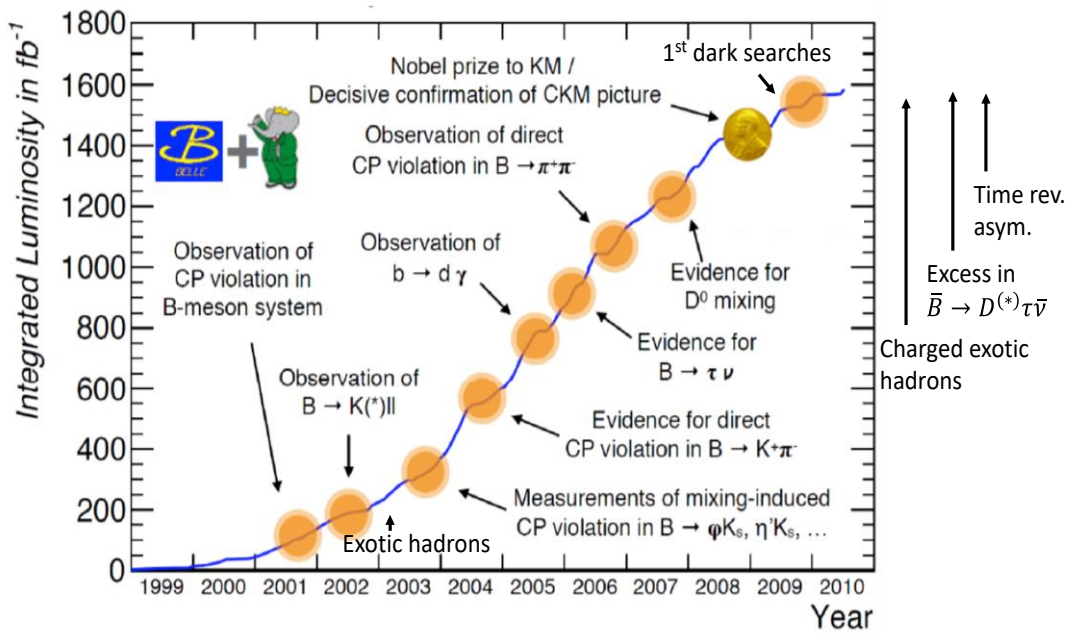
Recent highlights from Belle and Belle II

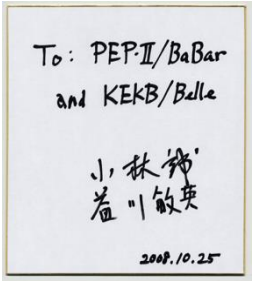
*Mario Merola**

on behalf of the Belle II Collaboration

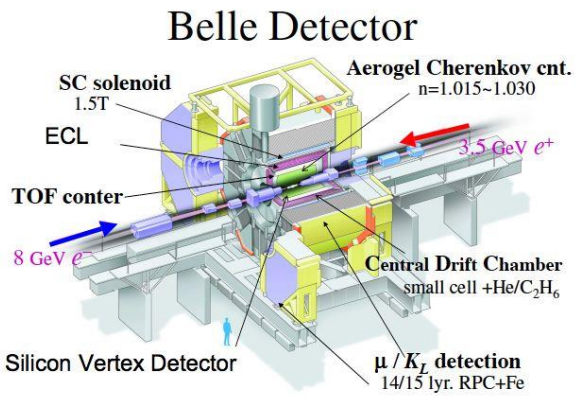
*University of Napoli Federico II, INFN Napoli (Italy)

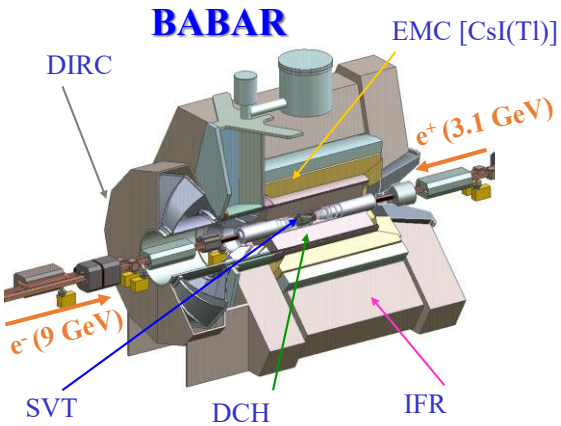
Babar and Belle achievements





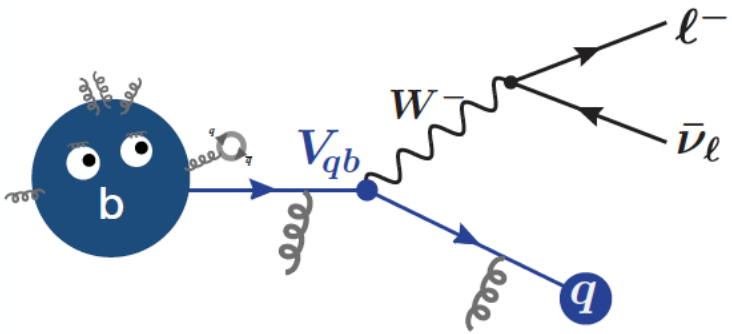
Kobayashi, Maskawa Nobel prize in 2008

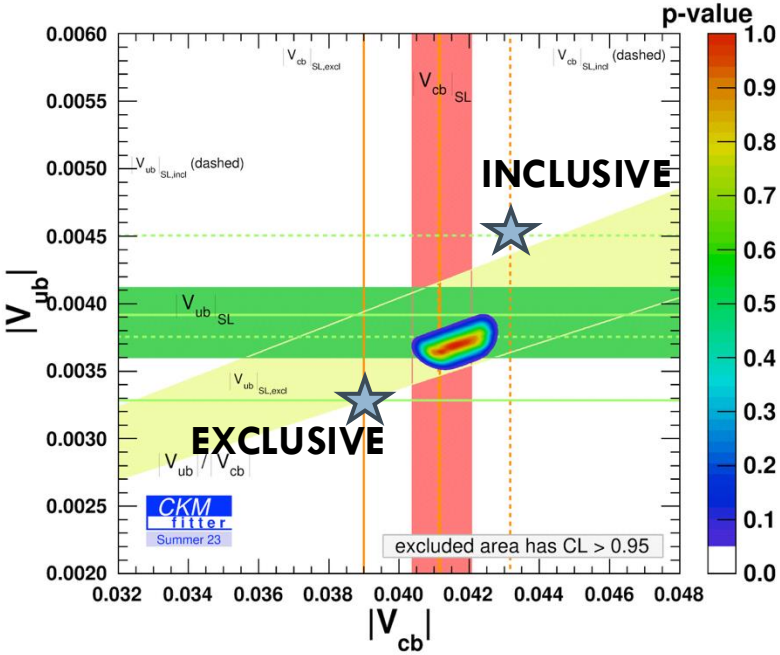




Successful experimental program
Established CP violation in B system and remarkable consistency of the CKM mechanism of the SM

Hot topics (1): Inclusive and exclusive V_{xb} determinations





CKMfitter Group (J. Charles et al.), Eur. Phys. J. C41, 1-131 (2005) [hep-ph/0406184]; updated results and plots available at: http://ckmfitter.in2p3.fr

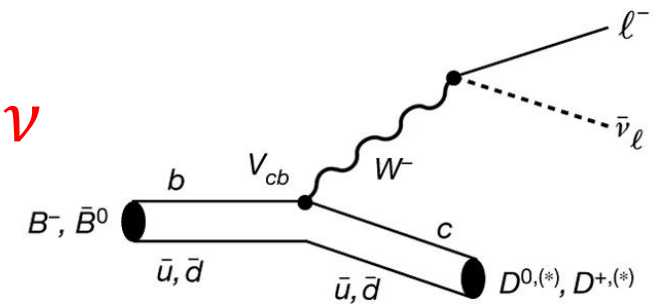
- **Tension** between inclusive and exclusive determinations via semileptonic B decays: ~3σ for both $|V_{cb}|$ and $|V_{ub}|$

- $X_c l \nu$ decays are a clear test of the SM Lepton Flavour Universality (LFU): **NP** (charged Higgs in 2 Higgs-doublet model or Leptoquarks) **can affect the BR and $|V_{cb}|$**

New physics or theoretical issue ?

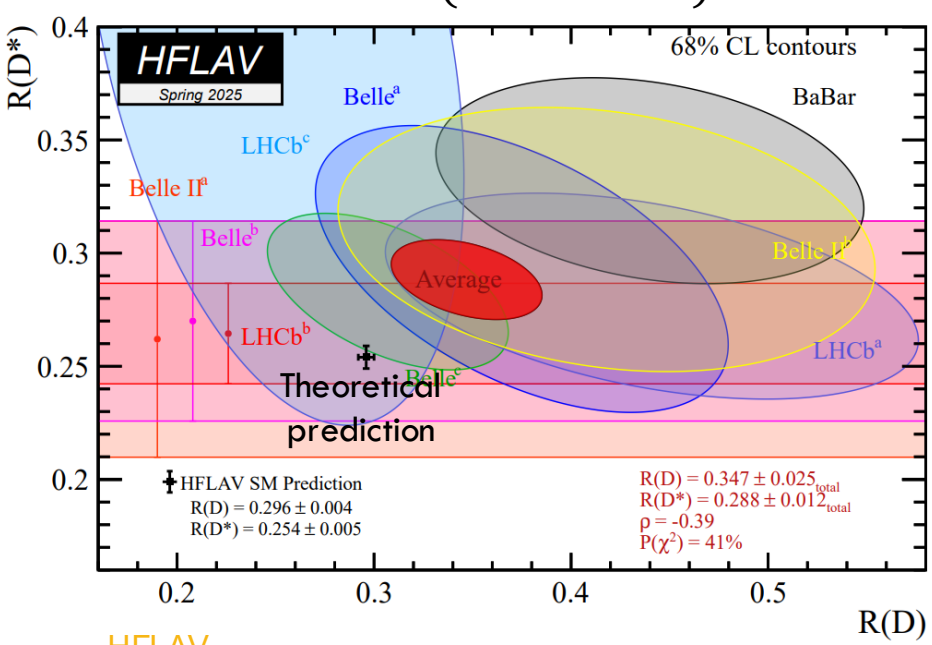
Hot topics (2): Lepton Flavour Universality (LFU) in B decays

$b \to c l \nu$

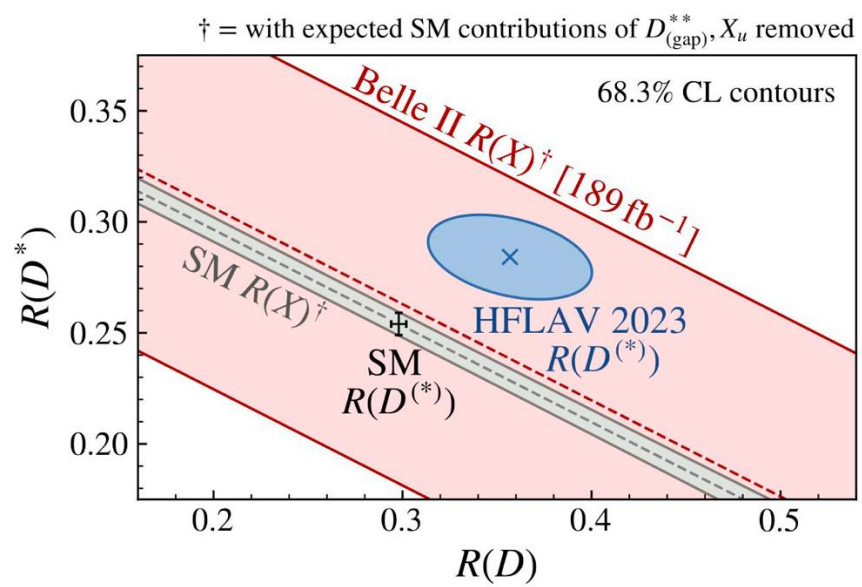


$$R(D^{(*)}) = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

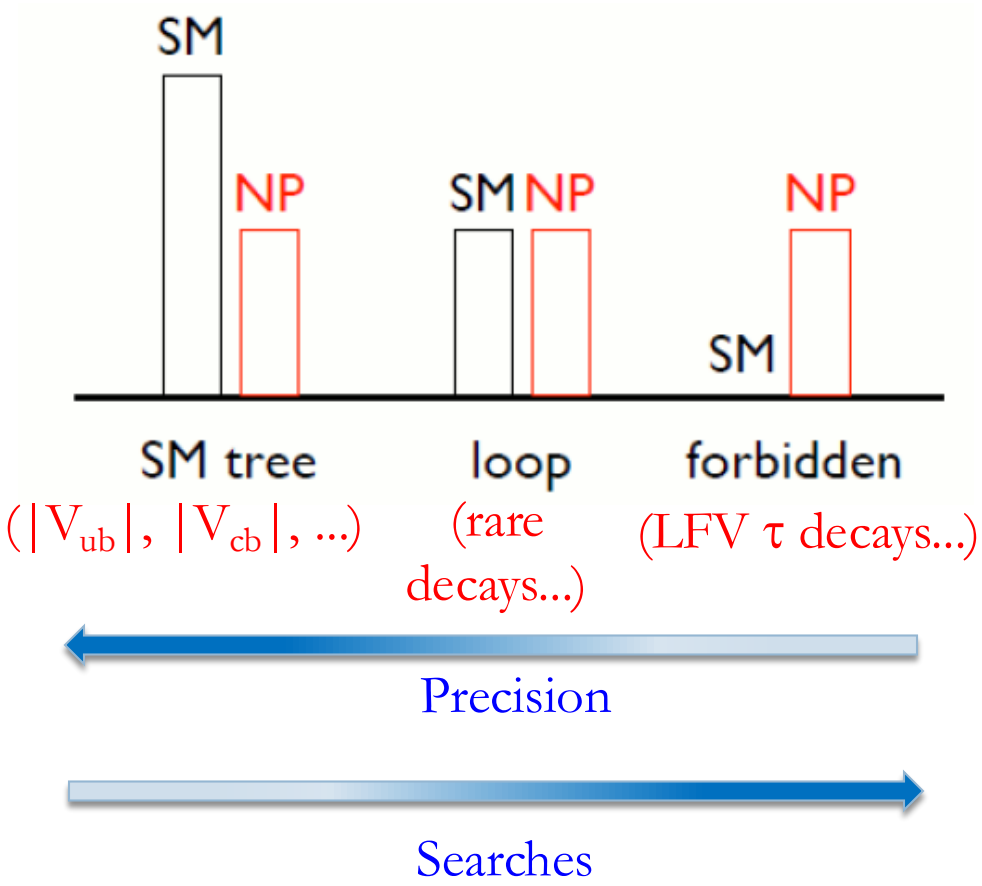
$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu)}{\mathcal{B}(B \to X\ell\nu)}$$



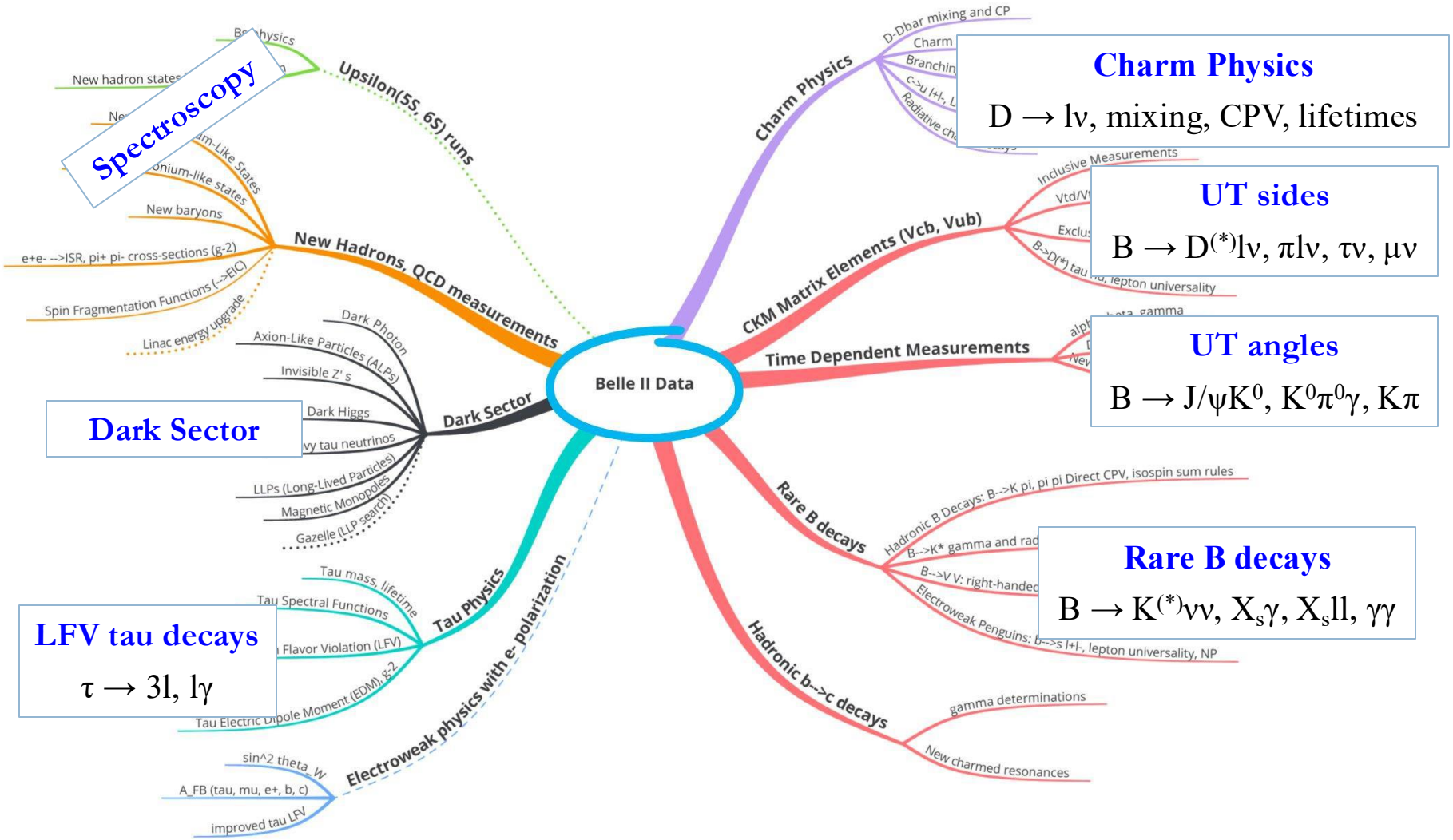
HFLAV



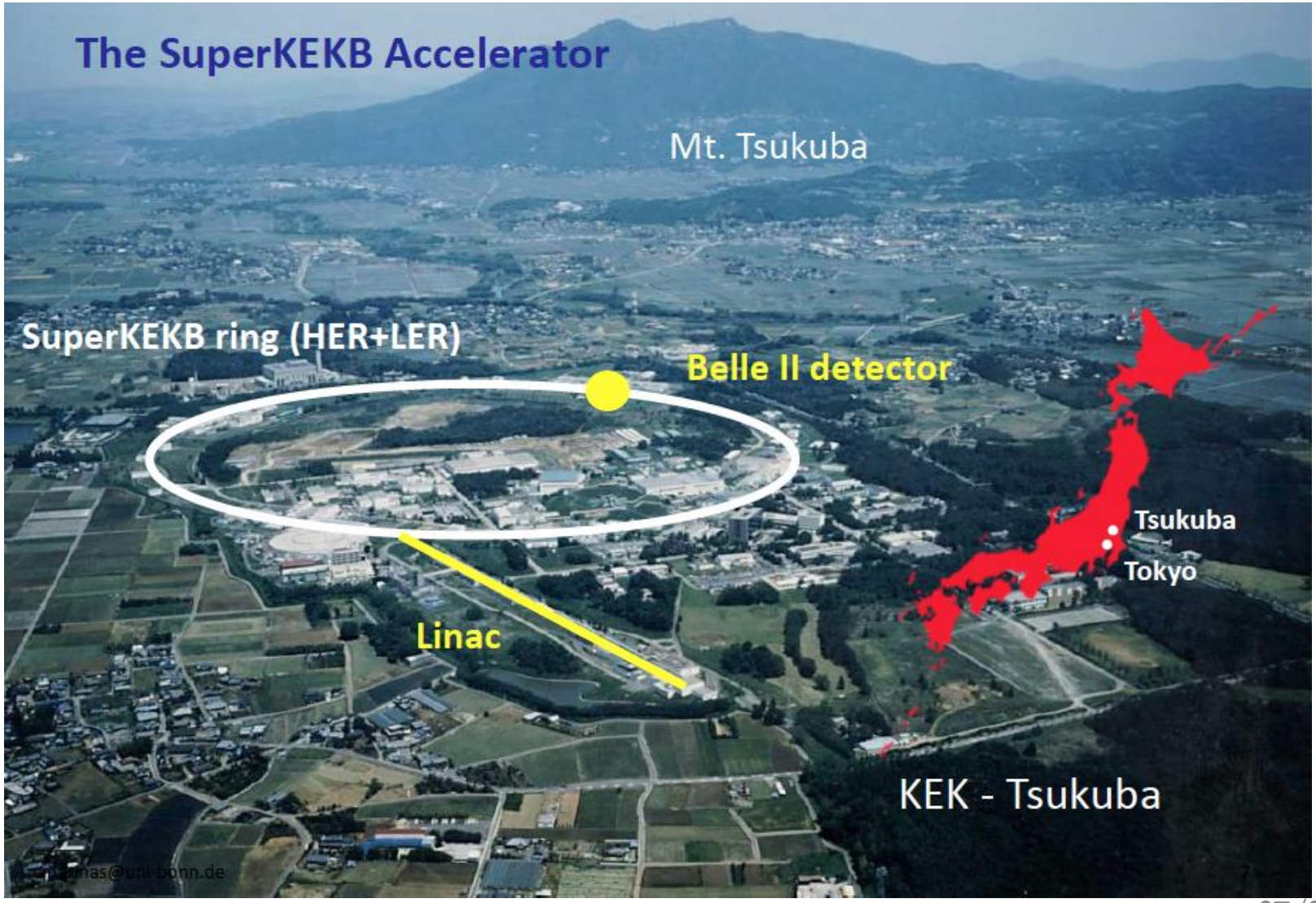
New Physics: how-to



Belle II physics program

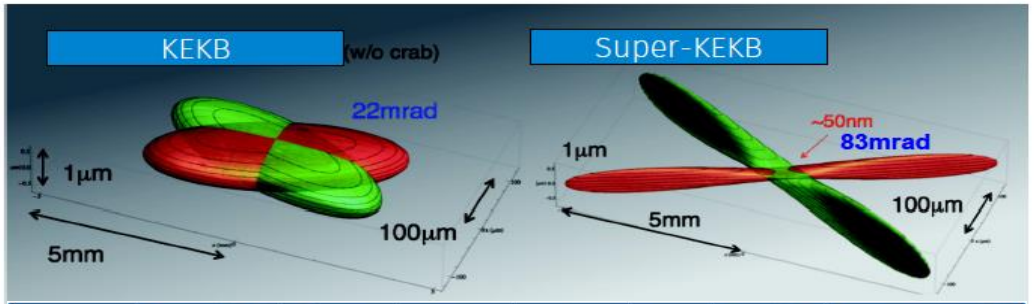


SuperKEKB


The SuperKEKB Accelerator
Mt. Tsukuba
SuperKEKB ring (HER+LER)
Belle II detector
Tsukuba
Tokyo
Linac
KEK - Tsukuba

