

Recent results from Belle II

Dark sector and rare decays searches at Belle II

XIX International Conference on Interconnections
between Particle Physics and Cosmology

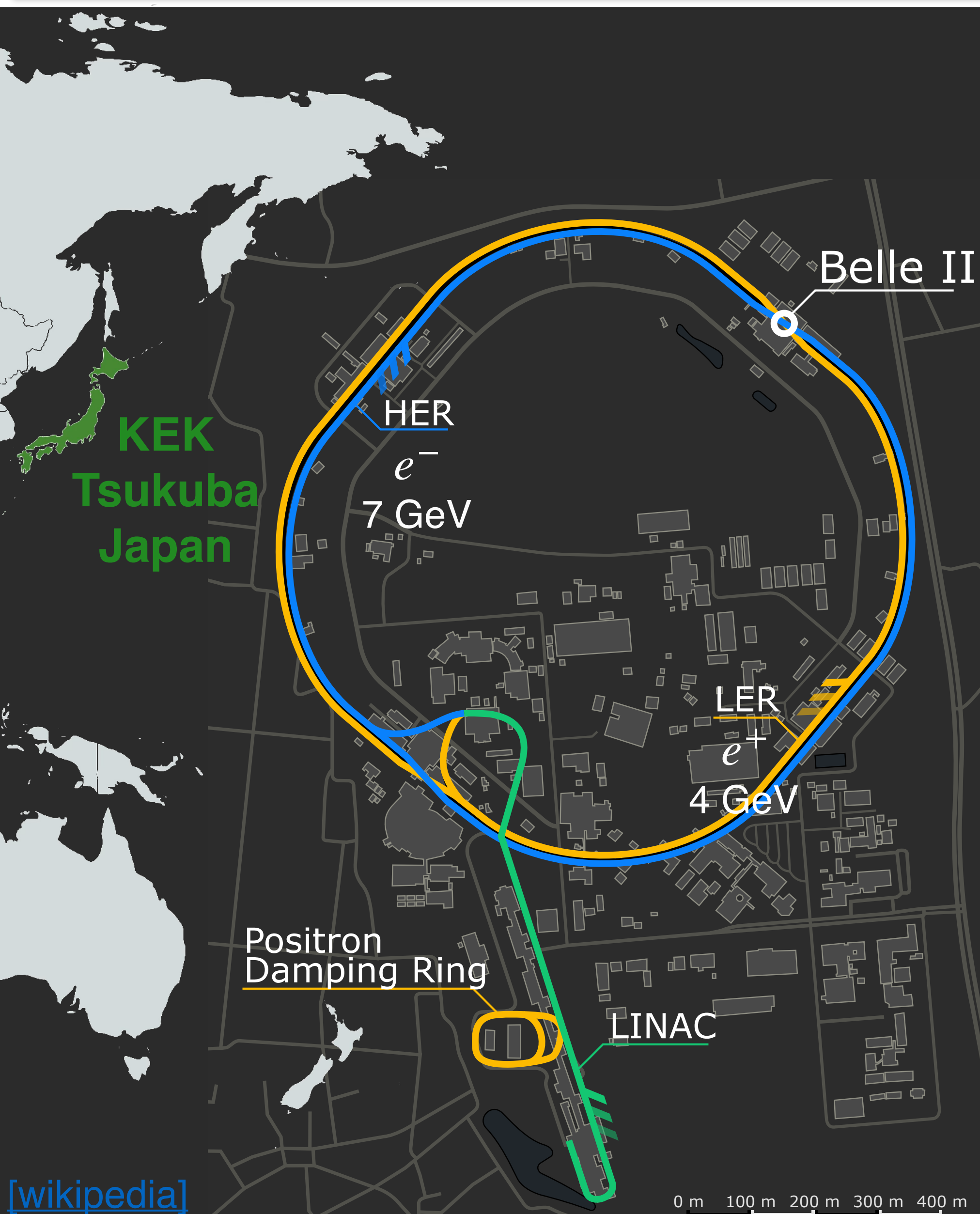
Robin Leboucher beyond Belle II collaboration



THE UNIVERSITY
OF BRITISH COLUMBIA



SuperKEKB and Belle II

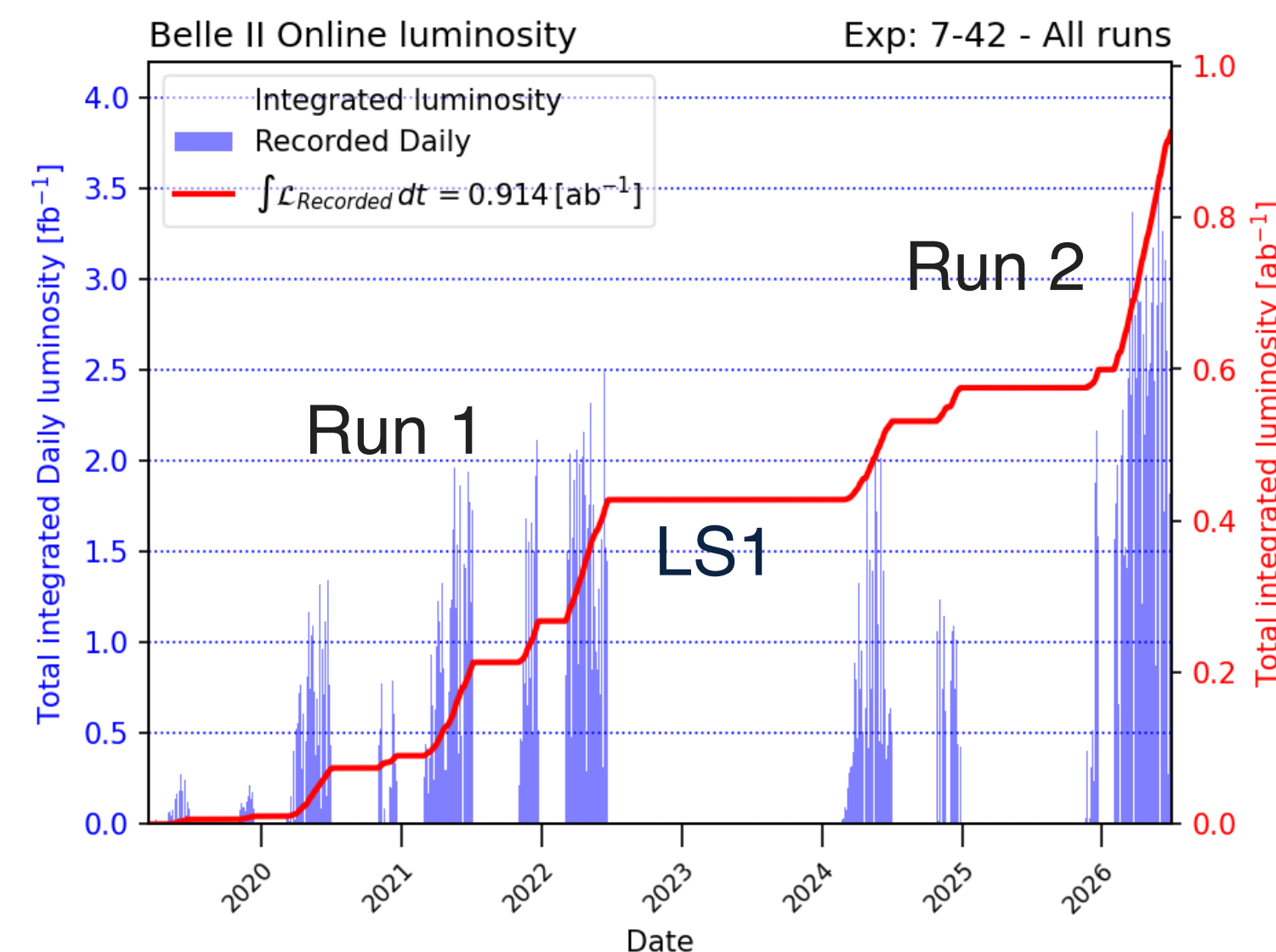


Belle (1999-2010):

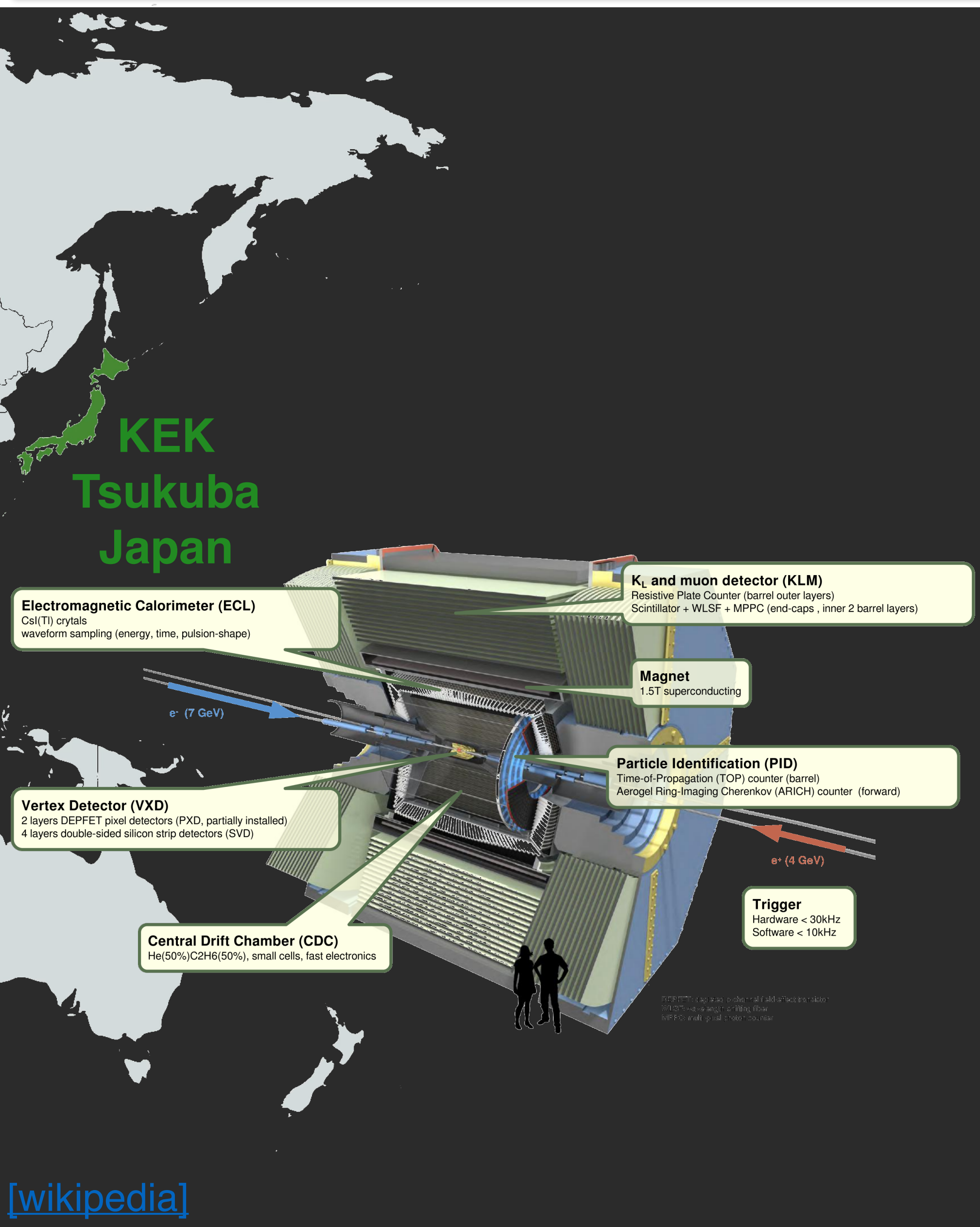
- Integrated luminosity $\approx 1 \text{ ab}^{-1}$

Belle II (2018-present):

- **Peak luminosity world record** = $5.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- Integrated luminosity = 914 fb^{-1}
Largest recorded $\Upsilon(4S)$ dataset 808 fb^{-1} , surpassing Belle
- Run 1 (2019-2022)
- Run 2 (2024...):
 - Stable data-taking at $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - Focused on physics data-taking
 - Since 2024 sudden beam loss the PXD has remained OFF



Why dark matter searches at Belle II ?



A B factory, but not only:

- Large sample (in Run1):

$$N_{B\bar{B}} \approx 380 \times 10^6$$

$$N_{\tau^-\tau^+} \approx 390 \times 10^6$$

$B, c\bar{c},$
 τ -factory
 and much more

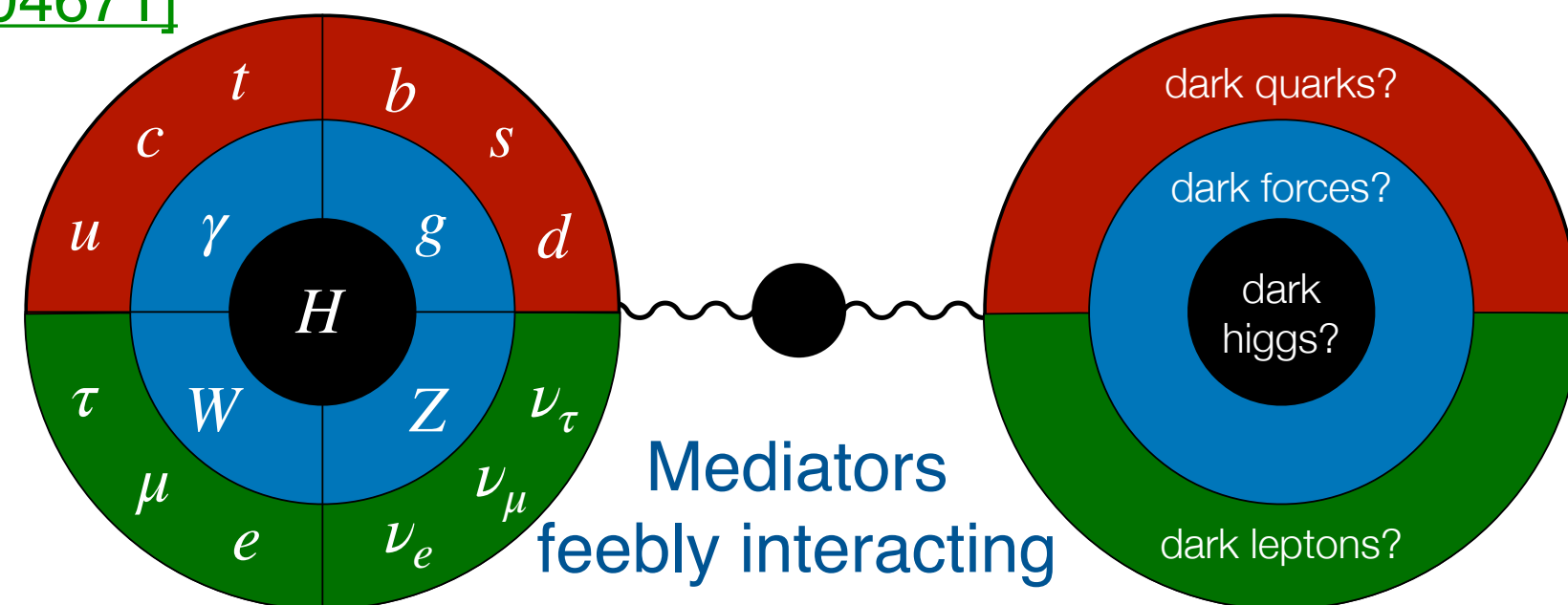
A unique place for dark sector searches:

- Excellent vertexing and track reconstruction
 - Good particle identification (lepton ID, π/K separation)
 - Special triggers for low-multiplicity
 - Single photon, single track...
 - Good missing energy reconstruction:
 - Clean collision environment
 - Hermetic detector (90% solid angle coverage)
- ➔ Excellent for decays with neutrals and/or missing energy

Which dark matter searches at Belle II ?

