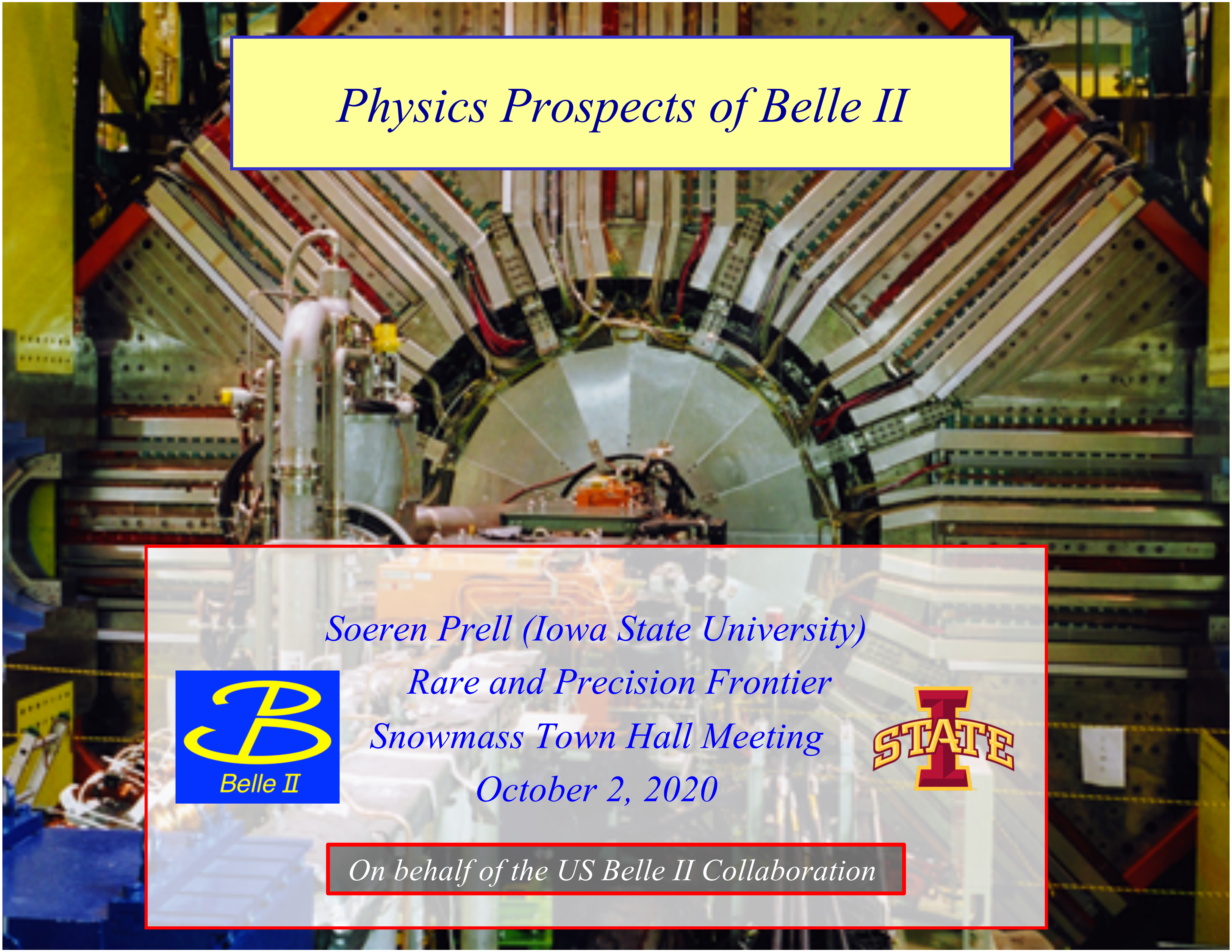


Physics Prospects of Belle II

Soeren Prell (Iowa State University)

Rare and Precision Frontier

Snowmass Town Hall Meeting

October 2, 2020

On behalf of the US Belle II Collaboration

Belle II @ Snowmass 2021

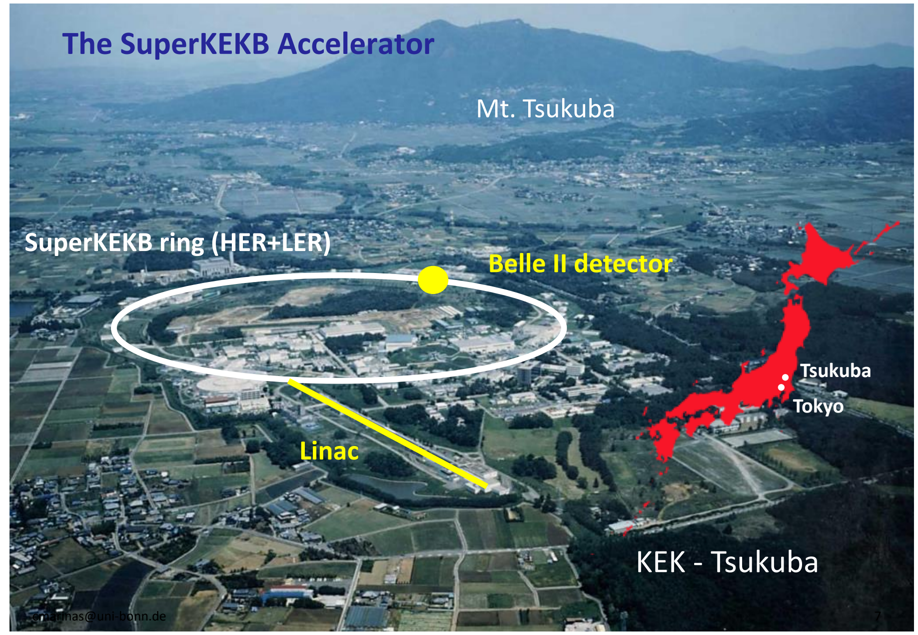
9 Belle II/SuperKEKB LOIs (Letters of Interest) submitted, and posted at
https://confluence.desy.de/display/BI/Snowmass+2021

1. Belle II/SuperKEKB upgrades and overview (AF05)
2. B physics at Belle II (RF01)
3. Charm Physics at Belle II (RF01, RF04)
4. Dark Sector at Belle II (RF06)
5. Tau Physics and Precision Electroweak Physics with Polarized Beams at SuperKEKB/Belle II (RF01-03, RF05-06, EF04,AF05)
6. Hadron Spectroscopy at Belle II (RF07)
7. Belle II/SuperKEKB capabilities for QCD (EF05-06, RF03)
8. Belle II Detector Upgrades (plans for the instrumentation frontier) (IF02-07)
9. Belle II plans for the computing frontier (CF03, CF05, CF07)

Several topical talks

EF06 Kick-off: Summary of proposed Belle II activities: Charmonium, Bottomonium, and XYZ states, Fulsom
EF06 Topical Group Meeting: Belle II Overview (Hadron Spectroscopy), Fulsom
Preparatory Joint Sessions on Open Questions and New Ideas: Hadron Spectroscopy (includes Belle II), Fulsom
RF5 WS CLFV - Tau Decays and Transitions: Tau LFV decays at Belle II, Banerjee
RF07 WS: Bottomonium (Experimental, includes Belle II), Pedlar
RF1/5 WS LFV and LUV in meson and baryon decays: LFV+LFU in neutral-current b/c decays at Belle II, Trabelsi; LFU in charged-current b decays at Belle II, Bernlochner
RF Town Hall meeting: CKM measurements and CPV in b decays at Belle II, Gaz; Rare b decays at Belle II, Schwartz; Charm physics at Belle II, Bennett; Hadron Spectoscopy at Belle II, Fulsom; Long-lived particles at Belle II, Westhoff; Dark sector studies at Belle II, Flood; CLFV in tau decays, Banerjee

- *Belle II is a multipurpose experiment at the SuperKEKB e^+e^- collider operating near the Υ(4S) resonance, and located at KEK in Tsukuba, Japan*
  - *SuperKEKB/Belle II succeeds KEKB/Belle*
  - *Latest in a long series of successful experiments (ARGUS, CLEO, and B Factories BELLE & BABAR), that made many crucial discoveries*
    - $B\bar{B}$ *oscillations*
    - $b \rightarrow u$ *transition*
    - *radiative and EW B penguin decays*
    - *CP violation in the b sector*
    - *charm mixing*
    - *Many new conventional and exotic states* (η_b, X(3872), Y(4260), Z^+(4430), D_{sJ}(2317), …)
- *Previous generation B factories BELLE & BABAR (1999 – 2008/10) have published together over 1,000 papers* (for a comprehensive review see EPJC 74 (2014) 3026)
- *BELLE II is expected to be similarly prolific*



The B Factories, Belle and BABAR, discovered large CP violation in the B system in 2001, compatible with the SM.

These provided the experimental foundation for the 2008 Nobel Prize to Kobayashi and Maskawa.

