La Thuile 2025

Les Rencontres de Physique de la Vallée d'Aoste
March 12, 2025

Tau and dark sector physics at Belle and Belle II

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on behalf of the Belle and Belle II collaborations

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Belle and Belle II experiments

B-factory concept

Experiments at symmetric e^+e^- colliders running mostly at the Y(4S) energy (=10.58 GeV), located at Tsukuba (JP).

- **KEKB (1998-2010)**
- **Super KEKB: major upgrade of KEKB (2019-ongoing)**
  - Target world highest instantaneous luminosity
    - 6×10^{35} cm^{-2}s^{-1} (x30 KEKB)
    - So far, world instantaneous luminosity of 5.1×10^{34}cm^{-2}s^{-1}

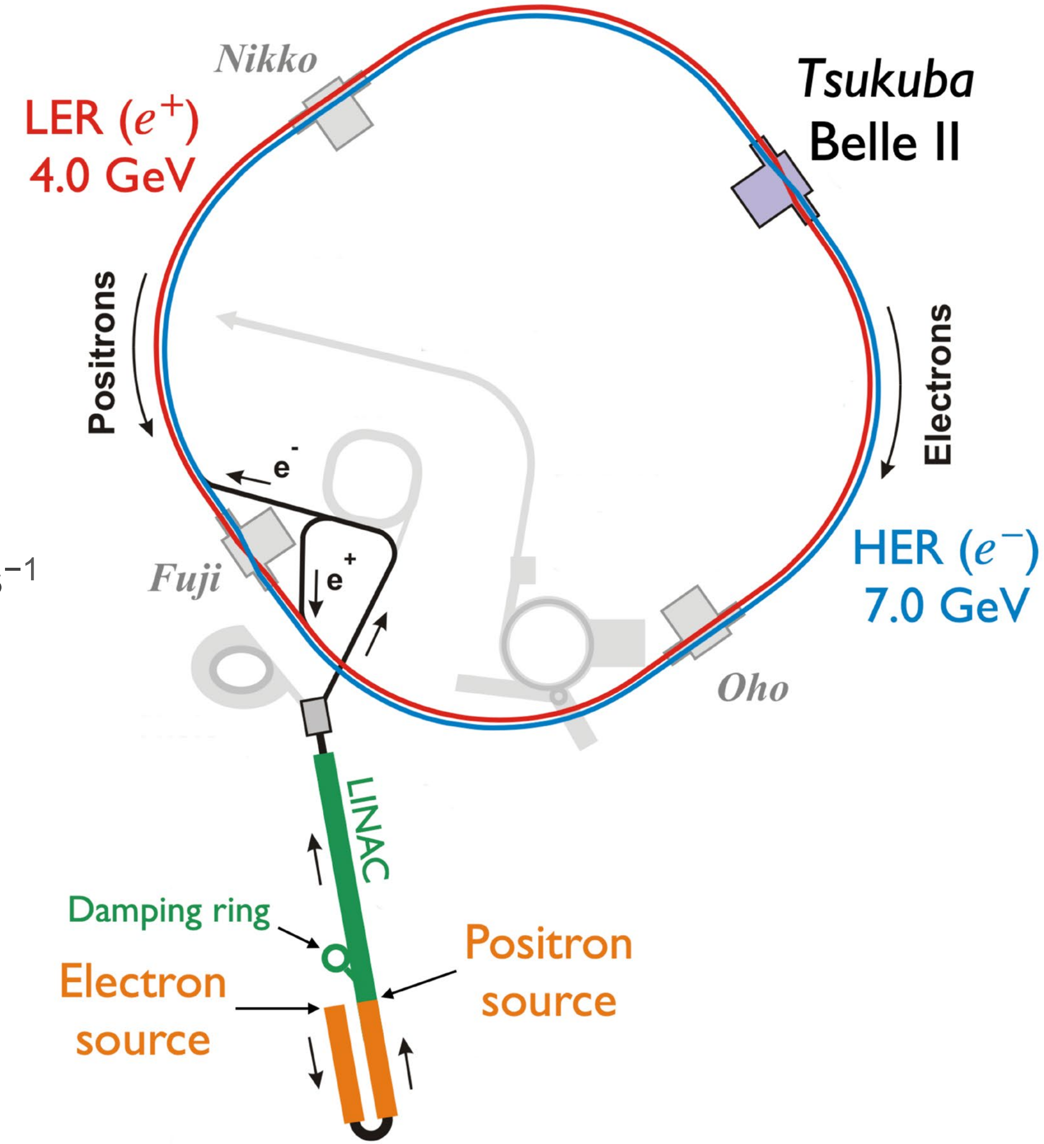
✓ **Available datasets: 1 ab^{-1} @Belle, 0.6 ab^{-1} @Belle II**

➢ **Rich physics program**

- **beauty, charm, *τ* and dark sector**

see
M. Veronesi talk

covered in this talk
and
F. Trantou young talk



Belle and Belle II experiments

Prog. Theo. Exp. Phys. 12 (2019)

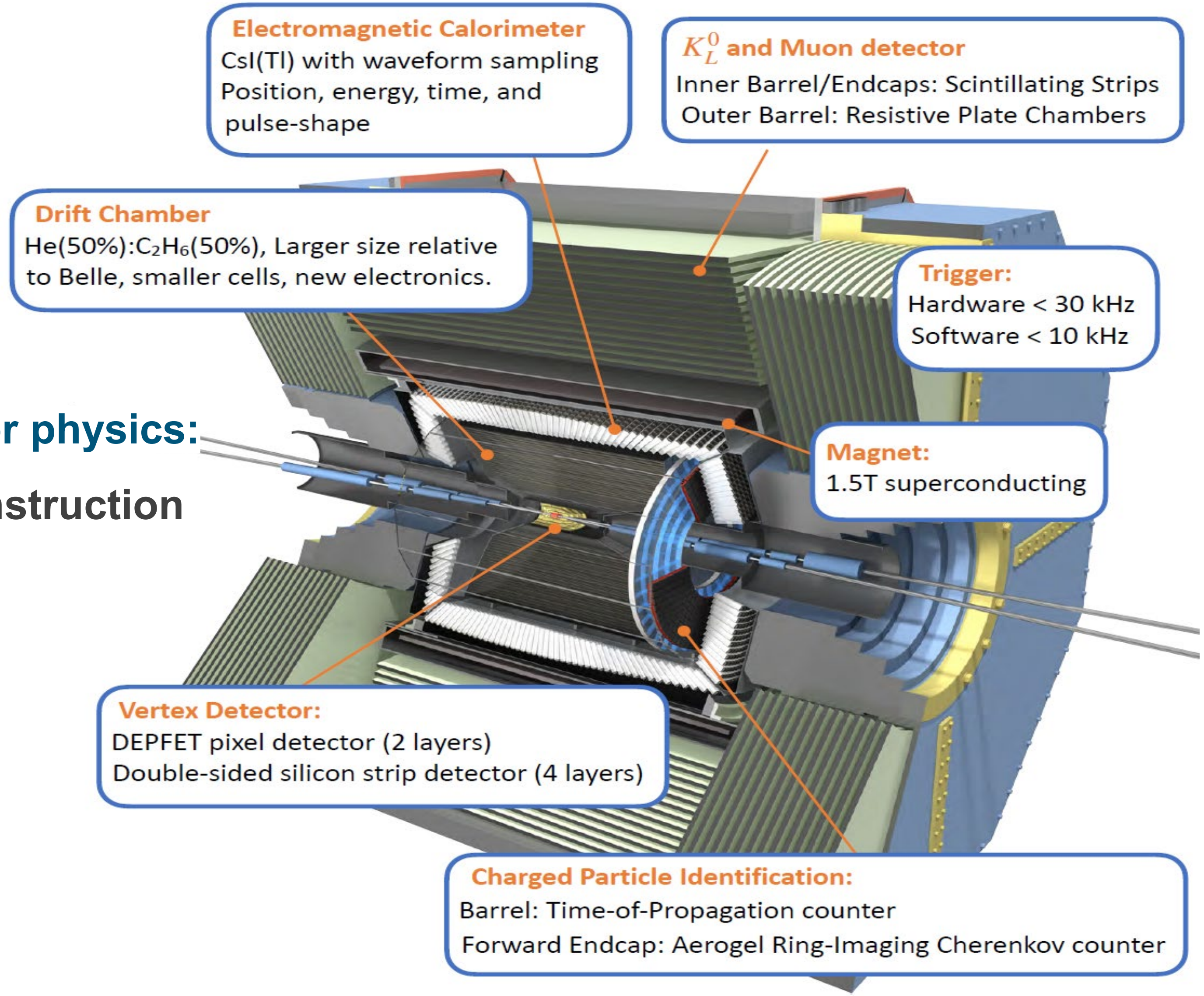
Detector overview

General purpose detectors

- Belle II is the major upgrade of Belle detector
  - Better resolution, particle identification and capability to cope with higher background

✓ Excellent capabilities for tau and dark sector physics:

- **Good missing energy and neutral reconstruction**
  - Well defined initial state
  - Hermetic detector coverage (almost 4π)
  - Clean environment
- **Good particle identification**
- **Excellent vertexing and tracking**
- Special **triggers dedicated to low-multiplicity events (@Belle II)**



Tau searches

Tau physics at Belle and Belle II

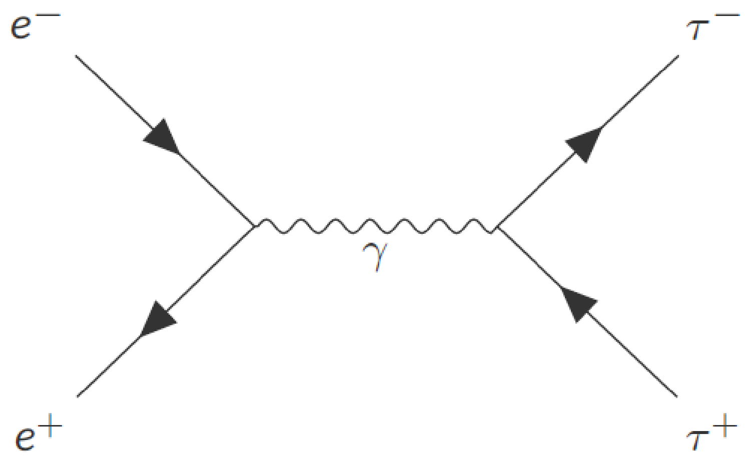
Overview

B-factories produce τ leptons pairs at high rate

- τ pairs cross-section equivalent to *BB* process

$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\,nb$$

$$\sigma(e^+e^- \to B\bar{B}) = 1.05\,nb$$



➢ **B-factories are also τ factories!**

➢ **Broad range of available measurements**

✓ **Precision measurements of τ properties**
- lifetime
- mass
- coupling (universality)

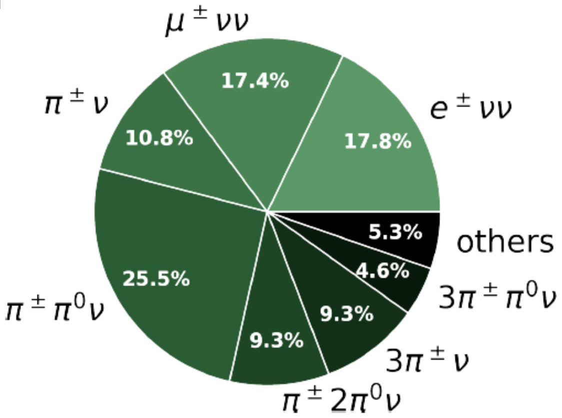
✓ **Searches for rare or forbidden processes**
- Mostly lepton flavor violating τ decays

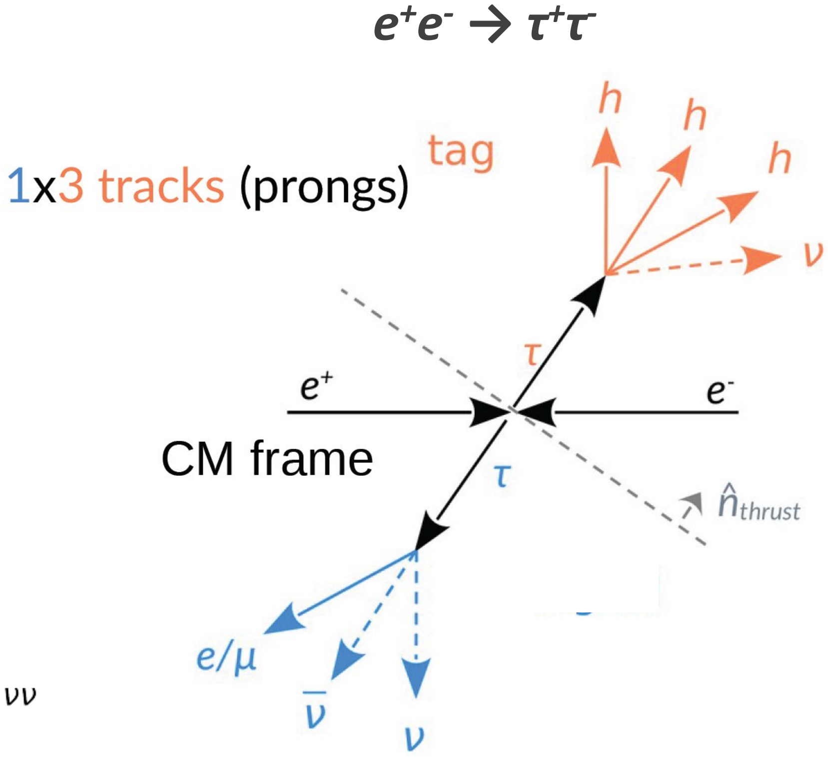
Tau physics at Belle and Belle II

Overview

Produced in pairs, back to back and boosted in the center-of-mass frame

- Identify events by reconstructing the thrust axis n_T (maximizes thrust T)
- Separate them in two opposite hemispheres
- Typically use one side to **tag** the event by reconstructing decays with
  - 1 charged track (1-prong) (BF ~ 81%) or
  - 3 charged tracks (3-prong) (BF ~ 14%)
- Reconstruct **signal** on other hemisphere





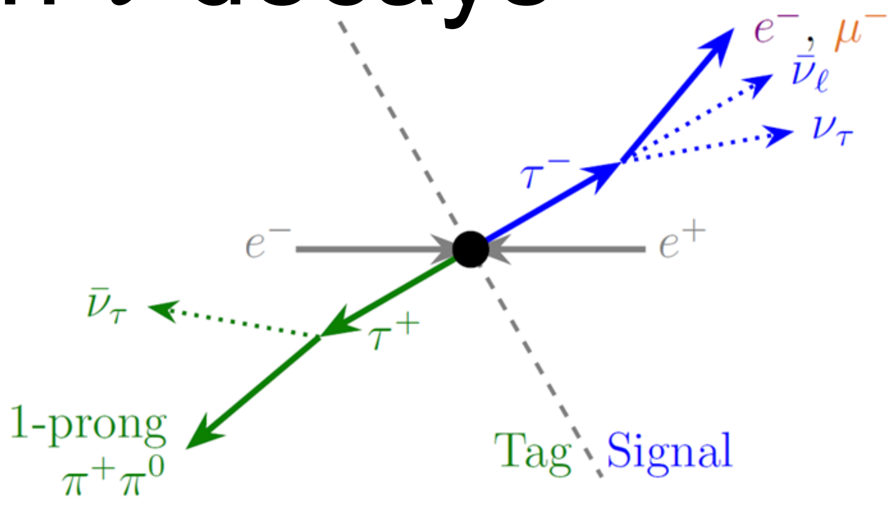
$$T = \max_{\hat{n}_T}\left(\frac{\sum_i |p_i \cdot \hat{n}_T|}{\sum_i |p_i|}\right)$$

Lepton Flavor Universality in τ decays

Overview

Test of ***μ-e* universality** in the τ decays

$$R_\mu = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \stackrel{\text{SM}}{=} 0.9726 \qquad \left(\frac{g_\mu}{g_e}\right)^2_\tau \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \stackrel{\text{SM}}{=} 1$$



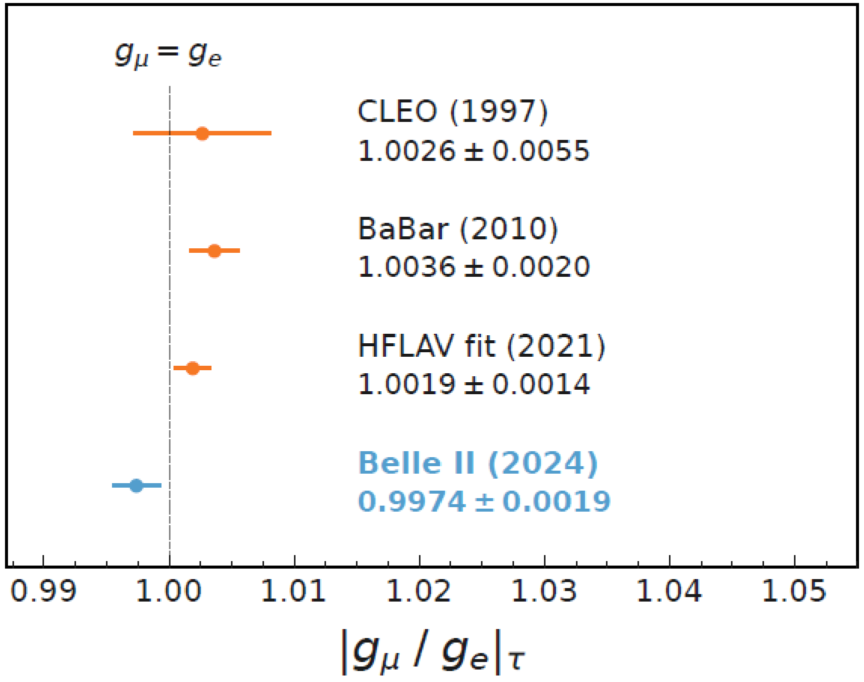
JHEP08(2024)205

R_μ measured in **1x1 prong topology** with $\pi^- + n\pi^0$ tag by Belle II with 365 fb^{-1}

Rectangular cuts and a neural network selection

- **94% purity with 9.6% signal efficiency**

Main systematics are from PID (0.32%) and trigger (0.1%)



$\boldsymbol{R_\mu}$ **= 0.9675 ± 0.0007 (stat.) ± 0.0036 (sys.)**

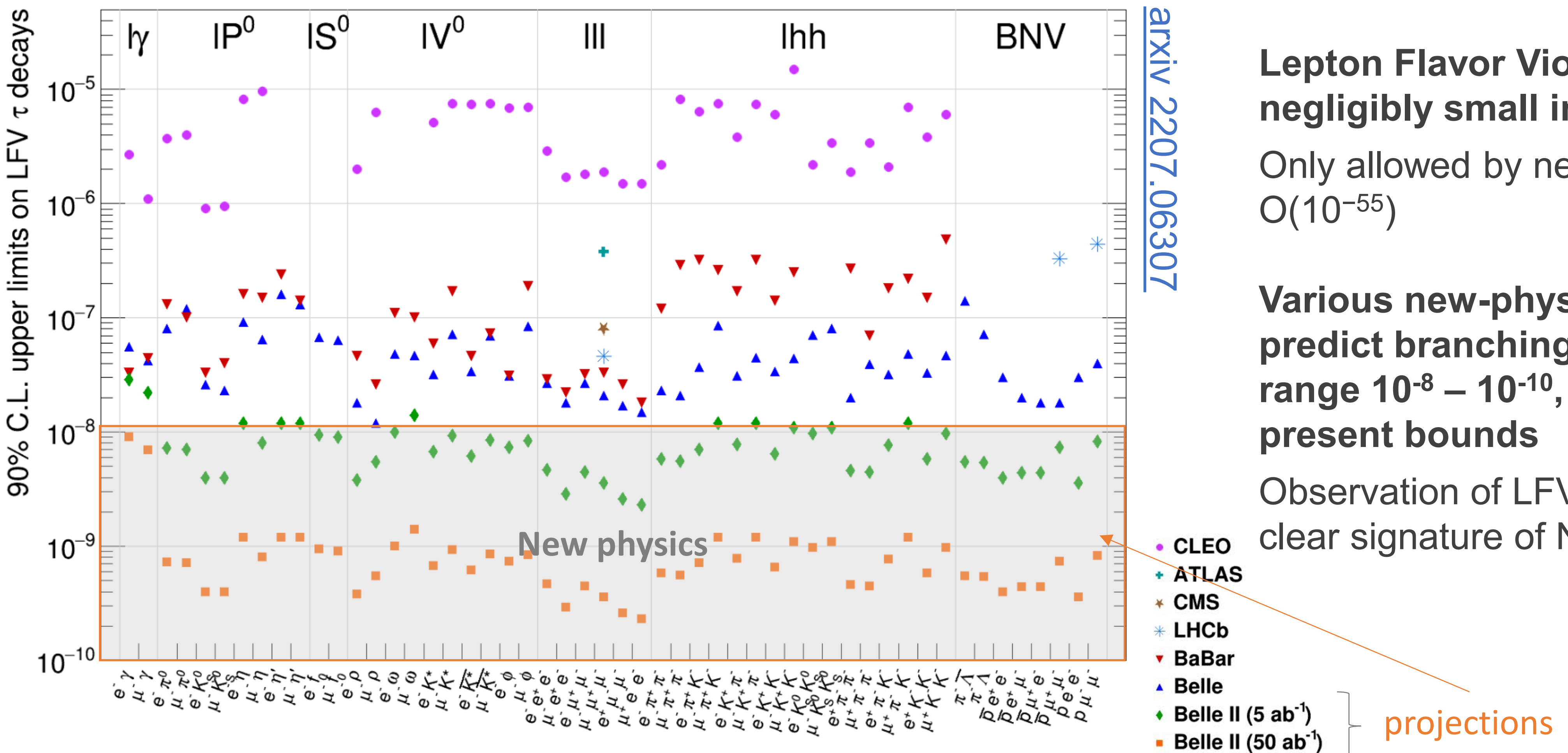
✓ **Most precise test of *e-μ* universality in τ decays from a single measurement**

✓ Consistent with SM expectation at the level of 1.4σ

Lepton Flavor Violation searches

Motivations

Existing and expected limits on LFV $\tau\tau$ decays



Neutrinoless 2-body or 3-body decays to **52 final states**.

