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

13 December, 2023

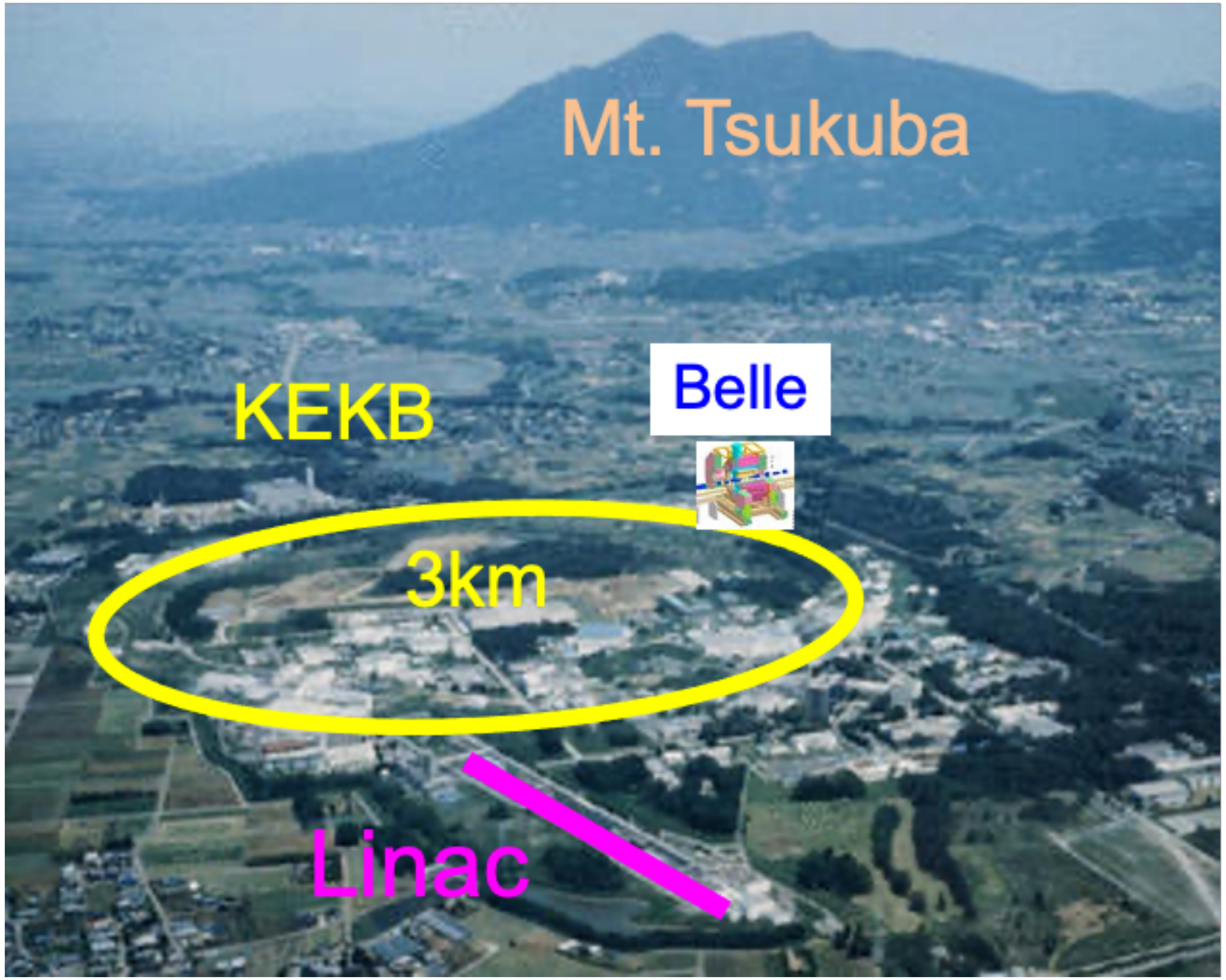
Sourav Dey
on behalf of the Belle Collaboration

