The 17th International Workshop on Tau Lepton Physics (TAU2023) | Louisville

Dark sector searches with tau-pair events at Belle and Belle II

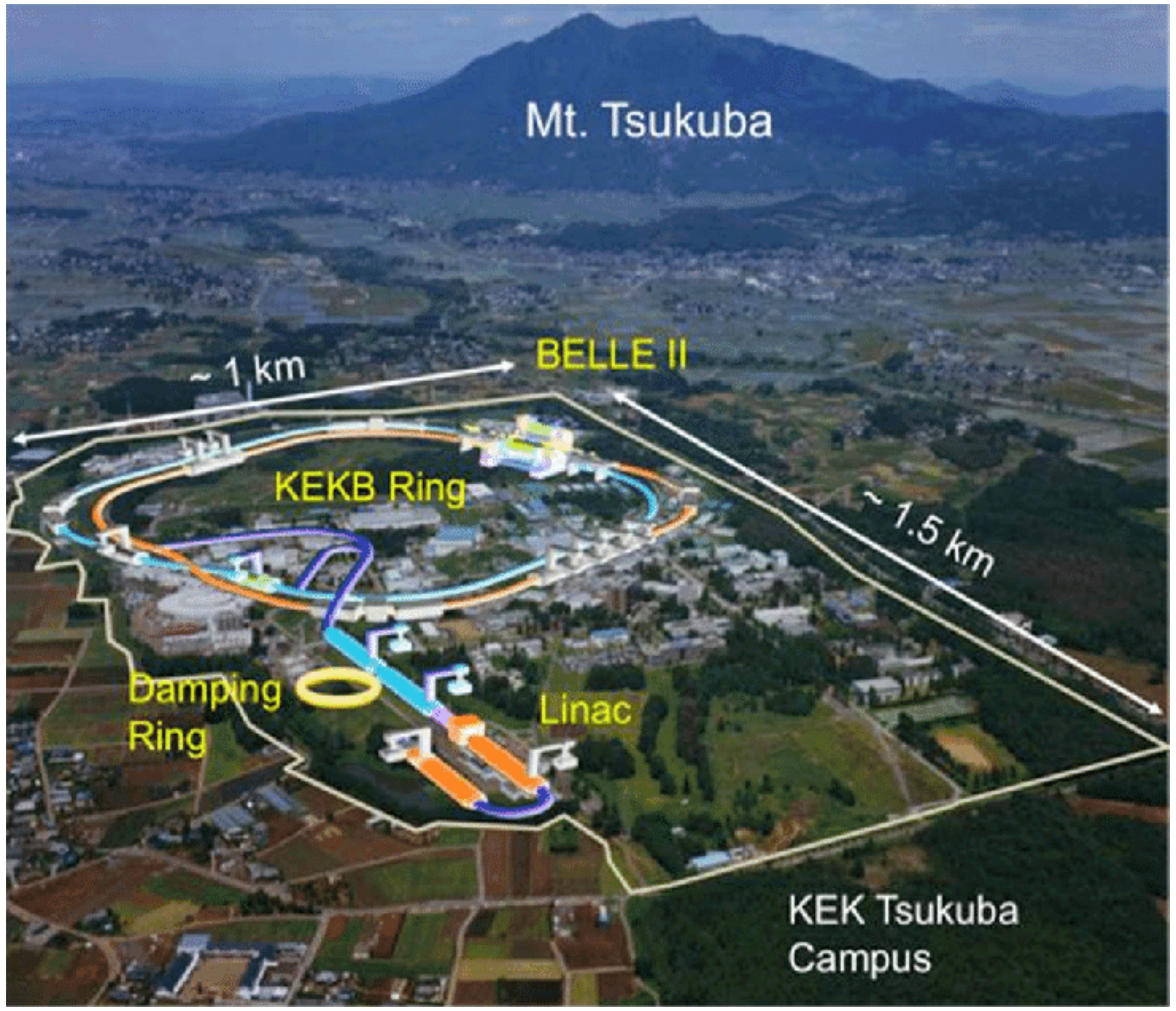
PRACTICE TALK

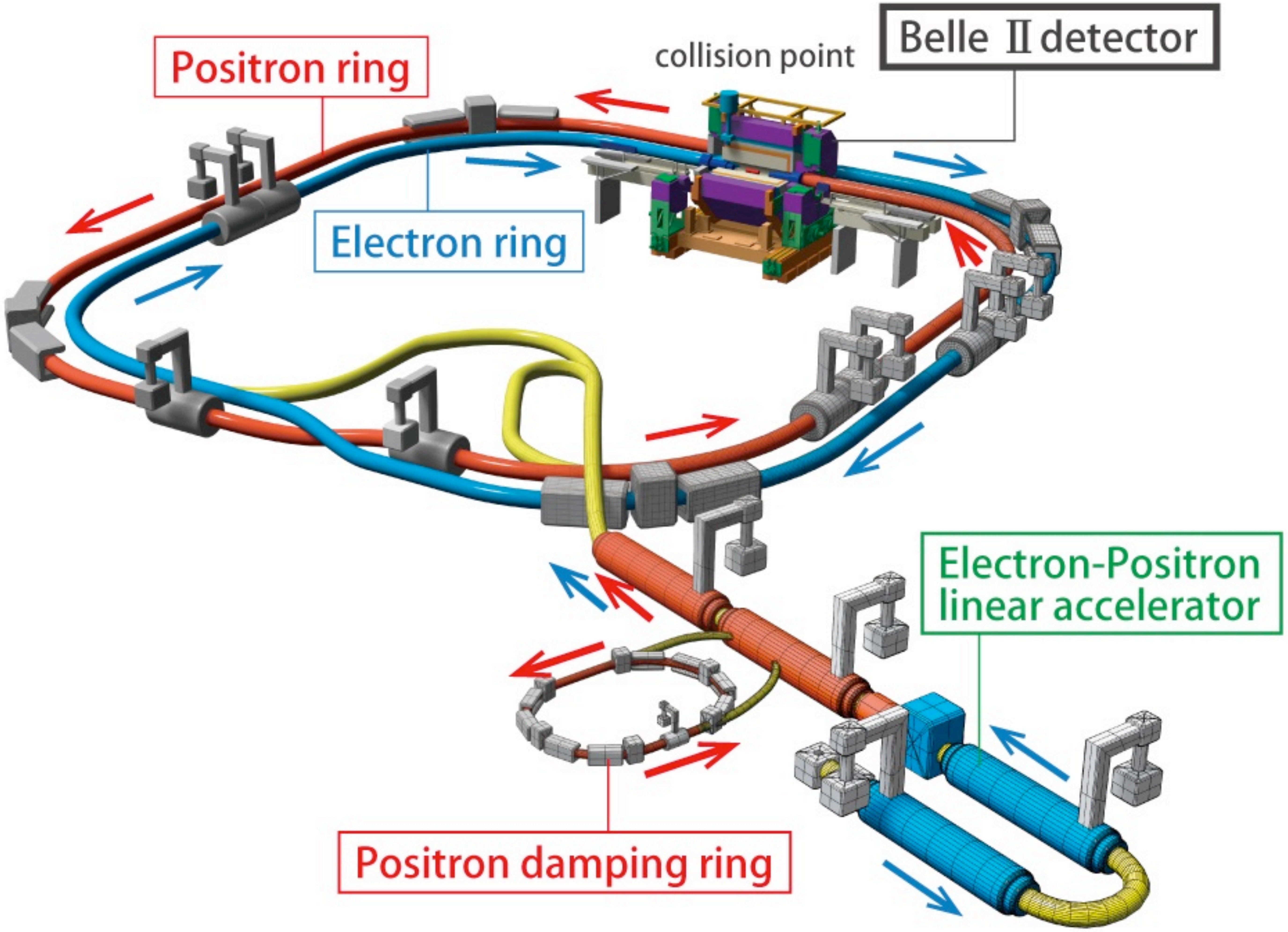
Sourav Dey
on behalf of the Belle and Belle II Collaboration

To Discuss:

- Search for a heavy neutral lepton that mixes predominantly with the τ neutrino (NEW RESULTS, to be submitted to PRL)
- Search for a dark leptophilic scalar produced in association with $\tau^+\tau^-$ pair in e^+e^-annihilation at center-of-mass energies near 10.58 GeV(to be submitted to PRL. Arxiv 2207.07476)
- Search for Lepton Flavor Violating τ Decays to a Lepton and an Invisible Boson at Belle II(PRL 130, 181803 (2023). Arxiv 2212.03634)

SuperKEKB

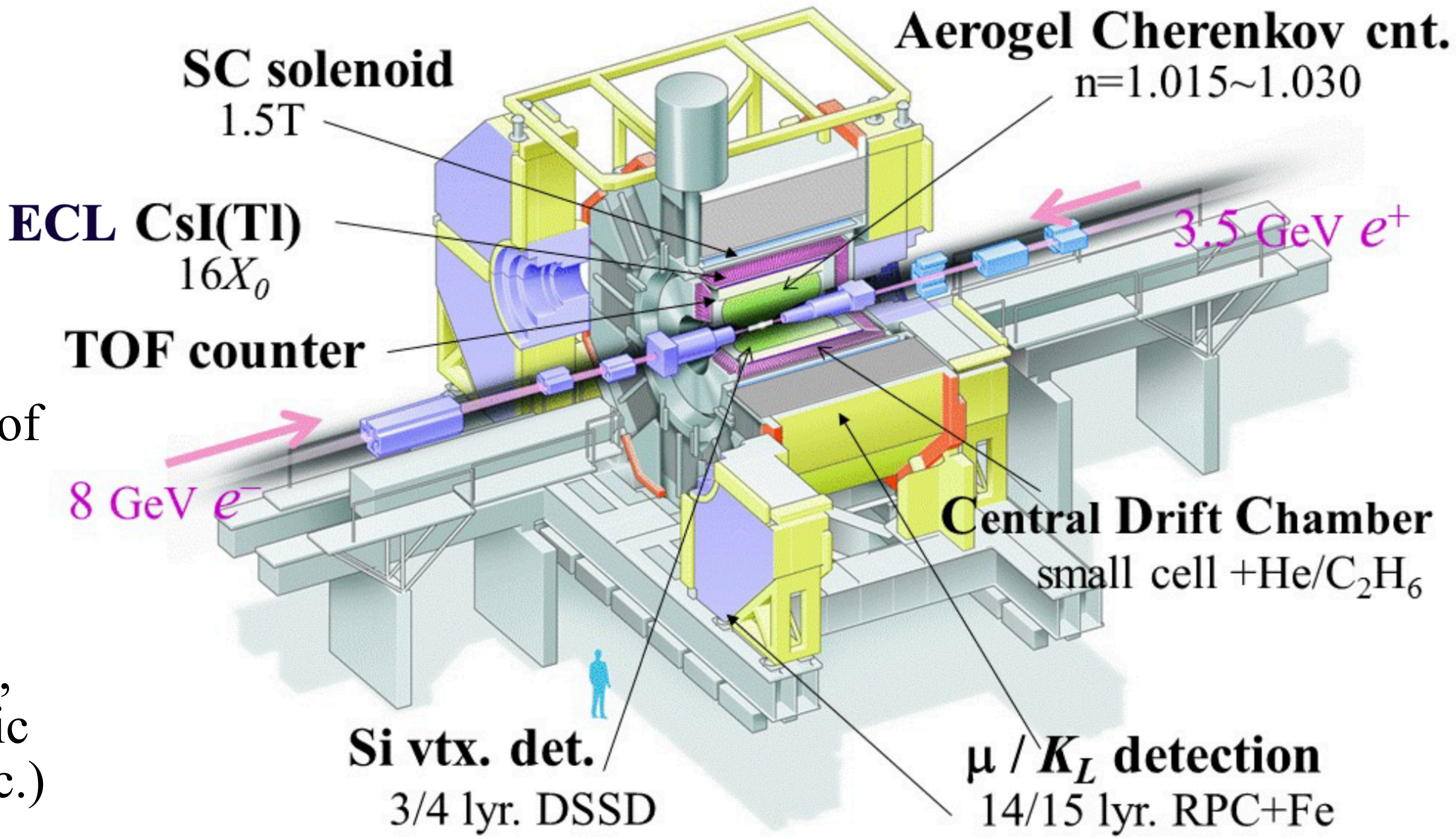

Mt. Tsukuba
~ 1 km
BELLE II
KEKB Ring
~ 1.5 km
Damping Ring
Linac
KEK Tsukuba Campus


Positron ring
collision point
Belle II detector
Electron ring
Electron-Positron linear accelerator
Positron damping ring

The Belle Detector

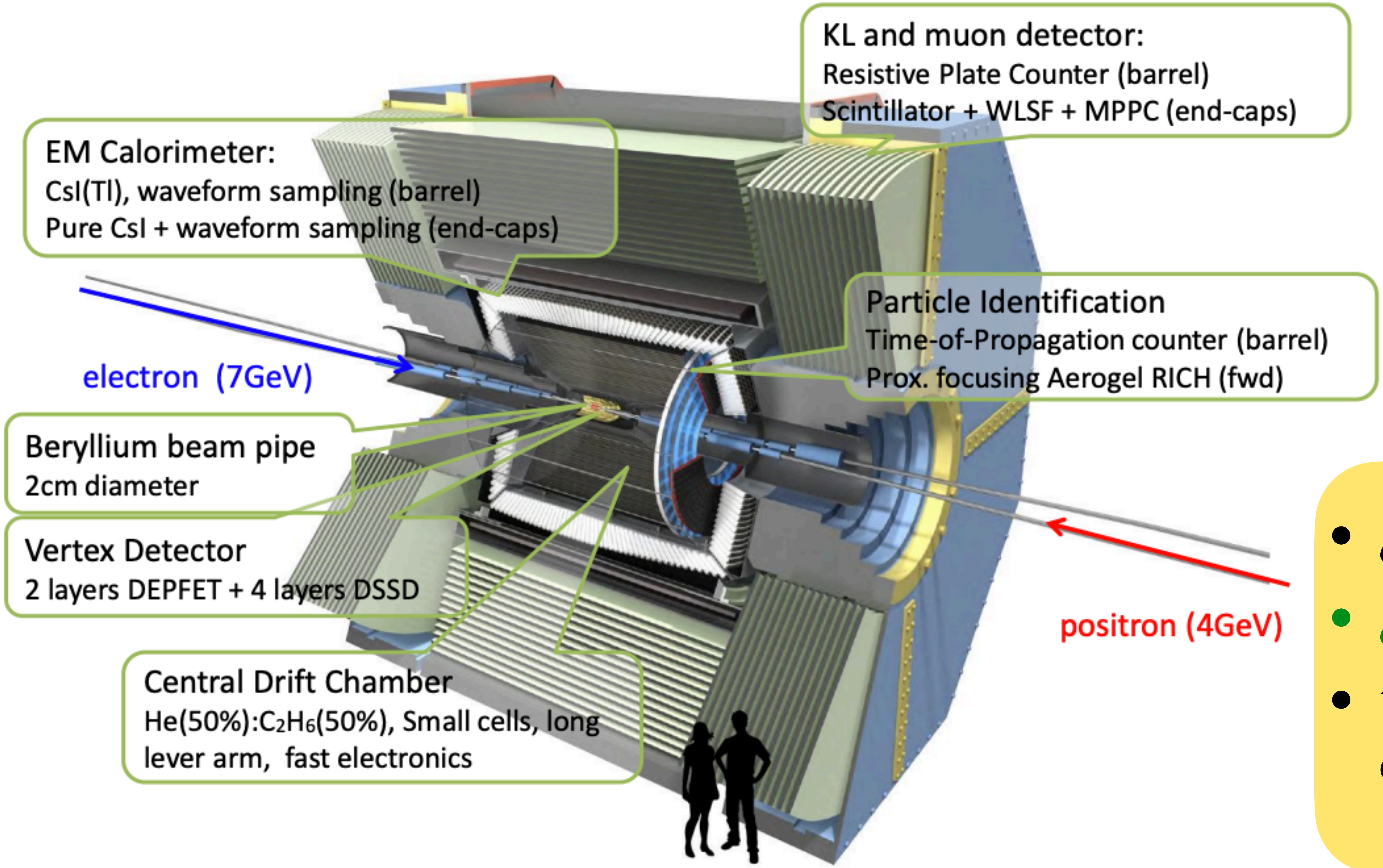
- The accelerator collides electron and positrons
- $\sqrt{s} = 10.58$ GeV : mass of $\Upsilon(4S)$
- $B\bar{B}$, $\tau^+\tau^-$ pair production with a boost of the center-of-mass system: asymmetric collider
- Prospect for studying a vast region of particle physics (Precision studies of B, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)

