Recent Results from Belle II

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On behalf of the Belle II Collaboration

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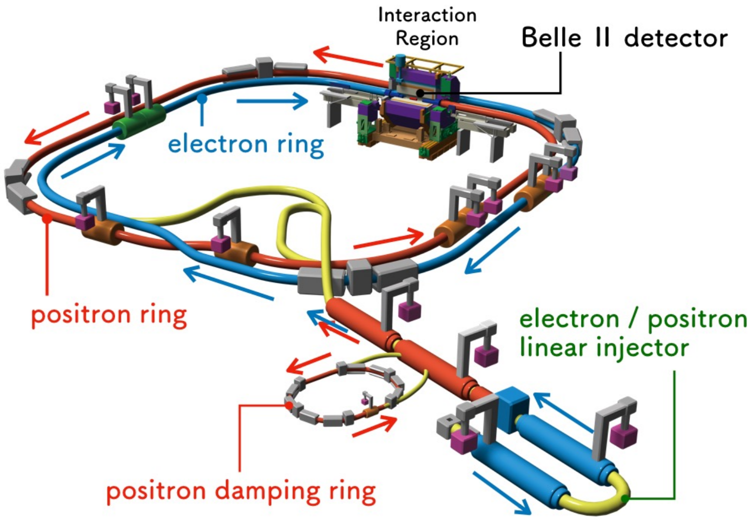
SuperKEKB and Belle II

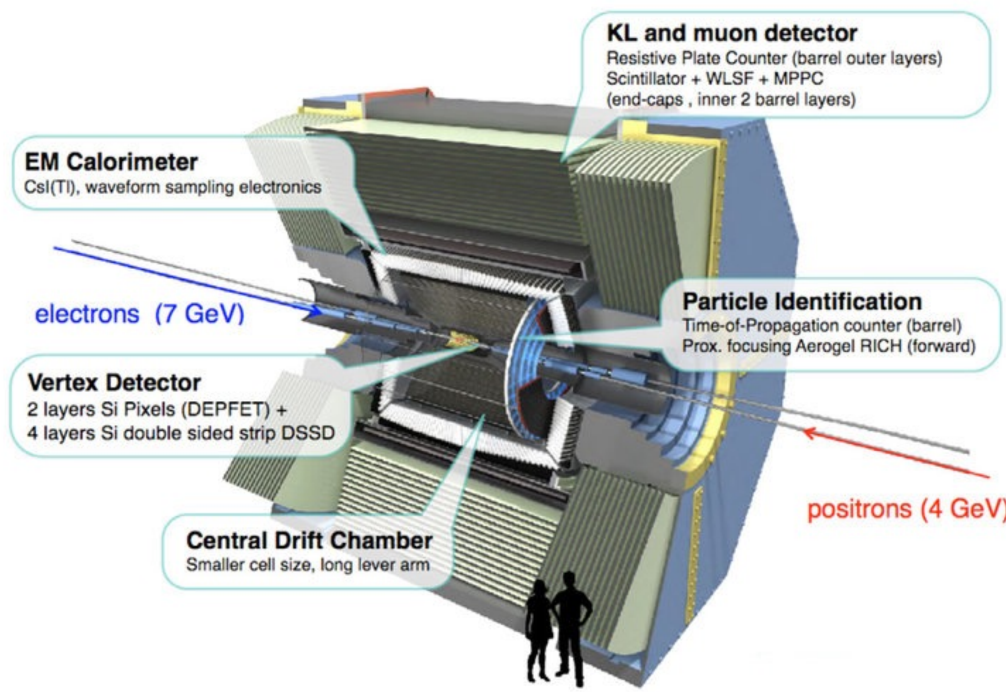


Asymmetric e^+e^- collider with CM energy at $\Upsilon(4S) = 10.58$ GeV resonance

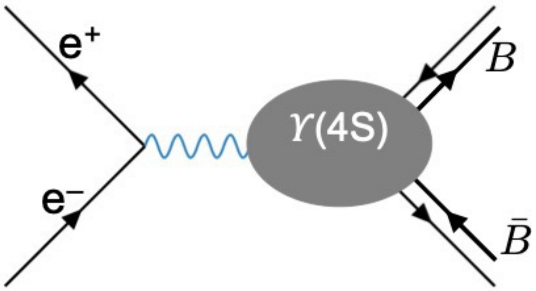
Belle II is a general purpose 4π detector
Good charged tracking reconstruction efficiency, gamma reconstruction, and particle identification for kaon, pion, proton, electron, muon and K_L

