Recent leptonic/rare decays results at Belle and Belle II

WG2 + WG3

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on behalf of Belle II collaboration

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CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
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Belle II

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Aix*Marseille université
Socialement engagée

Outline

Paving the way towards LFU tests:

- Path to $R_K(*)$ in B decays
- τ mass measurement in tau decays

Searches for rare/forbidden decays:

- $B^+ \rightarrow \mu^+\nu$
- $B^0 \rightarrow K^{*0}\tau\tau$
- $B_s \rightarrow \pi^0\pi^0$
- LFV τ decays

Measurement of radiative decay:

- Inclusive $B \rightarrow X_s\gamma$

See also previous talks:

LFV B decays : Gagan Mohanty (WG2)
LFU tests in $b \rightarrow cl\nu$: Robert Kowalewski (WG3)
$B \rightarrow K\nu\nu$: Slavomira Stefkova (WG2)
$B \rightarrow \rho\gamma$: Rahul Tiwar (WG3)

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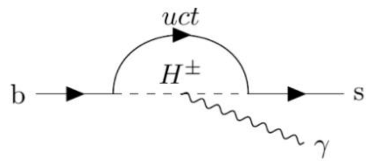
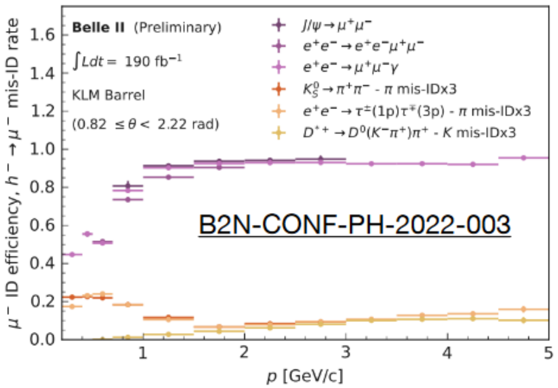
New physics contributions could be enhanced with respect to suppressed SM ones



Measure fundamental SM parameters
Understand QCD dynamic

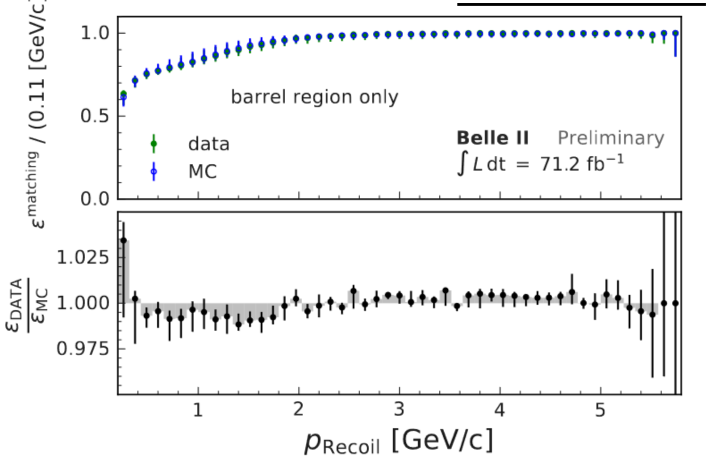
Advantages of Belle (II) for rare decays

- Excellent muon and electron ID efficiency



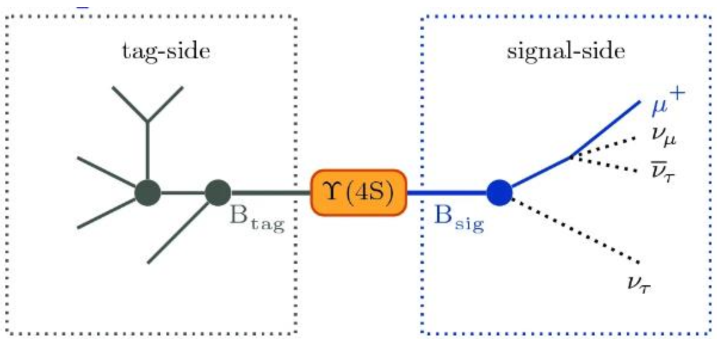
- High photon detection efficiency

B2N-2021-008



- Good hermiticity: useful for modes with missing energy

- Various levels of B-tagging



purity

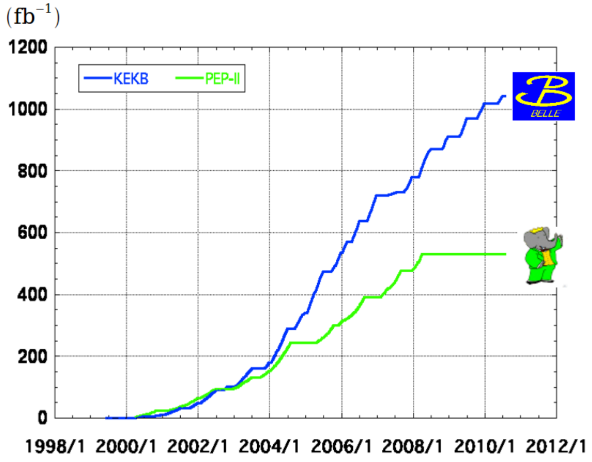
Hadronic tagging
Full knowledge of B_{tag} kinematic

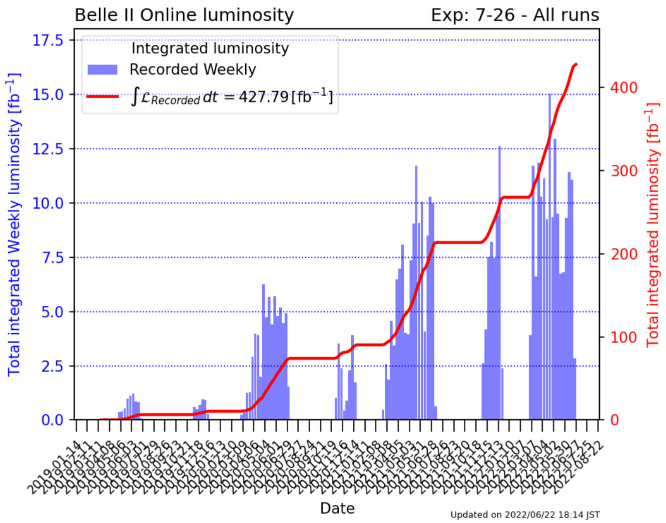
Semileptonic tagging
Partial knowledge of B_{tag} kinematic

Inclusive tagging
Indirect knowledge of B_{tag} kinematic
See e.g. PRL. 127, 181802

efficiency

Data sets





Data available for physics analysis (fb^{-1}) :

	Υ(4S)	Υ(5S)	Off-resonance*	others	Total
Belle	711	121	89	67	980
Belle II	362		42	20	424

*off resonance data are taken 60MeV below Υ(4S)

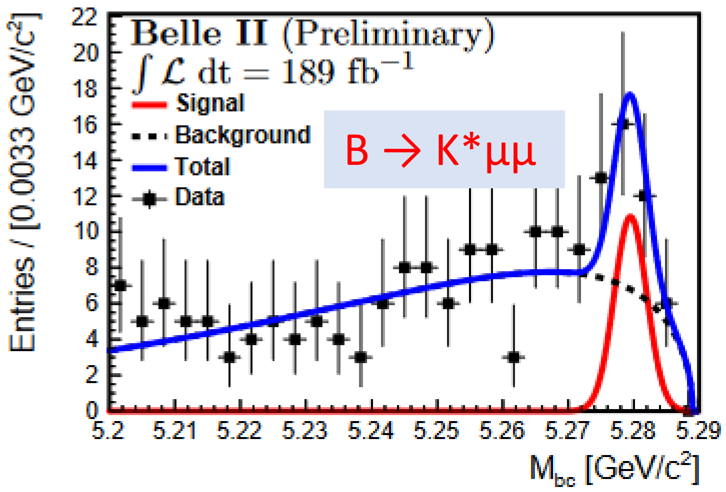
Unless stated, results presented here are based on full statistics

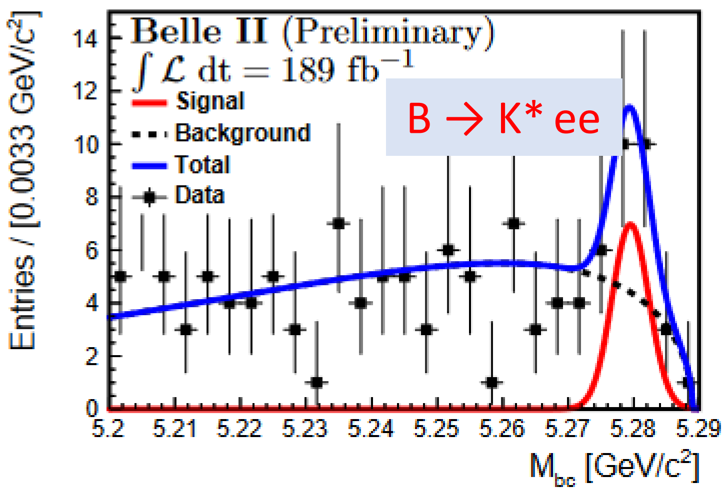
Towards $R_{K(*)}$: BR(B → K*ll)

arXiv:2206.05946

- First step : observation of B → K*ll decays at Belle II
- Combine B^+ and B^0 channels, using K*→K+π-, Ks π+, K+π0
- Signal yields obtained from 2D maximum likelihood fit of M_{bc} and ΔE $M_{\rm bc} = \sqrt{E_{\rm beam}^{*2} - p_B^{*2}}$ $\Delta E = E_B^* - E_{\rm beam}^*$.
- Similar performances for electrons and muons in terms of efficiency and background
- Exclude charmonium resonances and M(e+e-)<0.14GeV
- Using 189fb^{-1}, observe 22±6 B → K*μμ, 18±6 B → K*ee and 38±9 B → K*ll, giving :

$$\mathcal{B}(B \to K^*\mu^+\mu^-) = (1.19 \pm 0.31^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*\ell^+\ell^-) = (1.25 \pm 0.30^{+0.08}_{-0.07}) \times 10^{-6}.$$