8 GeV e^-, 3.5 GeV e^+



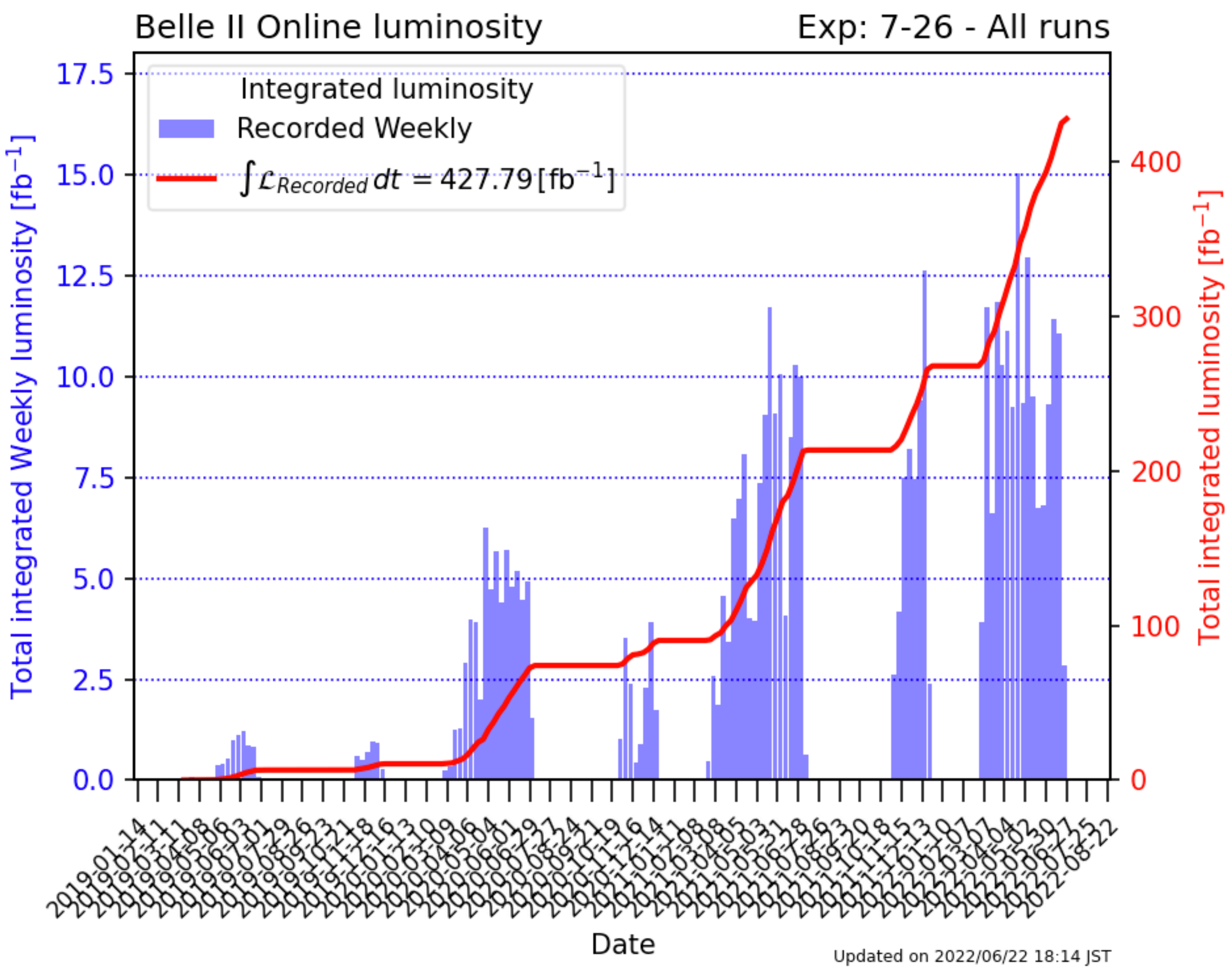
from Belle to The Belle II Detector

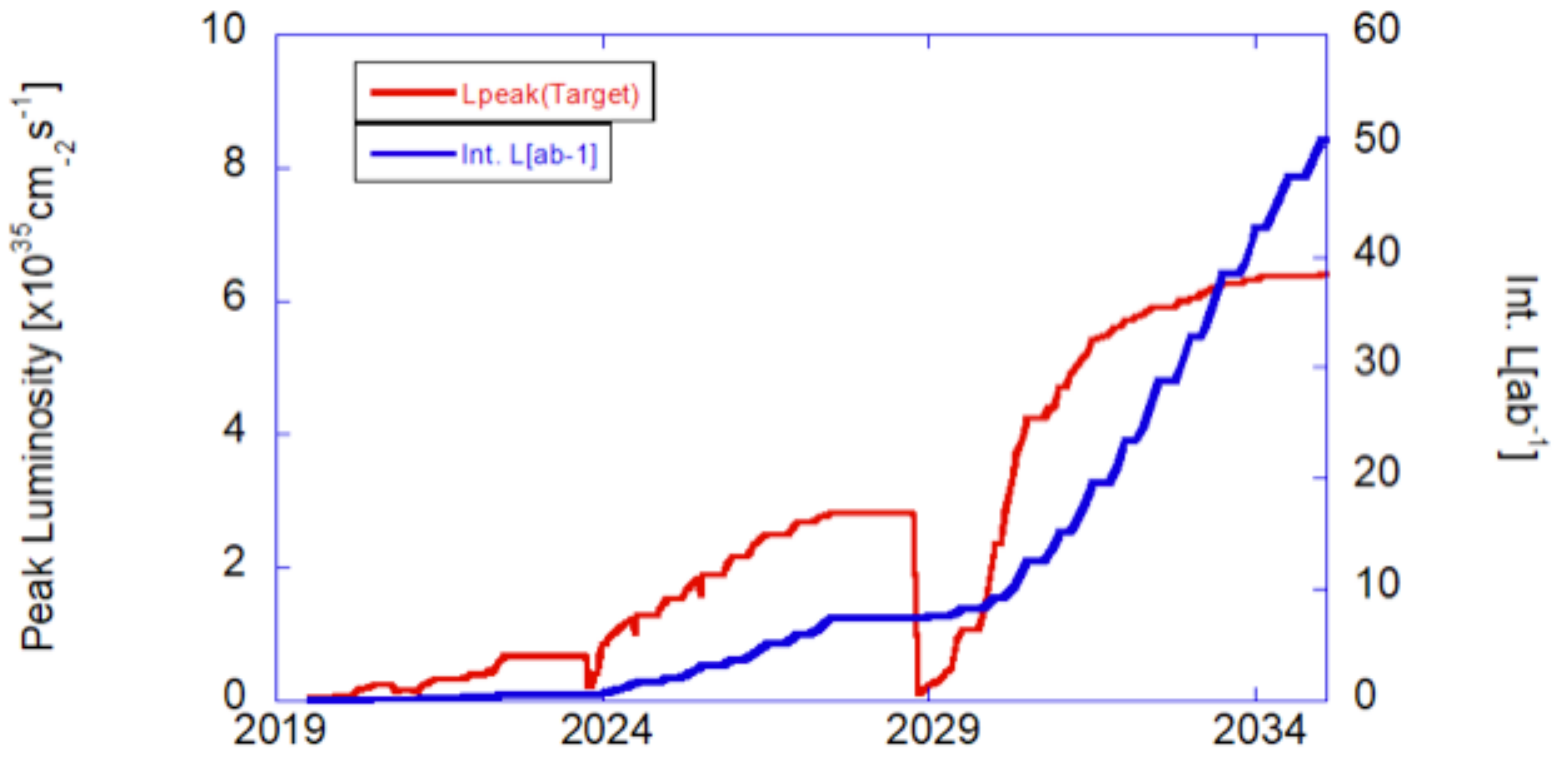
$7\ \mathrm{GeV}\ e^-$, $4\ \mathrm{GeV}\ e^+$



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

Luminosity





- Design 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

To Discuss:

- Search for a heavy neutral lepton that mixes predominantly with the τ neutrino (NEW RESULTS, at the stage of collaboration-wide review, to be submitted to PRL)

- Search for a dark leptophilic scalar produced in association with $\tau^+\tau^-$ pair in e^+e^-annihilation at center-of-mass energies near 10.58 GeV(to be submitted to PRL. Arxiv link)

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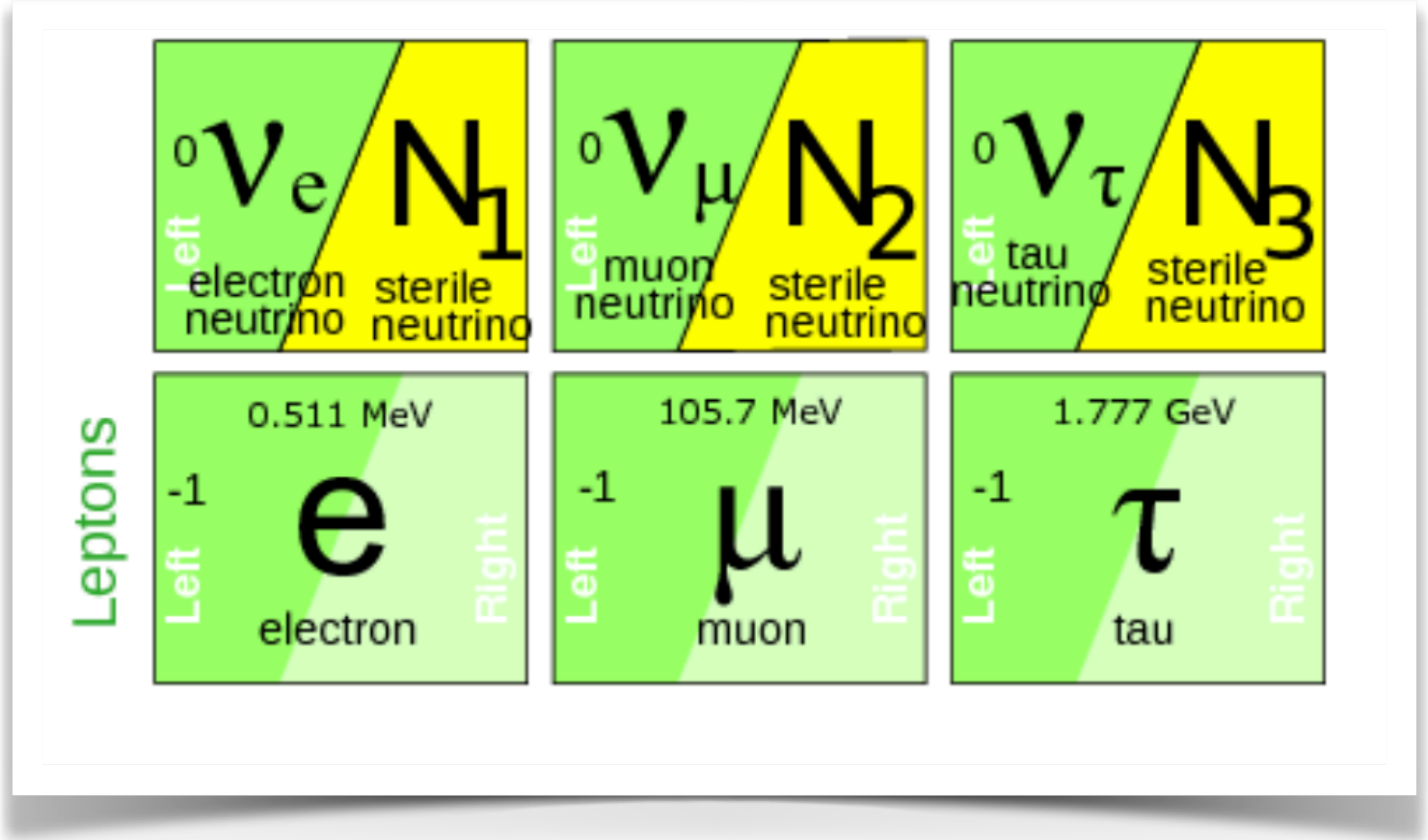
Heavy Neutral Lepton (N)

- Neutrino Oscillations: Neutrino has 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

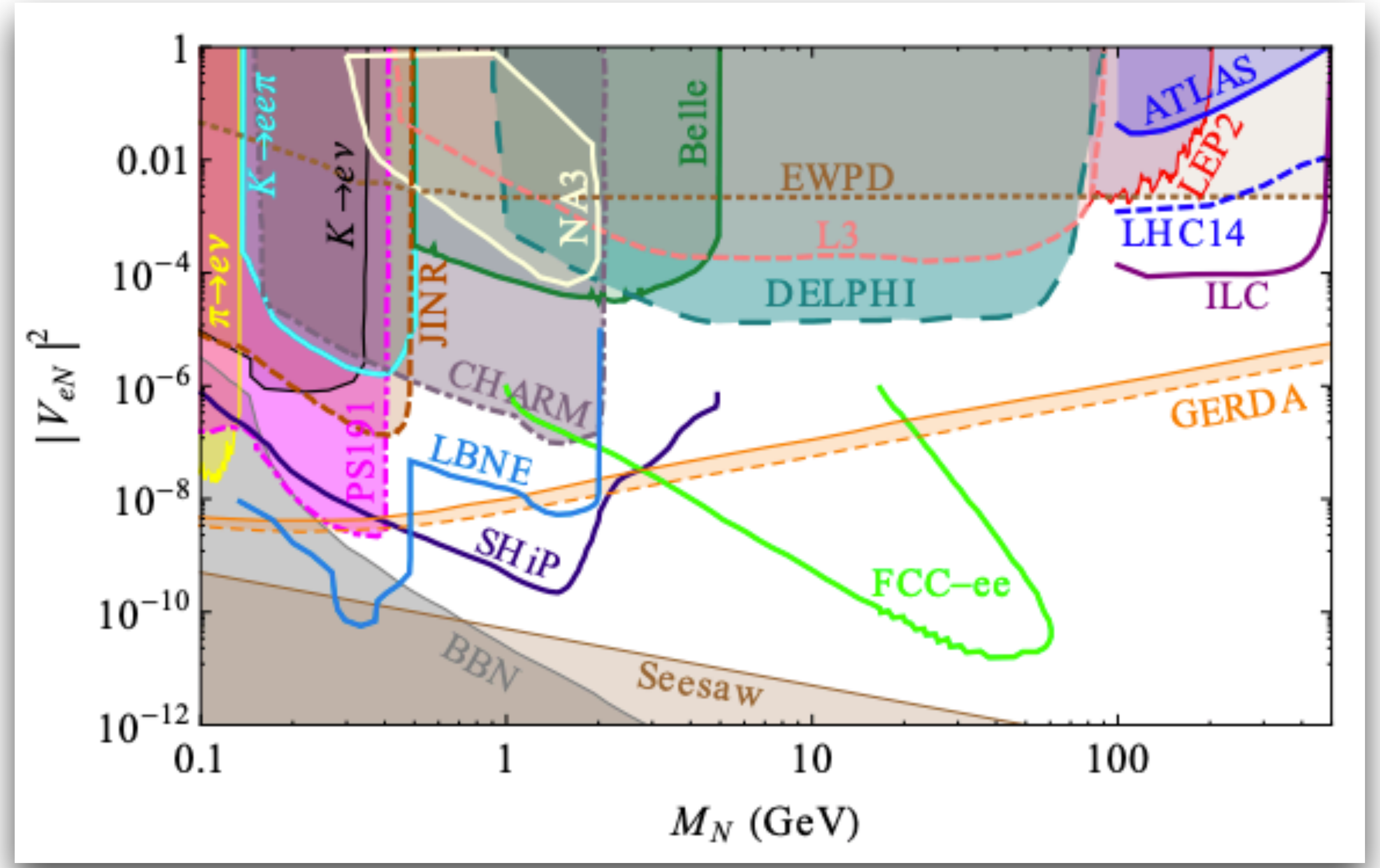
$M_N > M_Z$ Direct searches @LHC: $pp \to Nl^{\pm}$

$M_N < M_{Z,W}$

- Delphi($Z^0 \to \nu N$)
- ATLAS/CMS($W^{\pm} \to Nl^{\pm}$)

$M_N < M_{B,D,K}$ Belle, LHCb, beam-dump, NA62

arxiv 1502.06541



- Previous experiments explored M_N from 100 MeV to almost 1TeV arxiv 1502.06541

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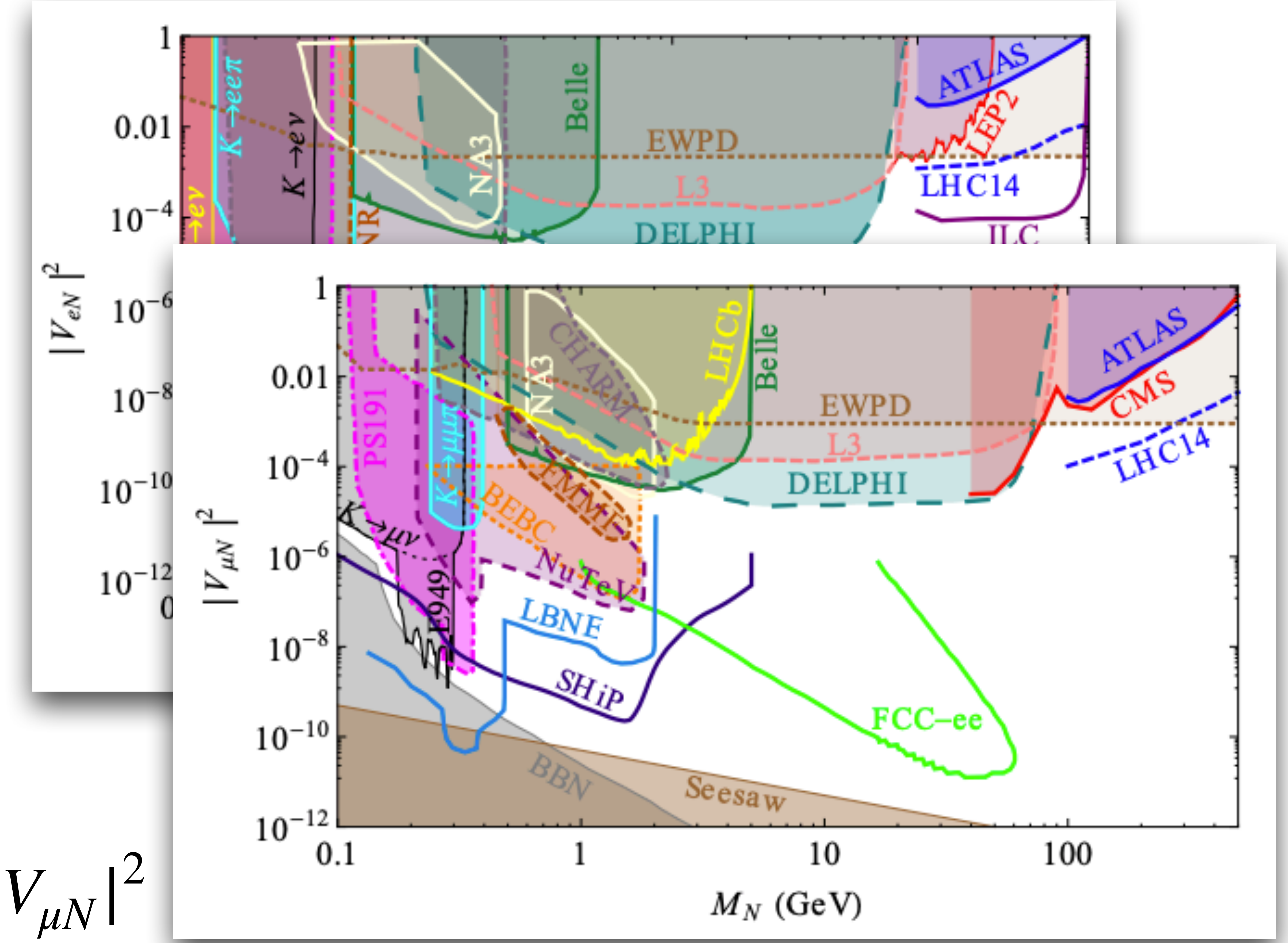

