Search for Heavy Neutral Leptons at Belle and Belle II

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on behalf of the Belle II collaboration

15th Rencontres du Vietnam

ICISE, Quy Nhon, 8 August 2019

15th Rencontres du Vietnam August 4–10

ICISE

3 Neutrinos and beyond 2019

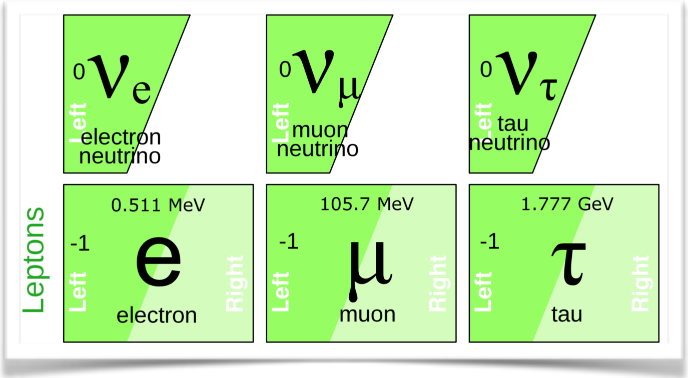
DESY.

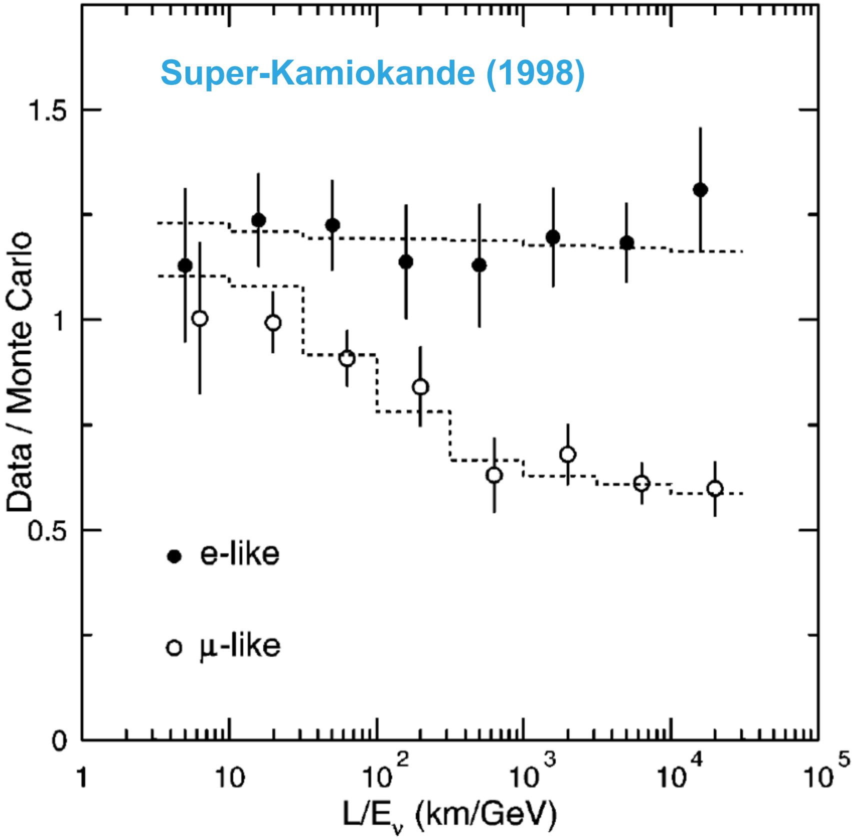
Belle II

Introduction

- Particle masses in the SM are generated by the coupling of the Higgs field to a given particles LH and RH components

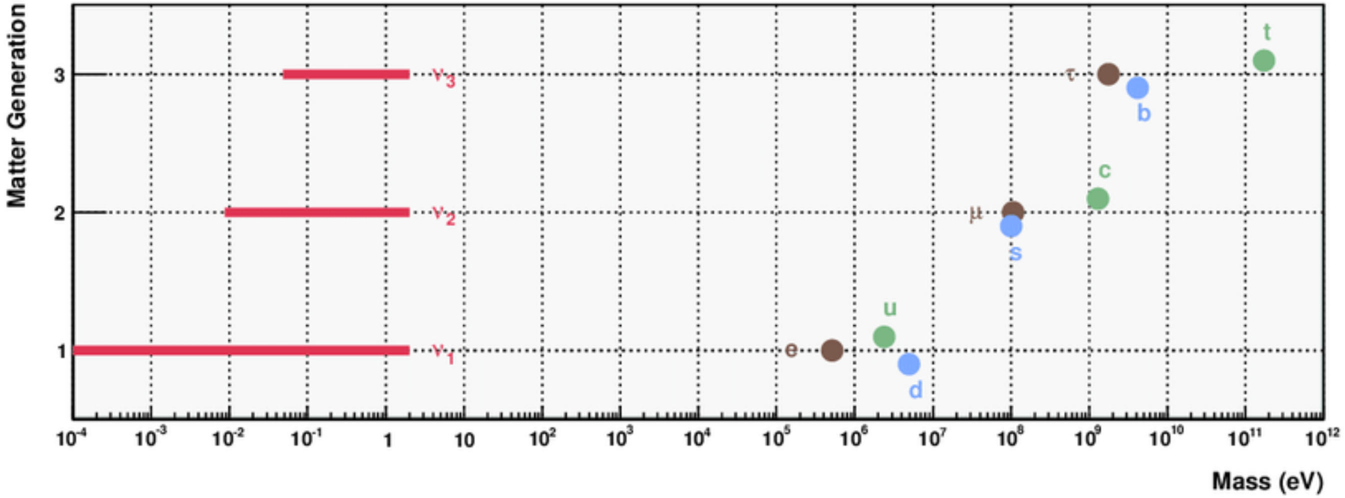
- In SM there are only LH neutrinos ⇒ **massless**





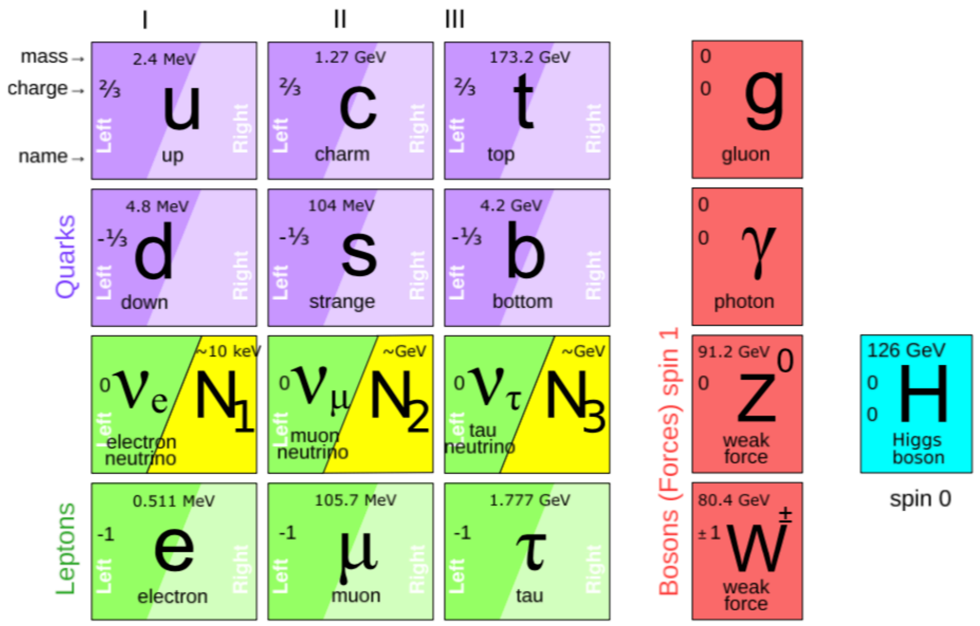
- **Neutrino oscillation** data shows they do have mass, and that these masses are much smaller than the other fermions

- A mechanism beyond the SM is necessary to explain m_ν…



Heavy Neutral Leptons

- Neutrino masses can be incorporated into the SM by introducing sterile RH (Majorana) neutrino(s)
- For example, the ***ν*MSM** model introduces three RH singlet HNLs (**N_1**, **N_2** and **N_3**). Can solve:
  - origin and smallness of SM neutrino masses (with GeV scale $N_{1,2}$ and see-saw mechanism)
  - dark matter (N_1 with mass ~keV)
  - BAU: leptogenesis due to Majorana mass term



- N is mostly RH neutrino, but small LH component allows it to interact with SM particles
- Interacts with ν_{SM} via $N \leftrightarrow \nu_{SM}$ mixing. Long lifetime due to small M_N and small mixing.
- HNLs also appear in other BSM models (SUSY, grand unification theories, exotic Higgs, …)

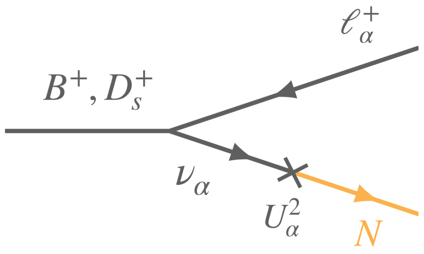
HNL Production and Decay

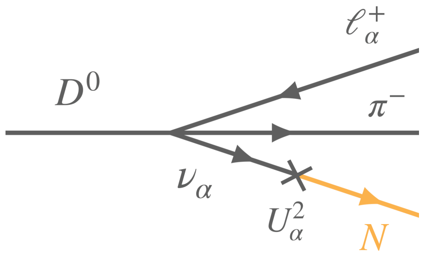
- Neutrino flavour and mass eigenstates need not coincide, but may be related through a unitary transformation $\nu_\alpha = \sum_i U_{\alpha,i}\nu_i, \quad \alpha = e, \mu, \tau, \ldots, \quad i = 1,2,3,4, \ \ldots$
- HNL production can occur through mixing with the SM neutrinos ⇒ suppressed by factor of $\mathbf{U_\alpha^2}$
- They can then decay (after long flight length) by mixing again with SM neutrinos ⇒ additional $\mathbf{U_\alpha^2}$

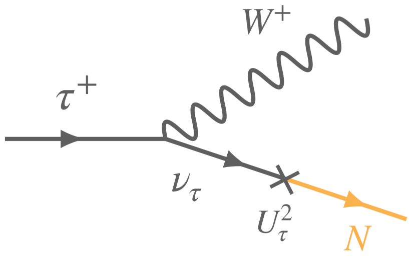
Production

Low mass

Semileptonic decay of mesons, τ decay

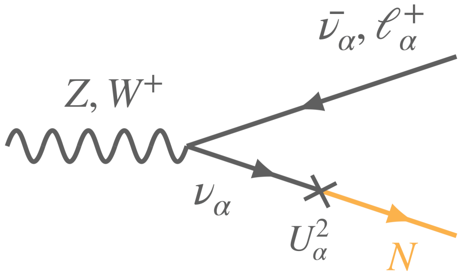






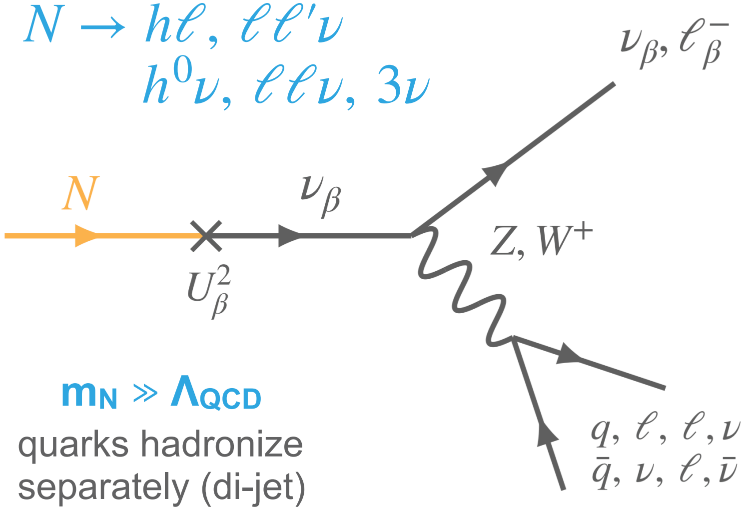
High mass

Decays of Z and W± bosons



Decay

$N \to h\ell, \ \ell\ell'\nu$
$h^0\nu, \ \ell\ell\nu, \ 3\nu$



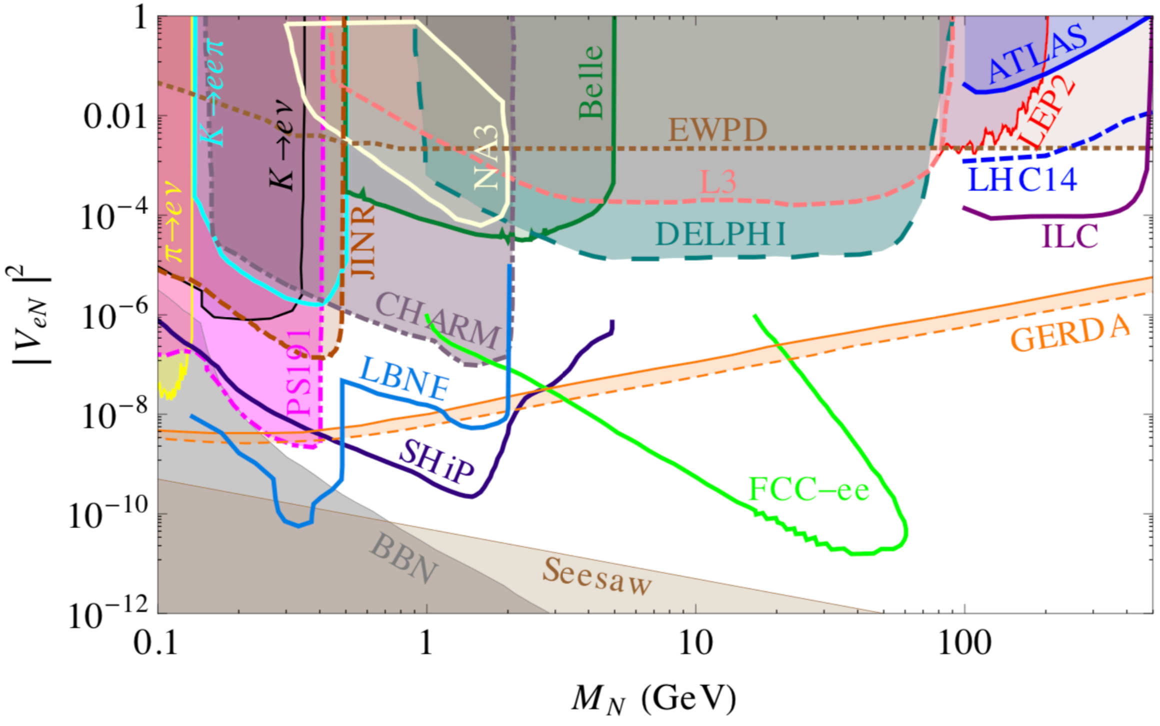
$\mathbf{m_N \gg \Lambda_{QCD}}$
quarks hadronize separately (di-jet)

