EWP decays with missing energy and LFV at Belle and Belle II

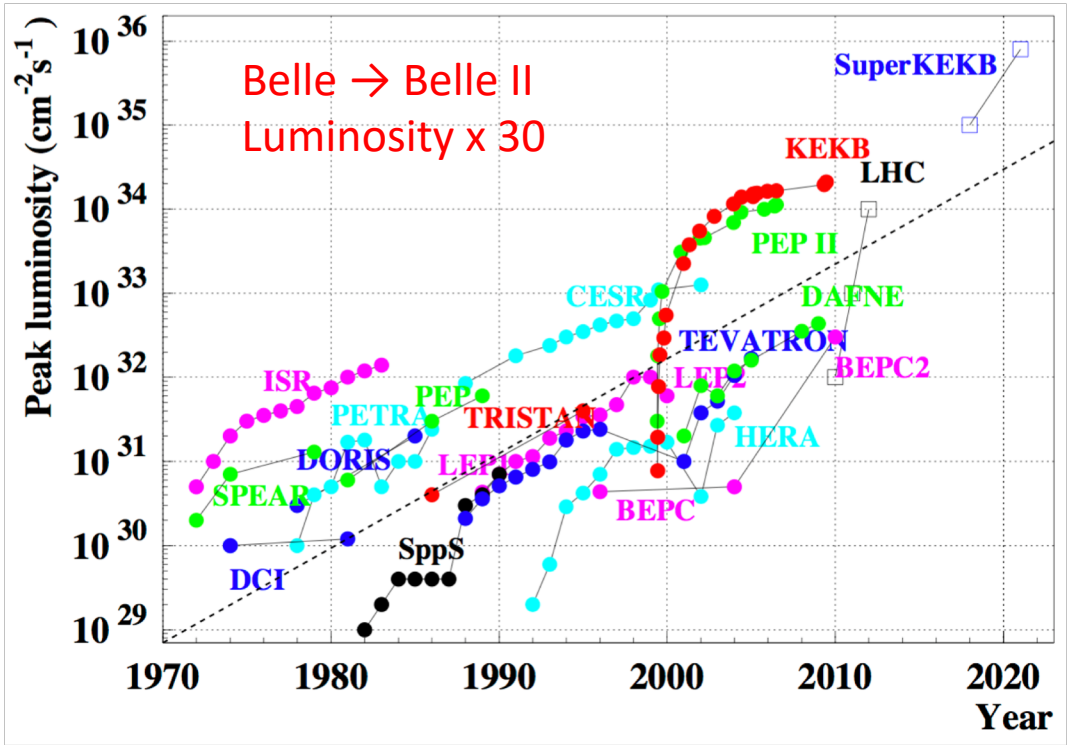
Tao Luo (Fudan University)
On Behalf of the Belle/Belle II Collaboration

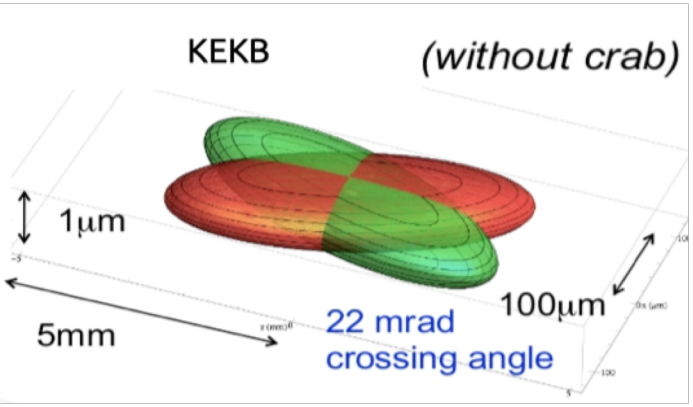
Nov. 22 - 26, 2021
11th International Workshop on the CKM Unitarity Triangle (CKM 2021)
Melbourne, Australia, online

SuperKEKB Accelerator

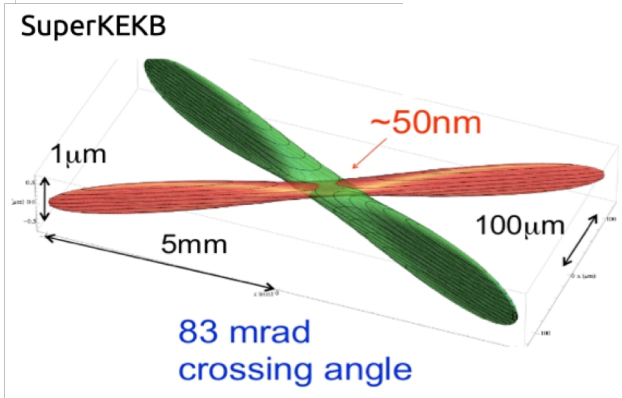
- Reduction in the beam size by 1/20 at the IP.
- 1.5 times increase in beam currents.

