Review of recent results at Belle and Belle II

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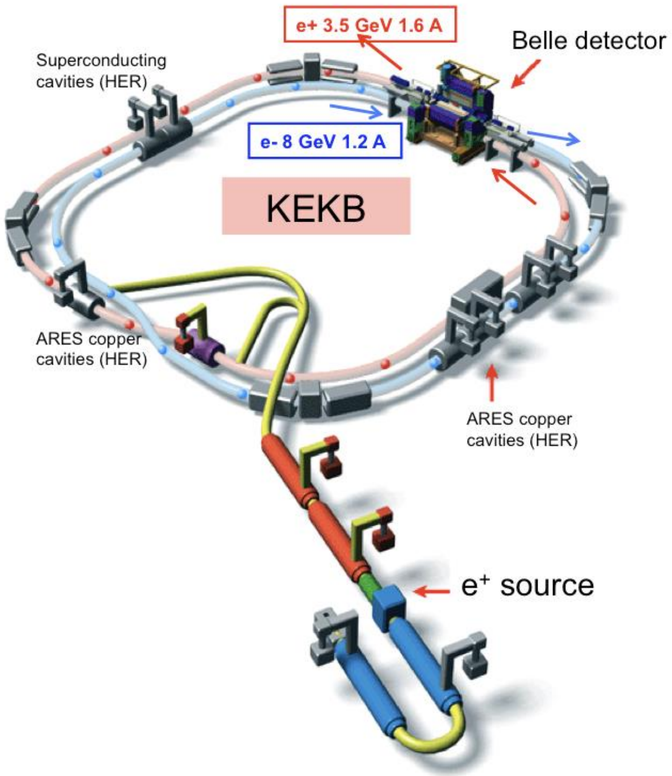
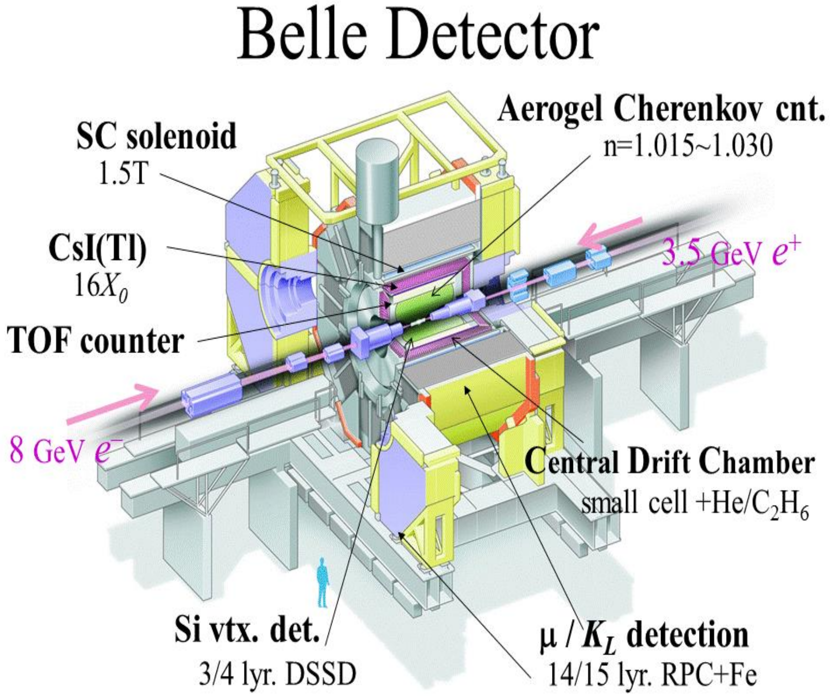
KEKB and Belle

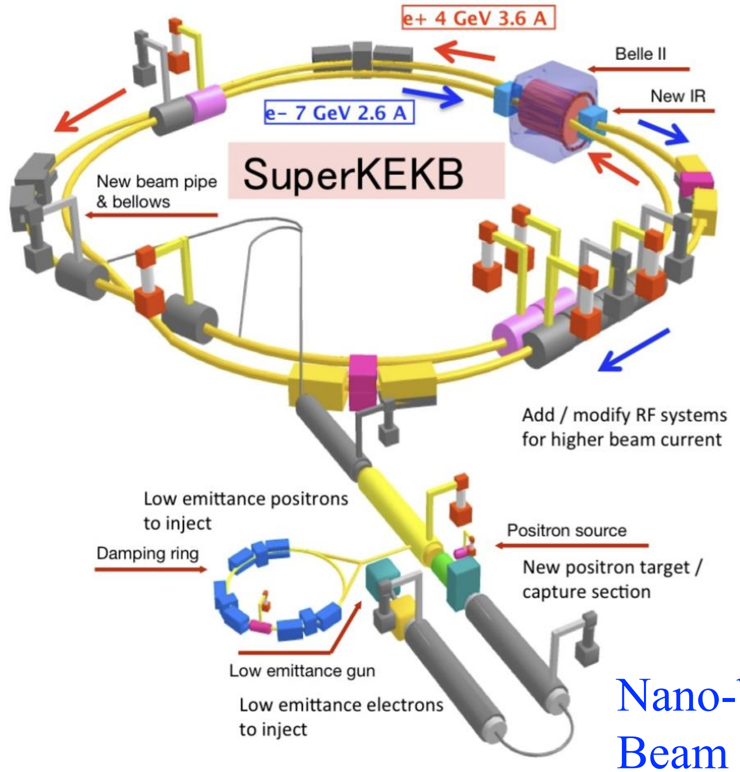
Peak luminosity: $2.11 \times 10^{34}\mathrm{cm}^{-1}\mathrm{s}^{-1}$
Integrated luminosity (~980 fb^{-1} in total):
$\Upsilon(5S)$: 121 fb^{-1}, $\Upsilon(4S)$: 711 fb^{-1}, $\Upsilon(3S)$: 3 fb^{-1},
$\Upsilon(2S)$: 25 fb^{-1}, $\Upsilon(1S)$: 6 fb^{-1}, continuum: 90 fb^{-1}





$\sqrt{s} \sim 10.6$ GeV

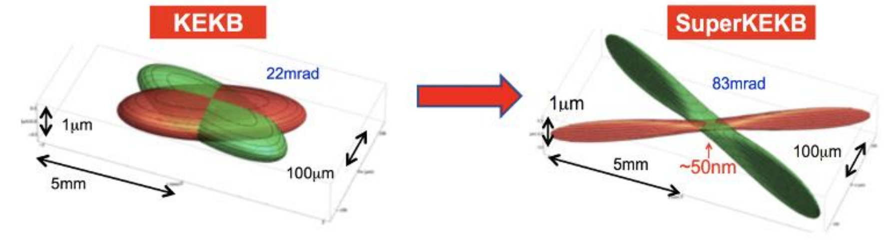
SuperKEKB and Belle II

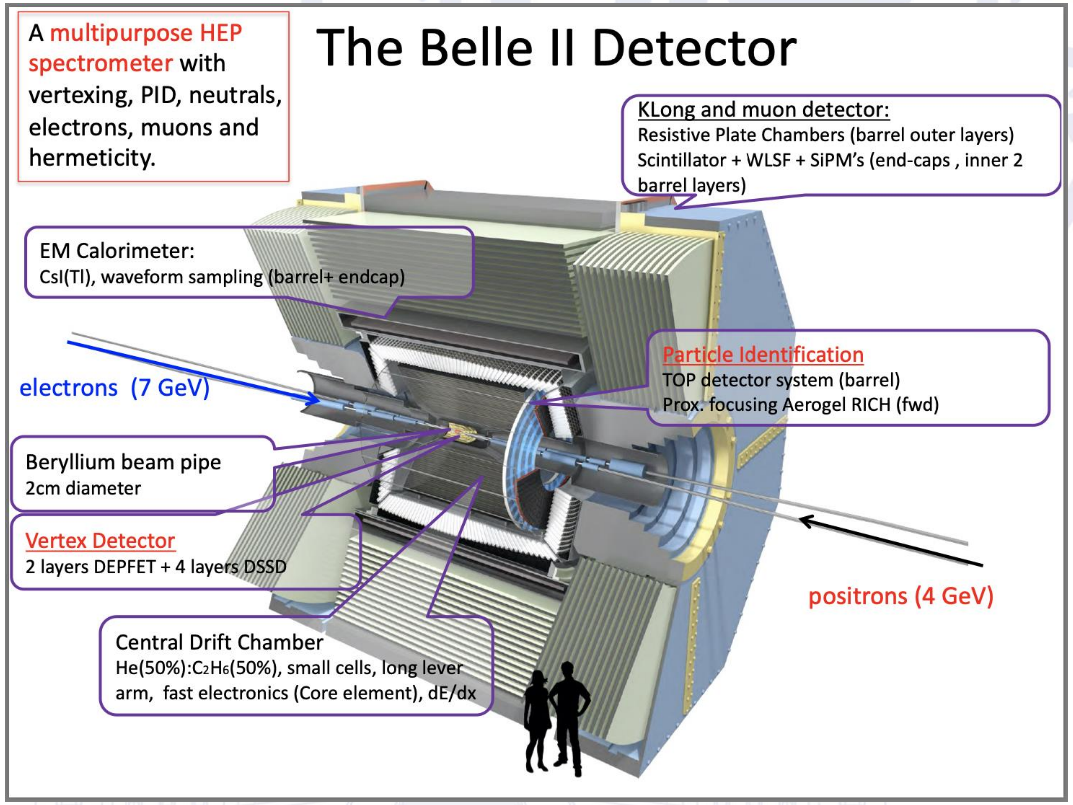


- Achieved peak luminosity: 4.7×10^{34} cm^{-2}s^{-1}
- Integrated luminosity: 427/fb [arXiv:2407.00965]
- Currently ~ 530/fb recorded

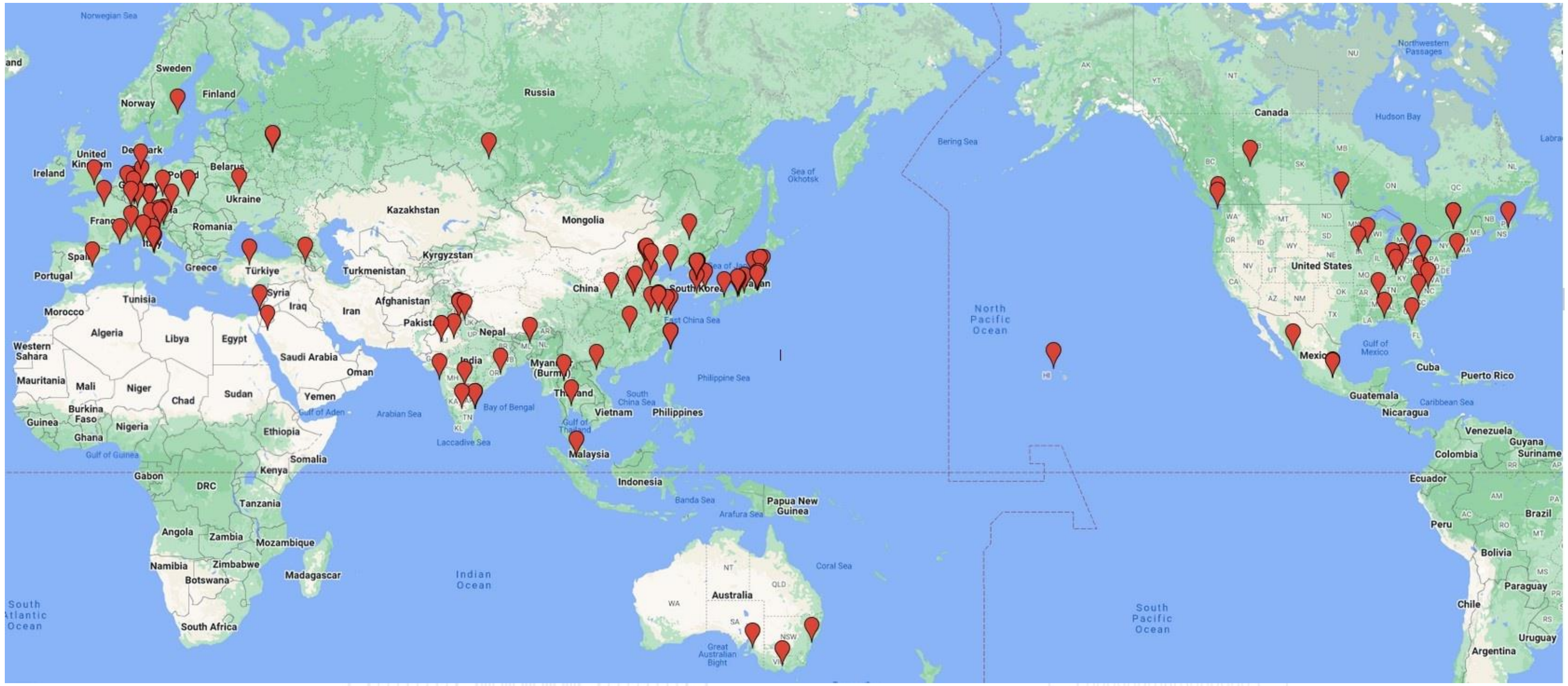
$\sqrt{s} \sim 10.58$ GeV

Nano-beam design:
Beam squeezing: ×20 smaller
Target luminosity: KEKB×40





International Belle II collaboration

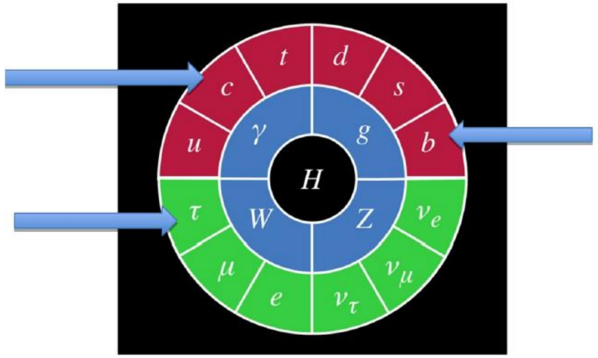


CHINA

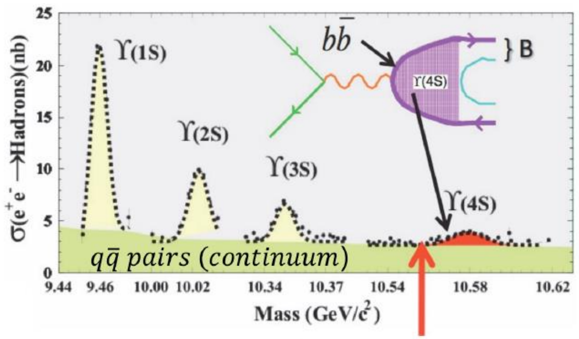
- Beihang: Beihang Univ.(BUAA)
- Fudan: Fudan Univ.
- HNU: Henan Normal University
- HUNNU: Hunan Normal University
- IHEP-China: Institute of High Energy Physics(IHEP)
- JLU: Jilin University
- LNNU: LiaoNing Normal University(LNNU)
- NNU: Nanjing Normal University
- Nankai: Nankai University
- SEU: Southeast University
- Shandong: Shandong University
- Soochow: Soochow University
- USTC: Univ. of Science and Technology of China(USTC)
- XJTU: Xi'an Jiaotong University
- ZZU: Zhengzhou University

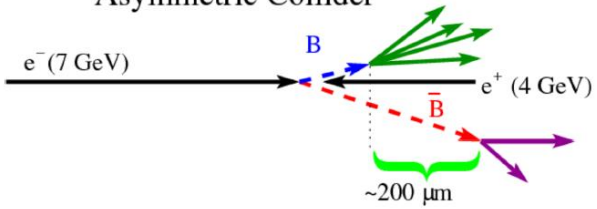
Belle II now has grown to ~1100 researchers (~600 authors) from 28 countries/regions

Productions in Belle/Belle II



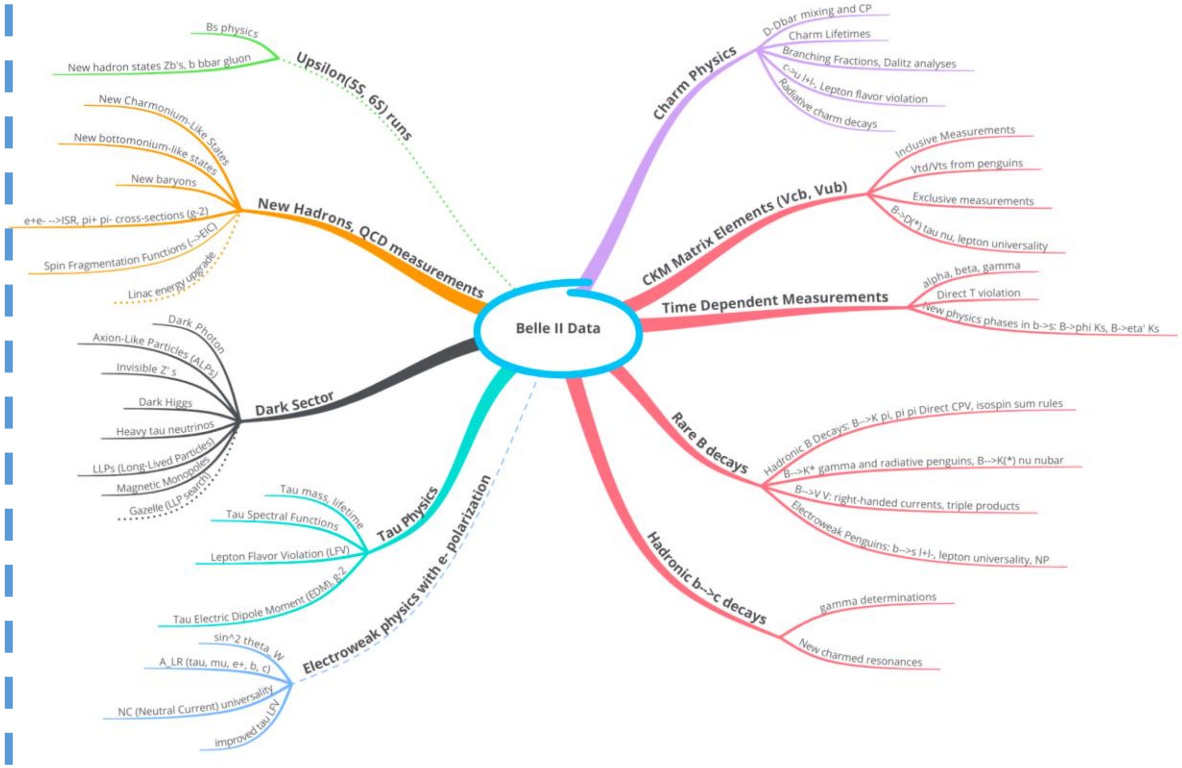
Physics process	Cross section [nb]
$\Upsilon(4S)$	1.110 ± 0.008
$u\bar{u}(\gamma)$	1.61
$d\bar{d}(\gamma)$	0.40
$s\bar{s}(\gamma)$	0.38
$c\bar{c}(\gamma)$	1.30





- B-factory: 10^9 pairs/ab^{-1}; $B\bar{B}$
- $\tau^+\tau^-$, $c\bar{c}$: 10^9 pairs/ab^{-1}.
- Expected Belle II data sample: $50 - 70$ ab^{-1}.
- Meanwhile, Belle II is considering the upgrade: $\mathcal{L} \times 5$

Belle/Belle II Physics



Wealth of new physics possibilities in different domains of HEP (weak, strong, electroweak interactions). Many opportunities for *initiatives* by young scientists.

