



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 ( $\phi_L$ ) in  $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$  at Belle;  
*Phys. Rev. D 109, 032002 (2024)*.
  - Heavy Neutral Leptons (HNL) in  $\tau$  decays at Belle;  
*Phys. Rev. D 109, L111102 (2024)*
- Summary.

## Other ongoing searches:

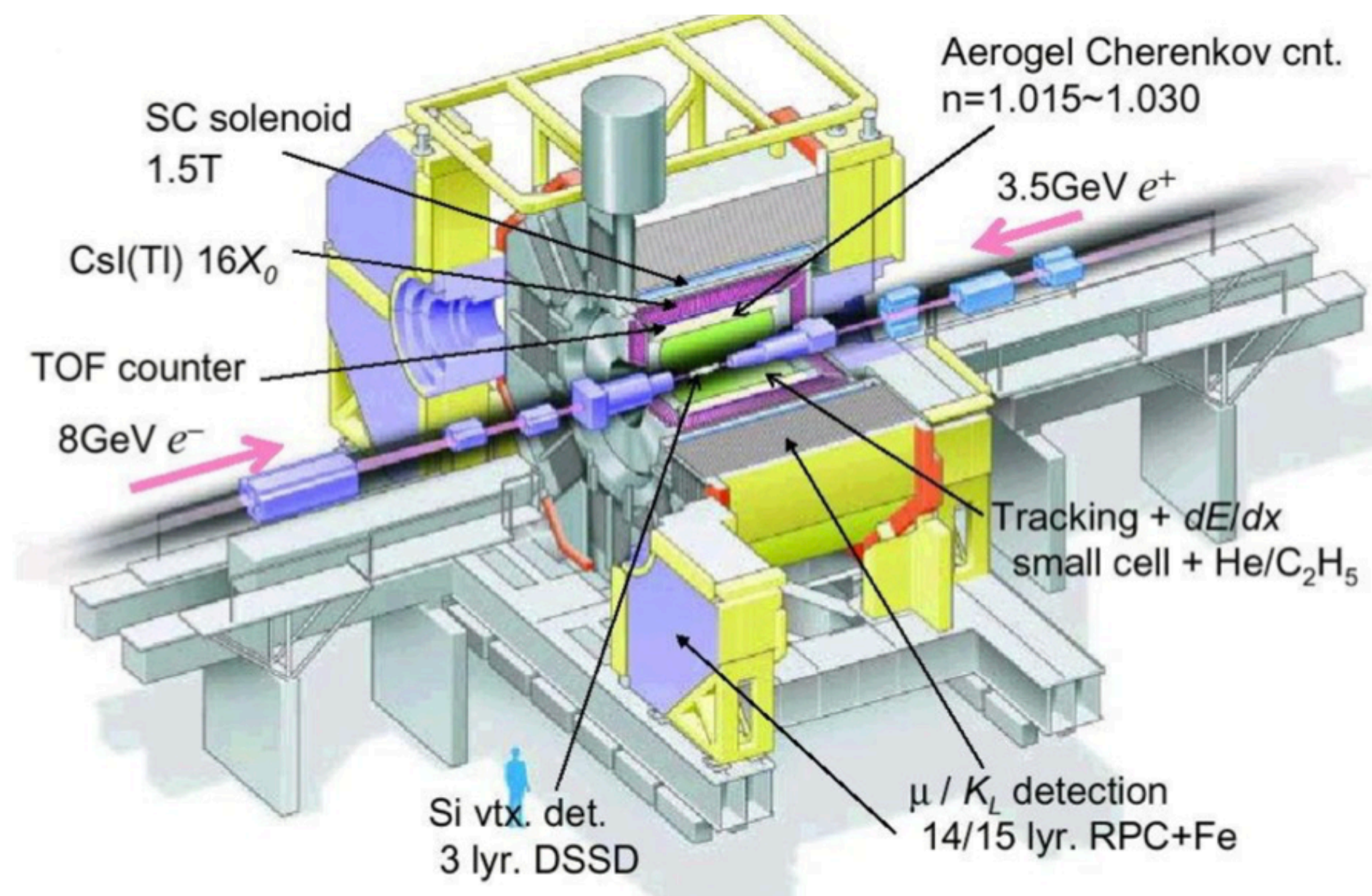
- Invisible  $Z'$  (update) (Belle II)
- Search for ALPs in  $e^+e^- \rightarrow \gamma a$ ,  $a \rightarrow \gamma\gamma$  (Belle II)
- Search for ALPs in  $B \rightarrow Ka(\rightarrow \gamma\gamma)$  (Belle)
- Dark photon.
- Inelastic Dark Matter.
- ... many more!



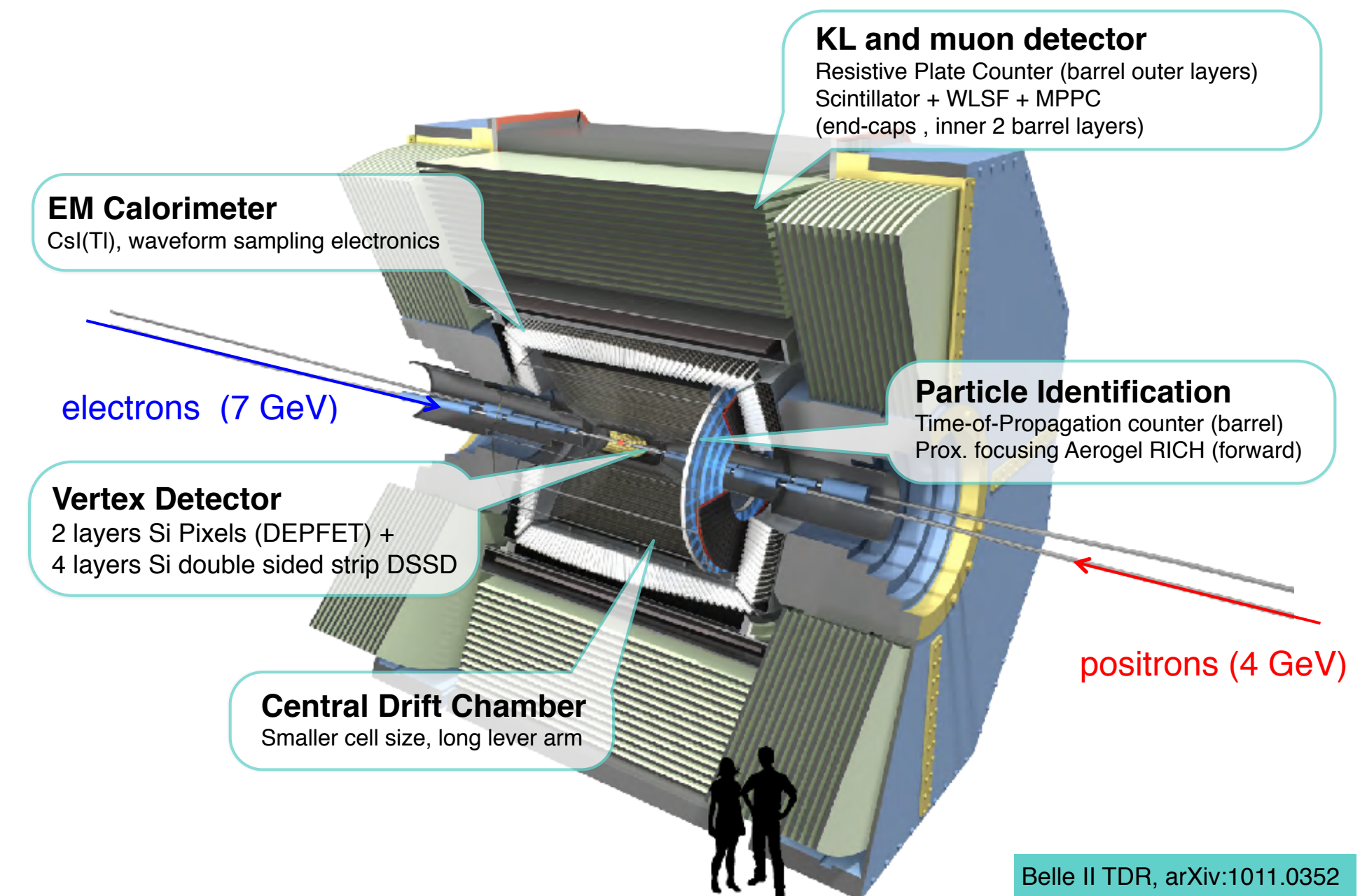
# Belle and Belle II experiments

- **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  $427 \text{ fb}^{-1}$  in Run1 (2018 - 2022) and  $103 \text{ fb}^{-1}$  in Run2 (2024 - )*



Belle II TDR, arXiv:1011.0352

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

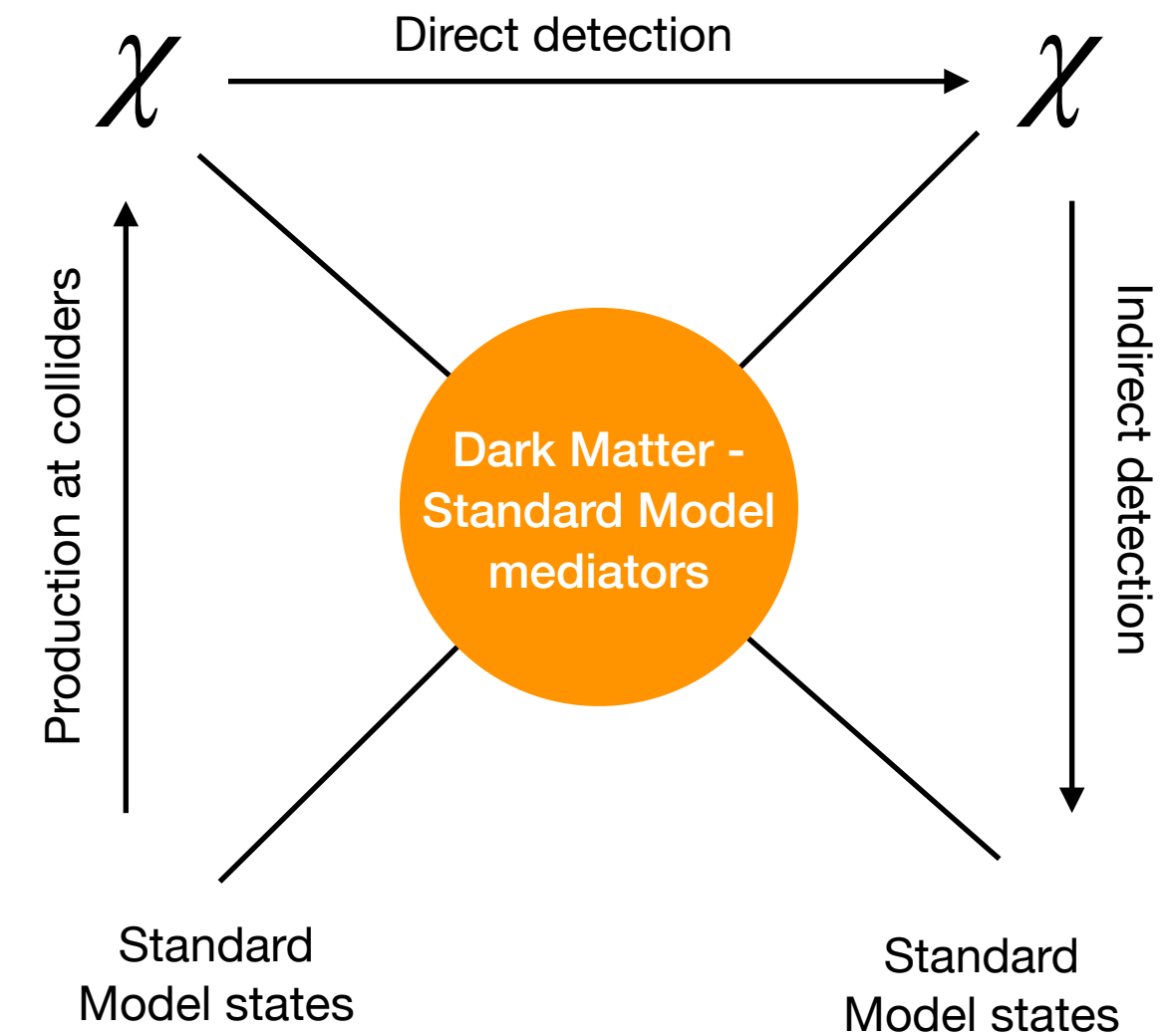
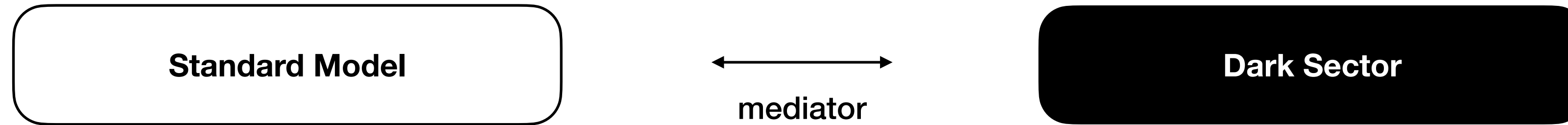
- Single photon trigger
- Single track trigger using neural networks
- Single muon trigger.



