Searches for Dark Sector Particles at Belle and Belle II

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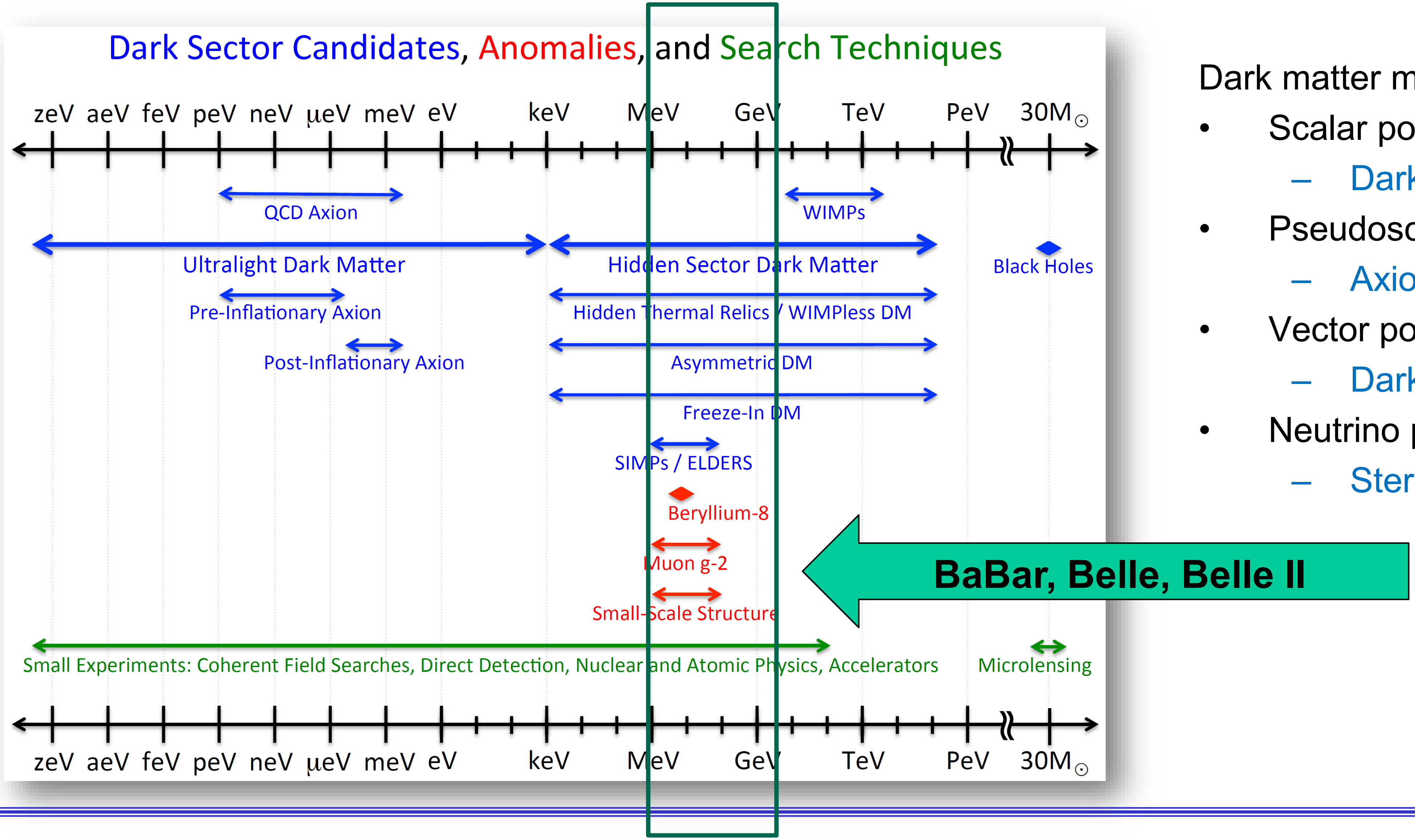
on behalf of the Belle and Belle II collaborations

July 11, 2024
15th International Workshop on the Identification of Dark Matter 2024
GSSI Rectorate, L'Aquila, Italy

Dark Sector Covered by e+ e- B-Factories

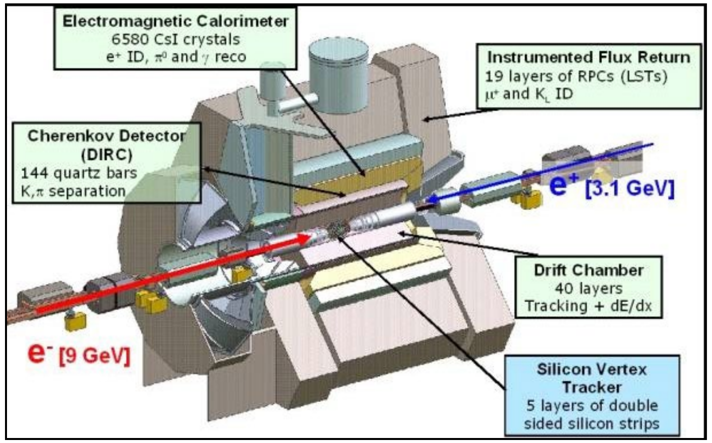


Dark matter mediators

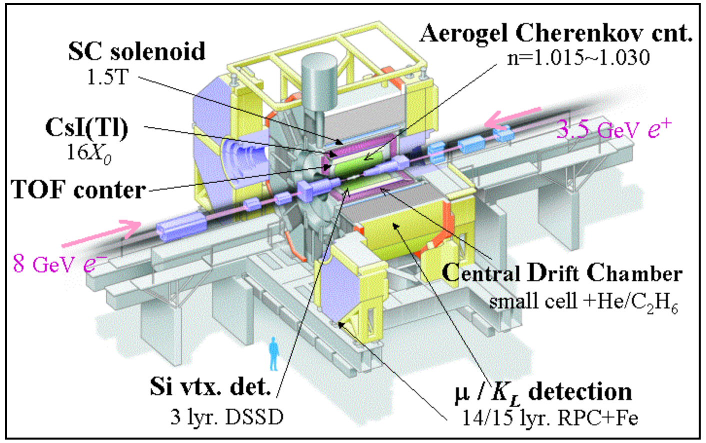
- Scalar portal
  - Dark Higgs, scalars
- Pseudoscalar portal
  - Axions or ALPs
- Vector portal
  - Dark photon, Z'
- Neutrino portal
  - Sterile neutrino

 US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report (Figure 1)

Asymmetric e^+e^- B Factories: Concept



BABAR / PEP II



Belle / KEKB

- Mass of B meson $(b\bar{q})$ is around 5~6 GeV.
  - B pairs can be generated plentifully using ~11 GeV $\Upsilon(4S)$ colliders
- Relatively lower energy → intensity up easily → intensity frontier
- First generation B factory
  - ARGUS/DORIS II at DESY 1982 – 1992
  - CLEO/CESR at Cornell 1979 – 2008 (including Cleo-c)
- Next, asymmetric B factory: one side flavor tag, the other side signal
  - BaBar/PEP-II at SLAC 1999 – 2008
  - Belle/KEKB at KEK 1999 – 2010
- 2nd generation asymm. B factory: Belle II/SuperKEKB at KEK 2019 –
- Detectors at B-Factories have versatile particle identification and reconstruction abilities.
  - Dark sector search is one of core projects at B-Factories.

The Belle II Detector

KL and muon detector
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

Reused Belle detector

Super Conducing Solenoid
1.5 T

Particle Identification
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (forward)

Trigger
Hardware < 30 Hz, Software < 10 Hz

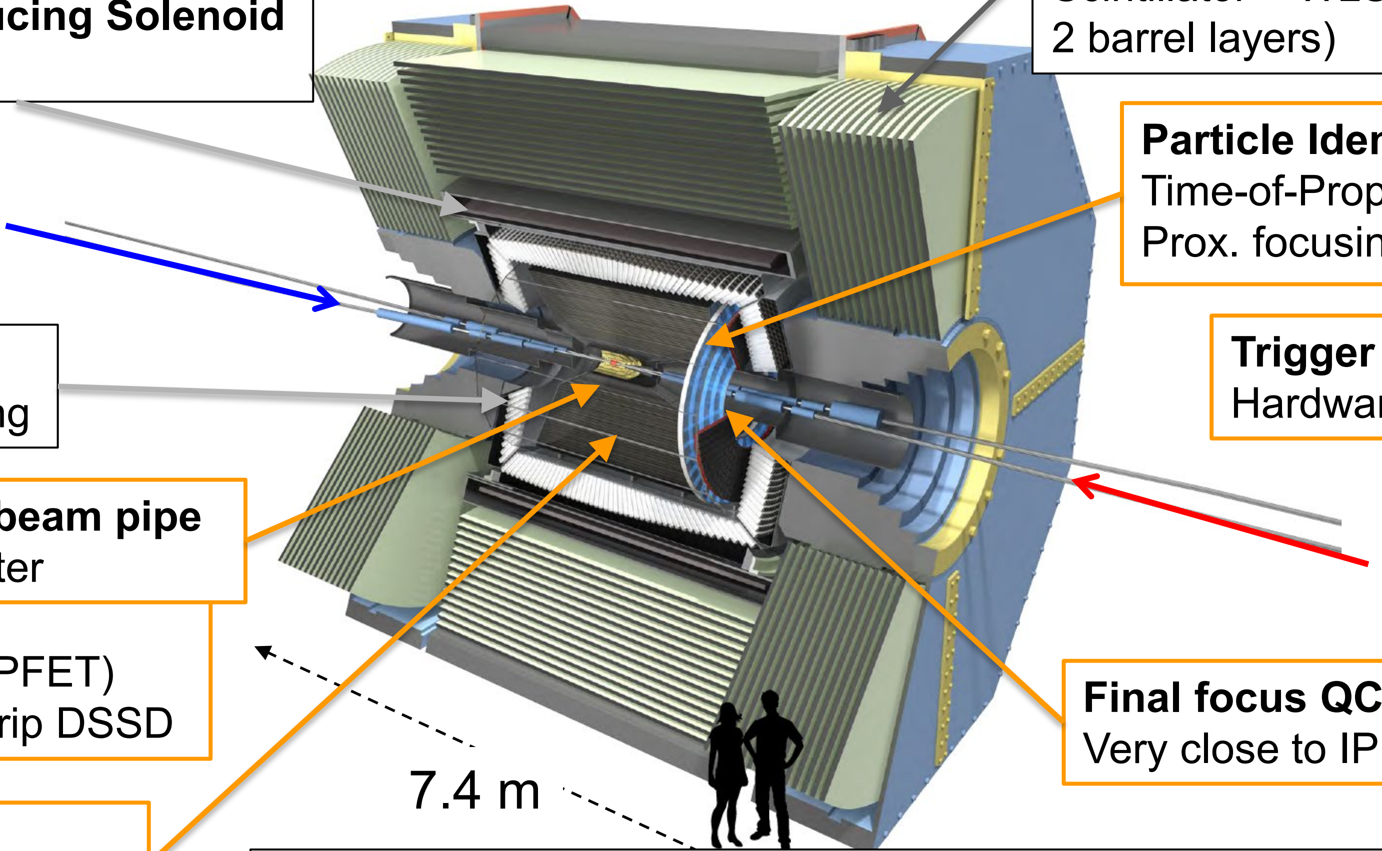
EM Calorimeter
CsI(Tl), waveform sampling

Beryllium beam pipe
2cm diameter

Vertex Detector
1 to 2 layers Si Pixels (DEPFET)
4 layers Si double sided strip DSSD

Central Drift Chamber
Smaller cell size, long lever arm

Final focus QCS
Very close to IP



New for Belle II

15 μm vertexing resolution, excellent tracking.

Hermetic detector makes full event reconstruction possible.

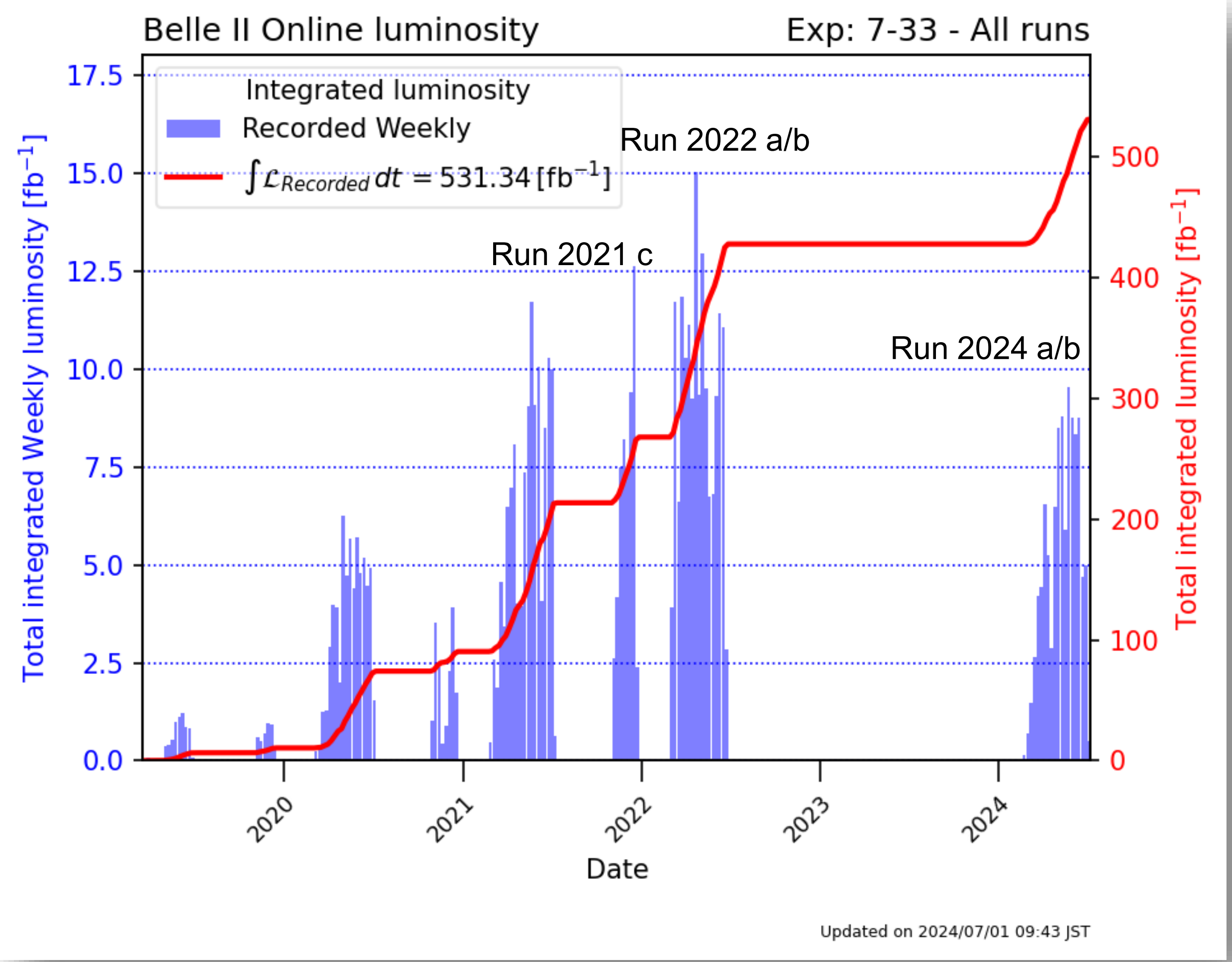
Photon efficiency 90% above p > 1.5 GeV.

Muon eff. 90% with 7% pion mis-ID. Electron eff. 86% with 0.4% pion mis-ID

Kaon ID in full momentum range, eff. 90% with 6% pion mis-ID.

SuperKEKB Luminosity: Current Status

- After SupepKEKB commissioning phases,
- Physics runs started spring 2019.
- Run 1 ended June 2022.
  - Peak luminosity at $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record set on June 22nd, 2022.
  - Run 1 integrated luminosity at $\int L_{recorded} dt = 424\ fb^{-1}$. (~ Babar, ~ ½ Belle sample size)
- Long shutdown 1 (LS1) 2022 – 2023.
- Run 2 started February 2024.
  - Integrated luminosity at $531\ fb^{-1}$ now.



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

- B-Factories are competitive in the light dark matter search from **1 MeV** to **~10 GeV.**

- Background is lower compared to hadron colliders.
- Closed detectors means the coverage is almost 4π.
  - Missing momentum and energy can be a signature of invisible particle(s).
  - Full event interpretation is possible.
- Neutral particle findings have high efficiencies.

- Dedicated trigger for low-multiplicity is introduced for Belle II.
  - Low multiplicity signature observation is possible.
  - Dark particle signatures in B and τ decays are available ($\sigma(b\bar{b}), \sigma(c\bar{c}), \sigma(\tau\bar{\tau})$ ~ 1nb).
  - Clean environment can compensate for lower production cross-section than LHCb.

