Status and Prospects Belle II

第三届强子与重味物理理论与实验联合研讨会

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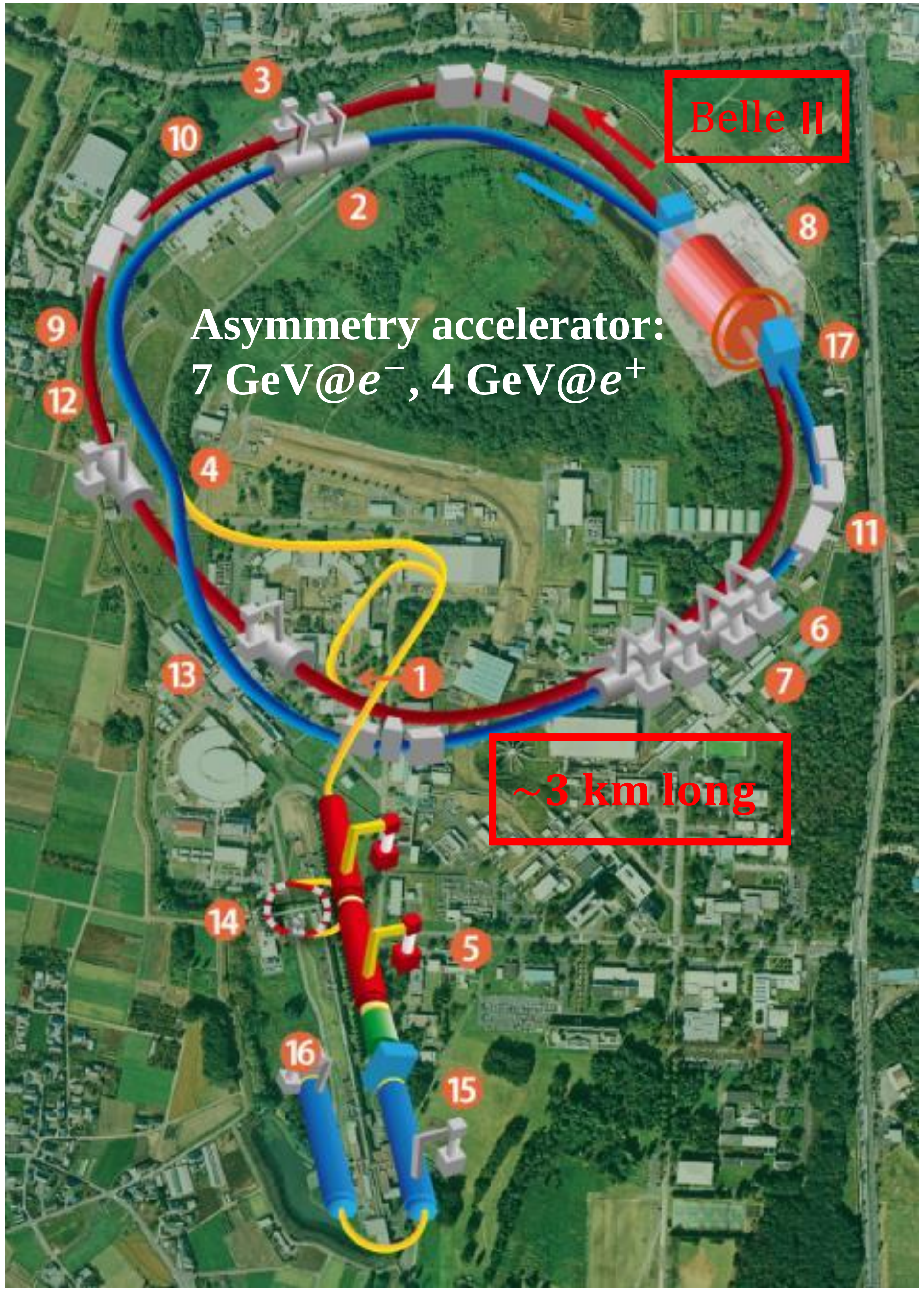
Xi’an Jiaotong University

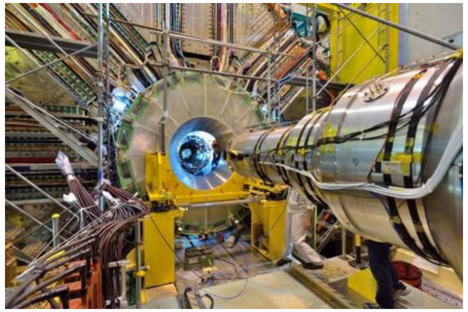
2024/04/08



Belle II

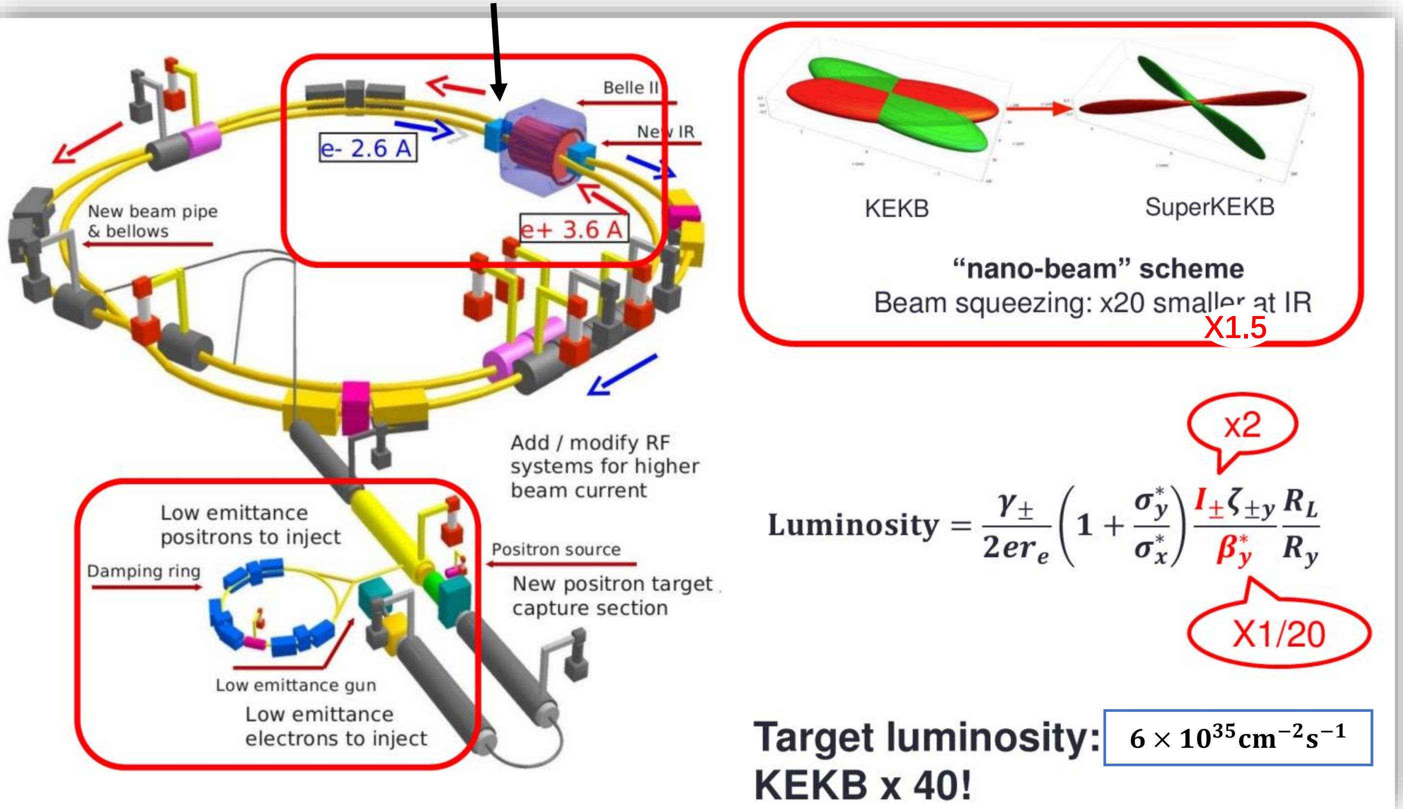
Asymmetry accelerator:
7 GeV@e^-, 4 GeV@e^+

~3 km long



- Accelerator: KEKB → SuperKEKB
- Detector: Belle → Belle II

final focus system: key of high luminosity



“nano-beam” scheme
Beam squeezing: x20 smaller at IR

X1.5

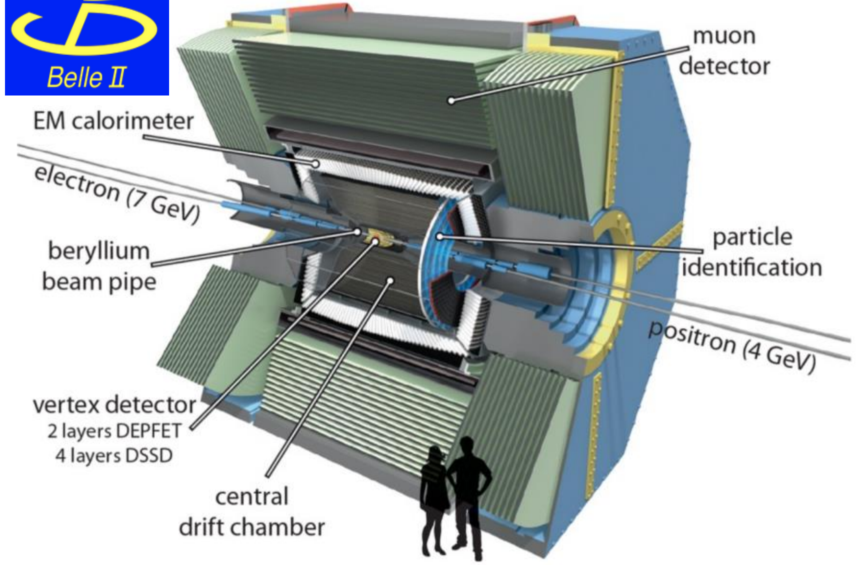
x2

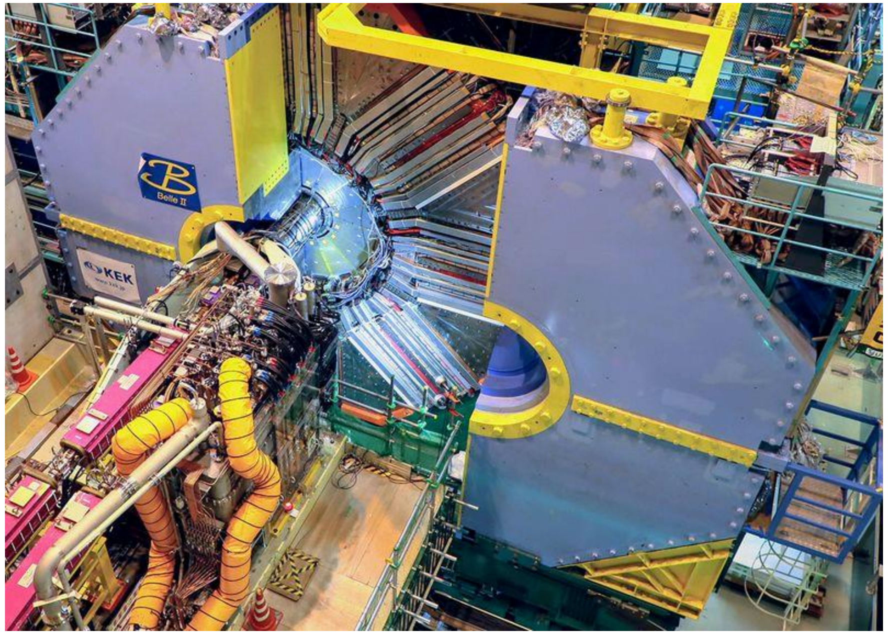
$$\text{Luminosity} = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \zeta_{\pm y}}{\beta_y^*}\frac{R_L}{R_y}$$

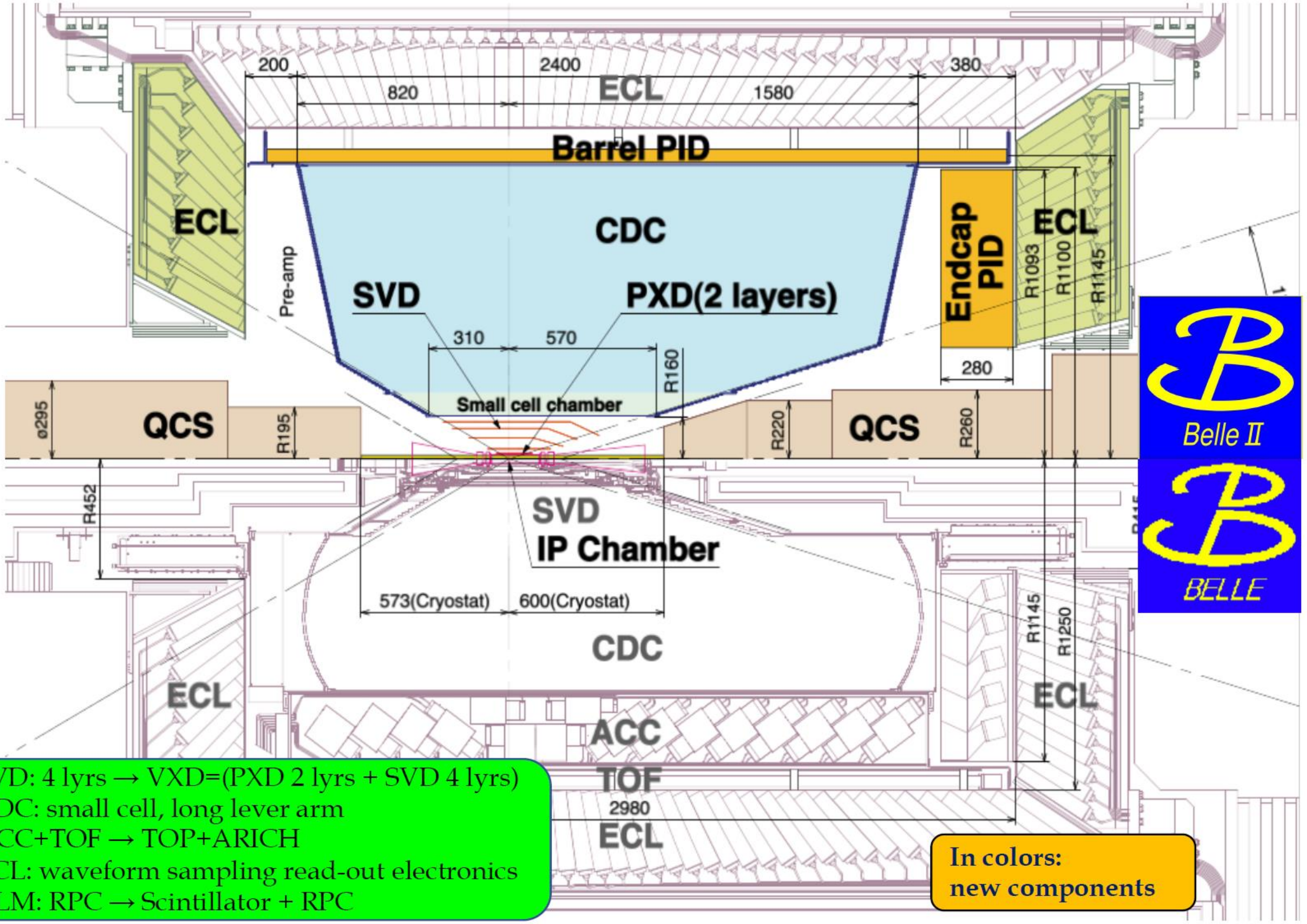
X1/20

Target luminosity: $6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
KEKB x 40!

➢ Detector: Belle → Belle II







SVD: 4 lyrs → VXD=(PXD 2 lyrs + SVD 4 lyrs)
CDC: small cell, long lever arm
ACC+TOF → TOP+ARICH
ECL: waveform sampling read-out electronics
KLM: RPC → Scintillator + RPC

In colors:
new components

$E(\gamma/e)$: $\sigma(E)/E \approx (1.6-4)\%$

P_t of charged-particle: $\sigma(P_t)/P_t$ = 0.4%/pT [GeV/c]

Hadron PID: 90% efficiency at 10% contamination

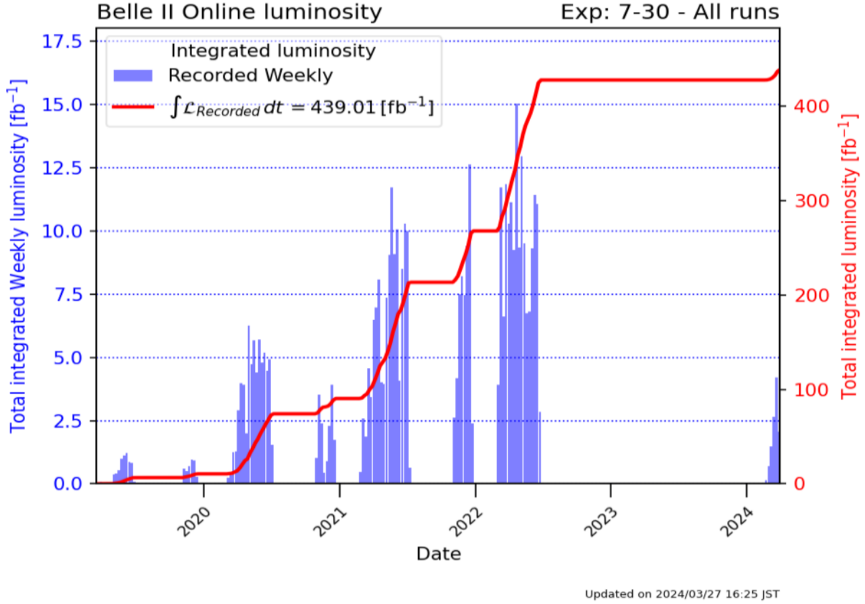
Lepton PID: e: 90% efficiency at 0.5% π contamination
μ: 90% efficiency at 7% K contamination

Operation with full detector started in 2019.

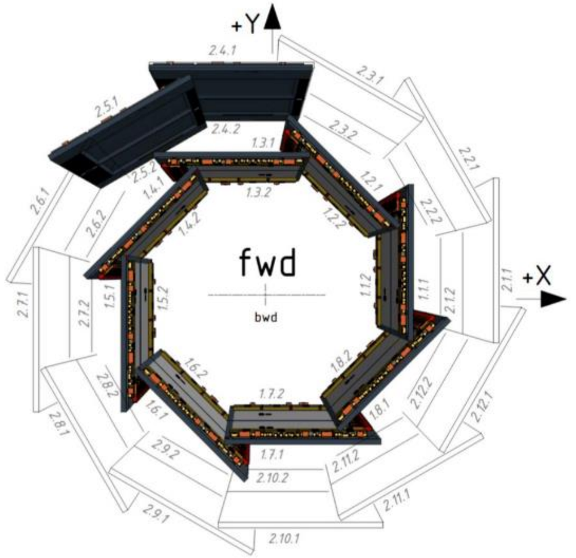
- Luminosity $4.7 \times 10^{34} cm^{-2} s^{-1}$ achieved (Jun 8, 2022).
  - ✓World record (~ ×2 of KEKB)
  - ✓Aiming one order higher.

