Prospects of the new physics search at Belle II by precise measurements of the CKM matrix elements

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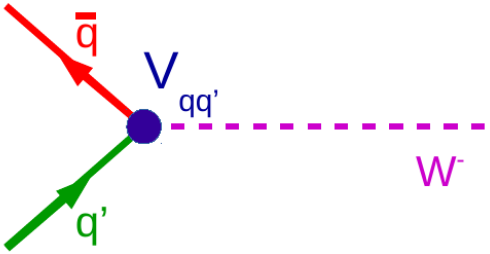
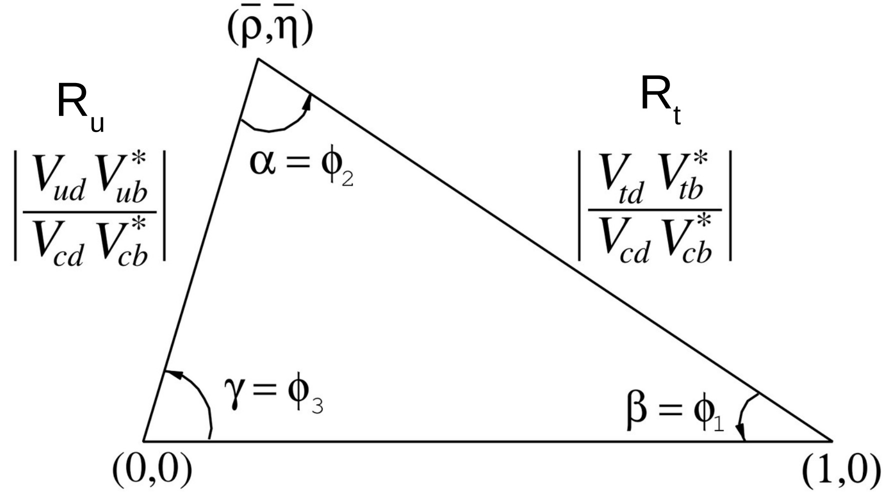
Introduction

- Cabibbo-Kobayashi-Maskawa (CKM) matrix
  - Three generations of quarks.
  - Each element ($V_{qq'}$) describes mixing of quacks via weak interaction in Standard Model (SM).



$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Unitarity triangle:



$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

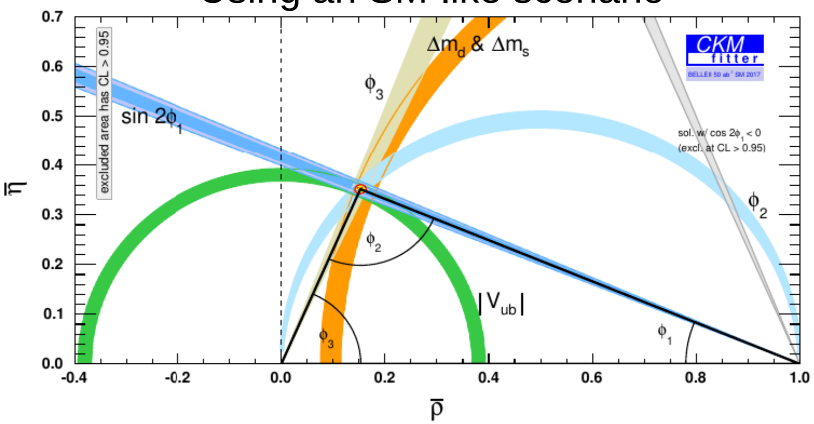
CKM @ Belle II

- Precise measurement on UT angles and sides is a powerful SM test at energised much higher than directly achieved at the energy frontier.
  - Deviation from theoretical results may indicate to new physics (NP).

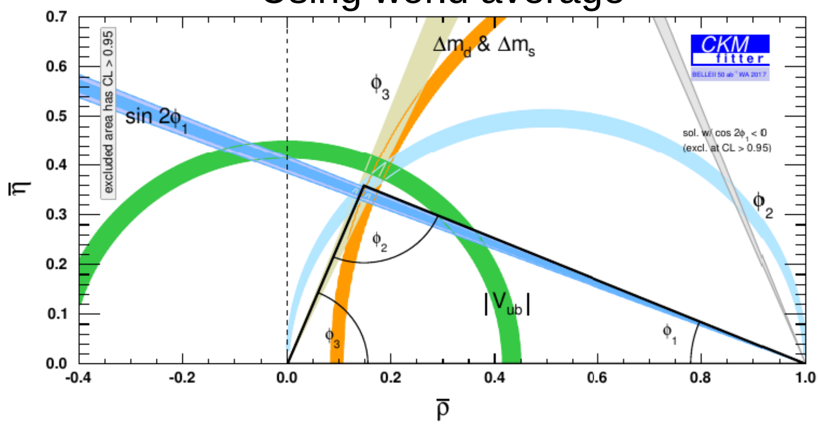
- The potential of Belle II:
  - Much larger data set (target at 50 ab^{-1}) thanks to SuperKEKB.
  - New hardware and software tools also improve the detection resolution and reduce systematic uncertainty in various aspects.
  - Belle II has unique/world leading access to many key decay modes, specially those involving neutral particle: K^0, π^0, $\eta^{(')}$, and missing particle (ν).

Extrapolation @ 50 ab^{-1}

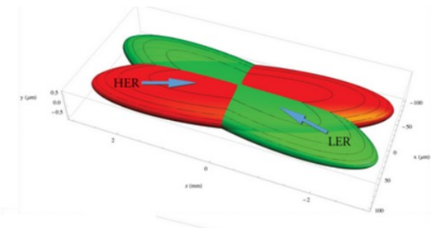
Using an SM-like scenario

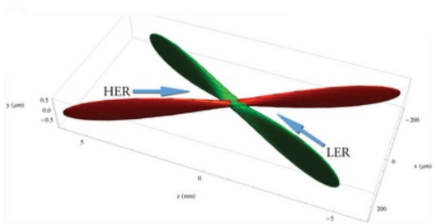


Using world average

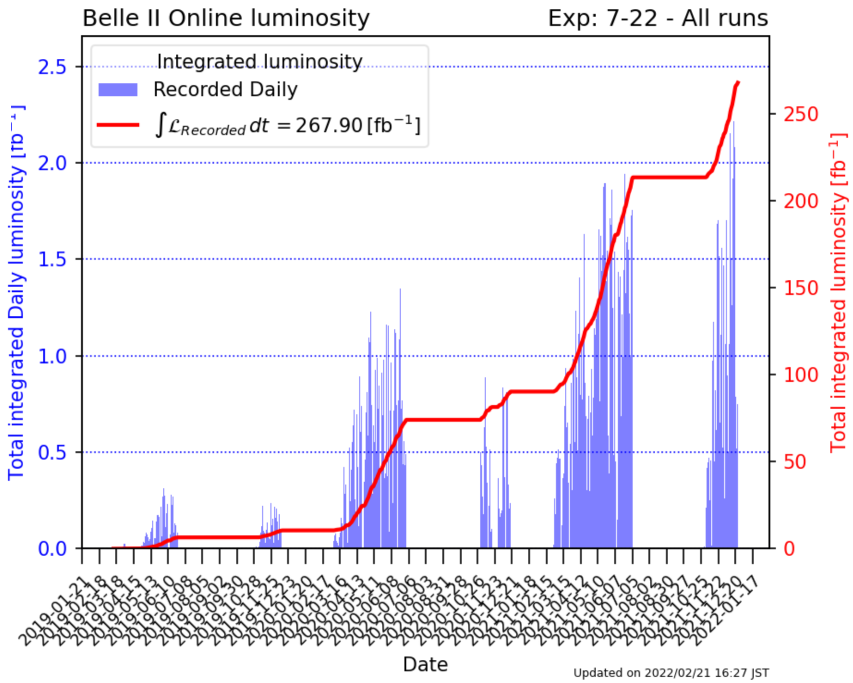


- Asymmetric energy collider:
  - 7.0 GeV e^- and 4.0 GeV e^+ for $\Upsilon(4S) \rightarrow B\bar{B}$.
- Upgrade from KEKB.
  - More than 30 times larger luminosity of KEKB with nano beam scheme.





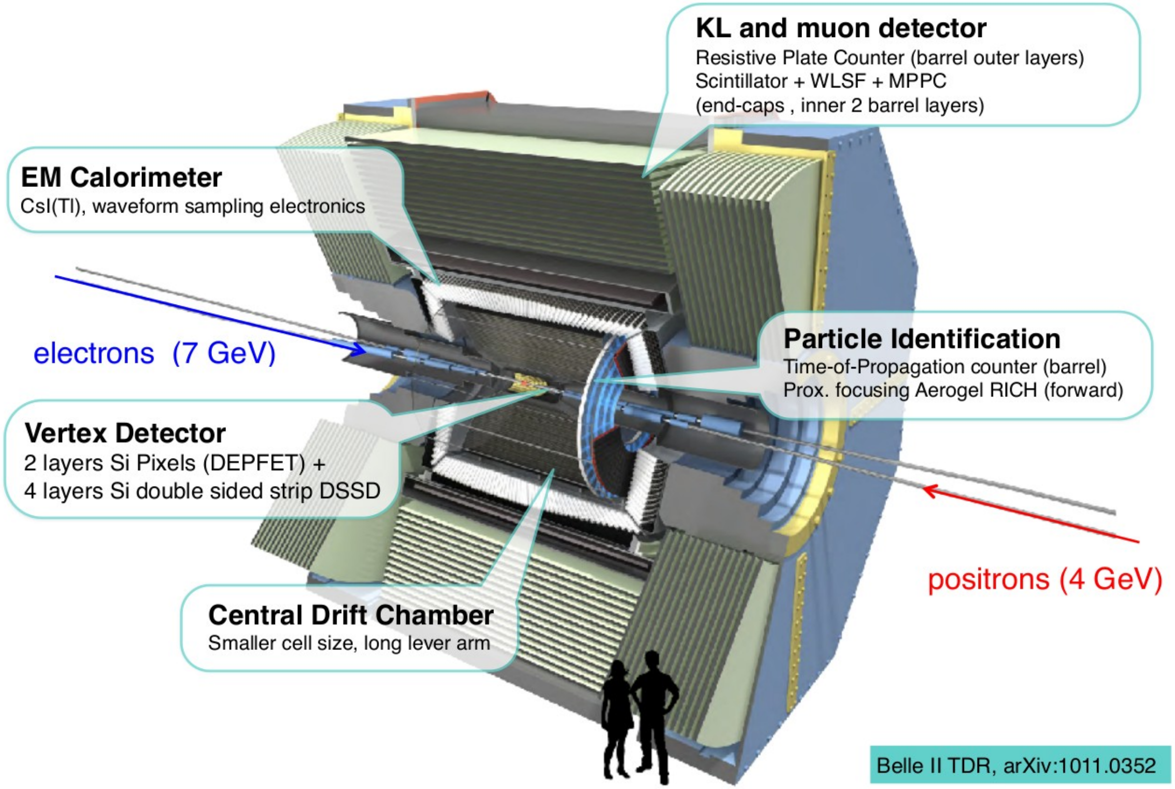
- Achievement so far:
  - L_{int} = 267.9 fb^{-1} up to Dec. 2021.
  - L_{peak} = 3.8 x 10^{34} $cm^{-2}s^{-1}$,
    new world record
    with smaller beam currents than
    those of KEKB.



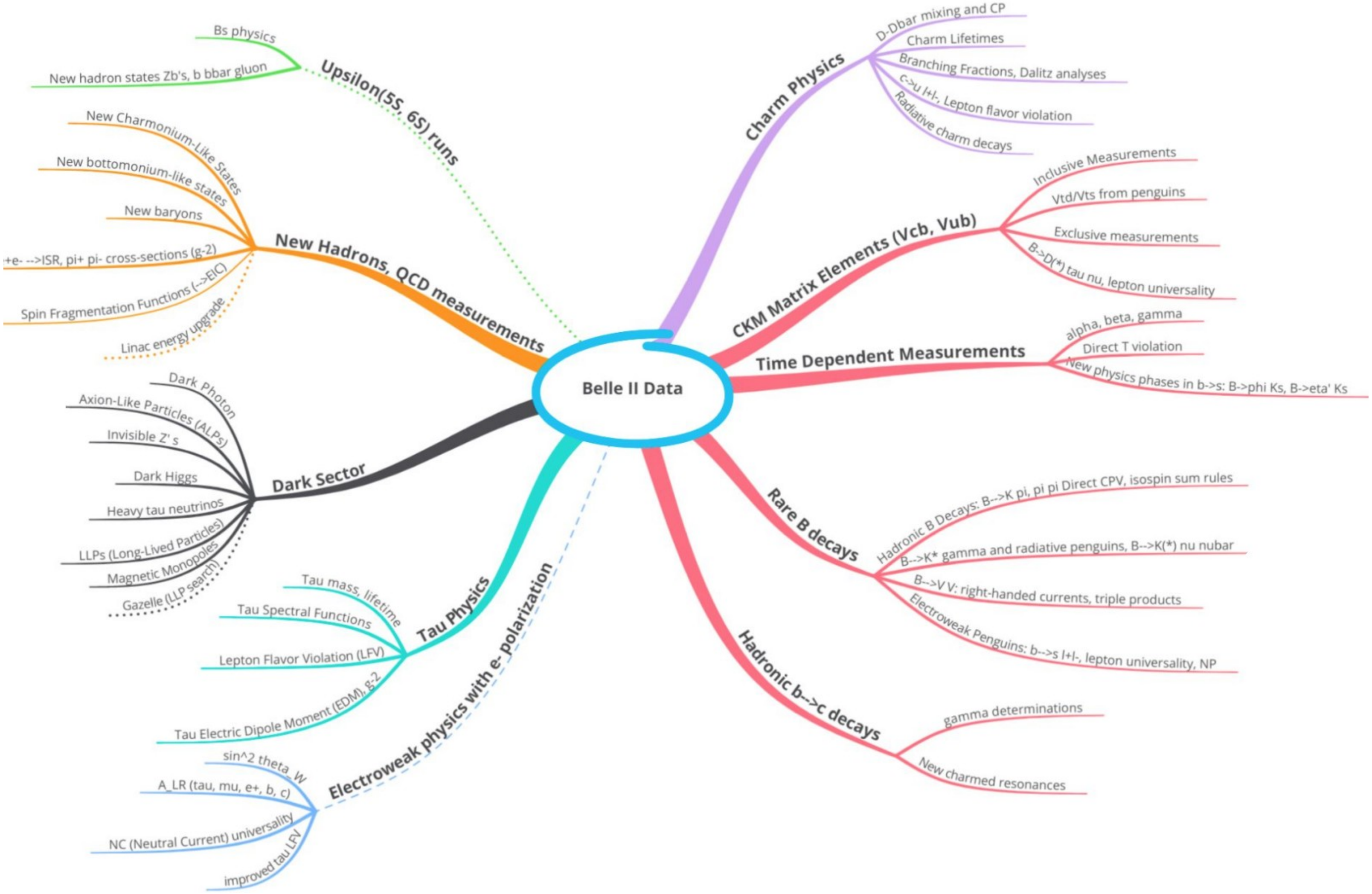
- Goal: > 6 x 10^{35} $cm^{-2}s^{-1}$

Belle II detector

- Newly-designed sub-detectors set to improve detection performance.
  - Vertexing: 1.5 ~ 2 times improvement compared with Belle.
  - PID: ~4σ for K/π suppression.
  - Pixel detector full installation will be complete in 2022 shut down.

