Recent results on dark sector searches at Belle II

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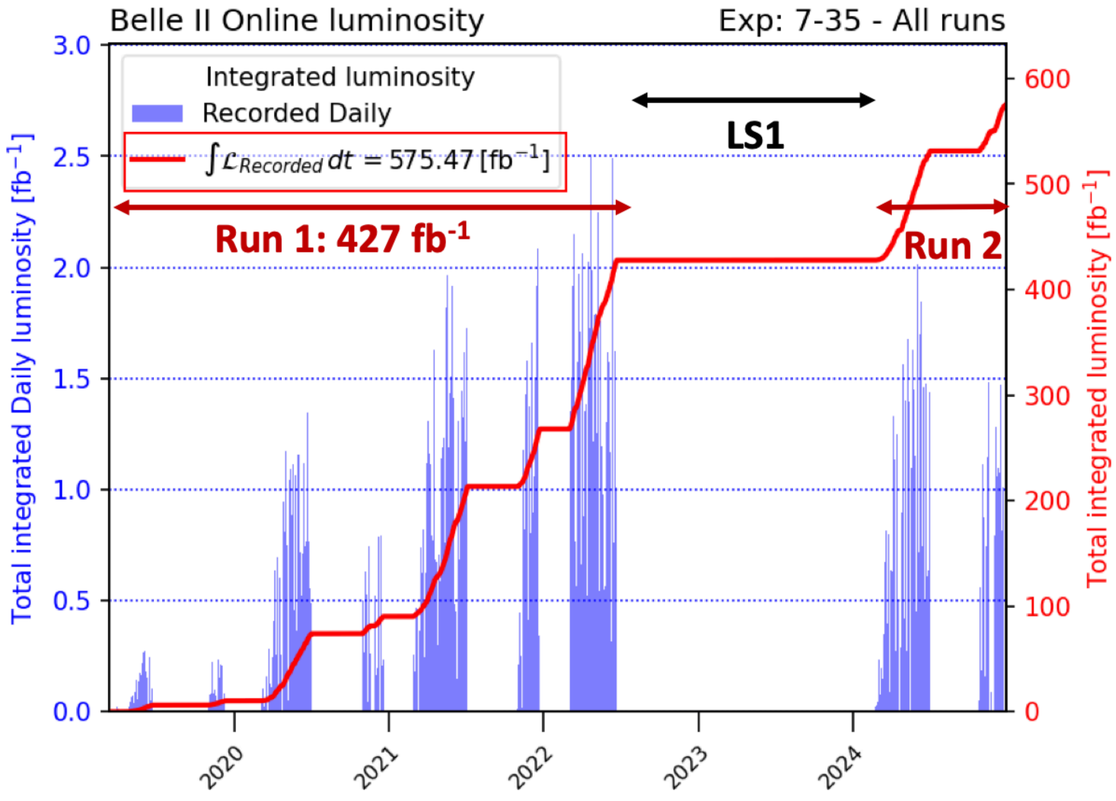
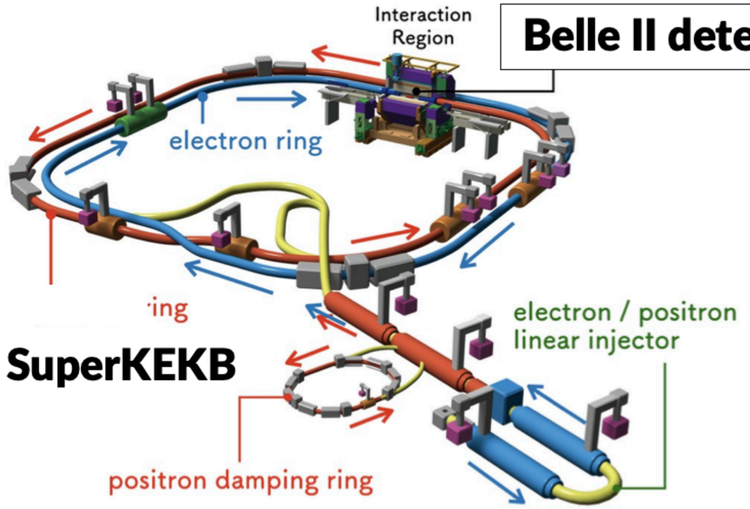
on behalf of the Belle II collaboration

The Belle II experiment at SuperKEKB

Belle II is a luminosity-frontier experiment looking for physics beyond the Standard Model
SuperKEKB : asymmetrical e^+e^- collider operating mostly at the $\Upsilon(4S)$ energy





- Long shutdown (LS1) - several accelerator and detector maintenance and improvements

✳ **Rich physics programs**

High Luminosity

Target	**Achieved:**
$\int \mathcal{L}dt = 50\ \mathrm{ab}^{-1}$	$\int \mathcal{L}dt > 570\ \mathrm{fb}^{-1}$
$\mathcal{L}_{peak} = 6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	$\mathcal{L}_{peak} = 5.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

- Operation back at $\mathcal{L}_{peak} = 4.34 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **world record luminosity!!**

Dark sector searches at Belle II

Many models proposed, possibly small couplings:

1. Signature based

2. Benefits from **clean environment** at lepton colliders + **hermetic detector:**
Belle II at **SuperKEKB** asymmetric-energy e+e- collider

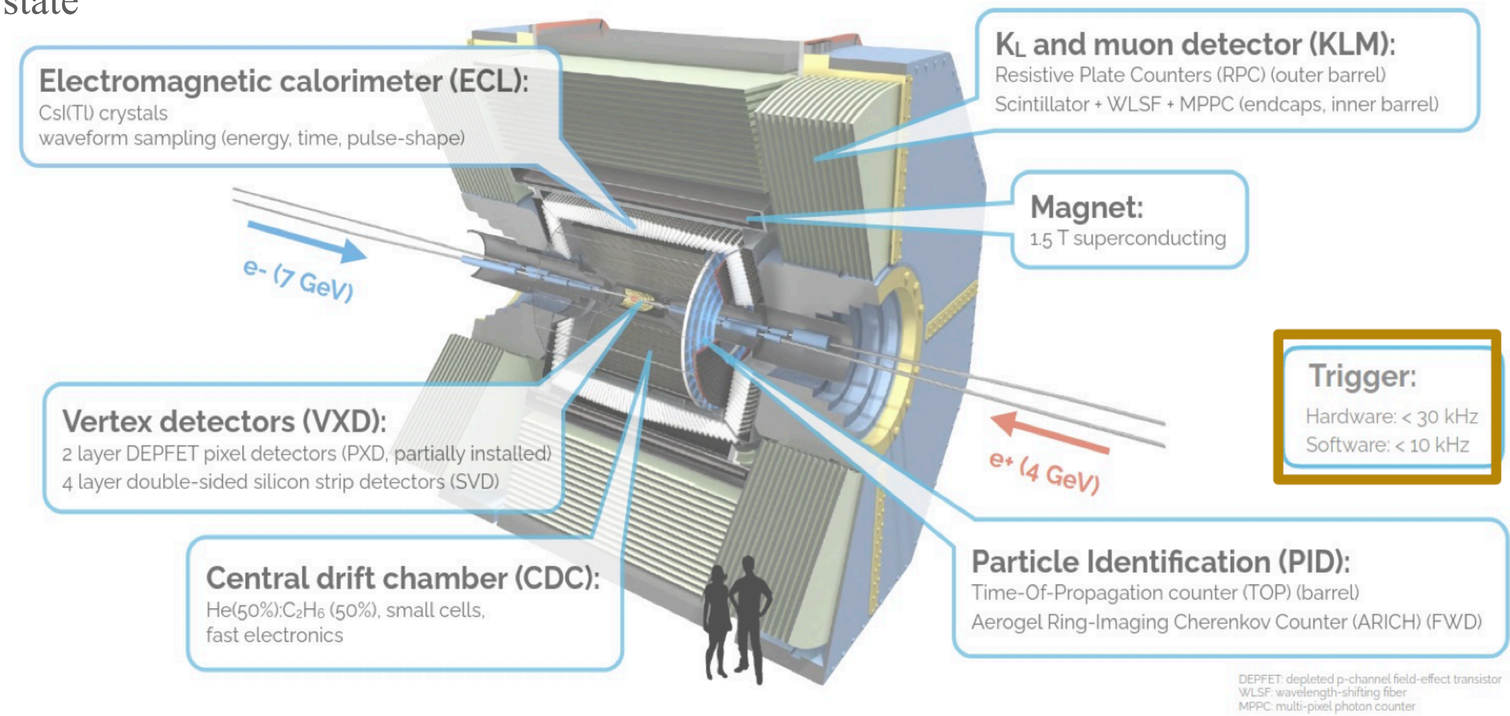
- Running mainly $\sqrt{s} = 10.58$ GeV, very **well-known** initial state
- Multipurpose detector with cylindrical symmetry

