New Results on Beauty, Charm, and Tau from Belle II

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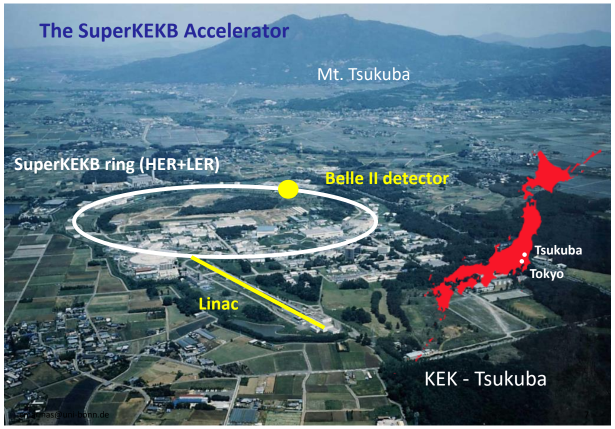
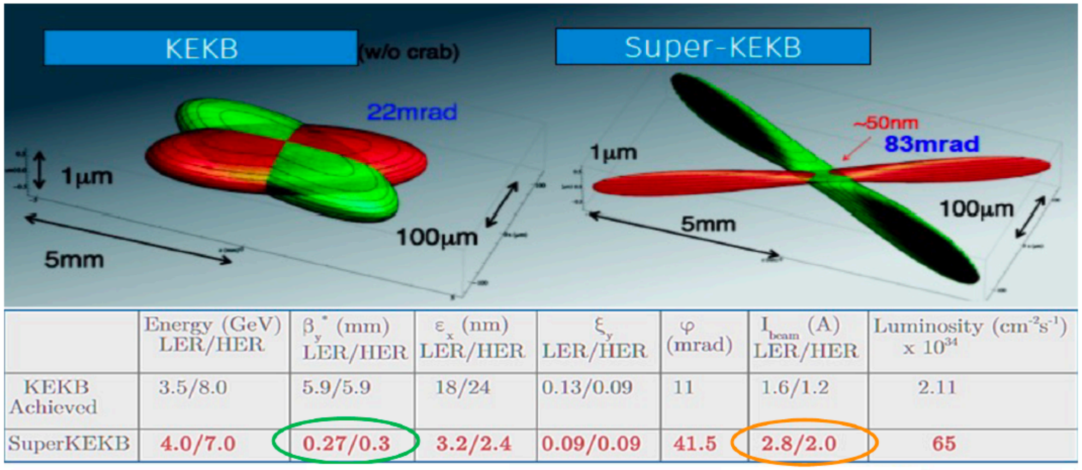
Belle II

On behalf of the Belle II Collaboration

Belle II & SuperKEKB Accelerator

- *Belle II is a multipurpose experiment at the SuperKEKB collider located at KEK (Tsukuba, Japan)*
  - *Asymmetric-energy e+ (4 GeV) e− (7 GeV) collider with E_{CM} near the $\Upsilon(4S)$ resonance (~10.6 GeV)*
- *Aims to collect a 50 ab^{-1} data sample (50 × Belle)*
- *Final design instantaneous luminosity of 6.5×10^{35} cm^{-2} s^{-1} (30 × that of KEKB) by*
  - *reducing beam size by factor 20 ("nano beams")*
  - *increasing beam current by factor 1.5*



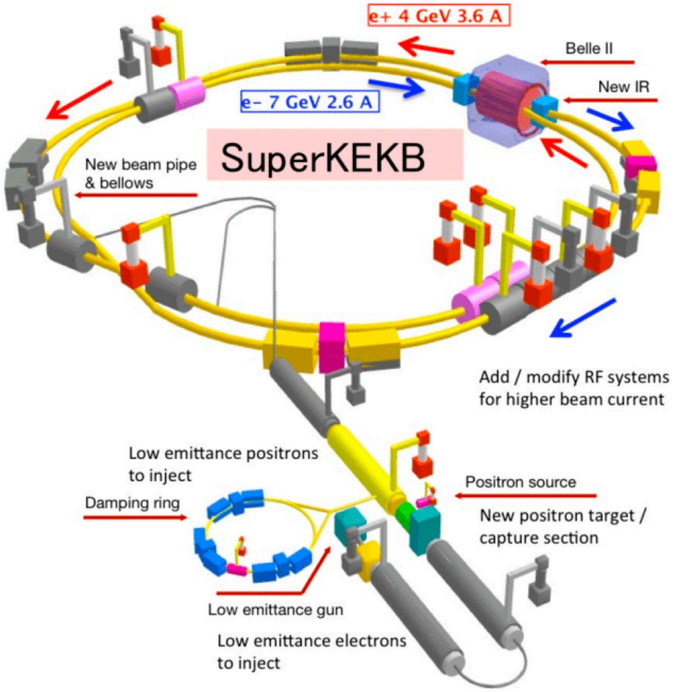


	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity ($cm^{-2}s^{-1}$) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

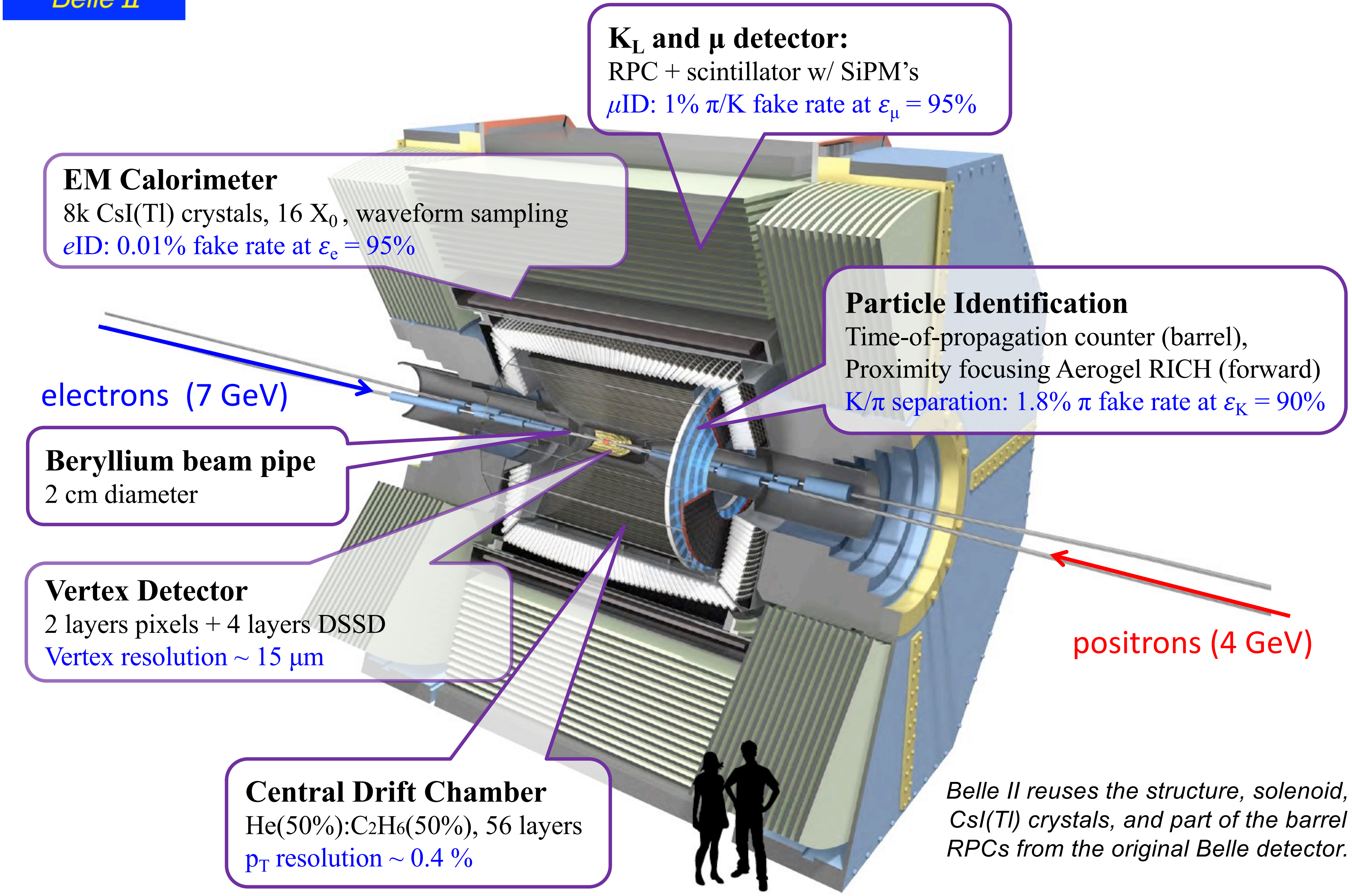
factor 20

factor 1.5

Factor ~30 in the luminosity



Belle II Detector



K_L and μ detector:
RPC + scintillator w/ SiPM's
μID: 1% π/K fake rate at $\varepsilon_\mu = 95\%$

EM Calorimeter
8k CsI(Tl) crystals, 16 X_0 , waveform sampling
*e*ID: 0.01% fake rate at $\varepsilon_e = 95\%$

Particle Identification
Time-of-propagation counter (barrel),
Proximity focusing Aerogel RICH (forward)
K/π separation: 1.8% π fake rate at $\varepsilon_K = 90\%$

electrons (7 GeV)

Beryllium beam pipe
2 cm diameter

Vertex Detector
2 layers pixels + 4 layers DSSD
Vertex resolution ~ 15 μm

positrons (4 GeV)

Central Drift Chamber
He(50%):C_2H_6(50%), 56 layers
p_T resolution ~ 0.4 %

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

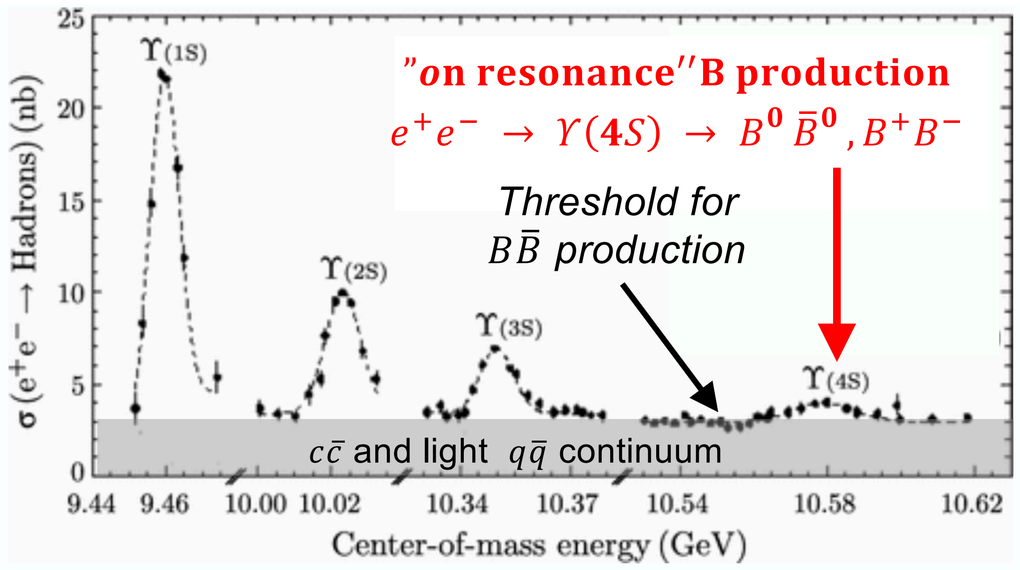
Belle II, a Super Heavy Flavor Factory

Belle II is …

- *a Super **B** Factory:*
  1.1 × 10^9 $B\bar{B}$ pairs per ab^{-1}
- *a Super **Charm** Factory:*
  1.3 × 10^9 $c\bar{c}$ pairs per ab^{-1}
- *a Super **τ** Factory:*
  0.9 × 10^9 $\tau^+\tau^-$ pairs per ab^{-1}

… and in addition, the clean e+e− environment allows the study/search of

- *Charmonium & bottomonium (SM & exotic X,Y,Z)*
- *Tetra- and penta-quarks*
- *Dark particles (dark γ/Higgs, ALPs, LLPs), …*

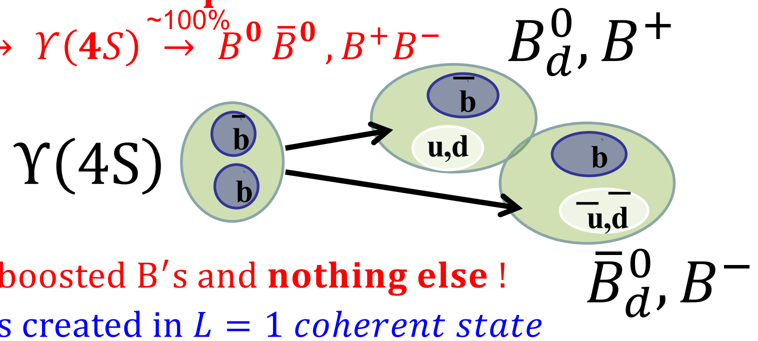


"on resonance" B production
$e^+e^- \rightarrow \Upsilon(\mathbf{4}S) \rightarrow B^{\mathbf{0}}\,\bar{B}^{\mathbf{0}}, B^+B^-$

Threshold for $B\bar{B}$ production

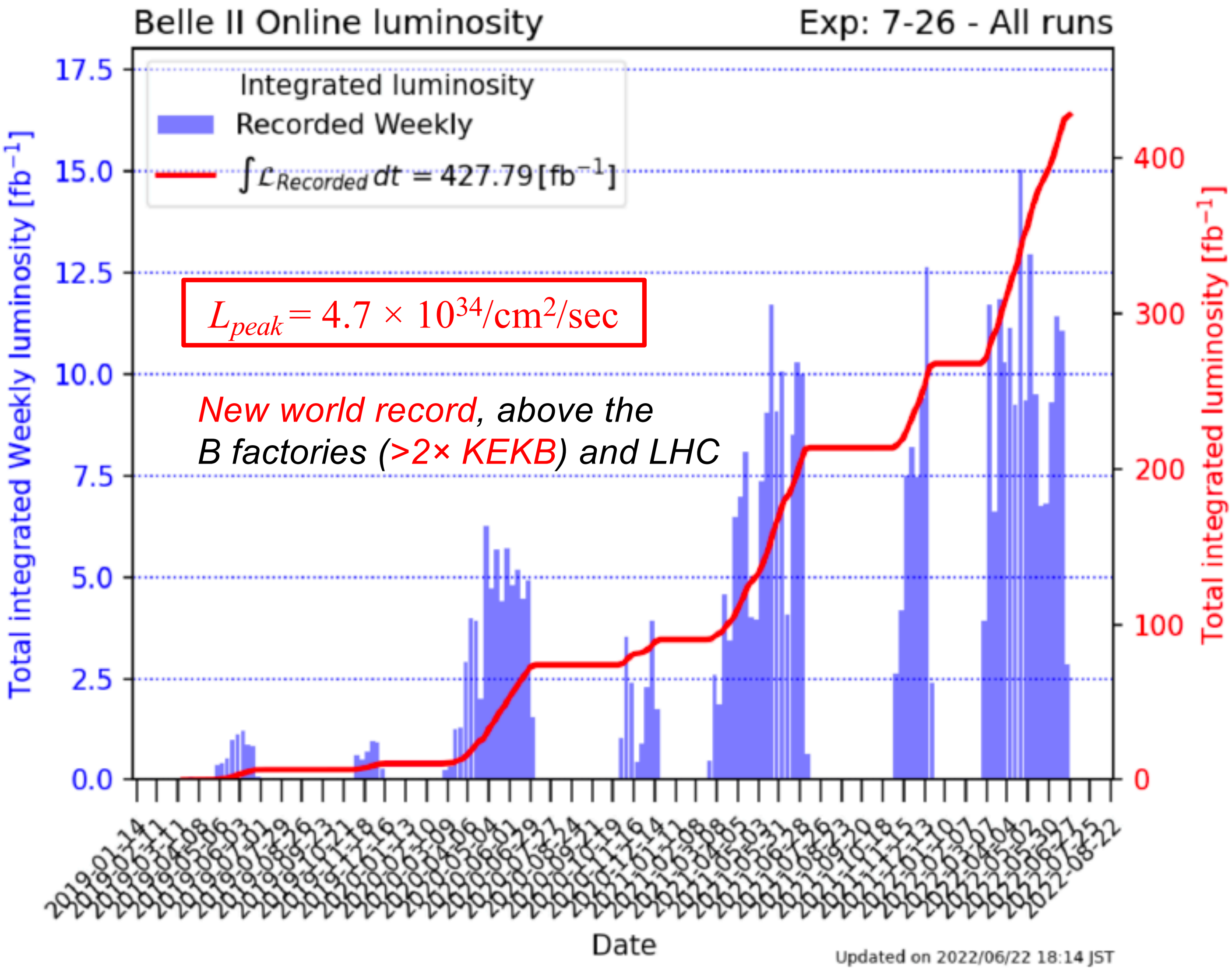
$c\bar{c}$ and light $q\bar{q}$ continuum

"on resonance" production
$e^+e^- \rightarrow \Upsilon(\mathbf{4}S) \xrightarrow{\sim 100\%} B^{\mathbf{0}}\,\bar{B}^{\mathbf{0}}, B^+B^-$



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

Belle II Luminosity



$L_{peak} = 4.7 \times 10^{34}/\mathrm{cm}^2/\mathrm{sec}$

New world record, above the B factories (>2× KEKB) and LHC

Belle II has recorded $428\ fb^{-1}$ in 2019-2022

- *On-$\Upsilon(4S)$: $363\ fb^{-1}$*
- *Below-$\Upsilon(4S)$: $42\ fb^{-1}$*
- *Unique 10.75 GeV scan: $19\ fb^{-1}$*

Today's results are based on up to $190\ fb^{-1}$ On-$\Upsilon(4S)$

Integrated luminosities of B factories for comparison:

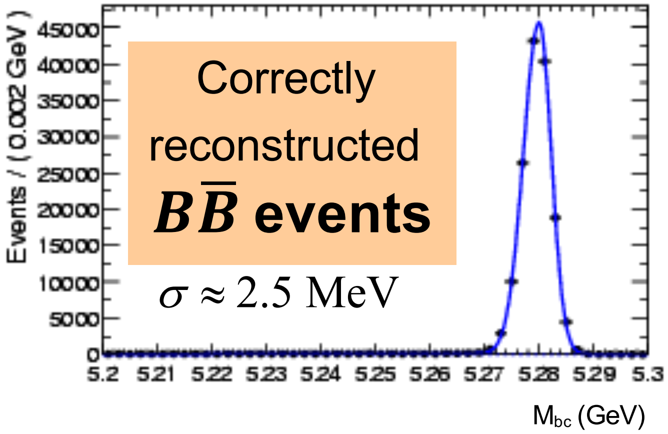
Belle ($711\ fb^{-1}$)
BaBar ($424\ fb^{-1}$)

Many Belle II results are starting to become statistically competitive, some measurements are already world's best !