# Dark Sector Searches

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

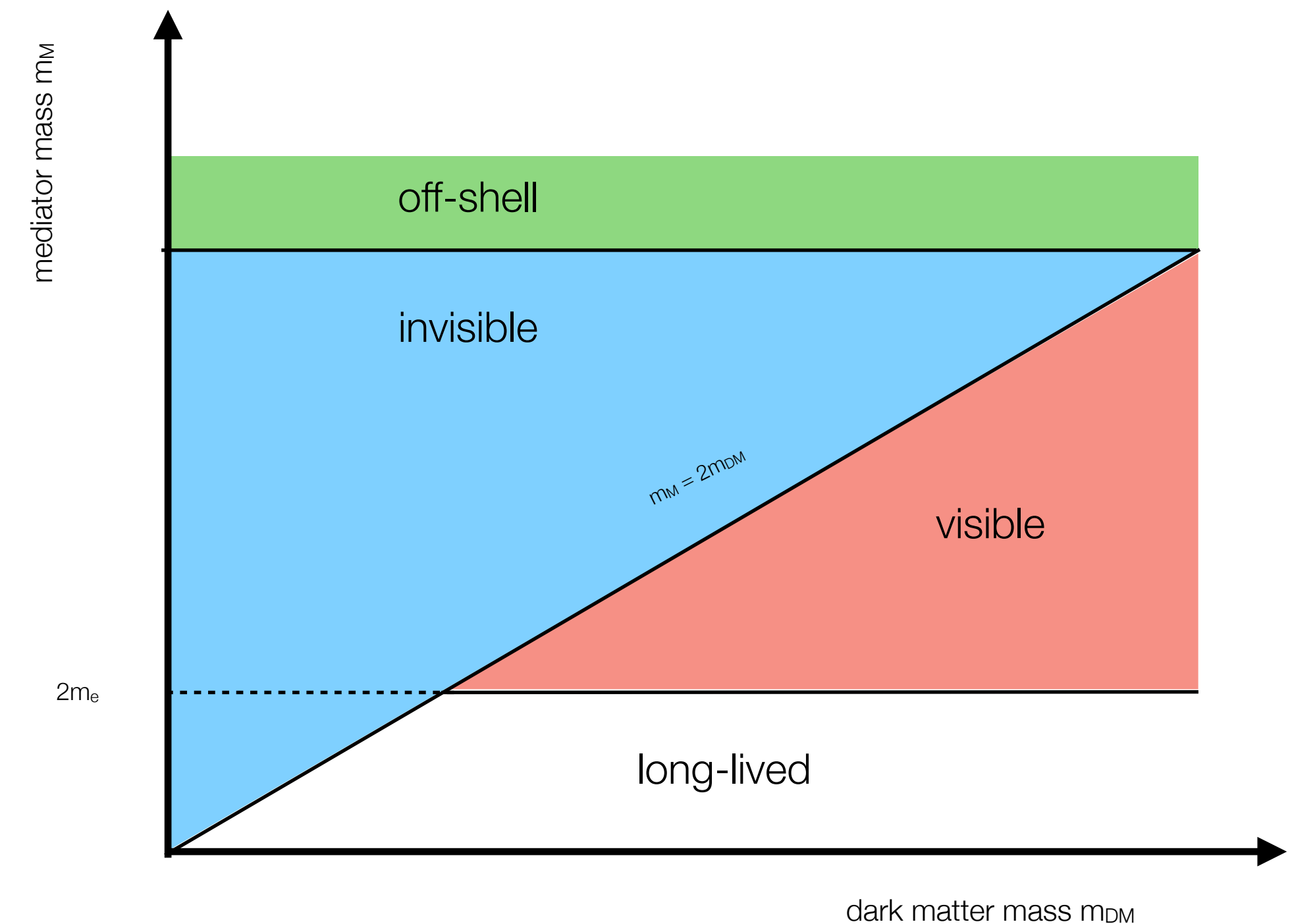
*Belle and Belle II have excellent sensitivity for dark sector searches in the MeV – GeV range.*



- 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

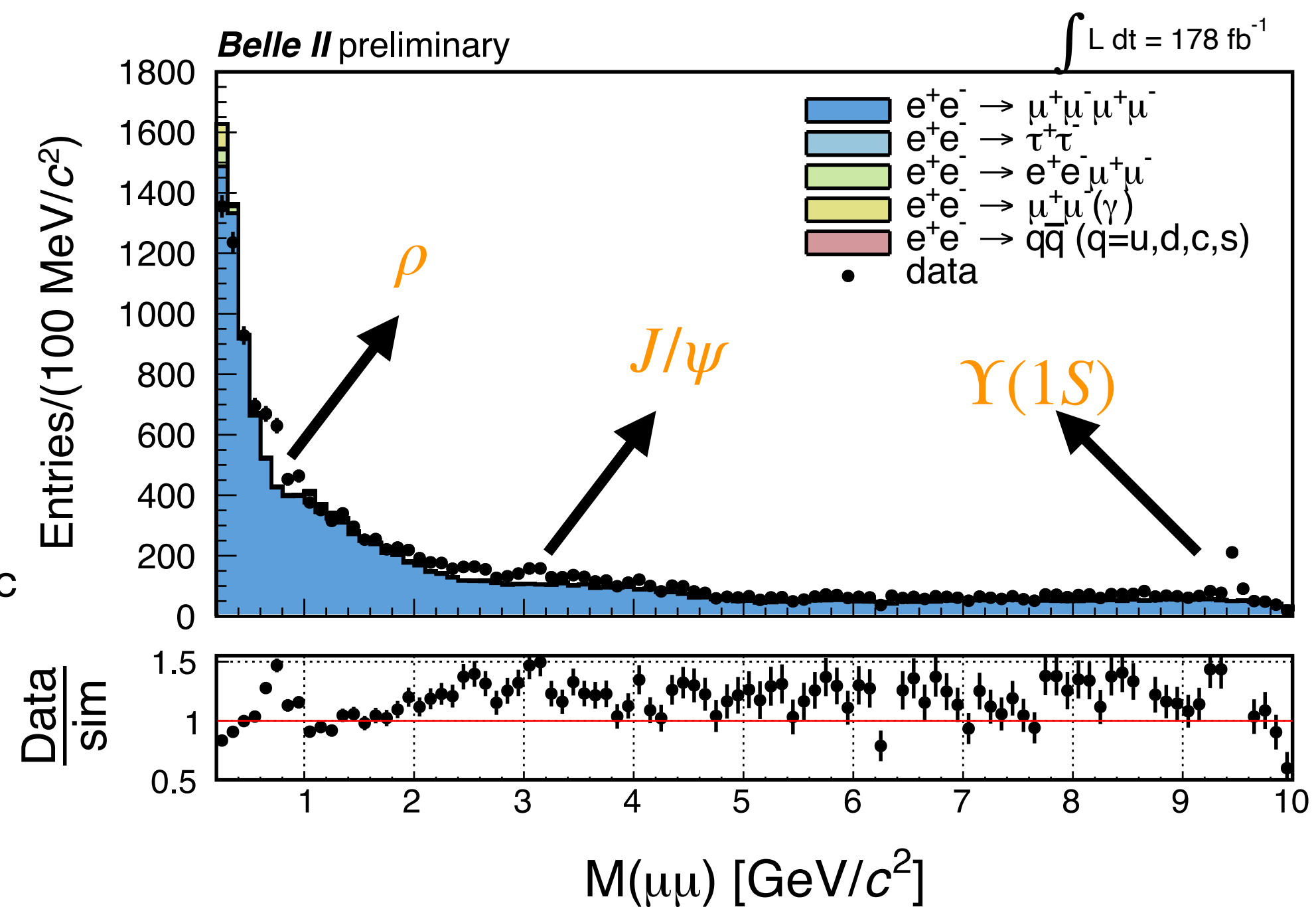
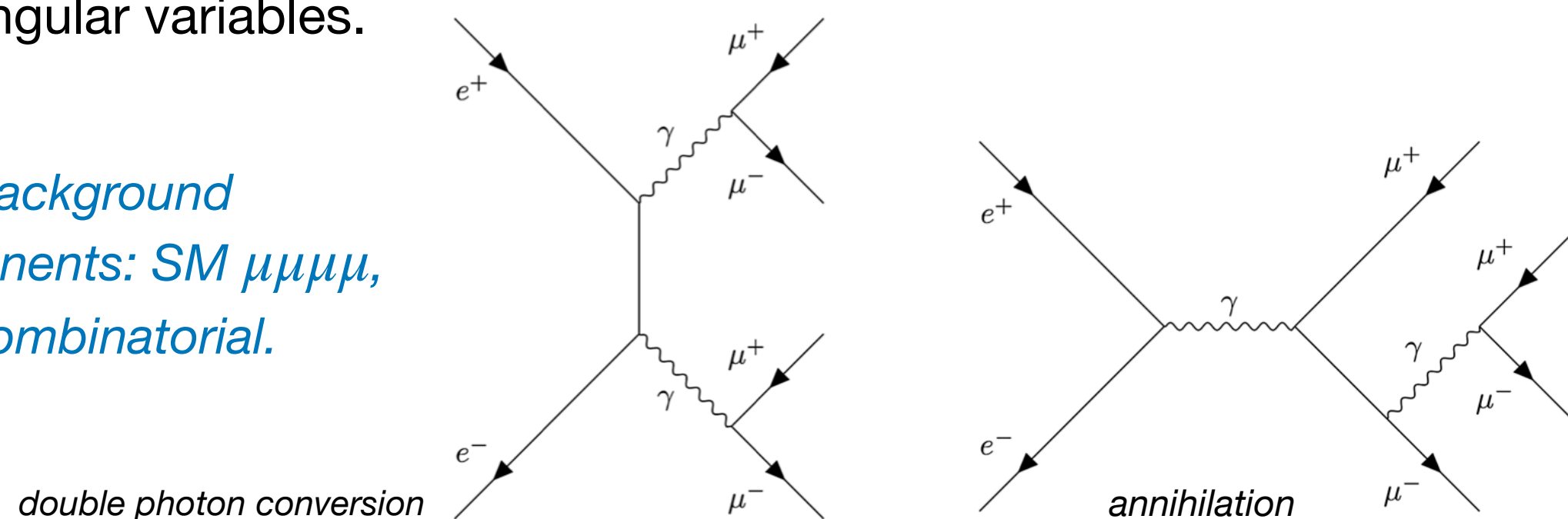
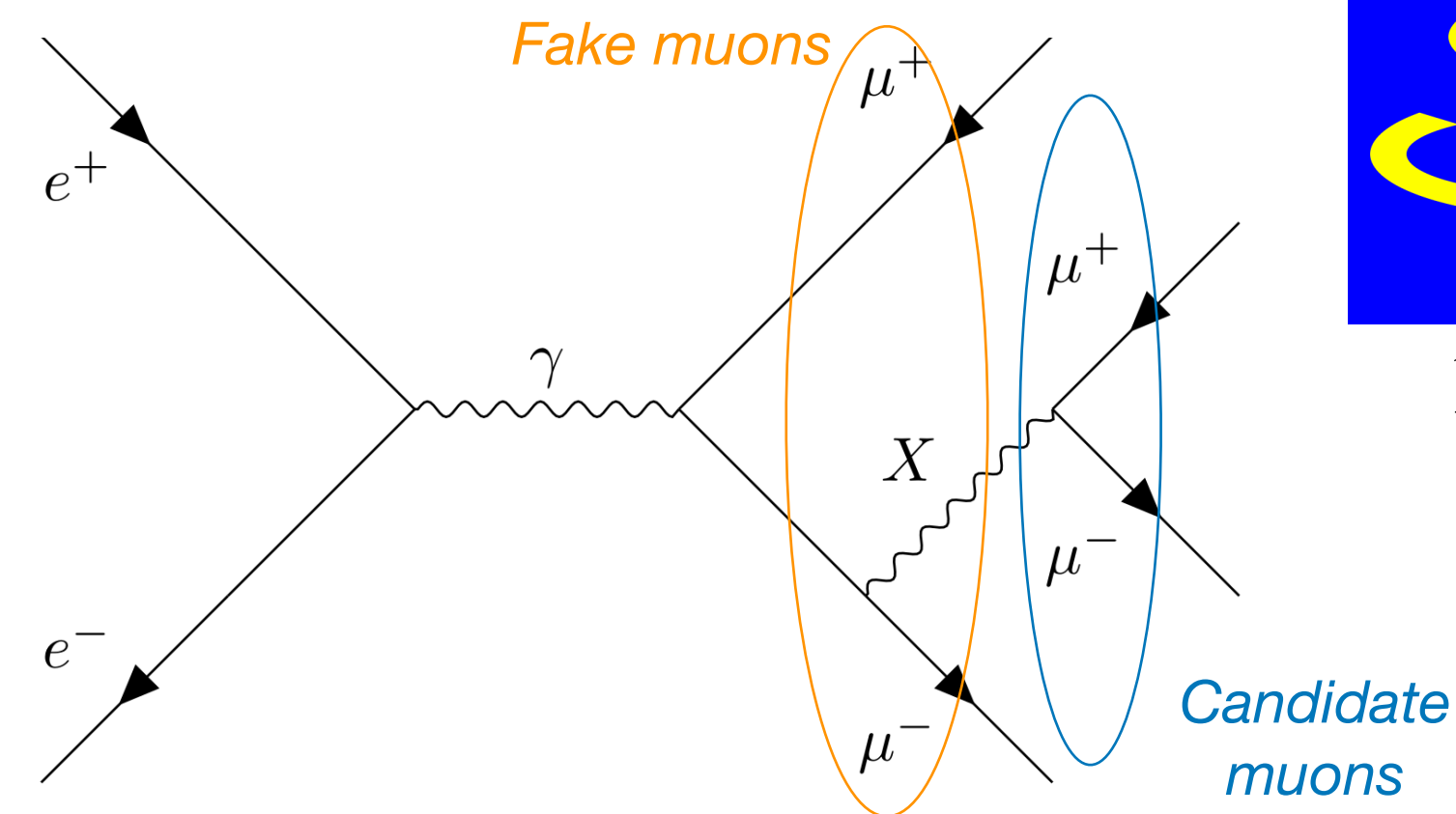


