Dark Matter Searches at B-Factories: BaBar, Belle and Belle II

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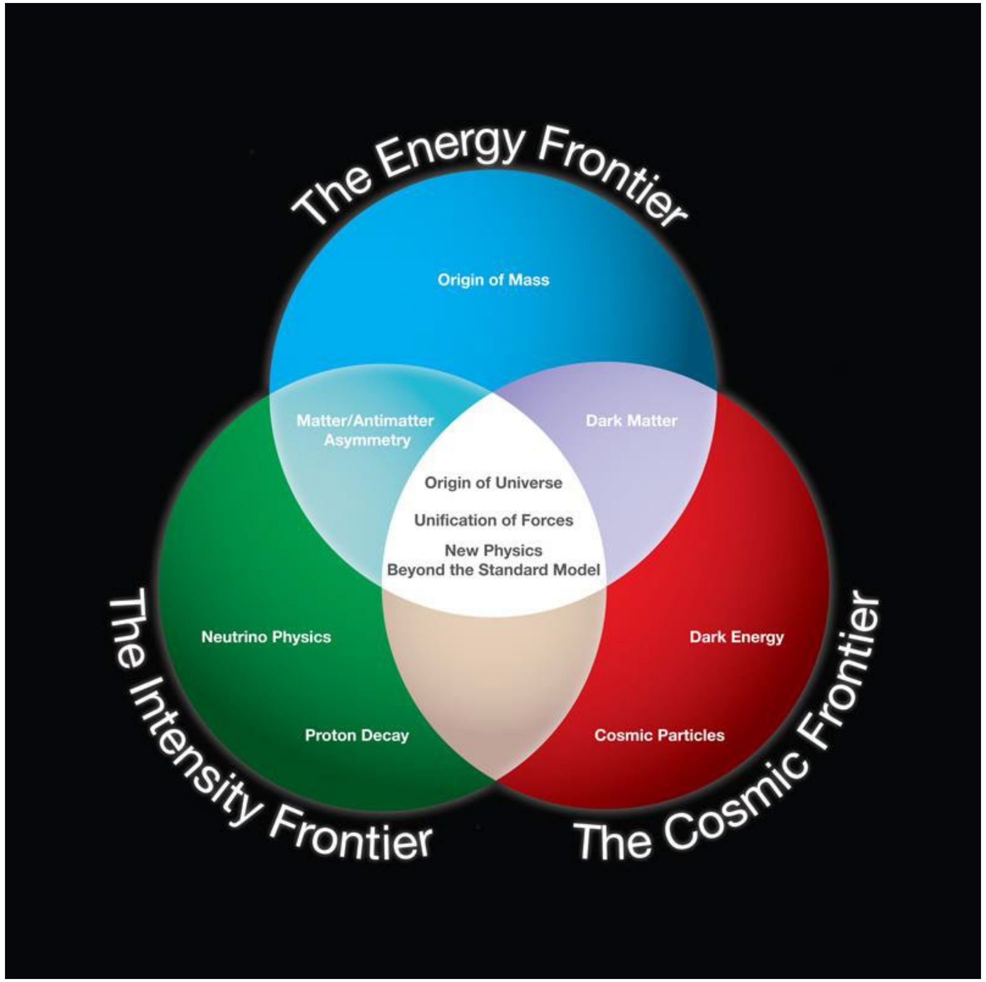
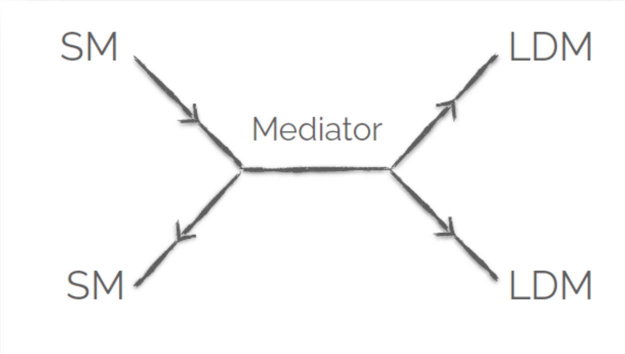
Belle II

DARK MATTER SEARCH IN EXPERIMENTS

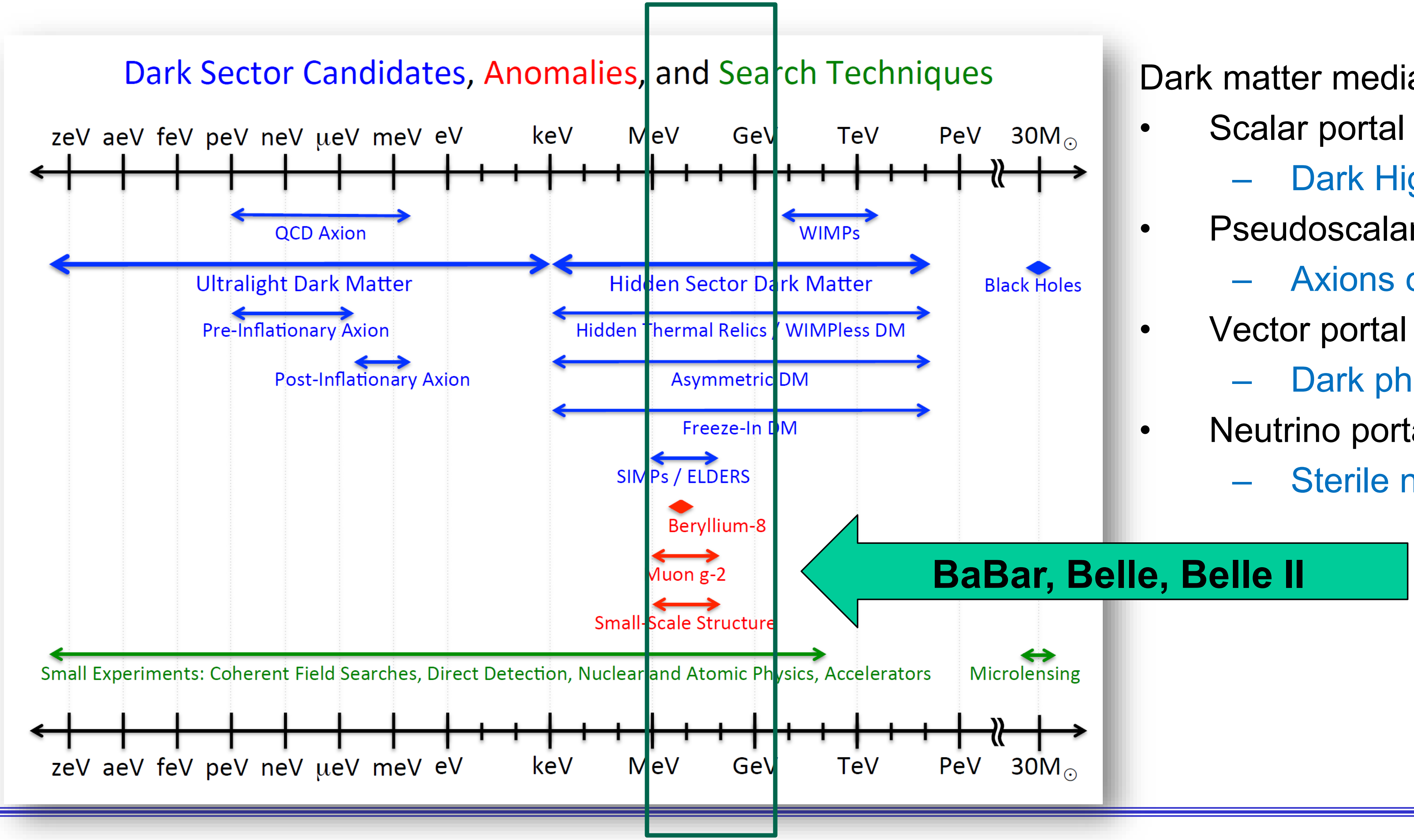
Three Frontiers



- Energy Frontier possibilities
  - Dark particles directly produced by the LHC collider, exploiting high beam energy.
- Cosmic Frontier
  - Dark particle searches in underground labs, etc.
- Intensity Frontier
  - Interaction mediators between SM particles and Light dark mater (LDM)
  - Mediators enter into various portals



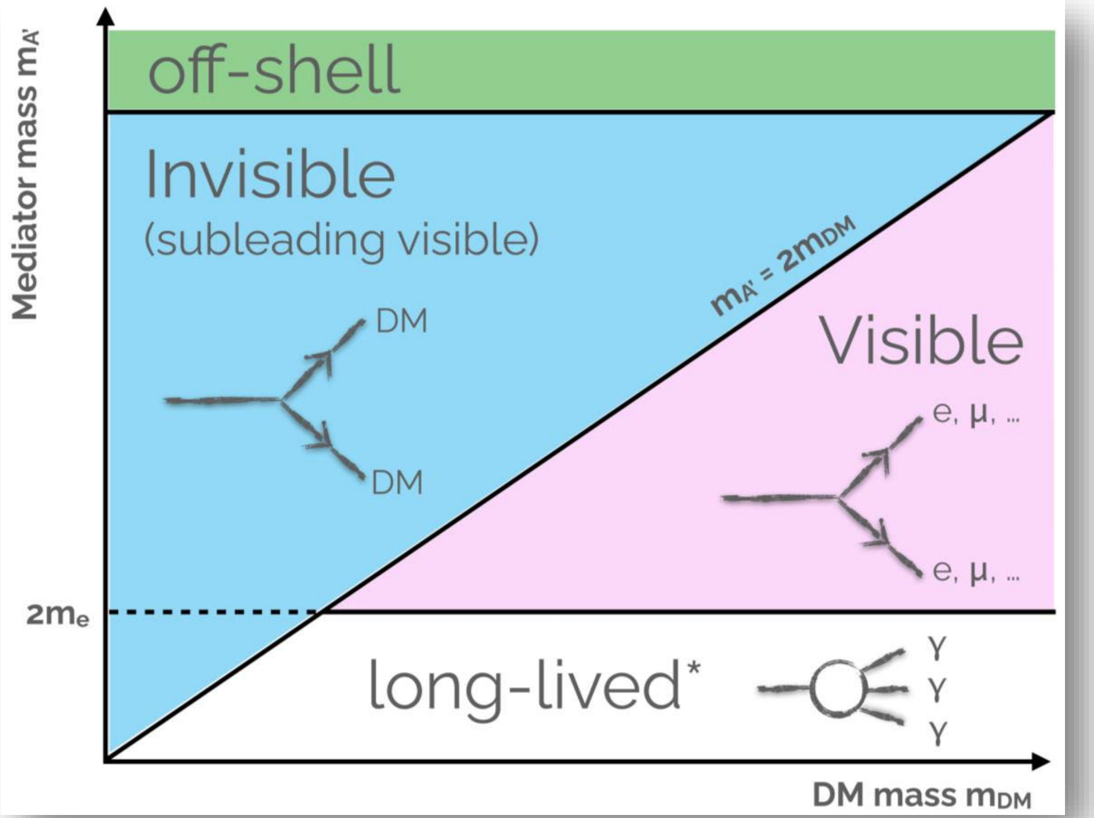
Dark Sector Covered by e+ e- B-Factories



Dark matter mediators

- Scalar portal
  - Dark Higgs, scalars
- Pseudoscalar portal
  - Axions or ALPs
- Vector portal
  - Dark photon, Z'
- Neutrino portal
  - Sterile neutrino

Dark Signatures at e+ e- Colliders

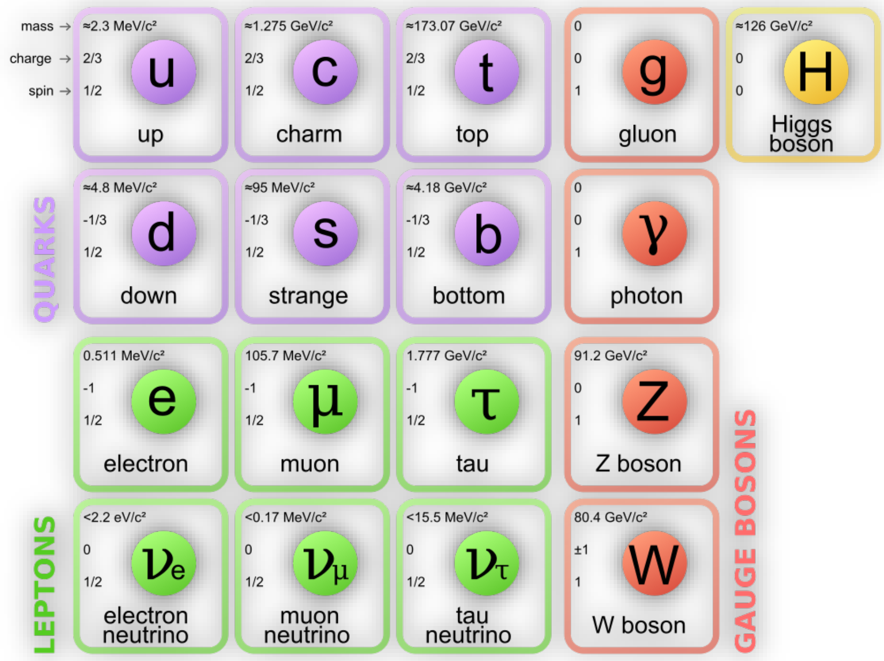


Search signature depends on the dark mediator mass

- $ll\ (\gamma)$ (+ missing)
  - Visible: ALP $\rightarrow$ ff
    minimal and non minimal dark photons
  - Invisible: dark photon. Z'
- $ll\ l'l'$
  - Visible: ALP $\rightarrow$ ff, scalars, $\mu\mu\ \tau\tau, \tau\tau\ \tau\tau$
    non minimal dark photons
- Single γ
  - Invisible: dark photon, ALP $\rightarrow \chi\chi$, IDM, LLP
- $\gamma\gamma$
  - Visible: ALP $\rightarrow \gamma\gamma$
- Long lived particles (LLP)
  - A', ALP $\rightarrow \chi\chi$, IDM, scalars
- B meson decays into dark particles

B FACTORIES- BASICS

Concept of e+ e- B Factory

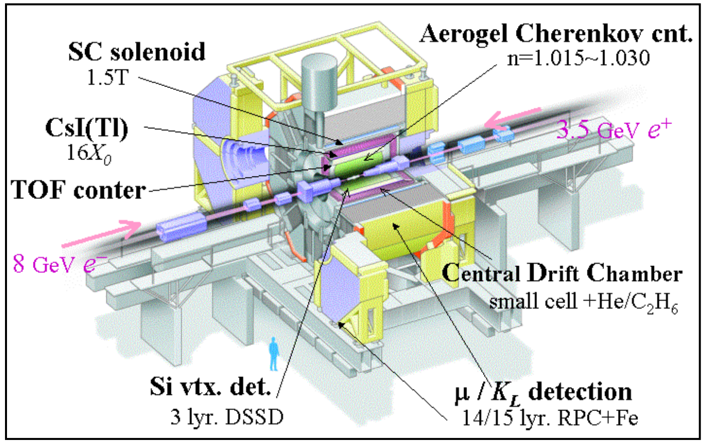


- B mesons $(b\bar{q})$ are heavy and can decay via many different hadronic, semi-leptonic, and leptonic modes.

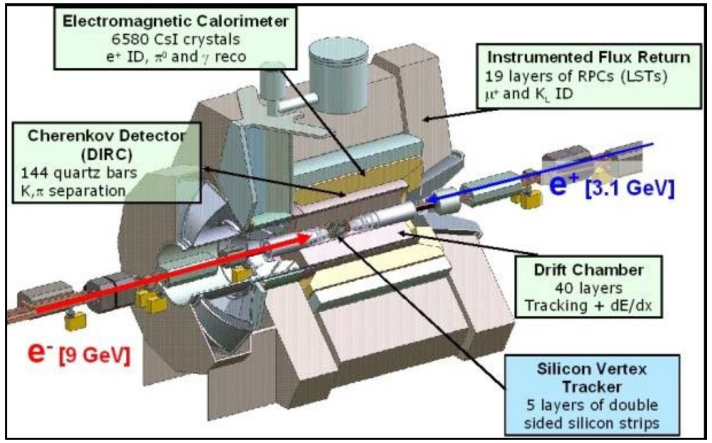
- Mass of B meson is around 5~6 GeV.
  - B pairs can be generated plentifully using ~ 11 GeV colliders
- Relatively lower energy makes it feasible to increase the intensity → intensity frontier
- First generation B factory:
  - ARGUS/DORIS II at DESY
  - CLEO/CESR at Cornell
- Next, asymmetric B factory:
  - BaBar/PEP-II at SLAC
  - Belle/KEKB at KEK
- 2nd generation asymm. Belle II/SuperKEKB at KEK
- Detectors at B-Factories have versatile particle identification+ reconstruction abilities
  - Dark sector searches are also effective and gaining interests.

