# Physics Prospects at Belle II

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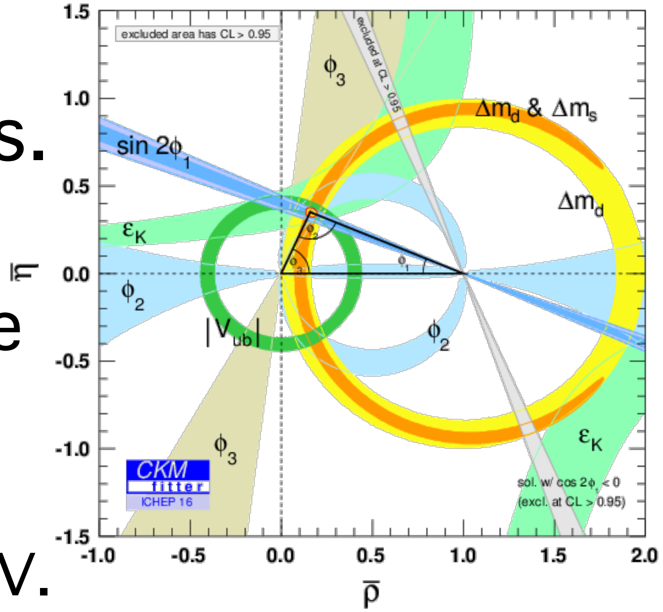
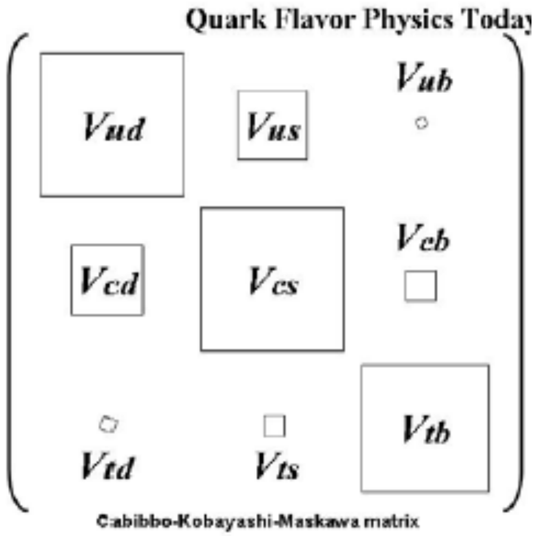
On behalf of the Belle II Collaboration

# 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.



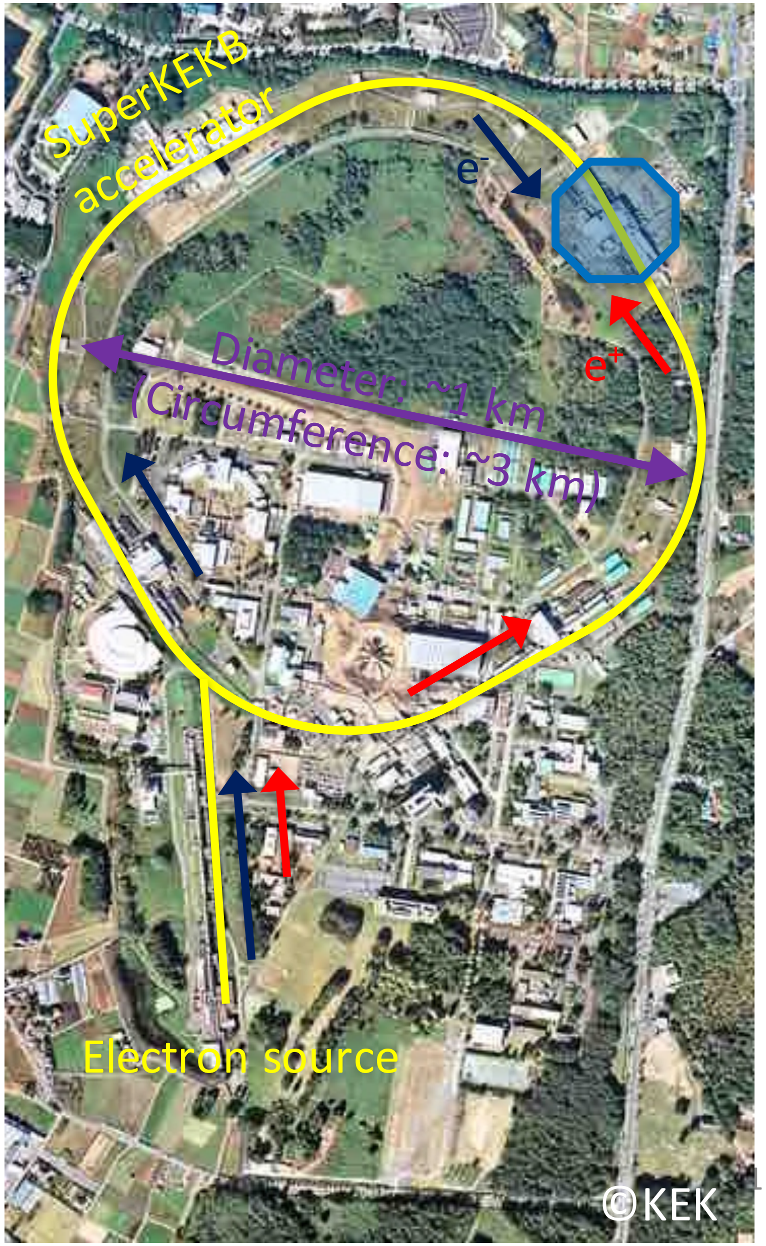

Belle II will search for new physics (NP) in the flavor sector at the intensity frontier.

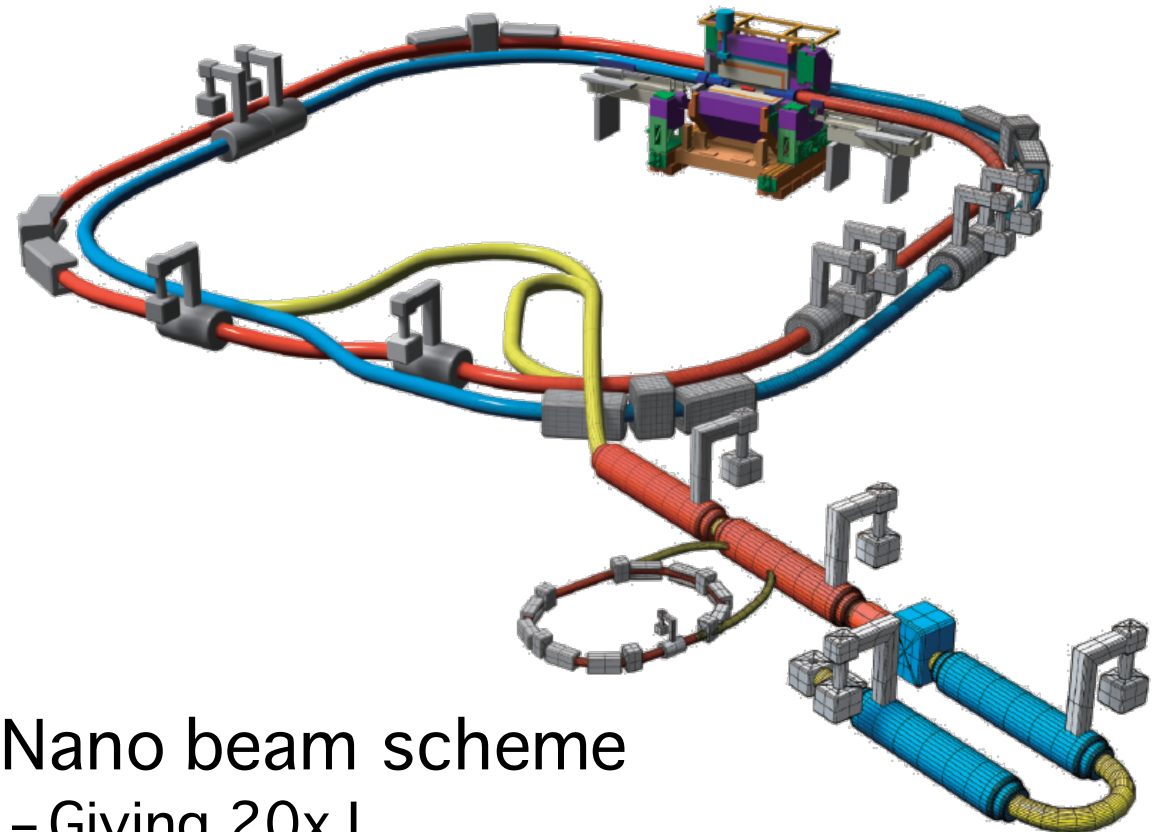
# Experimental strategy

- Upgrade the accelerator and detector.
  - Luminosity: L = $8 \times 10^{35}$ $cm^{-2}s^{-1}$ (40x Belle).
    - Intending to accumulate ∫ Ldt ~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 $\tau$.
  - Through quantum loop processes of Flavor Changing Neutral Current (FCNC).
  - Over-constraining the Unitary Triangle.

