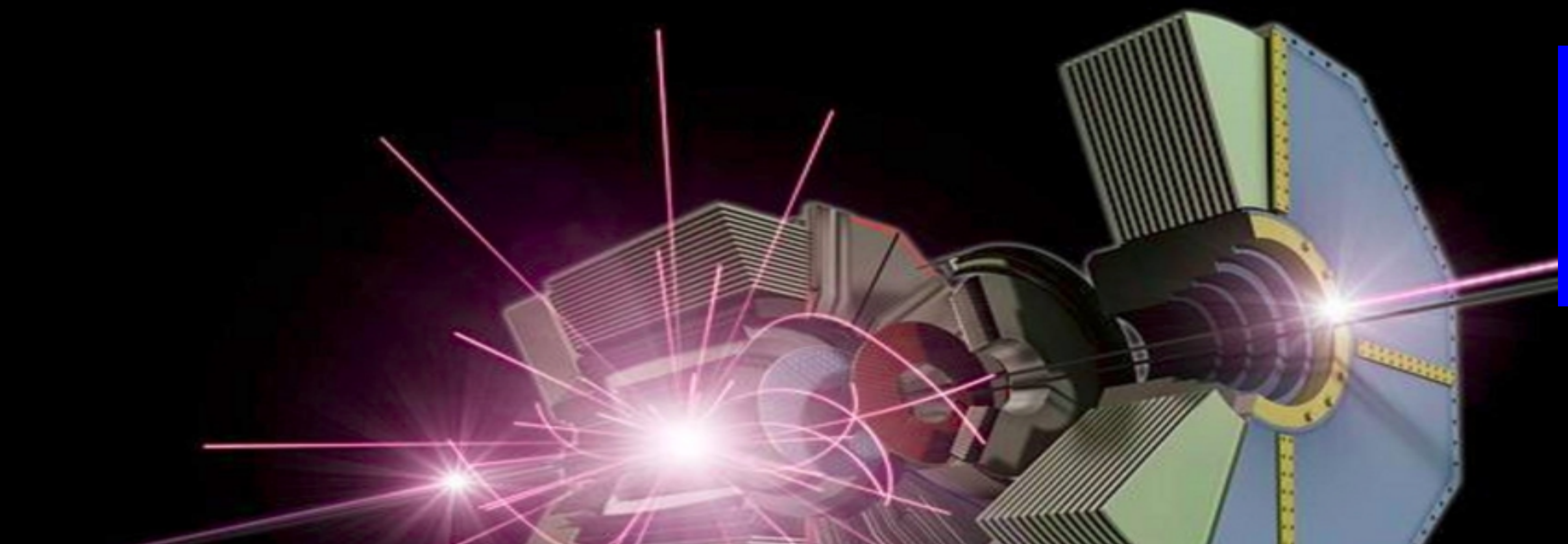


Recent searches for Long-Lived Particles @Belle and Belle II

Frontiers in Particle Physics 2024

Minakshi Nayak
on behalf of the Belle II Collaboration
IISc, Bangalore

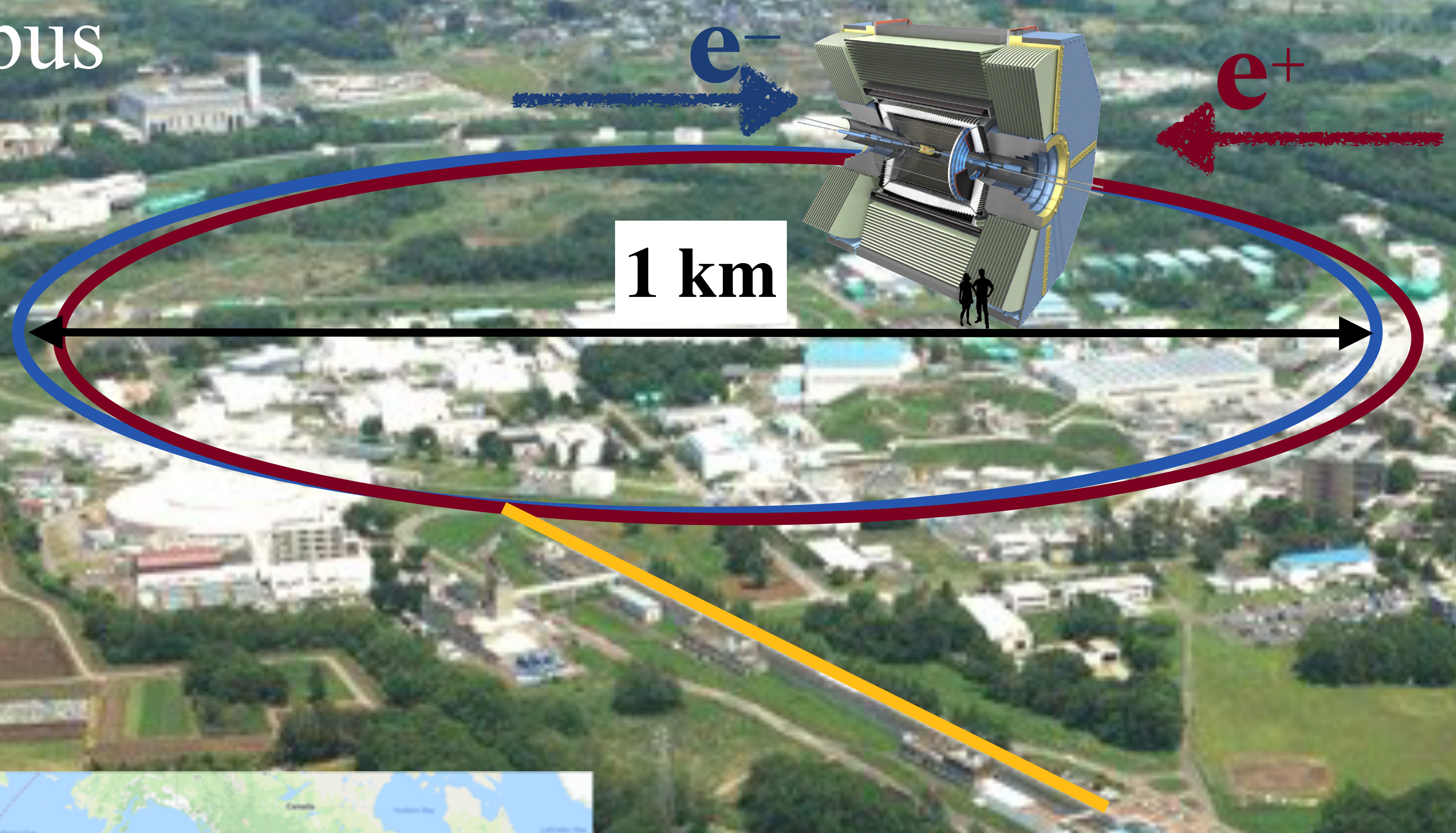
10th August, 2024

Belle II @ Super-KEKB

Intensity Frontier Flavor Factory Experiment

@ World's Highest-Luminosity Electron Positron Collider

Successor to **Belle** at KEKB



7 GeV e^- ★ 4 GeV e^+

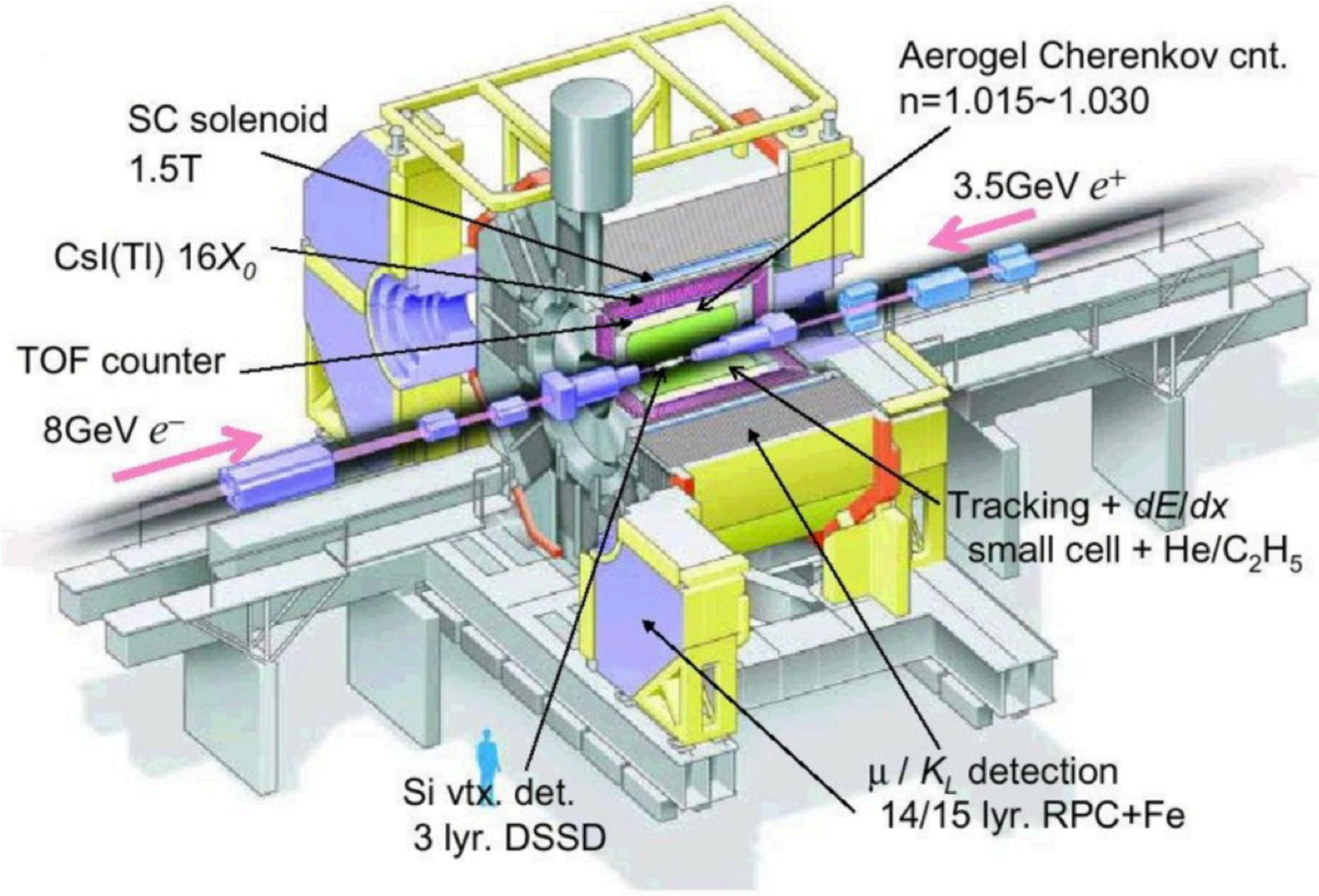
- Bunch crossing rate: 250 MHz
- Luminosity:
  - Latest L_{peak} : $4.7 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$
  - Target $L_{\text{peak}} > 8 \times 10^{35}\ \text{cm}^{-2}\text{s}^{-1}$

~1100 researchers 123 institutions
26 countries and regions

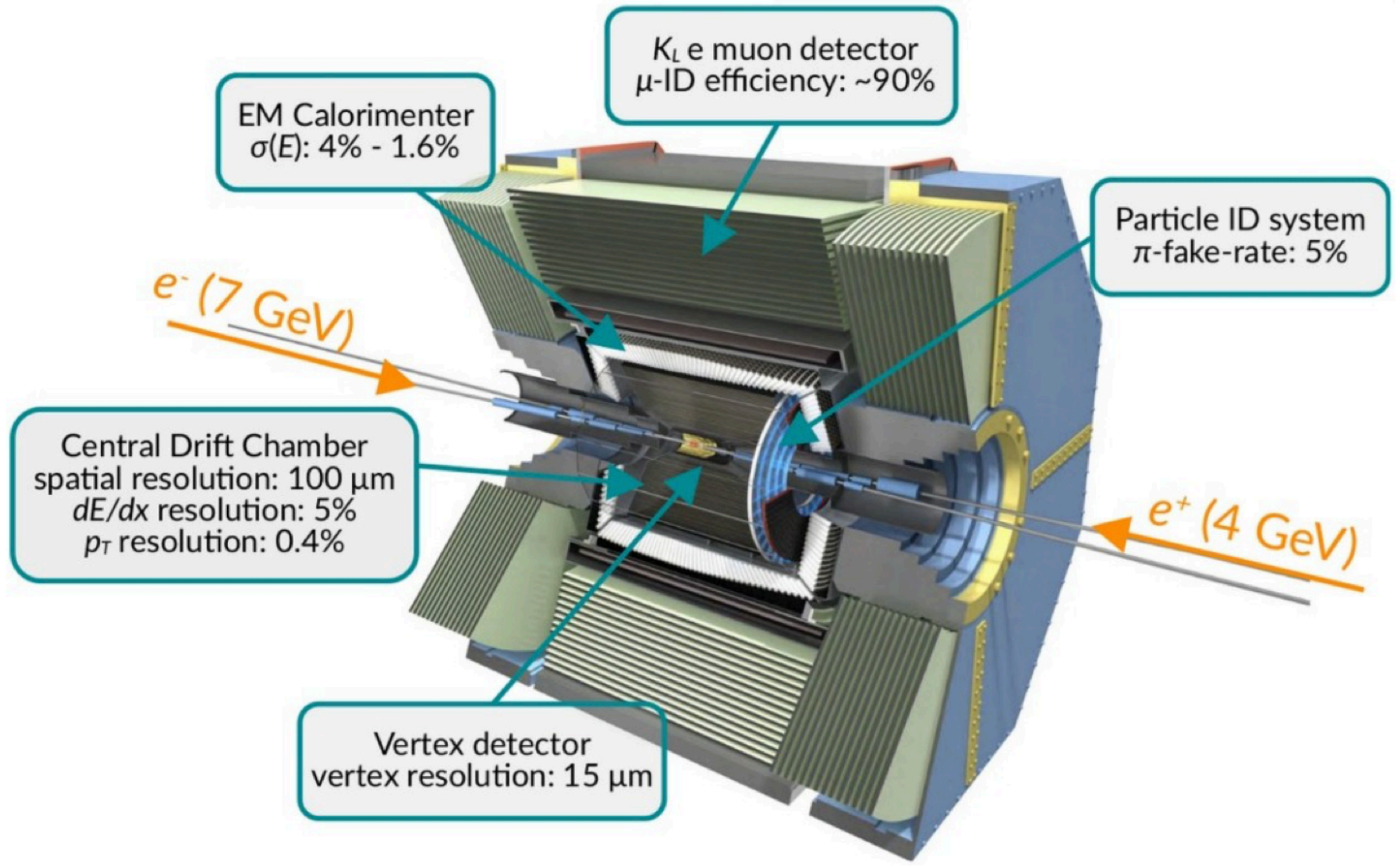
Belle and Belle II experiments

- Belle (1999 - 2010) and Belle II (2018 -): previous and current generation of B-factories
  - Asymmetric e^+e^- colliders running mainly at the $\Upsilon(4S)$ resonance, $\sqrt{s} = 10.58$ GeV
- Key features:
  - All known initial conditions
  - Hermetic detectors
  - Little/no pile-up and clean environment
  - Missing energy reconstruction
- Belle II Triggers:
  - $e^+e^- \to X \sim 1$ MHz
  - L1 < 30 kHz
  - HLT < 10 kHz
  - Dedicated triggers for low multiplicity @ Belle II

Belle @ KEKB, recorded ~1 ab^{-1}

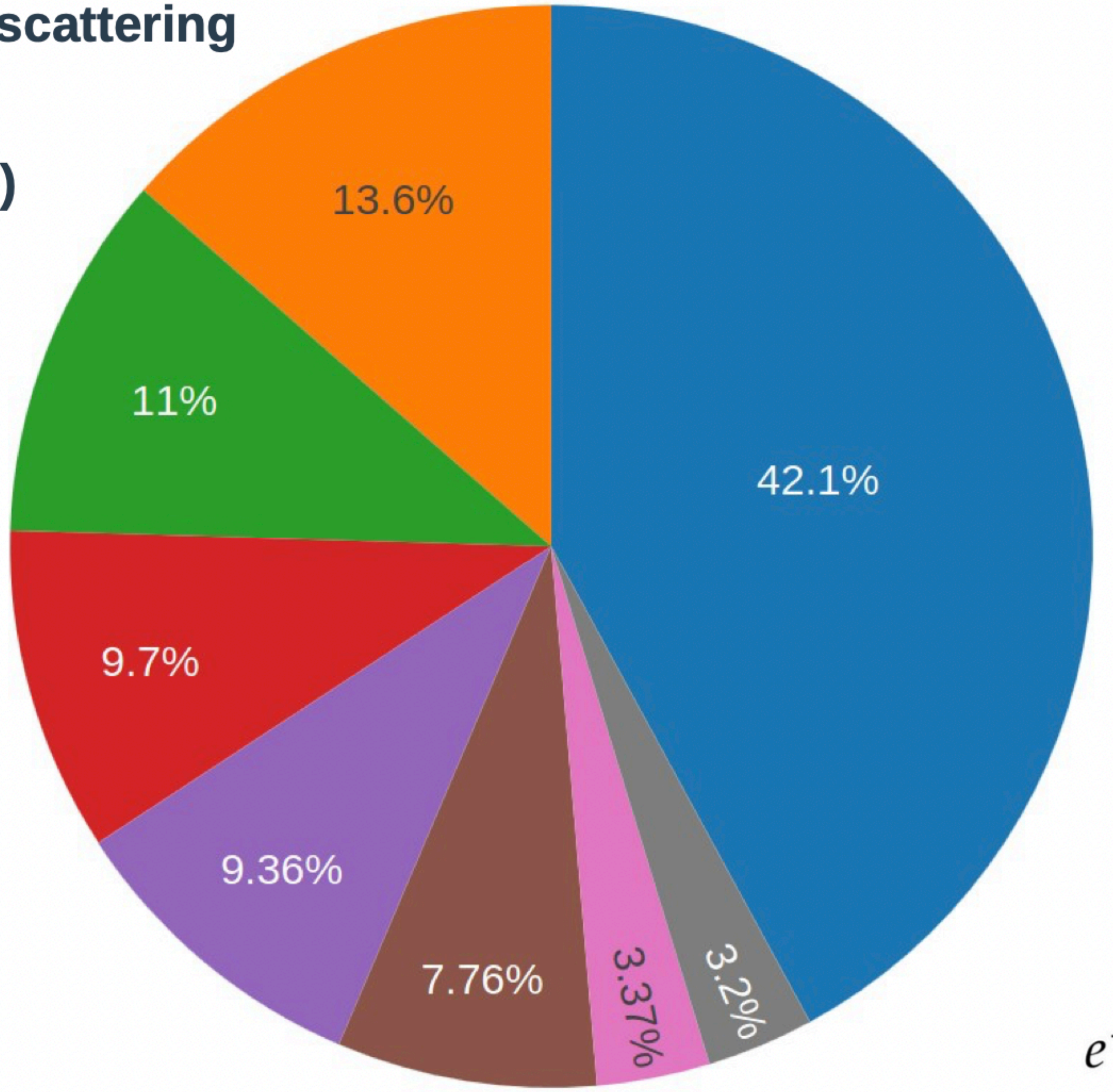


Belle @ SuperKEKB, recorded:
427 fb^{-1} in Run1 (2018 - 2022)
103 fb^{-1} in Run2 (2024 -)