Two Asymmetric B Factories from 1999

Belle / KEKB

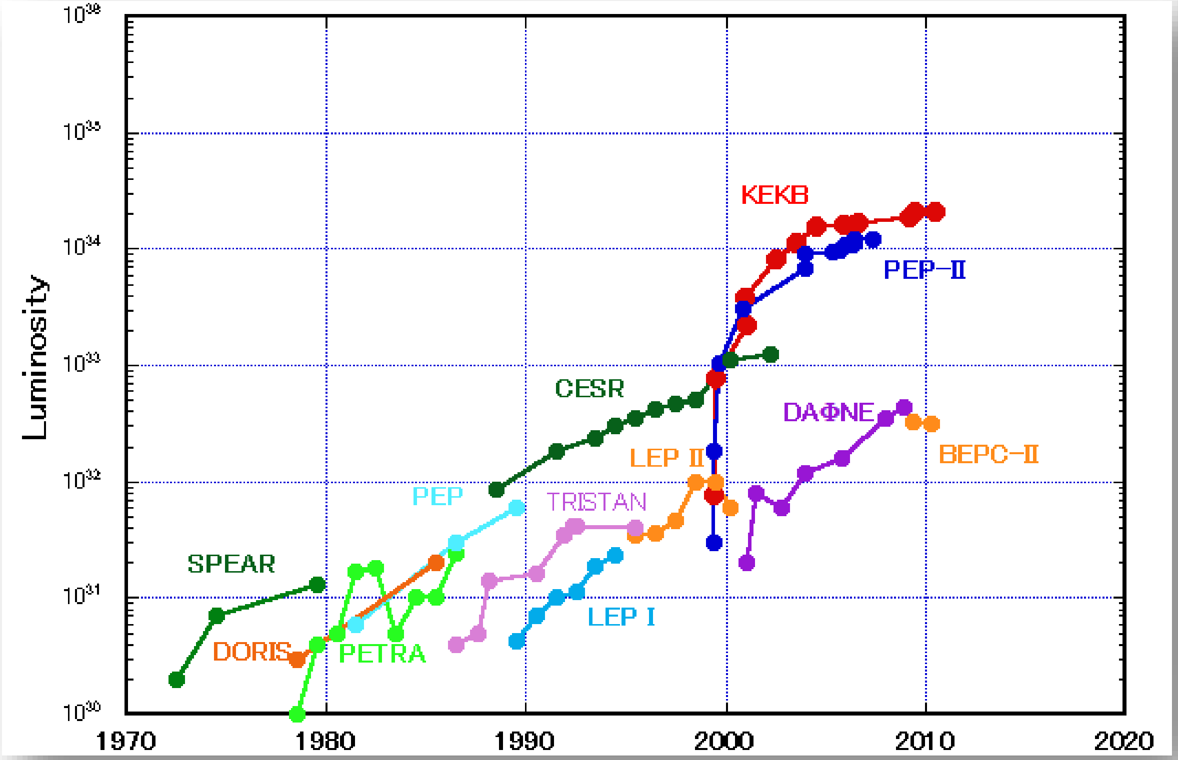


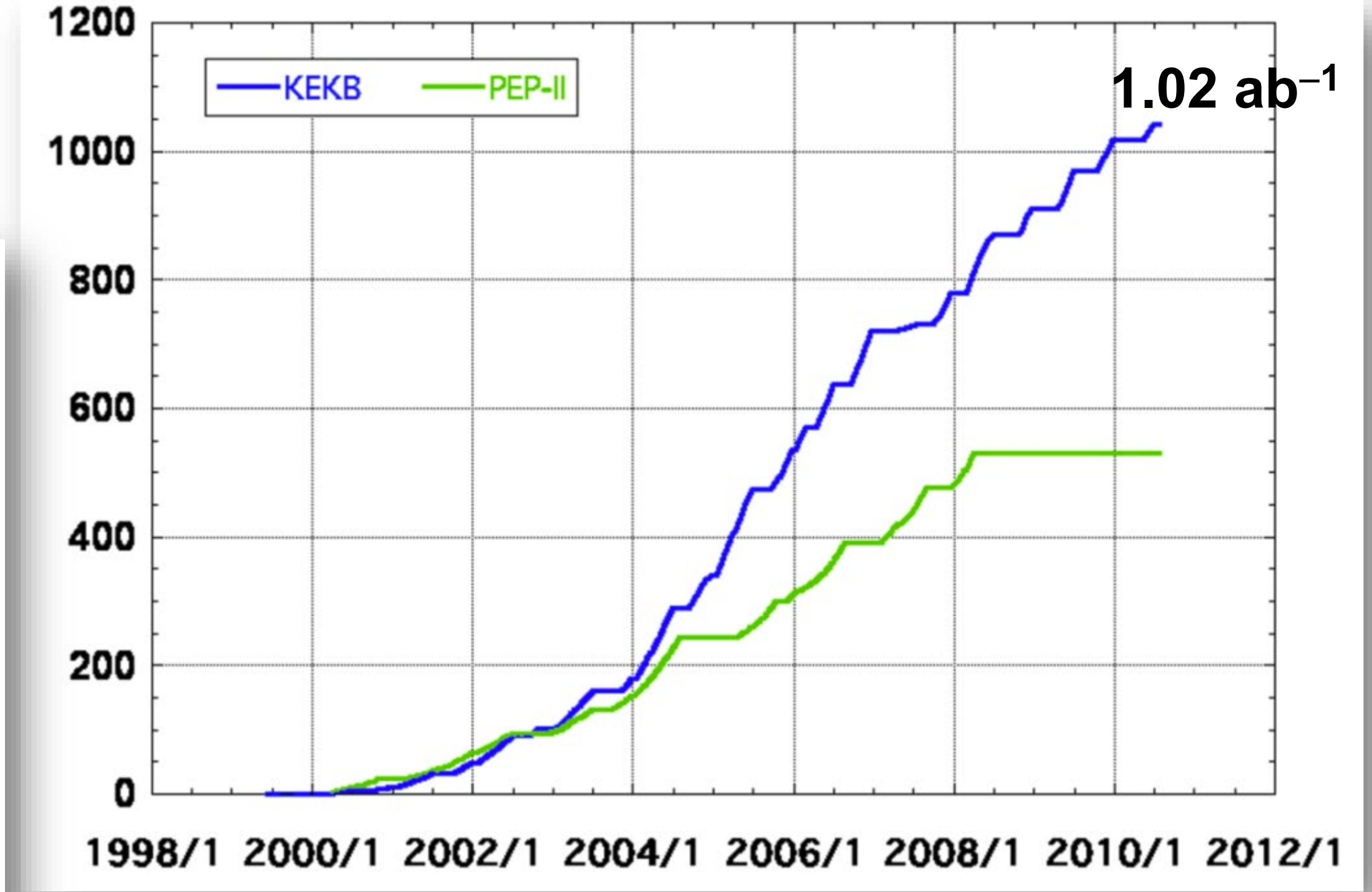
BABAR / PEP II



- CP Violation in the B section confirmed.
- Precision measurement of the CKM matrix. X(3872) and exotic particles.
- 2008 Nobel Prize, Kobayashi and Maskawa
- 2017 Hoam Prize (Korea), Sookyung Choi

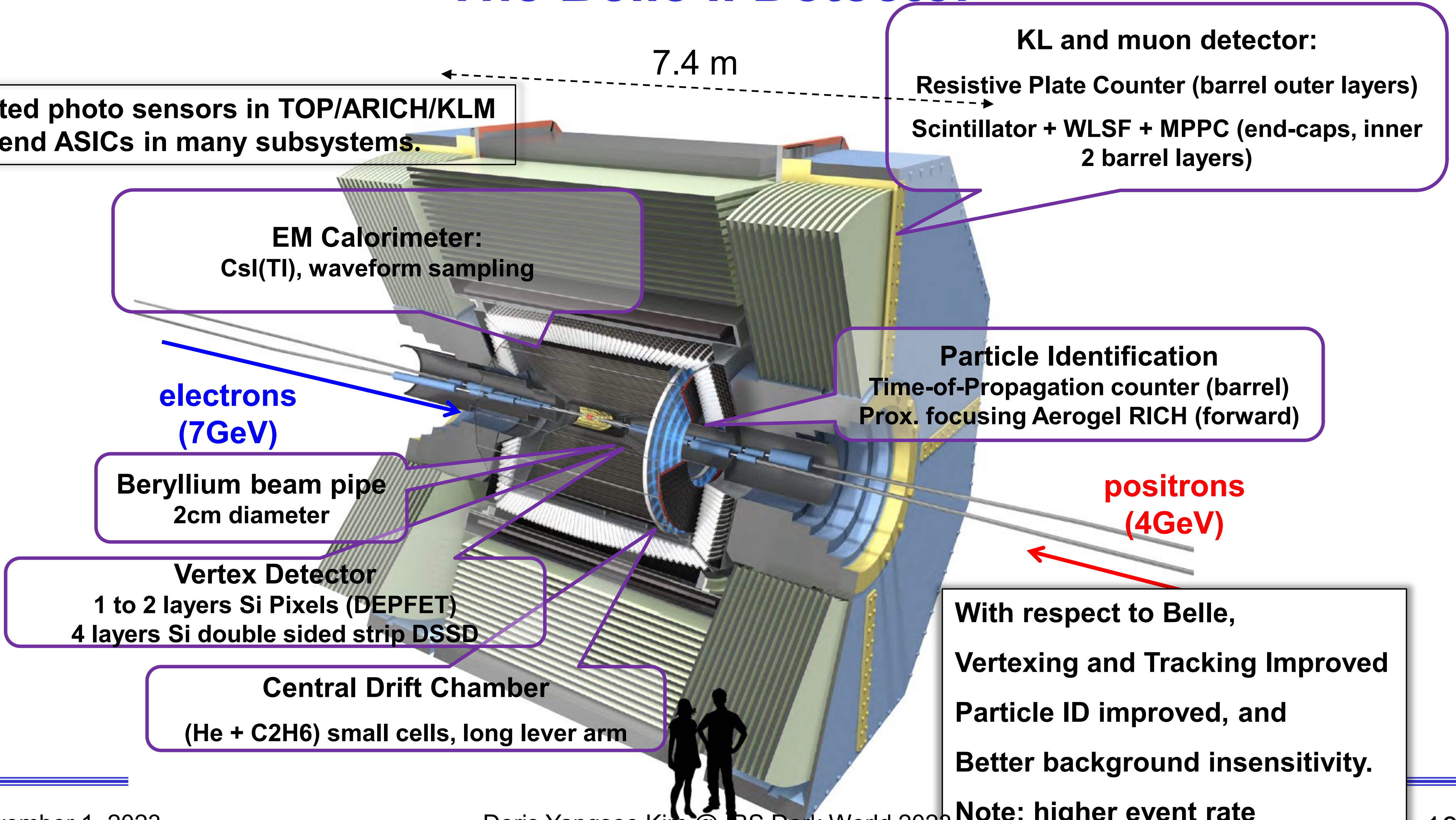
KEKB and PEP-II: Performance





The Belle II Detector

Pixelated photo sensors in TOP/ARICH/KLM
Front-end ASICs in many subsystems.



With respect to Belle,

Vertexing and Tracking Improved

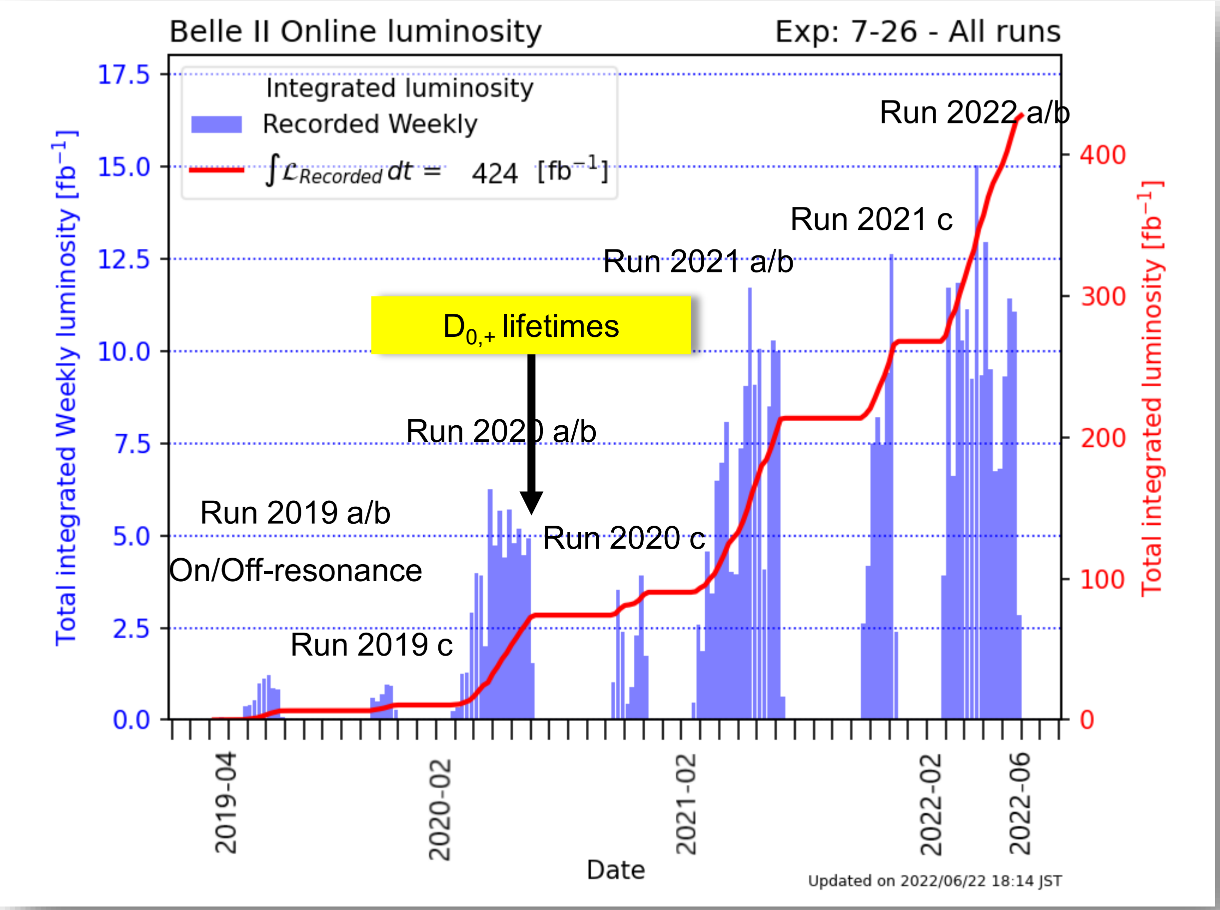
Particle ID improved, and

Better background insensitivity.

Note: higher event rate

SuperKEKB Luminosity: Current Status

- After the SupepKEKB commission phases, physics runs started spring 2019.
- Spring/summer 2022 run ended June.
  - Peak luminosity at $\boldsymbol{L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}}$, the current world record on June 22nd.
  - Current integrated luminosity at $\int L_{recorded} dt = 424\ fb^{-1}$. (~ Babar, ~ ½ Belle)
- Long shutdown 1 (LS1) started 2022 summer for upgrades (see later slides).
- Run 2 starts coming fall/winter.



https://confluence.desy.de/display/BI/Belle+II+Luminosity

Merits of Dark Search at e+ e- B-Factories

- The search region can reach lighter dark particles

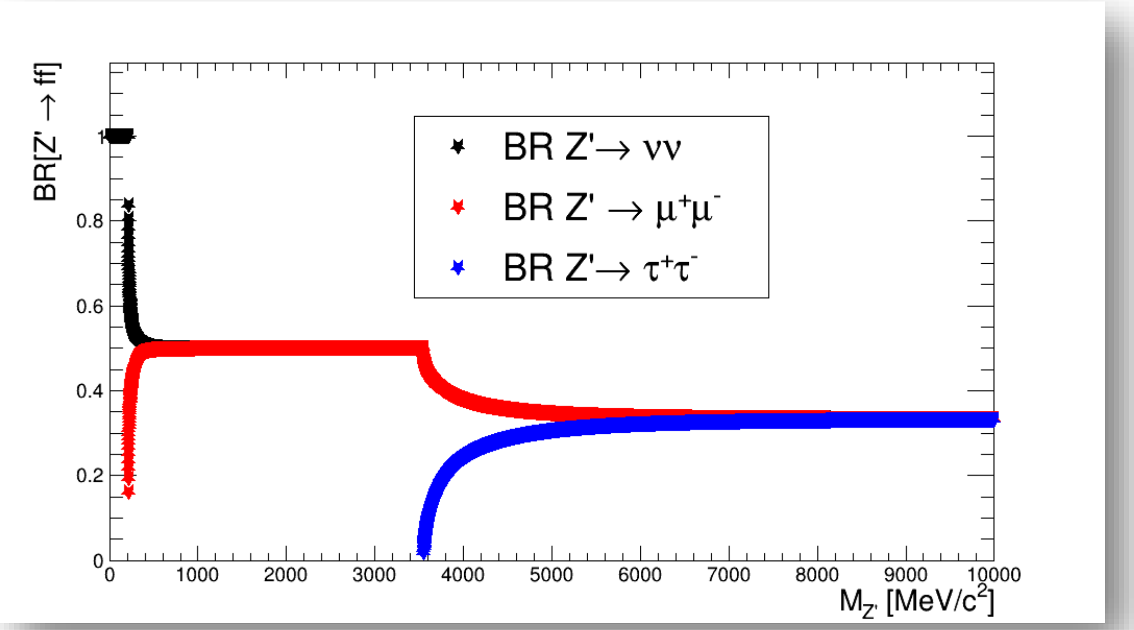
- Background is lower compared to hadron colliders.
- Closed detectors ~ 4π
  - Missing momentum and energy can be a signature of invisible particle(s)

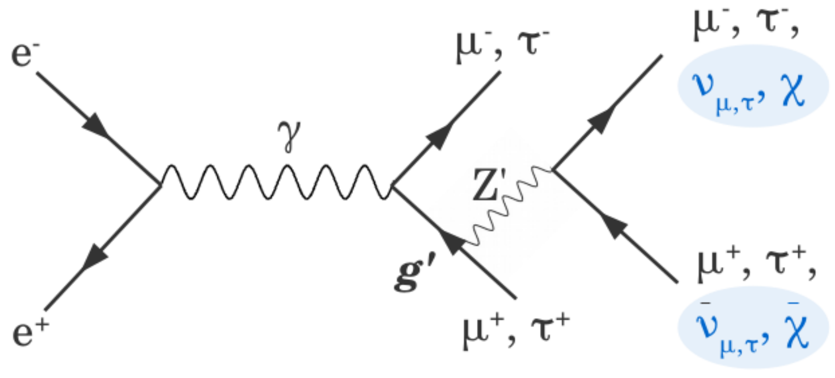
- High efficiency of neutral particle findings
- Easy to find signatures. Full event interpretation possible.
  - Low multiplicity signatures possible
  - Dark particle signatures in B and τ decays available
  - Clean environment can compensate for lower production cross-section.