… Belle II's focus is shifted towards New Physics

The International Belle II collaboration (geographically)

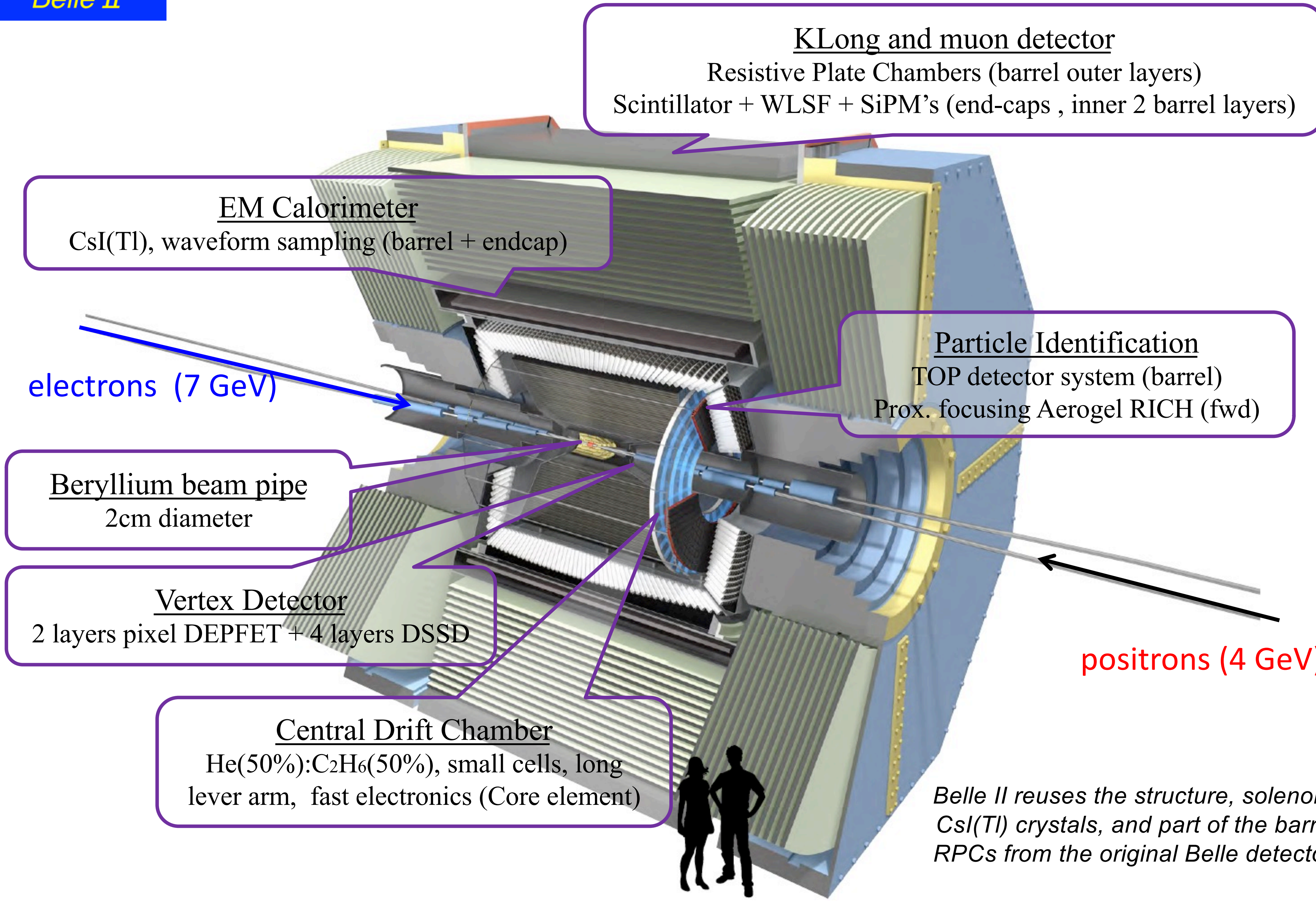
Belle II has grown to ~1000 researchers from 26 countries

Youth and potential: there are ~330 graduate students in the collaboration

US Belle II:
18 institutes,
120 members

Brookhaven National Laboratory (BNL)
Carnegie Mellon University
Duke University
Indiana University
Iowa State University
Kennesaw State University
Luther College
Pacific Northwest National Laboratory (PNNL)
University of Cincinnati
University of Florida
University of Hawai'i
University of Louisville
University of Mississippi
University of Pittsburgh
University of South Alabama
University of South Carolina
Virginia Tech
Wayne State University

Belle II Detector



Belle II reuses the structure, solenoid, CsI(Tl) crystals, and part of the barrel RPCs from the original Belle detector.

SuperKEKB/Belle II Luminosity

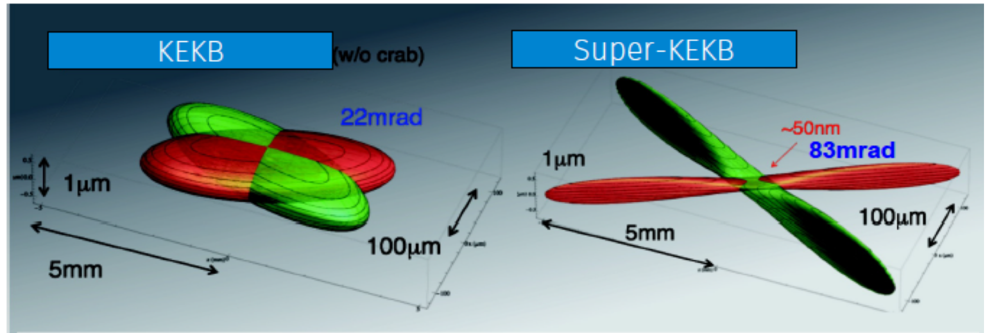
The KEKB collider provided Belle with 1 ab^{-1} between 1999 and 2010, SuperKEKB expected to deliver 50 ab^{-1}

"nano-beams" are the key; vertical beam size is 50 nm at the IP

Beam currents *only* a factor of 2-3 higher than KEKB (~ PEPII)

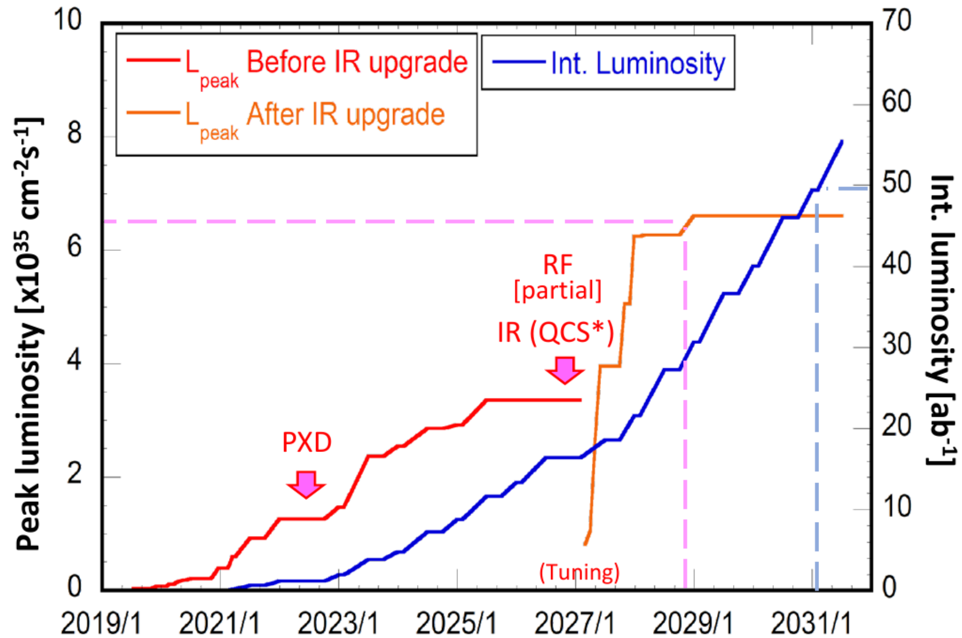
Superconducting Final Focus and IR (Interaction Region) need to be upgraded in ~2026

Luminosity profile has been recently updated



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20　factor 2-3



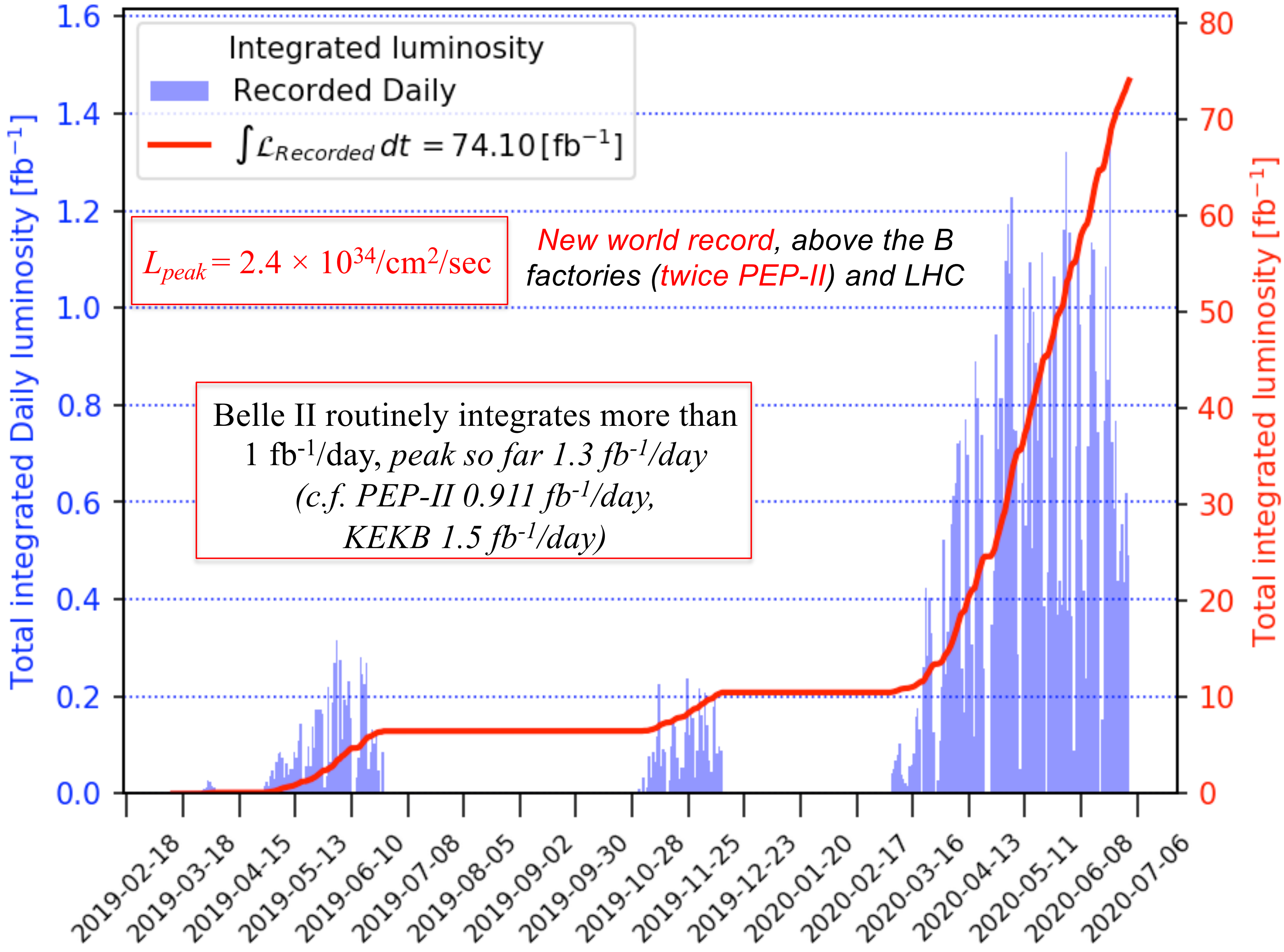
4 steps: *Intermediate luminosity* (1 × 10^{35} /cm^2/sec, 5 ab^{-1})