Targets:
Peak luminosity: $6\times10^{35}cm^{-2}s^{-1}$
Integrated luminosity: **50ab^{-1} by 2031**

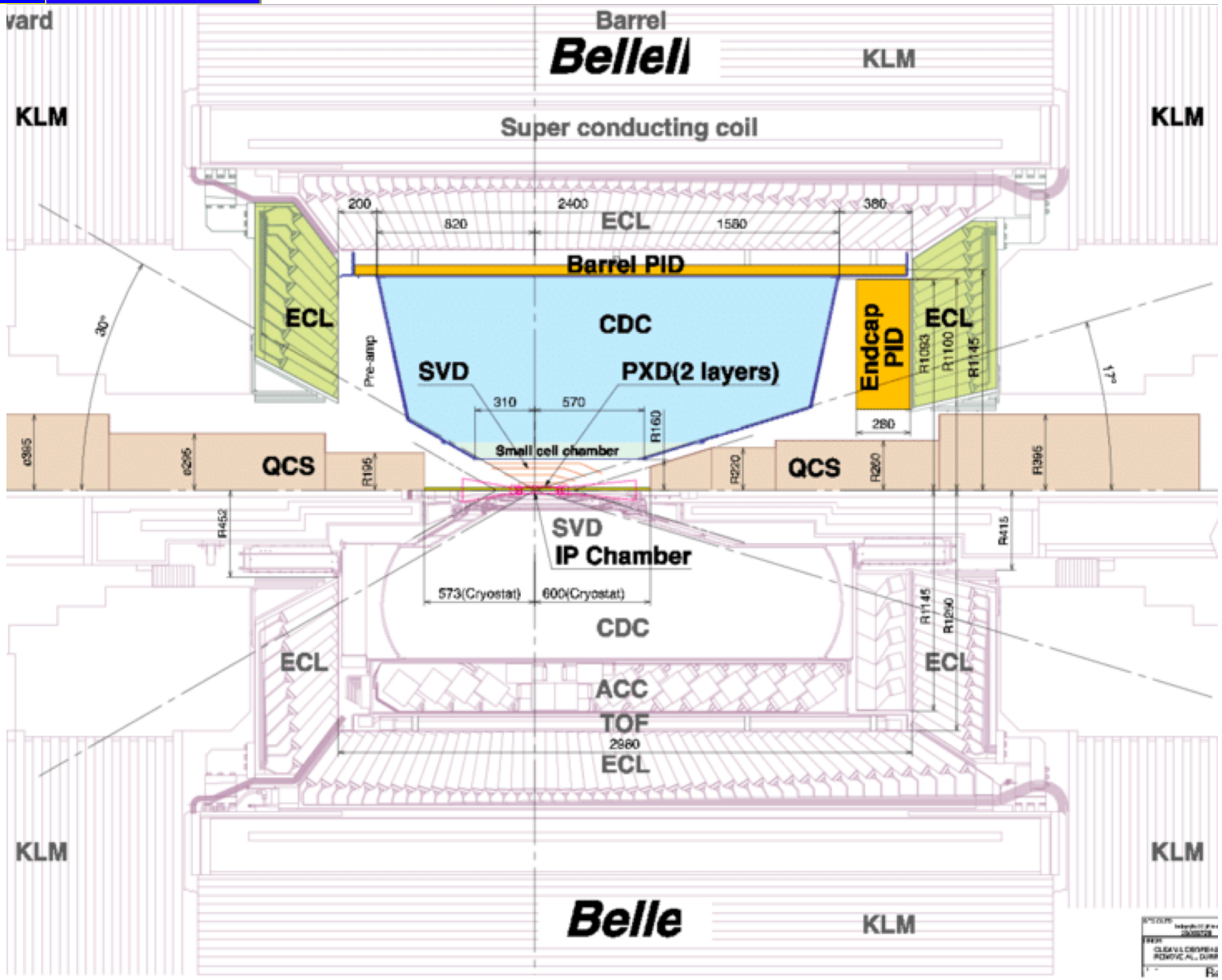




Nano-Beam scheme

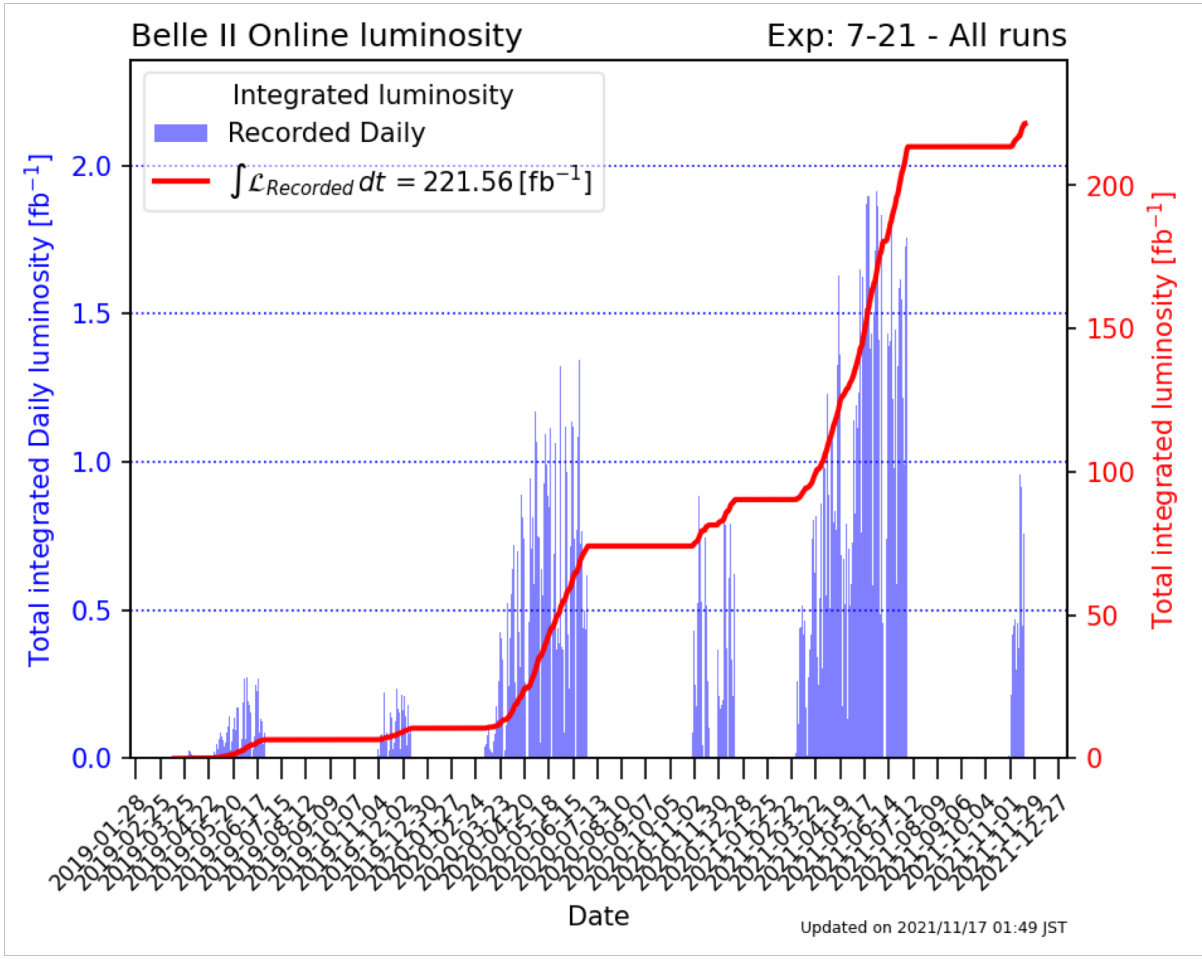


The Belle/Belle II Detector

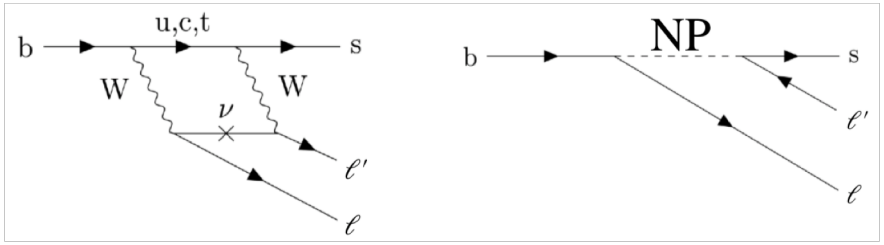


Status of Belle II data taking

- Belle collected data ~ 1 ab^{-1}
- Belle II collected data 215 fb^{-1}
  - ✓ ~30% of Belle data
  - ✓ ~50% of BaBar data
- Peak luminosity reached
  3.12 x 10^{34} cm^{-2} s^{-1}
  with beam current product
  factor 3.5 lower than KEKB
  (nanobeam enhancement)
  - ✓ 50% higher than previous world record by KEKB
  - ✓ factor 3 higher than KEKB (Belle) and PEP-II (BaBar) design luminosity
- 89.5% data taking efficiency during the pandemic situation
  (remote operation shifts)



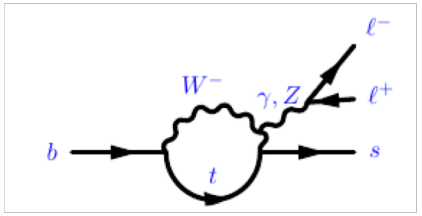
LFV AND B Anomalies

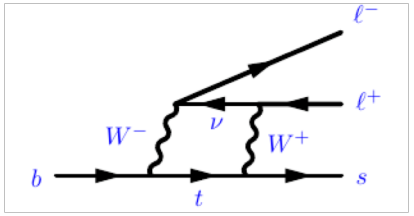


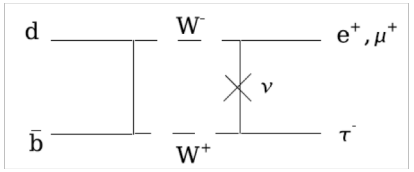
- Lepton Flavor Violating (LFV) decays:
  - ✓ Forbidden in the Standard Model w/o neutrino-oscillation
  - ✓ Can occur via *ν* mixing but are highly suppressed $(\frac{m_\nu^2}{m_W^2})$
