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Status and prospects of flavor physics at the Belle II experiment

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for the Belle II collaboration

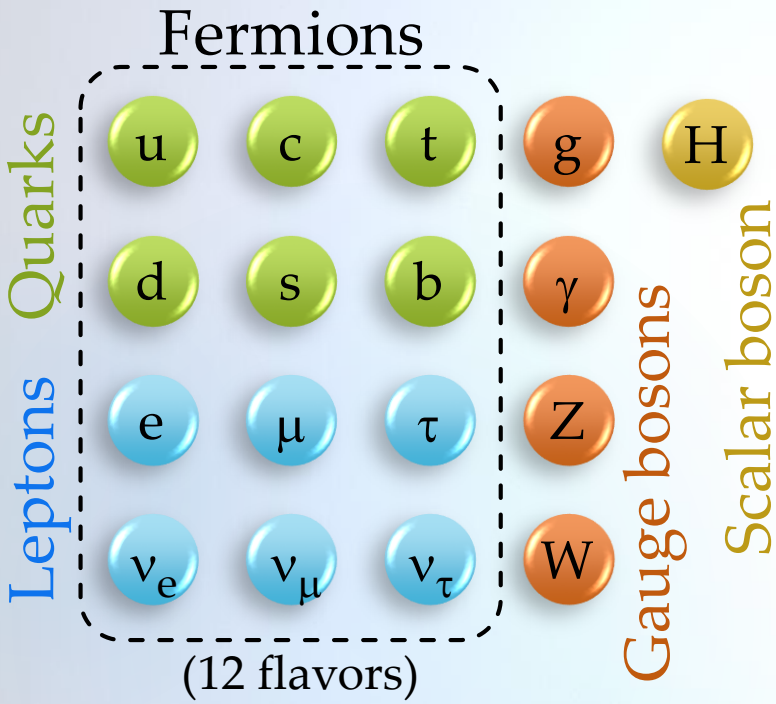
PACIFIC 2018, Kiroro, Hokkaido, Feb. 19, 2018

Contents

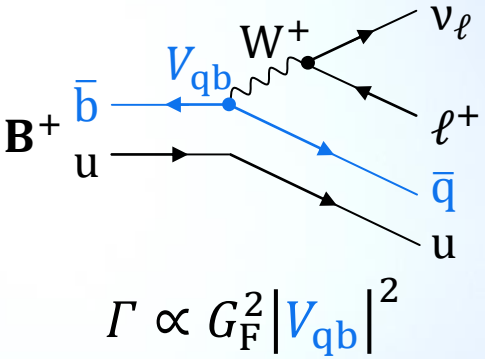
- Introduction: Flavor Physics
- Prospects of a part of Flavor Physics at Belle II
- Status and schedule of Belle II / SuperKEKB
- Summary

Flavor Physics

- In the Standard Model, quark flavor transition processes are described by Cabibbo-Kobayashi-Maskawa (CKM) matrix.



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$



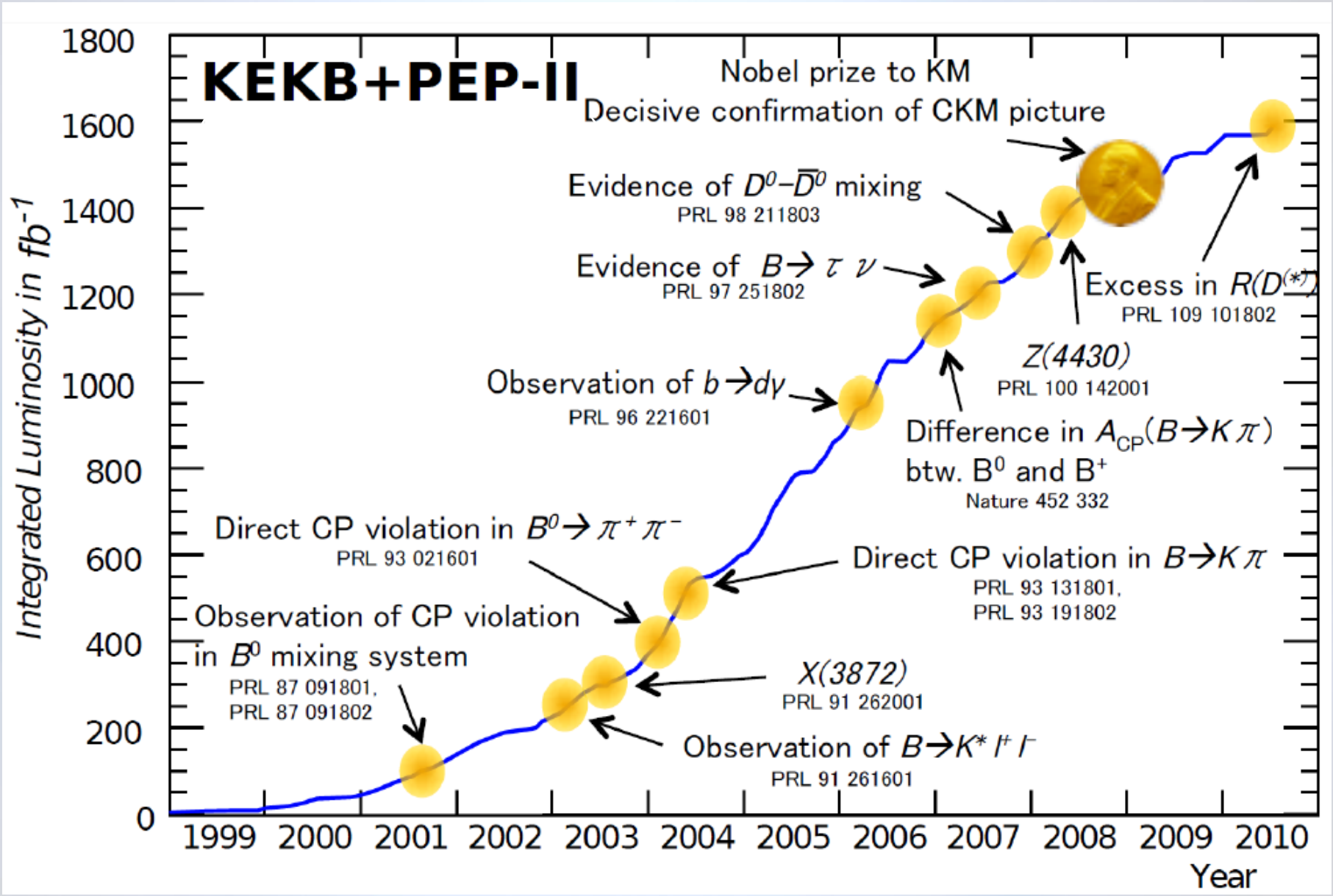
$$\Gamma \propto G_F^2 |V_{qb}|^2$$

CKM matrix

	d	s	b
u	0.974	0.225	0.004
c	0.225	0.974	0.041
t	0.009	0.040	0.999

B-factories produce a large number of B, D, τ, etc. and can extensively test the CKM paradigm.

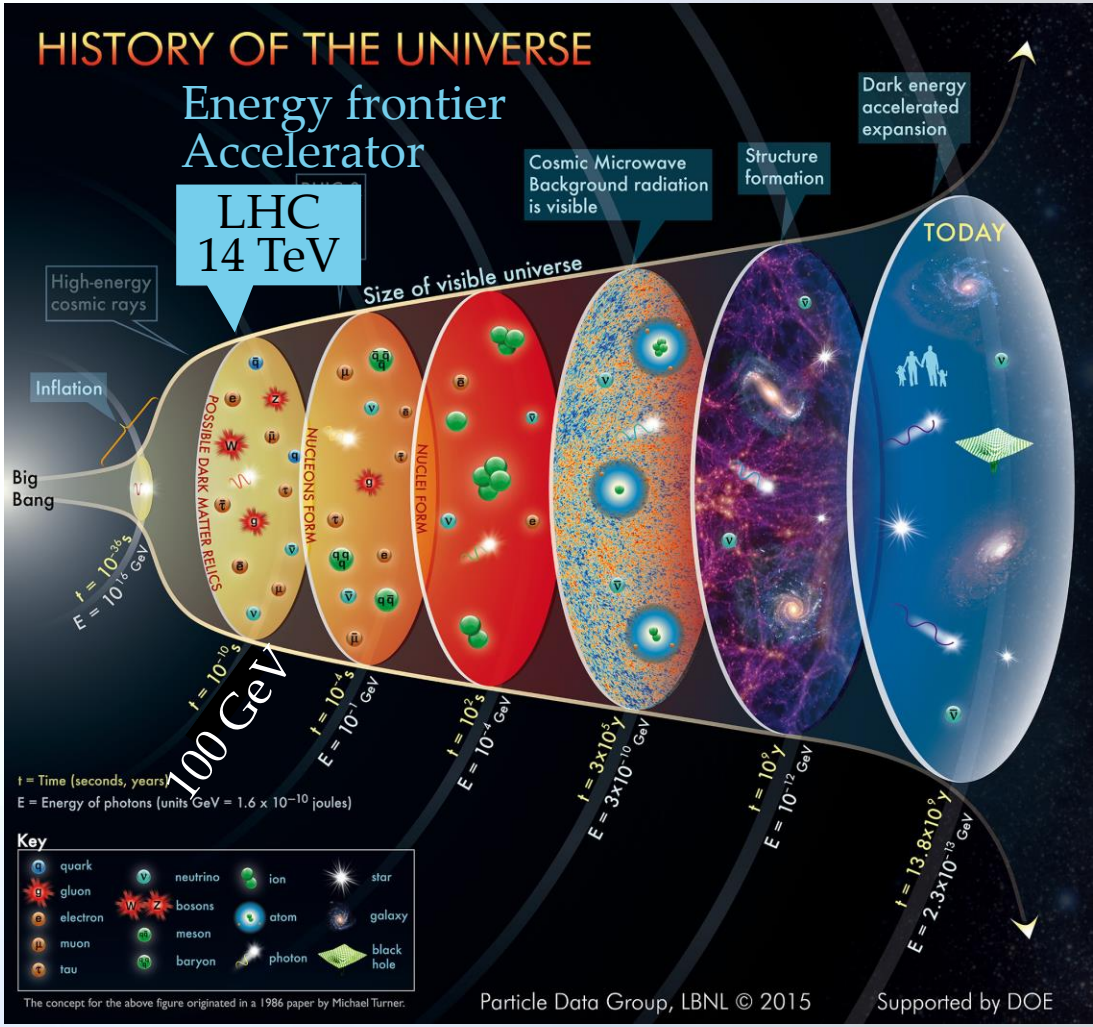
The B factory legacy



Beyond Standard Model

- The Standard Model has been tested greatly up to the weak scale, O(100) GeV.