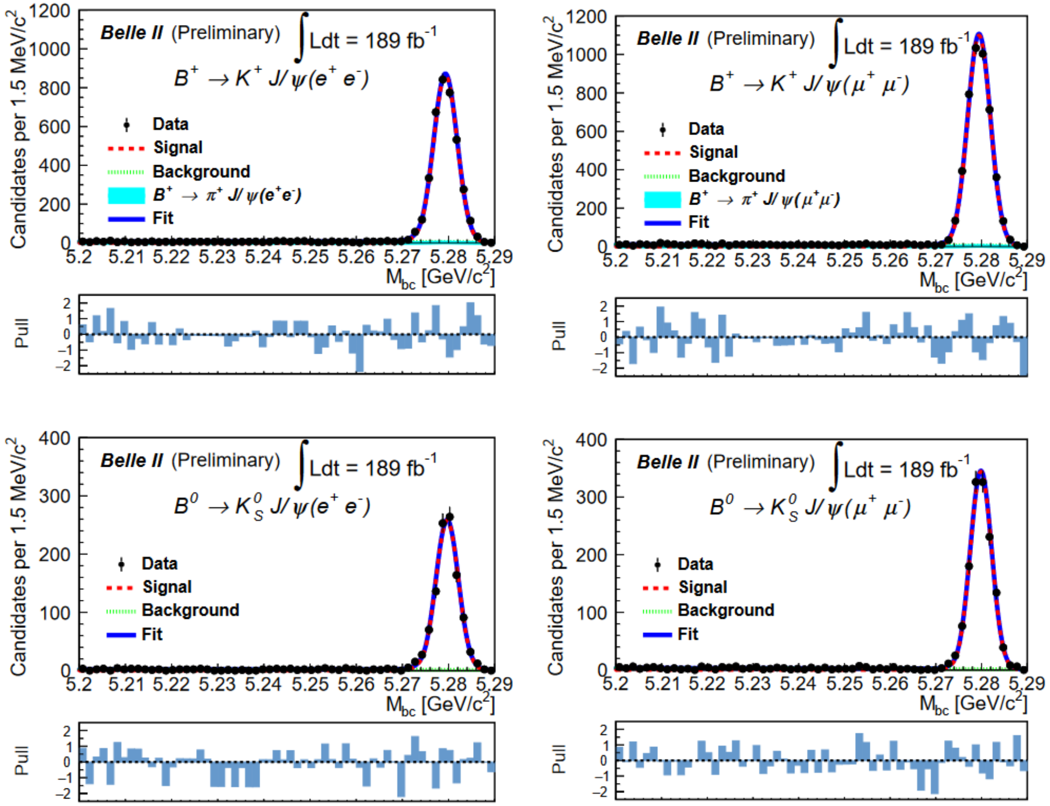




Towards $R_{K(*)}$: $R_K(J/\psi)$

arXiv:2207.11275

- Measurement validation using $B \to J/\psi K$ decays
- Use both B^+ and B^0 channels, also measure isospin asymmetries



$$R_K(J/\psi) = \frac{\mathcal{B}(B \to J/\psi(\mu^+\mu^-)K)}{\mathcal{B}(B \to J/\psi(e^+e^-)K)}$$

Observable	Measured value
$A_I\,(J/\psi(ee)K)$	$-0.022 \pm 0.016 \pm 0.030$
$A_I\,(J/\psi(\mu\mu)K)$	$-0.006 \pm 0.015 \pm 0.030$
$R_{K^+}\,(J/\psi)$	$1.009 \pm 0.022 \pm 0.008$
$R_{K^0_S}\,(J/\psi)$	$1.042 \pm 0.042 \pm 0.008$

Low systematic uncertainties thanks to very good control of lepton ID

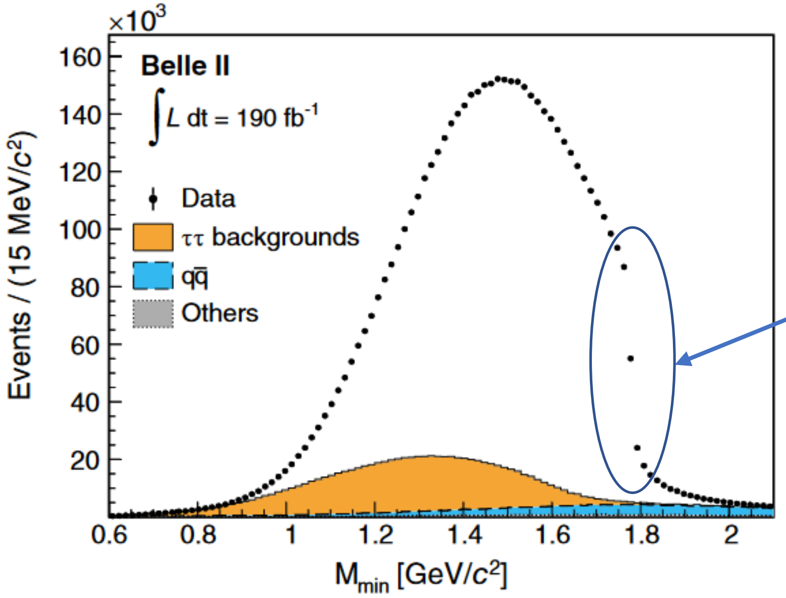
τ mass measurement

- m_τ is one of the fundamental parameter of the SM
- Crucial for SM predictions of BR and LFU tests
- Use kinematic of τ→ 3πν decays to measure the pseudomass $M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - p_{3\pi}^*)} \le m_\tau.$

$$\left(\frac{g_\mu}{g_e}\right)_\tau = \sqrt{R_\mu \frac{f(m_e^2/m_\tau^2)}{f(m_\mu^2/m_\tau^2)}}, \quad R_\mu = \frac{\mathcal{B}[\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau]}{\mathcal{B}[\tau^- \to e^- \bar{\nu}_e \nu_\tau]}$$

$$f(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$$

- m_τ is extracted from an empirical fit to M_{min}



Sharp edge corresponding to m_τ value, smeared by momentum resolution and ISR/FSR

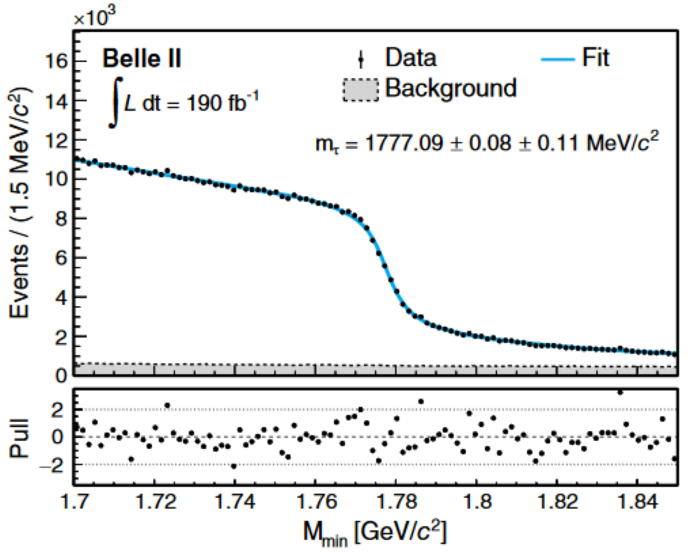
Control of beam energy and momentum are crucial (limiting systematics of previous B factory measurements)

τ mass measurement

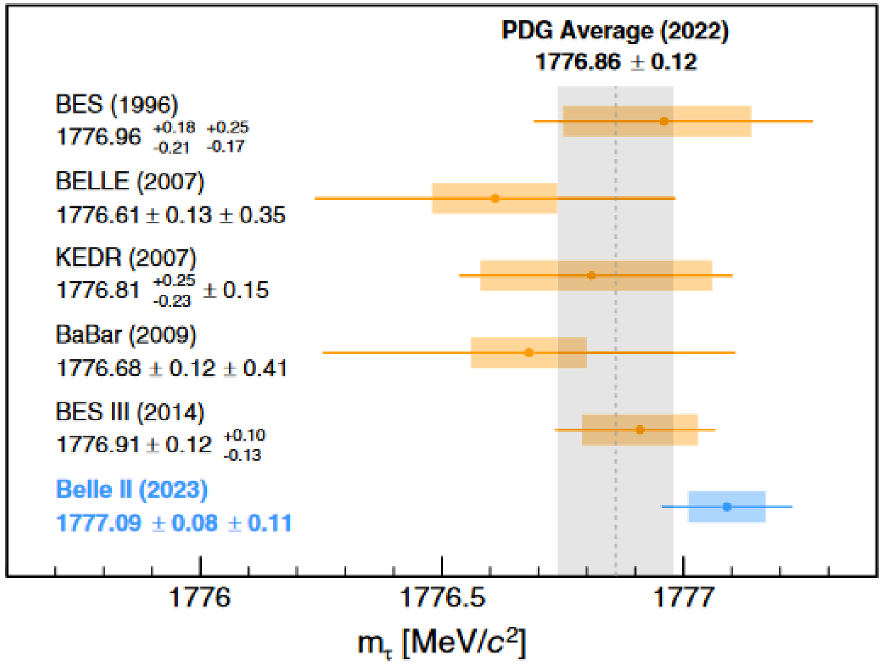
Phys. Rev. D 108, 032006

- Beam energy controlled using fully reconstructed B decays
- Momentum scale factor obtained measuring mass from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ decays
- Unbinned maximum likelihood fit to M_{min} ➡ m_τ = 1777.09 ± 0.08 ± 0.11 MeV

$$F(M_{\min}) = 1 - P_3 \cdot \arctan\left(\frac{M_{\min} - P_1}{P_2}\right) + P_4(M_{\min} - P_1) + P_5(M_{\min} - P_1)^2$$



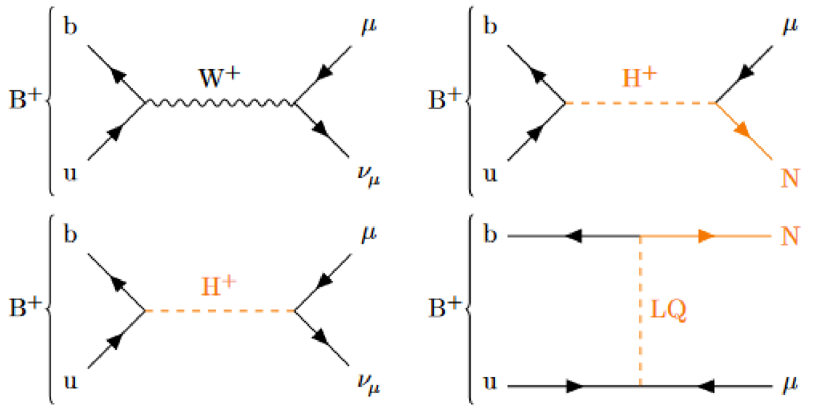
World's most precise measurement!