<u>High Luminosity</u> (6 × 10^{35}/cm^2/sec, **50 ab^{-1}**) with a detector upgrade

Polarization Upgrade, Advanced R&D

Ultra high luminosity (4 × 10^{36}/cm^2/sec, 250 ab^{-1}), R&D Project

<u>Early goal:</u> Demonstrate SuperKEKB physics running with acceptable backgrounds, and all the detector, readout, DAQ and trigger capabilities of Belle II including tracking, electron/muon ID, and hadron PID



See also https://cerncourier.com/a/kek-reclaims-luminosity-record/

Belle II Physics Program

https://arxiv.org/abs/1808.10567

Outcome of the B2TIP (Belle II Theory Interface) Workshops
Emphasis is on New Physics reach

Strong participation from theory community, lattice QCD community and Belle II experimenters

689 pages, ***published in Prog. Theor. Exp. Phys. (2019)***

KEK Preprint 2018-27
BELLE2-PAPER-2018-001
FERMILAB-PUB-18-398-T
JLAB-THY-18-2780
INT-PUB-18-047
UWThPh 2018-26

The Belle II Physics Book

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Big Questions and Belle II's avenues to address them

- *Are there **new CP-violating phases** in the quark sector ? SM CPV cannot explain baryon-antibaryon asymmetry.*
  - *CPV in B loop decays and charm*
- *Does nature have **multiple Higgs bosons** ?*
  - *Flavor transitions involving the tau lepton ($B \rightarrow \tau \nu$ & $B \rightarrow D^{(*)} \tau \nu$)*
- *Does nature have a **left-right symmetry**, and are there flavor changing neutral currents beyond the SM ?*
  - *CPV in $B \longrightarrow K^{*0} (K_s\pi^0)\gamma$; $B \longrightarrow K^{(*)}\nu\nu$, angular variables in $b \longrightarrow s,d\ l^+l^-$*
- *Are there sources of **lepton flavor violation** ?*
  - *LFV τ decays*
- *Is there a **dark sector** of particle physics at the same mass scale as ordinary matter ?*
  - *Search for MeV – GeV dark matter particles*
- *What is the **nature of the strong force** in binding hadrons?*
  - *In-depth study of recently discovered new states and search for new ones*

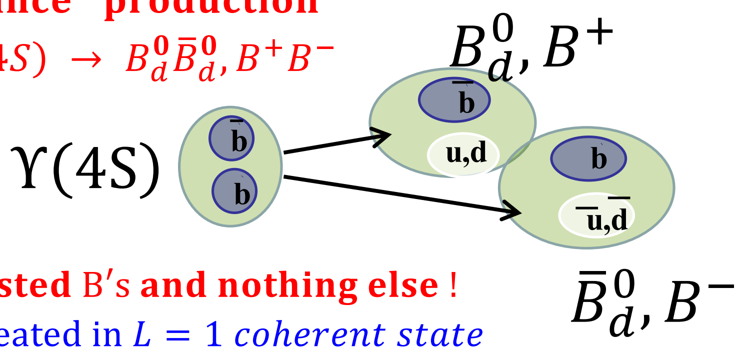
Belle II, a Super Flavor Factory

- plan to collect at least 50 ab^{-1} of asymmetric energy e^+e^- collisions at (*or near*) the $\Upsilon(4S)$ resonance, which will give us:

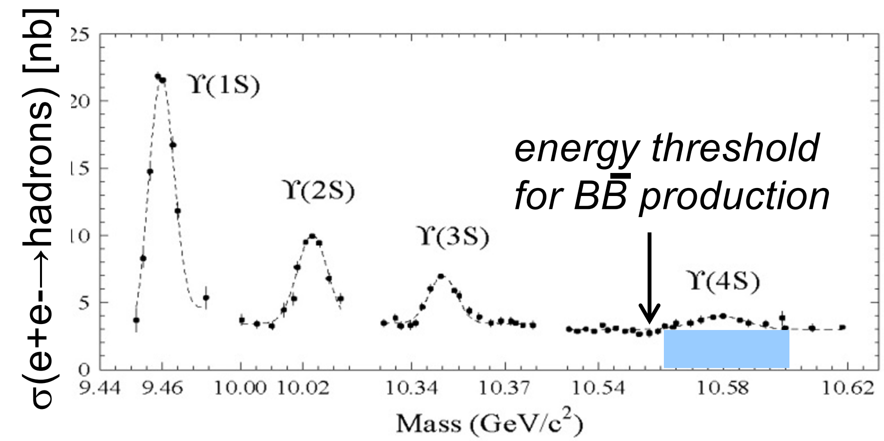
– *a **Super B Factory*** ($\sim 1.1 \times 10^9$ $B\bar{B}$ pairs per ab^{-1})

"on resonance" production

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_d^0\bar{B}_d^0, B^+B^-$

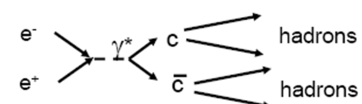


- **2 boosted B's and nothing else !**
- 2 B's created in $L = 1$ *coherent state*



(including $B^{(*)}{}_s$ from data taking at the $\Upsilon(5S)$)

– *a **Super Charm Factory*** ($\sim 1.3 \times 10^9$ $c\bar{c}$ pairs per ab^{-1})

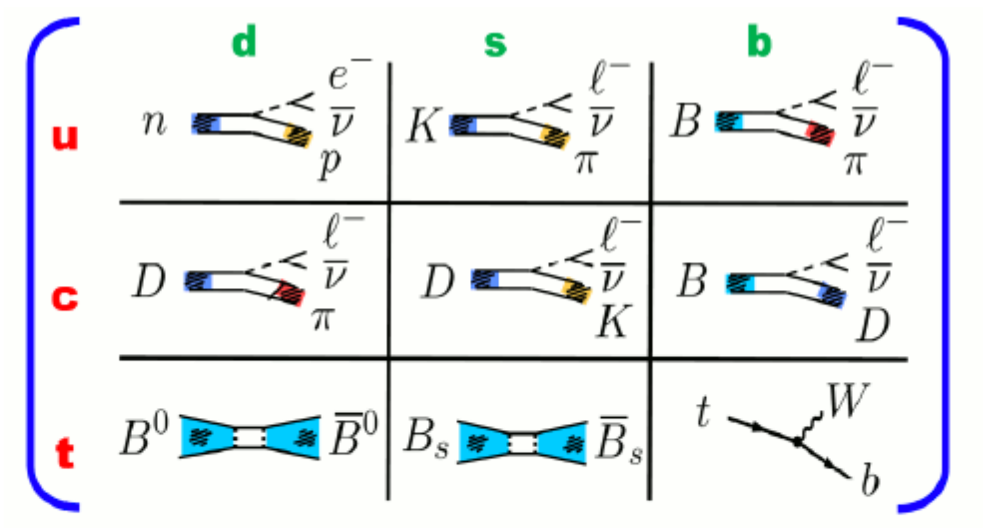


(but also charmonium, X, Y, Z, pentaquarks, tetraquarks, bottomonium, . . .)

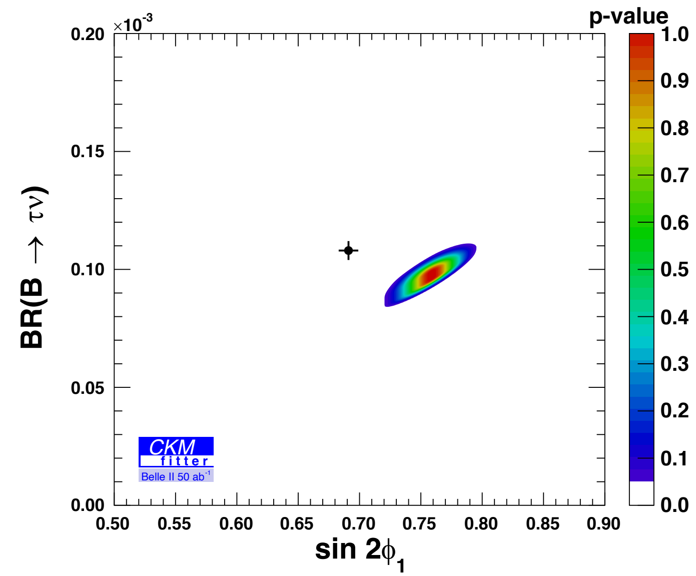
– *a **Super τ Factory*** ($\sim 0.9 \times 10^9$ $\tau^+\tau^-$ pairs per ab^{-1})

– exploit the clean e^+e^- environment to search for exotic hadrons, dark photons/Higgs , light Dark Matter particles, ALPs, LLPs . . .

