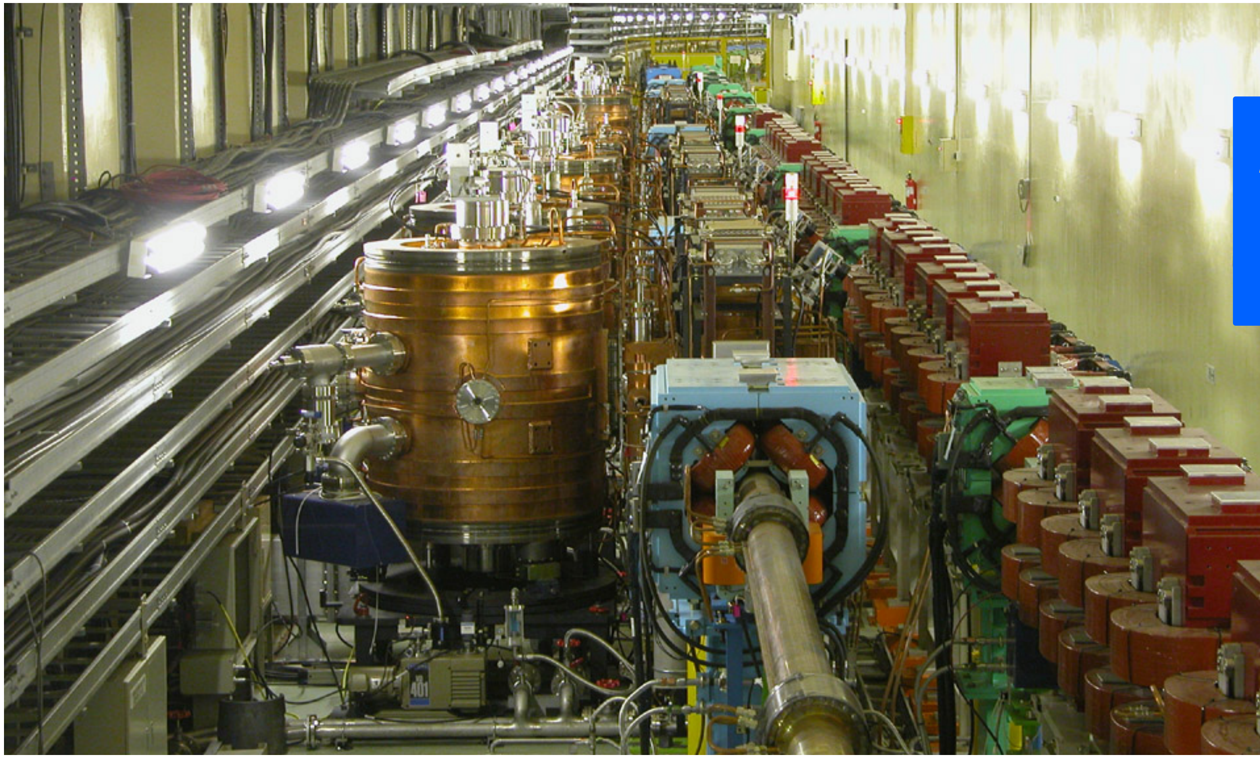


B factory results and Belle II prospects

Alan Schwartz
University of Cincinnati, USA
(on behalf of the Belle/Belle II Collaborations)

Interplay between Particle and Astroparticle Physics (IPA 2022)

Technische Universitat, Wien, Austria
6 September 2022

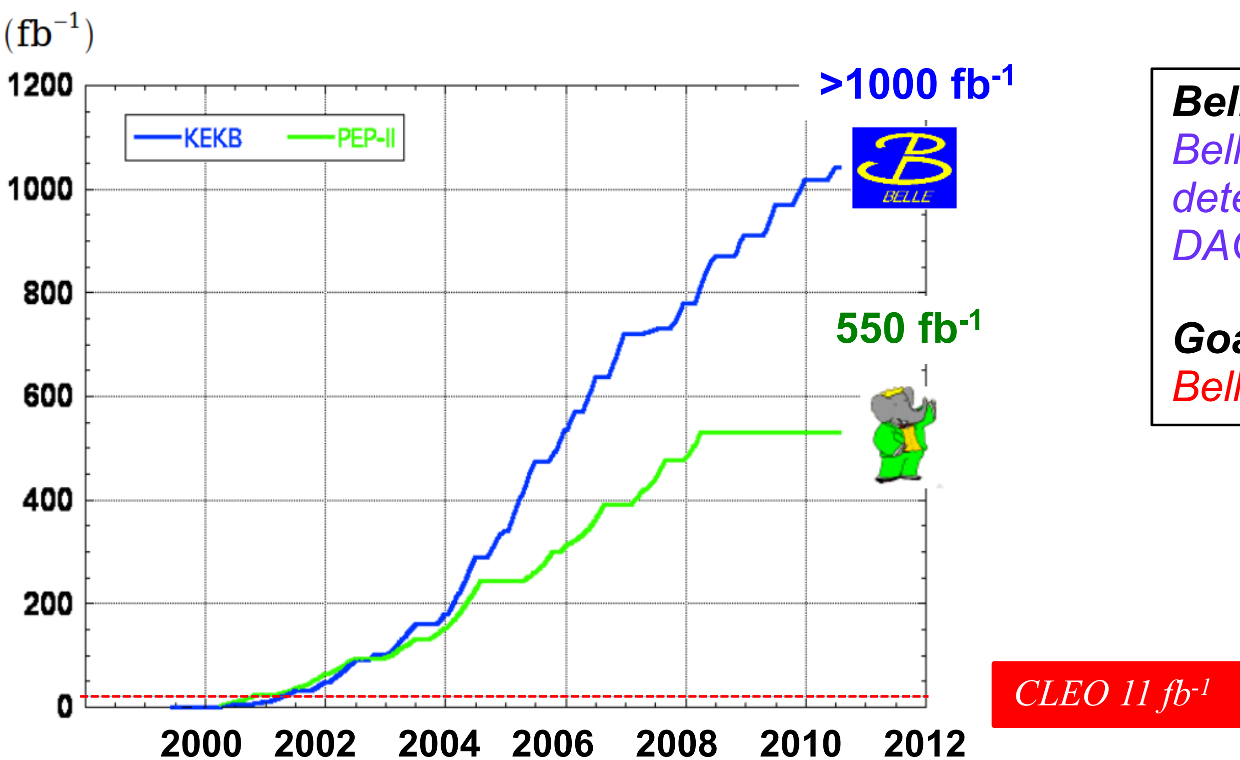
- *overview*
- *search for axion-like particles*
- *measurement of ϕ_3*
- *$|V_{cb}|$ and $|V_{ub}|$*
- *g_μ - 2*
- *future schedule and improvements*

