Recent Dark Sector results from Belle and Belle II

Sourav Dey

KEK, Japan

(on behalf of the Belle and Belle II Collaboration)

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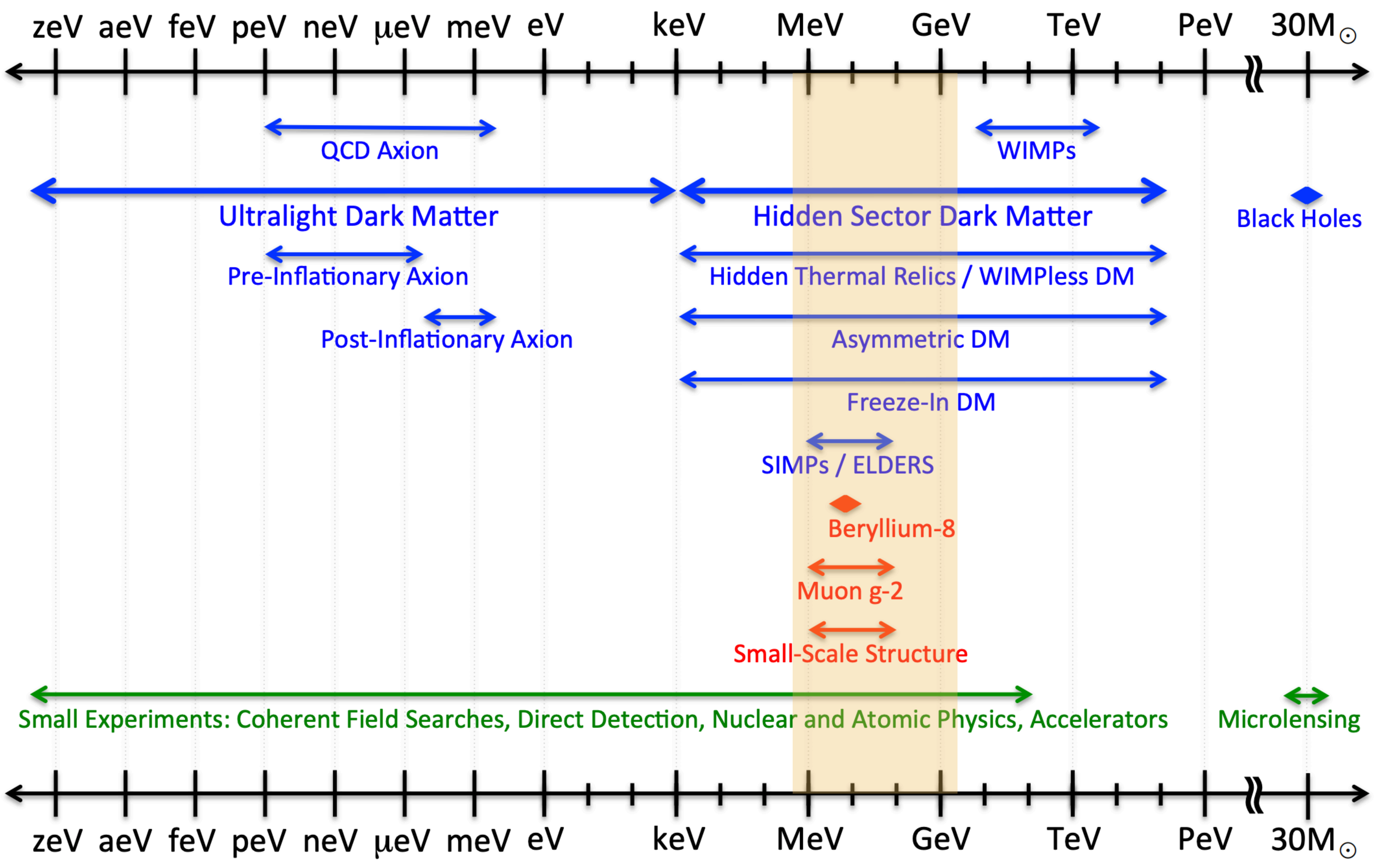
Dark Sector

- DM existence established in astrophysics, e.g. rotation curves of spiral galaxies, bullet clusters, ...
- No dark matter candidate in the Standard Model (SM)
  - One of the most convincing indications of new physics

- Sub-GeV Light Mediator portals:
  - Vector portal Dark Photons, Z' bosons
  - Pseudo-scalar portal Axion Like Particles (ALPs)
  - Scalar portal Dark Higgs / Scalars
  - Neutrino portal Sterile neutrinos

One from each covered in this talk

Dark Sector Candidates, Anomalies, and Search Techniques



Belle II

Light Dark Sectors

Dark Sector searches in Belle and Belle II

Vector portal Dark Photons, Z' bosons

- $e^+e^- \to \mu^+\mu^- Z', Z' \to$ invisible (Invisible: neutrino , dark matter)(Belle II : PRL 130.231801)
- $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$(Belle II : arXiv 2306.12294)
- $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$(Belle II : arXiv 2403.02841)

Pseudo-scalar portal Axion Like Particles (ALPs)

- $e^+e^- \to \gamma a, a \to \gamma\gamma$(Belle II : PRL 125.161806)
- $\tau \to l\alpha, \alpha$ invisible(Belle II : PRL 130.181803)

Scalar portal Dark Higgs / Scalars

- $e^+e^- \to \tau^+\tau^- l^+ l^-$(Belle : PRD 109.032002)
- $e^+e^- \to \mu^+\mu^-$ + invisible h'(Belle II : PRL 130.071804)

Neutrino portal Sterile neutrinos

- $\tau \to \pi N(\to \mu^+\mu^-\nu_\tau)$(Belle : arXiv 2402.02580)

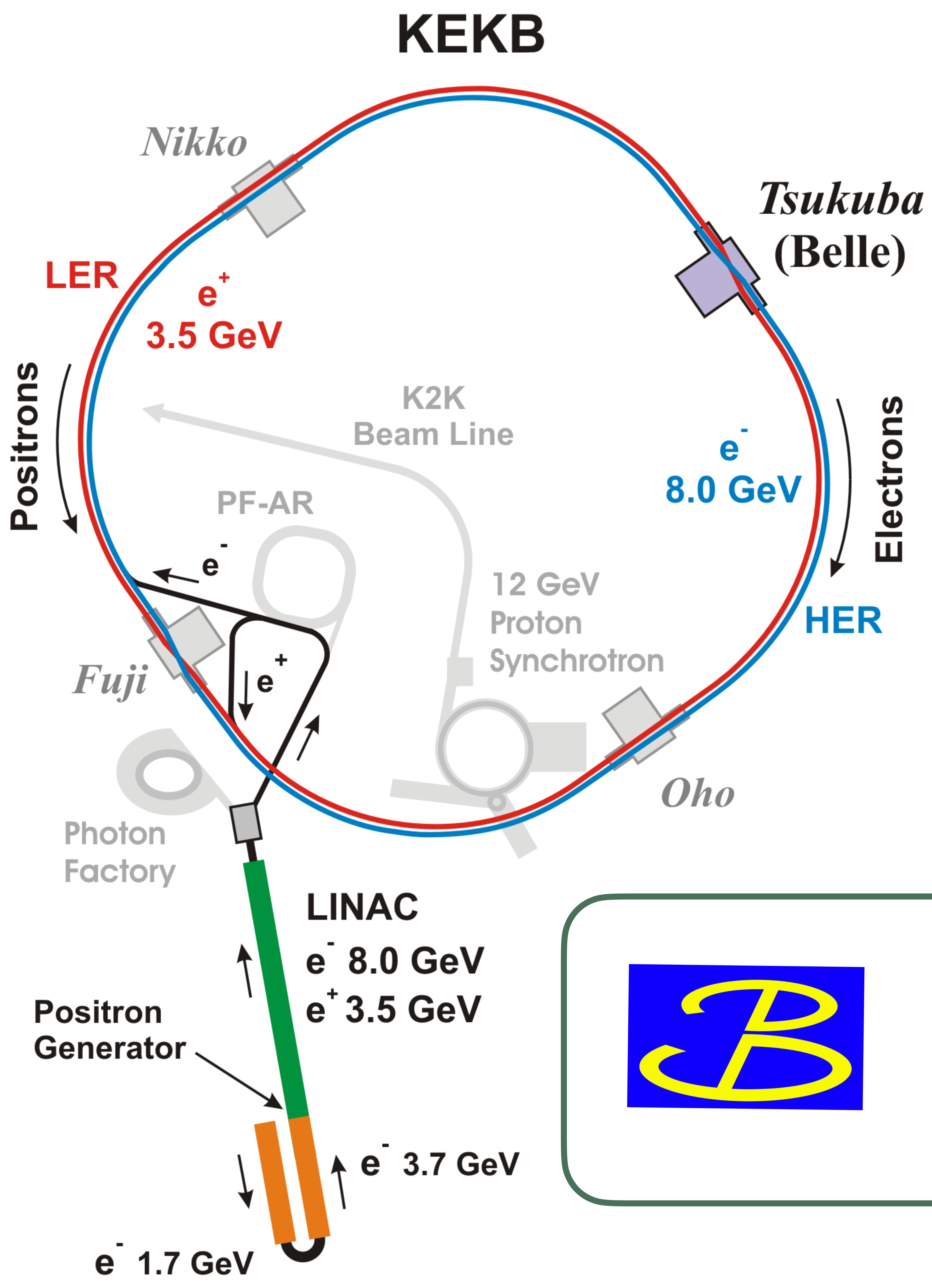
Analyses covered in this talk

Search for lepton-flavor-violating $\tau^- \to \mu^-\mu^+\mu^-$ decays at Belle II (To be submitted to JHEP) arXiv 2405.07386

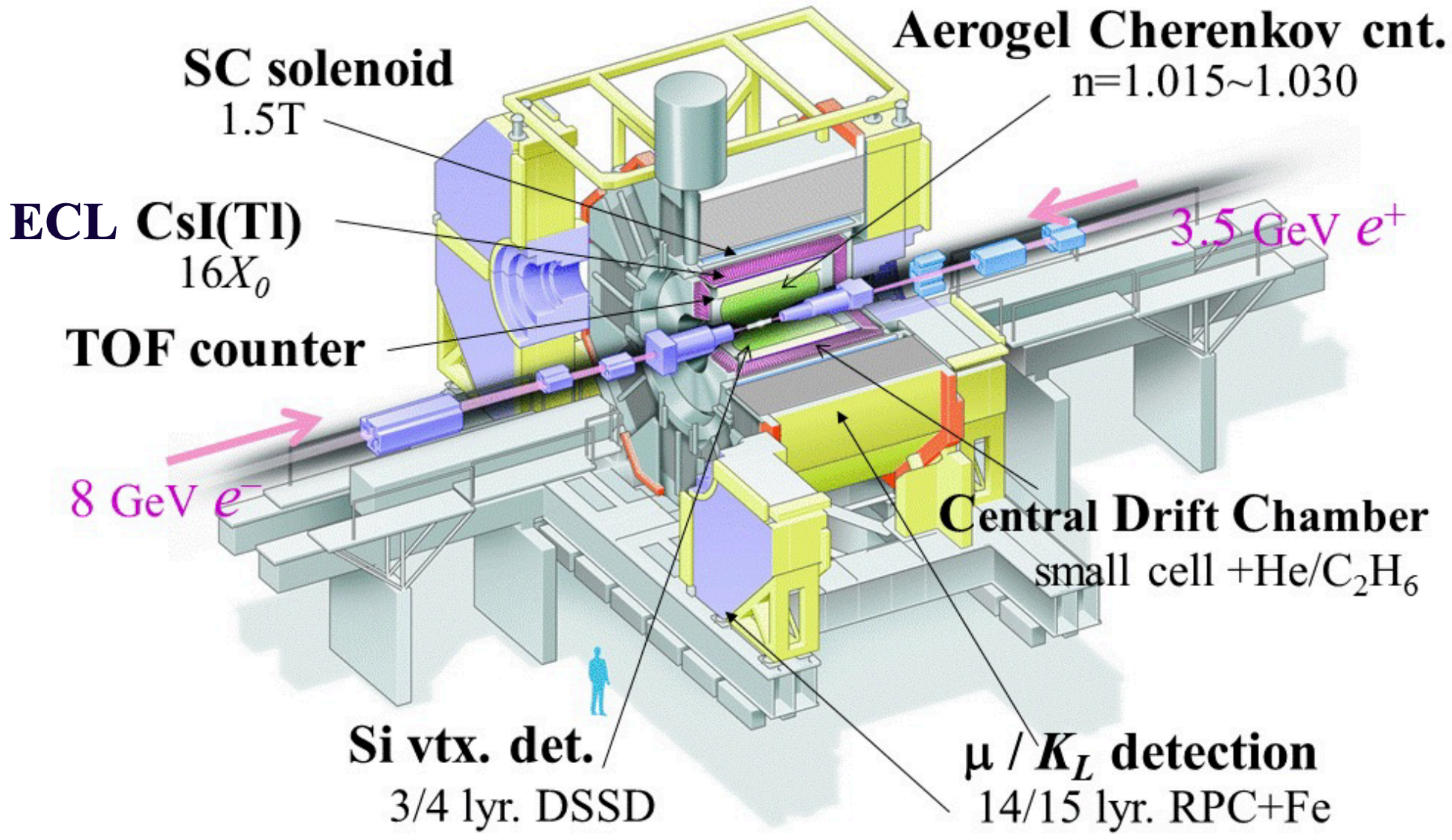
Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II (Submitted to PRD) arXiv 2403.02841

Search for a heavy neutral lepton that mixes predominantly with the tau neutrino (Submitted to PRD(L)) arXiv 2402.02580

The KEKB and the Belle Detector



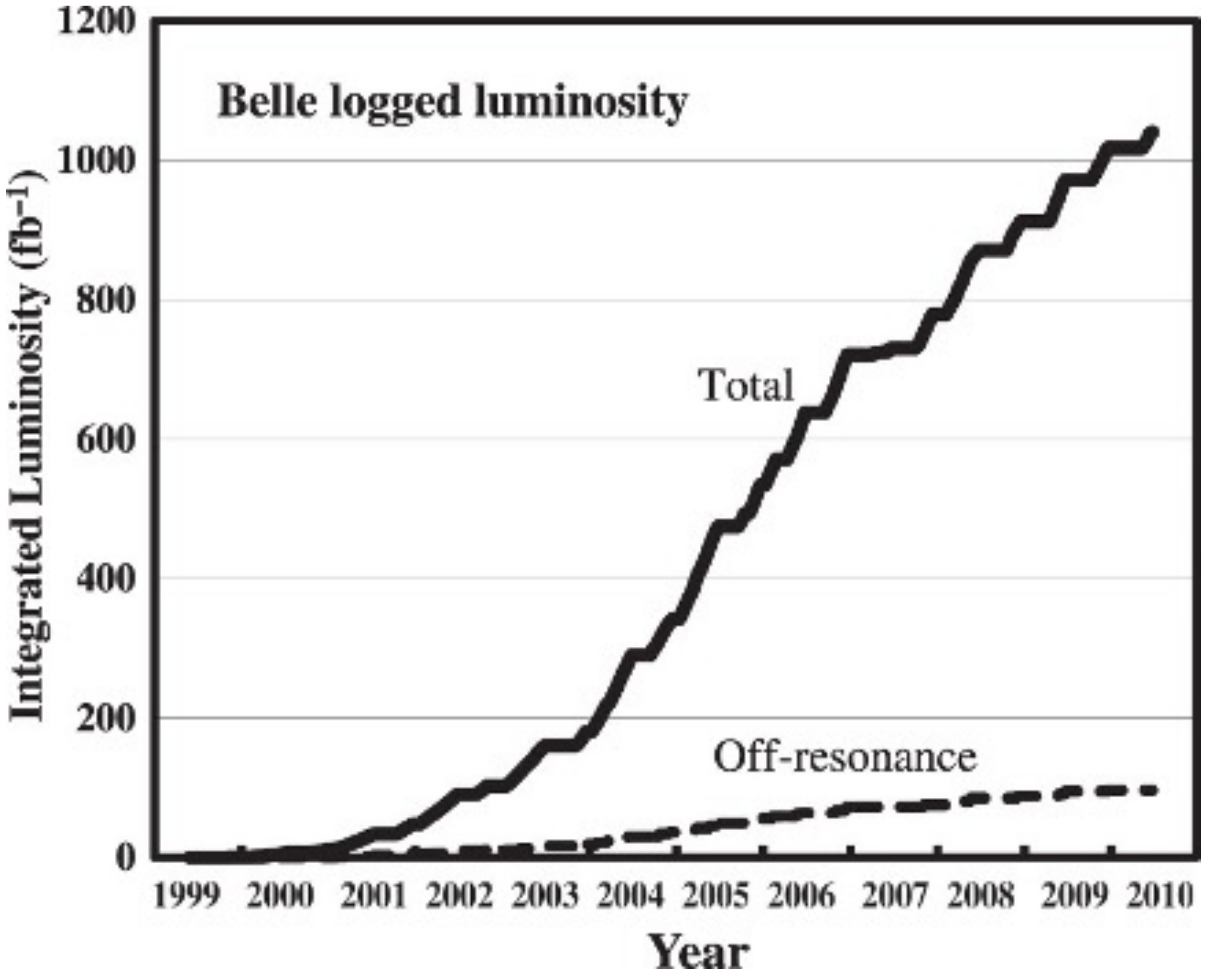
$8\ \mathrm{GeV}\ e^-$, $3.5\ \mathrm{GeV}\ e^+$