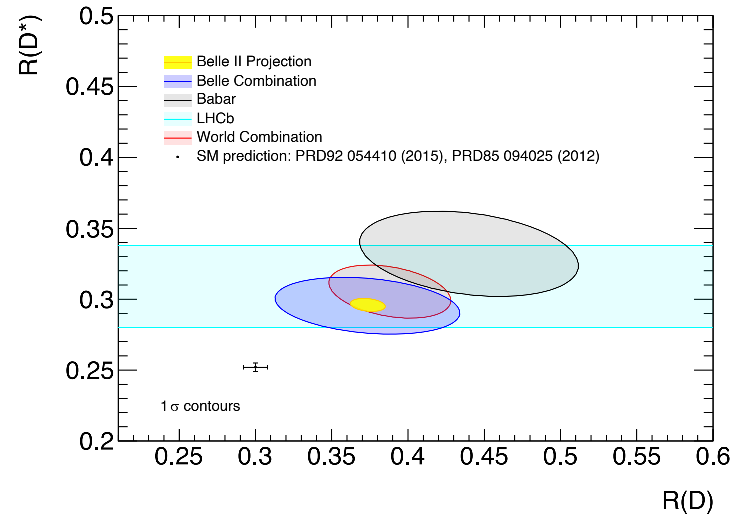
CKM Matrix: weak quark couplings



Testing *CKM matrix unitarity**: Belle II will provide input on the magnitudes of 7 out of 9 CKM matrix elements*



- *$|V_{cb}|$ and $|V_{ub}|$ ($\Delta|V_{ub,expt.}|$ ~ 1% expected) from semi-leptonic B decays with a variety of methods (excl./incl., full/partial reconstruction, untagged and had./SL tagged)*
  - *Measure $|V_{ub}|$ with $B \to \tau\nu$ as test of NP ($\Delta|V_{ub}|$ ~ 3% for each had.+SL tagged measurement)*
  - *Precision measurements of $B \to D^{(*)}\tau\nu$*
- *$|V_{td}|$ and $|V_{ts}|$ from $B\overline{B}$ mixing and radiative and EW penguin decays*
- *$|V_{cd}|$ and $|V_{cs}|$ from leptonic and semileptonic $D_{(s)}$ decays, or use to test LQCD ($\Delta f(D_s)$ ~ 0.3%)*
- *$|V_{us}|$ from τ decays to strange final states*



SM CPV: CKM and Unitarity Triangle

SM is very predictive: single complex phase in CKM matrix, related to apex of UT

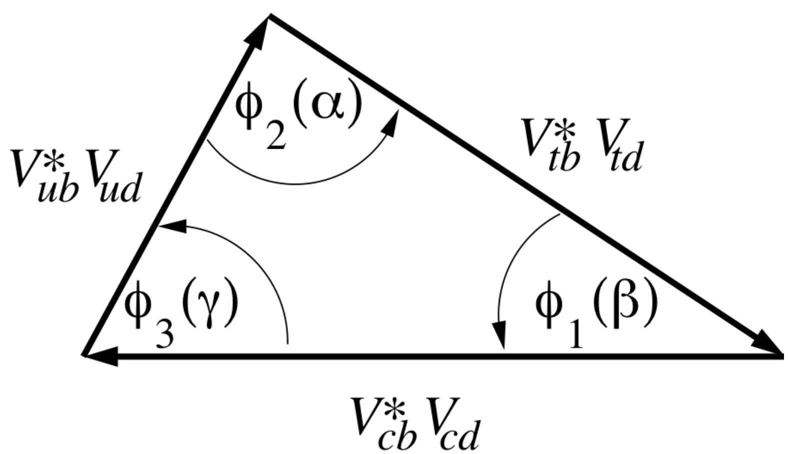
$$V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td} = 0$$

The internal angles of this triangle are phase differences that can be measured via ***various strategies****:*

$$\phi_1 = \beta \equiv \arg\left[-V_{cd}V_{cb}^*/V_{td}V_{tb}^*\right]$$
$$\phi_2 = \alpha \equiv \arg\left[-V_{td}V_{tb}^*/V_{ud}V_{ub}^*\right]$$
$$\phi_3 = \gamma \equiv \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$$

Isospin decomposition required to extract φ_2 (α) from $B \to \pi\pi$ and $B \to \rho\rho$

- $B \to \pi^+\pi^- / \pi^+\pi^0 / \pi^0\pi^0$
- $B \to \rho^+\rho^- / \rho^+\rho^0 / \rho^0\rho^0$
- $B^0 \to \rho\,\pi$
- $B^0 \to a_1(\rho\pi)^+\,\pi^-$



- $B^- \to D^{(*)}{}_{CP}\,K^{(*)-}$
- $B^0 \to D_{CP}\,K^{*0}$
- $B^- \to D^{(*)}(K^+\pi^-)\,K^{(*)-}$
- $B^- \to D^{(*)0}\,\pi^-$
- $B^- \to D^{(*)}(K_S\,\pi^+\pi^-)\,K^{(*)-}$
- $B^- \to D(\pi^0\pi^+\pi^-)\,K^-$
- $B^- \to D(K_S\,K^+\pi^-)\,K^-$

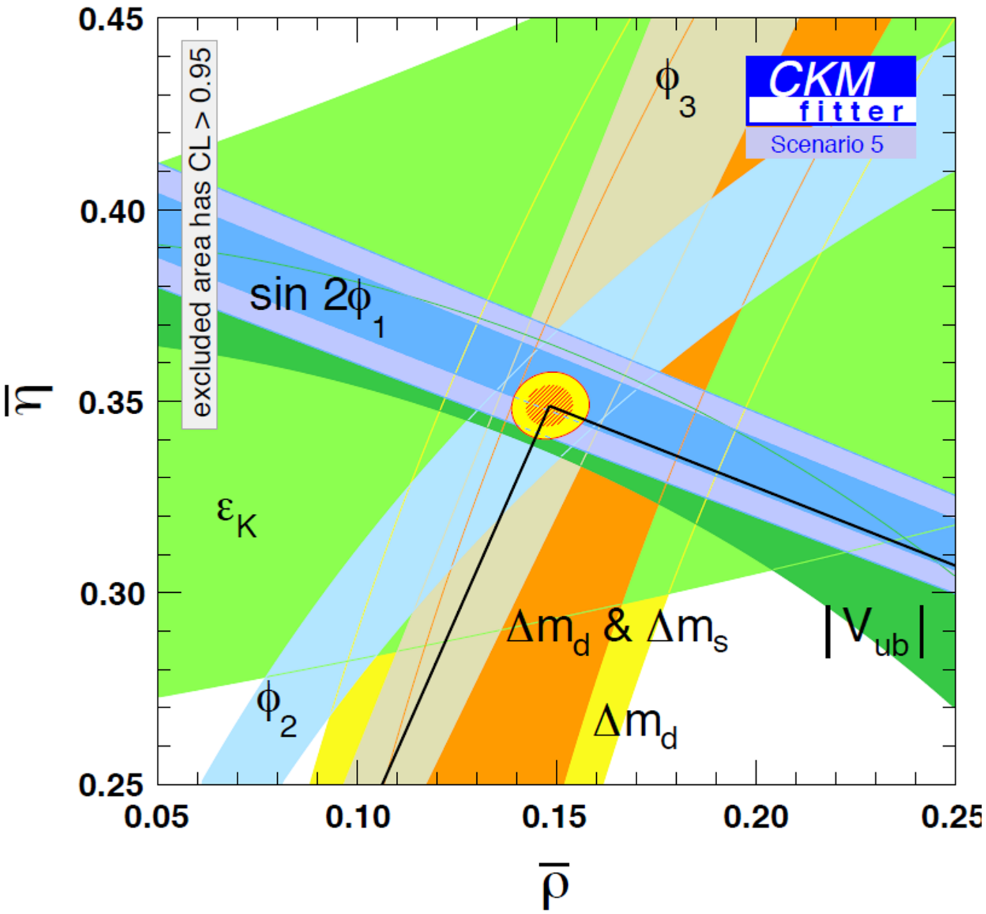
- $B^0 \to J/\psi\,K_S$
- $B^0 \to J/\psi\,K_L$
- $B^0 \to \psi'\,K_S$
- $B^0 \to \chi_c\,K_S$
- $B^0 \to \eta_c\,K_S$
- $B^0 \to D^{(*)}{}_{CP}\,h^0$
- $B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$
- $B^0 \to (K_S K_S/\rho^0/\omega)\,K_S$

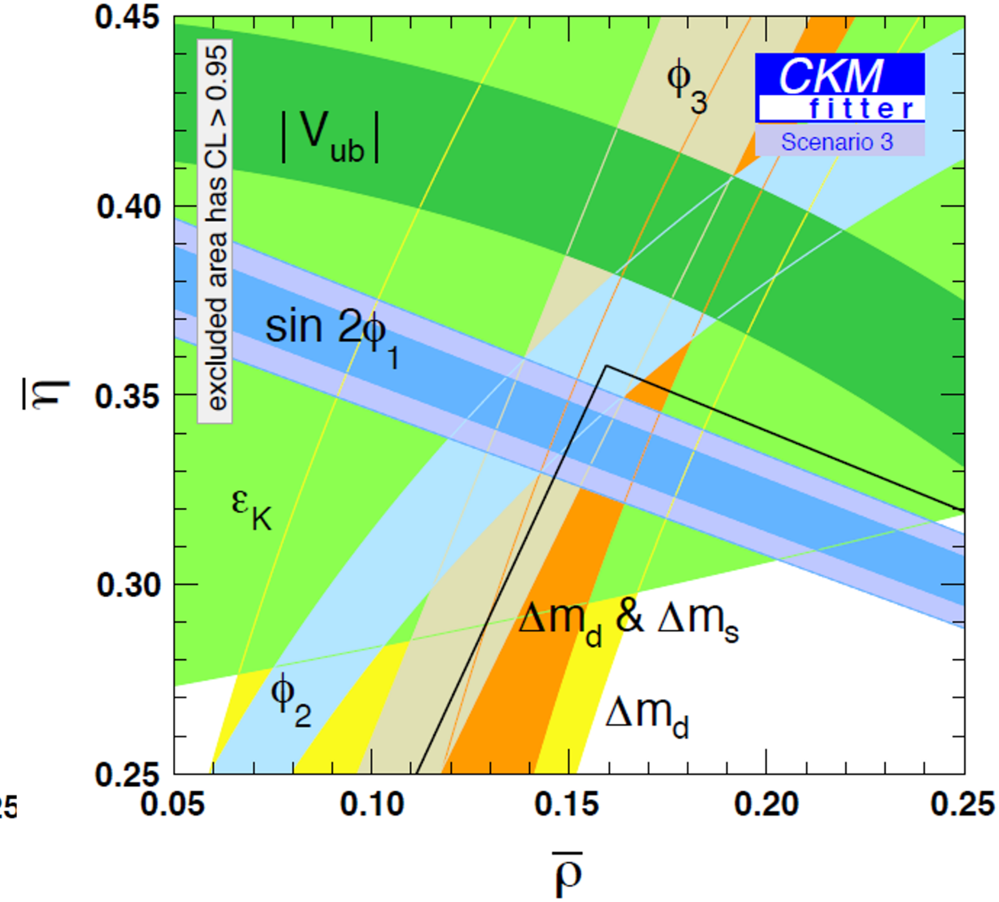
Φ_1 (β) and Φ_3 (γ) will also be precisely measured by LHCb

Overconstraining the Unitarity Triangle

SM CPV too small to explain baryon-antibaryon asymmetry.
Are there new CP violating phases in the quark sector?