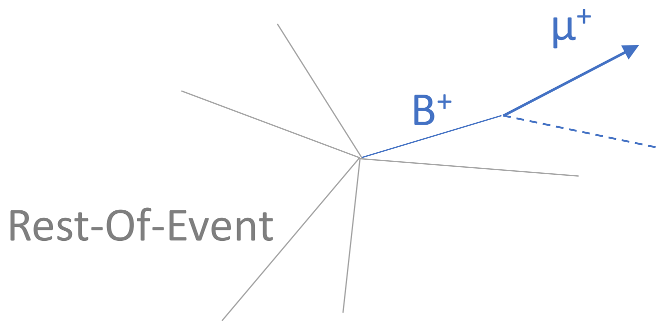


Search for $B^+ \to \mu^+ \nu$ with inclusive tagging

- CKM and helicity suppressed decay, expected BR in the range 3.8-4.3 x 10^{-7}, depending on V_{ub} value
- Sensitive to NP contribution such as charged Higgs or leptoquark, or sterile neutrinos
- Analysis strategy based on the monochromaticity of muon in the B rest frame
- Only the muon is explicitly reconstructed, remaining tracks and clusters form the ROE → boost in B^+ rest frame

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



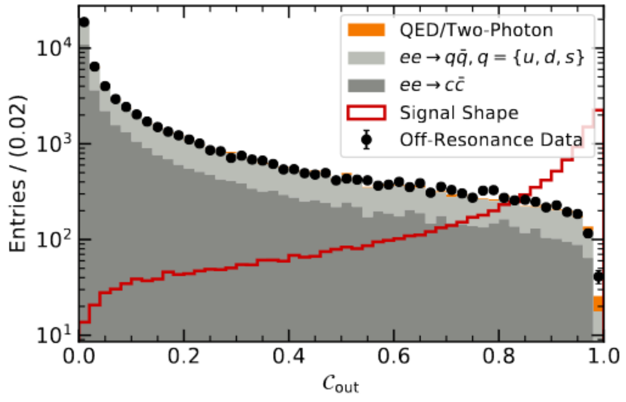


Search for $B^+ \rightarrow \mu^+\nu$ with inclusive tagging

- Resolution is improved with a calibration factor derived from simulation, accounting for particles that escape detection
- Main backgrounds are continuum and semileptonic $b \rightarrow u\mu\nu$ decays, mitigated using a BDT (C_{out}) and the muon direction in the B rest frame
- Events separated into 4 categories

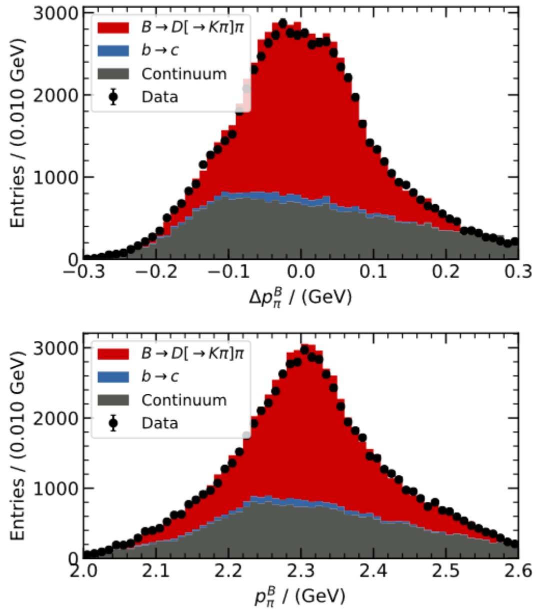
Category	C_{out}	$\cos\Theta_{B\mu}$	Signal Efficiency
I	[0.98,1.00)	[-0.13,1.00)	6.5 %
II	[0.98,1.00)	[-1.00,-0.13)	5.9 %
III	[0.93,0.98)	[0.04,1.00)	7.1 %
IV	[0.93,0.98)	[-1.00,0.04)	8.3 %

Signal enriched



Inclusive tagging validated using $B^+ \rightarrow D^0\pi^+$, $D^0 \rightarrow K^+\pi^-$ decays

$$\Delta p_\pi^B = p_\pi^B - p_\pi^{B_{sig}}$$



Search for $B^+ \to \mu^+\nu$ with inclusive tagging

Phys. Rev. D 101, 032007 (2020)

- $BR(B^+ \to \mu^+\nu)$ obtained from a simultaneous binned fit to p^B_μ in the 4 categories

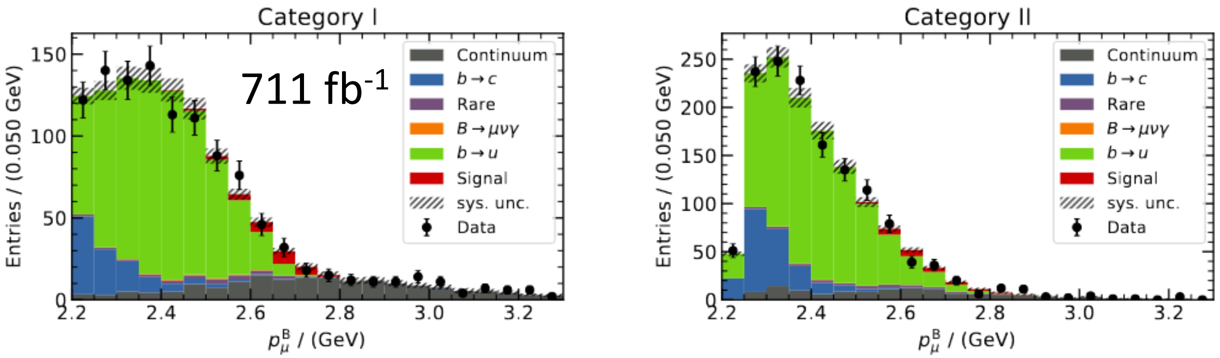
$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) = (5.3 \pm 2.0 \pm 0.9) \times 10^{-7},$$

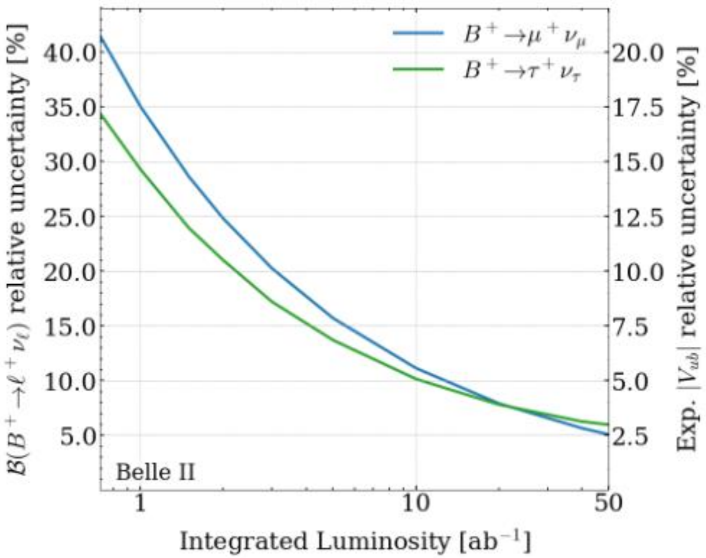
- No significant signal is observed (2.8σ), limit obtained with frequentist approach:

$$\mathcal{B}(B^+ \to \mu^+ \nu_\mu) < 8.6 \times 10^{-7} \text{ at } 90\% \text{ CL}.$$

best upper limit to date!

