Searches for LLP at Belle and Belle II

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on behalf of the Belle and Belle II collaborations

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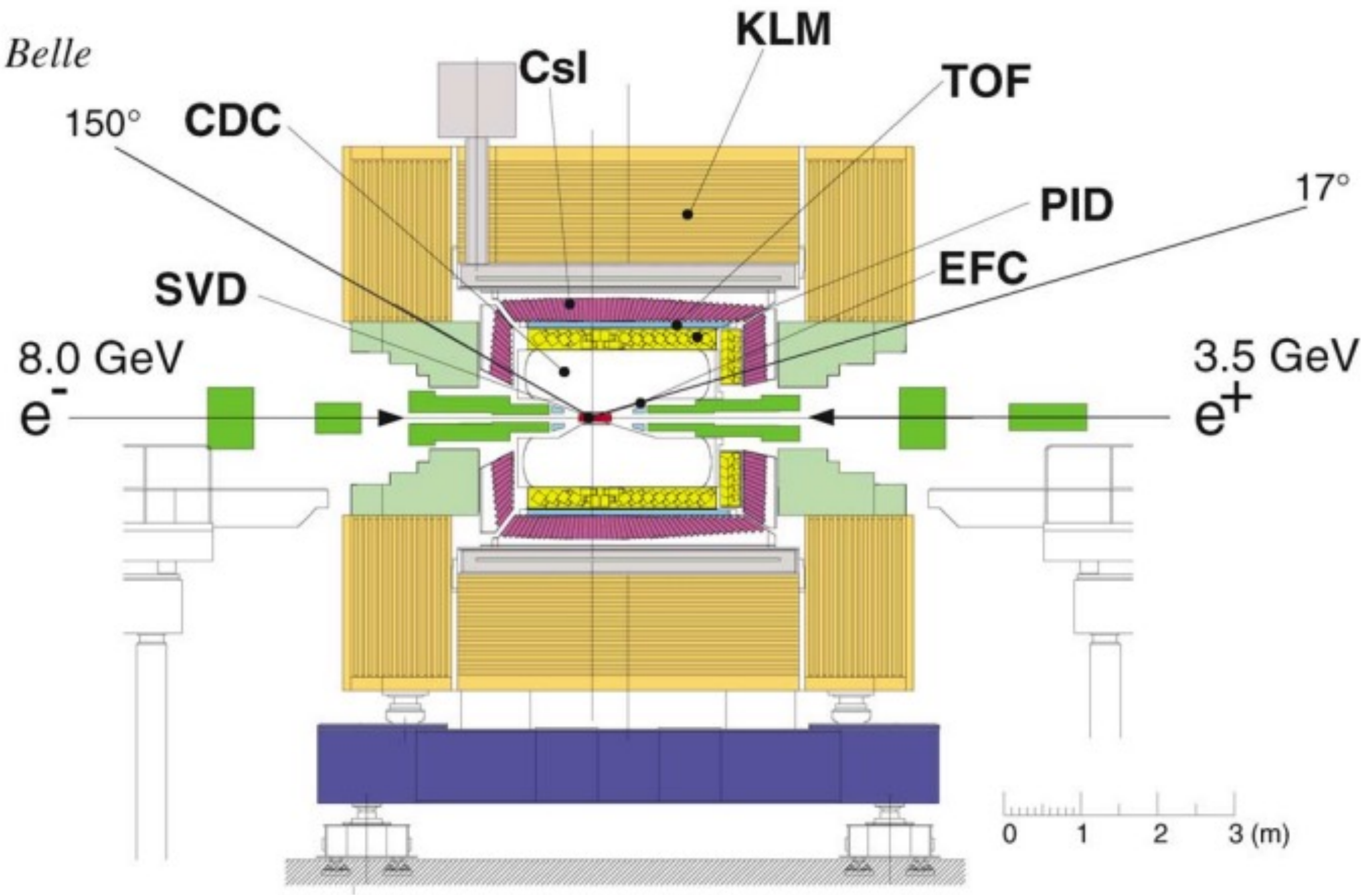
Contents

- Search for a heavy neutral lepton that mixes predominantly with the τ neutrino at Belle (PRD 109, L111102, Arxiv 2402.02580)

- Search for a long-lived spin-0 mediator in $b \to s$ transitions at the Belle II (PRD 108, L111104, Arxiv 2306.02830)

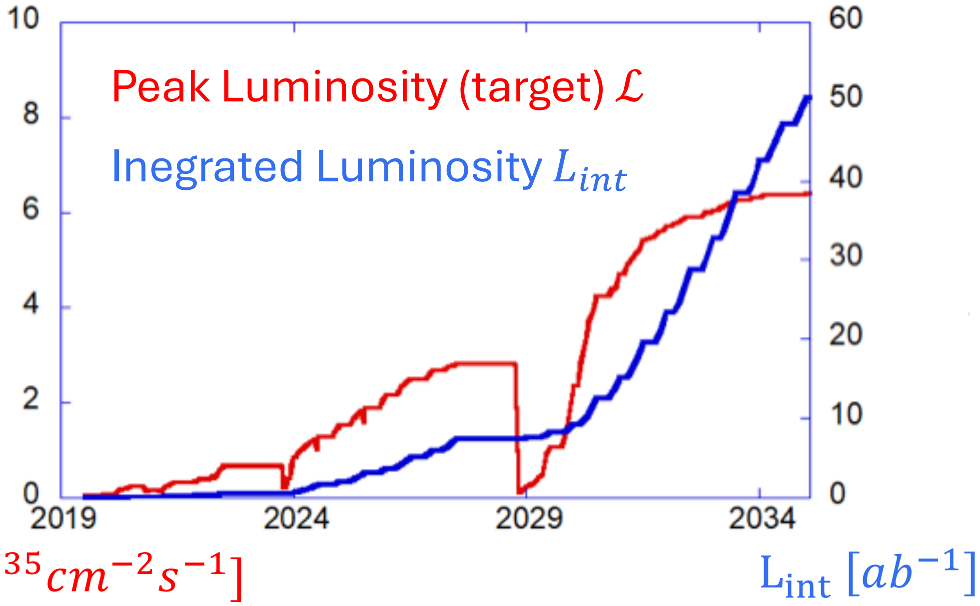
Belle experiment

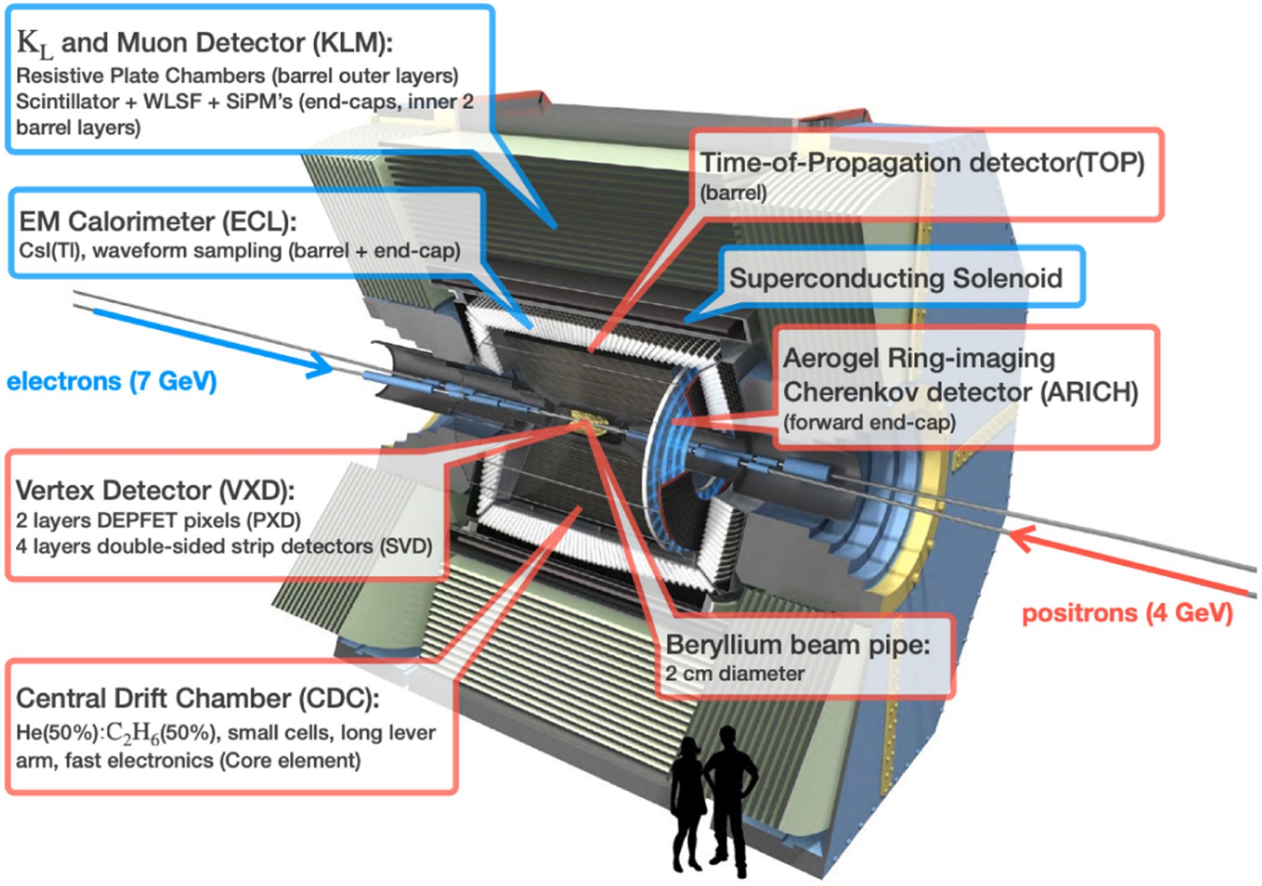
- The detector was located in KEKB e^+e^- accelerator in Tsukuba, Japan (1999-2010); ongoing analysis effort.
- Center of mass energy $\sqrt{s} = 10.58$ GeV
- B-factory:
  - $\sigma(e^+e^- \to b\bar{b}) \cong 1.05\, nb$
- But can be used to other studies:
  - $\sigma(e^+e^- \to \tau^+\tau^-) \cong 0.9\, nb$
  - $\sigma(e^+e^- \to c\bar{c}) \cong 1.3\, nb$
- Collected data of $\sim 1 ab^{-1}$.