⇒ Belle II will measure all 3 Unitarity Triangle angles ($\sin 2\varphi_1, \varphi_2, \varphi_3$)





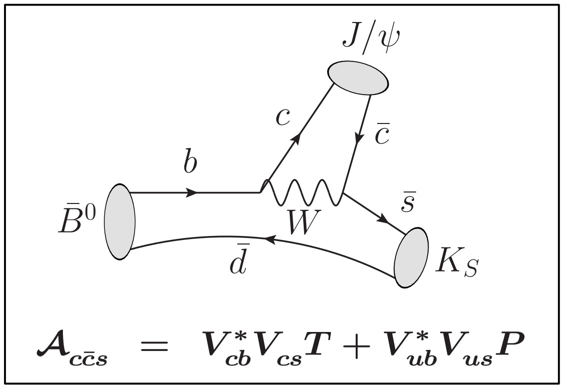
In ten years: no-tension SM … or observation of New Physics ?

Measurements of ϕ_1 (β)

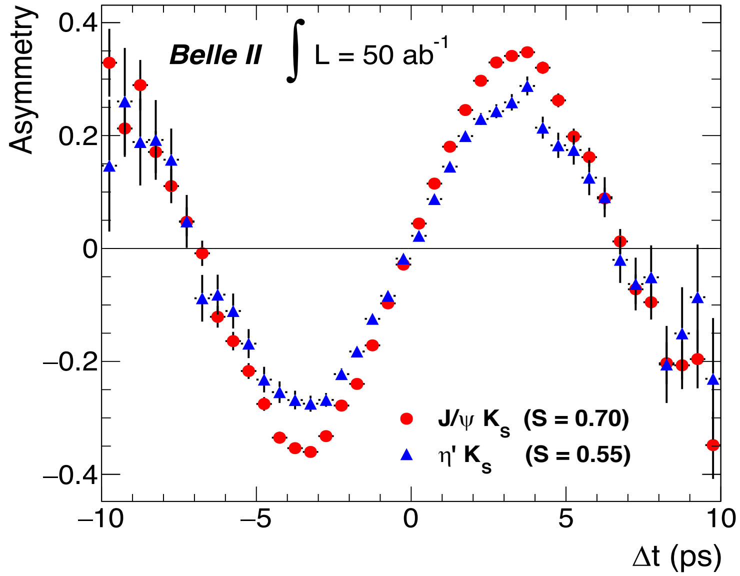
Use time-dependent CPV measurement techniques pioneered by Belle & BABAR (boosted L=1 $B\bar{B}$ system, vertexing/Δt with 2x better Δt resolution than Belle from pixel detector, and excellent B flavor tagging Q > 30%)

$B^0 \to J/\psi K_S$ ***(the "Golden" mode):***

→ constrains the UT

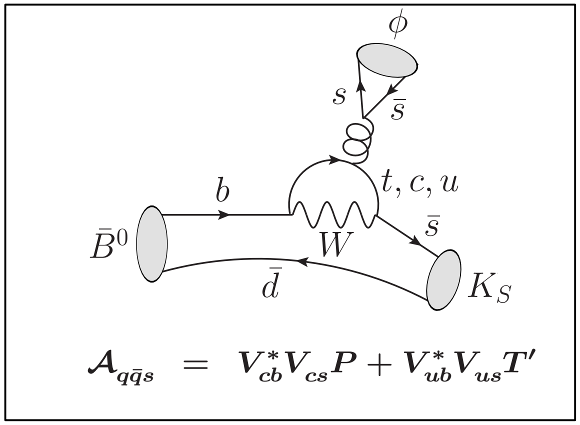


expected 50 ab^{-1} uncertainty: $\delta\phi_1$ = 0.4°
(less than the current theory error of 1-2°)



$$A_{CP} = A\cos(\Delta M\Delta t) + S\sin(\Delta M\Delta t)$$

$B^0 \to \phi K_S, \eta' K_S, \omega K_S, \pi^0 K_S$ ***("penguin" modes):***



	WA (2017)		5 ab^{-1}		50 ab^{-1}	
Channel	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$	$\sigma(S)$	$\sigma(A)$
$J/\psi K^0$	0.022	0.021	0.012	0.011	0.0052	0.0090
ϕK^0	0.12	0.14	0.048	0.035	0.020	0.011
$\eta' K^0$	0.06	0.04	0.032	0.020	0.015	0.008
ωK^0_S	0.21	0.14	0.08	0.06	0.024	0.020
$K^0_S\pi^0\gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K^0_S\pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

*Tree and penguin modes have same SM weak phase, but NP contributions in loop could contribute additional phases (**improve from 10-20% precision to 2-3%)***

Measurements of $\phi_2\,(\alpha)$ and $\phi_3\,(\gamma)$

Measurement of φ_2 in $B \to \pi\pi$, 3π, $\rho\rho$

ϕ_2 is determined from CP asymmetries and BFs of $B \to \pi\pi$, $B \to 3\pi$, and $B \to \rho\rho$ decays with an **isospin decomposition** of B^+ and B^0 decays **involving final states with π^0's**

- Belle II has good π^0 efficiency
- Expt. errors reduced by 2× - 10× depending on systematic error source
- Improved measurement of $A(B \to \pi^0\pi^0)$ will reduce discrete ambiguities
- **Expect error in ϕ_2 with 50/ab to be 0.6°** **(now 4.2°)**

	Value	0.8 ab^{-1}	50 ab^{-1}
$f_{L,\rho^+\rho^-}$	0.988	$\pm 0.012 \pm 0.023$ [725]	$\pm 0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm 0.20 \pm 0.15$ [729]	$\pm 0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ [10^{-6}]	28.3	$\pm 1.5 \pm 1.5$ [725]	$\pm 0.19 \pm 0.4$
$\mathcal{B}_{\rho^0\rho^0}$ [10^{-6}]	1.02	$\pm 0.30 \pm 0.15$ [729]	$\pm 0.04 \pm 0.02$
$A_{\rho^+\rho^-}$	0.00	$\pm 0.10 \pm 0.06$ [725]	$\pm 0.01 \pm 0.01$
$S_{\rho^+\rho^-}$	-0.13	$\pm 0.15 \pm 0.05$ [725]	$\pm 0.02 \pm 0.01$
	Value	0.08 ab^{-1}	50 ab^{-1}
$f_{L,\rho^+\rho^0}$	0.95	$\pm 0.11 \pm 0.02$ [716]	$\pm 0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ [10^{-6}]	31.7	$\pm 7.1 \pm 5.3$ [716]	$\pm 0.3 \pm 0.5$
	Value	0.5 ab^{-1}	50 ab^{-1}
$A_{\rho^0\rho^0}$	-0.2	$\pm 0.8 \pm 0.3$ [715]	$\pm 0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm 0.7 \pm 0.2$ [715]	$\pm 0.07 \pm 0.01$

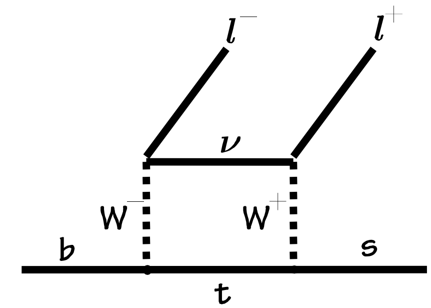
Precision measurement of ϕ_3 in $B \to D^{(*)}K^{(*)}$

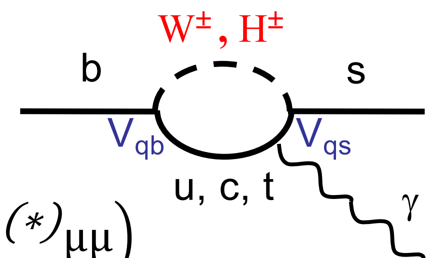
- *Reconstruct D decays to CP eigenstates, Cabibbo-favored and singly and doubly Cabibbo-suppressed decays and self-conjugate modes*
- ***Expect ϕ_3 error from GGSZ with 50/ab and strong phase measurement from BESIII to be 1.5° (WA 5°)***

Type of D decay	Method name	D final states studied
CP-eigenstates	GLW	CP-even: K^+K^-, $\pi^+\pi^-$; CP-odd $K_S^0\pi^0$, $K_S^0\eta$
CF and DCS	ADS	$K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^0$, $(K^\pm\pi^\mp\pi^+\pi^-)$
Self-conjugate	GGSZ	$K_S^0\pi^+\pi^-$, $(K_S^0K^+K^-)$, $(\pi^+\pi^-\pi^0)$, $(K^+K^-\pi^0)$, $(\pi^+\pi^-\pi^+\pi^-)$
SCS	GLS	$(K_S^0K^\pm\pi^\mp)$

Rare radiative and EW Penguin B Decays

- *Sensitive to NP contributing in the loop*
- *Belle II is uniquely sensitive to*
  - ***inclusive final states** $B \to X_{s,d}\gamma$ and $B \to X_{s,d}\, l^+ l^-$*
  - *final states with **photons, neutrinos, or taus***
  - *… and has **nearly equal μ and e efficiency** for LFU tests*
  - *B_{tag} reconstruction (FEI) improved ×2 wrt Belle*
- *Measure BF, A_{CP}, A_{FB}, ΔA_{CP}, Δ_{0+}, and angular variables in incl. and excl. $B \to X_{s,d}\gamma$ and $B \to X_{s,d}\, l^+ l^-$ final states*
- *Determine R_K and R_{K^*} with 3-4 % precision*
- *Expect Belle II to observe $B \to K^{(*)}\nu\nu$*