- Efficient reconstruction of **neutrals** (π^0, η)

- Specific **low-multiplicity triggers:** single track, muons, photons (previously not available at Belle and BaBar)

- Excellent particle identification system

- Excellent reconstruction capabilities for low multiplicities and missing energy signatures



Highlights

Inelastic dark matter with dark Higgs

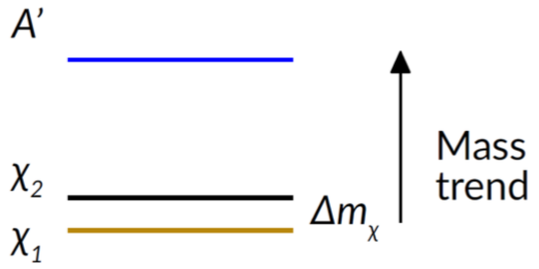
Search for Axion-Like particle in $B \to K^{(*)}a'(\to \gamma\gamma)$

Search for a $\mu^+\mu^-$ resonance in four-muons final states

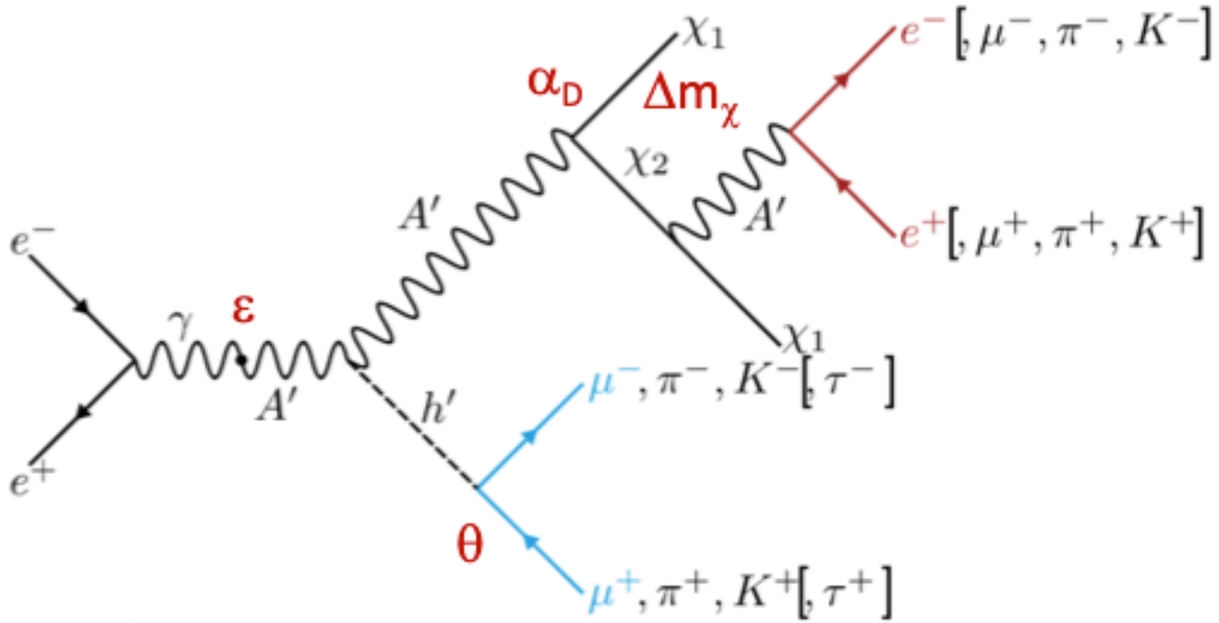
Inelastic dark matter with dark Higgs

NEW

- Dark photon A' and dark Higgs h'
- Two dark matter states χ_1 and χ_2 with a small mass splitting
- χ_1 is stable ⟶ relic dark matter candidate
- χ_2 is generally long lived
- h' is generally long-lived and mixes with SM H_0



Looking for h' and A' simultaneous production



Focus on m(A′) > $m(\chi_1) + m(\chi_2)$

- The decay $A' \to \chi_1\chi_2$ is favored

Up to two displaced vertices

- $\chi_2 \to \chi_1 A'$ non pointing + missing energy
- $h' \to x^+x^-$ pointing

Dataset: 365 fb^{-1} from Belle II

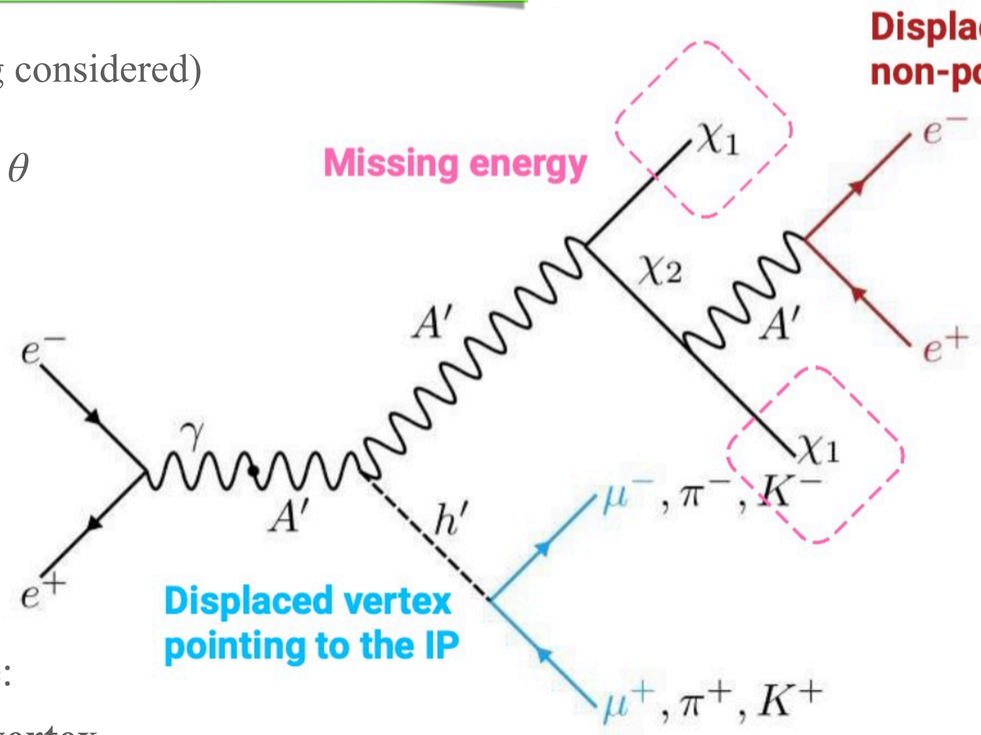
Inelastic dark matter with dark Higgs

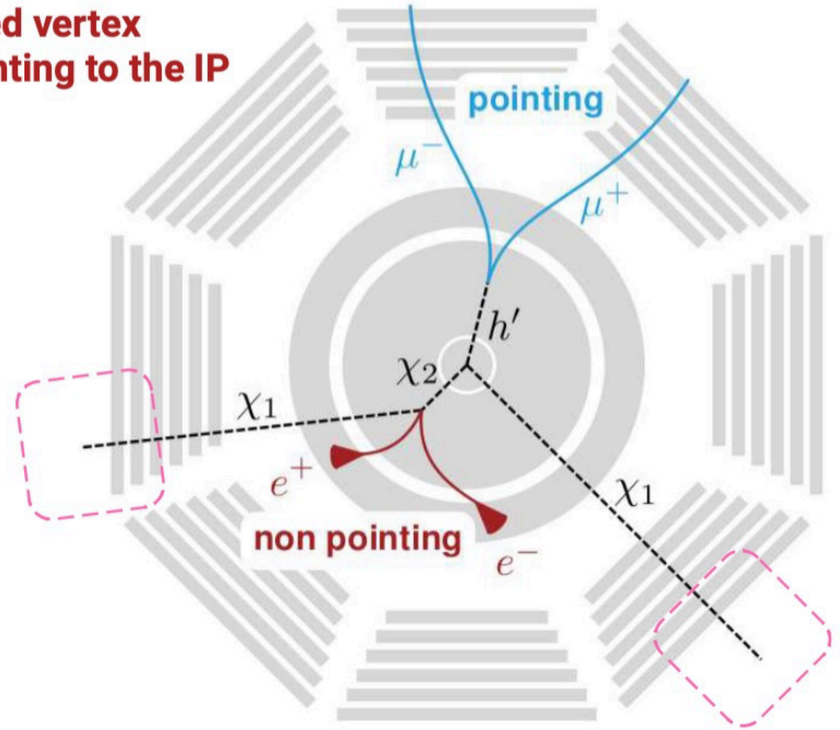
NEW

Strategy

- Challenging for tracking and trigger (displaced tracks)
  Almost zero background analysis