BELLE

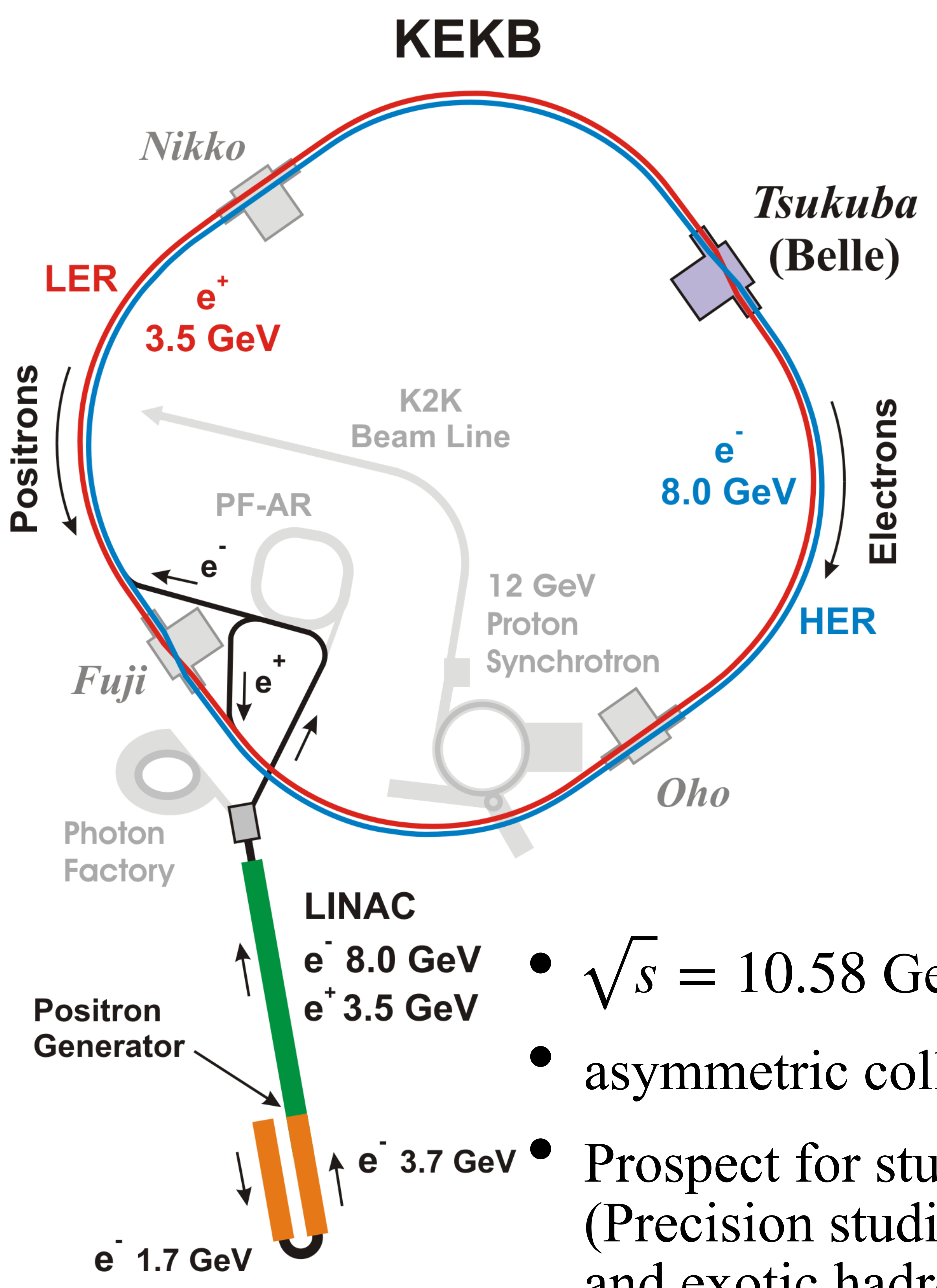
KEKB Quest for CPV kekb.jp

KEK

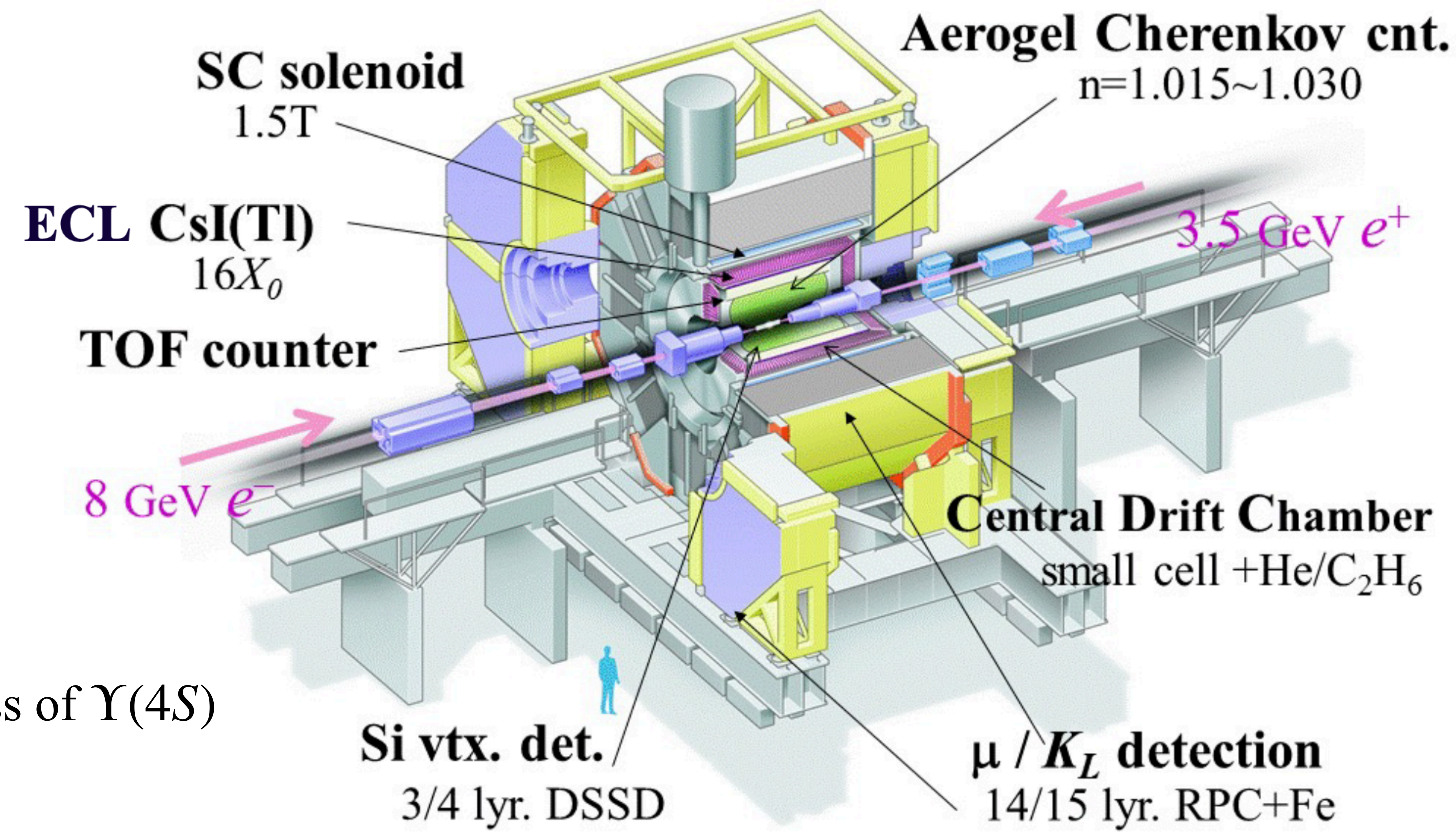
The Apparatus



The KEKB and the Belle Detector



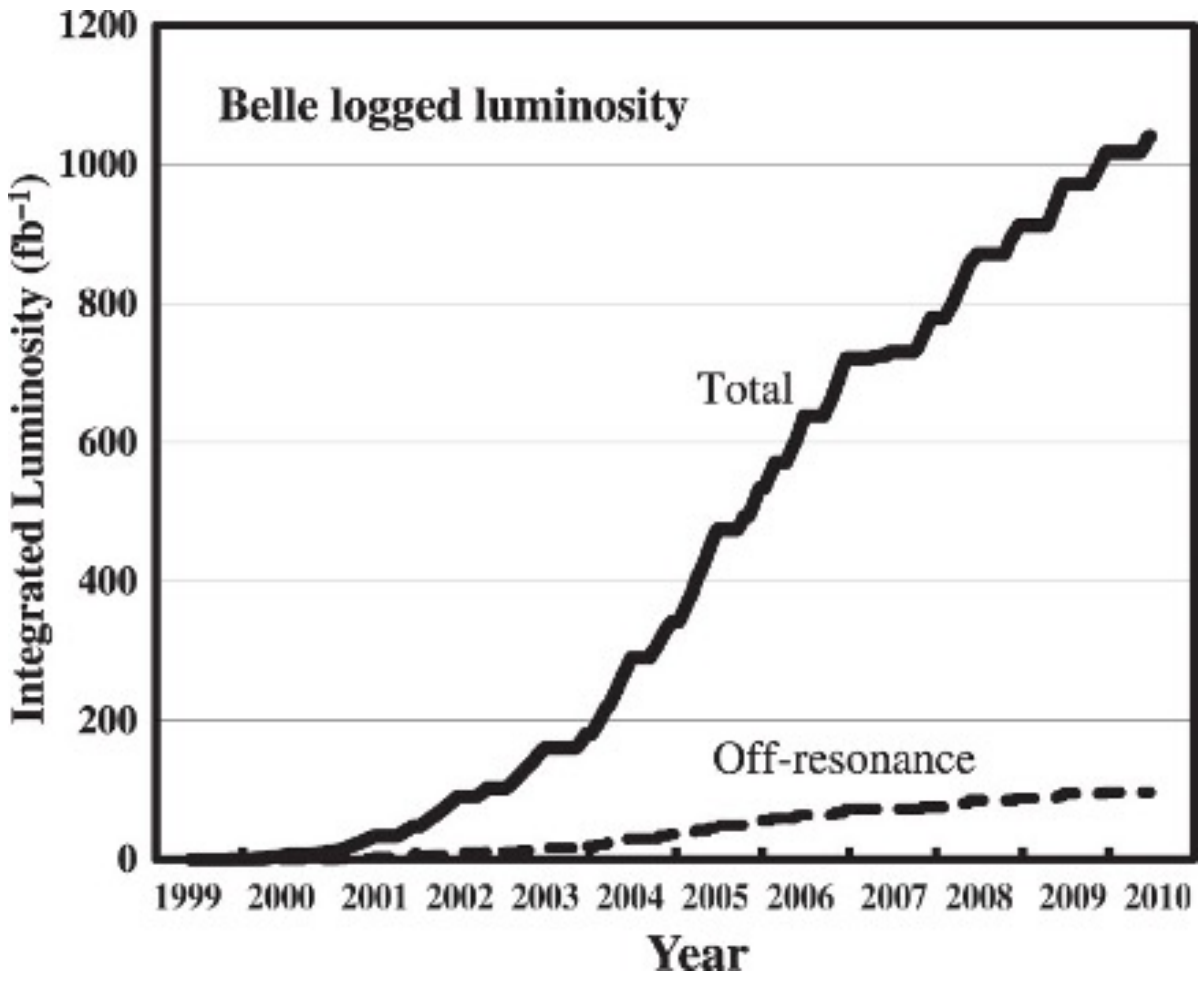
8 GeV e^-, 3.5 GeV e^+



- $\sqrt{s} = 10.58$ 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.)