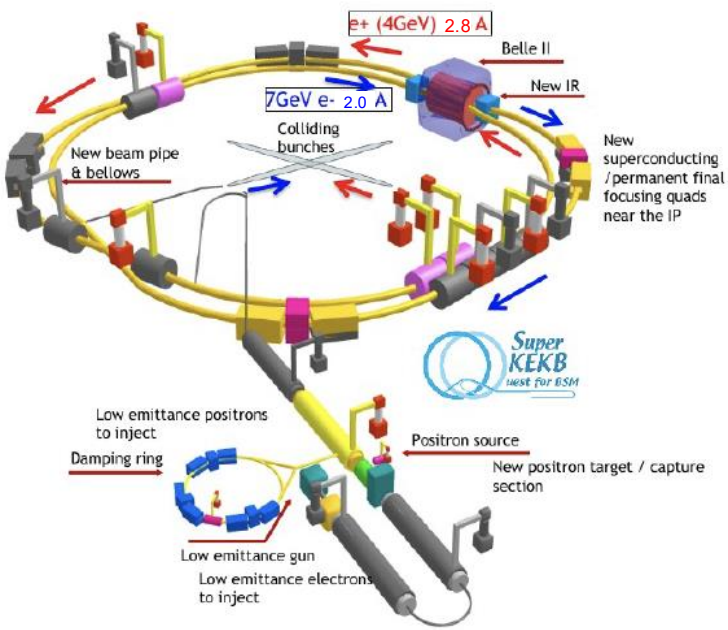
SuperKEKB

- Asymmetric energy $e^+(4\ \mathrm{GeV})\ e^-(7\ \mathrm{GeV})$ collider, at Υ(4S) mass
- Situated at KEK (Tsukuba, Japan), upgrade of KEKB

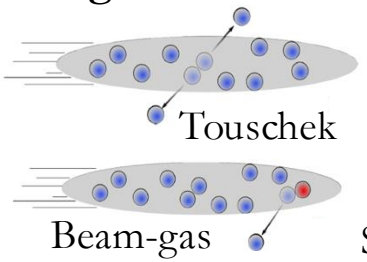


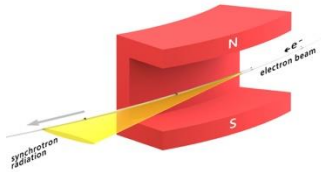
	Energy (GeV) LER/HER	β_y^* (mm) LER/HER	ε_x (nm) LER/HER	ξ_y LER/HER	φ (mrad)	I_{beam} (A) LER/HER	Luminosity ($cm^{-2}s^{-1}$) x 10^{34}
KEKB Achieved	3.5/8.0	5.9/5.9	18/24	0.13/0.09	11	1.6/1.2	2.11
SuperKEKB	4.0/7.0	0.27/0.3	3.2/2.4	0.09/0.09	41.5	2.8/2.0	65

factor 20 factor 1.5

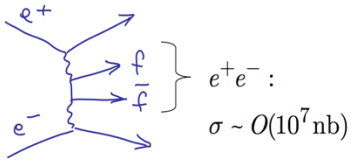


Higher machine induced and luminosity backgrounds



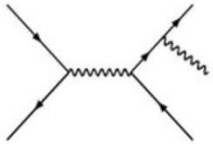


Synchrotron radiation



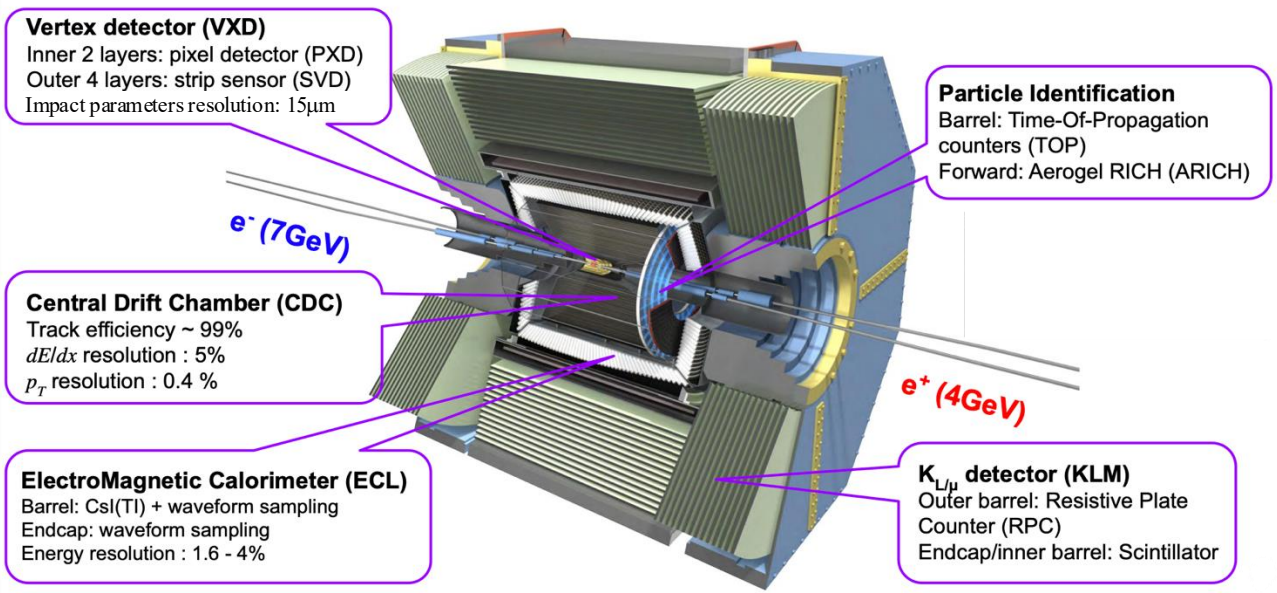
2-photon-processes

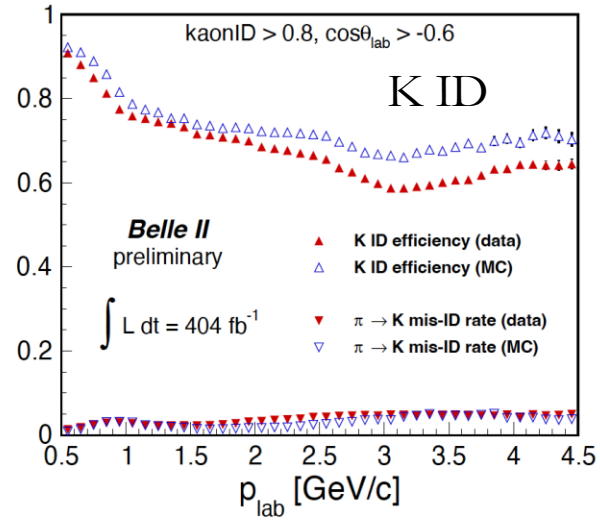
- Radiation damage
- Occupancy in inner detectors
- Fake tracks

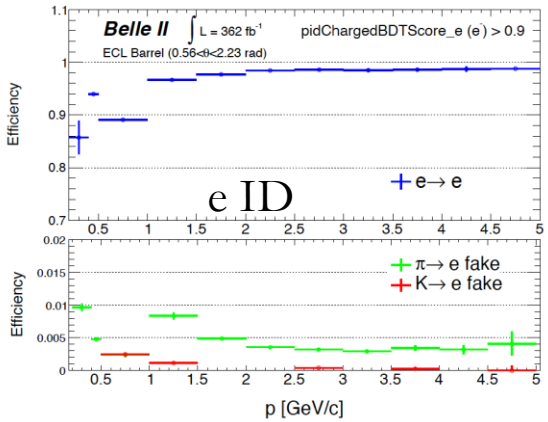


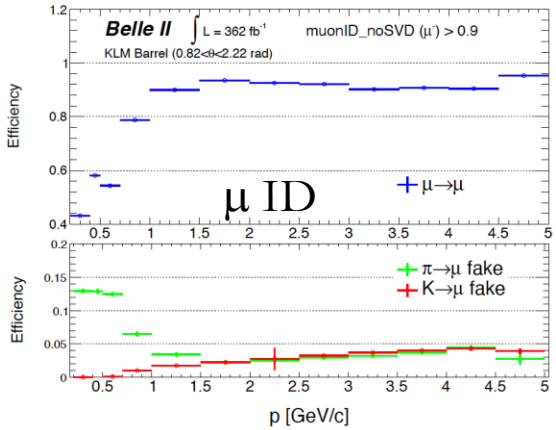
Radiative Bhabha

The Belle II Detector





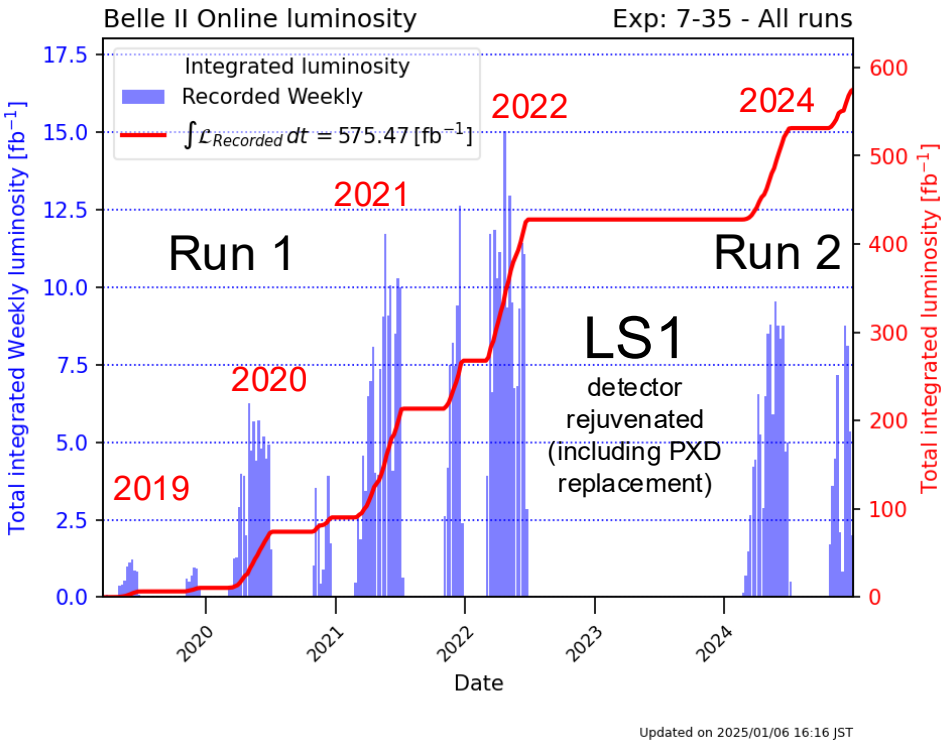


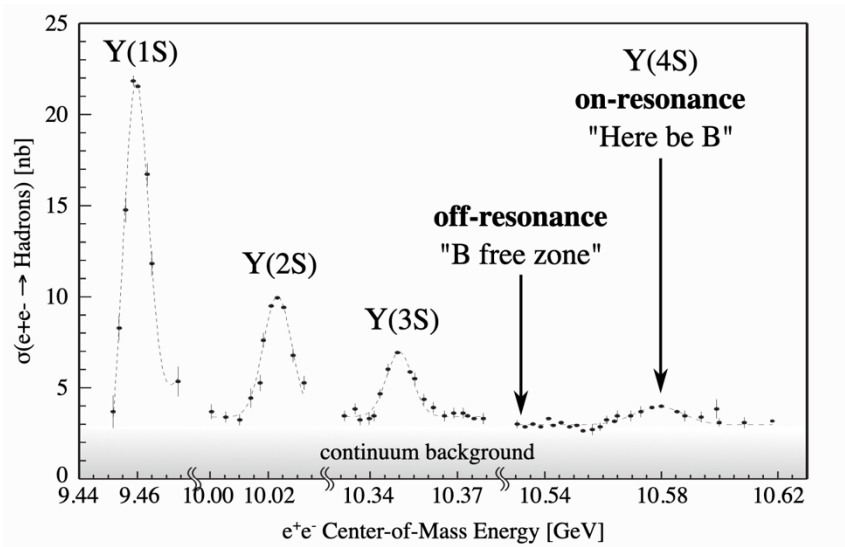


Particle ID and separation

- K/π: ε ~86% @ 5% fake (0.5 – 4.5 GeV/c)
- μ/π: ε~90% @ 3% fake (0.2 – 5.0 GeV/c)
- e/π: ε ~98% @ 0.5% fake (0.2 – 5.0 GeV/c)

Luminosity and current dataset





85% taken at Y(4S) peak – **BB pairs**
10% taken 60 MeV below Y(4S) – **continuum (qq, ll, 2γ)**
5% taken around 10.75 GeV - **spectroscopy**

$L_{int} \sim 575\ fb^{-1}$ > Babar dataset

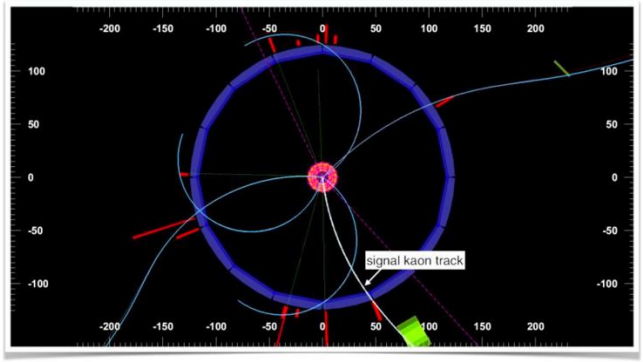
$L = 4.7 \times 10^{34}\ cm^{-2}\ Hz$ Run 1 record

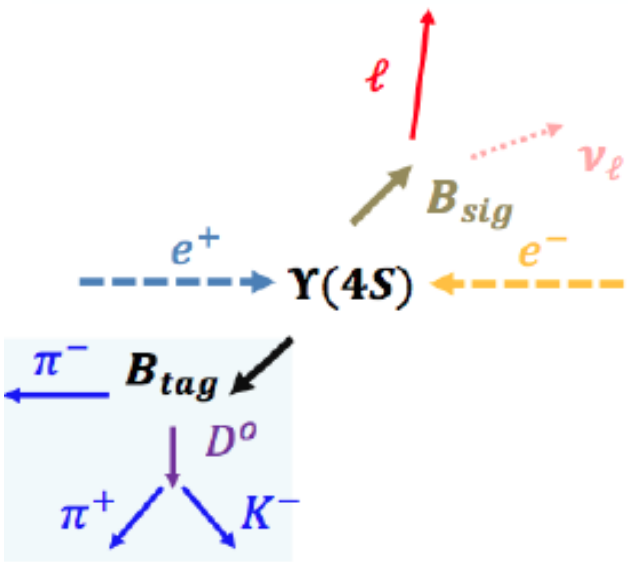
NEW RECORD
(December 2024)
$L = 5.1 \times 10^{34}\ cm^{-2}\ Hz$

Unique capabilities of e^+e^- B factories

- Beam energy constraint
- Clean experimental environment: high B, D, K, τ lepton reconstruction efficiency
- Long lived particles (e.g. K_S), π^0s and photons well reconstructed
- $B\bar{B}$ produced in quantum correlated state: high flavour tagging effective efficiency (37% vs 5%@LHCb)
- The full reconstruction of one B (B_{tag}) constraints the 4-momentum of the other B (B_{sig})
- Reconstruction of channels with missing energy

$$p_\nu = p_{e^+e^-} - p_{B_{tag}} - p_{B_{sig}}$$

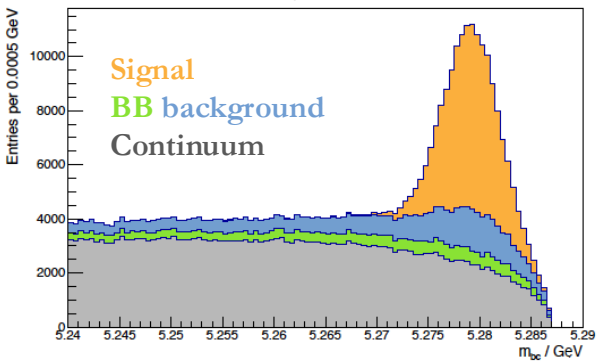




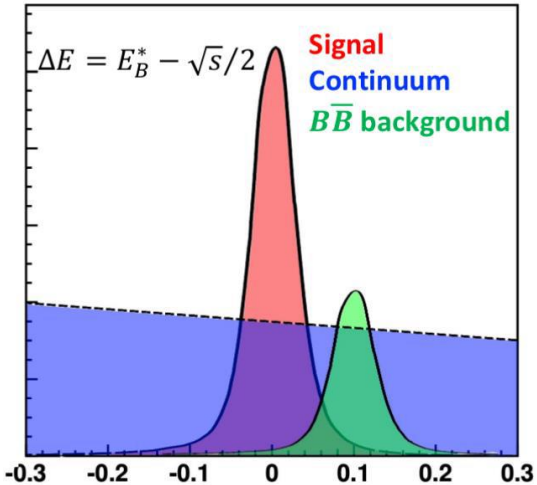
Unique capabilities of e^+e^- B factories

Stringent kinematic constraints

$$M_{bc} = \sqrt{s/4 - p_B^{*2}}$$

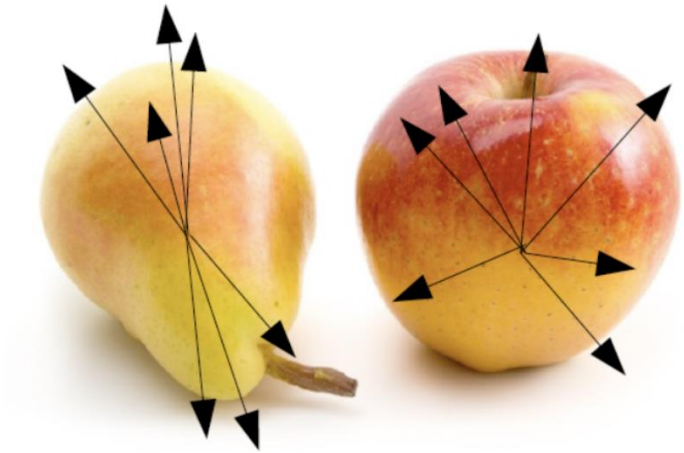


m_B with B energy replaced by half of the collision energy



Difference between expected and observed B energy

Use of event shape variables

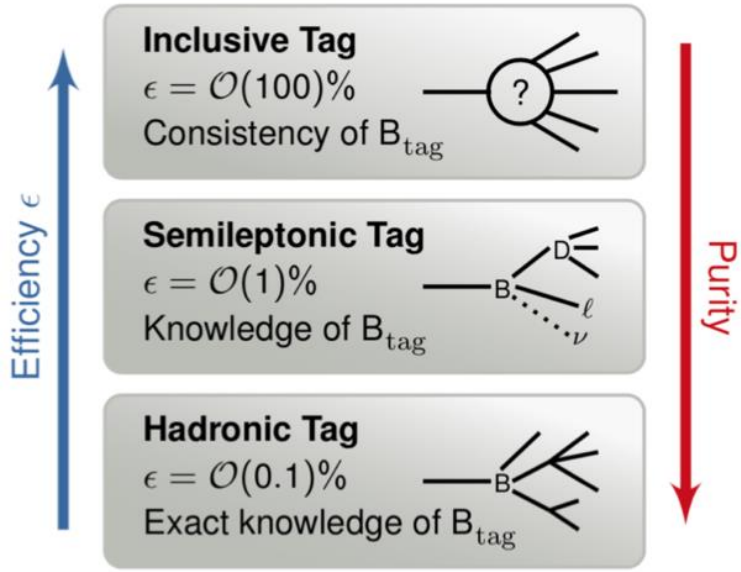


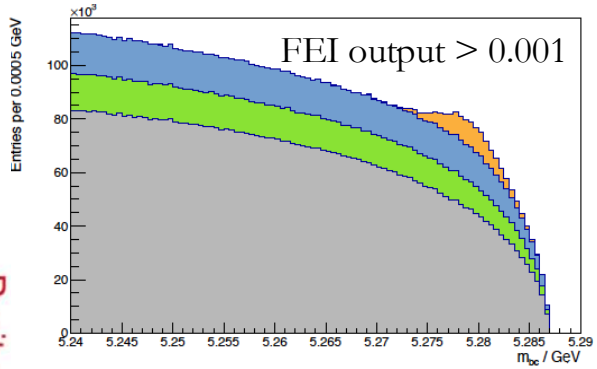
Continuum $p_q^* \approx 5$ GeV/c

$B\overline{B}$ $p_B^* \approx 0.3$ GeV/c

* c.m. quantities

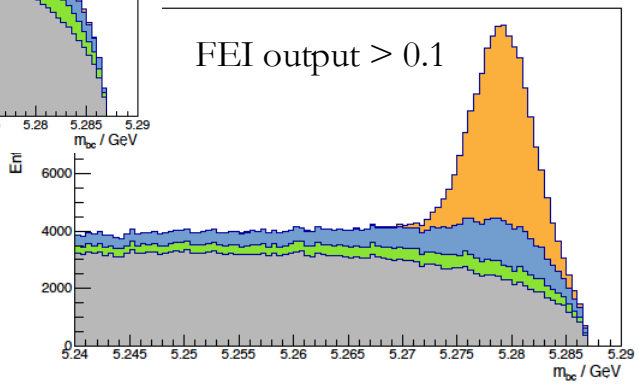
Reconstruction of events with missing energy: Full Event Interpretation (FEI)





M_{bc} (GeV)

Signal
BB background
Continuum



M_{bc} (GeV)

The FEI uses a multivariate technique to reconstruct the B-tag side (semileptonic or hadronic) through $O(10^3)$ decay modes in a $\Upsilon(4S)$ decay.

