Recent results from the Belle II experiment

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Belle II Collaboration

10th Large Hadron Collider Physics Conference
May 17, 2022

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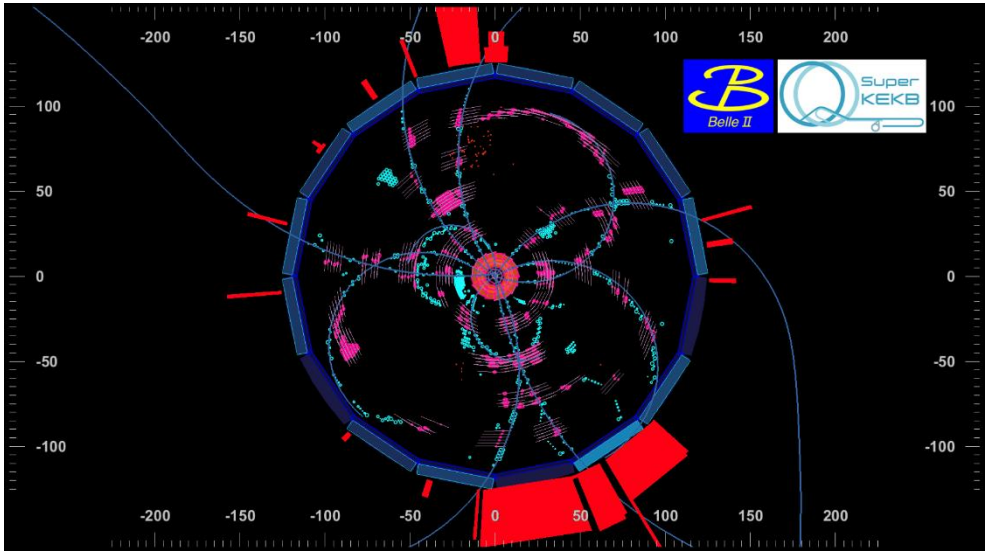


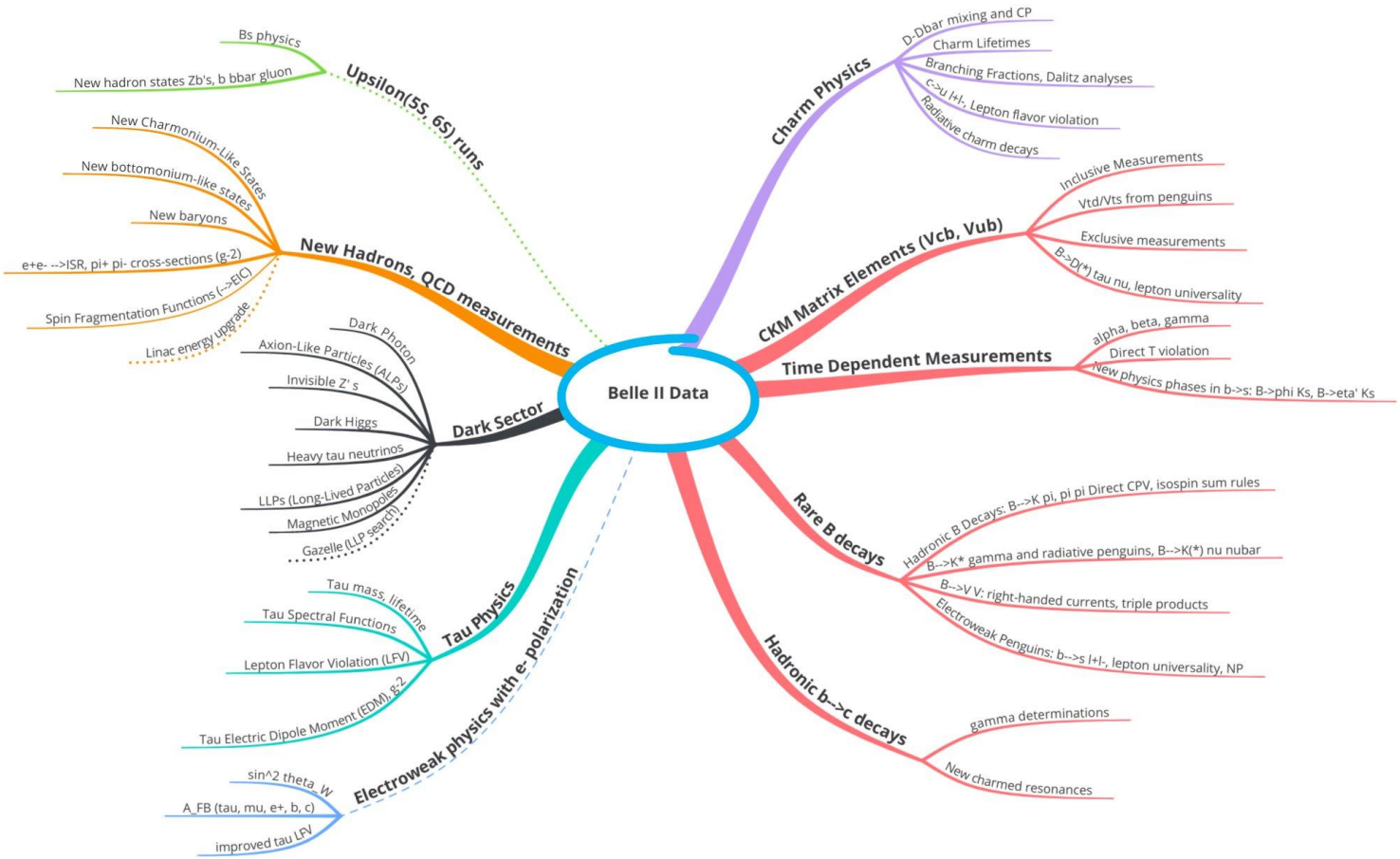
"B anti-B" like event

Tsukuba, Japan

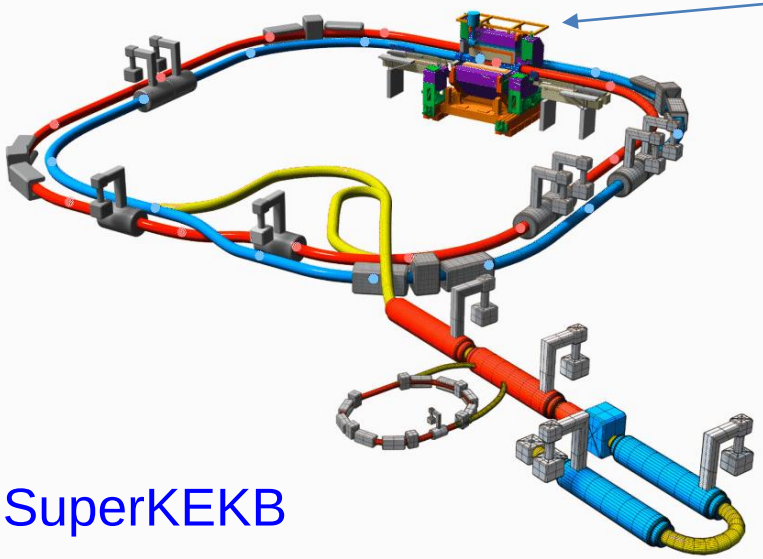
Physics at Belle II

- Intensity frontier experiment: Search for New Physics with precise measurements.
- Rich physics programs with B, charm, τ.

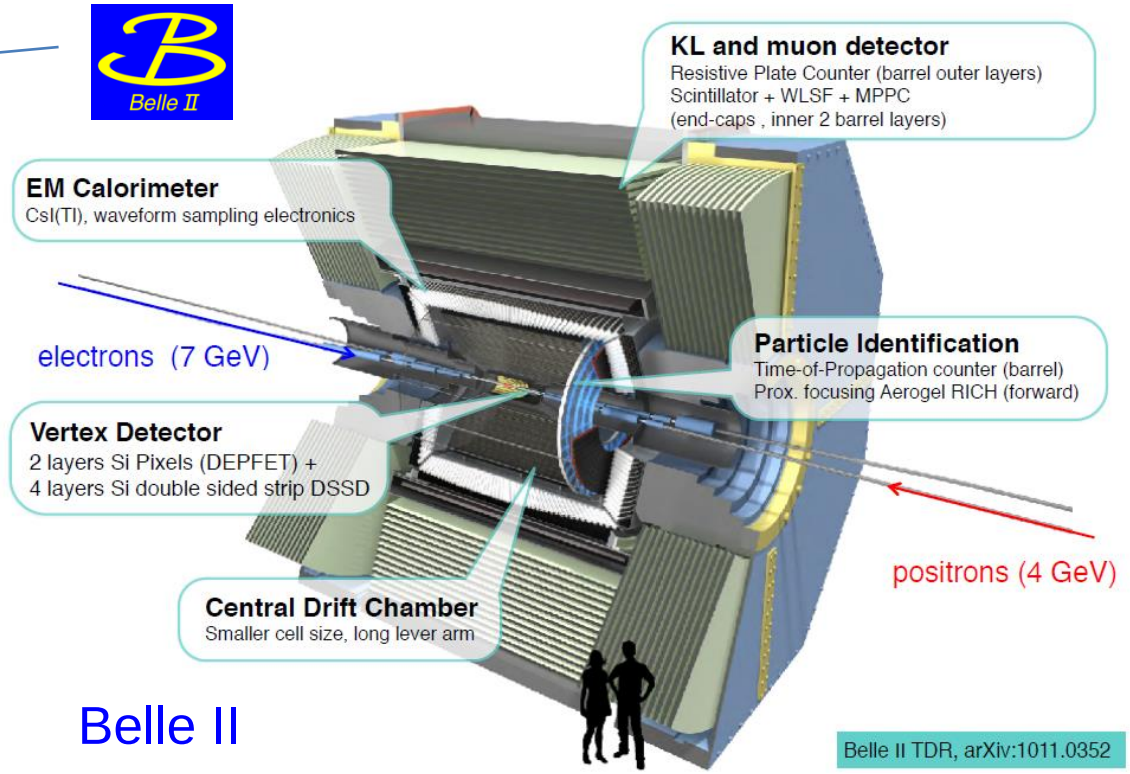
- Clean environment (e^+e^- collider) : advantage for the final states with neutral particles and missing particles.
  - ✓ e.g. $B^+ \to K^+\nu\bar{\nu}$



SuperKEKB and Belle II



SuperKEKB



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

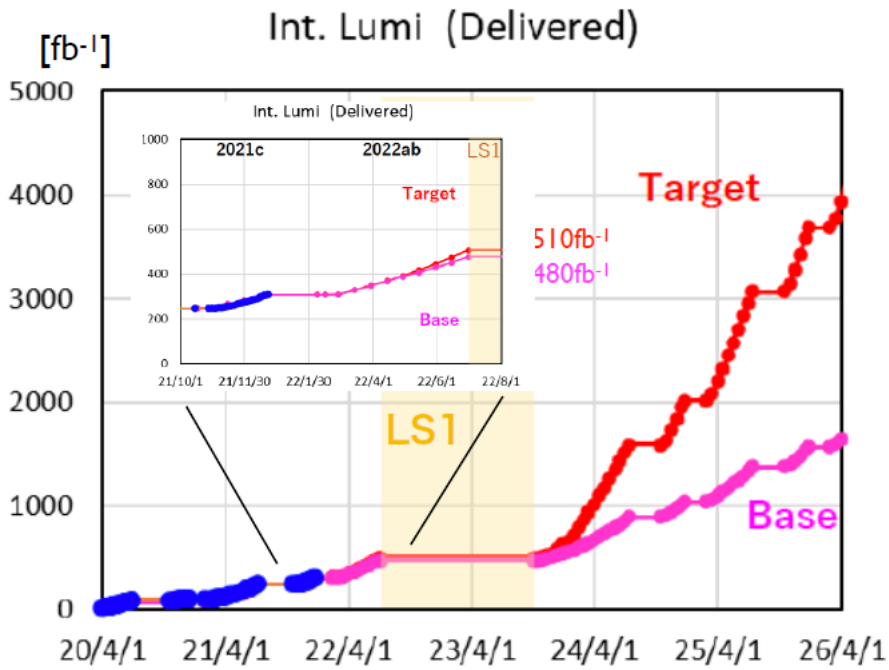
Belle II

- Belle II experiment at KEK: flavor physics experiment, successor of Belle.
- SuperKEKB asymmetric electron-positron collider: 4 GeV e^+ + 7 GeV e^-.
- Nano beam scheme to achieve high luminosity.
- General purpose Belle II detector.
  - ✓ Key components: vertex detector, particle identification.