- BR measurement also used to set constraints on 2HDM model and decays to sterile neutrino $B^+ \to \mu^+N$ for masses up to 1.5 GeV





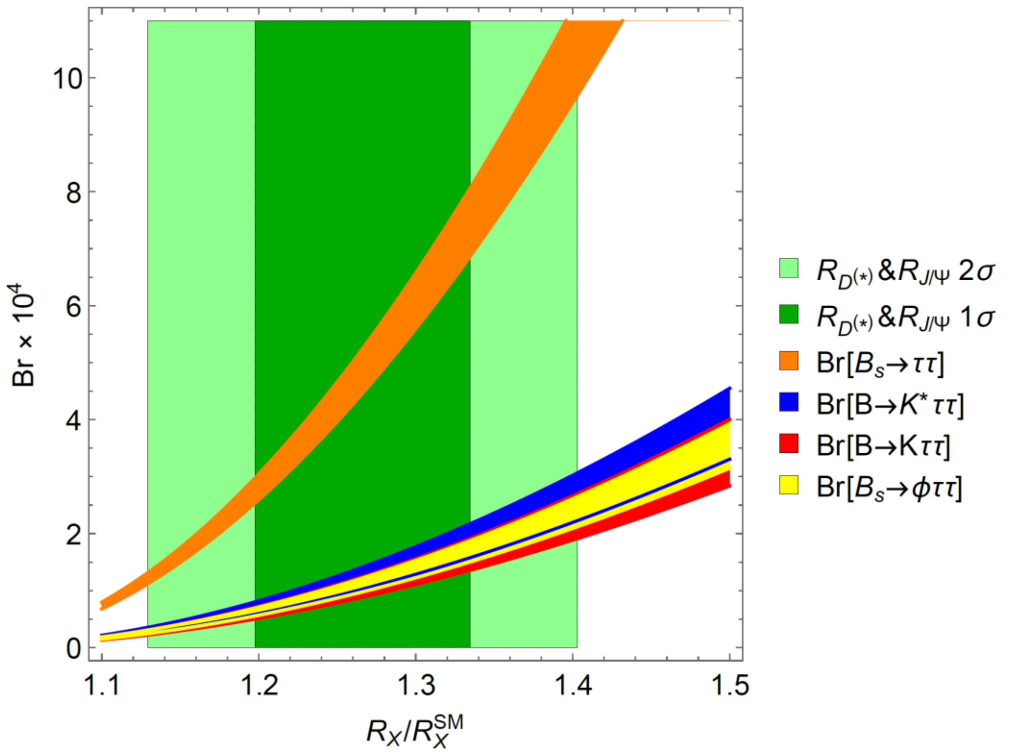
Projection of BR(B → μ/τ ν) uncertainty at Belle II

From Snowmass white paper arXiv:2207.06307

Search for $B^0 \rightarrow K^{*0}\tau\tau$

- Anomalies seen in violation of LFU suggest a special role of the third family, with enhancement of $b \rightarrow s\tau\tau$ decays
- $b \rightarrow s\tau\tau$ decays are much less well known than their e/μ counterparts, experimentally challenging due to at least 2 neutrinos in final state

Decays	SM prediction	Best 90% CL UL
$B^0 \rightarrow \tau\tau$	$(2.22\pm0.19)\ 10^{-8}$ [1]	$1.6\ 10^{-3}$ [3]
$B_s \rightarrow \tau\tau$	$(7.73\pm0.49)\ 10^{-7}$ [1]	$5.2\ 10^{-3}$ [3]
B0 → K*0ττ	$(0.98\pm0.10)\ 10^{-7}$ [2]	This result
B+ → K+ττ	$(1.20\pm0.12)\ 10^{-7}$ [2]	$2.25\ 10^{-3}$ [4]



B. Capdevila, A. Crivellin, S. Descotes-Genon, L. Hofer, et J. Matias, *PRL 120, 181802*

[1] PRL 112(2014)101801
[2] PRL 120(2018)181802
[3] LHCb PRL 118(2017)251802
[4] Babar PRL 118(2017)031802

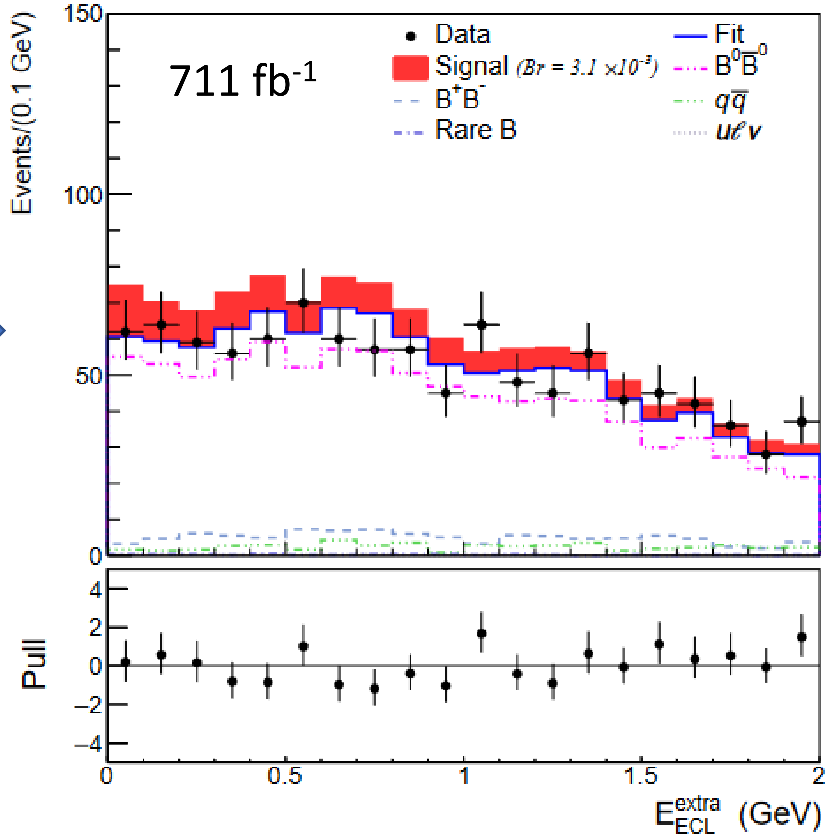
Search for $B^0 \to K^{*0}\tau\tau$

Phys. Rev. D 108, L011102 (2023)

- B hadronic tagging based on neural network
- Select event with 4 remaining tracks
- Reconstruct one prong τ decays $\tau \to e/\mu/\pi$
- Signal yield obtain by fitting the extra ECL energy (clusters not associated with B_{sig} or B_{tag})

$$N_{\text{sig}} = -4.9 \pm 6.0$$

Background only fit with signal superimposed



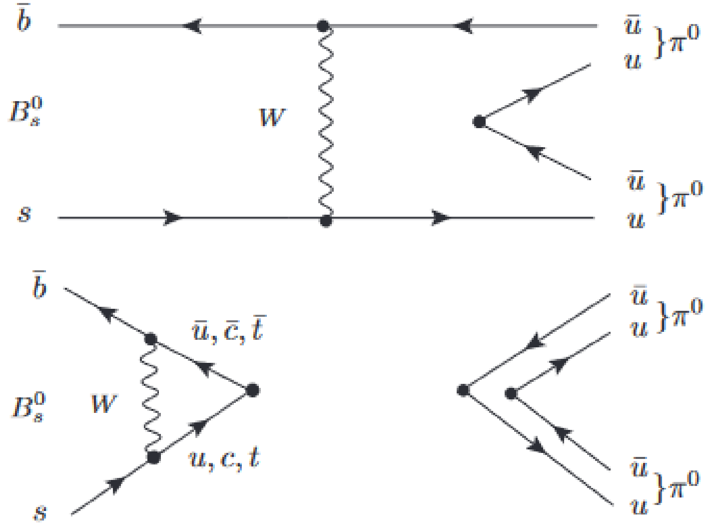
- Fit procedure validated on B→Dlν decays

Upper limit is set at 3.1×10^{-3} @90% C.L.

Improvements foreseen at Belle II: FEI, τ → ρ mode, multivariate analysis. Stay tuned!

Search for $B_s \to \pi^0\pi^0$

- Decay proceeds through W exchange and penguin annihilation diagram
- Measuring BR is important to understand QCD dynamic and validate theoretical calculations
- $BR(B_s \to \pi^+\pi^-)$ was measured by LHCb, showing tension with QCDF predictions
- Only a limit was set on $BR(B_s \to \pi^0\pi^0)$ by L3



Decay mode	Measurement	QCDF $(\times 10^{-7})$ [15]	pQCD $(\times 10^{-7})$
$B_s \to \pi^+\pi^-$	$(6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.4) \times 10^{-7}$ (LHCb, 2017) [13]	$(6.1^{+0.2+0.7}_{-0.4-0.6})$	$(5.10^{+1.96}_{-1.68}(a_2^\pi)^{+0.25+1.05+0.29}_{-0.19-0.83-0.20})$ [16]
$B_s \to \pi^0\pi^0$	$< 2.1 \times 10^{-4}$ (L3 Collaboration, 1995) [14]	$(1.3^{+0.1+0.3}_{-0.2-0.3})$	$(2.8^{+0.8+0.9+0.1}_{-0.7-0.5-0.0})$ [17]

where $a_2^\pi = 0.35 \pm 0.15$

[13] Aaij, et al., PRL 118 (2017)
[14] Acciarri, et al., Physical Letters B 363 (1995)
[15] Chang, et al., Physical Letters B 740 (2015)
[16] Xiao, et al., PRD 85 (2012) 94003
[17] Ali, et al., PRD 76 (2007)