History

The Belle + BaBar Era:

*The “B Factory” experiments Belle and BaBar ran for ~10 years (2000-2010): **1195 papers** published to date, many discoveries (CPV in $B^0 \to J/\psi K^0$, direct CPV in $B^0 \to \pi^+\pi^-$, D^0-D^0bar mixing, X(3872), D_{sJ}(2317), etc.), one Nobel prize (Kobayashi and Maskawa, 2008), but:*

most of the physics program/measurements were not envisioned when the experiments began



***Belle II** is a significant upgrade of Belle: new accelerator, new detector, new electronics, new DAQ, new trigger.*

***Goal:** 50 ab^{-1} of data, ~40x that of Belle+BaBar*

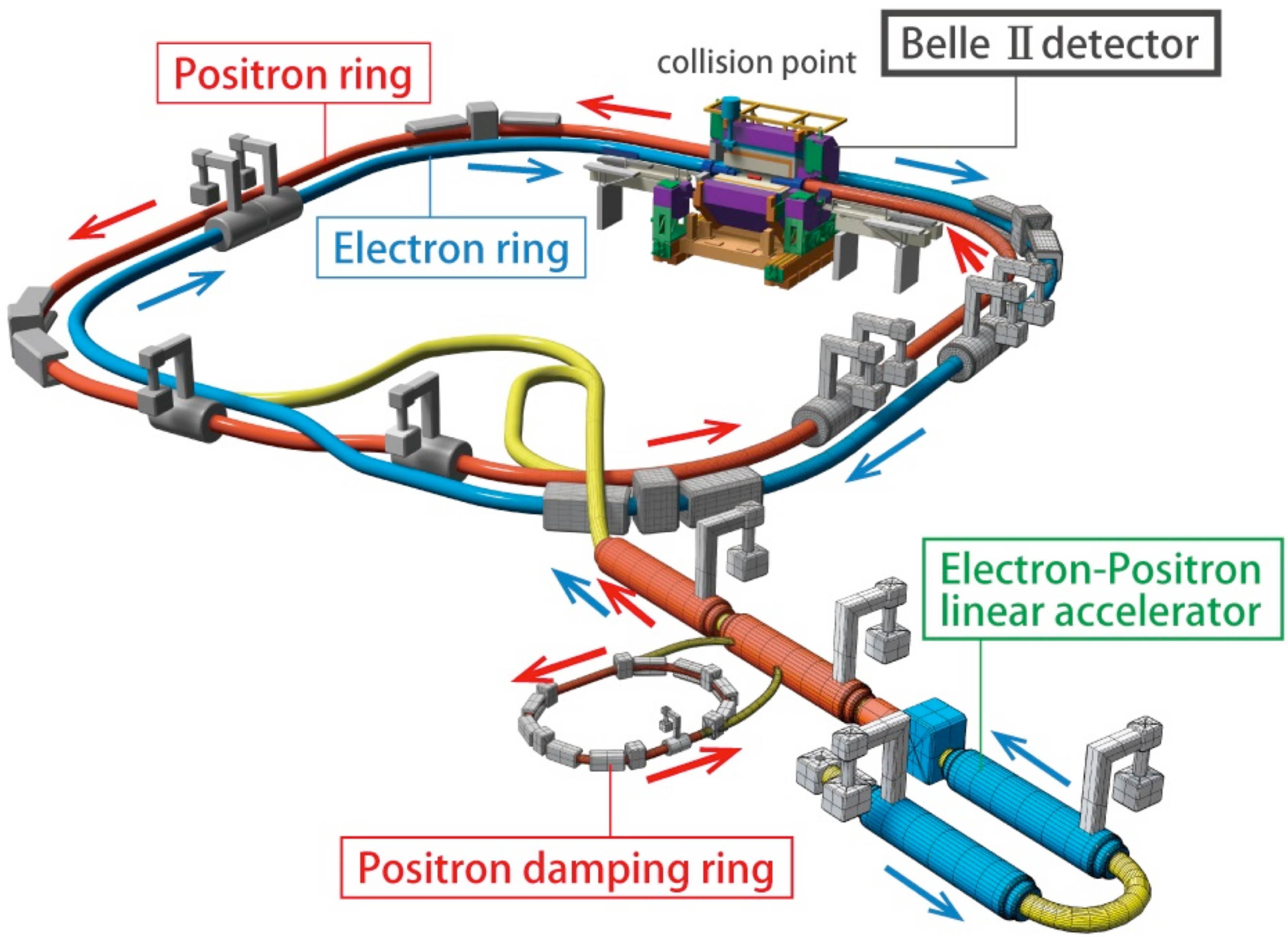
Major accelerator upgrade (KEKB → SuperKEKB)

e^+e^- collider running at the Upsilon(4S) [and Upsilon (5S)] resonances with 7 GeV (e^-) on 4 GeV(e^+) beams.
$\mathcal{L}$(design,2020) = 6.5 x 10^{35}/cm^2/sec.
New e^+ damping ring, new e^+ storage ring, new IR optics, Superconducting FF, new RF

Phase 1 (Feb-June 2016):
Optics commissioning, background studies

Phase 2 (April-July 2018):
Pilot run without VXD, commission e^+ damping ring, first collisions (0.5 fb^{-1})

Phase 3 (Spring+Fall 2020, 2021, Spring 2022):
Physics running, have integrated ~420 fb^{-1} so far



Belle II physics program

"The Belle II Physics Book"
E. Kou et al., PTEP 2019, 123C01 (2019)
[arXiv:1808.10567]