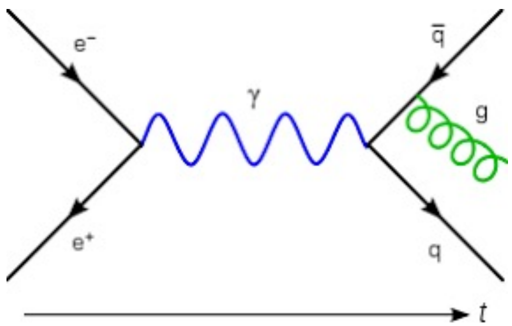
Design instantaneous luminosity: 6.5×10^{35} cm^{2}s^{-1}
30 times higher than its predecessor KEKB
Achieved: 4.22×10^{34} cm^{2}s^{-1}

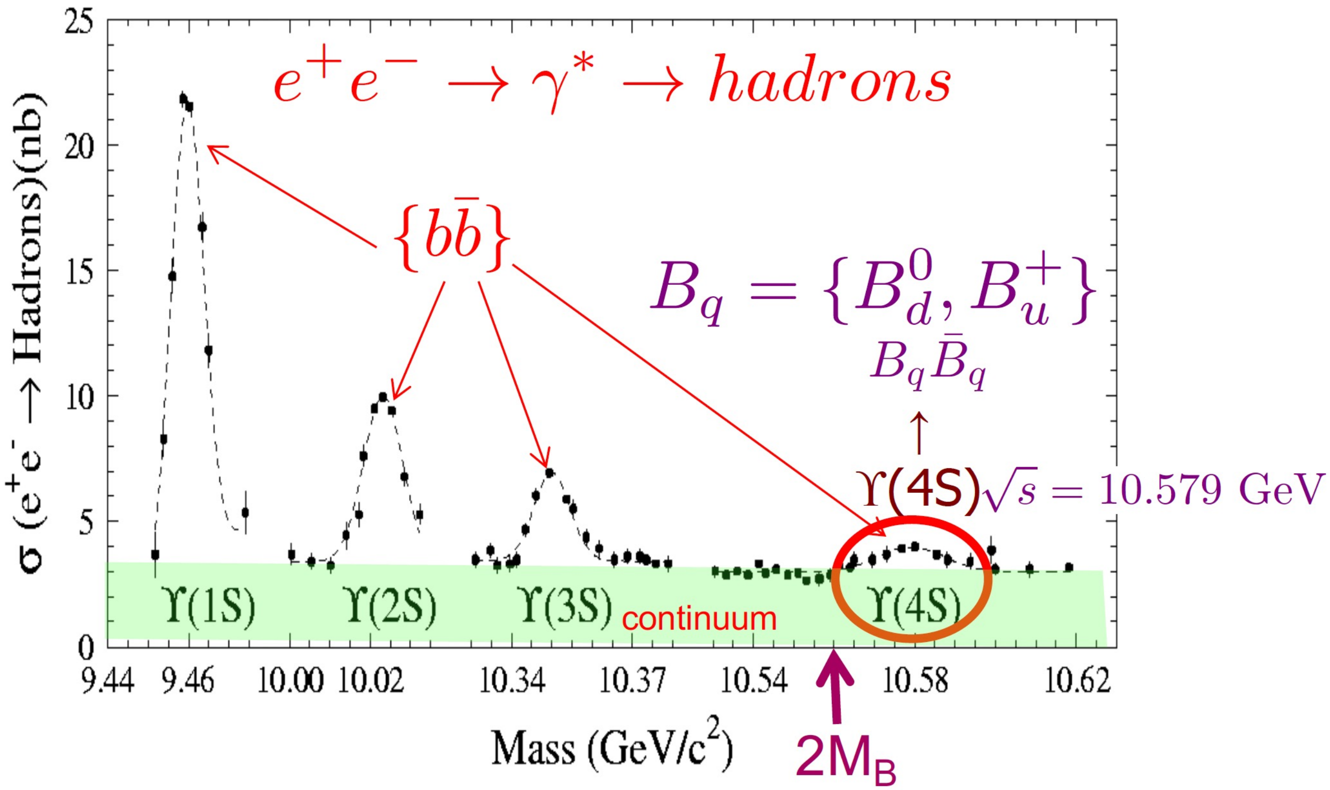
L1 Trigger: CDC+ECL+TOP+KLM
Maximum L1 DAQ: 30kHz
Inclusive trigger: ~ 100% efficiency