- χ_2 is long-lived (small mass splitting considered)
- h' long-lived for small mixing angle θ





Require four tracks in the final state:

- 2 forming a **pointing displaced vertex**
- 2 forming a **non-pointing displaced vertex**
- **Missing energy (χ_1, χ_2)**

  - 3 channels explored : $\mathbf{h'}(\rightarrow \mathrm{x}^+\mathrm{x}^-), \mathbf{x} = \mu, \pi, \mathbf{K}$

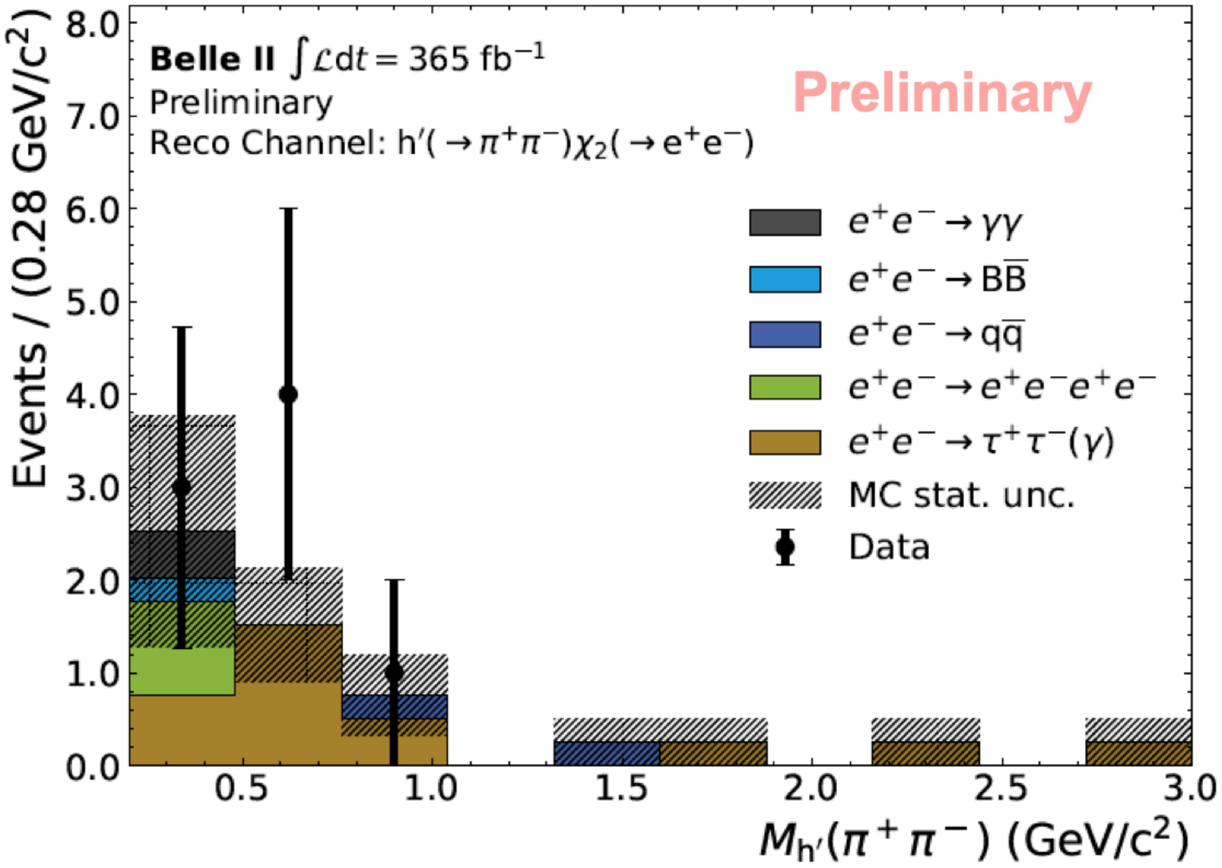
Inelastic dark matter with dark Higgs

NEW

Results

Signal selection using requirements on pointing angles and vertex distance from the interaction point

- **Very low SM background**



Expected background **estimated in data from sidebands to not relying on MC**

Cut & count strategy to extract Signal yields

No significant excess found in the individual final states or combination:

- 9 events observed (8 out of 9 are $\pi^+\pi^-$) consistent with expected background