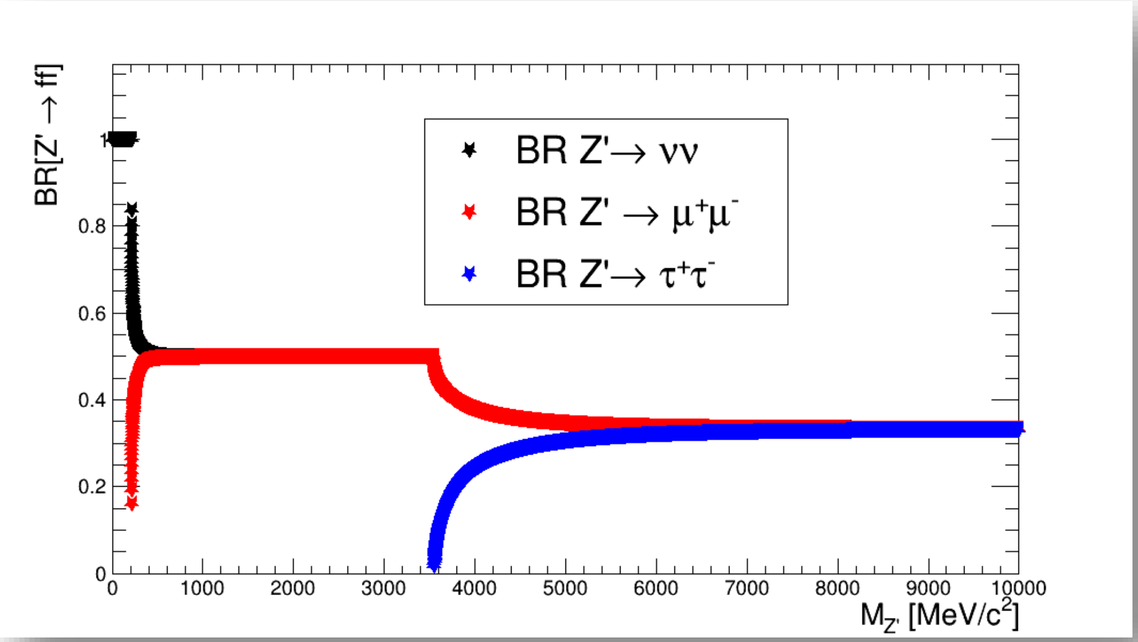
Z', S, ALP SEARCHES IN 2 LEPTON + X EVENTS

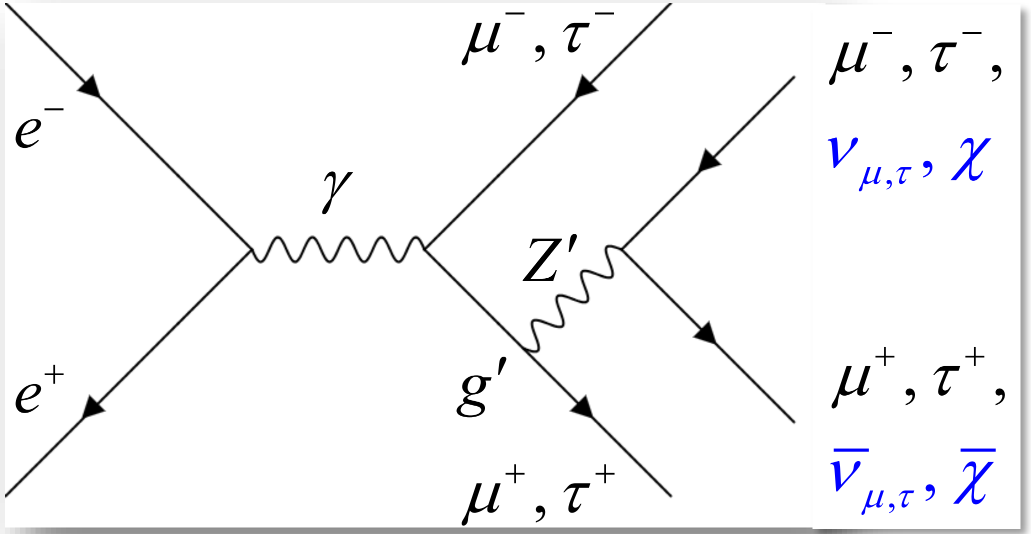
The $L_\mu - L_\tau$ Model

Shuve and Yavin, Phys. Rev. D **89**, 113004

Altmannshofer et al., JHEP 12 (2016), 106

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





Search for the signature of

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

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

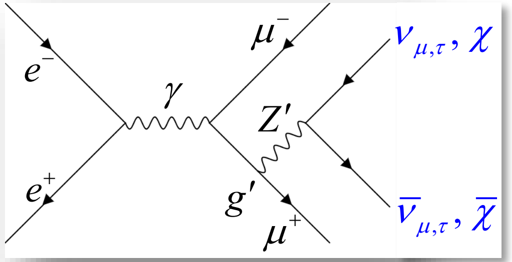
Invisible: neutrino, dark matter χ

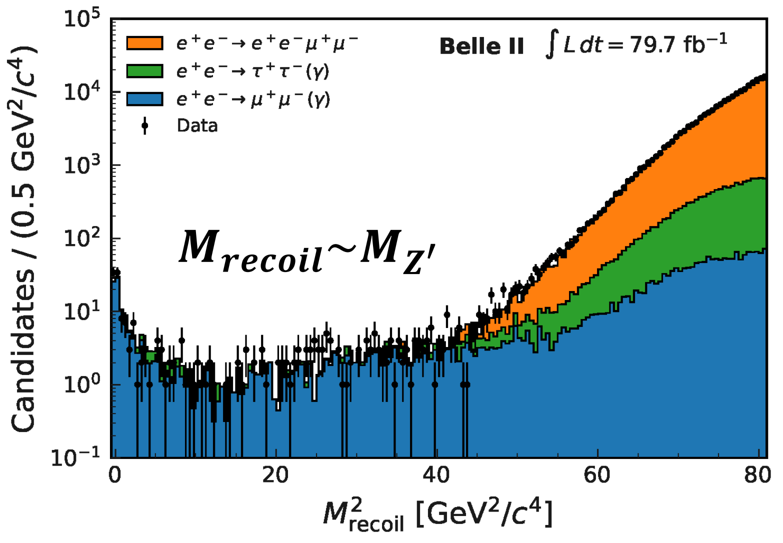
Search for $e^+e^- \to \mu^+\mu^-$ Z', (Z' to invisible)

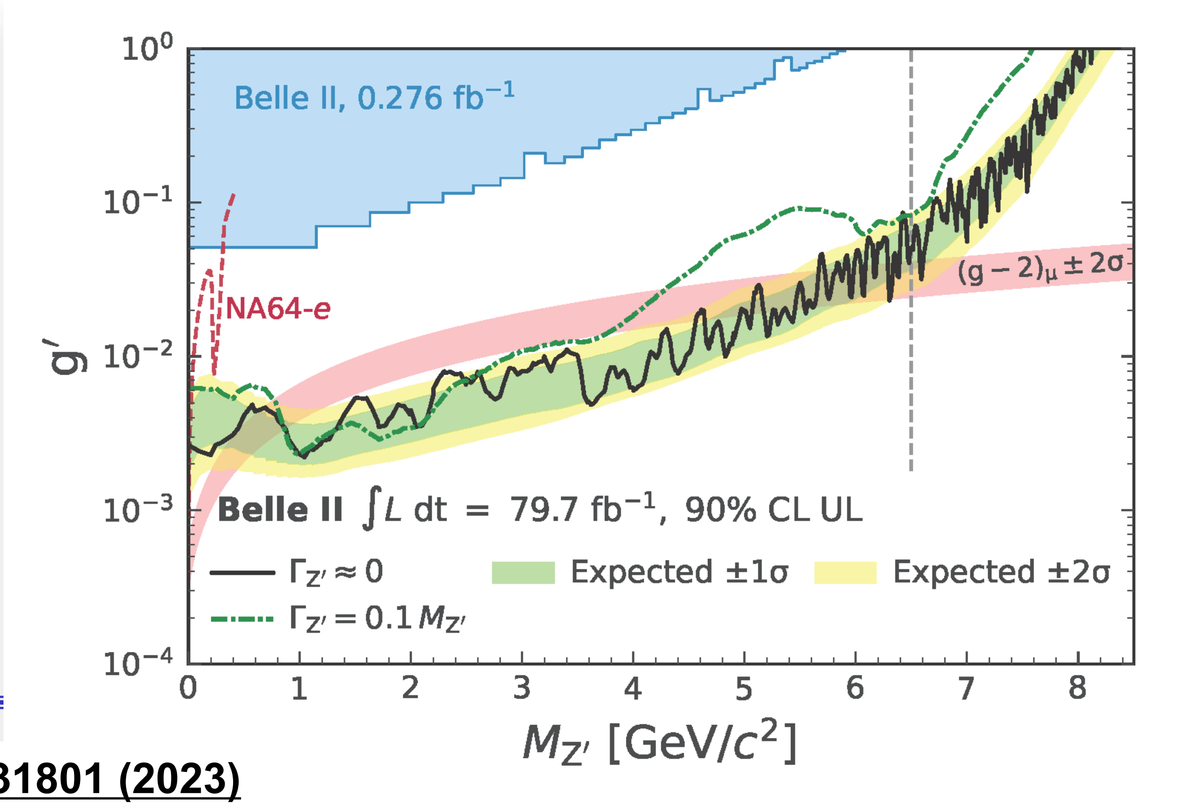
- **Belle II** 79.7 fb^{-1}: look for a narrow recoil mass peak (Z' candidate) against a $\mu^+\mu^-$ pair.
  - require no other particles in the event.
- Dominant backgrounds are two muons + missing E.
- No excess events are found in the recoil mass (Z' candidate).
- 90% CL upper limits on the cross-section and on g' were obtained. As a result,
- $(g-2)_\mu$ excluded from $0.8 < M(Z') < 5\ GeV/c^2$.

Fully invisible $L_\mu - L_\tau$ (100% decay to $\chi\bar{\chi}$)

For decay to the SM neutrinos, see the extra slide.



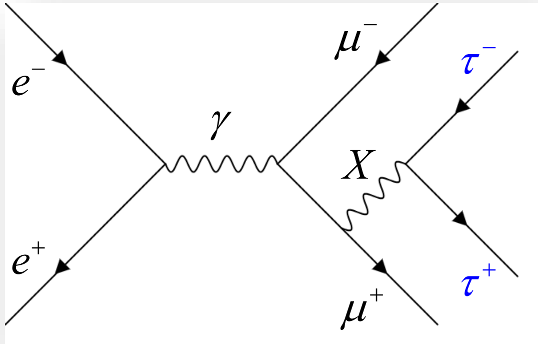




PRL 130, 231801 (2023)

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

Z' - Altmannshofer et al., JHEP 12 (2016), 106
S - Batell et al., Phys. Rev. D 95, 075003 (2017)
ALP - Bauer et al., JHEP 12 (2017), 44

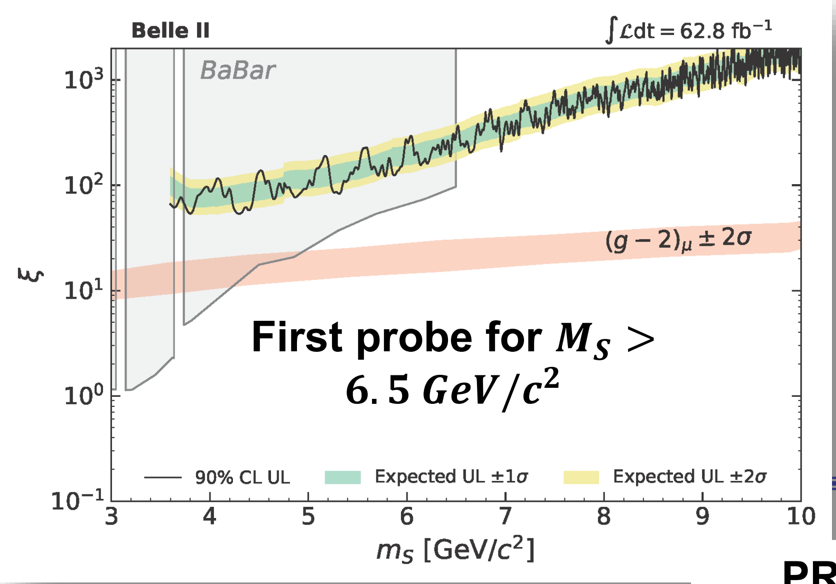


- **Belle II** 62.8 fb^{-1}. No excess events were found in the recoil mass of $\tau^-\tau^+$.
  - Use tau decay modes to one charged track + neutrals
- 90% CL upper limits on the cross-section are obtained.

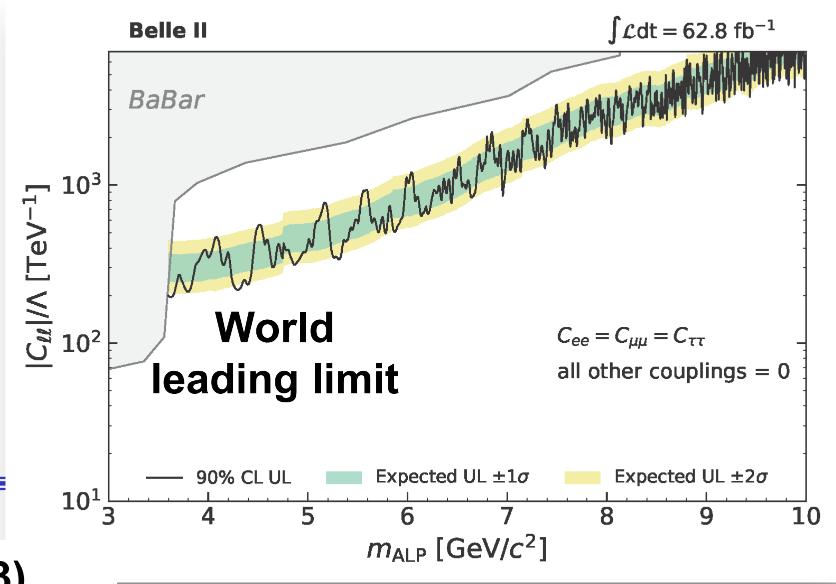
$$\sigma\left(e^+e^- \to \left(X \to \tau^+\tau^-\right)\mu^+\mu^-\right) = \sigma\left(e^+e^- \to X\mu^+\mu^-\right)\sigma\left(X \to \tau^+\tau^-\right), \quad X = S, \mathrm{ALP}, Z'$$

- Exclusion limits on the couplings for three dark particle models are also obtained. (For the Z' interpretation, see the extra slide.)

Leptophilic scalar (S)

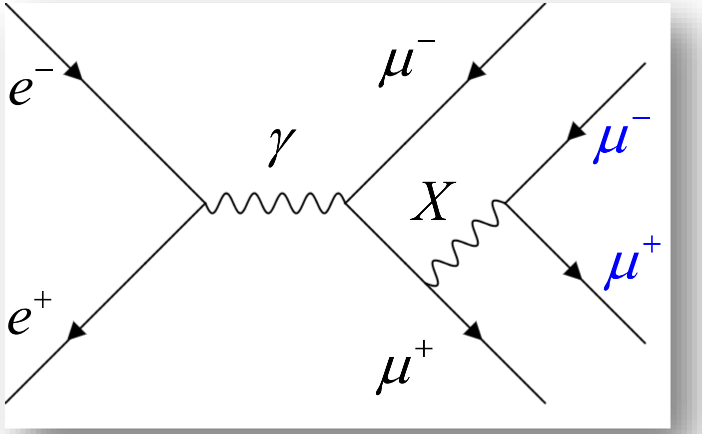


ALP



PRL 131, 121802 (2023)

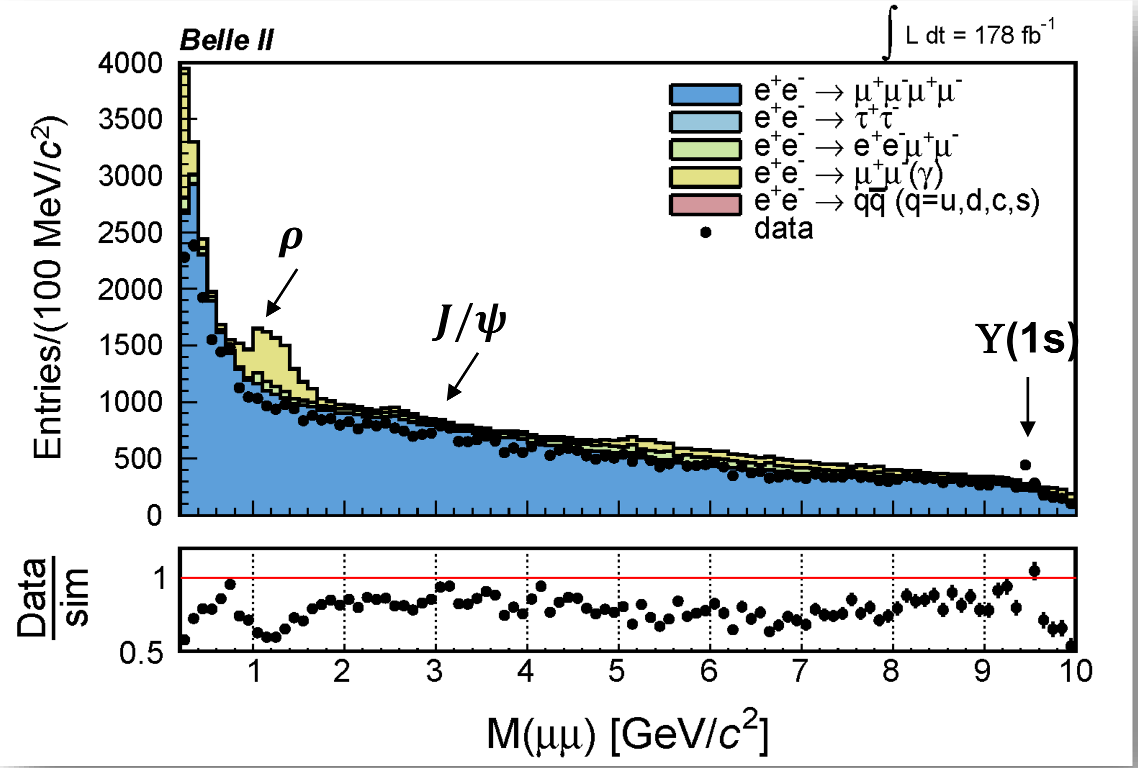
Search for X in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$



Harris et al. arXiv: 2207.08990 [hep-ph]

Capdevilla et al., JHEP 04 (2022) 129

- **Belle II** 178 fb^{-1}: The aim is to find a di-muon resonance in 4 lepton events. We look for a mass peak in the candidate muon pair.
  - At least three muons are identified.
  - Total charge is zero and M(4 tracks) ~ beam energy. No extra energy is allowed.
- Multi-layer Perceptron (MLP) is applied to suppress background peaks.
  - Signal production mechanism and background kinematics are considered.