Belle II experiment

- An upgrade of Belle.
- Located in SuperKEKB (KEKB upgrade).
- Regular data-taking since April 2019.
- Will collect much more data than Belle:





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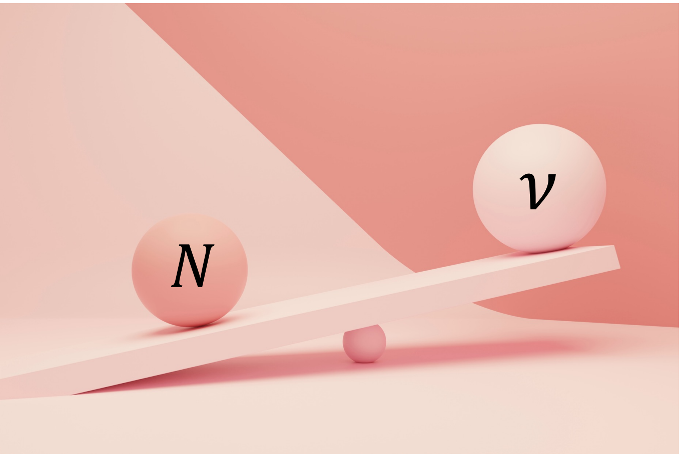
Heavy Neutral Lepton (HNL, N)



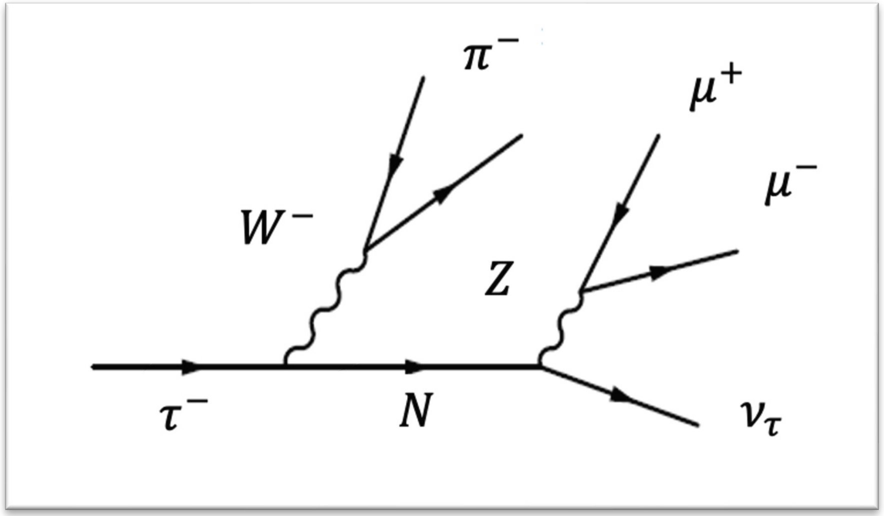
- Neutrino flavour oscillations ⇒ the neutrinos have masses $m_{i=1,2,3}$.
  Phys. Rev. Lett. 81
- m_i is small ⇒ seesaw mechanism with heavy neutral lepton.
- The HNL N mixes with SM neutrino ν_ℓ via $V_{\ell N}$ parameter.
- Searches probe general models, in which $V_{\ell N}$ and m_N are independent.
- A model of 3 generations of HNLs can account for:
  - Baryon asymmetry of the universe (through Leptogenesis)
    Phys.Lett,B 620(2005) 17-26
  - Dark matter (keV scale)
    Phys.Lett,B 631(2005) 151-156

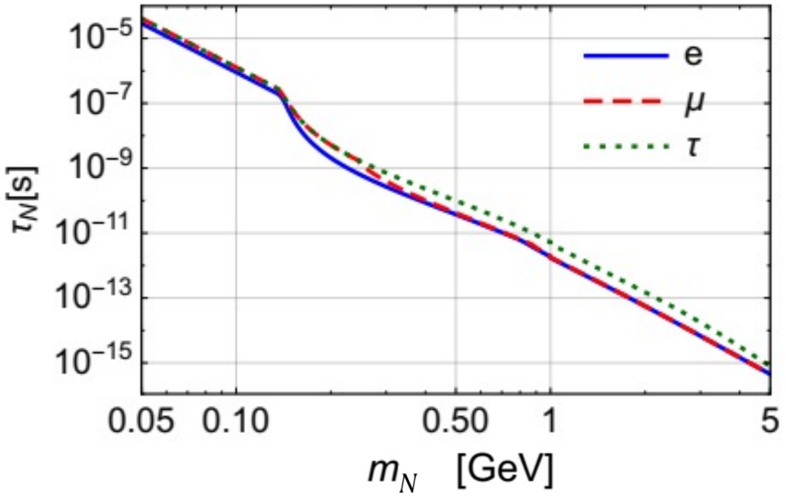
- We search HNL that mixes predominantly with tau neutrino.

- **HNL mass (m_N) range restriction:**
  - $m_N < m_\tau - \mathrm{m}_\pi = 1.63$ GeV

- **HNL lifetime:**
  - $c\tau_N \approx 0.324\ cm \times \left(\frac{m_N}{1GeV}\right)^{-5.44} |V_{\tau N}|^{-2}$ Phys Rev D 29,2539

> ➢ HNL is a long-lived particle (in our parameter space).
>
> ➢ $\mu^+\mu^-$ form a **displaced vertex (DV)**.





doi:10.1007/JHEP11(2018)032

Analysis

Data Samples

- Belle Data samples are collected from two main resonance states of e^+e^- collisions:
  - $\Upsilon(4S)$ with $\mathcal{L} \approx 790\ fb^{-1}$
  - $\Upsilon(5S)$ with $\mathcal{L} \approx 100\ fb^{-1}$

$$N_{\tau\tau} = (836 \pm 12)\times 10^6$$

MC – Signal Samples

- Generating $\tau^-_{sig} \to \pi^- N(\to \mu^+\mu^-\nu_\tau)$ signal samples.
- Mass range m_N: $300 - 1600$ MeV with 25 MeV gap.
- Lifetime $c\tau_0$: $10 - 30$ cm, to yield a reasonably large number of events in the fiducial volume of the analysis.

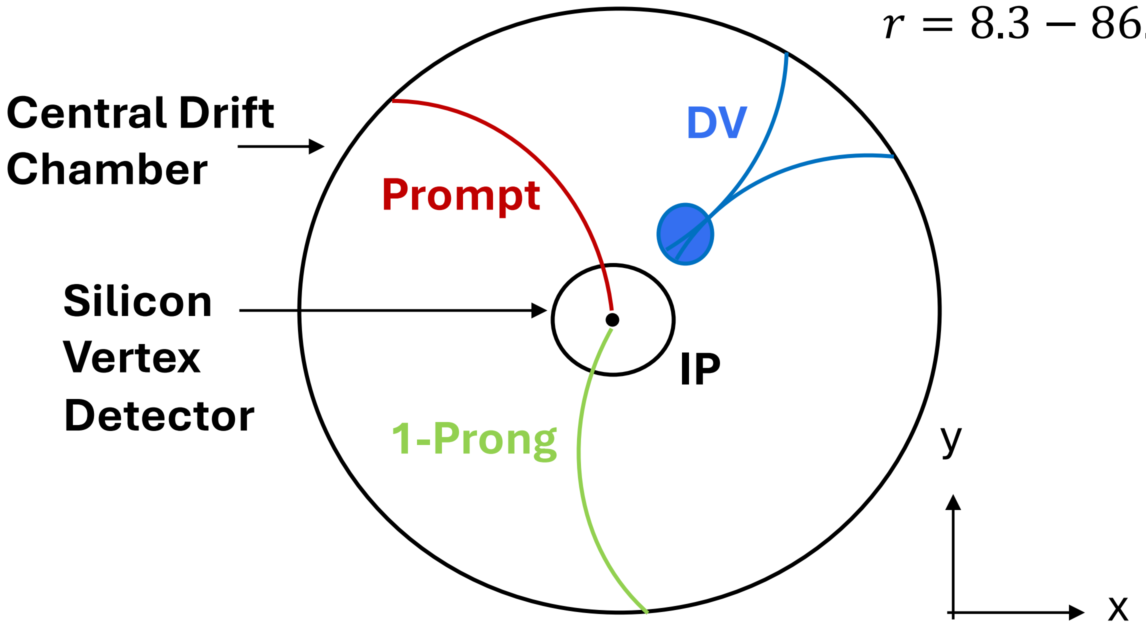
MC – General Background Samples

- Most dominant background processes: $e^+e^- \to \tau^+\tau^-$ and $e^+e^- \to q\bar{q}$.