Luminosity

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



To Discuss:

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

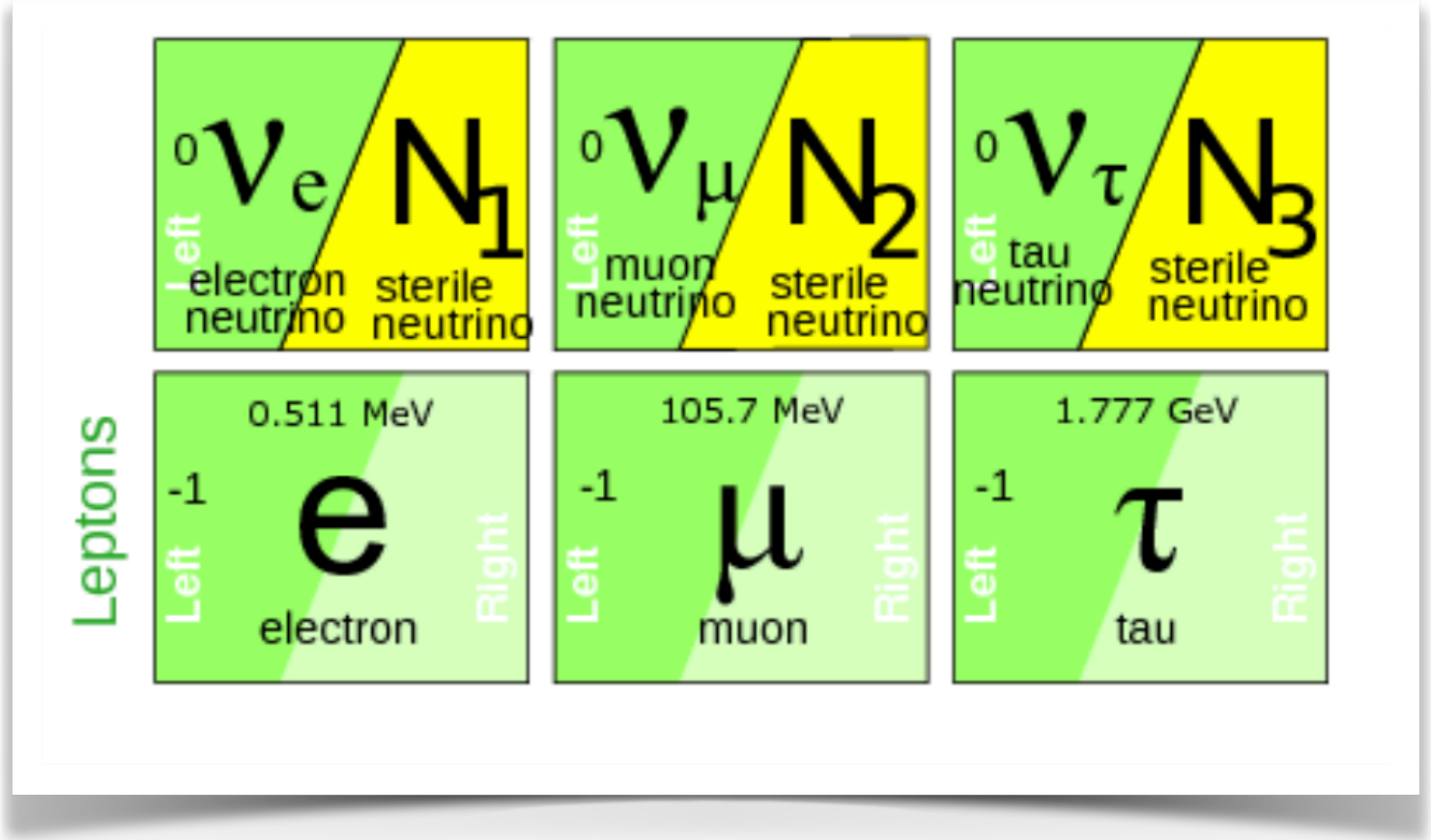
(NEW RESULT, to be submitted to PRL)

Heavy Neutral Lepton (N)

- Neutrino Oscillations: Neutrinos must have mass
- Neutrino masses can be incorporated to SM by introducing RH (Majorana) neutrinos
- Allows to solve some of the outstanding problems of the SM
    - Origin of the SM neutrino masses
    - Non-baryonic dark matter
    - Baryogenesis