Production cross section of heavy flavor (b, c, τ)

- **96.2 % of ee collisions do Bhabha scattering → Background**
- **Remaining 3.8 % compose Belle (II) physics program**
  - 9.7 % Y(4S) → BB
  - 7.76 % taupair production → 45 billion taupairs @ Belle II
    - High precision studies
    - Rare decay searches



$\sigma[e^+e^- \to \gamma\gamma(\gamma)] = 4.99\ nb$

$\sigma[e^+e^- \to uu] = 1.61\ nb$

$\sigma[e^+e^- \to cc] = 1.3\ nb$

$\sigma[e^+e^- \to \mu\mu] = 1.15\ nb$

$\sigma[e^+e^- \to \Upsilon(4S)] = 1.11\ nb$

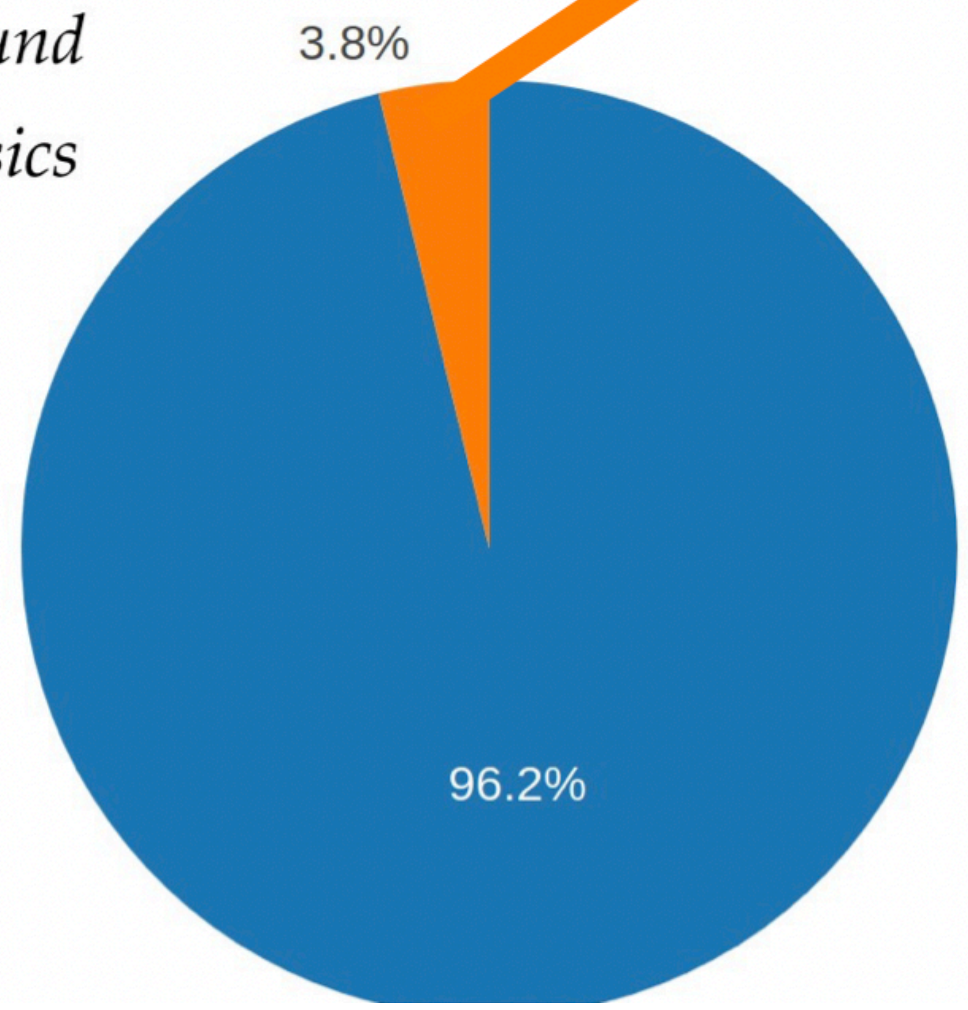
$\sigma[e^+e^- \to \tau\tau] = 0.9\ nb$

$\sigma[e^+e^- \to dd] = 0.4\ nb$

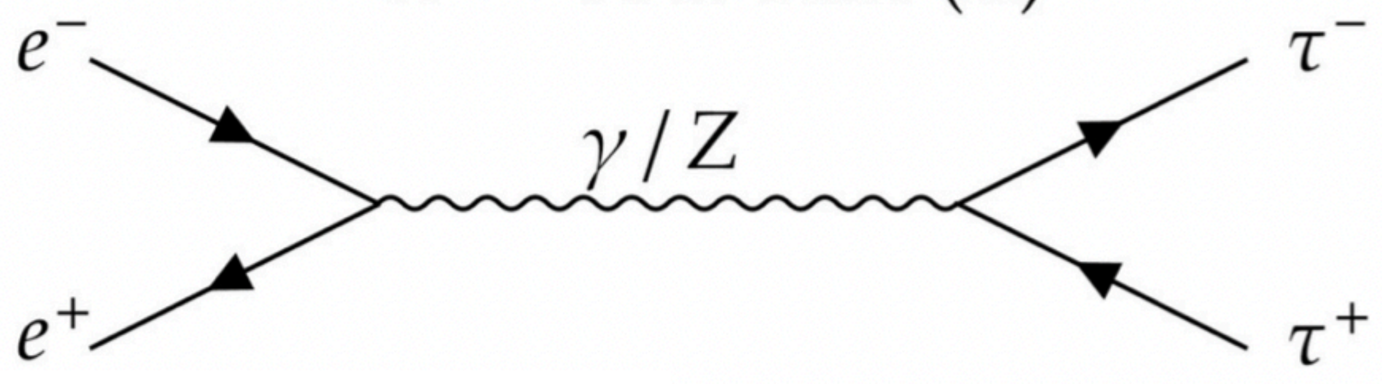
$\sigma[e^+e^- \to ss] = 0.38\ nb$

$\sigma[e^+e^- \to e^+e^-(\gamma)] = 300\ nb$ $\to$ *Background*

Belle (II) physics program



$ee \to \tau\tau$ *at Belle (II)*



Belle (II) vertex and tracking detector

Belle II

Beam Pipe:

- r = 10 mm

PXD config:

- Layer 1: r = 14 mm
- Layer 2: r = 22 mm

SVD config:

- Layer 3: r = 39 mm
- Layer 4: r = 80 mm
- Layer 5: r = 104 mm
- Layer 6: r = 135 mm

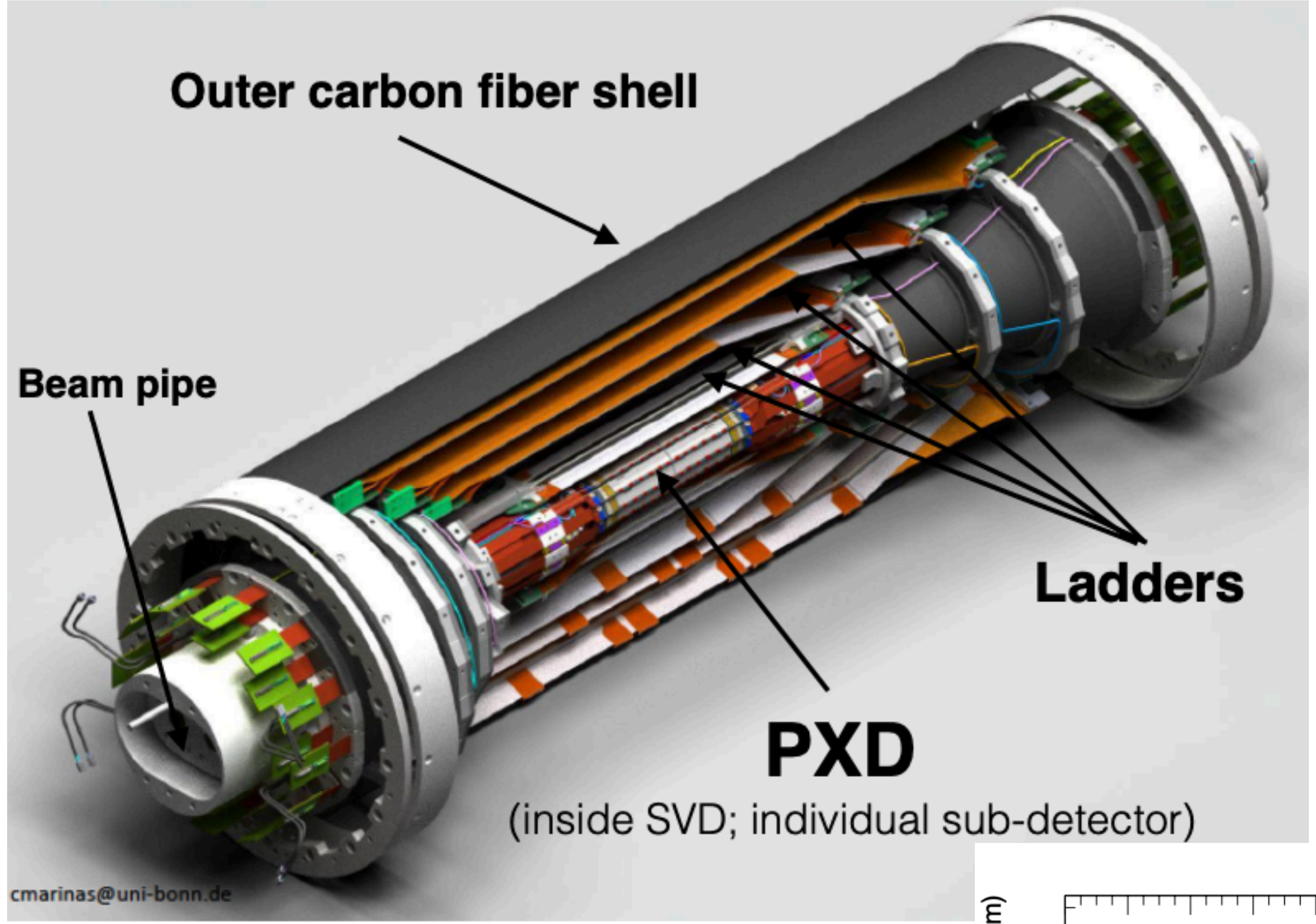
Belle

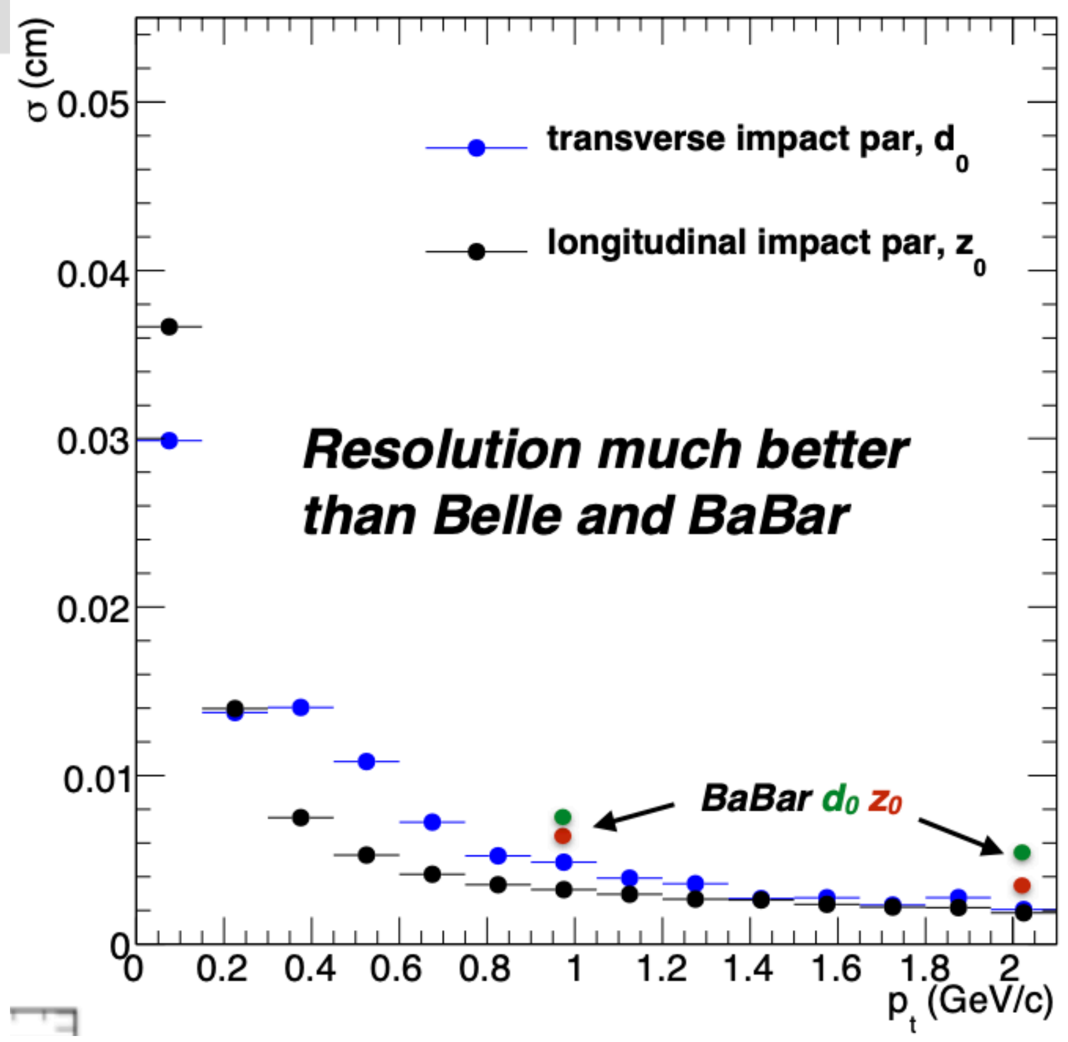
Beam Pipe:

- r = 15 mm

SVD config:

- Layer 3: r = 20 mm
- Layer 4: r = 44 mm
- Layer 5: r = 70 mm
- Layer 6: r = 88 mm