- However we know the Standard Model is not satisfactory to explain
  - Flavor structure
  - baryon asymmetry
  - dark matter
  - dark energy
  - …



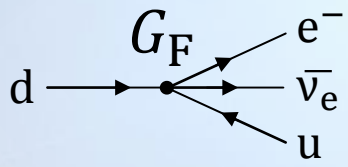
Search for New Physics in HEP

- Direct search (energy frontier: LHC)
  - Direct production of new particles; limited by the beam energy
- Indirect search (intensity frontier: SuperKEKB, etc.)
  - Precise investigation of virtual effects of new particles
    - The Standard Model must be the effective theory at $E \ll \Lambda_{\mathrm{NP}}$.

$$\mathcal{M} \propto \frac{c_{\mathrm{NP}}^2}{\Lambda_{\mathrm{NP}}^2}$$

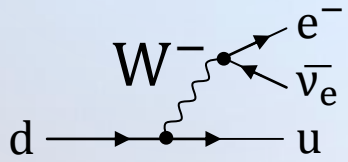
Larger statistics
→ higher energy scale / smaller coupling

cf. Fermi theory



$$\mathcal{M}_{\mathrm{Fermi}} = \langle \mathrm{p}|J_\mu^h|\mathrm{n}\rangle \frac{G_\mathrm{F}}{\sqrt{2}} \langle \bar{\nu}_\mathrm{e} \mathrm{e}^-|J^{\mu\ell}|0\rangle$$

$$\boxed{\frac{G_\mathrm{F}}{\sqrt{2}} = \frac{g^2}{8M_\mathrm{W}^2}}$$

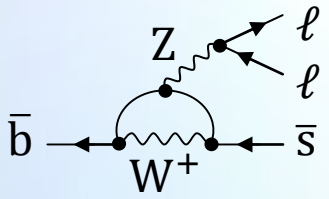


$$\mathcal{M}_{\mathrm{SM}} = \langle \mathrm{p}|J_\mu^h|\mathrm{n}\rangle \frac{g^2}{8} \frac{1}{q^2 - M_\mathrm{W}^2} \left(g^{\mu\nu} - \frac{q^\mu q^\nu}{M_\mathrm{W}^2} \right) \langle \bar{\nu}_\mathrm{e} \mathrm{e}^-|J_\nu^\ell|0\rangle$$

Process sensitive to New Physics

- Flavor Changing Neutral Current (FCNC)
  - Occur only via a loop diagram due to GIM mechanism, and moreover is highly suppressed.

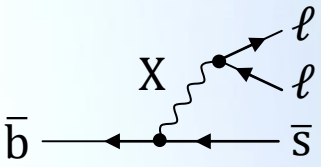
FCNC in the Standard Model



$$\mathcal{M}_{\mathrm{SM}} \propto e^2 \frac{g^2}{(4\pi)^2} \frac{1}{M_{\mathrm{W}}^2} V_{\mathrm{ts}}^* V_{\mathrm{tb}}$$

e.g. $\mathcal{B}(\mathrm{B}^0 \to \mathrm{K}^0 \mu^+ \mu^-) \sim 3 \times 10^{-7}$

FCNC with a new particle X



$$\mathcal{M}_{\mathrm{NP}} \propto \frac{c_{\mathrm{NP}}^2}{\Lambda_{\mathrm{NP}}^2}$$

e.g. in case that virtual effect of X appears with the same amplitude as the Standard Model ($\mathcal{M}_{\mathrm{SM}} = \mathcal{M}_{\mathrm{NP}}$):

$$\Lambda_{\mathrm{NP}} = c_{\mathrm{NP}} \frac{4\pi}{eg} M_{\mathrm{W}} \sqrt{\frac{1}{V_{\mathrm{ts}}^* V_{\mathrm{tb}}}} = O(10\ \mathrm{TeV}) \quad (c_{\mathrm{NP}} \sim 1)$$

Flavor anomalies

Orange: FCNC  : In particular (could) related to electroweak penguin

Discrepancy between measurement and theory

- $B \to K\pi$ A_{CP} (Belle, BaBar, LHCb, CDF)
- μ charge asymmetry in $B-\bar{B}$ mixing (DØ)
- $R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)}$ (BaBar, LHCb, Belle)
- $(g-2)_\mu$ BNL E821
- $B_s \to \phi\mu^+\mu^-$ (LHCb)
- ε'/ε (NA48, KTEV Kaons at the Tevatron)
- $B \to K^*\mu^+\mu^-$ angular distr. (P_5') (LHCb, Belle, ATLAS)
- ~~$|V_{ub}|$ and $|V_{cb}|$ inclusive/exclusive~~ (Belle, BaBar, LHCb, CLEO)
- $R_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}e^+e^-)}{\Gamma(B \to K^{(*)}\mu^+\mu^-)}$ (LHCb)
- ~~$h \to \tau\mu$ at 8 TeV~~ (CMS)
- $B \to VV$ f_L (LHCb, BaBar, Belle)

… Results of other experiments are consistent with SM

… QCD calculation uncertainties became larger

… poor statistics?

→ Yet to be verified with higher statistics and less uncertainties.

Belle II strategy for New Physics

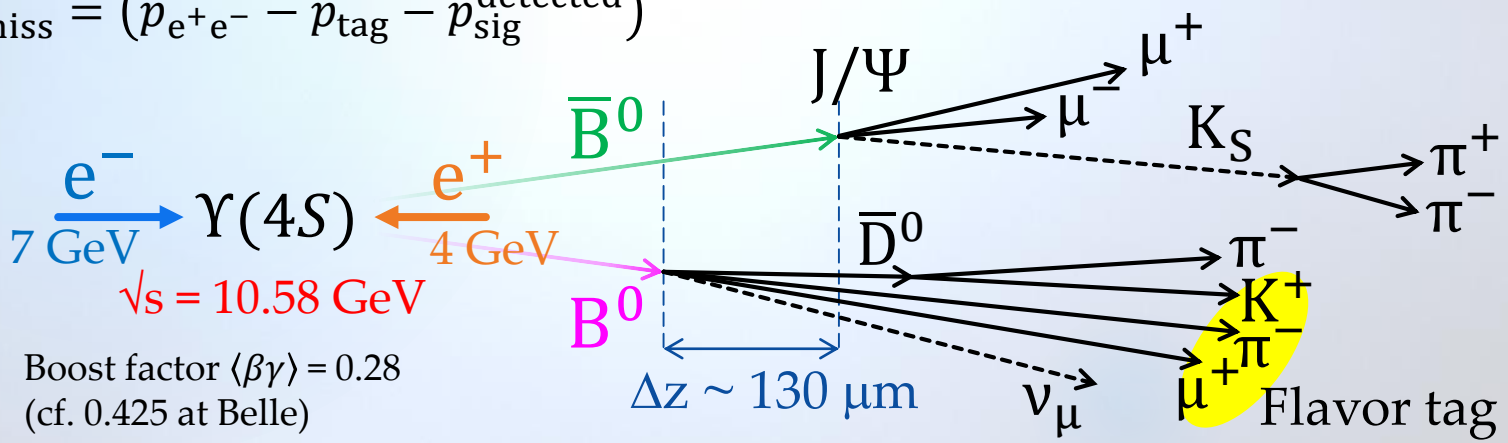
- **Statistics**: KEKB ~1 ab^{-1} → SuperKEKB 50 ab^{-1} ≈5e10 $B\bar{B}$ pairs
- Prediction of the Standard Model with small theoretical uncertainties
- Precise measurement with small systematic uncertainties

Features

- Collision at (or close to) $\Upsilon(4S)$
  - Well-known initial energy
  - No extra interactions
- Tagging one of the B's to infer the other B charge, flavor, momentum.
  - Powerful S/N separation
  - $m^2_{\mathrm{miss}} = \left(p_{e^+e^-} - p_{\mathrm{tag}} - p^{\mathrm{detected}}_{\mathrm{sig}}\right)^2$

