NAGOYA UNIVERSITY

Belle II

The Belle II experiment: status and physics prospects

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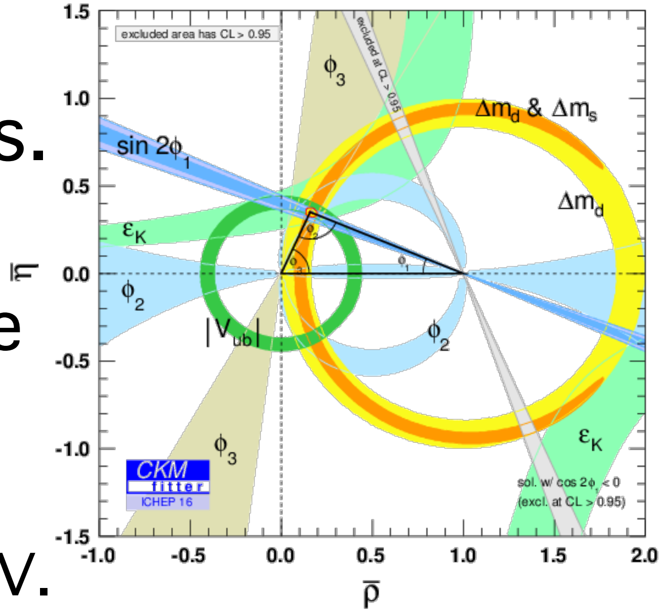
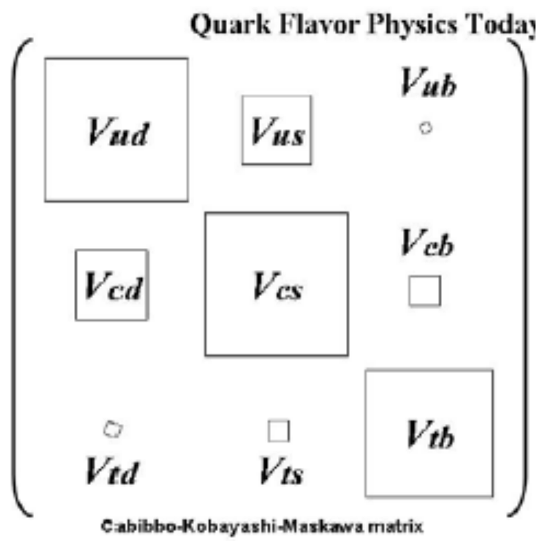
On behalf of the Belle II Collaboration

Physics motivations and goals

- CP violation (CPV) in the quark sector was elucidated by B-factories.
  - An essential part of the SM.
- The CPV is too small to account for the baryon-antibaryon asymmetry in the universe.
  - There must be undiscovered source(s) of CPV.
- The SM does not provide answers to various fundamental questions.
  - Fermion generations and mass hierarchy,
  - Diagonal hierarchy of the CKM matrix,
  - Constitution of Higgs sector, etc.





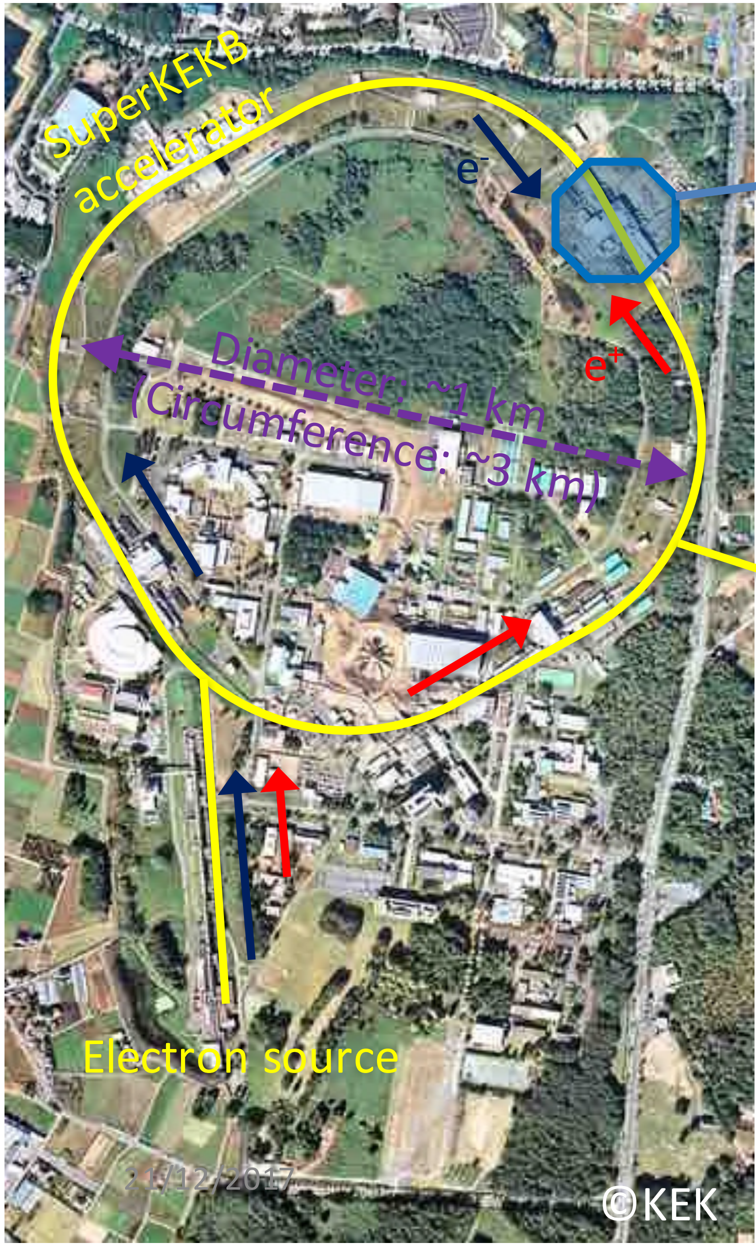
Belle II will search for new physics (NP) in the flavor sector at the intensity frontier.

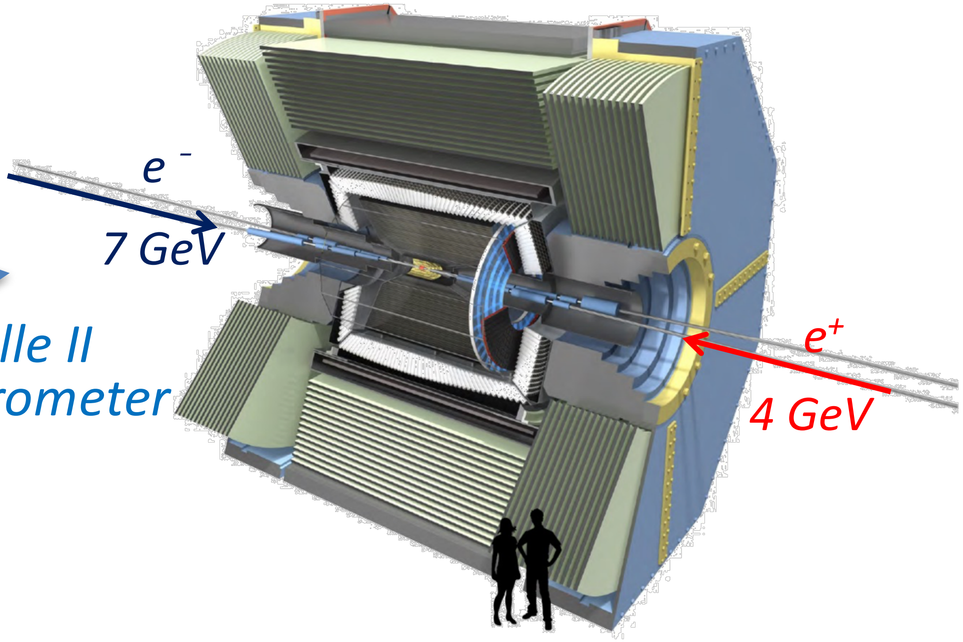
Experimental strategy

- Upgrade the accelerator and detector.
  - Luminosity: $L = 8\text{x}10^{35}\ cm^{-2}s^{-1}$ (40x Belle).
    - ➢Intending to accumulate $\int Ldt \sim 50\ ab^{-1}$ (50x Belle).
    - ➢Mitigating the beam BG level to be ~20x Belle.
  - Better detector performance.
    - ➢Tolerable to the high BG level.
- Running on $\Upsilon(4S)$ mostly, utilizing the clean e^+e^- collision environment and good detector hermiticity.
  - Full event reconstruction with kinematic constraint.
- Utilize the reach of indirect NP searches.
  - Reach of the NP energy scale can be pushed up to ~O(100 TeV).
  - Through $W^{\pm}$ exchange processes with τ.
  - Through quantum loop processes of Flavor Changing Neutral Current (FCNC).
  - Over-constraining the Unitary Triangle.
  - etc.

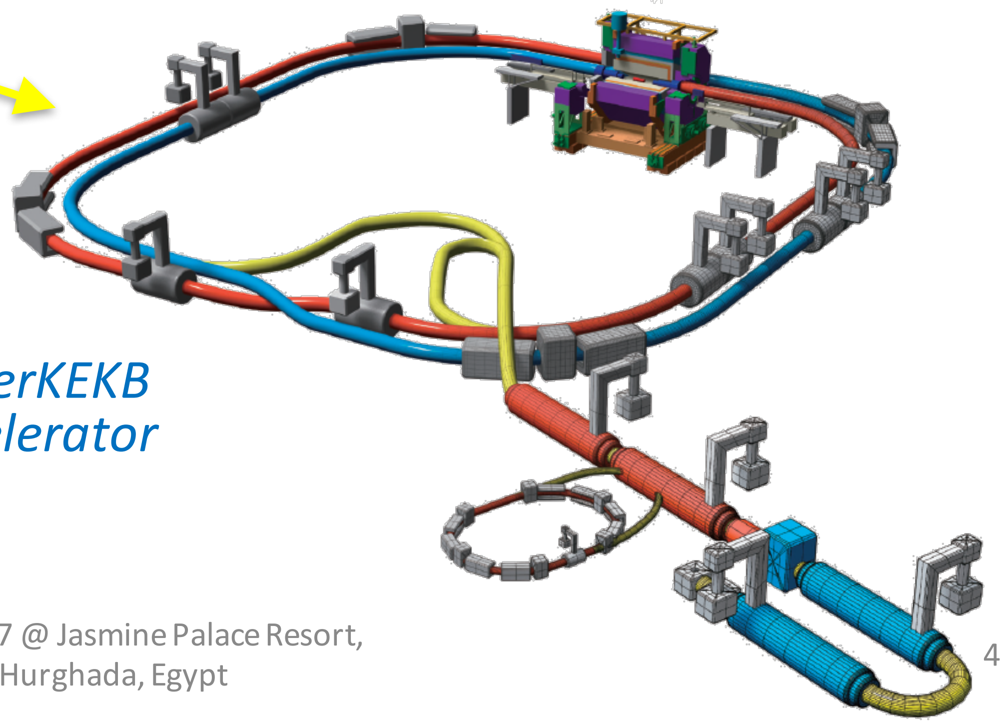
SuperKEKB and Belle II at KEK

KEK (Tsukuba, Japan)



