MC
Hadronic B^+	0.28 %	0.49 %	0.61 %
Semileptonic B^+	0.67 %	1.42 %	1.45 %
Hadronic B^0	0.18 %	0.33%	0.34 %
Semileptonic B^0	0.63 %	1.33%	1.25 %



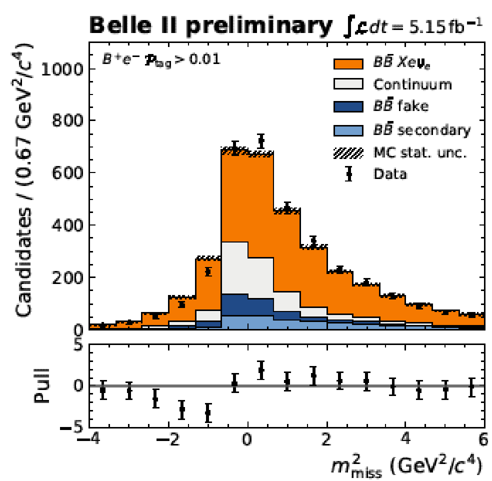
FEI with real data

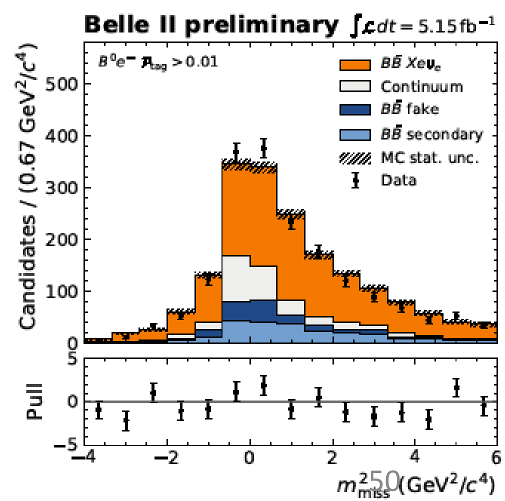
- FEI successfully reconstructed hadronic B decays





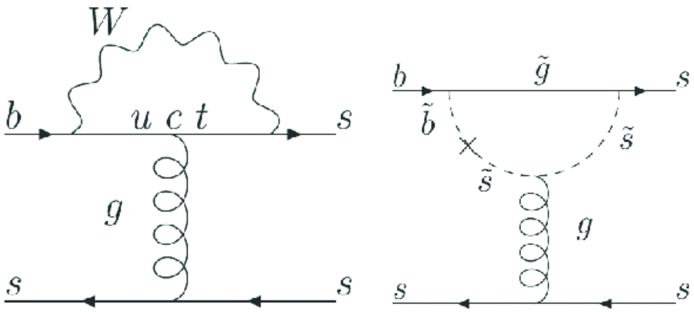
- Missing mass distributions for $B \rightarrow X e^+ \nu$ with the tagged B meson
  - Can be used for |Vcb| measurement and extraction of HQE parameters