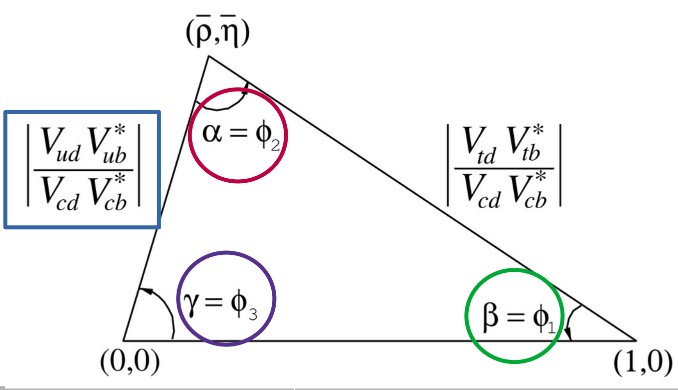


Trigger and DAQ system: Required to handle high data rate and high beam background.


Belle II Data
Upsilon(5S, 6S) runs
Bs physics
New hadron states Zb's, b bbar gluon
New Hadrons, QCD measurements
New Charmonium-Like States
New bottomonium-like states
New baryons
e+e- -->ISR, pi+ pi- cross-sections (g-2)
Spin Fragmentation Functions (-->EIC)
Linac energy upgrade
Dark Sector
Dark Photon
Axion-Like Particles (ALPs)
Invisible Z' s
Dark Higgs
Heavy tau neutrinos
LLPs (Long-Lived Particles)
Magnetic Monopoles
Gazelle (LLP search)
Tau Physics
Tau mass, lifetime
Tau Spectral Functions
Lepton Flavor Violation (LFV)
Tau Electric Dipole Moment (EDM), g-2
Electroweak physics with e- polarization
sin^2 theta_W
A_LR (tau, mu, e+, b, c)
NC (Neutral Current) universality
improved tau LFV
Charm Physics
D-Dbar mixing and CP
Charm Lifetimes
Branching Fractions, Dalitz analyses
c->u l+l-, Lepton flavor violation
Radiative charm decays
CKM Matrix Elements (Vcb, Vub)
Inclusive Measurements
Vtd/Vts from penguins
Exclusive measurements
B->D(*) tau nu, lepton universality
Time Dependent Measurements
alpha, beta, gamma
Direct T violation
New physics phases in b->s: B->phi Ks, B->eta' Ks
Rare B decays
Hadronic B Decays: B-->K pi, pi pi Direct CPV, isospin sum rules
B-->K* gamma and radiative penguins, B-->K(*) nu nubar
B-->V V: right-handed currents, triple products
Electroweak Penguins: b-->s l+l-, lepton universality, NP
Hadronic b-->c decays
gamma determinations
New charmed resonances

Outline

- This report will mainly introduce the methodology of measuring them, improvement and prospect in Belle II.
- Recent results will be also reported.



UT element	Mode	Methodology	Improvement from Belle II (other than statistics)
$\|V_{ub}\|$	$B \to \pi l \nu$ (excl.) $B \to X_u l \nu$ (incl.)	Tagged / Untagged	Tagging package (FEI)
$\|V_{cb}\|$	$B \to D^{(*)} l \nu$ (excl.) $B \to X_c l \nu$ (incl.)	Tagged / Untagged	Tagging package (FEI)
φ_1	$b \to c\bar{c}s$ $b \to sq\bar{q}$	Time-dependent CP violation	Vertexing, flavor tagging
φ_2	$B \to hh$ ($h=\pi,\rho$)	Isospin study with BF, A_{CP}, Time-dependent CP violation	Time-dependent CP violation of $B^0 \to \pi^0\pi^0$
φ_3	$B \to D^{(*)}K^{(*)}$	Amplitude ratio between D eigenstates	More decay modes with neutral particles

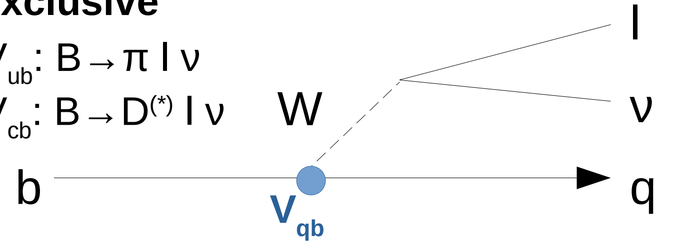
$|V_{ub}|$ & $|V_{cb}|$

- $|V_{ub} / V_{cb}|$: Constrains the length opposite to φ_1 (R_u) in the unitary condition.
  - SM reference as mainly from tree-level.
- Using **semileptonic B decay**.
  - Longstanding discrepancy (~3σ) between **inclusive and exclusive** results.
  - Hint of NP such as right-handed current? PRD 90, 094003 (2014)

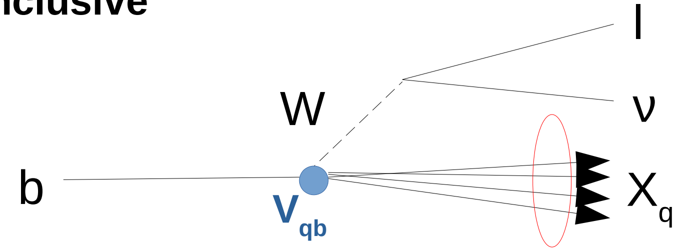
Exclusive

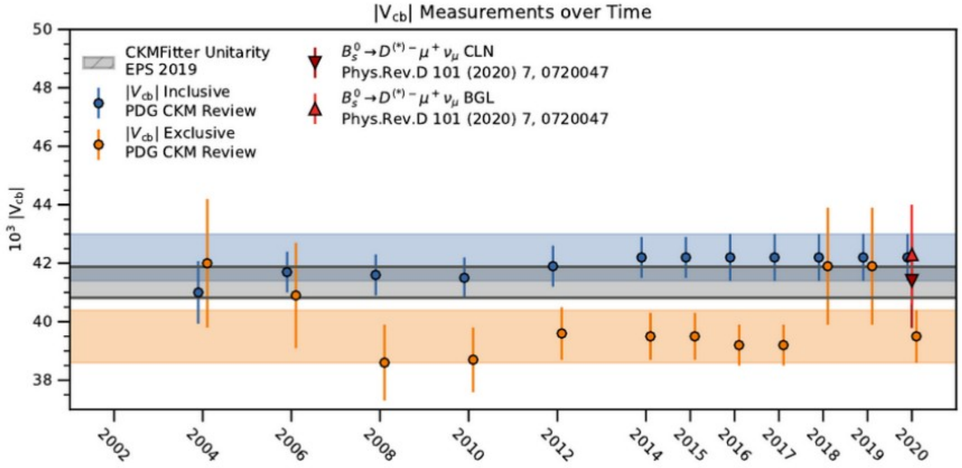
V_{ub}: $B \rightarrow \pi\, l\, \nu$

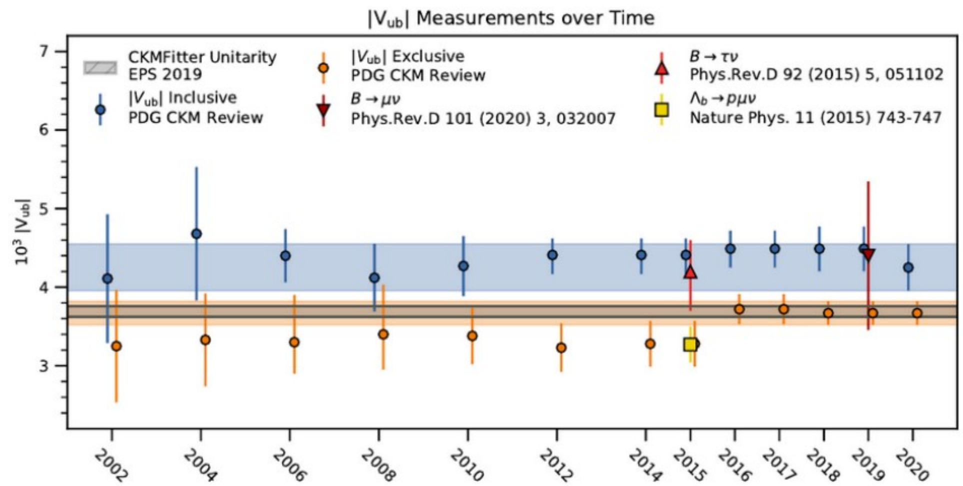
V_{cb}: $B \rightarrow D^{(*)}\, l\, \nu$



Inclusive

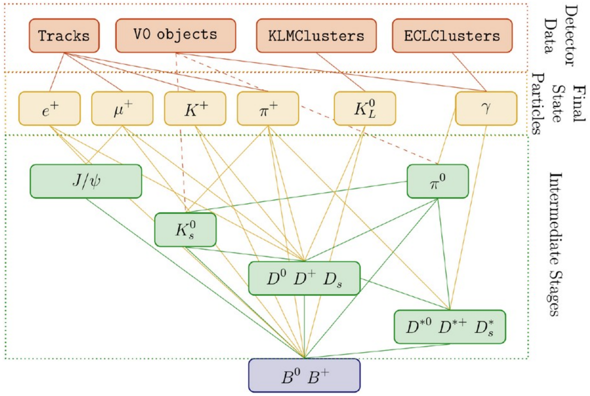




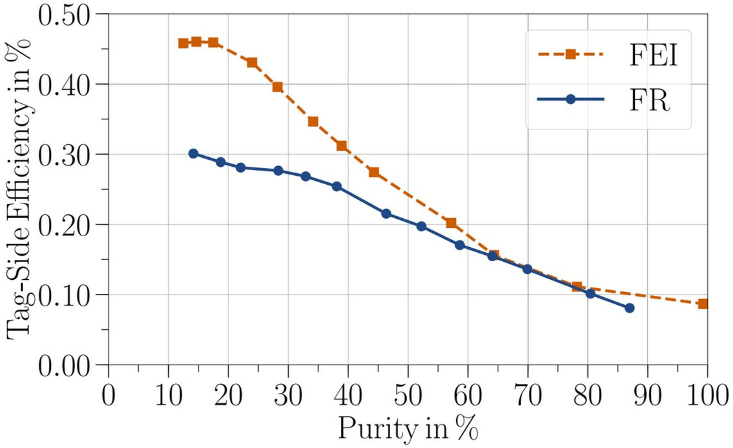


Tagging method

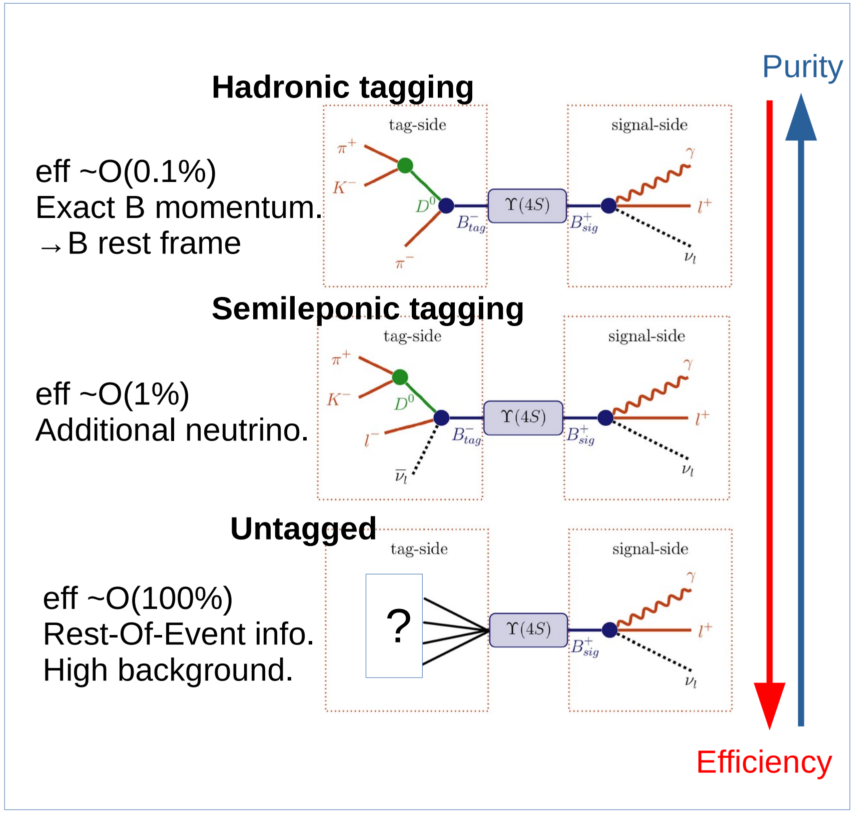
- New full event interpretation (FEI) package for Belle II from the Belle version (FR). **NIM A 654, 432-440 (2011)** **Comput Softw Big Sci 3, 6 (2019)**
- Hierarchical reconstruction on > 5000 B decays with MVA tool.
- Reduce systematic uncertainty due to tag-side calibration.
- 30%~50% increase on efficiency with same purity.



Tagging efficiency for B±



Tagging methods

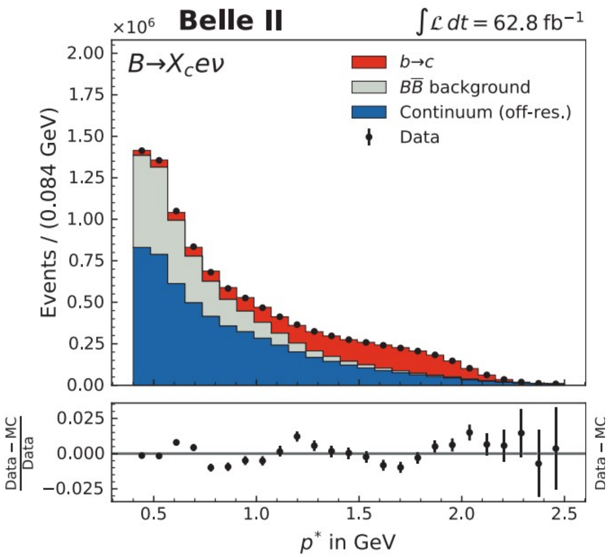


$|V_{cb}|$ inclusive: $B \to X_c l \nu$

- $|V_{cb}|$ is extracted by differential branching fraction (dBF) on the spectral moments (of lepton energy or hadron mass). JHEP 02 (2019) 177
- Non-perturbative elements can be determined at the same time.

Belle II $B \to X_c l \nu$
62.8 fb^{-1} Untagged

arXiv: 2111.09405 [hep-ex]



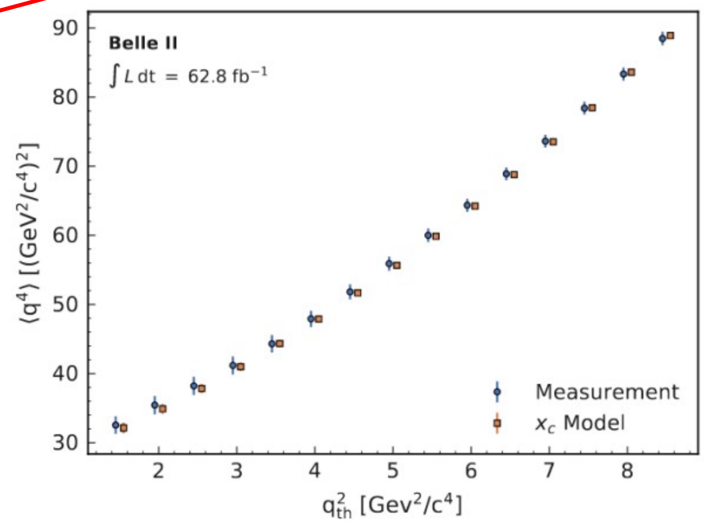
$$\mathcal{B}(B \to X_c e \nu_e) = (9.97 \pm 0.03(\text{stat}) \pm 0.38(\text{syst}))\%$$
$$\mathcal{B}(B \to X_c \mu \nu_\mu) = (9.47 \pm 0.05(\text{stat}) \pm 0.45(\text{syst}))\%$$
$$\mathcal{B}(B \to X_c \ell \nu_\ell) = (9.75 \pm 0.03(\text{stat}) \pm 0.47(\text{syst}))\%$$

Main source of syst.: X_c composition.