- Search for the process  $e^+e^- \rightarrow \mu^+\mu^-X, X \rightarrow \mu^+\mu^-$ .
- Probing two different models:  $L_\mu - L_\tau$  vector mediator ( $Z'$ ) (couples only to  $\mu, \tau$ ) [1]  
 Muonphillic Scalar ( $S$ ) (couple only to  $\mu$ ) (first time search) [2]
- Targeted luminosity is  $178 \text{ fb}^{-1}$ , which is  $\sim 2$ - $3$  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).
- $M(4\text{-tracks})$  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.

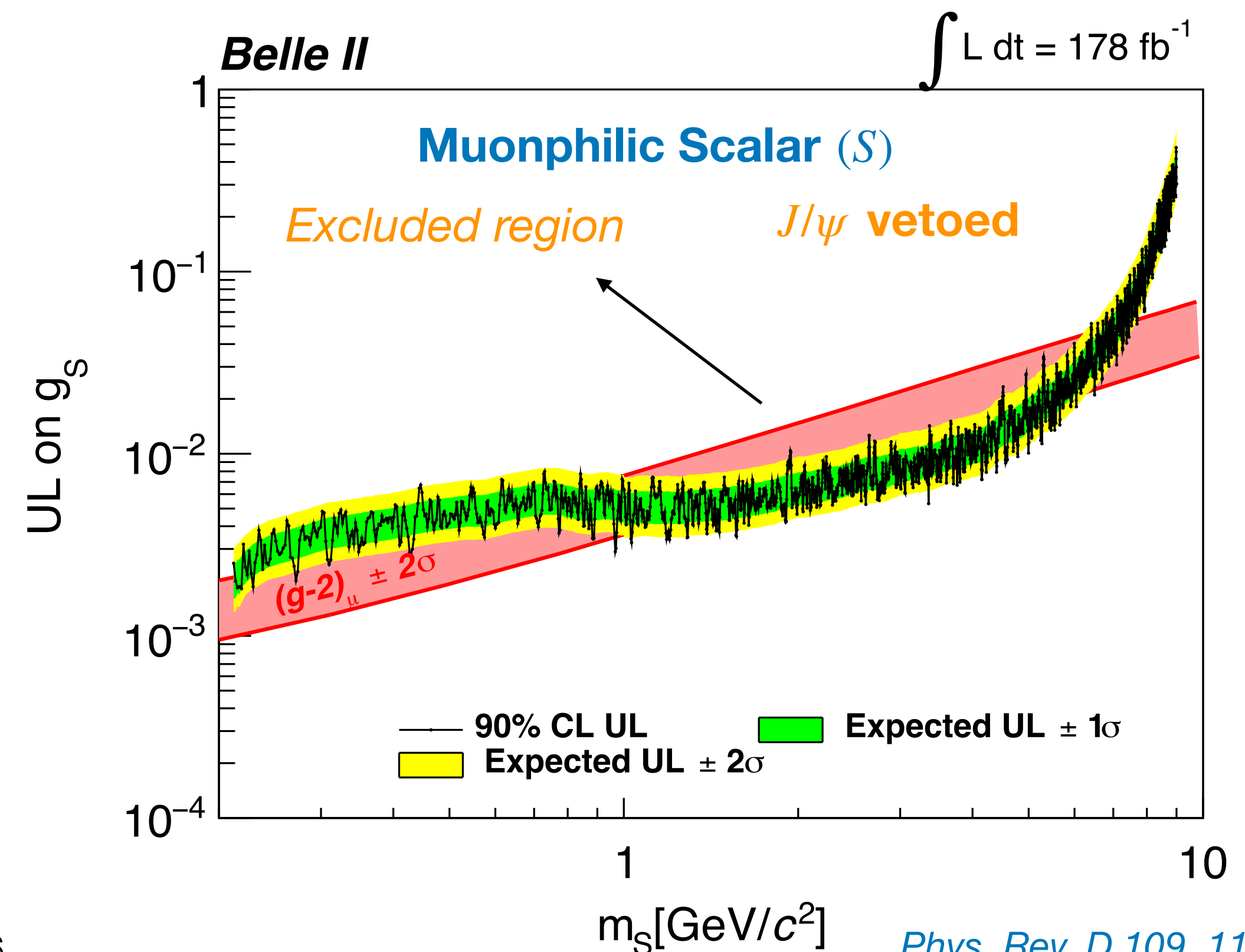
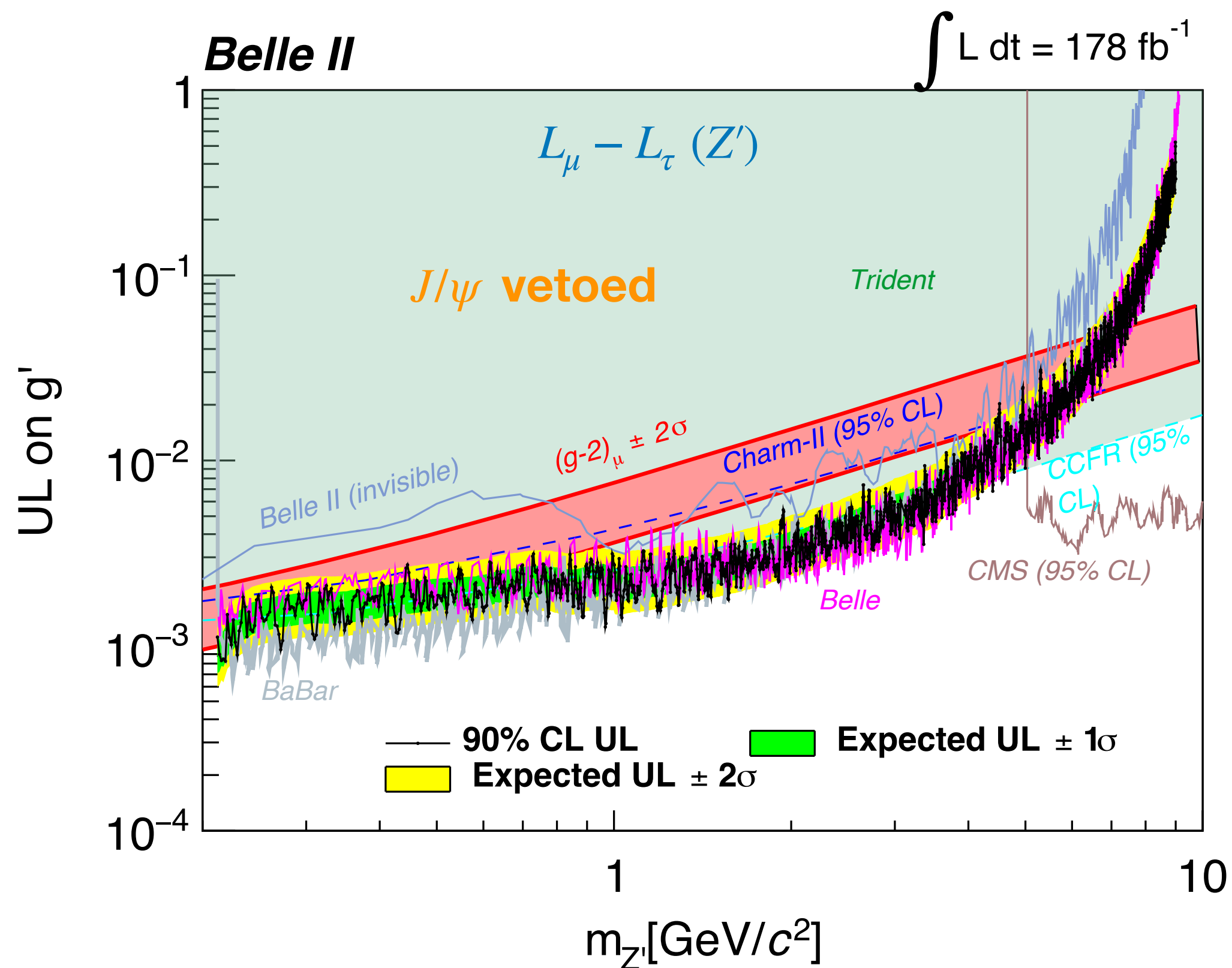


Data MC disagreement mainly due to missing ISR of the used generator

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

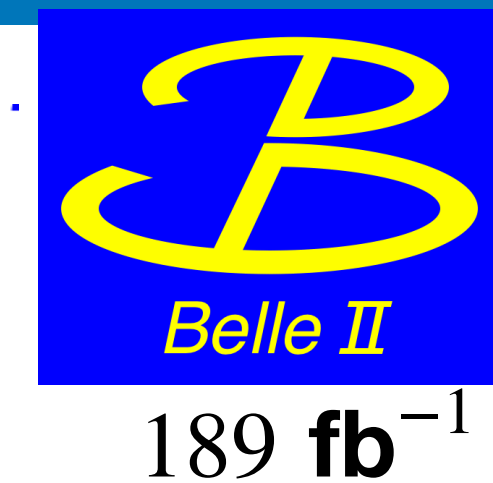


- Searched mass region: 0.212 - 9 GeV/c<sup>2</sup>.
- No significant excess found.
- Competitive 90% CL upper limits for  $g'$  coupling of the  $L_\mu - L_\tau$  model ( $Z'$ ); almost similar result of BaBar (~500 fb<sup>-1</sup>) and Belle (~600fb<sup>-1</sup>) with 178fb<sup>-1</sup> due to aggressive background suppression.
- First 90% CL upper limits for the muonphilic dark scalar ( $S$ ) model.