Tagging efficiency (evaluated on Belle MC) @10% purity

Tagging Algorithm	Had B^+/B^0 (%)	SL B^+/B^0 (%)
Full Reconstruction Belle	0.28/0.18	0.67/0.63
FEI Belle	0.78/0.46	1.80/2.04

Belle algorithm: NIM A 654, 432-440 (2011)
Belle II FEI: Comput Softw Big Sci 3, 6 (2019)

Recent results from Belle / Belle II

- Semileptonic and rare B decays: LFU test, $|V_{xb}|$, leptonic, EWP
- CP asymmetries in D decays
- Dark sector searches
- Tau sector: LFV searches
- Quarkonium

Results shown here are based on Belle data, $L_{int} \sim 711 fb^{-1}$, and Run1 Belle II data, $L_{int} \sim 420 fb^{-1}$ (or a fraction of it)

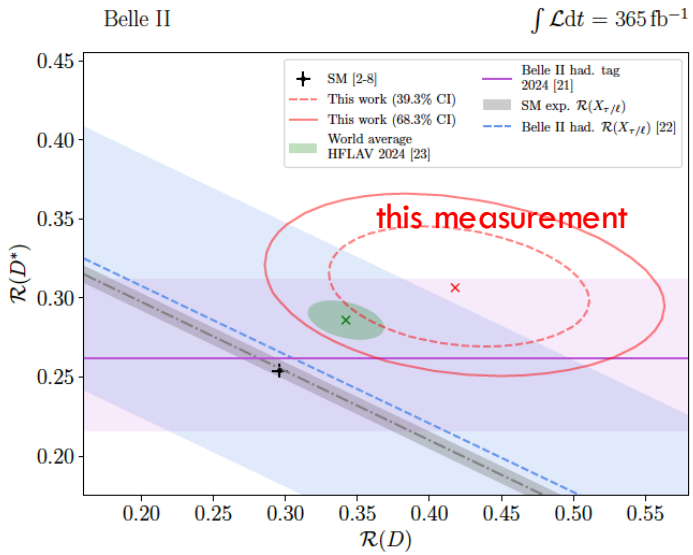
See 17th morning session for focused talk on CKM measurements

Test of lepton flavour universality: R(D) and R(D*)

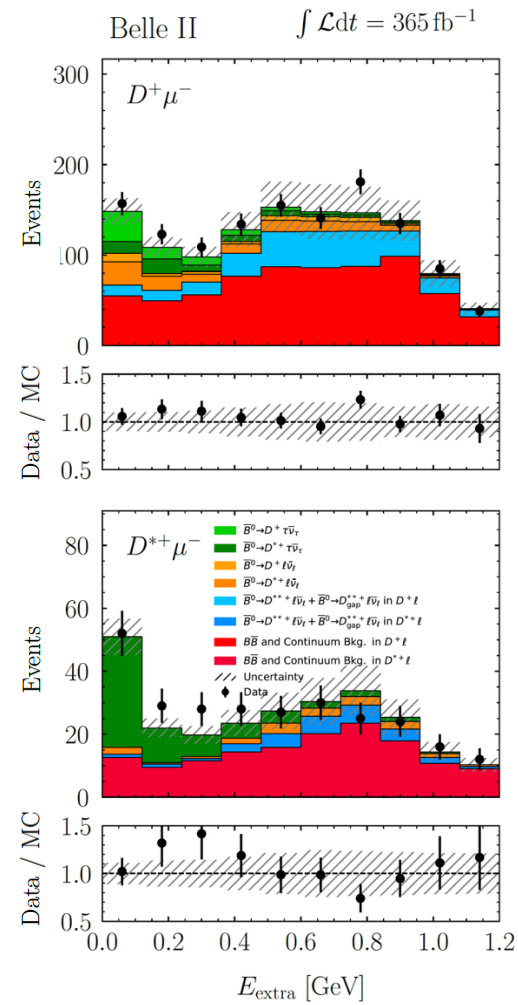
Semileptonic tag

$$R(D^{(*)}) = \mathcal{B}(B \to D^{(*)}\tau\nu) \,/\, \mathcal{B}(B \to D^{(*)}\ell\nu)$$

- 2D ML fit to BDTs to extract the signal and normalization yields simultaneously in 4 channels: $D^+e^-, D^+\mu^-, D^{*+}e^-, D^{*+}\mu^-$
- BDTs are built with variables discriminating $B \to D^{(*)}\tau\nu$, $B \to D^{(*)}\ell\nu$, $B \to D^{**}\ell\nu$ and backgrounds (BB, continuum)



Most discriminating variable is the residual energy in the calorimeter E_{ECL}^{extra}



$$\mathcal{R}(D^+) = 0.418 \pm 0.074\ (\mathrm{stat}) \pm 0.051\ (\mathrm{syst})$$
$$\mathcal{R}(D^{*+}) = 0.306 \pm 0.034\ (\mathrm{stat}) \pm 0.018\ (\mathrm{syst})$$

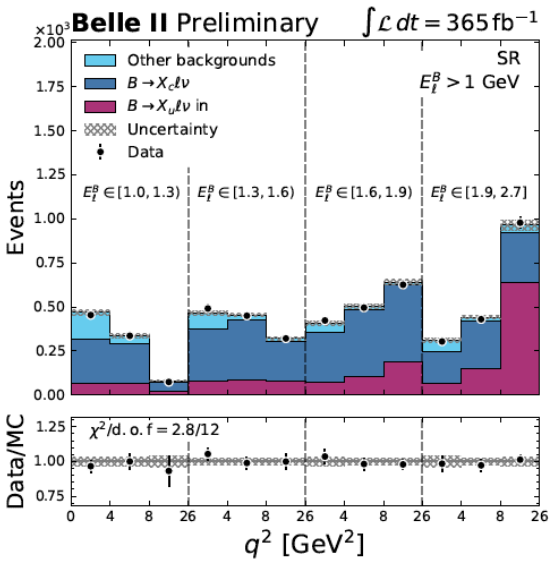
Consistent with SM within 1.7σ

arXiv:2504.11220 (2025)

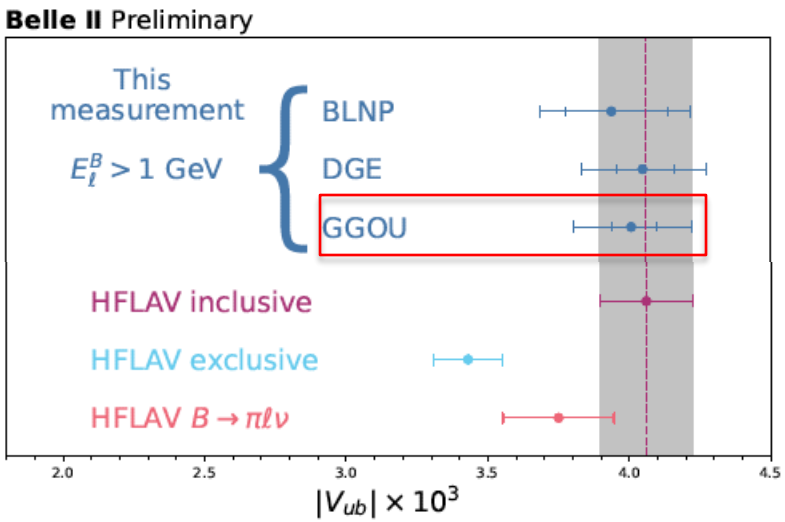
$|V_{ub}|$ determination from inclusive $B \to X_u \ell \nu$

- First Belle II measurement

- Kinematic variables to suppress main bkg. $B \to X_c \ell \nu$: lepton energy in B_{sig} rest frame E_ℓ^B, hadronic system invariant mass M_X, momentum transfer q^2



Hadronic tag



$|V_{ub}|$ is obtained from the branching fraction using the GGOU prediction for the partial decay rate:

$$|V_{ub}| = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u \ell \nu)}{\tau_B \Delta\Gamma(B \to X_u \ell \nu)}}$$

$$\Delta\mathcal{B}(B \to X_u \ell \nu) = (1.54 \pm 0.08 \pm 0.12) \times 10^{-3}$$

$$|V_{ub}| = (4.01 \pm 0.11 \pm 0.16^{+0.09}_{-0.07}) \times 10^{-3}$$

Competitive with other measurements of $|V_{ub}|$

Preliminary

BLNP: Phys. Rev. D 72, 073006
DGE: JHEP 01, 097 (2006)
GGOU: JHEP 10, 058 (2007)

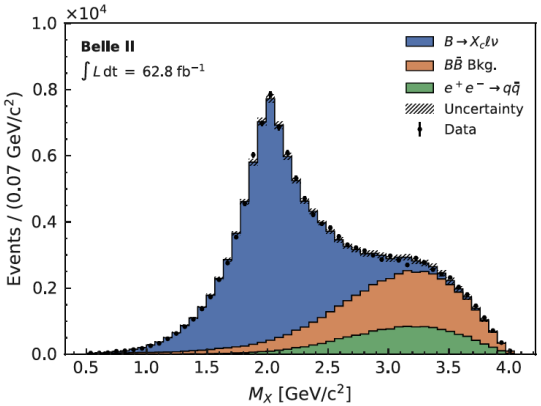
$|V_{cb}|$ determination: leptonic mass squared moments in $B \to X_c \ell \nu$

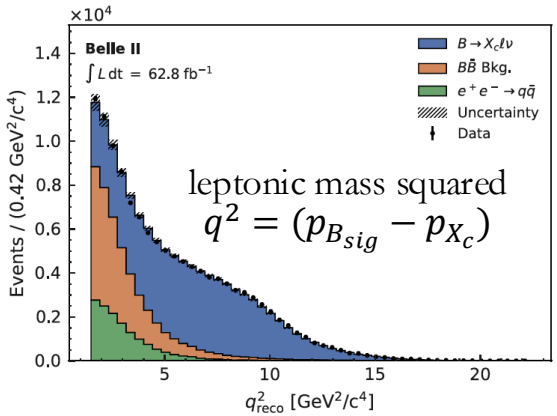
Hadronic tag

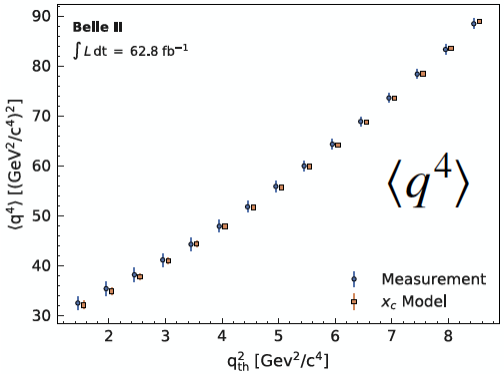
Total decay rate expressed as expansion of non-perturbative matrix elements (heavy quark expansion, HQE)

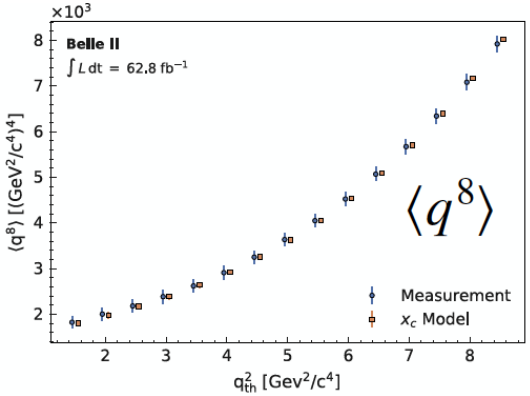
$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^2}|V_{cb}|^2\left(1 + \frac{c_5(\mu)\langle O_5\rangle(\mu)}{m_b^2} + \frac{c_6(\mu)\langle O_6\rangle(\mu)}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$$

Measure the **spectral moments** (moments of leptonic invariant mass, q^2) in order to simultaneously determine the non perturbative elements and $|V_{cb}|$









Novel approach to determine V_{cb} $\longrightarrow |V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$

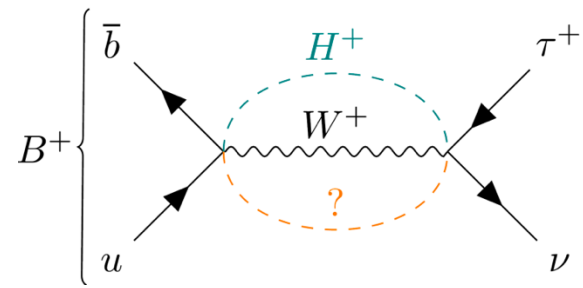
Competitive with world average $|V_{cb}^{incl}| = (42.19 \pm 0.78) \cdot 10^{-3}$

JHEP02(2019)177
PhysRevD.107.072002(2023)
JHEP10(2022)068

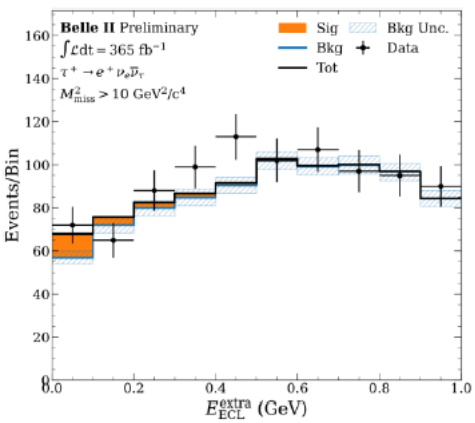
Leptonic B decays: $B \to \tau\nu$

- Leptonic decays are helicity suppressed
- Sensitive to New Physics (e.g. charged Higgs)
- Reconstruct signal in 1-prong τ decay modes
- 2D ML fits to E_{ECL}^{extra} and M_{miss}^2 in four τ decay categories simultaneously

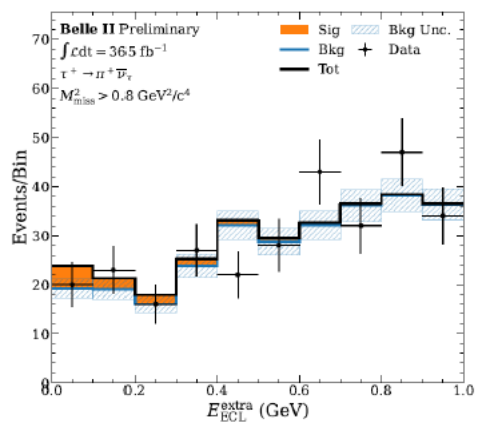
Hadronic tag



$\tau \to e\nu\nu$



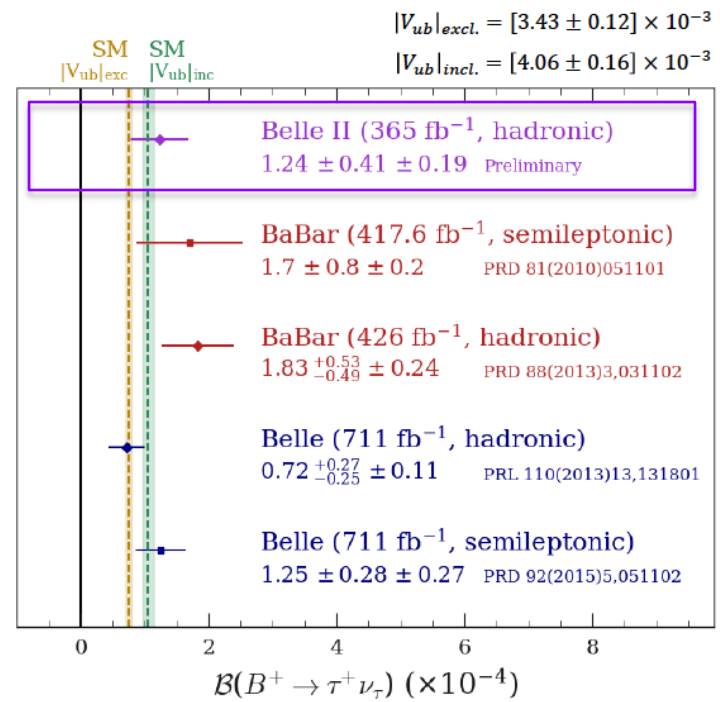
$\tau \to \pi\nu$



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

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

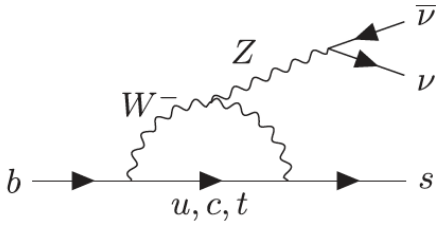
3.0σ from background-only hypothesis

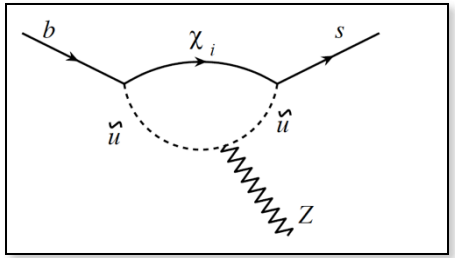


Despite the smaller dataset, the stat. uncertainty is comparable to the previous experiments due to the **improved tagging** and an **optimized selection**

Submitted to PRD, arXiv: 2502.04885 (2025)

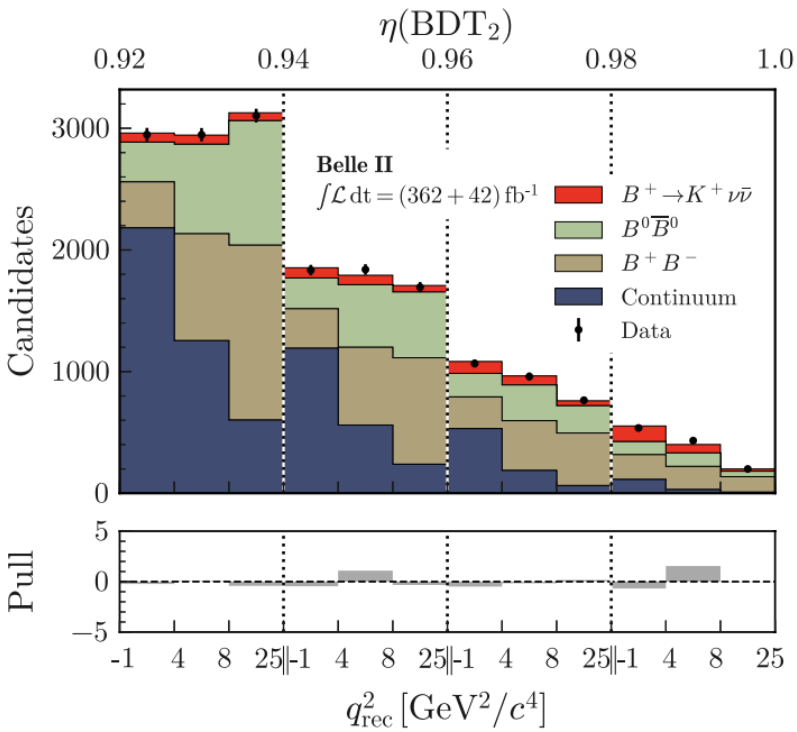
Rare decays: $B^+ \to K^+ \nu\bar{\nu}$



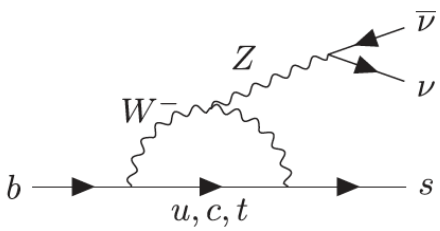


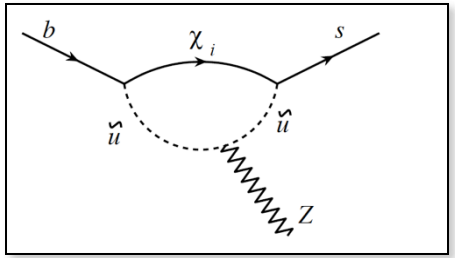
- Novel approach at Belle II: inclusive tagging (total eff. ~8%)
- Fit to invariant masses of neutrinos (q^2) and classifier exploiting topology of the signal

PhysRevD.109.112006 (2024)