    - well beyond any experimental sensitivity
- Recent measurements of b-hadron decays have provided experimental indications of the lepton flavor universality violation (LFUV) - deviations from:
  - ✓ μ/e universality in b→ sll neutral-current transitions BSM
  - ✓ τ/μ (and τ/e) universality in b → c$l\nu$ charged-current transitions
- LFUV is often accompanied by lepton flavor violation (LFV) in theoretical models (PRL 114 (2015), 091801)
- The observation of LFV in the charged sector would be a clear sign of physics beyond the Standard Model!

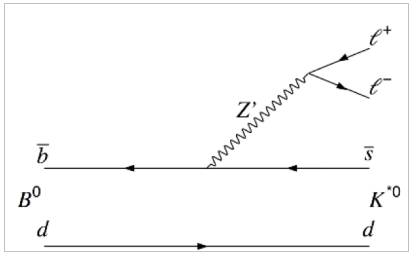
Electroweak Penguin decays

- In the SM:
  - ✓ forbidden at tree level
  - ✓ occur via box and loop diagrams.
  - ✓ branching fractions are very small, i.e. < 10^{-5}
  - →
- Sensitive to NP beyond the SM
  - ✓ New particle might appear in the loop
  - ✓ Can also decay via tree diagram for some of the new particles.
  - ✓ NP contribution to the Wilson coefficients
  - ✓ Provide many observables to probe for new physics: angular, asymmetries, etc.









