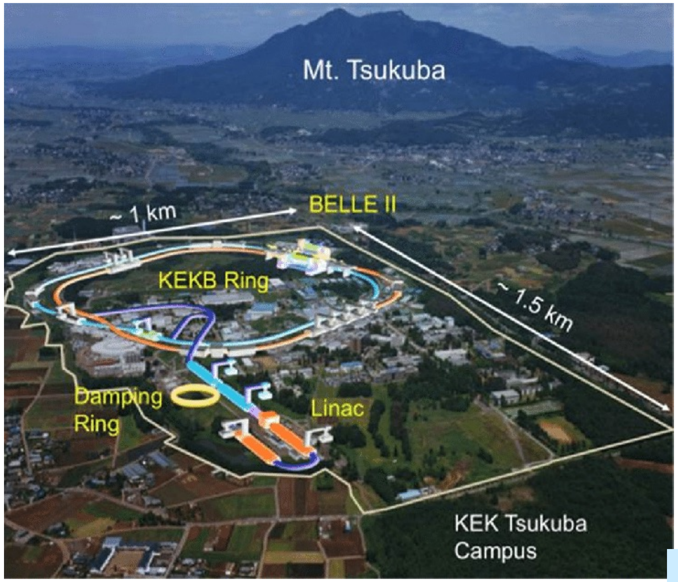
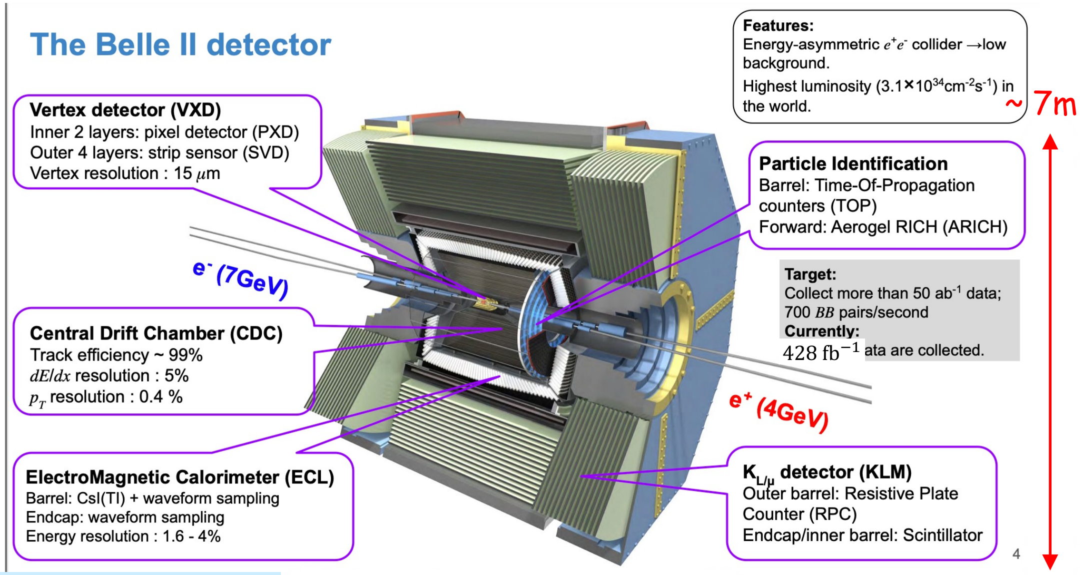
Hot Topic in Flavour at the B Factories

Chunhui Chen
Iowa State University
On behalf of the Belle and Belle II Collaborations

9th Workshop on Theory, Phenomenology and Experiments in Flavor Physics
June 19-21, 2024, Anacapri, Capri Island, Italy

Belle and Belle II experiments





Belle II TDR: arXiv:1011.0352

~ 7.5m $\beta\gamma = 0.28$

- Asymmetric $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ with production cross section $\sim 1.1nb$
  - ✓ Belle → Belle II: $e^+(3.5$ GeV$)e^-(8$ GeV$) \to e^+(4$ GeV$)e^-(7$ GeV$)$
  - ✓ Belle II has smaller boost but improved vertex resolution
- Belle (1999-2010): 1.4 ab^{-1} with 711 fb^{-1} at $\Upsilon(4S)$, $\mathcal{L}_{peak} = 2.1\times10^{34} cm^{-2}s^{-1}$
- Belle II collected 428 fb^{-1} data for Run 1 with record $\mathcal{L}_{peak} = 4.7\times10^{34} cm^{-2}s^{-1}$
  - ✓ Restart data taking in 2024, Final goal: 50 ab^{-1} data at $\mathcal{L}_{peak} = 6.5\times10^{35} cm^{-2}s^{-1}$
- Belle/BelleII: Knowledge of initial state: kinematic constraints for signal reconstruction

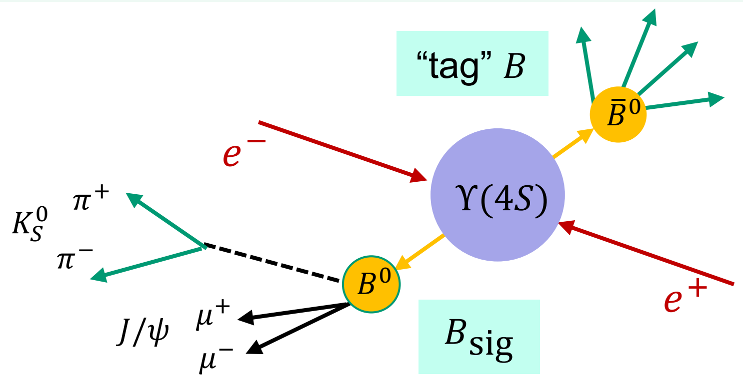
$$\Delta E = E_B^* - \sqrt{s}/2 \qquad M_{bc} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_B^{*2}|}$$

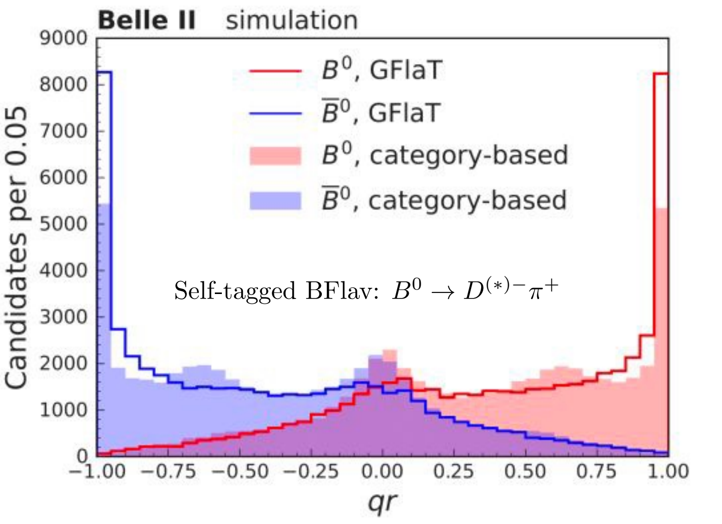
Outline of the talk

- This is not a review talk
  - ✓ Some selected recent results from Belle/Belle II
  - ✓ Focus on results sensitive to New Physics (NP)
  - ✓ Focus on measurements most sensitive at B factory
- Topics:
  - ✓ Measurements of CP Violation (CPV) in B decays
  - ✓ Rare B decays in the EWP final states
  - ✓ Rare and forbidden Charm meson decays
  - ✓ Rare and forbidden Tau decays
  - ✓ No Dark Sector: see the talk by Marita Laurenza
- Comparison to previous results and outlook in the future

B Flavor tagging at Belle II

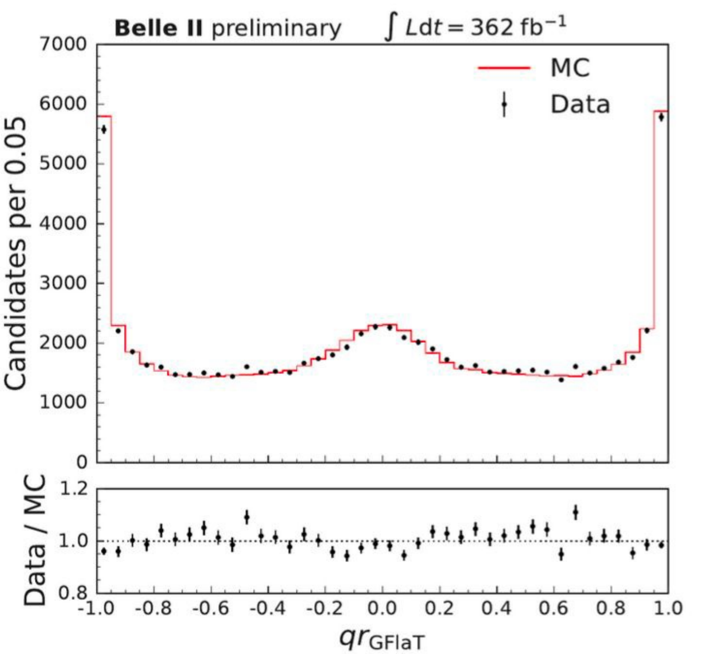
- B flavor tagging: Identify the flavor of the other B





- Belle II initial B tagging algorithm:
  - ✓ Category-based (CB): physics object as BDT input
  - ✓ Similar to Belle & Babar experiments
- Newly developed B tagging algorithm: GFlat
  - ✓ Graph convolutional neural network (GNN)
  - ✓ 25 variables for each track as GNN input
  - ✓ 18% improvement in performance

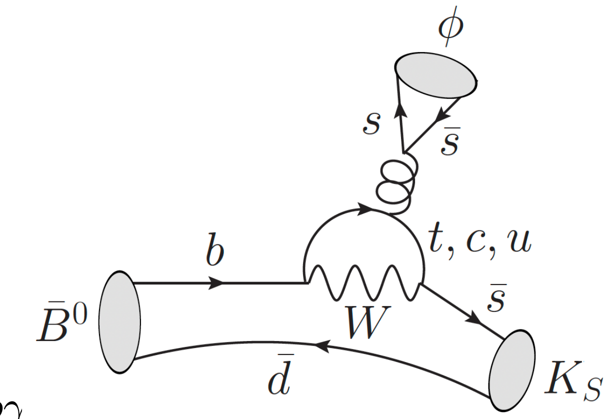
$$\epsilon_{\text{tag}}(\text{CB}) = (31.7 \pm 0.5 \pm 0.4)\,\%$$
$$\epsilon_{\text{tag}}(\text{GFlaT}) = (37.4 \pm 0.4 \pm 0.3)\,\%$$



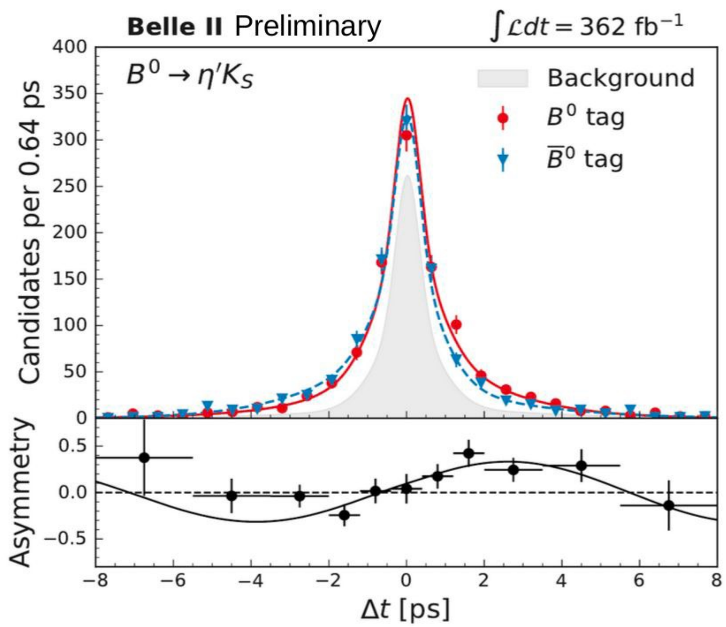
arXiv:2402.17260, Accepted by PRD

CPV in Penguin dominated B decays

NP may induce a large discrepancy between the CP Asymmetry in $b \to c\bar{c}s$ and $b \to q\bar{q}s, (q = u, d, s)$ transitions, such as $\eta' K_S^0,\ \phi K_S^0,\ K_S^0\pi^0,\ K_S^0 K_S^0 K_S^0$