SuperKEKB and Belle II

- Operation with full detector started in 2019.
- Luminosity $4.1 \times 10^{34}\,cm^{-2}\,s^{-1}$ achieved (May 17, 2022).
  - ✓ World record (~ ×2 of KEKB)
  - ✓ Aiming one order higher.
- ~380 fb^{-1} of data accumulated so far.
  - ✓ Belle: 1 ab^{-1} (= 1000 fb^{-1}) in 11 years' operation.
  - ✓ Belle II target: 50 ab^{-1}.

$1\ ab^{-1} \sim 10^9\ B\bar{B}$

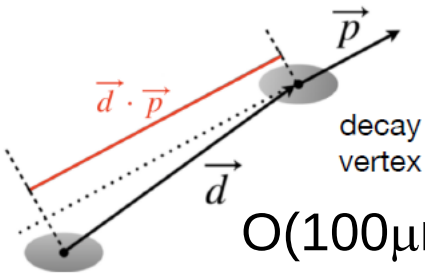


Base: assuming SuperKEKB parameters in 2021
Target: extrapolation with expected improvement

- Long shutdown (LS) 1 starts from summer 2022 for 15 months to fully install VXD.
- A SuperKEKB international taskforce is discussing additional improvements.
- LS2 for machine improvements could happen on the time frame of 2026-27

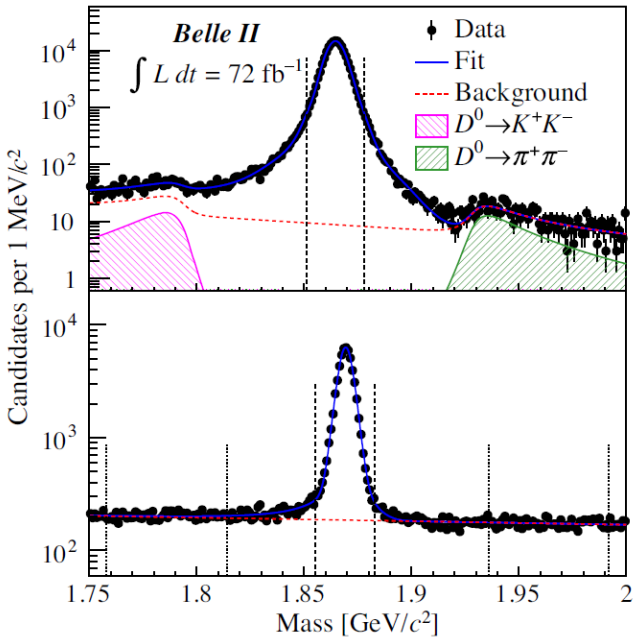
Lifetime of D^0, D^+ and Λ_c^+

- Large number of charm hadron s are produced at B factories.
- Belle II has better vertex resolution compared to Belle and BaBar thanks to new vertex detectors located at a closer position to the IP.
- Test of effective theory (weakly decay involving strong interaction at low energy).



O(100μm)

$$t = m\frac{\vec{d} \cdot \vec{p}}{p^2 \cdot c}$$



72 fb^{-1}

$D^0 \to K^-\pi^+$

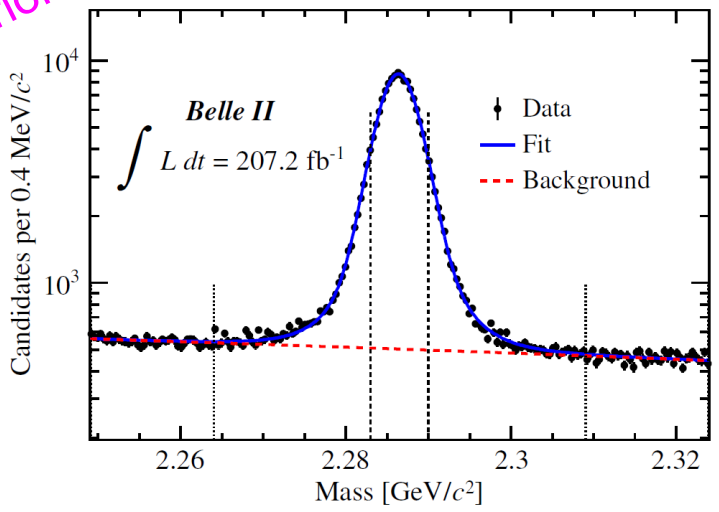
$D^+ \to K^-\pi^+\pi^+$

D from D* are selected
(D* → D + slow pion)

Preliminary (Moriond)

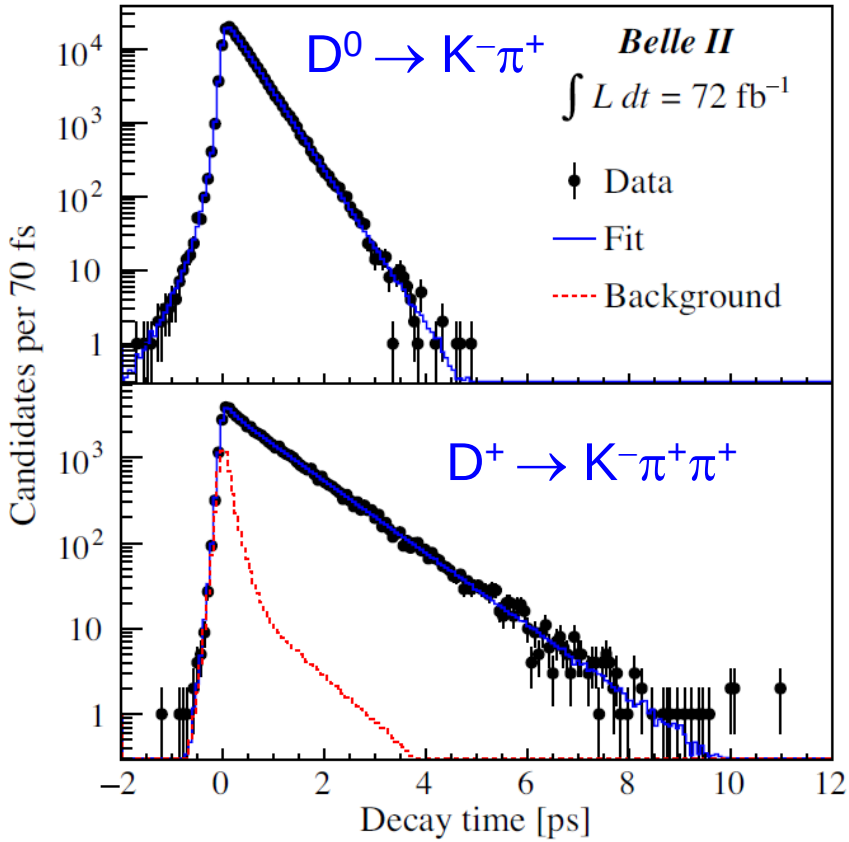
$\Lambda_c^+ \to pK^-\pi^+$

207 fb^{-1}



Lifetime of D^0, D^+ and Λ_c^+

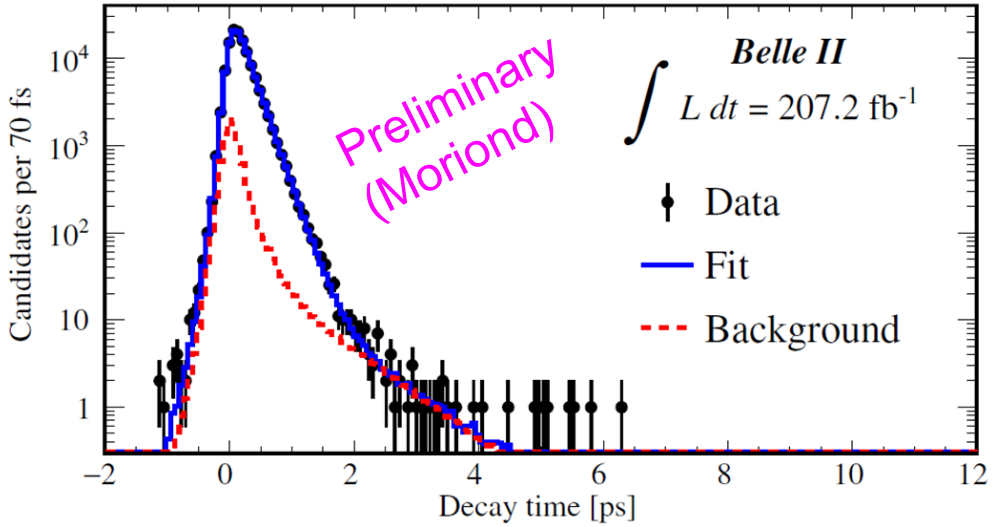
Decay time distribution and fit



[PRL 127, 211801]

Detector alignment is one of the major systematic error.

$\Lambda_c^+ \to pK^-\pi^+$ [paper in preparation]



$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8$ fs — 410.1 ± 1.5 fs

$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1$ fs — 1040 ± 7 fs

$\tau(\Lambda_c^+) = 204.1 \pm 0.8 \pm 0.7\ ^{-1.4}$ fs — 202.4 ± 3.1 fs

PDG

Ξ_c contamination

World's most precise measurement

B^0 Lifetime and Mixing Frequency

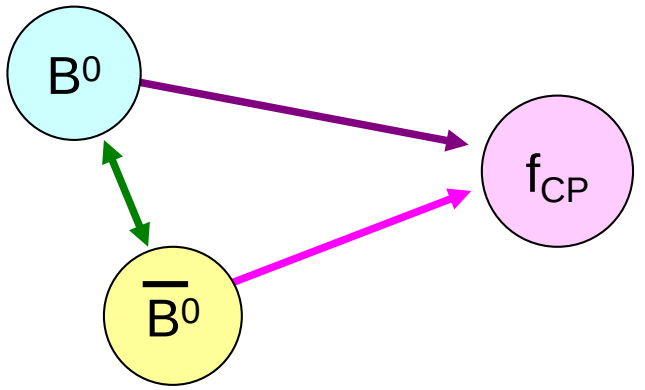
Mixing-induced CP asymmetry of B mesons

- B^0 and $\overline{B}^0$ decay to a common CP eigenstate f_{CP}.
- CP violation appears as a decay time difference.