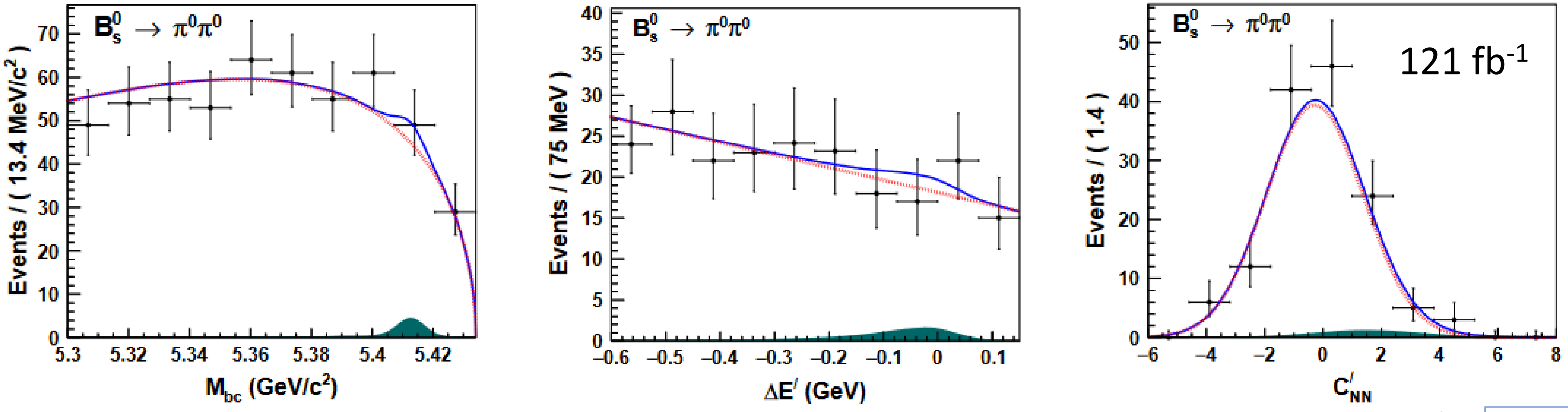
Search for $B_s \to \pi^0\pi^0$

arXiv:2301.08587

- Analysis using 121 fb^{-1} of Υ(5S) data, just above the $B_sB_s^*$ threshold
- Blind analysis, overall signal efficiency is 12.7%
- Signal yield obtained from a 3D fit using M_{bc}, ΔE and a neural network output C' against continuum backgrounds

$$M_{bc} = \frac{\sqrt{(E_{beam})^2 - |\vec{p}_{reco}|^2 c^2}}{c^2}, \quad \Delta E = E_{reco} - E_{beam} + M_{bc}c^2 - m_{B_s^0}c^2$$

- Signal PDF is the sum of all 3 production modes



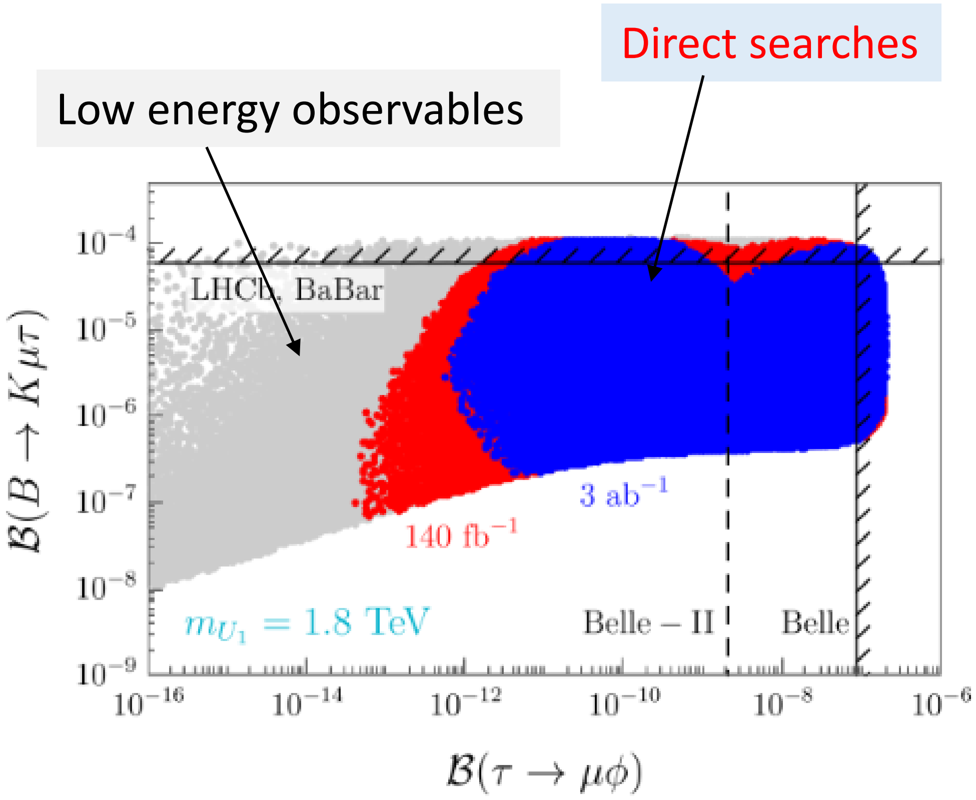
Transformed NN output

$$N^{sig}_{yield} = (5.7 \pm 5.8)$$

Upper limit is set at 7.7 x 10^{-6} @90% C.L.

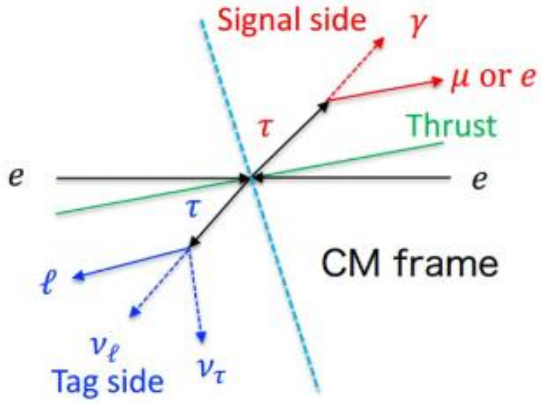
Search for τ LFV decays

- LFV decays expected at rate 10^{-50} in SM, observation would be a clear sign of NP
- Some channels are particularly sensitive to leptoquark models, ex: $\tau \to \ell\phi$ in the U(1) vector leptoquark hypothesis
- Most of best LFV limits have been set by Belle in the past using a selection based on the topology



Phys. Rev. D 104, 055017

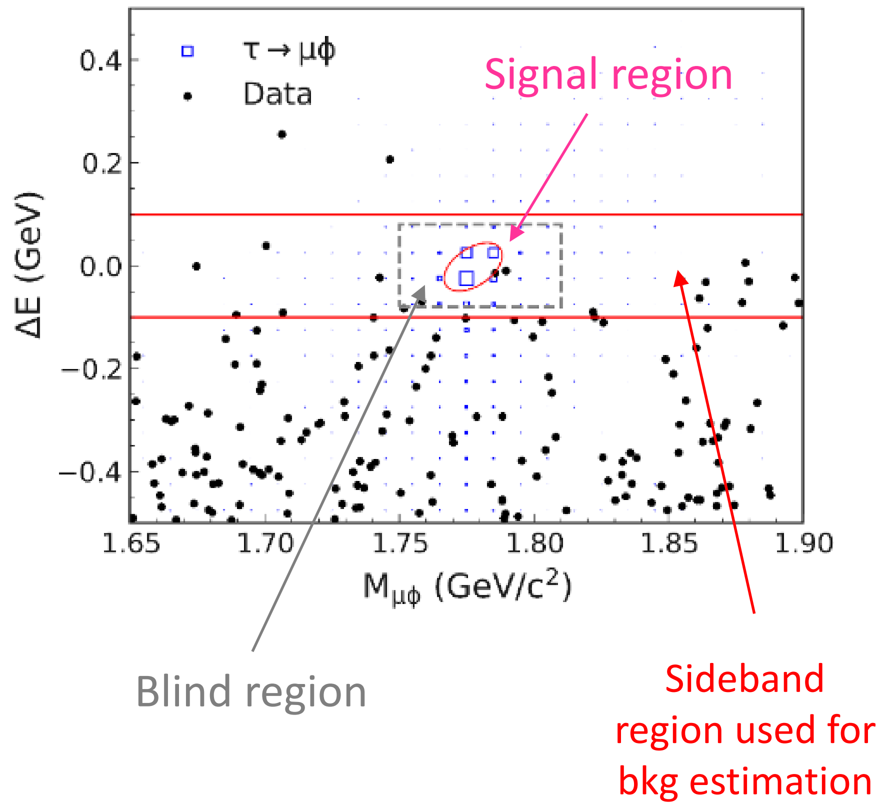
Jet-like geometry



Search for $\tau \to \ell V^0$

JHEP06(2023)118

- New Belle analysis using 980 fb^{-1}
- Use 3-prong decays of tagged τ in addition to 1-prong, and a BDT selection to suppress continuum background
- Signal is searched in 2D plane: $M_{\tau sig}$ and $\Delta E = E_{sig} - E_{beam}$



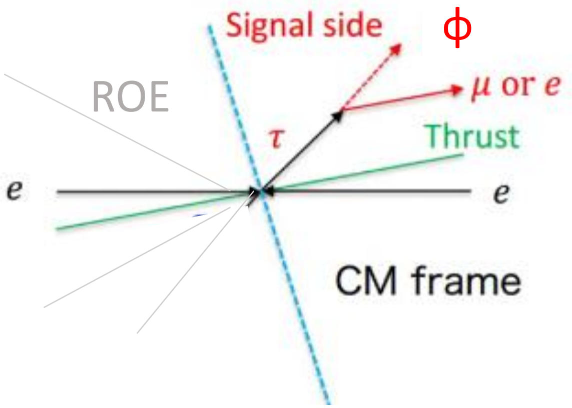
Mode	ε (%)	N_{BG}	σ_{syst} (%)	N_{obs}	$\mathcal{B}_{obs}$ ($\times 10^{-8}$)
$\tau^\pm \to \mu^\pm \rho^0$	7.78	0.95±0.20(stat.) ±0.15(syst.)	4.6	0	< 1.7
$\tau^\pm \to e^\pm \rho^0$	8.49	0.80±0.27(stat.) ±0.04(syst.)	4.4	1	< 2.2
$\tau^\pm \to \mu^\pm \phi$	5.59	0.47±0.15(stat.) ±0.05(syst.)	4.8	0	< 2.3 *
$\tau^\pm \to e^\pm \phi$	6.45	0.38±0.21(stat.) ±0.00(syst.)	4.5	0	< 2.0 *
$\tau^\pm \to \mu^\pm \omega$	3.27	0.32±0.23(stat.) ±0.19(syst.)	4.8	0	< 3.9 *
$\tau^\pm \to e^\pm \omega$	5.41	0.74±0.43(stat.) ±0.06(syst.)	4.5	0	< 2.4 *
$\tau^\pm \to \mu^\pm K^{*0}$	4.52	0.84±0.25(stat.) ±0.31(syst.)	4.3	0	< 2.9 *
$\tau^\pm \to e^\pm K^{*0}$	6.94	0.54±0.21(stat.) ±0.16(syst.)	4.1	0	< 1.9 *
$\tau^\pm \to \mu^\pm \overline{K}^{*0}$	4.58	0.58±0.17(stat.) ±0.12(syst.)	4.3	1	< 4.3 *
$\tau^\pm \to e^\pm \overline{K}^{*0}$	7.45	0.25±0.11(stat.) ±0.02(syst.)	4.1	0	< 1.7 *

