

Neutrino Physics with Belle & Belle II

Petar Rados (KMI, Nagoya University)

On behalf of the Belle II collaboration

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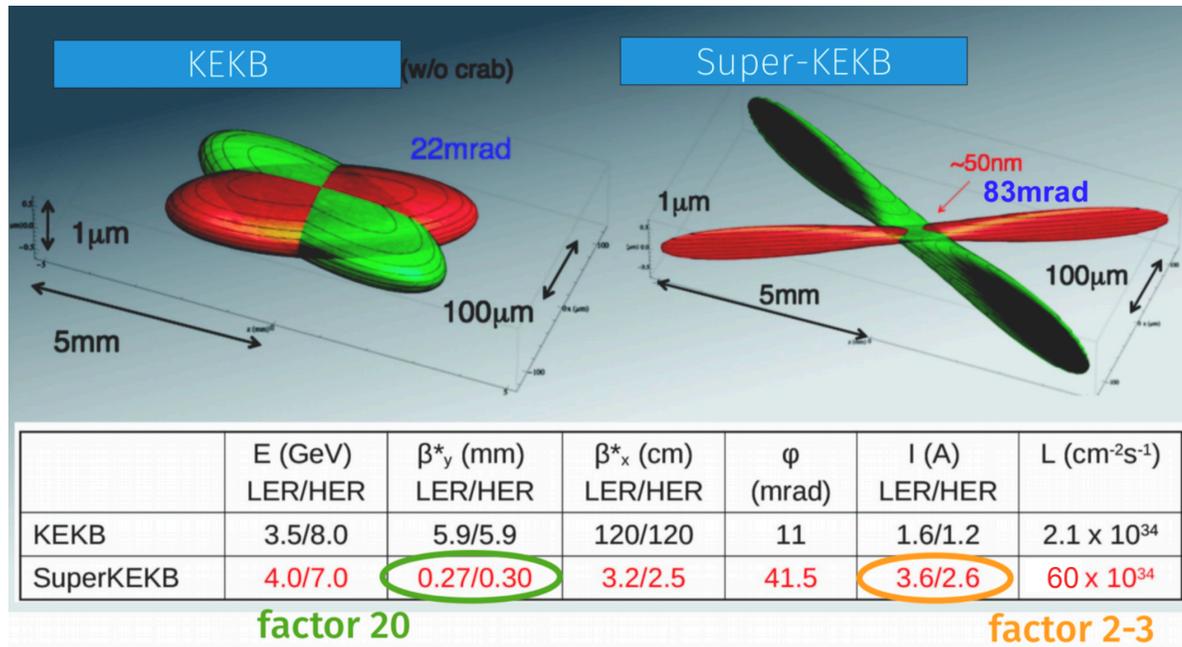


Kobayashi-Maskawa Institute
for the Origin of Particles and the Universe



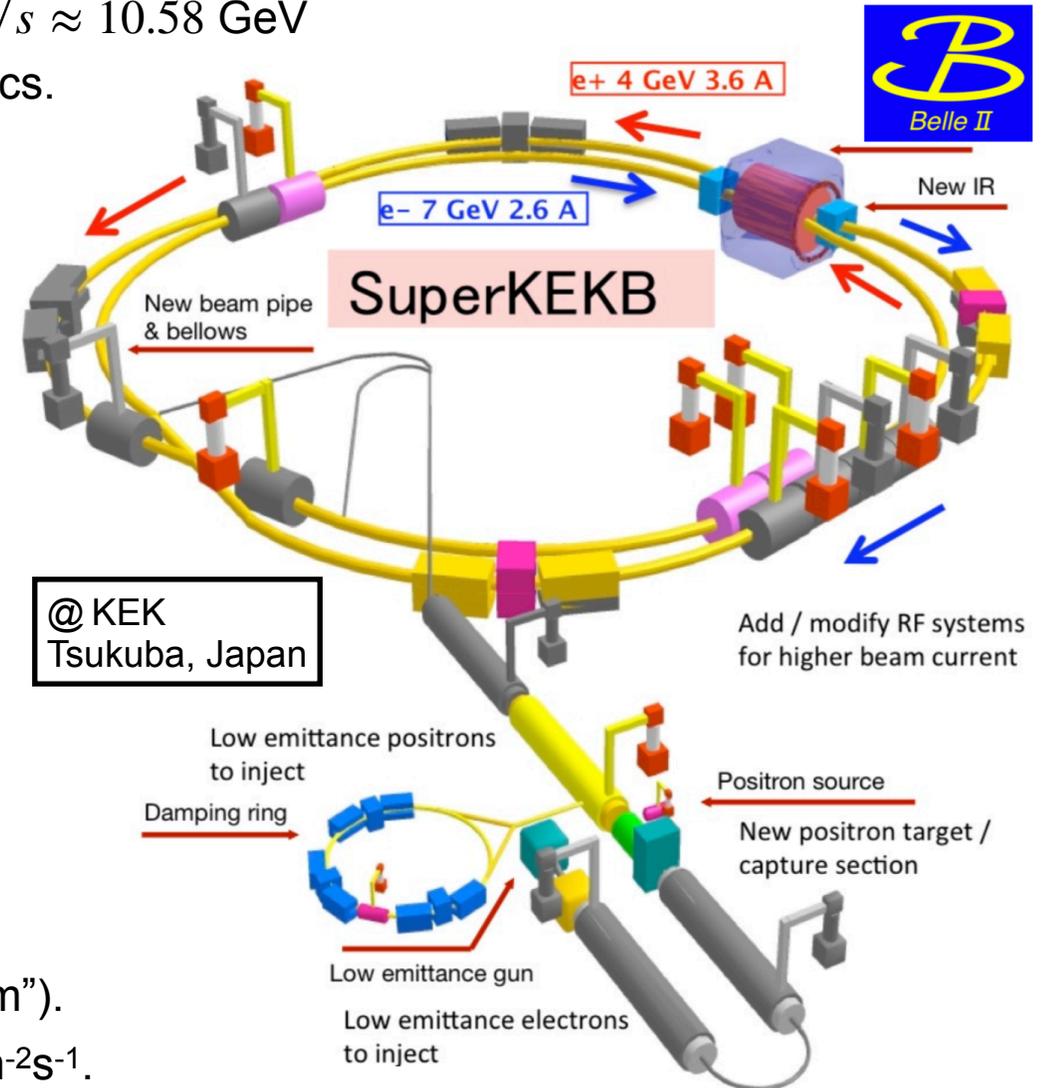
Accelerator

- **SuperKEKB**: next generation B-factory $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$, $\sqrt{s} \approx 10.58$ GeV
+ rich program of tau, dark sector and other low-multiplicity physics.

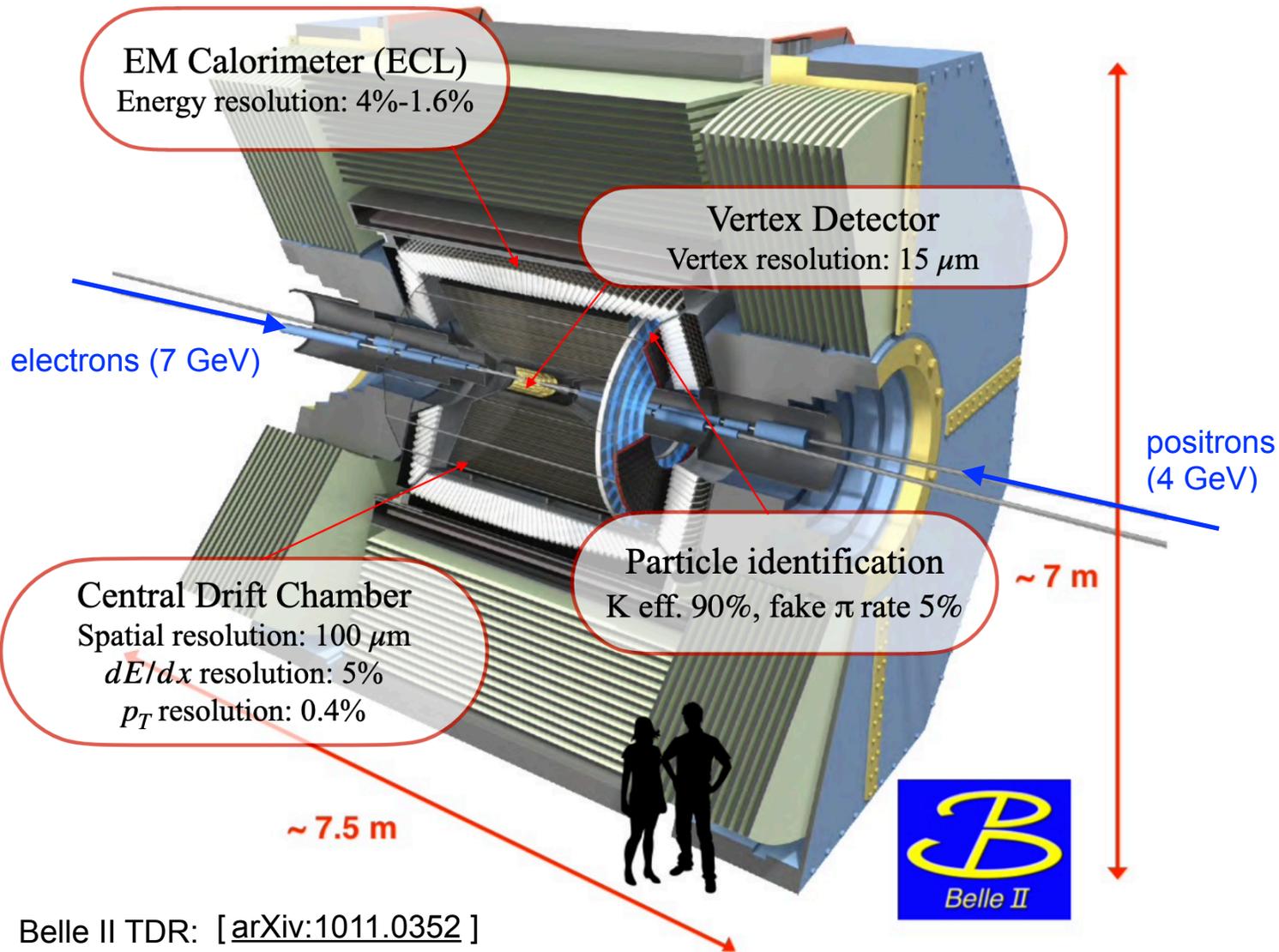


- **KEKB** → **SuperKEKB** accelerator

- ▶ 2x beam currents, 50nm vertical beam spot size (“nano beam”).
- ▶ Unprecedented design luminosity: $2.1 \times 10^{34} \rightarrow \sim 6.0 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$.

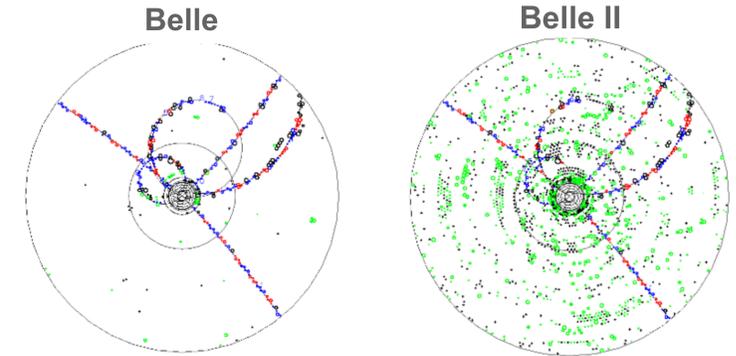


Detector



Belle II TDR: [arXiv:1011.0352]

- Consequently Belle II has higher beam backgrounds and event rates.



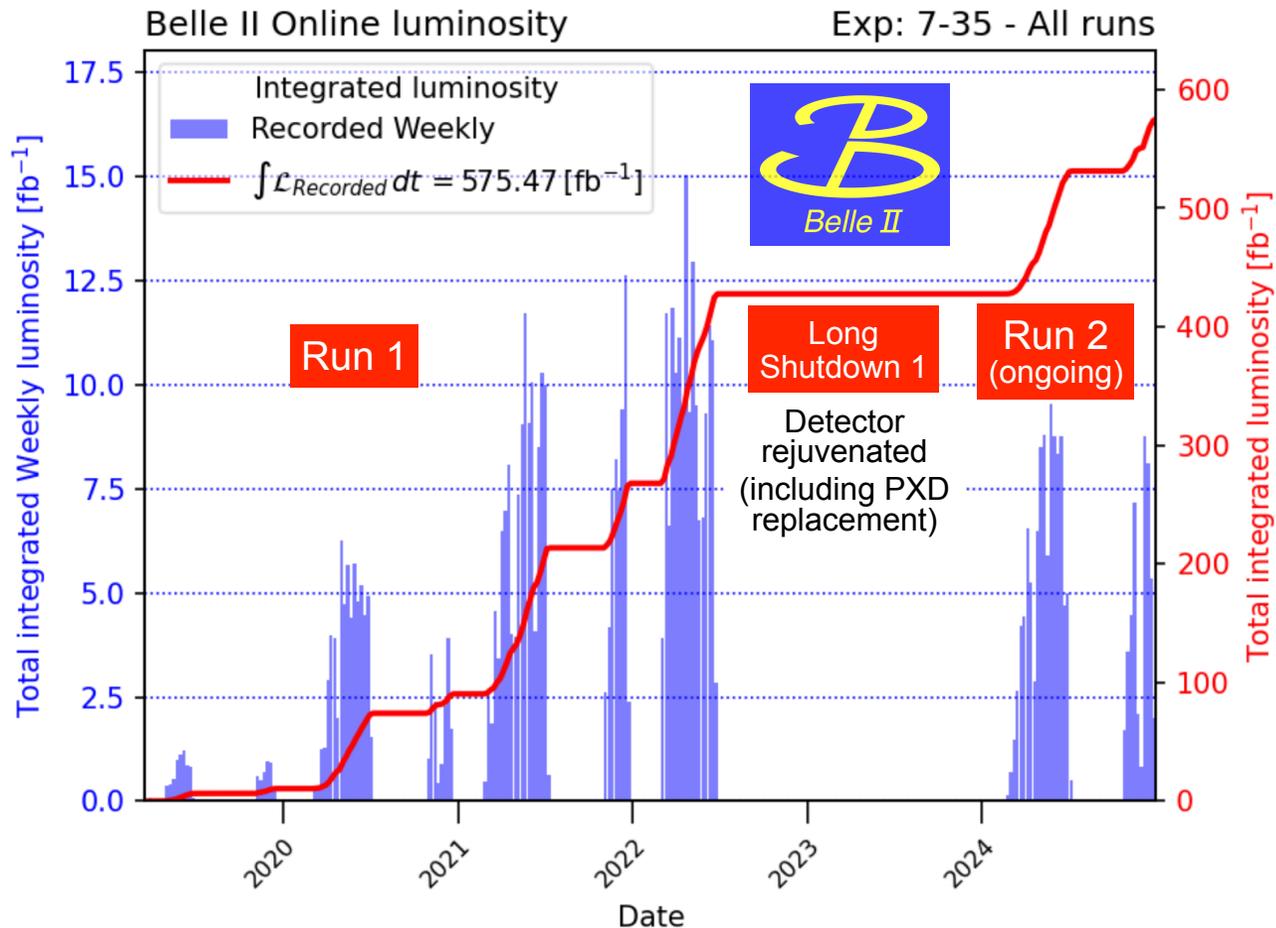
- **Belle** \rightarrow **Belle II** detector

- ▶ 2-layer Pixel Detector (**PXD**) with first layer at 1.4cm, significantly improves vertexing.
- ▶ 4-layer Silicon Vertex Detector (**SVD**) with larger acceptance.
- ▶ Central Drift Chamber (**CDC**) with larger outer radius.
- ▶ Improved particle ID: **TOP** + new **ARICH** (K/ π separation).
- ▶ Improved **trigger**, and faster electronics in general.

Performance to date

- **Belle** integrated luminosity from 1999-2010: $\sim 1 \text{ ab}^{-1}$

- **Belle II** from 2019-now: 575 fb^{-1}



Peak instantaneous luminosity

$5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
(new world record)

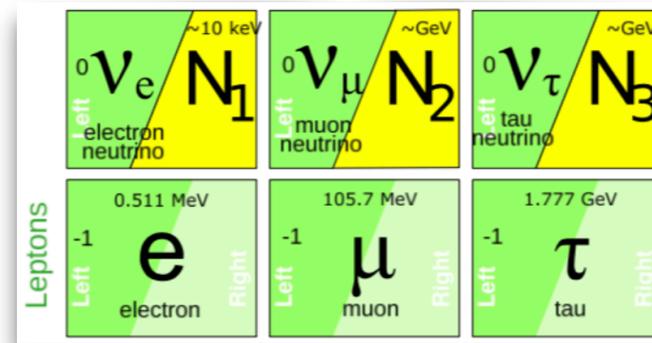
Integrated luminosity

495 fb^{-1} recorded at $\Upsilon(4S)$
 59 fb^{-1} at 60 MeV below $\Upsilon(4S)$,
for background studies
 19 fb^{-1} at 10.75 GeV,
for exotic hadron searches

- Aiming to collect 50 ab^{-1} over the next ~ 10 years (x50 Belle)

Heavy Neutrinos

- Neutrino masses can be incorporated into the SM by introducing heavy sterile neutrino(s).
- They can appear in many NP models, e.g. ν MSM introduces 3 such particles (N_1, N_2, 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 \sim keV)
 - ▶ BAU: leptogenesis via Majorana mass term

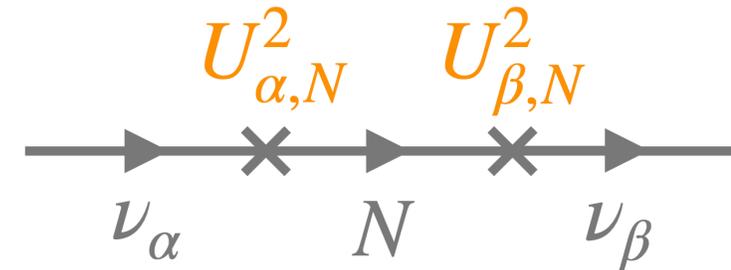
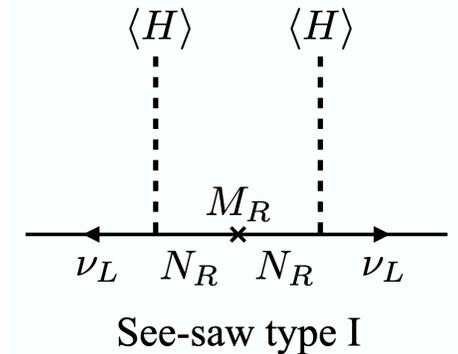


[Phys.Lett.B620:17-26,2005]



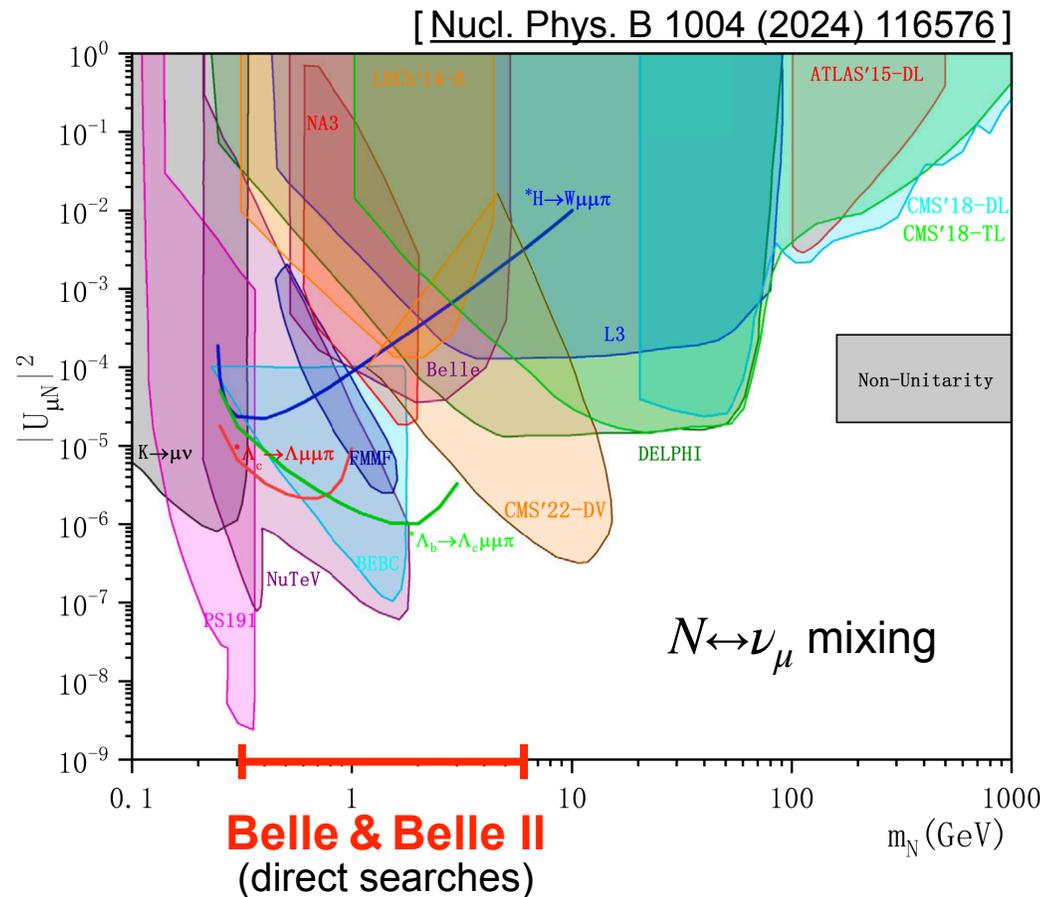
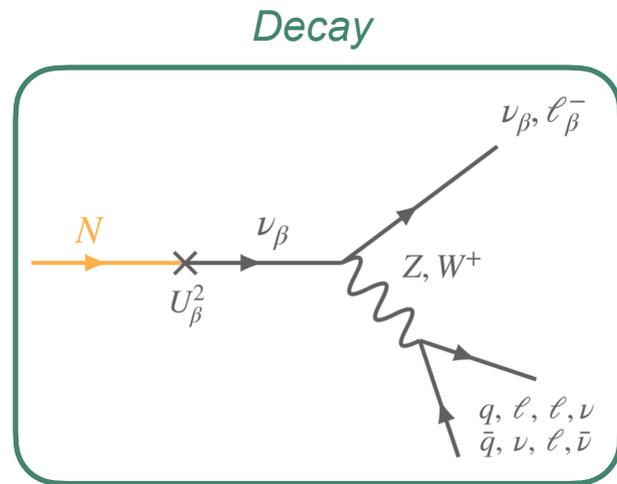
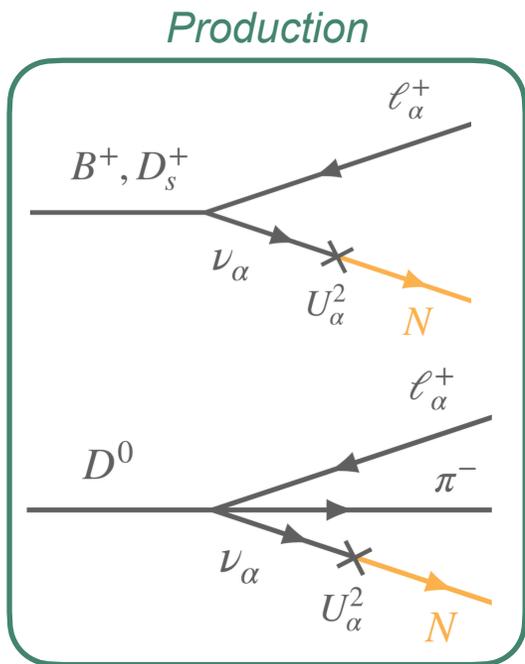
- Although mostly RH, smaller LH component can allow interaction with ν_{SM} via $N \leftrightarrow \nu_{SM}$ mixing.
- Neutrino flavour & mass eigenstates need not coincide, but may be related through a *unitary transformation*
 - ▶ Heavy neutrino *production* via mixing \Rightarrow suppressed by factor $U_{\alpha,N}^2$
 - ▶ Then *decay* (after long flight length) by mixing again \Rightarrow additional $U_{\beta,N}^2$

$$\nu_\alpha = \sum_i U_{\alpha,i} \nu_i \quad \alpha = e, \mu, \tau \quad i = 1, 2, 3, 4, \dots$$



Neutrino Physics at Belle & Belle II

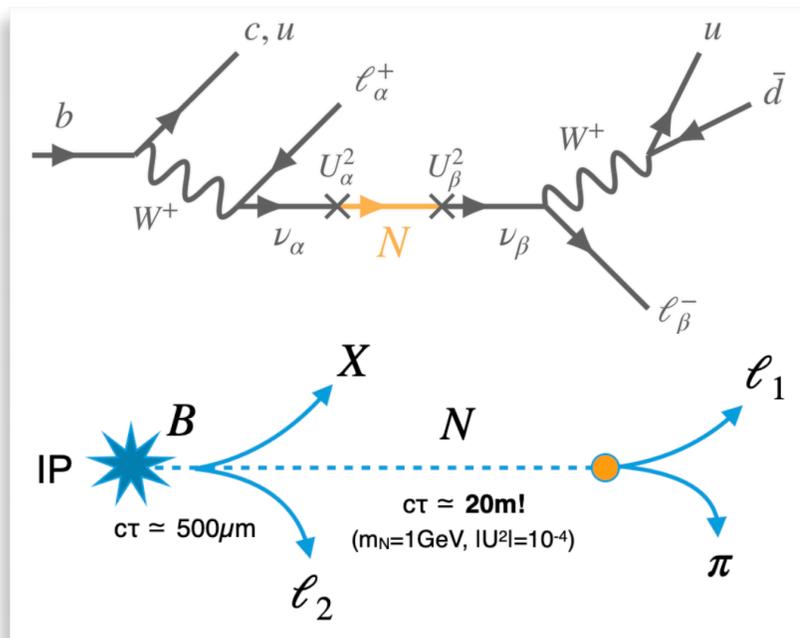
- While not primarily neutrino experiments, both Belle & Belle II are in a unique position to contribute
 - ▶ Well-defined initial state & clean environment, with hermetic detector & excellent vertexing. \Rightarrow Precise missing energy reconstruction (**invisible particles**), & recon. of displaced vertices (**visible decay of long-lived particles**).
 - ▶ **Direct searches** for heavy neutrinos in B & τ decays ($m_N < m_{B,\tau}$)
 - ▶ **Indirect constraints**, particularly from rare/forbidden decays e.g. $B \rightarrow K\nu\bar{\nu}$, $B \rightarrow X_S\nu\bar{\nu}$, $B \rightarrow \ell\nu$, LFV τ decays, ...