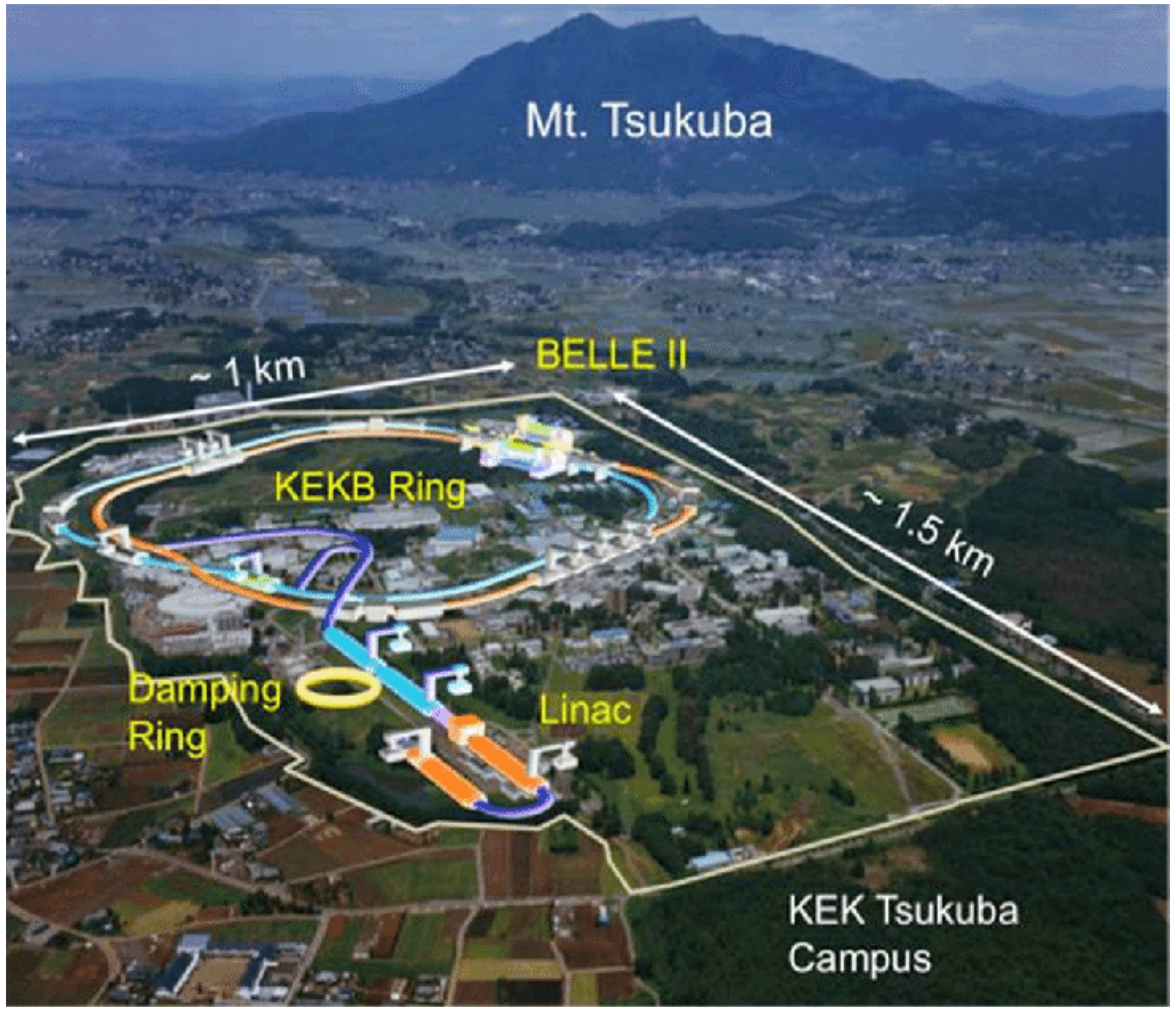
- $\sqrt{s} = 10.58$ GeV : mass of $\Upsilon(4S)$
- asymmetric collider
- Prospect for studying a vast region of particle physics (Precision studies of B, charm, and tau physics, QCD and exotic hadrons, searches for BSM particles etc.)