# SuperKEKB accelerator

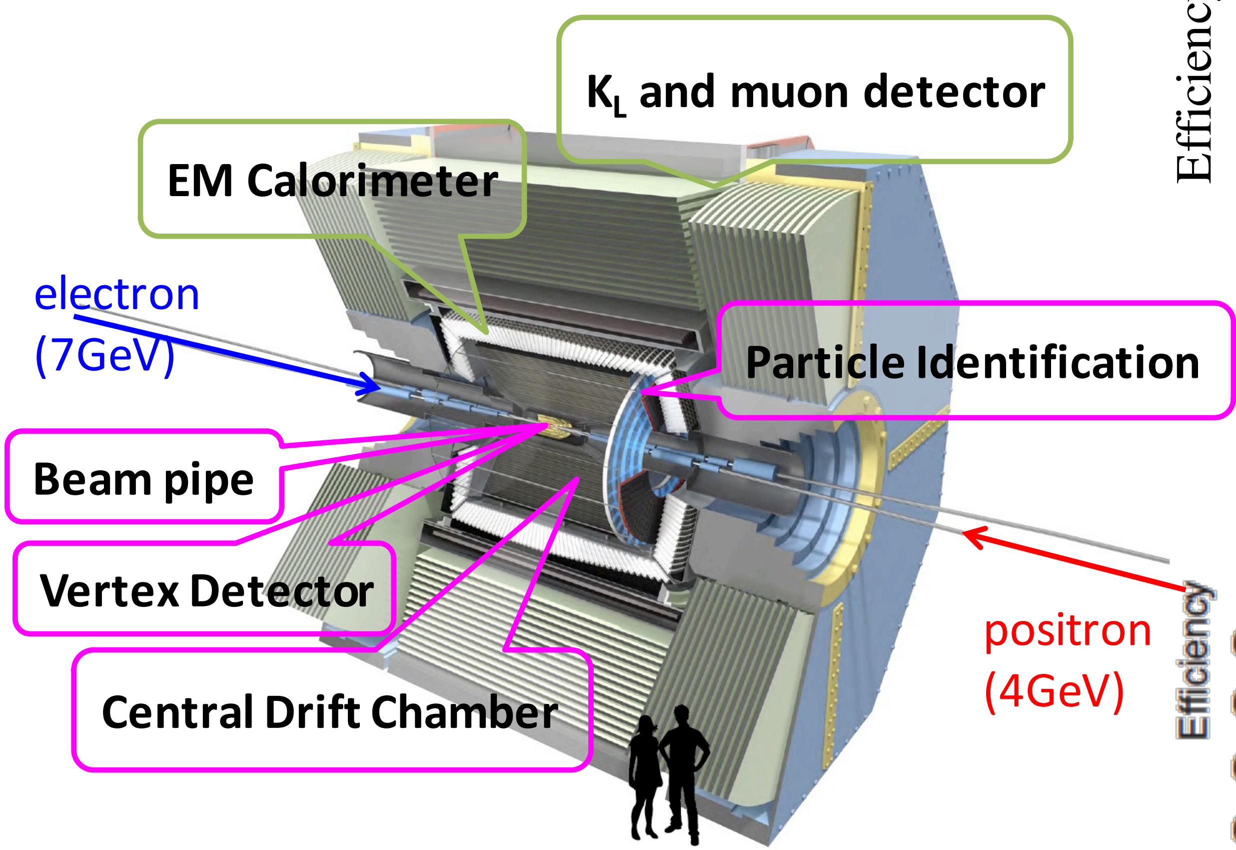
KEK (Tsukuba, Japan)

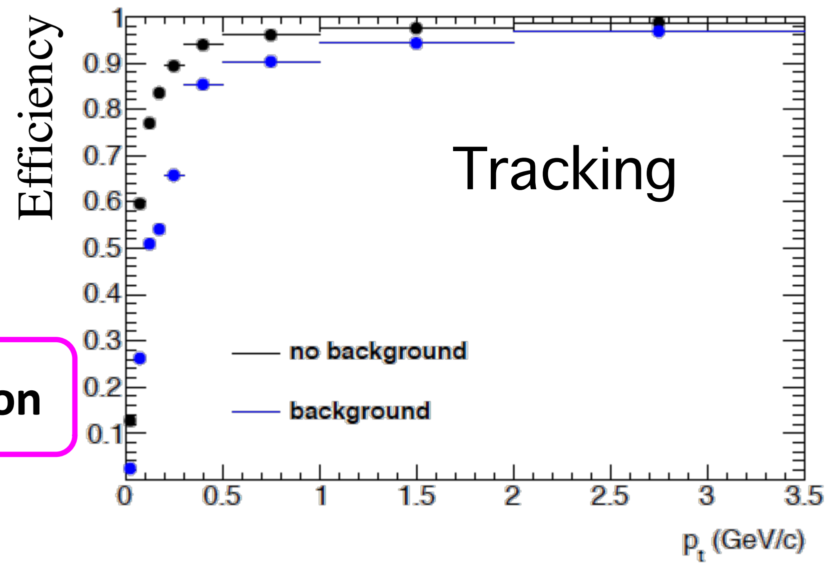


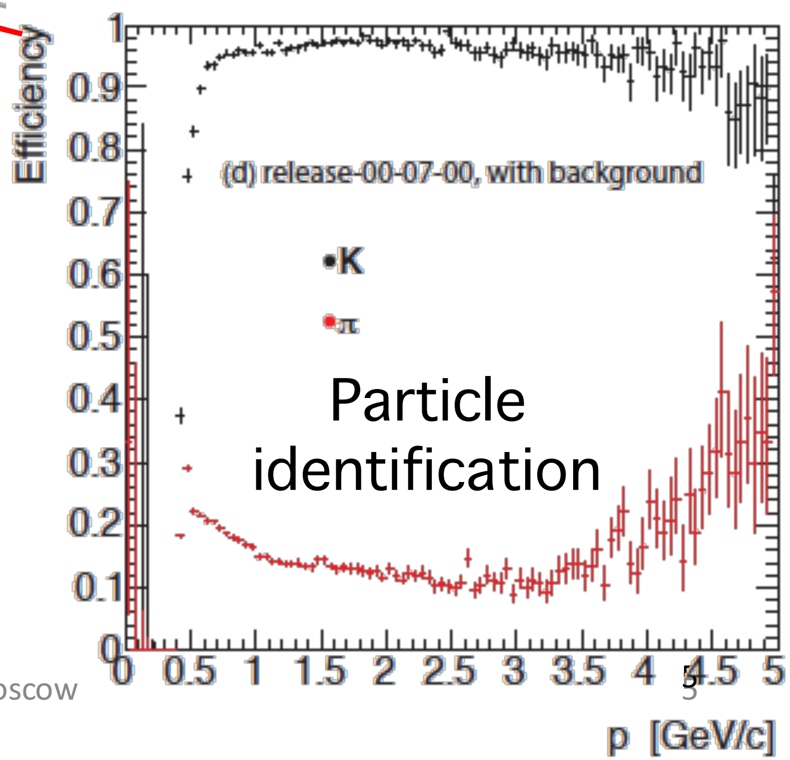



- Nano beam scheme
  - Giving 20x L.
- Doubled currents
  - Giving 2x L.
- Asymmetric energy collision
  - Time-dependent CP asymmetry meas.

