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

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

5 December, 2023

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 for this conference**, to be submitted to PRL)

BELLE

- 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(Arxiv 2207.07476)

BELLE

- Search for Lepton Flavor Violating τ Decays to a Lepton and an Invisible Boson at Belle II(PRL 130, 181803 (2023). Arxiv 2212.03634)

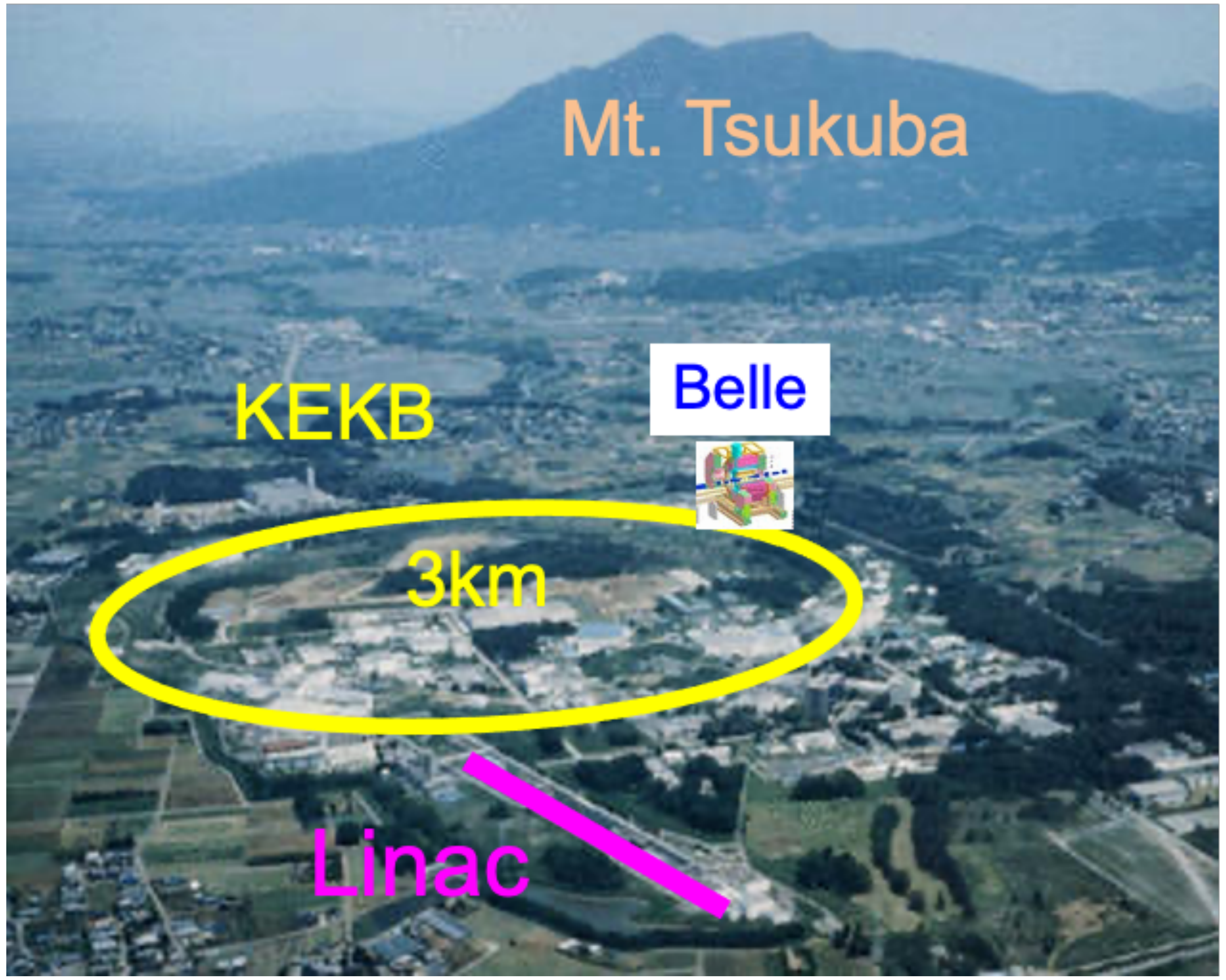
Belle II

- Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \rightarrow \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment(PhysRevLett.131.121802)

Not covered in this talk

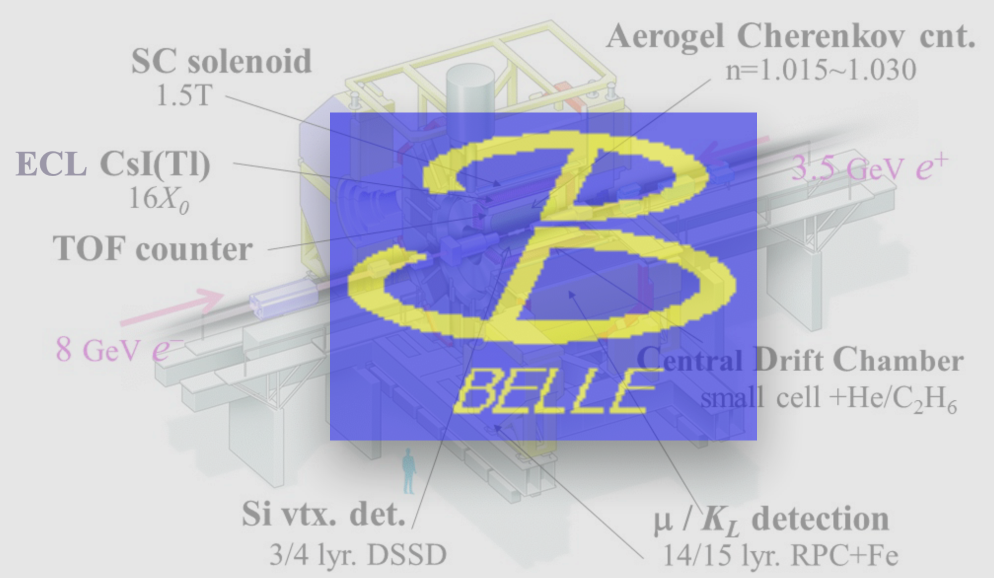
Belle II

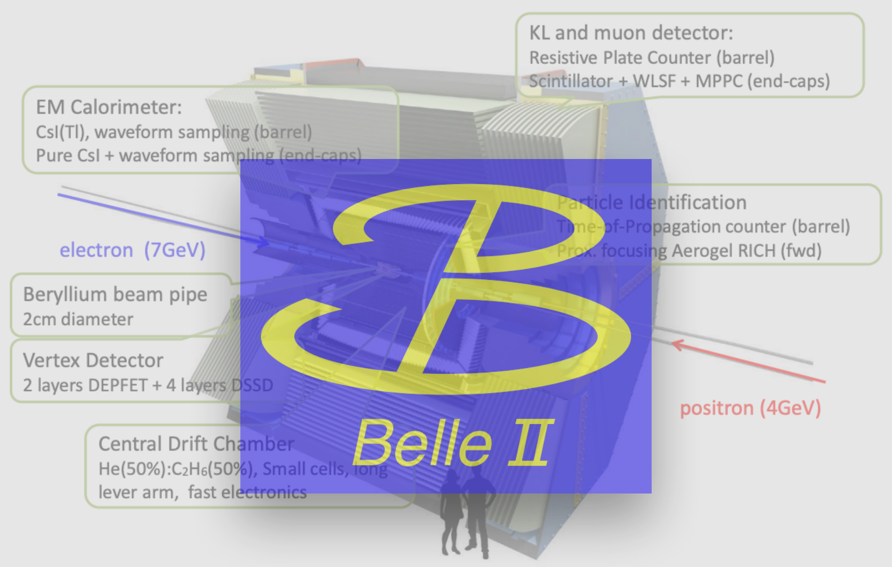
The Apparatus



KEKB
Quest for CPV
kekb.jp

Super
KEKB

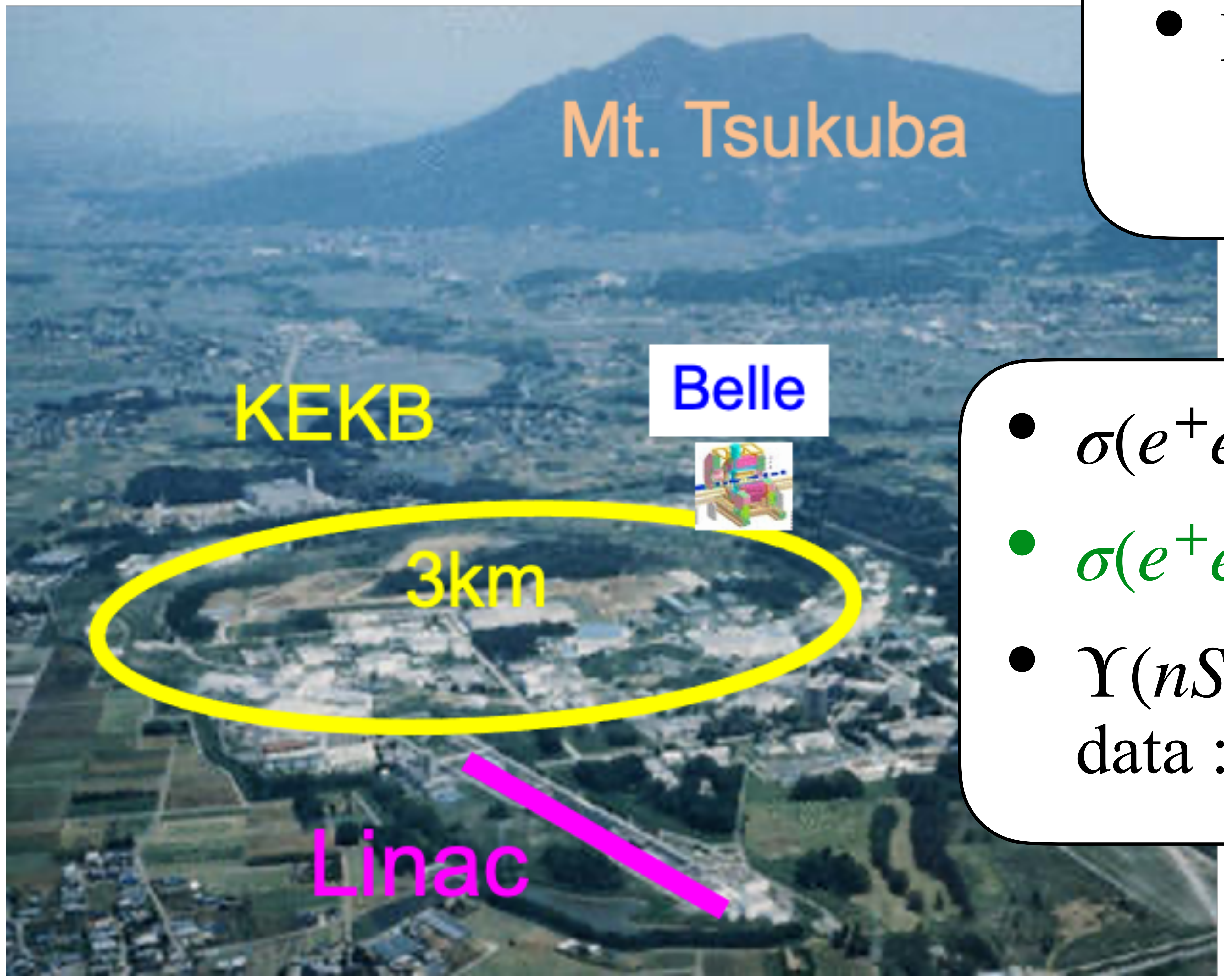




Analysis

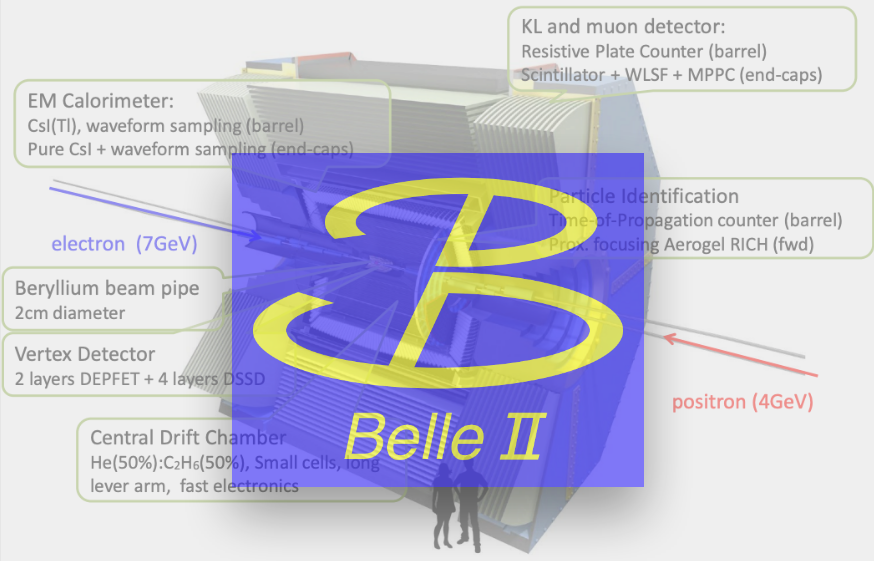
Analysis

The Apparatus



- Description of Belle detector:
  talk by Sourav Patra
- Description of Belle II detector:
  talk by Radek, talk by Paul

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



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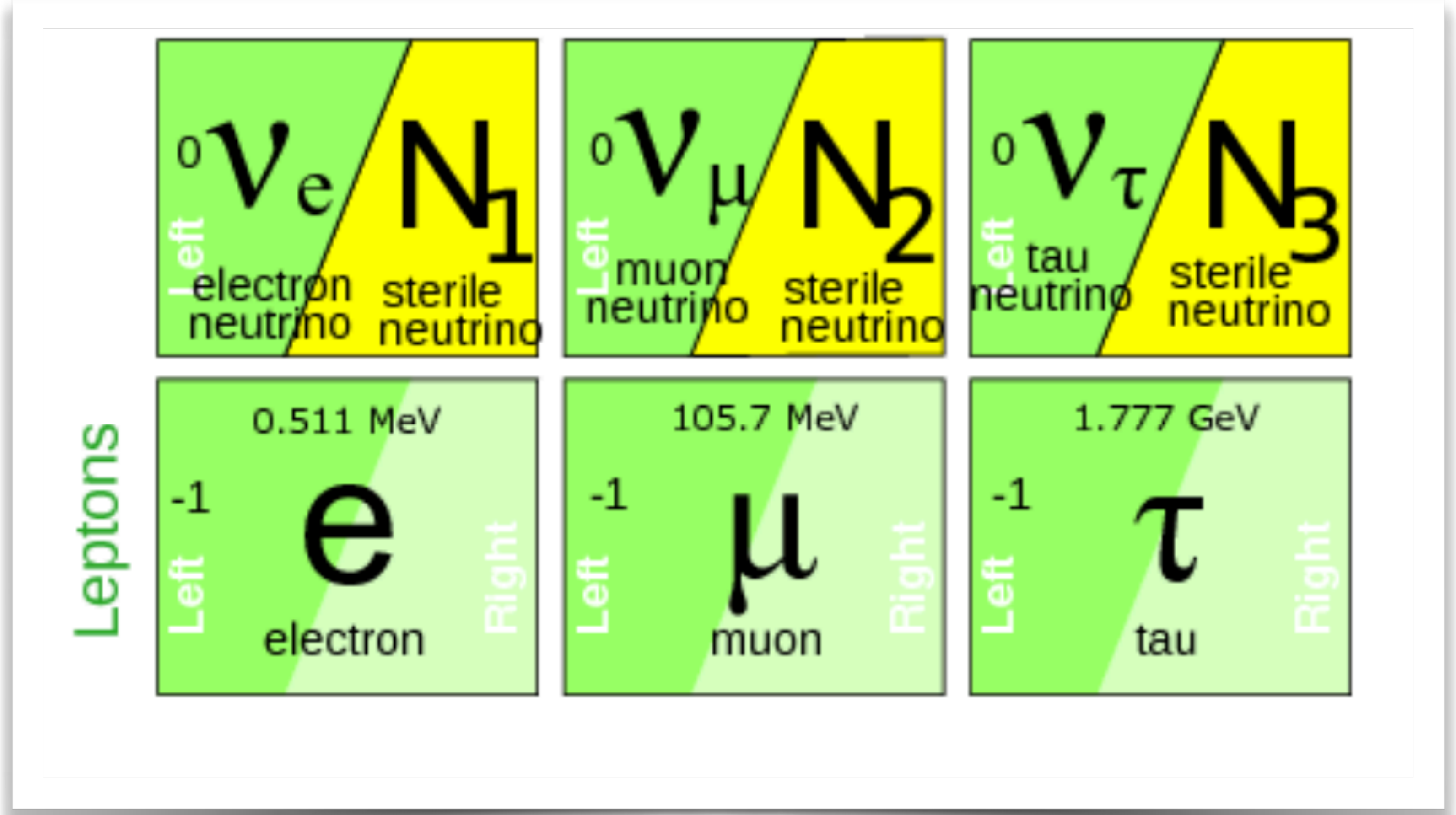
- Search for Lepton Flavor Violating τ Decays to a Lepton and an Invisible Boson at Belle II(PRL 130, 181803 (2023). Arxiv link)