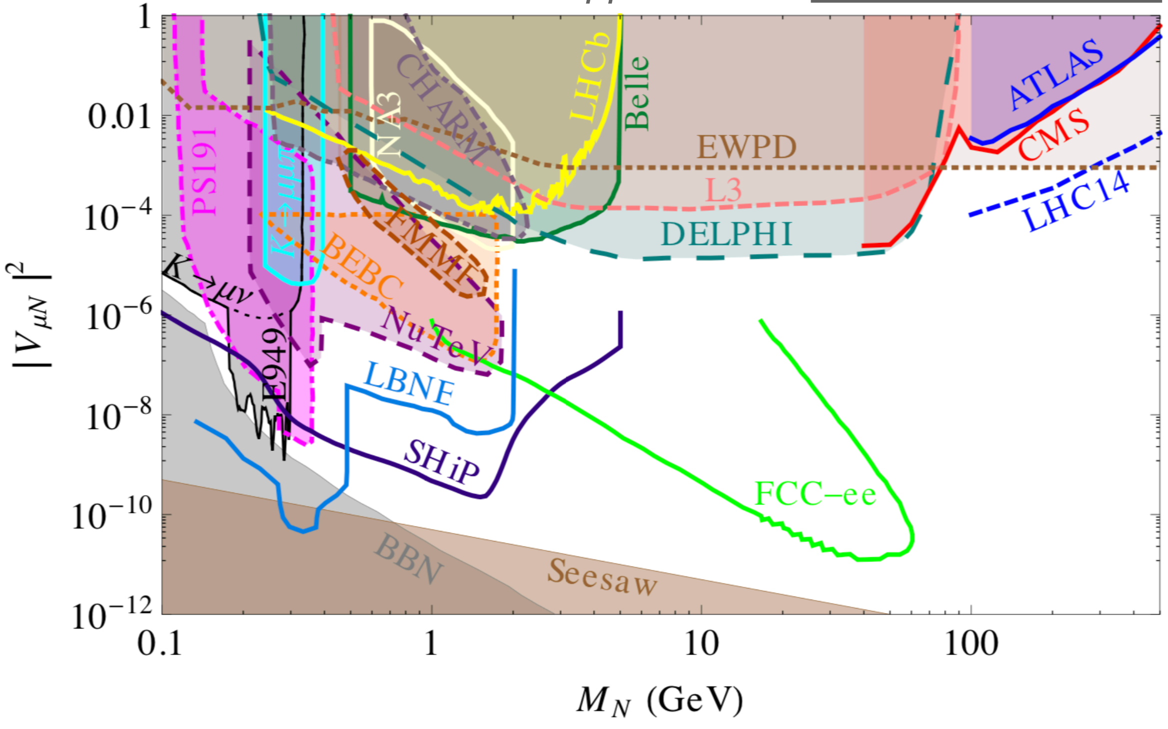
Status of Direct Searches for HNL

- Existing experiments have explored M_N from 100 MeV up to almost 1 TeV

- ***$M_N > M_Z$***
  direct search @LHC ($pp \rightarrow N l^{\pm}$)
- ***$M_N < M_{Z,W}$***
  DELPHI ($Z^0 \rightarrow \nu N$)
  ATLAS/CMS ($W^{\pm} \rightarrow N l^{\pm}$)
- ***$M_N < M_{B,D,K}$***
  beam-dump, NA62, etc.
  LHCb, **Belle**, soon also **Belle II**

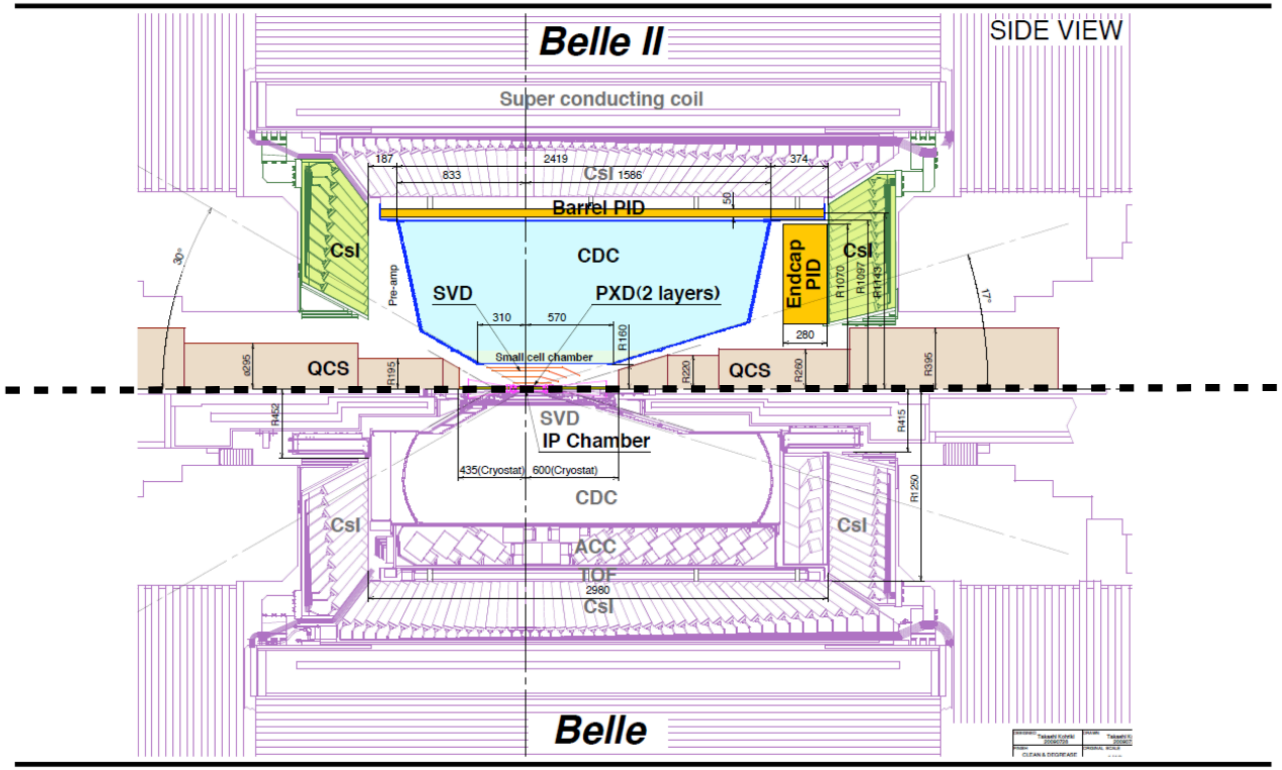
F. Deppisch et al: **aXiv:1502.06541v3**

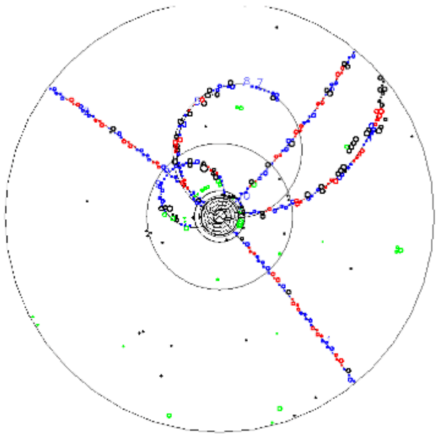


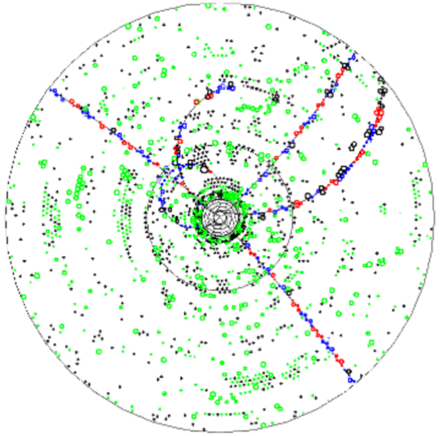


Belle and Belle II

- Energy asymmetric e^+-e^- colliders operating mostly at $\sqrt{s}=m_{\Upsilon(4s)}$, located at KEK near Tsukuba, Japan
- **KEKB → SuperKEKB accelerator**
  - 2x beam currents, 50nm vertical beam spot size ("nano beam")
  - design lumi $2.1\times10^{34} \rightarrow \mathbf{8.0\times10^{35}\ cm^{-2}s^{-1}}$





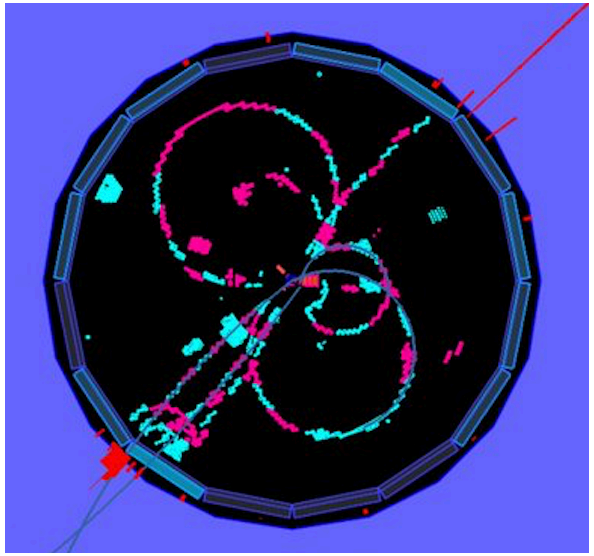


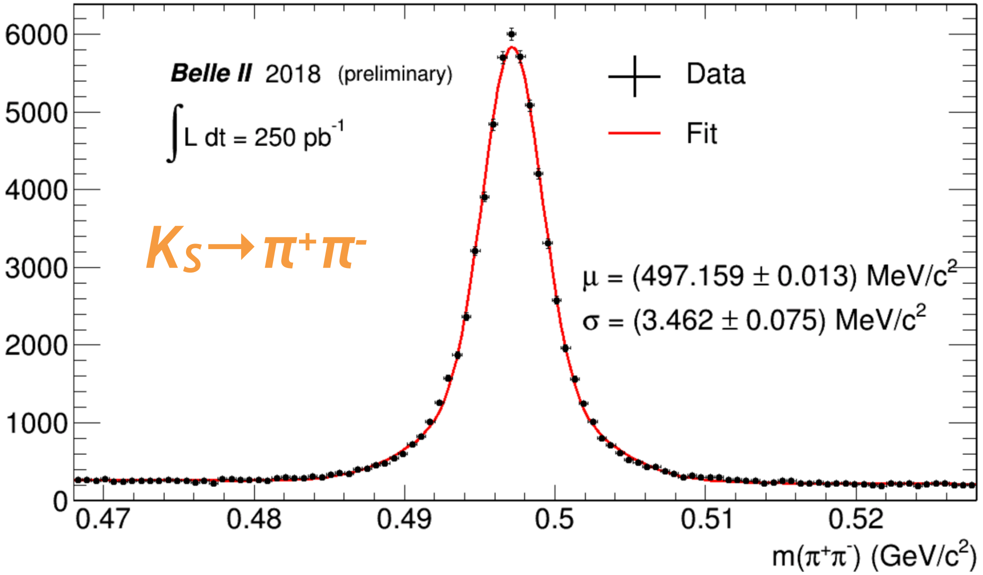
- Consequently, SuperKEKB has higher beam bkg conditions and event rates
- **Belle → Belle II detector**
  - PXD at r=1.4cm significantly improves vertexing
  - larger SVD acceptance and outer CDC radius
  - improved PID, TOP + new ARICH (K/π separation)
  - Faster electronics in general

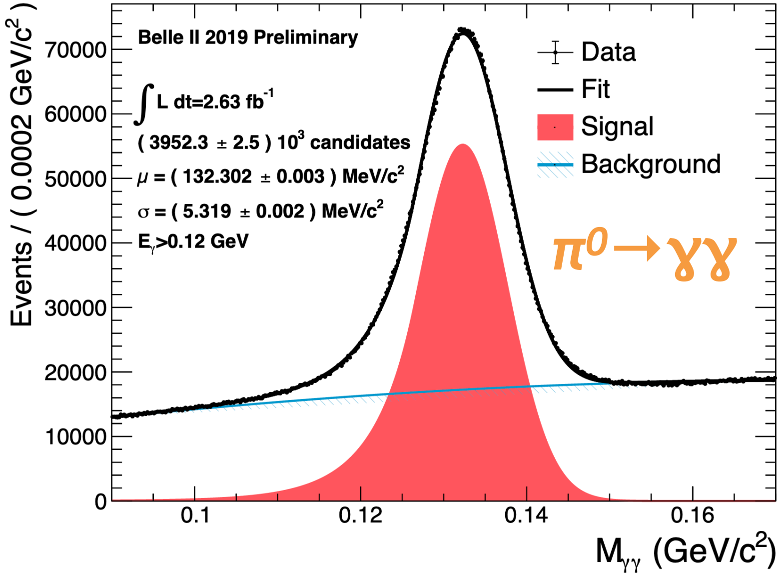
Dataset size: $1\ ab^{-1} \rightarrow 50\ ab^{-1}$ (by 2027)

First collisions @ Belle II

- First collisions recorded by Belle II on 26th April 2018
- During **Phase 2** (April-July 2018) about ~**0.5 fb^{-1}** of data was recorded
- **Phase 3** since March 2019 with ~**6.5 fb^{-1}** so far
- Good performance of the subsystems. Clear mass peaks observed from both tracks and photons.