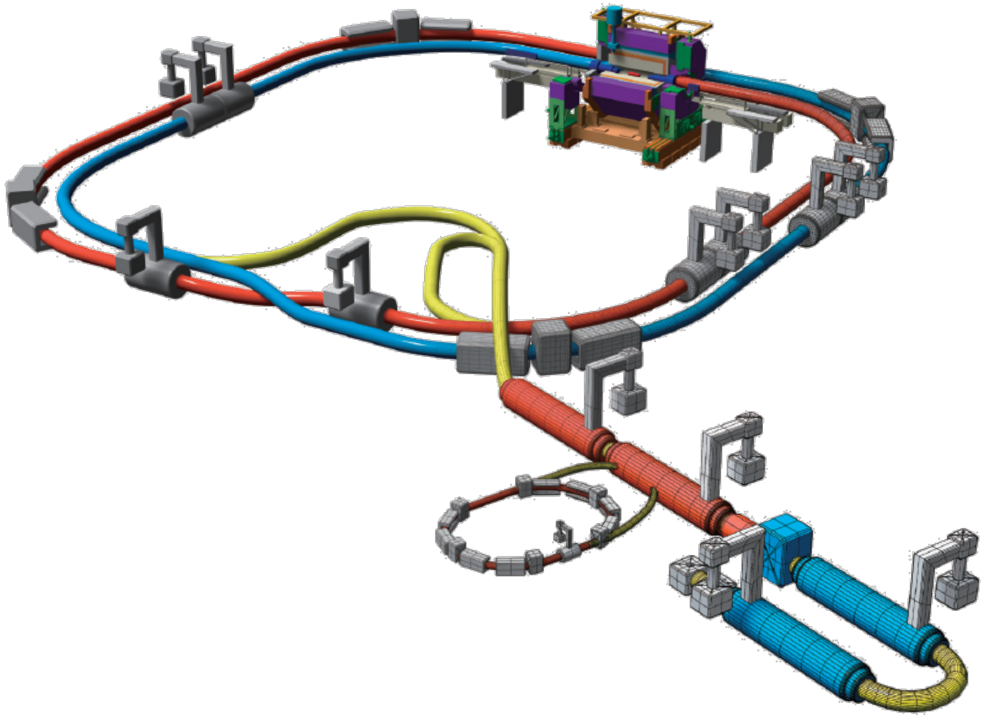


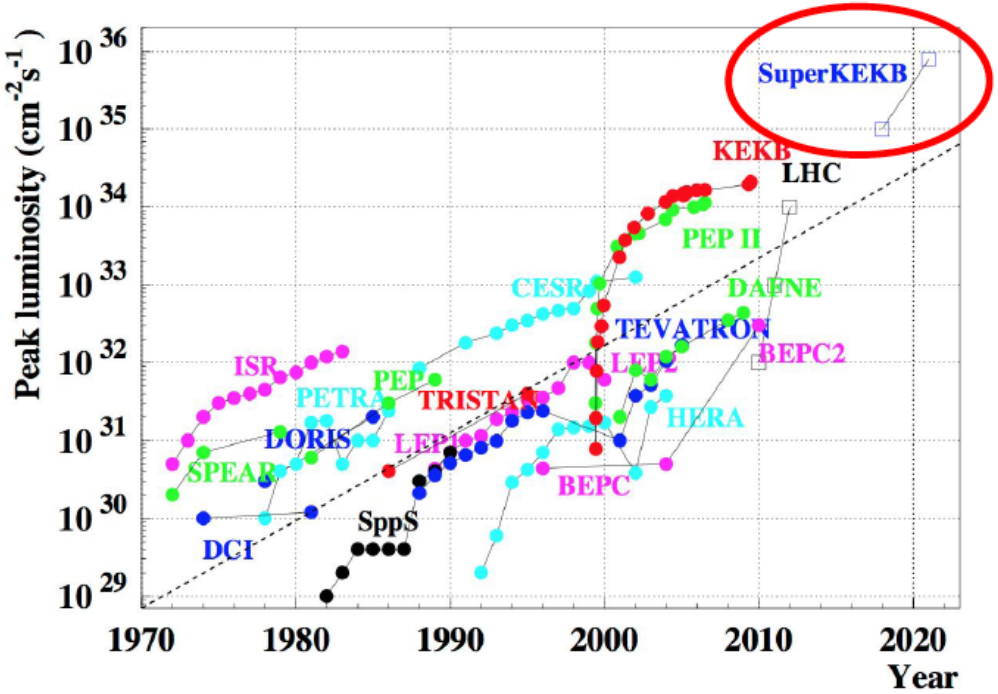
Belle II spectrometer



SuperKEKB accelerator

SuperKEKB accelerator



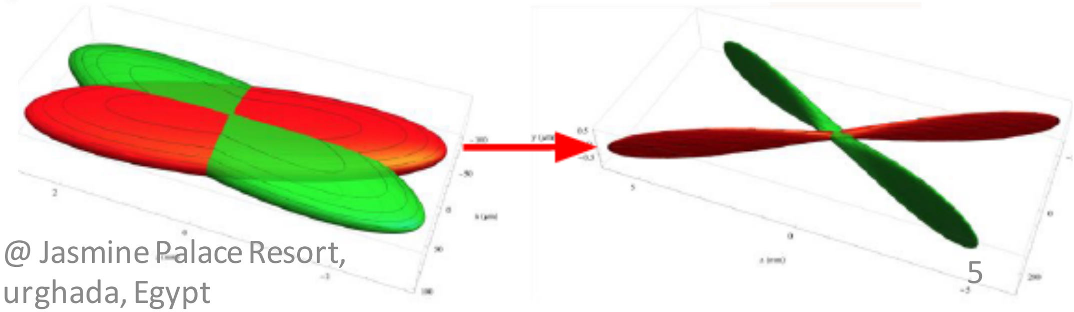


Factor of **2**

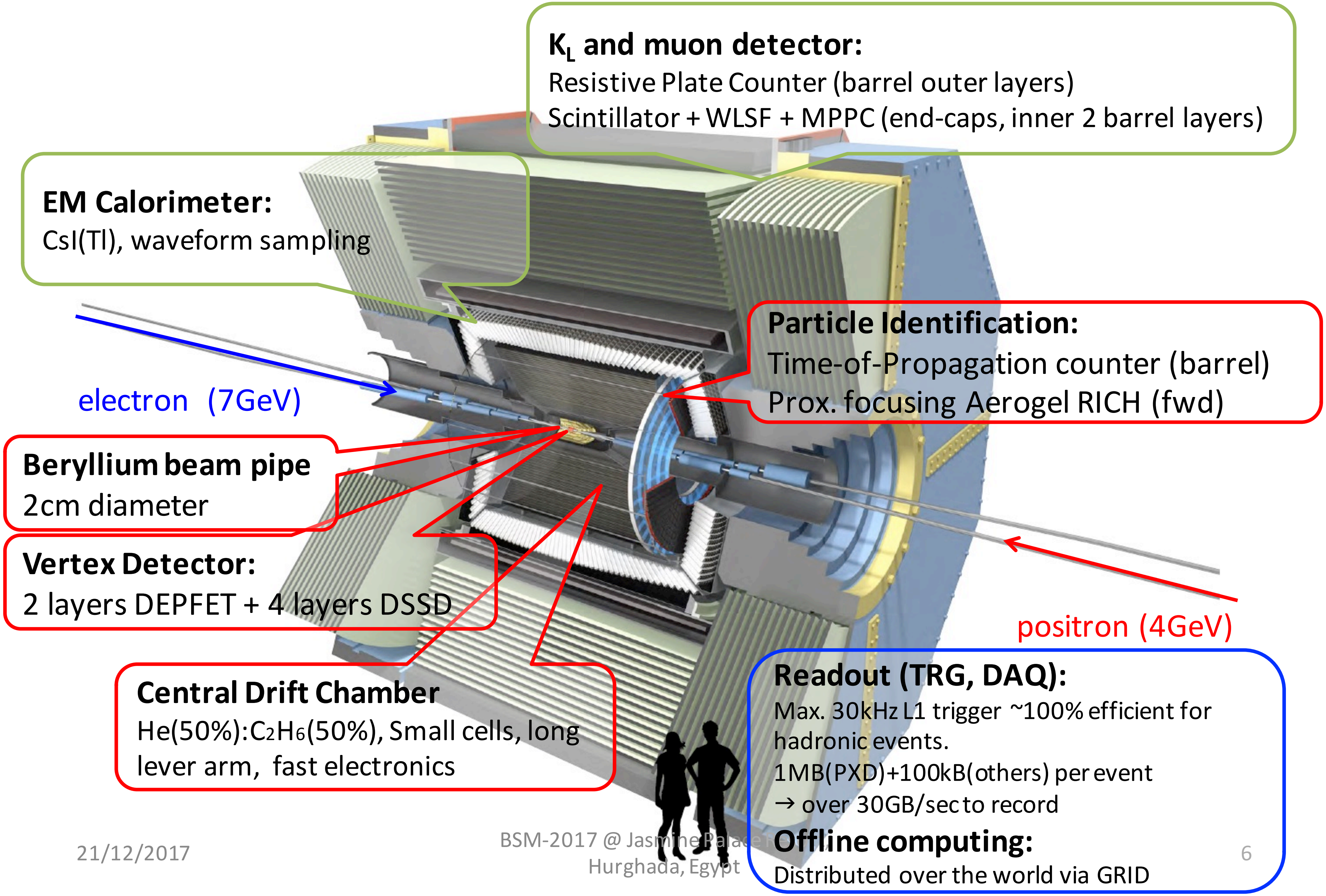
$$L = \frac{\gamma_{\pm}}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8\times 10^{35}\, cm^2 s^{-1}$$

Factor of **20**

Nano-beam scheme



Belle II detector



Construction/commissioning status

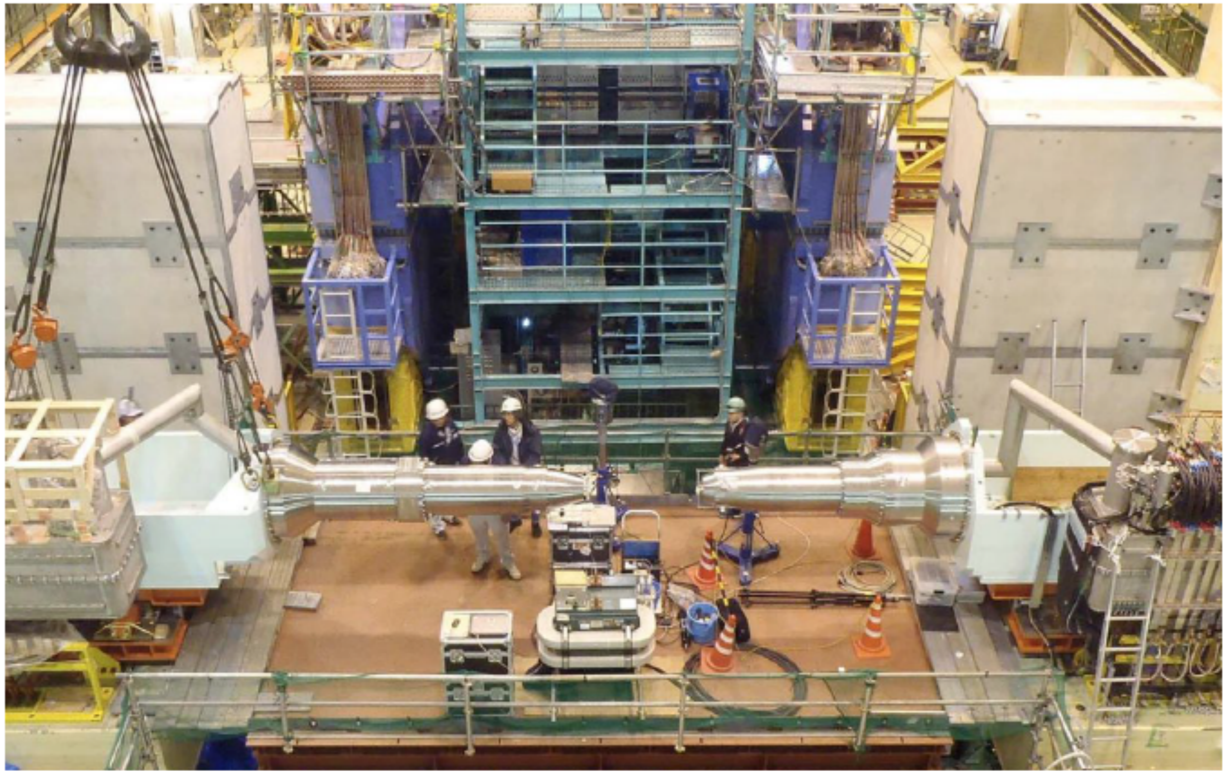
Accelerator status (1)

Phase I (complete)

- Circulate both beams, **no collisions, no Belle II**
- Tune accelerator optics
- Vacuum scrub
- Beam studies with BEAST II

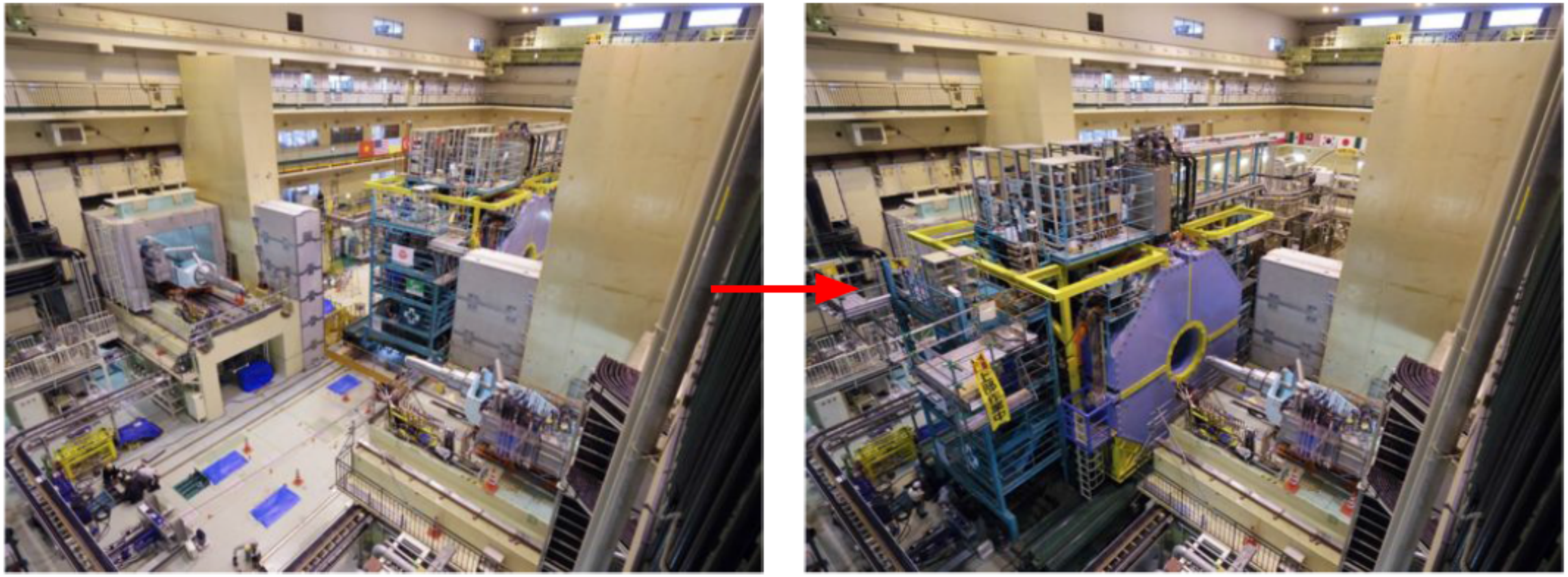
Accelerator status (2)

Install final focusing magnet systems **(complete)**



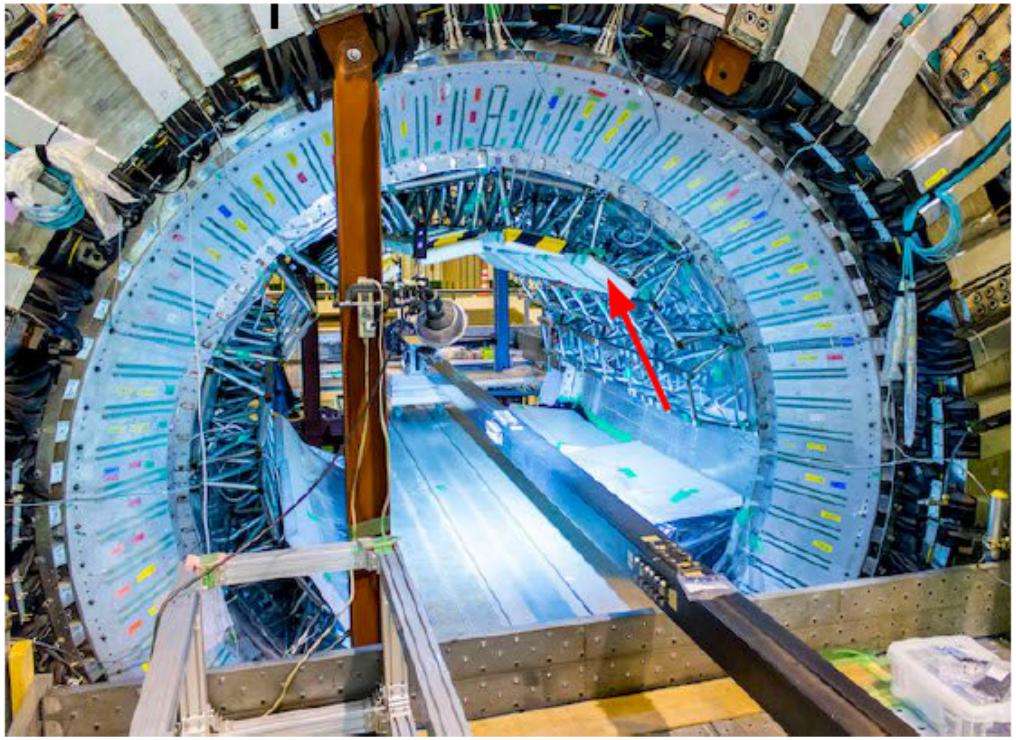
Accelerator status (4)

