

Der Wissenschaftsfonds.

Searches for dark sector particles at Belle and Belle II

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On behalf of Belle and Belle II collaboration

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- Belle and Belle II experiments.
- Introduction to Dark Sector Searches.
- Analyses shown today:
 - Search for X (Z' , S) in the $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ at Belle II;
Phys. Rev. D 109, 112015 (2024).
 - Long-lived scalar (S) in B decays at Belle II;
Phys. Rev. D 108, L111104 (2023).
 - Leptophilic scalar (ϕ_L) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ at Belle;
Phys. Rev. D 109, 032002 (2024).
 - Heavy Neutral Leptons (HNL) in τ decays at Belle;
Phys. Rev. D 109, L111102 (2024)
- Summary.

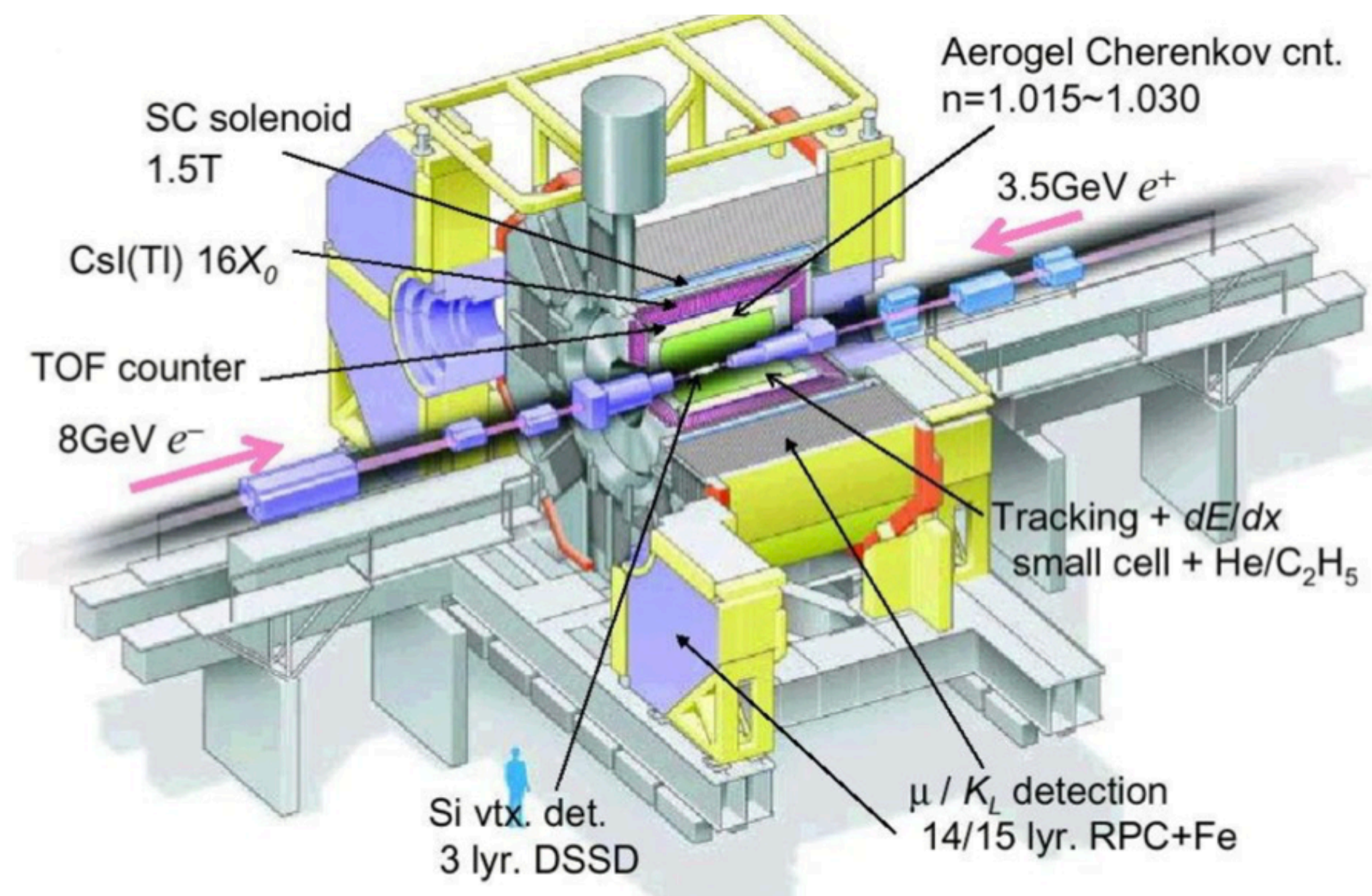
Other ongoing searches:

- Invisible Z' (update) (Belle II)
- Search for ALPs in $e^+e^- \rightarrow \gamma a$, $a \rightarrow \gamma\gamma$ (Belle II)
- Search for ALPs in $B \rightarrow Ka(\rightarrow \gamma\gamma)$ (Belle)
- Dark photon.
- Inelastic Dark Matter.
- ... many more!

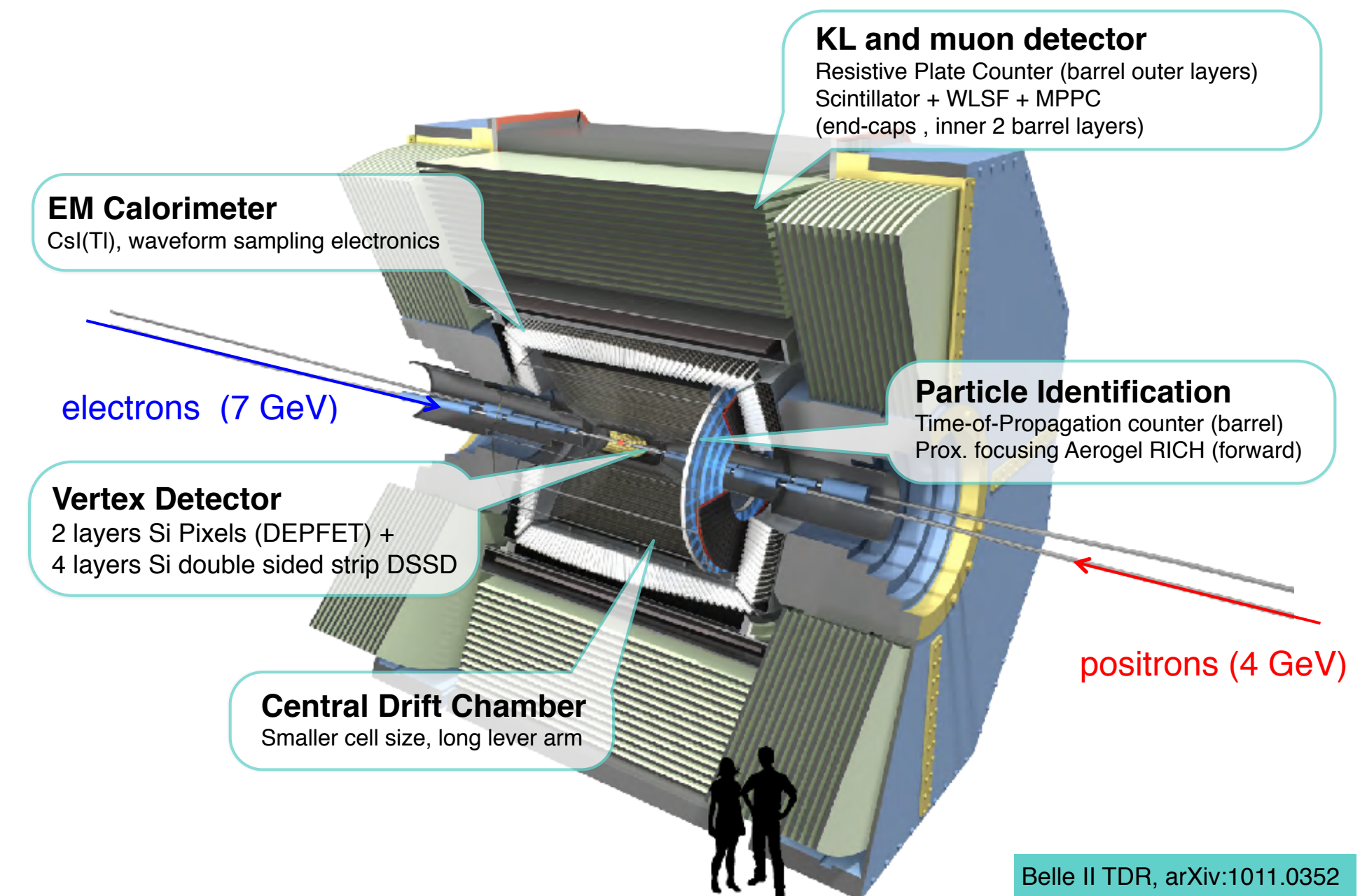
Belle and Belle II experiments

- **Belle (1999-2010)** and **Belle II (2018-)** are B -factories; located in Tsukuba - KEK laboratory - Japan.
- An asymmetric e^+e^- collider, operated around 10.58 GeV ($=m_{\Upsilon(4S)}$).
- Well known initial conditions, Clean environment, Hermetic detectors.

Belle: recorded $\sim 1 \text{ ab}^{-1}$



Belle II: recorded 427 fb^{-1} in Run1 (2018 - 2022) and 103 fb^{-1} in Run2 (2024 -)



Belle II TDR, arXiv:1011.0352

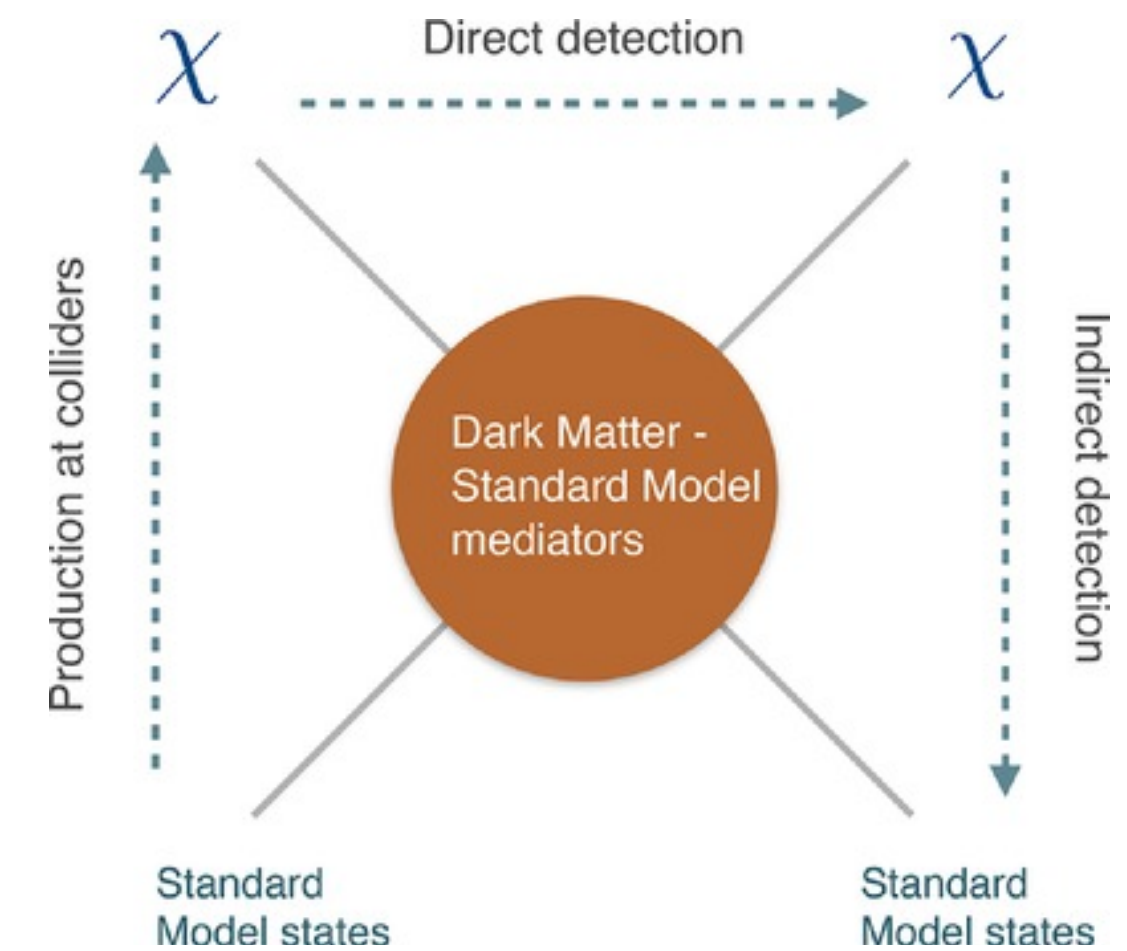
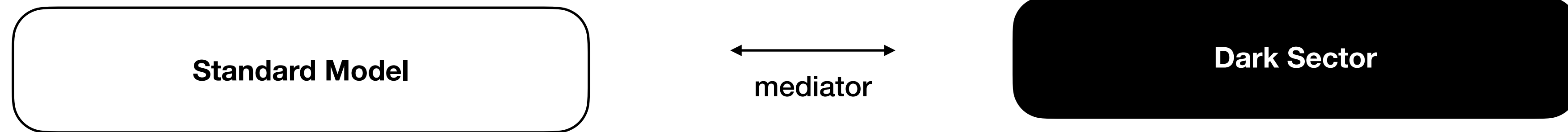
Dedicated dark sector/low-multiplicity trigger lines for **Belle II**:

- Single photon trigger
- Single track trigger using neural networks
- Single muon trigger.