$B^0 \to \eta' K_S^0$ with $\eta' \to \eta(\to \gamma\gamma, 3\pi)\pi^+\pi^-$ or $\eta' \to \rho\gamma$



arXiv:2402.03713, Accepted by PRD

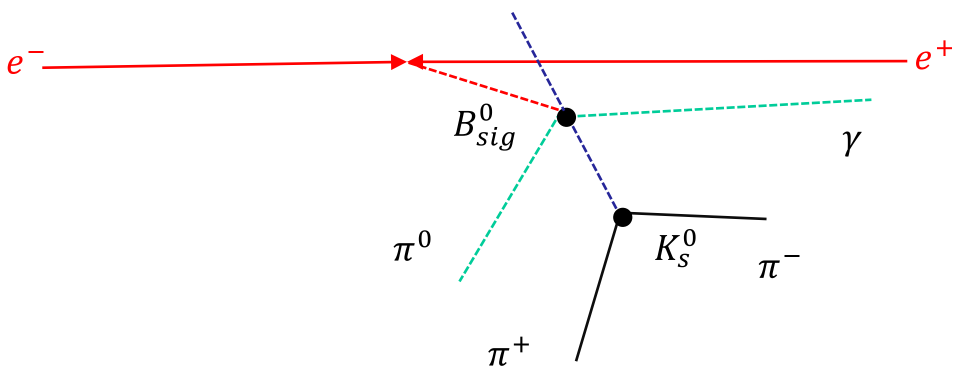
- Large $\mathcal{B}$, and theoretically clean
- Signa yield: 829 ± 35
- Still use the old Belle II CB tagging:

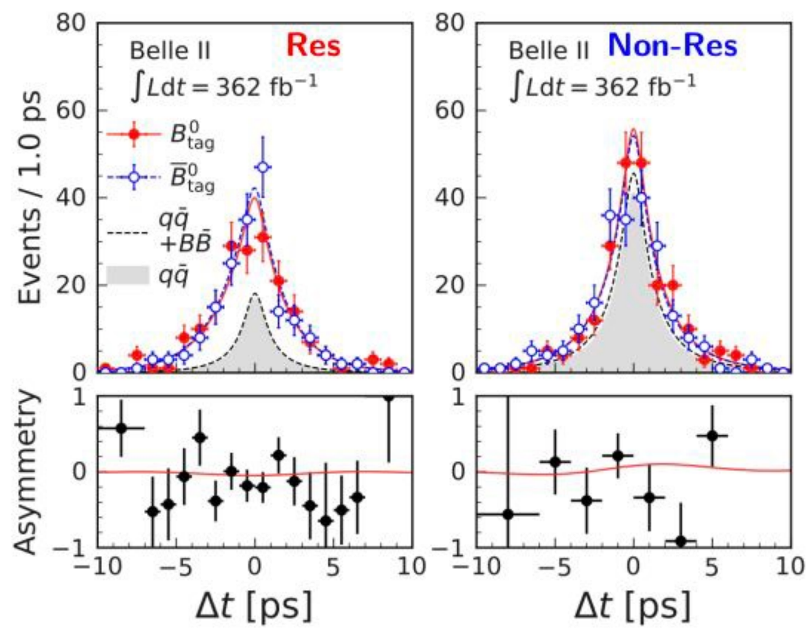
$$C_{\eta' K_S^0} = -0.19 \pm 0.08 \pm 0.03$$
$$S_{\eta' K_S^0} = +0.67 \pm 0.10 \pm 0.04$$

- Consistent with Belle measurement: 711 fb^{-1}
  - ✓ Use More final states ($K_S^0 \to \pi^0\pi^0,\ K_L$)
  - ✓ $\sigma_S = 0.07$
- Belle II expect ~10% improvement of σ_S for same data statistics using GFlaT

CPV in $B^0 \to K_S^0 \pi^0 \gamma$

- Amplitude dominated by electro-weak penguin loop
- Expect very small mixed-induced CPV in the Standard Model (SM)
  - ✓ $b \to s\gamma_R$ is helicity suppressed by (m_s/m_b) w.r.t. $b \to s\gamma_L$
  - ✓ $B^0 \to K_S^0\pi^0\gamma_L$ vs. $B^0 \to \bar{B}^0 \to K_S^0\pi^0\gamma_R$
- Measurements for resonance ($K^{*0} \to K_S^0\pi^0$) and non-resonance final states
- Vertex with beamspot constraints
  - ✓ Better vertexing of K_S^0 reconstruction at Belle II





$$C_{\rm Res} = 0.10 \pm 0.13 \pm 0.03$$
$$S_{\rm Res} = 0.00\,^{+0.27}_{-0.26}\,^{+0.03}_{-0.04}$$

$$C_{\rm Non-Res} = -0.06 \pm 0.25 \pm 0.07$$
$$S_{\rm Non-Res} = 0.04\,^{+0.45}_{-0.44} \pm 0.10$$

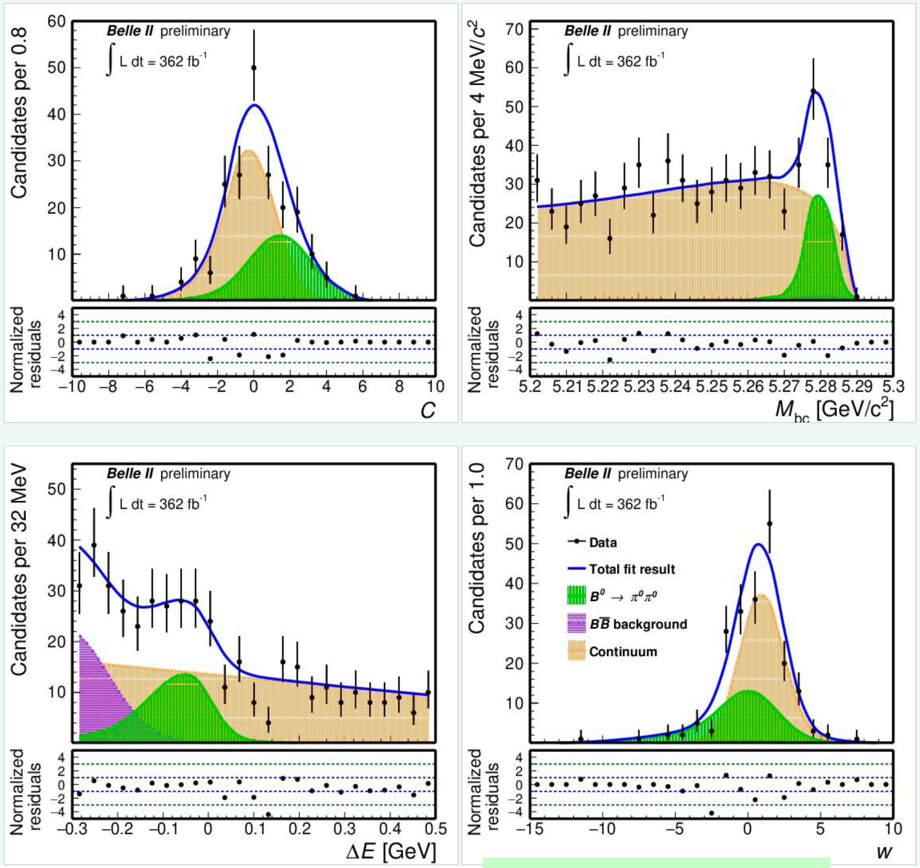
Most precise measurements
Use CB tagging
Belle (499 fb^{-1})
BaBar (436 fb^{-1})

To be submitted to PRL

Direct CPV in $B^0 \to \pi^0\pi^0$

- Update early Belle II measurement ($189\ \mathrm{fb}^{-1}$) of $\mathcal{B}$ and A_{CP}
- Improved selections, new flavour tagger (GFlaT), reduction of systemic uncertainties
  - Background dominated by continuum, then $B^+ \to \rho^+(\pi^+\pi^0)\pi^0$, $B^0 \to K_S^0(\pi^0\pi^0)\pi^0$
  - BDT photon selector, continuum suppression trained using off-resonance data
  - 4-D fit: m_{bc}, ΔE,continuum suppression BDT output, wrong B-tag probability

$$\mathcal{B} = (1.26 \pm 0.20 \pm 0.11)^{-6}$$
$$A_{\mathrm{CP}} = 0.06 \pm 0.30 \pm 0.06$$



- Compatible with previous results
- World-best branching fraction
- Compatible Direct CP precision
  - ✓ Belle ($499\ \mathrm{fb}^{-1}$) & BaBar ($436\ \mathrm{fb}^{-1}$)
  - ✓ World average

$$\mathcal{B} = (1.59 \pm 0.26)^{-6}$$
$$A_{\mathrm{CP}} = 0.30 \pm 0.20$$

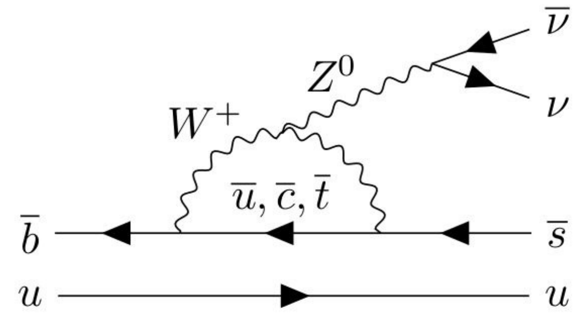
To be submitted to PRD

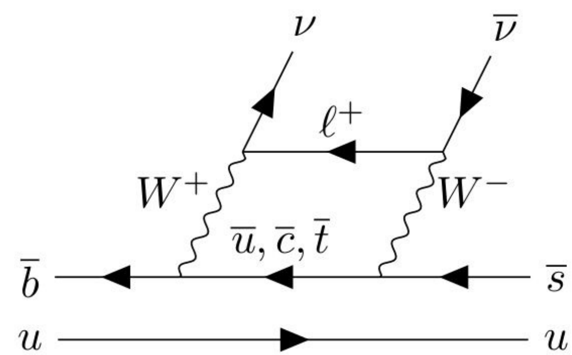
Electroweak Penguin dominated B decays

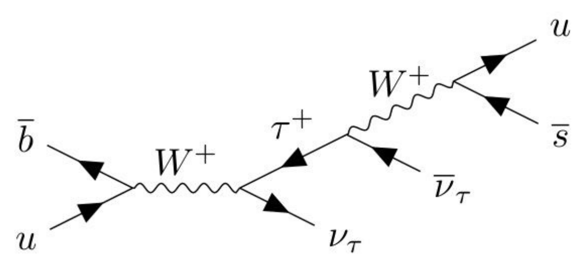
- NP may contributed in the EWP loops
  - ✓ $b \to s l^+ l^-, b \to s \nu \bar{\nu}$, and $b \to s \gamma$ transitions
- Some measurements have tension with SM
  - ✓ Branching fraction and angular observables
- Search for $B^+ \to K^+ \nu \bar{\nu}$ at Belle II
  - ✓ Theoretically clean (no photon exchange)
  - ✓ Experimentally challenging: two neutrinos in the final state, high background and small branching fraction

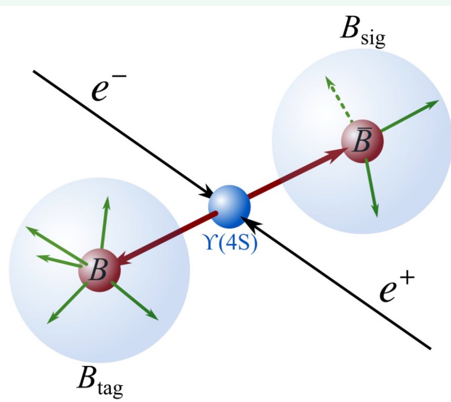
$$\mathcal{B}_{\rm SM} = (5.58 \pm 0.37) \times 10^{-6}$$