B Meson Reconstruction Techniques

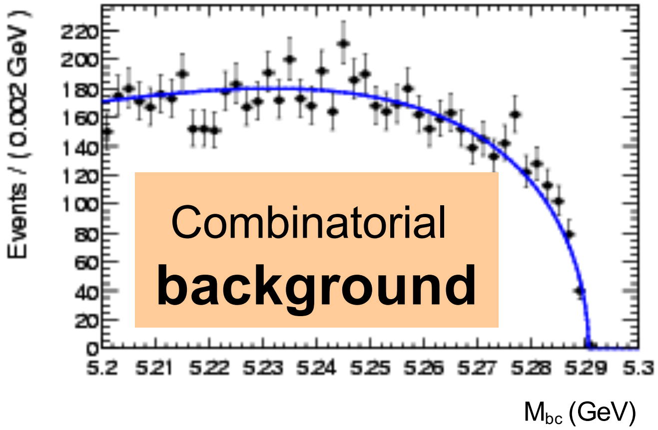
Exploit kinematics of $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ *for signal selection*

$$M_{bc} = \sqrt{(E^*_{beam})^2 - (p^*_B)^2}$$



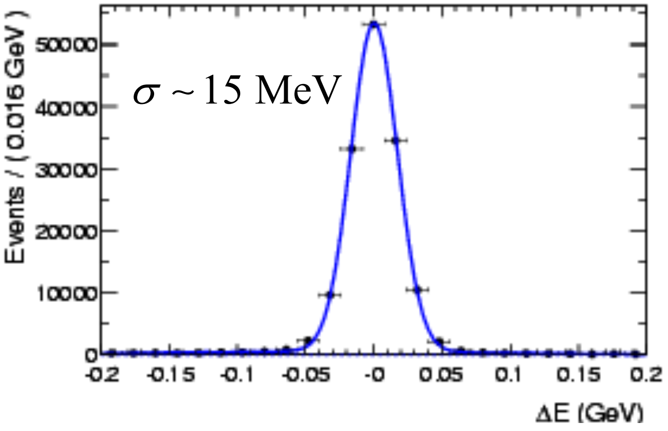
Correctly reconstructed **$B\bar{B}$ events**

$\sigma \approx 2.5$ MeV

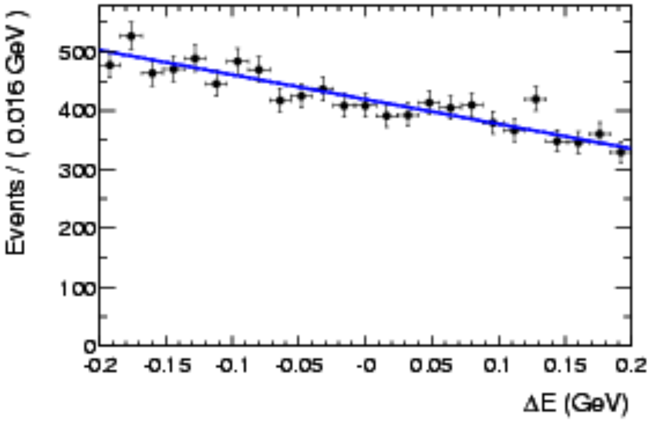


Combinatorial **background**

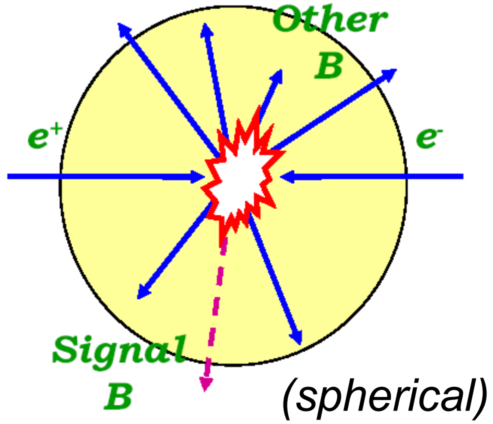
$$\Delta E = E^*_B - E^*_{beam}$$



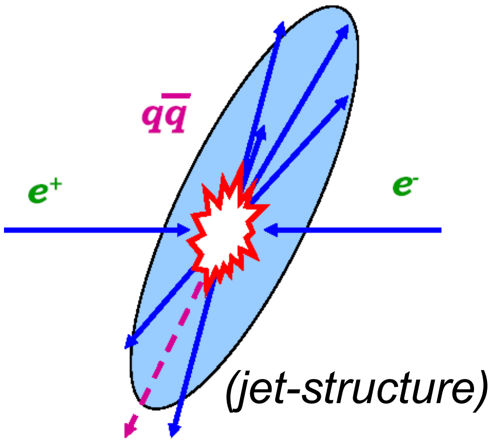
$\sigma \sim 15$ MeV



Event shape variables



(spherical)

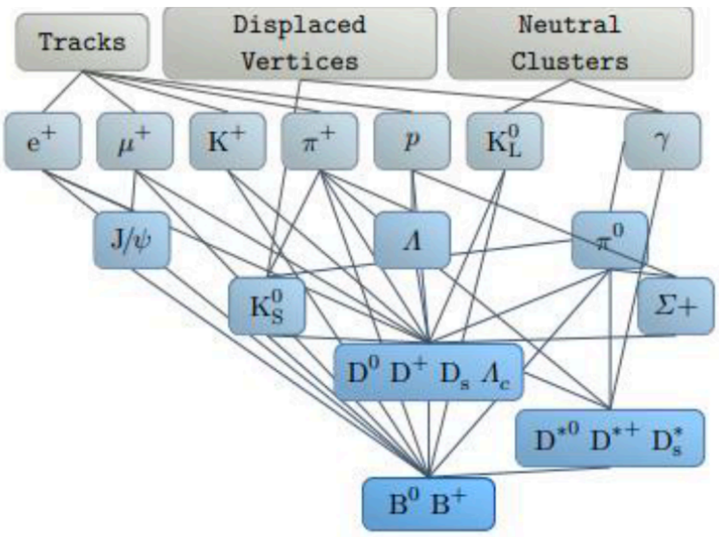


(jet-structure)

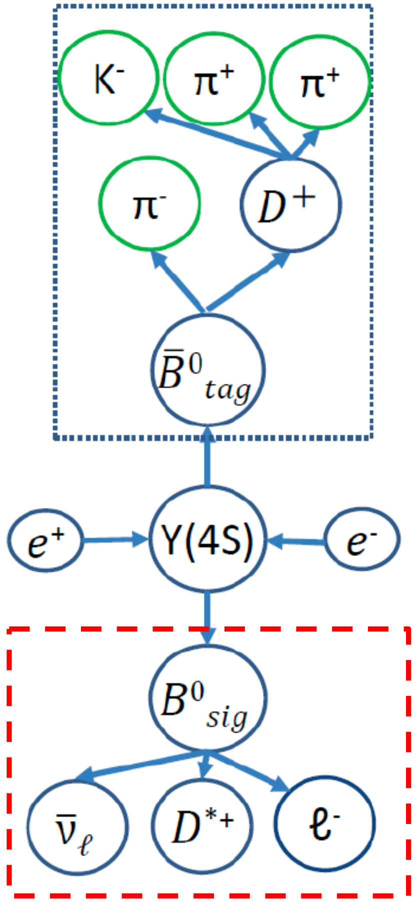
Full Event Interpretation

Comput. Softw. Big Sci. 3, 6 (2019)

- Reconstruct one B (B_{tag}) fully with a multivariate classifier
  - Sample dominated by large-BF, low-background final states
- Properties of B_{sig} (e.g. momentum) and invisible daughters (e.g. "missing mass") can be calculated with B_{tag} momentum
- Typical for values hadronic B_{tag} : $\varepsilon(B_{tag})$ ~0.XX%, purity ~ XX%

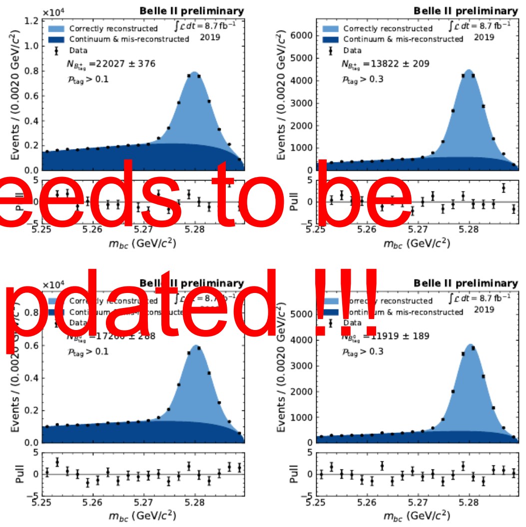


Example:



Hadronic decay of B_{tag}

Signal decay with invisible neutrino



Needs to be updated !!!

Measurements of quark mixing parameters

Amplitude for charged current quark transition $q_i \rightarrow W\, q_j$ is proportional to CKM matrix element V_{ij}

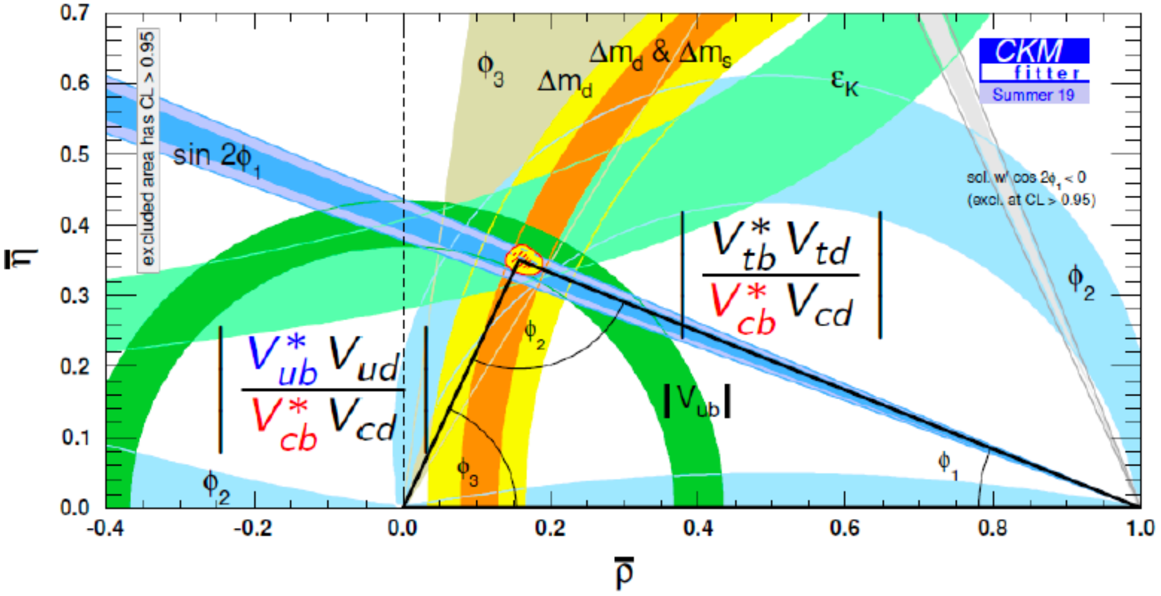
- *BFs ($\propto |V_{ij}|^2$) → magnitudes*
- *CP asymmetries (arising from interference of 2 amplitudes) → (complex) phases*

$$V_{\rm CKM} \equiv V_L^u V_L^{d\dagger} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Belle II can measure magnitudes of 7 of the 9 matrix elements and weak phase

In the SM, V_{CKM} is a unitary 3×3 matrix: measurements of Unitarity Triangle sides and angles must be consistent !!!

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



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

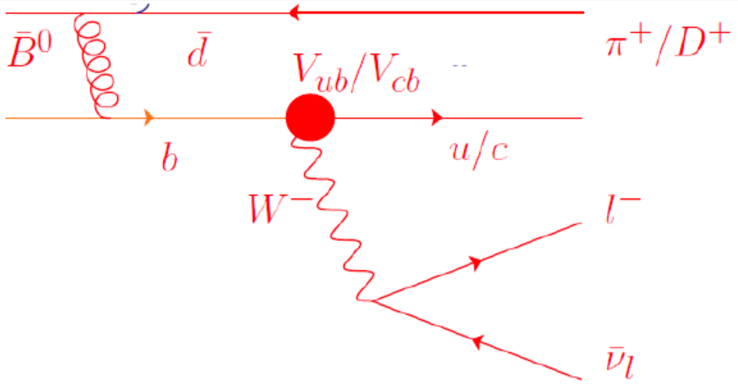
Horak, HF
Tue 17:00

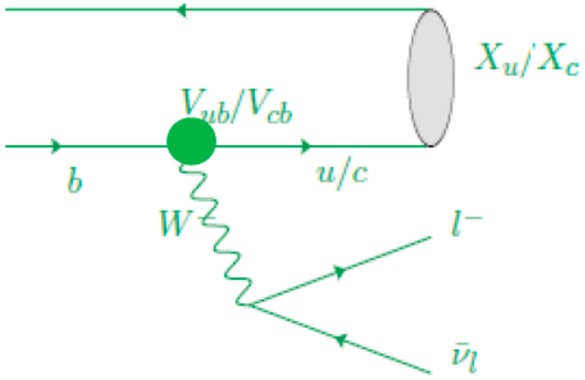
V_{ub} and V_{cb}

$|V_{ub}|$ and $|V_{cb}|$ are precisely measured with semileptonic B decays

Exclusive: B→π/ρ ℓν, B→D(*)ℓν etc.

Inclusive: B→X_uℓν, B→X_cℓν



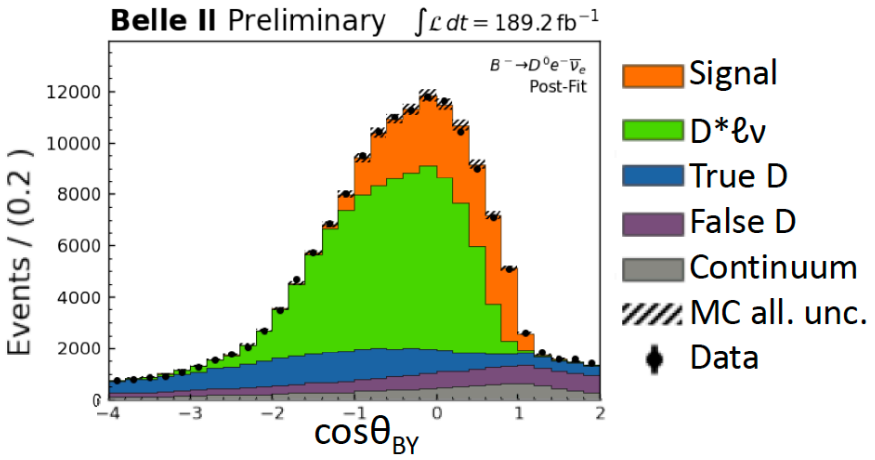


Parameter	Exclusive	Inclusive
$\lvert V_{cb}\rvert \times 10^{-3}$	39.10±0.50	42.19±0.78
$\lvert V_{ub}\rvert \times 10^{-3}$	3.51±0.12	4.19±0.12

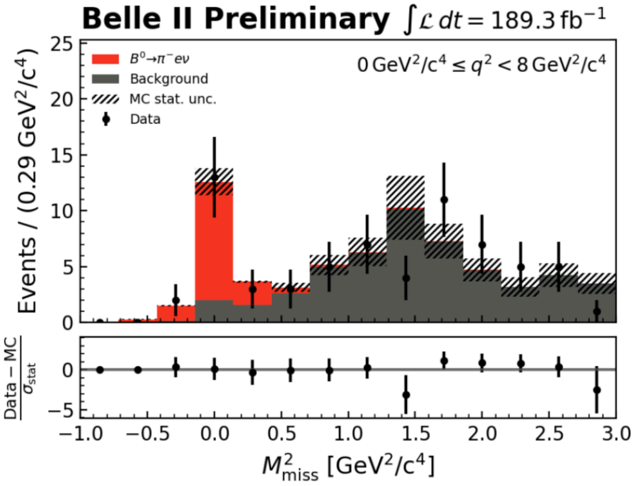
HFLAV, arXiv:2206.07501

discrepancy between inclusive and exclusive

V_{cb} from untagged $B \to D^* l\nu$ sample

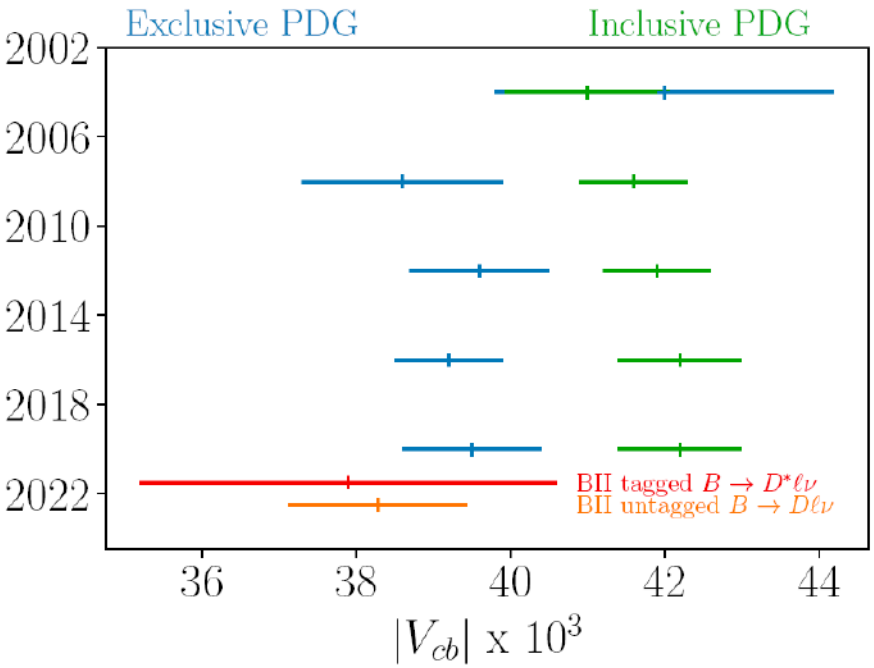


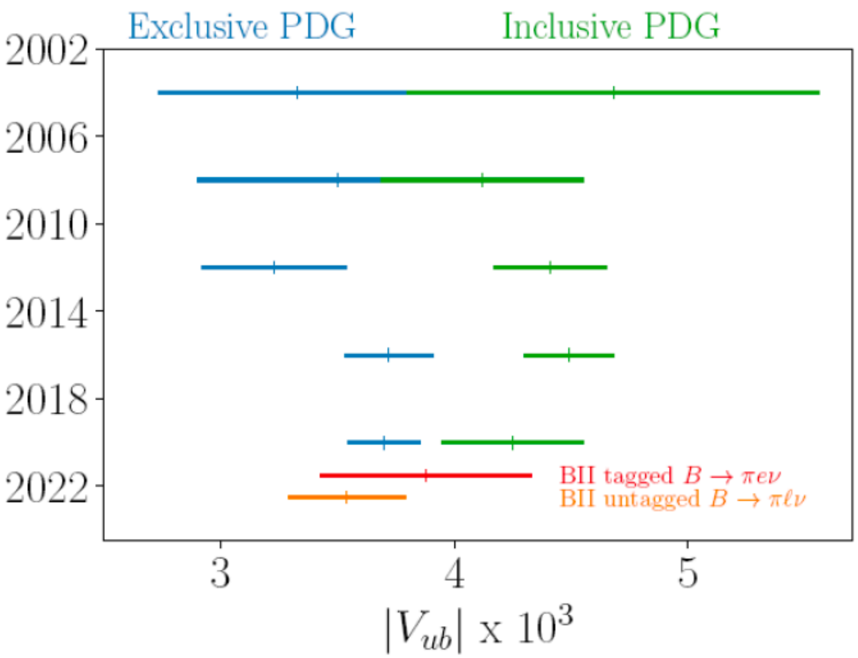
V_{ub} from tagged $B \to \pi l\nu$ sample



4 new excl. Vxb results from Belle II

$|V_{xb}|$	Signal B (B_{sig}) decay	Other B (B_{tag}) decay	Latest result
$|V_{cb}|$	$B_{sig} \to D\ell\nu$ (ℓ=e,μ)	untagged	$\eta_{EW}|V_{cb}| = (38.53 \pm 1.15) \times 10^{-3}$
$|V_{cb}|$	$B^0_{sig} \to D^*\ell\nu$ (ℓ=e,μ)	hadronically tagged	$\eta_{EW}|V_{cb}| = (38.2 \pm 2.8) \times 10^{-3}$
$|V_{ub}|$	$B^0_{sig} \to \pi\ell\nu$ (ℓ=e,μ)	untagged	$|V_{ub}|_{B^0\to\pi^-\ell^+\nu_\ell} = (3.54 \pm 0.12_{\mathrm{stat}} \pm 0.15_{\mathrm{sys}} \pm 0.16_{\mathrm{theo}}) \times 10^{-3}$
$|V_{ub}|$	$B_{sig} \to \pi e\nu$	hadronically tagged	$|V_{ub}| \times 10^3 = 3.88 \pm 0.45$ (stat.+sys.+theo.)