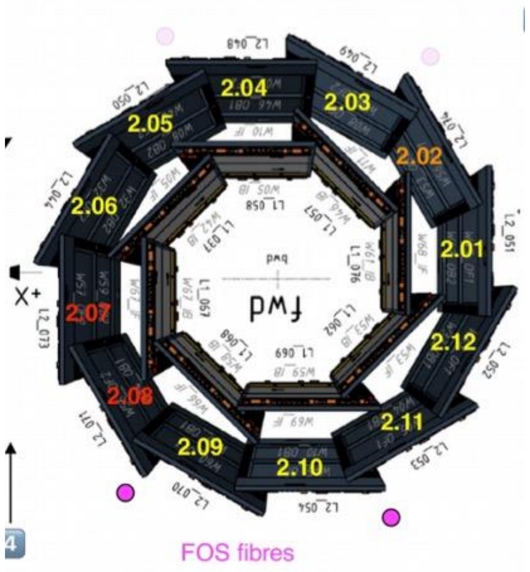
record of KEKB/Belle
$2\times10^{34}/\mathrm{cm}^2/\mathrm{s}$ currents > 1 A
record of PEPII/BaBar
$1\times10^{34}/\mathrm{cm}^2/\mathrm{s}$ currents > 2 A

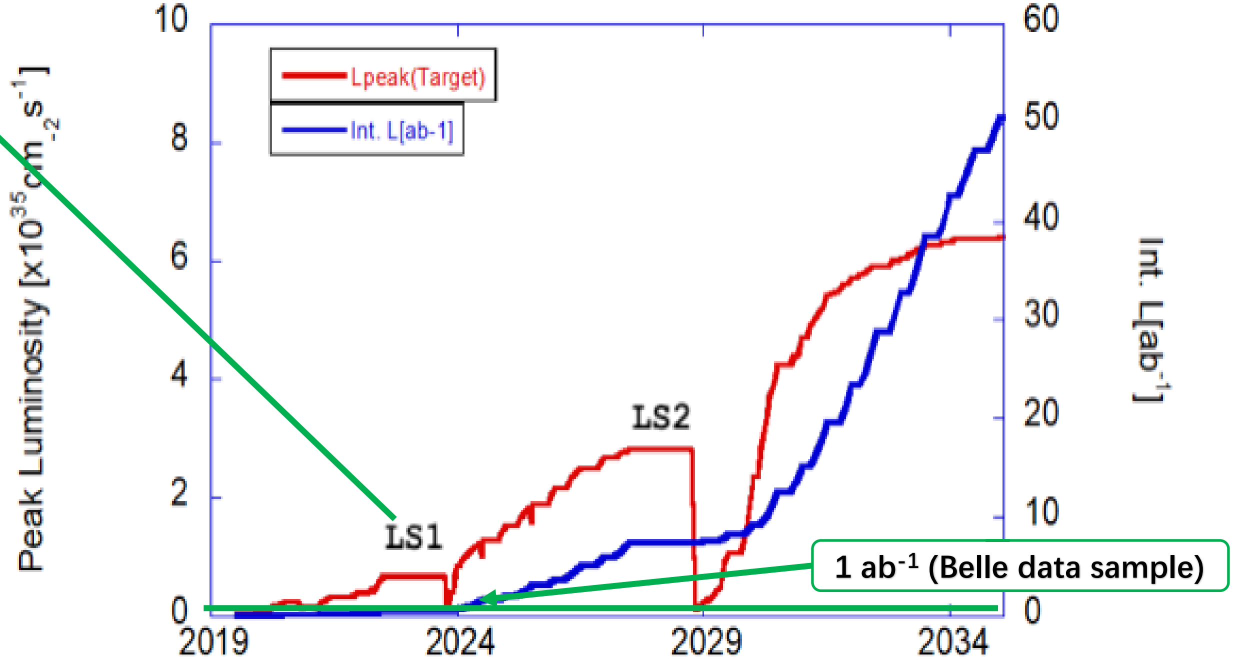
- 440 fb$_{-1}$ of data accumulated so far.
  - ✓Belle: 1 ab^{-1} (= 1000 fb^{-1}) in 11 years´ operation.
  - ✓Belle II target: 50 ab^{-1}.



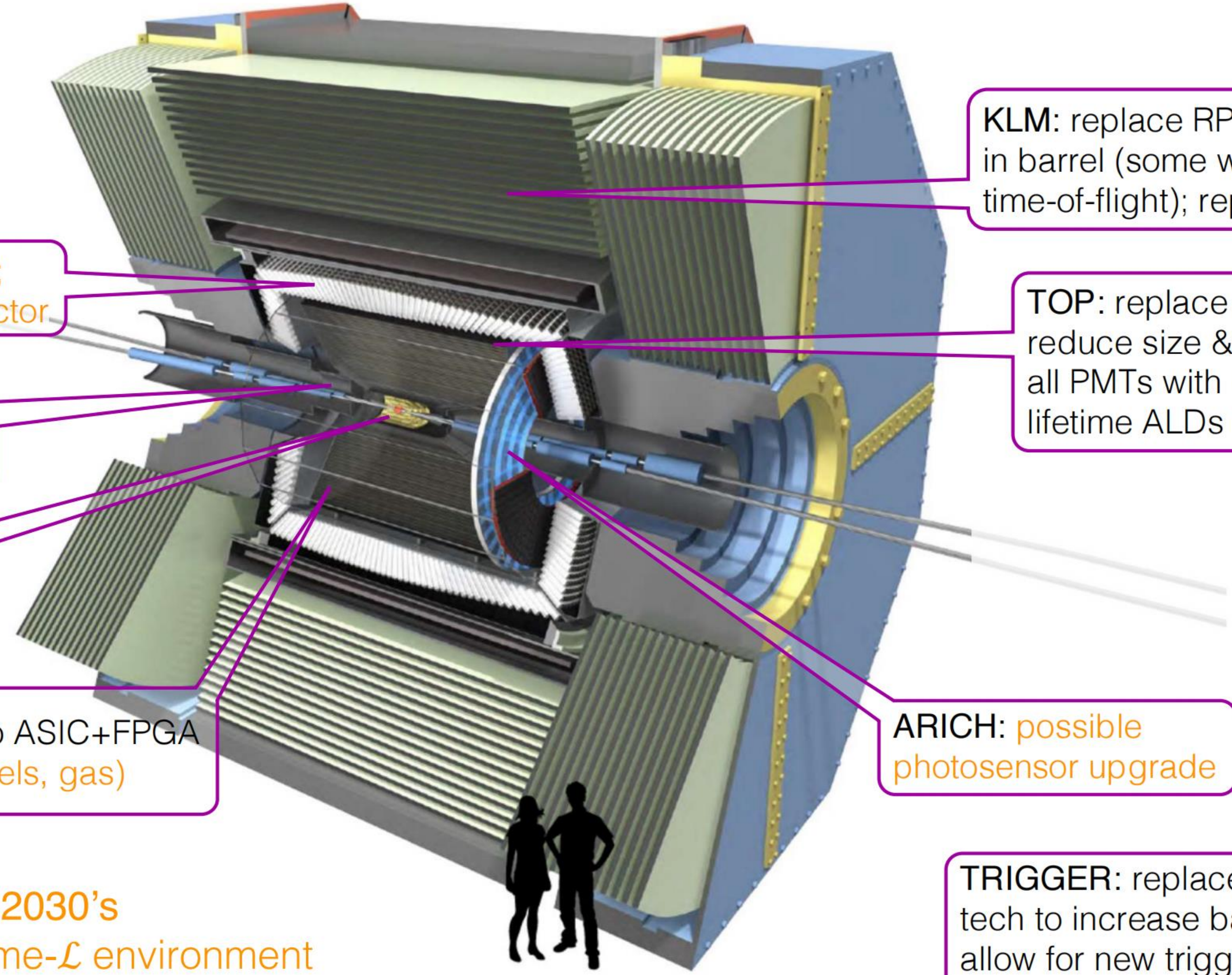
During Long Shut down:
- ➢ Belle II had the first long shutdown for PXD fully
- ➢ Improved CDC gas distribution and monitoring







Belle II Upgrades – LS2 and Beyond



KLM: replace RPCs with scintillators in barrel (some with fast timing for K_L time-of-flight); replace readout

ECL: replace crystals with pure CsI; APD readout; add pre-shower detector

TOP: replace readout to reduce size & power; replace all PMTs with extended-lifetime ALDs (or SiPMs?)

IR: accommodate QCS replacement and repositioning

VXD: all pixels DMAPS

Depleted Monolithic Active Pixel Sensors

CDC: replace r/o ASIC+FPGA
New tracker (pixels, gas)

ARICH: possible photosensor upgrade

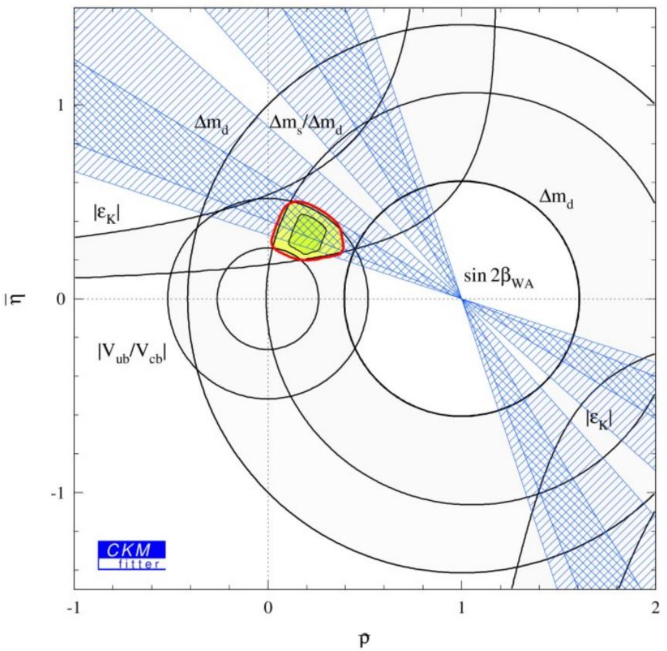
TRIGGER: replace with latest tech to increase bandwidth, allow for new trigger primitives

More distant future: ~mid-2030's
✓ Detector R&D for extreme-$\mathcal{L}$ environment

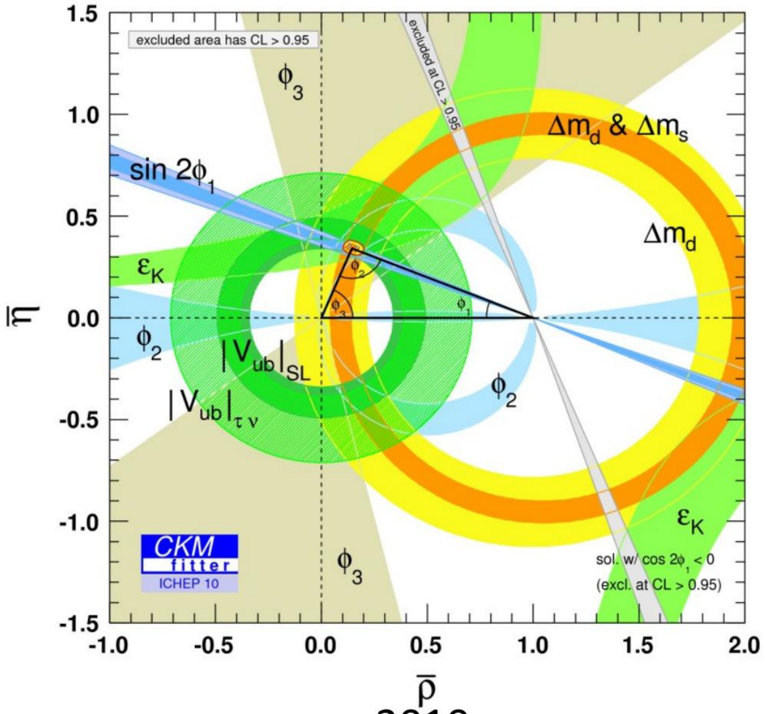
What Belle II can do?

- Flavor physics
  - **B**
    - CKM Unitarity Triangle
    - Rare decays
    - Lepton Flavor Universality
    - etc
  - Charm
    - CPV
    - mixing
    - Lifetime
    - etc
  - τ
    - Mass
    - Lifetime
    - CPV
    - EDM
    - etc
- QCD
  - Bottomonia, charmonia and exotic hadrons
  - HVP with radiative return for muon g-2
  - fragmentation
  - etc
- EW
  - Weak mixing angle
  - etc
- Light new particle searches
  - Dark sector mediators
  - etc
- And more
  - Bell's inequality
  - etc

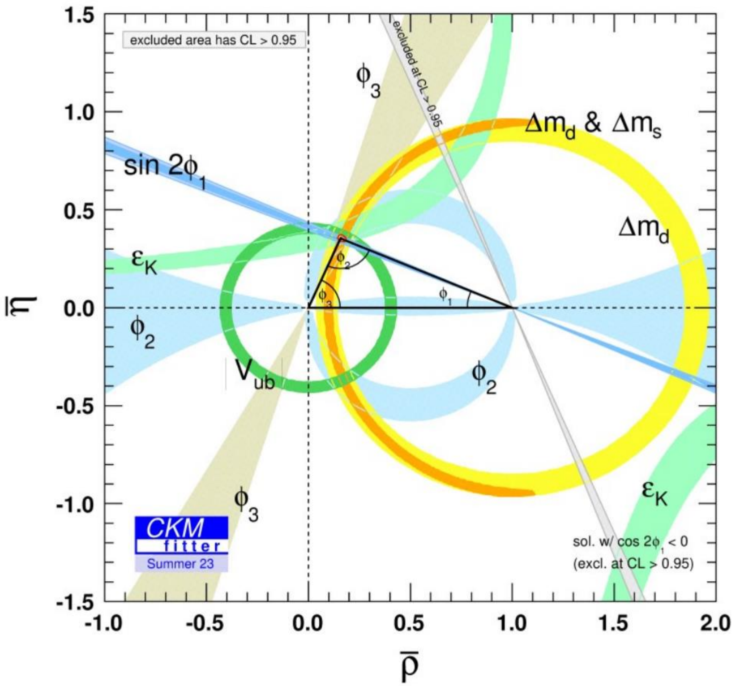
CKM



2001



2010

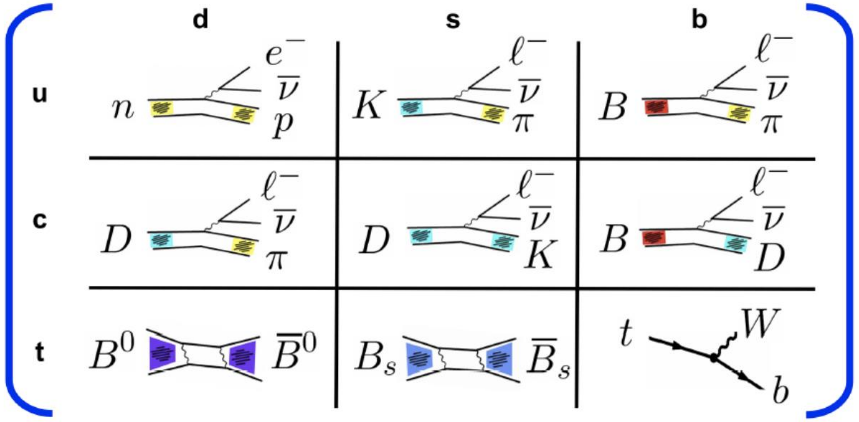


2023

$$\alpha = \phi_2 \qquad \beta = \phi_1 \qquad \gamma = \phi_3$$

- d → u: Nuclear physics (superallowed β decays)
- s → u: Kaon physics (KLOE, KTeV, NA62)
- **c → d, s: Charm physics (CLEO-c, Babar, Belle, BESIII)**
- **b → u, c and t → d, s: B physics (Babar, Belle, CDF, DØ, LHCb)**
- t → b: Top physics (CDF/DØ, ATLAS, CMS)

V =

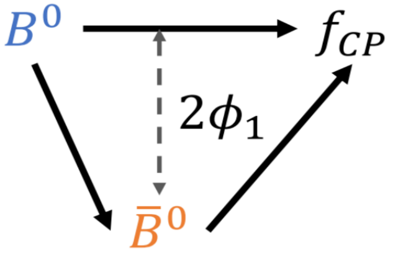


$\beta = \phi_1$: Decay-time-dependent CPV in B decays

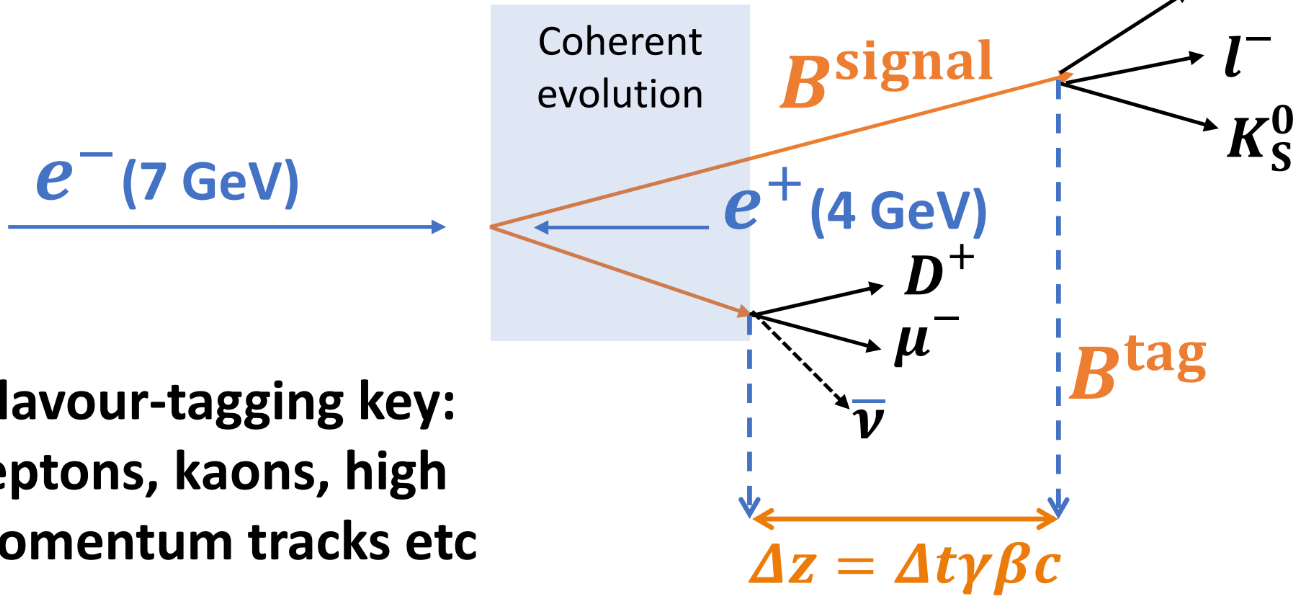
Error at 2.4%, dominated by systematic uncertainty (**vertex** and **flavor tag algorithm**)

arXiv:2402.17260 [hep-ex]