Belle II roll-in (**complete**) March 2017



Detector integration (1)

2016	2017	2018	2019
Phase 1		Phase 2	Phase 3



Belle II Detector Installation

- Barrel Cherenkov particle ID (TOP) installed **May 2016**
- Drift chamber (CDC) installed **October 2016**
- End-cap Cherenkov particle ID (ARICH) integration **August 2017**
- Global Cosmic Run DAQ **July 2017—**
- Vertex detector will be integrated after **phase 2**

Detector integration (2)

2016	2017	2018	2019
Phase 1		Phase 2	Phase 3

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Detector integration (3)

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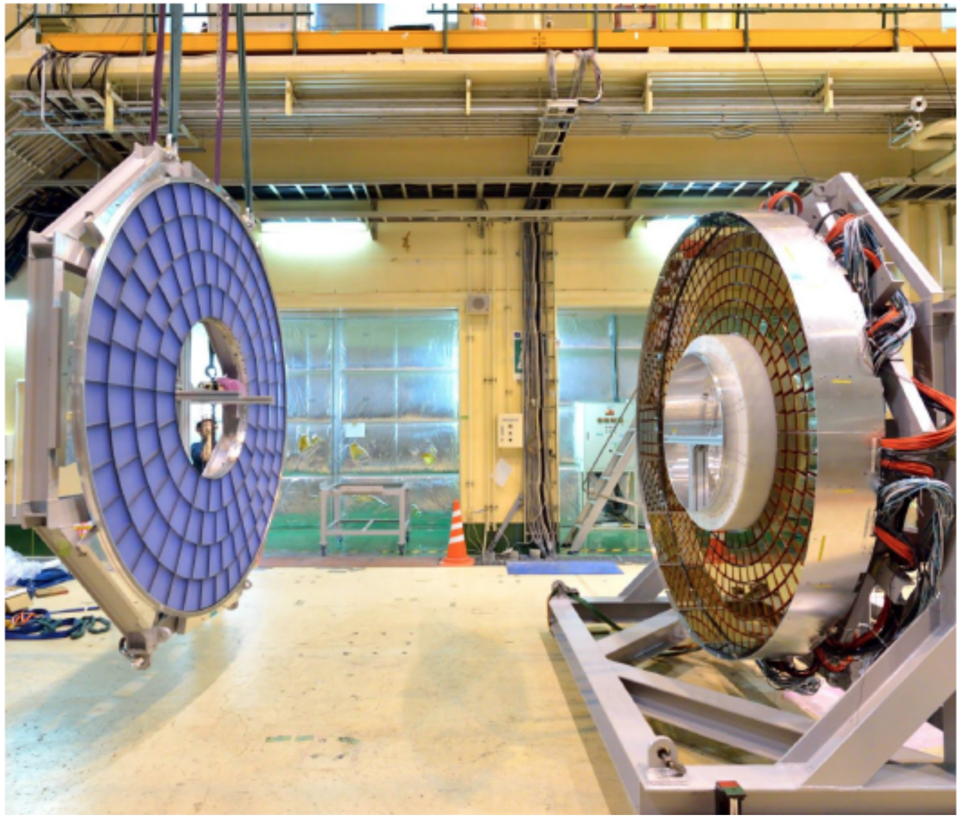

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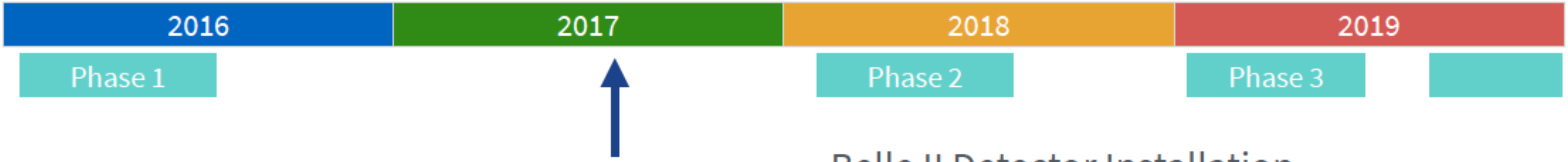
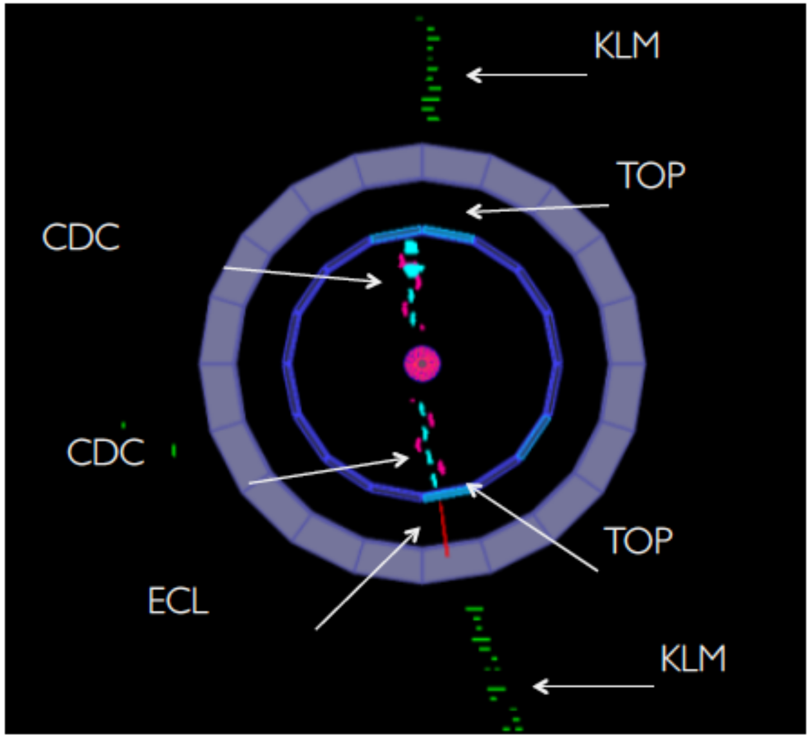
Detector commissioning





Hits in four outer subdetectors

Belle II Detector Installation

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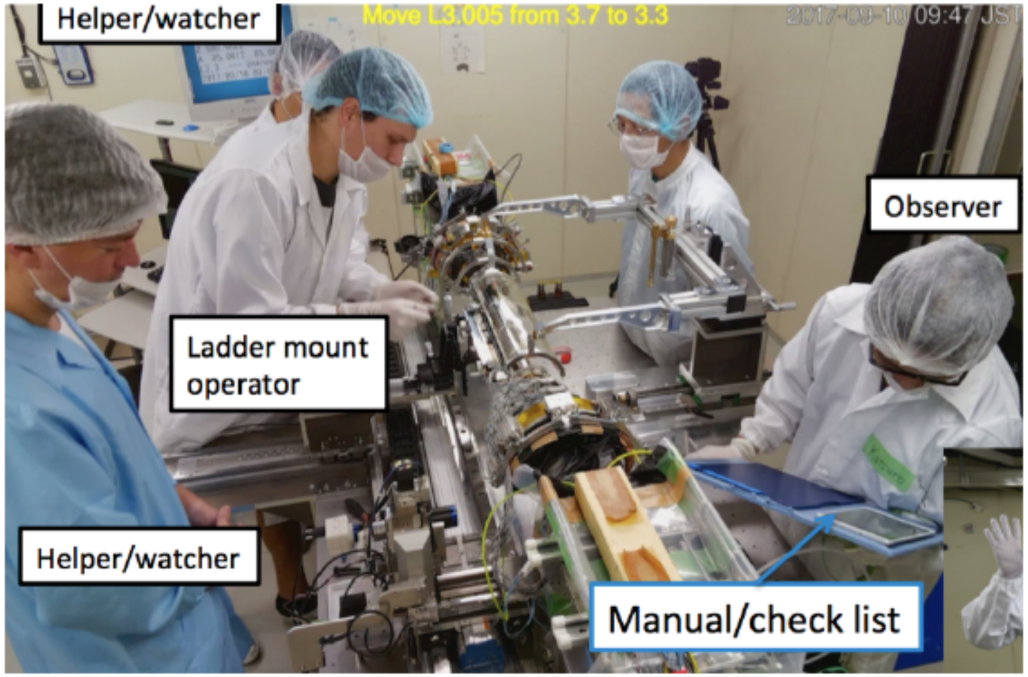
Vertex detector status



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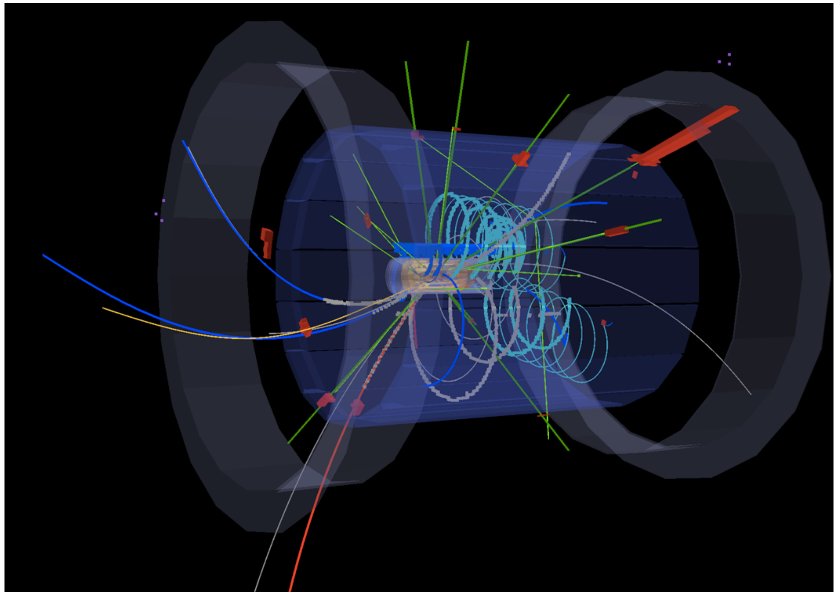
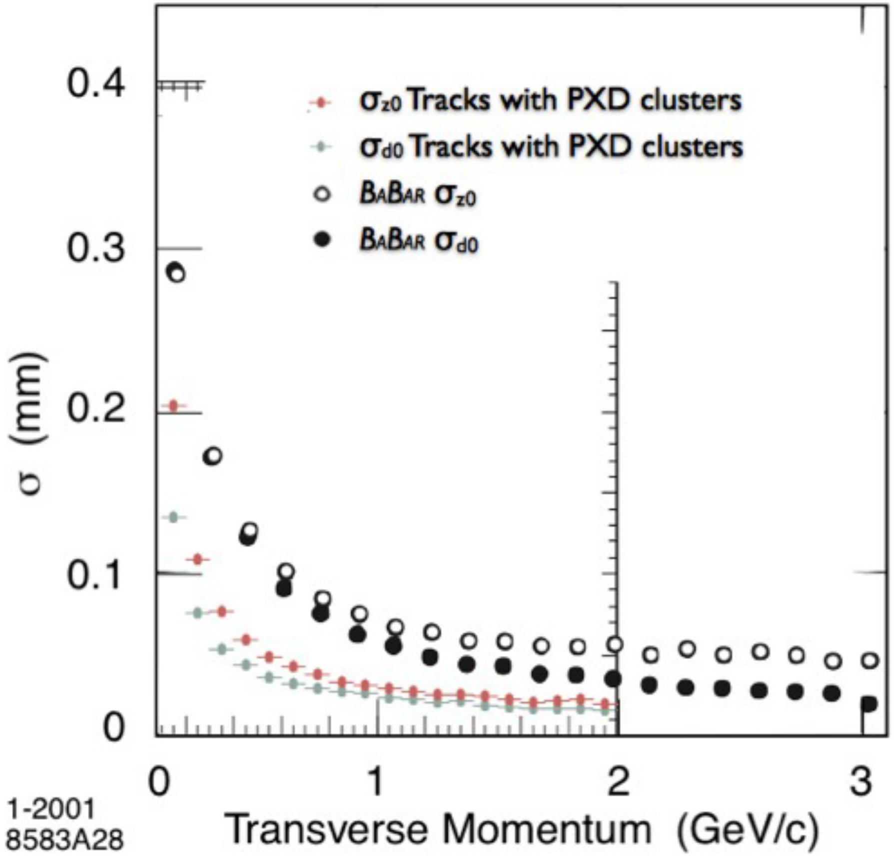
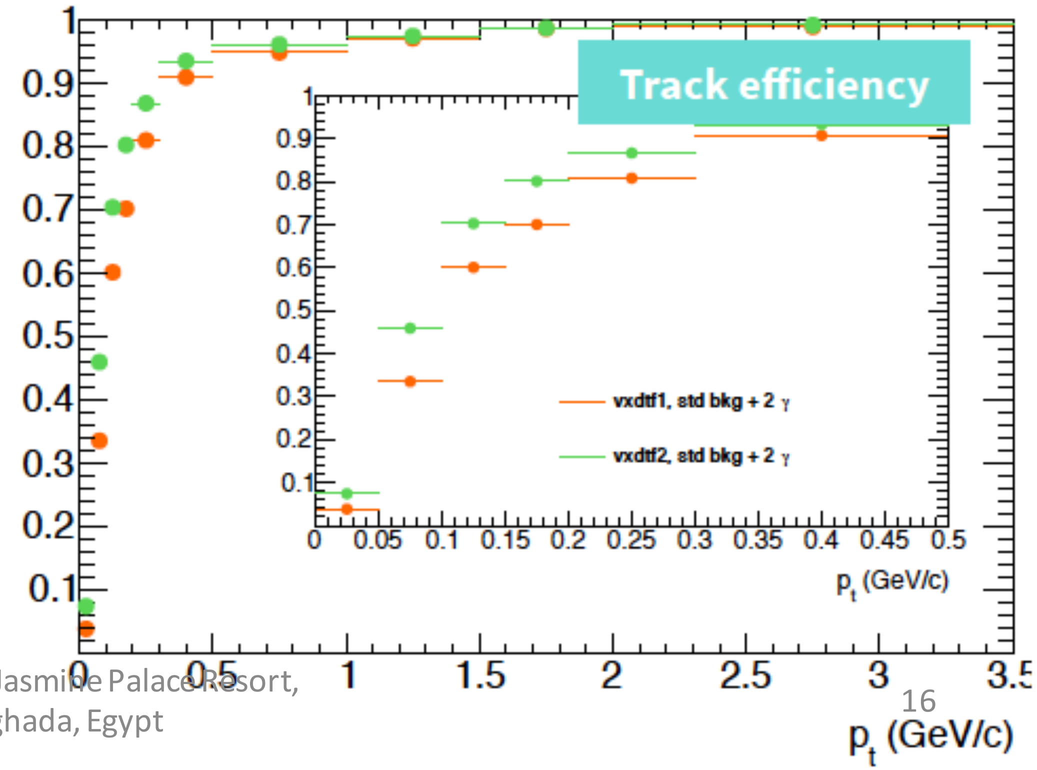
Analysis tools (1)

- Getting ready for experiment.



