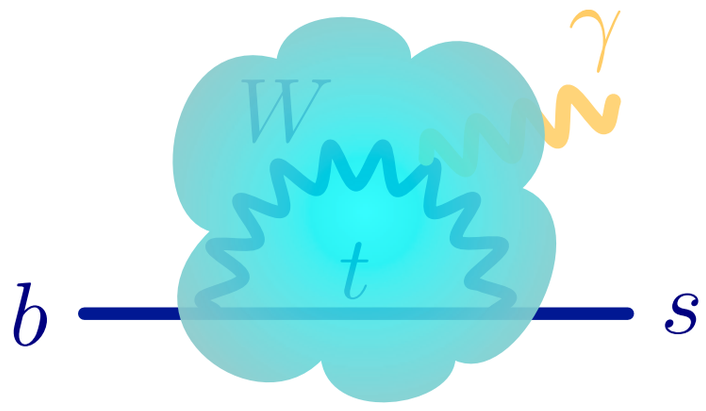
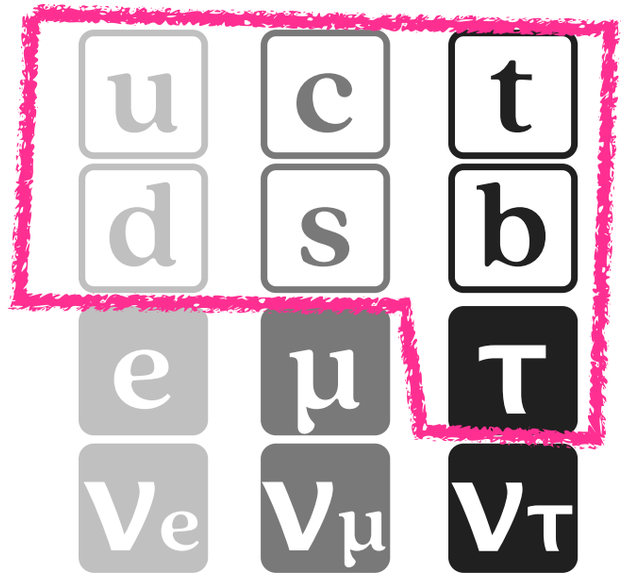
plan of the Belle II experiment to further elucidate the KM mechanism and beyond

Nanae Taniguchi (KEK IPNS)
on behalf of the Belle II collaboration

physics in B-factory

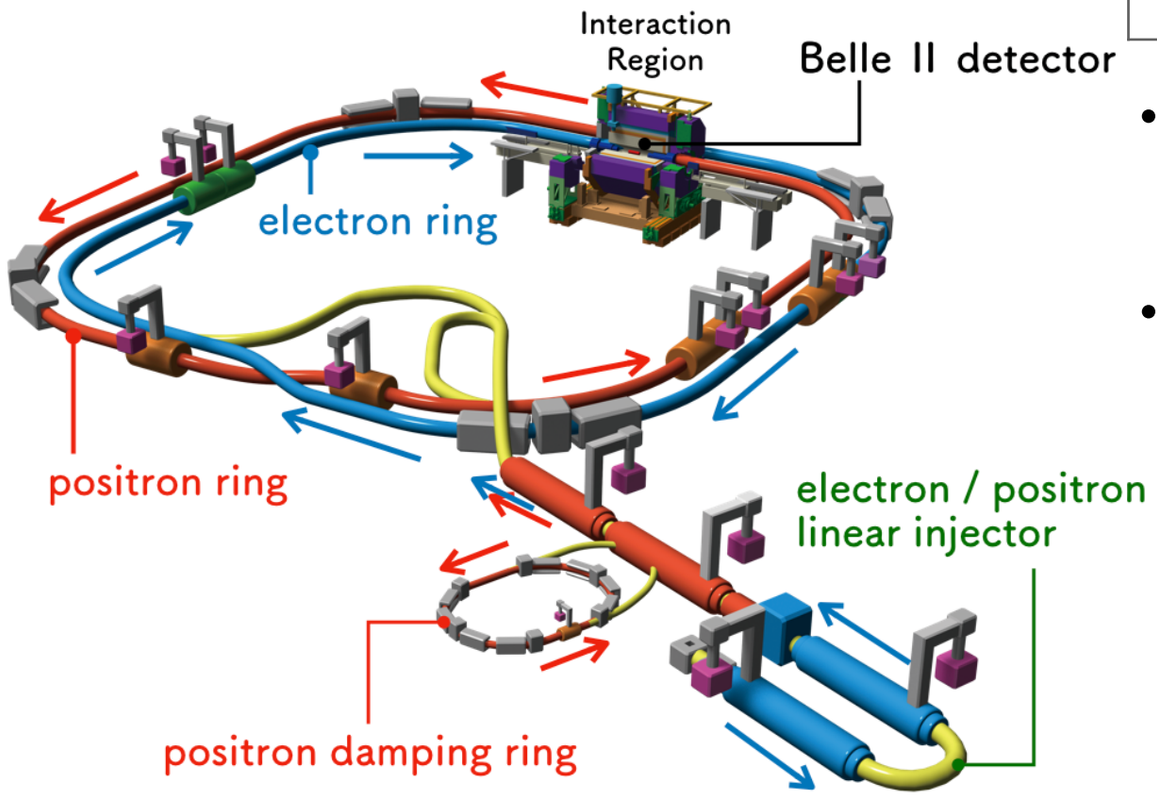




- Approach in flavor physics experiments is to search for new physics through quantum effect
- all quarks appear in B-factory
  - study coupling between new physics particles and each quark
  - include 3rd generation which is the key of CP violation
- heavy lepton, tau
  - B-factory is also tau-factory
    - Belle II collect large sample of tau-pair event

KEKB → SuperKEKB

	KEKB	SuperKEKB
electron/positron	8.0/3.5 GeV	7.0/4.0 GeV
beam size at IP (vertical β-function)	~6mm	~0.3mm
beam currents	1.4/1.7A	2.6/3.6A
Luminosity($cm^{-2}s^{-1}$)	2.1×10^{34}	60×10^{34}

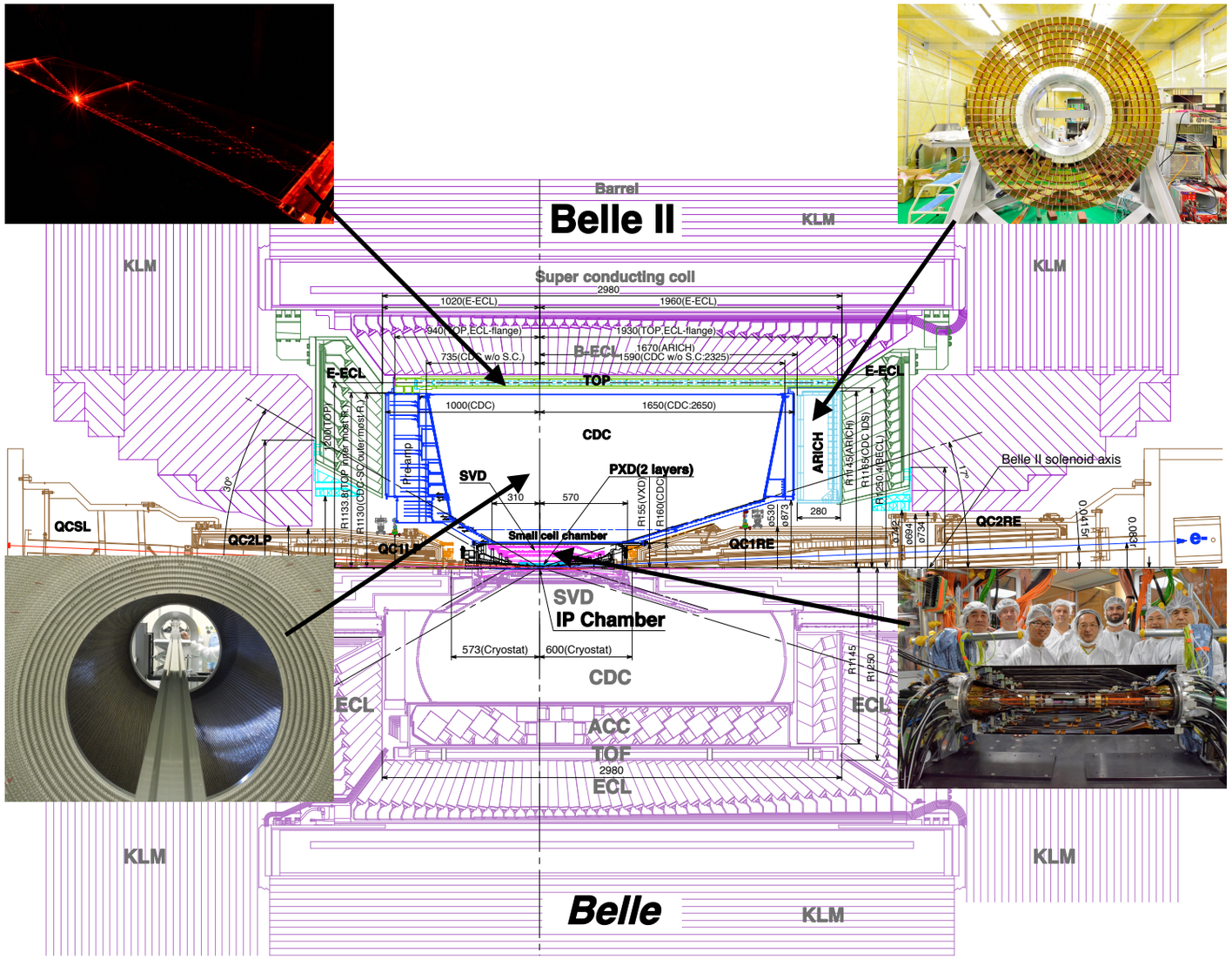


- SuperKEKB is unique ee collider at Y(4S) mass energy at this moment
- aiming to luminosity of 10^{35}
  - squeeze beam size at IP
  - increase beam currents
  - change beam energy to compensate beam life time

Belle → Belle II

multi-purpose detector

It is required to achieve higher performance at higher trigger rate and higher background condition



all detectors and systems are upgraded

background tolerance is improved by finer segment, higher time resolution

Trigger rate (500 Hz → 30kHz at Max.)