- Previous experiments explored M_N from 100 MeV to almost 1TeV
- All the experiments provide tight limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$

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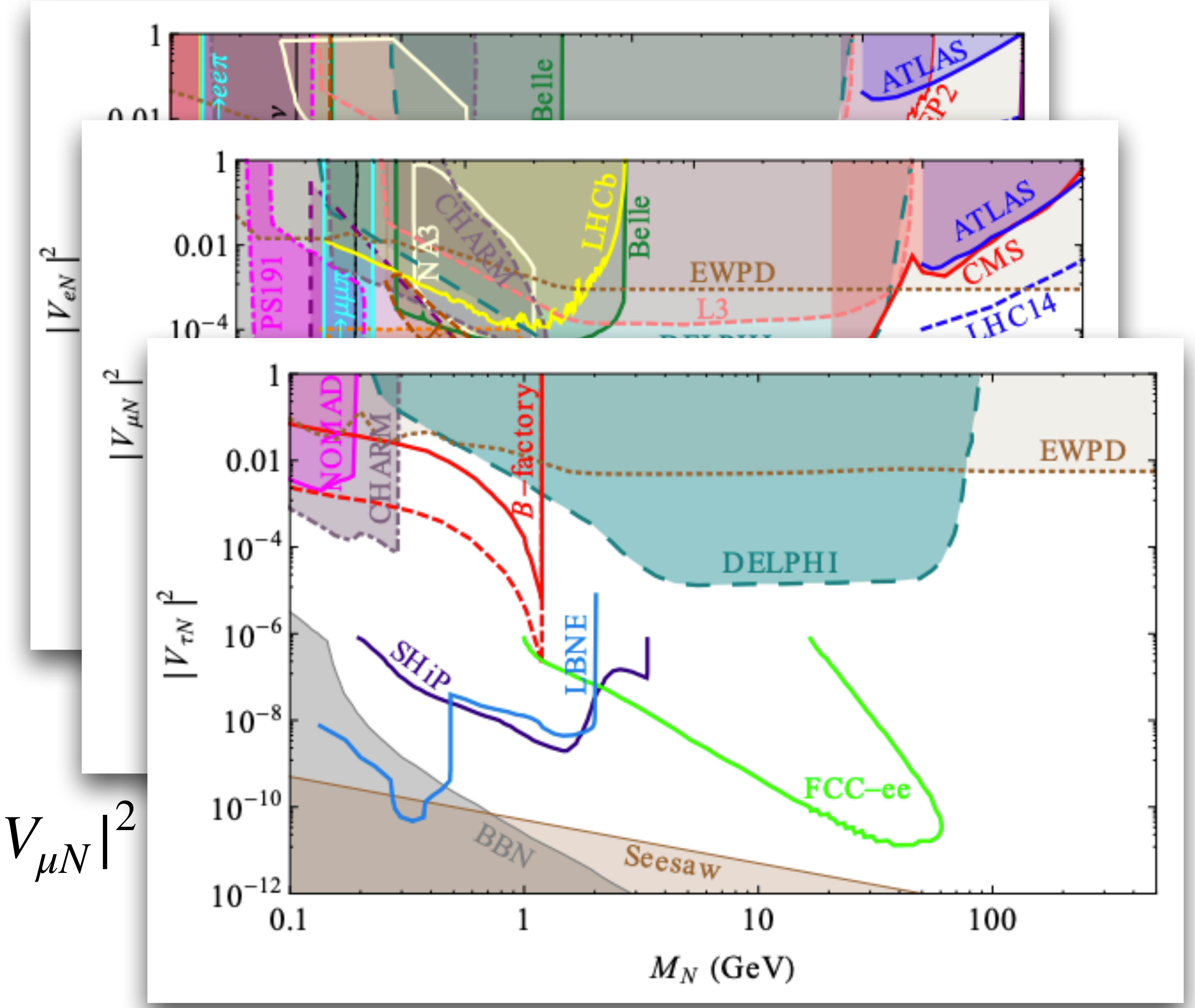
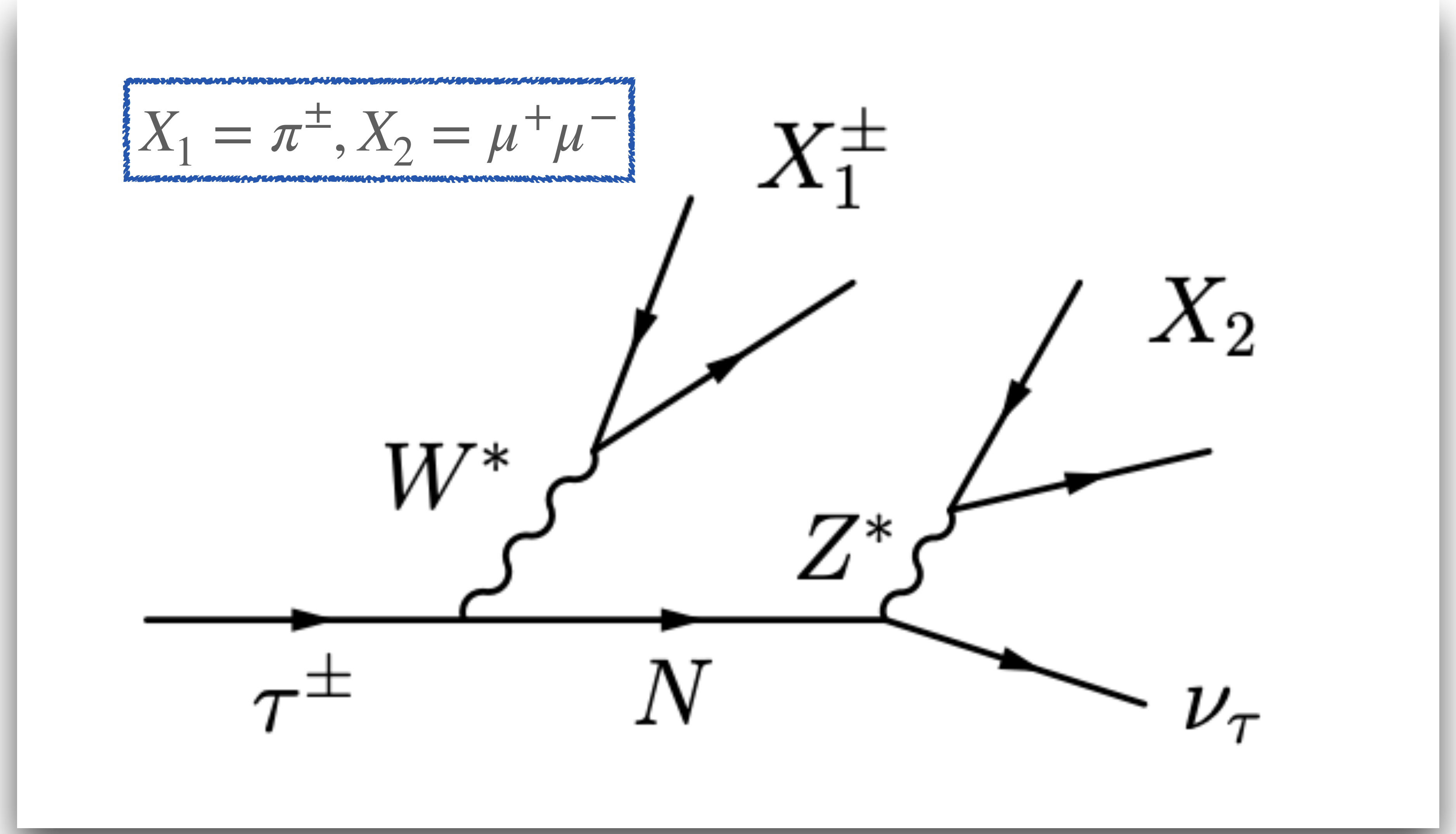
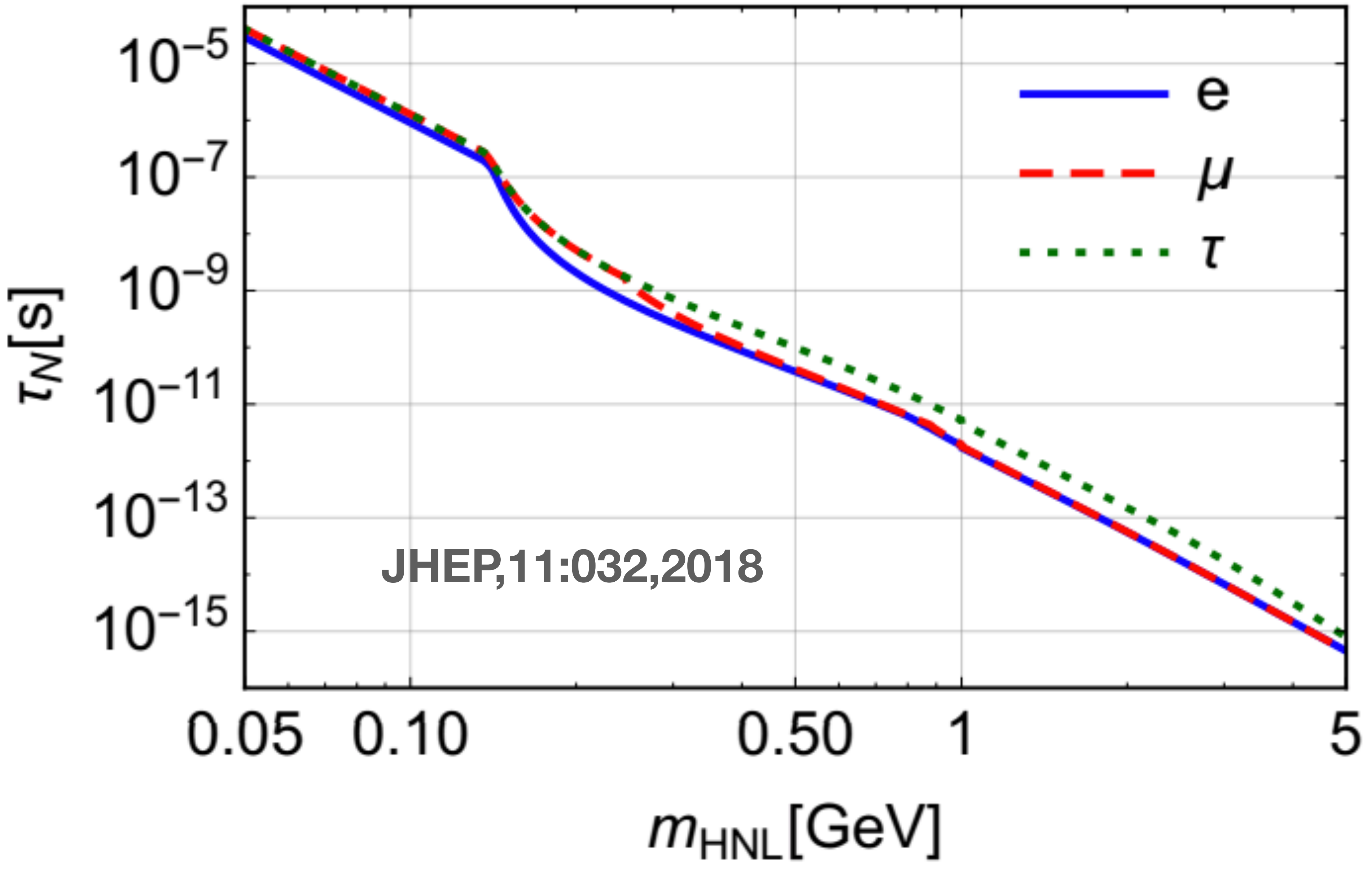


- Previous experiments explored M_N from 100 MeV to almost 1TeV
- All the experiments provide tight limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$
- Limits on $|V_{\tau N}|^2$ are much weaker
- This motivates us to overcome the experimental challenges and explore $|V_{\tau N}|^2$

- N decays via the weak neutral current
- This analysis probes $V_{\tau N}$ 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



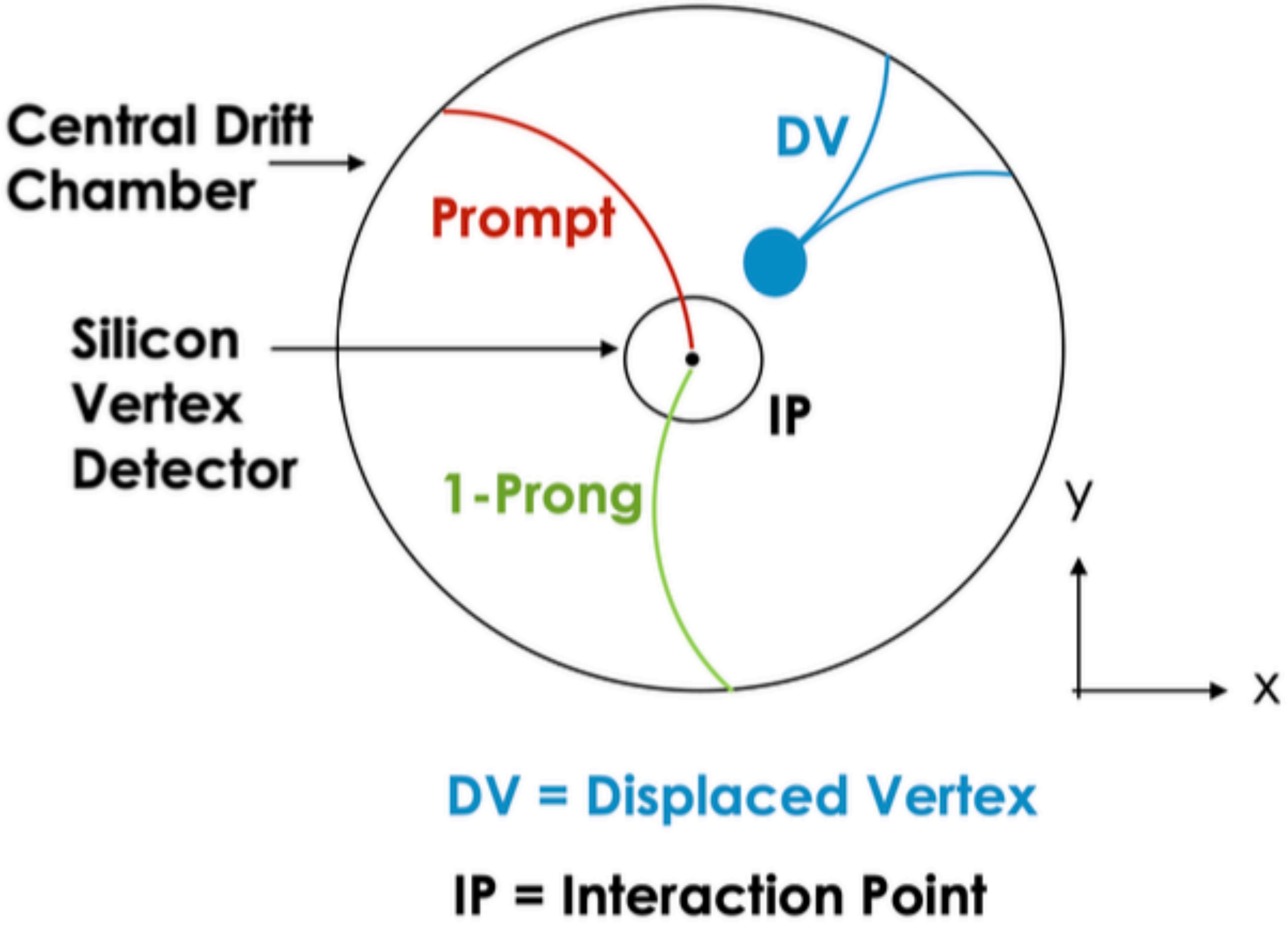


Full Belle data sample used

$(836 \pm 12) \times 10^6$ τ pairs

Analysis Method

- We look for a $\mu^+\mu^-$ displaced vertex(DV)
- Radial position of DV must be 15 cm away from CDC symmetry axis