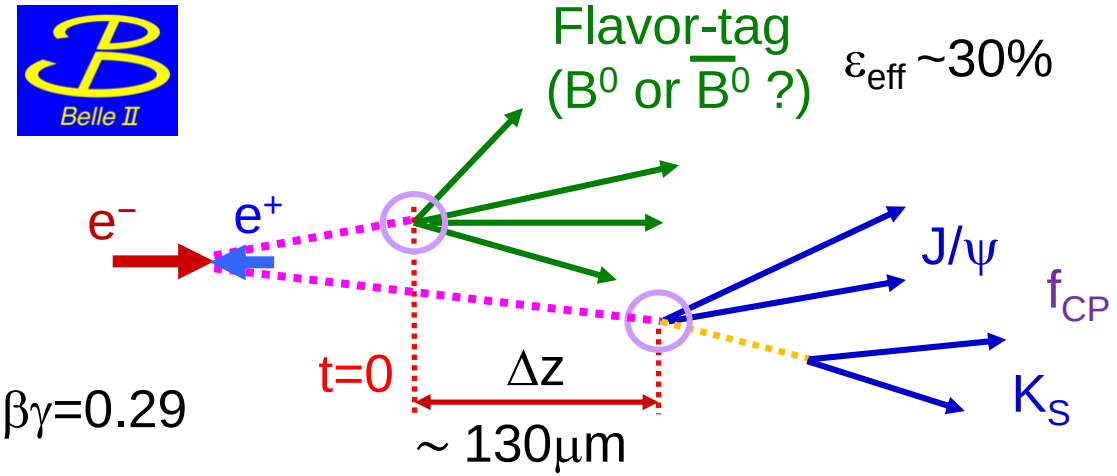
$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$

$$= S \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)$$

$S = -\xi \sin(2\phi_1)$ for $B \to J/\psi\, K_S$ $\quad (\phi_1=\beta)$

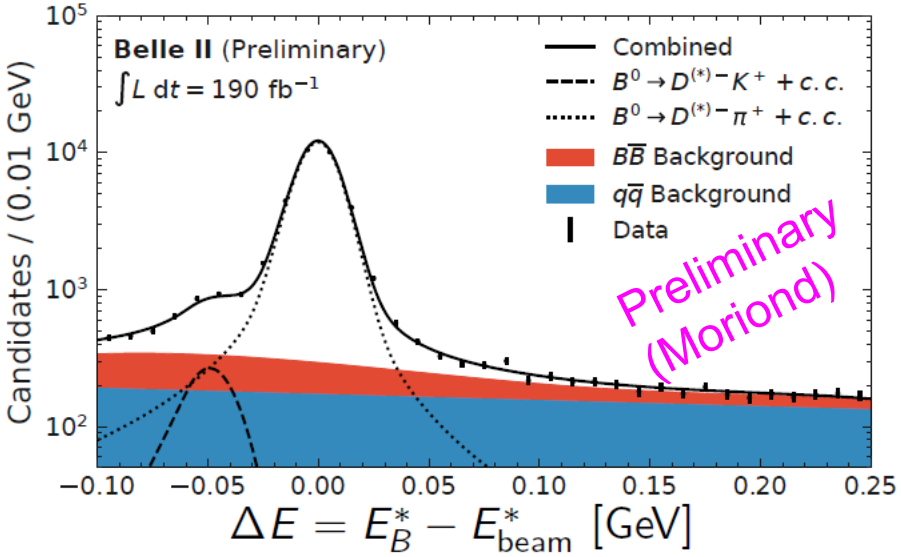


S : mixing induced CPV
A : direct CPV (=−C)

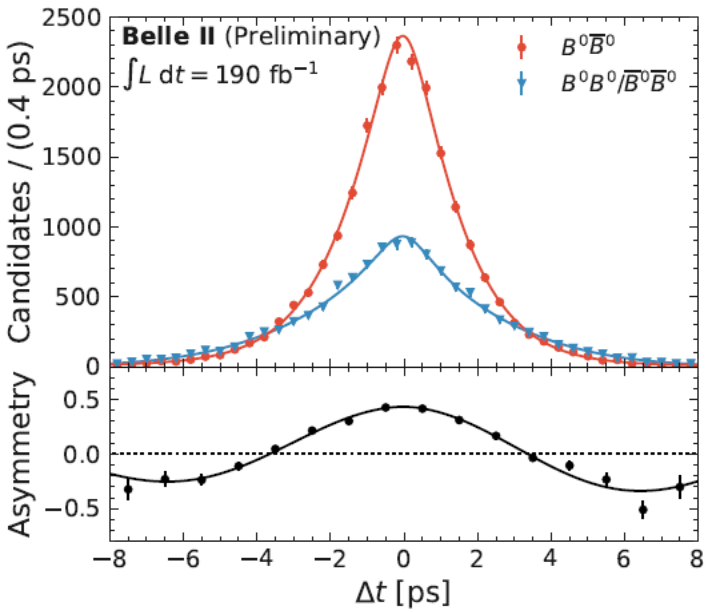


What is presented today:
Hadronic decay $B^0 \to D^{(*)0-}$ K^+/π^+ (instead of f_{CP})
→ Measurement of mixing frequency (Δm) and lifetime

B^0 Lifetime and Mixing Frequency



~40 k events reconstructed



190 fb^{-1}

Preliminary (Moriond)

$\tau(B^0) = 1.499 \pm 0.013 \pm 0.008$ ps

$\Delta m_d = 0.516 \pm 0.008 \pm 0.005\ ps^{-1}$

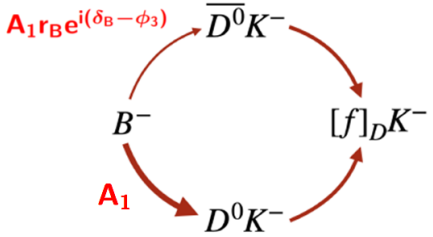
PDG $\tau(B^0) = 1.519 \pm 0.004$ ps

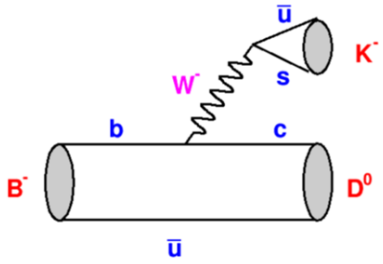
$\Delta m_d = 0.5065 \pm 0.0019\ ps^{-1}$

- Similar uncertainty as Belle and BaBar results: smaller systematic error.
- Semileptonic mode (D* l ν) not used yet. To be included.
- Next step: measurement of sin(2ϕ_1) (= sin(2β)).

ϕ_3 (γ) from Belle + Belle II

- ϕ_3 (γ) can be measured using the interference of tree $b \to c\bar{u}s$ and $b \to u\bar{c}s$.
- Tree process → SM reference. Precise measurement of ϕ_3 is necessary to search for New Physics contribution in CKM fit.

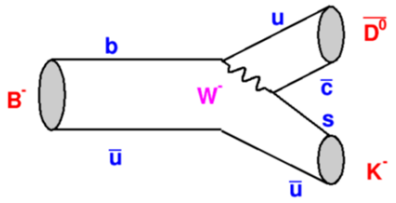




color favored

$B^- \to D^0 K^- \approx V_{cb} V_{us}^*$

A_1



color suppressed

$B^- \to \bar{D}^0 K^- \approx V_{ub} V_{cs}^*$

$A_1 r_B e^{i(\delta_B - \phi_3)}$

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

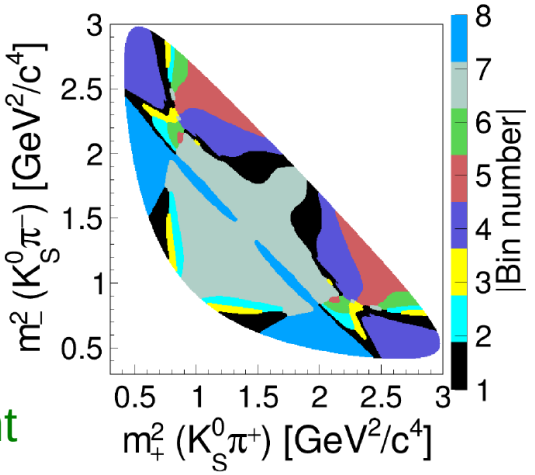
- Binned Dalitz plot analysis using $B^- \to D\, h^-$ with $D \to K_S h^+ h^-$ (BPGGSZ method [PRD 68. 054018 (2003)])

$$N_i^{\pm} = h_B^{\pm} \left[F_i + r_B^2 \overline{F}_i + 2\sqrt{F_i \overline{F}_i}(c_i x_{\pm} + s_i y_{\pm}) \right]$$

$$(x_{\pm}, y_{\pm}) = r_B \left(\cos(\phi_3 + \delta_B),\ \sin(\phi_3 + \delta_B) \right)$$

c_i, s_i: parameters of D^0-$\overline{D}^0$ strong phase difference (inputs from BES III / CLEO)

F_i: fraction of D decays to i-th bin



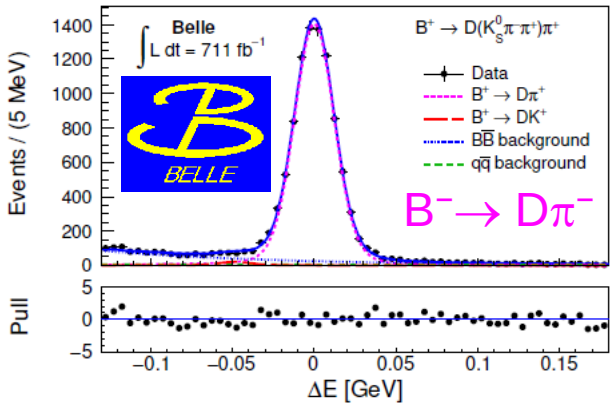
Model-independent method

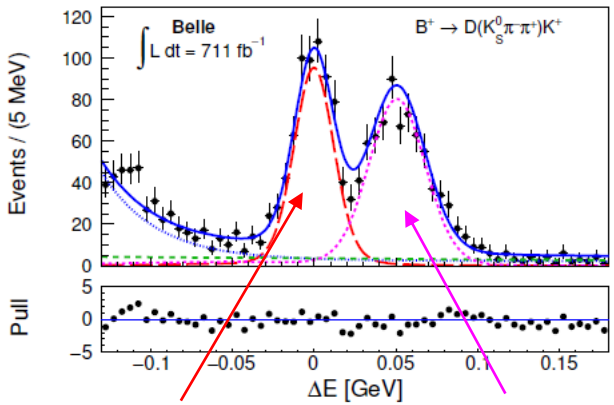
ϕ_3 (γ) from Belle + Belle II

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

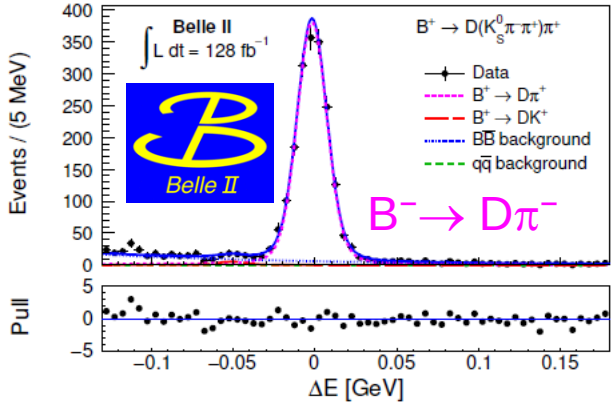
[JHEP 02 (2022) 063]