Dark matter is the most compelling question in particle physics. **What is the particle nature of dark matter?**

[arXiv:2209.04671]

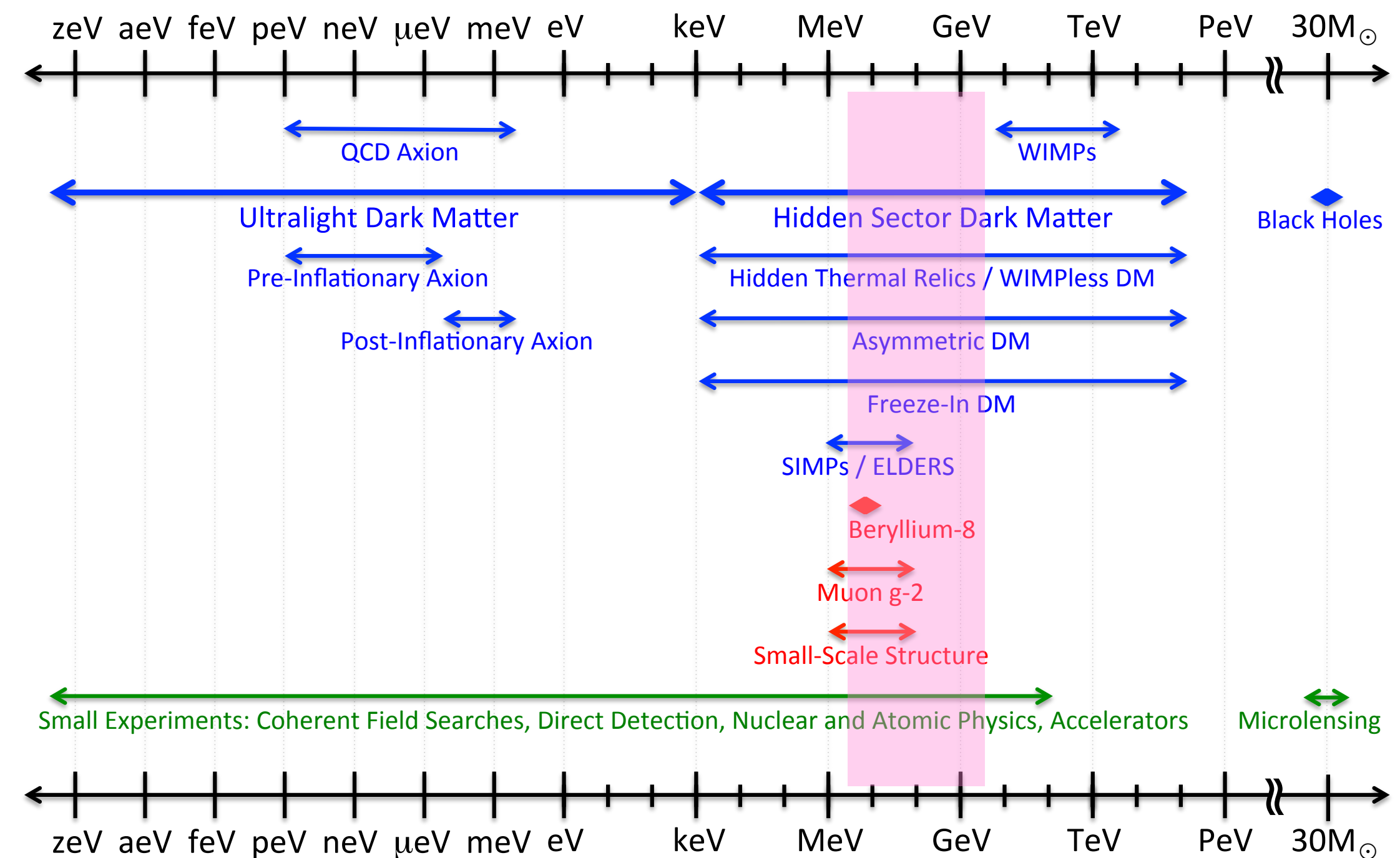


Belle II has access to many portal candidates to the **hidden-sector dark matter**:

- Vector (dark photon, dark boson...)
- Pseudo-scalar (axion-like particles)
- Scalar (dark Higgs)
- Neutrino (sterile neutrinos)

Low-mass and feebly coupled portals to the SM
 ➡ Intensity frontier (e.g. Belle II) well-suited

Dark Sector Candidates, Anomalies, and Search Techniques



[arXiv:1707.04591]

Which type of signatures ?

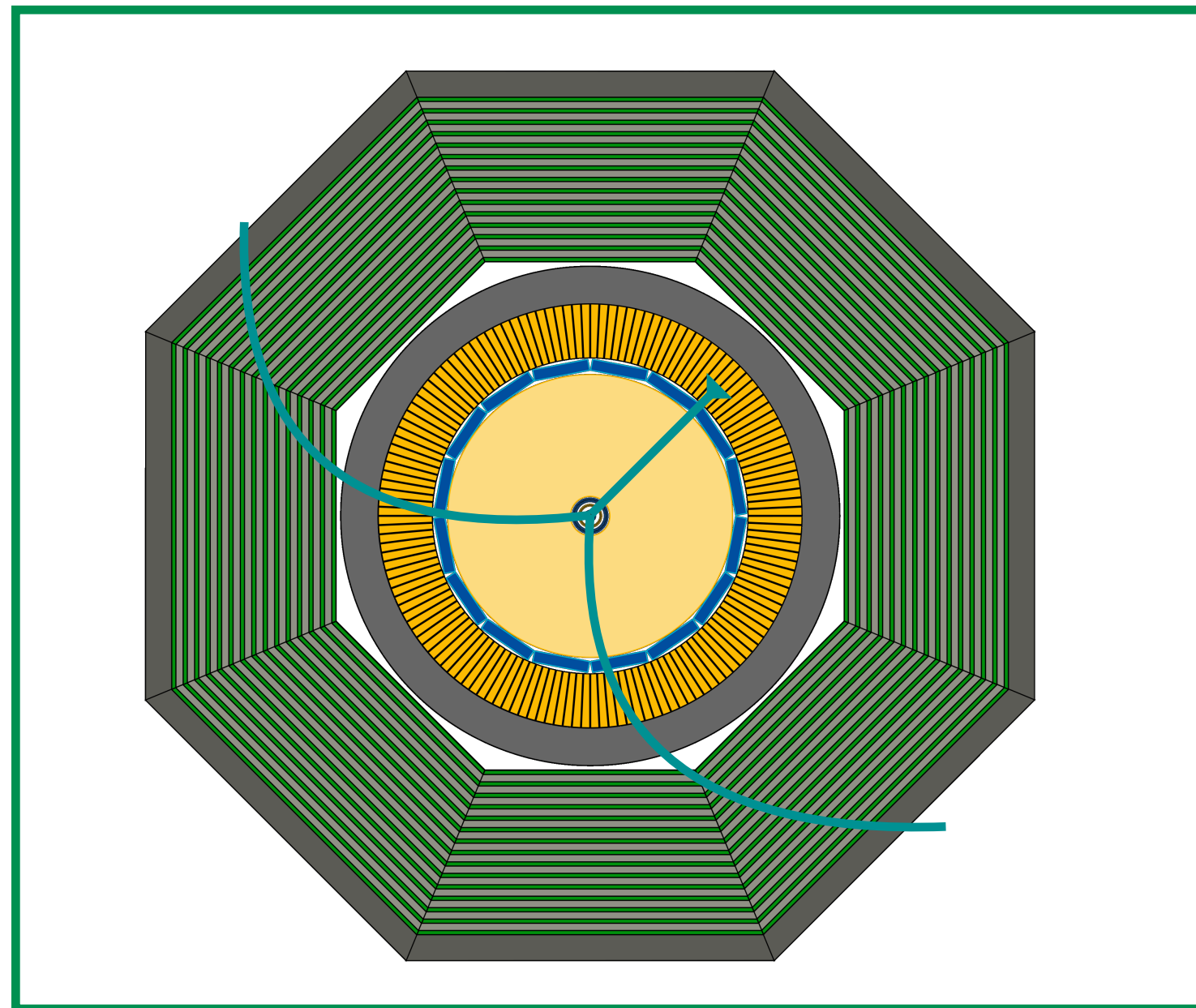
At Belle II we can look for different decay signatures:

Visible decays

Rare resonances

$$e^+e^- \rightarrow \gamma A' (\rightarrow \mu^+ \mu^-)$$

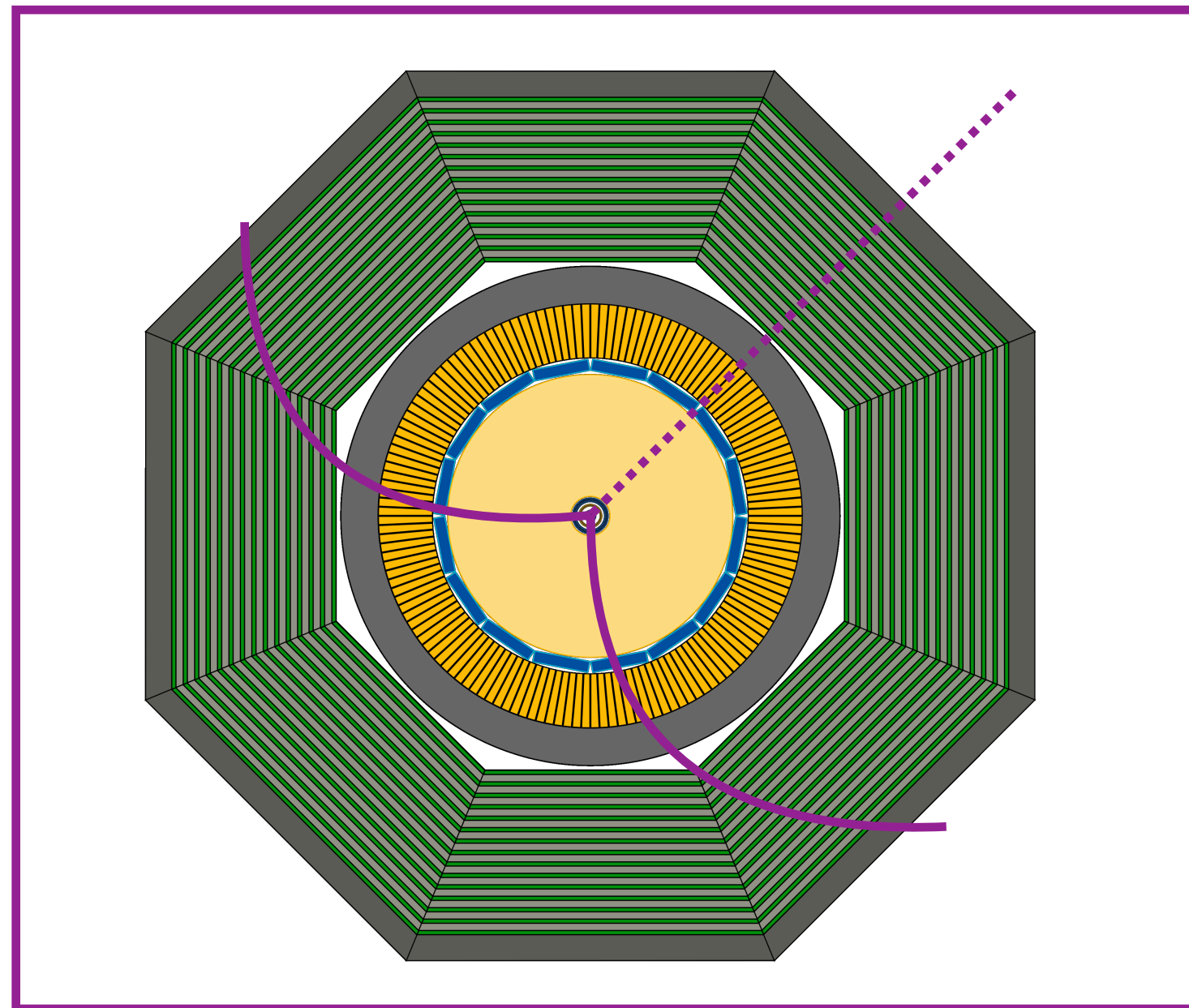
$$e^+e^- \rightarrow \gamma \alpha (\rightarrow \gamma \gamma)$$



Missing energy

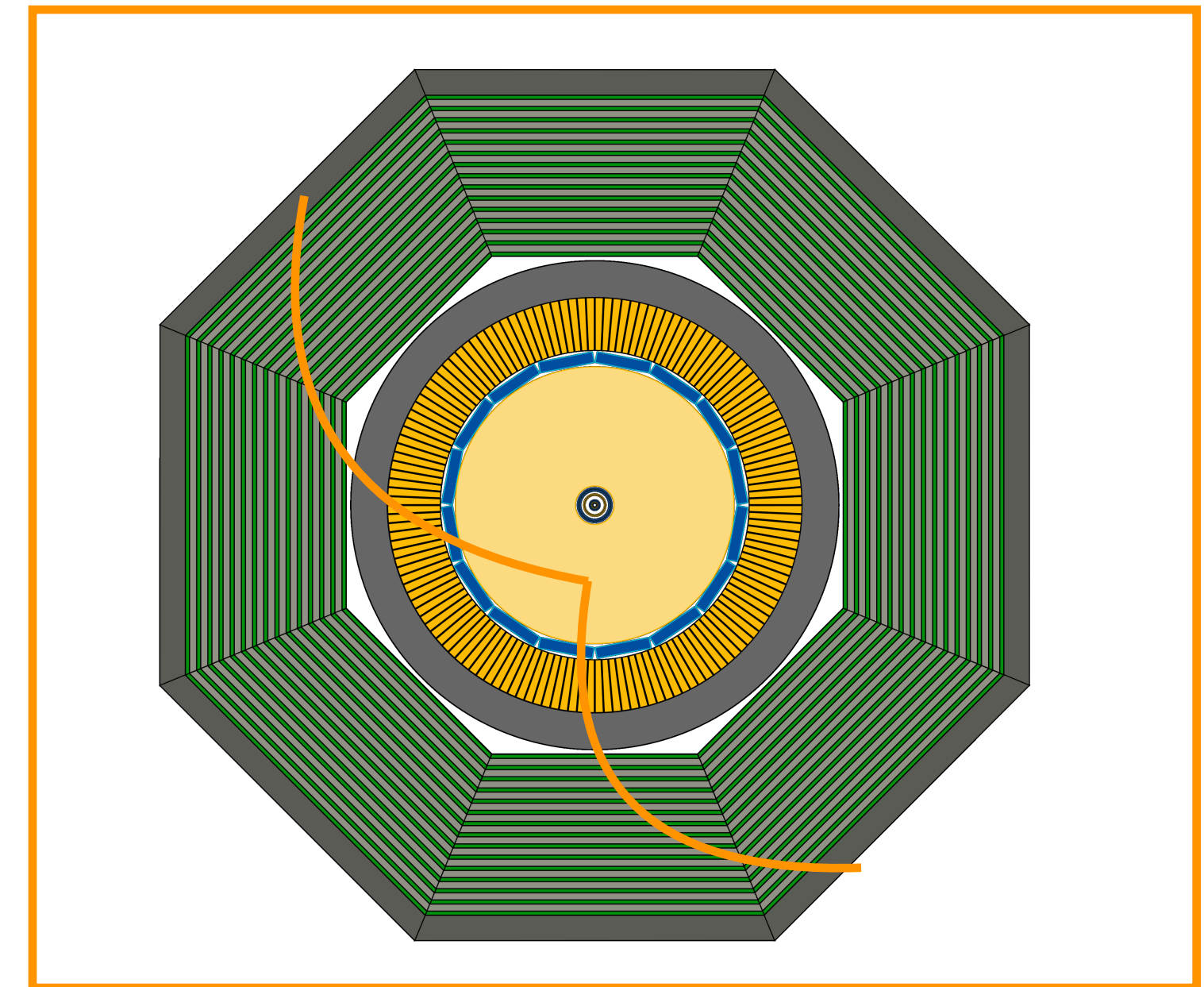
Invisible final states

$$B \rightarrow h X_{inv}$$



Displaced decays

Long-lived particles
(not talked today)



Search for ALPs in $e^+e^- \rightarrow \gamma\alpha(\rightarrow \gamma\gamma)$ at Belle II

Submitted to PRL ([arXiv:2607.07800](https://arxiv.org/abs/2607.07800))

Search for ALPs in $e^+e^- \rightarrow \gamma\alpha(\rightarrow \gamma\gamma)$

Submitted to PRL (arXiv:2607.07800)



Search for an axion-like particle in $e^+e^- \rightarrow \gamma\alpha(\rightarrow \gamma\gamma)$
for $0.17 < m_\alpha < 9.8 \text{ GeV}/c^2$

Motivations:

- The ALP couples to the SM γ with strength $g_{\alpha\gamma\gamma}$
- ALP can also couple to dark matter
- Can explain the relic density