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…

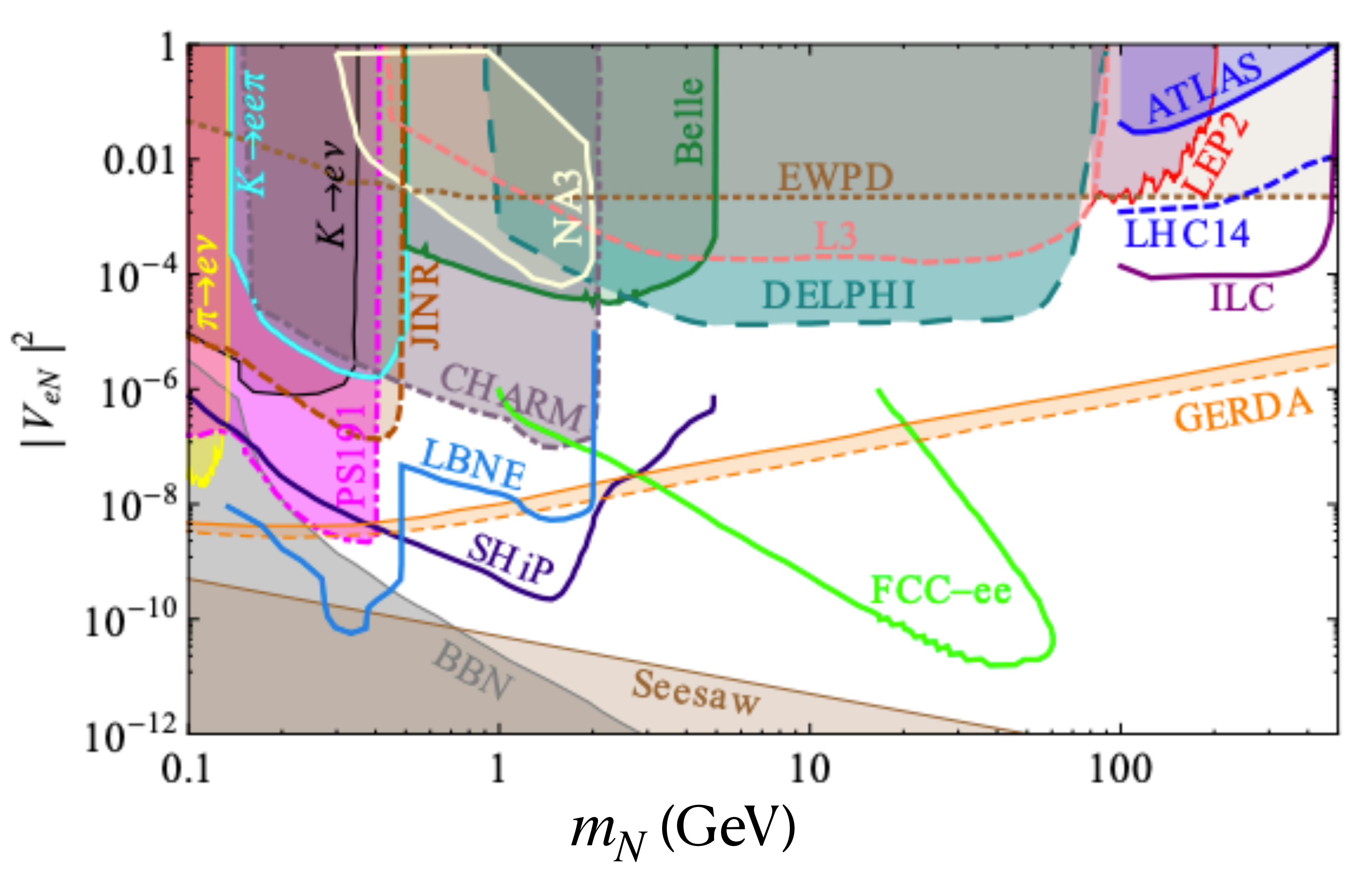


Heavy Neutral Lepton : Direct searches

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

- 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

arxiv 1502.06541



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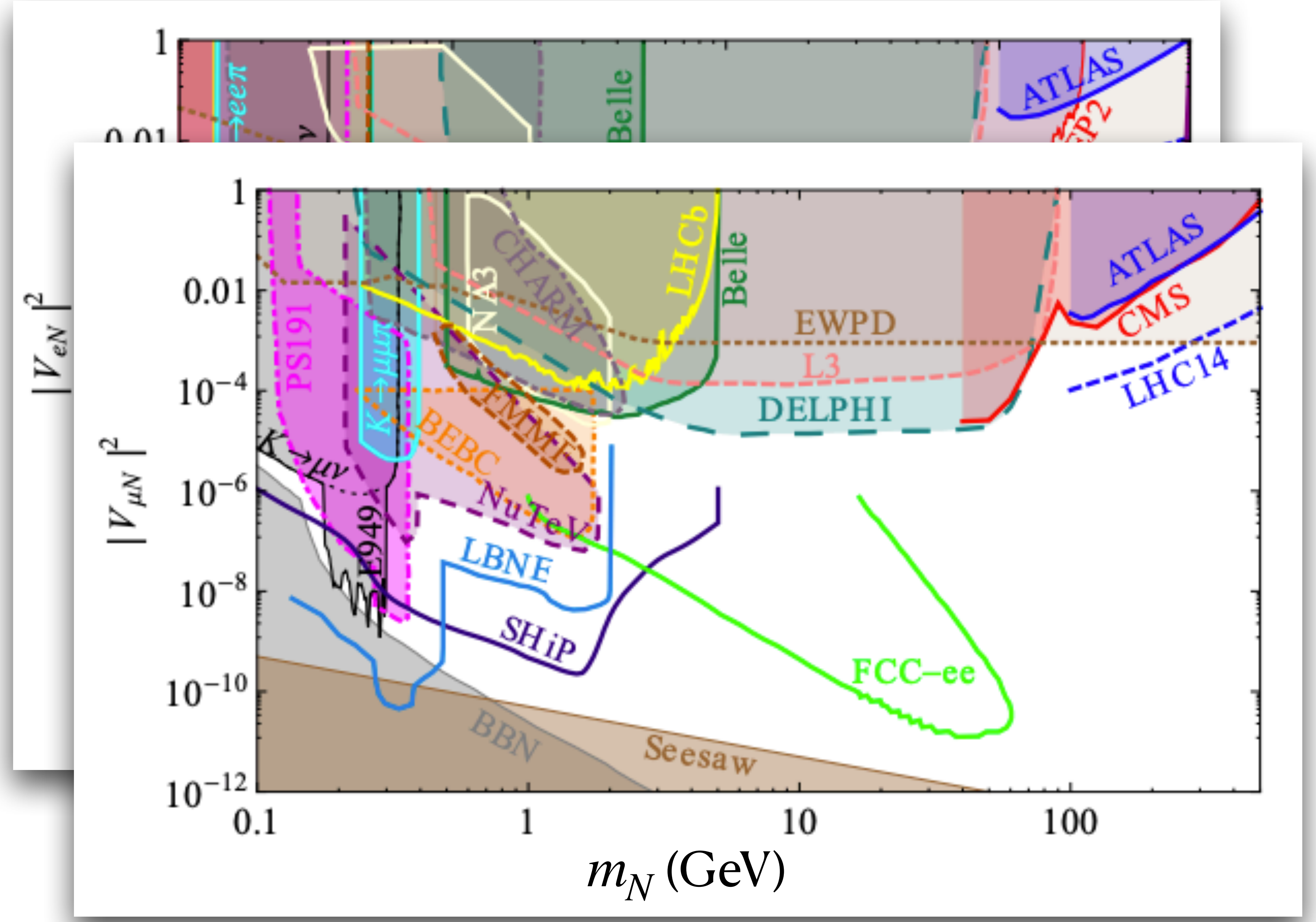
- All the experiments provide tight limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$



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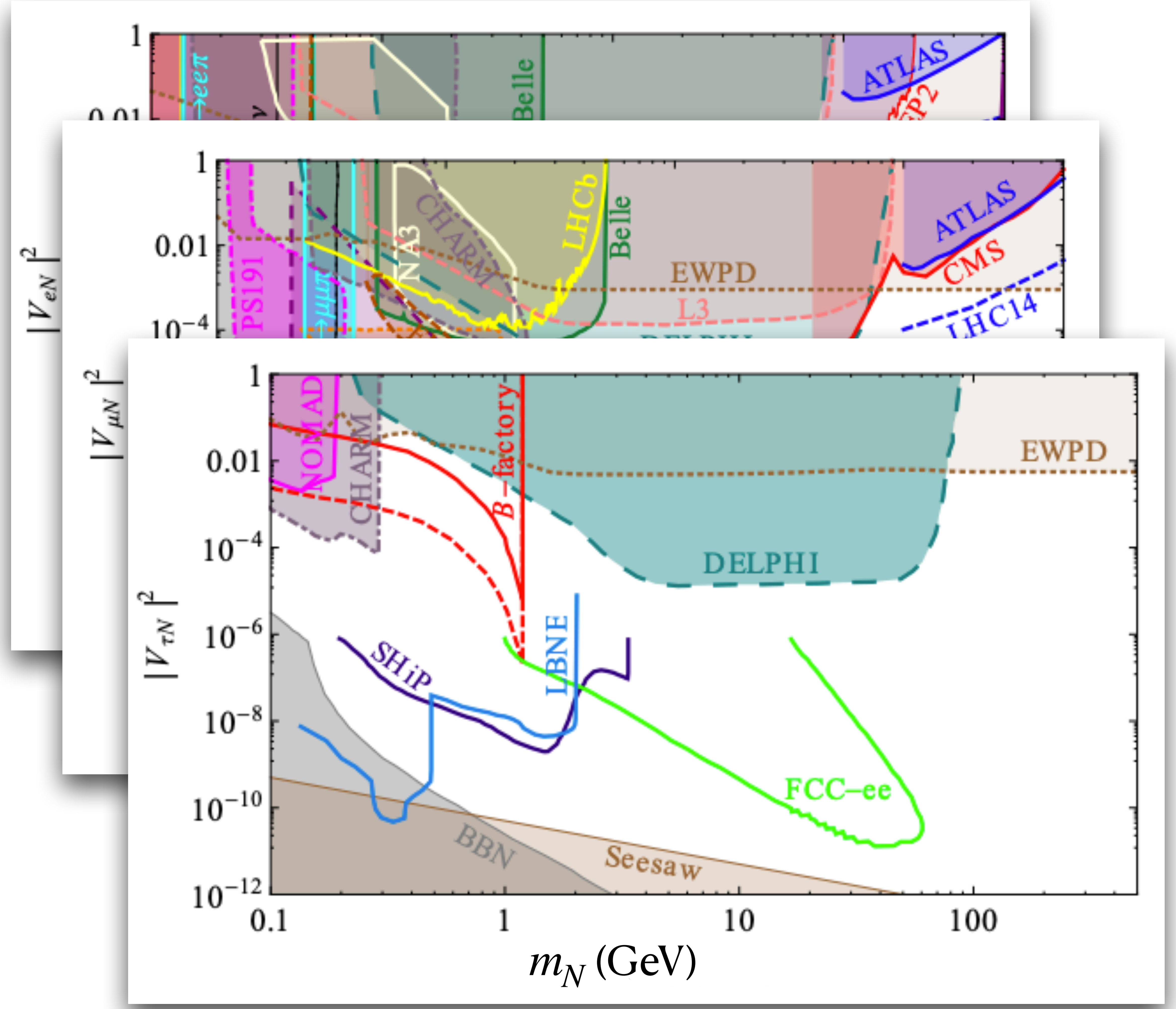
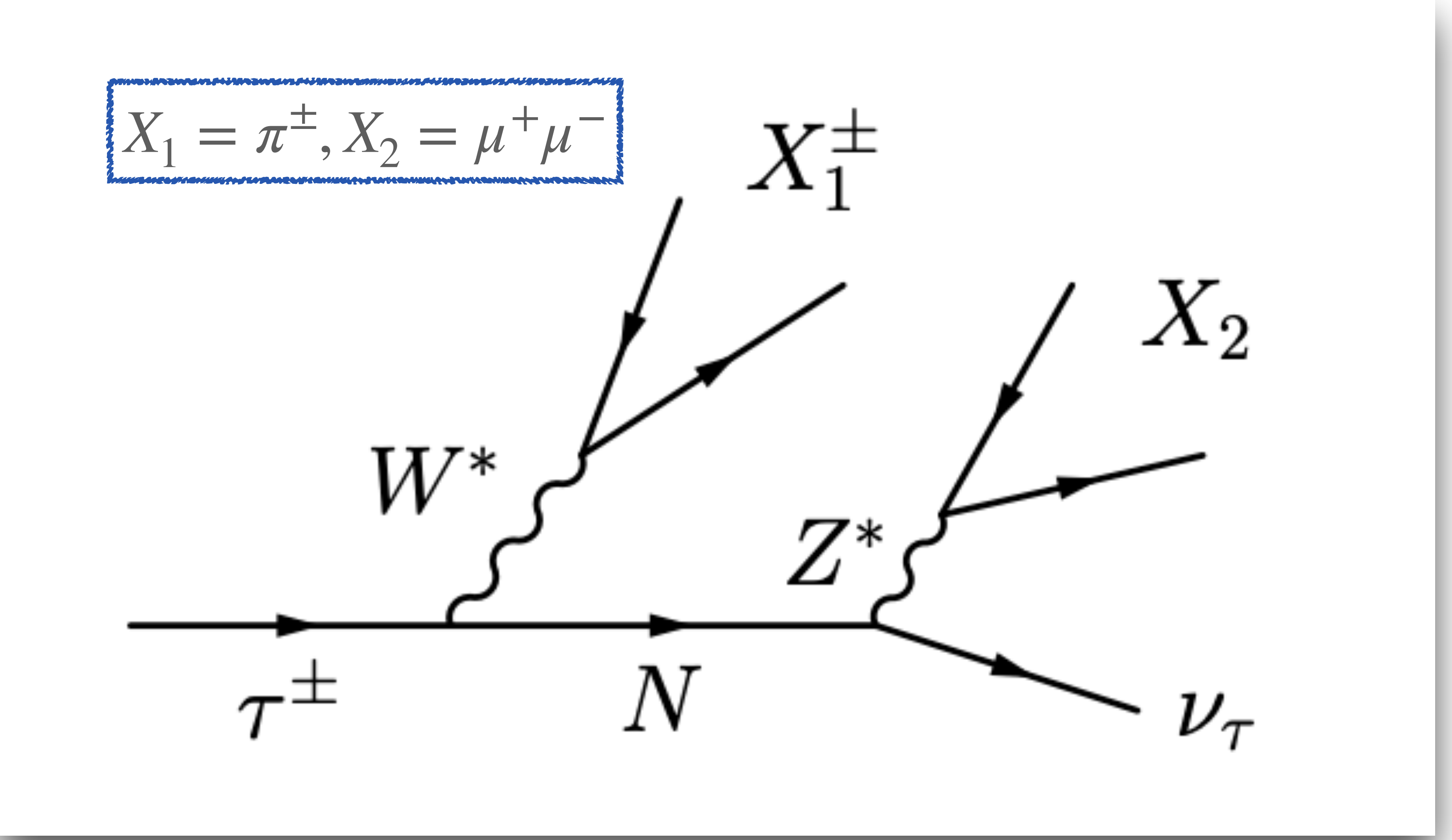
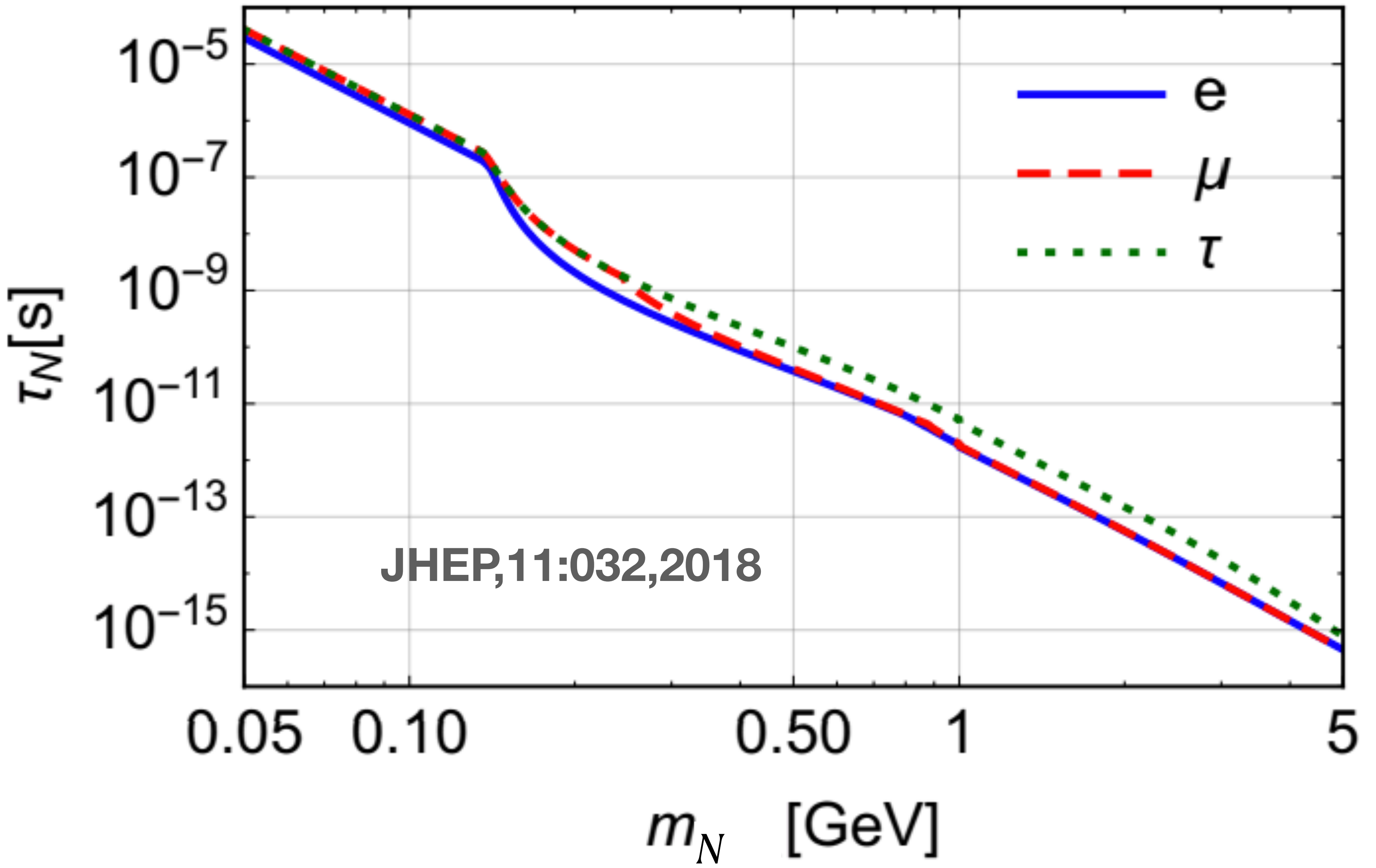
  - $m_N < m_{B,D,K}$ Belle, LHCb, beam-dump, NA62
- All the experiments provide tight limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$
- Limits on $|V_{\tau N}|^2$ are much weaker
- This motivates us to overcome the experimental challenges and explore $|V_{\tau N}|^2$



Analysis Method

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

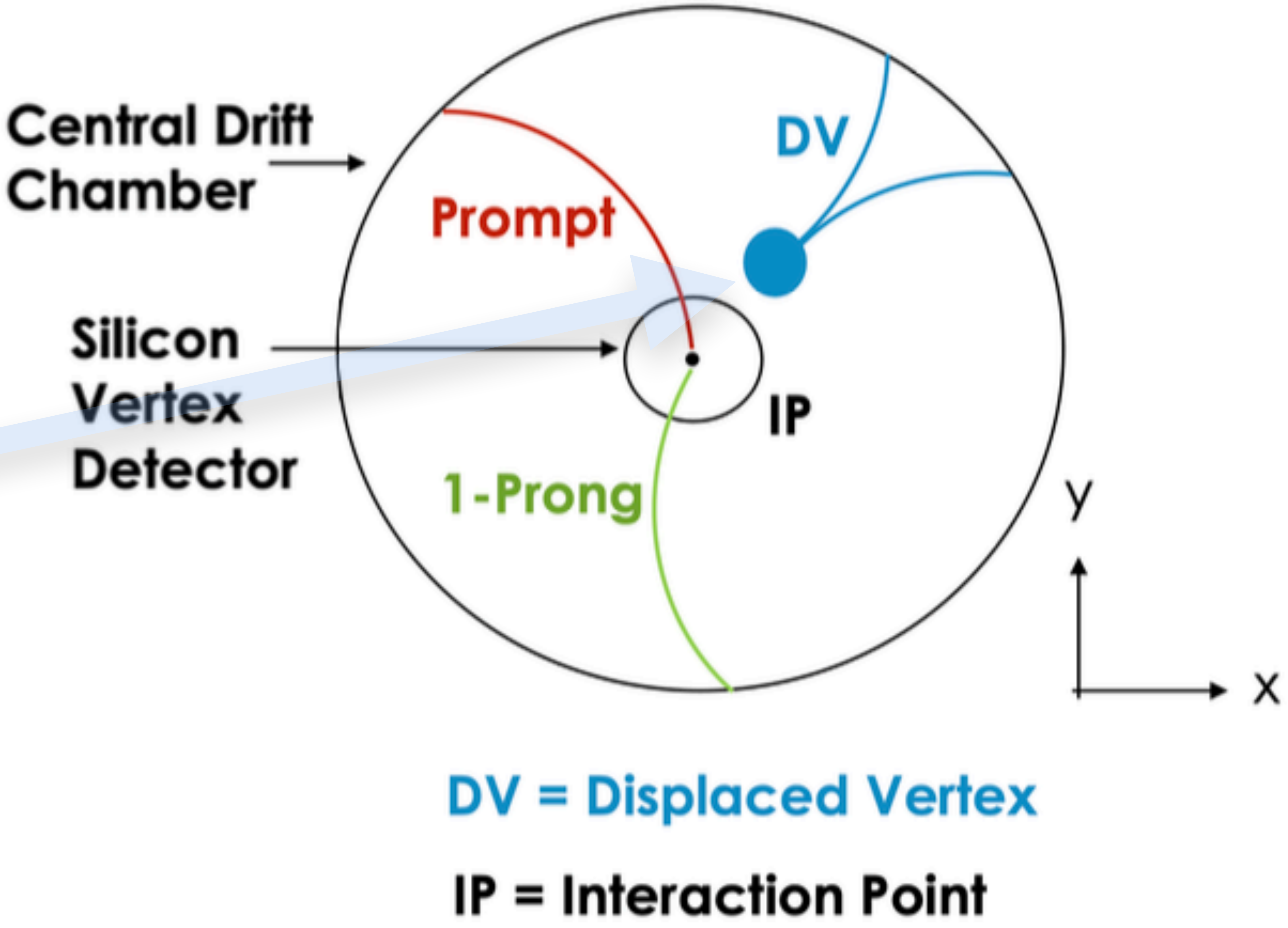
  $$\tau^+_{\text{tag}} \to \begin{cases} \pi^+\bar{\nu}_\tau \\ \pi^+\pi^0\bar{\nu}_\tau \\ l^+\nu_l\bar{\nu}_\tau \end{cases}$$

  Signal side:

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

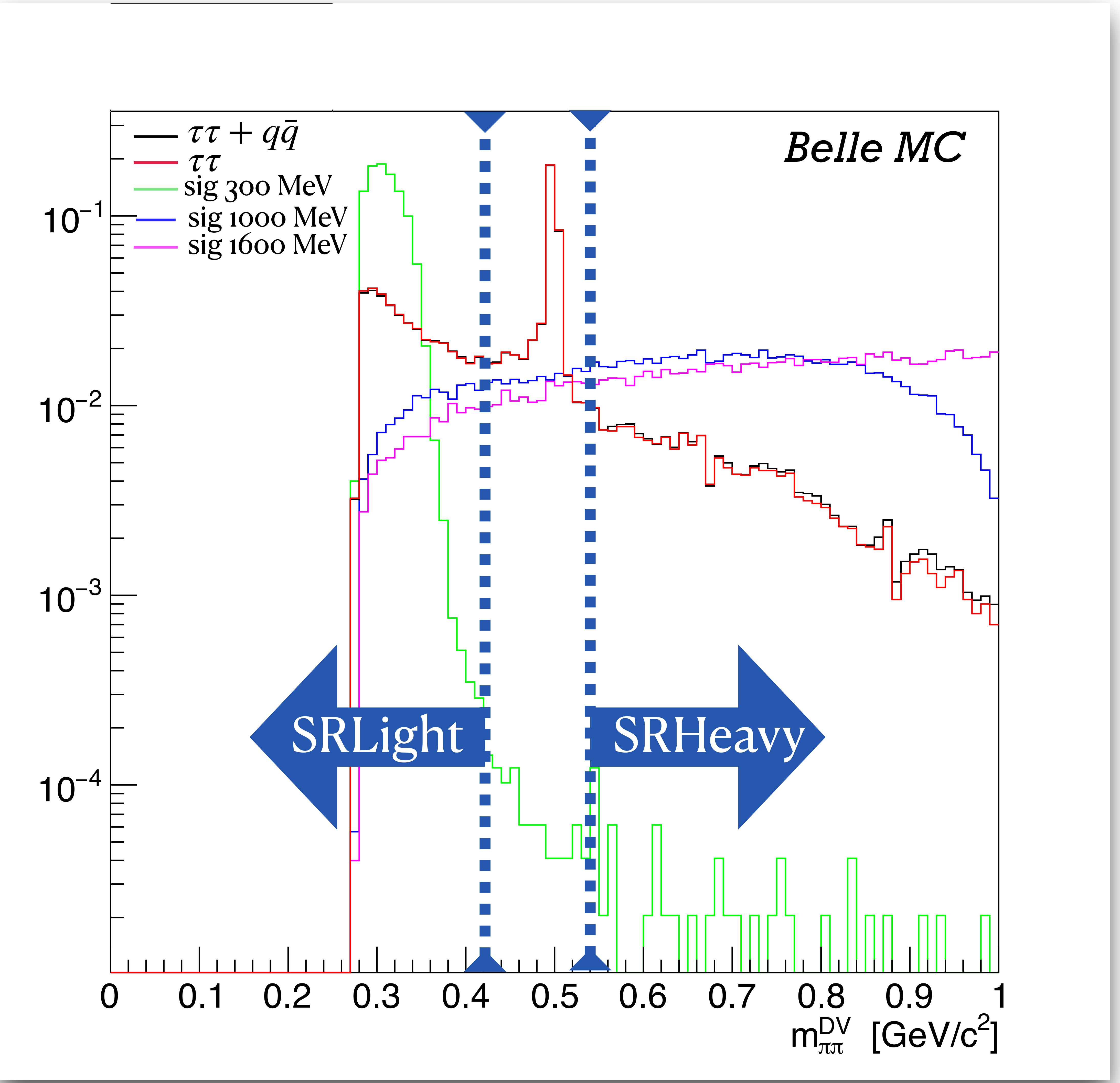
- We look for a $\mu^+\mu^-$ displaced vertex (DV)

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



K^0 rejection and definition of two signal regions

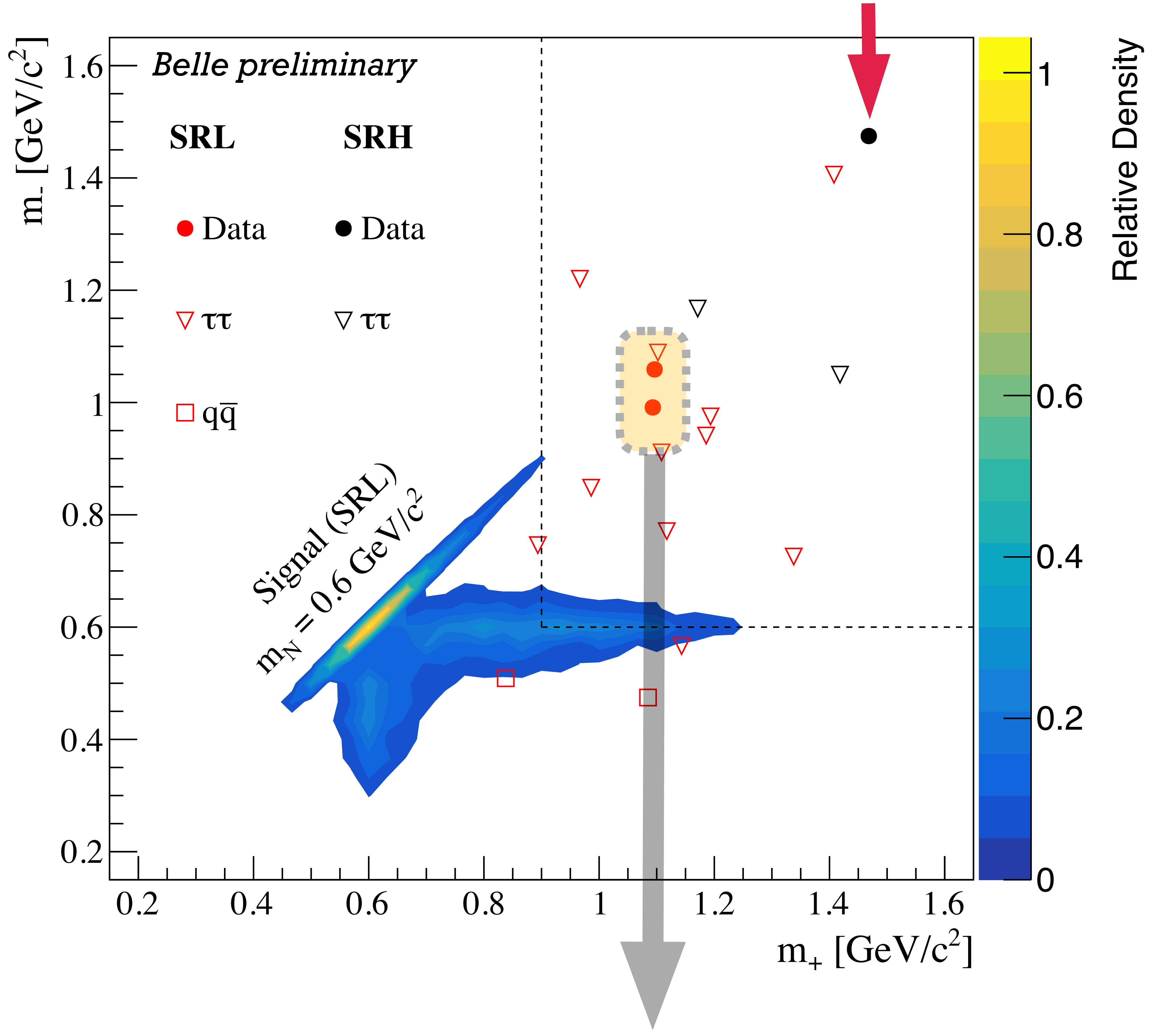
- $K^0 \to \pi^+\pi^-$: displaced vertex similar to N: removed the mass region
- We divide the signal region into Low mass and High mass signal region:
  - SRH: $m_{\pi\pi}^{DV} > 0.52\ GeV/c^2$
  - SRL: $m_{\pi\pi}^{DV} < 0.42\ GeV/c^2$
- Light N distribution is different from heavy N distribution



Result

- 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

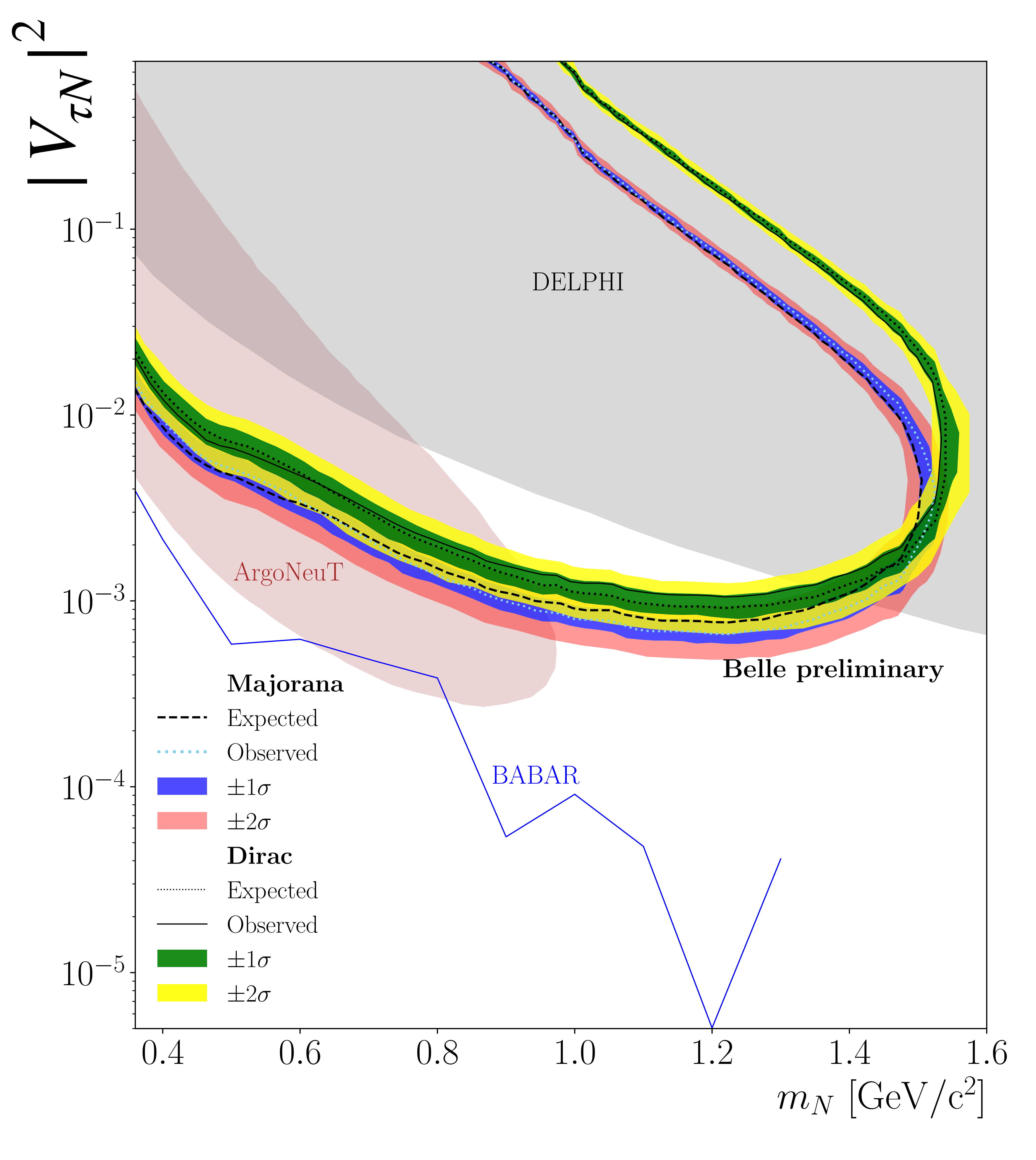
Results

- Uncertainties
  - N branching fraction
  - luminosity
  - 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 for TAU2023



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- 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(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 link)

Dark Leptophilic Scalar

- Scalars other than Higges bosons 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
- 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. $B \to K\phi$ and $K \to \pi\phi$
    - 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

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

ξ = coupling constant independent of lepton flavor,

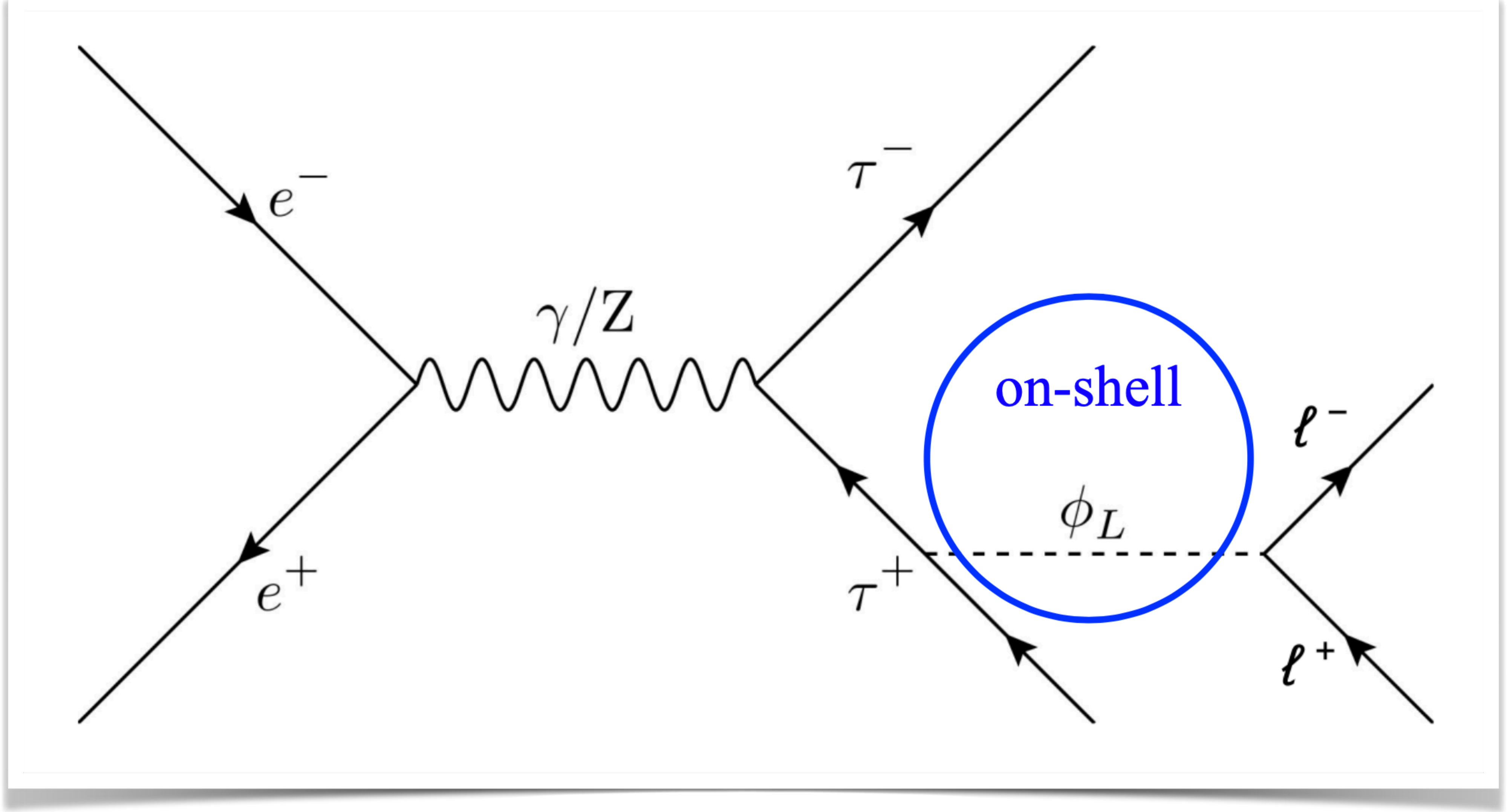
m_ℓ = mass of lepton

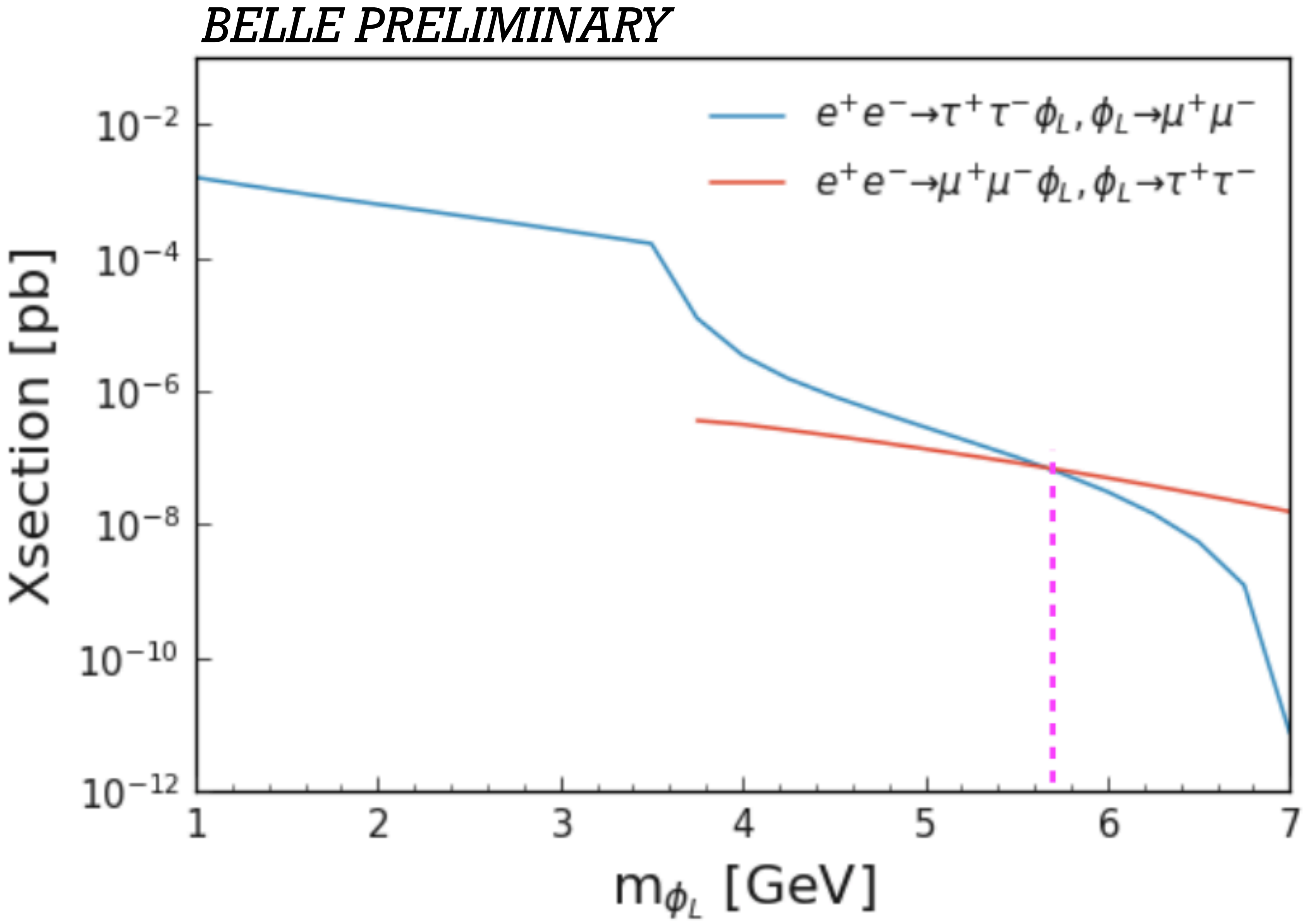
v = 246 GeV, is the vacuum expectation value of the Higgs field

Analysis Method

- $e^+e^- \to \tau^+\tau^-\phi_L, \quad \phi_L \to e^+e^-/\mu^+\mu^-$
- 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 ξ till $m_{\phi_L} < 6.5$ GeV