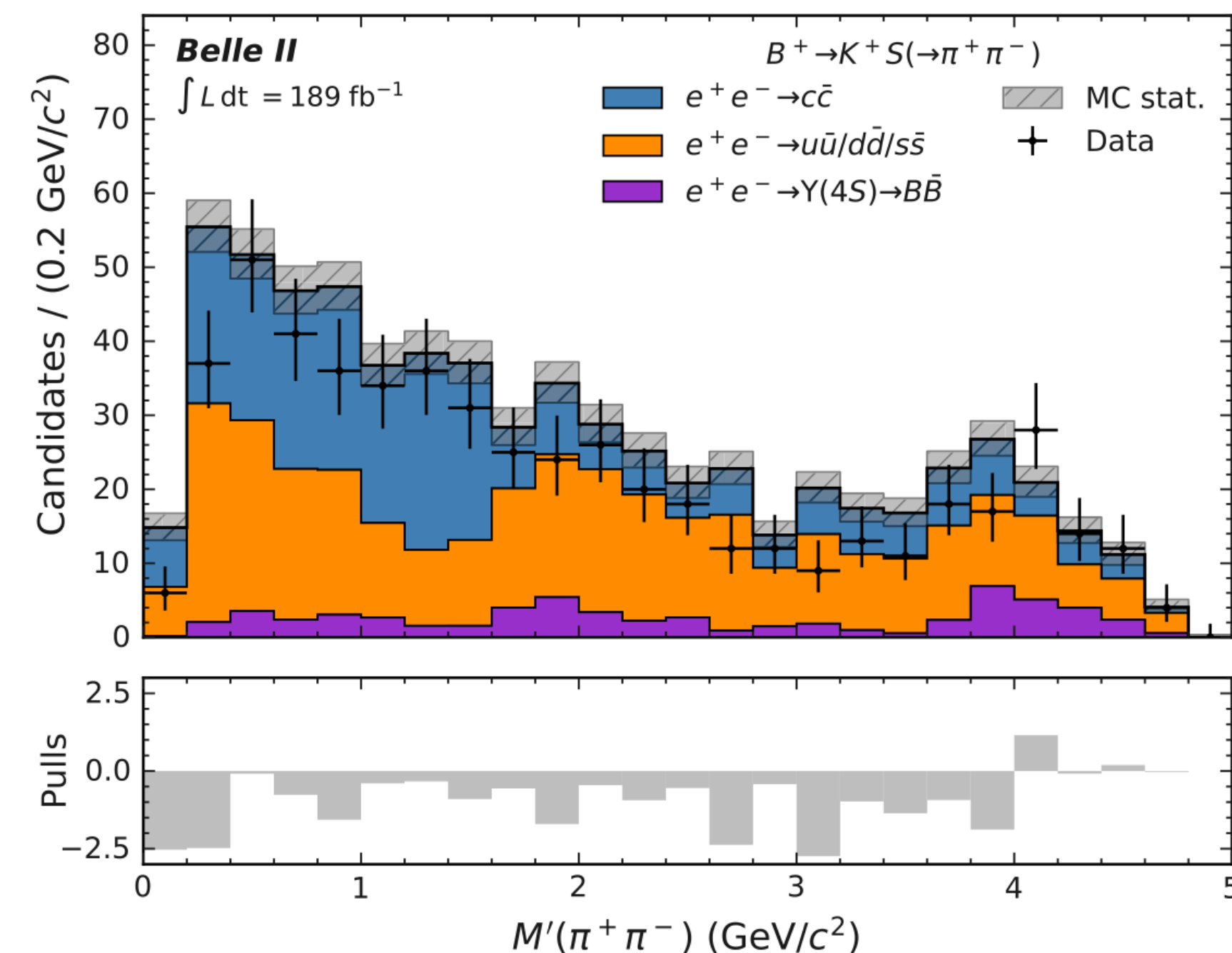
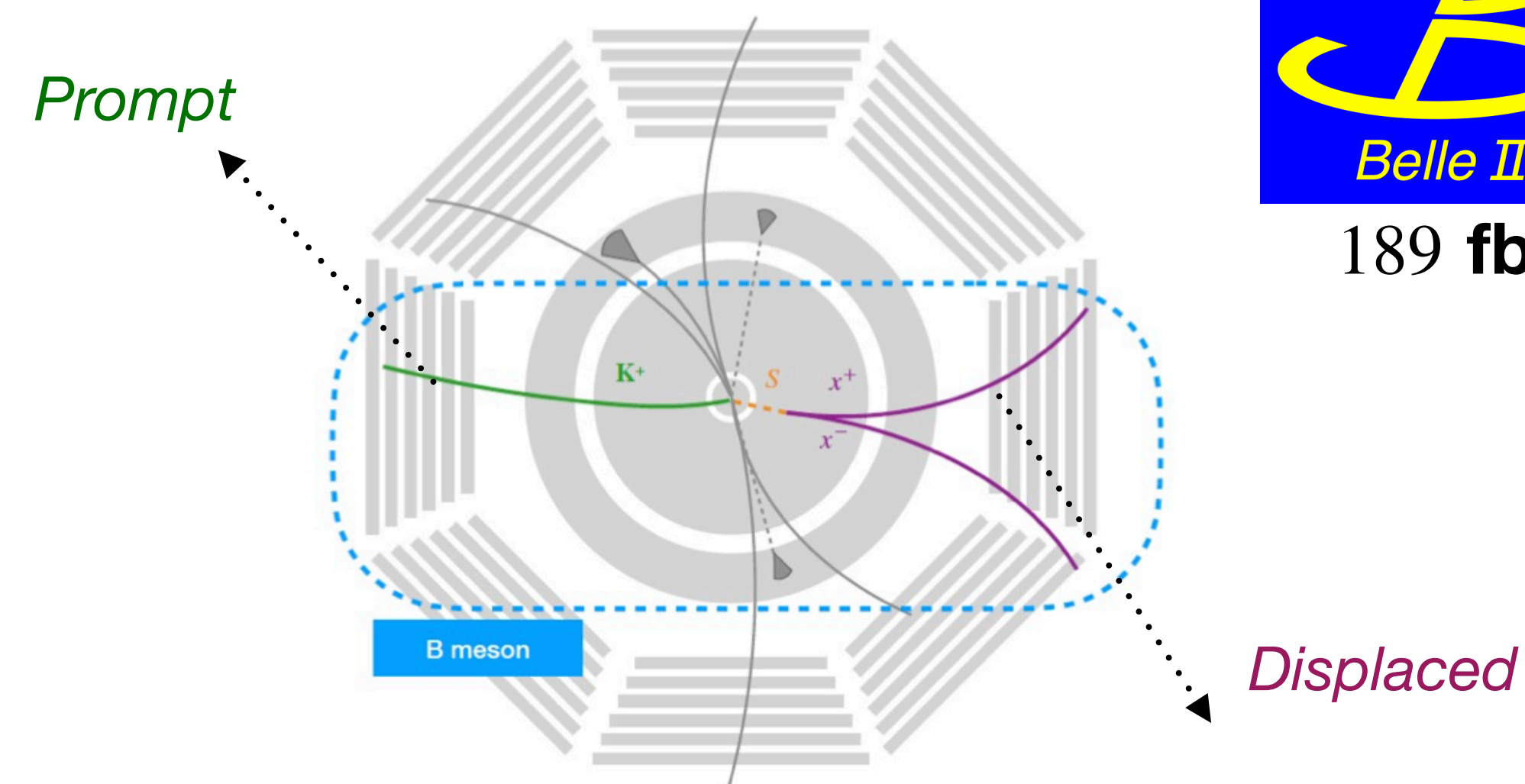




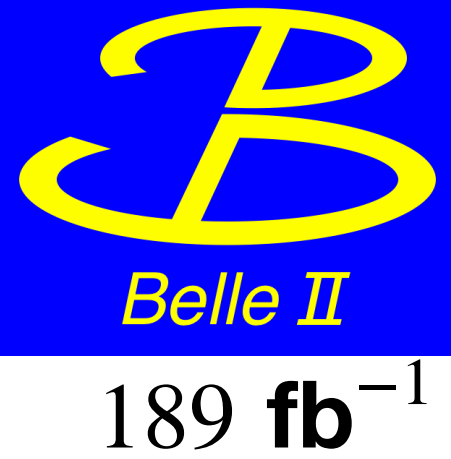
# Long-lived scalar ( $S$ ) in B decays at Belle II



- 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  $\theta$  [1-2].
- Model independent search. Dataset used  $189 \text{ fb}^{-1}$ .
- 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