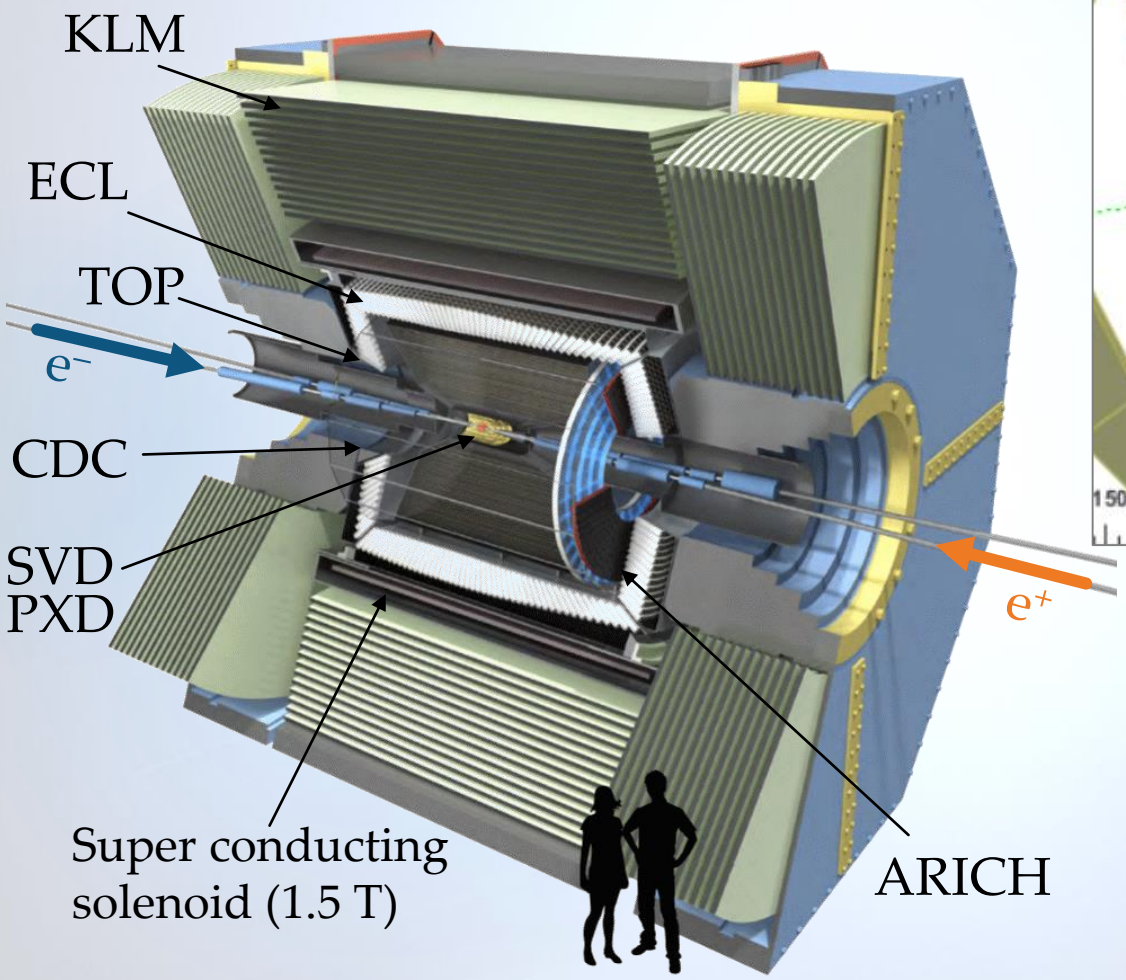
Observables

- Forbidden decays
- Enhanced/suppressed decay rate
- Asymmetries (CP, isospin)
- Angular distributions



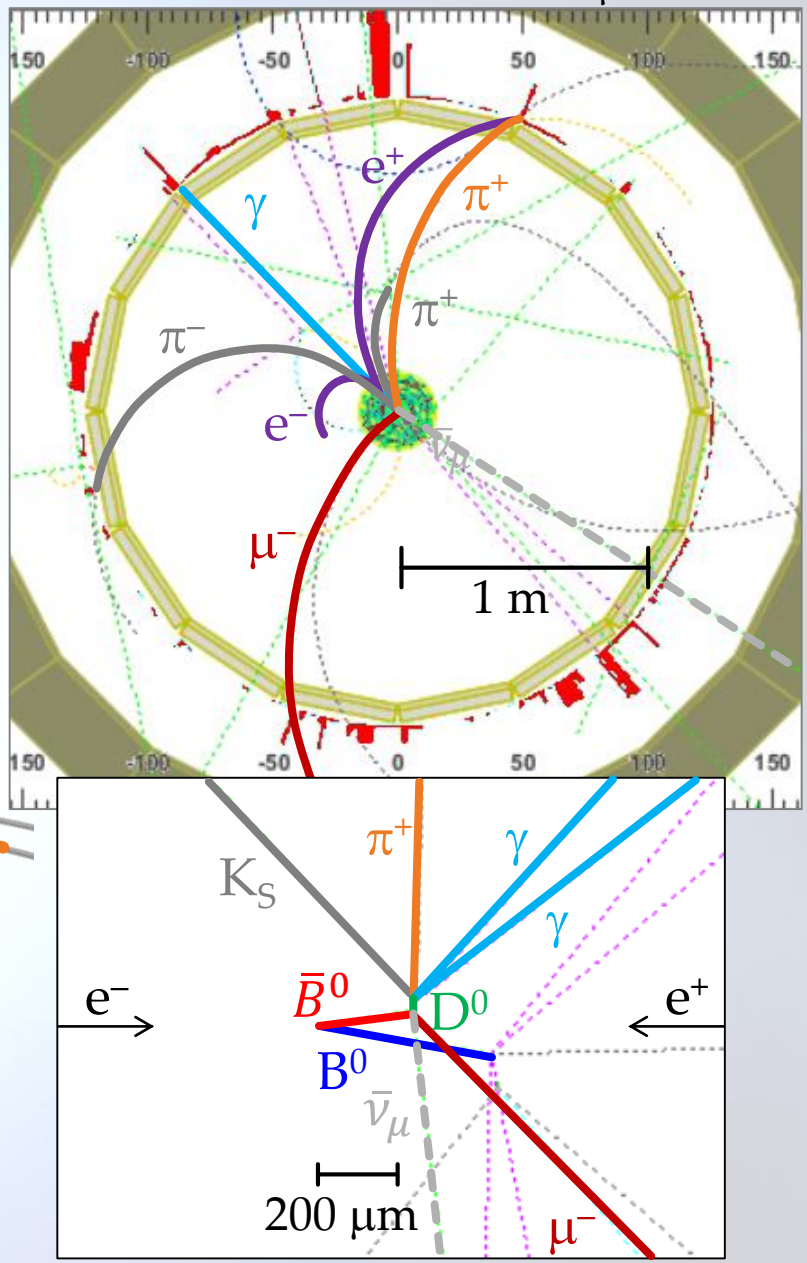
Belle II detector

A general purpose hermetic spectrometer composed of state-of-the-art detectors



Monte Carlo simulation

$\Upsilon(4S) \to B^0\bar{B}^0, \quad \bar{B}^0 \to D^+\mu^-\bar{\nu}_\mu$



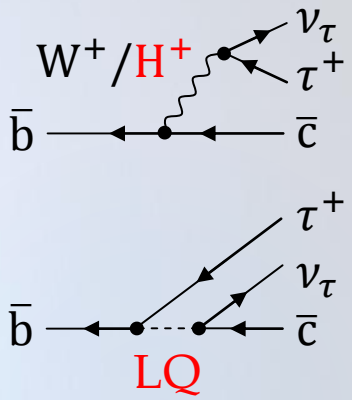
Lepton universality in $B \to D^{(*)}\tau\nu$

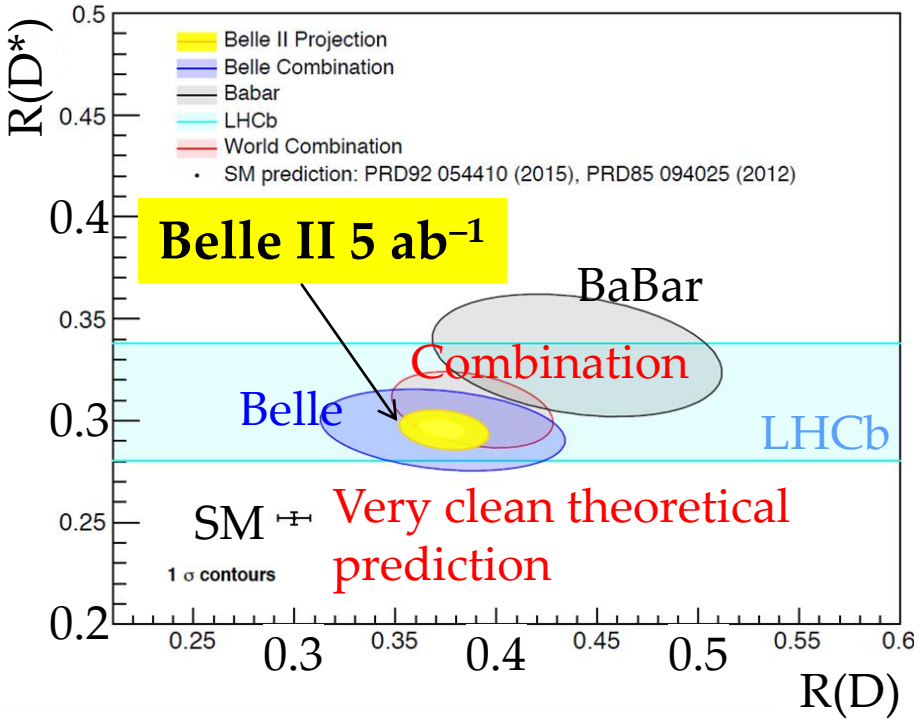
$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)}\tau\nu)}{\Gamma(B \to D^{(*)}\ell\nu)} \quad (\ell = e \text{ or } \mu)$$

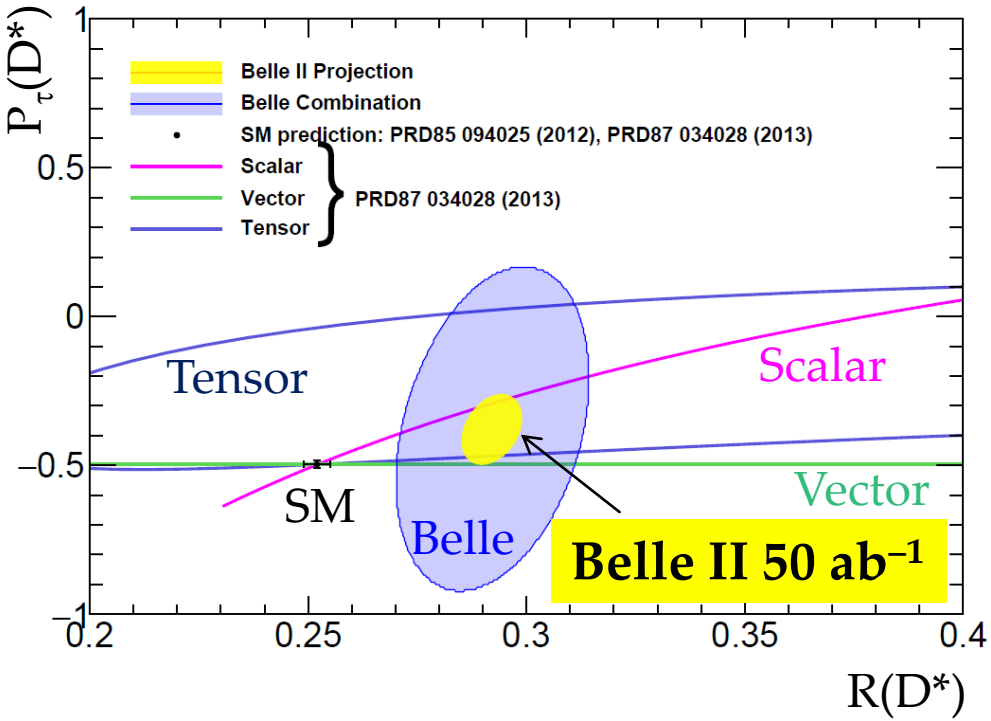
- Partial cancellation of theoretical uncertainties related to hadronic effects and measurement systematics.