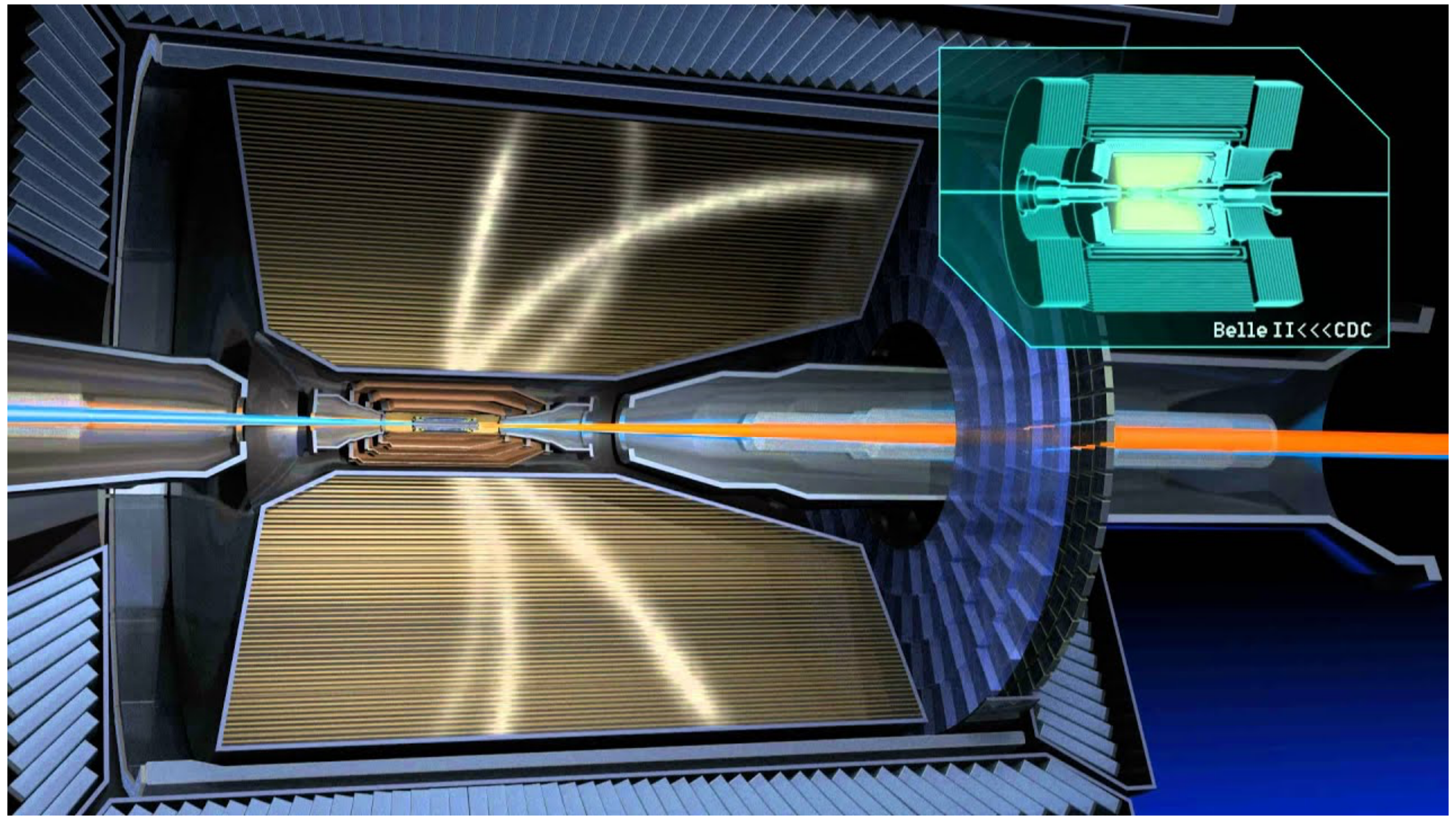


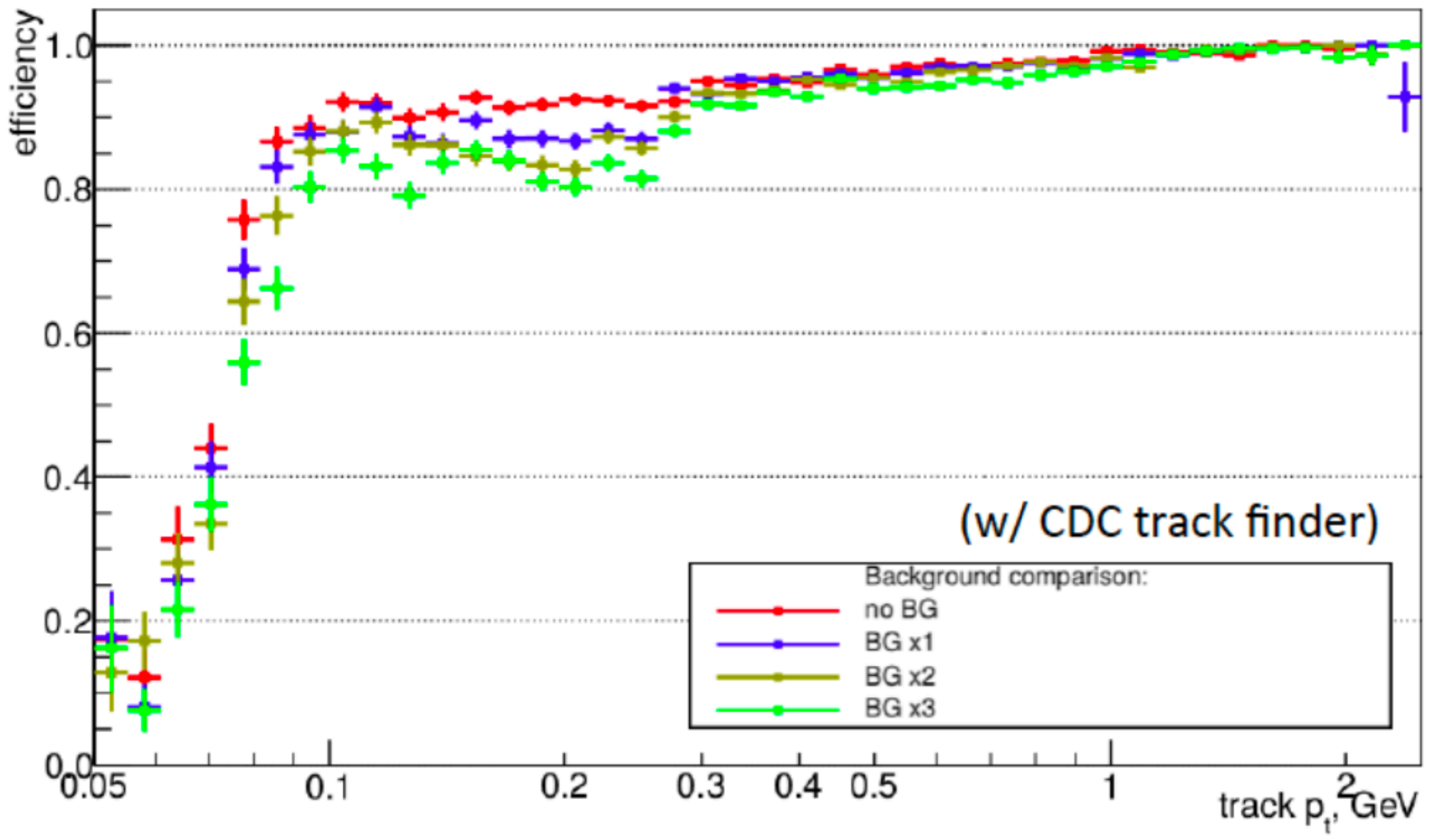


Belle II Impact parameter resolution

- $\sigma_{z0} \sim 20\ \mu$m (PXD and SVD)

Belle II vertex and tracking detector





Belle II CDC:

- r = 16 – 112 cm
- $-83 \leq z \leq 159$ cm

Belle CDC

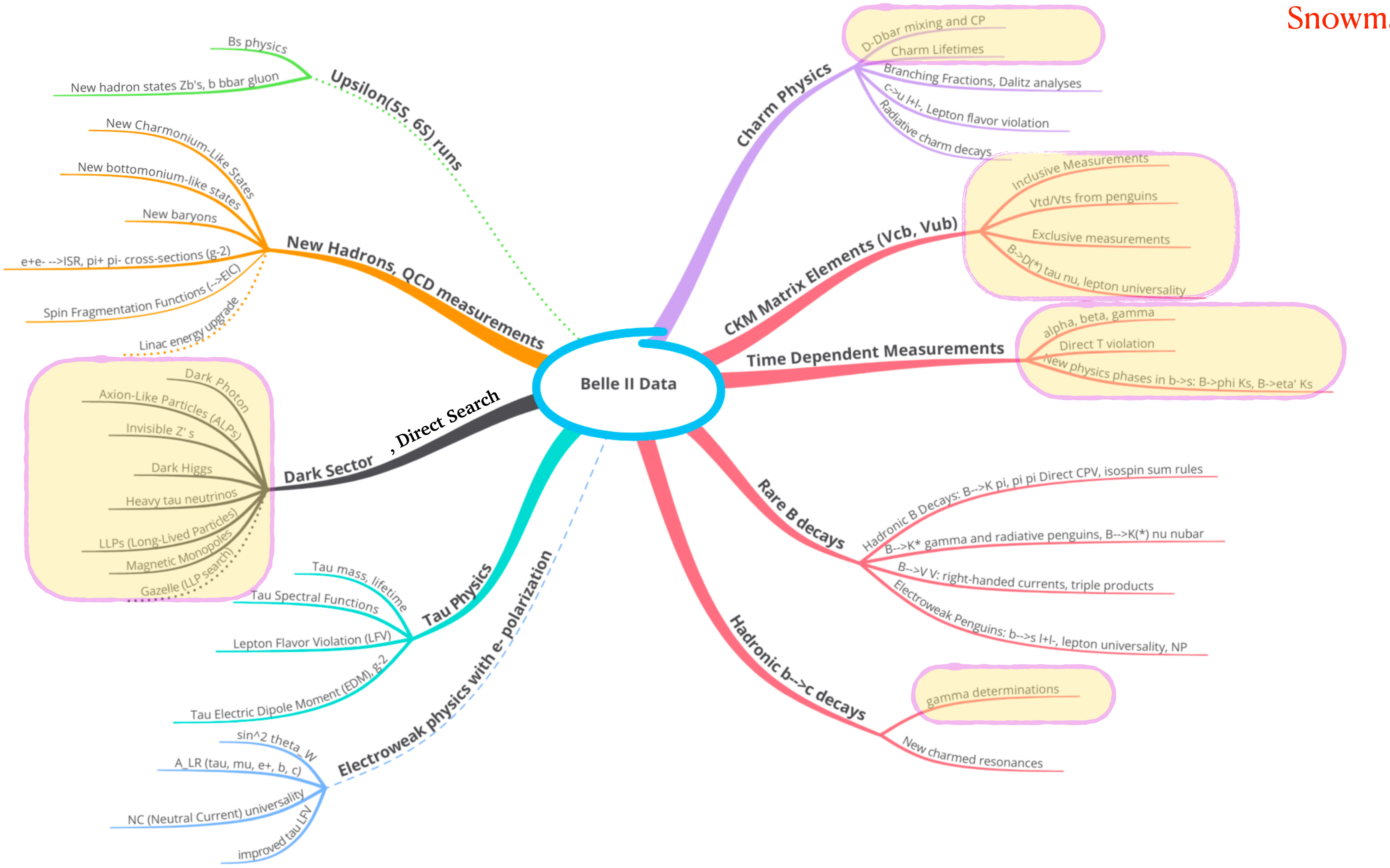
- r = 11 – 86 cm
- $-83 \leq z \leq 159$ cm

$$\sigma_{r\phi} = 100\ \mu\text{m},\ \sigma_z = 2\text{ mm}$$
$$\sigma_{p_t}/p_t = \sqrt{(0.2\% p_t)^2 + (0.3\%/\beta)^2}$$
$$\sigma_{p_t}/p_t = \sqrt{(0.1\% p_t)^2 + (0.3\%/\beta)^2}\ \text{(with SVD)}$$
$$\sigma_{dE/dx} = 5\%$$

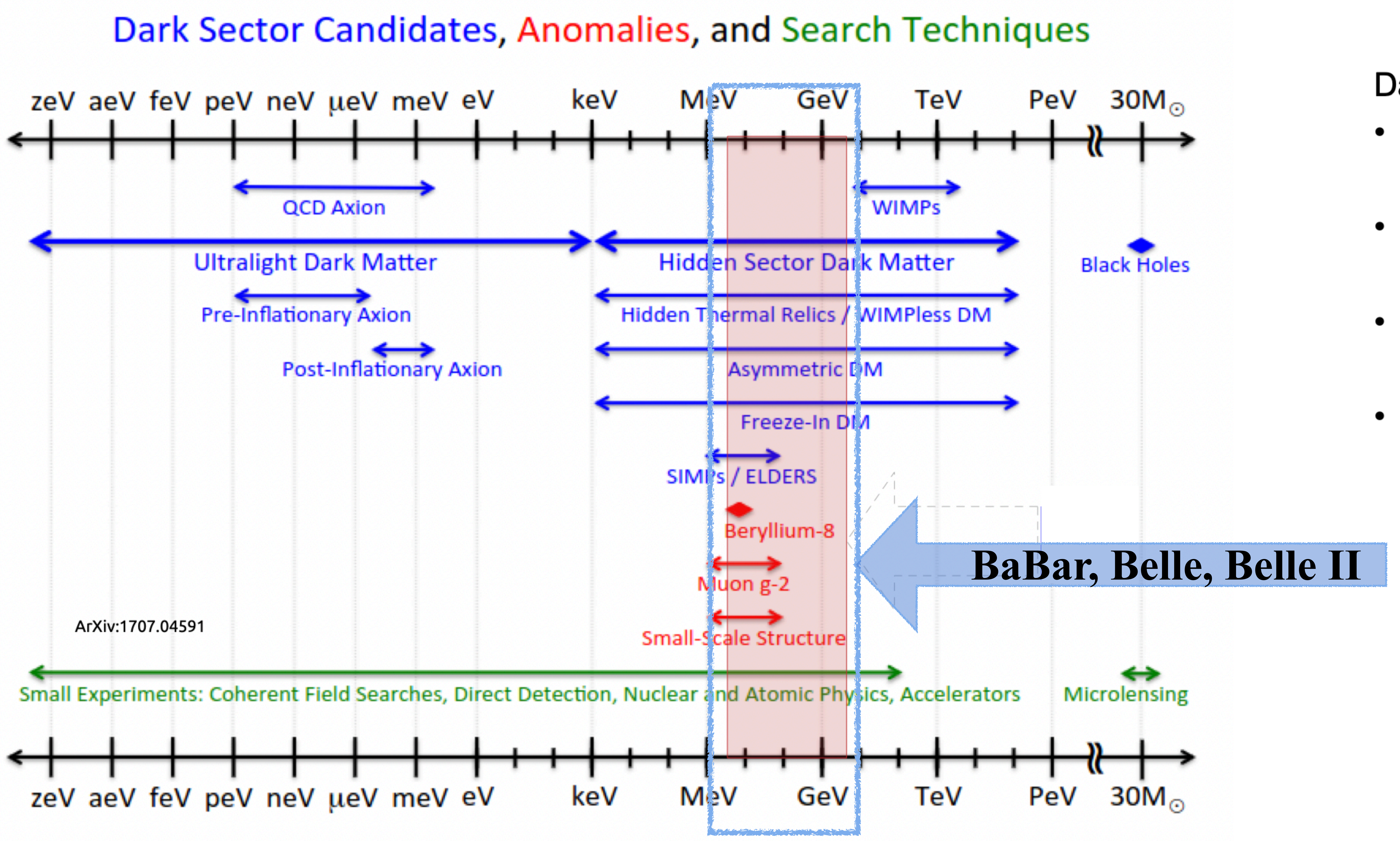
Increased tracking volume in both SVD and CDC compared to Belle ⇒ ~30% higher K_S efficiency

A diversified Physics Program

Snowmass white paper



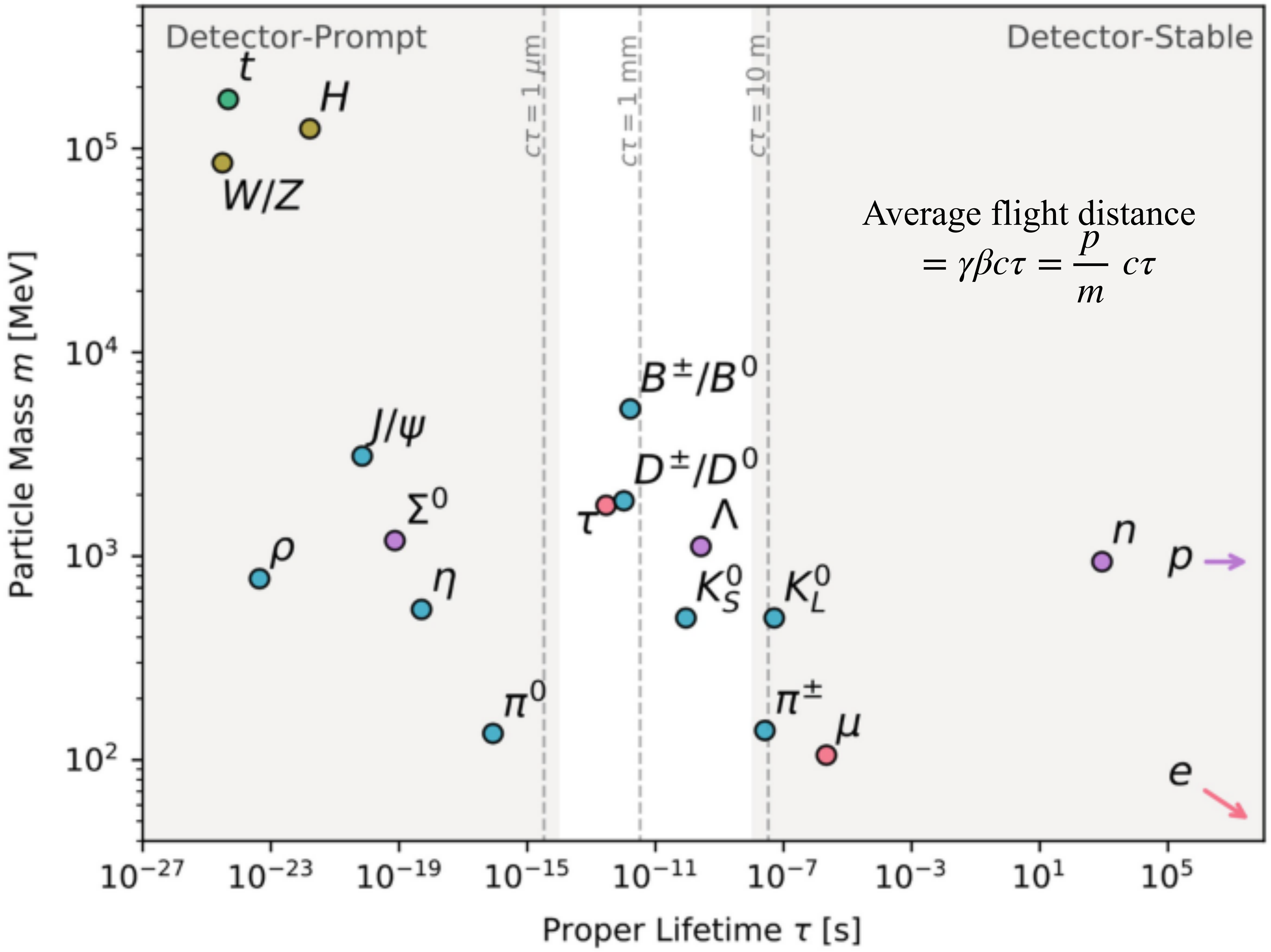
Dark sector covered by e^+e^- B-factories



Dark matter mediators

- Scalar portal
  - Dark Higgs, scalars
- Pseudoscalar portal
  - Axions or ALPs
- Vector portal
  - Dark photon, Z'
- Neutrino portal
  - Sterile neutrino

Particle lifetime categories



- Analyses shown today
  - Heavy Neutral Leptons that mixes predominantly with ν_τ in $\tau^- \to \pi^- N(N \to \mu^\pm \mu^\mp \nu_\tau)$ @ Belle
    Belle, Phys. Rev. D 109, L111102 (2024)
  - Heavy Neutrino in $\tau^- \to \pi^- \nu_h(\nu_h \to \pi^\pm l^\mp)$ decays @ Belle
    Belle, Phys. Rev. Lett. 131, 211802 (2023)
  - Long-lived scalar in $B \to KS$ decays @ Belle II
    Belle II, Phys. Rev. D 108, L111104 (2023)

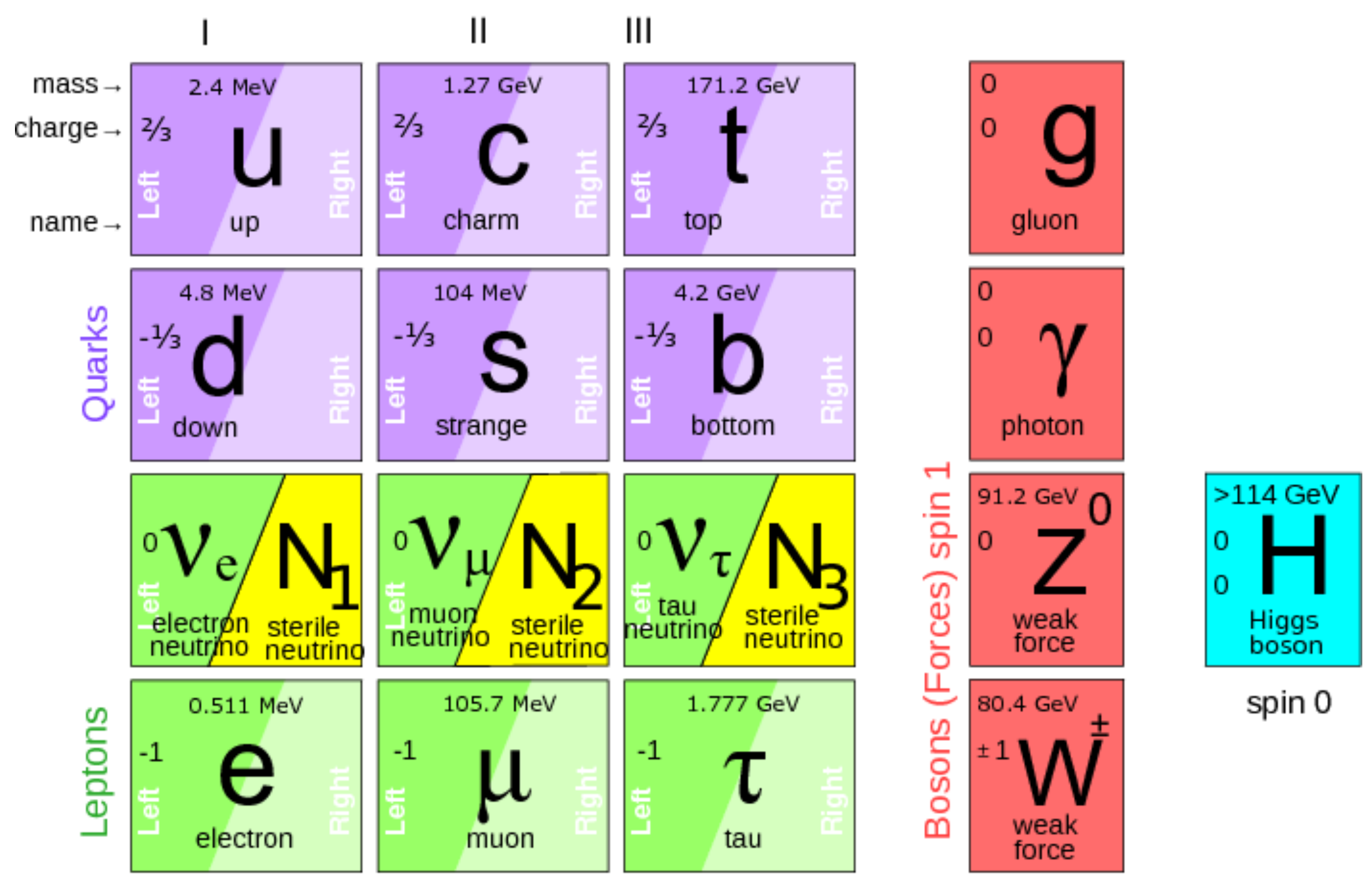
Heavy Neutral Lepton (N)