Inelastic dark matter with dark Higgs

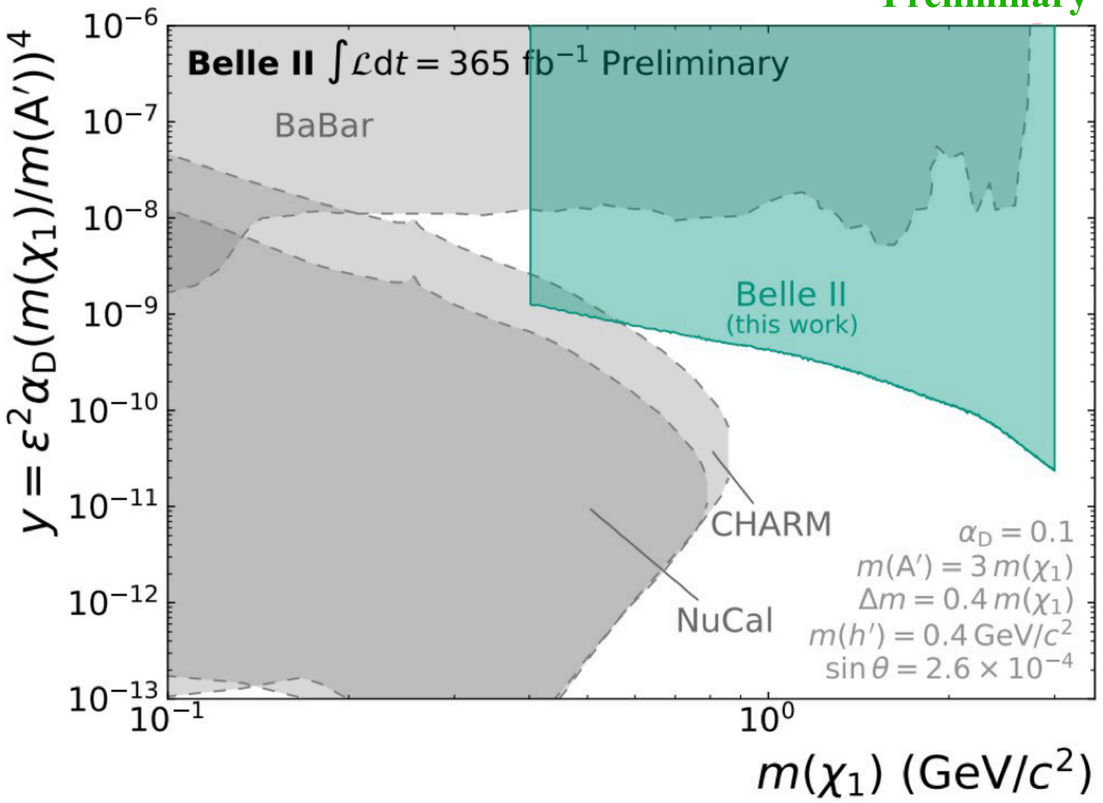
Results

NEW

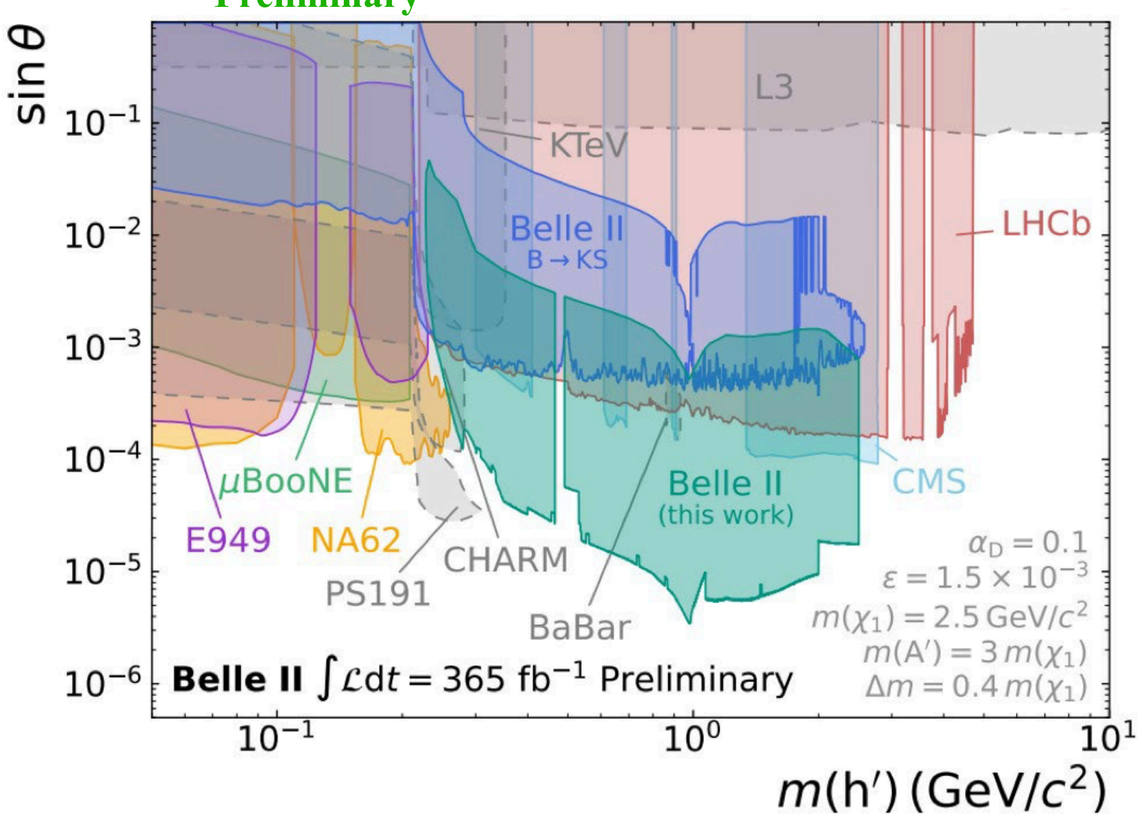
Strong limits on θ and $\epsilon \times \alpha_D$, but dependence on other 5 parameters

- **Explored many additional configurations (~ 30)**

Preliminary



Preliminary

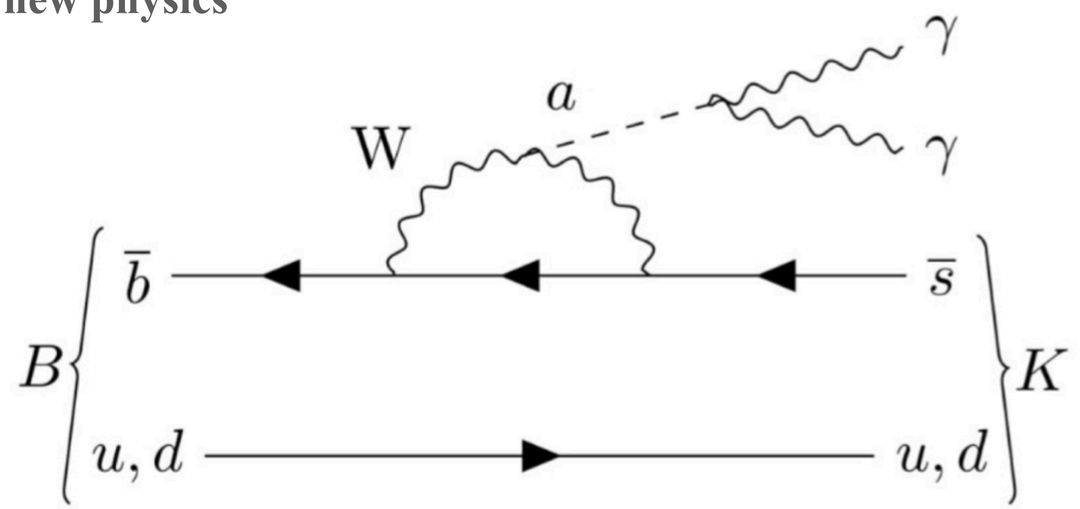


Overview

To be submitted to JHEP

Flavor changing neutral current B decays are a perfect testbed to search for new physics

- Extremely suppressed in SM
- New physics could appear at the same order of SM processes



Reporting a search for an axion-like particle in B → K*a' decays

- BR($a' \to \gamma\gamma$)$\simeq$ 100 % for $m_a \ll m_{W_\pm}$
- Mass region scanned 0.16 - 4.50 GeV/c^2

Existing constrained from recent search from BaBar (424 fb^{-1})

This study:

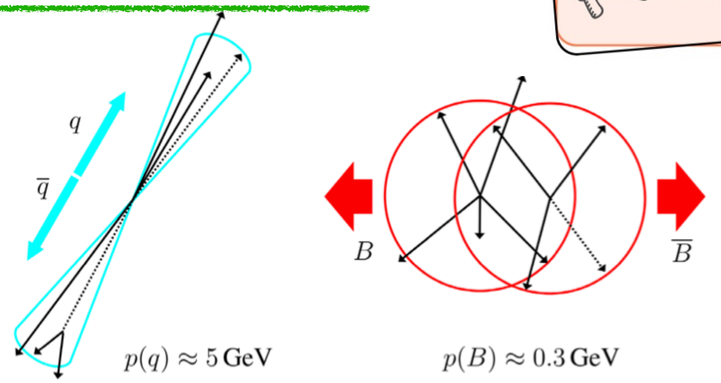
- Full Belle dataset (711 fb^{-1})
- Exploiting multiple kaon modes : $\mathbf{K^0_S}$, $\mathbf{K^+}$, $\mathbf{K^{*0}}$ and $\mathbf{K^{*+}}$

To be submitted to JHEP

NEW

Strategy

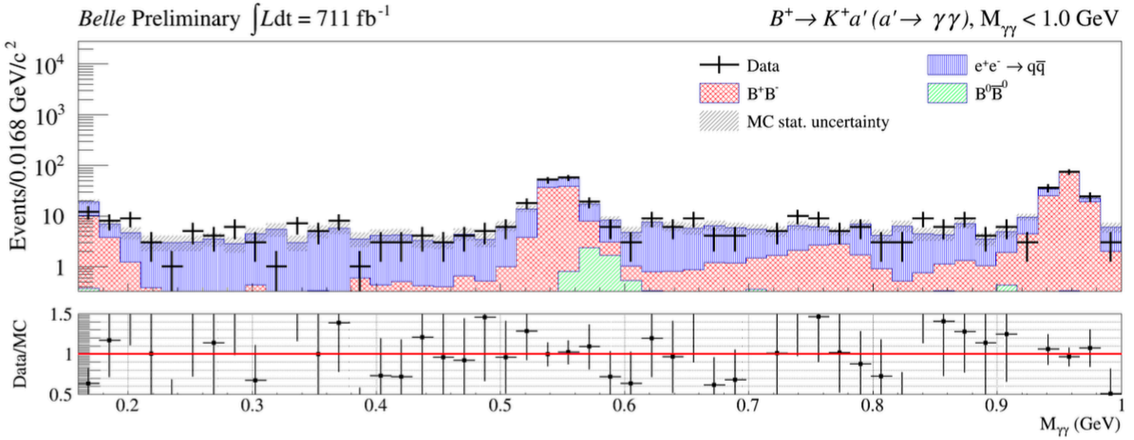
Signal B reconstructed combining a pair of photons with a track identified as kaon

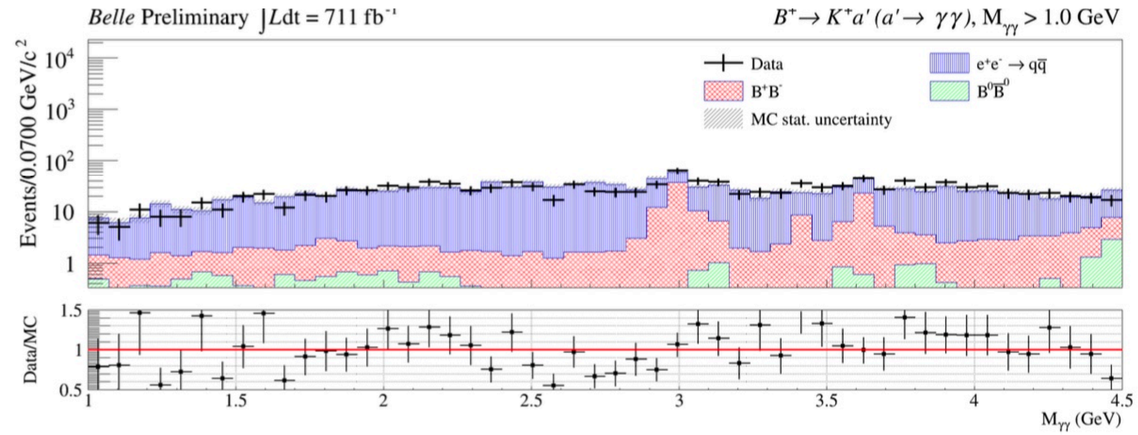


Main background from continuum, BB subdominant

Smooth background, but near SM pseudo scalar masses

- **Rejected using several BDTs exploiting :**
  - ✓ Differences from B nominal kinematics and event topology variables to separate signal from continuum
  - ✓ Calorimeter cluster variables to suppress π^0 background