$$P_\tau(D^*) = \frac{\Gamma^+ - \Gamma^-}{\Gamma^+ + \Gamma^-} \quad (\Gamma^{\pm}\text{: decay rate of } \pm\tau\text{−helicity})$$

- Another probe of New Physics

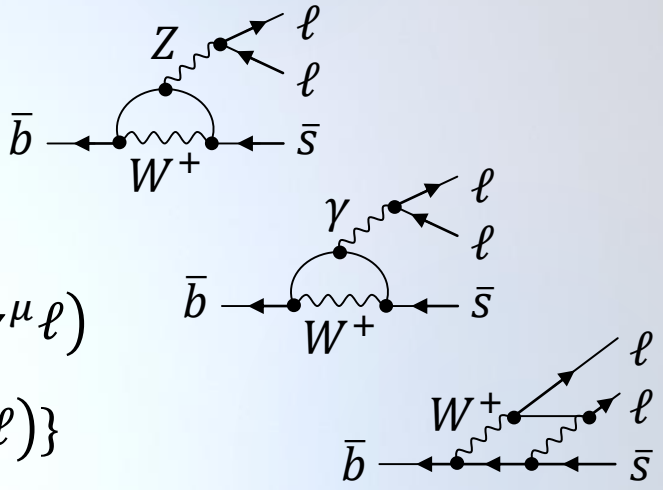




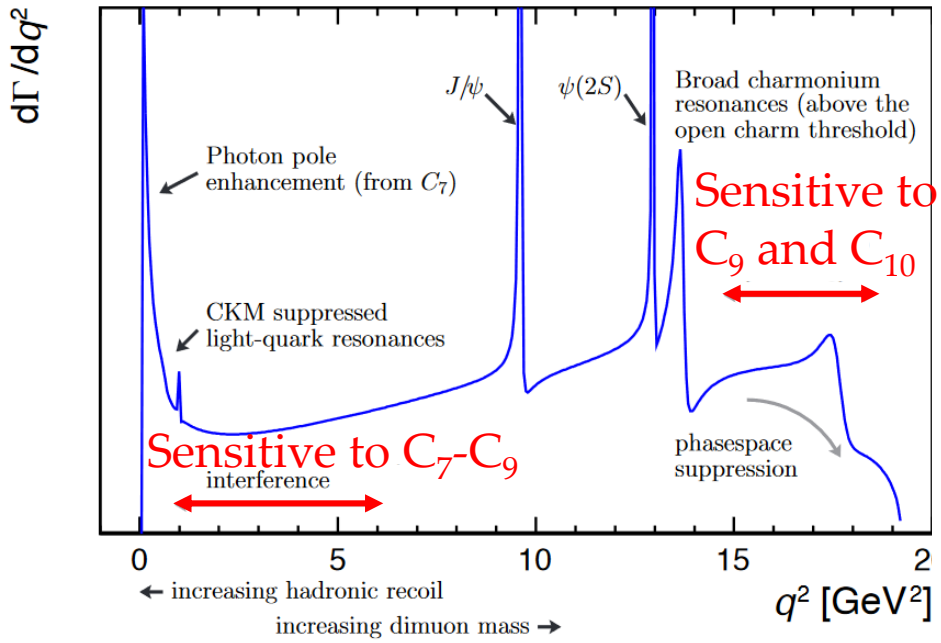


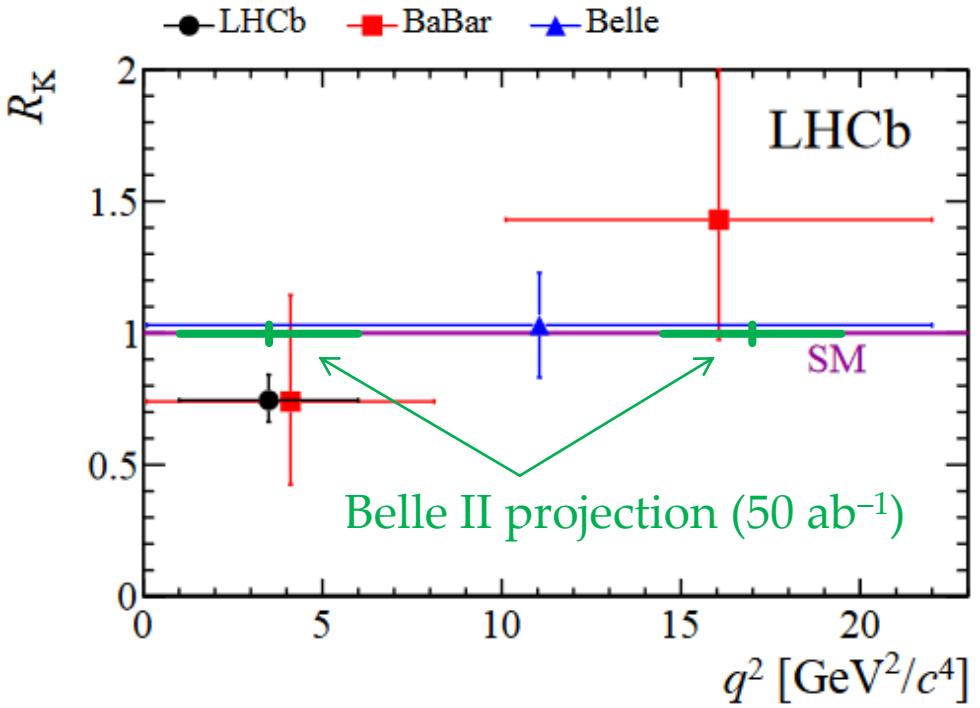
Lepton universality in $B \to K^* \ell^+ \ell^-$

$$\mathcal{M} = \frac{G_F \alpha_{EM}}{\sqrt{2}\pi} V_{ts}^* V_{tb} \{ C_9^{eff} \langle K^* | \bar{s} \gamma_\mu P_L b | B \rangle (\bar{\ell} \gamma^\mu \ell) - 2\, m_b / q^2 \cdot C_7^{eff} \langle K^* | \bar{s} i \sigma_{\mu\nu} q^\nu P_R b | B \rangle (\bar{\ell} \gamma^\mu \ell) + C_{10} \langle K^* | \bar{s} \gamma_\mu P_L b | B \rangle (\bar{\ell} \gamma^\mu \gamma_5 \ell) \}$$