B physics:

- *Angles of CKM unitarity triangle*
- *Sides of CKM unitarity triangle*
- *CP violation*
- *Semileptonic/leptonic decays (lepton flavor universality)*
- *Radiative decays*
- *Electroweak penguin decays*

Charm physics:

- *Mixing and indirect CP violation*
- *direct CP violation*
- *T violation via T-odd asymmetries*
- *Semileptonic/leptonic decays (|Vcd|, |Vcs|)*

Tau physics

Dark photon, dark sector searches

Quarkonium

Today:

Dingfelder: Flavor anomalies @ Belle II

LaCaprara:
Time-dependent CP violation @ Belle II

Bilka: Charm physics @ Belle II

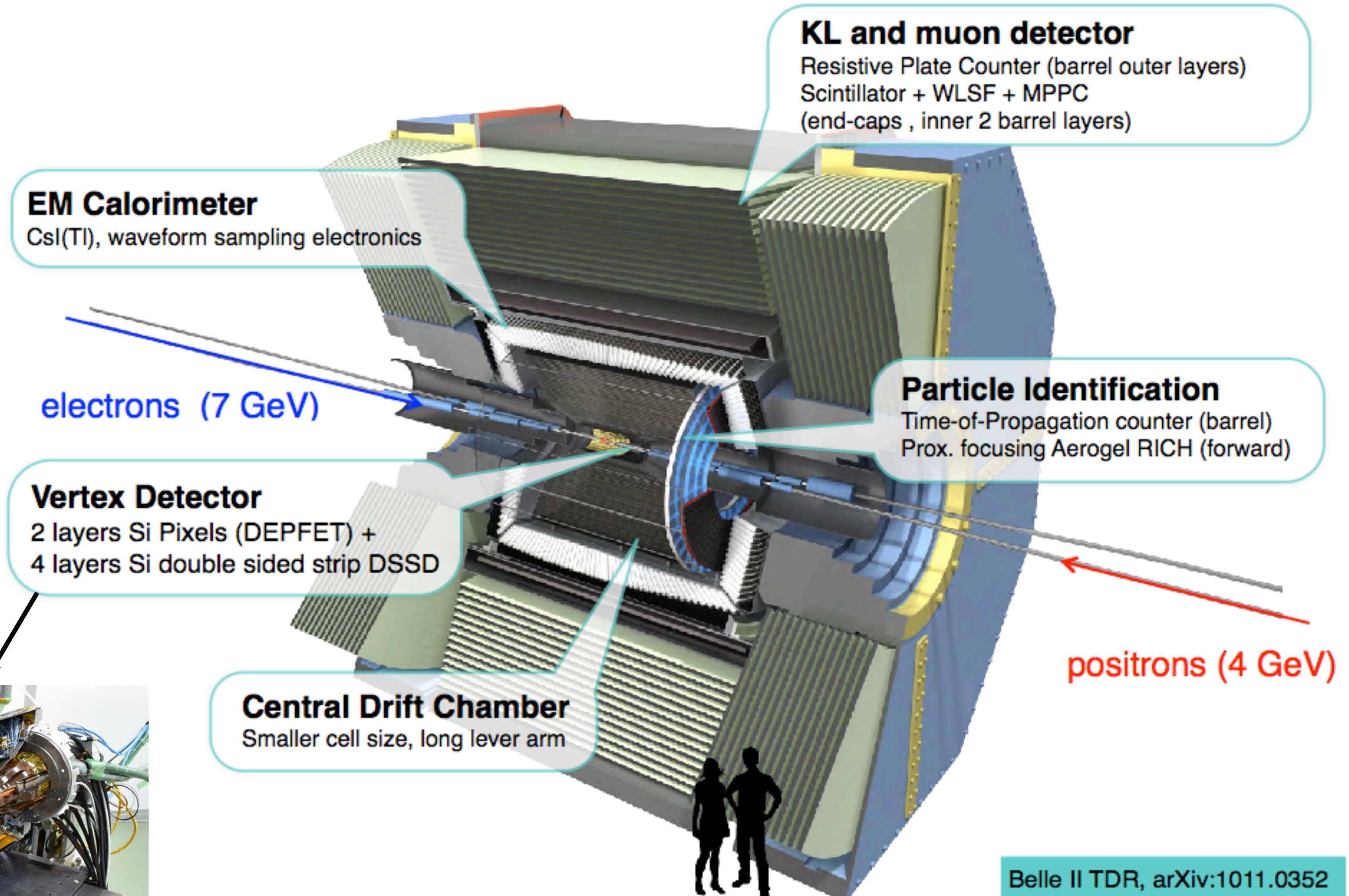
Basith, Boschetti:
Quarkonium @ Belle, Belle II

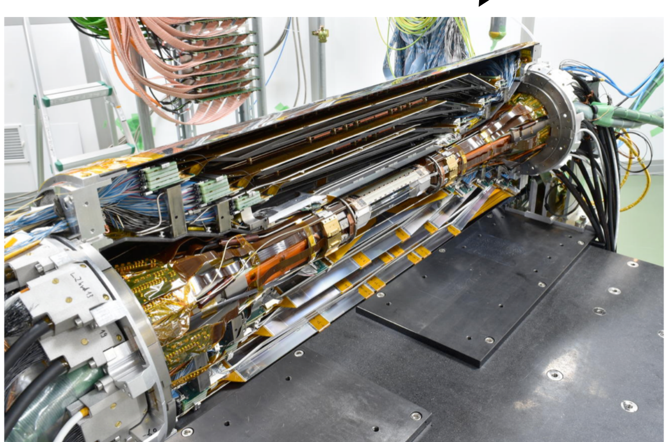
Thursday:

Banerjee, Martini:
Tau physics @ Belle, Belle II

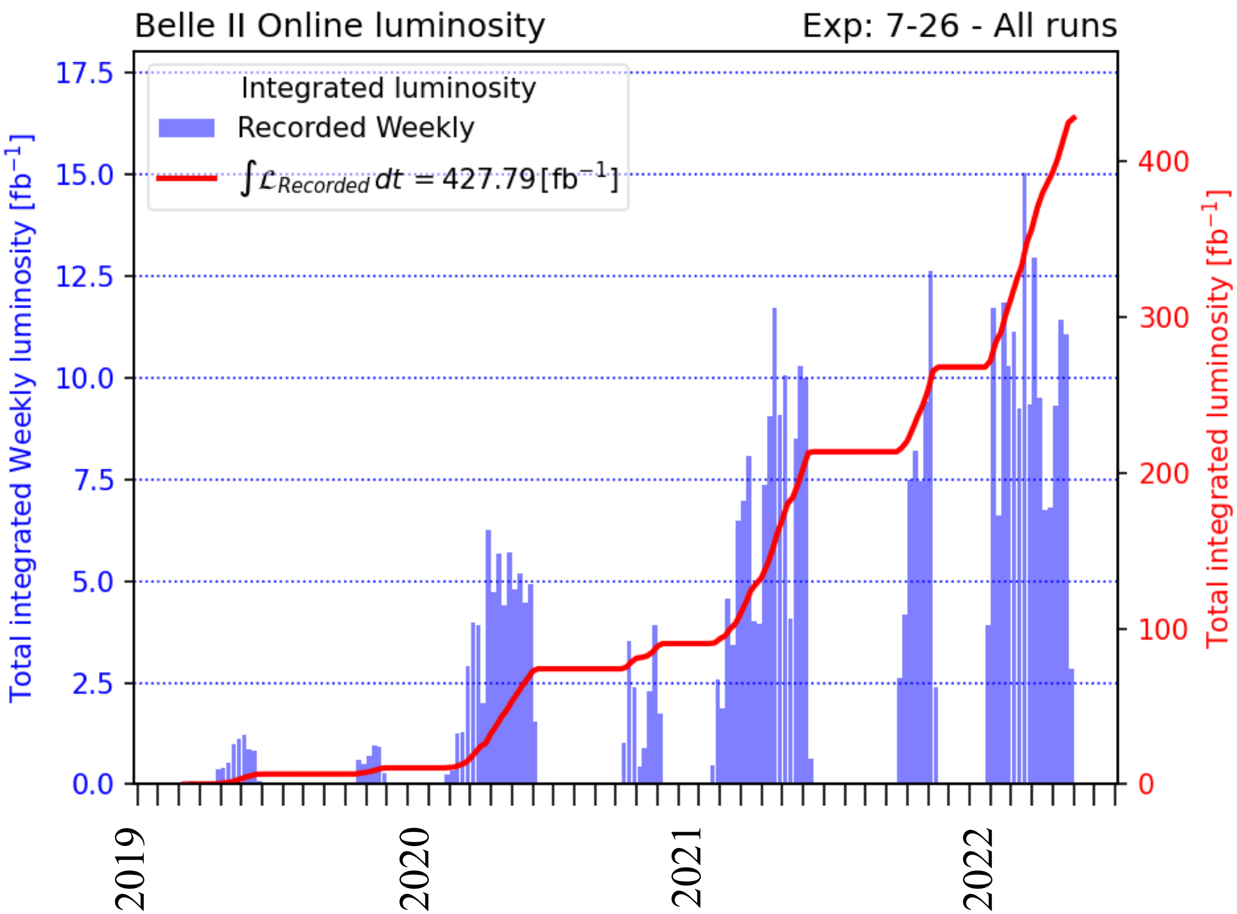
Friday:
Corona: Dark sector @ Belle II

The Belle II Detector





Performance to date



Peak instantaneous luminosity:
4.7×10^{34} cm^{-2} s^{-1}
(world record)

Integrated luminosity:

~362 fb^{-1} *recorded at $\Upsilon(4S)$,* which decays to BB ~1/5 of the time

~42 fb^{-1} *recorded 60 MeV below $\Upsilon(4S)$,* for background studies

~19 fb^{-1} *recorded at ~10.8 GeV* for exotic hadron searches

Physics publications: 10 submitted to-date

- Observation of $e^+ e^- \to$ omega χ_{bJ} and search for $\chi_B \to$ omega Upsilon(1S) at sqrt(s) near 10.75 GeV — *https://arxiv.org/abs/2208.13189*
- Measurement of the Ω_c lifetime at Belle II — *https://arxiv.org/abs/2208.08573*
- Search for a dark photon and an invisible dark Higgs boson in $\mu^+\mu^-$ and missing energy final states with the Belle II experiment — *https://arxiv.org/abs/2207.00509*
- Measurement of the Λ_c^+ lifetime — *https://arxiv.org/abs/2206.15227*
- Measurement of Lepton Mass Squared Moments in $B \to X_c\, \ell\, \nu_l$ Decays with the Belle II Experiment — *https://arxiv.org/abs/2205.06372*
- Combined analysis of Belle and Belle II data to determine the CKM angle ϕ_3 using $B^+ \to D(K^0_S h^+ h^-) h^+$ decays — *JHEP 02 (2022) 063*
- Precise measurement of the D^0 and D^+ lifetimes at Belle II — *PRL 127, 211801 (2021)*
- Search for $B^+ \to K^+ \nu\bar{\nu}$ decays using an inclusive tagging method at Belle II — *PRL 127, 181802 (2021)*
- Search for Axionlike Particles Produced in e^+e^- Collisions at Belle II — *PRL 125, 161806 (2020)*
- Search for an Invisibly Decaying Z' Boson at Belle II in $e^+e^- \to \mu^+\mu^-(e^\pm\mu^\mp)$ Plus Missing Energy Final States — *PRL 124, 141801 (2020)*