Signal extracted with a scan over $M_{\gamma\gamma}$

- Steps of signal mass resolution (~8 - 18 MeV)
- Peaking background regions vetoed

$B \to K^{(*)} a'(\to \gamma\gamma)$

Results

To be submitted to JHEP

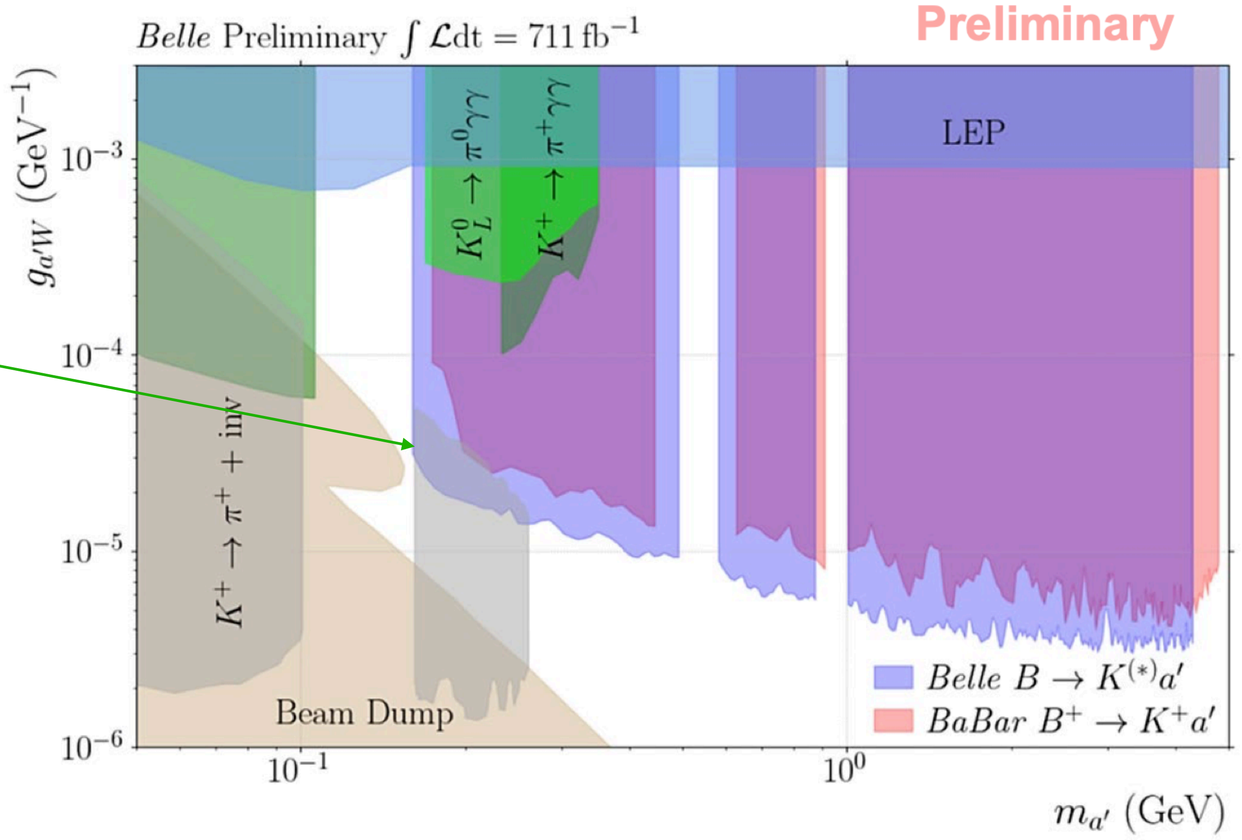
NEW

No significant excess observed in 711 fb^{-1}

- **Simultaneous fit on 4 kaon modes**

★ **World leading 90 % CL upper limits to $g_{a'W}$**

- ALP lifetime becomes important at low masses and couplings
- Signal efficiency drop due to long-lived ALP is taken into account in results



$L_\mu - L_\tau$ model : $Z' \to \mu\mu$

PRD 109, 112015 (2024)

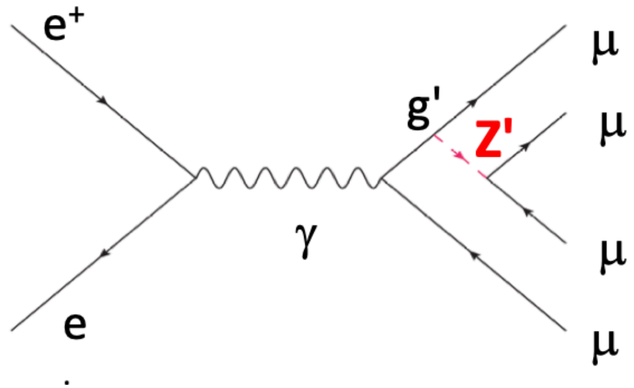
- Overview and Strategy

Two models:

$L_\mu - L_\tau$ model

Reinterpreted also as
Muonphilic scalar model

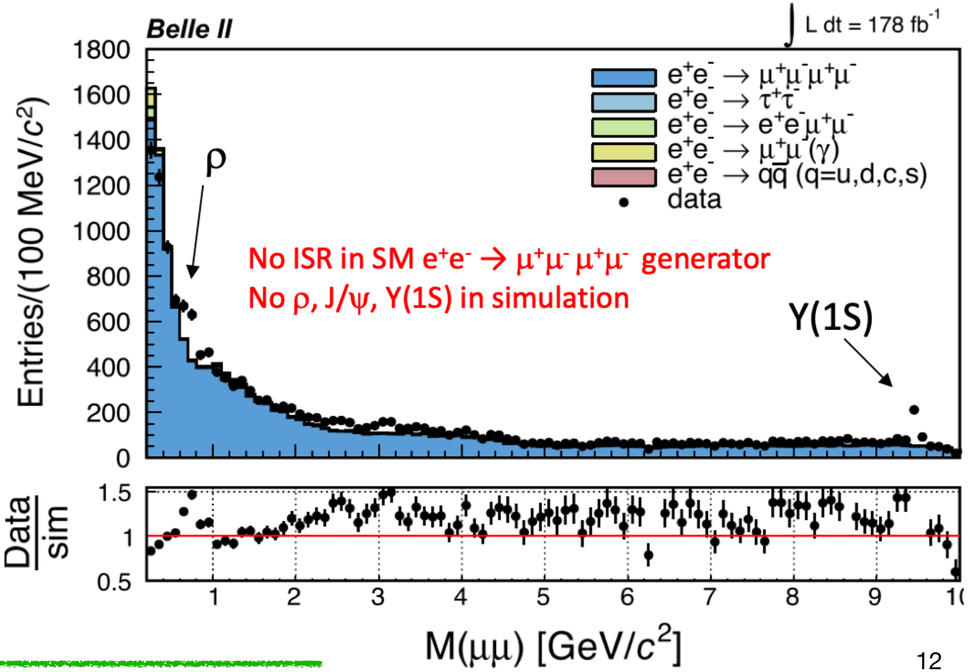
$S \to (g-2)_\mu$



$e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

- Events selected have **4 tracks : at least three identified as muons**
- M(4 tracks) ~ $\sqrt{s}$
- Negligible detected energy in addition to charged particles
- Signature : narrow $M(\mu\mu)$ peak
- Background : SM $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

Signal yield: series of fits to $M(\mu\mu)$ distribution



For background suppression: MLP NN based on kinematics variables :

- Characteristic background momentum scale
- Signal as FSR
- $\mu\mu$ helicity angles

$L_\mu - L_\tau$ model : $Z' \to \mu\mu$

PRD 109, 112015 (2024)