νMSM can explain origin of the SM neutrino masses

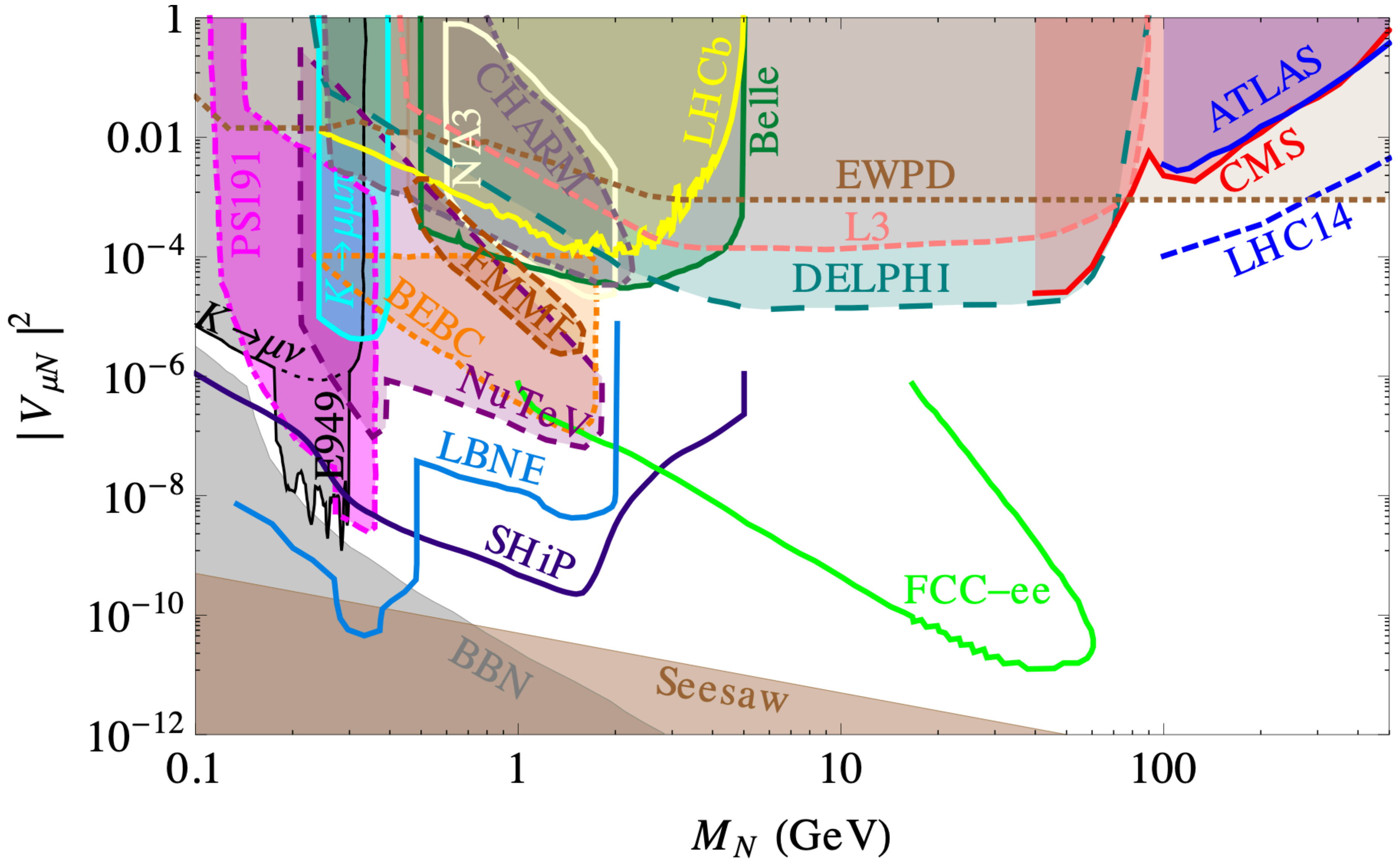
- mass in keV-scale could be a dark matter candidate
- In GeV-scale can explain the origin of baryon asymmetry

Interacts with ν_{SM} through mixing: $N \leftrightarrow \nu_{SM}$

nuMSM



- Different regions of M_N are being explored by different experiments
- All the experiments provide tight limits on $|V_{eN}|, |V_{\mu N}|$
- Limits on $|V_{\tau N}|$ are much weaker: which motivates to study $V_{\tau N}$
- Fewer experiments have directly probed $|V_{\tau N}|$
- Experimentally challenging, but $m_N \sim$ GeV presents opportunities for such interesting studies



Mass eigenstates, HNL production

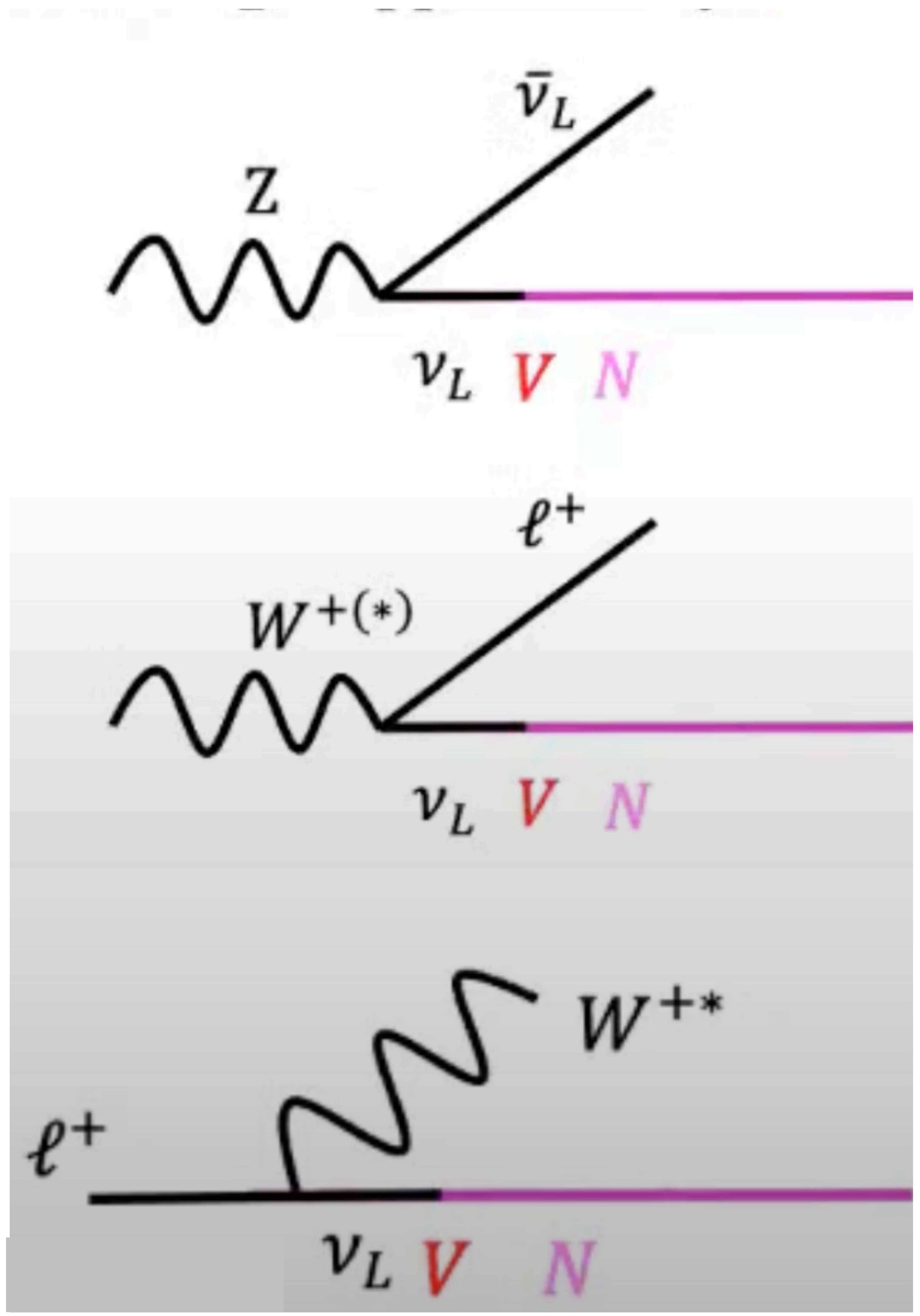
- The mass eigenstates can be written as a linear combination

$$|\nu\rangle \propto |\nu_L\rangle - V^* |\nu_R\rangle$$

$$|N\rangle \propto V|\nu_L\rangle + |\nu_R\rangle$$

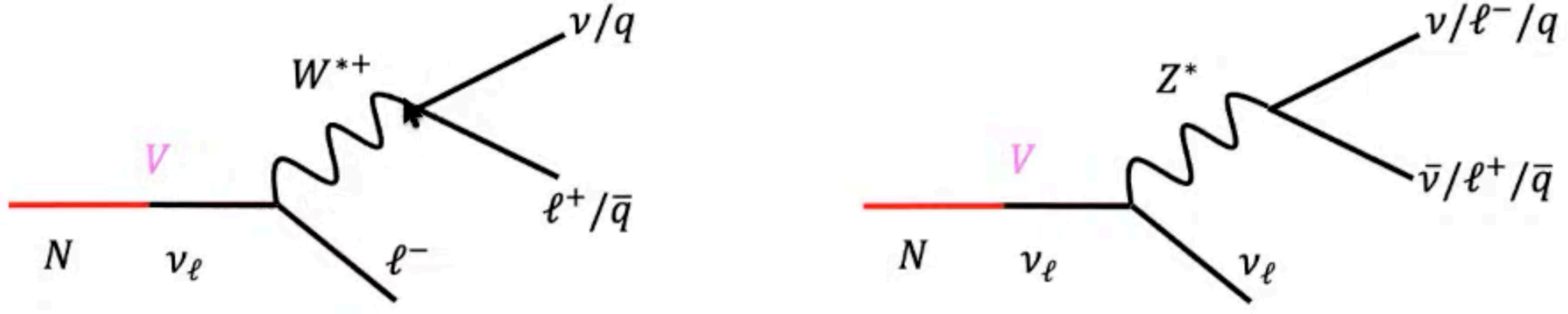
with $|V| << 1$

- N can undergo SM interactions just like ν_L, suppressed by V
- N can produce in Z, or W decays, or lepton decays:



HNL decay

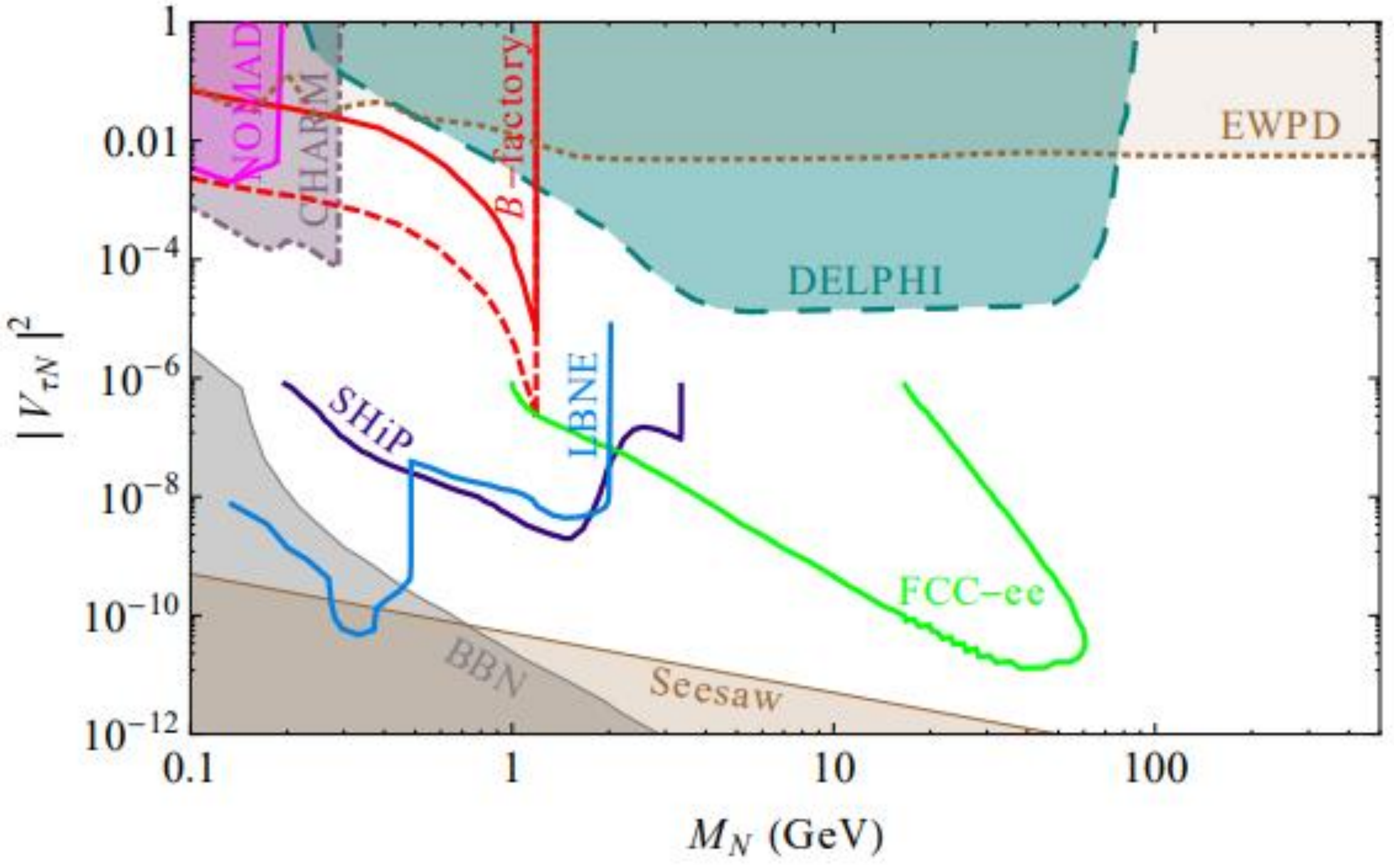
- The GeV-scale N would decay:



- And is long-lived: $c\tau_N \sim 1.4\ \mathrm{mm}\ \frac{1}{|V|^2}\left(\frac{GeV}{m_N}\right)^5$

Can we directly probe $V_{\tau N}$ for $m_N < \sim 2$ GeV?

- Not well studied
- Tough at LHC due to
  - $c\tau \sim m_N^{-5}$
  - Higher $\gamma\beta$
  - Hard to trigger on soft τ
- Best facility is B-factories
  - Small boost: $\frac{p_N}{m_N} \sim 3$
  - DV radius < 1000 mm
  - Larger acceptance than CMS/ATLAS for low-mass (very high lifetime) HNL

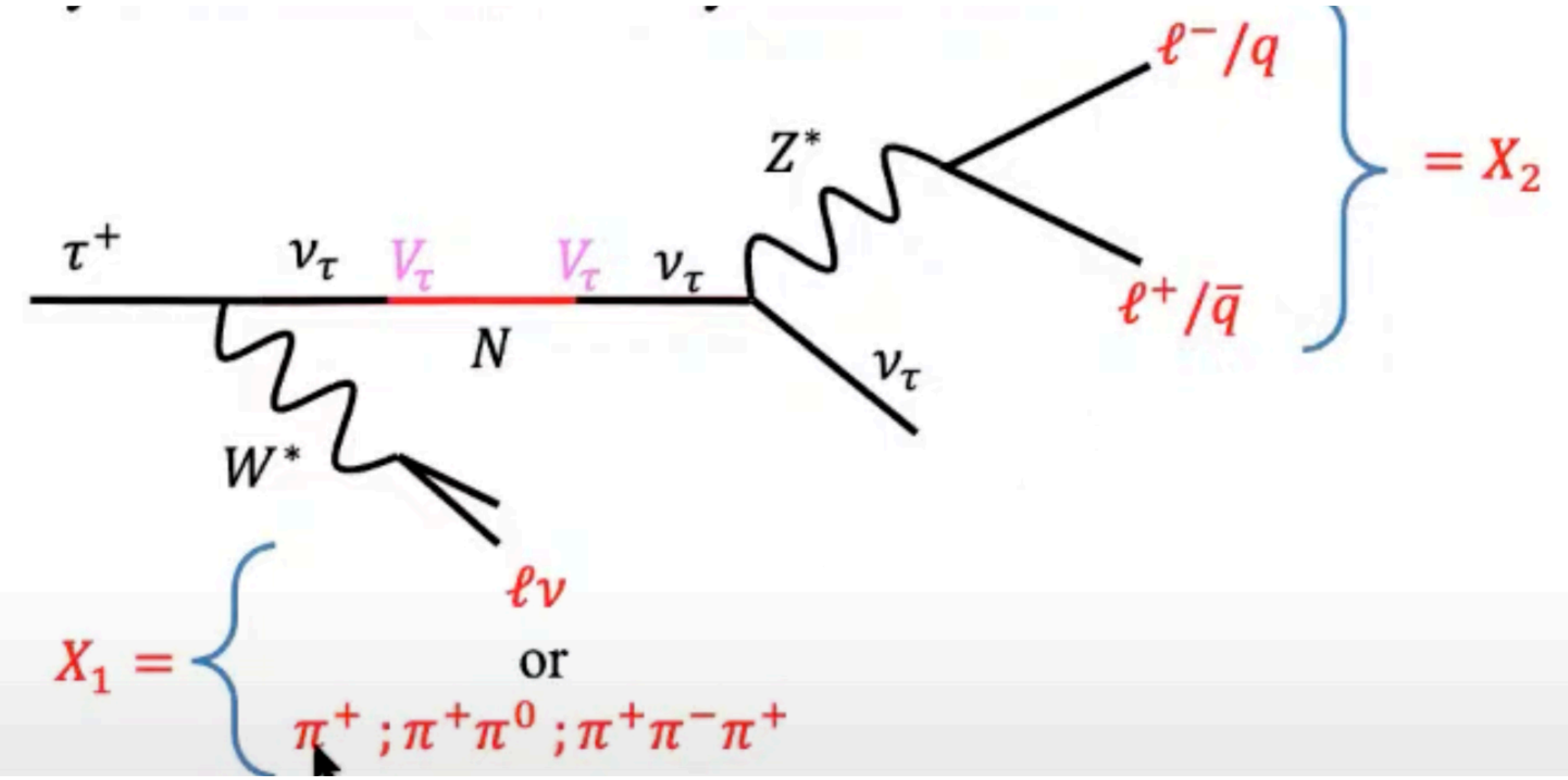


Unfilled curves show future limits from proposed searches.