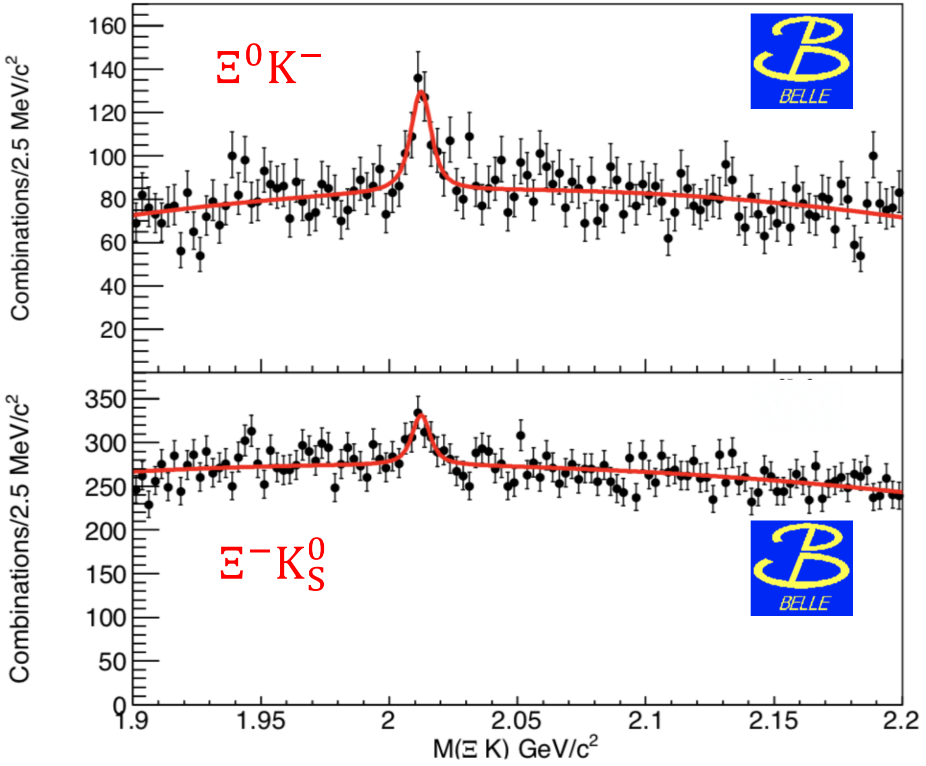
Keywords:

(Partial) definition: an e^+e^- *B* factory operates at the **intensity frontier** to collect samples of *B* mesons for **precision measurements** and searches for **rare/forbidden decays**, i.e., **indirect searches** for beyond-the-standard-model (BSM) physics with **high luminosity**

An important note: program is mostly **complementary** to that of LHCb and other hadron experiments

The $\Omega(2012)^-$ baryon

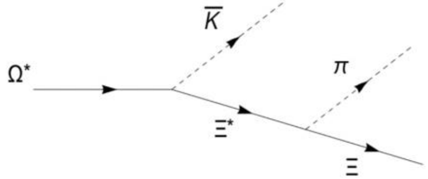
The $\Omega(2012)$ was first observed by Belle in $\Xi\bar{K}$ final states in $\Upsilon(1S, 2S, 3S)$ decays [PRL 121, 052003 (2018)].



The $\Omega(2012)^-$ was interpreted as a standard baryon or a $\Xi(1530)\bar{K}$ molecule.

Model	Comments	References
Standard baryon	The $\Omega(2012)^-$ decays dominantly to $\Xi\bar{K}$.	PRD 98, 034004 (2018), EPJC 78, 894 (2018), PRD 98, 114023 (2018), PRD 101, 016002 (2020), PRD 105, 094006 (2022), PRC 103, 025202 (2021), PRD 98, 014031 (2018), PRD 107, 034015 (2023), PRD 98, 014031 (2018), CPC 47, 063104 (2023), PRD 107, 014025 (2023)
$\Xi(1530)\bar{K}$ molecule	The $\Omega(2012)^-$ decays equally to $\Xi\bar{K}$ and $\Xi(1530)\bar{K}$. Or the $\Xi(1530)\bar{K}$ decay mode is dominant.	PRD 98, 054009 (2018), EPJC 78, 857 (2018), PRD 98, 076012 (2018), JPG 48, 025001 (2021), PRD 98, 056013 (2018), PRD 101, 094016 (2020), EPJC 80, 361 (2020), PRD 102, 074025 (2020), PRD 106, 034022 (2022), Few Body Syst. 64, 55 (2023).

$\Omega(2012)^- \to \Xi(1530)\bar{K}$



Measurement of the branching fraction for $\Omega(2012)^- \to \Xi(1530)\bar{K}$ is crucial to distinguish the nature of the $\Omega(2012)$!

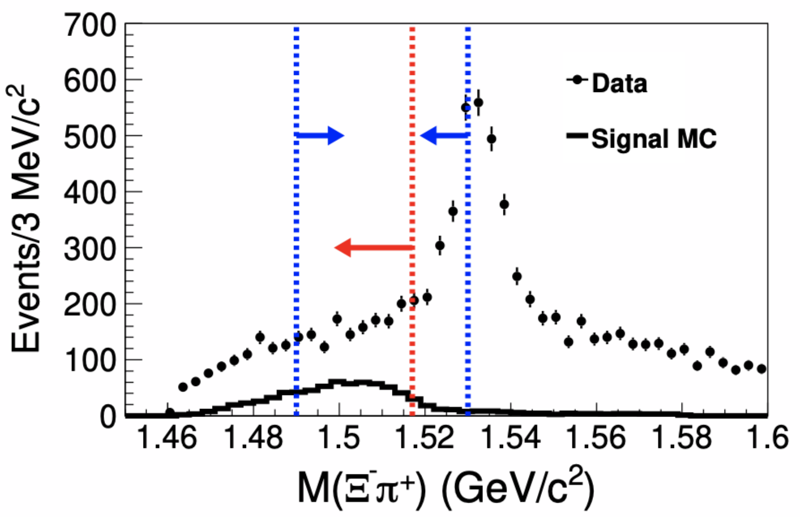
Revisit $\Omega(2012)^- \rightarrow \Xi(1530)\bar{K} \rightarrow \Xi\pi\bar{K}$

Preliminary results

BELLE

The comparisons between the previous analysis [PRD 100, 032006 (2019)] and this work.

Analysis strategy	The previous analysis [40]	This work
The requirement of $M(\Xi\pi)$	$1.49 < M(\Xi\pi) < 1.53$ GeV/c^2	$M(\Xi\pi) < 1.517$ GeV/c^2
The signal shape of $\Omega(2012)^-$	A Breit-Wigner function	A Flatté-like function [41]
ϕ-induced backgrounds	No requirement	$\lvert M(K^-K^+) - m_\phi \rvert > 10$ MeV/c^2



The Flatté-like function [PRD 81, 094028 (2010)]

$$T_n(M) = \frac{g_n k_n(M_n)}{|M_n - m_{\Omega(2012)} + \frac{1}{2}\sum_{j=2,3} g_j[\kappa_j(M_j) + ik_j(M_j)]|^2}$$

- g_n is the effective coupling of to the n–body final state.
- k_n and κ_n parameterize the real and imaginary parts of the $\Omega(2012)^-$self-energy.

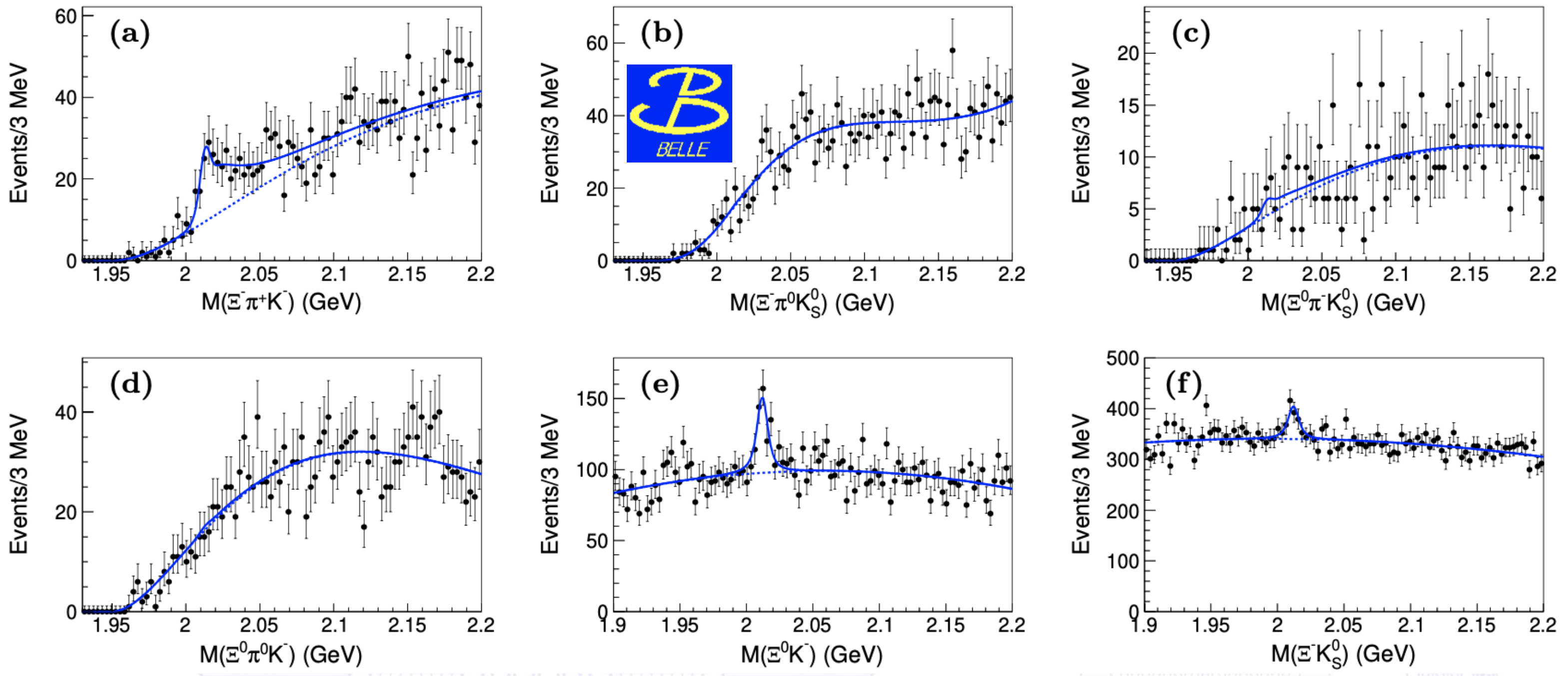
Above 2.02 GeV, the phase space k_3 increases sharply to cover more signal candidates.

The red arrow for this updated work; The blue arrow for the previous analysis.

Revisit $\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}$

Preliminary results

We fit simultaneously to the binned $\Xi^-\pi^+K^-$, $\Xi^-\pi^0K^0_S$, $\Xi^0\pi^-K^0_S$, $\Xi^0\pi^0K^-$, Ξ^0K^- and $\Xi^-K^0_S$ mass distributions from Υ(1S,2S,3S) data samples.



The mass and effective couplings :

$\Omega(2012)^-$ mass	$(2012.5^{+0.8}_{-0.7}\pm0.5)$ MeV
The coupling to $\Xi\bar{K}$	$(1.7^{+0.3}_{-0.3}\pm0.3)\times10^{-2}$
The coupling to $\Xi(1530)\bar{K}$	$(38.9^{+31.1}_{-38.9}\pm6.0)\times10^{-2}$

$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = \frac{\mathcal{B}(\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K})}{\mathcal{B}(\Omega(2012)^- \to \Xi\bar{K})}$$

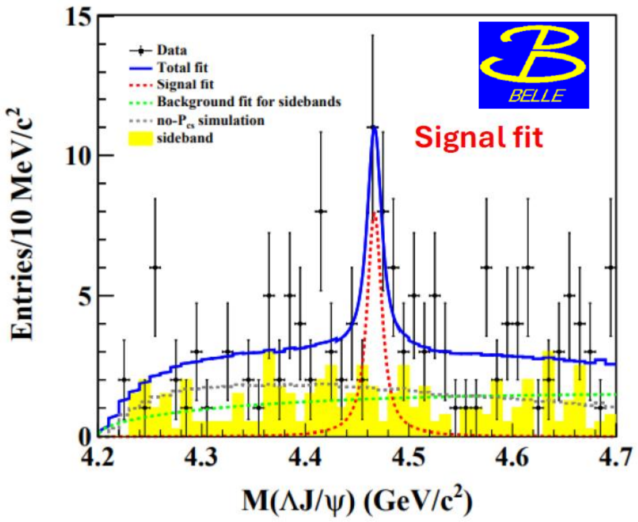
0.99±0.26(stat.)±0.06(syst.)

Our result is consistent with the molecular model of $\Omega(2012)^-$, which predicts comparable rates for $\Omega(2012)^-$ decay to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$.

Evidence of Pcs(4459) at Belle

preliminary

- OZI suppressed decays of Υ(1S) and Υ(2S) rich in gluons
  - enhanced baryon production
  - pentaquarks?
- Select inclusive Υ(1S,2S)→J/ψΛ + X decays, then search m(J/ψΛ) for pentaquark signal
  - **Background from sideband and off resonance**
- Use LHCb mass and width for their observation in Ξ_b decay (Sci. Bulletin **66**, 1278 (2021)
  - **3.3 standard deviation significance observation**
  - free mass and width 4 standard deviation local significance



Local significance is 4.0σ.

$$M = 4469.5 \pm 4.1 \pm 4.1\ MeV$$
$$\Gamma = 14.3 \pm 9.2 \pm 6.3\ MeV$$

c.f. $P_{cs}(4459)$ LHCb, SB 66, 1278 (2021)

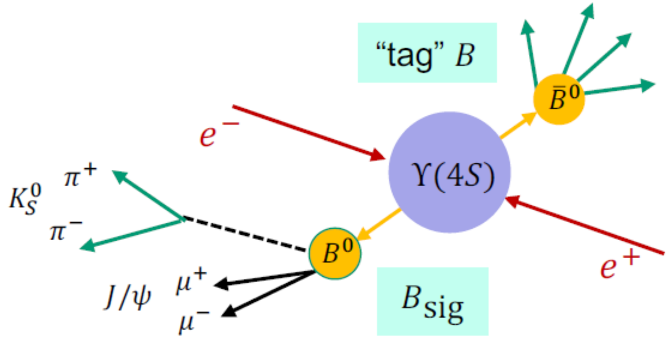
$$4458.8 \pm 2.9\,^{+4.7}_{-1.1}\ MeV$$
$$17.3 \pm 6.5\,^{+8.0}_{-5.7}\ MeV$$

Add Gaussian constraint on M and Γ

⇒ significance is 3.3σ including systematics.