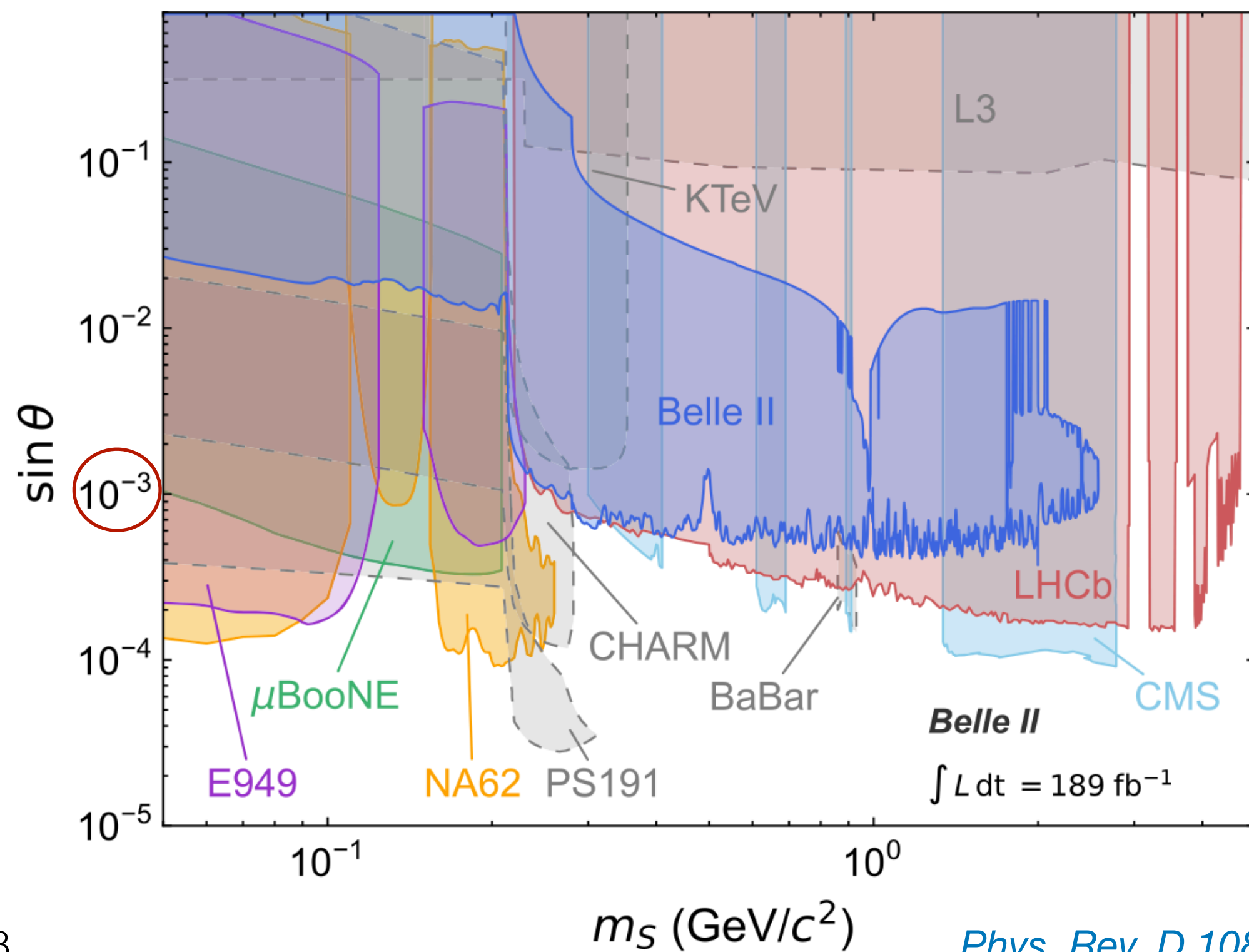
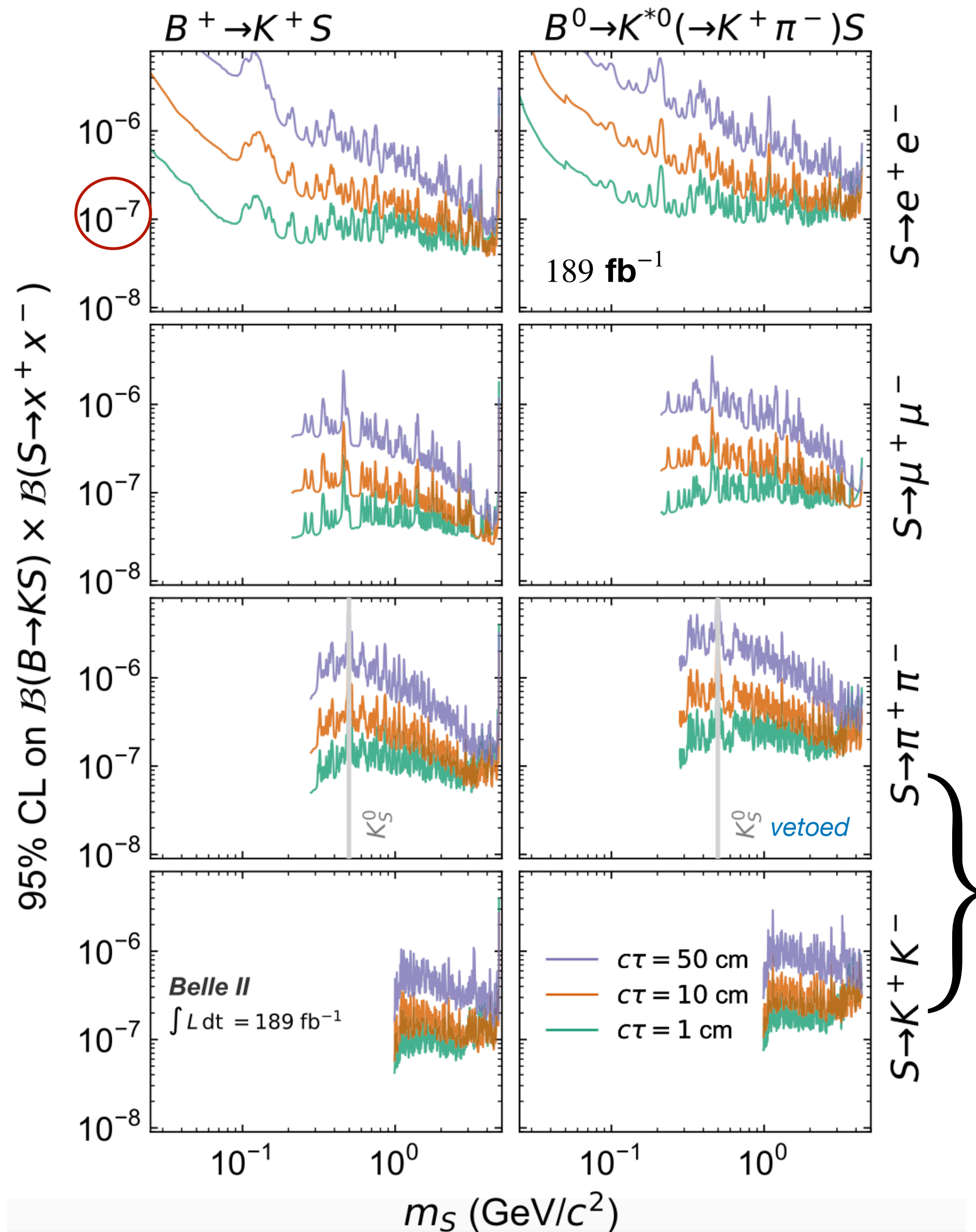
Model-independent upper limits on the product of branching fractions as functions of  $S$  mass and lifetime at the level of  $10^{-7}$ .

- 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  $\theta$  with SM Higgs



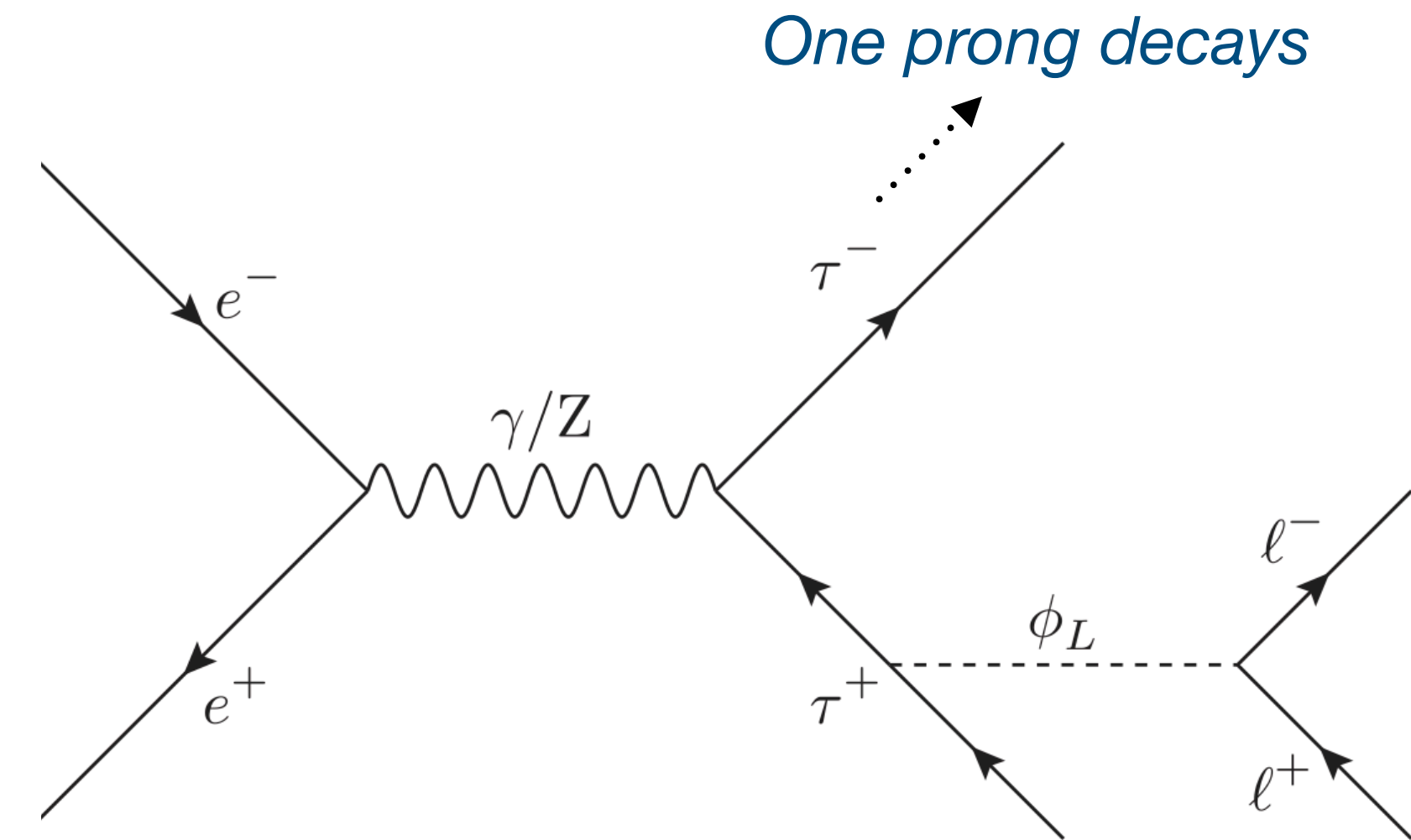


# Leptophilic scalar ( $\phi_L$ ) in $e^+e^- \rightarrow \tau^+\tau^-l^+l^-$ at Belle



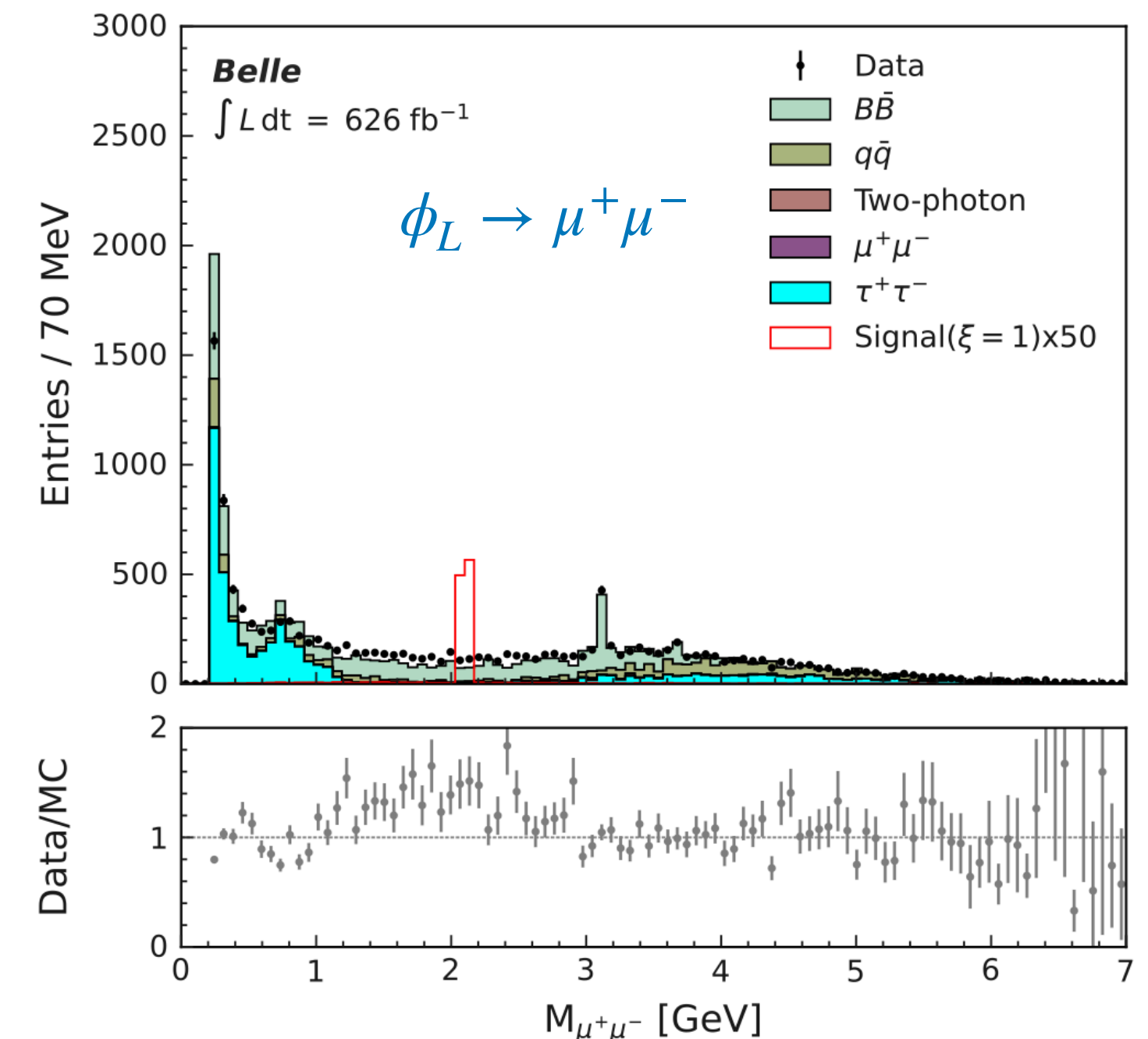
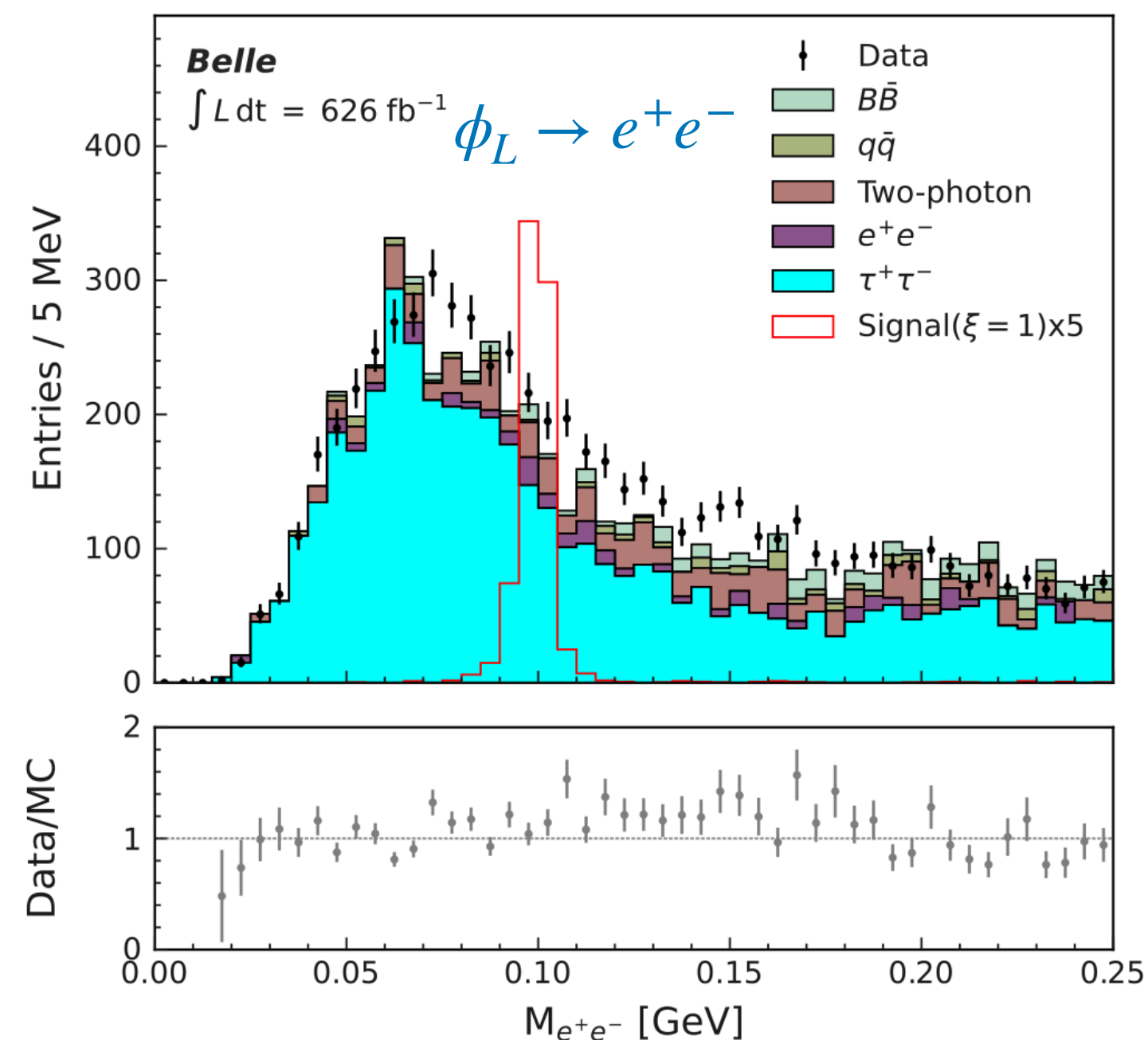
626 fb<sup>-1</sup>