arXiv:1606.00916

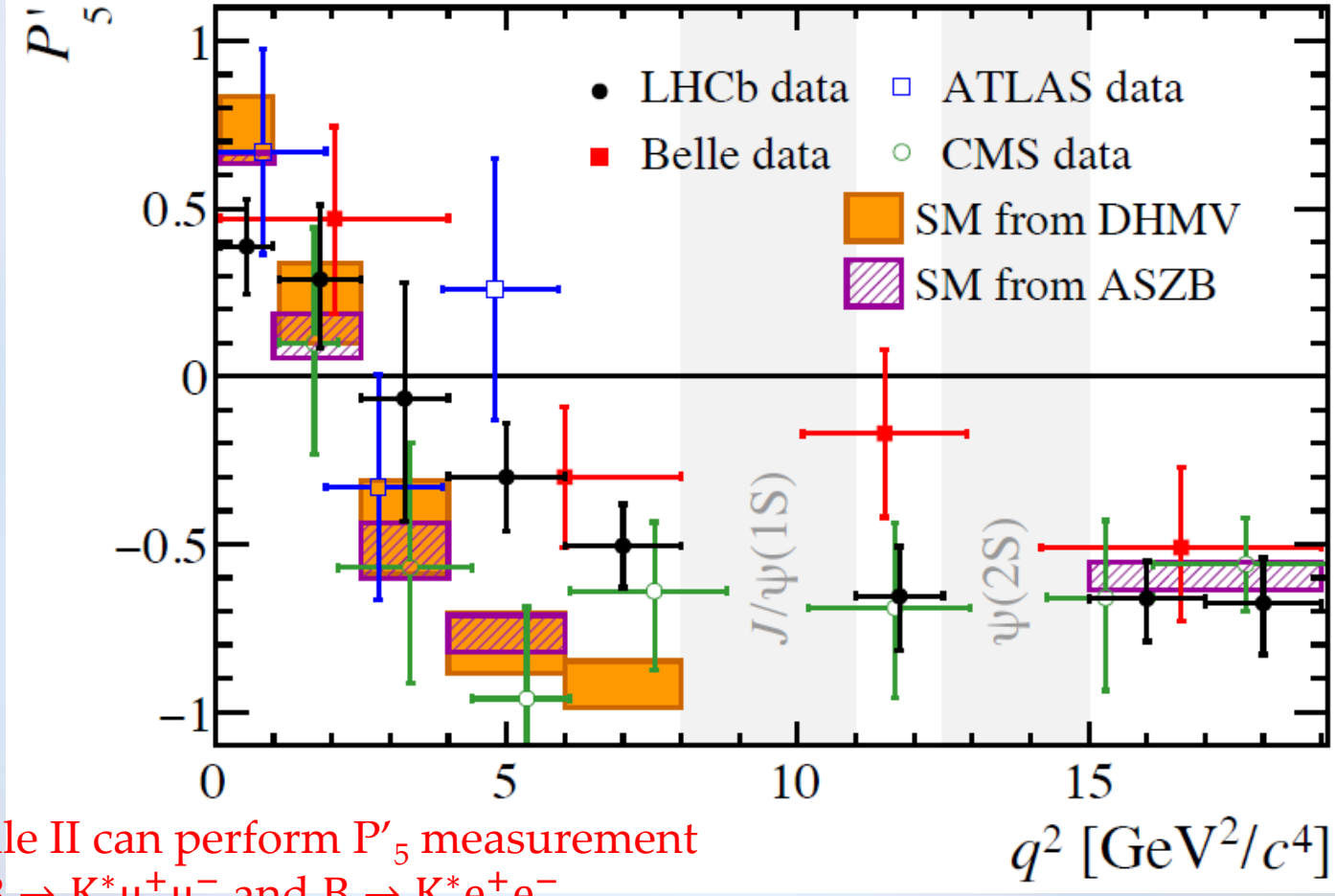




Lepton universality in $B \to K^* \ell^+ \ell^-$

$$P_5' = \sqrt{2}\,\frac{\mathrm{Re}\left(A_0^{\mathrm{L}} A_\perp^{\mathrm{L}*} - A_0^{\mathrm{R}} A_\perp^{\mathrm{R}*}\right)}{\sqrt{\left(|A_0^{\mathrm{L}}|^2 + |A_0^{\mathrm{R}}|^2\right)\left(|A_\parallel^{\mathrm{L}}|^2 + |A_\parallel^{\mathrm{R}}|^2 + |A_\perp^{\mathrm{L}}|^2 + |A_\perp^{\mathrm{R}}|^2\right)}}$$

J. Prisciandaro (FPCP2017)

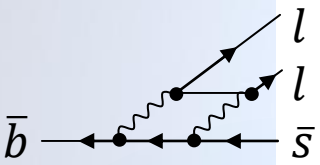


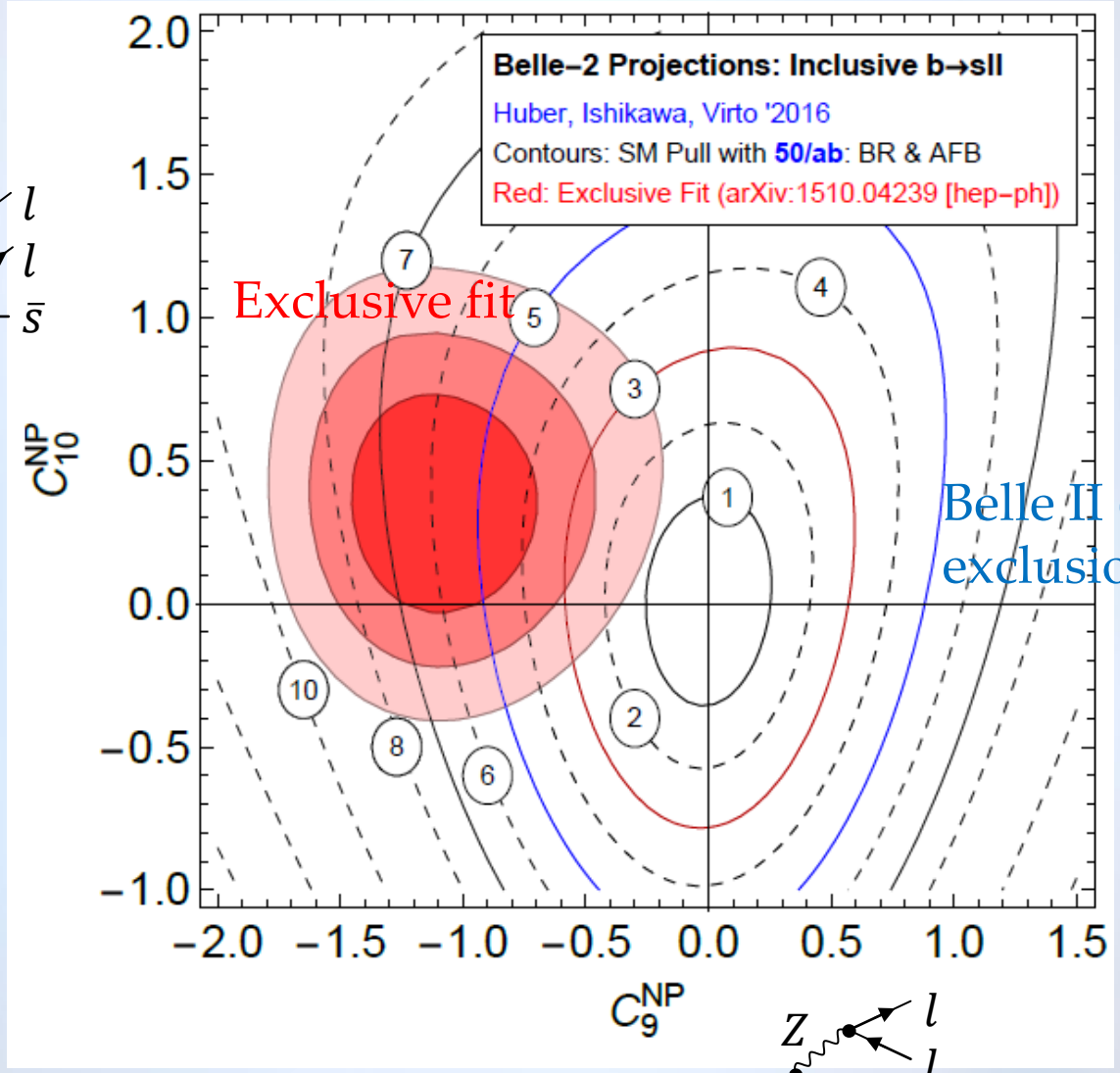
Belle / Belle II can perform P'_5 measurement both for $B \to K^* \mu^+ \mu^-$ and $B \to K^* e^+ e^-$

Could still be hadronic effects ($c\bar{c}$ loop)

Exclusive global fit / $B \to X_s \ell^+ \ell^-$

$B \to K^* \ell^+ \ell^-$, $B \to \mu^+ \mu^-$, $B \to K^* \gamma$





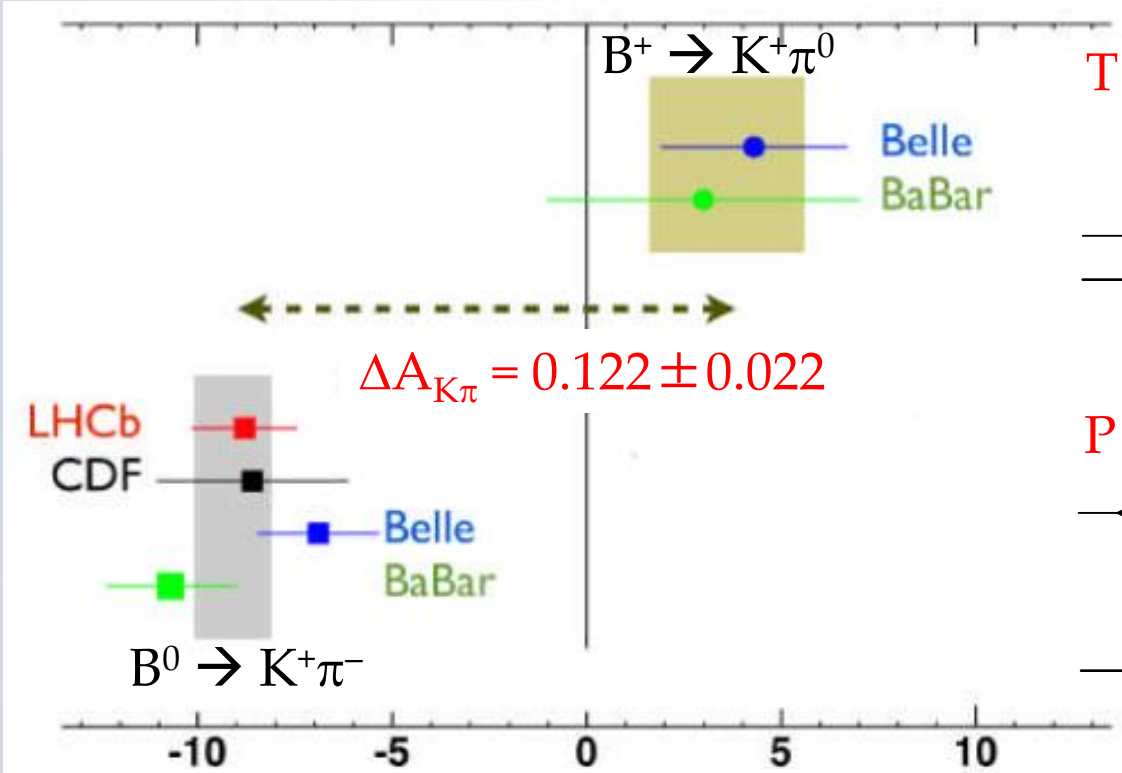
Direct CP asymmetry in B → Kπ

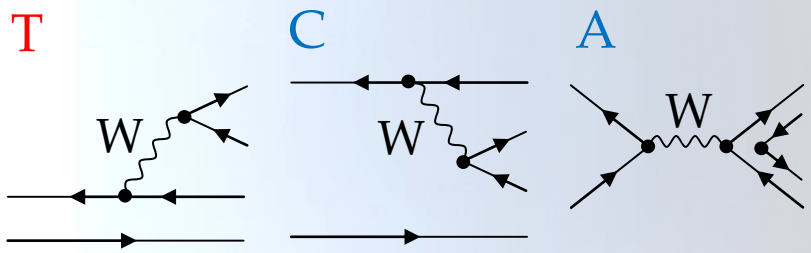
- Difference of CP asymmetry between B^0 and B^+
  - Enhanced C?
  - QCD?
  - New Physics in P_{EW}?

