What is dark matter? - Comprehensive study of the huge discovery space in dark matter

Search for a heavy neutral lepton that mixes predominantly with the tau neutrino

7 March, 2024

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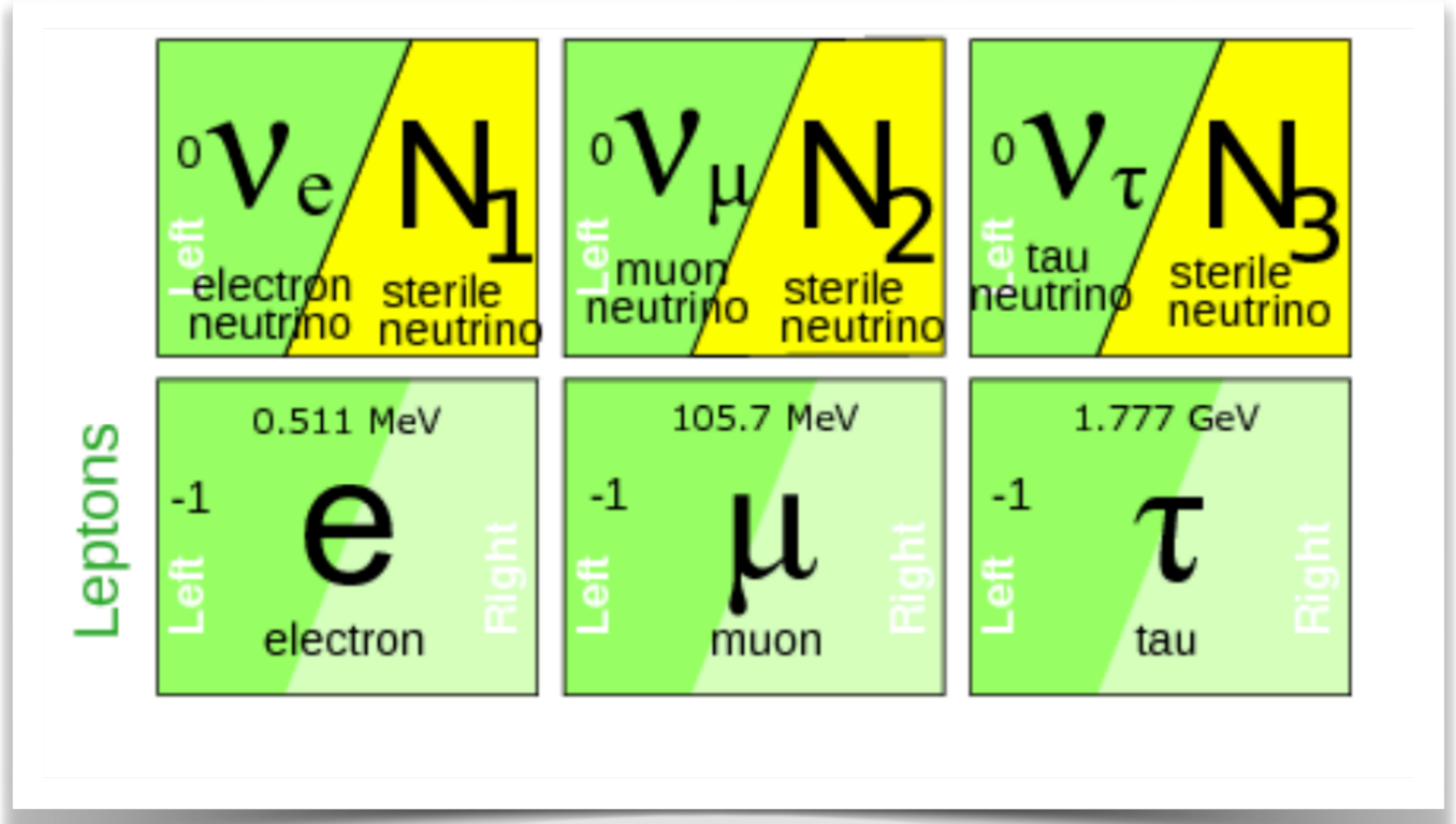
on behalf of the Belle Collaboration

Heavy Neutral Lepton (N)

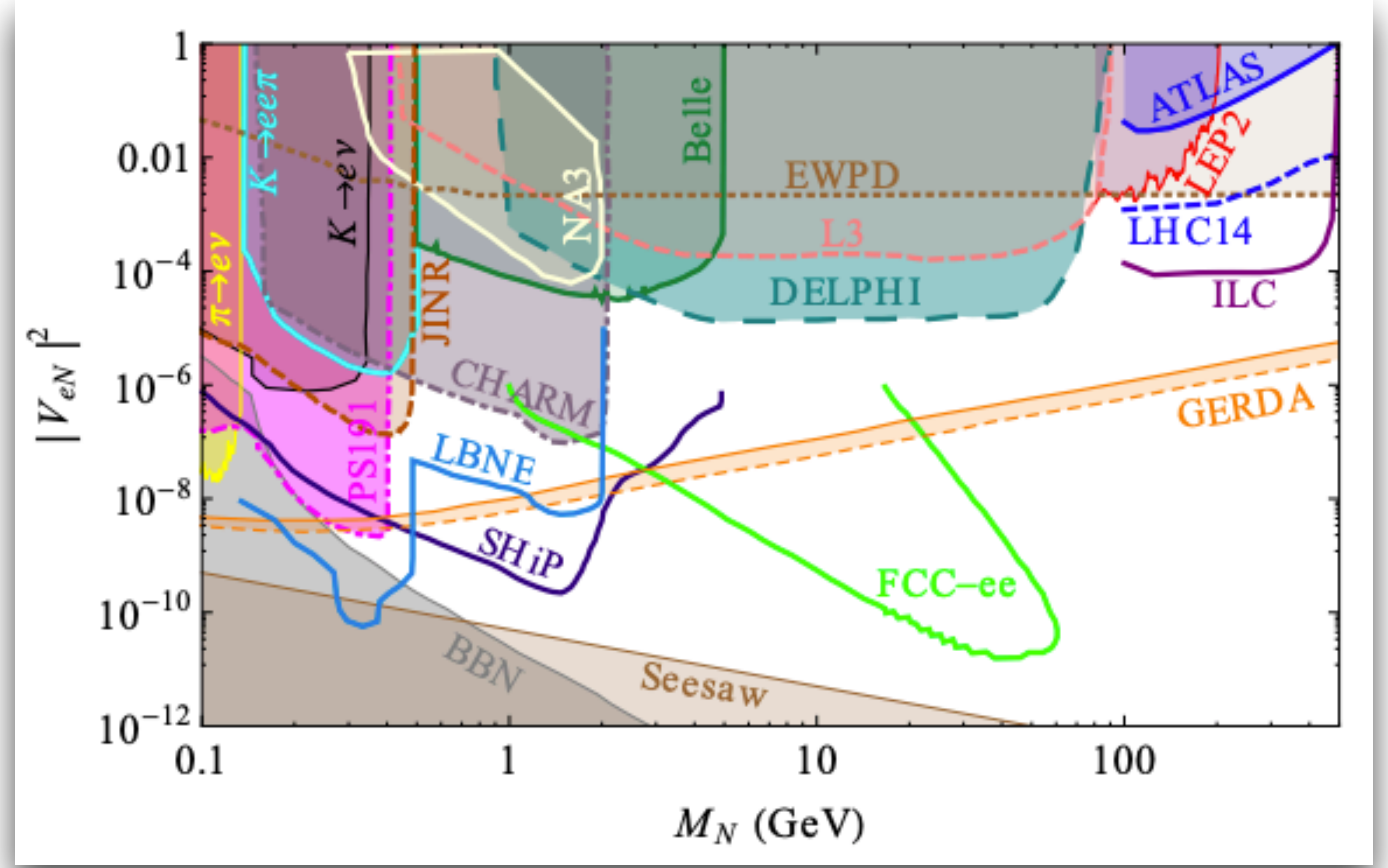
- Standard Model Neutrino: only Left handed, massless
- Neutrino Oscillations: Neutrinos must have mass
- Neutrino masses can be incorporated to SM by introducing Right Handed neutrinos or Majorana neutrinos.
- Heavy Neutral Lepton(HNL, notation: N): Neutrino eigenstate with mass much higher than SM neutrino
- N are sterile: Interacts with ν_{SM} through mixing: $N \leftrightarrow \nu_{SM}$
- Long lifetime of N: We consider a range of m_N and mixing, so that N decays within the detector acceptance
- Allows to solve some of the outstanding problems of the SM
  - Origin of the SM neutrino masses(Phys. Rev. D 23,165)
  - Non-baryonic dark matter(keV scale HNL)(Phys. Lett. B 631, 151–156)
  - Baryogenesis(GeV scale HNL)(Phys. Rev. Lett. 81, 1359)
- Heavy Neutral Lepton also appears in SUSY, exotic Higgs, GUT…



Heavy Neutral Lepton : Direct searches

$|V_{eN}|^2$, $|V_{\mu N}|^2$, $|V_{\tau N}|^2$ = mixing coefficients of ν_e, ν_μ, ν_τ with N

arxiv 1502.06541



- Previous experiments explored m_N from 100 MeV to ~ 1TeV
  - $m_N > m_Z$ Direct searches @LHC: $pp \rightarrow Nl^{\pm}$
  - $m_N < m_{Z,W}$ DELPHI($Z^0 \rightarrow \nu N$), ATLAS/CMS($W^{\pm} \rightarrow Nl^{\pm}$)
  - $m_N < m_{B,D,K}$ Belle, LHCb, beam-dump, NA62