- Search for the process:  $e^+e^- \rightarrow \tau^+\tau^-\phi_L(\rightarrow l^+l^-), l = e, \mu$ .
- $\phi_L$  is a dark leptophilic scalar that couples only to leptons [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/c<sup>2</sup>
  - $\phi_L \rightarrow \mu^+\mu^-$  for  $m_\phi > 2m_\mu$

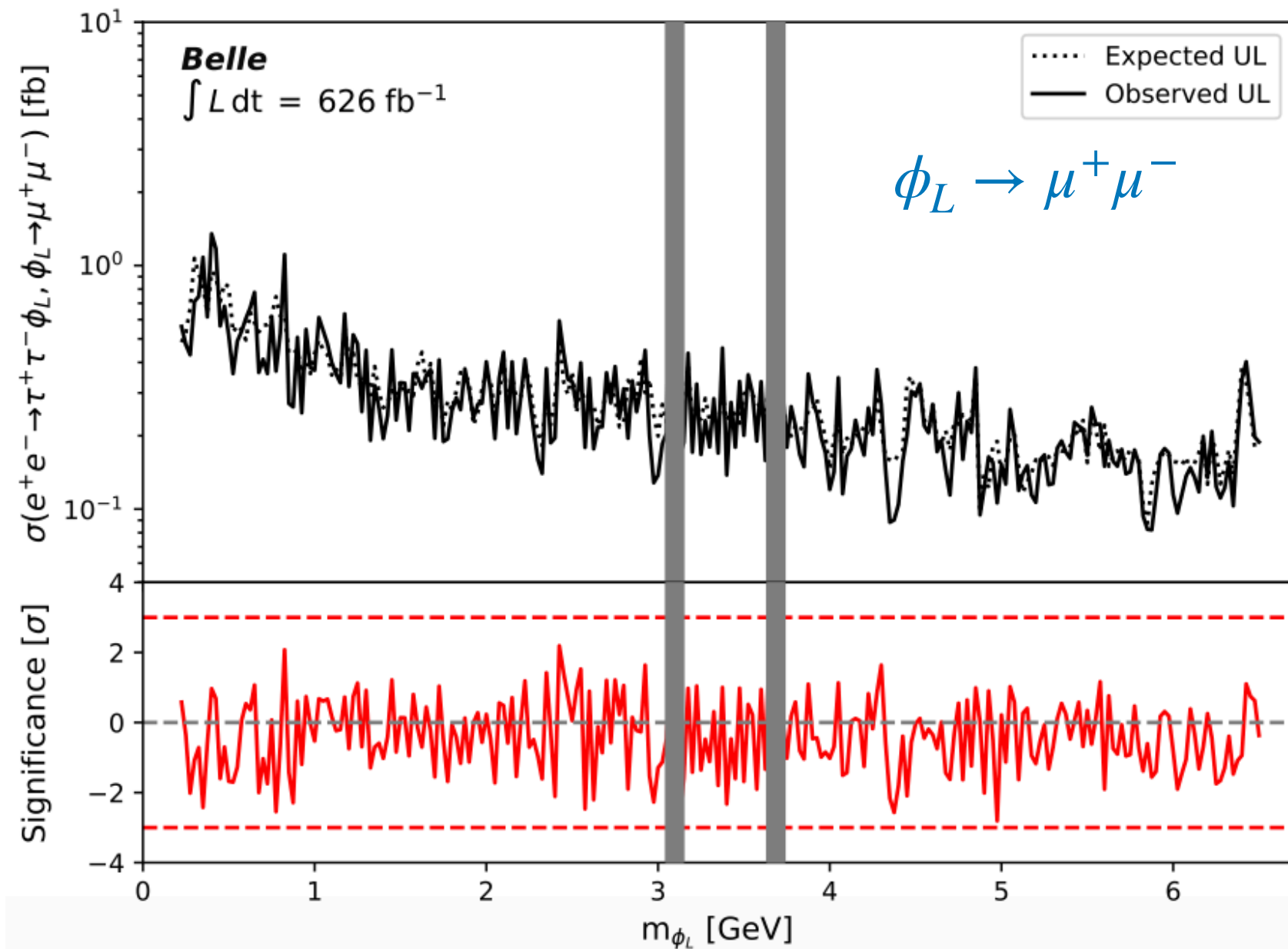
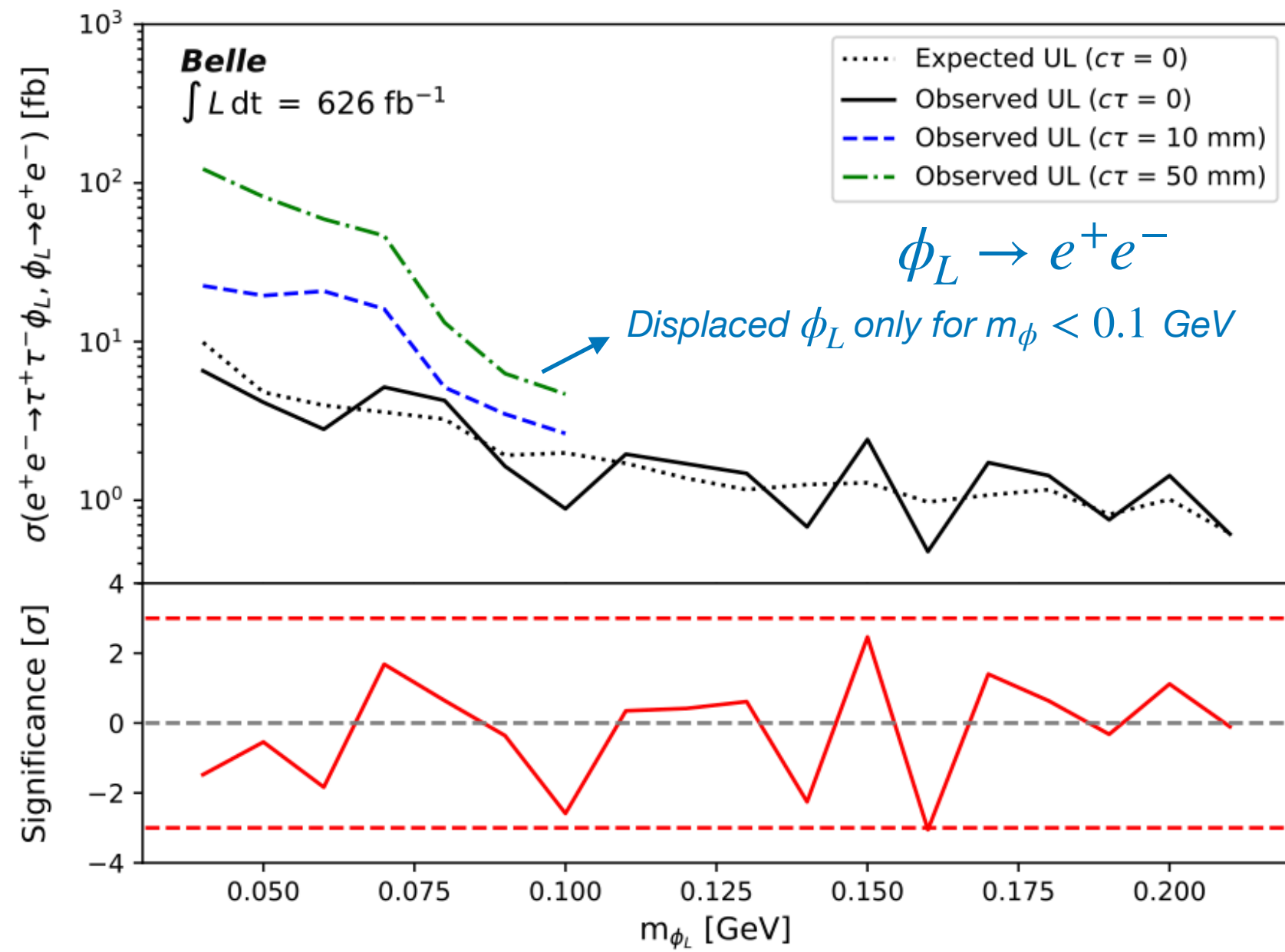
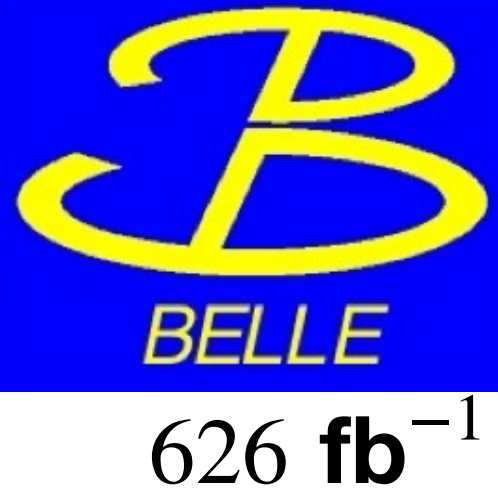


BDT score > 0.95 (signal region)