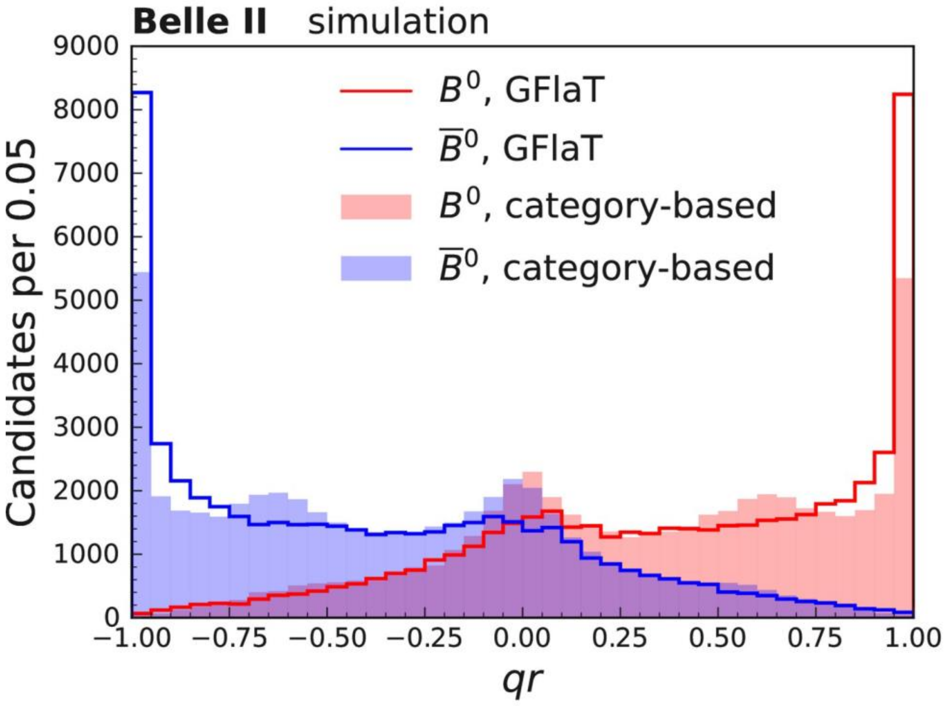
B Flavor tagging at Belle II

- B flavor tagging: Identify the flavor of the other B



- Belle II initial B tagging algorithm:
  - ✓ Category-based (CB): physics object as Boosted decision tree (BDT) input [Eur. Phys. J 82, 283 (2022)]
  - ✓ Similar to Belle & BaBar experiments
- Newly developed B tagging algorithm: GFlaT
  - ✓ Graph neural network (GNN)
  - ✓ 25 variables for each track as GNN input
  - ✓ 18% improvement in performance

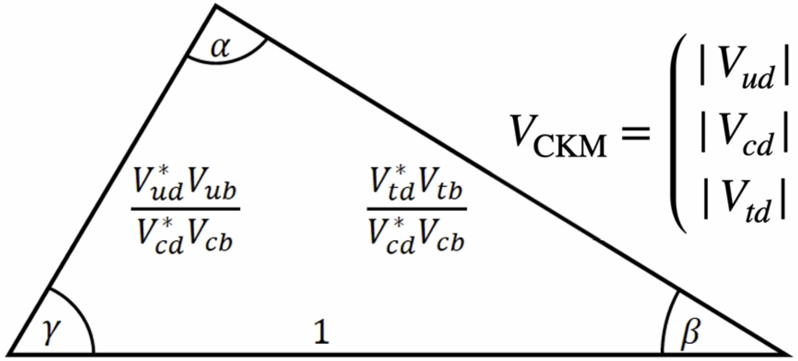
$$\epsilon_{\rm tag}(\rm CB) = (31.7 \pm 0.5 \pm 0.4)\,\%$$
$$\epsilon_{\rm tag}(\rm GFlaT) = (37.4 \pm 0.4 \pm 0.3)\,\%$$



arXiv:2402.17260
Accepted by PRD

CKM matrix: $|V_{cb}|$ & $|V_{ub}|$

- Important to constrain CKM unitarity triangle & test SM
- Determinations via **inclusive** or **exclusive** semileptonic B decays
- Long-standing "**Vxb-puzzle**": discrepancy btw. inclusive and exclusive determinations



$$V_{\rm CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix}$$

$$V_{\rm CKM} V_{\rm CKM}^\dagger = 1$$

Exclusive

$B \to \pi \ell \nu$, $B \to \rho \ell \nu$, $B \to D^{(*)} \ell \nu$, $\Lambda_b \to p \ell \nu$, etc.

$$\mathscr{B} \propto \left|V_{xb}\right|^2 f^2$$

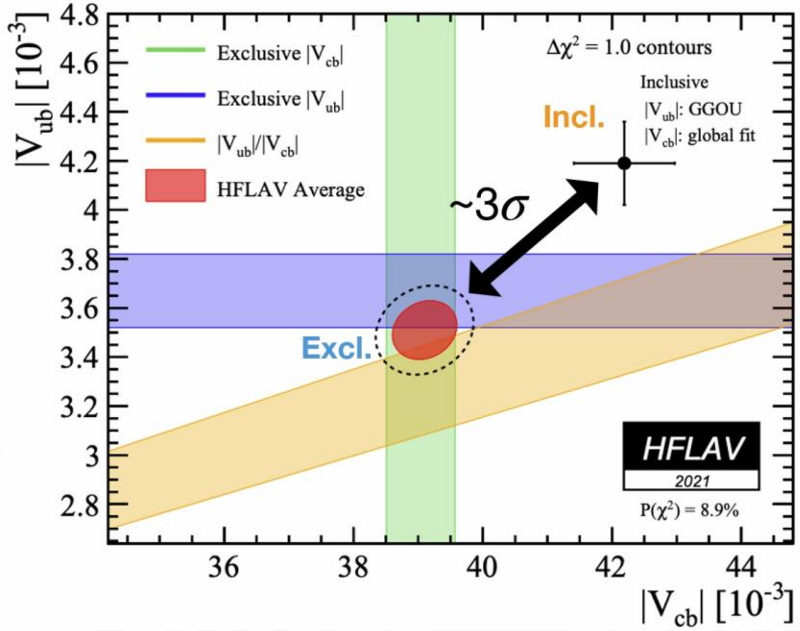
Form factor f (LCSR, LQCD)

Inclusive

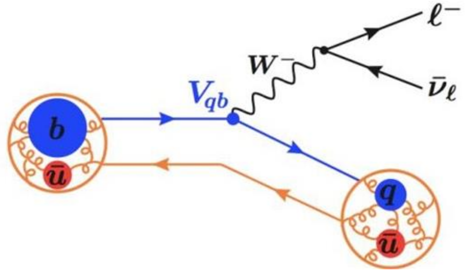
$$B \to X_u \ell \nu, \ B \to X_c \ell \nu$$

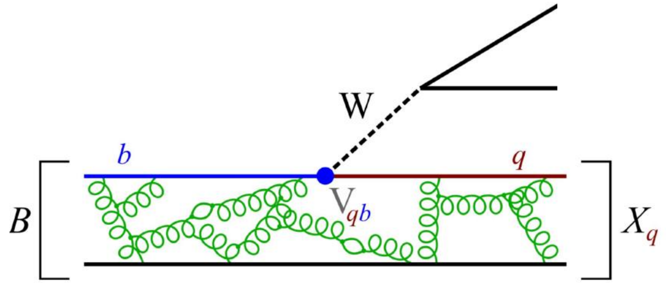
$$\mathscr{B} \propto \left|V_{xb}\right|^2 \left[1 + \frac{c_5(\mu)\langle O_5\rangle(\mu)}{m_h^2} + \frac{c_6(\mu)\langle O_6\rangle(\mu)}{m_h^3} + O\left(m_b^4\right)\right] \qquad \left|V_{xb}\right| = \sqrt{\frac{\Delta\mathscr{B}}{\tau_B \cdot \Delta\Gamma}}$$

+ Shape Function / Fermi Motion (OPE)

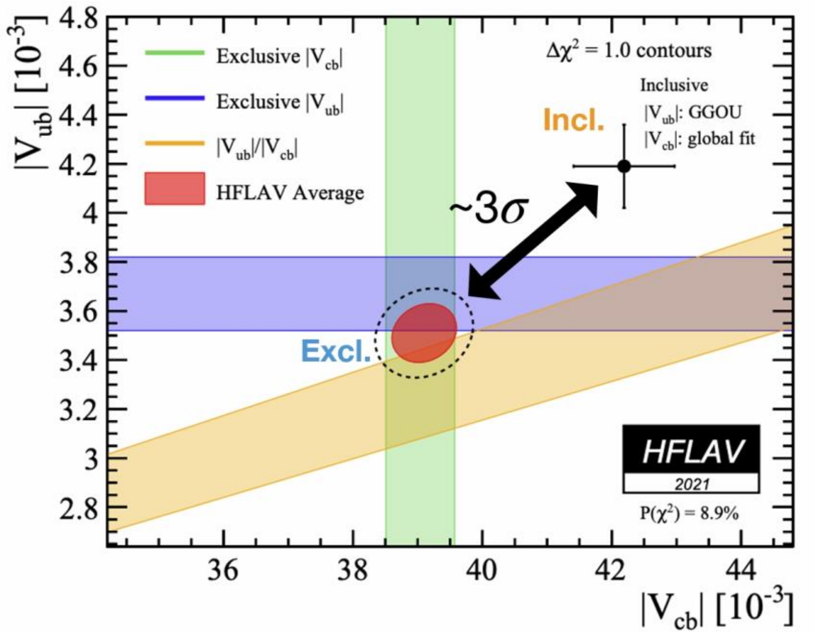


Semileptonic *B* decay: V_{cb}





$$\frac{d\Gamma}{dq^2} \propto |V_{qb}|^2 |f(q^2)|^2$$



New exclusive measurements from BaBar with $B \to D l \nu$ and Belle with $B \to D^* l \nu$ using **full differential information** for the first time

- $V_{cb} = (41.1 \pm 1.2) \times 10^{-3}$ [Babar arXiv:2311.15071]
- $V_{cb} = (41.0 \pm 0.7) \times 10^{-3}$ [Belle arXiv:2310.20286, to appear in PRL]

Compatible with inclusive – **perhaps we are on the right path to resolve these tensions?**

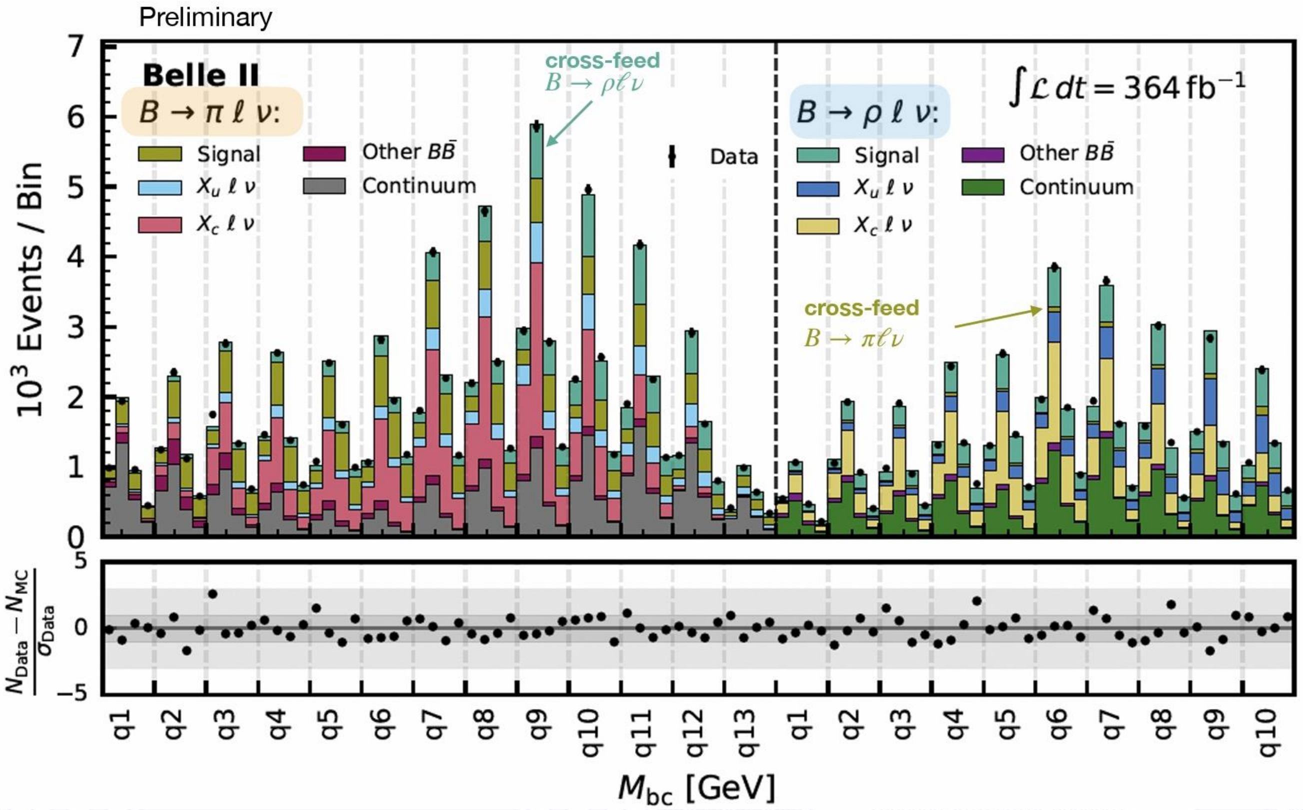
Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

Preliminary

NEW!!

arXiv:2407.17403

- Full **Run1** data of 364 fb^{-1} with untagged analysis strategy
- Novel method to simultaneously extract signals in 2D grid of beam-constrained mass M_{bc} and energy difference ΔE **for each bin of** q^2 : **13** bins for π mode, **10** bins for ρ mode



- Cross-feed signals are linked in two modes
- Dominant backgrounds are from $B \to X_c \ell \nu$ decays and continuum ($e^+e^- \to q\bar{q}$)

Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

Preliminary

NEW!!

- Partial branching factions in each q^2 bin obtained with fitted yields and efficiency corrections
- Total BR is a sum of partial bins

$$\mathcal{B}(B^0 \to \pi^- \ell^+ \nu_\ell) = (1.516 \pm 0.042 \pm 0.059) \times 10^{-4}$$
$$\mathcal{B}(B^+ \to \rho^0 \ell^+ \nu_\ell) = (1.625 \pm 0.079 \pm 0.180) \times 10^{-4}$$

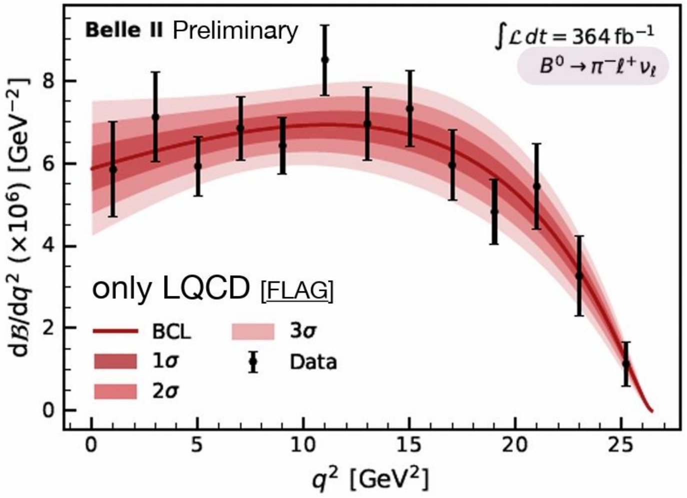
stat syst

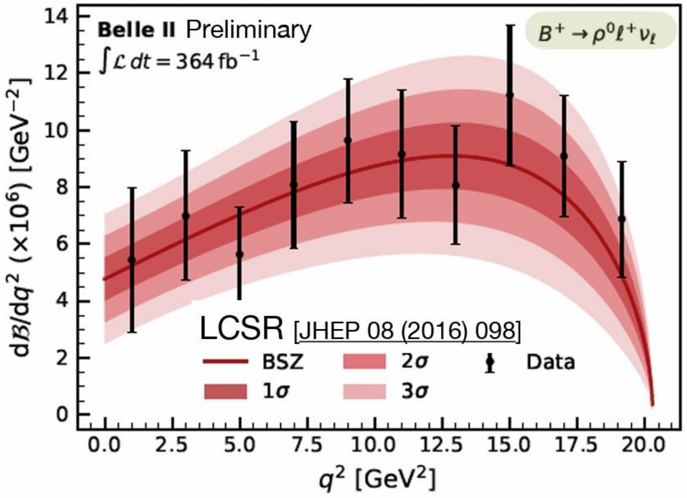
Consistent with world averages

Compatible precision as Belle/BaBar

arXiv:2407.17403

- Extracted $|V_{ub}|$ with lattice QCD and/or light-cone sum rules (LCSR) constraints of form factors

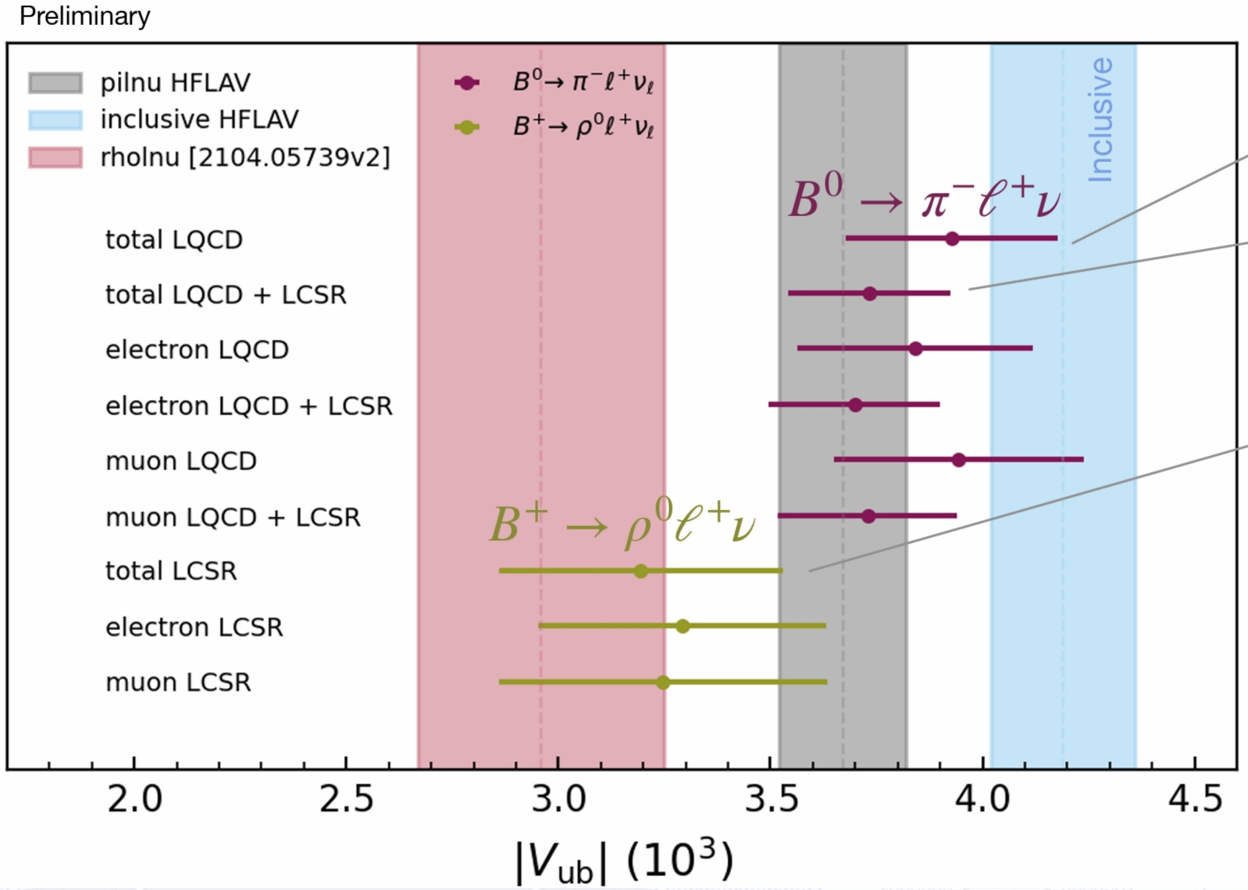




Simultaneous measurements of $B^0 \to \pi^- \ell^+ \nu$ and $B^+ \to \rho^0 \ell^+ \nu$

Preliminary
Belle II
NEW!!
arXiv:2407.17403

- Further split into e and μ modes to provide cross check
- Additional stability tests done by removing higher/lower q^2 bins



$$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.93 \pm 0.09 \pm 0.13 \pm 0.19) \times 10^{-3}$$

stat syst theo

LQCD

$$|V_{ub}|_{B\to\pi\ell\nu_\ell} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$$