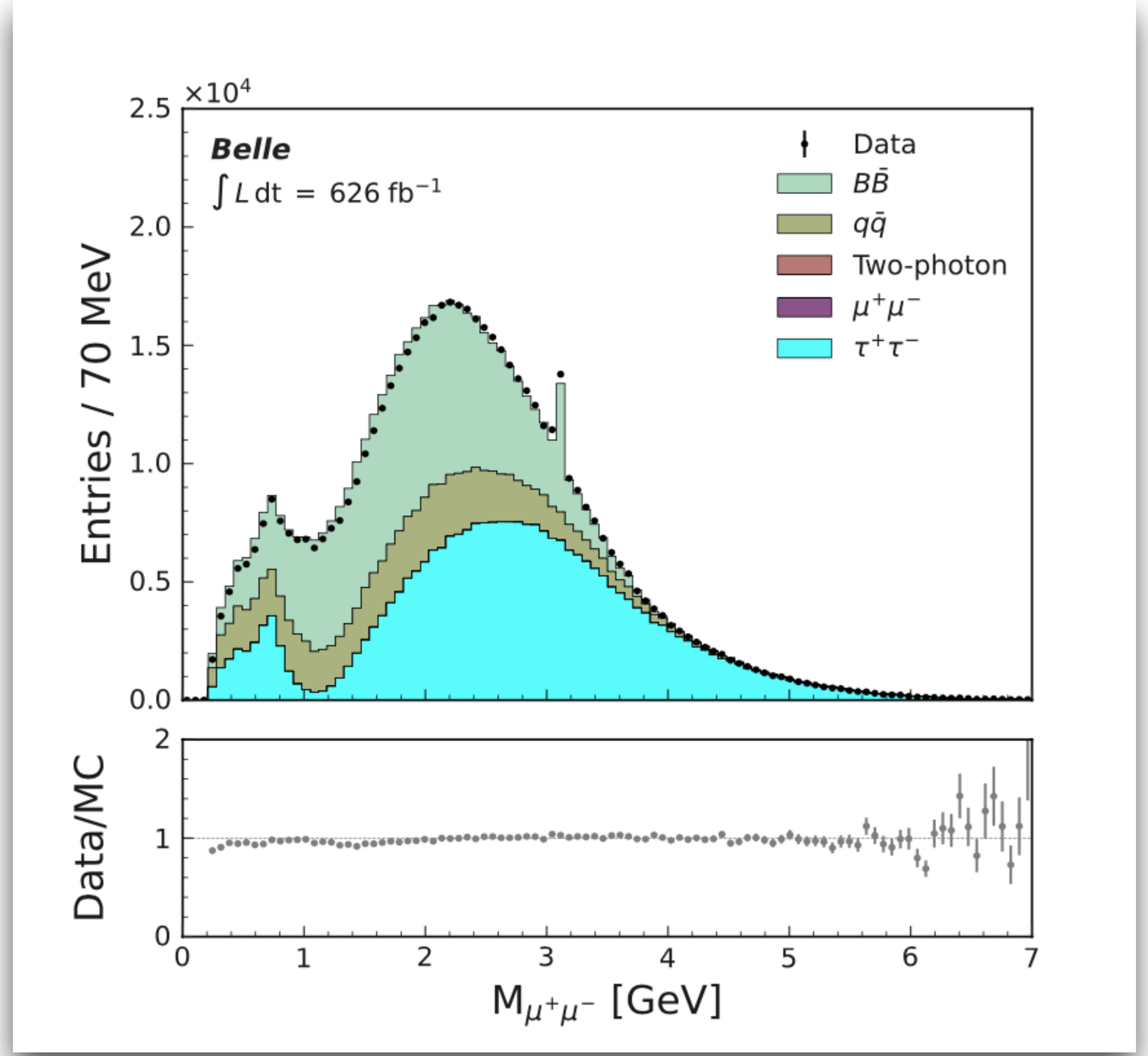
626 fb^{-1} data from Belle detector

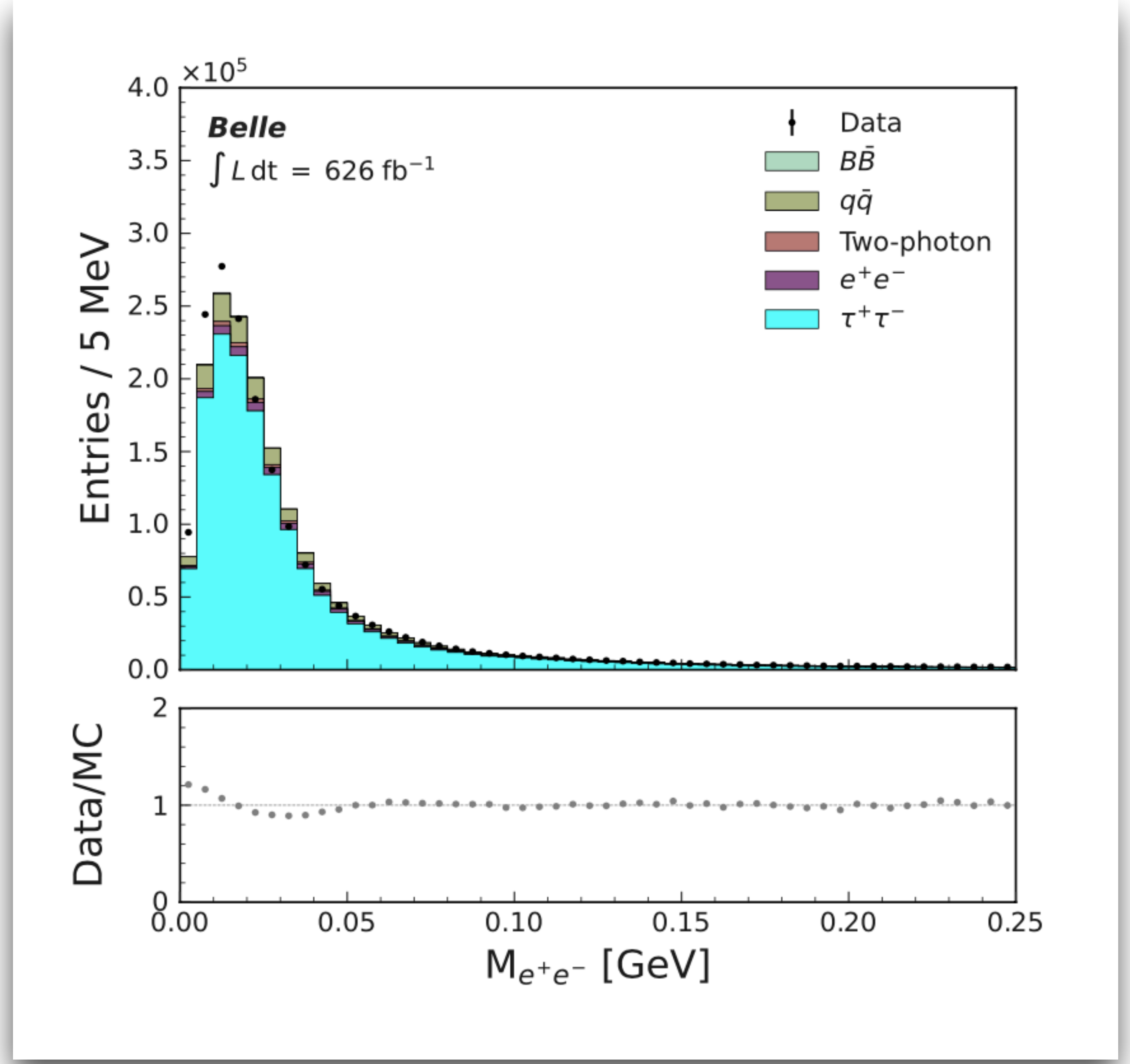




Results: data vs. Monte Carlo in Control Region

- Extraction of the signal:
  - fitting l^+l^- invariant mass distribution: simultaneous fit for both e^+e^- and $\mu^+\mu^-$ channel
  - evaluation at each mass point of ϕ_L
- Good agreement seen in data vs. Monte Carlo comparison in control regions: BDT < 0.5





Results: data vs. Monte Carlo in Signal Region

- Signal region: No obvious narrow peak structure is observed

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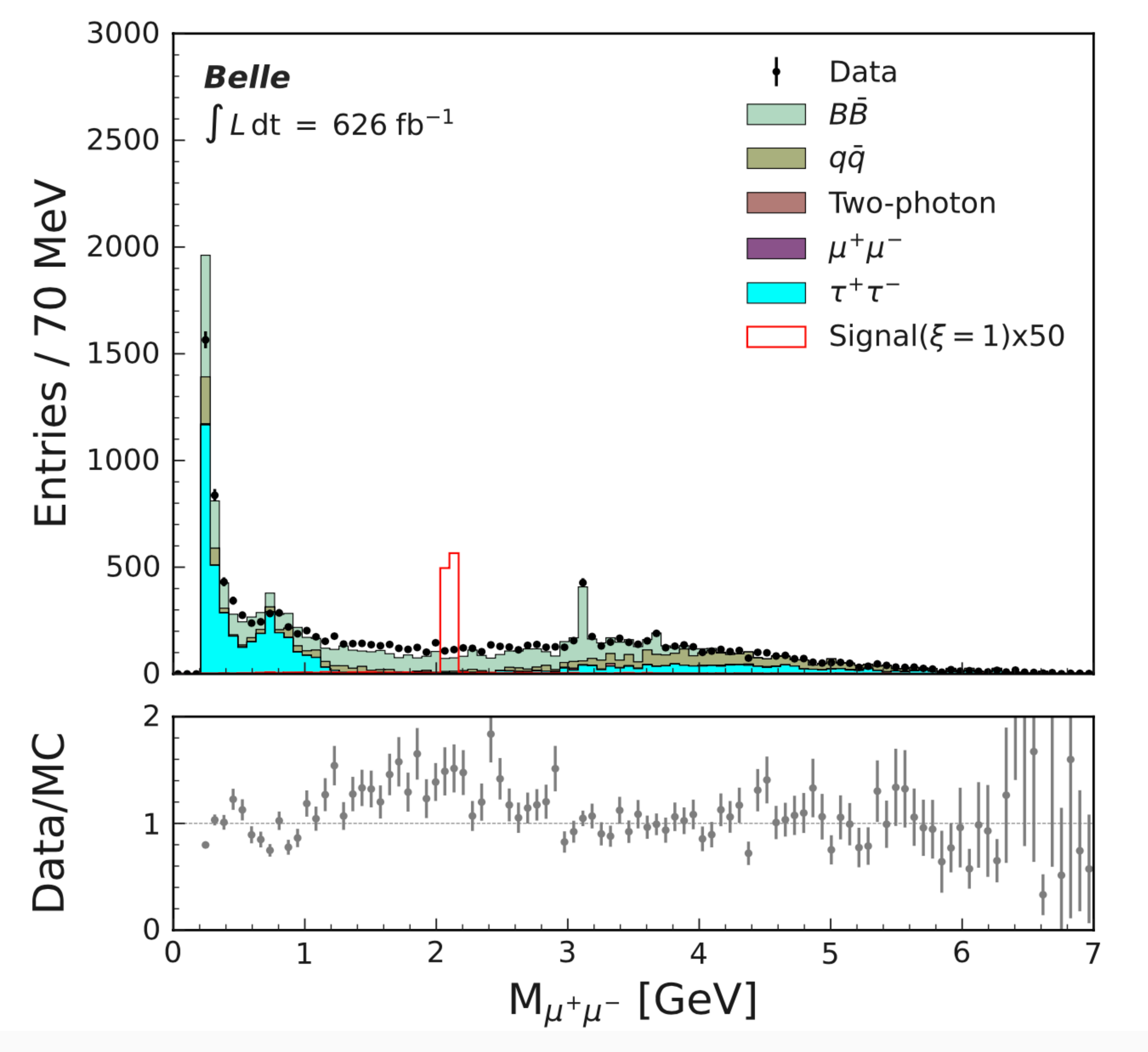
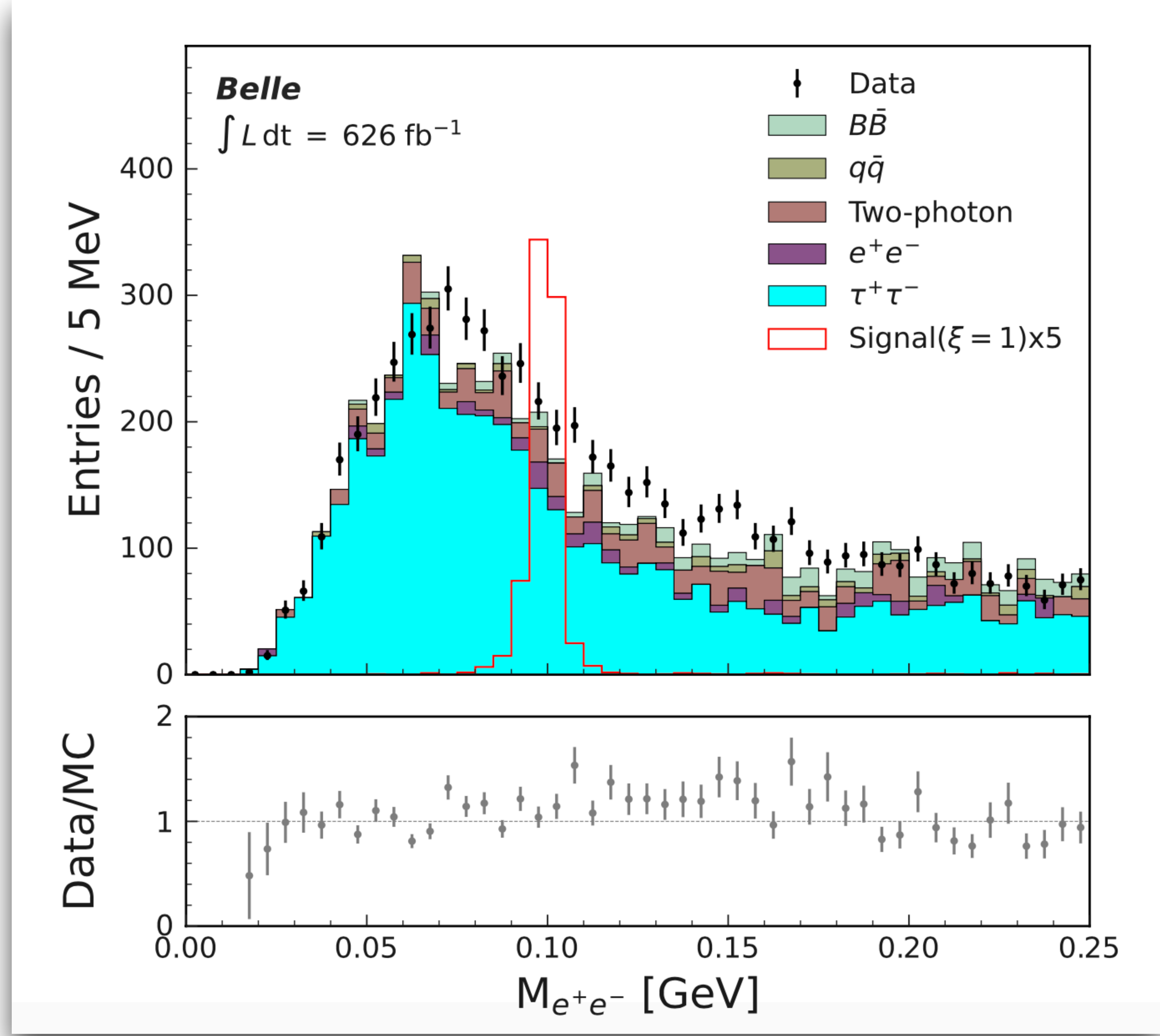
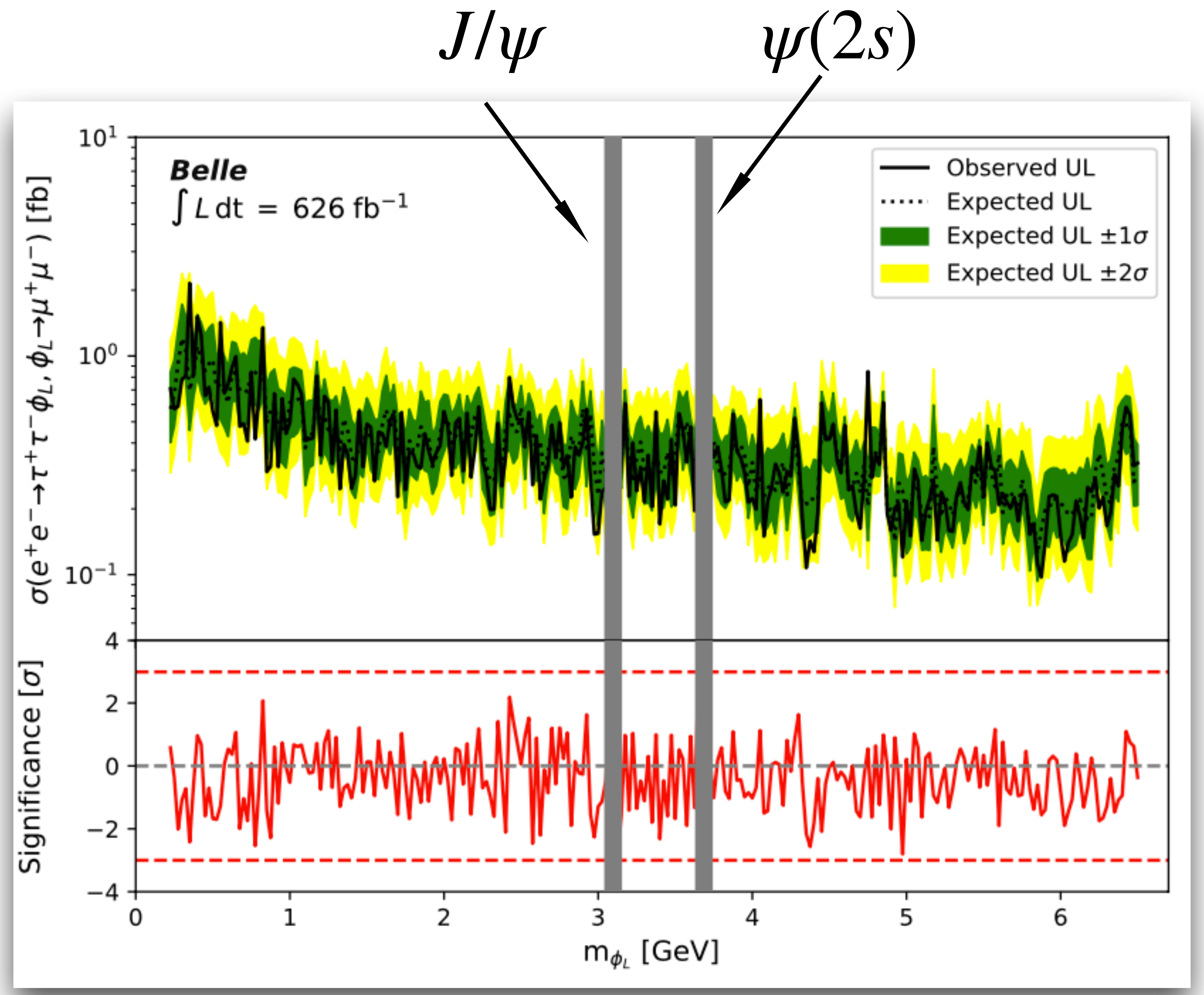
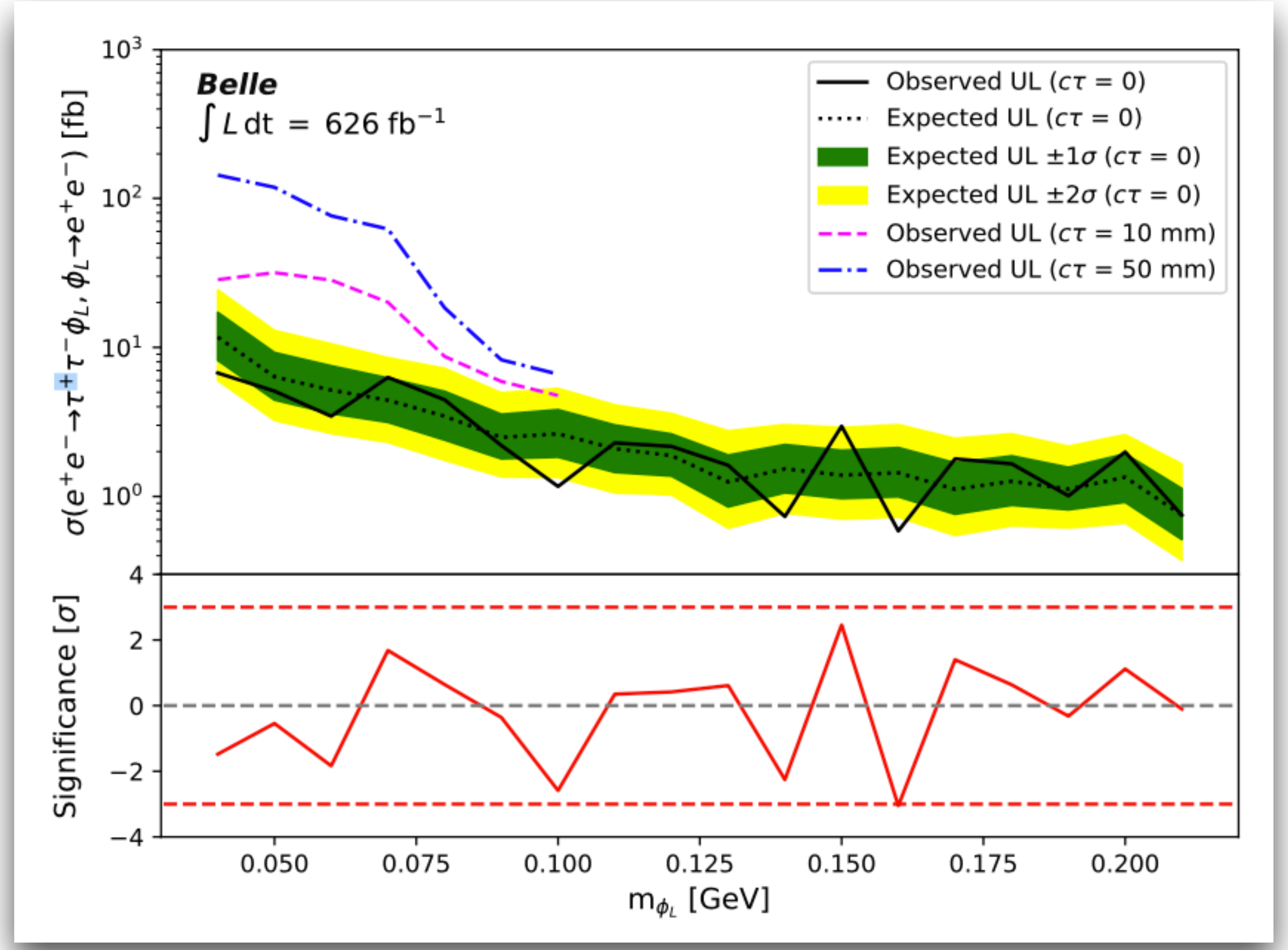