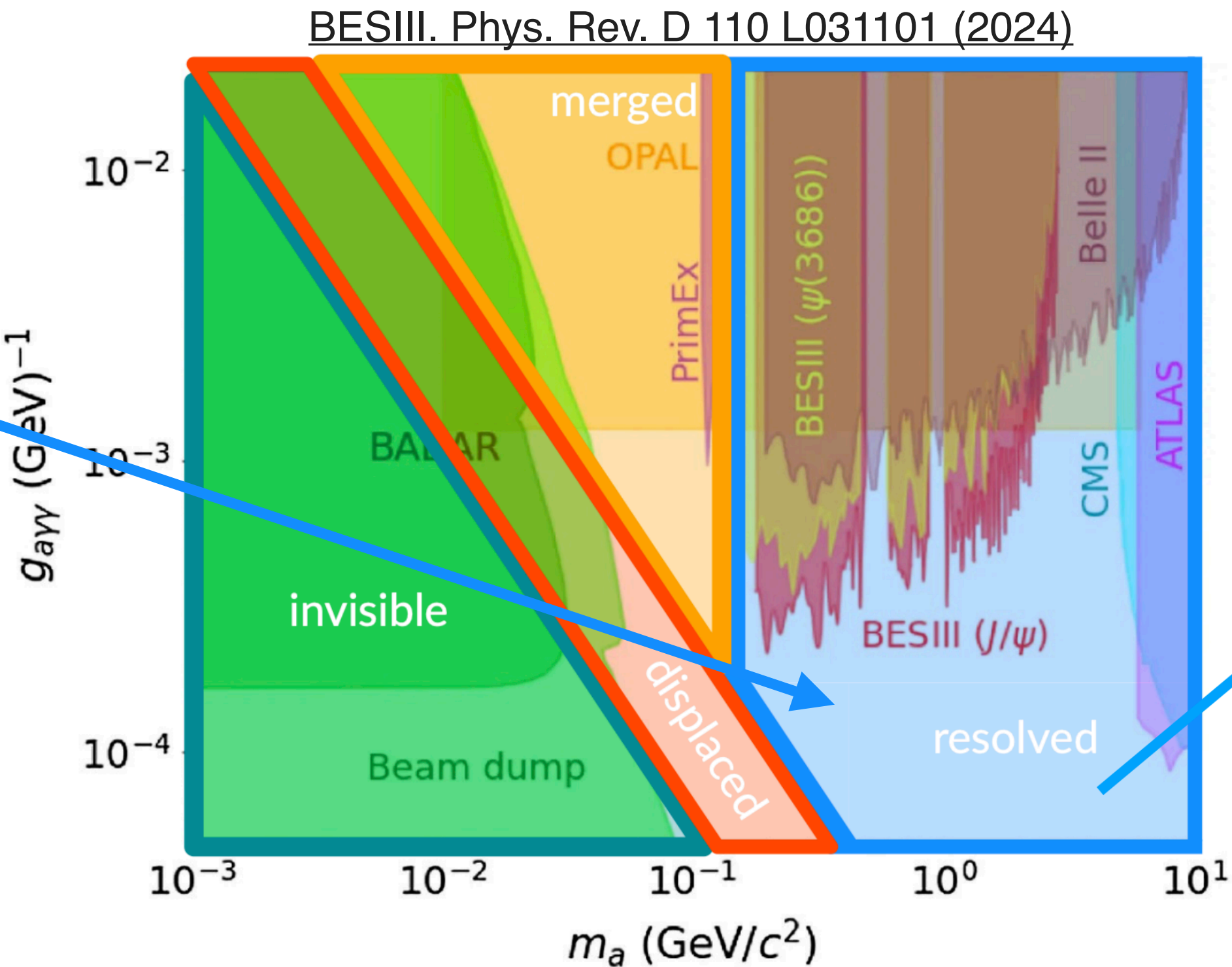
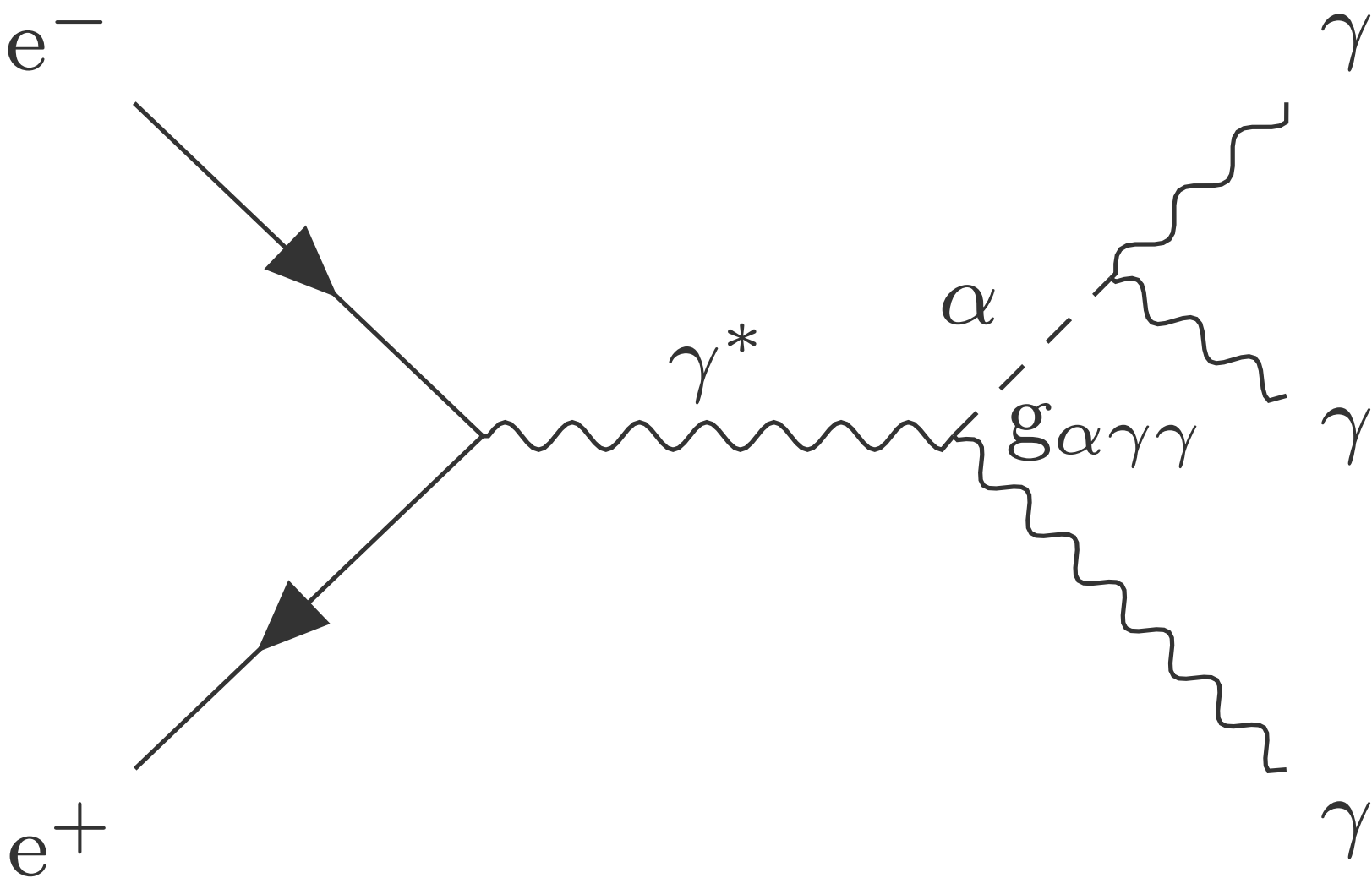
Dataset:

- 408 fb^{-1} at 10.58 GeV and below at Belle II

Focus on the mass region where ALP decay is prompt,
and the two photons are resolved.

Resolved: angle between the two photons larger than
calorimeter resolution

Merged: angle between the two photons smaller than
calorimeter resolution $\Rightarrow$ only one merged photon seen



Search for ALPs in $e^+e^- \rightarrow \gamma\alpha(\rightarrow \gamma\gamma)$

Submitted to PRL (arXiv:2607.07800)



Selection:

- 3 high-energy photons and nothing else
- $M_{3\gamma}$ close to $\sqrt{s}$ + kinematic fit
- Neural network on kinematic properties to discard SM $e^+e^- \rightarrow \gamma\gamma(\gamma)$

Signature:

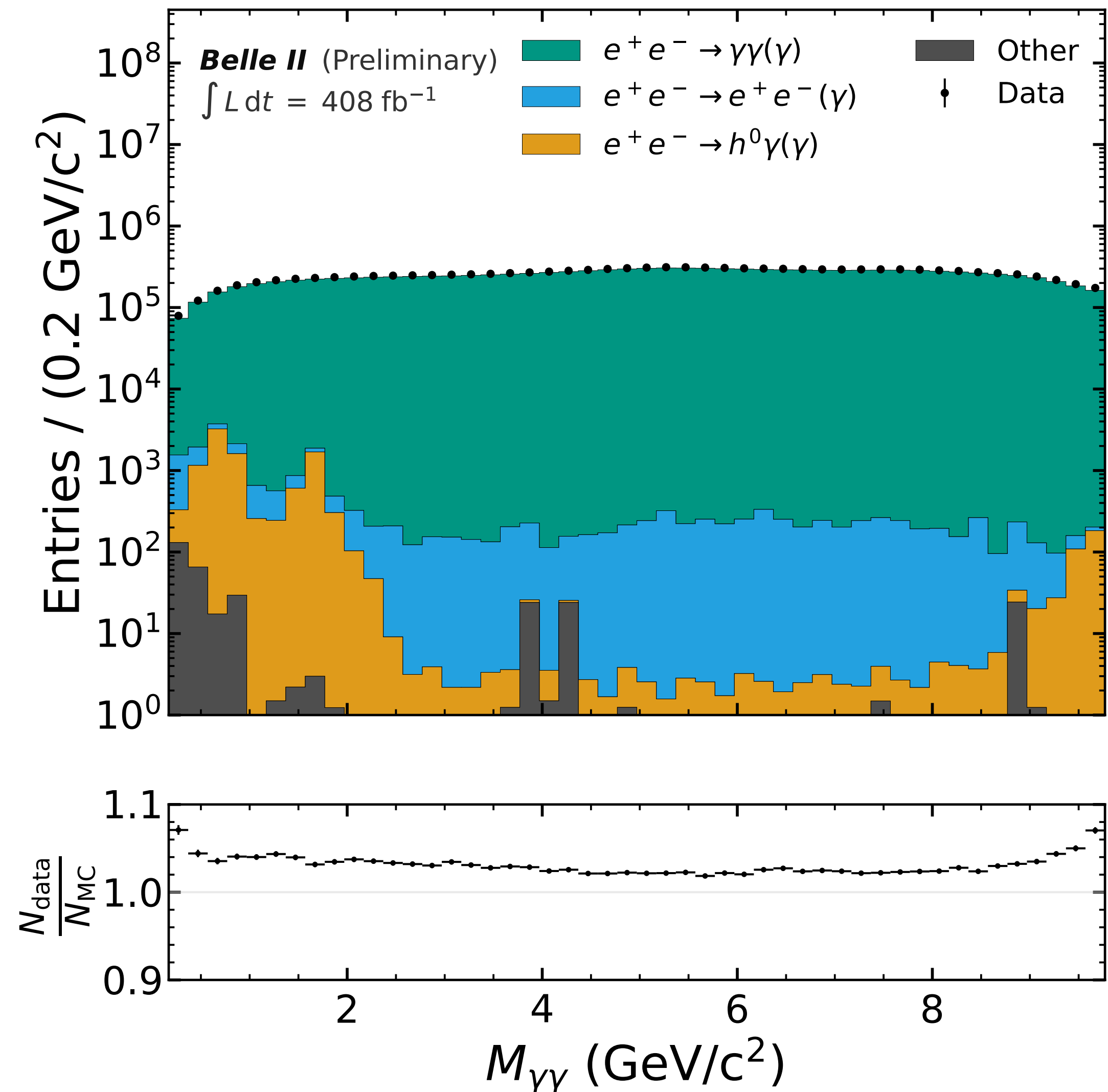
- Peak in the diphoton invariant mass $M_{\gamma\gamma}$
- Good data-MC agreement (4%, treated as systematics)

Signal extraction:

- Independent likelihood fit scan every 5 MeV
- η , and ω resonances are vetoed

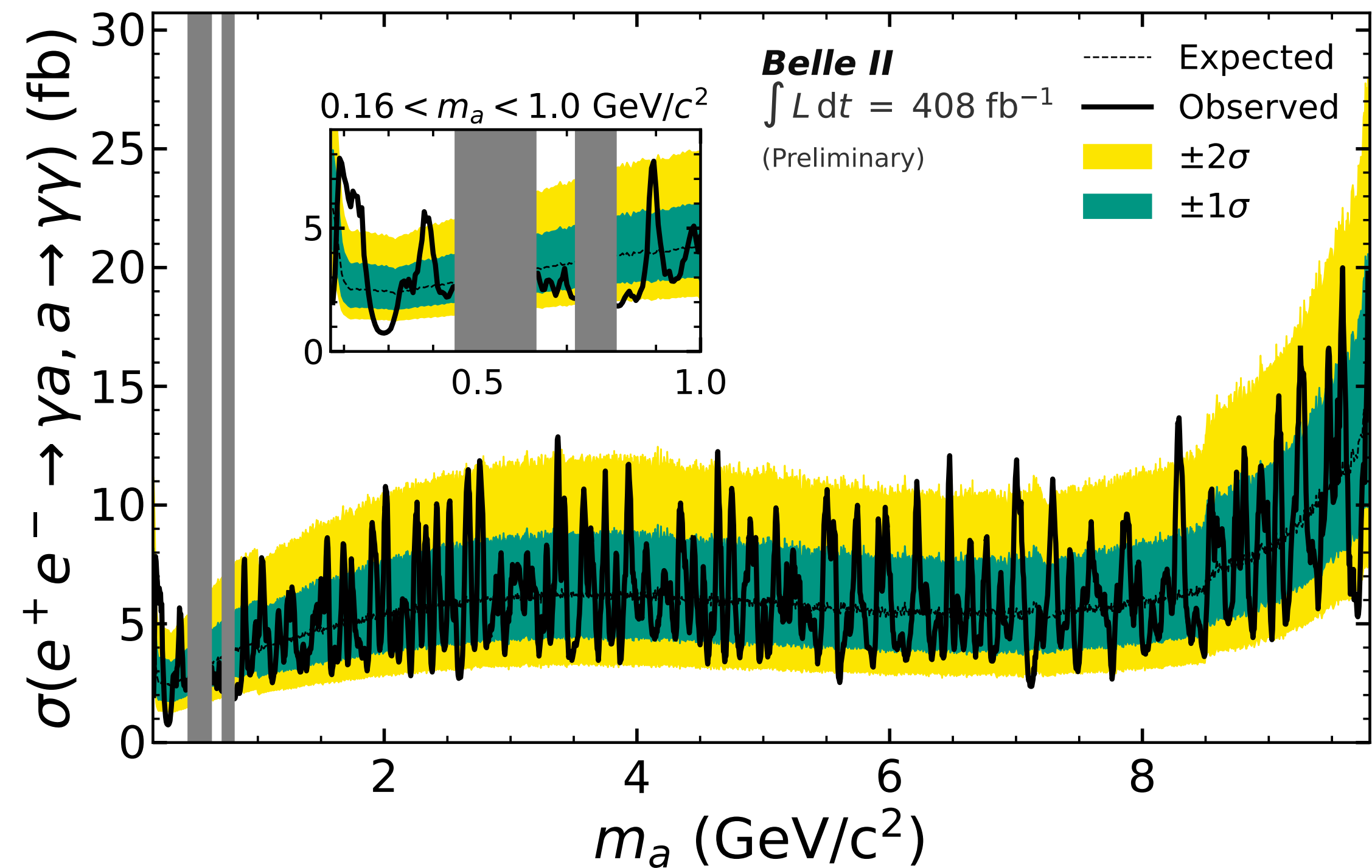
Systematics:

- Initial state radiation mismodelling at low masses (8%)
- Selection efficiency at high masses (4%)



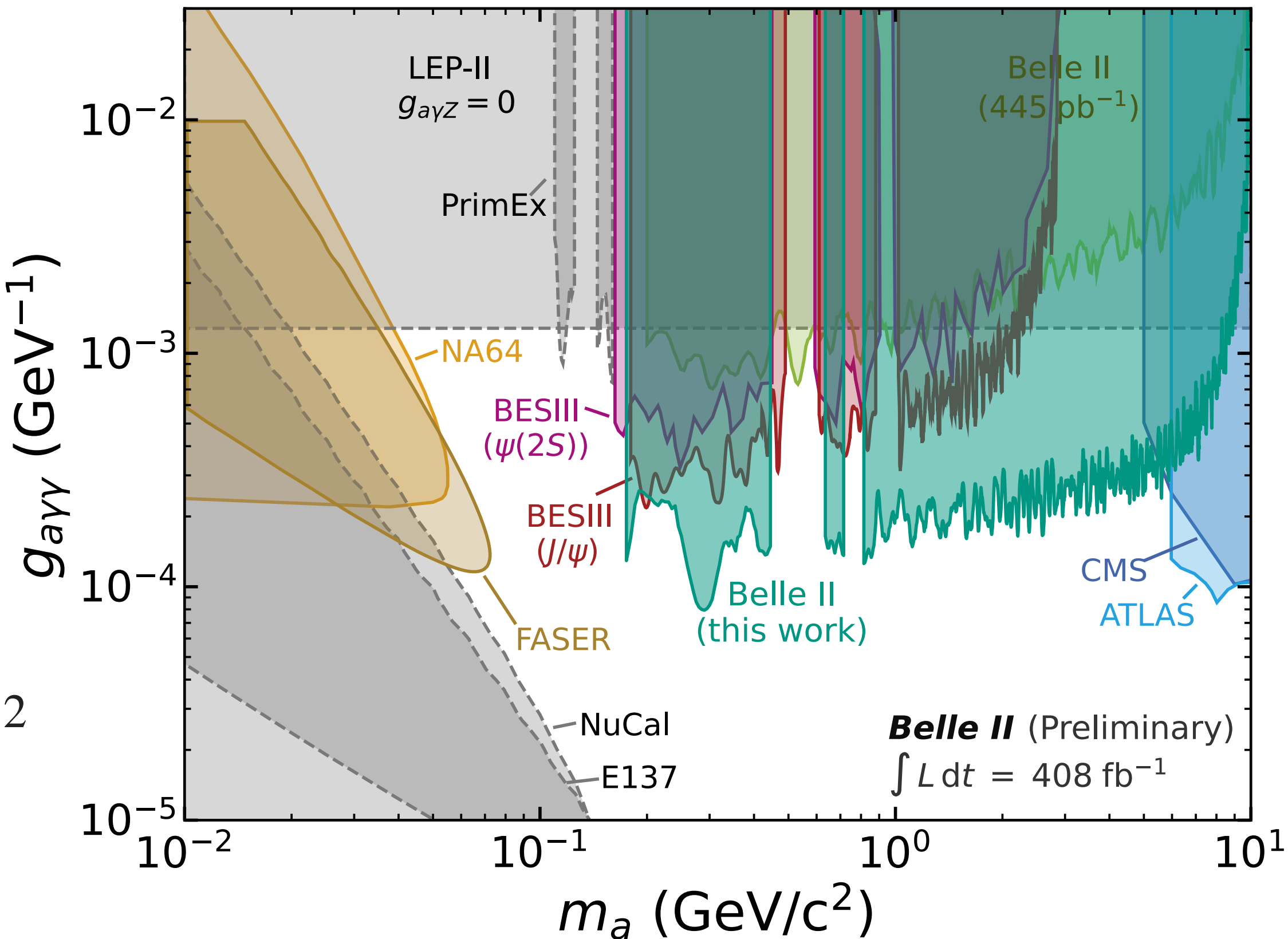
Search for ALPs in $e^+e^- \rightarrow \gamma\alpha(\rightarrow\gamma\gamma)$