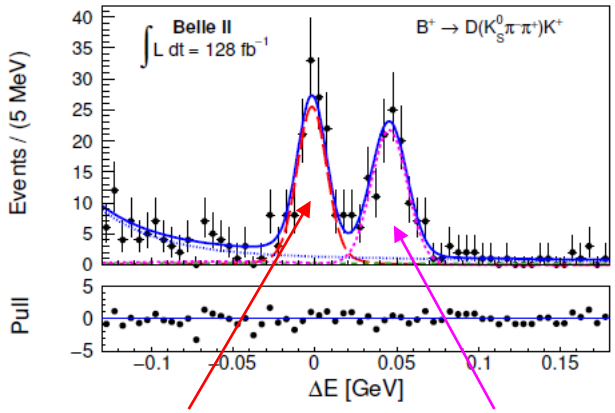
Belle





Belle II





$B^- \to D\,(K_S\pi^+\pi^-)\,\pi^-$ enhanced region

Belle:
$K_S^0\pi\pi$: 1467 ± 53
K_S^0KK: 194 ± 17

Belle II :
$K_S^0\pi\pi$: 280 ± 21
K_S^0KK: 34 ± 7

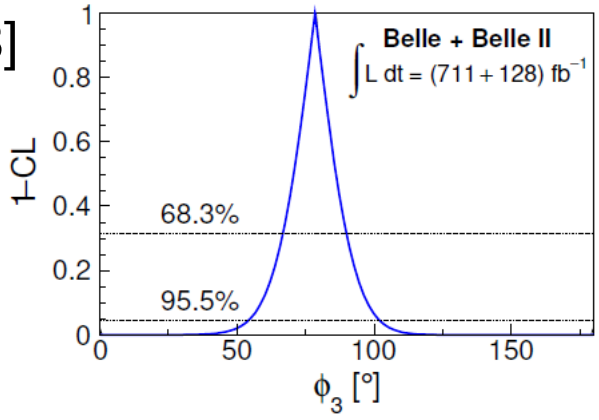
$B^- \to D\,(K_S\pi^+\pi^-)\,K^-$ enhanced region

ϕ_3 (γ) from Belle + Belle II

Result: [JHEP 02 (2022) 063]

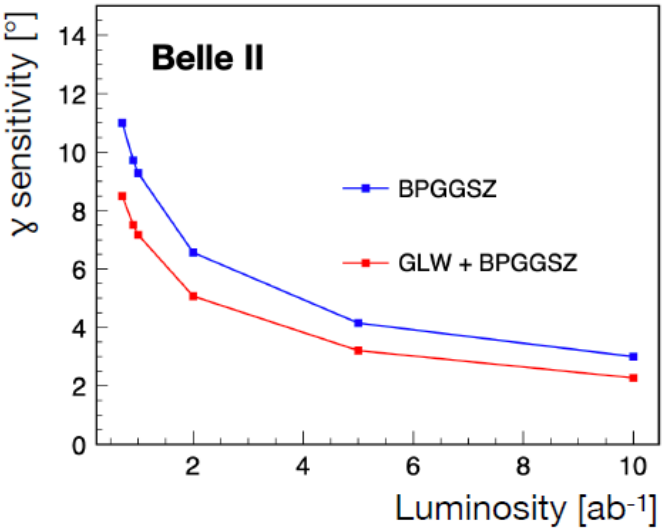
$\delta_B = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)°$
$r_B^{DK} = 0.129 \pm 0.024 \pm 0.001 \pm 0.002$
$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)°$

The third error is due to external strong-phase input from BES III



- Improvements from previous Belle result equivalent to doubling statistics (due to K_S selection and b.g. suppression)
- Latest inputs on strong-phase from BES III highly reduces statistics.
- Expected <3° uncertainty with 10 fb^{-1}, including also more D final states. Uncertainty will still be dominated by the size of the data sample.

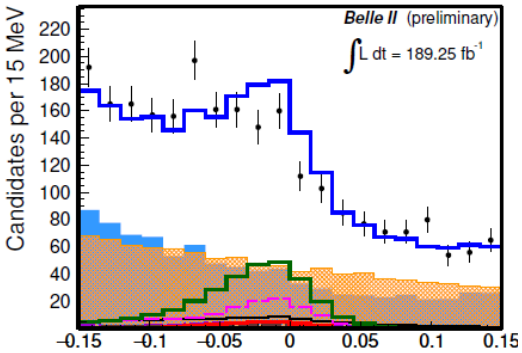
$\gamma = \phi_3 = (66.2 \, ^{+3.4}_{-3.6})°$ (HFAG)



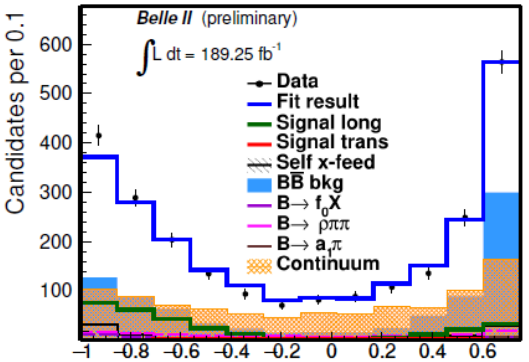
More Results related to CPV in B

$B^+ \to \rho^+(\to\pi^+\pi^0)\,\rho^0(\to\pi^+\pi^{0-})$

- Constrain ϕ_2 (=α) together with $B^0 \to \rho^0\rho^0$, $\rho^+\rho^-$ (Belle II can measure all)



$\Delta E = E^*_B - E^*_{\text{beam}}$ [GeV]



Preliminary

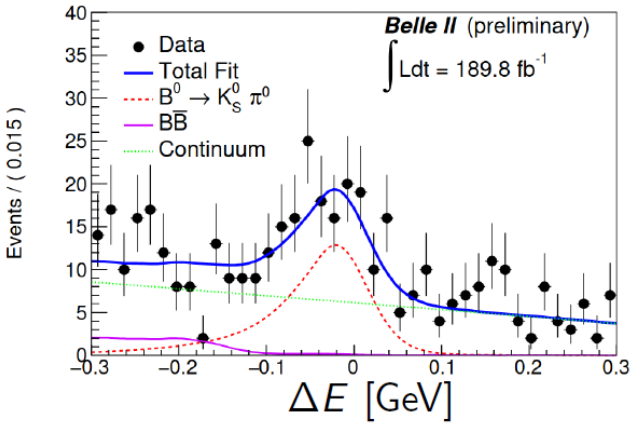
$\cos\theta_{\rho^+}$

$$A_{CP} = -0.069 \pm 0.068\ (\text{stat.}) \pm 0.060\ (\text{syst.})$$
$$\mathcal{B}(B^+ \to \rho^+\rho^0) = (23.2^{+2.2}_{-2.1}\ (\text{stat.}) \pm 2.7\ (\text{syst.})) \times 10^{-6}$$
$$f_L = 0.943^{+0.035}_{-0.033}\ (\text{stat.}) \pm 0.027\ (\text{syst.})$$

$B^0 \to K_S\pi^0$

- Hint of NP in $A_{CP}(B\to K\pi)$?
- Check isospin sum rule: $A_{CP}(B^0 \to K_S\pi^0)$ is important (unique to Belle II).

Preliminary (Moriond)



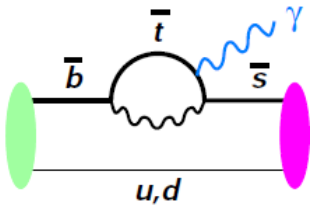
$$A_{CP} = -0.41^{+0.30}_{-0.32}\ (\text{stat.}) \pm 0.09\ (\text{syst.})$$
$$\mathcal{B} = (11.0 \pm 1.2\ (\text{stat.}) \pm 1.0\ (\text{syst.})) \times 10^{-6}$$

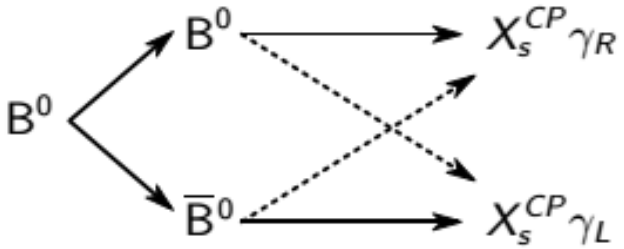
World average: $A_{CP} = 0.00 \pm 0.13$.

More Results related to CPV in B

$B^0 \to K_S\pi^0\gamma$

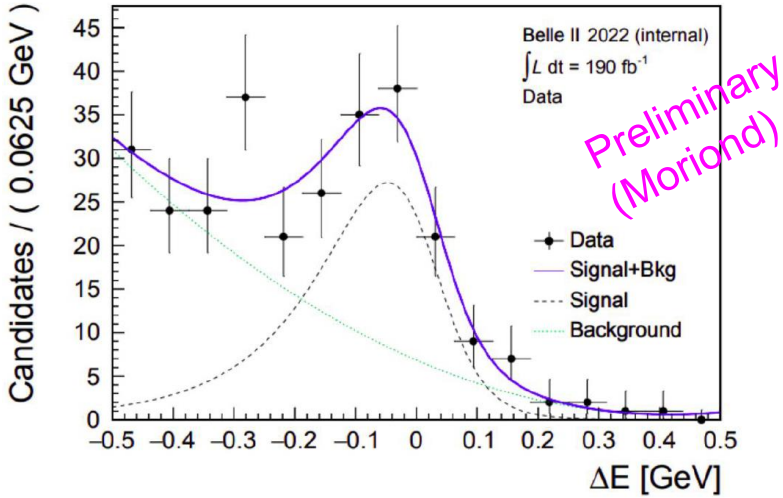
- SM electroweak is purely left-handed.
  - ✓ Photon from $b \to s\gamma$ is almost left-handed.
- Right-handed current is a signature of NP.
- In the SM, mixing induced CP violation does not occur in $b \to s\gamma$: $S \sim -2(m_s/m_b)\times\sin 2\phi_1$.
- Primary mode $B^0 \to K_S\pi^0\gamma$: unique to Belle II.
- In preparation to time-dependent analysis, branching fraction is measured.