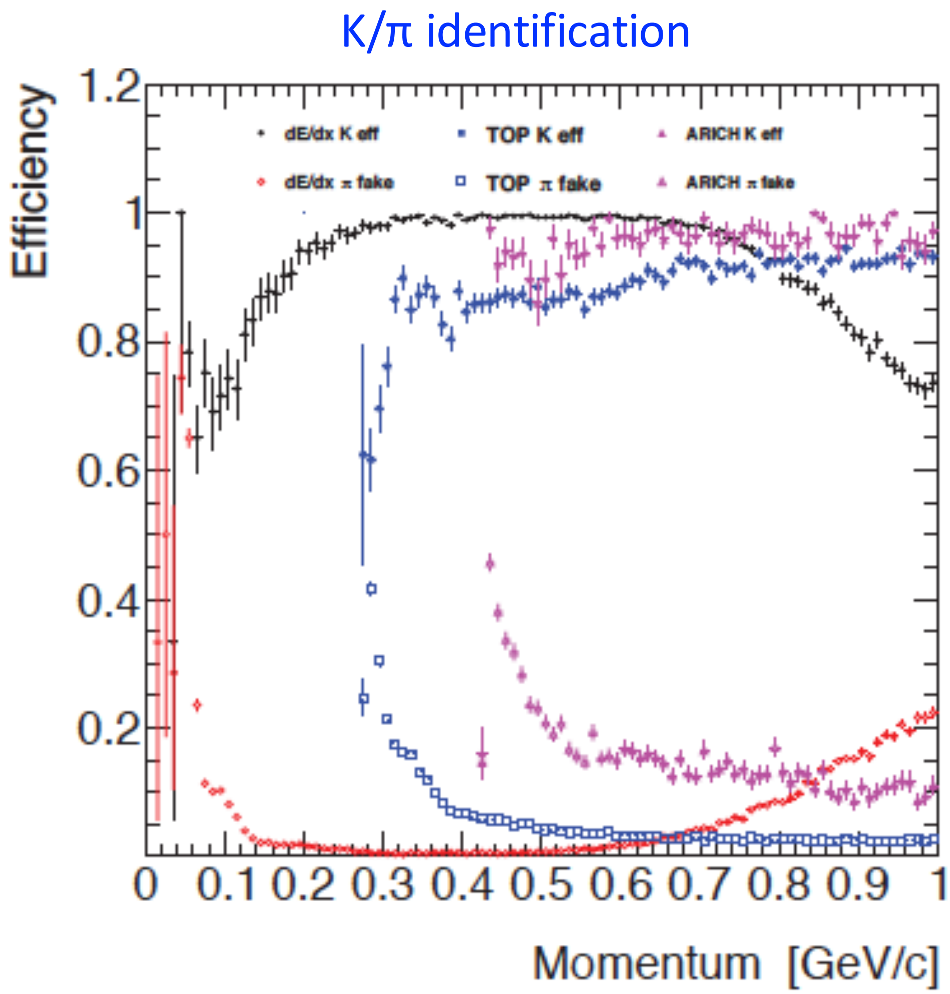
Impact parameter resolution

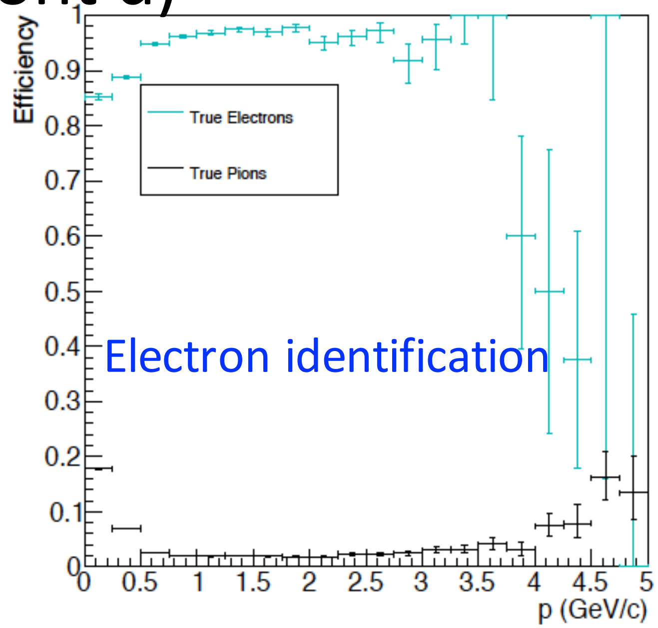


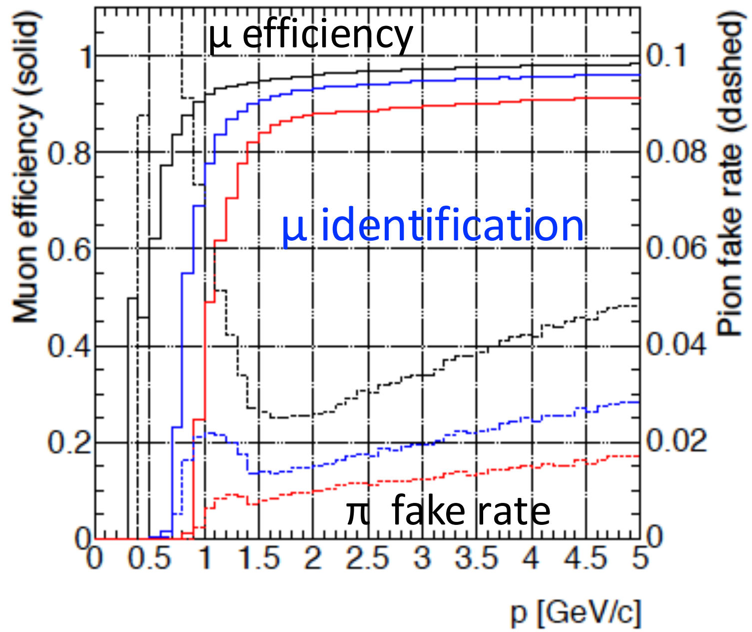


Analysis tools (2)

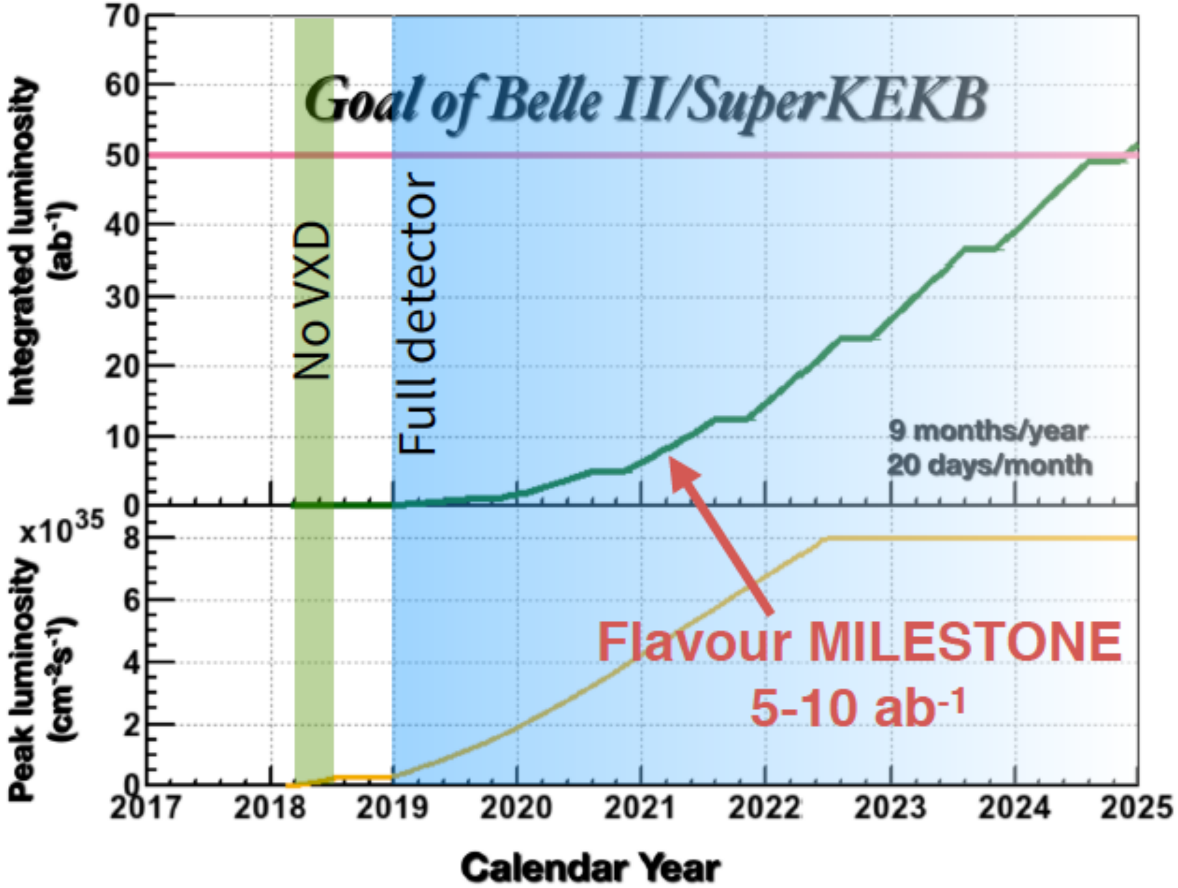
- Getting ready for experiment. (cont'd)







Luminosity projection



Phase 2:
Peak luminosity reaches
1 x 10^{34} cm^{-2}s^{-1} (Belle)
20 fb^{-1} for physics near Υ(4S)

Feb 1, 2018: Global cosmic ray runs.

Feb 23, 2018: First HER beam. Belle II off.

March 2, 2018: First LER beam.

April 2018: First collisions "**Phase 2**"

July 2018: End of commissioning run.

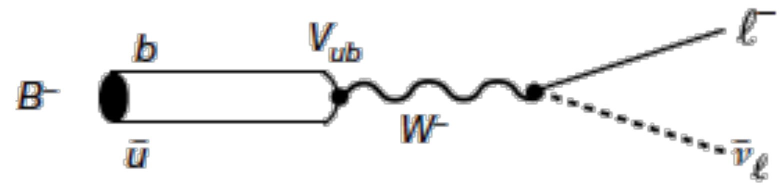
Phase 3:
50 ab^{-1} by 2025
50x Belle, 100x Babar

Early 2019: "**Phase 3**"

Physics prospect

Leptonic and semileptonic B decays (1)

- $B \to \tau\ \nu,\ \mu\ \nu$
  - BF is sensitive to NP.
    - ➢ 4 σ level $B \to \tau\ \nu$ evidences in Belle and BaBar.
    - ➢ Currently consistent with SM.
    - ➢ The uncertainty will be reduced to 5-6% at 50 ab^{-1} in Belle II.
  - Excellent mode to test the Lepton Flavor Universality.



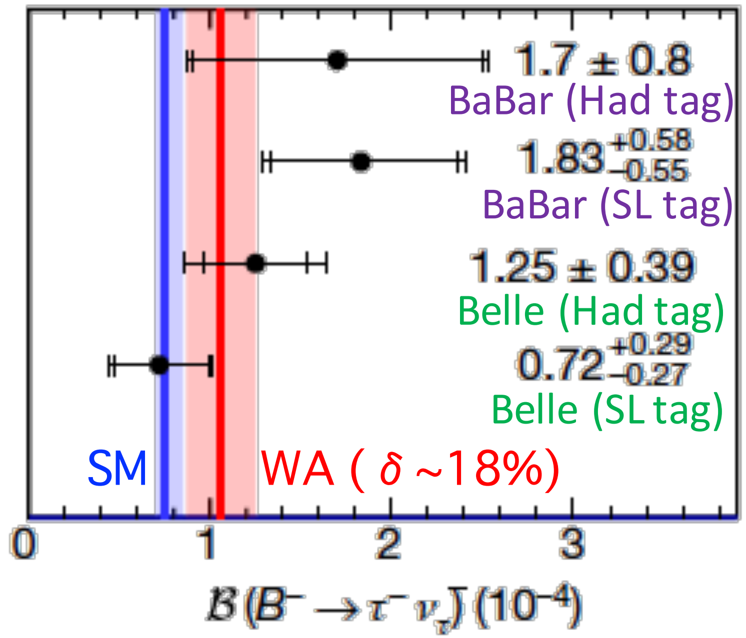
$$\Gamma^{SM}(B^- \to \ell^- \bar{\nu}_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} |V_{ub}|^2 \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2$$

$$\mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)_{NP} = \mathcal{B}(B^- \to \ell^- \bar{\nu}_\ell)_{SM} \times \text{NP}$$

$$\frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)}$$

Evidence is expected at ~2 ab^{-1}.

l	BF_{SM}	BF_{Exp} (WA)
τ	$(7.71 \pm 0.62) \times 10^{-5}$	$(1.06 \pm 0.19) \times 10^{-4}$
μ	$(3.46 \pm 0.28) \times 10^{-7}$	$< 1.0 \times 10^{-4}$
e	$(0.811 \pm 0.065) \times 10^{-11}$	$< 0.98 \times 10^{-4}$



Nature 22346

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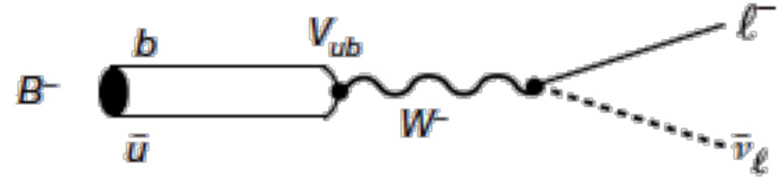
    - Currently consistent with SM.
    - The uncertainty will be reduced to 5-6% at 50 ab^{-1} in Belle II.
  - Excellent mode to test the Lepton Flavor Universality.
  - If no NP, can extract $|V_{ub}|$.
    - Independent from $b \to ul\nu$.