Z' SEARCH

The $L_\mu - L_\tau$ Model

- A new gauge boson Z' assumed to couple only the 2nd and 3rd generation leptons.
  - May contribute to muon g-2
  - May explain dark matter abundance





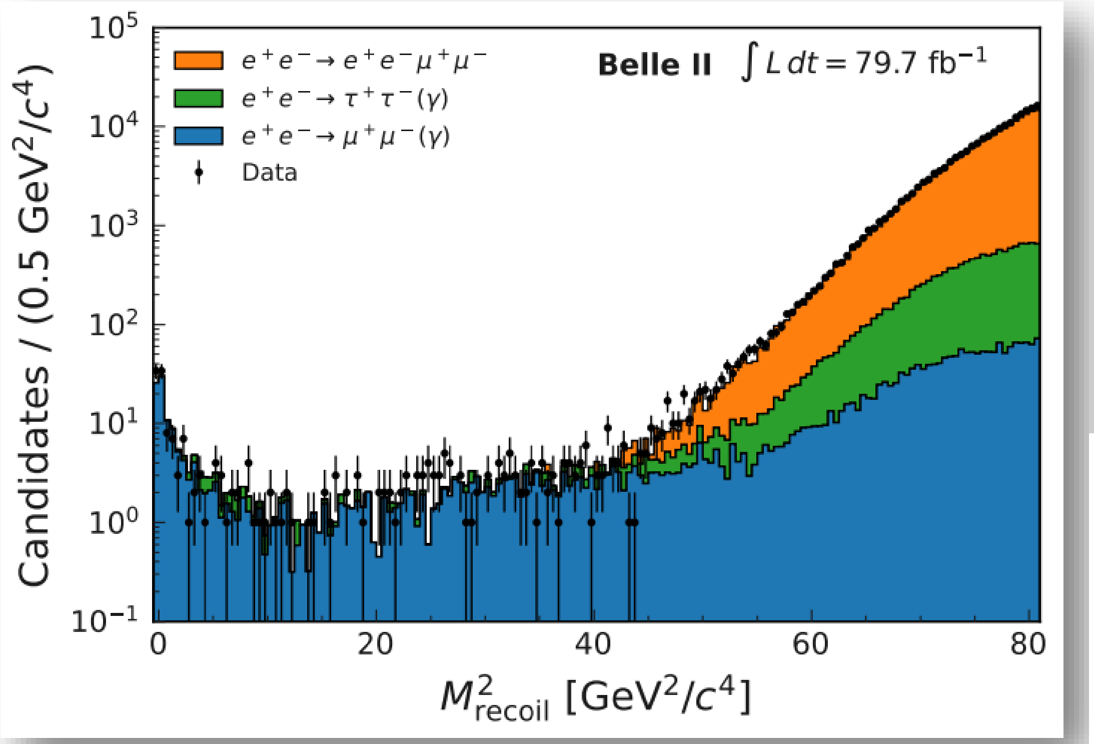
Search for signature of

$e^+e^- \to l\, l\, Z'$

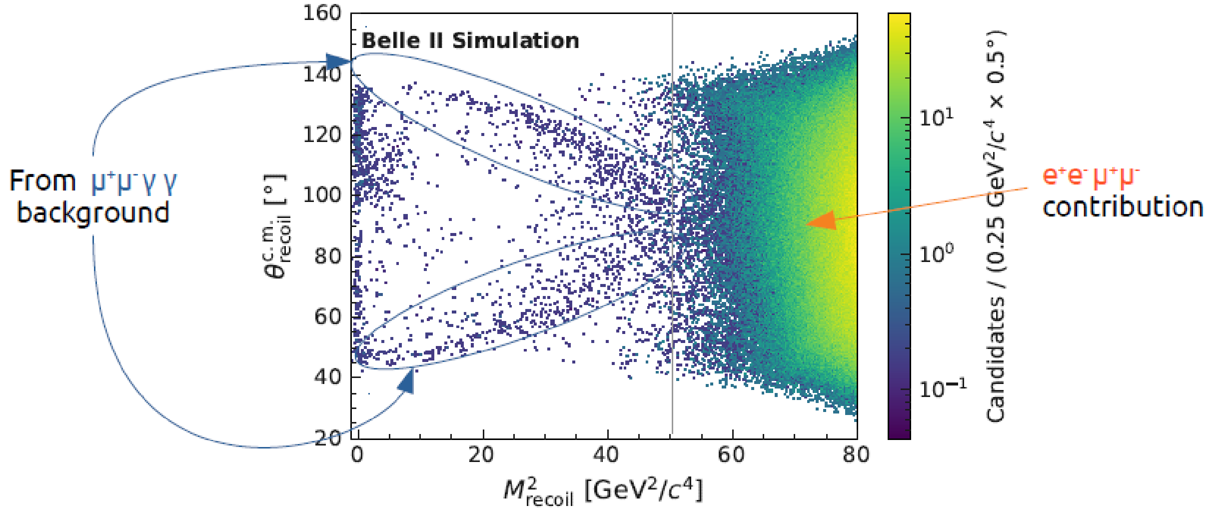
$Z' \to$ invisible, $\mu\mu, \tau\tau$

Invisible: neutrino, dark matter χ

Search for Invisible Z' : Belle II



- Belle II: $e^+e^- \to \mu^+\mu^- Z',\ \ Z' \to$ invisible
  - Invisible: neutrino (vanilla), dark matter χ
- Look for a narrow recoil mass peak against a $\mu^+\mu^-$ pair.
  - Requires no other particles in the event
- Dominant background is radiative QED processes.

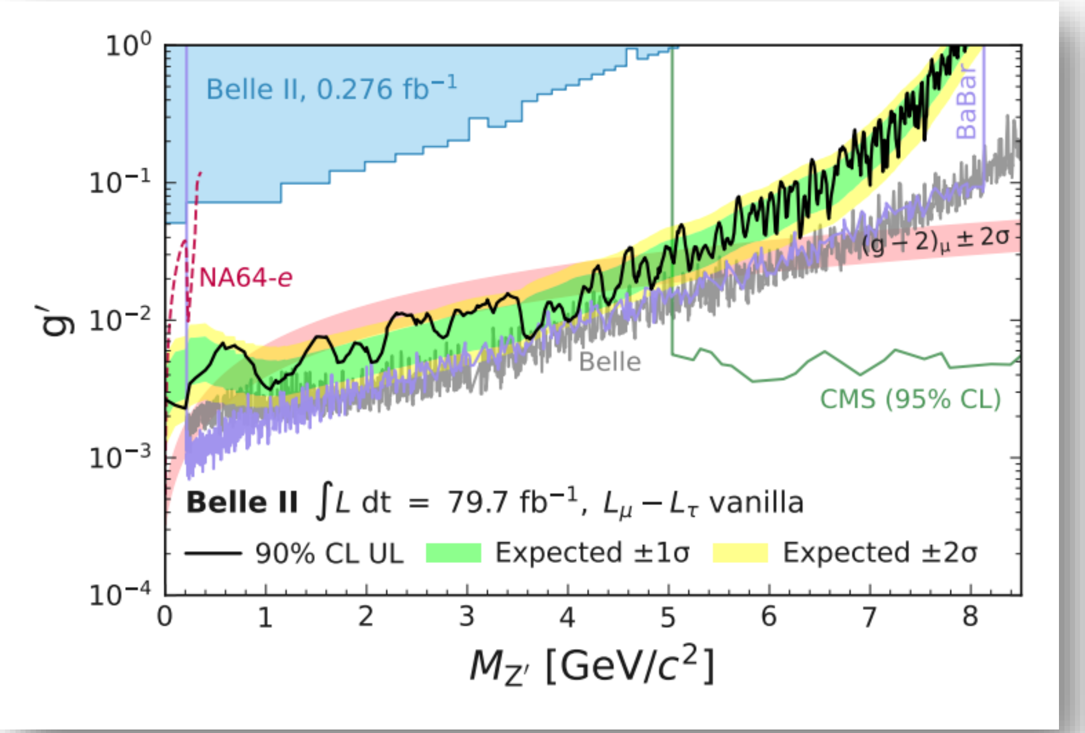


PRL 130, 231801

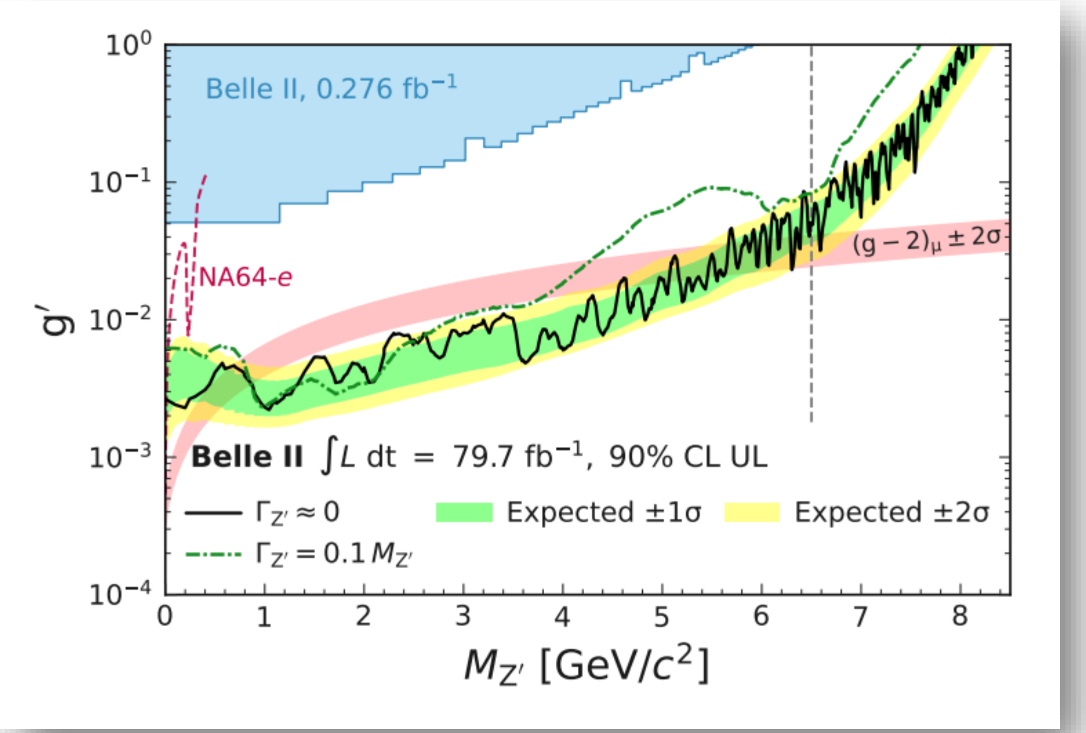
Search for Invisible Z'

- 79.7 fb^{-1}. No excess found in the recoil mass.
- 90% CL upper limits on the cross-section and on g'

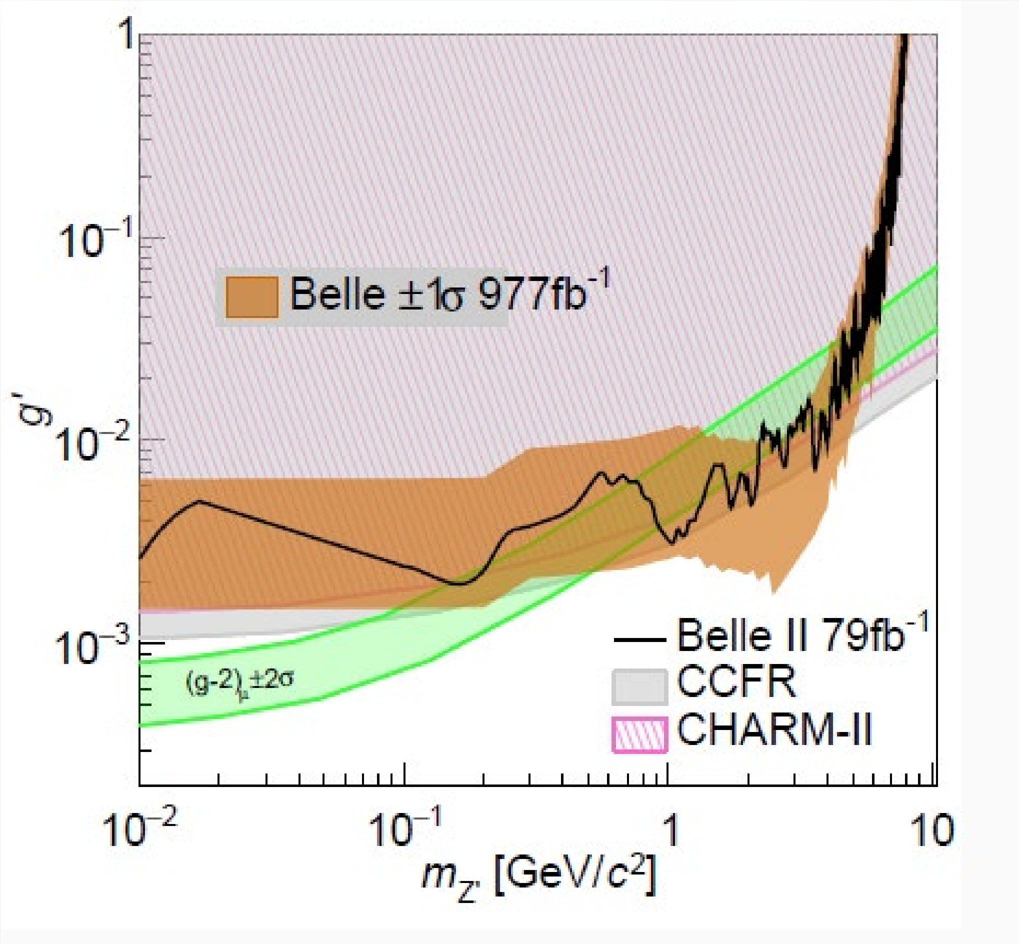
Vanilla



Fully invisible $L_\mu - L_\tau$

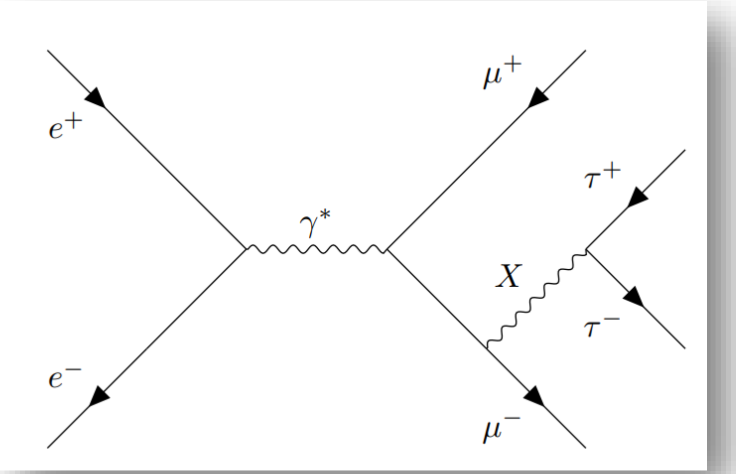


Search for Invisible Z': Belle

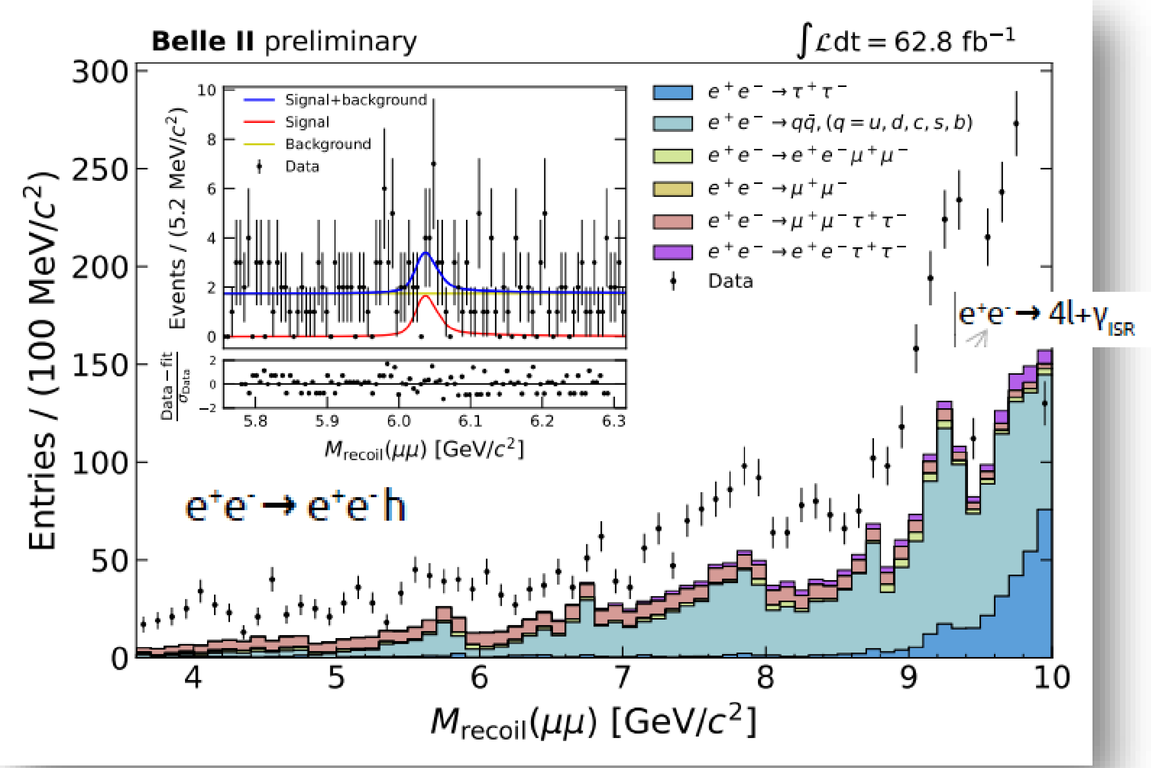


- Belle did the same search with the full sample.
- Comparison between Belle 977 fb^{-1} and Belle II 79.7 fb^{-1} shows the better sensitivity of Belle II

Search in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$



- Belle II: Search for di-tau resonance in 4 lepton events.
  - Tau decays to one charged track + neutrals
- Dominant background from 4 leptons suppressed by M (4 tracks) < 9.5 GeV/c^2
- Discrepancies between data and simulation are coming from non-simulated or unmodeled processes.