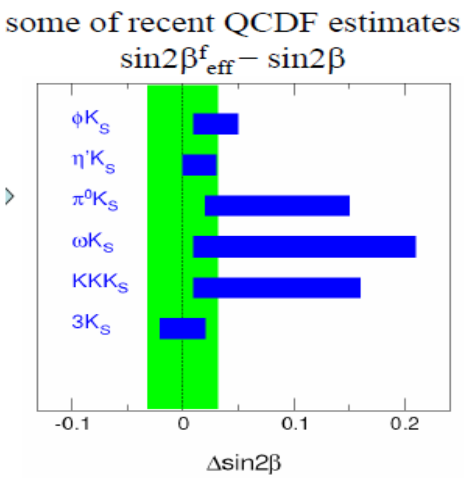


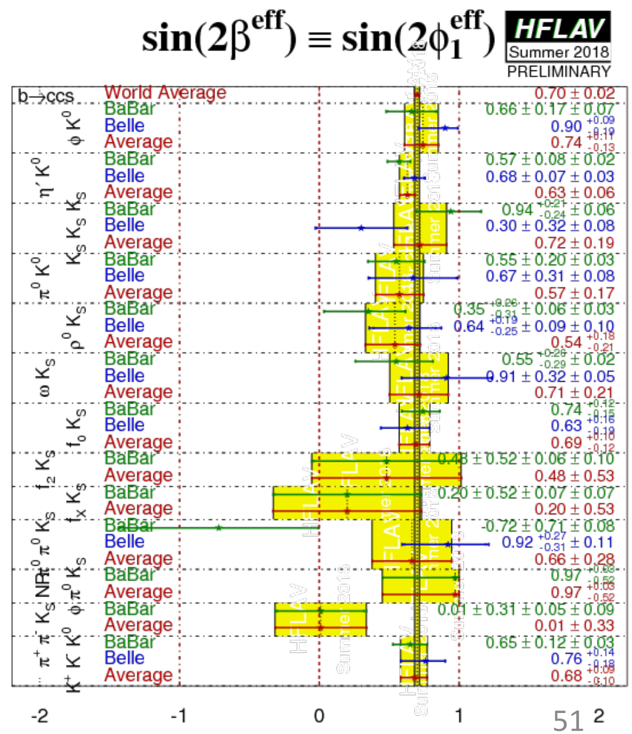
Time dependent CPV in b→s$\bar{q}$q decays

- b→s QCD penguin
  - In the SM, the CPV parameter $\sin2\phi_1^{eff}$ should be consistent with $\sin2\phi_1$ with $B \to J/\psi K^0$
  - New particles with new source of CPV phases can enter in the loop
  - If deviated from $\sin2\phi_1$, observation of NP



- Goldedn modes
  - B→φKs
  - B→η'Ks
  - B→KsKsKs
  - ~2% theoretical error



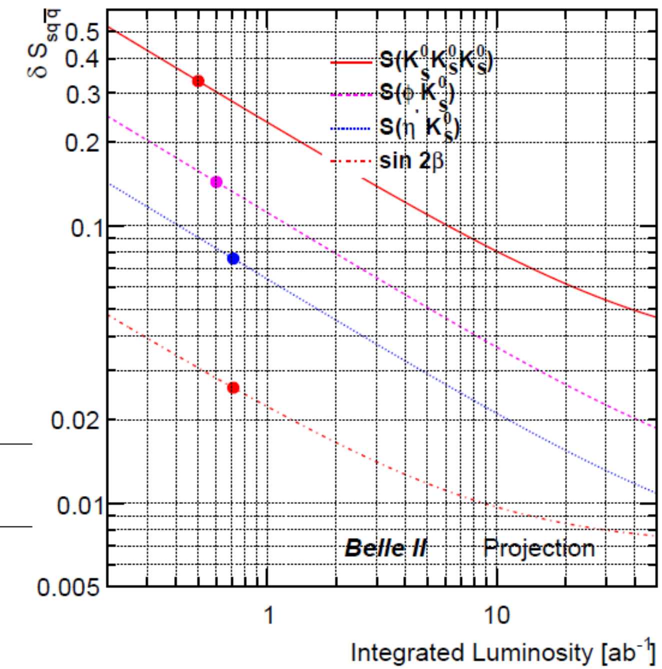


- Current measurements are consistent with $B \to J/\psi K^0$ with large errors

TDCPV in b→s$q\bar{q}$

- The error is comparable to theoretical uncertainty of 0.02

Observables	Belle		Belle II
	(2017)	5 ab^{-1}	50 ab^{-1}
$\sin 2\phi_1(B \to J/\psi K^0)$	$0.667 \pm 0.023 \pm 0.012$	0.012	0.005
$S(B \to \phi K^0)$	$0.90^{+0.09}_{-0.19}$	0.048	0.020
$S(B \to \eta' K^0)$	$0.68 \pm 0.07 \pm 0.03$	0.032	0.015



- Constraints on NP models
  - SU(5) SUSY GUT + degenerate ν_R with inverted hierarchy