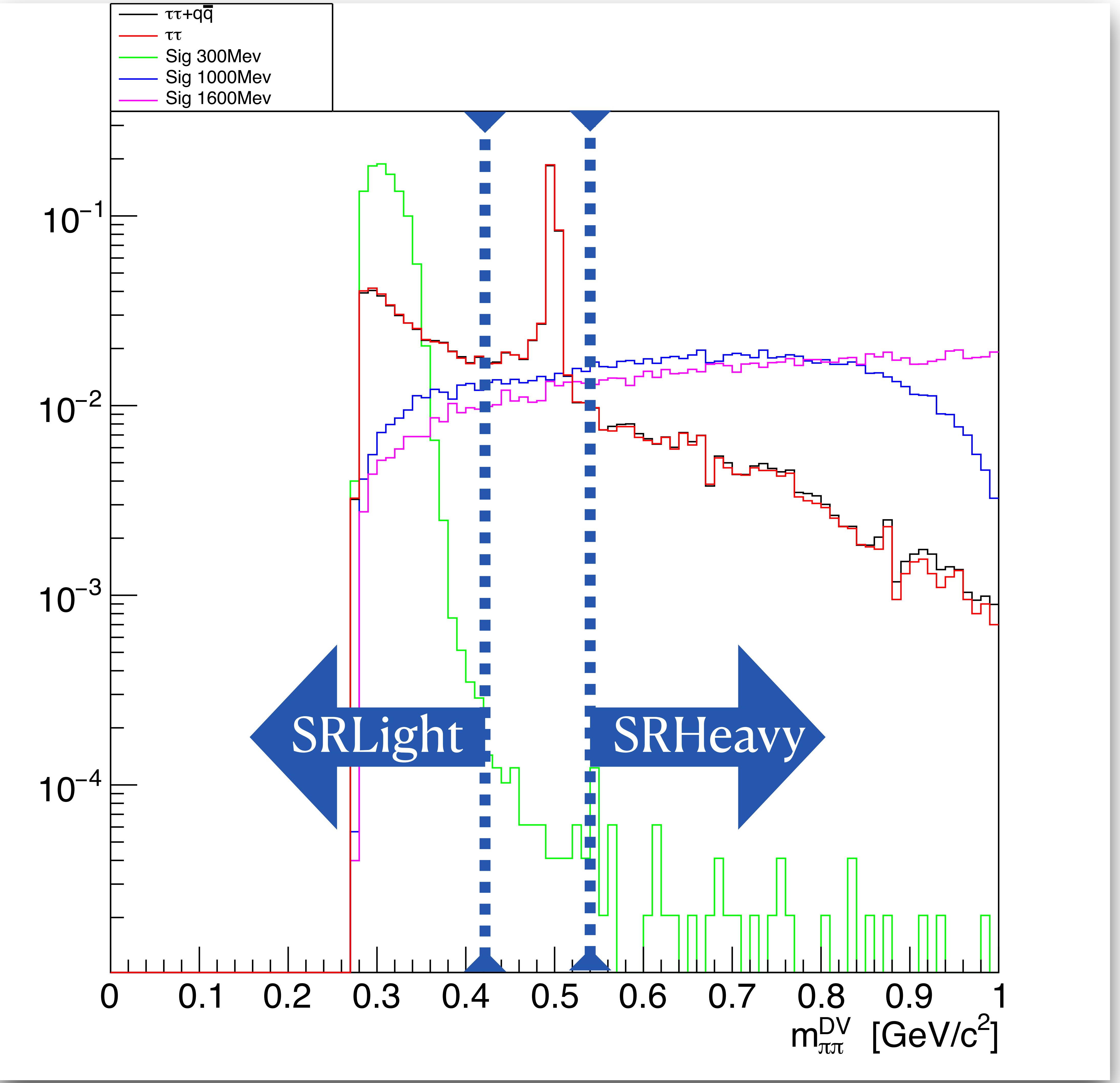
- Channel: $e^+e^- \to \tau^+_{\text{tag}}\tau^-_{\text{sig}}$
  - Tag side: 1-prong decay

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

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

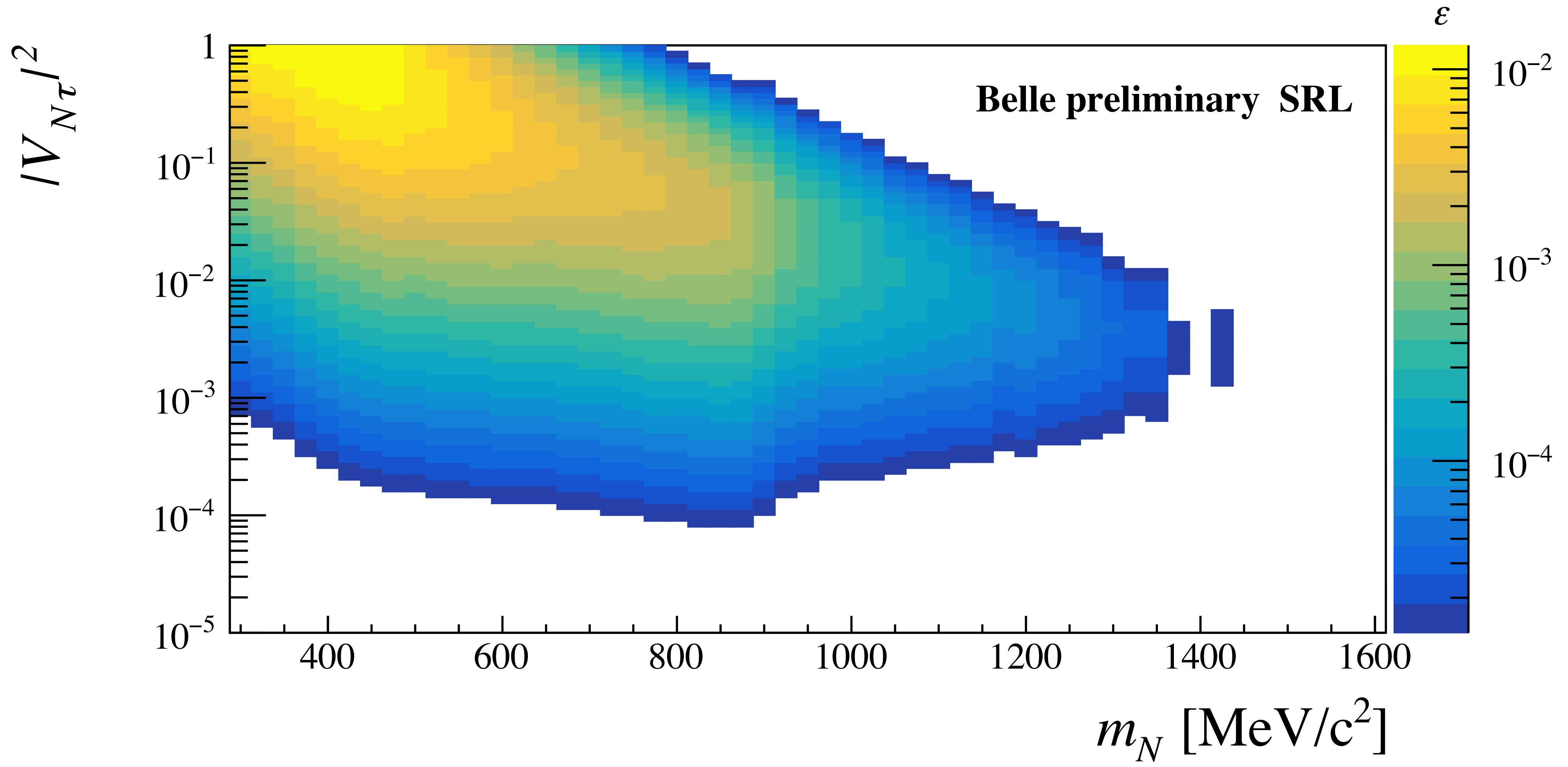
K_S^0 rejection and definition of two signal regions

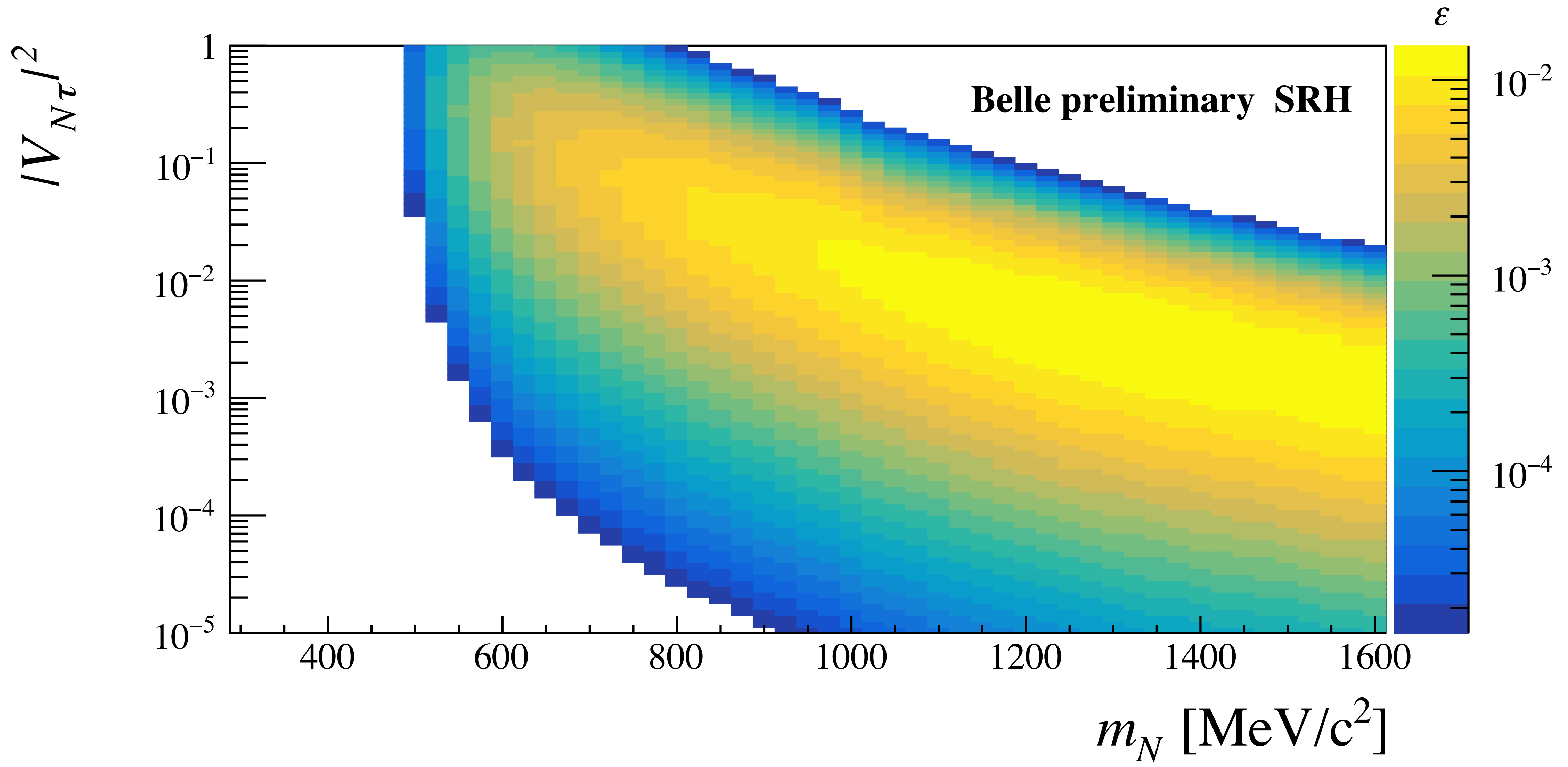
- $K_S^0 \rightarrow \pi^+\pi^-$ can produce a displaced vertex similar to N
- Reconstruct DV mass from two DV daughters
- Events are rejected if they satisfy 420<$m_{DV}(\pi\pi)$ <520, where $m_{DV}(\pi\pi)$ is the dimuon mass calculated with the pion mass hypothesis for the two muons.
- The way low mass N is distributed is different from high mass N distribution
- We divide the signal region into Low mass and High mass signal region:
  - SRH: $m_{\pi\pi}^{DV} > 0.52\ GeV/c^2$
  - SRL: $m_{\pi\pi}^{DV} < 0.42\ GeV/c^2$



more on Analysis Method

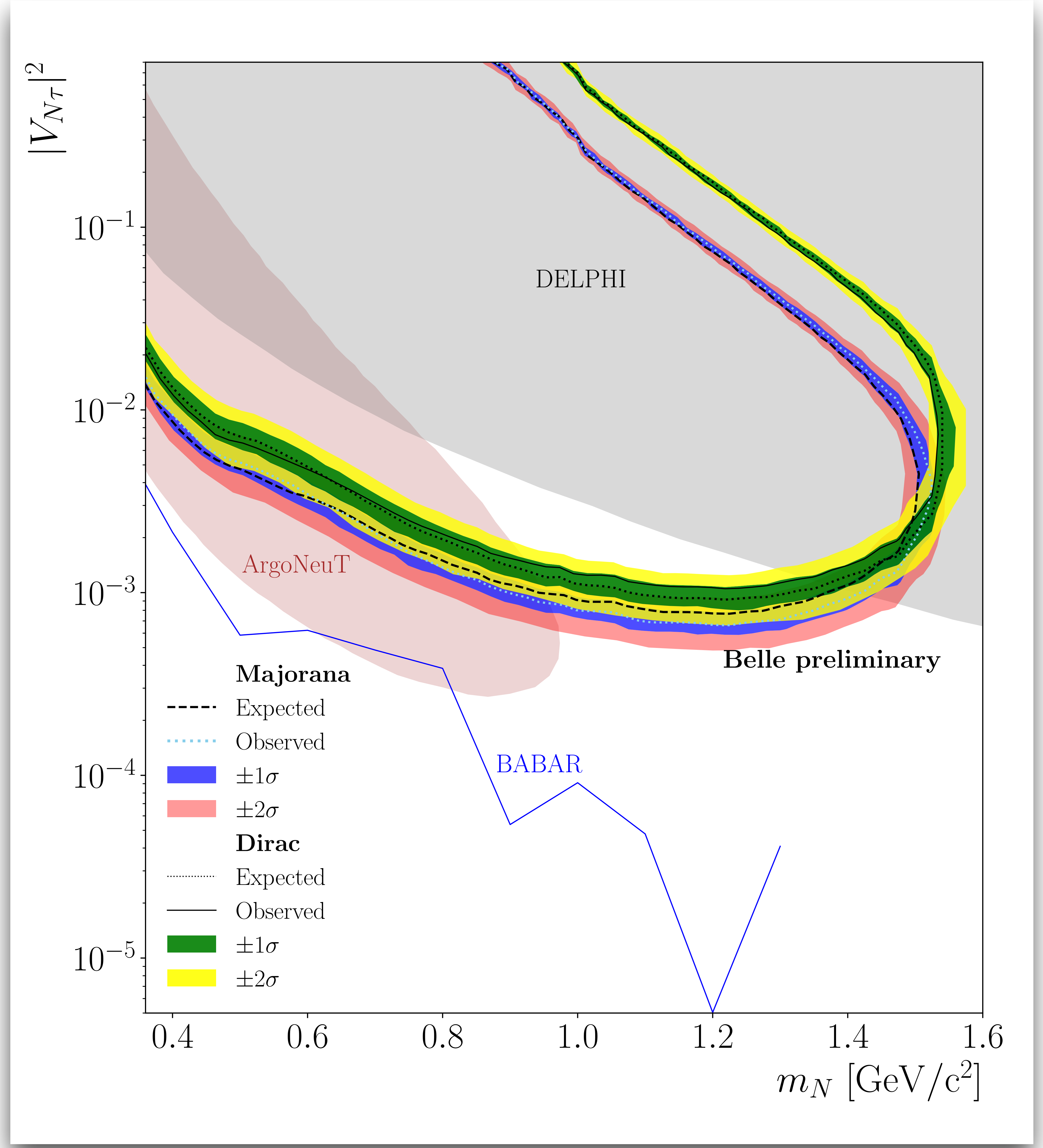
- The constraints of the signal decay enable reconstruction of the full kinematics of the signal-τ decay chain with a two-fold ambiguity
- $N_{signal} = N_{\tau\tau} \times B(\tau \to \pi N) \times B(N \to \mu^+\mu^-\nu_\tau) \times \epsilon$, where ϵ is the efficiency
- The total signal efficiencies in SRH and SRL as a function of $|V_{N\tau}|^2$ 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 CL_s prescription





Results

- In the signal regions targeting heavy and light HNLs we observe 1 and 0 events, respectively, in agreement with the background expectation.
- A grid in the m_N vs $|V_{N\tau}|^2$ parameter space. In m_N, grid points separated by 25 MeV. In $|V_{N\tau}|^2$, 20 points per decade
- For each point, we calculate observed CL_s values, expected CL_s values and expected CL_s values with $\pm 1\sigma$ and $\pm 2\sigma$
- The search method, used here for the first time, utilizes the displaced vertex originating from the long-lived Heavy Neutral Lepton decay and the ability to reconstruct the Heavy Neutral Lepton candidate mass to suppress the background to the single-event level.
- Allows for direct measurement of the N mass if a signal is observed
- Our limits are the most stringent to date



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Dark Leptophilic Scalar

- Scalars other than Higges boson appear in many BSM theories

- The mixing between this dark scalar ϕ_L and the SM Higgs boson gives rise to couplings proportional to SM fermion masses, described by

$$\mathcal{L} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \phi_L \ell$$

- Couples to both quarks and leptons, the existence of such particles is strongly constrained by the searches for rare flavor-changing neutral current decays of mesons, e.g. B → Kϕ and K → πϕ

  - However, these bounds are evaded if the coupling of the scalar to quarks is suppressed and this scalar interacts preferentially with leptons.