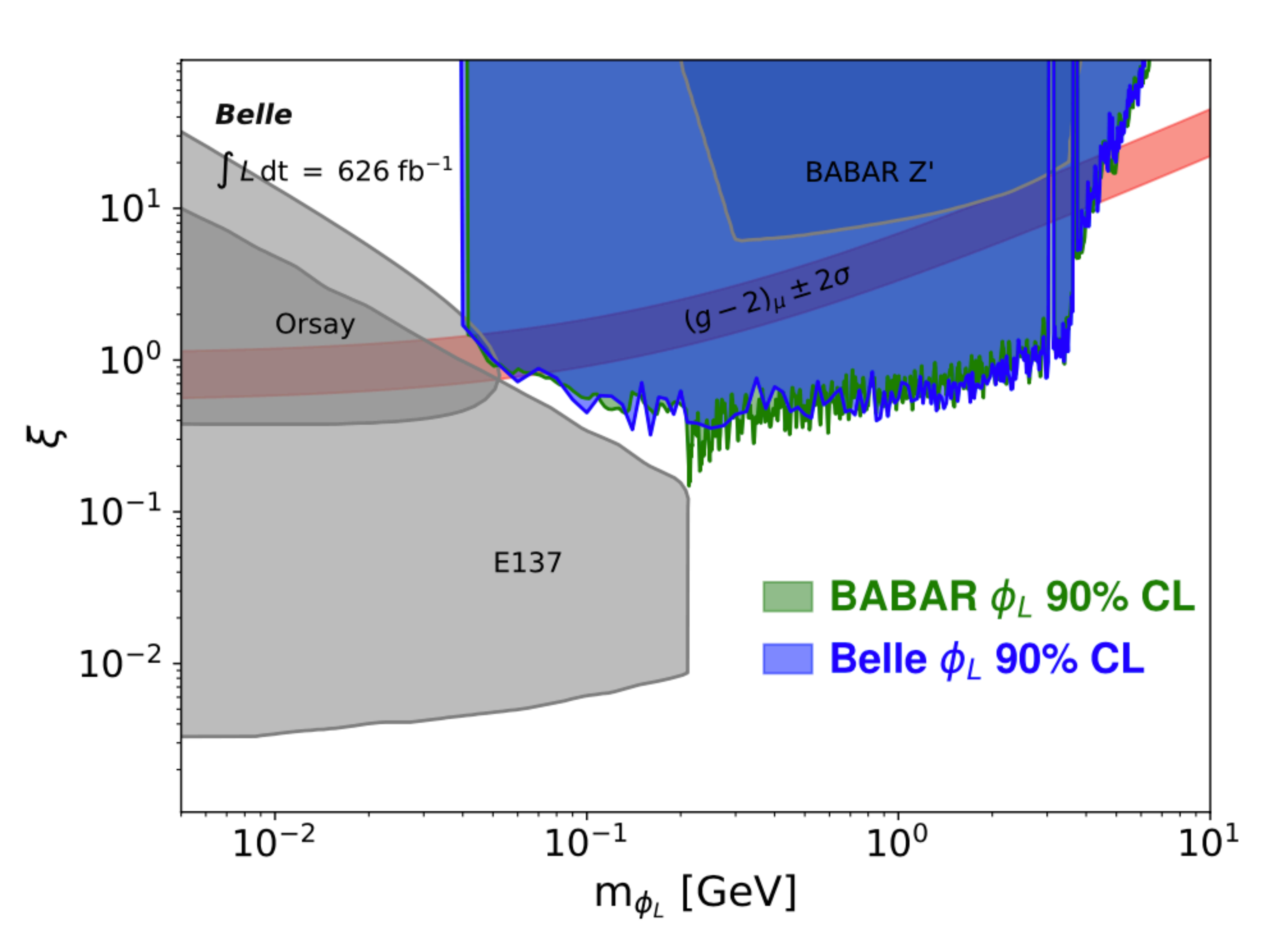
Results: upper limits on the signal cross-section

- 90% confidence level upper limits on the signal cross-section
- No significant excess in all masses





Results: level upper limits on the coupling constant



- 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 (PhysRevLett.124.211803)

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

- Lepton Flavor Universality check

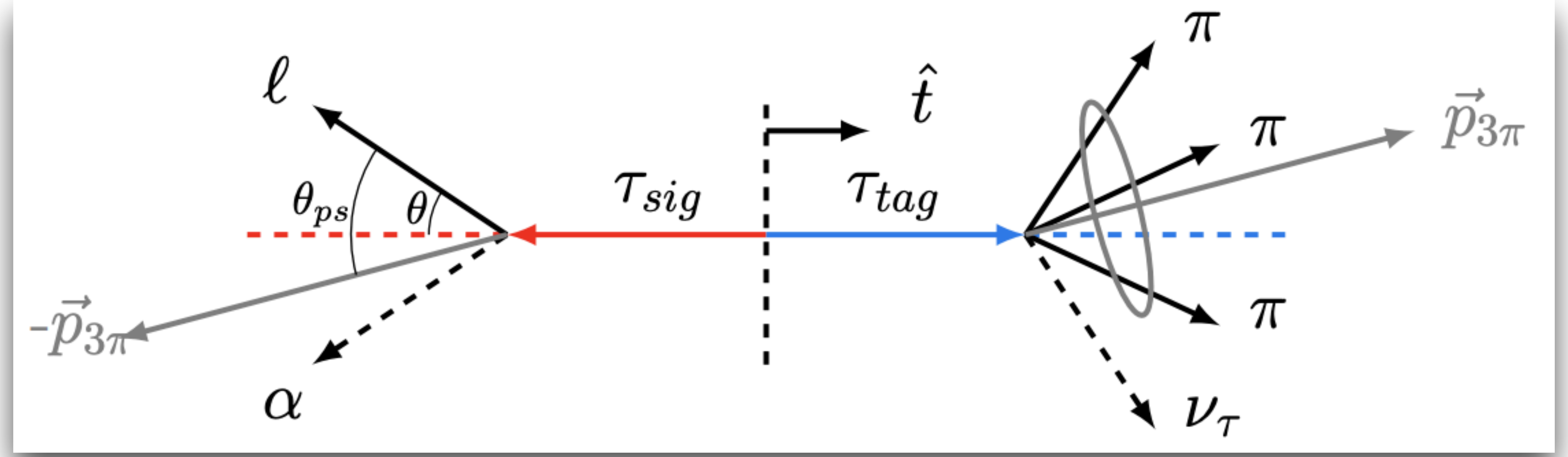
- This process was previously searched for by the MARK III and ARGUS collaborations (Z. Phys. C 68, 25-28 (1995)).

- 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)

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

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

- In center-of-mass frame: τ pairs: back to back
  - tag side: 3 charged particle from $\tau^- \to h^- h^+ h^- \nu_\tau (h = K, \pi)$
  - signal side: 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: $\hat{p}_\tau \approx \frac{-\vec{p}_{3h}}{|\vec{p}_{3h}|}, E_\tau \approx E_{CMS}/2$



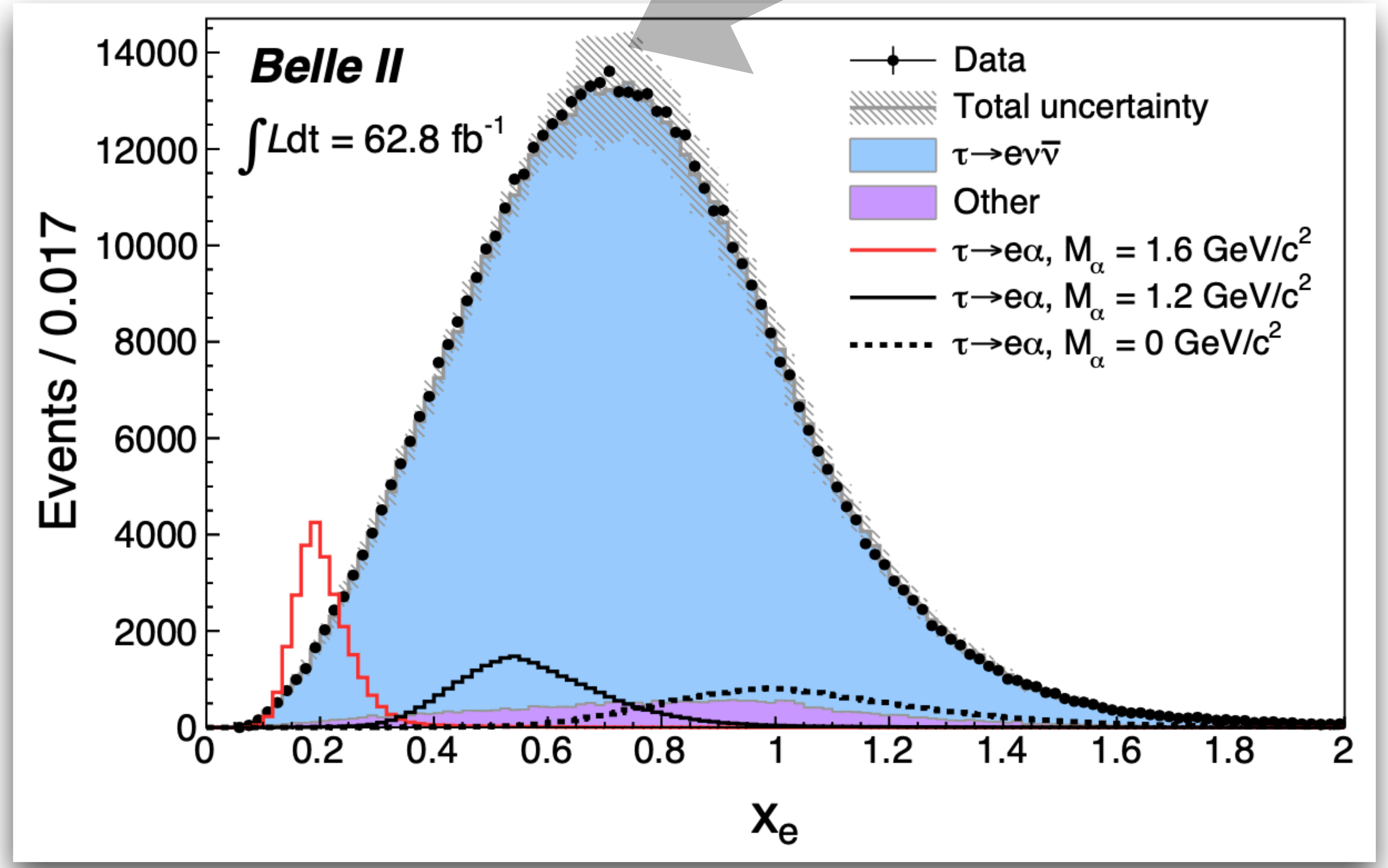
62.8 fb^{-1} data from Belle II detector:
57.7 Million τ pairs

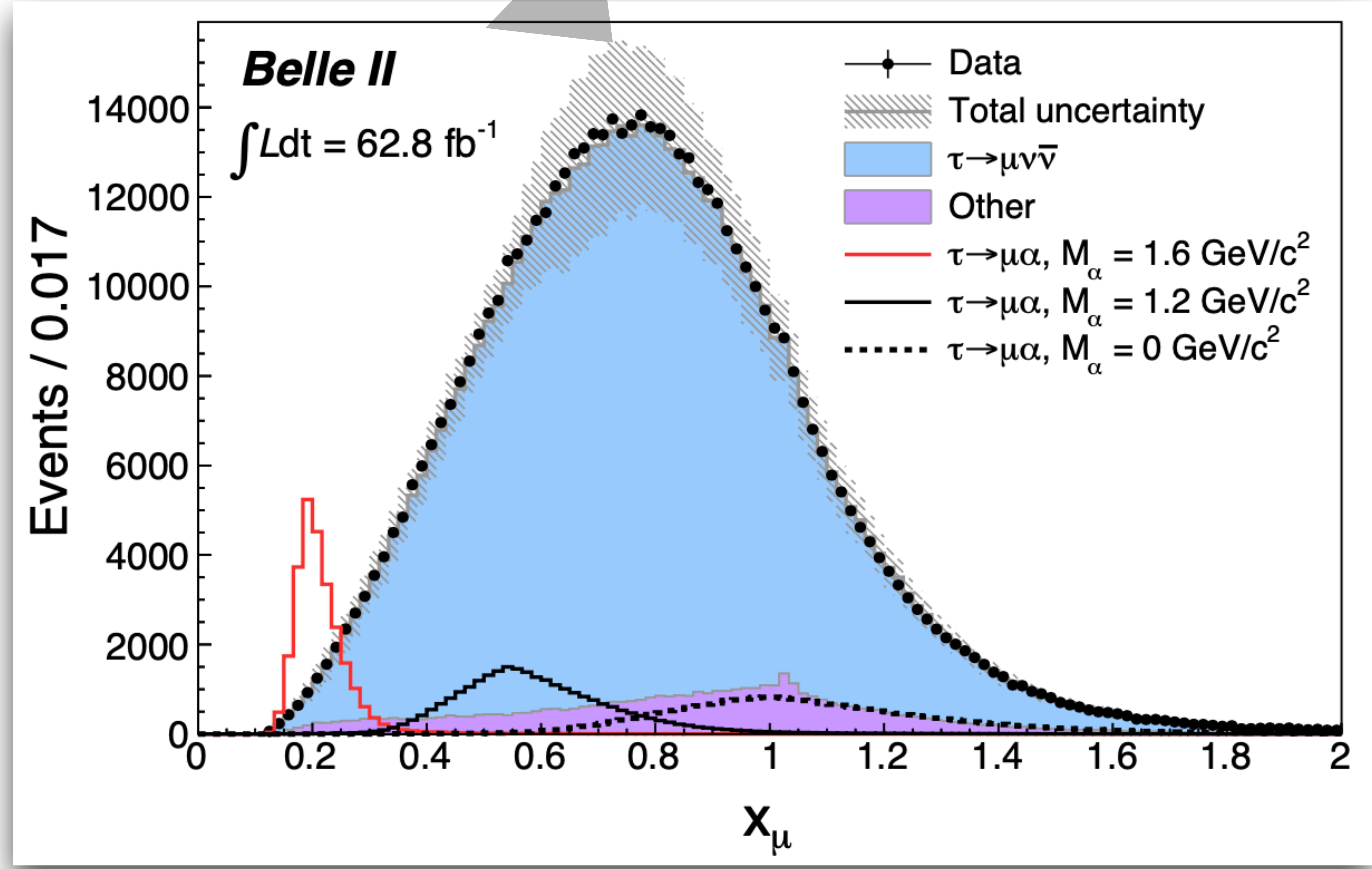
- Measure $\frac{\mathcal{B}_{\ell\alpha}}{\mathcal{B}_{\ell\bar{\nu}\nu}} = \frac{\mathcal{B}(\tau^- \to \ell^- \alpha)}{\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)}$

- Search for a peak in normalized lepton energy $x_\ell \equiv \frac{E^*_\ell}{m_\tau c^2/2}$, E^*_ℓ = energy of the charged lepton in τ pseudo rest frame

Results: Spectra of x_ℓ

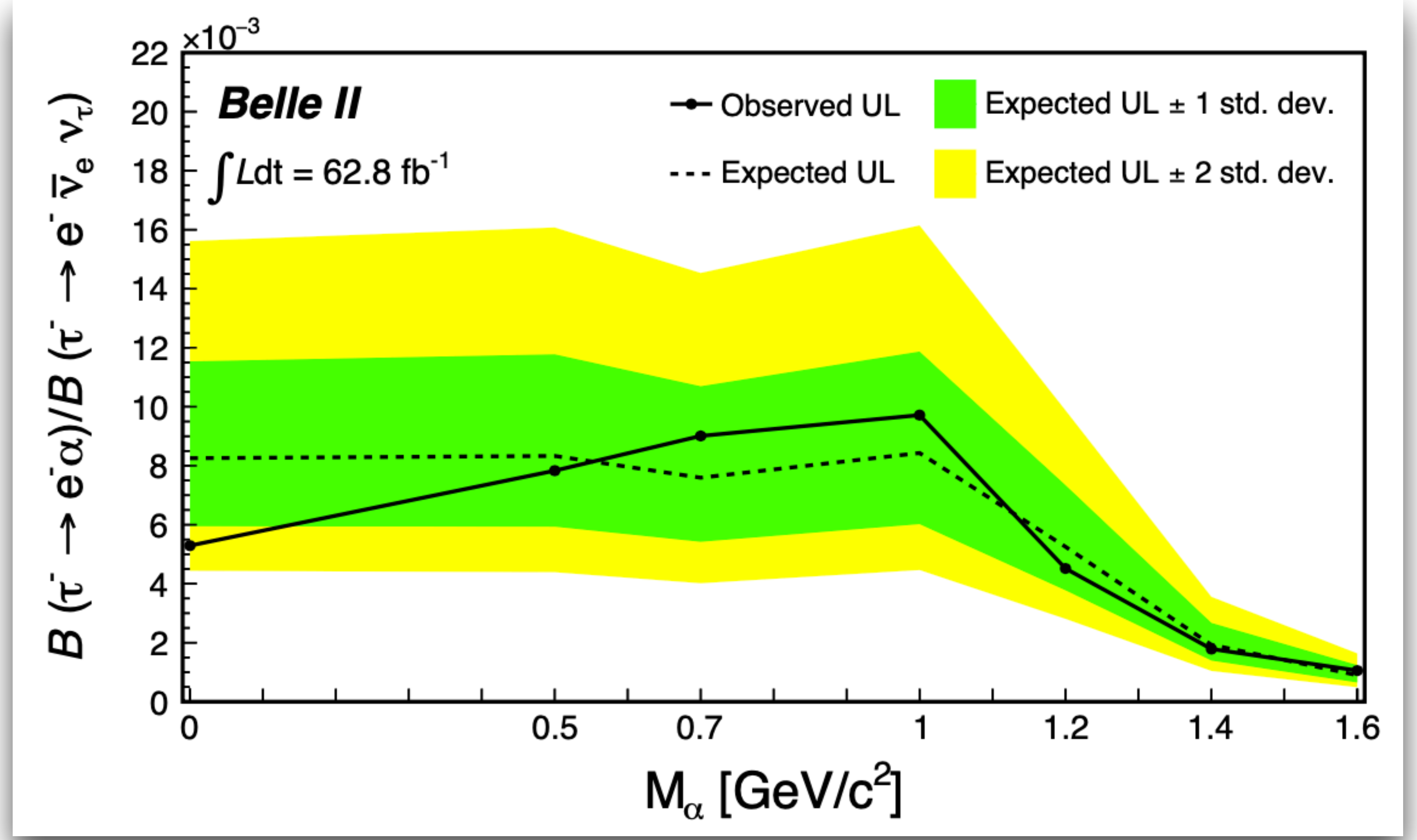
- Simulated spectra for standard-model processes: stacked, gray band: total uncertainty(dominated by the lepton-identification efficiency uncertainty)
- Remaining background processes combined together: collectively referred to as "other"
- The distributions for $\tau \to \ell^- \alpha$ are shown for three α masses assuming branching-fraction ratios of 5%