Search in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$

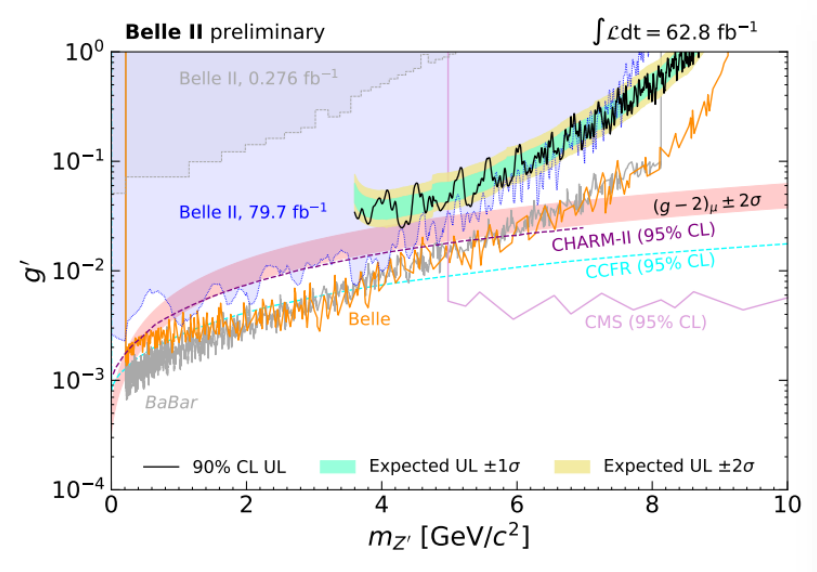
[2] W. Altmannshofer et. al. JHEP 12 (2016) 106
[3] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)
[4] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017)

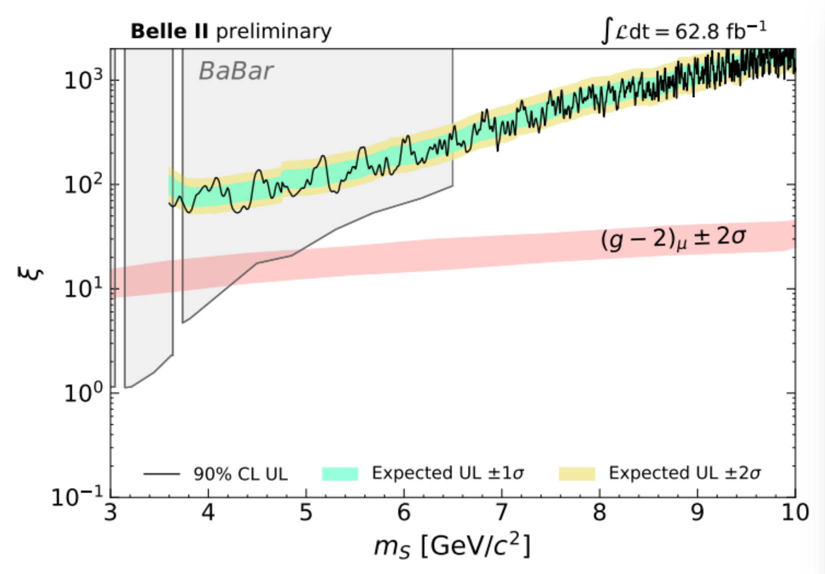
- 62.8 fb^{-1}. No excess found in the recoil mass.
- 90% CL upper limits on the cross-section

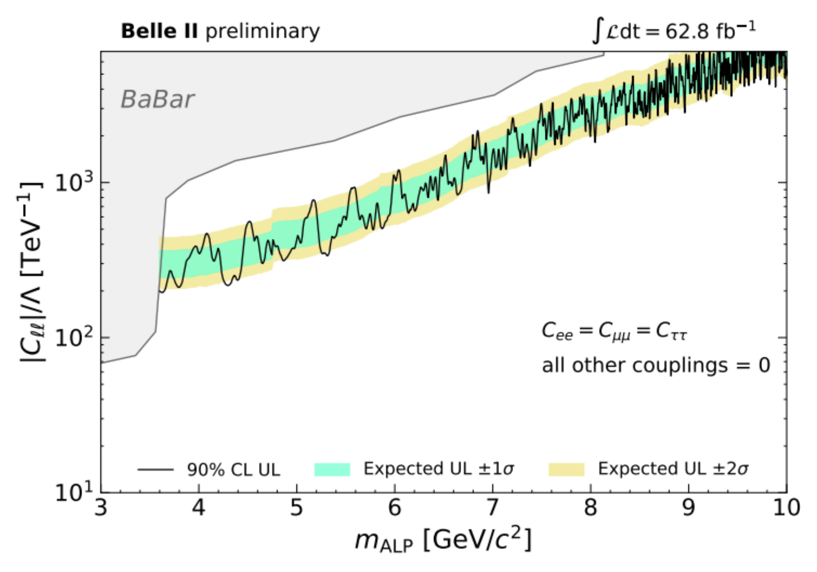
$$\sigma(e^+e^- \to (X \to \tau^+\tau^-)\,\mu^+\mu^-) = \sigma(e^+e^- \to X\,\mu^+\mu^-)B(X \to \tau^+\tau^-),\ \text{with } X = S, ALP, Z'$$

- Exclusion limits on the couplings for three dark particle models obtained.

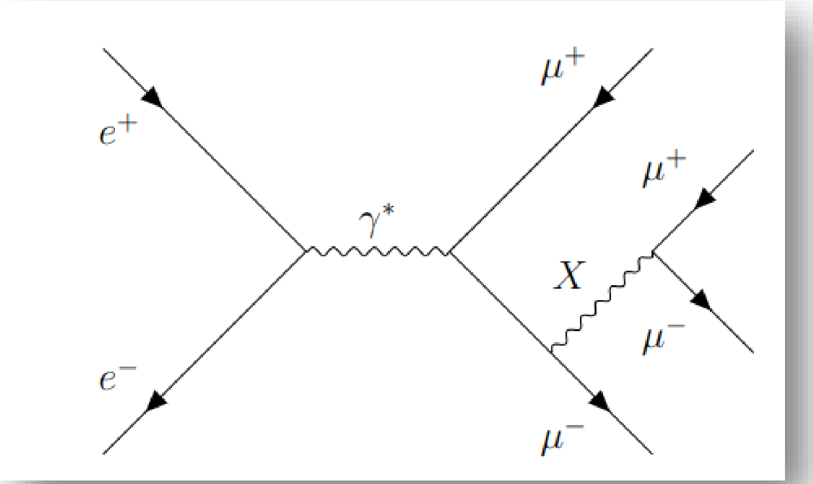
Z' | **Leptophilic scalar (S)** | **ALP**

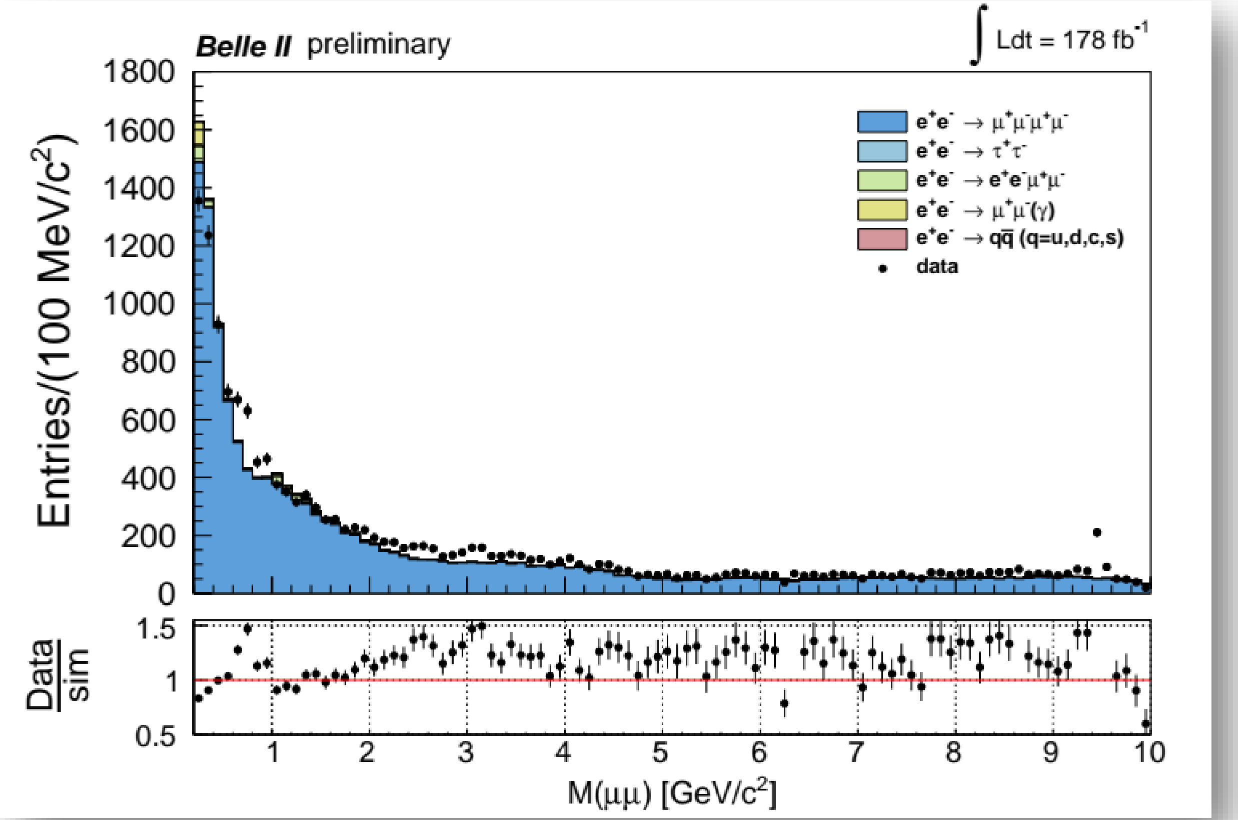






Search in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$

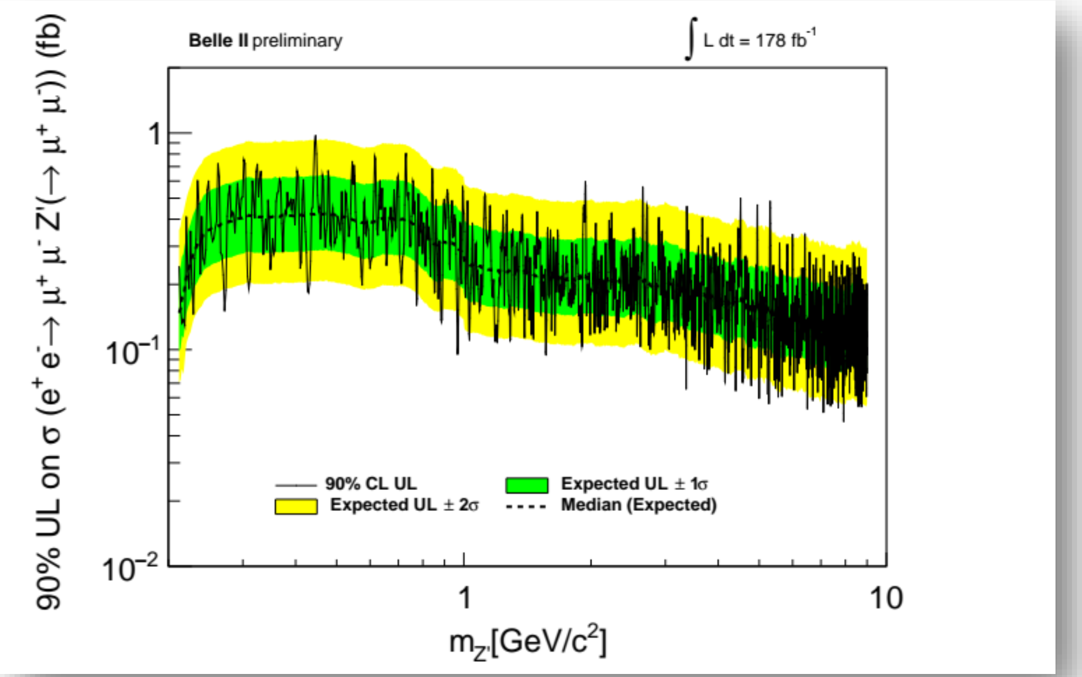


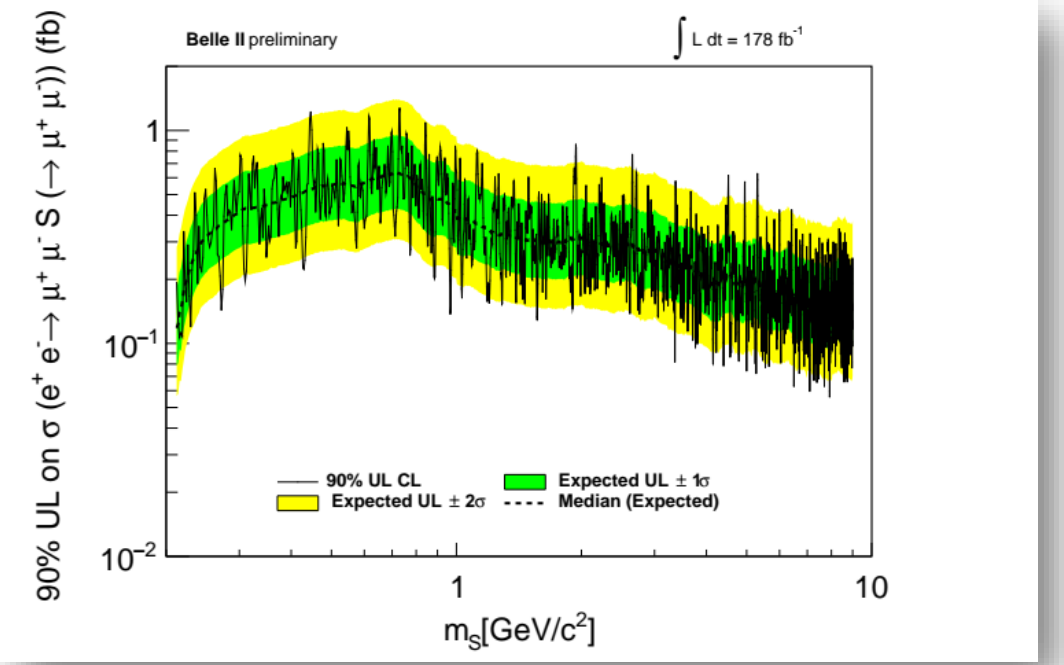


- Belle II: Search for di-muon resonance in 4 lepton events.
- Mass peak search in the candidate muon pair.
  - At least three muons identified.
  - Total charge zero, M(4 tracks) ~ beam energy. No extra energy.
- Multi-layer Perceptron (MLP) based background suppression

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

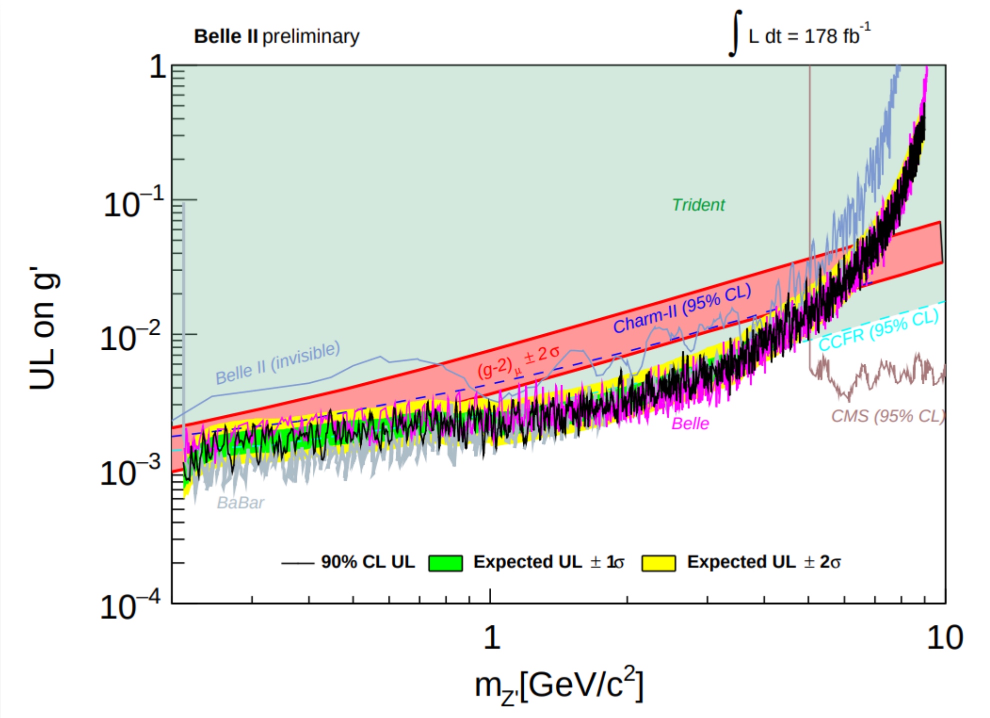
- 178 fb^{-1}. No excess found.
- 90% CL upper limits on the process cross-section **$\sigma(e^+e^- \to X\,\mu^+\mu^-)$** x **$B(X \to \mu^+\mu^-)$**, with X = Z', S