Direct searches for heavy neutrinos (displaced vertex) in B and τ decays

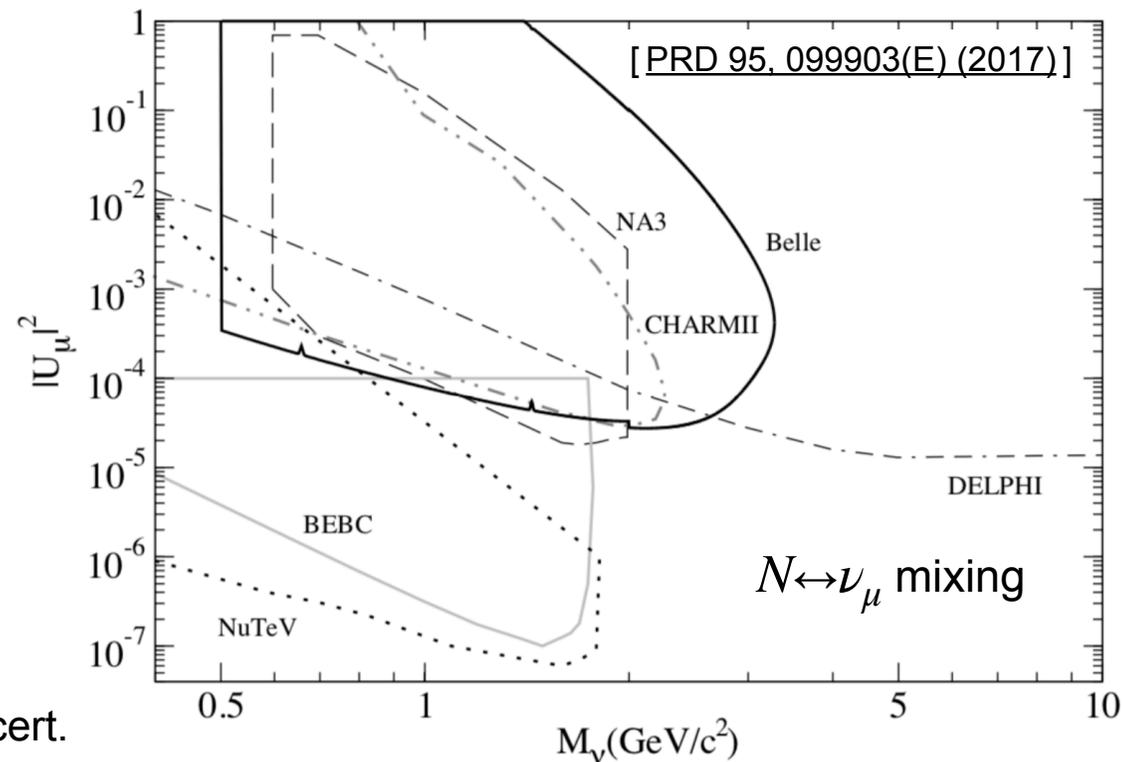
Direct search in B decays

- Heavy neutrino search in B decays at Belle (711 fb^{-1})
 - ▶ Sensitive to $N \leftrightarrow \nu_{e,\mu}$ mixing for $M_K < M_N < M_B$
- Produced via leptonic or semi-leptonic decays: $B \rightarrow X \ell N$
 - ▶ $X = D, D^*$, light meson (π, ρ, η) or “nothing” (leptonic)
 - ▶ $\ell = e$ or μ
- Detector signature: **displaced vertex** from $N \rightarrow \ell \pi$.
 - ▶ Three channels: $ee\pi, \mu\mu\pi, e\mu\pi$



- Bkg reduced by factor $\sim 10^6$ to only handful of events.
- Total systematic uncert. $\sim 25\%$, largest sources:
 - ▶ Vertex cuts ($\sim 10\%$)
 - ▶ Off-IP tracking (8.7%)

No significant excess observed. Set ULs.



Maximum sensitivity at $m_N \approx 2 \text{ GeV}$

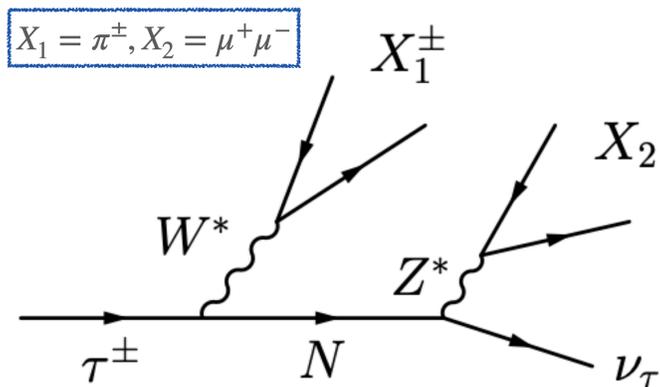
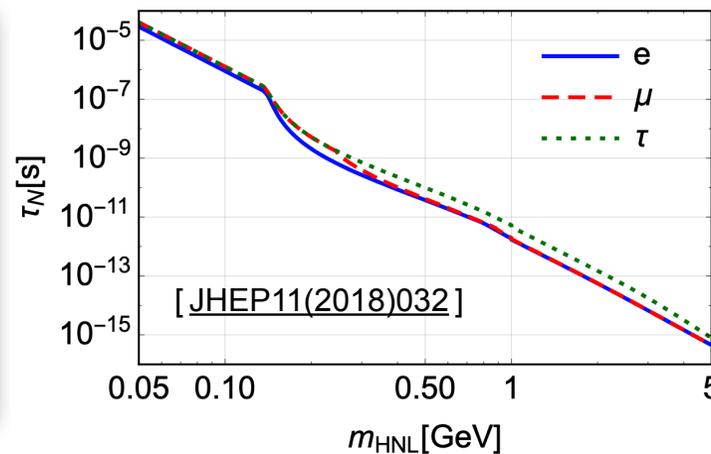
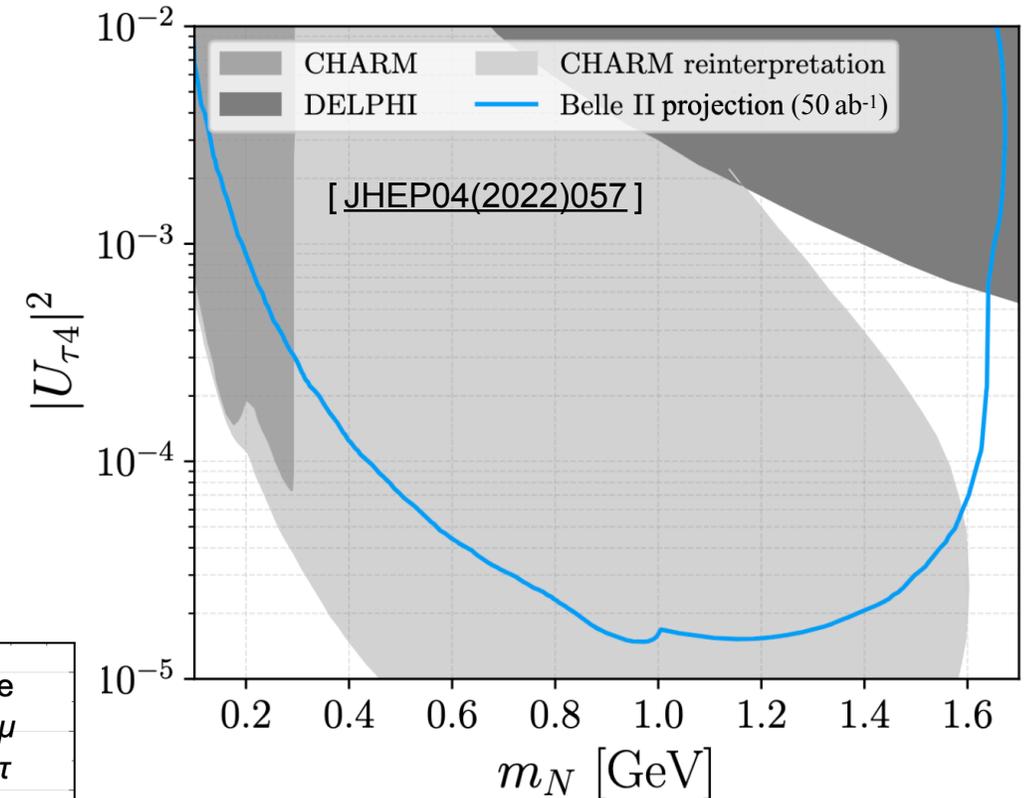
- ▶ 3.0×10^{-5} for $|U_{eN}|^2$ and $|U_{\mu N}|^2$
- ▶ 2.1×10^{-5} for $|U_{eN}| |U_{\mu N}|$

$$\mathcal{B}(B \rightarrow X \ell \nu_h) \times \mathcal{B}(\nu_h \rightarrow \ell \pi^+) < 7.2 \times 10^{-7}$$

Direct search in τ decays

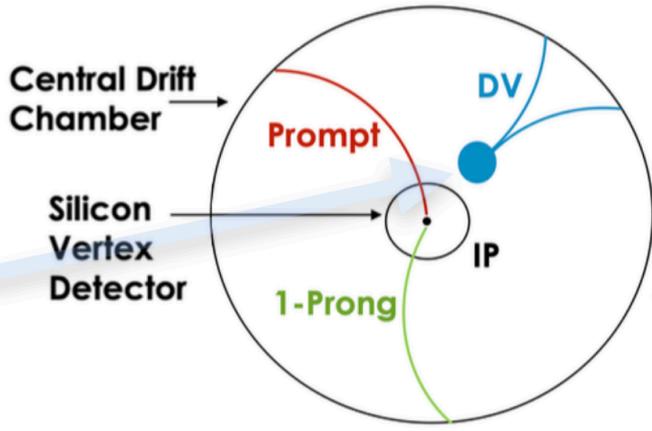
- Let's not forget that B -factories are also τ -factories.
- Existing constraints on $N \leftrightarrow \nu_\tau$ mixing are much weaker, & results from future experiments still many years away (e.g. SHiP, DUNE, FCCee).
 \Rightarrow In meantime, **Belle & Belle II can deliver important results!**
- **Recent result from Belle** (915 fb $^{-1}$, 836 x 10 6 τ -pairs), probe $|U_{\tau N}|^2 \gg |U_{\mu N}|^2, |U_{eN}|^2$ scenario [J. Phys. G 47, 010501]
- Look for N produced in τ decays, which then decays via weak neutral current. Can access $m_N < m_\tau - m_\pi$.

$$\sigma(e^+e^- \rightarrow b\bar{b}) = 1.05 \text{ nb} \text{ vs } \sigma(e^+e^- \rightarrow \tau^+\tau^-) = 0.92 \text{ nb}$$



- N is long-lived for range of $|U_{\tau N}|^2$ values we are sensitive to.
 Look for visible decay within detector.
 \Rightarrow **displaced vertex search.**

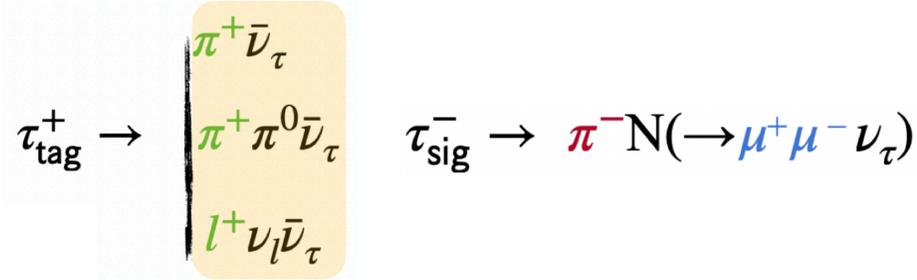
Direct search in τ decays



DV = Displaced Vertex

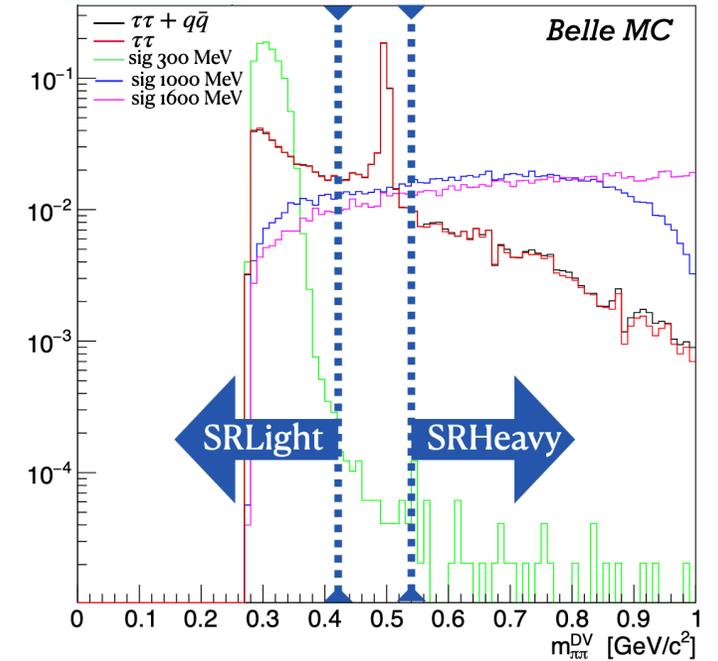
IP = Interaction Point

- Reconstruct $e^+e^- \rightarrow \tau_{tag}^+ \tau_{sig}^-$ events



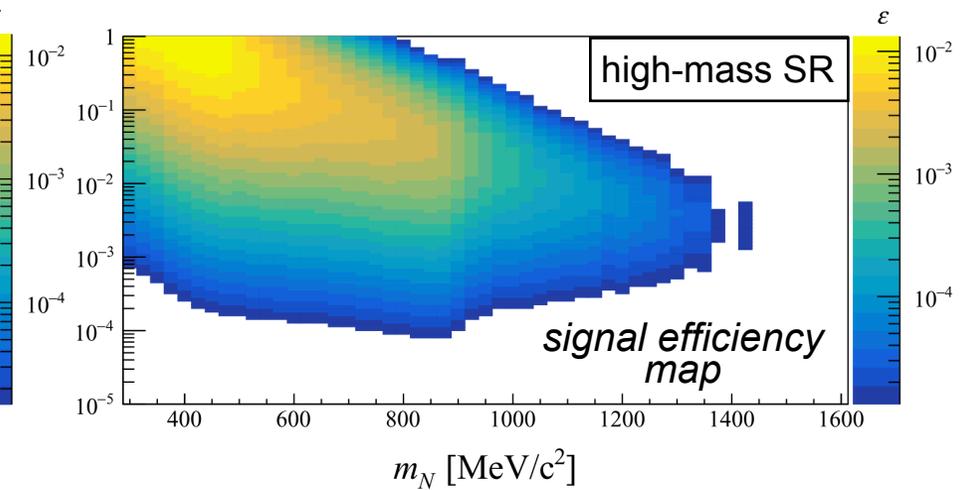
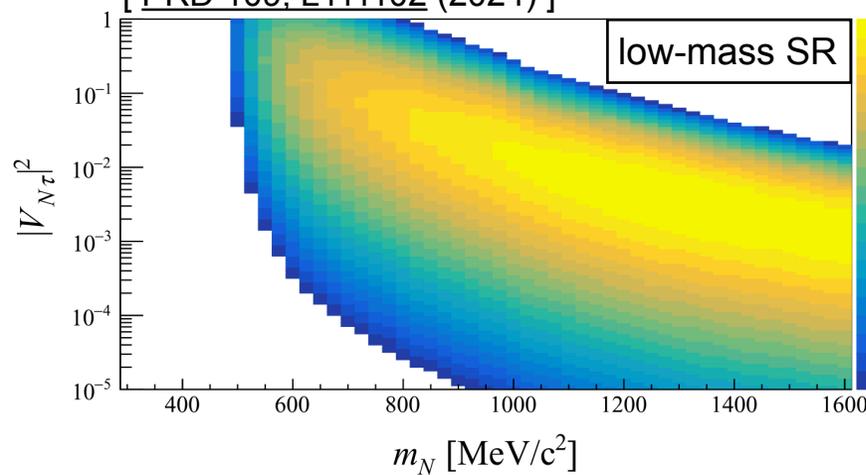
⇒ Look for $\mu^+ \mu^-$ displaced vertex, radial position > 15cm from beam axis.

Note: $K_S^0 \rightarrow \pi^+ \pi^-$ can produce similar DV. Suppress by vetoing mass region.



- Divide into **low-mass & high-mass** signal regions
- Full kinematics of signal-decay chain reconstructed with two-fold ambiguity (m_+ & m_-)
- Stat limited. Largest systematic from bkg yield expectation (34%).

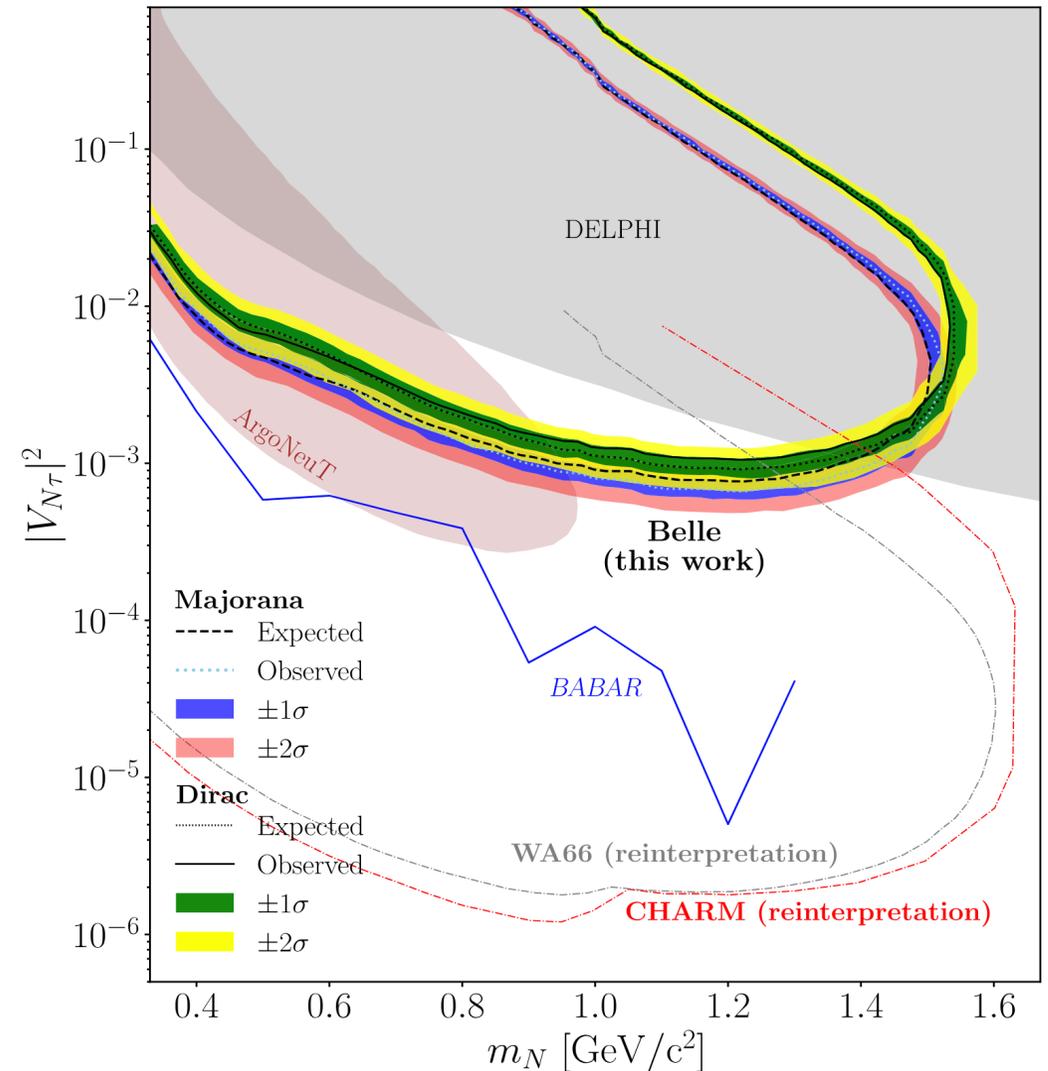
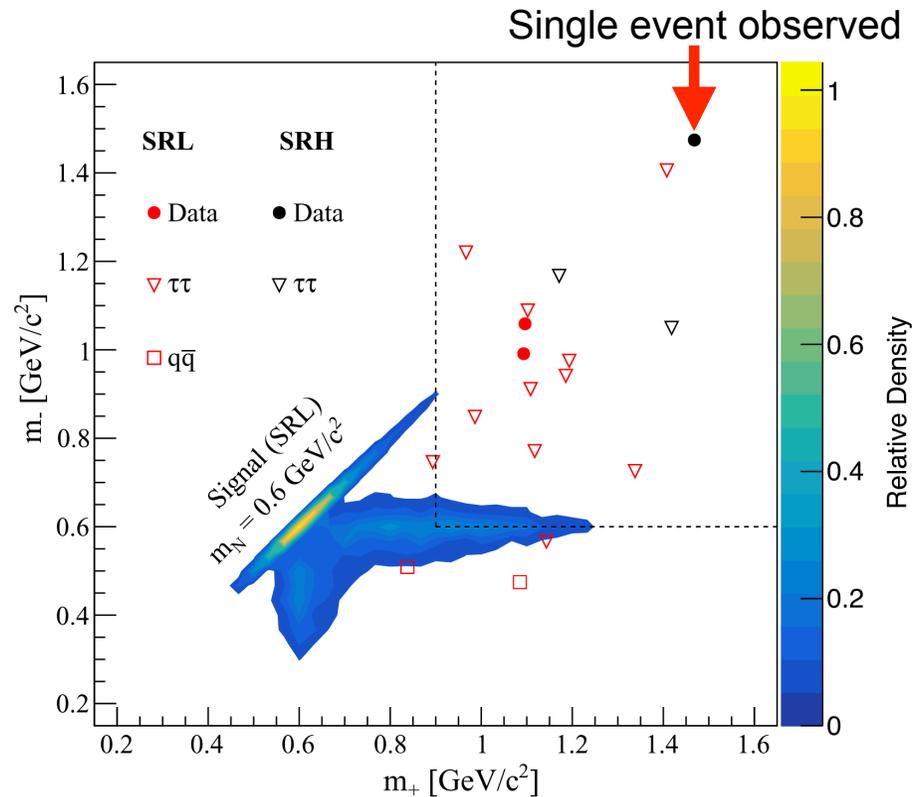
[PRD 109, L11102 (2024)]



Direct search in τ decays

- In the signal region targeting heavy & light sterile neutrinos we observe 1 & 0 events, respectively.
- In agreement with background expectation.