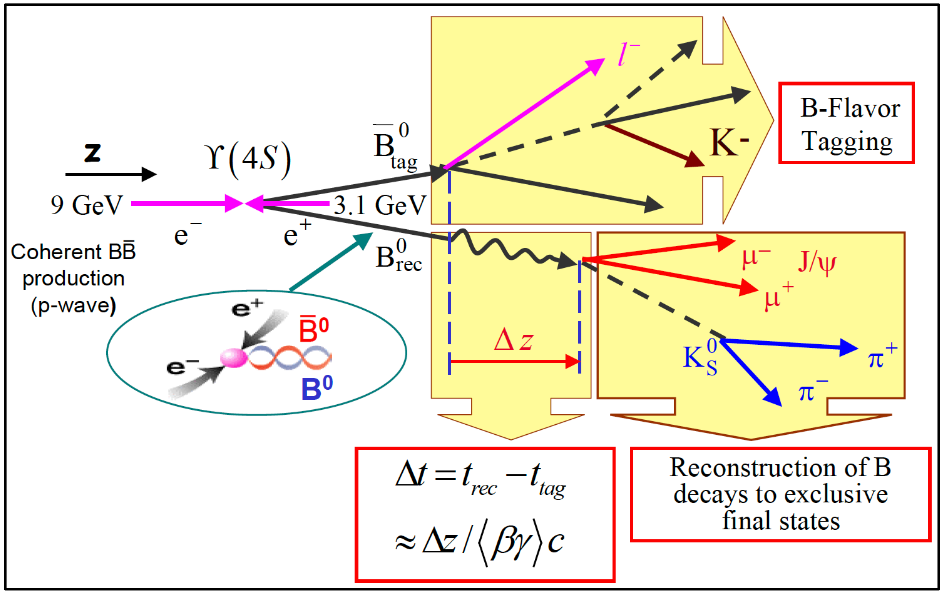


Belle II V_{xb} results are consistent with previous measurements, with precision approaching those of prev. results

Discrepancy between excl. and incl. may be due to unaccounted non-perturbative effects. Measurements of SL decay kinematics (Belle II, arxiv.org:2205.06372) may help resolve the issue.

Time-dependent asymmetries in B decays

- *TD measurements of B decays were pioneered by BABAR and Belle*
  - *Need good B flavor tagging and $\Delta t = t_{Sig} - t_{tag}$ measurement*



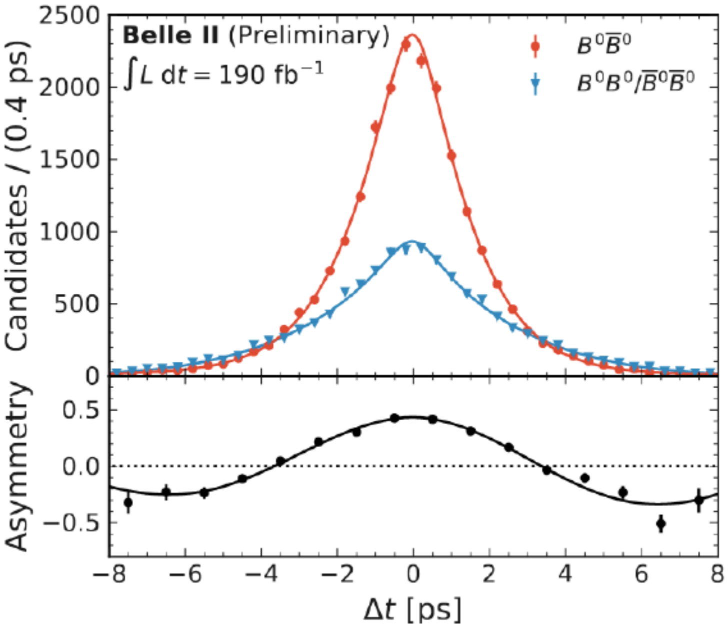
- *$B\bar{B}$ mixing asymmetry*

$$\mathcal{A}(\Delta t) = \frac{N_{B\bar{B}} - N_{BB,\bar{B}\bar{B}}}{N_{B\bar{B}} + N_{BB,\bar{B}\bar{B}}} = cos(\Delta m_d \Delta t)(1-2w) \otimes R(\Delta t)$$

- *New Belle II measurements of B lifetime and mixing frequency*

$$\tau_{B^0} = 1.499 \pm 0.013 \ \pm 0.008 \text{ ps}$$
$$\Delta m_d = 0.516 \pm 0.008 \ \pm 0.005 \text{ ps}^{-1}$$

  - *Measurements consistent with WAs*
  - *O(1%) precision in $\tau(B^0)$ and Δm_d demonstrate Belle II's excellent flavor tagging and vertexing performance*



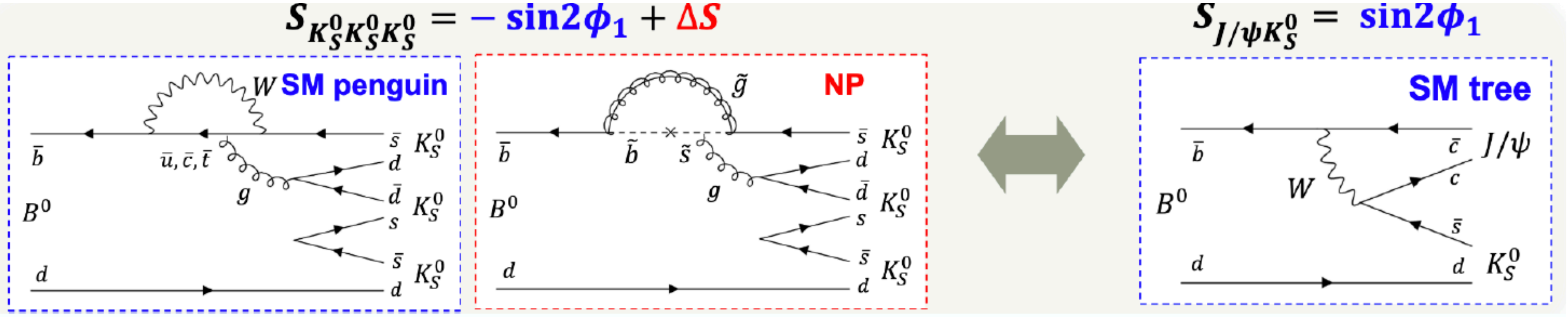
Measurement of CP asymmetry $\sin 2\phi_1$

Zlebcik, HF
Tue 13:30

$$\mathcal{A}^{raw}(\Delta t) = \frac{N(\bar{B}^0 \to f_{CP}) - N(B^0 \to f_{CP})}{N(\bar{B}^0 \to f_{CP}) + N(B^0 \to f_{CP})}(\Delta t) = A_{CP}\cos(\Delta m_d \Delta t) + S_{CP}\sin(\Delta m_d \Delta t)$$

direct CP asymmetry mixing-induced CP asymmetry

- *Expect* $S_{CP} = \sin 2\phi_1$ *for tree amplitude* $b \to c\bar{c}s$ *decays*
- *New physics could provide CP contribution in penguin decays*



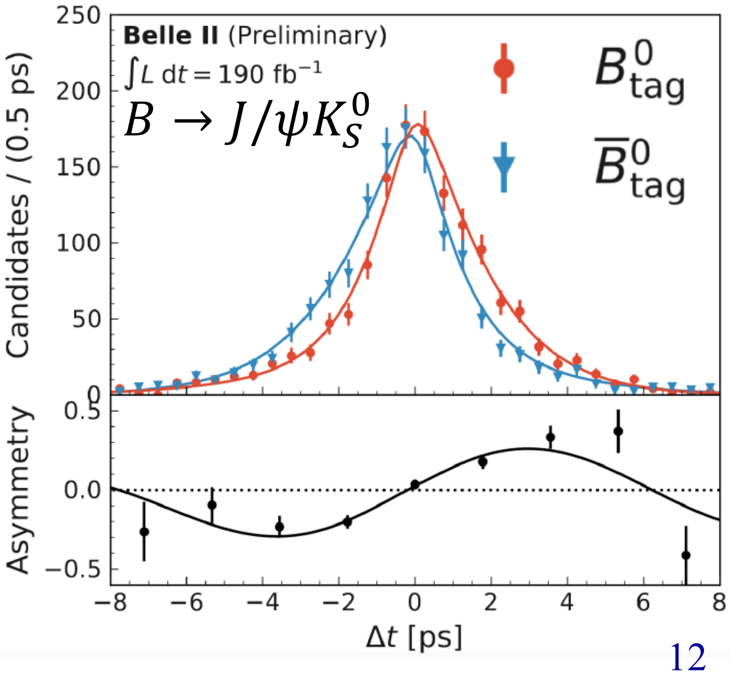
$$S_{K_S^0 K_S^0 K_S^0} = -\sin 2\phi_1 + \Delta S$$

$$S_{J/\psi K_S^0} = \sin 2\phi_1$$

- *New Belle II* $\sin 2\phi_1$ *measurement with golden mode* $B \to J/\psi K_S^0$

$$S_{CP} = 0.720 \pm 0.062\,(\text{stat}) \pm 0.016\,(\text{syst})$$
$$A_{CP} = 0.094 \pm 0.044\,(\text{stat})\ {}^{+0.042}_{-0.017}\,(\text{syst})$$

- *9% measurement is statistically dominated*
- *Consistent with WA*

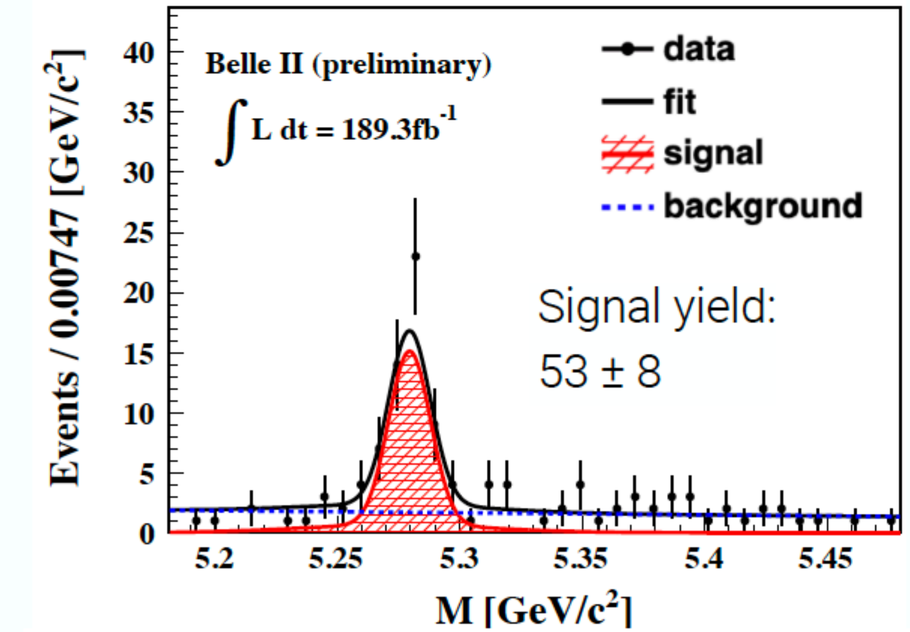


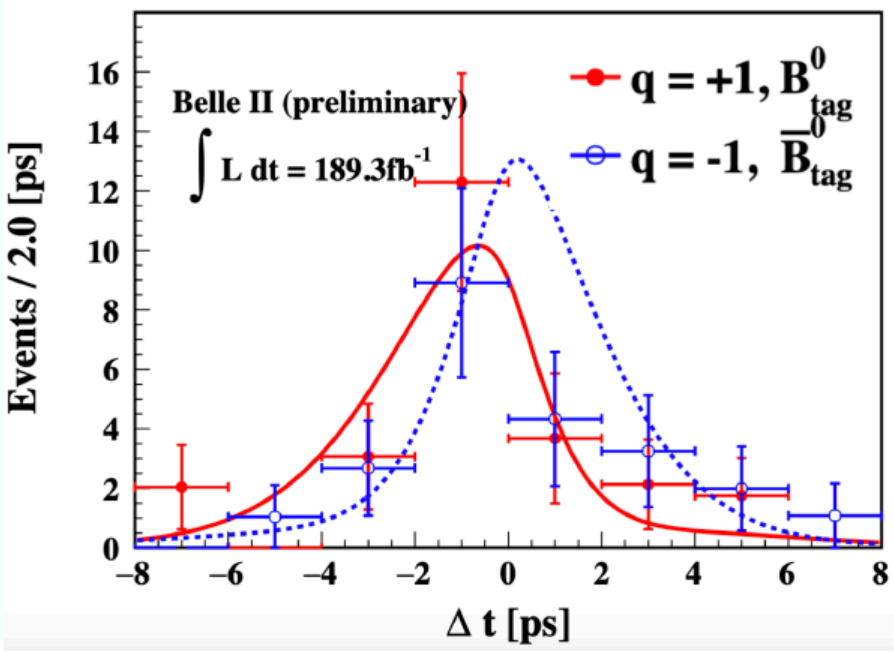
Time-dependent CPV in B penguins

- *Measure S_{CP} in penguin decay $B \rightarrow 3K_S^0$*
  - *Technically complicated measurement with no tracks from B_{sig} decay vertex*
  - *Small inner radius of PXD ensures most K_S^0 daughter tracks have pixel hit info*

- *Result consistent with SM predictions:*
  - $A_{CP}{\sim}0$ *and* $S_{CP}\sim-\sin 2\phi_1$

$$S_{CP} = \quad -1.86^{+0.91}_{-0.46}\ (\text{stat}) \pm 0.09\ (\text{syst})$$
$$A_{CP} = \quad -0.22^{+0.30}_{-0.27}\ (\text{stat}) \pm 0.04\ (\text{syst})$$





$K\pi$ Puzzle

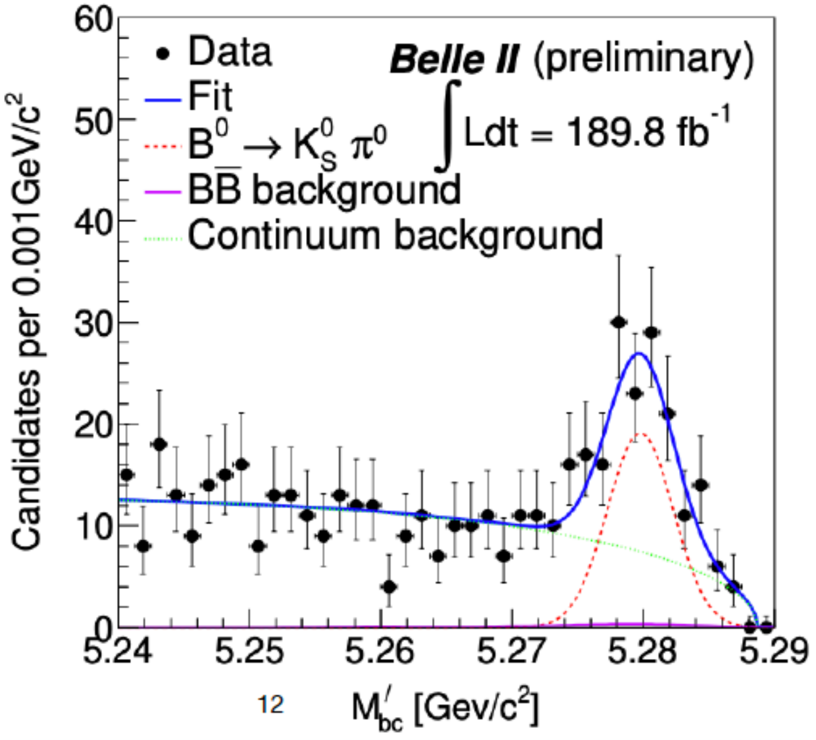
- *Unexpected large difference between CP asymmetries $A^{CP}_{K^+\pi^-}$ and $A^{CP}_{K^+\pi^0}$ in $B \rightarrow K\pi$ decays dominated by hadronic penguin amplitudes*
- *Isospin sum rule tests if discrepancy from sub-leading SM amplitudes*

$$I_{K\pi} = \mathcal{A}^{\mathrm{CP}}_{K^+\pi^-} + \mathcal{A}^{\mathrm{CP}}_{K^0\pi^+}\frac{\mathcal{B}_{K^0\pi^+}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^+\pi^0}\frac{\mathcal{B}_{K^+\pi^0}}{\mathcal{B}_{K^+\pi^-}}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}^{\mathrm{CP}}_{K^0\pi^0}\frac{\mathcal{B}_{K^0\pi^0}}{\mathcal{B}_{K^+\pi^-}} \approx 0$$

- *Current precision (XX%) limited by $A^{CP}_{K^0\pi^0}$.*
- *Only Belle II can measure all of these !*

New Belle II measurements:

$$A_{CP}^{K^+\pi^0} = 0.014 \pm 0.047 \ \pm 0.010$$
$$B_{K^+\pi^0} = (14.30 \pm 0.69 \ \pm 0.79)\times 10^{-6}$$
$$A_{CP}^{K^0\pi^0} = -0.41^{+0.30}_{-0.32} \pm 0.09$$
$$B_{K^0\pi^0} = (11.0 \pm 1.2 \ \pm 1.0)\times 10^{-6}$$