arXiv:1502.06541

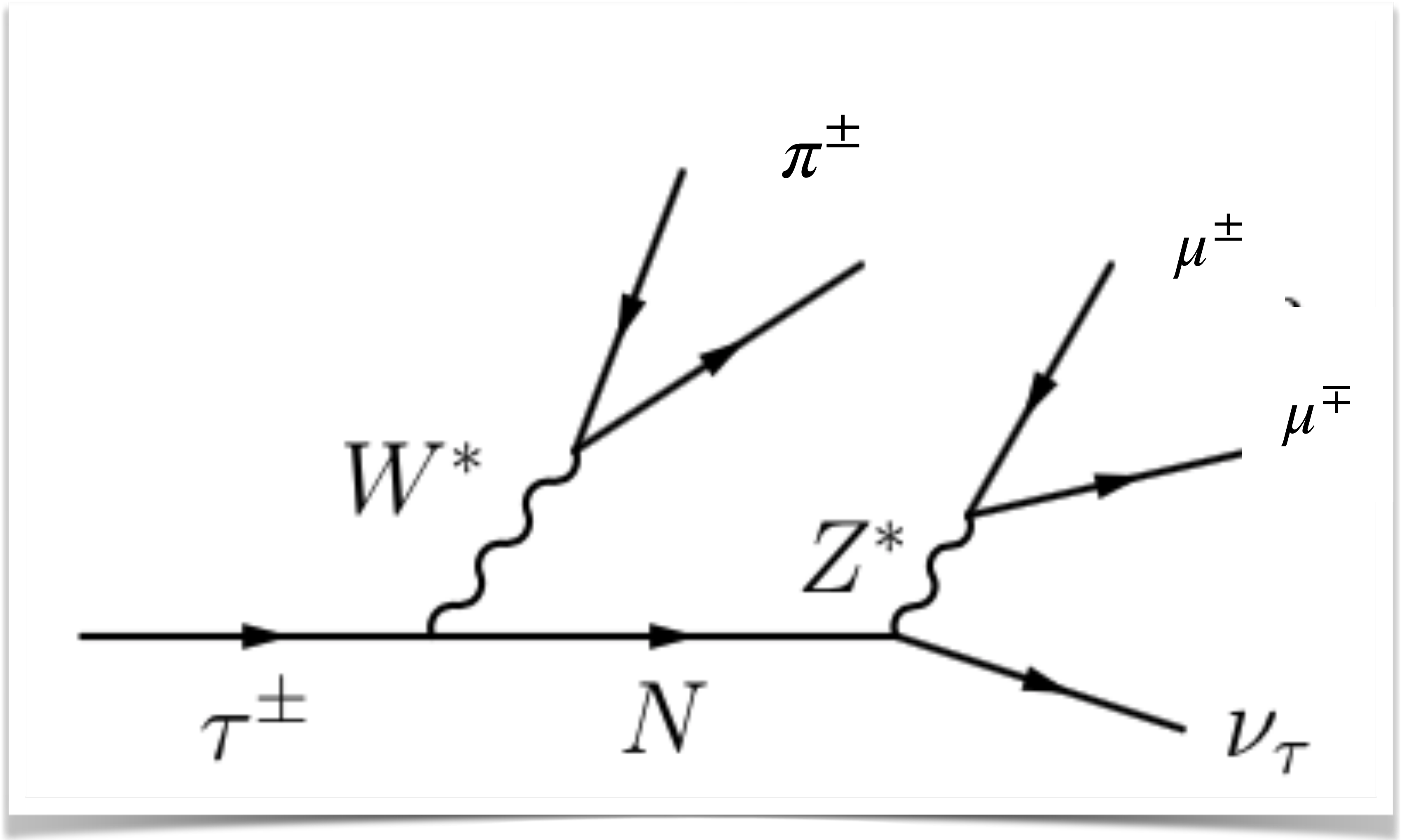
Can we directly probe $V_{\tau N}$ for $m_N < \sim 2$ GeV?

- Since $m_N < m_\tau$, only neutral-current N is allowed
- We studied only the hadronic-X_1 case, and muonic-X_2, that gives a better background suppression handle
- But leptonic-X_1, and other possible X_2 are possible, but it requires a study of full MC



Kinematic and vertex constraints

- 12 unknowns:
  - p_ν^μ, p_N^μ, p_τ^μ
- 12 constraints:
  - 8: 4-momentum conservation in the τ and N decays
  - 2: Known masses of m_τ and m_{ν_τ}
  - 2: $\hat{p}_N$ the direction of $\overrightarrow{p}_N$ (line from τ^+ decay point to X_2 displaced vertex)



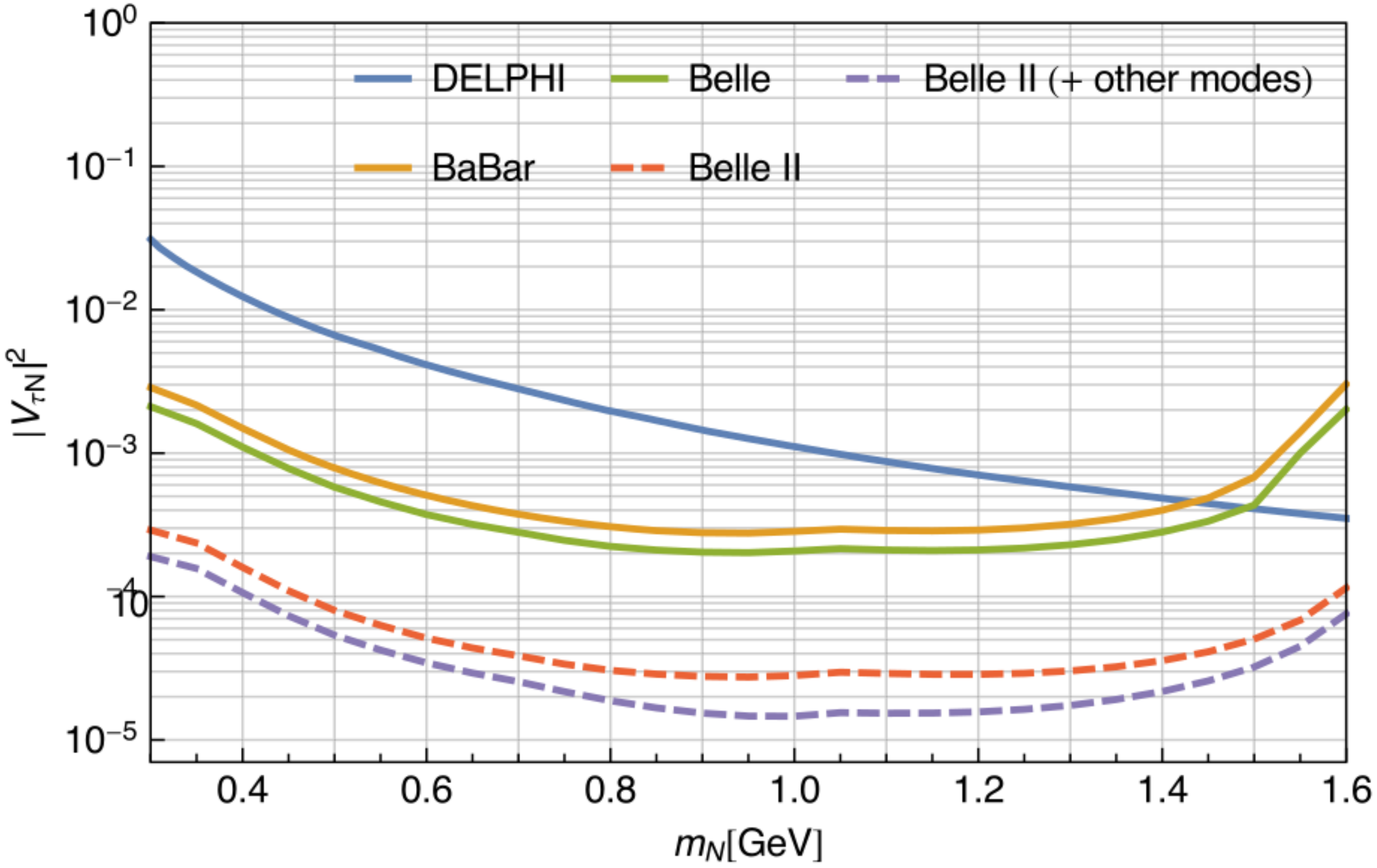
- Thus all 4-momenta (hence m_N) can be solved analytically
  - up to 2-fold ambiguity due to quadratic equation
  - This was first publication of this idea

Sensitivity estimate

Phys. Rev. D 101, 093003(2020)

Dib, Helo, M . Nayak, Neill, Soffer, Zamora-Saa

- Using this constraints, we estimated negligible background at Belle and found that the sensitivity will be up to 100 times better than that of DELPHI



Analysis at Belle

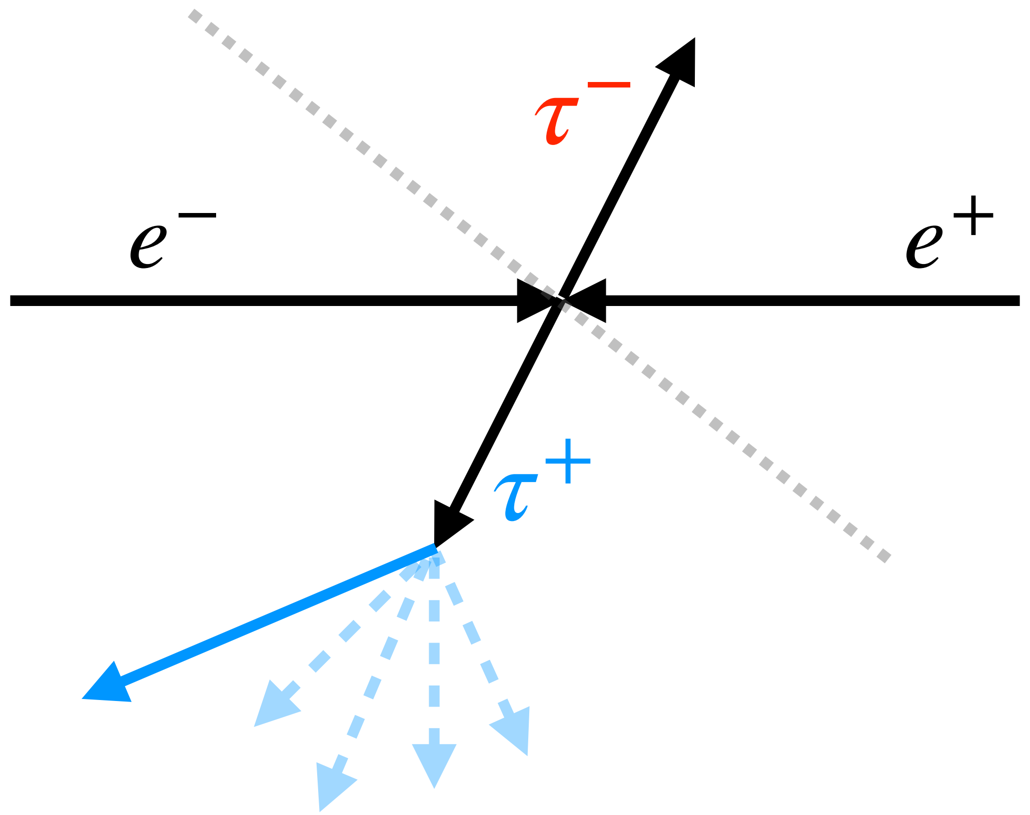
M. Nayak et al. (Belle Collaboration), Phys. Rev. D 109, L111102 (2024)

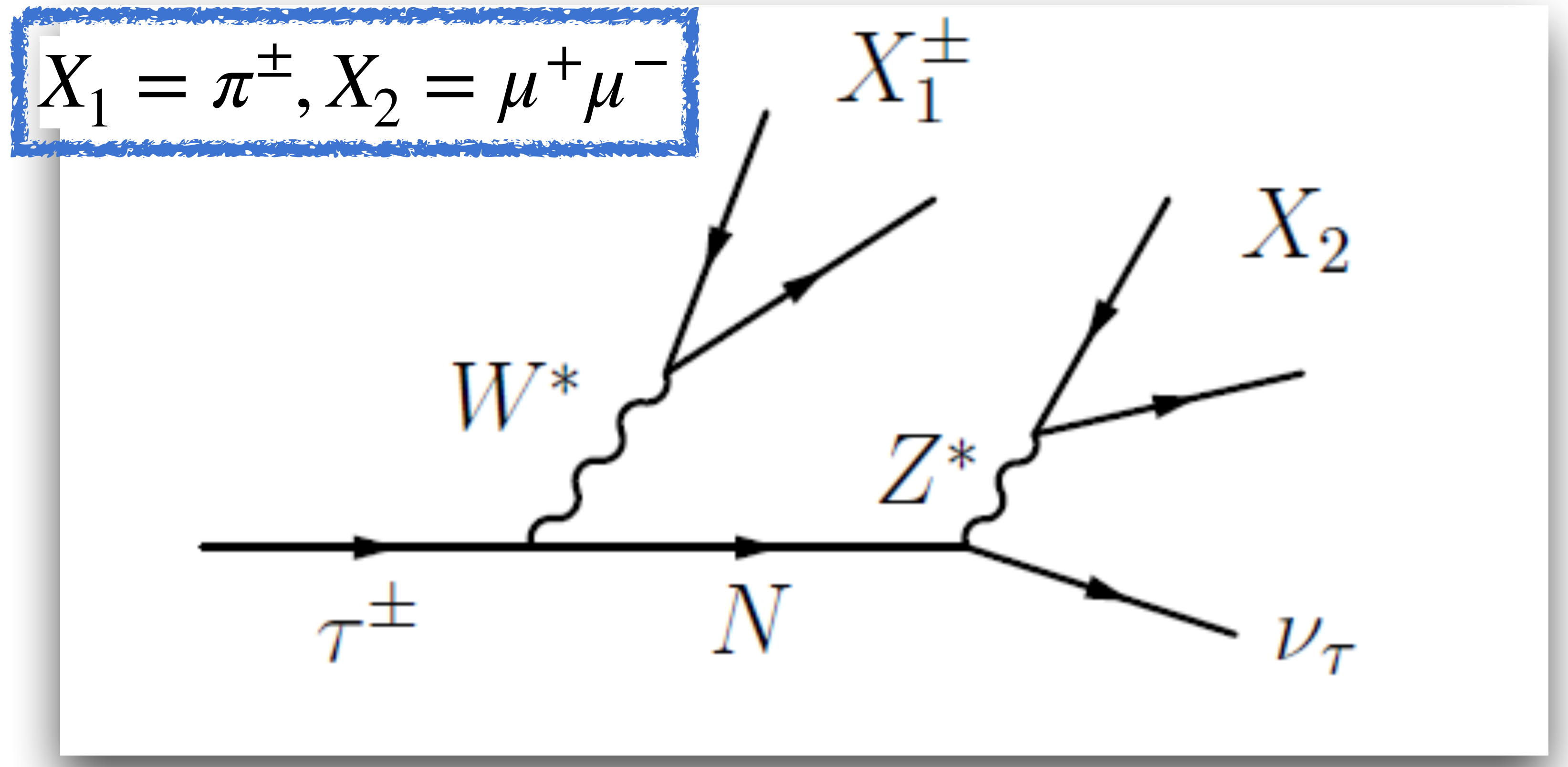
With Ori Fogel, Abner Soffer, Sourav Dey

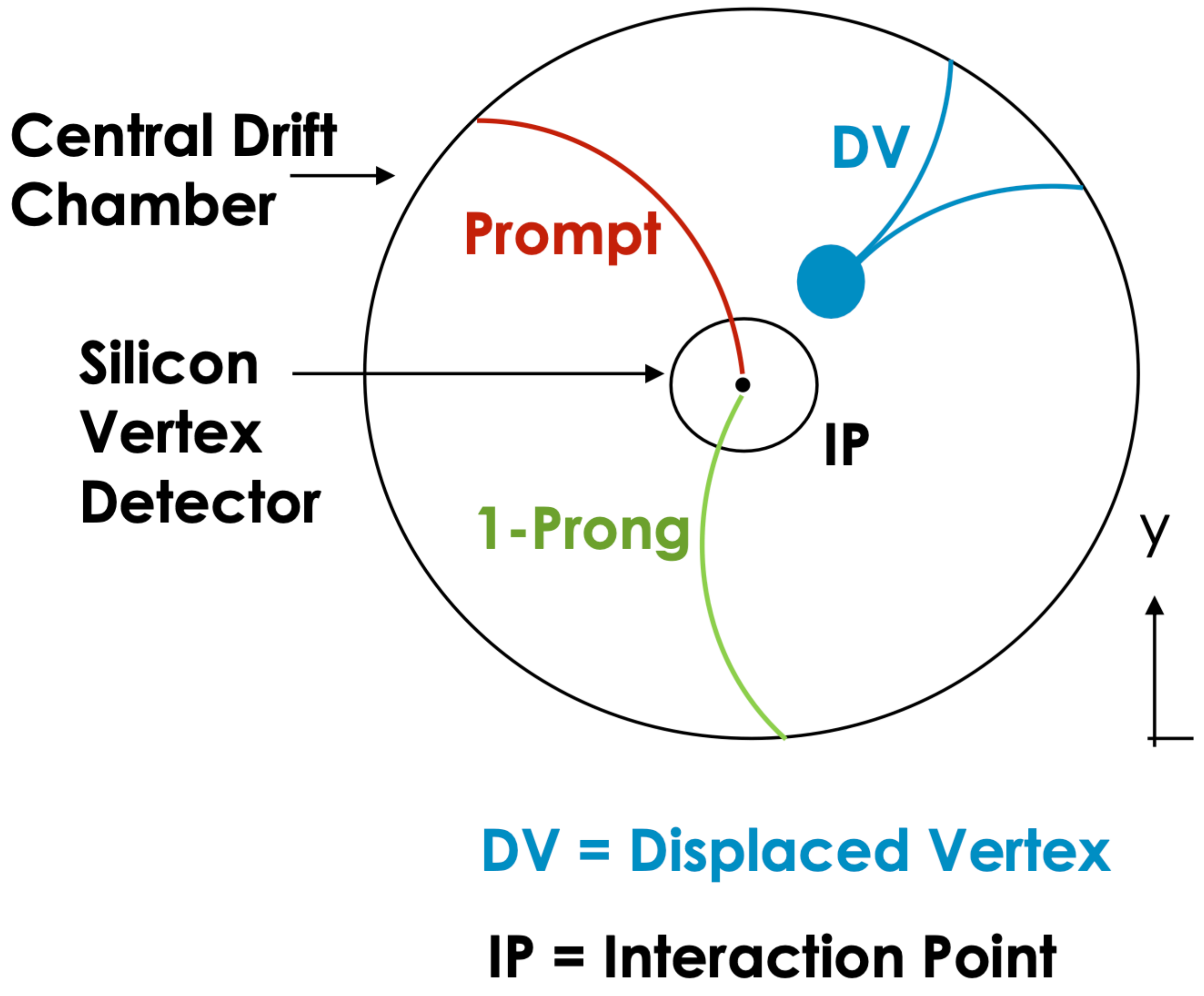
- Belle has lower efficiency than Belle II, due to
  - Smaller drift chamber
  - Less efficient mu-ID and tracking for highly displaced tracks
- Large data set already available
  - $L \simeq 980\ \text{fb}^{-1}$
  - $\sigma(e^+e^- \to \tau^+\tau^-) \approx 0.919\ \text{nb}$
  - $(836 \pm 12) \times 10^6\ e^+e^- \to \tau^+\tau^-$ events