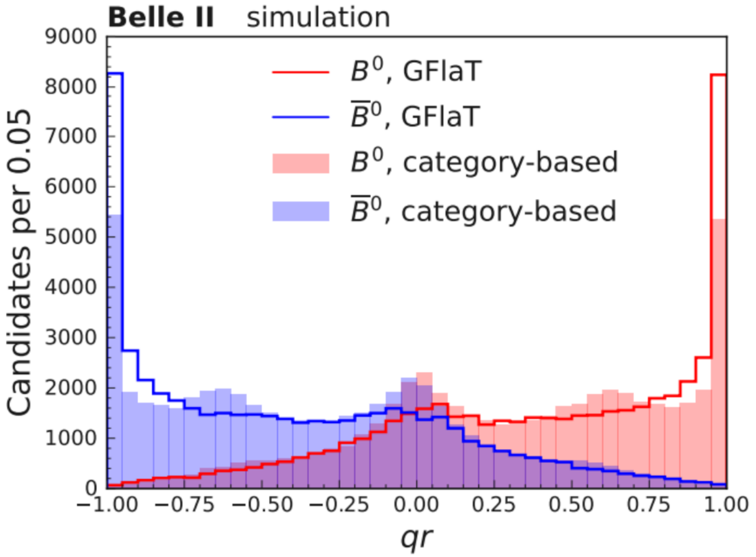
Flavour tagging improvements



$$\propto \ |V_{td}|^2 e^{2i\phi_1}$$



Flavour-tagging key: leptons, kaons, high momentum tracks etc



Graph-neural-network approach has improved our tagging by 18%

$$\boldsymbol{\epsilon(1-2\omega) = 37.4\%}$$

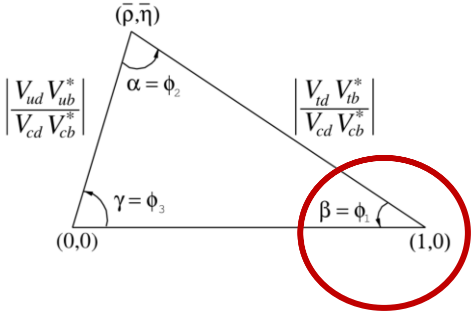
$\beta = \phi_1$: Decay-time-dependent CPV in B decays

$$\mathcal{A}_{\mathrm{CP}}(\Delta t) = \frac{\mathcal{B}(\bar{B}^0 \to f_{\mathrm{CP}})(\Delta t) - \mathcal{B}(B^0 \to f_{\mathrm{CP}})(\Delta t)}{\mathcal{B}(\bar{B}^0 \to f_{\mathrm{CP}})(\Delta t) + \mathcal{B}(B^0 \to f_{\mathrm{CP}})(\Delta t)} = S\sin(\Delta m_d \Delta t) + A\cos(\Delta m_d \Delta t)$$

The SM predicts A = 0 and S = −η sin 2ϕ1

Mixing-induced CPV

Direct CPV

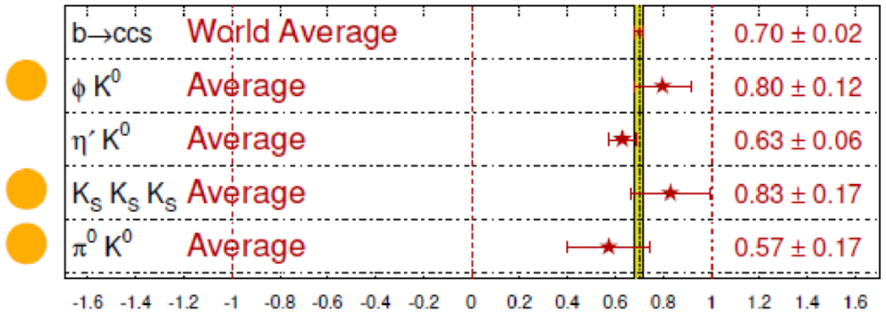


Belle II is the **only** experiment capable of pursuing these measurements

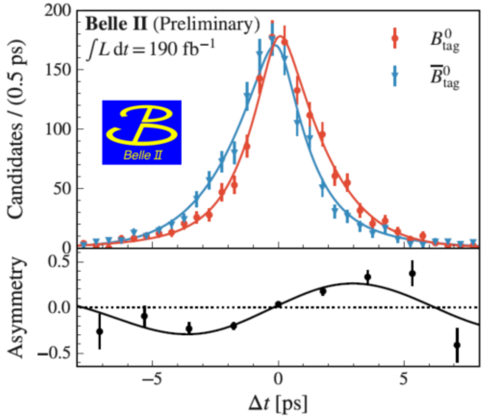
Hinting BSM

New

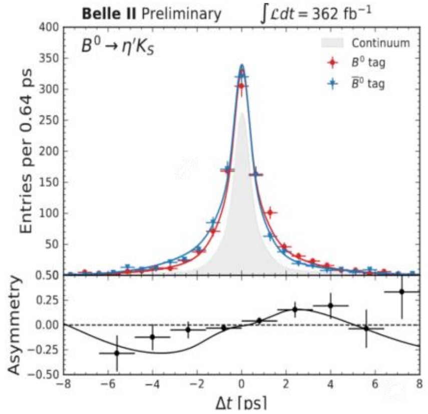
$\sin(2\beta^{\mathrm{eff}}) \equiv \sin(2\phi_1^{\mathrm{eff}})$ HFLAV 2021



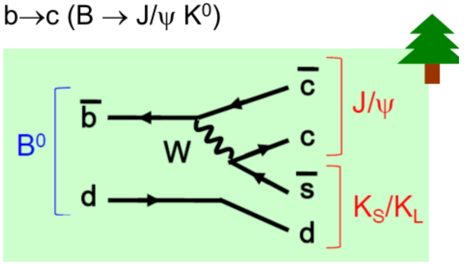
$B^0 \to J/\psi K_S^0$



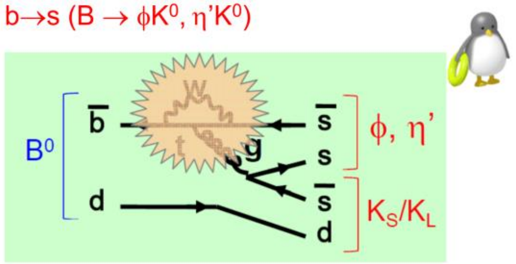
$B^0 \to \eta' K_S^0$



b→c (B → J/ψ K0)



b→s (B → ϕK0, η’K0)



sin(2ϕ1) = 0.720 ± 0.062 ± 0.016

A = 0.094 ± 0.044 $^{+0.047}_{-0.017}$

$\sin(2\phi_1') = 0.67 \pm 0.10 \pm 0.04$

$K_S^0\pi^0\gamma$	σ_S^{stat}	σ_S^{syst}	$\rho^0\gamma$	σ_S^{stat}	σ_S^{syst}
1 ab^{-1}	0.31	0.02	1 ab^{-1}	0.469	0.133
5 ab^{-1}	0.14	0.01	5 ab^{-1}	0.210	0.061
10 ab^{-1}	0.10	0.01	10 ab^{-1}	0.148	0.044
50 ab^{-1}	0.04	0.01	50 ab^{-1}	0.066	0.024

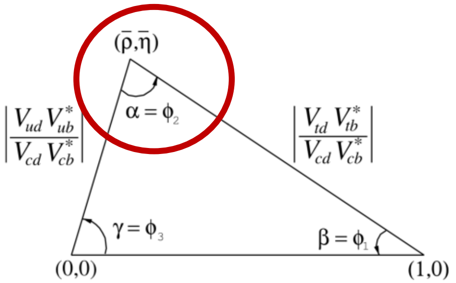
$(c\bar{c})K^0$	σ_S^{stat}	σ_S^{syst}
1 ab^{-1}	0.018	0.011
5 ab^{-1}	0.008	0.008
10 ab^{-1}	0.006	0.008

$\eta' K_S^0$	σ_S^{stat}	σ_S^{syst}	ϕK_S^0	σ_S^{stat}	σ_S^{syst}
1 ab^{-1}	0.054	0.031	1 ab^{-1}	0.103	0.038
5 ab^{-1}	0.024	0.017	5 ab^{-1}	0.046	0.030
10 ab^{-1}	0.017	0.015	10 ab^{-1}	0.033	0.029
50 ab^{-1}	0.007	0.013	50 ab^{-1}	0.015	0.028

$\alpha = \phi_2$: TDCPV in $b \to d$

Least known CKM angle

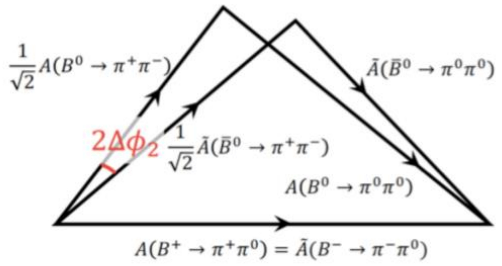
$(82^{+4.8}_{-4.3})^{\circ}$



- Dominated by $b \to u\bar{u}d$(tree), but with sizeable $b \to d$ penguin amplitude.
  - ➢ hard to interpret in perturbative calculations
- $B \to \pi\pi$.
  - ➢ Penguin and tree contributions can be disentangled using the isospin relations:

$\bar{A}_{\pi^+\pi^0} = \frac{1}{\sqrt{2}}\bar{A}_{\pi^+\pi^-} + \bar{A}_{\pi^0\pi^0}$ and $A_{\pi^+\pi^0} = \frac{1}{\sqrt{2}}A_{\pi^+\pi^-} + A_{\pi^0\pi^0}$ **(Isospin sum rules)**

M. Gronau and D. London, Phys Rev. Lett. **65**, 3381 (1990).

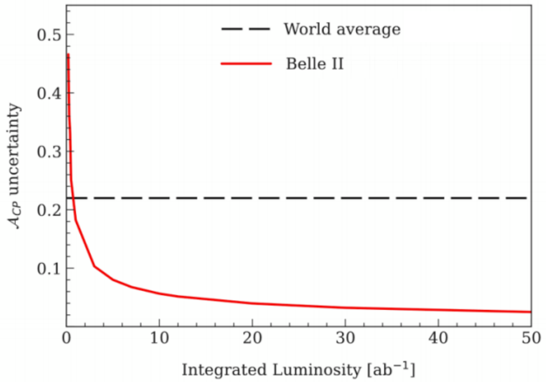


Dominated uncertainty:

$\mathcal{B}\left(B^0 \to \pi^0\pi^0\right) = (1.59 \pm 0.26) \times 10^{-6}$

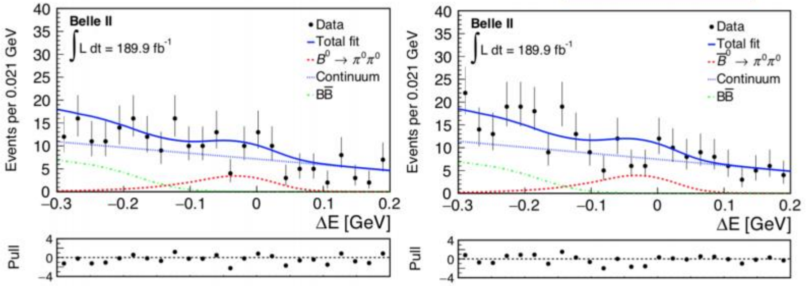
$A_{CP}\left(B^0 \to \pi^0\pi^0\right) = 0.33 \pm 0.22$ (1 order larger than others)

Further uncertainty of $A_{CP}\left(B^0 \to \pi^0\pi^0\right)$



arXiv:2303.08354

Belle II 189 fb^{-1}

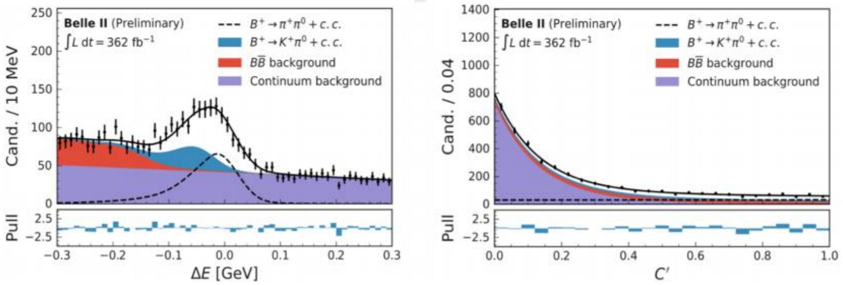


$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.14 \pm 0.46 \pm 0.07.$

Belle (772M $B\bar{B}$) : $A_{CP} = +0.14 \pm 0.36$ (stat.) $\pm$ 0.10 (syst.)

$B^+ \to \pi^+\pi^0$

Belle II 362 fb^{-1}



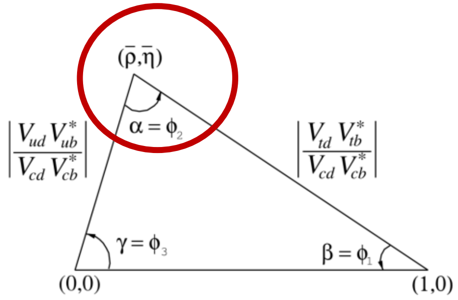
$A_{CP}(B^+ \to \pi^+\pi^0) = -0.08 \pm 0.05 \pm 0.01$

Belle (772M $B\bar{B}$) : $A_{CP} = +0.025 \pm 0.043 \pm 0.007$

$\alpha = \phi_2$: TDCPV in $b \to (uu)d$

Least known CKM angle

$(82^{+4.8}_{-4.3})^{\circ}$



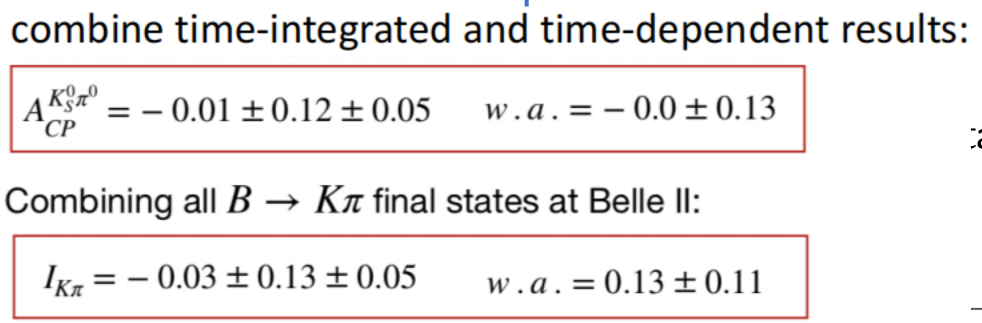
- Most promising channel: $B \to \rho\rho$: uncertainty of 4 degrees.
  - ➢ almost all longitudinally polarized → purely CP-even
  - ➢$\mathcal{B}(B^0 \to \rho^0\rho^0)/\mathcal{B}(B^{0,+} \to \rho^+\rho)$~4% →small penguin contribution

Main Systematic uncertainties:

data-simulation mismodeling in angular distributions

π^0 reconstruction efficiency

$\Big\}$ improve with luminosity.



combine time-integrated and time-dependent results:

$$A_{CP}^{K_S^0\pi^0} = -0.01 \pm 0.12 \pm 0.05 \qquad w.a. = -0.0 \pm 0.13$$

Combining all $B \to K\pi$ final states at Belle II:

$$I_{K\pi} = -0.03 \pm 0.13 \pm 0.05 \qquad w.a. = 0.13 \pm 0.11$$

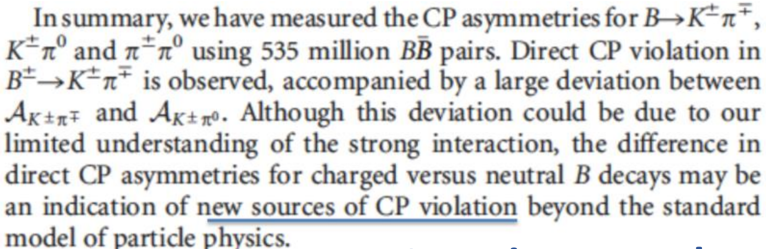
Future Precision:

- ☐ 2.5 degrees using under 10 ab^{-1}
- ☐ 0.6 degrees using under 50 ab^{-1}

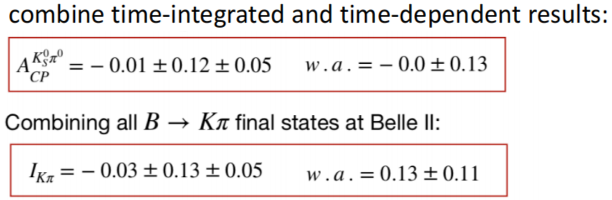
ainty of A_{CP} $(B^0 \to \pi^0\pi^0)$

$K\pi$ puzzle

CPV in $B \to K\pi$ decay differ from SM about 3σ



In summary, we have measured the CP asymmetries for $B \to K^{\pm}\pi^{\mp}$, $K^{\pm}\pi^0$ and $\pi^{\pm}\pi^0$ using 535 million $B\bar{B}$ pairs. Direct CP violation in $B^{\pm} \to K^{\pm}\pi^{\mp}$ is observed, accompanied by a large deviation between $\mathcal{A}_{K^{\pm}\pi^{\mp}}$ and $\mathcal{A}_{K^{\pm}\pi^0}$. Although this deviation could be due to our limited understanding of the strong interaction, the difference in direct CP asymmetries for charged versus neutral B decays may be an indication of new sources of CP violation beyond the standard model of particle physics.