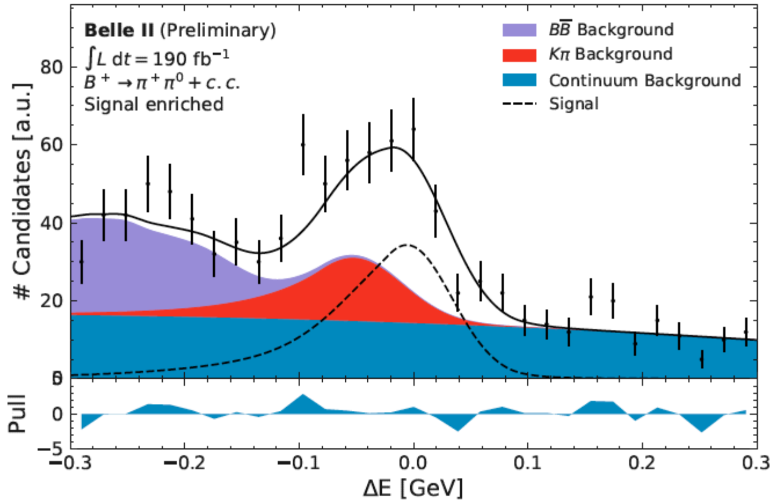
Previous Belle II results with 63 fb^{-1}: $K^+\pi^-$ and $K^0\pi^+$ (arXiv:2106.03766), $K^0\pi^0$ (arXiv:2104.14871), and $K^+\pi^0$ (arXiv:2105.04111),

Measurement of ϕ_2 from $B \to \pi\pi$ and $B \to \rho\rho$

CKM angle ϕ_2 accessible through measurements of BFs and CP asymmetries in set of $b \to u$ dominated $B \to \pi\pi$ and $B \to \rho\rho$ decays

- *Isospin decomposition is necessary to account for penguin pollution*

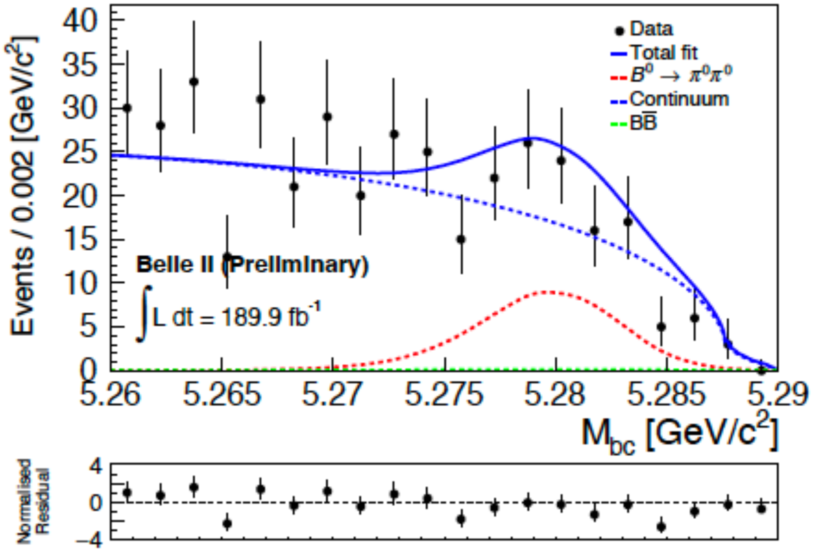
$B^+ \to \rho^+\rho^0$, $B^0 \to \rho^0\rho^0$, $B^0 \to \rho^+\rho^-$ or
$B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$, $B^0 \to \pi^0\pi^0$



New Belle II $B \to \pi\pi$ measurements:

$$A_{CP}^{\pi^+\pi^0} = -0.085 \pm 0.085\ \pm 0.019$$
$$B_{\pi^+\pi^0} = (6.12 \pm 0.53\ \pm 0.53)\times 10^{-6}$$
$$A_{CP}^{\pi^0\pi^0} = 0.14 \pm 0.46 \pm 0.07$$
$$B_{\pi^0\pi^0} = (1.27 \pm 0.25\ \pm 0.17)\times 10^{-6}$$

WA: $A_{CP}^{\pi^0\pi^0} = 0.33 \pm 0.22, B_{\pi^0\pi^0} = (1.59 \pm 0.26)\times 10^{-6}$



Although ρρ is a VV final state, similar isospin analysis as in ππ possible since only longitudinal amplitude dominant

New Belle II $B \to \rho\rho$ measurements:

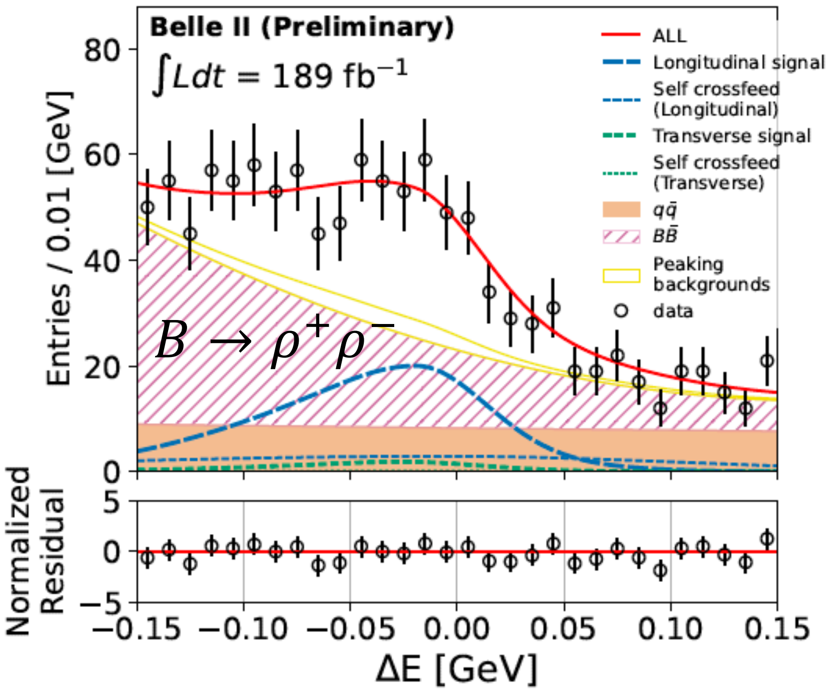
$$B_{\rho^+\rho^-} = (26.7 \pm 2.8 \ \pm 2.8)\times 10^{-6}$$
$$f_L^{\rho^+\rho^-} = 0.956 \pm 0.035 \pm 0.033$$

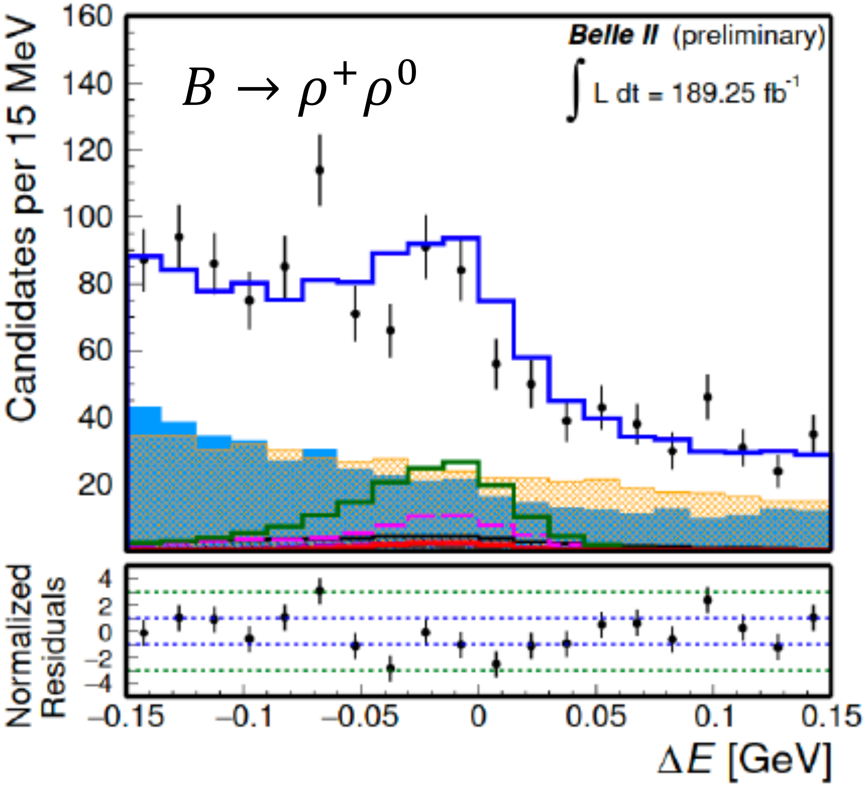
WA: $B_{\rho^+\rho^-} = (27.7 \pm 1.9)\times 10^{-6}$

$$A_{CP}^{\rho^+\rho^0} = -0.069 \pm 0.068 \ \pm 0.060$$
$$B_{\rho^+\rho^0} = (23.2^{+2.2}_{-2.1} \pm 2.7)\times 10^{-6}$$
$$f_L^{\rho^+\rho^0} = 0.943^{+0.035}_{-0.033} \pm 0.027$$

WA: $A_{CP}^{\rho^+\rho^0} = -0.05 \pm 0.05, B_{\rho^+\rho^0} = (24.0 \pm 1.9)\times 10^{-6}$

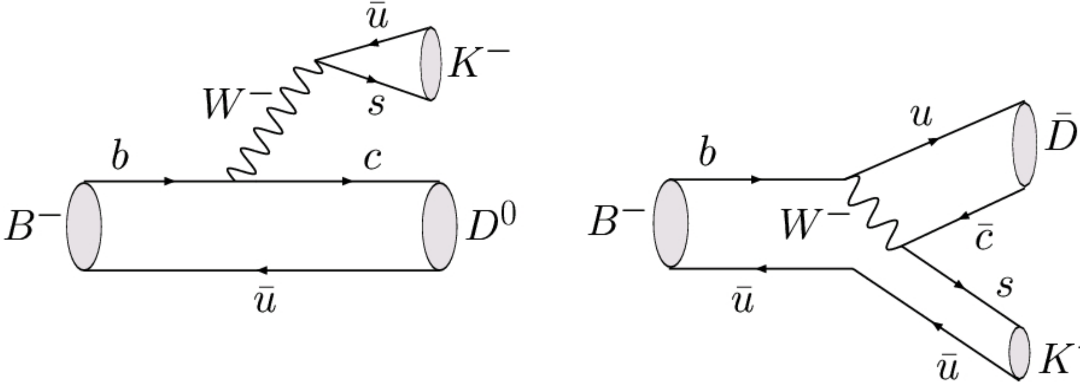
Previous Belle II results with 63 fb^{-1}: $\pi^+\pi^-$ (arXiv:2106.03766), $\pi^0\pi^0$ (arXiv:2107.02373), and $\rho^+\rho^0$(arXiv:2206.12362),





Measurement of ϕ_3 with $B^\pm \to D(K_S^0 h^+ h^-)K^\pm$

Measure ϕ_3 through interference of $b \to c$ and $b \to u$ amplitudes in bins of $D \to K_S^0 h^+ h^-$ Dalitz plot



Strong phase in D decay from CLEO and BESIII used as external input

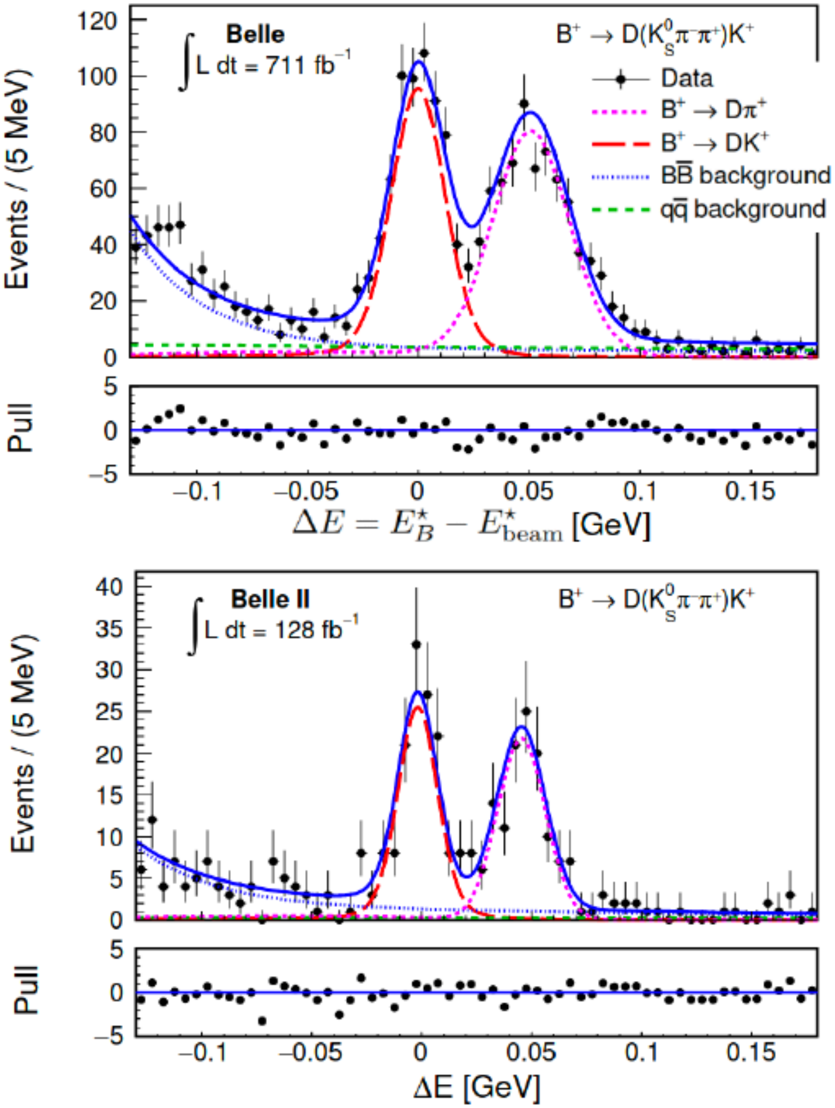
$$\boxed{\phi_3 = (78.4\ \pm 11.4 \pm 0.05 \pm 1.0)^\circ}$$

WA: $\phi_3 = \left(65.9^{+3.3}_{-3.5}\right)^\circ$

First joint Belle (711 fb^{-1}) and Belle II (128 fb^{-1}) analysis !

Belle & Belle II, JHEP 02 (2022) 063

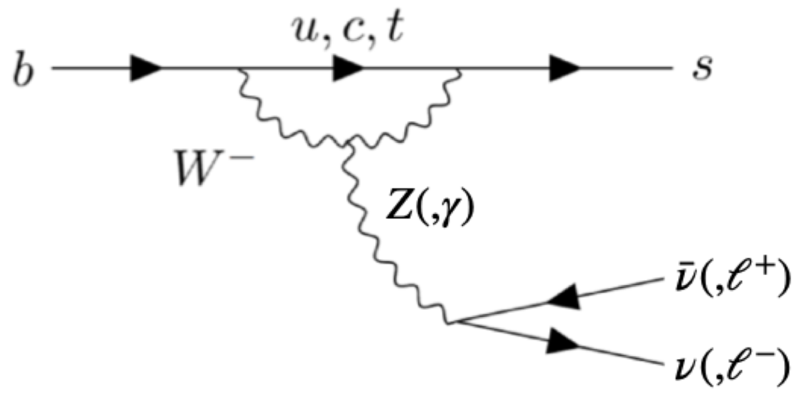
Belle: $N(K_S^0\pi\pi) = 1467 \pm 53$, $N(K_S^0KK) = 194 \pm 17$



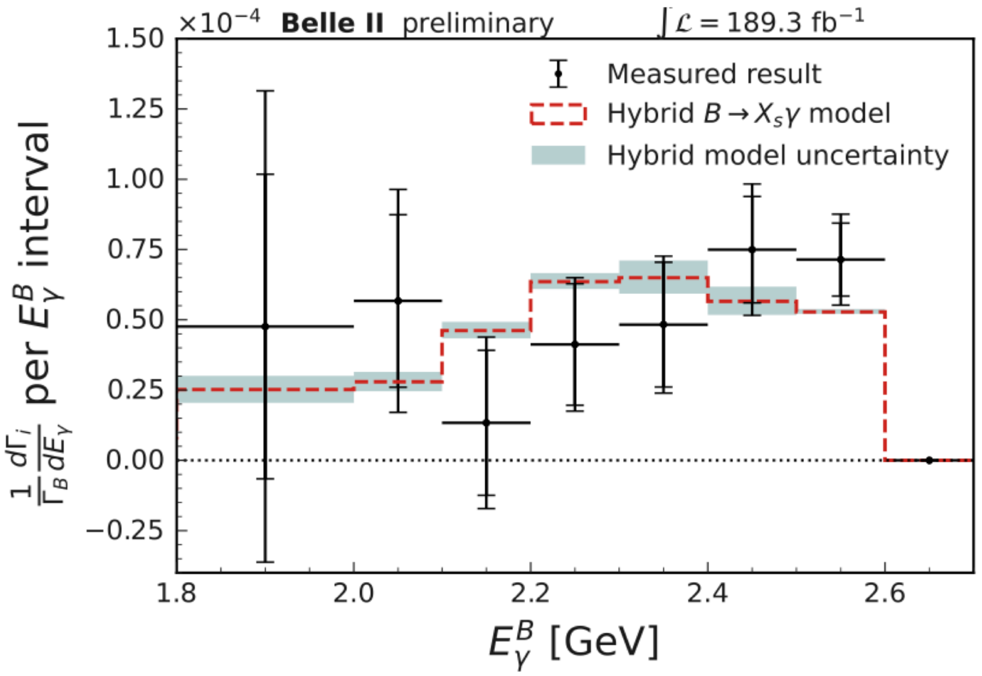
Belle II: $N(K_S^0\pi\pi) = 280 \pm 21$, $N(K_S^0KK) = 34 \pm 7$

Radiative and EW Penguin B Decays

- *Flavor-changing neutral currents: in SM due to b → s transitions at one-loop level*
  - *Sensitive to New Physics particles in the loop*
- *BF ratios, asymmetries and angular observables can be precisely predicted in SM*
- *New Belle II incl. BR(b → s γ) measurement*
  - *Apply cut-off due to large background at low E(γ)*



E_γ^B threshold, GeV	$\mathcal{B}(B \to X_s\gamma)(10^{-4})$
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)

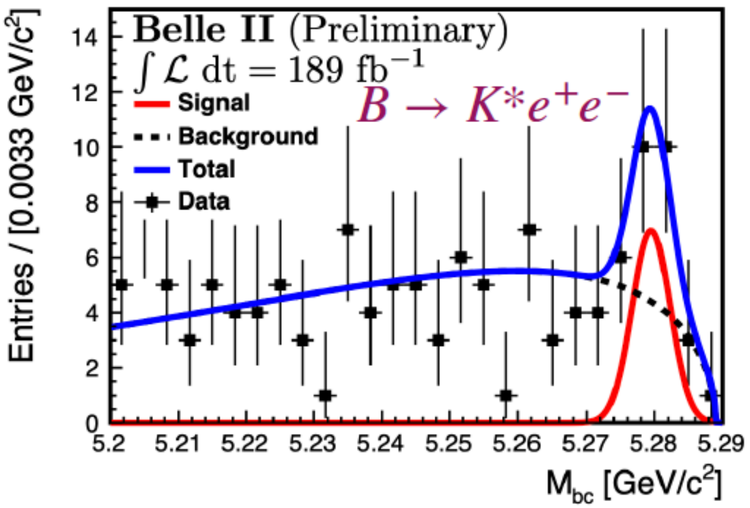


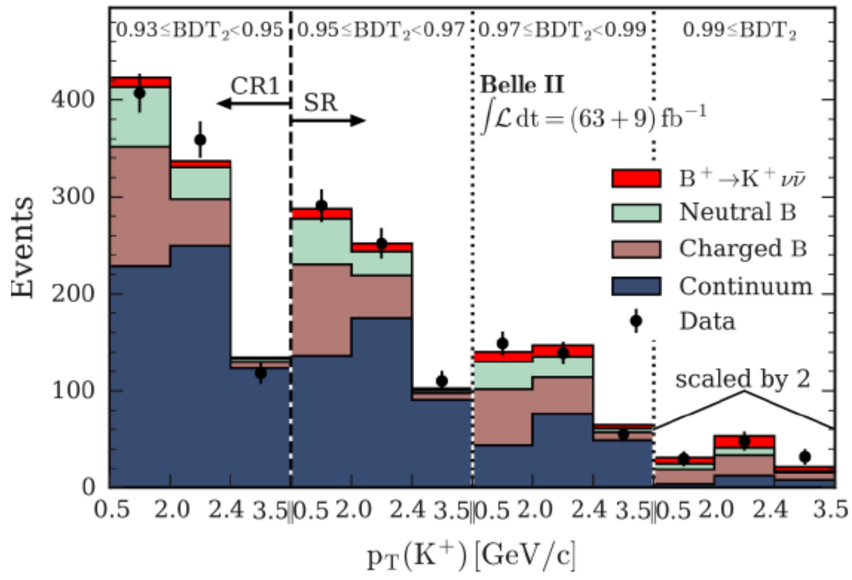
SM prediction for $E_\gamma^B > 1.6$ GeV: $(3.40 \pm 0.17)\times 10^{-4}$ [JHEP06(2020)175]