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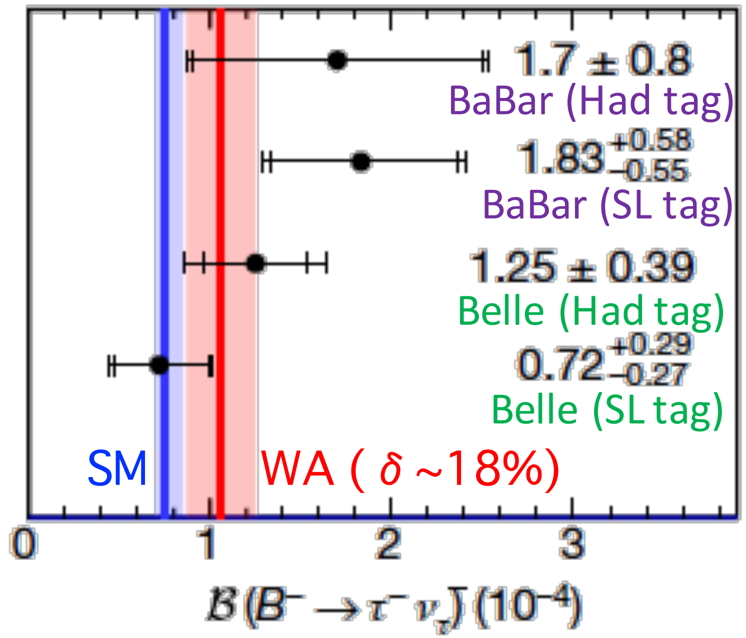
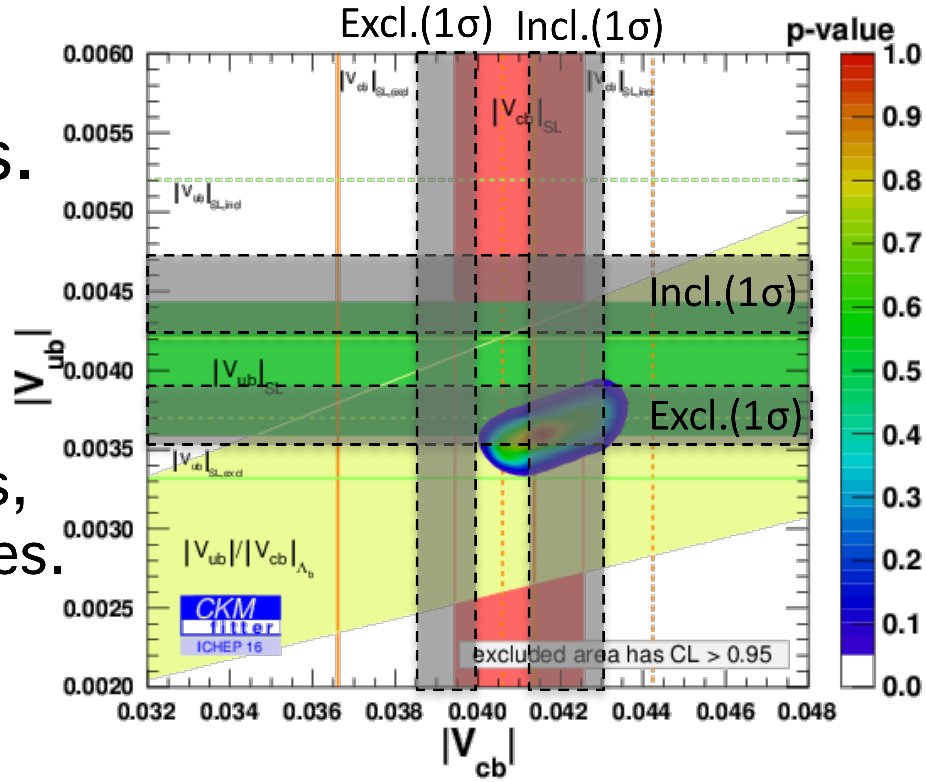


Nature 22346

Leptonic and semileptonic B decays (2)

- $b \to u l \nu$, $c l \nu$ ($l = \mu, e$)
  - $|V_{ub}|$ and $|V_{cb}|$ determinations.
    - ➢ Using incl. and excl. final states.
    - ➢ $\delta|V_{ub}| \sim 5\%$, $\delta|V_{cb}| \sim 2\%$.
    - ➢ Large $X_c l \nu$ BG in $X_u l \nu$ mode.
    - ➢ QCD predictions for form factors, inclusive processes, quark masses.
  - Tension: incl. vs excl. meas.
    - ➢ $|V_{ub}|$: $X_u l \nu$ vs $\pi l \nu$
    - ➢ $|V_{cb}|$: $X_c l \nu$ vs $D^{(*)} l \nu$



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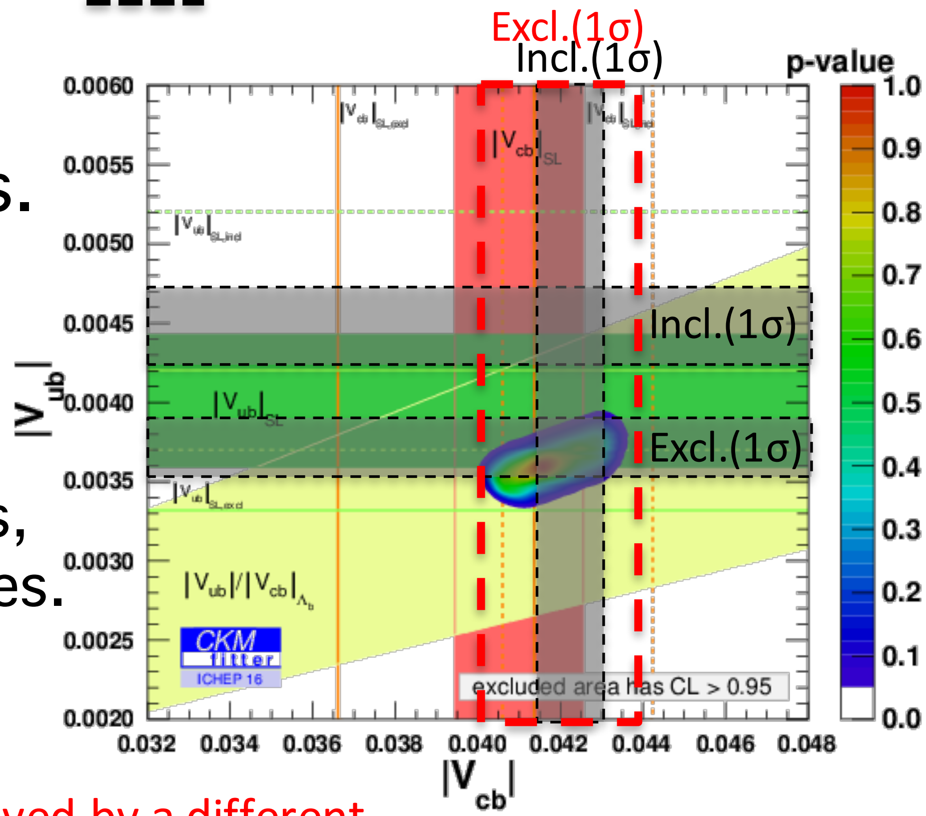
    - $|V_{ub}|$: $X_u l \nu$ vs $\pi l \nu$
    - $|V_{cb}|$: $X_c l \nu$ vs $D^{(*)} l \nu$

Seems to be solved by a different form factor parameterization.

  - Major effort with much higher statistics at Belle II is required to improve the precisions.
    - More detailed BG decomposition.
    - Further progress in QCD calc.



$B \to \pi l \nu$ full simulation

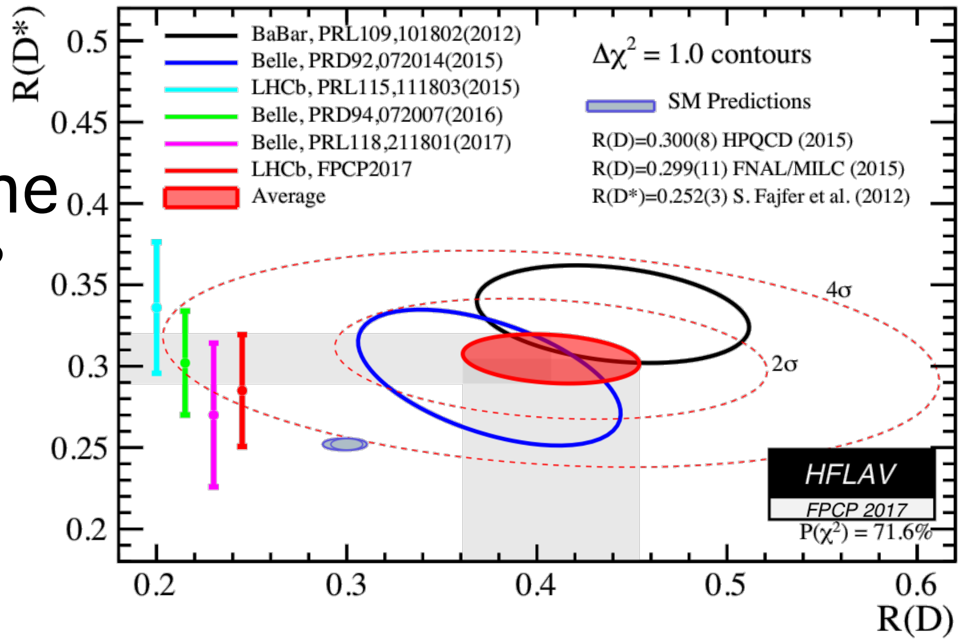
$\mathcal{L}$ [ab^{-1}]		σ_B (stat$\pm$sys)	$\sigma^{forecast}_{LQCD}$	$\sigma_{V_{ub}}$
1	tagged	3.6 ± 4.4	current	6.2
	untagged	1.3 ± 3.6		3.6
5		1.6 ± 2.7	in 5 yrs	3.2
		0.6 ± 2.2		2.1
10		1.2 ± 2.4	in 5 yrs	2.7
		0.4 ± 1.9		1.9
50		0.5 ± 2.1	in 10 yrs	1.7
		0.2 ± 1.7		1.3

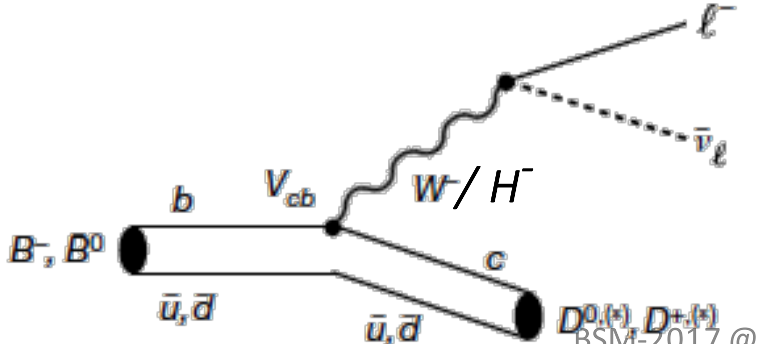
Leptonic and semileptonic B decays (3)

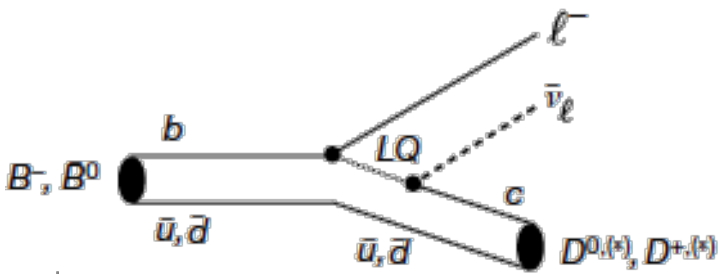
- B→D$^{(*)}$ τ ν
  – R(D$^{(*)}$) measurements show deviations from the SM.
    - ➢ Combined result is 4.1 σ away from the SM.
  – Hint of NP which violates the Lepton Flavor Universality?
    - ➢ Charged Higgs, leptoquark, ⋯

$$R(D^{(*)}) \equiv \frac{\Gamma(B \to \bar{D}^{(*)}\tau^{+}\nu_{\tau})}{\Gamma(B \to \bar{D}^{(*)}\ell^{+}\nu_{\ell})}$$

l = e, μ







Leptonic and semileptonic B decays (3)

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  - $R(D^{(*)})$ measurements show deviations from the SM.
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    - Charged Higgs, leptoquark, ⋯
  - The uncertainties will be reduced to 2-3% at 50 ab^{-1} in Belle II.