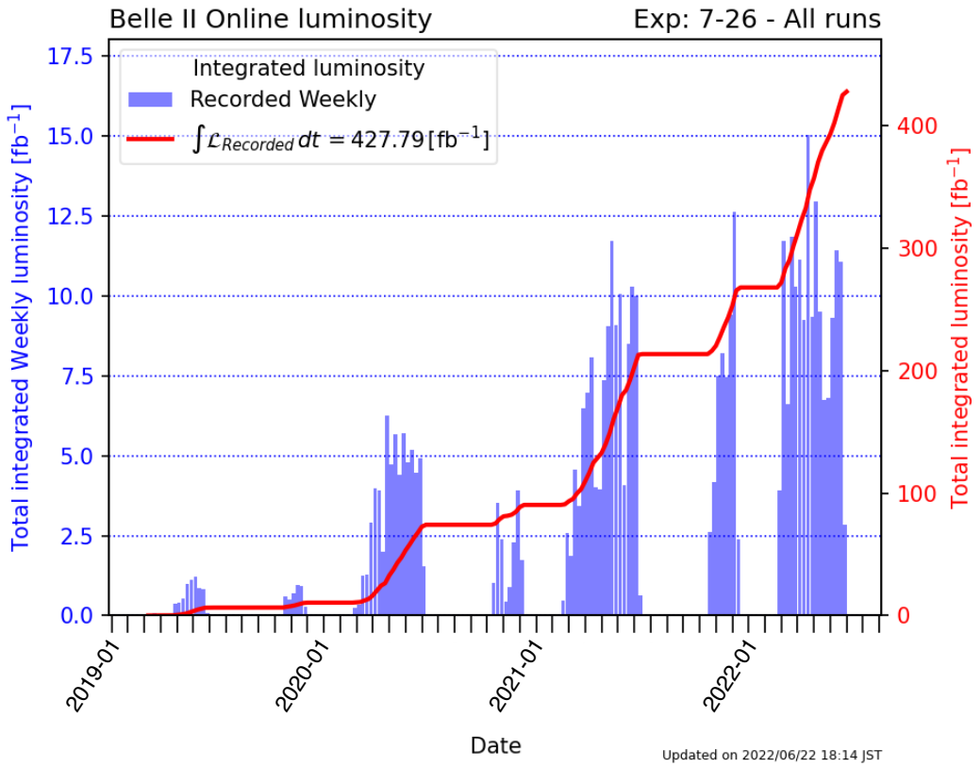
← pipe-line signal readout is implemented

new vertex detector: Pixel detector provide excellent vertexing with Si strip detector

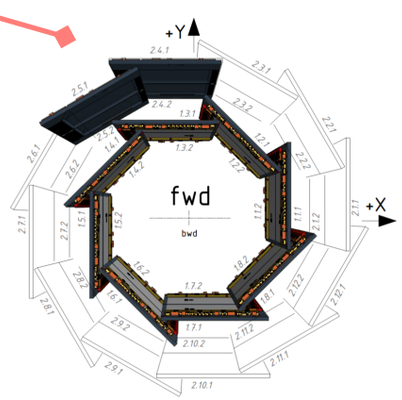
new particle ID detectors: Time Of Propagation and Aerogel Ring Image Cherenkov counter

Highlight

- 2019: physics run started
- 2020: updated luminosity record of KEKB(2×10^{34})
- 2022: L=4.7×10^{34}. new world record
- integrated luminosity 427/fb until 2022 summer
  - competitive with Babar, almost half of Belle-I
- long shutdown until 2023 autumn
  - installation of pixel detector with full 2nd layer
  - many updates and maintenance works of machine and detector are ongoing

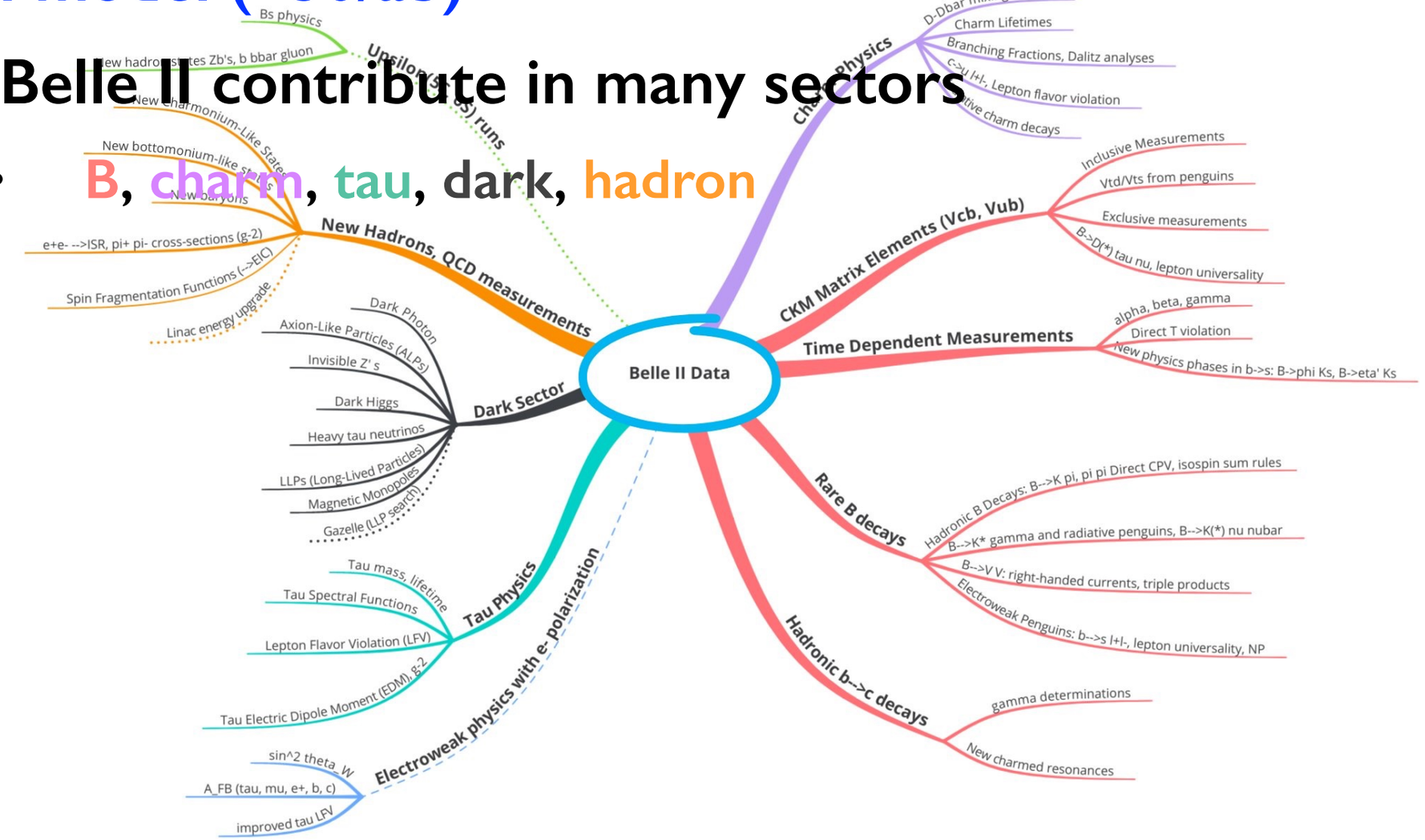


New and difficult accelerator.
Additional operational complexity during the pandemic



Belle II physics program

- Belle (1999 - 2010) : was constructed to substantiate KM model (~1/ab) achieved!!
- Belle II (2018 -) : is designed to find new physics beyond KM model (~50/ab)
  - Belle II contribute in many sectors
  - B, charm, tau, dark, hadron



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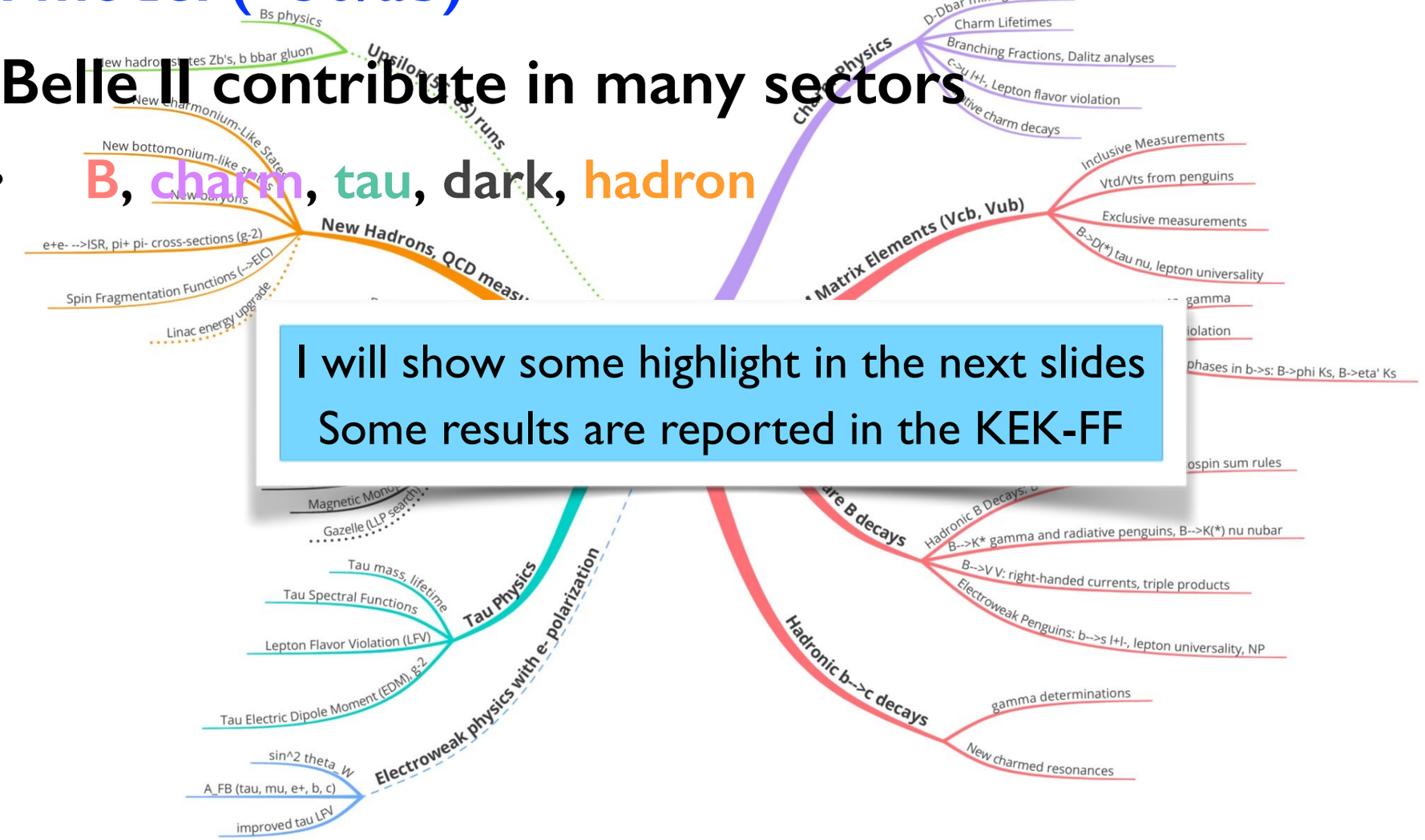
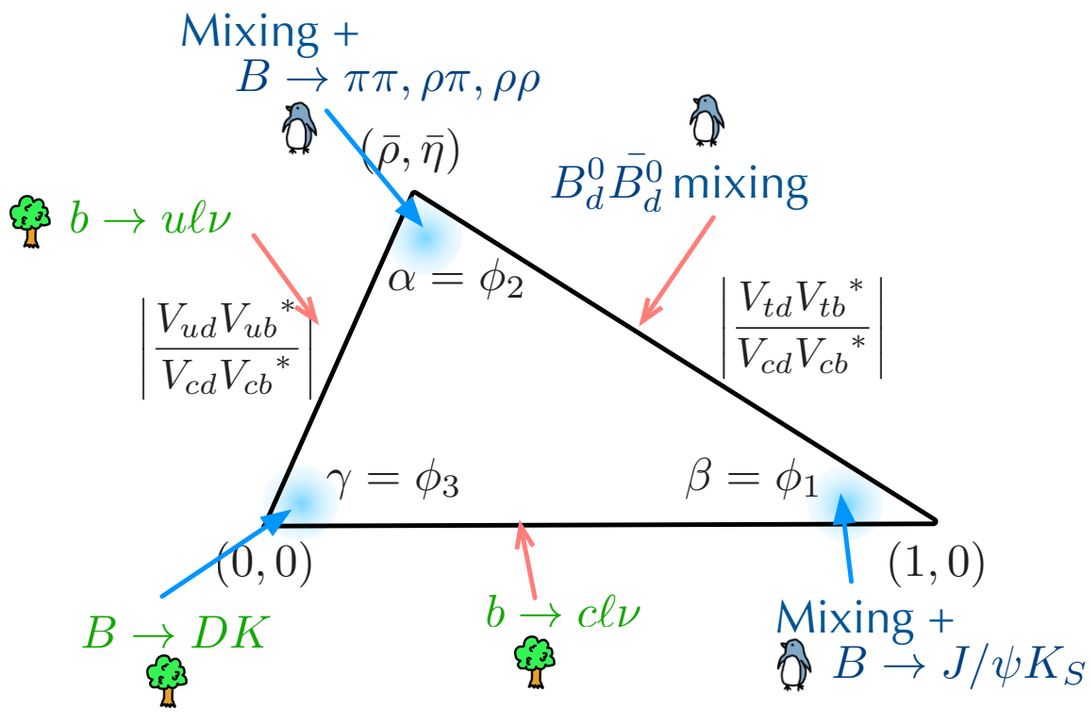