New for JPS

Belle II $B \to X_c l \nu$
62.8 fb^{-1} tagged

To be submitted to PRD



q^2 ($=(p_l + p_\nu)^2$) moment for n = 1-4 order determined as a function of q^2 threshold.

$|V_{cb}|$ exclusive: $B \to D^{(*)} l \nu$

- Fit on data to obtain dBF on hadron recoil parameter (w)
- Extract $|V_{cb}|$ by dBF/dw with phenomenological form-factor.

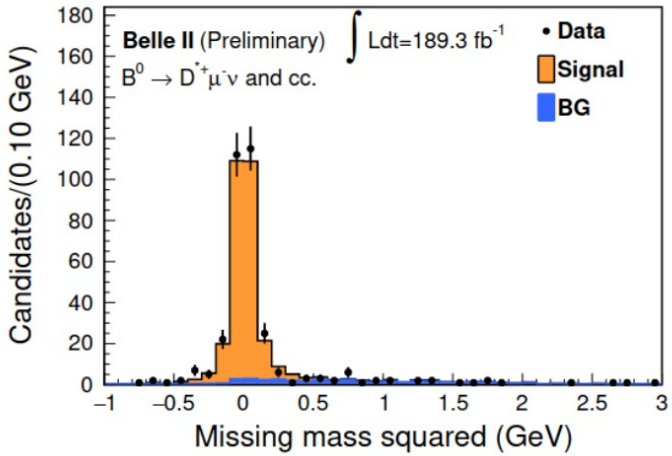
Belle II $B^0 \to D^{*-} l \nu$
189.3 fb^{-1} Tagged

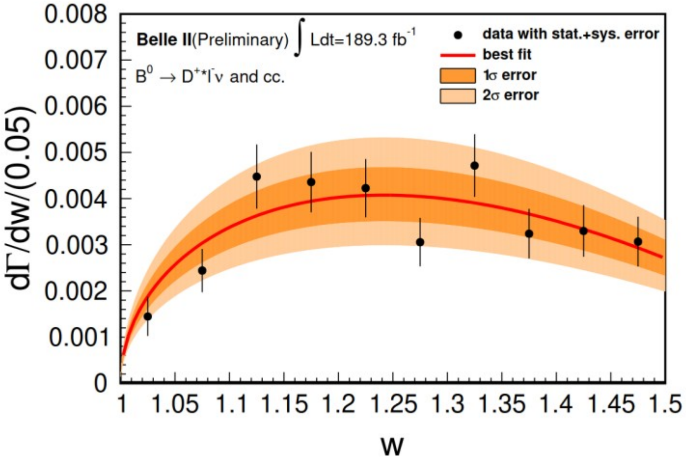
New for JPS

$$\frac{d\Gamma}{dw} = \frac{\eta_{\rm EW}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2$$

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

Nucl. Phys. B 196 (1982) 83-92
PRD 79 (2009) 014506
Nucl. Phys. B 530 (1998) 153-181





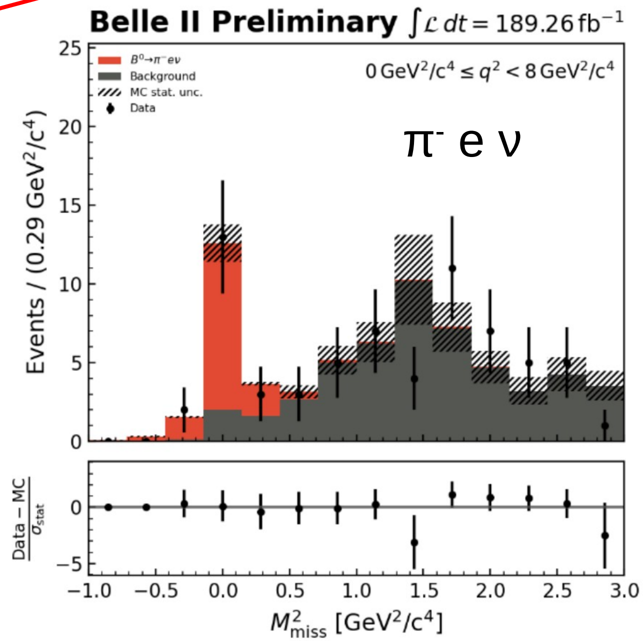
$$\mathcal{B}\left(B^0 \to D^{*-} l^+ \nu_\ell\right) = 0.0527 \pm 0.0022(\text{stat.}) \pm 0.0038(\text{syst.})$$

$$|V_{cb}| = 0.0373 \pm 0.0029 \;(\text{stat.+syst.})$$

$|V_{ub}|$ exclusive: $B \to \pi l \nu$

New for JPS

Belle II $B \to \pi l \nu$
189.3 fb^{-1} tagged

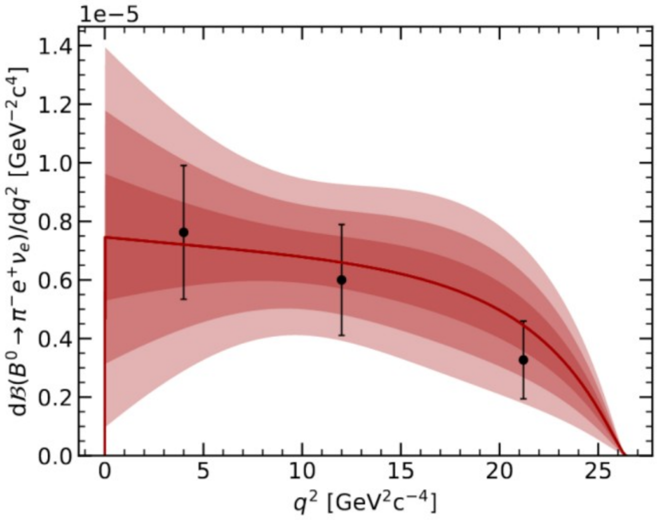


Decay mode	Fitted $\lvert V_{ub}\rvert$
$B^0 \to \pi^- e^+ \nu_e$	$(3.71 \pm 0.55)\ \times 10^{-3}$
$B^+ \to \pi^0 e^+ \nu_e$	$(4.24 \pm 0.55)\ \times 10^{-3}$
Combined fit	$(3.94 \pm 0.42)\ \times 10^{-3}$

- Tagging by FEI.
- Fit on $M^2_{miss} = (p(e^+e^-) - p(B_{tag}) - p(\pi) - p(l))^2$ to extract signal within q^2 ($=(p_l + p_\nu)^2$) bins.
- Extract $|V_{ub}|$ by the dBF(q^2) with form factor.

$$\frac{d\mathcal{B}(B \to \pi l \nu)}{dq^2} = |V_{ub}|^2 \frac{G_F^2 \tau_B}{24\pi^3} p_\pi^3 |f_+^{B\pi}(q^2)|^2$$

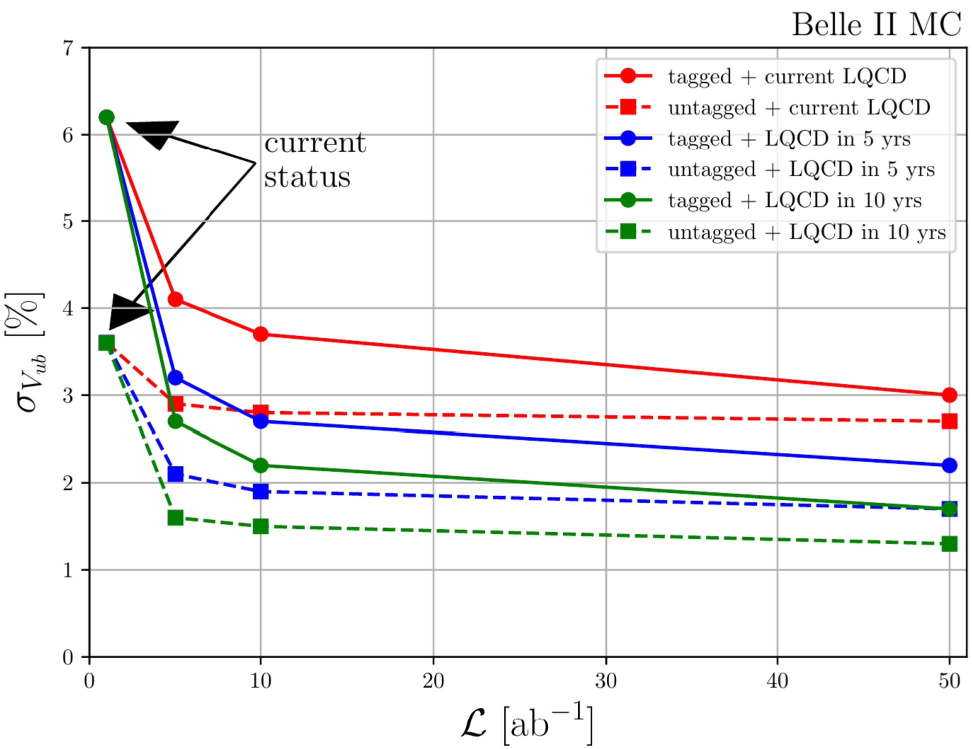
dBF/dq^2 of π^- e ν

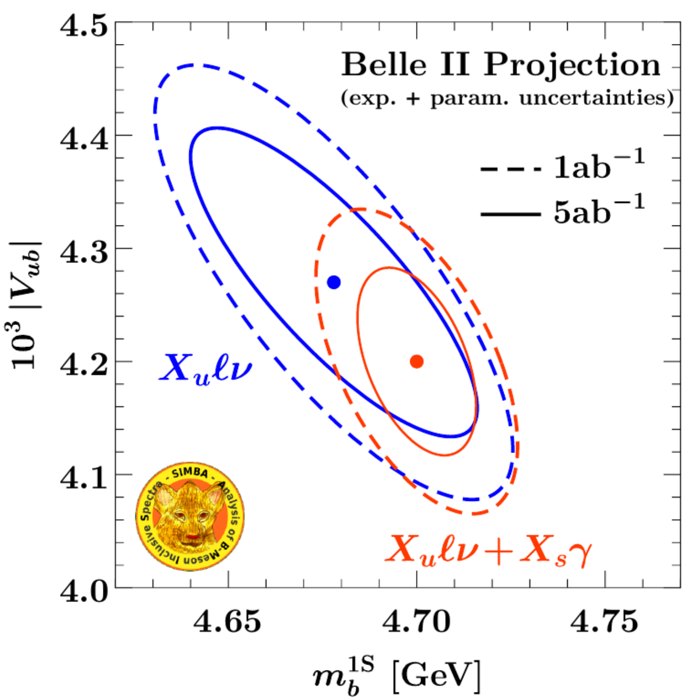


LQCD: PRD 92 (2015) 1 014024

$|V_{ub}|$ & $|V_{cb}|$: Belle II prospect

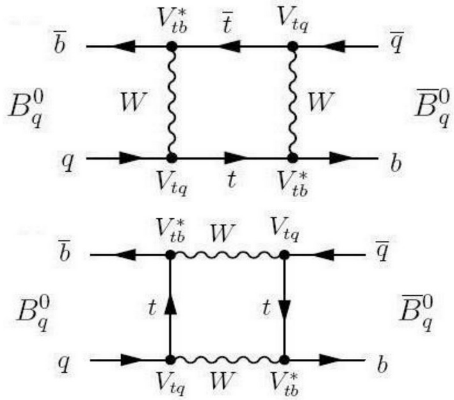
- Belle II: both inclusive and exclusive measurement.
  LHCb: mainly exclusive Λ_b and B_s decays
- Exclusive: Uncertainty from lattice QCD dominates for now.
- Inclusive $|V_{ub}|$: Unknown shape function (b quark motion with B meson).
  - Simultaneous fit on $X_c\, l\, \nu + X_u\, l\, \nu + X_s\, \gamma$.





Time-dependent CP violation

- Time-dependent CP violation (TDCPV)
  - To determine φ_1 (mixing) and φ_2 (mixing + $b \rightarrow u$).

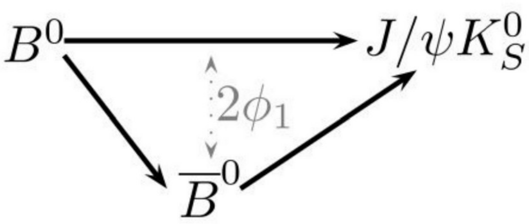


- Decay rate asymmetry as a function of decay time:
  - Δm_B: Mass difference between eigenstates.

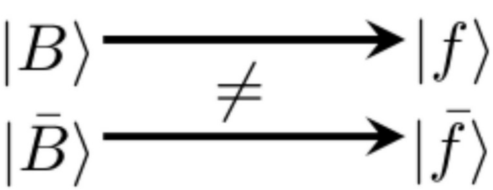
$$\mathcal{A}_f(\Delta t) = \frac{\Gamma(\bar{B}^0 \to J/\psi K_S^0) - \Gamma(B^0 \to J/\psi K_S^0)}{\Gamma(\bar{B}^0 \to J/\psi K_S^0) + \Gamma(B^0 \to J/\psi K_S^0)}$$

$$= S_f \sin(\Delta m_B \Delta t) + A_f \cos(\Delta m_B \Delta t)$$

S_f: mixing-induced CPV



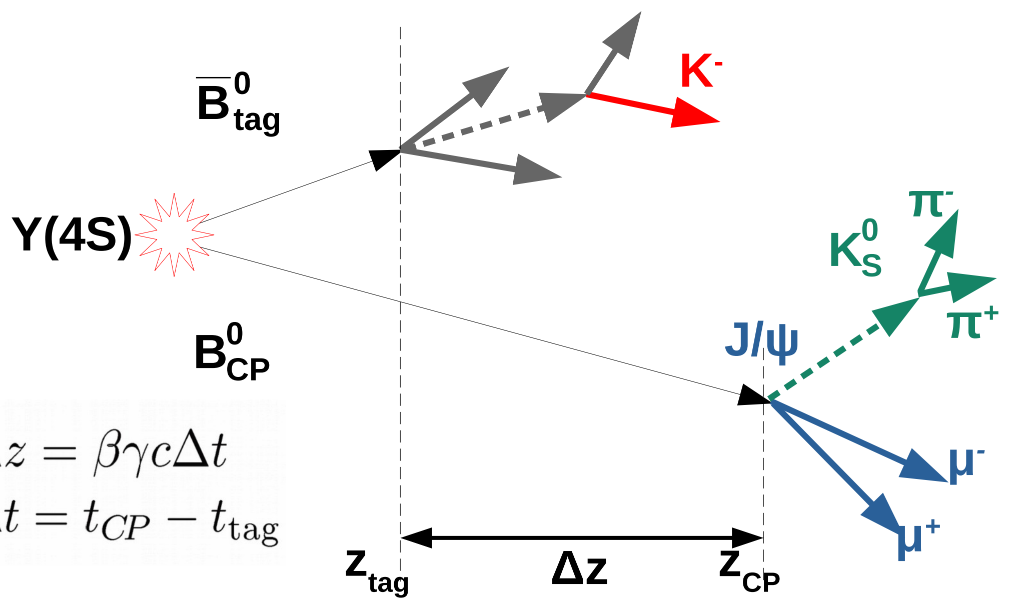
A_f: Direct CPV



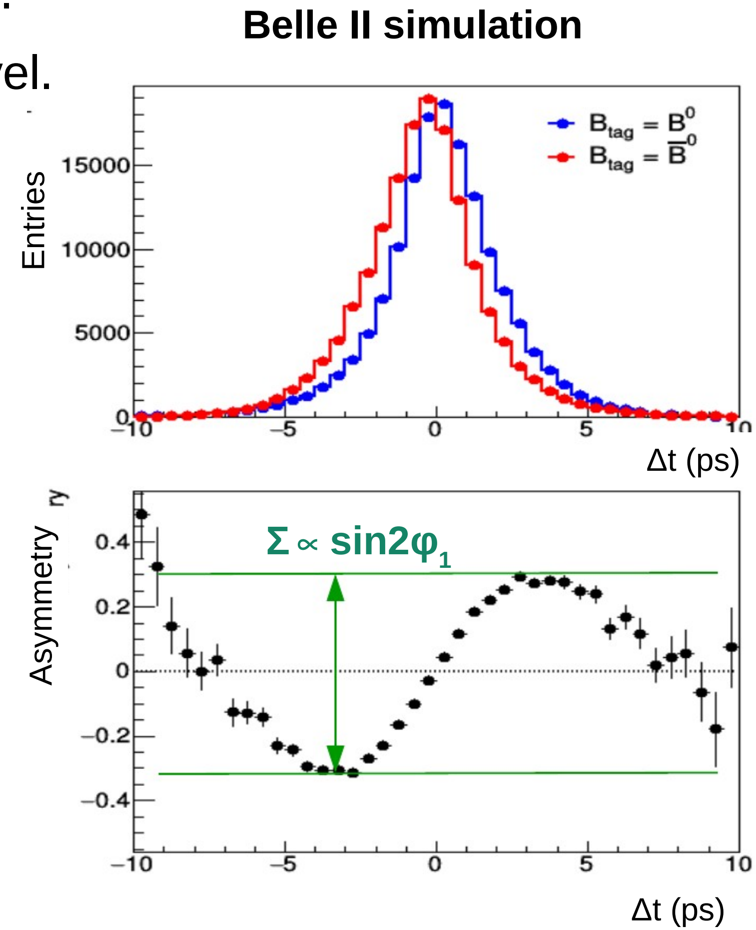
At tree-level: $S_f \sim \sin 2\varphi_1$, $A_f \sim 0$