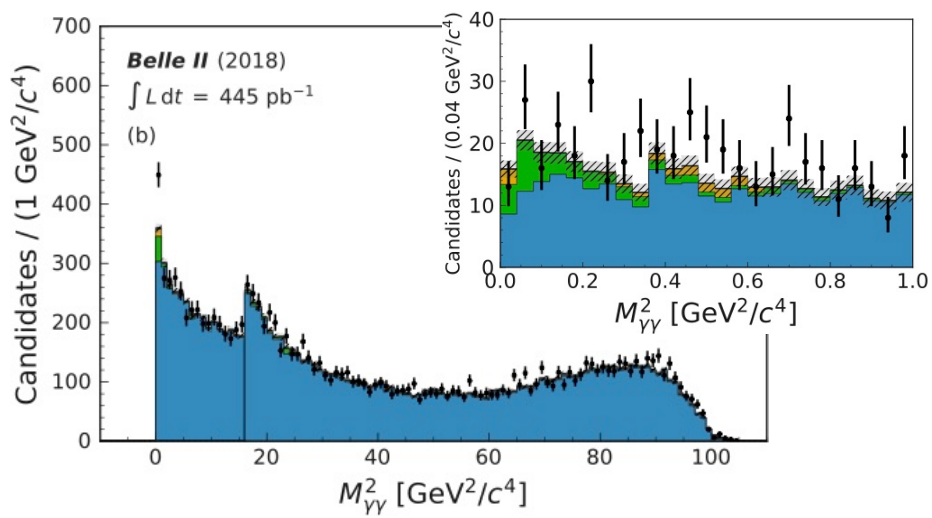
Search for axion-like particles

- When a global symmetry is spontaneously broken → pseudo-Goldstone bosons, called axion-like particles (ALPs)
- ⇒ If there are beyond-SM global symmetries that are spontaneously broken → beyond-SM ALPs
- Characteristic: in the simplest models, ALPs predominantly couple to pairs of gauge bosons, e.g., $\gamma\gamma$, W^+W^-, etc. The WW coupling gives rise to flavor-changing neutral currents (FCNC); see Izaguirre et al, PRL 118, 111802 (2017).
- Their observability depends on (a) the final state into which an ALPs decays (b) the coupling strength to gauge bosons (c) the ALPs mass

Two searches:

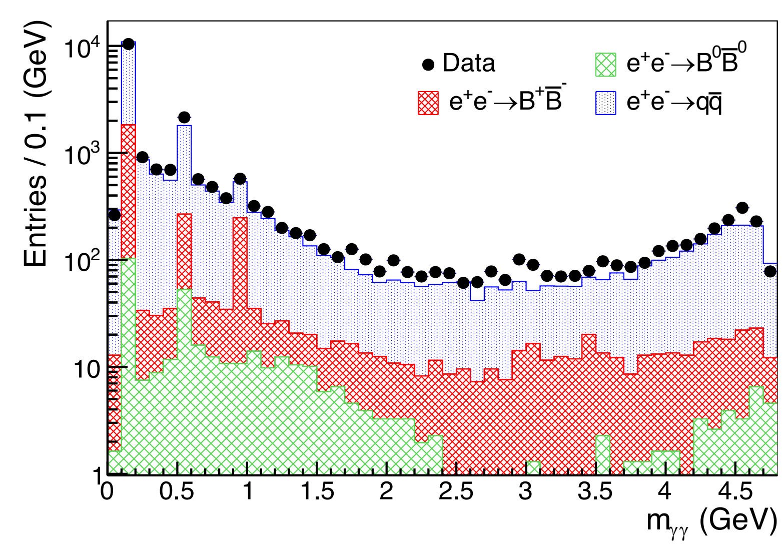
[PRL 125, 161806 (2020)]

0.5 fb^{-1}: $e^+e^- \to \gamma$ **a**, **a** $\to \gamma\gamma$



[PRL 128, 131802 (2022)]

424 fb^{-1}: $B^\pm \to K^\pm$ **a**, **a** $\to \gamma\gamma$



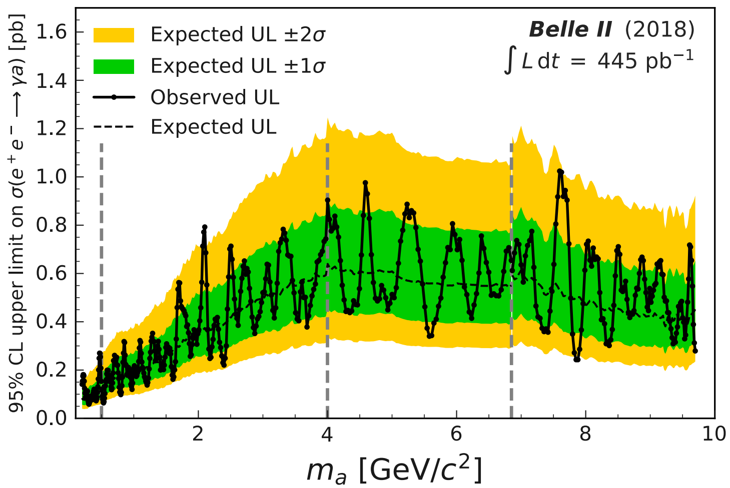
Search for axion-like particles

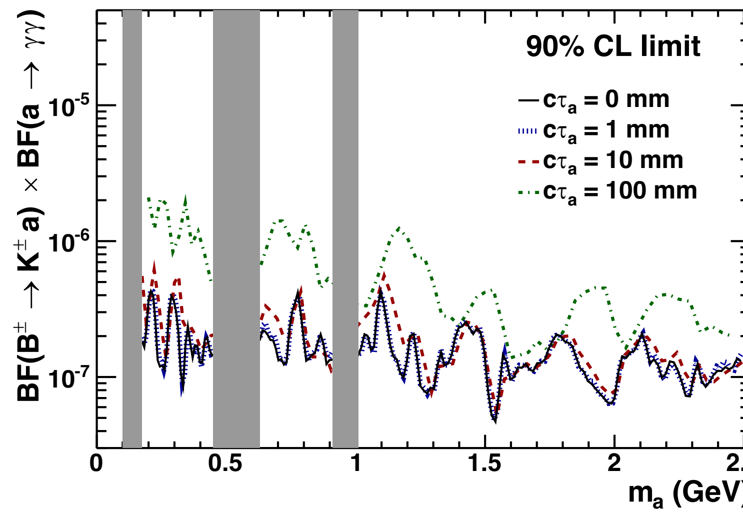
[Belle, PRL 125, 161806 (2020)]
[Babar, PRL 128, 131802 (2022)]

Two searches:

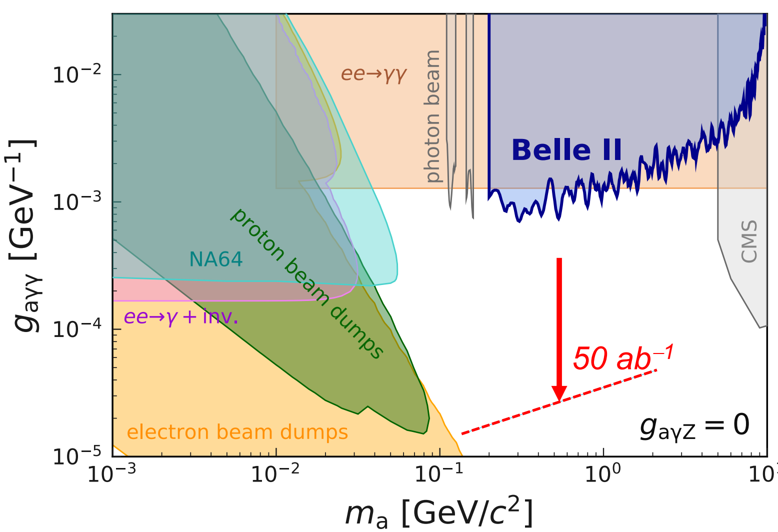
0.5 fb^{-1}: $e^+e^- \to \gamma\, a,\ a \to \gamma\gamma$

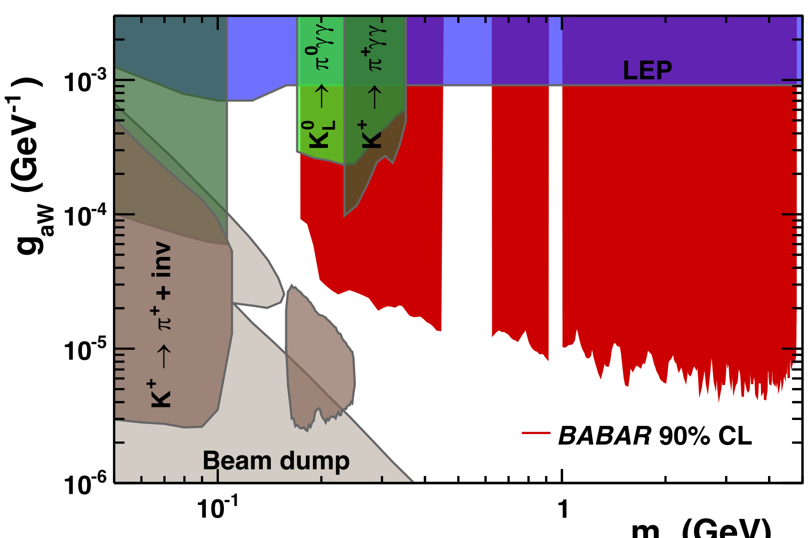
424 fb^{-1}: $B^\pm \to K^\pm a,\ a \to \gamma\gamma$





$$\sigma_a = \frac{g_{a\gamma\gamma}^2\, \alpha_{\rm QED}}{24}\left(1 - \frac{m_a^2}{s}\right)^3$$





⇒ *even with ~small amounts of data, significant regions of parameter space are excluded*

CKM Unitarity triangle

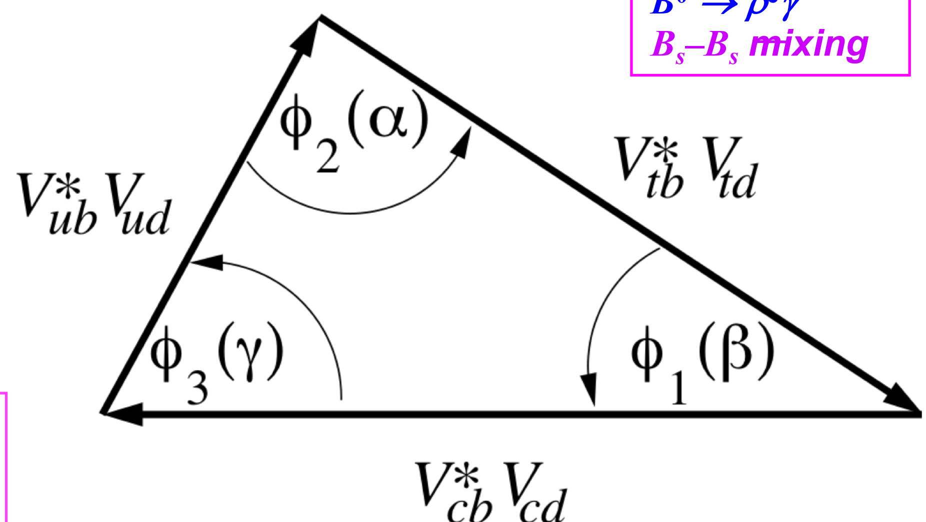
Belle
LHCb

$$V^*_{ub}V_{ud} + V^*_{cb}V_{cd} + V^*_{tb}V_{td} = 0$$

$B \to \pi^+\pi^- / \pi^+\pi^0 / \pi^0\pi^0$
$B \to \rho^+\rho^- / \rho^+\rho^0 / \rho^0\rho^0$
$B^0 \to \rho\,\pi$
$B^0 \to a_1(\rho\pi)^+\,\pi^-$

$B^0 \to \rho^0\gamma$
B_s–B_s mixing

$B^0 \to \pi\,\ell^+\,\nu$
$B^0 \to X_u\,\ell\,\nu$
$B^+ \to \tau^+\,\nu$
$\Lambda_b \to p\,\ell\,\nu$