  - ✓ Only accessible at B-factories (constraint using well-know initial kinematics)





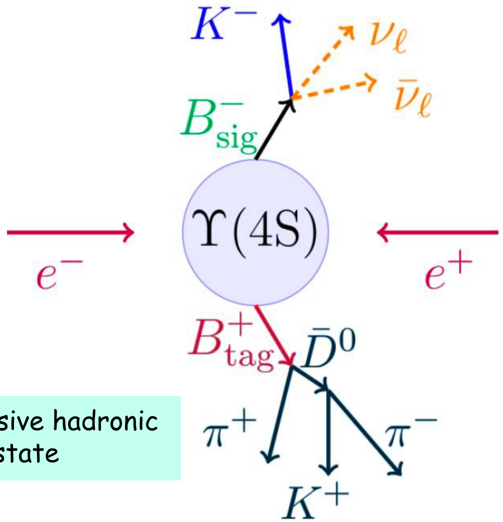




Search for $B^+ \to K^+\nu\bar{\nu}$

Belle II

Two parallel reconstructions



Exclusive hadronic final state

Hadronic Tag Analysis (HTA):

- Fully reconstruct "tag" B:
  - ✓ Better measurement of $B_{\rm sig}$ Kinematic variables
- Full-Event-Interpretation (FEI) at Belle II
  - ✓ Multivariate classification using BDT
  - ✓ 50% tag efficiency improvement vs Belle
- Small efficiency but significantly reduce bg
  - ✓ Signal eff = 0.4%, purity = 3.5%
- Extract signal via a BDT output

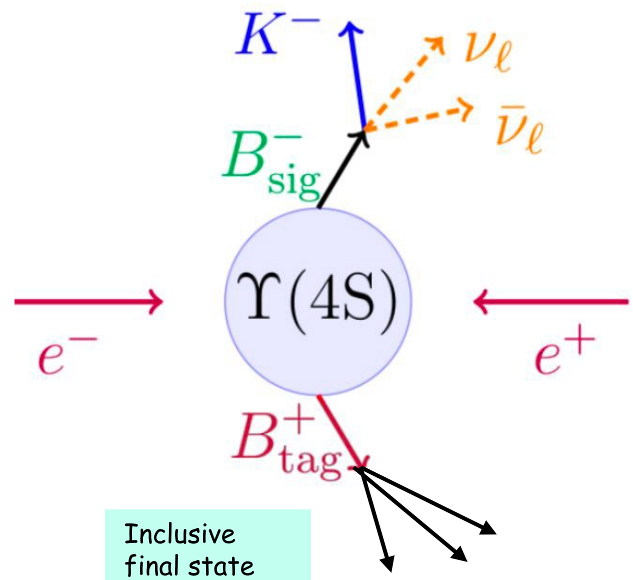
Comput. Softw. Big Sci. 3, 6 (2019)

Inclusive Tag Analysis (ITA):

- Non exclusive reconstruction of "tag" B:
- Select signal kaon that minimize

$$q^2_{\rm rec} = s/(4c^4) + m^2_K - \sqrt{s}E^*_K/c^4$$

- Larger efficiency but significantly more bg
  - ✓ Signal eff = 8%, purity = 0.9%
- Extract signal using BDT output and q^2_{rec}

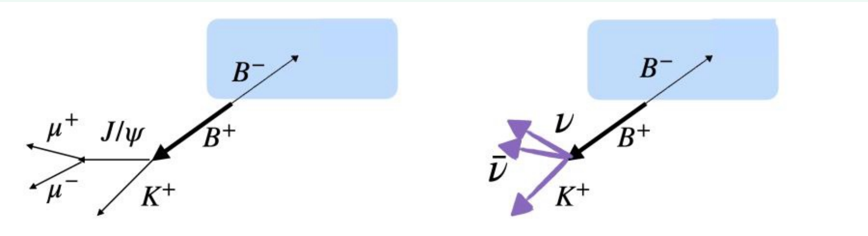


Inclusive final state

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

Data driven approach with many validations

- Signal efficiency check using $B \to J/\psi(\mu\mu)K$
  - ✓ Remove J/ψ and correct kaon kinematics to match signal distributions



- Continuum validation with off-resonance data
- $B \to X_c(\to K_L^0)$ validate from pion enriched sideband
- Signal like $B \to K^+ K_L^0 K_L^0$ check with $B \to K^+ K_S^0 K_S^0$
- Similar validation for $B \to K^+ K_S^0 K_L^0$ and $B \to K^+ nn$
- Validate method to measure $B \to K^0 \pi^+$
  - ✓ $\mathcal{B} = (2.5 \pm 0.5) \times 10^{-5}$
  - ✓ Consistent with PDG: $(2.38 \pm 0.08) \times 10^{-5}$

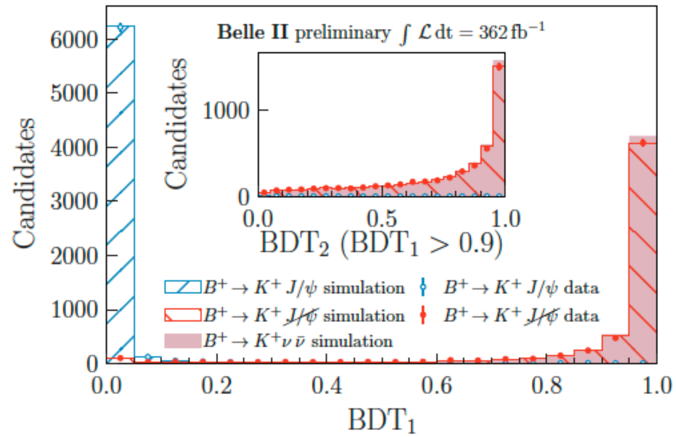


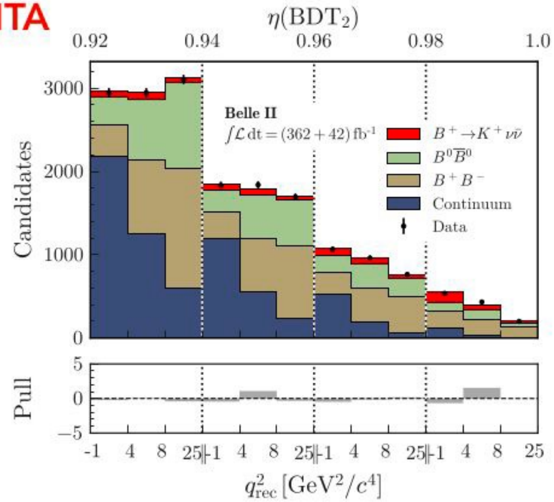
FIG. 7. Distribution of the classifier output BDT_1 (main figure) and BDT_2 for $\mathrm{BDT}_1 > 0.9$ (inset). The distributions are shown before ($B^+ \to K^+ J/\psi$) and after ($B^+ \to K^+ \cancel{J/\psi}$) the muon removal and replacement of the kaon momentum of selected $B^+ \to K^+ J/\psi$ events in simulation and data. As a reference, the classifier outputs directly obtained from simulated $B^+ \to K^+ \nu\bar{\nu}$ signal events are overlaid. The simulation histograms are scaled to the total number of $B^+ \to K^+ J/\psi$ events selected in the data.

arXiv:2311.14647, Accepted by PRD

Results of $B^+ \to K^+\nu\bar{\nu}$

Belle II

ITA



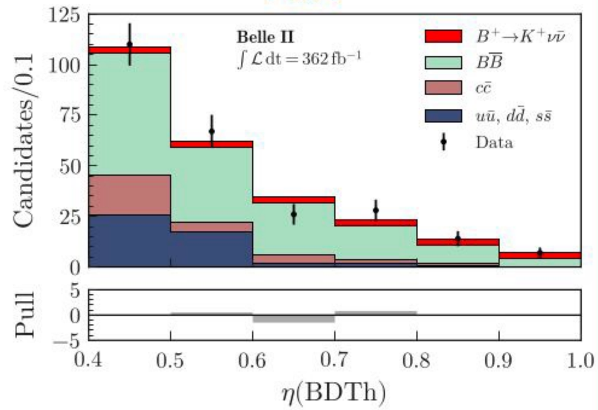
$\mu = 5.4 \pm 1.0(\mathrm{stat}) \pm 1.1(\mathrm{syst})$

corresponding to

$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = 2.7 \pm 0.5(\mathrm{stat}) \pm 0.5(\mathrm{syst}) \times 10^{-5}$

- $3.5\ \sigma$ compatibility wrt bkg only
- $2.9\ \sigma$ compatibility wrt to the SM

HTA



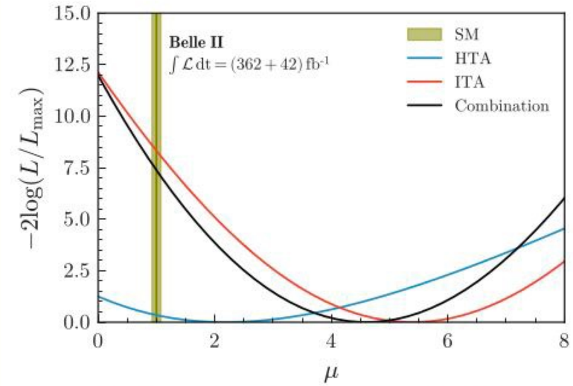
$\mu = 2.2^{+1.8}_{-1.7}(\mathrm{stat})^{+1.6}_{-1.1}(\mathrm{syst})$

corresponding to

$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = [1.1^{+0.9}_{-0.8}(\mathrm{stat})^{+0.8}_{-0.5}(\mathrm{syst})] \times 10^{-5}$

- $1.1\ \sigma$ compatibility wrt bkg only
- $0.6\ \sigma$ compatibility wrt to the SM

Combination



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

corresponding to

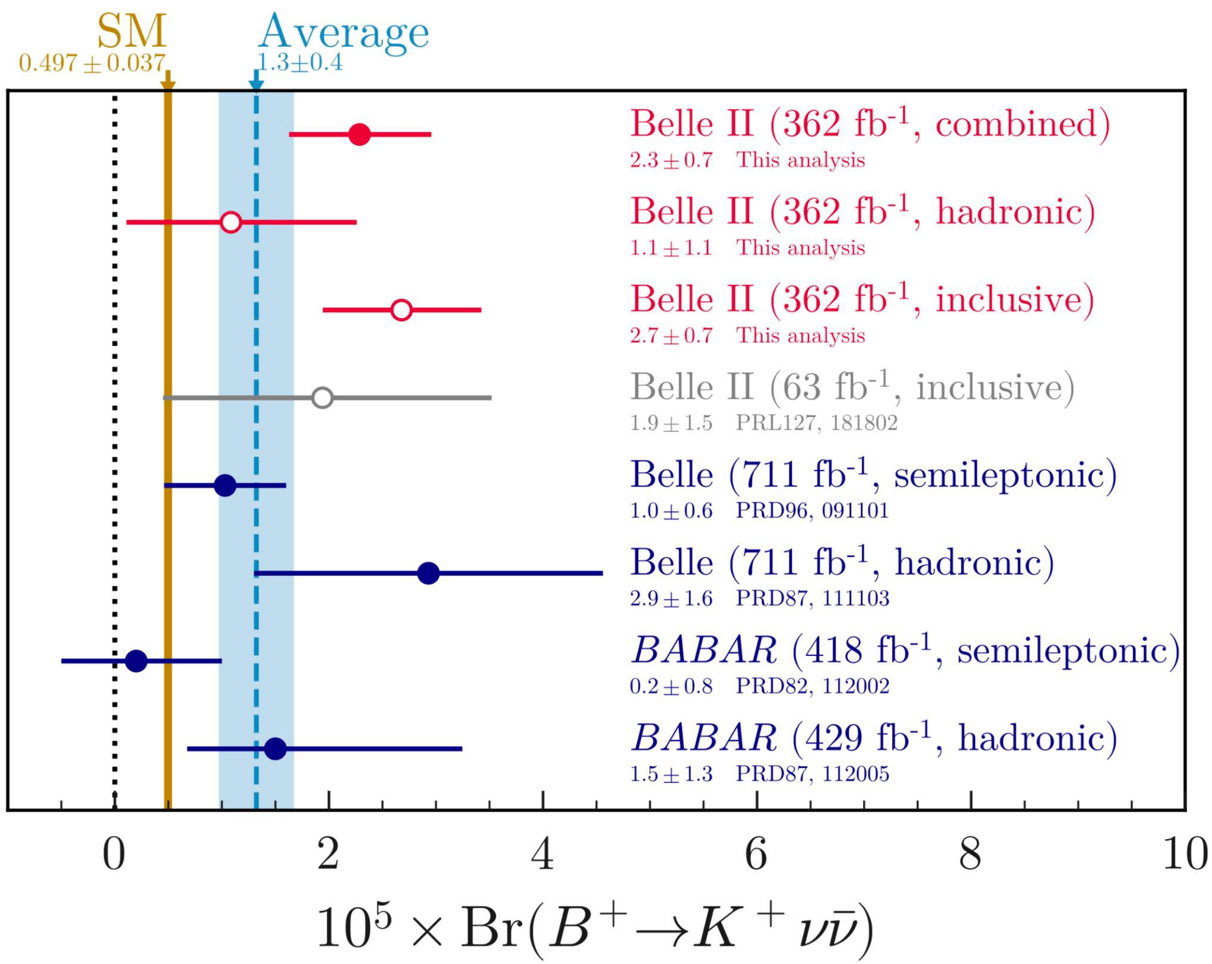
$\mathcal{B}(B^+ \to K^+\nu\bar{\nu}) = [2.3 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})] \times 10^{-5}$