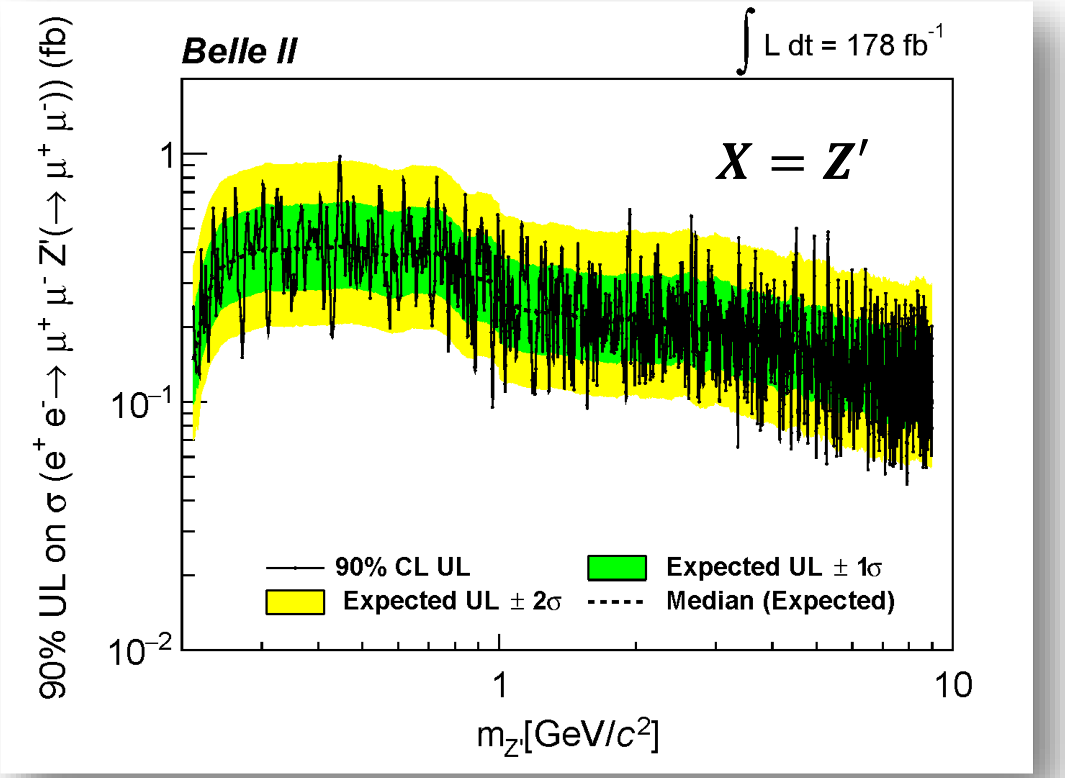


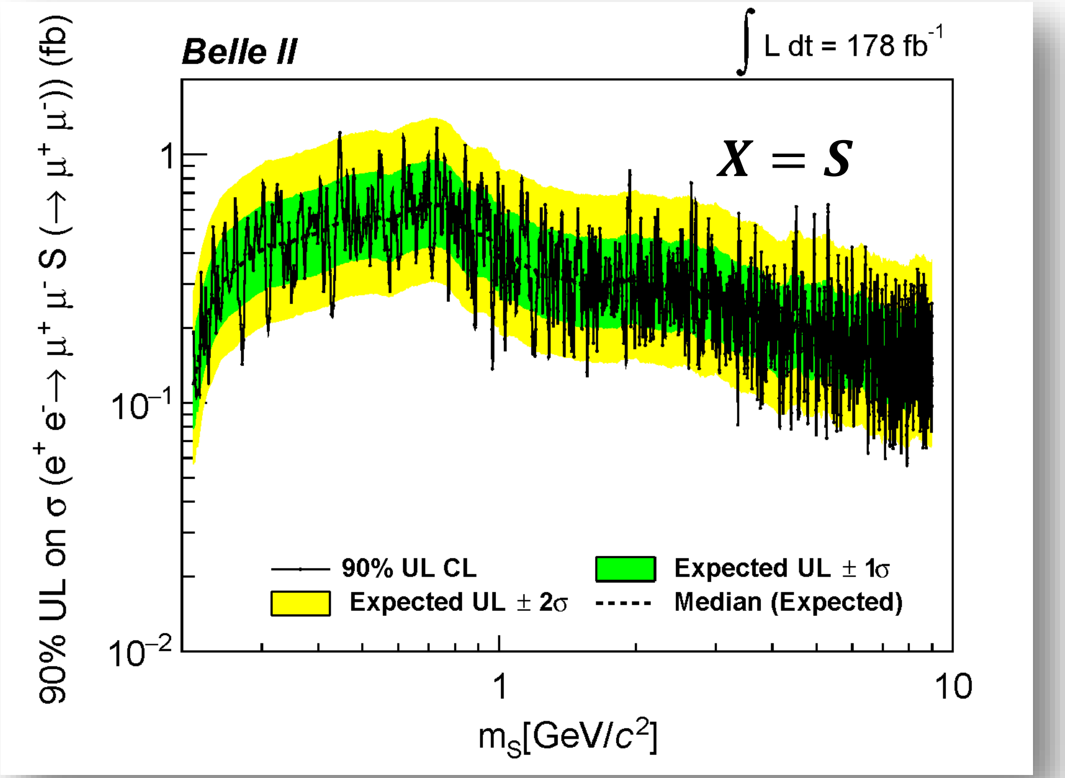
Before MLP is applied

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

- **Belle II** 178 fb^{-1}. No excess events are found.
- 90% CL upper limits on the process cross-section are obtained.

$$\sigma\left(e^+e^- \to \left(X \to \mu^+\mu^-\right)\mu^+\mu^-\right) = \sigma\left(e^+e^- \to X\mu^+\mu^-\right)\sigma\left(X \to \mu^+\mu^-\right), \quad X = Z', S$$

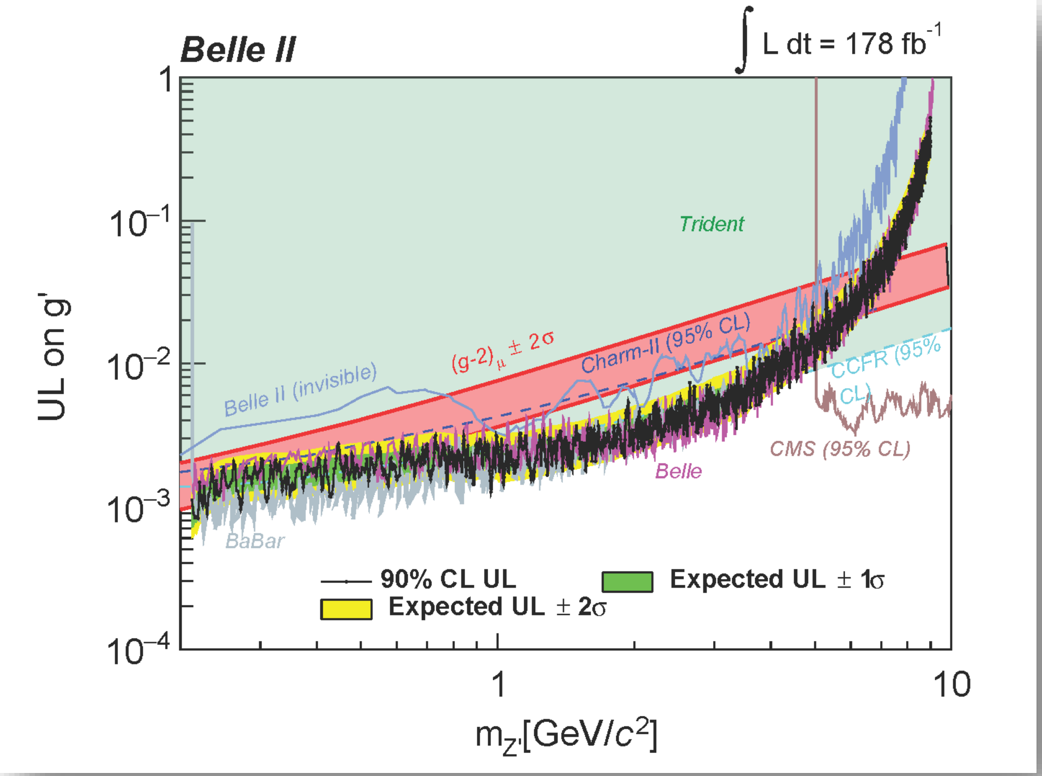


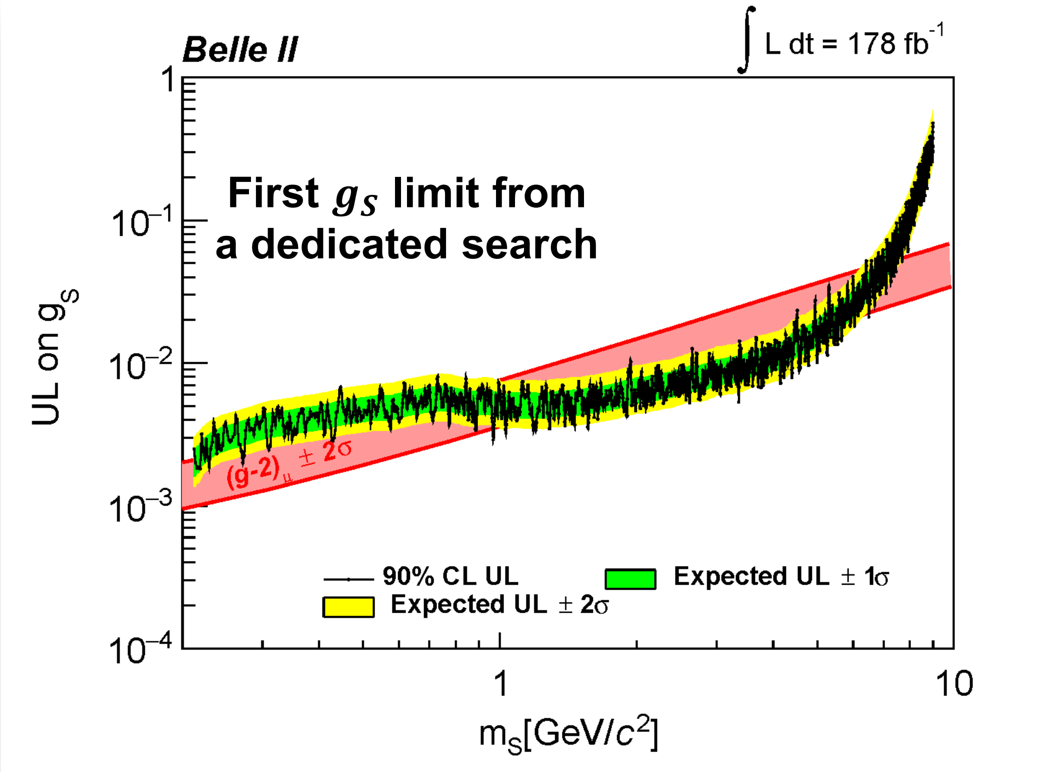


PRD 109, 112015 (2024), **arXiv:2403.02841**

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

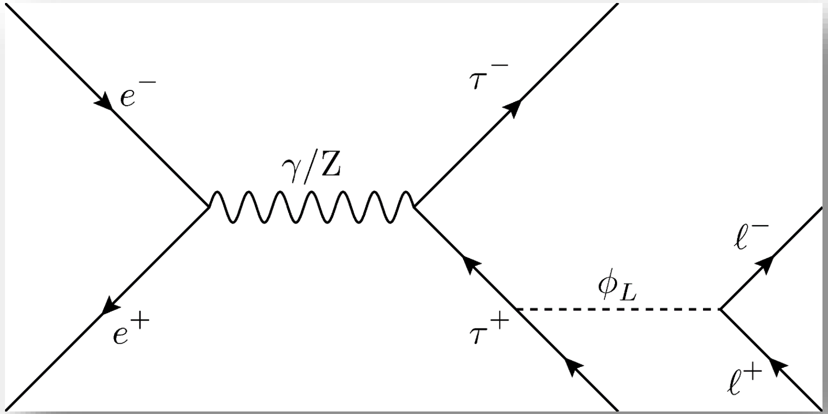
- **Belle II** 178 fb^{-1}. No excess events are found.
- Cross-section limits are translated into upper limits on the coupling constant for respective hypotheses,
  - g' for the $L_\mu - L_\tau$ model
  - g_S for the muon-philic dark scalar S model.





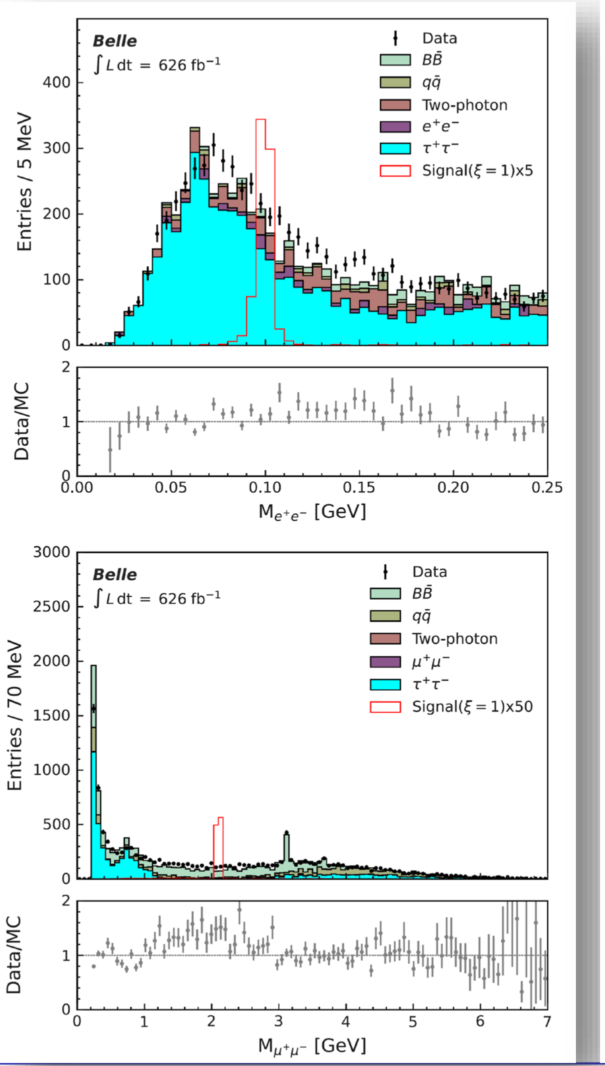
PRD 109, 112015 (2024), arXiv:2403.02841

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

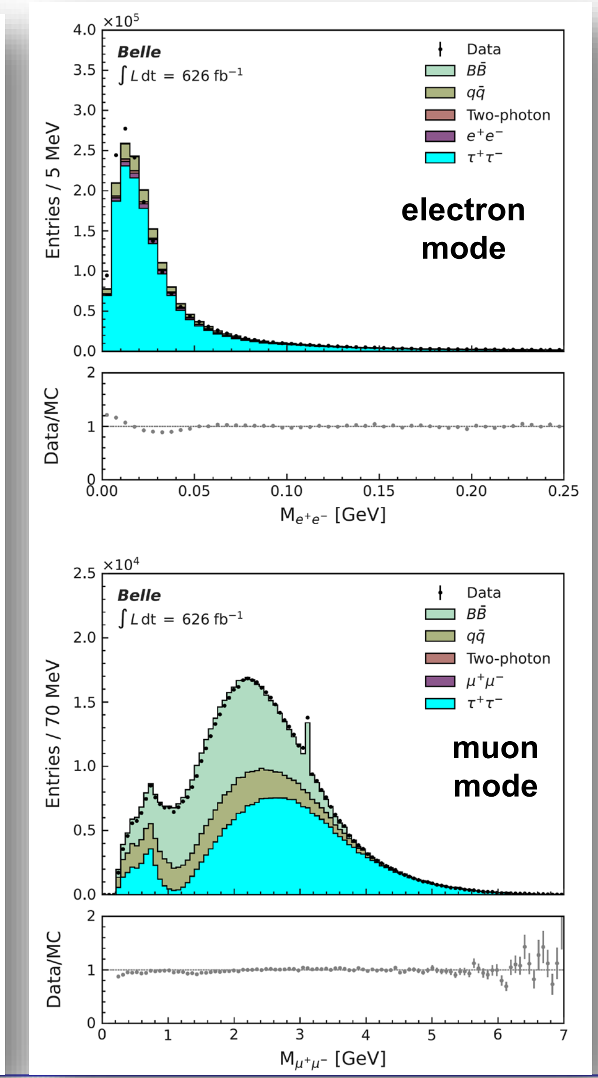


- **Belle** on 626 fb^{-1}: search for leptophilic dark scalar (ϕ_L) in 2 tau (1-prong decay) + 2 lepton events.
  - 1-prong: one charged track + neutrals
  - This mode can affect $(g-2)_\mu$ results.
- Lepton = muon or electron
- A major background is $e^+e^- \to \tau^+\tau^-$.
- Radiative Bhabha (photon decaying to two muons) are removed by cuts on missing energy and its angle.
- Boosted Decision Tree (GradientBoostingClassifier, scikit) is used to suppress backgrounds.