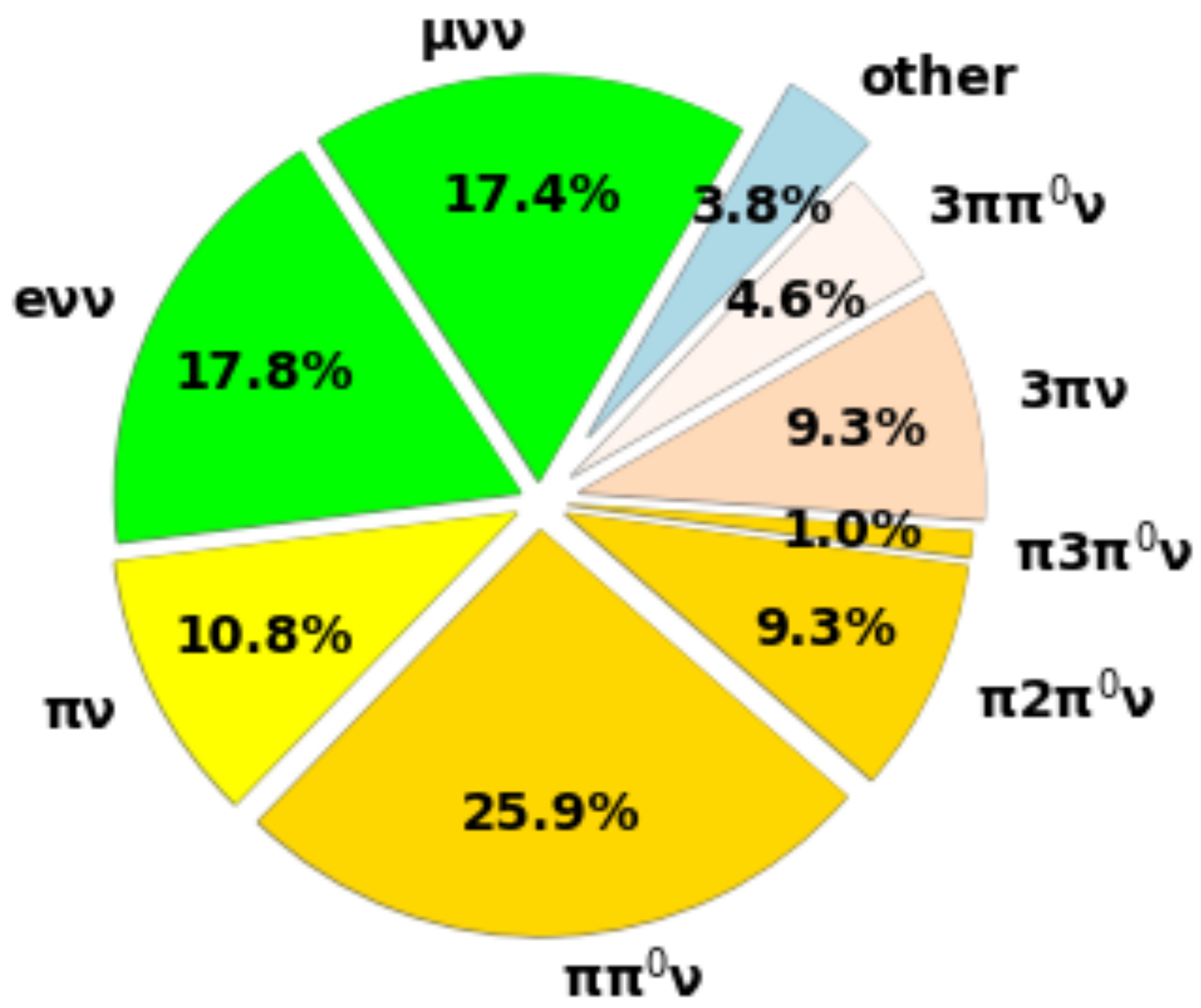
Analysis method

- This analysis probes $V_{\tau N}$ directly
- Channel: $e^+e^- \rightarrow \tau^+_{\text{tag}}\tau^-_{\text{sig}}$
    - Tag side: all SM allowed channels
    - Signal side: $\tau^-_{\text{sig}} \rightarrow \pi^-\text{N}(\rightarrow\mu^+\mu^-\nu_\tau)$
    - We look for $\mu^+\mu^-$ displaced vertex (DV)
    - Radial position of the DV use be 15 cm away from the CDC symmetry axis



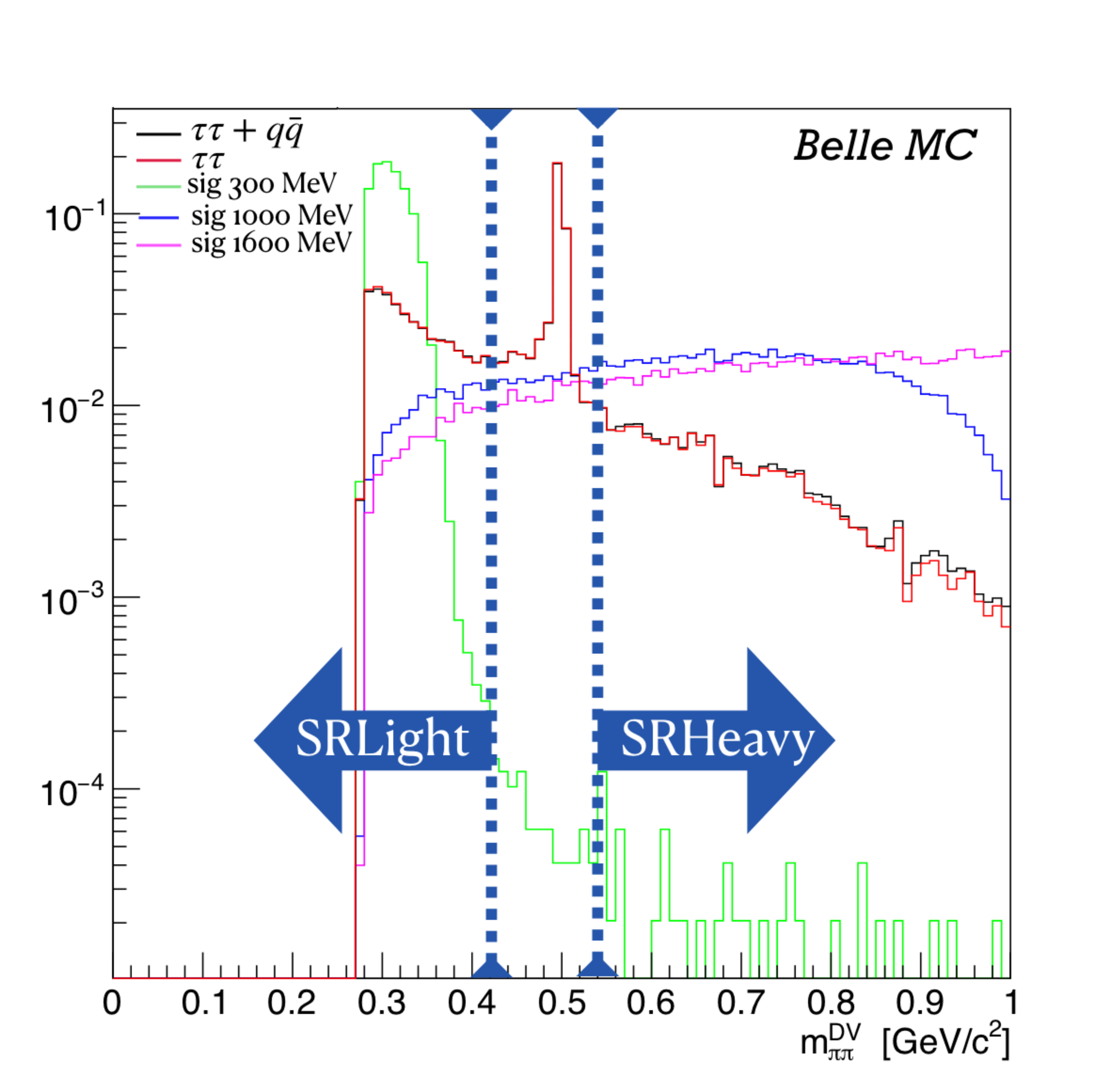






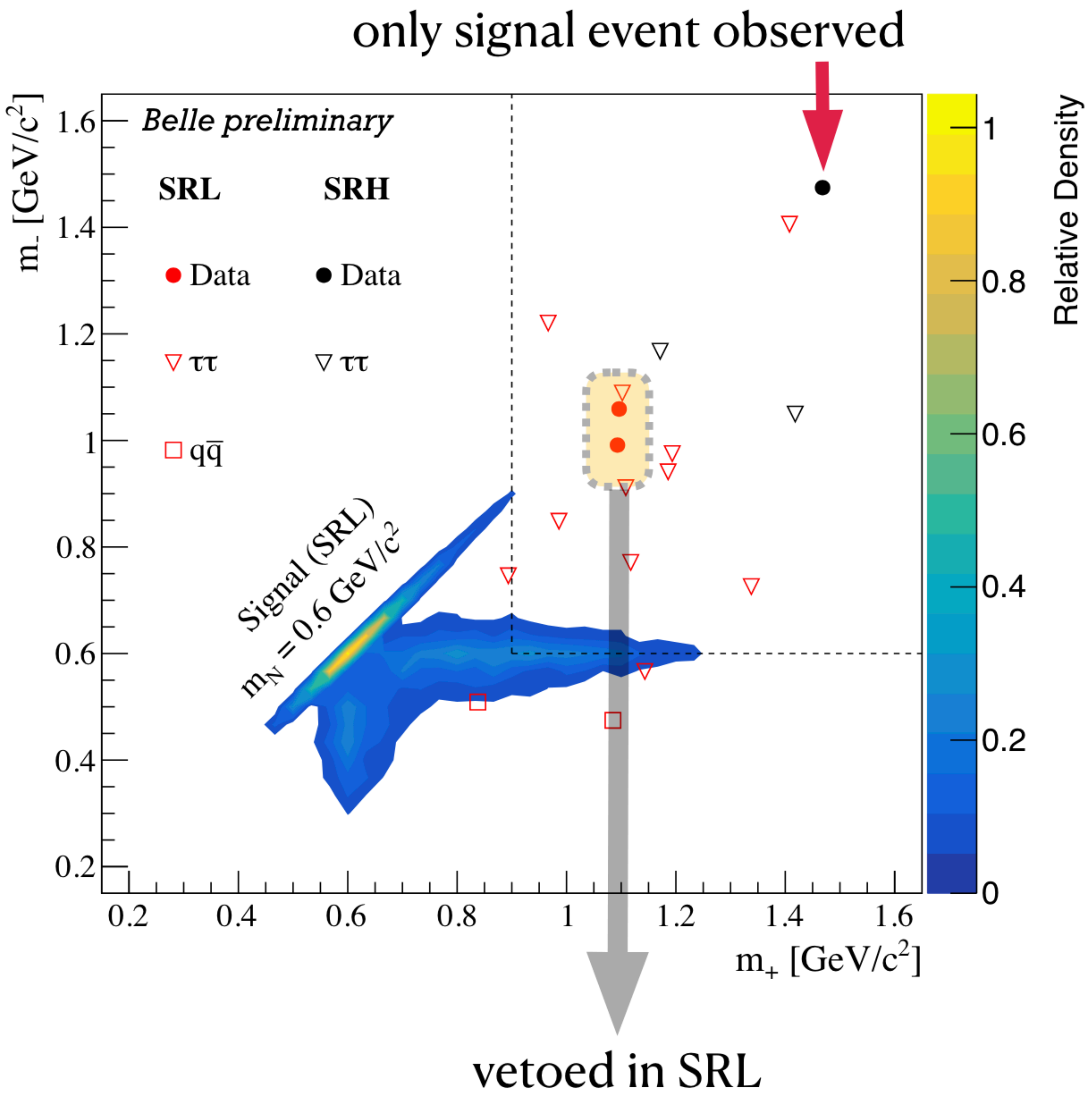
Analysis overview

- K_S^0 is a long-lived neutral particle, so it can produce a DV similar to the HNL
- Exclude the K_S^0 mass region
- We define two signal regions targeting low- and high-mass HNLs
  1. SRh: $M_{\pi\pi}^{DV} > 0.52$ GeV/c^2
  2. SRl: $M_{\pi\pi}^{DV} < 0.42$ GeV/c^2
- From MC, expect 0.8 and 0.4 events in these SRs
- Data driven background estimate using control regions: $X_2 = \mu^{\pm}\pi^{\mp}$
- Validate the model with 3 validation regions:
  - $X_2 = \pi^{\pm}\pi^{\mp}$ (outside and inside the K_S^0 region)
  - $X_2 = \mu^{\pm}\mu^{\pm}$
- Control and validation regions are also divided as CRh, CRl and VRh, VRl (similar to signal region)



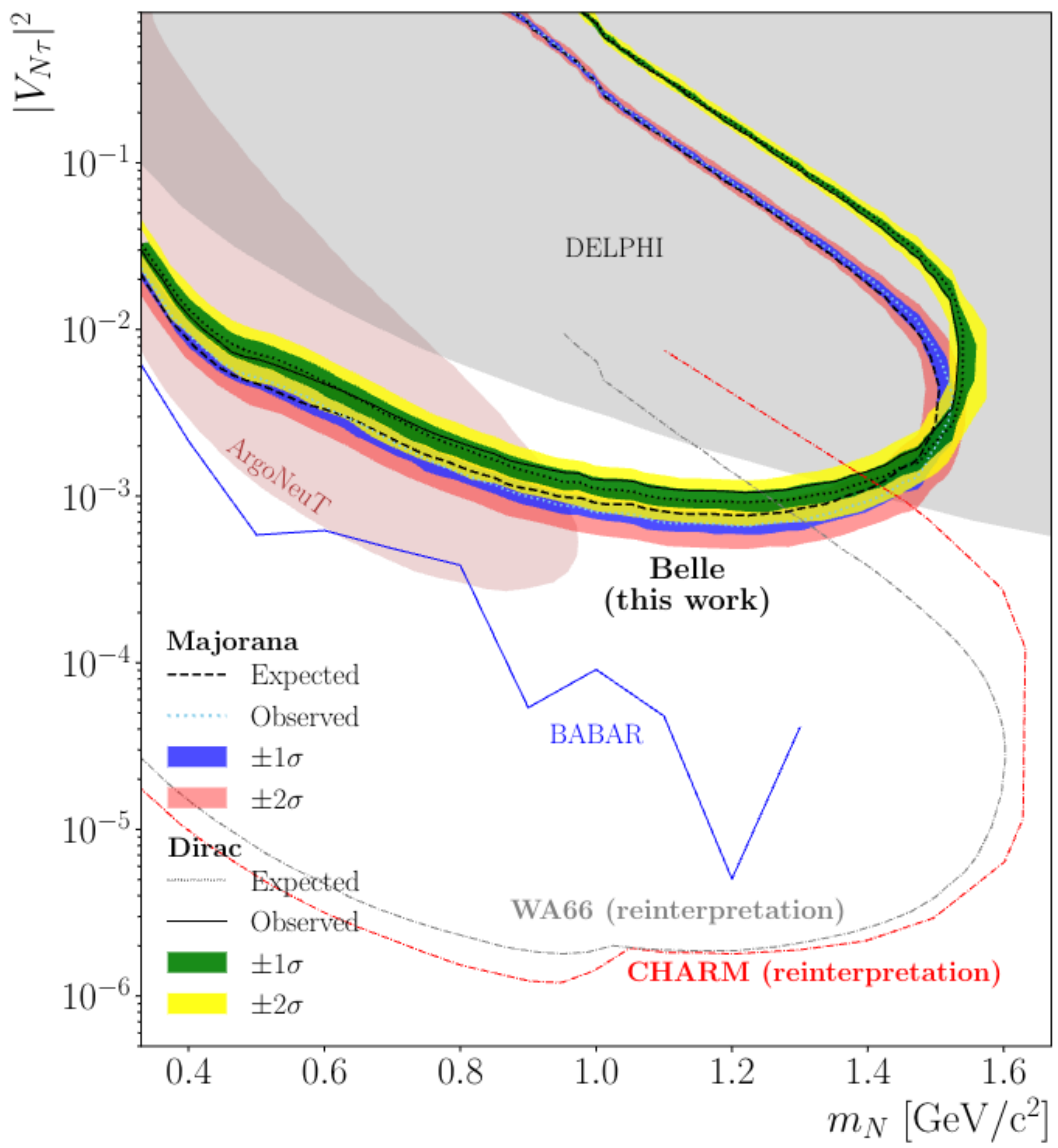
Results

- In SRL, a cut for high m_+, m_- exclusion is applied.
- In SRH and SRL, we observe 1 and 0 signal events respectively.
- This is in agreement with the background expectation.