# Belle II detector



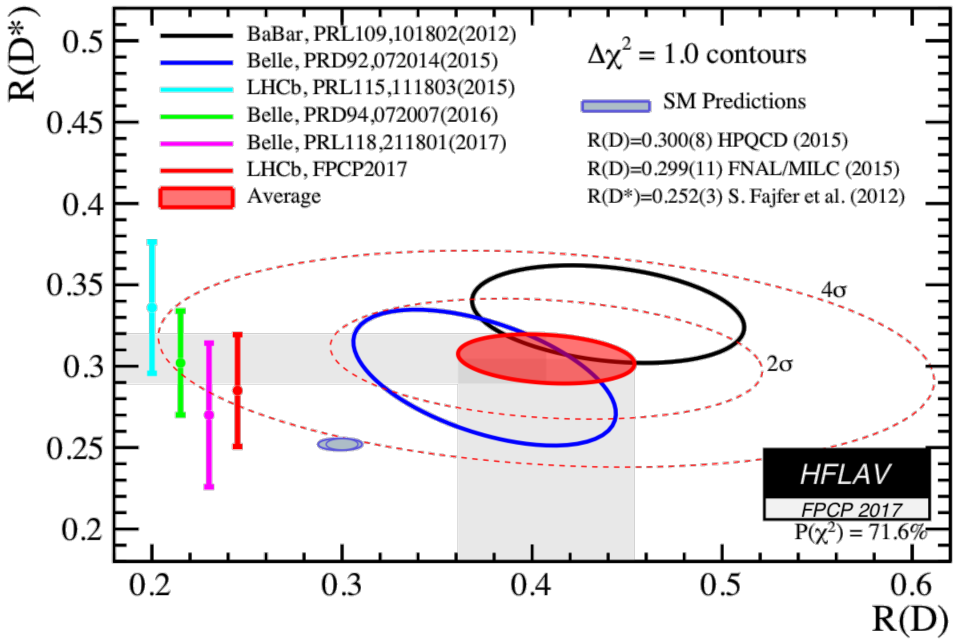

Detector and software tools are getting ready.

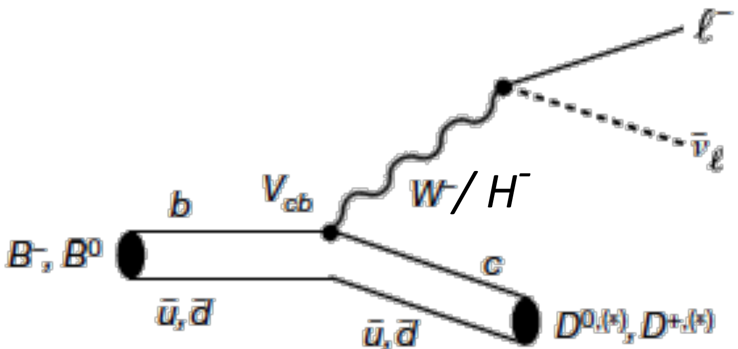
# Leptonic and semileptonic B decays (1)

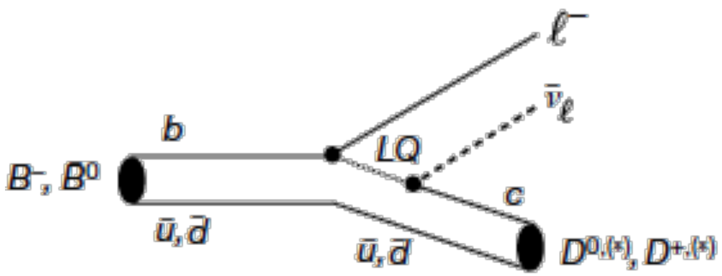
- $B \to D^{(*)} \tau \nu$
  - $R(D^{(*)})$ measurements show deviations from the SM.
    - ➢ Combined result is 4.1 $\sigma$ away from the SM.
  - Hint of NP which violates the lepton universality?
    - ➢ Charged Higgs, leptoquark, ⋯

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

l = e, μ



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  - Hint of NP which violates the lepton universality?
    - ➢ Charged Higgs, leptoquark, ···
  - The uncertainties will be reduced to 2-3% at 50 ab$^{-1}$ in Belle II.

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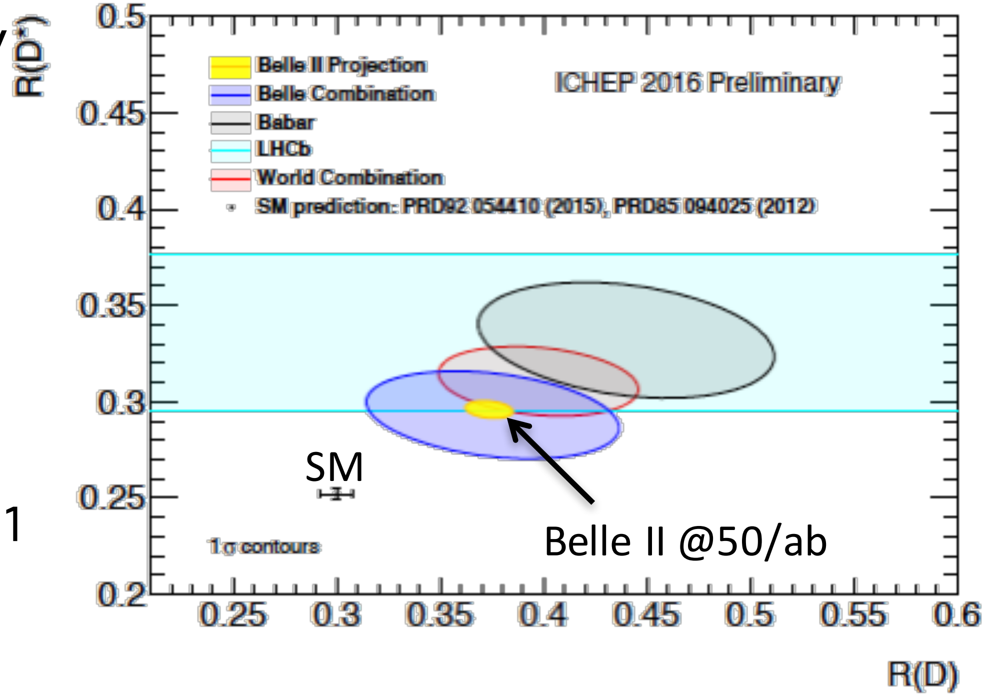
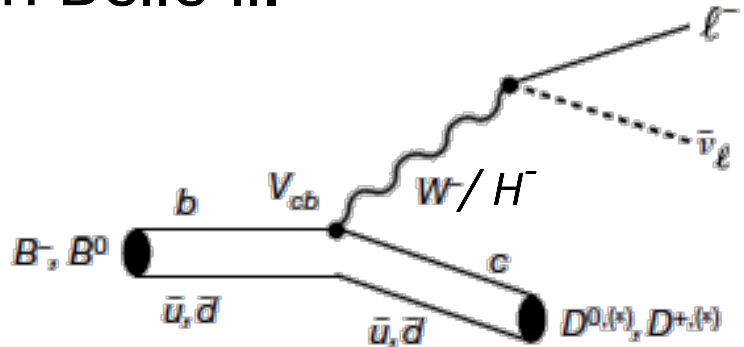
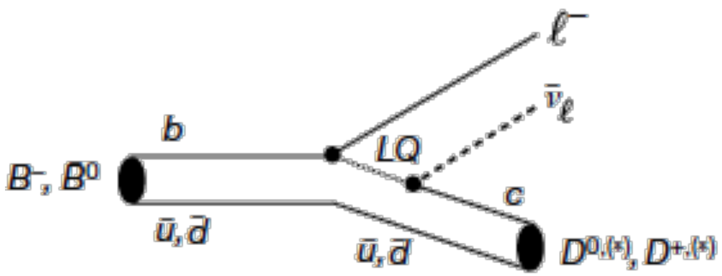
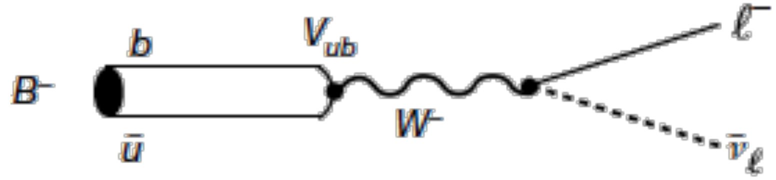


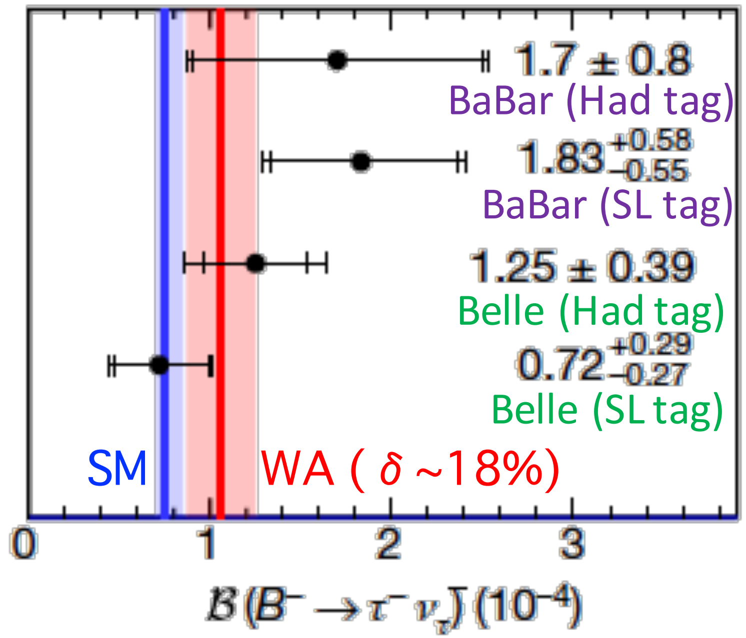
# Leptonic and semileptonic B decays (2)

- $B \to \tau\ \nu$
  - BF is sensible to NP.
    - 4 $\sigma$ level signal evidences in Belle and BaBar.
    - Currently consistent with SM.
    - The uncertainty will be reduced to 5-6% at 50 $ab^{-1}$ in Belle II.