Collision Environment







$$c\bar{c},\ s\bar{s},\ u\bar{u},\ d\bar{d},\ \ell^+\ell^- \leftarrow e^+e^- \rightarrow \Upsilon(\mathrm{nS}) \rightarrow B^{(*)}\bar{B}^{(*)}$$

- Complete annihilation ⇒ event CMS = e^+e^- CMS
- Average multiplicity (chg+neutral) ~15-20

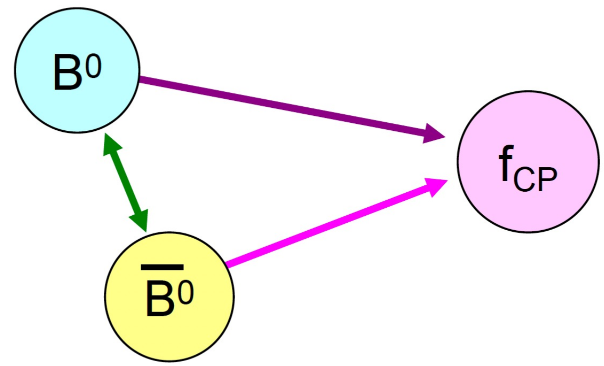
$\Upsilon(4S) \to B^+B^-$ **(~51.5%)**
$\Upsilon(4S) \to B^0\bar{B}^0$ **(~48.5%)**

Rich Physics program (not only New Physics)

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}
- Asymmetry is dependent on the time difference

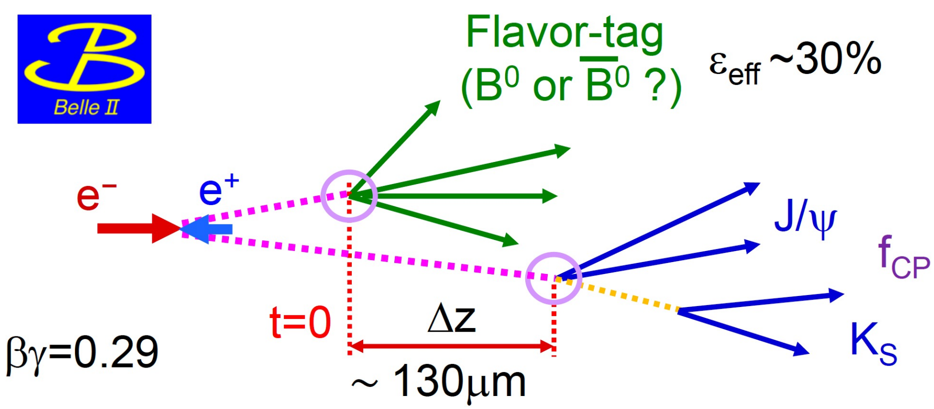


$$A_{CP}(\Delta t) = \frac{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) - \Gamma(B^0(\Delta t) \to f_{CP})}{\Gamma(\overline{B}^0(\Delta t) \to f_{CP}) + \Gamma(B^0(\Delta t) \to f_{CP})}$$