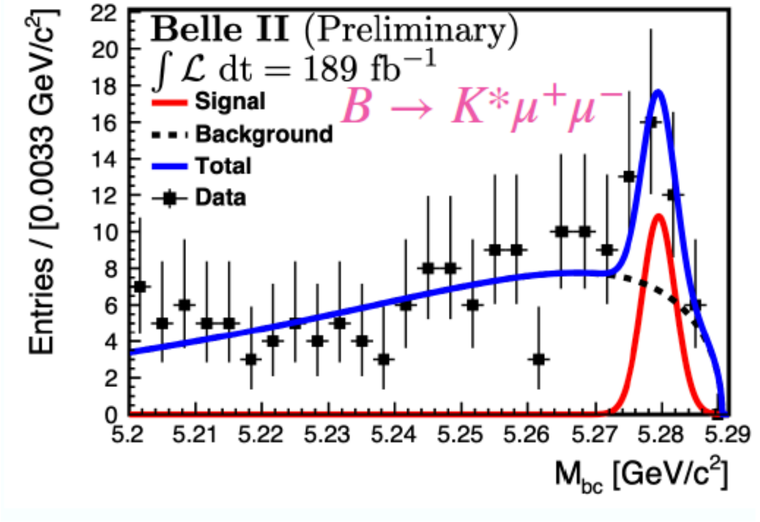
$B \to K^* l^+ l^-$ and $B \to K\nu\bar{\nu}$

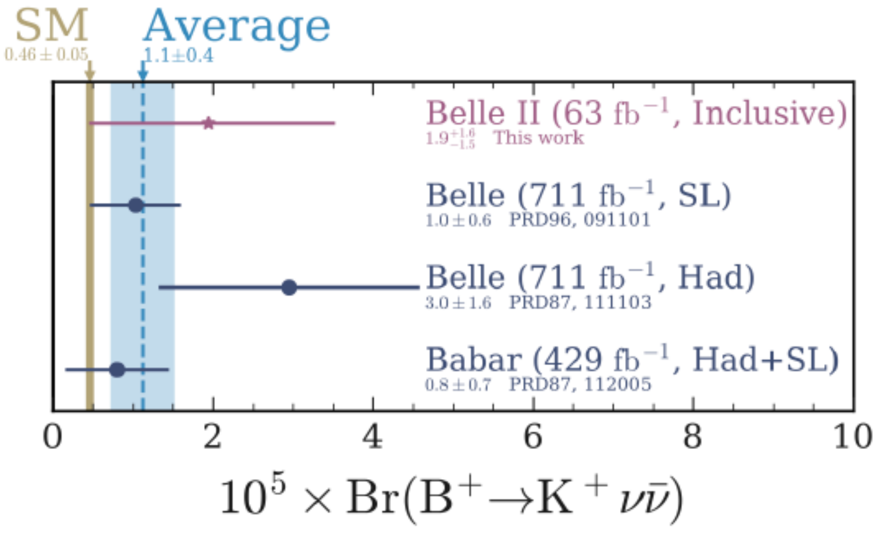
Martel, HI
Thu 16:30

New measurements of $BR(B \to K^* l^+ l^-)$ and $BR(B \to K\nu\bar{\nu})$ (fully-incl.)









Decay	Belle II (10^{-6})	PDG (10^{-6})
$B \to K^* e^+ e^-$	$1.42 \pm 0.48 \pm 0.09$	1.19 ± 0.20
$B \to K^* \mu^+ \mu^-$	$1.19 \pm 0.31^{+0.08}_{-0.07}$	1.06 ± 0.09

$\mathrm{BF}(B^+ \to K^+ \nu\bar{\nu}) < 4.1 \times 10^{-5}$

Fully-inclusive method improves sensitivity 20%-350% over previous measurements !

LFU in $B \to D^{(*)}l\nu$

Meier, HF
Sat 15:30 &
Hara, HI
Sat 14:00

- *Tensions observed recently in excl. semi-leptonic BF ratios $R(D^{(*)}) = BR(B \to D^{(*)}l\nu)/BR(B \to D^{(*)}\tau\nu)$*

- *Predictions for incl. R(X):*

$$\mathrm{R}(X_{c,\tau/l})_{SM} = 0.223 \pm 0.004$$

PRD 92 (2015) 054018

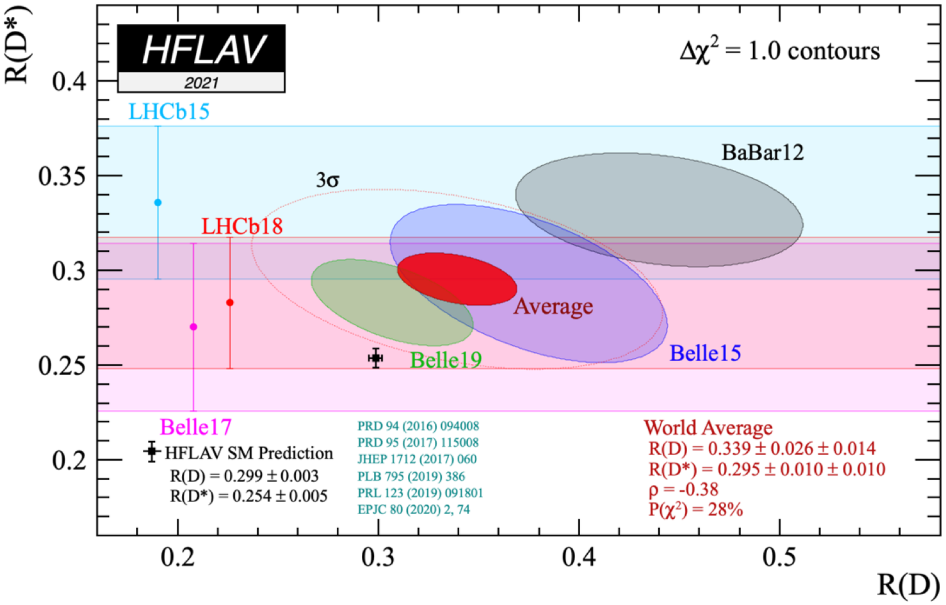
$$\mathrm{R}(X_{c,e/\mu})_{SM} = 1.006 \pm 0.001$$

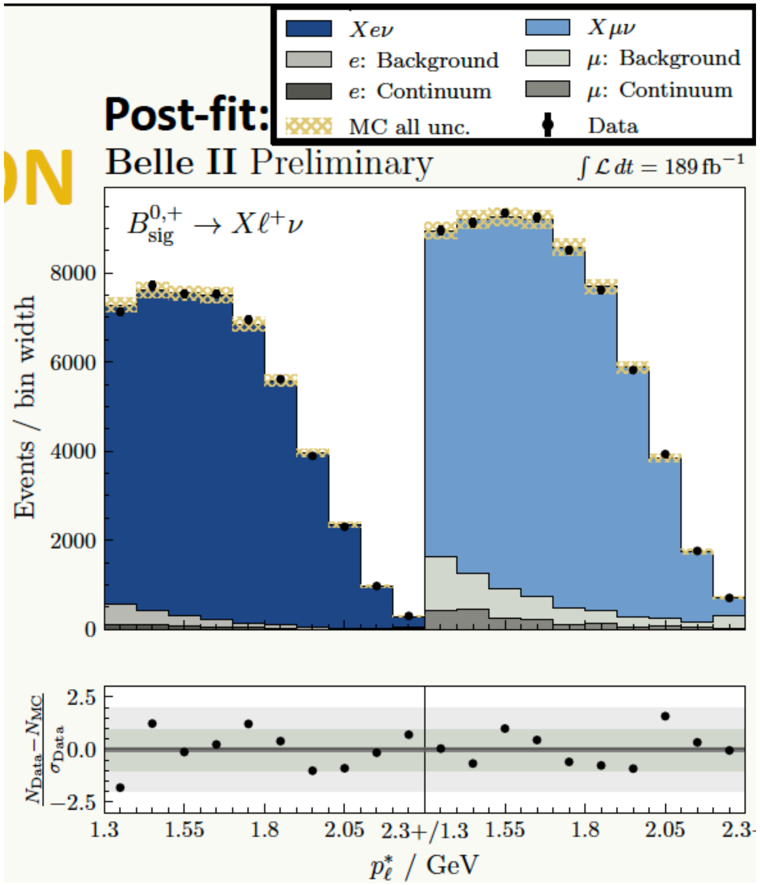
Vos & Rahimi, in progress

- *Since incl. measurements are hard, esp. with τ, measure $\mathrm{R}(X_{e/\mu})$ first*

$$\boxed{\mathrm{R}(X_{c,e/\mu}) = 1.003 \pm 0.010 \pm 0.020}$$

Most precise LFU test with semi-leptonic B decays to date !





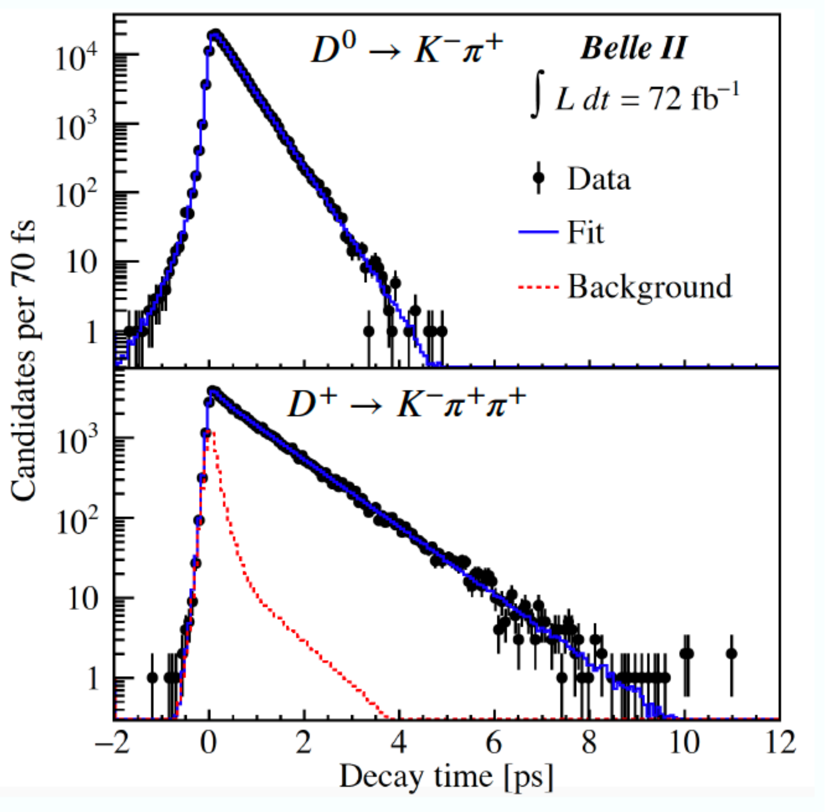
Charm meson lifetimes

- *First D^0 and D^+ lifetime measurements in 2 decades*

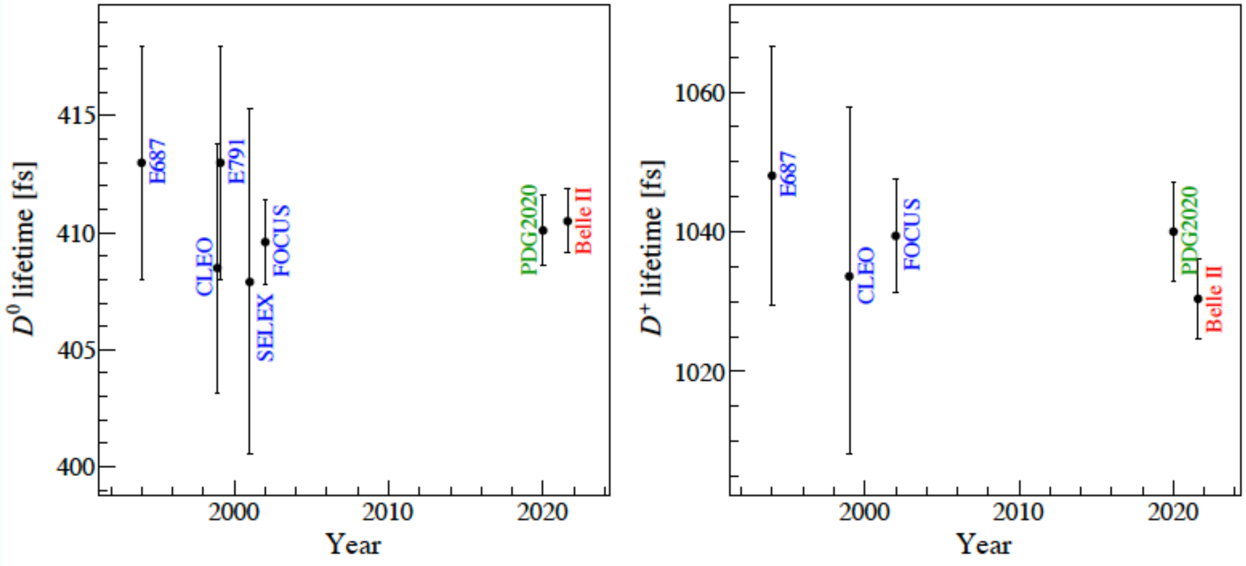
Belle II, PRL 127 (2021) 021801

$$\tau(D^0) = \quad 410.5 \pm 1.1\ (\text{stat}) \pm 0.8\ (\text{syst})\ \text{fs}$$
$$\tau(D^+) = 1030.4 \pm 4.7\ (\text{stat}) \pm 3.1\ (\text{syst})\ \text{fs}$$

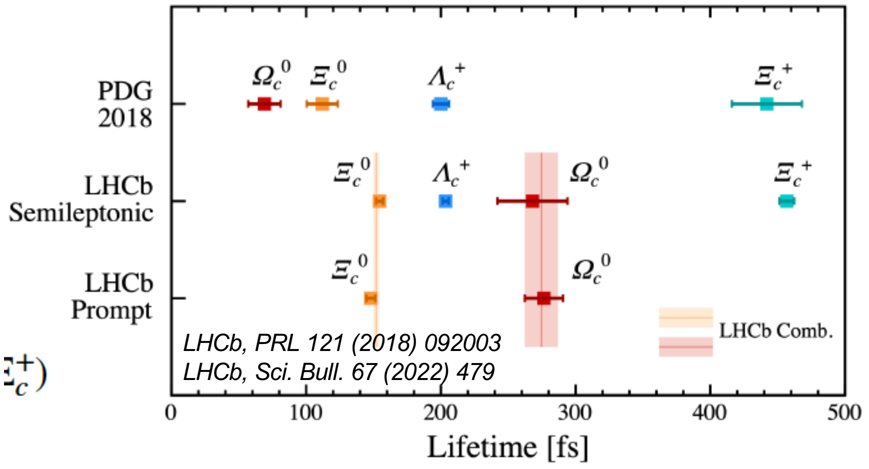
- *Belle II results are more precise than and consistent with previous measurements*



0.5% precision (incl. syst.) demonstrates excellent performance and understanding of Belle II vertex detector



Charm baryon lifetimes



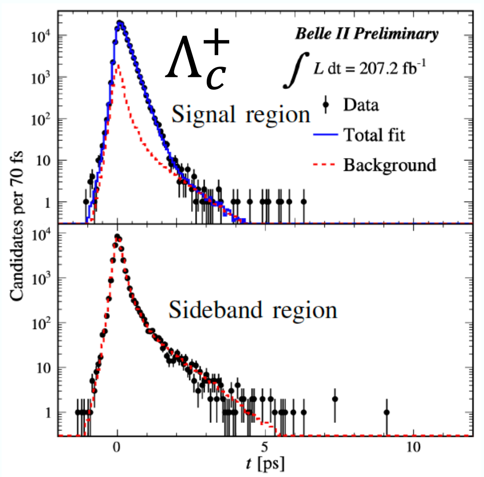
LHCb, PRL 121 (2018) 092003
LHCb, Sci. Bull. 67 (2022) 479

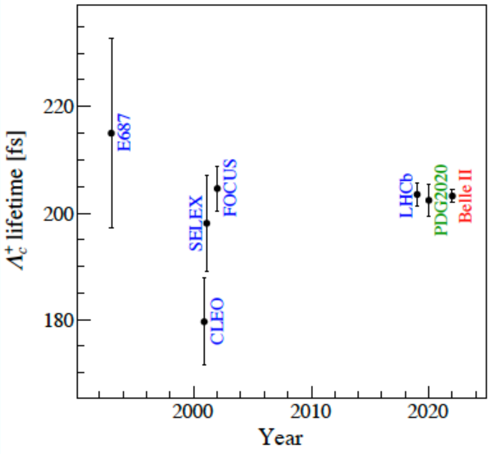
- *Recent LHCb Λ_c^+ and Ξ_c^0 lifetime measurements changed order of charm baryon lifetimes*
- *New Belle II results:*

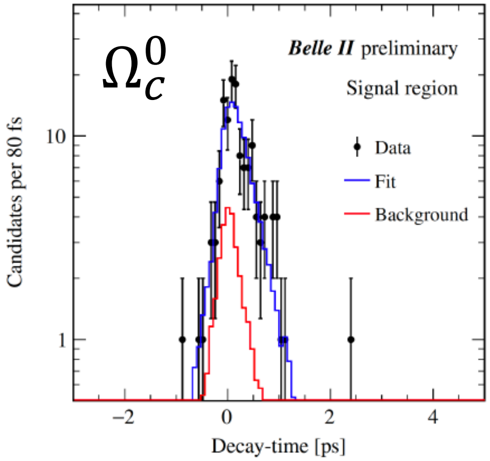
$$\tau(\Lambda_c^+)$$
$$= 203.2 \pm 0.9\ (\mathrm{stat}) \pm 0.8\ (\mathrm{syst})\ \mathrm{fs}$$
$$\tau(\Omega_c^0)$$
$$= \quad 243 \pm 48\ (\mathrm{stat}) \pm 11\ (\mathrm{syst})\ \mathrm{fs}$$