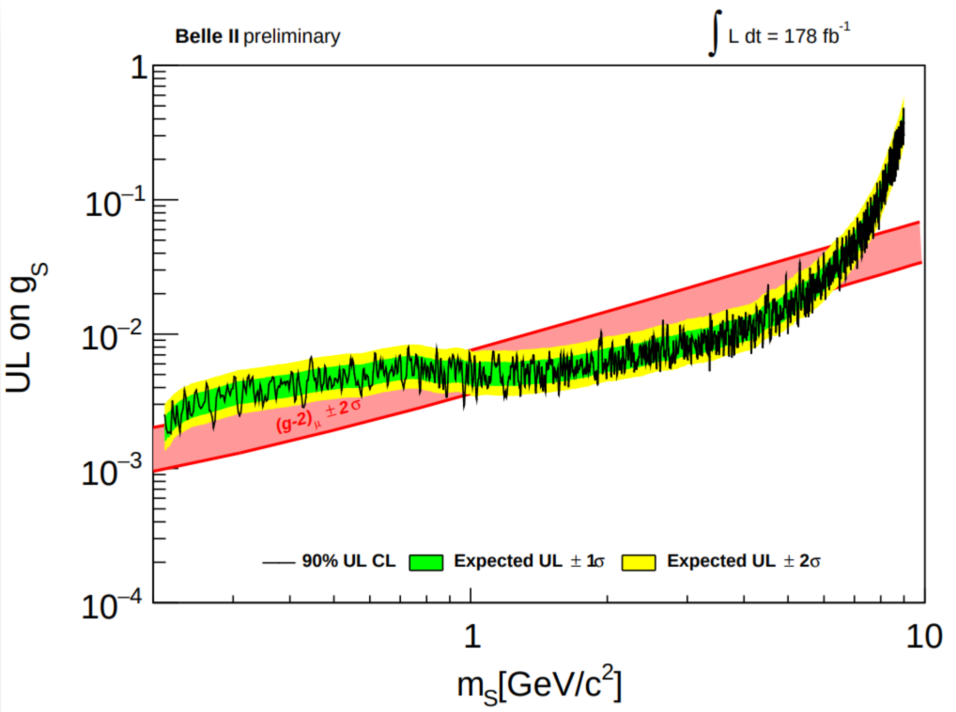




Search in $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$

- 178 fb^{-1}. No excess found.
- Cross-section limits translated into upper limits on the coupling constant
  - g' for the $L_\mu\ L_\tau$ model
  - g_s for the muonphilic dark scalar S

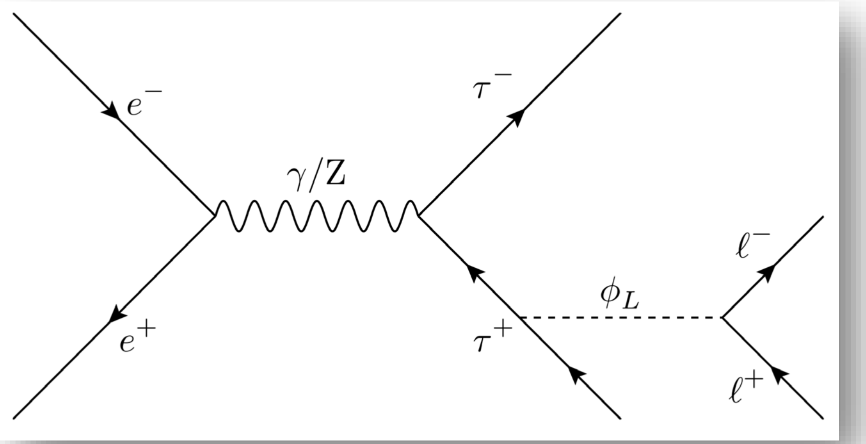




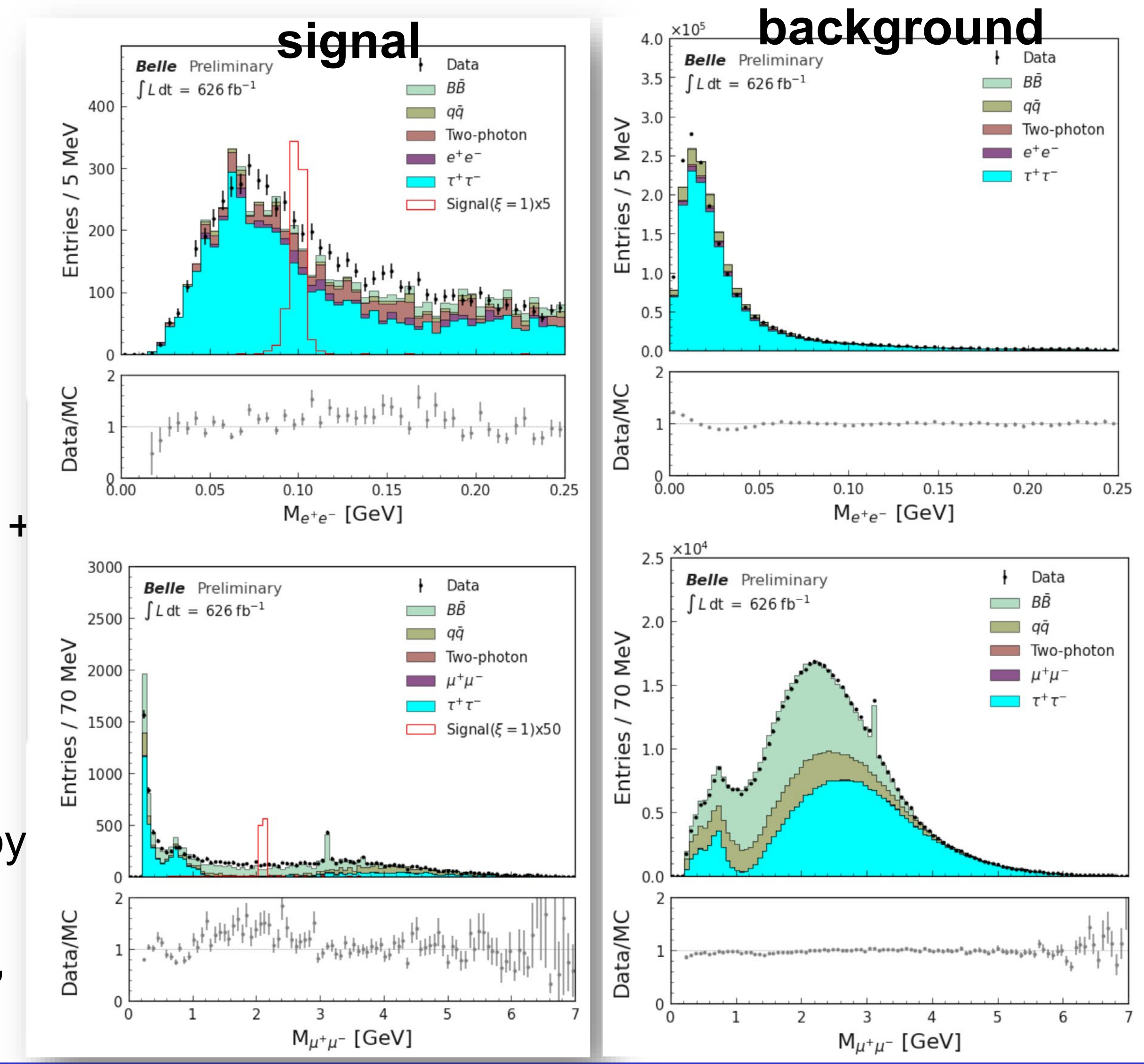
PRL 131, 121801 (2023)

DARK HIGGS SEARCH

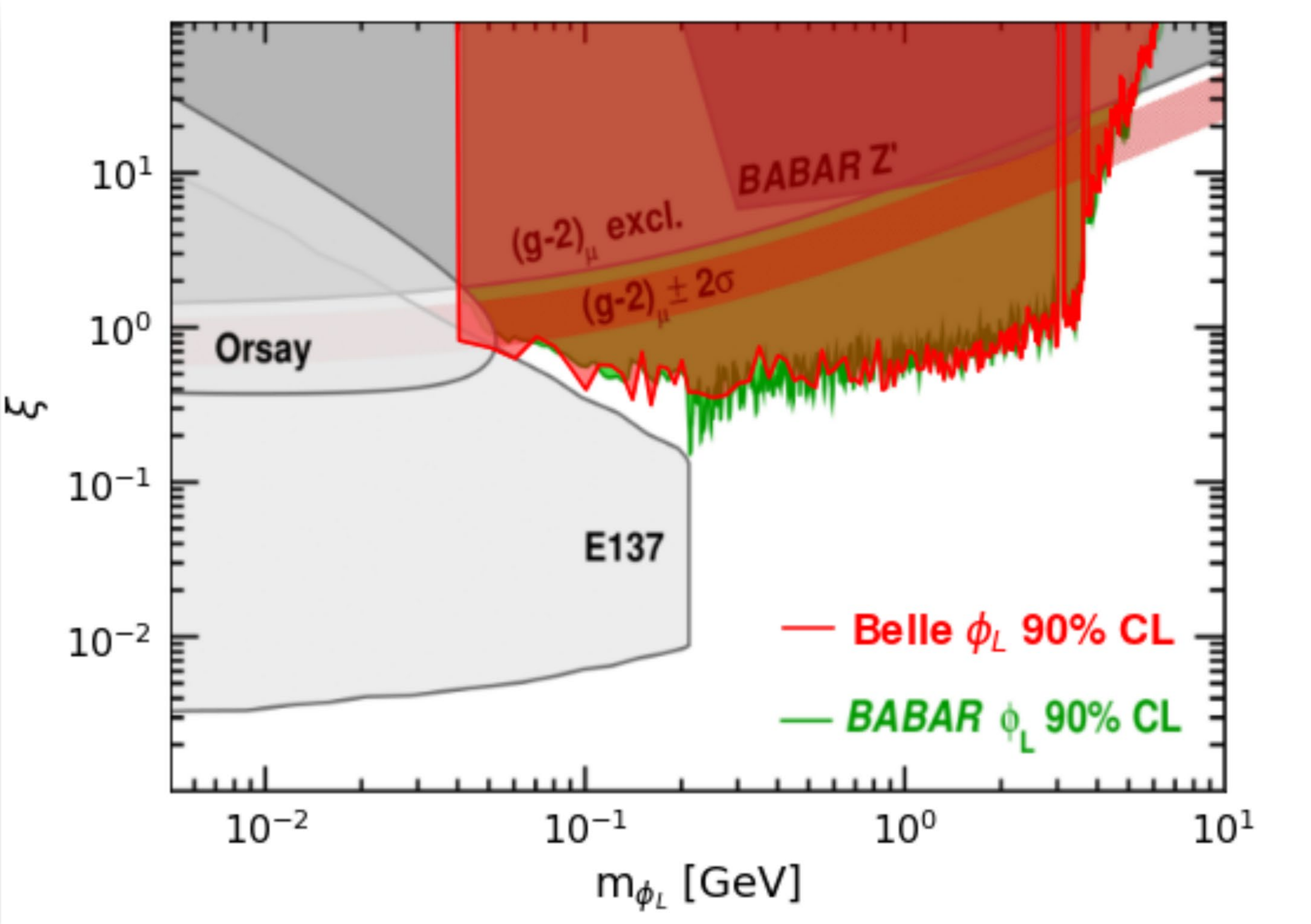
Search in $e^+e^- \to \tau^+\tau^- l^+l^-$



- Belle: Search for leptophilic dark Higgs (ϕ_L) in 4 tau + 2 lepton events.
  - This mode can affect muon (g-2) results.
- Lepton = muon or electron, ξ: coupling strength
- Major background is $e^+e^- \to \tau^+\tau^-$.
- Radiative Bhabha (photon to two muons) removed by cuts on missing energy and its angle.
- Boosted Decision Tree (GrandientBoostingCassifier, scikit) is used to suppress backgrounds.

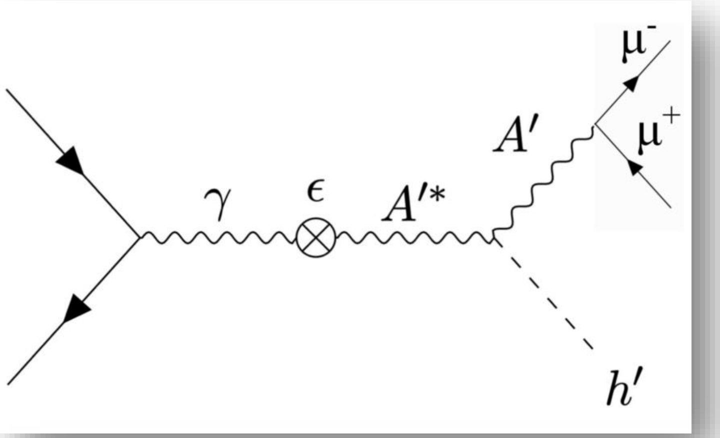


Search in $e^+e^- \to \tau^+\tau^- l^+ l^-$

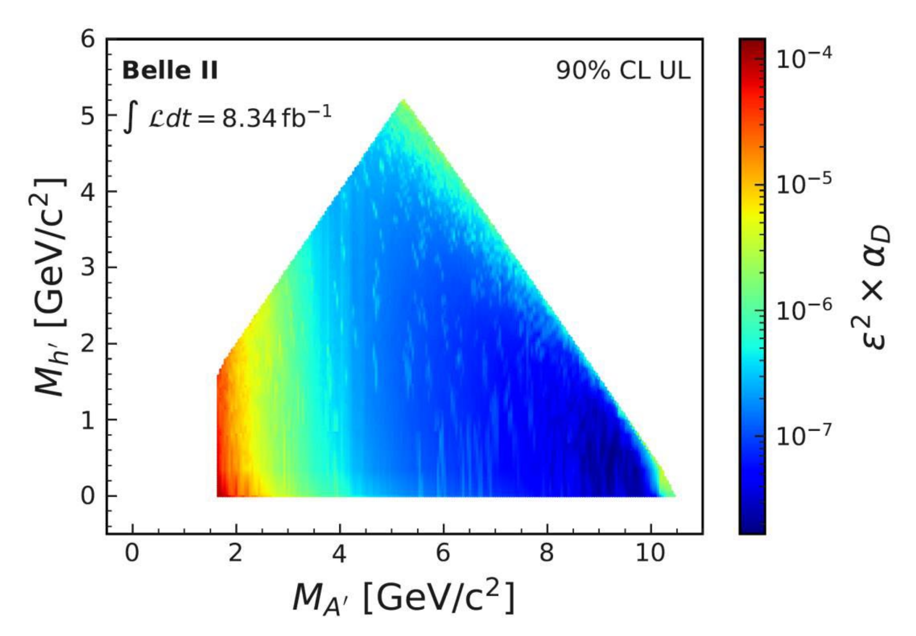


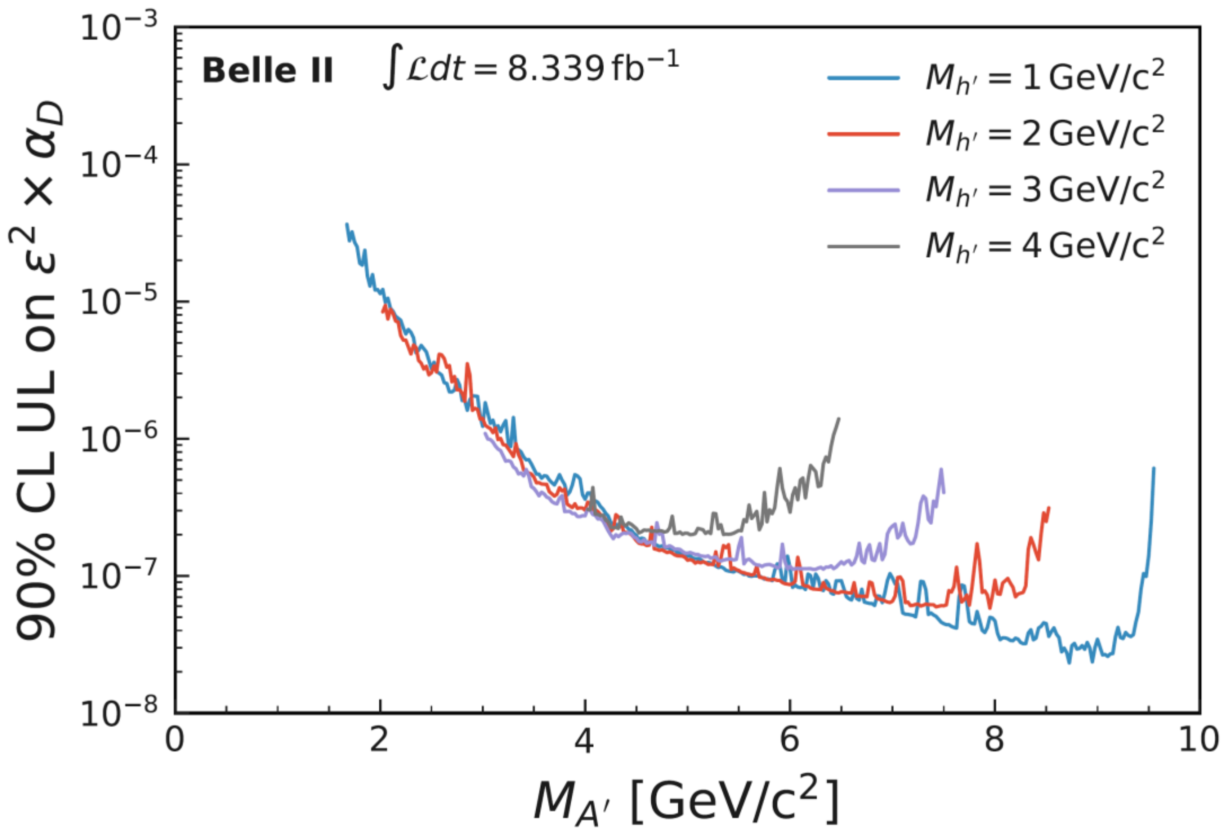
- 626 fb^{-1} Belle sample
- 90% CL limit on ξ and mass of the dark scalar shown.
- More searches on the Belle full sample continues for a while.