Analysis

- Using $e^+e^- \to \tau^-_{sig}\tau^+_{tag}$.
- Signal side:
  - $\tau^-_{sig} \to N(\to \mu^+\mu^-\nu_\tau)\pi^-$
- Tag side: 1-prong decay
  - $\tau^+_{tag} \to \begin{cases} \pi^+\nu_\tau \\ \pi^+\pi^0\nu_\tau \\ l^+\nu_\tau\overline{\nu_l} \end{cases}$
- Selecting only 4-tracks samples.
- DV transverse distance from IP > 15 cm.

Belle CDC radius:
$r = 8.3 - 86.3\ cm$



DV = Displaced Vertex

IP = Interaction Point

Analysis

- Background:
  - $\tau^- \to K_S^0(\to \pi^+\pi^-)\pi^-\nu_\tau$
  - $\tau^- \to K_L^0(\to \pi^\mp\mu^\pm)\pi^-\nu_\tau$
  - Material interaction
  - $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ with misreconstructed prompt pions

- Define a control region (CR):
  - $\tau^- \to DV(\to \mu^\pm\pi^\mp)\pi^-$

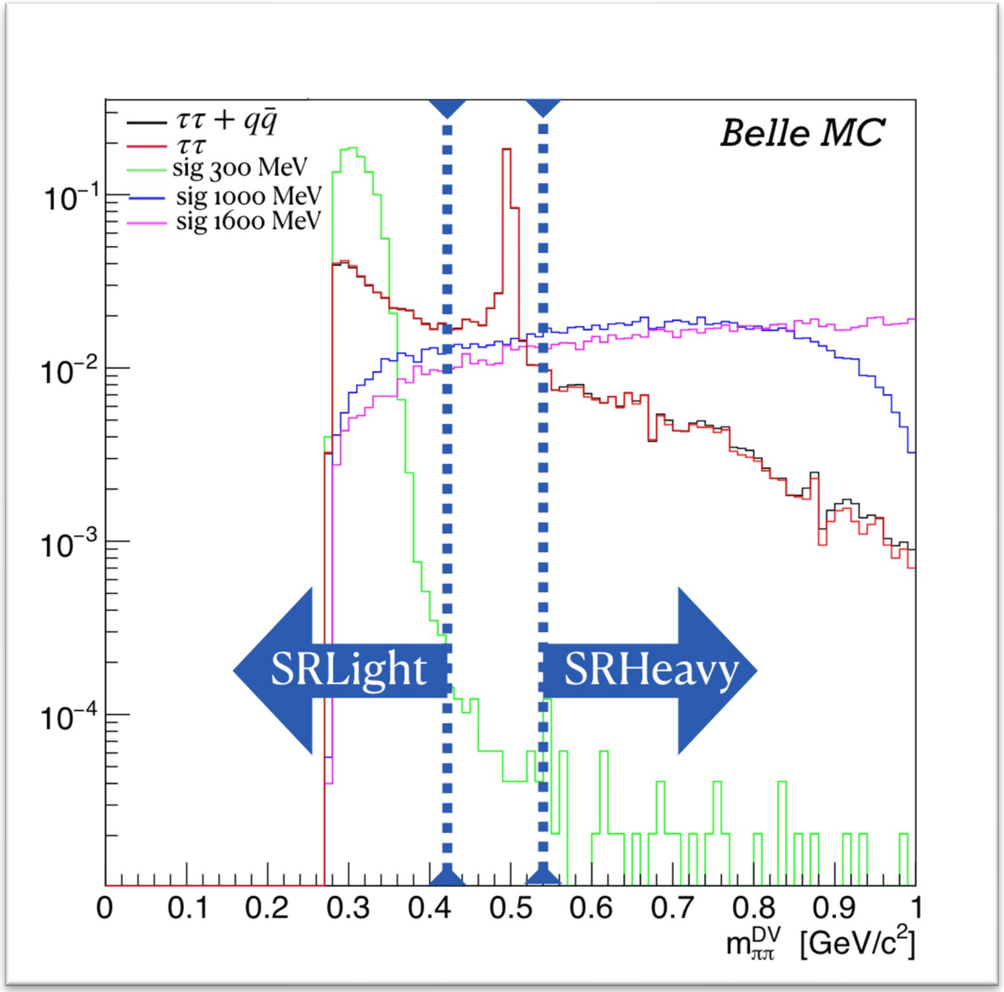
→ Used with the fit in the SR to determine the background expectation.

- Define 3 validation regions (VR):
  - $\tau^- \to DV(\to \mu^+\mu^+)\pi^-$
  - $\tau^- \to DV(\to \pi^+\pi^-)\pi^-$ (K_S exclusion)
  - $\tau^- \to DV(\to \pi^+\pi^-)\pi^-$ (K_S selection)

→ Used for the background systematic uncertainty.

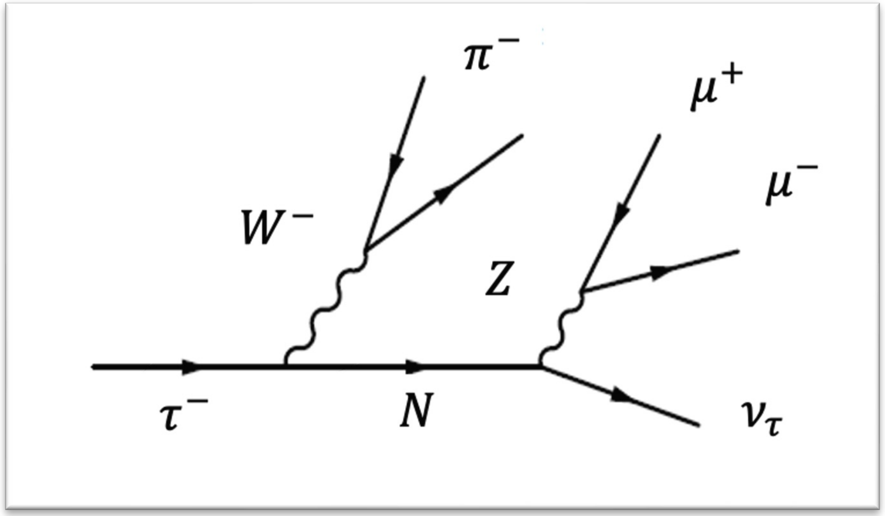
K_S^0 rejection and definition of 2 signal regions

- $K_S^0 \to \pi^+\pi^-$ (with pions misidentified as muons) produces a DV similarly to the HNL.
- We identify K_S^0 with $m_{\pi\pi}^{DV}$ = DV mass reconstructed with the π mass hypothesis for the two DV daughters.
- Low mass HNLs distribute differently from high mass HNLs.
- Hence, we divide the signal region into 2 regions:
  - SRH: $m_{\pi\pi}^{DV} > 0.52$ GeV
  - SRL: $m_{\pi\pi}^{DV} < 0.42$ GeV



HNL mass reconstruction

- Despite the unobservable neutrino, we can reconstruct the decay chain kinematics completely, up to 2-fold ambiguity.
  - 12 unknowns: $p_{\nu}^{\mu}, p_{\mathrm{N}}^{\mu}, p_{\tau}^{\mu}$
  - 12 constraints:
    - p^{μ} conservation in the τ and N decays (8)
    - Known masses of τ and ν_{τ} (2)
    - Unit vector from the production point of the π system to that of the DV system, which is the direction of $\overrightarrow{p_N}$ (2)

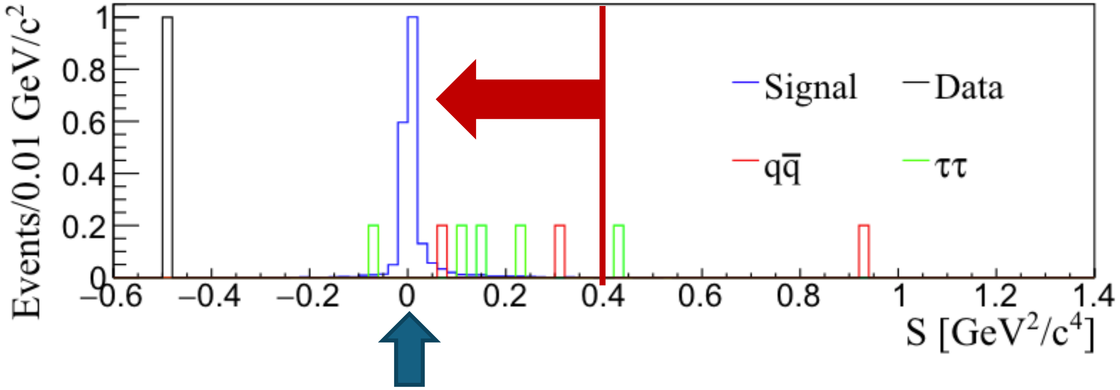


Quadratic equation

(Using the square root argument S for a cut)