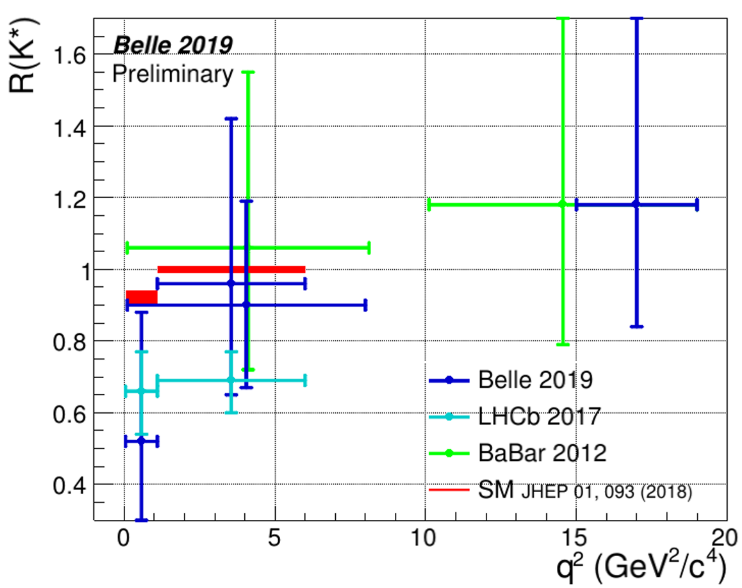




$$R_{K^{(*)}} = \frac{\mathbf{Br}\left(B \to K^{(*)}\mu\mu\right)}{\mathbf{Br}\left(B \to K^{(*)}ee\right)}$$

SM prediction very robust: $R_K(SM) = 1$

[up to tiny QED *and* lepton mass effects]



Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$	$< 19 \times 10^{-6}$	30%	11%
$A_{CP}(B \to X_{s+d}\gamma)$ $[10^{-2}]$	$2.2 \pm 4.0 \pm 0.8$	1.5	0.5
$S(B \to K^0_S\pi^0\gamma)$	$-0.10 \pm 0.31 \pm 0.07$	0.11	0.035
$S(B \to \rho\gamma)$	$-0.83 \pm 0.65 \pm 0.18$	0.23	0.07
$A_{FB}(B \to X_s\ell^+\ell^-)$ $(1 < q^2 < 3.5\ \mathrm{GeV}^2/c^4)$	26%	10%	3%
$Br(B \to K^+\mu^+\mu^-)/Br(B \to K^+e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	28%	11%	4%
$Br(B \to K^{*+}(892)\mu^+\mu^-)/Br(B \to K^{*+}(892)e^+e^-)$ $(1 < q^2 < 6\ \mathrm{GeV}^2/c^4)$	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	–

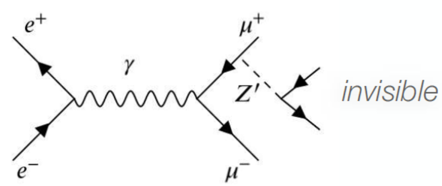
New Physics in Charm Physics

- *10^{11} D decays in low-background environment*
- *Belle II will reduce errors of **D mixing parameters** x and y by factors >2 and > 3 resp., with $D \to K_S \pi^+ \pi^-$ Dalitz analysis*
  - *Errors are then systematics dominated*
- *Search for **indirect CPV** via q/p benefits from improved decay time resolution due to pixel detector*
  - *$\Delta\arg(q/p)$ expected 4° (now 11°)*
- *Belle II will search for **direct CPV** in final states with neutrals*
  - *dCPV recently observed by LHC in all-charged final states KK and ππ*
- *Study of **rare radiative and EW penguin decays** $D \to X \gamma$ and $D \to X\, l^+ l^-$*

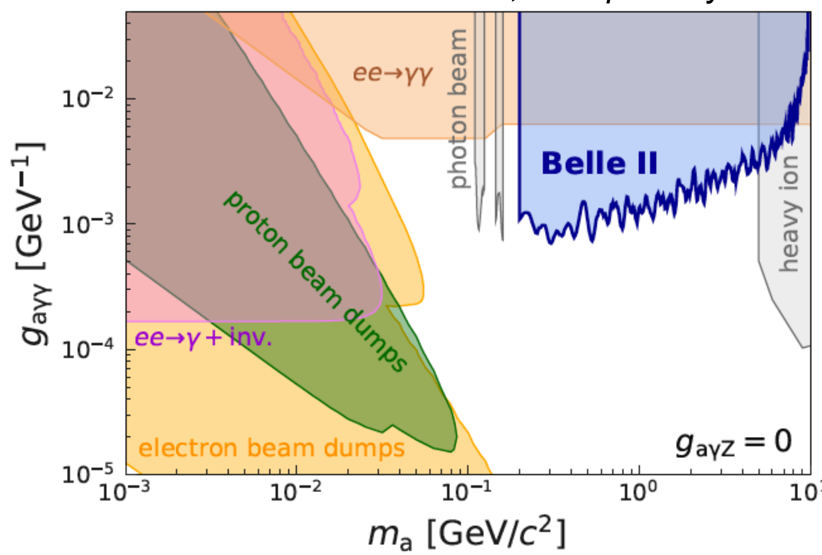
Channel	Observable	Belle/BaBar Measurement		Scaled	
Rare and Radiative Decays					
$D^0 \to \rho^0 \gamma$	A_{CP}	0.943	$+0.056 \pm 0.152 \pm 0.006$	± 0.07	± 0.02
$D^0 \to \phi \gamma$	A_{CP}		$-0.094 \pm 0.066 \pm 0.001$	± 0.03	± 0.01
$D^0 \to \overline{K}^{*0} \gamma$	A_{CP}		$-0.003 \pm 0.020 \pm 0.000$	± 0.01	± 0.003
Mixing and Indirect (time-dependent) CP Violation					
$D^0 \to K^+ \pi^-$	x'^2 (%)	0.976	0.009 ± 0.022	± 0.0075	± 0.0023
(no CPV)	y' (%)		0.46 ± 0.34	± 0.11	± 0.035
(CPV allowed)	$\lvert q/p \rvert$	World Avg. [230]	$0.89\,^{+0.08}_{-0.07}$	± 0.20	± 0.05
	$\phi\,(^\circ)$	with LHCb	$-12.9\,^{+9.9}_{-8.7}$	$\pm 16^\circ$	$\pm 5.7^\circ$
$D^0 \to K^+ \pi^- \pi^0$	x''	0.384	$2.61\,^{+0.57}_{-0.68} \pm 0.39$	-	± 0.080
	y''		$-0.06\,^{+0.55}_{-0.64} \pm 0.34$	-	± 0.070
$D^0 \to K^0_S \pi^+ \pi^-$	x (%)	0.921	$0.56 \pm 0.19\,^{+0.04}_{-0.08}\,^{+0.06}_{-0.08}$	± 0.16	± 0.11
	y (%)		$0.30 \pm 0.15\,^{+0.04}_{-0.05}\,^{+0.03}_{-0.07}$	± 0.10	± 0.05
	$\lvert q/p \rvert$		$0.90\,^{+0.16}_{-0.15}\,^{+0.05}_{-0.04}\,^{+0.06}_{-0.05}$	± 0.12	± 0.07
	$\phi\,(^\circ)$		$-6 \pm 11 \pm 3\,^{+3}_{-4}$	± 8	± 4
Direct (time-integrated) CP Violation in %					
$D^0 \to K^+ K^-$	A_{CP}	0.976	$-0.32 \pm 0.21 \pm 0.09$	± 0.10	± 0.03
$D^0 \to \pi^+ \pi^-$	A_{CP}	0.976	$+0.55 \pm 0.36 \pm 0.09$	± 0.16	± 0.05
$D^0 \to \pi^0 \pi^0$	A_{CP}	0.966	$-0.03 \pm 0.64 \pm 0.10$	± 0.28	± 0.09
$D^0 \to K^0_S \pi^0$	A_{CP}	0.966	$-0.21 \pm 0.16 \pm 0.07$	± 0.08	± 0.02
$D^0 \to K^0_S K^0_S$	A_{CP}	0.921	$-0.02 \pm 1.53 \pm 0.17$	± 0.66	± 0.23
$D^0 \to K^0_S \eta$	A_{CP}	0.791	$+0.54 \pm 0.51 \pm 0.16$	± 0.21	± 0.07
$D^0 \to K^0_S \eta'$	A_{CP}	0.791	$+0.98 \pm 0.67 \pm 0.14$	± 0.27	± 0.09
$D^0 \to \pi^+ \pi^- \pi^0$	A_{CP}	0.532	$+0.43 \pm 1.30$	± 0.42	± 0.13
$D^0 \to K^+ \pi^- \pi^0$	A_{CP}	0.281	-0.60 ± 5.30	± 1.26	± 0.40
$D^0 \to K^+ \pi^- \pi^+ \pi^-$	A_{CP}	0.281	-1.80 ± 4.40	± 1.04	± 0.33
$D^+ \to \phi \pi^+$	A_{CP}	0.955	$+0.51 \pm 0.28 \pm 0.05$	± 0.12	± 0.04
$D^+ \to \pi^+ \pi^0$	A_{CP}	0.921	$+2.31 \pm 1.24 \pm 0.23$	± 0.54	± 0.17
$D^+ \to \eta \pi^+$	A_{CP}	0.791	$+1.74 \pm 1.13 \pm 0.19$	± 0.46	± 0.14
$D^+ \to \eta' \pi^+$	A_{CP}	0.791	$-0.12 \pm 1.12 \pm 0.17$	± 0.45	± 0.14
$D^+ \to K^0_S \pi^+$	A_{CP}	0.977	$-0.36 \pm 0.09 \pm 0.07$	± 0.05	± 0.02
$D^+ \to K^0_S K^+$	A_{CP}	0.977	$-0.25 \pm 0.28 \pm 0.14$	± 0.14	± 0.04
$D^+_s \to K^0_S \pi^+$	A_{CP}	0.673	$+5.45 \pm 2.50 \pm 0.33$	± 0.93	± 0.29
$D^+_s \to K^0_S K^+$	A_{CP}	0.673	$+0.12 \pm 0.36 \pm 0.22$	± 0.15	± 0.05