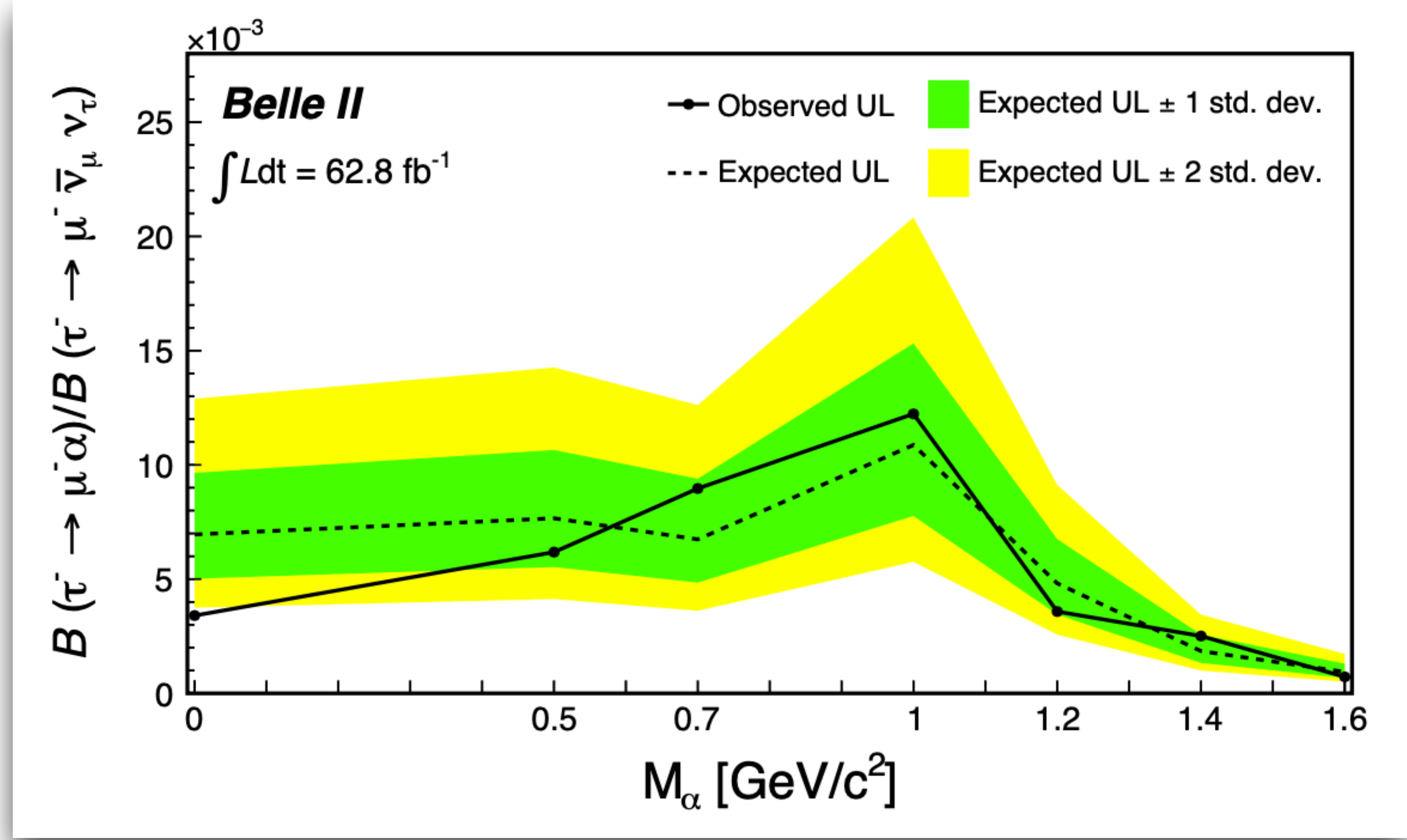




Results

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





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

Summary

- No significant excess observed
- Stringent limits in all three analyses
- Search for a heavy neutral lepton that mixes predominantly with the τ neutrino
  - 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 and suppress background to the single-event level
- 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
  - No ϕ_L can explain observed excess in $(g-2)_\mu$ for $m_{\phi_L} < 4$ GeV
- Search for Lepton Flavor Violating τ Decays to a Lepton and an Invisible Boson at Belle II
  - most stringent limits on invisible spin-0 boson production from τ lepton decays to date

Long shutdown now : for upgrades, will resume data taking in 2024 : improved detector, and more data, hope for more exciting results in the future

THANK YOU FOR YOUR ATTENTION

Backups

Search for a $\tau^+\tau^-$ Resonance in $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ Events with the Belle II Experiment (PhysRevLett.131.121802)

- First search for $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ in 3.6 - 10 GeV/c^2 range
- 62.8 fb^{-1} Belle II data
- Probes three different models
  - spin-1 particle coupling only to the heavier lepton families
  - a Higgs-like spin-0 particle that couples preferentially to charged leptons
  - an an axionlike particle

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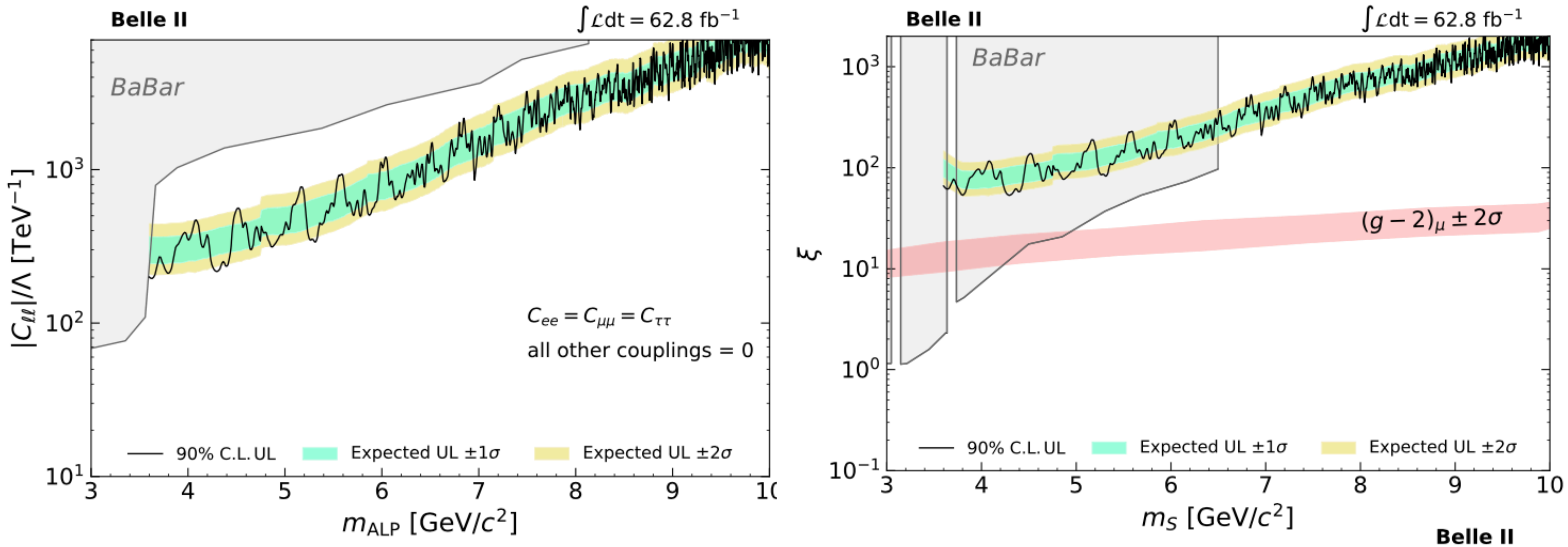
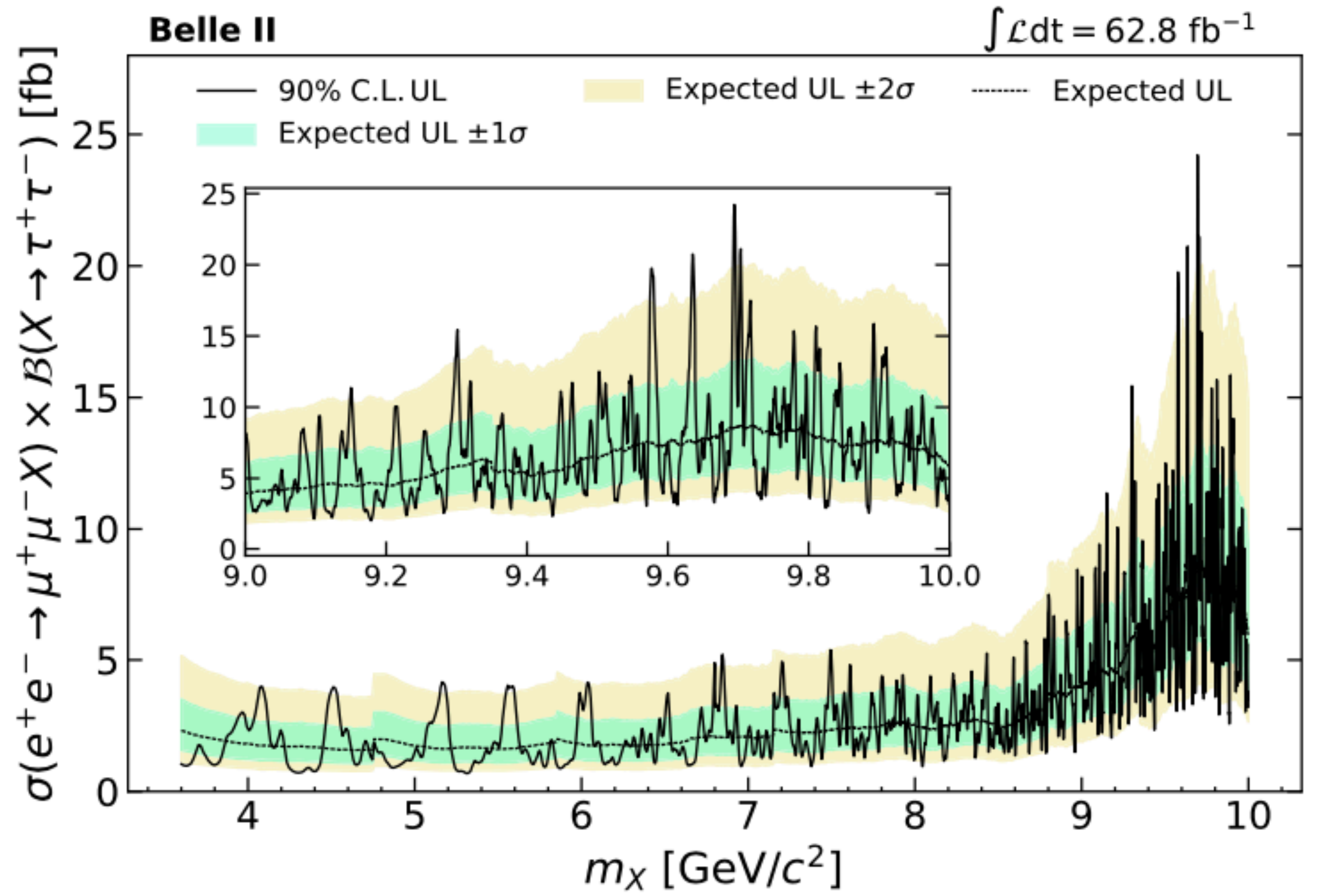


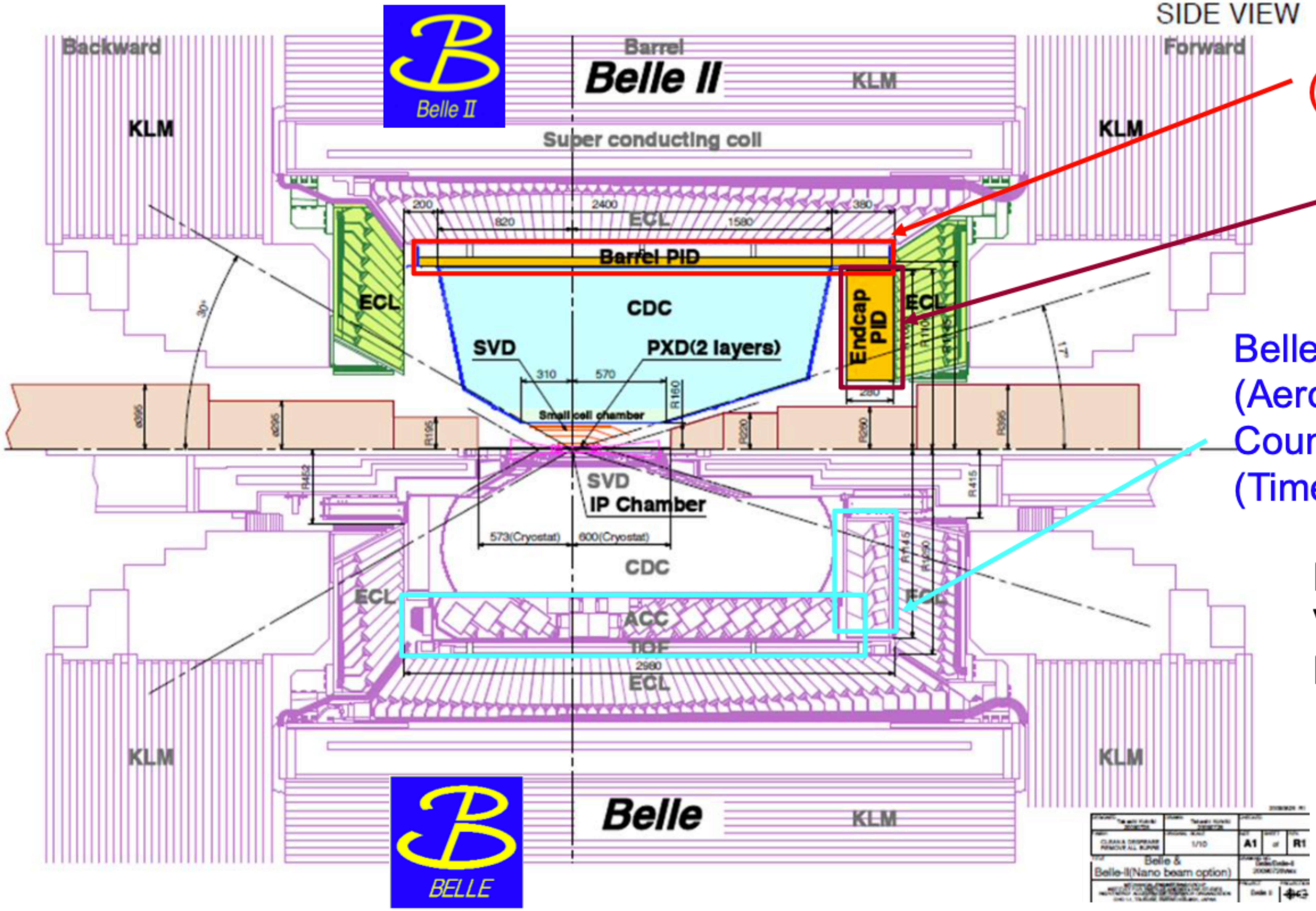
Leptophilic scalar

ALP mass coupling to leptons

$X = (Z', S, ALP)$



from Belle to The Belle II Detector



TOP (barrel)

ARICH (forward endcap)

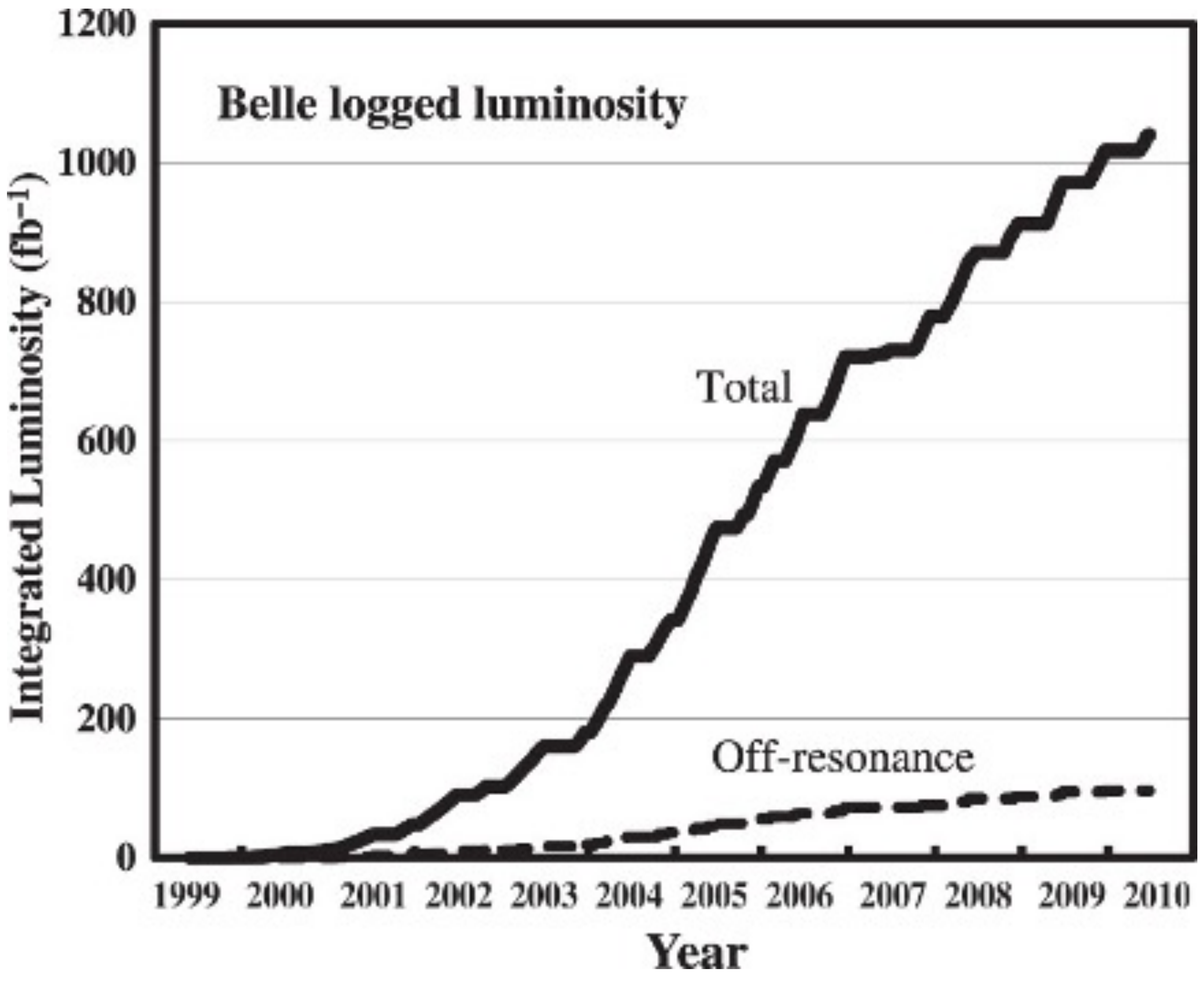
Belle equipped ACC (Aerogel Cherenkov Counter) and TOF (Time Of Flight)

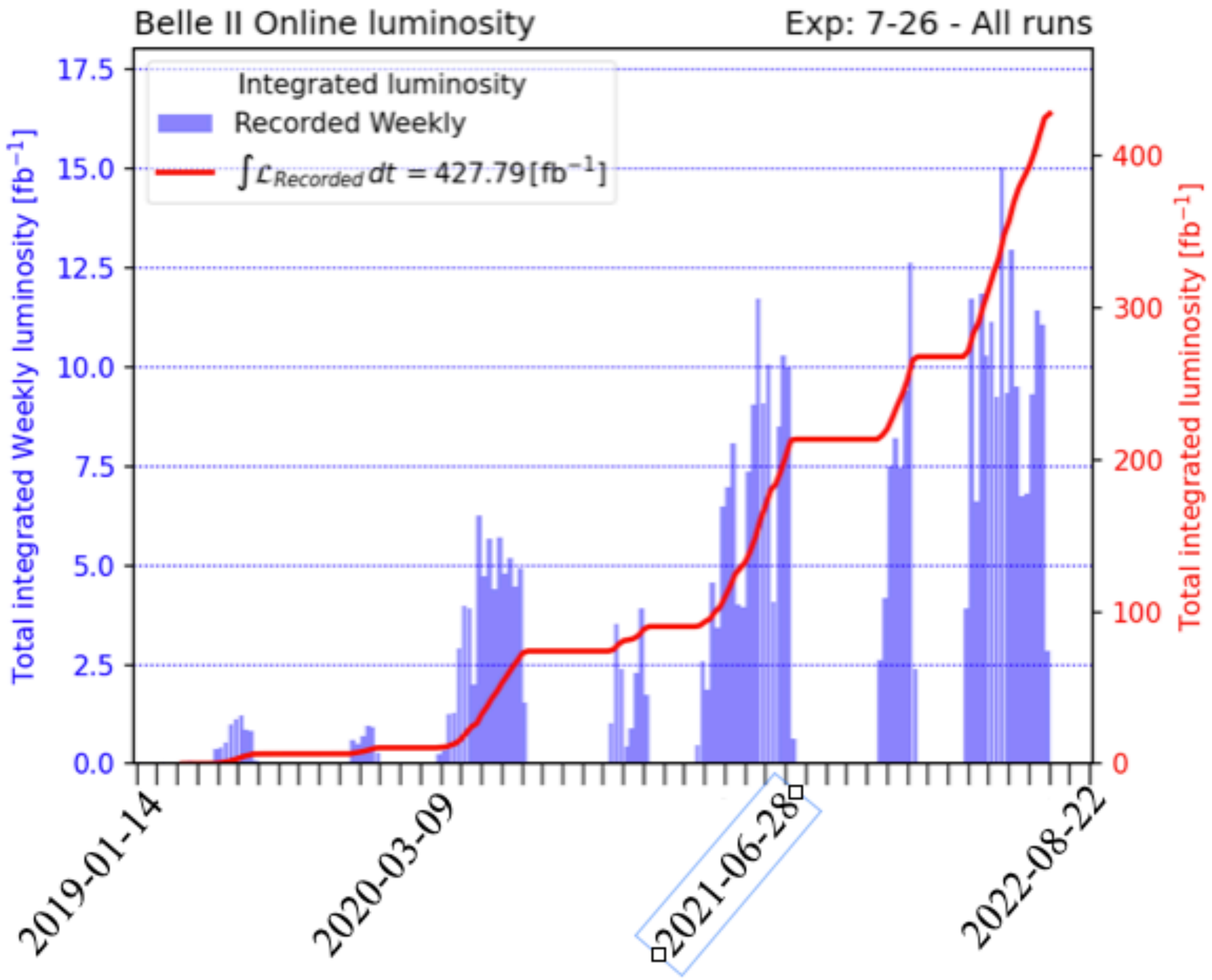
More space to VXD and CDC at Belle II

Luminosity

- Belle data taking period: 1999-2010 : 1040 fb^{-1}
- Belle II: Regular data-taking since April 2019
- Current integrated luminosity 424 fb^{-1}
- long shutdown for accelerator and detector upgrades, will resume data taking in 2024
- Belle II Design integrated luminosity 50 ab^{-1}