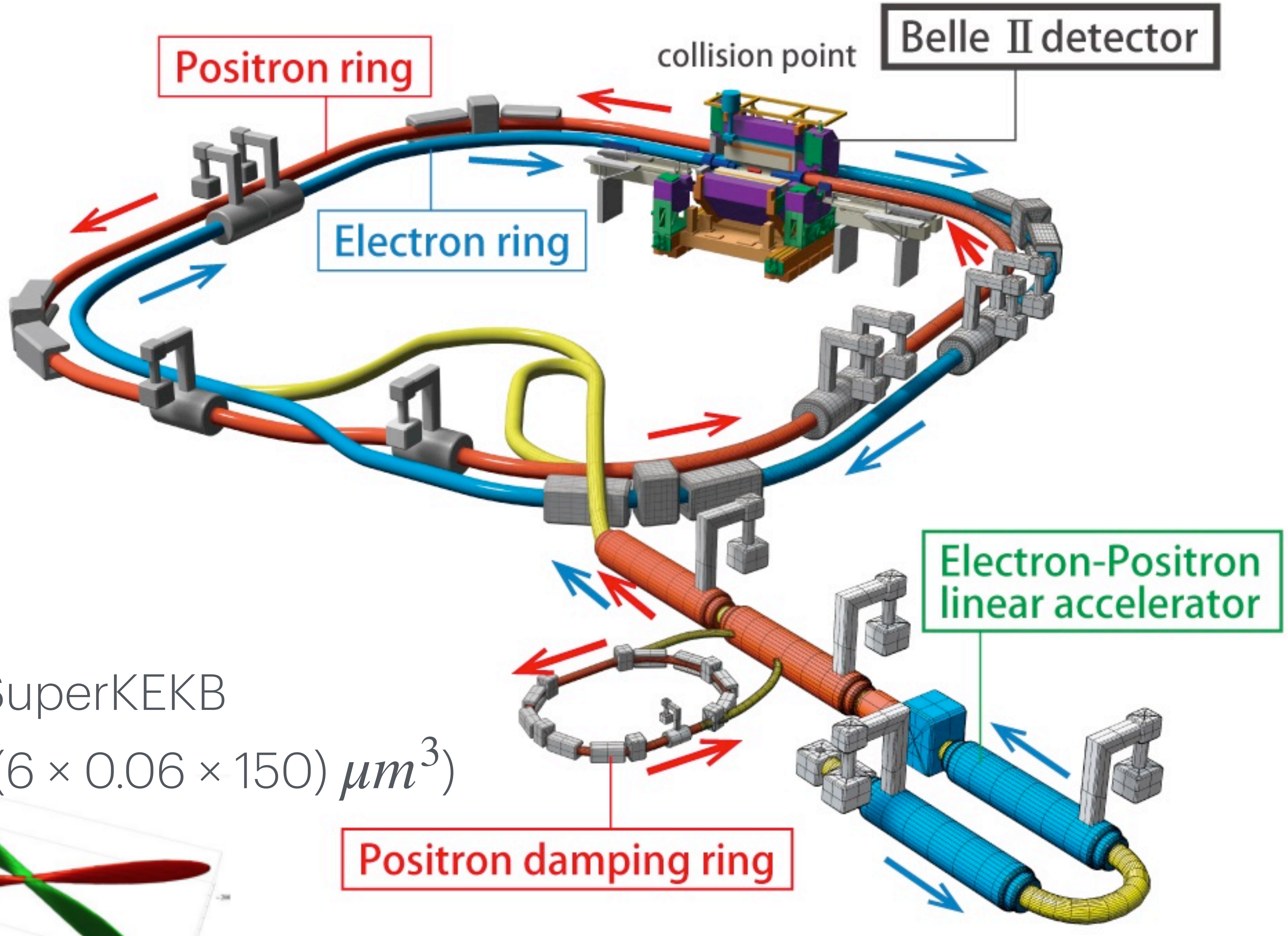
Luminosity

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



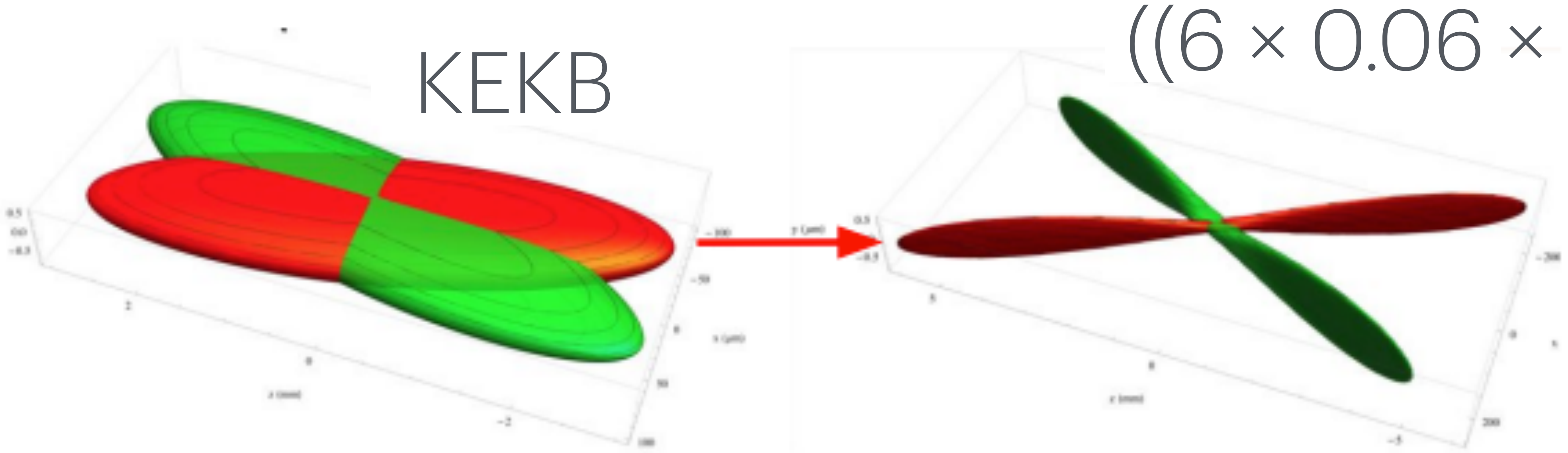
The SuperKEKB and the Belle II Detector



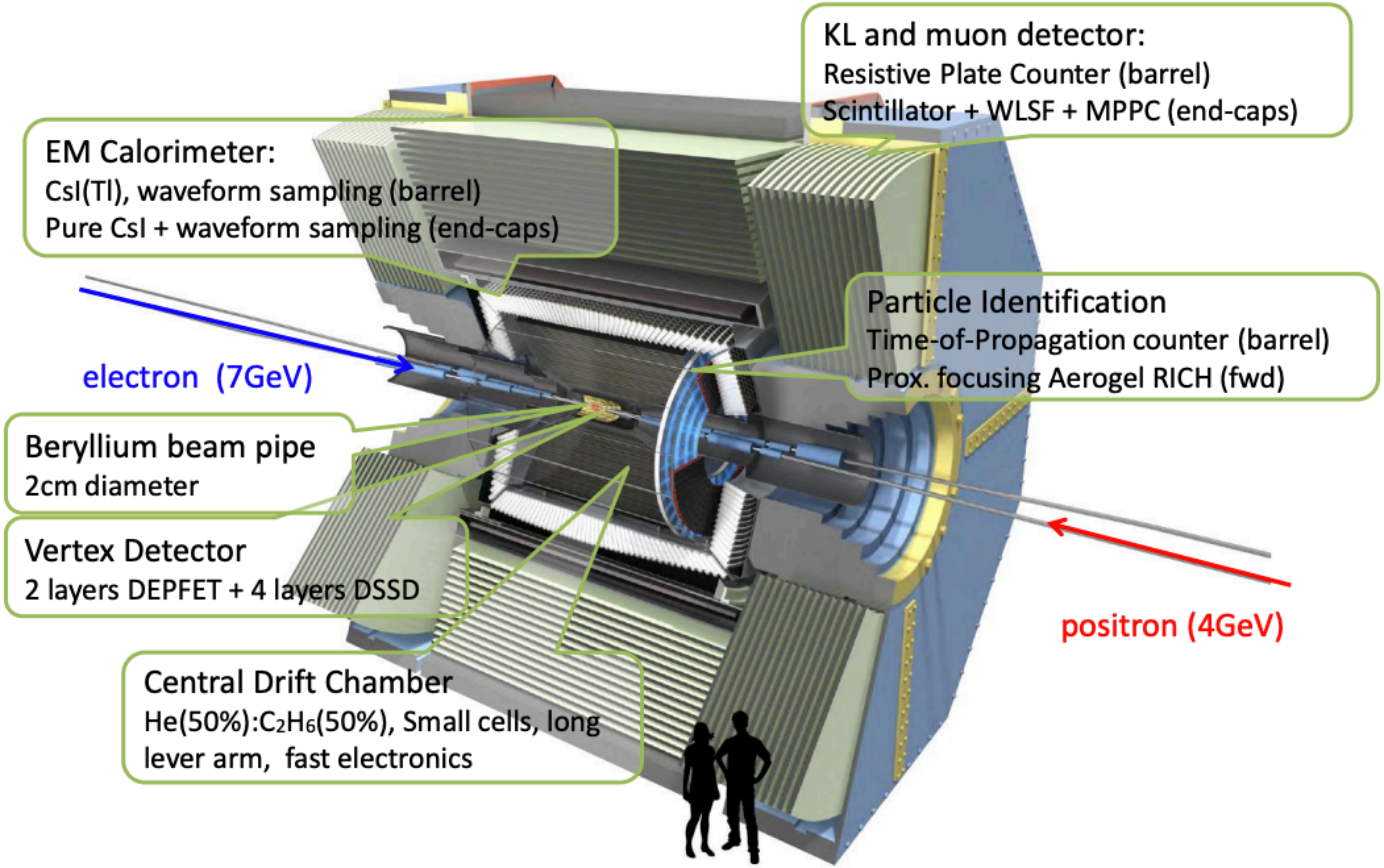


SuperKEKB
$((6 \times 0.06 \times 150)\ \mu m^3)$

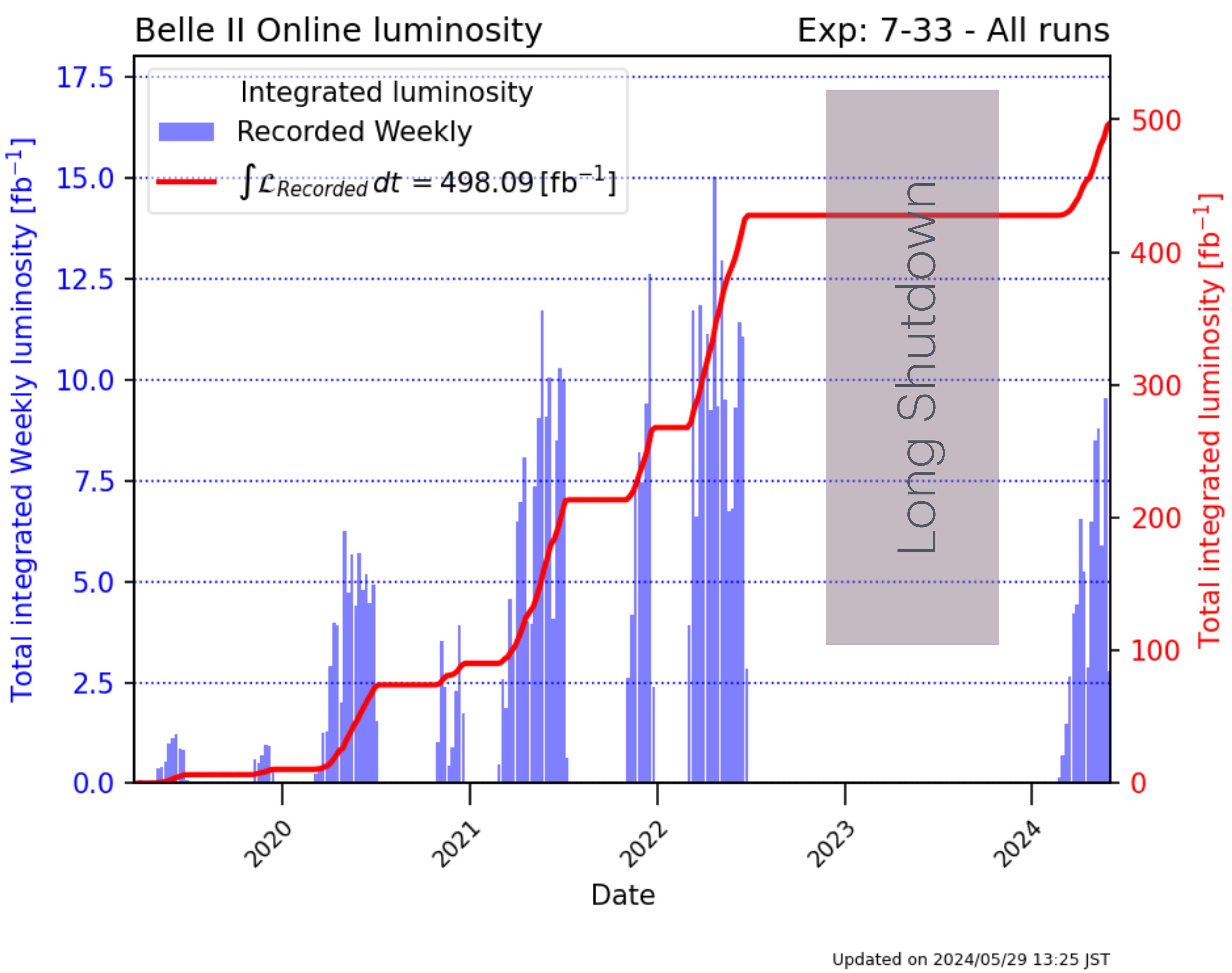
KEKB

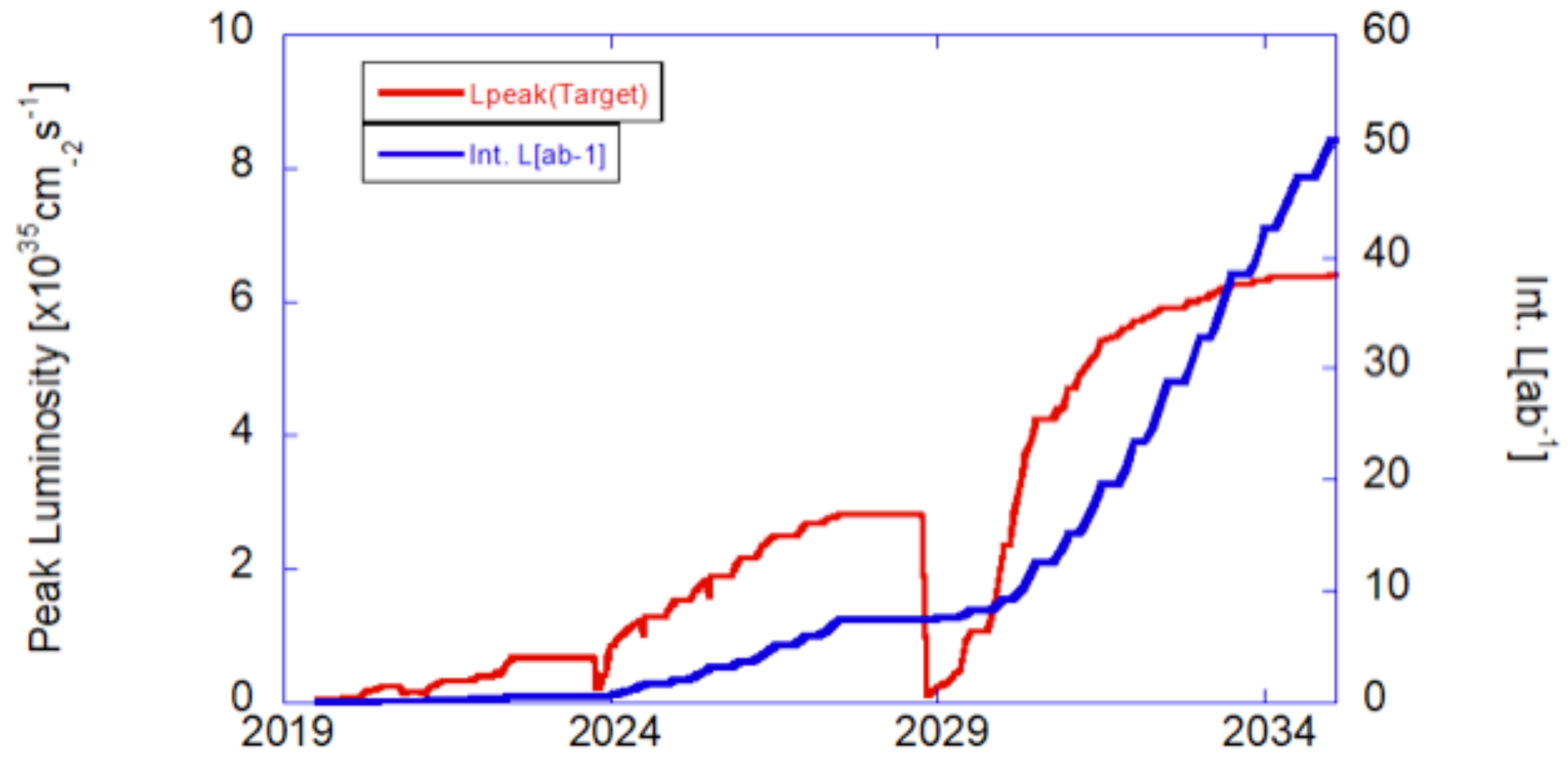


the Belle II Detector



Luminosity



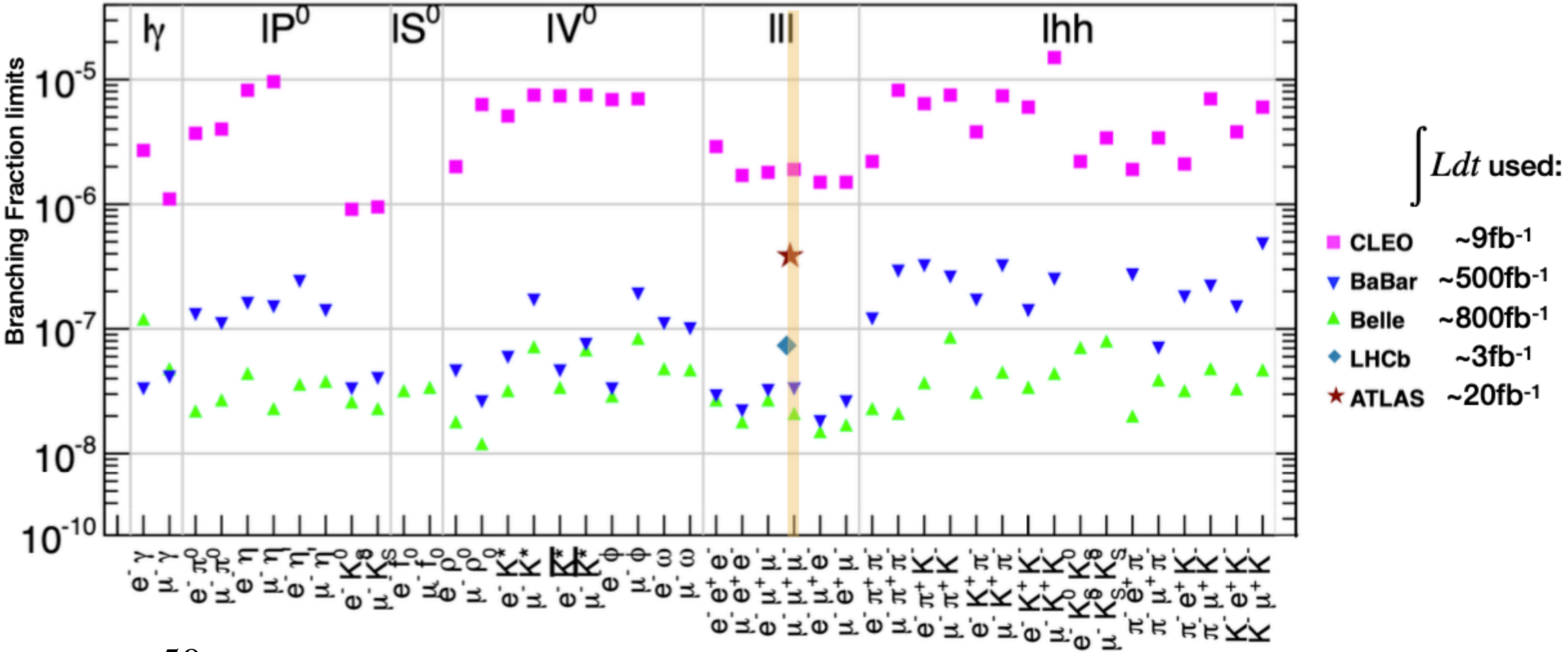


- Design integrated luminosity 50 ab^{-1}
- Regular data-taking since April 2019
- At present, we are taking data
- Current integrated luminosity 498 fb^{-1}

$\tau \to \mu^-\mu^+\mu^-$: Motivation

DATA used: 424 fb^{-1}, 389 M $e^+e^- \to \tau^+\tau^-$ events

- Lepton Flavor Violation (LFV) is allowed in various extensions of the Standard Model (SM) but it has never been observed



- Predicted LVF rates 10^{-50} , with neutrino mixing, well below the sensitivities of any experiment.
- The observation of LFV decays would, therefore, provide indisputable evidence of physics beyond the SM.
- Previous searches: Belle, CLEO, BaBar, LHCb, ATLAS and CMS

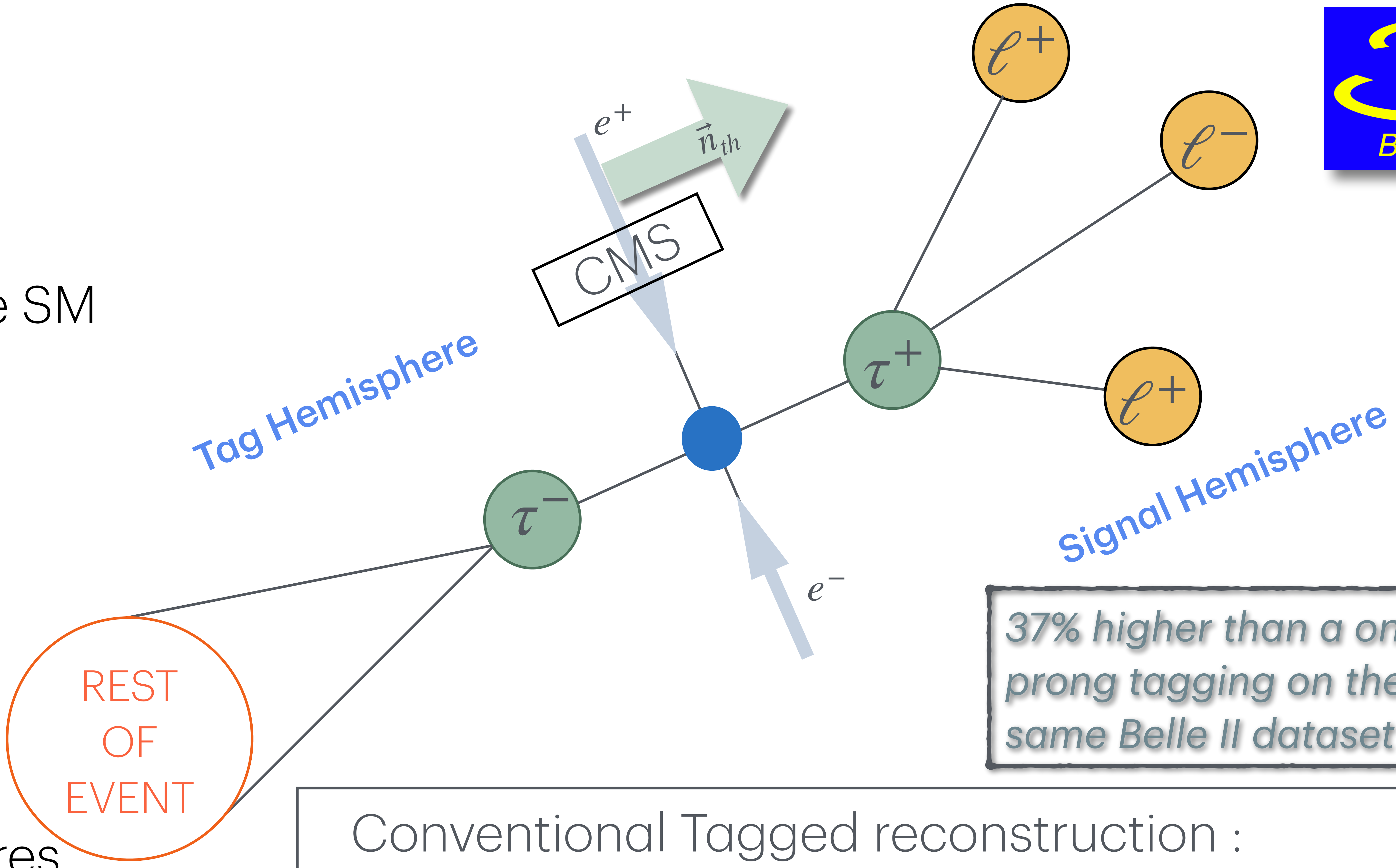
Not a dark sector analysis

$\tau \to \mu^-\mu^+\mu^-$: Analysis Method

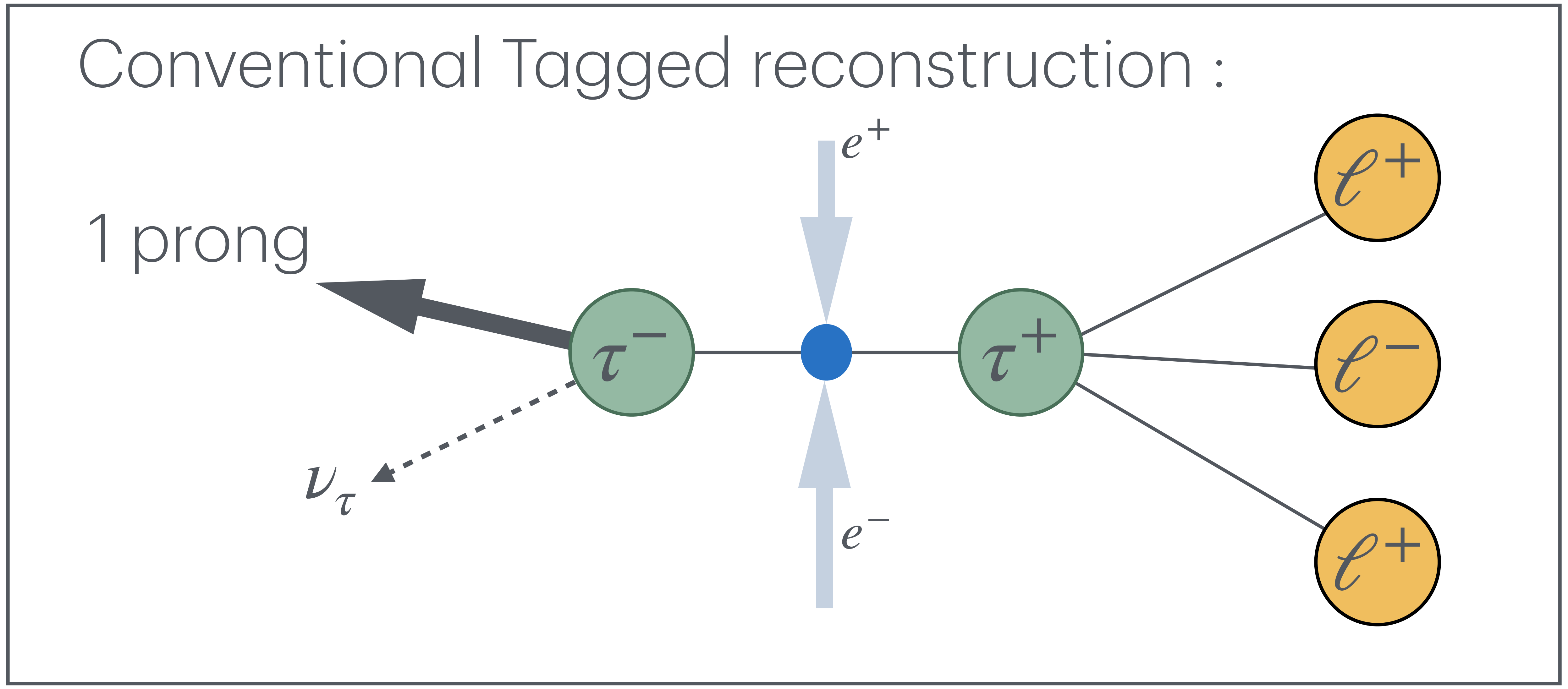
- We cannot fully reconstruct τ in the SM due to neutrinos
- We use thrust axis $\vec{n}_{th}$.
  - $\vec{n}_{th}$ is defined such that V_{th} is maximized

$$V_{th} = \frac{\Sigma_i |\vec{p}_i^{\,CM} . \vec{n}_{th}|}{\Sigma_i |\vec{p}_i^{\,CM}|}$$

- Event is divided into two hemispheres
- Inclusive (or untagged) reconstruction : signal τ is reconstructed into three muons, all the other tracks and clusters are used to form a Rest-of-Event (ROE)
  - Selection and background rejection based on BDT