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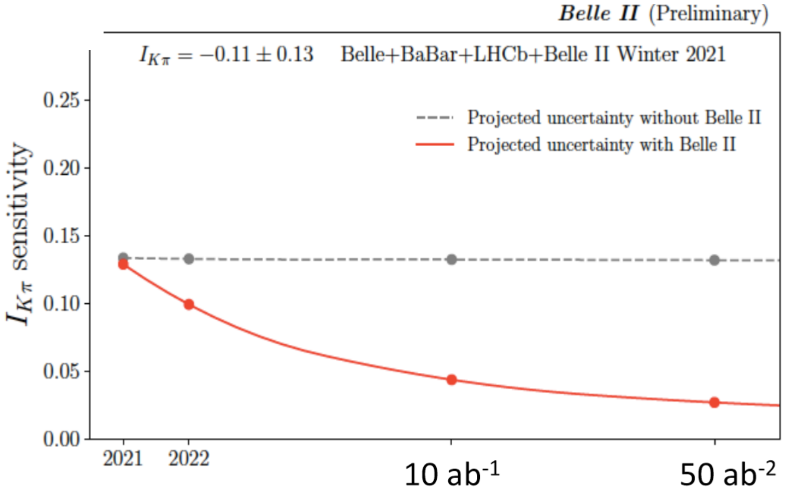


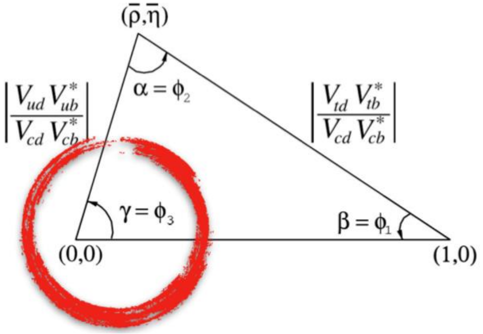
Isospin sum rules

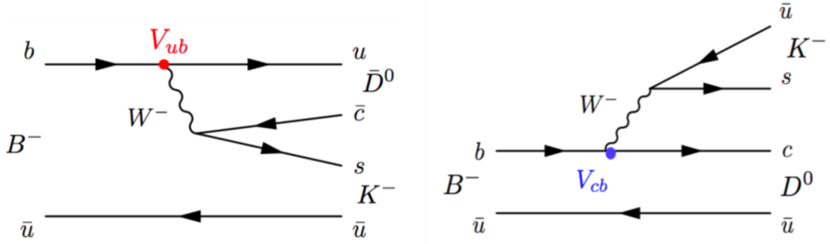
$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)}$$

≈ 0 with $O(0.01)$

$\gamma = \phi_3$: tree-level decays with D

- **Theoretical uncertainty on measurement is $\frac{\delta\phi_3}{\phi_3} \sim 10^{-7}$**
- **Test physics beyond SM**
- **CPV in the interference $b \to c\bar{u}s$ and $b \to u\bar{c}s$:**

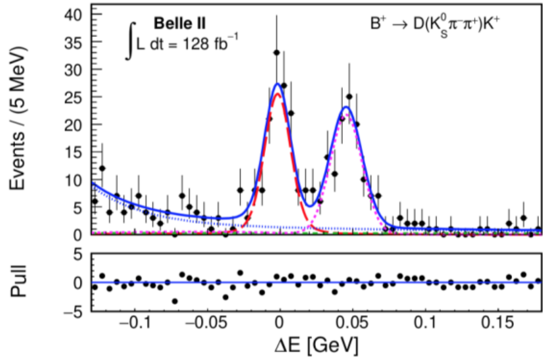


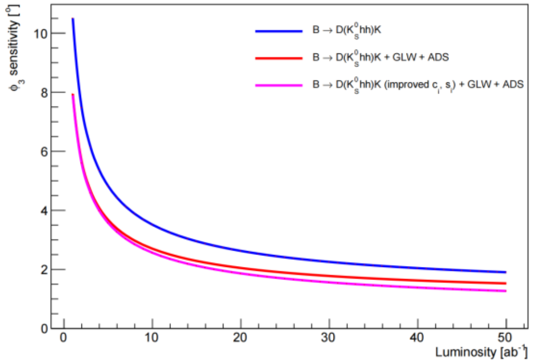


$$\frac{\mathcal{A}^{\text{suppr.}}\left(B^- \to \bar{D}^0 K^-\right)}{\mathcal{A}^{\text{favor.}}\left(B^- \to D^0 K^-\right)} = r_B e^{i(\delta_B+\gamma)}$$

JHEP02(2022)063

$$\boxed{\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ}$$





~ 1.5° (50 ab^{-1} @Belle II)

Data limited!

-- $B^0 \to D(\to K_S h^+h^-)K^{*0}$

LHCb-PAPER-2023-009

- Limited statistics,
- CPV still observed in some bins

$$\boxed{\phi_3 = (49^{+23}_{-18})^\circ}$$

-- $B^- \to D^*(\to D(\to K_S h^+h^-)\pi^0/\gamma)h^-$

LHCb-PAPER-2023-012

$$\boxed{\phi_3 = (69 \pm 14)^\circ}$$

-- $B^- \to D(\to K^+K^-\pi^+\pi^-))h^-$

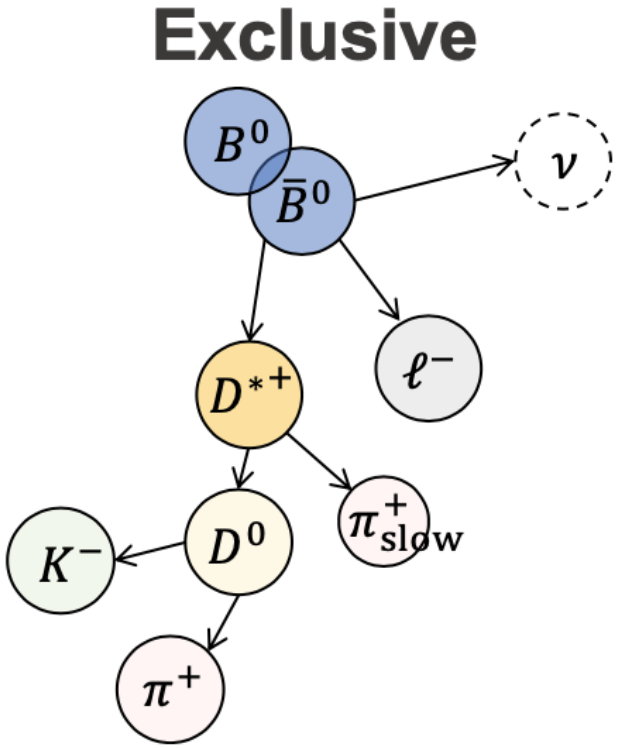
Eur. Phys. J. **C83** (2023) 547

$$\boxed{\phi_3 = (116^{+12}_{-14})^\circ}$$

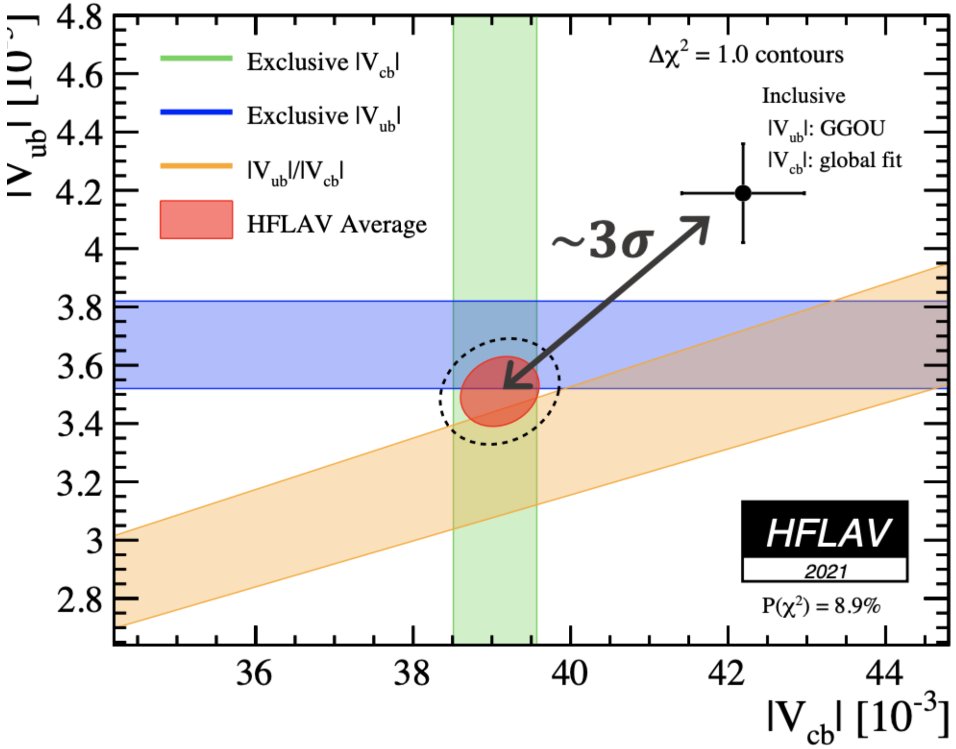
Precision in 2013	LHCb 2018	Upgrade I (50 fb^{-1})	Upgrade II (300 fb^{-1})
~10−12°	4°	1°	0.35°

Semileptonic B Decays

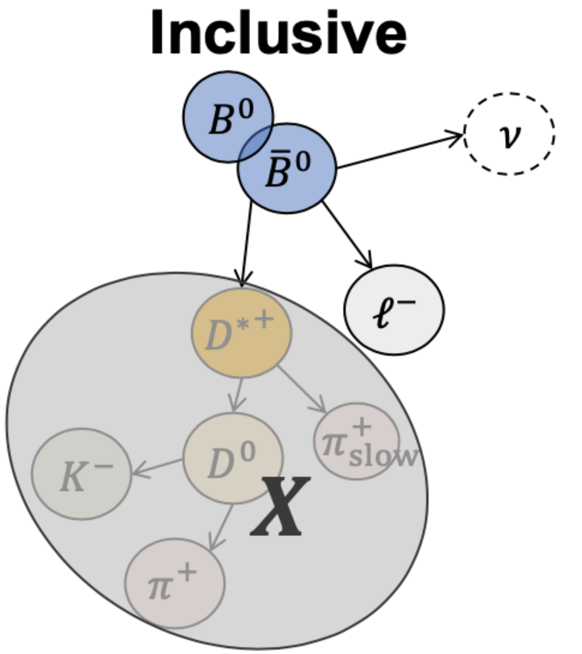
❖ determine the CKM elements $|V_{cb}|$ and $|V_{ub}|$



Reconstruct all daughters through specific channels exclusively.



The current experimental focus is on understanding the origin of this discrepancy.



Reconstruct a lepton and assign other tracks and clusters as an inclusive daughter X.

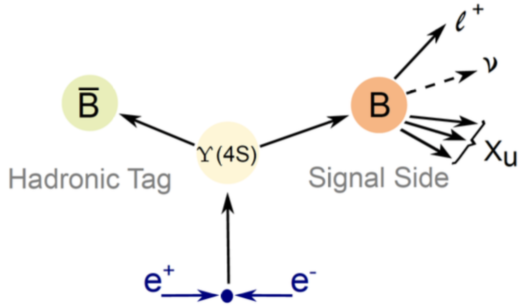
Semileptonic B Decays

$|V_{ub}|$:

$$|V_{ub}^{\text{excl.}}| = (3.51 \pm 0.12) \times 10^{-3}$$
$$|V_{ub}^{\text{incl.}}| = (4.19 \pm 0.16) \times 10^{-3}$$

Ratio = 0.84 ± 0.04

3.7σ from unity!!



Excl. $(3.78 \pm 0.23_{\text{stat}} \pm 0.16_{\text{syst}} \pm 0.14_{\text{theo}}) \times 10^{-3}$

Incl. $(3.88 \pm 0.20_{\text{stat}} \pm 0.31_{\text{syst}} \pm 0.09_{\text{theo}}) \times 10^{-3}$

Ratio $0.97 \pm 0.12 \quad (\rho = 0.11)$ compatible with the world average within 1.2σ

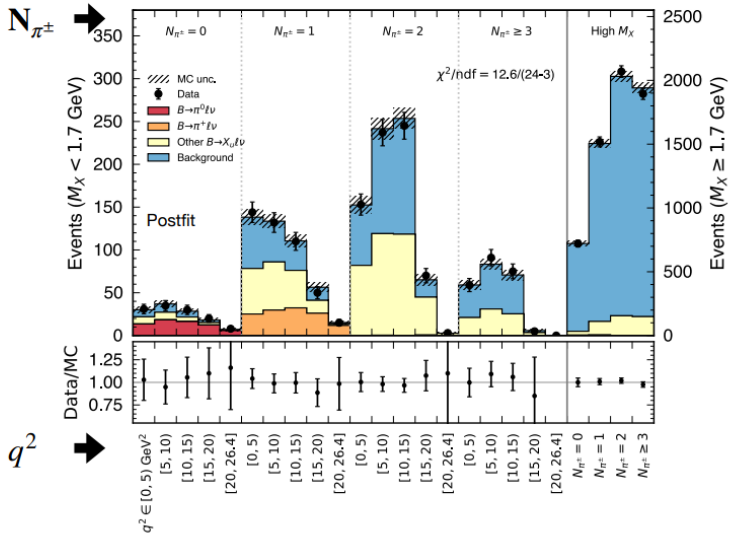
PRL131.211801(2023)

$|V_{ub}^{CKM}|$:

$(3.6 \pm 0.07) \times 10^{3}$

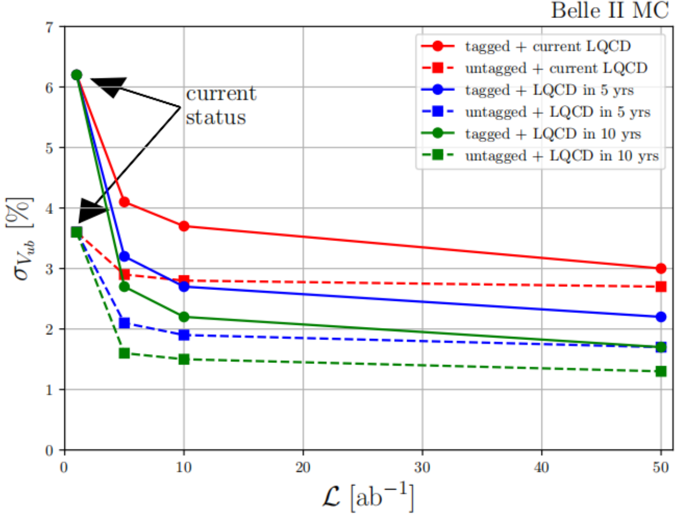
$$|V_{ub}^{\text{excl.}}| = \sqrt{\frac{\mathscr{B}(B \to \pi \ell \nu)}{\tau_B \cdot \Gamma_{\text{FF}}}}$$

$$|V_{ub}^{\text{incl.}}| = \sqrt{\frac{\Delta\mathscr{B}(B \to X_u \ell \nu)}{\tau_B \cdot \Delta\Gamma_{\text{GGOU}}}}$$



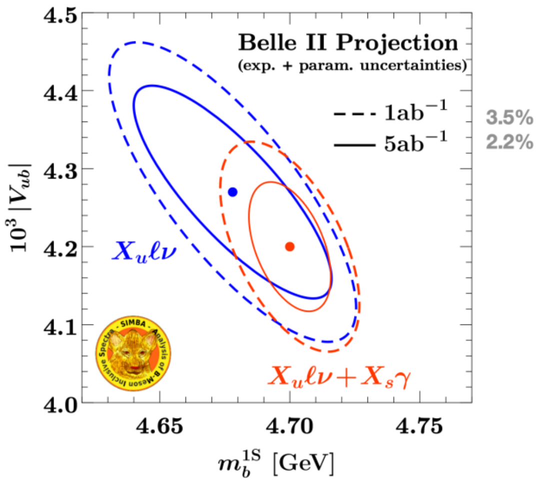
Exclusive: most effective channel: $B \to \pi \ell^- \bar{\nu}_\ell$

Uncertainties of 3% or better are expected



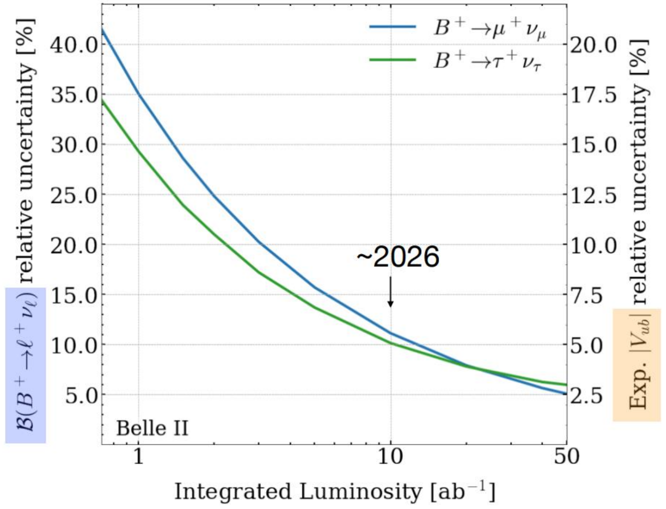
Inclusive:

Uncertainties of 2.2% under $5ab^{-1}$



$B \to \tau\nu, \mu\nu$

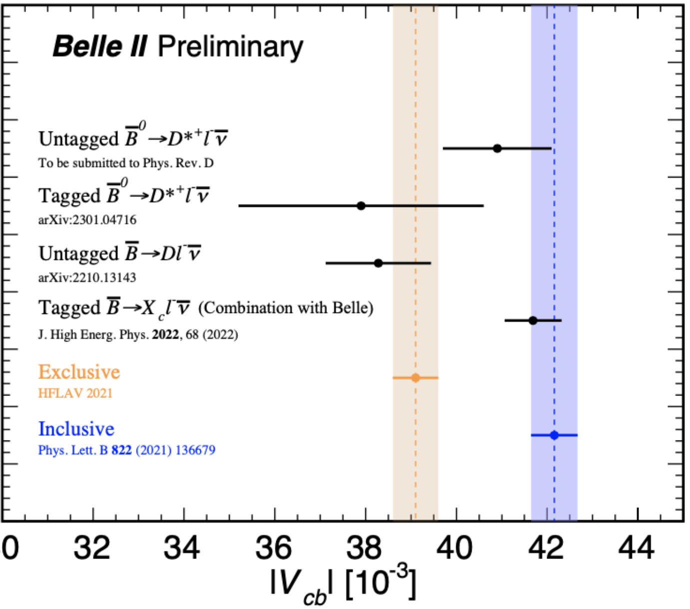
Uncertainties of 2.5% under $5ab^{-1}$



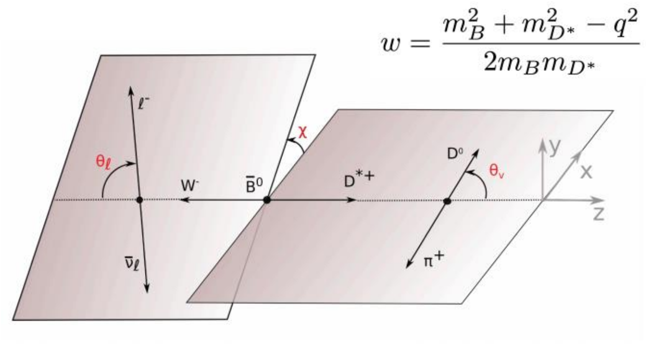
Semileptonic B Decays

$|V_{cb}|$: Belle II has an edge over any existing or foreseen experiment

Decay chain: $B^0 \rightarrow D^{*+} \ell\nu$, $D^{*+} \rightarrow D^0\pi^+_{slow}$, $D^0 \rightarrow K^- \pi^+$



- Untagged strategy (higher efficiency than tagged)
- Select energetic signal lepton $p^{CM} > 1.2$ GeV
- Measured total $\mathscr{B}$ and differential spectra: recoil parameter w, and angles $\cos\theta_\ell$, $\cos\theta_v$, χ
- **Extract $|V_{cb}|$, lepton angular asymmetry, D* longitudinal polarization fractions**


$$w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}$$

Parameterisations
Caprini-Lellouch-Neubert (CLN) [Nucl. Phys. B530, 153]
Boyd-Grinstein-Lebed (BGL) [Phys. Rev. D56, 6895]

Inclusively:

$$|V_{cb}| = (41.99 \pm 0.65) \cdot 10^{-3}$$

$$|V_{cb}|_{\mathrm{BGL}} = (40.57 \pm 0.31 \pm 0.95 \pm 0.58) \times 10^{-3}$$

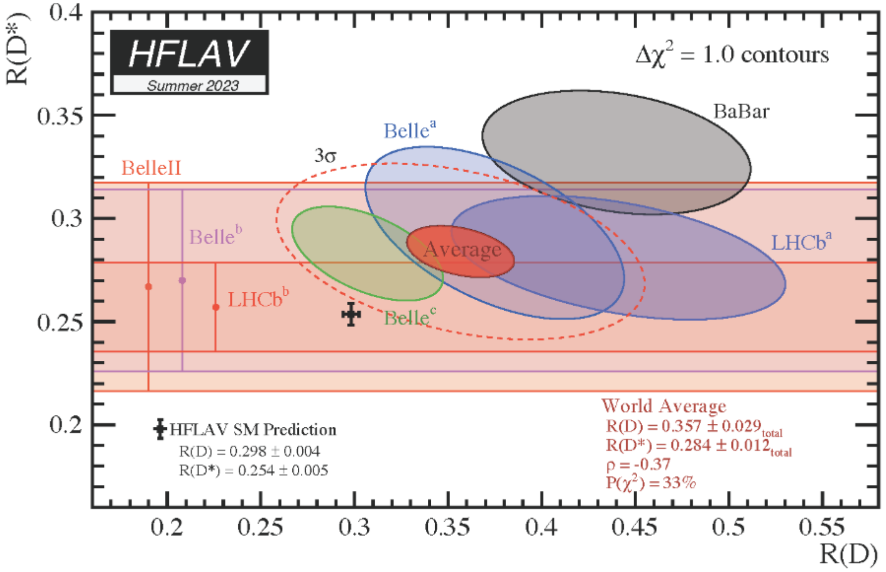
$$|V_{cb}|_{\mathrm{CLN}} = (40.13 \pm \underset{\text{stat.}}{0.27} \pm \underset{\text{syst.}}{0.93} \pm \underset{\text{LQCD uncertainty on F(1)}}{0.58}) \times 10^{-3}$$

(dominated by slow pion tracking eff. leptonID)

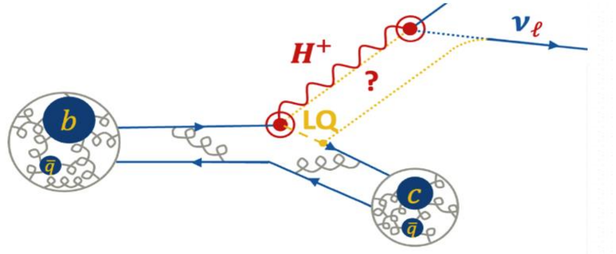
Ultimately Belle II will accomplish measurements of |Vcb| to $O(0.01)$ precision.