Rare decays: $B^+ \to K^+ \nu\bar{\nu}$





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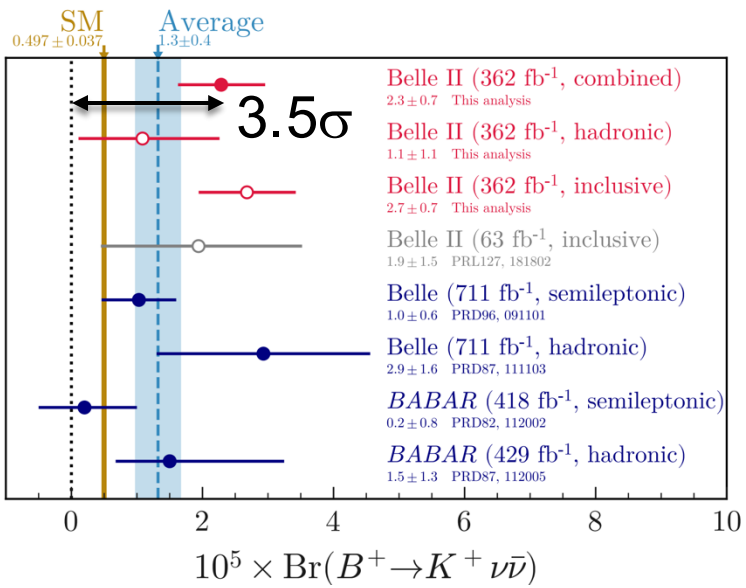
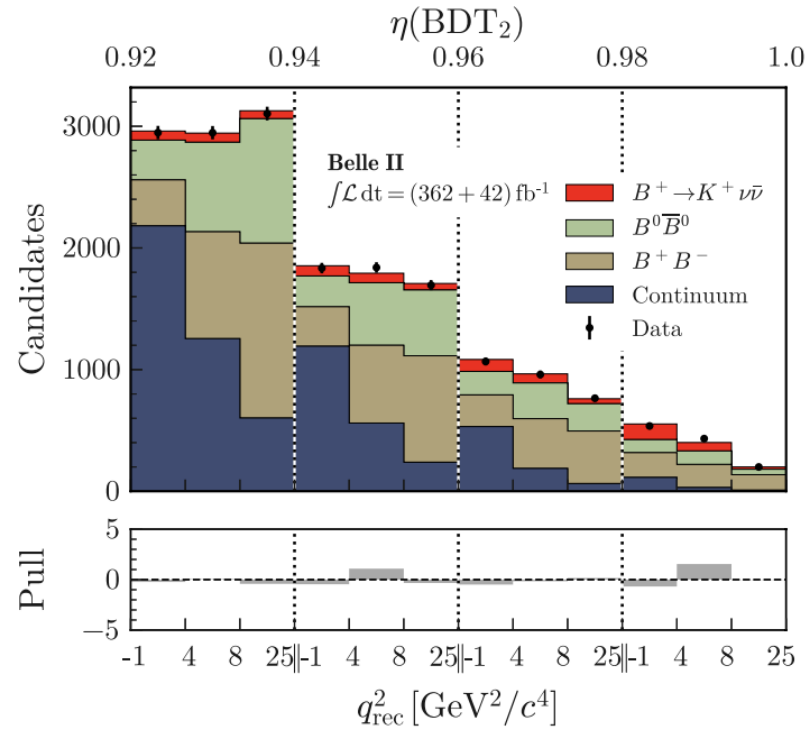


PhysRevD.109.112006 (2024)



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

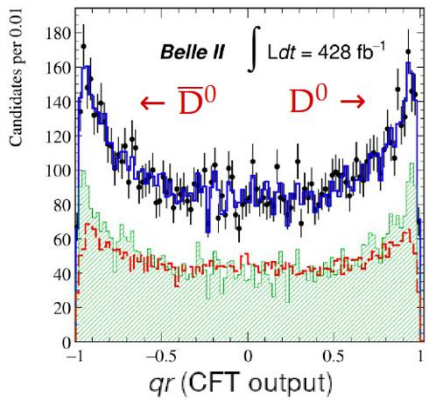
Tension with SM at 2.7σ

Checked with hadronic tag and combined with 10% increase in precision

CP asymmetries in D decays

- CP violation smaller in charm than in beauty sector
- CPV in charm only observed by LHCb in 2019
- Belle / Belle II studied CP asymmetries in $D \to K_S K_S$, $D \to \pi\pi$, $D \to \pi^+\pi^-\pi^0$

$D^0 \to K_S K_S$



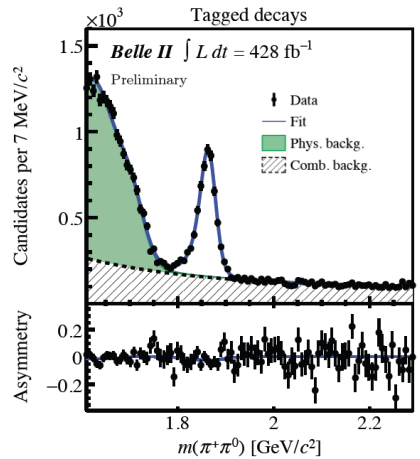
NEW: Use of Charm Flavour Tagger (CFT)

A_{CP} = (− 0.6 ± 1.1 ± 0.1) %

World's best determination, combining Belle and Belle II measurements

PRD 111, 012015 (2025), arXiv:2504.15881

$D^+ \to \pi^+\pi^0$

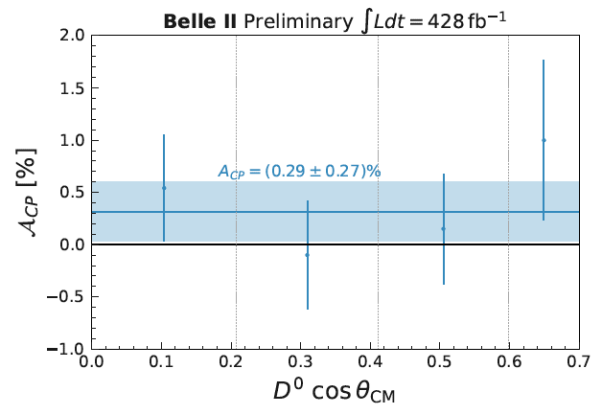


A_{CP} = (− 1.8 ± 0.9 ± 0.1) %

30% (stat.) improvement w.r.t to Belle with only half statistics

arXiv:2506.07879

$D^0 \to \pi^+\pi^-\pi^0$



A_{CP} = (0.29 ± 0.27 ± 0.13)%

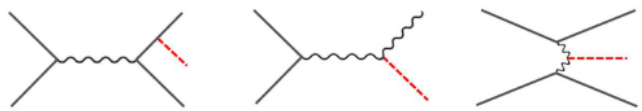
34% (stat.) improvement w.r.t to world's best (BaBar)

preliminary

Dark sector searches

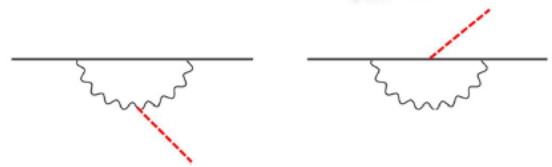
Direct production from collision

$e^+e^- \to X_{Dark} X_{SM}$



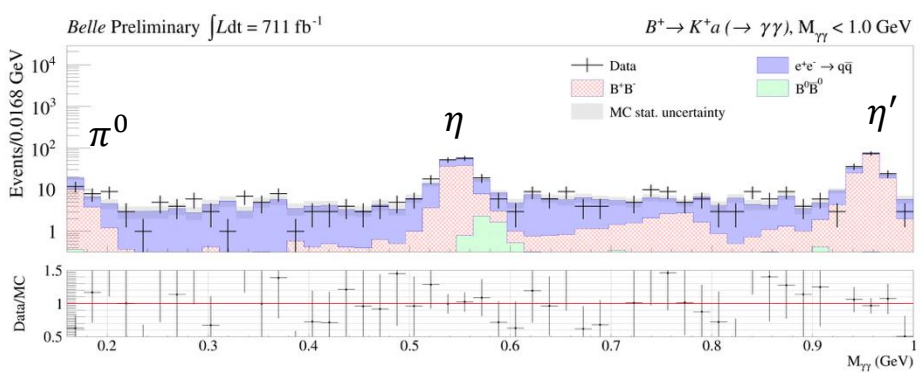
Production in SM particle decays

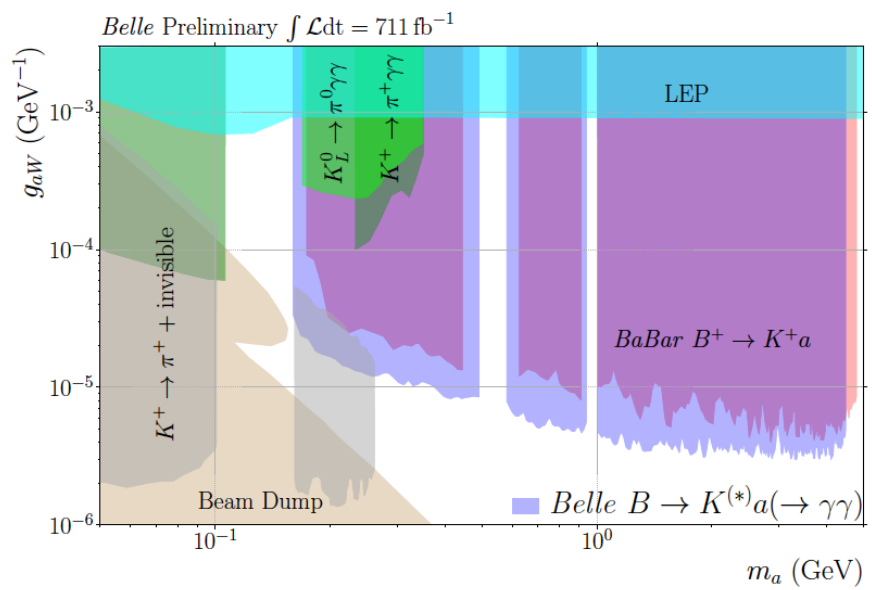
$B/D/\tau/\ldots \to X_{Dark} X_{SM}$



Special triggers for low-multiplicity events: single track, muon, photon

- Search for ALP in the MeV-GeV scale: $B \to K^{(*)} a\ (\to \gamma\gamma)$ using Belle dataset (711fb^{-1})
- Four kaon modes included ($K^{0,+}$ $K^{*0,+}$)
- Fit to di-photon invariant mass
- Limits on the coupling g_{aW} improved by a factor 2 from BaBar





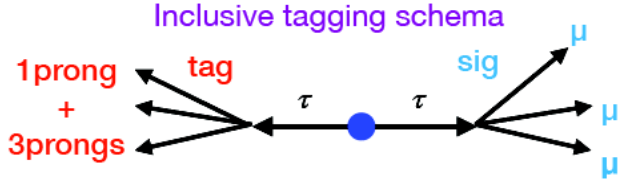
submitted to JHEP, arXiv :2507.01249 (2025)

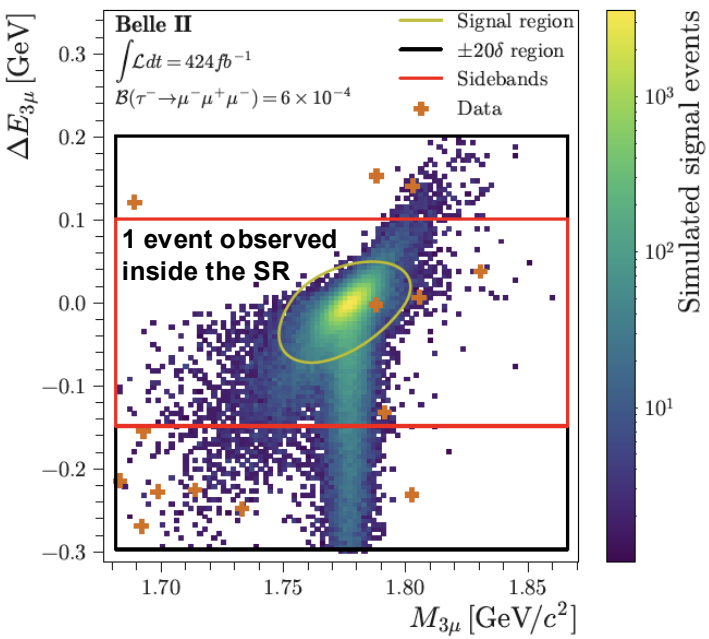
LFV in τ sector

At $\sqrt{s} = 10.58$ GeV: $\sigma_{bb} \sim \sigma_{\tau\tau} \sim 1$ nb → Belle II is also a τ-lepton factory !

$\tau \to \mu\mu\mu$

Inclusive tagging schema



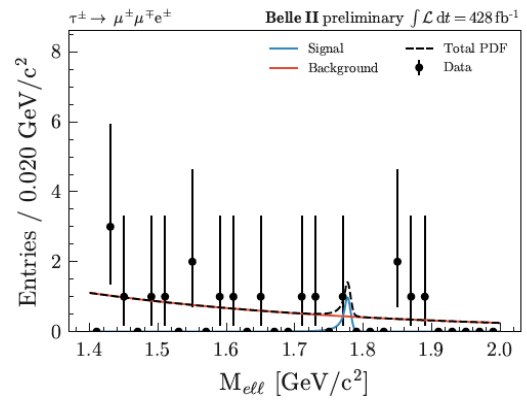


Obtained most stringent limit 1.9 x 10^{-8}

JHEP09(2024)062

$\tau \to e\ell\ell$

inclusive tagging

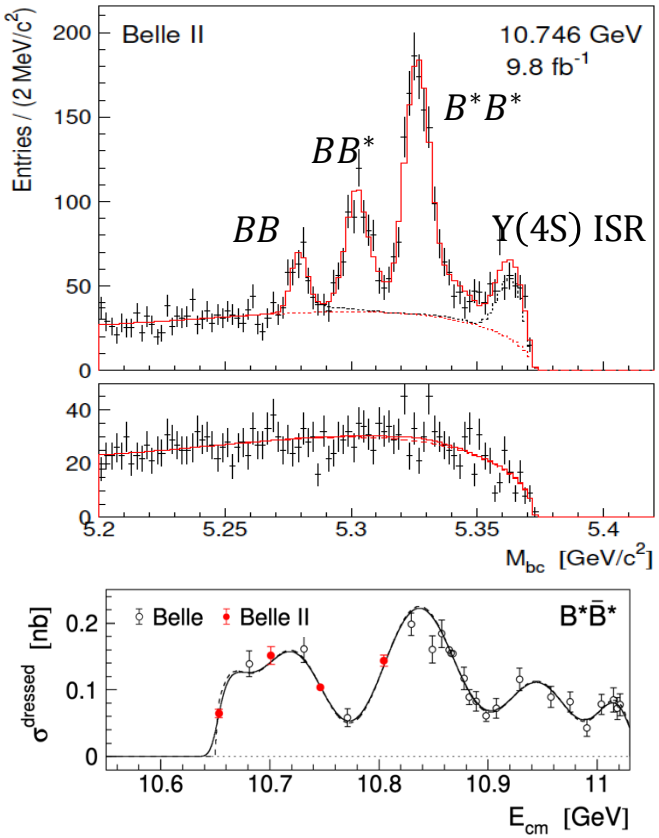


	N_{exp}	N_{obs}	C_{bg}	$\mathcal{B} \times 10^{-8}$	$\mathcal{B}^{UL}_{exp} \times 10^{-8}$	$\mathcal{B}^{UL}_{obs} \times 10^{-8}$
$e^-e^+e^-$	$6.1^{+4.3}_{-2.9}$	5	$0.52^{+2.64}_{-2.60}$	0	2.7	2.5 ★
$e^-e^+\mu^-$	$12.1^{+5.7}_{-4.3}$	12	$-0.40^{+1.67}_{-1.68}$	0	2.1	1.6 ★
$e^-\mu^+e^-$	$10.5^{+5.3}_{-4.3}$	17	$-2.90^{+1.48}_{-1.54}$	0	1.7	1.6
$\mu^-\mu^+e^-$	$20.7^{+6.6}_{-5.5}$	18	$-2.50^{+1.45}_{-1.52}$	$0.48^{+0.90}_{-0.48}$	1.6	2.4 ★
$\mu^-e^+\mu^-$	$7.5^{+4.5}_{-3.2}$	9	$-0.34^{+1.93}_{-1.94}$	0	1.4	1.3 ★

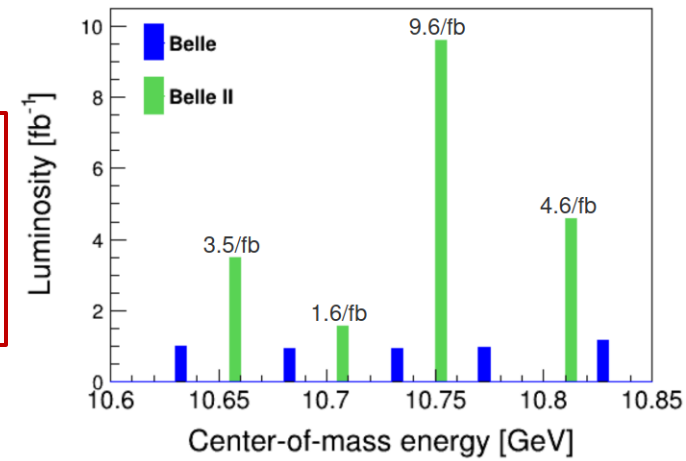
★ most stringent limits to date

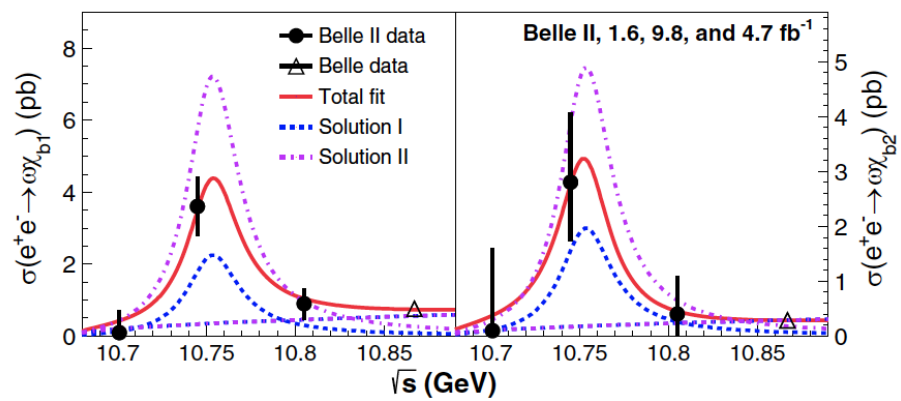
Preliminary

Quarkonium



In 2021, SuperKEKB ran above Υ(4S) resonance





Measurement of the energy dependence of the $ee \to BB, BB^*, B^*B^*$ cross sections

JHEP10(2024)114

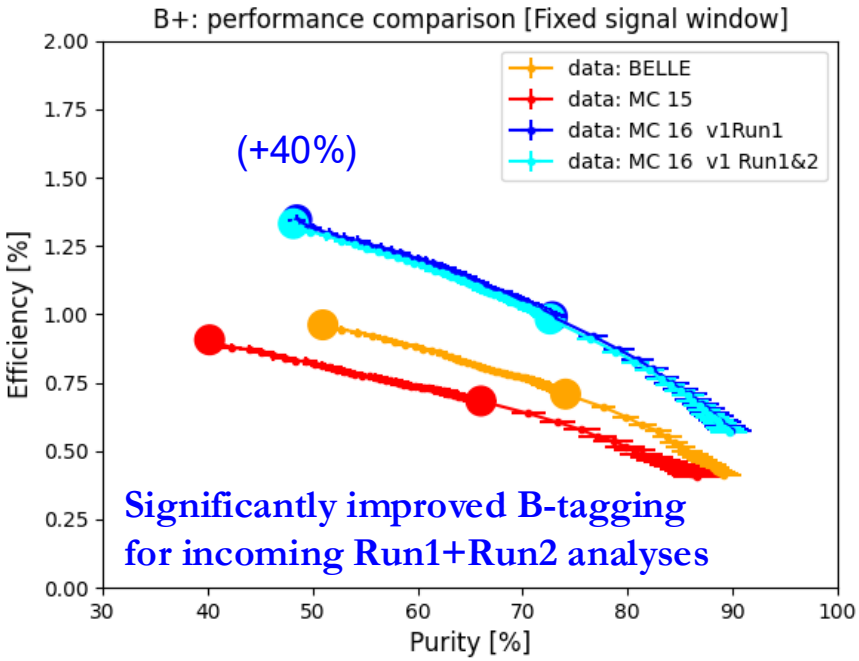
- Measurement of cross-section peak, consistent with Υ(10753) state
- First observation of $\omega\ \chi_{bJ}(1P)$ signal at 10.745 GeV

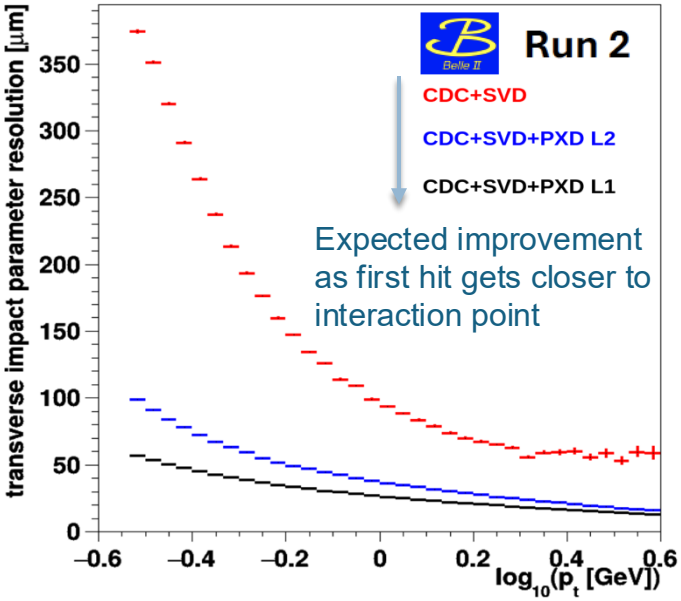
PRL 130, 091902 (2023)

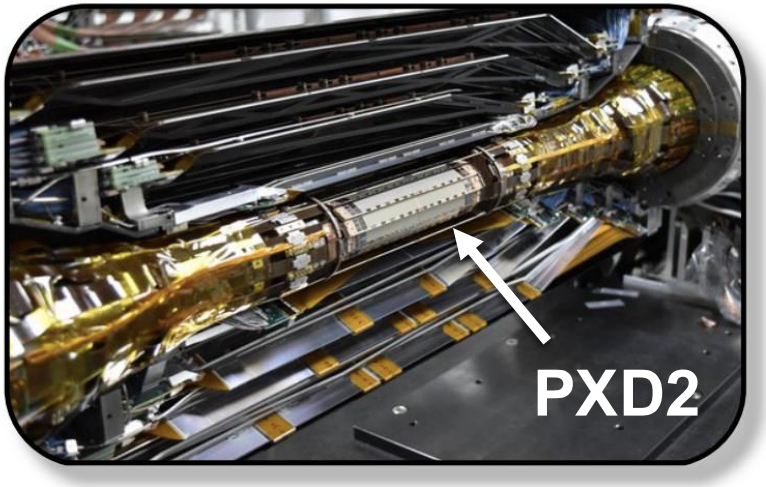
Run II and improvements

LS1 (2022-2024):