Dark Sector Searches

- Different methods of Dark Matter searches: Direct searches, Indirect searches, collider searches

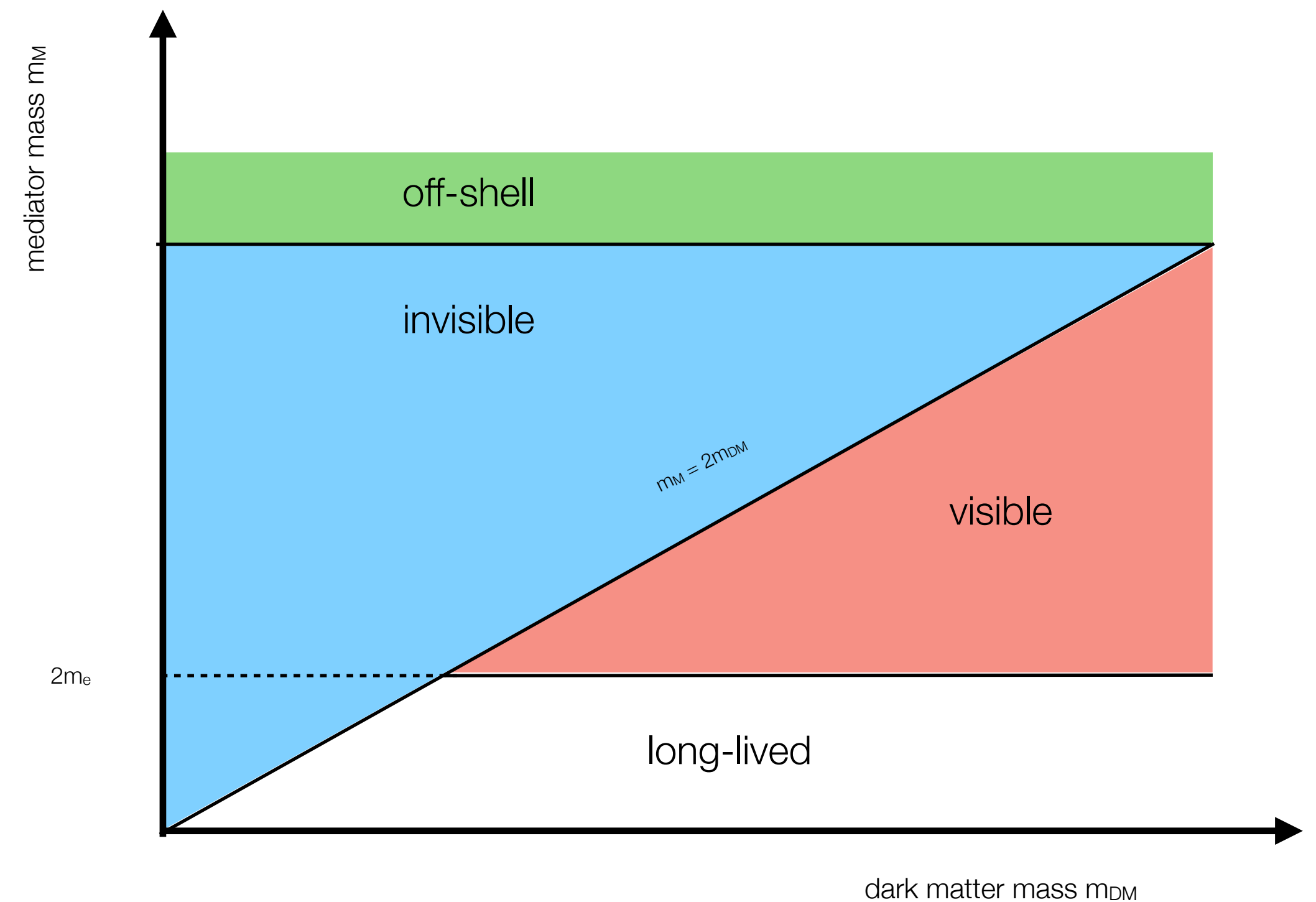
Belle and Belle II have excellent sensitivity for dark sector searches in the MeV – GeV range.



- Possible portals between Standard Model and Dark Sector.

- Vector portal (dark photon (A'), Z').
- Pseudo-scalar: ALPs
- Scalar portal: Dark Higgs
- Neutrino: Sterile Neutrinos

- Typical signatures : low multiplicity, missing energy, isolated mono photon, displaced tracks etc.



Search for X (Z' , S) in the $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ at Belle II



- Search for the process $e^+e^- \rightarrow \mu^+\mu^-X, X \rightarrow \mu^+\mu^-$.
- Probing two different models: $L_\mu - L_\tau$ vector mediator (Z') [$\mathcal{L} = \sum_l \theta g' \bar{l} \gamma^\mu Z'_\mu l$] [1]

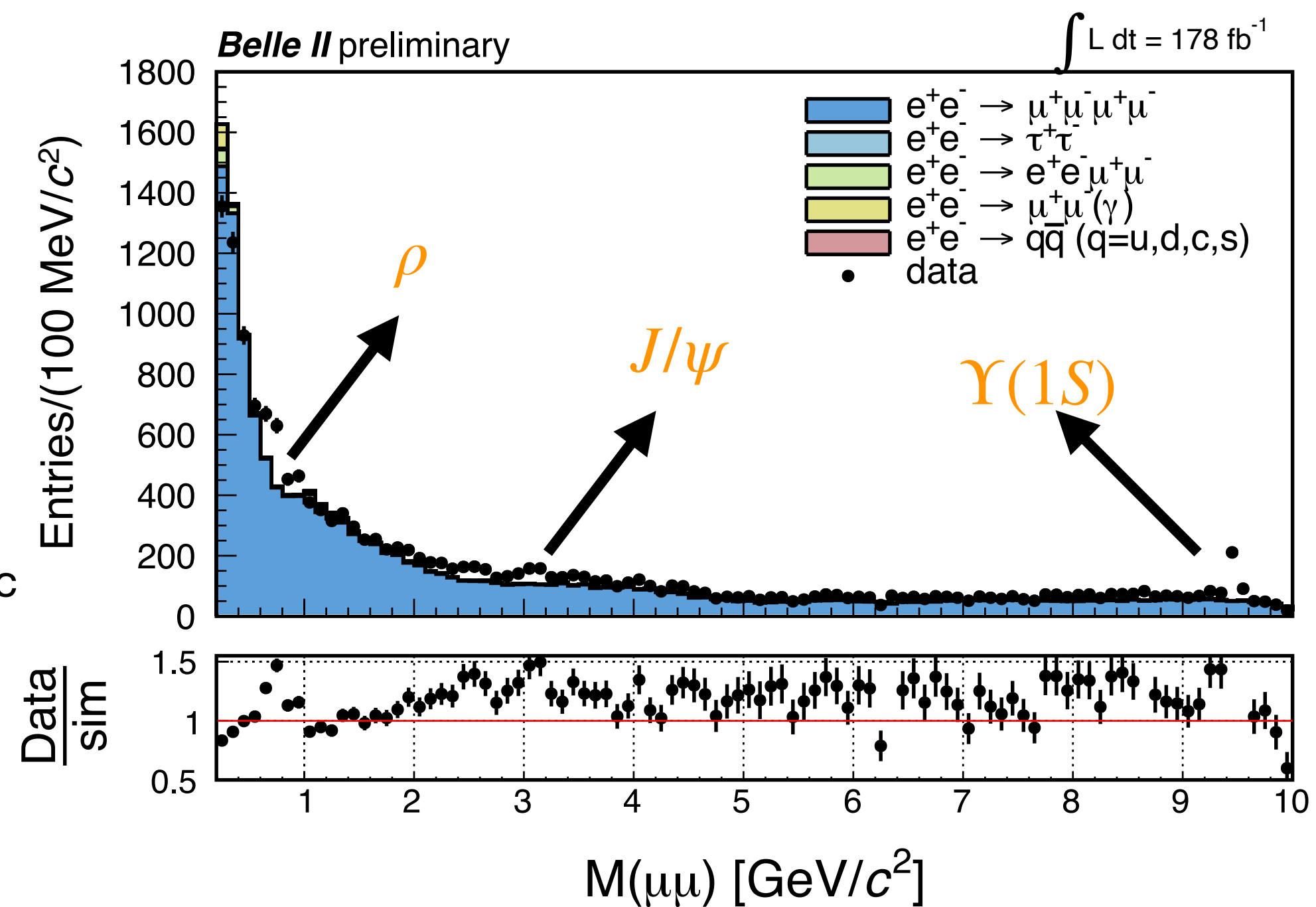
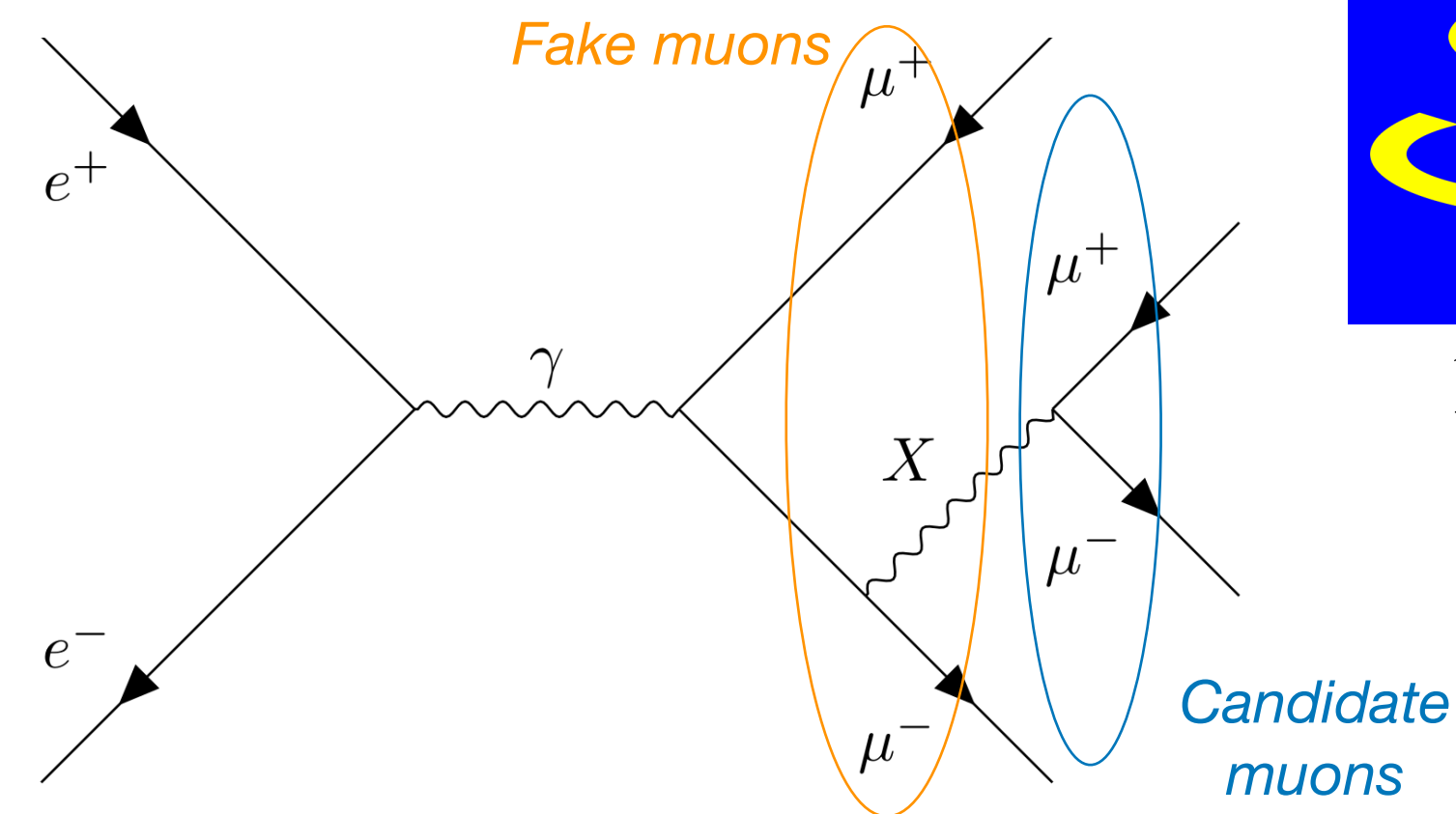
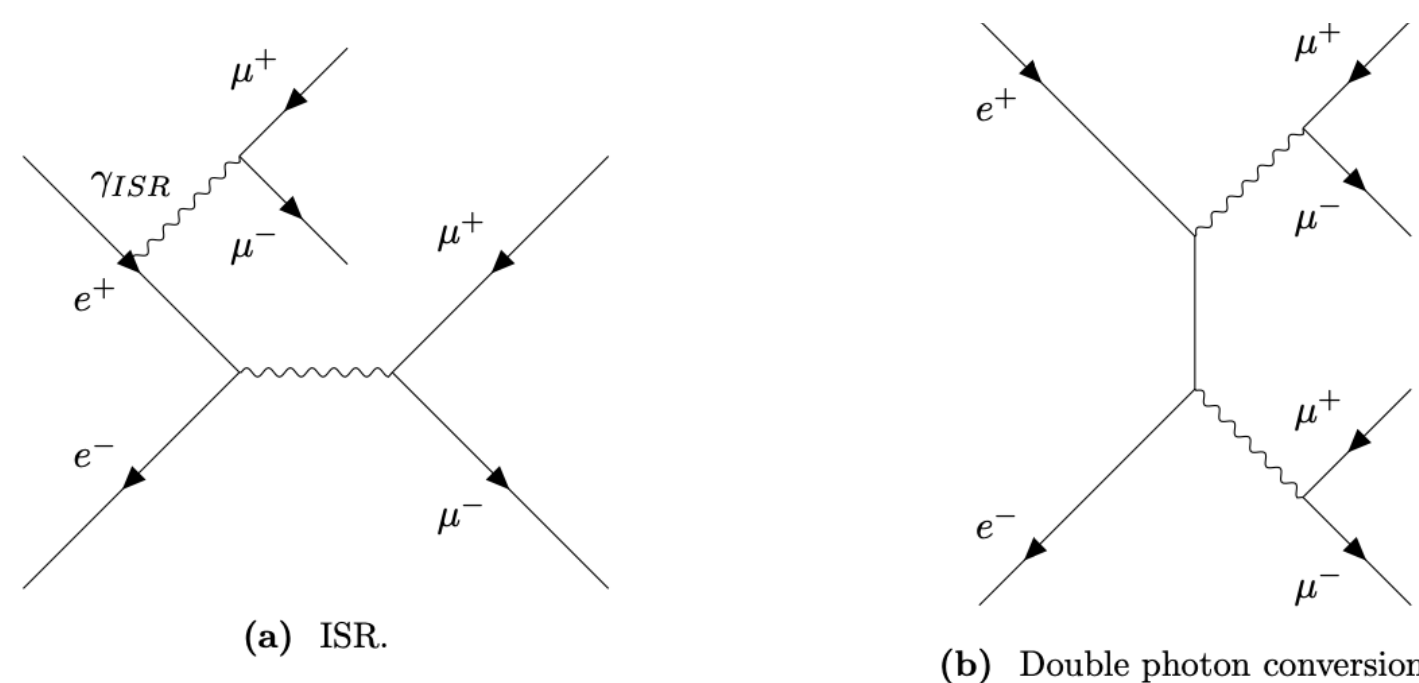
Muonphillic Scalar (S) [$\mathcal{L} \supset g_s S \bar{\mu} \mu$] (first time search) [2]