LQCD+LCSR

$$|V_{ub}|_{B\to\rho\ell\nu_\ell} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$$

LCSR

- Leading systematic unc. are the modelling of continuum and non-resonant $B \to X_u \ell \nu$ decays
- Overall **theoretical** uncertainty dominating

Lepton-Flavor Universality

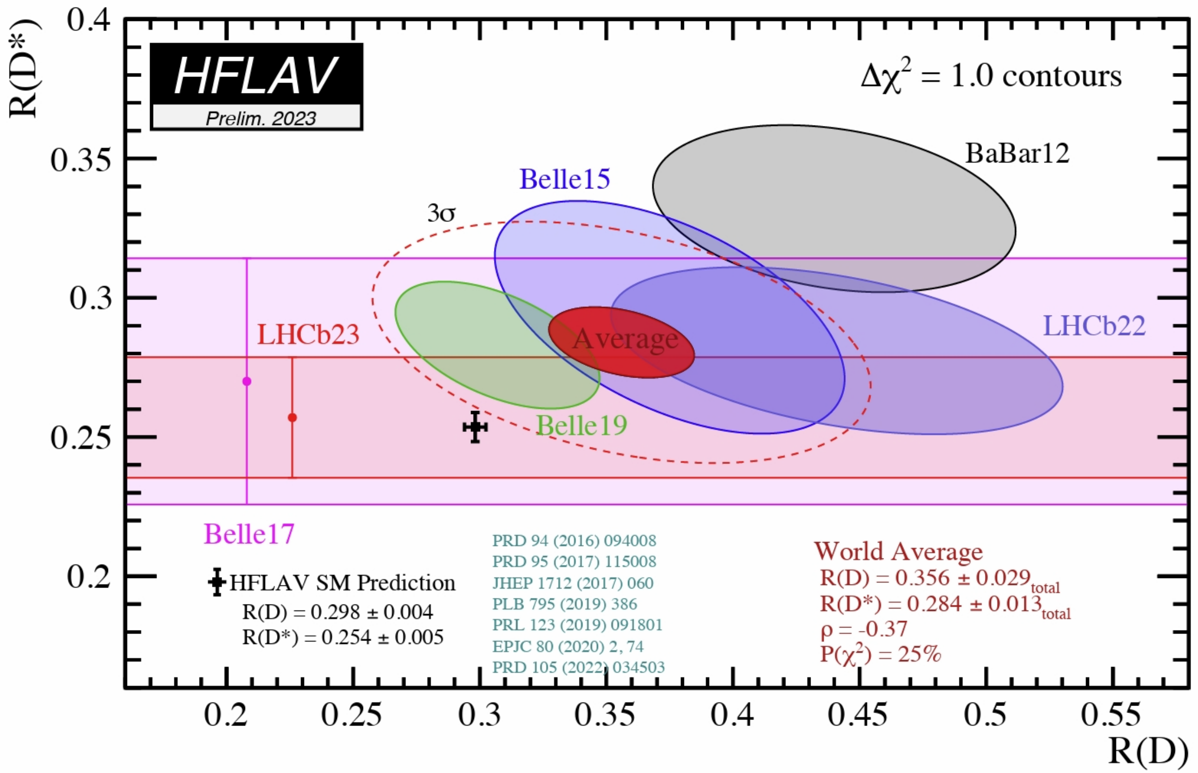
- In SM, the W boson couples equally to τ, μ, e => **Lepton-Flavor Universality (LFU)**
- Semileptonic B decays are sensitive to new physics beyond SM
- **Ratio measurements** provide stringent LFU tests: branching fractions, angular asymmetry, etc.
  - Normalization ($|V_{xb}|$) cancels
  - Part of theoretical, experimental uncertainties cancels

$$R(H_{\tau/\ell}) = \frac{\mathscr{B}(B \to H\tau\nu)}{\mathscr{B}(B \to H\ell\nu)}$$

$$H = D, D^*, X, \pi, \text{etc}. \qquad \ell = e, \mu$$

final state can involve different hadrons

Tension of R(D$^{(*)}$) with SM ~3σ



R(D*) using hadronic B tagging at Belle II

arXiv:2401.02840
Preliminary

- Use 189 fb^{-1} dataset with hadronic tagging strategy
- Signal decays: $B \to D^*(\tau,\ell)\nu,\ D^{*+} \to D^0\pi^+, D^+\pi^-$ and $D^{*0} \to D^0\pi^0$, and leptonic τ decays
- Data-driven validation of modelling in sideband regions
- Extract R(D*) using 2D fit on M^2_{miss} and residual energy in the calorimeter E_{ECL}

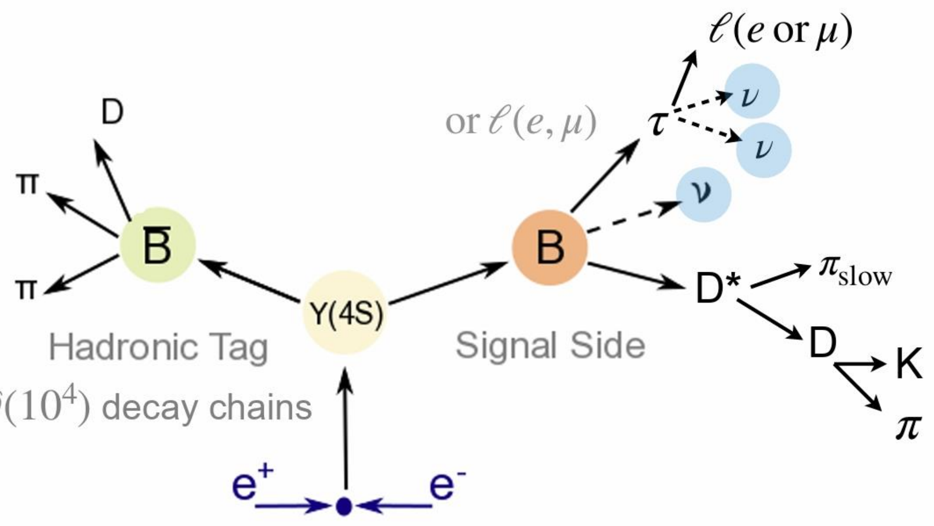
Reconstruct B$_{tag}$

Full Event Interpretation

Comput.Softw.Big Sci. 3 (2019) 1, 6

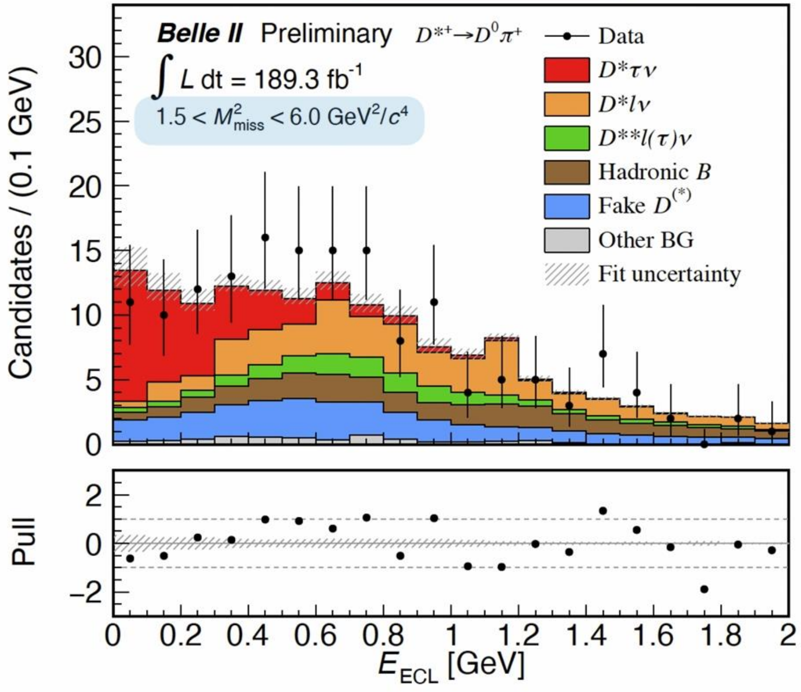
$\epsilon(B^+) \approx 0.35\,\%$ $\epsilon(B^0) \approx 0.27\,\%$

In the rest of event (ROE), require no remaining tracks/π^0.



$$M^2_{\text{miss}} = (E^*_{\text{beam}} - E^*_{D^*} - E^*_\ell)^2 - (-\vec{p}^{\,*}_{B_{\text{tag}}} - \vec{p}^{\,*}_{D^*} - \vec{p}_\ell^{\,*})^2$$

$D^{*+} \to D^0\pi^+$



R(D*) using hadronic B tagging at Belle II

arXiv:2401.02840
Preliminary

$$R(D^*) = 0.262 \,^{+0.041}_{-0.039}(\text{stat}) \,^{+0.035}_{-0.032}(\text{syst})$$

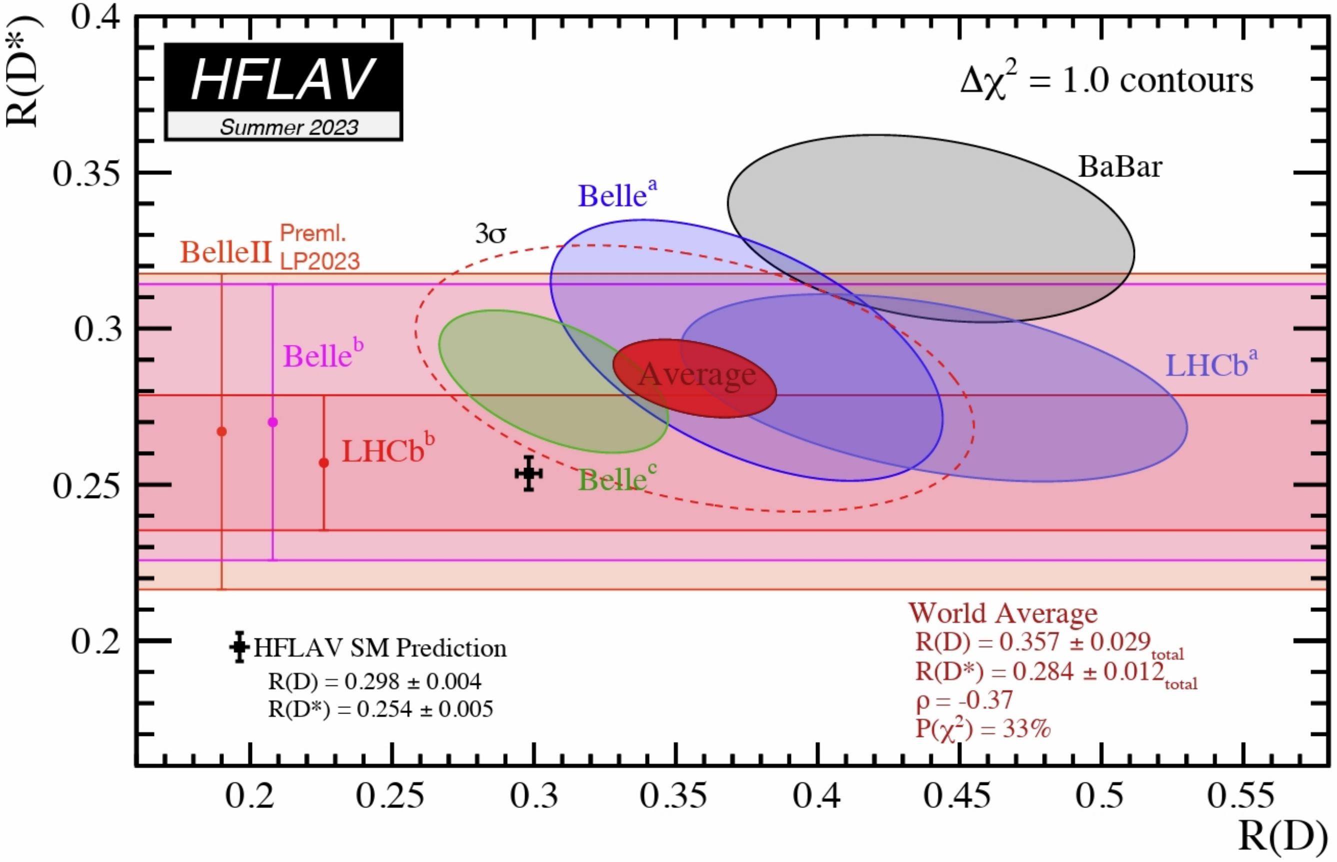
comparable stat. precision as Belle

dominant by PDF shapes, MC sample size

consistent with SM predictions [HFLAV 23]

- Previous version presented in Lepton Photon 2023
- Minor updates applied

Update to full Run1 dataset and include R(D) is ongoing

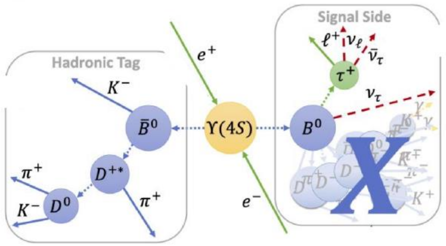


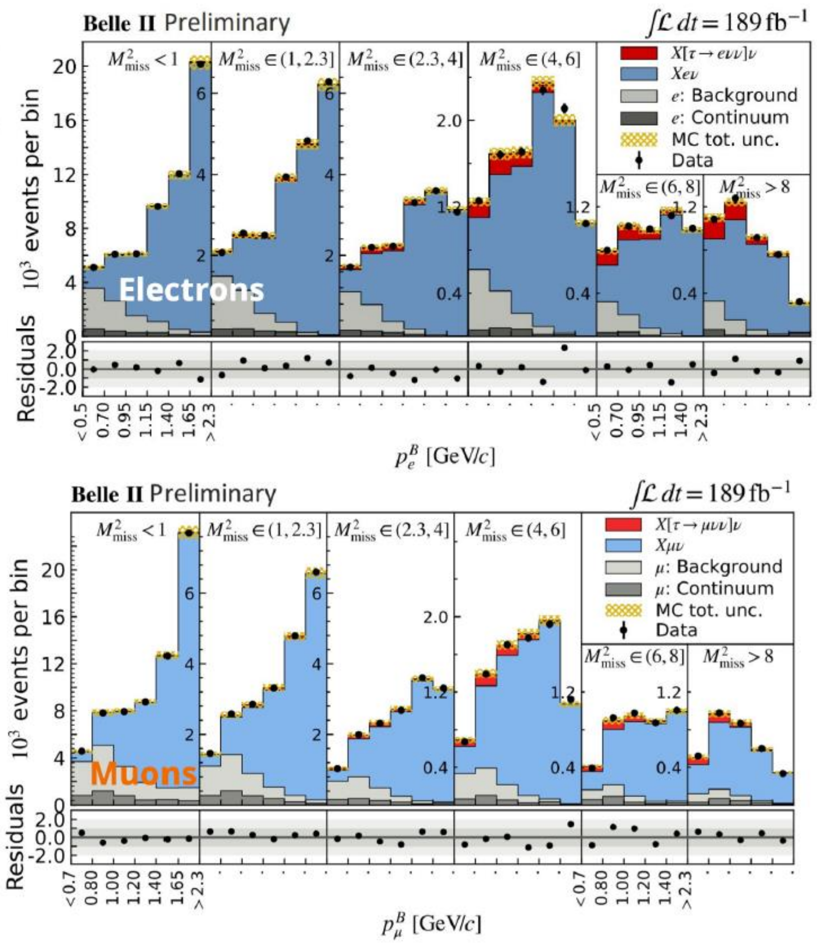
Measurement of R(X)

PhysRevLett.132.211804
Editors' suggestion

- Inclusive ratio R(X) = B(B→Xτν)/B(B→Xℓν) with τ leptonic decays
- Hadronic-tagging method with 189 fb^{-1}

  Hadronic tag pioneered by BaBar [PRL 92, 071802]; MVA version at Belle II [Comput. Softw. Big Sci. 3 (2019) 1, 6]
- Use missing-mass squared and B candidate momentum to extract signal
- Result agrees with SM prediction: $R(X)_{SM} = 0.223 \pm 0.005$





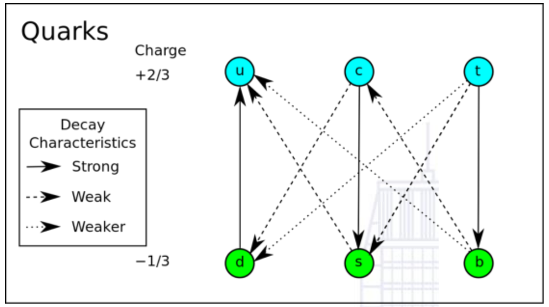
- 2D binned maximum likelihood fit to extract the signal and normalisation yields for the electron and muon modes simultaneously
- In bins of p_l^B and $M^2_{missing}$

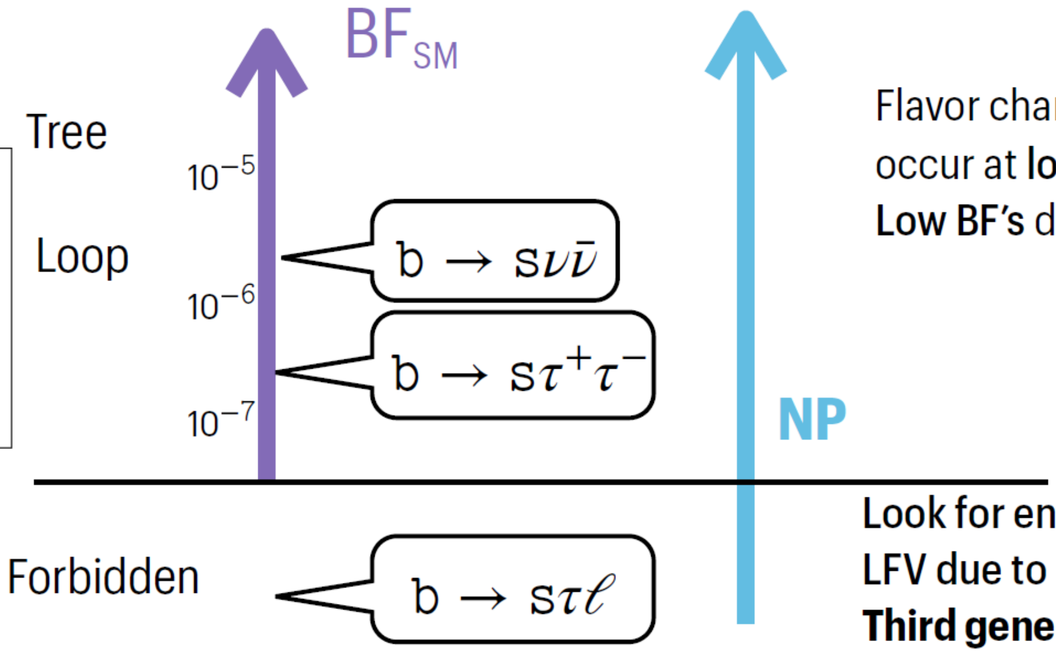
-e channel: $R(X_{\tau/e}) = 0.232 \pm 0.020(\text{stat}) \pm 0.037(\text{syst})$