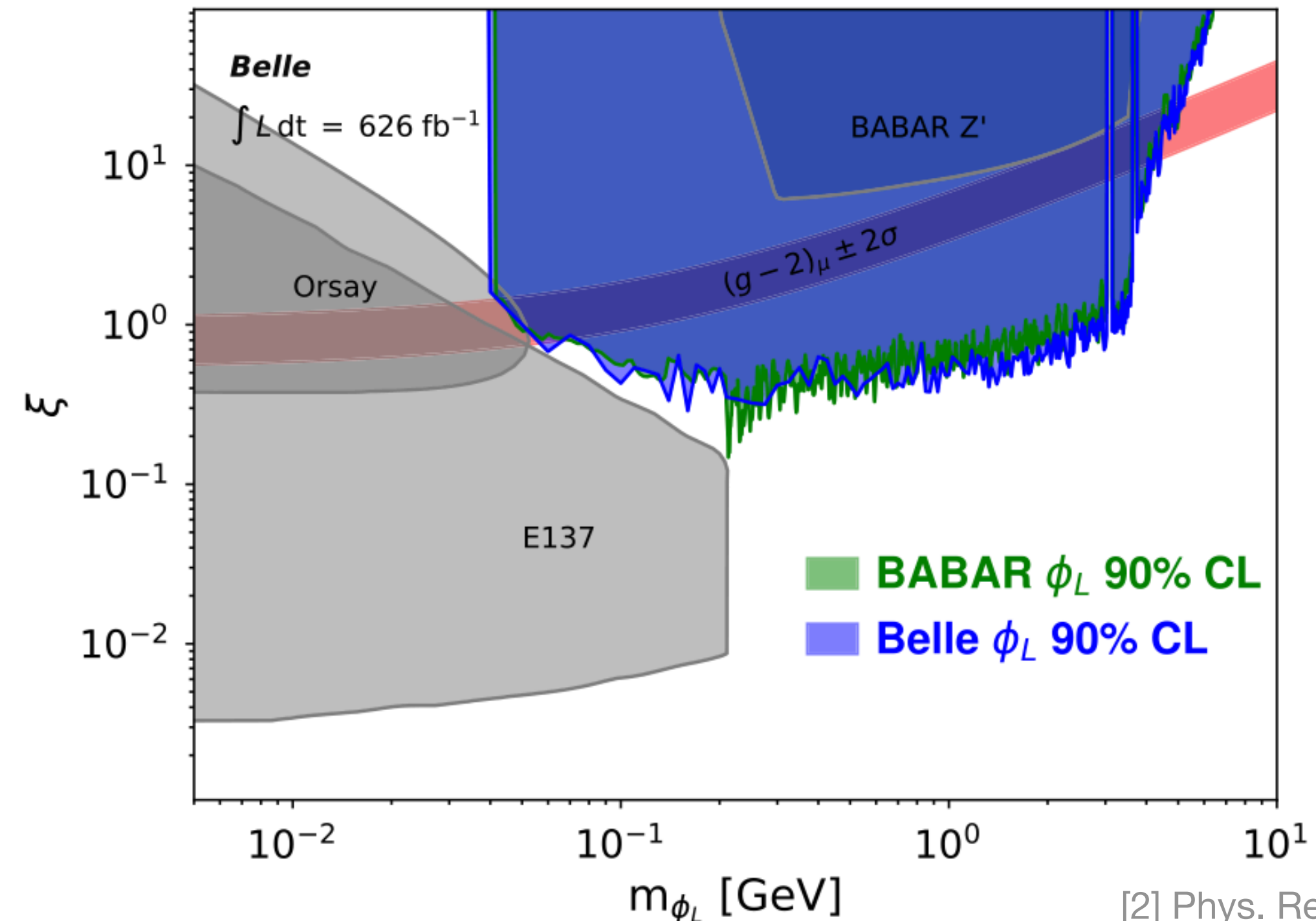
- Explored mass region upto 6.5 GeV/c<sup>2</sup>
- Event selection: 4 charge tracks, large missing energy.
- Main source of background is  $\tau^+\tau^-$ .
- BDT is used to suppress the backgrounds and the classifier response is used to define different control regions.



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



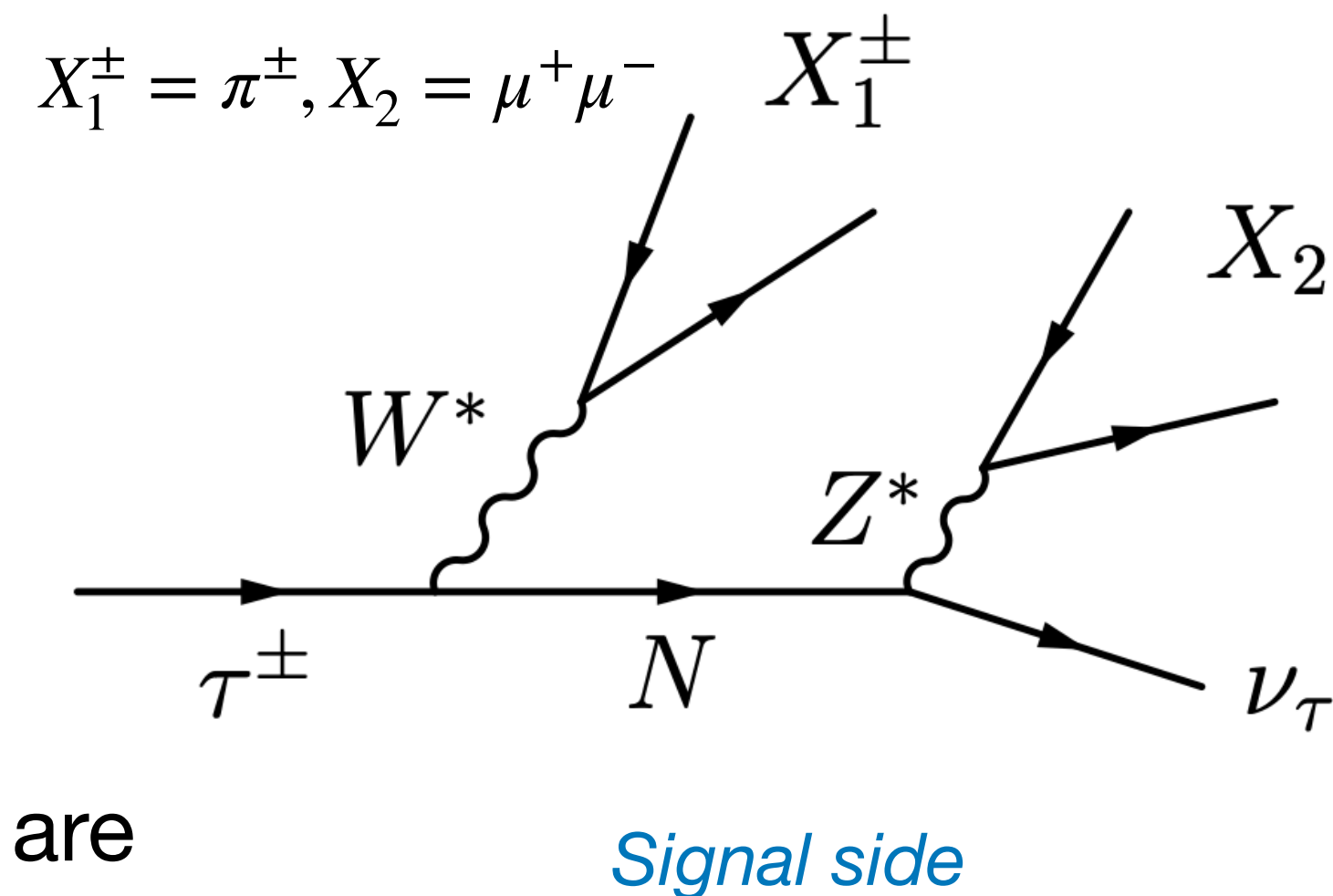
- No significant excess found in  $626 \text{ fb}^{-1}$ .
- 90% CL upper limits on  $\sigma(e^+e^- \rightarrow \tau^+\tau^-\phi_L(\rightarrow l^+l^-))$  and coupling constant  $\xi$ .
- Limits are on average 19% more constraining w.r.t BaBar [2].
- Ruled out the leptophilic scalar with mass less than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



[2] Phys. Rev. Lett. **125**, 181801  
 Phys. Rev. D **109**, 032002 (2024)



# Heavy Neutral Leptons (HNL) in $\tau$ 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 leptons are considered negligible [2].

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

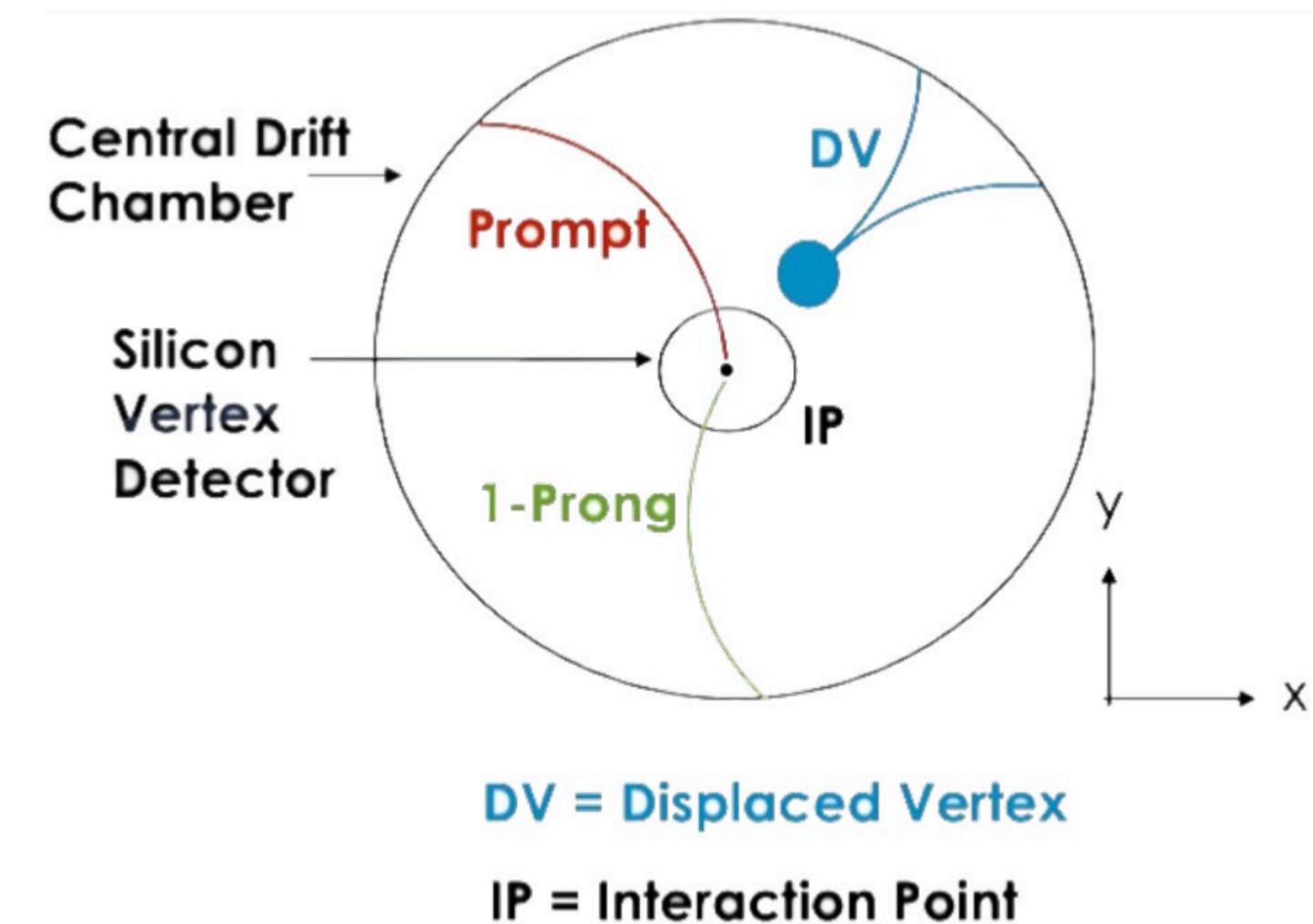
**signal side:**  $\tau^- \rightarrow \pi^- N; N \rightarrow \mu^+ \mu^- \nu_\tau$ , where  $N$  forms displaced vertex (DV);  
tag side: 1-prong decays.