T. Asaka, S. Blanchet, M. Shaposhnikov, *Phys. Lett. B* ***631****, 151-156 (2005)*

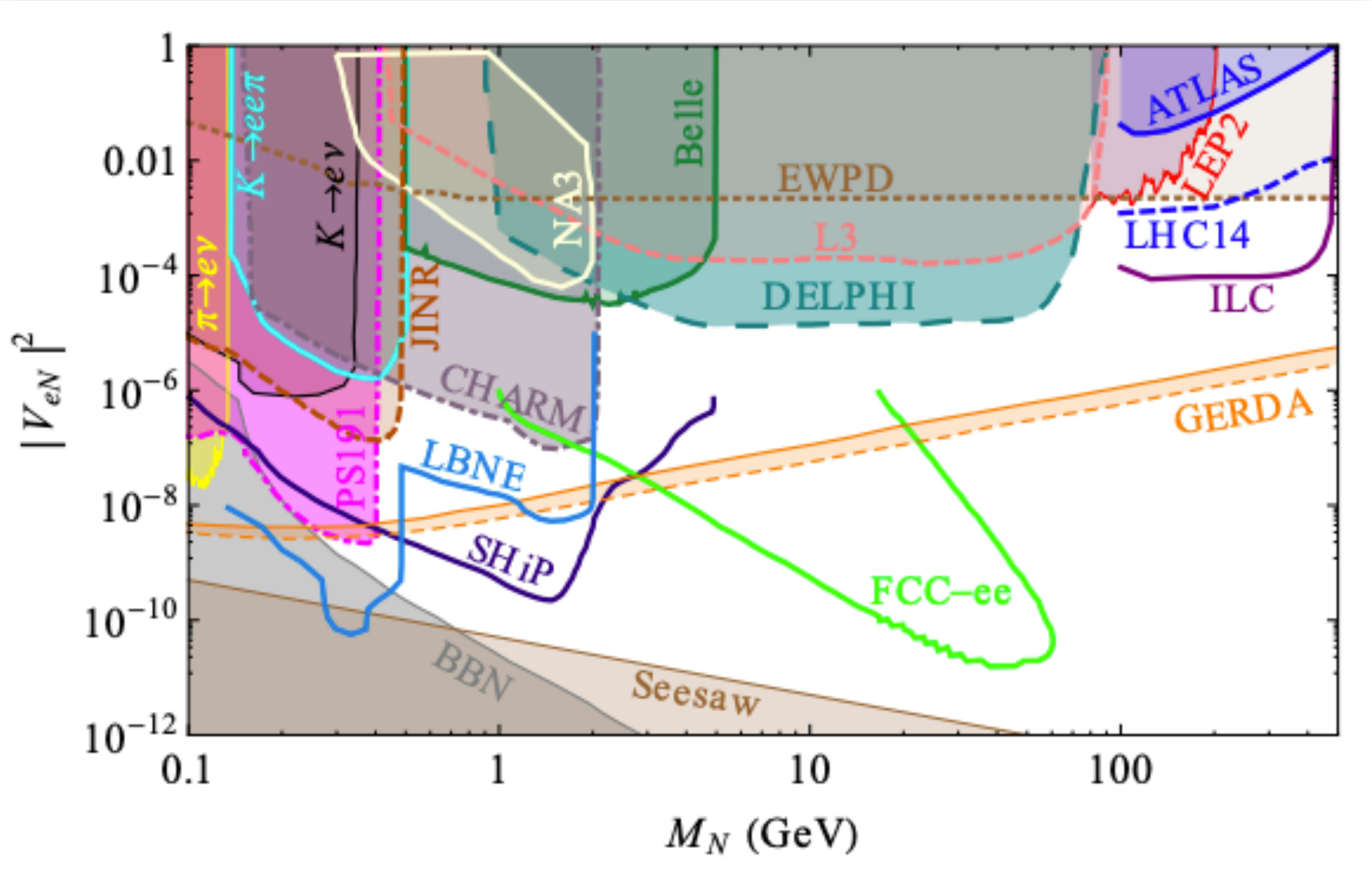
- N are sterile: Interacts with ν_{SM} through mixing: $N \leftrightarrow \nu_{SM}$
- Long lifetime of N: due to small m_N and small mixing
- Heavy Neutral Lepton also appears in SUSY, exotic Higgs, GUT…



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: $pp \to Nl^{\pm}$
  - $m_N < m_{Z,W}$ DELPHI($Z^0 \to \nu N$), ATLAS/CMS($W^{\pm} \to Nl^{\pm}$)
  - $m_N < m_{B,D,K}$ Belle, LHCb, beam-dump, NA62

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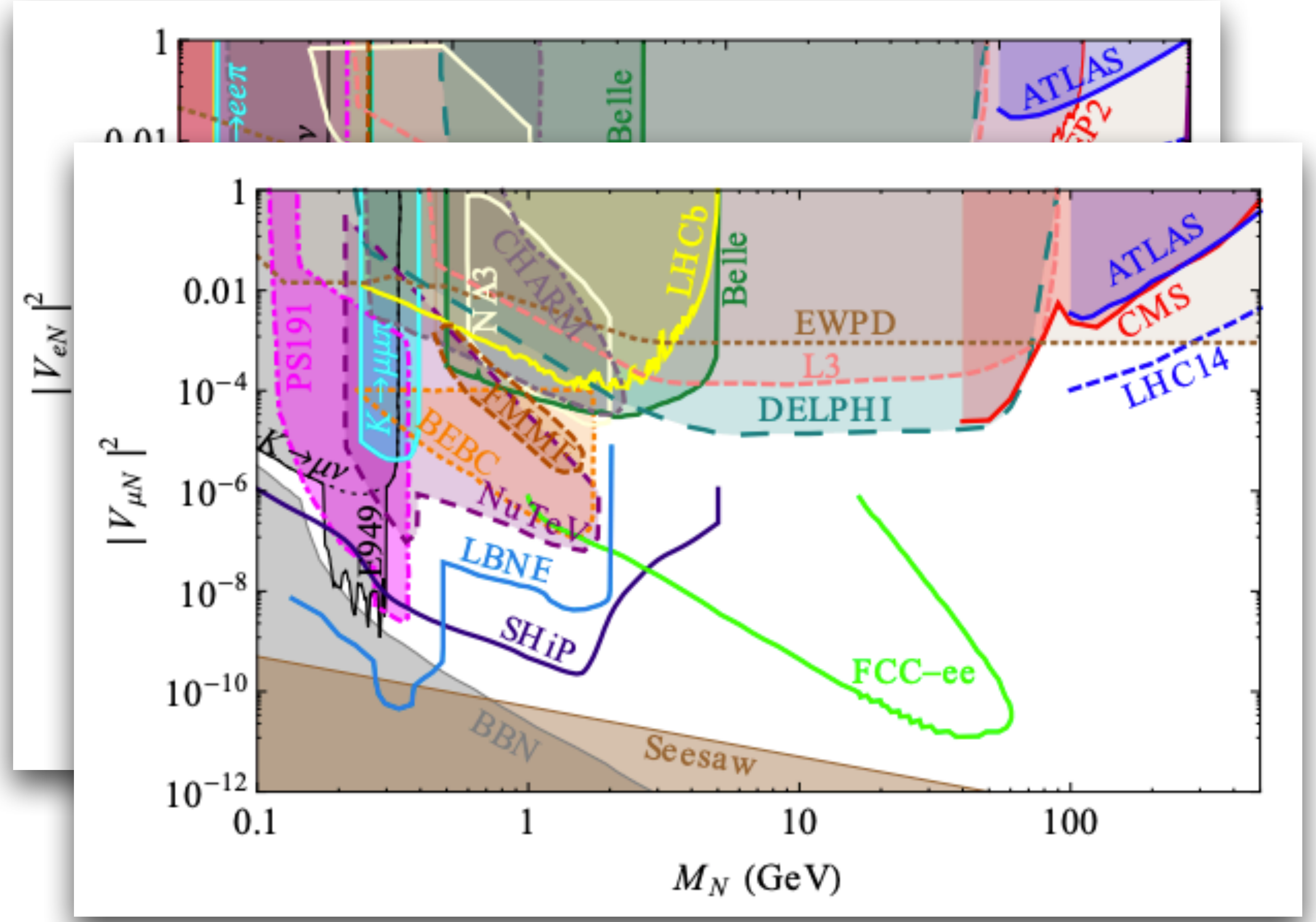