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

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

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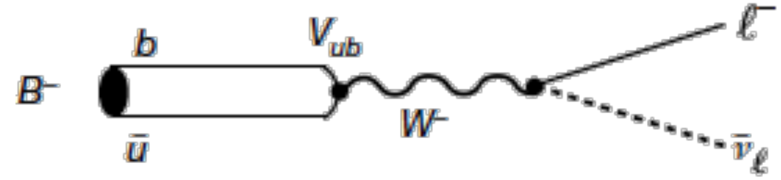


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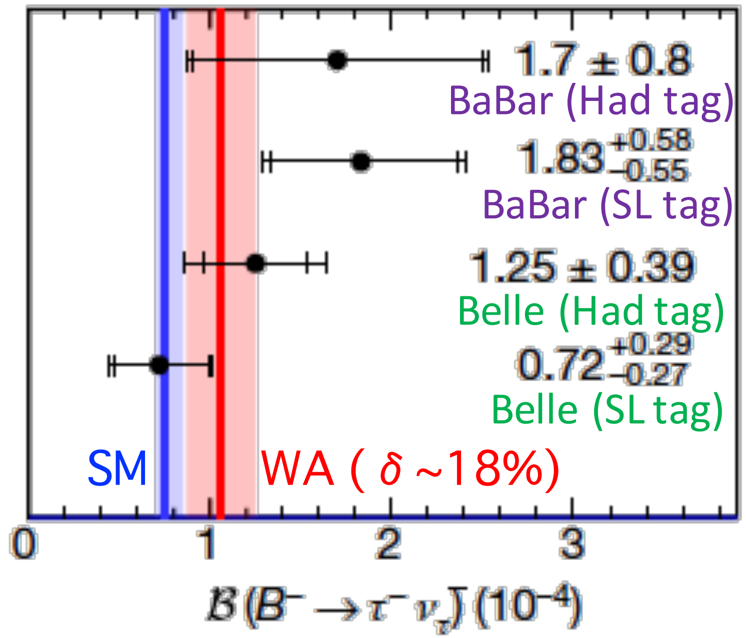
$$\frac{\mathcal{B}(B^- \to \tau^- \bar{\nu}_\tau)}{\mathcal{B}(B^- \to \mu^- \bar{\nu}_\mu)}$$

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

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

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# Leptonic and semileptonic B decays (2)

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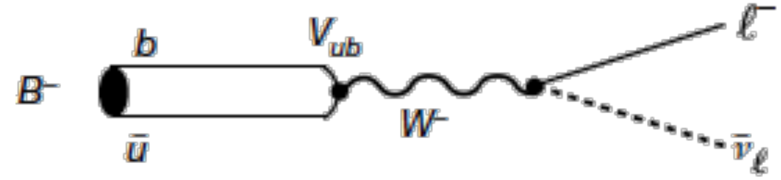
  - BF is sensible to NP.
    - 4 $\sigma$ level signal evidences in Belle and BaBar.
    - Currently consistent with SM.
    - The uncertainty will be reduced to 5-6% at 50 $ab^{-1}$ in Belle II.
  - Another excellent mode to test the lepton universality.
  - If no NP, can extract $|V_{ub}|$.
    - Independent from $b\to ul\nu$ .




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

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

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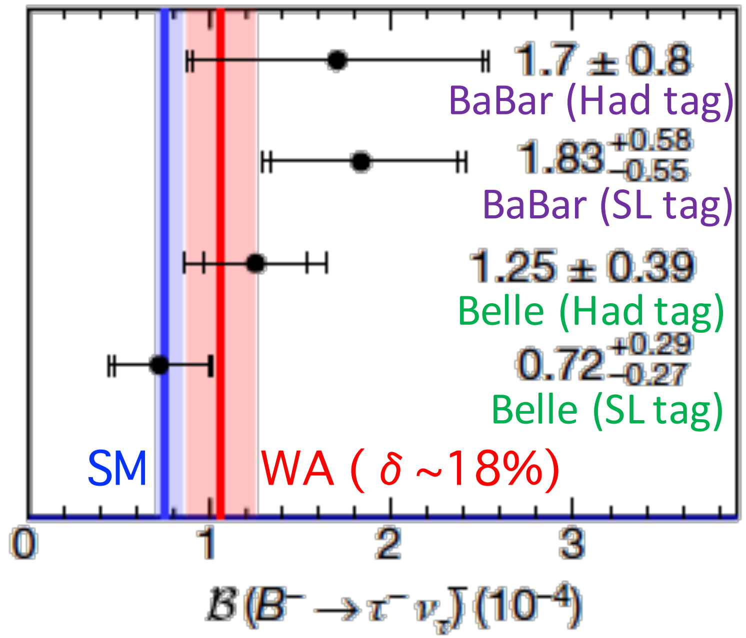


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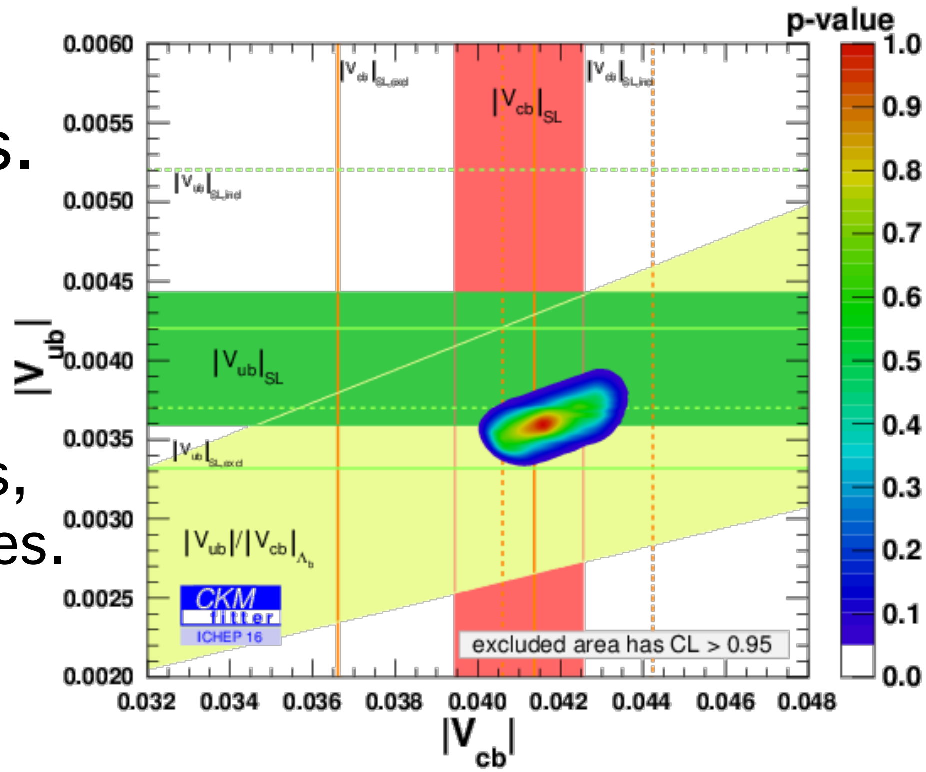
# Leptonic and semileptonic B decays (3)

- $b \to ul\nu$, $cl\nu$ ($l = \mu, e$)
  - $|V_{ub}|$ 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.