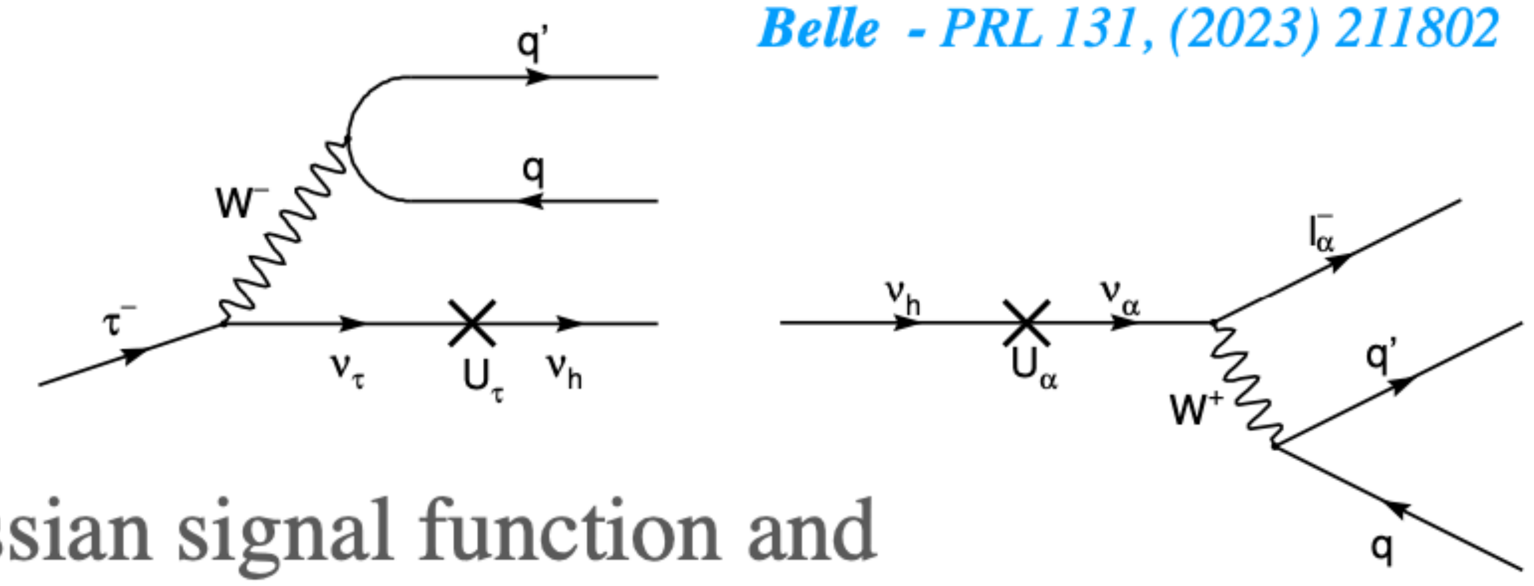
Results

- 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.
- Innovative analysis technique exploited!



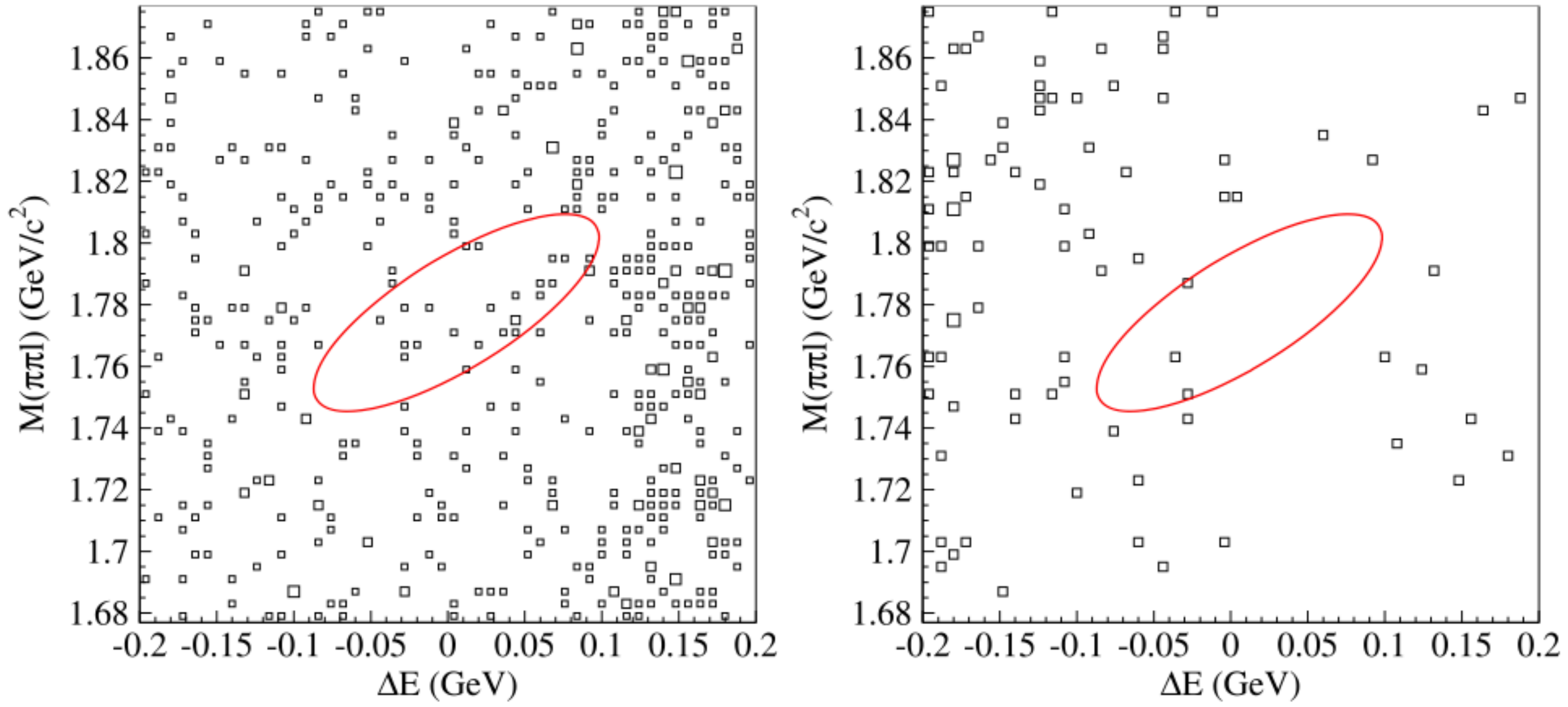
Search for $\tau^- \to \pi^- \nu_h(\nu_h \to \pi^\pm l^\mp)$ decay @ Belle

Belle - PRL 131, (2023) 211802

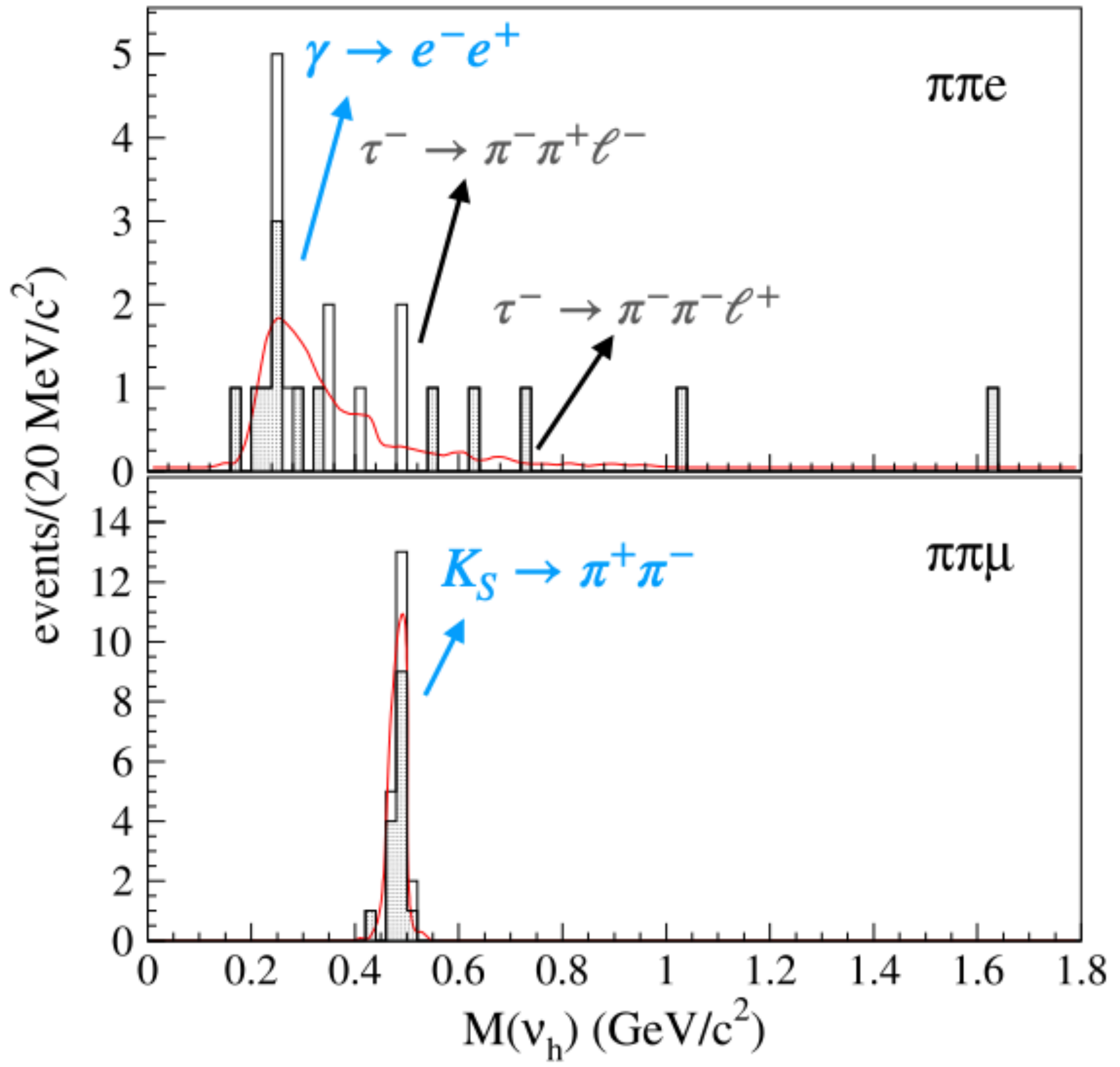


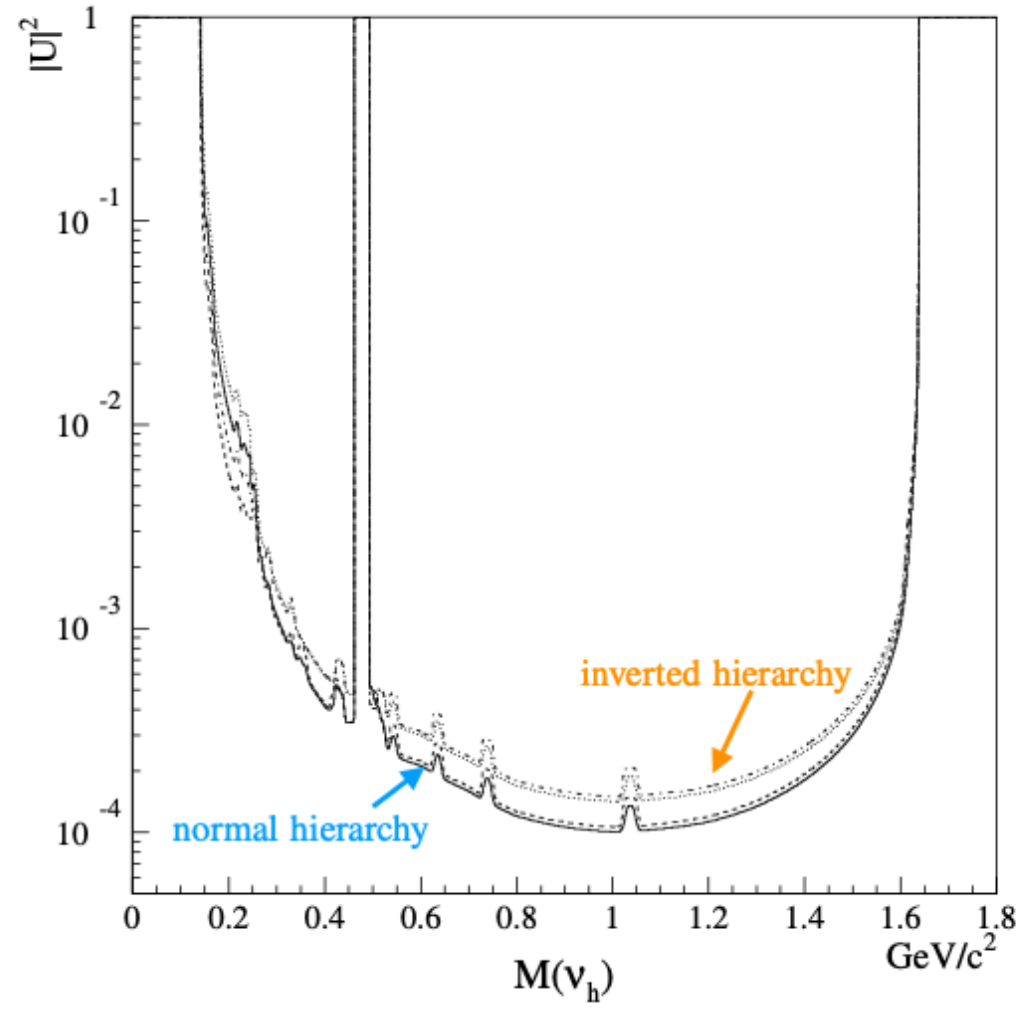
Search for a heavy neutrino $200 < M_{\nu_h} < 1600$ MeV

- ➡ The search uses the data set of Belle with $N_{\tau\tau} = (912 \pm 13) \times 10^6$
- ➡ Signature: prompt pion and **long-lived**, heavy neutrino $\nu_h \to \pi^\pm \ell^\mp$
- ➡ A series of binned likelihood fits to the mass distributions using the sum of a Gaussian signal function and background varying the mass hypothesis in each fit.
- ➡ No significant access
- ➡ Set 95% C.L. upper limits on $|U|^2 = |U_e|^2 + |U_\mu|^2 + |U_\tau|^2$ as a function of M_{ν_h} for the two neutrino-mass hierarchy scenarios



(a) (b)