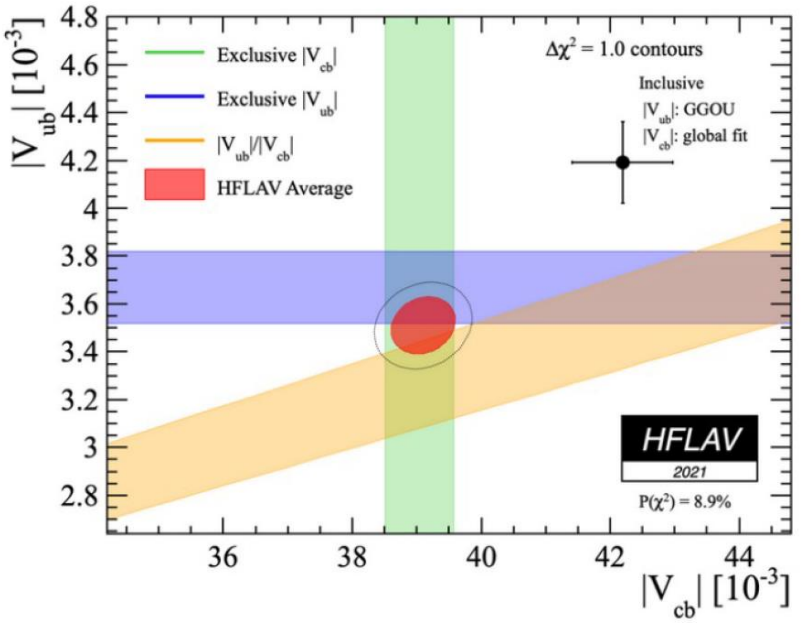
$$\mathcal{B} = (7.3 \pm 1.8\ (\text{stat.}) \pm 1.0\ \text{syst}) \times 10^{-6}$$

Compatible with world average
$\mathcal{B} = (7.0 \pm 0.4) \times 10^{-6}$

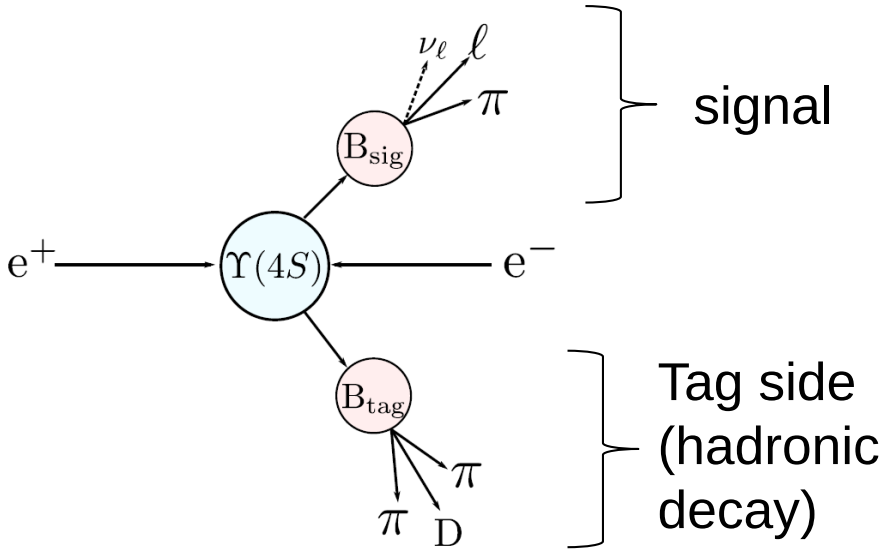


Semileptonic B Decays

- $|V_{ub}|$ and $|V_{cb}|$ can be measured with semileptonic B decays.
- Longstanding discrepancy between the inclusive and exclusive analyses.
- New measurements of $|V_{ub}|$ and $|V_{cb}|$ at Belle II.



Useful technique: tag-side reconstruction



- Full Event Interpretation (FEI): tag side is reconstructed with ~10000 hadronic decays [Comput Softw Big Sci (2019) 3: 6.]
- Tag efficiency ~0.5 (0.3)% for B^+ (B^0)
- Useful for signal modes with missing particles.

Semileptonic B Decays

$B \to \pi e \nu$ ($B^0 \to \pi^- e^+ \nu$ and $B^+ \to \pi^0 e^+ \nu$)

189 fb^{-1}

- Fit $M^2_{\rm miss}$ in 3 bins of q^2.

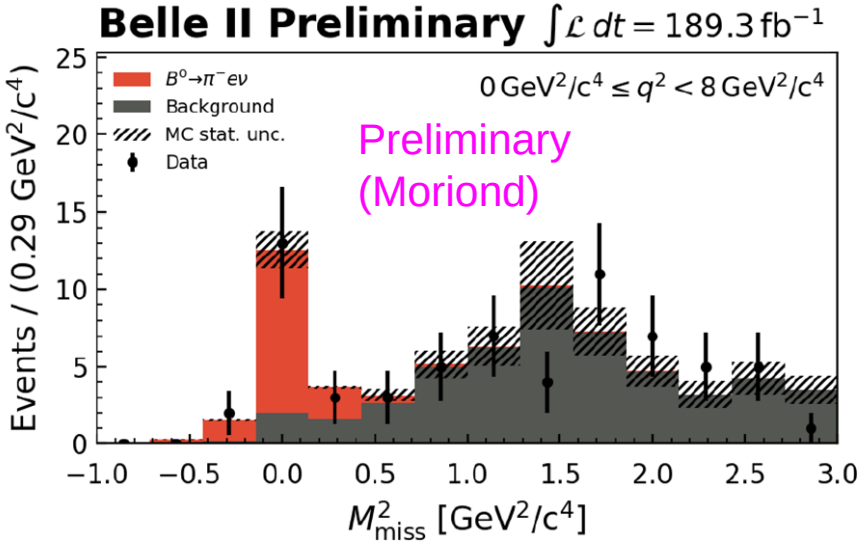
$$M^2_{\rm miss} = (p_{e^+e^-} - p_{B_{\rm tag}} - p_e - p_\pi)^2$$

$$q^2 = m^2_{\ell\nu} = (p_{e^+e^-} - p_{B_{\rm tag}} - p_\pi)^2$$

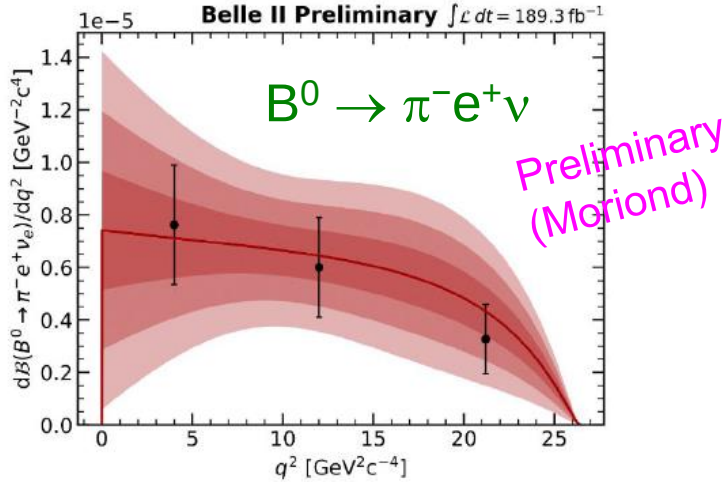
- Measure $|V_{ub}|$ by

$$\frac{d\mathcal{B}}{dq^2}(B \to \pi\ell\nu) \propto |V_{ub}|^2 f_+^2(q^2)$$

with Lattice QCD input from Fermi MILC.
[PRD 92 (2015) 1 014024]



$$\mathcal{B}(B^0 \to \pi^- e^+ \nu) = (1.34 \pm 0.27 \pm 0.07) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \pi^0 e^+ \nu) = (8.33 \pm 1.67 \pm 0.55) \times 10^{-5}$$



$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$ (PDG: $(3.67 \pm 0.15) \times 10^{-3}$)

Consistent with PDG, but still statistically limited.
More precise measurement expected with larger dataset.

Semileptonic B Decays

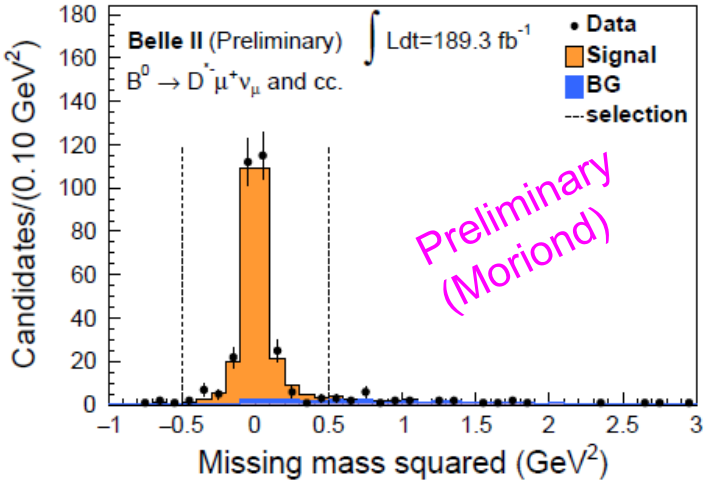
$B^0 \to D^{*-} l^+ \nu$ (l=e,μ)

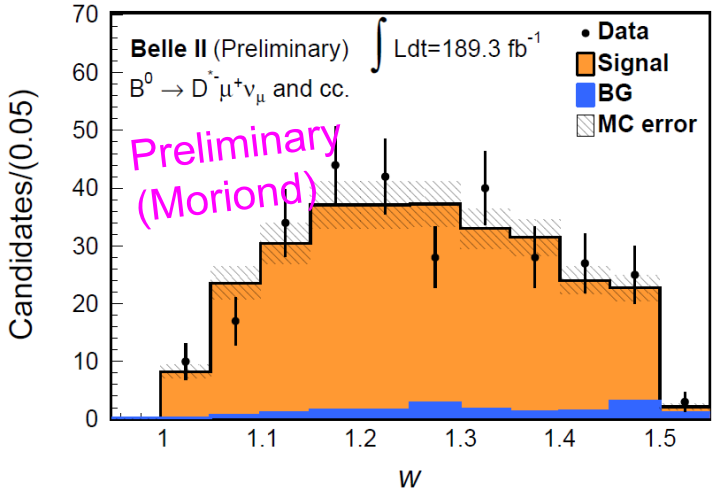
189 fb^{-1}

$$\frac{d\Gamma}{dw} \propto \mathcal{F}^2(w)|V_{cb}|^2 \eta_{EW}^2$$

form factor

EW correction





$B(B^0 \to D^{*-} l^+ \nu) = 0.0527 \pm 0.0022 \pm 0.0038$

$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$ (PDG: $(39.5 \pm 0.9) \times 10^{-3}$)

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

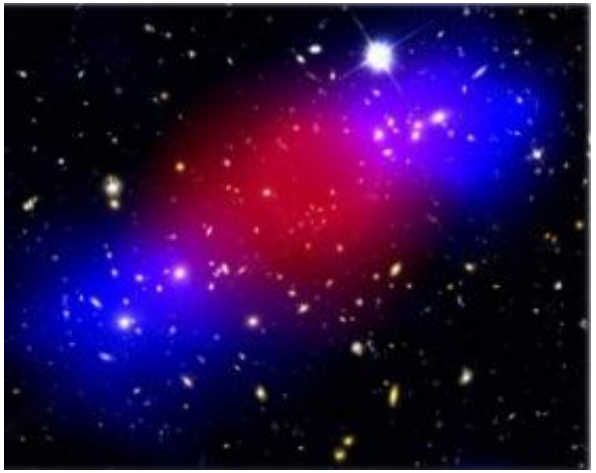
Belle II and Belle have reported several new results on the inclusive analysis.