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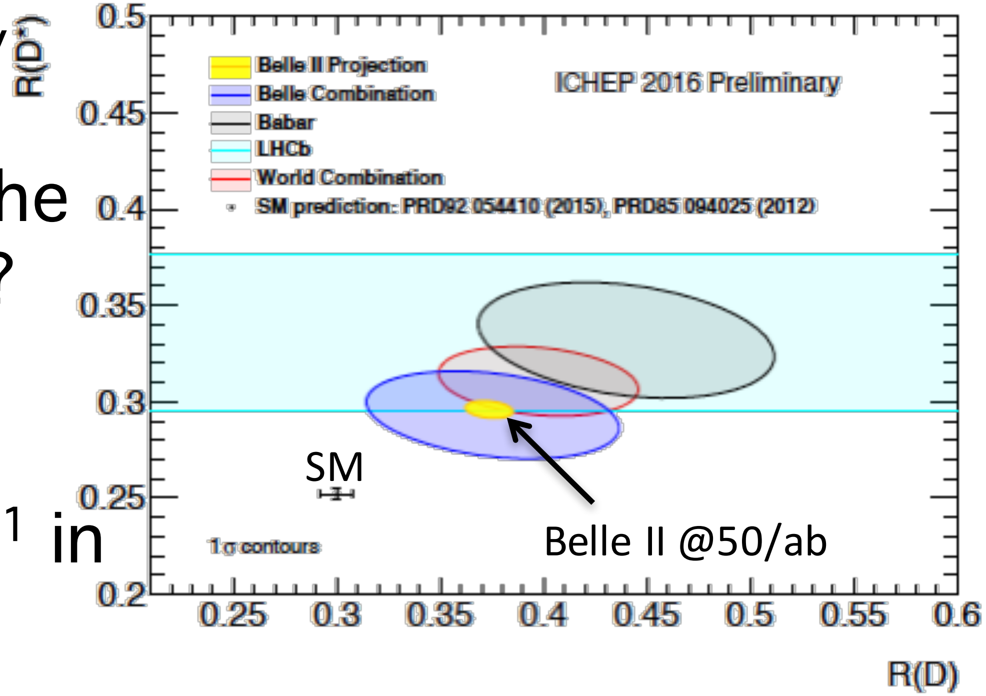
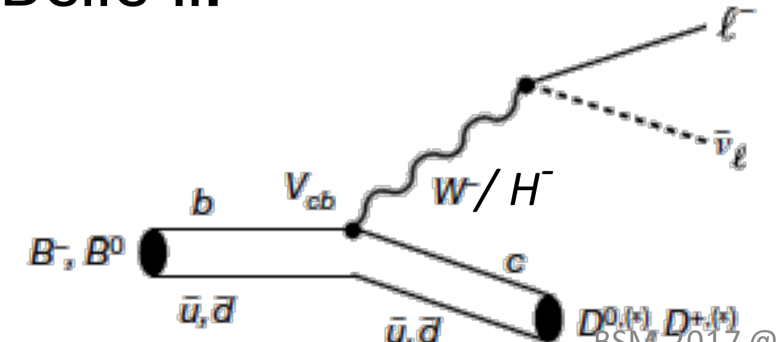
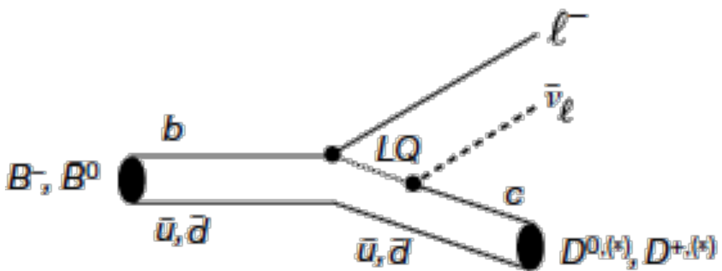
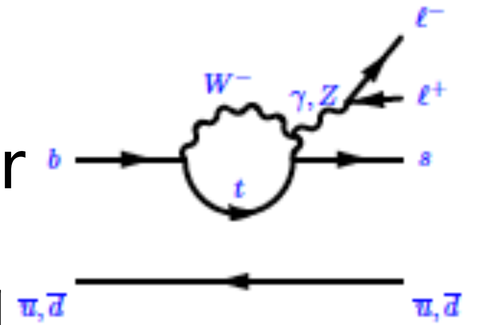


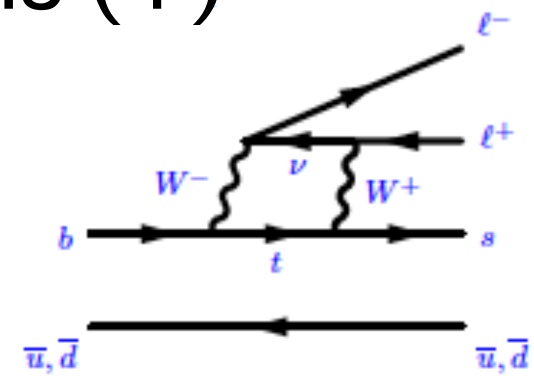




EW penguin b→s transitions (1)

- B→K$^{(*)}$ll (l = μ, e)
  - Test on the Lepton Flavor Universality: R(K$^{(*)}$).

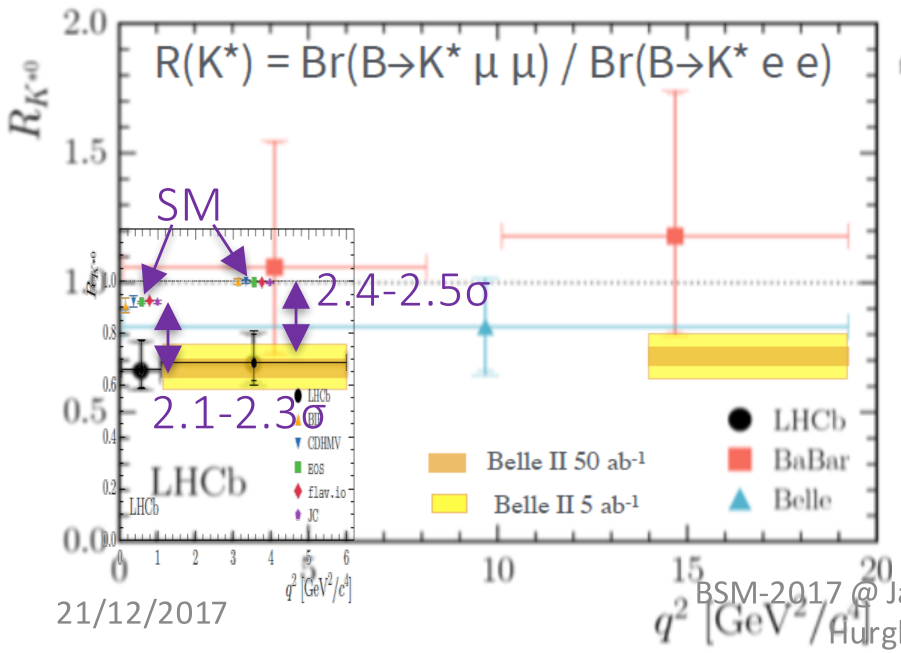


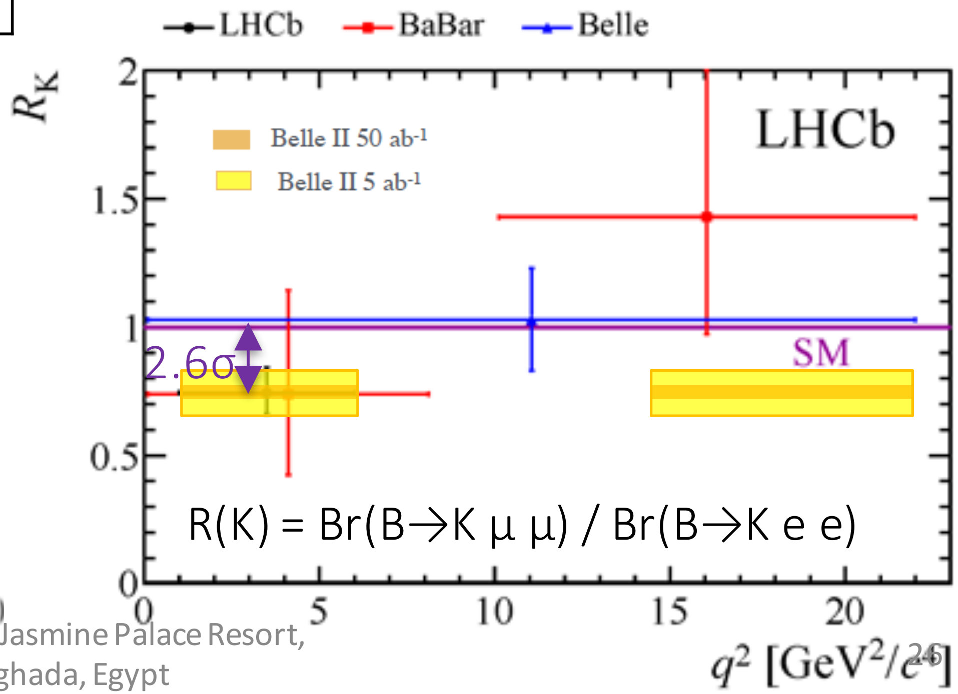


	q² range [GeV²/c⁴]	Belle 0.71/ab	Belle II 5/ab	Belle II 50/ab
R(K*)	1 – 6	26%	10%	3.2%
R(K*)	> 14.4	24%	9.2%	2.8%
R(K)	1 – 6	28%	11%	3.6%
R(K)	> 14.4	30%	12%	3.6%

$R(K^*) = Br(B^0 \to K^{*0} \mu^+ \mu^-)/Br(B^0 \to K^{*0} e^+ e^-)$

$R(K) = Br(B^+ \to K^+ \mu^+ \mu^-)/Br(B^+ \to K^+ e^+ e^-)$

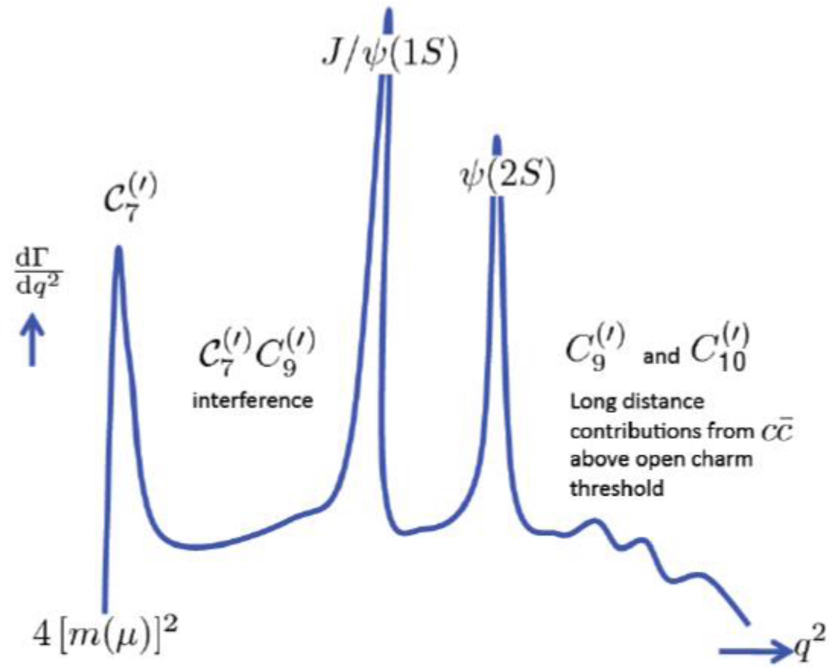




EW penguin b→s transitions (2)

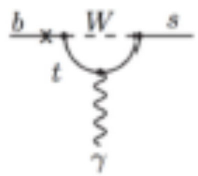
- B→$K^{(*)}$ll (l = μ, e)
  - The Angular distribution can be expressed in terms of helicity amplitudes that depend on
    - di-lepton invariant mass squared (q^2),
    - Wilson coefficients C_7, C_9, C_{10}, → Probe to NP contribution
    - B→K^* form factors.

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i (\underbrace{C_i \mathcal{O}_i}_{\text{left-handed part}} + \underbrace{C_i' \mathcal{O}_i'}_{\text{right-handed part suppressed in SM}})$$

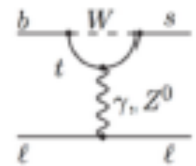


C_i: Wilson coefficients (short distance effect)
O_i: Operators (depend on hadronic form factors)

i=7 photon



i=9 vector current
i=10 axial-vector current

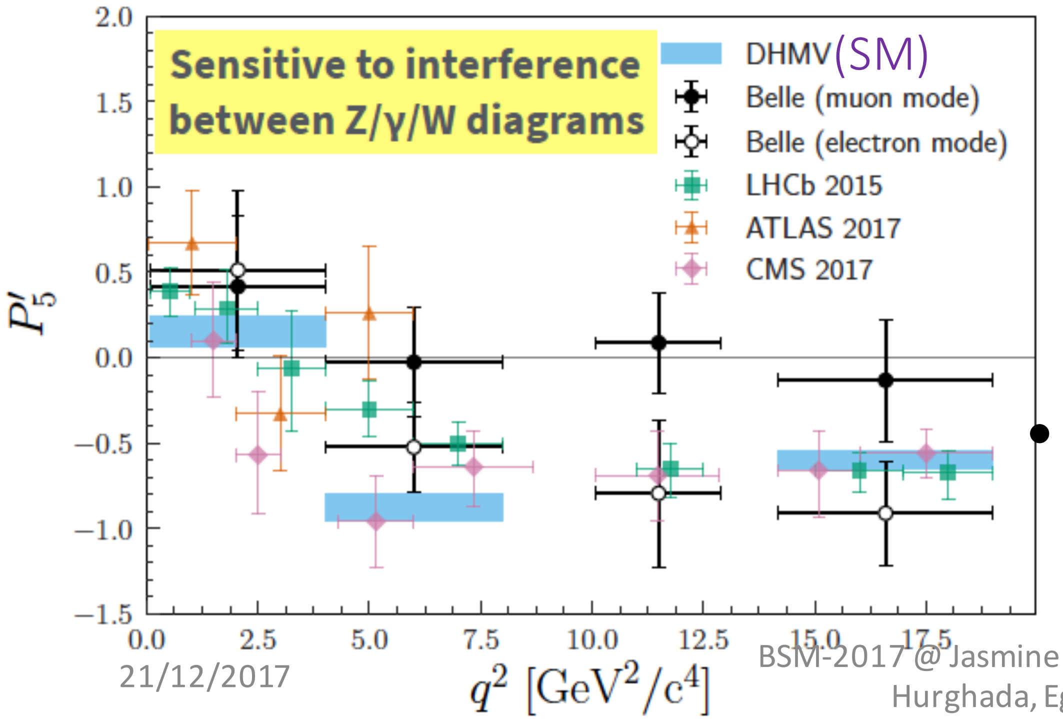


EW penguin b→s transitions (2)

- $B \to K^{(*)} ll$ ($l = \mu$, e)
  - Test on the anomaly in the $B \to K^* ll$ angular analysis: P'_5.
    - ➢ Insensitive to form factors.
    - ➢ LHCb meas. shows 3.3 σ to SM.
    - ➢ Consistent with the Belle meas.

$$P'_5 = \sqrt{2}\frac{\mathrm{Re}\left(A_0^L A_\perp^{L*} - A_0^R A_\perp^{R*}\right)}{\sqrt{\left(|A_0^L|^2 + |A_0^R|^2\right)\left(|A_\parallel^L|^2 + |A_\parallel^R|^2 + |A_\perp^L|^2 + |A_\perp^R|^2\right)}}$$

$A_{0,\parallel,\perp}^{L,R}$: decay amplitudes for different
- K^{*0} transversity states (subscript),
- di-lepton chiralities (superscript).