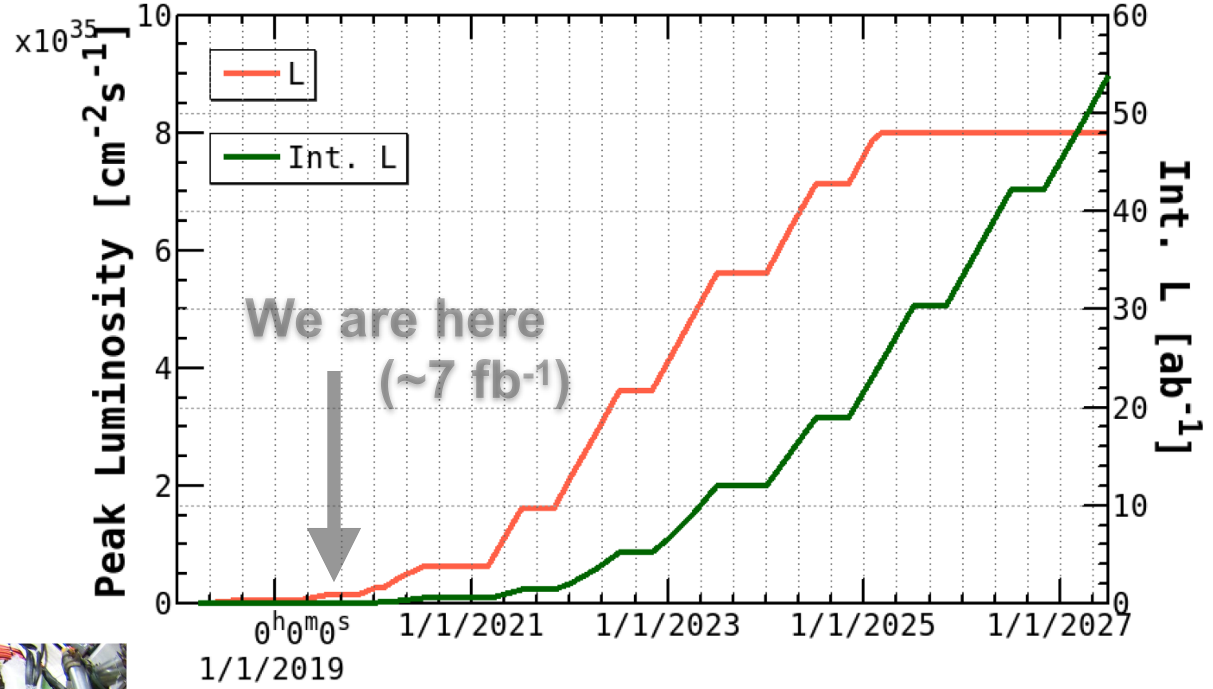




Belle II Schedule

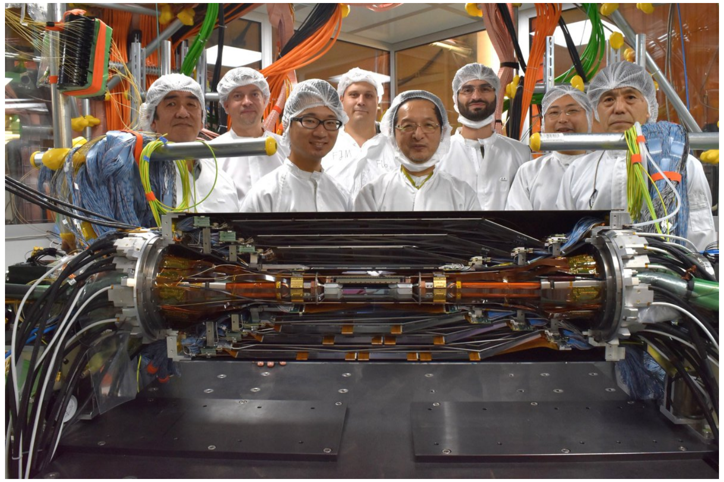
- Belle and Belle II are ***B*-meson** + **τ-lepton** factories
  - $\sigma(e^+e^-\to\Upsilon(4s))$ = 1.05 nb, $\sigma(e^+e^-\to\tau^+\tau^-)$ = 0.92 nb

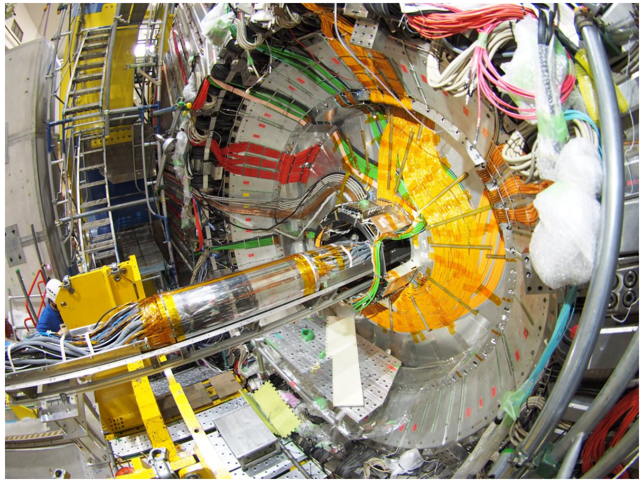
- Over its lifetime Belle II aims to record 50 ab^{-1} of e$^+$e$^-$ collision data (x50 that of Belle)
  - 5.25×10^{10} $B\bar{B}$ and 4.6×10^{10} $\tau\tau$ events
  - **unique environment to search for HNLs that are produced in B and τ decays!**



Phase II
(2018, 3 months)

Phase III
(began March 2019)



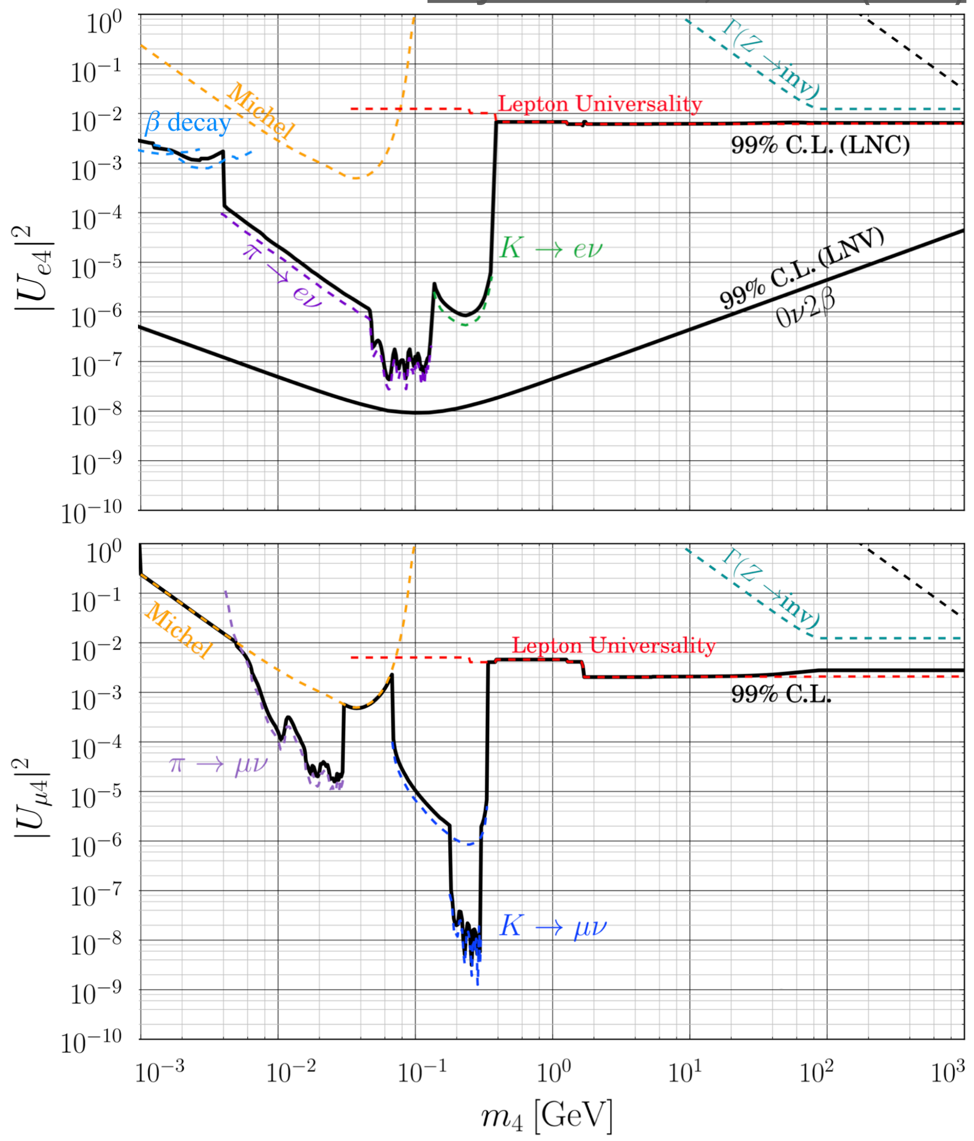


- Data taking in **Phase II** was performed with all subsystems, except full vertex detector
- VXD installed and running during **Phase III**

Global constraints on N↔ν mixing

- Direct searches for **visible** HNL decay products can strongly constrain $|U_{\alpha N}|$
  - ⇒ e.g. search in B decays with N→lπ @ Belle
- In addition, more model independent global constraints can be set assuming
  - (i) **invisible** HNL decay (to SM ν, dark matter, …)
  - (ii) HNL too heavy to be produced in a given process
- For these constrains, the main input from **Belle** comes from tests of **lepton universality**, for example:
  - B-meson decays $\frac{Br(B \to D^{(*)}\tau\nu)}{Br(B \to D^{(*)}\ell\nu)}$ $\frac{Br(B \to K^{*}\mu\mu)}{Br(B \to K^{*}ee)}$
  - D and τ decays $\frac{Br(D_s \to \tau\nu)}{Br(D_s \to \mu\nu)}$ $\frac{Br(\tau \to e\nu\bar{\nu})}{Br(\tau \to \mu\nu\bar{\nu})}$
  - and many more…

A. de Gouvêa et al: **Phys. Rev. D 93, 033005 (2016)**



Search for HNL at Belle

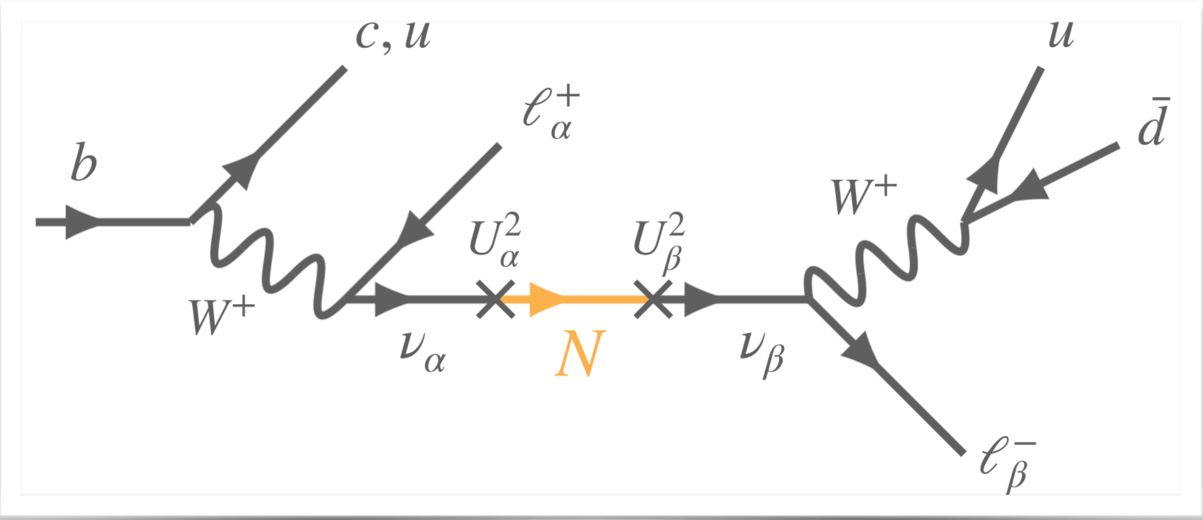
- Direct search for Majorana HNL in B decays using the Belle detector

  Phys. Rev. D. 87, 071102 (2013)

  Phys. Rev. D 95, 099903(E) (2017)

- Data sample of 722×10^6 $B\bar{B}$ pairs (711 fb^{-1}), collected at $\sqrt{s} = M_{\Upsilon(4s)}$

- Sensitivity to $N \leftrightarrow \nu_{SM}$ mixing for $M_K < M_N < M_B$



HNL production

- Both leptonic and semi-leptonic B decays $\quad B \to X\ell N$

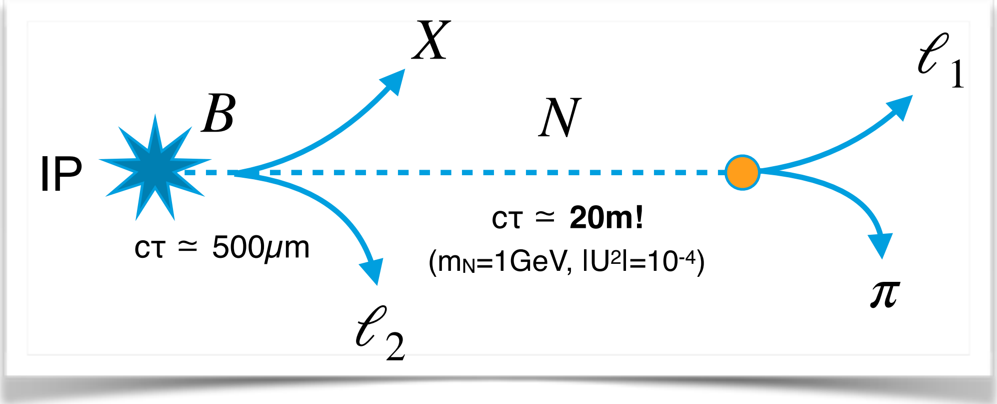
where: $\ell = e, \mu \quad X = D, D^*$, light meson (π,ρ,η,…), ‘nothing’ (leptonic decay)

Detector Signature

- HNL decays to **eπ/μπ** after a very long flight length
  e.g M_N = 1 GeV, $|U_{e,\mu}|^2 = 10^{-4}$, $\Rightarrow c\tau \simeq$ 20m!
- Final state: $X\ell\ell\pi$
  - **eeπ**, **μμπ** or **eμπ** (Majorana ⇒ OS or SS leptons)
  - eπ or μπ originate from a **displaced vertex**

Reconstruction and selections

- Partial reconstruction technique
  - Partial B decay candidate $\Rightarrow \ell_2 \ell_1 \pi$
  - HNL candidate $\Rightarrow$ OS charge $\ell_1 \pi$ from **displaced vertex**
- Analysis split into two M_N regimes
  - **low-mass** (<2 GeV): targets dominant $B \to D^{(*)} \ell \nu$ mode
  - **high-mass** (2-5 GeV): inclusive production



Selections

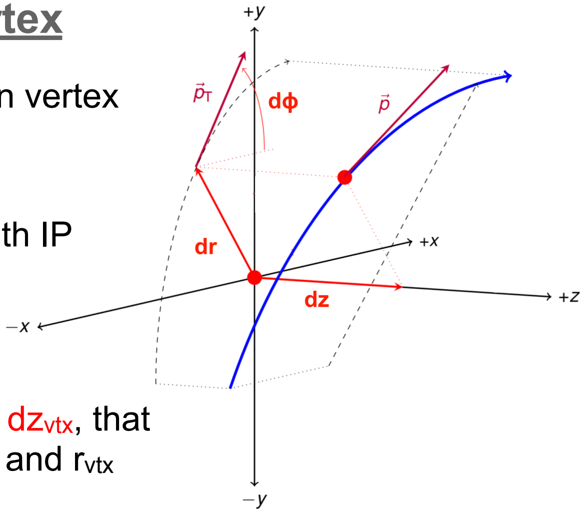
- ≥4 tracks, p_T > 0.5 GeV
- tight lepton ID (ee, μμ or eμ)
  - lepton veto for π
- **Low-mass** regime:
  - $B \to D^{(*)} \ell \nu$ selected via **recoil mass** (1.4-2.4 GeV)

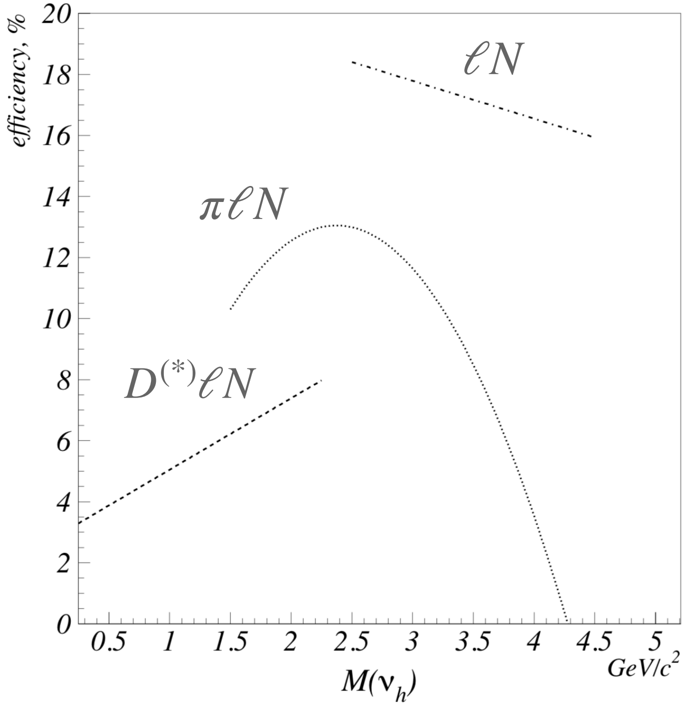
$$M_X^2 = (E_{CM} - E_{\ell\ell\pi})^2 - P_{\ell\ell\pi}^2 - P_B^2$$