- detector improvements, mainly installation of full **two-layer pixel detector** (PXD2)
- accelerator improvements, e.g. non-linear collimators to combat beam background



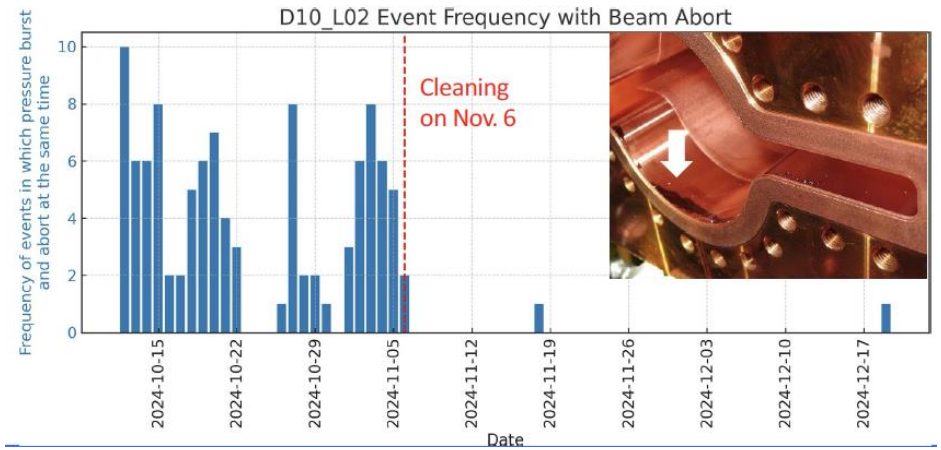


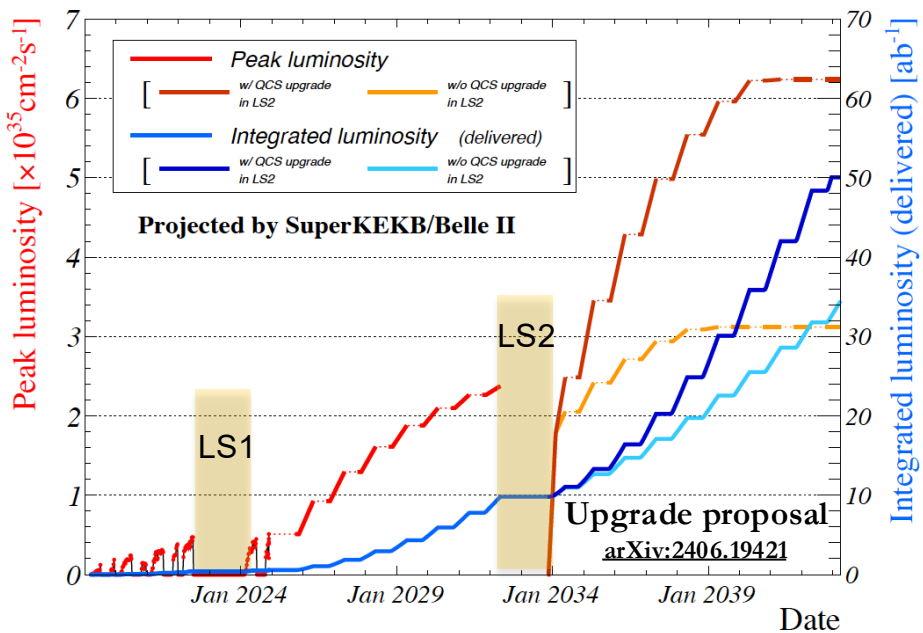


Run II and luminosity projections

Run 2 (2024 –)

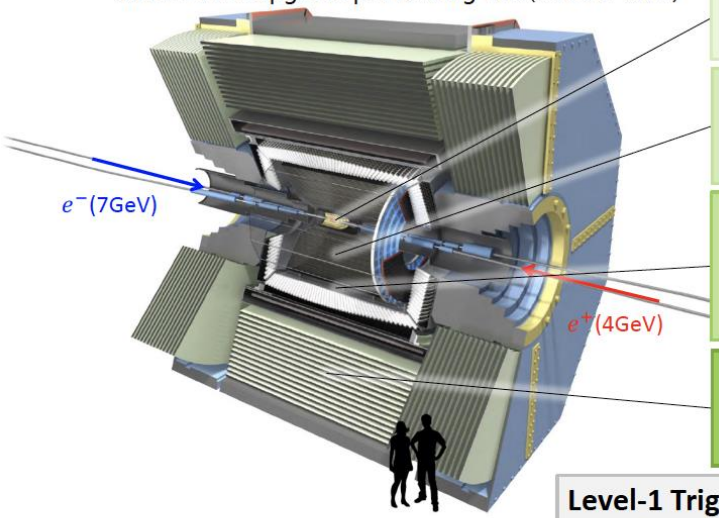
- back to operations at $4 \times 10^{34}\ cm^{-2}s^{-1}$, but… sudden beam loss has happened frequently that can lead to very large dose in the detector
- Two such losses led to damage of 2% of PXD gates → turned off PXD as a precautionary measure until beam losses mitigated
- Black stains found inside beam pipe flanges, probably caused by vacseal residual (high vacuum sealant)
- We'll resume collisions in Nov 2025 and plan to exceed $10^{35}\ cm^{-2}s^{-1}$ by LS2





Belle II upgrade during LS2

Middle-term upgrade plan during LS2 (2028 or later)



Vertex detector
- Fully-pixelated CMOS DMAPS detector

Drift chamber (CDC)
- New front-end electronics (less cross-talk, better radiation hardness, and less power)

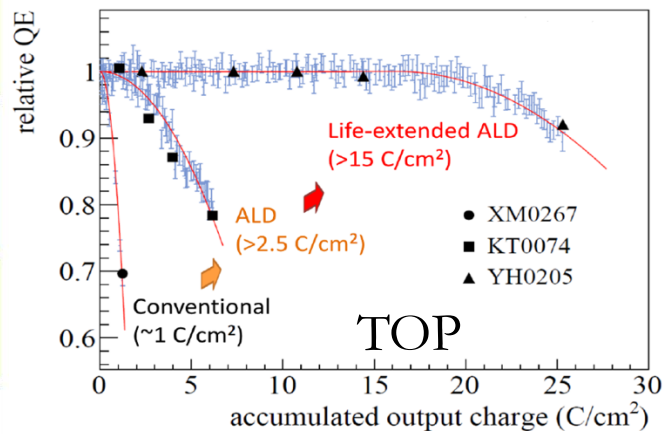
Particle identification

Barrel: Time-Of-Propagation counters (TOP)
- Replace w/ life-extended PMTs
- New front-end electronics (less power)

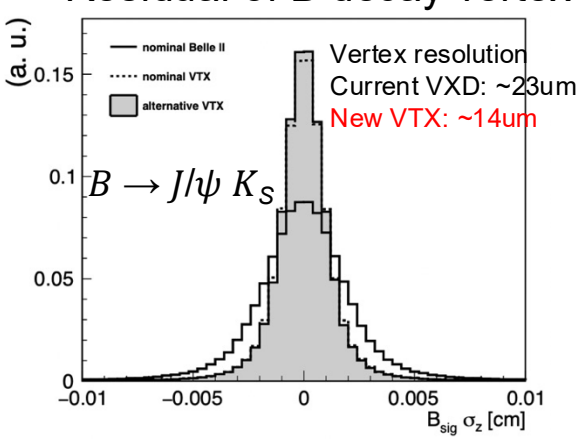
K_L/μ detector (RPC + scintillator)
- Option 1: Replace RPC w/ scintillator
- Option 2: RPC avalanche mode operation

Level-1 Trigger
- Replace electronics with latest technology to allow more sophisticated ML algorithm and more data bandwidth

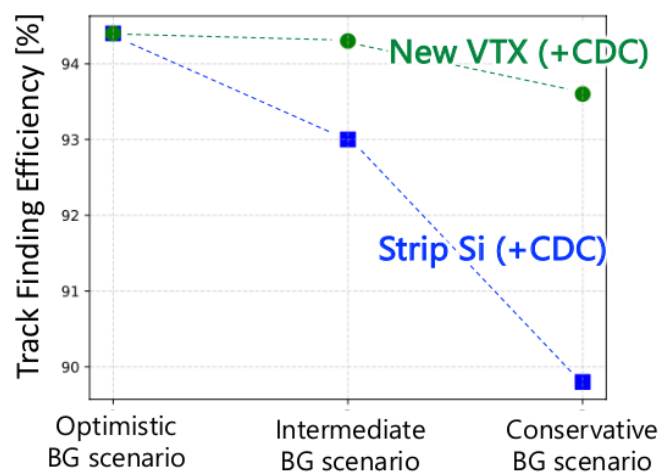
Photocathode lifetime improvements



Residual of B decay vertex



See July 22nd afternoon session for focused talk on Belle II upgrade program



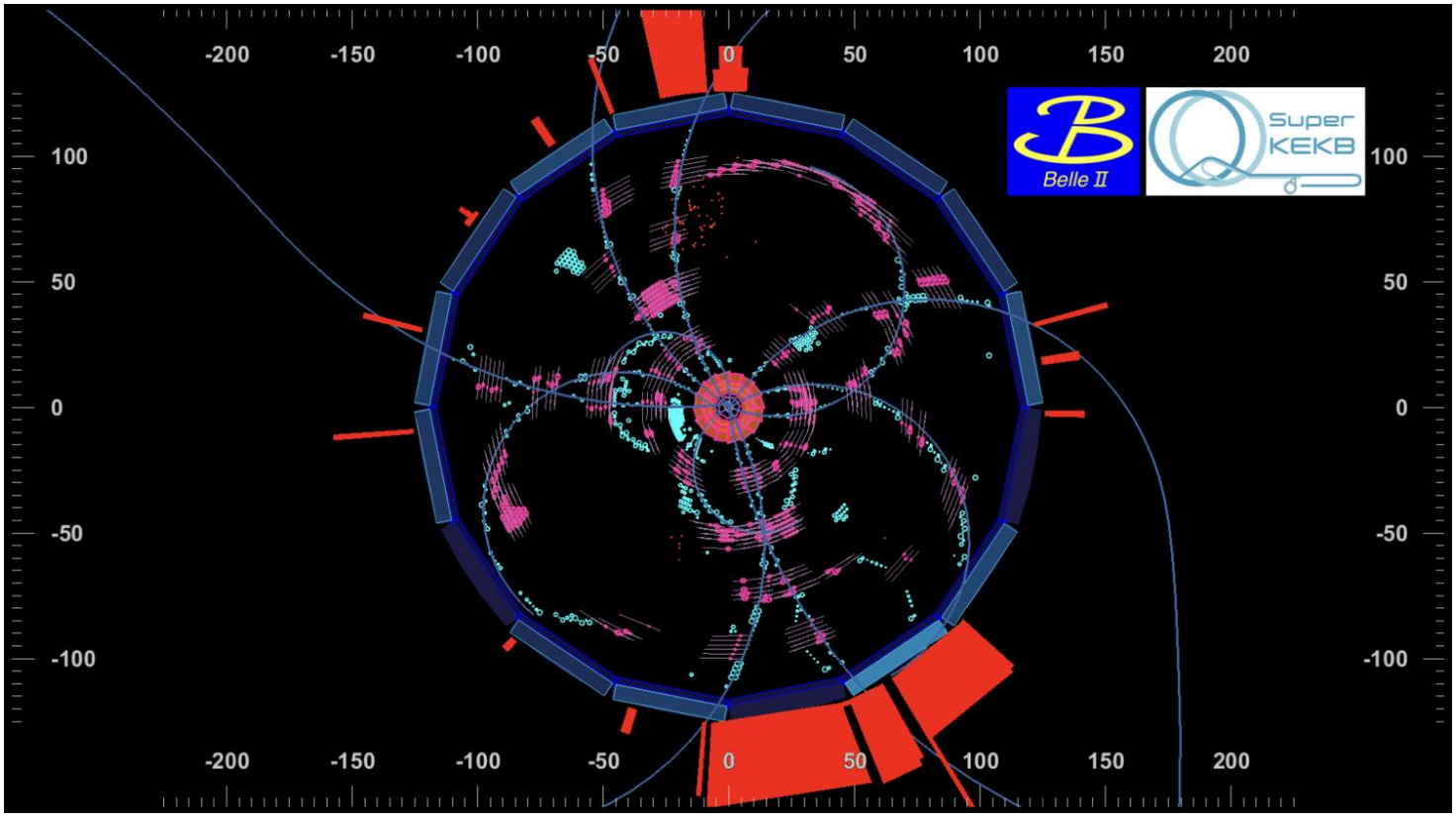
Conclusions

Belle II experiment has collected a sample that exceeds the size of BaBar's and is more than half the size of Belle's.

Belle II is not only a high luminosity Belle Experiment. With the use of novel analyses techniques we have already achieved results that compete with previous measurements and some results that are exclusive to us.

After LS1, we resumed collisions in March 2024 (Run 2) and in few years Belle II will get the sensitivity to shed light on the anomalies in the Standard Model

Thanks!


-200
-150
-100
-50
0
50
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150
200
100
50
0
-50
-100
Belle II
Super KEKB

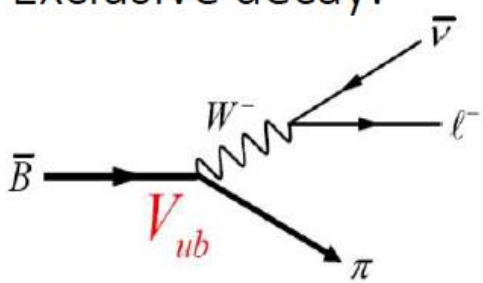
Backup

- 31: exclusive inclusive B decays
- 32: RD systematics
- 33-34: R(X)
- 35-36: Vub from B-> pilnu and B->rholnu
- 37: Vub from B->Xulnu systematics
- 38-39: B-> Ktautau
- 40: g-2
- 41-46: CP asymmetries B->pi0pi0, B->rhorho, Isospin sum rule
- 47: tau physics summary
- 48-49: Vcb from spectral moments
- 50-51: B->D*lnu angular asymmetries
- 52-53: charm lifetimes
- 54: tau mass
- 55: Belle II projections

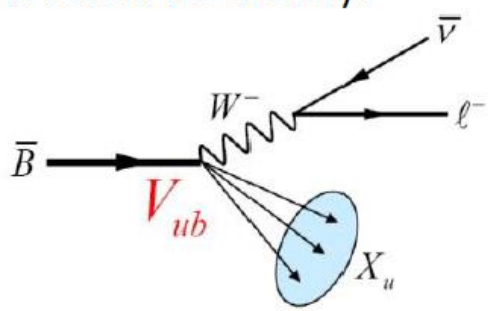
Exclusive and inclusive B decays

	Experiment	Theory
Exclusive	1. Lower signal efficiency 2. Lower background	Lattice QCD $dB/dq^2 \propto \lvert V_{qb}\rvert^2 FF(q^2)$ (LQCD, LCSR)
Inclusive	1. Higher signal efficiency 2. Higher background	Heavy Quark Effective Theory (HQET) $BF(B \to X\ell\nu) \propto \lvert V_{qb}\rvert^2 (1 + 1/m_b \times \cdots)$ (OPE)

Exclusive decay:



Inclusive decay:



$R(D^{(*)})$ systematics

TABLE I. Systematic uncertainties on $\mathcal{R}(D^+)$ and $\mathcal{R}(D^{*+})$ ranked by the magnitude of the uncertainty on $\mathcal{R}(D^+)$. The percentage values in brackets indicate the relative uncertainty.

Systematic Uncertainty	$\Delta\mathcal{R}(D^+)$	$\Delta\mathcal{R}(D^{*+})$
Additive		
MC sample size	0.033 (8.0%)	0.014 (4.7%)
Gap $\mathcal{B}$	0.027 (6.4%)	0.001 (0.1%)
LID efficiency (μ)	0.022 (5.1%)	0.001 (0.1%)
Fake rates (e)	0.012 (2.9%)	0.003 (0.9%)
$\pi^\pm$ from $D^* \to D\pi$	0.003 (0.7%)	0.001 (0.1%)
Continuum fraction	0.002 (0.6%)	0.001 (0.2%)
$\overline{B} \to D^{(*)}\ell\bar{\nu}_\ell$ / $\tau\bar{\nu}_\tau$ FFs	0.002 (0.5%)	0.002 (0.7%)
Gap FFs	0.002 (0.5%)	0.001 (0.2%)
$\mathcal{B}(\overline{B} \to D^{**}\ell\bar{\nu}_\ell)$	0.002 (0.5%)	0.001 (0.1%)
$\overline{B} \to D^{**}\ell\bar{\nu}_\ell$ FFs	0.001 (0.3%)	0.001 (0.2%)
BDT modeling	0.001 (0.3%)	0.001 (0.2%)
LID efficiency (e)	0.001 (0.1%)	0.001 (0.2%)
Fake rates (μ)	0.001 (0.1%)	0.001 (0.1%)
Total Additive Uncertainty	0.050 (12%)	0.015 (4.8%)
Multiplicative		
$\overline{B} \to D^{(*)}\ell\bar{\nu}_\ell$ / $\tau\bar{\nu}_\tau$ FFs	0.009 (2.1%)	0.011 (3.5%)
MC sample size	0.007 (1.7%)	0.004 (1.2%)
LID efficiency (e)	0.001 (0.2%)	0.001 (0.2%)
$\mathcal{B}(\tau^- \to \ell^-\overline{\nu}_\ell\nu_\tau)$	0.001 (0.2%)	0.001 (0.2%)
LID efficiency (μ)	0.001 (0.1%)	0.001 (0.1%)
Tracking efficiency	0.001 (0.1%)	0.001 (0.1%)
$\pi^\pm$ from $D^* \to D\pi$	– (–)	0.001 (0.2%)
Total Multiplicative Uncertainty	0.012 (2.8%)	0.011 (3.7%)
Total Syst. Uncertainty	0.051 (12%)	0.018 (6.2%)
Total Stat. Uncertainty	0.074 (18%)	0.034 (11%)
Total Uncertainty	0.090 (22%)	0.039 (13%)

Test of lepton flavour universality: inclusive $B \to X\ell\nu$

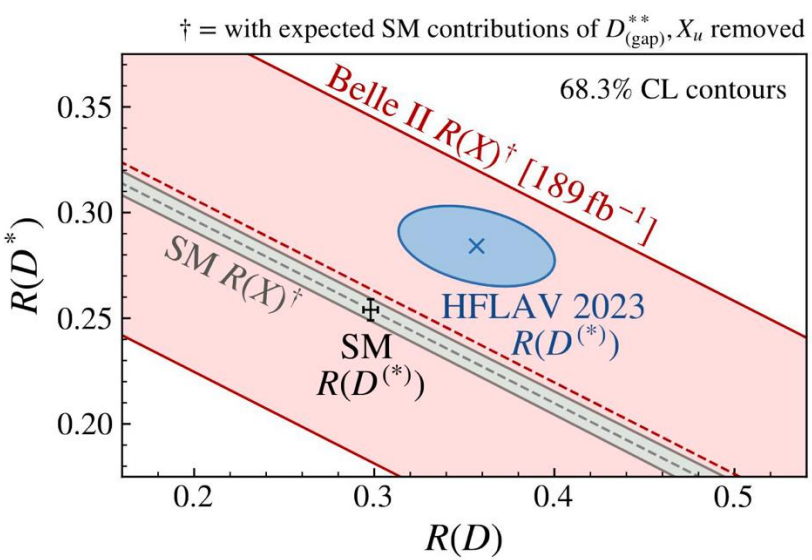
$$R(X_{\tau/l}) = \mathcal{B}(B \to X\tau\nu)/\,\mathcal{B}(B \to Xl\nu)$$

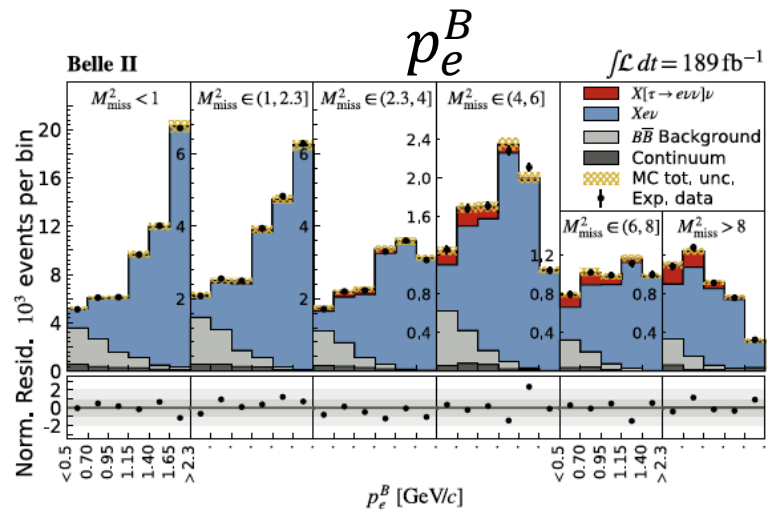
Hadronic tagged analysis

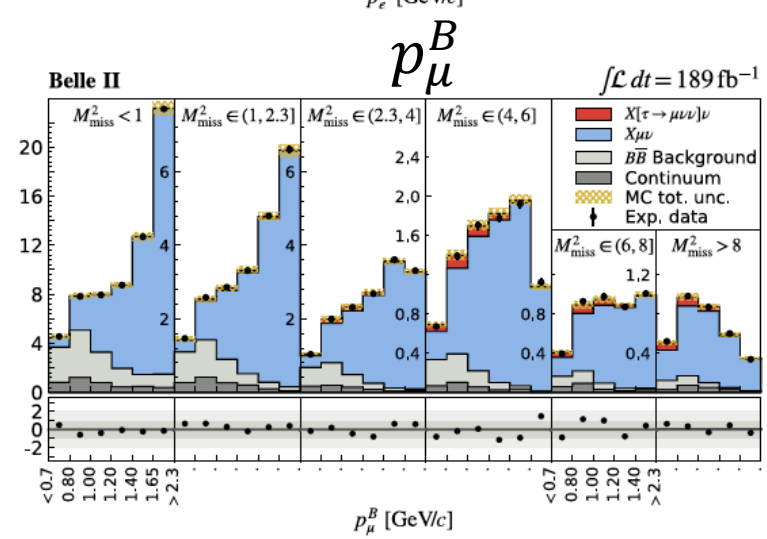
- 2D ML fit to extract the signal and normalization for electon and muon modes simultaneously, in bins of p_l^B and M^2_{miss}

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

- Consistent with SM and $R(D^{(*)})$ anomalies







PhysRevLett.132.211804 (2024)

$R(X_{\tau/l}) = \mathcal{B}(B \to X\tau\nu) / \mathcal{B}(B \to Xl\nu)$

TABLE I. Relative statistical and systematic uncertainties on the value of $R(X_{\tau/\ell})$ for electrons, muons, and their combination (ℓ). Detailed descriptions of each source are provided in the text.