Lepton Flavor Violation (LVF) is negligibly small in SM

Only allowed by neutrino oscillations $O(10^{-55})$

Various new-physics models predict branching fractions in the range 10^{-8} – 10^{-10}, i.e. just below the present bounds

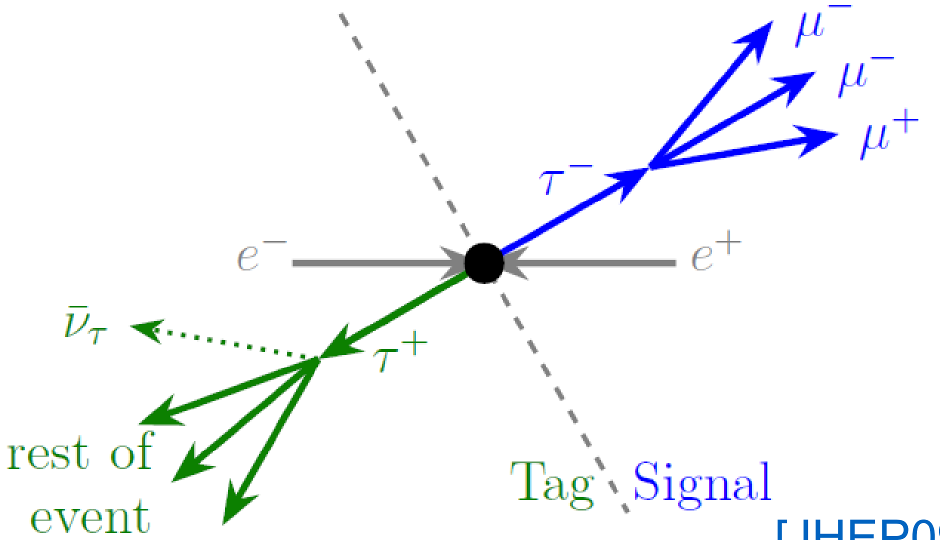
Observation of LFV decays would be a clear signature of New Physics

$\tau \rightarrow 3\mu$

Results

Belle II search for the clean channel: $\tau \rightarrow 3\mu$
- Good reconstruction of τ mass end energy
- Low SM background

Already probed by Belle and LHC experiments

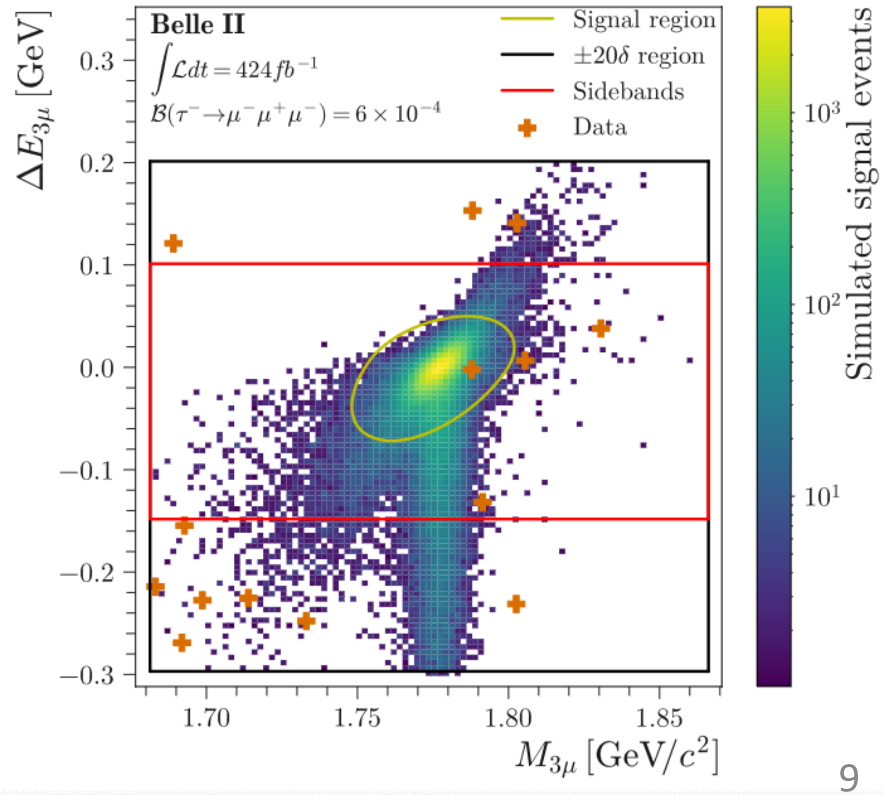


[JHEP09(2024)062]

Use untagged reconstruction

3 well identified muons on the signal side and BDT classifier to reject the main $e^+e^- \rightarrow qq$ backgrounds
- x3 efficiency compared to Belle

Extract signal yield from 2D plane ($M_{3\mu}$, $\Delta E_{3\mu} = E_\tau - E_{beam}$)
- 1 event in the signal region in 424 fb^{-1} consistent with data-driven background prediction (0.5 events)



Set 90% CL upper limits: $B(\tau \rightarrow 3\mu) < 1.9 \times 10^{-8}$

✓ **New most stringent results**

$\tau \to e2\ell$

new result

Results

Extend previous study to 5 more modes:
with at least one electron in the final state

- $e^-e^+e^-$, $e^-e^+\mu^-$, $e^-\mu^+e^-$, $\mu^-\mu^+e^-$, $\mu^-e^+\mu^-$
  - **Higher background contamination**

Use **untagged reconstruction**

Data driven BDT classifier trained on sideband in data

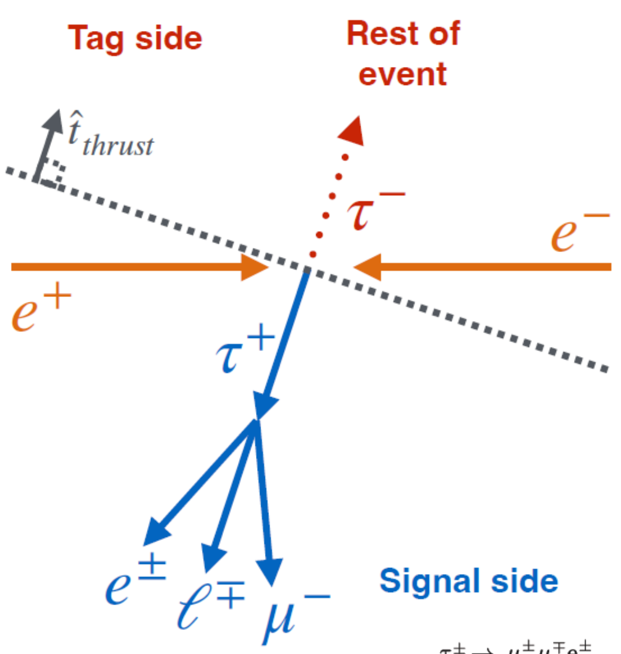
- Rely on rest of event and kinematic variables
- Reject the main four leptons backgrounds

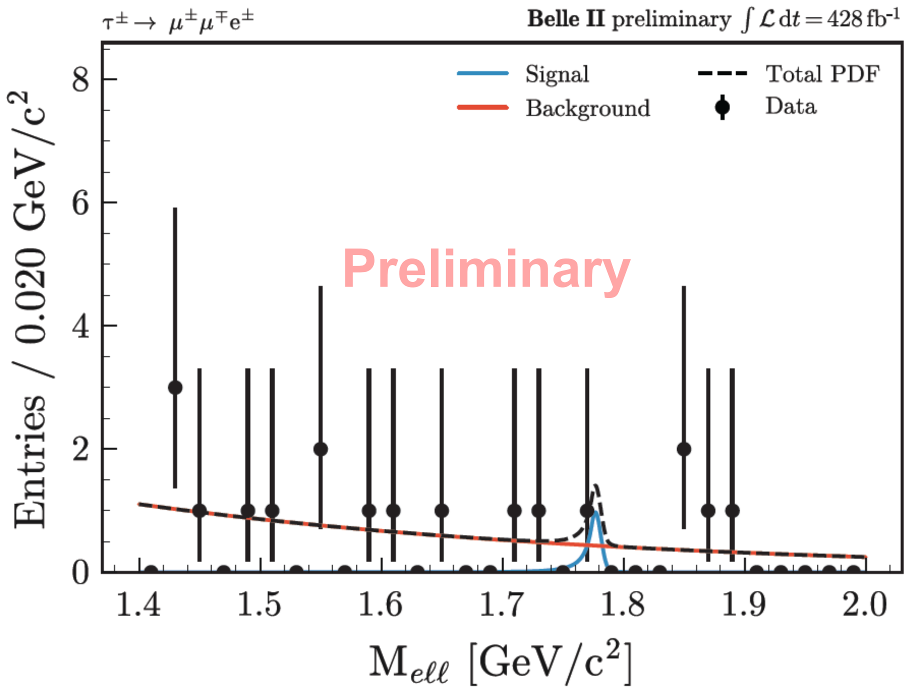
Signal extracted by fitting M_{ell}

No significant excess was observed in 424 fb^{-1}

- **Set 90% CL upper limit on BF in all the modes:** $\sim \mathbf{1-3\times 10^{-8}}$

✓ **Most stringent upper limit on all modes**





$\tau^- \to \ell^- K_S^0$ new result

Results

Belle + Belle II search for $\tau^- \to \ell^- K_S^0$ (ℓ=e, μ)

Reconstruct 4 charged particles (0 net charge) in **1x3 topology**

- K_S^0 reconstructed from $\pi^+\pi^-$

Preselection rectangular cuts and BDT classifier

- Use track kinematics, event shape and neutral variables
- Resulting efficiency: 10%

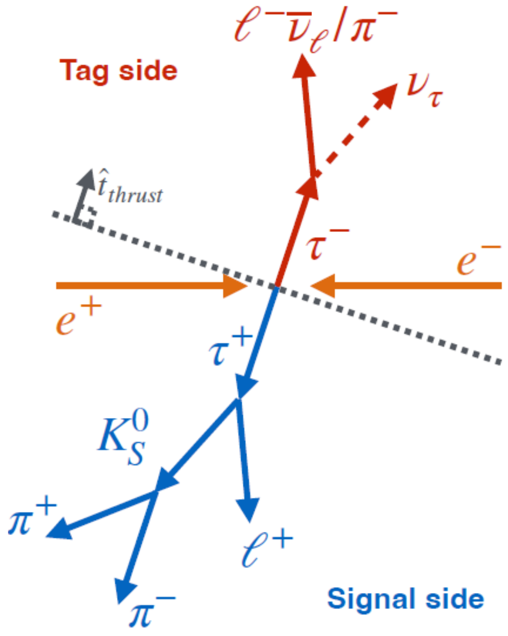
Extract signal yield from 2D plane $(\mathrm{M}_\tau,\ \Delta E = \mathrm{E}_\tau - \mathrm{E}_{\mathrm{beam}})$

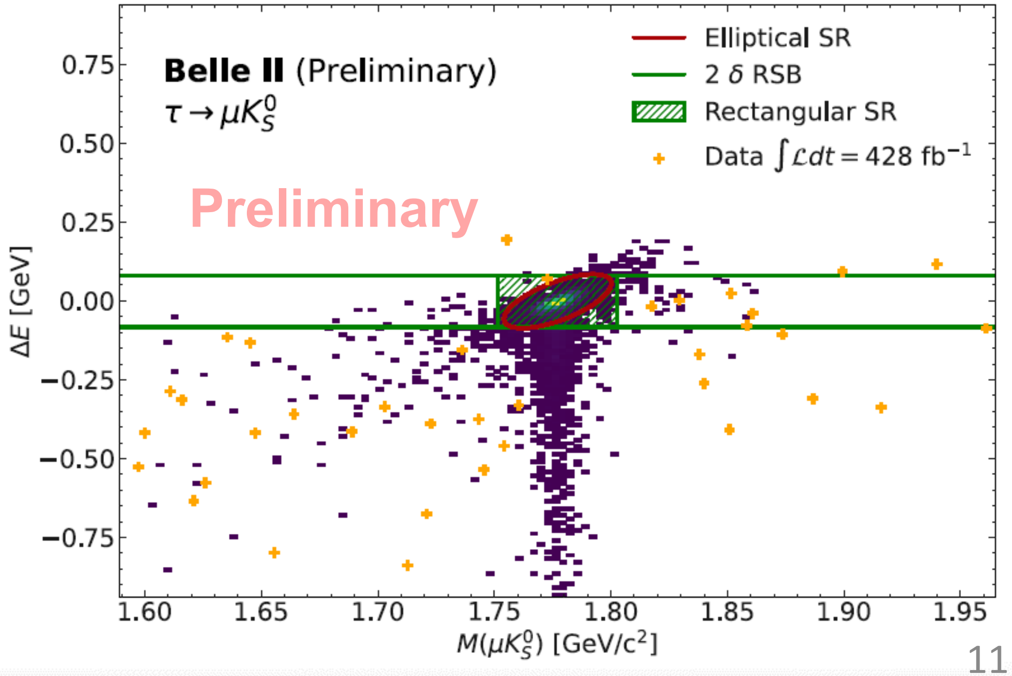
No significant signal was observed in 424 fb^{-1} + 980 fb^{-1} (Belle + Belle II)

Set a combined 90% CL upper limit on the BR

$$B(\tau \to \mathrm{K_S^0}e) < 0.8\times10^{-8}$$
$$B(\tau \to \mathrm{K_S^0}\mu) < 1.2\times10^{-8}$$

✓ **World most stringent upper limit on all modes**





dark sector searches

Dark sector at Belle (II)

Motivations

[1] Essig et al., arXiv:1311.0029 (2013)

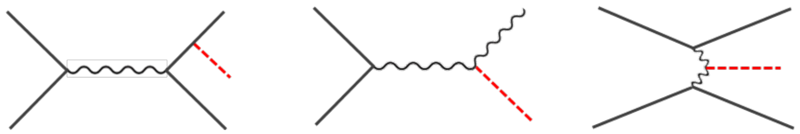
The particle nature of dark matter is still a compelling question

- No evidence of DM at electro-weak scale in experiments motivates a considerable focus on **“dark sector” models** [1]:
  - Light dark matter particles
  - New dark force carriers with feeble interactions with the SM (portals)

B-factories can access the mass range favored by light dark sectors

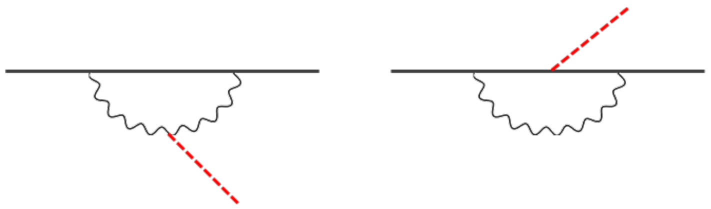
- Able to explore on-shell mediators in the MeV – 10 GeV range in

$e^+e^- \to X_{Dark} X_{SM}$

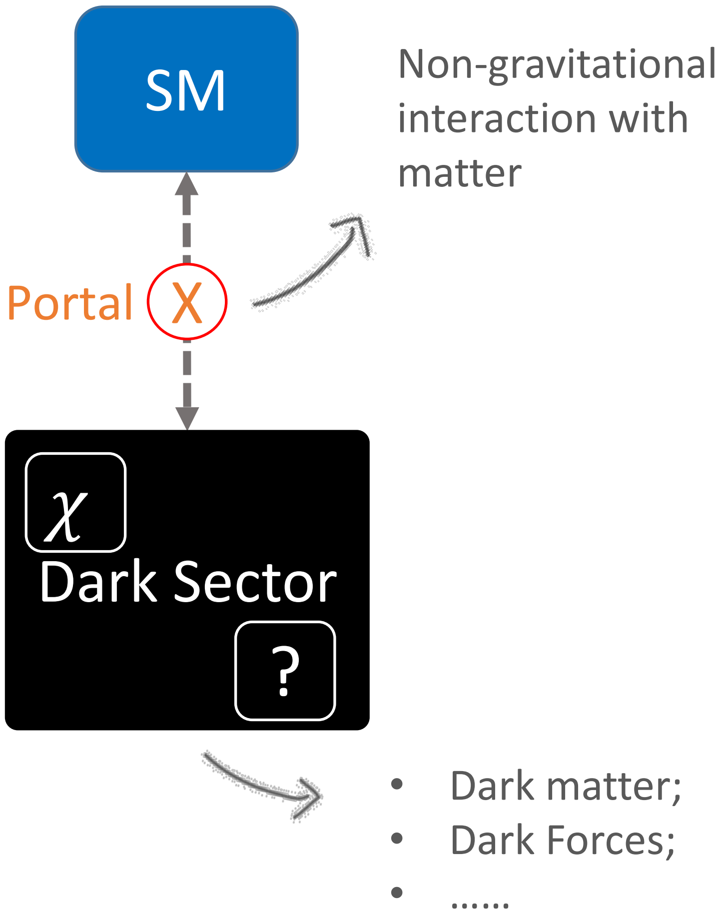


direct production

$B/D/\tau/\ldots \to X_{Dark} X_{SM}$



production in SM decays

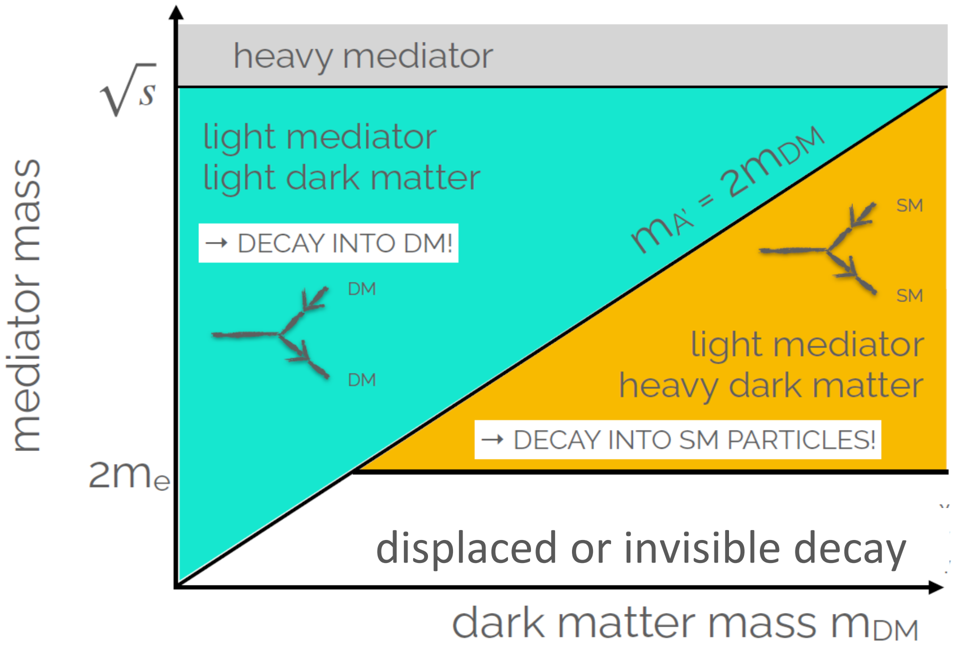


Dark sector at Belle (II)

Overview

Different topologies depending on the mediator and DM candidate mass hypothesis:

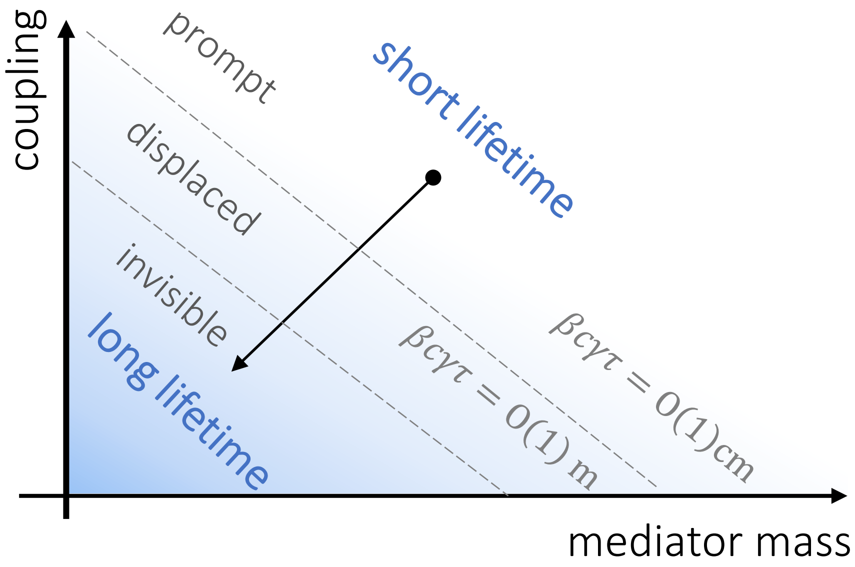
- DM kinematically accessible -> **invisible decay**:
  - **Missing energy or momentum signature**
- Otherwise, decay to SM -> **visible decay**:
  - **Bump hunt search**



An additional player: mediator lifetime.

- Usually life-time is proportional to some inverse power of the coupling and of the mediator mass
- Long lifetime -> long decay length:
  - decay-length < O(1)m: **displaced decay vertices**
  - decay-length > O(1)m: decay outside the detector, i.e. invisible

~ drift chamber radius

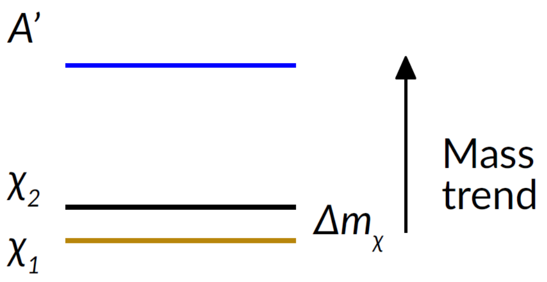


Inelastic dark matter with a dark Higgs **new result**

Overview

Non minimal dark sector with a dark photon A’, a dark higgs h’ and two **dark matter states with a small mass splitting [1]:**

- χ_1 is stable (relic DM candidate)
- χ_2 is long-lived



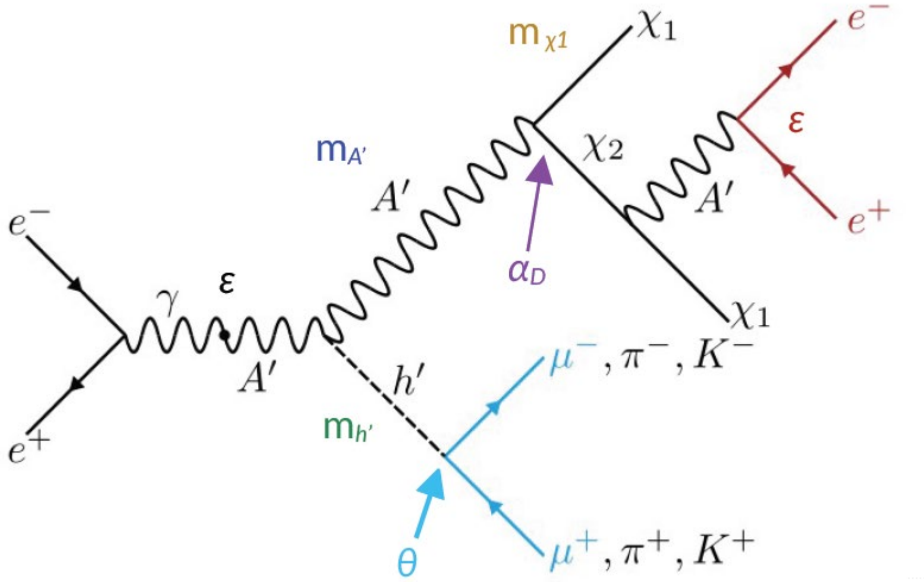
Can explain the lack of a signal in direct detection. [1] PRD 64, 043502 (2001)

Here looking for A’ and h’ simultaneous production:

$e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-)$, $x = \mu, \pi, K$

- h' mixes with SM Higgs with strength θ
- A’ mixes with SM photon with strength ϵ
- focus on $m_{A'} > m_{\chi_1} + m_{\chi_2}$
  - the decay $A' \rightarrow \chi_1\,\chi_2$ is favored

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



4 dark sector particles: $A', h', \chi_1\ \chi_2$
7 parameters: $m_{A'}, m_{h'}, m_{\chi_1}, m_{\chi_2}, \theta, \epsilon, \alpha_D$

Inelastic dark matter with a dark Higgs

new result

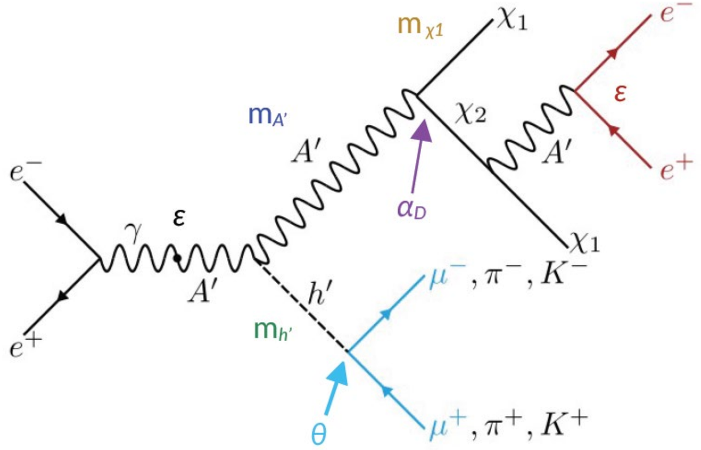
Strategy

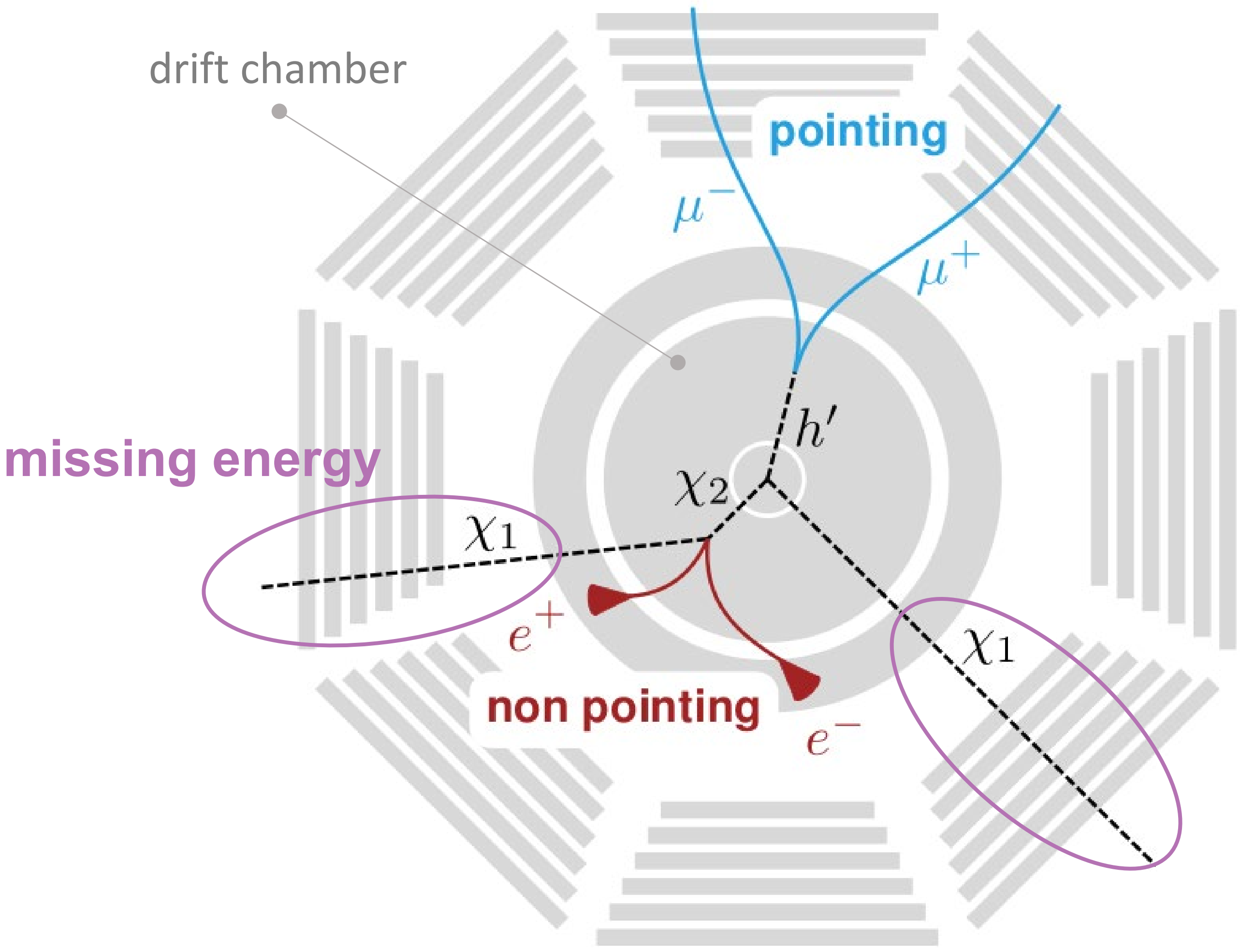
Challenging analysis for tracking (and trigger)