  - proton veto

Displaced Vertex

- $\ell_1 \pi$ is fit to common vertex
  $\Rightarrow \chi^2$/ndof < 16
- then $\ell_1 \ell_2 \pi$ is fit with IP constraint
  $\Rightarrow \chi^2$/ndof < 4
- cuts on track dr, dϕ, dz_{vtx}, that vary with nCDCHits and r_{vtx}
- $dr_{fh} = min(r_\ell, r_\pi) - r_{vtx}$ above -2 cm, for large r_{vtx}



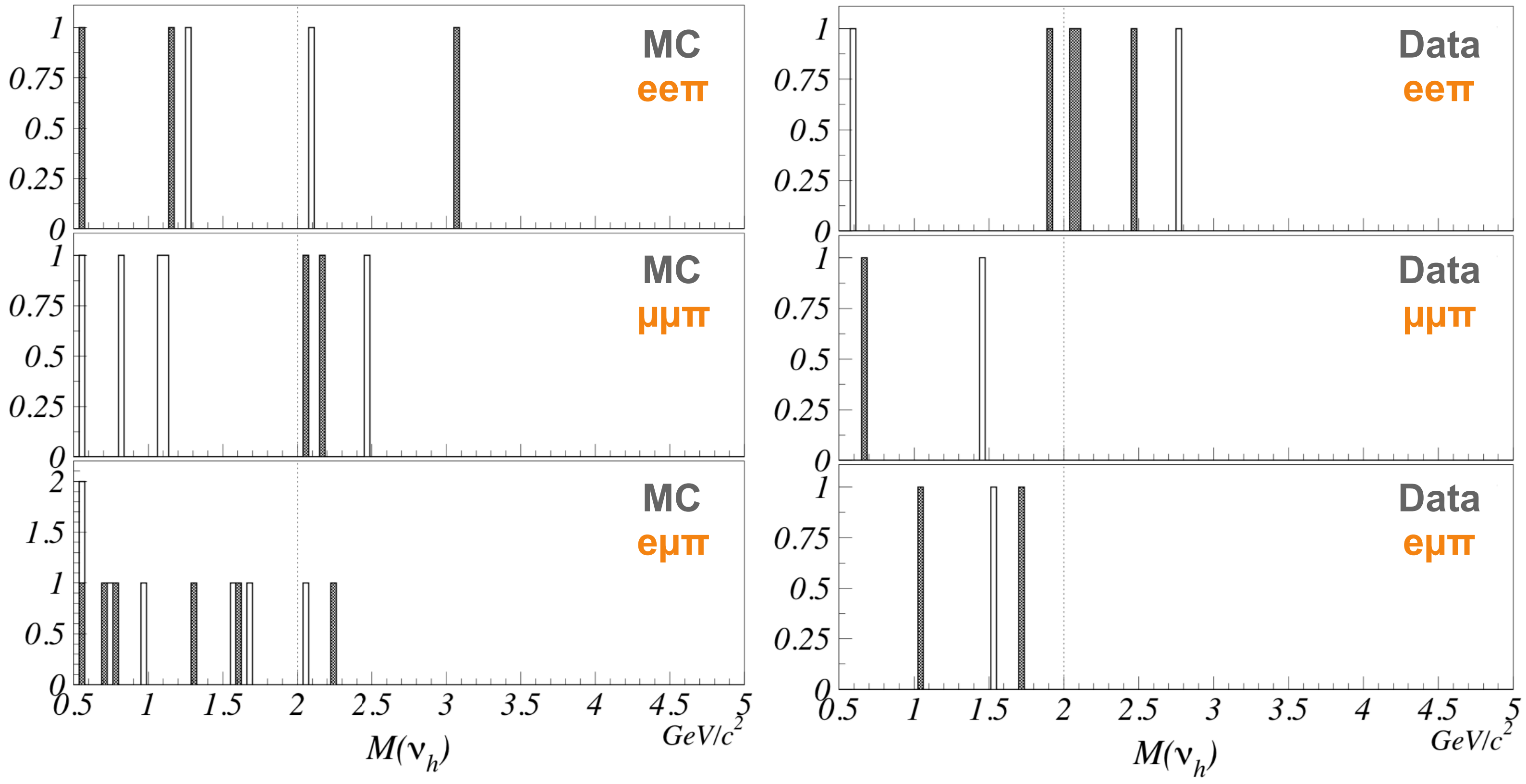


M_N distributions

- **Signal MC**: 500k signal events for each production mode
- **Background MC**: known SM $B\bar{B}$ decays from b→c processes (3× data stats)

Backgrounds reduced by factor of ~10^6 to only a handful of events

⇒ **no evidence for HNL in Belle data**



Requirement	Applied to	Supp. eff., %	Signal eff., %	Syst. error, %
$\chi_1^2/ndf < 16$	All	35	99	2.9
$\chi_2^2/ndf < 4$	All	27	85	10.1
$\mathcal{R}_e(\ell_1) > 0.9$	All	40	45	2.2
$\mathcal{R}_\mu(\ell_1) > 0.99$	All	17	35	4.9
$\mathcal{R}_e(\ell_2) > 0.9$	All	38	53	3.0
$\mathcal{R}_\mu(\ell_2) > 0.9$	All	25	38	3.1
Lepton veto	All	86	99	1.8
$d\phi < 0.03\,\mathrm{cm}$	Type I	39	95	
$d\phi < 0.03\,\mathrm{cm}$	Type II	5	80	
$d\phi < 0.04\,\mathrm{cm}$	Type III	11	85	5.8
$d\phi < 0.09\,\mathrm{cm}$	Type IV	66	96	
$d\phi < 0.15\,\mathrm{cm}$	Type V	51	94	
$dr > 0.09\,\mathrm{cm}$	Type I	5	97	
$dr > 0.1\,\mathrm{cm}$	Type II	7	98	
$dr > 3\,\mathrm{cm}$	Type III	1	79	3.7
$dr > 3\,\mathrm{cm}$	Type IV	10	94	
$dr > 5\,\mathrm{cm}$	Type V	42	95	
$dz_{\mathrm{vtx}} < 0.4\,\mathrm{cm}$	Type I	37	94	
$dz_{\mathrm{vtx}} < 0.4\,\mathrm{cm}$	Type II	17	74	
$dz_{\mathrm{vtx}} < 0.5\,\mathrm{cm}$	Type III	21	75	10.0
$dz_{\mathrm{vtx}} < 0.9\,\mathrm{cm}$	Type IV	36	80	
$dz_{\mathrm{vtx}} < 2\,\mathrm{cm}$	Type V	68	83	
$dr_{\mathrm{fh}} > -2\,\mathrm{cm}$	$r_{\mathrm{vtx}} > 6\,\mathrm{cm}$	32	84	2.9
Recoil mass	Small mass	24	99	4.1
Proton veto	Small mass	94	97	1.6

Limits on N↔$\nu_{e,\mu}$ mixing

- Number of HNL decays detected by Belle:

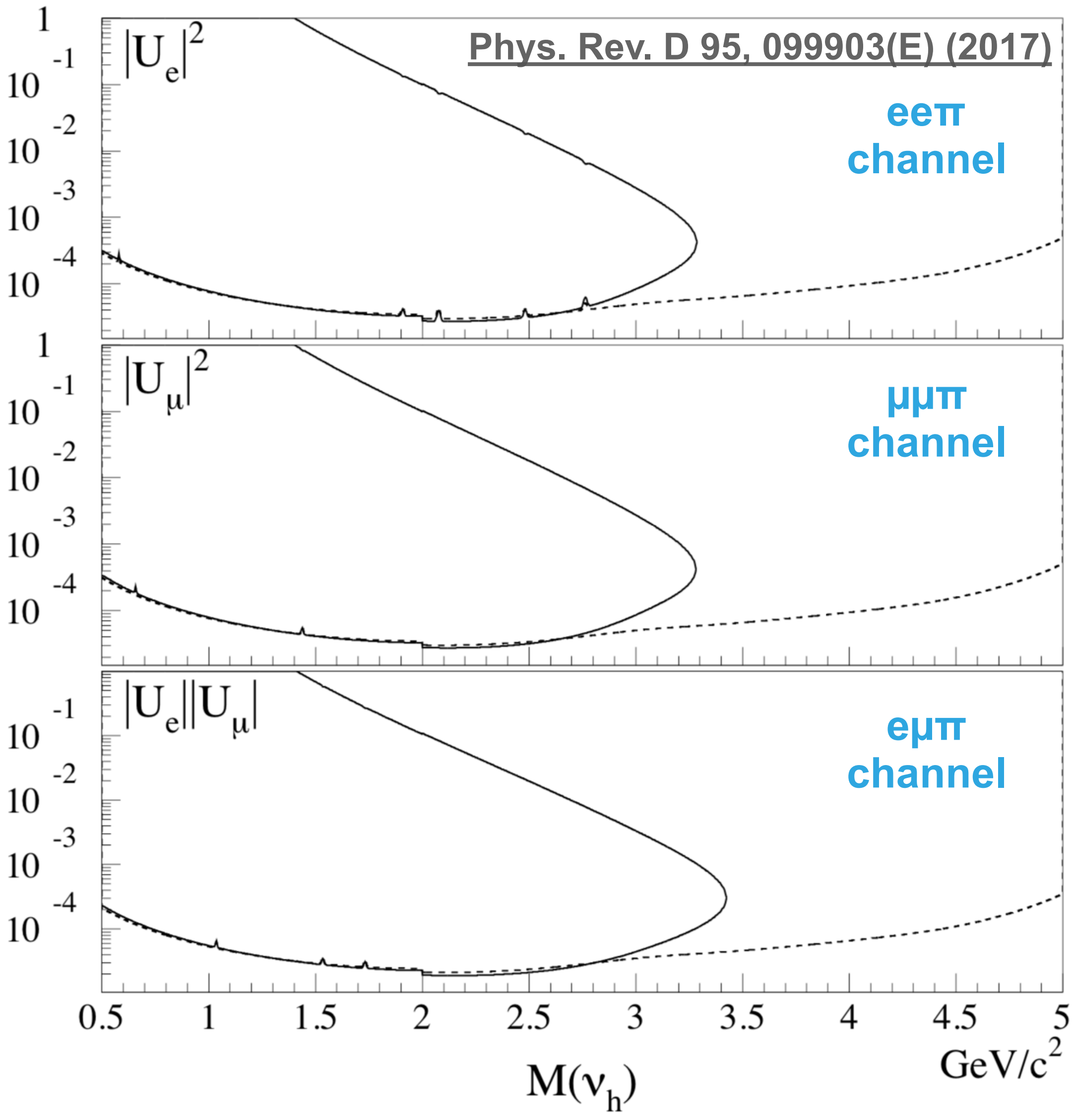
$$n(\nu_h) = 2N_{BB}\ \mathcal{B}(B\to\nu_h)\ \mathcal{B}(\nu_h\to\ell\pi)\int\frac{m\Gamma}{p}\exp\Big(-\frac{m\Gamma R}{p}\Big)\varepsilon(R)dR$$
$$= |U_\alpha|^2|U_\beta|^2\ 2N_{BB}\ f_1(m)\ f_2(m)\ \frac{m}{p}\int\exp\Big(-\frac{m\Gamma R}{p}\Big)\varepsilon(R)dR$$

$\Rightarrow$ solved for $|U|^2$ to obtain upper limits

- Total systematic uncertainty of **25.0%** and **25.4%** for small and large-mass regimes. Largest contributions:
  - χ^2/ndof and dz vertex cuts (10.1%, 10.0%)
  - tracking of HNL daughter particles (8.7% per-track)

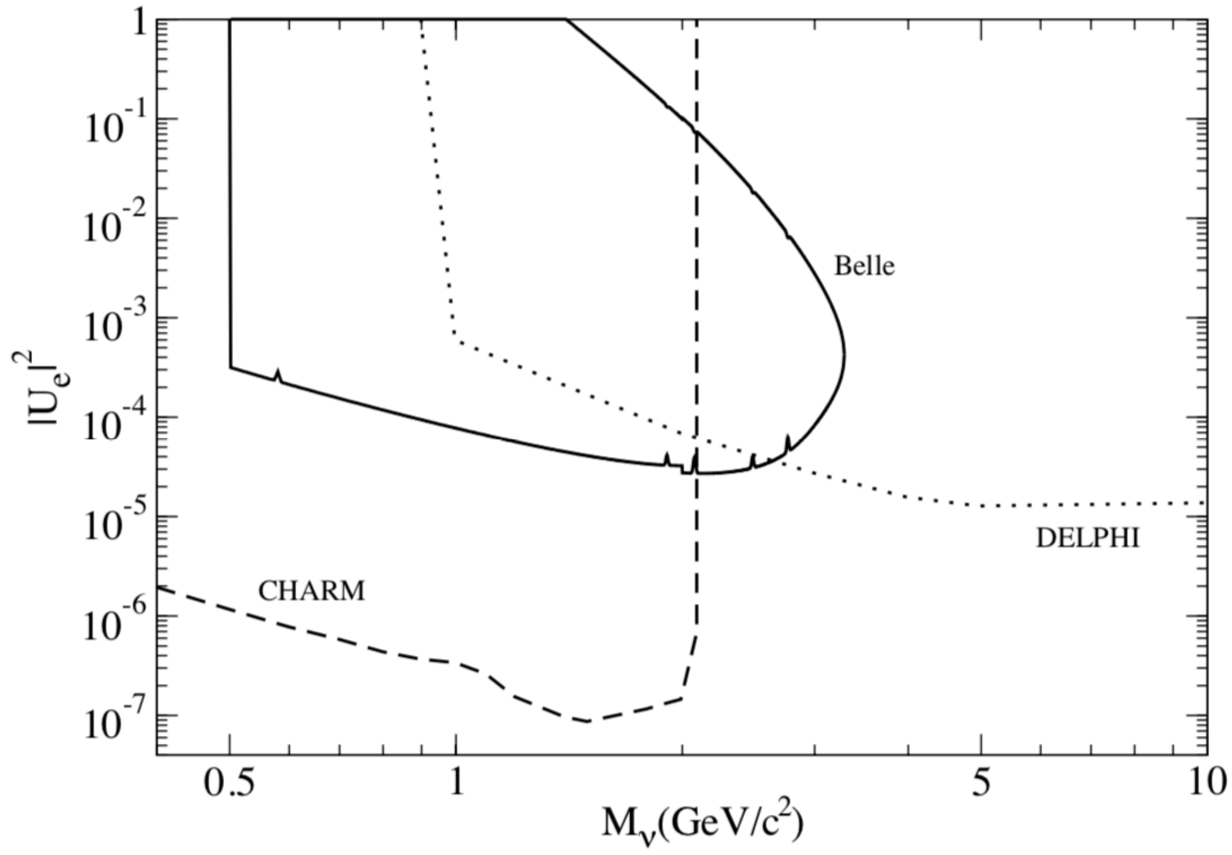
- Maximum sensitivity at $M_N \simeq 2$ GeV
  - **3.0×10^{-5}** for $|U_{eN}|^2$ and $|U_{\mu N}|^2$
  - **2.1×10^{-5}** for $|U_{eN}|\,|U_{\mu N}|$