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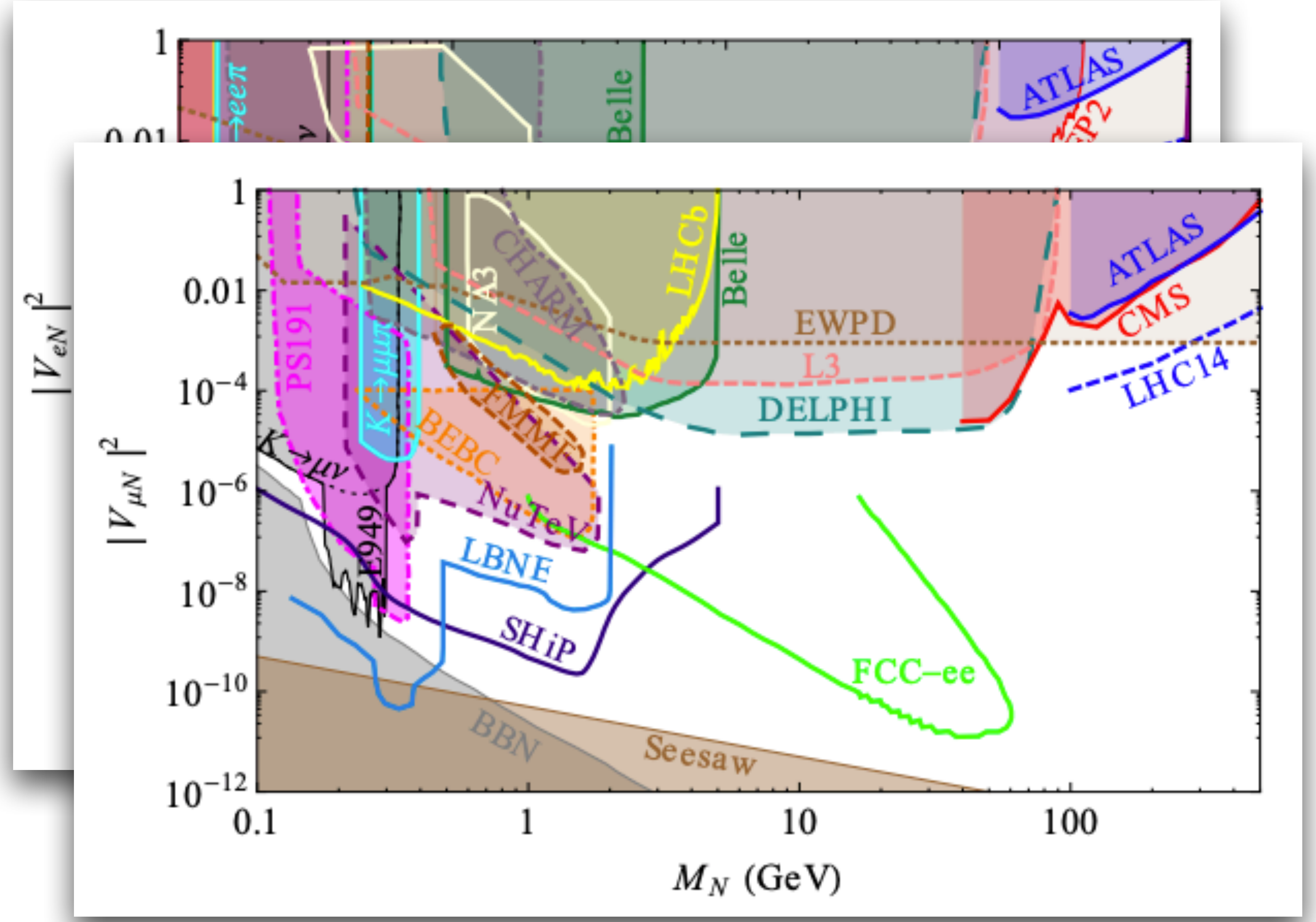

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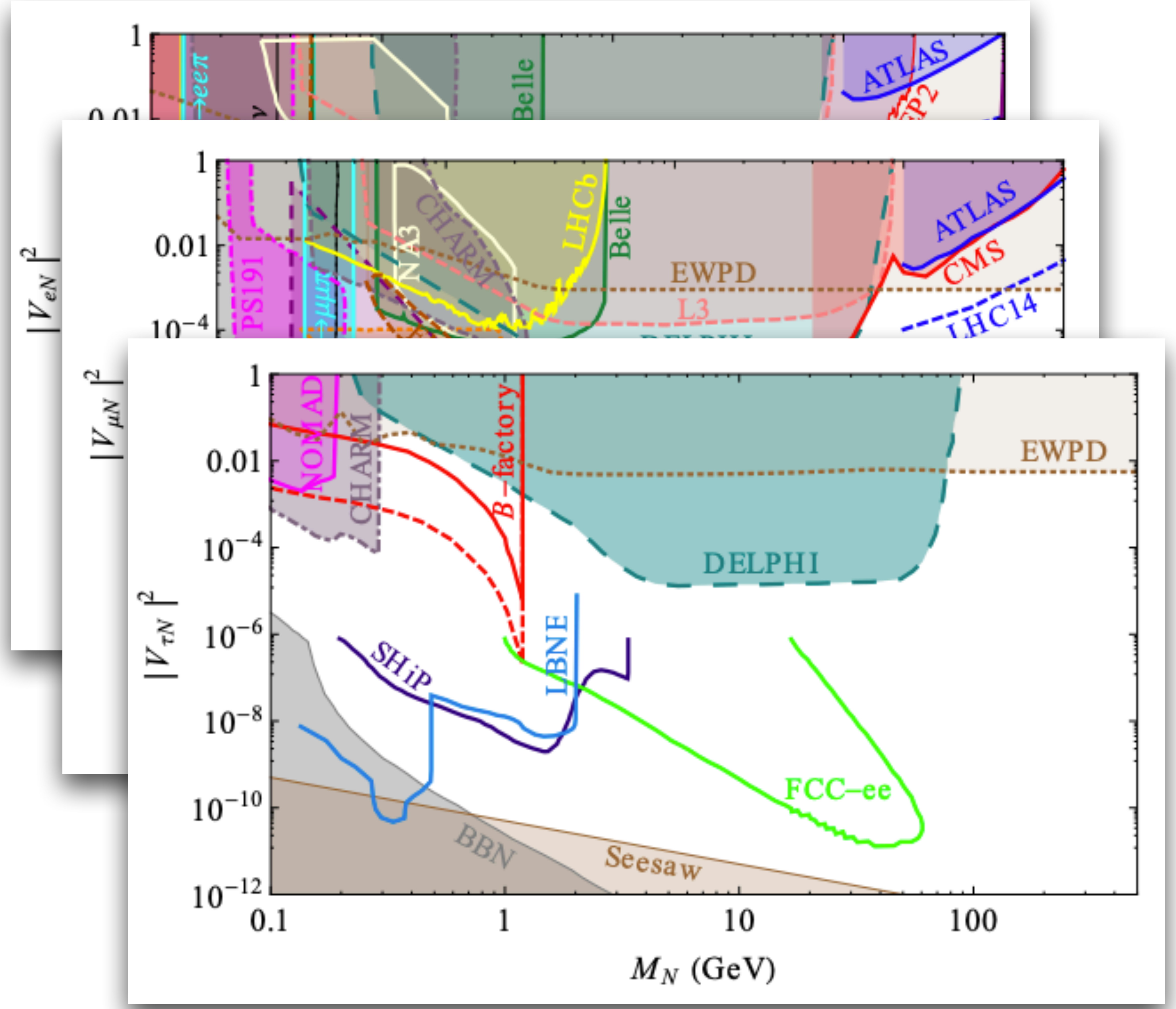