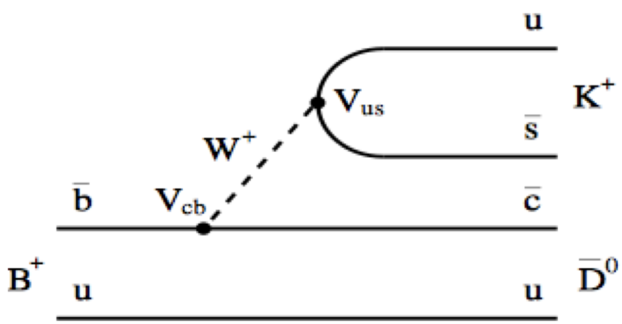
$B^- \to D^{(*)}_{CP}\,K^{(*)-}$
$B^0 \to D_{CP}\,K^{*0}$
$B^- \to D^{(*)}(K^+\pi^-)\,K^{(*)-}$
$B^- \to D^{(*)0}\,\pi^-$
$B^- \to D^{(*)}(K_S\,\pi^+\pi^-)\,K^{(*)-}$
$B^- \to D(\pi^0\pi^+\pi^-)\,K^-$
$B^- \to D(K_S\,K^+\pi)\,K^-$

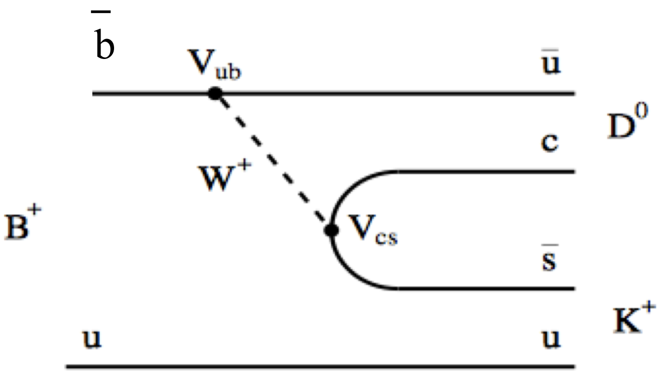
$B^0 \to D^{(*)}\ell\,\nu$
$B^0 \to X_c\,\ell\,\nu$ (ℓ energy, hadron mass moments)
$B^0 \to X_s\,\gamma$ (γ energy moments)

$B^0 \to J/\psi\,K_S$
$B^0 \to J/\psi\,K_L$
$B^0 \to \psi'\,K_S$
$B^0 \to \chi_c\,K_S$
$B^0 \to \eta_c\,K_S$
$B^0 \to D^{(*)}_{CP}\,h^0$
$B^0 \to (\phi/\eta'/\pi^0/f^0)K^0$
$B^0 \to (K_SK_S/\rho^0/\omega)K_S$

Measurement of ϕ_3 with a Dalitz analysis

Giri, Grossman, Soffer, and Zupan, PRD 68, 054018 (2003);
Bondar, Proc. of BINP Anal. Meeting on Dalitz Analysis, 24-26 Sept. 2002





Decay rate depends on interference of the two amplitudes ⇒ sensitivity to ϕ_3:

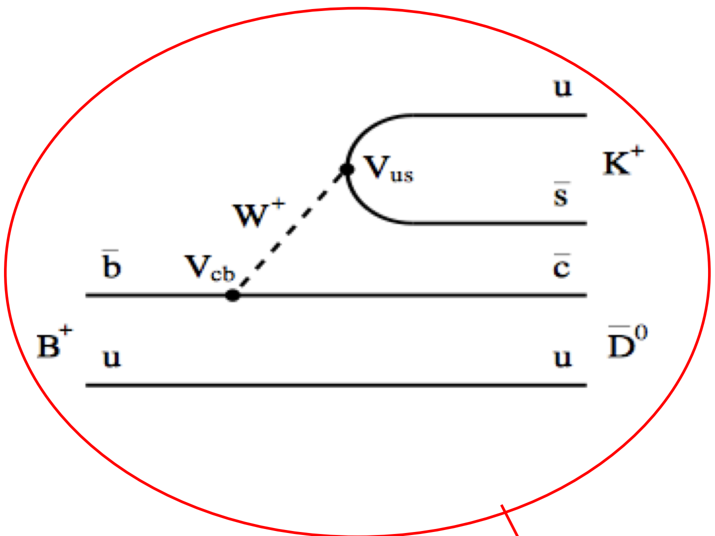
Defining:

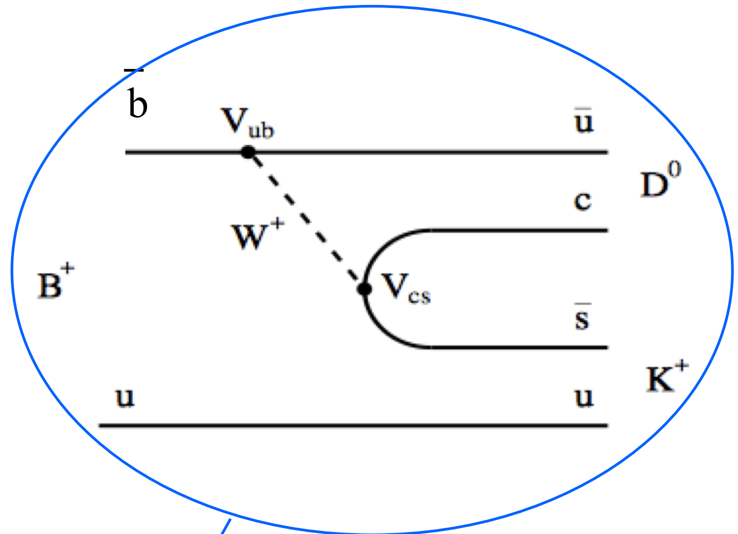
$$\frac{\mathcal{A}(B^+ \to D^0 K^+)}{\mathcal{A}(B^+ \to \overline{D}{}^0 K^+)} \equiv r_B\, e^{i(\delta_B - \phi_3)}$$

gives:

$$\frac{d\Gamma[B^+ \to (m_+^2, m_-^2)]}{d(\text{phase space})} \propto |\mathcal{A}_{\overline{D}{}^0}|^2 + r_B^2 |\mathcal{A}_{D^0}|^2 + 2 r_B |\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D}{}^0}| \left[\cos\delta_D \cos(\delta_B - \phi_3) - \sin\delta_D \sin(\delta_B - \phi_3)\right]$$