-μ channel: $R(X_{\tau/\mu}) = 0.222 \pm 0.027(\text{stat}) \pm 0.050(\text{syst})$

$$R(X_{\tau/l}) = 0.228 \pm 0.016(\text{stat}) \pm 0.036(\text{syst})$$

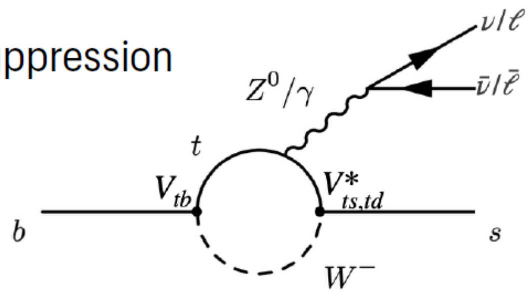
Electroweak Penguin and LFV @ Belle (II) experiment





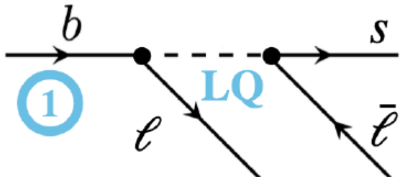
Flavor changing neutral currents **FCNC** $b \to s$ occur at **loop level** in the SM

Low BF's due to CKM and GIM suppression

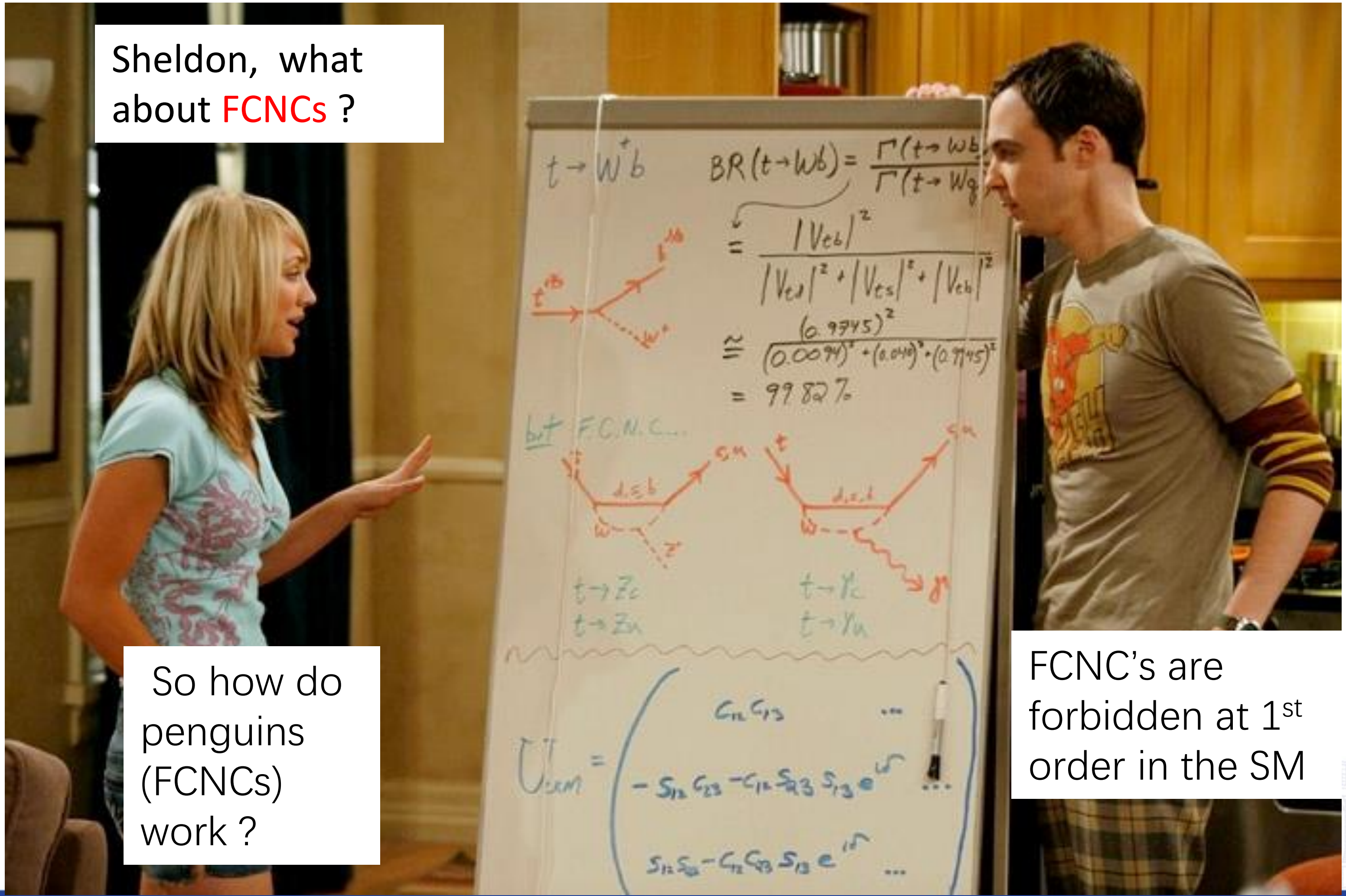


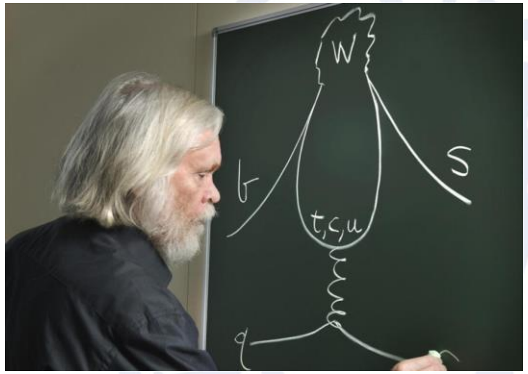
Look for enhancements in FCNC and LFV due to NP contributions

Third generation coupling



Big Bang Theory Episode (FCNCs)





John Ellis, the CERN theorist who coined the name "Penguin" (a type of FCNC).

Examine the following b→s γ decay modes in the Belle II Phase 3 dataset.

$$B^0 \to K^{*0} g \to K^+ p^- g$$

$$B^+ \to K^{*+} g \to K^+ p^0 g$$

$$B^+ \to K^{*+} g \to K^0_S p^+ g$$

Radiative penguin: B→ γK^*

- Flavour changing neutral current decays sensitive to new physics
- CP (A_{CP}) and isospin (Δ_{+0}) asymmetries are theoretically clean thanks to form factor cancellations
- Latest Belle measurement found evidence of isospin asymmetry at 3.1σ [Phys. Rev. Lett. 119, 191802 (2017)]

$$A_{CP} = \frac{\Gamma(\overline{B} \to \overline{K^*}\gamma) - \Gamma(B \to K^*\gamma)}{\Gamma(\overline{B} \to \overline{K^*}\gamma) + \Gamma(B \to K^*\gamma)}$$

$$\Delta_{+0} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^+ \to K^{*+}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) + \Gamma(B^+ \to K^{*+}\gamma)}$$

Goal

Using the 362 fb^{-1} Belle II run 1 dataset

- Measure $\mathcal{B}(B^{\pm,0} \to K^{*\pm,0}\gamma)$ with $K^* \to K^+\pi^-, K_S^0\pi^0, K^+\pi^0$ and $K_S^0\pi^+$
- Measure Δ_{+0} and A_{CP} for all modes except $B^0 \to K^{*0}(\to K_S^0\pi^0)\gamma$

Radiative penguin: B→ γK^*

2D M_{bc}-ΔE fit to extract Simultaneously yields of B and anti-B for self-tagged modes for A_{CP} and B

preliminary

- Consistent with World average and SM
- Similar sensitivity as Belle despite smaller sample (thanks mainly to improved ΔE resolution, K_S^0 efficiency and continuum suppression)
- Asymmetries statistically limited

$$\mathcal{B}[B^0 \to K^{*0}\gamma] = (4.16 \pm 0.10 \pm 0.11) \times 10^{-5},$$

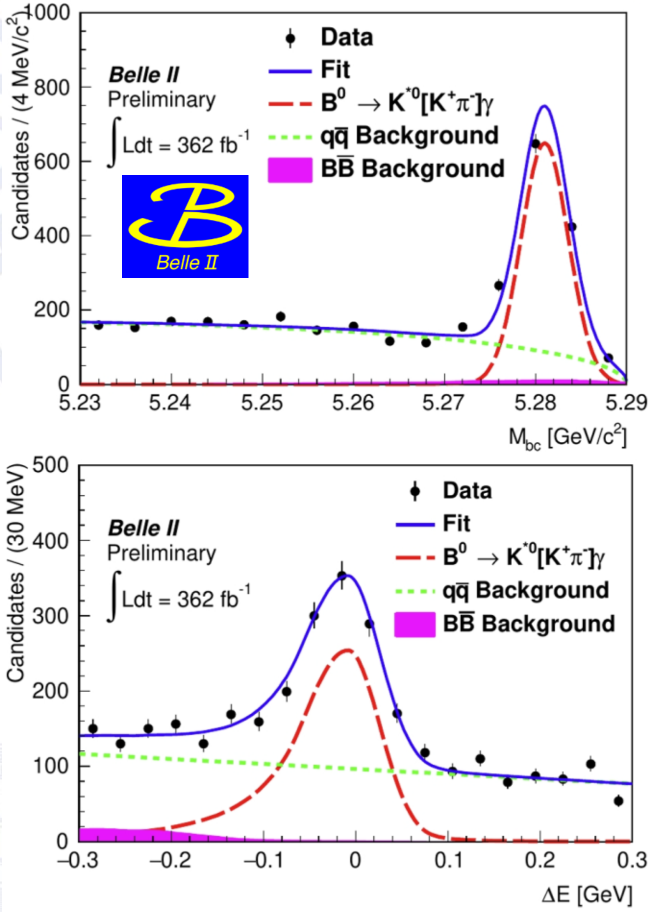
$$\mathcal{B}[B^+ \to K^{*+}\gamma] = (4.04 \pm 0.13 \pm 0.13) \times 10^{-5},$$

$$\mathcal{A}_{CP}[B^0 \to K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\%,$$

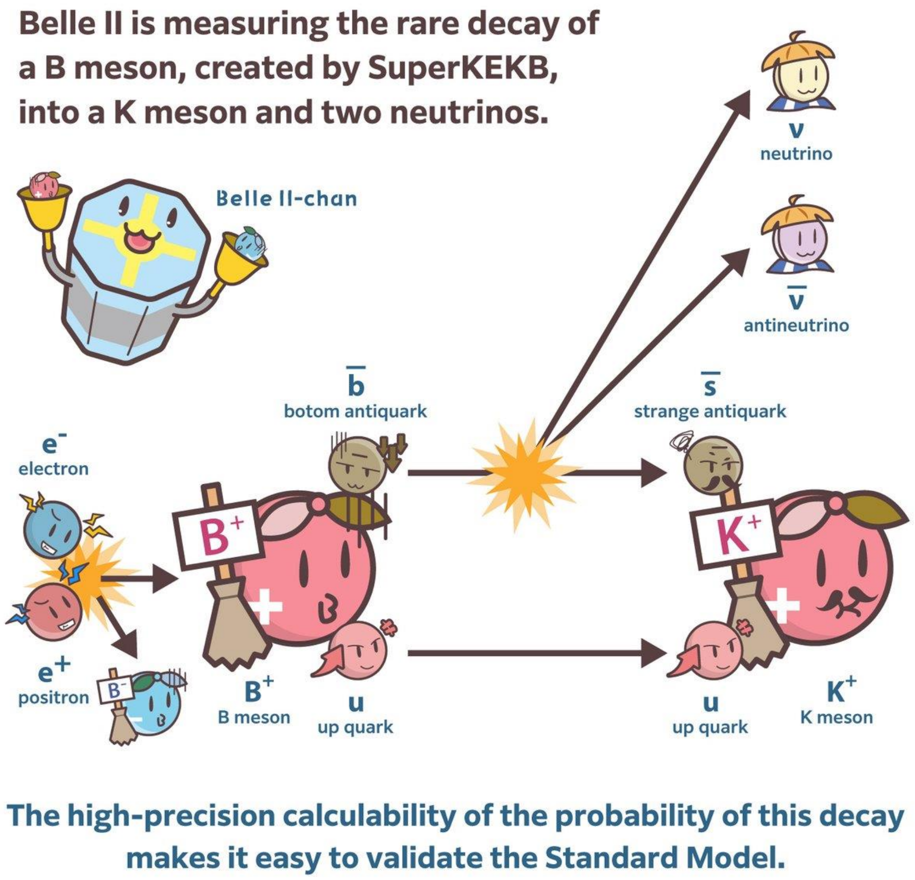
$$\mathcal{A}_{CP}[B^+ \to K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\%,$$

$$\Delta\mathcal{A}_{CP} = (2.2 \pm 3.8 \pm 0.7)\%, \text{ and}$$

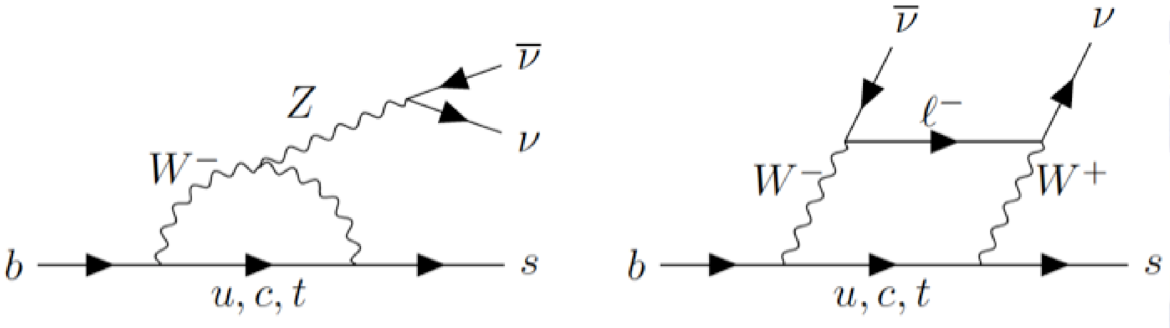
$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.5)\%,$$



$B \to K\nu\bar{\nu}$: BSM without hadronic uncertainties

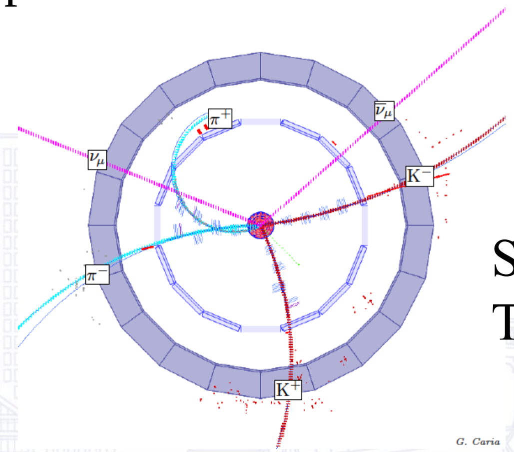


A b quark has charge -1/3, an s quark has charge -1/3 so this decay is a flavor changing neutral current (FCNC).



(a) Penguin diagram (b) Box diagram

The $B \to K^{(*)} \nu \bar{\nu}$ missing energy modes are accessible to Belle II (and Belle), but might be difficult at a hadron experiment.

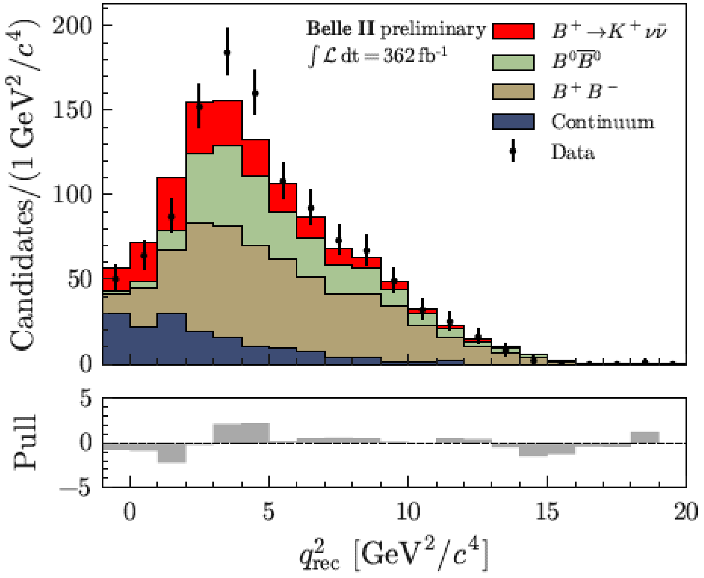


Signal: $B \to K \nu \bar{\nu}$
Tag mode: $B \to D\pi$; $D \to K\pi$

a 3.5σ excess or "evidence" signal: B→K $\nu\bar{\nu}$

Belle II

PRD 109, 112006 (2024)



- **Signal candidate:**
  - an identified charged kaon that gives the minimal mass of the neutrino pair q^2_{rec} (computed as K^+ recoil)

Event (pre-selection):
- $4 \le N_{track} \le 10$
- $E_{total} > 4$ GeV
- $17^o < \vartheta_{miss} < 160^o$

→ **BDT$_1$ (first filter):**
- 12 event-shape based kinematic variables

→ **BDT$_2$ (final selection):**
- *35 input variables:* using signal, event, and their correlations

Distributions for the signal-enhanced region in the ITA (Inclusive tagged analysis)

Fits in bins of BDT2 and q^2

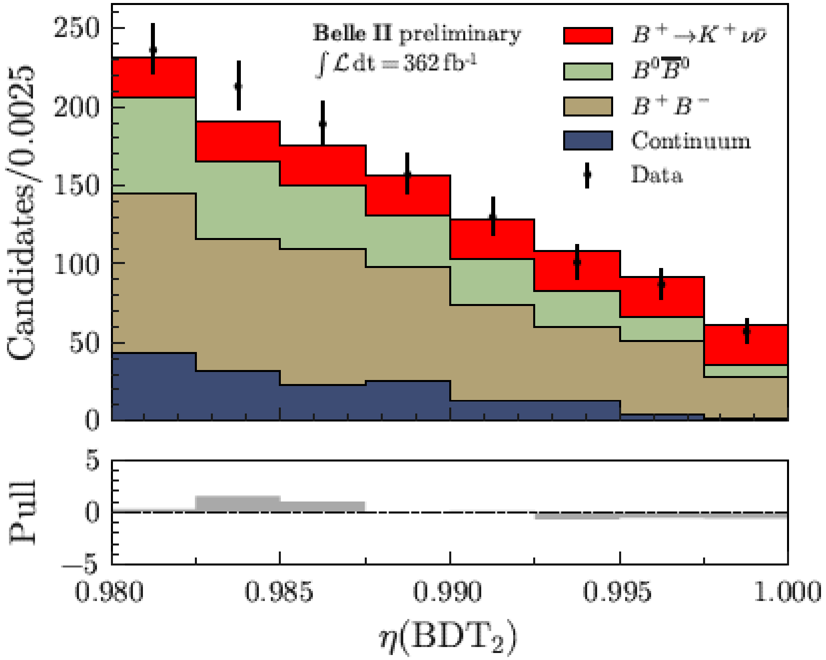
New Technique from Belle II with inclusive ROE (Rest of the Event) tagging. (X 10-20 ε compared to FEI, but large bkgs).