# Leptonic and semileptonic B decays (3)

- $b \to u l \nu$, $c l \nu$ ($l = \mu$, e)
  - $|V_{ub}|$ and $|V_{cb}|$ determinations.
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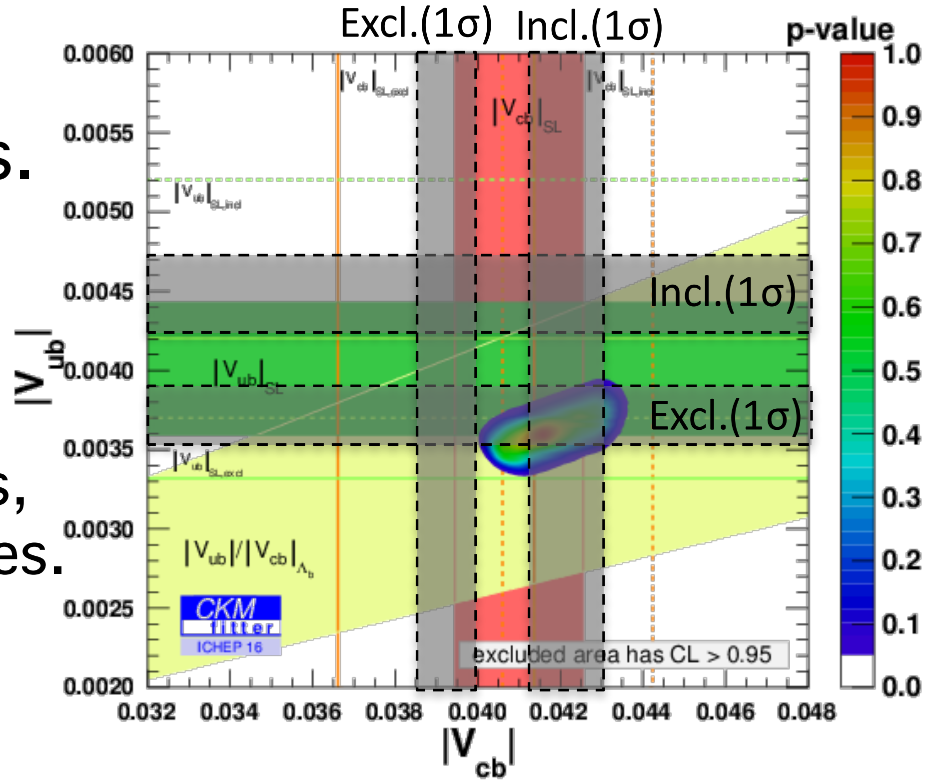
    - QCD predictions for form factors, inclusive processes, quark masses.
  - Tension: incl. vs excl. meas.
    - $|V_{ub}|$: $X_u l \nu$ vs $\pi l \nu$
    - $|V_{cb}|$: $X_c l \nu$ vs $D^{(*)} l \nu$



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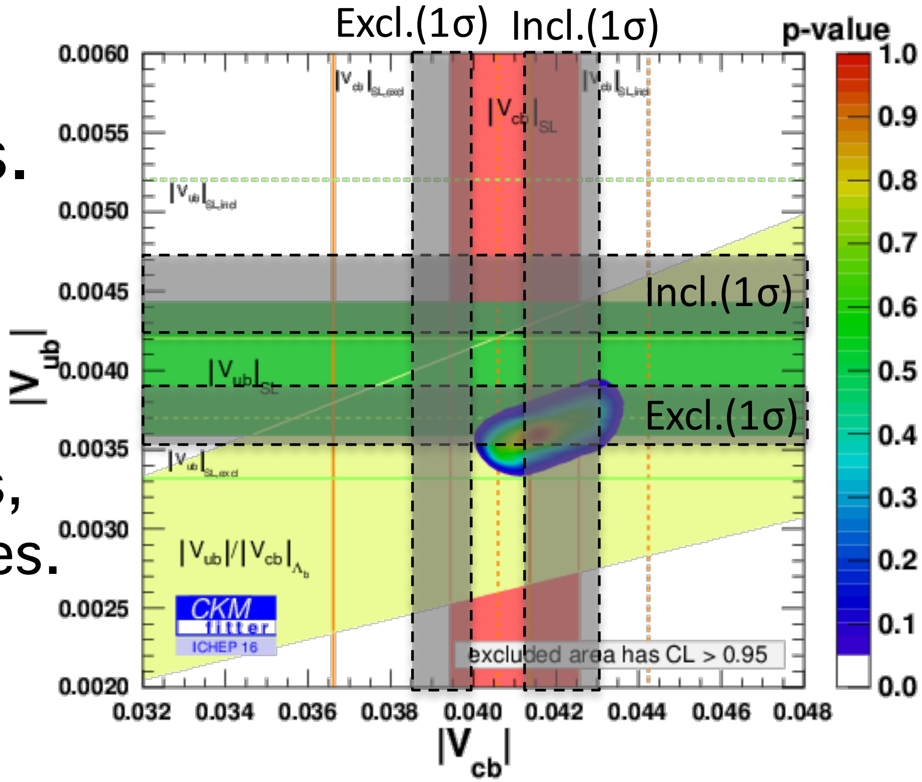
    - ➢ QCD predictions for form factors, inclusive processes, quark masses.
  - Tension: incl. vs excl. meas.
    - ➢ $|V_{ub}|$: $X_u l \nu$ vs $\pi l \nu$
    - ➢ $|V_{cb}|$: $X_c l \nu$ vs $D^{(*)} l \nu$
  - Major effort with much higher statistics at Belle II is required to improve the precisions.
    - ➢ More detailed BG decomposition.
    - ➢ Further progress in QCD calc.

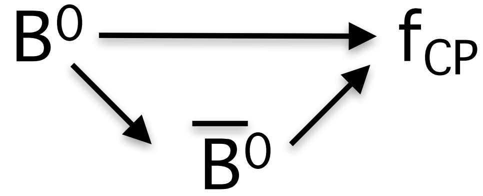



$B \to \pi l \nu$ full simulation

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

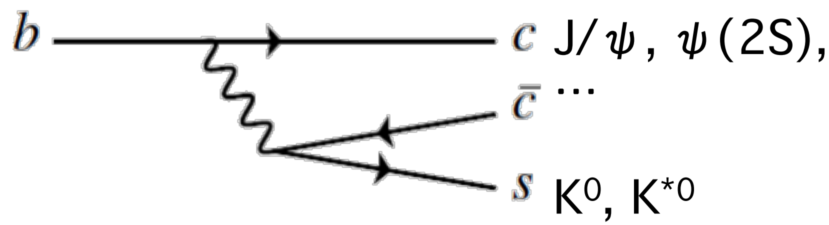
# QCD penguin b→s transitions (1)

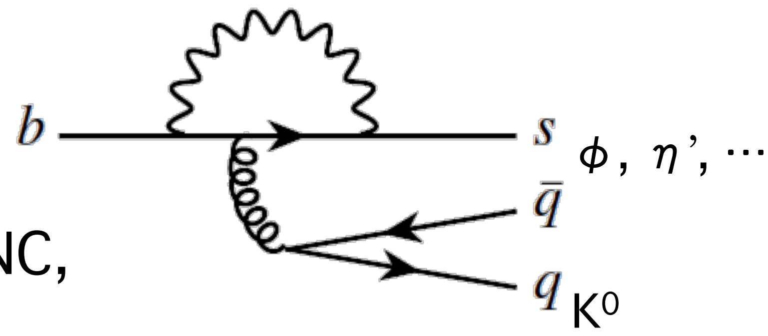
- Indirect CPV (ICPV) in $b \to s\bar{q}q$
  - ICPV: interference between the non-mixed and mixed decays to a CP eigenstate.
    - Giving a time-dependent CP asymmetry ($A(\Delta t)$).
  - For the tree-dominant $b \to c\bar{c}s$ transitions,
    - $S = -\eta_f \sin 2\phi_1$, $C = 0$,
    - $\eta_f$: 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.