- q^2 moments of $B \to X_c l \nu$ (Belle II 62.3 fb^{-1}) [journal paper in preparation]
- Partial B.F. of $B \to X_u l \nu$ (Belle) [PRD 104, 012008 (2021)]
- Differential B.F. of $B \to X_u l \nu$ (Belle) [PRL 127, 261801 (2021)]
- q^2 moments of $B \to X_c l \nu$ (Belle) [PRD 104, 112011 (2021)]

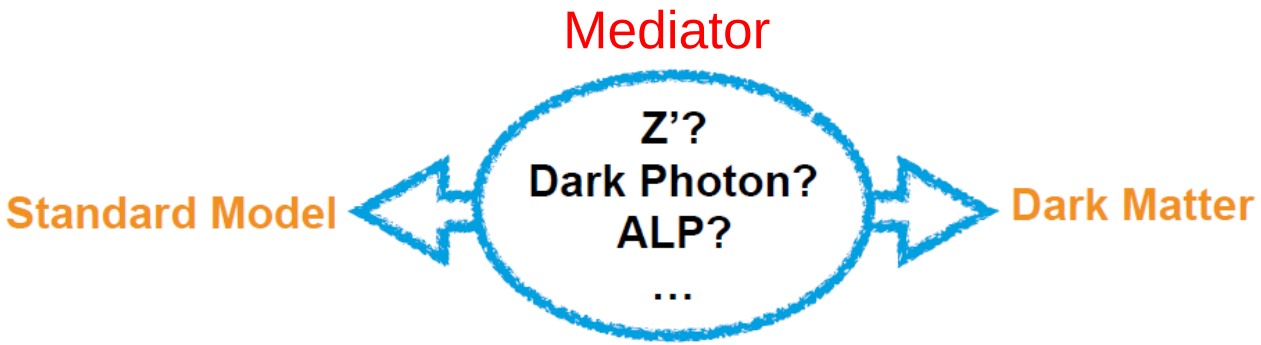
More results on semileptonic B decays will come

Dark Sector at Belle II

- The nature of the dark matter (DM) is unknown.
- WIMP DM (@ 30-3000 GeV) has been most intensively searched, but no hint has been seen so far.
- Notable possibility of DM in MeV to GeV mass region.
- Belle II is an ideal place to study it.
  - ✓ ~10 GeV CM energy → search DM up to O(1) GeV



Collision of galaxy clusters
red: matter, blue: DM



Bonus : A', Z' may explain the discrepancy of $(g-2)_\mu$ between theory and experiment.

- Typical process at Belle II
  - ✓ $e^+ + e^- \rightarrow$ SM particles + Mediator
  - ✓ B (or other hadron) → SM particles + Mediator
- Some of these processes have not been searched in BaBar or Belle (due to trigger setting etc.) and can be searched with initial Belle II data.

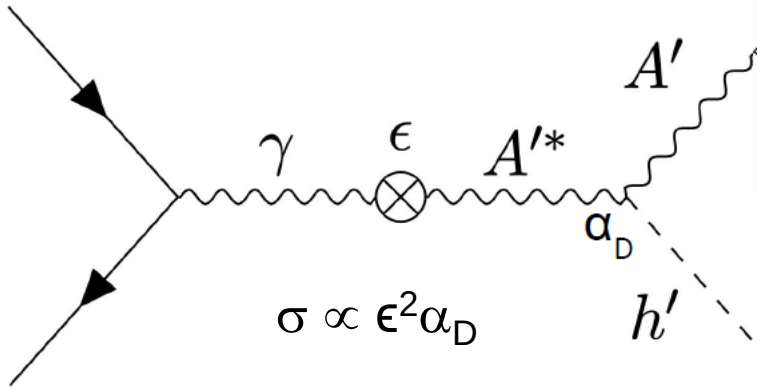
Dark Higgsstrahlung

$e^+e^- \to A' (\to \mu^+\mu^-)\, h'$ (invisible) 8.34 fb^{-1}

Next to minimal dark photon model

- Dark photon (A') couples to SM photon via kinetic mixing parameter ϵ.
- A' mass can be generated via a spontaneous breaking mechanism, adding, dark Higgs boson (h') to the theory [PRD 79, 115008 (2009)].

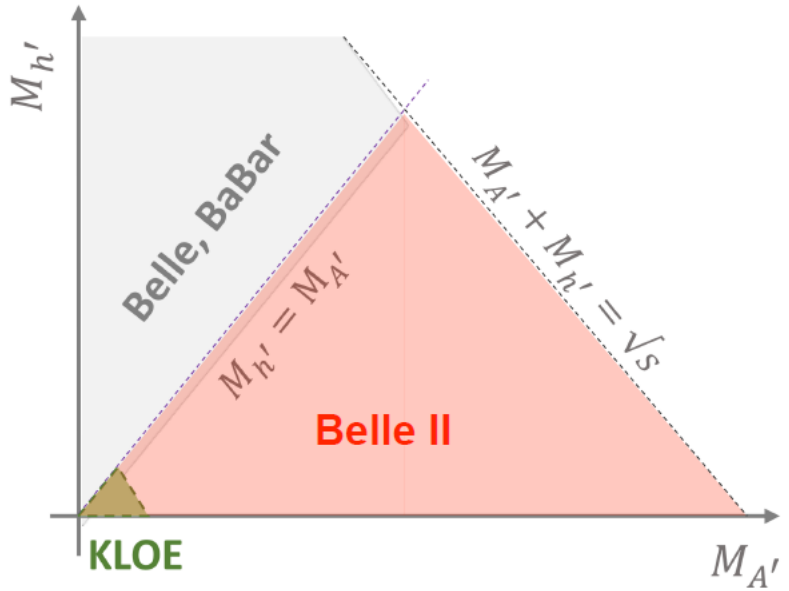
Dark Higgsstrahlung Process



α_D : dark coupling constant

Mass hierarchy scenarios

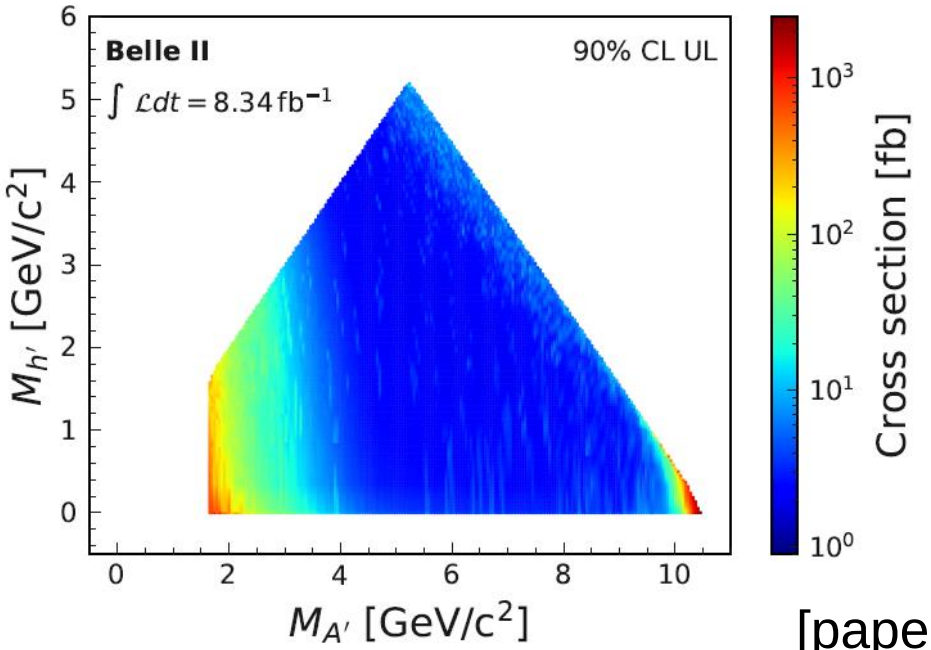
- $M_{h'} > M_{A'}$: $h' \to A'A'^{(*)} \to$ 4 leptons etc.
  - ✓ Investigated by BaBar and Belle.
- $M_{h'} < M_{A'}$: h' is long-lived and thus invisible.
  - ✓ Partially constrained by KLOE.
  - ✓ Exploring unconstrained region at Belle II



BaBar: PRL 108, 211801 (2012)
Belle: PRL 114, 211801 (2015)
KLOE: PLB 747, 365 (2015)

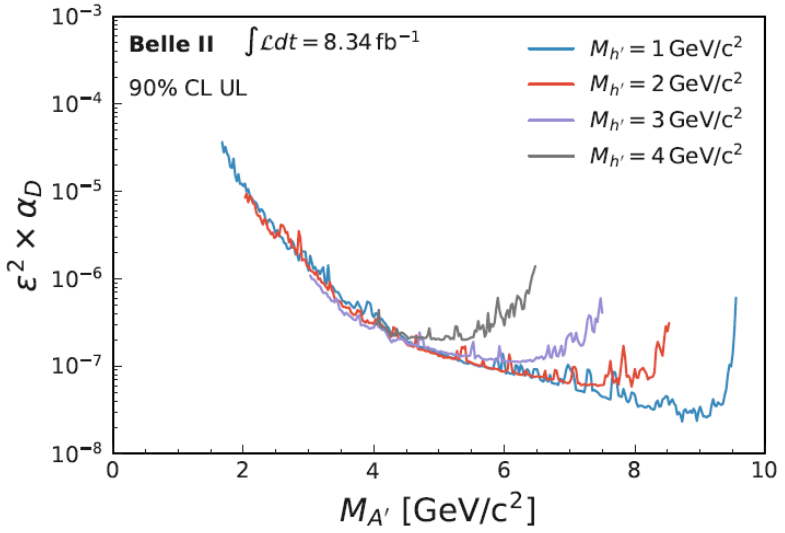
Dark Higgsstrahlung

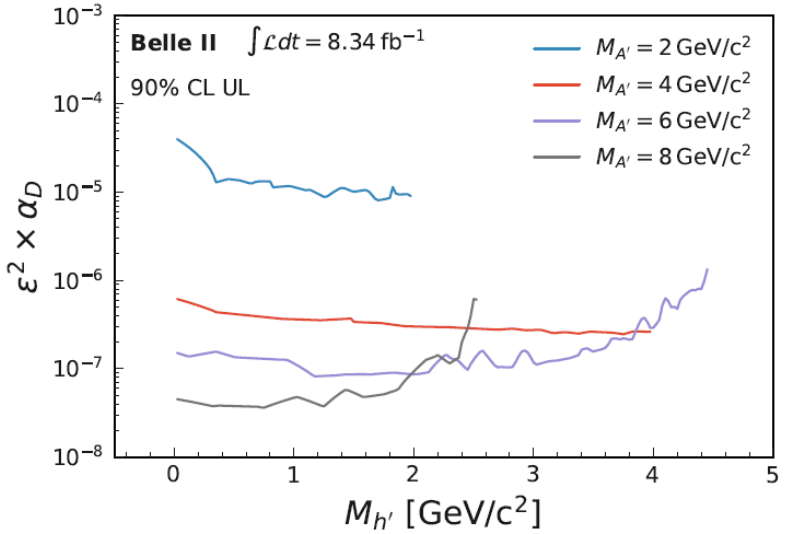
- Upper limits are set on σ and $\epsilon^2\alpha_D$ for $1.65<M_{A'}<10.51$ GeV and $M_{h'} < M_{A'}$
- 90% CL UL on σ ranges from 1.7 to 5 fb.
  - ✓ $M_{A'}<4$ GeV: low sensitivity due to trigger eff.
  - ✓ $M_{A'}>9$ GeV: large dimuon background