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

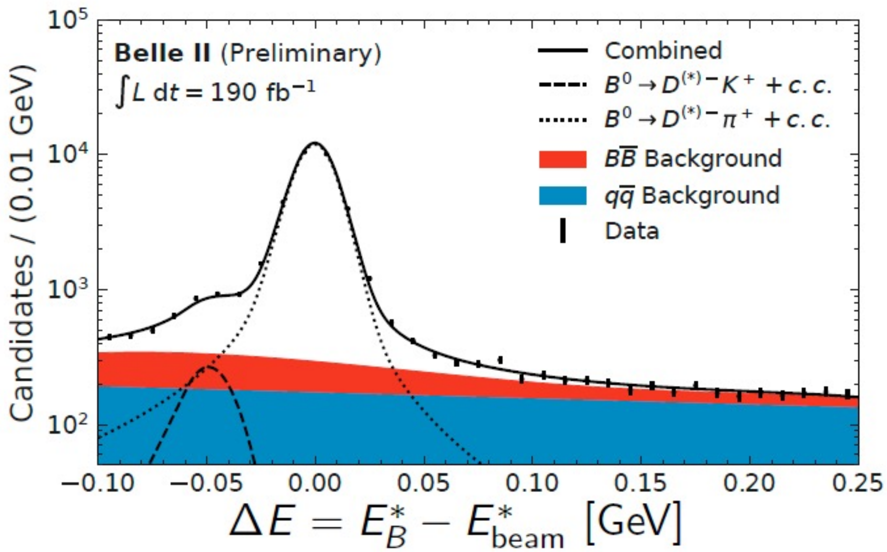
$S = -\xi \sin(2\phi_1)$ for $B \to J/\psi K_S$ $\quad(\phi_1 = \beta)$

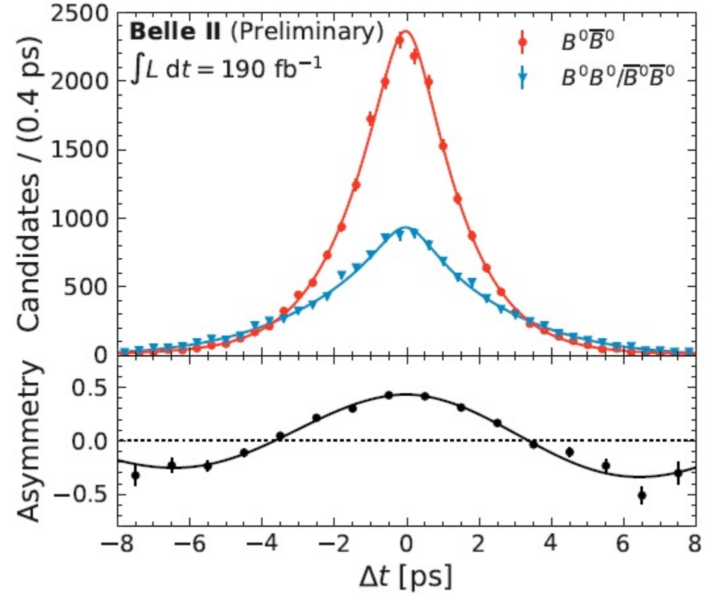
A: direct CPV (=−C)
S: mixing induced CPV



Crucial parameters for time-dependent studies
- Vertex resolution
- Tagging efficiency

B^0 Lifetime and Mixing Frequency





~40k events reconstructed

$\tau(B^0) = 1.499 \pm 0.013 \pm 0.008$ ps
$\Delta m_d = 0.516 \pm 0.008 \pm 0.005$ ps^{-1}

Compared to the best measurement of Belle & BABAR:

- Slightly worse statistical uncertainty which will improve
- Better alignment and background systematics
- Comparable resolution modeling systematics