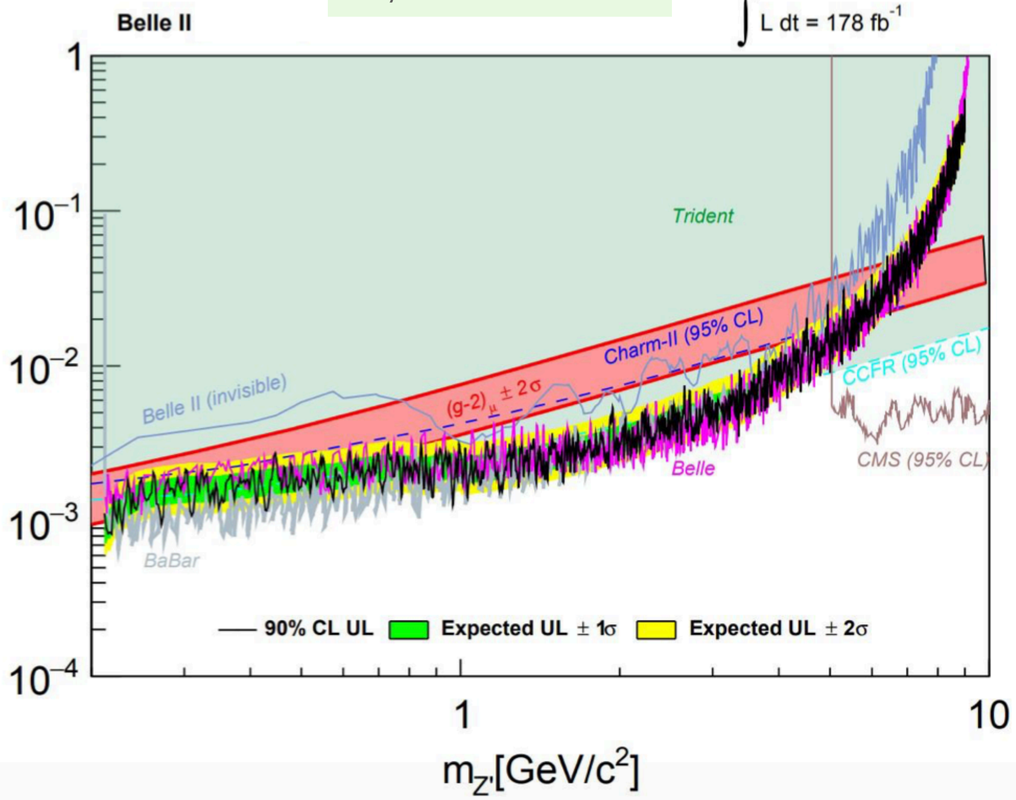
- Results
  - **No significant excess observed in 178 fb^{-1}**

→**90%** CL upper limits on the process cross section, $\sigma(e^+e^- \to X\mu^+\mu^-)B(X \to \mu^+\mu^-)$ with X= S, Z'

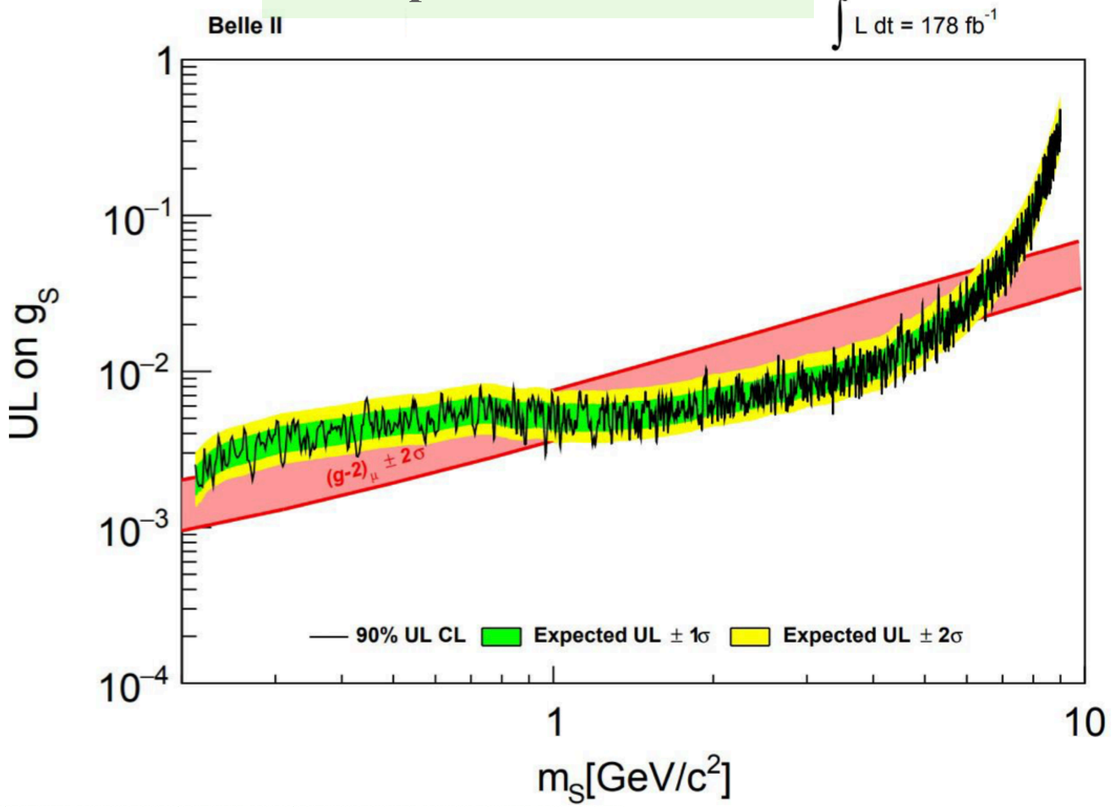
- Cross section limits are translated into upper limits on the **g' coupling constant for ($L_\mu - L_\tau$) model** and on the **g_s coupling constant for the muonphilic dark scalar S**[5]

[5] P. Harris, P. Schuster, and J. Zupan, arXiv:2207.08990 [hep-ph]; R. Capdevilla, D. Curtin, Y. Kahn, and G. Krnjaic,J. High Energy Phys. 04 (2022) 129

$L_\mu - L_\tau$ model



Reinterpreted also as **Muonphilic scalar model**



Conclusions

- Belle II has a unique sensitivity to light dark sector
  - Complementary to higher energy colliders and beam-dump experiments
  - World- leading results published with partial Run 1 dataset
- **Many frontiers of improvements** :
  - ➡ Increase data sample size
  - ➡ Improve analysis techniques
  - ➡ Reduce systematic uncertainties

Luminosity and physics output expected to continue to ramp up with the next data-taking period

Stay tuned!

Thank you for your attention

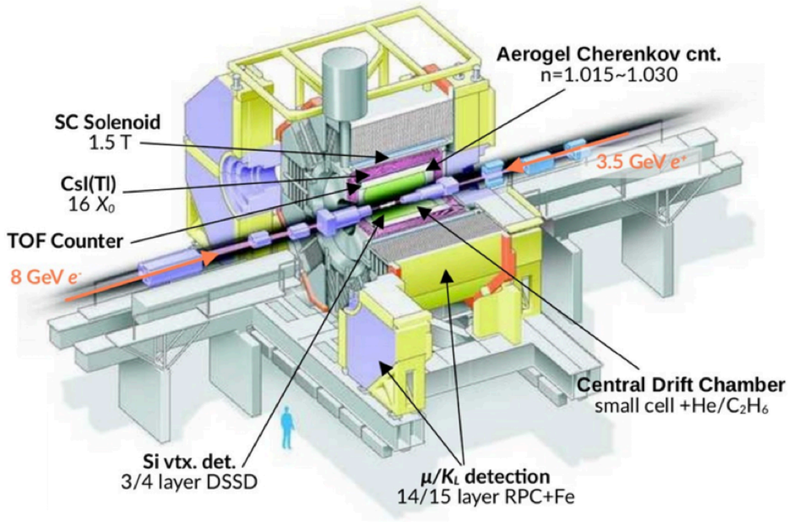
Back up slides

Experiments

✓ Belle (1999-2010) & Belle II(2018-current) operate at asymmetric e^+e^- colliders

- Collisions at or near $\Upsilon(4S)$: $\sqrt{s} = 10.58$ GeV
- Belle @ KEKB (1999-2010) : $\mathscr{L}_{peak} = 2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, $\mathscr{L}_{int} = 1\ \mathrm{ab}^{-1}$
- Belle II @ SuperKEKB (2019-current) : $\mathscr{L}_{peak} = 4 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, $\mathscr{L}_{int} = 0.42\ \mathrm{ab}^{-1}$