	Uncertainty [%]		
Source	e	μ	ℓ
Experimental sample size	8.8	12.0	7.1
Simulation sample size	6.7	10.6	5.7
Tracking efficiency	2.9	3.3	3.0
Lepton identification	2.8	5.2	2.4
$X_c\ell\nu$ reweighting	7.3	6.8	7.1
$B\bar{B}$ background reweighting	5.8	11.5	5.7
$X\ell\nu$ branching fractions	7.0	10.0	7.7
$X\tau\nu$ branching fractions	1.0	1.0	1.0
$X_c\tau(\ell)\nu$ form factors	7.4	8.9	7.8
Total	18.1	25.6	17.3

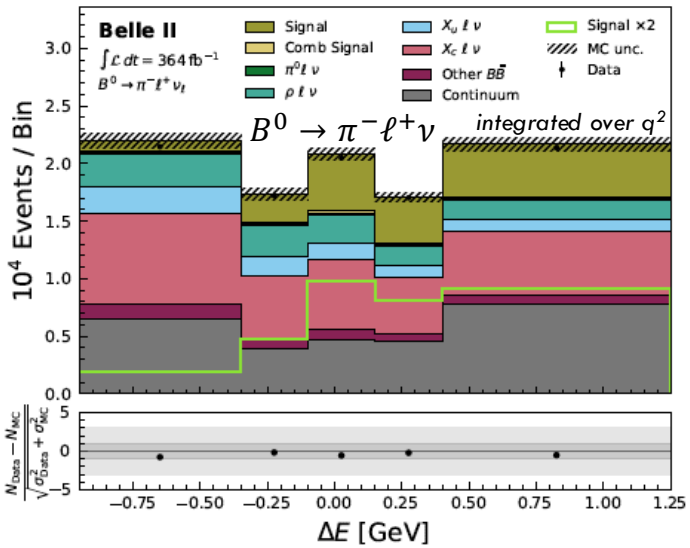
$|V_{ub}|$ determination from $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$

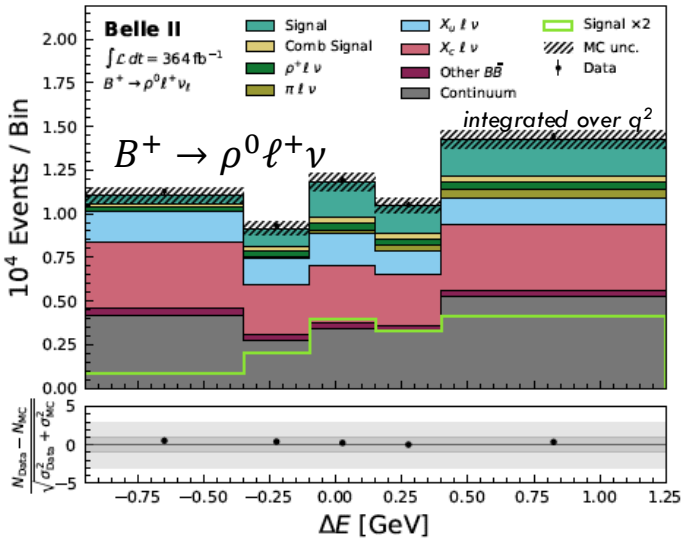
- 2D fit to M_{bc} and ΔE in bins of $q^2 = (p_B - p_X)^2$
- Main unc.: theoretical and off-resonance sample size
- Results consistent with SM predictions and precision comparable with Belle/Babar

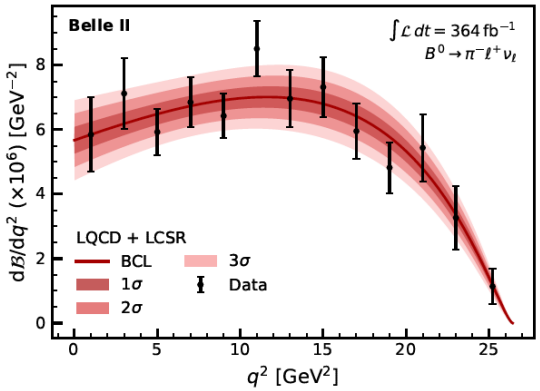
$|V_{ub}|_{B\to\pi l\nu} = (3.73 \pm 0.07 \pm 0.07 \pm 0.16) \times 10^{-3}$
LQCD+LCSR

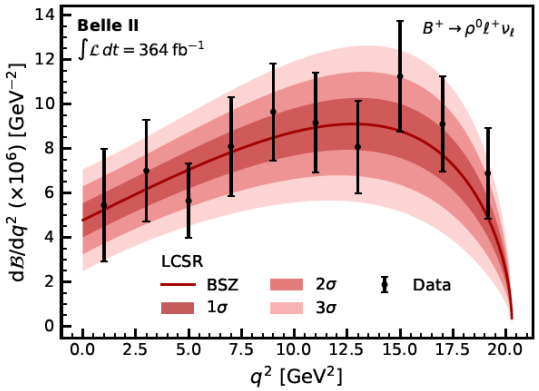
$|V_{ub}|_{B\to\rho l\nu} = (3.19 \pm 0.12 \pm 0.17 \pm 0.26) \times 10^{-3}$
LCSR stat syst theo

Untagged analysis









arXiv:2407.17403 (2024)

$|V_{ub}|$ determination from $B \to \pi \ell \nu$ and $B \to \rho \ell \nu$

$$\chi^2 = \sum_{i,j=1}^{N} (\Delta\mathcal{B}_i - \Delta\Gamma_i \tau) C_{ij}^{-1} (\Delta\mathcal{B}_j - \Delta\Gamma_j \tau) + \sum_m \chi^2_{\mathrm{Theory},m},$$

$$\chi^2_{\mathrm{LQCD}} = \sum_{k,l=1}^{5} (b_k - b_k^{\mathrm{LQCD}}) C^{-1}_{\mathrm{LQCD},kl} (b_l - b_l^{\mathrm{LQCD}})$$

		$B^0 \to \pi^- \ell^+ \nu_\ell$ LQCD	$B^0 \to \pi^- \ell^+ \nu_\ell$ LQCD + LCSR
$\lvert V_{ub}\rvert$ (10^{-3})		3.93 ± 0.25	3.73 ± 0.19
$f_+(q^2)$	b_0^+	0.42 ± 0.02	0.45 ± 0.02
	b_1^+	-0.52 ± 0.05	-0.52 ± 0.05
	b_2^+	-0.81 ± 0.21	-1.02 ± 0.18
$f_0(q^2)$	b_0^0	0.02 ± 0.25	0.59 ± 0.02
	b_1^0	-1.43 ± 0.08	-1.39 ± 0.07
χ^2/ndf		$8.39/7$	$8.36/7$

Table VIII: Summary of fractional uncertainties in % on the extracted $|V_{ub}|$ values.

	$B^0 \to \pi^- \ell^+ \nu_\ell$ LQCD	$B^0 \to \pi^- \ell^+ \nu_\ell$ LQCD + LCSR	$B^+ \to \rho^0 \ell^+ \nu_\ell$ LCSR
Detector effects	0.64	0.24	0.44
Beam energy	0.05	0.03	0.09
Simulated sample size	1.51	0.78	1.41
BDT efficiency	0.31	0.21	0.28
Physics constraints	0.61	0.43	0.88
Signal model	0.38	0.13	0.41
ρ lineshape	0.26	0.21	0.13
Nonres. $B \to \pi\pi\ell\nu_\ell$	0.43	0.11	1.97
DFN parameters	0.64	0.32	0.88
$B \to X_u \ell \nu_\ell$ model	0.61	0.40	1.56
$B \to X_c \ell \nu_\ell$ model	0.51	0.43	0.50
Continuum	2.39	1.37	4.91
Total systematic	3.26	1.91	5.33
Statistical	2.31	1.82	3.76
Theory	4.83	4.29	8.15
Total	6.40	5.13	10.34

$|V_{ub}|$ determination from $B \to X_u \ell \nu$

TABLE VI. Systematic uncertainty breakdown of the branching fraction uncertainty for all fits.

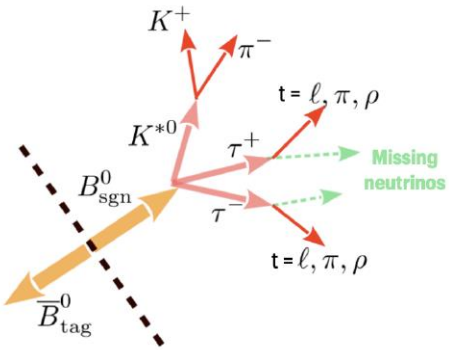
	Relative uncertainty (%)		
Uncertainty source	Fit 1	Fit 2	Fit 3
DFN parameters	4.4	4.5	5.7
DFN $\to$ BLNP	0.2	0.8	1.3
γ_S	1.7	2.1	2.1
$B \to \pi\ell\nu$ form factors	0.3	0.3	0.3
$B \to \rho\ell\nu$ form factors	0.3	0.3	0.2
$B \to \omega\ell\nu$ form factors	0.1	0.1	0.1
$B \to \eta/\eta'\ell\nu$ form factors	< 0.1	< 0.1	< 0.1
$B^\pm \to X_u\ell\nu$ branching fractions	0.9	0.6	0.5
$B^0 \to X_u\ell\nu$ branching fractions	0.6	0.5	0.5
$B \to D^{**}_{\text{Broad}}$ form factors	0.5	0.1	0.2
$B \to D^{**}_{\text{Narrow}}$ form factors	0.1	< 0.1	< 0.1
$B \to D/D^*\ell\nu$ form factors	< 0.1	< 0.1	< 0.1
$B^\pm \to X_c\ell\nu$ branching fractions	0.7	0.5	0.2
$B^0 \to X_c\ell\nu$ branching fractions	0.6	0.2	0.1
D decay branching fractions	0.1	0.3	0.1
SR $X_c\ell\nu$ normalisation	1.6	3.5	3.4
CR $X_c\ell\nu$ normalisation	1.0	1.1	0.4
Other backgrounds normalisation	0.3	N/A	N/A
X_u fragmentation	0.3	4.4	3.9
$N_{\Upsilon(4S)}$	1.4	1.4	1.4
FEI	1.3	1.3	1.4
π_s	0.4	0.2	0.3
ℓ identification	0.7	0.7	0.6
$f^{\pm/00}$	0.6	0.7	0.6
Continuum calibration	0.2	0.2	0.2
Tracking	0.3	0.3	0.3
K^0_S efficiency	0.1	0.1	< 0.1
$K^\pm$ ID	< 0.1	< 0.1	< 0.1
Simulated data statistics	1.1	1.1	0.8
Fit bias	2.6	2.3	1.8
Composition uncertainty	1.3	5.7	0.2
$B \to X_c\ell\nu$ overestimation correction	2.6	0.4	1.3
Total systematic	7.8	10.5	9.7
Statistical	5.4	5.6	4.5
Total	9.5	11.9	10.7

Rare decays: $B^0 \to K^{*0}\tau^+\tau^-$

- FCNC process $\mathcal{B}_{SM}(B^0 \to K^{*0}\tau^+\tau^-) = (0.98 \pm 0.10) \times 10^{-7}$ sensitive to NP models involving third-generation fermion couplings

PhysRevLett.120.181802

- Simultaneous fit to BDT of all categories ($\ell\ell$, $\ell\pi$, $\pi\pi$, ρX)

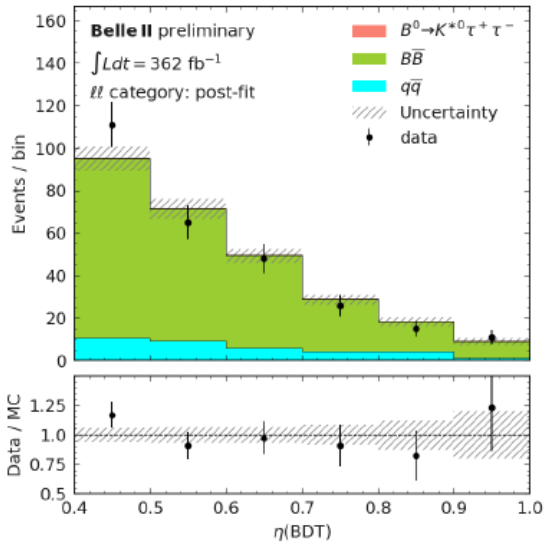


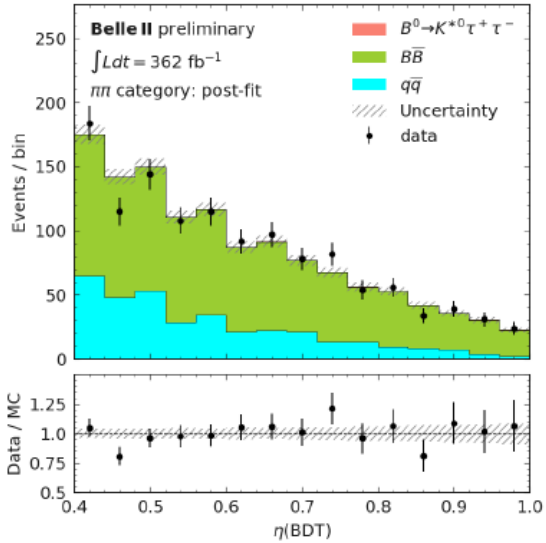
- Main systematics: simulated sample size, knowledge of D** backgrounds

$$\mathcal{B} < 1.8 \times 10^{-3} \text{ at } 90\% \text{ C.L.}$$

Most stringent limit, twice better than world best, with half statistics

Hadronic tag





https://arxiv.org/pdf/2504.10042

Rare decays: $B^0 \to K^{*0}\tau^+\tau^-$

Table II: The systematic uncertainties for the branching fraction of $B^0 \to K^{*0}\tau^+\tau^-$, which were computed following the procedure in Ref. [37].

Source	Impact on $\mathcal{B} \times 10^{-3}$
$B \to D^{**}\ell/\tau\nu$ branching fractions	0.29
Simulated sample size	0.27
$q\bar{q}$ normalization	0.18
ROE cluster multiplicity	0.17
π and K ID	0.14
B decay branching fraction	0.11
Combinatorial $B\overline{B}$ normalization	0.09
Signal and peaking $B^0\overline{B}^0$ normalization	0.07
Lepton ID	0.04
π^0 efficiency	0.03
f_{00}	0.01
$N_{\Upsilon(4S)}$	0.01
$D \to K_L^0$ decays	0.01
Signal form factors	0.01
Luminosity	< 0.01
Total systematics	0.52
Statistics	0.86

Table I: Signal efficiencies (ε) and expected background yields, for $\eta(\mathrm{BDT}) > 0.4$. The signal categories are ordered according to the expected sensitivity.

Signal category	$\varepsilon \times 10^5$	$B\overline{B}$	$q\overline{q}$
$\ell\ell$	4.0	275	39
$\pi\ell$	7.6	1058	230
ρ	15.5	3279	845
$\pi\pi$	4.0	1077	424

Low multiplicity physics:

Measurement of $e^+e^- \to \pi^+\pi^-\pi^0$ cross section

- Theory uncertainty on $a_\mu = g - 2/2$ dominated by HVP (hadron vacuum polarisation)
- Cross section of $e^+e^- \to$ hadrons as input for theo. calculation of HVP

Muon anomalous magnetic moment

$$a_\mu = \frac{g-2}{2} = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{QCD}}$$

Hadron contribution term

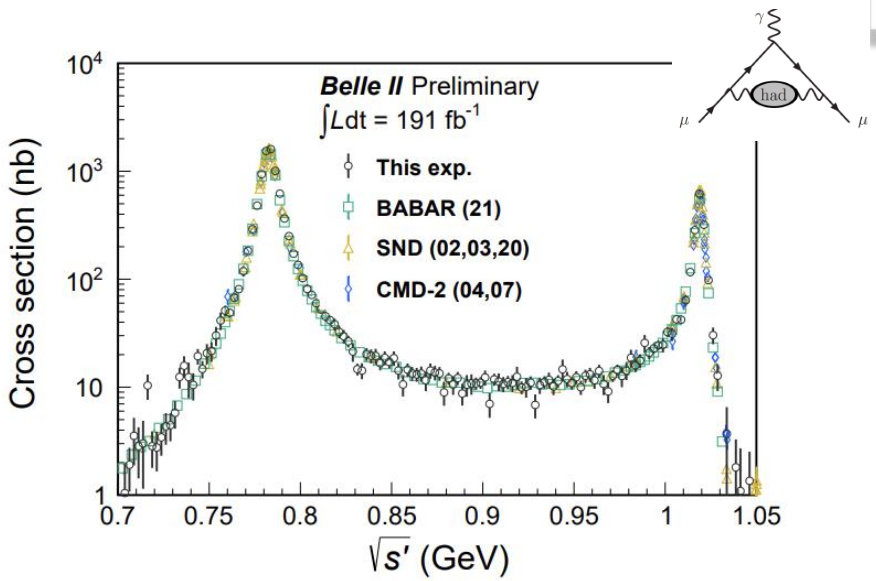
$$a_\mu^{\mathrm{QCD}} = a_\mu^{\mathrm{HVP}} + a_\mu^{\mathrm{HLbL}}$$

Leading-order HVP rerm

$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{ds}{s}R(s)K(s)$$

Hadronic R-ratio

$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$



a_μ^{HVP} is found to be 2.5σ higher than Babar meas. and world combination, corresponding to 10% of the difference $\Delta a_\mu = a_\mu(\mathrm{Exp}) - a_\mu(\mathrm{SM})$

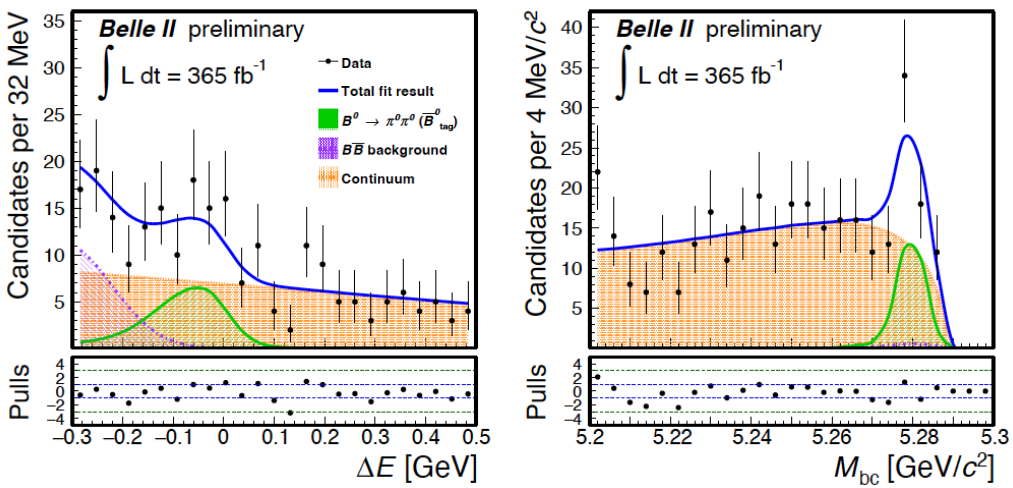
Latest lattice calculation a_μ
https://arxiv.org/pdf/2407.10913 (2024)

arXiv:2404.04915 (2024)

CP asymmetries: $B^0 \to \pi^0\pi^0$

PhysRevD.111.L071102

- $B \to \pi\pi$ and CP asymmetries set constraints on the least known CKM angle α (ϕ_2)
- New result for $B^0 \to \pi^0\pi^0$ from Belle II exploiting graph neural network flavour tagging (e_{tag}~37%, PhysRevD.110.012001)
- Experimentally challenging: no tracks, 4 photons



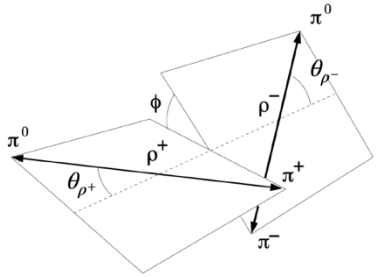
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = \frac{\Gamma(\overline{B}^0 \to \pi^0\pi^0) - \Gamma(B^0 \to \pi^0\pi^0)}{\Gamma(\overline{B}^0 \to \pi^0\pi^0) + \Gamma(B^0 \to \pi^0\pi^0)}$$

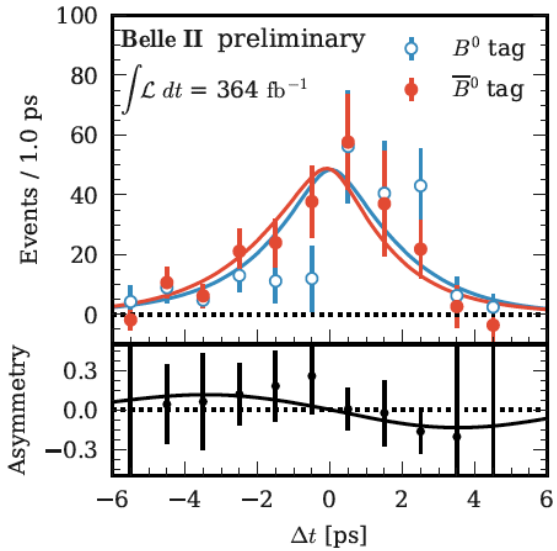
$$\mathcal{B}(B^0 \to \pi^0\pi^0) = (1.25 \pm 0.20 \pm 0.11) \times 10^{-6}$$
$$\mathcal{A}_{CP}(B^0 \to \pi^0\pi^0) = 0.03 \pm 0.30 \pm 0.04$$