- Targeted luminosity is 178 fb^{-1} , which is ~ 2 -3 times less data used by Babar [3] and Belle [4] experiments for the Z' search.

Event selections:

- 4 charge track coming from the collision point (net total charge zero).
- M(4-tracks) within $\Upsilon(4S)$.
- Particle ID: at least 3 tracks are identified as muon and other track is not an electron.
- No extra energy.
- Aggressive background suppression using Neural Network, exploiting different kinematic and angular variables.

Main background components: SM $\mu\mu\mu\mu$, $\mu\mu\gamma$, combinatorial.

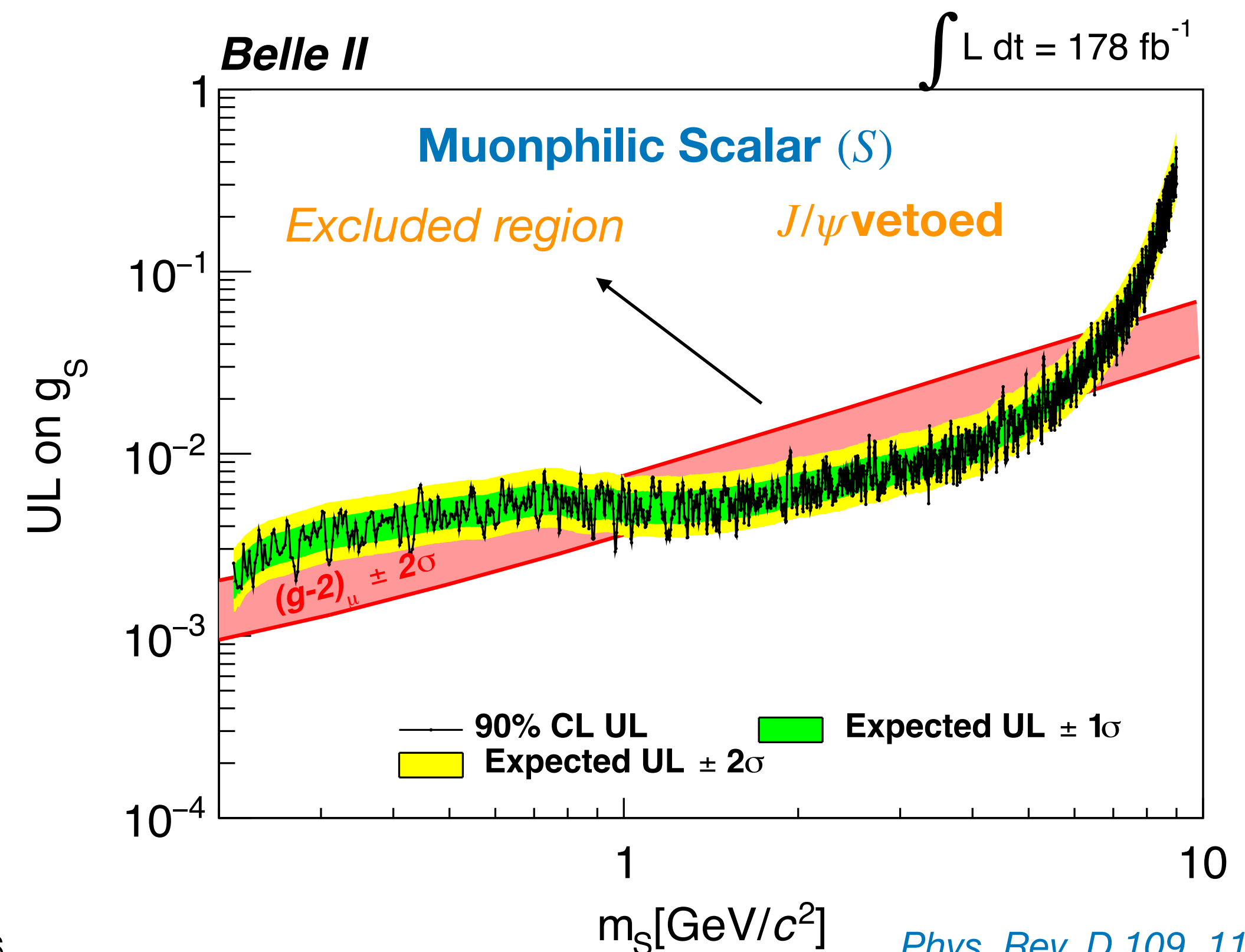
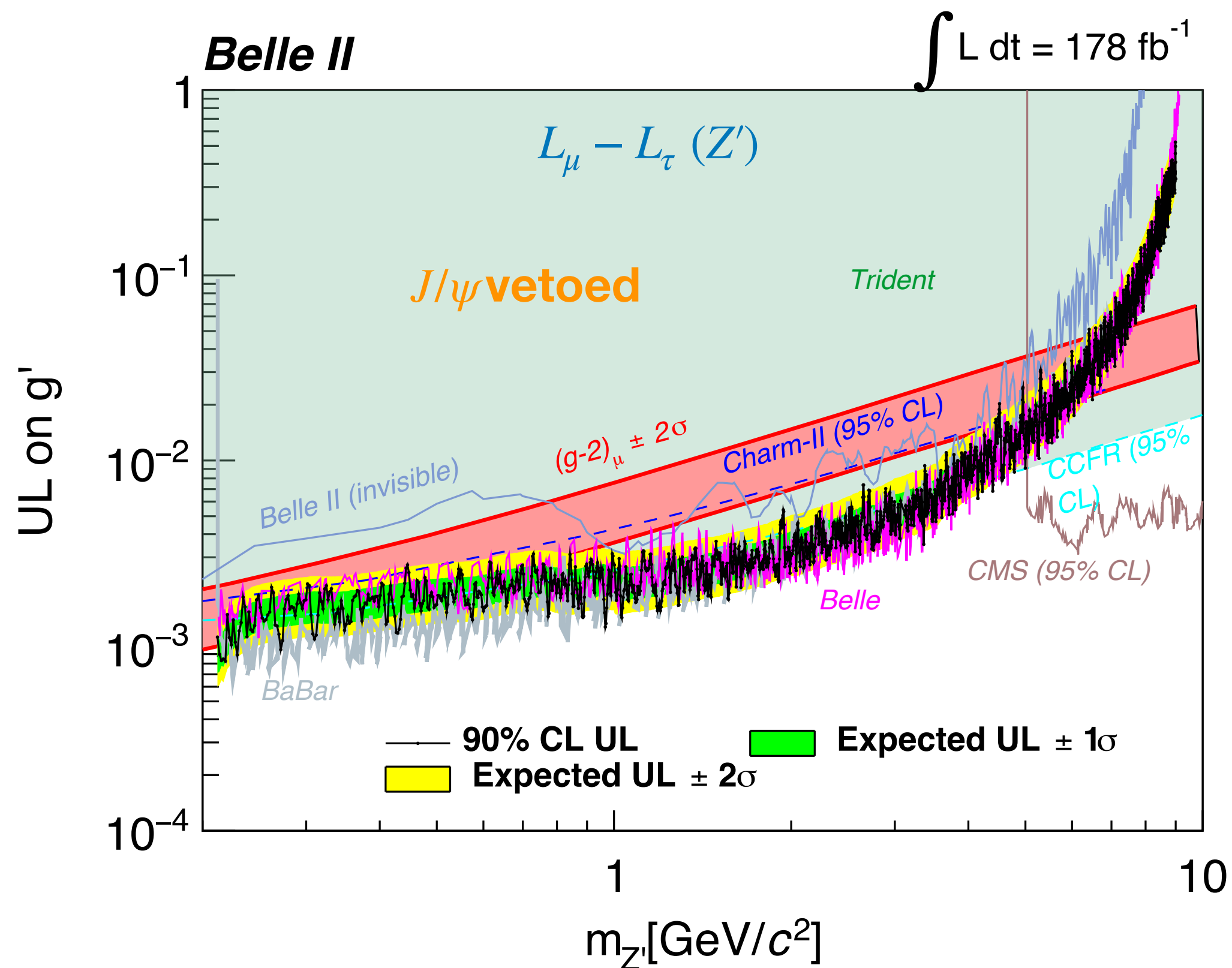


Data MC disagreement mainly due to missing ISR of the used generator

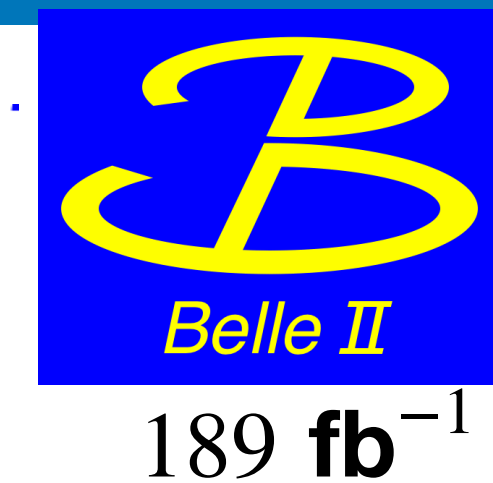
Search for X (Z' , S) in the $e^+e^- \rightarrow \mu^+\mu^-\mu^+\mu^-$ at Belle II