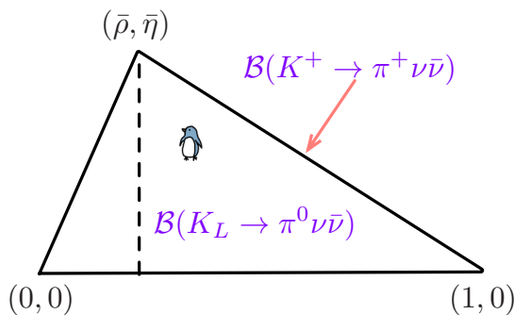
I will show some highlight in the next slides
Some results are reported in the KEK-FF

search for new physics in Mixing

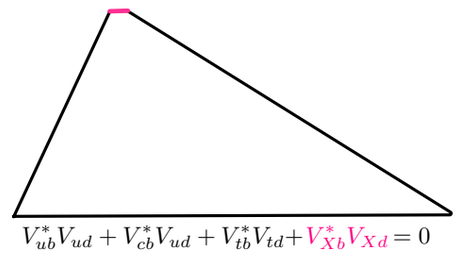
- After era of Belle and Babar, CKM elements become a precision test of the SM
- only Belle II can measure all six observables (sides and angles of unitarity triangle) precisely
- discrepancy between Tree and Loop → clear evidence of new physics !



difference from
Kaon system(2nd generation)

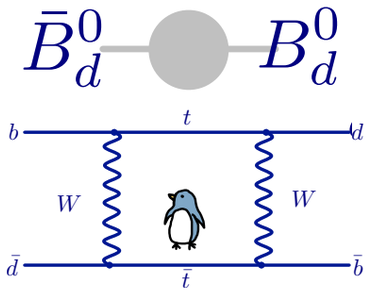


not triangle ?

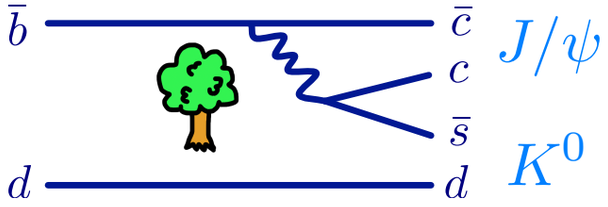


$\Phi_1(\beta)$ measurement

- Φ_1 is known as first observed CP violation in B meson
- CP violation is caused by interference between direct decay and decay via mixing
- $B \to J/\psi K_S$ decay allow to measure CKM angle Φ_1 precisely
  - Time dependent CP asymmetry. Amplitude ~ $\sin 2\Phi_1$



$b \to c\bar{c}s$ tree



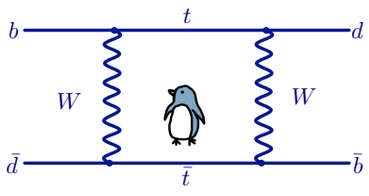
tree diagram is dominant.
it can be measured precisely.
good probe as SM reference

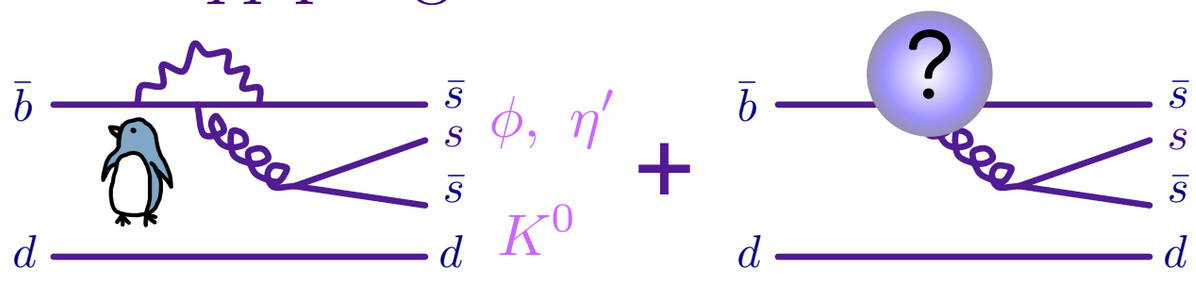
$$|B^0(t)\rangle = e^{-\frac{\Gamma_t}{2}}\left[\cos(\frac{\Delta mt}{2})|B^0\rangle + e^{i(\frac{\pi}{2}-2\phi_1)}\sin(\frac{\Delta mt}{2})|\bar{B}^0>\right]$$

$$Asymmetry(t) = \frac{|\langle J/\psi K^0_s|\bar{B}^0(t)\rangle|^2 - |\langle J/\psi K^0_s|B^0(t)\rangle|^2}{|\langle J/\psi K^0_s|\bar{B}^0(t)\rangle|^2 + |\langle J/\psi K^0_s|B^0(t)\rangle|^2}$$

$$= \sin 2\phi_1 \sin \Delta mt$$

$b \to s\bar{q}q$ penguin $\quad \sin 2\phi_1^{sq\bar{q}} \approx \sin 2\phi_1^{c\bar{c}s}$





contribution of new physics particle with CPV-phase cause deviation from SM prediction