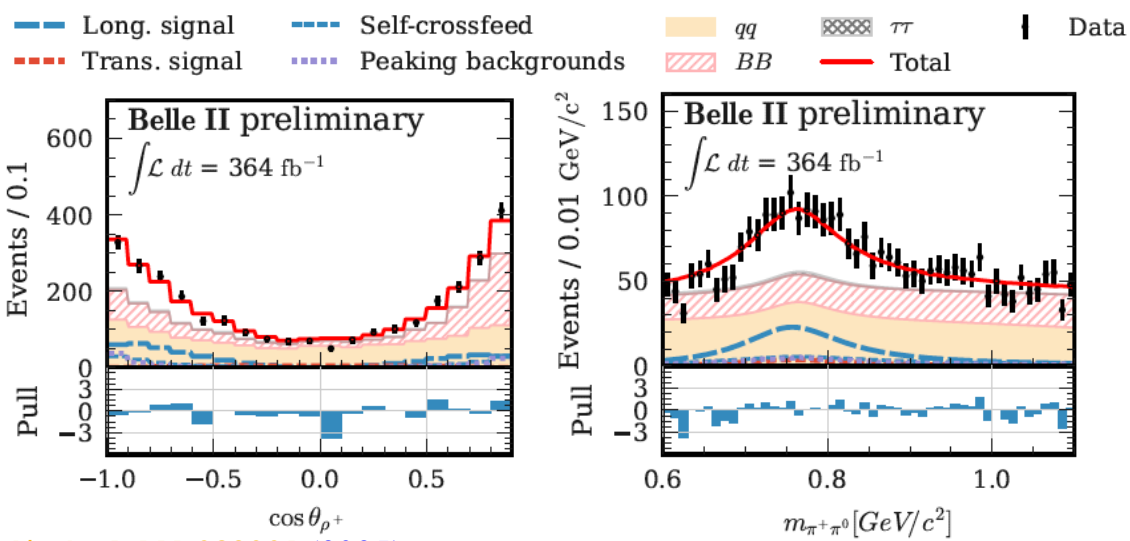
World best determination of $\mathcal{B}$ and A_{CP} on par with world best

ϕ_2: $B^0 \to \rho^+\rho^-$

- Golden channel to measure ϕ_2, from the measurement of fraction of longitudinal polarization f_L, branching ratio and CP asymmetry parameters
- Signal candidates $\rho^+ \to \pi^+\pi^0(\to \gamma\gamma)$
- Main uncertainties: systematics from π^0 efficiency and MC mismodeling







$$\mathcal{B}(B^0 \to \rho^+\rho^-) = (29.0^{+2.3}_{-2.2}{}^{+3.1}_{-3.0}) \times 10^{-6}$$

$$f_L(B^0 \to \rho^+\rho^-) = 0.921^{+0.024}_{-0.022}{}^{+0.017}_{-0.015}$$

$$\boxed{\phi_2 = (92.6^{+4.5}_{-4.8})^\circ}$$

6% improvement in ϕ_2 precision

PhysRevD.111.092001 (2025)

CP asymmetries: $B^0 \to \pi^0\pi^0$

Source	$\mathcal{B}$	$\mathcal{A}_{CP}$
π^0 efficiency	8.6 %	n/a
$\Upsilon(4S)$ branching fractions $(1 + f^{+-}/f^{00})$	2.5 %	n/a
Continuum-suppression efficiency	1.9 %	n/a
$B\overline{B}$-background model	1.7 %	0.034
Sample size $N_{B\bar{B}}$	1.5 %	n/a
Signal model	1.2 %	0.021
Continuum-background model	0.9 %	0.025
Wrong-tag probability calibration	n/a	0.008
Total systematic uncertainty	9.6 %	0.048
Statistical uncertainty	15.9 %	0.303

TABLE I. Fractional systematic uncertainties on the branching fraction and absolute systematic uncertainties on the CP asymmetry. Total systematic uncertainties, resulting from their sums in quadrature, are also given, and compared with statistical uncertainties.

ϕ_2: $B^0 \to \rho^+\rho^-$

Table VI. Systematic uncertainties for $\mathcal{B}$ and f_L. Relative uncertainties are shown for the $\mathcal{B}$.

Source	$\mathcal{B}$ [%]	f_L
Tracking	±0.54	—
π^0 efficiency	±7.67	—
PID	±0.08	—
$\mathcal{T}_C$	±2.87	—
MC statistics	±0.24	±0.002
f_{+-}/f_{00}	±2.60	—
N_{BB}	±1.45	—
Best candidate selection	±0.55	±0.003
SxF ratio	$^{+2.97}_{-2.45}$	$^{+0.002}_{-0.003}$
$\mathcal{B}$'s of peaking backgrounds	$^{+0.94}_{-0.98}$	±0.001
$\tau^+\tau^-$ background yield	$^{+0.65}_{-0.69}$	±0.000
Signal model	$^{+1.14}_{-2.02}$	±0.002
$q\bar{q}$ model	$^{+0.49}_{-0.51}$	$^{+0.001}_{-0.002}$
$B\bar{B}$ model	$^{+1.00}_{-0.40}$	$^{+0.003}_{-0.001}$
$\tau^+\tau^-$ model	$^{+0.17}_{-0.26}$	$^{+0.000}_{-0.001}$
Peaking model	$^{+1.37}_{-1.01}$	$^{+0.003}_{-0.005}$
Interference	±1.20	±0.005
Data-MC mis-modeling	$^{+3.51}_{-1.70}$	$^{+0.008}_{-0.003}$
Fit bias	±1.03	±0.012
Total systematic uncertainty	$^{+10.29}_{-9.74}$	$^{+0.017}_{-0.015}$
Statistical uncertainty	$^{+7.93}_{-7.58}$	$^{+0.024}_{-0.025}$

Table VII. Systematic uncertainties for S and C.

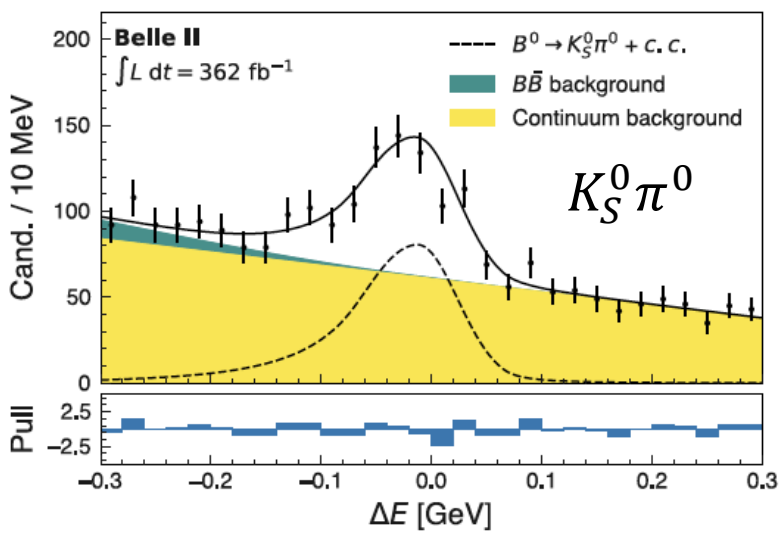
Source	S	C
$\mathcal{B}$'s of peaking backgrounds	$^{+0.006}_{-0.005}$	±0.001
$\tau^+\tau^-$ background yield	±0.009	$^{+0.000}_{-0.001}$
Data-MC mis-modeling	$^{+0.006}_{-0.011}$	$^{+0.015}_{-0.006}$
Best candidate selection	±0.013	±0.019
SxF ratio	$^{+0.005}_{-0.004}$	$^{+0.007}_{-0.000}$
Signal model	$^{+0.011}_{-0.014}$	$^{+0.003}_{-0.004}$
$q\bar{q}$ model	$^{+0.022}_{-0.010}$	±0.002
$B\bar{B}$ model	±0.009	$^{+0.007}_{-0.005}$
$\tau^+\tau^-$ model	±0.001	±0.000
Peaking model	$^{+0.008}_{-0.004}$	$^{+0.002}_{-0.004}$
Fit bias	±0.020	±0.006
Interference	±0.028	±0.017
$\mathcal{B}$ and f_L statistical uncertainty	$^{+0.009}_{-0.010}$	±0.006
Δt PDF for $q\bar{q}$ and $B\bar{B}$	$^{+0.038}_{-0.018}$	$^{+0.007}_{-0.001}$
Resolution	$^{+0.034}_{-0.044}$	$^{+0.019}_{-0.014}$
Wrong tag fractions	$^{+0.002}_{-0.003}$	±0.005
τ and Δm_d	$^{+0.014}_{-0.016}$	±0.003
Tag side interference	±0.005	±0.021
Background CP Violation	$^{+0.038}_{-0.036}$	$^{+0.041}_{-0.037}$
Mis-alignment	±0.014	±0.005
Total systematic uncertainty	$^{+0.083}_{-0.078}$	$^{+0.061}_{-0.054}$
Statistical uncertainty	±0.188	±0.121

CP asymmetries: Isospin sum rule

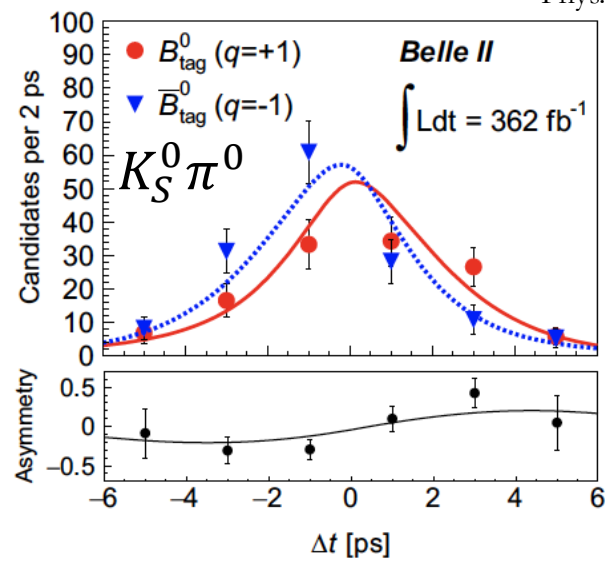
CP asymmetries in B → Kπ decays. Dynamical symmetries (isospin, heavy-quark, and SU(3) flavor) relate CP asymmetries and BF into a reliable and precise SM null test

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B^0}}{\tau_{B^+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

Phys. Lett B627 (2005) 82-8



PhysRevD.109.012001 (2024)



Fit to decision-tree combination of discriminating variables separates bkg

PhysRevLett.131.111803 (2023)

$$A_{K^0\pi^0} = -0.01 \pm 0.12(stat) \pm 0.05(syst)$$

$$\mathcal{B}_{K^0\pi^0} = [11.15 \pm 0.68(stat) \pm 0.62(syst)] \times 10^{-6}$$

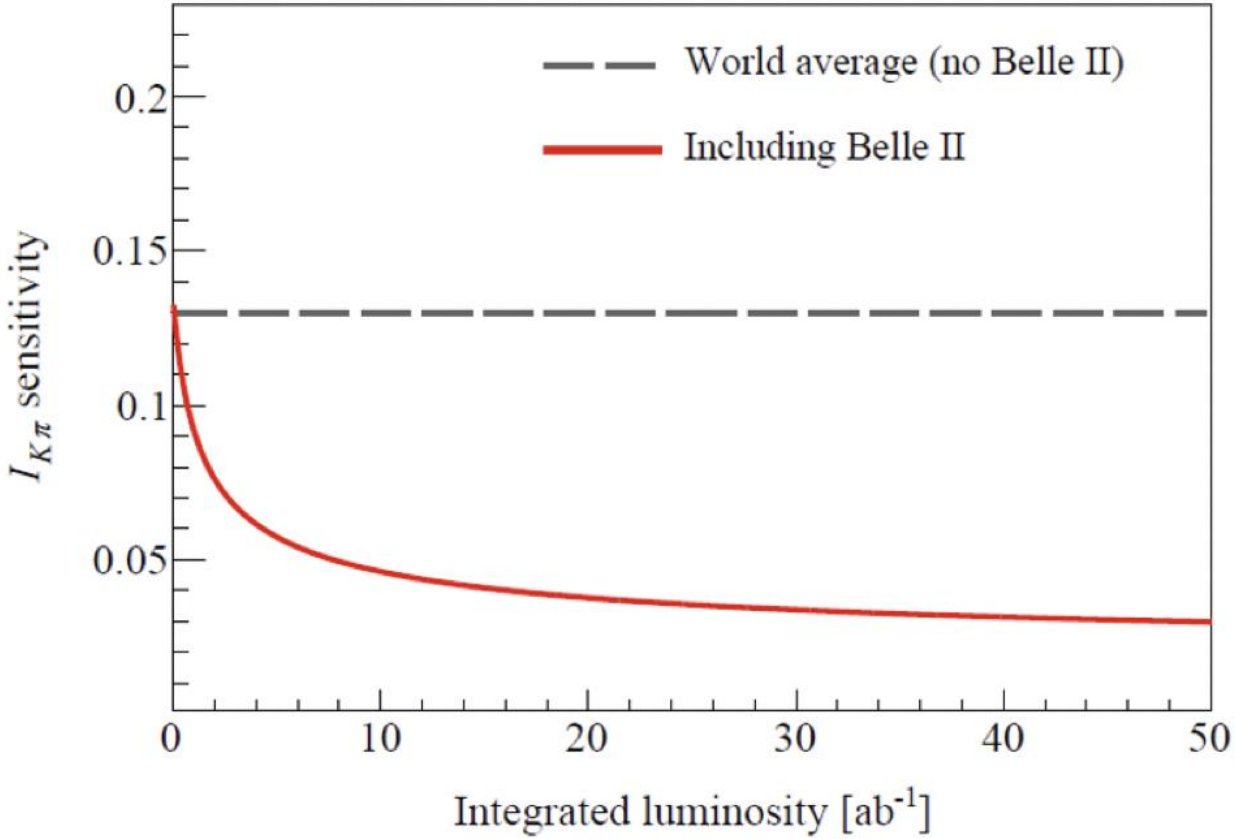
$$I_{K\pi} = -0.03 \pm 0.13(stat) \pm 0.04(syst)$$

Competitive with world-average -0.13 ± 0.11

Belle II measures all final states, with unique access to $B \to K^0\pi^0$

Testing the SM in hadronic B decays: Isospin sum rule

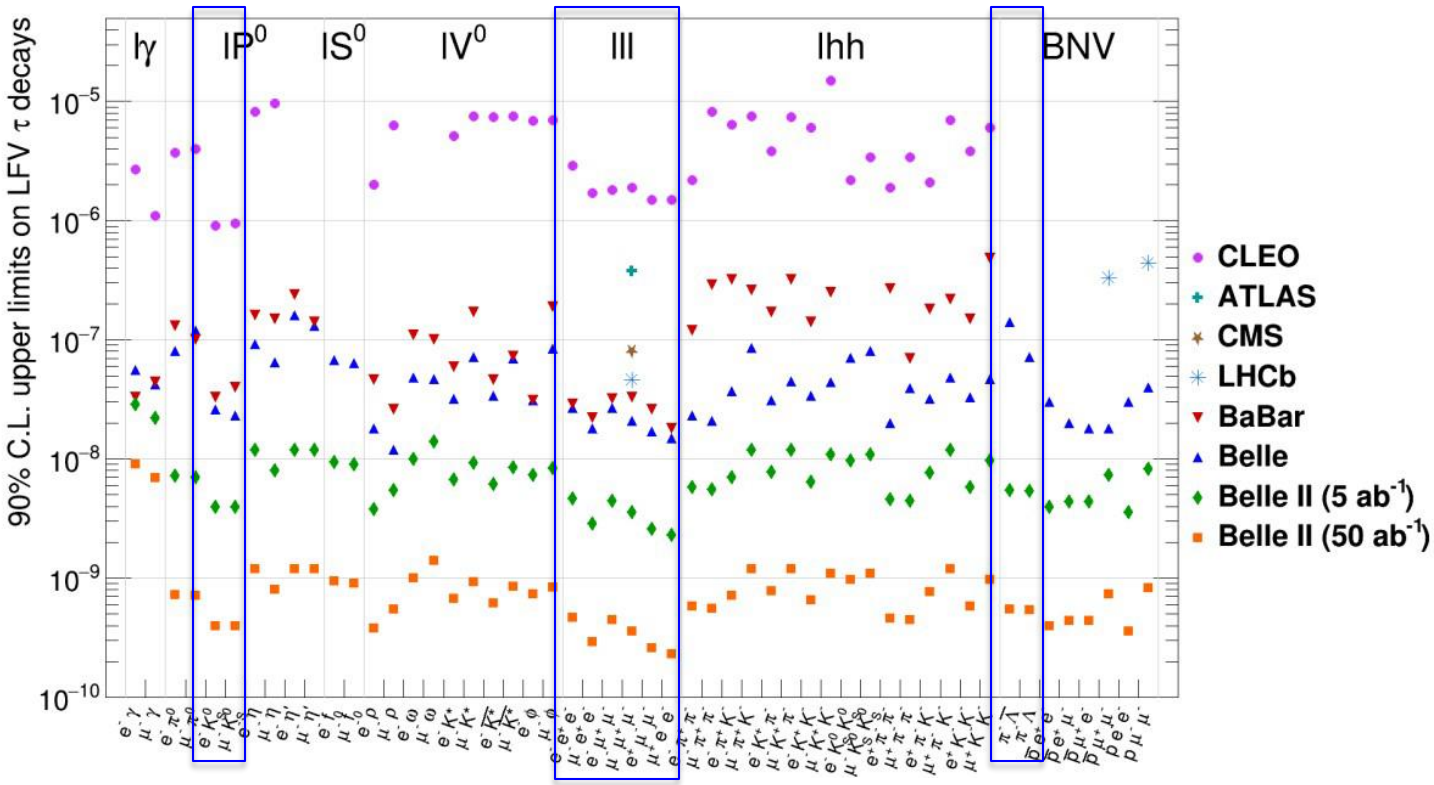
arxiv:2207.06307



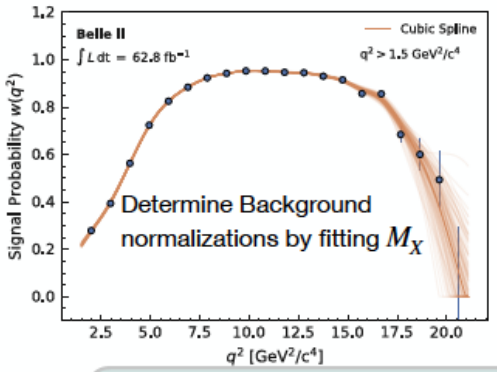
Belle II world-leading in most final states with π^0 and/or K^0 now and for the foreseeable future

τ physics

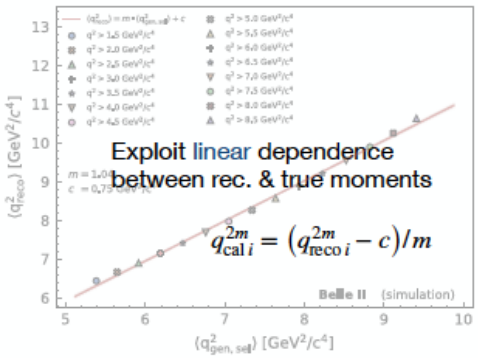
Model	Reference	τ→μγ	τ→μμμ
SM+ ν oscillations	EPJ C8 (1999) 513	10^{-40}	10^{-14}
SM+ heavy Maj ν_R	PRD 66 (2002) 034008	10^{-9}	10^{-10}
Non-universal Z'	PLB 547 (2002) 252	10^{-9}	10^{-8}
SUSY SO(10)	PRD 68 (2003) 033012	10^{-8}	10^{-10}
mSUGRA+seesaw	PRD 66 (2002) 115013	10^{-7}	10^{-9}
SUSY Higgs	PLB 566 (2003) 217	10^{-10}	10^{-7}



$|V_{cb}|$ from q^2 spectral moments



Step #1: Subtract Background

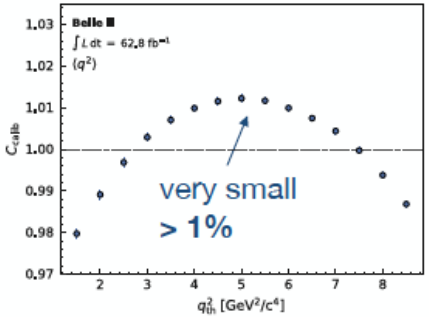


Step #2: Calibrate moment

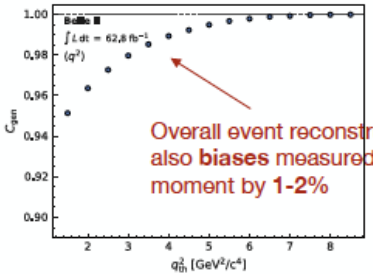
Event-wise **Master-formula**

$$\langle q^{2n}\rangle = \frac{\sum_i^{N_{\mathrm{data}}} w(q_i^2) \times q^{2n}_{\mathrm{calib},i}}{\sum_j^{N_{\mathrm{data}}} w(q_j^2)} \times \mathcal{C}_{\mathrm{calib}} \times \mathcal{C}_{\mathrm{gen}}$$