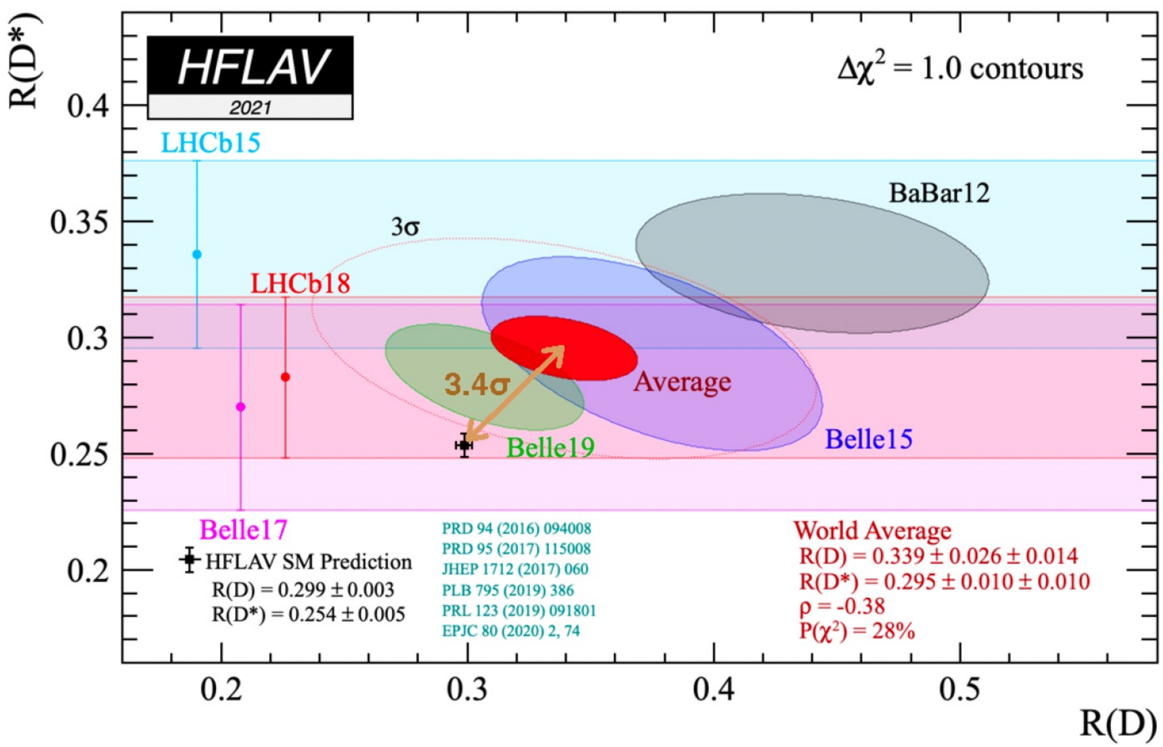
PDG $\tau(B^0) = 1.519 \pm 0.004$ ps
$\Delta m_d = 0.5065 \pm 0.0019$ ps^{-1}

Keystone achievement in establishing Belle II readiness for time-dependent measurements

Lepton Flavor Universality in $B \to D^{(*)}\ell\nu_\ell$

$B \to D^{(*)}\tau\nu_\tau$ is used to probe LFU

SM Prediction: $R(D^{(*)}) = \dfrac{\mathcal{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathcal{B}(B \to D^{(*)}\ell\nu_\ell)} = 0.300(0.252) \pm \mathcal{O}(10^{-3})$ $\qquad \ell = e,\mu$



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

[HFLAV average]

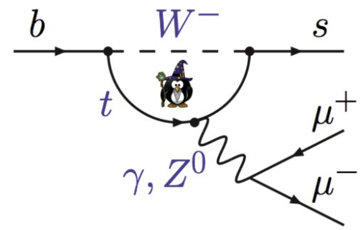
Discrepancy with the combined average (BABAR, Belle, LHCb):

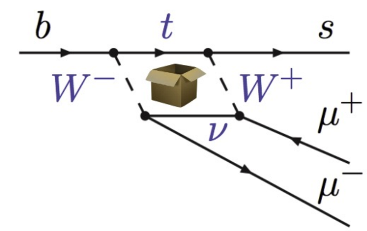
- R(D): 1.4σ
- $R(D^*)$: 2.9σ
- Combined: 3.4σ

Belle II preliminary:
$|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$

PDG: $(39.5 \pm 0.9) \times 10^{-3}$

Lepton Flavor Universality in $B \to K^{(*)}\ell\ell$





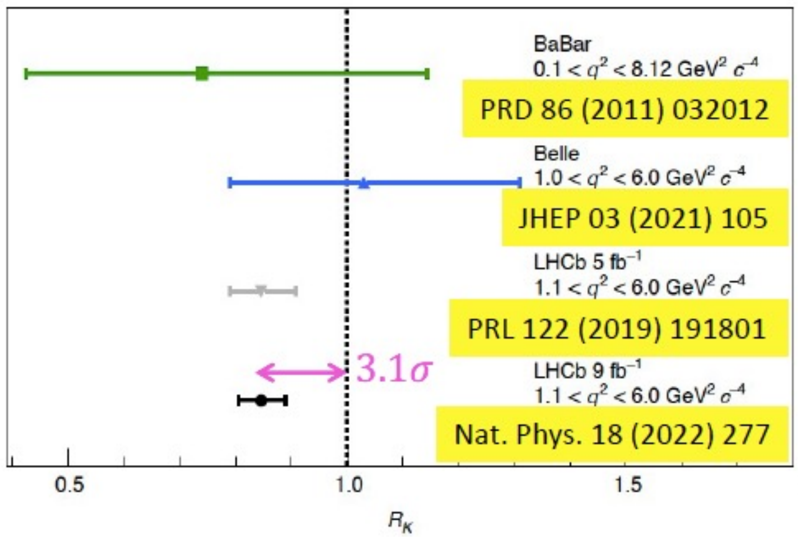
$B \to K^{(*)}\ell\ell$ ($b \to s\ell\ell$) is used to probe LFU