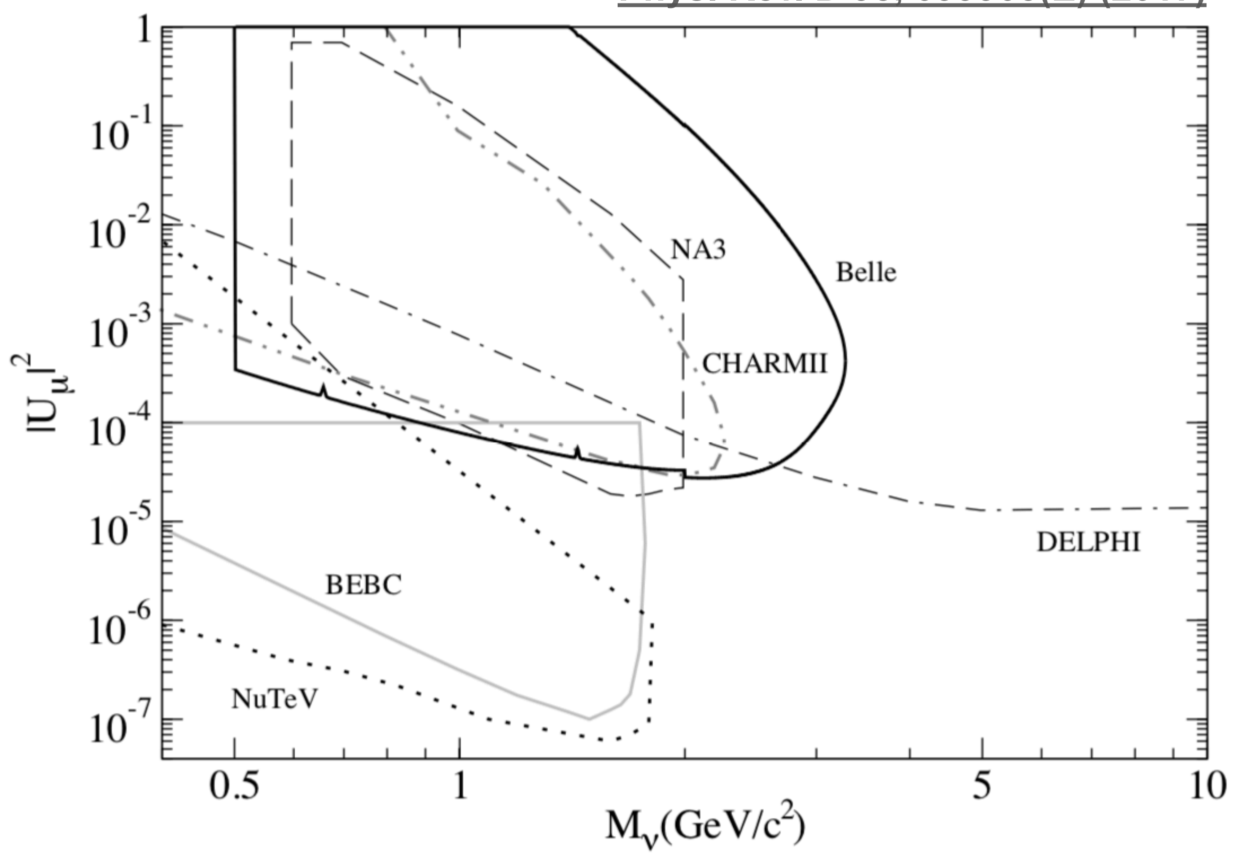
$$\mathcal{B}(B\to X\ell\nu_h)\times\mathcal{B}(\nu_h\to\ell\pi^+) < 7.2\times10^{-7}$$



Comparison with other experiments

Phys. Rev. D 95, 099903(E) (2017)





- Results are shown from Belle, CHARM, CHARMII, DELPHI, NuTeV, BEBC and NA3

B→μN search at Belle

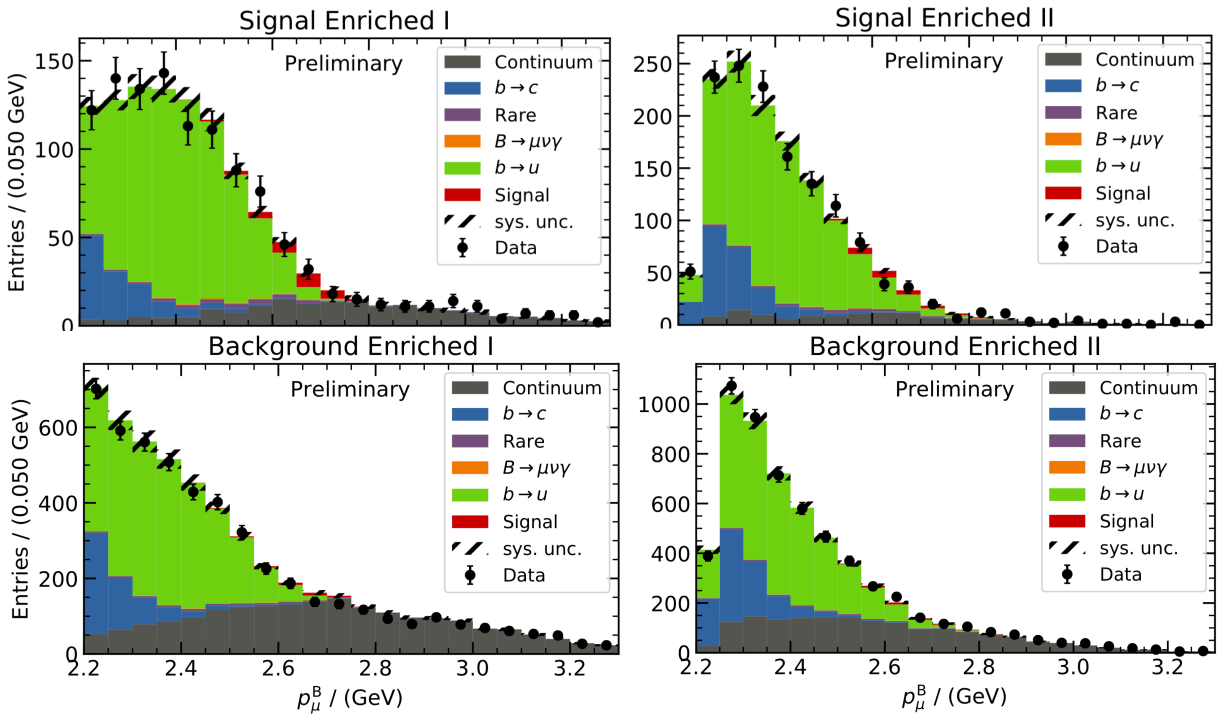
- Recent result on SM **B→μν$_\mu$** from Belle (talk @ Moriond EW 2019, *M. Prim* et al.)

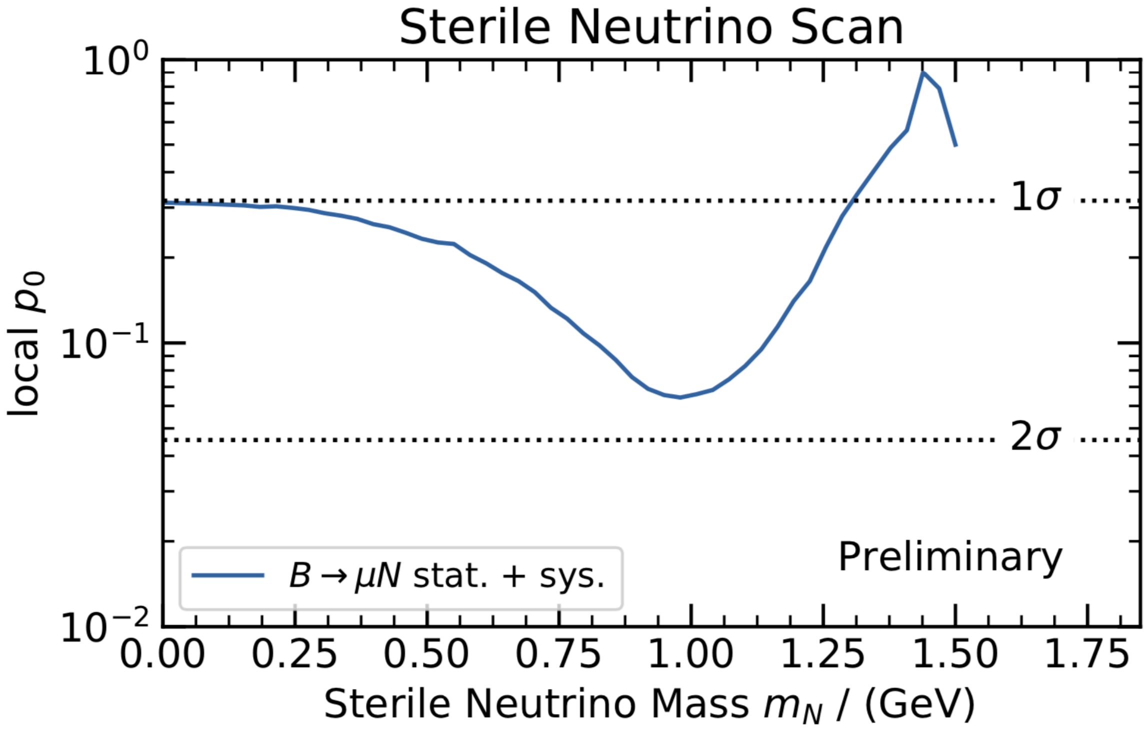
$$\mathcal{B}(B \to \mu\nu_\mu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7} \text{ @ } 2.8\,\sigma$$

SM = 4.26 × 10^{-7}

- μ recoil against HNL (**N→invisible**) would shift momentum spectrum
  ⇒ **SM result recast with M$_N$ scan**

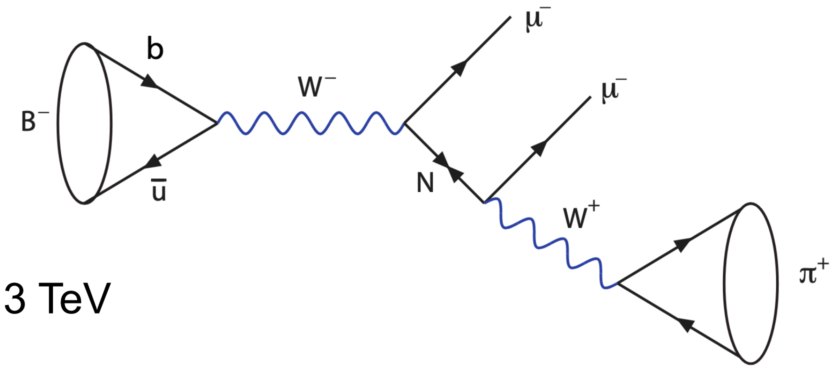
$$\mathcal{B}(B \to \mu + \text{missing energy}) = \mathcal{B}(B \to \mu\nu_\mu) + \mathcal{B}(B \to \mu N)$$

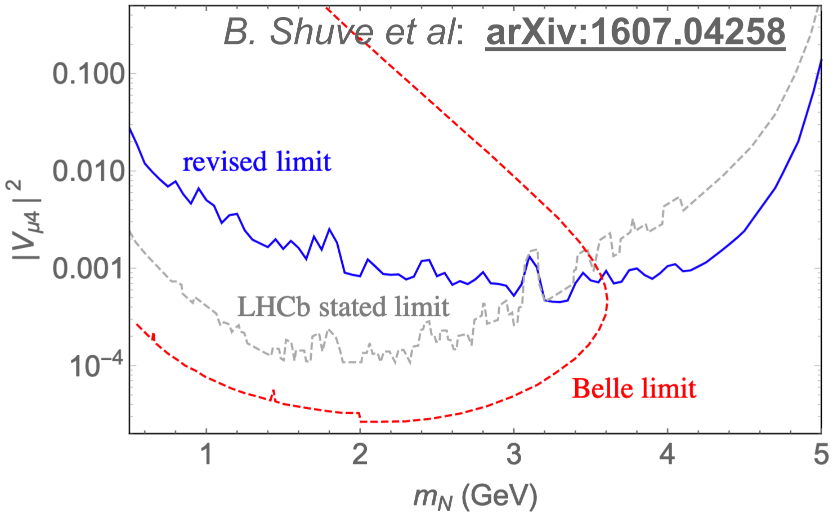


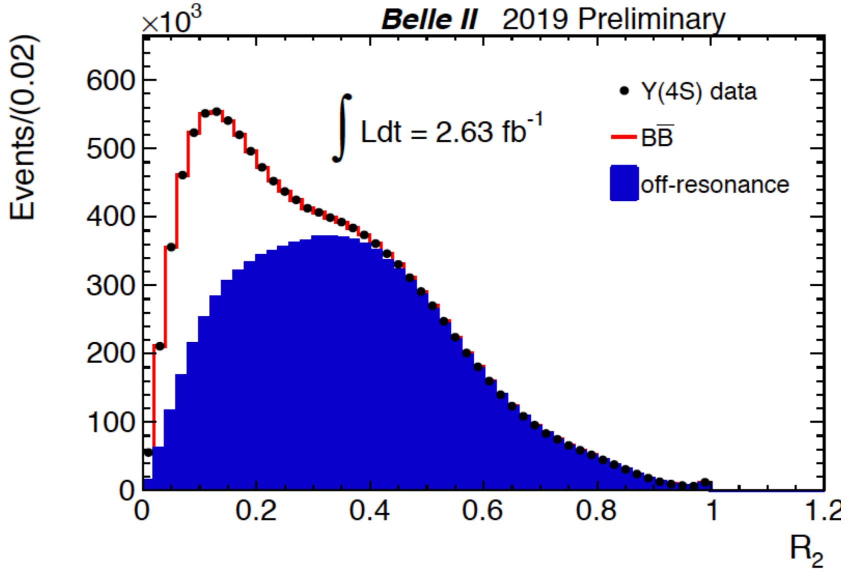


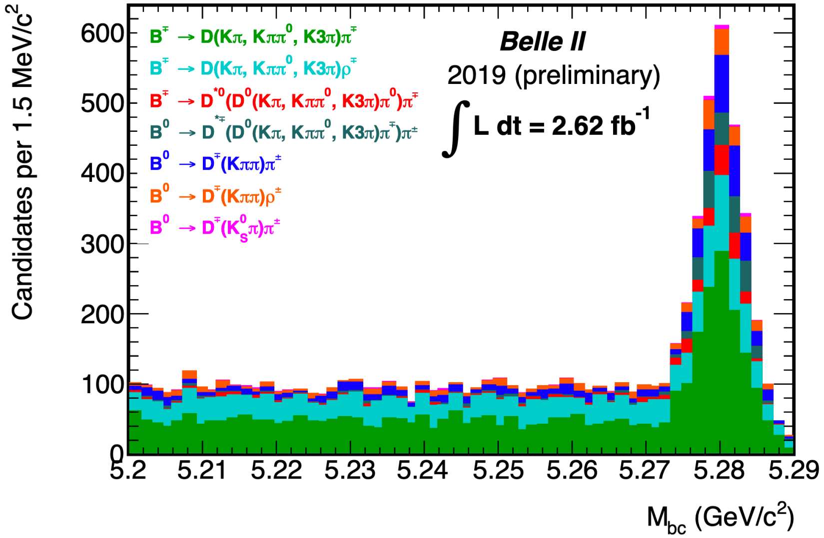
LHCb and Belle II Prospects

- Since the Belle result, **LHCb** has also performed a Majorana HNL search with displaced vertex in *B* decays
- 3fb^{-1} of pp data at $\sqrt{s}$=7,8 TeV
- Approaching the Belle limits
- Updated results are expected using the Run 2 dataset at $\sqrt{s}$=13 TeV