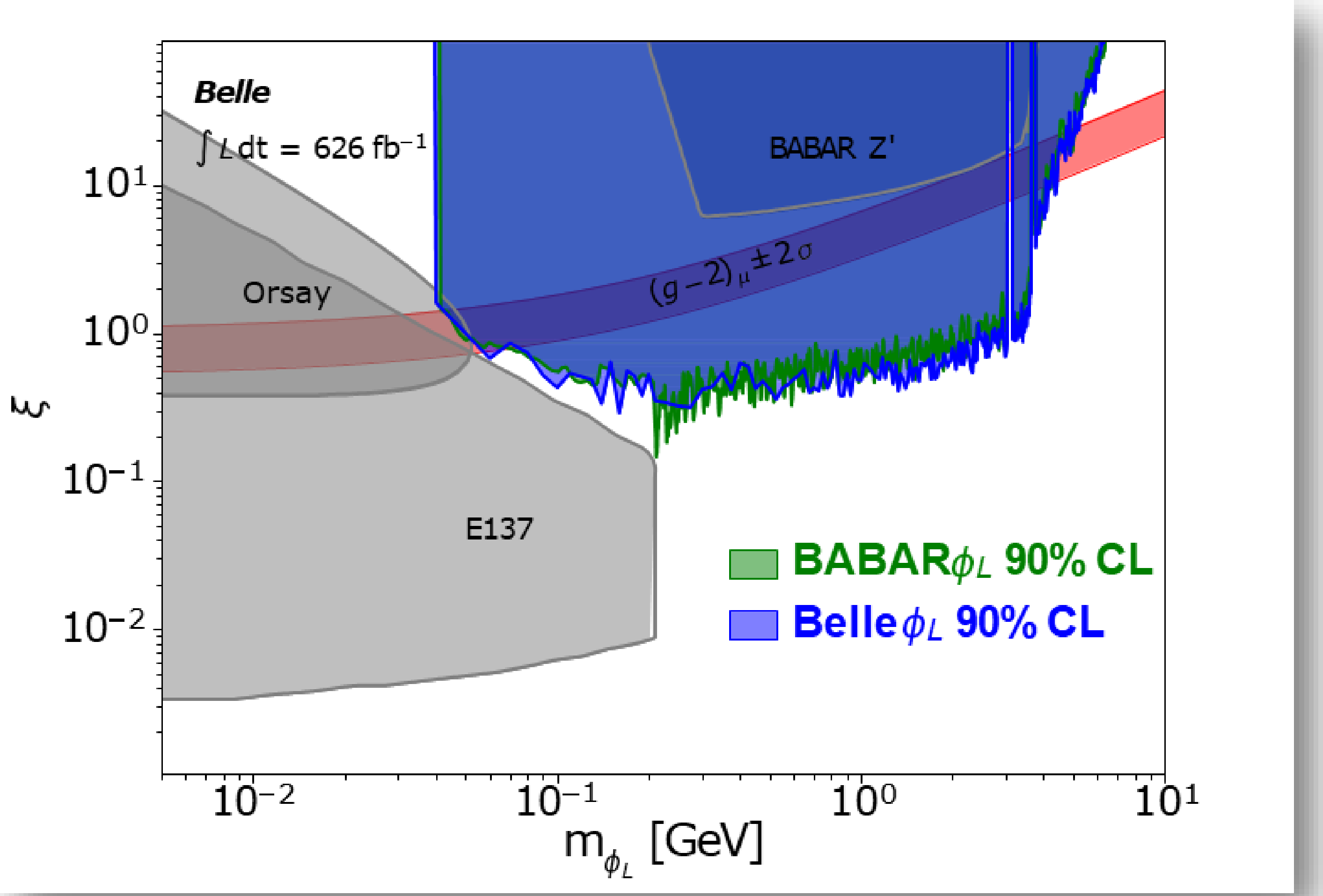
Signal sample



Background sample



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



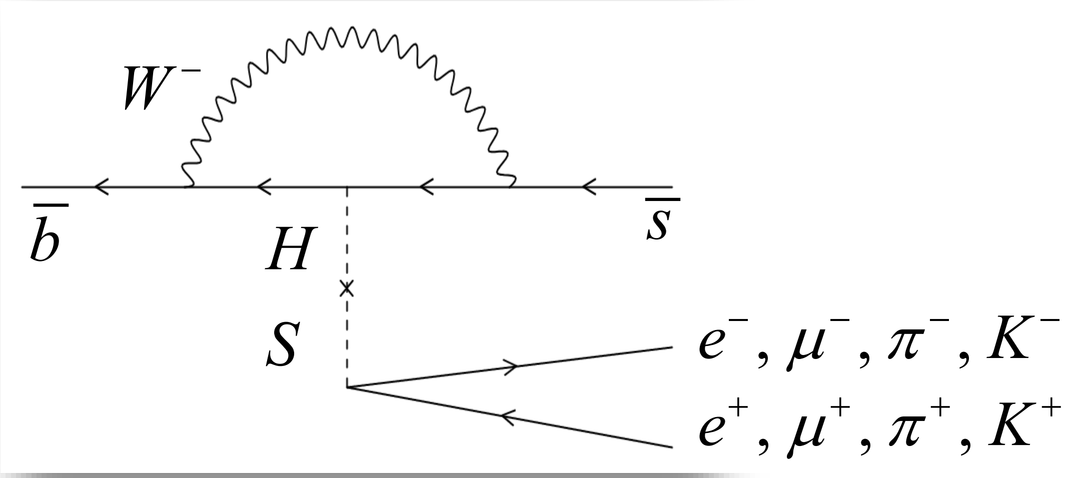
- Results shown here are from
  - **Belle 626 fb^{-1}**
  - **BaBar 514 fb^{-1}**
- 90% CL limits on
  - ξ (flavor-independent coupling to leptons) and
  - the mass of the dark scalar (ϕ_L)

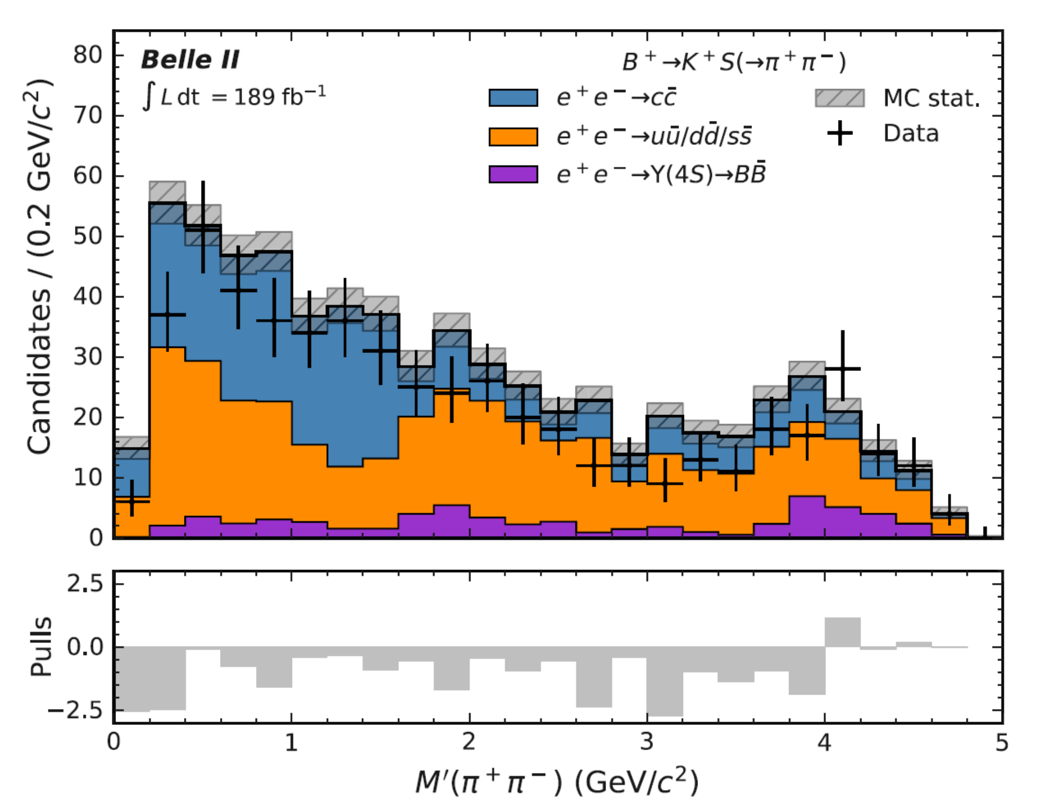
  are obtained.
- More searches on the full Belle sample is continuing.

DARK PARTICLE SEARCHES IN B DECAYS

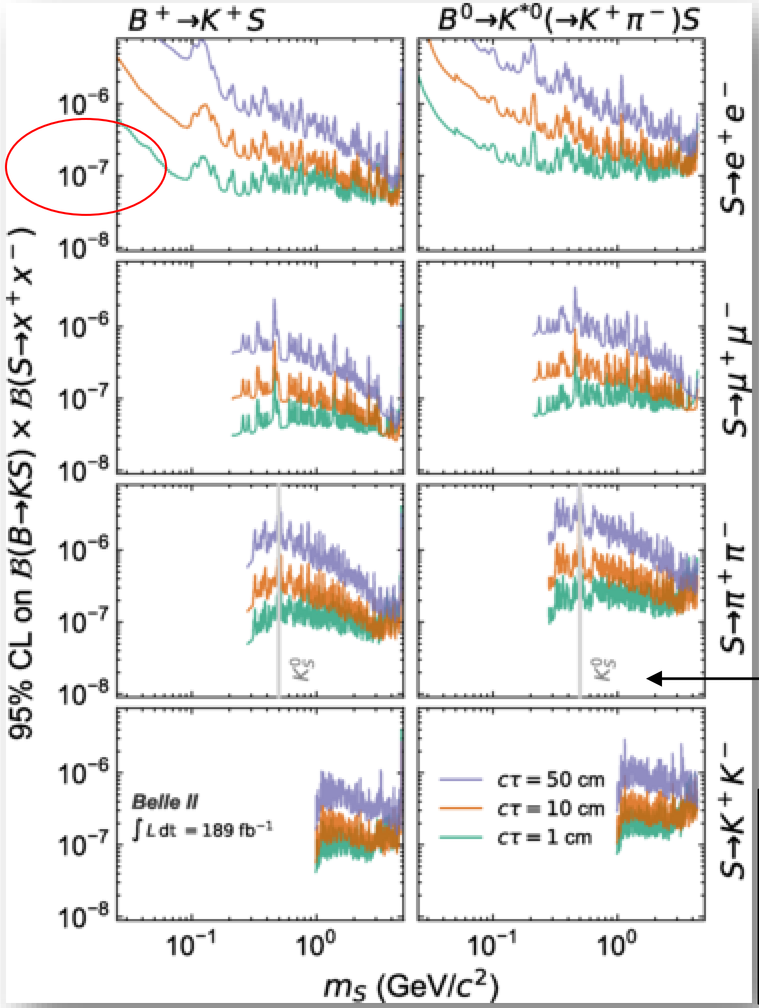
Search for $B^{+/0} \to K^{+/*0}S, S \to x^+x^-, x = e, \mu, \pi, K$

- Search parameters are mass of dark scalar S and mixing angle θ between the SM Higgs and S.
- **Belle II:** search for long lived spin-0 mediator S in B decays ($e^+e^- \to \Upsilon(4S) \to B\bar{B}$).
- Channels studied: $B^+ \to K^+S$, $B^0 \to K^{*0}(K^+\pi^-)\, S$.
- S is assumed to decay to a pair of charged tracks.
- S is assumed to live long: S decay vertex is far from the beam interaction point.





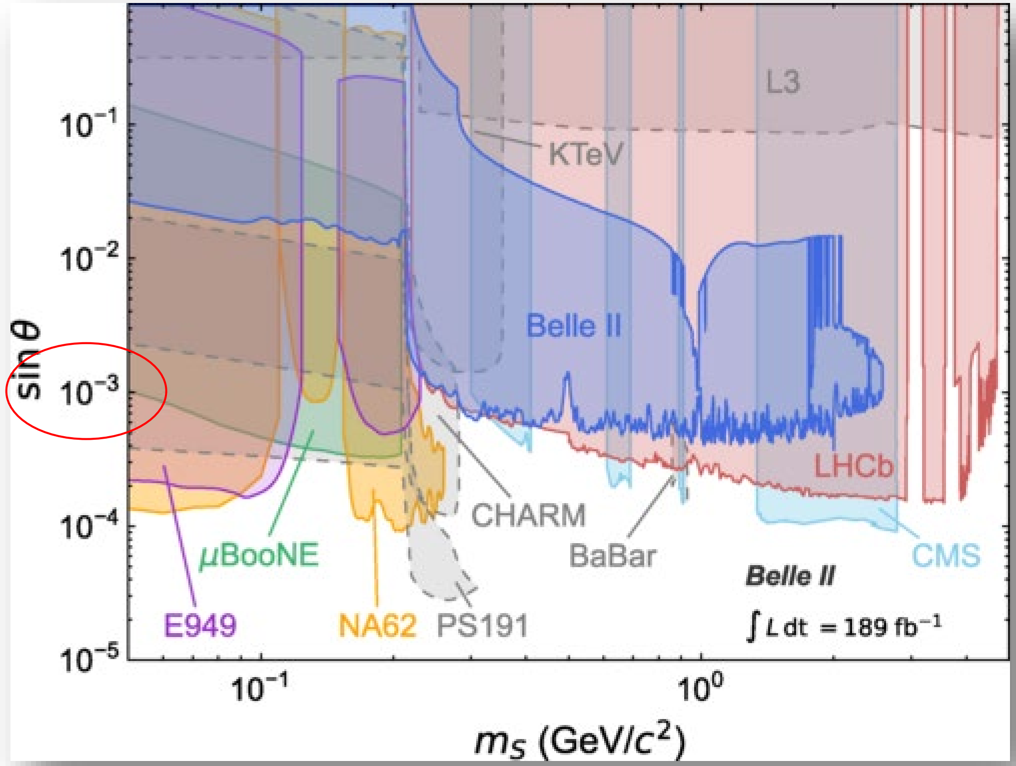
Search for $B^{+/0} \to K^{+/*0} S, S \to x^+x^-, x = e, \mu, \pi, K$



K_S^0 veto

la.	$c\tau = 50$ cm
or.	$c\tau = 10$ cm
gr.	$c\tau = 1$ cm

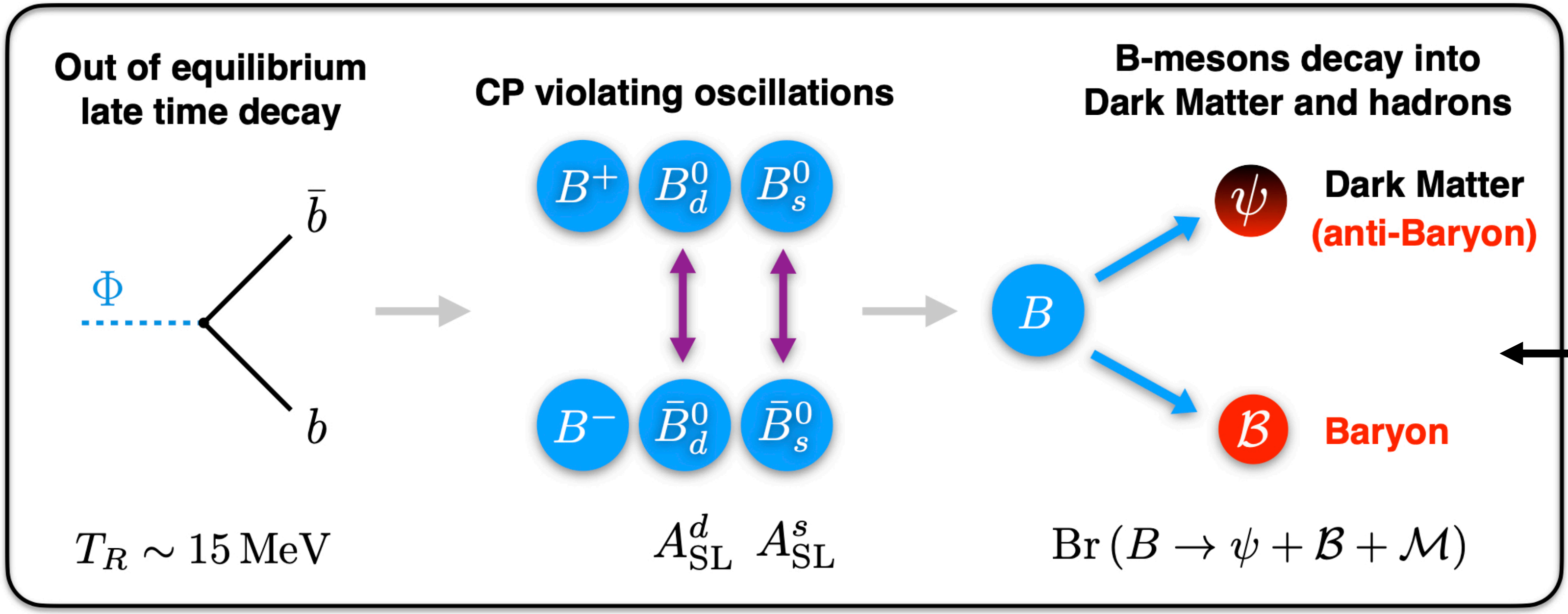
- **Belle II** 189 fb^{-1} : 95% CL exclusion region is obtained.
  - Limits on branching fractions and mixing angle $\sin\theta$
- First measurements for exclusive hadronic states.