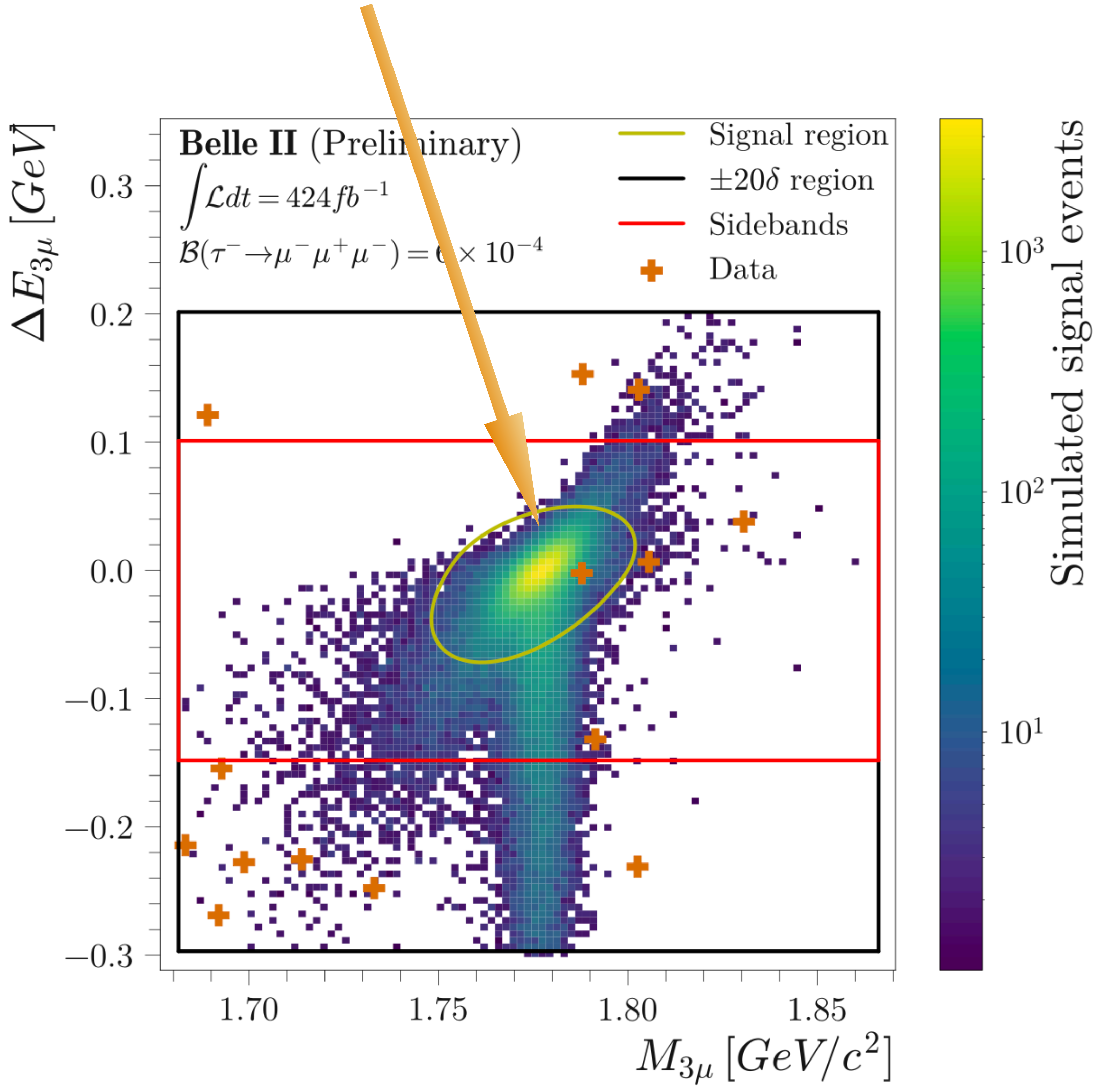


37% higher than a one-prong tagging on the same Belle II dataset



$\tau \rightarrow \mu^-\mu^+\mu^-$

- We observe one event in the signal region



- Tight signal region: large background reduction using $\Delta E_{3\mu} \equiv E_{\tau sig} - E_{beam}$ and $M_{3\mu}$
- Backgrounds arise from:
  - radiative dilepton and four-lepton final states (low-multiplicity backgrounds) with potential electrons misidentified as muons,
  - incorrectly reconstructed SM $e^+e^- \rightarrow \tau^+\tau^-$ events
  - continuum hadronization processes from $e^+e^- \rightarrow q\bar{q}$ events, where pions are misidentified as muons.
- Background events suppressed with selection cuts and boosted decision tree classifier
- Dominant systematics from lepton ID efficiency : Negligible impact on the limit

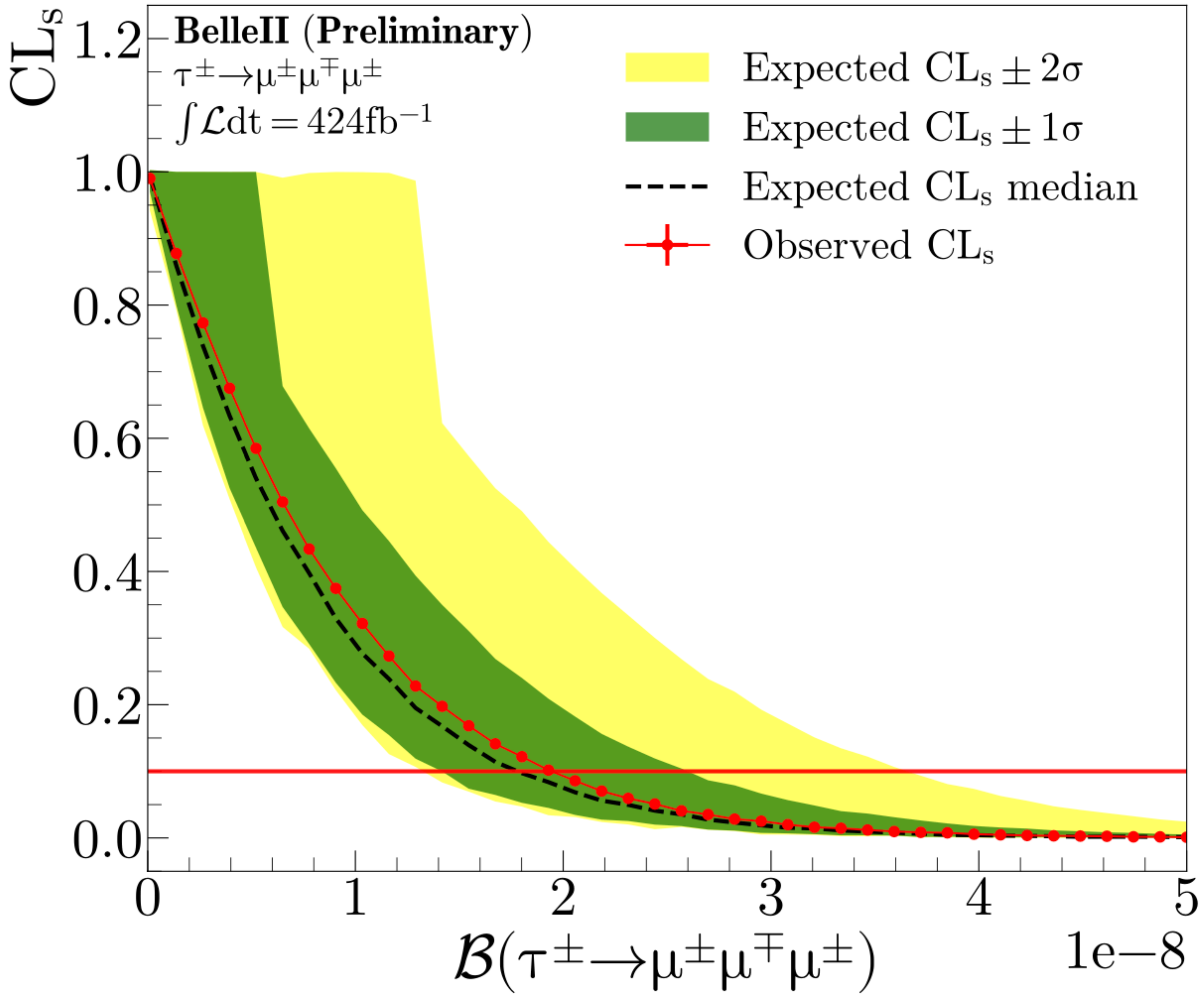
$\tau \to \mu^-\mu^+\mu^-$: Result

DATA used: 424 fb^{-1}, 389 M $e^+e^- \to \tau^+\tau^-$ events

Previous Belle result :
2.1×10^{-8}@90% CL with 782 fb^{-1}

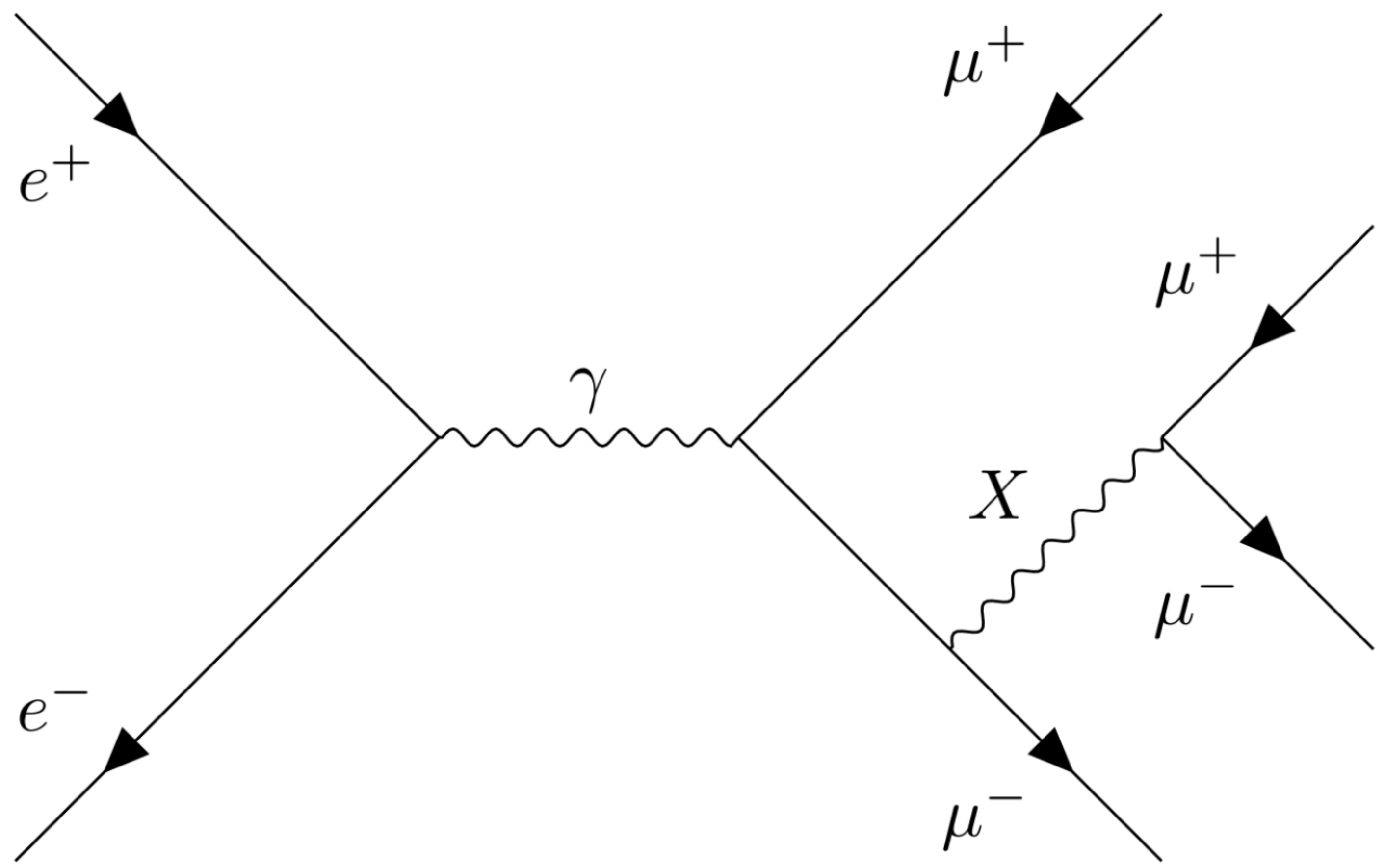
Belle II result(observed limit) : 1.9×10^{-8}@90% CL

- We compute a 90% confidence level (CL) upper limit on the branching fraction
- 2.5 times the efficiency than in the latest Belle analysis
- Most stringent bound to date



DATA used: 178 fb^{-1}

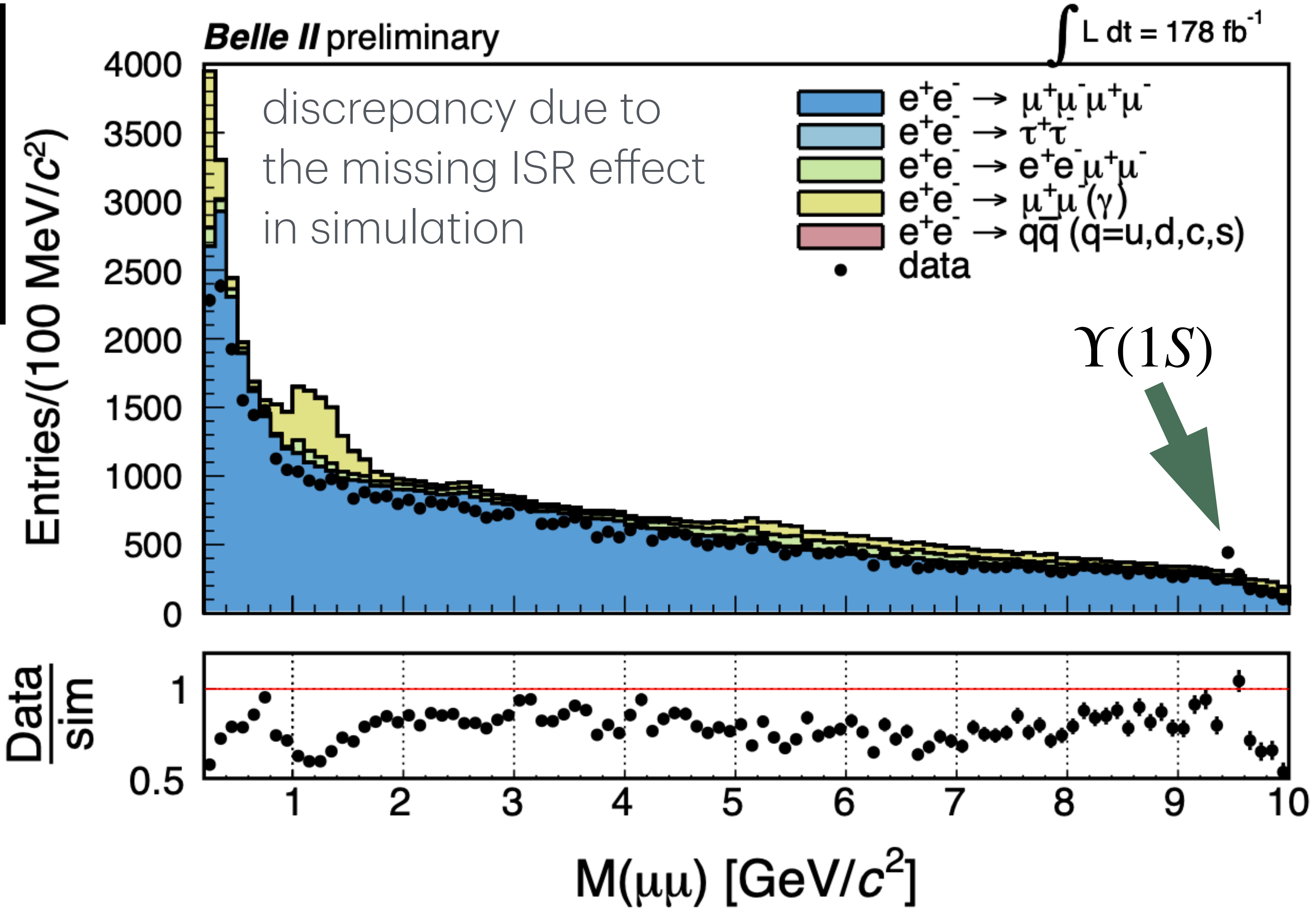
$\mu^+\mu^-$ resonance in four-muon final state



- Search for the process $e^+e^- \to \mu^+\mu^- X$, with $X \to \mu^+\mu^- (X = Z', S)$
  - We look for a peak in the opposite charge di-muon mass distribution in e +e - → μ +μ - μ +μ - events

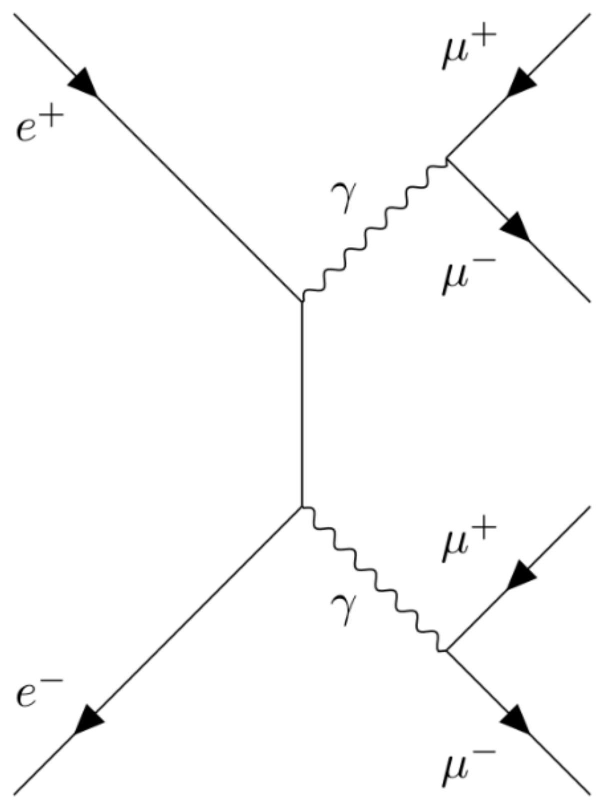
- $(L_\mu - L_\tau)$ model : used as benchmark
- muonphilic dark scalar (S) model : performance checked

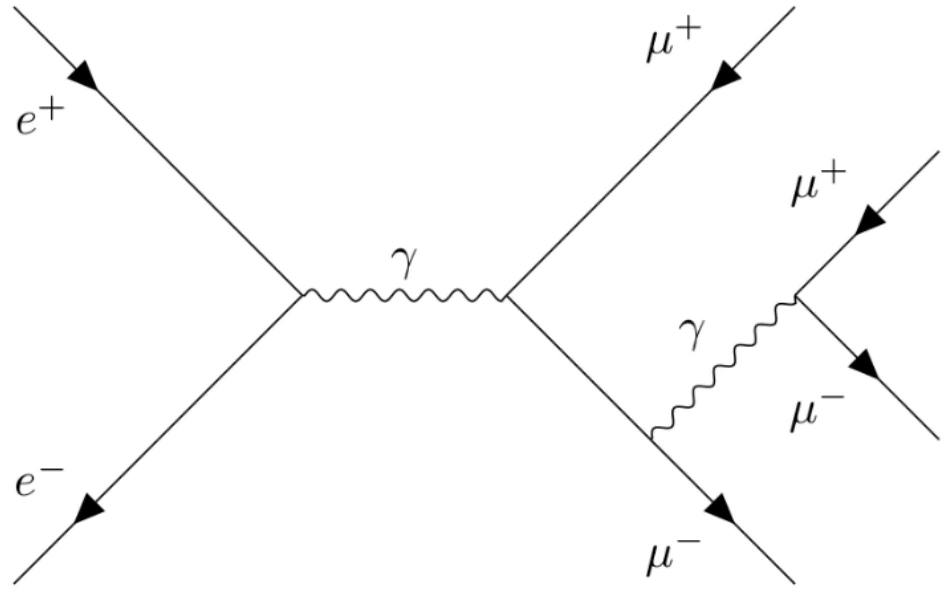
- Events selected have
  - 4 charged particles
  - At least three identified as muons
  - M(4-track) $\sim \sqrt{s}/c^2$
  - No extra energy