Semileptonic B Decays

- Tests of lepton universality, $R\left(D^{(*)}\right), R\left(K^{(*)}\right)$

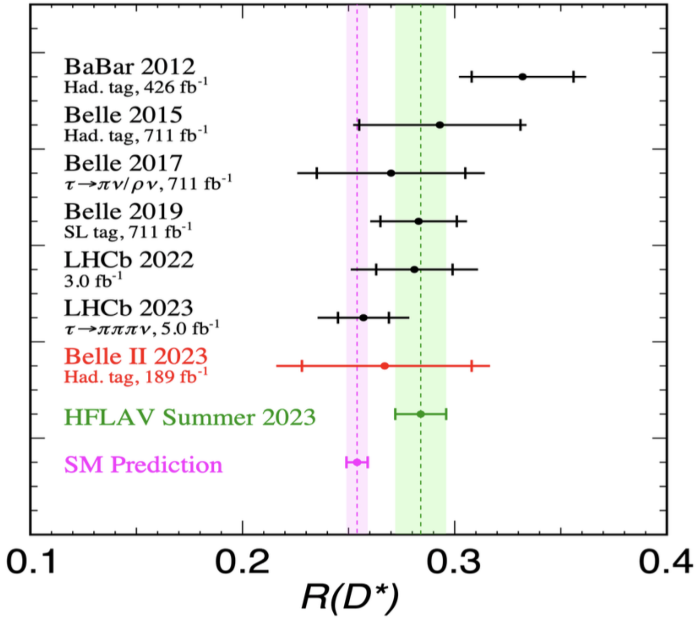


$$R_D^{(*)} = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathscr{B}(B \to D^{(*)}\ell\nu_\ell)}$$

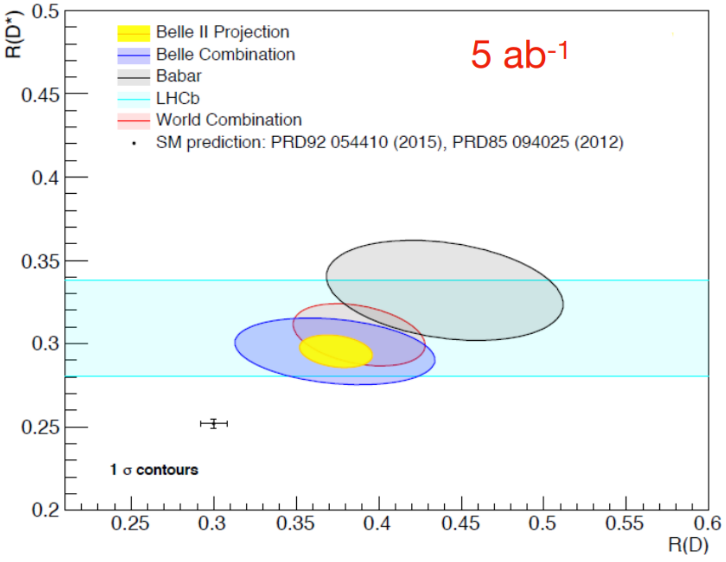


- LHCb: PRD 108 012018 (2023)
  =>reduce tension 2.49σ → 2.15σ
- Belle II: PRL 131 181801 (2023)
  => 40% improvement in statistical precision over Belle at the same sample size

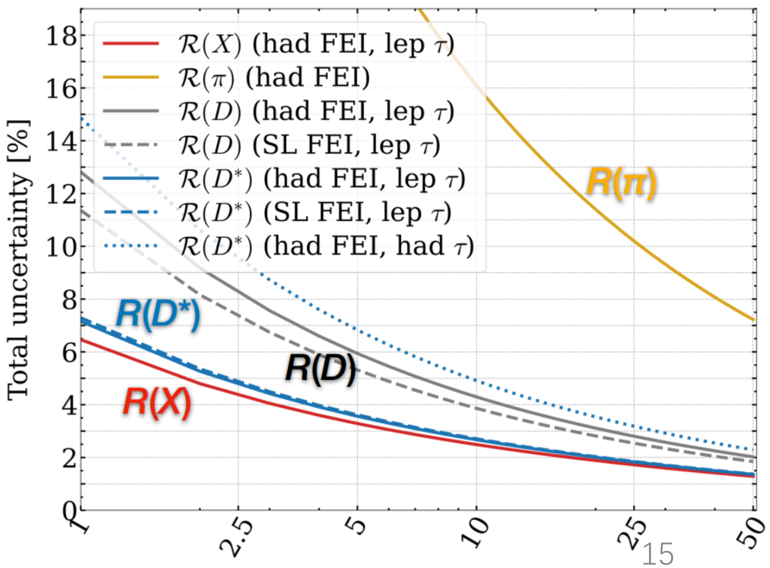
LHCb: arXiv 2302.02886
=> simultaneous measurement of $R(D)$ and $R(D^*)$, 1.9σ tension



The Belle II Physics Book, PTEP 2019, 123C01



arXiv:2207.06307

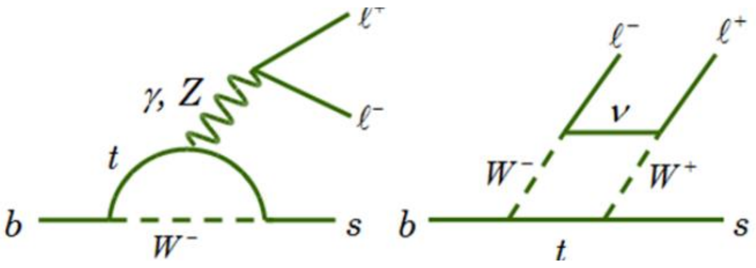


Semileptonic B Decays

- $b \to s\ell\ell$

~3σ discrepancy from the SM prediction

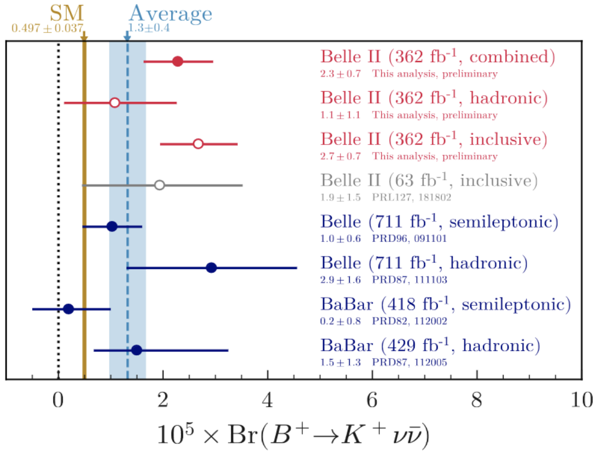
- ✓ LFU in B → $K^{(*)}e^+e^-$, $K^{(*)}\mu^+\mu^-$
- ✓ LFU in B → $D^{(*)}\tau^+\nu$, $D^{(*)}l^+\nu$ (l=e, μ)
- ✓ Angular observables in B → $K^*\mu^+\mu^-$



Amplitudes from
- ∘ electromagnetic penguin: C_7
- ∘ vector electroweak: C_9
- ∘ axial-vector electroweak: C_{10}

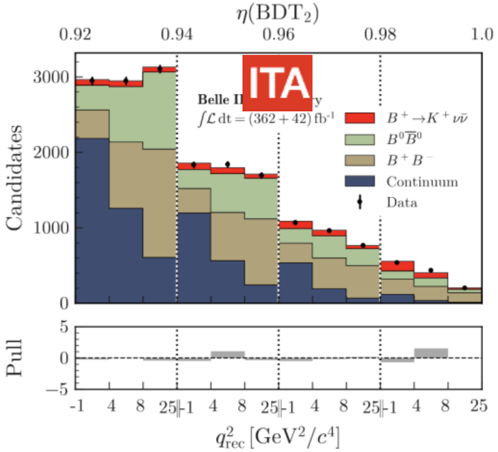
may interfere
w/ contributions from NP

- $B^+ \to K^+\nu\nu$ arXiv:2311.14647

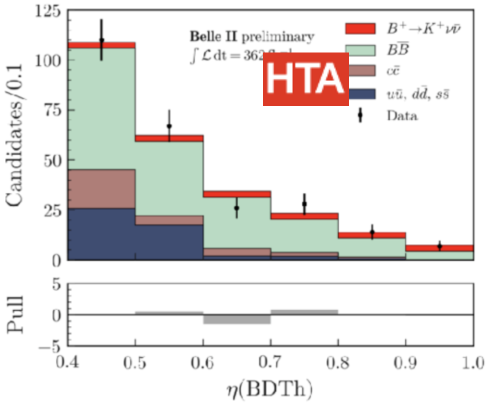


Combined result
Evidence @ 3.5σ
Tension with SM (0.6×10⁻⁵) @ 2.7σ

$\mathcal{B}(B^+ \to K^+\nu\nu)$ WRT SM :
3σ (5σ) for the baseline (improved)



wrt SM is 2.9σ



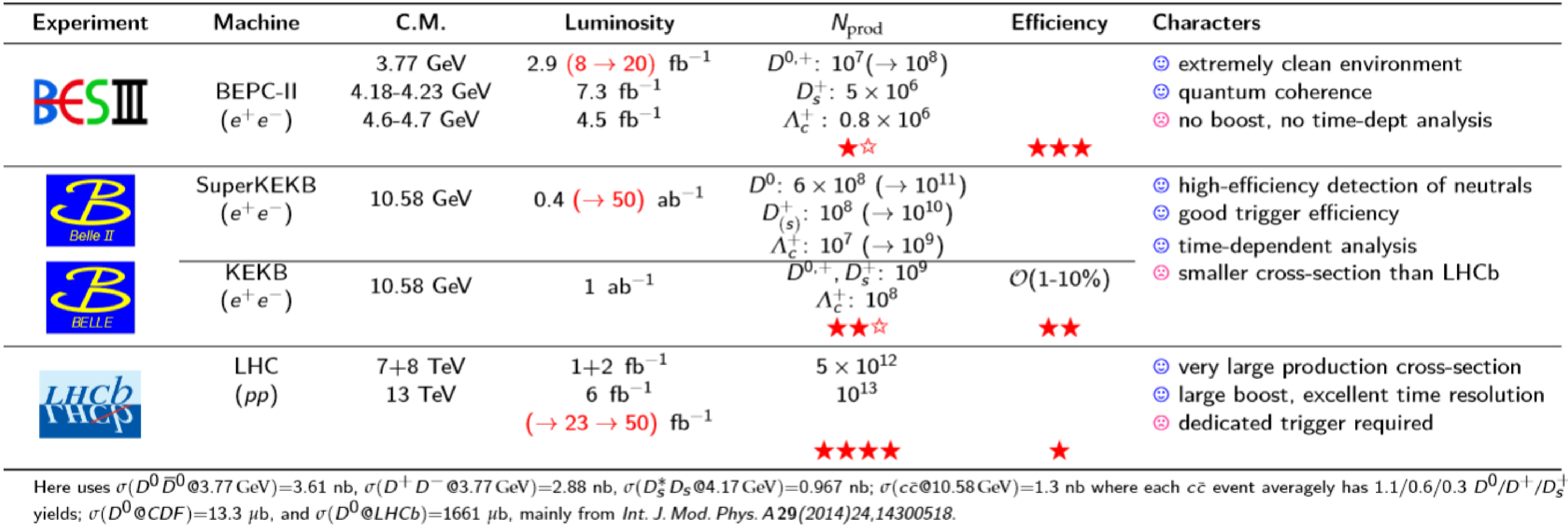
wrt SM is 0.6σ

Belle II is the only experiment capable of exploring these key channels

Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K^0_S\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

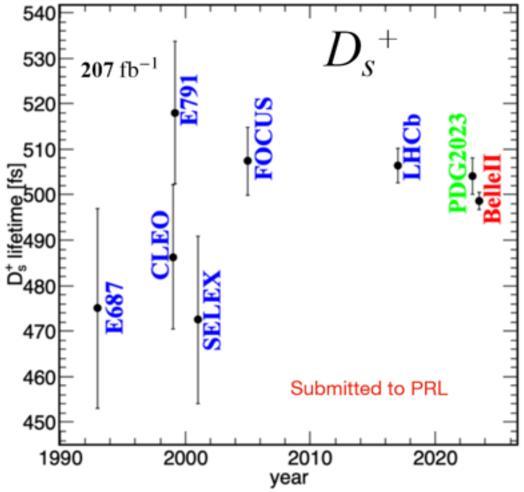
Charm Physics

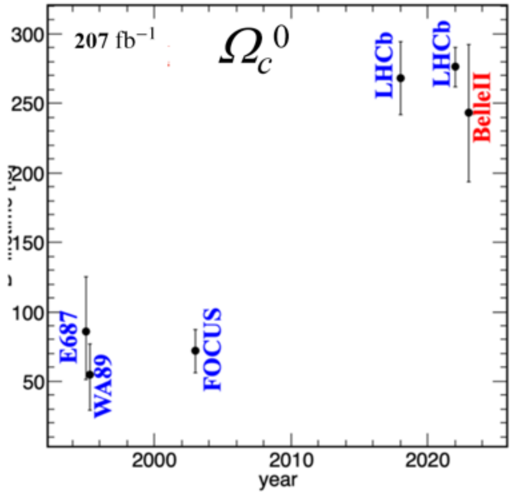
Table from Longke

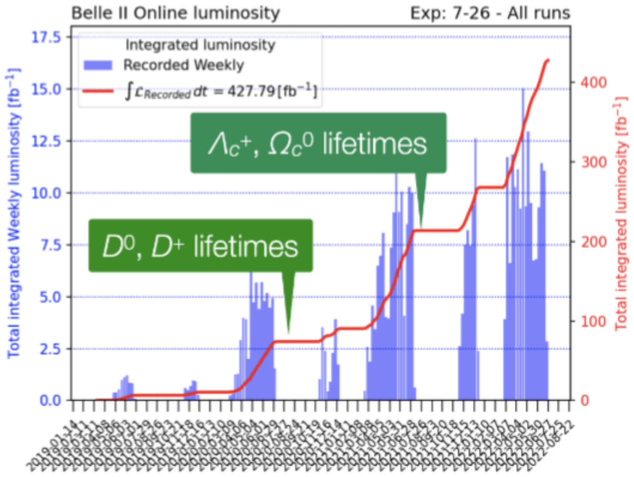


Experiment	Machine	C.M.	Luminosity	N_{prod}	Efficiency	Characters
BESIII	BEPC-II (e^+e^-)	3.77 GeV 4.18-4.23 GeV 4.6-4.7 GeV	2.9 $(8 \to 20)$ fb^{-1} 7.3 fb^{-1} 4.5 fb^{-1}	$D^{0,+}$: $10^7(\to 10^8)$ D_s^+: 5×10^6 Λ_c^+ : 0.8×10^6 ★☆	★★★	☺ extremely clean environment ☺ quantum coherence ☹ no boost, no time-dept analysis
Belle II	SuperKEKB (e^+e^-)	10.58 GeV	0.4 $(\to 50)$ ab^{-1}	D^0: 6×10^8 $(\to 10^{11})$ $D^+_{(s)}$: 10^8 $(\to 10^{10})$ Λ_c^+: 10^7 $(\to 10^9)$		☺ high-efficiency detection of neutrals ☺ good trigger efficiency ☺ time-dependent analysis ☹ smaller cross-section than LHCb
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	$D^{0,+}, D_s^+$: 10^9 Λ_c^+: 10^8 ★★☆	$\mathcal{O}$(1-10%) ★★	
LHCb	LHC (pp)	7+8 TeV 13 TeV	1+2 fb^{-1} 6 fb^{-1} $(\to 23 \to 50)$ fb^{-1}	5×10^{12} 10^{13} ★★★★	★	☺ very large production cross-section ☺ large boost, excellent time resolution ☹ dedicated trigger required

Here uses $\sigma(D^0\bar{D}^0$@3.77 GeV$)$=3.61 nb, $\sigma(D^+D^-$@3.77 GeV$)$=2.88 nb, $\sigma(D_s^*D_s$@4.17 GeV$)$=0.967 nb; $\sigma(c\bar{c}$@10.58 GeV$)$=1.3 nb where each $c\bar{c}$ event averagely has 1.1/0.6/0.3 $D^0/D^+/D_s^+$ yields; $\sigma(D^0$@$CDF)$=13.3 μb, and $\sigma(D^0$@$LHCb)$=1661 μb, mainly from *Int. J. Mod. Phys. A* **29***(2014)24,14300518.*







Λ_c^+, Ω_c^0 lifetimes

D^0, D^+ lifetimes

Charm Physics

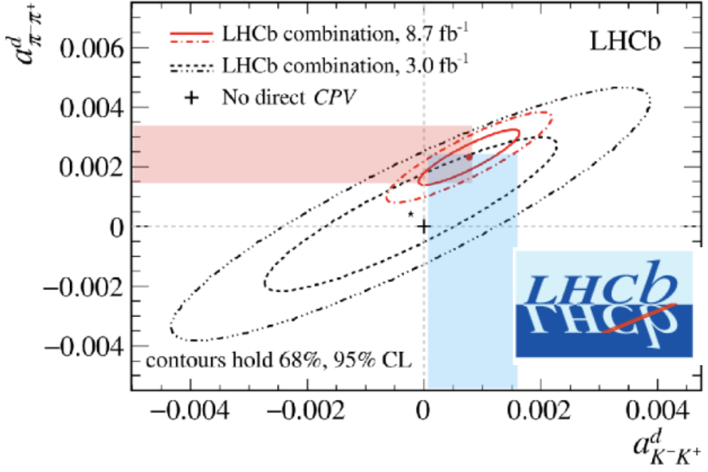
CP violation effects are small at charm sector $\leq O(10^{-3})$