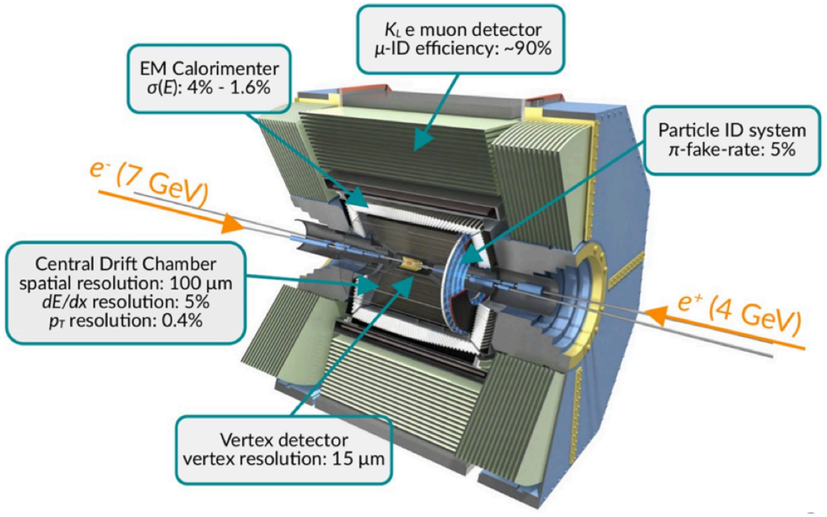
BELLE @ KEKB



✓ Belle & Belle II are now **synergic** experiments

- Belle data can be analysed with the **Belle II analysis software**
  - Analysis can be performed with a combination of Belle and Belle II data
  - Important for charm analysis, where large statistics is crucial to improve the precision

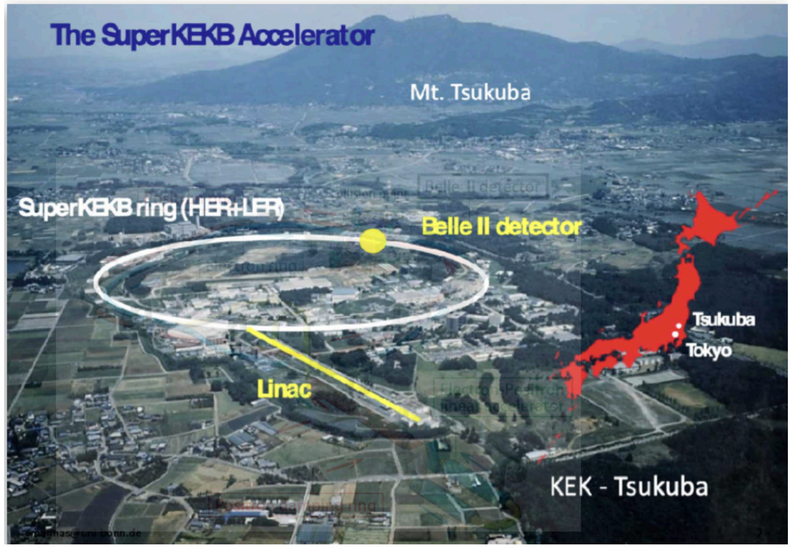
Belle II @ SuperKEKB



- Well-known **initial state** condition & **clean environment**
- Efficient reconstruction of **neutrals**
- Boosted center of mass that allows for time-dependent measurements
- Hermetic detectors with excellent PID and tracking performance

KEK-SUPERKEKB complex

- Asymmetric e^+e^- colliders
- Collisions mainly at 10.58 GeV , i.e at $\Upsilon(4S)$ resonance



KEKB

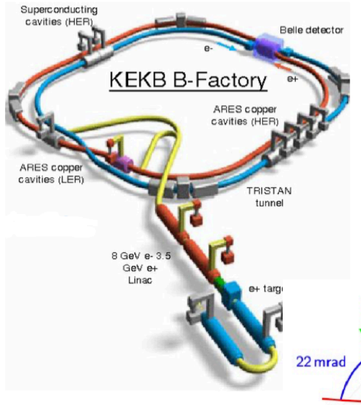
1999-2010

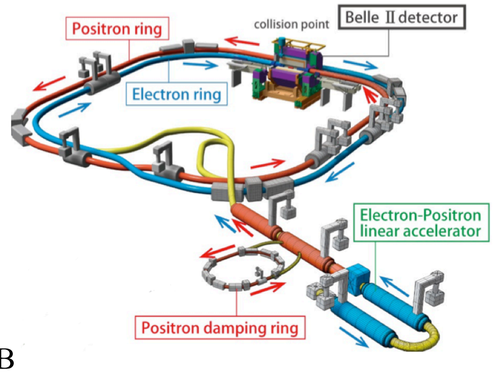
- e^+ (3.5 GeV) e^-(8 GeV)
- L_{peak}: $2.1 \times 10^{34}\ cm^{-2}s^{-1}$ [achieved]

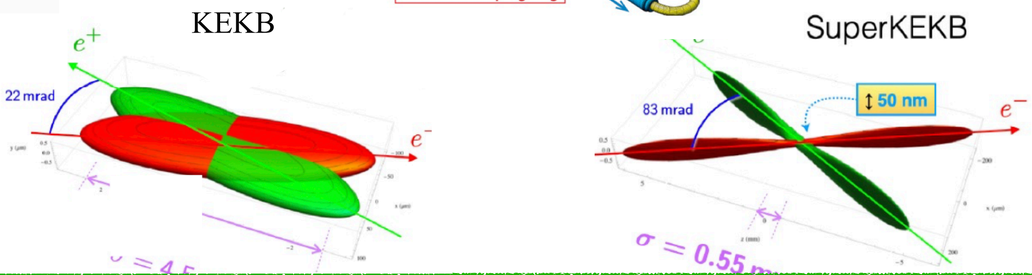
SuperKEKB

2019-current

- e^+ (4 GeV) e^-(7 GeV)







Target:

$\int Ldt = 50\ ab^{-1}$

$L_{peak} = 6 \times 10^{35}\ cm^{-2}s^{-1}$

Achieved:

$\int Ldt > 530\ fb^{-1}$

$L_{peak} = 4.7 \times 10^{34}\ cm^{-2}s^{-1}$

Current world record

Beyond the SM physics

Open question unexplained by SM → New Physics beyond the SM

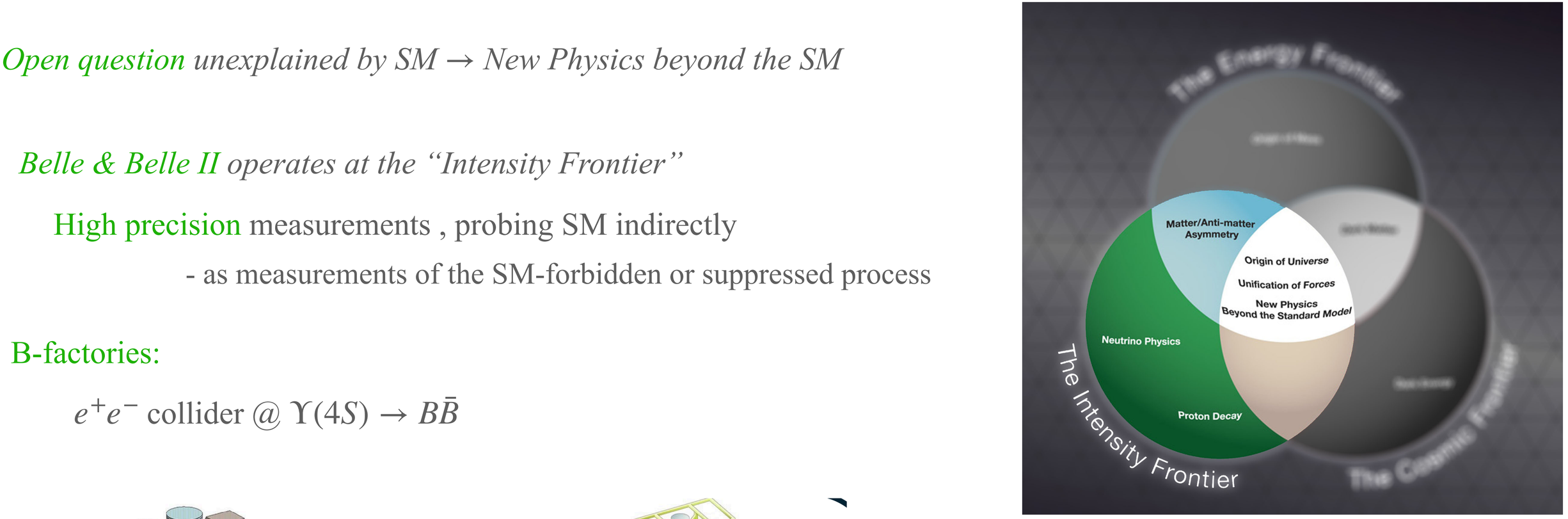
Belle & Belle II operates at the "Intensity Frontier"