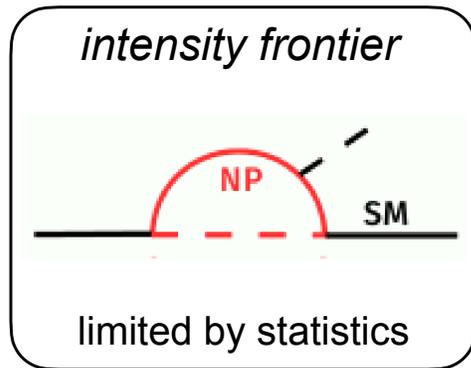
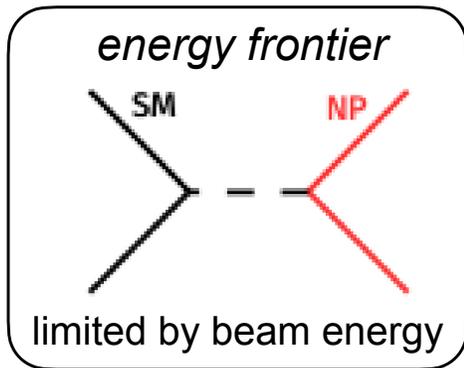
[PRD 109, L111102 (2024)]



- ▶ Belle II is expected to push forward these constraints by 1-2 orders of magnitude! [JHEP04(2022)057]

Constraints on heavy neutrino models from rare/forbidden B and τ decays

Rare & Forbidden B decays



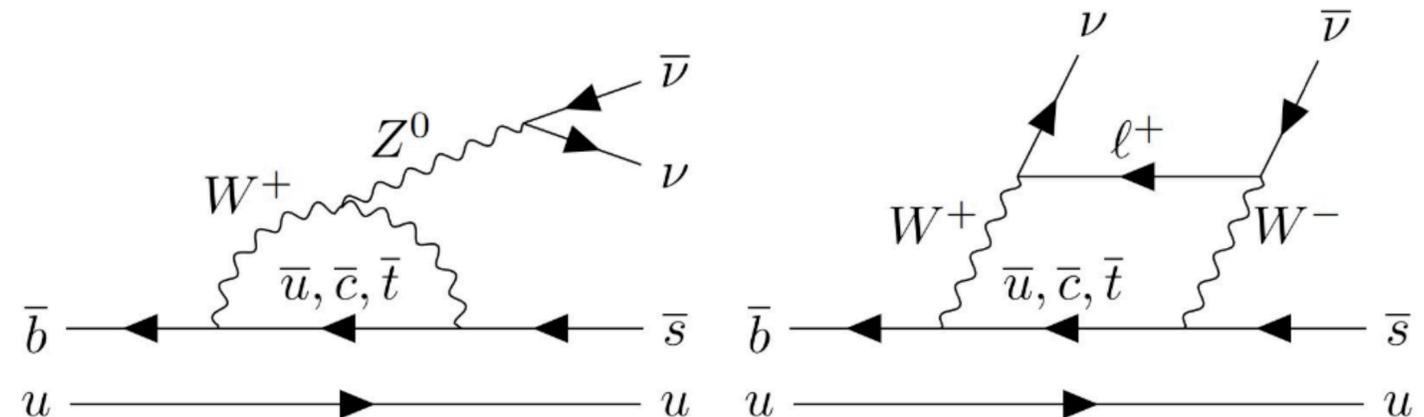
- At the **intensity frontier**, new particles might contribute to loop or tree level diagrams
 - ▶ Enhancing decay rates
 - ▶ Modifying angular distribution of final-state particles
- **Can probe NP beyond the direct reach of LHC**

- For example $B \rightarrow K\nu\bar{\nu}$, FCNC strongly suppressed in SM:
- **Heavy neutrinos** might enhance the BF significantly
e.g. [[Eur. Phys. J. C 84, 795 \(2024\)](#)]

$$\mathcal{B}(B^+ \rightarrow K^+ \nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6}$$

[[PRD107,014511 \(2023\)](#)]

- Very challenging experimentally:
 - Low BF, high background contribution
 - 3-body decay, no peaking variable to isolate signal
 - No observation yet



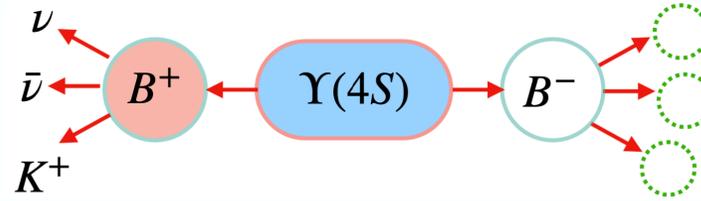
⇒ **Unique opportunity for Belle II**

First evidence of $B \rightarrow K\nu\bar{\nu}$

- **Recent result from Belle II** with full Run 1 data (362 fb⁻¹).
- Two complementary analyses with different **tagging methods**.
- Background suppression is challenging: use **two BDTs in cascade**, targeting $q\bar{q}$ & other B decays
- **Extensive studies** to validate MC modeling in control samples:
 - ▶ Background control validated for each kind of bkg source.
 - ▶ Signal efficiency validated by embedding in $B \rightarrow KJ/\psi(\mu\mu)$.
 - ▶ Closure test: extract BF of $B \rightarrow K^0\pi$ as function of q_{rec}^2 .
 - ▶ & many more!

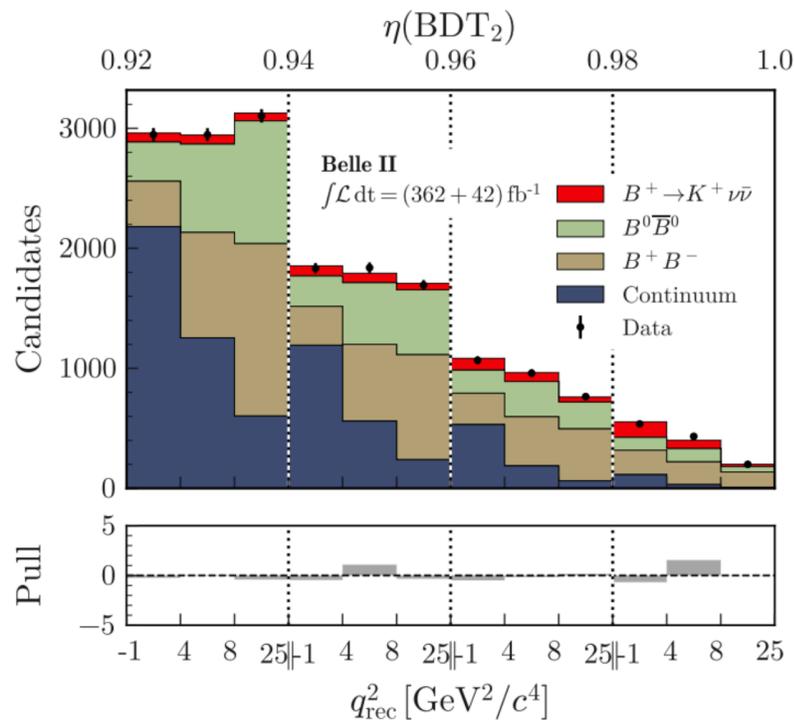
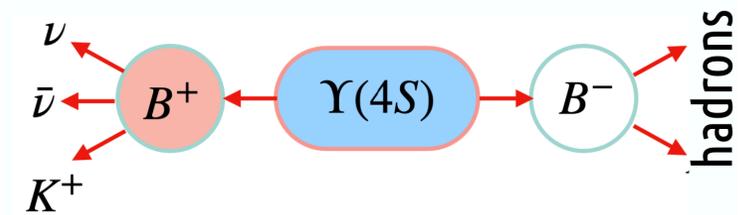
Inclusive tag

higher efficiency ($\epsilon=8\%$)
novel & more sensitive

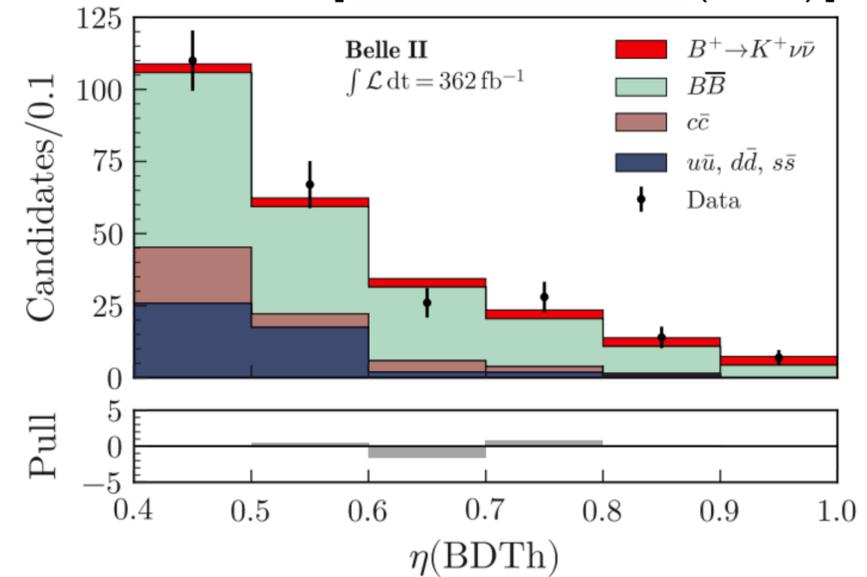


Hadronic tag

higher purity ($\epsilon=0.4\%$)
more conventional

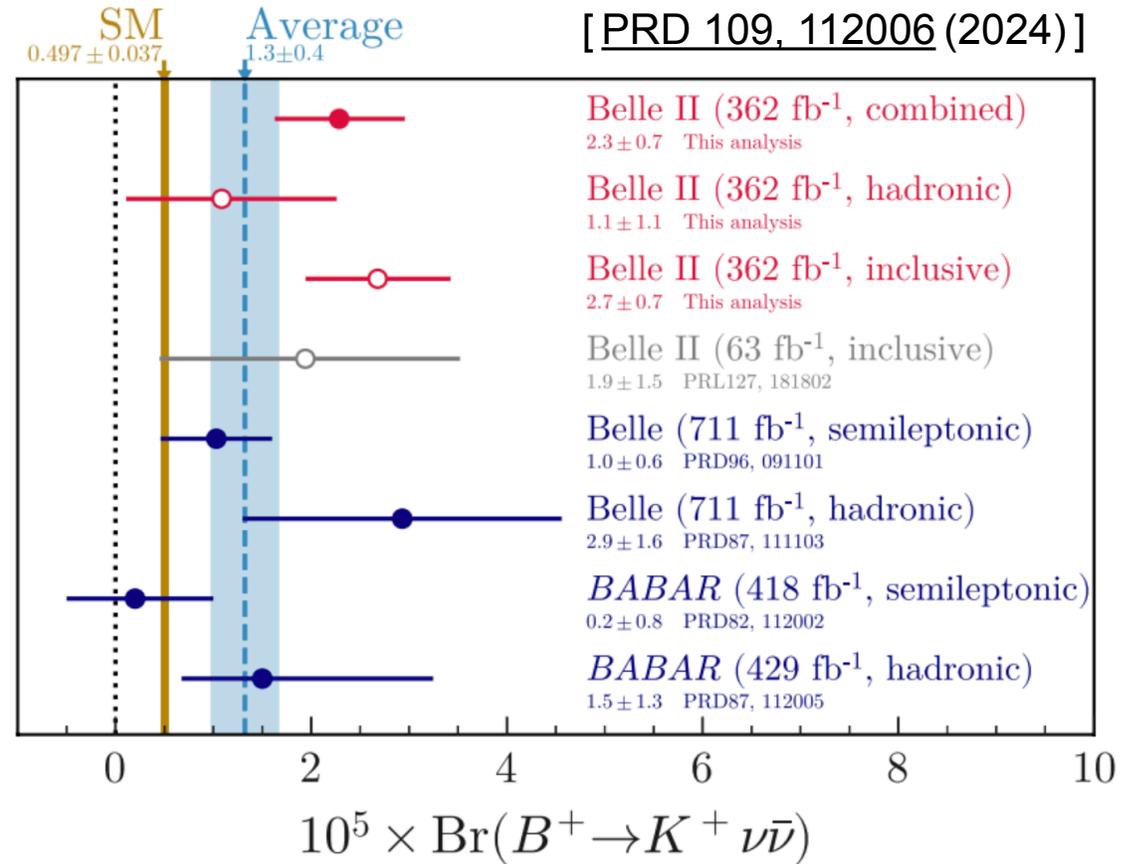
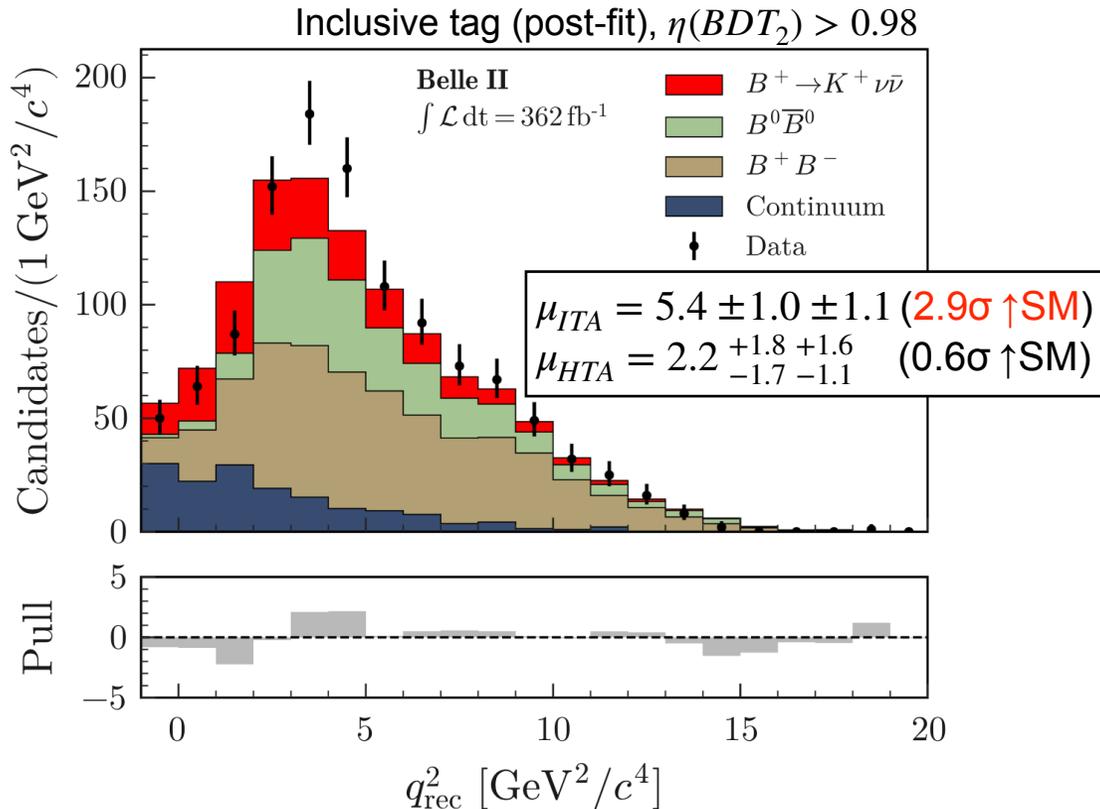


[PRD 109, 112006 (2024)]



First evidence of $B \rightarrow K\nu\bar{\nu}$

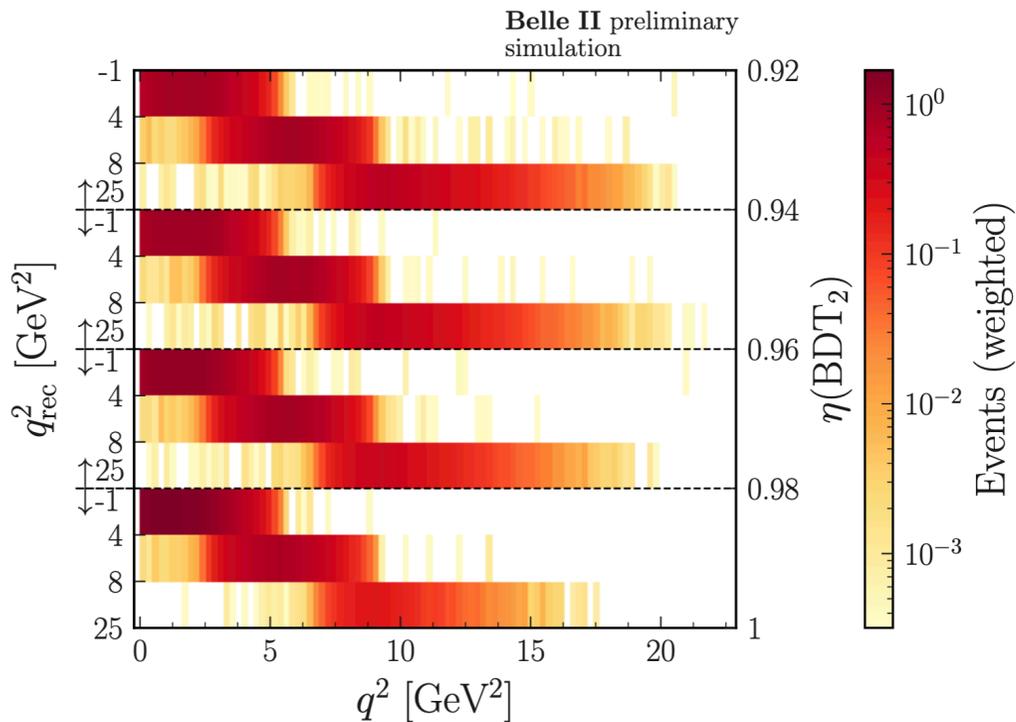
- Maximum likelihood fit to data using signal and background templates.
- Systematics with largest impact on σ_μ for inclusive (hadronic) tag:
 - $B\bar{B}$ bkg normalization: 0.90 (0.91).
 - Simulated sample size: 0.52 (0.60).



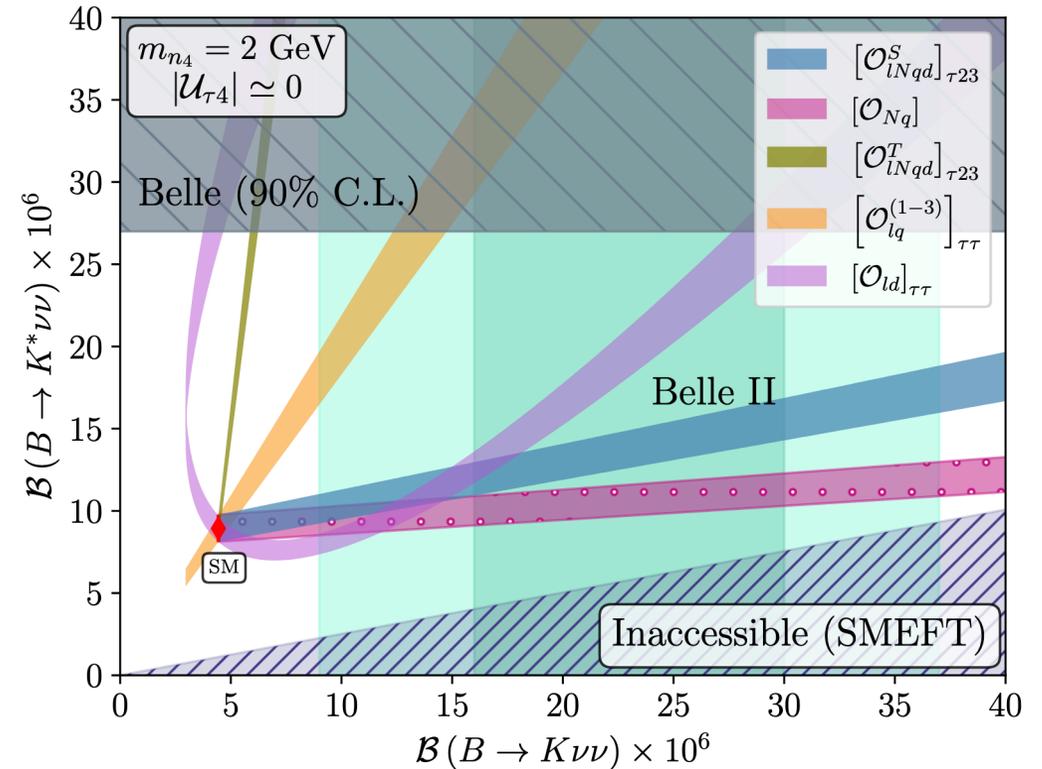
$\mu_{\text{combined}} = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{sys})$ $3.5\sigma \uparrow \text{bkg-only}$
 $BF = [2.3 \pm 0.5(\text{stat})^{+0.5}_{-0.4}(\text{sys})] \times 10^{-5}$ $2.7\sigma \uparrow \text{SM}$

$B \rightarrow K\nu\bar{\nu}$ reinterpretation

- **New paper from Belle II on arXiv since last week:**
[[arXiv:2507.12393](https://arxiv.org/abs/2507.12393) (2025)]
- We release full analysis likelihood & all necessary material needed by theorists to reinterpret under any arbitrary model.
 - ▶ **Will be on HEP data very soon!**
- **Test case:** 3.3σ for Weak Effective Theory, vector+tensor contribution preferred vs SM.

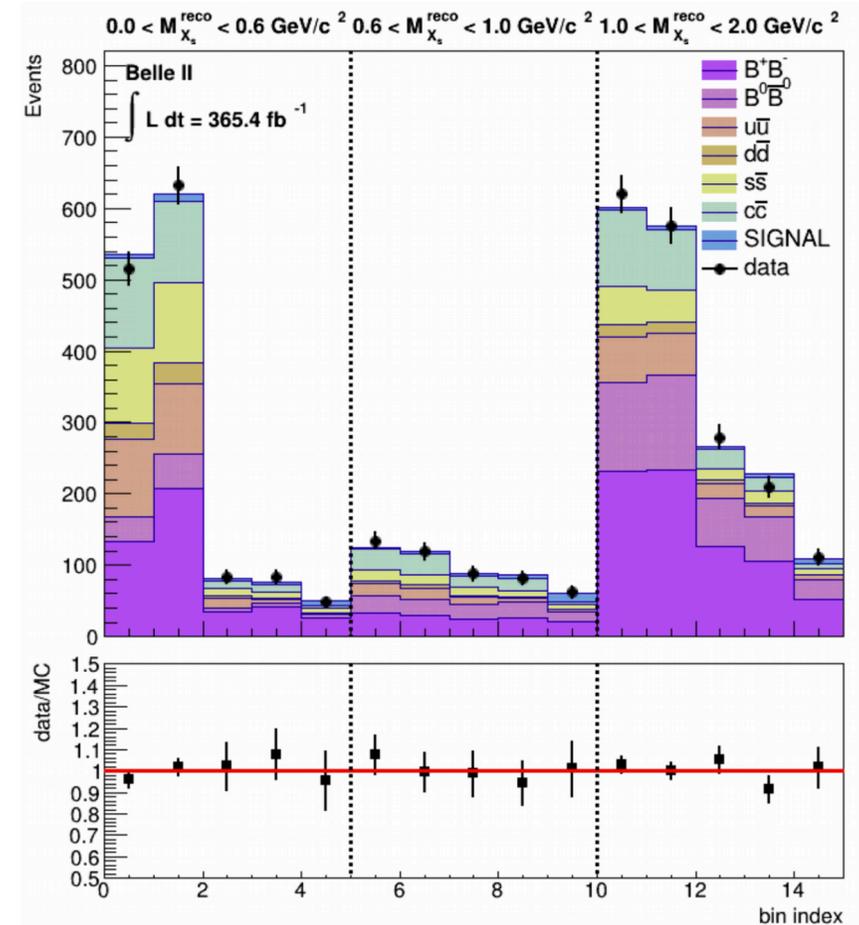


- Can have significant implications for several models with **heavy neutrino(s)**
- e.g. νSMEFT extended by relatively light RH neutrino
 - ▶ Details in [[Eur. Phys. J. C 84, 795](https://arxiv.org/abs/2405.12345) (2024)]
 - ▶ Sensitive to rate of $B \rightarrow K\nu\bar{\nu}$ vs $B \rightarrow K^*\nu\bar{\nu}$



- Ongoing efforts to confirm the observed excess
 - More final states $B \rightarrow K^{(*)}\nu\bar{\nu}$ with incl. tag ($K^{(*)} = K^+, K_S^0, K^{*0}, K^{*+}$)
 - Cross-check with traditional tagging method (semileptonic)
 - Repeat with Belle data & extend to Belle II - Run 2 data.
- In addition, check inclusive $B \rightarrow X_S\nu\bar{\nu}$ decays \Rightarrow **New Result!**
 - Sensitive to different NP parameters [JHEP 12(2021)118]
 - Sum over 30 modes (93% of inclusive)
 - Hadronic tag + BDT for bkg suppression.
 - Validation:
 - Off-resonance sample for $q\bar{q}$, BDT sideband for $B\bar{B}$.
 - $B \rightarrow X_S J\psi$ embedding as control sample.