PRD 108, L111104 (2023), arXiv:2306.02830

Baryogenesis and Dark Matter in B Decays

Baryogenesis and Dark Matter from B Mesons: *B-Mesogenesis*

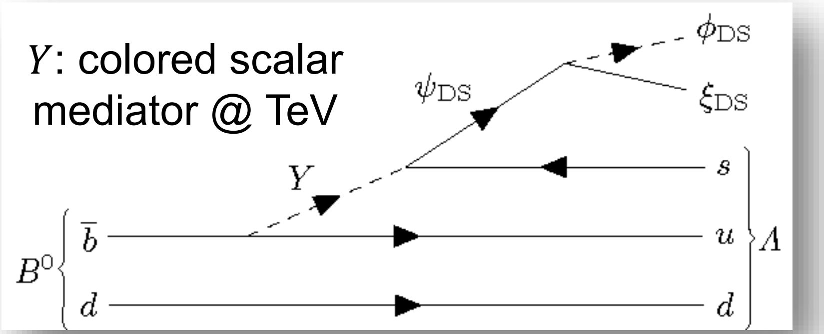


Elor, Escudero, and Nelson
PRD 99, 035031 (2019)
arXiv:1810.00880

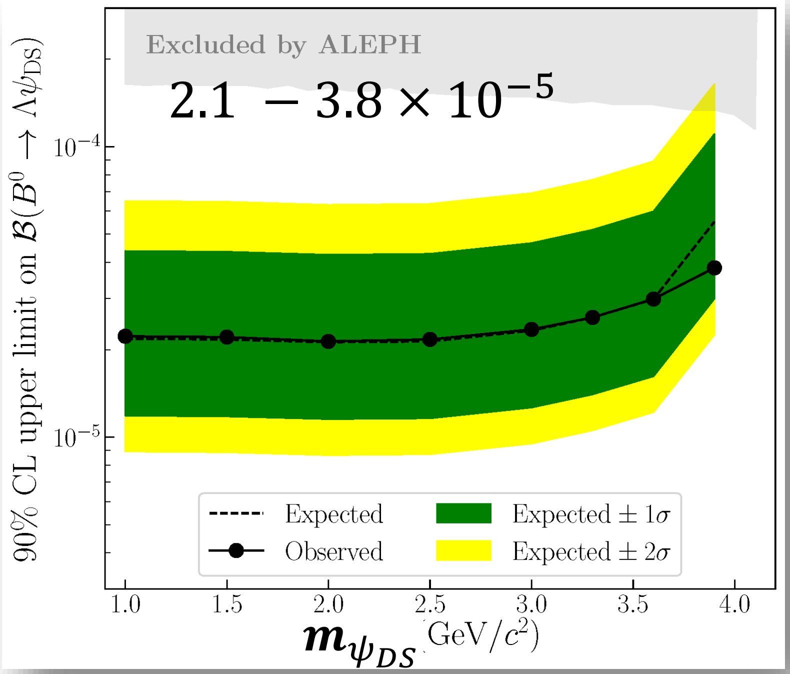
EAlonso-Álvarez, Elor, and Escudero
PRD 104, 035028 (2021)
arXiv:2101.02706

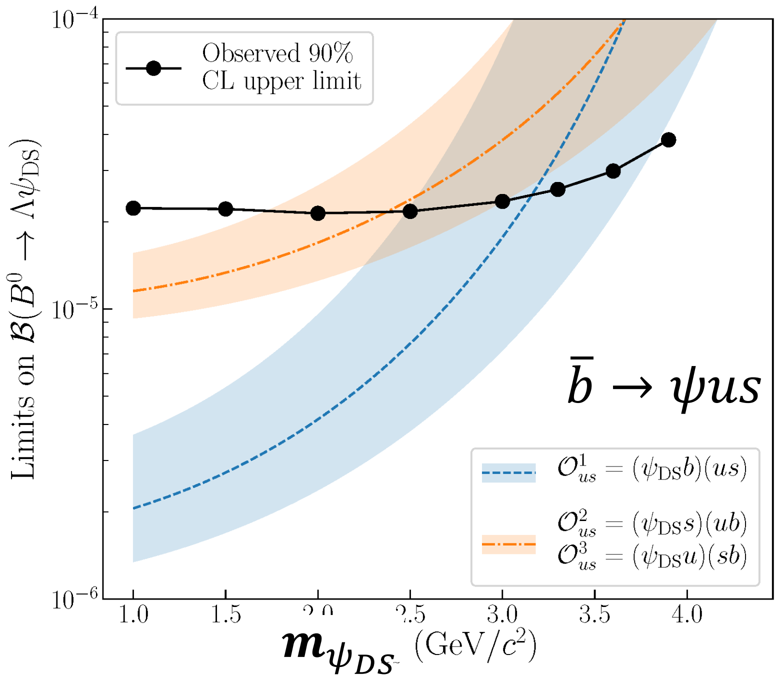
- In the early universe, $b\bar{b}$ were created than hadronized into B mesons.
- B mesons can decay into a baryon + a dark baryon + other mesons.
- Due to CP violating $B^0 - \bar{B}^0$ oscillations, matter-antimatter asymmetry gets created.
- Which can result in accesses in visible baryon number and in dark anti-baryon number.
  - Baryon number gets conserved, but visible sector will show access matter baryons.

Search for $B^0 \to \Lambda\, \psi_{DS}$



- **Belle** 711 fb^{-1}: search for dark baryon (ψ_{DS}) as missing energy accompanied by Λ in B^0 decays.
- 90% CL UL on B branching ratio into dark baryon is obtained.
- The limit is also interpreted as constraints on the related operators.



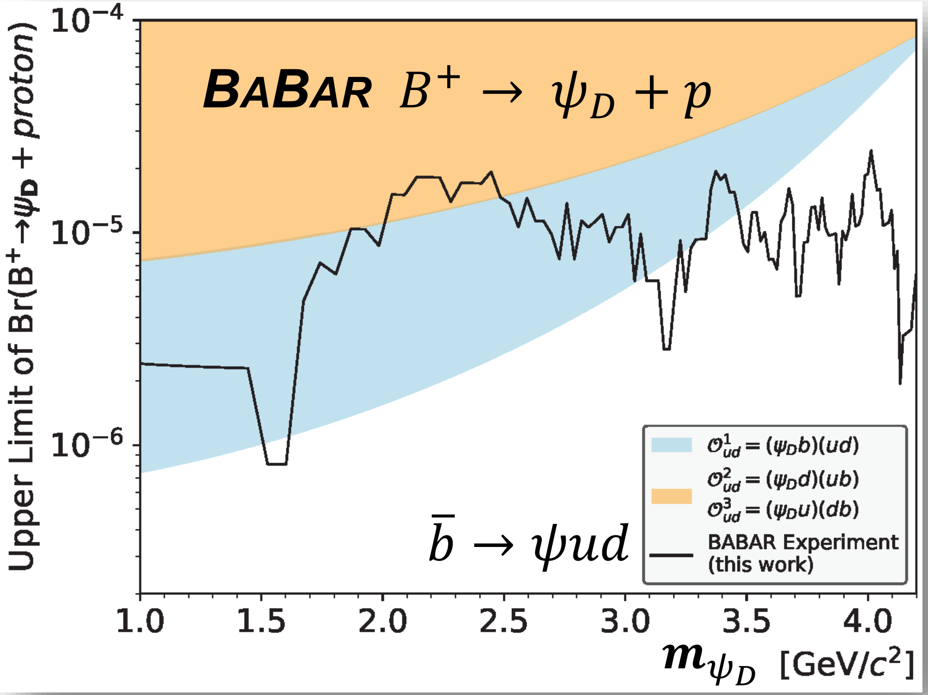


PRD 105, L051101 (2022), arXiv:2110.14086

Other Possibilities in B Decays at Colliders

- The baryon asymmetry in this B meso-genesis mechanism is related to
  - a leptonic charge asymmetry in neutral B decays, A_{SL}^{q}, which is another possibility.
- A dark particle can manifest itself in a decay of a B meson into a baryon + missing energy.
- It can also manifest itself in a decay of a b baryon into mesons + missing energy.

- At B factories, $B^+ \to \psi_D + p$ and $B^0 \to \psi_D + \pi^- + \Lambda_c^+$ are also excellent targets.
  - *BABAR* excluded more operator regions in $B^0 \to \psi_D + \Lambda$ and $B^+ \to \psi_D + p$ recently.
  - Belle II will examine the remaining regions.



PRL 131, 201801 (2023), arXiv:2306.08490

Summary

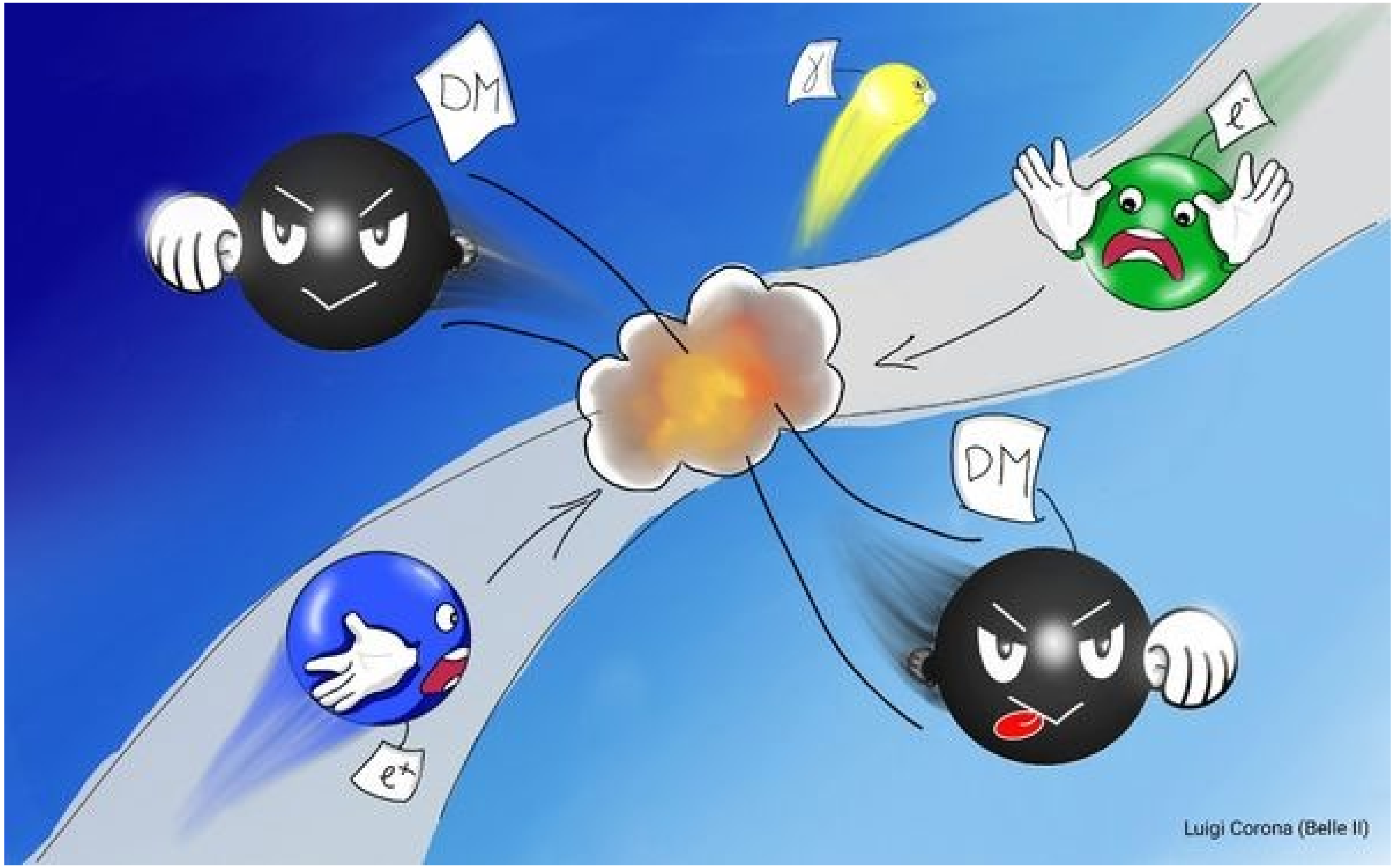
- e^+e^- B factories provide unique opportunities to study dark sector.
  - Belle and Belle II are actively producing search results in the field.

- SuperKEKB has achieved $L_{peak} = 4.7 \times 10^{34} cm^{-2} s^{-1}$, the world record at the end of Run 1 on June 22nd, 2022.
  - It is a super B factory and Belle II swung into the full mode for physics analyses.

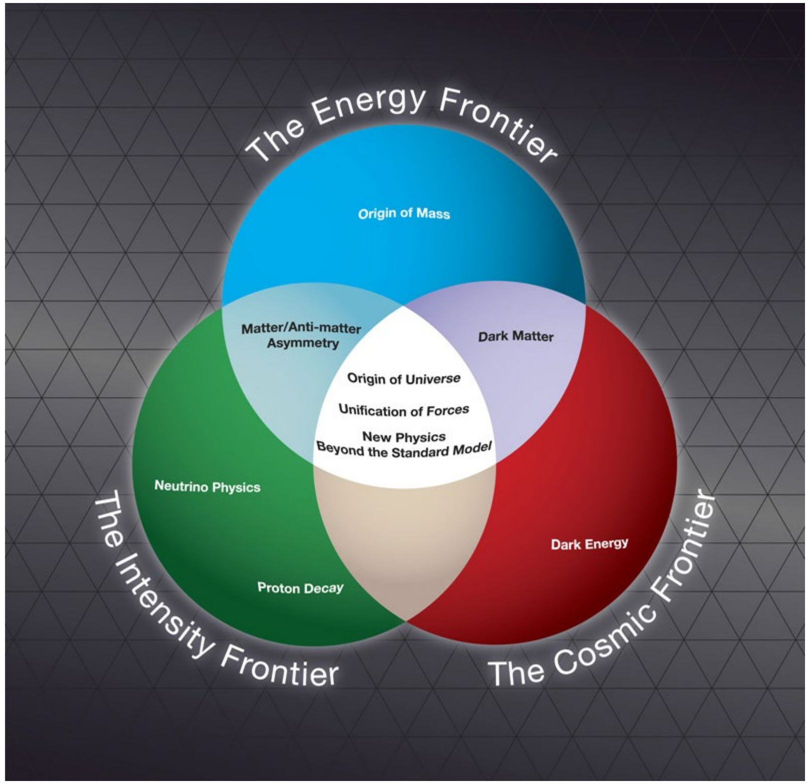
- B decays and τ channels became new search fields.
  - Many new possibilities are opened, both in theory and experiment.

- Belle II started Run 2 this year (2024). Please stay tuned for new search results beyond the Standard Model with the upcoming data, especially in the Dark Sector.

EXTRA

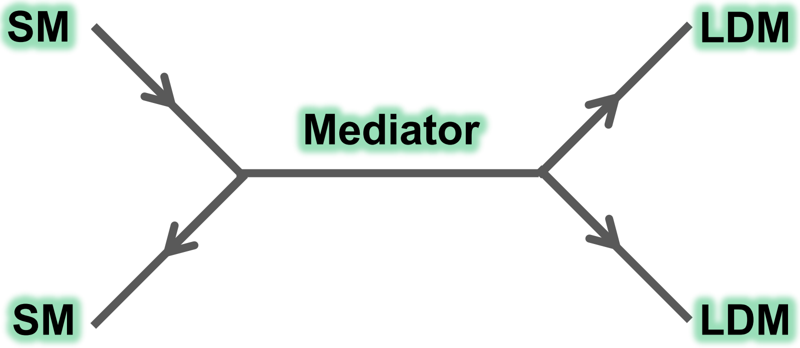


Three Frontiers

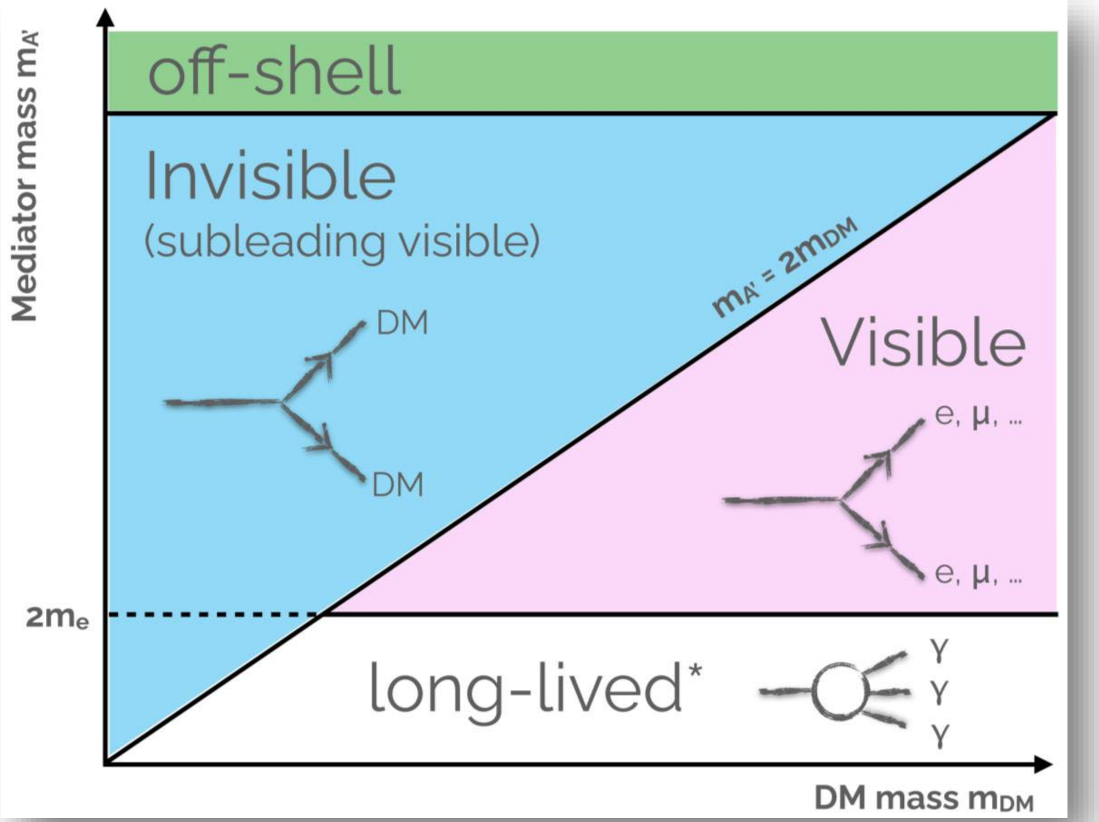


https://science.osti.gov/

- Energy Frontier possibilities
  - Dark particles can be directly produced by the LHC collider by exploiting high beam energy.
- Cosmic Frontier
  - Dark particle searches are active in underground labs, etc.
- **Intensity Frontier**
  - Theories propose interaction mediators between SM particles and Light dark mater (LDM).
  - Mediators enter into various portals, which are accessible at this frontier.