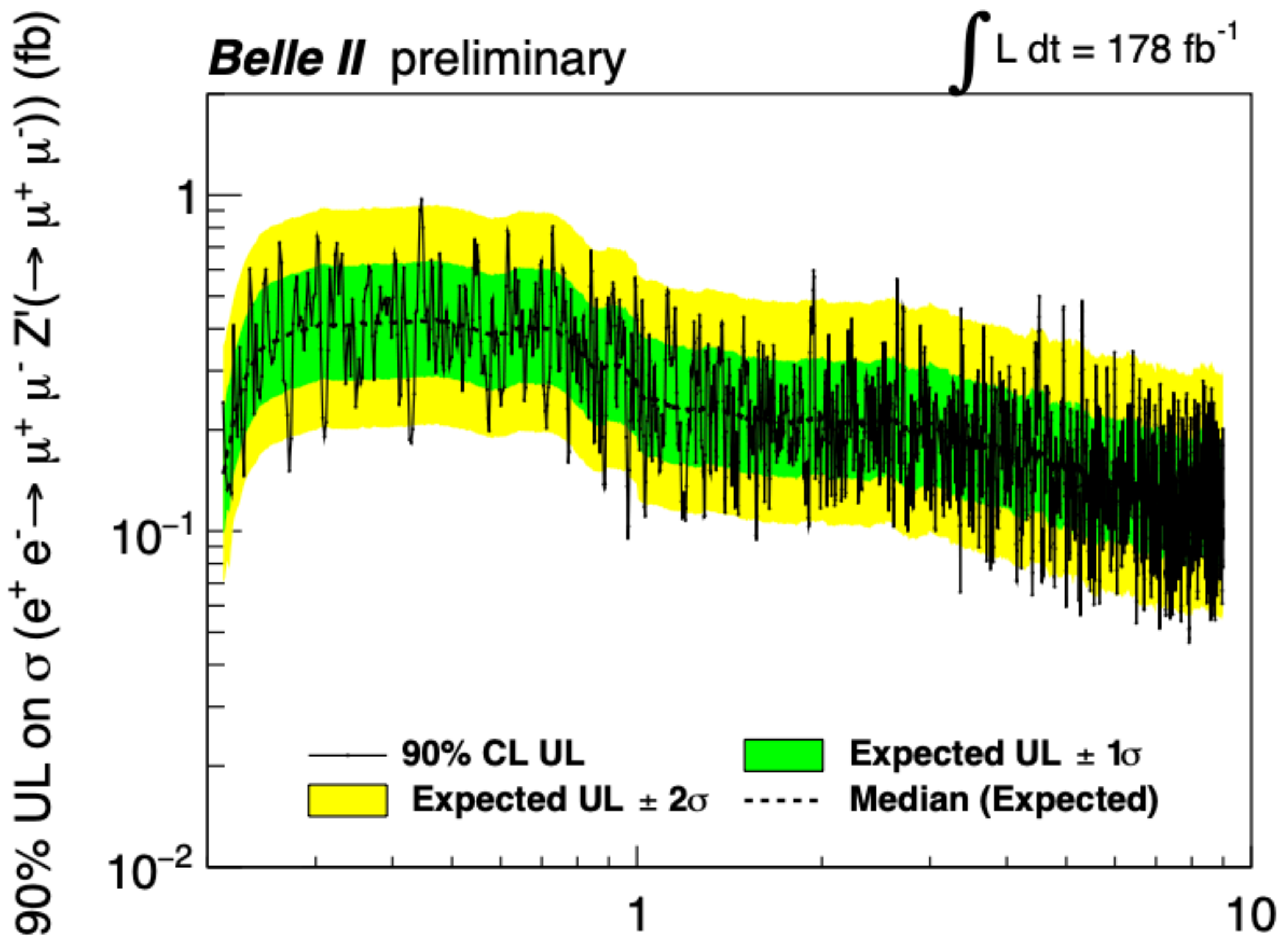


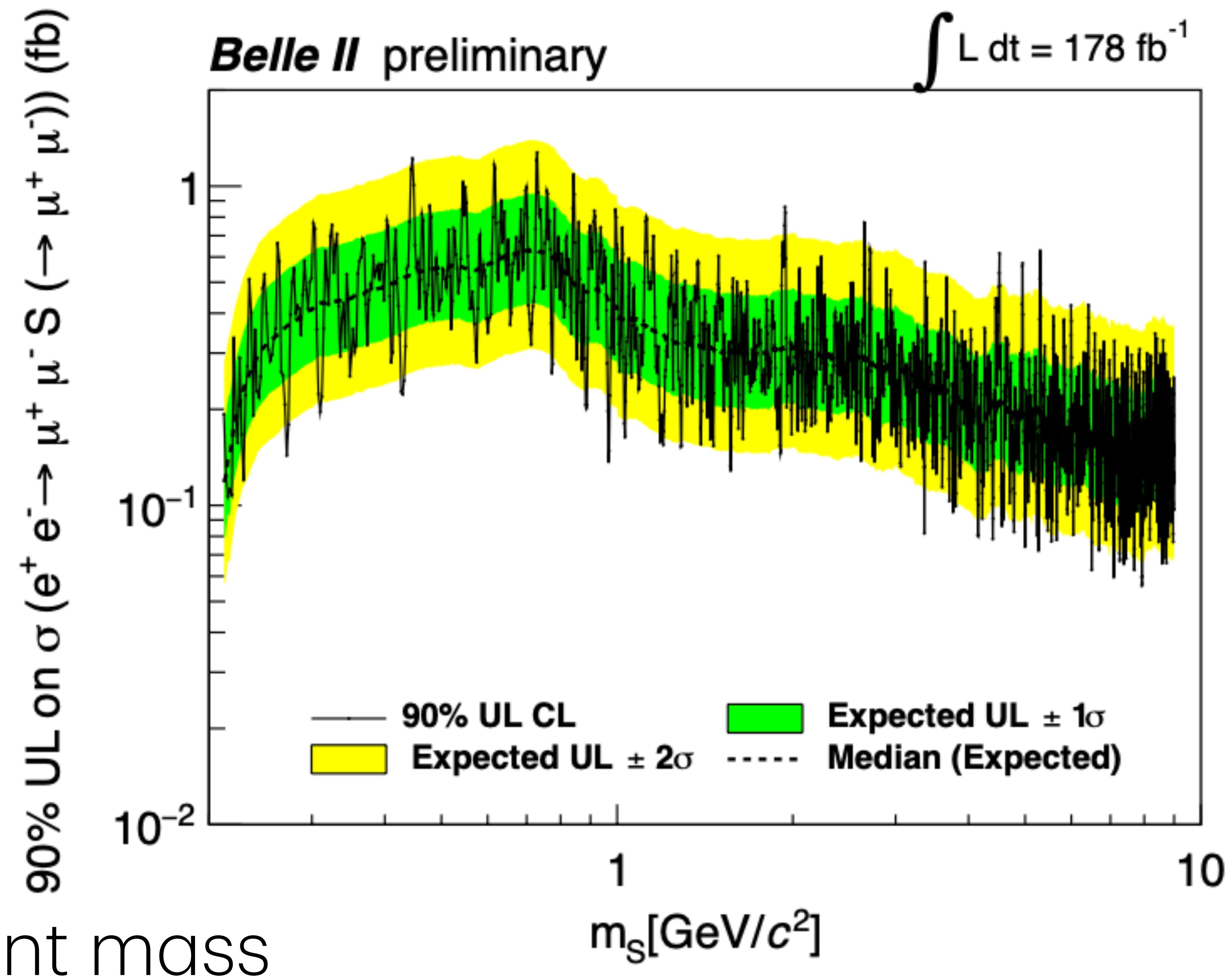
$\mu^+\mu^-$ resonance in four-muon final state

- Dominant background: SM $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$
  - Aggressive background suppression : applying five neural-networks, trained in different mass ranges and exploiting the features of kinematic distributions in signal events (presence of a resonance in both candidate and recoil muon pairs)



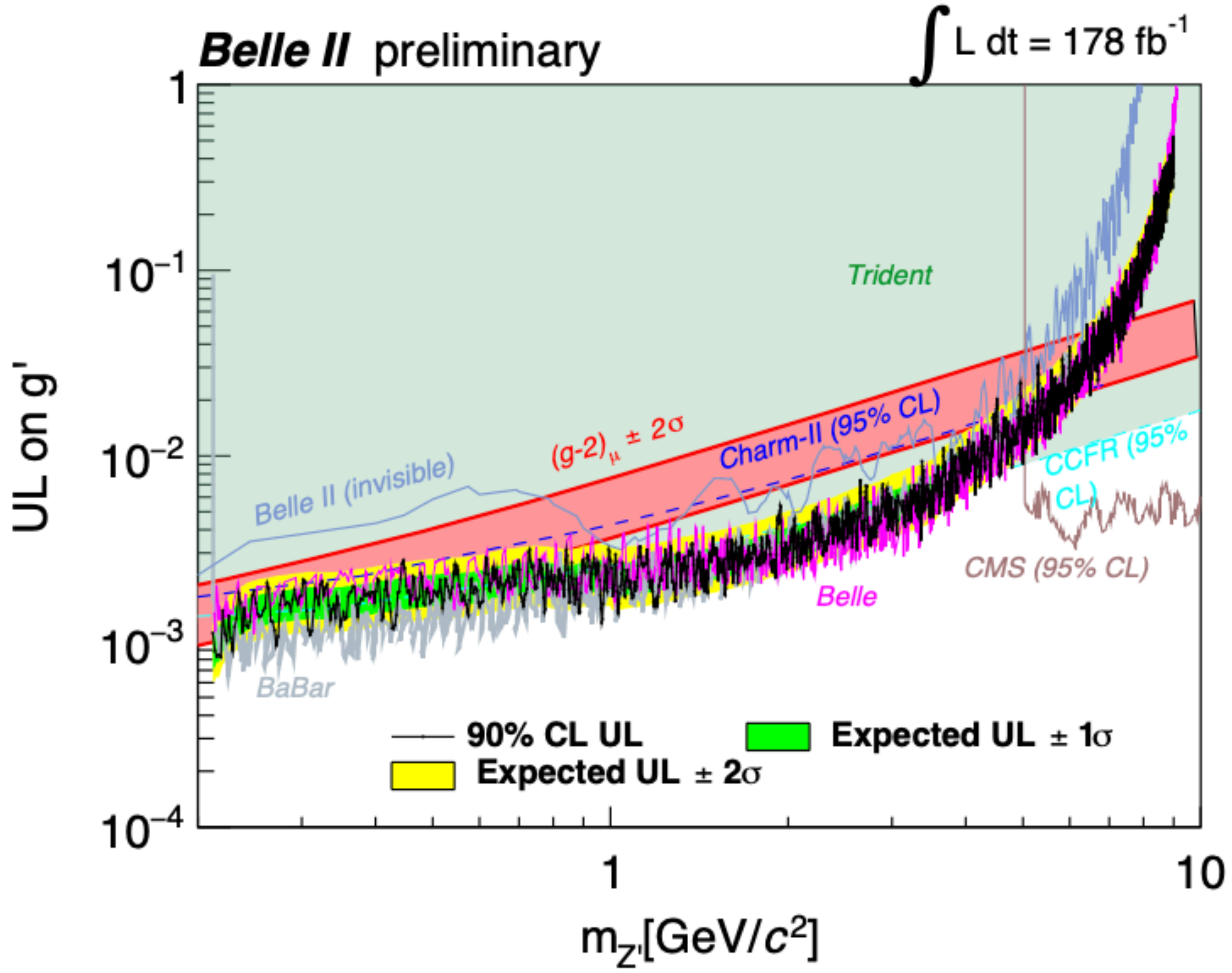


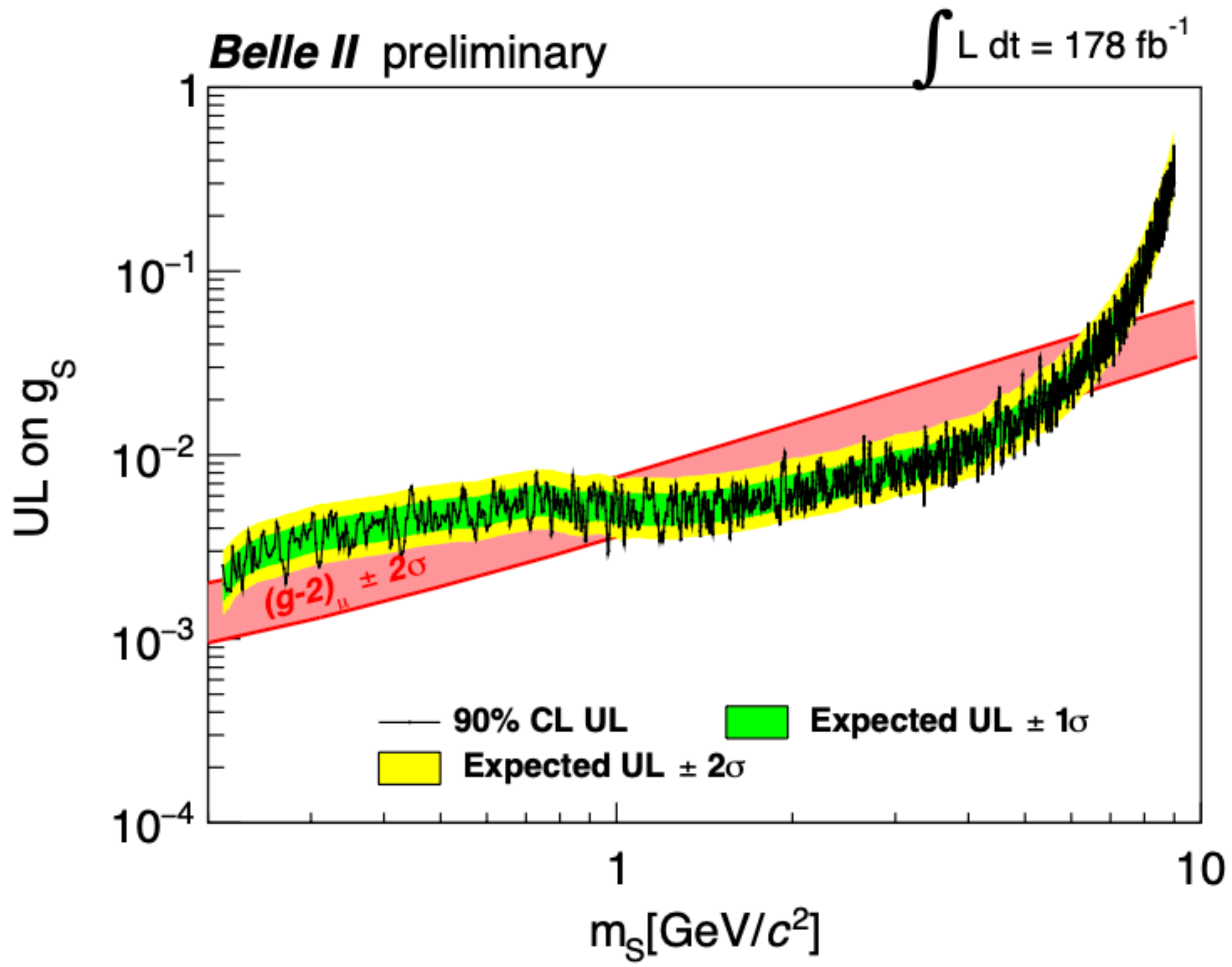




- Unbinned maximum likelihood fits over the dimuon invariant mass
- No significant excess observed in 178 fb^{-1}
- 90% CL upper limits on the process cross-section $\sigma(e^+e^- \to X\mu^+\mu^-) \times \mathscr{B}(X \to \mu^+\mu^-)$, with $X = S, Z'$