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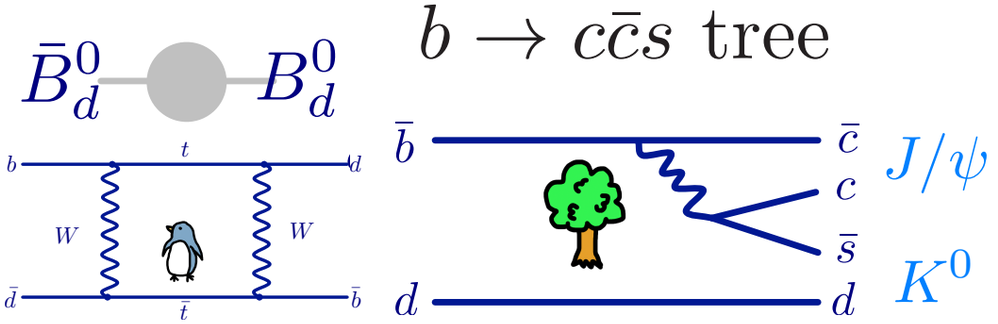
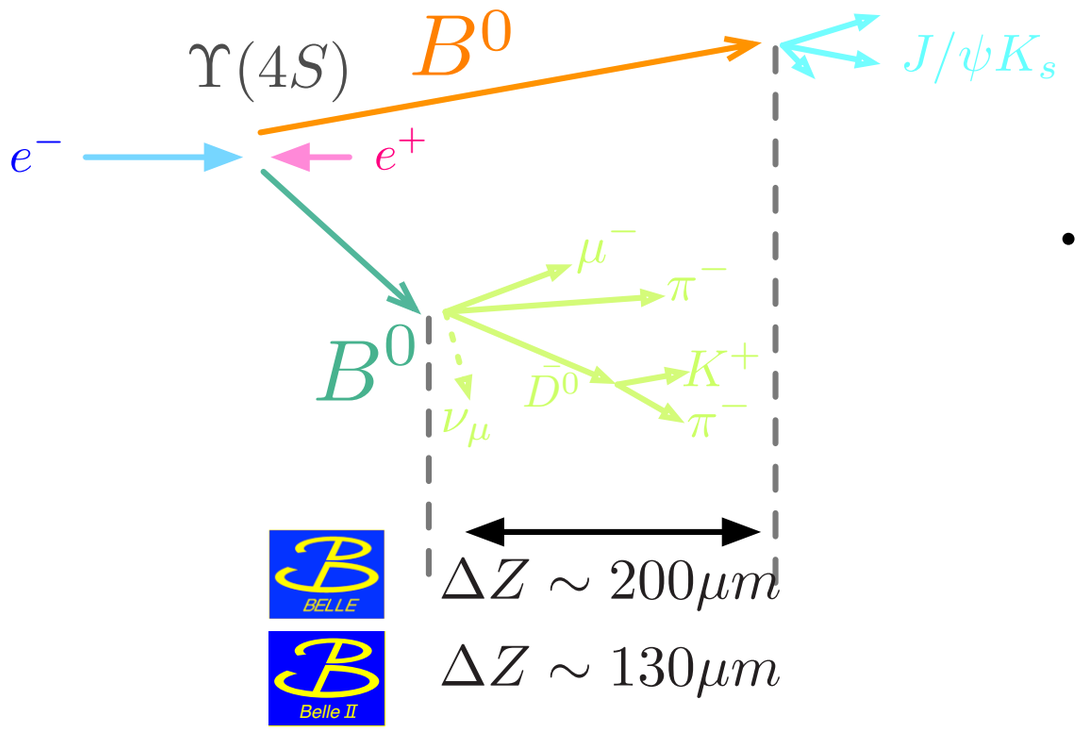
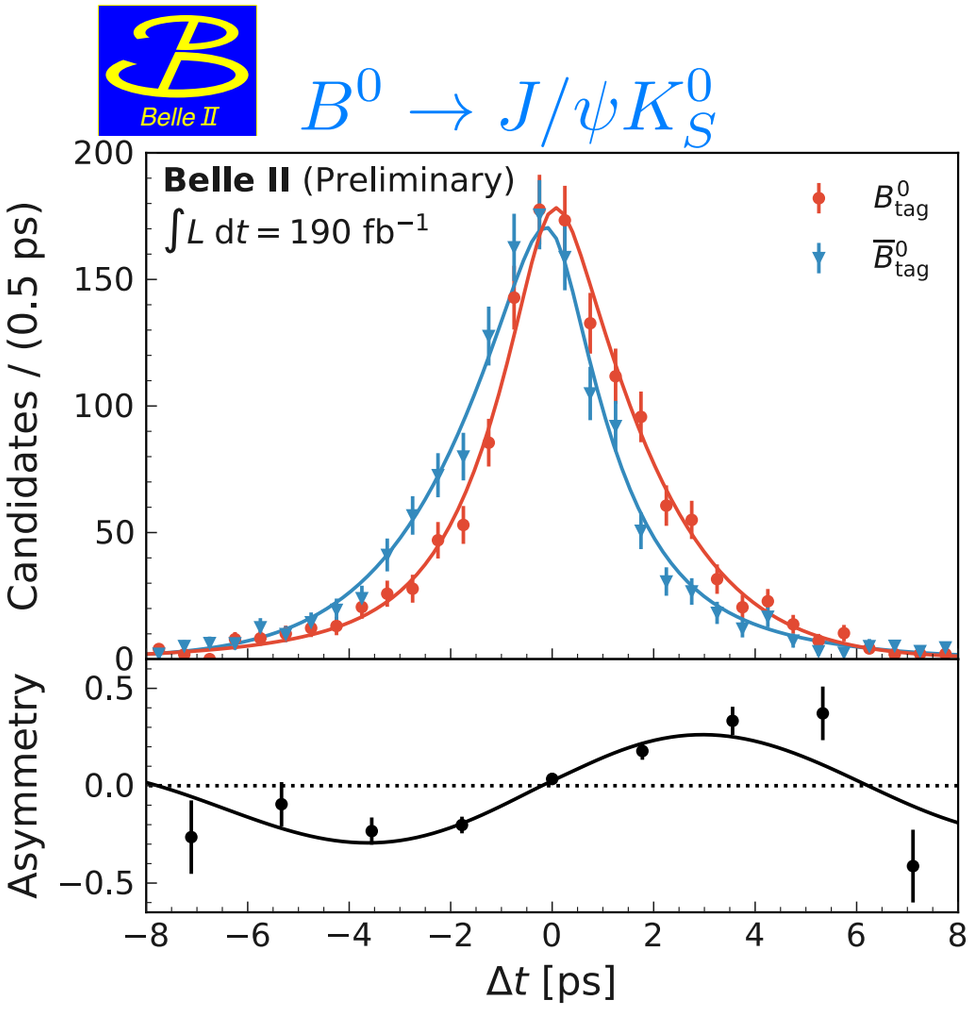




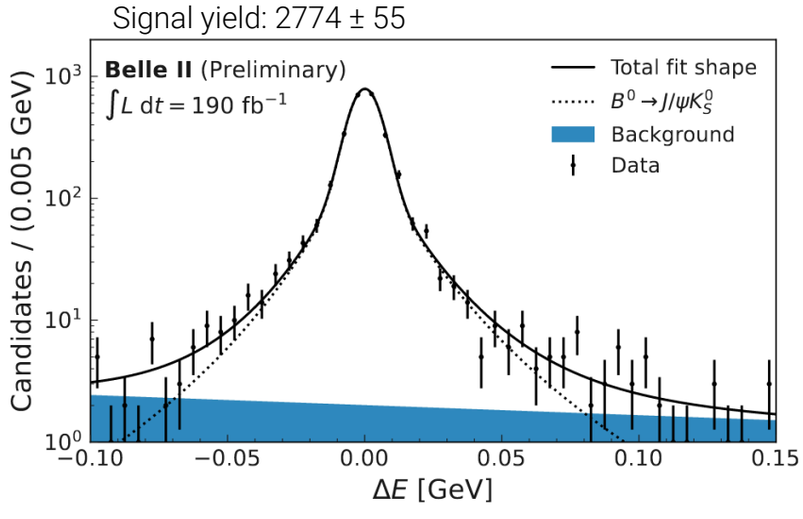
- Thanks to excellent performance of vertex detector, vertex resolution is improved
  - factor 2 better than Belle
  - small radius of beam pipe(1.5cm→1cm) recover precision on Δz since detector can close to IP
- smaller beam size give advantage on measurement of decay vertex

Φ1 measurement



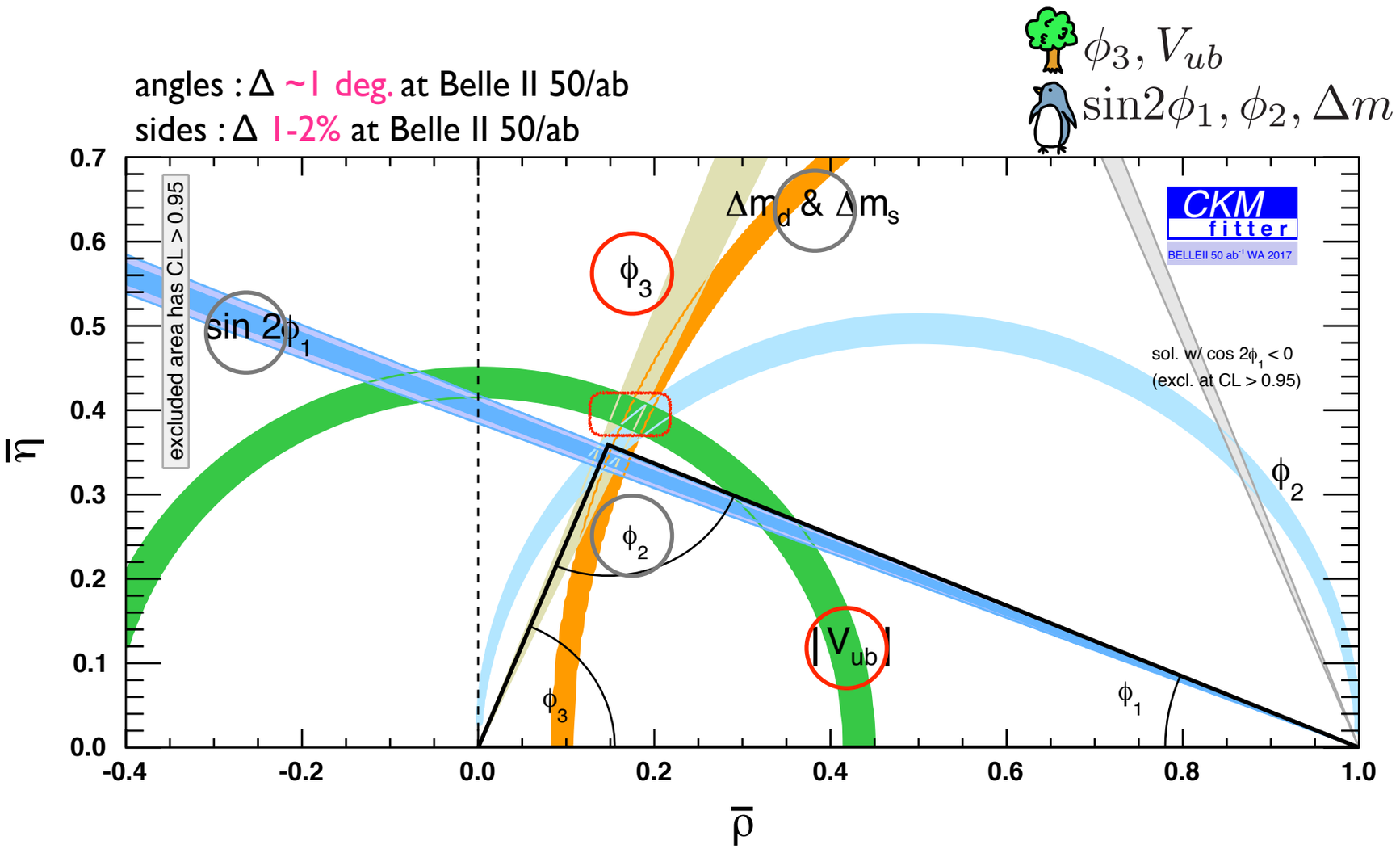
- Belle II first measurement
- consistent result with Belle
  - systematic error is comparable with Belle, thanks to improvement of detector performance
- further improvement is expected as integrated luminosity increase

$\sin 2\phi_1$ $(J/\psi K^0_S)$	
$+0.720 \pm 0.062(\text{stat}) \pm 0.016(\text{syst})$	190/fb(Belle II)
$+0.670 \pm 0.029(\text{stat}) \pm 0.013(\text{syst})$	771/fb(Belle)



Belle II prospect

- At Belle II (50/ab), angles and sides are expected to be measured with ~1deg. and 1-2% uncertainties respectively
- extrapolating the world average of 2017, clear discrepancy between tree and loop is expected