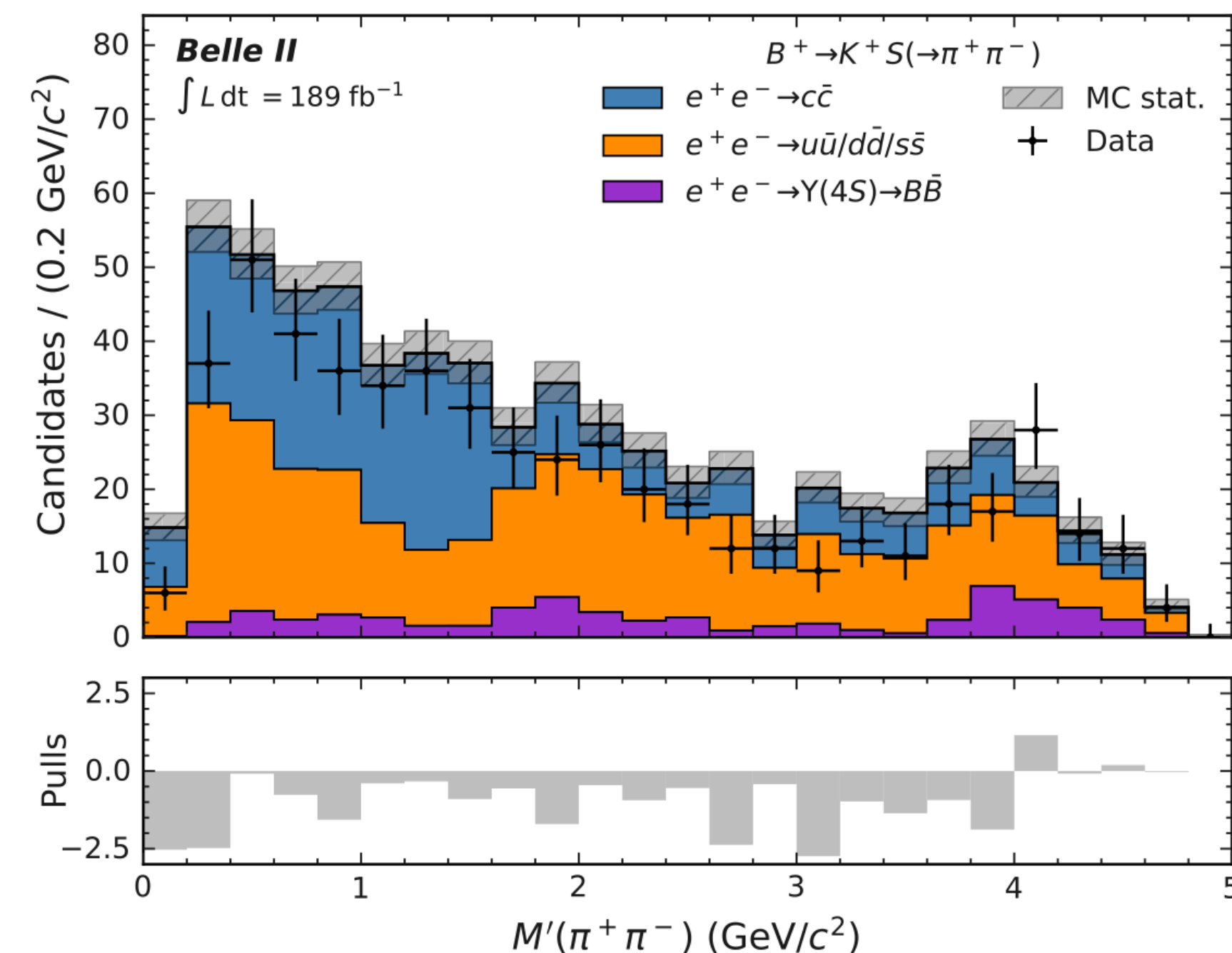
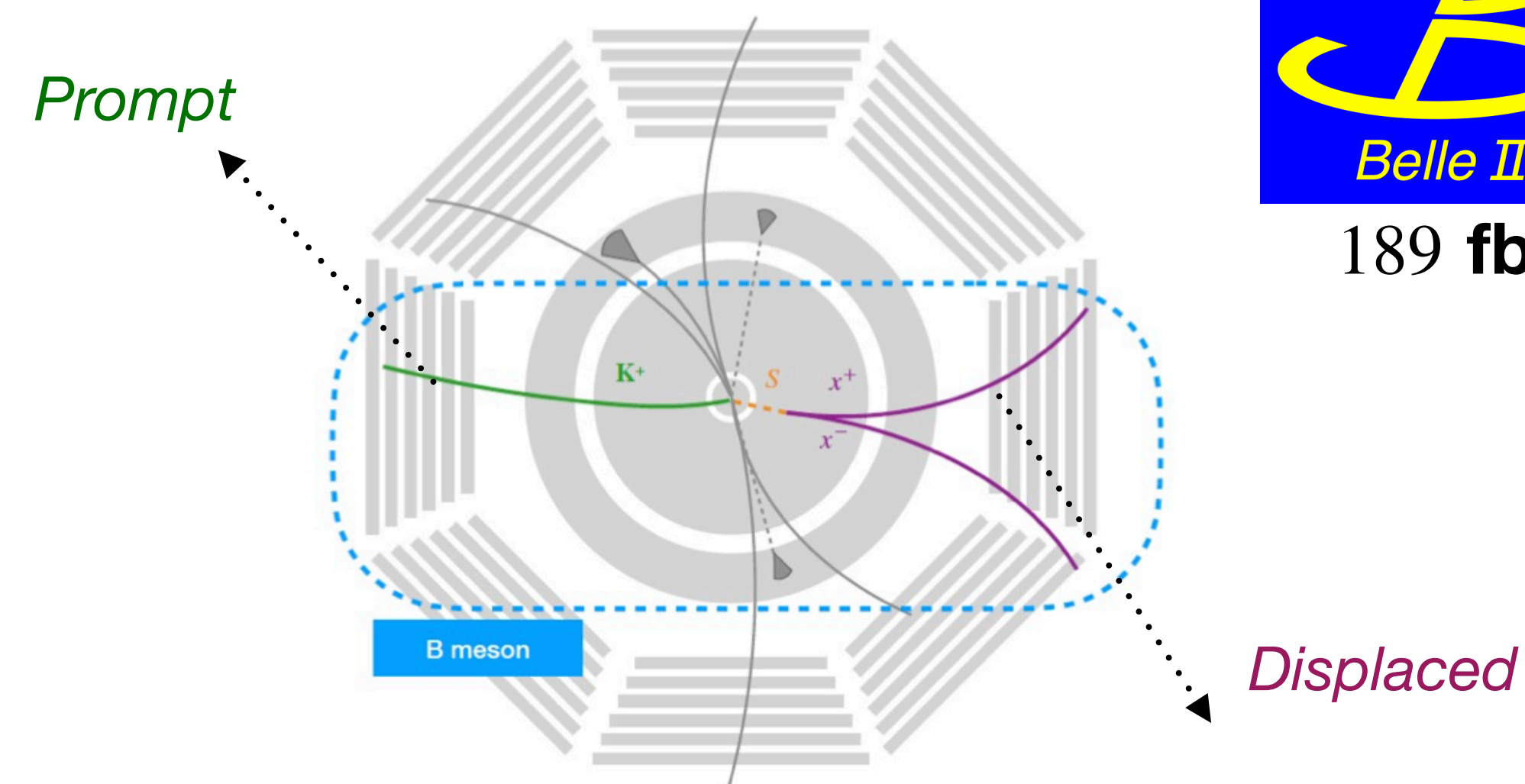
- Searched mass region: 0.212 - 9 GeV/c².
- No significant excess found.
- Competitive 90% CL upper limits for g' coupling of the $L_\mu - L_\tau$ model (Z'); almost similar result of BaBar (~500 fb⁻¹) and Belle (~600fb⁻¹) with 178fb⁻¹ due to aggressive background suppression.
- First 90% CL upper limits for the muonphilic dark scalar (S) model.



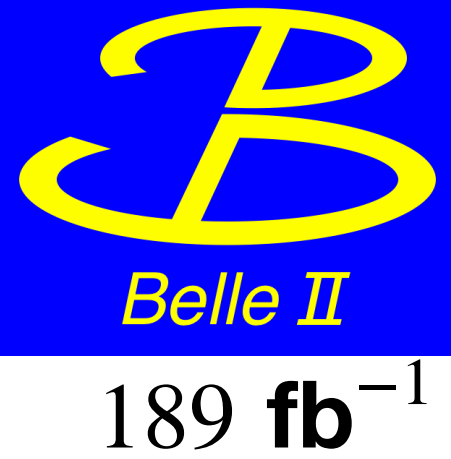
Long-lived scalar (S) in B decays at Belle II



- First Belle II long-lived spin-0 (S) particle search.
- Such a new scalar would mix with the SM Higgs boson through a mixing angle θ [1-2].
- Model independent search. Dataset used 189 fb^{-1} .
- Channels studied:
 $B^+ \rightarrow K^+ S$, $B^0 \rightarrow K^{*0}(K^+ \pi^-) S$; $S \rightarrow x^+ x^-$, $x = e, \mu, \pi, K$
- Signal B – meson fully reconstructed :
 - tracks originating from the interaction point (**prompt**).
 - and from a vertex separated macroscopic distance (**displaced**) (very far from IP).
- Other B non reconstructed
- Main source of Backgrounds: $q\bar{q}(\gamma)$, $\tau\tau(\gamma)$; reduced by requiring kinematics similar to B-meson expectations.