Search in $e^+e^- \to \mu^+\mu^-$ + invisible h'



- Belle II: Search for a peak in the dimuon mass + 2nd peak in the recoil mass in the system.

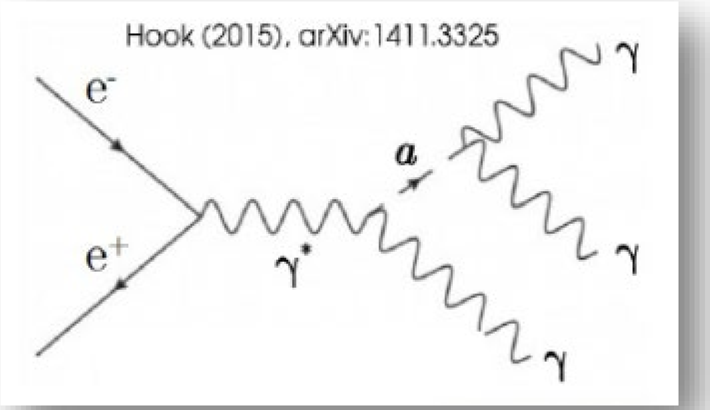




ALP SEARCH

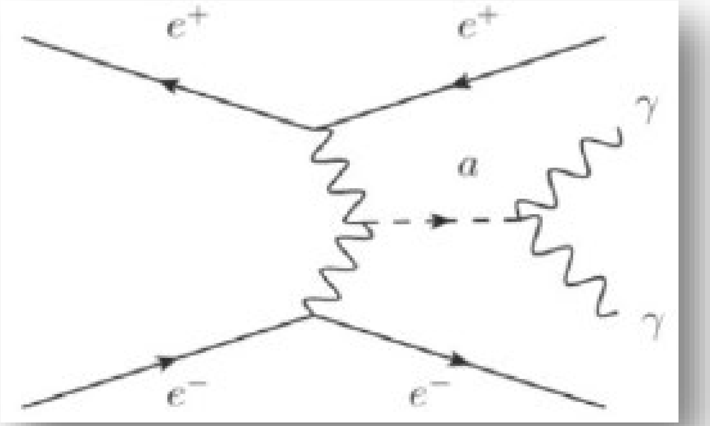
Axion Like Particle (ALP)

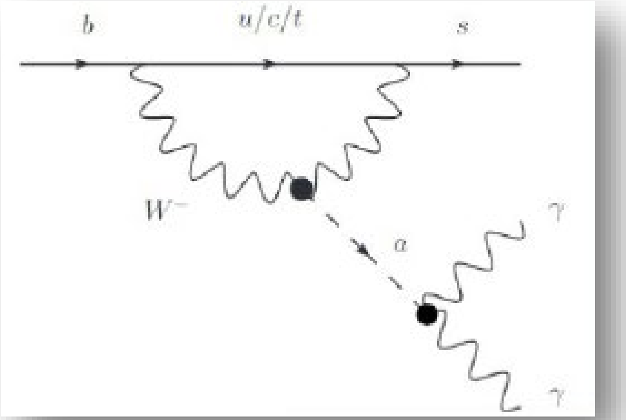
ALP strahlung

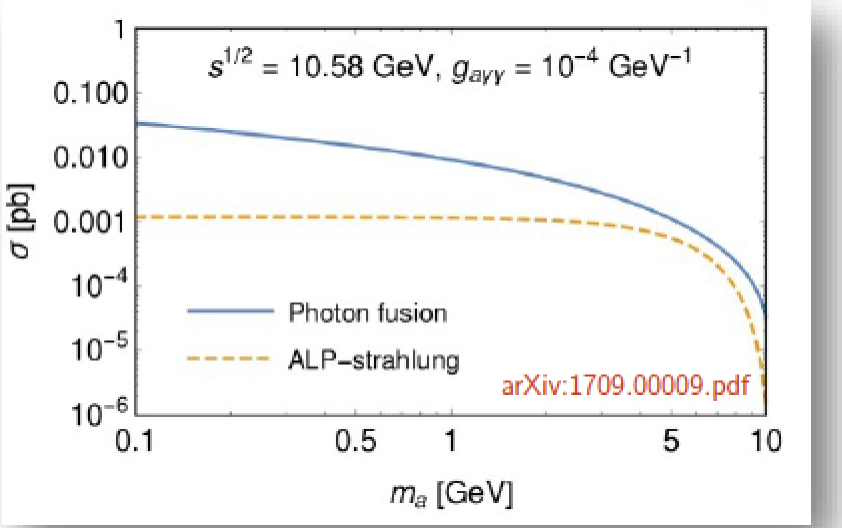


- ALP: pseudo-scalars couple to bosons.
  - Difference to QCD axions: no relation between the coupling and the mass
- ALP-strahlung: to study photon coupling $g_{a\gamma\gamma}$
- B → K a decays: to study g_{aW} couplings

Photon fusion

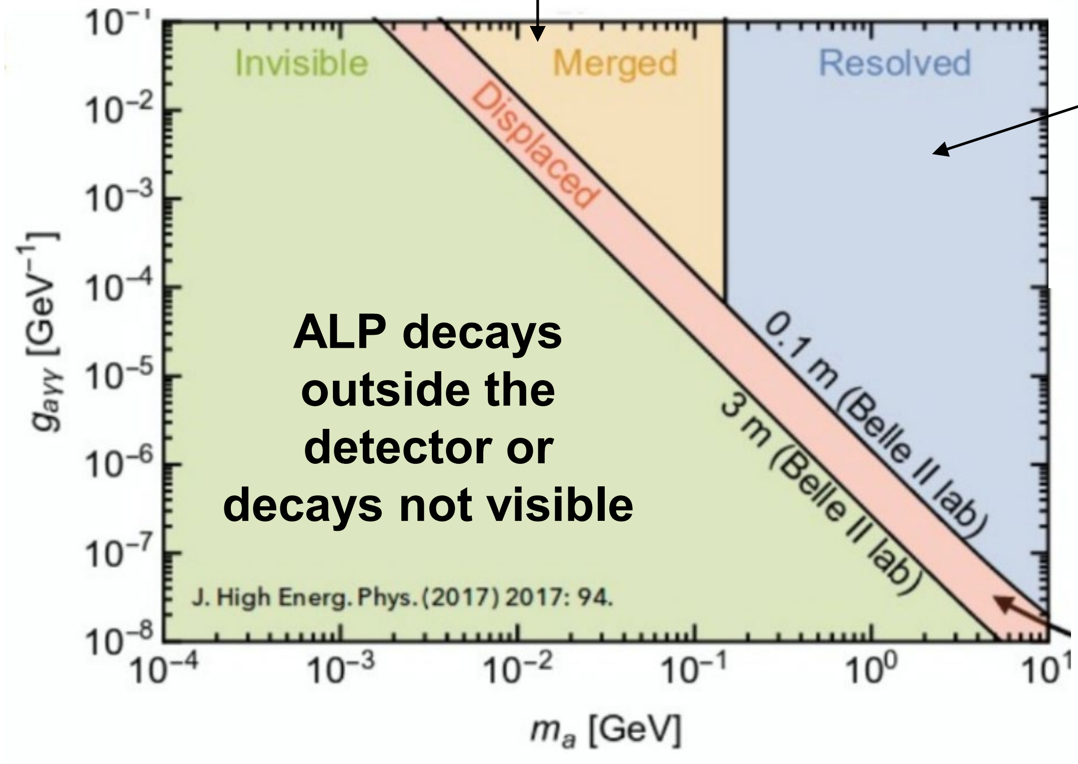


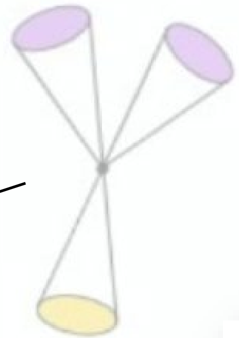




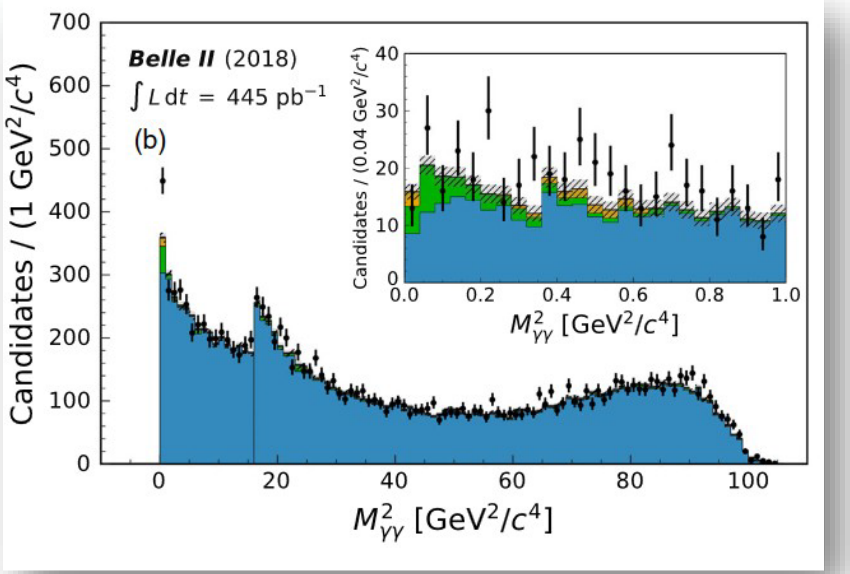
Search for $e^+e^- \rightarrow \gamma a, a \rightarrow \gamma\gamma$

Two photos
merged or overlap





- Belle II search: Required 3 clear, resolved photons as the signature.
- Total mass should be the center of mass energy.
- Used calorimeter trigger.
  - ECL efficiency almost 100%

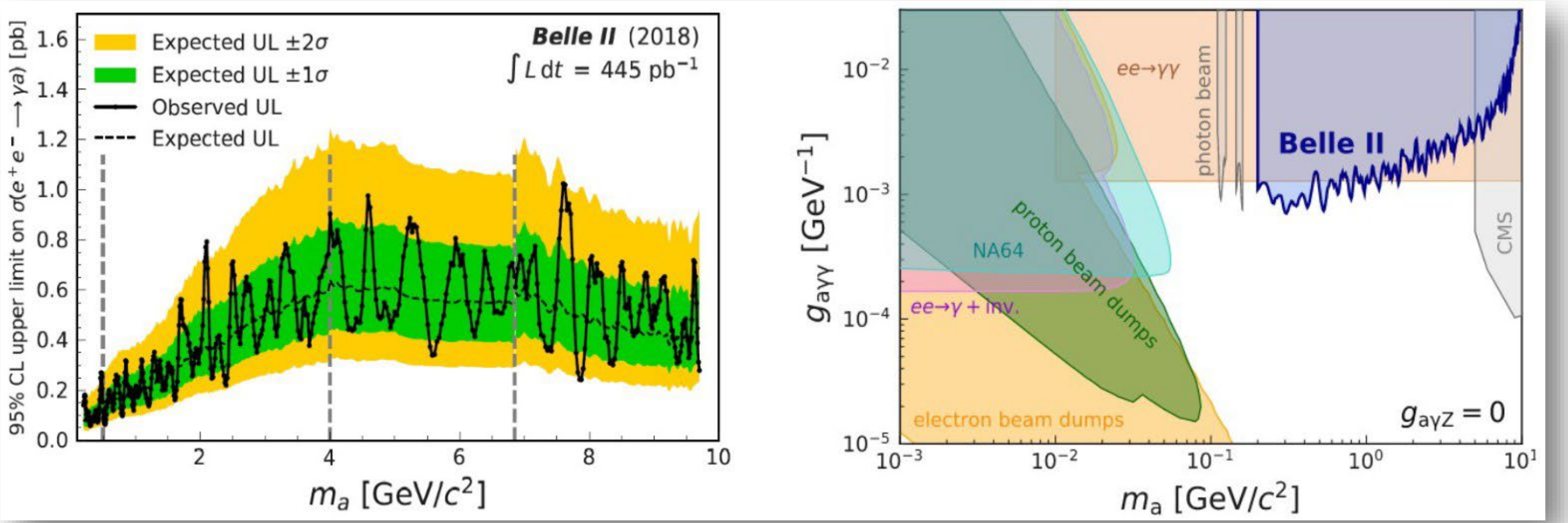


Diphoton invariant mass for ma in [0.2, 6.85] GeV/C^2

Search for $e^+e^- \to \gamma a, a \to \gamma\gamma$

$$\sigma_a = \frac{g_{a\gamma\gamma}^2 \alpha_{\text{QED}}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$ → World's best limit around 500 MeV

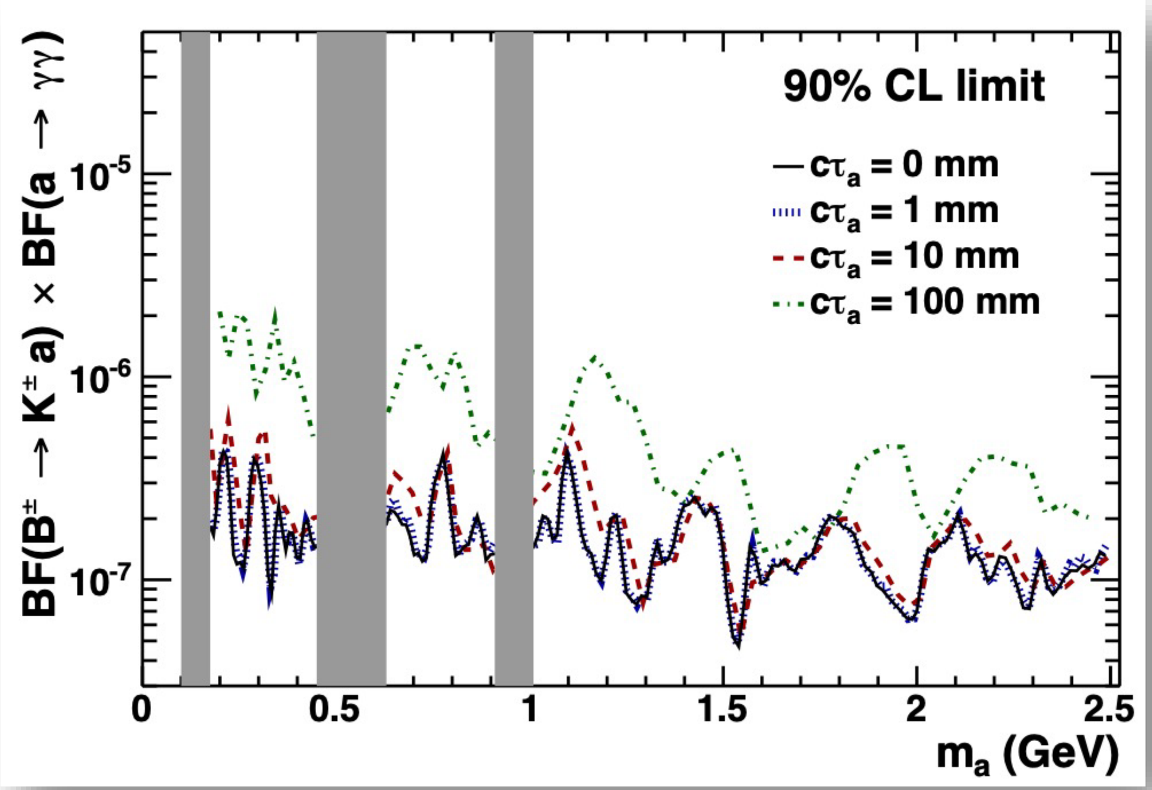
- Belle II 445 pb^{-1} sample.
- 95% CL upper limits on the signal cross section and coupling $g_{a\gamma\gamma}$

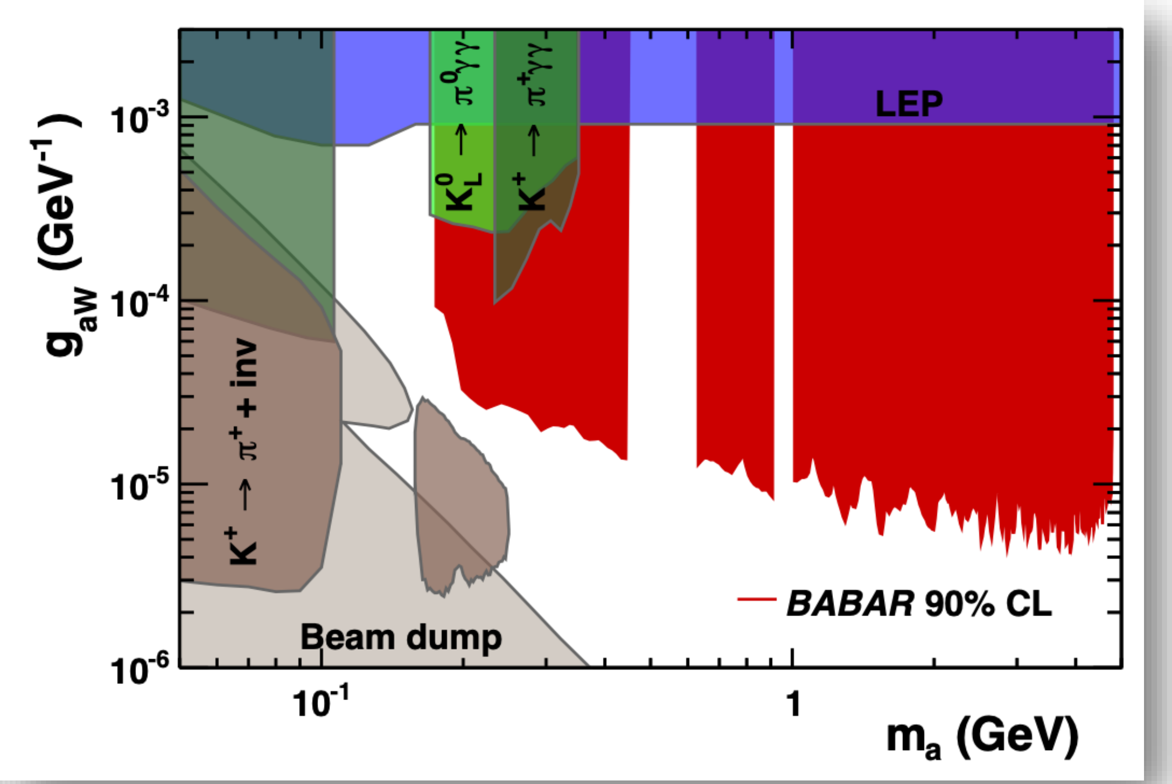


PRL 125, 161806 (2020)