TDCPV measurement @ Belle II

- **1. Flavor tagging**: Obtain the flavor of B mesons.
- **2. Vertexing**: Δz → Δt.
- **3. Δt distributions** for B^0 and $\overline{B}^0$ separately.
- **4. Asymmetry(Δt): S_f ~ sin(2φ_1)** at tree-level.



$$\Delta z = \beta\gamma c\Delta t$$
$$\Delta t = t_{CP} - t_{\text{tag}}$$



Flavor tagging

- Study B^0-$\overline{B}^0$ mixing and CP violation by identify the flavor of B mesons.
- Belle II new algorithm: MVA-based, more variables included. arXiv:2110.00790 [hep-ex] arXiv:2008.02707 [hep-ex]
- Effective tagging efficiency with Belle II MC:
  - **(37.16±0.03)%** , ~30% for Belle package.
  - Validated with Belle MC/data.

Concept:

1. Final state info (kaon, pion, proton, lepton).
2. Flavor of charmed particle (D, Λ_c).
3. Flavor of B.

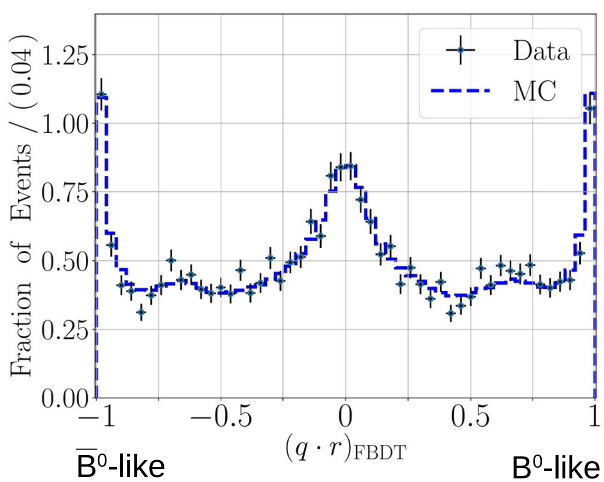
$$\overline{B}^0 \to D^{*+}\ \overline{\nu}_\ell\ \ell^- ,\quad D^{*+} \to D^0\ \pi^+ ,\quad D^0 \to X\ K^-$$

$$\overline{B}^0 \to D^+\ \pi^-\ (K^-) ,\quad D^+ \to K^0\ \nu_\ell\ \ell^+$$

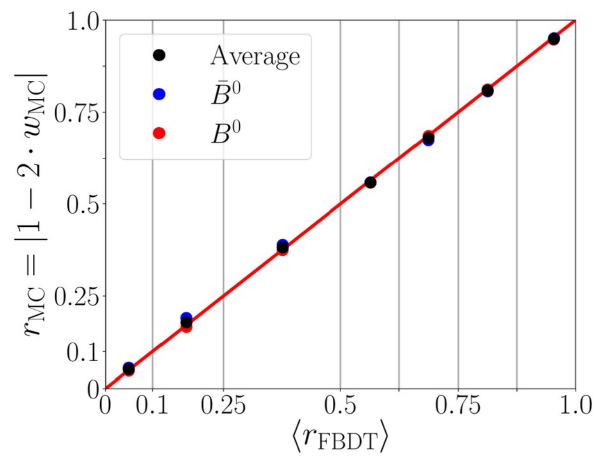
$$\overline{B}^0 \to \Lambda_c^+\ X^- ,\quad \Lambda_c^+ \to \Lambda\ \pi^+ ,\quad \Lambda \to p\ \pi^-$$

Validation with Belle data/MC

q: tagged flavor
r: quality flag



Belle II simulation



Linearity test

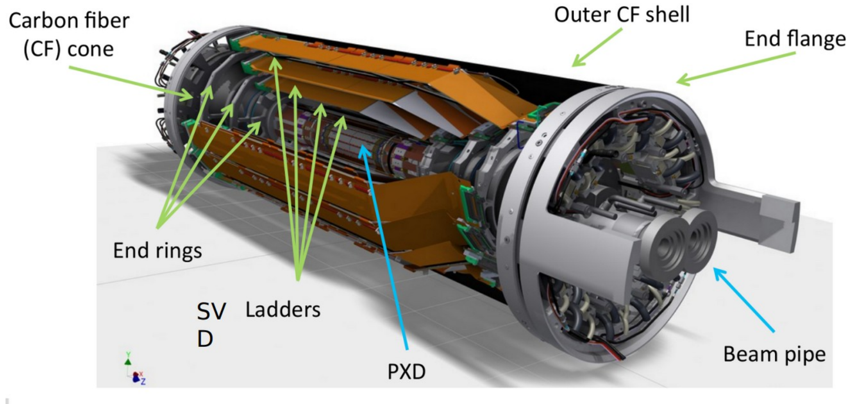
Decay time measurement

- Improved resolution in spite of reduced boost (βγ):
  - New inner vertex detectors:
    pixel vertex detector and silicon strip tracker.
  - Improved vertex fit softwares. IEEE TNS, 58, 434 – 444 (2011) CMS-NOTE-2008-033 NIMA552, 566–575 (2005)

$$\Delta z = \beta\gamma c \Delta t$$
$$\Delta t = t_{CP} - t_{\rm tag}$$

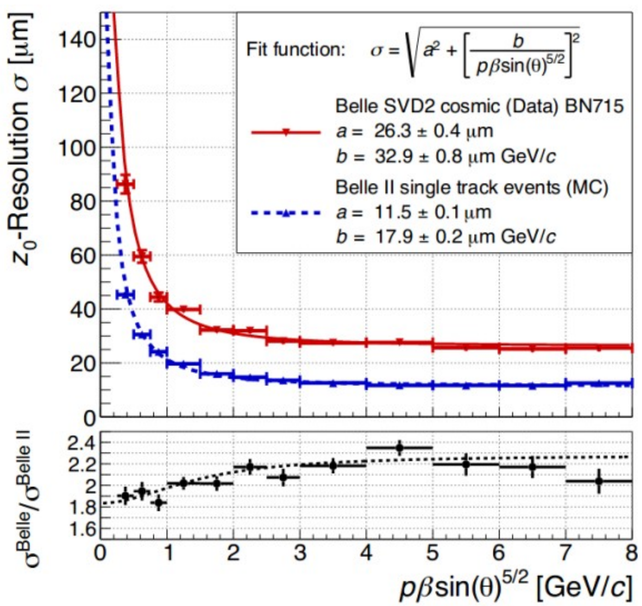
- A factor of 1.5~2 improvement compared to that of Belle.

Belle II pixel vertex detector



z resolution

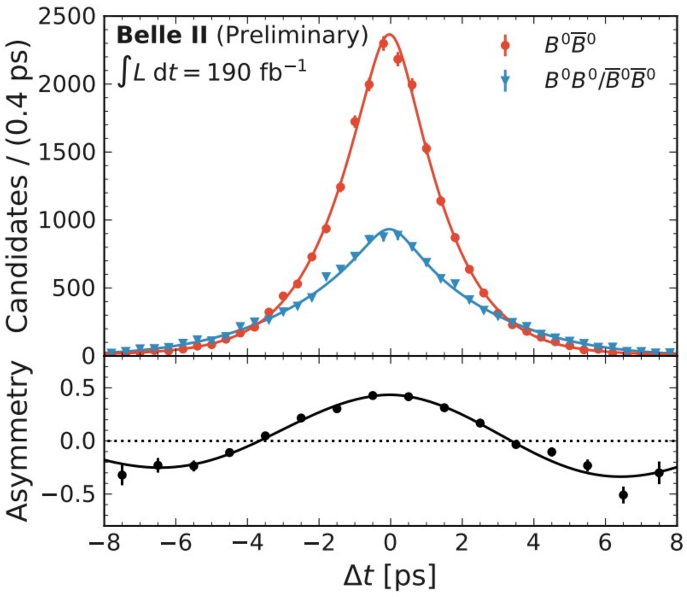
Belle data v.s. Belle II MC



Time-dependent mixing measurement

- Δm_B: Mass difference between eigenstates.
  - From B^0-$\overline{B}^0$ mixing measurement using flavor tagging.

- Belle II recent result:
  - Systematic uncertainty is smaller than that in Belle and BaBar.



New for JPS

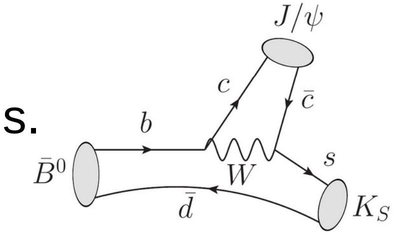
Belle II $B^0 \to D^{(*)-} K/\pi$
190 fb^{-1}

Δm_B = (0.516 ± 0.008 (stat.) ± 0.005 (syst.)) ps^{-1}

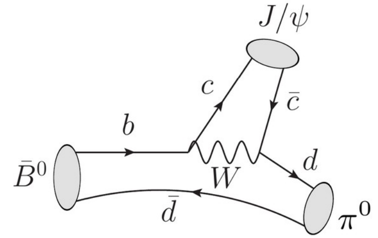
World average: Δm_B = (0.5065 ± 0.0019) ps^{-1}

φ_1: $b \to c\bar{c}s$

$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$



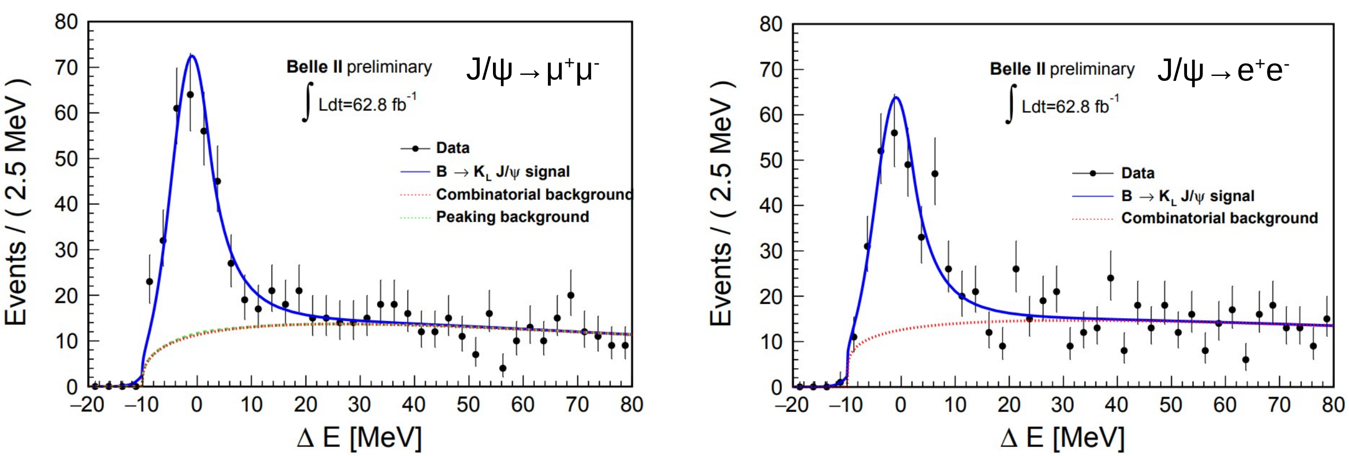
- φ_1 measurement with $\mathbf{b \to c\bar{c}s}$
  - Theoretical clean. Small contribution from other diagrams.
    $S_f \sim \xi_f \sin2\varphi_1$, ξ_f : CP eigenstate.
    $\mathbf{B^0 \to J/\psi\, K^0}$ golden mode. PRL 95, 221804 (2005)



- $\sin(2\varphi_1)$ world average: 0.699 ± 0.017
- Belle II sensitivity of $B^0 \to J/\psi\, K^0_S$ @ 50 ab^{-1}
  - Penguin pollution is not negligible:
    Constraint from $b \to c\bar{c}d$ e.g. $B^0 \to J/\psi\, \pi^0$ or other SU(3) related modes.
  - Systematic uncertainty dominates.
  - < 0.01 uncertainty on S_f.

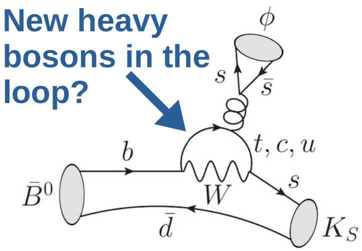
Belle II $\mathbf{B^0 \to J/\psi\, K^0_L}$ 62.8 fb^{-1}

arXiv: 2106.13547 [hep-ex]



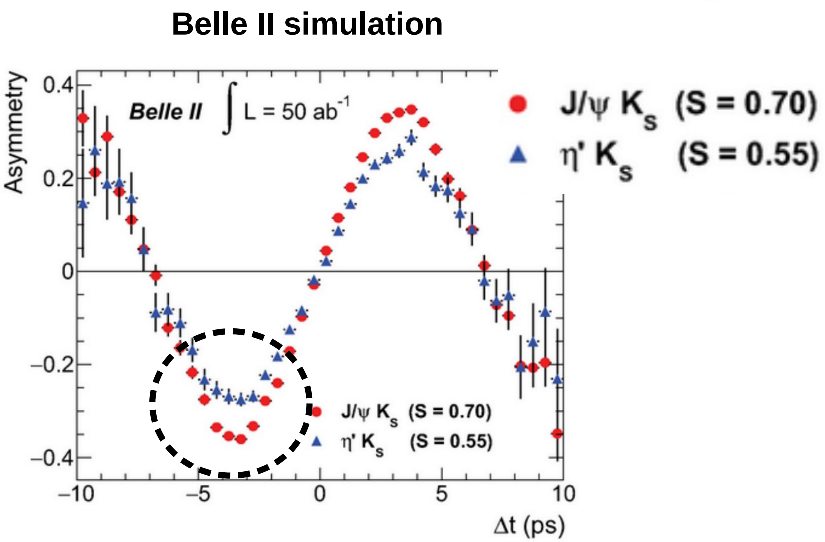
φ_1: $b \to s\bar{q}q$

- **$b \to s\bar{q}q$**:
  - $S_f = -\xi_f \sin 2\varphi_1^{eff} \sim -\xi_f \sin 2\varphi_1$ assuming only SM penguin.
  - Difference from **$b \to c\bar{c}s$**: NP in penguin loop.