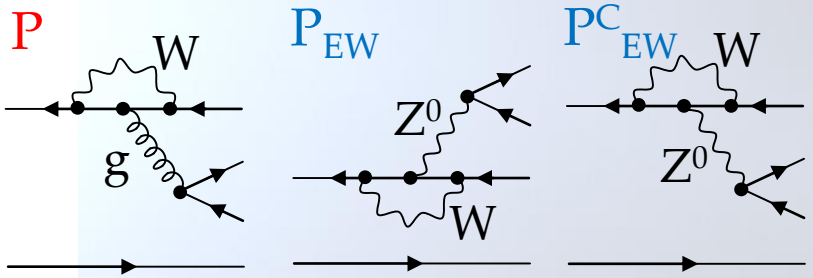
$B^+ \rightarrow K^+\pi^0$: T + P + C + P_{EW} + P^C_{EW} + A

$B^0 \rightarrow K^+\pi^-$: T + P + P^C_{EW}

Dominant Sub-dominant







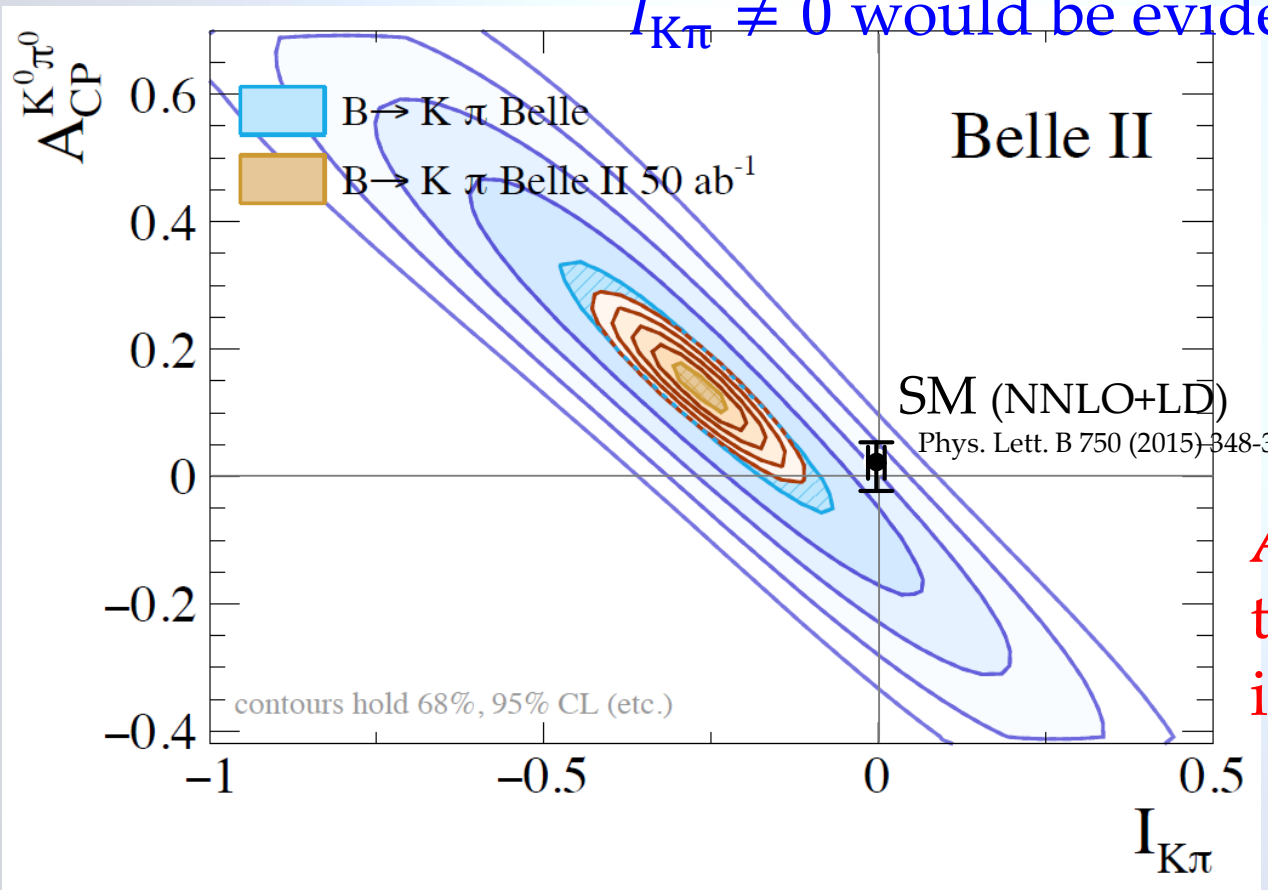
$$A_{CP}(B \rightarrow f) = \frac{\Gamma(\bar{B} \rightarrow \bar{f}) - \Gamma(B \rightarrow f)}{\Gamma(\bar{B} \rightarrow \bar{f}) + \Gamma(B \rightarrow f)} \quad (\%)$$

Direct CP asymmetry in B → Kπ

- Sum rule of A_{CP} was proposed: [Phys. Lett. B 627 (2005) 82-88]

$$I_{K\pi} \equiv A_{CP}(K^+\pi^-) + A_{CP}(K^0\pi^+)\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} - 2A_{CP}(K^+\pi^0)\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_0}{\tau_+} - 2A_{CP}(K^0\pi^0)\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} \approx 0$$

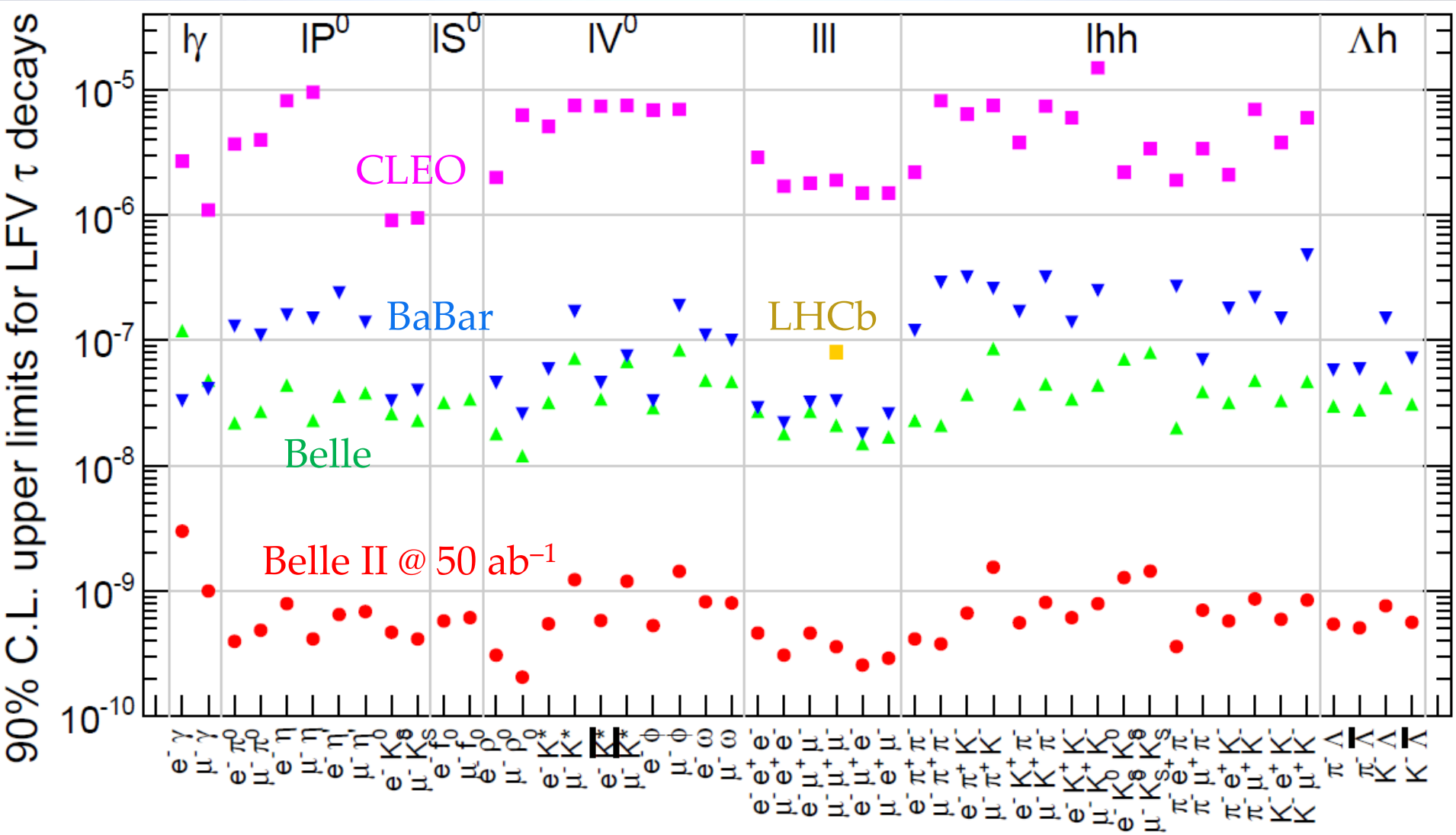
$I_{K\pi} \neq 0$ would be evidence for New Physics