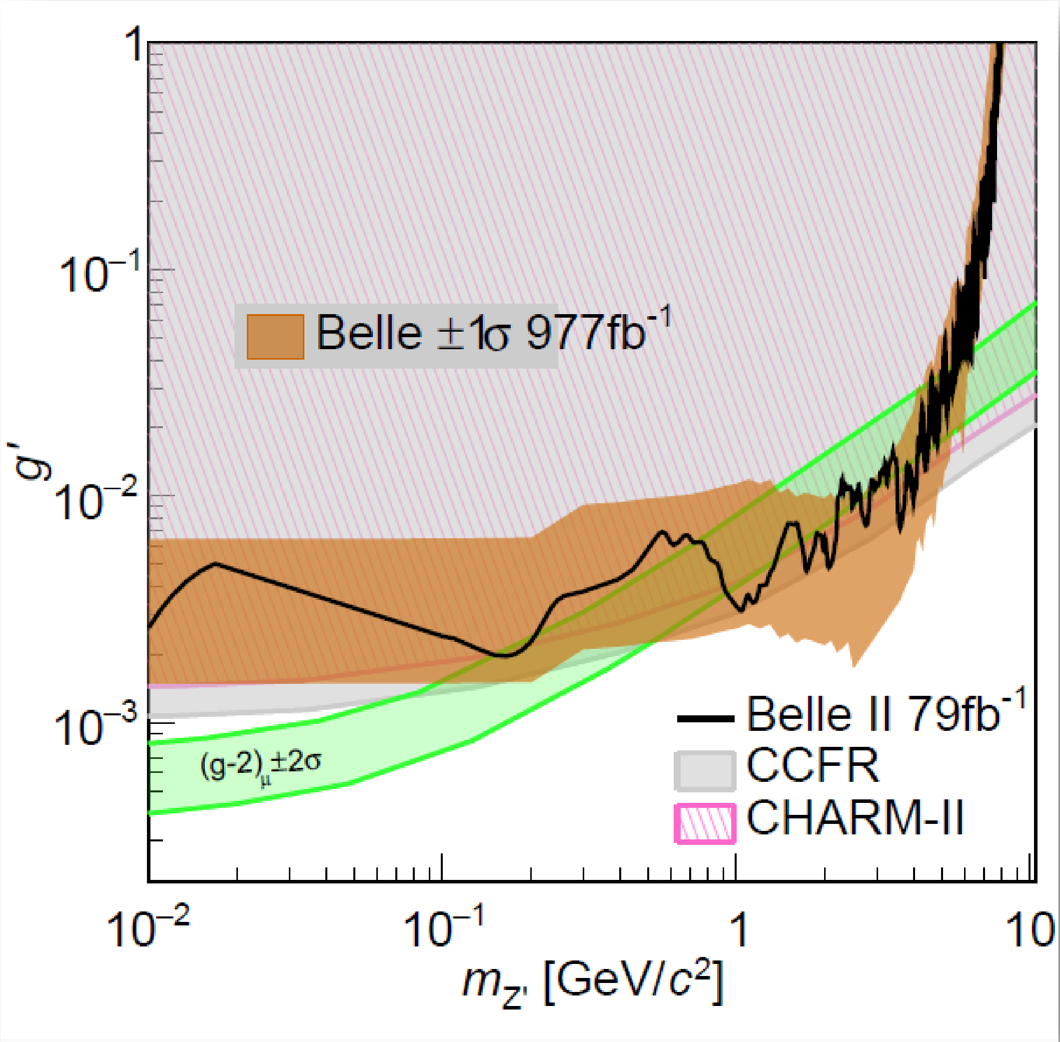
Dark Signatures at e+ e- Colliders



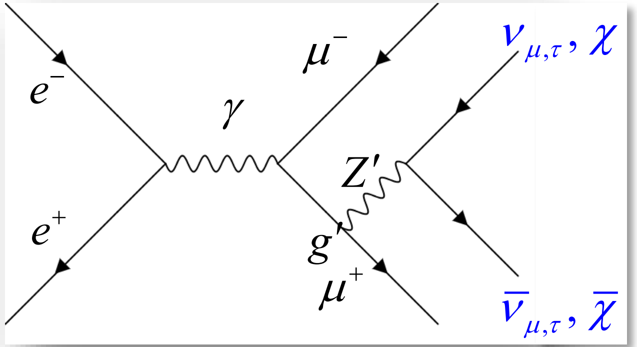
Search signature depends on the dark mediator mass

- $ll\,(\gamma)$ (+ 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

Search for Invisible Z': Belle vs Belle II



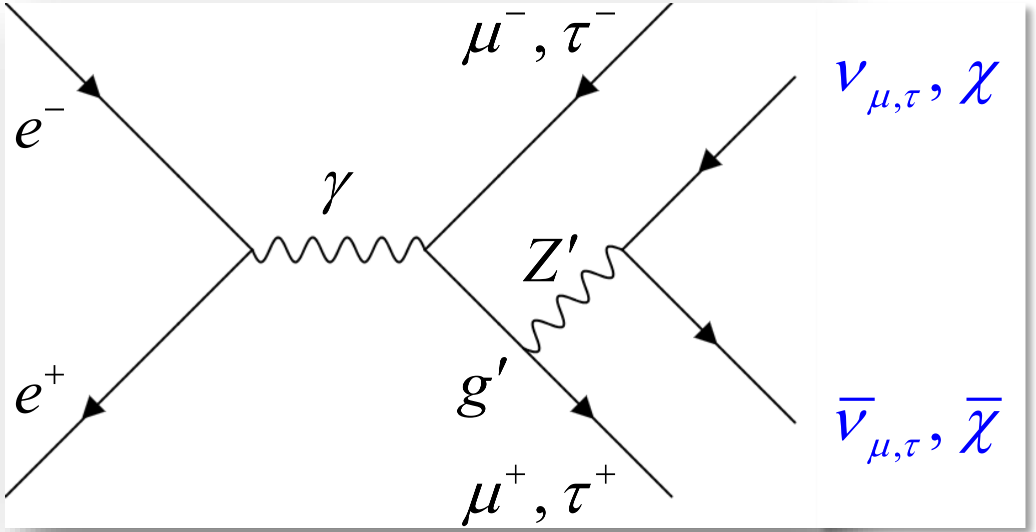
- **Belle preliminary** did the same search with the full sample.
- Comparison between Belle 977 fb^{-1} and Belle II 79.7 fb^{-1} shows the better sensitivity of Belle II.
- This is due to improvements built in the Belle II detector such as dedicated triggers.

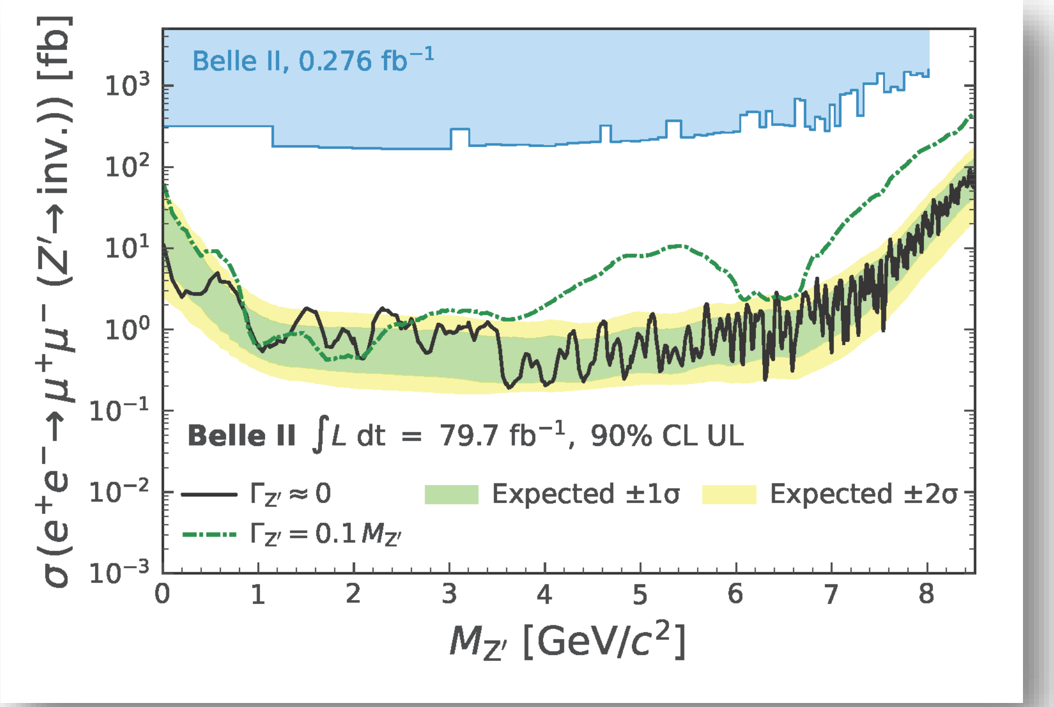


Search for Invisible Z': Belle II

- **Belle II** 79.7 fb^{-1}. No excess events are found in the recoil mass (Z' candidate).
- 90% CL upper limits on the cross-section and on g' are established.
- $(g-2)_\mu$ excluded from $0.8 < M(Z') < 5\ GeV/c^2$.

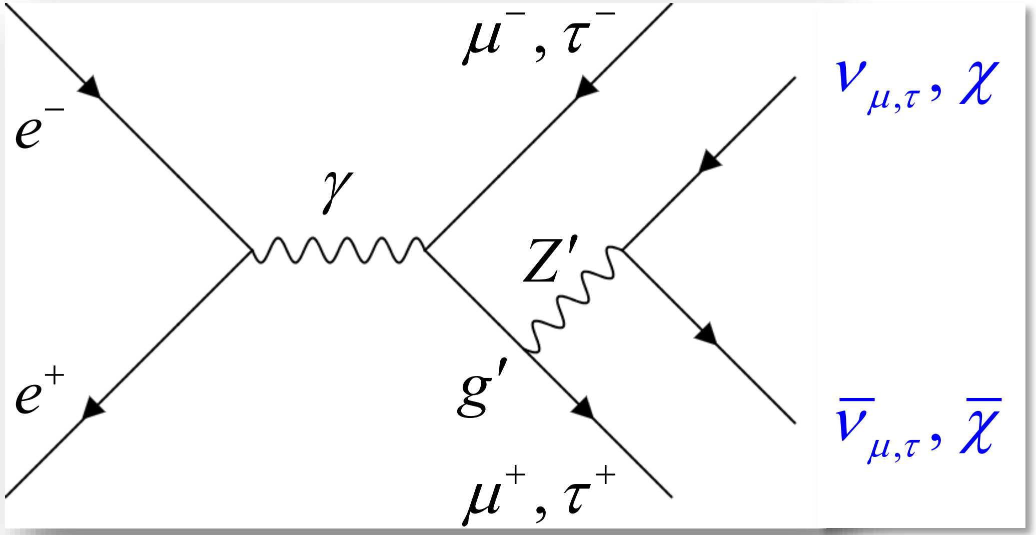
Fully invisible $L_\mu - L_\tau$ (100% decay to $\chi\bar{\chi}$)



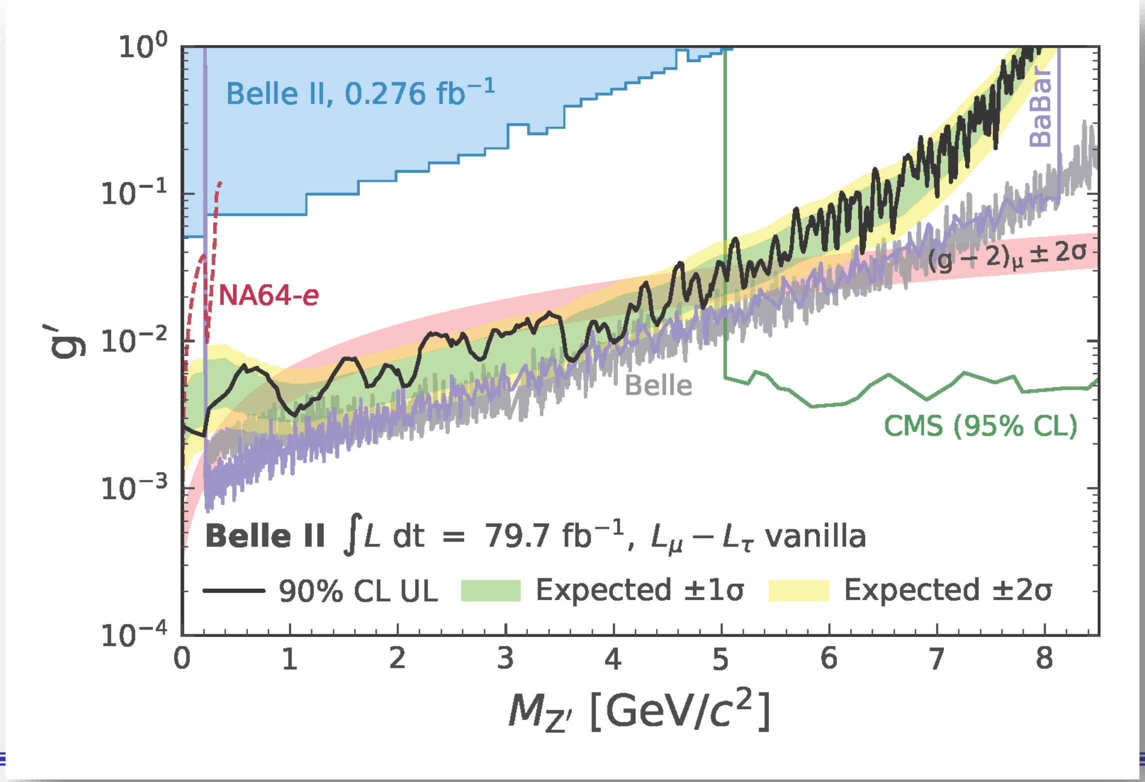


Search for Invisible Z'

- **Belle II** 79.7 fb^{-1}. No excess events are found in the recoil mass (Z' candidate).
- 90% CL upper limits on the cross-section and on g' are obtained.
- $(g-2)_\mu$ excluded from $0.8 < M(Z') < 5\ GeV/c^2$.

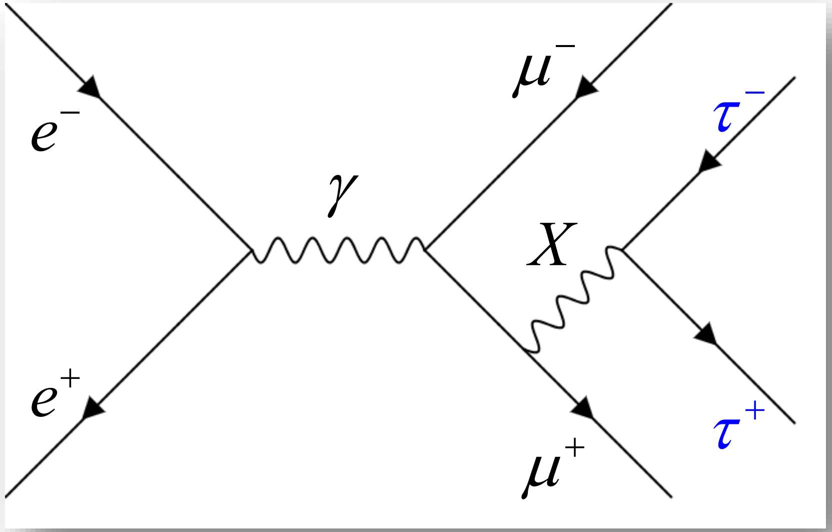


Z' decaying to Standard Model neutrinos

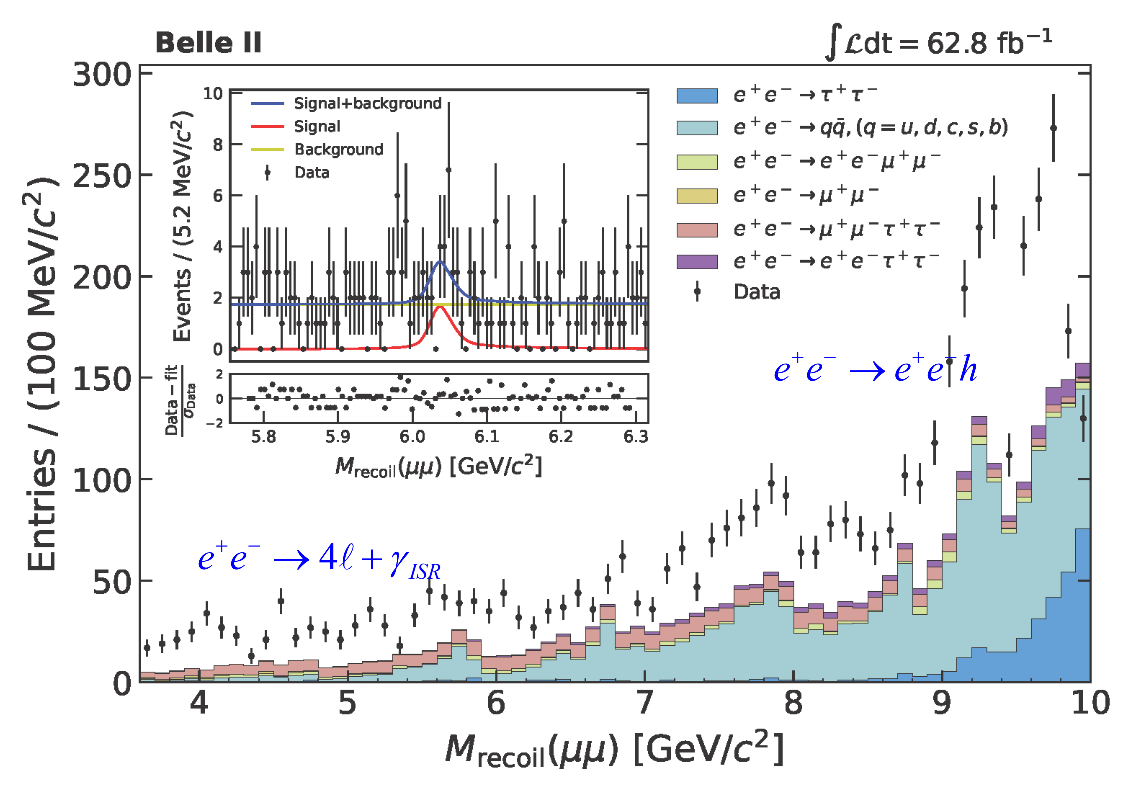


PRL 130, 231801 (2023)

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



- **Belle II**: Search for di-tau resonance in 4 lepton events.
  - Use tau decays to one charged track + neutrals
- Dominant backgrounds from 4 leptons are suppressed by requiring M (4 tracks) < 9.5 GeV/c^2
- Exploit the assumption that X is radiated from one muon.