Long-lived scalar (S) in B decays at Belle II



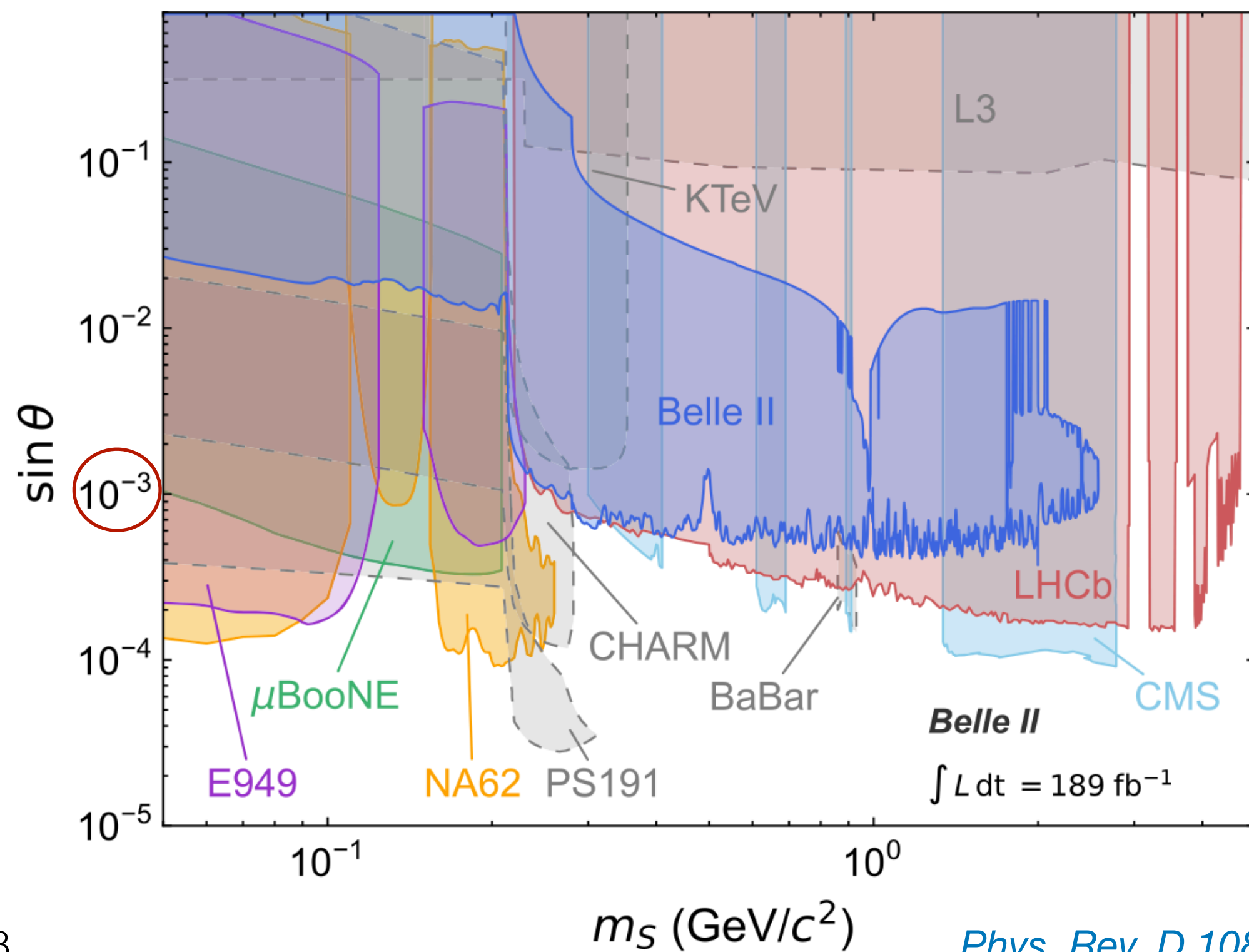
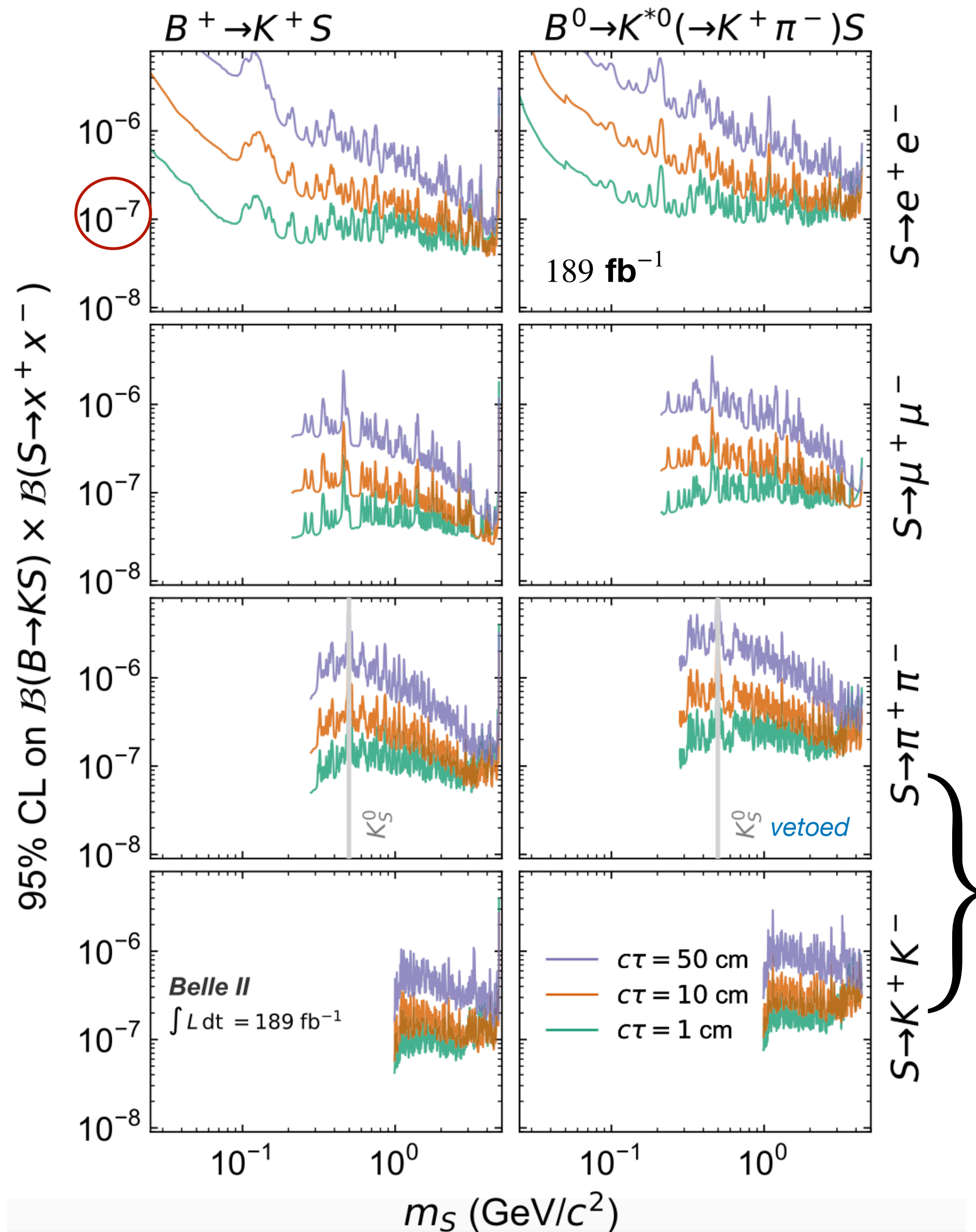
Model-independent upper limits on the product of branching fractions as functions of S mass and lifetime at the level of 10^{-7} .

- Explored mass regions: $22 \text{ MeV}/c^2 - 4.78 \text{ GeV}/c^2$ for $B^+ \rightarrow K^+ S$ and $4.38 \text{ GeV}/c^2$ for $B^0 \rightarrow K^{*0} S$.

- No observed excess.

- First model-independent limits for exclusive $B^0 \rightarrow K^{(*)} S; S \rightarrow \text{hadrons}$ as a function of mass and lifetime.

- Interpretation as dark scalar with the sine of the mixing angle θ with SM Higgs



Leptophilic scalar (ϕ_L) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ at Belle



626 fb⁻¹

- Search for the process: $e^+e^- \rightarrow \tau^+\tau^-\phi_L(\rightarrow l^+l^-), l = e, \mu$.

- ϕ_L is a dark leptophilic scalar that couples only to leptons;

$$\mathcal{L} = -\xi \sum_{l=e,\mu,\tau} \frac{m_l}{v} \bar{l} \phi_L l \quad [1].$$

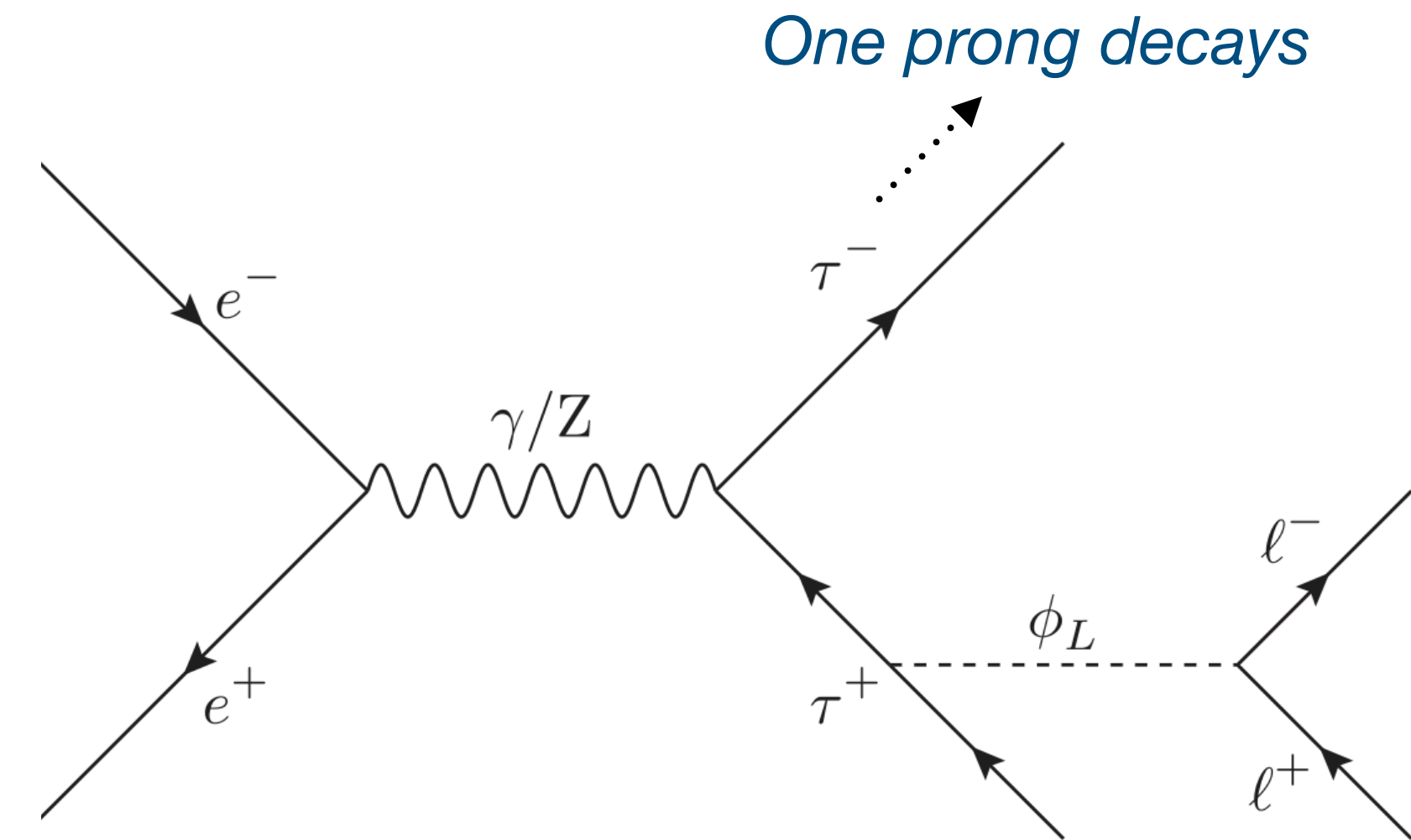
- Explored mass region:

- $\phi_L \rightarrow e^+e^-$ for $m_\phi < 2m_\mu$
 $10 < c\tau_\phi < 50$ mm for $m_\phi < 0.1$ GeV/c²
- $\phi_L \rightarrow \mu^+\mu^-$ for $m_\phi > 2m_\mu$
- Explored mass region upto 6.5 GeV/c²