Now add on some ML/AI (boosted decision trees or BDTs) to help us tame the large backgrounds.

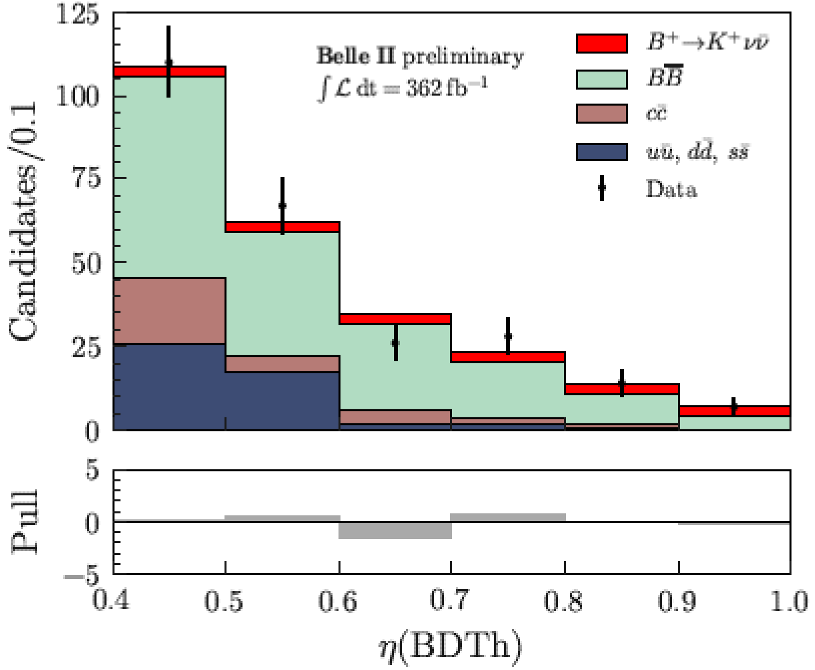
a 3.5σ excess or "evidence" signal: B→K ν $\bar{\nu}$

PRD 109, 112006 (2024)

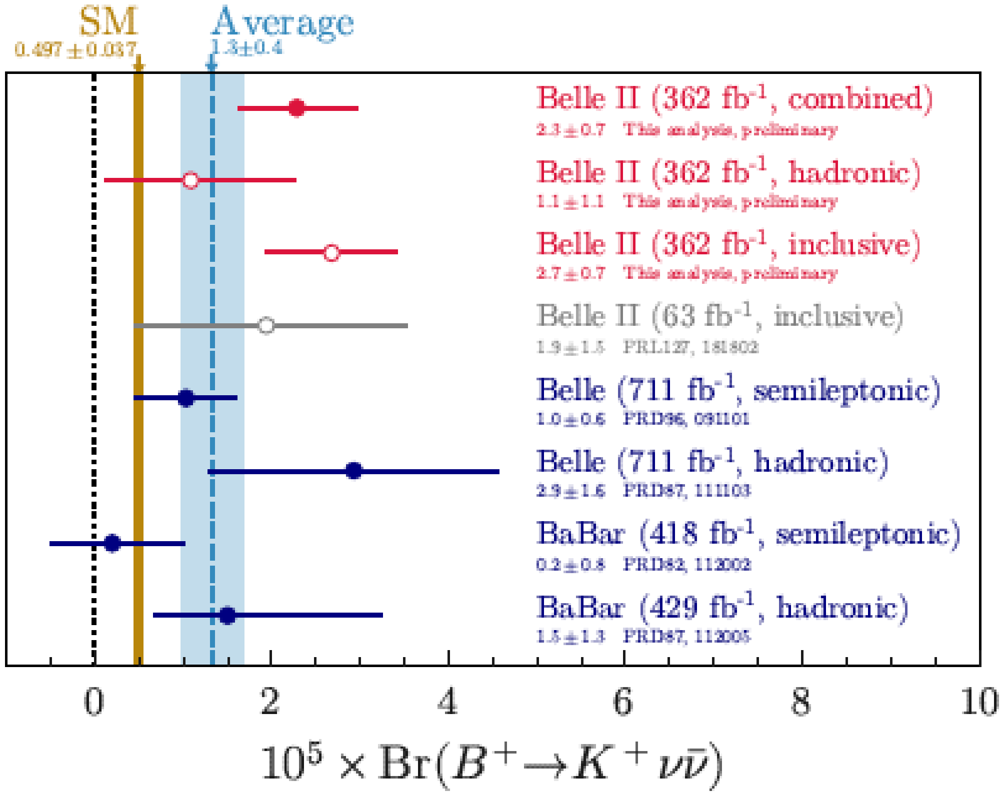
Inclusive tagged analysis



Consistency check with the lower sensitivity FEI hadronic tag.



Combination and comparison with other measurements



PRD 109, 112006 (2024)

$$\mathrm{B}(B^+ \to K^+ \nu\bar{\nu}) = \left(2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right) \times 10^{-5}$$

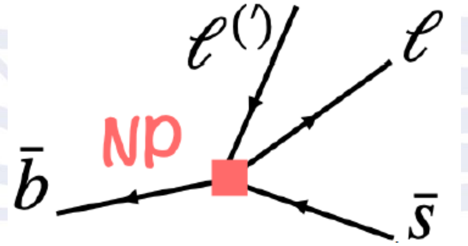
Significance of signal excess is 3.5 standard deviations. The signal is 2.7σ above the SM expectation.

Maybe third generation couplings $b \to s\, \tau^+\tau^-$ are enhanced

Program: In the future, Belle II should be able to measure B→K nu nubar, K* nu nubar, q^2 spectra and K^* polarization.

Search for $B^0 \to K_s^0 \tau^\pm \ell^\mp$ at Belle and Belle II

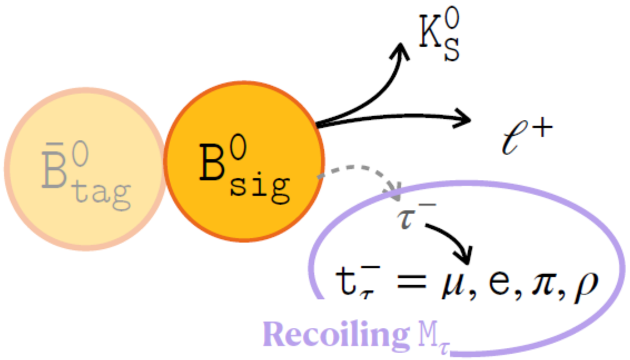
- The BSM extensions predict that the decay rates for LFV $b \to s\tau\ell$ decays are close to current experimental sensitivity
- Third-generation couplings + τ lepton mass → sensitivity to new

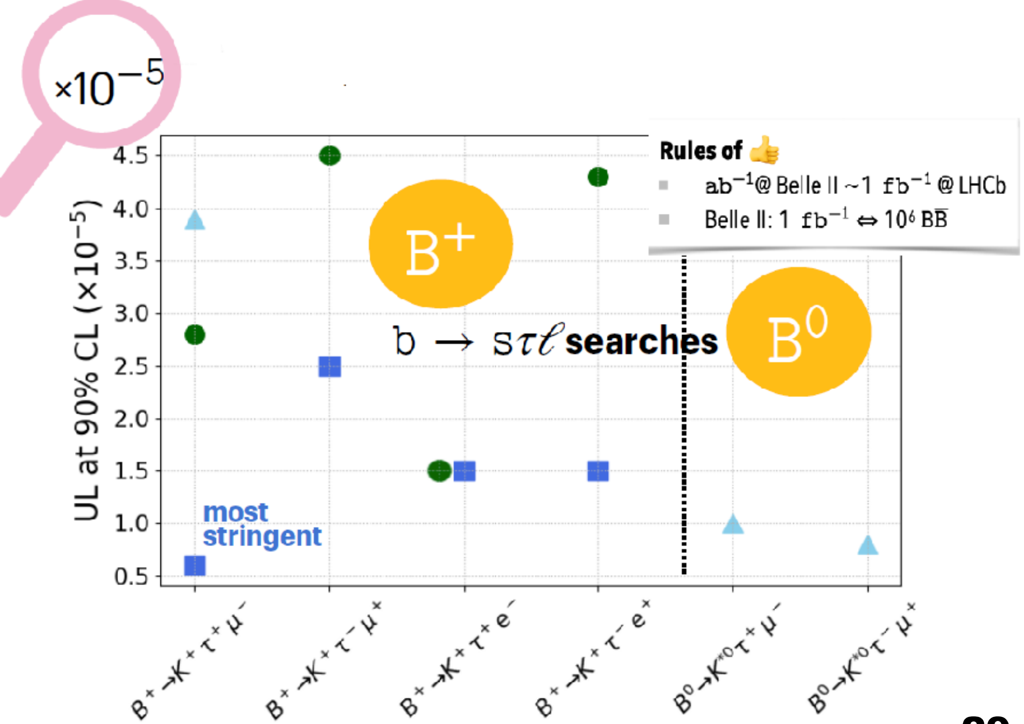


- ● **BaBar** (428 fb^{-1}) $B^+ \to K^+\tau^\pm\ell^\mp$ [PRD86, 012004, 2012]
- ■ **Belle** (711 fb^{-1}) $B^+ \to K^+\tau^\pm\ell^\mp$ [PRL130, 261802, 2023]
- ▲ **LHCb** (9 fb^{-1}) $B^+ \to K^+\tau^+\mu^-$, $B^0 \to K^{*0}\tau^\pm\mu^\mp$ [JHEP06,129,2020] [JHEP06,143,2023]

Today: first search in $B^0 \to K_S^0\tau^\pm\ell^\mp$

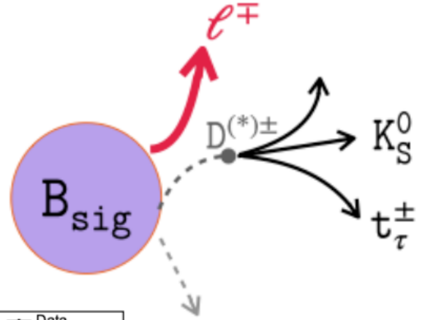
BELLE+Belle II (711+362 fb^{-1}) + hadronic B-tagging



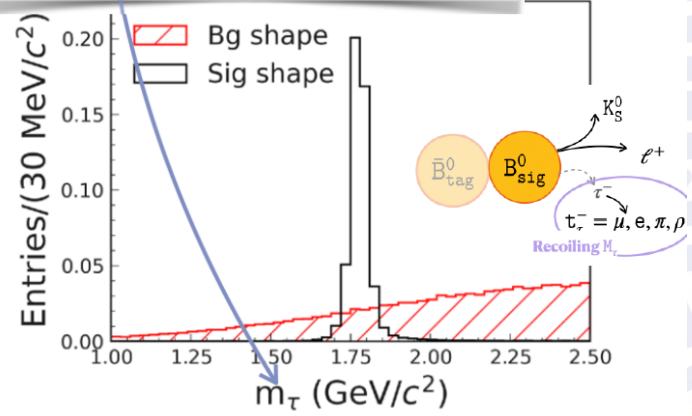


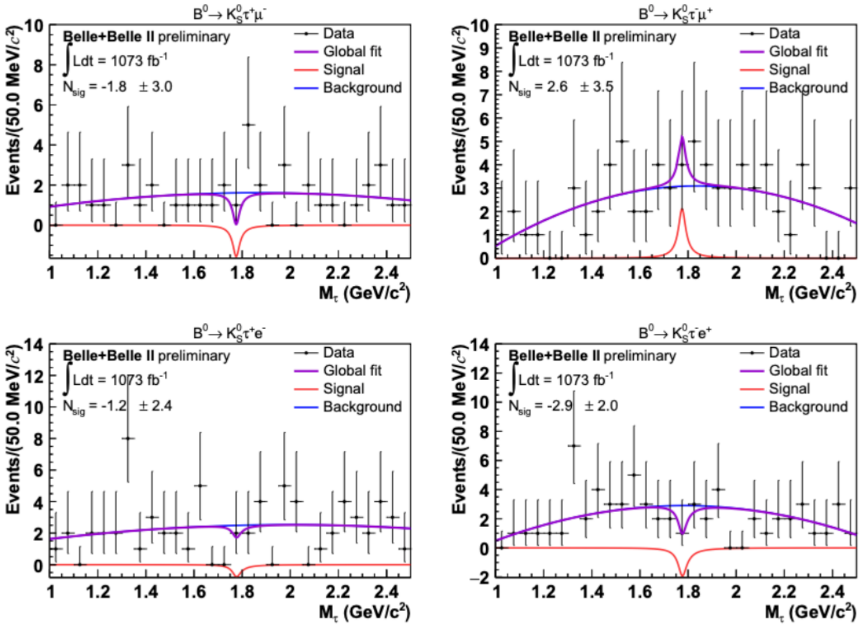
Search for $B^0 \to K_S^0 \tau^\pm \ell^\mp$ at Belle and Belle II

- Has **neutrinos only from one τ** $\Leftrightarrow$ can compute recoiling mass of τ
  (unlike $B^+ \to K^+ \nu\bar{\nu}$, $B^0 \to K^{*0}\tau^+\tau^-$ etc)
- K_S^0 purity is larger than 98%
- Reject dominant bkg: **B semi-leptonic decay**
- BDT for remaining bkg suppression



$$M^2_{recoil} = m_\tau^2 = (p_{e^+e^-} - p_K - p_\ell - p_{B_{tag}})^2$$





$$\mathcal{B}(B^0 \to K_S^0\tau^+\mu^-) < 1.1 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^-\mu^+) < 3.6 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^+e^-) < 1.5 \times 10^{-5}$$
$$\mathcal{B}(B^0 \to K_S^0\tau^-e^+) < 0.8 \times 10^{-5}$$

The results are among the most stringent limit

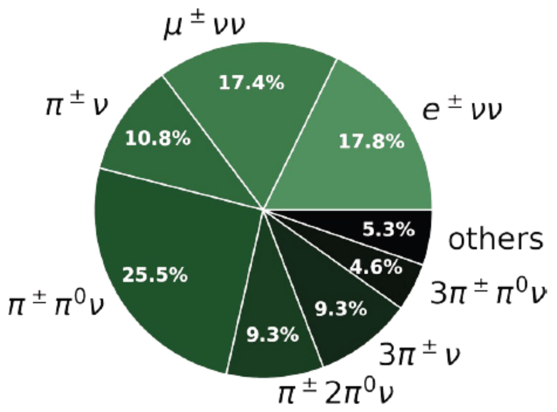
Belle II τ physics program

Why τ physics ?
- Heaviest lepton $\rightarrow$ many decay modes
- Only lepton to decay into hadrons
- Tests of the Standard Model
- Search for New Physics

Belle II τ physics program :
- τ mass measurement (PRD 108 ,032006)
- τ lifetime measurement
- V_{us} measurement
- LFU test (this talk)
- CP violation in $\tau \rightarrow K^0_S \pi \nu$

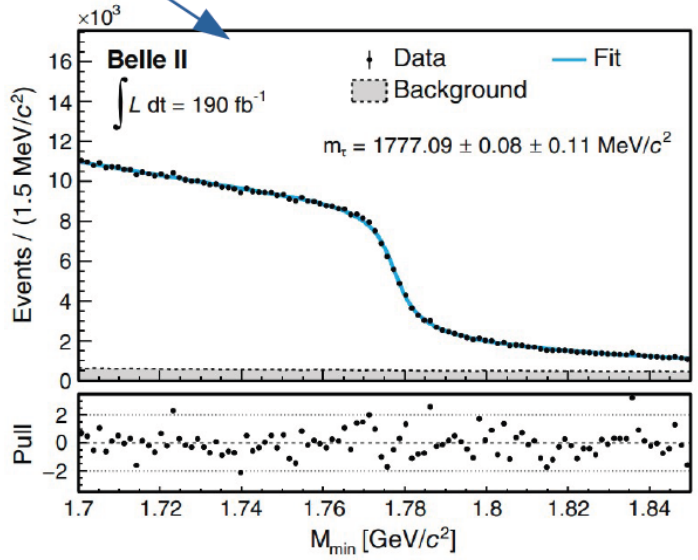
-and more

- LFV searches :
  - $\tau \rightarrow \ell\alpha$ (PRL 130, 181803)
  - $\tau \rightarrow \ell\phi$ (arXiv:2305.04759)
  - $\tau \rightarrow \Lambda\pi$ (arXiv:2407.05117)
  - $\tau \rightarrow \mu\mu\mu$ (this talk)
  - and other modes…