Two HNL mass solutions : m_+, m_-

$S < 0.4\ \mathrm{GeV}^2/\mathrm{c}^4$

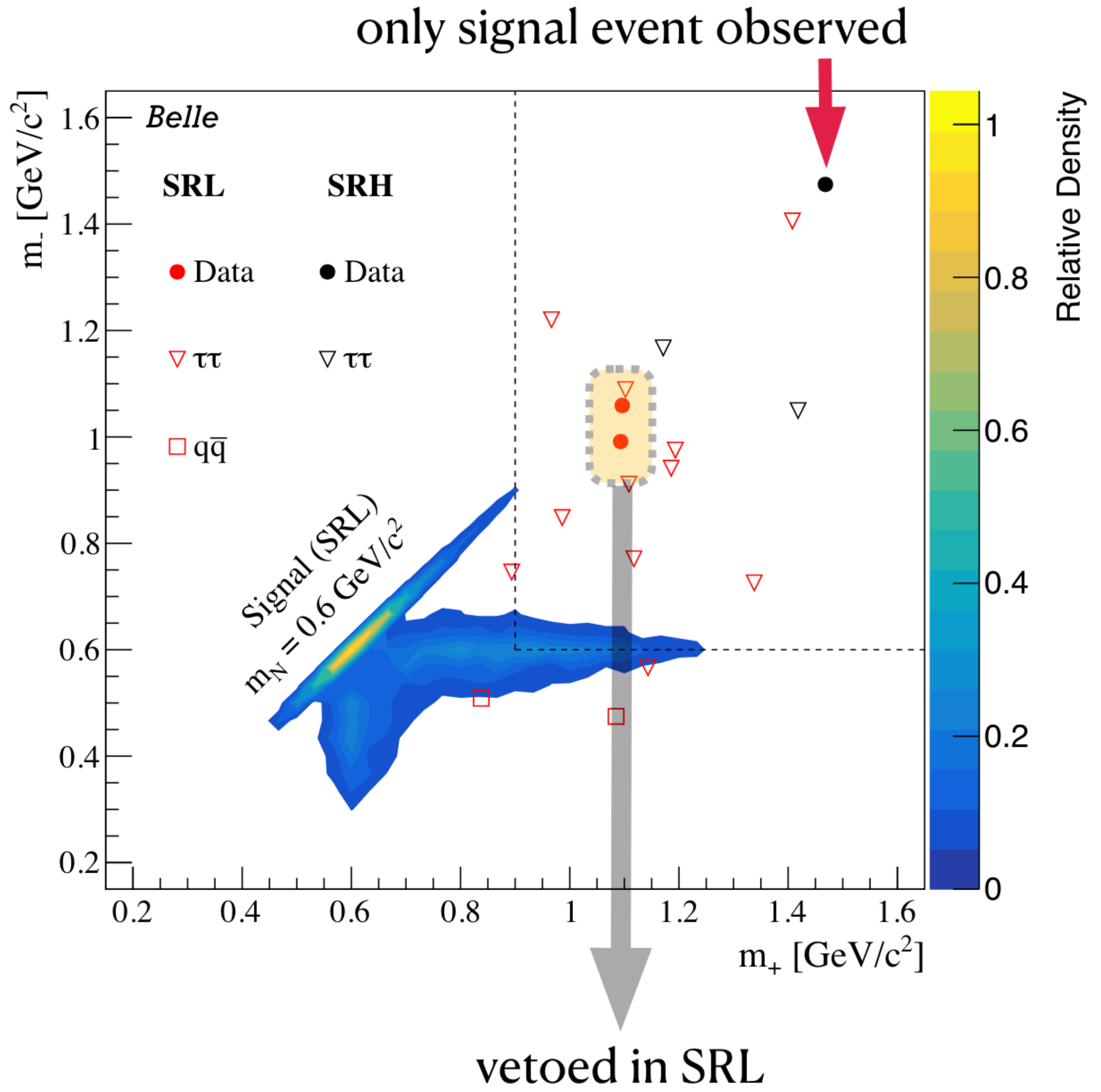


$if\ S < 0 \Rightarrow S = 0$

Results

- In SRL, a cut for high m_+, m_- exclusion is applied.
- In SRH and SRL, we observe 1 and 0 signal events respectively.

Region	N_{obs}	N_{bgd}	$\frac{N_{\text{obs}}}{N_{\text{bgd}}}$	$N^{\sigma}_{\text{obs,bgd}}$	Postfit
SRH	1	0.40 ± 0.28	2.5	2.1	0.59 ± 0.31
SRL	0	0.80 ± 0.40	0	-2.0	0.69 ± 0.45
CRH	95	73.6 ± 3.8	1.29	2.0	93 ± 8
CRL	43	37.2 ± 2.7	1.16	0.8	41 ± 6
VRH$\pi\pi$	273	191 ± 6	1.43	4.7	
VRL$\pi\pi$	165	127 ± 6	1.30	2.7	
VRK_S	7917	7728 ± 39	1.02	2.0	
VRHss	0	0.40 ± 0.28	0		
VRLss	0	0	0		



Systematic uncertainties

- Background yield expectation: we take the relative systematic uncertainty to be the largest percentage change in the background model needed to bring the data and MC to 1σ agreement in the VRs:

$$\sigma(N_{bgd}) = \left(\frac{N_{data} - N_{MC}}{\sqrt{\sigma_{data}^2 + \sigma_{MC}^2}} - 1\right)\frac{\sqrt{\sigma_{data}^2 + \sigma_{MC}^2}}{N_{MC}} \approx 34\%$$

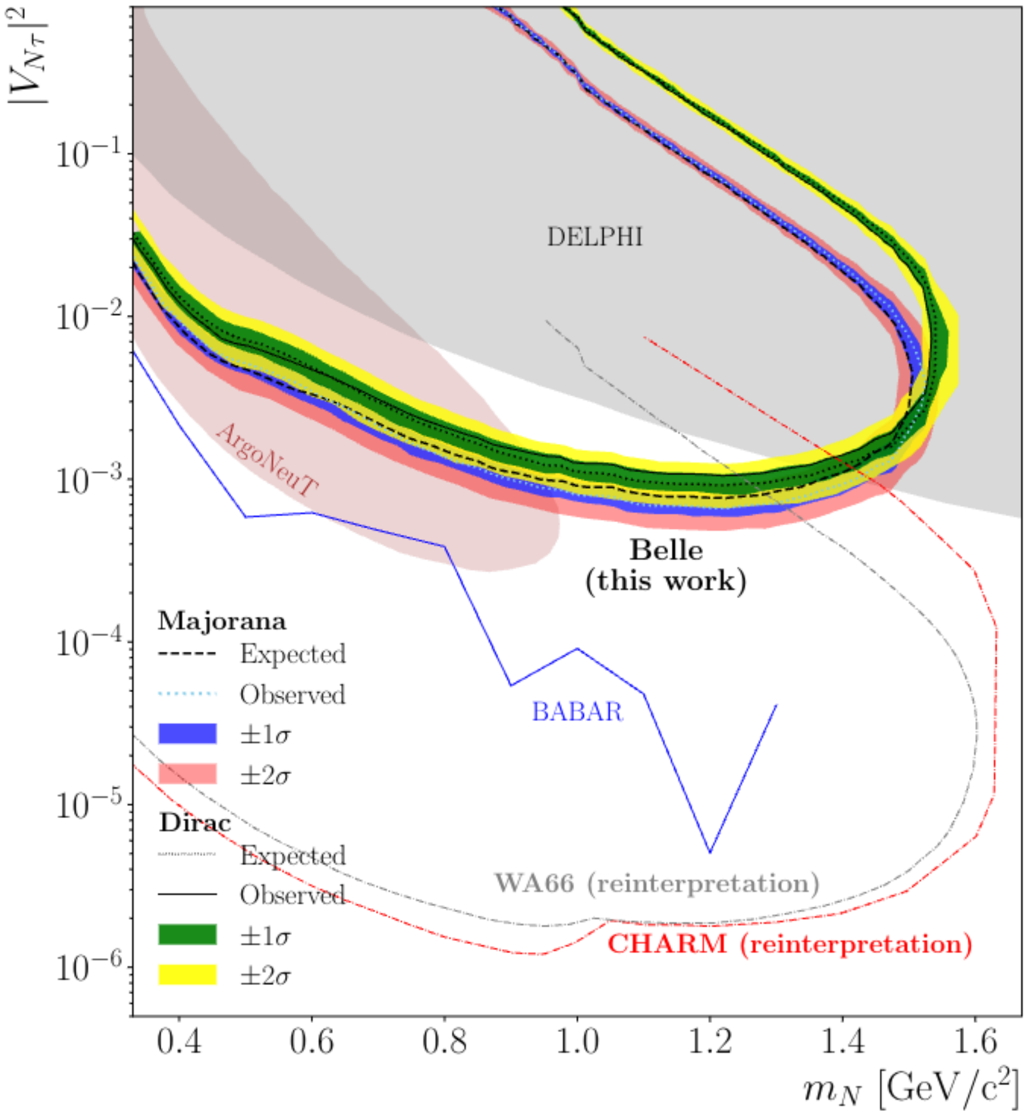
- More:

Uncertainty type	Value
N branching fraction	5%
Luminosity	1.4%
reconstruction of the two prompt tracks	0.7%

- All uncertainties handled with the nuisance parameters using CLs prescription.

Results

- We use the model predictions and the efficiency to determine the numbers of expected signal events in the two signal regions.
- We plot the 95% CL exclusion of the experiment.
- BABAR uses a missing-energy method that has much higher efficiency but depends on understanding of the $\tau \rightarrow 3\pi\nu_\tau$ background.
- Very tight limits are obtained from reinterpretation of other searches at the previous CHARM and WA66 experiments.