- Combination improves the ITA-only precision by 10%
- $3.5\ \sigma$ significance wrt bkg
- $2.7\ \sigma$ significance wrt SM

arXiv:2311.14647, Accepted by PRD

- First evidence of $B^+ \to K^+\nu\bar{\nu}$ (3.5σ), branching fraction in excess of SM 2.7σ
- Measurement enabled by new inclusive techniques

Results of $B^+ \to K^+\nu\bar{\nu}$



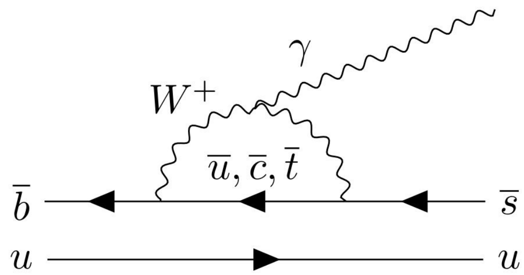
Other $B \to K\nu\bar{\nu}$ analysis ongoing at Belle II
Expect some results soon

Measurements of $B \to K^*(892)\gamma$

Large branching fraction and clean experimental signal

$$\mathcal{B} = \frac{N_{\overline{B}}/\epsilon_{\overline{B}} + N_B/\epsilon_B}{2 \times N_{B\overline{B}} \times f^{+-}(f^{00})}, \quad \Delta_{0+} = \frac{(\tau_+/\tau_0) \times \mathcal{B}(B^0 \to K^{*0}\gamma) - \mathcal{B}(B^+ \to K^{*+}\gamma)}{(\tau_+/\tau_0) \times \mathcal{B}(B^0 \to K^{*0}\gamma) + \mathcal{B}(B^+ \to K^{*+}\gamma)},$$

$$\mathcal{A}_{CP} = \frac{N_{\overline{B}}/\epsilon_{\overline{B}} - N_B/\epsilon_B}{N_{\overline{B}}/\epsilon_{\overline{B}} + N_B/\epsilon_B}, \quad \Delta\mathcal{A}_{CP} = \mathcal{A}_{CP}(B^+ \to K^{*+}\gamma) - \mathcal{A}_{CP}(B^0 \to K^{*0}\gamma),$$



Belle II Results: 362 fb^{-1}

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

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

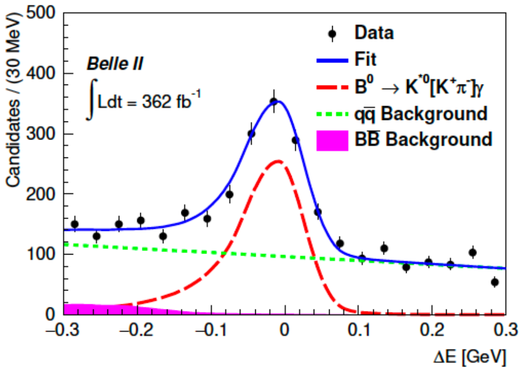
$$\mathcal{A}_{CP}[B^0 \to K^{*0}\gamma] = (-3.2 \pm 2.4 \pm 0.4)\%,$$

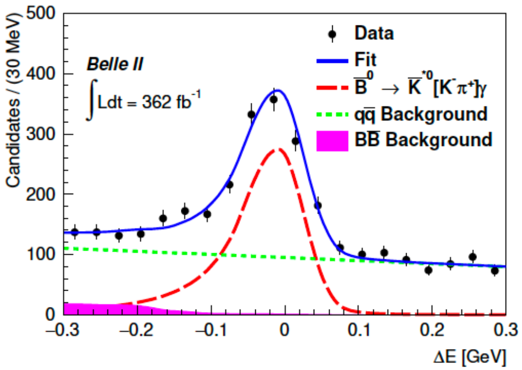
$$\mathcal{A}_{CP}[B^+ \to K^{*+}\gamma] = (-1.0 \pm 3.0 \pm 0.6)\%,$$

$$\Delta A_{\rm CP} = (2.2 \pm 3.8 \pm 0.7)\%$$

$$\Delta_{0+} = (5.1 \pm 2.0 \pm 1.0 \pm 1.1)\%$$

Stat Syst f^{+-}/f^{00}





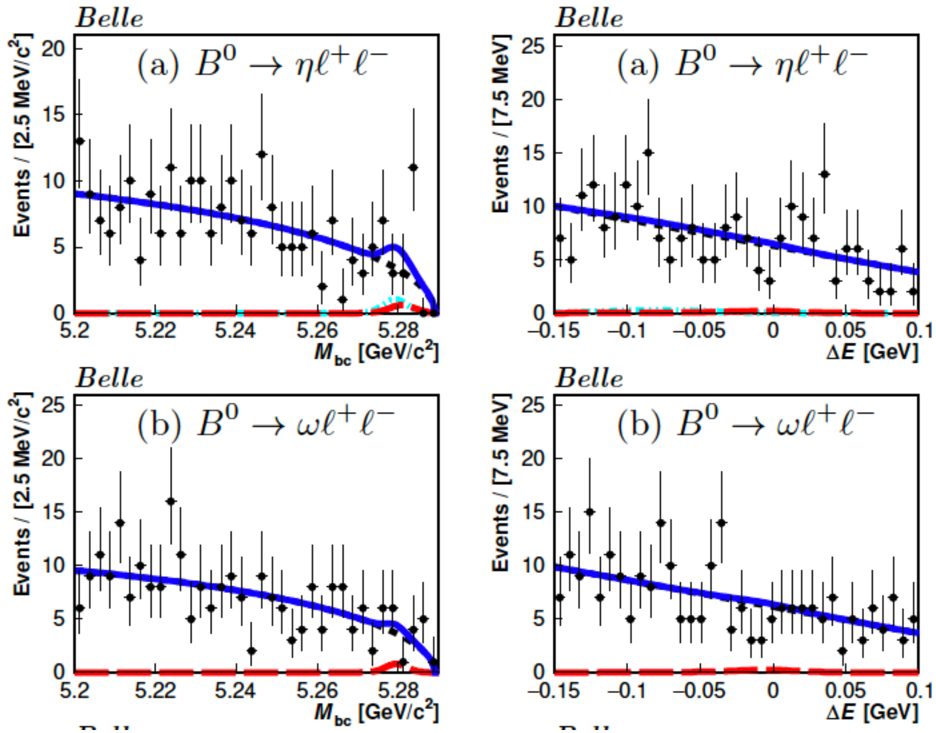
Consistent with the world average and the SM expectation
Systematic uncertainties can be reduced with more data

To be submitted to JHEP

Search for rare $b \to dl^+l^-$ transition

- $b \to dl^+l^-$ process via loops and highly suppressed, $\mathcal{B}_{SM} \sim O(10^{-8})$
  - ✓ LHCb ($3\ \text{fb}^{-1}$) observed final state with $\pi^\pm$ in dimuon mode
- Sensitive to NP contribution in the loop
  - ✓ Rate measurement, Lepton flavor universality

	$\mathcal{B}^{UL}(10^{-8})$	$\mathcal{B}(10^{-8})$
$B^0 \to \eta e^+e^-$	< 10.5	$0.0^{+4.9}_{-3.4} \pm 0.1$
$B^0 \to \eta\mu^+\mu^-$	< 9.4	$1.9^{+3.4}_{-2.5} \pm 0.2$
$B^0 \to \eta\ell^+\ell^-$	< 4.8	$1.3^{+2.8}_{-2.2} \pm 0.1$
$B^0 \to \omega e^+e^-$	< 30.7	$-2.1^{+26.5}_{-20.8} \pm 0.2$
$B^0 \to \omega\mu^+\mu^-$	< 24.9	$7.7^{+10.8}_{-7.5} \pm 0.6$
$B^0 \to \omega\ell^+\ell^-$	< 22.0	$6.4^{+10.7}_{-7.8} \pm 0.5$
$B^0 \to \pi^0 e^+e^-$	< 7.9	$-5.8^{+3.6}_{-2.8} \pm 0.5$
$B^0 \to \pi^0\mu^+\mu^-$	< 5.9	$-0.4^{+3.5}_{-2.6} \pm 0.1$
$B^0 \to \pi^0\ell^+\ell^-$	< 3.8	$-2.3^{+2.1}_{-1.5} \pm 0.2$
$B^+ \to \pi^+ e^+e^-$	< 5.4	$0.1^{+2.7}_{-1.8} \pm 0.1$
$B^0 \to \rho^0 e^+e^-$	< 45.5	$23.6^{+14.6}_{-11.2} \pm 1.1$
$B^+ \to \rho^+ e^+e^-$	< 46.7	$-38.2^{+24.5}_{-17.2} \pm 3.4$
$B^+ \to \rho^+\mu^+\mu^-$	< 38.1	$13.0^{+17.5}_{-13.3} \pm 1.1$
$B^+ \to \rho^+\ell^+\ell^-$	< 18.9	$2.5^{+14.6}_{-11.8} \pm 0.2$



Belle ($711\ \text{fb}^{-1}$)