PRL 120 (2018), 181802; JHEP 10 (2015),184; JHEP 09 (2017), 40

Recent results on EWP decays at Belle / Belle II

- Belle
  - ✓ Search for $B^0 \to K^* \tau^+ \tau^-$ at Belle (arXiv: 2110. 03871)
  - ✓ Search for $B^0_{(d)} \to \tau^{\mp} \ell^{\pm}$ at Belle (arXiv: 2108. 11649)

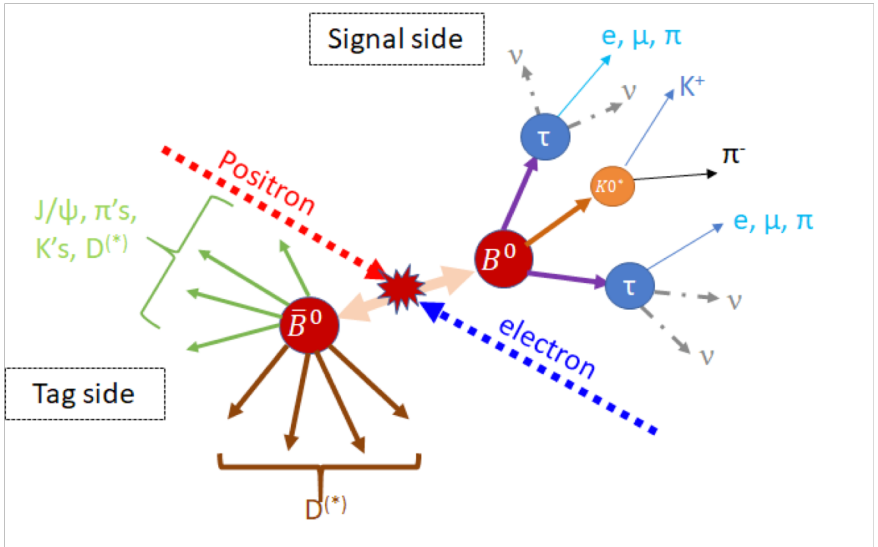
- Belle II
  - ✓ Search for $B^+ \to K^+ \upsilon \bar{\upsilon}$ at Belle II (Phys. Rev. Lett. 127 (2021) 181802)

$B^0 \to K^* \tau^+ \tau^-$ at Belle

- Highly suppressed in the SM and can only proceed via FCNC, with predicted B of order $\mathcal{O}(10^{-7})$
- With the effect of NP, $\mathcal{B}$ can be at level of 10^{-4} [PRL 120, 181802 (2018)]
- The BaBar collaboration sets an upper limit for $B^+ \to K^+ \tau^+ \tau^-$ [Phys. Rev. Lett. 118, 031802 (2017].
  - ✓ $\mathcal{B}(B^+ \to K^+ \tau^+ \tau^-) < 2.25 \times 10^{-3}$ at 90% C.L. (using 471 million $B\bar{B}$ pairs)
- Currently, no limit is set for $B^0 \to K^* \tau^+ \tau^-$ decay mode
- The presence of at least two neutrinos in the final state originating from τ lepton decays make full reconstruction of the decay impossible.

Search for $B^0 \to K^*\tau^+\tau^-$ at Belle

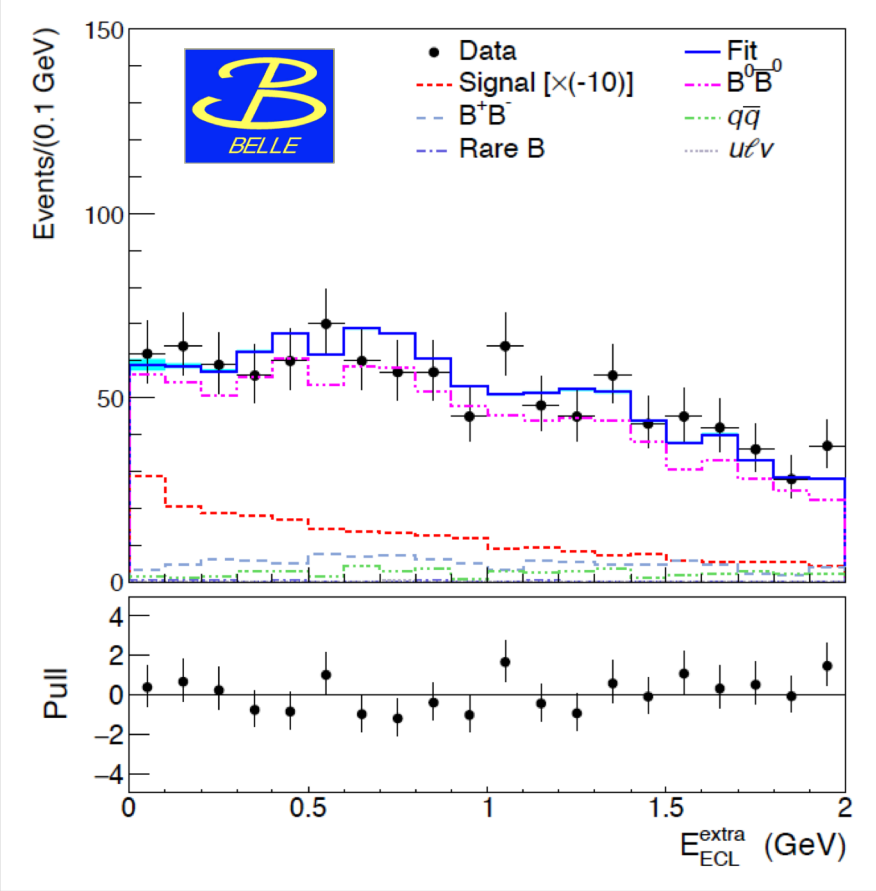
- Tag side (B_{tag}) → reconstructed in 489 exclusive B^0 meson decay channels using hierarchal neural networks algorithm. Full Belle dataset: 711 fb^{-1}
- Searching signal in the rest of event.
  - ✓ Require 4 charged tracks, net charge=0.
- Supressing background
  - ✓ requirement on mass of tau pair, mass of the two leptons,
  - ✓ veto events having K_S, π^0, and more than one K_L
- More background suppression using missing mass squared (M^2_{miss}) and $M(K^{*0}\pi)$ variables (depending on final state particles).