$\mu^+\mu^-$ resonance in four-muon final state





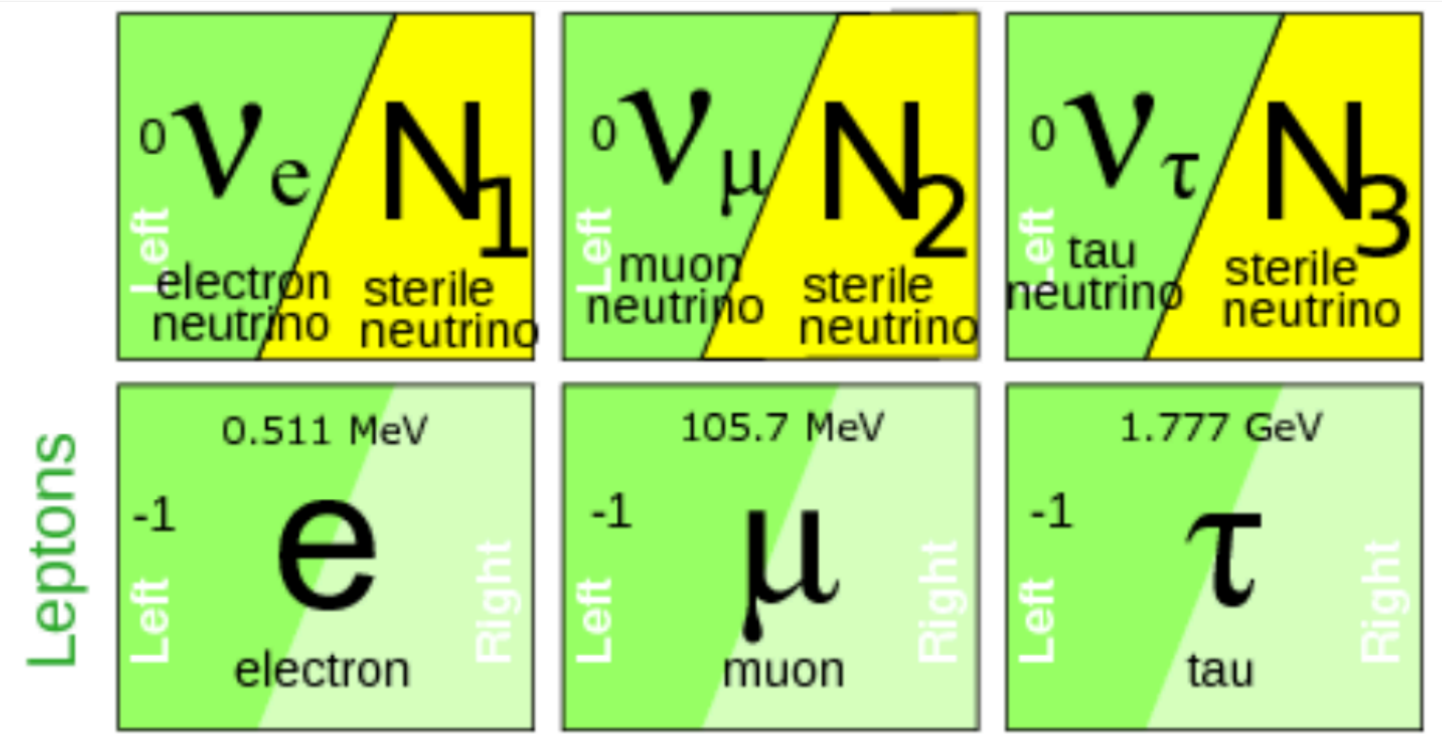
- Cross section limits are translated into upper limits on the g' coupling constant for the $L_\mu - L_\tau$ model and on the g_S coupling constant for the muonphilic dark scalar S
- previous searches with much larger luminosity : still upper limits are competitive
- First g_S upper limit obtained from a dedicated search
- These limits exclude the $L_\mu - L_\tau$ model and the muonphilic scalar model as explanations of the $(g-2)_\mu$ anomaly for 0.8 < $m_{Z'}$ < 4.9 GeV/c2 and 2.9 < m_S < 3.5 GeV/c2, respectively

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)*

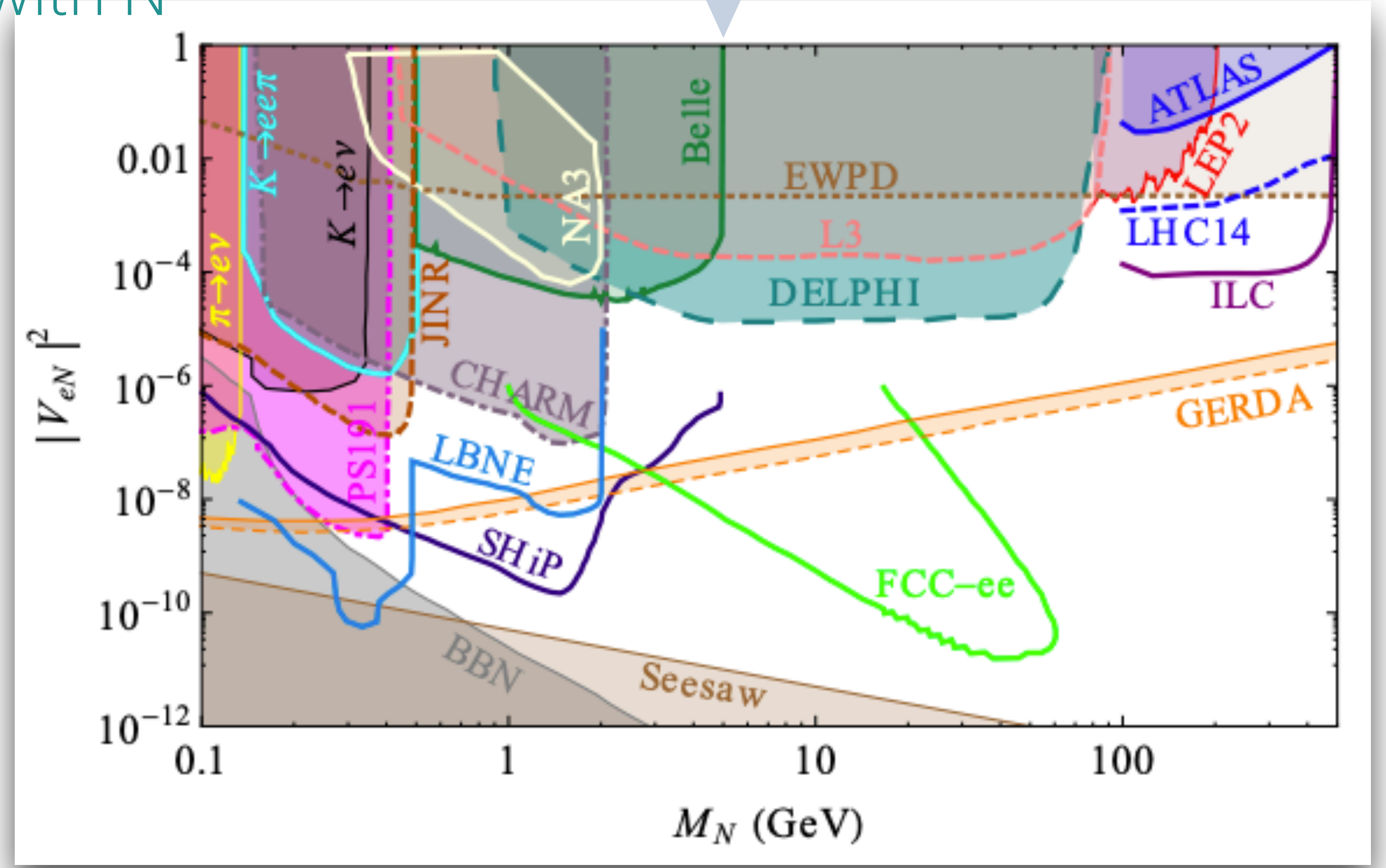
- N are sterile: Interacts with ν_{SM} through mixing: $N \leftrightarrow \nu_{SM}$
- Long lifetime of N: due to small m_N and small mixing
- Heavy Neutral Lepton also appears in SUSY, exotic Higgs, GUT…



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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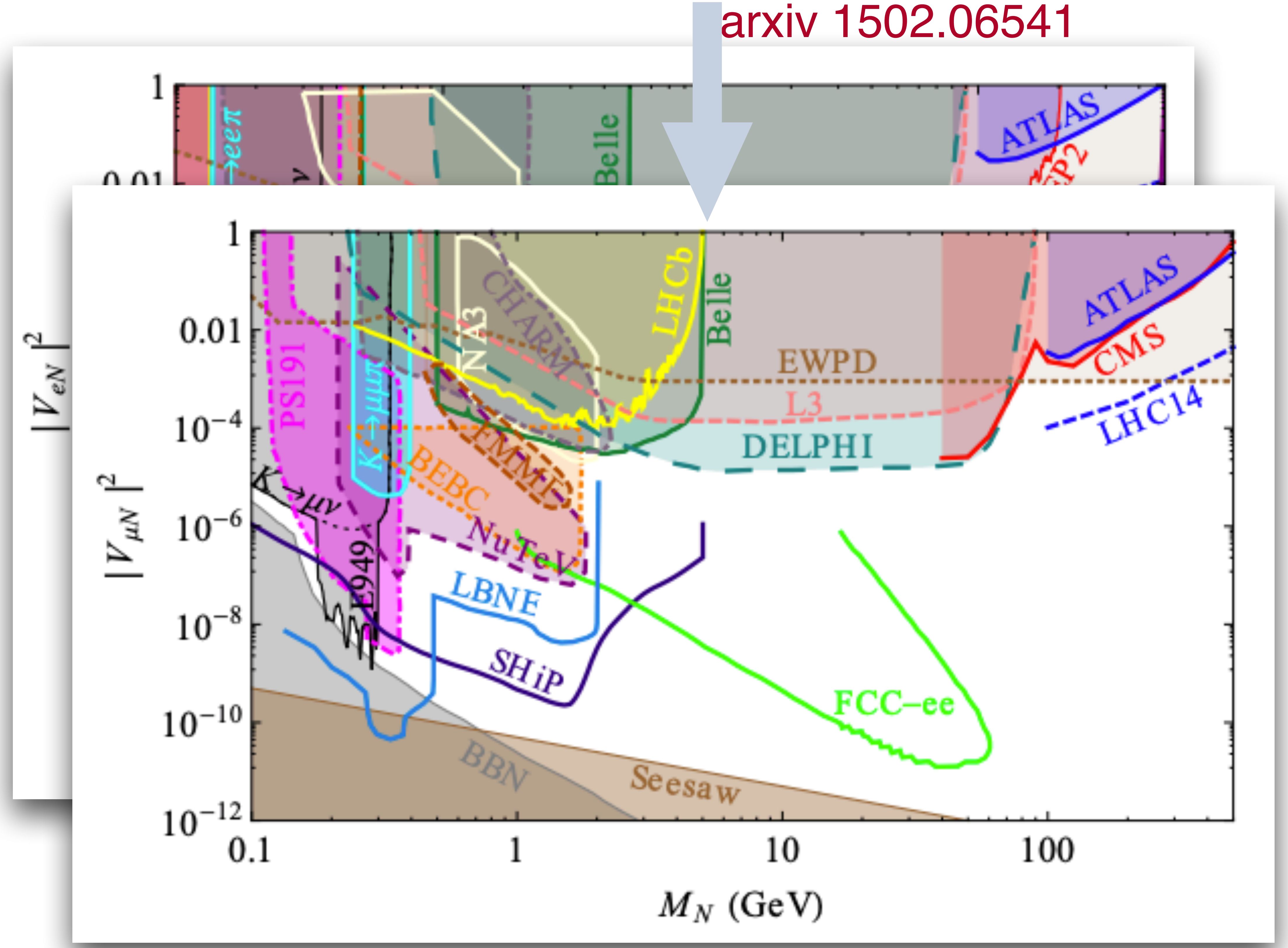

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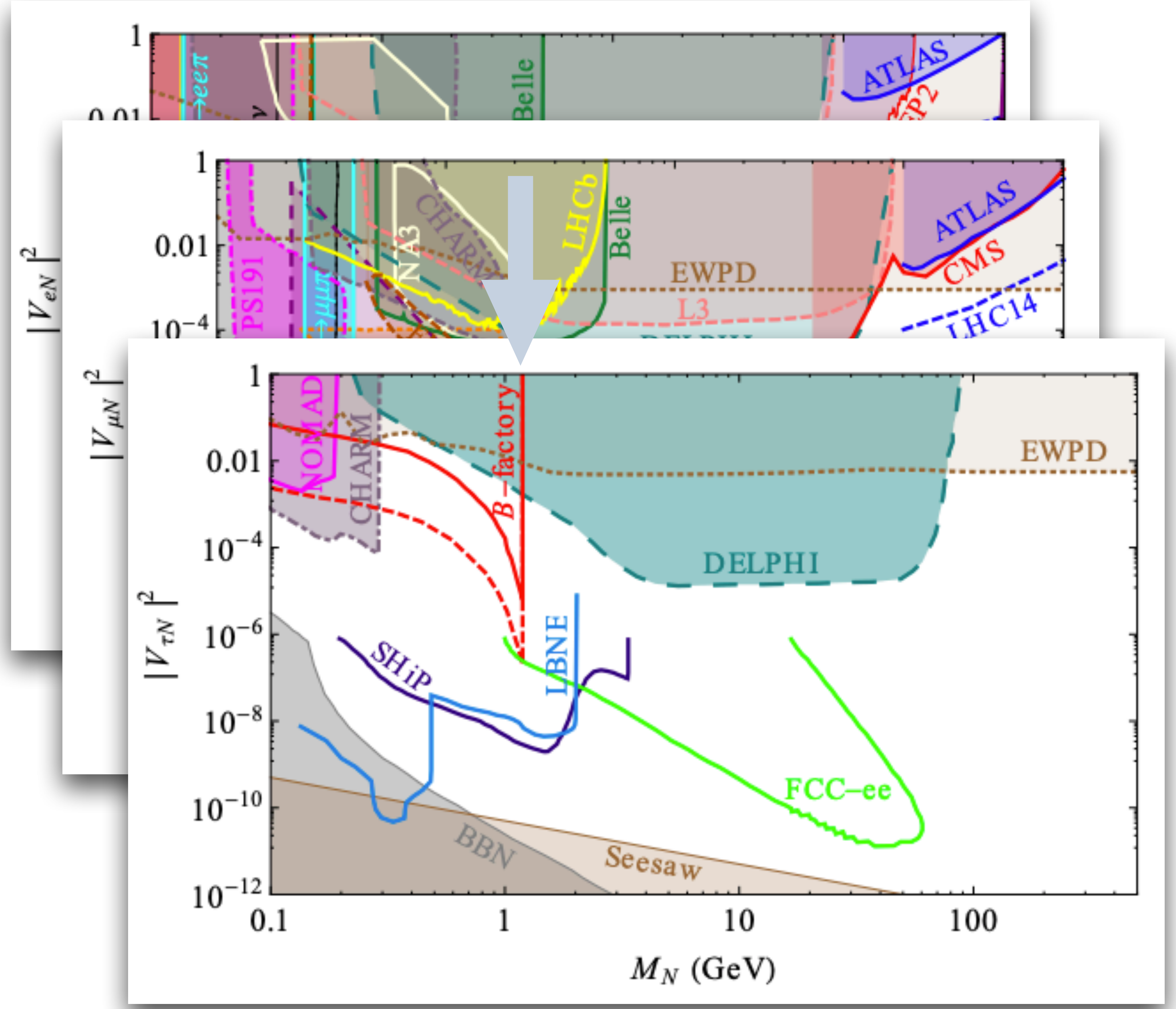
  - $m_N < m_{B,D,K}$ Belle, LHCb, beam-dump, NA62
- All the experiments provide tight limits on $|V_{eN}|^2$, $|V_{\mu N}|^2$
- Limits on $|V_{\tau N}|^2$ are much weaker
- This motivates us to overcome the experimental challenges and explore $|V_{\tau N}|^2$