- 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** $(\chi_1\ \chi_2)$
    - **3 channel explored:** ***h'*(→ x^+x^-), *x* = μ, π, *K***





Transverse view of the Belle II detector

Inelastic dark matter with a dark Higgs new result

Results

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

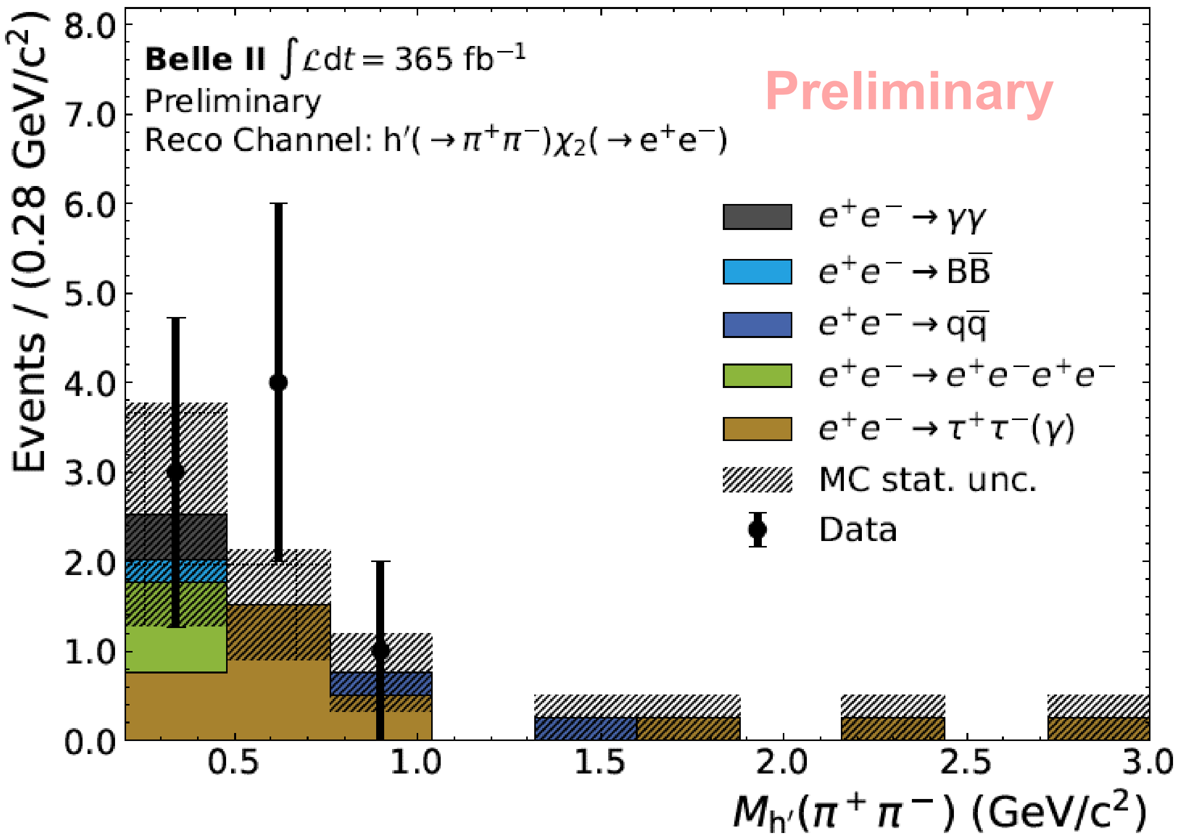
- **very low SM background**

Expected background estimated in data from sidebands to not rely on MC

Counting strategy to extract signal yields

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

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

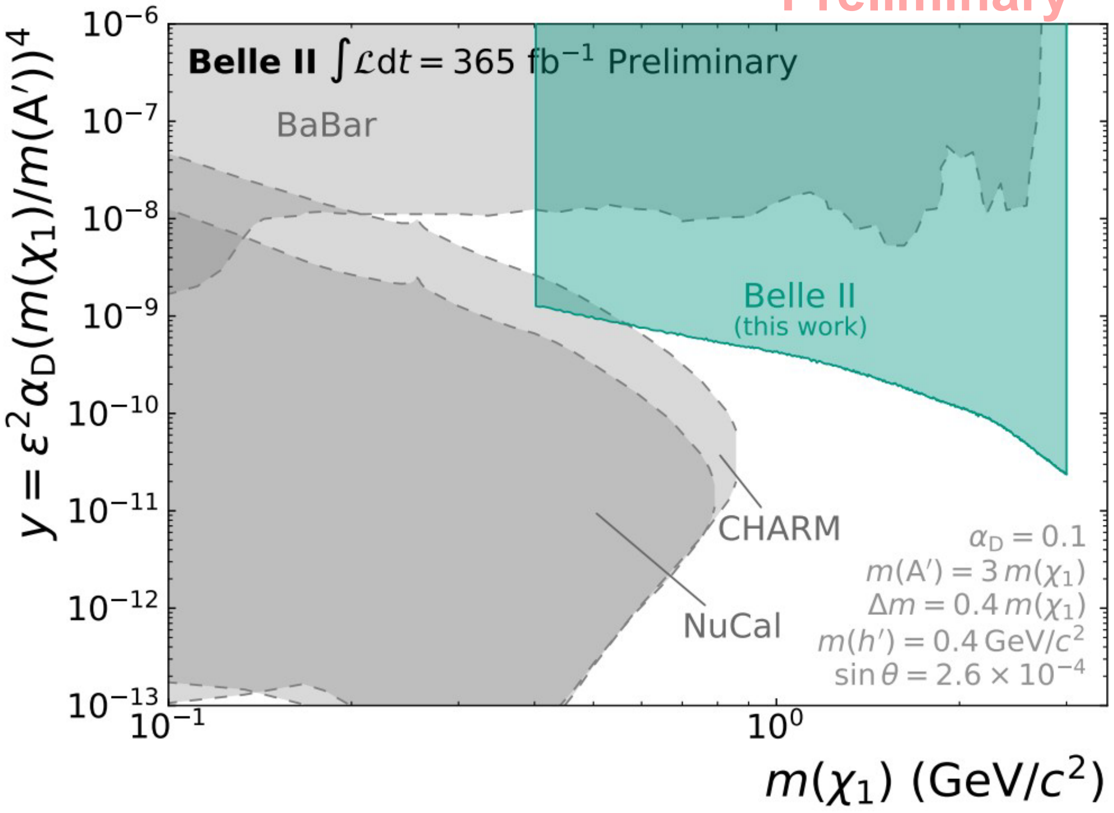


Inelastic dark matter with a dark Higgs new result

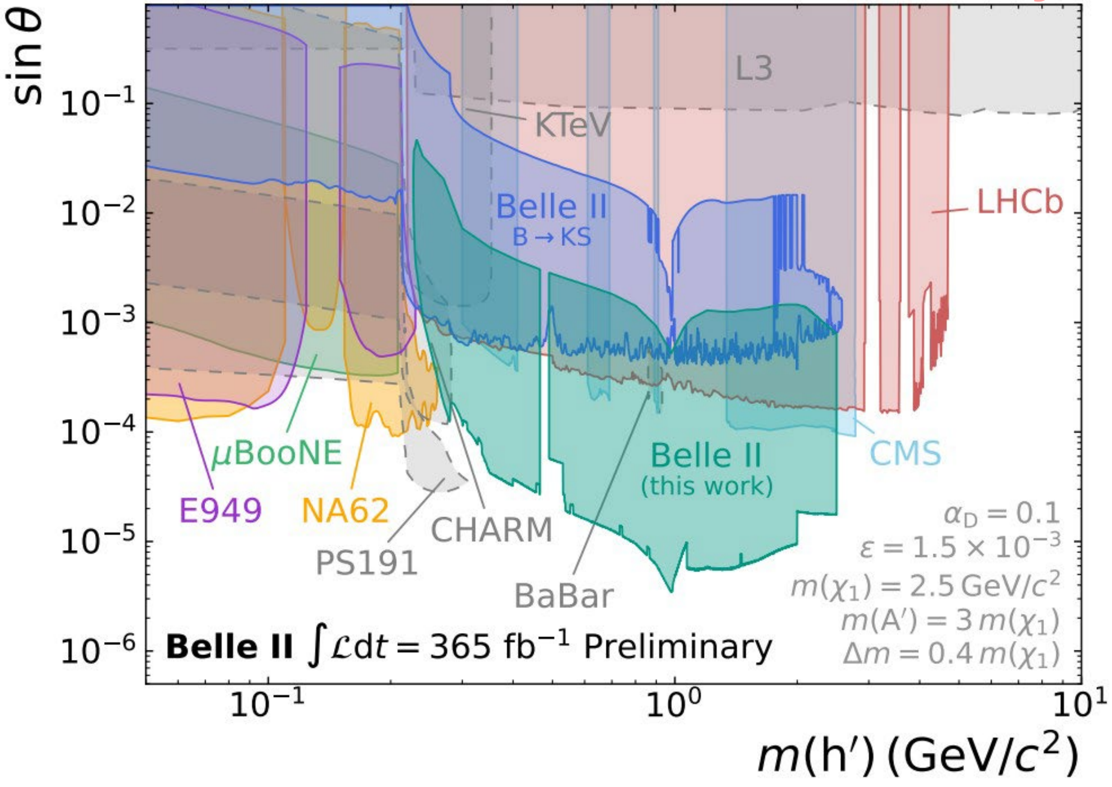
Results

- ✓ **Model independent limits on the cross section of the process**
- ✓ **Strong limits on θ and $\epsilon \times \alpha_D$, but dependence on 5 other parameters.**
  - Many more (~30) plots for different parameter configurations

Preliminary



Preliminary



$\mathrm{B} \rightarrow \mathrm{K}^{(*)}\, a(\rightarrow \gamma\gamma)$ new result

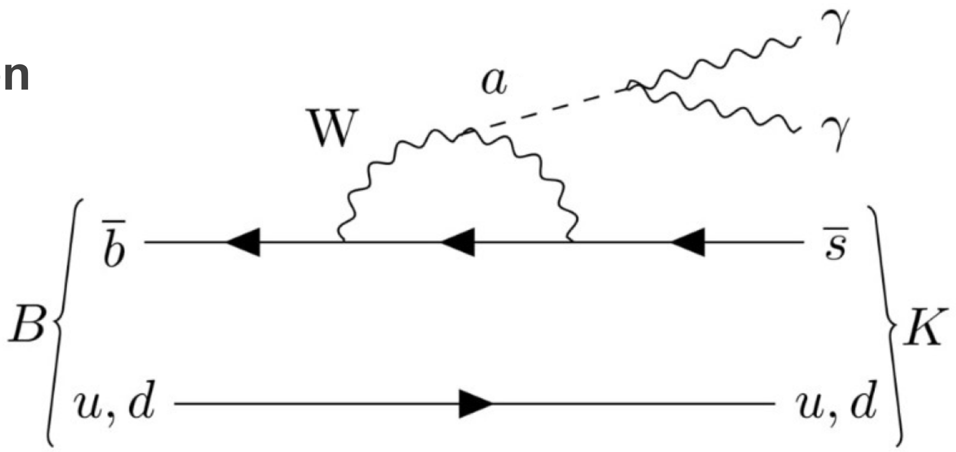
Overview

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

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

Here searching for an Axion-Like particle emission by $W^{\pm}$ boson in $\mathrm{B} \rightarrow \mathrm{K}(*)\, a$ decays

- $\mathrm{BR}(a \rightarrow \gamma\gamma) \simeq 100\%$ for $m_a \ll m_{W^{\pm}}$
- Mass region investigated 0.16 – 4.50 (4.20) GeV/c^2



Existing constraints from BaBar (424 fb^{-1})

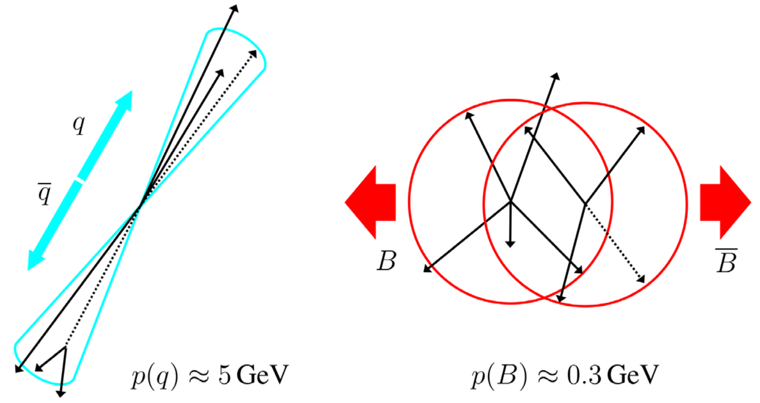
This analysis:

- **full Belle dataset (711 fb^{-1})**
- **exploiting multiple kaon modes: K^0_S , K^+, K^{*0}, and K^{*+}**

$\mathrm{B} \rightarrow \mathrm{K}^{(*)}\, a(\rightarrow \gamma\gamma)$ new result

Strategy

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

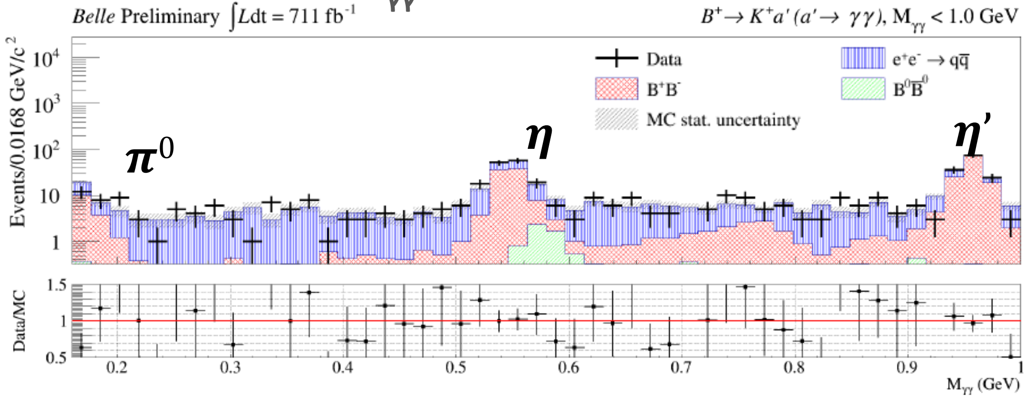


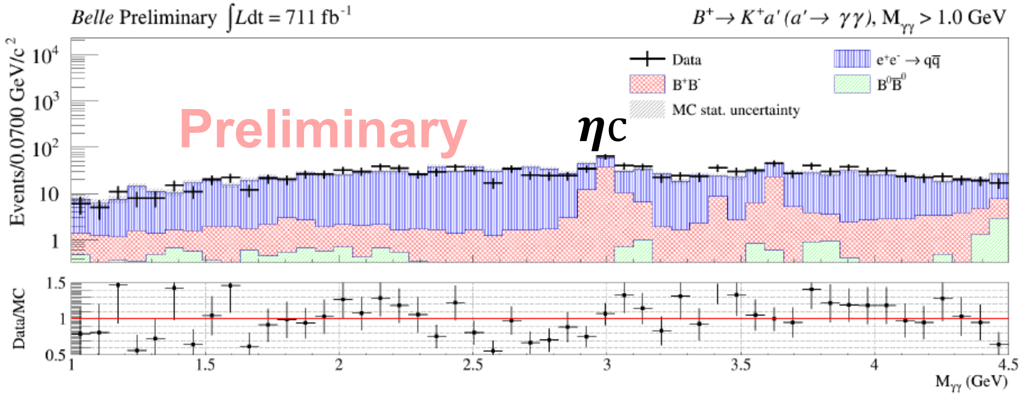
Continuum vs BB event topology

Main background from continuum, while *BB* subdominant.
Smooth backgrounds, but near SM pseudoscalars masses.

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

$M_{\gamma\gamma}$ for the K^+ mode





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

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

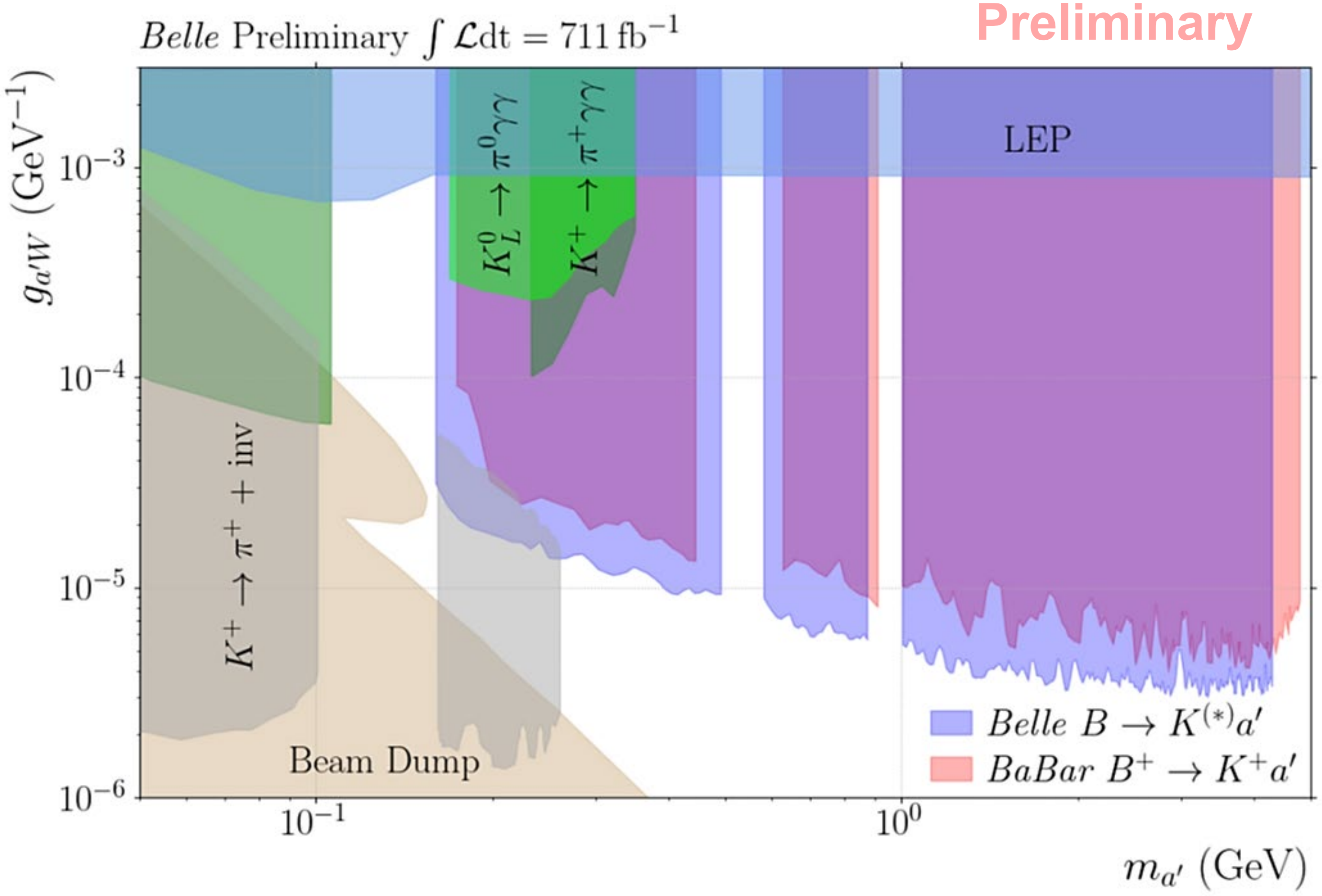
$B \to K^{(*)} a(\to \gamma\gamma)$ new result

Results

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

- **Simultaneous fit on 4 kaon modes**

✓ **World leading 90% CL upper limits to g_{aW}**



❖ ALP lifetime becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$)

❖ Signal efficiency drop due to long-lived ALP is taken into account in results

Conclusion

Belle and Belle II are unique facilities with many exciting dark sector and tau physics opportunities

Covered in this talk:

- **Several new world best limits on high-profile τ LFU / LFV searches proving that Belle and Belle II are also τ-factories**
    - Test of Lepton Flavor Universality in τ decays JHEP08(2024)205
    - Search for lepton-flavor-violating $\tau \to 3\mu$ JHEP09(2024)062
    - Search for lepton-flavor-violating $\tau \to e2\ell$ new
    - Search for lepton-flavor-violating $\tau \to \ell K_S^0$ new

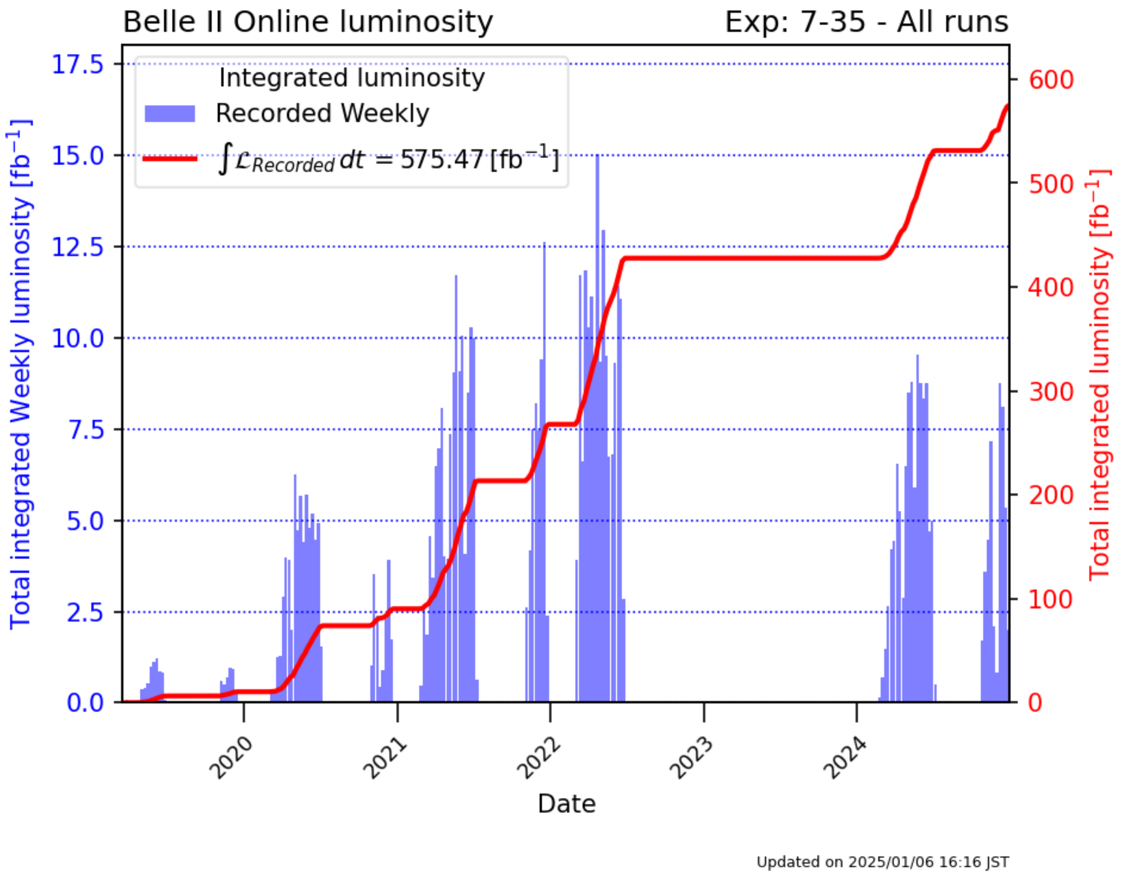
- **Unique limits for light dark sectors searches including displaced vertices and missing energy**
    - Search for inelastic dark matter with a dark Higgs new
    - Search for ALPs in B meson decays new

many more recent results at Belle and Belle II (see backup)

Conclusion

Belle and Belle II are unique facilities with many exciting dark sector and tau physics opportunities

Still many frontiers of improvements:
- Increase data sample size;
- Improved analysis techniques, and reduced systematic uncertainties



- ➢ **Luminosity and physics output expected to continue to ramp up with next data-taking period**
- ➢ **Stay tuned, new results are coming….**

Spares

Tau and dark sector at Belle (II)

Recent published results at Belle and Belle II

Further analysis in τ physics		
BII	Baryon/lepton num. viol. in $\tau^- \to \overset{(-)}{\Lambda}\pi^-$	[PRD 110 (2024) 112003]
BII	Lepton-flavor violation in $\tau^- \to \ell^-\phi$	[arXiv:2305.04759]
BII	Lepton-flavor violation in $\tau^- \to \ell^-\alpha$	[PRL 130 (2023) 181803]
B	Michell Parameters in $\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau$	[PRL 131 (2023) 021801]
B	Electric Dipole Moment of the τ	[JHEP 04 (2022) 110]