	$B^0\bar{B}^0$			B^\pm		
K	K_S^0			K^\pm		
$K\pi$	$K^\pm\pi^\mp$	$K_S^0\pi^0$		$K^\pm\pi^0$	$K_S^0\pi^\pm$	
$K2\pi$	$K^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp$	$K_S^0\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0$	$K^\pm\pi^0\pi^0$
$K3\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp$	$K_S^0\pi^\pm\pi^\mp\pi^0$	$K^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm$	$K_S^0\pi^\pm\pi^0\pi^0$
$K4\pi$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^0\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^\mp\pi^0$	$K_S^0\pi^\pm\pi^\mp\pi^\pm\pi^0$	$K^\pm\pi^\mp\pi^\pm\pi^0\pi^0$
$3K$	$K^\pm K^\mp K_S^0$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm\pi^\mp$	$K^\pm K^\mp K_S^0\pi^0$		$K^\pm K^\mp K^\pm\pi^0$	$K_S^0 K^\pm K^\mp\pi^\pm$	

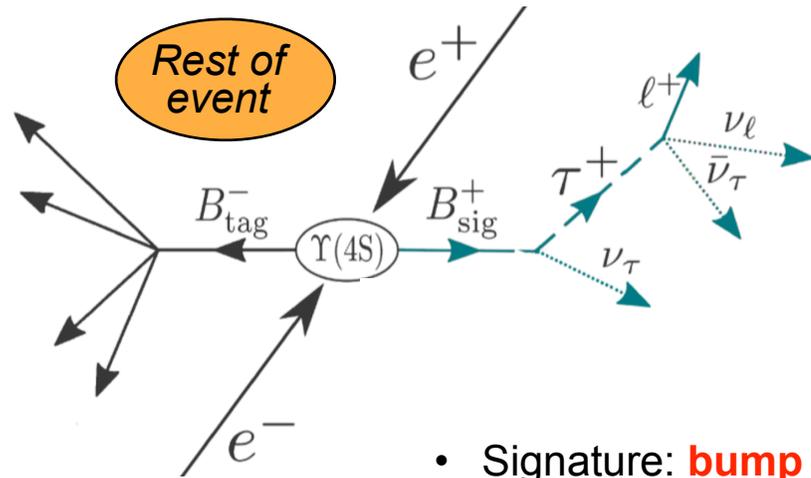
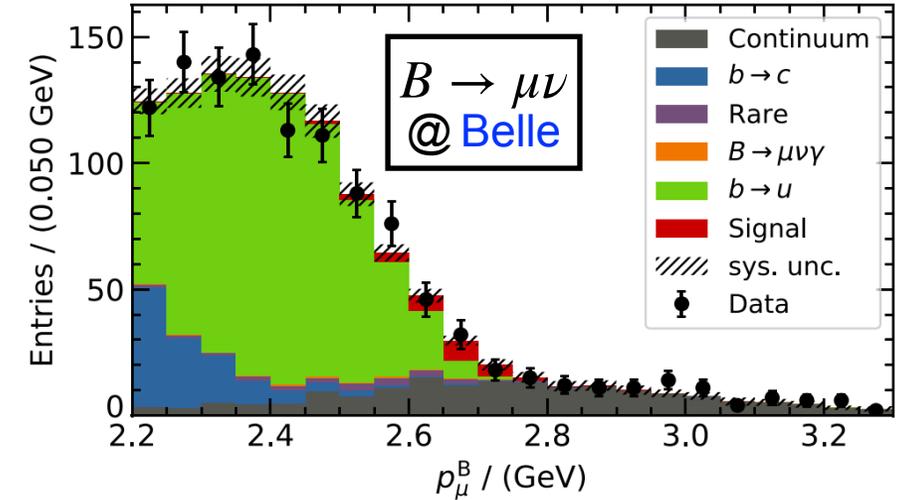
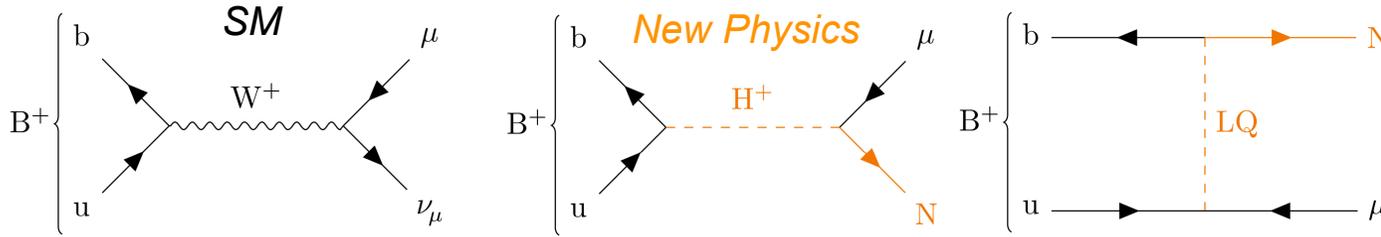


No significant excess. **Set world-best UL.**
 $\mathcal{B}(B \rightarrow X_S\nu\bar{\nu}) < 3.6 \times 10^{-4}$ Compatible with $B \rightarrow K\nu\bar{\nu}$ HTA

Search for $B \rightarrow \ell \nu$

- Leptonic decays of B mesons offer a unique tool to search for NP models with **heavy neutrinos**. Helicity suppressed in SM.
- Clean theoretically, but hard experimentally

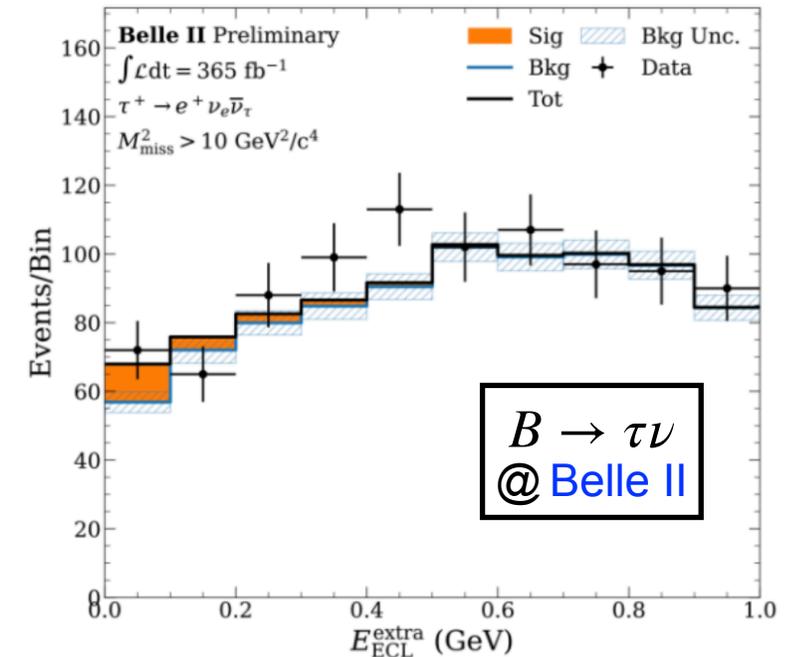
$$\mathcal{B}(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B,$$



- Strategy (so far) for tagging the non-signal B decay:

Tag	$B \rightarrow \mu \nu$ Belle	$B \rightarrow \tau \nu$ Belle	$B \rightarrow \tau \nu$ Belle II
Inclusive	✓		
Leptonic		✓	
Hadronic		✓	✓

- Signature: **bump** in lepton momentum spectrum, or excess at low total (cleaned) cluster energy in **ROE**.



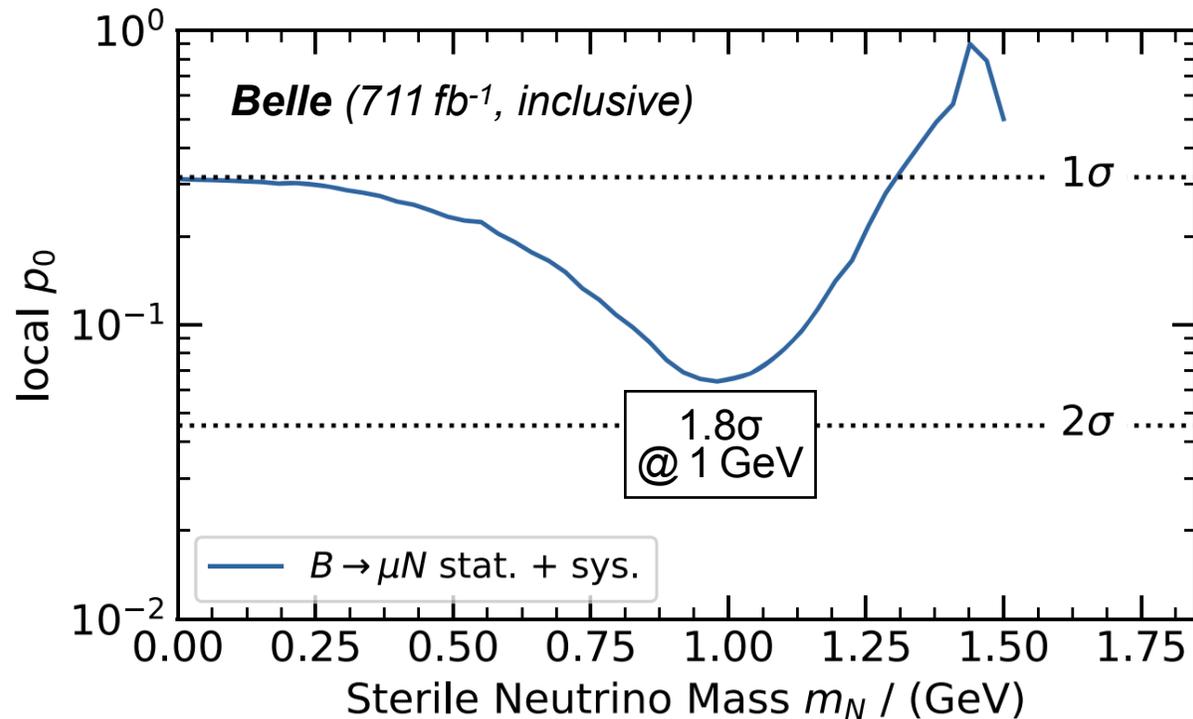
$B \rightarrow \ell \nu$ results

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

[PRD 101, 032007 (2020)]

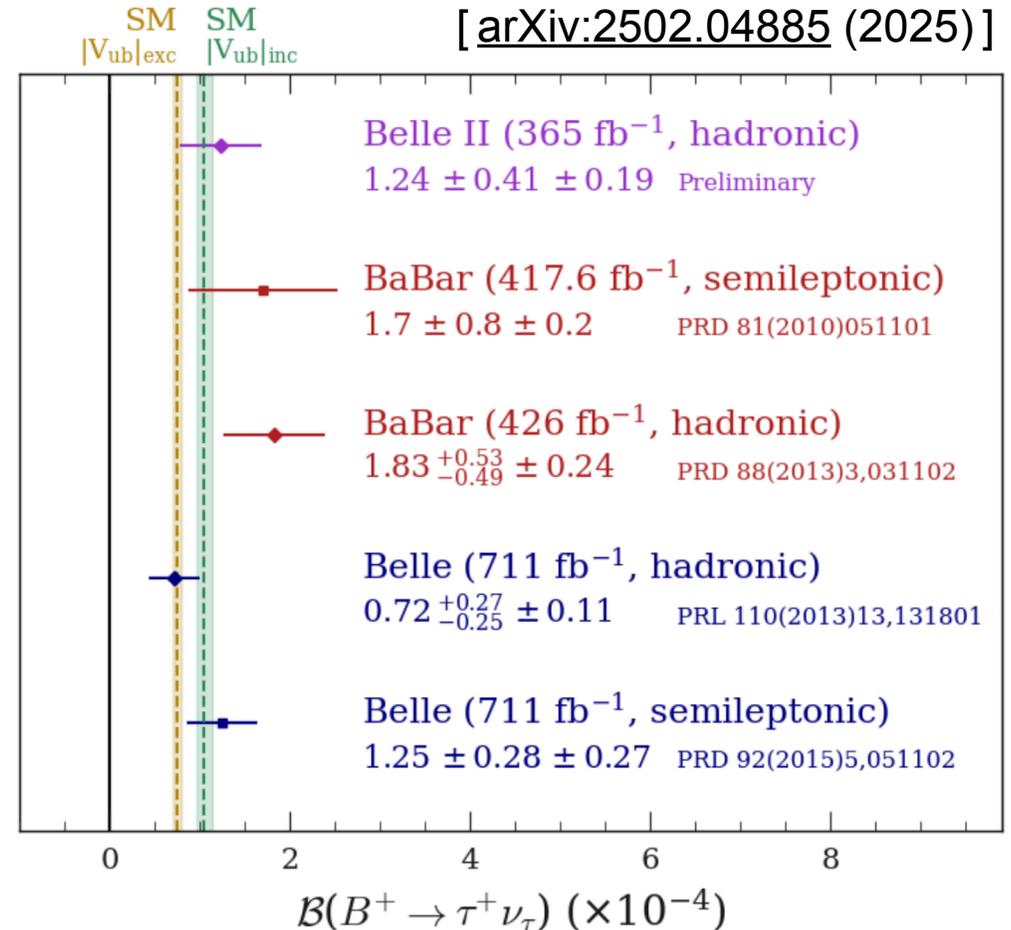
SM = 4.26×10^{-7}

- μ recoil against massive sterile neutrino ($N \rightarrow$ invisible) would shift p_μ spectrum. **SM result recast with m_N scan.**



- Recent Belle II result for $B \rightarrow \tau \nu @ 3.0\sigma$, compared to past experiments**

[arXiv:2502.04885 (2025)]

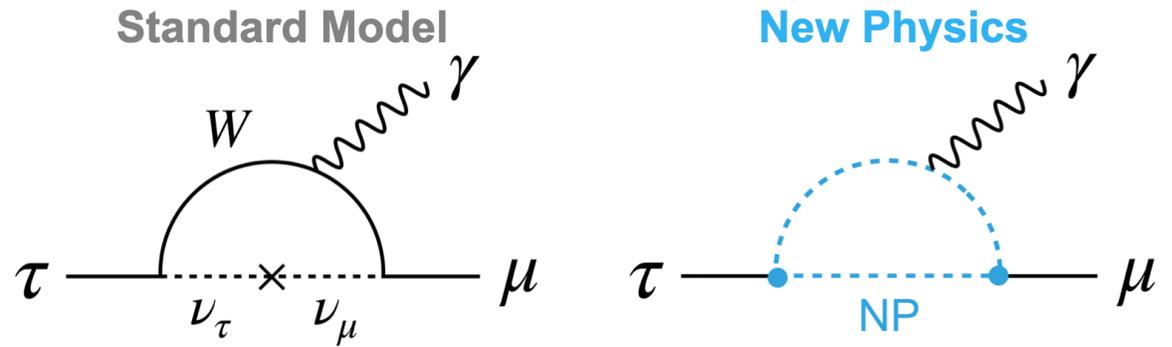
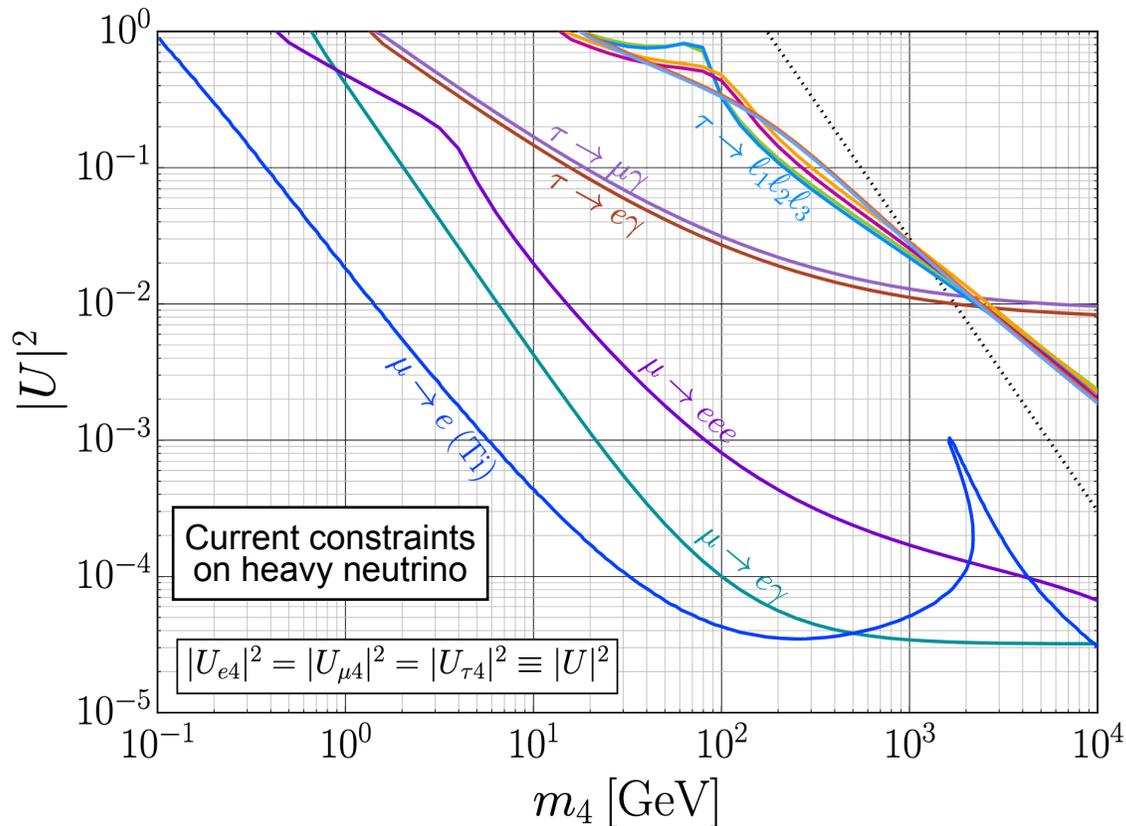


Forbidden τ decays

- In the SM, LFV decays of charged leptons via neutrino oscillation are highly suppressed & immeasurably small.

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

⇒ **Observation would be a clear signature of NP!**



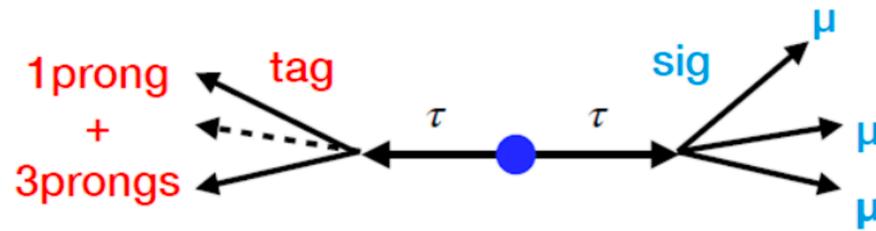
- If there is a **heavy neutrino** with mass $\gtrsim 1$ MeV, rates can be increased to 10^{-8} - 10^{-10} level, just below current experimental sensitivity! [arXiv:1511.00683]
- $\tau \rightarrow e/\mu$ transitions have significantly weaker ULs. **B-factories provide most stringent constraints.**

Belle II already delivering world-leading results:

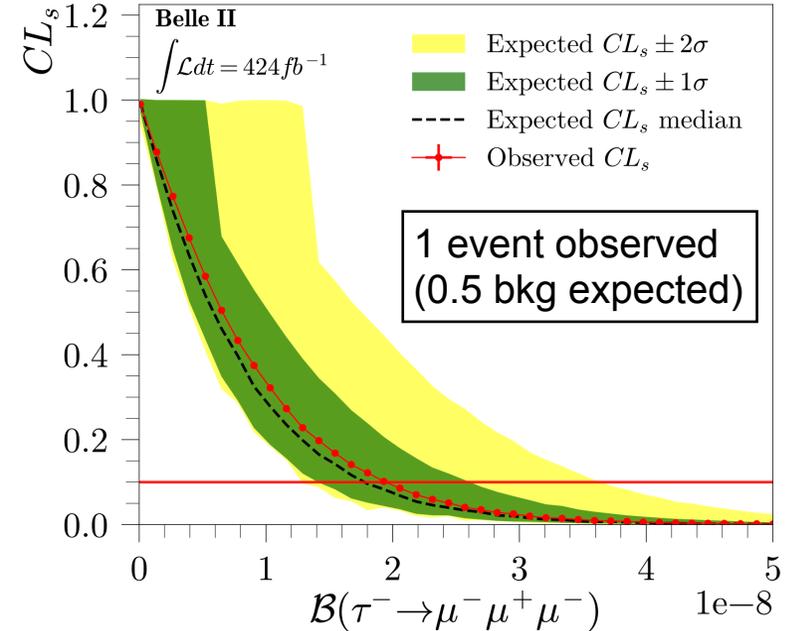
- $\tau \rightarrow 3\mu$ [JHEP 2024, 062 (2024)]
- $\tau \rightarrow \Lambda\pi$ [PRD 110, 112003 (2024)]
- $\tau \rightarrow eK_S^0$ [arXiv:2504.15745 (2025) Submitting soon to JHEP. Accepted into JHEP.]
- $\tau \rightarrow e2\ell$

Search for LFV $\tau \rightarrow 3\mu$

- One of the “golden channels”. Neutrinoless 3-body decay (3μ).
- Analysis strategy:
 - ▶ **inclusive tag** (3x1 & 3x3 prong)
 - ▶ bkg rejection using **BDT**



⇒ **signal efficiency 2.7x Belle**



- Extract signal yield in 2D plane:

$$M_{3\mu} = \sqrt{E_{3\mu}^2 - P_{3\mu}^2}$$

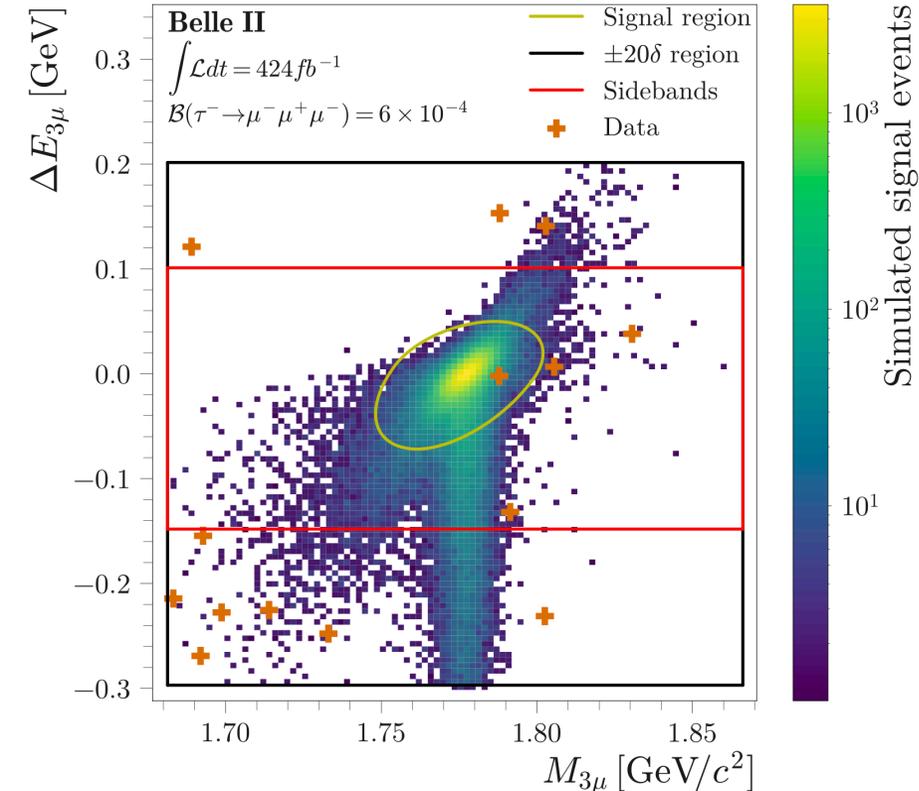
$$\Delta E_{3\mu} = E_{3\mu}^{CM} - E_{\text{beam}}^{CM}$$

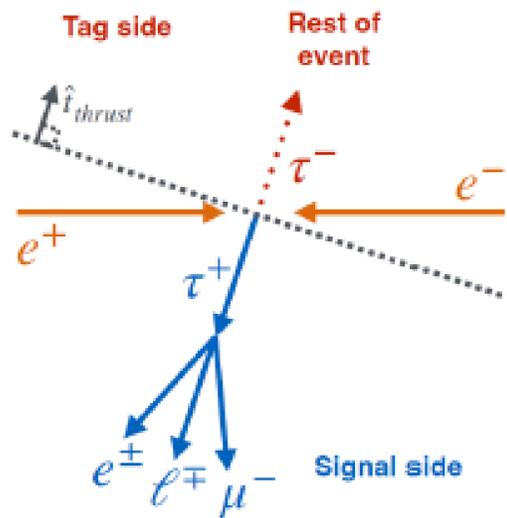
- Signal around $(M_\tau, 0)$. Tails due to initial and final state radiation.

Belle II with 424 fb⁻¹ could set world's best upper limit!

[JHEP09(2024)062]

	UL at 90% C.L. on $\mathcal{B}(\tau \rightarrow 3\mu)$
ATLAS	3.8×10^{-7} ($\mathcal{L} = 20.3 \text{ fb}^{-1}$)
LHCb	4.6×10^{-8} ($\mathcal{L} = 3.0 \text{ fb}^{-1}$)
CMS	2.9×10^{-8} ($\mathcal{L} = 131 \text{ fb}^{-1}$)
Belle	2.1×10^{-8} ($\mathcal{L} = 782 \text{ fb}^{-1}$)
BaBar	3.3×10^{-8} ($\mathcal{L} = 486 \text{ fb}^{-1}$)
Belle II	1.9×10^{-8} ($\mathcal{L} = 424 \text{ fb}^{-1}$)





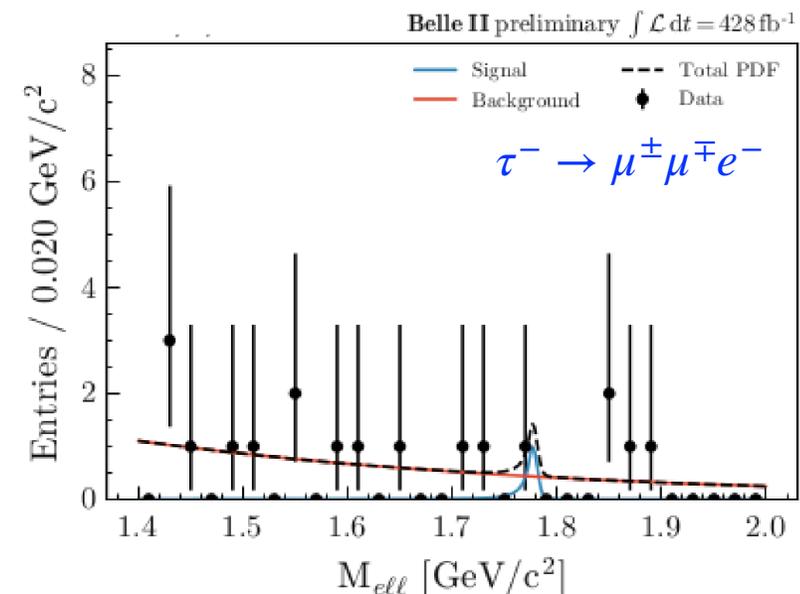
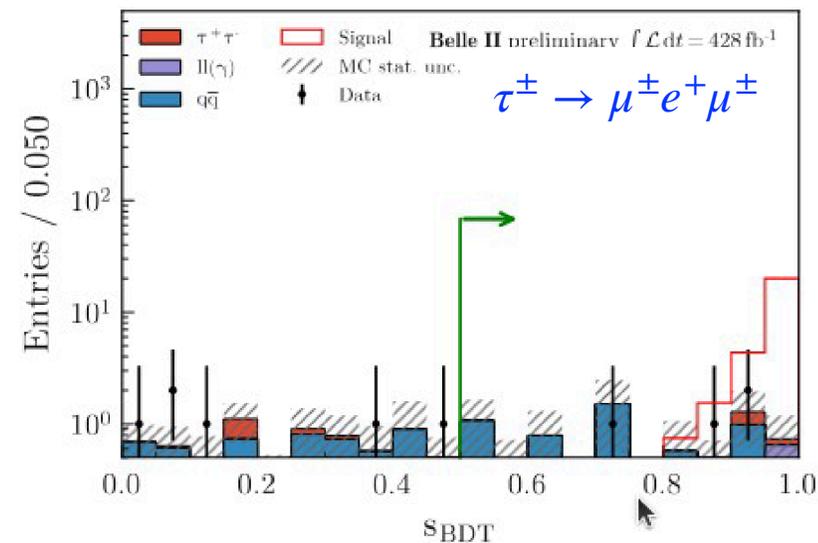
- Extend previous study to **5 more modes** with at least one electron in the final state:
 - $\tau^- \rightarrow e^-e^+e^-, e^-e^+\mu^-, e^-\mu^+e^-, \mu^-\mu^+e^-, \mu^-e^+\mu^-$
- Inclusive tagging** reconstruction.
- BDT** to suppress $ll\gamma$ & $llll$ backgrounds
 - rely on ROE & kinematic variables
 - trained on sideband in data
 - high signal efficiency (15-24%)

- Signal extraction using unbinned max. likelihood fits to M_{ell} distributions. Using sidebands to extrapolate expected background yields.