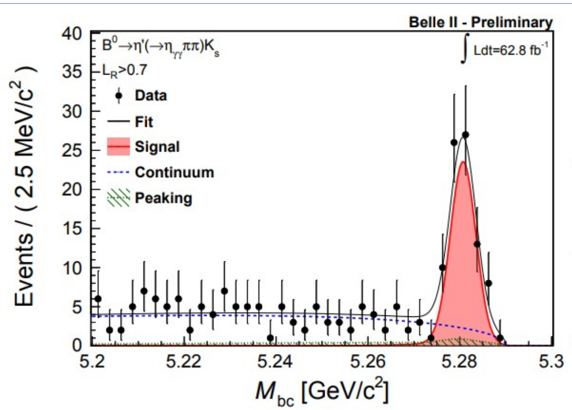
- Belle II Golden modes: $B^0 \to \eta' K^0$, $B^0 \to \varphi K^0$, $B^0 \to K^0 K^0 K^0$.
  - Advantage: neutral particle. Expect to have the best sensitivity.

- Belle II simulation @ 50 ab^{-1}
  - S_f of $B^0 \to \eta' K^0$ and $B^0 \to J/\psi K^0$
  - Able to see the difference if any.



Belle II $B \to \eta' K$
62.8 fb^{-1}

arXiv: 2104.06224 [hep-ex]



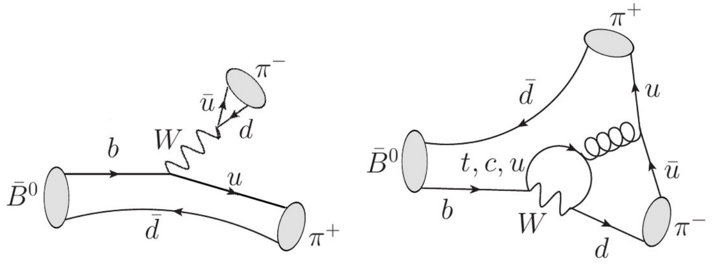
$$M_{bc} \equiv \sqrt{s/(4c^4) - (p_B^*/c)^2}$$

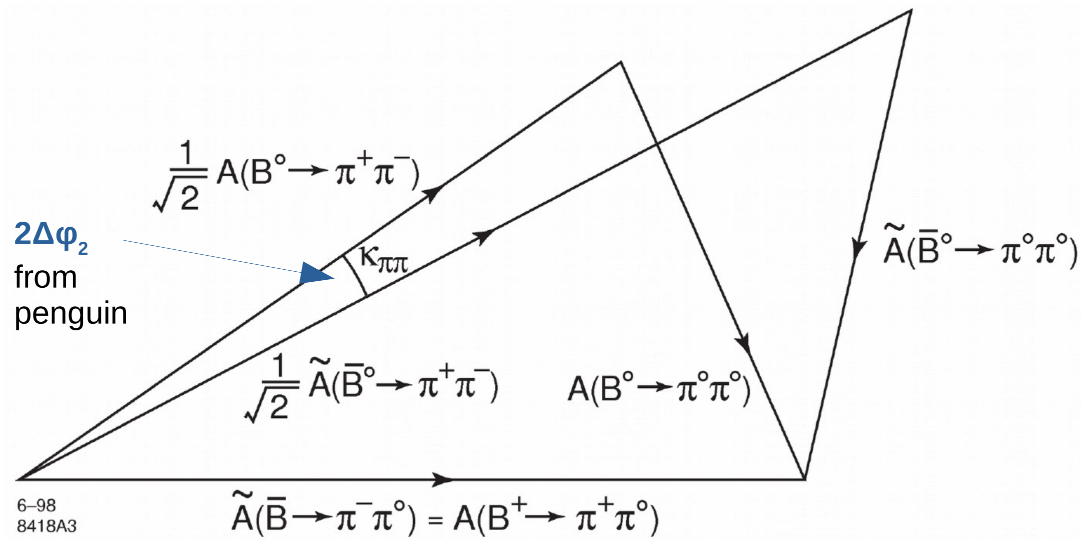
Channel	This analysis $\mathcal{B}$ ($\times 10^6$)	World average [9]
$B^\pm \to \eta' K$	$63.4\ ^{+3.4}_{-3.3}$(stat) ± 3.4(syst)	70.4 ± 2.5
$B^0 \to \eta' K^0$	$59.9\ ^{+5.8}_{-5.5}$(stat) ± 2.7(syst)	66 ± 4

φ_2

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

- φ_2 measurement: From $b \to u$ tree with non-negligible $b \to d$ penguin.
  - Isospin analysis with $B \to hh$ modes ($h=\pi,\rho$).
- Compared with LHCb, Belle II can measure all of these isospin modes.





Eur. Phys. J. C77 (2017) no. 8, 574

φ_2: B→hh

- Charmless hadronic B decays:
  - Challenge: large combinatorial background from $e^+e^- \to q\bar{q}$ continuum process.
  - PID: K/π suppression.
  - Continuum suppression: Based on MVA tool (BDT).

- Belle II recent results:
  - 2D fit with ΔE and M_{bc}.

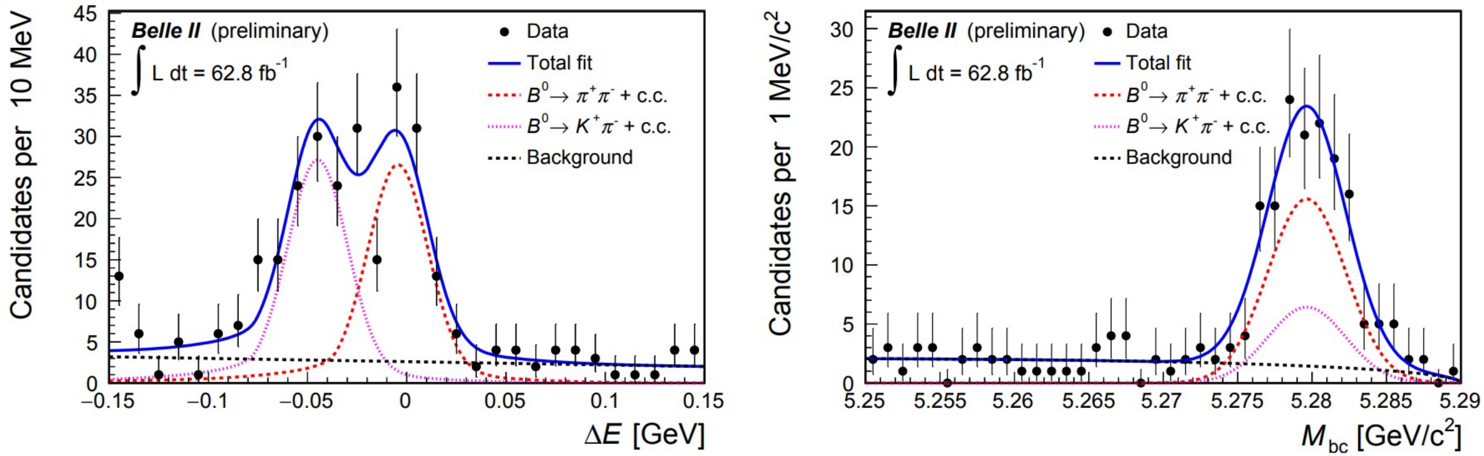
$$\Delta E \equiv E_B^* - \sqrt{s}/2$$

$$M_{\rm bc} \equiv \sqrt{s/(4c^4) - (p_B^*/c)^2}$$

defined in center-of-momentum frame

Belle II $B^0 \to h^+\pi^-$ 62.8 fb^{-1}

arXiv:2106.03766 [hep-ex]



$$\mathcal{B}(B^0 \to \pi^+\pi^-) = [5.8 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})] \times 10^{-6}$$

Also see: **Belle II $B^+ \to h^+\pi^0$ 62.8 fb^{-1}** arXiv:2105.04111 [hep-ex]

φ_2: B → ρρ

Preliminary

- $B^0 \to \rho^0\rho^0$: Golden mode for φ_2 determination.
- $B^+ \to \rho^0\rho^+$: Estimate penguin pollution

- Challenge:
  Combinatorial background due to pion-only final state and wide ρ peak.

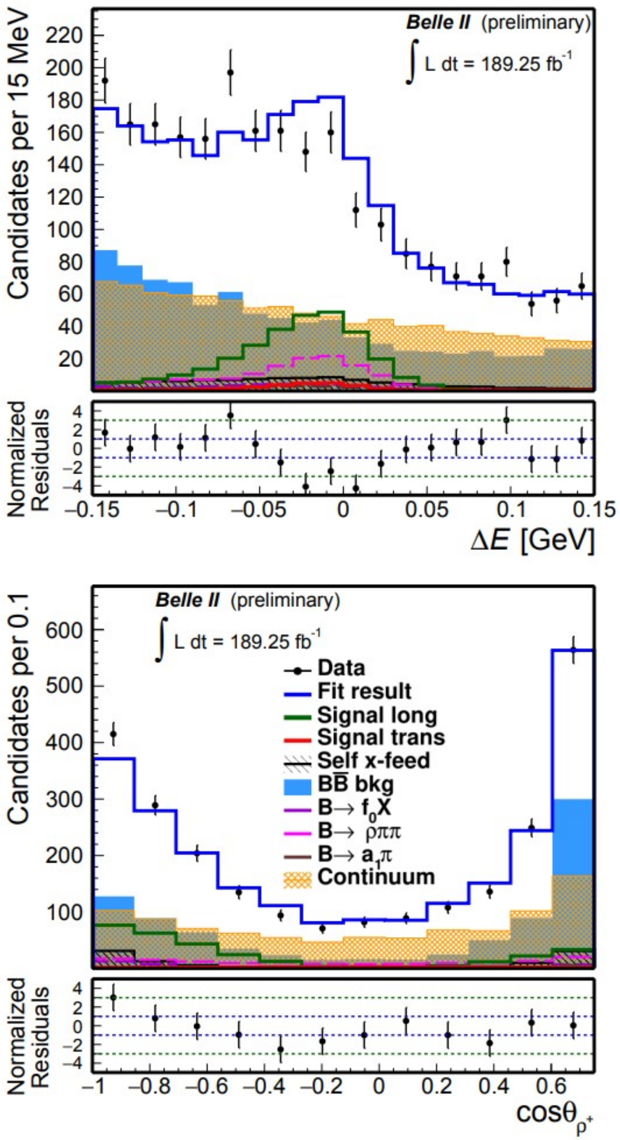
- 6D fit:
  - Angular analysis: need to measure longitudinal polarization fraction (f_L).
  - ΔE, continuum suppression, ρ masses (2), cosine of the helicity angle of ρ (2).

$$\mathcal{B}(B^+ \to \rho^+\rho^0) = [22.1^{+\,2.1}_{-\,2.0}(\mathrm{stat}) \pm 2.6(\mathrm{syst})] \times 10^{-6},$$

$$f_{\mathrm{L}} = 0.943^{+\,0.035}_{-\,0.033}(\mathrm{stat}) \pm 0.026(\mathrm{syst}),$$

$$\mathcal{A}_{\mathrm{CP}} = -0.069 \pm 0.068(\mathrm{stat}) \pm 0.039(\mathrm{syst}).$$

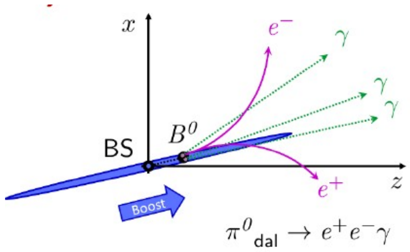
Belle II $B^+ \to \rho^+\rho^0$ 189.3 fb^{-1}



φ_2: Belle II prospect

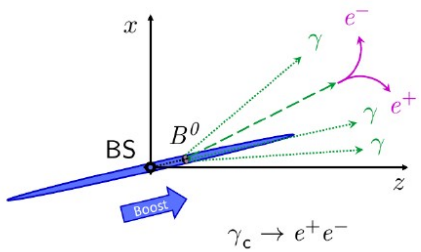
- TDCPV of $B^0 \to \pi^0\pi^0$ is unique for Belle II with target full data.
  - Use **π^0 Dalitz decay ($\to \gamma\ e^+\ e^-$)** and **γ ($\to e^+\ e^-$) conversion** for vertexing.
  - @ 50 ab^{-1}: Expect ~270 signal yields, uncertainty of $S(\pi^0\pi^0)$ ~ 0.28

π^0 Dalitz decay



Δt resolution
= 1.14 ± 0.03 ps

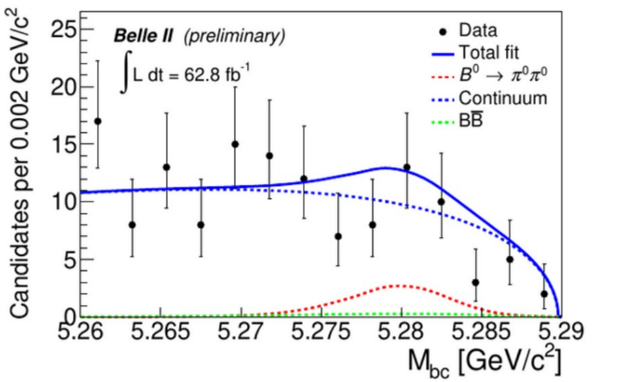
γ conversion



Δt resolution
= 1.12 ± 0.04 ps

arXiv:2107.02373 [hep-ex]

Belle II $B^0 \to \pi^0\pi^0$ 62.8 fb^{-1}
($\pi^0 \to \gamma\gamma$)



$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (0.98^{+0.48}_{-0.39} \pm 0.27) \times 10^{-6}$$

significance: 3.4σ

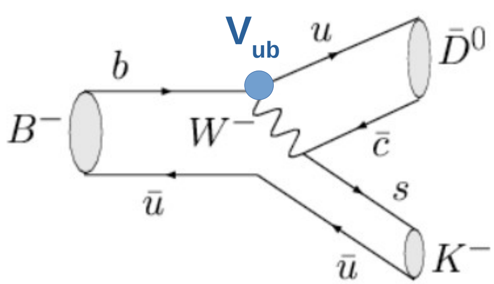
- Belle II prospect:
  - $S(\pi^0\pi^0)$: reduce the ambiguity in φ_2 determination by a factor of 2 or 4.
  - Combining all $\rho\rho + \pi\pi + S(\pi^0\pi^0)$: φ_2 sensitivity ~ 0.6° @ 50 ab^{-1}

φ_3

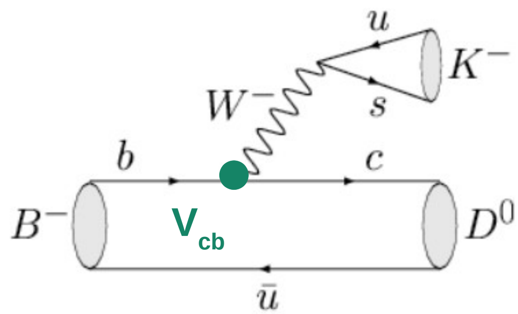
$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

- φ_3 is measured by the phase difference between tree amplitudes of $B\to D^{(*)}K^{(*)}$ decays
  - Interference between b → c (favored) and b → u (suppressed).
  - As no penguin contribution, theoretical uncertainty is small. $\delta\varphi_3/\varphi_3 \sim 10^{-7}$ JHEP 01, 015 (2014)

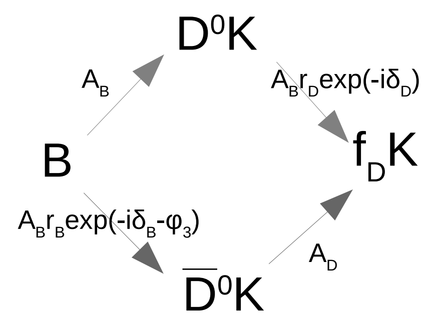
b → u (suppressed)



b → c (favored)



Using self-conjugate D^0 decay



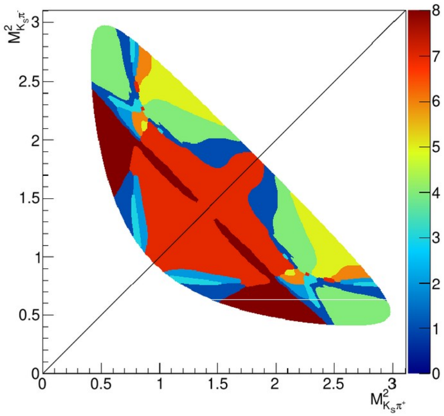
$$\frac{A(B^-\to\overline{D}^0K^-)}{A(B^-\to D^0K^-)} = r_Be^{i(\delta_B-\phi_3)}$$

r_B : ratio of amplitudes ~ 0.1
HFLAV16, Eur. Phys. J. C 77 (2017) 895

δ_B : strong phase difference. External input from charm factory.