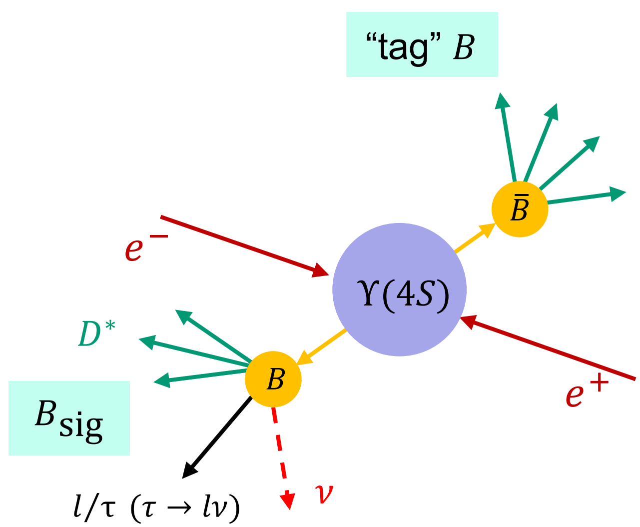
World best limits in all channels. First search for ωl^+l^-, $\rho^0 e^+e^-$, $\rho^\pm l^+l^-$ modes

arXiv:2404.08133, submitted to PRL

Measurements of R_{D^*} and R_D

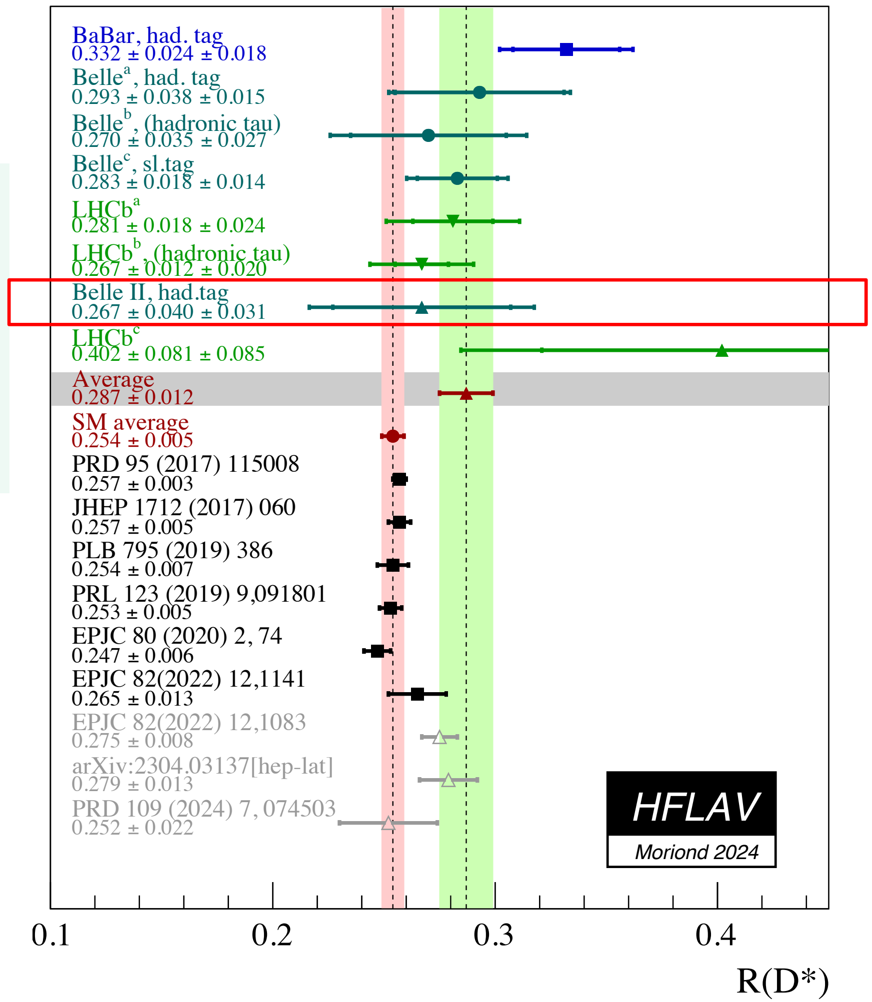
$$R_{D^*} = \frac{\mathcal{B}(B \to D^*\tau\nu)}{\mathcal{B}(B \to D^*l\nu)} \qquad R_D = \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to Dl\nu)}$$

- Uncertainty from form factor and V_{cb} drop out
  - ✓ Small uncertainty for the SM prediction
- Ratios test lepton universality
  - ✓ NP change rate, angular and q^2 distributions
- Measurements above the SM prediction



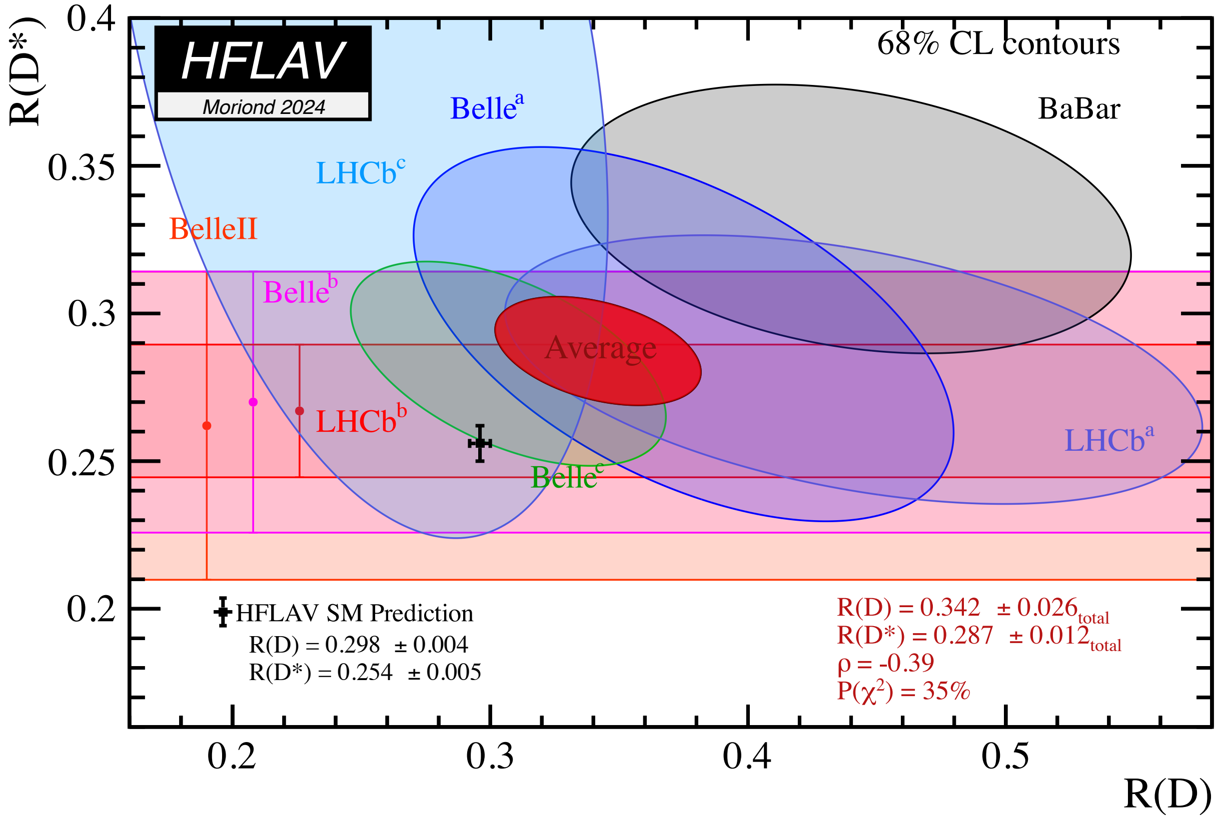
$$R_{D^*} = 0.267^{+0.041}_{-0.039}(\text{stat.})^{+0.028}_{-0.033}(\text{syst.})$$

arXiv:2401.02840, submitted to PRD



- Belle II: 189 fb^{-1} data
- Improved sensitivities from FEI
- Dominant systematic due to MC statistics and E_{ECL} can be reduced with more data

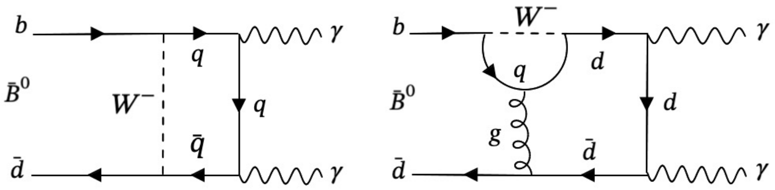
Measurements of R_{D^*} and R_D



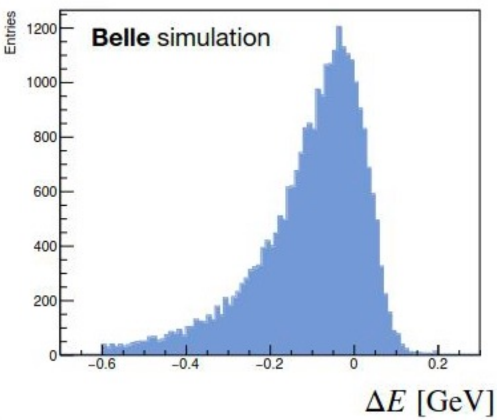
Measurement of R_D and R_{D^*} exceed the SM predictions by 1.6σ & 2.5σ, respectively, the combined deviation above the SM is 3.31σ

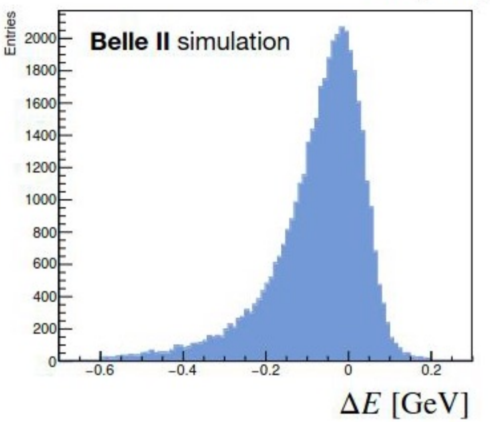
- ➢ Other ongoing Belle II measurements
  - ✓ Not systematic limited, reduce with more data
- ➢ Future measurement as a function of q^2 and angular distributions

Measurements of $B \to \gamma\gamma$



- Combined Belle ($694\ \mathrm{fb}^{-1}$) and Belle II ($362\ \mathrm{fb}^{-1}$) measurement
- Small branching fraction & high background
- Analysis strategy:
  - ✓ Dedicated BDT to suppress continuum, $\pi^0 \to \gamma\gamma$ and $\eta^0 \to \gamma\gamma$
  - ✓ Multivariable fit to: $\Delta E, M_{bc}$, and BDT output
  - ✓ Control sample: $B^0 \to K^*(892)[K^+\pi^-]\gamma$
- Significant improvement at Belle II vs Belle
  - ✓ Better signal efficiency
  - ✓ Improved ΔE resolution





	Belle	Belle II
Sig efficiency	23%	31%
Exp. bkg/fb^{-1}	~ 0.8	

Measurements of $B \to \gamma\gamma$

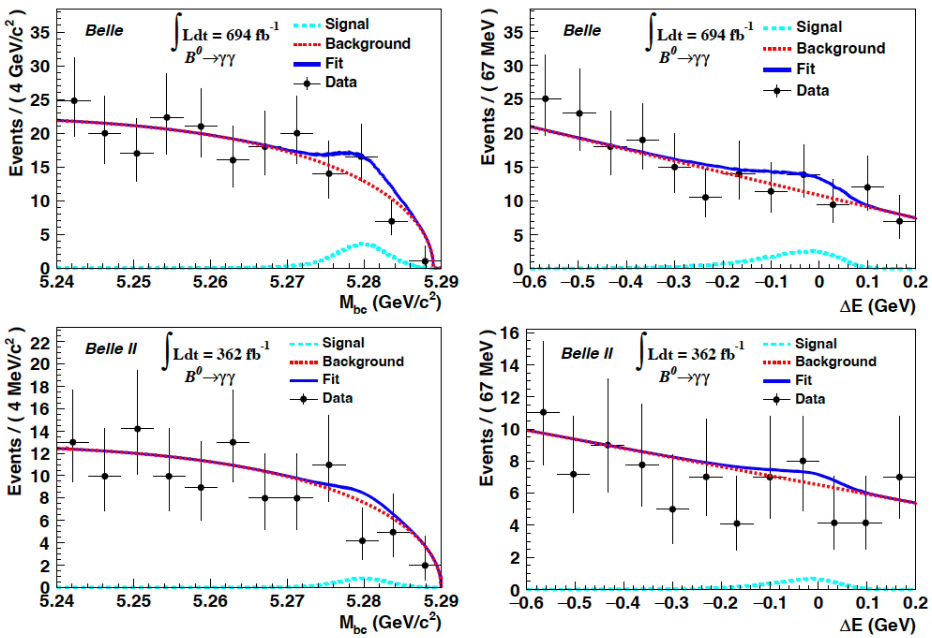


TABLE III. Summary of $\mathcal{B}(B^0 \to \gamma\gamma)$ measurements and UL's at 90% credibility level.