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

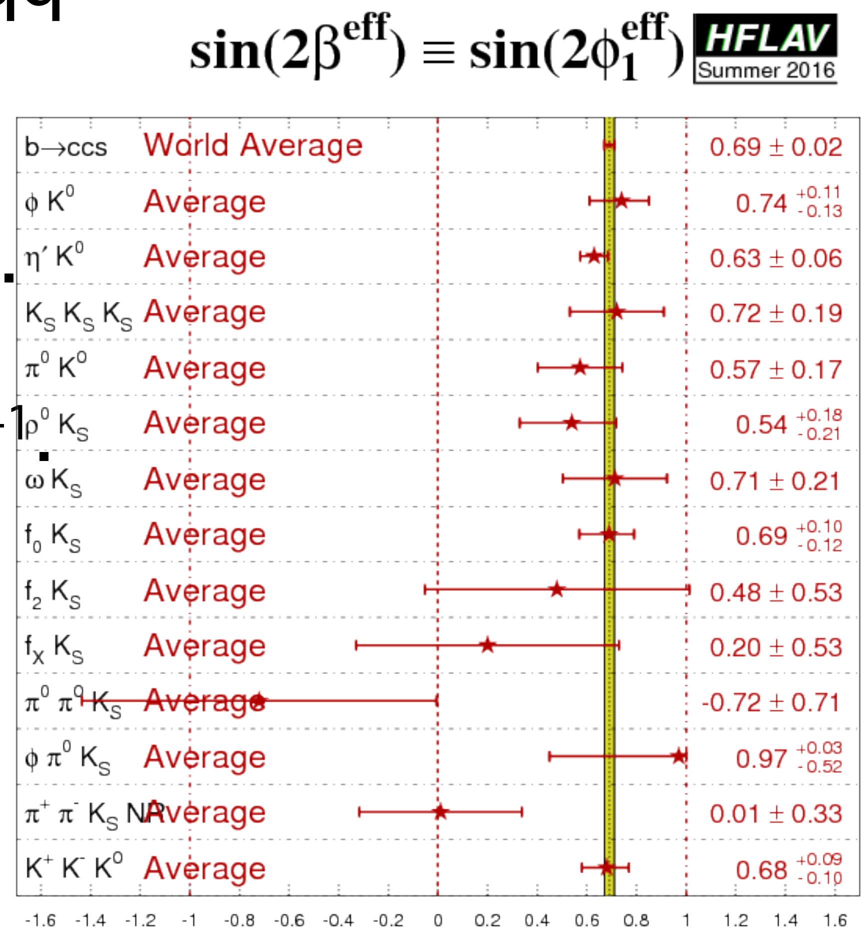
$\Delta t$: decay time difference between $B^0$ and $\bar{B}^0$



# 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 ( $\delta$ ) will be reduced significantly at 50 $ab^{-1}$.
    - ➢ $b \to c\bar{c}s$: to 20-25% of present $\delta$, systematics limited.
    - ➢ $b \to sqq$: to ~15% of present $\delta$, 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→K$\pi$
  - DCPV: interference between amplitudes to a final state.
    - Giving a time-integrated CP asymmetry ($A_{CP}$).

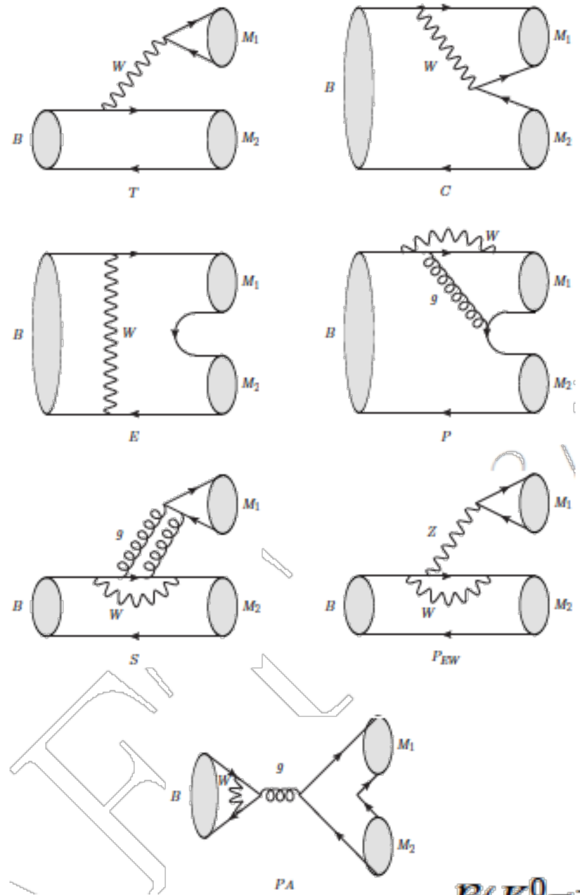
$$A_{CP}(B \to f) \equiv \frac{\Gamma(\bar{B} \to \bar{f}) - \Gamma(B \to f)}{\Gamma(\bar{B} \to \bar{f}) + \Gamma(B \to f)}$$

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

# 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 $b \to s\bar{q}q$.

Phys. Lett. B 627, 82 (2005)




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

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  - DCPV: interference between amplitudes to a final state.
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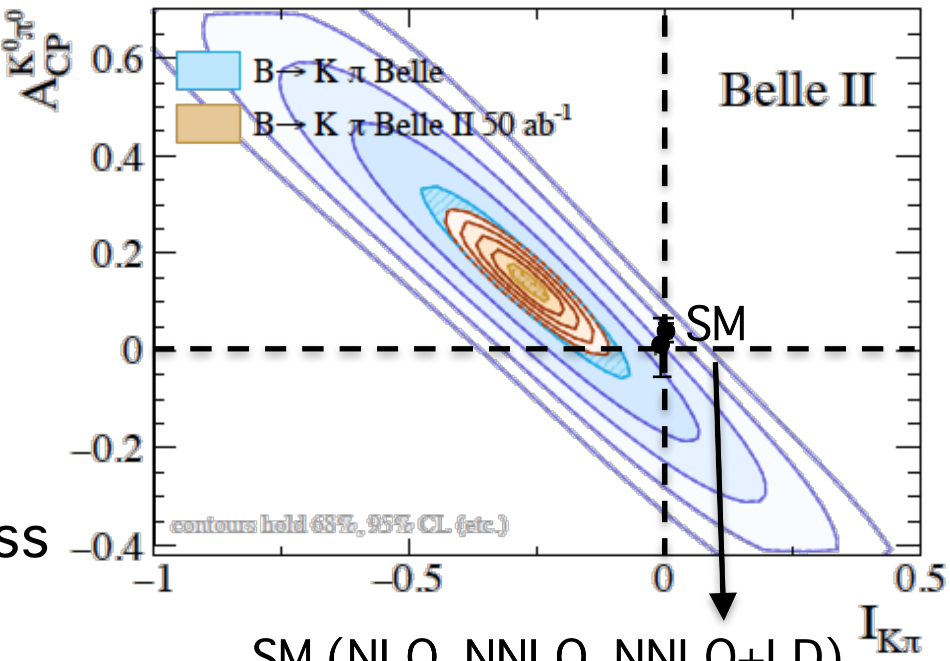
  - A sum rule of $A_{CP}$ was proposed.
    - ➢ Applying the isospin symmetry to the leading contributions.
    - ➢ Violation could be NP in b→s$\bar{q}$q.
  - Important to systematically study all K$\pi$ modes with high precision in Belle II.