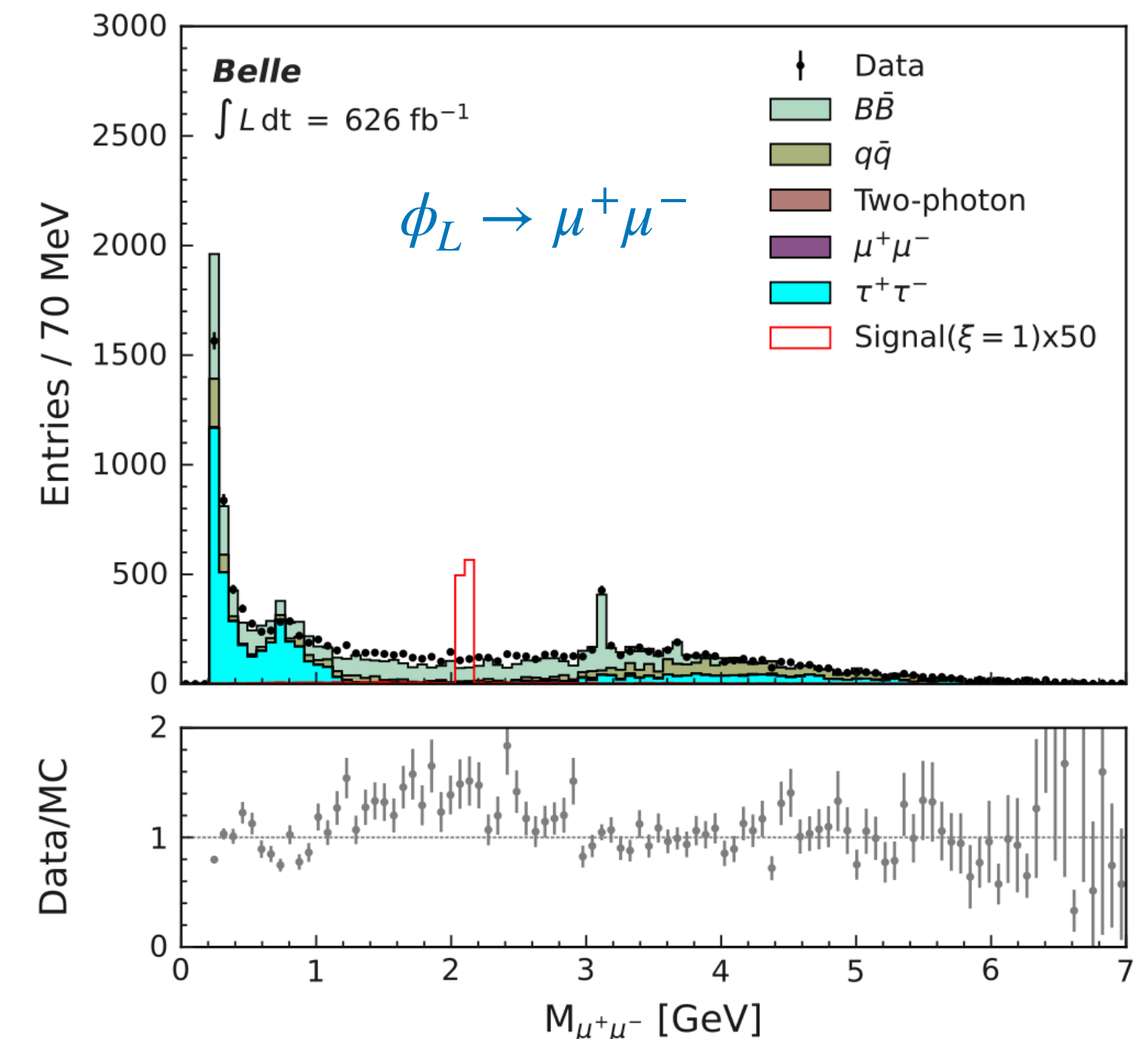
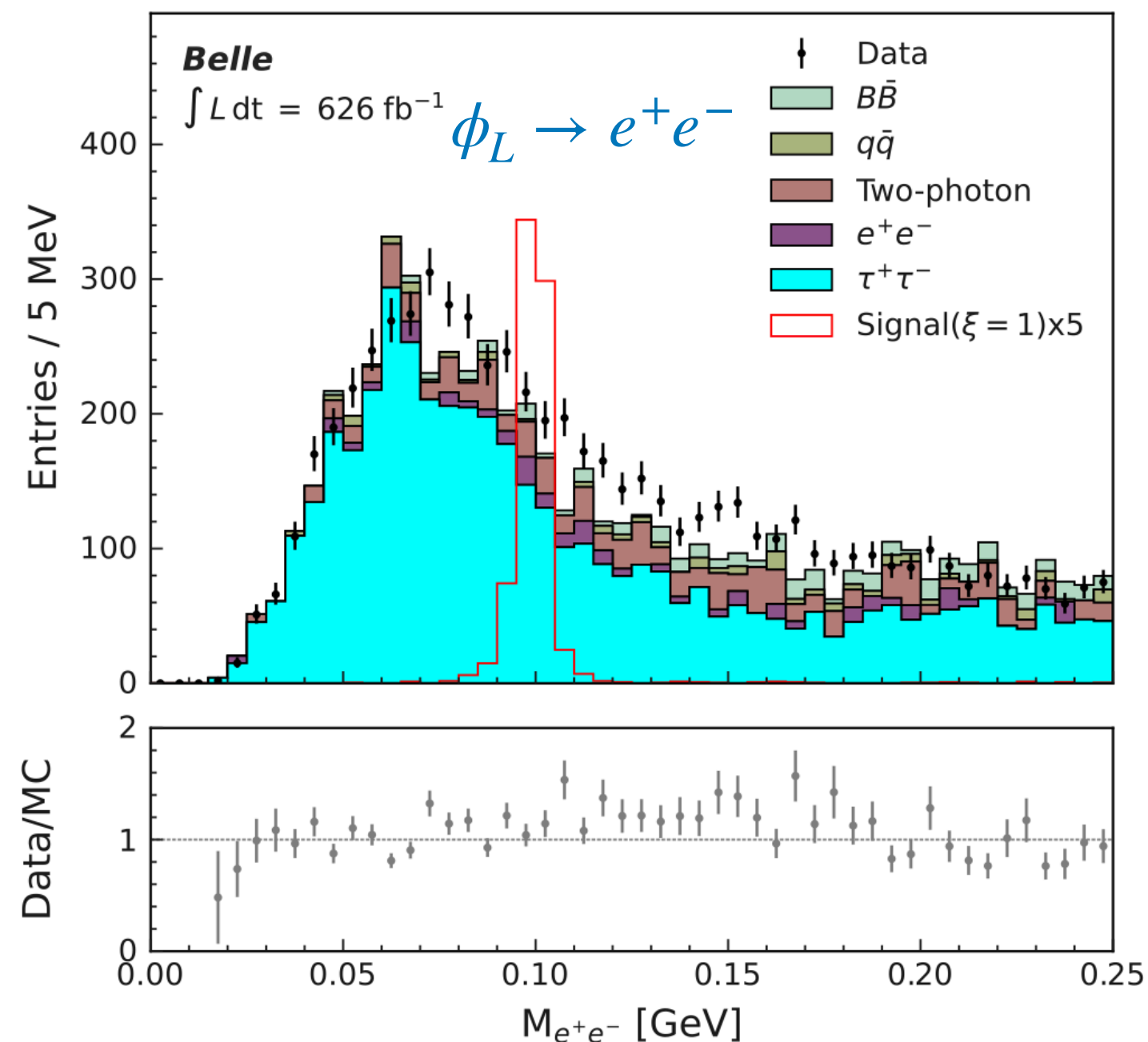
- Event selection: 4 charge tracks, large missing energy.

- Main source of background is $\tau^+\tau^-$.

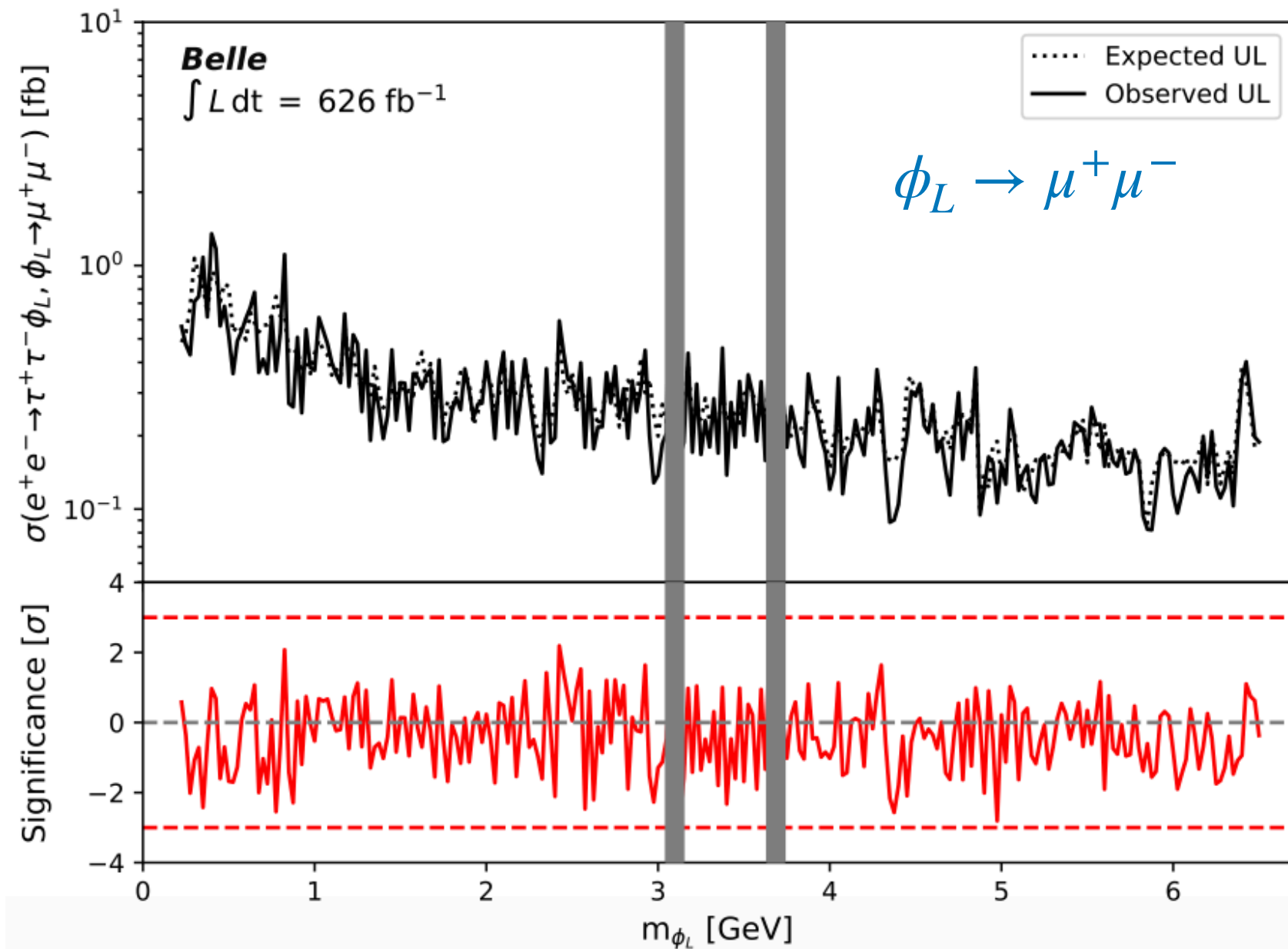
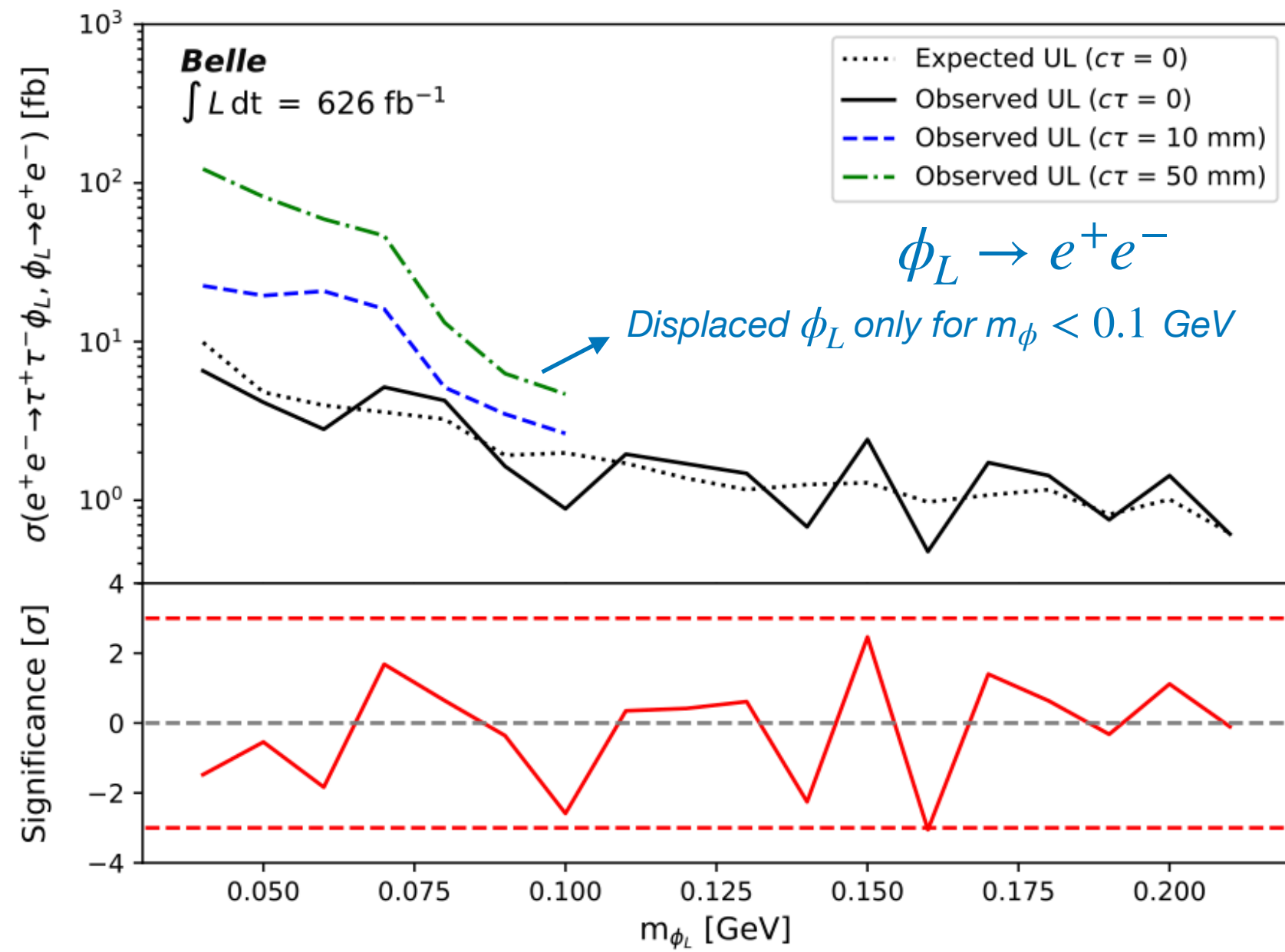
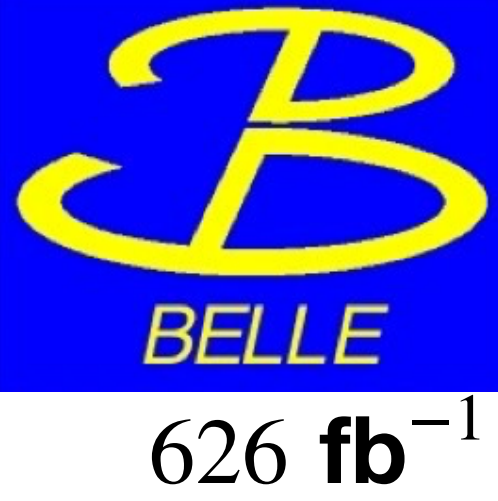
- BDT is used to suppress the backgrounds and the classifier response is used to define different control regions.