Belle II prospect for NP

Assuming new physics contribution to B mixing

mixing amplitude

$$M_{12} = (M_{12})_{\mathrm{SM}} \times (1 + h_d e^{2i\sigma_d})$$

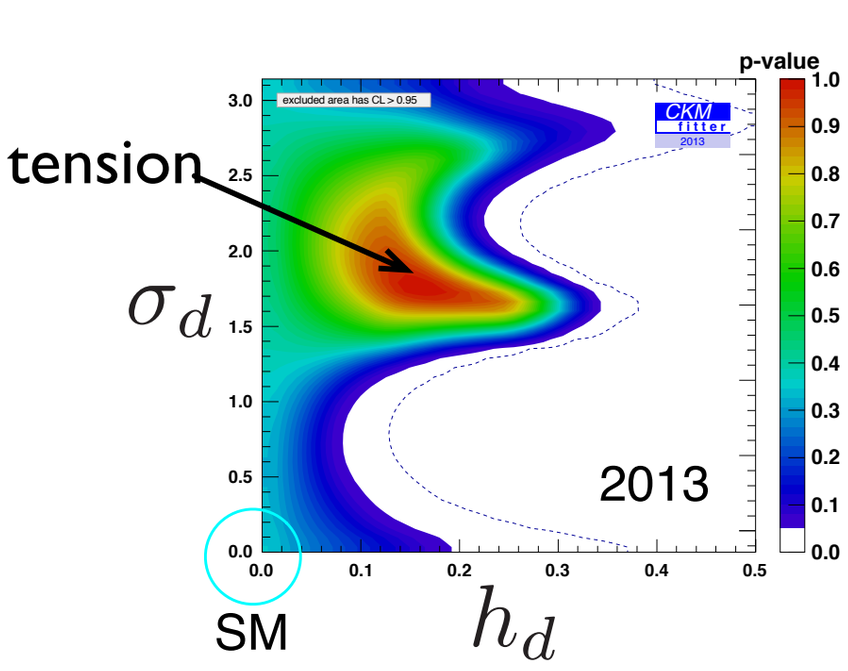
deviation from SM

coupling

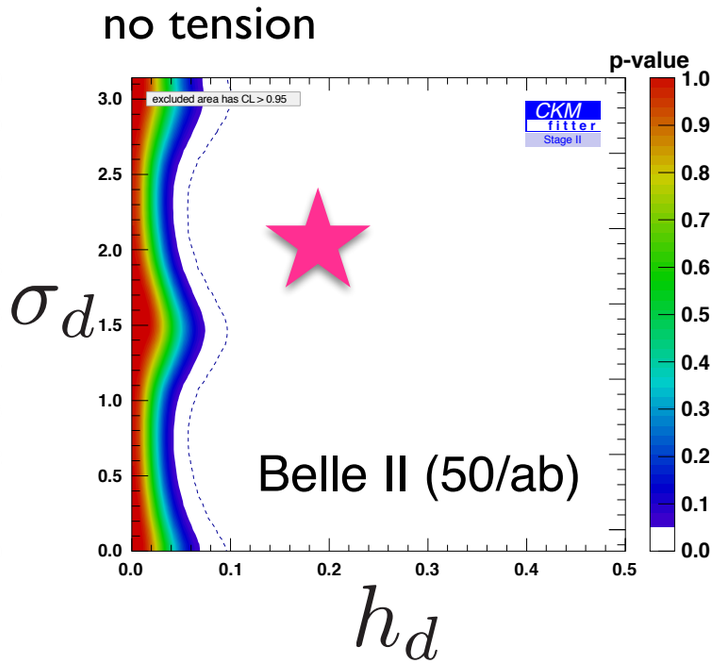
$$h \simeq \frac{|C_{bd}^{\mathrm{NP}}|^2}{|V_{tb}{}^* V_{td}|^2} \left(\frac{4.5\ \mathrm{TeV}}{\Lambda_{\mathrm{NP}}}\right)$$

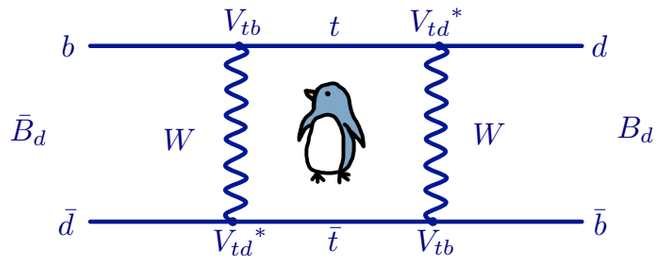
energy scale of new physics (NP) in Bd mixing

- NP flavor mixing is CKM-like : O(1)-O(10)TeV
- coupling is 1 : O(100)-O(1000)TeV



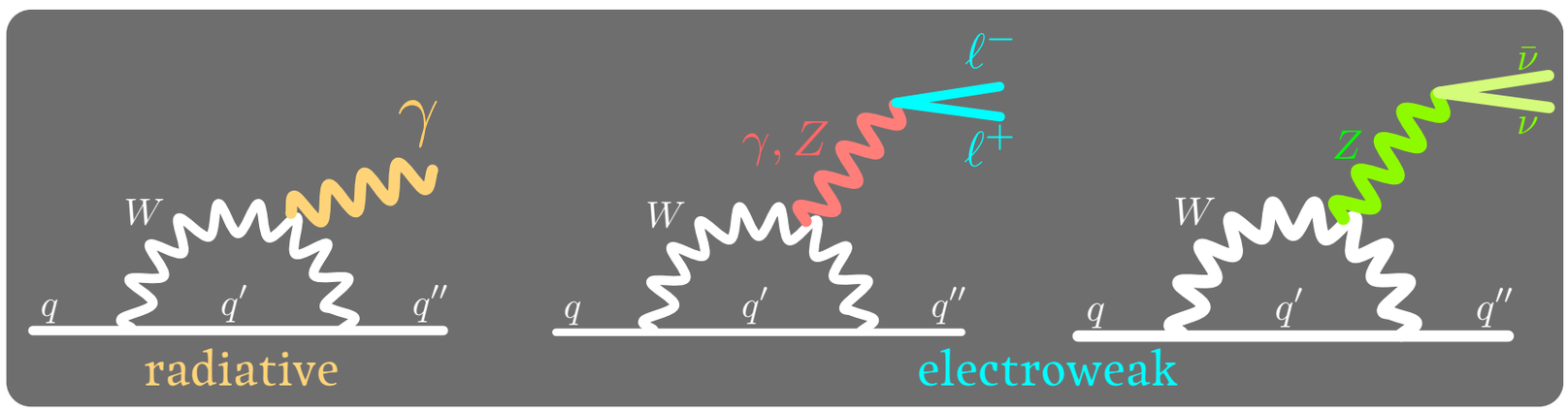
no tension





if center value doesn't change, signs of NP can be detected.

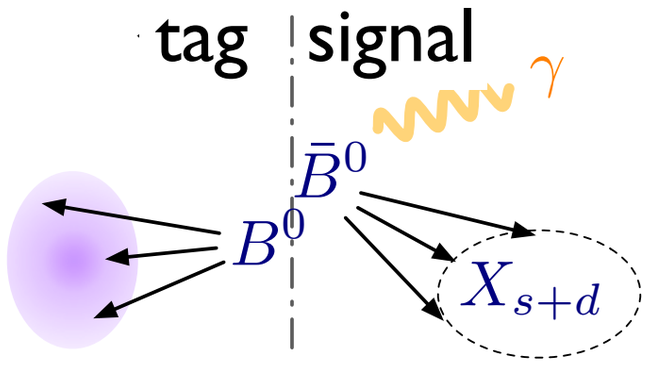
Flavor Changing Neutral Current process



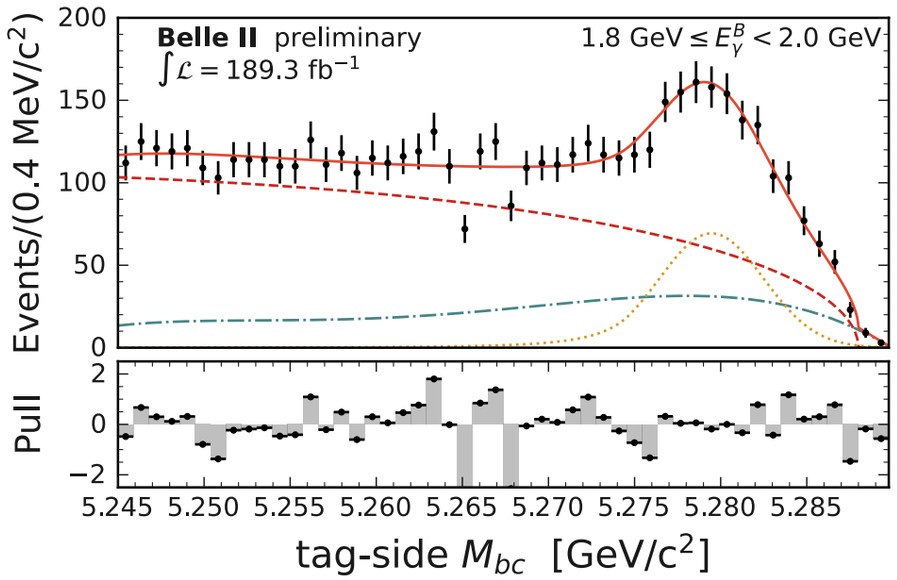
- Flavor changing neutral current b→s(d)
- loop diagram is dominant in SM → good probe for BSM
- contribution of BSM appear as deviation from SM prediction
- photon or leptons in final state → uncertainty of theoretical calculation is small
  - however, large uncertainty of hadronization (e.g. B→K*) in exclusive branching fraction(BF) measurement
- inclusive measurement
  - theoretically clean
  - experimentally difficult

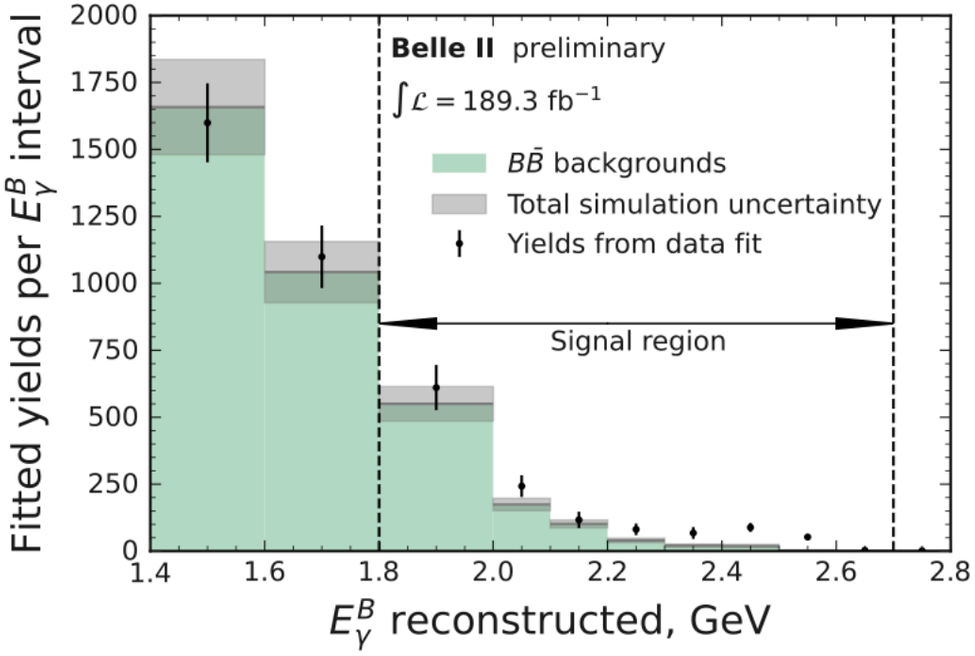
Inclusive B.F(B→Xsγ) measurement

Belle II measure B.F of inclusive b→sγ with hadronic tag.