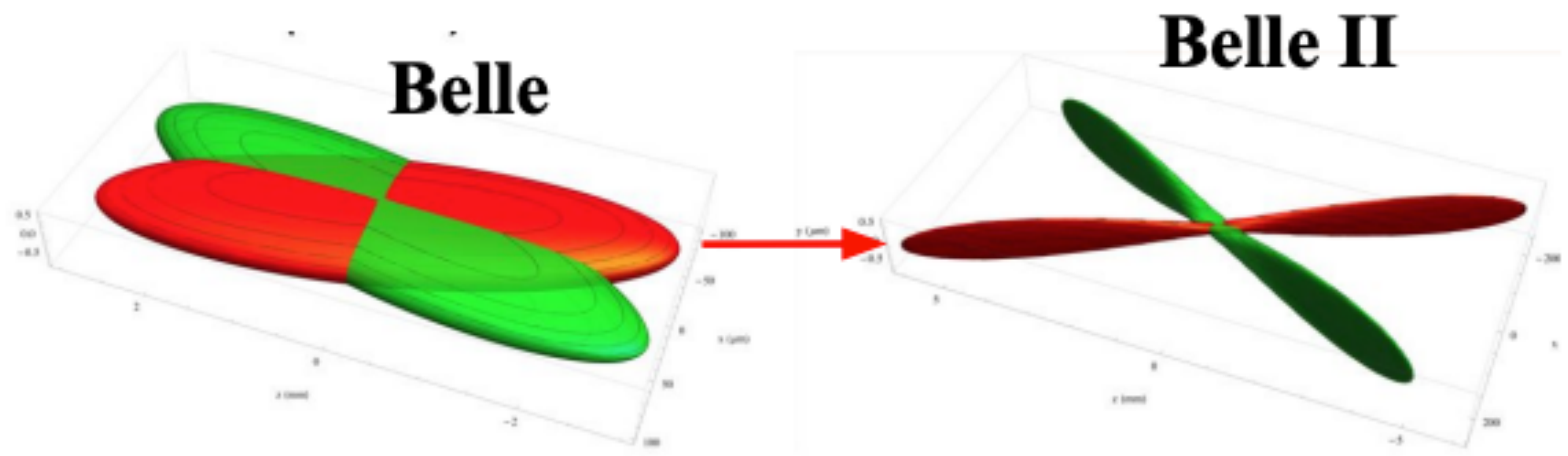
- $\sigma(e^+e^- \rightarrow b\bar{b}) = 1.05\ nb$
- $\sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92\ nb$
- $\Upsilon(nS)\epsilon[n = 1,..,5]$, use of off resonance data : B factories are also τ factories

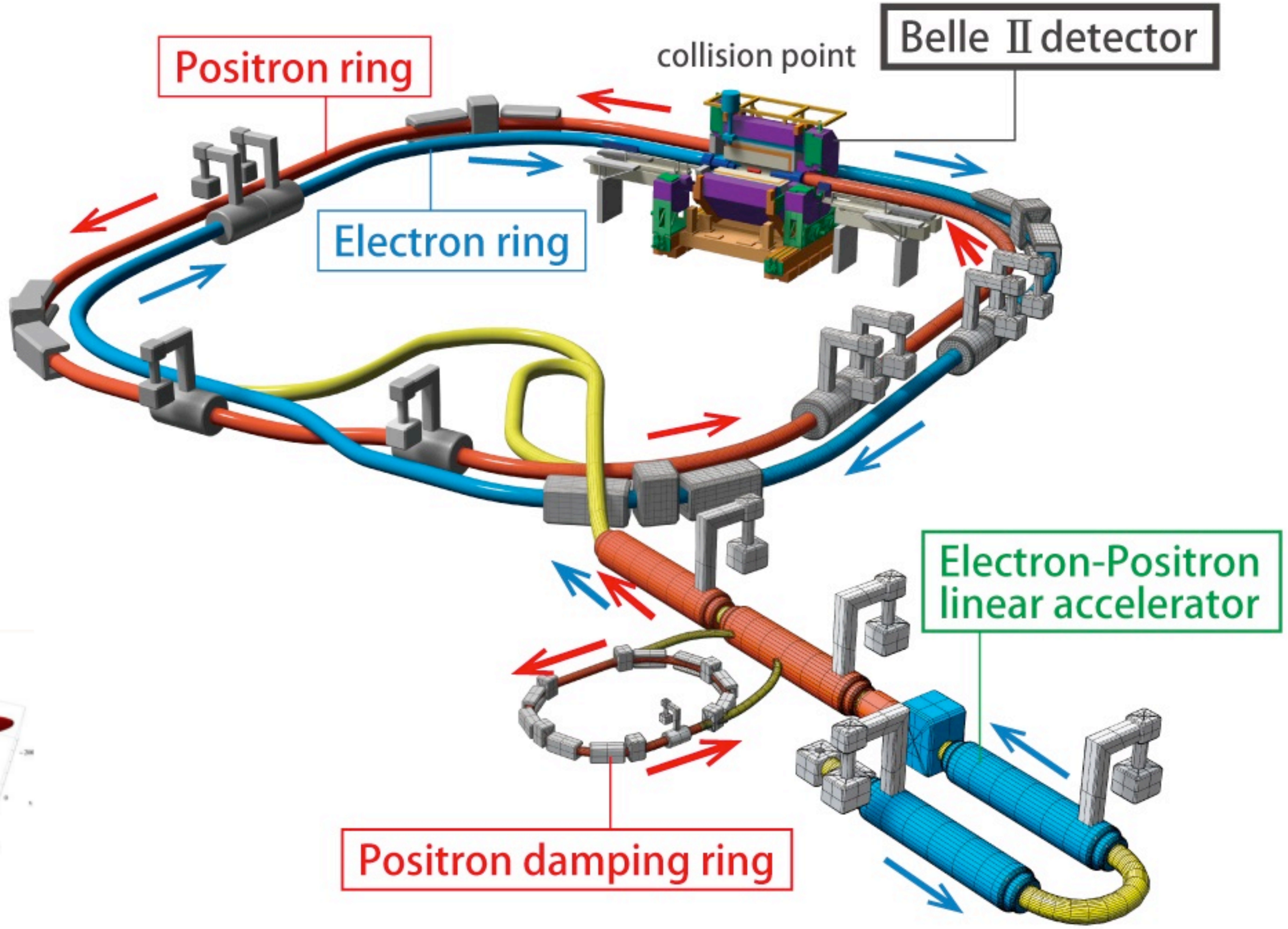




from KEKB to SuperKEKB

- 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 $\tau^- \to DV(\to \mu^\mp\mu^\pm)\pi^-$
- 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^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)

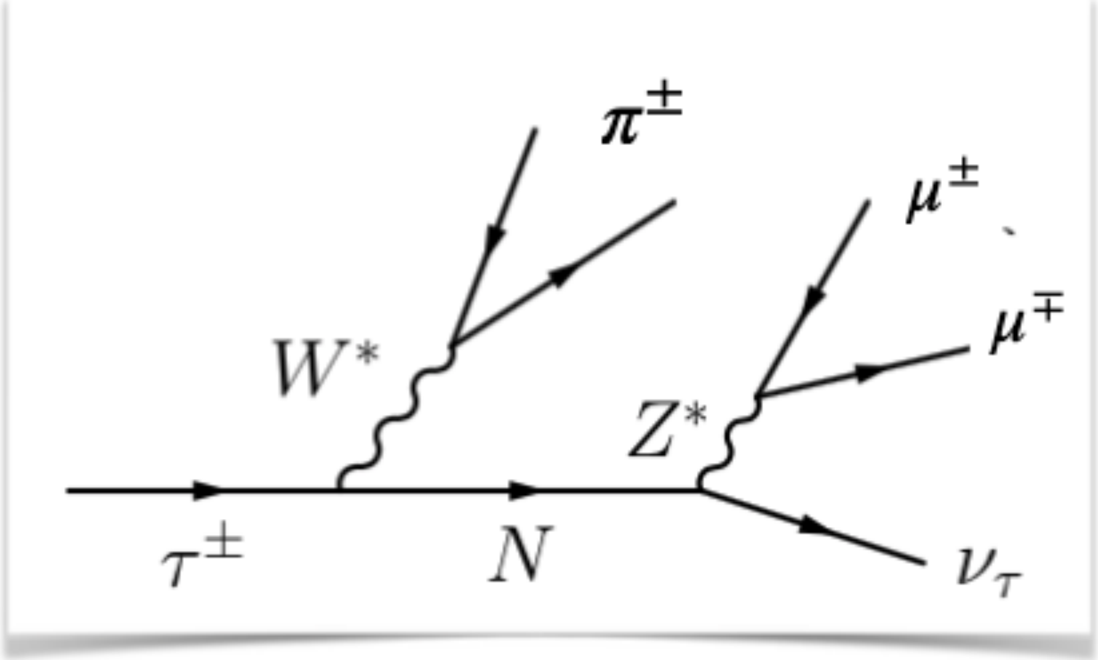
Quadratic equation

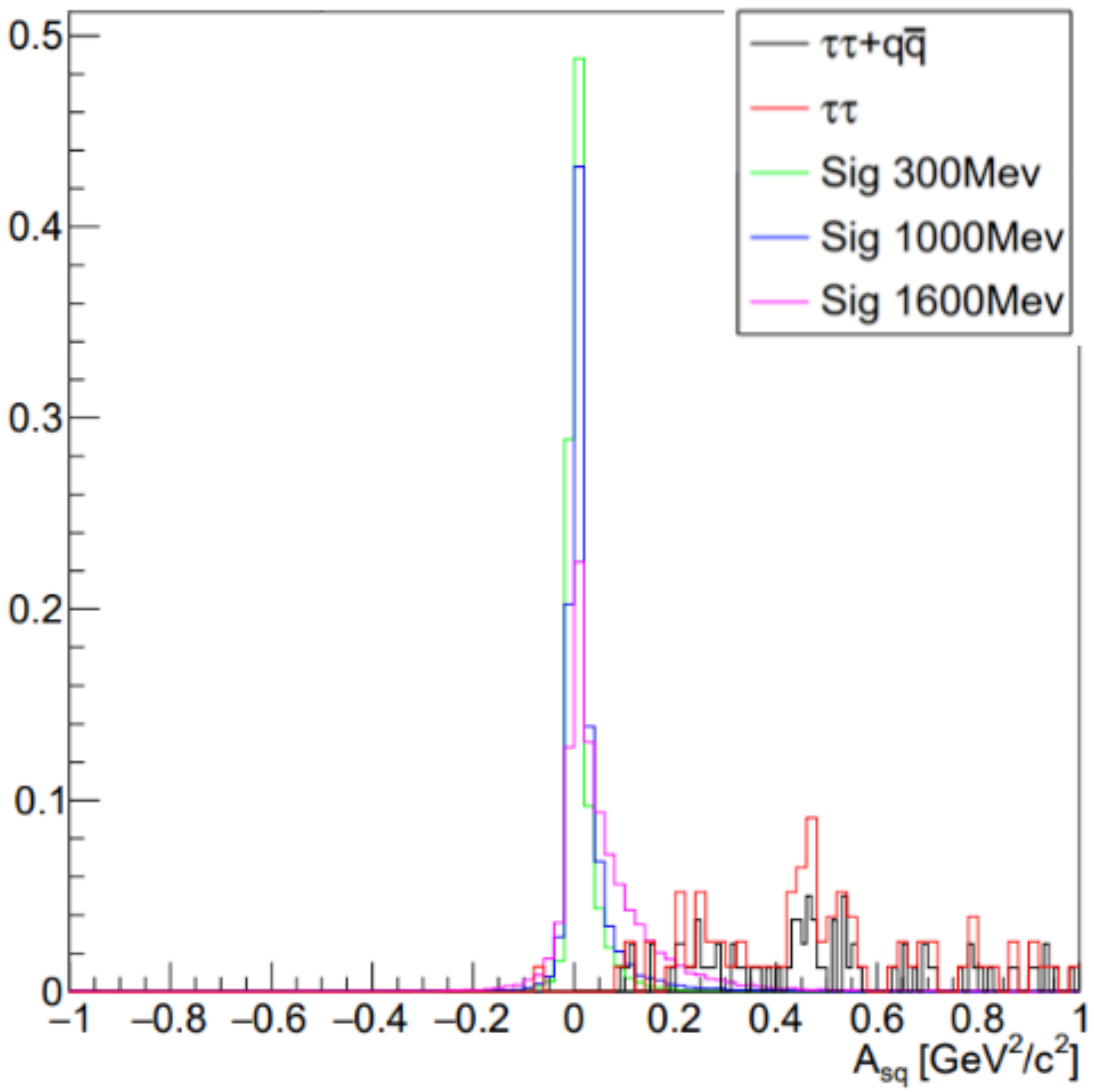
(Using the square root argument $A_{sq} = b^2 - 4ac$ for cut)