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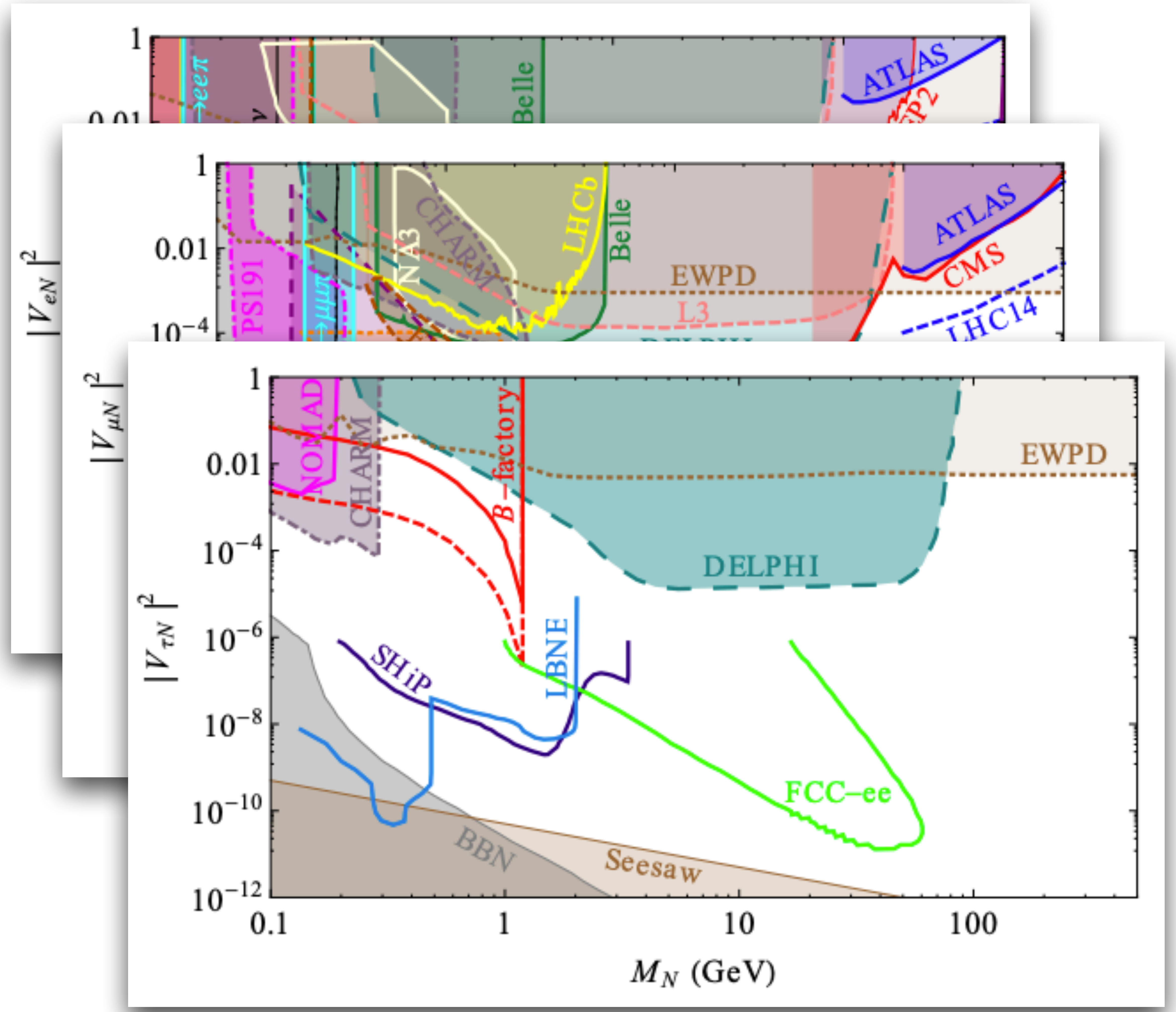
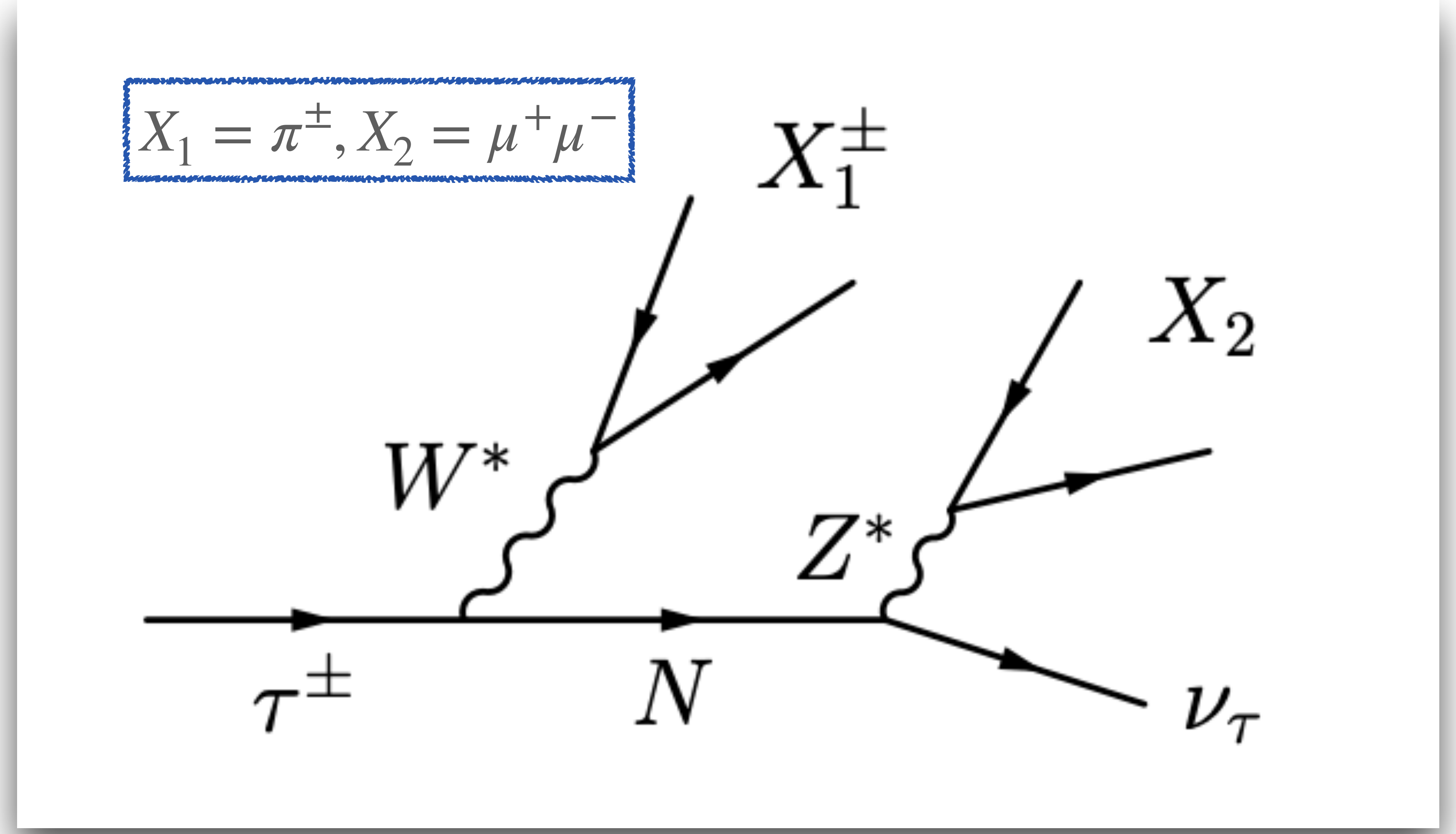
- All the experiments provide tight limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$
- Limits on $|V_{\tau N}|^2$ are much weaker
- This motivates us to overcome the experimental challenges and explore $|V_{\tau N}|^2$