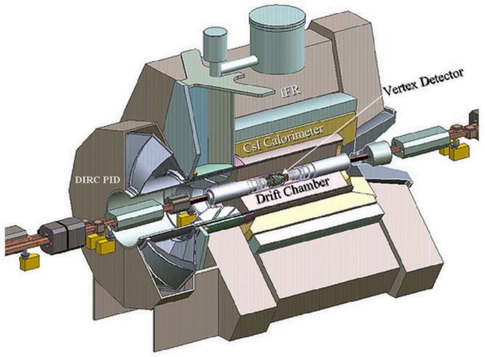
High precision measurements , probing SM indirectly

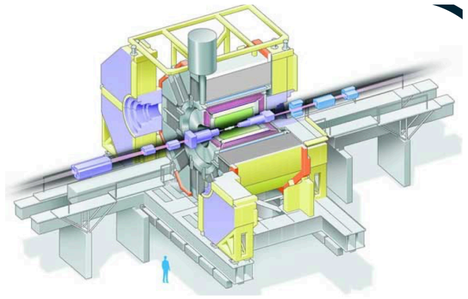
- as measurements of the SM-forbidden or suppressed process

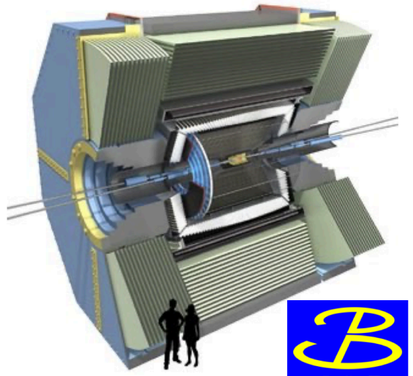
B-factories:

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









BABAR SLAC-PEP II collider : 462 fb^{-1} @ $\Upsilon(4S)$ [1999-2008]

BELLE KEKB collider : 711 fb^{-1} @ $\Upsilon(4S)$ [1999-2010]

Belle II SuperKEKB collider : 530 fb^{-1} @ $\Upsilon(4S)$ [2019-current]

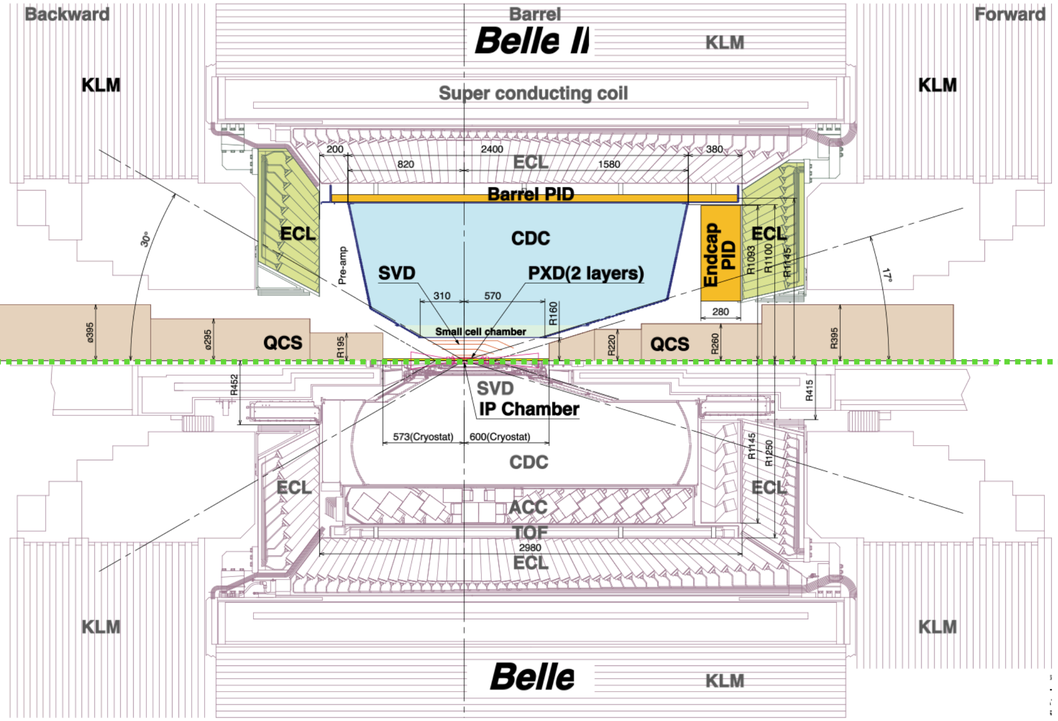
Belle & Belle II detectors

ECL (electromagnetic calorimeter): Updated electronics

PID (Particle Identification): Better K/π separation under higher bkg level

CDC (Central drift chamber): larger volume, smaller drift cells and faster electronics

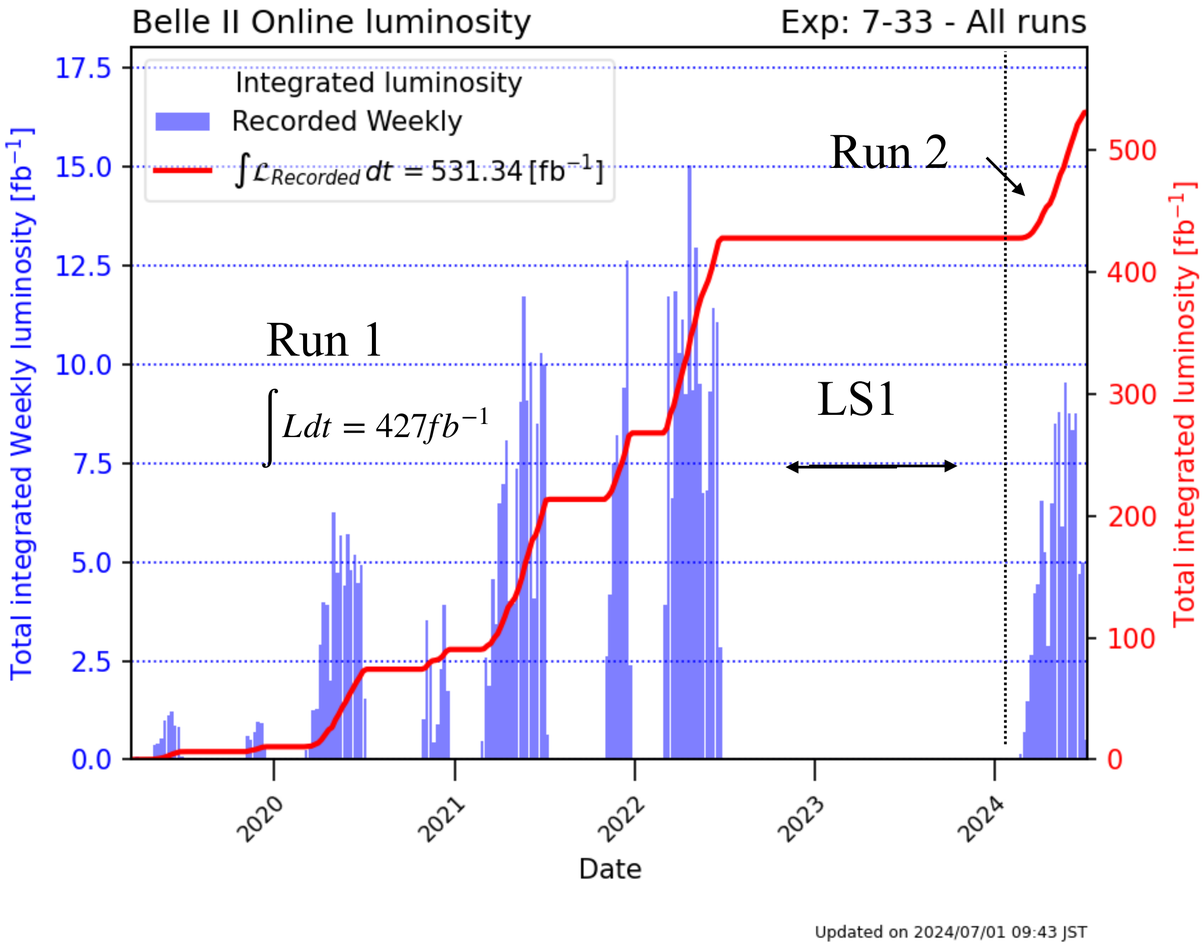
VTX: + 2 layers PXD (pixel detector)
+ 4 layers SVD (Silicon vertex detector)



Belle II TDR

- Well-known **initial state** condition
- Benefits from **clean environment**
- Efficient reconstruction of **neutrals**
- Boosted center of mass that allows for time-dependent measurements
- Hermetic detectors ⟶ ideal for studying neutral or invisible decays

Belle II data -taking



We are suffering from **sudden beam loss events**, with large doses at the interaction region.

In a couple of them two channels of **PXD were damaged**

- as a precaution, it has been decided to **keep PXD off** while investigating the sources of the sudden beam loss and implement countermeasures to stabilize the beam operation