$A_{sq} < 0.4$ GeV^2

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

Two HNL mass solutions: m_+, m_-

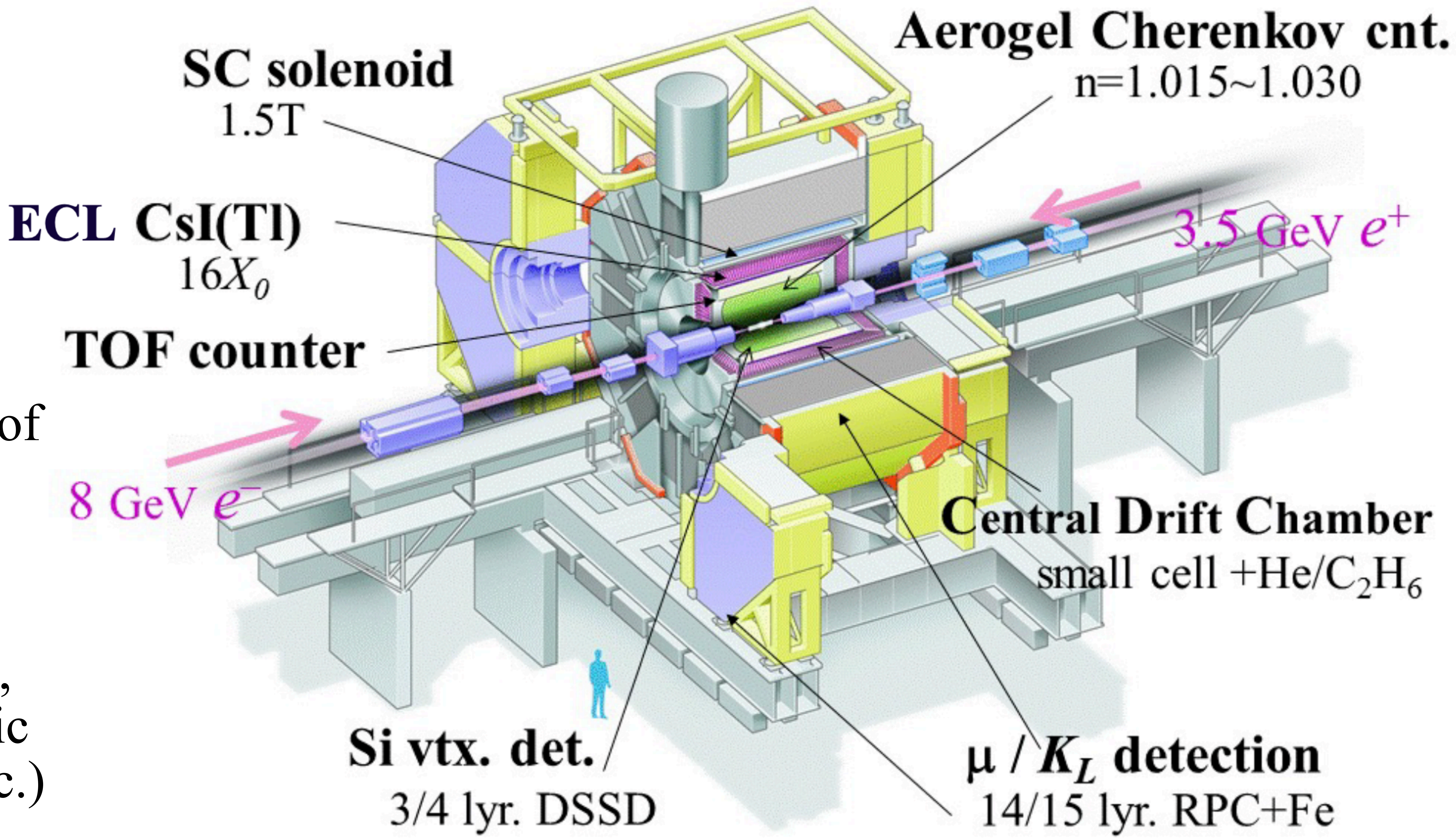




The Belle Detector

- The accelerator collides electron and positrons

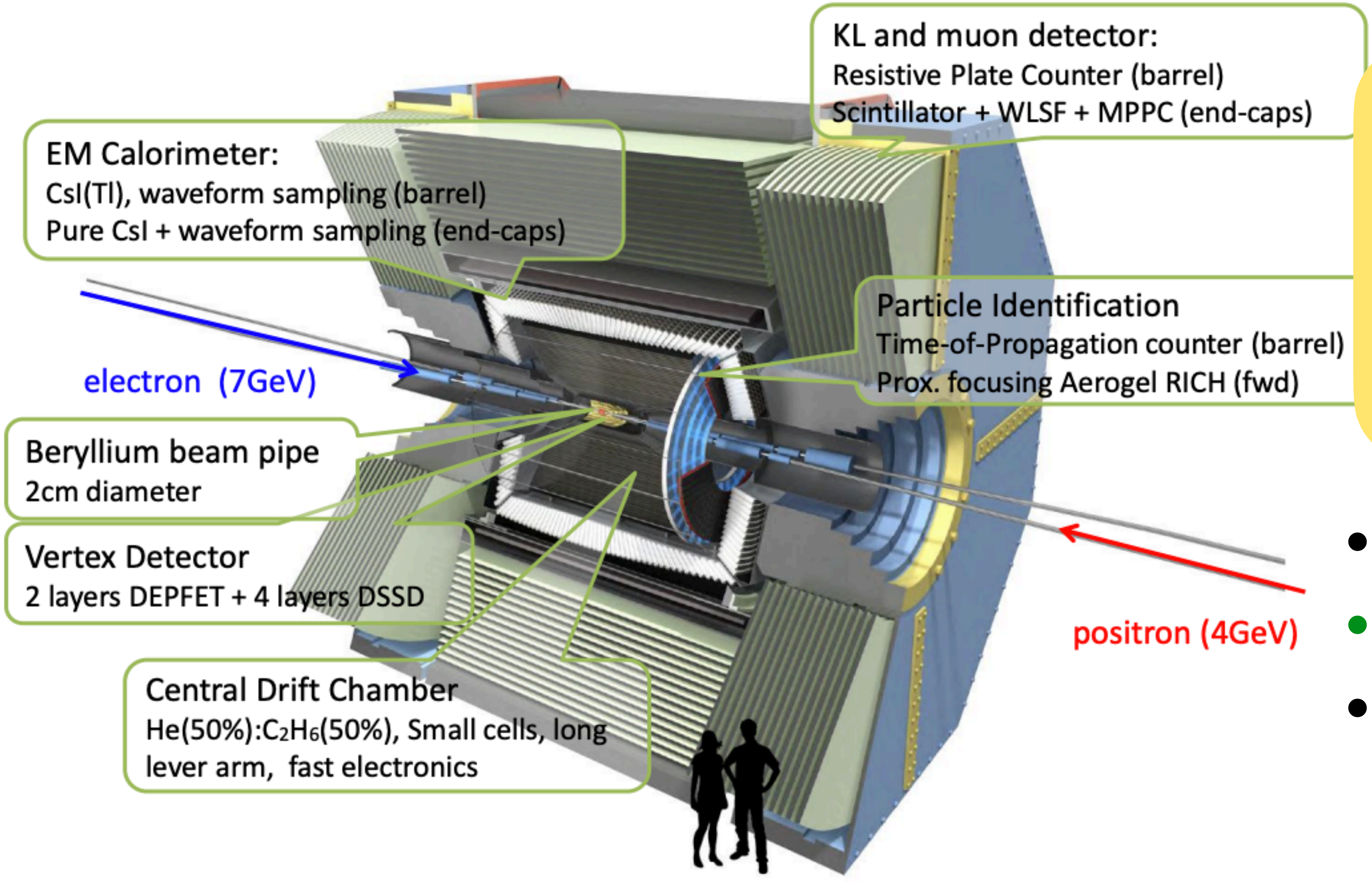
8 GeV e^-, 3.5 GeV e^+



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

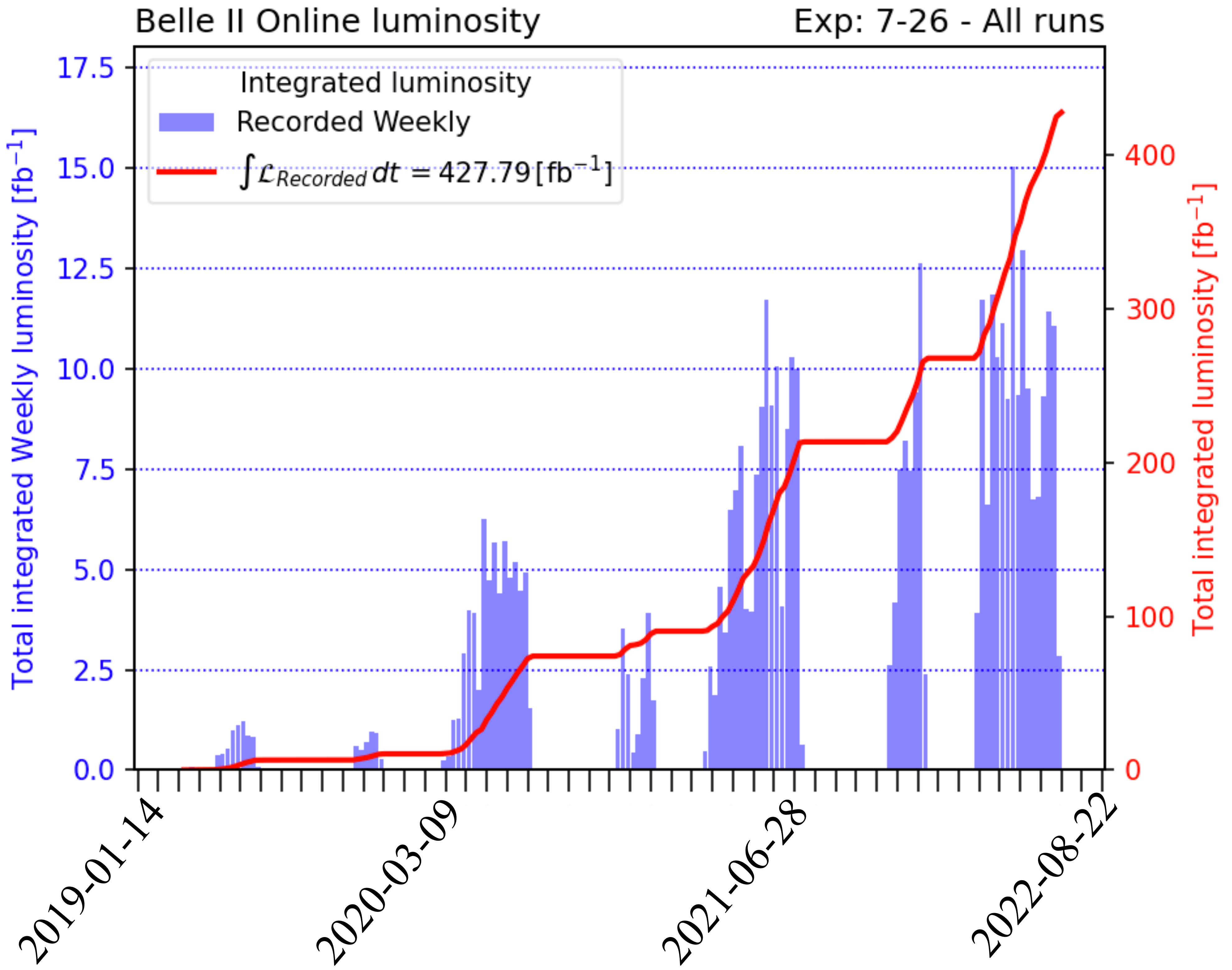
from Belle to The Belle II Detector

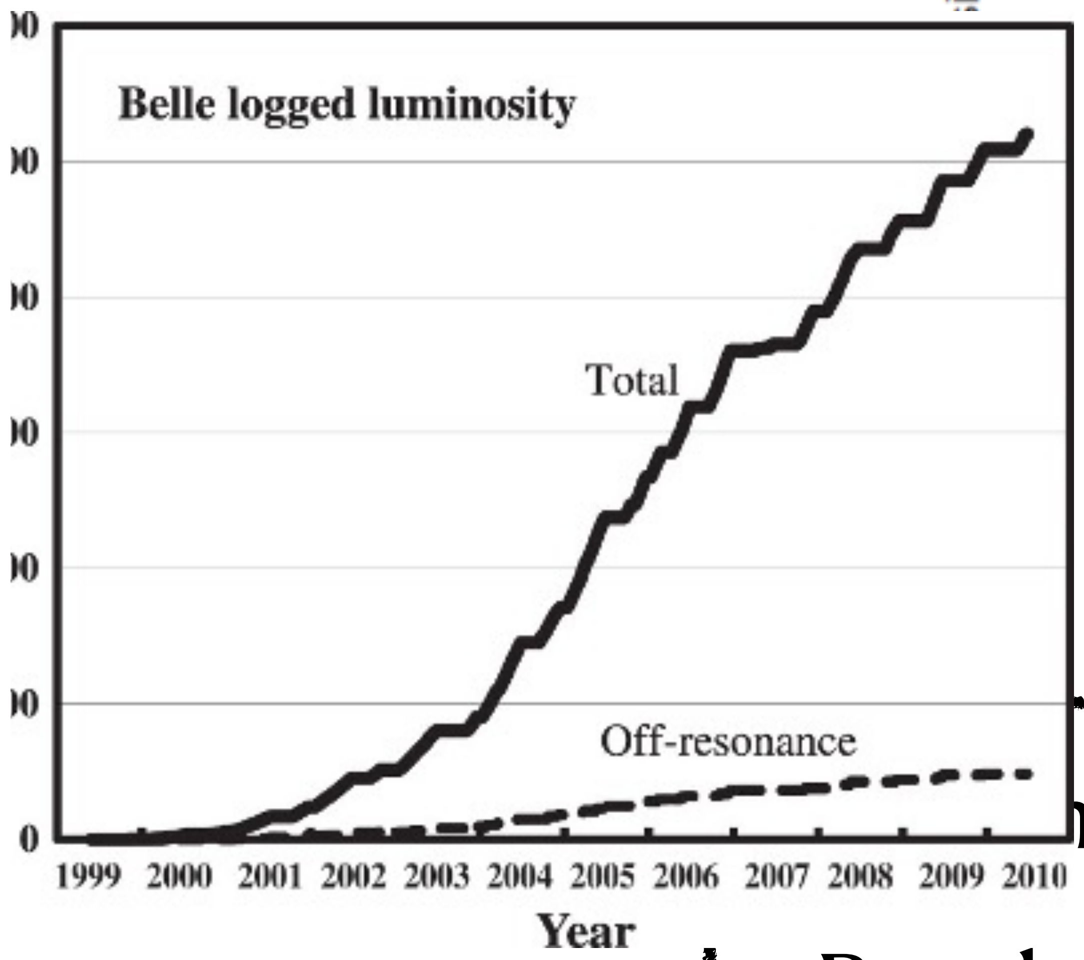
$7 \text{ GeV } e^-$, $4 \text{ GeV } e^+$

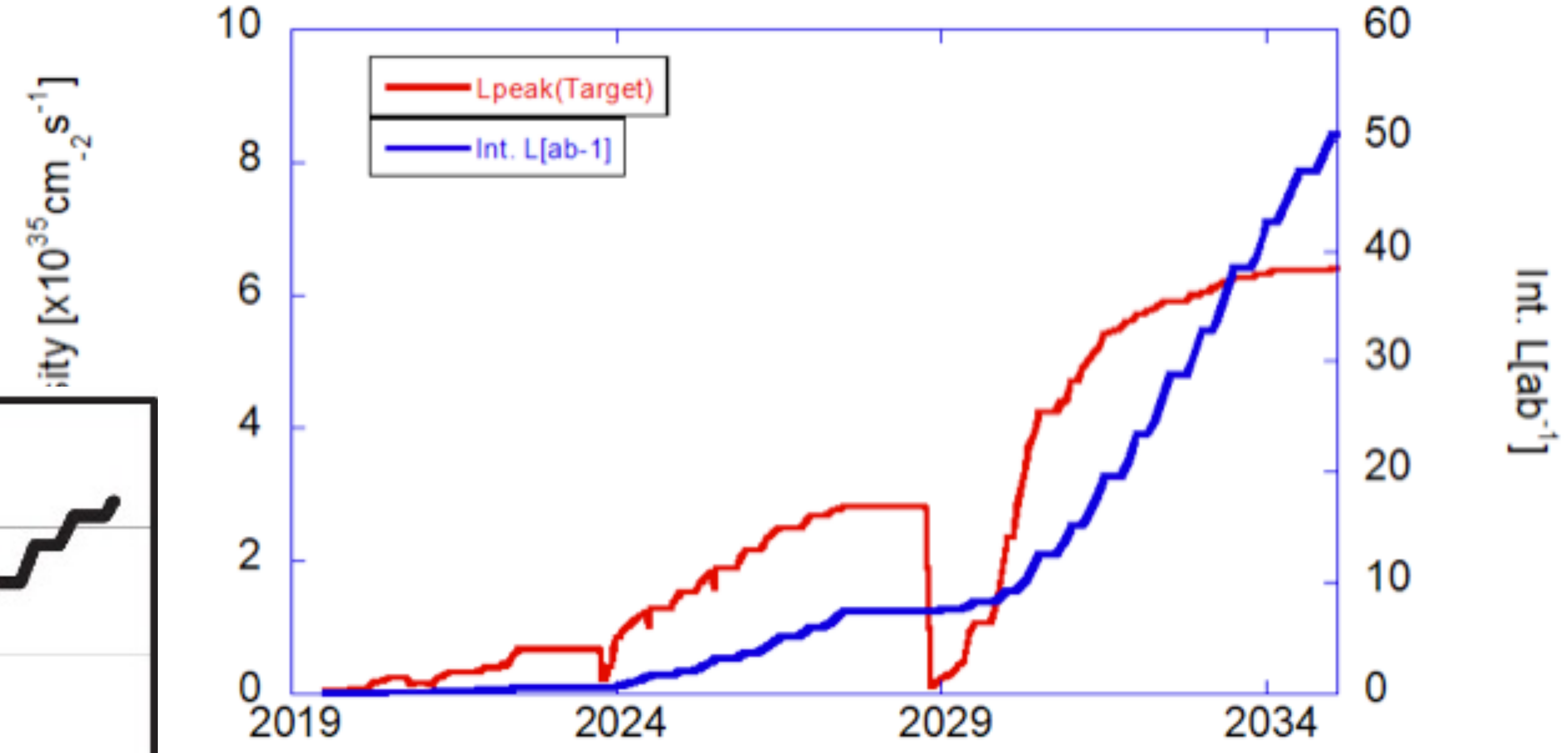


- $\sigma(e^+e^- \to b\bar{b}) = 1.05\ nb$
- $\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\ nb$
- $\Upsilon(nS)\epsilon[n = 1,..,5]$, use of off resonance data : B factories are also τ factories

Luminosity





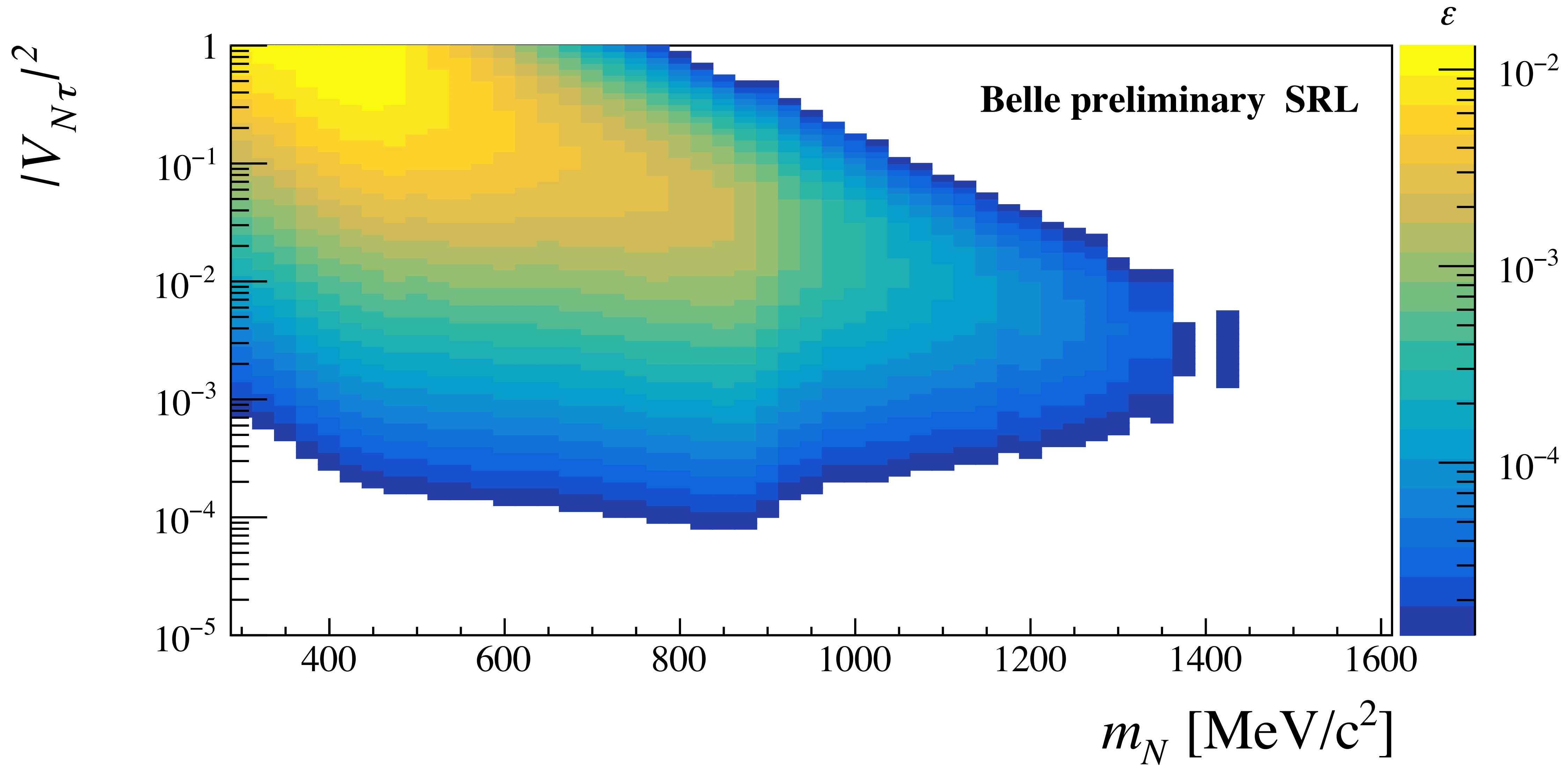


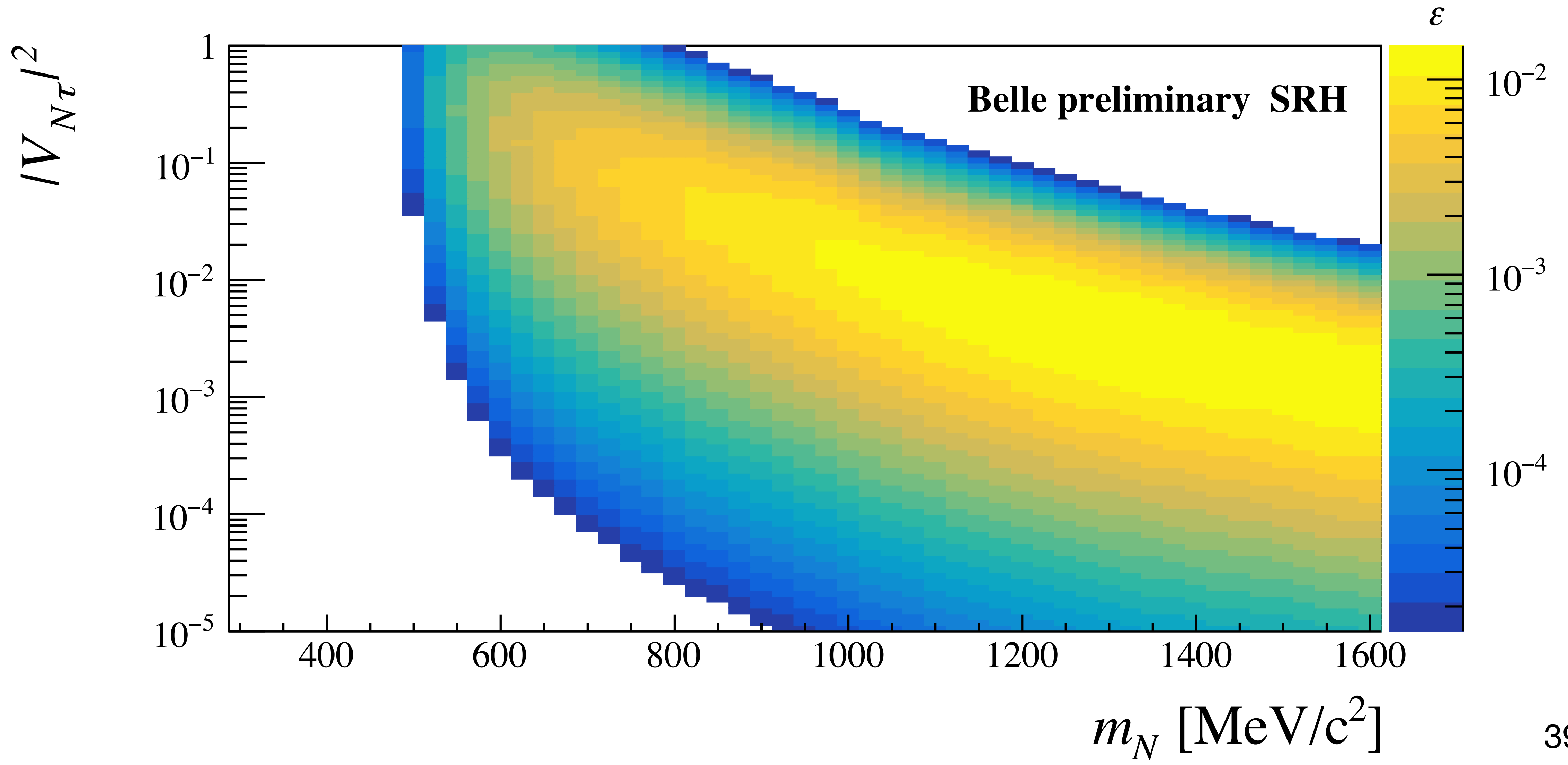
n integrated luminosity 50 ab^{-1}

- 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

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
- 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





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