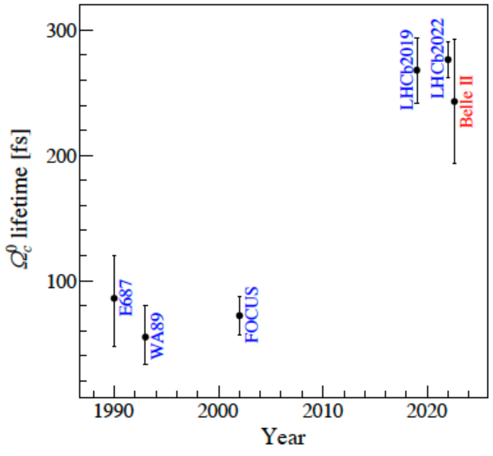
  - *Most precise Λ_c^+ lifetime measurement*
- *Confirms that Ω_c^0 is not shortest-lived singly-charmed baryon*
  - *Consistent with LHCb results*
  - *Inconsistent with pre-LHCb world average by 3.4sigma*

arXiv: 2206.15227





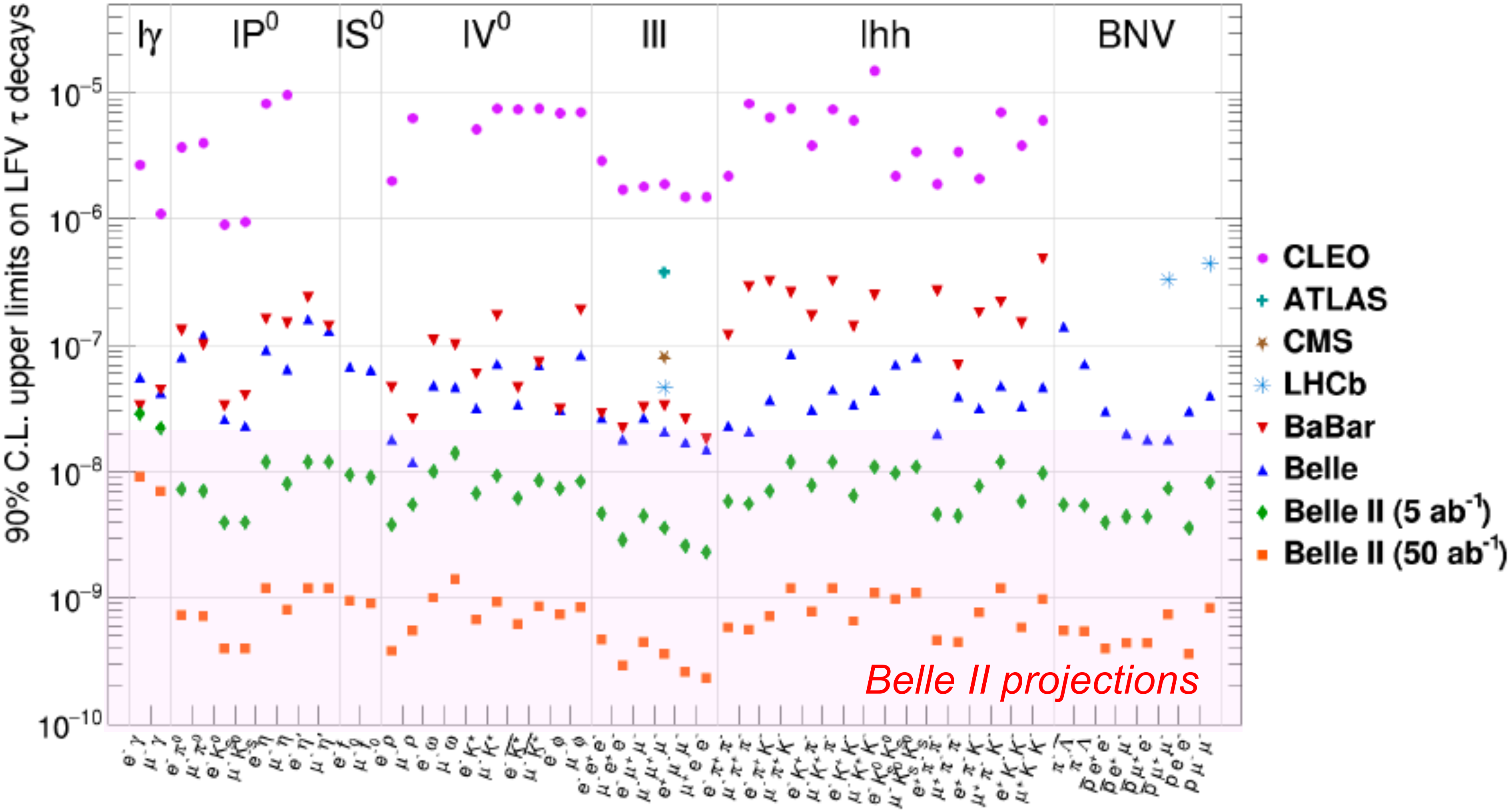




LFV searches in τ decays

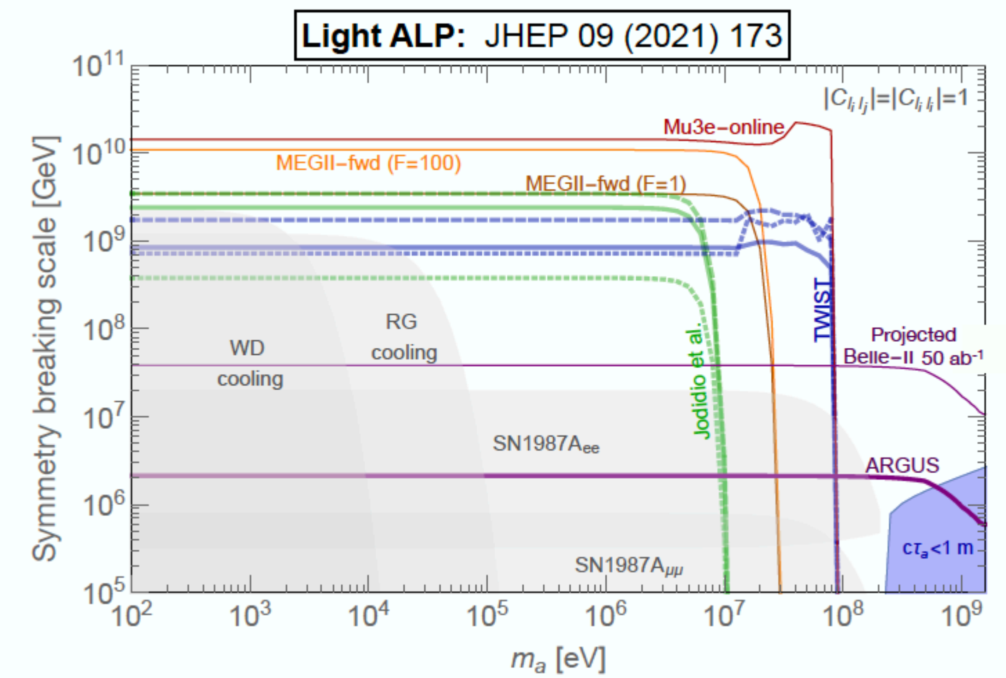
Banerjee, HI
Thu 17:00

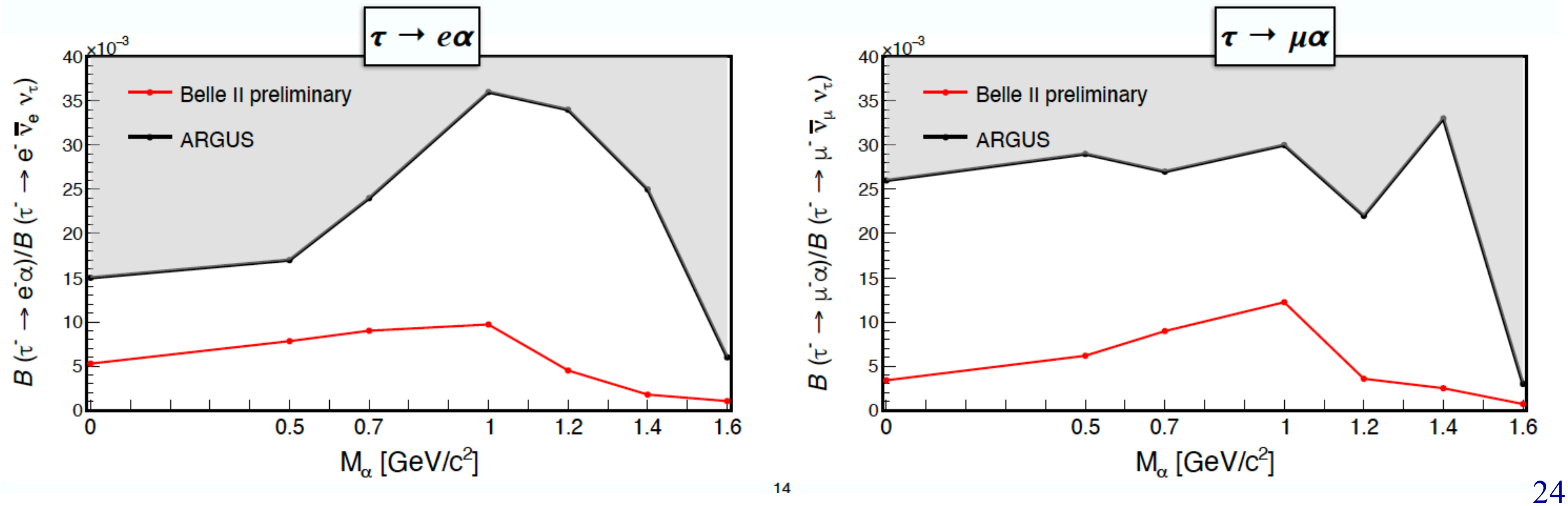
Many new physics models predict cLVF at 10^{-7}-10^{-10}



$\tau \to e/\mu + \alpha\ (invisible)$

- *Invisble particle occur in NP models such as light ALP*
- *Previous best upper limits for 0.1 < M_α < 1.6 GeV from ARGUS* ***(add ref)***
- *Compare* $\tau \to e/\mu\ + invisible$ *rate with* $\tau \to e/\mu\ \nu\bar{\nu}$ *prediction*
  - *Improved limits set for* $BR(\tau \to e/\mu + \alpha)/BR(\tau \to e/\mu\ \nu\bar{\nu})$ *for* $M_\alpha < 1.6\ GeV$





Conclusions

- *SuperKEKB is delivering e^+e^- collision data at world-record luminosity*
  - *Expect to improve a factor of 6 before LS2*
- *Belle II detector demonstrates excellent performance*
  - *E.g. in incl. reco., neutrals (γ, π^0) & vertex measurements*
- *Belle II is a Super Flavor Factory, already producing many results with first 190 fb^{-1} (of 424 fb^{-1} recorded)*
  - *New B, Charm, and τ physics results are at precisions comparable to those of BABAR and Belle*
  - *Similarly, many new and unique results on dark sector searches & heavy quarkonium (not covered in this talk)*

Back-Up Slides

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* $(B \to \tau \nu$ & $B \to D^{(*)} \tau \nu)$
- *Does nature have a* ***left-right symmetry****, and are there flavor changing neutral currents beyond the SM ?*
  - *CPV in* $B \to K^{*0} (K_s\pi^0)\gamma$; $B \to K^{(*)}\nu\nu$, *angular variables in* $b \to s,d\ l^+l^-$
- *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*

SM CPV: CKM and Unitarity Triangle

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

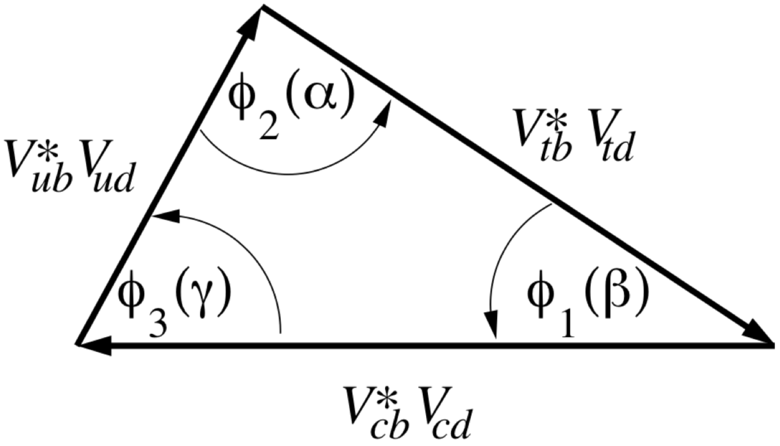
*The internal angles of this triangle are phase differences that can be measured via **various strategies**:*

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

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

$B \rightarrow \pi^{+}\pi^{-} / \pi^{+}\pi^{0} / \pi^{0}\pi^{0}$
$B \rightarrow \rho^{+}\rho^{-} / \rho^{+}\rho^{0} / \rho^{0}\rho^{0}$
$B^{0} \rightarrow \rho\, \pi$
$B^{0} \rightarrow a_{1}(\rho\pi)^{+}\ \pi^{-}$

Isospin decomposition required to extract φ₂ (α) from B → ππ and B → ρρ



$B^{-} \rightarrow D^{(*)}{}_{CP}\, K^{(*)-}$
$B^{0} \rightarrow D_{CP}\, K^{*0}$
$B^{-} \rightarrow D^{(*)}(K^{+}\pi^{-})\, K^{(*)-}$
$B^{-} \rightarrow D^{(*)0}\, \pi^{-}$
$B^{-} \rightarrow D^{(*)}(K_{S}\, \pi^{+}\pi^{-})\, K^{(*)-}$
$B^{-} \rightarrow D(\pi^{0}\pi^{+}\pi^{-})\, K^{-}$
$B^{-} \rightarrow D(K_{S}\, K^{+}\pi^{-})\, K^{-}$

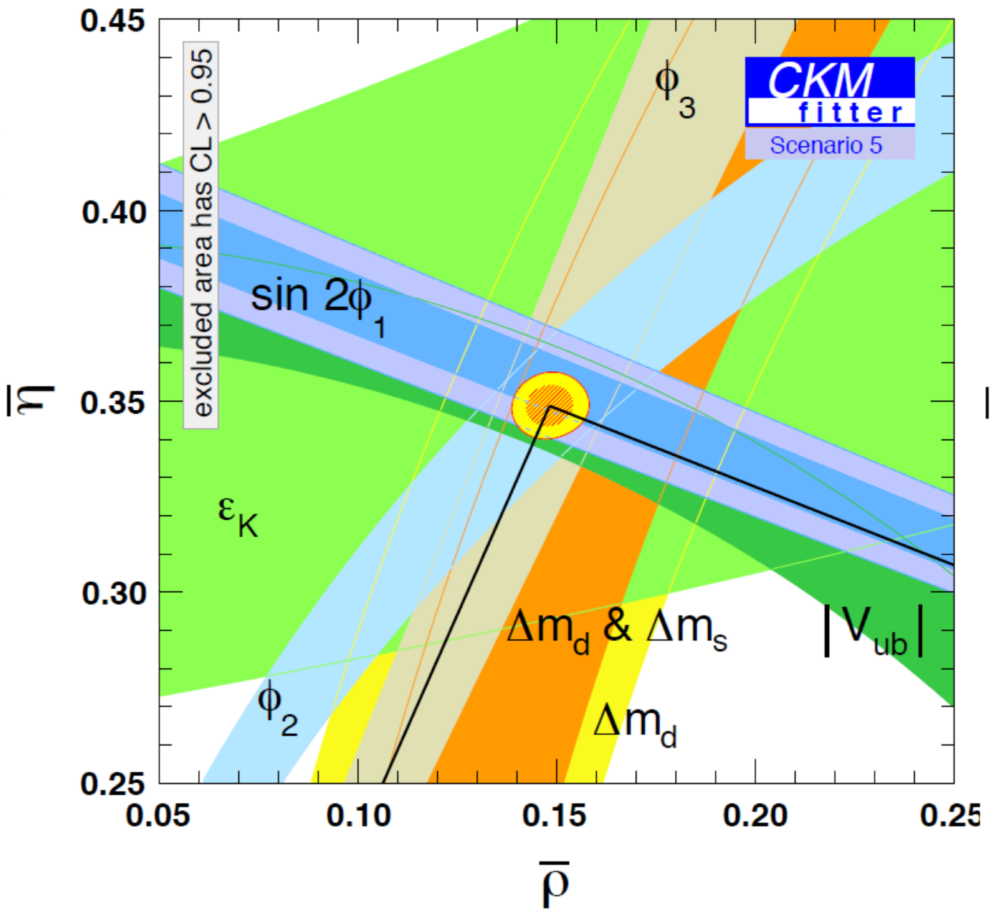
$B^{0} \rightarrow J/\psi\, K_{S}$
$B^{0} \rightarrow J/\psi\, K_{L}$
$B^{0} \rightarrow \psi'\, K_{S}$
$B^{0} \rightarrow \chi_{c}\, K_{S}$
$B^{0} \rightarrow \eta_{c}\, K_{S}$
$B^{0} \rightarrow D^{(*)}{}_{CP}\, h^{0}$
$B^{0} \rightarrow (\phi/\eta'/\pi^{0}/f^{0})K^{0}$
$B^{0} \rightarrow (K_{S}K_{S}/\rho^{0}/\omega)\, K_{S}$

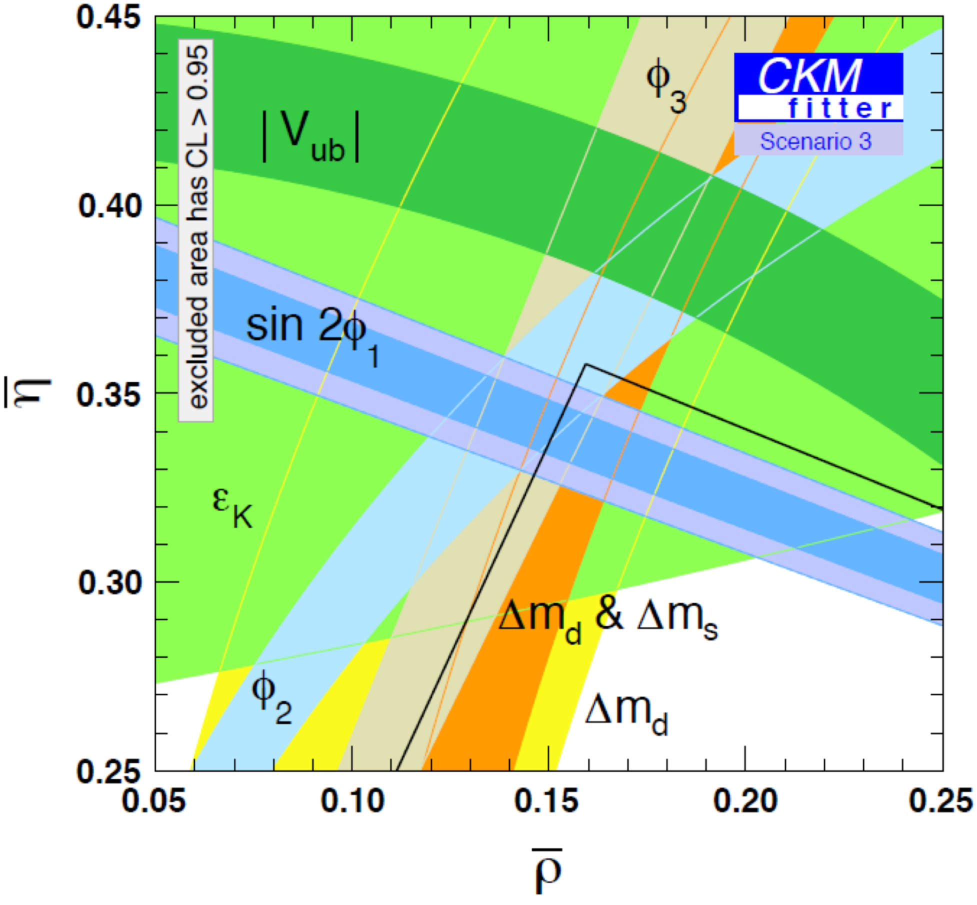
Φ₁ (β) and Φ₃ (γ) will also be precisely measured by LHCb

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 ($\sin2\varphi_1, \varphi_2, \varphi_3$)





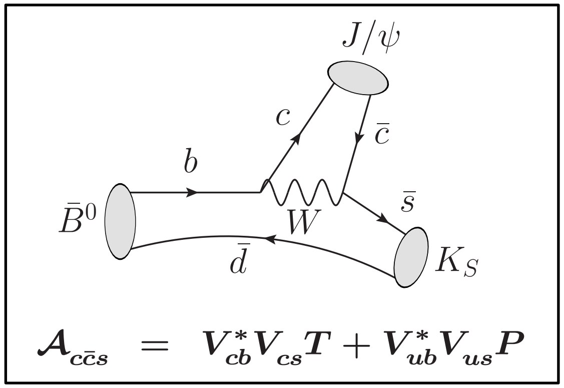
In ten years: no-tension SM … or observation of New Physics ?