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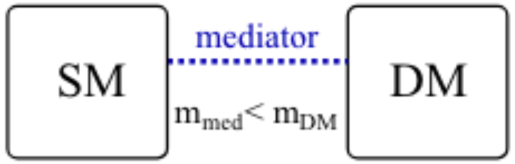
Spin-0 mediator

- BSM models that suggest an additional S scalar particle:



Phys. Lett. B 662, 53 (2008)

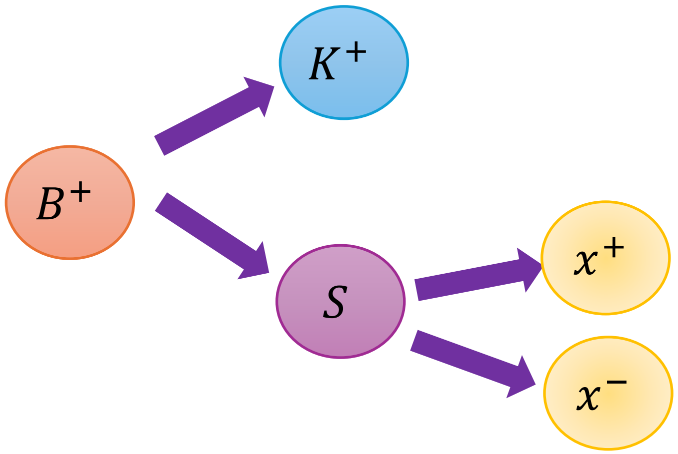
  - **Dark Scalar:** Gives mass to DM and mixes with the SM Higgs boson through mixing angle θ.
    J. Phys. G 47, 010501 (2020), Phys. Rev. D 75, 037701 (2007)
  - **Axionlike particle (ALP):** with a predominant coupling f_a to fermions.
    J. Phys. G 47, 010501 (2020), JHEP 03, 171 (2015)

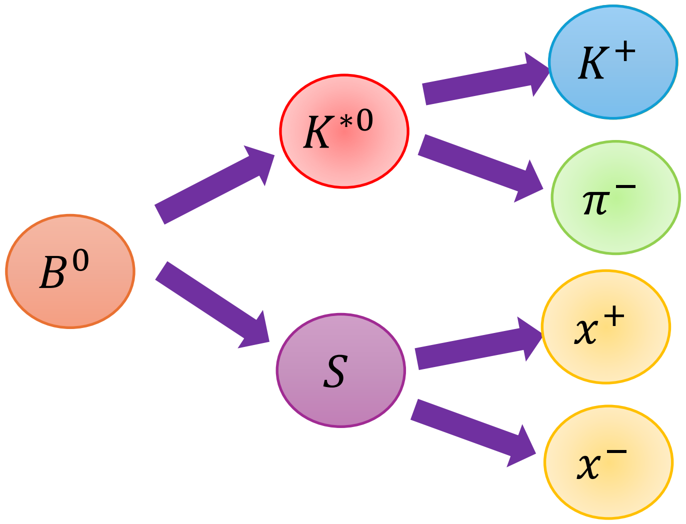
Lifetime-dependent models.

- We also search model independent limits.

Analysis

- We search S in the following B-meson decays (and their charged conjugation):





- Where:
  - $x^+x^- = e^+e^-, \mu^+\mu^-, \pi^+\pi^-, \mathrm{K}^+\mathrm{K}^-$
  - $K^{*0} = K^*(892)^0$ (short-lived)

- Both decays mediated by flavor-changing neutral current $b \to s$

Analysis

Data Samples

- Belle II $\Upsilon(4S)$ resonance with $\mathcal{L} \approx 189\ fb^{-1}$ which corresponds to $N_{B\bar{B}} = (198 \pm 3)\times 10^6$.

MC – Signal Samples

- Generating $B^+ \to \mathrm{K}^+\mathrm{S}(\to x^+x^-)$ and $B^0 \to \mathrm{K}^*(\to K^+\pi^-)\mathrm{S}(\to x^+x^-)$ signal samples.
- Mass range m_N: $0.025 - 4.78\ \mathrm{GeV}$ with 90 steps with varying sizes.
- Lifetime $c\tau$: $0.001 - 400\ \mathrm{cm}$ with variable steps

MC – General Background Samples

- From most dominant to least:
  - $e^+e^- \to c\bar{c}$
  - $e^+e^- \to u\bar{u}/d\bar{d}/s\bar{s}$
  - $e^+e^- \to B\bar{B}$
  - $e^+e^- \to \tau^+\tau^-$

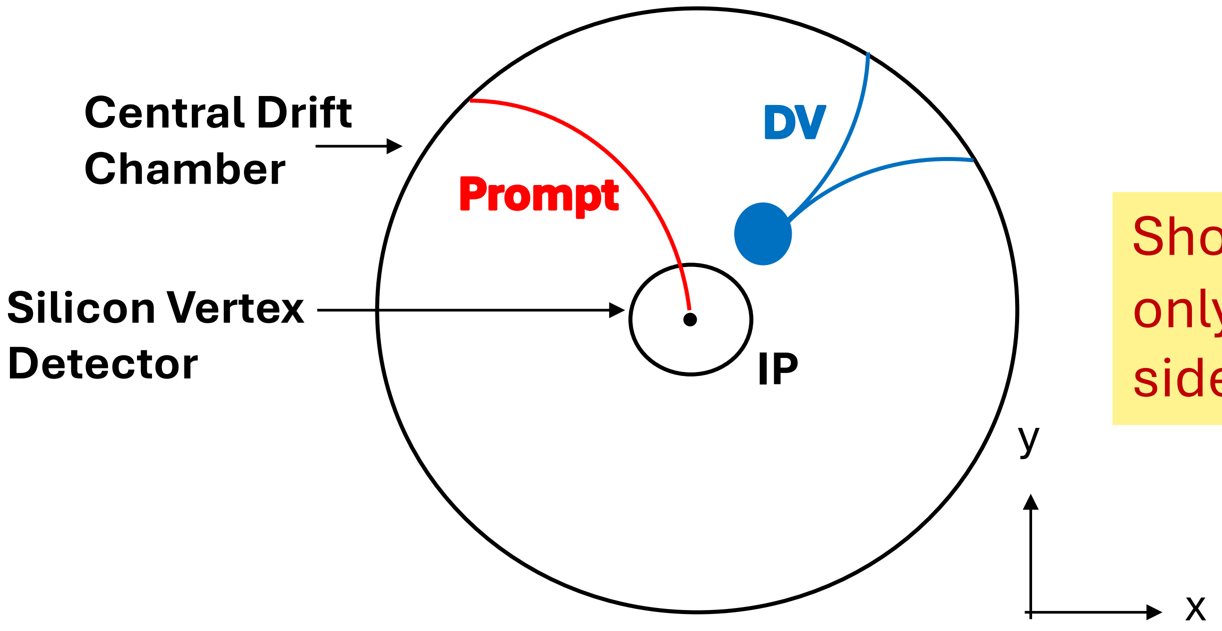
Analysis

B^+ signal

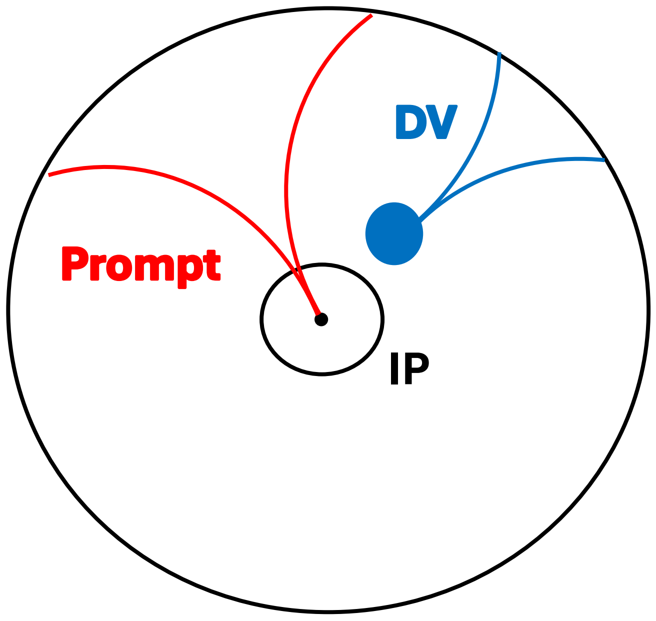
$B^+ \to K^+ S(\to \chi^+ \chi^-)$

B^0 signal

$B^0 \to K^*(892)^0(\to K^+\pi^-) S(\to \chi^+ \chi^-)$



Showing only signal-side tracks!