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

- Signal region divided in:

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

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

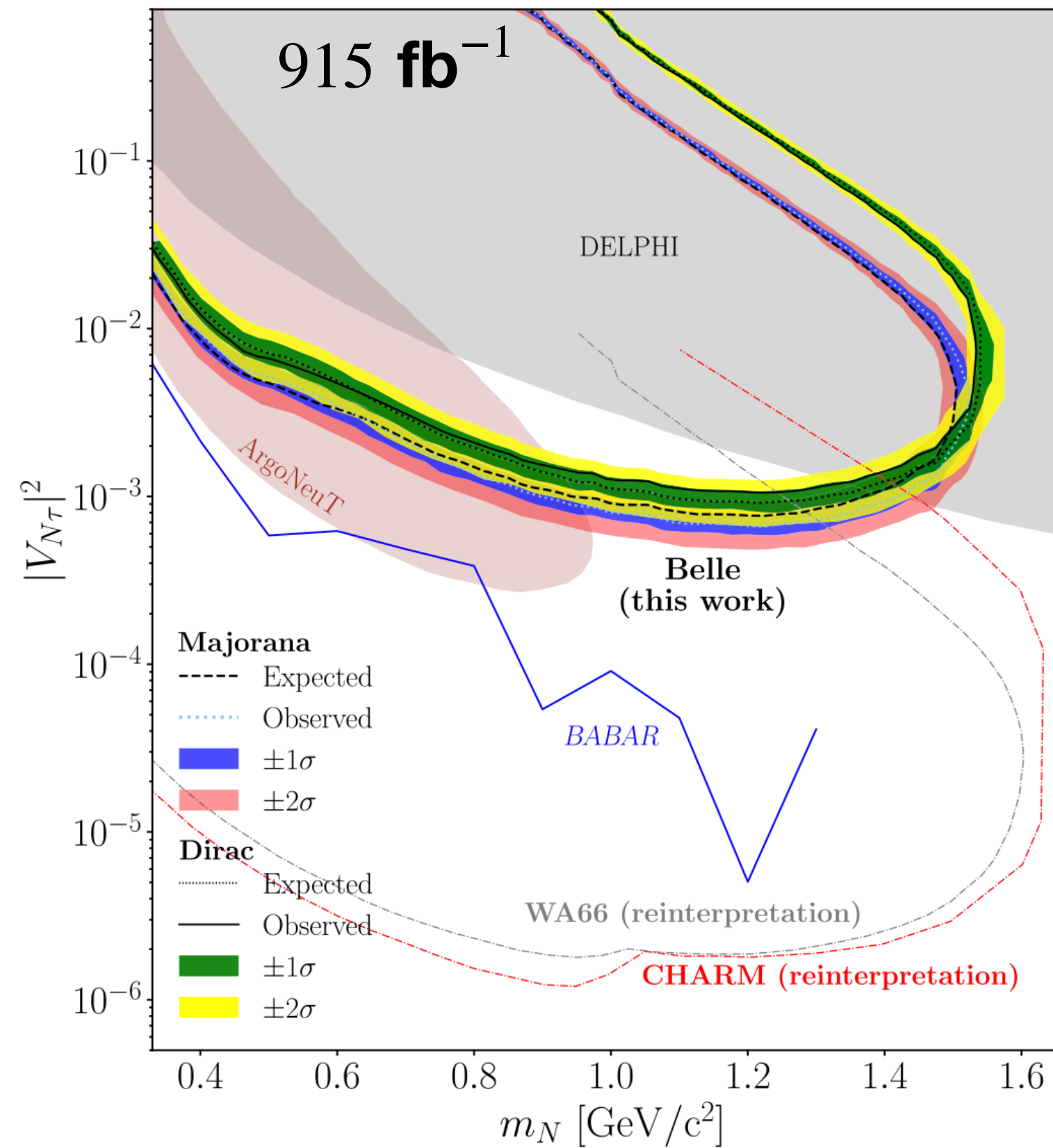
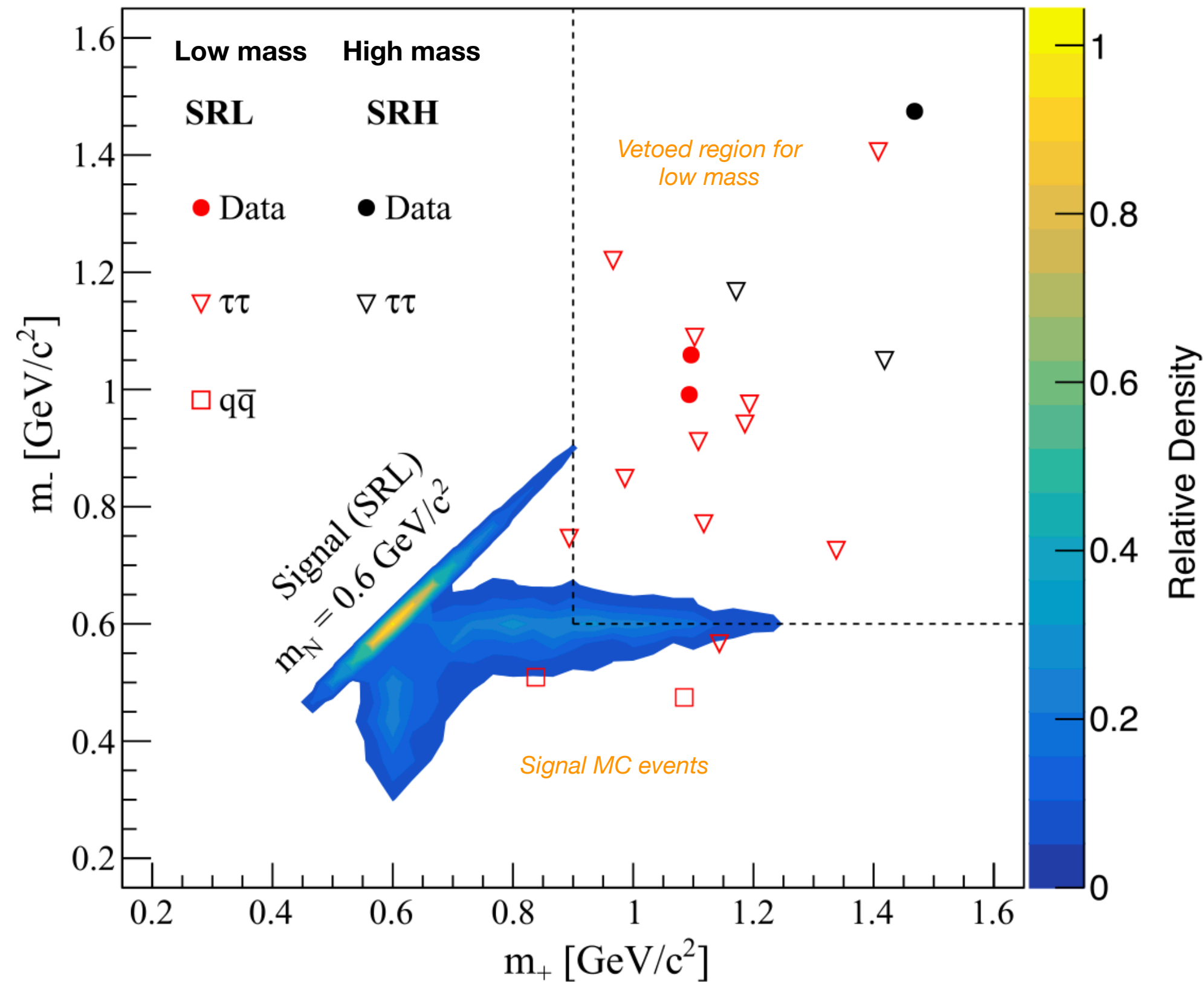


# Heavy Neutral Leptons (HNL) in $\tau$ decays at Belle



915 fb<sup>-1</sup>

- 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].
- Low mass and high mass regions have only 0 and 1 events respectively.
- Since no significant excess is observed for 915 fb<sup>-1</sup> (4S + 5S combined), 95% CL upper limits on  $|V_{N\tau}|^2$  for masses in the range  $300 < m_N < 1600$  MeV/c<sup>2</sup>.



- First Displaced vertex search for Belle.

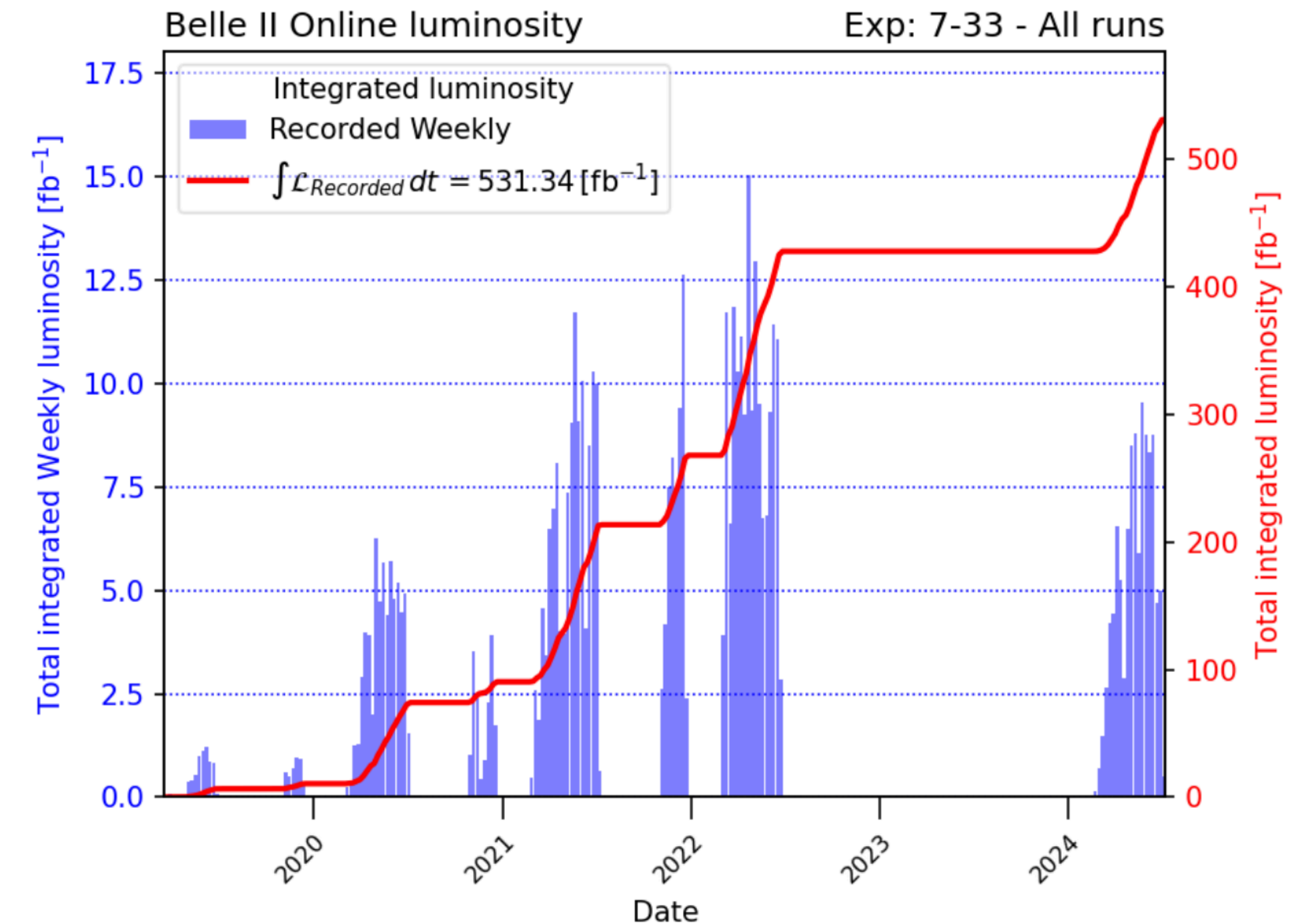
[3] Phys. Rev. D 101, 093003 (2020)

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 ( $\phi_L$ ) : limits are on average 19% more constraining than previous searches.
  - Heavy Neutral Leptons (HNL) : put most stringent limits in  $|V_{N\tau}|^2$  for 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!*