τ decay modes

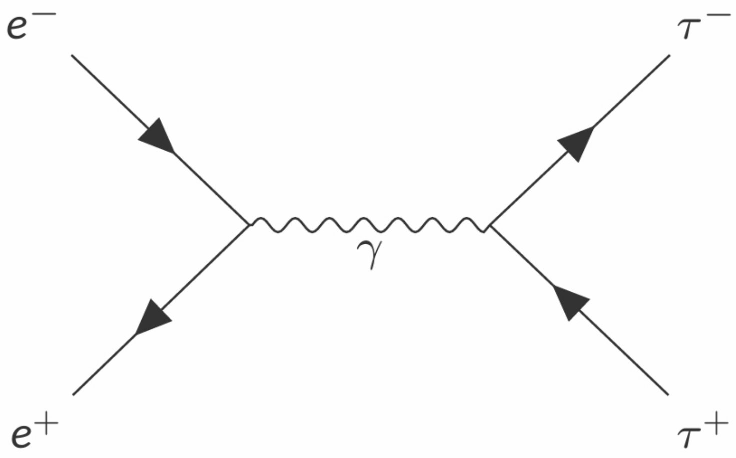
Most precise measurement of the τ mass : 1777.09 $\pm$0.08$\pm$0.11 MeV/c²



Lepton Flavour Universality measurement in τ decays

SuperKEKB as a τ **factory**:

- e^+e^- **collider produce τ leptons pairs at high rate**



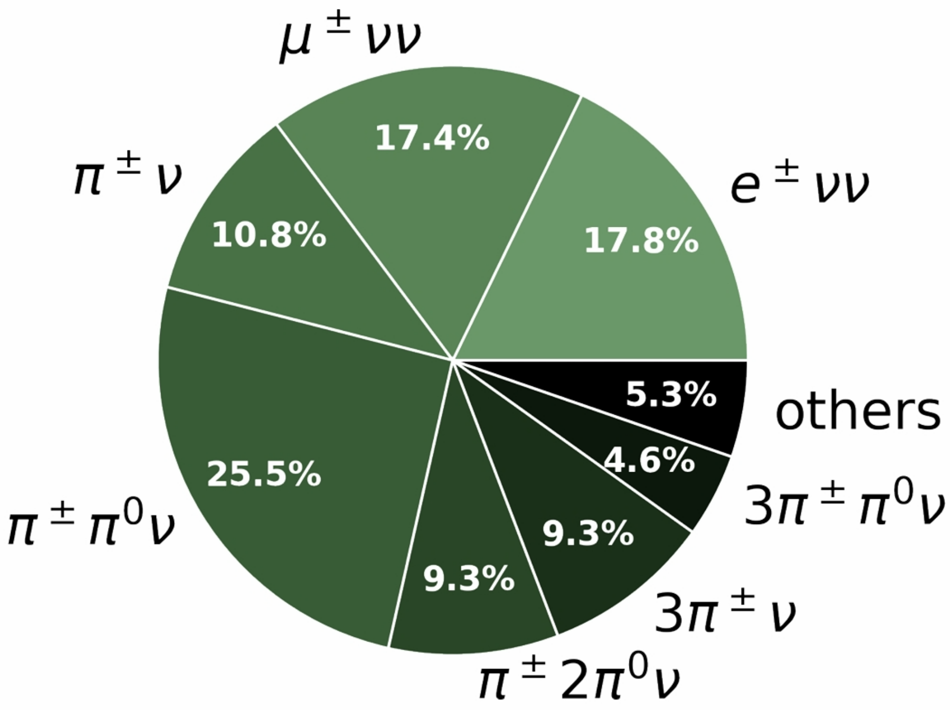
$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.92\ nb$$

$$\sigma(e^+e^- \to B\bar{B}) = 1.05\ nb$$

- cross section equivalent to $B\bar{B}$ process

τ **decays:** arXiv:2405.14625

- Massive enough to decay into **lighter lepton & hadrons**
- Mostly **one or three charged particles** in final states
- Challenging reconstruction with neutrinos in the final state

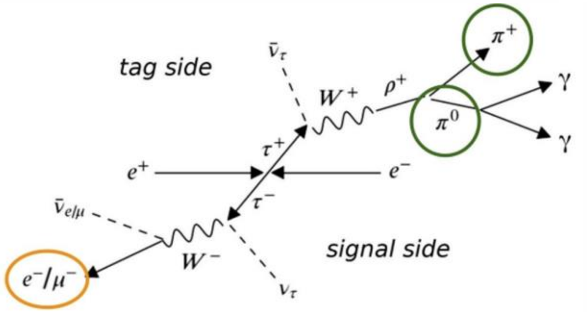


Lepton Flavour Universality measurement in τ decays

- Measurement of coupling of light leptons to EW gauge bosons:

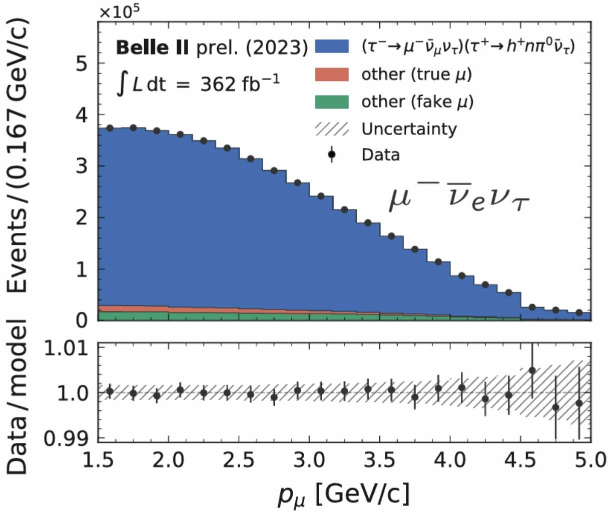
$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{\frac{\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)}\frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}} \stackrel{SM}{=} 1$$

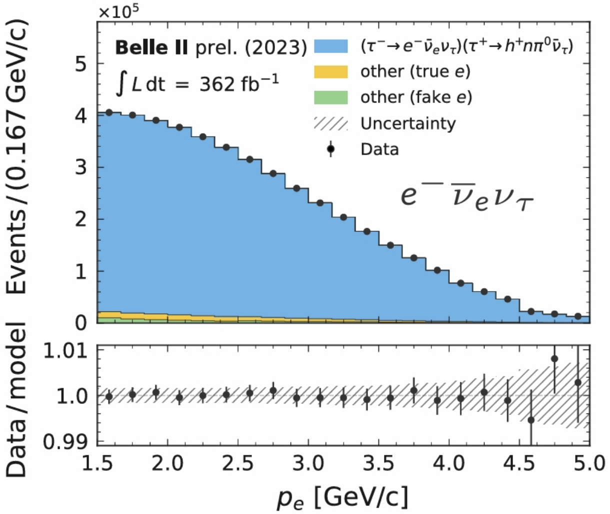
$$R_\mu = \frac{\mathcal{B}(\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau)}{\mathcal{B}(\tau^- \to e^-\overline{\nu}_e\nu_\tau)} \stackrel{SM}{=} 0.9726$$

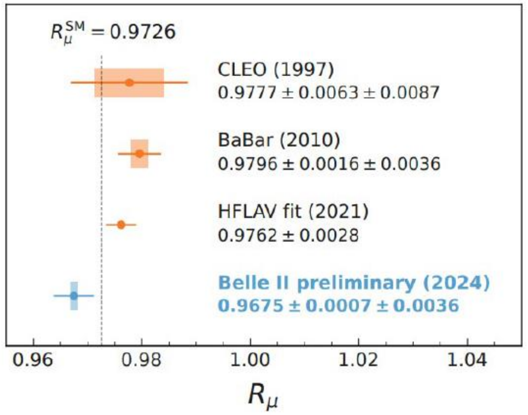


- Event selection is performed with rectangular cuts and neural network
- **94% purity with 9.6% signal efficiency for the combined sample**
- Mains systematics coming from PID (0.32%) and trigger (0.1%)

Extract R_μ by fitting the lepton momentum [1.5, 5] GeV/c







arXiv:2405.14625
JHEP accepted

- Most precise e/μ universality from τ^- decays in a single measurement with 362 fb^{-1}

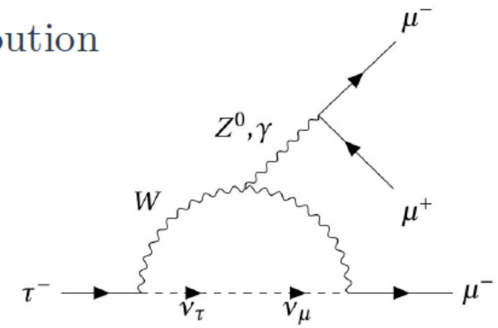
$$R_\mu = 0.9675 \pm 0.0007(stat) \pm 0.0036(sys)$$

Lepton Flavour Violation (LFV) searches in τ decays

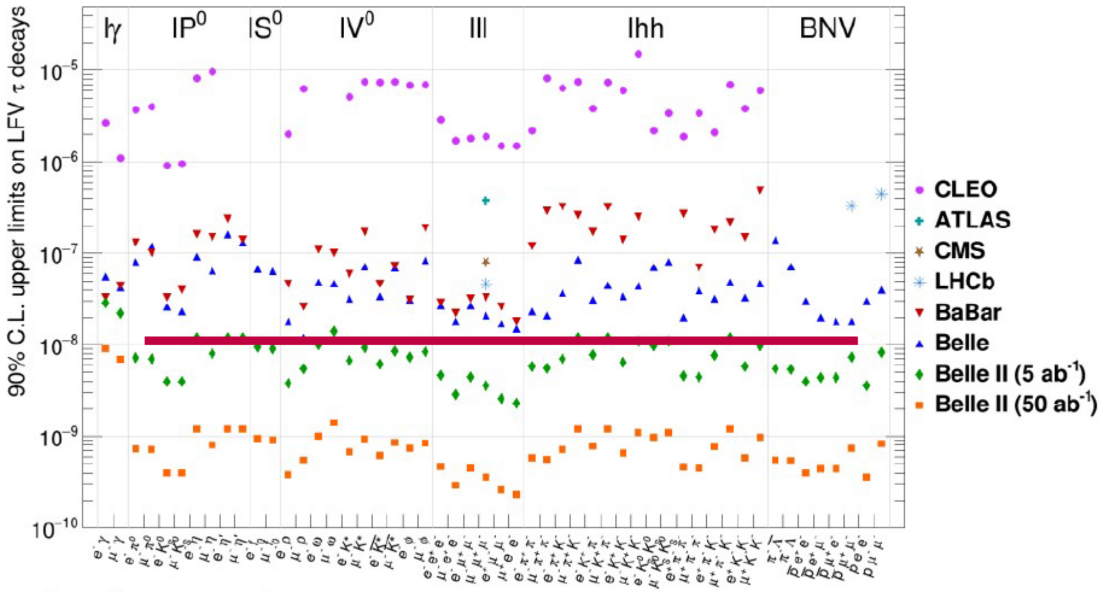
- Charged Lepton Flavour Violation (cLFV) in the Standard Model **through weak charged current and neutrino oscillations** @ rates ~ 10^{-55}
  → Clear prediction : no LFV in current experiments !

- Various BSM models predict LFV at observable rates ~ $10^{-8} - 10^{-10}$
  (e.g leptoquarks for $\tau \to \ell\phi$, related to anomalies in $b \to c\tau\nu$)

SM contribution



Physics Models	$\mathcal{B}(\tau \to \mu\mu\mu)$
SM	$10^{-53} \sim 10^{-55}$
SM + seesaw	10^{-10}
SUSY + Higgs	10^{-8}
SUSY + SO(10)	10^{-10}
Non-universal Z'	10^{-8}

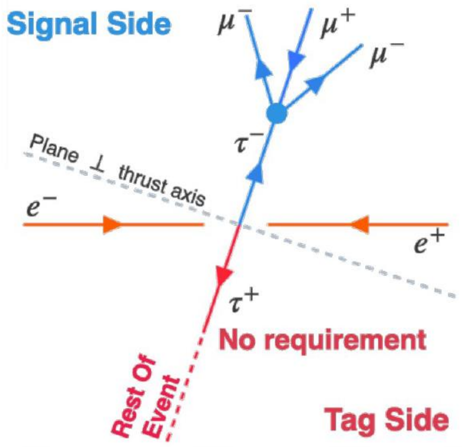


Banerjee et al., 2022a; Kou et al., 2019a

A lot of interest in LFV decays at e^+e^- colliders, with ~ 50 modes :
$\tau \to \ell\gamma, \tau \to \ell\phi, \tau \to \ell\ell\ell$, etc.

These are rare decays : it's all about **maximizing** the number of events !

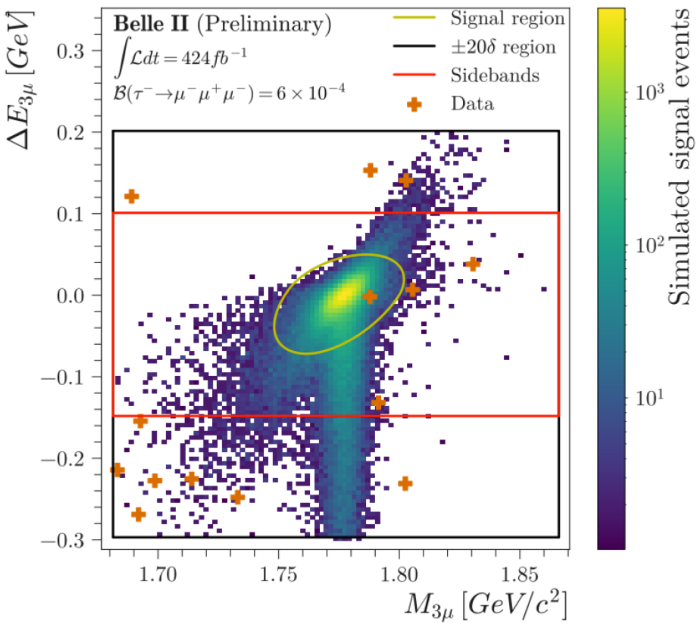
LFV : search for $\tau^\pm \to \mu^\pm \mu^\mp \mu^\pm$



$\tau^\pm \to \mu^\pm \mu^\mp \mu^\pm$:

- Almost free from SM background
- Very good resolution on the energy and momentum
- Can also be probed by LHC experiments

Existing measurements : 2.1×10^{-8} by Belle (Phys.Lett.B687)
2.9×10^{-8} by CMS (Phys.Lett.B853)



- Signal yield is extract with a poisson counting experiment
- Signal region defined as an ellipse in the 2D plane $(M_{3\mu}, \Delta E_{3\mu})$

$(\Delta E_{3\mu} = E_{beam}/2 - E_{3\mu})$

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{N_{obs} - N_{exp}}{2\sigma_{\tau\bar{\tau}} \cdot \mathcal{L} \cdot \epsilon_{3\mu}}$$

Number of expected background $N_{exp} = 0.7^{+0.6}_{-0.5} \pm 0.01$ obtained by rescaling the yields from the sidebands data in the signal region

Observed 1 event in the signal region

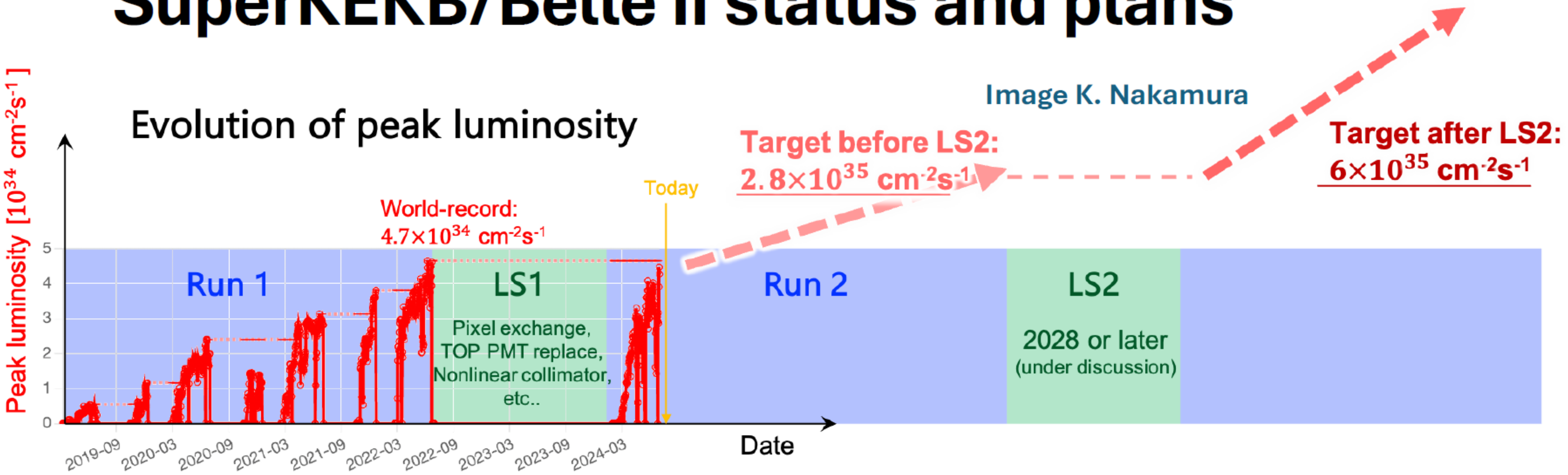
90 % CL upper limit on the branching fraction

$\mathcal{B}(\tau \to \mu\mu\mu) < 1.9\times 10^{-8}$

World's best limit!