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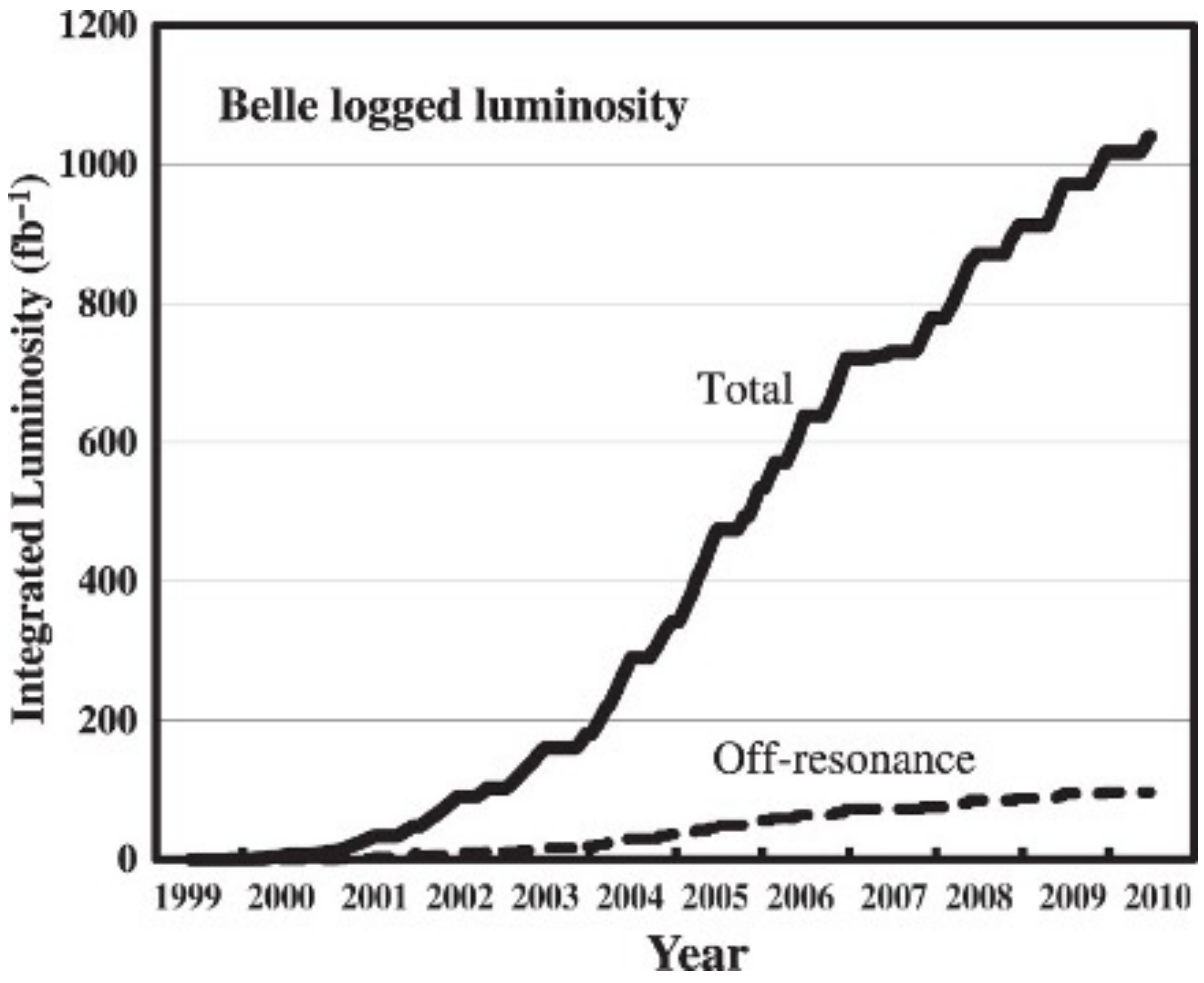
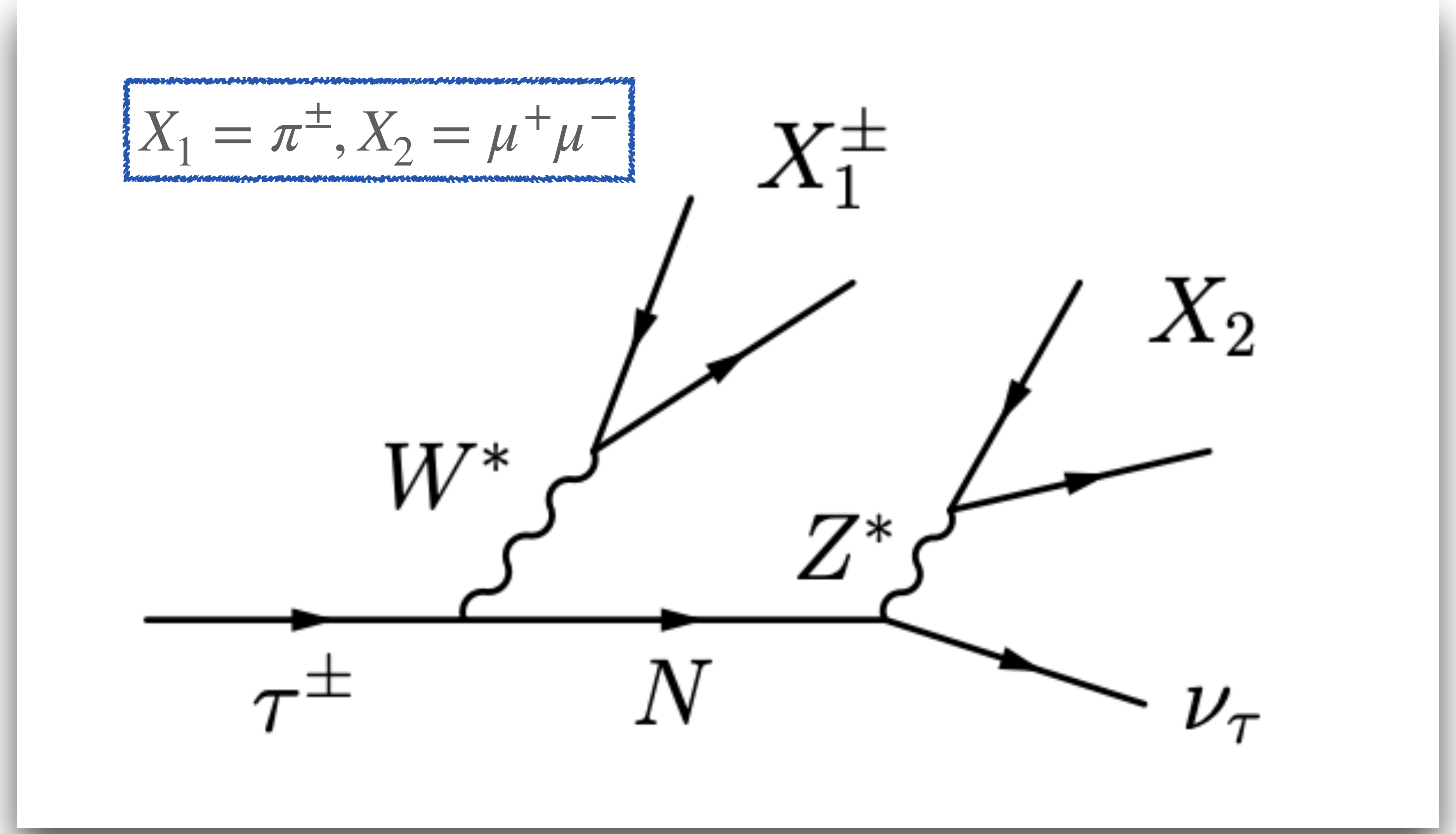
- Limits on $|V_{\tau N}|^2$ are much weaker
- This motivates us to overcome the experimental challenges and explore $|V_{\tau N}|^2$

We can do τ Physics!

- Belle data taking period: 1999-2010 : 1040 fb^{-1}
- $\sigma(e^+e^- \to b\bar{b}) = 1.05\ nb$
- $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\ nb$
- $\Upsilon(nS)\epsilon[n = 1,...,5]$, use of off resonance data : B factories are also τ factories

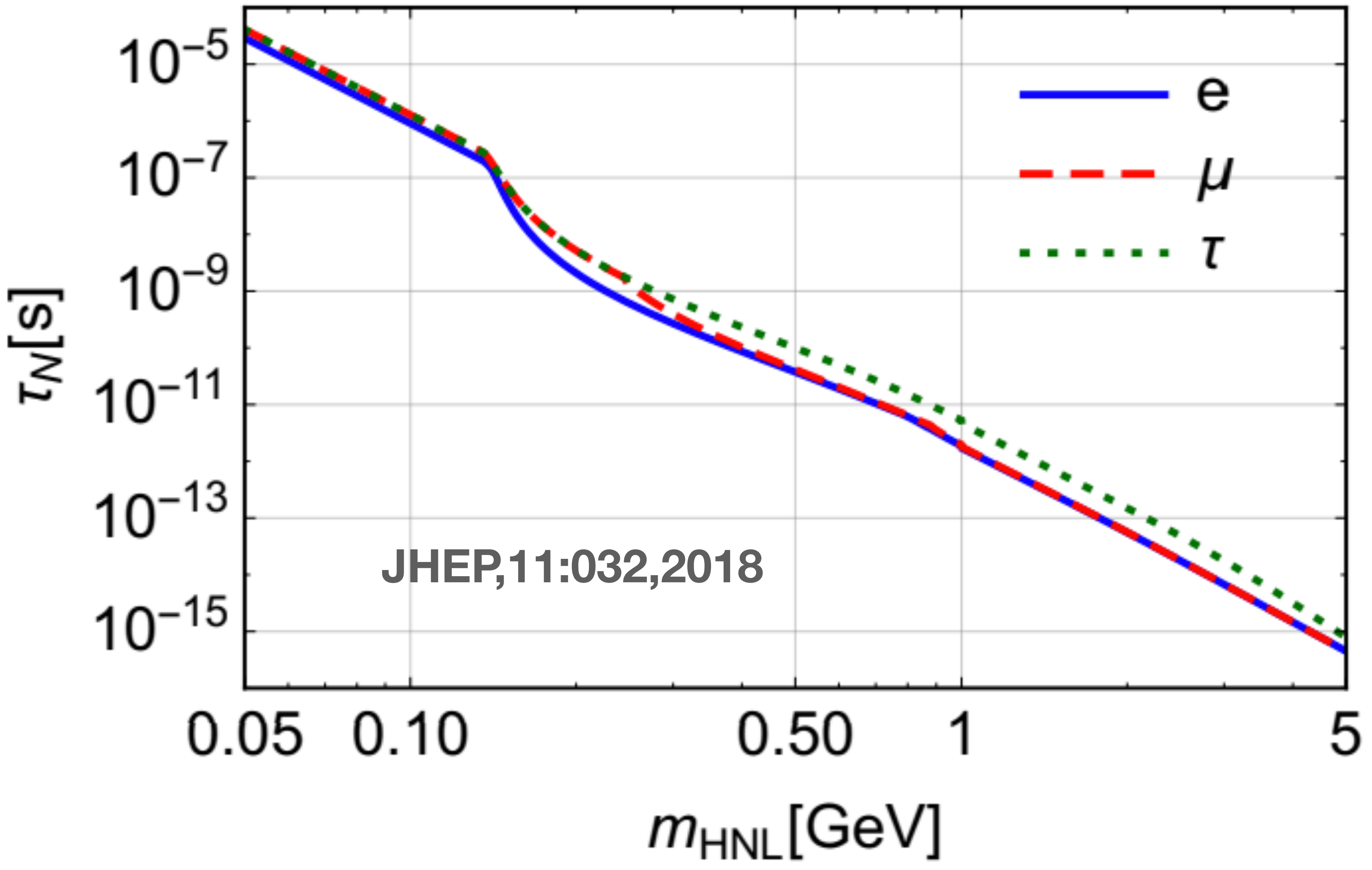


- N decays via the weak neutral current
- This analysis probes $|V_{N\tau}|^2$ directly
- This production mechanism implies $m_N < m_\tau - m_\pi$
- N is long-lived for a range of $|V_{N\tau}|^2$ values that we are sensitive to



Full Belle data sample used

$(836 \pm 12) \times 10^6$ τ pairs



Analysis Method

- $e^+e^- \to \tau^+_{tag}\tau^-_{sig}$

  Tag side:

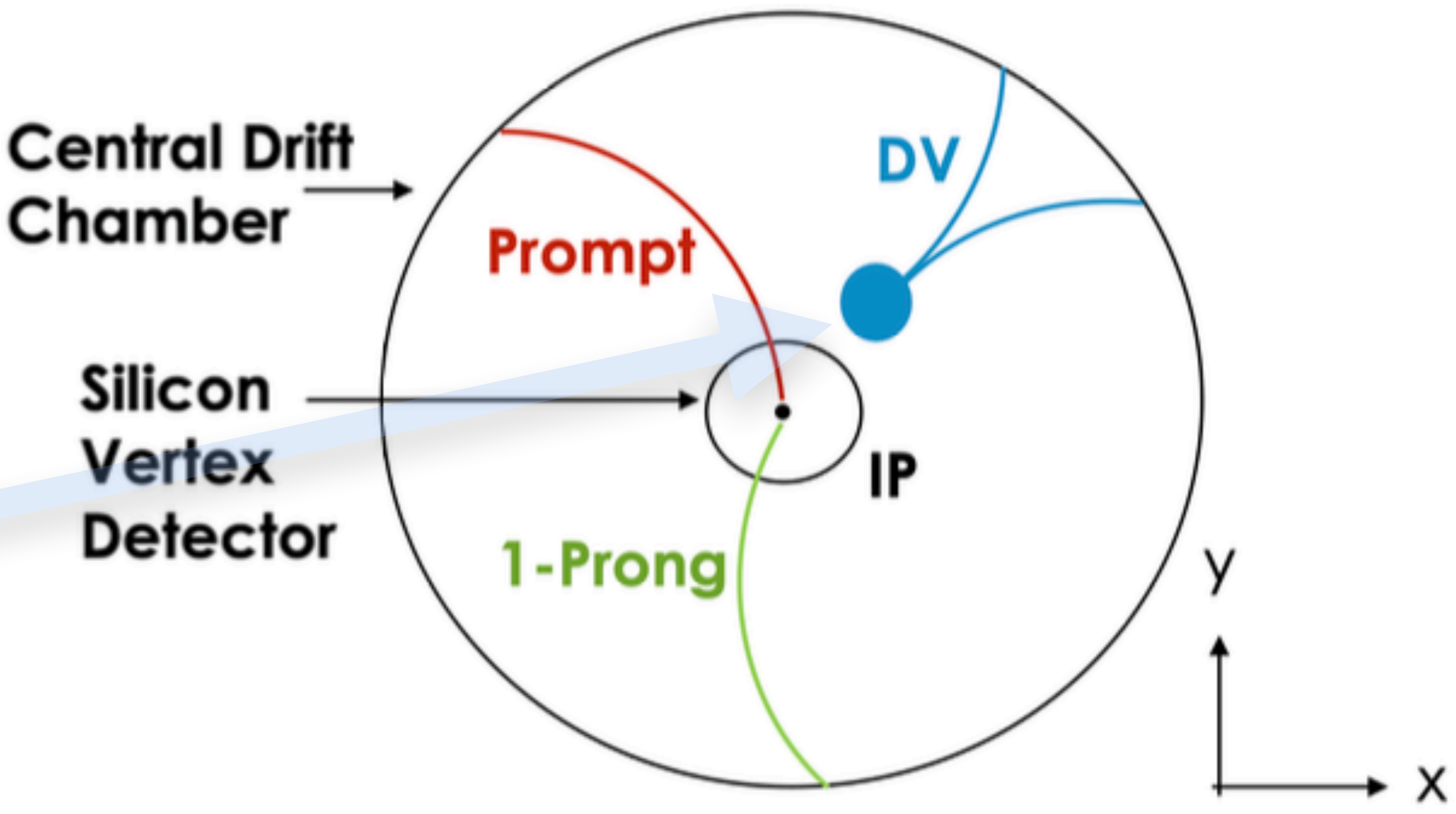
  $$\tau^+_{\text{tag}} \to \begin{cases} \pi^+\bar{\nu}_\tau \\ \pi^+\pi^0\bar{\nu}_\tau \\ l^+\nu_l\bar{\nu}_\tau \end{cases}$$

  Signal side:

  $$\tau^-_{\text{sig}} \to \pi^-\mathrm{N}(\to\mu^+\mu^-\nu_\tau)$$

- We look for a $\mu^+\mu^-$ displaced vertex (DV)

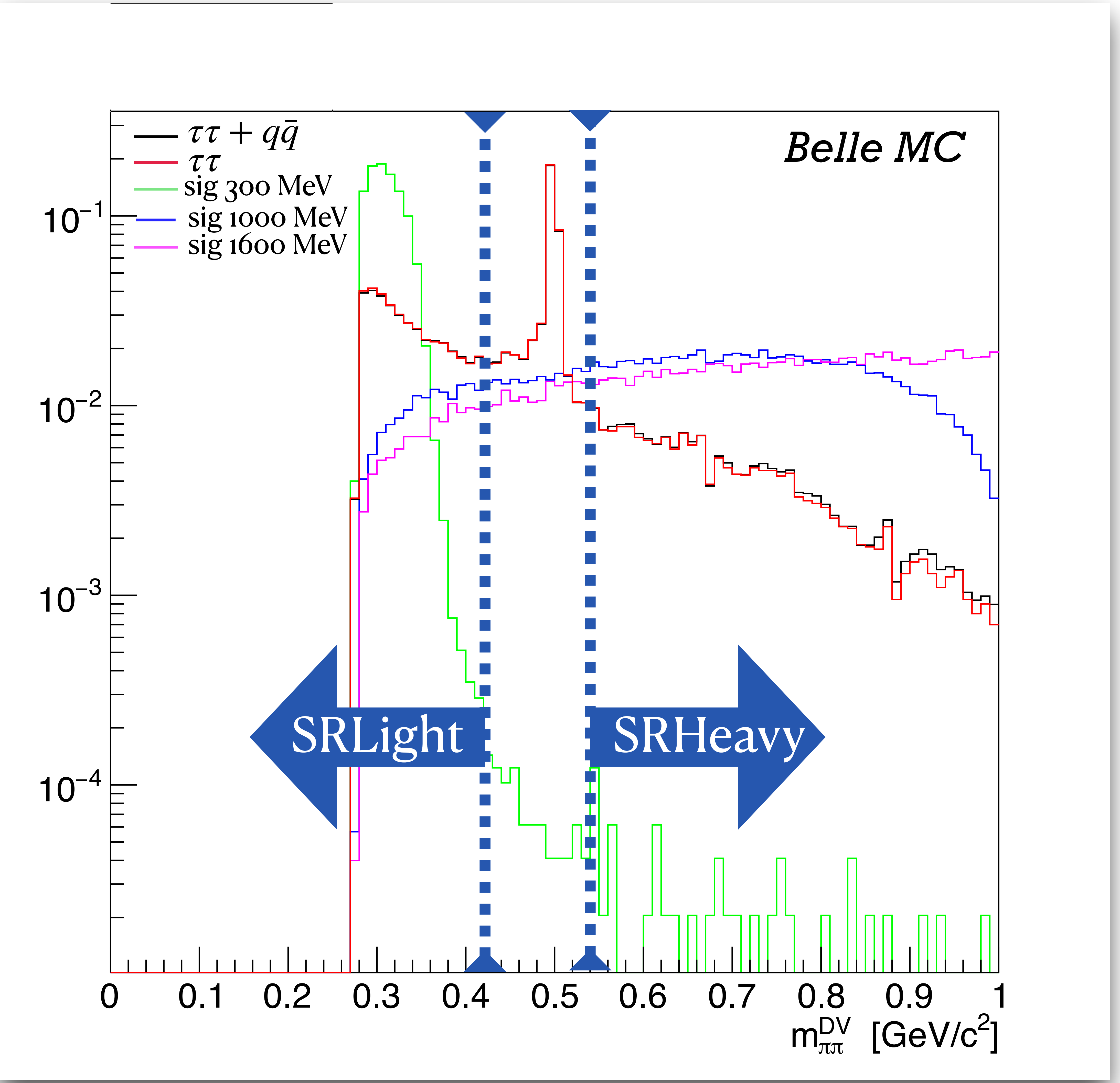
- Radial position of DV > 15 cm from the beam axis



DV = Displaced Vertex

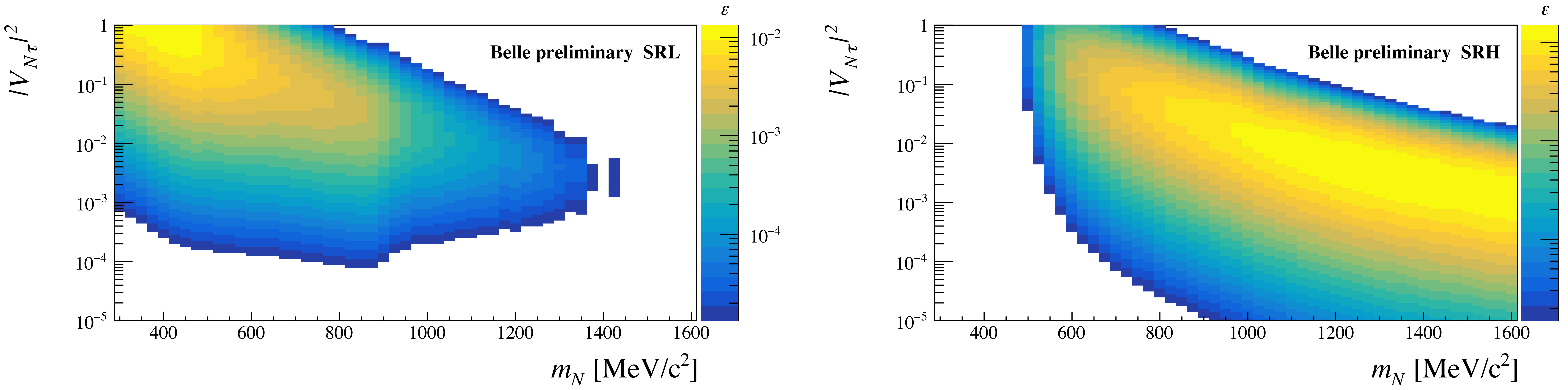
IP = Interaction Point

- $K^0 \to \pi^+\pi^-$: displaced vertex similar to N: removed the mass region
- We divide the signal region into Low mass and High mass signal region:
  - SRH: $m_{\pi\pi}^{DV} > 0.52\ GeV/c^2$
  - SRL: $m_{\pi\pi}^{DV} < 0.42\ GeV/c^2$
- Light N distribution is different from heavy N distribution