DV = Displaced Vertex

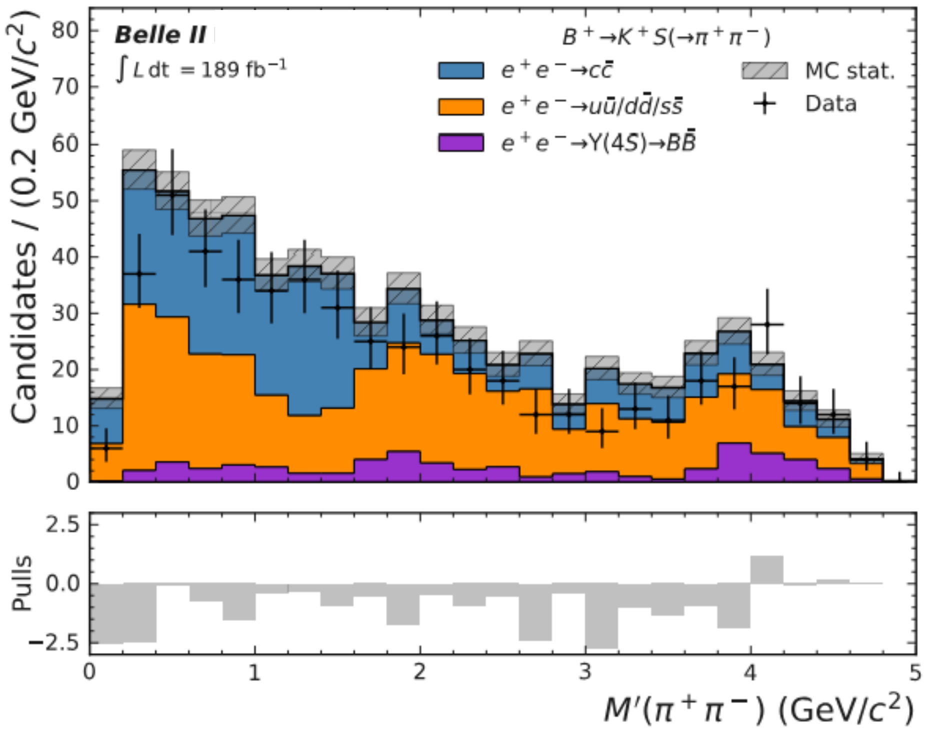
IP = Interaction Point

Belle II CDC radius:
$r = 16 - 113\ cm$

Analysis

Selection Criteria

- **Long lived particles**: DV transverse distance from IP > 0.05 cm
- **Suppressing $e^+e^- \to q\bar{q}(\gamma), e^+e^- \to \tau^+\tau^-(\gamma)$ background:**
  - Energy differences: $|\Delta E| = \left|E_B^* - \sqrt{s}/2\right| < \begin{cases} 0.05 \text{ GeV}, & x \neq \pi \\ 0.035 \text{ GeV}, & x = \pi \end{cases}$
  - Beam-constrained mass $M_{BC} = \sqrt{\frac{s}{4} - |p_B^*|^2} > 5.2 \text{ GeV/c}^2$
- **Suppressing K_S^0 for $x = \pi$:**
  - $0.498 < M(\pi^+\pi^-) < 0.507 \text{ GeV}/c^2$

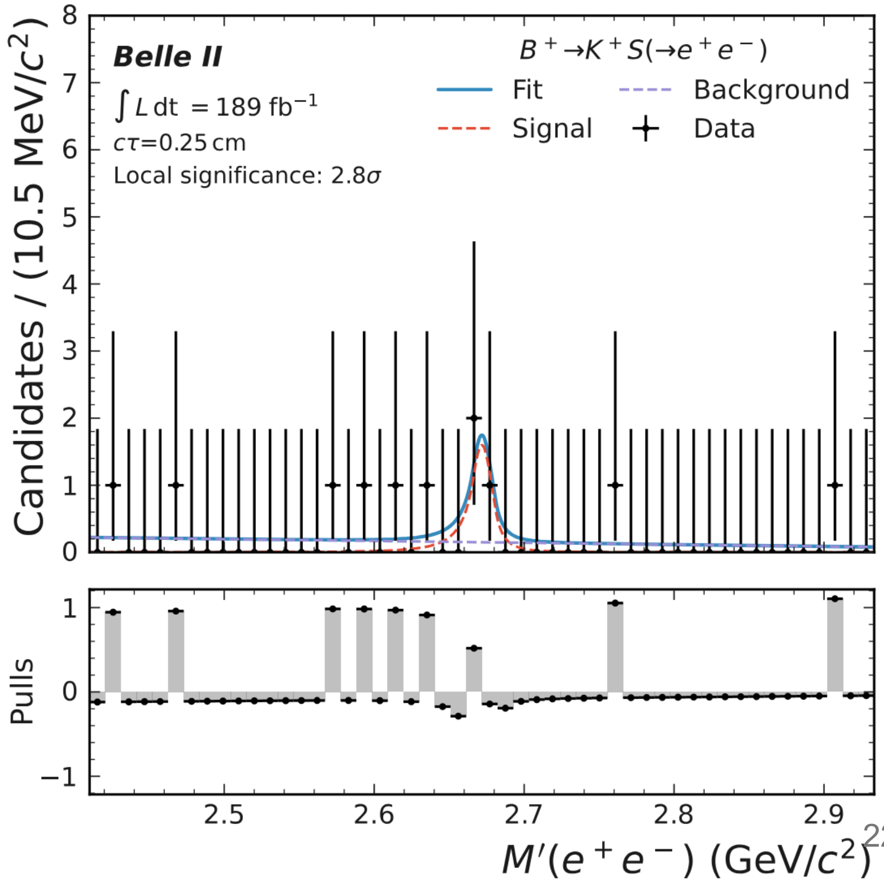


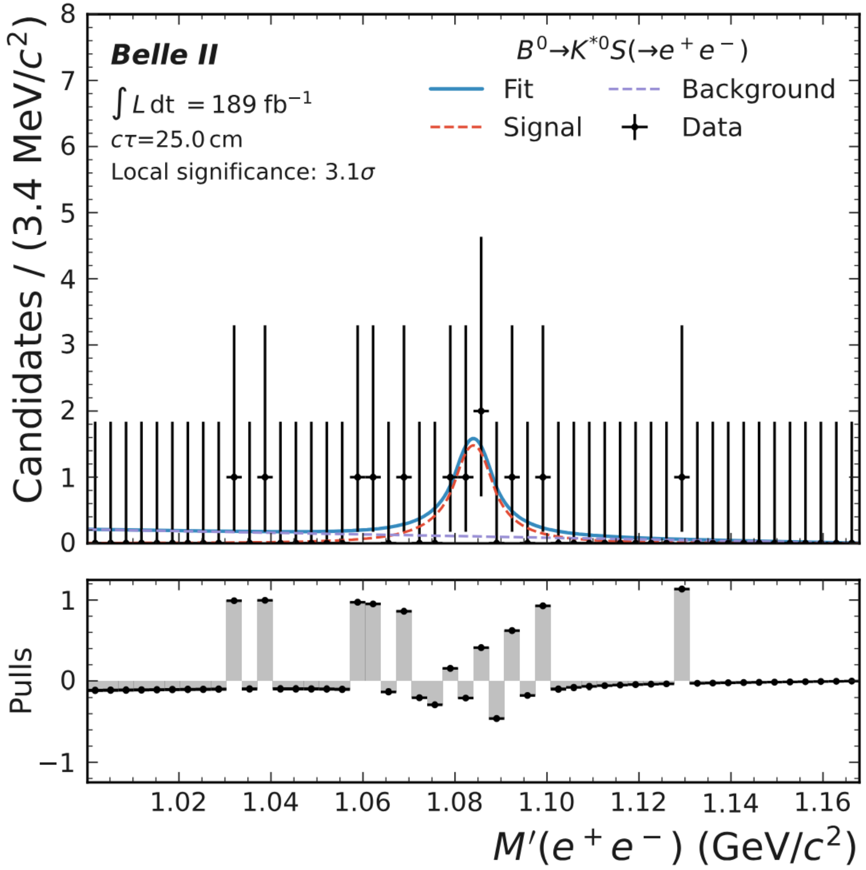
Signal yields extraction

- Modified mass is defined: $M'(x^+x^-) = \sqrt{M^2(x^+x^-) - 4m_x^2}$

Results

- We fit for a narrow nonnegative-yield signal peak, at various values of S mass and assuming various lifetimes, over a smooth background.





Systematic uncertainties

Uncertainty type	Value
Difference in track finding efficiency for displaced tracks between data and MC: depending linearly on DV position	$0 - 45\%$
Signal efficiency	4% ($\sim 10\%$ for lightest m_s)
Combination of $B\bar{B}$ yield and $b \to s$ ratio	2.9% (for larger m_s)
Identification efficiency of K^{*0}	3%

- All uncertainties handled with the nuisance parameters using CLs prescription.

Results

Independent model:

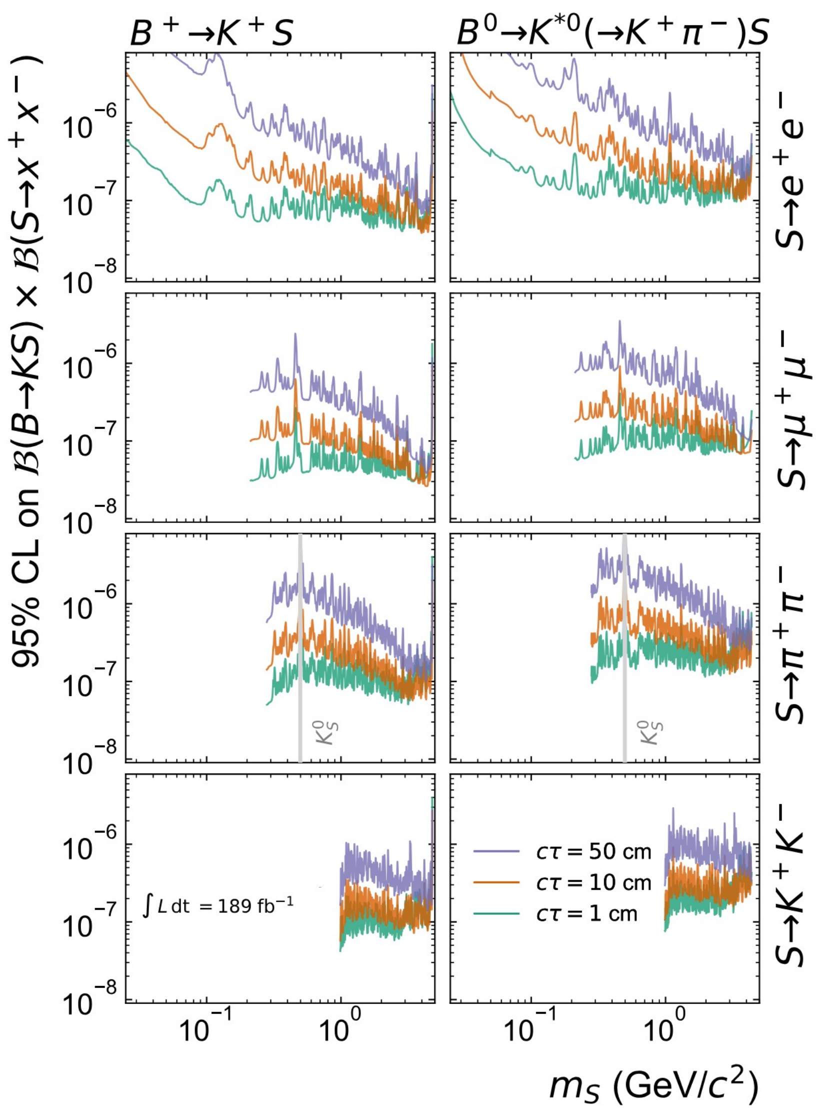
- Using the signal yields and $N_{B\bar{B}}$, we obtain the products of the $\mathcal{BR}$s of the B mesons and S decays.

- We plot the 95% CL exclusion for different life-times.

These limits are:

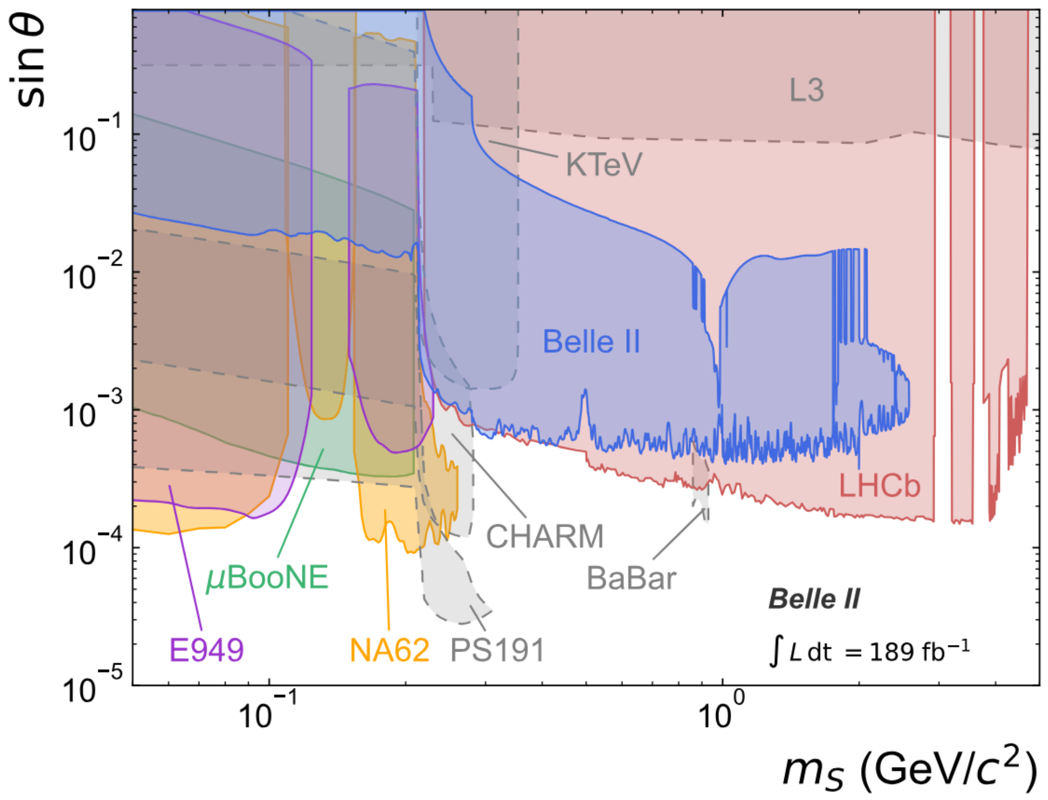
- First for exclusive hadronic final states.

- Most constraining from a direct search for $K^{*}e^{+}e^{-}$ final states.