arxiv 1502.06541

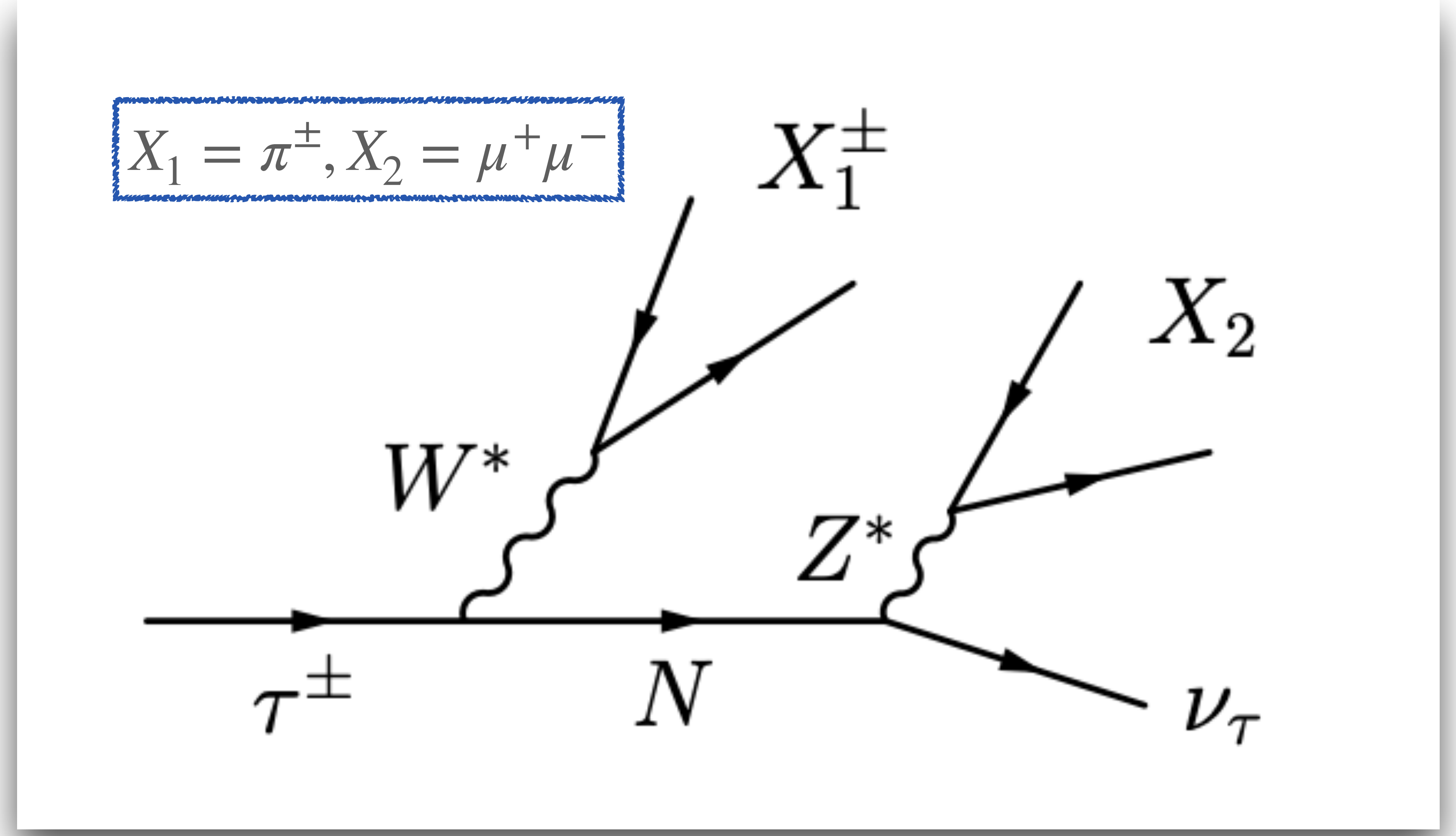


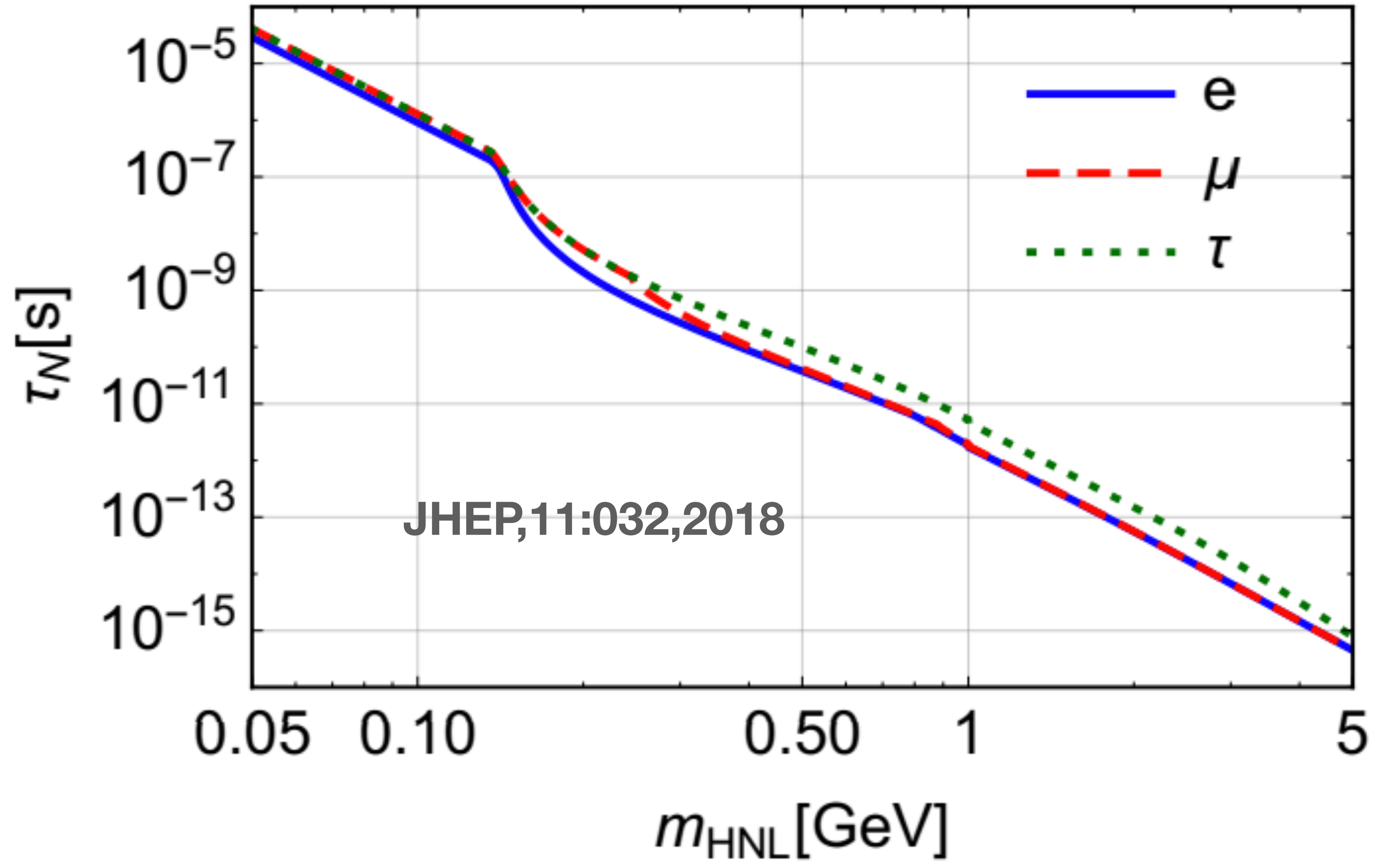
Analysis Method

- 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

$(836 \pm 12) \times 10^6\ \tau$ pairs





Analysis Method

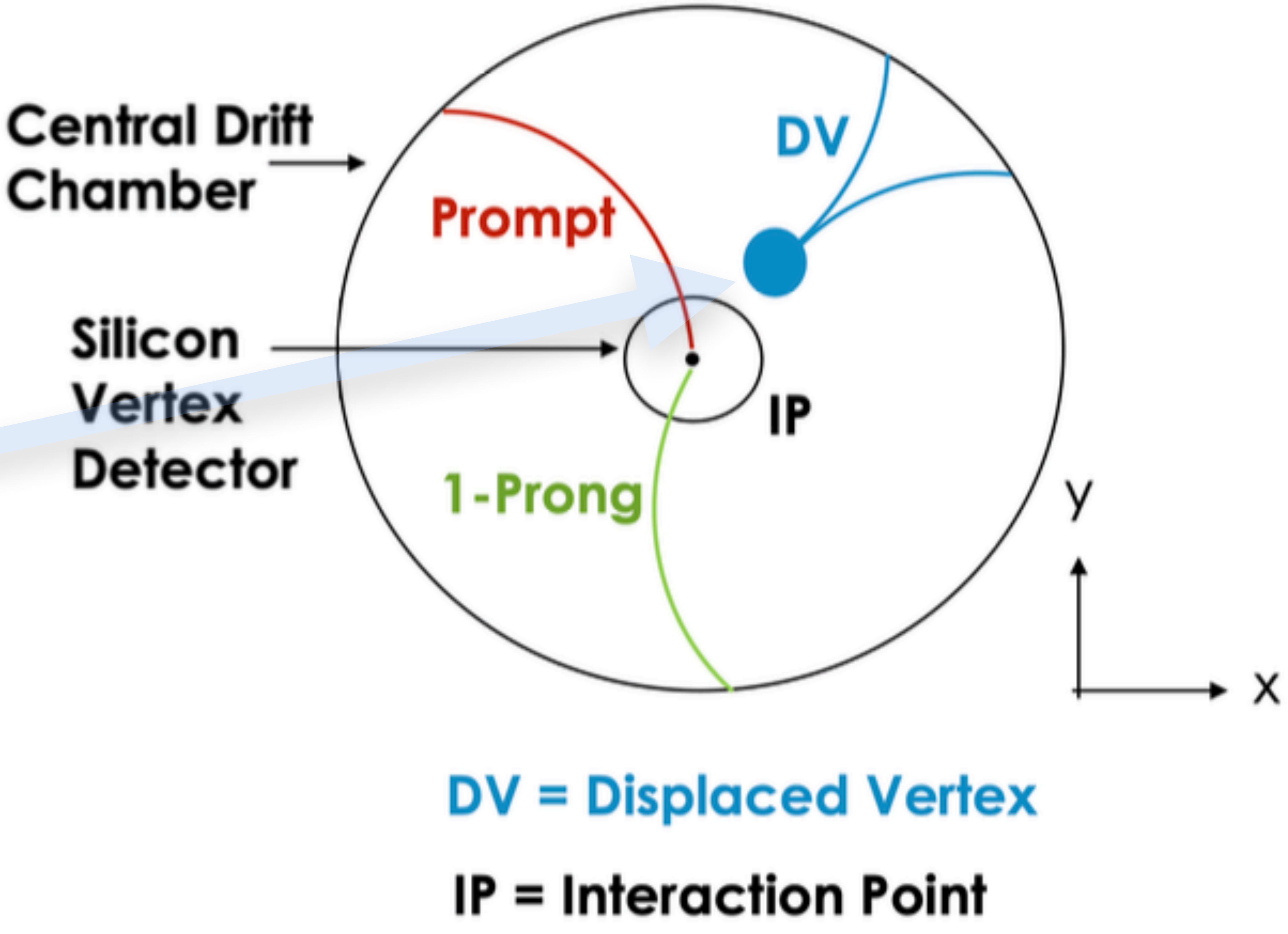
- $e^+e^- \to \tau^+_{tag}\tau^-_{sig}$
  - Tag side:

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

  - Signal side:

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

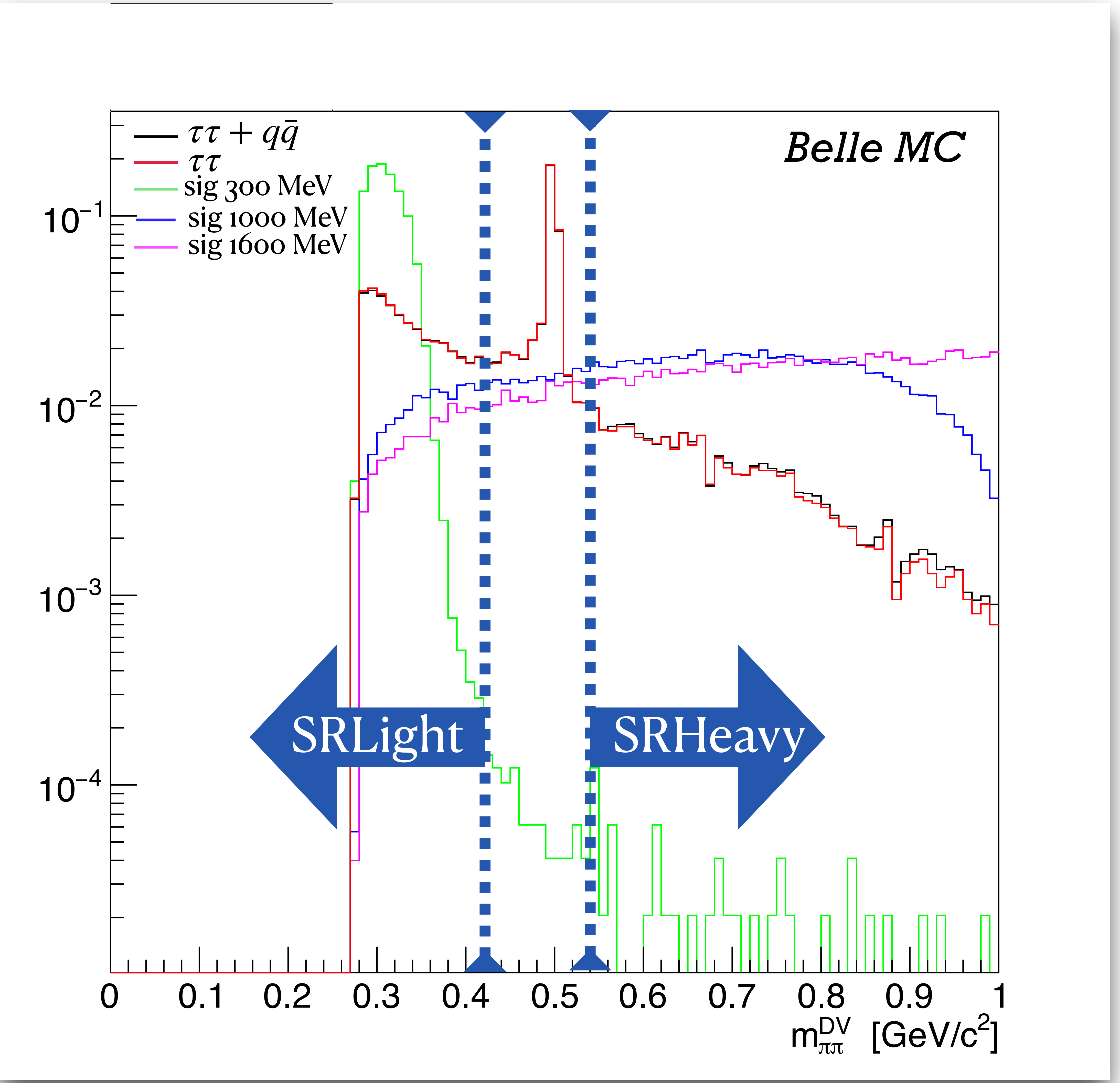
- We look for a $\mu^+\mu^-$ displaced vertex (DV)



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

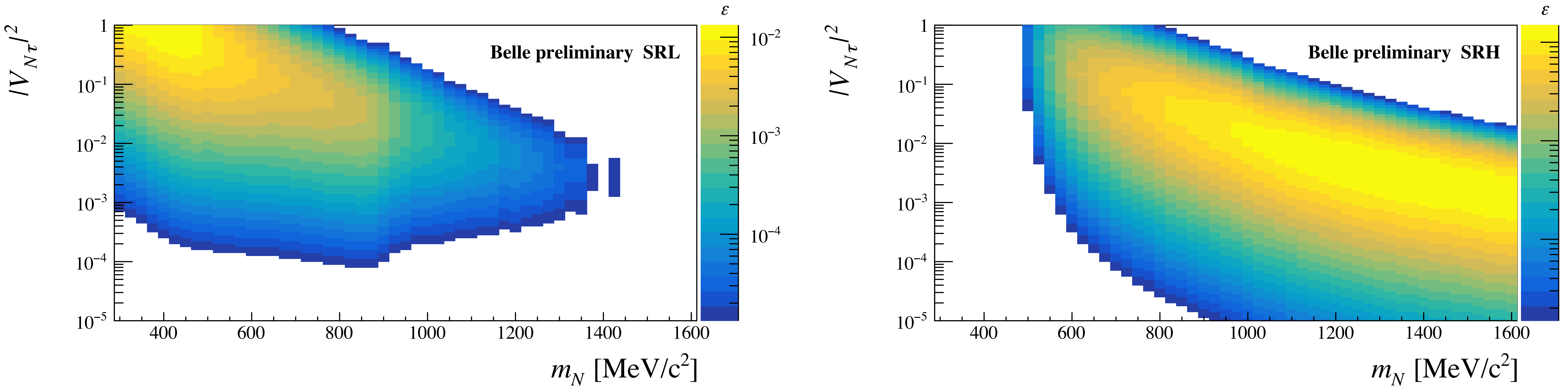
K_S^0 rejection and definition of two signal regions

- $K^0 \rightarrow \pi^+\pi^-$: 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

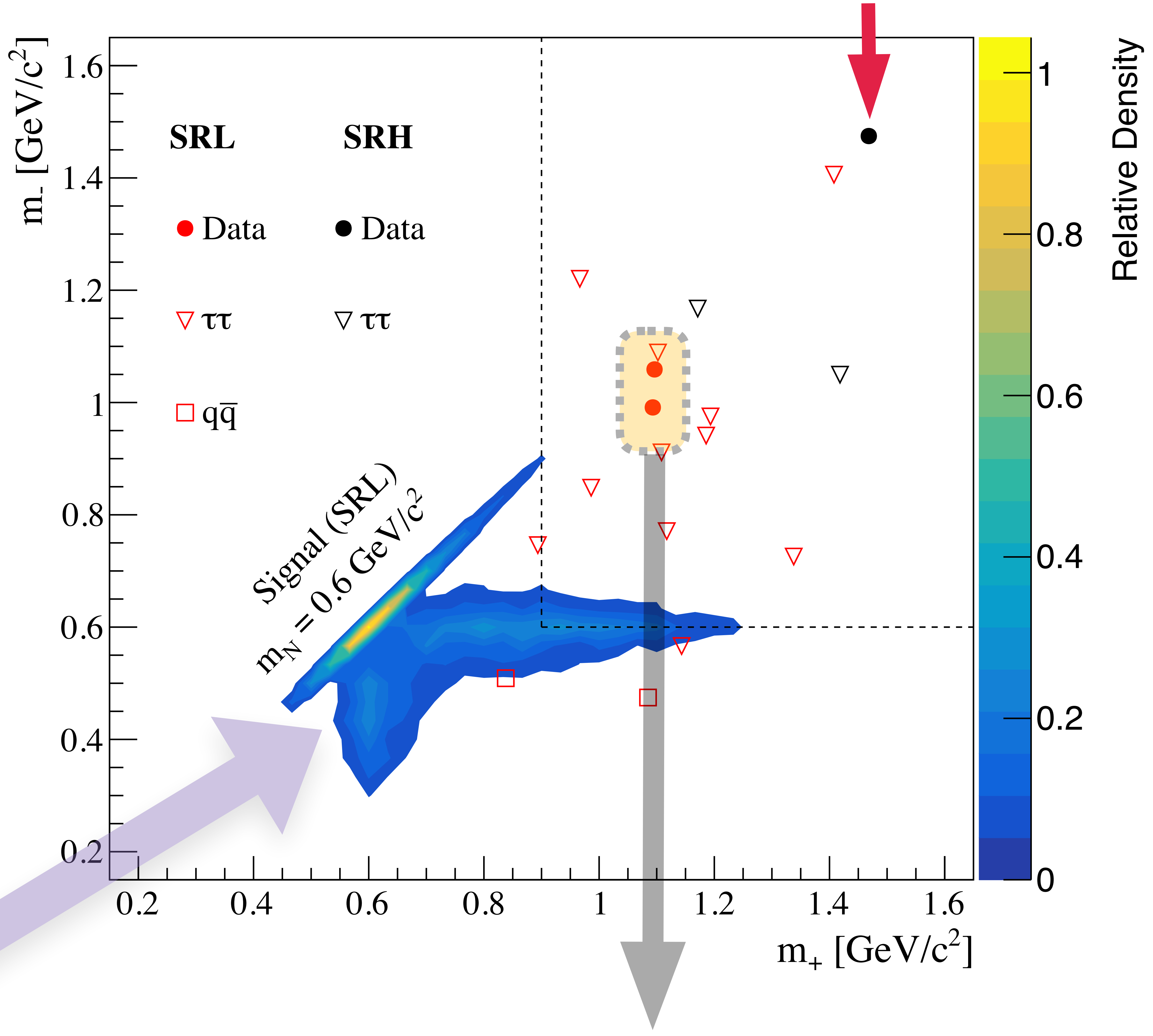


more on Analysis Method

- 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 one signal candidate observed