more on Analysis Method

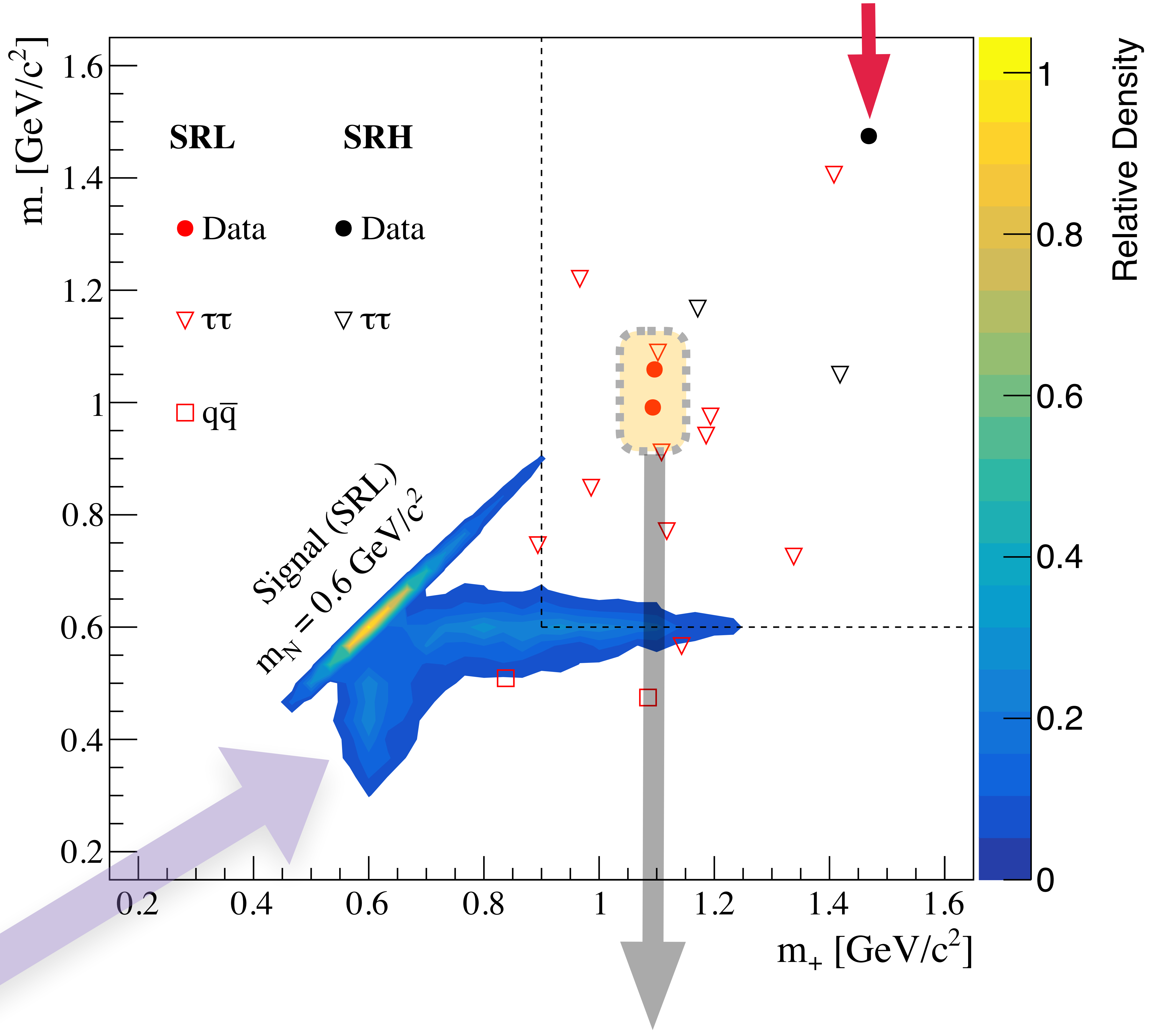
- $N_{signal} = N_{\tau\tau} \times B(\tau \to \pi N) \times B(N \to \mu^+\mu^-\nu_\tau) \times \epsilon$, where ϵ is the efficiency
- Signal efficiencies in SRH and SRL as a function of $|V_{N\tau}|^2$ and m_N: efficiency map



- Full kinematics of the signal-decay chain reconstructed with a two-fold ambiguity(m_+ and m_-)
- In the signal regions targeting heavy and light Ns we observe 1 and 0 events, respectively,
    - in agreement with the background expectation.

distribution of signal-MC events with m_n= 600 MeV/c2 in the SRL

only signal event observed



vetoed in SRL

Results

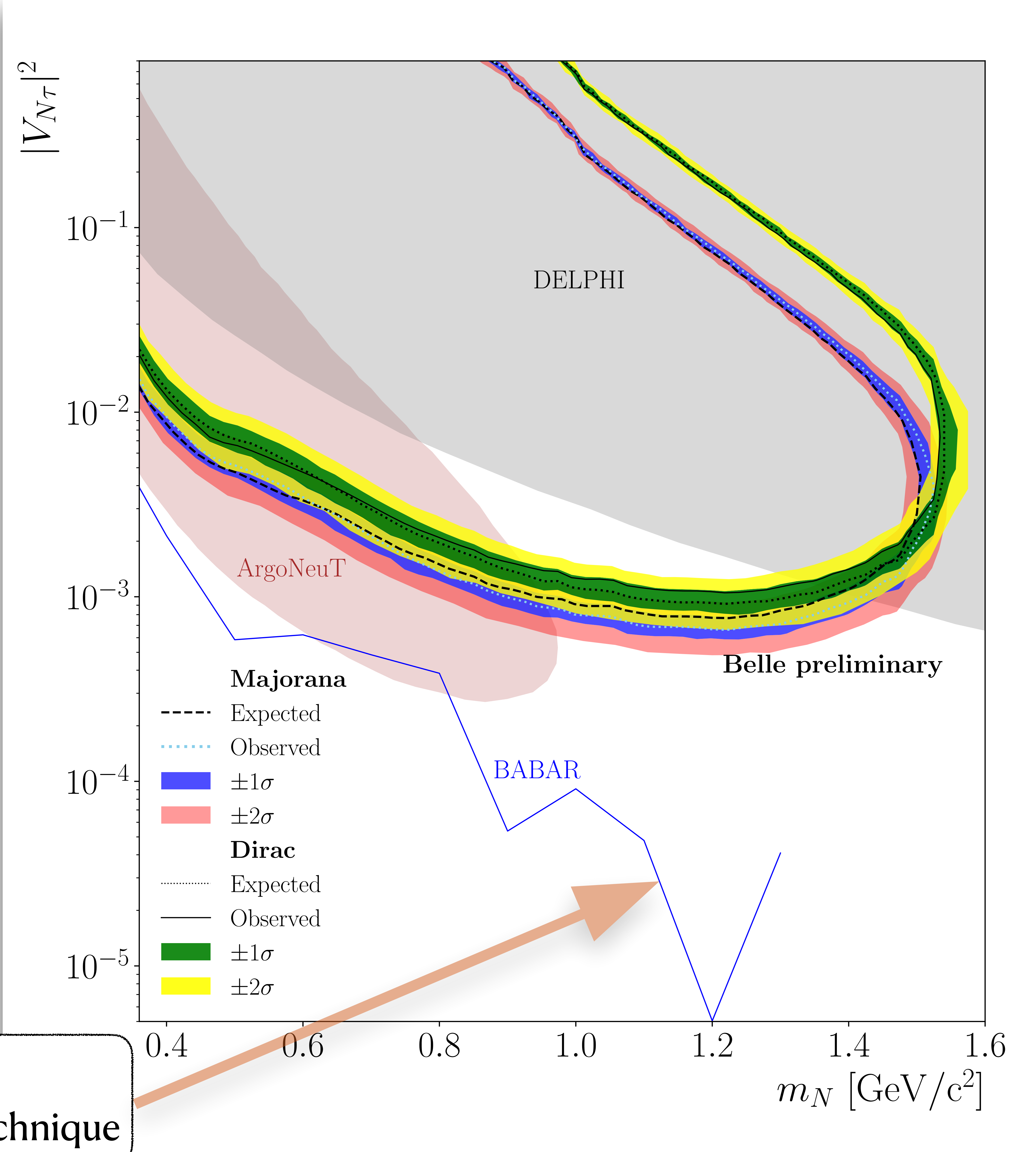
- Uncertainties
  - N branching fraction
  - luminosity
  - decay modeling
  - cross section
  - uncertainty on the reconstruction of the two prompt tracks
  - the background yield expectations(largest)
- Handled with the nuisance parameters using CL_s prescription