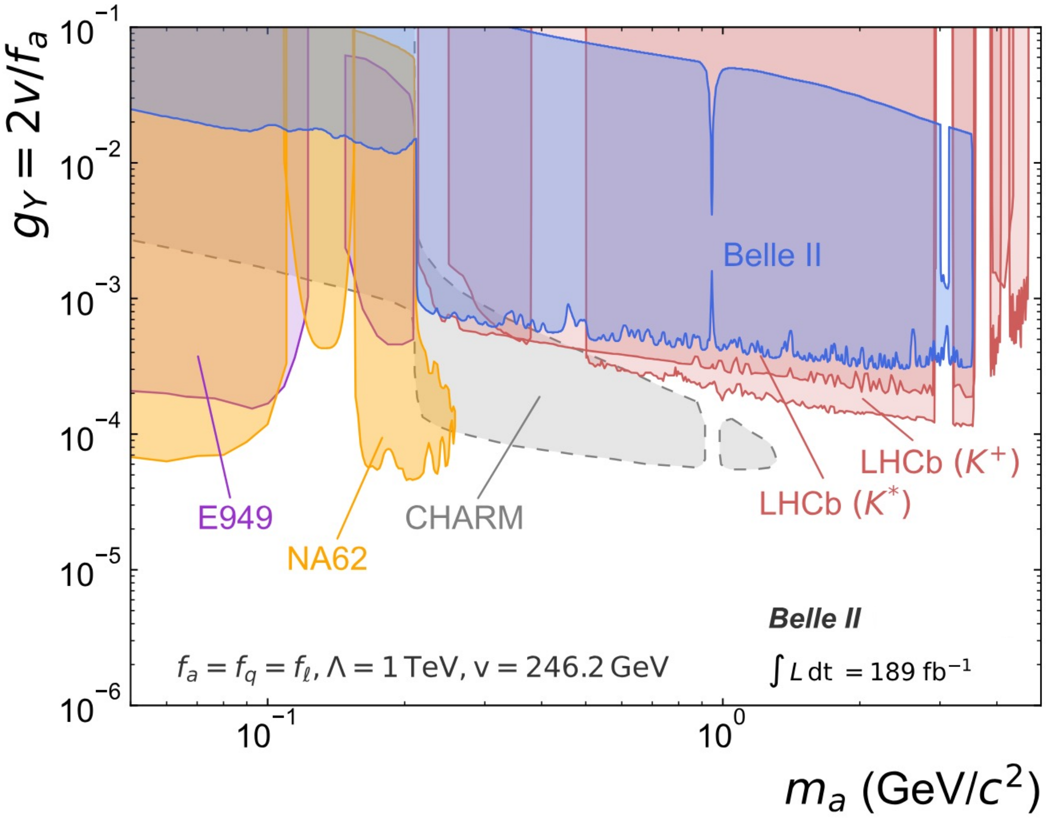


Results

Dark scalar model

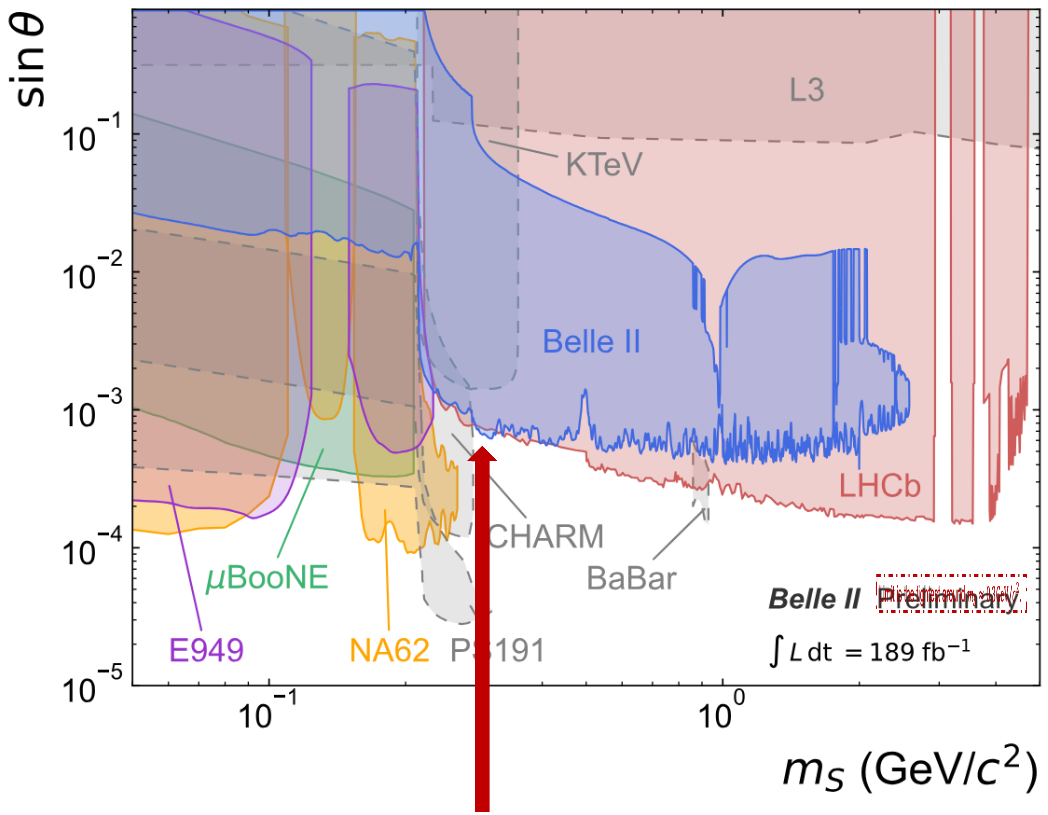


ALP model

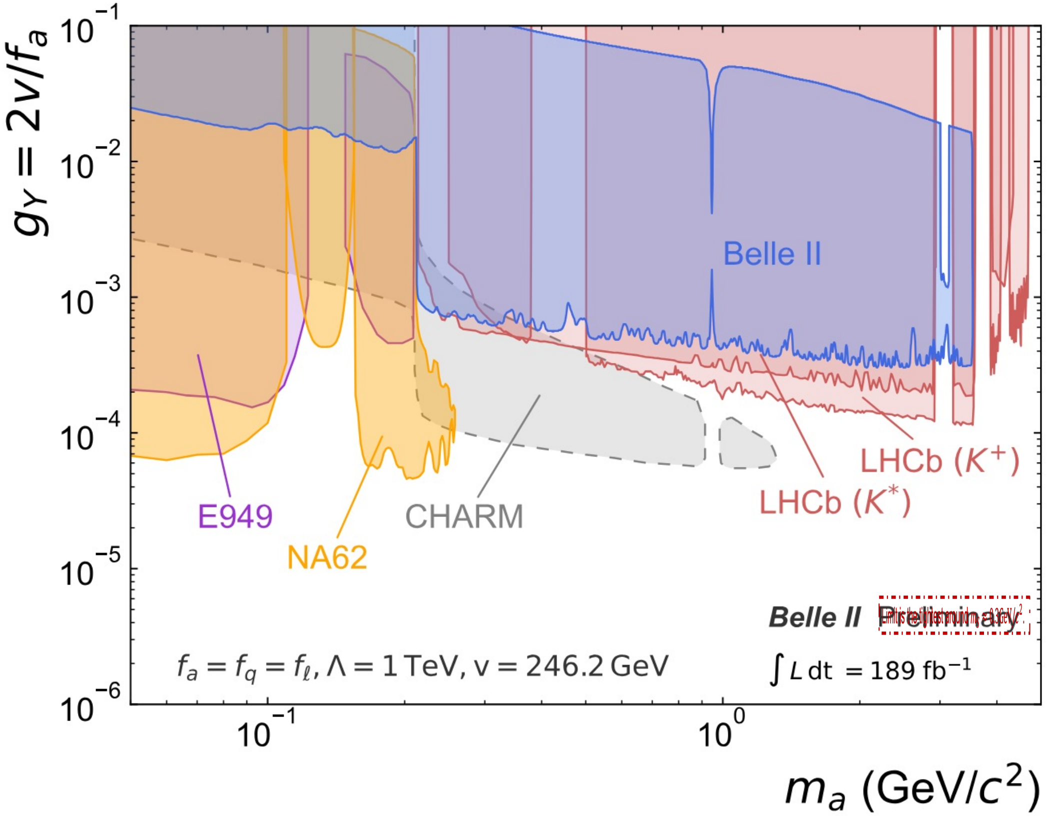


Results

Dark scalar model



ALP model



Limit is the tightest around $m_S \approx 0.3 \mathrm{GeV}/c^2$.

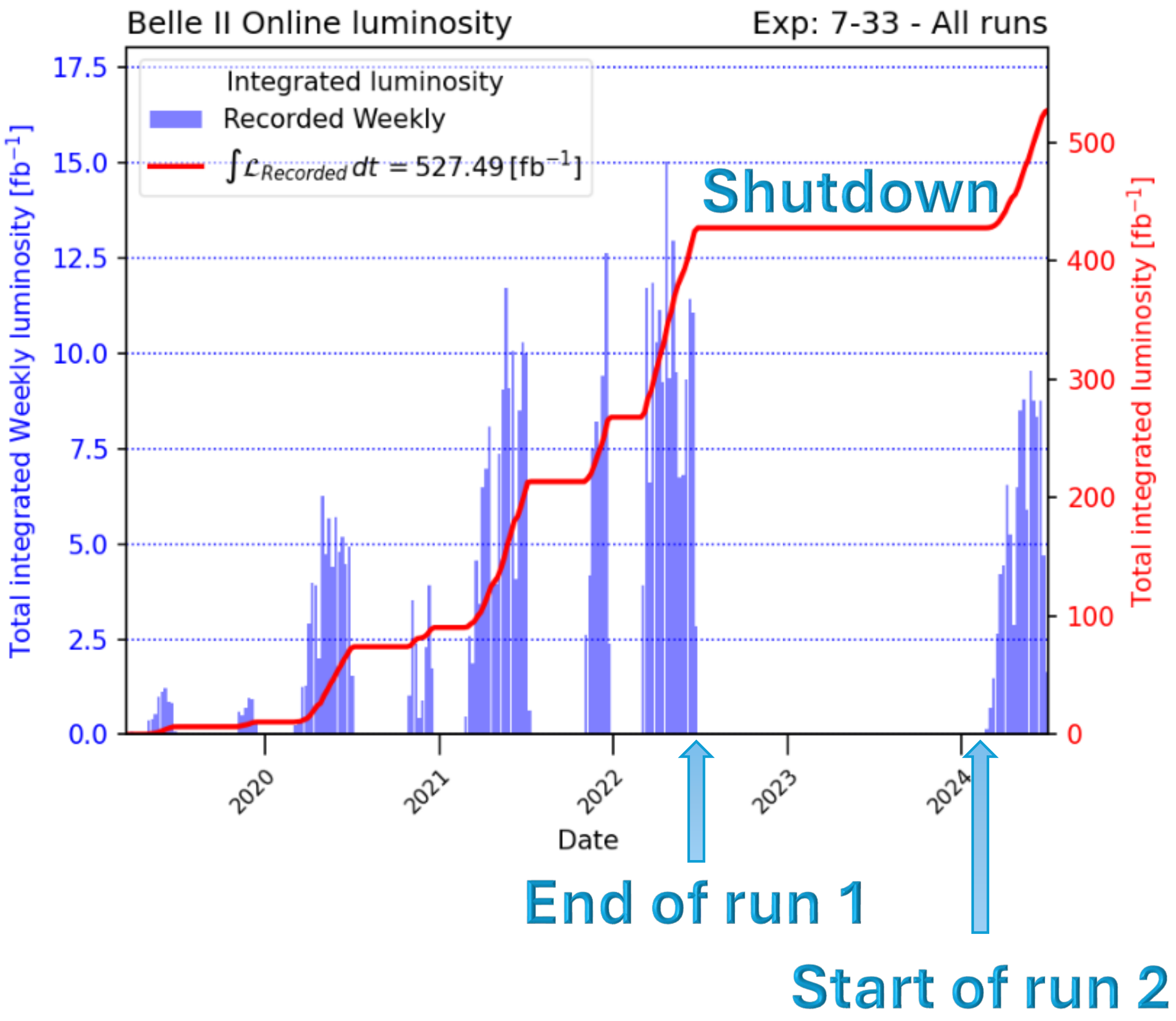
Summary

- No observation of significant excess of events consistent with a signal processes.
- Search for a heavy neutral lepton that mixes predominantly with the τ neutrino at Belle
  - For the first time, utilizes the DV originating from the decay of a long-lived HNL produced in an identified tau decay.
  - Ability to reconstruct the HNL candidate mass and suppress background to the single-event level.
- Search for a long-lived spin-0 mediator in $b \rightarrow s$ transitions at the Belle II
  - First for exclusive hadronic final states of the signal processes.
  - Most constraining from a direct search for $K^{*}e^{+}e^{-}$ final states.
  - Sensitivities from Belle II and LHCb in the region up to $\sim 4\ \mathrm{GeV}$ are comparable.
  - Belle II is collecting more data: hopefully improved results in the future!

Thank You!

Backup

Equations of HNL reconstruction



TOTAL INTEGRATED LUMINOSITY FOR GOOD RUNS in run 1

- Total integrated luminosity: **424 fb-1**
- Total integrated luminosity at the Y(4S) resonance: **363 fb-1**
- Total integrated luminosity below Y(4S) resonance: **42 fb-1**
- Total integrated luminosity above Y(4S) resonance: **19 fb-1**

Belle II status

$$(B^2 - 1)p_N^2 + (2AB - D)p_N + A^2 - C = 0. \qquad (1)$$

$$\begin{aligned}
A &= \left(m_\tau^2 + m_{\mu\mu}^2 - m_\pi^2\right)/2E, \\
B &= \left(q_{\mu\mu} + q_\pi\right)/E, \\
C &= \left(E_{\mu\mu}(m_\tau^2 - m_\pi^2) - E_\pi m_{\mu\mu}^2\right)/E, \\
D &= 2\left(E_{\mu\mu} q_\pi - E_\pi q_{\mu\mu}\right)/E, \qquad (2)
\end{aligned}$$

$$m_N^2 = (D + C p_N)/E^2. \qquad (3)$$