Search for $B \to Ka, a \to \gamma\gamma$

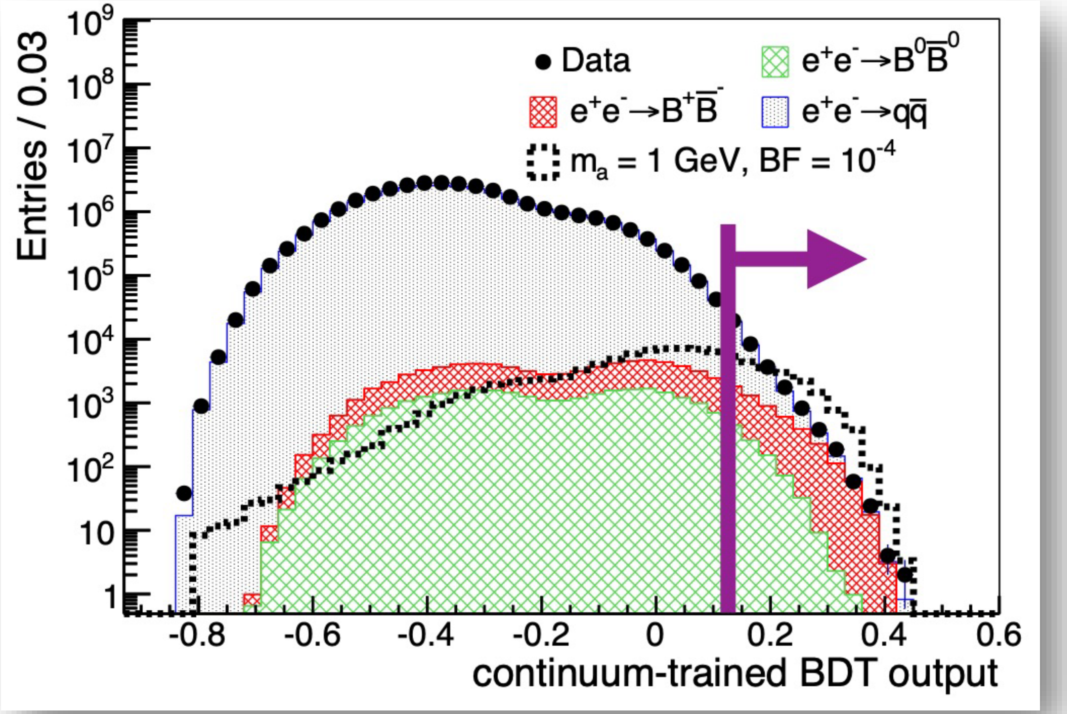
- BaBar results shown here: 90% CL limits on signal branching fraction and coupling.
- Cf) Belle II study on dark sector in B decays, arXiv:2306.02830, submitted to PRL.

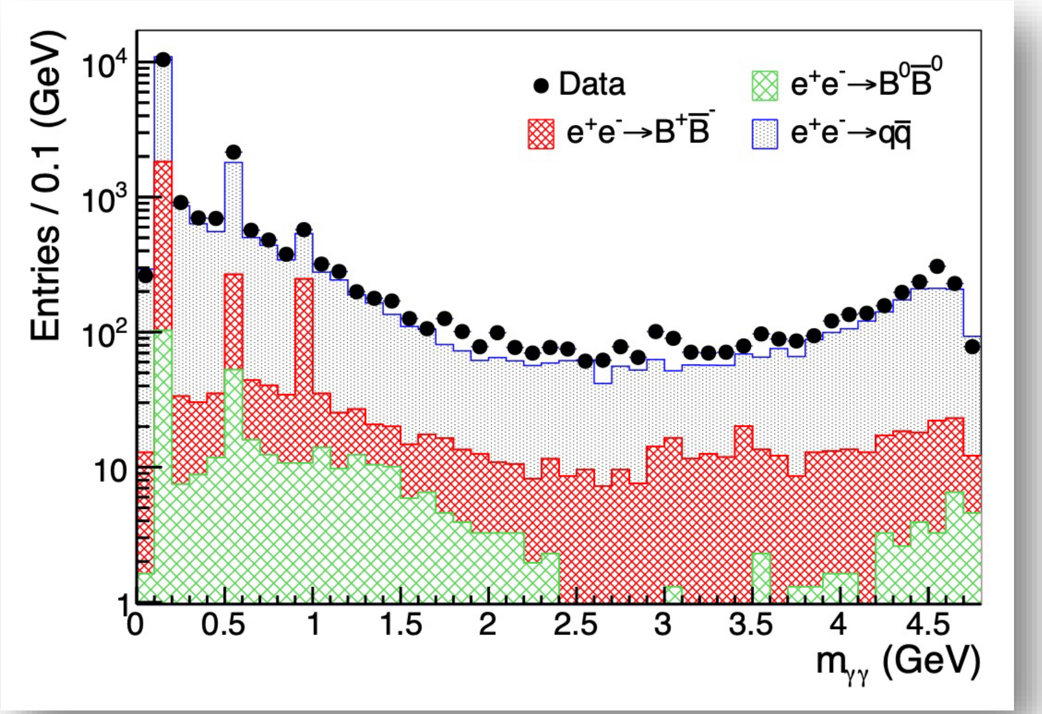




Search for $\mathrm{B} \to K a, a \to \gamma\gamma$

- BaBar: look for two photon mass peak originated from B decays.
- Train separated boosted decision trees to separate backgrounds.

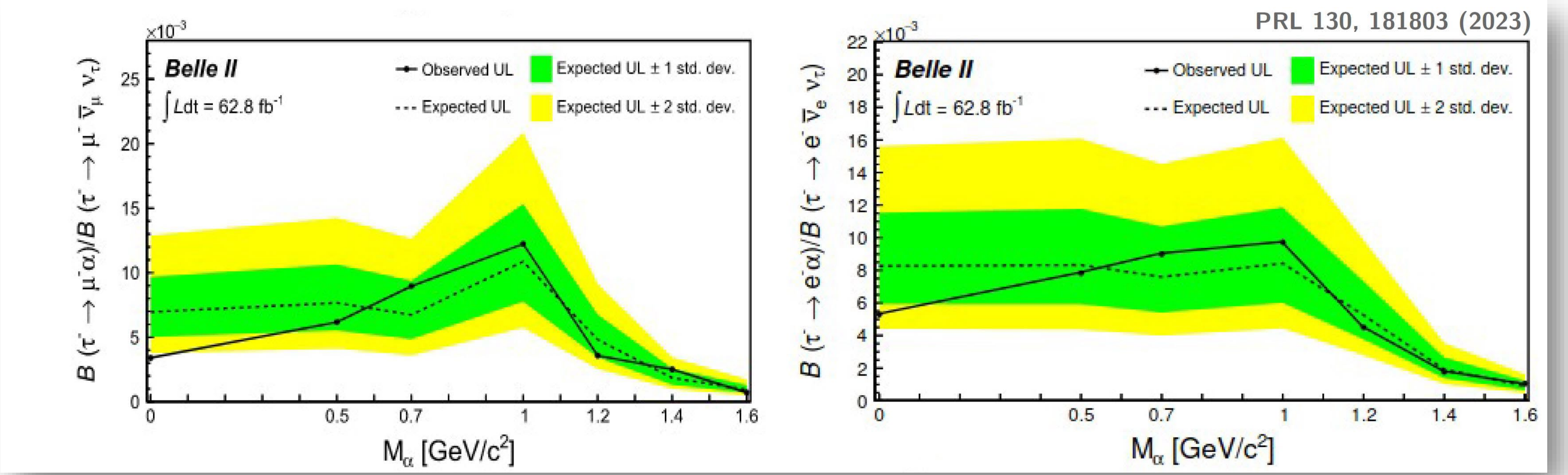




PRL 128, 131802 (2022), arXiv:2111.01800

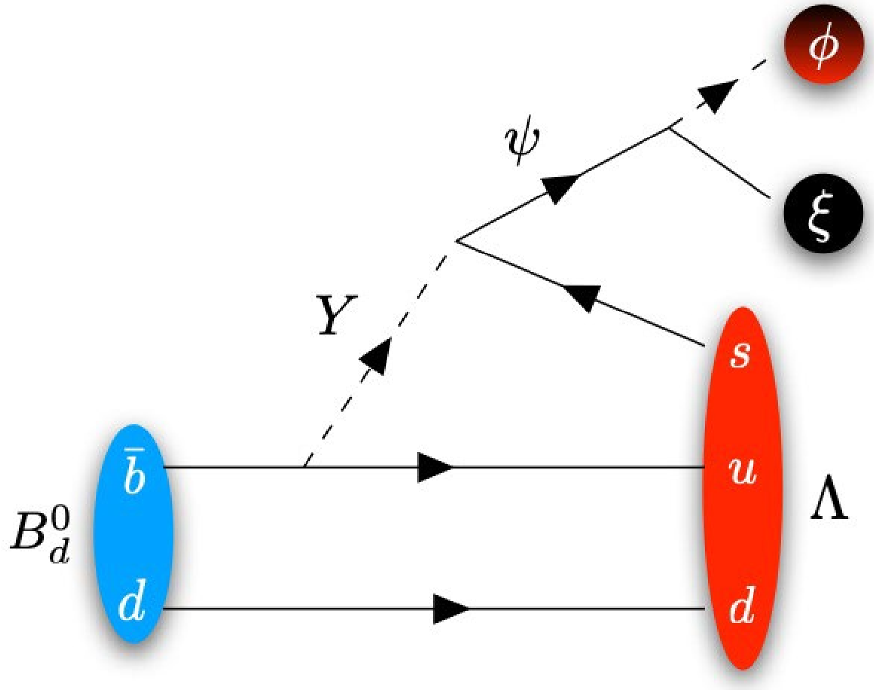
Search for $\tau \to l\, \alpha$, α invisible

- Belle II: look for an invisible boson α in tau decays. α can be an ALP candidate.
- One tau (tag) decays into 3 charged pions. The other tau (signal) decays into one lepton and a missing particle signature.
- No significant excess in 62.8 fb^{-1}.
- 95% CL upper limits on BF ratios of $\mathbf{BF}(\tau_{sig} \to \ell\alpha) / \mathbf{BF}(\tau_{SM} \to \ell\nu\bar{\nu})$
  - 2 ~ 14 tighter limit than the previous ARGUS result



B MESOGENESIS

B-Mesogenesis



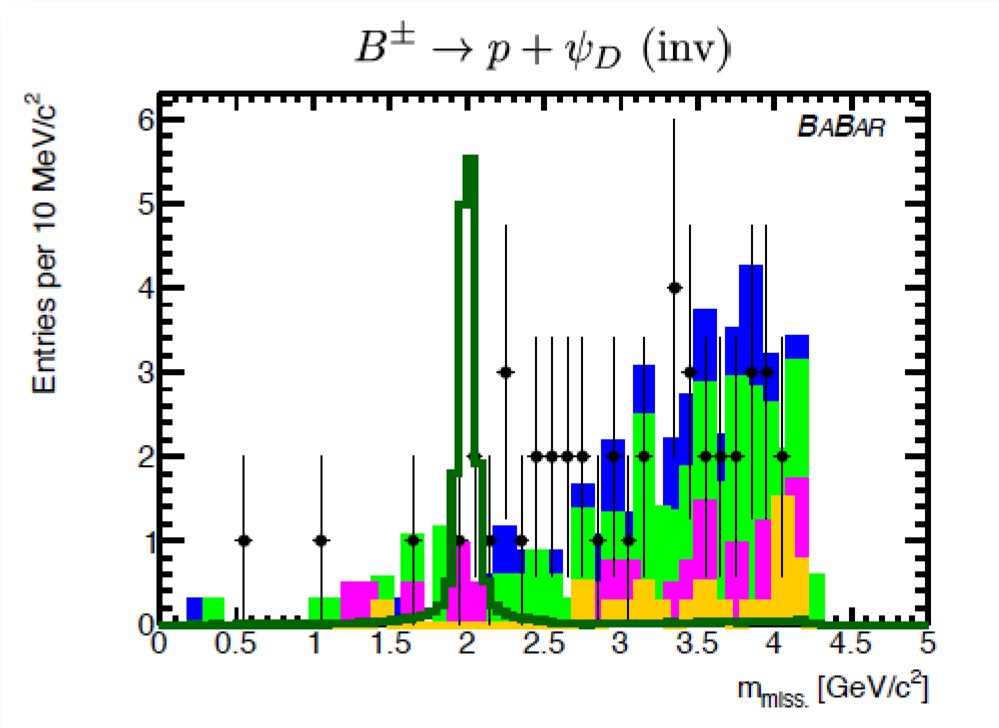
Brian Shuve @ BNL Forum

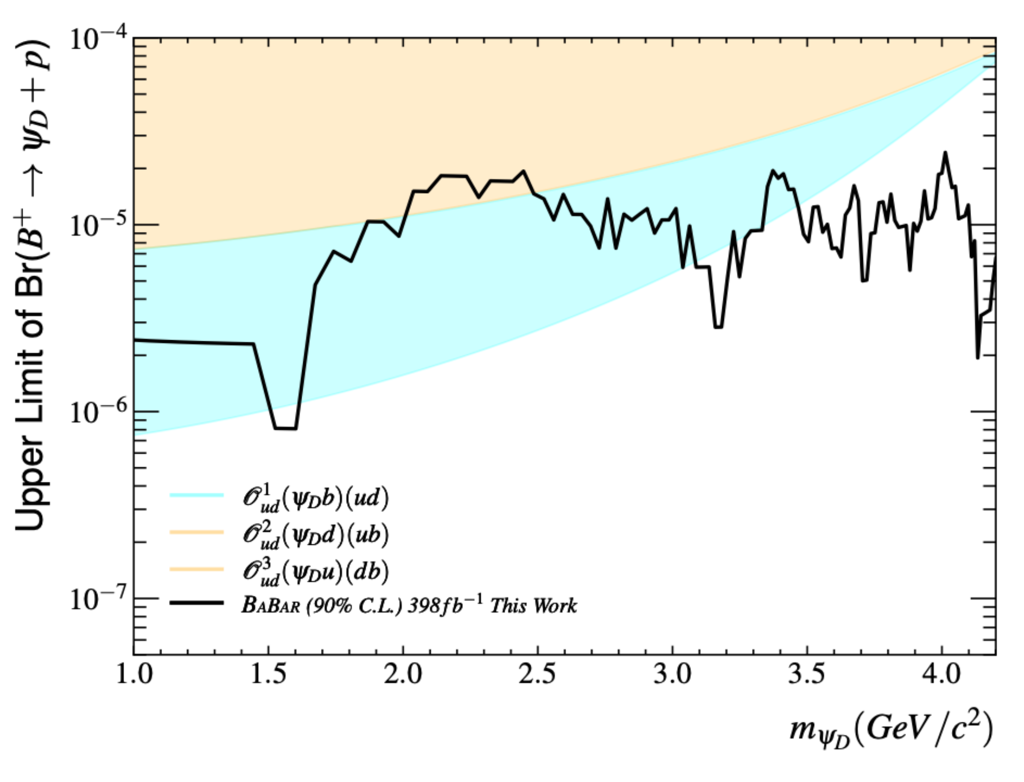
- PRD 99, 035031 (2019) & PRD 105, 055024 (2022)
- Dark baryons produced in CPV decays of B mesons.
  - Can be a factor of baryogenesis and dark matter.
  - Example) $B^0 \to \Lambda + \psi_D$, $B^\pm \to p + \psi_D$ where ψ_D are invisible.
- Tagging B: Fully reconstructed B hadron decays
- Signal: single SM baryon + missing mass
- BDT used to separate signal from backgrounds.