Accepted by JHEP (arXiv:2405.07386)

SuperKEKB/Belle II status and plans

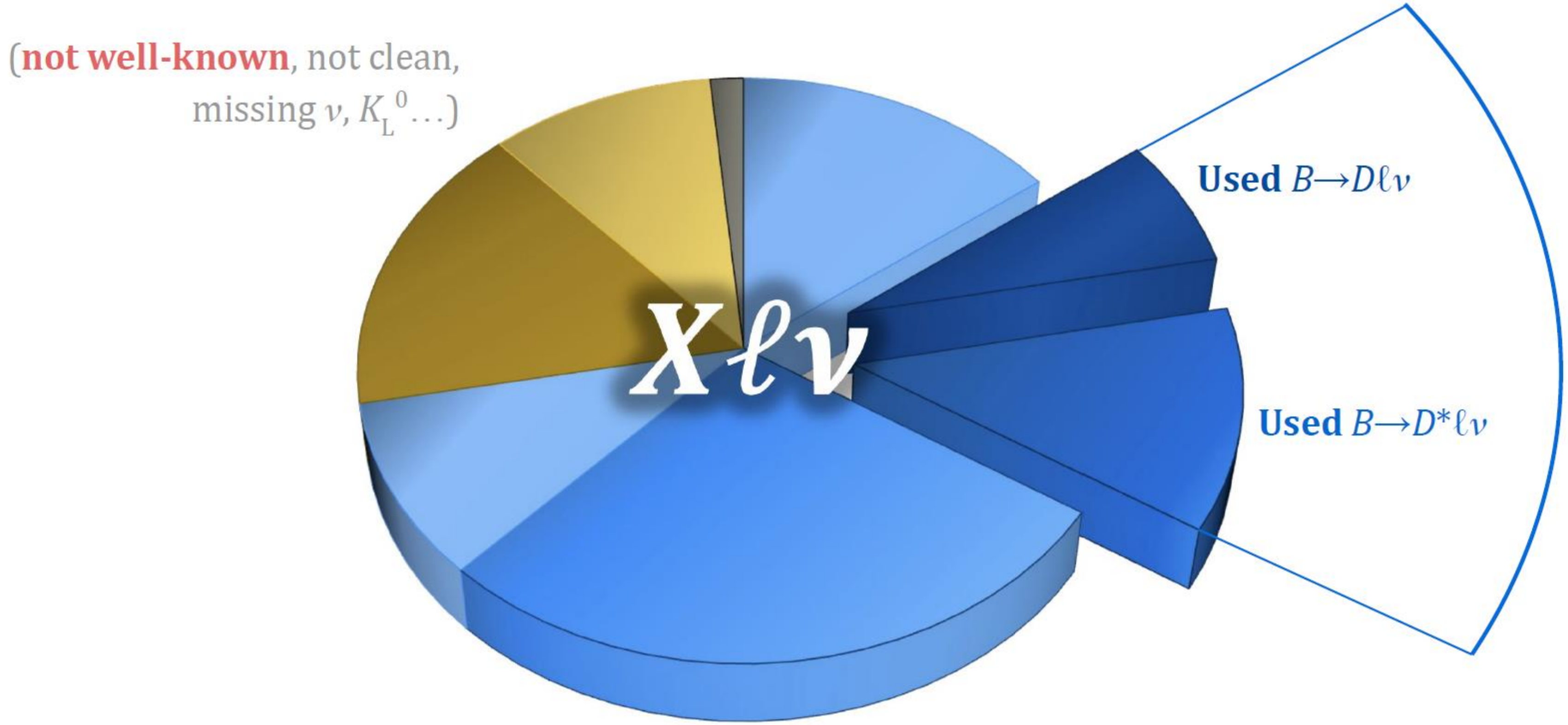


- Run 2 is long – end 2028 or later
  - Steady accumulation at ~2 x 10^{35} cm^{-2}s^{-1} for several ab^{-1} – 2nd generation
  - After Run 2 – upgrade proposal for reach design luminosity and tens of ab^{-1}

Summary

- Belle II started operation in 2019, and the luminosity has achieved $\sim 0.5 \times 10^{35} cm^{-2} s^{-1}$.
- After 18 months of LS1, SuperKEKB is resuming for the second data taking in Jan. 2024, with a goal of $(1-2) \times 10^{35} cm^{-2} s^{-1}$.
- Belle II is getting more and more productive in publications, based on the excellent performance of the Belle II detector.
- R&D works for Belle II upgrade are on the way, and the CDR is under review by BPAC, going to be released soon.

Composition of $B \to X\ell\nu$ events



Used: <20%

Well-known, clean decays (mostly $K^{\pm}$,$\pi^{\pm}$)

No missing particles

*So then: how can we use "**not well-known**" as the signal?*

Data-driven corrections

The ***invariant mass of the X system*** controls the **physics** we know the least about

Control variable

$$M_X^2 = \begin{pmatrix} E_X \\ \overrightarrow{p_X} \end{pmatrix}^2$$

Extraction variable

$$M_{\text{miss}}^2 = \left[\begin{pmatrix} E_{\text{CMS}} \\ \overrightarrow{p_{\text{CMS}}} \end{pmatrix} - \begin{pmatrix} E_{\text{CMS}}/2 \\ -\overrightarrow{p_{B_{\text{tag}}}} \end{pmatrix} - \begin{pmatrix} E_\ell \\ \overrightarrow{p_\ell} \end{pmatrix} - \begin{pmatrix} E_X \\ \overrightarrow{p_X} \end{pmatrix} \right]^2$$

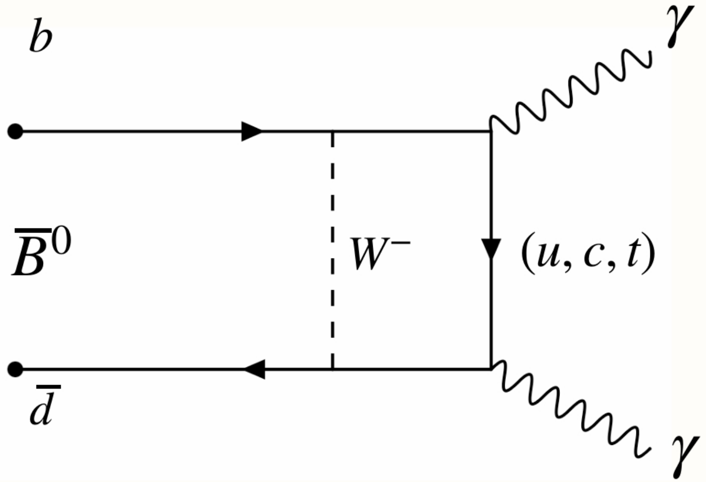
Independent test variable

$$q^2 = \left[\begin{pmatrix} E_{\text{CMS}}/2 \\ -\overrightarrow{p_{B_{\text{tag}}}} \end{pmatrix} - \begin{pmatrix} E_X \\ \overrightarrow{p_X} \end{pmatrix} \right]^2$$

*Using M_X to reweight the signal **fixes*** the observed mismodeling*

Study of the rare decay $B^0 \to \gamma\gamma$ decay at Belle and Belle II

- This mode is sensitive to new physics that could enhance branching fraction due to the possible contribution of non-SM heavy particles.



Previous searches	Measurement at 90 % CL
L3 collaboration ($\int \mathcal{L}dt$=73 pb^{-1})	$< 3.9 \times 10^{-5}$
Belle collaboration ($\int \mathcal{L}dt$=104 fb^{-1})	$< 6.2 \times 10^{-7}$
BABAR collaboration ($\int \mathcal{L}dt$=426 fb^{-1})	$< 3.2 \times 10^{-7}$

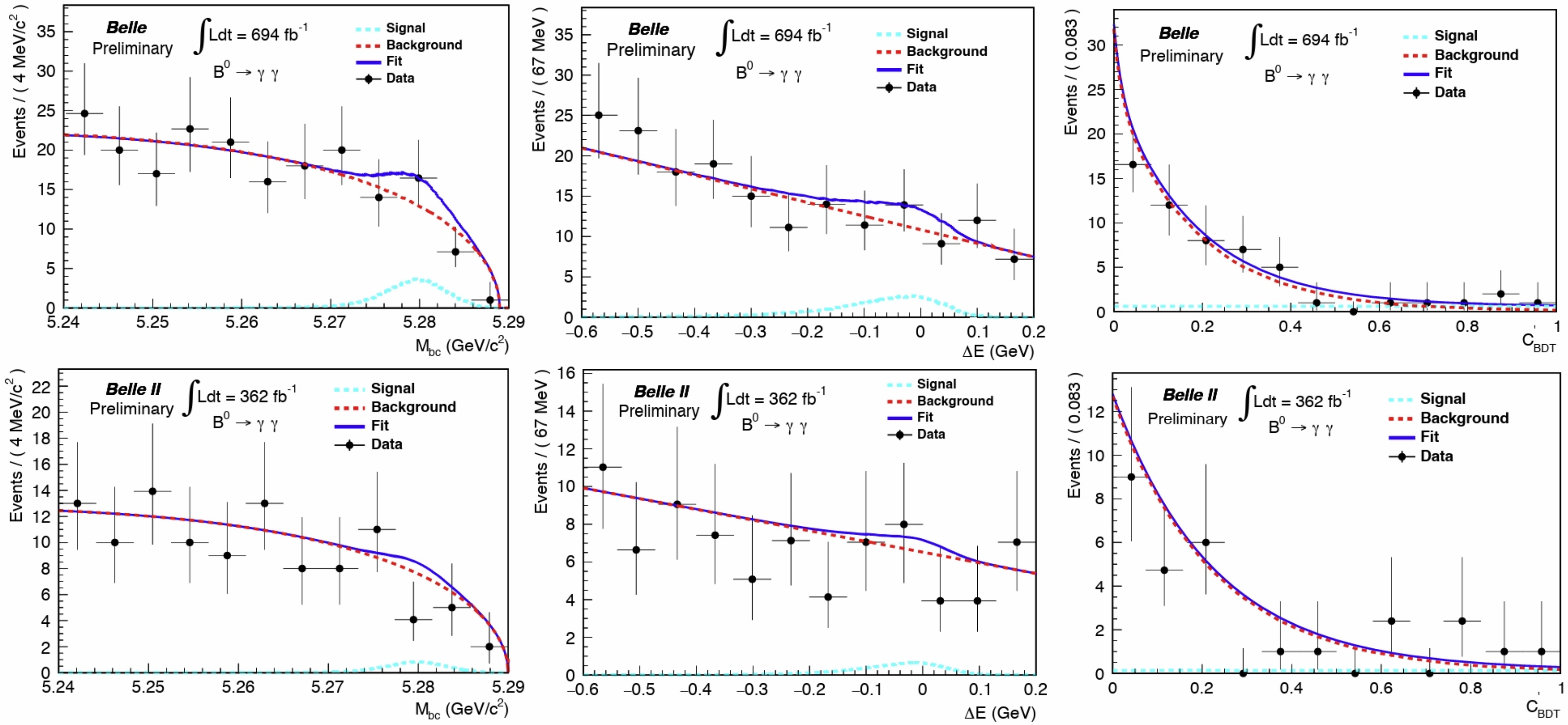
Phys. Lett. B363 137
Phys. Rev. D.73.051107
Phys. Rev. D.83.032006

Theoretically, the BF of this decay mode is expected to be $1.4^{+1.4}_{-0.8} \times 10^{-8}$ [1].

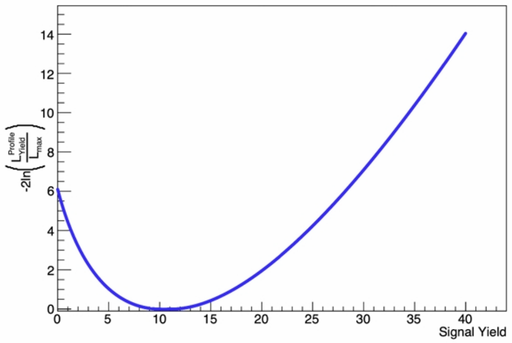
1 Yue-Long Shen et al. (2020), Journal of High Energy Physics, 169 (2020)

- We perform the first Belle and Belle II measurement using a data set of 694 fb^{-1} from Belle and the dataset of Belle II (≈ 362 fb^{-1}) from the Run1 period.

Study of the rare decay $B^0 \to \gamma\gamma$ decay at Belle and Belle II



PRDL (accepted)
arXiv:2405.19734



Signal Significance

$(\sqrt{-2(\ln \mathscr{L}_0/\mathscr{L}_{max})})$

$= 2.5\,\sigma$

- Simultaneous 3D unbinned ML fitting on M_{bc}, ΔE and C'_{BDT} using Belle and Belle II data sets.

Signal Yield = $11^{+6.5}_{-5.5}$ 2.5σ significance wrt the background only hypothesis

Approaching SM sensitivity

Study of the rare decay $B^0 \to \gamma\gamma$ decay at Belle and Belle II

PRDL (accepted)
arXiv:2405.19734

- No signal evidence -> set UL at 90% CL
- $\mathscr{B}(B^0 \to \gamma\gamma) < 6.4 \times 10^{-8}$ at 90% CL.
- Improvement by a factor of five over the previous UL set by the Babar experiment with 426 fb^{-1} ($< 3.2 \times 10^{-7}$ at 90% CL).

Improvements

Increased Statistics (Belle+Belle II)

Improved analysis techniques.

Better Signal Efficiency

Improved Background reduction

$$\mathscr{B}(B^0 \to \gamma\gamma) = (3.7^{+2.2}_{-1.8}(\text{stat}) \pm 0.7(\text{sys})) \times 10^{-8}$$

Upper limit on Branching fraction: $< 6.4 \times 10^{-8}$ at 90% CL

World Best UL (Previous world best $< 3.2 \times 10^{-7}$) [BaBar, PRD.83.032006]

Search for $B^0 \to K^{*0}\tau^+\tau^-$

Belle II

- FCNC processes are suppressed in SM at tree level.
- NP models that accommodate the $b \to c\tau\ell$ anomalies predict an enhancement of several orders of magnitude with $\tau\tau$ **pair** in the final state.
- NP couplings are those involving the **third-fermion generation.**

Belle (711 fb^{-1}) $\mathscr{B}^{UL}(B^0 \to K^{*0}\tau^+\tau^-)$<3.1×10^{-3} [PRD 108 L011102 (2023)]

BaBar (428 fb^{-1}) $\mathscr{B}^{UL}(B^+ \to K^+\tau^+\tau^-)$<2.3×10^{-3} [PRL 118 032012 (2017)]

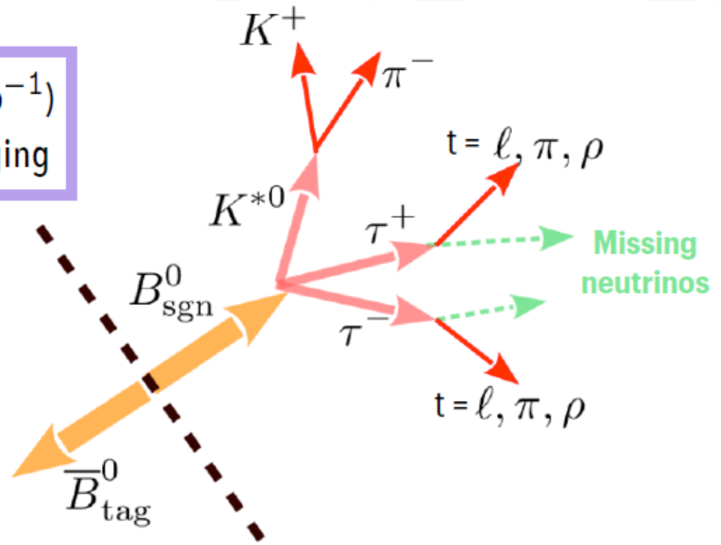
$BF_{SM} = (0.98 \pm 0.10) \times 10^{-7}$ [PRD 53, 4964 (1996)]

Challenges

Similar as $B^+ \to K^+\nu\bar{\nu}$

- Low BF
- No signal peaking kinematic observable
- Large backgrounds+more than 3 prompt track
- Up to **4 neutrinos** orignating from τ
- K^{*0} has **low momentum** due to the phase space

Belle II (362 fb^{-1})
hadronic B-tagging

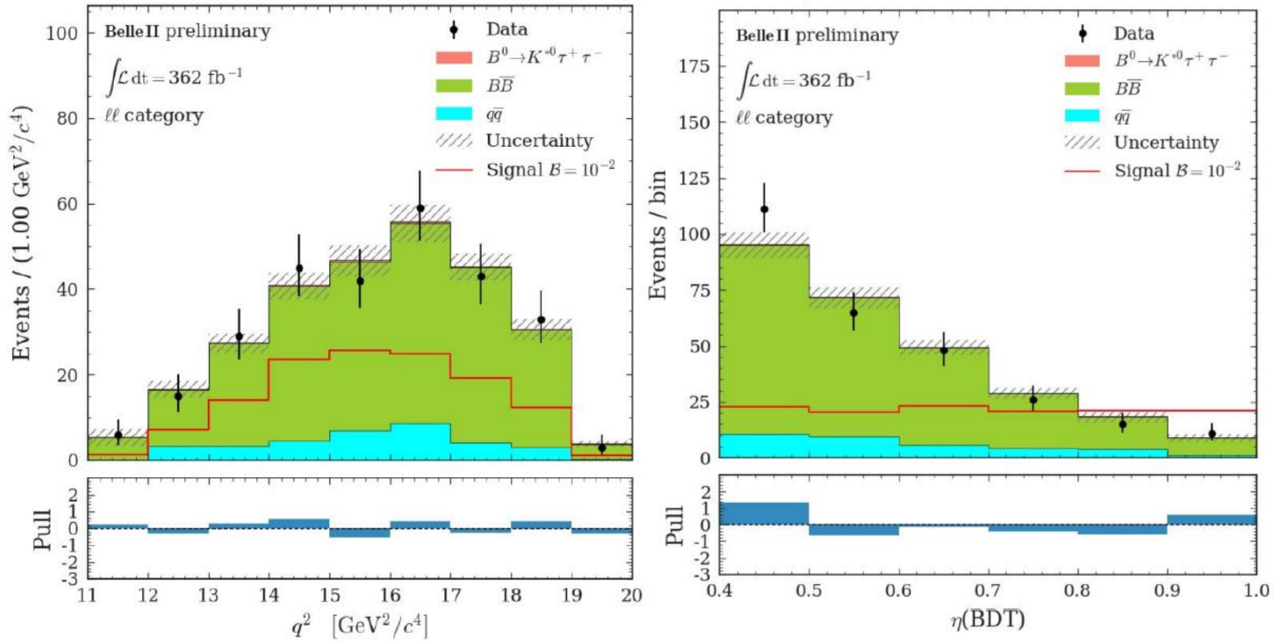


博學而篤志 切問而近思

Search for $B^0 \to K^{*0}\tau^+\tau^-$

- Combinations of sub-track from τ lead to 4 categories: $\ell\ell, \ell\pi, \pi\pi, \rho X$
- $\ell\ell$ has the best sensitivity
- **BDT** is trained using missing energy, extra cluster energy in EM calorimeter, $M(K^{*0}t)$, q^2, etc.
- BDT output η(BDT) is used to extract the signal yield with simultaneous fit to 4 categories

$\ell\ell$ as an example



$\mathscr{B}^{\mathrm{UL}} = 1.8 \times 10^{-3}$ at 90% confidence level

Twice better with only half sample wrt Belle!
Better tagging + more categories + BDT classifer…

The most stringent limit on the $B^0 \to K^{*0}\tau^+\tau^-$ decay and in general on $b \to s\tau\tau$ transition!