- Discrepancies between data and simulation are coming from non-simulated or unmodeled processes.

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

- **Belle II** 62.8 fb^{-1}. No excess are found in the recoil mass.
- 90% CL upper limits on the cross-sections are obtained.

Z' - Altmannshofer et al., JHEP 12 (2016), 106

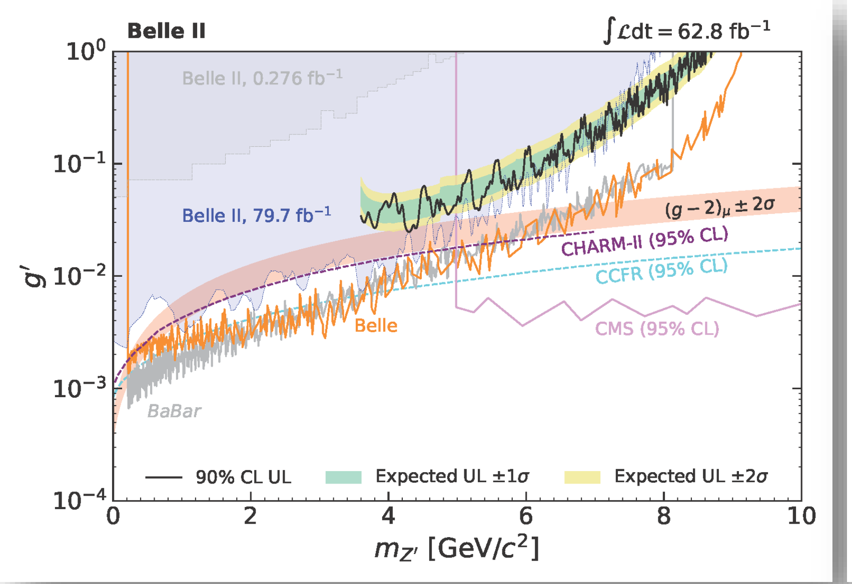
S - Batell et al., Phys. Rev. D 95, 075003 (2017)

ALP - Bauer et al., JHEP 12 (2017), 44

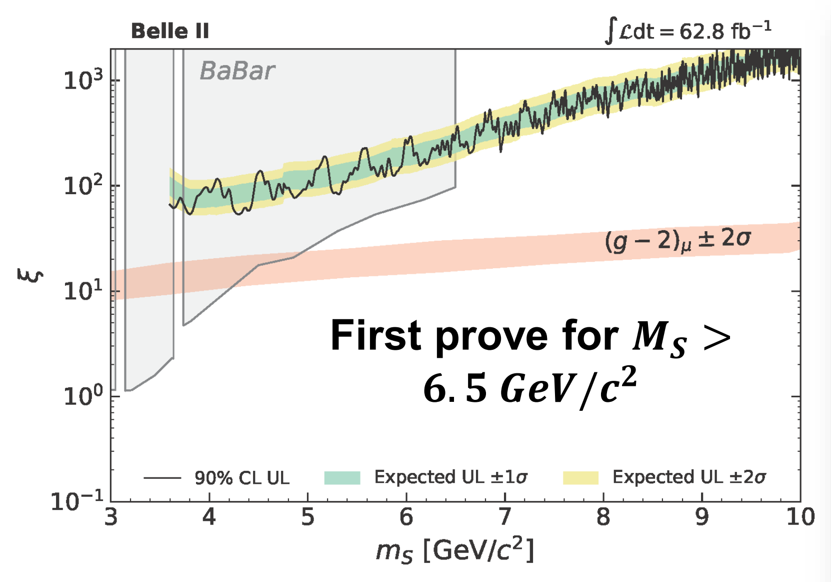
$$\sigma\left(e^+e^- \to \left(X \to \tau^+\tau^-\right)\mu^+\mu^-\right) = \sigma\left(e^+e^- \to X\mu^+\mu^-\right)\sigma\left(X \to \tau^+\tau^-\right), \quad X = S, \mathrm{ALP}, Z'$$

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

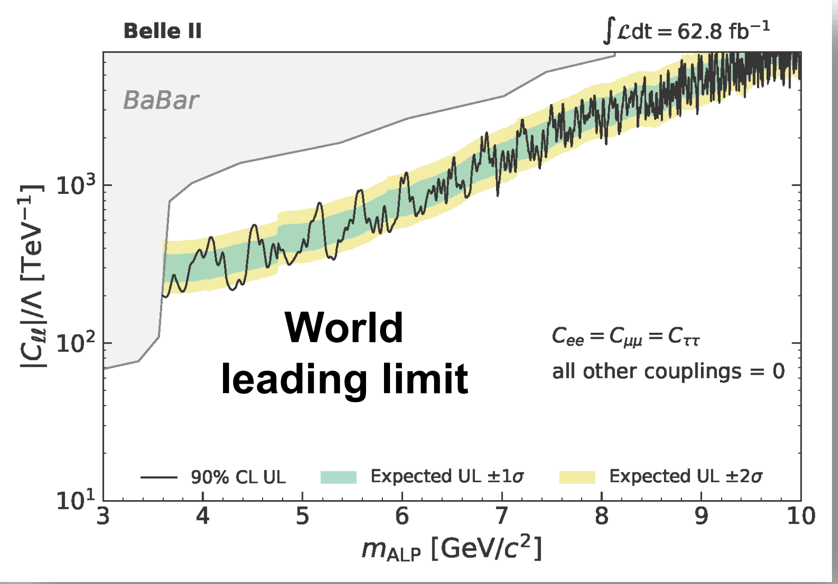
Z'



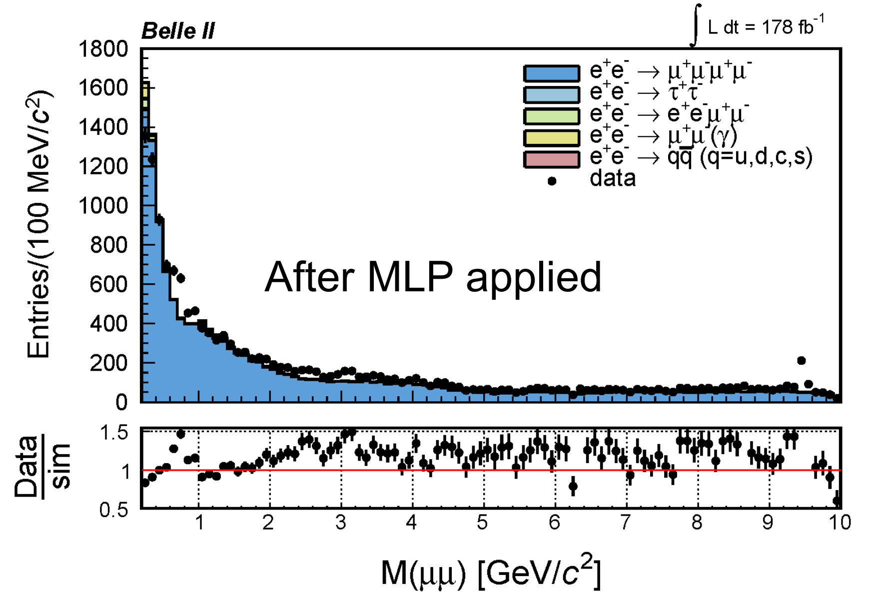
Leptophilic scalar (S)

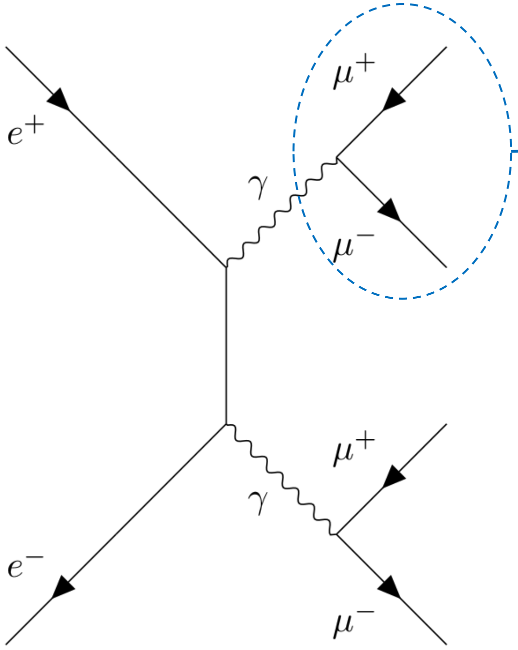


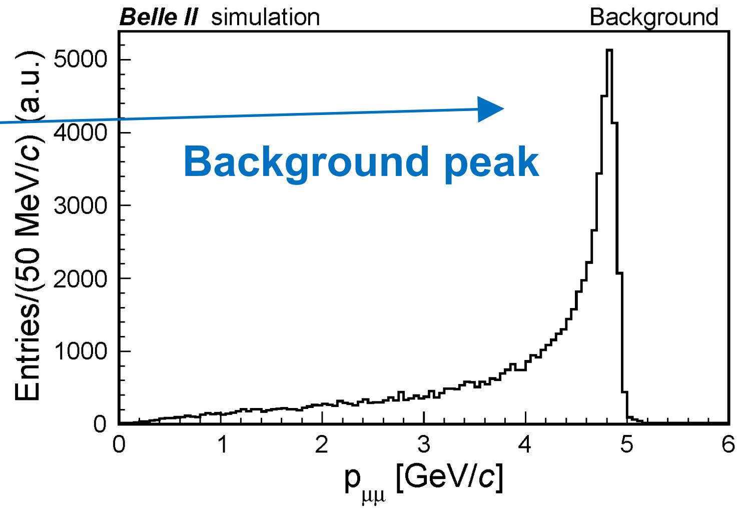
ALP

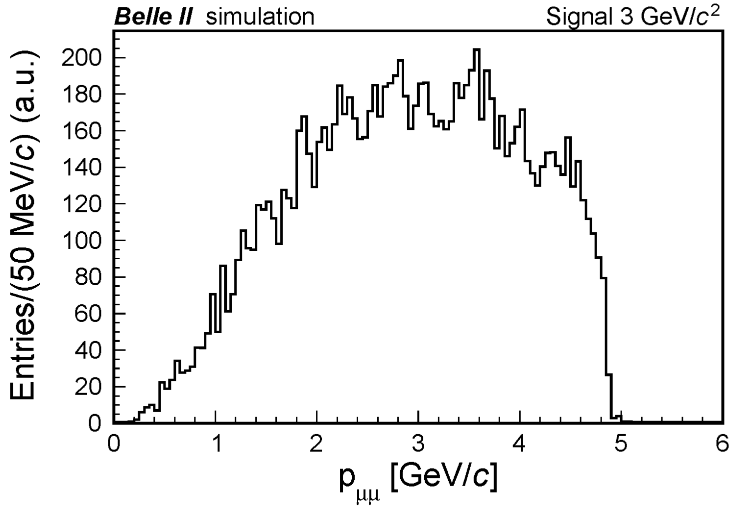


Search for X in $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$







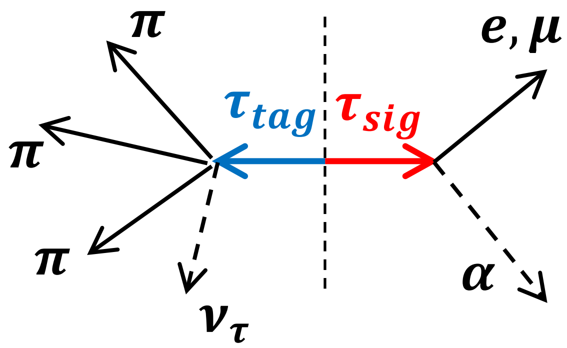


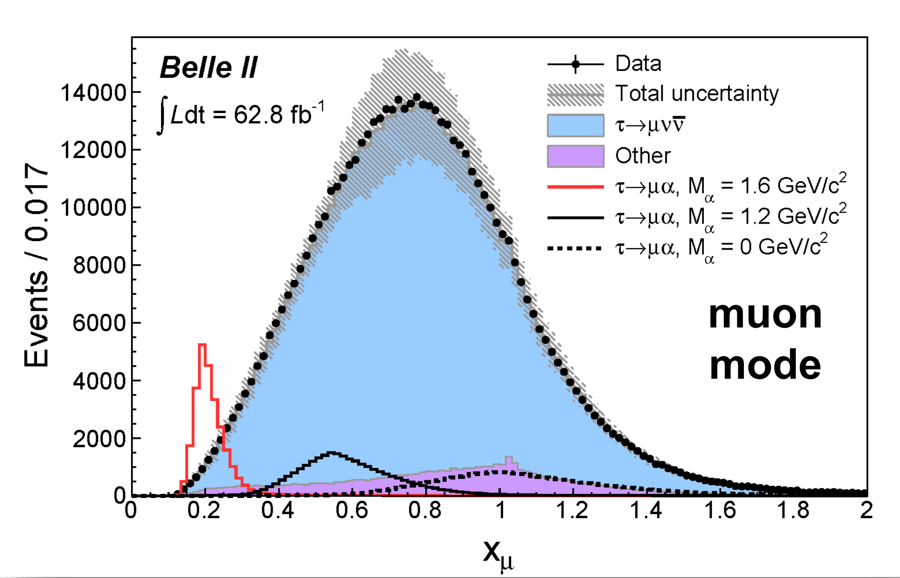
- **Belle II** 178 fb^{-1}: The aim is to find a di-muon resonance in 4 lepton events.
- Multi-layer Perceptron (MLP) is applied to suppress background peaks.
  - Signal production mechanism and background kinematics are considered.