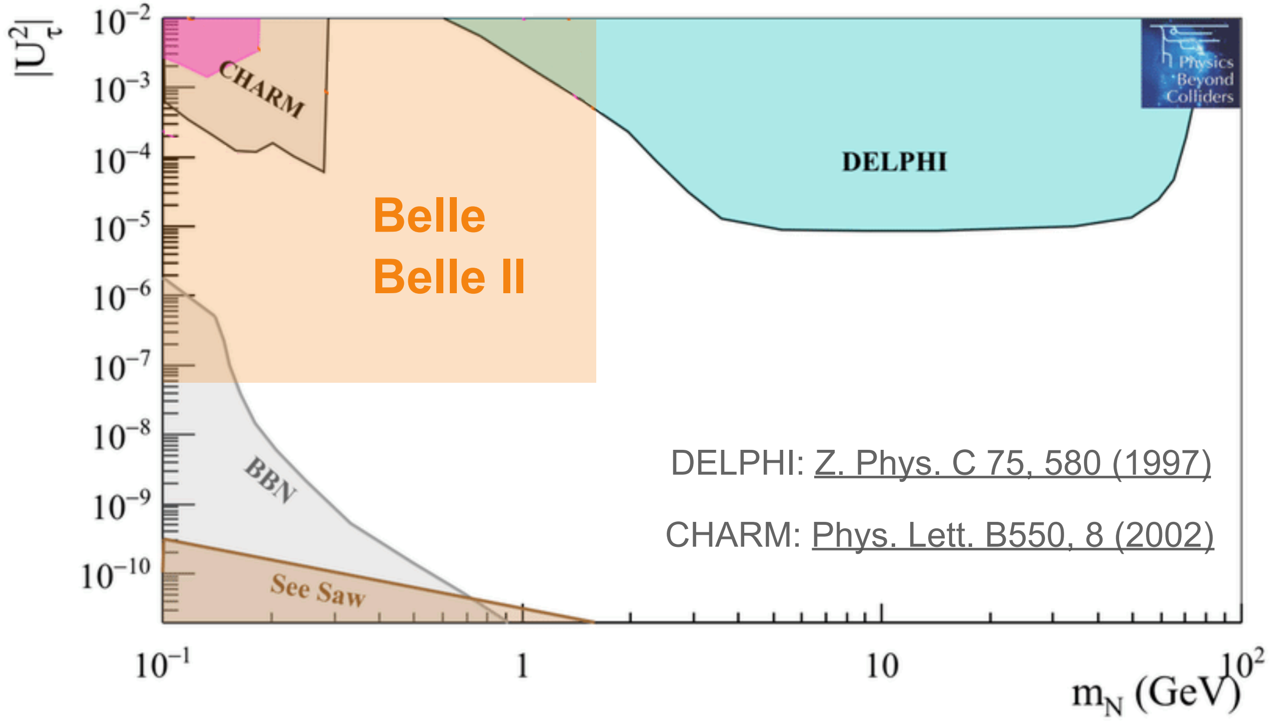




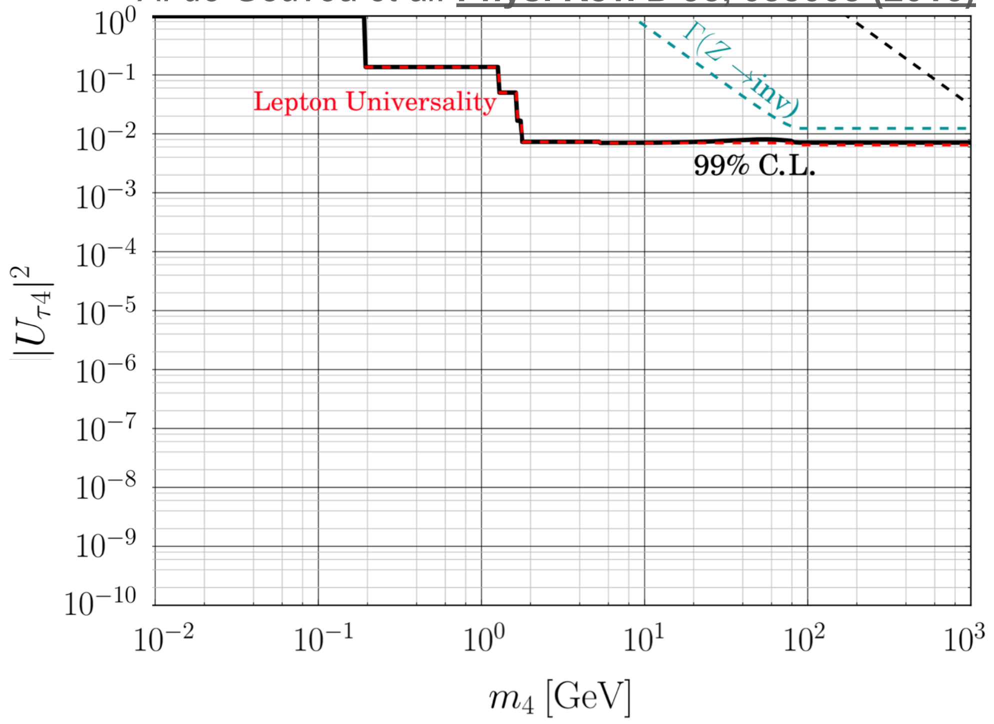
- *B*-physics @ **Belle II** is in the early stages
- Rediscovery of known $B\overline{B}$ decays using Phase 2 and early Phase 3 data
- **Belle II will be a major player in HNL physics via *B*-decays in the near future!**

Constraints on N↔ν_τ mixing

- Tight limits already exist on HNL mixing with ν_e and ν_μ
- Limits on $|U_{\tau N}|^2$ are weaker, motivating $|U_{\tau N}|^2 \gg |U_{eN}|^2, |U_{\mu N}|^2$
  - **Global constraints** ⇒ below $\mathcal{O}(10^{-2} - 10^{-1})$, for M_N > 200 MeV
  - **CHARM** ⇒ below $\mathcal{O}(10^{-4} - 10^{-1})$, for 20 MeV < M_N < 300 MeV
  - **DELPHI** ⇒ below $\mathcal{O}(10^{-5} - 10^{-3})$, for 1 GeV < M_N < 60 GeV



A. de Gouvêa et al: Phys. Rev. D 93, 033005 (2016)

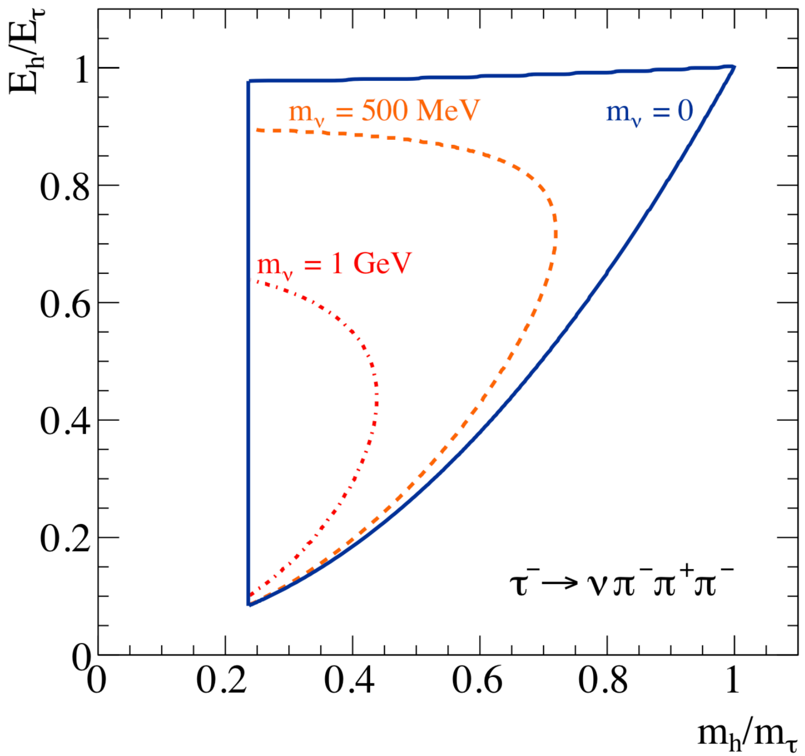


- By studying τ decays at **Belle** and **Belle II**, we can improve existing limits for $M_N < M_\tau$
- **No measurement yet!**
  Sensitivity studies will be shown in coming slides.

HNL in τ decay kinematics

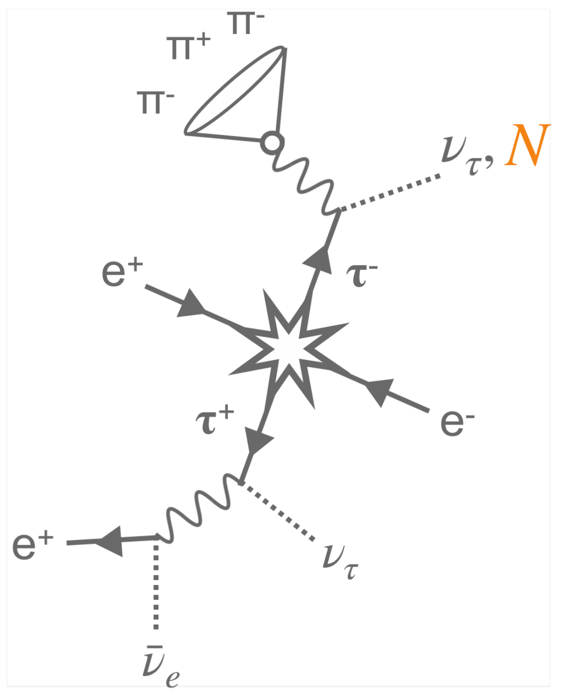
- Proposed search for HNL in $\tau \rightarrow 3\pi\nu$ decays *A. Kobach et al.* **arXiv:1412.4785v2**
- Phase space of 3π-system could be superposition of massless neutrinos and HNL

$$\frac{d\Gamma_{\rm tot}(\tau^- \to \nu h^-)}{dm_h dE_h} = (1-|U_{\tau 4}|^2)\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{m_\nu=0} + |U_{\tau 4}|^2 \left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{m_\nu=m_4}$$



- Kinematics of **τ** decay will contain info on whether 3π recoiled against HNL
- **General idea**:

  Measure a crescent-shaped endpoint in the $E_{3\pi}$-$M_{3\pi}$ plane

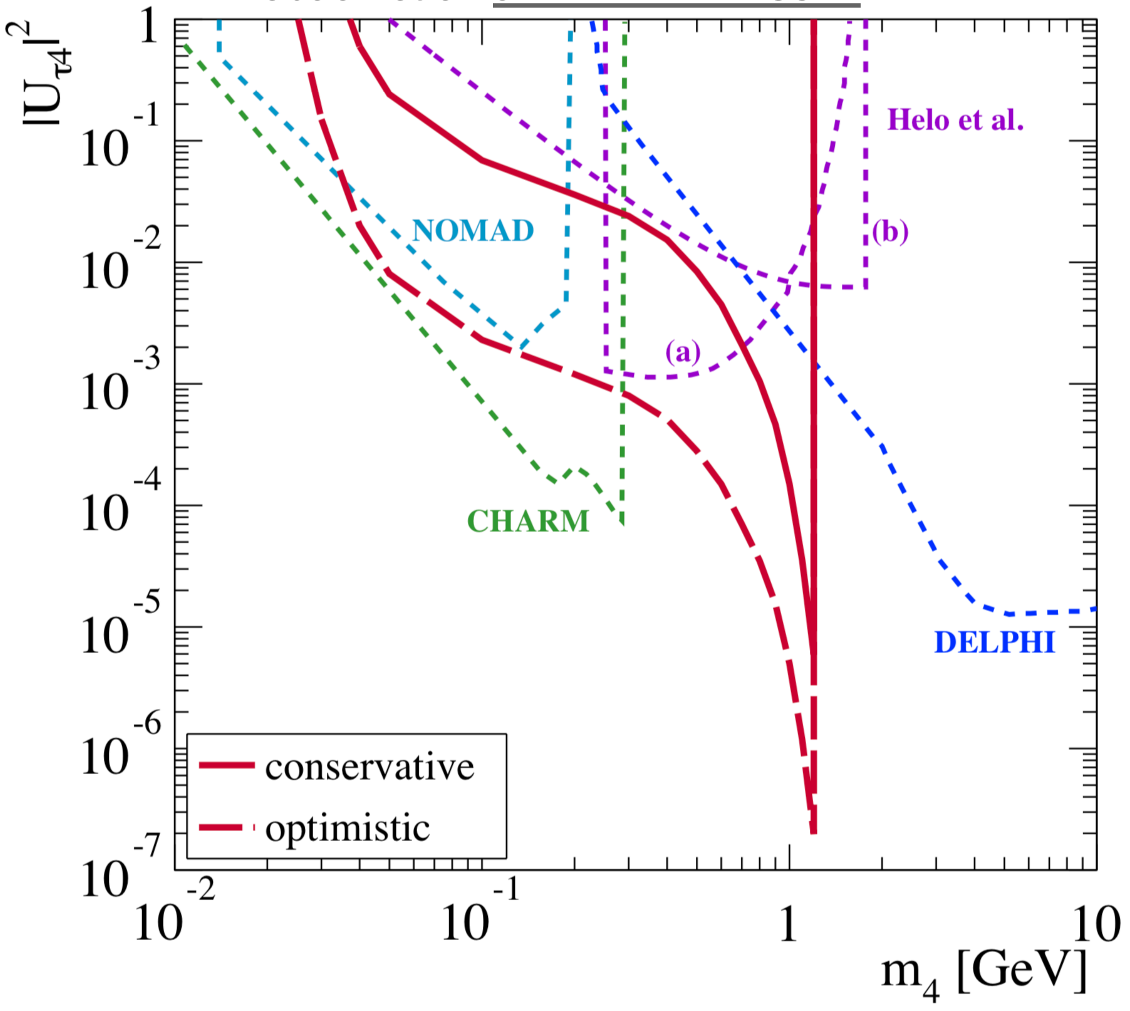


- Method is insensitive to details of HNL decay, lifetime or whether it is Majorana/Dirac
- Would require large data statistics and excellent E/M resolution

  ⇒ Possible at Belle and Belle II!