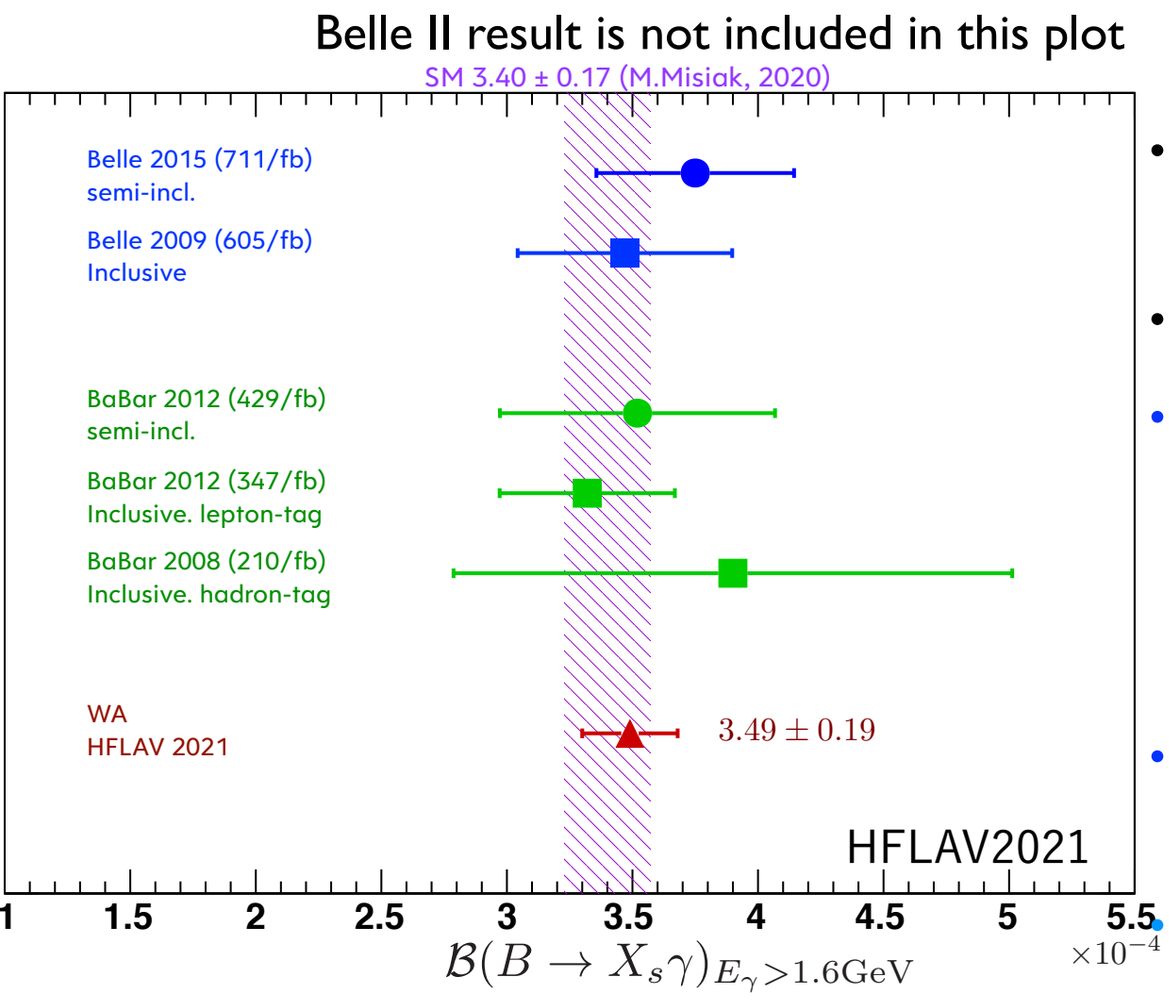
- **Hadronic-tag**
  - fully reconstruct B_{tag}→DX
  - higher background reduction, but signal efficiency is small O(0.01)%
- **Leptonic-tag**
  - require high momentum lepton of B→$D^{(*)}$lν
  - flavor (B or anti-B) is determined by a charge of lepton (l =e,μ)
  - measurement of Acp(B→Xsγ) is possible





E_γ^B threshold(GeV)	$\mathcal{B}(B \to X_s\gamma)(10^{-4})$
Belle II (189/fb) 1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
Belle II (189/fb) 2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)
Babar (210/fb) 1.9	3.66 ± 0.85 (stat.) ± 0.60 (syst.)

prospect of inclusive B.F(B→Xsγ) measurement

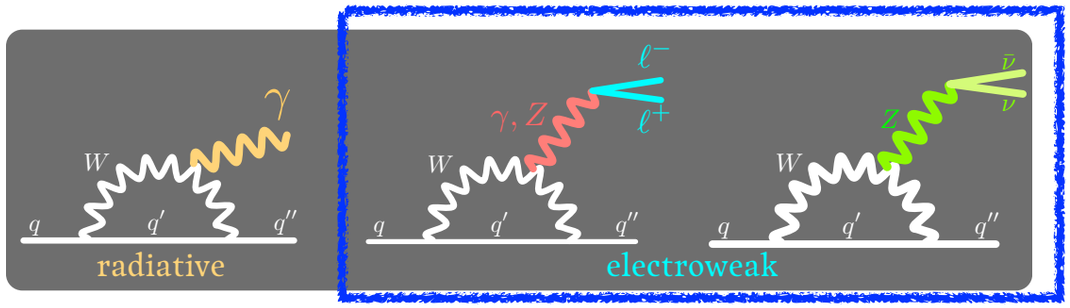


- World average is consistent with SM prediction
- theoretical and experimental errors are competitive ~ 5%
- systematic error is dominant in measurements
- Belle II expect to improve 5→3%
  - dominant systematic error in lepton-tag come from fake signal due to neutral hadron
- Theoretical uncertainty is also expected to become comparable

New physics scale

- constraint on charged Higgs mass.
- M(H+) > ~900GeV at Belle II (~580GeV by Belle)

electroweak penguin



- electroweak penguin decays are further suppressed
  - BF~10^{-6} = BF(b→sγ)x10^{-2}

$b \to s\ell\ell$

- charged lepton can be detected
- experimentally clean measurement
- inclusive measurement is possible in Belle II
- At Belle II, electron and muon modes have similar efficiency
  - electron mode is challenging at LHCb
- both low and high-q2(=Mll) regions are possible

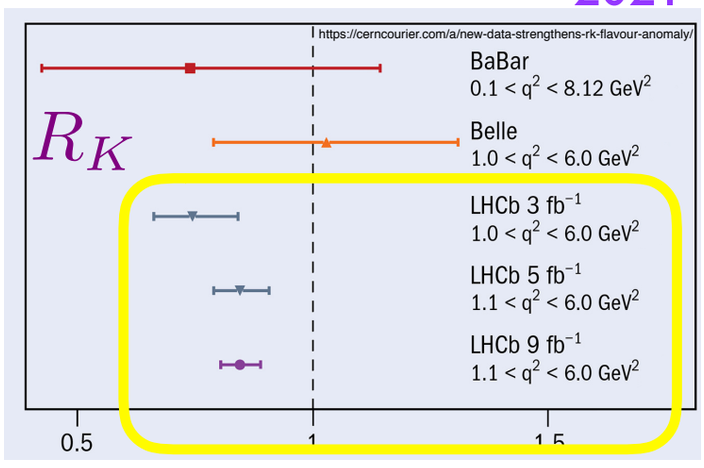
Test of Lepton Flavor Universality

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}$$

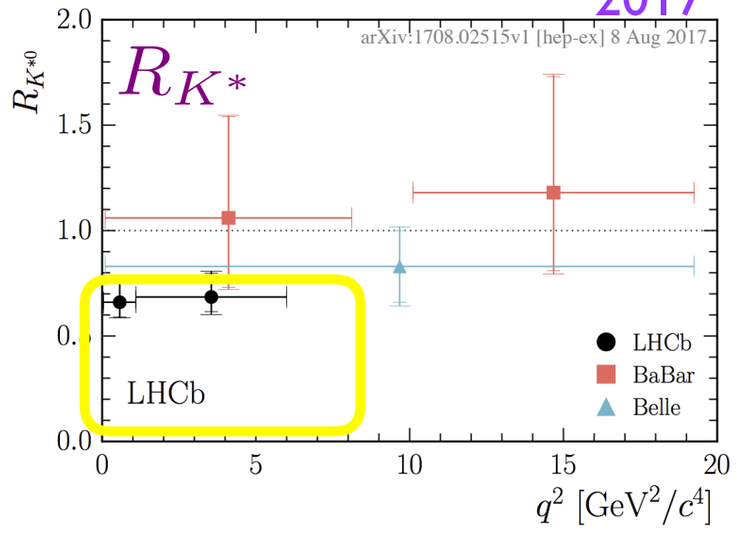
R=1 in SM(assuming universality of lepton)