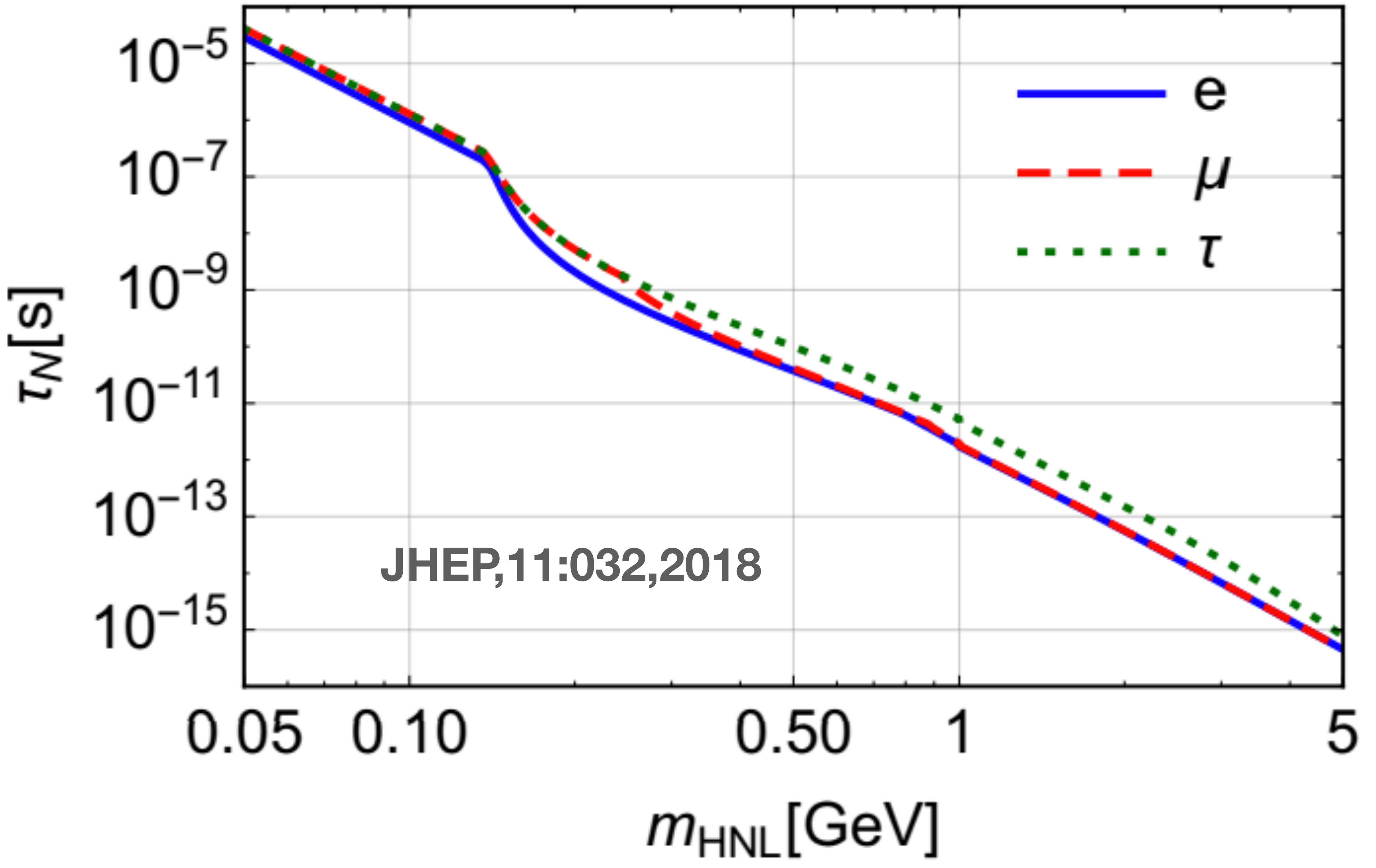


- N decays via the weak neutral current
- This analysis probes $|V_{N\tau}|^2$ directly
- This production mechanism implies $m_N < m_\tau - m_\pi$
- N is long-lived for a range of $|V_{N\tau}|^2$ values that we are sensitive to

Full Belle data sample used

$(836 \pm 12) \times 10^6$ τ pairs





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

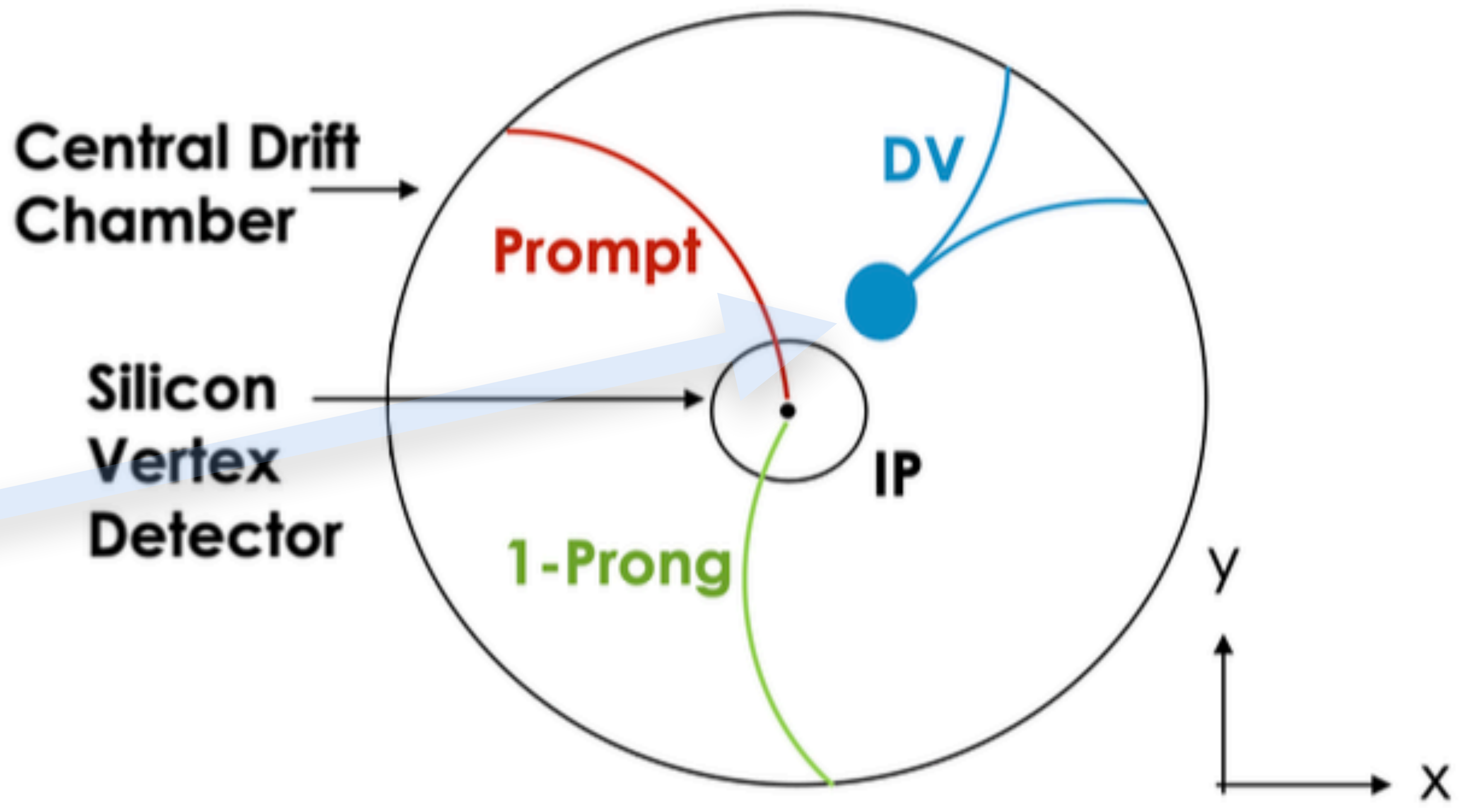
Tag side:

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

Signal side:

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

- We look for a $\mu^+\mu^-$ displaced vertex (DV)
- Radial position of DV > 15 cm from the beam axis

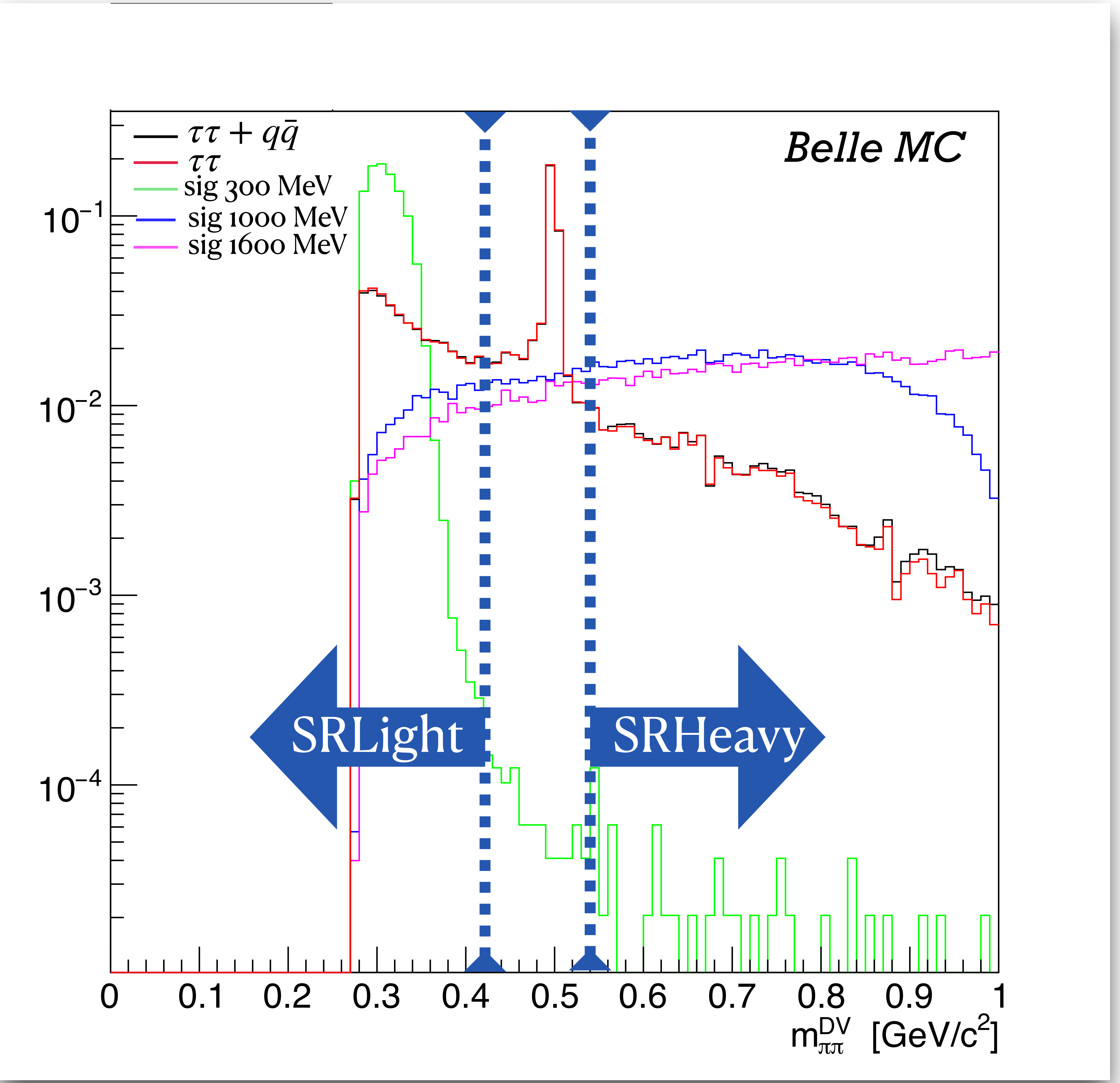


DV = Displaced Vertex

IP = Interaction Point

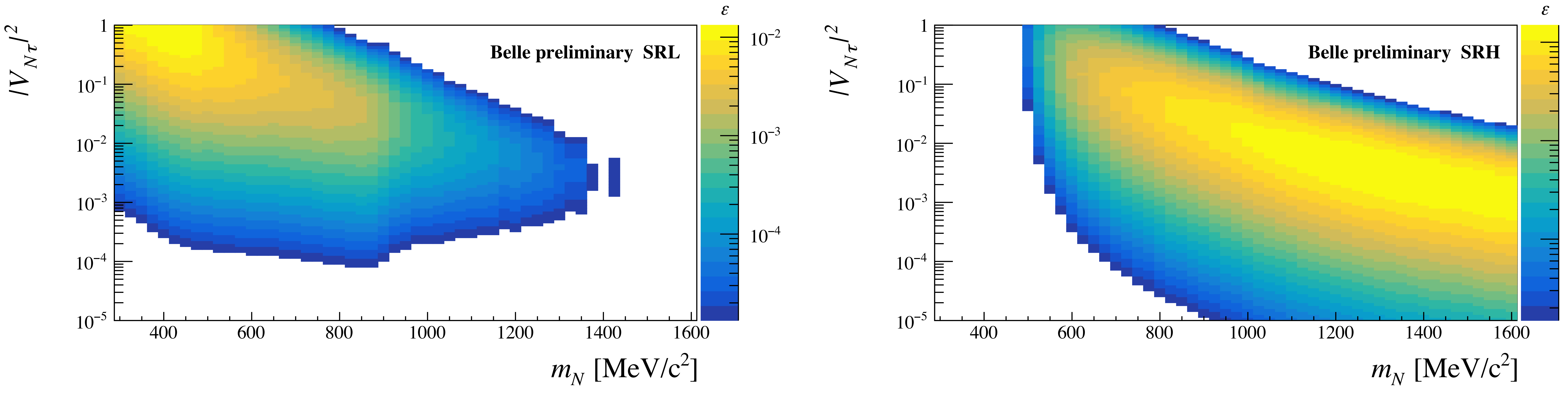
K_S^0 rejection and definition of two signal regions

- $K^0 \rightarrow \pi^+\pi^-$: 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: $m_{\pi\pi}^{DV} < 0.42\ GeV/c^2$
- LightN distribution is different from heavy N distribution