HNL in τ decay kinematics

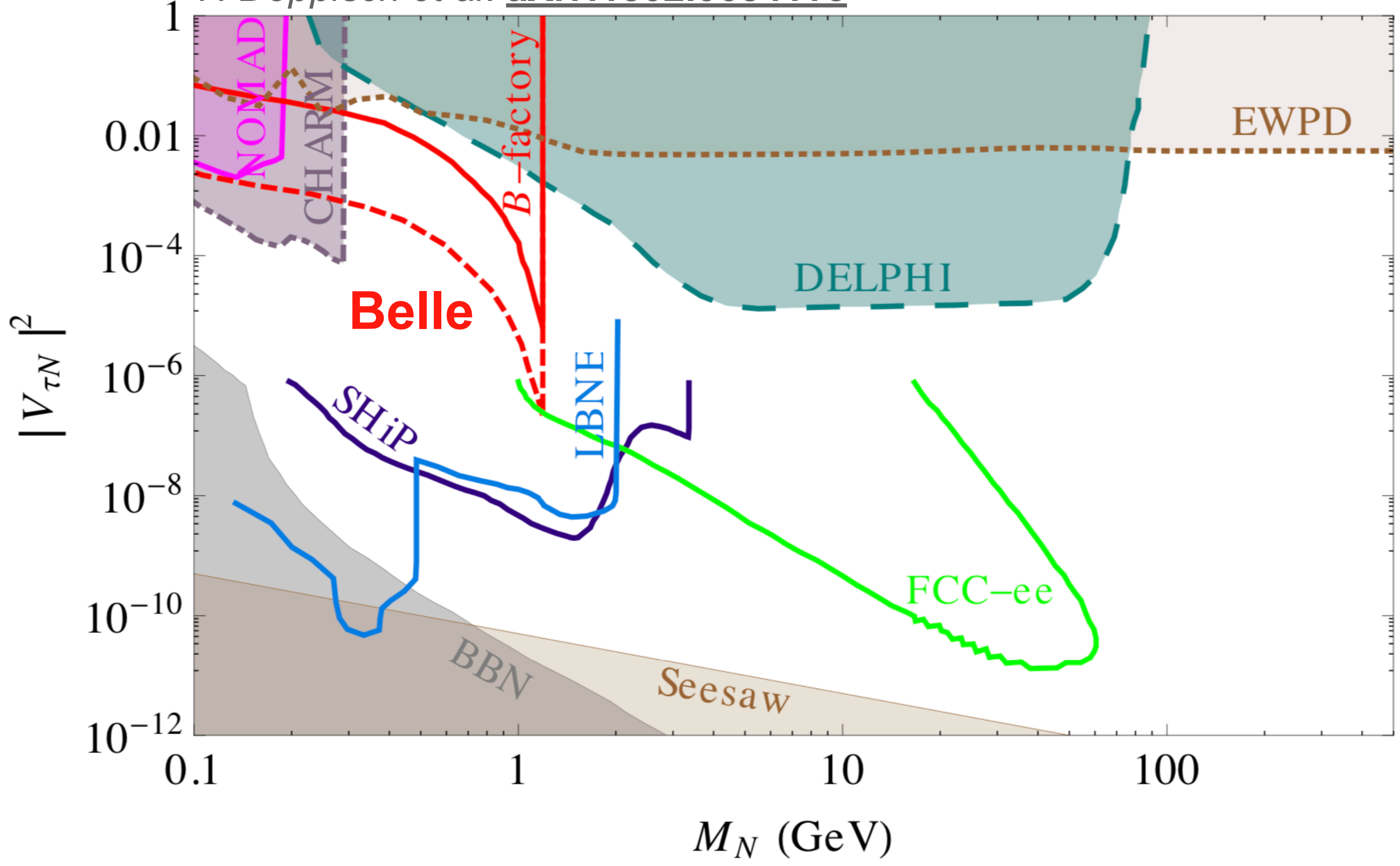
A. Kobach et al. **arXiv:1412.4785v2**



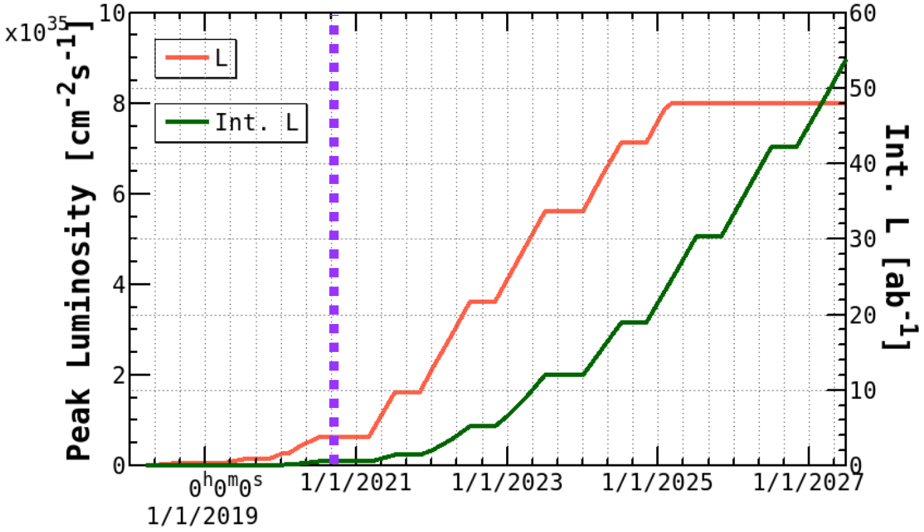
- Sensitivity estimate based on pseudo-data study
- MC sample of ee→ττ with τ→3πν decay(s)
  - assuming Belle lumi, √s=11 GeV
  - smearing to mimic typical Belle resolution
  - both optimistic and conservative scenarios wrt systematics
- **Belle** may be able to place stringent limits on $|U_{\tau N}|^2$ as low as $\mathcal{O}$(**10^{-7}** - **10^{-3}**) for **100 MeV ≲ M_N ≲ 1.2 GeV**

Belle vs upcoming experiments

F. Deppisch et al: **aXiv:1502.06541v3**



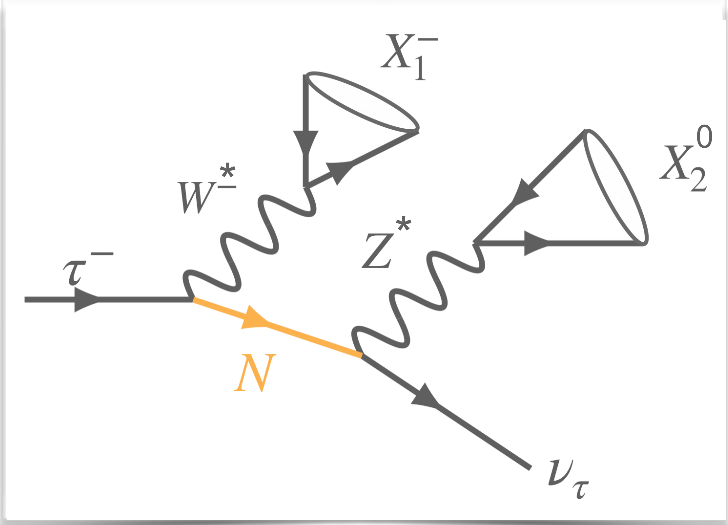
- **Belle** (1 ab^{-1}) compared to future experiments (**SHiP**, **LBNE**, **FCC-ee**)

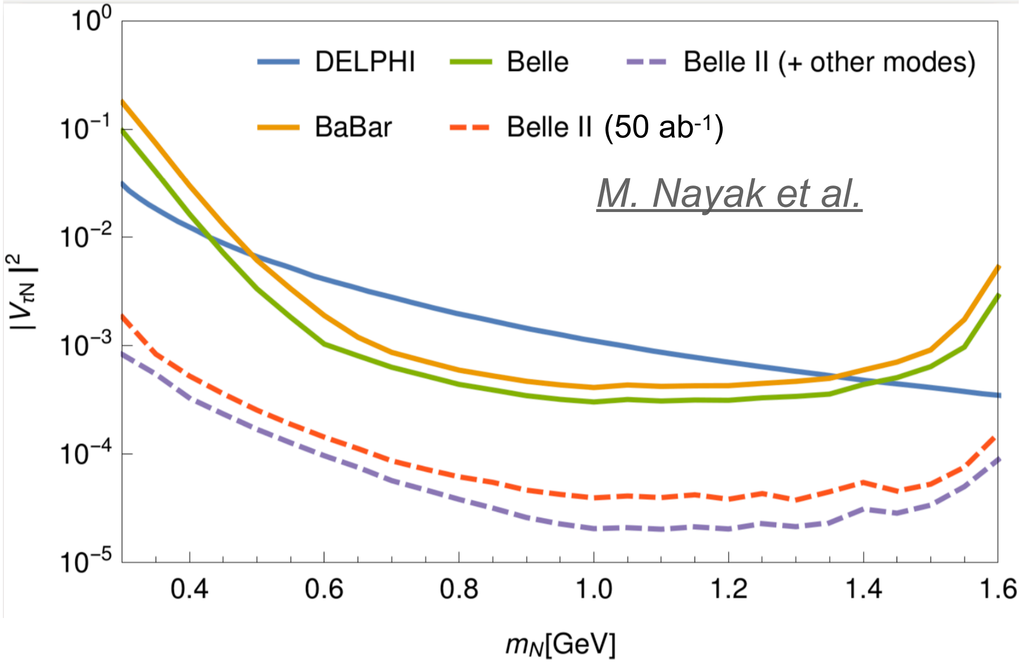


- **Belle II should exceed Belle in 2020** (50x statistics by 2027)

Search for HNL vertex with taus

- Proposed search for displaced HNL vertex in $ee \to \tau\tau \to$ 1x3 prong
- For $|U_{\tau N}|^2 \gg |U_{eN}|^2, |U_{\mu N}|^2$ and $m_N < m_\tau$, decay occurs via $N \to \nu_\tau (Z^* \to X^0)$
- For this preliminary sensitivity study:
  - **X_1** restricted to π or $\pi\pi^0$
  - **X_2** restricted to $\mu\mu$ or **ee** (hadronic X_2 could enter final analysis)
- Long lifetime ($c\tau \propto |U_{\tau N}|^{-2} m_N^{-5}$) $\Rightarrow$ tiny background but low signal efficiency





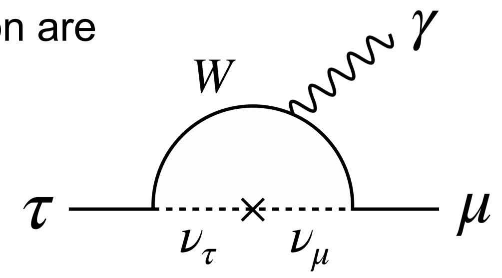
- Bkg suppression driven by $N \to ee/\mu\mu$ vertex-based constraints and flight length > 10 cm
- Signal yields extracted from fit to reconstructed M_N distribution
- Assumption of zero background search
  - achievable based on studies with official Belle II MC
  - more comprehensive bkg studies are ongoing

In this channel alone, Belle or Belle II could exceed DELPHI limits!

Constraints from LFV τ decays

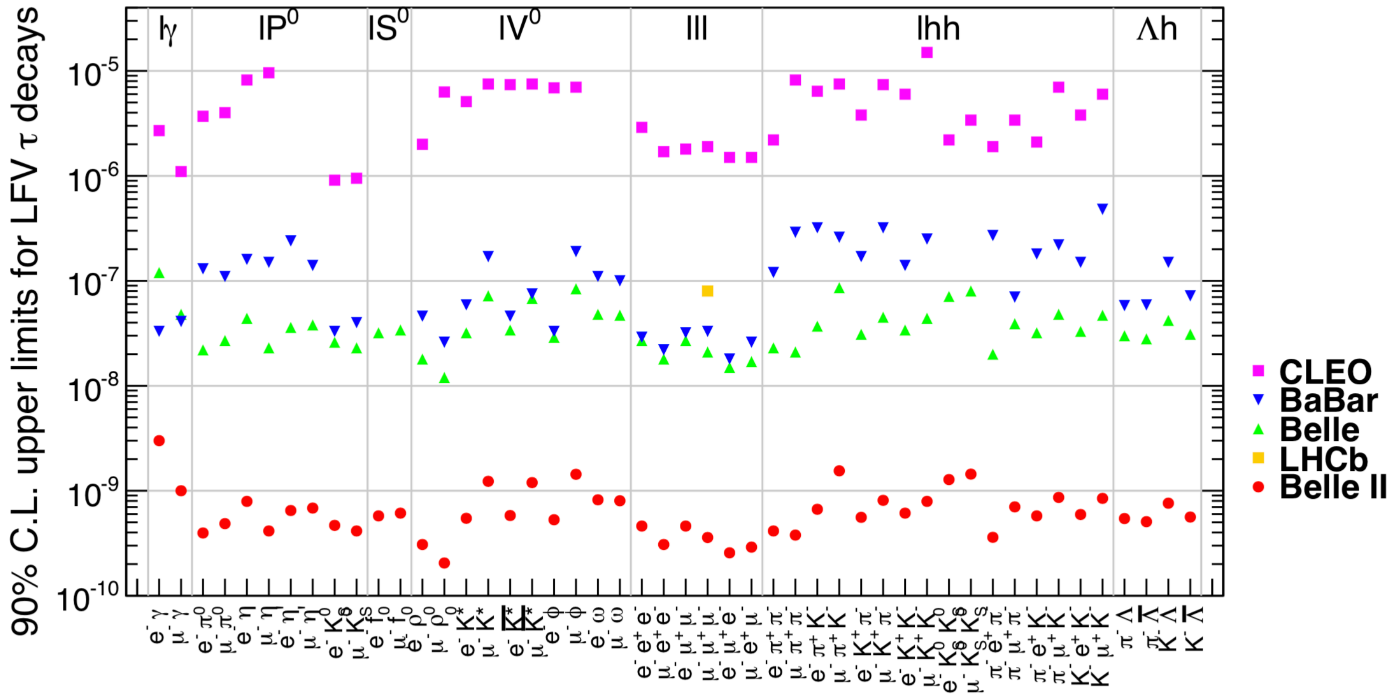
- In SM, charged LFV decays via ν_{SM} oscillation are highly suppressed and immeasurably small

$$Br(\ell_1 \to \ell_2 \gamma)_{SM} \propto \left(\frac{\delta m_\nu^2}{m_W^2}\right)^2 \sim 10^{-54}\text{-}10^{-49}$$

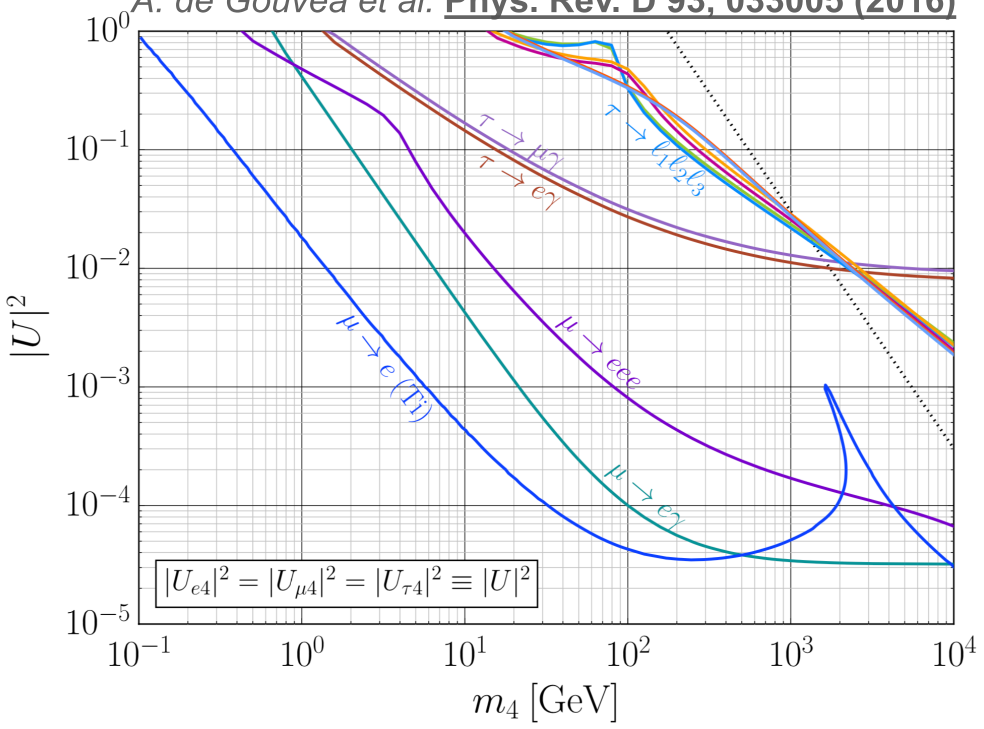


- If there is a HNL with $M_N \gtrsim 1$ MeV, the BR can be enhanced to the point of being observable!