Step #3: If you fail, try again

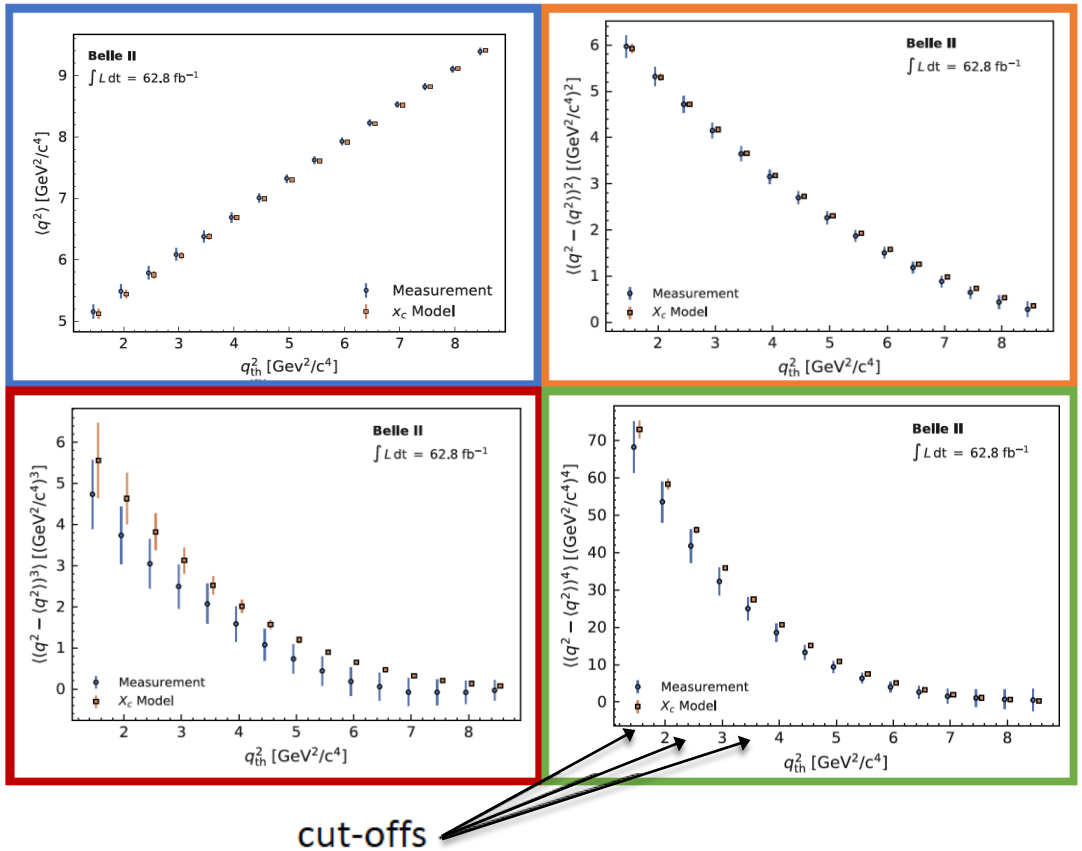


Step #4: Correct for selection effects



$|V_{cb}|$ from q^2 spectral moments

$\langle q^2 \rangle$ Moments



First raw moment: Mean
Measures the location

Second central moment: Variance
Measures the spread

Third central moment: Skewness
Measures asymmetry

Fourth central moment: Kurtosis
Measures "tailedness"

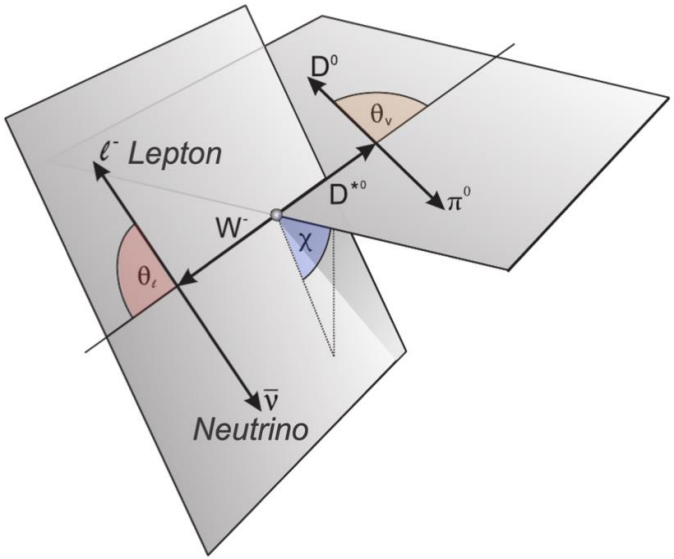
Novel approach to determine $V_{cb} \rightarrow |V_{cb}| = (41.69 \pm 0.63) \cdot 10^{-3}$

Competitive with world average $\left|V_{cb}^{incl}\right| = (42.19 \pm 0.78) \cdot 10^{-3}$

Test of lepton flavour universality: angular asymmetries in $B \to D^* \ell \nu$

We tested lepton universality by comparing five angular asymmetries of e and μ

$$\Delta\mathcal{A}_x(w) = \mathcal{A}_x^{\mu}(w) - \mathcal{A}_x^{e}(w)$$



Recoil parameter $w = \dfrac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}}$

A_{FB} : $dx = d(\cos\theta_\ell)$

S_3 : $dx = d(\cos 2\chi)$

S_5 : $dx = d(\cos\chi \cos\theta_V)$

S_7 : $dx = d(\sin\chi \cos\theta_V)$

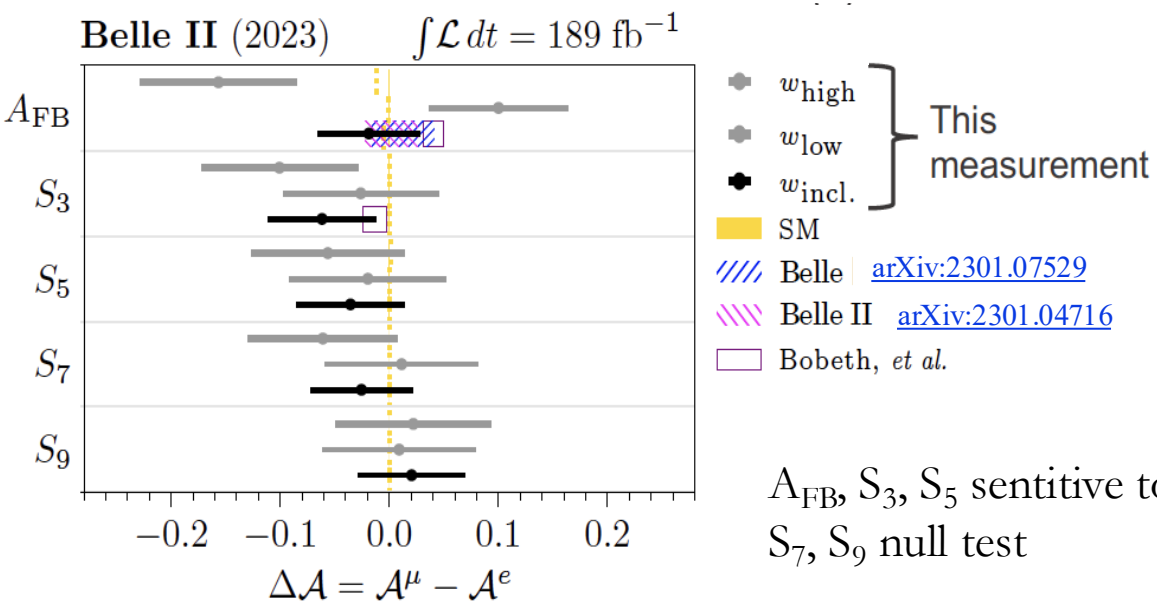
S_9 : $dx = d(\sin 2\chi)$

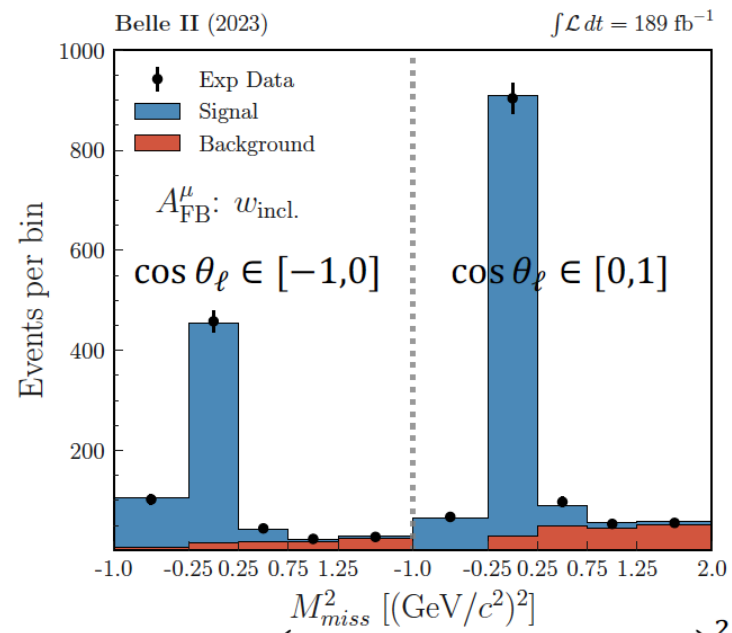
$$\mathcal{A}_x(w) = \frac{N^+ - N^-}{N^+ + N^-}$$ forward backward asymmetry

Test of lepton flavour universality: angular asymmetries in $B \to D^* \ell \nu$

Signal events determined with fits of the missing mass distribution - peaks at zero (neutrino mass) for signal

Hadronic tagged analysis





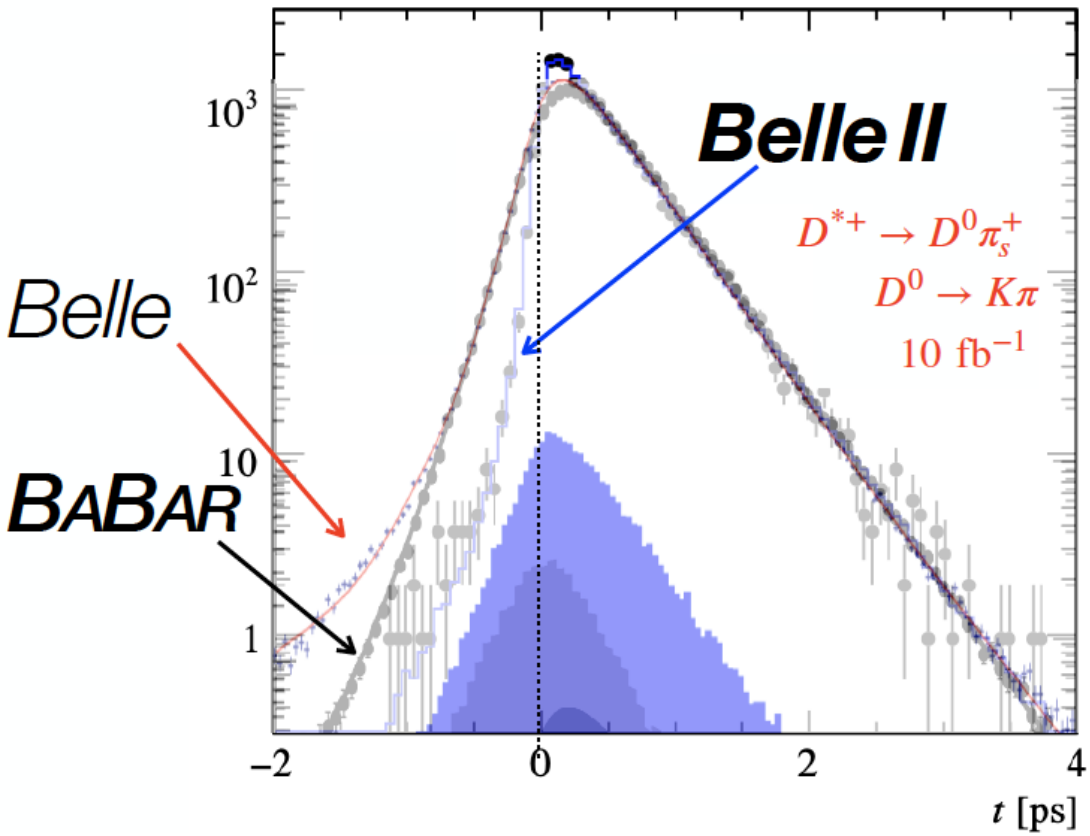
$$M^2_{\text{miss}} \equiv \left(p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_\ell\right)^2$$

A_{FB}, S_3, S_5 sentitive to LFUV

S_7, S_9 null test

Consistent with SM within 5-10%

Charm lifetimes

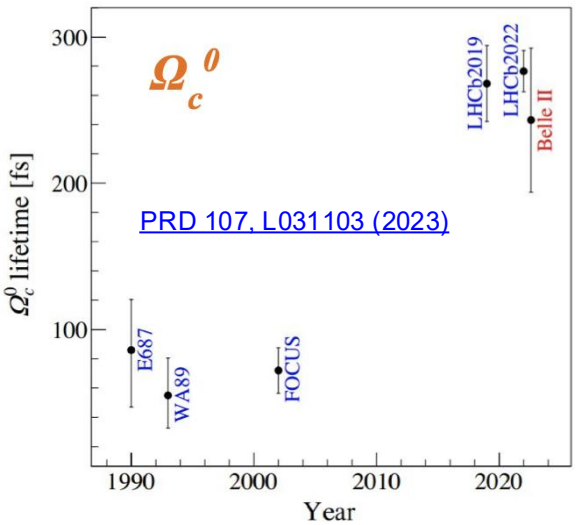


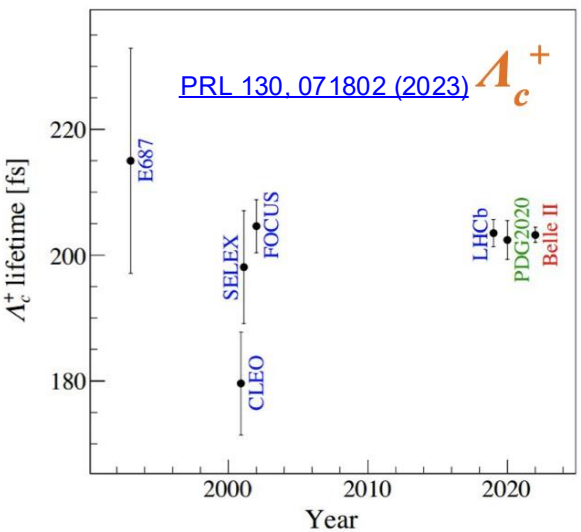
Improved proper time resolution:
2x better decay time resolution than Belle

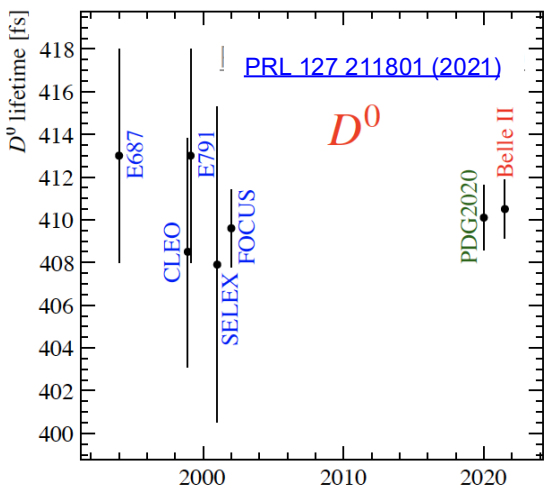
Charm lifetimes

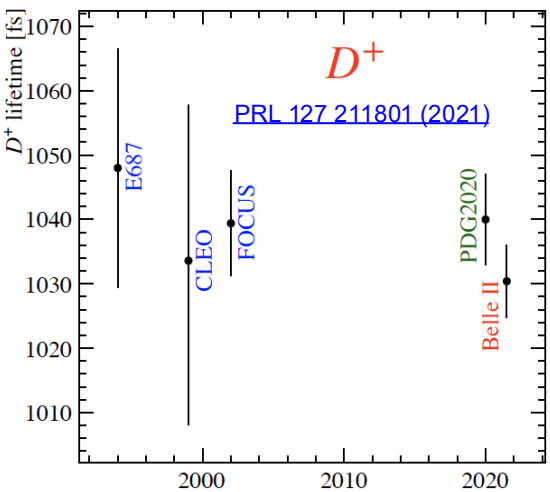
- HQE predicted hierarchy of hadron lifetimes, disproved by LHCb Ω_c lifetime measurement*
- Belle II confirms the new picture !
- World's most precise measurements of the Λ_c (~200/fb), D^0 and D^+ lifetimes (72/fb)
- Few per-mill accuracy establishes the excellent performance of our detector!

*PRL, 121, 092003 (2018)







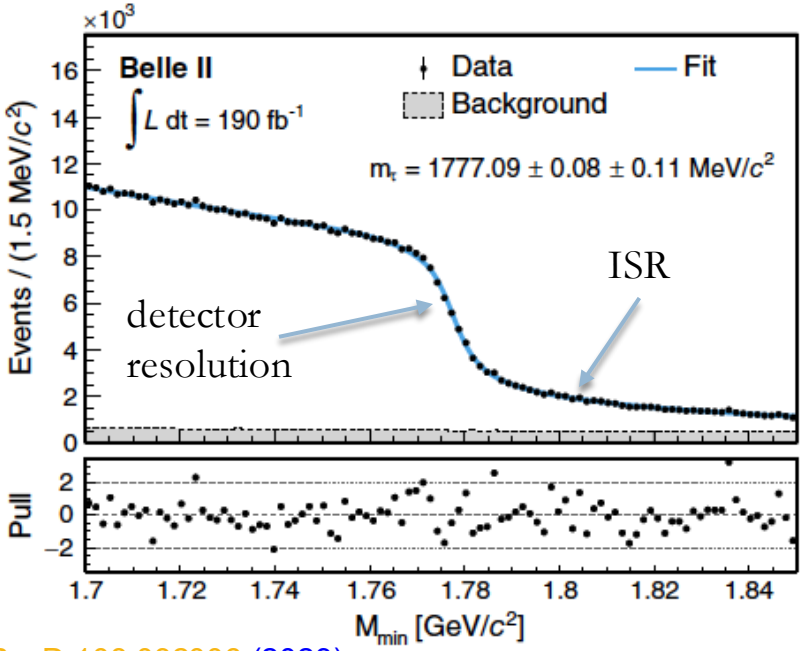


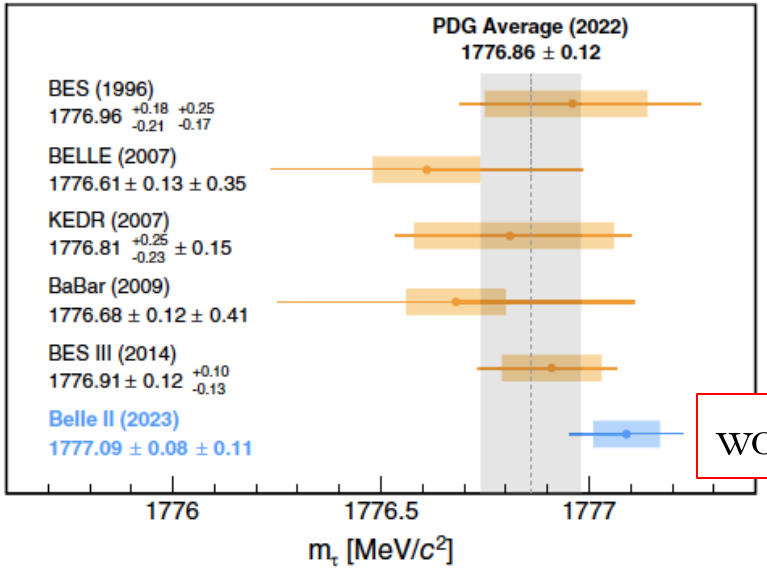
Tau-lepton mass measurement

Belle II is also a tau-lepton factory !

Using 1-prong and 3-prong events for tag side
Crucial knowledge of beam energy and its resolution (ARGUS method)

$$M_{\min} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi}^*)(E_{3\pi}^* - P_{3\pi}^*)} \leq M_\tau.$$





world best

PhysRevD.108.032006 (2023)

Outlook

Luminosity matters

Observable	Past 2022 Belle(II), BaBar	Soon Belle-II 5 ab^{-1}	Target Belle-II 50 ab^{-1}	Dream Belle-II 250 ab^{-1}
$\sin 2\beta/\phi_1$	0.03	0.012	0.005	0.002
γ/ϕ_3 (Belle+BelleII)	11°	4.7°	1.5°	0.8°
α/ϕ_2 (WA)	4°	2°	0.6°	0.3°
$\lvert V_{ub}\rvert$ (Exclusive)	4.5%	2%	1%	< 1%
$S_{CP}(B \to \eta' K^0_S)$	0.08	0.03	0.015	0.007
$A_{CP}(B \to \pi^0 K^0_S)$	0.15	0.07	0.025	0.018
$S_{CP}(B \to K^{*0}\gamma)$	0.32	0.11	0.035	0.015
$R(B \to K^*\ell^+\ell^-)^\dagger$	0.26	0.09	0.03	0.01
$R(B \to D^*\tau\nu)$	0.018	0.009	0.0045	<0.003
$R(B \to D\tau\nu)$	0.034	0.016	0.008	<0.003
$\mathcal{B}(B \to \tau\nu)$	24%	9%	4%	2%
$B(B \to K^*\nu\bar{\nu})$	–	25%	9%	4%
$\mathcal{B}(\tau \to \mu\gamma)$ UL	42×10^{-9}	22×10^{-9}	6.9×10^{-9}	3.1×10^{-9}
$\mathcal{B}(\tau \to \mu\mu\mu)$ UL	21×10^{-9}	3.6×10^{-9}	0.36×10^{-9}	0.073×10^{-9}

Table 2: Projected precision (total uncertainties, or 90% CL upper limits) of selected flavour physics measurements at Belle II.(The † symbol denotes the measurement in the momentum transfer squared bin $1 < q^2 < 6$ GeV/c^2.)

Snowmass White Paper:
Belle II physics reach and plans for the next decade and beyond

https://arxiv.org/abs/2207.06307

Snowmass Whitepaper:
The Belle II Detector Upgrade Program

https://arxiv.org/abs/2203.11349