φ_3: GGSZ

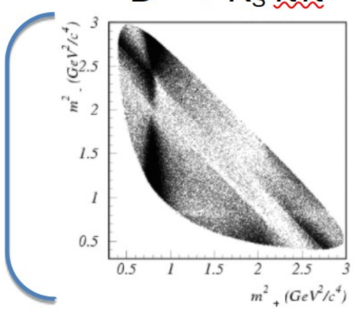
- Belle II Golden mode: GGSZ with amplitude analysis
  - Model-independent amplitude analysis:
    ~9% uncertainty due to amplitude modeling at Belle and BaBar.
  - Fit on symmetrical bins to obtain yields from D flavor eigenstates.



Dalitz binning (from CLEO)

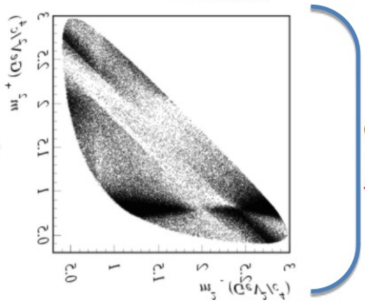
PRD 82, 112006 (2010)

$D^0 \rightarrow K^0_S \pi\pi$



$$+r_B e^{\pm i\phi_3 + i\delta_B}$$

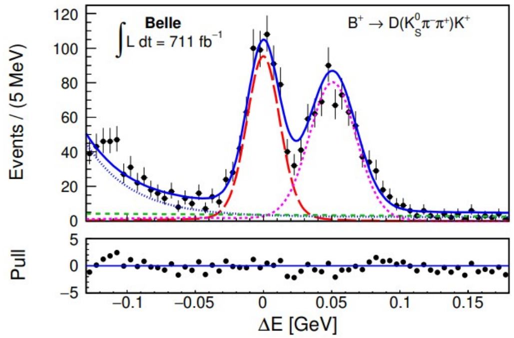
$\overline{D}^0 \rightarrow K^0_S \pi\pi$

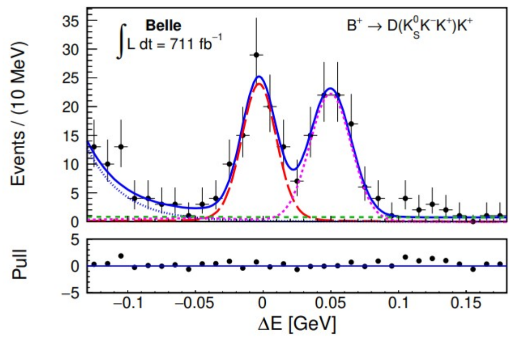


observable Dalitz plane

$$\mathrm{d}\Gamma_{B^-}(m_+^2, m_-^2) \propto |A_+|^2 + r_B^2|A_-|^2 + 2r_B|A_+||A_-|\left(\cos\delta_D\cos(\delta_B+\phi_3) - \sin\delta_D\sin(\delta_B+\phi_3)\right)\mathrm{d}p$$

- **The latest result with Belle (771 fb^{-1}) + Belle II (128 fb^{-1}): 1st paper with combined data!** JHEP 02 2022, 063 (2022)





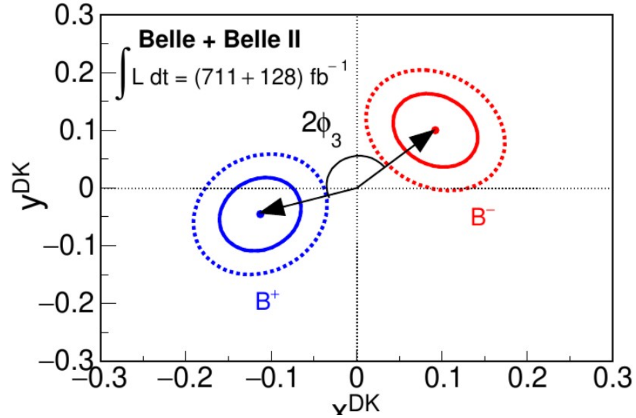
Belle: PRD 85, 112014 (2012)

$$\phi_3 = (77.3^{+15.1}_{-14.9} \pm 4.1 \pm 4.3)^\circ$$

Belle + Belle II:

$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ\,,$$
$$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002,$$
$$\delta_B^{DK} = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ\,.$$

3rd uncertainty: ext. input



$$(x_\pm, y_\pm) = r_B(\cos(\delta_B \pm \phi_3), \sin(\delta_B \pm \phi_3))$$

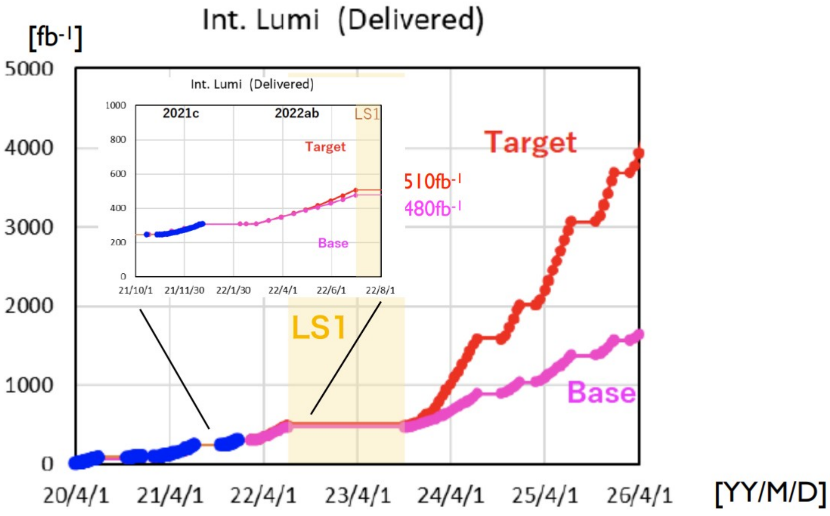
- Belle II prospect:
  - Present precision by LHCb: 4°.
  - Assume 10 fb^{-1} ψ(3770) data from BES-III:
    $\delta\varphi_3$(50 ab^{-1}) = 3° using GGSZ
    $\delta\varphi_3$(50 ab^{-1}) = 1.6° with other D decay modes.

Summary

- Measurements on CKM matrix elements offer a good probe for SM precision test and NP search in flavor sector.

- Belle II will play a key role in it.
  - Much larger data set.
  - Improvements on software, methodologies, and systematics.
  - Unique sensitivity and capability of most decay modes.
  - Preliminary studies with Belle II early data have been performed for each.

- Stay tuned with us to look forward to more results from Belle II.



LS1: Full pixel detector installation, readout upgrade for DAQ, etc.

Other Belle II talks with new results @ JPS Spring 2022

- 15aA561
  - 10. 伊藤慎太郎「Belle-II 実験における heavy QCD axion を伴った $B^+ \rightarrow K^+ a$ 崩壊の探索」
- 16pA573
  - 8. 植松祐真 「Belle II 実験における B0→$K_S^0\pi^0\gamma$ 過程の時間依存 CP 非対称度の解析に向けた研究」
  - 9. 杉浦亮平 「Belle II 実験における B0→$K^+K^-K^0_S$ 崩壊過程の時間依存 CP 非対称度の解析に向けた研究」
  - 10. 古賀太一朗 「BelleII 実験における B->D*lnu 崩壊分岐比と CKM 行列要素 |Vcb| の測定」
  - 11. 裵漢郁 「Belle II 実験における $B^0 \rightarrow$ eta' K_S 崩壊課程での時間依存 CP 対称性破れ測定の研究」
  - 12. 楠戸愛美 「Belle II 実験における $B^0 \rightarrow J/\psi K^{*0}(\rightarrow K^+\pi^-)$ モードによるフレーバー識別の較正と Δt 分解能の評価」
  - 13. 谷川輝 「Belle II 実験における B0→$K_S^0K_S^0K_S^0$ 過程の時間依存 CP 非対称度の測定」
- 19pS06
  - 4. 大強度ビームと標的技術が拓く素粒子・原子核実験の新展開
    吉原圭亮 「高ルミノシティマシンで探す新たな物理法則」

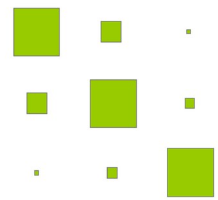
Backup

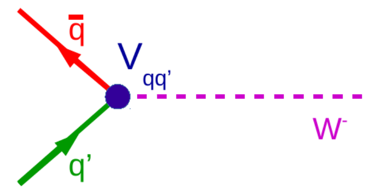
CKM matrix

- Cabibbo-Kobayashi-Maskawa (CKM) matrix
  - Describes mixing of quacks via weak interaction in Standard Model (SM).

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Relative magnitude





The complex phase represents the source of CV violation in SM.

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Wolfenstein parameterization

- Unitarity:

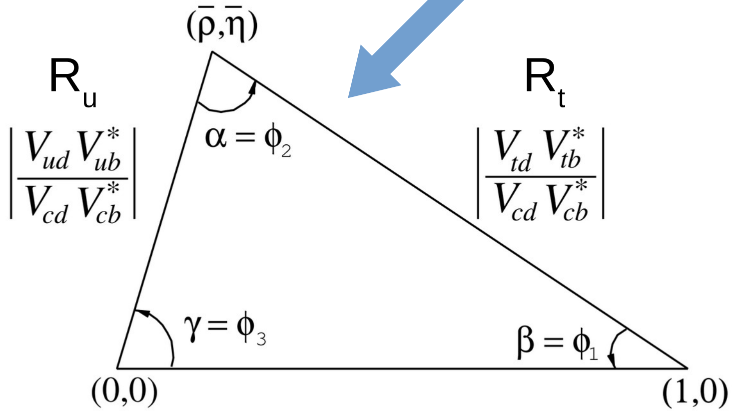
$$V^\dagger V = 1 \Rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$\lambda^3 * 1$ $\lambda^2 * \lambda$ $1 * \lambda^3$

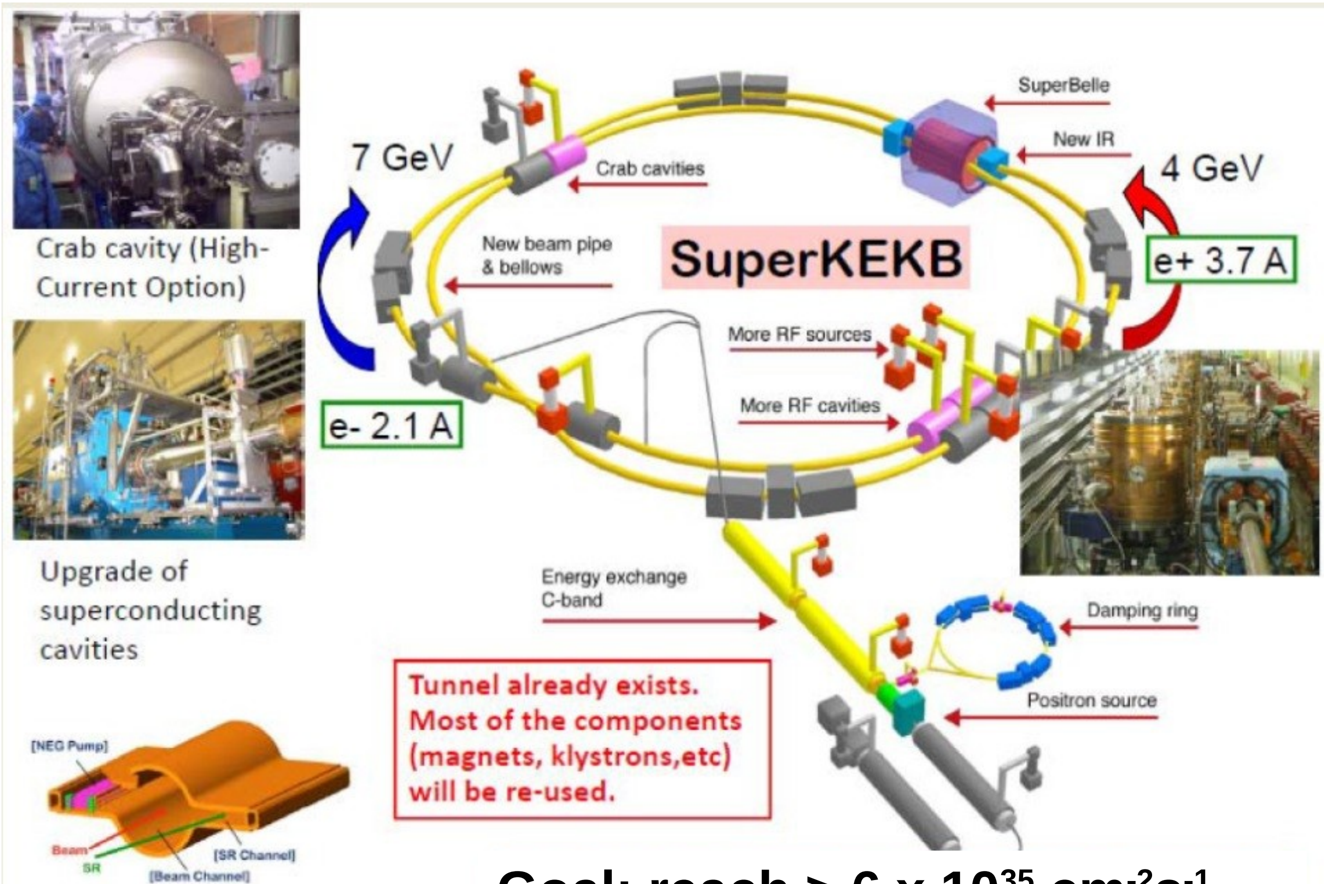
$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$



SuperKEKB



Goal: reach > 6 x 10^{35} $cm^{-2}s^{-1}$

- Current results:

Global git by CKM fitter

$\beta = \varphi_1 = (23.7 ^{+1.3}_{-1.2})°$

$\alpha = \varphi_2 = (91.8 ^{+2.7}_{-2.1})°$

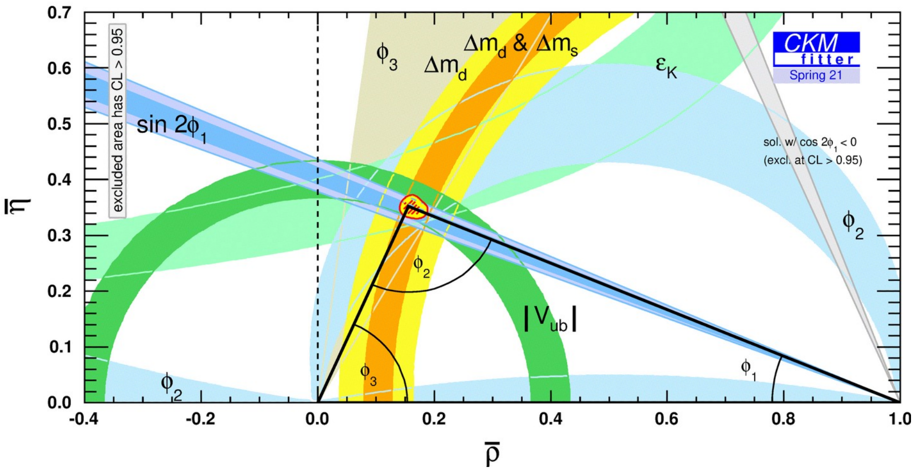
$\gamma = \varphi_3 = (65.6 ^{+0.9}_{-2.6})°$

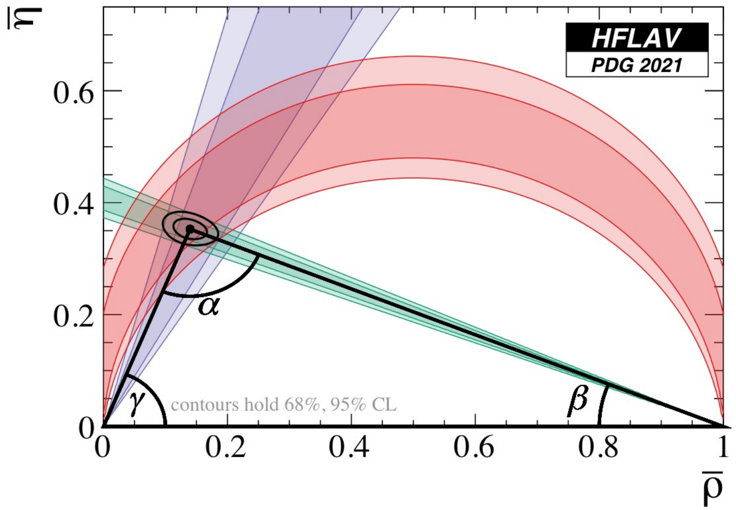
World average by HFLAV

$\beta = \varphi_1 = (22.2 \pm 0.7)°$

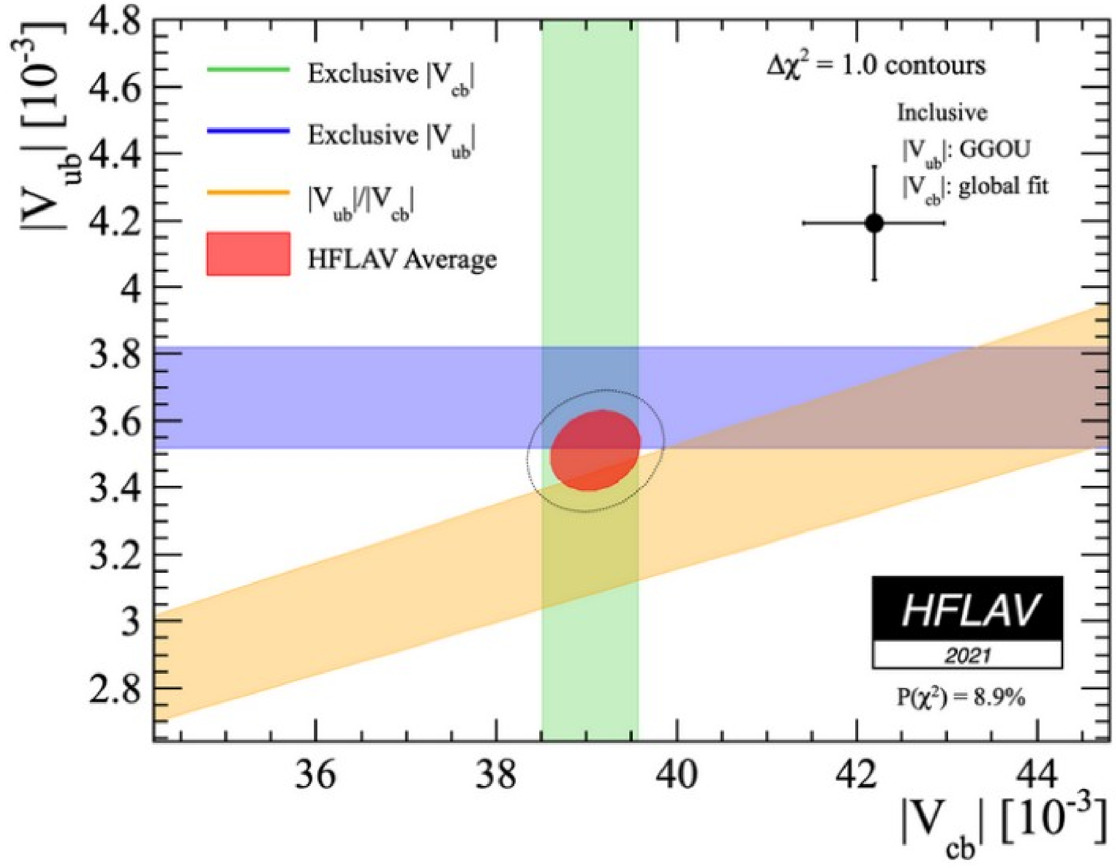
$\alpha = \varphi_2 = (85.2 ^{+4.8}_{-4.3})°$

$\gamma = \varphi_3 = (66.2 ^{+3.4}_{-3.6})°$





- Current results:



$|V_{cb}|$ exclusive determination

- dBF of $B \to D^{(*)} l \nu$ as a function of w:
  - η_{EW} is electroweak correction: 1.006

Prog. Theor. Phys. 49, 652
Phys. Rept. 245, 259

Nucl. Phys. B 196 (1982) 83-92
PRD 79 (2009) 014506
Nucl. Phys. B 530 (1998) 153-181

$$\frac{d\Gamma}{dw} = \frac{\eta_{\rm EW}^2 G_F^2}{48\pi^3} m_{D^*}^3 (m_B - m_{D^*})^2 g(w) F^2(w) |V_{cb}|^2$$

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

$$g(w)F^2(w) = h_{A_1}^2(w)\sqrt{w^2-1}(w+1)^2 \left\{ 2\left[\frac{1-2wr+r^2}{(1-r)^2}\right] \times \left[1 + R_1^2(w)\frac{w-1}{w+1}\right] + \left[1 + (1-R_2(w))\frac{w-1}{1-r}\right]^2 \right\}$$

$$r = \frac{m_{D^*}}{m_B}$$

- $h_{A1}(w)$, $R_1(w)$, $R_2(W)$: form factors, CLN parameterization:
- ρ, $h_{A1}(1)$, $R_1(1)$, $R_2(1)$: form factor constants.

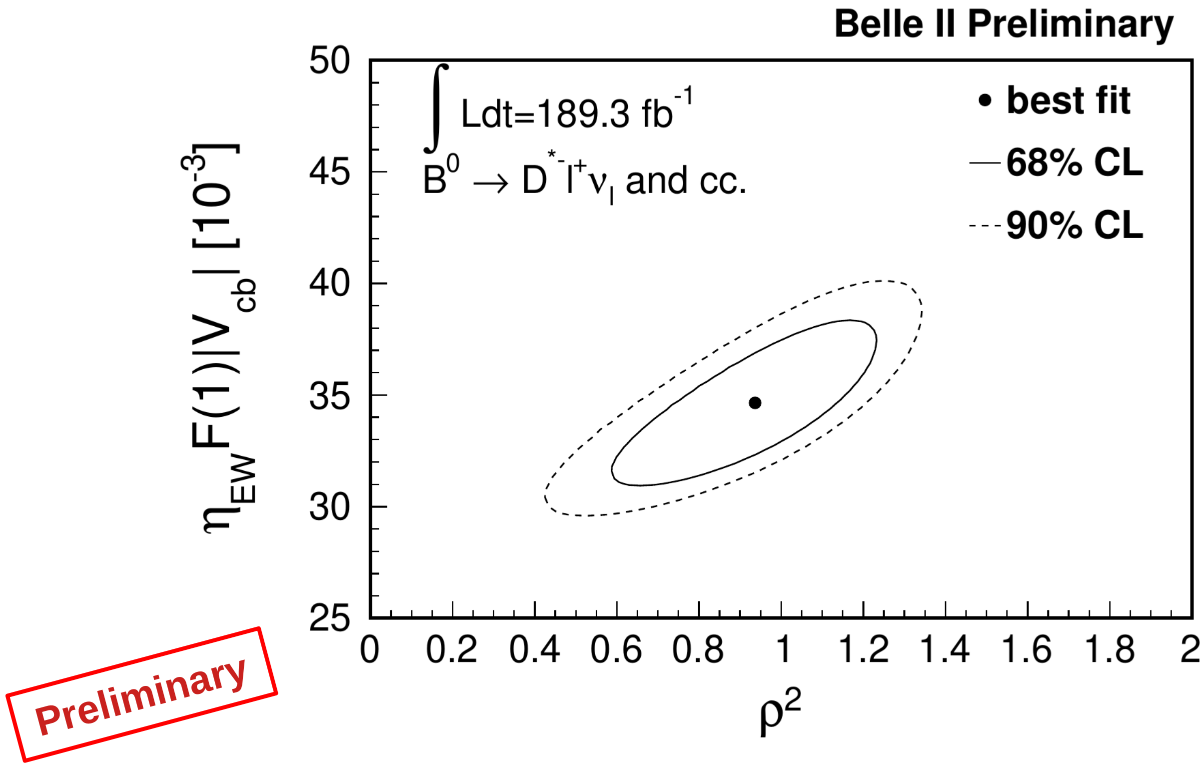
$$h_{A_1}(w) = h_{A_1}(1)\left[1 - 8\rho^2 z + (53\rho^2 - 15)z^2 - (231\rho^2 - 91)z^3\right]$$

$$R_1(w) = R_1(1) - 0.12(w-1) + 0.05(w-1)^2$$

$$R_2(w) = R_2(1) - 0.11(w-1) - 0.06(w-1)^2$$

$$z = \frac{\sqrt{w+1} - \sqrt{2}}{\sqrt{w+1} + \sqrt{2}}$$

$|V_{cb}|$ exclusive determination



$$\eta_{EW} F(1)|V_{cb}| \left(B^- \to D^{*0} l^- \overline{\nu}_\ell\right) = 0.0351 \pm 0.0030(stat. + syst.)$$

$$\rho^2 \left(B^- \to D^{*0} l^- \overline{\nu}_\ell\right) = 1.03 \pm 0.27(stat. + syst.)$$

$$\eta_{EW} F(1)|V_{cb}| \left(B^0 \to D^{*-} l^+ \nu_\ell\right) = 0.0352 \pm 0.0028(stat. + syst.)$$

$$\rho^2 \left(B^0 \to D^{*-} l^+ \nu_\ell\right) = 1.04 \pm 0.22(stat. + syst.)$$

$|V_{ub}|$ prospect

	Statistical	Systematic (reducible, irreducible)	Total Exp	Theory	Total
$\|V_{ub}\|$ exclusive (had. tagged)					
711 fb^{-1}	3.0	(2.3, 1.0)	3.8	7.0	8.0
5 ab^{-1}	1.1	(0.9, 1.0)	1.8	1.7	3.2
50 ab^{-1}	0.4	(0.3, 1.0)	1.2	0.9	1.7
$\|V_{ub}\|$ exclusive (untagged)					
605 fb^{-1}	1.4	(2.1, 0.8)	2.7	7.0	7.5
5 ab^{-1}	1.0	(0.8, 0.8)	1.2	1.7	2.1
50 ab^{-1}	0.3	(0.3, 0.8)	0.9	0.9	1.3
$\|V_{ub}\|$ inclusive					
605 fb^{-1} (old B tag)	4.5	(3.7, 1.6)	6.0	2.5–4.5	6.5–7.5
5 ab^{-1}	1.1	(1.3, 1.6)	2.3	2.5–4.5	3.4–5.1
50 ab^{-1}	0.4	(0.4, 1.6)	1.7	2.5–4.5	3.0–4.8
$\|V_{ub}\|$ $B \to \tau\nu$ (had. tagged)					
711 fb^{-1}	18.0	(7.1, 2.2)	19.5	2.5	19.6
5 ab^{-1}	6.5	(2.7, 2.2)	7.3	1.5	7.5
50 ab^{-1}	2.1	(0.8, 2.2)	3.1	1.0	3.2
$\|V_{ub}\|$ $B \to \tau\nu$ (SL tagged)					
711 fb^{-1}	11.3	(10.4, 1.9)	15.4	2.5	15.6
5 ab^{-1}	4.2	(4.4, 1.9)	6.1	1.5	6.3
50 ab^{-1}	1.3	(2.3, 1.9)	2.6	1.0	2.8

φ_1: $b \to c\bar{c}s$, Belle II prospect

- $B^0 \to J/\psi K_S^0$ @ 50 ab^{-1}: Systematic uncertainty dominates.
- Penguin pollution is not negligible @ 50 ab^{-1}: constraint from $b \to c\bar{c}d$ such as $B^0 \to J/\psi \pi^0$ or other SU(3) related modes.

Belle $B^0 \to J/\psi K_S^0$ PRL, 108, 171802 (2012)

$$S_{J/\psi K_S^0} = +0.670 \pm 0.029(\text{stat}) \pm 0.013(\text{syst}),$$

sin($2\varphi_1$) = 0.699 ± 0.017 (world average)

$$A_{J/\psi K_S^0} = -0.015 \pm 0.021(\text{stat}) \,^{+0.045}_{-0.023}(\text{syst}).$$

Ultimate sensitivity by Belle II on $B^0 \to J/\psi K_S^0$ @50 ab^{-1}

Irreducible syst.: Alignment of the vertex detector

	Refer to Belle	Assume 50% improvement on vertexing related syst,	use only leptonic categories in flavor tagging
	No improvement	Vertex improvement	Leptonic categories
$S_{J/\psi K_S^0}$ (50 ab^{-1})			
stat.	0.0035	0.0035	0.0060
syst. reducible	0.0012	0.0012	0.0012
syst. irreducible	0.0082	0.0044	0.0040
$A_{J/\psi K_S^0}$ (50 ab^{-1})			
stat.	0.0025	0.0025	0.0043
syst. reducible	0.0007	0.0007	0.0007
syst. irreducible	$^{+0.043}_{-0.022}$	$^{+0.042}_{-0.011}$	0.011

Belle II Physics Book PTEP 2019, 123C01

φ_1: $b \to c\bar{c}q$, Belle II prospect (cont'd)

- $b \to c\bar{c}s$ @ 50 ab^{-1}.
- ξ_f (CP eigenstate) = -1 : $B^0 \to J/\psi K^0_S$, $B^0 \to \psi(2S) K^0_S$, $B^0 \to \chi_{c1} K^0_S$.
  ξ_f (CP eigenstate) = +1 : $B^0 \to J/\psi K^0_L$
- Other $b \to c\bar{c}X$ modes: $B^0 \to \psi(X) K^0_S$, $B^0 \to J/\psi V$, $B^0 \to D^{(*)+}D^{(*)-}$.