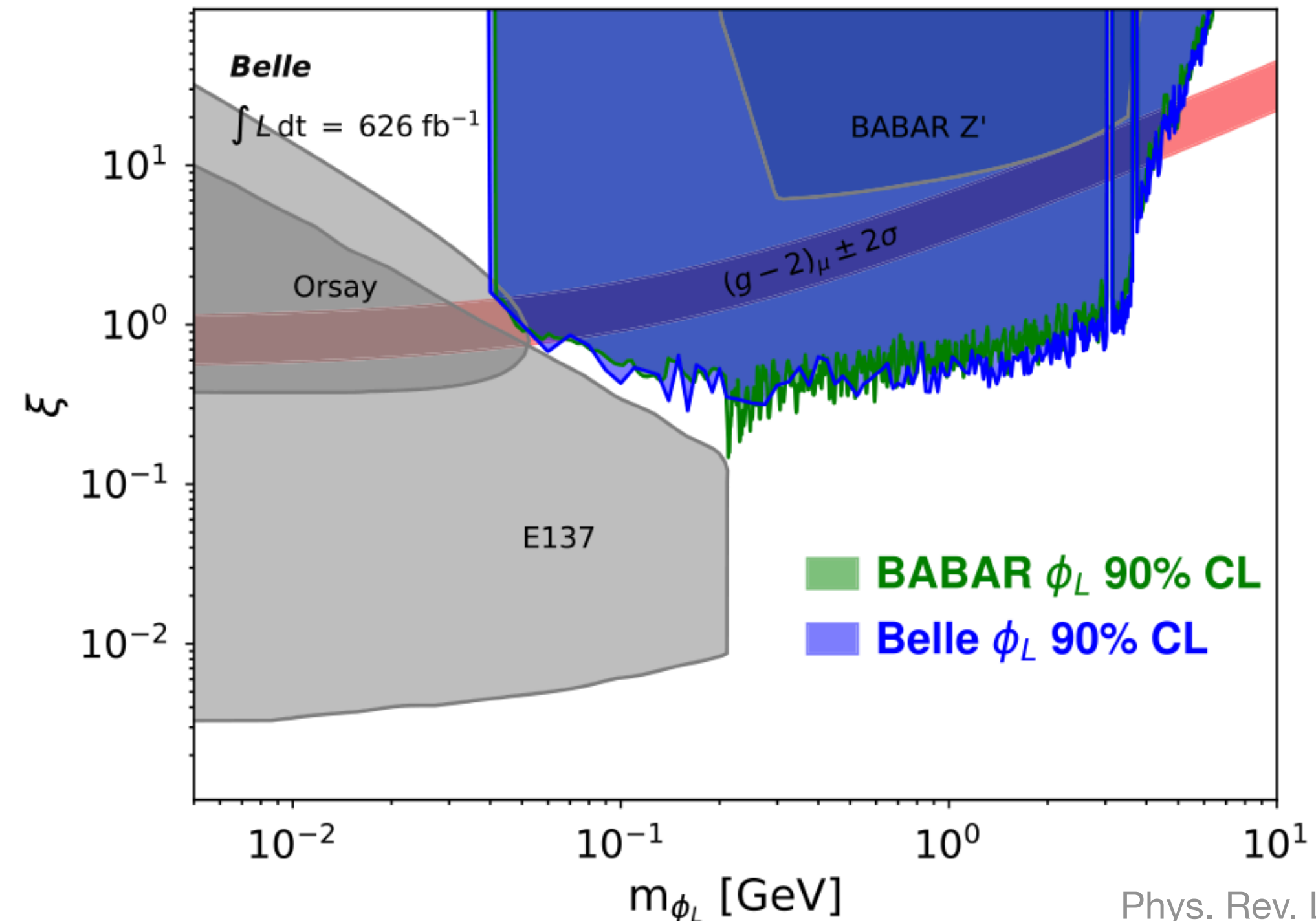
BDT score > 0.95



Leptophilic scalar (ϕ_L) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ at Belle



- No significant excess found in 626 fb^{-1} .
- 90% CL upper limits on $\sigma(e^+e^- \rightarrow \tau^+\tau^-\phi_L(\rightarrow l^+l^-))$ and coupling constant ξ .
- Limits are on average 19% more constraining w.r.t BaBar [2].
- Ruled out the leptophilic scalar with mass less than 4 GeV that could explain the observed excess in $(g-2)_\mu$



Heavy Neutral Leptons (HNL) in τ decays at Belle



- Many extensions of SM predicts heavy sterile neutrinos N [1].
 - N mixes with SM neutrinos.
 - It could be long-lived due to small coupling with SM neutrinos.

- The search model probes $|V_{N\tau}|^2$ and couplings with other lepton considered negligible [2].

- Process: $e^+e^- \rightarrow \tau^+\tau^-$;

signal side: $\tau^- \rightarrow \pi^- N; N \rightarrow \mu^+ \mu^- \nu_\tau$, where N forms displaced vertex (DV);

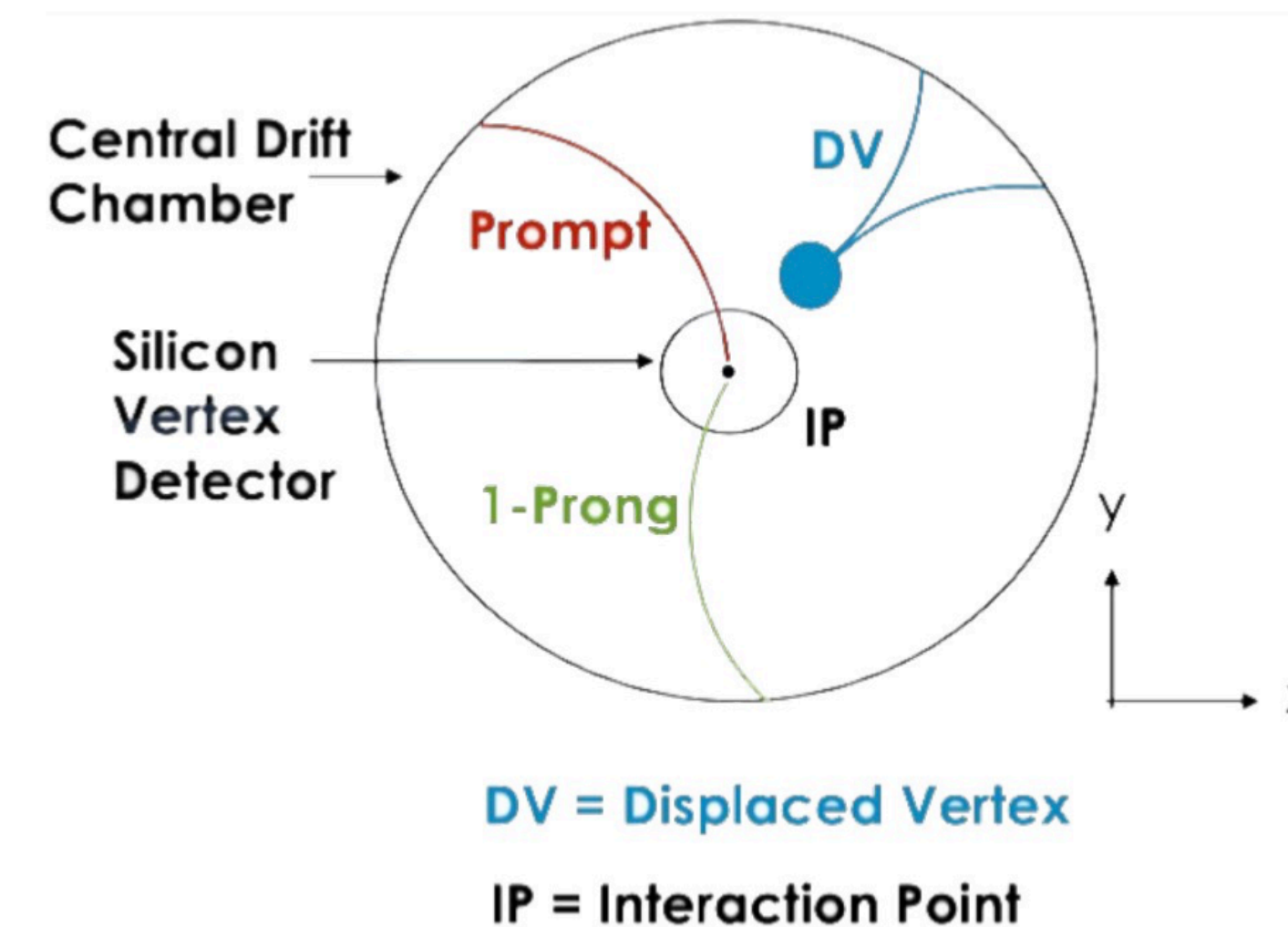
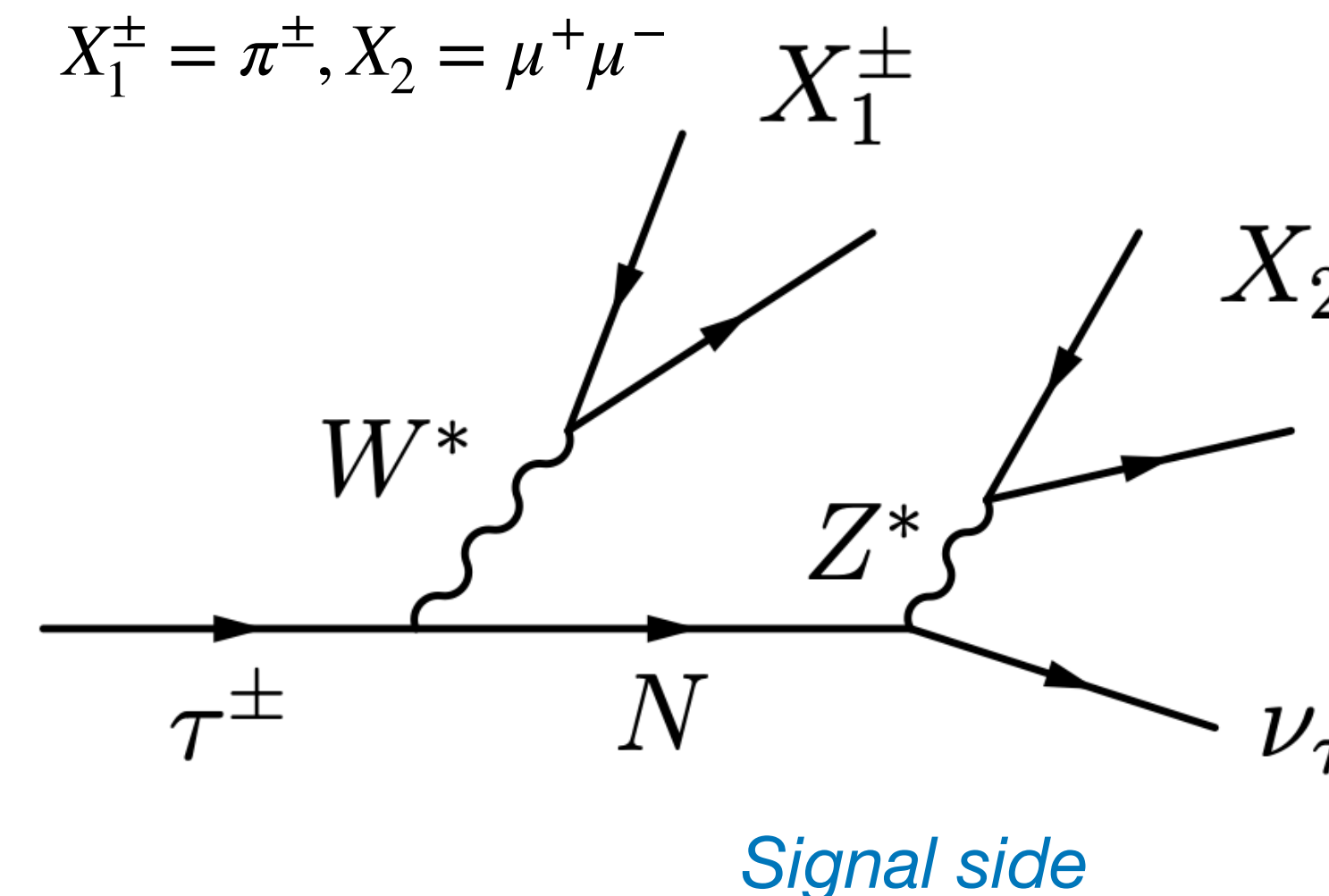
tag side: 1-prong decays.

- Main background $K_S^0 \rightarrow \pi^+\pi^-$ is vetoed (420-520 MeV/c^2).