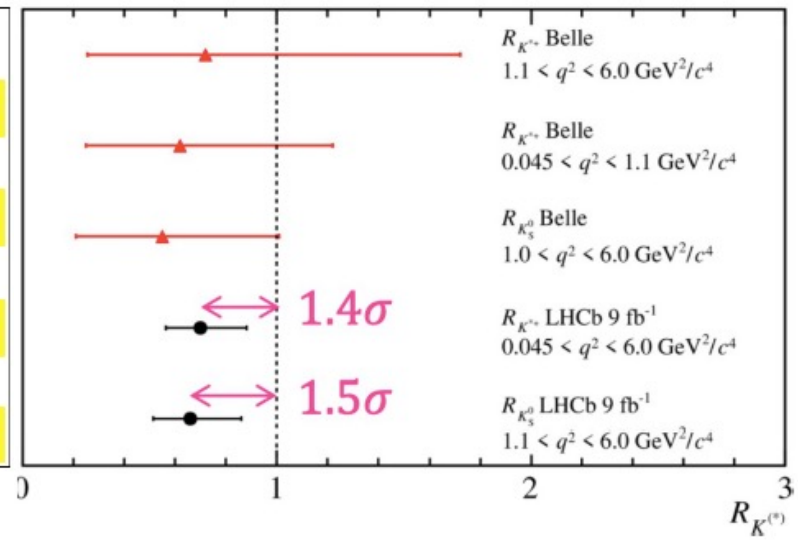
Standard Model Prediction:

$$R\left(K^{(*)}\right) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)} = 1 \pm \mathcal{O}(10^{-2})$$

New physics can affect these observables

Discrepancy observed by LHCb





Belle II preliminary:

	PDG $\mathcal{B} \times 10^6$
$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6}$	0.94 ± 0.05
$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6}$	$1.03 \pm .19$
$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}$	0.99 ± 0.12

Similar precision for *e* & μ modes

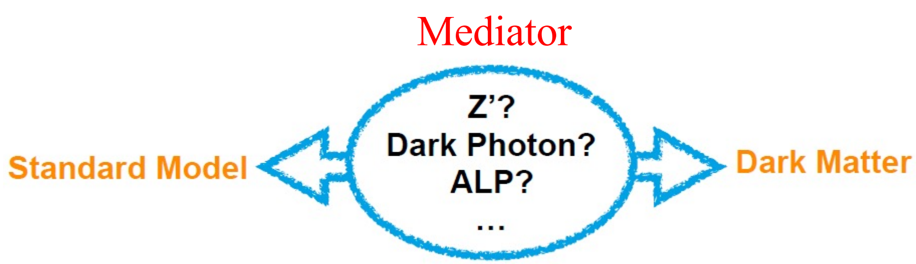
Longer-term effort: ~5 ab^{-1}, Belle II will be able to probe LFU to $\mathcal{O}(10\%)$

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 $\rightarrow$ search for DM up to O(a few) GeV

Collision of galaxy clusters
red: matter, blue: DM



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

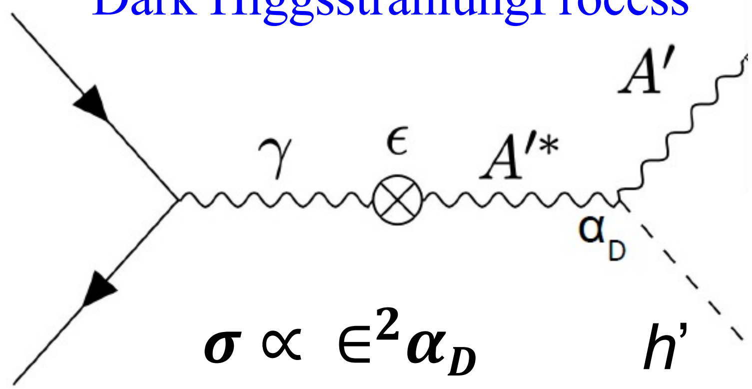
- Typical process at Belle II
  - $e^+ + e^- \rightarrow$ SM particles + Mediator
  - B (or other hadron) $\rightarrow$ SM particles+ Mediator
- Some of these processes have not been searched in *BABAR* or Belle (e.g., due to trigger setting) & can be searched for with initial Belle II data