$A_{CP}(K^0\pi^0)$ is one of the key measurements in Belle II

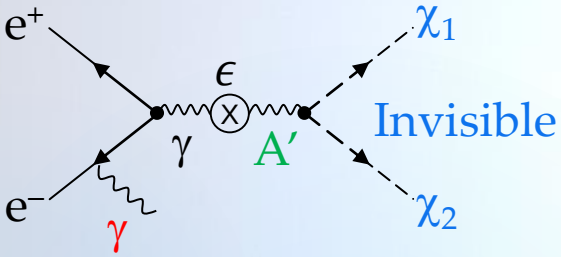
Lepton flavor violating τ decays

… FCNC in the lepton sector

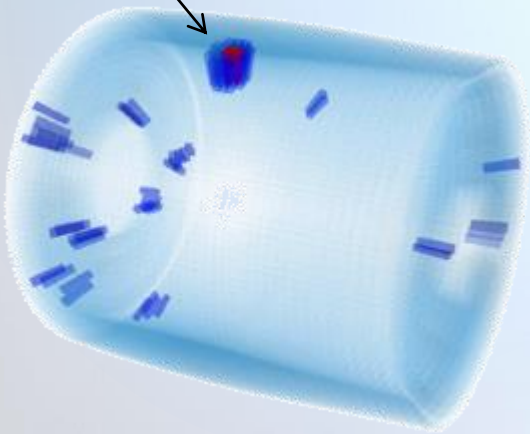


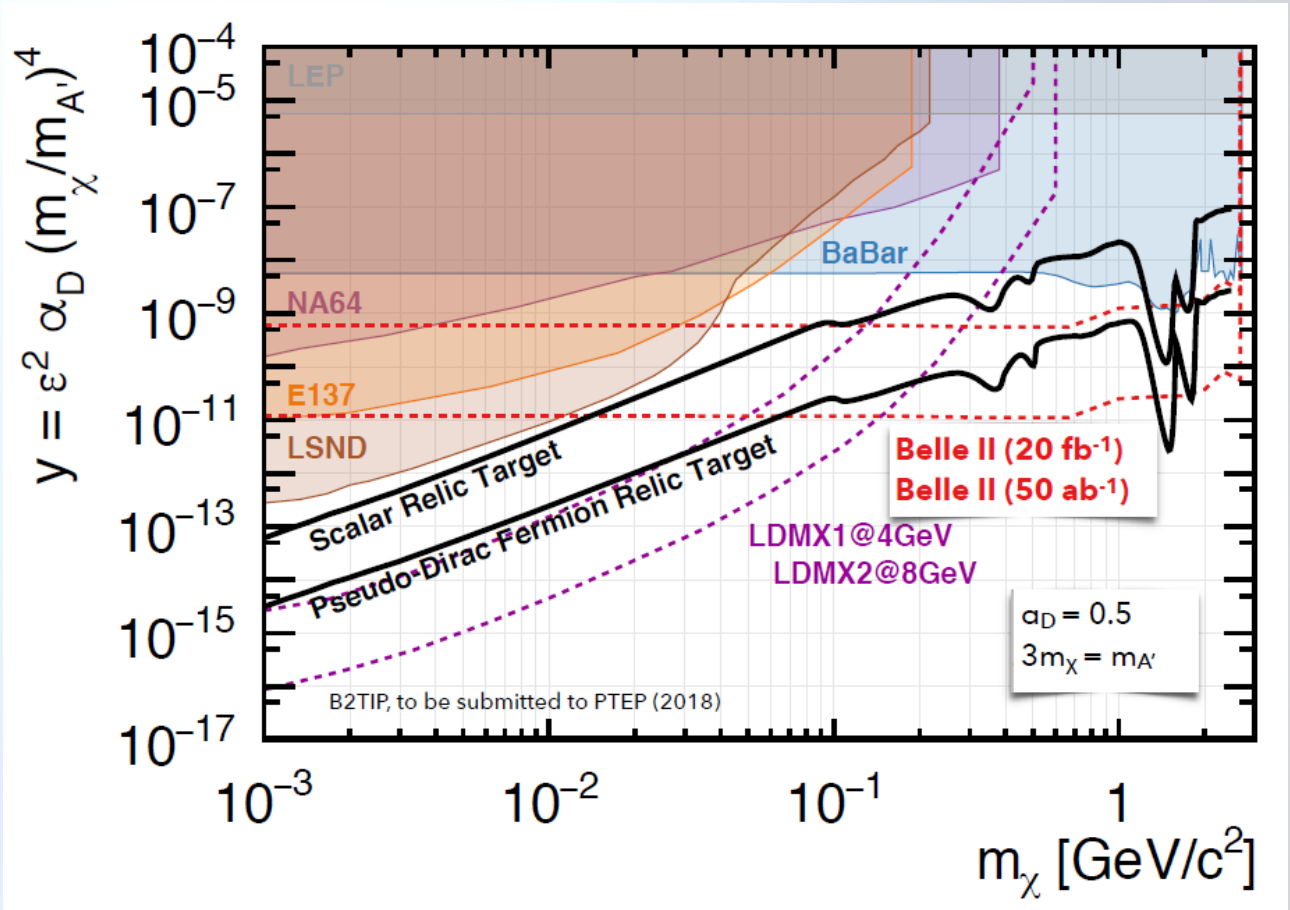
Dark sectors

- New triggers will be used in Belle II to search for dark matter and dark photons.
  - Single photon trigger with ~1 GeV threshold to search for dark photon decaying into light dark matter

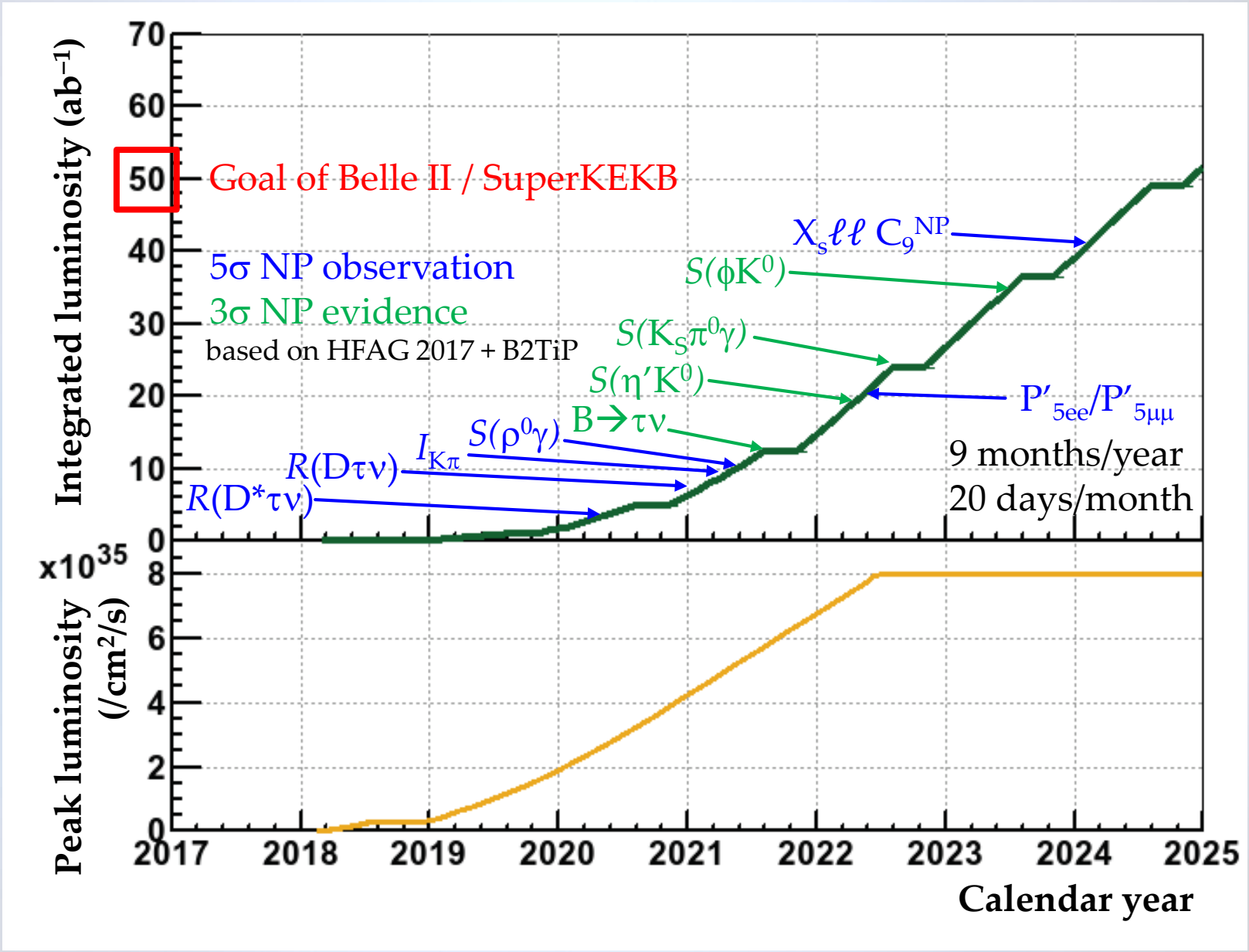


$$E_\gamma = \frac{E_{CM}^2 - M_{A'}^2}{2E_{CM}}$$



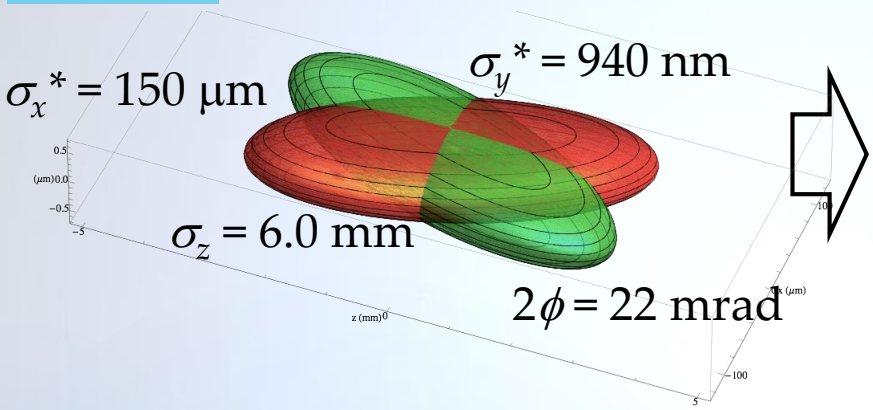


Prospect

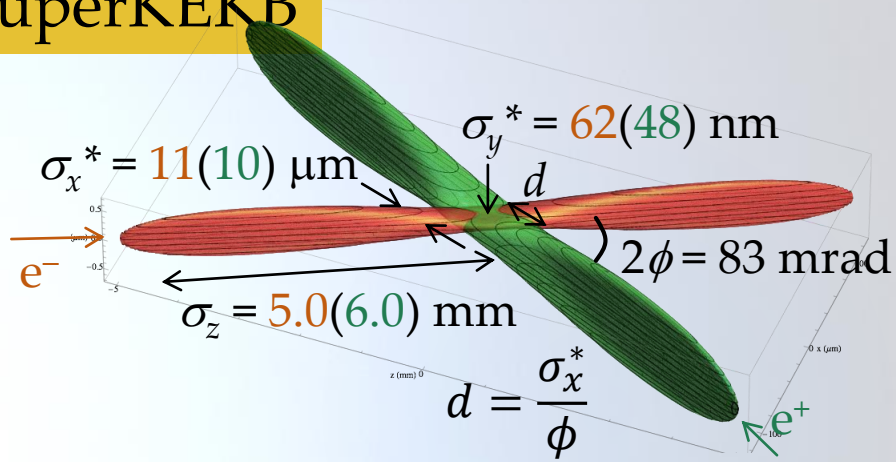

Integrated luminosity (ab⁻¹)
70
60
50
40
30
20
10
0
Goal of Belle II / SuperKEKB
5σ NP observation
3σ NP evidence
based on HFAG 2017 + B2TiP
X_s ℓℓ C_9^NP
S(φK^0)
S(K_S π^0 γ)
S(η′K^0)
P′_5ee/P′_5μμ
B→τν
S(ρ^0γ)
I_Kπ
R(Dτν)
R(D*τν)
9 months/year
20 days/month
x10^35
Peak luminosity (/cm²/s)
8
6
4
2
0
2017
2018
2019
2020
2021
2022
2023
2024
2025
Calendar year