- Signal region divided in:

Low-mass region (SRL) $m_{\text{DV}} < 420 \text{ MeV}/c^2$

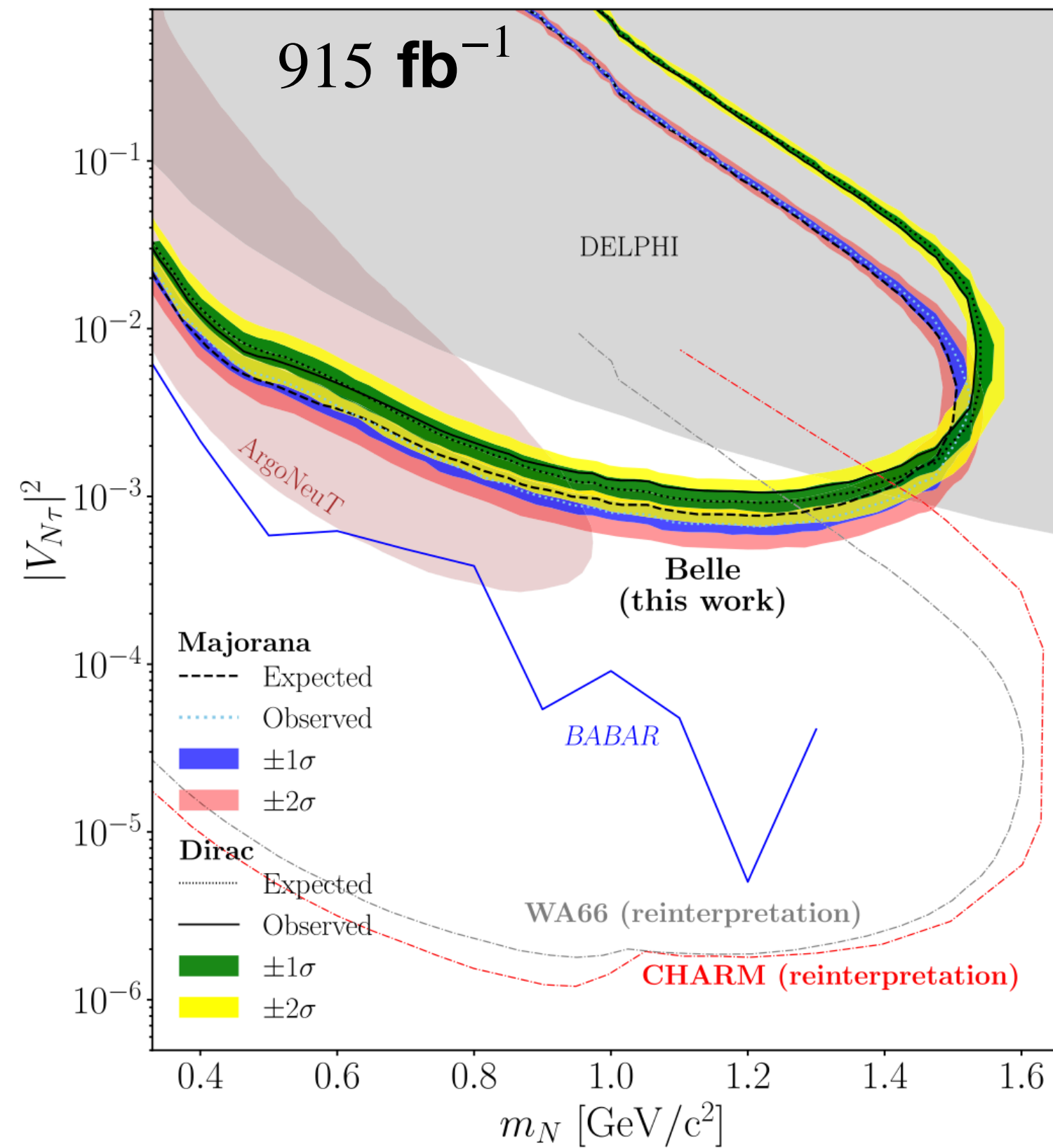
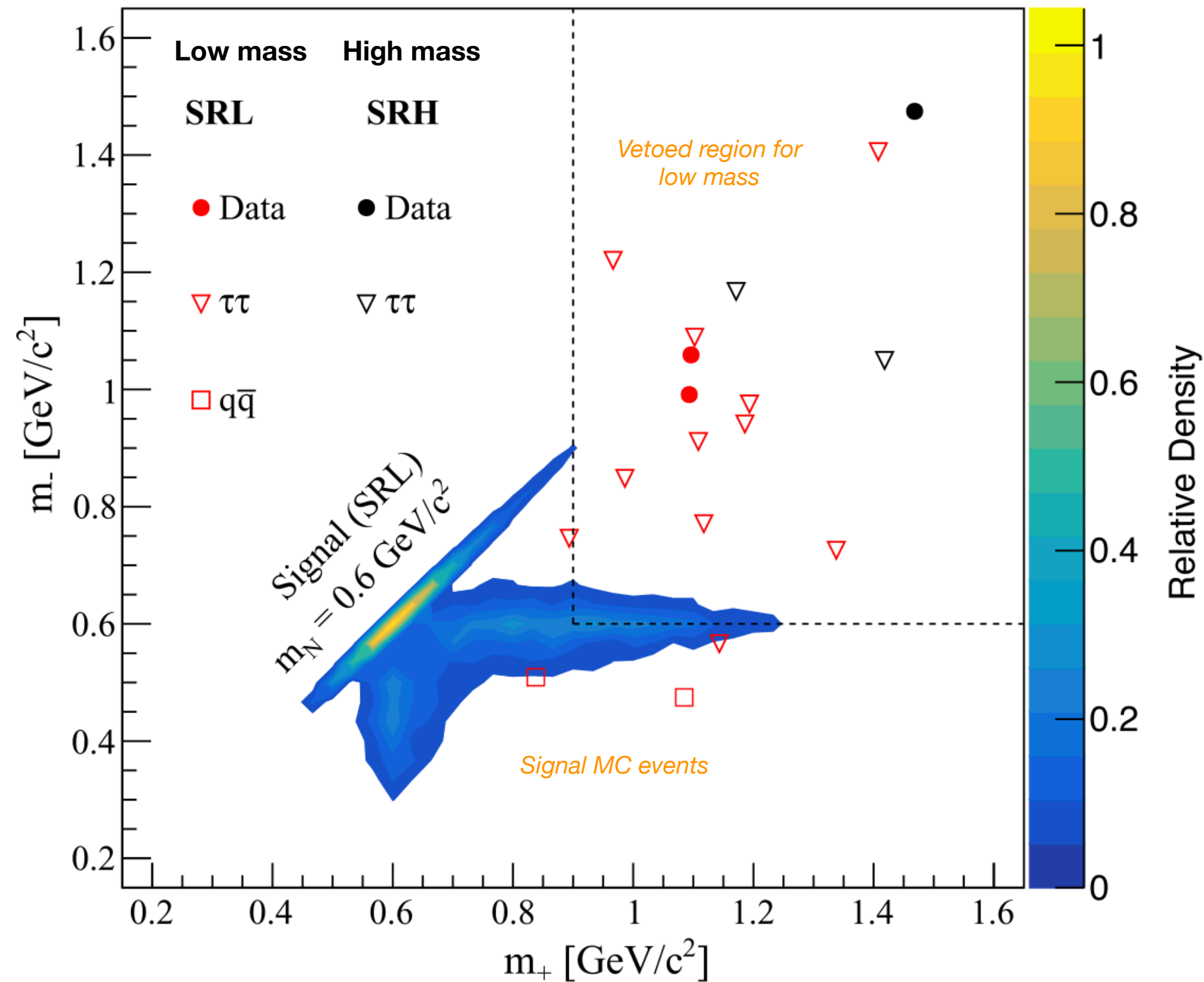
High-mass region (SRH) $m_{\text{DV}} > 520 \text{ MeV}/c^2$.



Heavy Neutral Leptons (HNL) in τ decays at Belle



- Despite the neutrino in the final state, the constraints of the signal decay allows reconstruction of full kinematics with a two-fold ambiguity on m_N (m_+ and m_-) [3].
- SRL and SRH have only 0 and 1 events respectively.
- Since no significant excess is observed for 915 fb^{-1} (4S + 5S combined), 95% CL upper limits on $|V_{N\tau}|^2$ for masses in the range $300 < m_N < 1600 \text{ MeV}/c^2$.



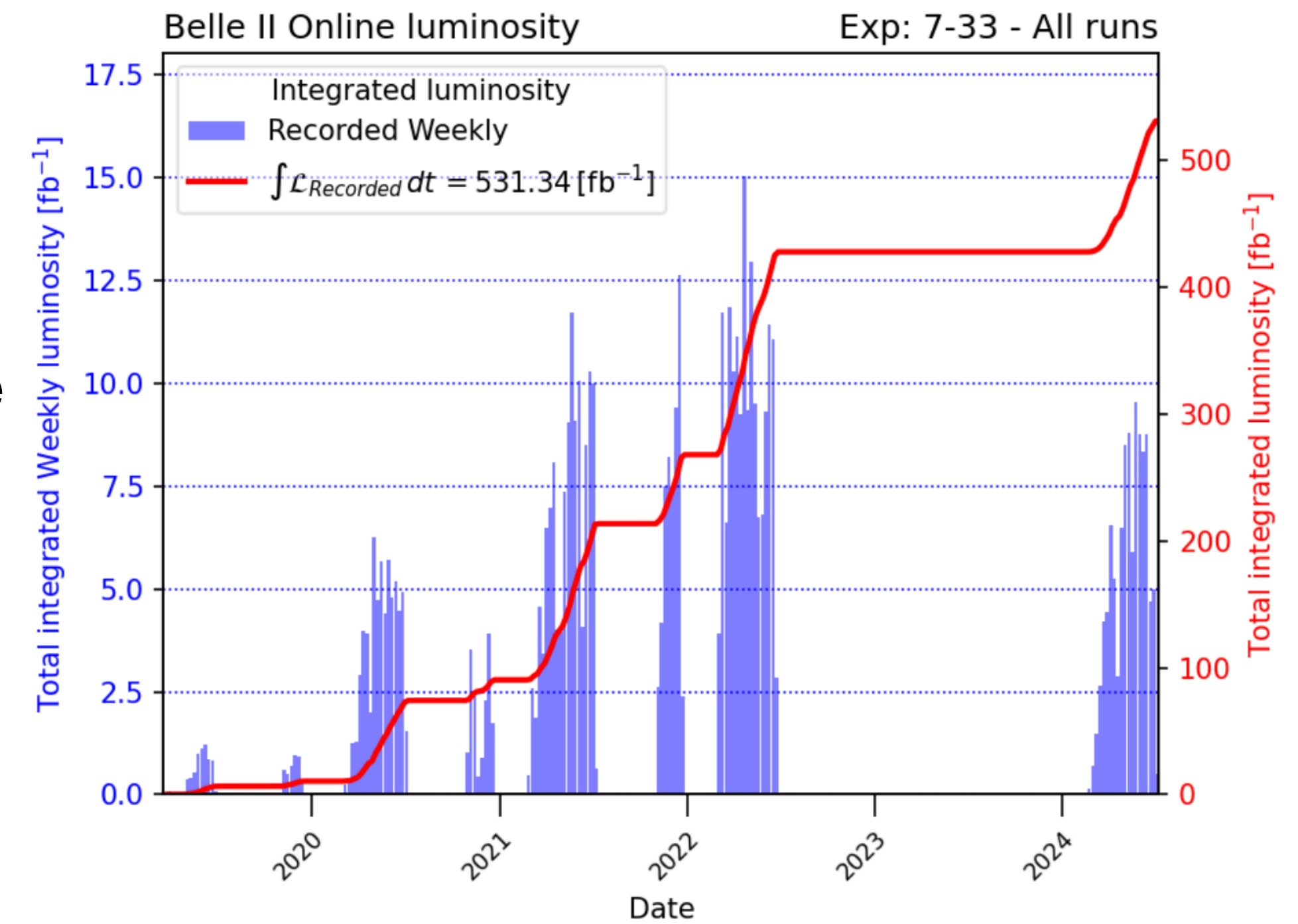
- First Displaced vertex search for Belle.

[3] Phys. Rev. D 101, 093003 (2020)

Phys. Rev. D 109, L111102 (2024)

Summary

- Broad and active program of Dark Sector physics at Belle and Belle II experiment.
- Competitive or world leading results for Belle and Belle II:
 - Search for X (Z' , S) : competitive results from the previous measurements despite being used few available dataset.
 - Long-lived scalar (S) : first model-independent limits for exclusive hadronic decays of S .
 - Leptophilic scalar (ϕ_L) : limits are on average 19% more constraining than previous searches.
 - Heavy Neutral Leptons (HNL) : put most stringent limits in the mass interval $1.3 < m_N < 1.4$ GeV.
- Many more measurements are in the pipeline, Belle II will be leading the field of light dark matter searches in the coming years.



Thank you!