	$\mathcal{B}(B^0 \to \gamma\gamma)$	UL on $\mathcal{B}(B^0 \to \gamma\gamma)$
Belle	$(5.4^{+3.3}_{-2.6} \pm 0.5) \times 10^{-8}$	$< 9.9 \times 10^{-8}$
Belle II	$(1.7^{+3.7}_{-2.4} \pm 0.3) \times 10^{-8}$	$< 7.4 \times 10^{-8}$
Combined	$(3.7^{+2.2}_{-1.8} \pm 0.5) \times 10^{-8}$	$< 6.4 \times 10^{-8}$

Experiment	Integrated Luminosity ($\int \mathcal{L}\, dt$)	Limit @ 90 C.L.
L3	73 pb^{-1}	3.9 $\times 10^{-5}$
Belle	104 fb^{-1}	6.2 $\times 10^{-7}$
Babar	426 fb^{-1}	3.2 $\times 10^{-7}$

- Combined signal yield: $11.0^{+6.5}_{-5.5}$
  - ✓ 2.5σ significance
- Sensitivity approach SM prediction
  - ✓ SM: $\mathcal{B} = (1.4^{+1.4}_{-0.8})\times 10^{-8}$

    JHEP 12, 169 (2020)
  - ✓ Expected UL: $\mathcal{B} < 4.4\times 10^{-8}$
- UL has 5x improvement over previous best UL by Babar
- Significant better sensitivity improvement at Belle II

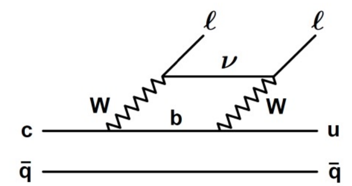
arXiv:2405.19734, submitted to PRD

L3: PLB 363 (1995) 137-144
Belle: PRD 73, 051107 (2006)
BaBar: PRD 83, 032006 (2011)

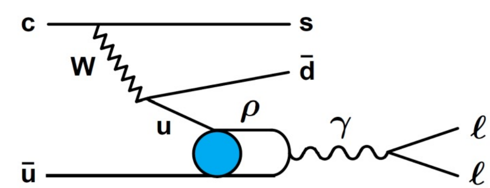
Search for Rare Charm decays: $D^0 \to h^+h^-e^+e^-$

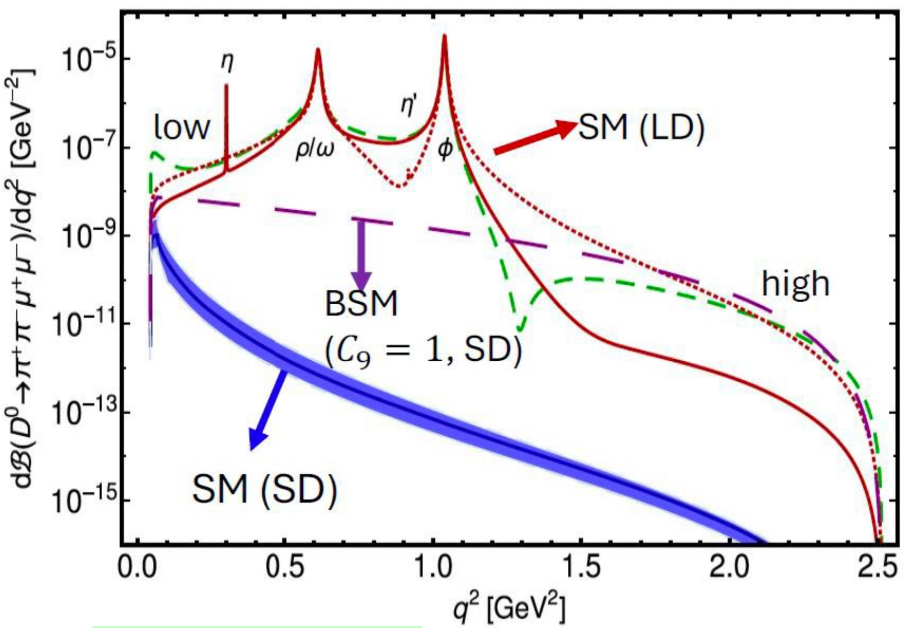
- Flavor changing neutral current (FCNC) $c \to ull$ process is supppressed in the SM
- LD mainly from vector meson dominated mode
- Search for NP and Lepton Flavor Universality (LFU) test

Short distance (SD)



Long distance (LD)





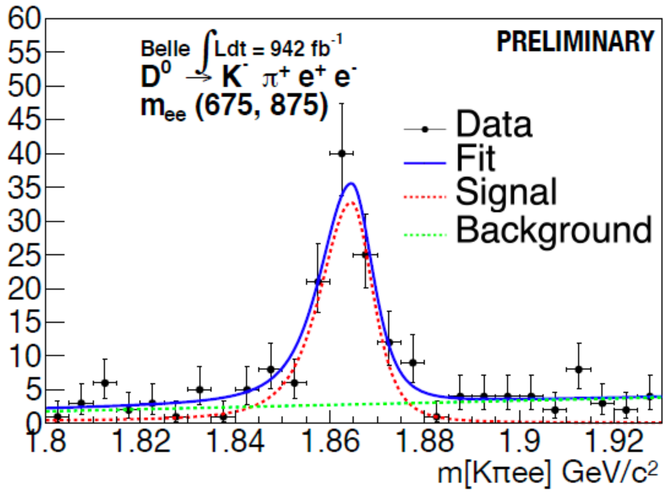
PRD 98, 035041 (2018)

Some previous measurements of Br and UL @90%

Experiment	$K^-K^+e^+e^-$	$\pi^-\pi^+e^+e^-$	$K^-\pi^+e^+e^-$
Babar (2019)			$40.0 \pm 5.0 \pm 2.3$ (ρ^0/ω) stat syst
BESIII (2019)	< 110	< 70	< 410
	$K^-K^+\mu^+\mu^-$	$\pi^-\pi^+\mu^+\mu^-$	$K^-\pi^+\mu^+\mu^-$
LHCb (2016-2017)	$1.54 \pm 0.27 \pm 0.19$	$9.64 \pm 0.48 \pm 1.10$	$4.17 \pm 0.12 \pm 0.40$ (ρ^0/ω)

BaBar: PRL 122, 081802 (2019)
BESIII: PRD 97, 072015 (2019)
LHCb: PLB 517, 558 (2016); PRL 119, 181805 (2017)

Search for rare charm decays: $D^0 \to h^+h^-e^+e^-$



To be submitted to PRL

- Belle measurement with 942 fb^{-1} data
- Observe $D^0 \to K^-\pi^+e^+e^-$ in ρ/ω region (11.8σ)
  - ✓ Compatible with Babar and SM expectation

$$\mathcal{B} = (39.06 \pm 4.5(\text{stat}) \pm 2.9(\text{syst})) \times 10^{-7}$$

- No significant signal on other final states
  - ✓ UL at 90% around $(2.3 - 7.7)\times 10^{-7}$
  - ✓ World's best limits to date

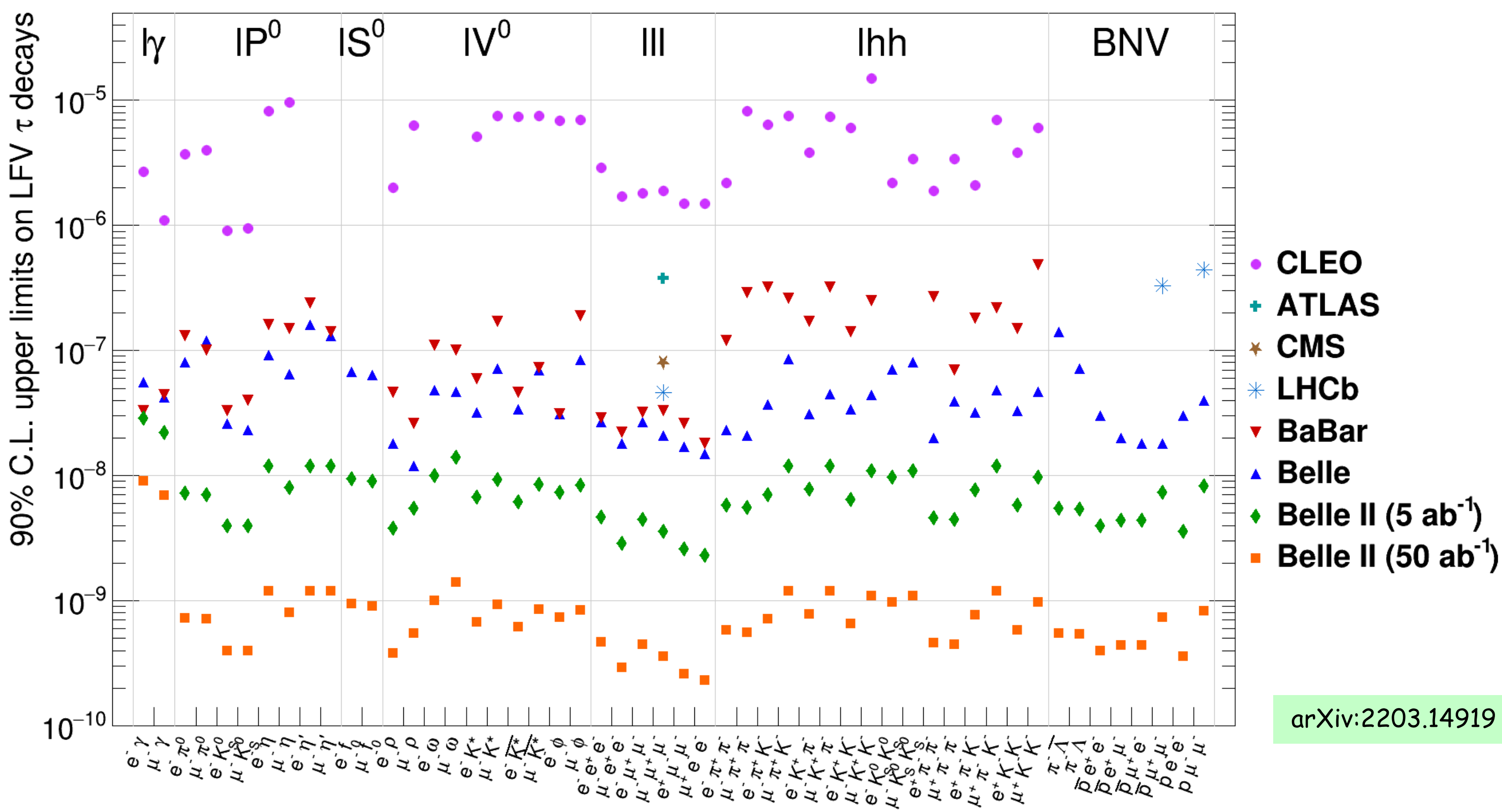
TABLE I. $D^0 \to h^-h^{(\prime)+}e^+e^-$ modes yields, significance, branching fractions, branching fraction upper limits, and the efficiencies of each m_{ee} region [$\times 10^{-7}$]. A fitted yield and a branching fraction are not reported for $K^-K^+e^+e^-$ mode with m_{ee} in the m_η region since only one event is observed, and the significance is determined from the CL$_s$ distribution.

m_{ee} region	[MeV/c^2]	Yield	Significance	$\mathcal{B}$	UL @ 90% CL	Efficiency
$K^-K^+e^+e^-$						
η	520-560	-	$< 0.1\sigma$	-	< 2.3	3.53 ± 0.04
ρ^0/ω	> 675	2.6 ± 1.8	2.0σ	$1.2 \pm 0.9 \pm 0.1$	< 3.0	6.00 ± 0.06
non-resonant	> 200 [a]	3.5 ± 3.3	1.5σ	$3.1 \pm 3.0 \pm 0.4$	< 7.7	3.19 ± 0.04
$\pi^-\pi^+e^+e^-$						
η	520-560	0.6 ± 2.3	0.3σ	$0.4 \pm 1.4 \pm 0.2$	< 3.2	5.31 ± 0.05
ρ^0/ω	675-875	3.7 ± 4.1	0.9σ	$2.0 \pm 2.2 \pm 0.8$	< 6.1	5.69 ± 0.05
ϕ	995-1035	3.6 ± 3.2	1.1σ	$1.1 \pm 1.1 \pm 0.2$	< 3.1	9.41 ± 0.06
non-resonant	> 200	-0.2 ± 4.1	$< 0.1\sigma$	$-0.2 \pm 3.4 \pm 0.9$	< 7.2	3.69 ± 0.04
$K^-\pi^+e^+e^-$						
η	520-560	4.0 ± 2.7	1.6σ	$2.2 \pm 1.5 \pm 0.5$	< 5.6	5.09 ± 0.04
ρ^0/ω	675-875	110 ± 13	11.8σ	$39.6 \pm 4.5 \pm 2.9$	-	8.01 ± 0.06
ϕ	990-1034	4.6 ± 2.4	2.5σ	$1.4 \pm 0.8 \pm 0.3$	< 2.9	9.19 ± 0.06
non-resonant	> 560	2.2 ± 4.2	0.4σ	$1.3 \pm 2.4 \pm 0.6$	< 6.5	4.89 ± 0.09

[a] Excluding resonance regions, which is same for all three modes.