Results for $B^0 \to K^*\tau^+\tau^-$ at Belle

arXiv: 2110. 03871, submitted to PRD

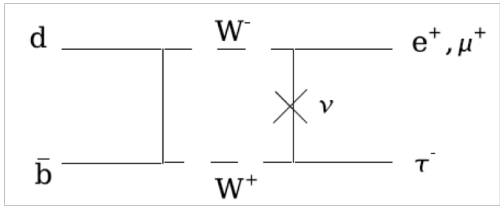
- Binned extended maximum-likelihood fit to the extra calorimeter energy, E_{ECL}^{extra} distribution.



- E_{ECL}^{extra} is the total energy of the neutral clusters detected in the ECL not associated with either B_{tag} or B_{sig}. "$E_{missing}$"
- The overall selection efficiency, $\epsilon = 1.2\times10^{-5}$
- $N_{sig} = -4.9 \pm 6.0$
- The upper limit:
  - ✓ $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0\times10^{-3}$ at 90% C.L.
- The first experimental limit on the decay $B^0 \to K^{*0}\tau^+\tau^-$.

$B^0_{(d)} \to \tau^{\mp} \ell^{\pm}$

- Forbidden in the SM without neutrino oscillations, but in principle it can occur via neutrino mixing. The rate is significantly below current and future experimental sensitivities (~10^{-40}).



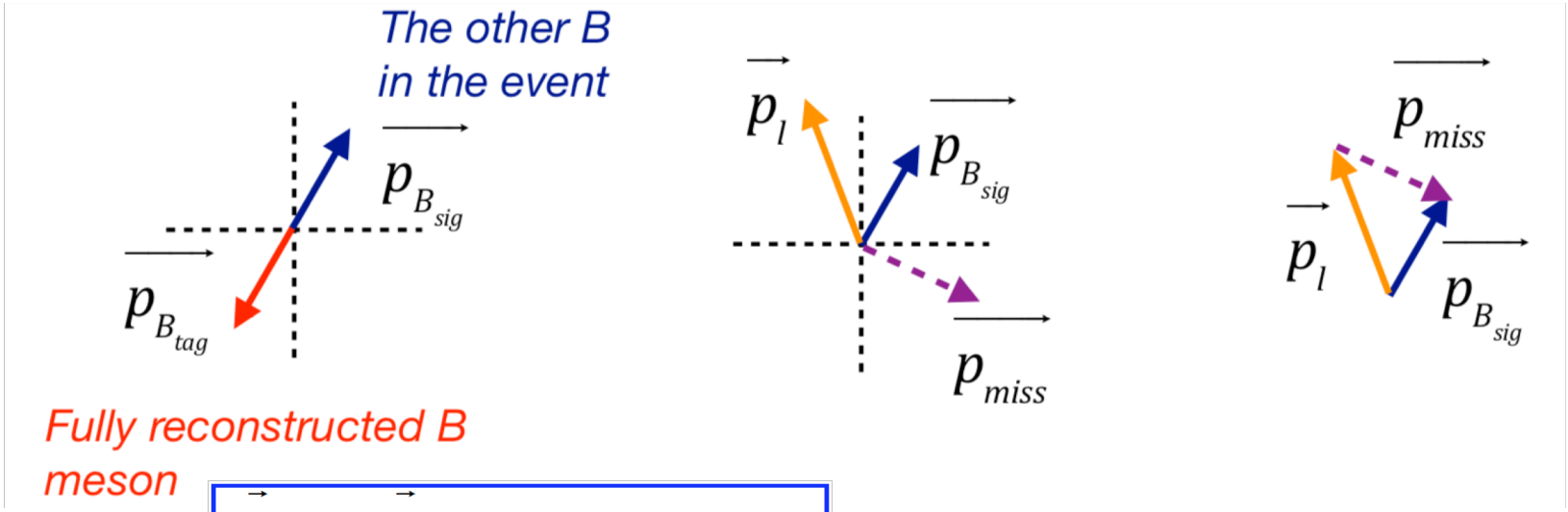
- NP models such as leptoquarks [Mod. Phys. Lett. A 33, 1850019 (2018)] or Higgs-mediation in supersymmetric seesaw models [Phys. Lett. B 549, 159 (2002)] give rise to branching fractions (~10^{-9} – 10^{-10}).

Experimental status

90 % C.L.	CLEO (9.6 M $B\bar{B}$) *Phys.Rev.Lett. 93, 241802 (2004)*	BABAR (378 M $B\bar{B}$) *Phys. Rev. D 77, 091104(R) (2008)*	LHCb (3fb^{-1} of pp collisions) *Phys. Rev. Lett. 123, 211801 (2019)*
$\mathcal{B}(B_{(d)}^0 \to \tau^{\mp} e^{\pm})$	< 1.3×10^{-4}	< 2.8×10^{-5}	–
$\mathcal{B}(B_{(d)}^0 \to \tau^{\mp} \mu^{\pm})$	< 3.8×10^{-5}	< 2.2×10^{-5}	< 1.2×10^{-5}