- Allows for direct measurement of the N mass if a signal is observed

In the mass range 1.3 - 1.4 GeV/c^2, our limits are the most stringent to date

New Result

Arxiv 2402.02580



BABAR did not use displaced-vertex technique

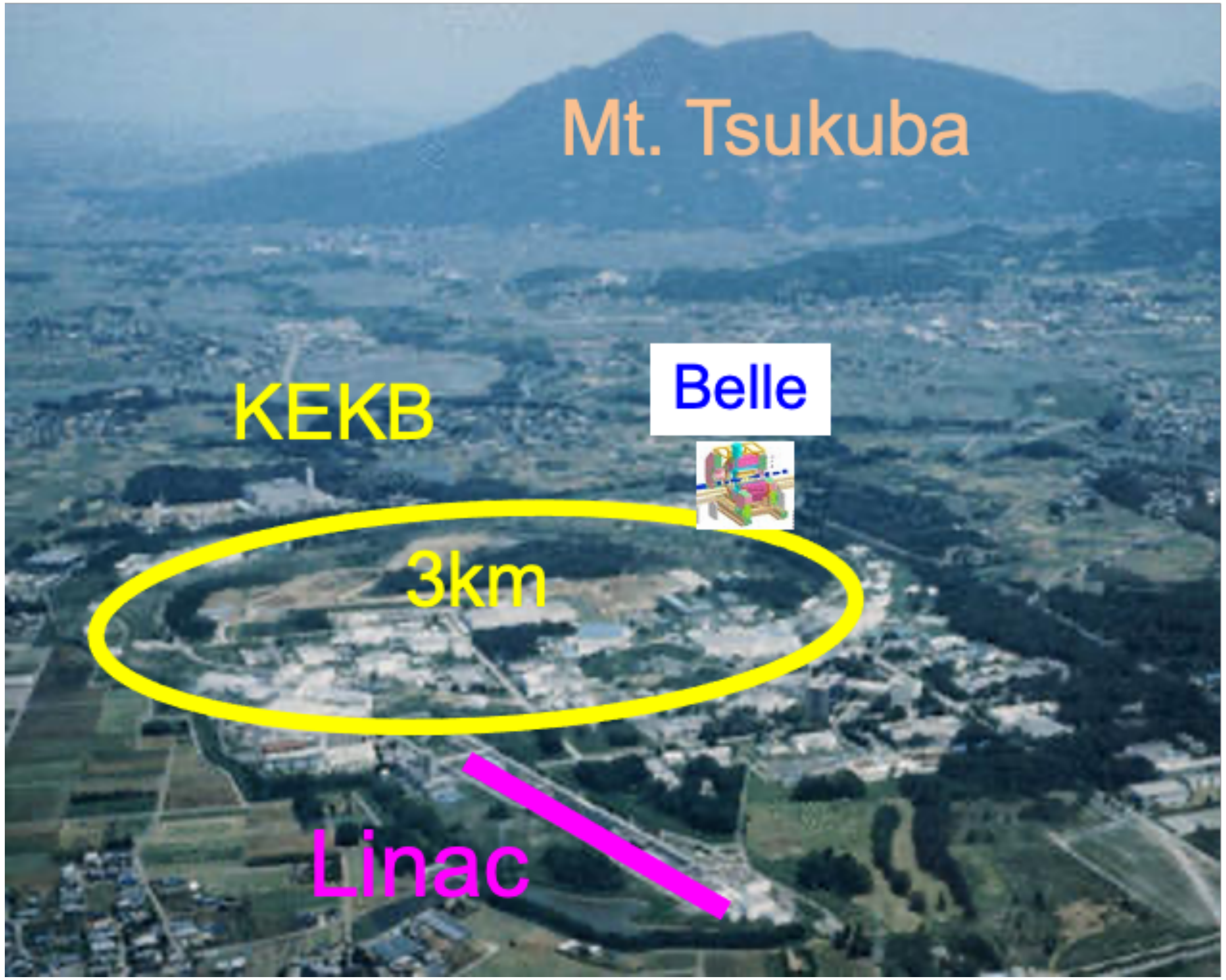
Summary

- No significant excess observed
- Stringent limits in 1.3 - 1.4 GeV/c^2
- For the first time, utilizes the displaced vertex originating from the long-lived Heavy Neutral Lepton decay
- Ability to reconstruct the Heavy Neutral Lepton candidate mass to suppress the background to the single-event level
- We have moved from Belle to Belle II era. With an improved detector, and more data, we hope for an improved result in the future

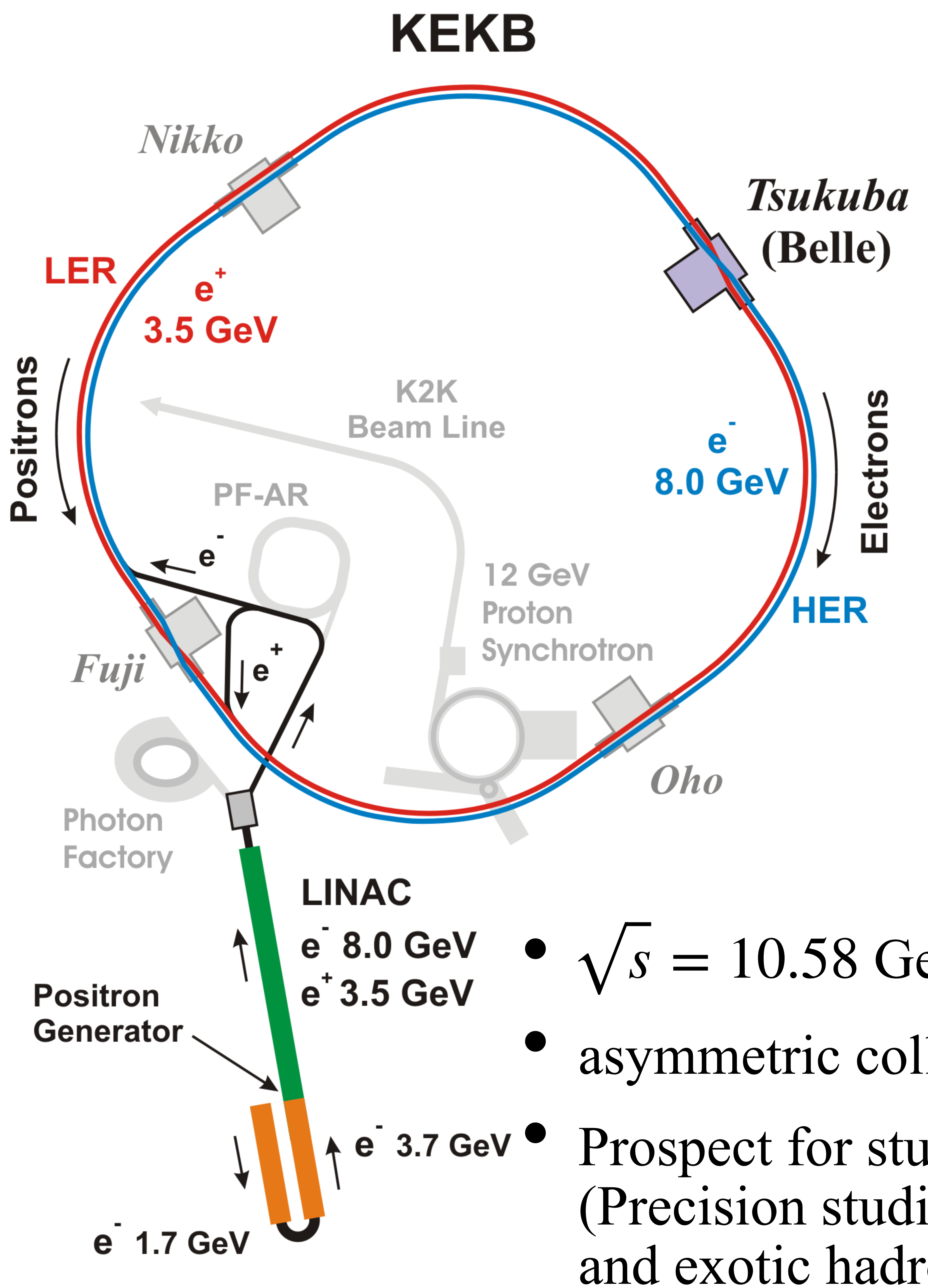
THANK YOU FOR YOUR ATTENTION

Backups

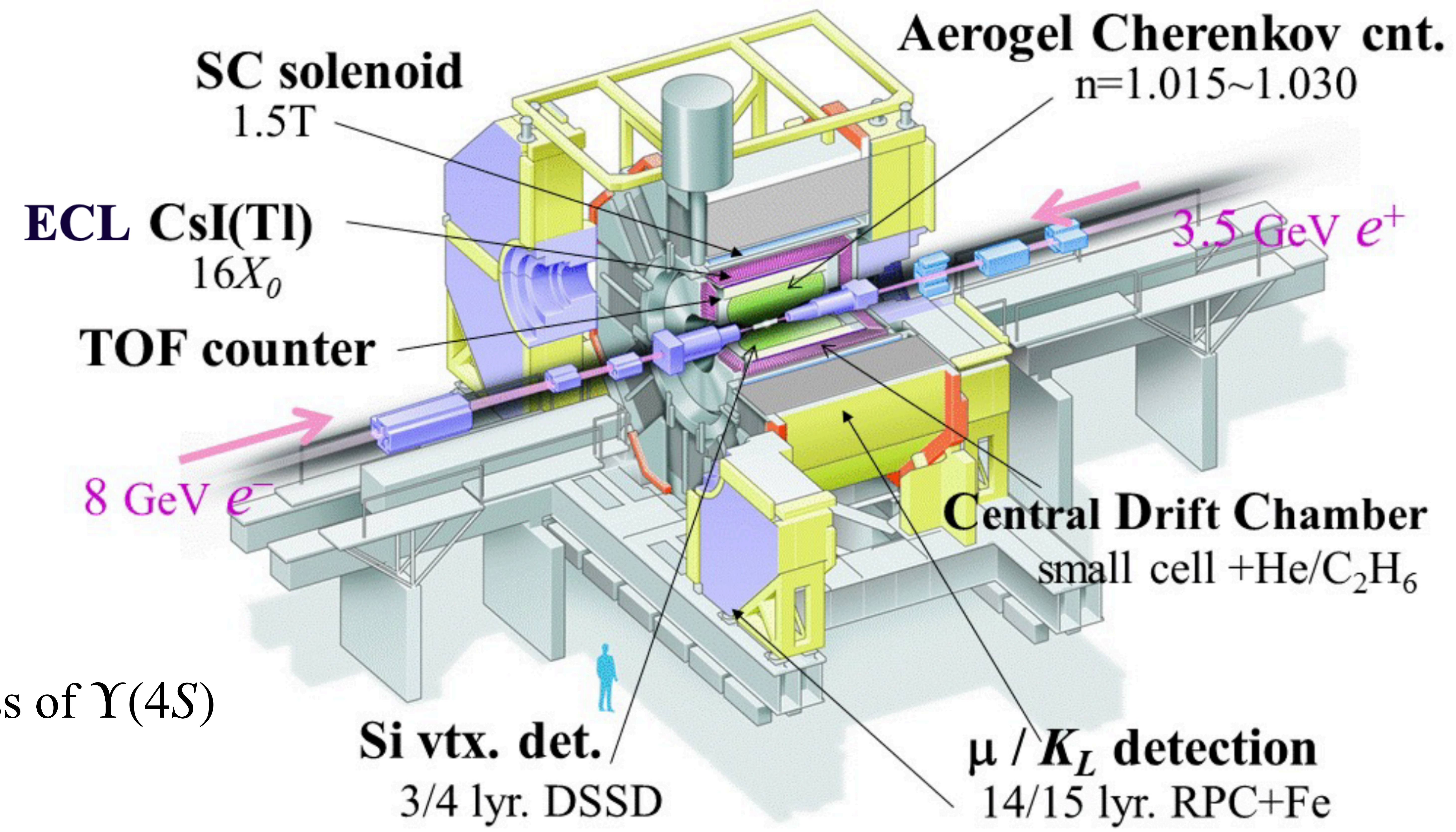
The Apparatus



The KEKB and the Belle Detector



8 GeV e^-, 3.5 GeV e^+



- $\sqrt{s} = 10.58$ GeV : mass of $\Upsilon(4S)$
- asymmetric collider
- Prospect for studying a vast region of particle physics (Precision studies of B, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)