deviation from R=1 was observed

2021

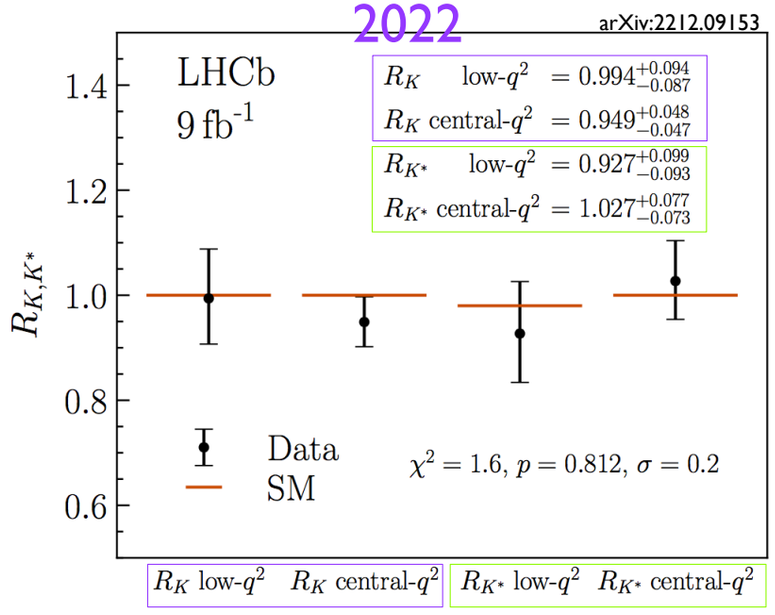


2017



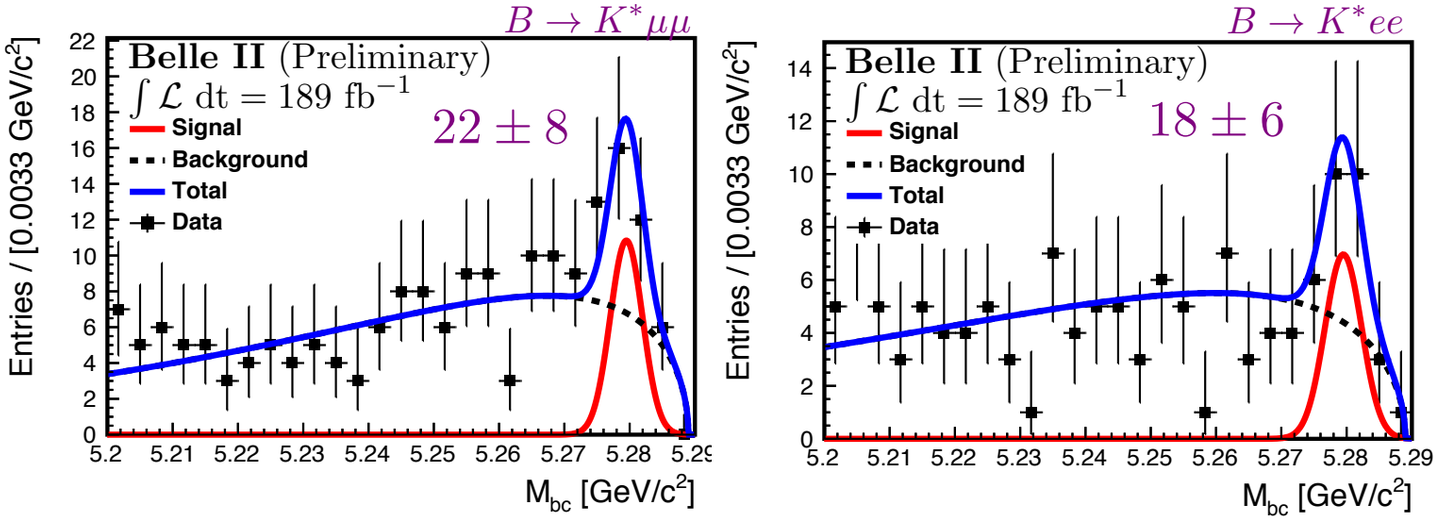
recent results of LHCb agree with SM

2022



electroweak penguin

$B \to K^* \ell\ell$



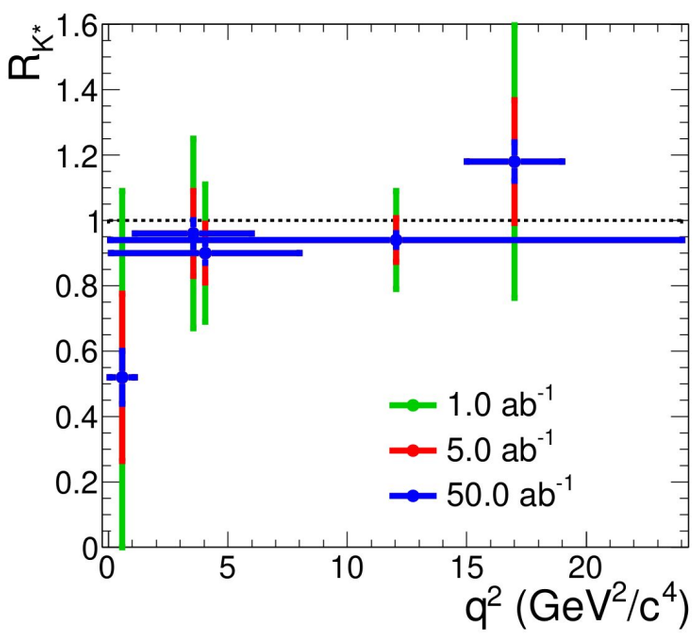
Belle II (189/fb)

$$\mathcal{B}(B \to K^* \mu\mu) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$$
$$\mathcal{B}(B \to K^* ee) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$$

similar performance for muon and electron channels

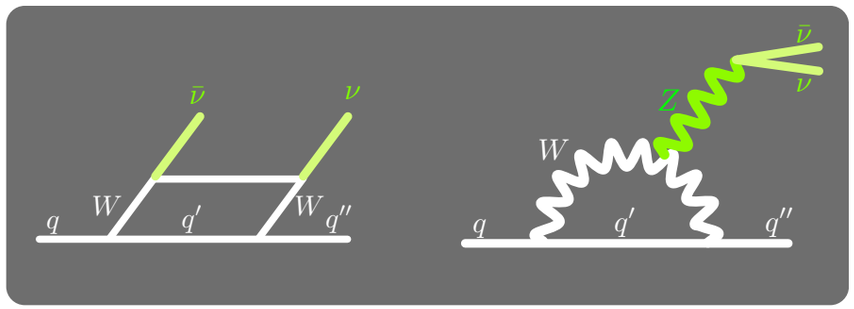
R(K(*)) perspective

Based on Belle PRL 126, 161801 (2021)



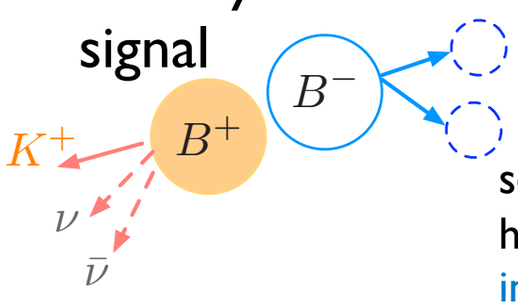
- Belle and Belle II performance for R(K) and R(K*) is similar
- Uncertainties are dominated by statistics
- Scaling uncertainties to different luminosities, about **3%** precision is possible for q^2 bin [1-6] GeV^2/c^4 for 50 ab^{-1} data sample.

electroweak penguin



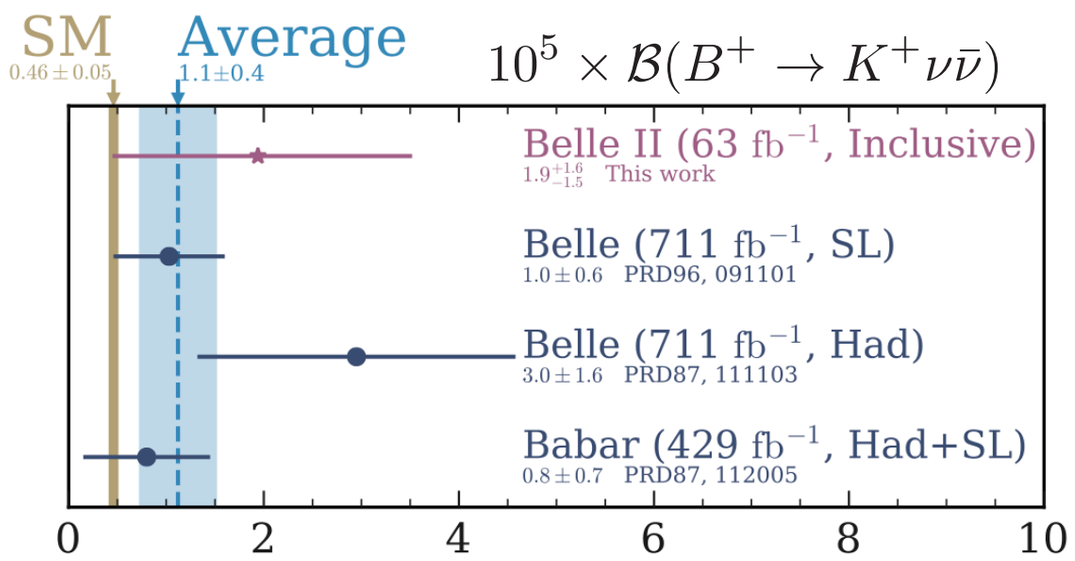
$B \to K\nu\nu$ search in Belle II (63/fb)

- new analysis approach: inclusive tag.
- Signal Kaon
  - require charged track with highest Pt
  - particle identification
- All remaining tracks and clusters are associated to other B in the event
- higher reconstruction efficiency, but higher background → suppressed with BDT(boosted decision tree) classifiers that identify the distinctive characteristic of signal



semi-leptonic tag : ε=O(0.1)% Belle
hadronic tag : ε=O(0.01)% BaBar
inclusive tag : ε=O(1)% Belle II

- $K^{(*)}\nu\nu$
  - no observation
  - small theoretical uncertainty compared with sll
  - challenging due to 2 neutrinos in the final state.
  - **Belle II is a only experiment to observe this mode.**
    - Δ(B.F) ~ 10% at 50/ab



$$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) < 4.1 \times 10^{-5} (90\%\ \mathrm{CL})$$

similar accuracy to Belle 711/fb Hadron-tag

tau physics

- Belle II collect large sample of tau-pair event
- Belle II can provide rich physics program of high precision measurement
  - lifetime and mass) consistency test of SM
  - Lepton Flavor Violation
  - Lepton Flavor Universality Violation
  - $\tau \to \ell\, \alpha$ (invisible)
  - Vus measurement ($\tau \to Xs\nu$, $K\nu$..)