Submitted to PRL (arXiv:2607.07800)



No excess signal observed:

- Highest local significance: 3.3σ for $m_\alpha = 0.22 \text{ GeV}/c^2$
- Global significance: 1.4σ
- Set upper limit at 95% CL on $\sigma(e^+e^- \rightarrow \gamma\alpha(\rightarrow\gamma\gamma))$
World best upper limit between $0.17 < m_\alpha < 5 \text{ GeV}/c^2$



Search for dark photon in $e^+e^- \rightarrow \gamma A' (\rightarrow \mu^- \mu^+)$ at Belle II

Preliminary (to be submitted to PRL)

Search for $e^+e^- \rightarrow \gamma A' (\rightarrow \mu^- \mu^+)$

Preliminary



Search for a dark photon particle in $e^+e^- \rightarrow \gamma A' (\rightarrow \mu^- \mu^+)$
for $0.2 < m_{A'} < 10.3 \text{ GeV}/c^2$

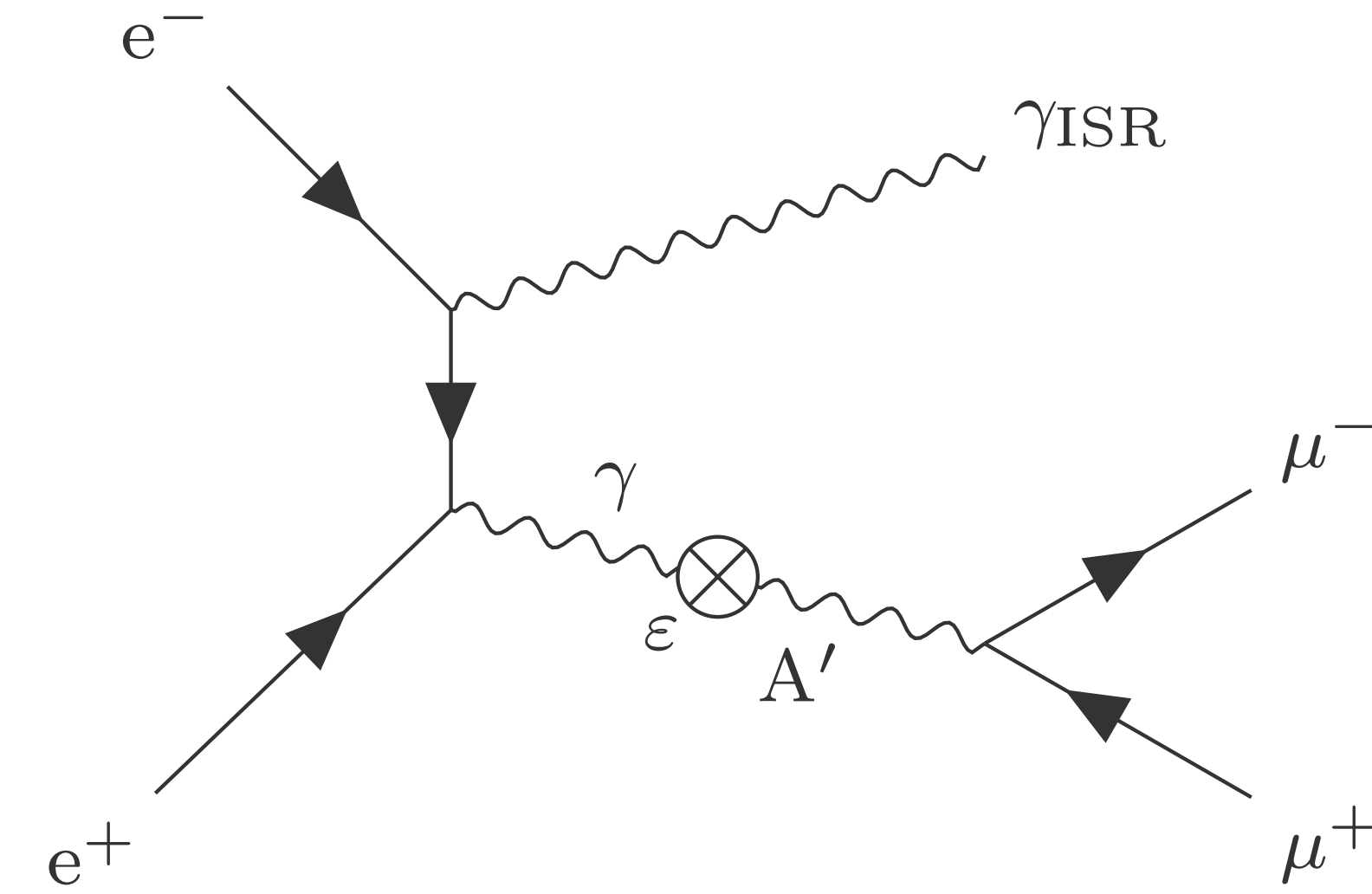
Motivations:

- Straightforward model
- The dark photon couples to the SM photon with the strength ε
- Dark photon can also couple to dark matter and explain the relic density

Dataset:

552 fb^{-1} at 10.58 GeV and below at Belle II

➡ Run 1 + Run 2 (2024) ⇒ **First time in Dark sector group**



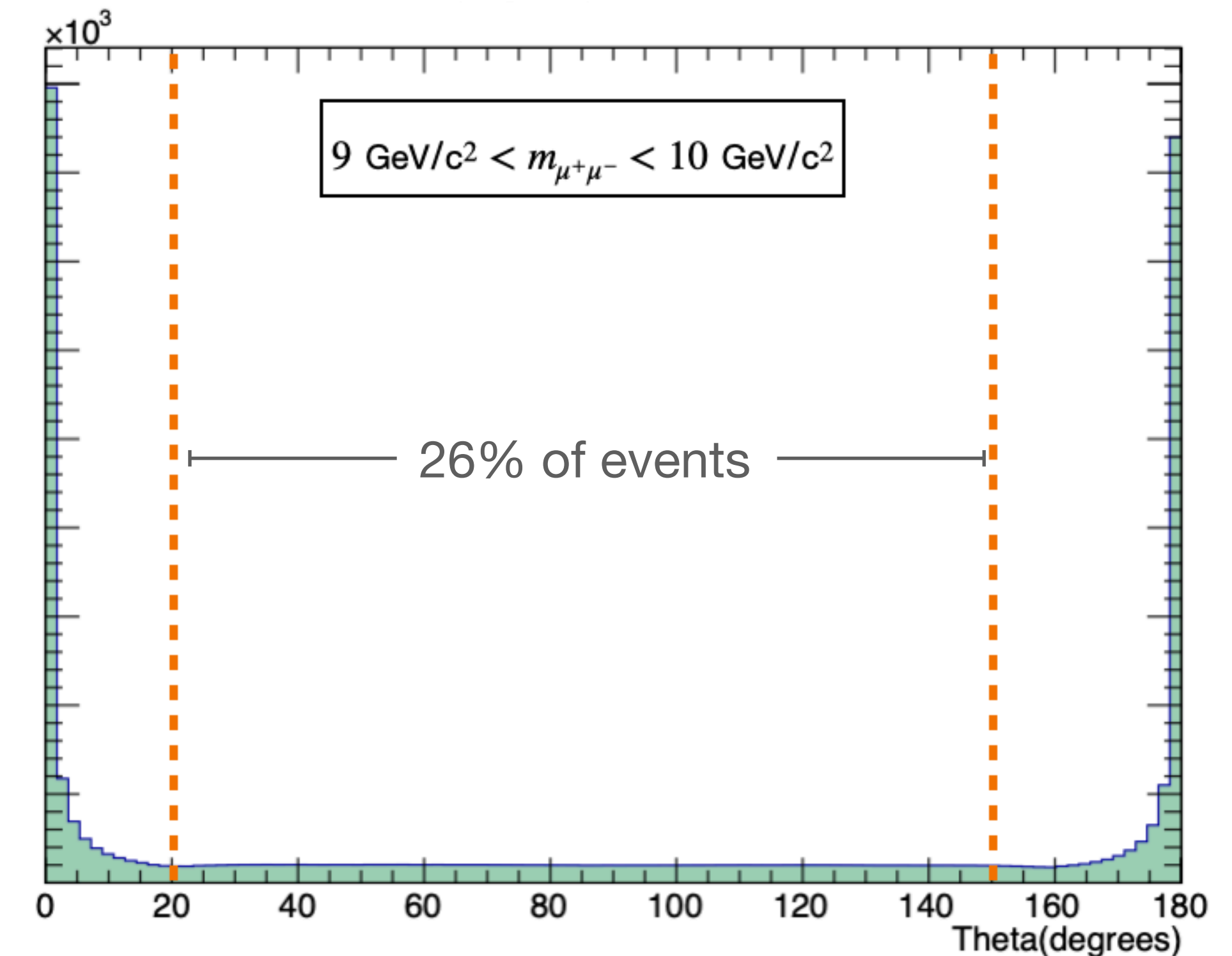
Search for $e^+e^- \rightarrow \gamma A' (\rightarrow \mu^- \mu^+)$

Preliminary



Method (BESIII): [Phys. Lett. B 774 252-257 \(2017\)](#)

- No direct reconstruction of the initial-state radiation γ_{ISR}
- Instead 4C kinematic fit to the dimuon system + unmeasured photon + beam constraint
- ➔ Allows reconstruction of the photon outside calorimeter acceptance (large statistics)
- ➔ Worsening the purity of the sample: $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$, and $e^+e^- \rightarrow \tau^-\tau^+$ backgrounds



Search for $e^+e^- \rightarrow \gamma A' (\rightarrow \mu^- \mu^+)$

Preliminary



Selection:

- Strict kinematic fit χ^2 selection suppresses SM background

Signature:

- Peak in the dimuon invariant mass $M_{\mu\mu}$

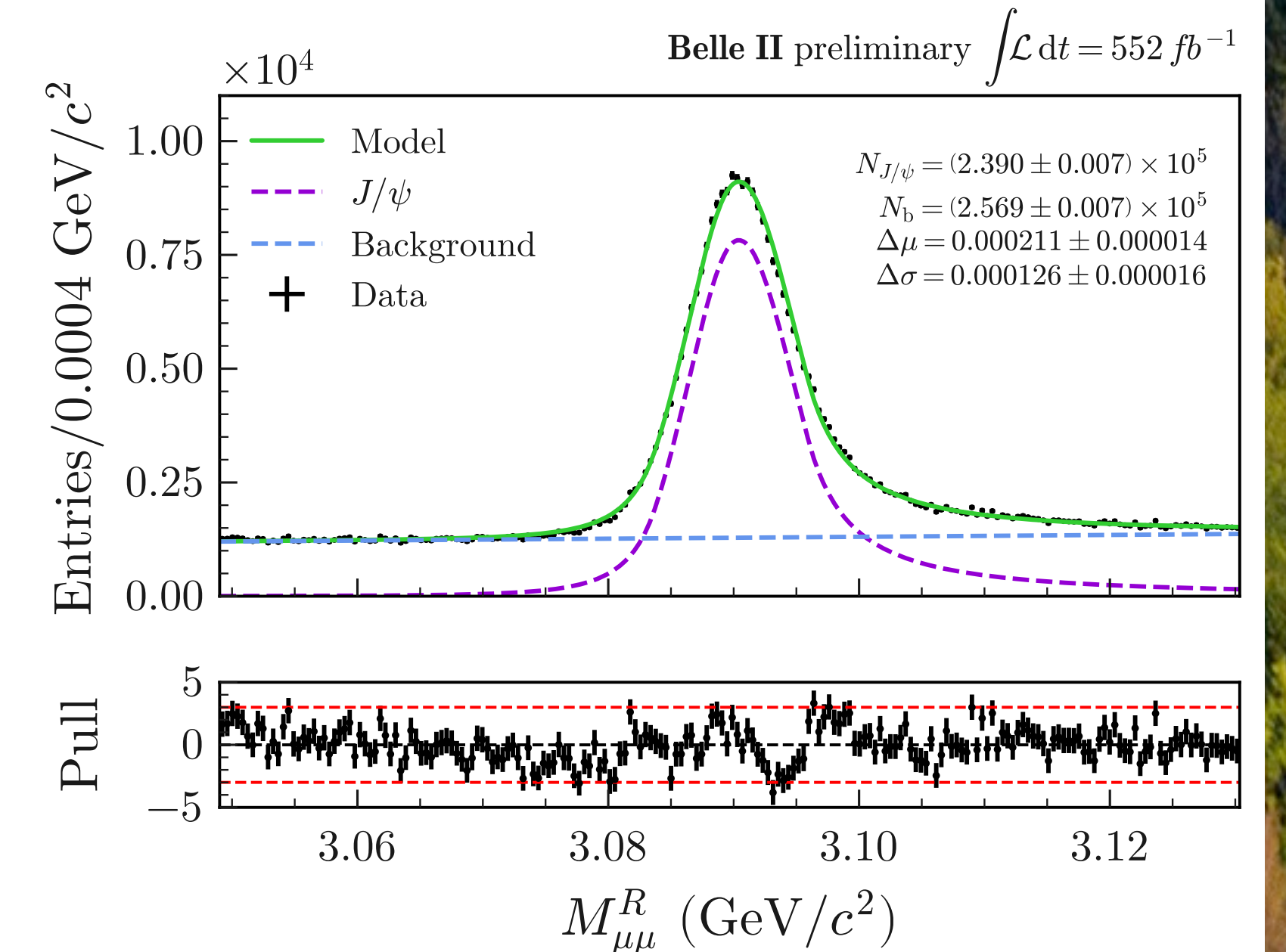
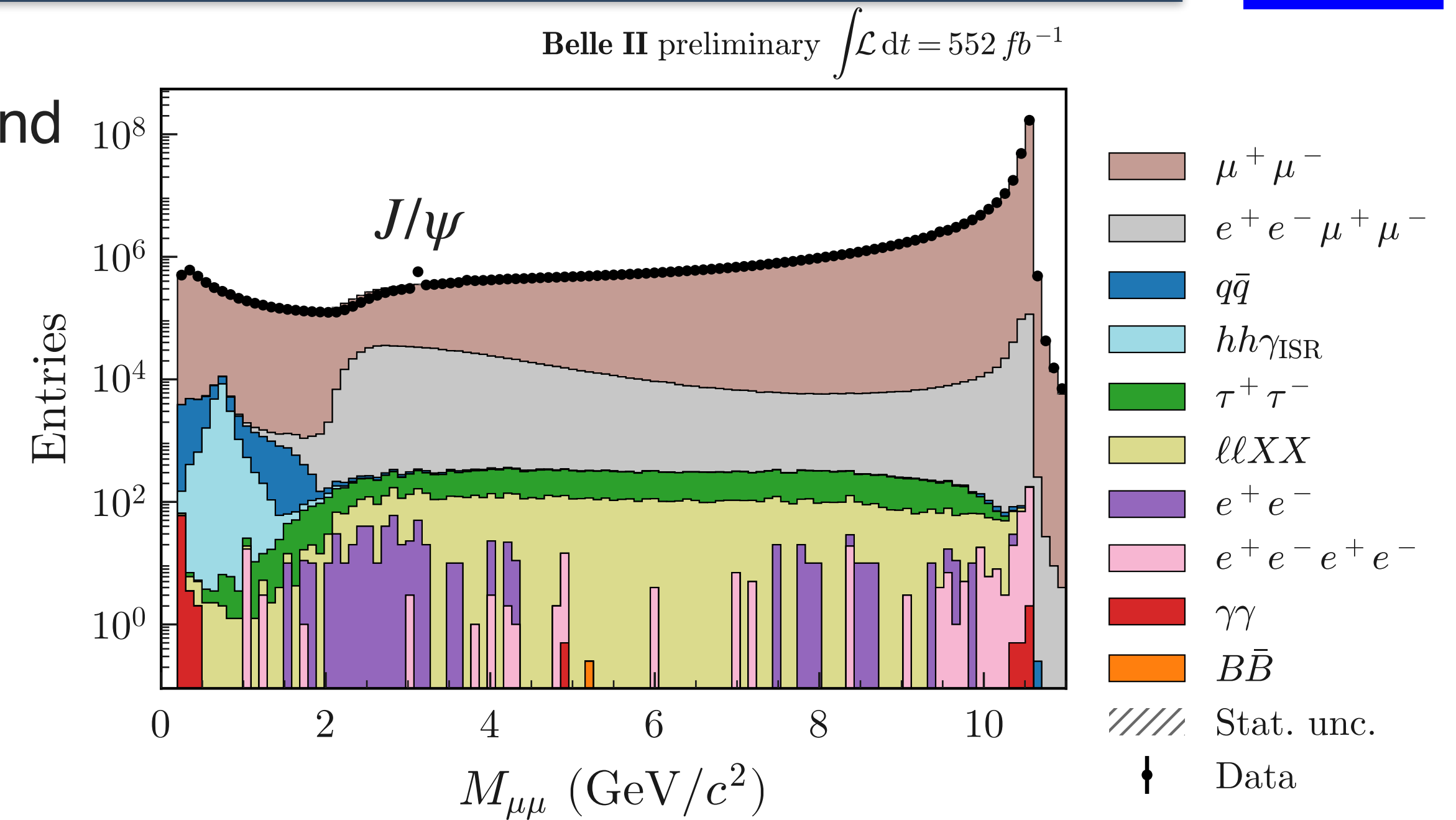
Signal extraction:

- Independent likelihood fit scanned every $0.5\sigma_{res}$ step
- ω , ϕ , J/ψ , $\psi(2S)$, and $\Upsilon(1(23)S)$ resonances vetoed

$$\varepsilon^2 \propto \frac{d\sigma(e^+e^- \rightarrow A'\gamma_{ISR} \rightarrow \mu^+\mu^-\gamma_{ISR})}{d\sigma(e^+e^- \rightarrow \gamma^*\gamma_{ISR} \rightarrow \mu^+\mu^-\gamma_{ISR})}$$

Phys. Rev. D 80 075018 (2009)

- Cancels absolute signal efficiency dependence
- Cancels major systematic uncertainties:
 - Trigger efficiency
 - Particle identification
 - ...