Search for Rare τ lepton decays

- Many rare or forbidden τ decays are excellent probes to NP beyond the SM
- B-factories generated large τ decay data samples
  - ✓ Searches in many different final states with high precisions
  - ✓ Not limited by systematics, sensitivities increases with higher luminosity
  - ✓ Better sensitives than other experiments in many final states

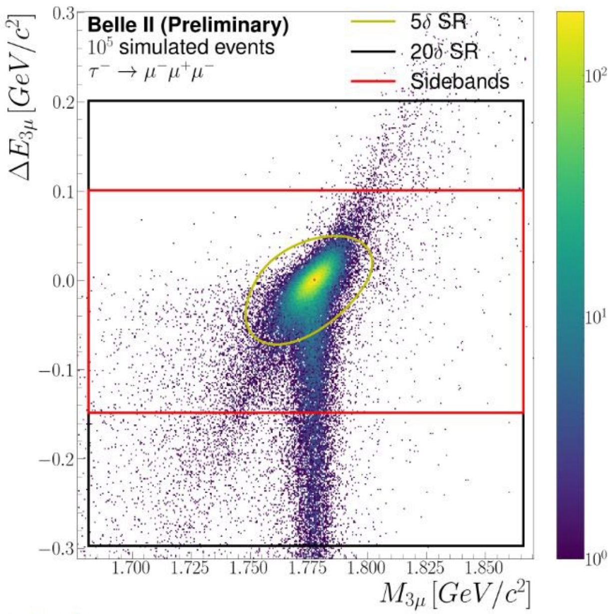


arXiv:2203.14919

Search for LFV $\tau \to \mu\mu\mu$ decay

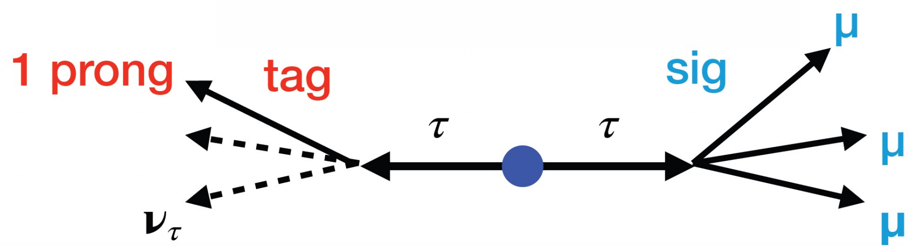
- Belle II measurements: $424\ \text{fb}^{-1}$ data
- Fully reconstructed final state
- Two independent variables:

$$
\begin{aligned}
M_{3\mu} &= \sqrt{E_{3\mu}^2 - |\vec{p}_{3\mu}|^2} \\
\Delta E &= E_{3\mu}^{\text{CM}} - E_{\text{beam}}^{\text{CM}}
\end{aligned}
$$



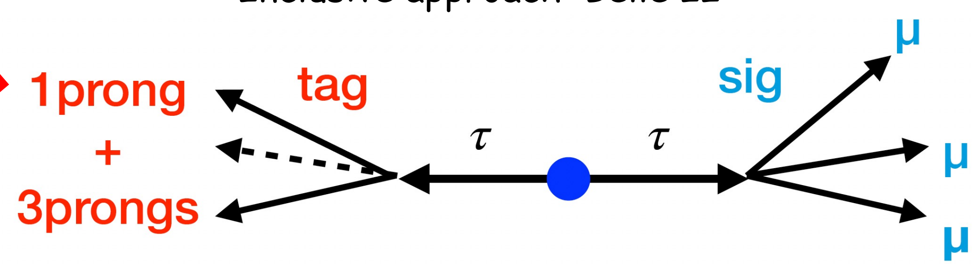
$M_{3\mu}$ close to τ mass, ΔE close to zero
Tail due to initial and final radiations

1-prong: Belle & BaBar method



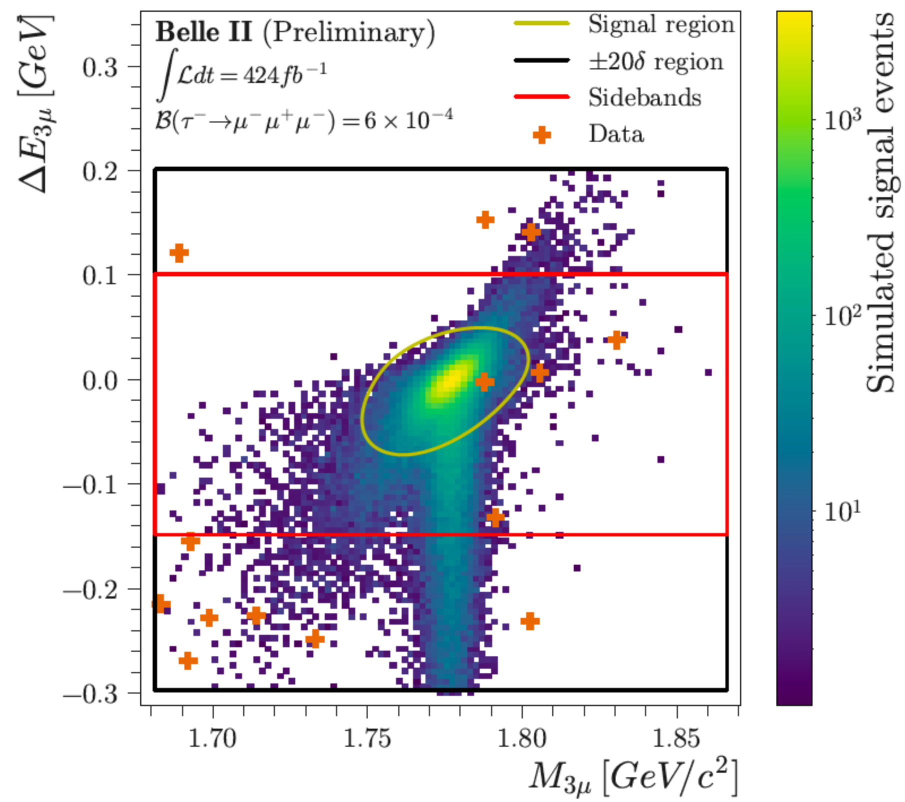
- Cut-based selection
- Signal efficiency: 14.9% (2 × Belle efficiency)
- Expected background: 0.43 (simulation)

Inclusive approach: Belle II



- Boost Decision Tree based selection
- Signal efficiency: 20.4% (2.7 × Belle efficiency)
- Expected background: 0.5 (simulation)

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



Experiment	Upper Limit at 90% C.L.
ATLAS	3.8×10^{-7} ($\mathscr{L} = 20.3$ fb^{-1})
LHCb	4.6×10^{-8} ($\mathscr{L} = 3.0$ fb^{-1})
CMS	2.9×10^{-8} ($\mathscr{L} = 131$ fb^{-1})

CMS - PLB 853 (2024) 138633

Experiment	Upper Limit at 90% C.L.
Belle	2.1×10^{-8} ($\mathscr{L} = 782$ fb^{-1})
BaBar	3.3×10^{-8} ($\mathscr{L} = 486$ fb^{-1})
Belle II	1.9×10^{-8} ($\mathscr{L} = 424$ fb^{-1})

Belle II - arXiv:2405.07386

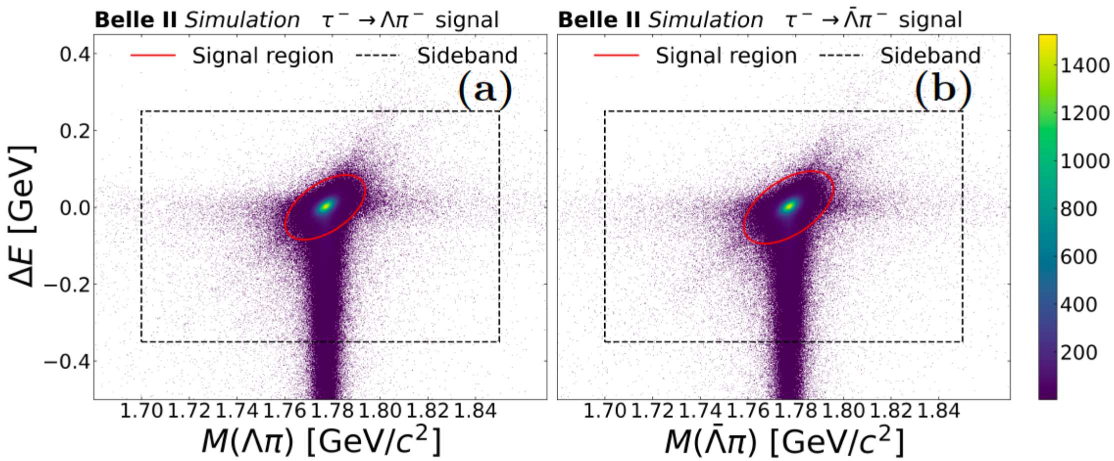
Most stringent limit to date

Lepton & baryon number violating τ decay

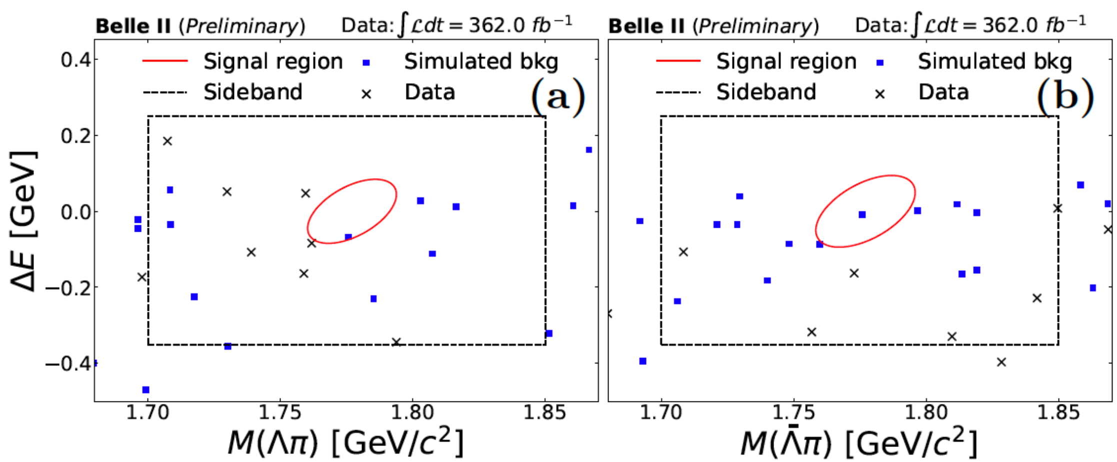
- Search for Lepton number & baryon number violating τ decays

$$\tau^- \to \Lambda\pi^- \quad \text{and} \quad \tau^- \to \bar{\Lambda}\pi^-$$

- Belle II measurements: 362 fb^{-1} data, Similar to $\tau \to \mu\mu\mu$ analysis



$$\mathcal{B}(\tau^- \to \Lambda\pi^-) < 4.7 \times 10^{-8} \quad @90\,\%\text{CL}$$
$$\mathcal{B}(\tau^- \to \bar{\Lambda}\pi^-) < 4.3 \times 10^{-8} \quad @90\,\%\text{CL}$$