direct NP search

$$\Upsilon(4S) : 1.05(\mathrm{nb})$$

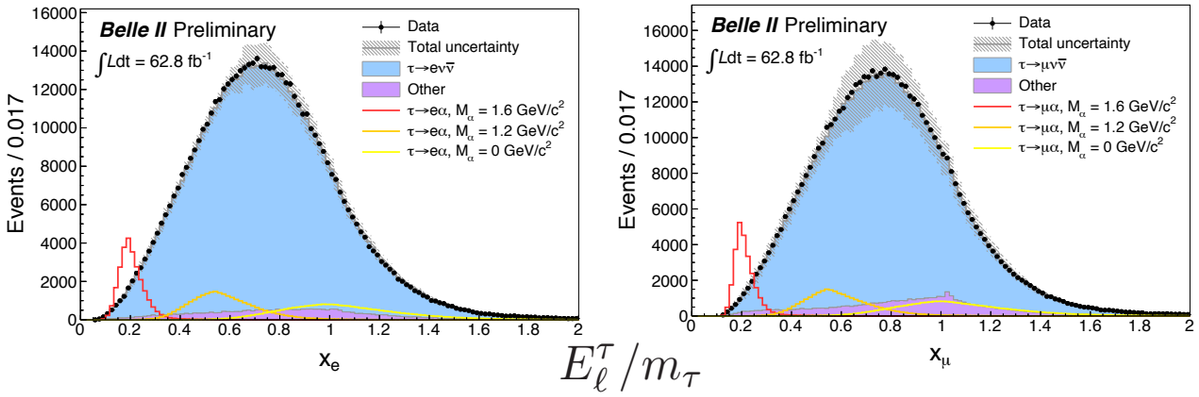
$$\tau^+\tau^- : 0.919(\mathrm{nb})$$

not only B but also tau factory !

advantages at Belle II
- tau produces in pairs
- well defined initial state energy
- clean environment
- high hermeticity of detector

Belle II

LFV search $\tau \to \ell\alpha(\ell = e, \mu)$



E_ℓ^τ / m_τ

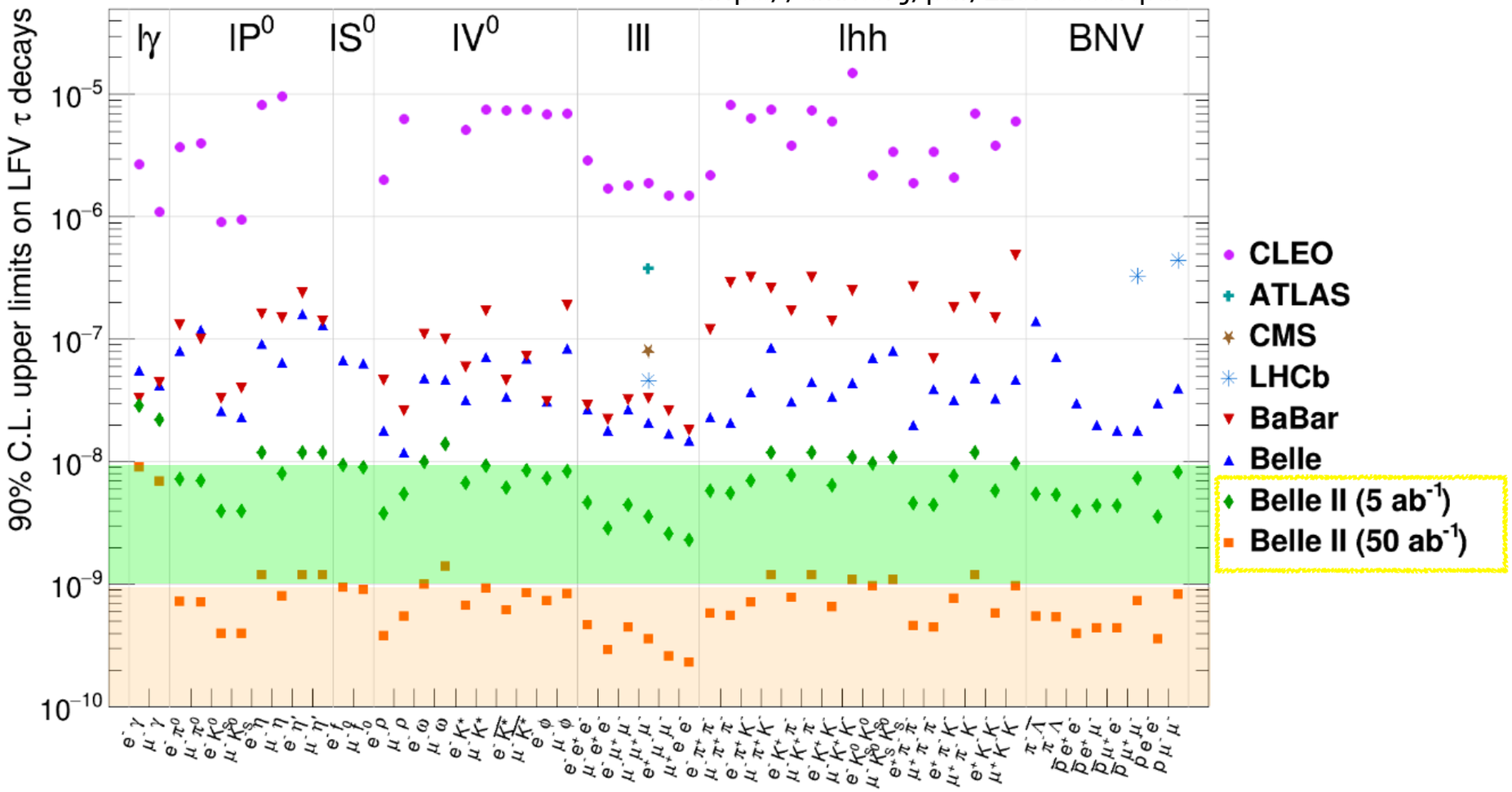
no significant excess observed → set world leading limits

arXiv:2212.03634v1

	Upper Limit at 95% CL	
	$\mathcal{B}(\tau^- \to e^-\alpha)/\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\mu)$	$\mathcal{B}(\tau^- \to \mu^-\alpha)/\mathcal{B}(\tau^- \to e^-\bar{\nu}_e\nu_\mu)$
Belle II (62.8/fb)	$(1.1 - 9.7) \times 10^{-3}$	$(0.7 - 12.2) \times 10^{-3}$
ARGUS (0.5/fb)	$(6 - 36) \times 10^{-3}$	$(3 - 34) \times 10^{-3}$

tau physics

https://arxiv.org/pdf/2207.06307.pdf



- Tau LFV searches (1~50/ab)
  - unambiguous signatures of new physics
  - $\tau \to \mu\gamma$, 3-leptons and many modes > 40
  - Unique to Belle II, leading every modes

dark sector prospect

- Study of dark sector is active at Belle II
- dark matter may interact with SM particles through several portal interaction
  - vector portal (dark photon A', Z'), pseudo-scalar portal (axion-like particles)
- Belle II can search region of 100 MeV - a few GeV
  - trigger is a key; single photon trigger, single track(muon) trigger
    - challenging due to higher background
  - thanks to upgrade of TRG and DAQ system at Belle II, search for dark sector is very active and wide-ranging program

$\mathrm{ALP} \to \gamma\gamma$

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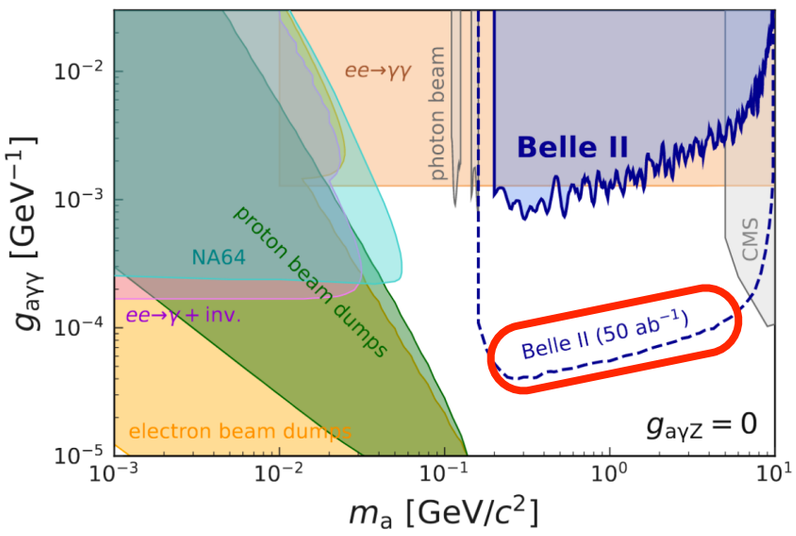
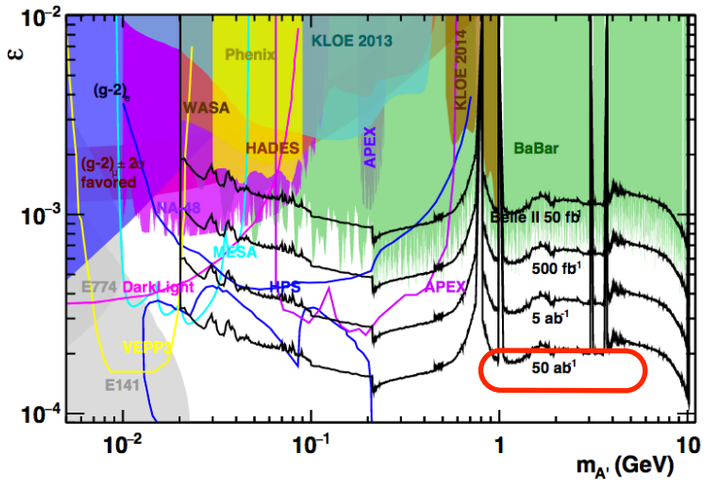
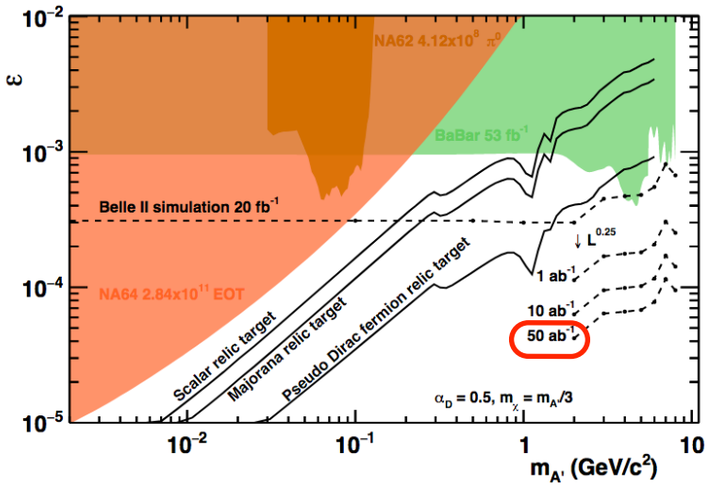


dark photon

visible



invisible



summary

- At KEK, chronicle of ee collider
  - TRISTAN → KEKB → SuperKEKB
- SuperKEKB has achieved 4.7×10^{34}, new world record
  - super B factory now
- Belle II has started to produce new results
- we expect a new, exciting era of discoveries, looking for new physics beyond the Standard Model