Search for $B^0_{(d)} \to \tau^{\mp} \ell^{\pm}$ at Belle

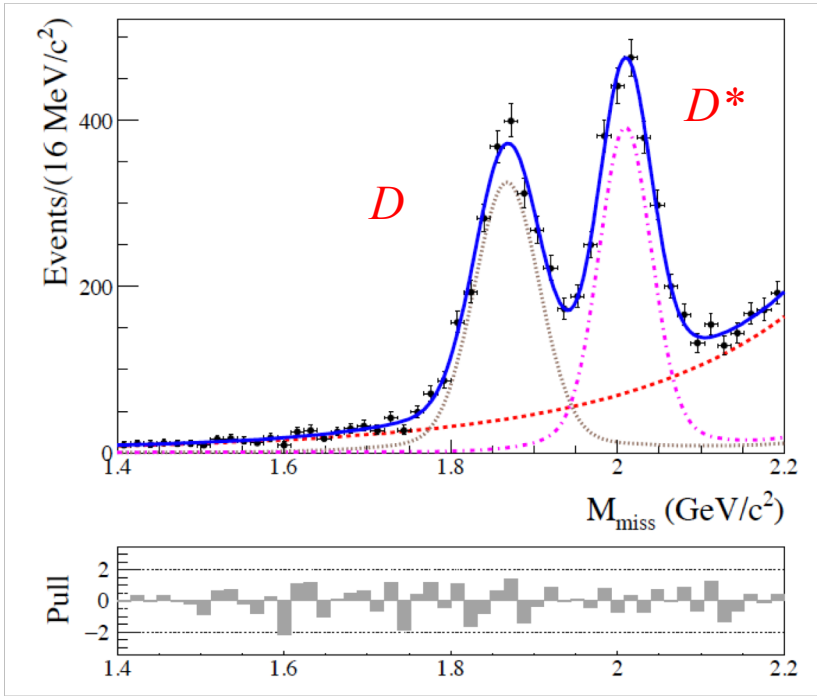
- Because $B^0 \to \tau^{\mp} \ell^{\pm}$ are two-body decays, the momentum of the τ lepton can be inferred from the momentum of B_{sig} and the momentum of $\ell^{\pm}$; thus the $\tau^{\mp}$ does not need to be reconstructed.



$$\vec{p}_{B_{SIG}} = -\vec{p}_{B_{TAG}}, \quad E_{B_{SIG}} = E_{BEAM}$$
$$\vec{p}_{miss} = \vec{p}_{B_{SIG}} - \vec{p}_l$$
$$E_{miss} = E_{BEAM} - E_l$$

$$M_{miss} = \sqrt{E_{miss}^2 - \left(\vec{p}_{miss}\right)^2}$$

Validate the analysis procedure with control sample



arXiv: 2108. 11649，accepted by PRD (letter)

Applied the same event selection criteria used in $B^0 \to \tau\,\mu$. D / D^* are missing

Signal Efficiencies:

$B^0 \to D\,\pi$: 1.0 x 10^{-3}

$B^0 \to D^*\pi$: 1.0 x 10^{-3}

N_{sig}

$B^0 \to D\,\pi$: 2136.4 ± 71.0

$B^0 \to D^*\,\pi$: 2071.1 ± 74.0

Branching fraction × 10^{-3}

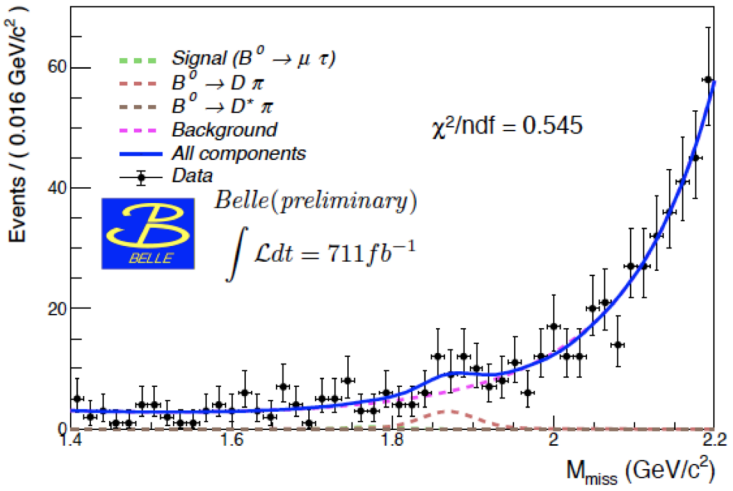
Mode	World average	This measurement
$B^0 \to D^- \pi^+$	2.52 ± 0.13 (stat+sys)	2.54 ± 0.11 (stat)
$B^0 \to D^{*-} \pi^+$	2.74 ± 0.13 (stat+sys)	2.67 ± 0.12 (stat)

Results for $B^0_{(d)} \to \tau^{\mp} \ell^{\pm}$ at Belle

arXiv: 2108. 11649，accepted by PRD (letter)

- Unbinned extended maximum-likelihood fit to the M_{miss} distribution.