Dark Sector Searches

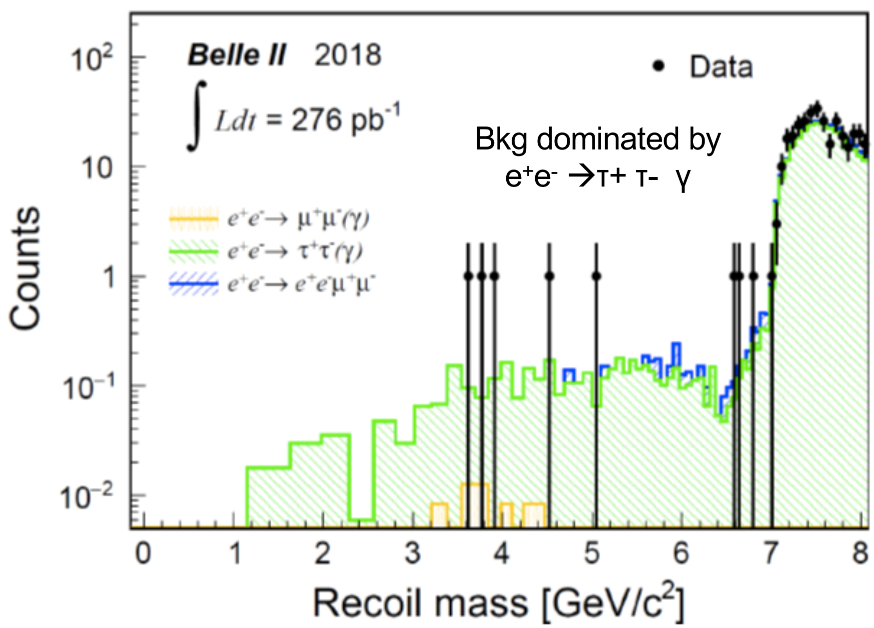
- *DS searches at Belle II benefit from large data sample, clean e^+e^- environment, and special high-efficiency triggers for low-multiplicity final states*
- *Many **DS benchmark models** will be studied, e.g.*
  - *Vector mediator (dark photon, Z')*
  - *Scalar mediator (dark Higgs)*
  - *Neutrino-like mediator*
  - *Axion-like mediator*
  - *Long-lived particles*

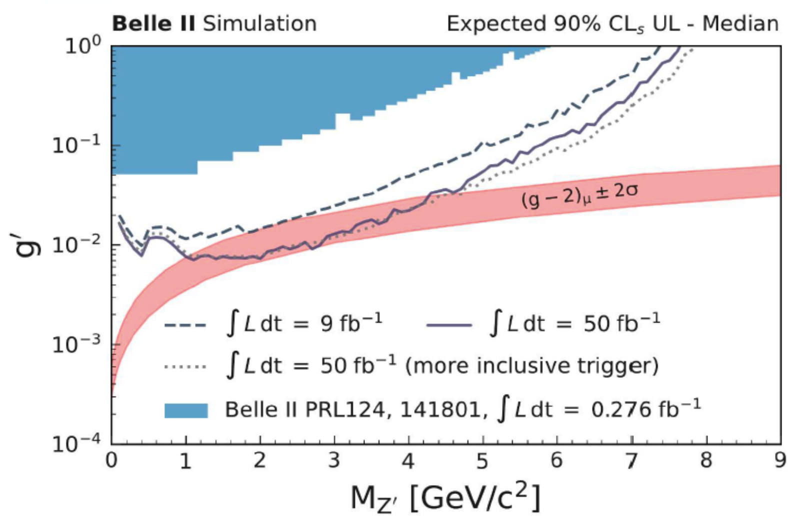


Search for ALP in $e^+e^- \to a(\gamma\gamma)\gamma$
arXiv:2007.13071, accepted by PRL



Search for invisible Z' in $e^+e^- \to Z'\mu^+\mu^- / e^\pm\mu^\mp$
PRL 124, 141801 (2020)

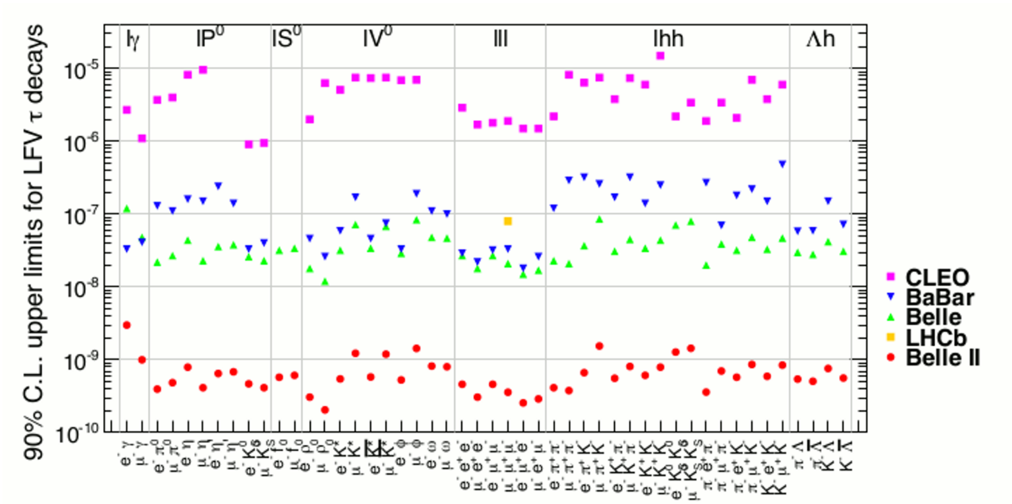




New Physics Searches with τ leptons

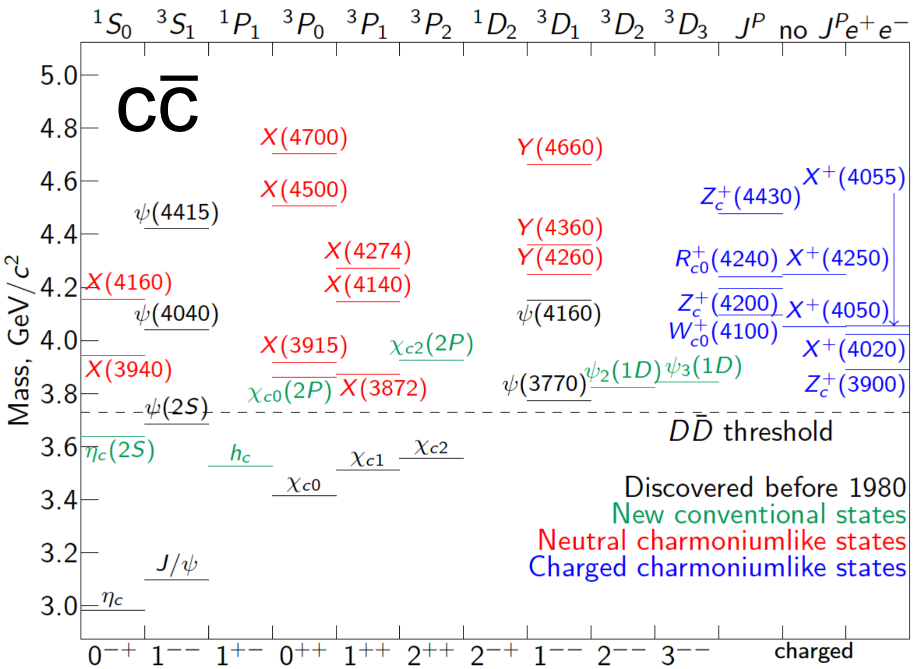
Many extensions of the SM include cLFV

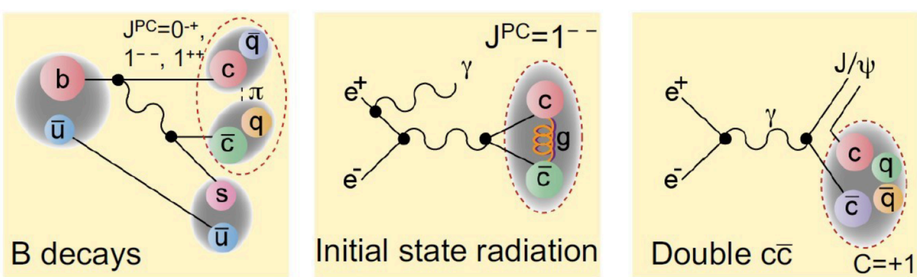
Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z’	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}

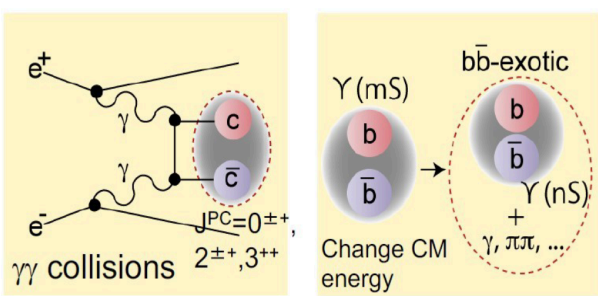


- *Belle II is sensitive to **charged LFV** in τ decays at BFs of 10^{-9} to a few 10^{-10}*
  - *NP models predict cLFV at 10^{-7}-10^{-10}*
- *Search for NP contributions to isospin-suppressed **2nd class currents***
- *Limit **τ electric and magnetic moments** through precise measurements of Michel parameters in leptonic and radiative decays several orders of magnitude below current bounds*
- *Search for new **CP-violating couplings** in τ decays*
- *Sensitivities could be improved with beam polarization upgrade*

Hadron Spectroscopy





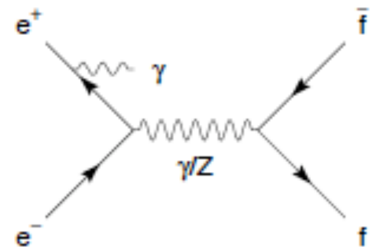


Heavy quarkonium production mechanisms at Belle II

- *Plethora of new exotic **Charmonium states***
  - *Many new states discovered by Belle and other experiments (X(3872), Y(4260), Z_c^+(4430),…)*
  - *Several do not fit into the conventional framework*
- *Belle II will also study new*
  - ***bottomonium** states (such as Z_b^+(10610/50) at the Υ(5S))*
  - ***open-charm excited states***
  - ***charm baryons***
  - ***exotic light quark states** (e.g. glueballs)*
- *Understand how QCD forms these exotic states*
  - *At Belle II states are produced in a **wide variety of processes** (B decays, ISR, γγ, double-charmonium events, …)*

Precision Neutral Current Electroweak Program
with SuperKEKB Upgraded to have Polarized e^- Beams

At 10.58 GeV, e^- polarization enables A_{LR} measurements sensitive to Z-γ interference;