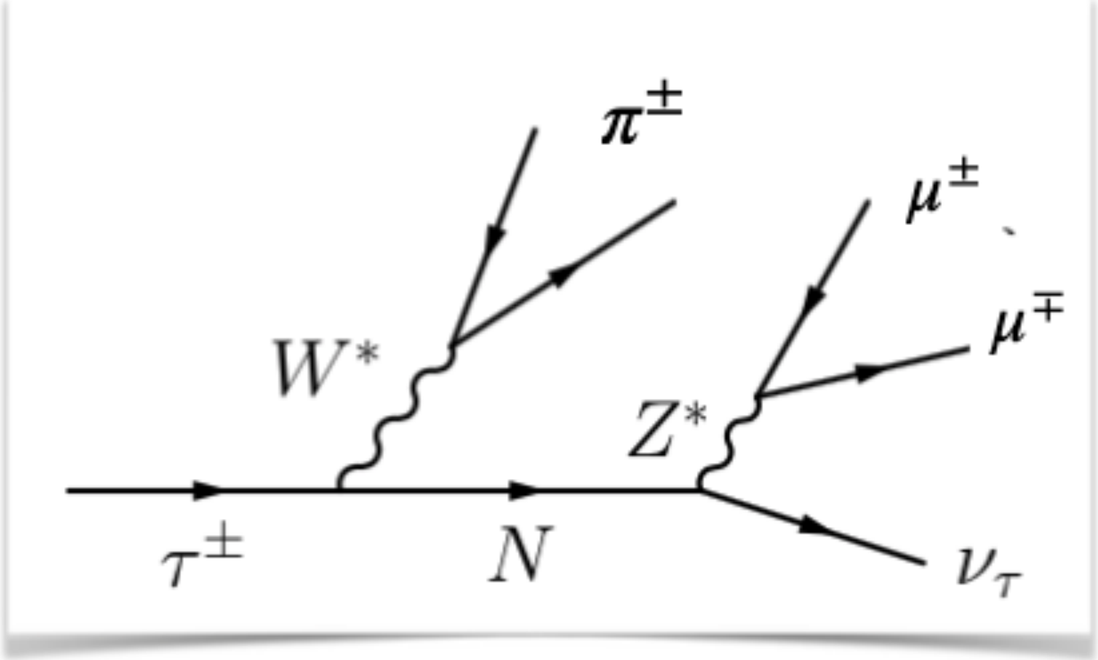
Signal, Control and Validation regions

- Signal region: Reconstruct as $\tau^- \to \mathrm{DV}(\to \mu^\mp \mu^\pm)\pi^-$
- Control region: Reconstruct as $\tau^- \to \mathrm{DV}(\to \mu^\mp \pi^\pm)\pi^-$ (used in the fit for data-driven background estimate)
- Validation region for Data-MC agreement:
  - Reconstruct as $\tau^- \to \mathrm{DV}(\to \mu^- \mu^-)\pi^+$
  - Reconstruct as $\tau^- \to \mathrm{DV}(\to \pi^+ \pi^-)\pi^-$ with $m_{\pi\pi} < 0.42$ GeV and $m_{\pi\pi} > 0.52$ GeV
  - Reconstruct as $\tau^- \to \mathrm{DV}(\to \pi^+ \pi^-)\pi^-$ with $0.480 < m_{\pi\pi} < 0.515$ GeV

- Control and validation regions are also divided as CRh, CRl and VRh, VRl (similar to signal region)

HNL mass reconstruction

- Despite the neutrino, we can reconstruct the decay chain kinematics completely, up to 2-fold ambiguity.
  - 12 unknowns: p_ν^μ, p_N^μ, p_τ^μ
  - 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 $\vec{p}_N$ (2)

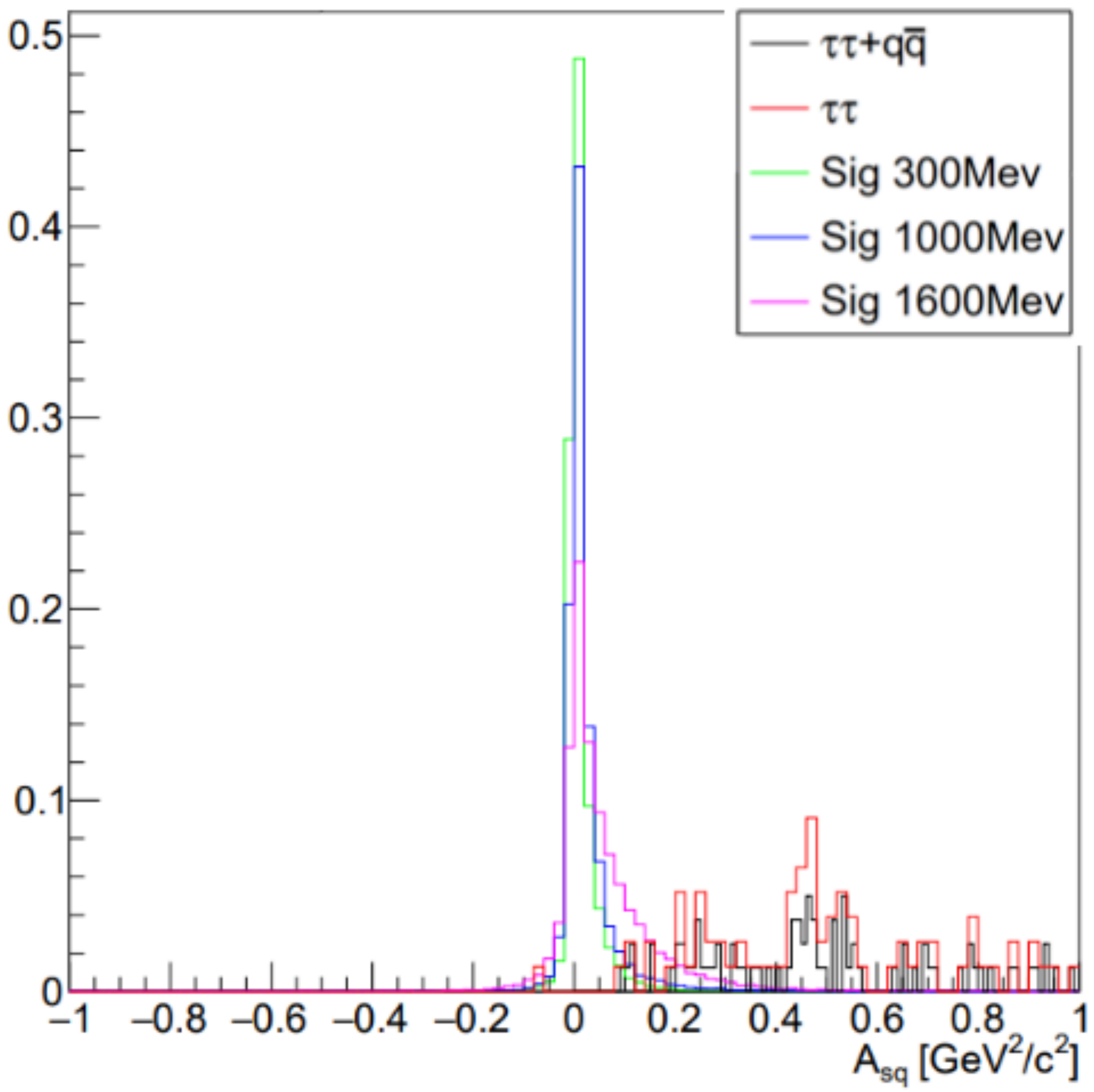


Quadratic equation

(Using the square root argument $A_{sq} = b^2 - 4ac$ for cut)