*World leading

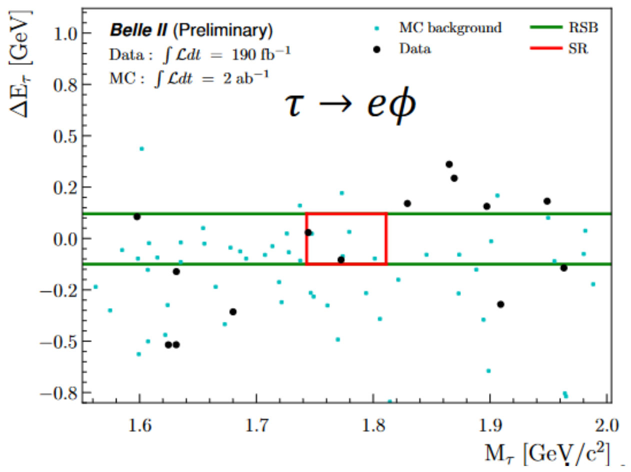
Limits improved by ~30% wrt previous Belle results

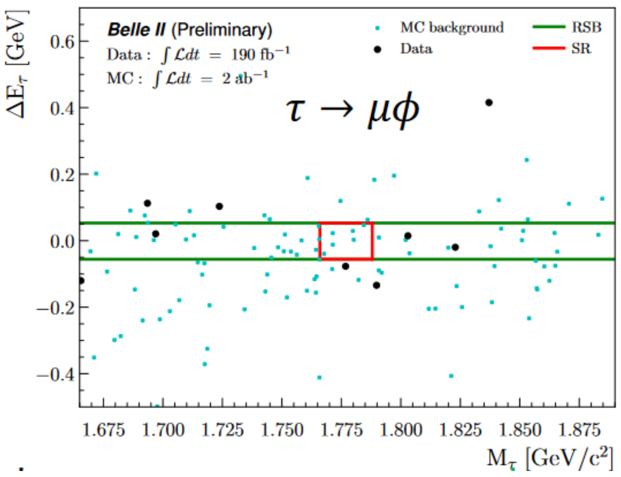
Search for τ→ ℓϕ

arXiv:2305.04759



- Novel inclusive strategy developed at Belle II on 190fb^{-1}
- Reconstruct only the signal τ
- Use Rest-of-Event properties to discriminate background





Quantity	Region	Mode $e\phi$	Mode $\mu\phi$
Signal efficiency $\varepsilon_{\ell\phi}$	SR	$(6.1 \pm 0.9$ (syst))%	$(6.5 \pm 0.6$ (syst))%
r_{MC}	SR / RSB	$0.23^{+0.16}_{-0.10}$ (stat)	$0.12^{+0.07}_{-0.04}$ (stat)
N_{data}	RSB	$1.0^{+2.3}_{-0.8}$ (stat)	$3.0^{+2.9}_{-1.6}$ (stat)
N_{exp}	SR	$0.23^{+0.55}_{-0.21}$ (stat)	$0.36^{+0.39}_{-0.23}$ (stat)
N_{obs}	SR	$2.0^{+2.6}_{-1.3}$ (stat)	$0.0^{+1.8}_{-0.0}$ (stat)

Obs. $B_{\mathrm{UL}}(\tau \to e\phi) = 23\times10^{-8}$
Exp. $B_{\mathrm{UL}}(\tau \to e\phi) = 15\times10^{-8}$

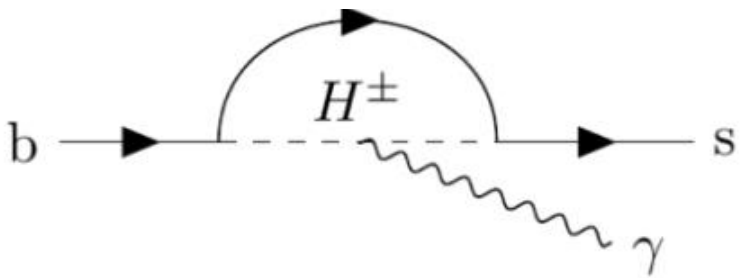
Obs. $B_{\mathrm{UL}}(\tau \to \mu\phi) = 9.7\times10^{-8}$
Exp. $B_{\mathrm{UL}}(\tau \to \mu\phi) = 9.9\times10^{-8}$

Promising technique for coming Belle II statistics

Inclusive $B \to X_s \gamma$

arXiv:2210.10220

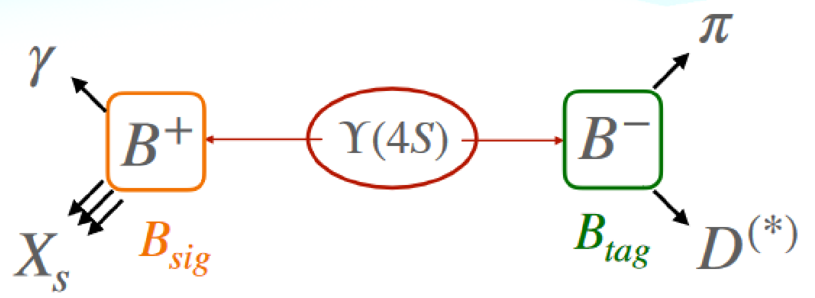
- Measurement only possible in clean environment of B factories, highly sensitive to NP particles in the loop



- Based on the full reconstruction of the other B in a hadronic mode thanks to the *Full Event Interpretation*

  ➡ Tagging efficiency is (0.44±0.02)%

- Knowledge of flavour and momentum of B_{tag} allows to access the photon energy in the B_{sig} frame, E_γ^B
- Moments of E_γ^B gives information on HQE parameters m_b and μ_π^2
- Inclusive and high purity reconstruction also allows measurement of CP and isospin asymmetries



36 B+ and 32 B0 modes

Inclusive B→ $X_s\gamma$

arXiv:2210.10220

- Measure B(B→ $X_s\gamma$) with 189 fb^{-1} in 8 bins of E_γ^B , for E_γ^B > 1.8 GeV
- Fit of the tag side M_{bc} in bins of E_γ^B to determine yields of correctly reconstructed B events, continuum and combinatorial B background

$$M_{\rm bc} = \sqrt{(\sqrt{s}/2)^2 - p_{\rm tag}^2}$$

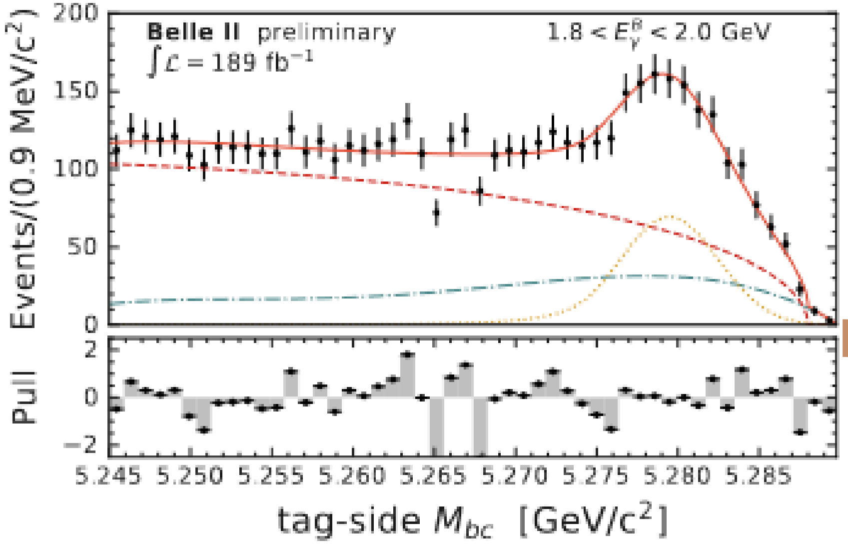
- Differential BR computed as:

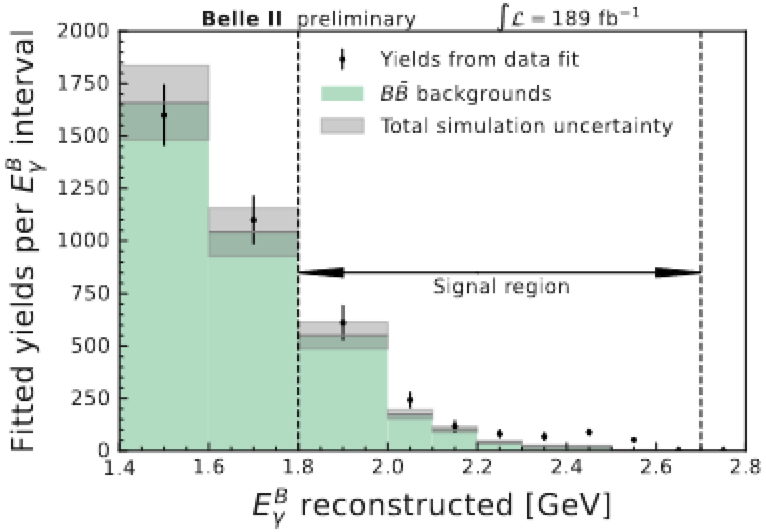
Unfolding factor

$$\frac{1}{\Gamma_B}\frac{d\Gamma_i}{dE_\gamma^B} = \frac{\mathcal{U}_i \times (N_i^{\rm DATA} - N_i^{\rm BKG,\ MC} - N_i^{B\to X_d\gamma})}{\varepsilon_i \times N_B},$$