- search for invisible Z' [PRL 124, 141801 (2020)]
- search for Axion-like [PRL 125, 161806 (2020)]

Dark Higgsstrahlung

$e^+e^- \rightarrow A'(\rightarrow \mu^+\mu^-)h'(\text{invisible})$

Dark HiggsstrahlungProcess



$\sigma \propto \epsilon^2 \alpha_D$

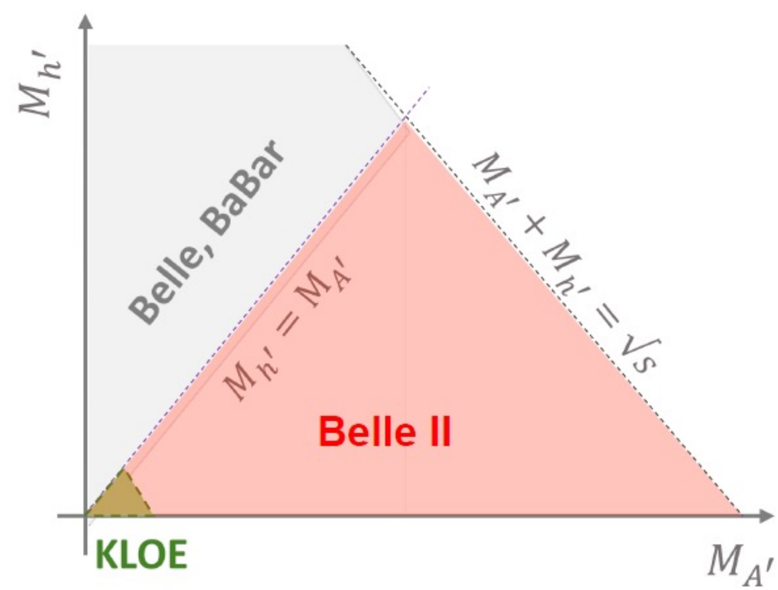
α_D: dark coupling constant

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 a dark Higgs boson (h') to the theory [PRD 79, 115008 (2009)]

Mass hierarchy scenarios

- $M_{h'} > M_{A'}$: h' → A'A'$^{(*)}$ → 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