Further dark-sector searches		
B	Heavy neutral lepton in $\nu_h \to \pi^+\ell^-$	[PRL 131 (2023) 21180]
B	Leptophilic scalar in association with $\tau^-\tau^+$	[PRD 109 (2024) 032002]
BII	Long-lived spin-0 mediator in $b \to s$	[PRD 108 (2023) L111104]
BII	Dark Photon and Higgs in $\mu^+\mu^-$	[PRL 130 (2023) 071804]
BII	Axionlike particle decaying to $\gamma\gamma$	[PRL 125 (2020) 161806]

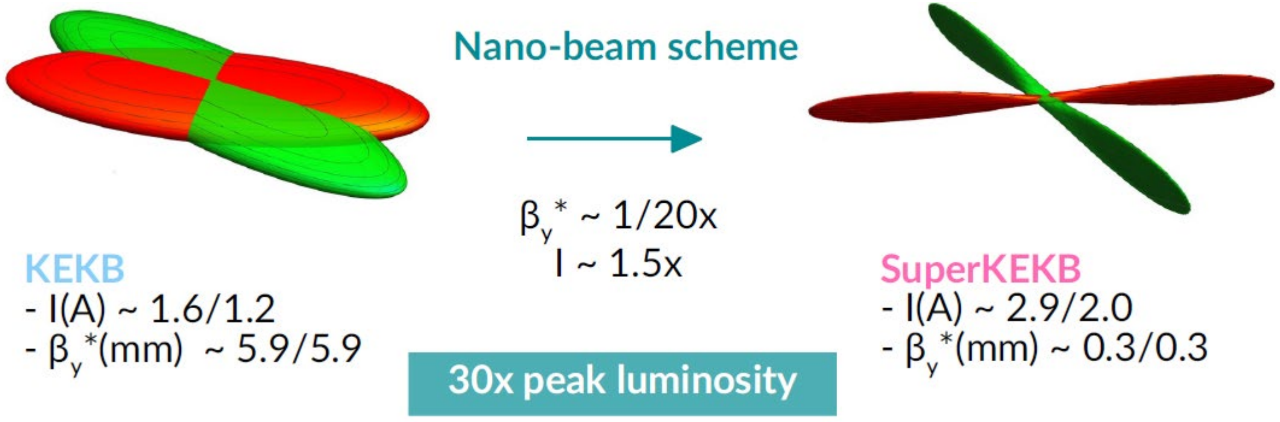
SuperKEKB & Belle II

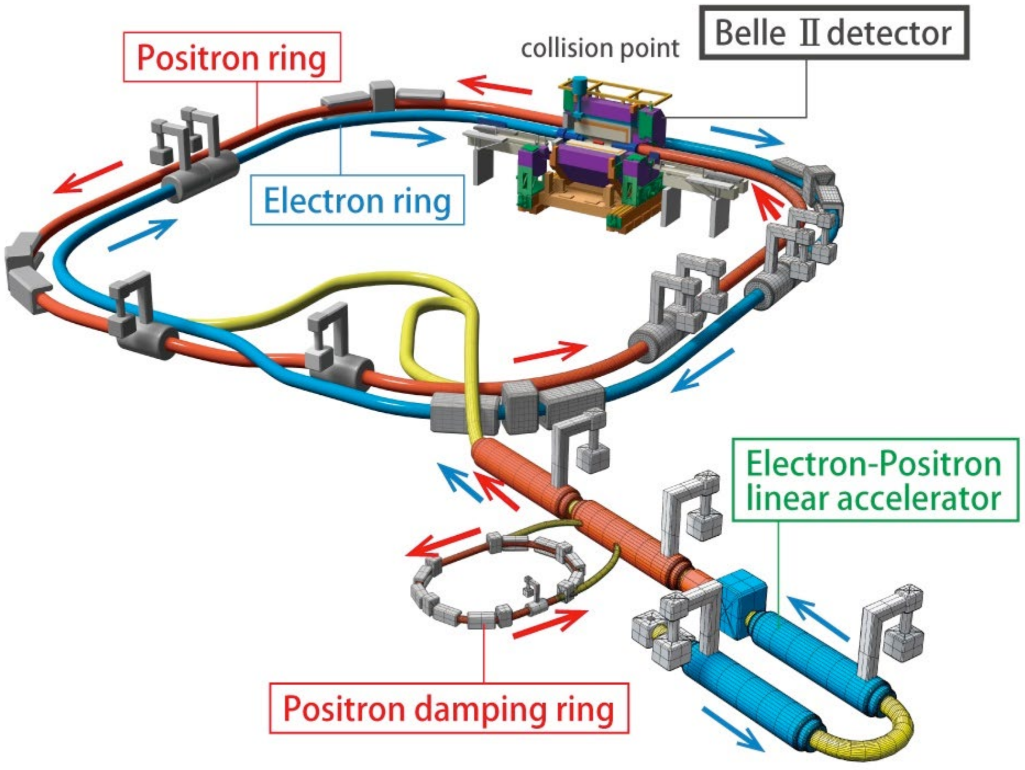
A 2nd generation B-factory

SuperKEKB is a 2nd generation asymmetric e^+e^- collider at the $\Upsilon(4S)$ energy located at Tsukuba (Japan).
Major upgrade of KEKB.

- Target word highest instantaneous luminosity: 6×10^{35} $cm^{-2}s^{-1}$ (x30 KEKB/Belle):
  - 1.5x higher beam currents;
  - 20x smaller beam spot ("nano beam scheme" [1]);

KEKB beams **SuperKEKB nanobeams**





[1] P. Raimondi et al., arXiv:0709.0451

B-factory experiments

Overview

Asymmetric e⁺e⁻ colliders optimized for the production of B meson pairs;

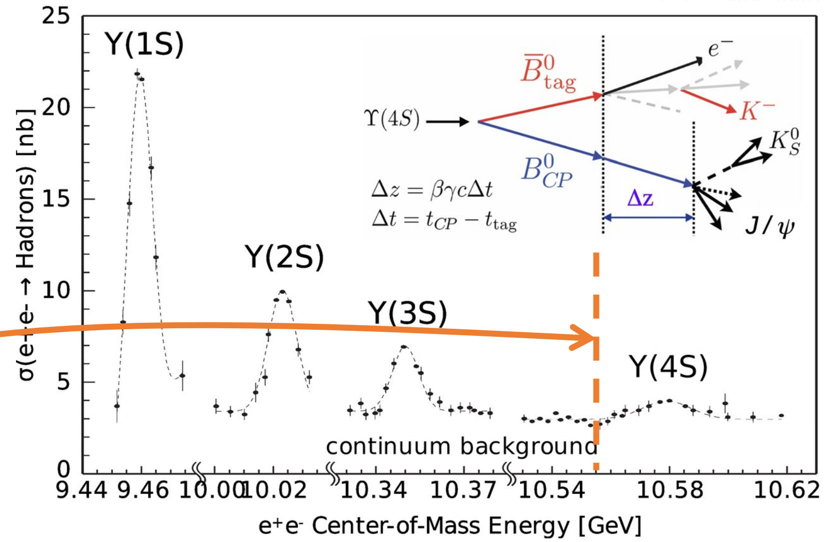
Collision at Υ(nS) resonances, mainly Υ(4S) → 10.58 GeV:

- just above the production threshold of $B\bar{B}$ (10.56 GeV);
  - $BR(\Upsilon(4S) \to BB) > 96\%$;
- $B\bar{B}$ pair (charged or neutral) almost at rest in the CMS frame;

Asymmetric beam energies: e.g. 9.0/3.0 GeV (e^-/e^+) (BaBar):

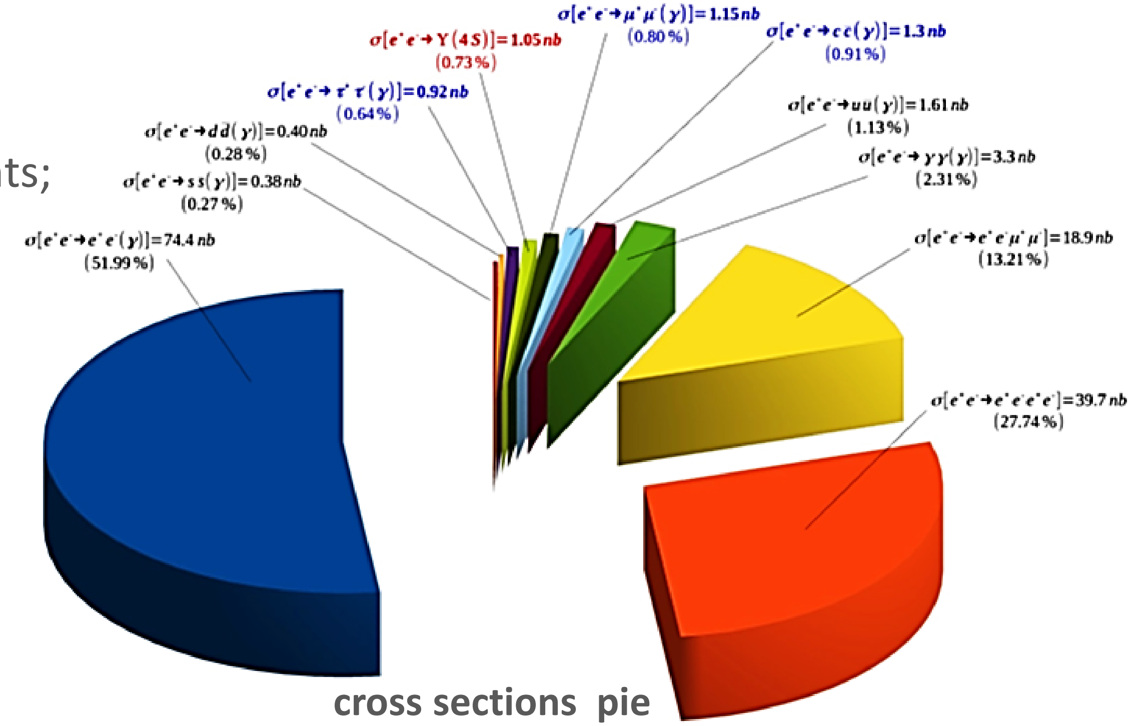
- Boosted $B\bar{B}$ pairs for CP-violation time-dependent measurements;

Large instantaneous luminosity: > 10^{34} cm^{-2} s^{-1} ;



Not just $B\bar{B}$ production:

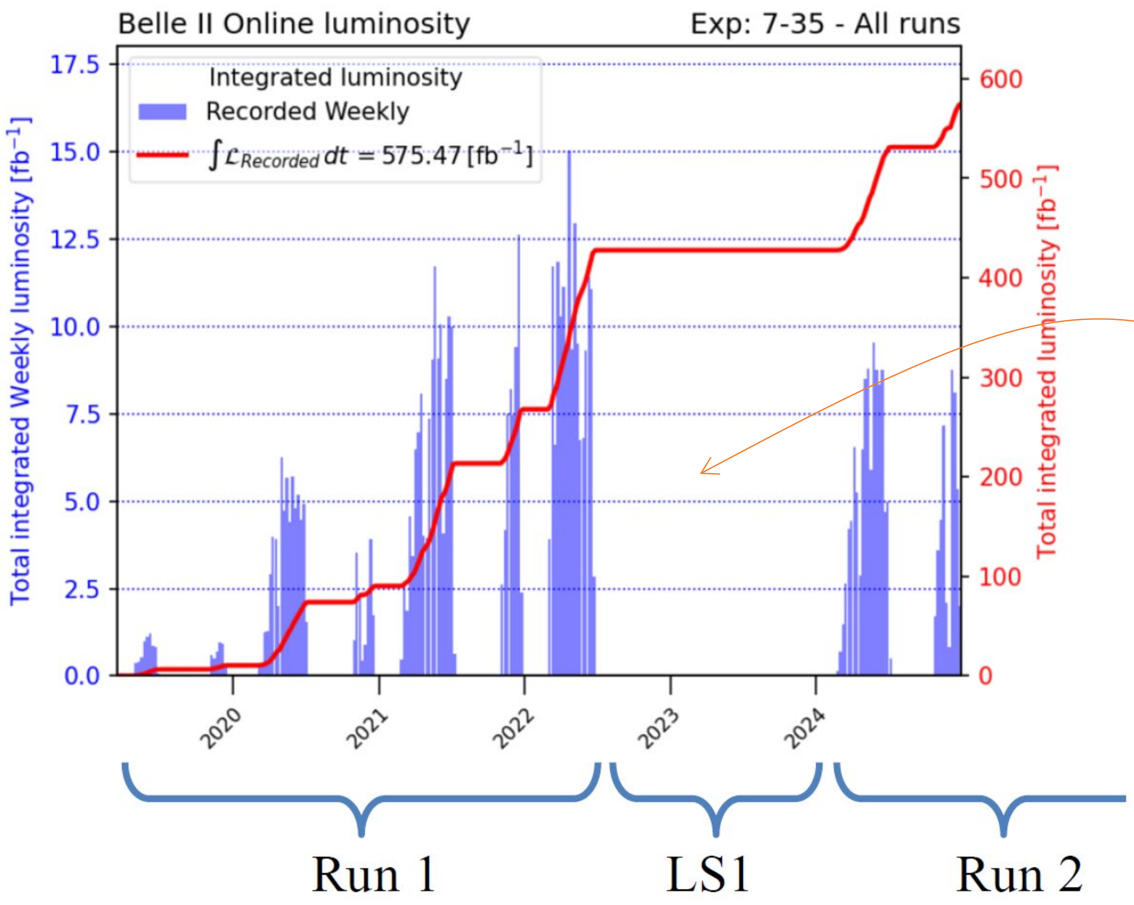
- **rich charm, τ, quarkonium and low-multiplicity program;**



cross sections pie

SuperKEKB & Belle II

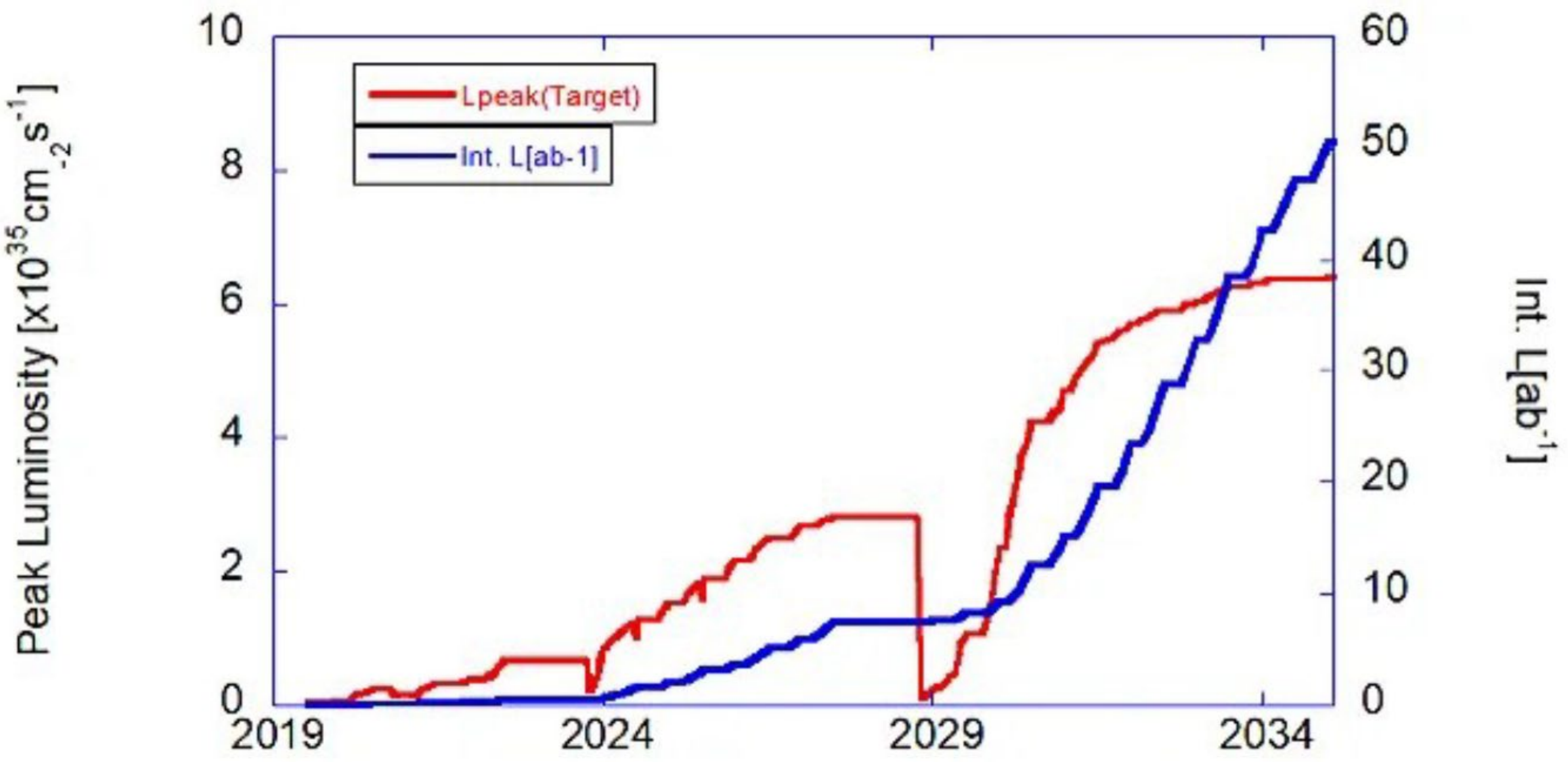
Schedule



- **Data-taking from 20198;**
- **Achieved world record instantaneous luminosity: 5.1×10^{34} cm^{-2}s^{-1}**
- **Long shutdown 1 (2022-2024)**
  - detector improvements – mainly installation of full two-layer pixel detector (PXD2);
  - accelerator improvements, e.g., non-linear collimators to combat beam background;
- **Restarted collision in Feb 2024. So far collected 575 fb^{-1} (RUN 1 + 2);**
- **Target dataset: 50 ab^{-1}**

SuperKEKB & Belle II

Schedule

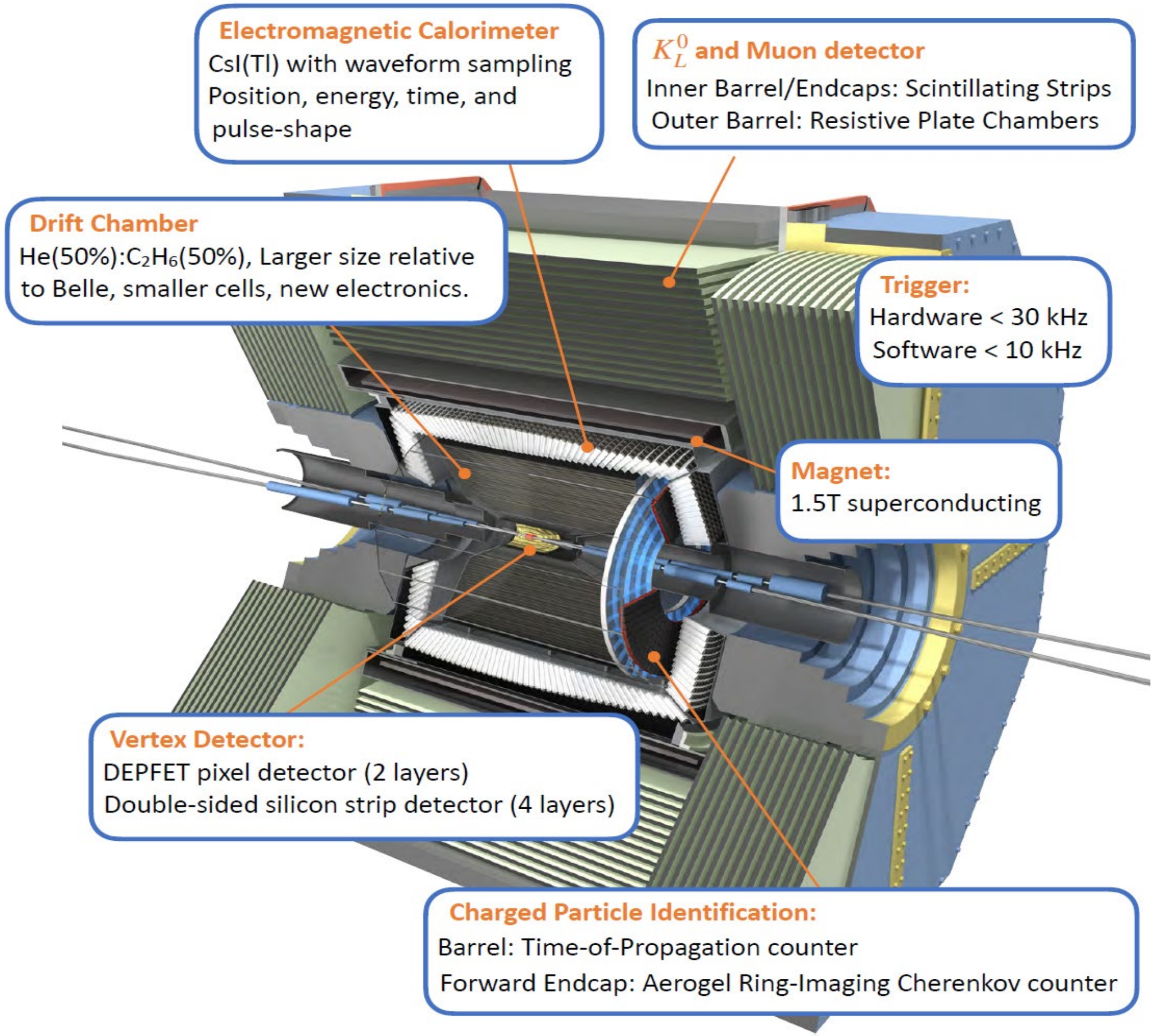


Belle II

Detector overview

- 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% pic mis-ID.