Search for $e^+e^- \rightarrow \gamma A' (\rightarrow \mu^- \mu^+)$

Preliminary



Belle II preliminary $\int \mathcal{L} dt = 552 \text{ fb}^{-1}$

Remaining systematics:

- Purity (3%)
- Branching fraction ($< 10\%$)

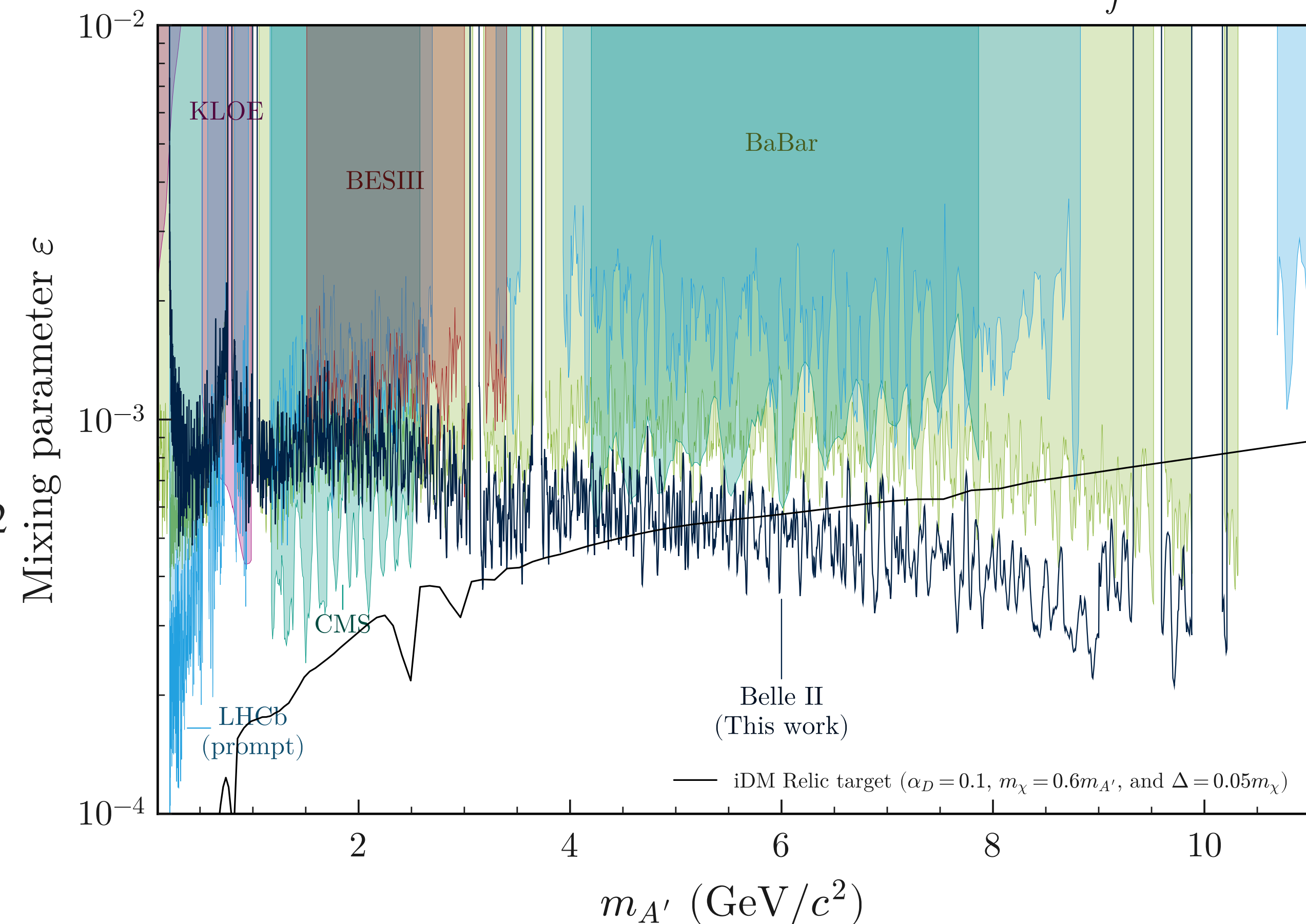
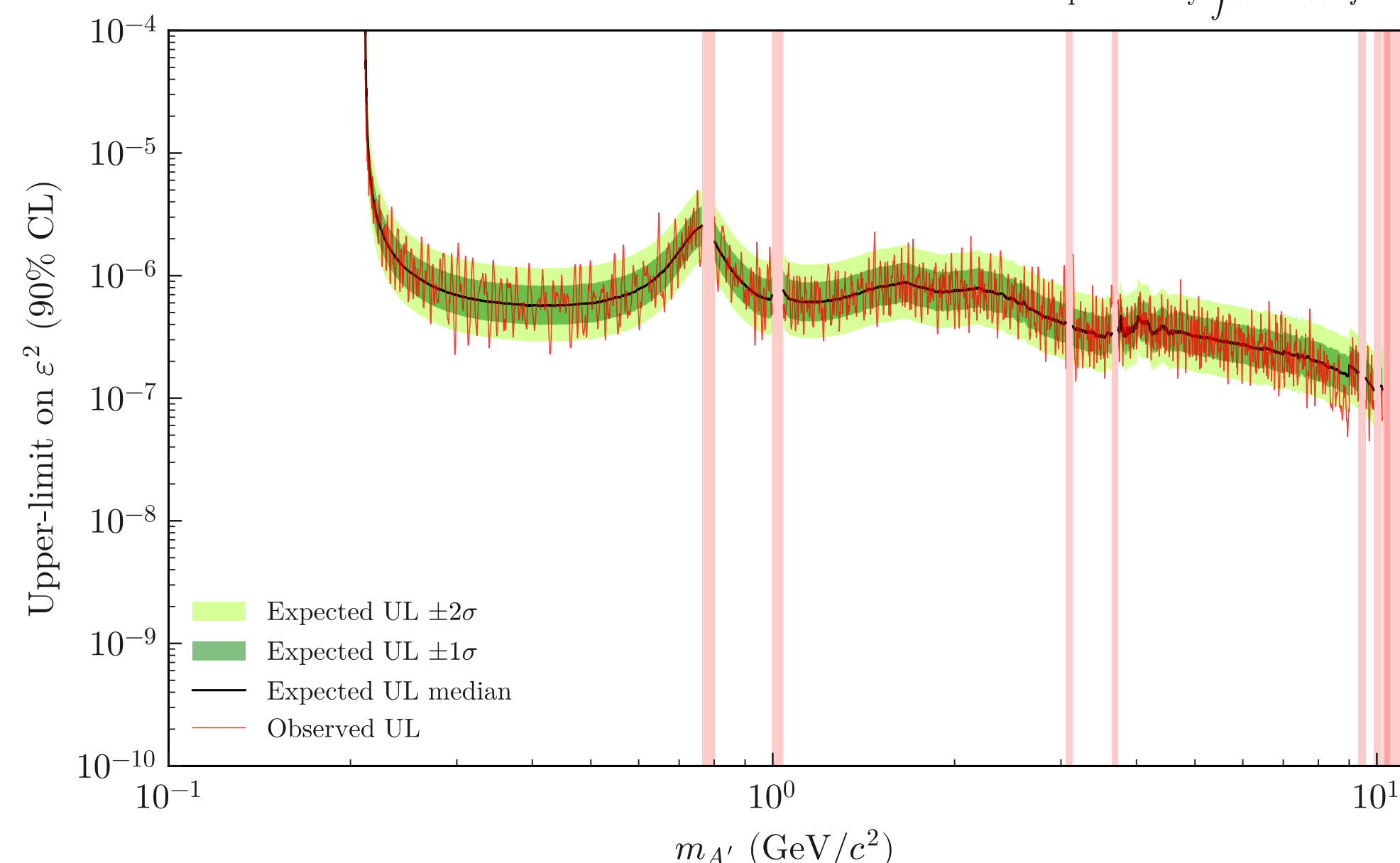
No signal excess observed:

- Highest local significance: 3.4σ at $3.141 \text{ GeV}/c^2$
- Global significance: $< 3\sigma$

Set upper limit at 90% CL on mixing strength ε :

World best upper limit between $3.0 < m_{A'} < 10.3 \text{ GeV}/c^2$

Belle II preliminary $\int \mathcal{L} dt = 552 \text{ fb}^{-1}$

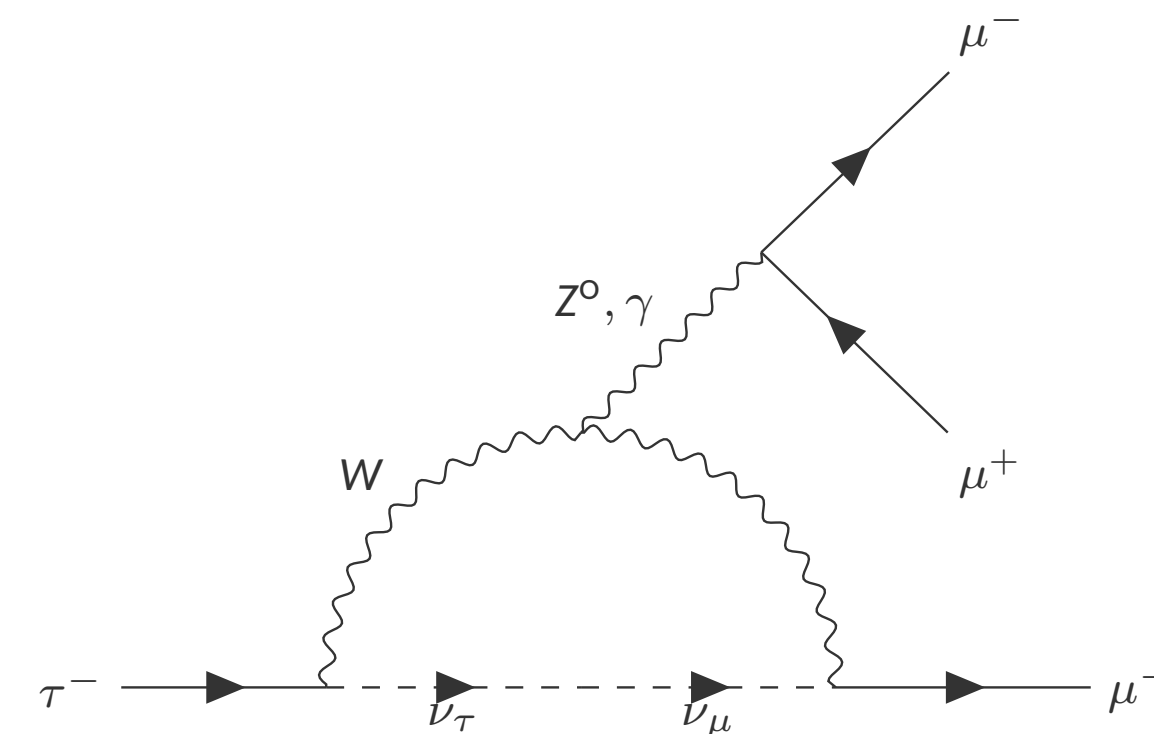


Search for lepton flavour violation $\tau \rightarrow \ell \alpha$ decay at Belle II

Preliminary (to be submitted to PRL)

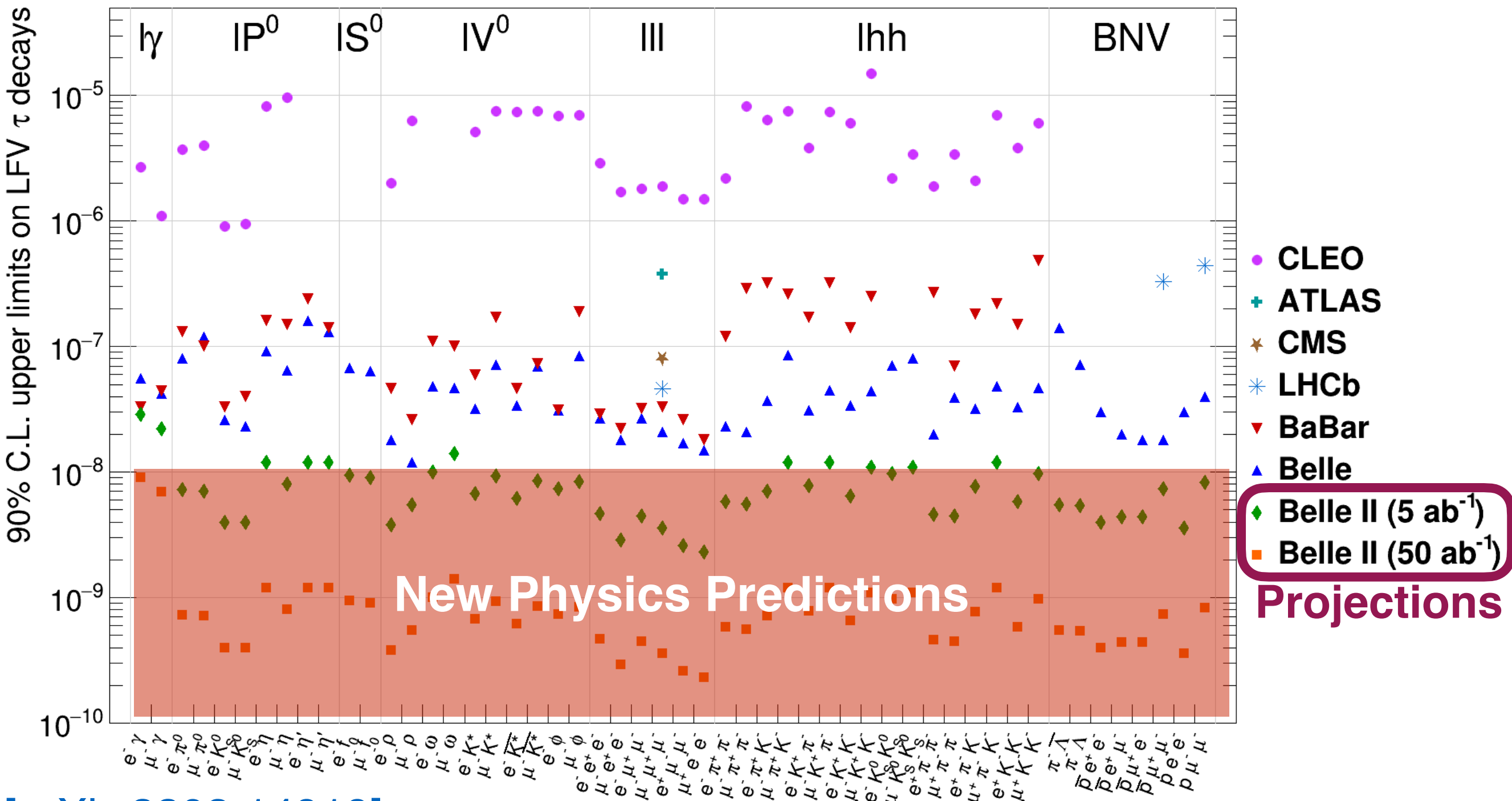
Search for LFV $\tau^- \rightarrow \ell^- \alpha$ decay