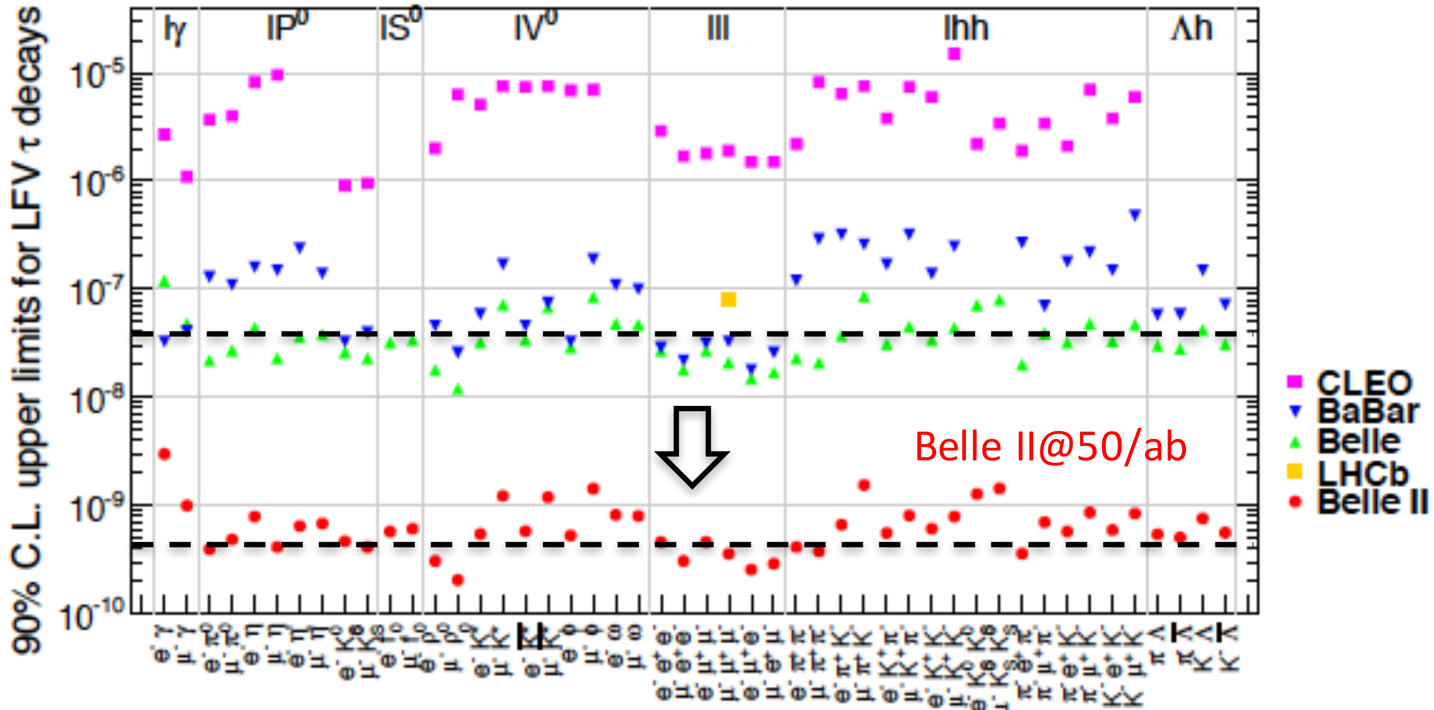



SM (NLO, NNLO, NNLO+LD)
Phys. Lett. B 627, 82 (2005)

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

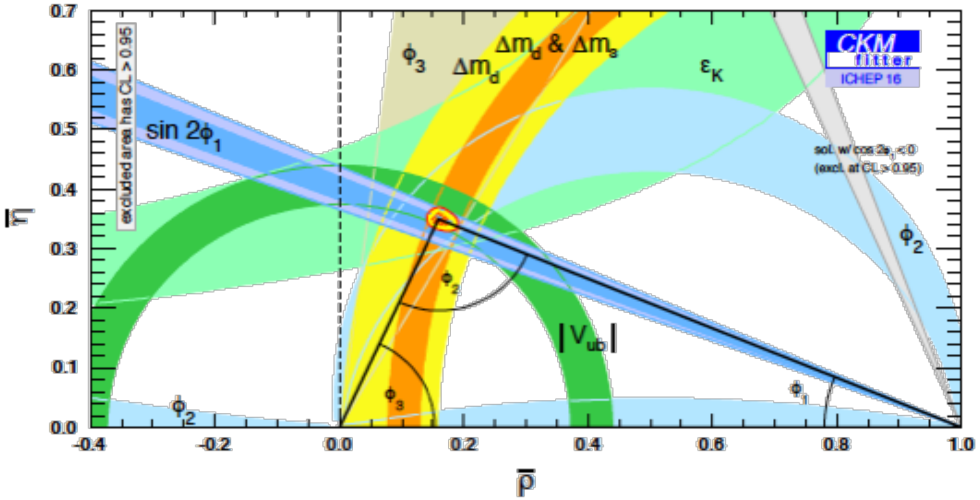
# $\tau$ decays

- Lepton Flavor Violation (LFV) decays
  - The BFs/ULs are expected to be improved by ~2 orders of magnitude at Belle II.
  - Any enhancement from the SM predictions ($BF \sim 10^{-25}$) indicate clear signal of NP.
    - ➢ NP can enhance BFs up to $10^{-8}$.



# Prospect on Unitarity Triangle

Present



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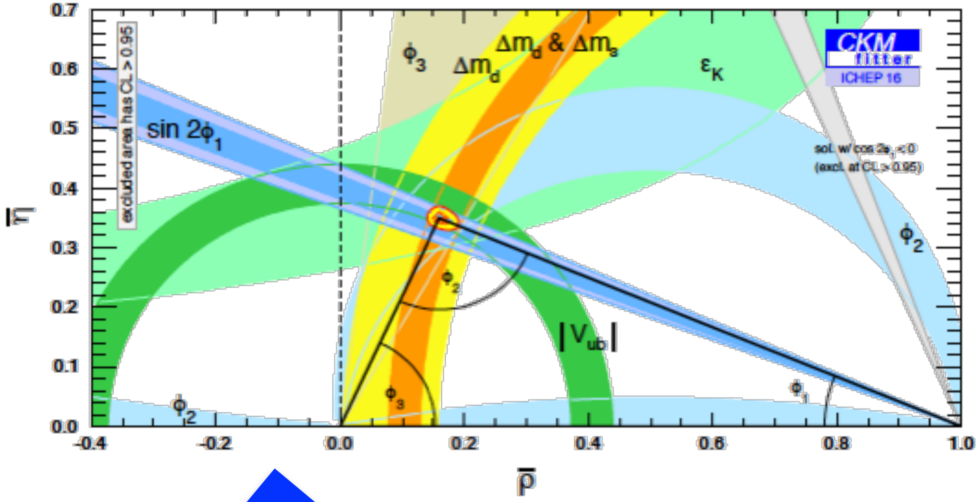
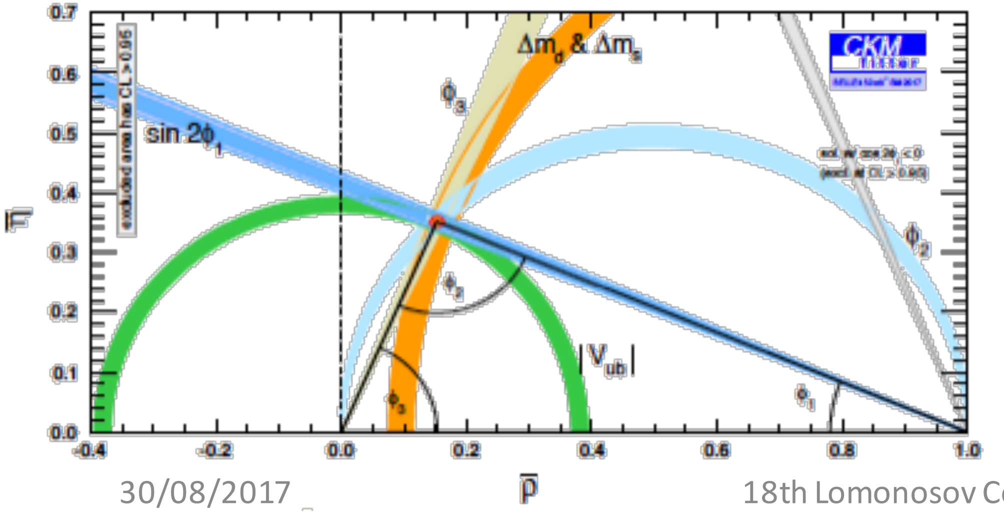



For a SM-like scenario

Belle II @ 50 $ab^{-1}$




| Observable | Uncertainty |
|---|---|
| $\phi_1$ [deg.] | 0.4 |
| $\phi_2$ [deg.] | 1.0 |
| $\phi_3$ [deg.] | 1.0 (w/ LHCb) |
| $\|V_{cb}\|$ incl. | 1% |
| $\|V_{cb}\|$ excl. | 1.5% |
| $\|V_{ub}\|$ incl. | 3% |
| $\|V_{ub}\|$ excl. | 2% (w/LHCb) |