Prog. Theo. Exp. Phys. 12 (2019)



Belle II

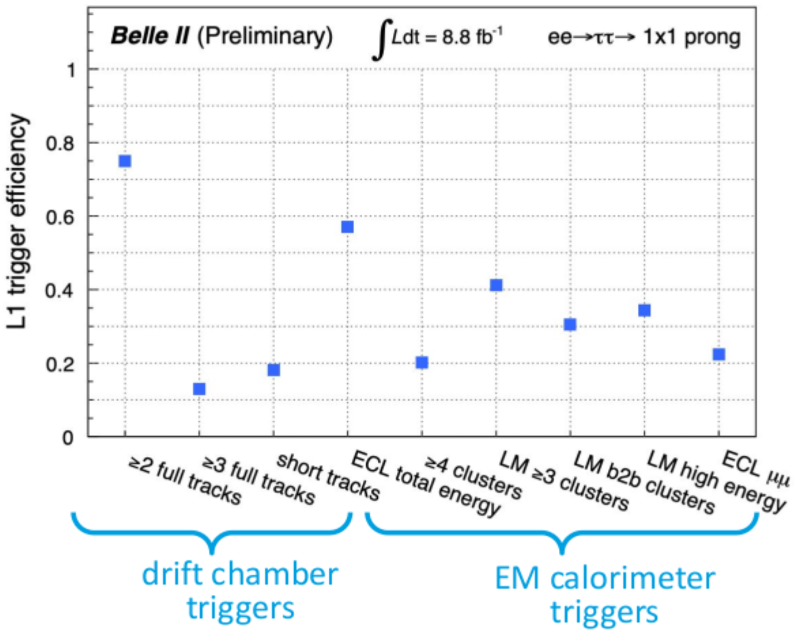
Trigger performances

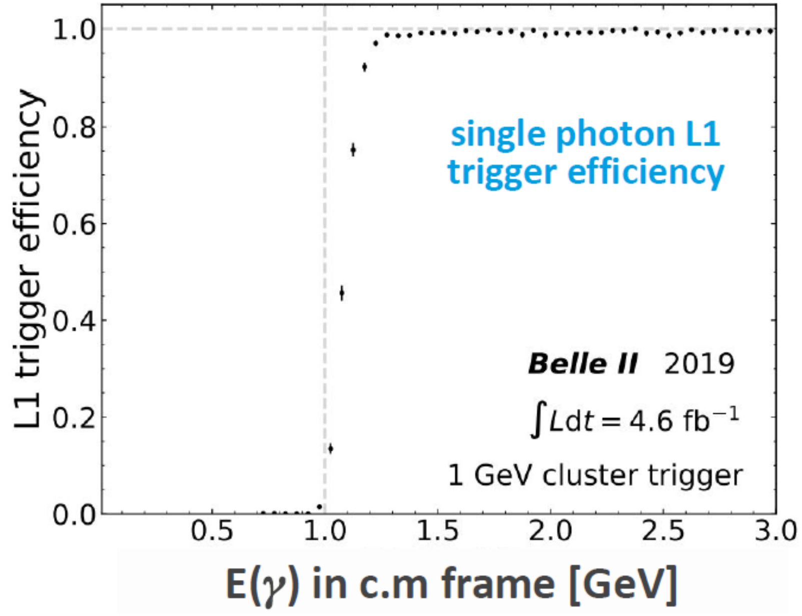
essential for dark-sector and tau physics

- typical signatures include low-multiplicity of tracks, and energy deposits in EM calorimeter
- large background from radiative Bhabha and two-photon processes

some of the dedicated low-multiplicity triggers:

- single muon
  - combine drift chamber and muon detector information
- single track:
  - neural-net based hardware trigger
- single photon:
  - high efficiency for $E(\gamma) > 1$ GeV



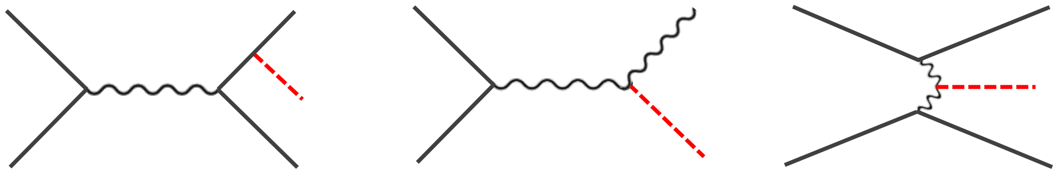


Dark sector searches

Decay signatures

direct production

$e^+e^- \to X_{Dark}X_{SM}$

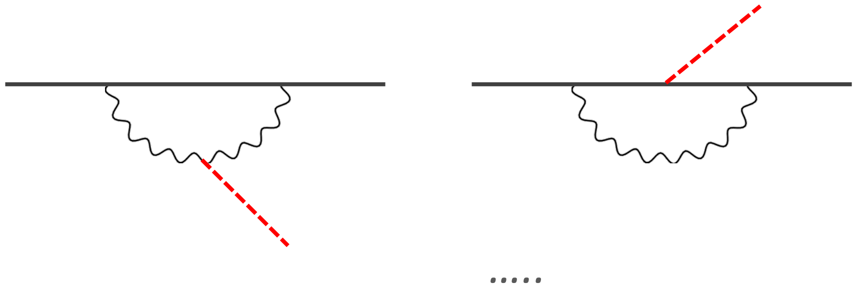


Directly produced in SM particle collisions (e.g. photon fusion, ALP-strahlung)

- **probe mediator masses up to $\sqrt{s}$;**

SM decay production

$B/D/\tau/\ ...\to X_{Dark}X_{SM}$



Produced in mesons (B, *tau* or other) decay

- **probe mediator masses up to respective meson mass;**

Dark sector searches

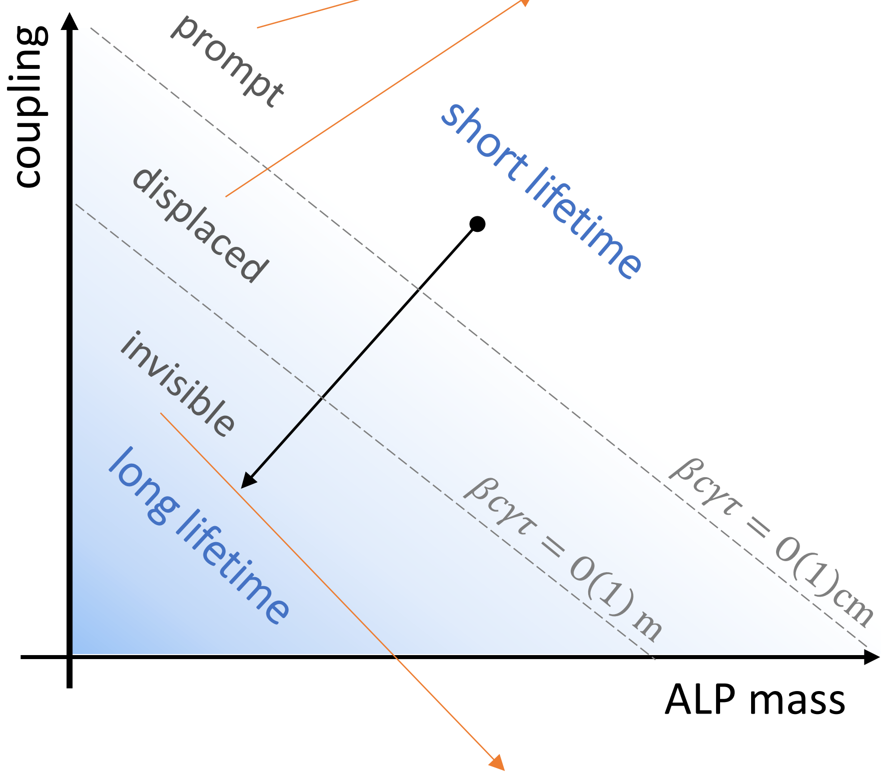
Decay signatures

Different decay modes depending on kinematically allowed final states, favored coupling, etc.

Life-time is an additional player:

- proportional to some inverse power of the coupling and of the mediator mass;
- long lived particles can decay inside the detector and leave traces of displaced decay products or they transverse the detector and are reconstructed as missing energy from the remainder of the event:
  - decay-length < O(1)m: **displaced decay vertices**;
  - decay-length > O(1)m: **decay outside the detector (invisible);**

bump in the decay produts invariant mass



same signature as decay to DM ⟺ missing energy signature

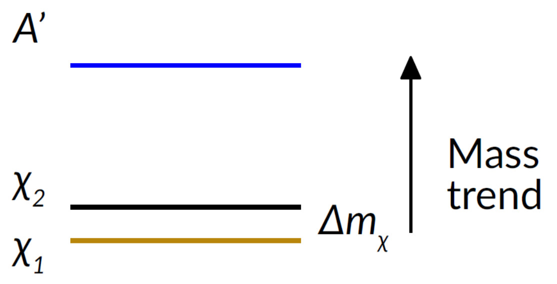
Inelastic dark matter with a dark Higgs

Overview

Non minimal dark sector with a dark photon A’, a dark higgs h’ and two **dark matter states with a small mass splitting [1]:**

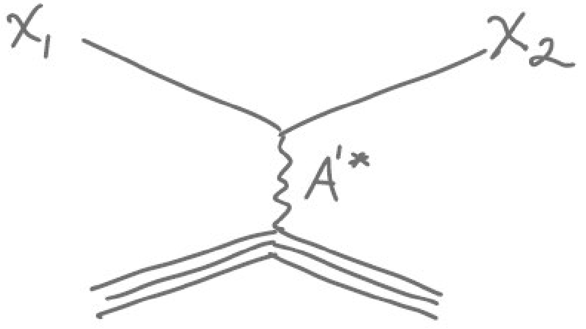
- χ_1 is stable (relic DM candidate)
- χ_2 is long-lived

Can explain the lack of a signal in direct detection.

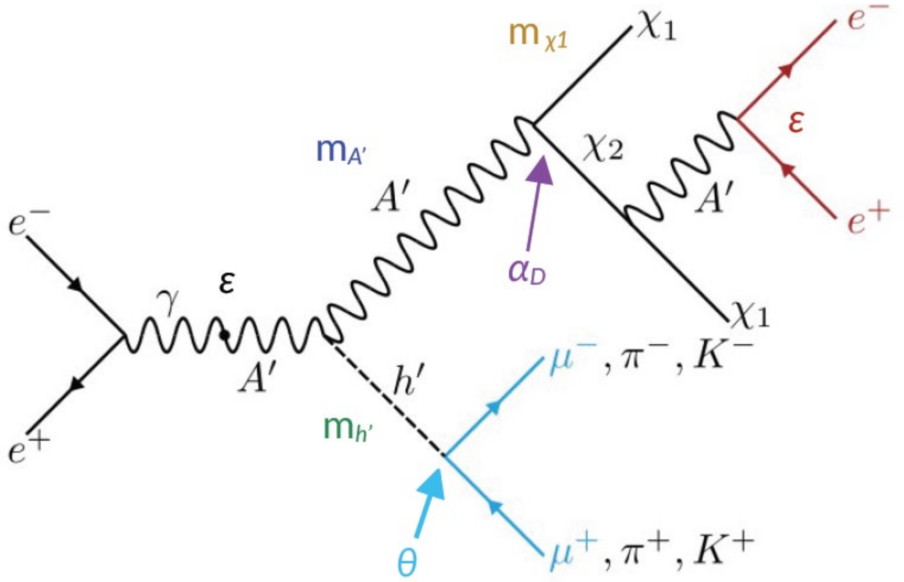


[1] PRD 64, 043502 (2001)

$e^+e^- \rightarrow h'(\rightarrow x^+x^-)A'(\rightarrow \chi_1\chi_2(\rightarrow \chi_1 e^+e^-), x = \mu, \pi, K$

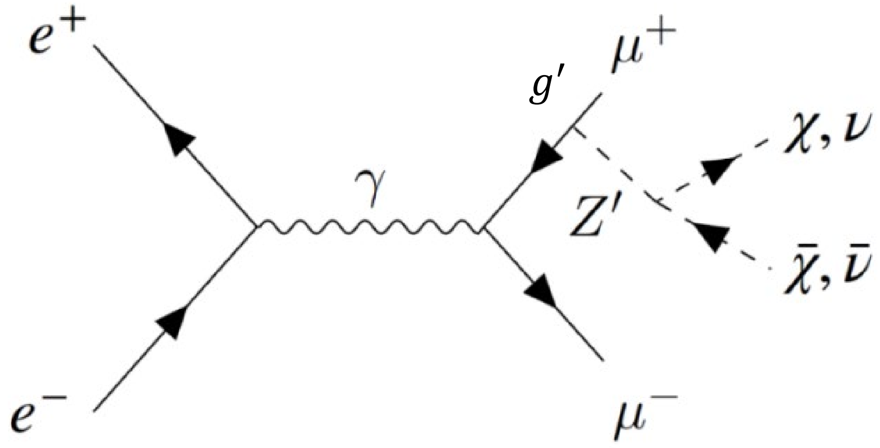


production of heavier χ_2 is kinematically forbidden for low-momentum χ_1.



Search for an invisible Z’

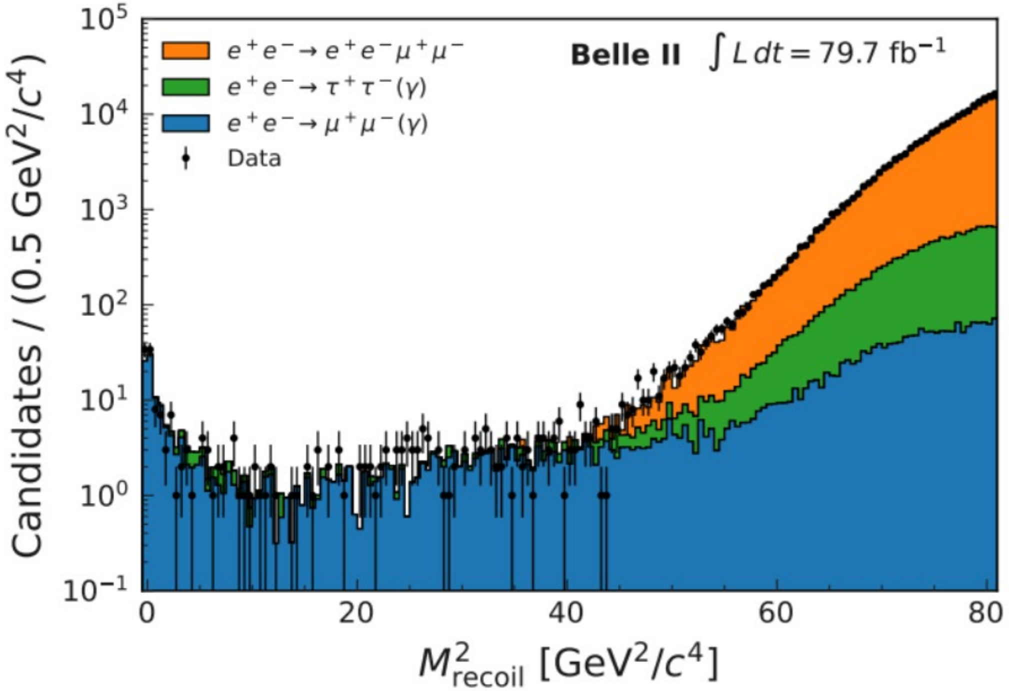
Strategy



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

Analysis in short:

- muons used to reconstruct recoil mass (peaking for Z’ signal);
- Background from QED processes with 2 particles identified as muons and missing momentum. Mainly due to $\mu\mu(\gamma), \tau\tau, ee\mu\mu$;
- Analysis selections:
  - Two opposite sign muon tracks; $p_T^{\mu\mu} > 0.1$ GeV/c
  - Recoil points to barrel calorimeter ($M_{\mathrm{recoil}} < 2\ \mathrm{GeV/c^2}$);
  - Low activity in the calorimeter; γ veto;
  - Neural-Network exploiting FSR nature of Z’ production;
- Signal extraction by fitting over the 2d distribution θ_{recoil} vs. M^2_{recoil};



First measurement with 2018 dataset: ~279 $\mathrm{pb^{-1}}$;

New analysis with 2019-20 dataset: ~ 79.7 $\mathrm{fb^{-1}}$

- higher luminosity; analysis strategy improved; new triggers.

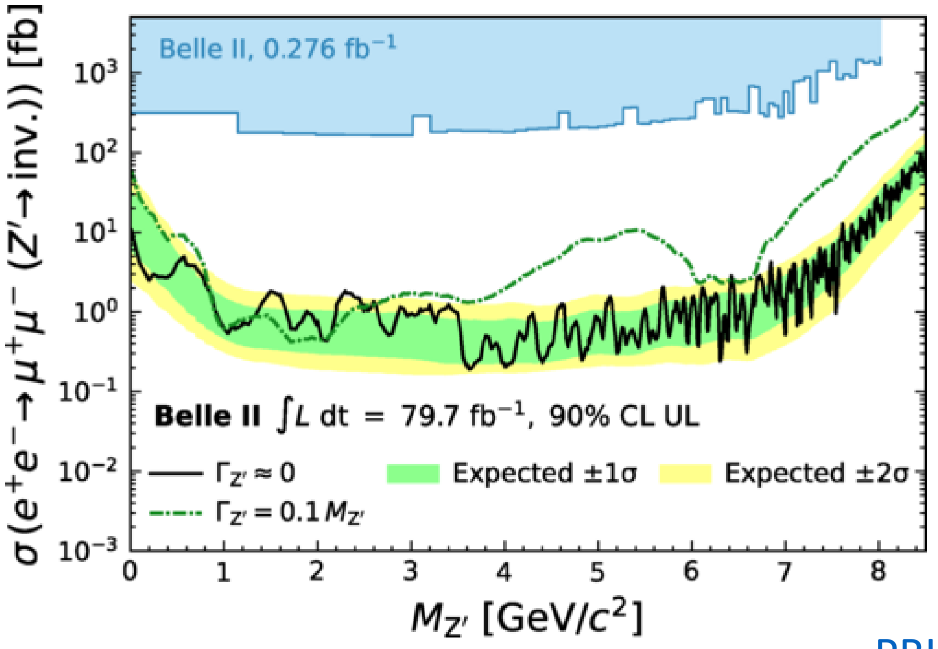
Search for an invisible Z’

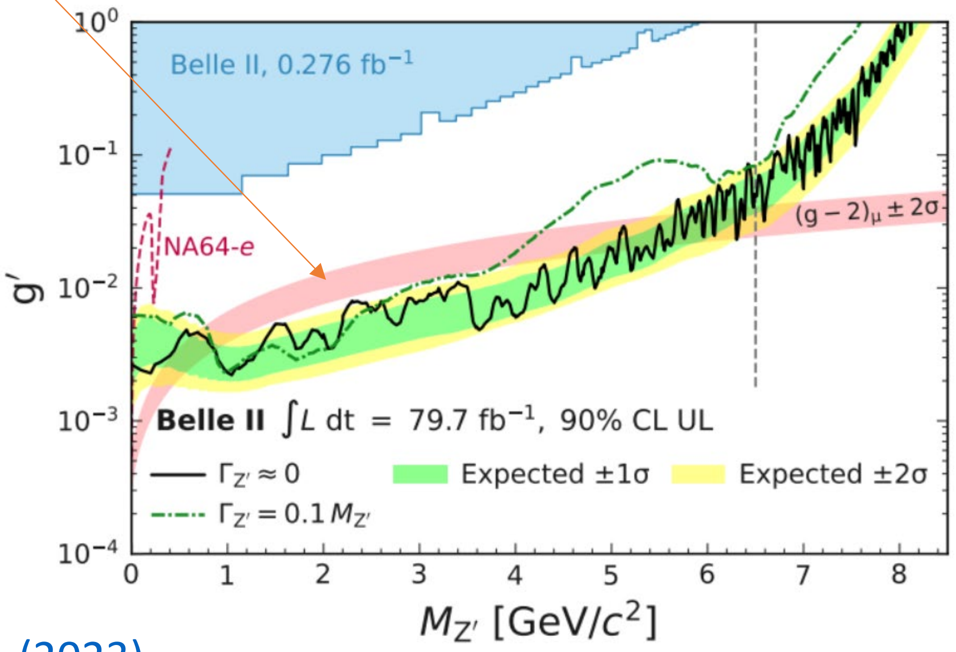
Results

No significant excess over the expected background;

Set 90% CL exclusion limits on cross section and coupling:

- **World-leading UL for a fully invisible Z’ (100% BR to invisible);**
- **First exclusion of a fully invisible Z’ boson as an explanation of the $(g-2)_\mu$ anomaly for 0.8 < $M_{Z'}$ < 5 GeV/c²;**





[PRL 130, 231801 (2023)]

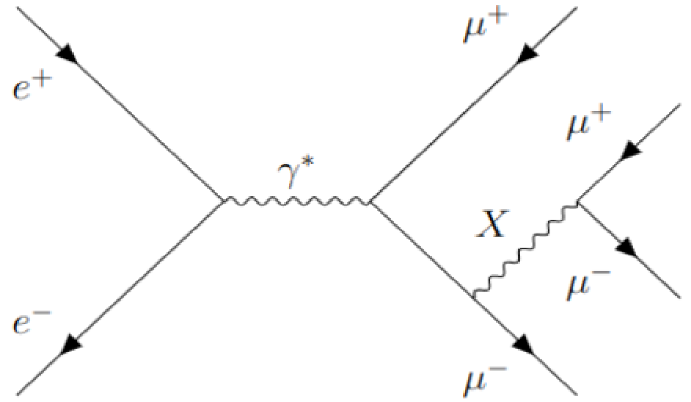
Search for Z’ decay in $\mu\mu$

Strategy

Search for di-muon resonance in 4 muon events with 178 fb^{-1}

- Z’ model as benchmark;
- Reinterpreted also as muonphilic dark scalar S;

may explain: $(g-2)_\mu$ [1, 2]

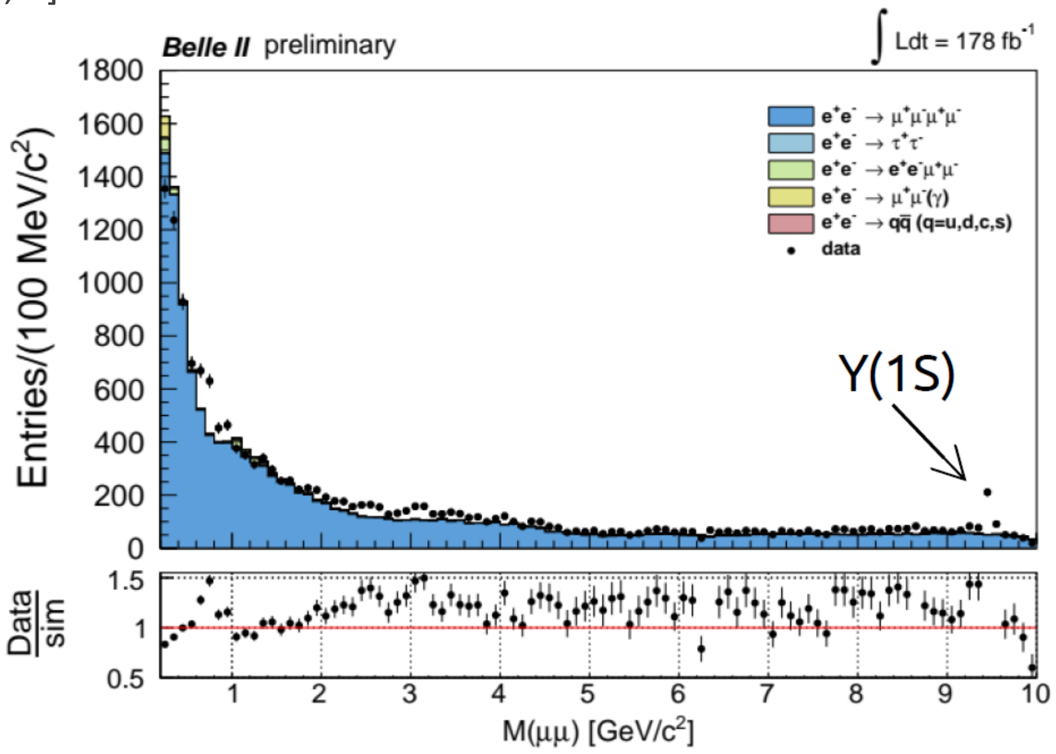


Selections in brief:

- At least three muons identified;
- Total charge zero;
- M(4 tracks) ~ beam energy;
- No extra energy;
- Multi-layer Perceptron (MLP) based background suppression;

Analysis strategy:

- Fit on the dimuon reduced mass spectrum;



[1] P. Harris, P. Schuster, and J. Zupan, arXiv:2207.08990 [hep-ph];

[2] R. Capdevilla, D. Curtin, Y. Kahn, and G. Krnjaic,J. High Energy Phys. 04 (2022) 129

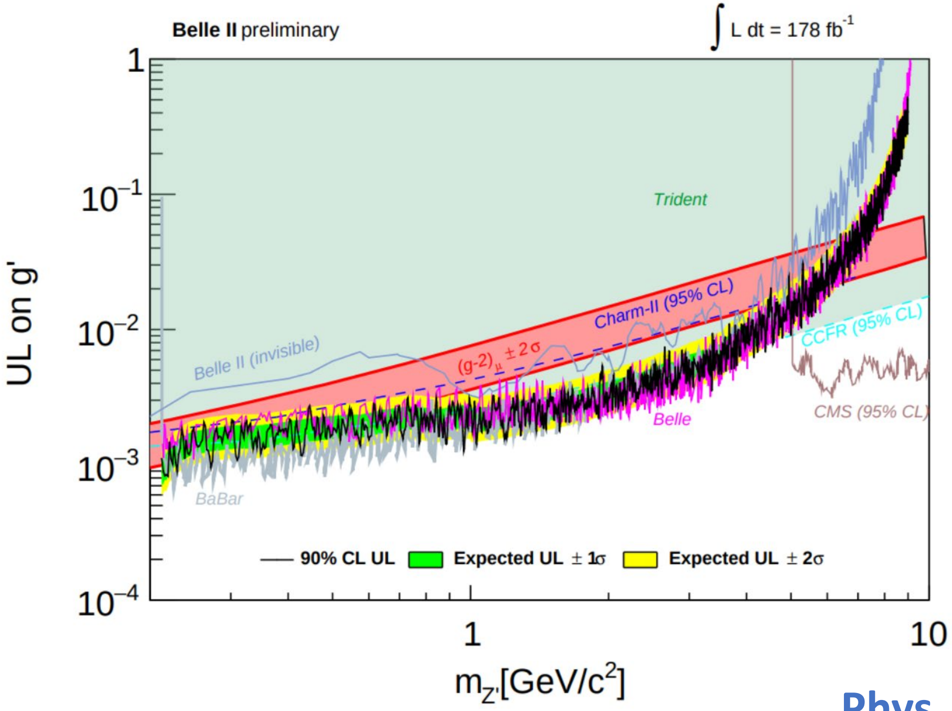
Search for Z' decay in $\mu\mu$

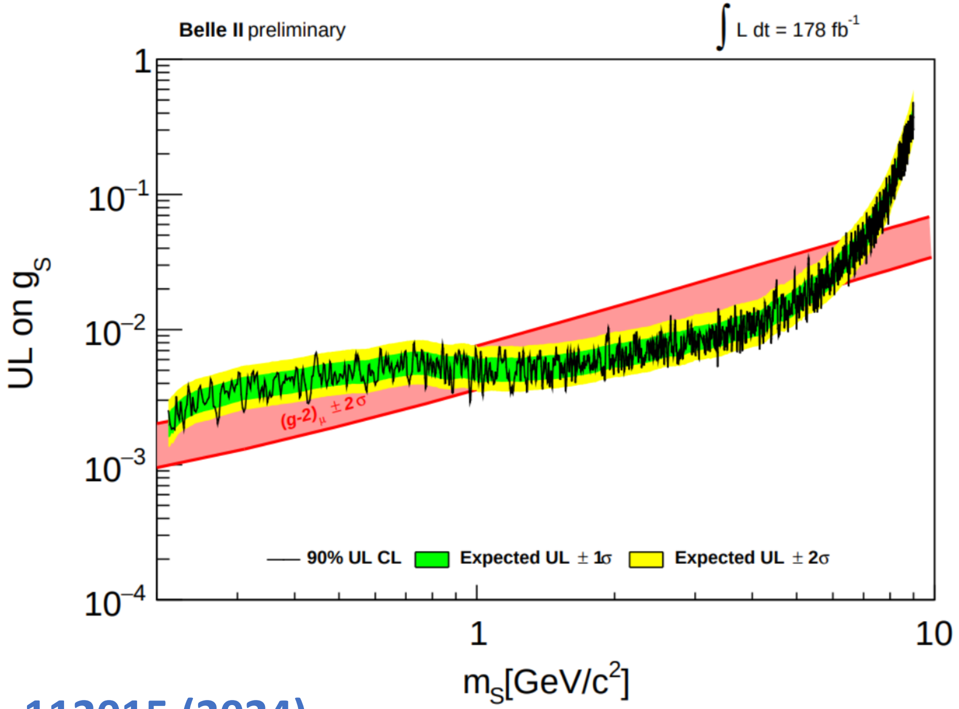
Results

No excess found -> 90% CL upper limits on the process cross-section: **σ(e⁺e⁻ → X μ⁺μ⁻)** x **B(X → μ⁺μ⁻)**, with X = Z', *S*