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

$$D \to \pi^+\pi^-$$

VALUE (%)				
$0.07 \pm 0.14 \pm 0.11$		[1] AAIJ	2017M	LHCB
$0.22 \pm 0.24 \pm 0.11$	215k	[2] AALTONEN	2012B	CDF
$-0.24 \pm 0.52 \pm 0.22$	63.7k	[3] AUBERT	2008M	BABR
$0.43 \pm 0.52 \pm 0.12$	51k	[4] STARIC	2008	BELL

$A_{CP}(\pi^+\pi^-) = A(K^+K^-) - \Delta A_{CP}$



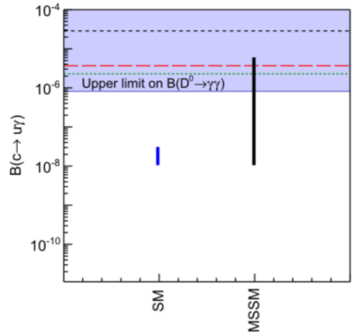
Belle have advantage in channel with γ:

Int. luminosity	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$\sigma_{A_{CP}}(D^+ \to \pi^+\pi^0)$	1.64%	0.74%	0.52%	0.23%
$\sigma_{A_{CP}}(D^0 \to \pi^0\pi^0)$	0.49%	0.22%	0.15%	0.07%

Belle II will dominate the precision and be the only existing experiment able to precisely measure $A_{cp}(D^0 \to \pi^0\pi^0)$

Rare charm decays

$B(D^0 \to \gamma\gamma) < 8.5 \times 10^{-7}$ at 90% CL two orders of magnitude above the SM prediction

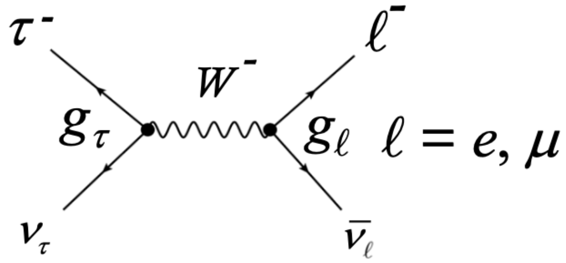


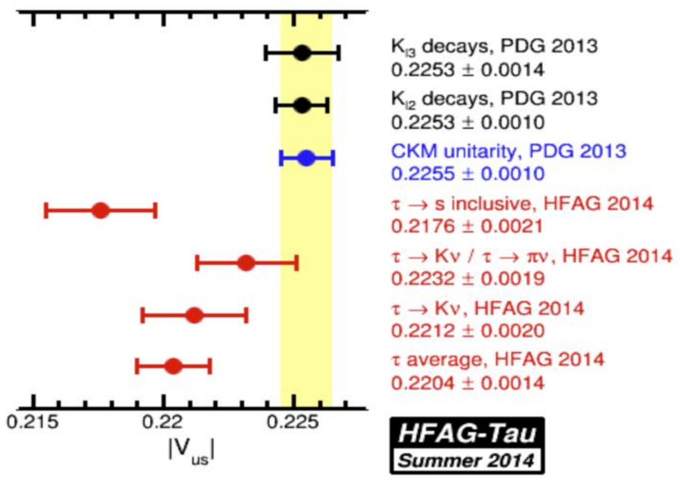
Int. luminosity	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}
$\mathcal{B}^{90\%}_{UL}(D^0 \to \gamma\gamma)$ (10^{-7})	8.5	4.9	2.7	1.5

τ Physics

@10.58 GeV: $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92\,nb$

$\sigma(e^+e^- \rightarrow \Upsilon(4S)) = 1.11\,nb$



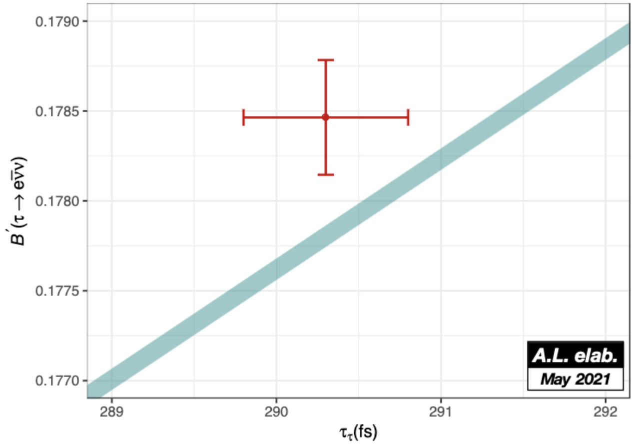


$$\Gamma\left(L^- \rightarrow \ell^- \,\bar{\nu}_\ell\, \nu_L(\gamma)\right) = \frac{\mathcal{B}(L^- \rightarrow \ell^- \,\bar{\nu}_\ell\, \nu_L(\gamma))}{\tau_L} = \frac{g_L^2 g_\ell^2}{32 M_W^4} \frac{m_L^5}{192\pi^3} f\left(\frac{m_\ell^2}{m_L^2}\right) F_{corr}\,(m_L, M_\ell)$$

$$\mathrm{f(x) = 1\ - 8x + 8x^3 - x^4 - 12x^2\, ln(x)}$$

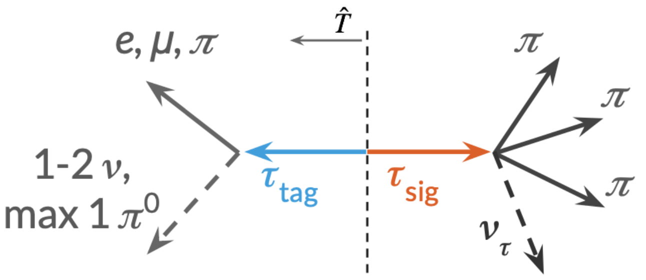
$$\mathrm{F_{corr}\,(m_L, M_\ell) = f(\frac{m_\ell}{m_L})(1 + \frac{3m_\ell^2}{5M_W^2})(1 + \frac{\alpha(m_L)}{2\pi}(\frac{25}{4} - \pi^2))}$$

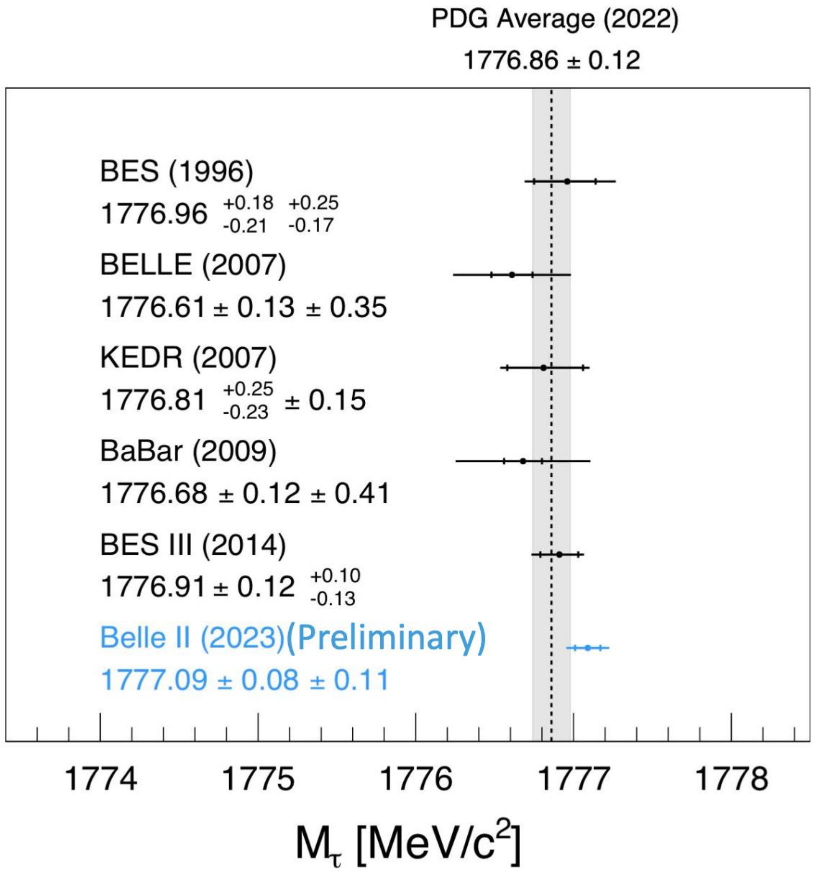
W. Marciano and A. Sirlin PRL. 61, 1815 (1988)

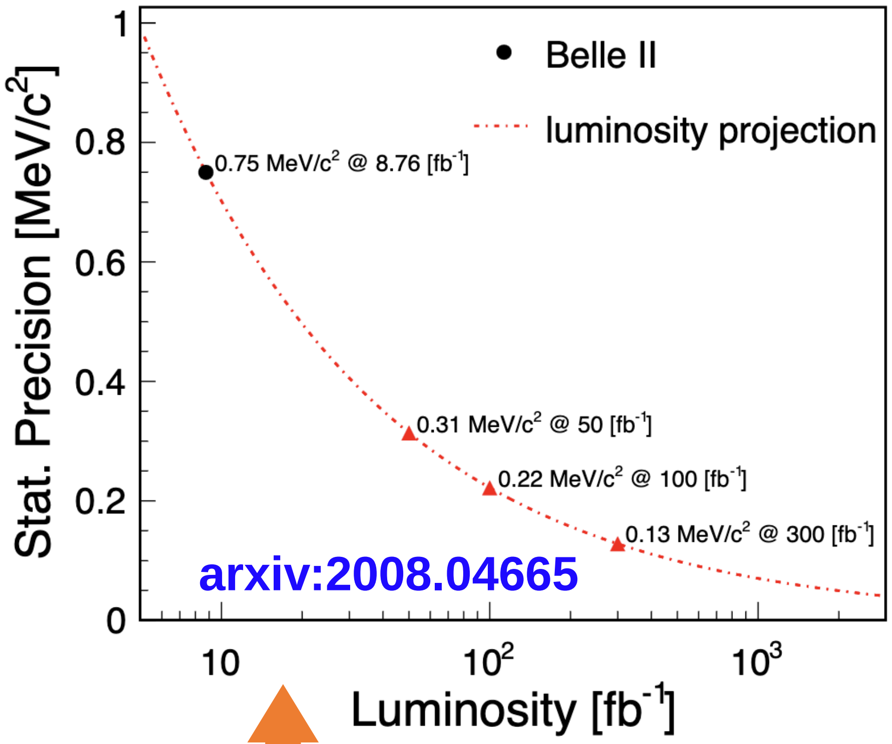


input	Uncertainty (%)	Best Measurement
$\mathcal{B}(\tau^- \rightarrow \ell^- \,\bar{\nu}_\ell\, \nu_\tau(\gamma))$	0.180	ALEPH
τ_τ	0.172	Belle
m_L	0.007	BES III

Measurement of τ mass







arxiv:2008.04665

World's best measurement of the τ mass!

half data size as Belle and BaBar,
BUT better statistical precision!

Even better than our estimation when using 8.75 fb^1 data!

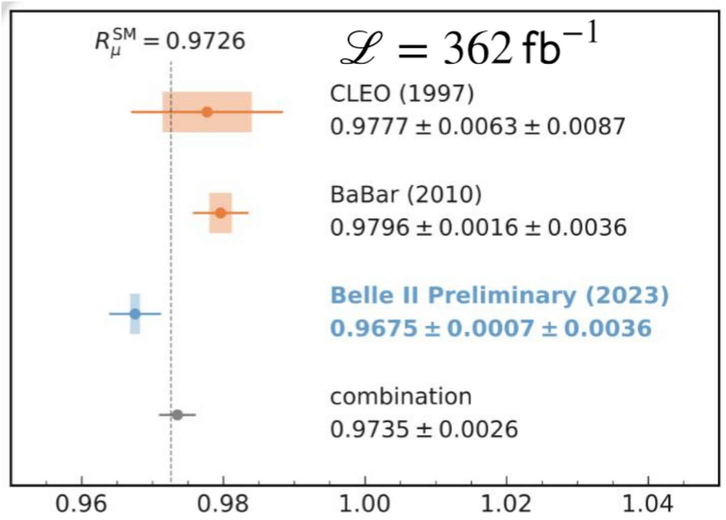
Lepton Flavor Universality Violation

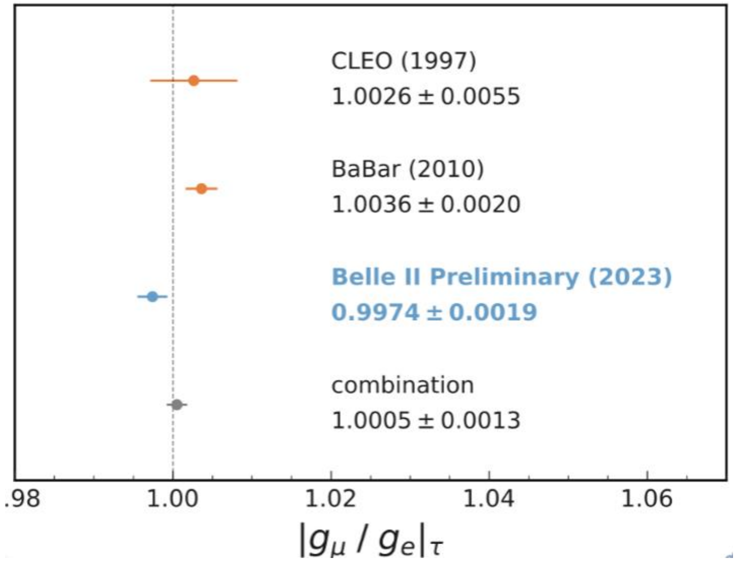
- Precise test of $\mu - e$ universality:

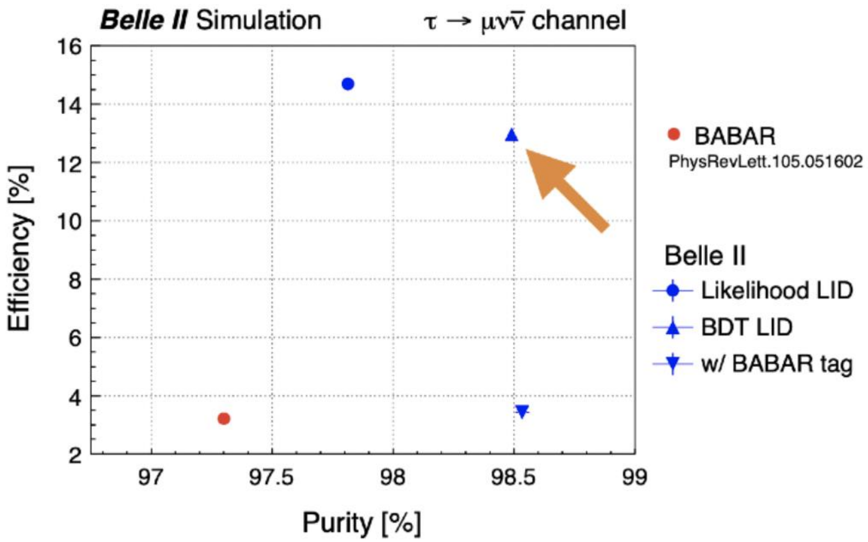
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}$$

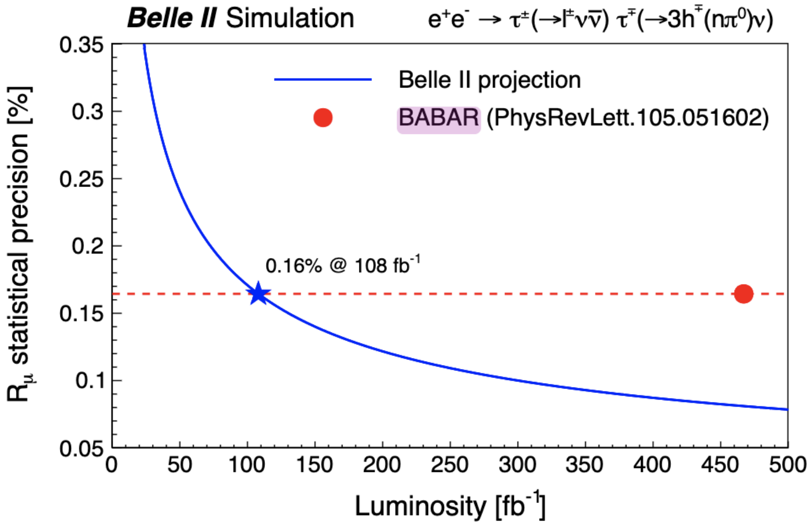
$$R_\mu = \frac{\mathscr{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau(\gamma))}{\mathscr{B}(\tau^- \to e^- \bar{\nu}_e \nu_\tau(\gamma))} \overset{\text{SM}}{=} 0.9726$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$









CPV

- No CPV is observed in the charged leptons sector (in the SM, it is predicted only in quarks sector)

- The most promising modes for the studies: $\tau^- \to K^-\pi^0\nu_\tau$, $\tau^- \to K_S^0\pi^-\nu_\tau$, $\tau^- \to K_S^0\pi^-\pi^0\nu_\tau$, $\tau^- \to (\rho\pi)^-\nu_\tau$, $\tau^- \to (\omega\pi)^-\nu_\tau$, and $\tau^- \to (a_1\pi)^-\nu_\tau$

The first measurement of the CP asymmetry was performed by BaBar in $\tau^- \to \pi^- K_S^0 \nu_\tau$:

Phys.Rev.D 85 (2012) 031102

$$A_\tau = \frac{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) - \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}{\Gamma(\tau^+ \to \pi^+ K_S^0 \bar{\nu}_\tau) + \Gamma(\tau^- \to \pi^- K_S^0 \nu_\tau)}$$

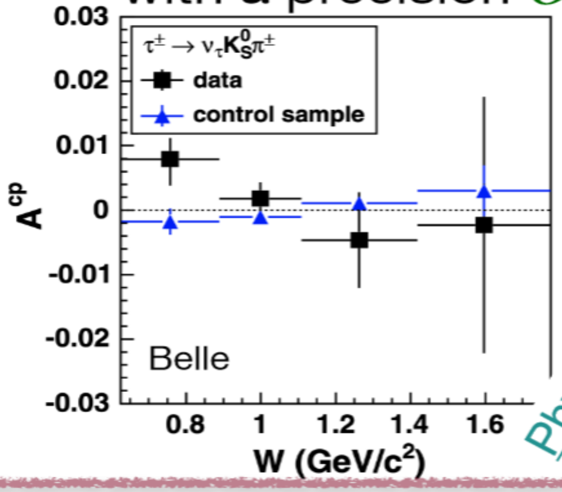
$$A_\tau^{\text{SM}} = (0.36 \pm 0.01)\,\%$$

$$A_\tau = (-0.36 \pm 0.23 \pm 0.11)\,\%$$

- It is also possible to use a modified asymmetry with differential distributions integrated over a limited volume in the phase space with a specially selected kernel (done by Belle) →

- More complicated and most powerful method is to use unbinned maximum likelihood fit in the full phase space (not done at B-factories)