Strategies to increase luminosity

KEKB



SuperKEKB



	KEKB Achieved		SuperKEKB Nano-beam	
	LER (e^+)	HER (e^-)	LER (e^+)	HER (e^-)
I_{beam} [A]	1.6	1.2	3.6	2.6
β_y^* [mm]	5.9	5.9	0.27	0.30
ξ_y	0.09	0.12	0.088	0.081
L [/cm²/s]	2.1×10^{34}		8.0×10^{35}	

Nano-Beam scheme

(P. Raimondi)

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}\frac{R_L}{R_{\xi_y}}$$

$\times 2$

$\times \frac{1}{20}$

→ × 40 luminosity

Major upgrades for SuperKEKB

Gray is reused, colored is new.

Taking advantage of existing items

- **the KEKB tunnel,**
- **the KEKB components as much as possible!**

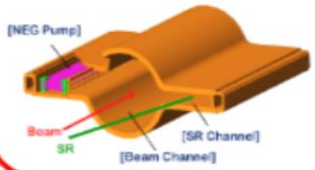
Belle detector is upgraded to Belle II

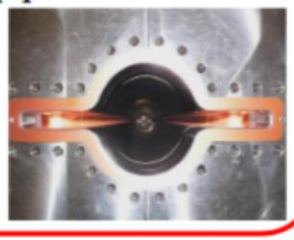
New QCS magnet for Nano-beam scheme

New superconducting final focusing quads

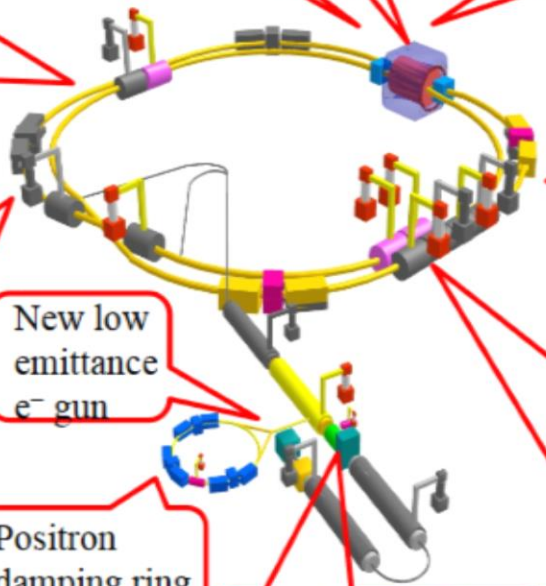
New beam pipe& bellows

TiN-coated beam pipe with antechambers





New design for IR



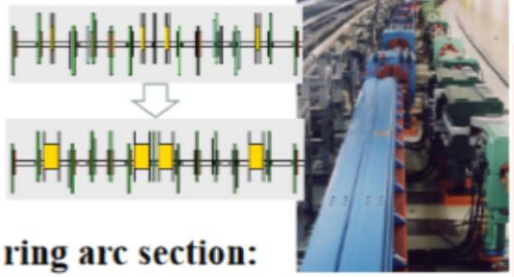
Add / modify RF systems for higher beam current

Main ring arc and straight section:

Redesign the lattices of both rings to reduce the emittance

KEKB

Super KEKB



Main ring arc section:

LER: Replace all main dipoles

HER: Preserve the present cells

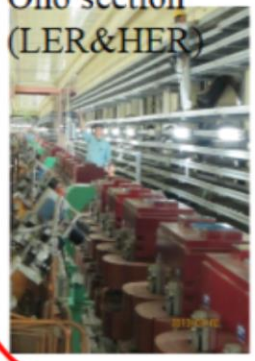
New low emittance e^- gun

Positron damping ring

New e^+ source

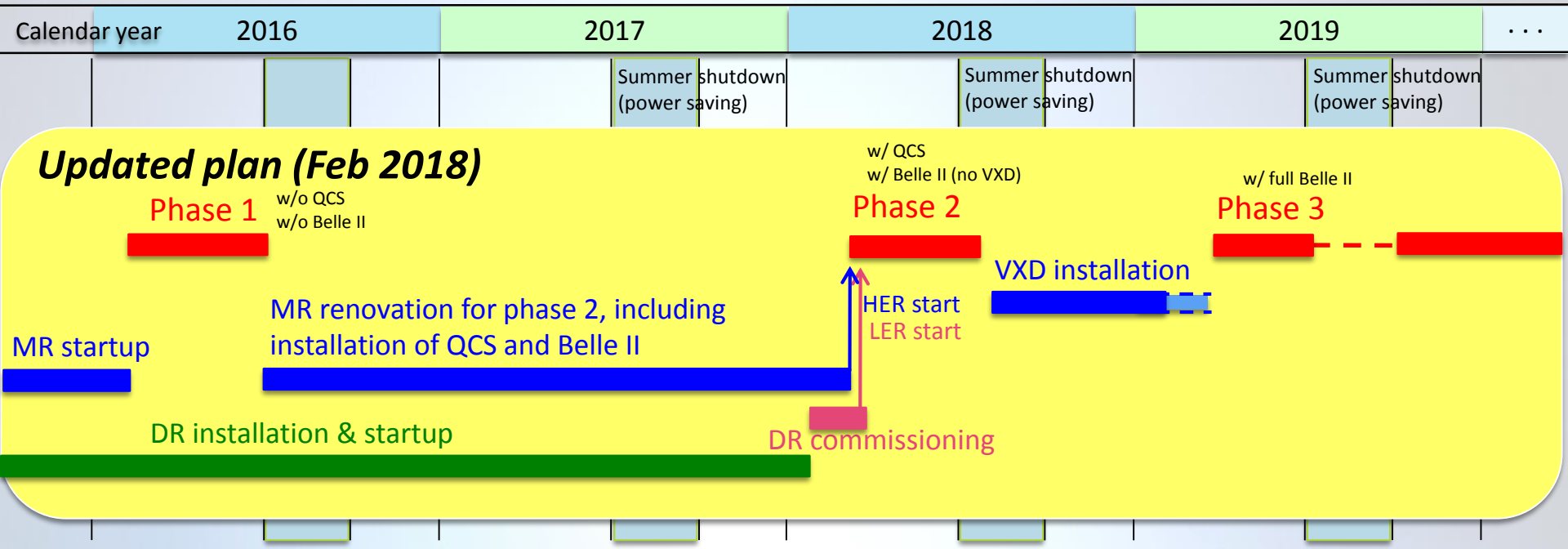
New and re-use wiggler magnets are mixed:

Oho section (LER&HER)



Nikko section (LER)

Schedule



Phase 1
Without QCS or Belle II

Vacuum scrubbing
Basic machine tuning
… Finished in success

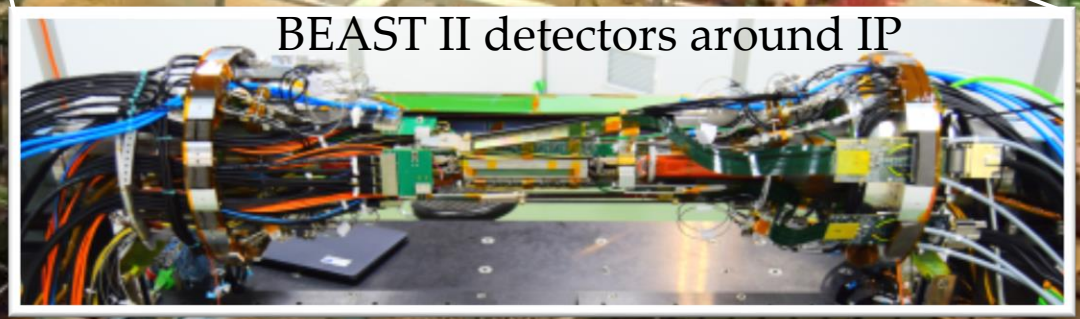
Phase 2
With QCS and Belle II
Without VXD

Background study
Establish the nano-beam scheme
Luminosity tuning
(target: 2 x 10^{34} /cm^2/s = KEKB)
Physics with 20-40 fb^{-1} (dark sector etc.)

Phase 3
Full setup

Physics run
Luminosity tuning
(target: 8 x 10^{35} /cm^2/s)

Belle II and the whole SuperKEKB have been connected together, getting ready for the beam in March and first collision in April!



Feb.12, 2018

Summary

- Belle II aims to search for New Physics in the flavor sector with 50 ab^{-1} data collected at SuperKEKB.
  - FCNC is one of the sensitive processes to New Physics and holds some anomalies.
  - Should be tested with higher statistics and less theoretical and experimental uncertainties.

- After long construction, SuperKEKB / Belle II is finally about to collide the nano-beams and take data.

Exciting time is coming soon!