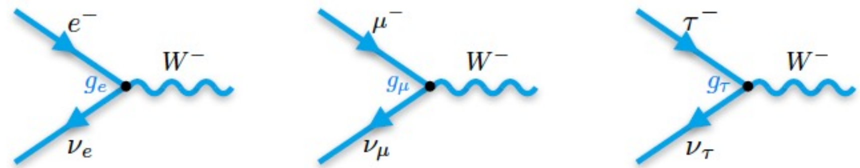


To be submitted to PRD

Test of Lepton flavour universality in τ decay

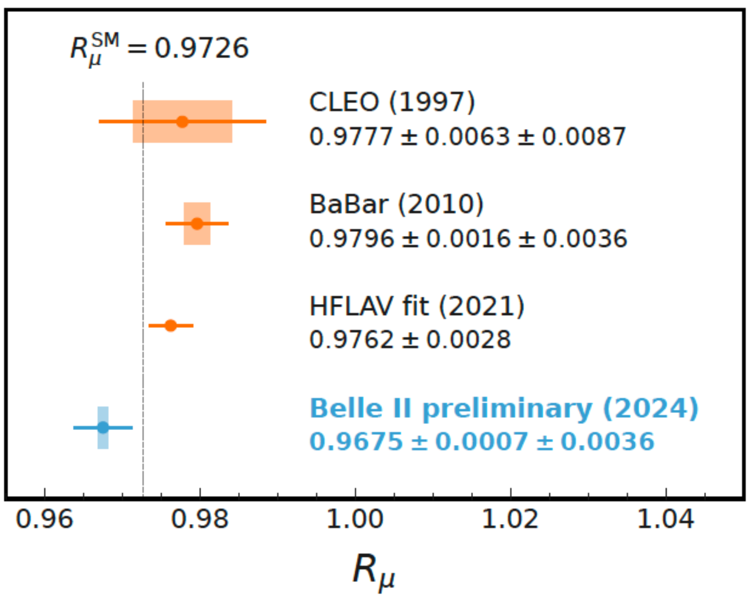
- Coupling between lepton and W is flavour-independent in the SM
- Test $\mu - e$ universality in τ decays by measuring decay rates ($362\ \mathrm{fb}^{-1}$)

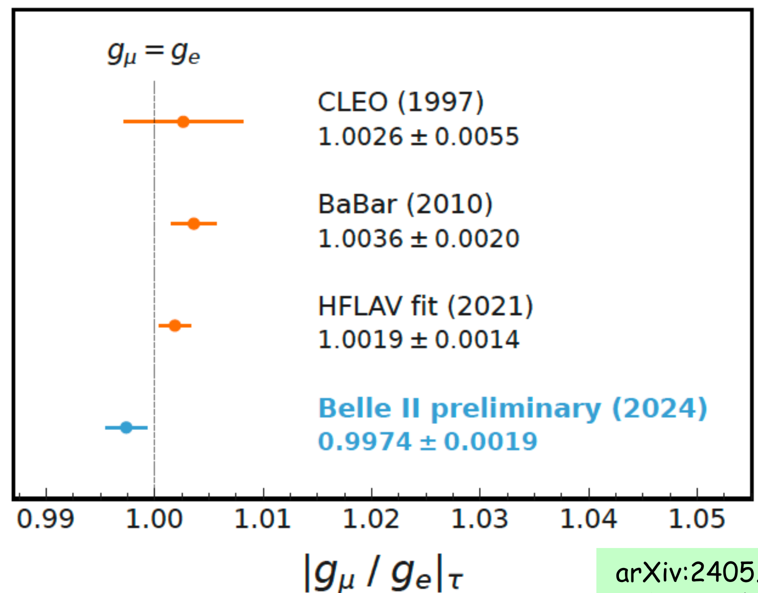
$$g_e = g_\mu = g_\tau$$



$$R_\mu = \frac{B(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau)}{B(\tau^- \to e^- \bar{\nu}_e \nu_\tau)} \overset{\mathrm{SM}}{=} 0.9726$$

$$\left(\frac{g_\mu}{g_e}\right)_\tau^2 \propto R_\mu \times \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)} \overset{\mathrm{SM}}{=} 1$$





arXiv:2405.14625
Submitted to PRD

- Most precise test of $\mu - e$ universality in τ decays by a single measurement
- Consistent with the SM expectation at 1.4σ level
- Dominated by the systematic uncertainty: can be reduced with more data

Summary and Prospect

- A few selected recent highlights from Belle(II)
- Improved sensitivities at Belle II (better detector and analysis)
- **More exciting results will eventually come with more data (soon)**

Roadmap of possible new evidences and observations

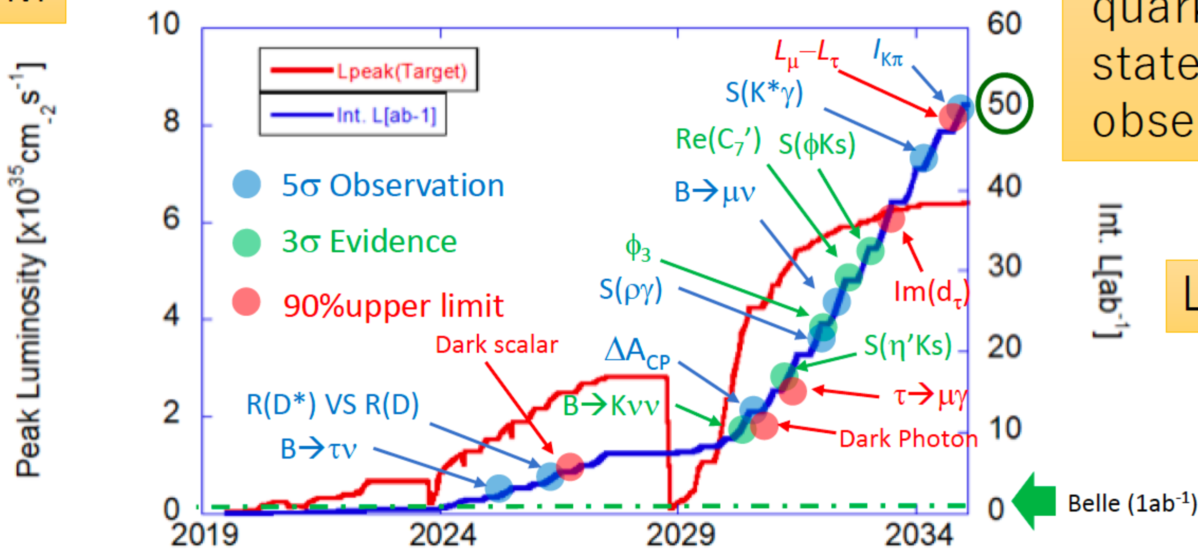
Rare decay BSM

Dark Sector

Connection to Lattice

Anomalies

Additional CP violation in Quark Sector



Many interesting quark composite states will be also observed.

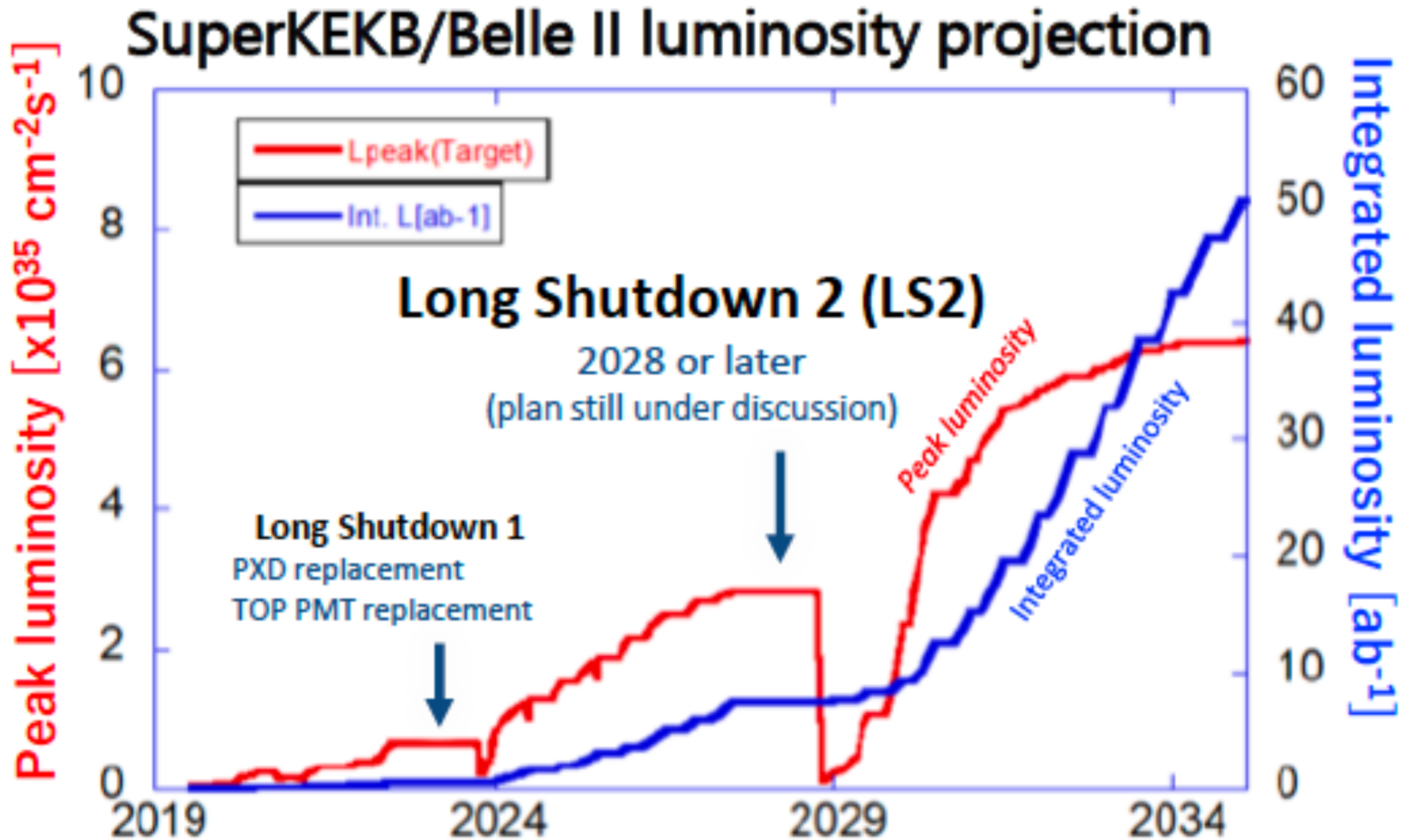
LFV

Model Independent?

Both Particle Phys.+
Nuclear Phys.
can enjoy.

Insight through Accelerators. KEK

Backup



SuperKEKB/Belle II luminosity projection
Peak luminosity [x10^35 cm^-2s^-1]
Integrated luminosity [ab^-1]
Lpeak(Target)
Int. L[ab-1]
Long Shutdown 2 (LS2)
2028 or later
(plan still under discussion)
Long Shutdown 1
PXD replacement
TOP PMT replacement
Peak luminosity
Integrated luminosity
10
8
6
4
2
0
60
50
40
30
20
10
0
2019
2024
2029
2034