	N_{exp}	$\mathcal{B}_{\text{exp}}^{UL} \times 10^{-8}$	$\mathcal{B}_{\text{obs}}^{UL} \times 10^{-8}$
$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	2.7	2.5 ★
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	2.1	1.6 ★
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	1.7	1.6
$\mu^-\mu^+e^-$	$20.7^{+6.6}_{-5.5}$	1.6	2.4 ★
$\mu^-e^+\mu^-$	$7.5^{+4.5}_{-3.2}$	1.4	1.3 ★

No significant excess observed in 428 fb⁻¹.

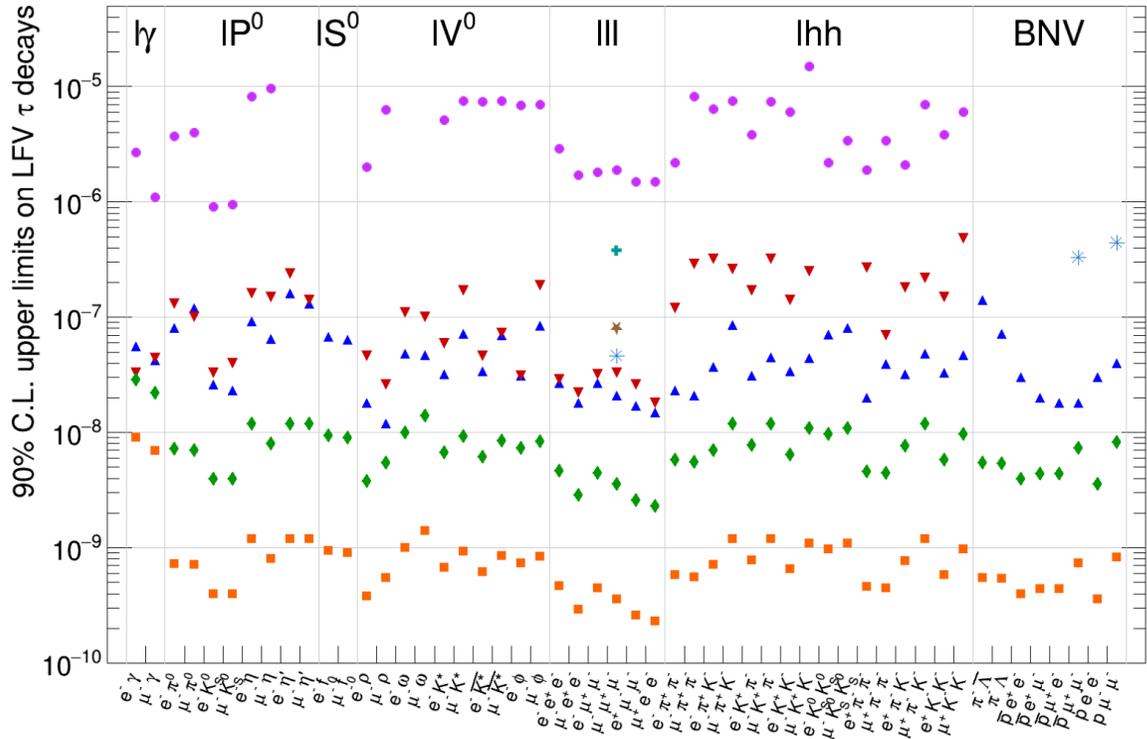
Most stringent ULs to date in four modes ★



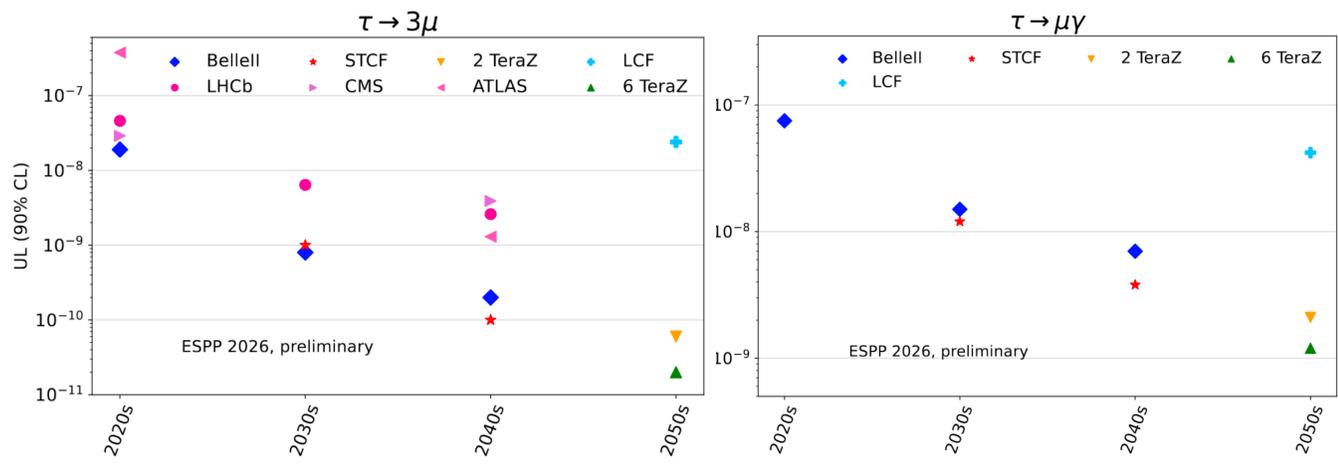
Prospects τ LFV

- Wide variety of decays to study: *radiative* ($\tau \rightarrow \ell\gamma$), *leptonic* ($\tau \rightarrow \ell\ell\ell$), *semileptonic* ($\tau \rightarrow \ell h(h)$) + more.
- Over 60 modes to be studied at Belle II over the coming years.

Belle II is expected to probe LFV in many channels $\approx \mathcal{O}(10^{-9})$ to $\mathcal{O}(10^{-10})$ with 50 ab^{-1}



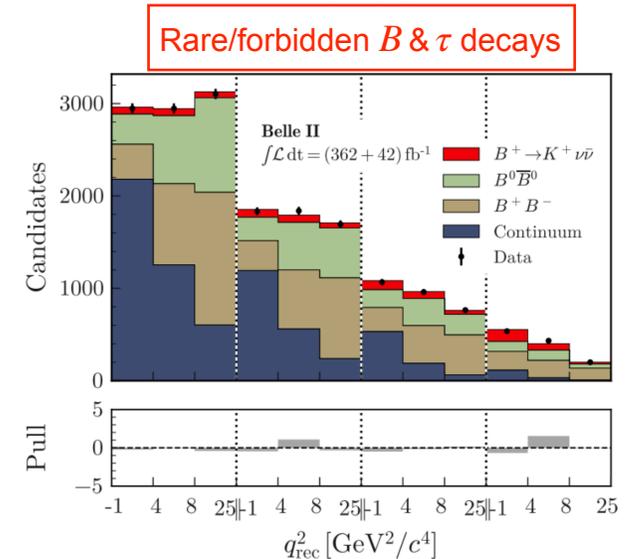
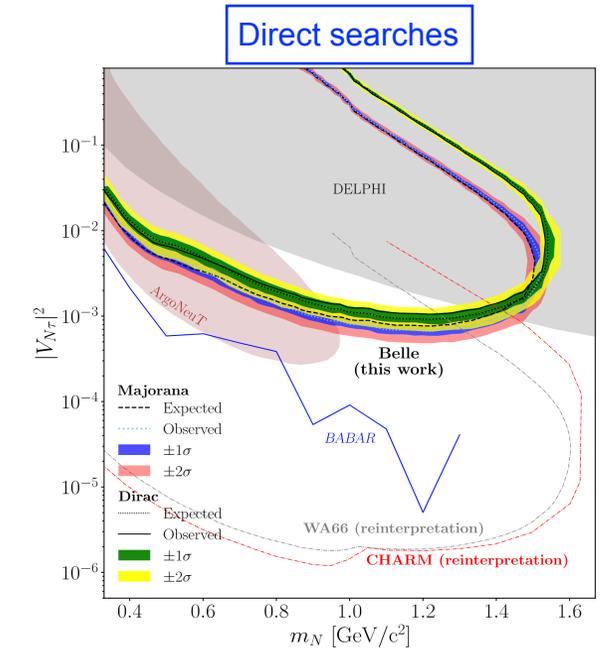
- CLEO + ATLAS * CMS * LHCb ▼ BaBar
- ▲ Belle ◆ Belle II (5 ab^{-1}) ■ Belle II (50 ab^{-1})



- Belle II & STCF will provide best limits for the next ~20 years, until Tera-Z experiments enter the game in 2050s.

Summary

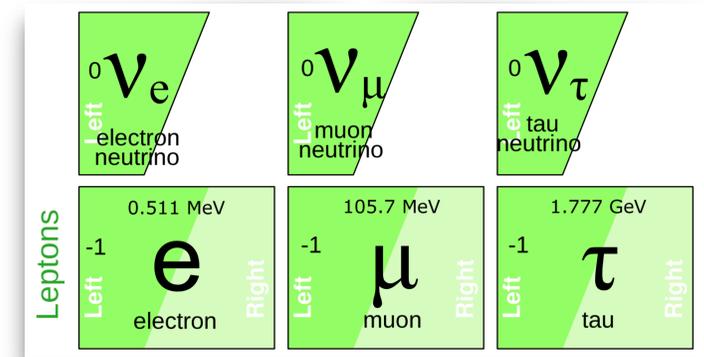
- While not primarily neutrino experiments, both Belle & Belle II are in a unique position to contribute.
- One avenue is **direct searches** for heavy neutrinos:
 - ▶ Displaced vertex searches in B and τ decays at Belle: [PRD 95, 099903(E) (2017)] [PRD 109, L111102 (2024)]
- Also, **rare/forbidden decays** can be reinterpreted to provide powerful constraints on heavy neutrino models
 - ▶ First evidence of $B \rightarrow K\nu\bar{\nu}$ at Belle II: [PRD 109, 112006 (2024)]
 - ▶ $B \rightarrow K\nu\bar{\nu}$ reinterpretation: [arXiv:2507.12393 (2025), submitted to PRD]
 - ▶ Inclusive $B \rightarrow X_s\nu\bar{\nu}$ at Belle II: [Submitting soon to PRL]
 - ▶ Search for $B \rightarrow \mu\nu$ at Belle: [PRD 101, 032007 (2020)]
 - ▶ Search for $B \rightarrow \tau\nu$ at Belle II: [arXiv:2502.04885 (2025), submitted to PRD]
 - ▶ Search for $\tau \rightarrow 3\mu$ at Belle II: [JHEP09(2024)062 (2024)]
 - ▶ Search for $\tau \rightarrow e2\ell$ at Belle II: [Submitting soon to JHEP]
 - ▶ + much more!
- Rich program of results to come as luminosity ramps up at Belle II.
Exciting times ahead!



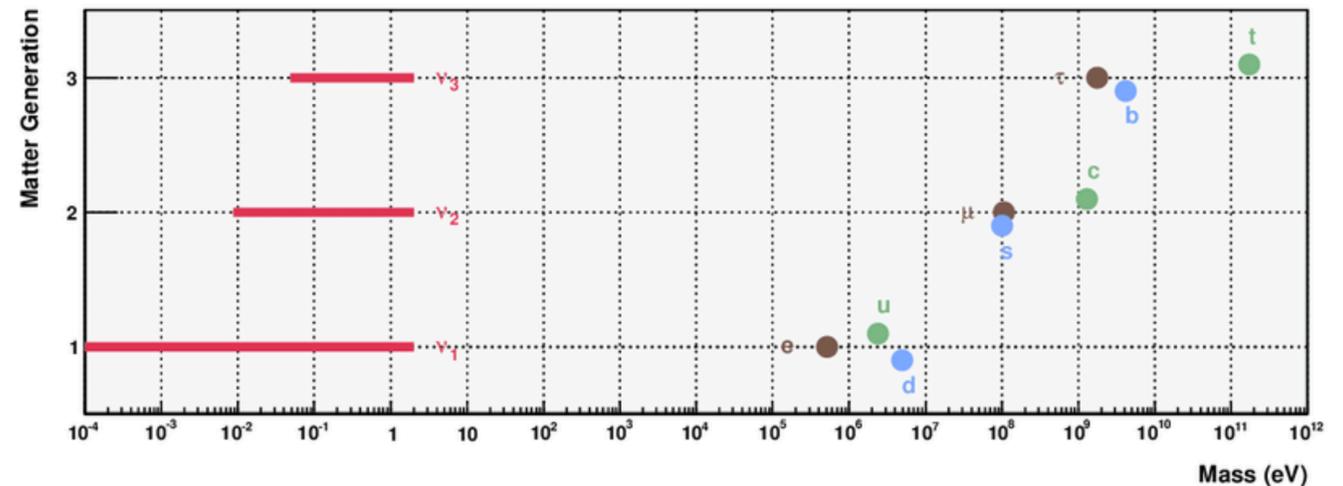
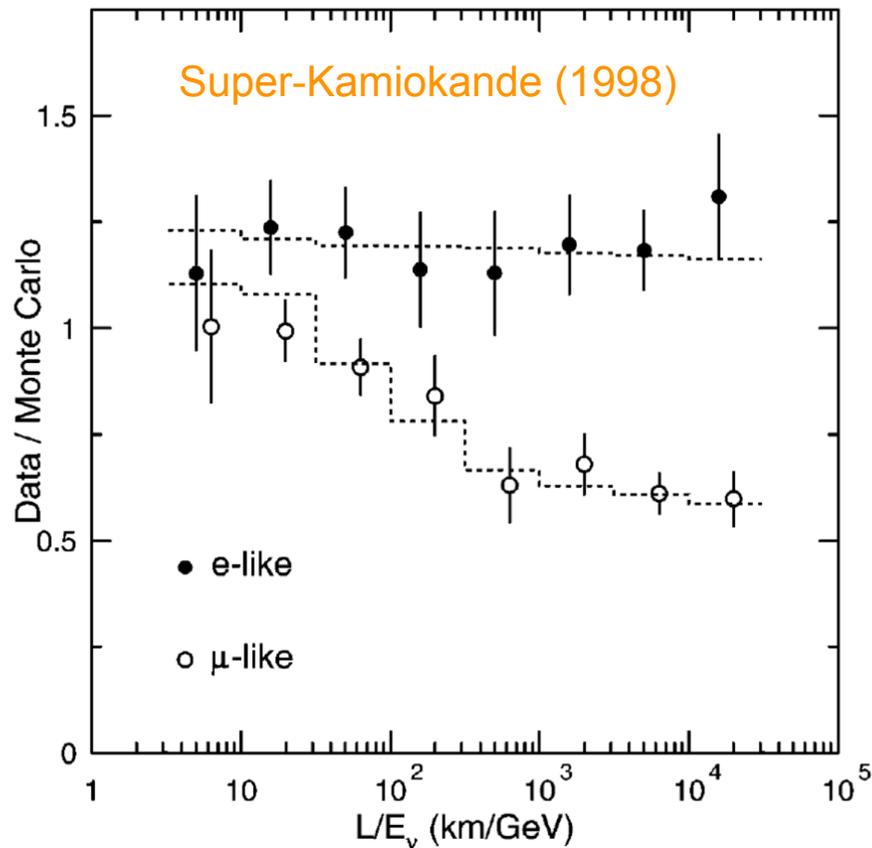
BACKUP

Introduction

- Particle masses in the SM are generated by the coupling of the Higgs field to a given particles LH & RH components.
- In SM there are only LH neutrinos \Rightarrow 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 ...

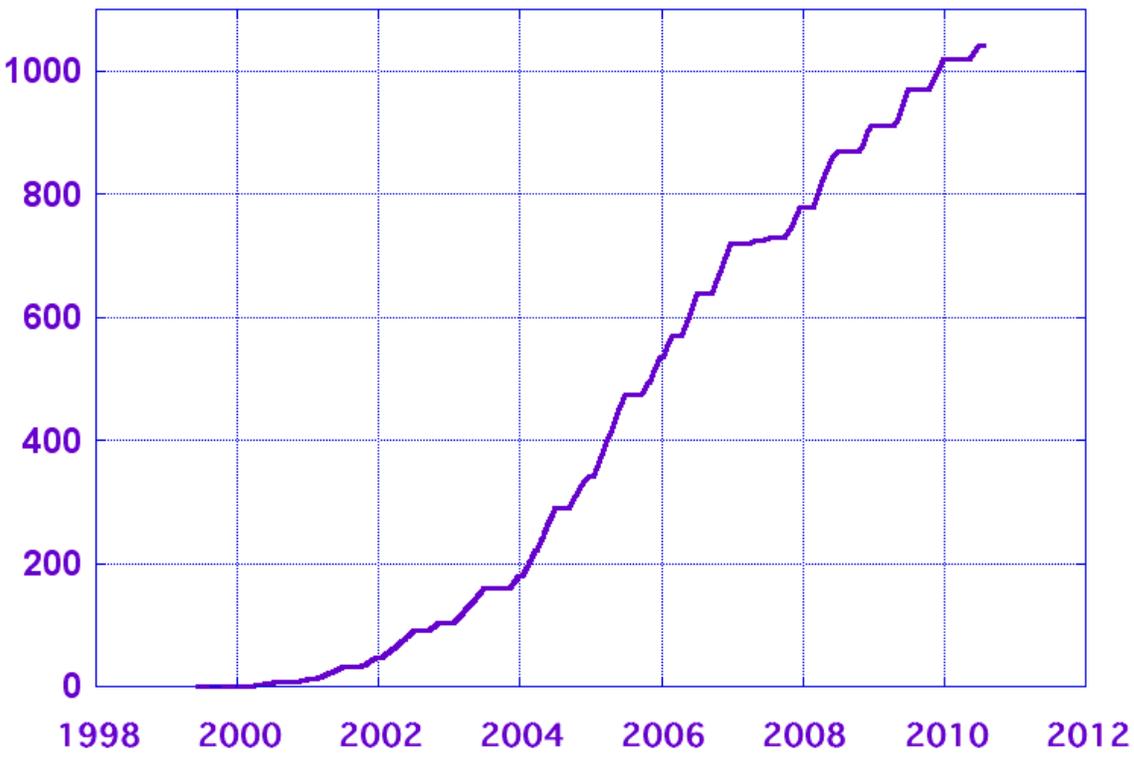


Luminosity Status

Belle from 1999 to 2010: $\sim 1 \text{ ab}^{-1}$

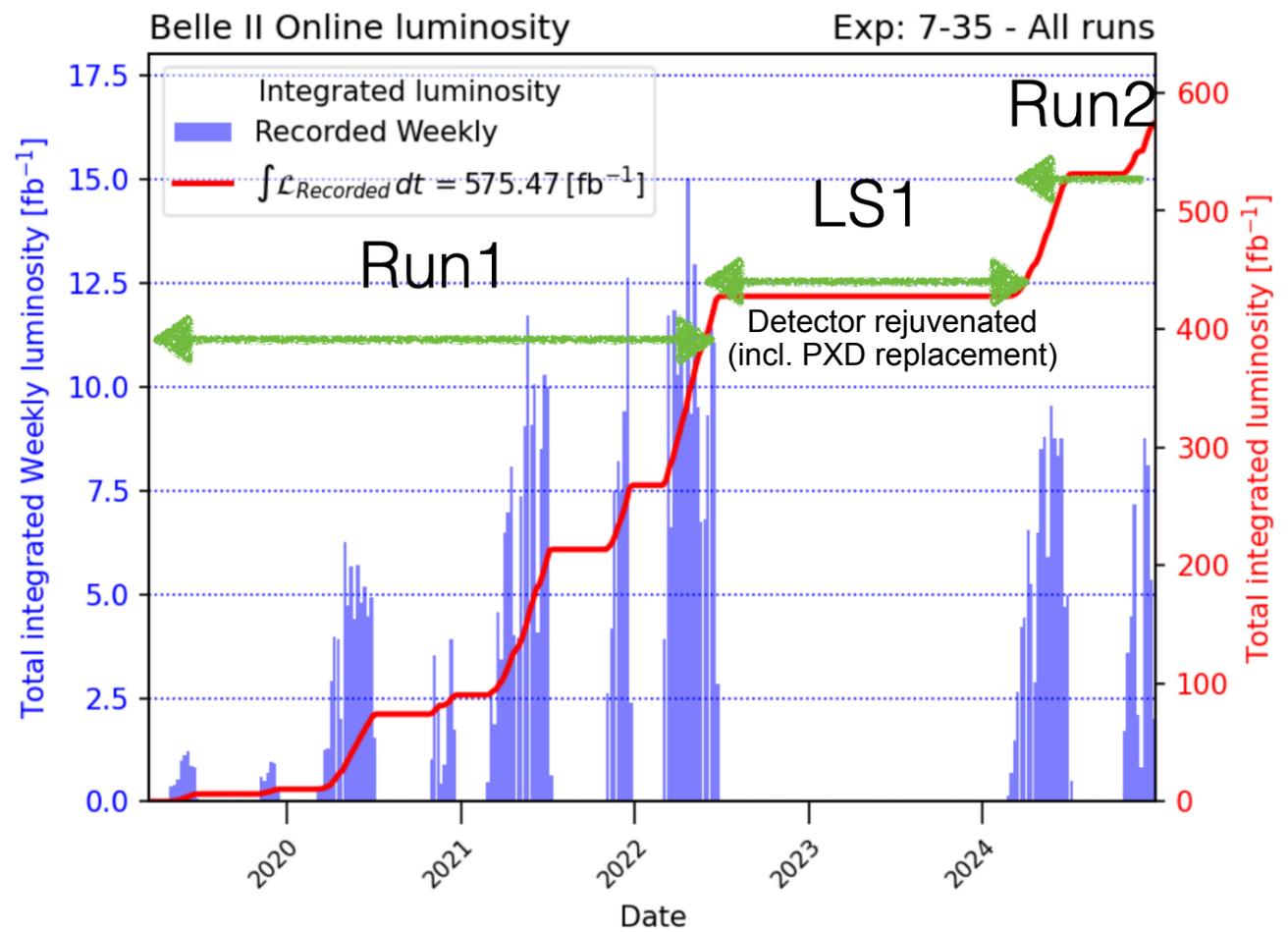
$$L_{\text{peak}} = 2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

Integrated Luminosity [fb⁻¹]



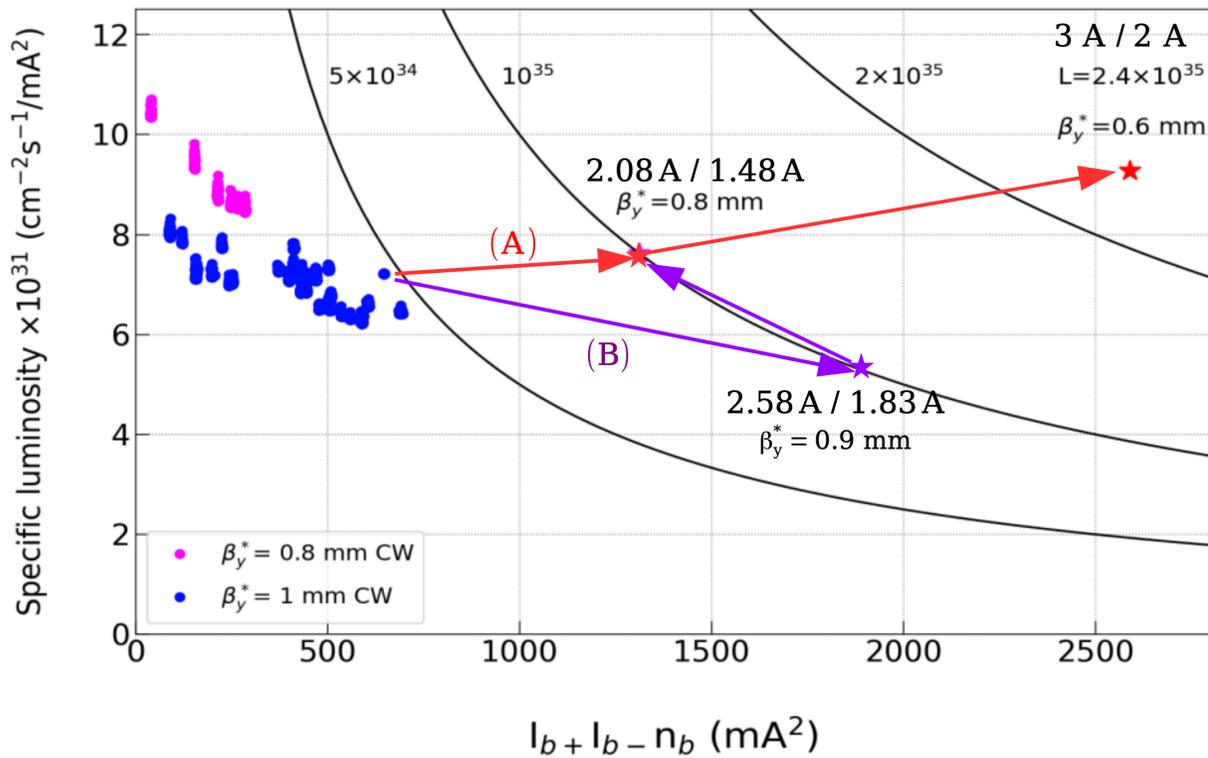
Belle II from 2019 to now: 575 fb^{-1}

$$L_{\text{peak}} = 5.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \Rightarrow \text{world record!}$$