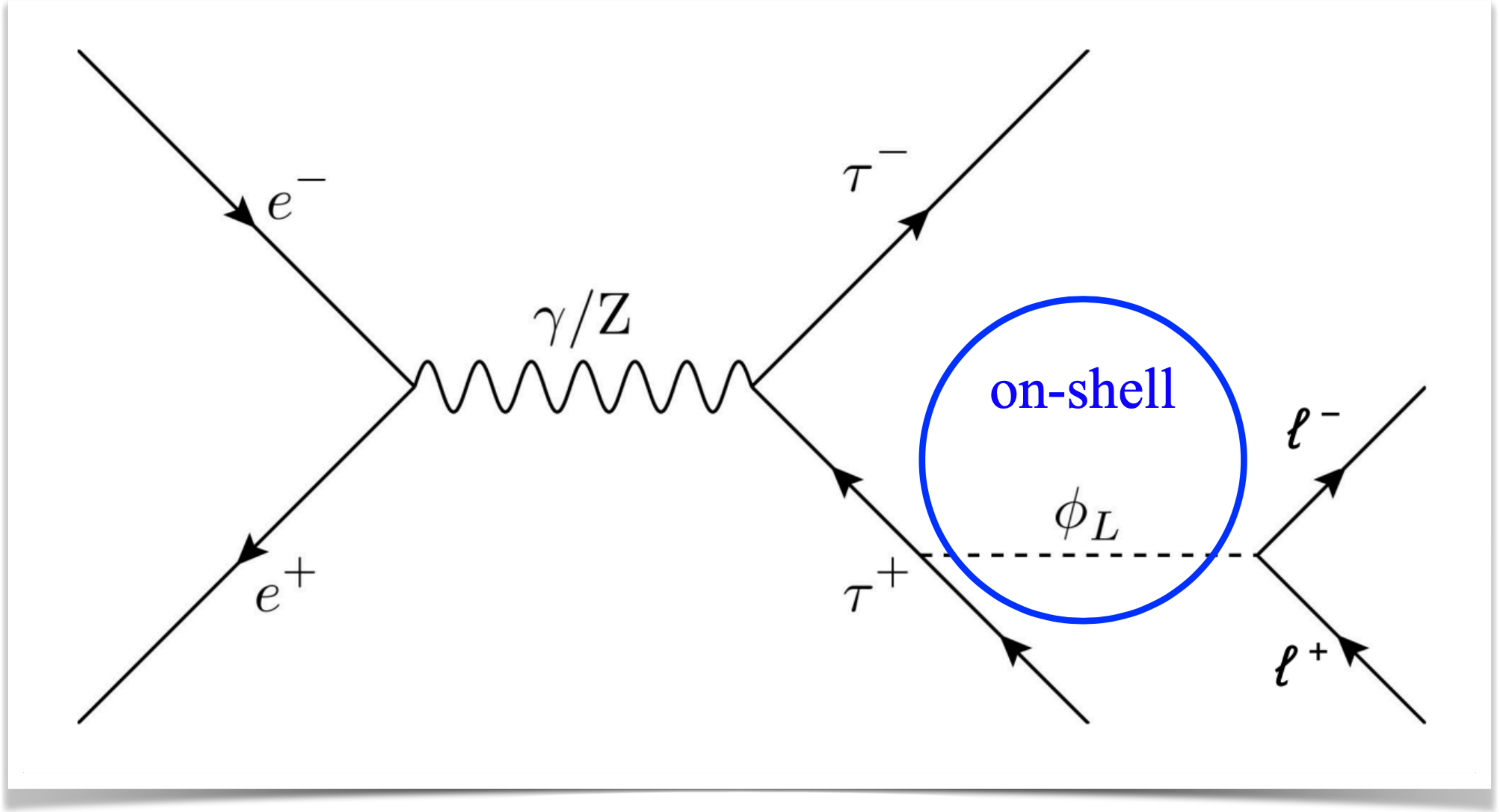
- Can explain
  - $(g-2)_\mu$ anomaly
  - Lepton flavor universality violation

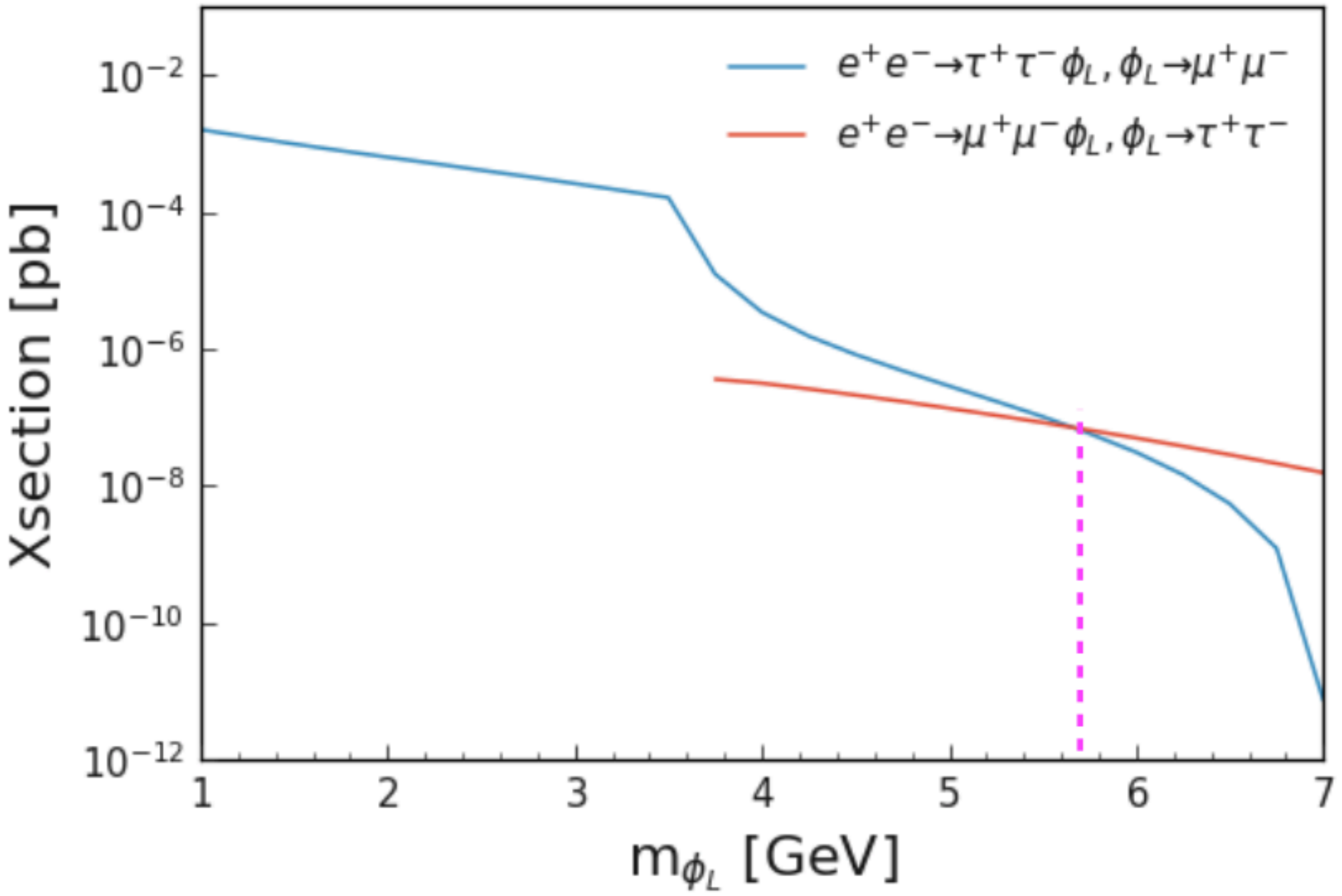
ξ = coupling constant independent of lepton flavor,

m_ℓ = mass of lepton

v = 246 GeV, is the vacuum expectation value of the Higgs field

- $e^+e^- \to \tau^+\tau^-\phi_L, \phi_L \to e^+e^-/\mu^+\mu^-$
- The scalar decays to a pair of leptons: search for narrow peak in lepton pair invariant mass distribution
  - $\phi_L \to e^+e^-$ for $m_{\phi_L} < 2m_\mu$
  - $\phi_L \to \mu^+\mu^-$ for $m_{\phi_L} > 2m_\mu$
- High production cross-section times branching ratio in the region 40 MeV < m_{ϕ_L} < 6.5 GeV.
- Our search has sensitivity to place competitive limits on till m_{ϕ_L} < 6.5 GeV

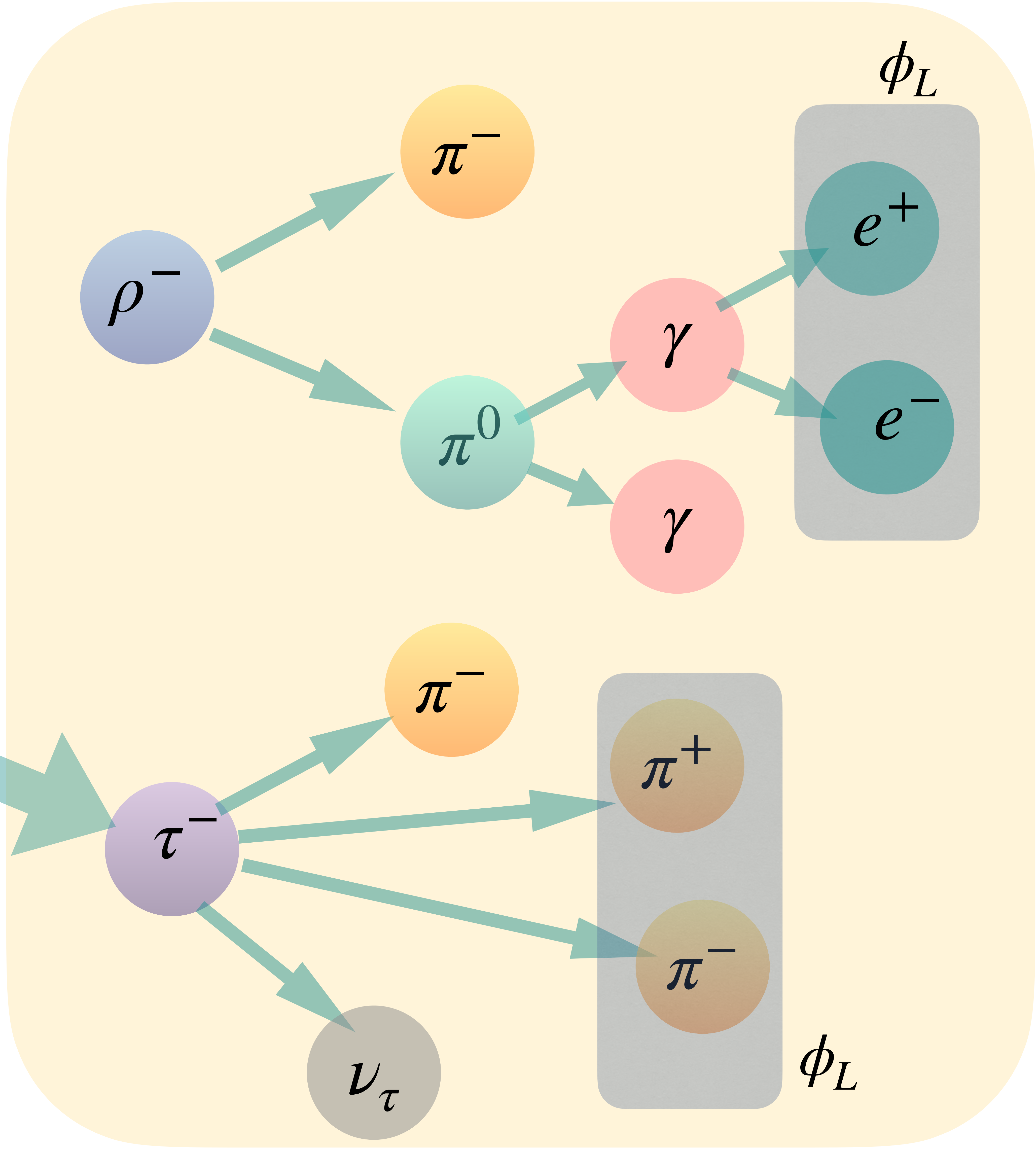




$626\ fb^{-1}$ data from Belle detector

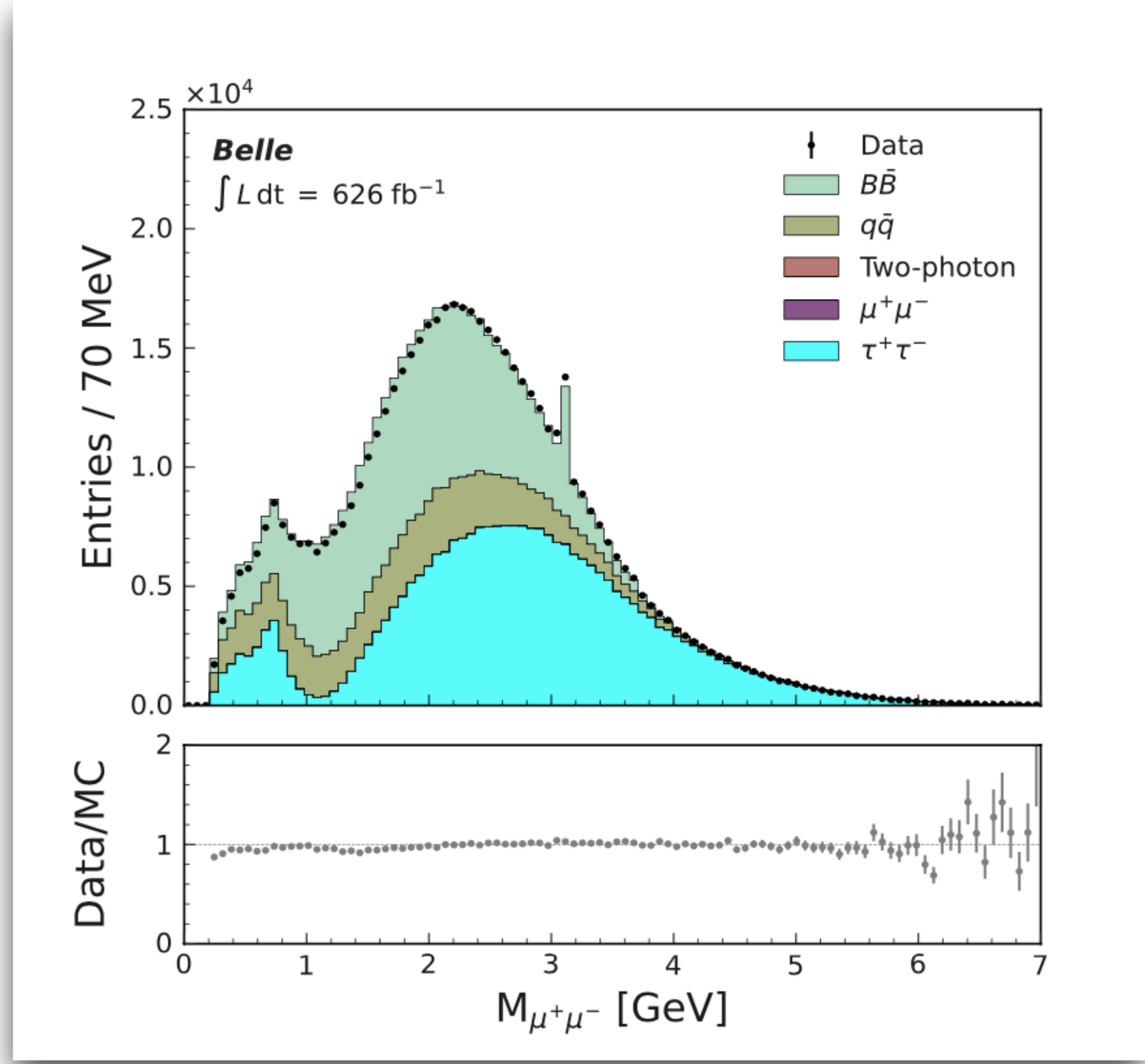
Analysis Method: Event reconstruction and background