- Non signal B subtracted using simulation
- b→ dγ contribution removed assuming same shape and selection efficiency as signal, with a factor

$$|V_{td}/V_{ts}|^2 \approx 4.3\%$$

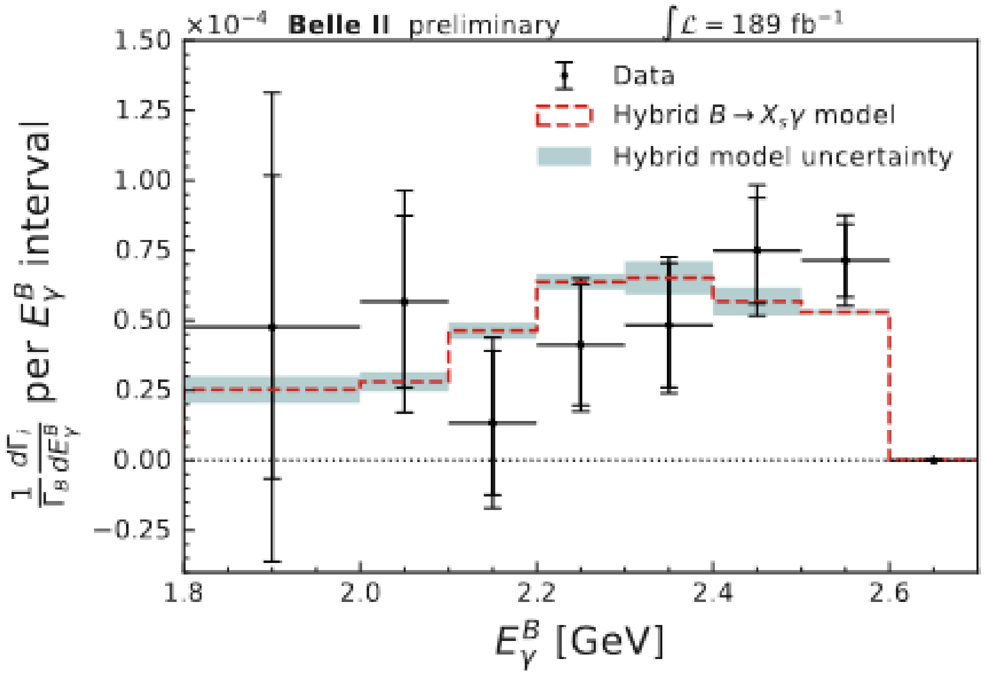




Inclusive B→ $X_s\gamma$

arXiv:2210.10220

E_γ^B threshold [GeV]	$\mathcal{B}(B \to X_s\gamma)$ $[10^{-4}]$	Observed signal yield (tot. unc.)
1.8	3.54 ± 0.78 (stat.) ± 0.83 (syst.)	343 ± 122
2.0	3.06 ± 0.56 (stat.) ± 0.47 (syst.)	285 ± 68
2.1	2.49 ± 0.46 (stat.) ± 0.35 (syst.)	219 ± 50



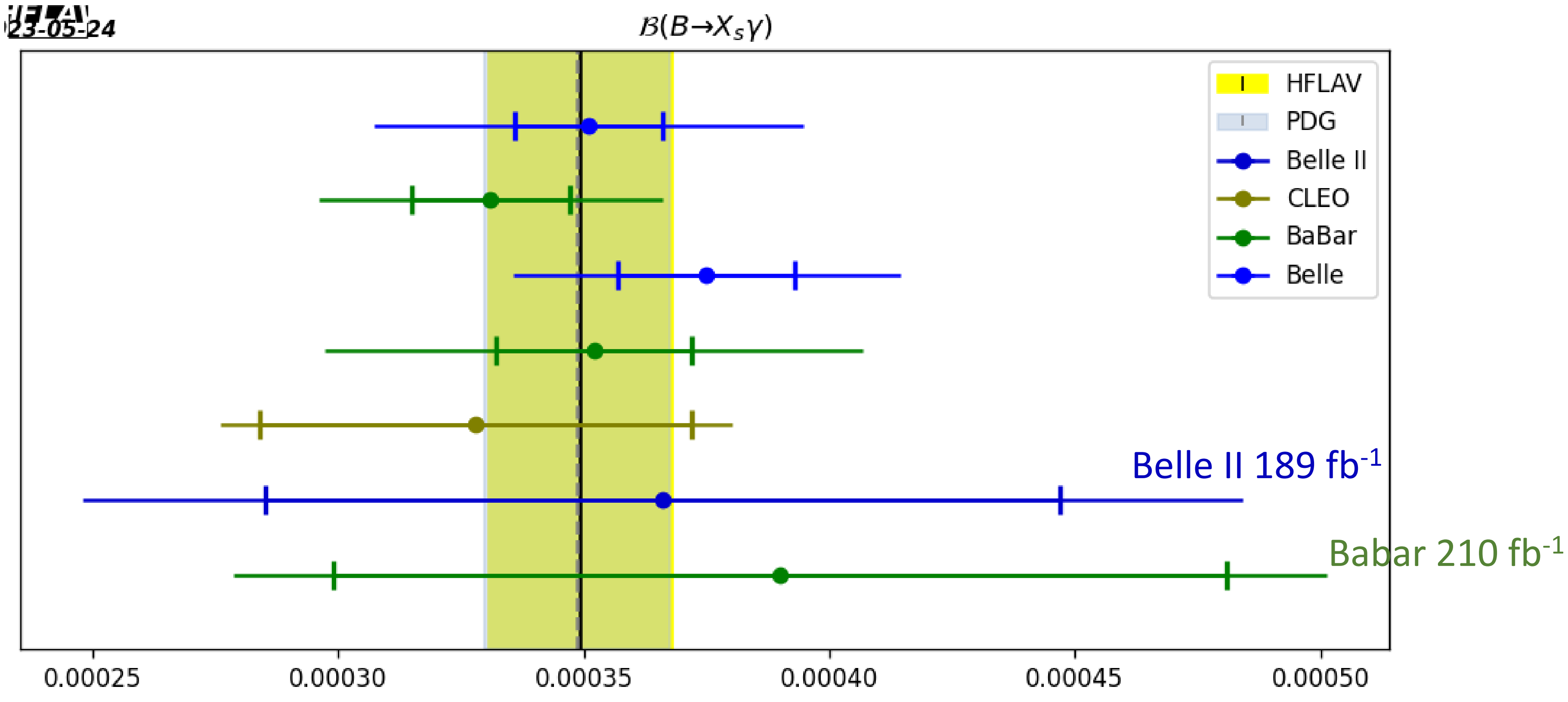
The threshold value introduces different biases in the phenomenological interpretation of the moments

Main systematic uncertainties are coming from the fit procedure (B background shape and M_{bc} end-point) and simulation statistics

Inclusive $B \to X_s \gamma$

arXiv:2210.10220

Plot available from latest rare decays HLFAV webpage



Competitive with Babar result !

Summary

Belle

- First experimental result on $B^0 \to K^{*0}\tau\tau$
- Improvement of existing limit on $\mathcal{B}(B_s \to \pi^0\pi^0)$ by 2 order of magnitude
- World best limit on $B^+ \to \mu^+\nu$ thanks to an inclusive tagging technique
- Improved limits on $\tau \to \ell V^0$

Belle II

- Open path towards $R_{K(*)}$ measurements with Belle II data
- Most precise measurement of τ mass
- New inclusive technique for τ LFV searches
- First inclusive analysis of $B \to X_s\gamma$ showing competitive results with 189 fb^{-1}

Belle II already demonstrated excellent tagging performances and control of systematic uncertainties ☺