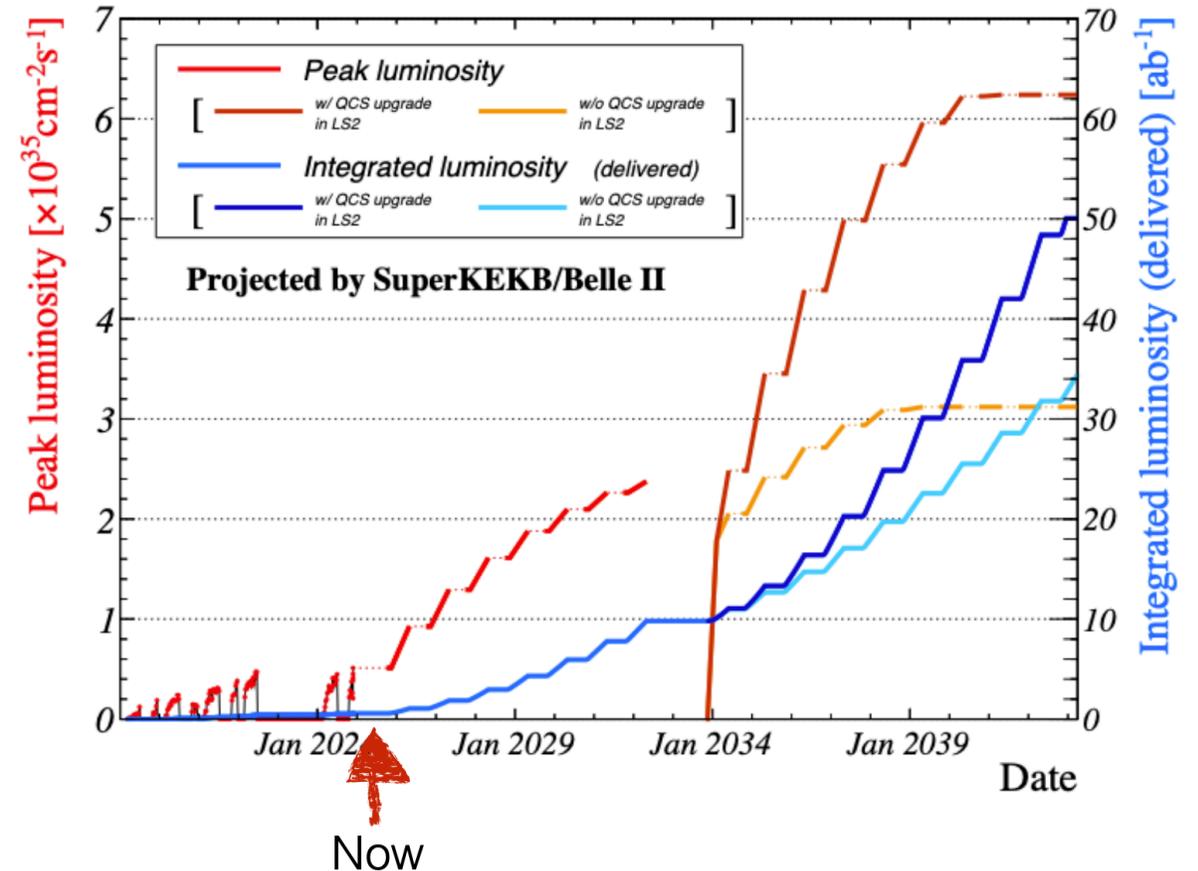


Luminosity Goals

- Resume data taking in Nov 2025 for long run (7 months)
- Path toward $> 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ ($\sim 1 \text{ ab}^{-1} / \text{year}$)



- Aiming for 50 ab^{-1} over next ~ 10 years (50x Belle)



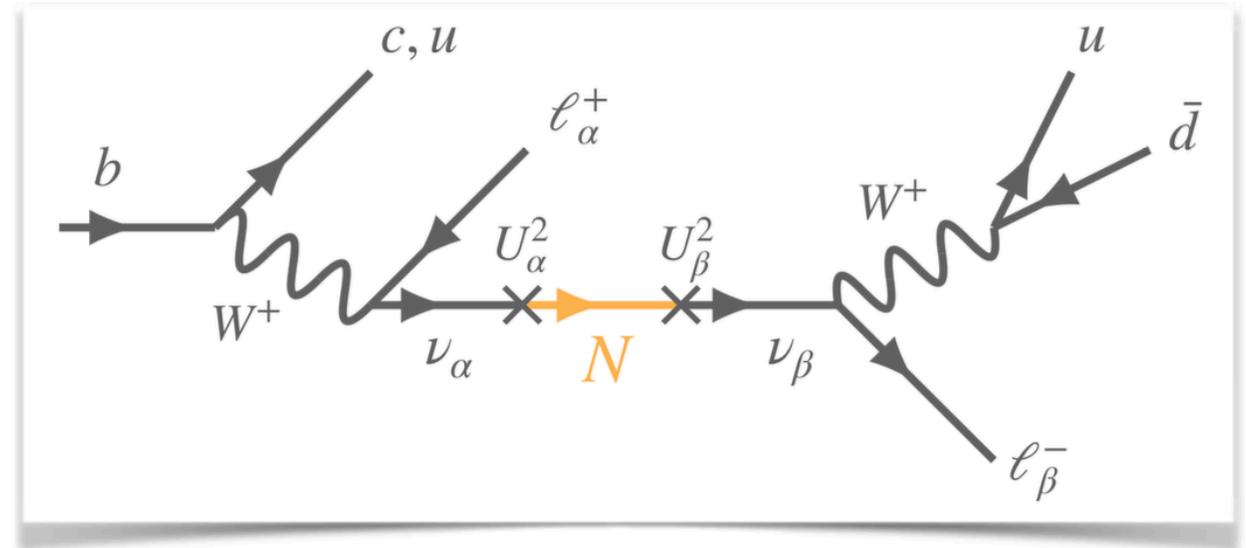
Direct search in B decays

- 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 $\sqrt{s} = M_{Y(4s)}$
- Sensitivity to $N \leftrightarrow \nu_{\text{SM}}$ mixing for $M_K < M_N < M_B$



HNL production

- ▶ Both leptonic and semi-leptonic B decays

$$B \rightarrow X \ell N$$

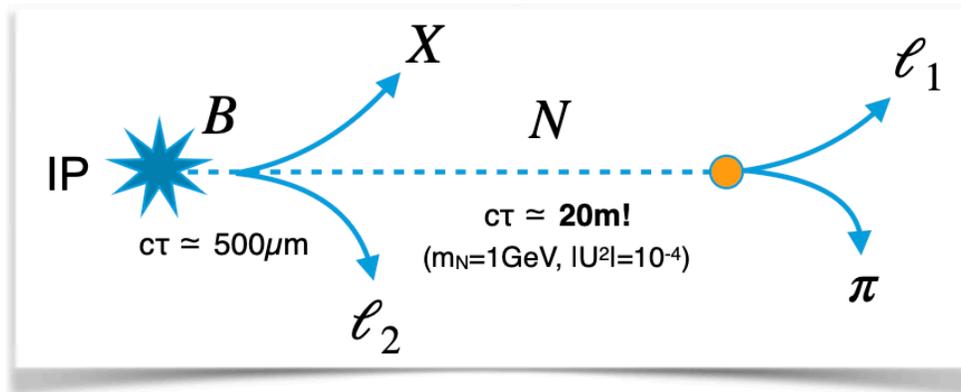
where: $\ell = e, \mu$
 $X = D, D^*$,
 light meson (π, ρ, η, \dots),
 'nothing' (leptonic decay)

Detector Signature

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

Direct search in B decays

- ▶ 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 $B \rightarrow D^{(*)} \ell \nu$ mode
 - **high-mass** (2-5 GeV): inclusive production

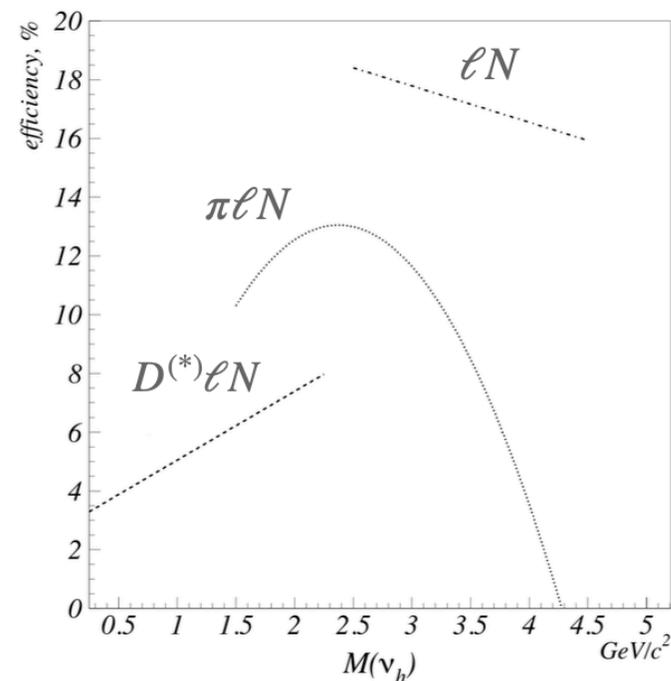
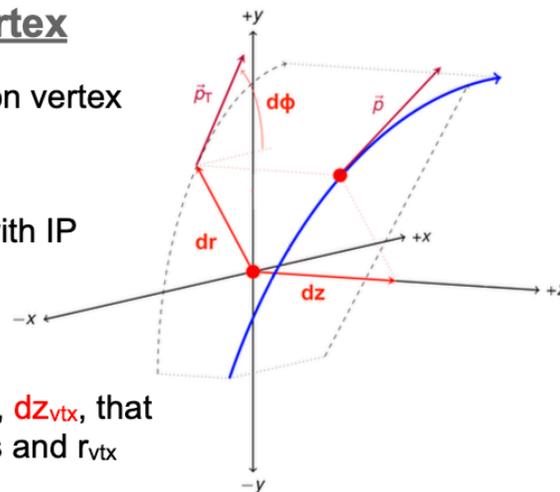


Selections

- ≥ 4 tracks, $p_T > 0.5$ GeV
 - tight lepton ID (ee, $\mu\mu$ or $e\mu$)
 - lepton veto for π
 - **Low-mass** regime:
 - $B \rightarrow D^{(*)} \ell \nu$ 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

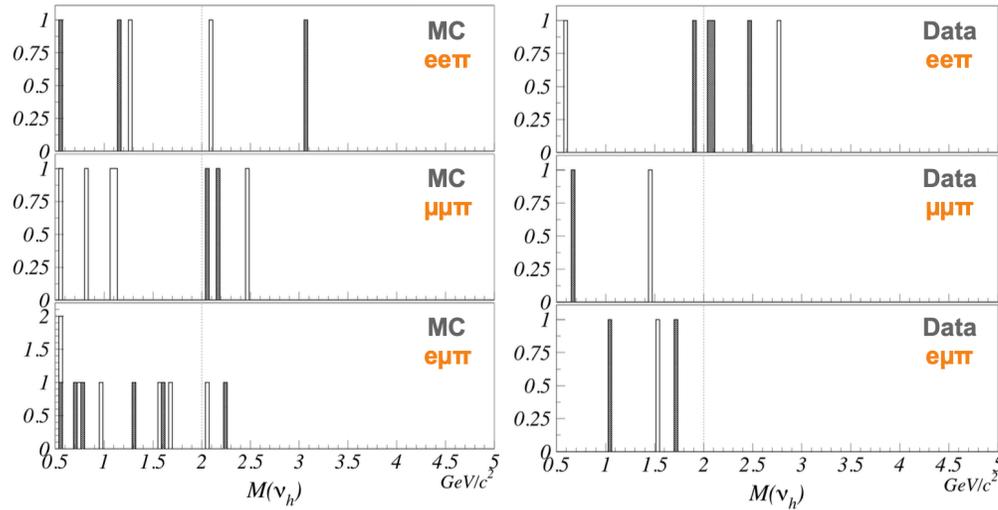
Displaced Vertex

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



Direct search in B decays

- Backgrounds reduced by factor $\sim 10^6$ to only handful of events.

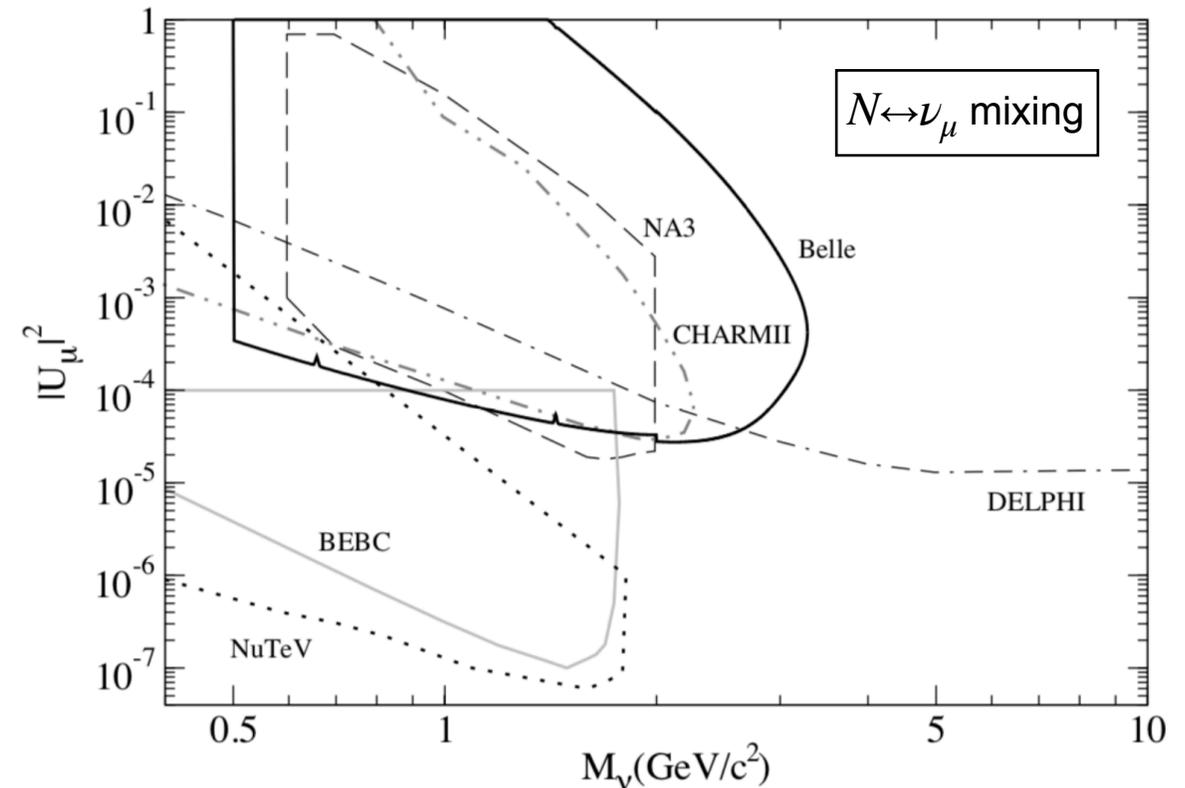


- **No evidence for heavy neutrinos observed.**
Set upper limits on $N \leftrightarrow \nu_{SM}$ mixing parameters.
- Total sys uncertainty $\sim 25\%$ in small & large mass regimes.
Largest contributions:
 - ▶ χ^2/ndof and dz vertex cuts ($\sim 10\%$)
 - ▶ Tracking of daughter particles (8.7% per-track)

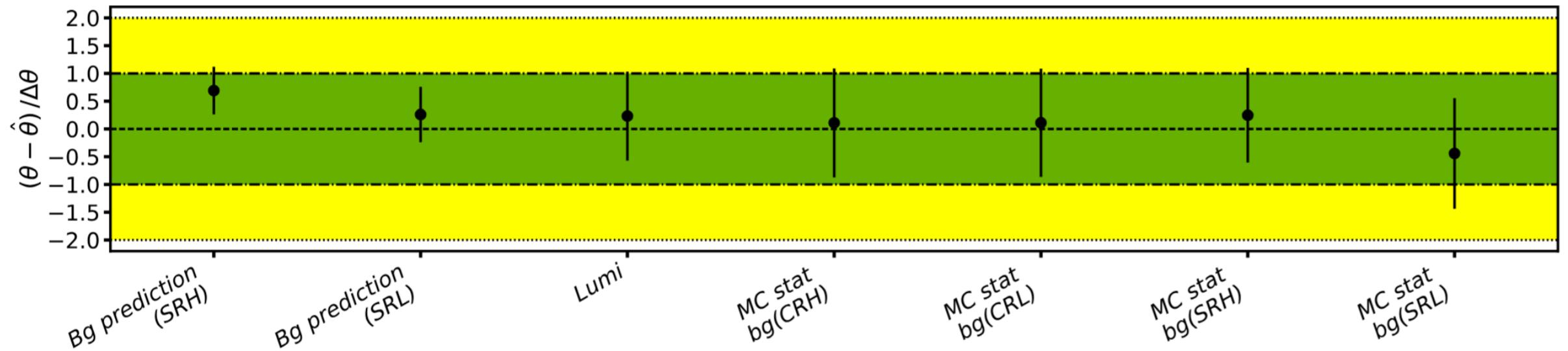
Maximum sensitivity at $m_N \approx 2$ GeV

- ▶ 3.0×10^{-5} for $|U_{eN}|^2$ and $|U_{\mu N}|^2$
- ▶ 2.1×10^{-5} for $|U_{eN}| |U_{\mu N}|$

$$\mathcal{B}(B \rightarrow X \ell \nu_h) \times \mathcal{B}(\nu_h \rightarrow \ell \pi^+) < 7.2 \times 10^{-7}$$



Direct search in τ decays



Direct search in τ decays

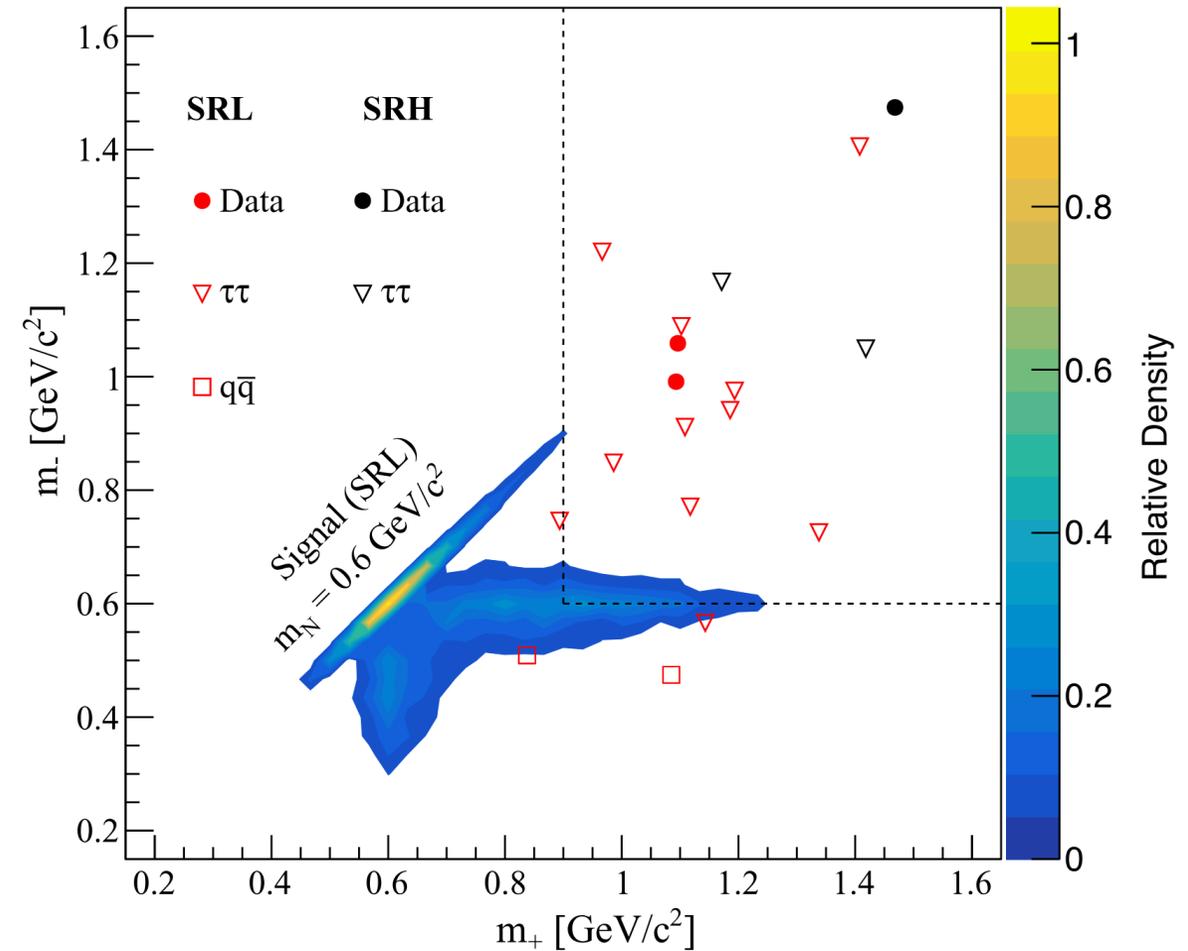
Despite the neutrino in the final state, the constraints of the signal decay enable reconstruction of the full kinematics of the signal- τ decay chain with a twofold ambiguity [37], which arises from a quadratic equation in the magnitude p_N of the HNL momentum,

$$(B^2 - 1)p_N^2 + (2AB - D)p_N + A^2 - C = 0. \quad (1)$$

Eq. (1) tends to be larger for background than for signal. We require it to satisfy $S < 0.4 \text{ GeV}^2$, retaining more than 98% of signal events. Given a solution for p_N , the squared HNL mass is

$$m_N^2 = (D + Cp_N)/E^2. \quad (3)$$

The two solutions for m_N are referred to as m_+ and m_- , depending on the sign in front of the square root of the quadratic-equation solution. For events with $S < 0$ we set $S = 0$, in which case $m_+ = m_-$.



Search for $B \rightarrow K\nu\bar{\nu}$

- FCNC, strongly suppressed in the SM:

$$\mathcal{B}(B^+ \rightarrow K^+ \nu\bar{\nu}) = (5.58 \pm 0.37) \times 10^{-6} \quad [\text{PRD } 107, 014511 \text{ (2023)}]$$

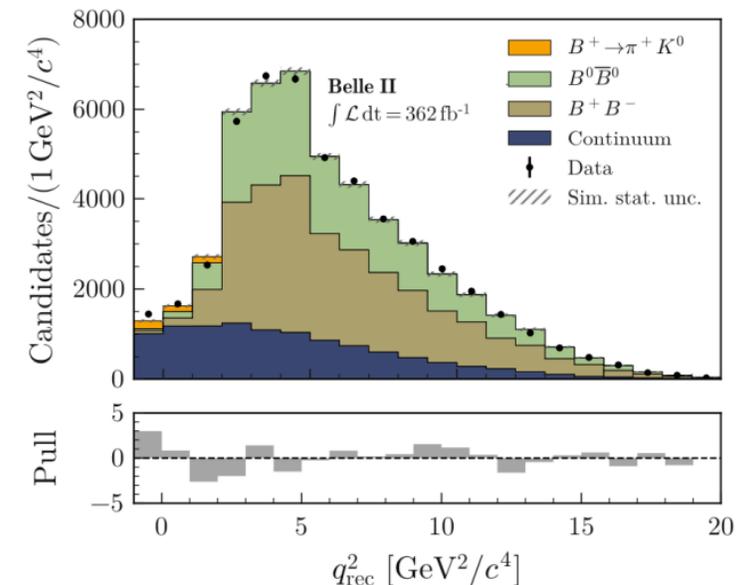
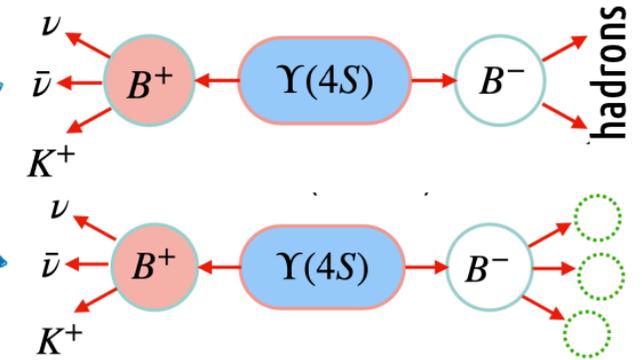
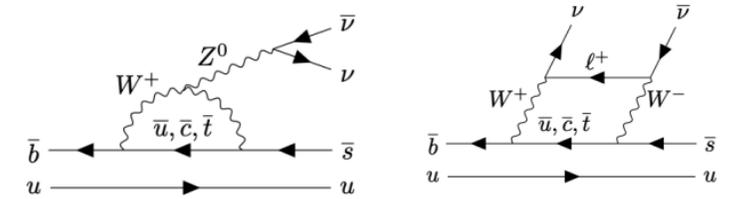
- NP can enhance the BF (for instance [\[PRD, 98, 055003 \(2018\)\]](#))

- Tagging: combination of two methods, (almost) statistically independent:

- **hadronic-tagging:** higher purity (more conventional)
- **inclusive tagging:** higher efficiency (more sensitive)

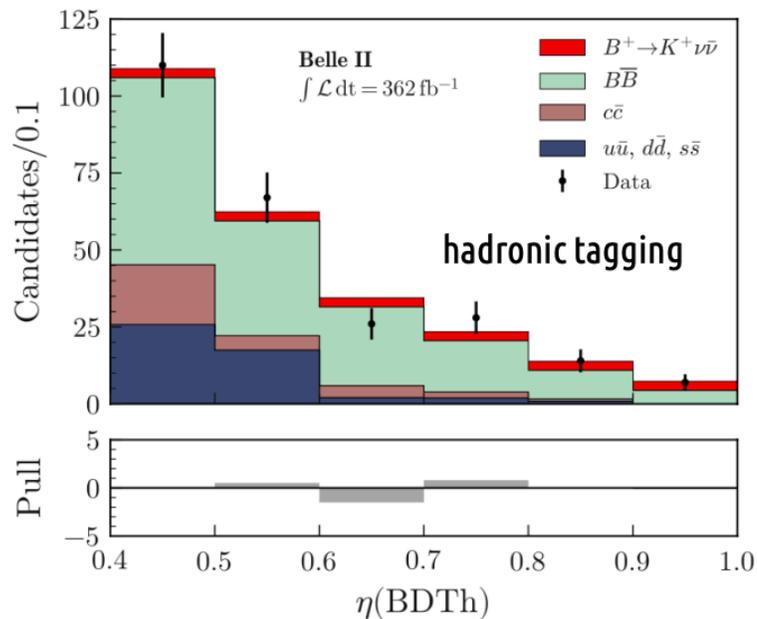
- Bkg suppression and control** is extremely challenging: only one K track, two neutrino in the final state

- Bkg suppressed with **two BDT in cascade** targeting $q\bar{q}$ and other B decays
- **Bkg control validated** for each specific source of bkg
- **Signal efficiency validated** with $B \rightarrow K^+ J/\psi(\rightarrow \mu\mu)$, without matching the muons
- **Closure test:** extraction of the BF of $B \rightarrow K^0 \pi^+$, as a function of $q_{rec}^2 = s + M_K^2 - \sqrt{s}E_K^* \Rightarrow$ found consistent with w.a.