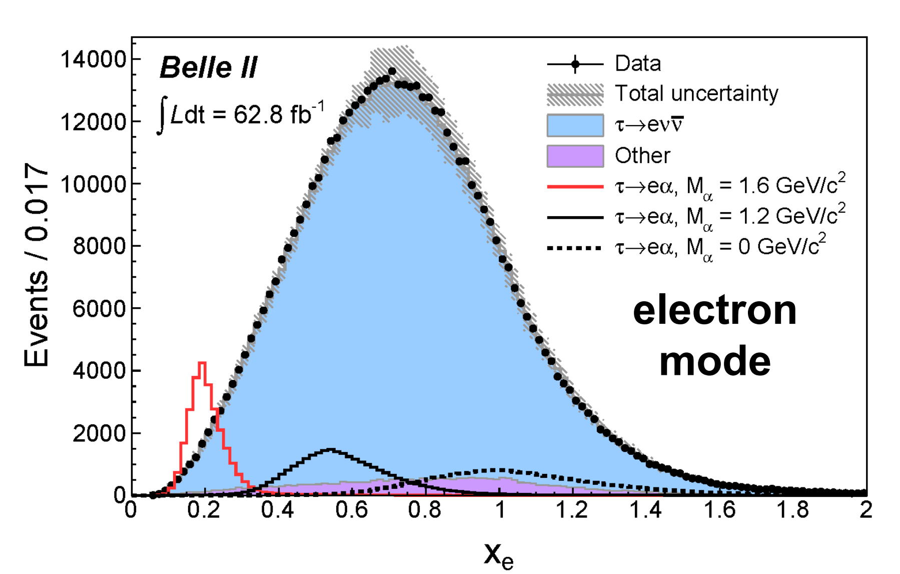
Search for $\tau \to l\, \alpha$, α invisible

- **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.
- The observable is the normalized lepton energy in the tau pseudo rest frame:

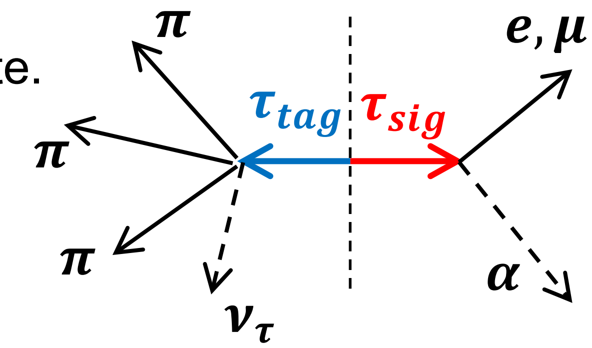
$$x_\ell \equiv \frac{E_\ell^*}{m_\tau c^2 / 2}$$



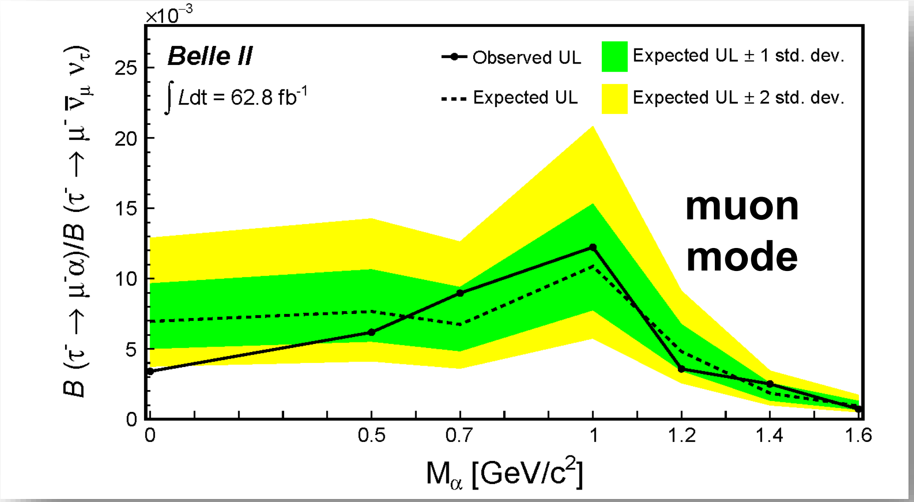


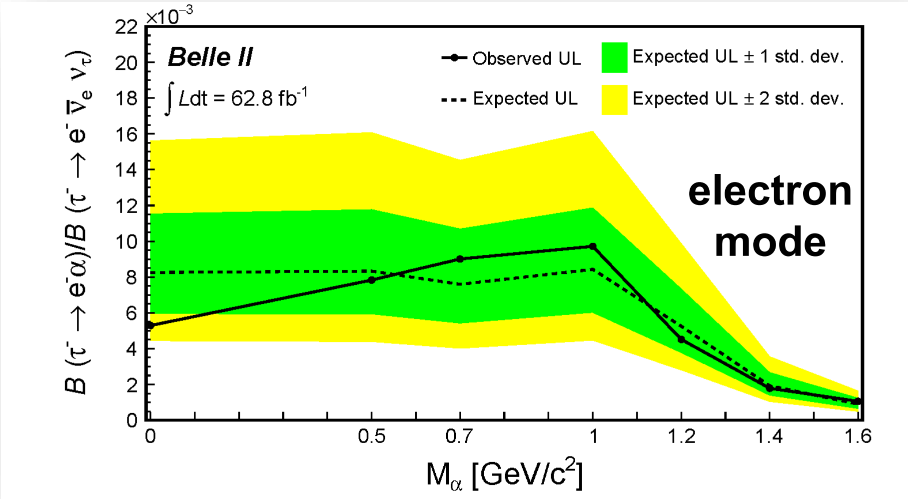


Search for $\tau \to l\,\alpha$, α invisible



- **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 (two-body decay. BG is 3-body).
- 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 (1995) due to luminosity 120 times.





EXTRA: BELLE II

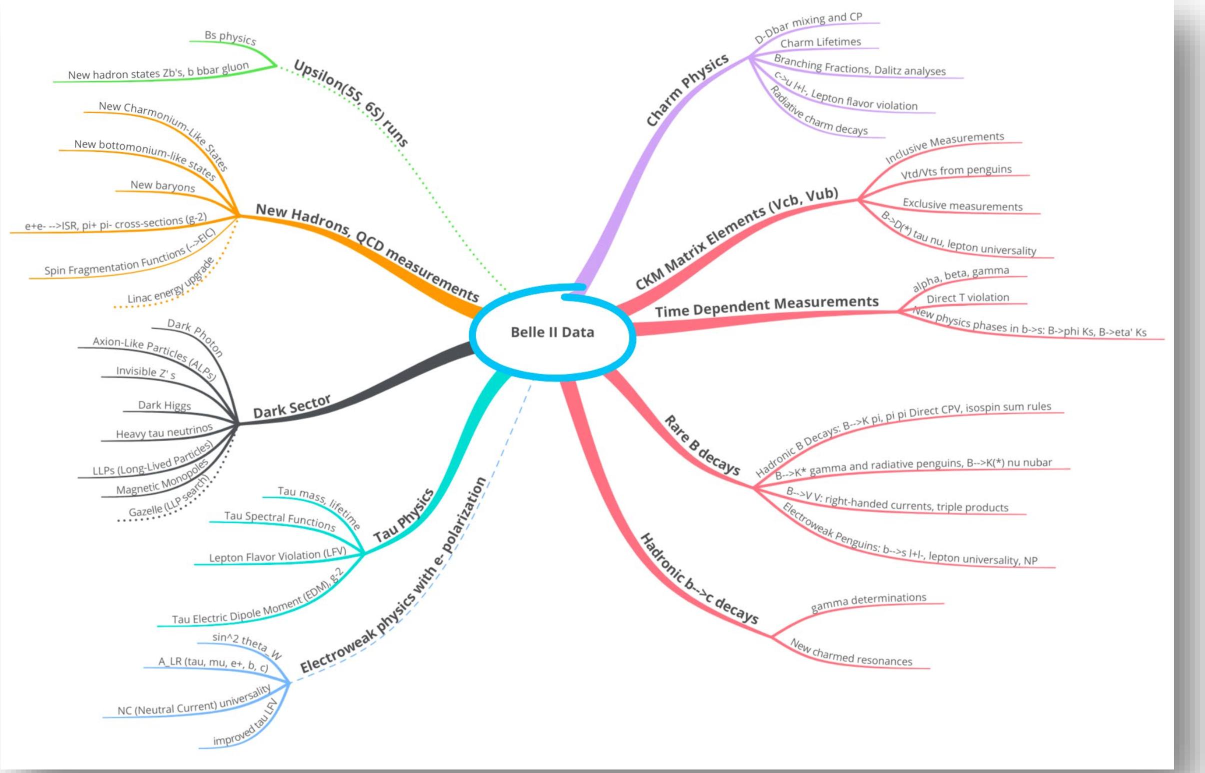
Belle II Experiment in a Nutshell

- 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, which requires 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 in the closed Belle II detector.
- Direct detection of neutrals such as γ, π^0, K_L is highly efficient.
- 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 qualities.
  - For example, search for LFV τ decays at $O(10^{-9})$ possible.

Belle II Physics Prospects

- 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

https://www.belle2.org/info/snowmass2021/

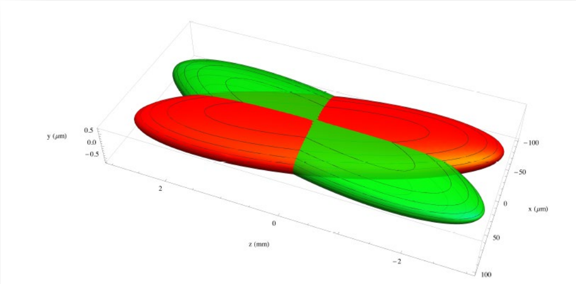


Belle II Physics Book, PTEP 2019, 123C01

KEKB to SuperKEKB: Accomplished

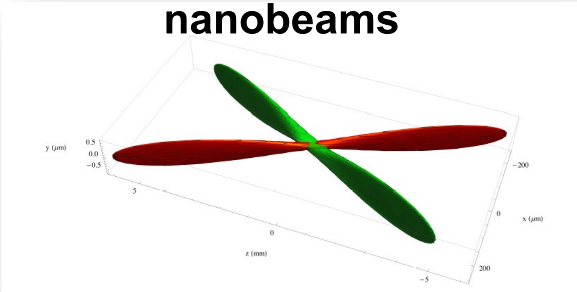
- Nano beam scheme + Crab waist optics
- Target: vertical beta function β_y^* 5.9 mm (KEKB) to 0.3 mm (SuperKEKB)
- Increase beam currents $I_{e\pm}$
- Increase beam-beam interaction ξ_y

KEKB beams

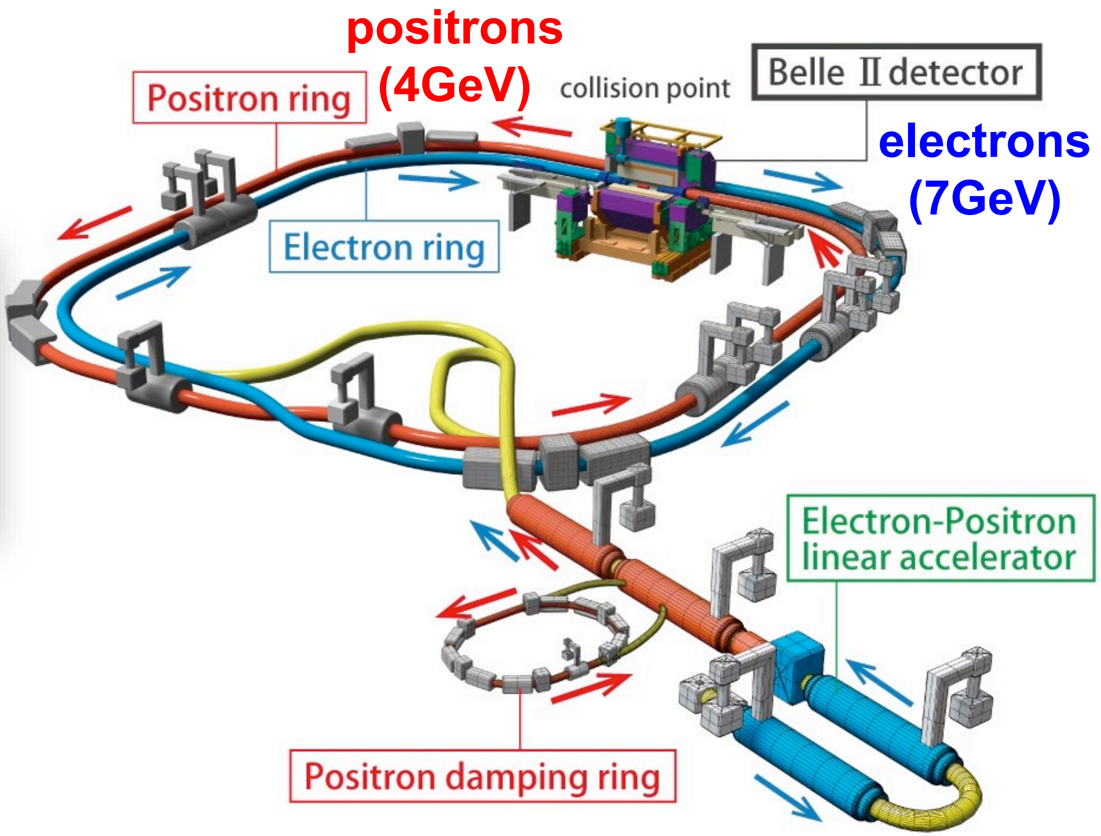


Beam crossing angle 22mrad

SuperKEKB nanobeams



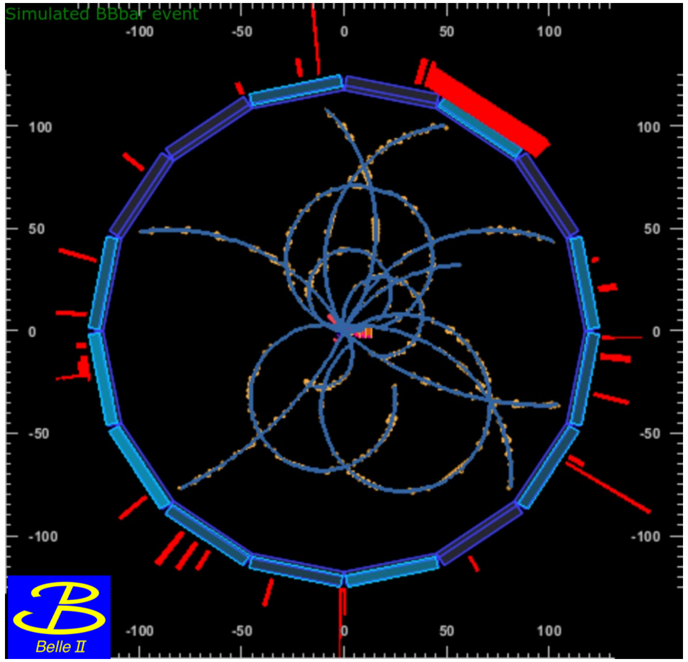
Beam crossing angle 83mrad



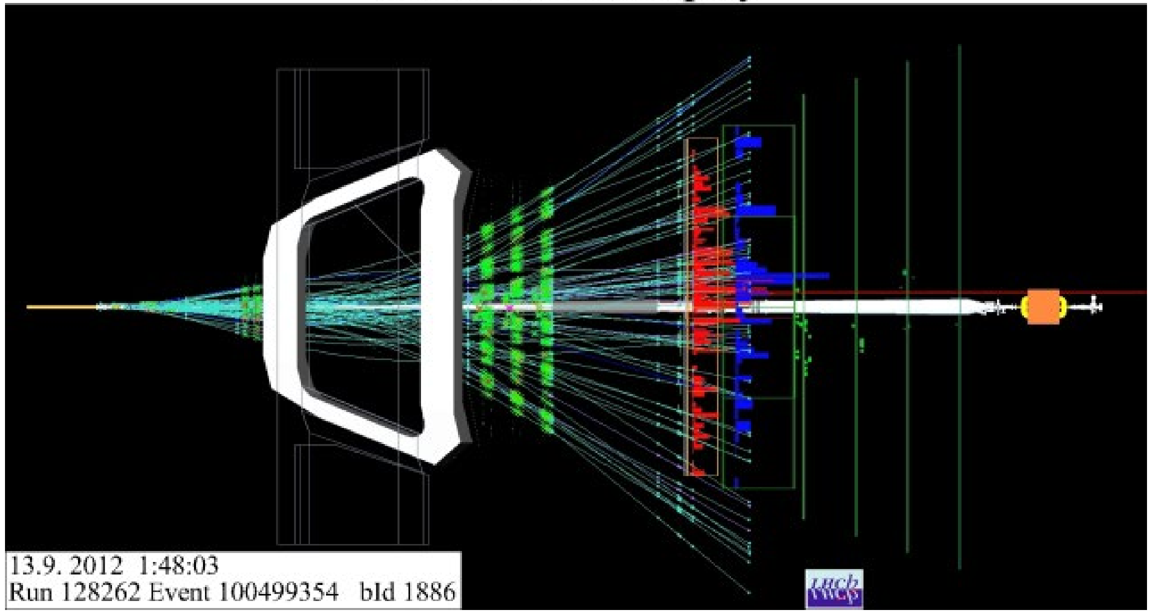
$$L = \frac{\gamma_{e\pm}}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\cdot\xi_{y,e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

Belle II and LHCb

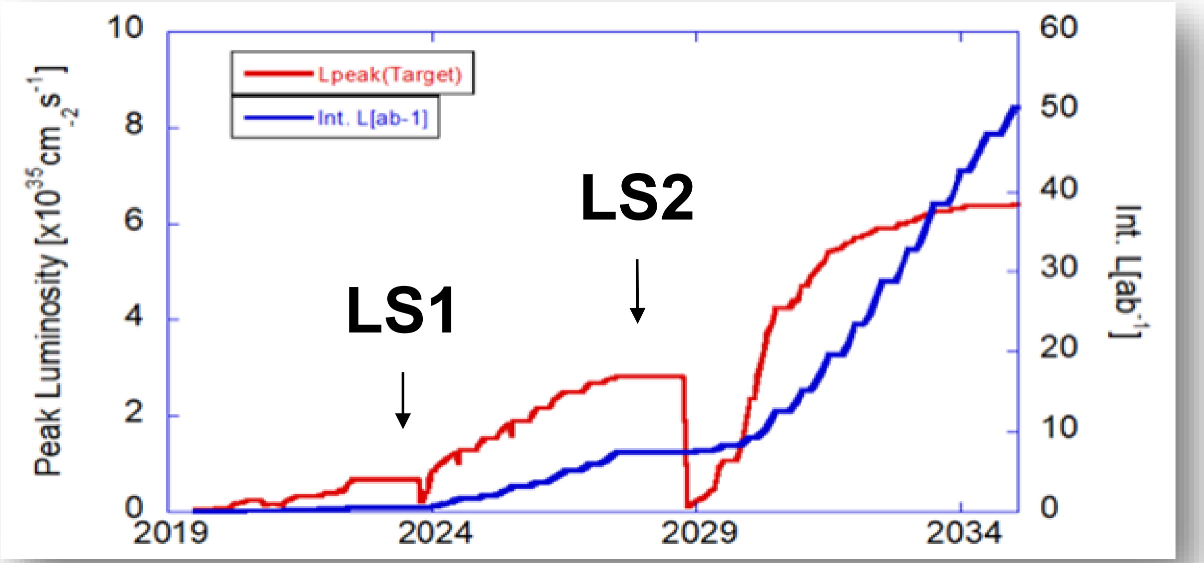
- Belle II and LHCb have different systematics
  - Two experiments are required to establish New Physics.
  - LHCb: large $b\bar{b}$ cross-section (LHCb 1 fb^{-1} ~ Belle II 1 ab^{-1}). Good sensitivity and S/N with di-muon modes and charged tracks with a vertex.



LHCb Event Display



Belle II Future Plan



- Medium term: another long shutdown (LS2) is planned after 2027-2028
  - Upgrade of interaction region is being considered.
- Long term: Chiral Belle (polarized beam) scheme is proposed.
- Belle II announced the FCDR document, arXiv:2406.19421