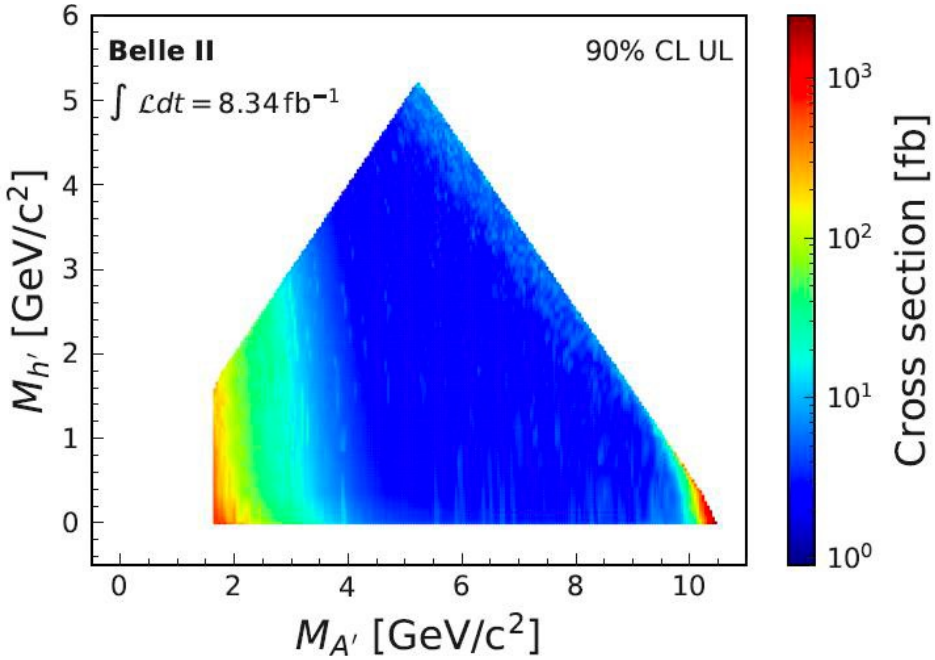


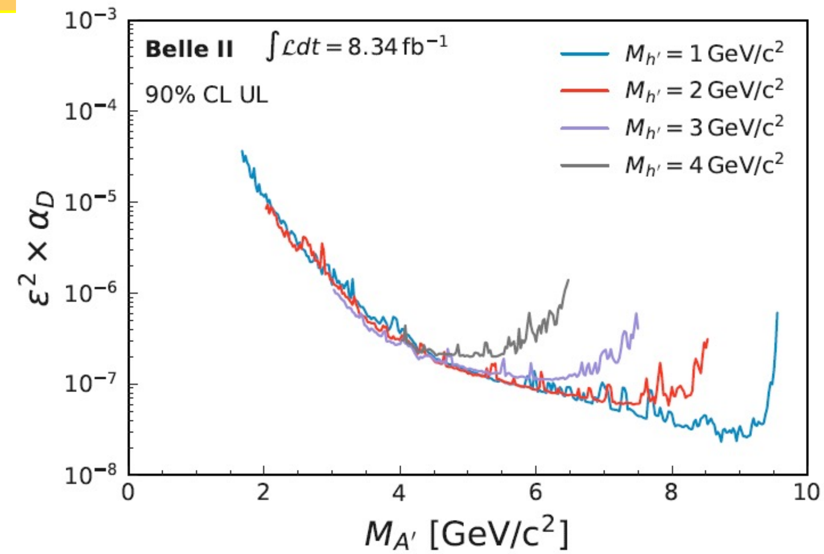
BaBar: PRL 108, 211801 (2012)
Belle: PRL 114, 211801 (2015)
KLOE: PLB 747, 365 (2015)

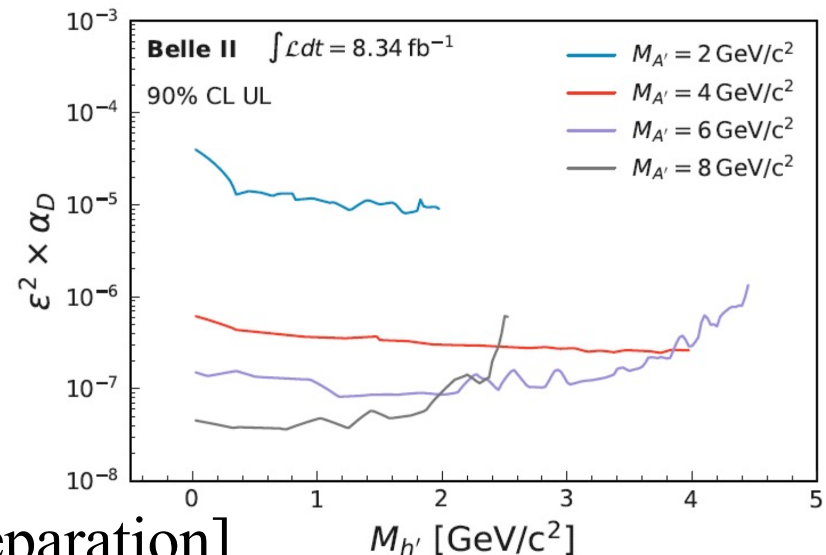
Dark Higgsstrahlung

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







World-leading result in previously unexplored region

[paper in preparation]

Summary

$e^+e^-@\Upsilon$ region: powerful event environment, rich physics

- Belle II is running, has accumulated over 400 fb^{-1} so far
- Only a few results were presented
  - B^0 Lifetime and Mixing Frequency
  - Lepton Flavor Universality in $B \to D^{(*)}\ell\nu_\ell$
  - Lepton Flavor Universality in $B \to K^{(*)}\ell\ell$
  - Dark Higgsstrahlung
- Many more results were not presented …
- And even more results will be coming soon!