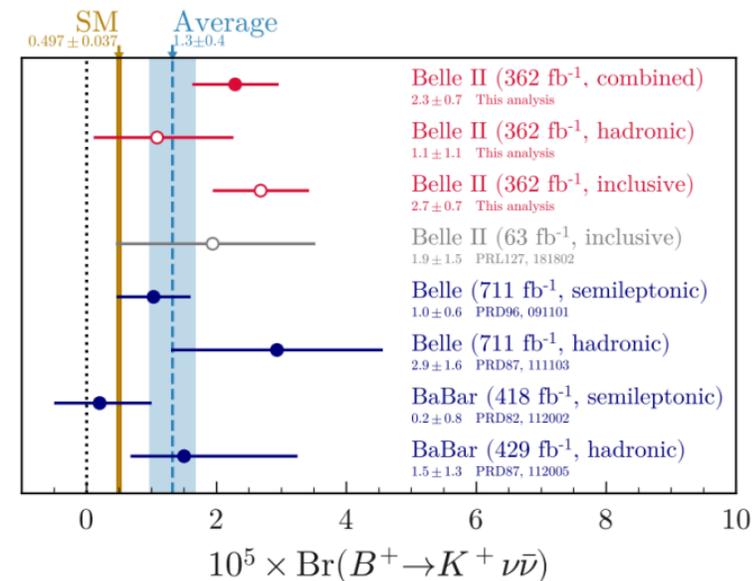
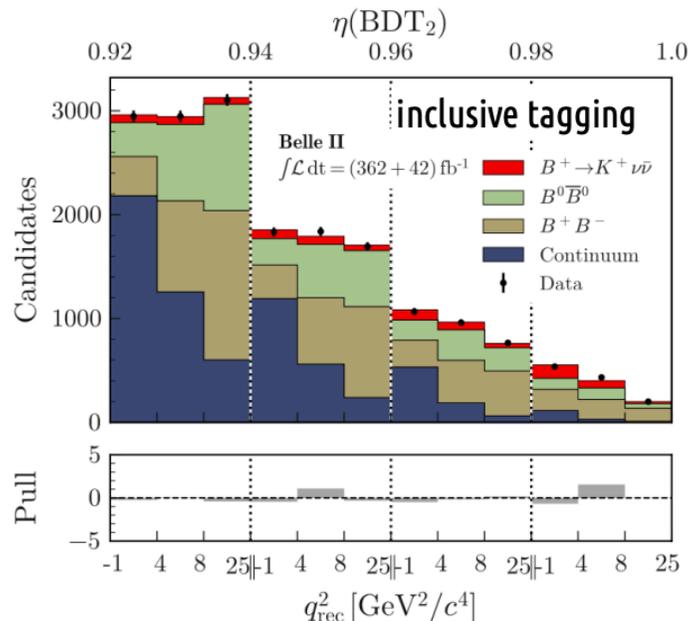


Search for $B \rightarrow K\nu\bar{\nu}$

Hadronic tagging: fit in bin of **BDT output (η)**



Inclusive tagging: fit in bin of **BDT output (η) and dineutrino mass q_{rec}^2**



Combined result:

$$\mu = 4.6 \pm 1.0(\text{stat}) \pm 0.9(\text{syst})$$

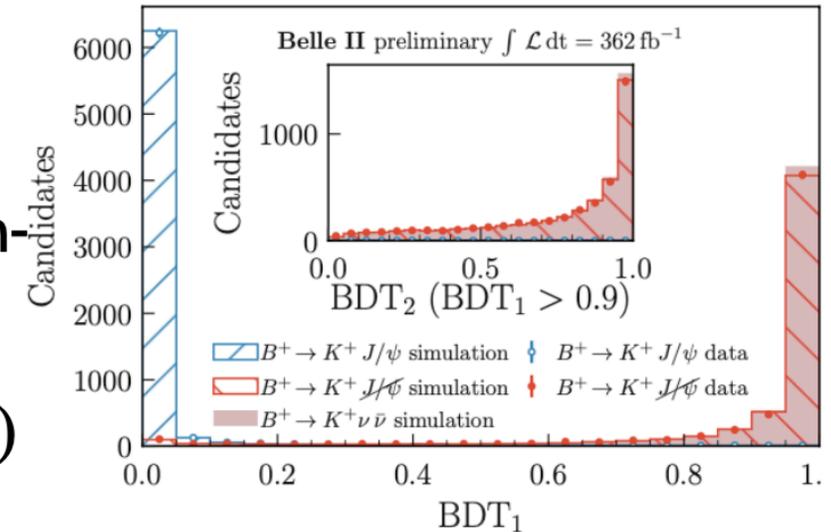
$$BF(B^+ \rightarrow K^+ \nu \bar{\nu}) = [2.3 \pm 0.5(\text{stat})_{-0.4}^{+0.5}(\text{syst})] \times 10^{-5}$$

3.5 σ above the bkg-only hypothesis

2.7 σ above the SM prediction

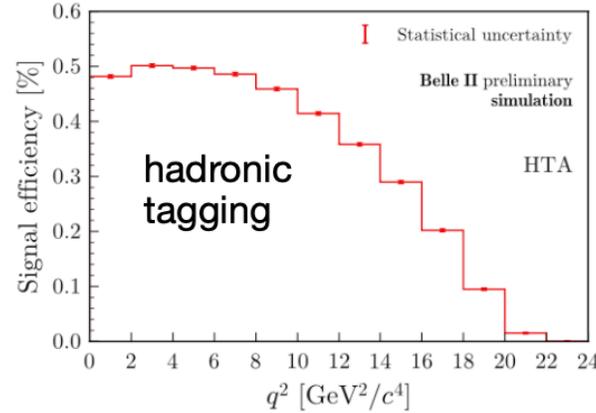
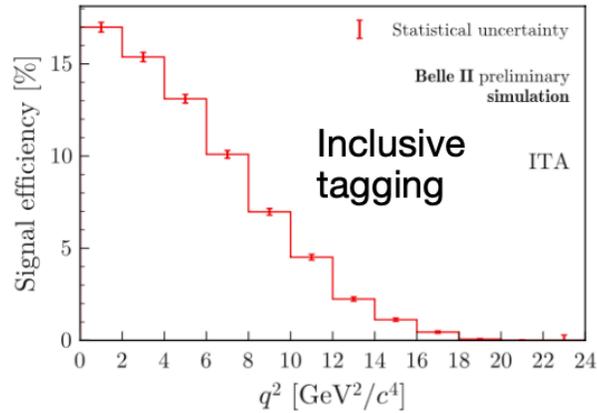
Dedicated bkg validations:

- $ee \rightarrow q\bar{q}$ bkg simulation validated with off-resonance (60 MeV below $\Upsilon(4S)$) data
- $B \rightarrow X_c(\rightarrow K_L^0 X)$ bkg validated with lepton- and pion-enriched control sidebands
- Undetected K_L^0 validated with $e^+e^- \rightarrow \gamma\phi(\rightarrow K_L^0 K_S^0)$
- $B \rightarrow K^+ K^0 K^0$ bkg simulation constrained with previous measurements ($B \rightarrow K^+ K_S^0 K_S^0$, $B \rightarrow K^+ K^- K_S^0$)



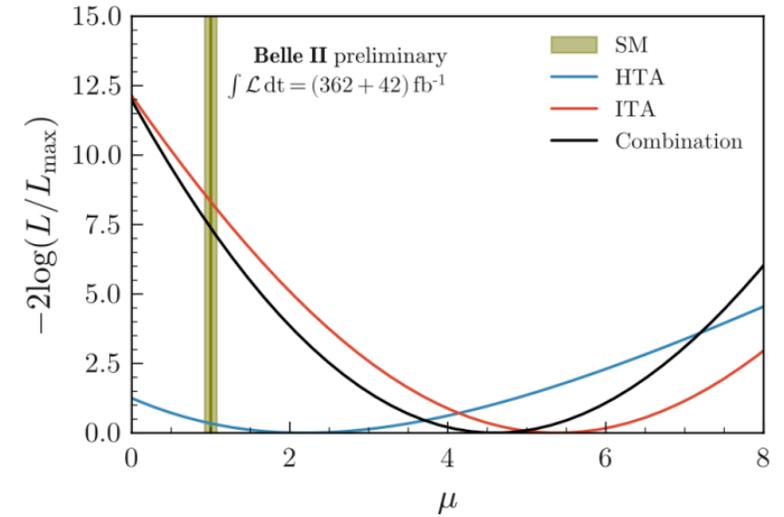
Search for $B \rightarrow K\nu\bar{\nu}$

Efficiency:



Combination:

- profile likelihood fit
- including correlation in syst
- Excluding common events from inclusive tagging fit



Results separated in the two tagging approaches:

- **Hadronic tag:** $\mu = 2.2^{+1.8}_{-1.7}$, $\text{BF} = (1.1^{+0.9}_{-0.8} \text{ } ^{+0.8}_{-0.5}) \times 10^{-5}$ 1.1σ above bkg only, 0.6σ above SM
- **Inclusive tag:** $\mu = 5.4 \pm 1.0 \pm 1.1$, $\text{BF} = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$, 3.5σ above bkg only, 2.9σ above SM

Search for $B \rightarrow K\nu\bar{\nu}$

Systematics
inclusive
tagging

Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of BB background	—	Global, 2	50%	0.90
Normalization of continuum background	—	Global, 5	50%	0.10
Leading B -decay branching fractions	—	Shape, 5	$O(1\%)$	0.22
Branching fraction for $B^+ \rightarrow K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.49
p-wave component for $B^+ \rightarrow K^+ K_S^0 K_L^0$	q^2 dependent $O(100\%)$	Shape, 1	30%	0.02
Branching fraction for $B \rightarrow D^{**}$	—	Shape, 1	50%	0.42
Branching fraction for $B^+ \rightarrow K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.20
Branching fraction for $D \rightarrow K_L^0 X$	+30%	Shape, 1	10%	0.14
Continuum-background modeling, BDT_c	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.01
Integrated luminosity	—	Global, 1	1%	< 0.01
Number of $B\bar{B}$	—	Global, 1	1.5%	0.02
Off-resonance sample normalization	—	Global, 1	5%	0.05
Track-finding efficiency	—	Shape, 1	0.3%	0.20
Signal-kaon PID	p, θ dependent $O(10 - 100\%)$	Shape, 7	$O(1\%)$	0.07
Photon energy	—	Shape, 1	0.5%	0.08
Hadronic energy	-10%	Shape, 1	10%	0.37
K_L^0 efficiency in ECL	-17%	Shape, 1	8%	0.22
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.02
Global signal efficiency	—	Global, 1	3%	0.03
Simulated-sample size	—	Shape, 156	$O(1\%)$	0.52

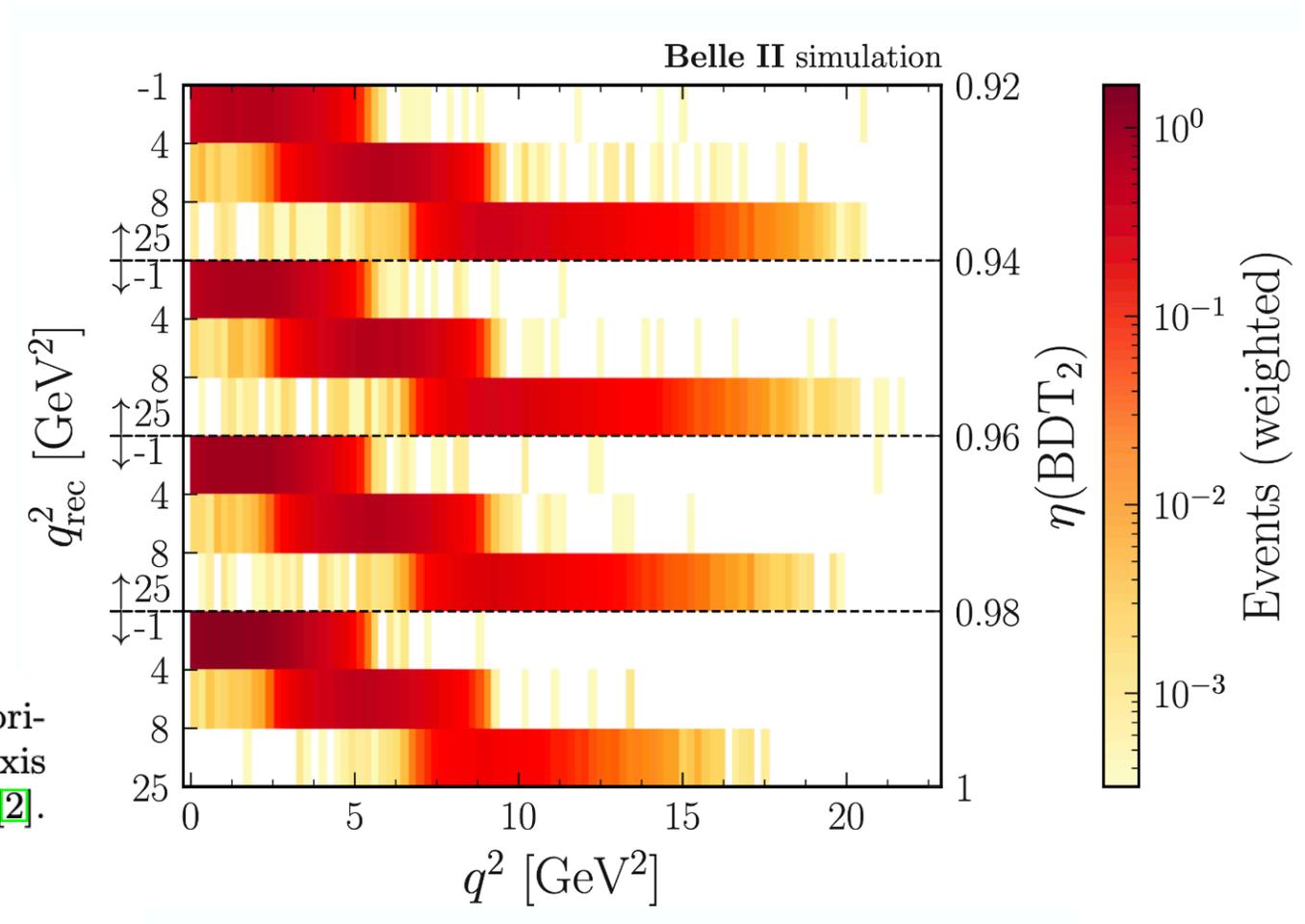
Systematics
hadronic
tagging

Source	Correction	Uncertainty type, parameters	Uncertainty size	Impact on σ_μ
Normalization of BB background	—	Global, 1	30%	0.91
Normalization of continuum background	—	Global, 2	50%	0.58
Leading B -decay branching fractions	—	Shape, 3	$O(1\%)$	0.10
Branching fraction for $B^+ \rightarrow K^+ K_L^0 K_L^0$	q^2 dependent $O(100\%)$	Shape, 1	20%	0.20
Branching fraction for $B \rightarrow D^{**}$	—	Shape, 1	50%	< 0.01
Branching fraction for $B^+ \rightarrow K^+ n\bar{n}$	q^2 dependent $O(100\%)$	Shape, 1	100%	0.05
Branching fraction for $D \rightarrow K_L^0 X$	+30%	Shape, 1	10%	0.03
Continuum-background modeling, BDT_c	Multivariate $O(10\%)$	Shape, 1	100% of correction	0.29
Number of $B\bar{B}$	—	Global, 1	1.5%	0.07
Track finding efficiency	—	Global, 1	0.3%	0.01
Signal-kaon PID	p, θ dependent $O(10 - 100\%)$	Shape, 3	$O(1\%)$	< 0.01
Extra-photon multiplicity	$n_{\gamma\text{extra}}$ dependent $O(20\%)$	Shape, 1	$O(20\%)$	0.61
K_L^0 efficiency	—	Shape, 1	17%	0.31
Signal SM form-factors	q^2 dependent $O(1\%)$	Shape, 3	$O(1\%)$	0.06
Signal efficiency	—	Shape, 6	16%	0.42
Simulated-sample size	—	Shape, 18	$O(1\%)$	0.60

$B \rightarrow K\nu\bar{\nu}$ reinterpretation

- Not easy to fit plot from paper (ϵ_{sig} varies with bin)
- Based on [EPJC84(2024)693] you can build model agnostic likelihood & reweight to any model
 - ▶ **Allows theorists to properly interpret the excess.**
Will be on HEP data very soon!
- *Test case:* 3.3σ for Weak Effective Theory, vector+tensor contribution preferred vs SM

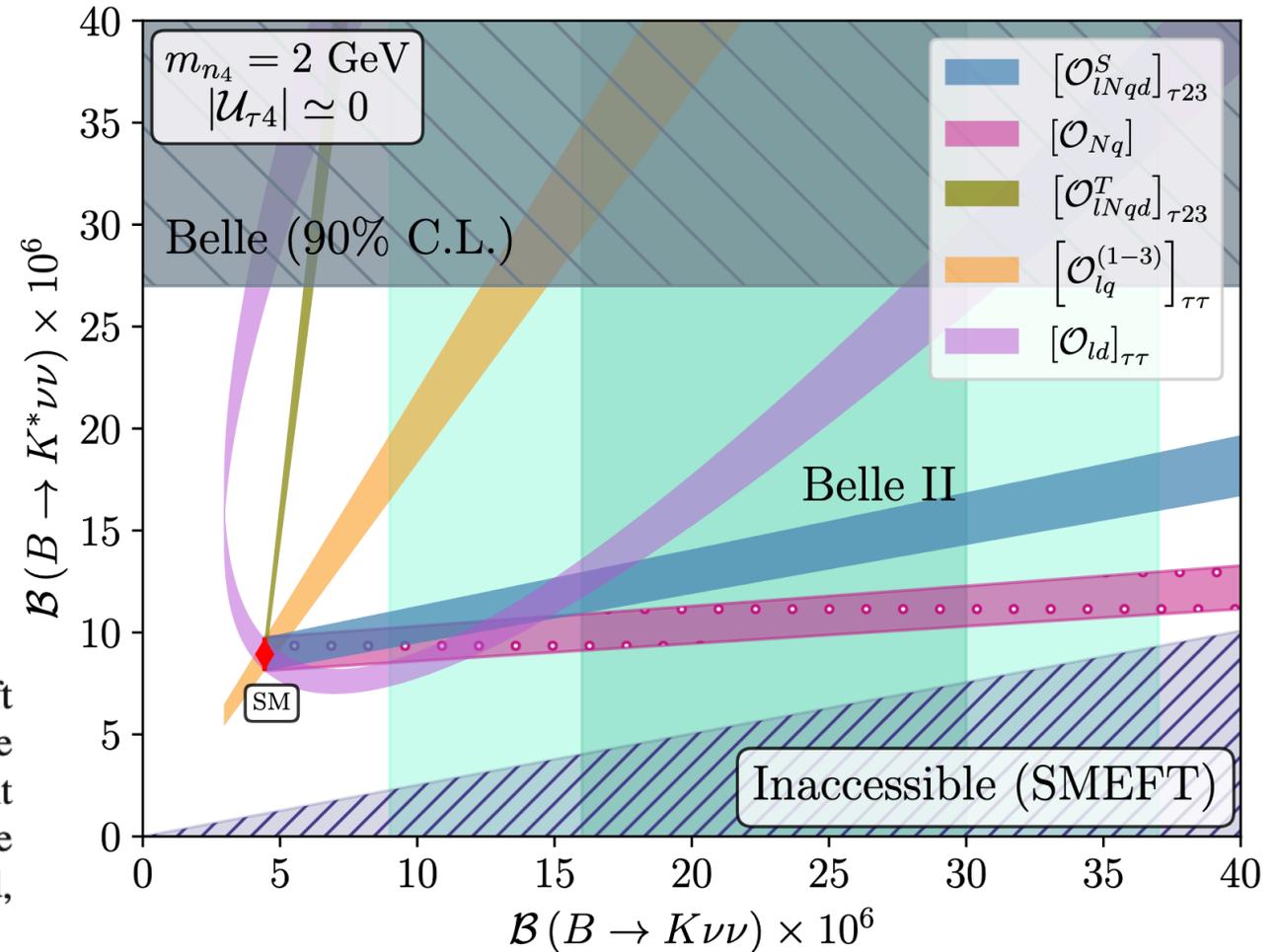
Figure 1. The ITA binned joint number densities. The horizontal axis corresponds to the generated q^2 . The vertical axis represents the binning used in the $B^+ \rightarrow K^+ \nu\bar{\nu}$ analysis [2]. The heatmap shows the weighted signal events.



$B \rightarrow K\nu\bar{\nu}$ reinterpretation

Abstract The first observation of $\mathcal{B}(B^+ \rightarrow K^+\nu\nu)$ by the Belle II experiment lies almost 3σ away from the Standard Model expectation. In this letter we study this result in the SMEFT, extended by a light right-handed neutrino. We explore the correlations between the measured decay rate and other observables, such as $\mathcal{B}(B \rightarrow K^*\nu\nu)$ and $F_L(B \rightarrow K^*\nu\nu)$, showing that they could disentangle among scenarios involving left-handed neutrinos and those with the right-handed ones. Furthermore, we find that the high- p_T tails of Drell–Yan processes studied at LHC provide important constraints that help us exclude some of the scenarios consistent with the Belle II result.