Belle all $b \to c\bar{c}s$

$$S_{c\bar{c}s} = 0.667 \pm 0.023(\text{stat}) \pm 0.012(\text{syst}),$$

$$A_{c\bar{c}s} = 0.006 \pm 0.016(\text{stat}) \pm 0.012(\text{syst}),$$

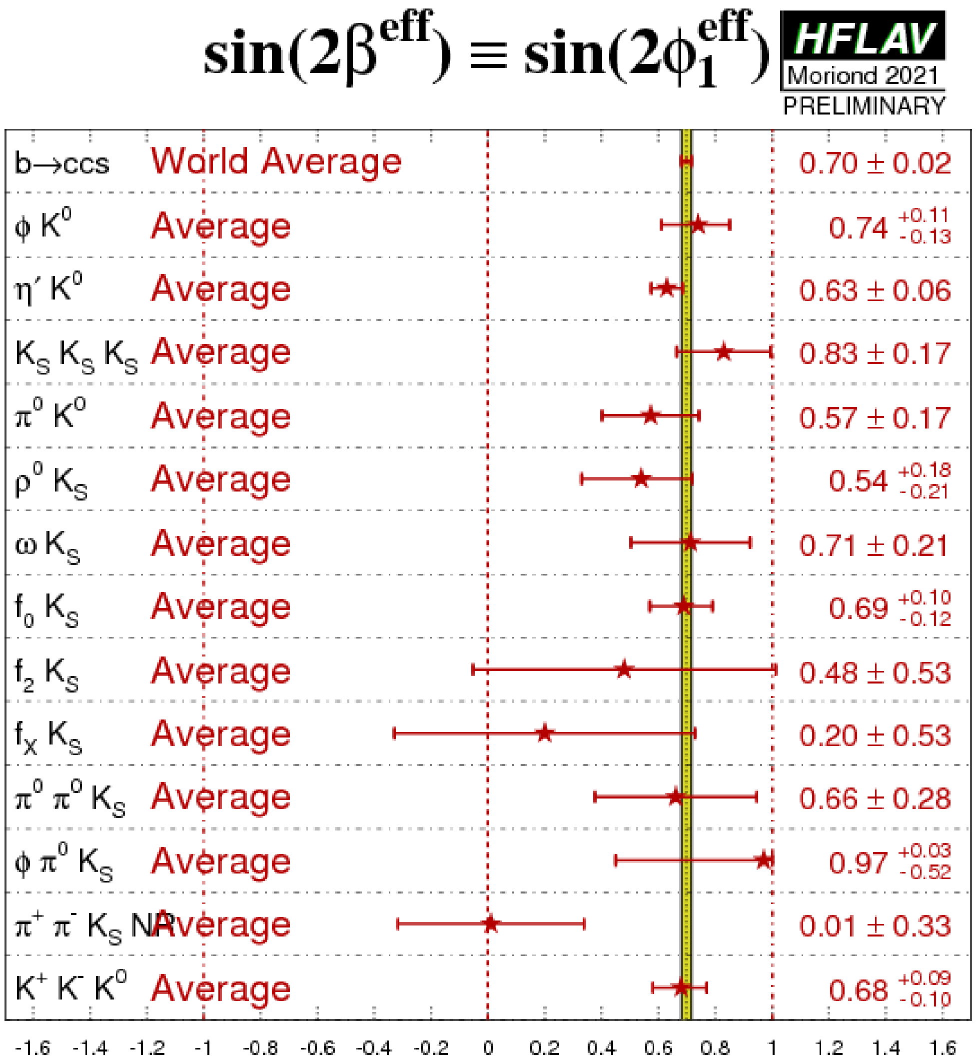
$\sin(2\varphi_1)$ = 0.699 ± 0.017 (world average)

Belle II sensitivity on all $b \to c\bar{c}s$ @50ab^{-1}

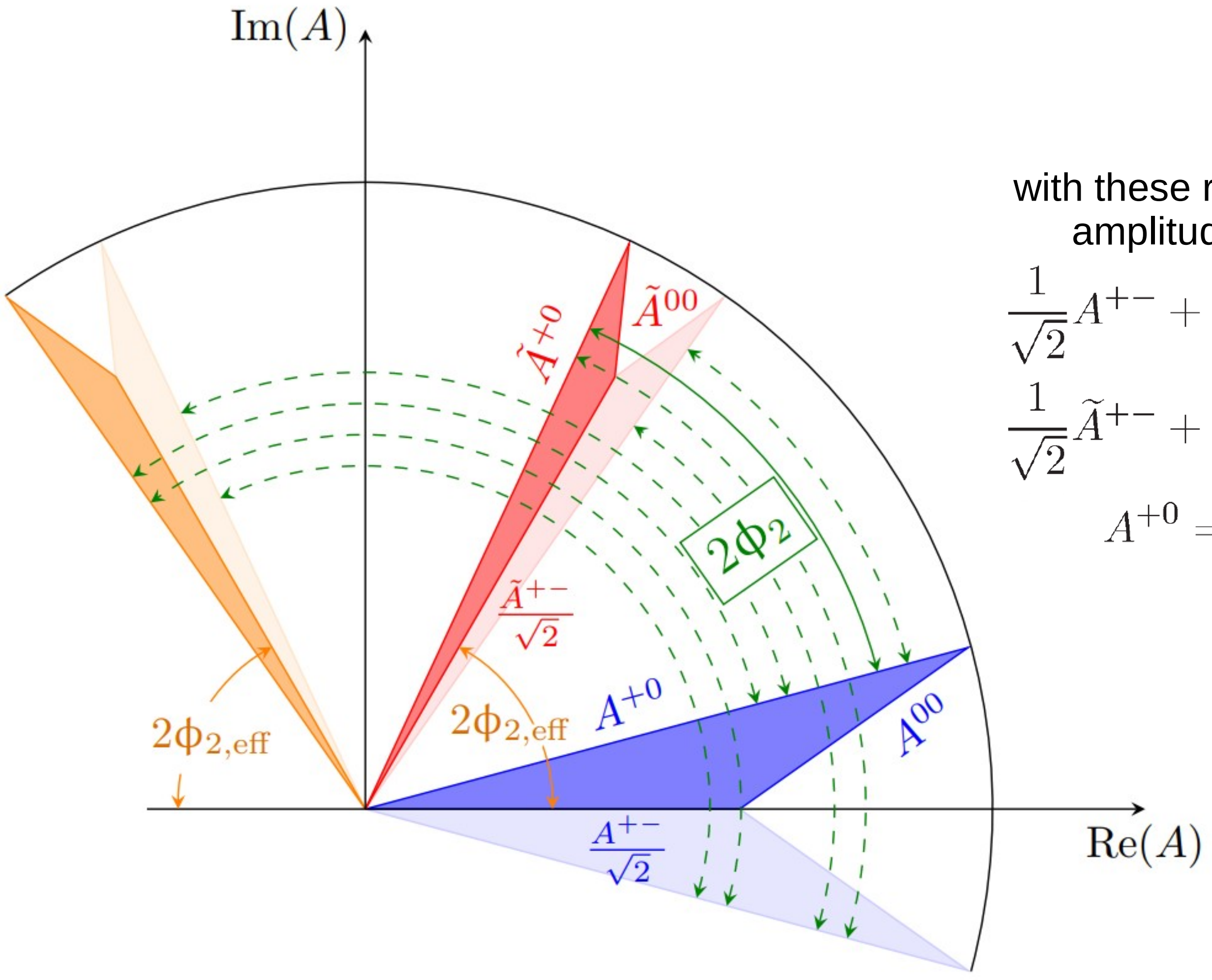
	Refer to Belle No improvement	Assume 50% improvement on vertexing related syst, Vertex improvement	use only leptonic categories in flavor tagging Leptonic categories
$S_{c\bar{c}s}$ (50 ab^{-1})			
stat.	0.0027	0.0027	0.0048
syst. reducible	0.0026	0.0026	0.0026
syst. irreducible	0.0070	0.0036	0.0035
$A_{c\bar{c}s}$ (50 ab^{-1})			
stat.	0.0019	0.0019	0.0033
syst. reducible	0.0014	0.0014	0.0014
syst. irreducible	0.0106	0.0087	0.0035

Belle II Physics Book PTEP 2019, 123C01

$\sin(2\varphi_1^{eff})$ for $b \to s q\bar{q}$ penguin



φ$_2$: Isospin analysis



with these relations on amplitudes hold:

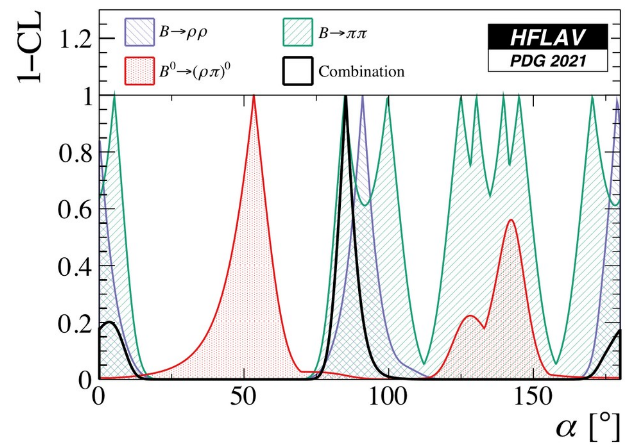
$$\frac{1}{\sqrt{2}}A^{+-} + A^{00} = A^{+0}$$

$$\frac{1}{\sqrt{2}}\tilde{A}^{+-} + \tilde{A}^{00} = \tilde{A}^{+0}$$

$$A^{+0} = \tilde{A}^{+0}$$

φ_2: Belle II Prospect

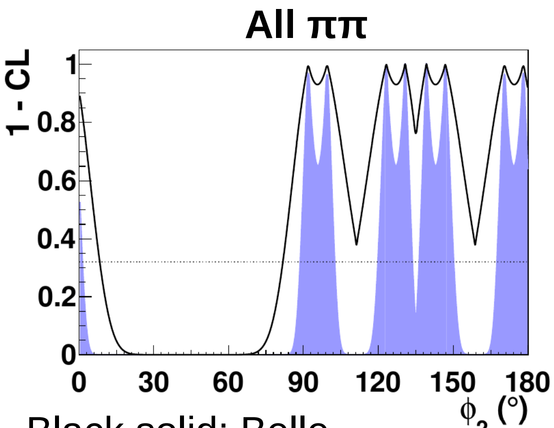
- $S(\pi^0\pi^0)$ would reduce the ambiguity in φ_2 determination by a factor of 2 or 4, depending on the measured central value.



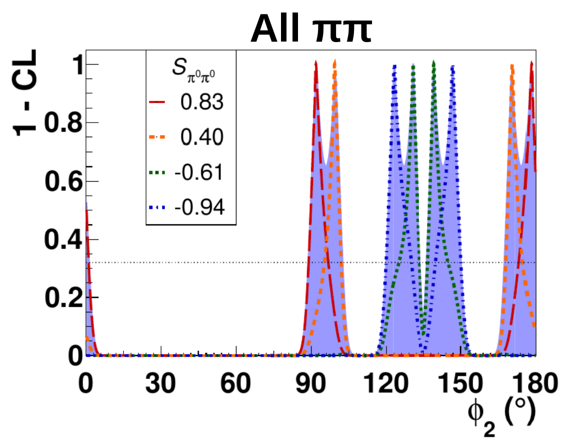
- $(85.2^{+4.8}_{-4.3})°$ by World average (HFLAV)
- $(91.8^{+2.7}_{-1.0})°$ by Global fit (CKM fitter)

- Belle II combining all $\rho\rho + \pi\pi + S(\pi^0\pi^0)$:
  - φ_2 sensitivity ~ 0.6° @50 ab^{-1}

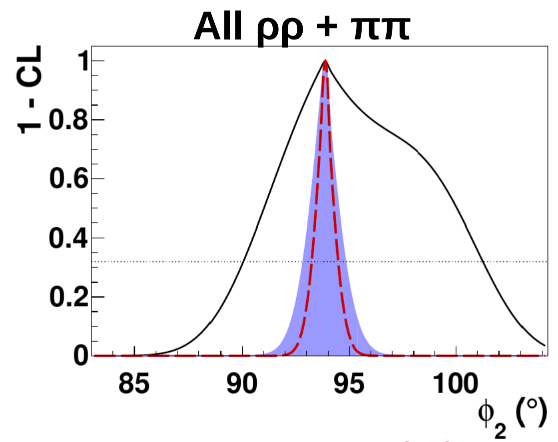
- Other prospect: All $B\to\rho\pi$ by $B\to\pi\pi\pi$ amplitude analysis. Phys. Rev. D 48, 2139 (1993)



Black solid: Belle
Blue filled: Belle II @ 50 ab^{-1} extrapolated from Belle's.



Dashed: Belle II + $S(\pi^0\pi^0)$ @ 50 ab^{-1}



Dashed: Belle II, $S(\pi^0\pi^0)$ = 0.75, $S(\rho^0\rho^0)$ = -0.14 @ 50 ab^{-1}

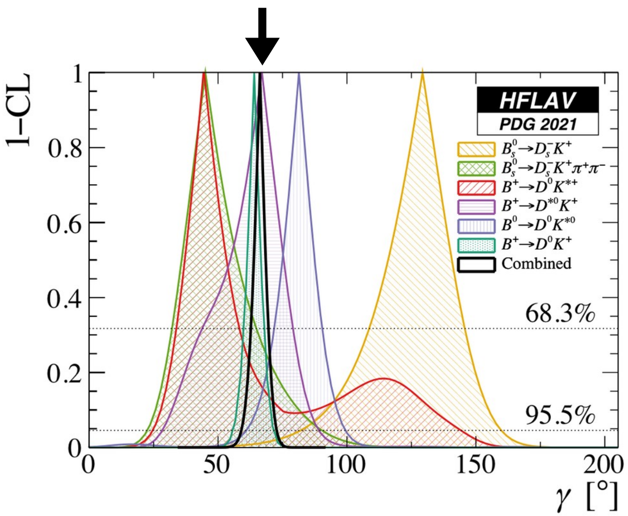
φ_3 measurement methods

- Main methods based on different D decay modes:
  - CP eigenstates (GLW): PLB 253, 483 (1991) PLB 265, 172 (1991)
    K^+K^-, $\pi^+\pi^-$ (CP-even), $K_S^0\pi^0$, $K_S^0\eta$ (CP-odd).
  - Cabibbo-favored and doubly-Cabibbo-suppressed decays (ADS):
    $K^+ + n\pi$ PRD 63, 036005 (2001)
  - **Self-conjugate three-body decays (GGSZ):** PRD 68, 054018 (2003)
    $K_S^0 h^+h^-$ with amplitude analysis
    Golden mode for Belle II
  - Singly-Cabibbo-suppressed decays (GLS): PRD 67 071301 (2003)
    $K_S^0 K^+\pi^-$

φ_3: Belle II prospect

- Current limit:
  - $(78^{+15}_{-16})°$ by Belle
  - $(69^{+17}_{-16})°$ by BaBar PRD 87 052015 (2013)
  - (67±4)° by LHCb LHCb-CONF-2018-002 LHCb-CONF-2020-003
  - $(66.2^{+3.4}_{-3.6})°$ by World average (HFLAV)
  - $(65.6^{+0.9}_{-2.6})°$ by Global fit (CKM fitter)

World average
$D^0 \to K_S^0 \pi\pi$ dominates



- Belle II prospect:
  - Neutral reconstruction: More D decay modes at Belle II.
  - Strong phase: external input from BES-III.
  - Assume 10 fb^{-1} ψ(3770) data from BES-III, expected by Belle II:
    $\delta\varphi_3(50\ ab^{-1}) = 3°$ using GGSZ
    $\delta\varphi_3(50\ ab^{-1}) = 1.6°$ with other D decay modes.

φ_3 sensitivity in Belle II using GGSZ