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%)

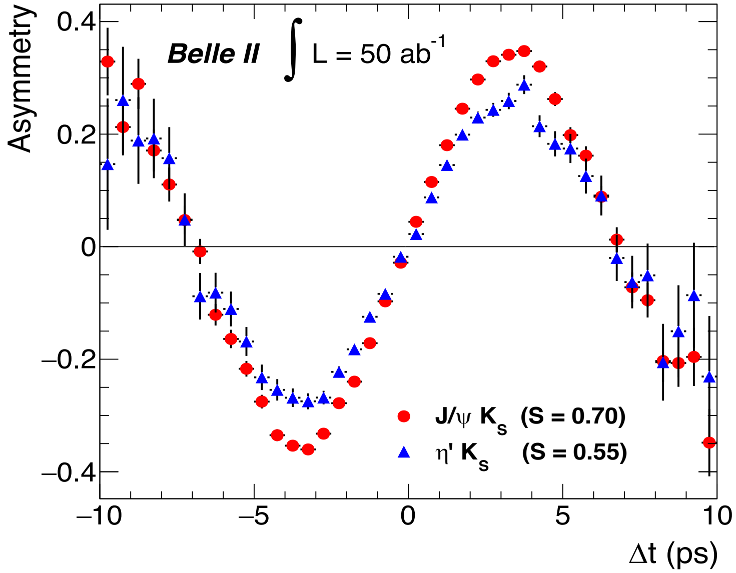
$B^0 \to J/\psi\, K_S$ ***(the "Golden" mode):***

→ constrains the UT



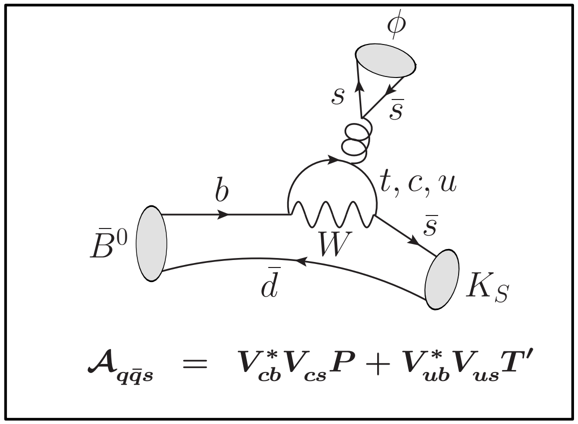
$$\mathcal{A}_{c\bar{c}s} = V_{cb}^* V_{cs} T + V_{ub}^* V_{us} P$$

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):***



$$\mathcal{A}_{q\bar{q}s} = V_{cb}^* V_{cs} P + V_{ub}^* V_{us} T'$$

	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_S^0	0.21	0.14	0.08	0.06	0.024	0.020
$K_S^0 \pi^0 \gamma$	0.20	0.12	0.10	0.07	0.031	0.021
$K_S^0 \pi^0$	0.17	0.10	0.09	0.06	0.028	0.018

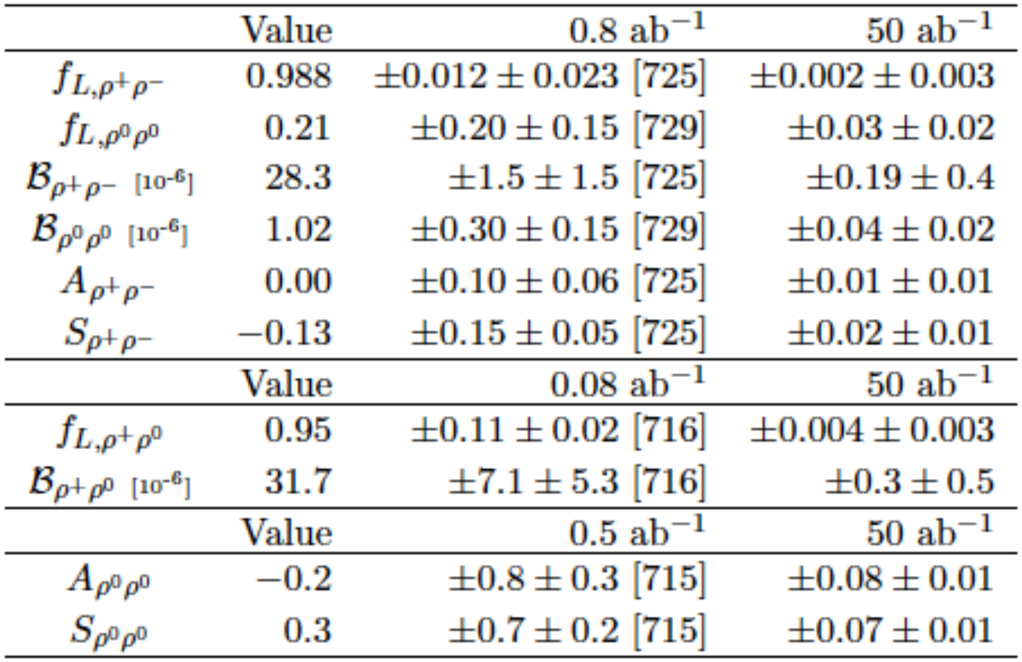
*Tree and penguin modes have same SM weak phase, but NP contributions in loop could contribute additional phases (**improve from 10-20% precision to 2-3%)***

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

Measurement of φ_2 in B → ππ, 3π, ρρ

ϕ_2 is determined from CP asymmetries and BFs of B → ππ, B → 3π, and B → ρρ decays with an **isospin decomposition** of B^+ and B^0 decays **involving final states with π^0's**

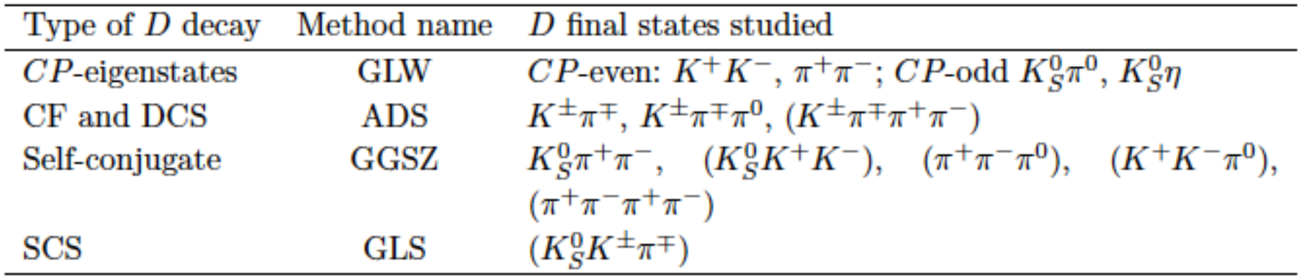
- Belle II has good π^0 efficiency
- Expt. errors reduced by 2× - 10× depending on systematic error source
- Improved measurement of A(B→ π^0 π^0) will reduce discrete ambiguities
- **Expect error in ϕ_2 with 50/ab to be 0.6°** **(now 4.2°)**



	Value	$0.8\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
$f_{L,\rho^+\rho^-}$	0.988	$\pm0.012 \pm 0.023$ [725]	$\pm0.002 \pm 0.003$
$f_{L,\rho^0\rho^0}$	0.21	$\pm0.20 \pm 0.15$ [729]	$\pm0.03 \pm 0.02$
$\mathcal{B}_{\rho^+\rho^-}$ $[10^{-6}]$	28.3	$\pm1.5 \pm 1.5$ [725]	$\pm0.19 \pm 0.4$
$\mathcal{B}_{\rho^0\rho^0}$ $[10^{-6}]$	1.02	$\pm0.30 \pm 0.15$ [729]	$\pm0.04 \pm 0.02$
$A_{\rho^+\rho^-}$	0.00	$\pm0.10 \pm 0.06$ [725]	$\pm0.01 \pm 0.01$
$S_{\rho^+\rho^-}$	-0.13	$\pm0.15 \pm 0.05$ [725]	$\pm0.02 \pm 0.01$
	Value	$0.08\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
$f_{L,\rho^+\rho^0}$	0.95	$\pm0.11 \pm 0.02$ [716]	$\pm0.004 \pm 0.003$
$\mathcal{B}_{\rho^+\rho^0}$ $[10^{-6}]$	31.7	$\pm7.1 \pm 5.3$ [716]	$\pm0.3 \pm 0.5$
	Value	$0.5\ \mathrm{ab}^{-1}$	$50\ \mathrm{ab}^{-1}$
$A_{\rho^0\rho^0}$	-0.2	$\pm0.8 \pm 0.3$ [715]	$\pm0.08 \pm 0.01$
$S_{\rho^0\rho^0}$	0.3	$\pm0.7 \pm 0.2$ [715]	$\pm0.07 \pm 0.01$

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

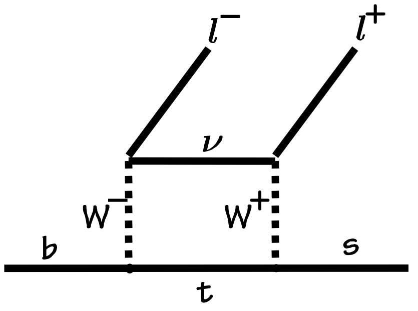
- *Reconstruct D decays to CP eigenstates, Cabibbo-favored and singly and doubly Cabibbo-suppressed decays and self-conjugate modes*
- ***Expect ϕ_3 error from GGSZ with 50/ab and strong phase measurement from BESIII to be 1.5° (WA 5°)***

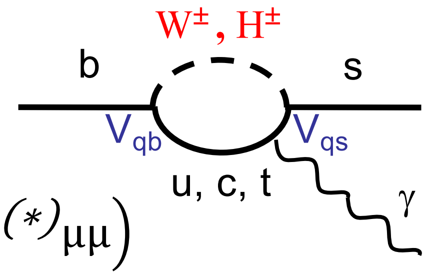


Type of D decay	Method name	D final states studied
CP-eigenstates	GLW	CP-even: K^+K^-, $\pi^+\pi^-$; CP-odd $K^0_S\pi^0$, $K^0_S\eta$
CF and DCS	ADS	$K^\pm\pi^\mp$, $K^\pm\pi^\mp\pi^0$, $(K^\pm\pi^\mp\pi^+\pi^-)$
Self-conjugate	GGSZ	$K^0_S\pi^+\pi^-$, $(K^0_SK^+K^-)$, $(\pi^+\pi^-\pi^0)$, $(K^+K^-\pi^0)$,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

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 $B \to K^{(*)}\nu\nu$*





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

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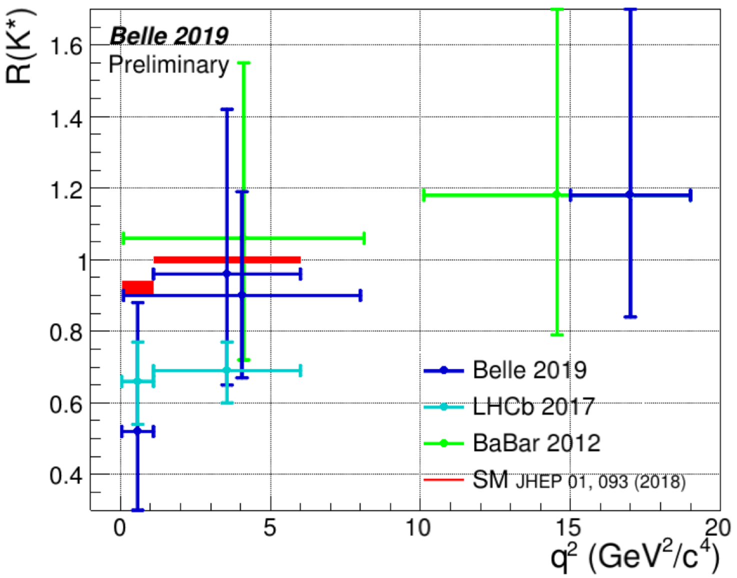
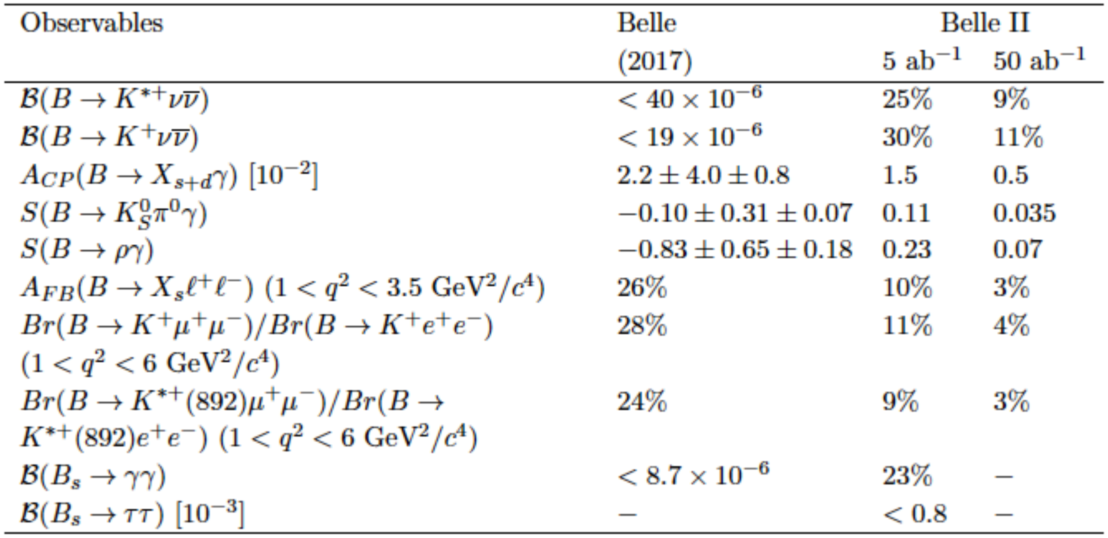
[up to tiny QED *and* lepton mass effects]

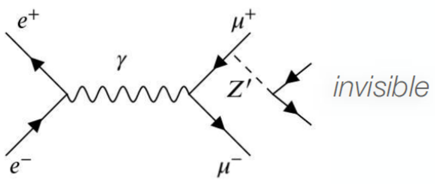




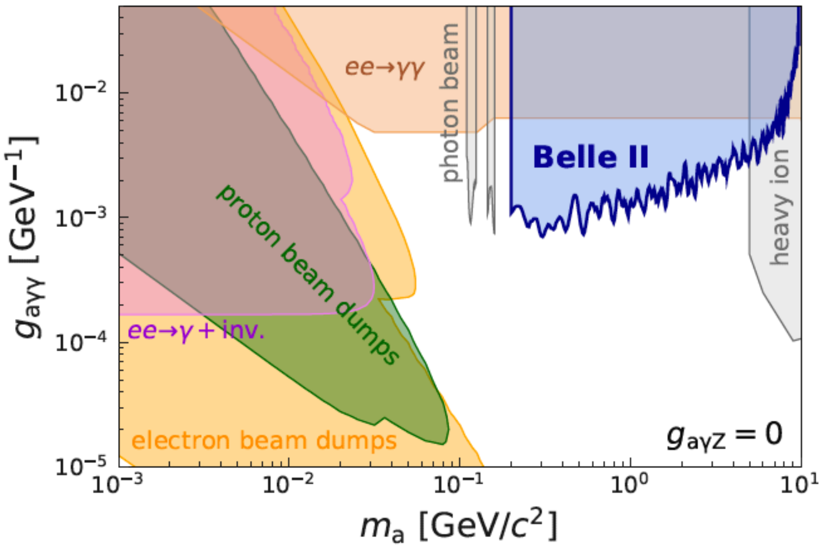
Observables	Belle	Belle II	
	(2017)	5 ab^{-1}	50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\overline{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+}\nu\overline{\nu})$	$< 19 \times 10^{-6}$	30%	11%
$A_{CP}(B \to X_{s+d}\gamma)$ [10^{-2}]	$2.2 \pm 4.0 \pm 0.8$	1.5	0.5
$S(B \to K^0_S \pi^0 \gamma)$	$-0.10 \pm 0.31 \pm 0.07$	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	–

Dark Sector Searches

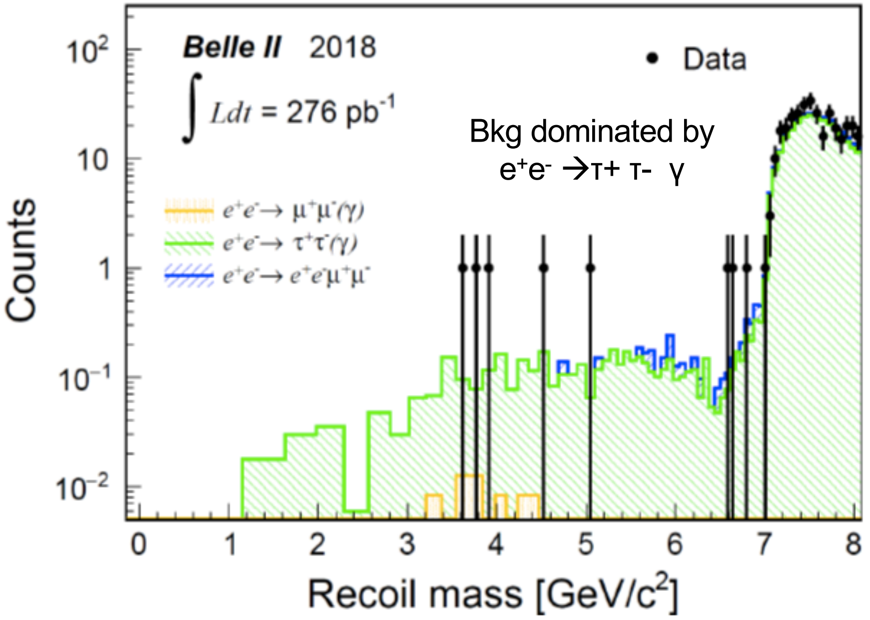
- *DS searches at Belle II benefit from large data sample, clean e^+e^- environment, and special high-efficiency triggers for low-multiplicity final states*
- *Many **DS benchmark models** will be studied, e.g.*
  - *Vector mediator (dark photon, Z')*
  - *Scalar mediator (dark Higgs)*
  - *Neutrino-like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