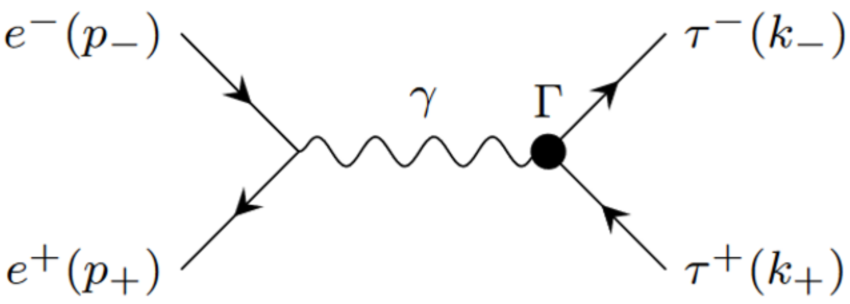
A^{CP} is compatible with zero with a precision $O(10^{-3})$



Phys.Rev.D 107 (2011) 131801

Belle II (FL) can approach the sensitivity level of 10^{-4}

Electric Dipole and Magnetic Dipole Moments



$$q = k_+ + k_-; \quad q^2 \geq 4m_\tau^2 \quad e > 0; \quad \sigma^{\mu\nu} = \frac{\mathrm{i}}{2}\left[\gamma^\mu, \gamma^\nu\right]$$

$$\langle \tau^-(k_-), \tau^+(k_+), \text{out}|J^\mu_{\text{em}}|0\rangle = -e\bar{u}(k_-)\Gamma^\mu v(k_+)$$

$$\Gamma^\mu = \underbrace{F_1\left(q^2\right)\gamma^\mu}_{\text{radiative corrections}} + \underbrace{F_2\left(q^2\right)\frac{1}{2m_\tau}\mathrm{i}\sigma^{\mu\nu}q_\nu}_{\text{MDM}} + \underbrace{F_3\left(q^2\right)\frac{1}{2m_\tau}\sigma^{\mu\nu}q_\nu\gamma_5}_{\text{EDM}}$$

In SM: $\boldsymbol{a_\tau = 117721(5) \times 10^{-8}}$ $\boldsymbol{d_\tau \approx 10^{-37} ecm}$

EDM measurement by Belle ($\mathscr{L} = 833\ \text{fb}^{-1}$)

Triple momentum and spin correlation observables (so called optimal observables)

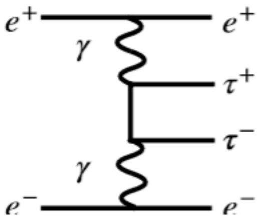
$$O_{\Re} = \frac{M^2_{\Re}}{M^2_{\text{SM}}}, \quad O_{\Im} = \frac{M^2_{\Im}}{M^2_{\text{SM}}} \quad \begin{aligned}\langle O_{\Re}\rangle &= a_{\Re}\Re(d_\tau) + b_{\Re} \\ \langle O_{\Im}\rangle &= a_{\Im}\Im(d_\tau) + b_{\Im}\end{aligned}$$

$$-1.85 \cdot 10^{-17} < \Re(d_\tau) < 6.1 \cdot 10^{-18}\ \text{ecm}\ (95\ \%\ \text{CL})$$

$$-1.03 \cdot 10^{-17} < \Im(d_\tau) < 2.3 \cdot 10^{-18}\ \text{ecm}\ (95\ \%\ \text{CL})$$

Belle II (FL) expects $|\Re, \Im(d_\tau)| < 10^{-18} - 10^{-19}$

MDM measurement by DELPHI

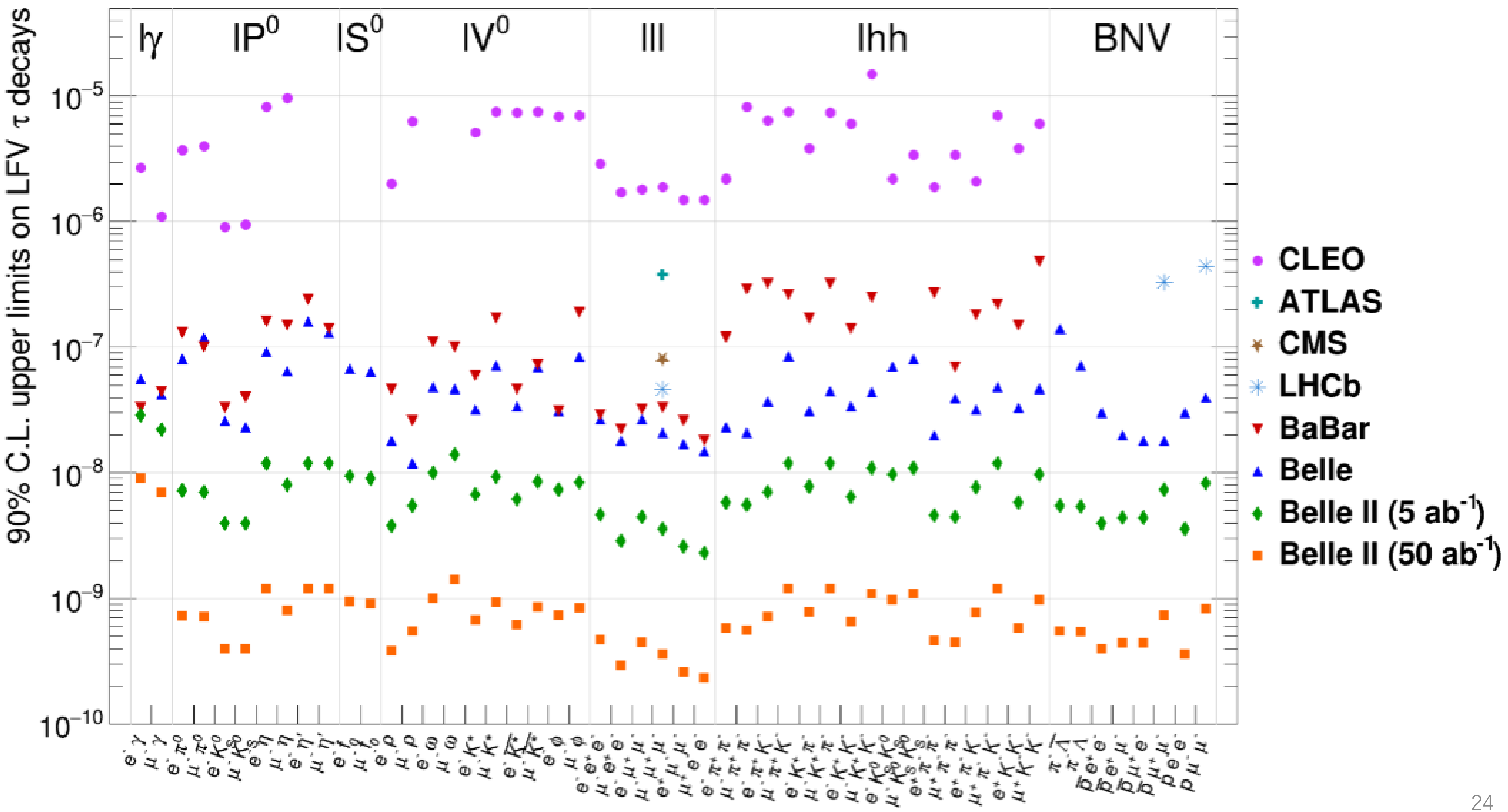


Two photon approach is used

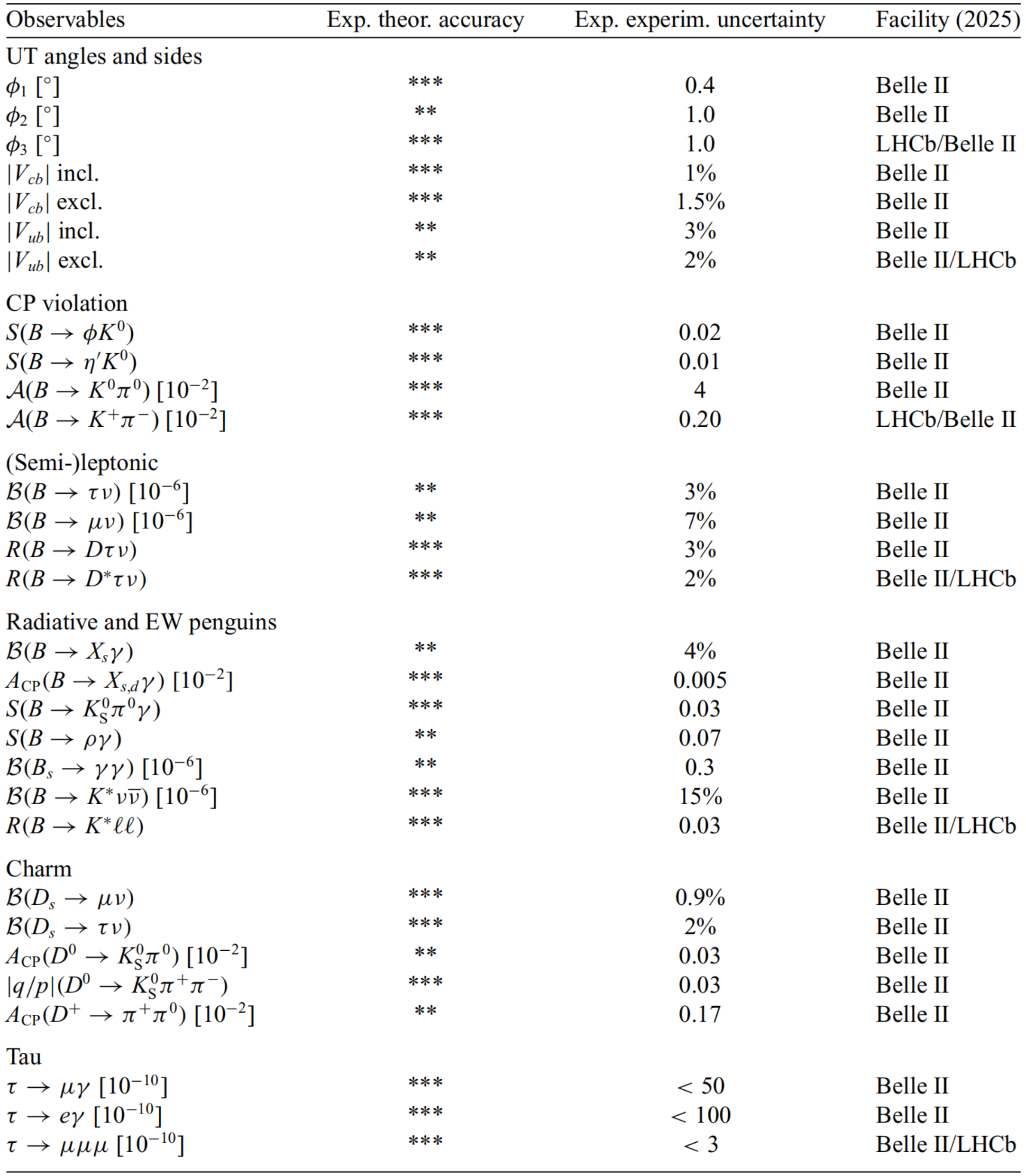
$$-0.052 < a_\tau < 0.013\ (95\ \%\ \text{CL})$$

Belle II (FL) expects $|a_\tau^{\text{NP}}| < 2 \times 10^{-5}$

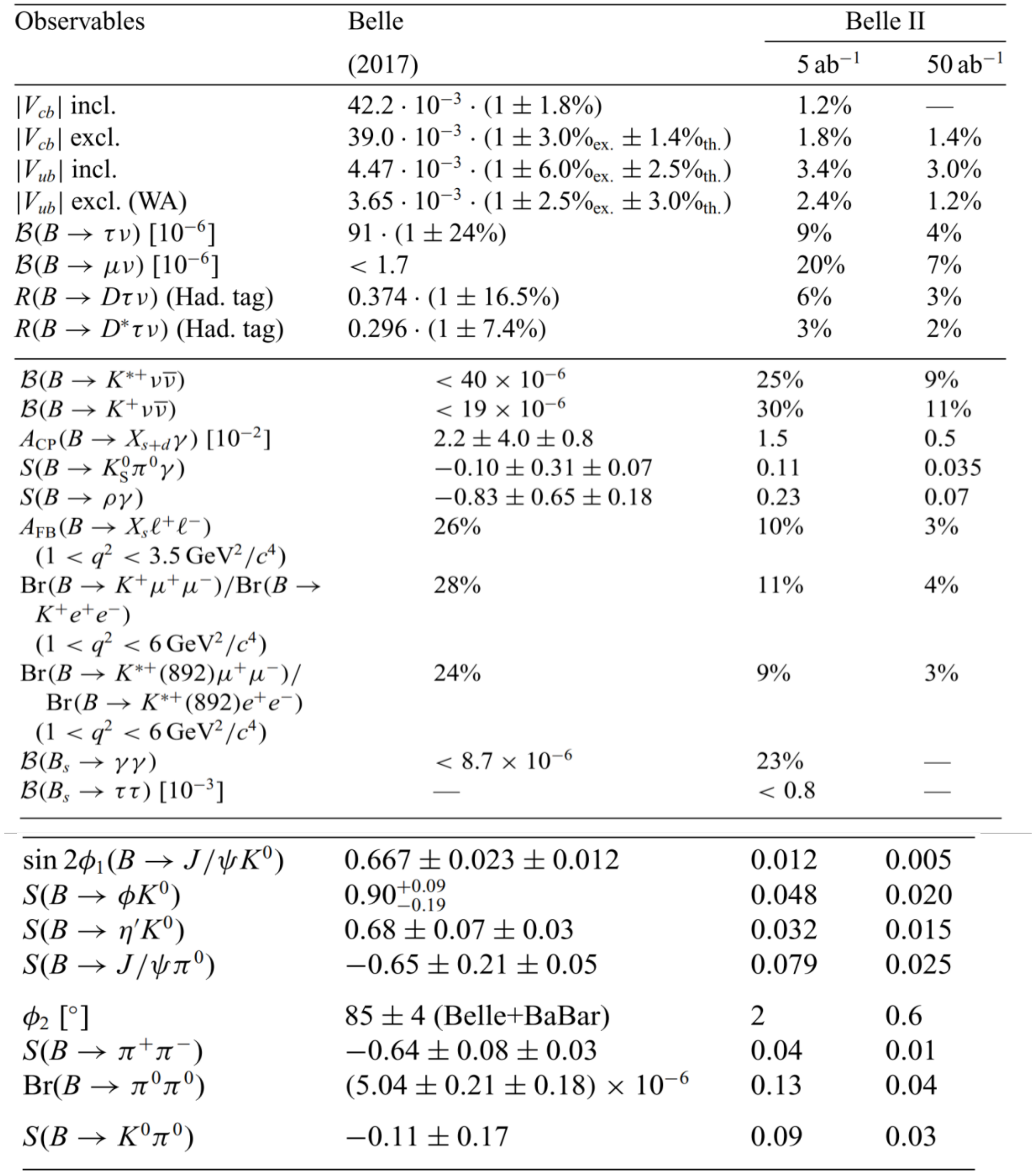
LFV


90% C.L. upper limits on LFV τ decays
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
lγ
IP^0
IS^0
IV^0
lll
lhh
BNV
CLEO
ATLAS
CMS
LHCb
BaBar
Belle
Belle II (5 ab^{-1})
Belle II (50 ab^{-1})
$e^-\gamma$
$\mu^-\gamma$
$e^-\pi^0$
$\mu^-\pi^0$
$e^-K^0_S$
$\mu^-K^0_S$
$e^-\eta$
$\mu^-\eta$
$e^-\eta'$
$\mu^-\eta'$
e^-f_0
μ^-f_0
$e^-\rho^0$
$\mu^-\rho^0$
$e^-\omega$
$\mu^-\omega$
e^-K^{*0}
μ^-K^{*0}
$e^-\overline{K}^{*0}$
$\mu^-\overline{K}^{*0}$
$e^-\phi$
$\mu^-\phi$
$e^-e^+e^-$
$\mu^-e^+e^-$
$e^-\mu^+\mu^-$
$\mu^-\mu^+\mu^-$
$e^+\mu^-\mu^-$
$\mu^+e^-e^-$
$e^-\pi^+\pi^-$
$\mu^-\pi^+\pi^-$
$e^-\pi^+K^-$
$\mu^-\pi^+K^-$
$e^-K^+\pi^-$
$\mu^-K^+\pi^-$
$e^-K^+K^-$
$\mu^-K^+K^-$
$e^-K^0_SK^0_S$
$\mu^-K^0_SK^0_S$
$e^+\pi^-\pi^-$
$\mu^+\pi^-\pi^-$
$e^+\pi^-K^-$
$\mu^+\pi^-K^-$
$e^+K^-K^-$
$\mu^+K^-K^-$
$\pi^-\Lambda$
$\pi^-\overline{\Lambda}$
$\overline{p}e^+e^-$
$\overline{p}e^+\mu^-$
$\overline{p}\mu^+e^-$
$\overline{p}\mu^+\mu^-$
pe^-e^-
$p\mu^-\mu^-$

Summy:

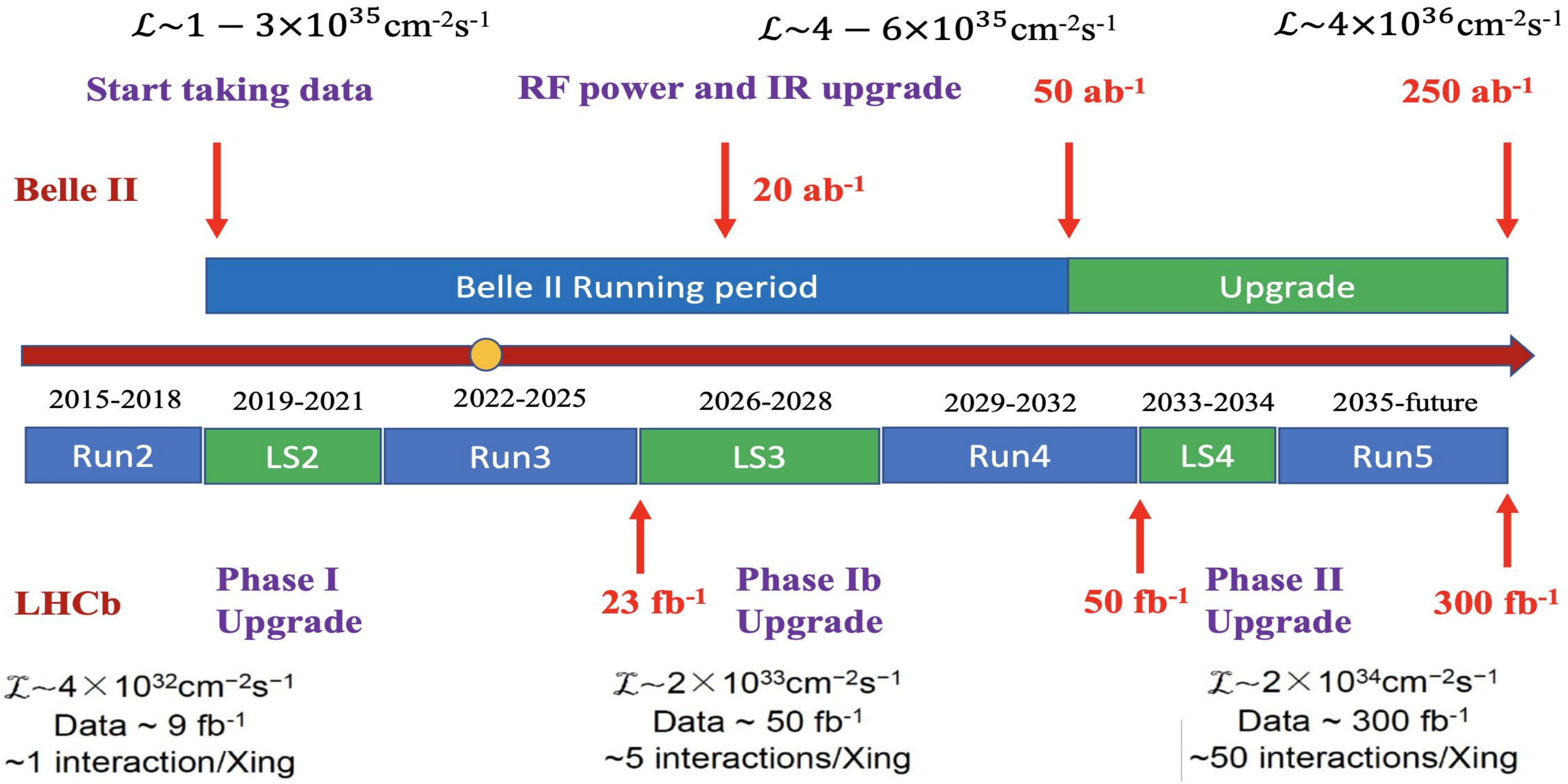


Observables	Exp. theor. accuracy	Exp. experim. uncertainty	Facility (2025)
UT angles and sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)$ $[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative and EW penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{\rm CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{\rm CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$A_{\rm CP}(D^+ \to \pi^+\pi^0)$ $[10^{-2}]$	**	0.17	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb



Observables	Belle	Belle II	
	(2017)	5 ab^{-1}	50 ab^{-1}
$\|V_{cb}\|$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	—
$\|V_{cb}\|$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\rm ex.} \pm 1.4\%_{\rm th.})$	1.8%	1.4%
$\|V_{ub}\|$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$	3.4%	3.0%
$\|V_{ub}\|$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\rm ex.} \pm 3.0\%_{\rm th.})$	2.4%	1.2%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	20%	7%
$R(B \to D\tau\nu)$ (Had. tag)	$0.374 \cdot (1 \pm 16.5\%)$	6%	3%
$R(B \to D^*\tau\nu)$ (Had. tag)	$0.296 \cdot (1 \pm 7.4\%)$	3%	2%
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^+\nu\overline{\nu})$	$< 19 \times 10^{-6}$	30%	11%
$A_{\rm CP}(B \to X_{s+d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$	1.5	0.5
$S(B \to K_S^0\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07
$A_{\rm FB}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 3.5\,{\rm GeV}^2/c^4)$	26%	10%	3%
${\rm Br}(B \to K^+\mu^+\mu^-)/{\rm Br}(B \to K^+e^+e^-)$ $(1 < q^2 < 6\,{\rm GeV}^2/c^4)$	28%	11%	4%
${\rm Br}(B \to K^{*+}(892)\mu^+\mu^-)/{\rm Br}(B \to K^{*+}(892)e^+e^-)$ $(1 < q^2 < 6\,{\rm GeV}^2/c^4)$	24%	9%	3%
$\mathcal{B}(B_s \to \gamma\gamma)$	$< 8.7 \times 10^{-6}$	23%	—
$\mathcal{B}(B_s \to \tau\tau)$ $[10^{-3}]$	—	< 0.8	—
$\sin 2\phi_1(B \to J/\psi K^0)$	$0.667 \pm 0.023 \pm 0.012$	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
$S(B \to J/\psi\pi^0)$	$-0.65 \pm 0.21 \pm 0.05$	0.079	0.025
ϕ_2 [°]	85 ± 4 (Belle+BaBar)	2	0.6
$S(B \to \pi^+\pi^-)$	$-0.64 \pm 0.08 \pm 0.03$	0.04	0.01
${\rm Br}(B \to \pi^0\pi^0)$	$(5.04 \pm 0.21 \pm 0.18) \times 10^{-6}$	0.13	0.04
$S(B \to K^0\pi^0)$	-0.11 ± 0.17	0.09	0.03

Summy:



$\mathcal{L}\sim1-3\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\mathcal{L}\sim4-6\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ $\mathcal{L}\sim4\times10^{36}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Start taking data **RF power and IR upgrade** **50 ab^{-1}** **250 ab^{-1}**

Belle II **20 ab^{-1}**

Belle II Running period | Upgrade

2015-2018	2019-2021	2022-2025	2026-2028	2029-2032	2033-2034	2035-future
Run2	LS2	Run3	LS3	Run4	LS4	Run5

LHCb **Phase I Upgrade** **23 fb^{-1}** **Phase Ib Upgrade** **50 fb^{-1}** **Phase II Upgrade** **300 fb^{-1}**

$\mathcal{L}\sim4\times10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Data ~ 9 fb^{-1}
~1 interaction/Xing

$\mathcal{L}\sim2\times10^{33}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Data ~ 50 fb^{-1}
~5 interactions/Xing

$\mathcal{L}\sim2\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
Data ~ 300 fb^{-1}
~50 interactions/Xing

Belle II Cons and Pros (vs. LHCb)

- Pros.

– Smaller background cross section (O(1)nb vs. O(10)mb)

-

~3.4nb for $ee \rightarrow qq$, ~1.08nb for $ee \rightarrow Y(4S) \rightarrow BB$

– Almost 100% trigger efficiency for BB events (11 charged + 5 photons in average).

- Main triggers

– 3-track || 2-track with opening angle|| ECL energy sum >1GeV || ECL # of Clusters >=4

- Absolute BF measurement possible.

– Two level trigger system for low multiplicity events

- Many dark sectors signature (X+missing) can be triggered

– High hermeticity 4π x 94%

- High reconstruction efficiency of O(1)~O(10)%.
- Full reconstruction of B meson possible (tagging of the other B meson)

– More than one missing neutrino modes ➔ $B \rightarrow D(*)\tau\nu, B \rightarrow \tau\nu, B \rightarrow K^{(*)}\nu\nu, B \rightarrow K\tau\tau, B \rightarrow \nu\nu$

- 4 momentum conservation usable ➔ dark sector searches

– 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

- reconstruction of γ, π0 and Ks efficiently ➔ sum-of-exclusive method for $B \rightarrow X_s l\,l, B \rightarrow \pi^0\pi^0, B_{(s)} \rightarrow \gamma\gamma$
- Better energy resolution of hard γ ➔ $B \rightarrow K^*\gamma$ background to $B \rightarrow \rho\gamma$ can be suppressed

Belle II Cons and Pros (vs. LHCb)

- Cons.

– Statistics of b hadrons!! (cross section 1nb vs. 144μb)

- We will only have 10^{11} B mesons with $50ab^{-1}$ on Y(4S) and 5×10^8 B_s with $5ab^{-1}$ on Y(5S)

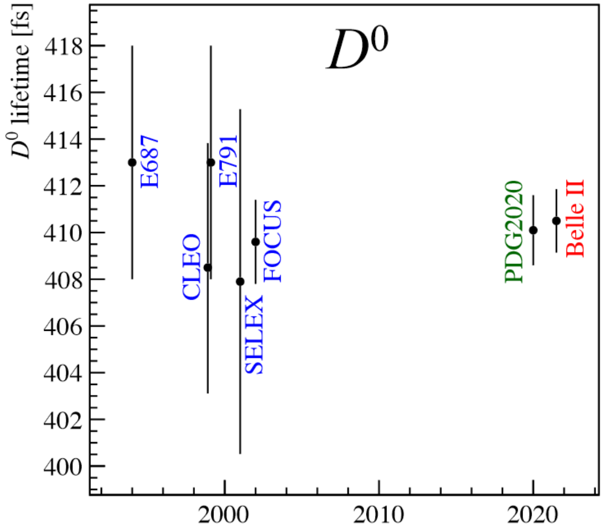
– No large samples of b baryons and B_c

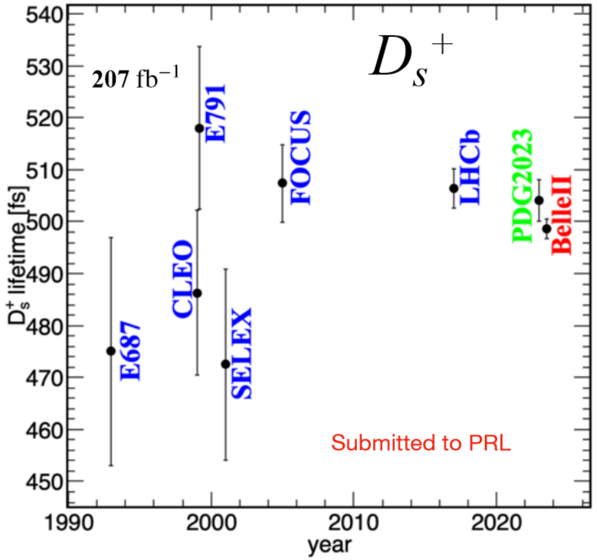
- Production of these hadrons are not yet established at e^+e^- collisions around Y(nS).

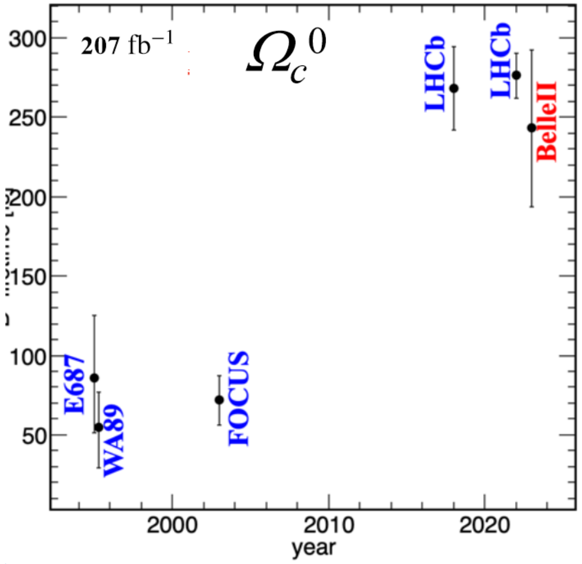
– Proper time resolution is worse and B meson is not so boosted.

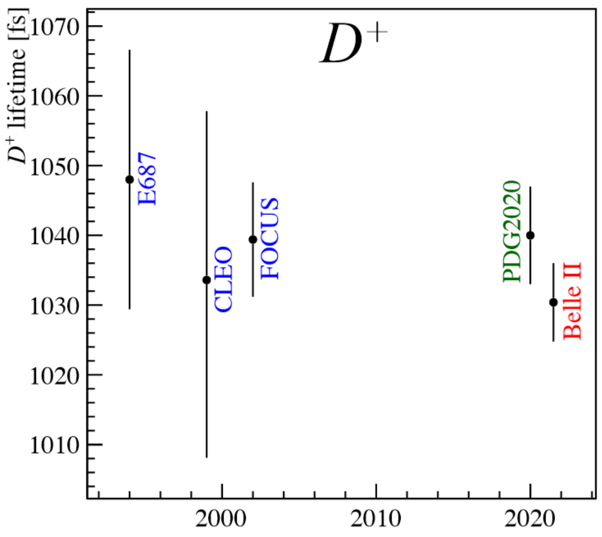
- Background suppression with B vertex displacement is not so easy
- Bs mixing (Δm_s) can not be measured (while $\Delta\Gamma_s$ can be measured).

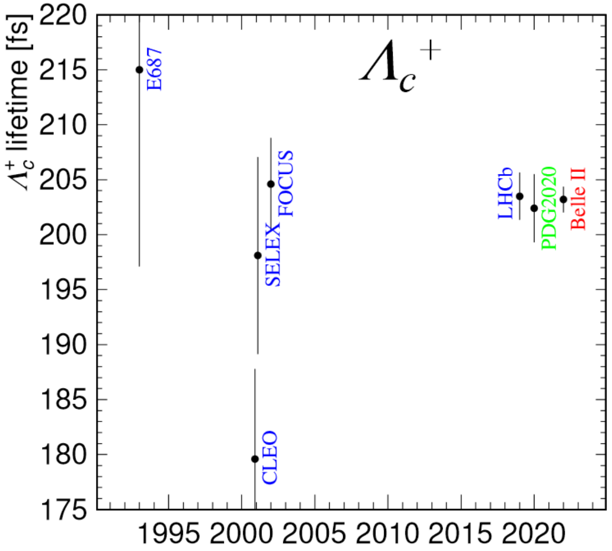
Lifetime summary



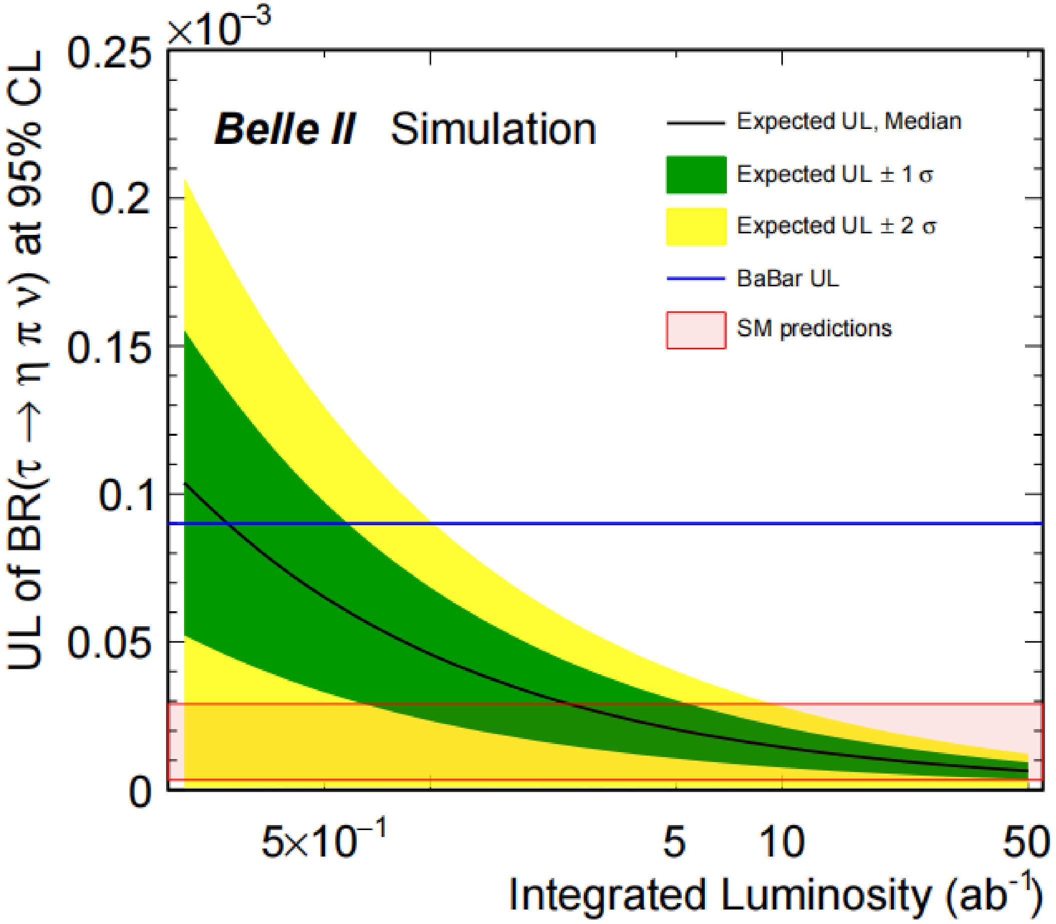


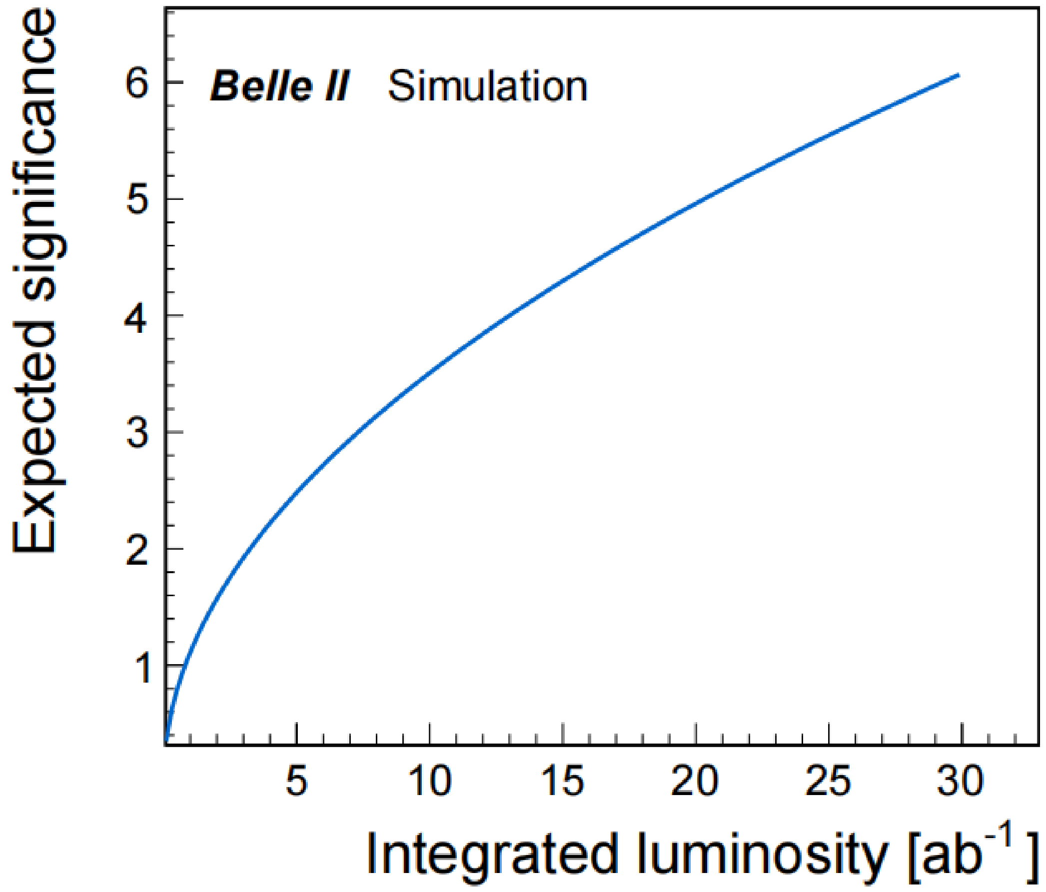






- *In all cases except for Ω_c^0, Belle II has made the world's highest precision measurement (in some cases after 20 years)*
- *For Ω_c^0, the Belle II measurement confirms the longer lifetime measured by LHCb*


Belle II Simulation
Expected UL, Median
🟩 Expected UL ± 1 σ
🟨 Expected UL ± 2 σ
BaBar UL
🟥 SM predictions
UL of BR(τ → η π ν) at 95% CL
×10^{-3}
0.25
0.2
0.15
0.1
0.05
0
5×10^{-1}
5
10
50
Integrated Luminosity (ab^{-1})


Belle II Simulation
Expected significance
6
5
4
3
2
1
5
10
15
20
25
30
Integrated luminosity [ab^{-1}]