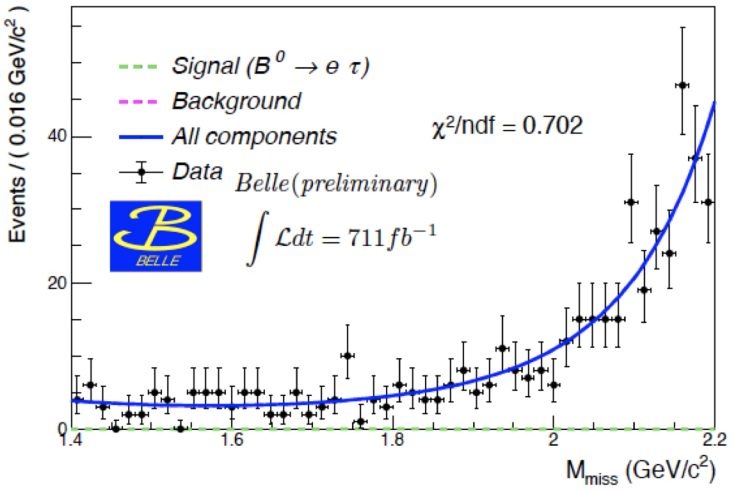
$B \to \tau \mu$



Signal Efficiency: 1.1 x 10^{-3}

$$N_{sig} = 1.8^{+8.2}_{-7.6}$$

$B \to \tau e$



Signal Efficiency: 1.0 x 10^{-3}

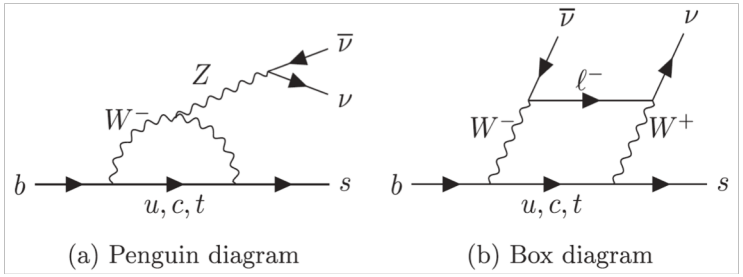
$$N_{sig} = 0.3^{+8.8}_{-8.2}$$

- The upper limits: $\mathcal{B}(B^0 \to \tau\mu) < 1.5\times10^{-5}$, $\mathcal{B}(B^0 \to \tau e) < 1.6\times10^{-5}$ at 90 C.L.
  Electron mode: the most stringent limit to date

Search for $B^+ \to K^+ \nu\bar{\nu}$ at Belle II

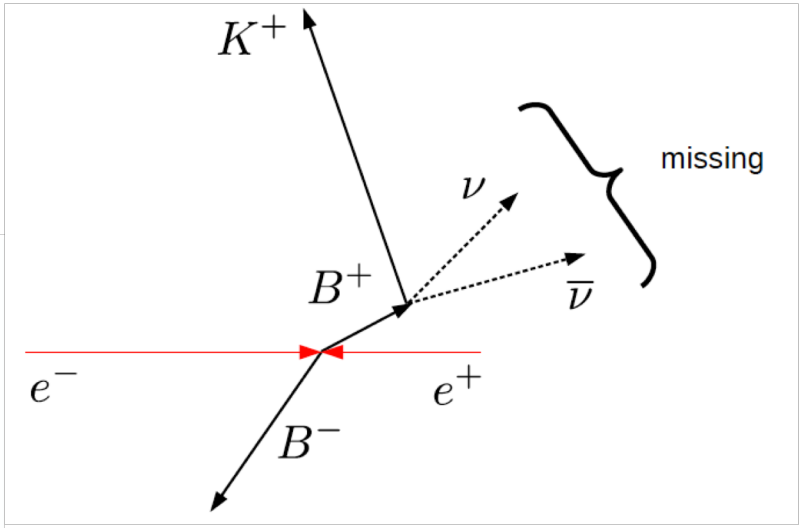
Phys. Rev. Lett. 127 (2021) 181802

- Rare decay belonging to family $b \to sll$ with SM $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (4.6 \pm 0.5) \times 10^{-6}$
- Sensitive to BSM physics
- Not observed yet! Published limits set by other B-factories use either SL or Hadronic tag reconstruction
- This measurement uses novel inclusive tag approach (see next slide)
- SM reference taken from Buras et al: https://arxiv.org/abs/1409.4557



(a) Penguin diagram (b) Box diagram

Experiment	Year	Observed limit on $\mathrm{BR}(B^+ \to K^+ \nu\bar{\nu})$	Approach	Data [fb^{-1}]
BABAR	**2013**	$< 1.6 \times 10^{-5}$ **[Phys.Rev.D87,112005]**	**SL + Had tag**	429
Belle	**2013**	$< 5.5 \times 10^{-5}$ **[Phys.Rev.D87,111103(R)]**	**Had tag**	711
Belle	**2017**	$< 1.9 \times 10^{-5}$ **[Phys.Rev.D96,091101(R)]**	**SL tag**	711