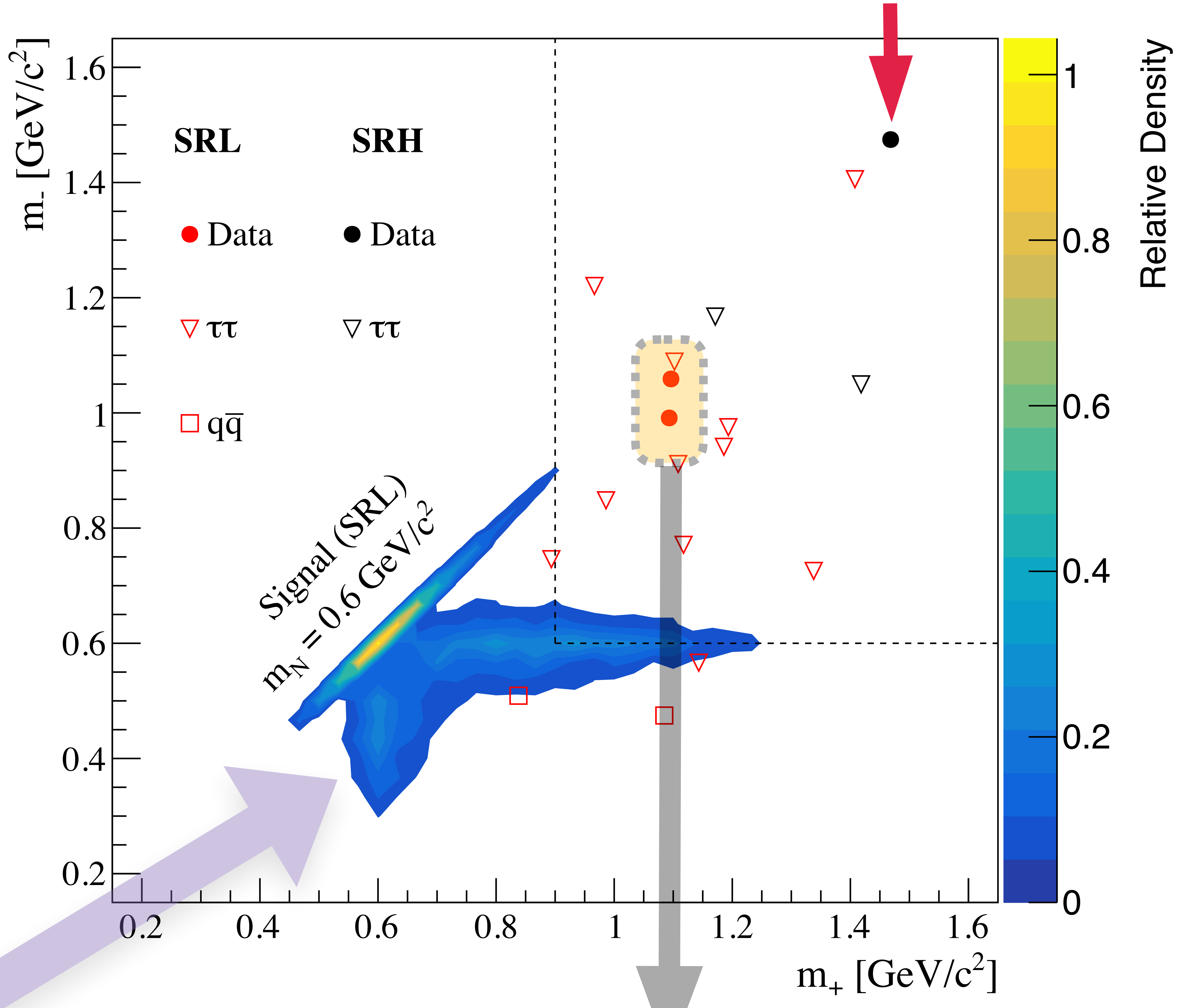
more on Analysis Method

- $N_{signal} = N_{\tau\tau} \times B(\tau \to \pi N) \times B(N \to \mu^+\mu^-\nu_\tau) \times \epsilon$, 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.

only signal event observed



vetoed in SRL

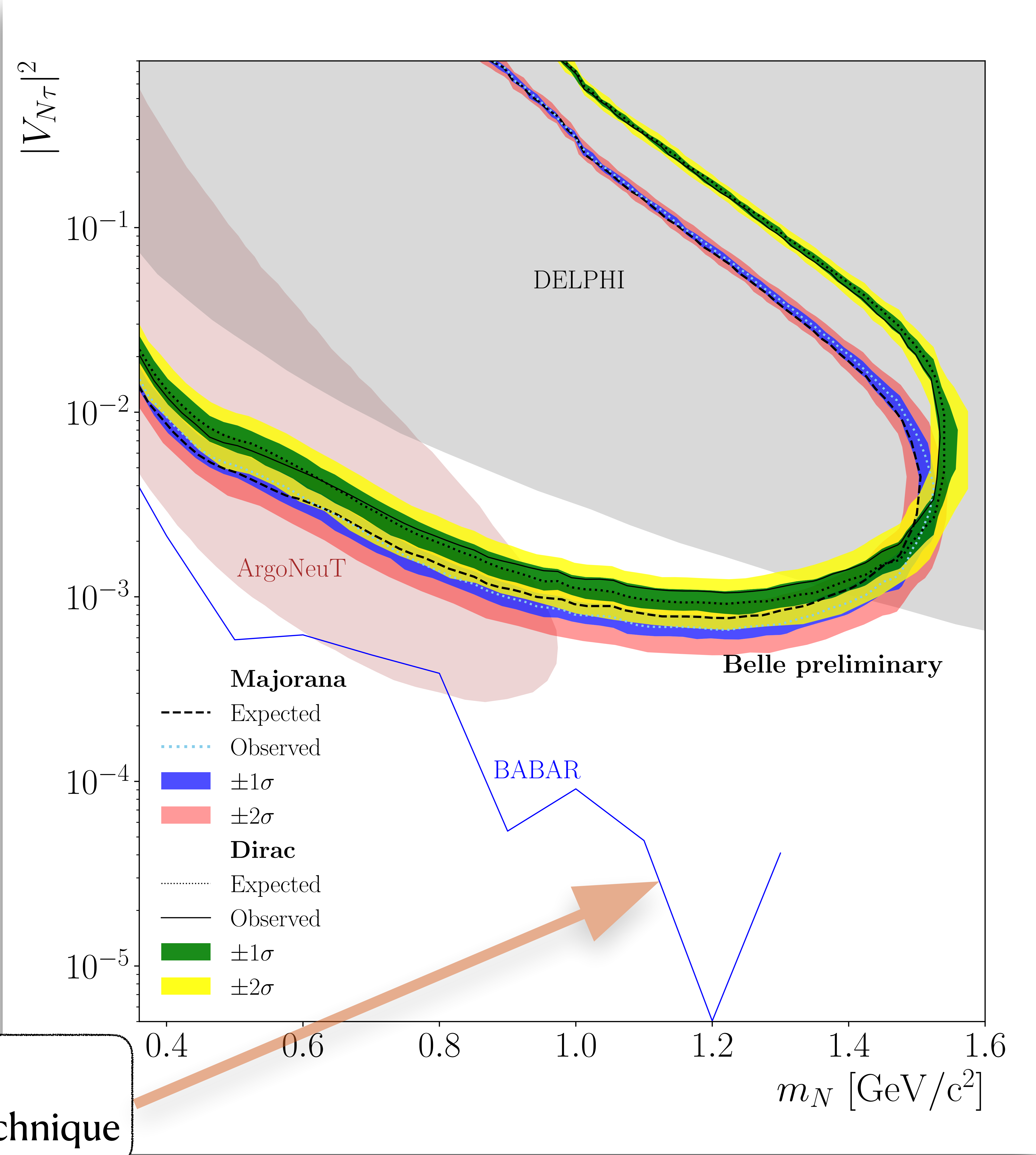
distribution of signal-MC events with m_n= 600 MeV/c2 in the SRL

Results

- Uncertainties
  - N branching fraction
  - decay modeling
  - uncertainty on the reconstruction of the two prompt tracks
  - the background yield expectations(largest)
  - luminosity
  - cross section
- 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



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

Signal, Control and Validation regions

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

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

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

Two HNL mass solutions: m_+, m_-