Backup

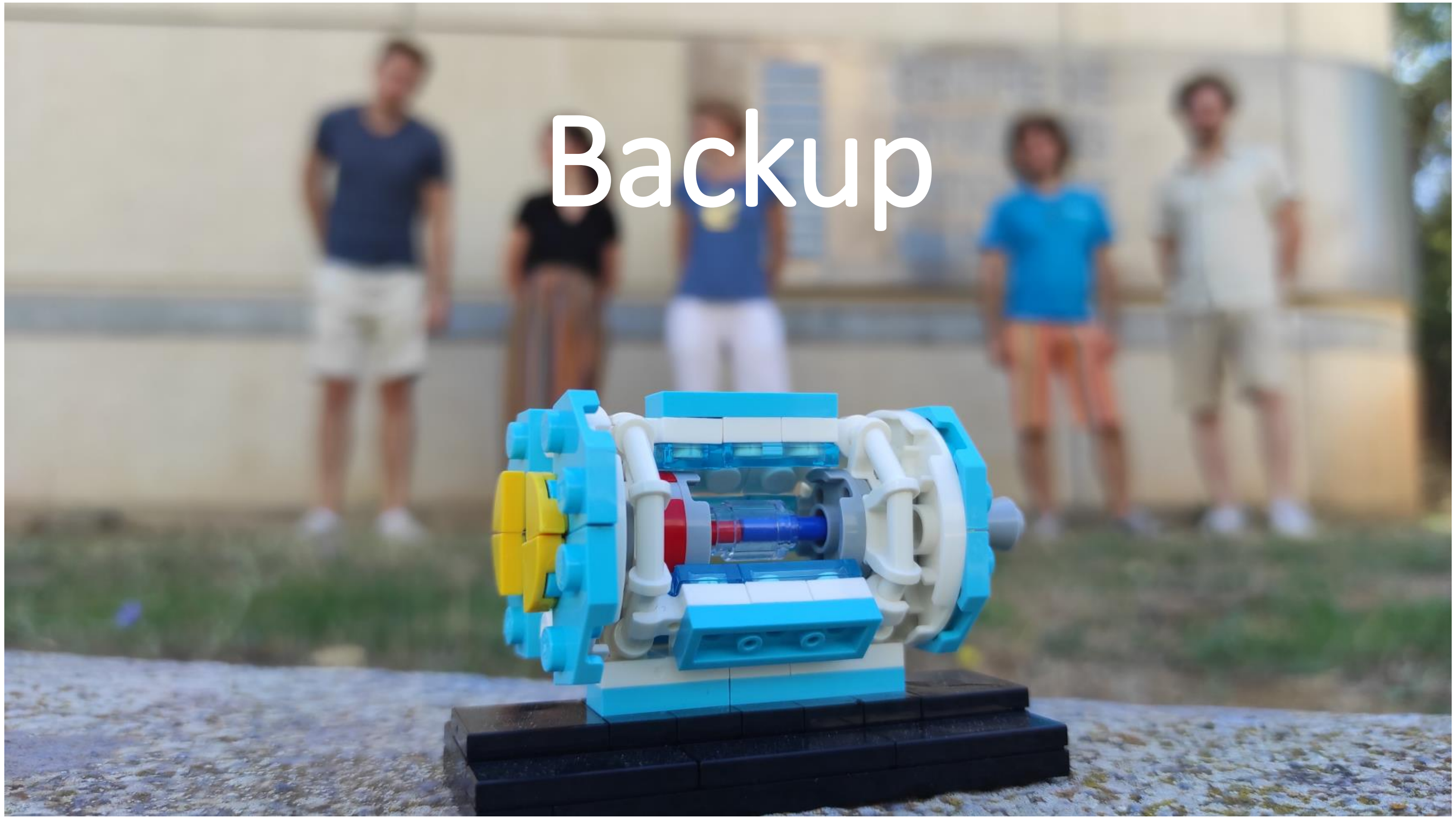
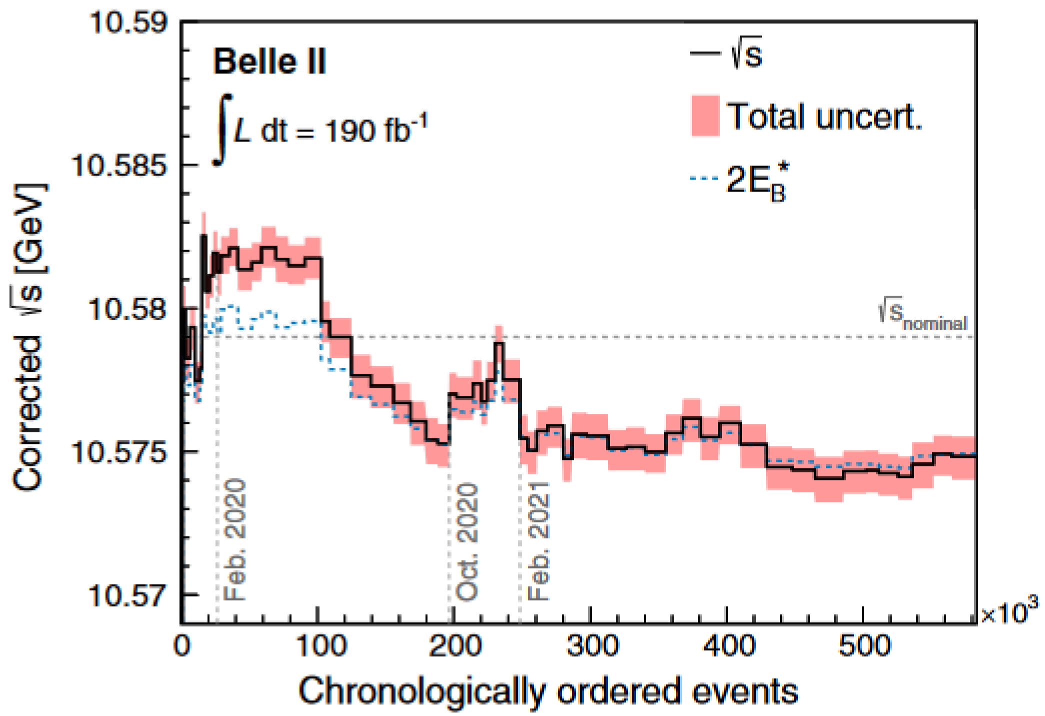
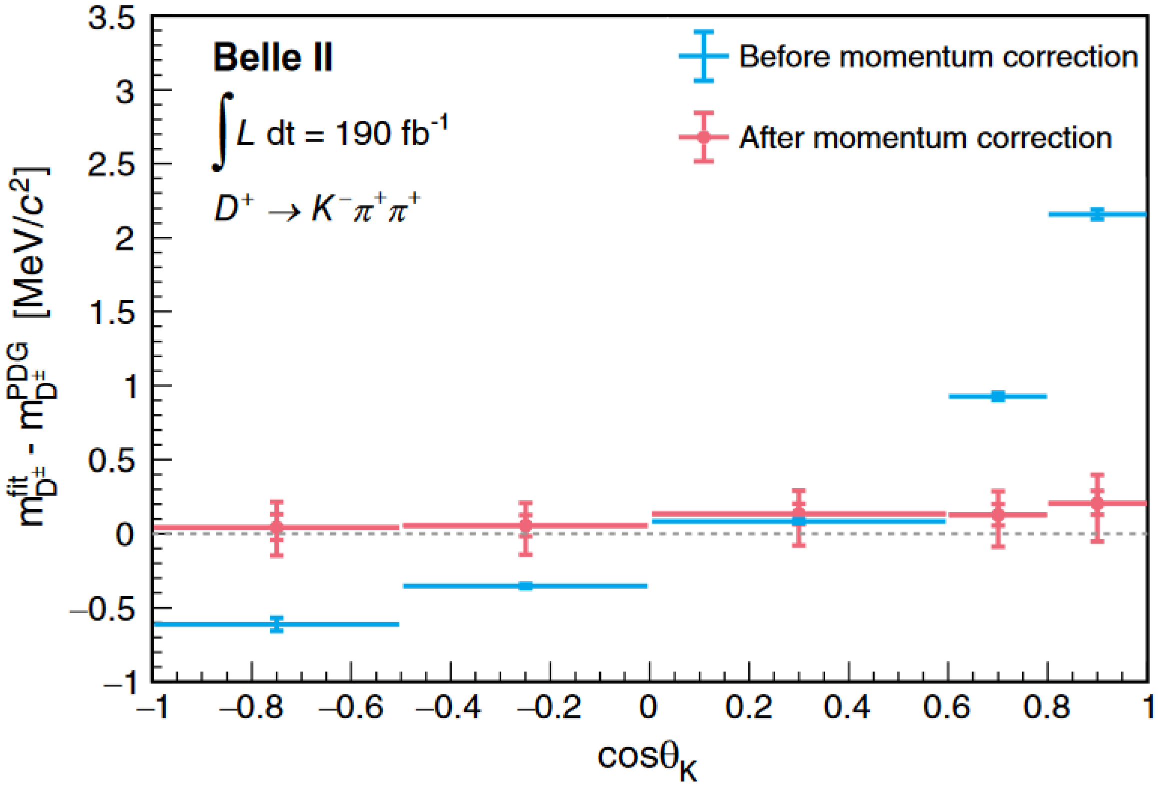


Table III. Relative systematic uncertainties (%) on $\mathcal{B}(B \to J/\psi K)$, $R_K(J/\psi)$, and absolute uncertainty on $A_I(B \to J/\psi K)$.

Source	$\mathcal{B}(B \to KJ/\psi)$				R_K		A_I	
	K^+	K^+	K^0_S	K^0_S	K^+	K^0		
	e^+e^-	$\mu^+\mu^-$	e^+e^-	$\mu^+\mu^-$			e^+e^-	$\mu^+\mu^-$
Number of $B\overline{B}$ events	1.5	1.5	1.5	1.5	–	–	–	–
PDF shape	0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Electron identification	0.6	–	0.6	–	0.6	0.6	–	–
Muon identification	–	0.4	–	0.4	0.4	0.4	–	–
Kaon identification	0.2	0.2	–	–	–	–	0.1	0.1
K^0_S reconstruction	–	–	3.0	3.0	–	–	1.5	1.5
Tracking efficiency	0.9	0.9	1.2	1.2	–	–	0.4	0.4
Simulation sample size	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$\Upsilon(4S)$ branching fraction	2.6	2.6	2.6	2.6	–	–	2.6	2.6
(τ_{B^+}/τ_{B^0})	–	–	–	–	–	–	0.2	0.2
Total	3.2	3.2	4.4	4.4	0.8	0.8	3.0	3.0

Tau mass





Correction factors range from 0.99660 to 1.00077 depending on charge and polar angle

TABLE II. Summary of systematic uncertainties in the τ-mass measurement.

Source	Uncertainty (MeV/c^2)
Knowledge of the colliding beams:	
Beam-energy correction	0.07
Boost vector	<0.01
Reconstruction of charged particles:	
Charged-particle momentum correction	0.06
Detector misalignment	0.03
Fit model:	
Estimator bias	0.03
Choice of the fit function	0.02
Mass dependence of the bias	<0.01
Imperfections of the simulation:	
Detector material density	0.03
Modeling of ISR, FSR and τ decay	0.02
Neutral particle reconstruction efficiency	≤ 0.01
Momentum resolution	<0.01
Tracking efficiency correction	<0.01
Trigger efficiency	<0.01
Background processes	<0.01
Total	0.11

Mostly from uncertainty on BB cross section energy dependence

pT dependence of scale factor, D mass uncertainty, modeling of D0 signal peak, difference in angular distribution of tau and D decays

Obtained from fit to simulation with different tau mass values

Alternative fits with function previously used by Babar/Belle

That can affect the P1 estimator bias

+ consistency checks as function of data taking periods, kinematic regions, tau decay model.