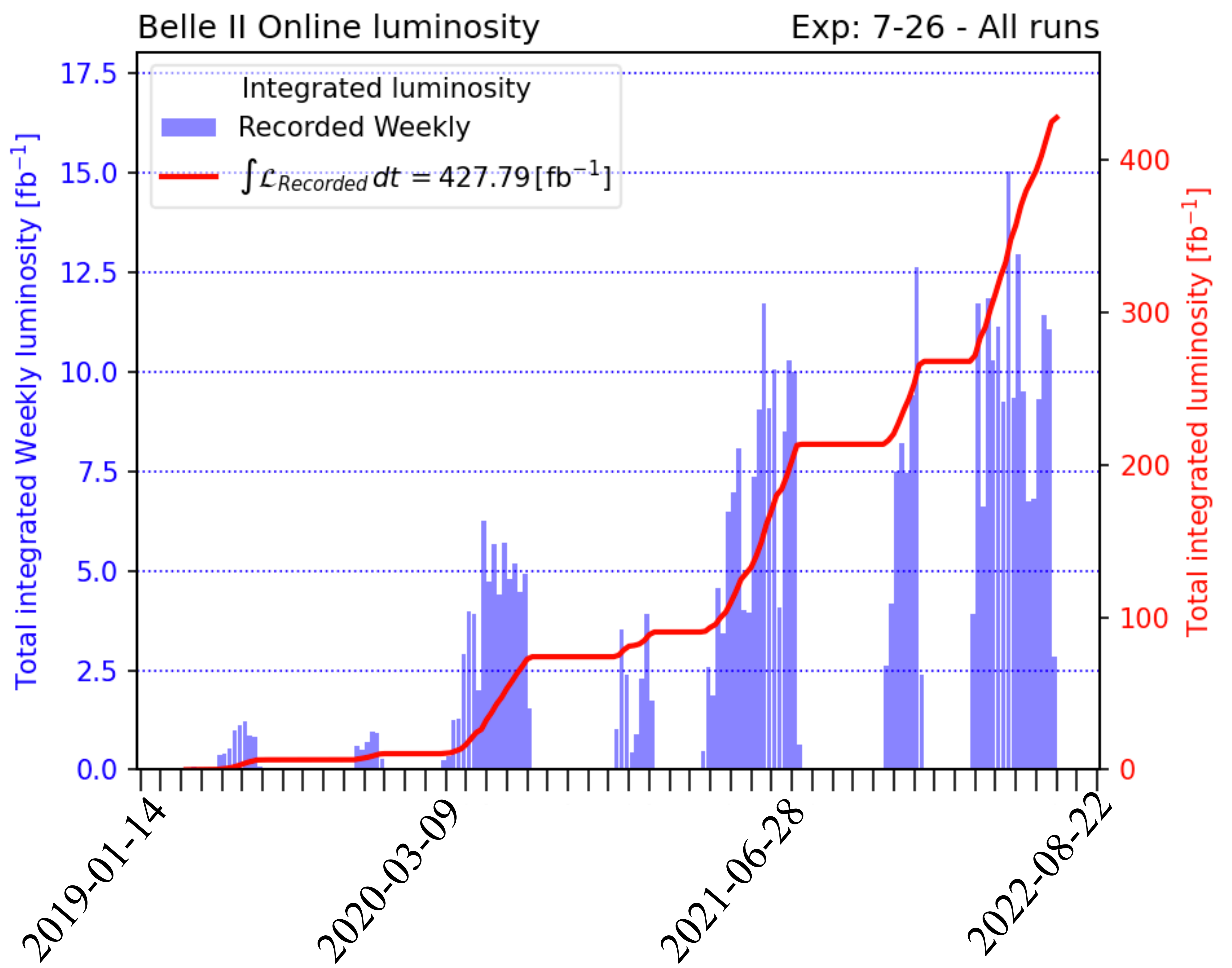
$A_{sq} < 0.4\ \text{GeV}^2$

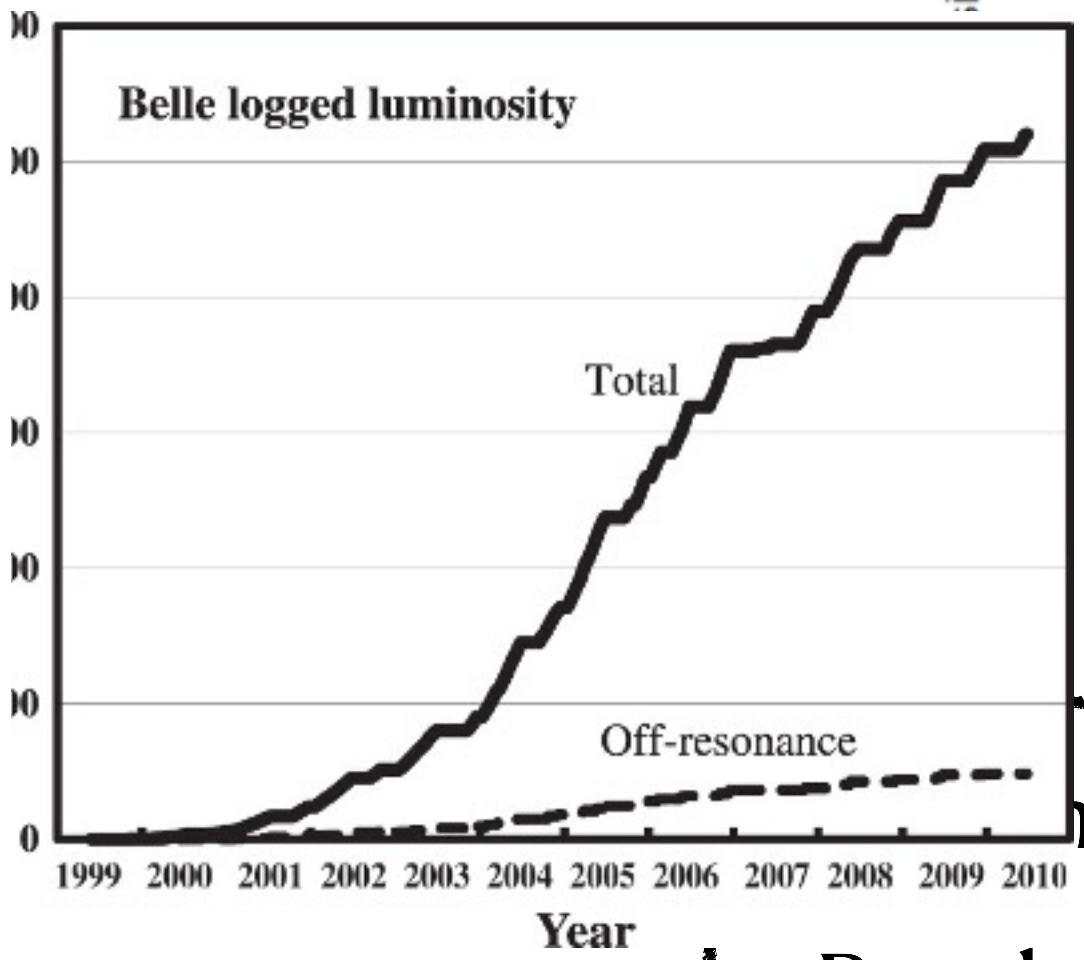
If A_{sq} is -ve then we set it to 0

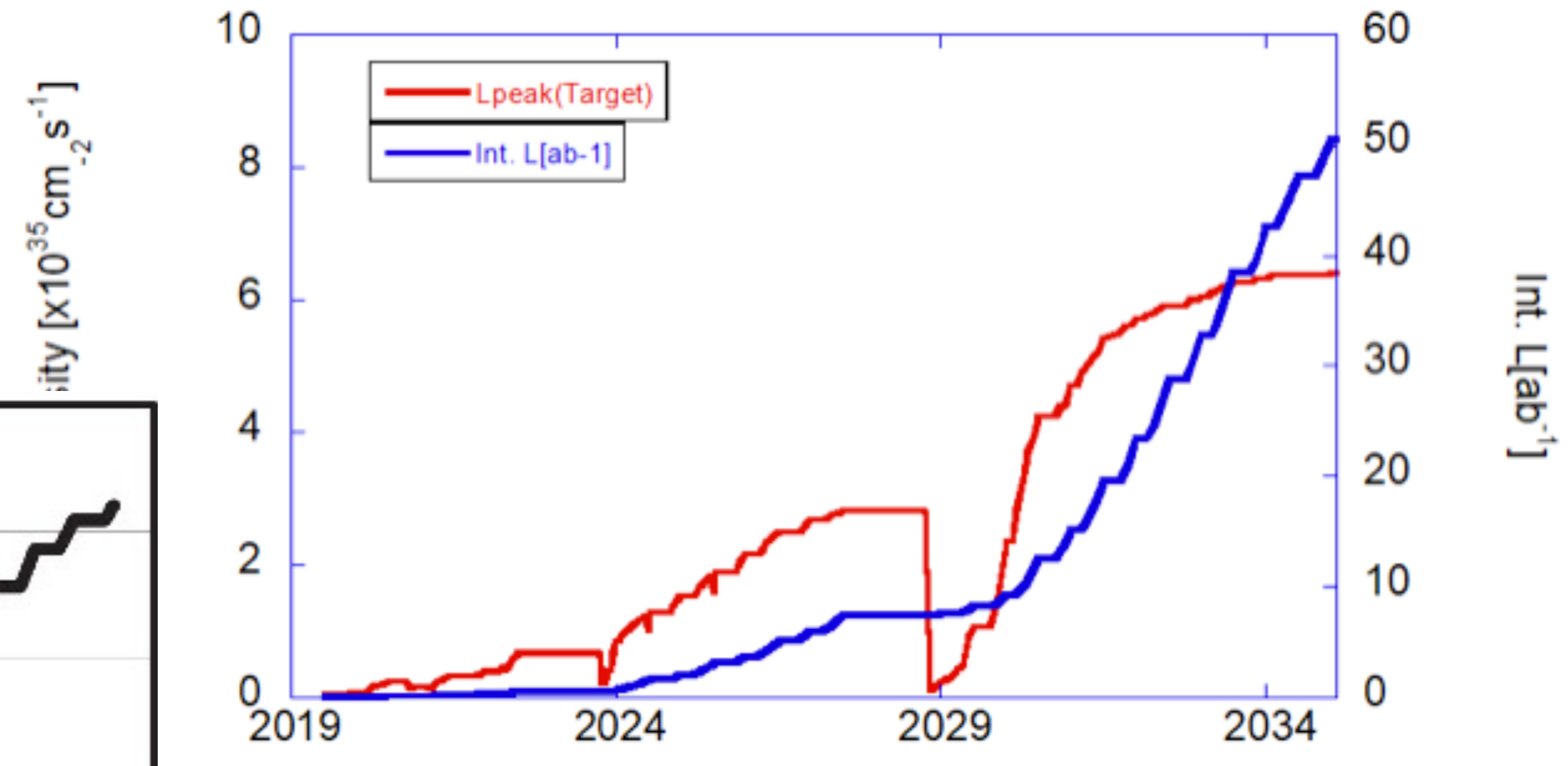


Two HNL mass solutions: m_+, m_-

Luminosity







- n integrated luminosity 50 ab^{-1}
- Regular data-taking since April 2019
- Current integrated luminosity 424 fb^{-1}
- Peak luminosity recorded : $4.7 \times 10^{34} cm^{-1} s^{-1}$
- At present, we have a long shutdown for accelerator and detector upgrades, will resume data taking in 2024

- $N_{signal} = N_{\tau\tau} \times B(\tau \to \pi N) \times B(N \to \mu^+\mu^-\nu_\tau) \times \epsilon$, where ϵ is the efficiency
- Signal efficiencies in SRH and SRL as a function of $|V_{N\tau}|^2$ and m_N: efficiency map
- largest relative systematic uncertainty: the background yield expectations
- Other uncertainties
  - N branching fraction
  - 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 CL_s prescription