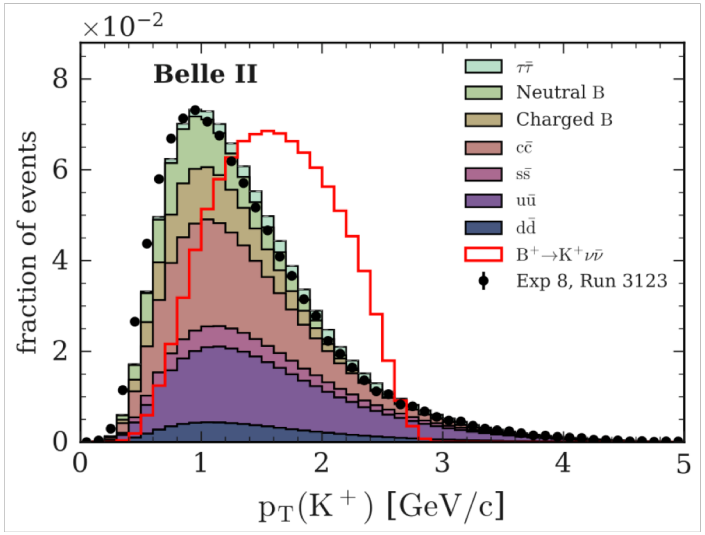


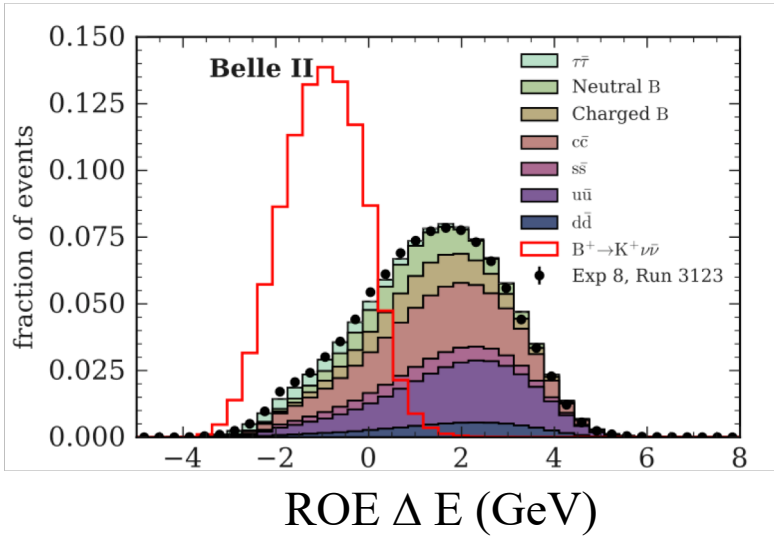
Search for $B^+ \to K^+ \nu\bar{\nu}$ at Belle II

63 fb^{-1} data set

- Signal reconstructed as the highest p_T track (correct match ≃80 %)
- Inclusive reconstruction of the rest of the event (ROE)
- New technique: Two consecutive BDTs are trained and applied to suppress the backgrounds (FastBDT algorithm), 51 input parameters
  - ✓ BDT #1 for the event selection
  - ✓ BDT #2 for background suppression
- No signal yet: upper limit determined

Phys. Rev. Lett. 127 (2021) 181802





$B^+ \to K^+ \nu\bar{\nu}$ at Belle II

Phys. Rev. Lett. 127 (2021) 181802

- First Belle II B-physics paper
- Binned simultaneous ML fit to on-resonance + off-resonance data is performed

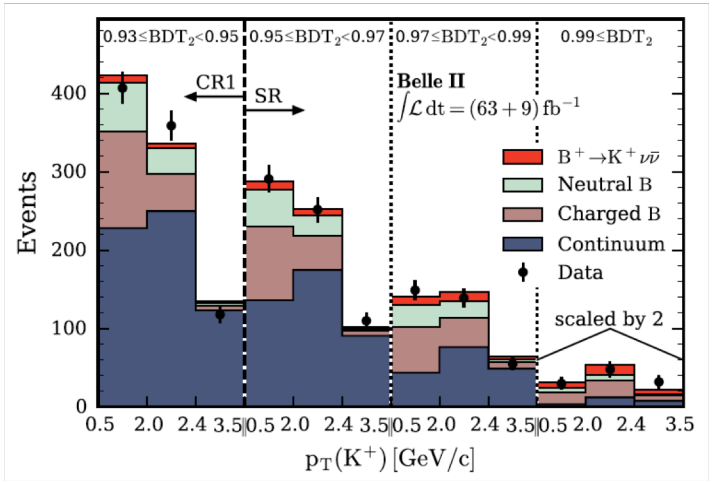
Measured signal strength $\mu = 4.2^{+2.9}_{-2.8}(\text{stat})^{+1.8}_{-1.6}(\text{syst})$

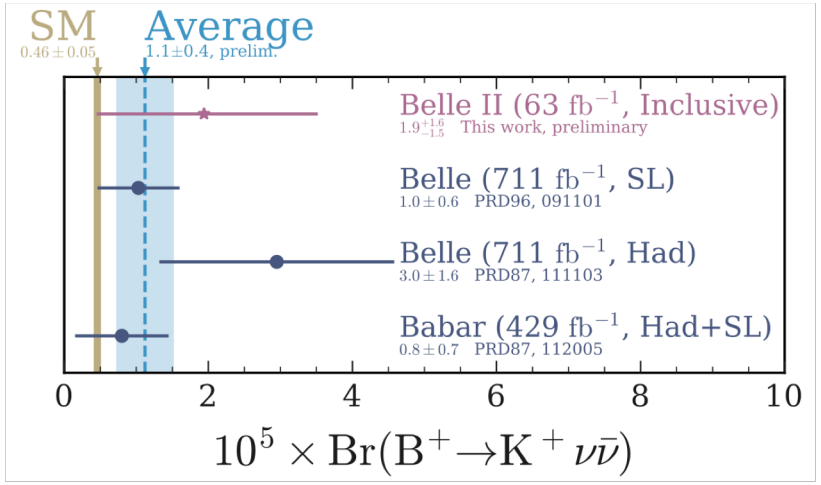
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = 1.9^{+1.6}_{-1.5} \times 10^{-5}$$

- No significant signal is observed, so limit on BF is set with CL_s method

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) < 4.1 \times 10^{-5} \text{ at 90 C.L}$$

Similar upper limit as Belle and BaBar





Summary

- The first experimental limit on the decay $B^0 \to K^{*0}\tau^+\tau^-$ at Belle

  $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0\times10^{-3}$ at 90% C.L.

- Search for $B^0_{(d)} \to \tau^{\mp}\ell^{\pm}$ at Belle
  - ✓ Electron mode: the most stringent limit to date
- Belle II is stably accumulating data
- First Belle II B-physics paper has been published in channel with missing energy: $B^+ \to K^+\nu\bar{\nu}$; a competitive limit has been set with only 63 fb^{-1} data

Belle II BELLE

FUDAN UNIVERSITY 1905 復旦大學 FUDAN UNIVERSITY

Thank you for your attention