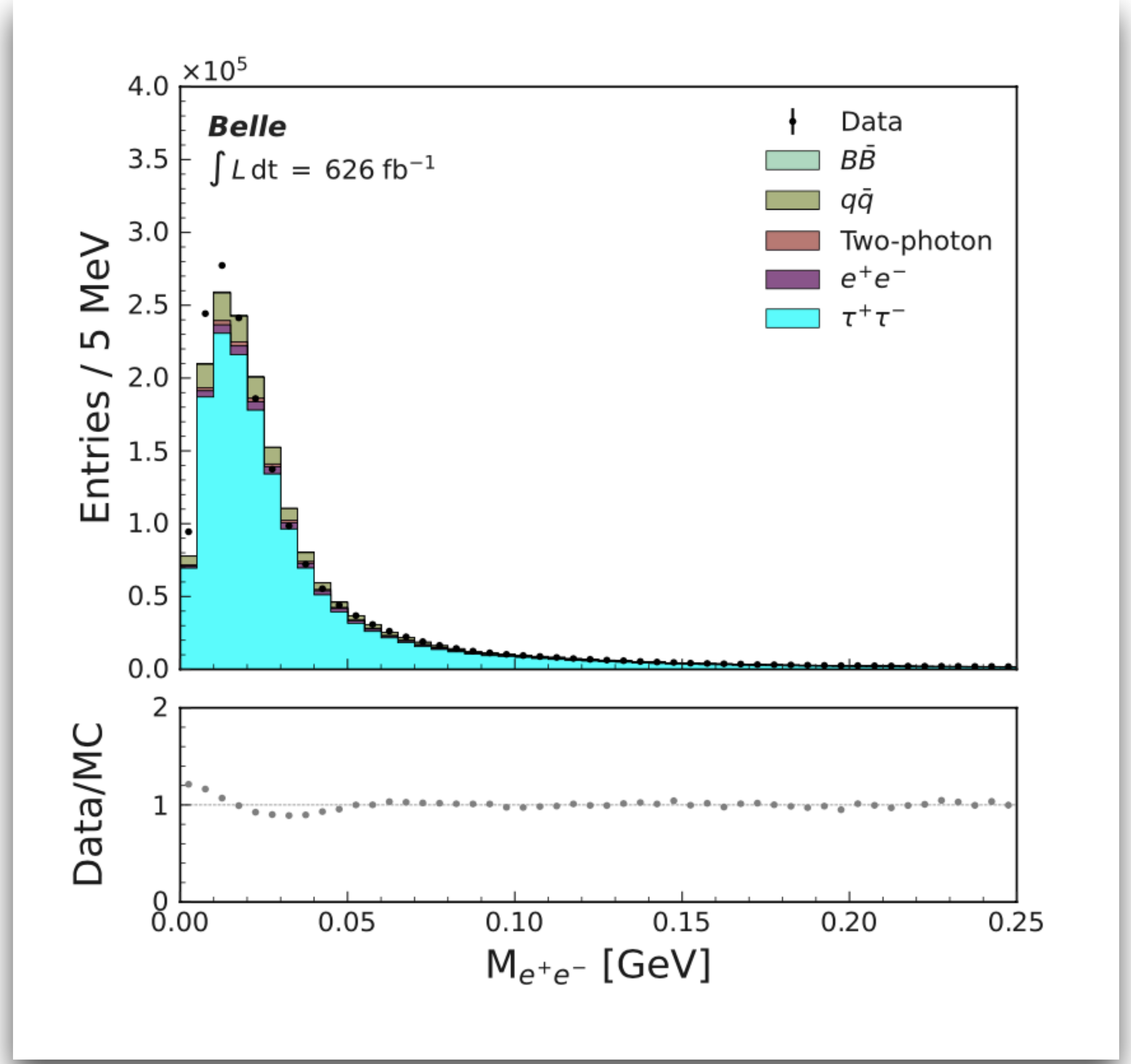
- Requirement of 4 track events with net charge 0
- At least two tracks are identified as $e/\mu \rightarrow$ Same vertex
- Two known backgrounds
  - also $q\bar{q}, l^+l^-, l^+l^-l^+l^-, l^+l^-h^+h^-$ backgrounds
- backgrounds are suppressed using BDTs



Results

- Extraction of the signal:
  - fitting l^+l^- invariant mass distribution
  - evaluation at each mass point of ϕ_L
- Good agreement seen in data vs. Monte Carlo comparison in control regions: BDT < 0.5





Results

- Signal region: No obvious narrow peak structure is observed

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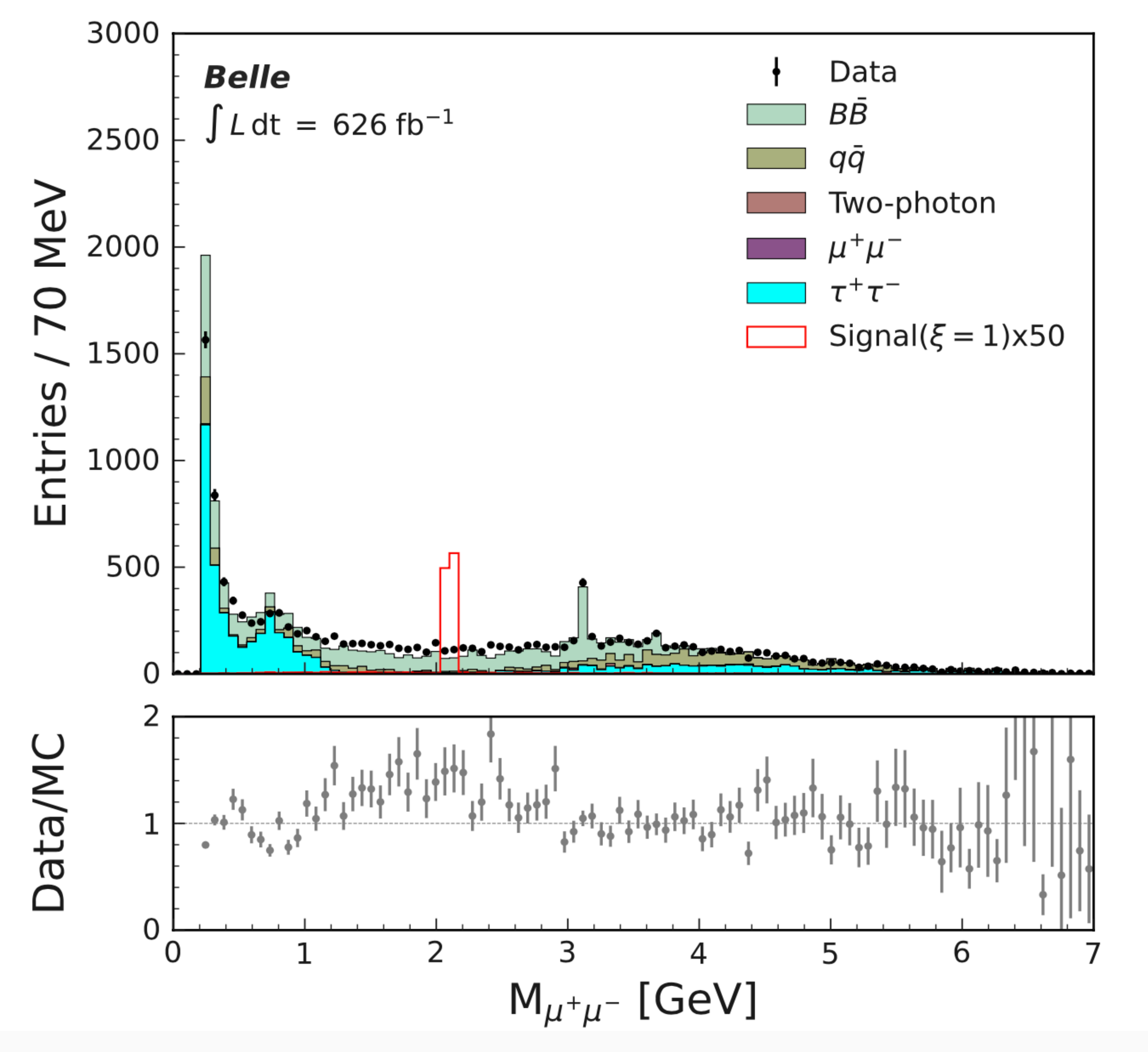
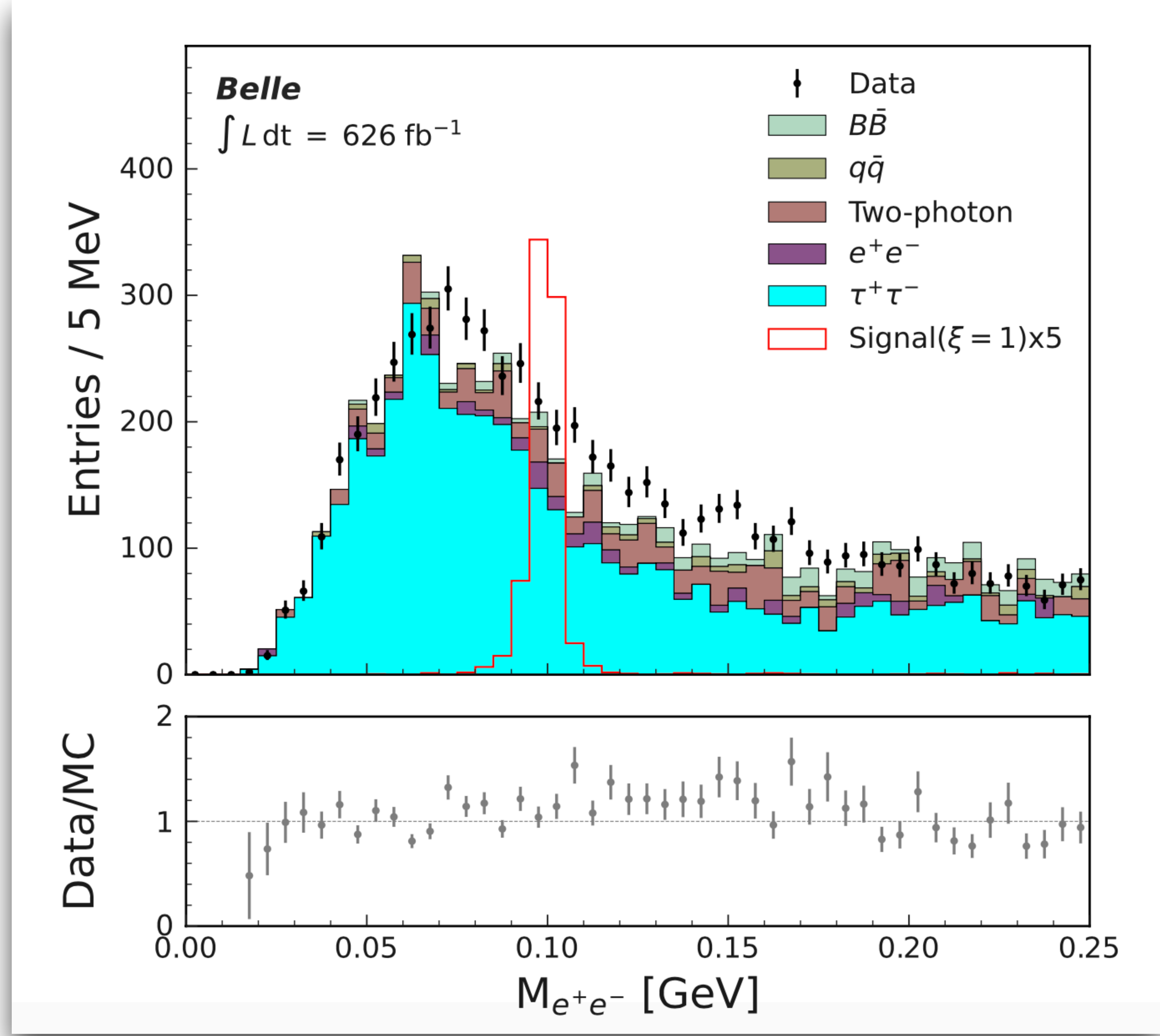
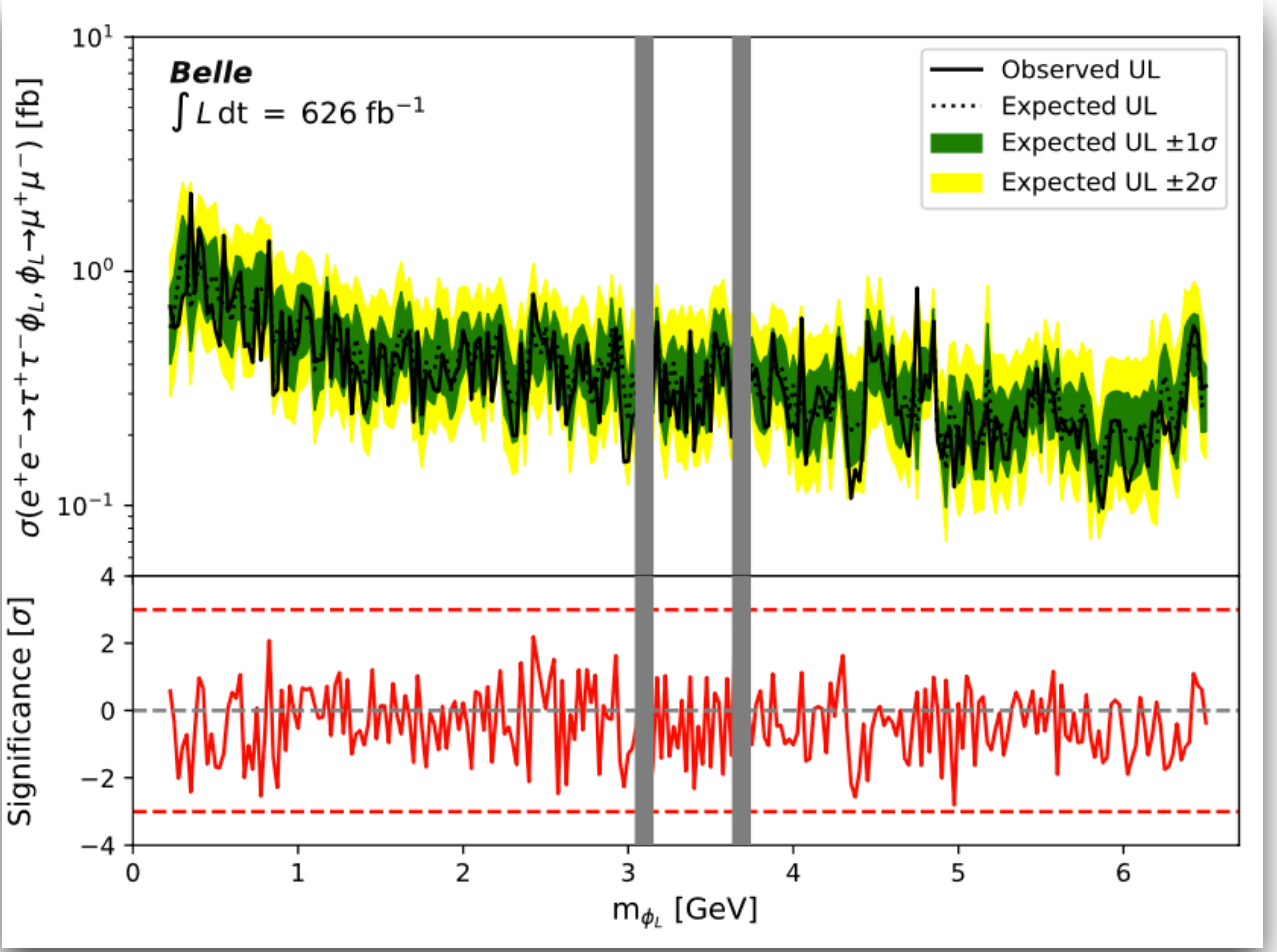
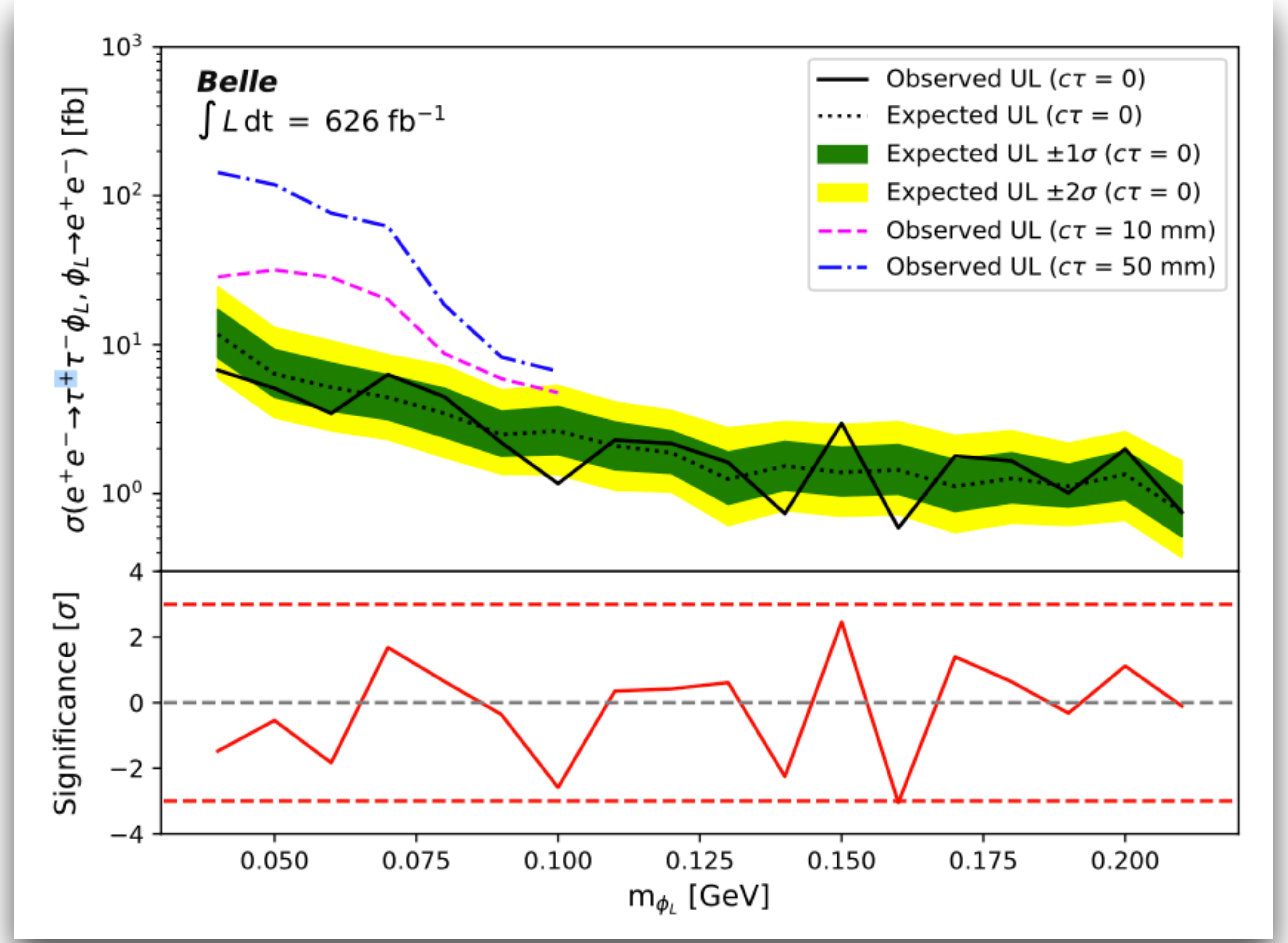