- In SM, the Charged Lepton Flavour Violation is allowed through weak charged current and neutrino oscillation
 - Order $\mathcal{O}(10^{-55}) \Rightarrow$ **no Flavour Violation in current experiments**
- Various **New Physics predict Lepton Flavour Violation** at observable rates $\mathcal{O}(10^{-8} - 10^{-10})$
 - e.g leptoquarks for $\tau^- \rightarrow \ell^- V^0$ related $b \rightarrow c\tau\nu$ anomalies



Physics Models	$\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$
SM	10^{-55}
SM + Seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

[PhysRevD.77.073010]



[arXiv.2203.14919]

Among the 50 modes probed in the past, Belle II has already set limits on the following ones:

- $\tau^- \rightarrow \ell^- \alpha$ new boson candidate for dark matter
- $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ most accessible
- $\tau^- \rightarrow \ell^- \phi$ linked to $b \rightarrow c\tau\nu$ within the Leptoquarks models
- $\tau^- \rightarrow \Lambda(\bar{\Lambda})\pi^-$ violated the Baryon number $\Rightarrow$ condition for matter/antimatter asymmetry

Search for Lepton flavour violating $\tau^- \rightarrow \ell^- \alpha$ decay

Preliminary



Search for a beyond SM invisible particle α

Assumed to be light ($m_\alpha < 1.6 \text{ GeV}/c^2$) and spin-0, e.g. an axion-like particle (ALP)

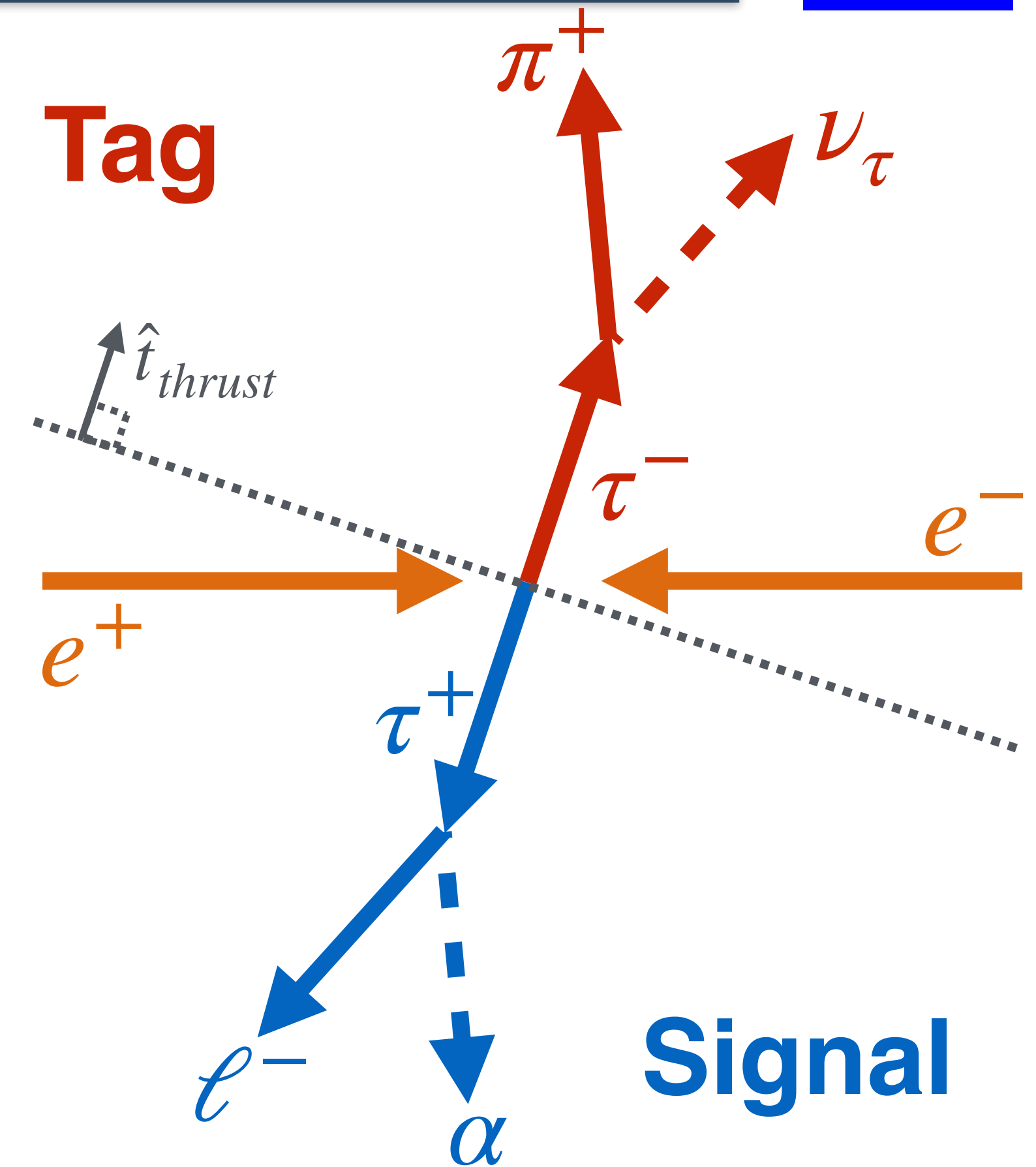
The signature is similar to the SM decay $\tau^- \rightarrow \ell^- \nu \bar{\nu}$, but the signal appears as a peaking structure in τ rest frame

Dataset:

- 365 fb^{-1} at 10.58 GeV at Belle II

Event signature:

- 1 electron or muon + ALPs assumed to be invisible on the signal side
- 1 charged particle on the tag side



Search for Lepton flavour violating $\tau^- \rightarrow \ell^- \alpha$ decay

Preliminary



Signature:

- Peak in the plane M_{min}^2, M_{max}^2 [Phys. Rev. D 102 115001 (2020)]

- Event-based variable such $M_{min}^2 \leq m_\alpha^2 \leq M_{max}^2$
- Expressed in terms of the event kinematic variables

$$M_{min, max}^2 = s \frac{-B_0 \mp \sqrt{B_0^2 - 4A_0C_0}}{2A_0}$$

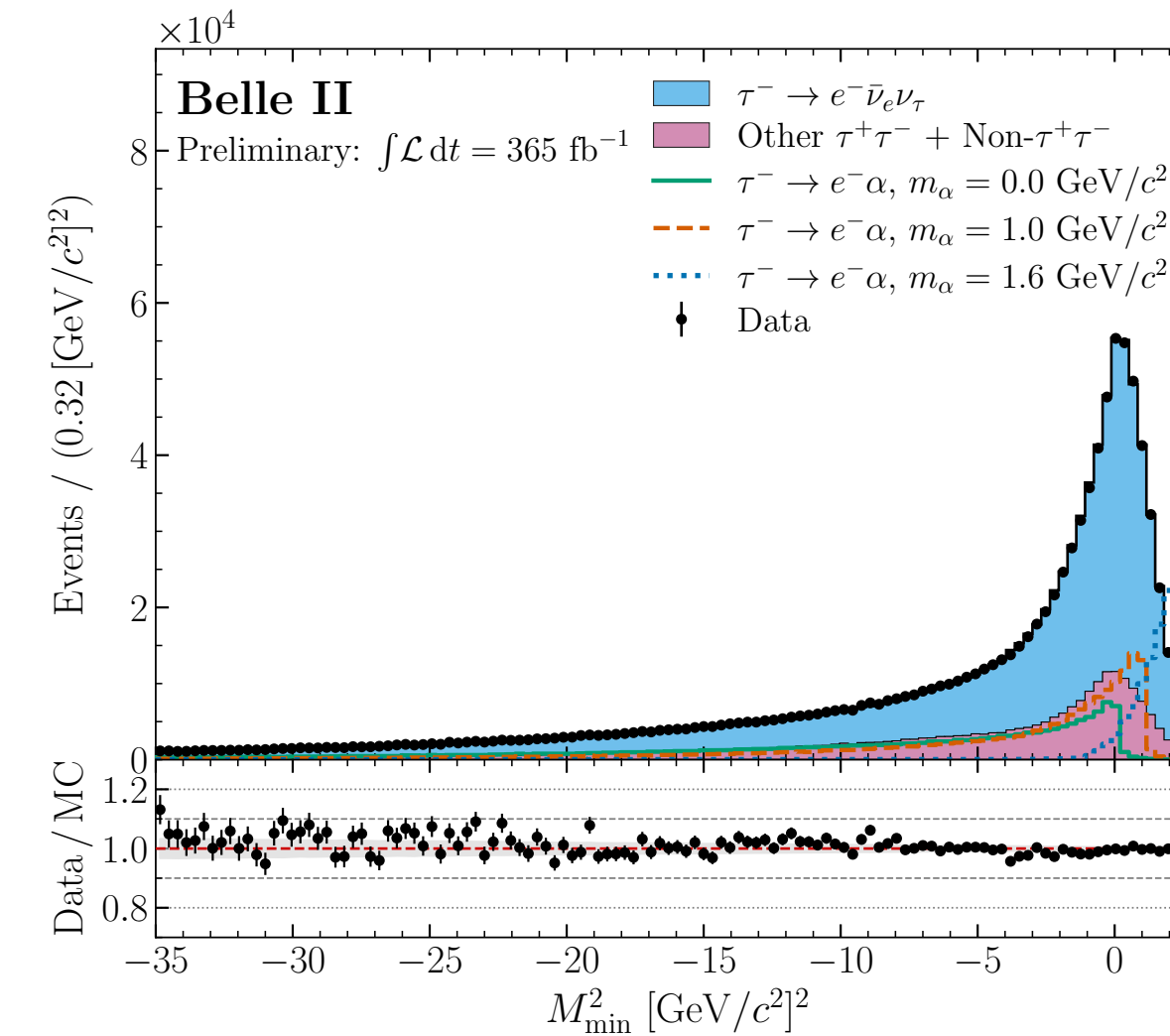
- Built from event kinematics alone: the minimum and maximum values of m_α kinematically allowed

Background rejection:

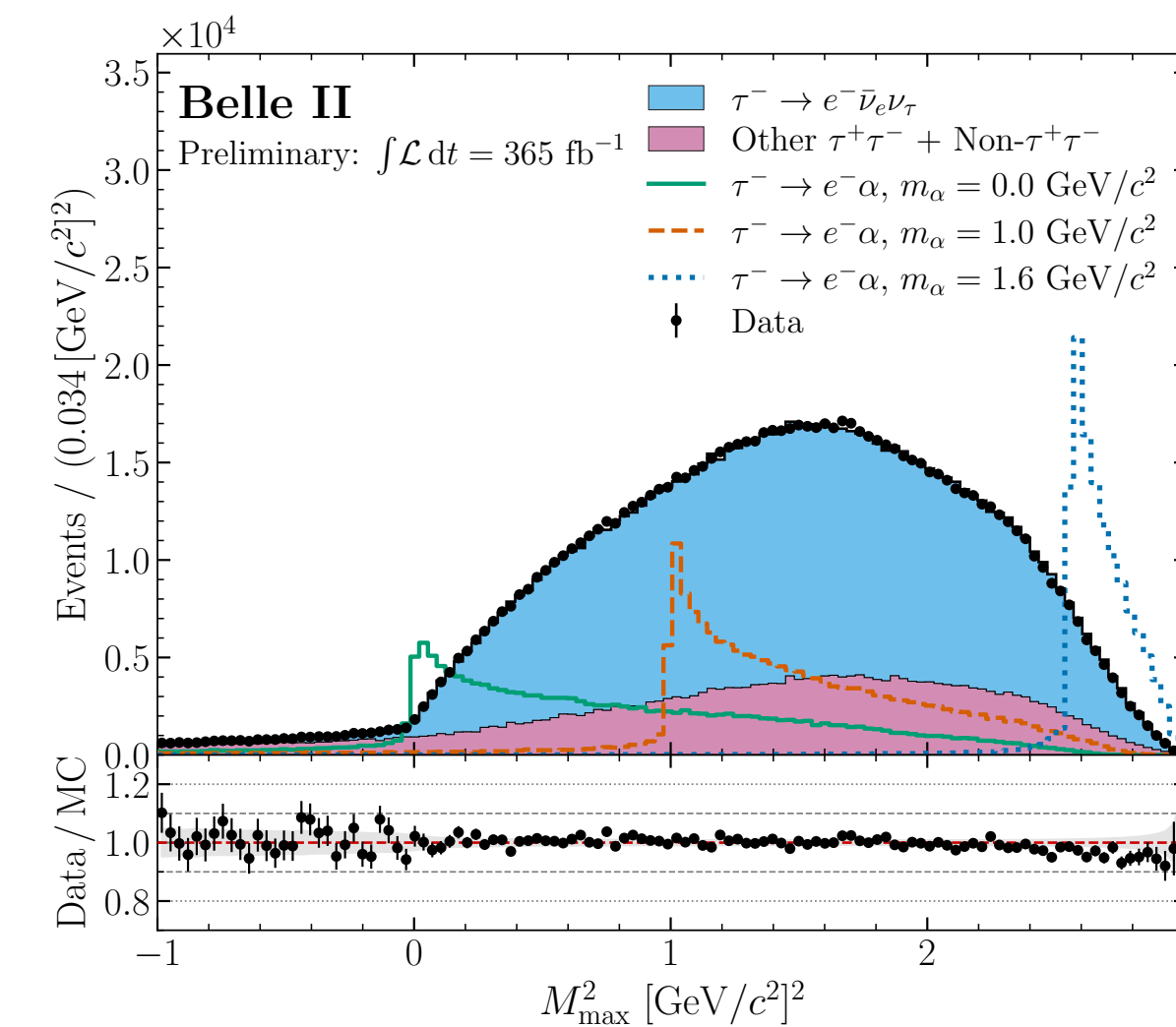
- Optimised selections on ten variables to achieve τ -pair purity of 98.8% (99.6%)

Signal extraction:

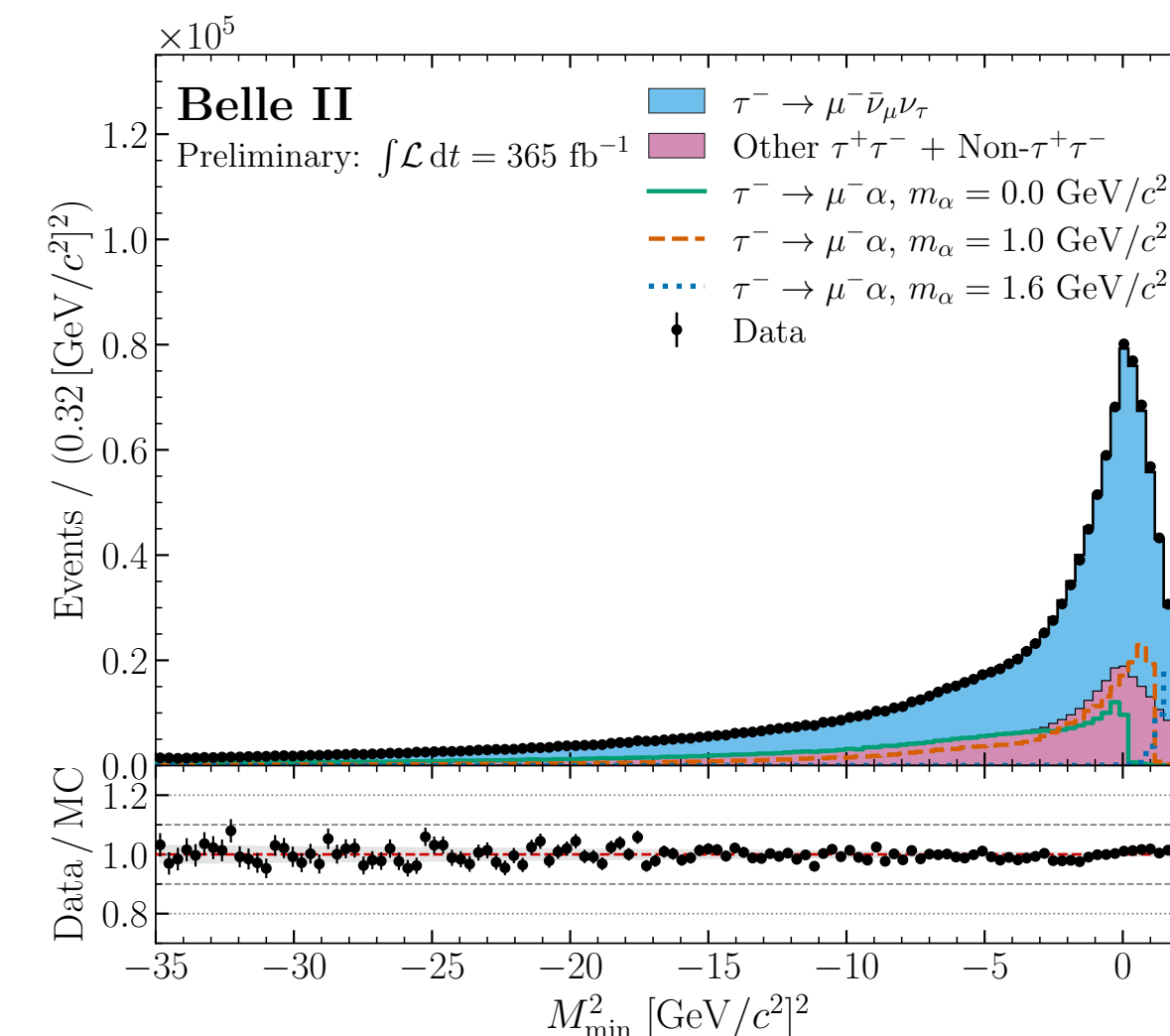
- 2D binned maximum-likelihood fit



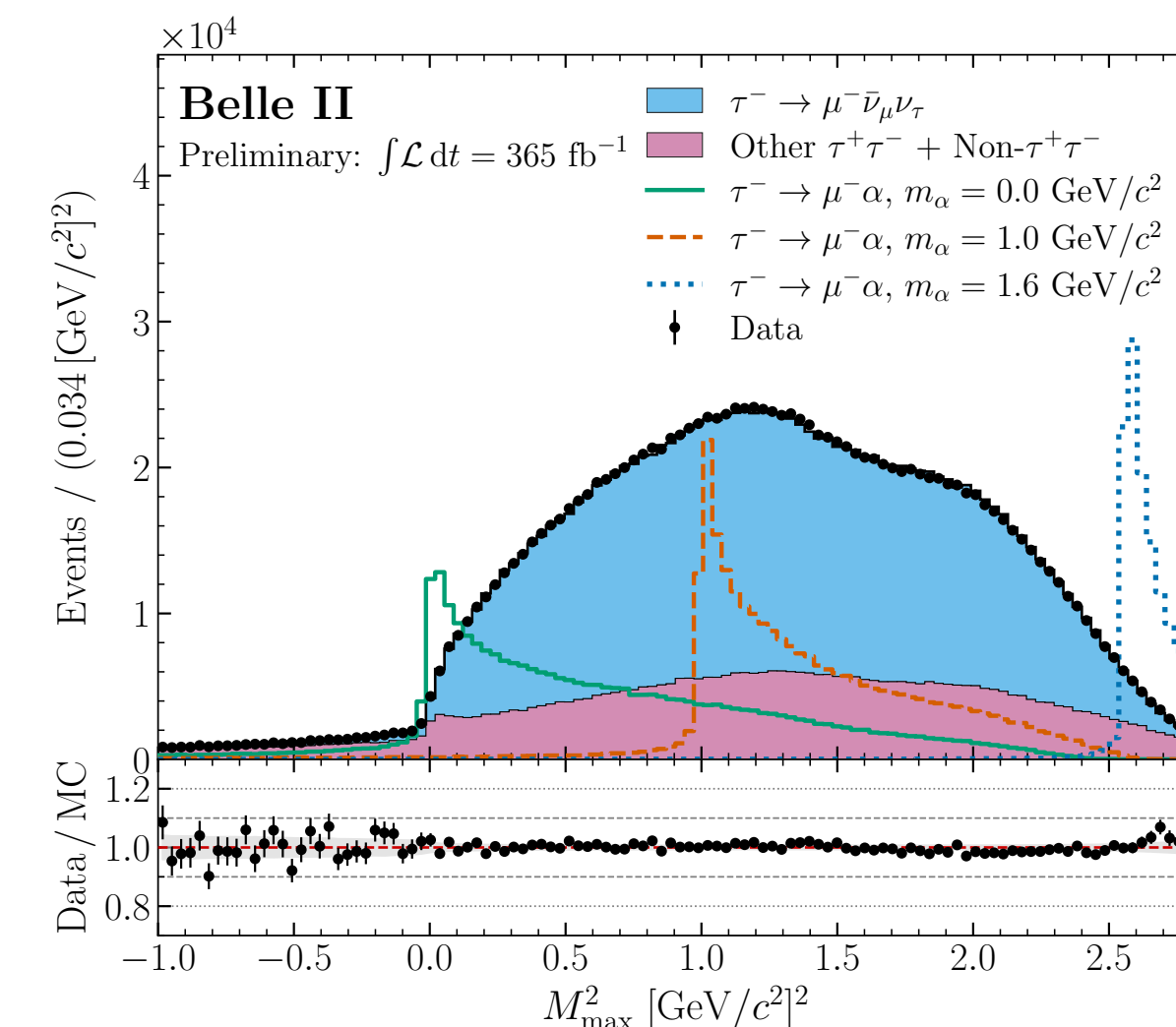
(a) e channel: M_{min}^2



(b) e channel: M_{max}^2



(c) μ channel: M_{min}^2



(d) μ channel: M_{max}^2

Search for Lepton flavour violating $\tau^- \rightarrow \ell^- \alpha$ decay

Preliminary



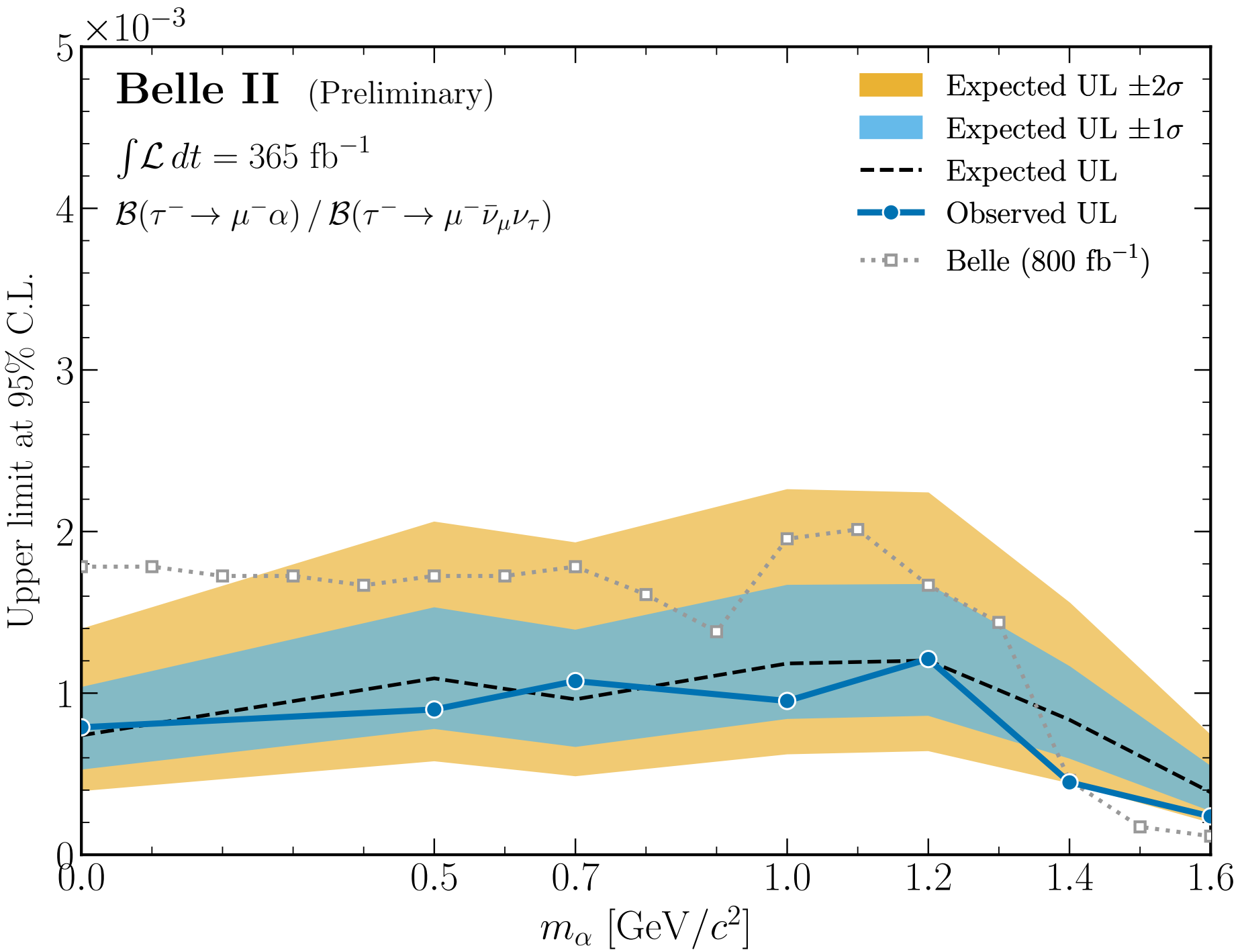
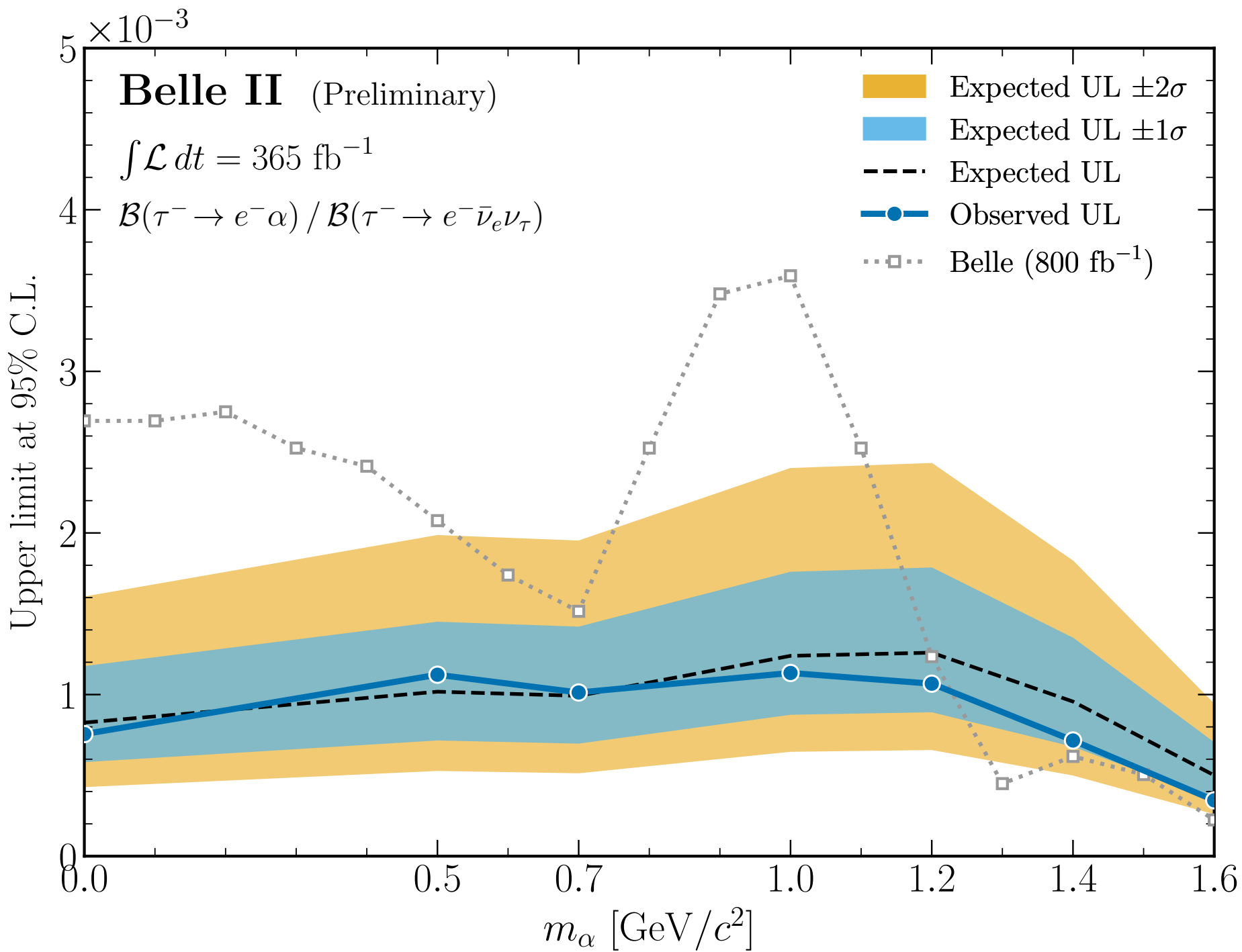
No signal excess observed

Set upper limit at 95% CL on $\mathcal{B}(\tau^- \rightarrow \ell^- \alpha) / \mathcal{B}(\tau^- \rightarrow \ell^- \bar{\nu}_\ell \nu_\tau)$

World-best upper limit between $m_\alpha < 1.2(1.4)$ GeV/c² in both electron and muon channels

Despite:

- using ~50% less data than Belle [JHEP 08 155 (2025)]
- using the 1x1 topology alone instead of 1x3



Search for $B \rightarrow hX_{inv}$ at Belle

Phys. Rev. Lett. 136, 231802 (2026)

Search for $B \rightarrow hX_{inv}$

Phys. Rev. Lett. 136, 231802 (2026)



Search for feeble interacting particle in $B^\pm \rightarrow h^\pm X(\rightarrow inv)$, with $h^\pm = \pi^\pm, K^\pm, D_s^\pm, p$ and $B^0 \rightarrow \bar{D}^0 X(\rightarrow inv)$

Dataset:

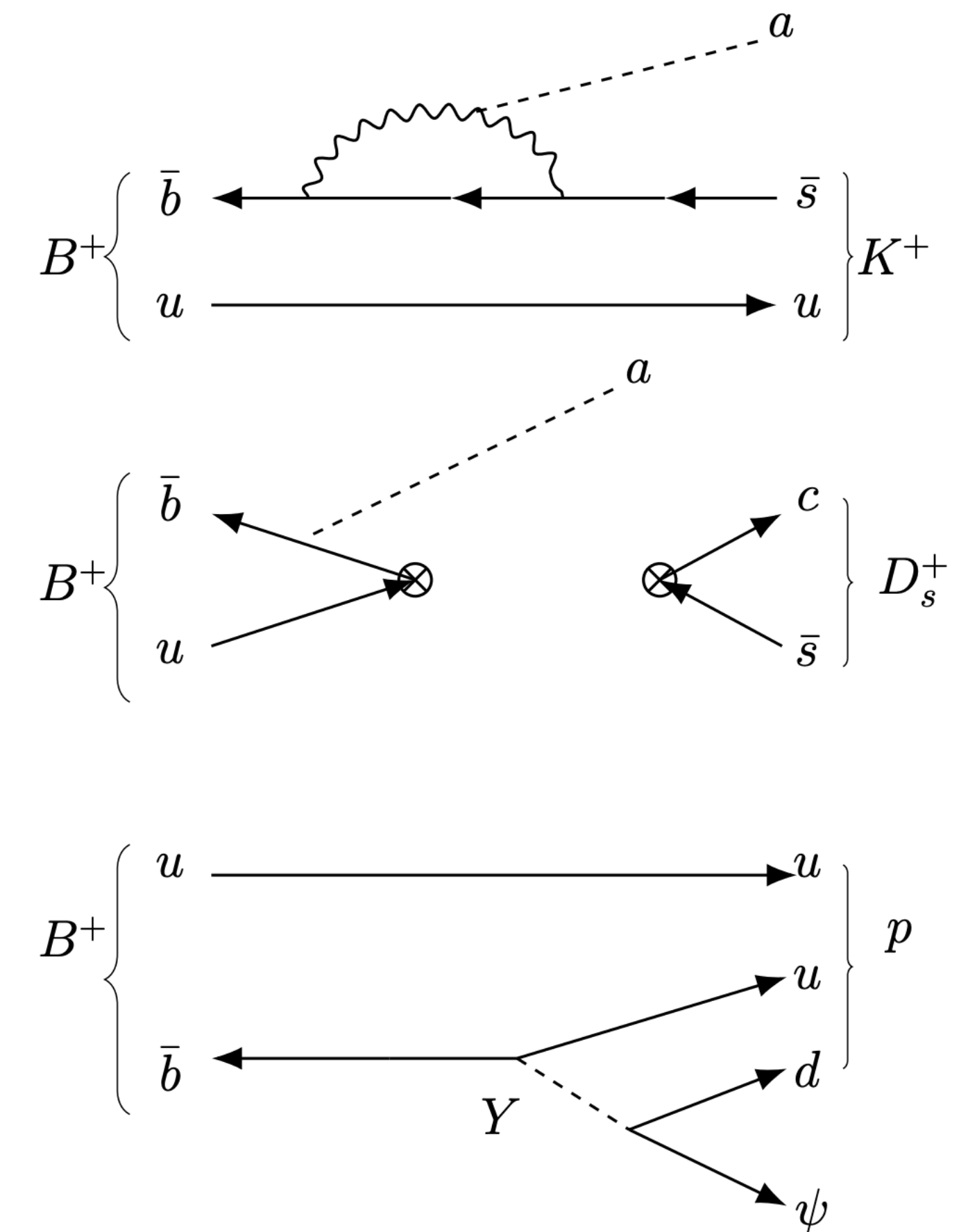
- $711 fb^{-1}$ at 10.58 GeV at Belle

Signature:

- Peak in the momentum of the recoiling hadron h system

Selection Strategy:

- Reconstruct the B^{tag} into hadronic decay channels
 - using the [Full Event Interpretation algorithm](#)
 - method only possible in B-factories, allowing to exploit the tag side
- Used boosted decision trees to remove backgrounds
- Analysis is optimised for the two-body decay





Search for $B \rightarrow hX_{inv}$

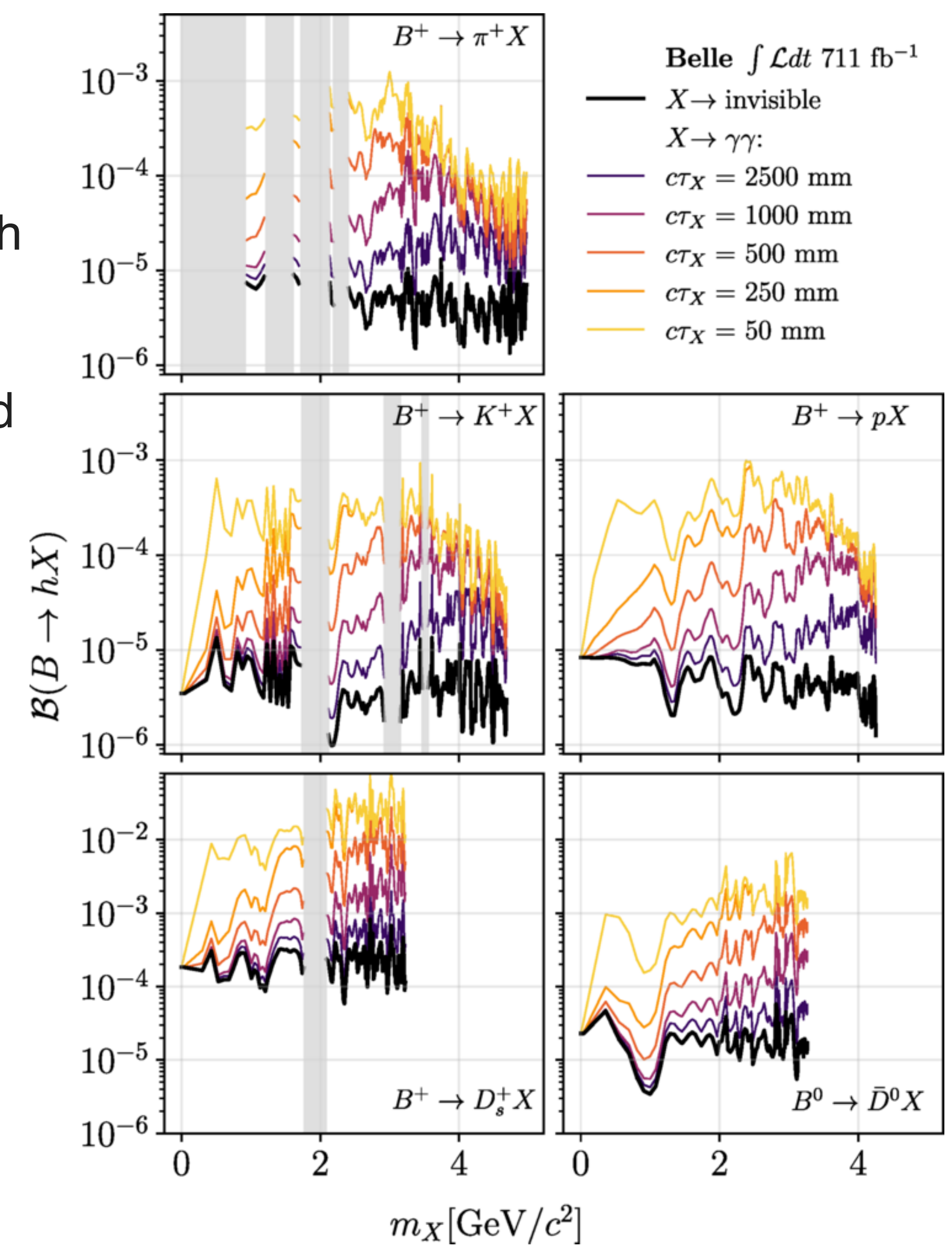
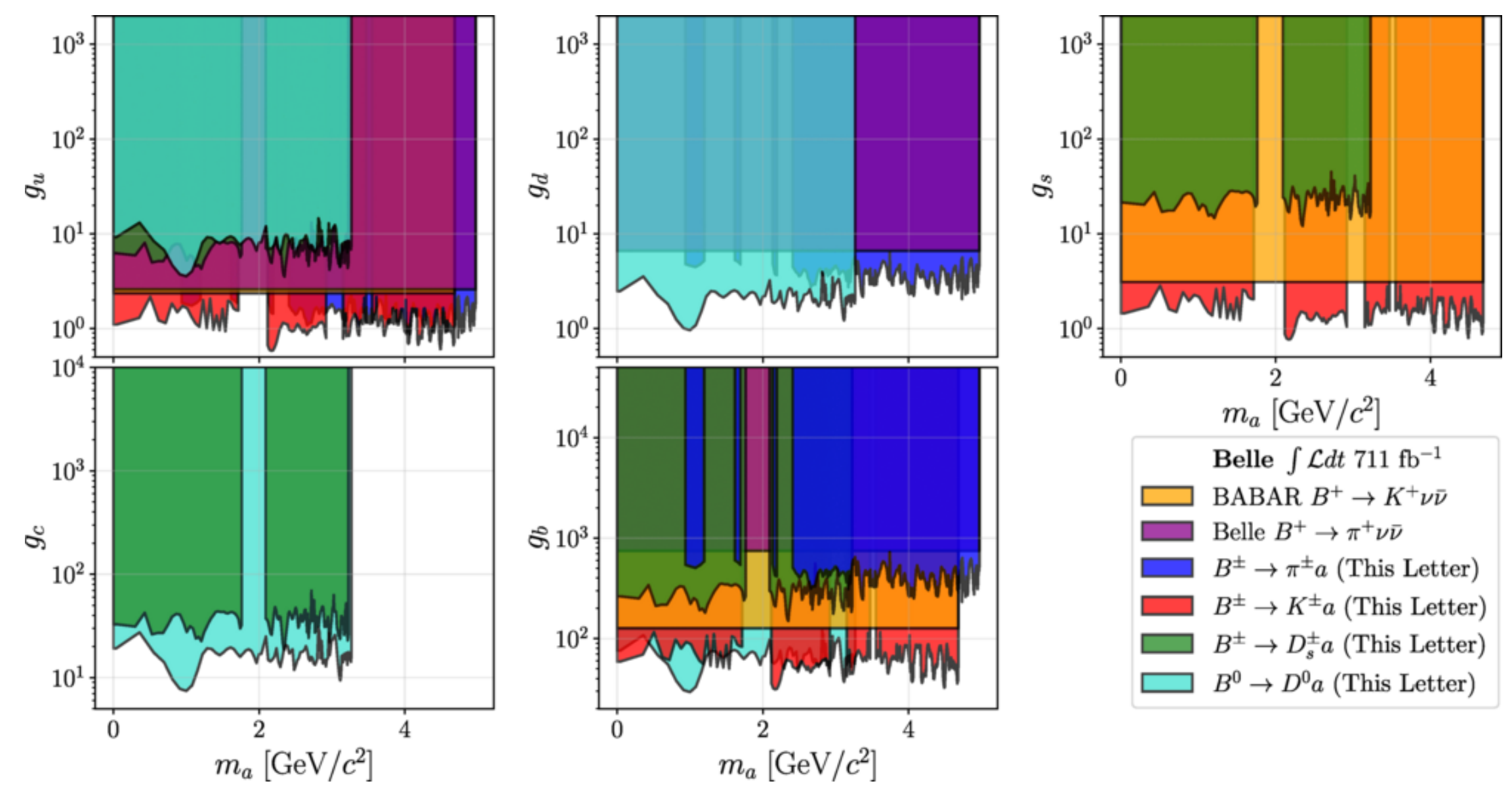
No significant excess in any channel

World leading 90% CL upper-limits to $Br(B \rightarrow hX) \times Br(X \rightarrow inv)$

And on $Br(B \rightarrow hX) \times Br(X \rightarrow \gamma\gamma)$ to quantify at what lifetimes such decays would mimic the invisible scenario

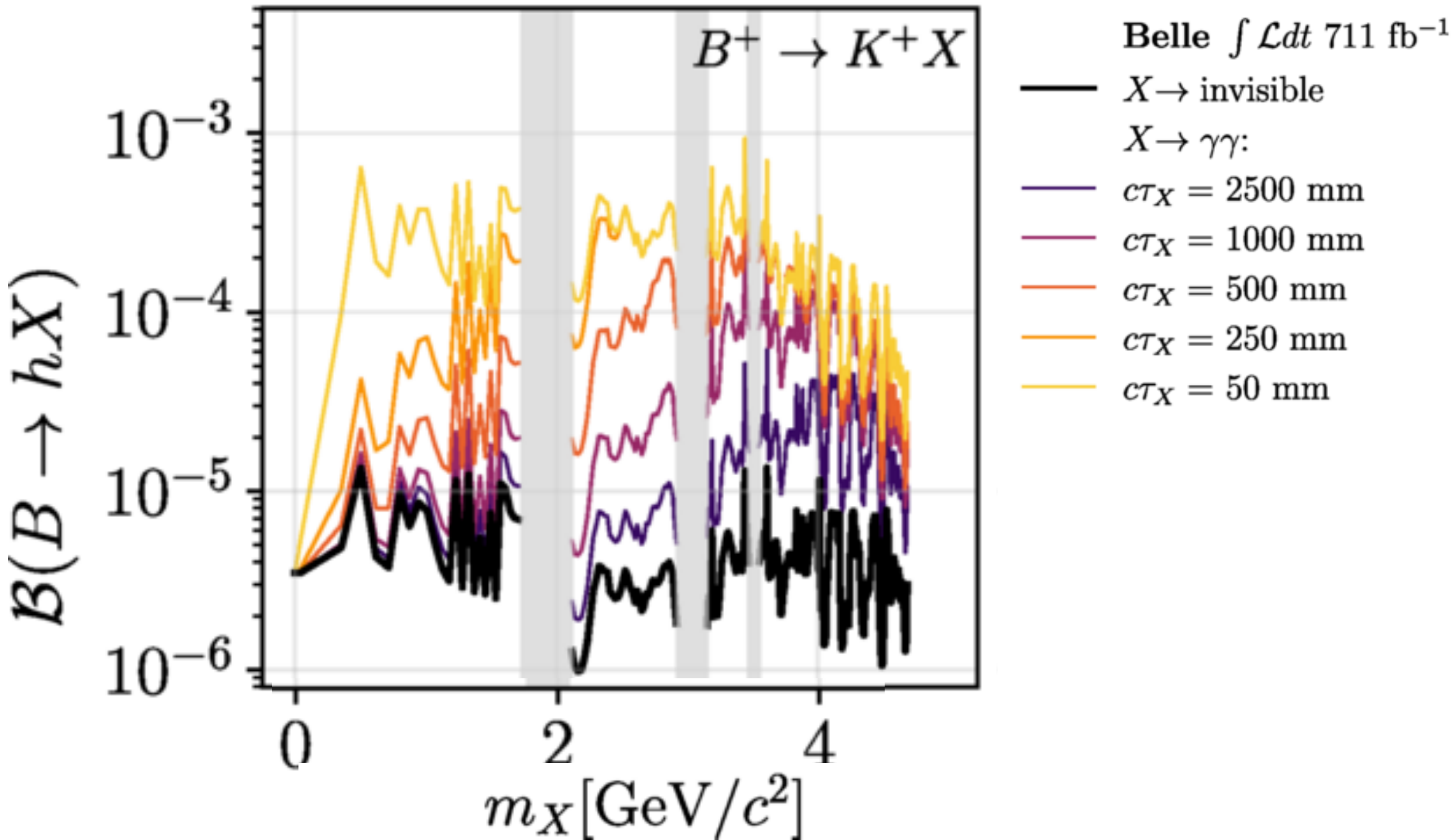
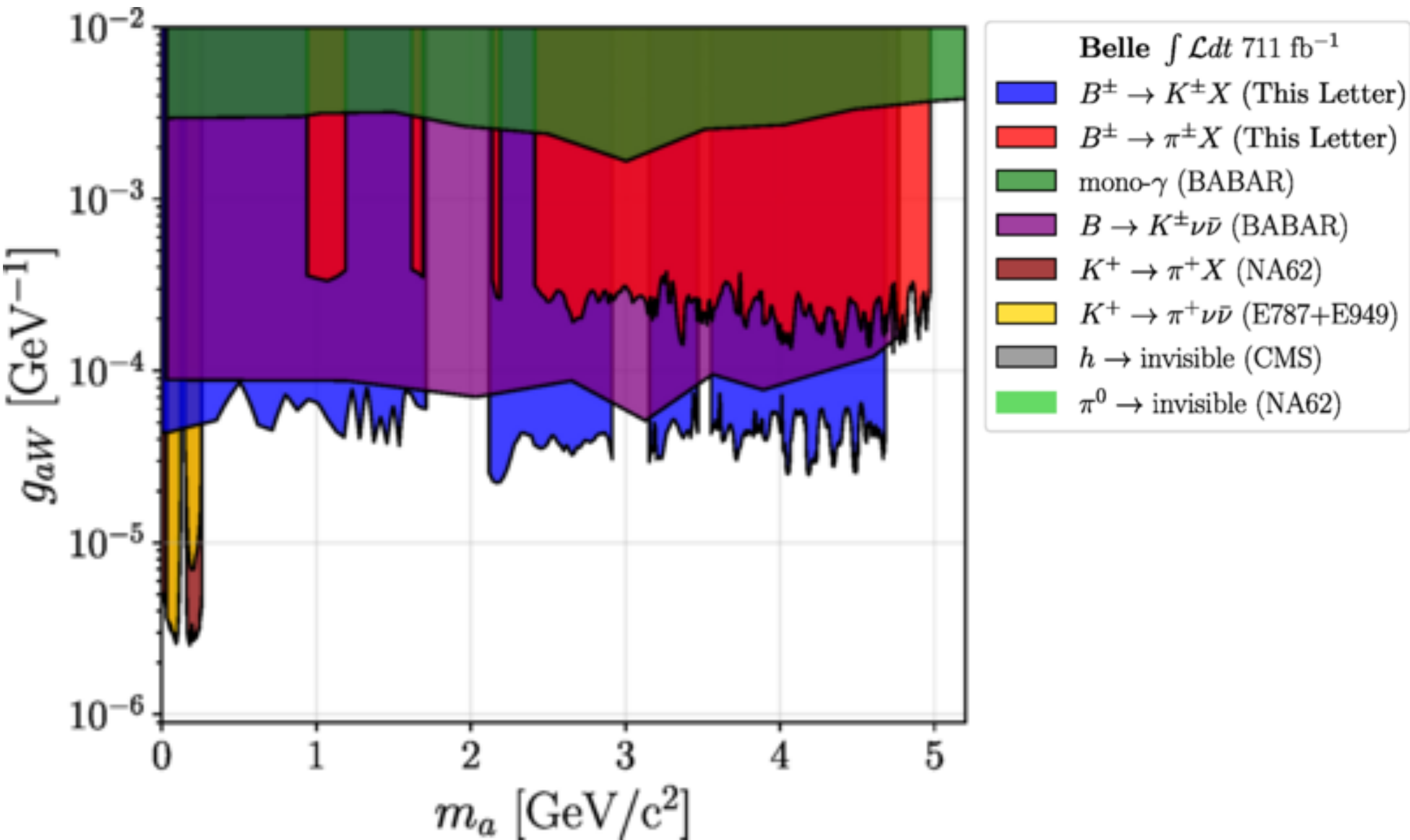
Limits interpreted in several models: ALP-W, ALP-quark couplings and dark scalar-Higgs mixing parameters

➔ world-leading results





The hypothesis of a 2-body decay to explain $B \rightarrow K\nu\nu$ the Belle II [Phys. Rev. D 109 112006 (2024)] excess is suppressed by the results on $B^+ \rightarrow K^+X$



Summary

The Belle II collaboration is competitive in many dark portal searches and signatures.

Thanks to a combination of:

Clean initial states, low pile-up, high precision and high luminosity

Gather multiple up-to-date world-best upper limits on:

- Axion-like particle $e^+e^- \rightarrow \gamma\alpha (\rightarrow \gamma\gamma)$
- Visible dark photon $e^+e^- \rightarrow \gamma A' (\rightarrow \mu^+\mu^-)$
- Lepton flavour-violating $\tau \rightarrow \ell\alpha$ decay
- Feeble interacting particle in rare decay $B \rightarrow hX_{inv}$ (scalar, pseudoscalar, and B-mesogenesis assumptions)

Optimistic future:

- Today's results are only using a partial dataset of Belle II
- 2025-2026 data-taking period was fruitful, from $\sim 500 fb^{-1}$ to $1 ab^{-1}$
- Plenty of different candidates and signatures to look at:
 - Single photon
 - Dark Higgs
 - Long-lived particles
 - Displaced τ LFV decays

Thank you!