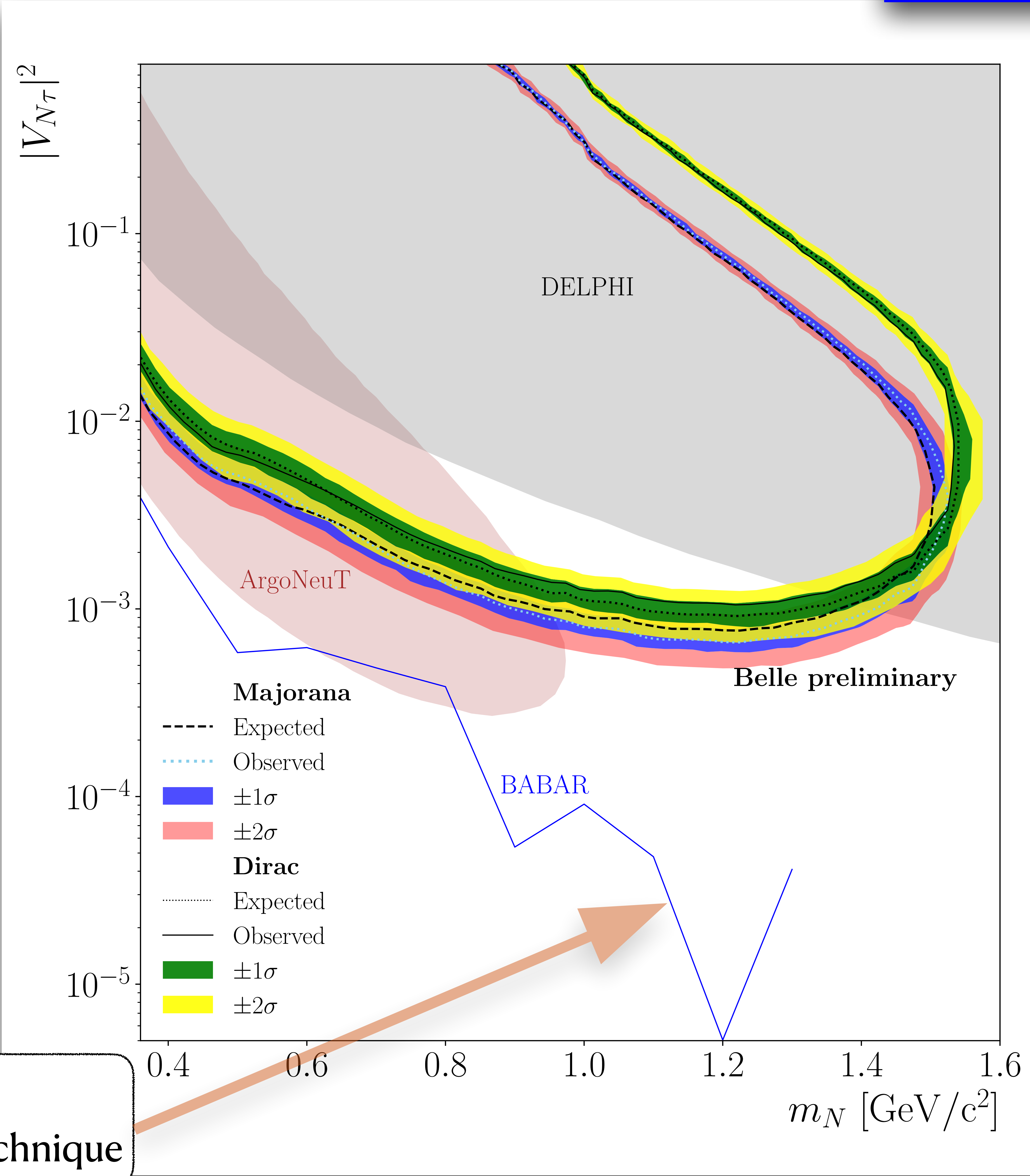
vetoed in SRL

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

Result

- 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



BABAR did not use displaced-vertex technique

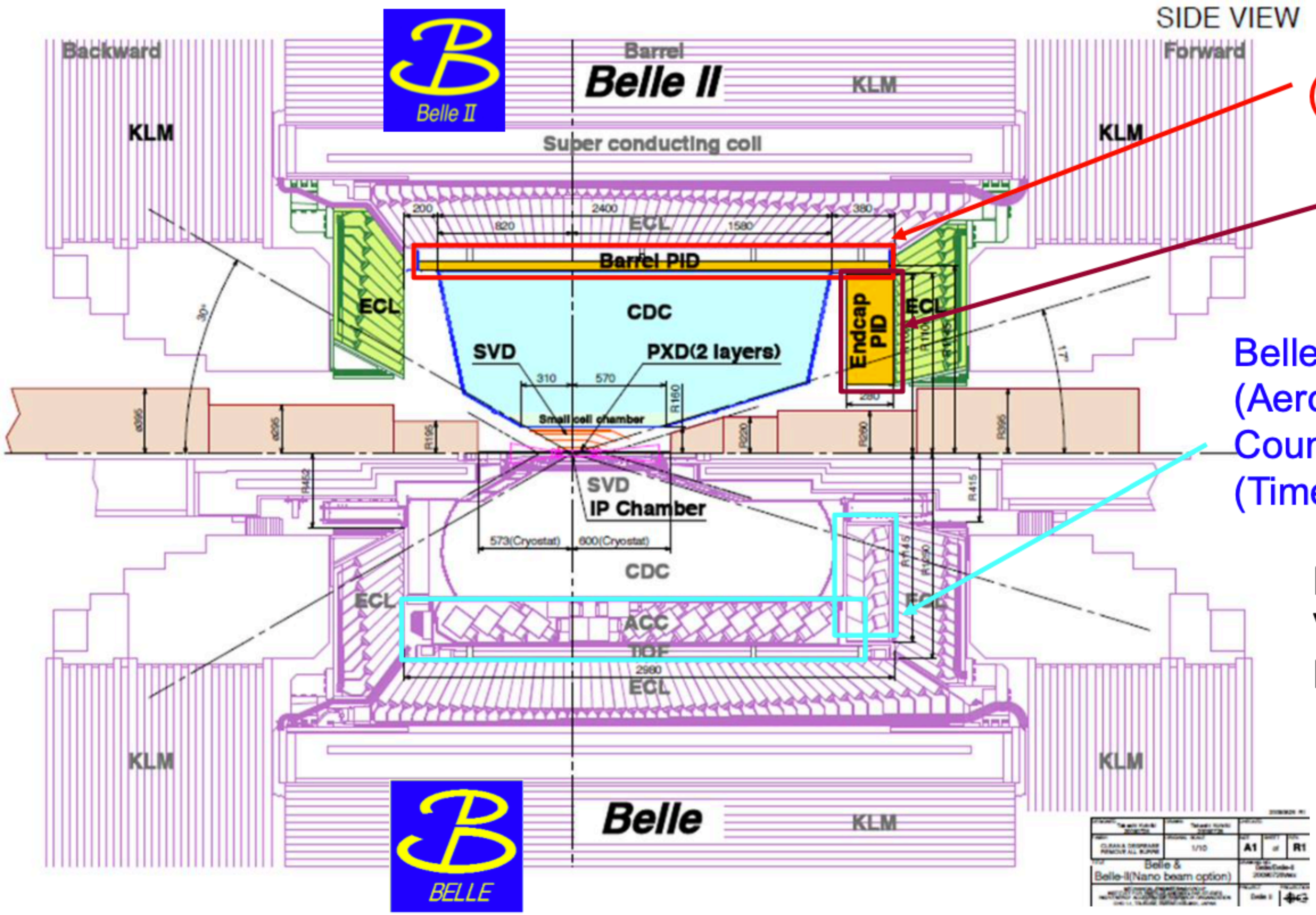
Summary

- No significant excess observed in any analysis
- Most stringent bound to date on branching fraction with $\tau \to \mu^-\mu^+\mu^-$ analysis
- In $\mu^+\mu^-$ resonance analysis, first g_S upper limit obtained from a dedicated search
- HNL: Most 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, more exiting results to come in the future

THANK YOU FOR YOUR ATTENTION

Backup

From the Belle to the Belle II Detector



TOP (barrel)

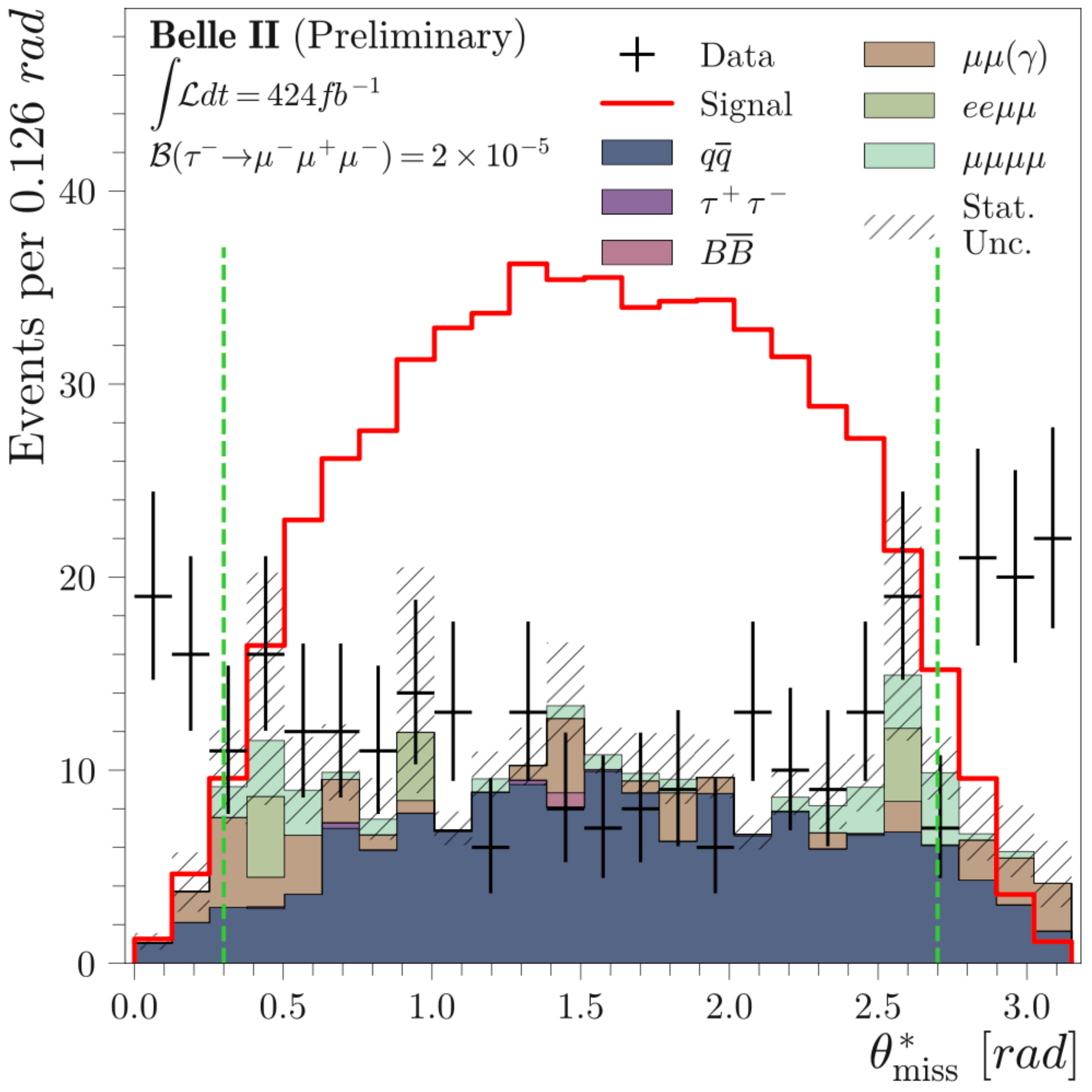
ARICH (forward endcap)

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

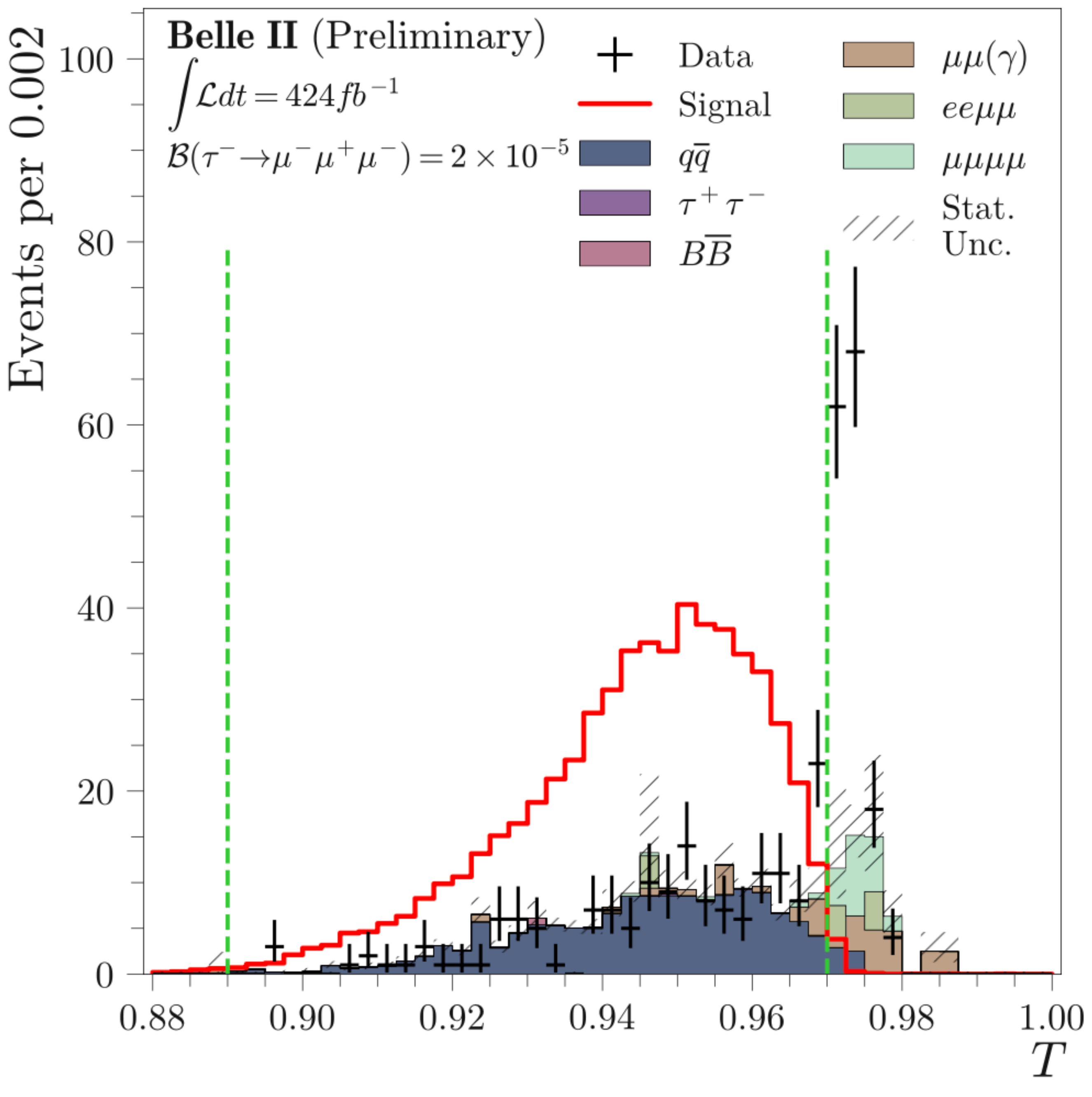
More space to VXD and CDC at Belle II

$\tau \to \mu^-\mu^+\mu^-$: Analysis

- DATA used: 424 fb^{-1}, collected between 2019 and 2022, 389 M $e^+e^- \to \tau^+\tau^-$ events
- Backgrounds arise from:
  - radiative dilepton and four-lepton final states (low-multiplicity backgrounds) with potential electrons misidentified as muons,
  - incorrectly reconstructed SM $e^+e^- \to \tau^+\tau^-$ events
  - continuum hadronization processes from $e^+e^- \to q\bar{q}$ events, where pions are misidentified as muons.
- Background events suppressed with selection cuts and boosted decision tree classifier



Polar angle of the missing momentum



Thrust

$\tau \to \mu^-\mu^+\mu^-$: Systematics

Quantity	Source	Uncertainty(%)	
		Low	High
$\epsilon_{3\mu}$	PID	2.1	2.4
	Tracking	1.0	1.0
	Trigger	0.9	0.9
	BDT	1.5	1.5
	Signal Region	3.9	2.9
N_{exp}	Momentum Scale	16	16
Luminosity		0.6	0.6
$\sigma_{\tau\tau}$		0.3	0.3

$\tau \to \mu^-\mu^+\mu^-$: Result

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{obs} - N_{exp}}{\mathcal{L} \times 2\sigma_{\tau\tau} \times \epsilon_{3\mu}} = (2.1^{+5.1}_{-2.4} \pm 0.4) \times 10^{-9}$$

- We observe one event in the signal region