Results translated into upper limits on the coupling constant:

- g' for the $L_\mu - L_\tau$ model (results comparable to Babar and Belle results with much less luminosity);
- g_s for the muonphilic dark scalar S → first limits on S with a dedicated search;





[Phys. Rev. D 109, 112015 (2024)]

Search for $\tau^+\tau^-$ resonance in $\mu\mu\tau\tau$ events

Strategy

[1] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D 95, 075003 (2017)
[2] M. Bauer, M. Neubert, and A. Thamm, J. High Energy Phys. 2017, 44 (2017)

Search for a di-tau resonance with 63.3 fb^{-1} :

$$e^+e^- \to \mu^+\mu^- X,$$
$$X \to \tau^+\tau^-$$

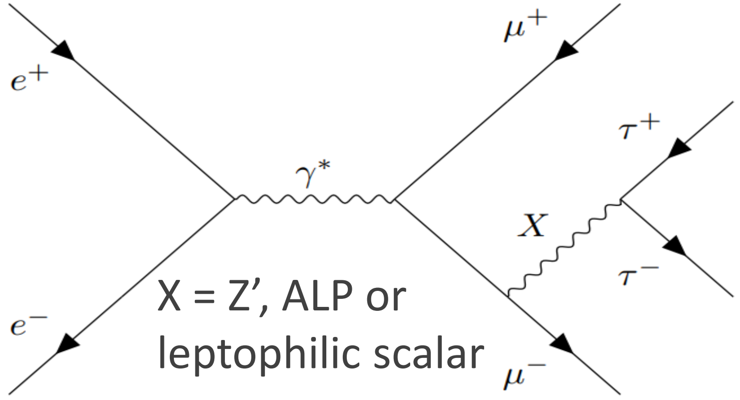
(first time search)

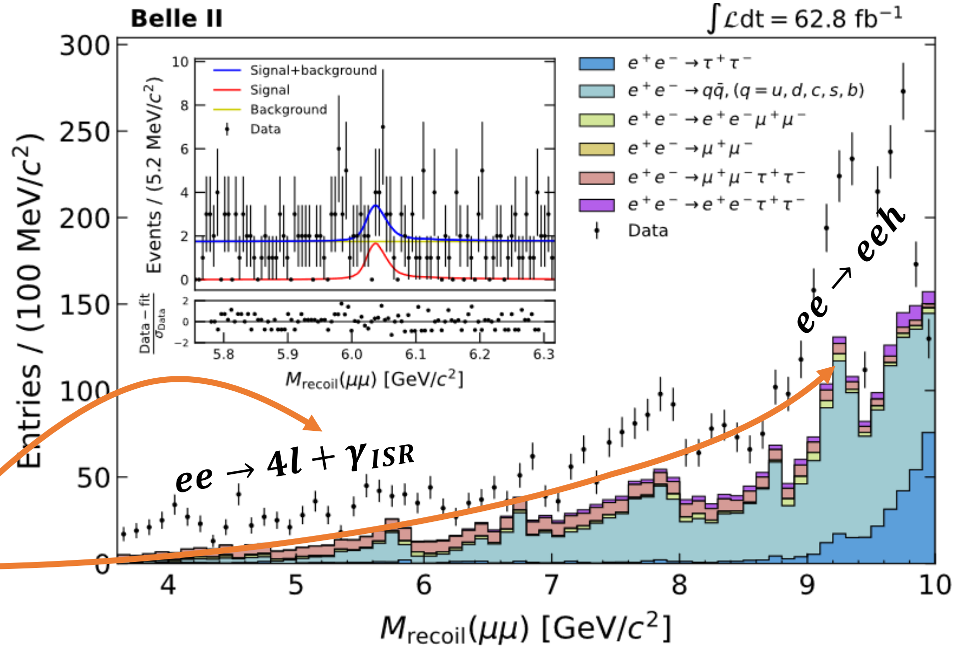
Z' model as benchmark. Results re-cast for:

- Leptophilic scalar **S** [1];
- **Axion-like-particle** with tau couplings [2];

Analysis in brief:

- Select taus decays to one-charged particle (+nh^0)
- Event signature is four tracks (2 μ) with missing energy;
- Muons used to compute recoil mass (peaking for signal);
- Dominant background from 4 leptons suppressed by M(4tracks) < 9.5 GeV/c^2;
- MLP exploiting the FSR nature of the signal and that the system recoiling against the 2 muons is a tau pair.





Data/simulation discrepancy from non-simulated/unmodeled processes

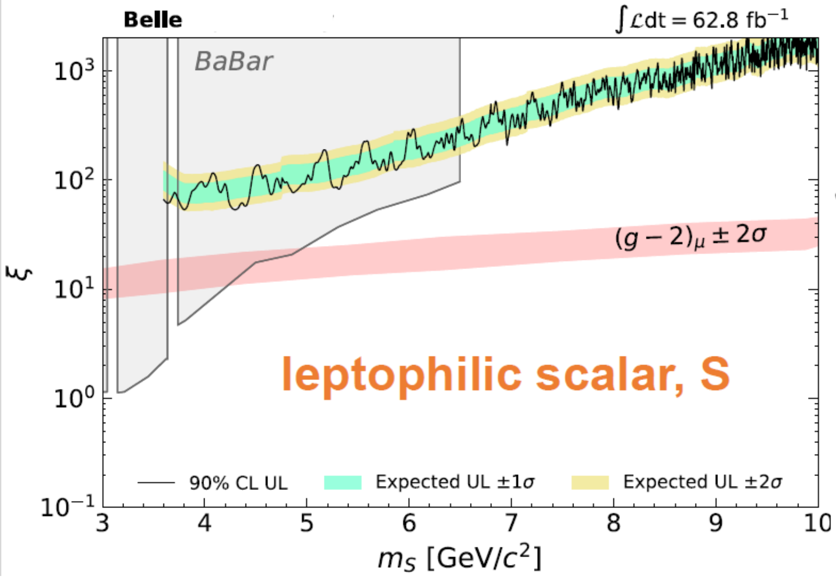
Background determined directly in data

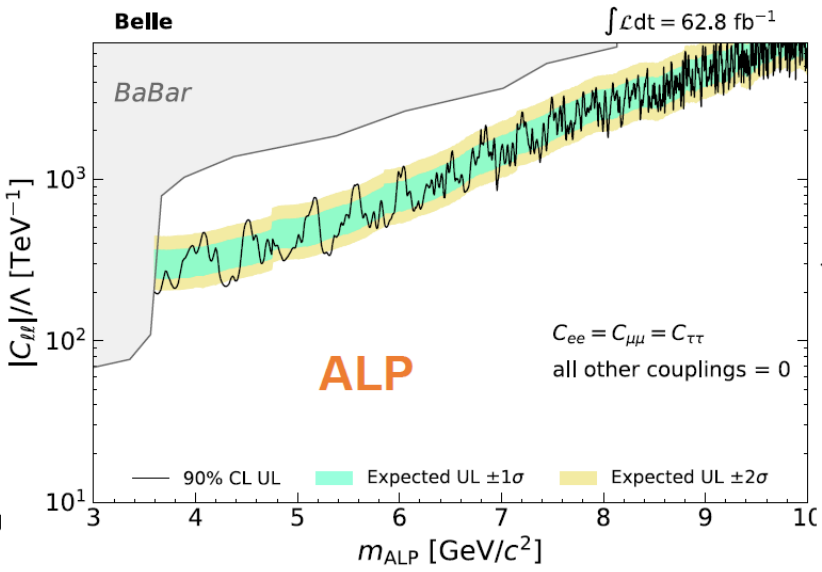
Search for $\tau^+\tau^-$ resonance in $\mu\mu\tau\tau$ events

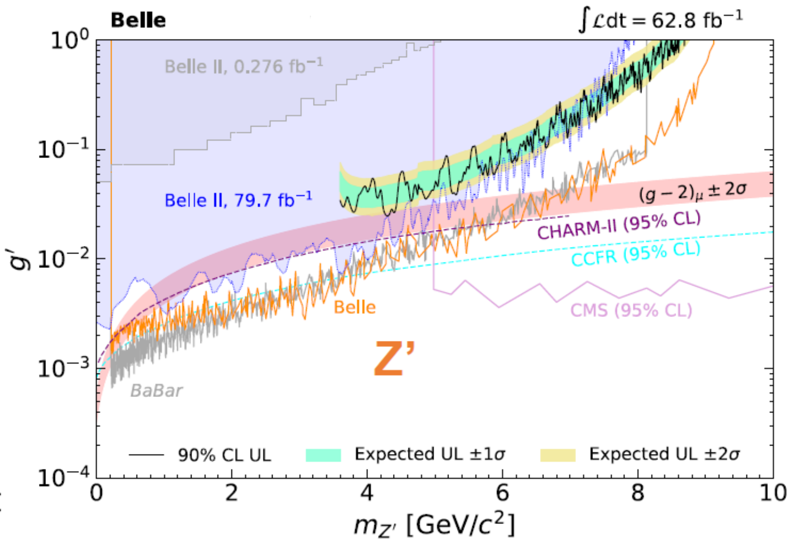
Results

No excess found. -> 90% CL upper limits on the cross section: **$\sigma(e^+e^- \to (X \to \tau^+\tau^-)\,\mu^+\mu^-) = \sigma(e^+e^- \to X\,\mu^+\mu^-)B(X \to \tau^+\tau^-)$**, with X = S, ALP, Z'

- Results translated to limits on leptophilic scalar, ALP and Z' mediator couplings:
  - **First constraints on S for M_S > 6.5 GeV/c^2 ;**
  - **First direct constraints for ALP → $\tau\tau$;**





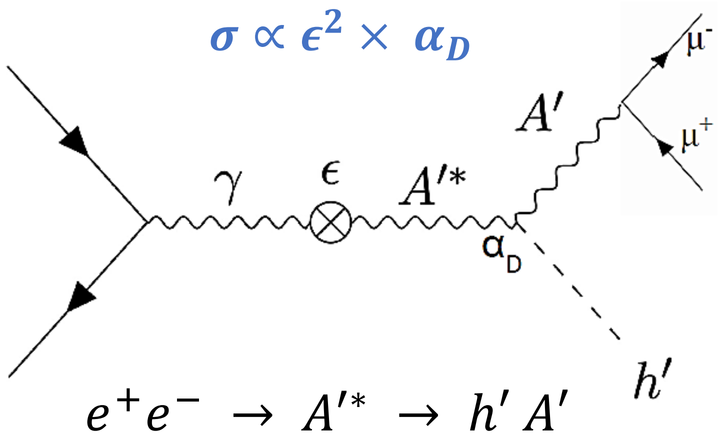


PRL 131, 121801 (2023)

Dark Higgsstrahlung search

Strategy

[1] B. Batell, et al., *Phys. Rev. D* **79**, 115008 (2009)



Massive (spin=1) gauge boson A' coupling to the SM hypercharge through the kinetic mixing with strength ε:

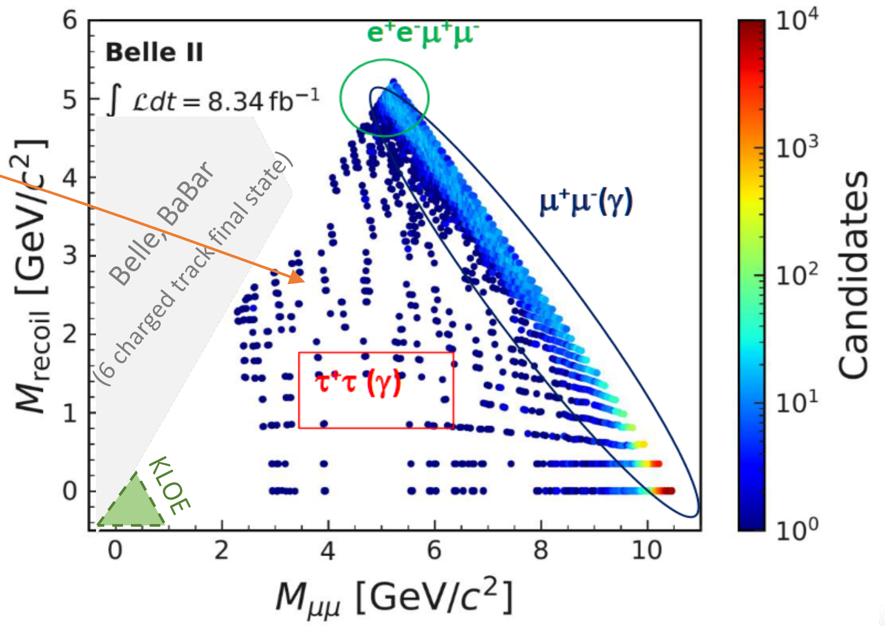
- A' mass generated by adding a dark Higgs boson h' to the theory [1];

Searching for A', h' production in a **dark Higgsstrahlung** process, with the hypothesis of $M_{h'} < M_{A'}$: h' is long-lived -> invisible.

Analysis in brief:

- two tracks + missing energy and a 2D peak in $M^2_{\mu\mu}$ vs M^2_{recoil}:
  - scan and count in search windows;
- Backgrounds mainly due to $\mu\mu(\gamma), \tau\tau, ee\mu\mu$;
- Analysis selections:
  - Two opposite sign muons, $p_T^{\mu\mu} > 0.1$ GeV/c;
  - Recoil points to barrel calorimeter;
  - Low activity in the calorimeter;
  - Final suppression exploiting helicity angle;
    - C_η = |cos($\theta_{helicity}$)| flat for signal, peak at 1 for bkg;

Observed yields



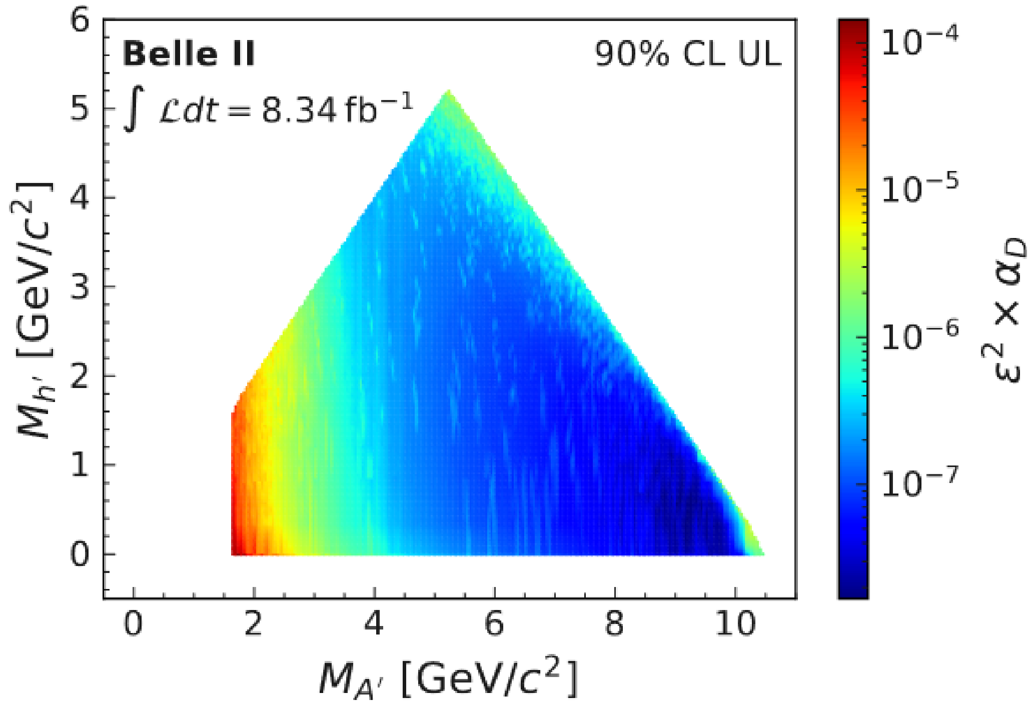
Dark Higgsstrahlung

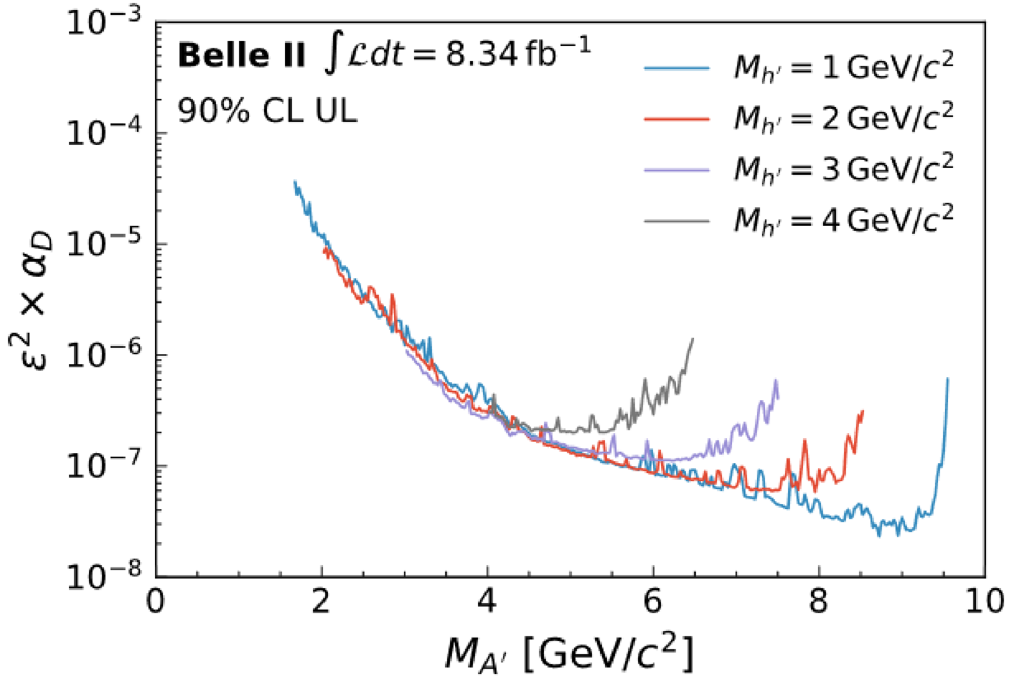
Results

Search performed with 2019 data -> 8.34 fb^{-1} .

No significant excess observed -> 90% CL UL on σ and $\epsilon^2 \times \alpha_D$;

- **World's first results for 1.65 < $M_{A'}$ < 10.51 GeV and $M_{h'}$ < $M_{A'}$**



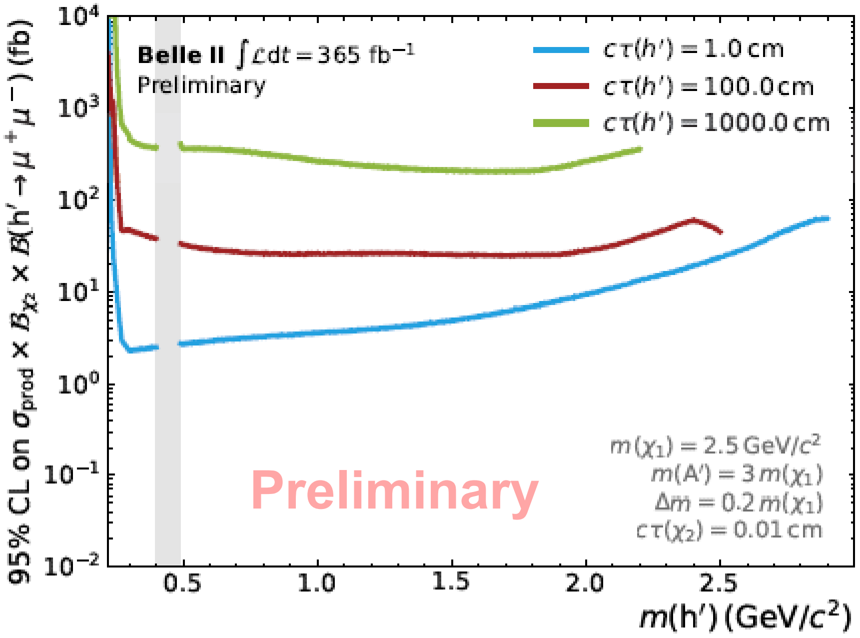


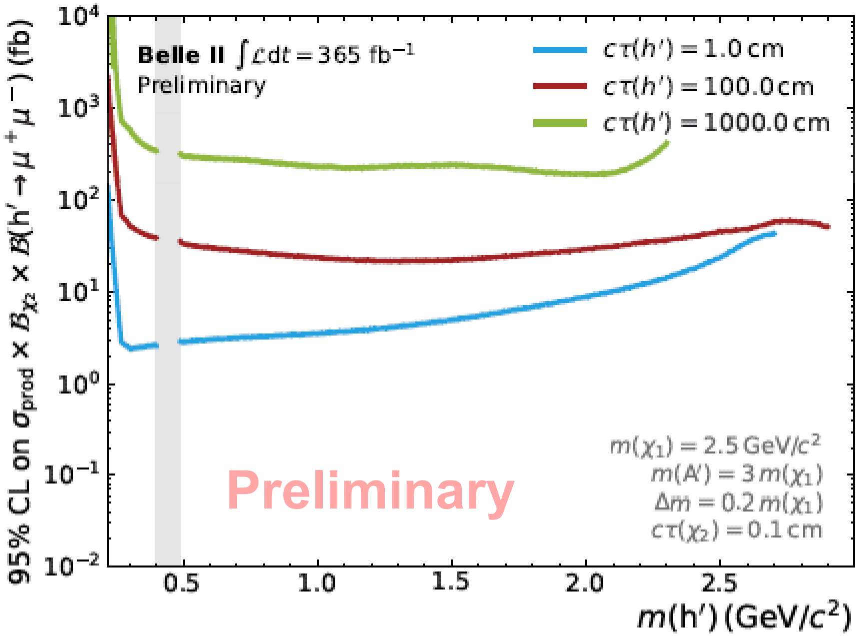
PRL 130, 071804 (2023)

Inelastic dark matter with a dark Higgs **new result**

Results

- ✓ **Model independent limits on the cross section of the process**
- ✓ **Strong limits on θ and $\epsilon \times \alpha_D$, but dependence on 5 other parameters.**
  - Many more (~30) plots for different parameter configurations





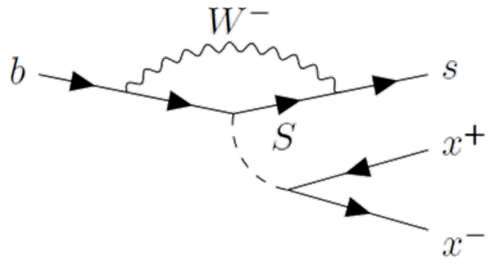
Light (pseudo)scalars in B-meson decays

Strategy

Extensions of SM predict **dark matter mass generation via light scalar S** that can mix with the SM Higgs boson with angle θ

S could be produced in b to s transitions:

- $B^+ \to K^+ S$;
- $B^0 \to K^{*0}(\to K^+\pi^-)S$;



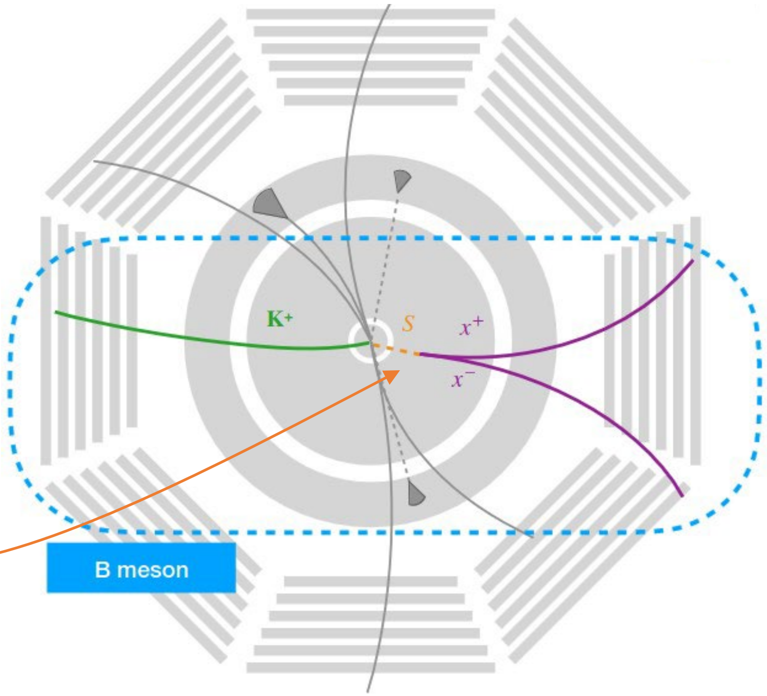
At small angles S is **long lived**:

- prompt K + two opposite signed tracks from a **displaced vertex;**

Strategy:

- Look for S decays into $ee, \mu\mu, \pi\pi, KK$;
- Search for a bump in the reduced invariant mass of tracks coming from a displaced vertex: $M'(x^+x^-) = \sqrt{M^2_{S\to x^+x^-} - 4m_x^2}$
- Require signal B to be fully reconstructed for background rejection ($ee \to q\bar{q}$);
- SM long-lived K_S^0 mass region vetoed;
    - excellent control sample in data to evaluate LLP performance (efficiencies, shapes);

Transverse view of the Belle II detector



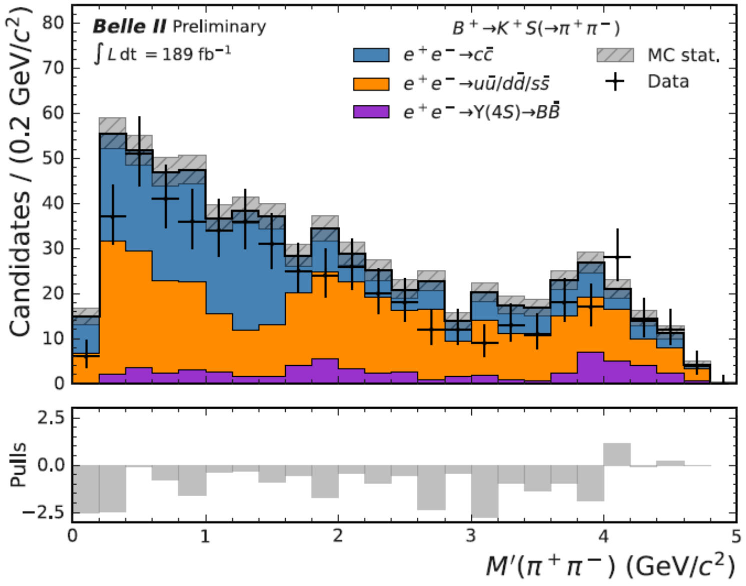
Probe lifetimes between $10^{-5} < c\tau < 4\,\mathrm{m}$

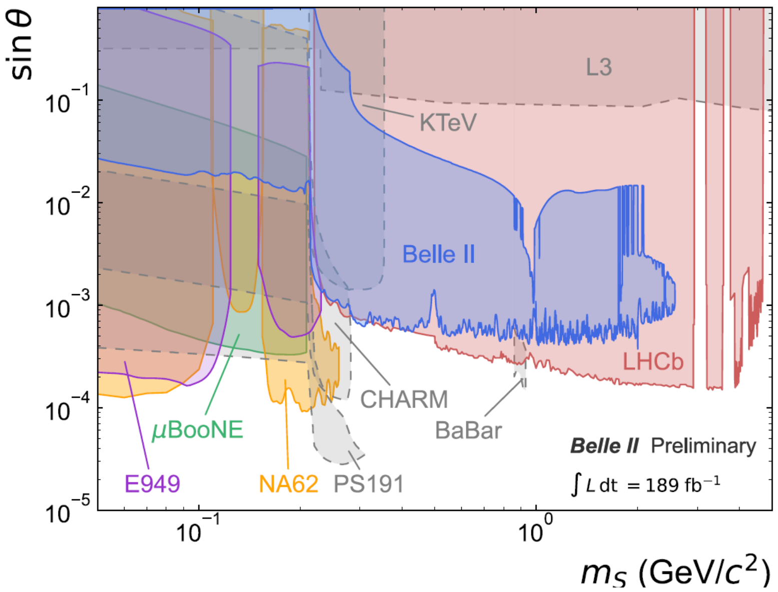
Light (pseudo)scalars in B-meson decays

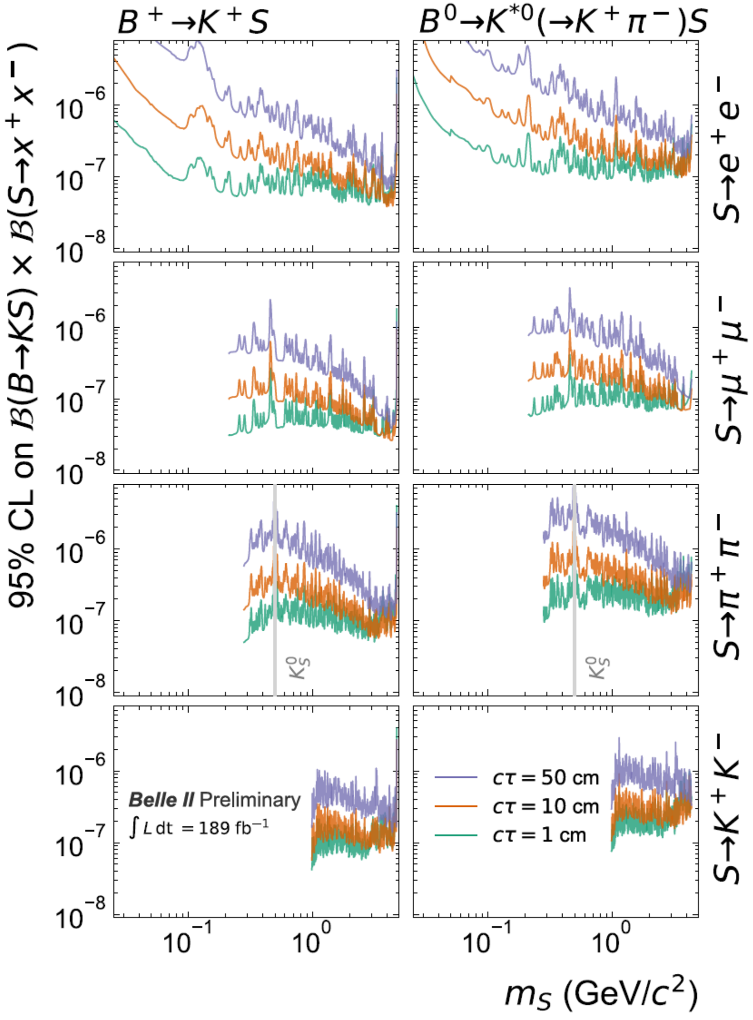
Results

No significant excess observed in 189 fb[-1].

- First limits on exclusive hadronic final states;
- Best sensitivity for direct search for $K^*e^+e^-$ final state;
- Dark Higgs-like scalar interpretation ;
- Pseudo-scalar (ALP) interpretation;







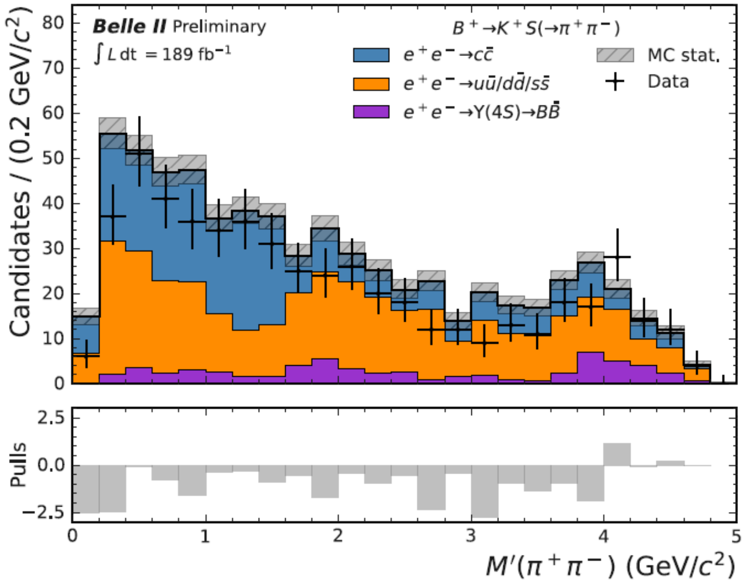
[Phys. Rev. D 108, L111104 (2023)]

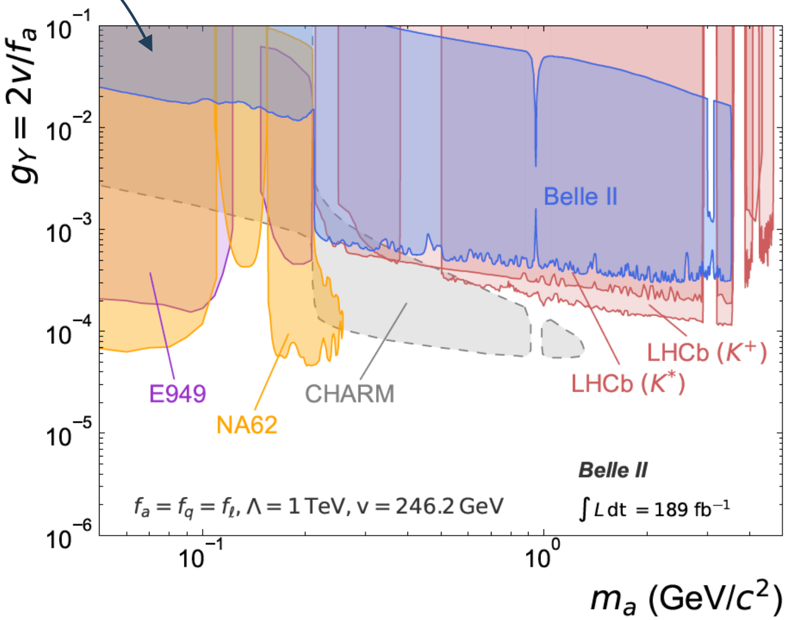
Light (pseudo)scalars in B-meson decays

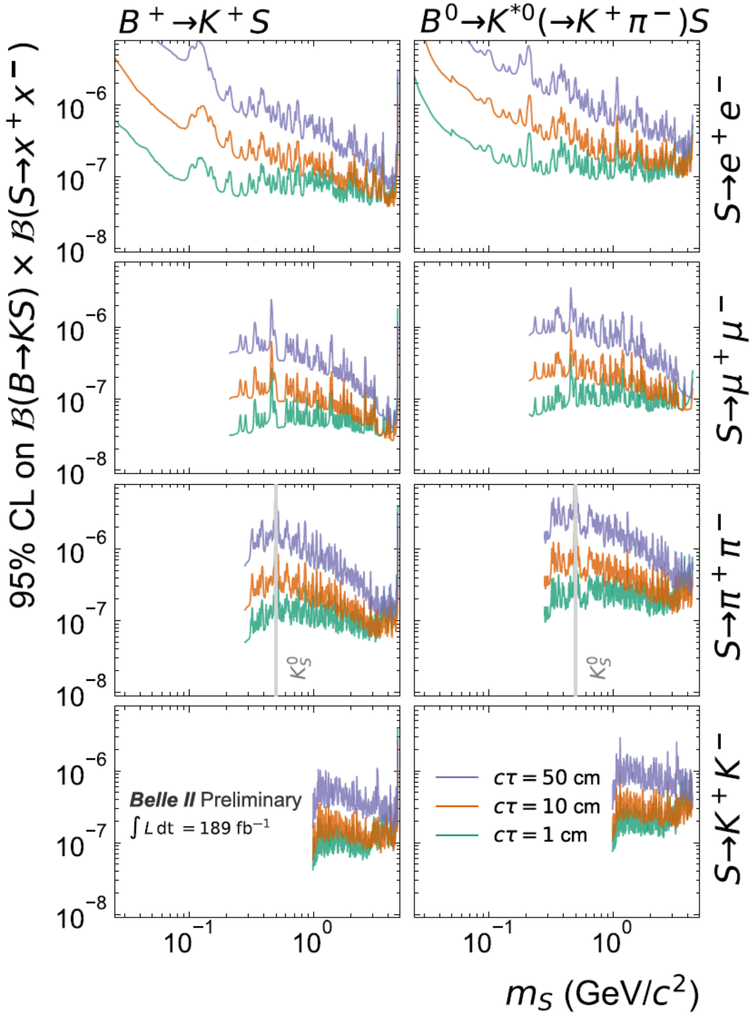
Results

No significant excess observed in 189 fb^{-1}.

- First limits on exclusive hadronic final states;
- Best sensitivity for direct search for $K^*e^+e^-$ final state;
- Dark Higgs-like scalar interpretation ;
- Pseudo-scalar (ALP) interpretation;







Phys. Rev. D 108, L111104 (2023)

Invisible boson in lepton-flavor violating τ decays

Strategy

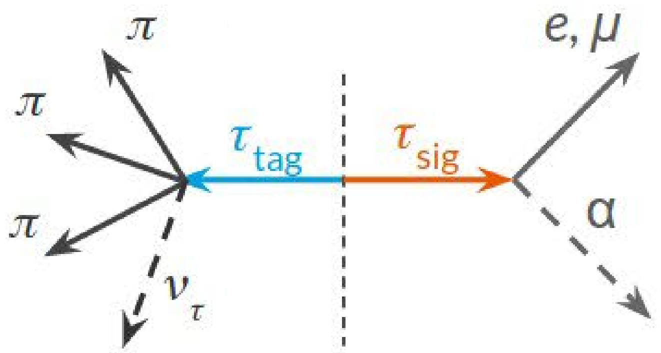
[1] M. Bauer, et al. Phys. Rev. Lett. 124, 211803 (2020)

Look for an invisible α boson produced in a LFV tau decay

$\tau \rightarrow \ell\alpha$

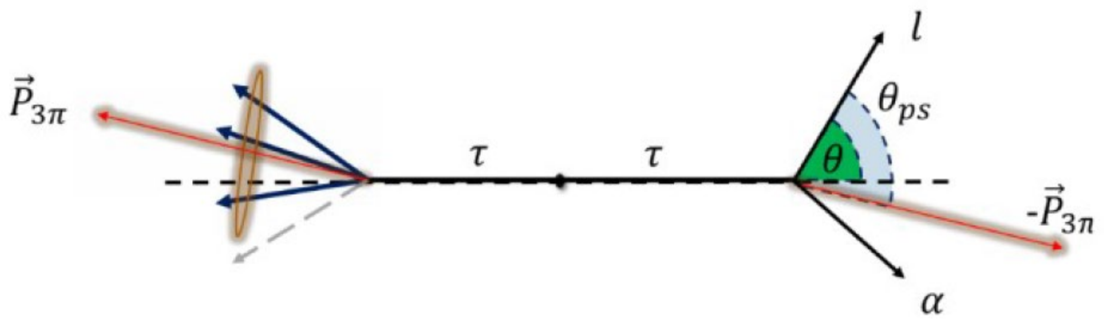
$\alpha \rightarrow$ invisible

α can be an ALP candidate [1].

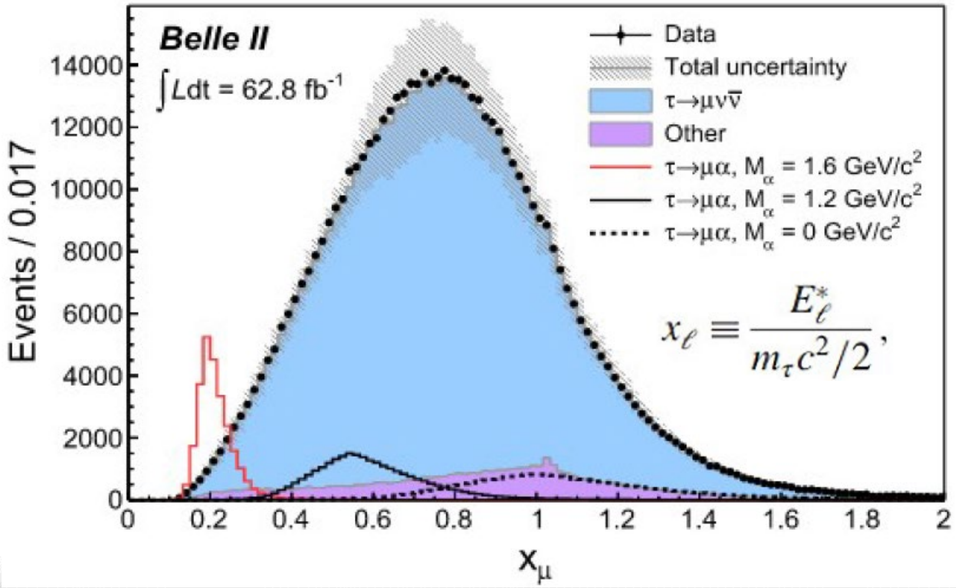


Analysis in brief:

- three tracks on the **tag** side, one track on the **signal** side (ℓ=e or ℓ=μ);
- background from $\boldsymbol{\tau_{SM} \rightarrow \ell\nu\nu}$
- exploit the **shape differences**: *2-body* decay for signal (peaking in the normalized lepton energy x_l in the $\boldsymbol{\tau_{sig}}$ pseudo-rest frame) over *3-body* decay of irreducible background;



approximate $\boldsymbol{\tau_{sig}}$ pseudo-rest frame as $E_{sig} \sim \sqrt{s}/2$ and $\hat{p}_{sig} \approx -\vec{p}_{\tau_{tag}}/|\vec{p}_{\tau_{tag}}|$



Invisible boson in lepton-flavor violating τ decays

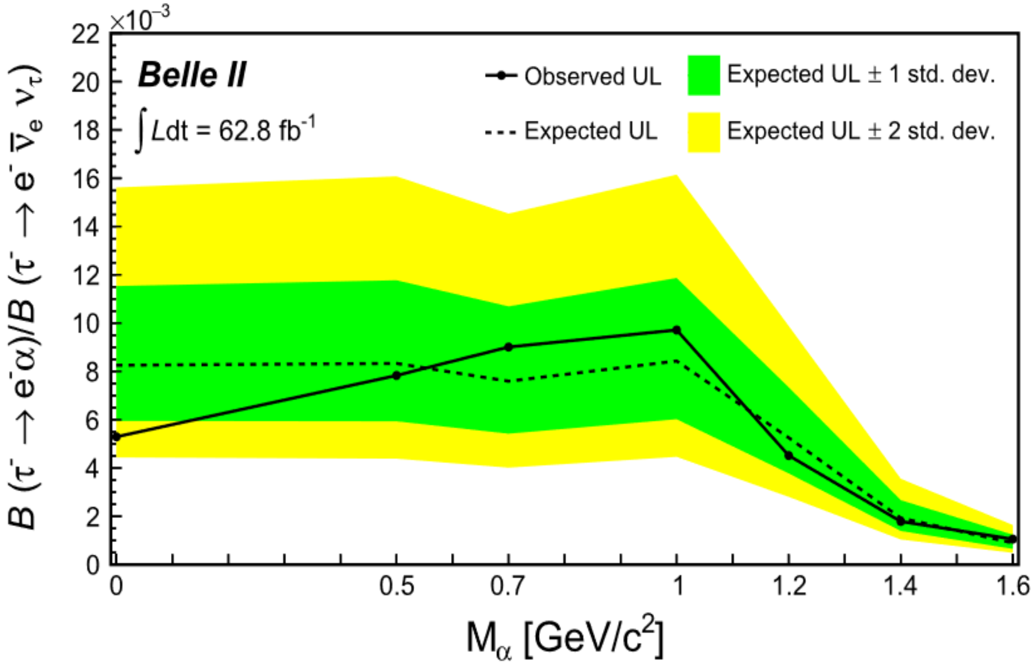
Results

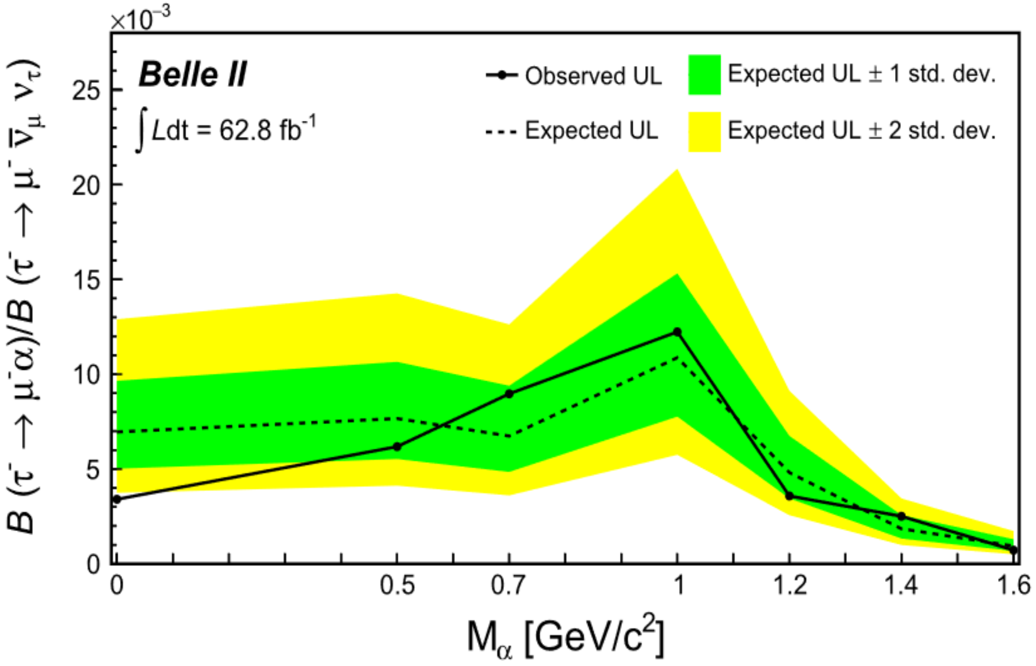
[1] ARGUS Collaboration, Z. Phys. C 68, 25 (1995)

No significant excess in 62.8 fb^{-1}.

95% CL upper limits on BF ratios of **BF(τ_{sig} →ℓα)** normalized to BF(τ_{SM}→ ℓνν);

- 2-14 tighter limits on the previous Argus results [1];

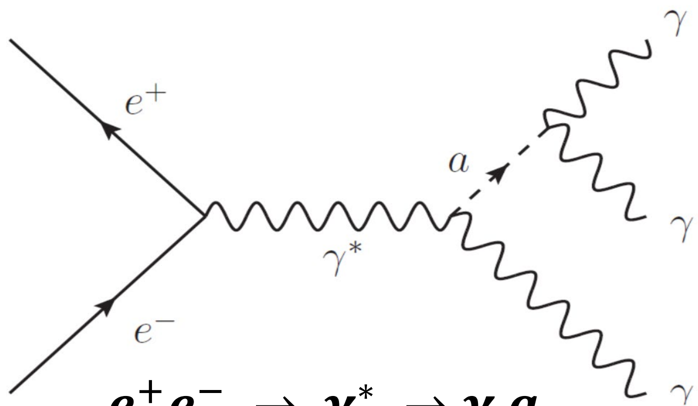




PRL 130, 181803 (2023)

Search for the ALP-strahlung

Results



$$e^+e^- \to \gamma^* \to \gamma\, a,\quad a \to \gamma\gamma$$

Search for ALP-strahlung in the 3γ resolved final state:

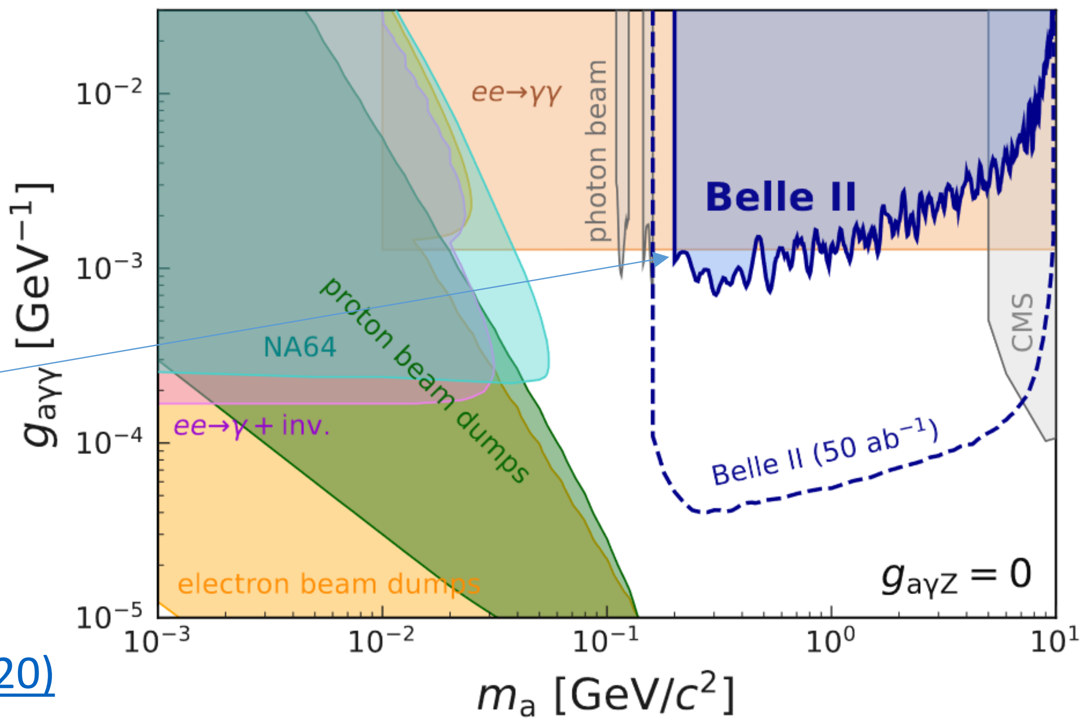
Analysis in brief:

- 3γ that add up to the beam energy;
- Search for a peak either in the recoil invariant mass (high ma) or in the diphoton mass (low ma);
- Background from $\gamma\gamma(\gamma)$; $e^+ e^- (\gamma)$; $P\, \gamma(\gamma)$ with $P = \pi^0, \eta, \eta'$;

Used first data from 2018 commissioning run (0.455 fb^{-1});

No excess observed and 90% CL UL on $g_{a\gamma\gamma}$ down to O(10^{-3}).