Results

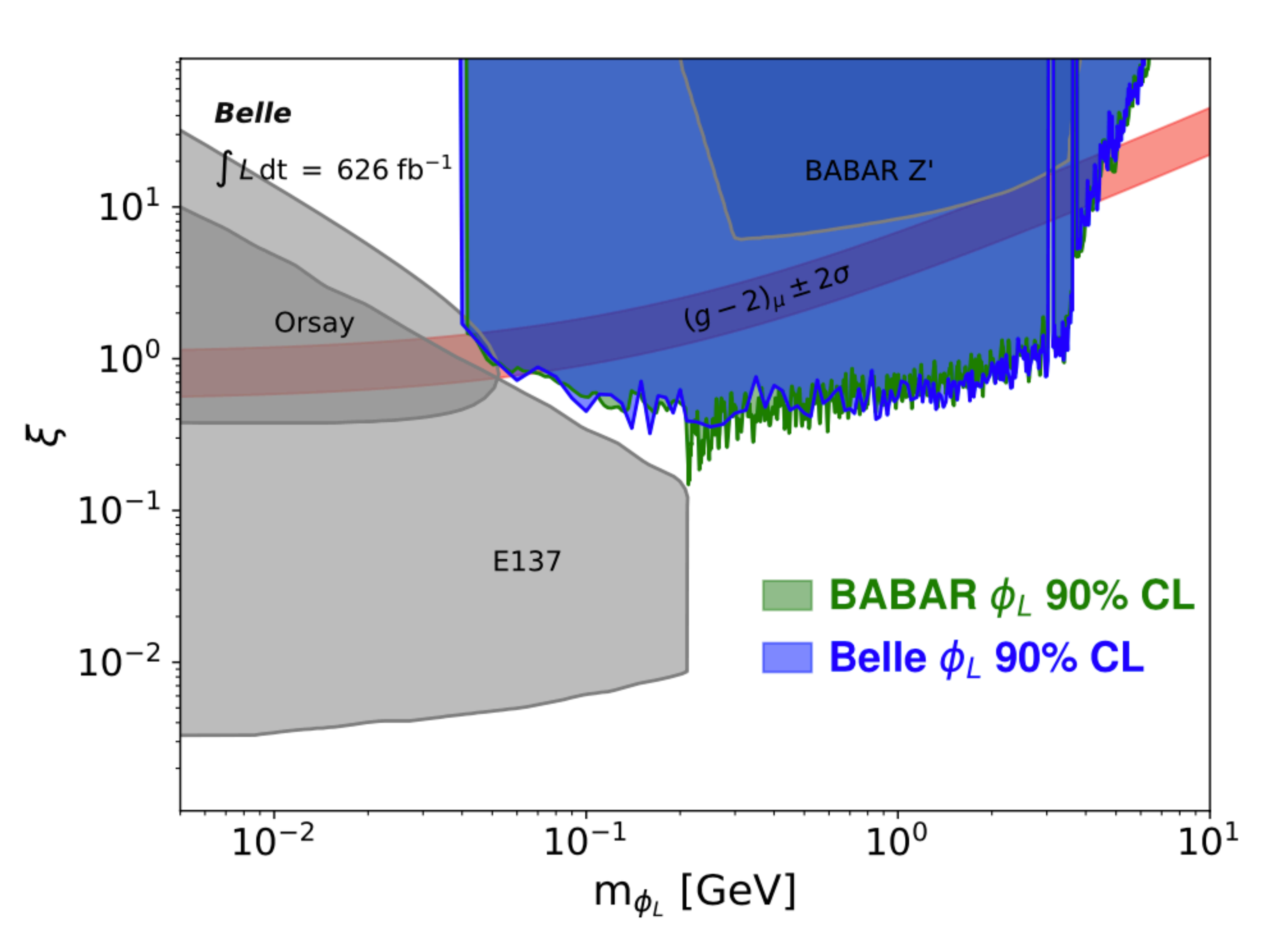
- Good agreement seen in data vs. Monte Carlo comparison in control regions: BDT < 0.5
- 90% confidence level upper limits on the signal cross-section
- No significant excess in all masses





Results

- Good agreement seen in data vs. Monte Carlo comparison in control regions: BDT < 0.5
- 90% confidence level upper limits on the signal cross-section
- No significant excess in all masses
- 90% confidence level upper limits on the coupling constant
- No ϕ_L can explain observed excess in $(g-2)_\mu$ for $m_{\phi_L} < 4$ GeV



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Motivation

- Light, beyond-the-standard-model bosons(α) that are not directly detectable (invisible) are predicted in models with, e.g., axion-like particles(link)

- Direct search in $\tau^- \to \ell^- \alpha$ ($\ell = e/\mu$)

- This process was previously searched for by the MARK III and ARGUS collaborations(link).

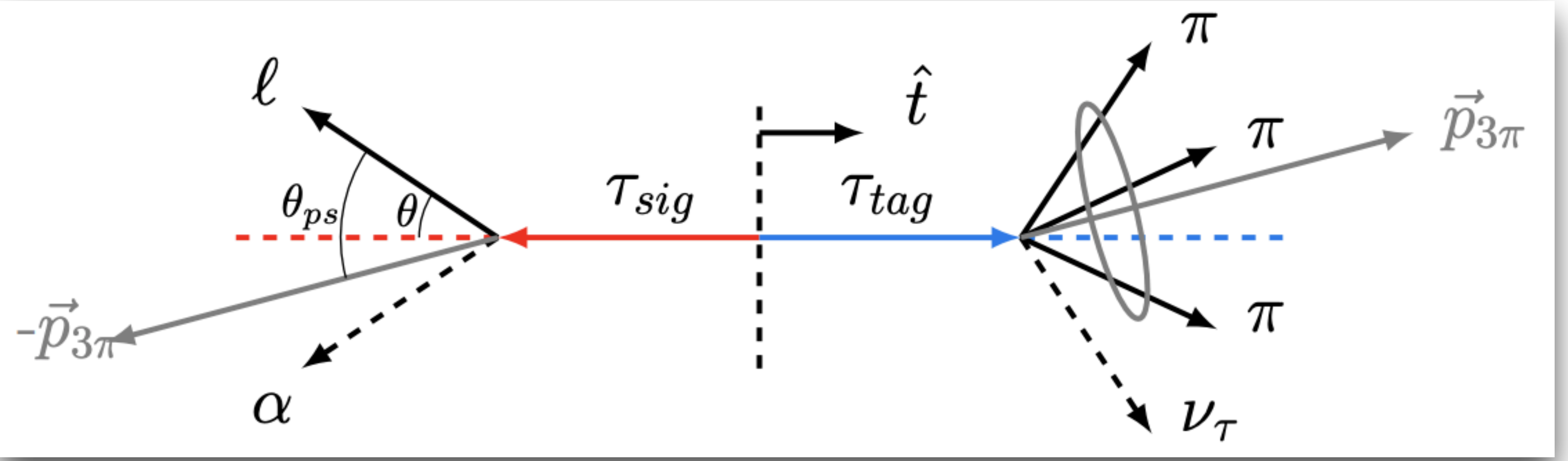
- The current best upper limits on the $\tau^- \to \ell^- \alpha$ branching fractions(at 95% confidence level where the range indicates their dependence on the α mass in the (0–1.6) GeV/c^2 range)

  - $\dfrac{\mathscr{B}(\tau^- \to e^- \alpha)}{\mathscr{B}(\tau \to e^- \bar{\nu}_e \nu_\tau)} < (6 - 36) \times 10^{-3}$

  - $\dfrac{\mathscr{B}(\tau^- \to \mu^- \alpha)}{\mathscr{B}(\tau \to e^- \bar{\nu}_\mu \nu_\tau)} < (3 - 34) \times 10^{-3}$

Analysis Method

- In the center-of-mass frame, τ pairs are produced back to back
- Requirements:
  - tag side: contain 3 charged particle from $\tau^- \to h^-h^+h^-\nu_\tau (h = K, \pi)$
  - signal side: contain one charged particle



- $\tau \to \ell^- \bar{\nu}_\ell \nu_\tau$: irreducible background: however. the magnitude of the lepton momentum depends only on the α mass : the difference thus exploited
- τ pseudo rest frame is formed: $\hat{p}_\tau \approx \dfrac{-\vec{p}_{3h}}{|\vec{p}_{3h}|}$
- Search for a peak in normalized lepton energy $x_\ell \equiv \dfrac{E^*_\ell}{m_\tau c^2/2}$,

  E^*_ℓ = is the energy of the charged lepton in the τ pseudo rest frame
- Then measure the branching-fraction ratio

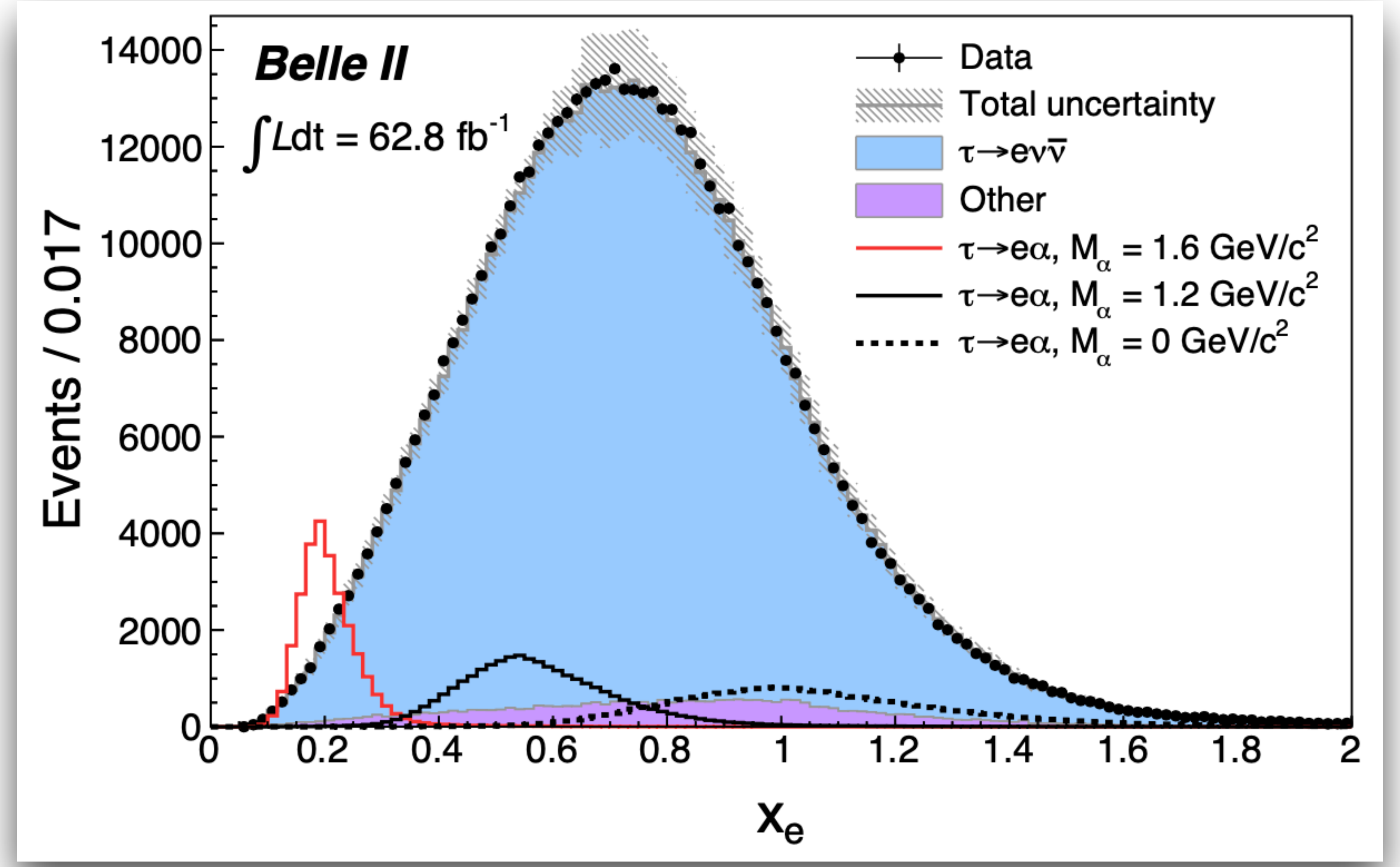
$$\frac{\mathcal{B}_{\ell\alpha}}{\mathcal{B}_{\ell\bar{\nu}\nu}} = \frac{\mathcal{B}(\tau^- \to \ell^- \alpha)}{\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)}$$

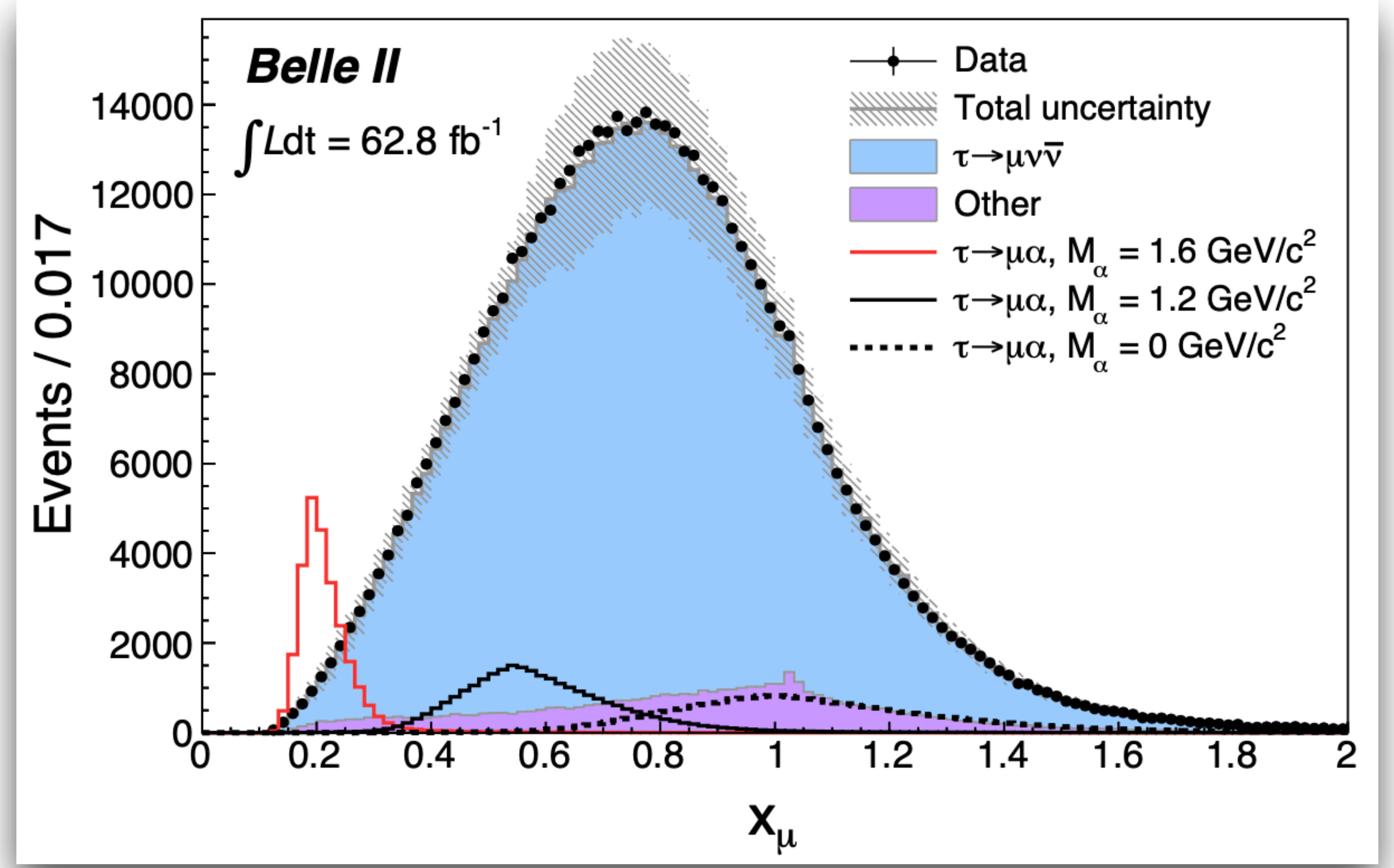
62.8 fb^{-1} data from Belle II detector: 57.7 Million τ pairs

Only 15% of the second pixel layer was installed when the data used in this work were collected.