Word-leading result in previously unexplored region

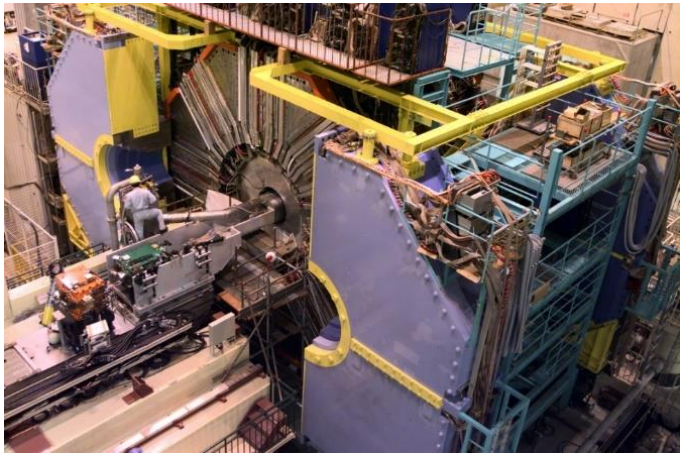
[paper in preparation]





Summary

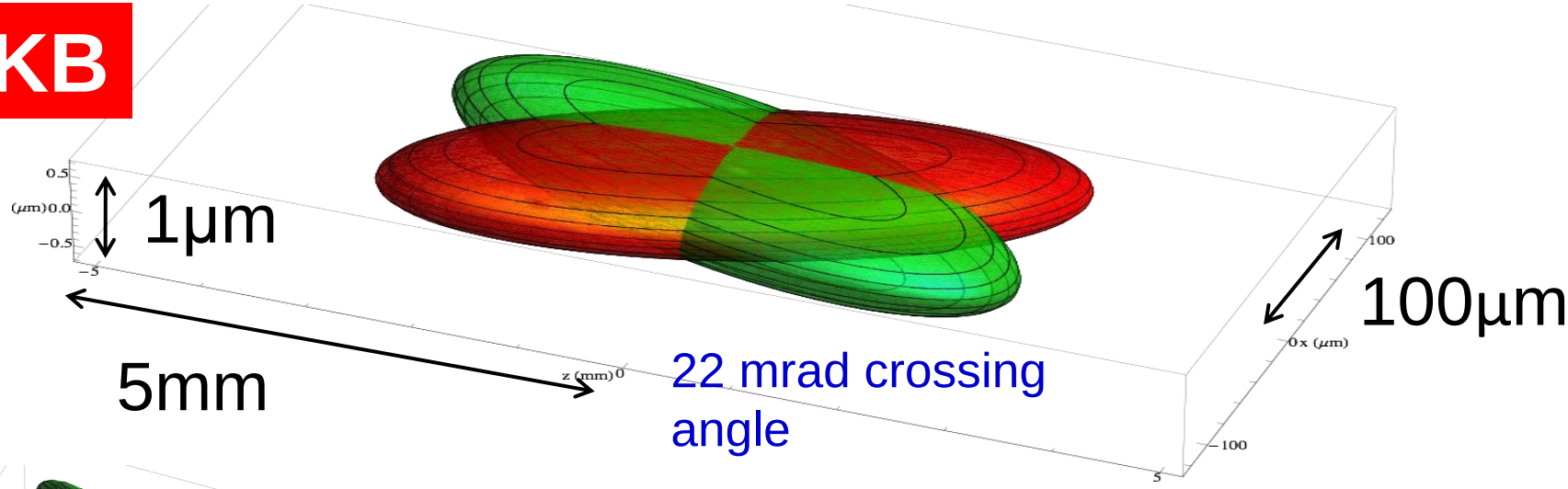
- Belle II is running, accumulating close to 400 fb^{-1} so far.
- Several recent results are presented.
  - ✓ Lifetime of D^0, D^+ and Λ_c^+ : world's most precise
  - ✓ B^0 lifetime and mixing frequency : important step for $\sin(2\phi_1)$
  - ✓ Measurement of ϕ_3 (γ) : Belle + Belle II analysis
  - ✓ Semileptonic B decays.
  - ✓ Search for Dark Sector.
- Other results that cannot be covered today show the potential of Belle II.
  - ✓ Electroweak penguin B decays $B \to K^* l^+ l^-$, $B^+ \to K^+ \nu\bar{\nu}$.
  - ✓ Hadron spectroscopy (Belle II took energy scan data above $\Upsilon(4S)$ in 2021).
  - ✓ …
- More results will be coming soon.

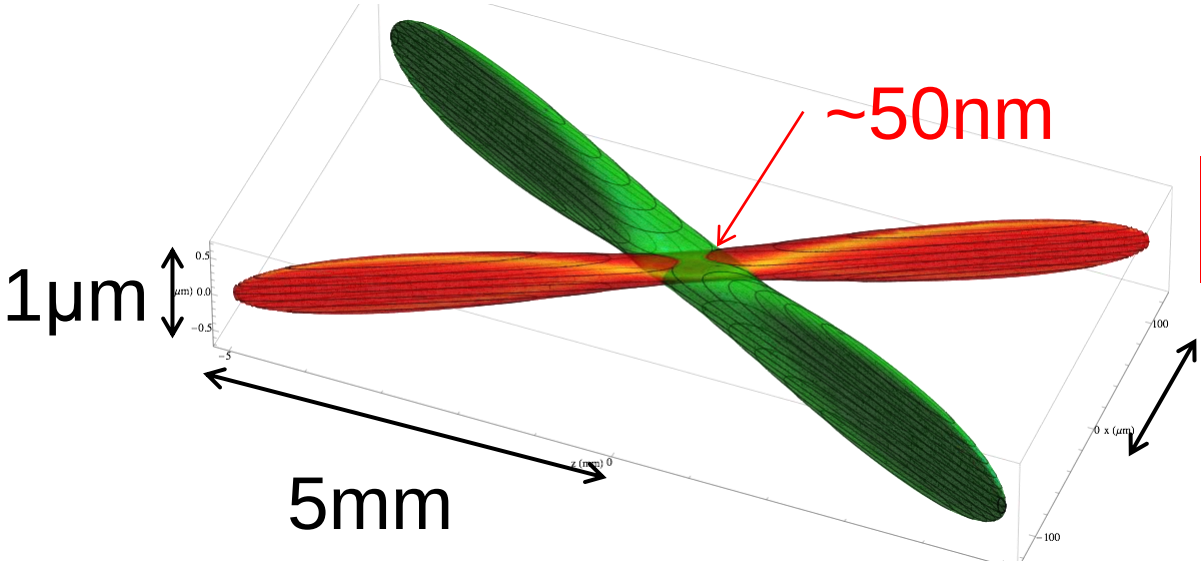


Backup

SuperKEKB

KEKB





SuperKEKB

83 mrad crossing angle

Lifetime of D^0, D^+ and Λ_c^+

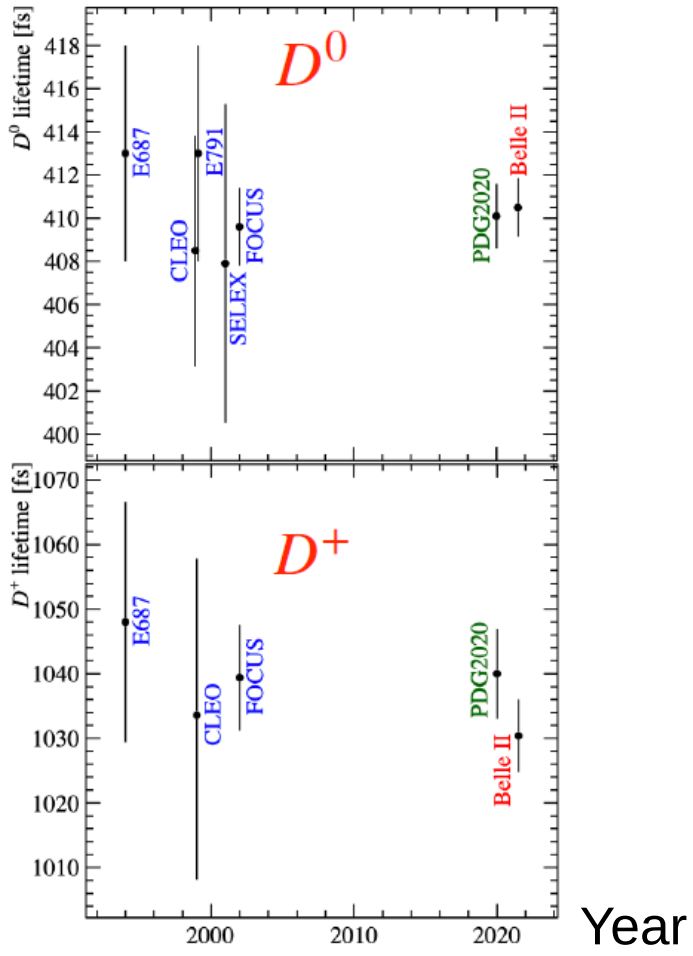
Systematic Uncertainties

$D^0 \to K^-\pi^+$ $D^+ \to K^-\pi^+\pi^+$

Source	$\tau(D^0)$ [fs]	$\tau(D^+)$ [fs]
Resolution model	0.16	0.39
Backgrounds	0.24	2.52
Detector alignment	0.72	1.70
Momentum scale	0.19	0.48
Total	0.80	3.10

$\Lambda_c^+ \to pK^-\pi^+$

Source	Uncertainty [fs]
Resolution model	0.46
Backgrounds	0.20
Detector alignment	0.46
Momentum scale	0.09
Ξ_c contamination	1.39
Total	$0.69_{-1.39}$



World's most precise measurement

$B^0 \to K_S\pi^0$

Model independent detection of NP in the B→K π system

Isospin sum rule

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

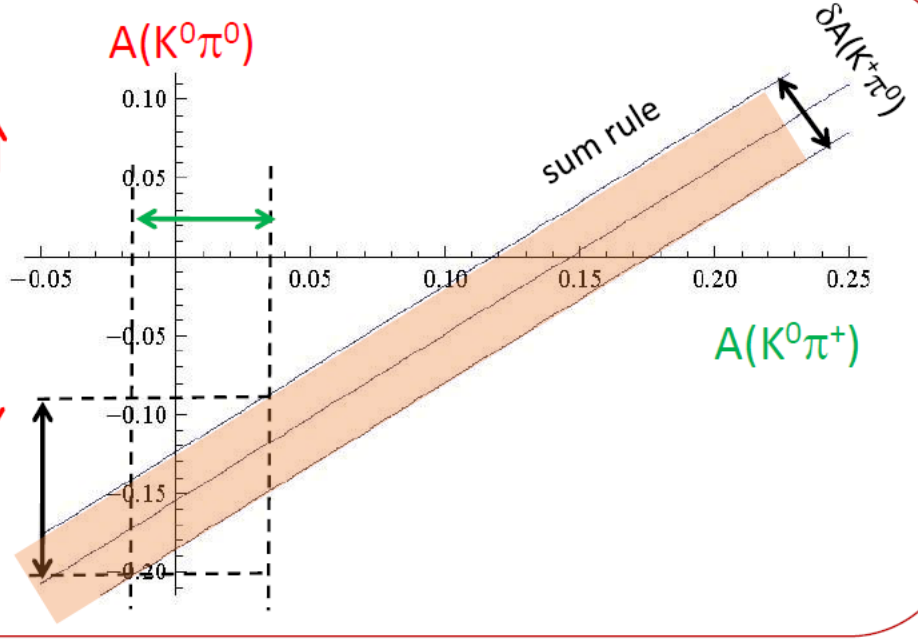
$$2A_{CP}(B^0 \to K^+\pi^-) + 1.3A_{CP}(B^+ \to K_S\pi^+) - 1.2A_{CP}(B^+ \to K^+\pi^0) - A_{CP}(B^0 \to K_S\pi^0) \approx 0$$