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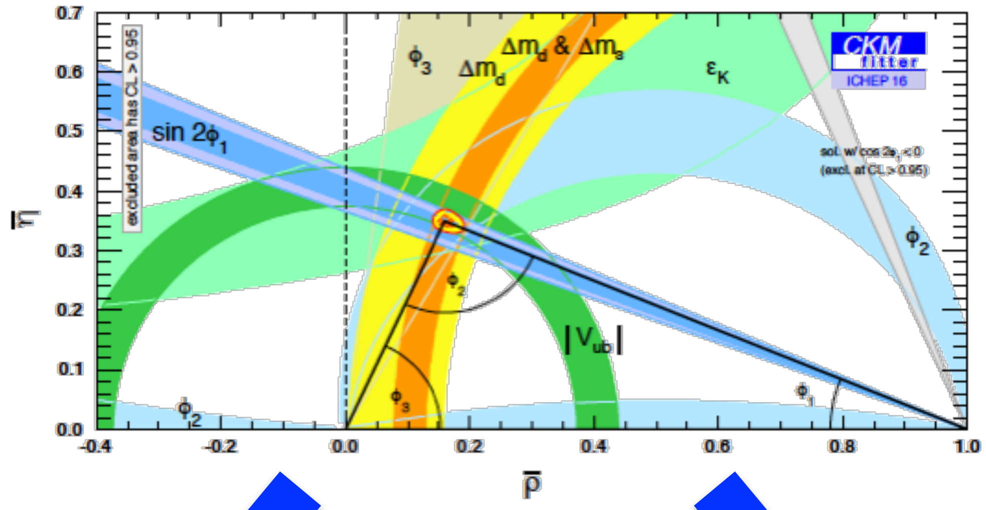
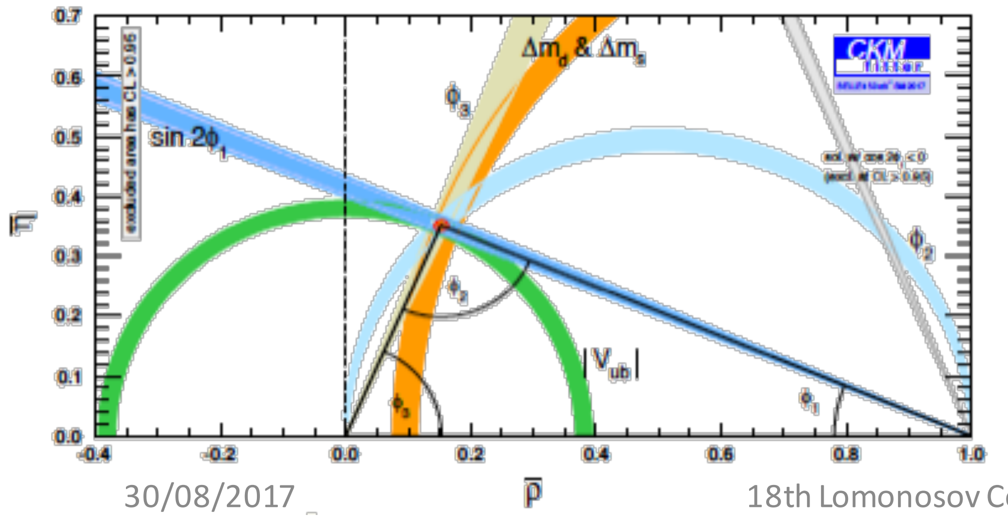
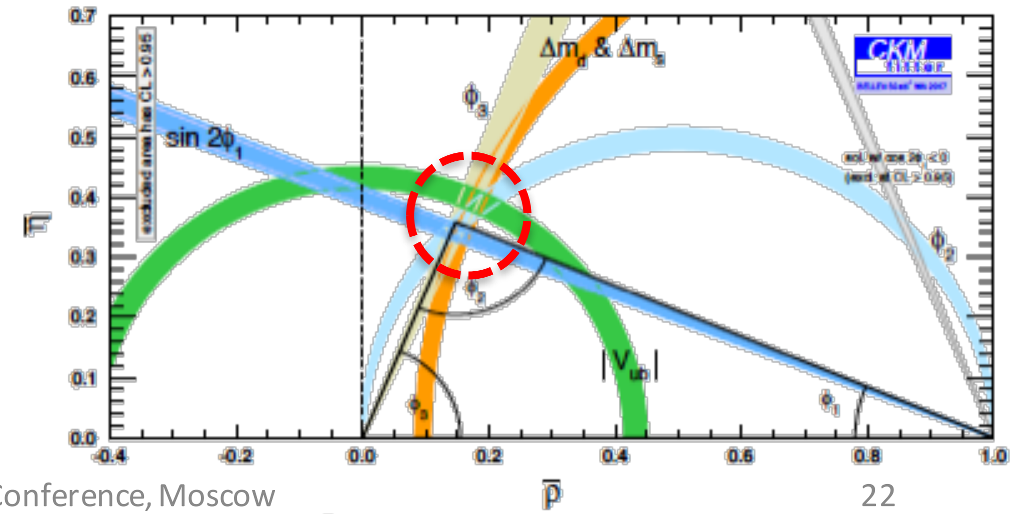



For a SM-like scenario

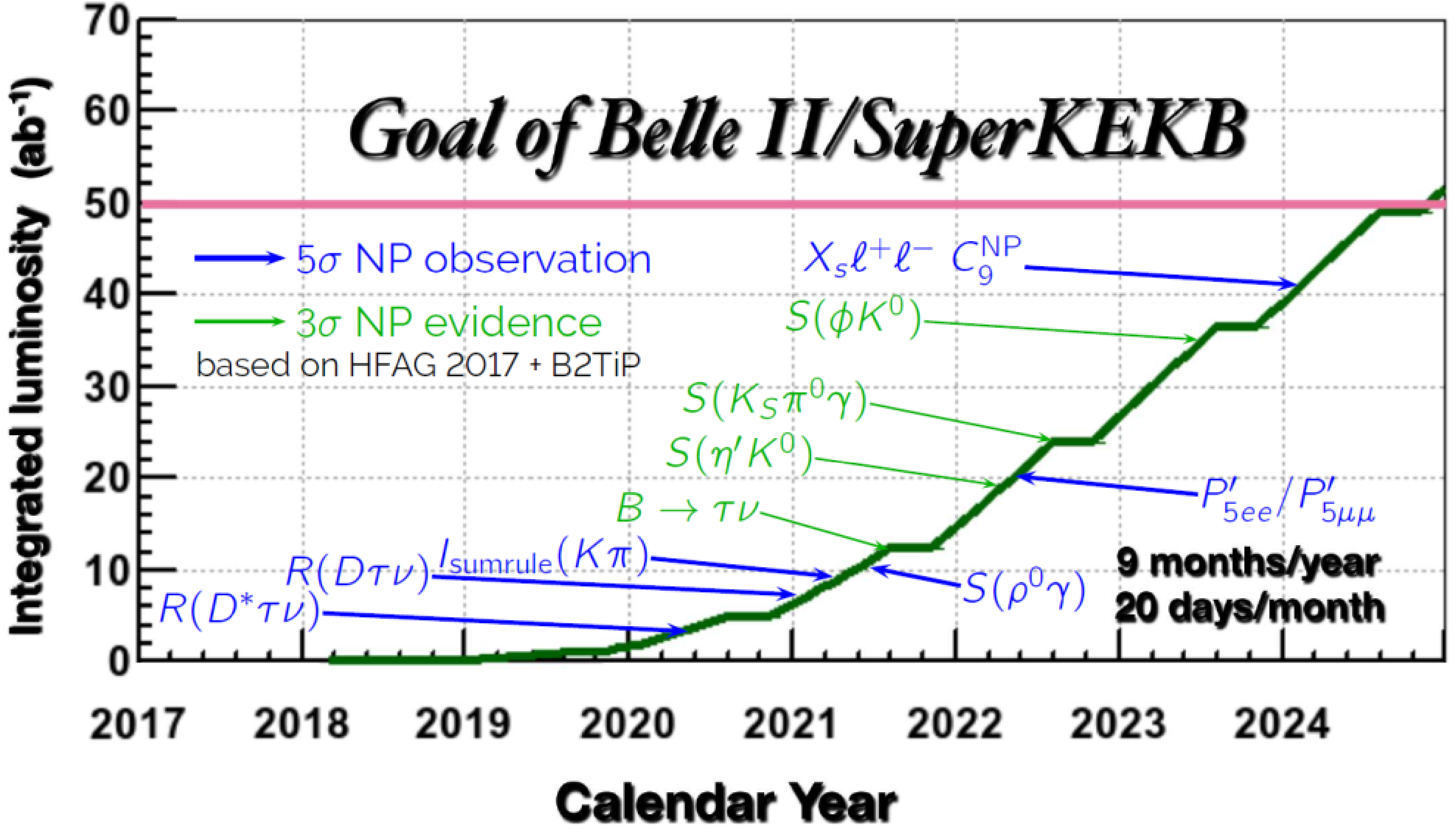
Belle II @ 50 ab$^{-1}$

If the current WAs hold



# Future prospect



# Summary

- Belle II will search for new physics beyond the SM in the flavor sector at the intensity frontier.
  - W-exchanging process with $\tau$ ,
  - 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.