Results

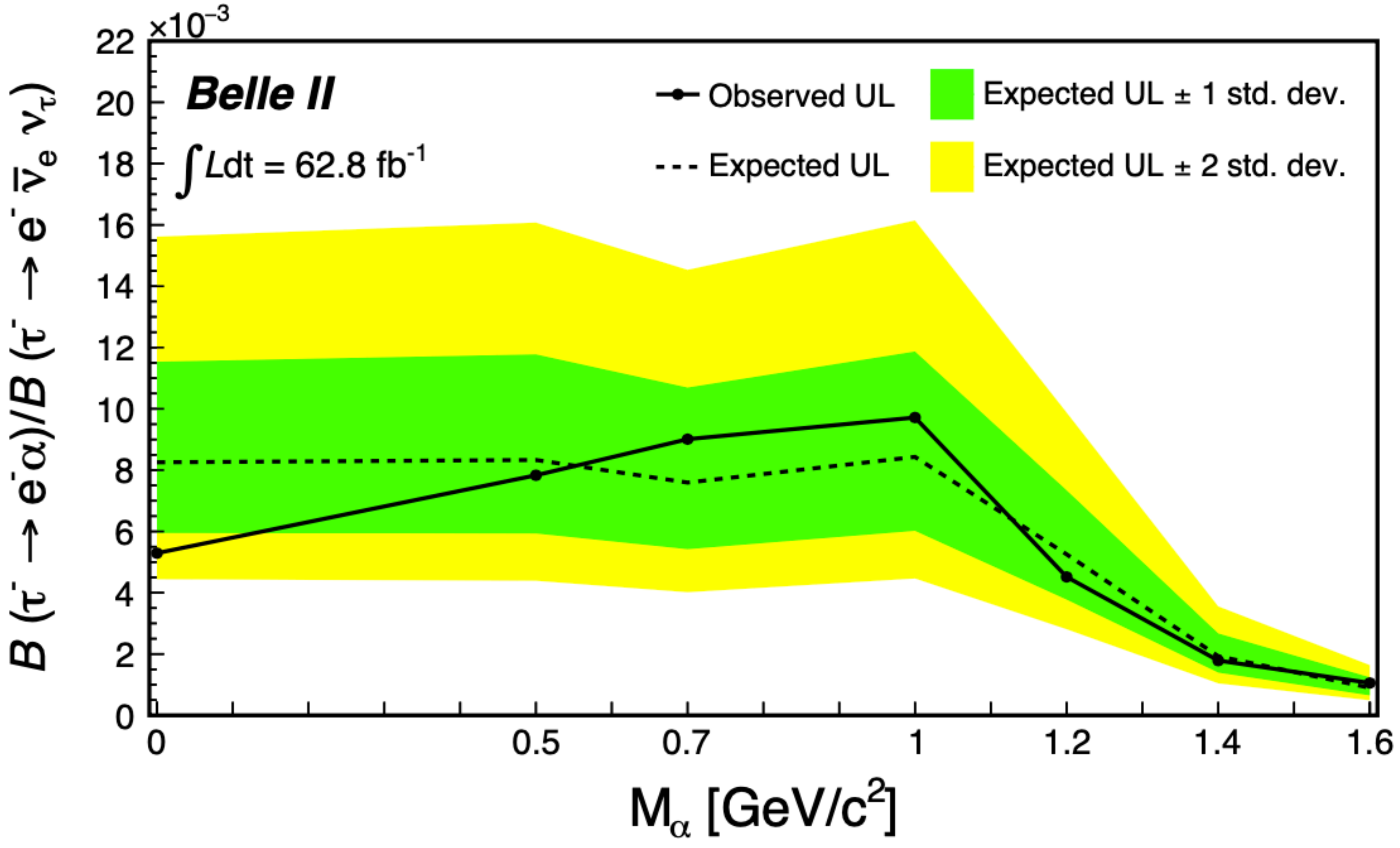
- In Spectra of x_l for electrons and muons in simulation and experimental data
- Simulated spectra for standard-model processes are shown stacked, with the gray band indicating the total uncertainty
- Total uncertainty is dominated by the lepton-identification efficiency uncertainty
- Remaining background processes other than $\tau \to \ell^- \bar{\nu}_\ell \nu_\tau$ contributing to the spectrum are combined together and collectively referred to as "other"
- The distributions for $\tau \to \ell^- \alpha$ are shown for three α masses assuming branching-fraction ratios of 5%

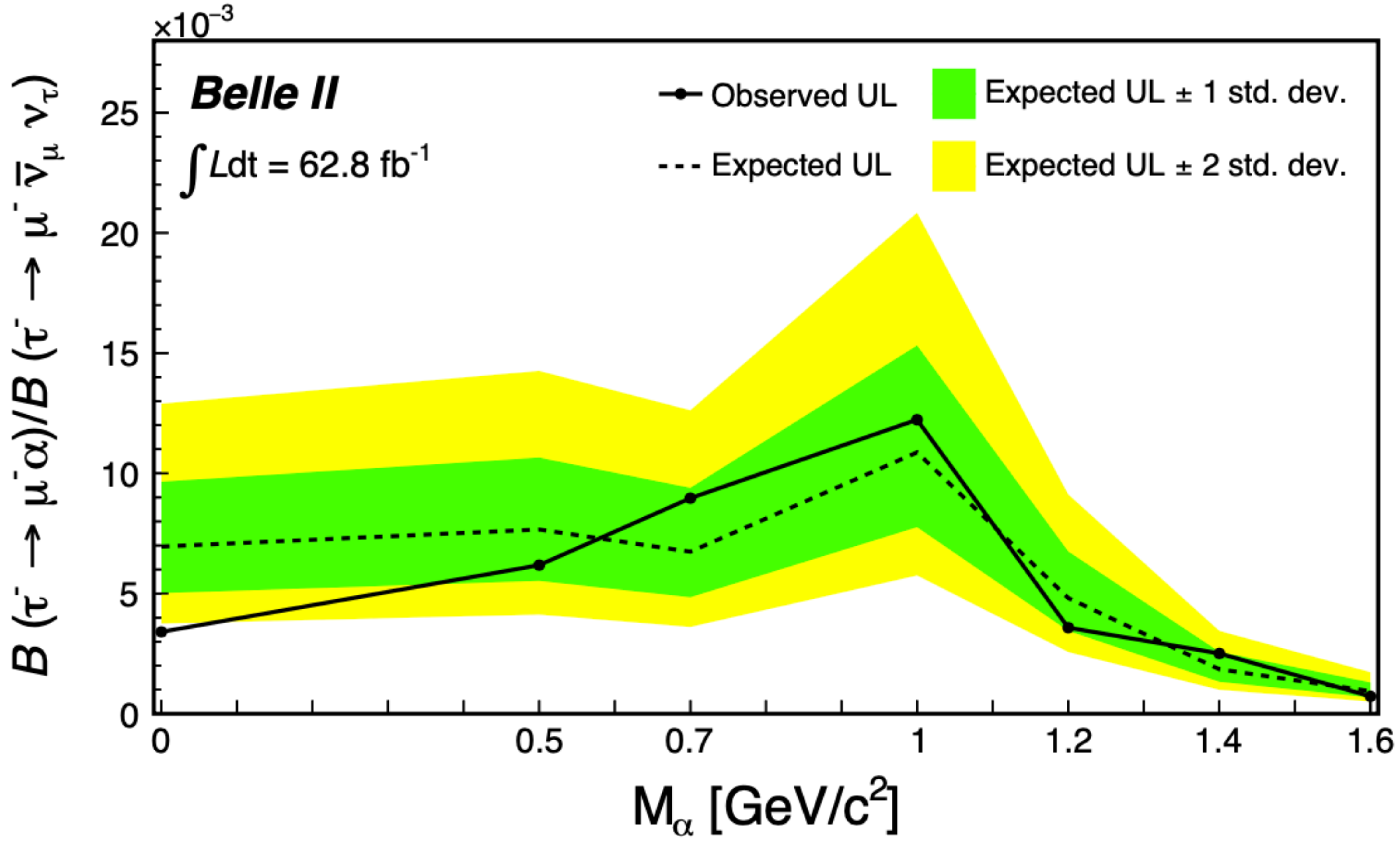




Results

- Fit with SM and SM+NP expectations, compare likelihood of the two models
- No statistically significant signal observed
- Upper limis on 95% CL





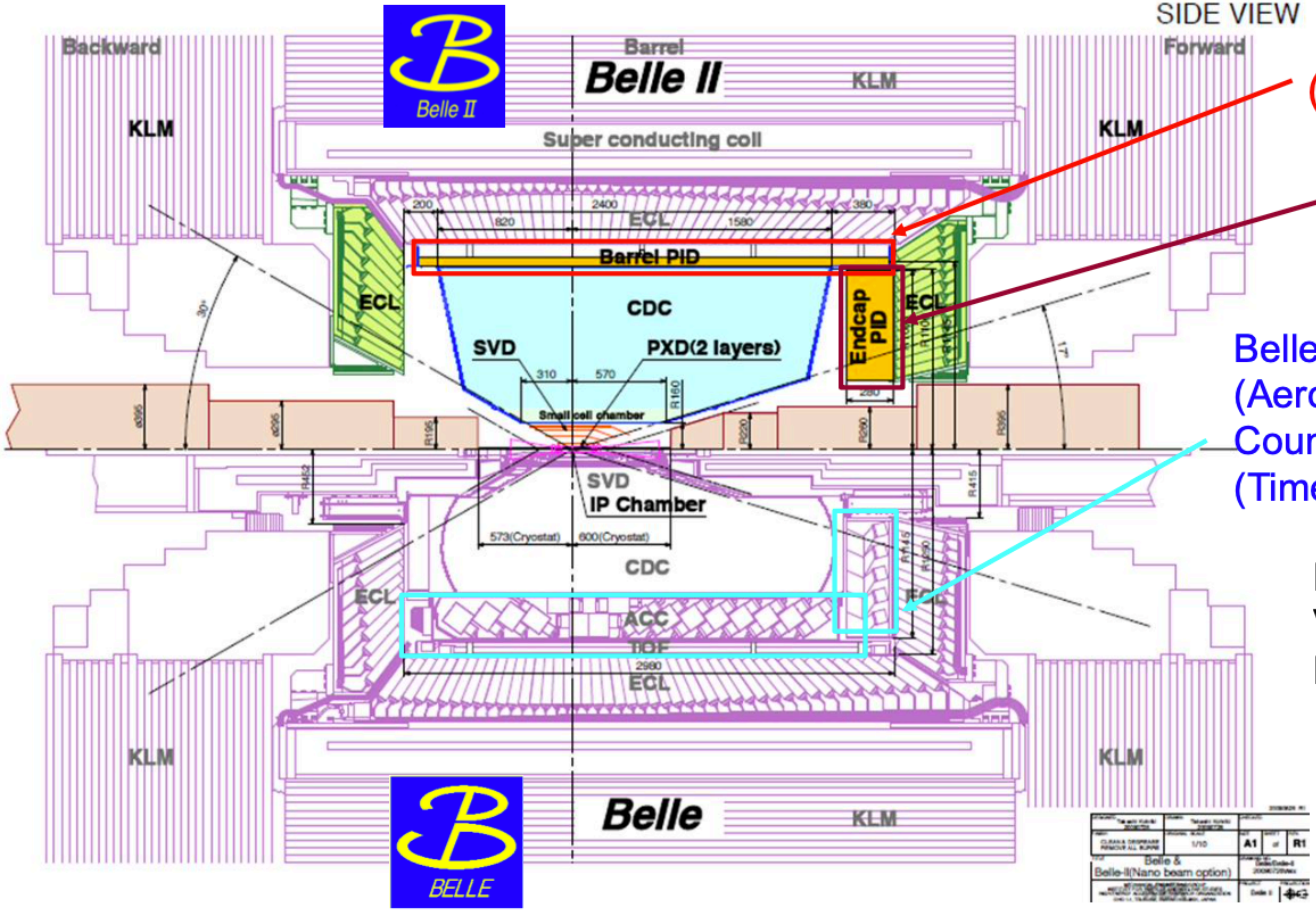
most stringent limits on invisible spin-0 boson production from τ lepton decays till date

Summary

- No significant excess observed
- Most stringent limits in all three analyses

Backups

from Belle to The Belle II Detector



TOP (barrel)

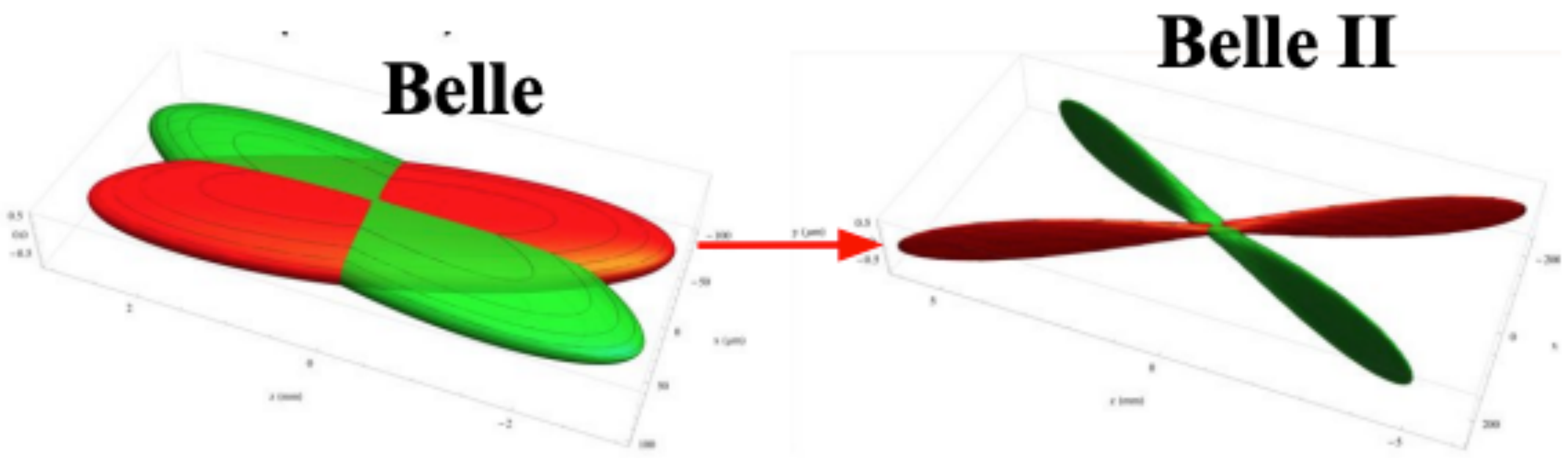
ARICH (forward endcap)

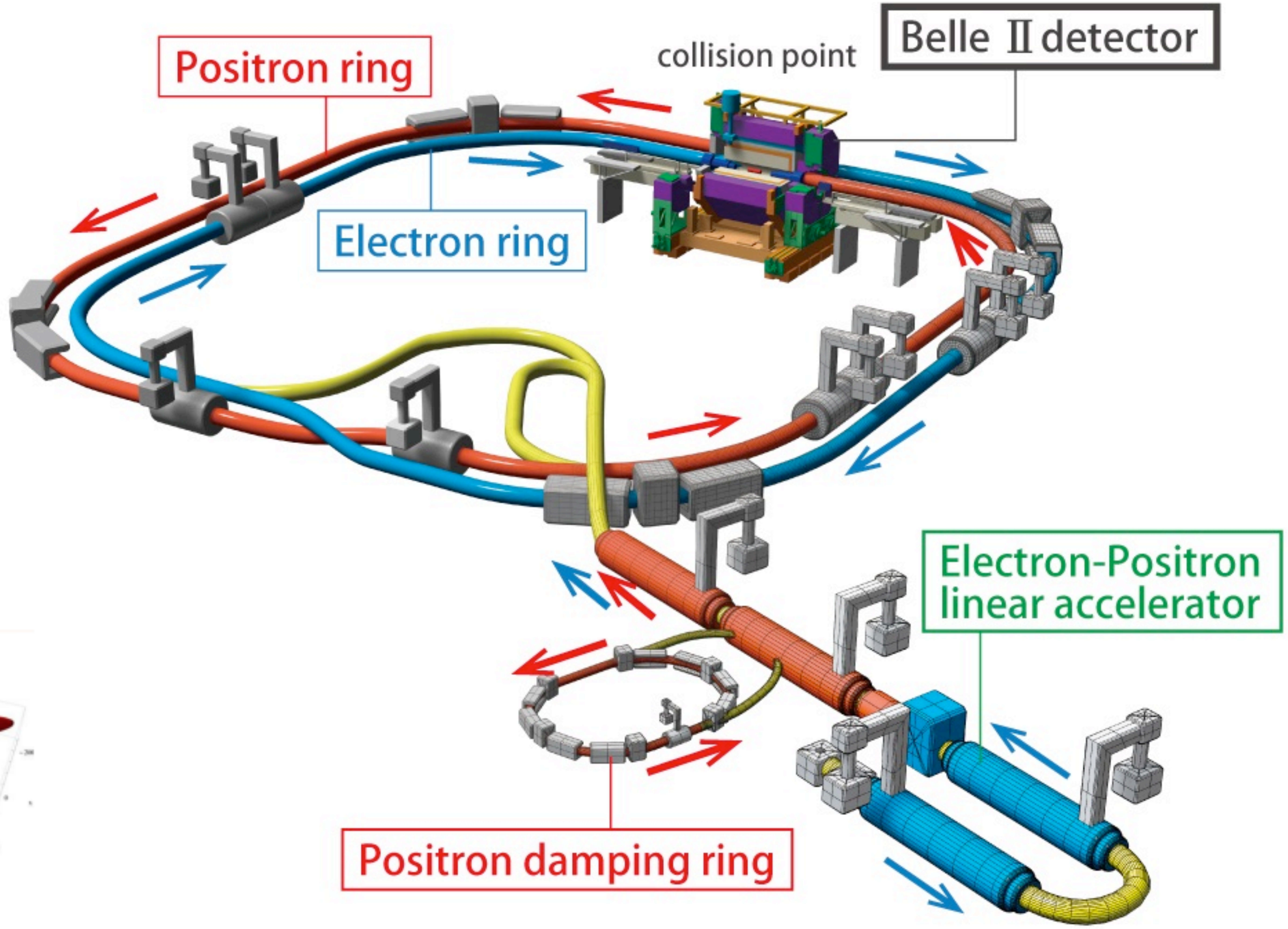
Belle equipped ACC (Aerogel Cherenkov Counter) and TOF (Time Of Flight)

More space to VXD and CDC at Belle II

from KEKB to SuperKEKB

- 40 times larger luminosity than previous generation KEKB
- using nano-beam scheme with a tiny beam spot:
  - 60 nm x 10 μm x few 100 μm in y, x, z
- a few hundred atomic layers in y





Signal, Control and Validation regions

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

$A_{sq} < 0.4$ GeV^2 →

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

↓

Two HNL mass solutions: m_+, m_-