BABAR, PRD 107, 092001 (2023), arXiv:2306.08490 (submitted to PRL)

B-Mesogenesis

- BaBar Results: No significant signal
- 90% CL limits on signal branching fraction
- Shaded regions: branching fraction prediction by B-mesogenesis





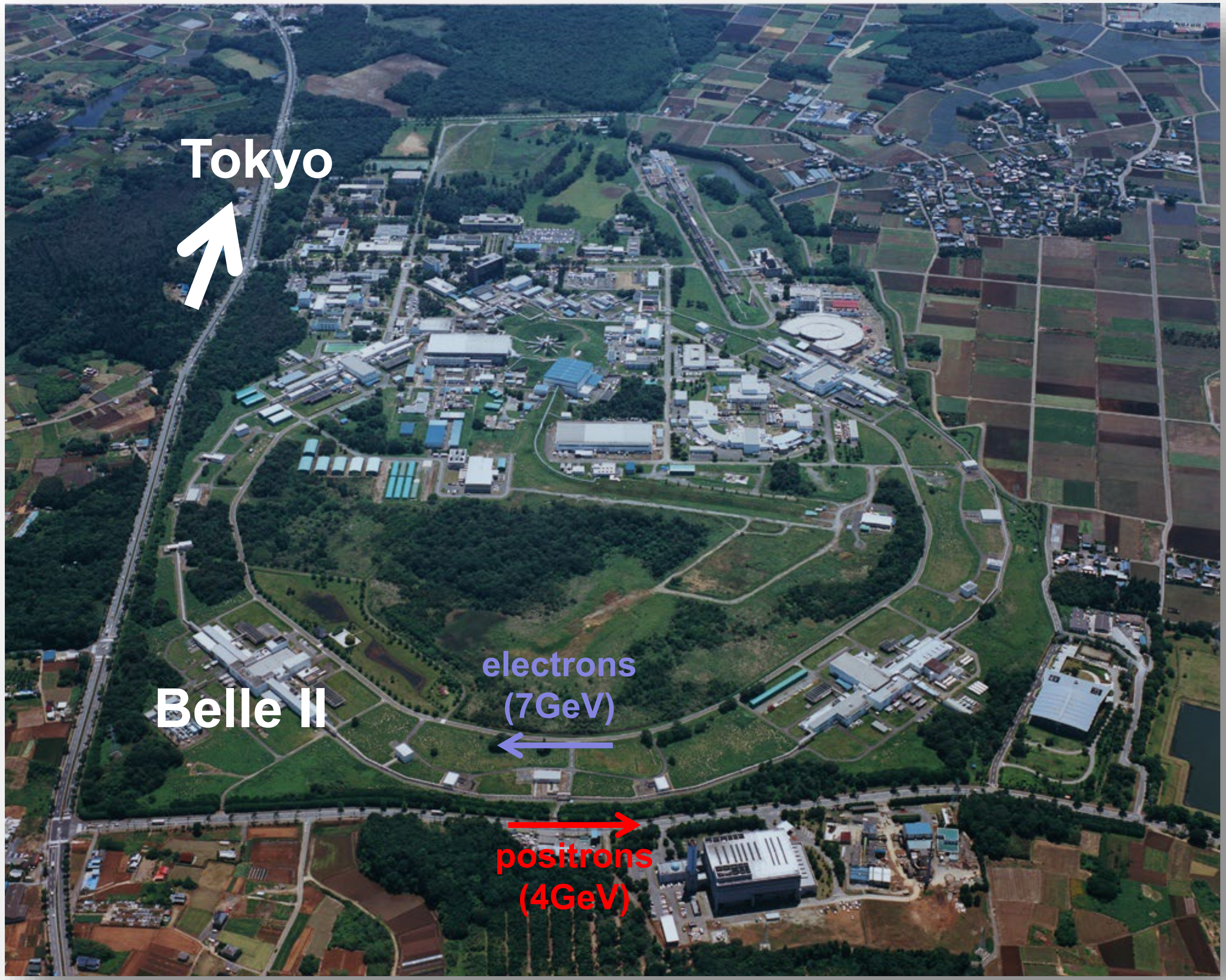
Brian Shuve @ BNL Forum

Summary

- e+ e- B-factories provide unique opportunities to study dark sector
  - BaBar and Belle spearheaded the search in this area.
- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record on June 22nd, 2022.
  - It is a super B factory and in the full mode for physics analysis.
- Analysis techniques have been upgraded to the 2nd generation.
  - Many new possibilities opened, both in theory and experiment
- This is a very exciting time to look for new physics beyond the Standard Model, especially in the Dark Sector.

EXTRA

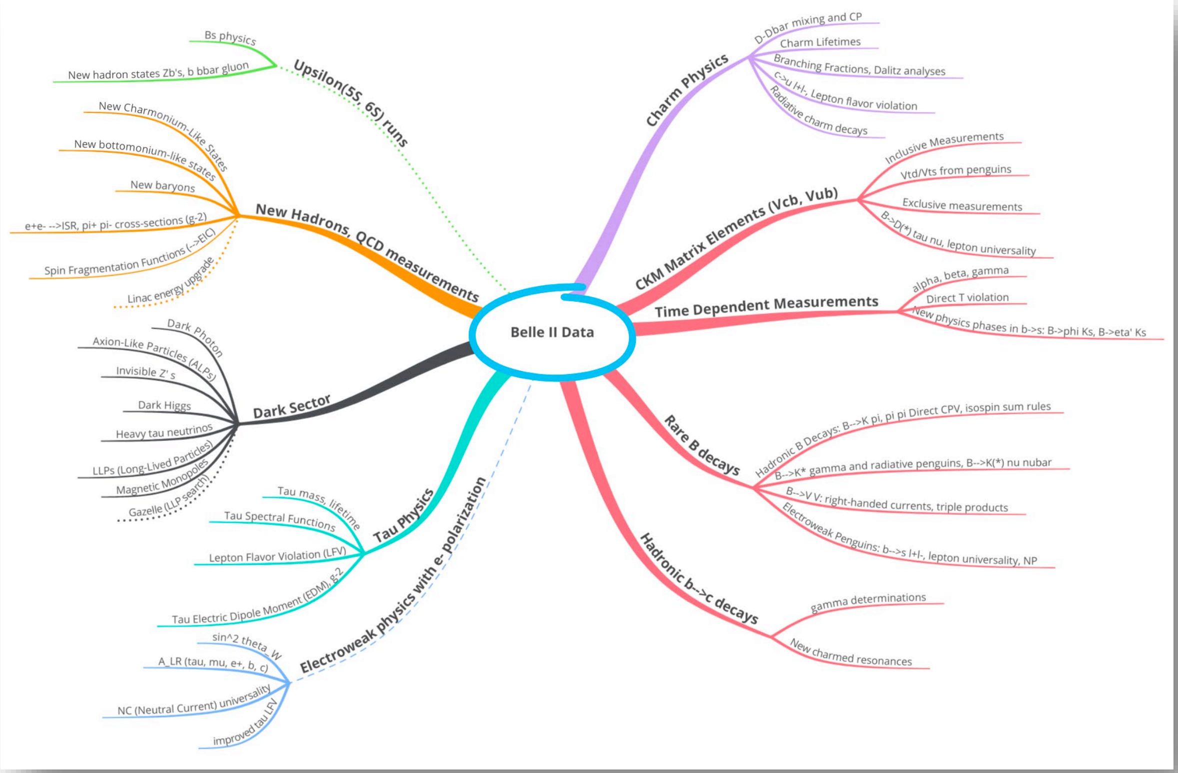
SuperKEKB Collider at Tsukuba, Japan



Belle II Physics Prospects

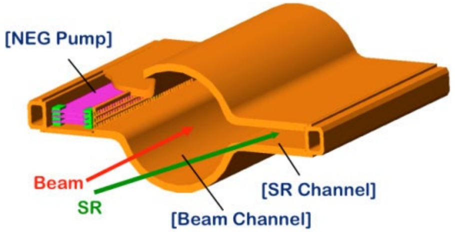
https://confluence.desy.de/display/BI/Snowmass+2021

- Charm decays
- Next precision CKM matrix
  - Semileptonic B decays (CKM elements)
  - Hadronic B decays (angles and CPV)
  - Time dependent CP violation
- τ physics
- Hadron spectroscopy
- Rare decays, FCNC
- New physics
  - Lepton flavor violation
  - Dark sector, long lived particles

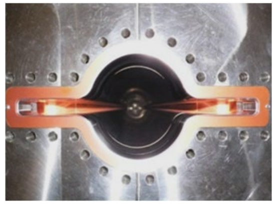


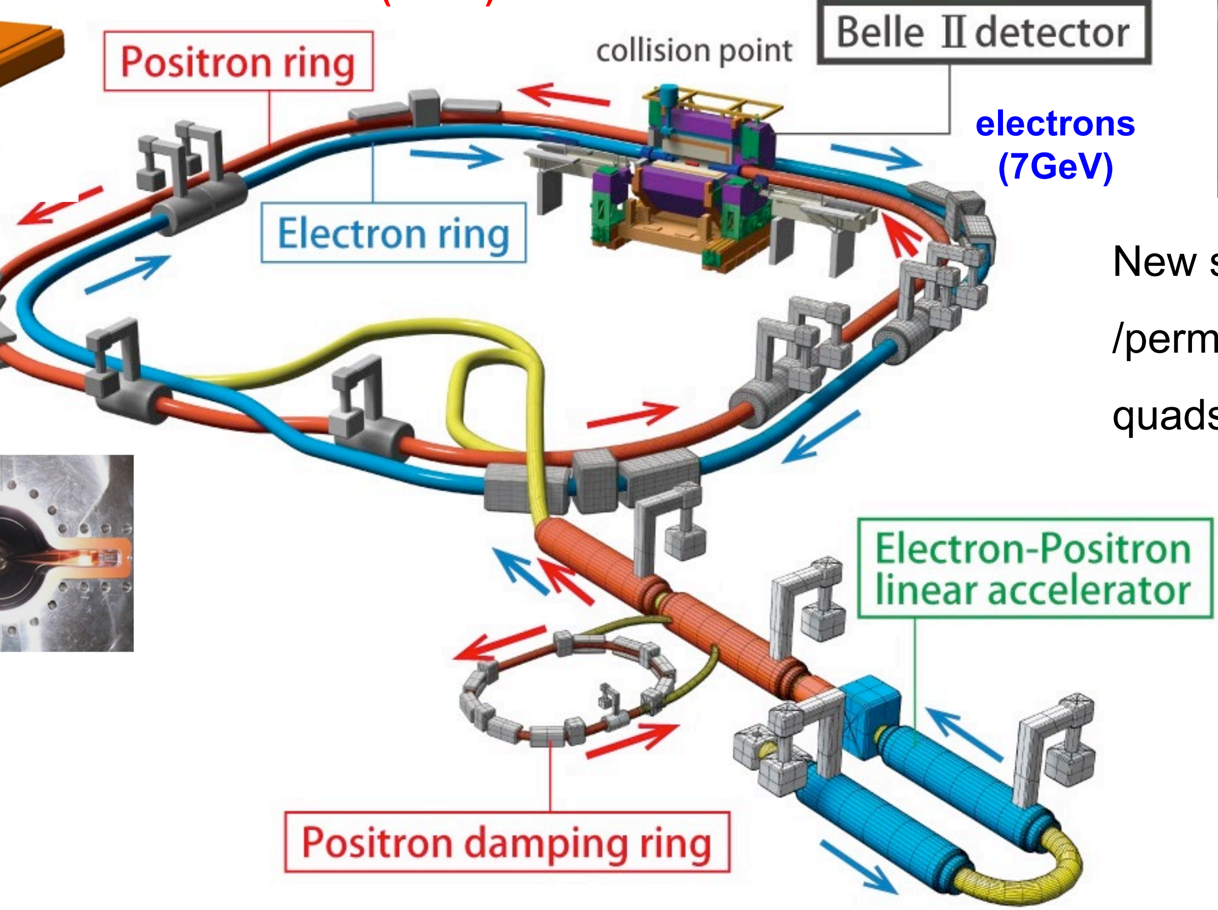
Belle II Physics Book, PTEP 2019, 123C01

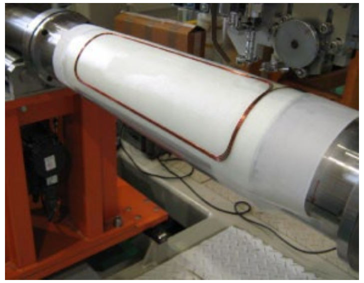
SuperKEKB Structure



TiN-coated beam pipe with antechambers

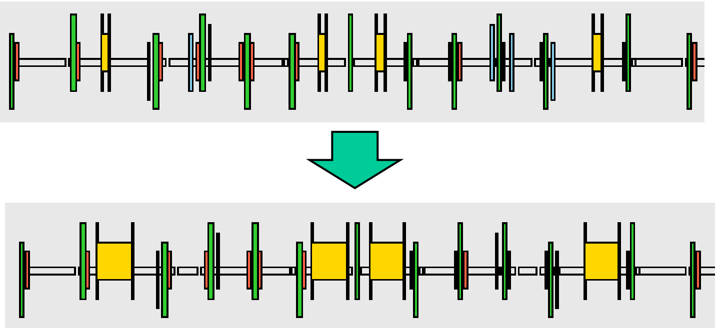






New superconducting /permanent final focusing quads near the IP

Longer dipoles for LER

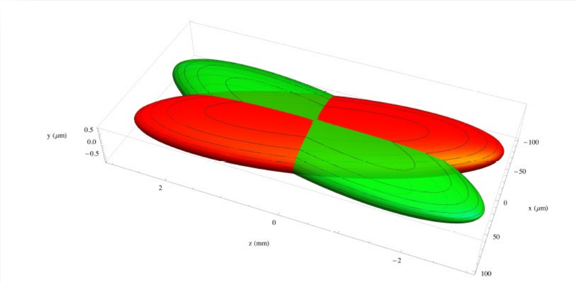


Lattice redesigned to squeeze emittance

KEKB to SuperKEKB: Accomplished

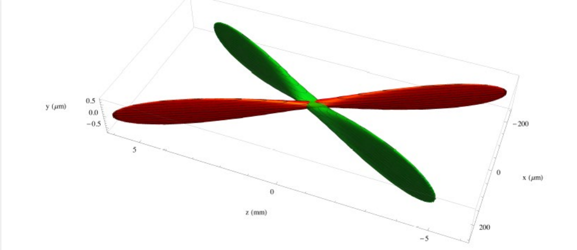
- Nano beam scheme + Crab waist optics
- Target: vertical beta function β_y^* 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction ξ_y

KEKB beams

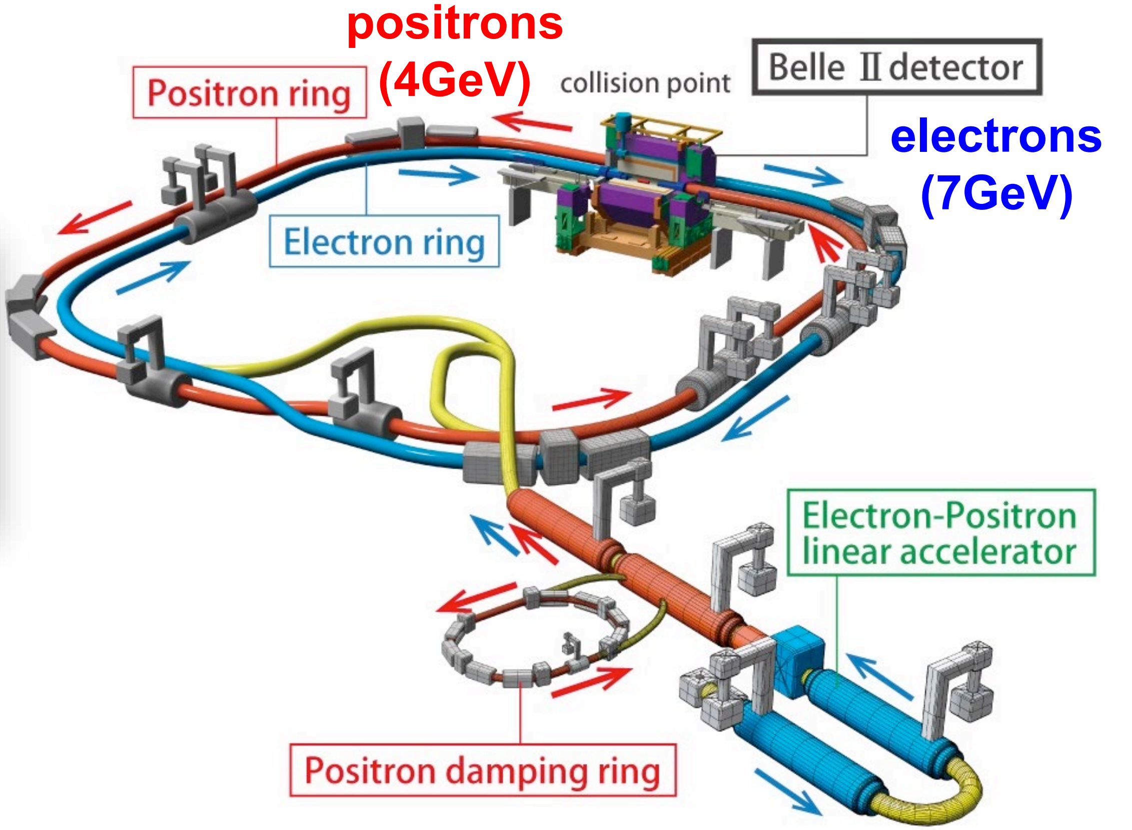


Beam crossing angle 22mrad

SuperKEKB nanobeams



Beam crossing angle 83mrad



$$L = \frac{\gamma_{e\pm}}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\cdot\xi_{y,e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Belle II Experiment in a Nutshell

- HEP experiments have seen huge accomplishments during the last decades.
  - CPV/CKM, discovery of XYZ/tetra/penta particles, discovery of Higgs, etc.
  - Next major theme: New Physics, requiring more precision and larger samples.
- Belle II/SuperKEKB is the upgrade of Belle/KEK.
- Upsilon(4S) decays into $B\,\bar{B}$ meson pairs, coherently with no additional fragments.
  - Full event reconstruction tagging possible
- Direct detection of neutrals such as γ, π^0, K_L.
- A hermetic detector:
  - Detection of neutrinos or invisibles as missing energy/momentum.
- Large continuum charm and τ samples in addition to B samples.
  - Detect both e and μ with similar performance.
  - For example, search for LFV τ decays at $O(10^{-9})$ possible.

Belle II and LHCb

- Belle II and LHCb have different systematics
  - Two experiments are required to establish NP.
  - LHCb: large $b\bar{b}$ cross-section (LHCb 1 fb^{-1} ~ Belle II 1 ab^{-1}). Good sensitivity and S/N with di-muon modes and charged tracks with a vertex.