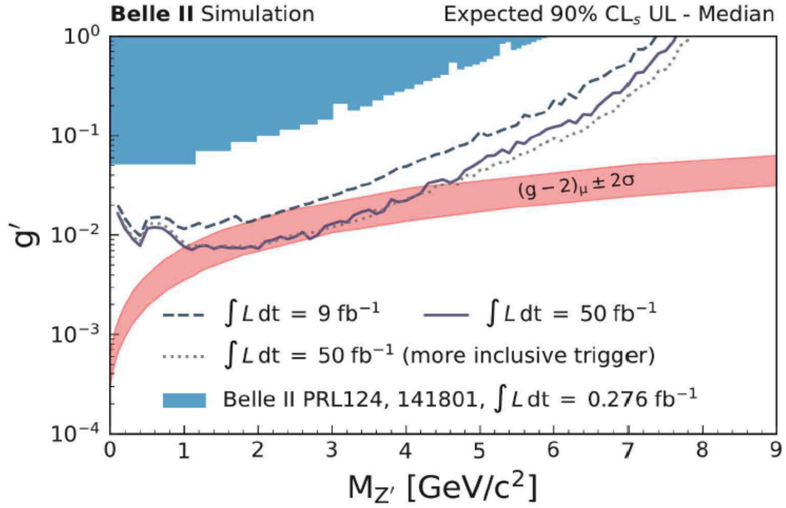
Search for ALP in $e^+e^- \to a(\gamma\gamma)\gamma$
arXiv:2007.13071, accepted by PRL



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



Bkg dominated by
e+e- →τ+ τ- γ



Outline 1

- *SuperKEKB & Belle II detector*
  - *B factories legacy*
  - *Luminosity records and planned profile*
  - *Strength wrt LHCb (inclusive, neutrals & invisibles)*
  - *Heavy Flavor factory (B, charm, tau)*

Outline 2

- *B Results*
  - Vcb and Vub from B -> D(*) l nu and B -> pi l nu (see Koga, ICHEP talk)
    - Measurement of Moments of the q2 Spectrum in B -> Xc l nu Decays, subm. to PRD (2205.06372), old ?
  - **B lifetime and mixing, sin(2phi1) with J/psi KS, 3KS, K0S pi0 (see La Licata ICHEP talk)**
  - **Kpi puzzle, alpha from pipi and rho pi, Gamma (Belle + Belle II) (see Skorupa ICHEP talk)**
  - **B -> Xs gamma, BR(B->K*ll),** B -> J/psi K (see Ganiev ICHEP talk)
  - **Studies of B+ -> K+ nu nubar decay using an inclusive tagging method at Belle II, Phys Rev Lett 127, 181802 (2021)**
  - **R(X)$_{e/mu}$**

Outline 3

- *Charm results*
  - **Measurement of the D0 and the D+ Lifetimes, Phys Rev Lett 127, 211801 (2021)**
  - **Measurement of Lambda_c lifetime**
  - **Measurement of the Omega_c lifetime, ICHEP 2022**
- *Tau results*
  - **LFV Tau -> l + alpha (invisible) (see Tenchini ICHEP 2022 talk)**
- *Heavy quarkonium*
  - Search for e+e- -> omega chi_{bJ} (J=0,1,2) at near 10.751 GeV at Belle II, ICHEP 2022
  - Amplitude analysis of e+ e- -> J/psi X, Moriond 2022 ???
- *Dark results*
  - *Will not cover, mention on conclusions slide*

- *Conclusions & Outlook*

Notes

- *No LHCb plenary talk @ CIPANP 2022*

- *Belle (II) talks for Summary*
  - *CPV in Belle II, Radek, Zlebcik, HF, Tue 13:30*
  - *Excl. SL decays at Belle II, Philippe Horak, HF, Tue 17:00*
  - *Belle II results on inclusive B -> X l nu, Frank Meier, HF, Sat 15:30*
  - *Latest results on B -> K nu nu and EWP decays at Belle II, Lucas Martel, HI, Thu 16:30*
  - *Recent results and future plans in the study of hadronization at Belle (II) and CLAS12, Anselm Vossen, PDF, Sat 15:55*

  - *LFV in SL b -> c l nu decays, Koji Hara, HI, Sat 14:00 & cLFV in tau, Swagato Banerjee, HI, Thu, 1700*

- *Mention heavy quarkonium & dark results*

The International Belle II collaboration (geographically)

Belle II has grown to ~1000 researchers from 26 countries

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

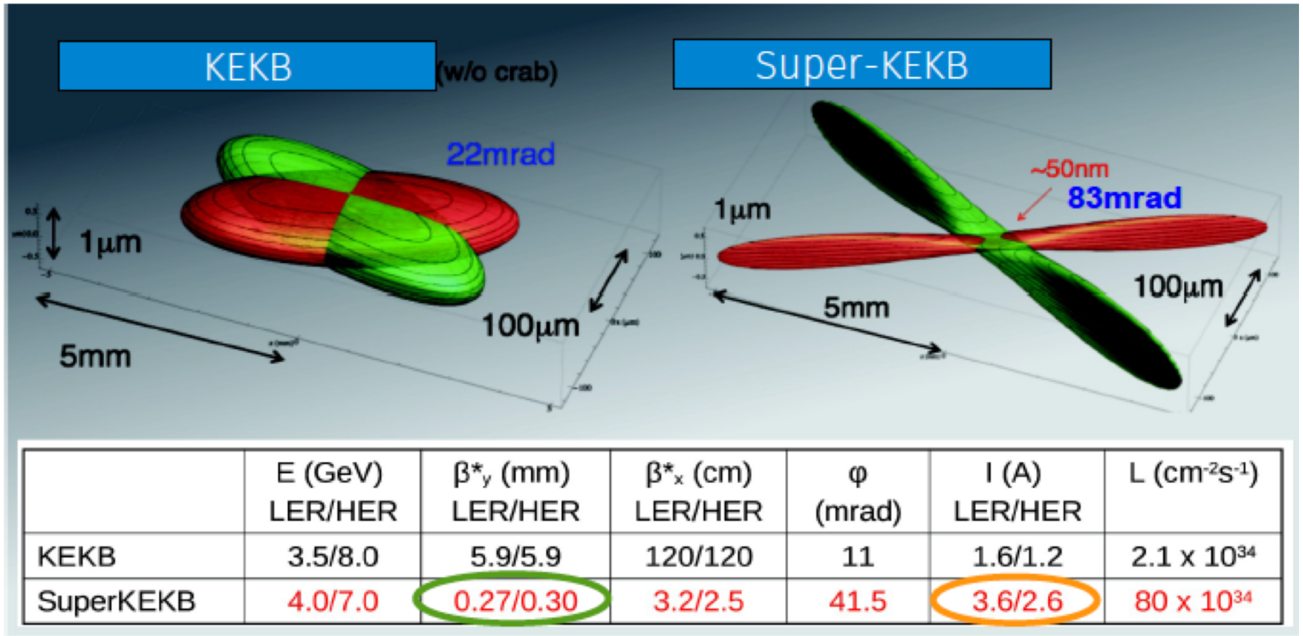
Geometrical reduction factors (crossing angle, hourglass effect)

(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 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

beam size:

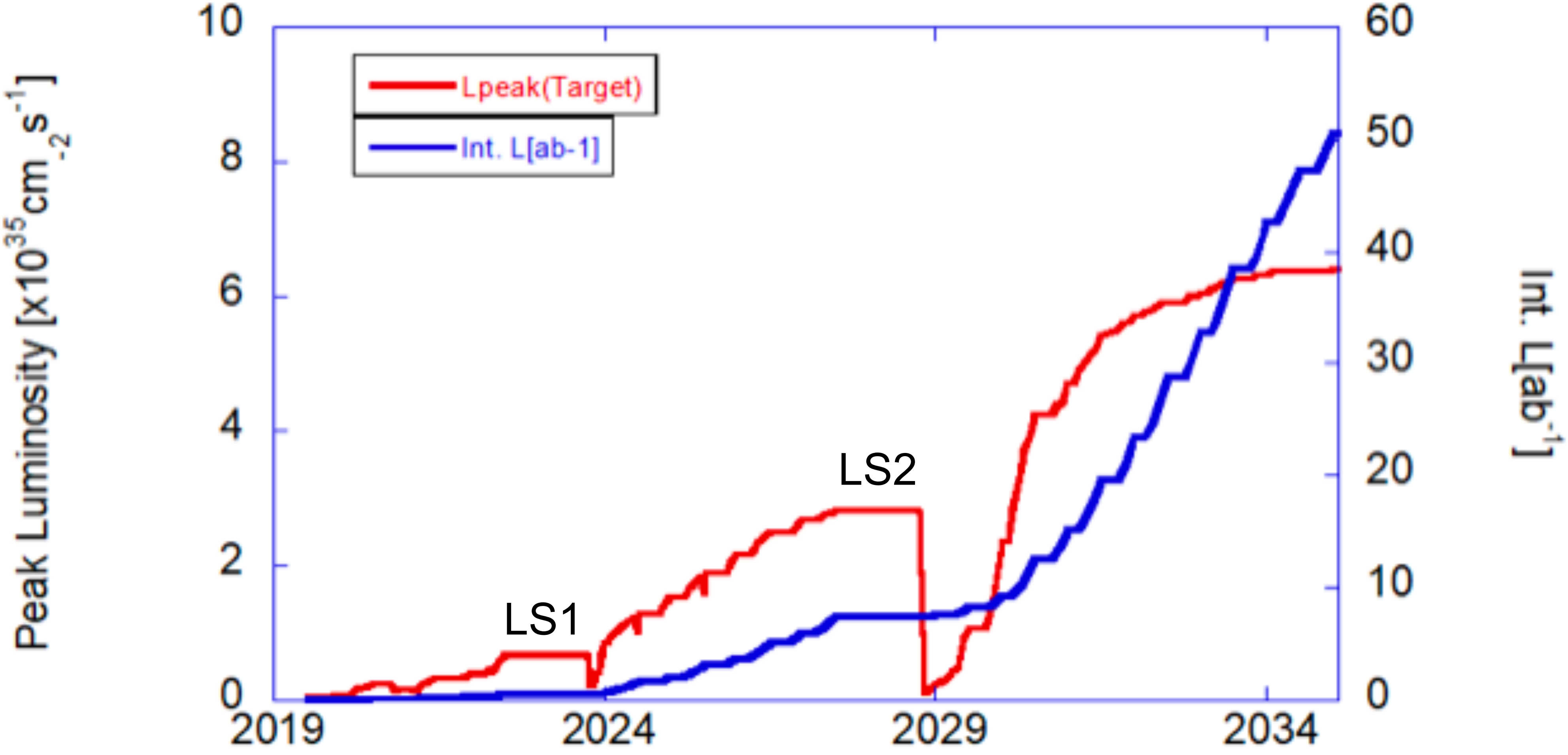
100 μm(H) x 2 μm(V)

→ *10 μm(H) x 59 nm(V)*

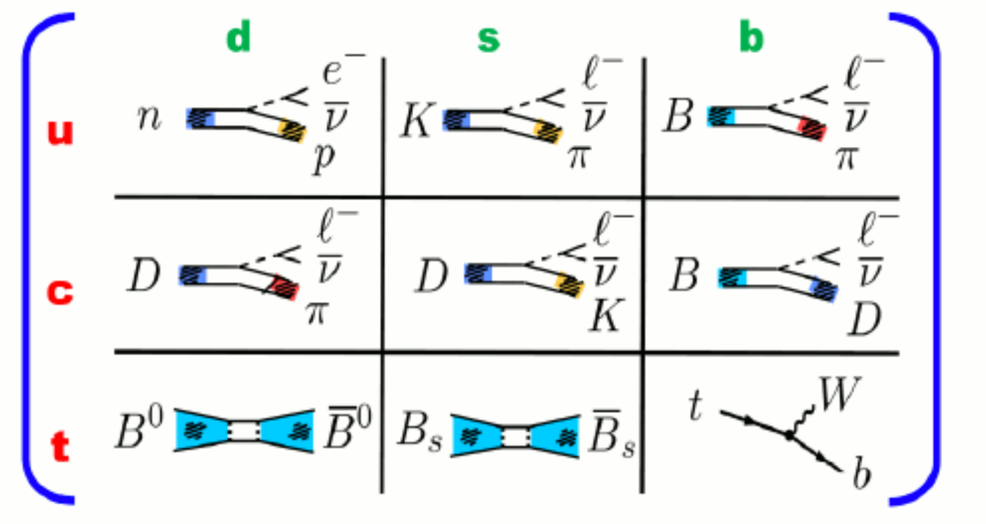
Belle-II Goal:

40 x Belle = 8 x 10^{35}

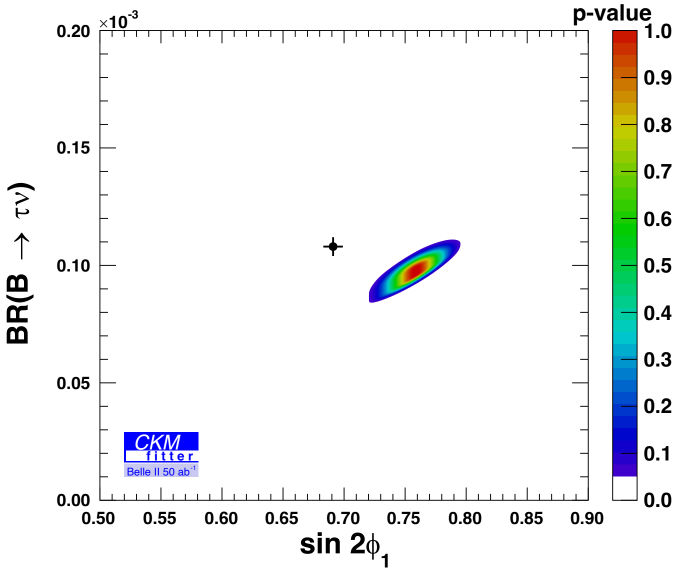
SuperKEKB Luminosity projection

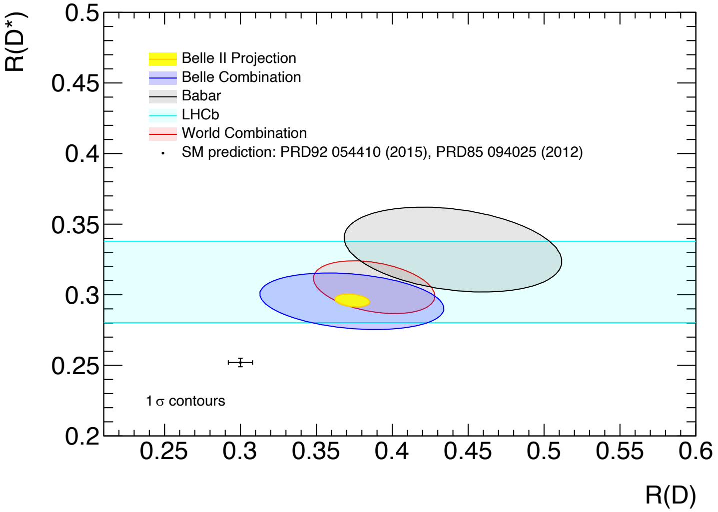


CKM Matrix: weak quark couplings



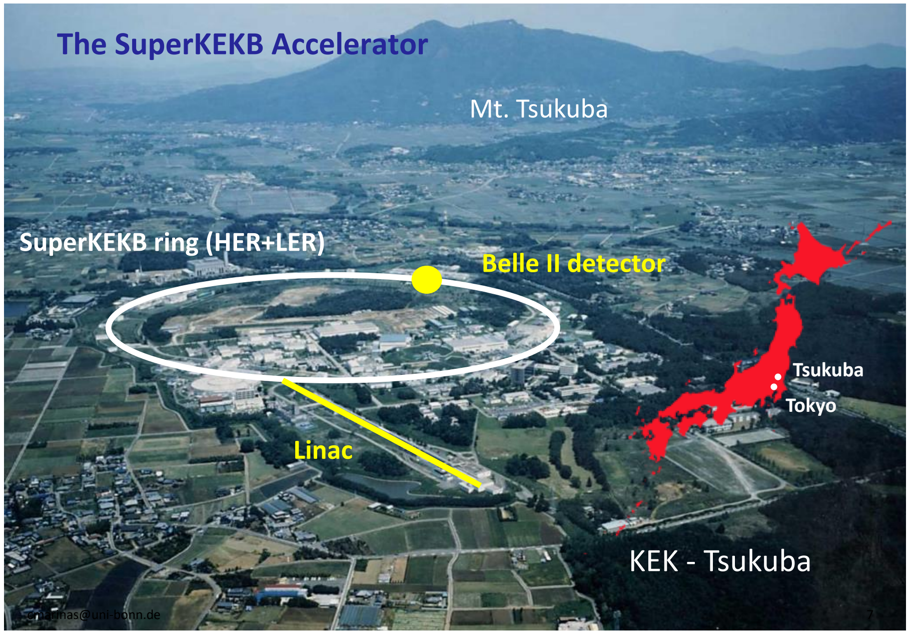
Testing CKM matrix unitarity: Belle II will provide input on the magnitudes of 7 out of 9 CKM matrix elements





- *$|V_{cb}|$ 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 $B \rightarrow \tau\nu$ as test of NP ($\Delta|V_{ub}|$ ~ 3% for each had.+SL tagged measurement)*
  - *Precision measurements of $B \rightarrow D^{(*)}\tau\nu$*
- *$|V_{td}|$ and $|V_{ts}|$ from BB 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*

- *Belle II is a multipurpose experiment at the SuperKEKB e^+e^- collider operating near the Y(4S) resonance, and located at KEK in Tsukuba, Japan*
  - *Latest in a long series of successful experiments (ARGUS, CLEO, and B Factories BELLE & BABAR), that made many crucial discoveries*
    - *BB oscillations*
    - *b → 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*

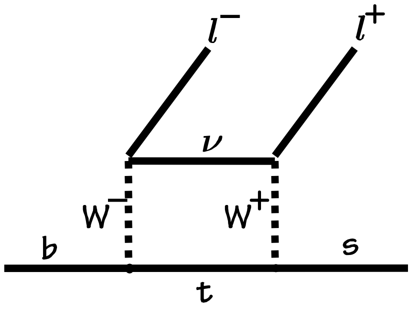
The B Factories, Belle and BABAR, discovered large CP violation in the B system in 2001, compatible with the SM.

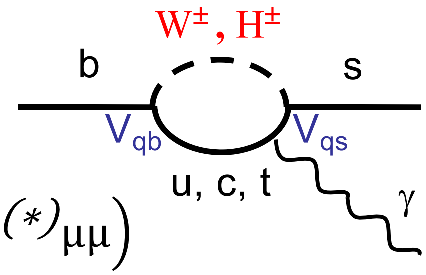
These provided the experimental foundation for the 2008 Nobel Prize to Kobayashi and Maskawa.

… Belle II's focus is shifted towards New Physics

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 $B \to K^{(*)}\nu\nu$*





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