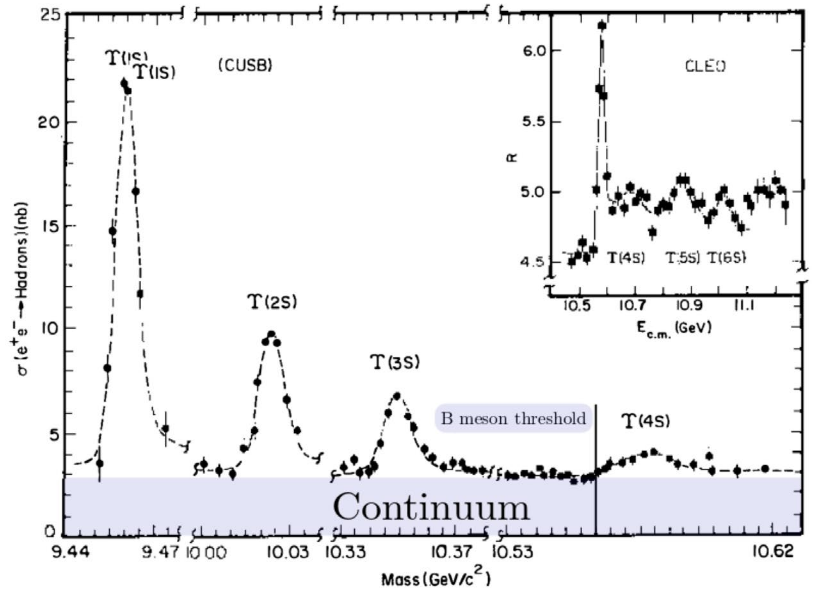
- First results ever for ALPs @ B-factories

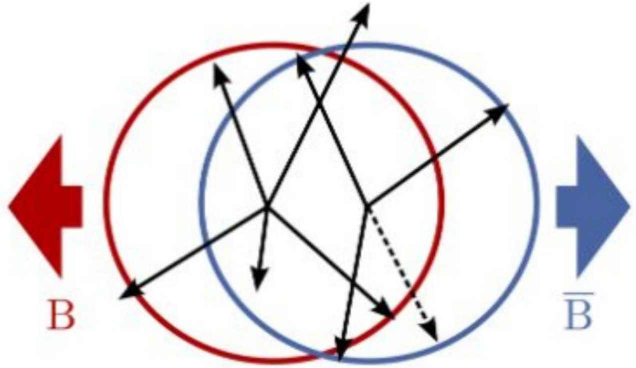


PRL **125**, 161806 (2020)

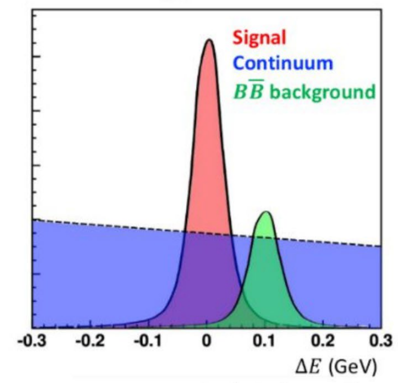
Belle II

Continuum rejection



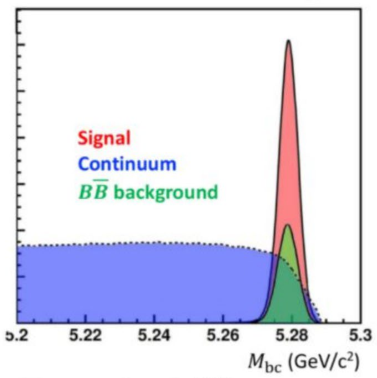


$$\Delta E = E_B^* - \sqrt{s}/2$$



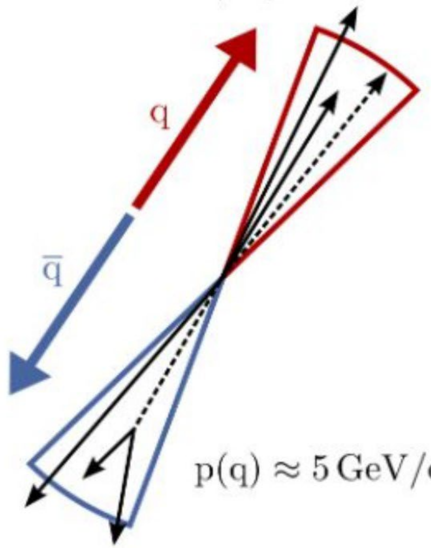
Expected ΔE = 0

$$M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{*2}|}$$



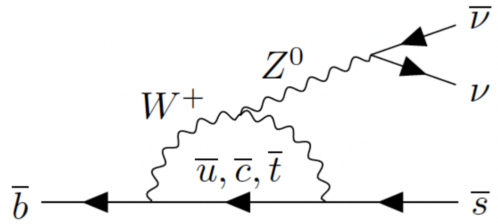
Expected $M_{bc} = m_B$

Different event shape to separate B events from continuum background



Evidence for $B^+ \to K^+\nu\nu$

Overview and strategy

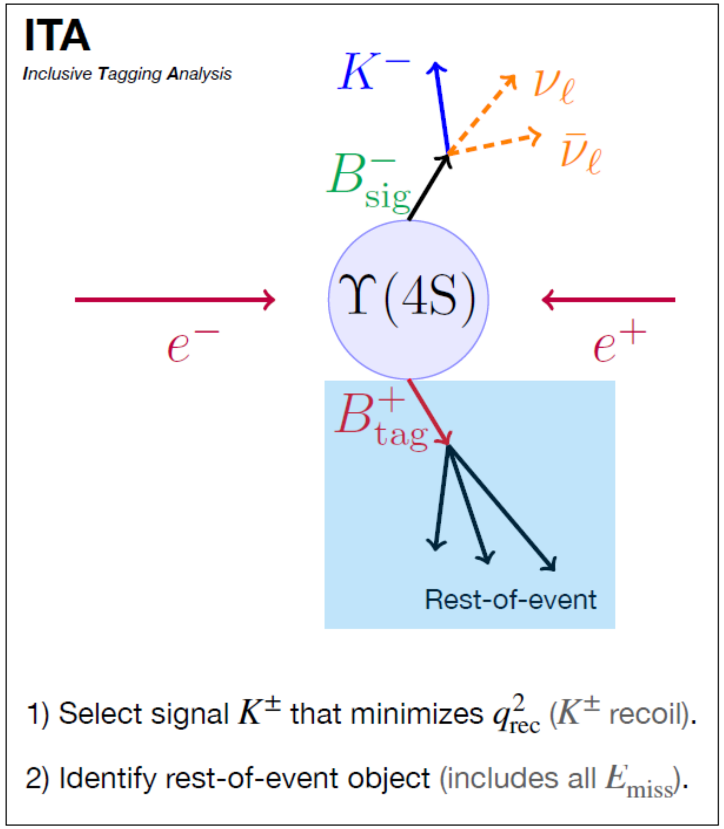


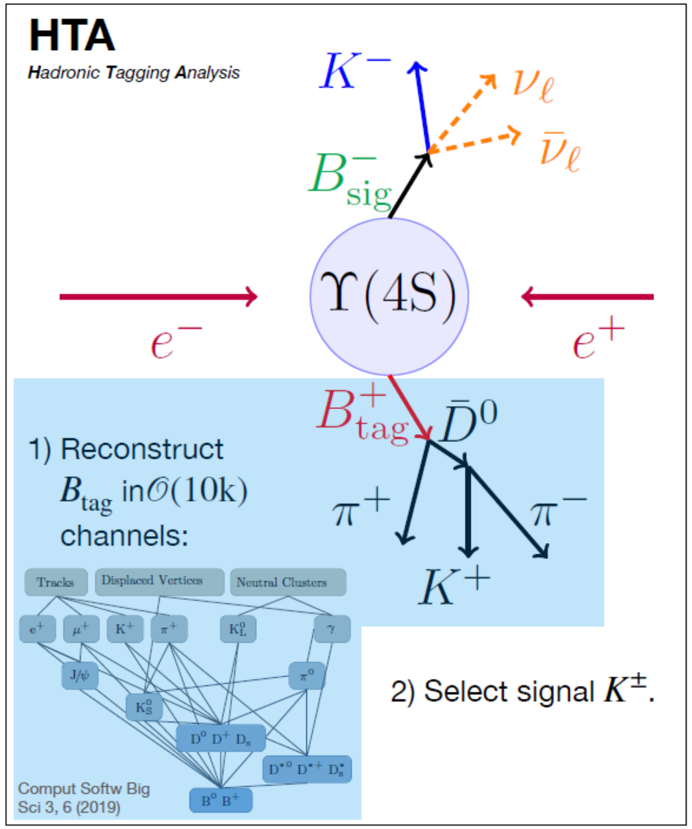
Reliable SM prediction, never observed before, possibly affected by NP (ALPs, dark scalars, Z', leptoquarks…)

- Experimentally challenging for the 2 neutrinos in the final state;
- Used two complementary B tag approach:
  - low purity-high efficiency (0.8% - 8%)
  - its opposite (3.5% - 0.4%)

Strategy:

- Event selection by combining signal kaon, event topology, rest-of-event info in MVA classifiers
- Background from continuum, semileptonic B decays
- Signal efficiency and bkg estimation corrected and validated using a variety of control channels



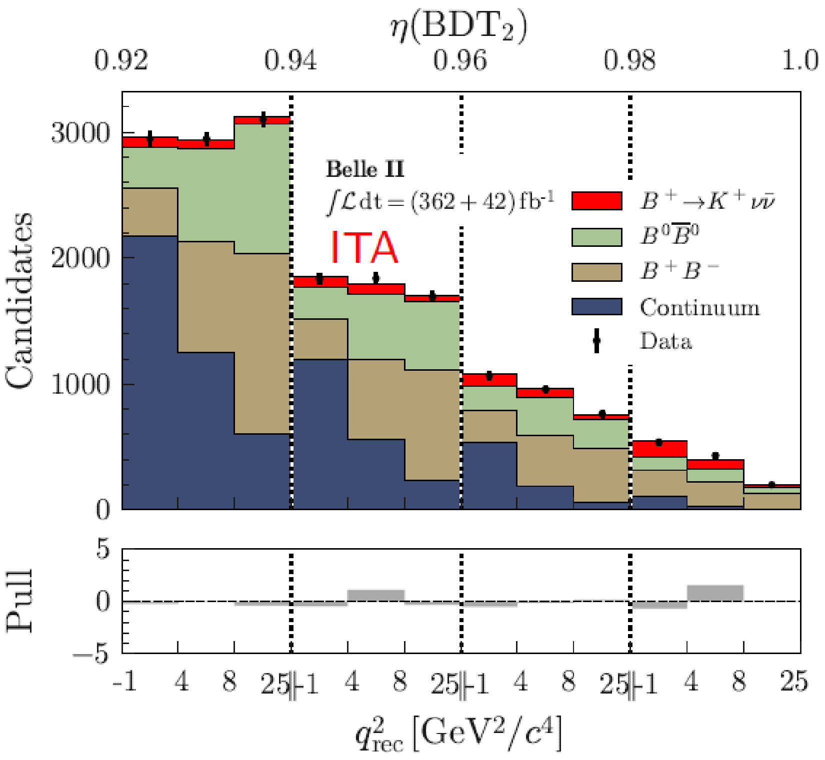


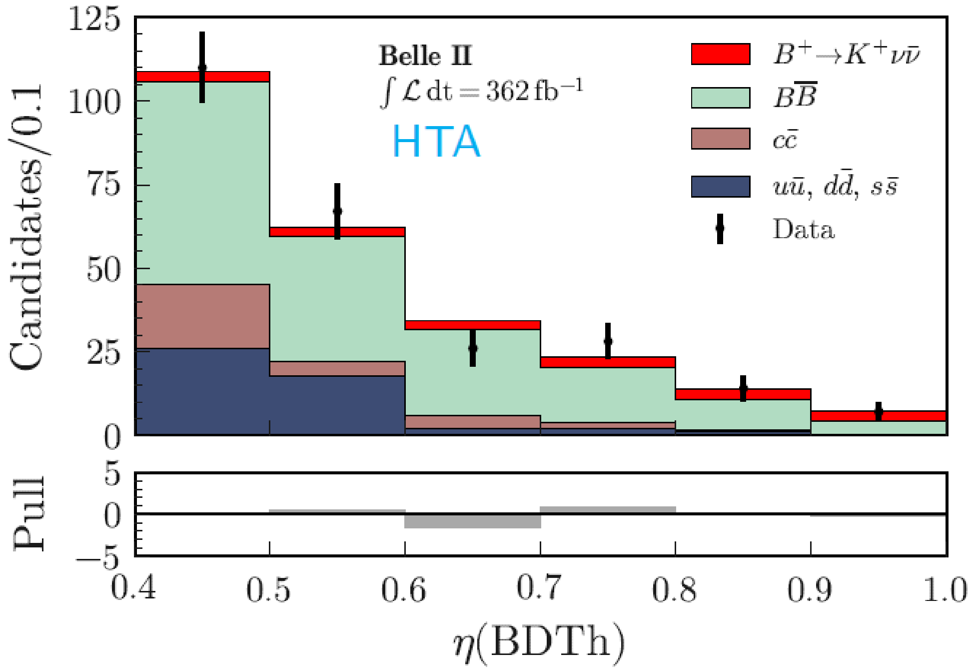
Evidence for $B^+ \to K^+\nu\nu$

Strategy

Perform binned maximum likelihood fit:

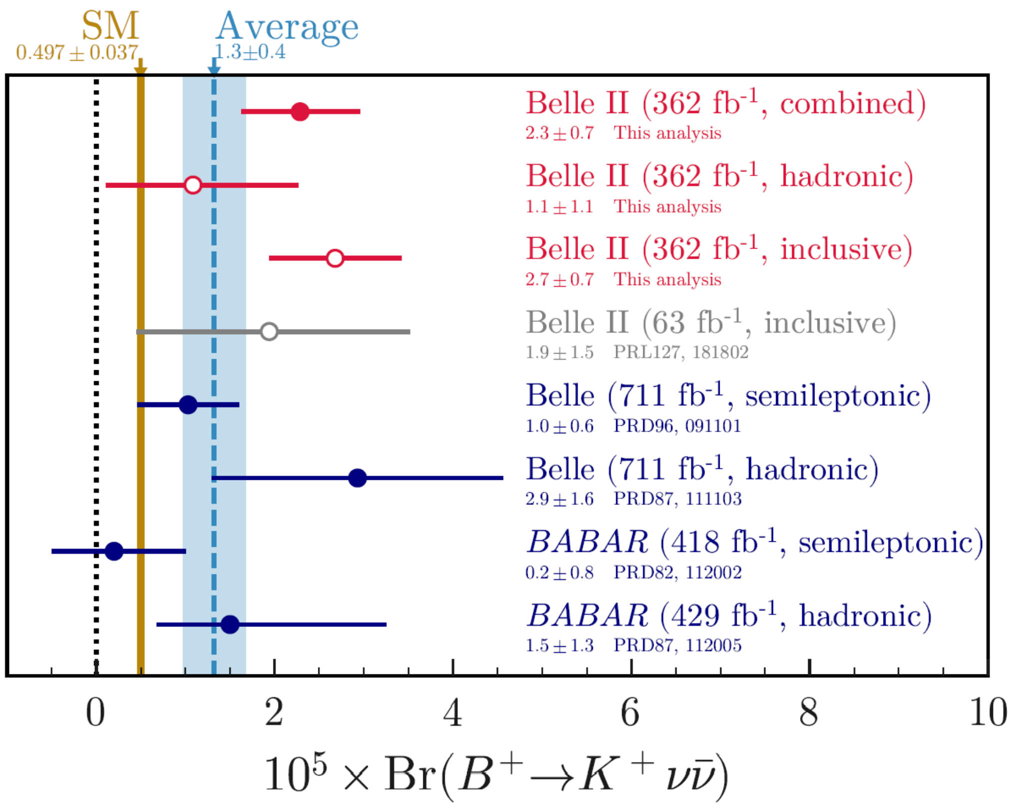
- Inclusive tag: in bins of q^2 and classifier output
- Hadronic tag: in bins of classifier output





Evidence for $B^+ \to K^+\nu\nu$

Results



ITA: $\mathrm{BF}= (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$

HTA: $\mathrm{BF}=(1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$

Combined: $\mathrm{BF}=(2.3 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$

3.5 σ excess, 2.7 σ from SM

Tau physics at Belle and Belle II

Overview

B-factories are also τ factories

- τ pairs cross-section equivalent to BB procces

B-factories are also τ factories

- τ pairs cross-section equivalent to BB procces

Testbed for:

✓ **precision SM measurements**

- τ lifetime, mass, coupling (universality)

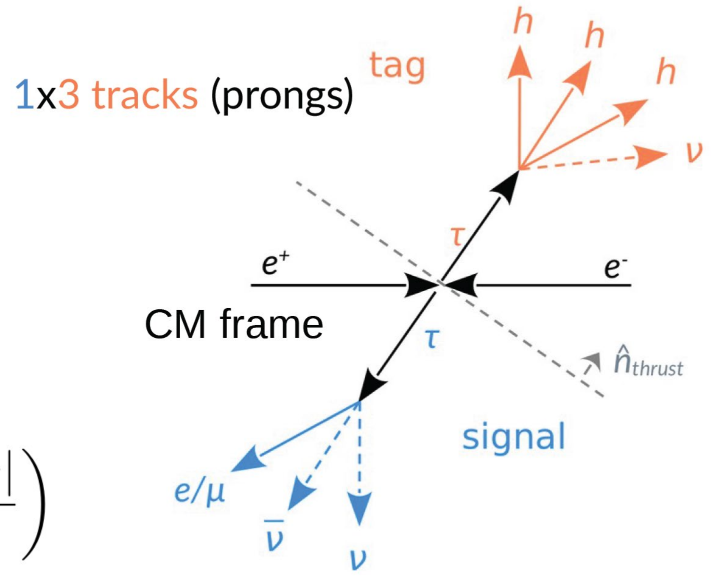
✓ **searches for rare or forbidden processes**

- Mostly lepton flavor violating τ decays

Produced in pairs: $e^+e^- \rightarrow \tau^+\tau^-$

- **Back to back and boosted in the center-of-mass frame**
- Identify events by reconstructing the thrust axis n_T (maximizes thrust T)
- Separate them in two opposite hemispheres
- Typically use one side to tag the event by reconstructing decays with 1 charged track (1-prong) or 3 charged tracks (3-prong)
  - Reconstruct signal on other hemisphere

$$T = \max_{\hat{n}_T} \left(\frac{\sum_i |p_i \cdot \hat{n}_T|}{\sum_i |p_i|} \right)$$

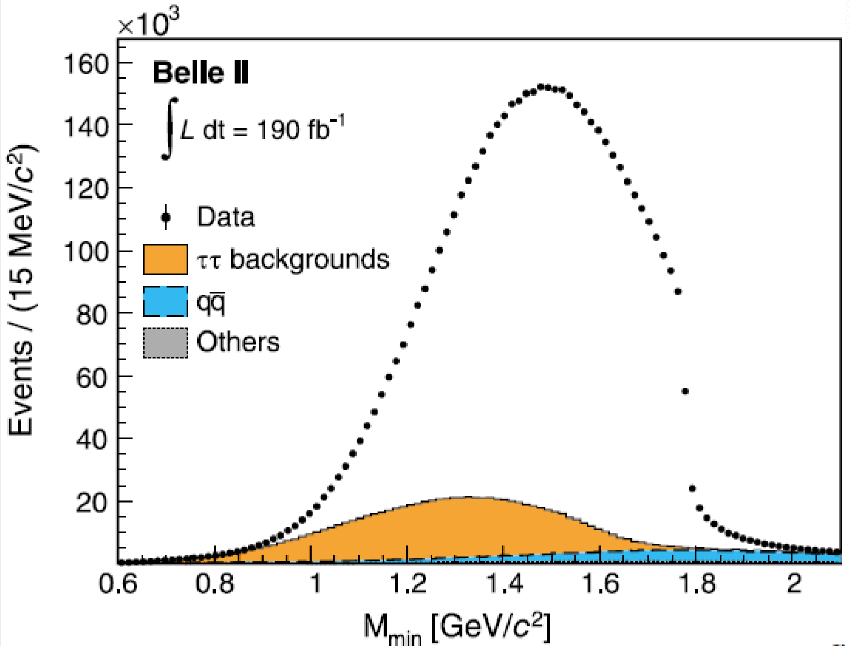


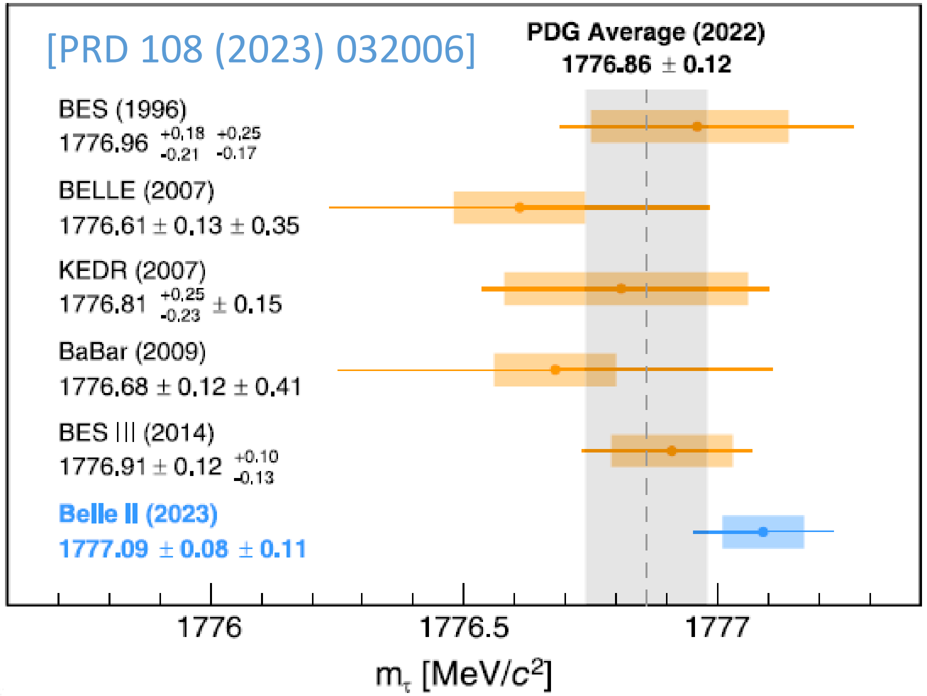
Tau Mass Measurement

Strategy and results

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} < m_\tau$$

- Fundamental physics parameter and important input, e.g. for lepton-universality tests
- Pseudomass method in $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$
  - $M_{\min}$ distribution ends at m_τ
  - Smeared by resolution and initial and final state radiation
- Accuracy determined by
  - Beam energy $\sqrt{s}/2$
    - Calibrated using $B\bar{B}$ events
  - Final-state particle momentum
    - Calibrated using $D^0 \to K\pi$ standard candle
- Belle II provides World's most precise result





Tau Mass Measurement

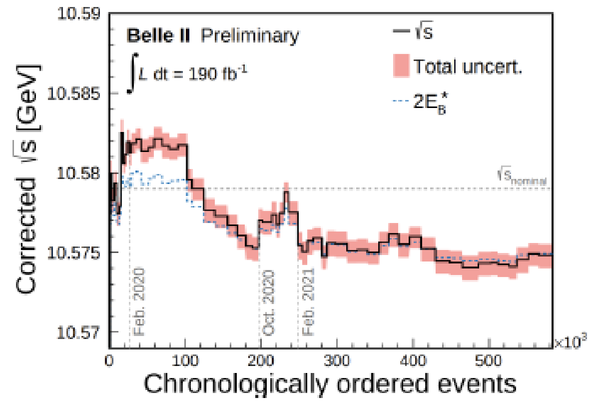
Strategy and results

- Measurement dominated by systematics uncertainties: $M_{min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)}$

Source	Uncertainty MeV/c^2
Knowledge of the colliding beams:	
Beam energy correction	0.07
Boost vector	$\leq$ 0.01
Reconstruction of charged particles:	
Charged particle momentum correction	0.06
Detector misalignment	0.03
Fitting procedure:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	$\leq$ 0.01
Imperfections of the simulation:	
Detector material budget	0.03
Modeling of ISR and FSR	0.02
Momentum resolution	$\leq$ 0.01
Neutral particle reconstruction efficiency	$\leq$ 0.01
Tracking efficiency correction	$\leq$ 0.01
Trigger efficiency	$\leq$ 0.01
Background processes	$\leq$ 0.01
Total	**0.11**

Beam energy callibration

Use B meson hadronic decays method and $\Upsilon(4S)$ lineshape measurement to get $\sqrt{s}$



Momentum scale factor

- Cure bias due to imperfect magnetic field
- Extract polar angle $cos\theta_{track}$ dependant correction: comparing $D^0 \to K\pi$ mass peak w.r.t PDG mass