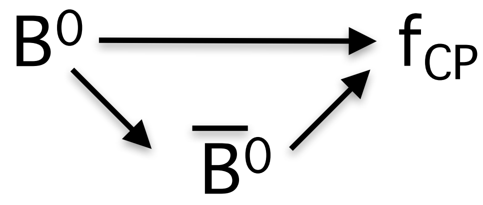
q^2 range [GeV^2/c^4]	Belle 0.71/ab	Belle II 5/ab	Belle II 50/ab
1 – 2.5	0.47	0.17	0.054
2.5 – 4	0.42	0.15	0.049
4 – 6	0.34	0.12	0.040
> 14.2	0.23	0.088	0.027

36-38% 11-12%

- Belle II also has access to
  - $B \to K^{(*)} \tau^+ \tau^-$, $B \to K^{(*)} \bar{\nu} \nu$.

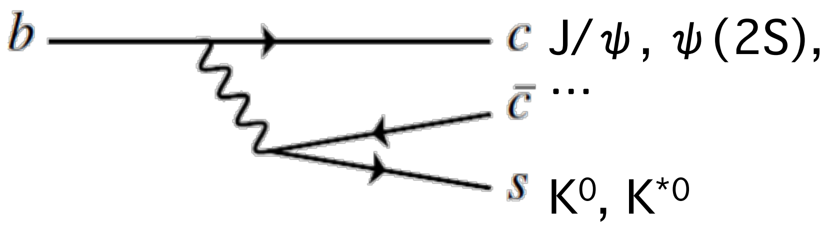
QCD penguin b→s transitions (1)

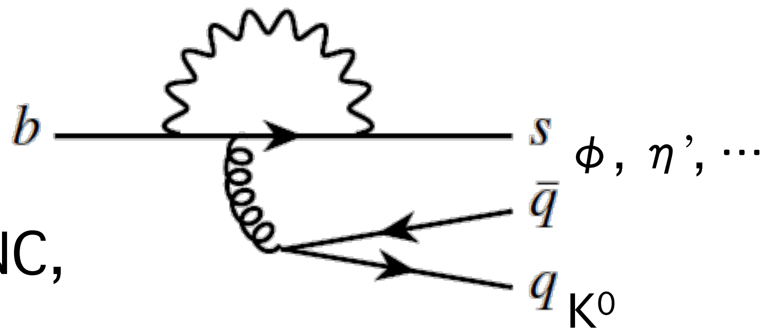
- Indirect CPV (ICPV) in $b \to s\bar{q}q$
  - ICPV: interference between the non-mixed and mixed decays to a CP eigenstate.
    - ➢ Giving a time-dependent CP asymmetry ($A(\Delta t)$).
  - For the tree-dominant $b \to c\bar{c}s$ transitions,
    - ➢ $S = -\eta_f \sin 2\phi_1$, $C = 0$,
    - ➢ η_f: CP eigenvalue of the final state.
  - For the penguin-dominant $b \to s\bar{q}q$ transitions,
    - ➢ Same as $b \to c\bar{c}s$ in SM.
    - ➢ If NP exists through the loop of FCNC, the S and C terms may change.



$$\mathcal{A}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)}$$
$$= S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t)$$

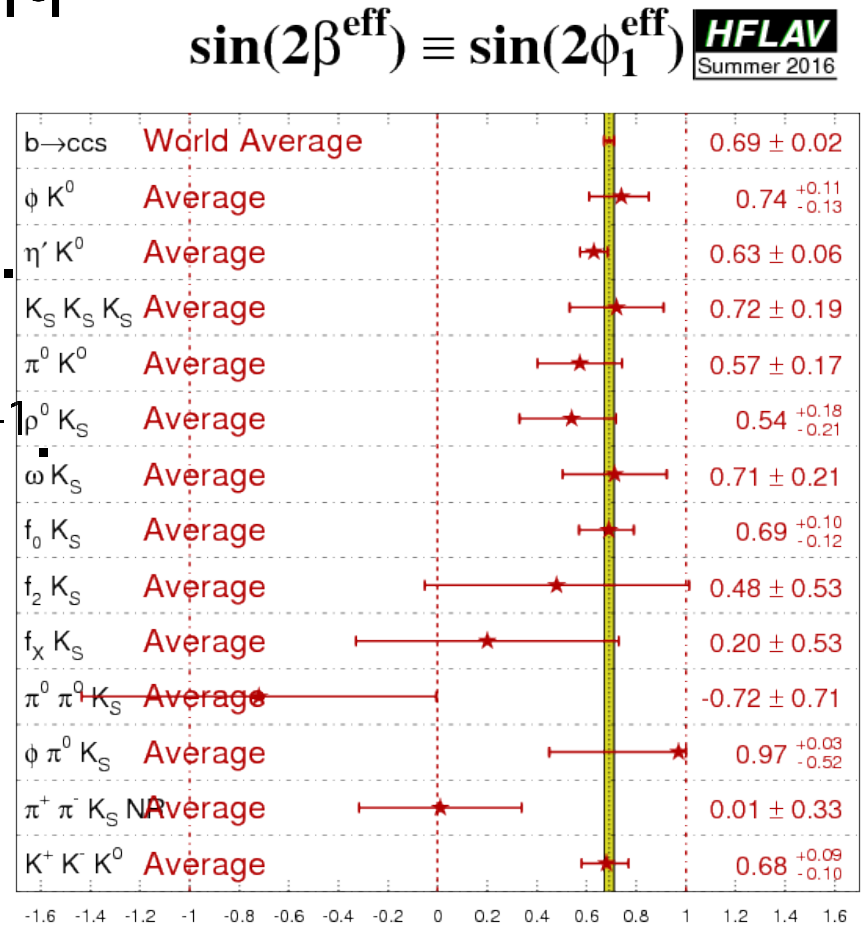
Δt: decay time difference between B^0 and $\bar{B}^0$





QCD penguin b→s transitions (2)

- Indirect CPV (ICPV) in $b\to s\bar{q}q$ (cont'd)
  - Currently $b\to s\bar{q}q$ show consistent results with $b\to c\bar{c}s$.
  - The uncertainties (δ) will be reduced significantly at 50 ab^{-1}.
    - ➢ $b\to c\bar{c}s$: to 20-25% of present δ , systematics limited.
    - ➢ $b\to sqq$: to ~15% of present δ , mostly scaled to the luminosity.
    - ➢ Both are theoretically clean.
  - Will probe NP through the precision meas. on $\sin 2\phi_1$.



QCD penguin b→s transitions (3)

- Direct CPV (DCPV) in B→Kπ
  - DCPV: interference between amplitudes to a final state.
    - Giving a time-integrated CP asymmetry (A_{CP}).

$$A_{\mathrm{CP}}(B \to f) \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

$= -C$ for $f = f_{CP}$

QCD penguin b→s transitions (3)

- Direct CPV (DCPV) in $B \to K\pi$
  - DCPV: interference between amplitudes to a final state.
    - ➢ Giving a time-integrated CP asymmetry (A_{CP}).
  - Non-negligible contributions from several diagrams.
    - ➢ Because of suppressed charmless $b \to u$, s transitions.
  - A sum rule of A_{CP} was proposed.
    - ➢ Applying the isospin symmetry to the leading contributions.
    - ➢ Violation could be NP in $b \to s\bar{q}q$.

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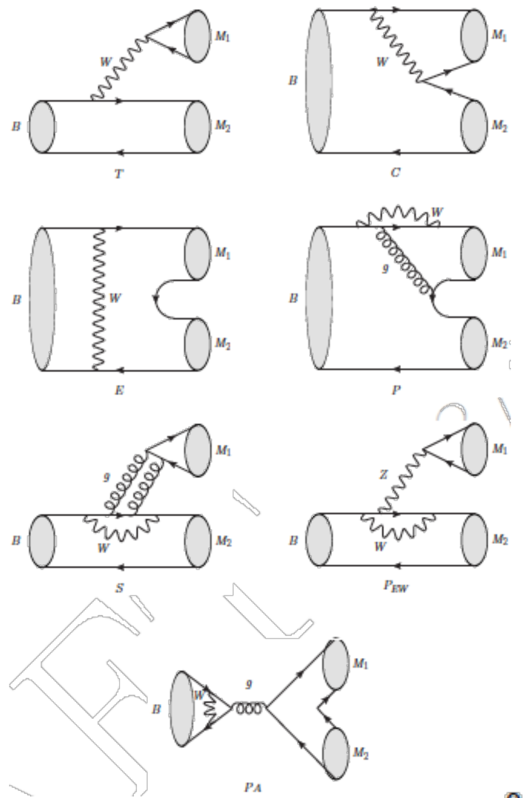
$$A_{CP}(B \to f) \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

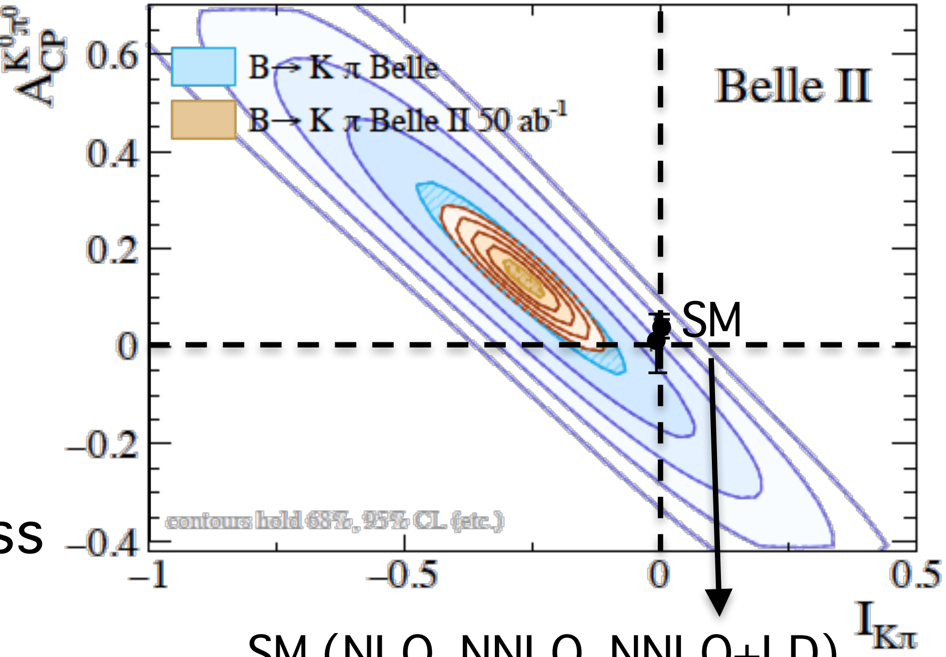
$$= -C \text{ for } f = f_{CP}$$



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

QCD penguin $b \to s$ transitions (3)

- Direct CPV (DCPV) in $B \to K\pi$
  - DCPV: interference between amplitudes to a final state.
    - ➢ Giving a time-integrated CP asymmetry (A_{CP}).
  - Non-negligible contributions from several diagrams.
    - ➢ Because of suppressed charmless $b \to u$, s transitions.
  - A sum rule of A_{CP} was proposed.
    - ➢ Applying the isospin symmetry to the leading contributions.
    - ➢ Violation could be NP in $b \to s\bar{q}q$.
  - Important to systematically study all $K\pi$ modes with high precision in Belle II.

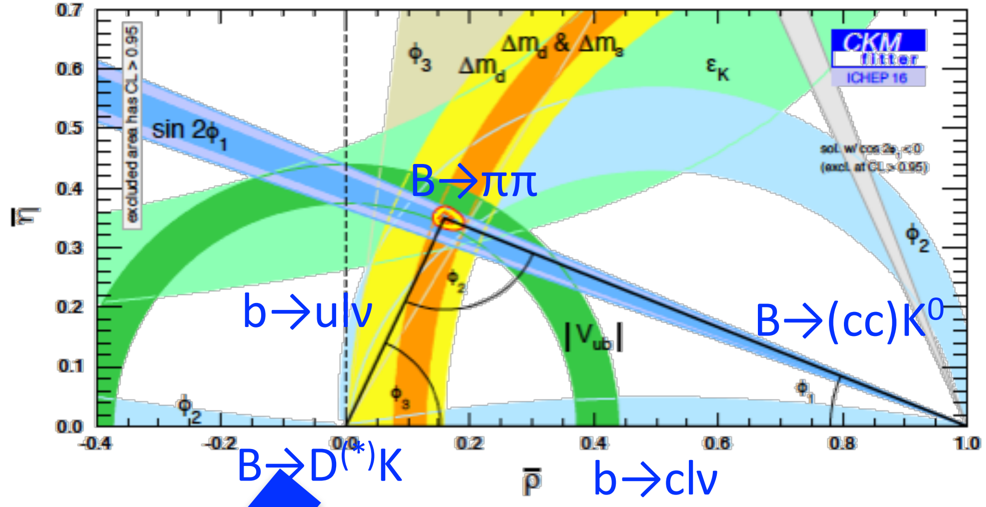


SM (NLO, NNLO, NNLO+LD)
Phys. Lett. B 627, 82 (2005)