Belle II: **arXiv:1808.10567**



A. de Gouvêa et al: **Phys. Rev. D 93, 033005 (2016)**

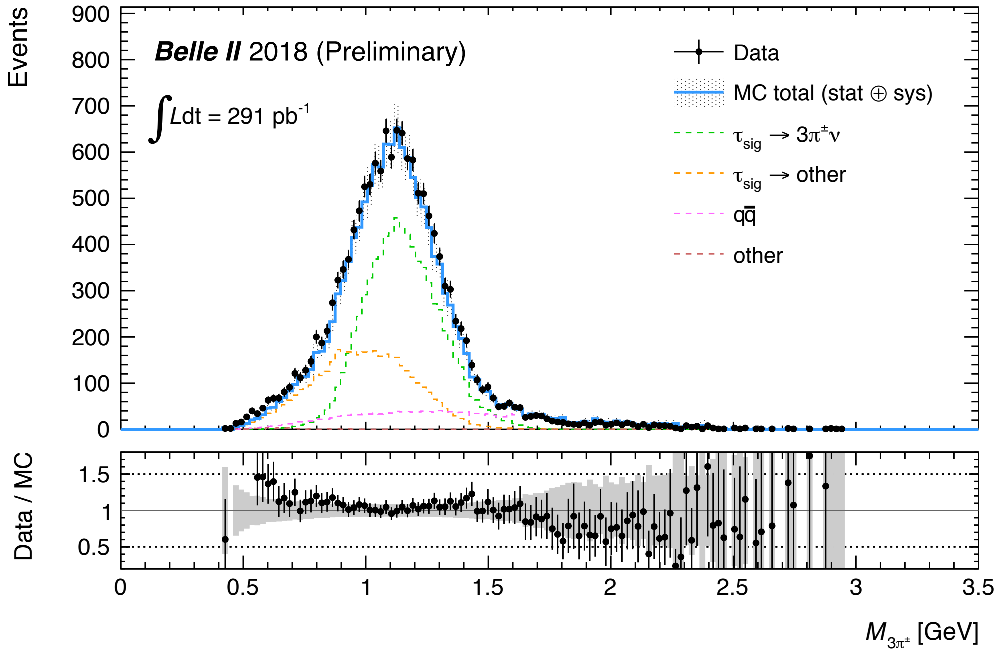


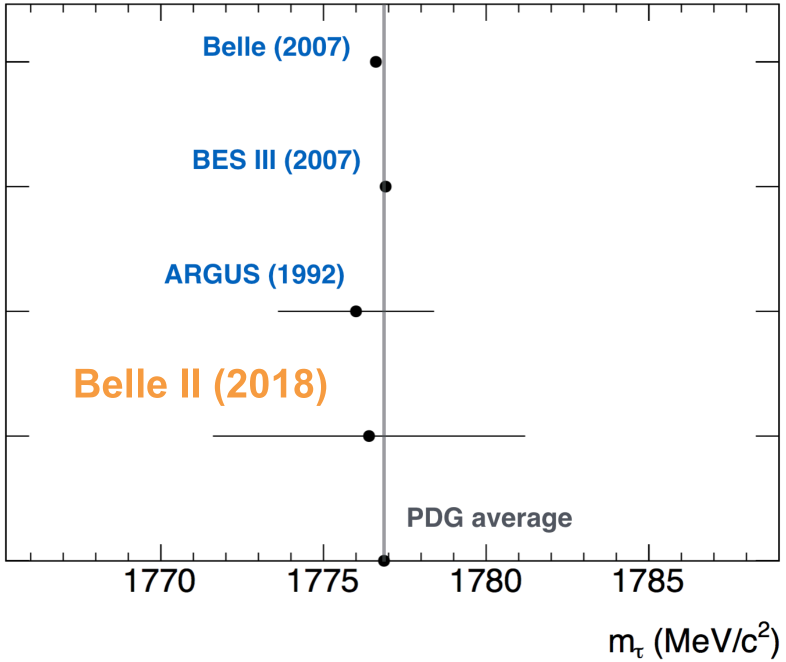
- Searches for LFV **μ→e** and **τ→e/μ** transitions can be re-cast as constraints on **N↔ν_{SM}** mixing
- Constraints on **τ→e/μ** have come mostly from last-gen B-factories (**Belle** and **BaBar**)
  - **Belle II** can improve the existing limits by at least one order of magnitude!

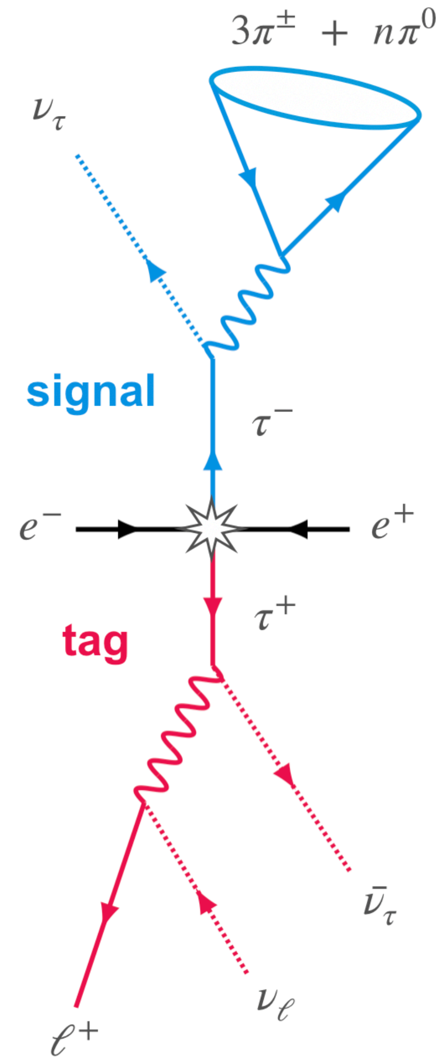
Tau leptons in early Belle II data

- As with *B*-physics, the τ-physics program at Belle II is in the early stages
- Rediscovery of ee→$\tau\tau$ targeting 3-by-1 prong decay: $\tau_{tag} \rightarrow \ell^{\pm} \nu_{\ell} \bar{\nu}_{\tau}$ $\tau_{signal} \rightarrow 3\pi^{\pm} \nu_{\tau} + n\pi^{0}$
- We observe clear evidence of τ-pair production in the Phase 2 data
- First measurement of **m_τ @ Belle II** by fitting M_{min} to an empirical edge pdf from 1.7-1.85 GeV

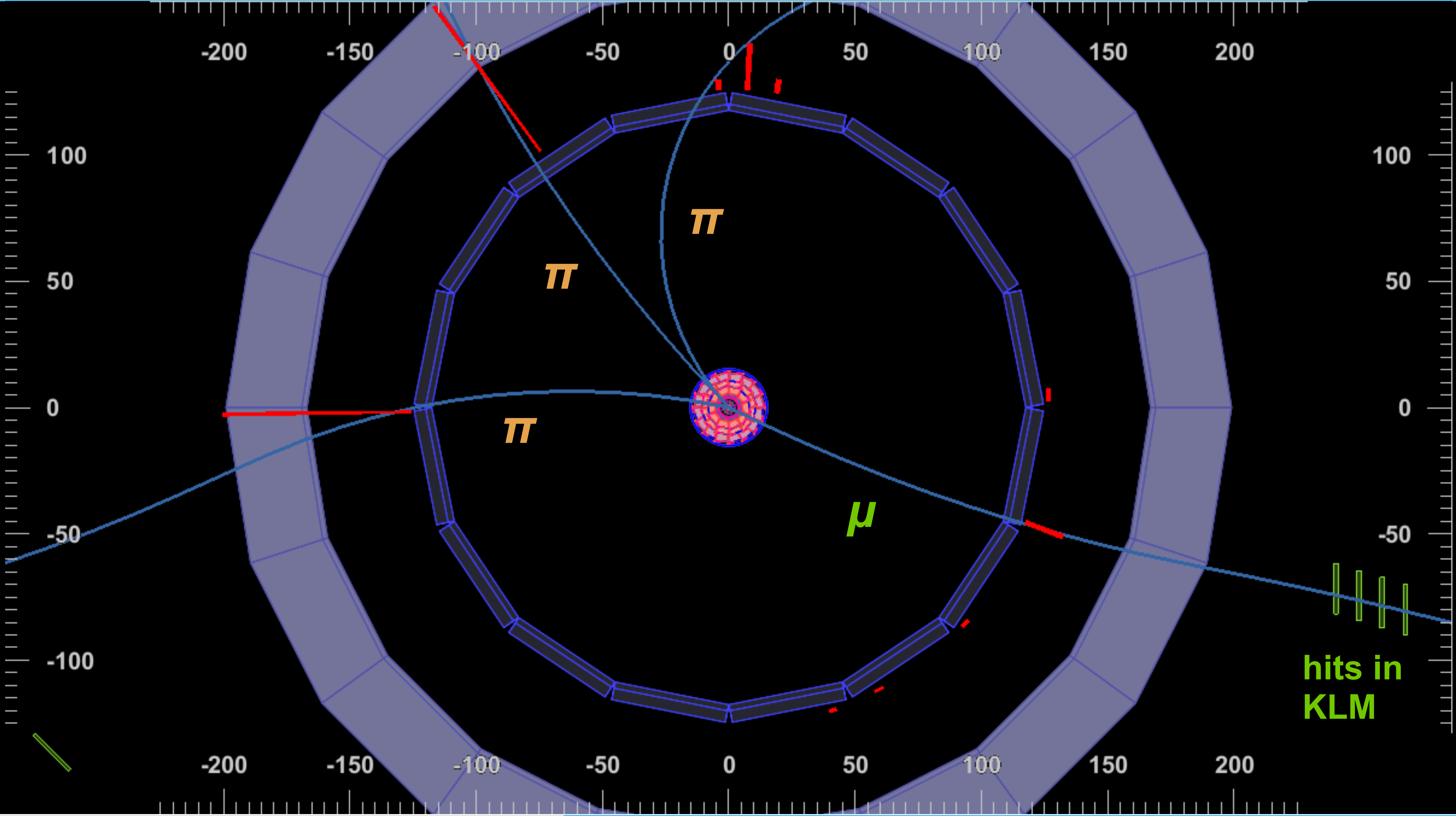
$$M_{min} = \sqrt{M_{3\pi}^2 + 2(E_{beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})}$$







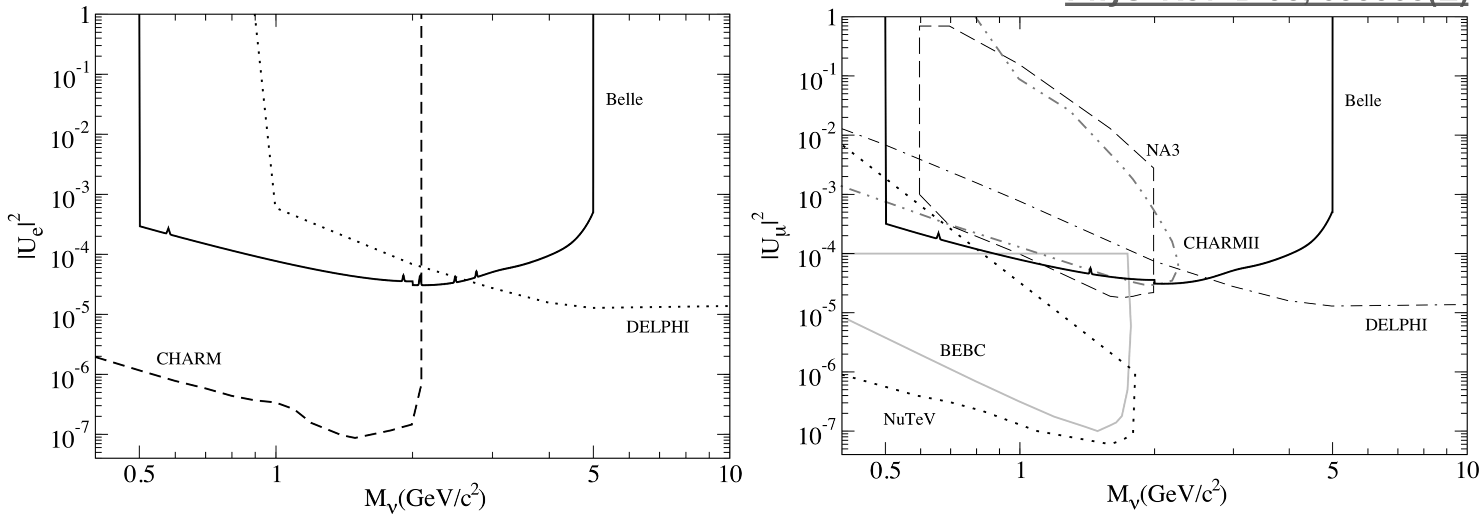
$e^+e^- \rightarrow \tau^+\tau^-$ event candidate



Summary and Outlook

[Phys. Rev. D 95, 099903(E)]

- **Belle** searched for HNL produced in *B* decays with displaced vertex
- Limits were set on $|U_{e,\mu N}|^2$ below $\mathcal{O}(10^{-4}\text{-}10^{-5})$ for $0.5 < M_N < 5.0$ GeV
- M_N scan in recent $B \to \mu\nu_\mu$ result ($N \to$invisible), no significant excess



- Existing constraints on $\mathbf{N \leftrightarrow \nu_\tau}$ mixing are much weaker, motivating scenario where $|U_{\tau N}|^2 \gg |U_{eN}|^2, |U_{\mu N}|^2$. No results yet from **Belle** or **Belle II** with τ decays. Sensitivity studies show promise.
- B- and τ-physics programs at **Belle II** are in the early stage. Rediscoveries of known SM processes.
- **Belle II** will become a major player in HNL physics in the near future. **Exciting times ahead!**