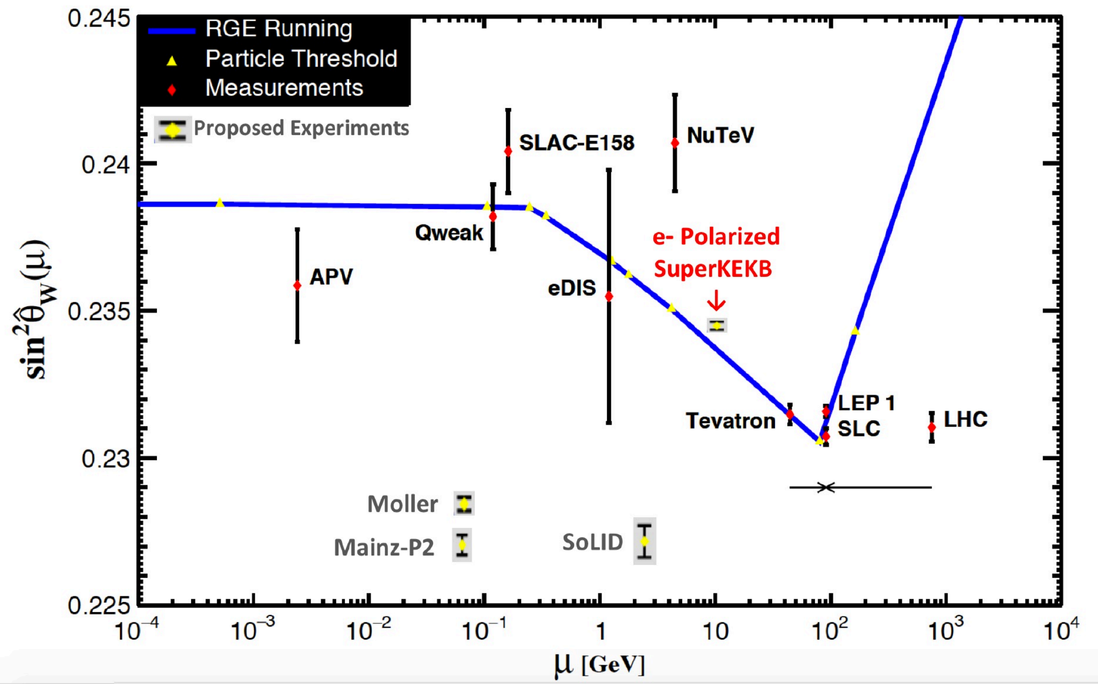


$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{4}{\sqrt{2}}\left(\frac{G_F s}{4\pi\alpha Q_f}\right) g_A^e g_V^f \langle Pol \rangle$$

$$\propto T_3^f - 2Q_f \sin^2\theta_W$$

20 ab^{-1} and 70% polarization at IP gives:

- World's most precise $\sin^2\theta_W$ ($\sigma_{\sin 2\theta W} \sim 0.00016$) and probe of its running
- Unprecedented and clean NC universality studies for e, μ, τ, b and c since beam polarization error cancels (e.g. < 0.05% relative error for b-to-c, *cf* 4% now)
- $\sin^2\theta_W$ with light quarks at 10.58 GeV
- Sensitivity to Z' > TeV scale and dark sector parity-violating Z'_D below M_Z



More information at arxiv.org/abs/1907.03503

Beyond EW e- polarization at SuperKEKB:

- enables more precise τ EDM and $(g\text{-}2)_\tau$,
- reduces backgrounds in $\tau \to \mu\gamma$ and $\tau \to e\gamma$ searches and distinguishes Left & Right-handed New Physics currents
- can be used to probe dynamical mass generation in QCD via polarized Λ

Planning for implementation ~2026 with upgrade proposal to be included in KEK Roadmap for MEXT to be submitted 2021

Conclusions

- *Belle II is an active and important Super Flavor Factory with a large US contribution*
  - *covers a broad physics spectrum with many crucial and unique measurements*
    - *CPV and rare decays of charm and bottom, exotic states, Dark Sector, LFV, …*
  - *already produces world class results on Dark Sector searches with < 1% of expected data set*
- *Expected to record 50 ab^{-1} (50x the Belle data set) over the next decade*
- *Upgrades to the detector and accelerator are necessary to reach full potential*

Back-Up Slides

How to get 50x integrated luminosity?

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

Lorentz factor

Beam current

Beam-Beam parameter

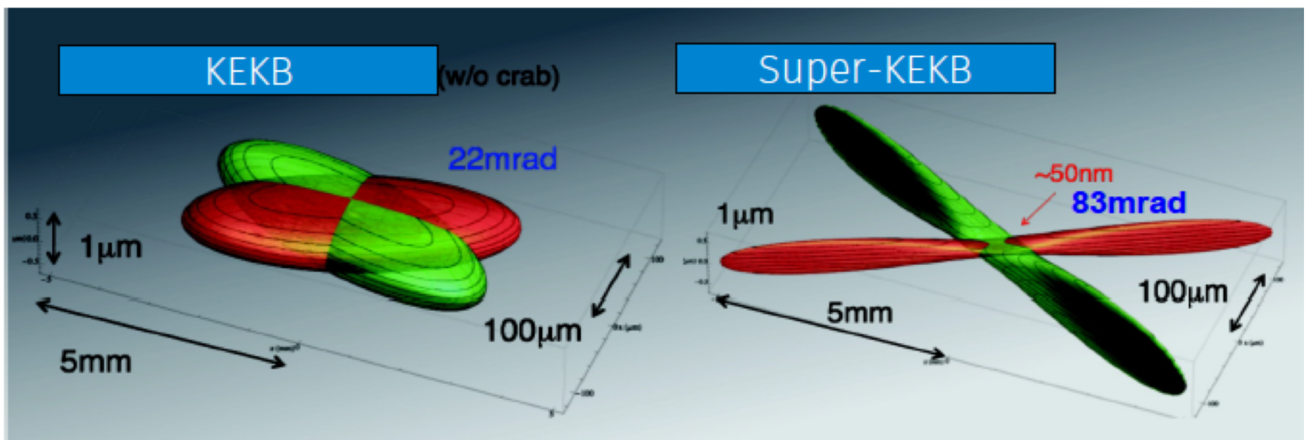
Geometrical reduction factors (crossing angle, hourglass effect)

(0.8-1.0)

Vertical beta function at IP

Beam aspect ratio at IP

(0.01-0.02)



	E (GeV) LER/HER	β^*_y (mm) LER/HER	β^*_x (cm) LER/HER	φ (mrad)	I (A) LER/HER	L ($cm^{-2}s^{-1}$)
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20 factor 2-3

beam size:

100 μm(H) x 2 μm(V)

→ *10 μm(H) x 59 nm(V)*

Belle-II Goal:

40 x Belle = 8 x 10^{35}

FAQ: How do Belle II and LHCb capabilities compare ?

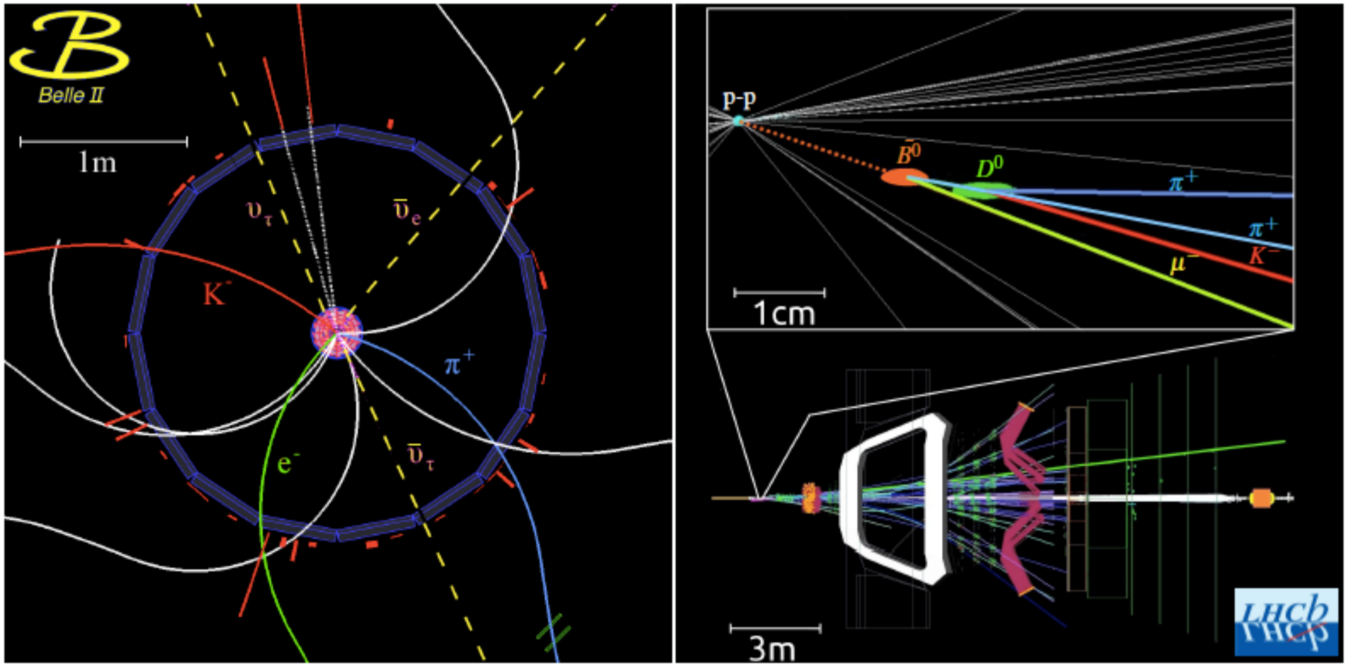


Figure credit:
G. Ciezarak et al,
Nature
546, 227 (2017)

+ Belle II can do the Dark Sector

1. LHCB has a large b bbar cross-section (hundreds of microbarns versus nanobarns) and good sensitivity, signal to background, for modes with dimuons, and all charged final states using vertexing. Triggering and flavor tagging effs. are much lower than in e^+e^-.

Rule of thumb for statistics in this case:
1 fb^{-1} at LHCb is 1 ab^{-1} at Belle II.
(→ Need good SuperKEKB performance)

2. Belle II has a simple event environment with B-anti B pairs produced in a coherent QM state with no additional particles.

3. Belle II can measure inclusive processes

4. Belle II can measure electrons as well as muons. (important for lepton universality checks).

5. Belle II can measure final states with gamma's, Kshorts and missing neutrinos well.