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

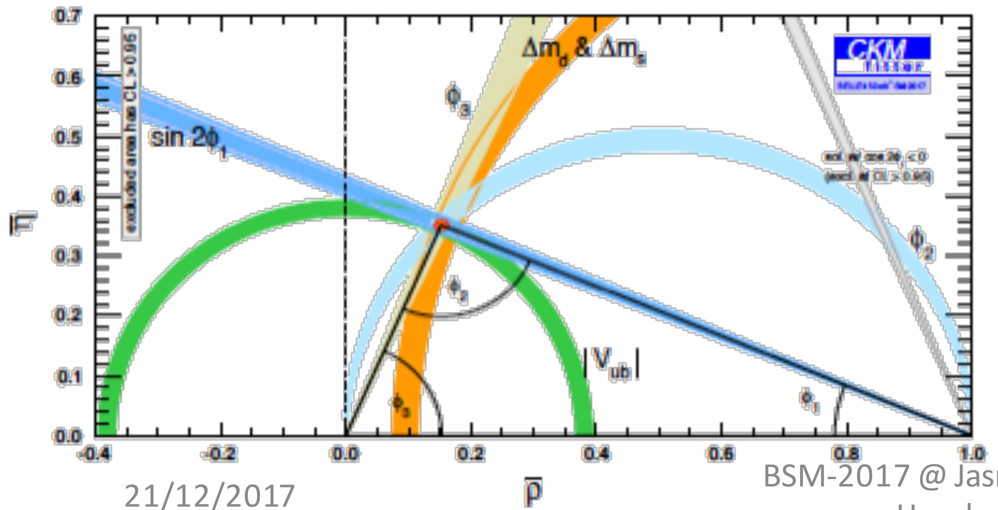
Prospect on Unitarity Triangle

Present



For a SM-like scenario

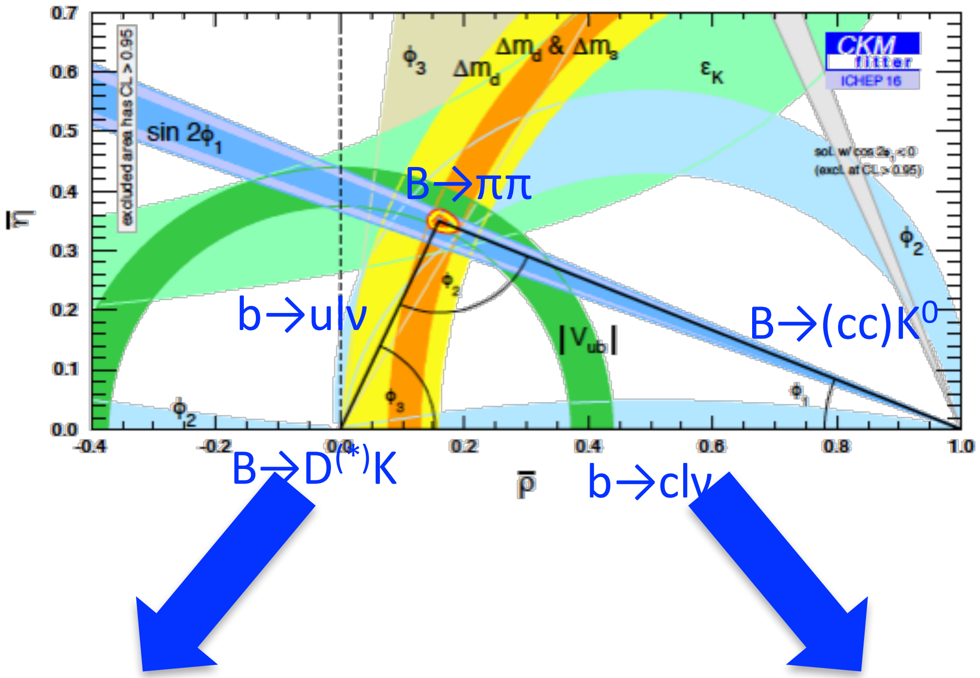
Belle II @ 50 ab^{-1}



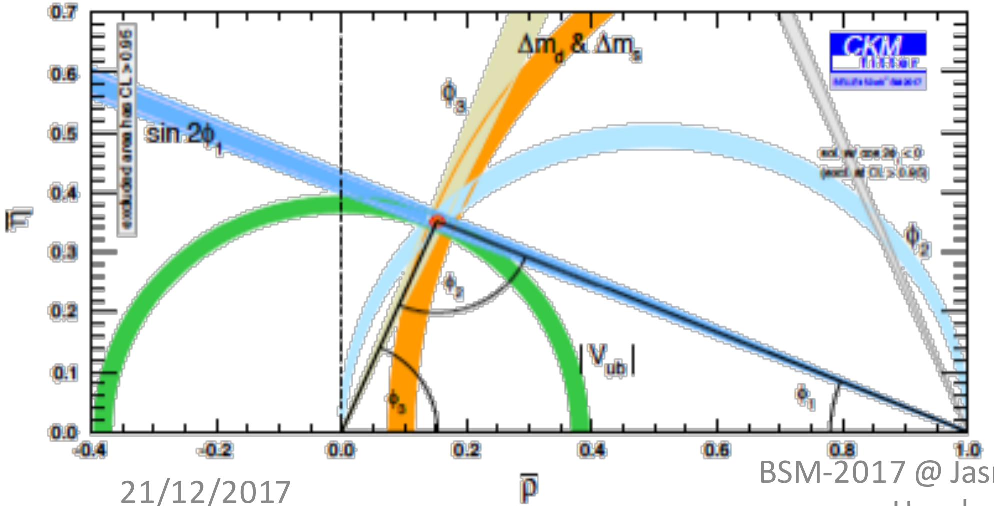
Observable	Uncertainty
ϕ_1 [deg.]	0.4
ϕ_2 [deg.]	1.0
ϕ_3 [deg.]	1.0 (w/ LHCb)
$\|V_{cb}\|$ incl.	1%
$\|V_{cb}\|$ excl.	1.5%
$\|V_{ub}\|$ incl.	3%
$\|V_{ub}\|$ excl.	1.5%

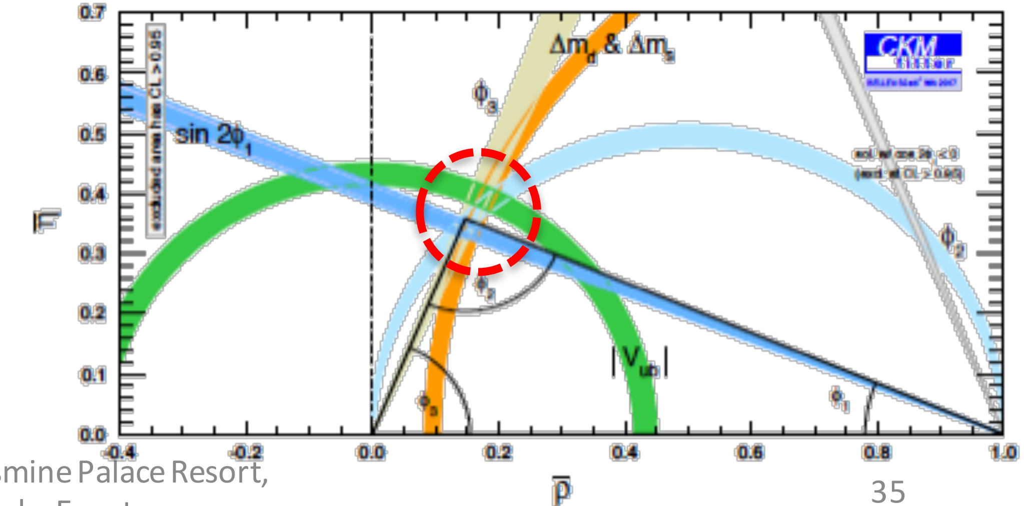
Prospect on Unitarity Triangle

Present



For a SM-like scenario   Belle II @ 50 ab^{-1} If the current WAs hold

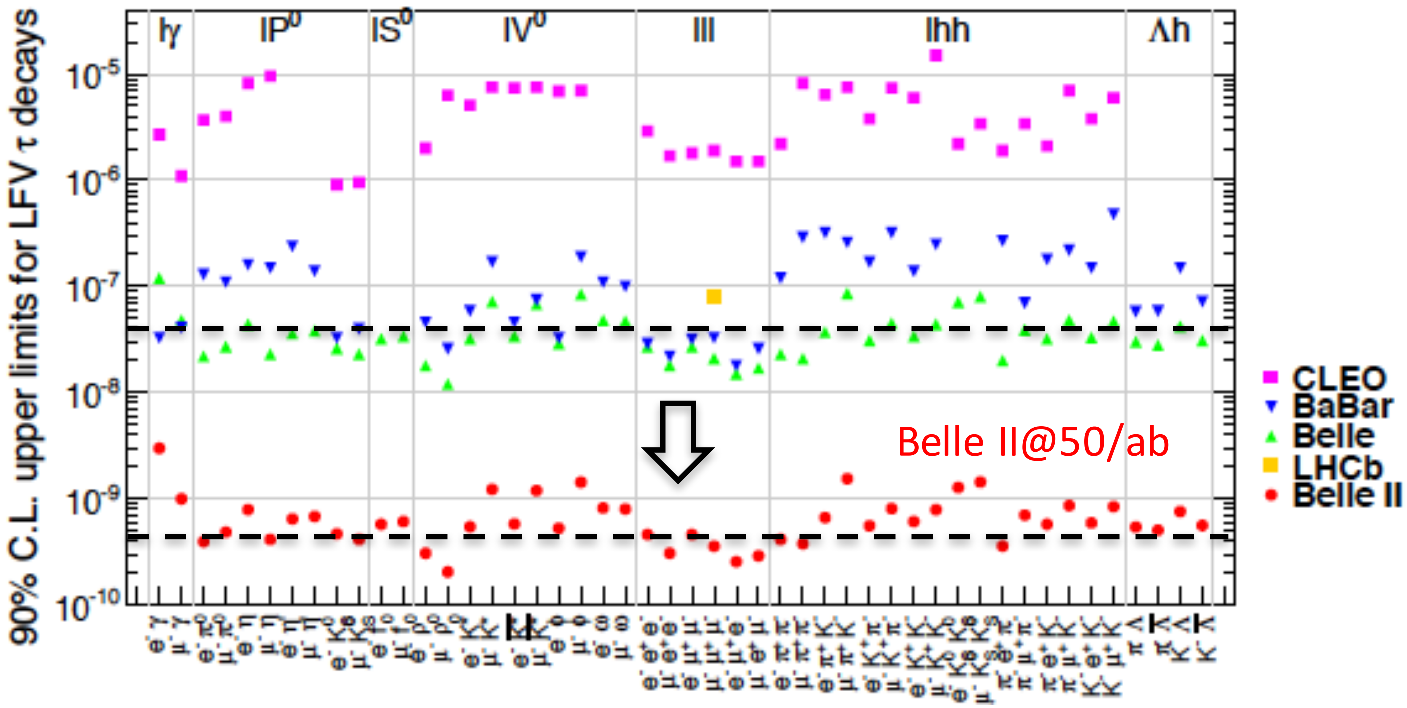




Non-B physics

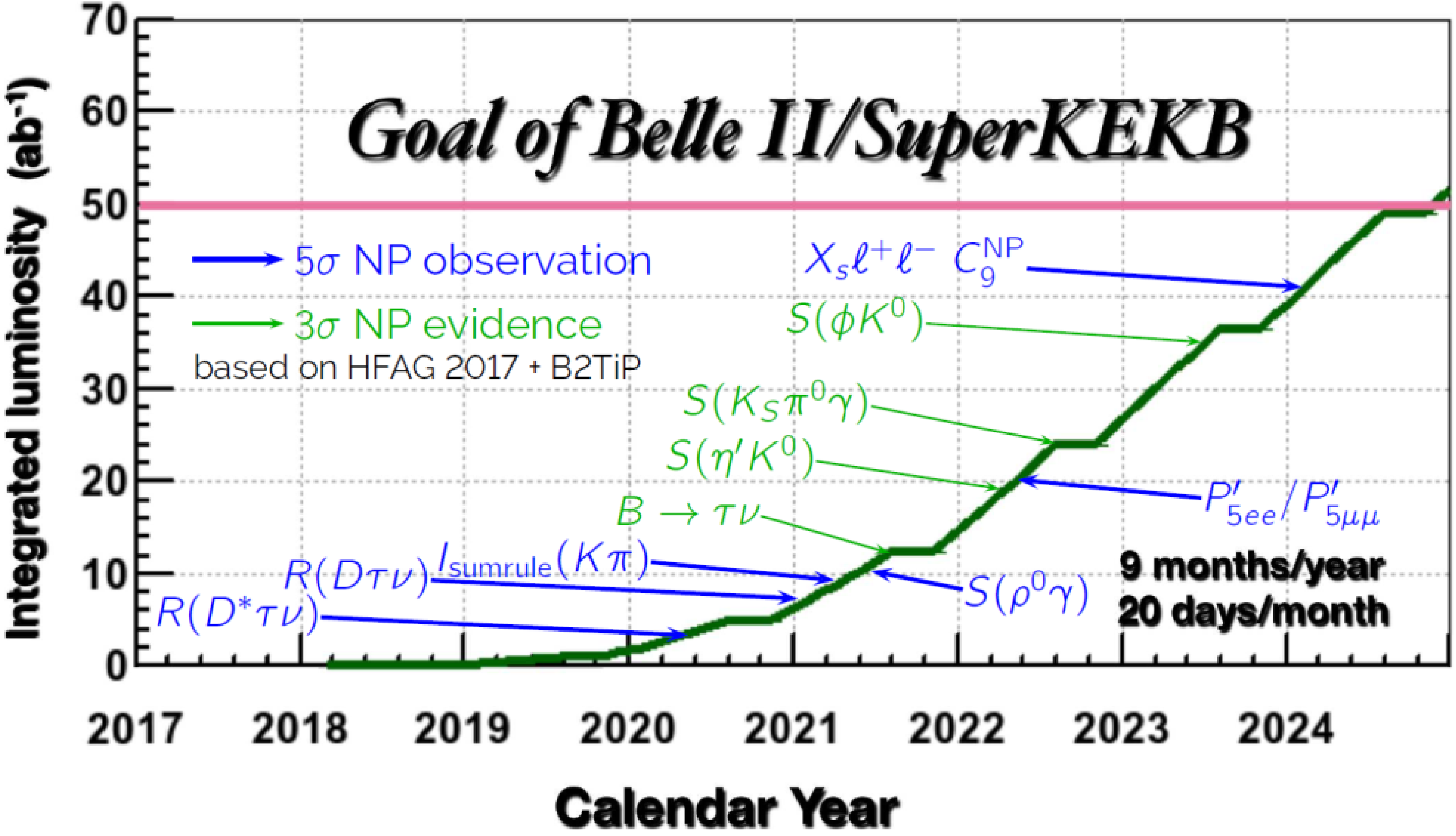
- Various decays will be used
  - to probe new physics beyond SM,
  - to have significant progress in flavor physics.
  - τ decays, charm decays, dark sectors, quarkonium(-like)/exotic states, ⋯

Lepton flavor violation in τ decays



"The Belle II Physics Book": https://confluence.desy.de/display/BI/B2TiP+ReportStatus

Future prospect



Summary

- SuperKEKB and Belle II are in the final integration and commissioning phase.
  - The detector systems, except the vertex detectors, have been in commissioning with cosmic rays.
  - The "Phase 2" commissioning will start in early 2018.
- Belle II will search for new physics beyond the SM in the flavor sector at the intensity frontier.
  - W-exchanging process with τ,
  - One loop FCNC processes,
  - Over-constraining the Unitarity Triangle.
- The physics prospects at Belle II indicate exciting future.
  - New physics hunting,
  - Significant progress in flavor physics.