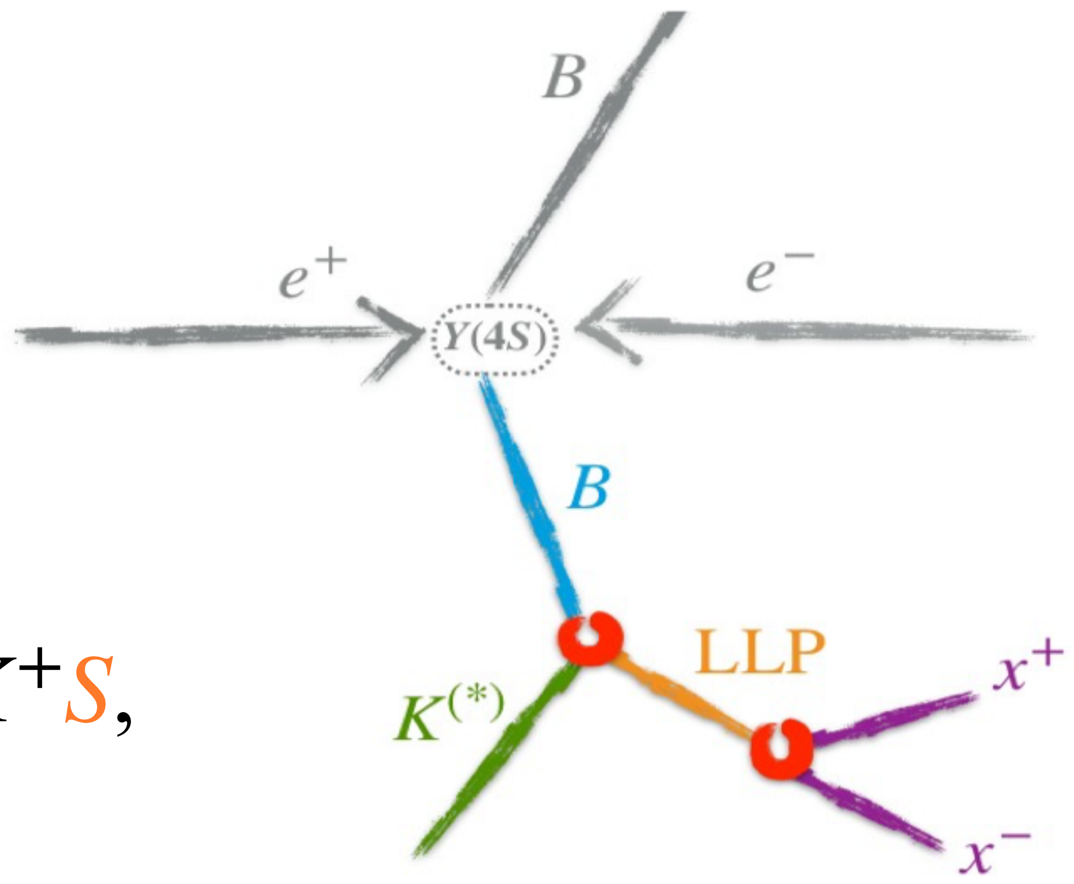


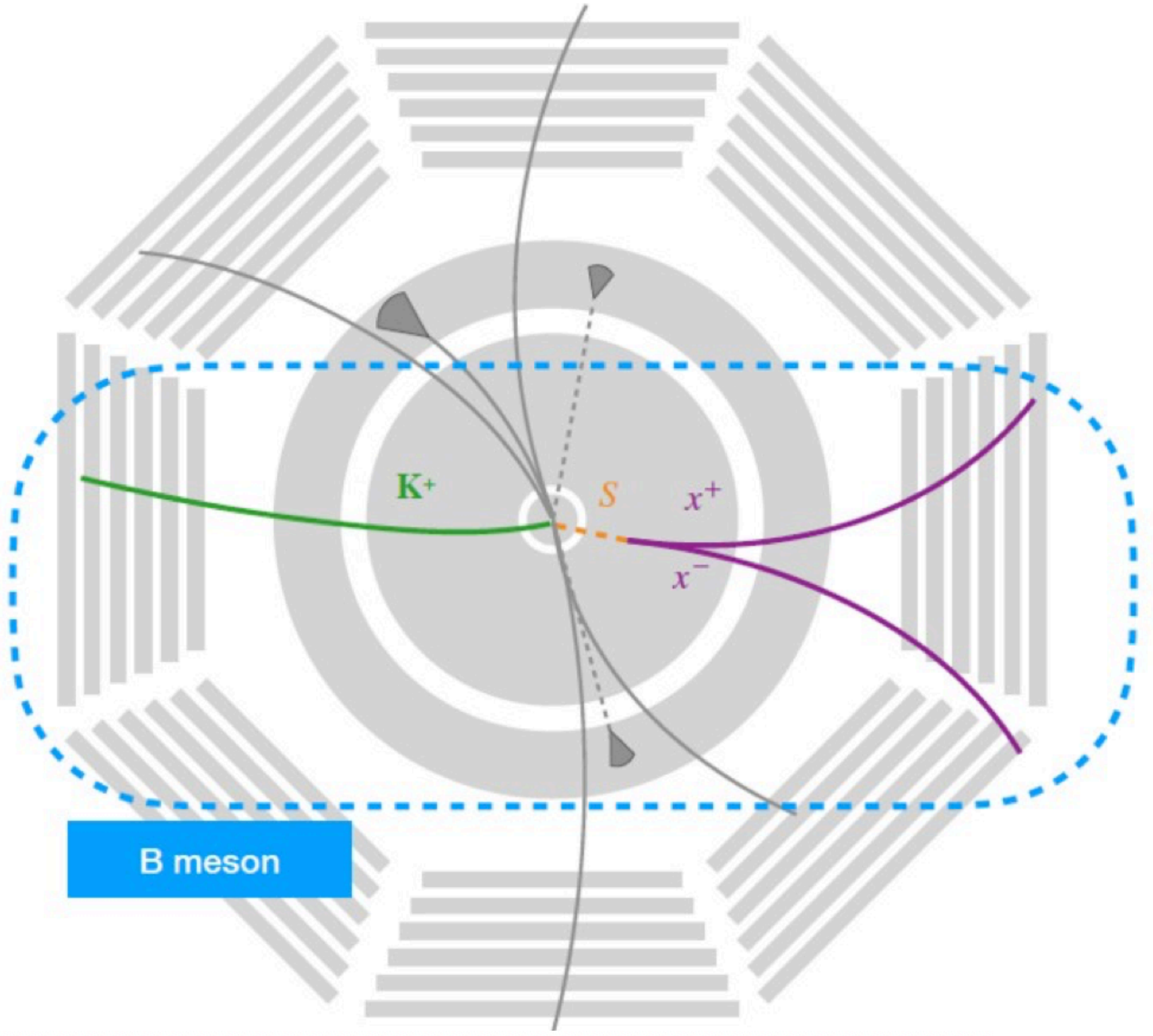


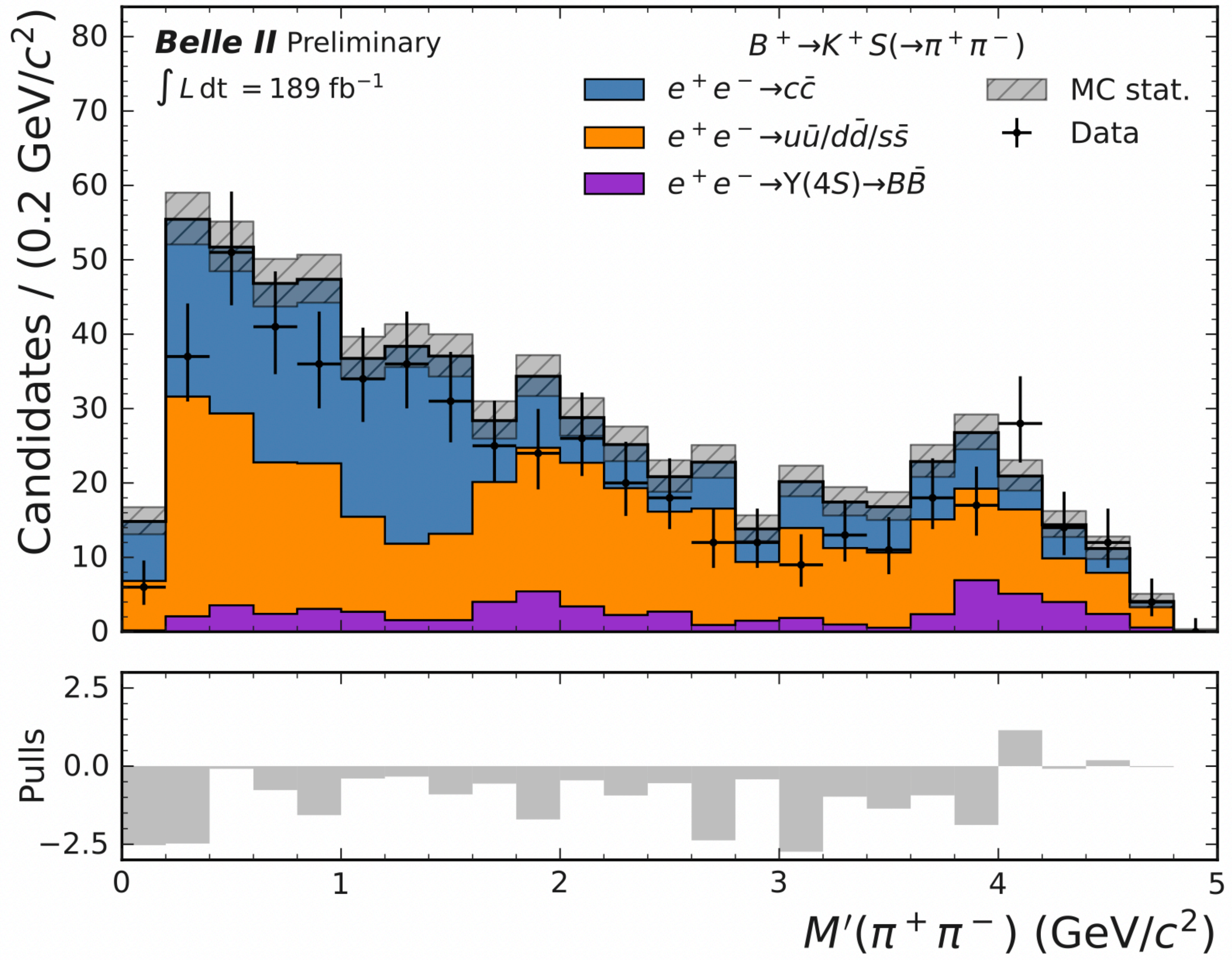
Long-lived scalar in B decays @ Belle II

Belle II, Phys. Rev. D 108, L111104 (2023)

- First Belle II long-lived particle search
- Possible mixing with SM Higgs with mixing angle θ_s
- Search for scalar S decays in eight visible B channels: $B^+ \to K^+S$, $B^0 \to K^{*0}(\to K^+\pi^-)S$
  - $S \to e^+e^-/\mu^+\mu^-/\pi^+\pi^-/K^+K^-$
- Signal B-meson fully reconstructed
- B-meson kinematics to reject combinatorial $e^+e^- \to q\bar{q}$ background
- Further peaking backgrounds suppressed by tighter displacement selection
- Bump hunt in dark scalar mass distribution using unbinned maximum likelihood fits

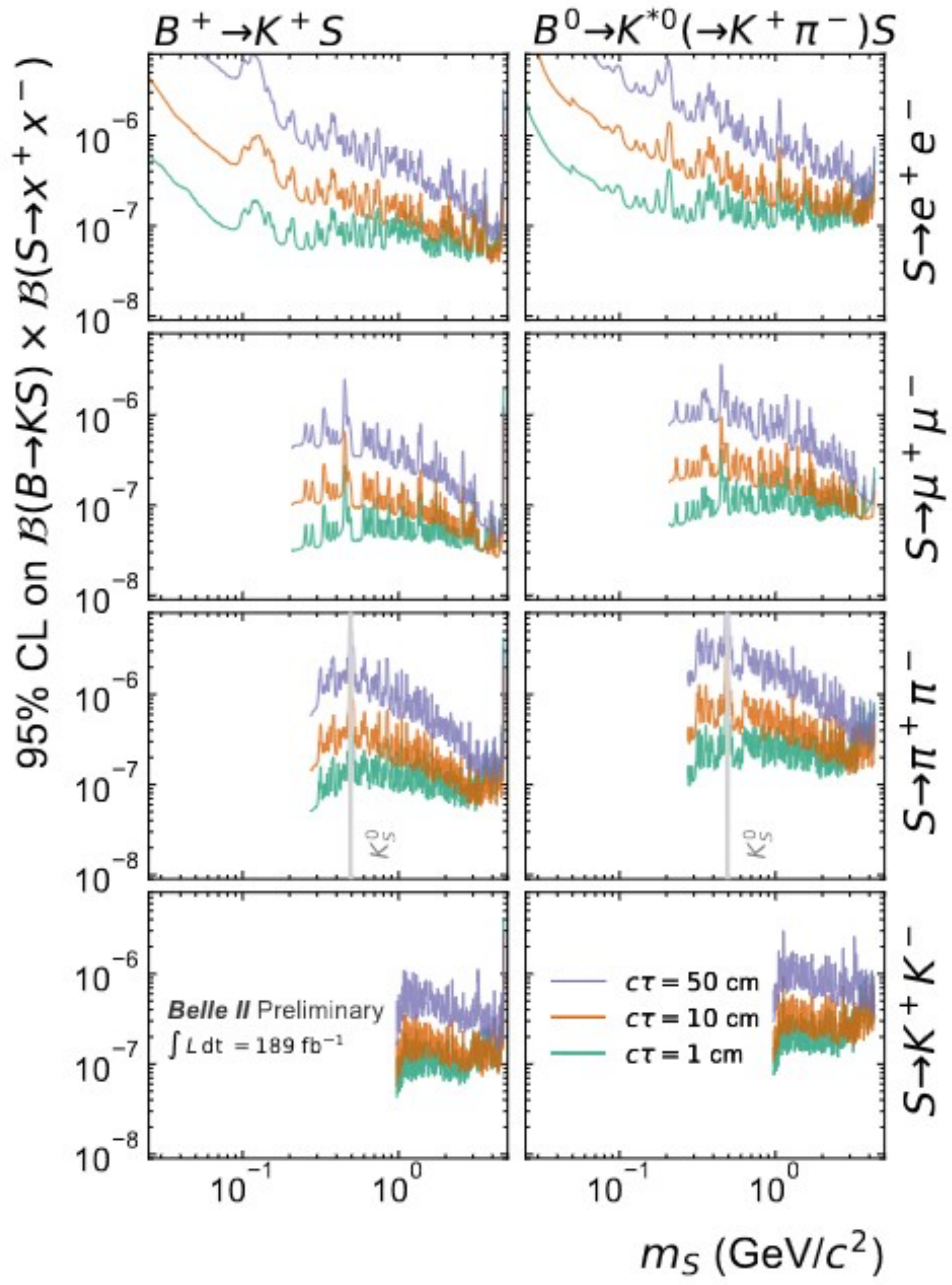




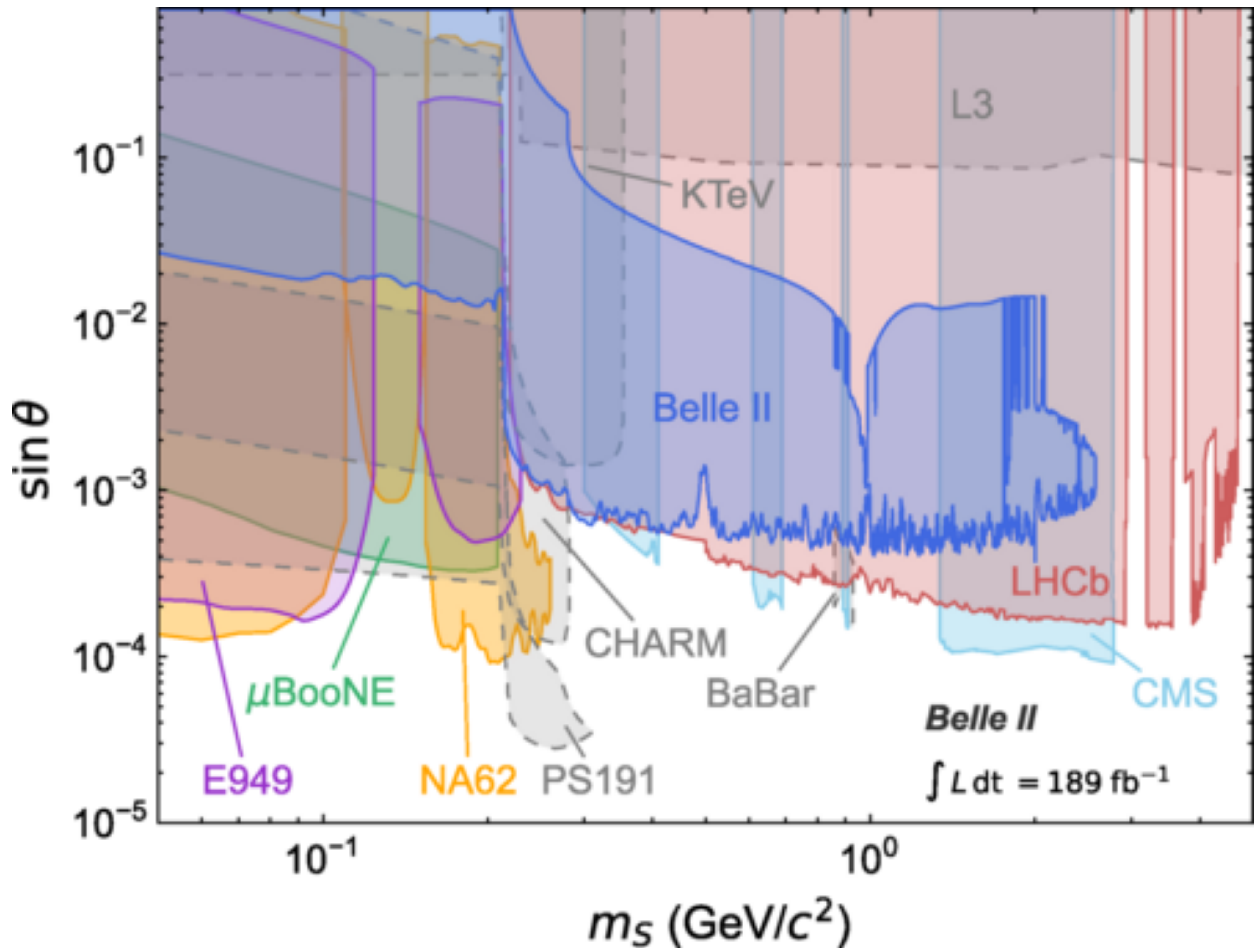


Long-lived scalar in B decays @ Belle II

Belle II, Phys. Rev. D 108, L111104 (2023)



- First model-independent limits for hadronic final states
- Interpretation as dark scalar with mixing angle θ with SM Higgs



Big Picture

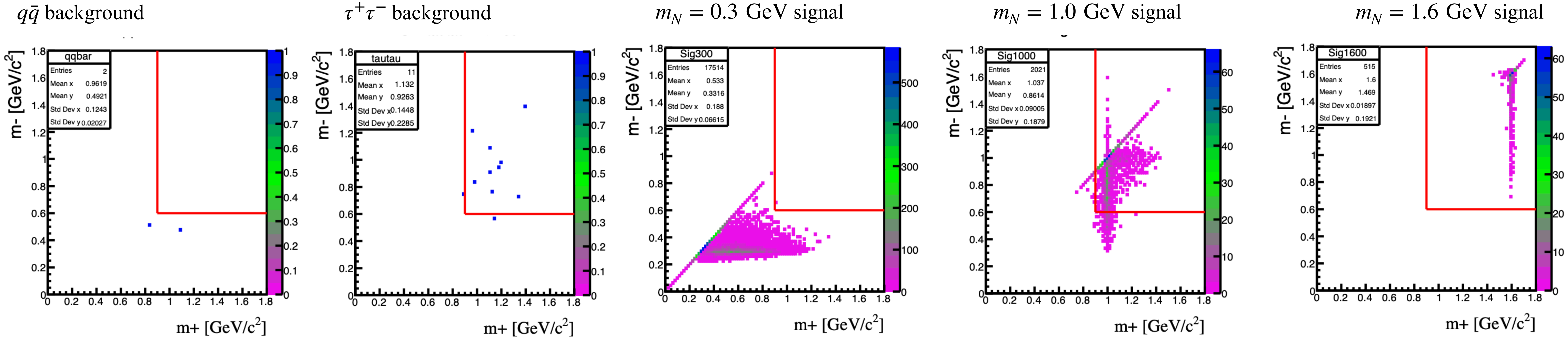
- Belle II/SuperKEKB is a unique environment to search for light dark matter or mediators
- Excellent sensitivity for dark sector searches in the MeV – GeV range
- At Belle II: world leading or competitive results even with a subset of the available data
- So far Belle II recorded ~531 fb^{-1}, more results with higher statistics and improved analyses are in the pipeline
- Very active and very diverse program of direct searches at flavor factories

Thank you

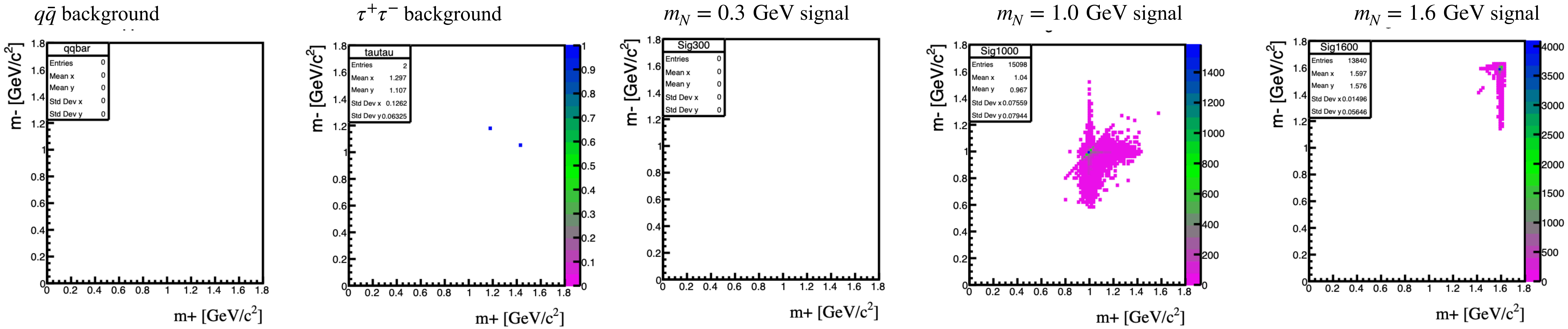
m_{+}vs m_{-} plots in the SR for $\tau^{+}\tau^{-}$, $q\bar{q}$, and signal samples

- In SRl, low signal mass samples (e.g., 300 MeV) tend to distribute at the bottom-left part of the m_{+}vs. m_{-} parameter space.
- Background (after all previous cuts) distributes at the top right part.
- Hence, in SRl, a cut for high m_{+}, m_{-} exclusion is applied.
- In SRl, high mass samples (e.g., 1600 MeV) lose events. However, more than 95% of these samples' events are in SRh anyway.

SRl ($m_{\pi\pi}^{DV} < 0.42$ GeV)



SRh ($m_{\pi\pi}^{DV} > 0.52$ GeV)



Results

- The constraints of the signal decay enable reconstruction of the full kinematics of the signal-τ decay chain with a two-fold ambiguity
- $N_{signal} = N_{\tau\tau} \times B(\tau \to \pi N) \times B(N \to \mu^+\mu^-\nu_\tau) \times \epsilon$, where ϵ is the efficiency
- The total signal efficiencies in SRH and SRL as a function of $|V_{\tau N}|^2$ and m_N are estimated
- The background yield expectations is the source of largest relative systematic uncertainty
- Other uncertainties arise from HNL branching fraction and decay modeling, luminosity, cross section the uncertainty on the reconstruction of the two prompt tracks
- All systematic uncertainties are handled with the nuisance parameters using CLs prescription