B →Kπ HFAG, ICHEP08

$A(K^0\pi^+)$=0.009 ±0.025
$A(K^+\pi^0)$=0.050 ±0.025
$A(K^+\pi^-)$=-0.098 ±0.012
$A(K^0\pi^0)$=-0.01 ±0.10

measured (HFAG)

expected (sum rule)



B →Kπ HFLAV, 2019

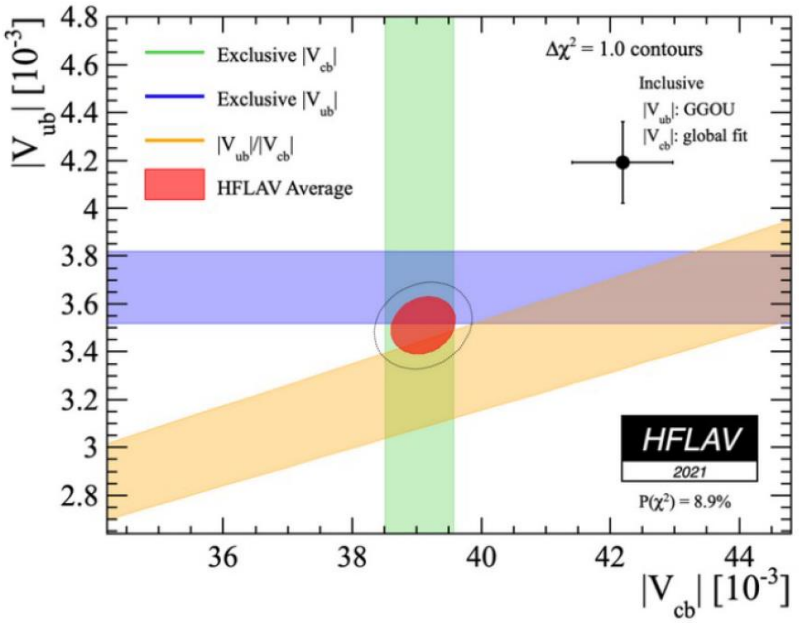
$A(K^0\pi^+)$=−0.017 ±0.016
$A(K^+\pi^0)$=0.040 ±0.021
$A(K^+\pi^-)$=−0.084 ±0.004
$A(K^0\pi^0)$=−0.01 ±0.10

Sum rule proposed by:

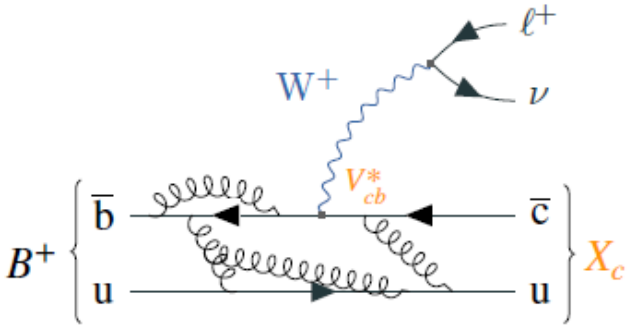
M. Gronau, PLB 627, 82 (2005); D. Atwood & A. Soni, Phys. Rev. D 58, 036005(1998).

$B \to X_c\, l\, \nu$

- $|V_{ub}|$ and $|V_{cb}|$ measurements have a longstanding discrepancy between the inclusive and exclusive analyses.
- New measurement of the inclusive $B \to X_c\, l\, \nu$ with tagged method at Belle II.
  - ✓ The other B is reconstructed with FEI (Full Invent Interpretation) algorithm.
- $B \to X_c\, l\, \nu$ decay width Γ is expressed with HQE (heavy-quark expansion) parameters.



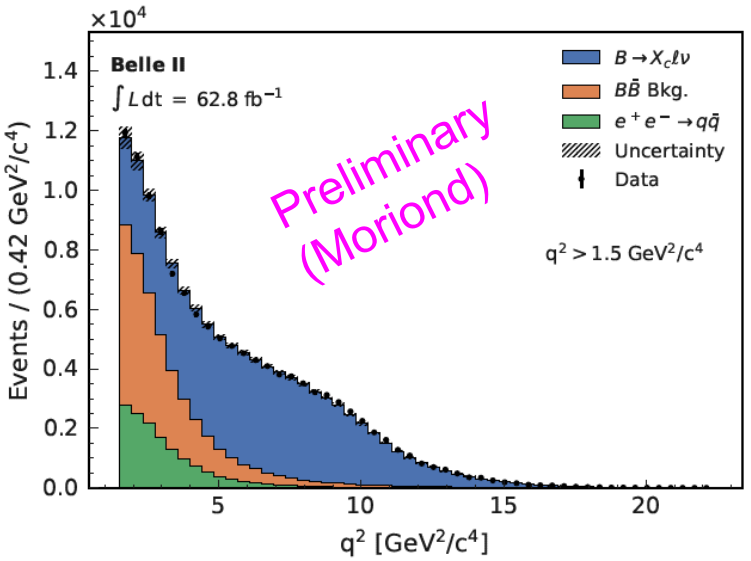
- Novel idea: reduction of HQE parameters (13 → 8) by reparametrization [arXiv:1812.00747].
- Parameter reduction is valid for q^2 moments: a new measurement of $\langle (q^2)^n \rangle$ for n=1, ..., 4.



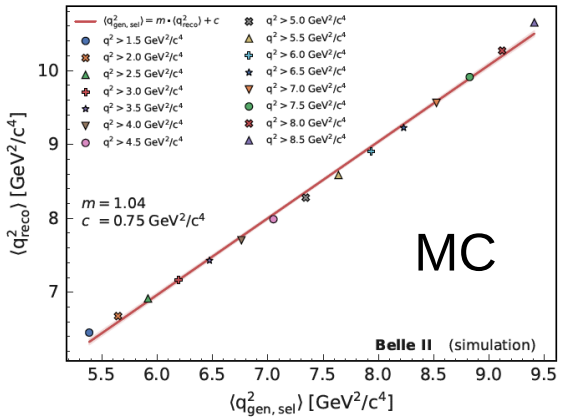
$B \to X_c\, l\, \nu$

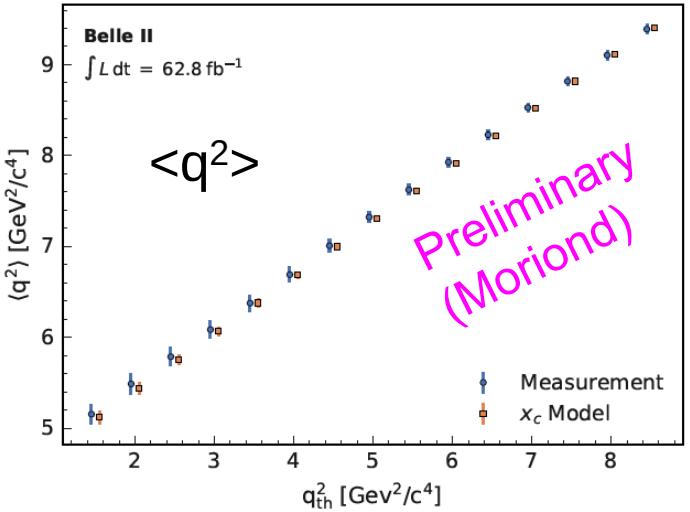
[paper in preparation]

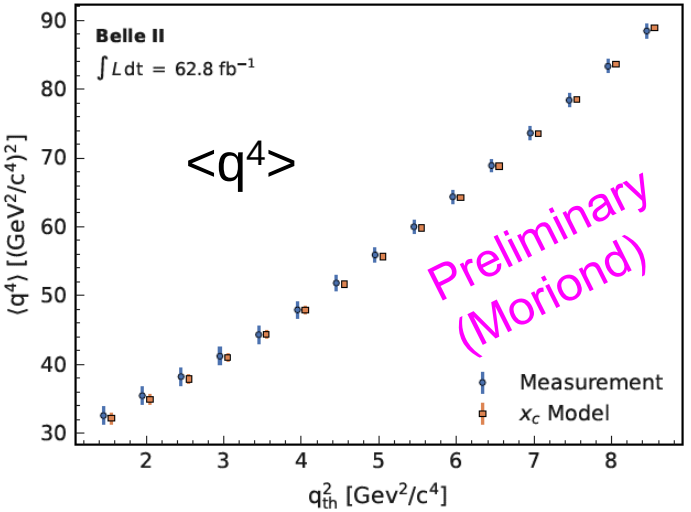
- Belle II measurement with 62.3 fb^{-1}.
- M_X fit to determine the background component.
- q^2 calibration (reconstructed v.s. generated moments).
- q^2 moments $\langle (q^2)^n \rangle$ for n=1, ..., 4 as a function of q^2 threshold are obtained.
- Expect new fit of $|V_{cb}|$ in near future.



q^2 calibration





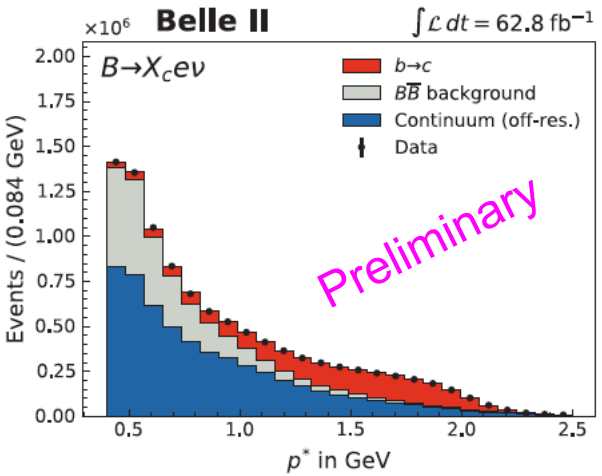


Other Belle II Results

- Dark Sector
  - ✓ $e^+e^- \to \mu^+\mu^- Z'$, $Z' \to$ invisible (0.28 fb^{-1}) [PRL124 (2020), 141801]
  - ✓ ALP (Axion-Like Particle) $e^+e^- \to a(\to\gamma\gamma)\,\gamma$ (0.44 fb^{-1}) [PRL125 (2020), 161806]

$B \to X_c l \nu$ (untagged)

[BELLE2-CONF-PH-2021-012
arXiv:2111.09405]

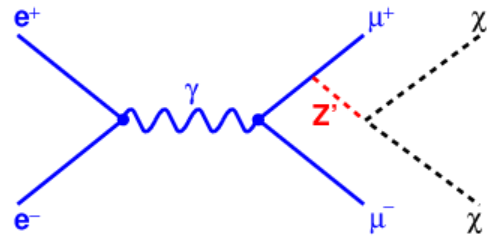


Z'→ invisible

Z'→ invisible : First physics result from Belle II !!

[PRL124 (2020), 141801]

- 0.276 fb^{-1} data from Belle II Phase II run.
  - ➢ Phase II: commissioning run in 2018 taken without inner vertex detector.
- $e^+e^- \to \mu^+\mu^-$ + missing energy and search for a bump in recoil mass.



$e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \chi\chi$