Fig. 1 Correlation between $\mathcal{B}(B \rightarrow K\nu\nu)$ and $\mathcal{B}(B \rightarrow K^*\nu\nu)$ (left panel) when including the effect of one single NP operator at a time and $m_{n_4} \ll m_B - m_K$. The red point corresponds to the SM result and the (light) green regions to the Belle II result at $1(2)\sigma$. The hatched areas on the left panel correspond to the Belle upper bound,



Search for inclusive $B \rightarrow X_s \nu \bar{\nu}$

- $B_{SM} = (2.9 \pm 0.3) \times 10^{-5}$ [JHEP02 (2015) 184]
- $B < 6.4 \times 10^{-4}$ at 90% C.L. [ALEPH, EPJC 19 (2001) 213]
- using Belle II sample of 362 fb^{-1}
- Hadronic B-tagging
- Sum-of-exclusive from 30 decay modes ($\sim 90\%$ of inclusive)

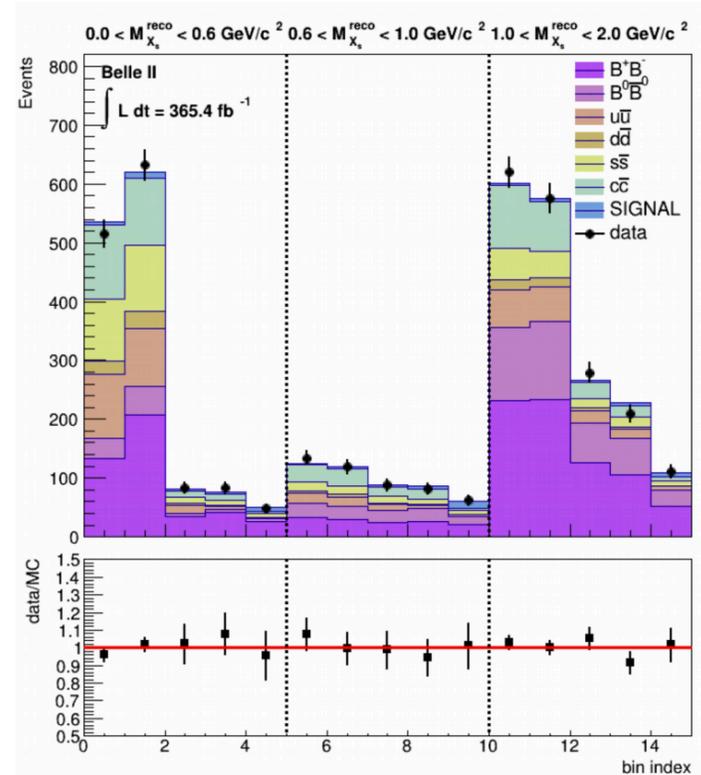
	$B^0 \bar{B}^0$			B^\pm		
K	K_S^0			K^\pm		
$K\pi$	$K^\pm \pi^\mp$	$K_S^0 \pi^0$		$K^\pm \pi^0$	$K_S^0 \pi^\pm$	
$K2\pi$	$K^\pm \pi^\mp \pi^0$	$K_S^0 \pi^\pm \pi^\mp$	$K_S^0 \pi^0 \pi^0$	$K^\pm \pi^\mp \pi^\pm$	$K_S^0 \pi^\pm \pi^0$	$K^\pm \pi^0 \pi^0$
$K3\pi$	$K^\pm \pi^\mp \pi^\pm \pi^\mp$	$K_S^0 \pi^\pm \pi^\mp \pi^0$	$K^\pm \pi^\mp \pi^0 \pi^0$	$K^\pm \pi^\mp \pi^\pm \pi^0$	$K_S^0 \pi^\pm \pi^\mp \pi^\pm$	$K_S^0 \pi^\pm \pi^0 \pi^0$
$K4\pi$	$K^\pm \pi^\mp \pi^\pm \pi^\mp \pi^0$	$K_S^0 \pi^\pm \pi^\mp \pi^\pm \pi^\mp$	$K_S^0 \pi^\pm \pi^\mp \pi^0 \pi^0$	$K^\pm \pi^\mp \pi^\pm \pi^\mp \pi^0$	$K_S^0 \pi^\pm \pi^\mp \pi^\pm \pi^0$	$K^\pm \pi^\mp \pi^\pm \pi^0 \pi^0$
$3K$	$K^\pm K^\mp K_S^0$			$K^\pm K^\mp K^\pm$		
$3K\pi$	$K^\pm K^\mp K^\pm \pi^\mp$	$K^\pm K^\mp K_S^0 \pi^0$		$K^\pm K^\mp K^\pm \pi^0$	$K_S^0 K^\pm K^\mp \pi^\pm$	

- For background suppression, use BDT (include sum of remaining energy in ECL)
- signal extraction in $(\text{BDT output}) \times M_{X_s}$ plane

$$B(B \rightarrow X_s \nu \bar{\nu}) < \begin{cases} 2.5 \times 10^{-5} & (0.0 < M_{X_s} < 0.6 \text{ GeV}/c^2) \\ 1.0 \times 10^{-4} & (0.6 < M_{X_s} < 1.0 \text{ GeV}/c^2) \\ 3.5 \times 10^{-4} & (1.0 < M_{X_s}) \end{cases}$$

$$B(B \rightarrow X_s \nu \bar{\nu}) < 3.6 \times 10^{-4} \text{ at } 90\% \text{ C.L.}$$

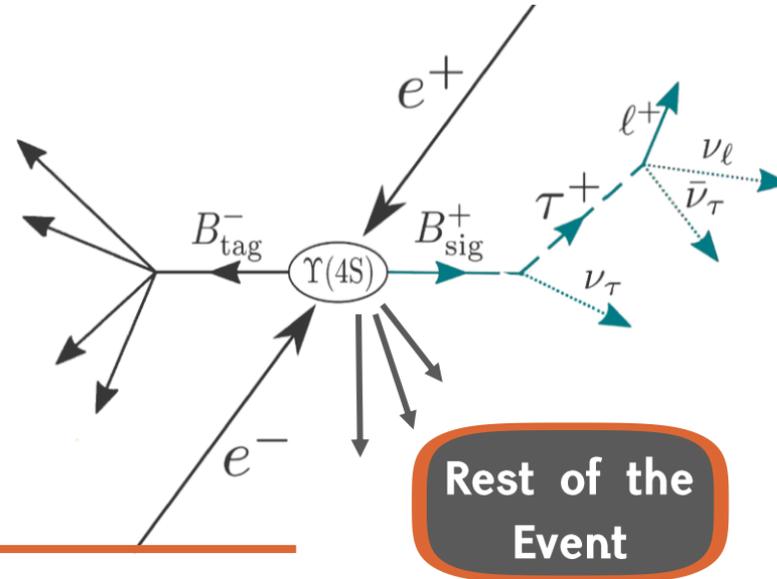
\Rightarrow The most stringent upper limit on $B \rightarrow X_s \nu \bar{\nu}$ decay



Search for $B \rightarrow \tau \nu$

One B meson is fully reconstructed using a multivariate algorithm, Full Event Interpretation (FEI) with Hadronic Tagging.

1. $\mathcal{O}_{FEI} > 10^{-2}$
2. $-0.15 < \Delta E = E_B^* - \sqrt{s}/2 < 0.1 \text{ GeV}$
3. $M_{bc} c^2 = \sqrt{s/4 - (p_B^* c)^2} > 5.27 \text{ GeV}$



Signal is searched through τ decays

1. $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$
2. $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$
3. $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$
4. $\tau^+ \rightarrow \rho^+ \bar{\nu}_\tau$ with $\rho^+ \rightarrow \pi^+ \pi^0$

Backgrounds

$e^+ e^- \rightarrow q \bar{q}$
$e^+ e^- \rightarrow \tau^+ \tau^-$
$e^+ e^- \rightarrow B^+ B^-$
$e^+ e^- \rightarrow B^0 \bar{B}^0$

Rest of the Event:

It is crucial to reject fake photons in the ECL from background

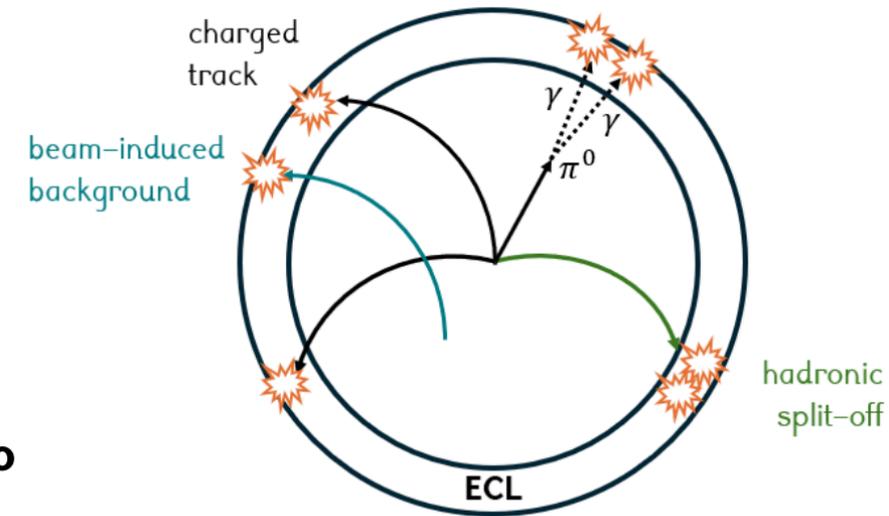
Sum of all the cleaned clusters energy $\rightarrow E_{ECL}^{extra}$.

Missing Quantities:

We build the missing part of each event using also the information of the Rest of Event:

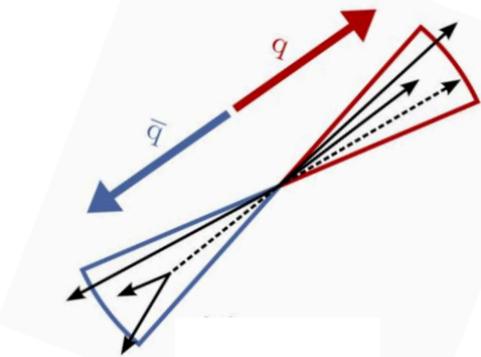
$$p_{miss} = p_{beams} - p_{B_{tag}} - p_{track} - p_{ROE}$$

We will use the Extra ECL Energy and the missing mass squared to extract the signal yield



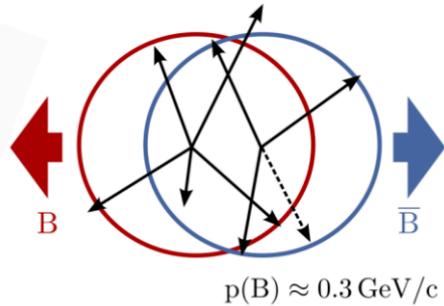
Search for $B \rightarrow \tau \nu$

Continuum



$e^+e^- \rightarrow \tau^+\tau^-$
 $e^+e^- \rightarrow q\bar{q}$ ($q \in \{u, d, s, c\}$)

$B\bar{B}$



$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$

Continuum Suppression

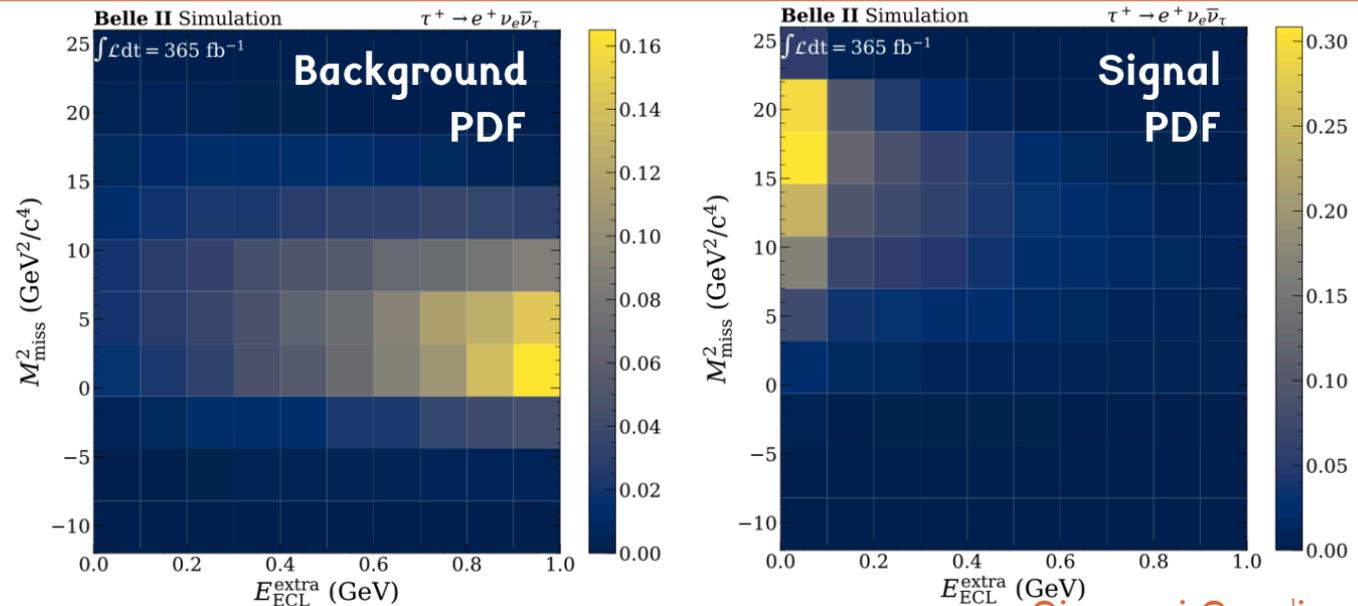
MVA: 2 BDTs trained, one for leptonic and one for hadronic τ^+ decays. **BDT output** $\rightarrow \mathcal{O}_{CS}$
 Features = only variables not correlated with our fit variables.
 Plots in the backup.

Signal Enhancement

The selection optimization is done performing **maximum likelihood fits** E_{ECL}^{extra} vs M_{miss}^2 on simulation PDFs.

Important variables to enhance the signal:

- **Momentum of the π/ρ (higher than the background)**
- **Continuum Suppression Output**



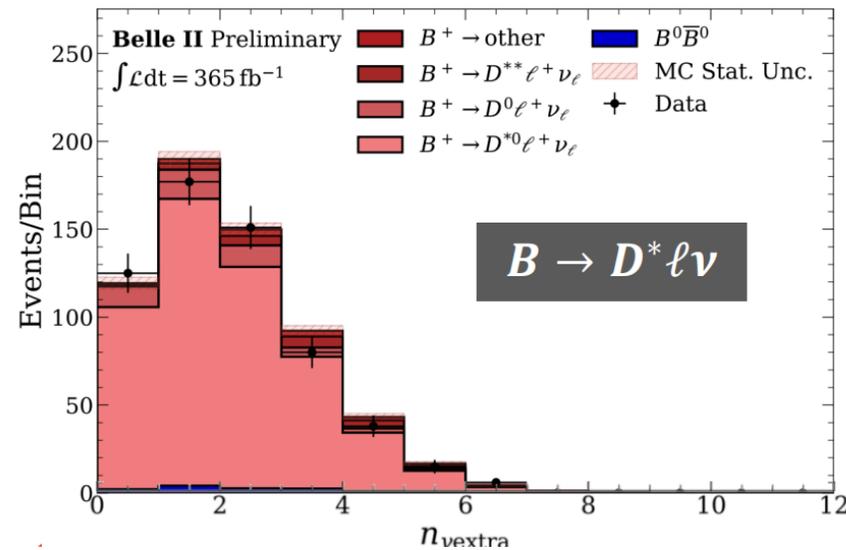
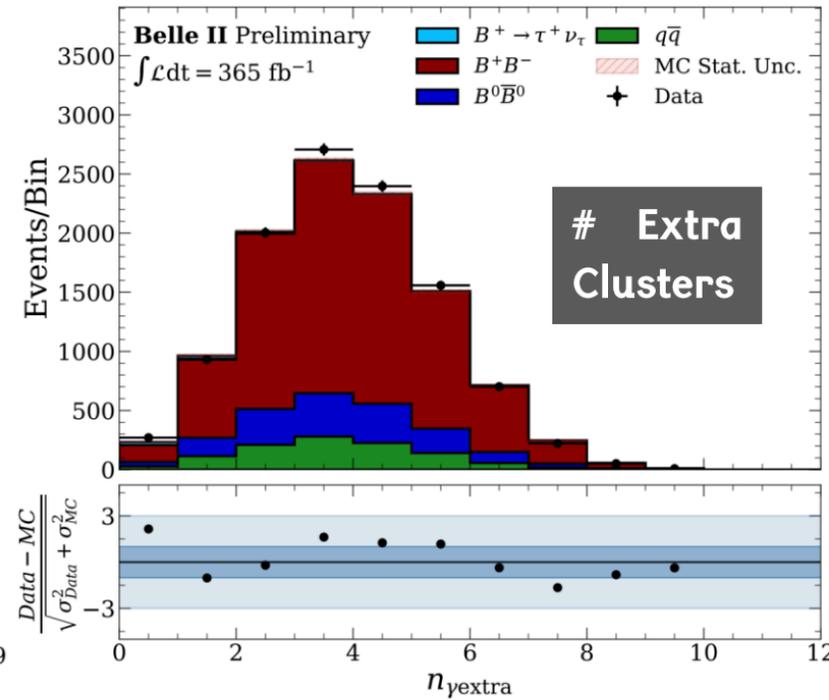
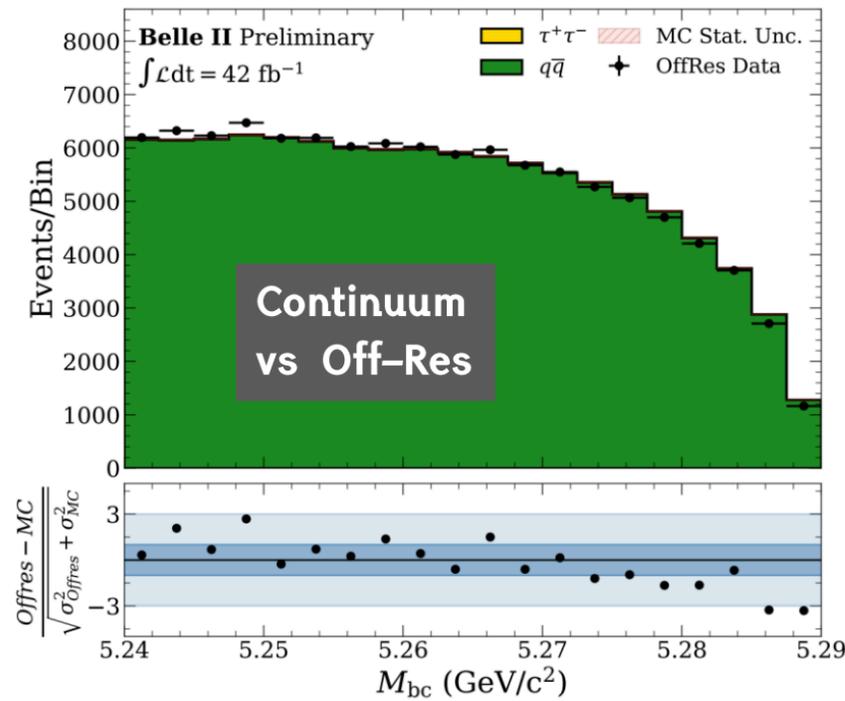
Search for $B \rightarrow \tau \nu$

Continuum normalization and validation

$q\bar{q}$ backgrounds validated in data sample collected 60 MeV below $\Upsilon(4S)$ resonance

Validation of extra clusters efficiency

Use control samples in the table below to validate simulation of energy deposit in the calorimeter and correct extra photons multiplicity



Validate signal efficiency

Embedding: Reconstruct $B^+ \rightarrow J/\psi K^+$, and replace $J/\psi K^+$ with $\tau \nu$ for data and MC

Similar Channel: Reconstruct $B^+ \rightarrow D^{*0} \ell \nu$ to double check the signal efficiency

Main Sample	Continuum	$B\bar{B}$	Sig. $\tau \rightarrow \ell \nu \nu$	Sig. $\tau \rightarrow h \nu$
Control Sample	Off-resonance Data	Extra Tracks	$B \rightarrow D^* \ell \nu$	Double Tag

Search for $B \rightarrow \tau \nu$

Statistical uncertainty dominates (**33% stat, vs 15% syst.**)

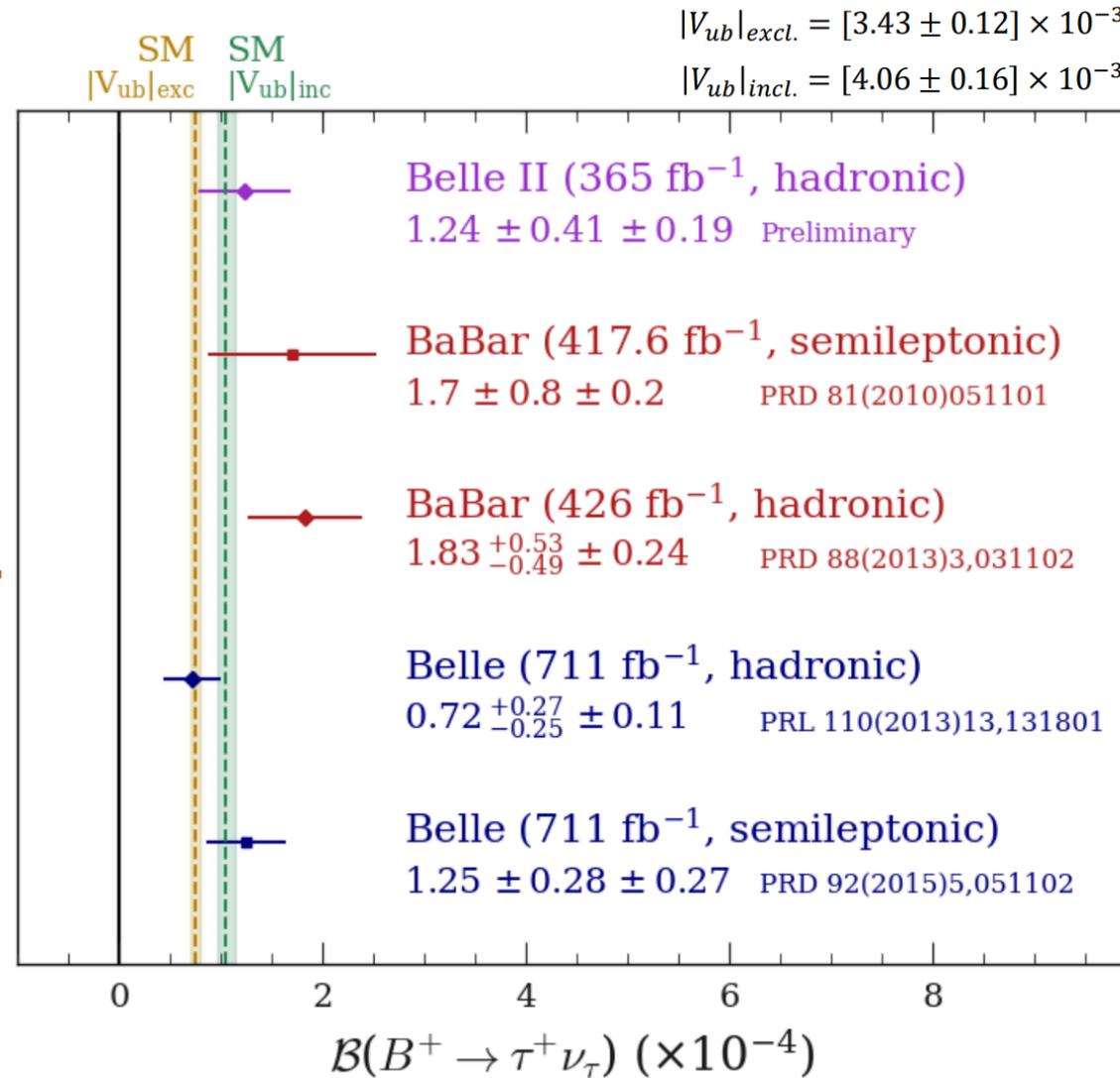
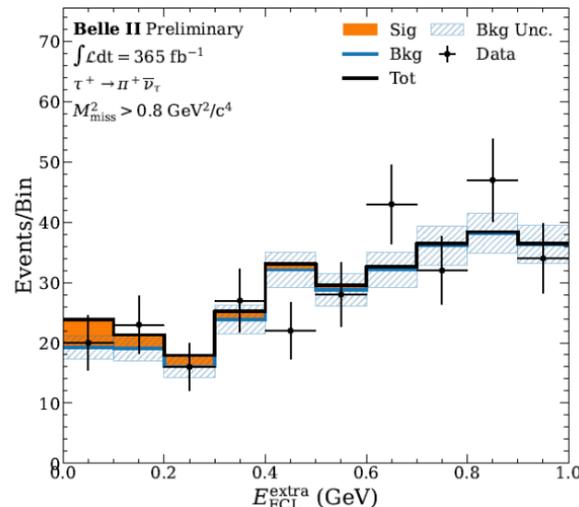
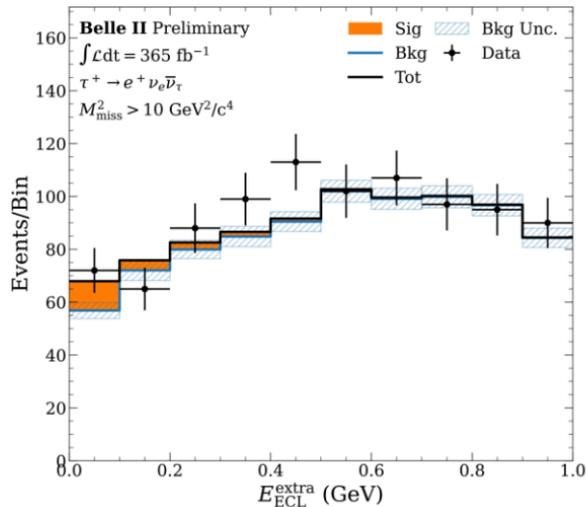
Main Systematics:

1. Simulation sample size
2. Fit variables PDF corrections
3. Decays branching fraction in PDG

3.0 σ with respect to background-only hypothesis

Assuming the SM, and using $f_B = 190.0 \pm 1.3$ MeV from Lattice QCD:

$$|V_{ub}| = (4.41^{+0.74}_{-0.89}) \times 10^{-3}$$



$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.24 \pm 0.41(\text{stat.}) \pm 0.19(\text{syst.})) \times 10^{-4}$$

Search for $B \rightarrow \tau \nu$

Source	Syst.	
Simulation statistics	13.3%	➔ It is expected to reduce using more simulations.
Fit variables PDF corrections	5.5%	➔ It is expected to reduce with increasing luminosity and better modeling of ECL photons in MC simulations.
Decays branching fractions in MC	4.1%	
Tag B^- reconstruction efficiency	2.2%	
Continuum reweighting	1.9%	The effect of each source on the final result is estimated by fluctuating the assumptions several times and propagating the effect on the PDF shapes, generating in this way a set of alternative PDFs.
π^0 reconstruction efficiency	0.9%	
Continuum normalization	0.7%	
Particle identification	0.6%	
Number of produced $\Upsilon(4S)$	1.5%	
Fraction of $B^+ B^-$ pairs	2.1%	➔ When uncertainties do not affect the signal yields, they are propagated directly to the BR.
Tracking efficiency	0.2%	
Total	15.5%	