Measurement of ϕ_3 with a Dalitz analysis





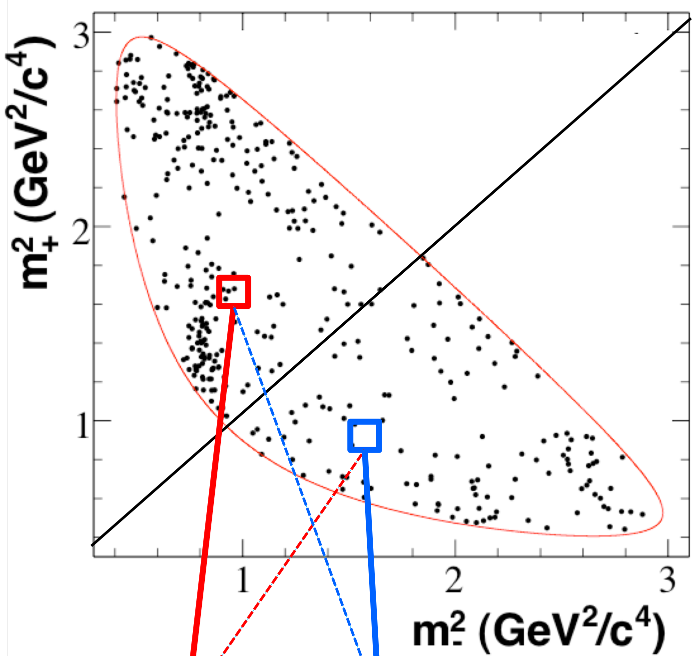
gives:

$$\frac{d\Gamma[B^+ \to (m_+^2, m_-^2)]}{d(\text{phase space})} \propto |\mathcal{A}_{\overline{D}^0}|^2 + r_B^2 |\mathcal{A}_{D^0}|^2 + 2r_B |\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D}^0}| \left[\cos\delta_D \cos(\delta_B - \phi_3) - \sin\delta_D \sin(\delta_B - \phi_3)\right]$$

Measurement of ϕ_3 with a Dalitz analysis

Use $(D^0, \overline{D}^0) \to K_S^0 \pi^+\pi^-$ decays, determine decay rates into bins of Dalitz plot:

$$\begin{aligned} m_+^2 &= m_{K^0\pi^+}^2 \\ m_-^2 &= m_{K^0\pi^-}^2 \end{aligned}$$



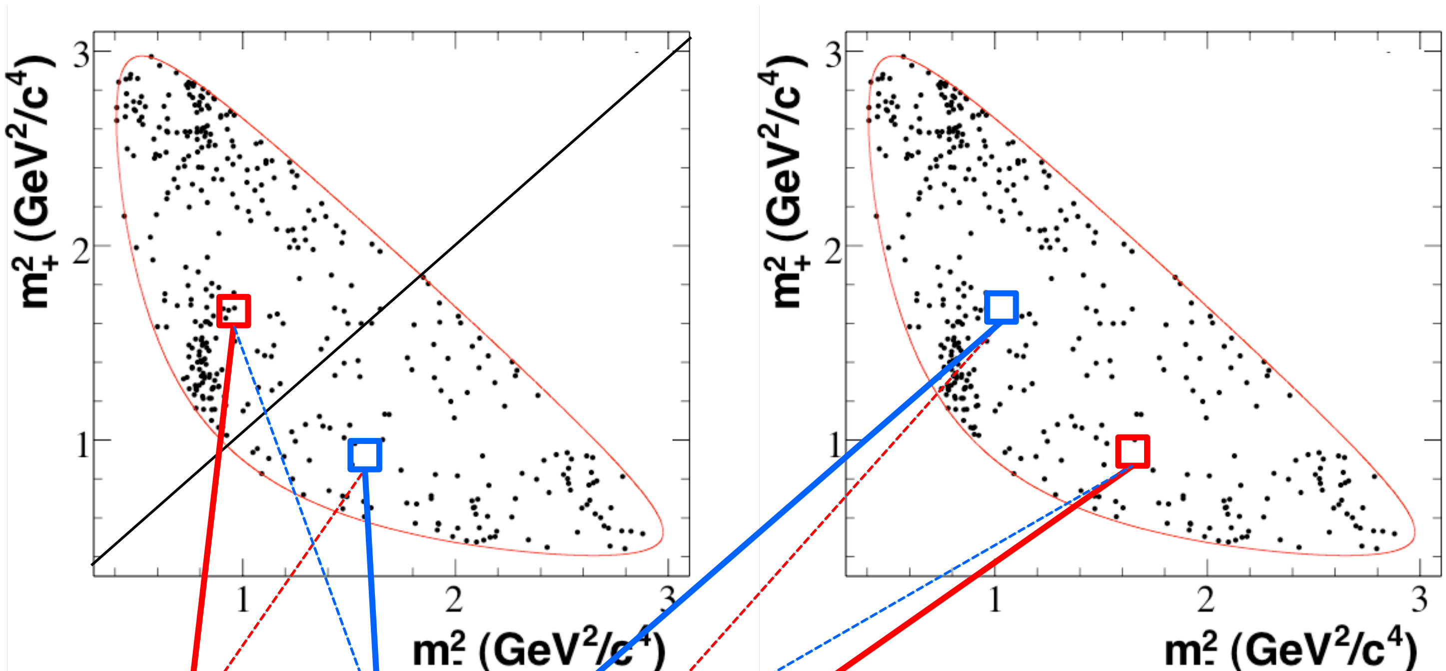
gives:

$$\frac{d\Gamma[B^+ \to (m_+^2, m_-^2)]}{d(\text{phase space})} \propto |\mathcal{A}_{\overline{D}^0}|^2 + r_B^2 |\mathcal{A}_{D^0}|^2 + 2r_B |\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D}^0}| \left[\cos\delta_D \cos(\delta_B - \phi_3) - \sin\delta_D \sin(\delta_B - \phi_3)\right]$$

Measurement of ϕ_3 with a Dalitz analysis

Use $(D^0, \overline{D}^0) \to K_S^0 \pi^+ \pi^-$ decays, determine decay rates into bins of Dalitz plot:

$$m_+^2 = m_{K^0\pi^+}^2$$
$$m_-^2 = m_{K^0\pi^-}^2$$



gives:

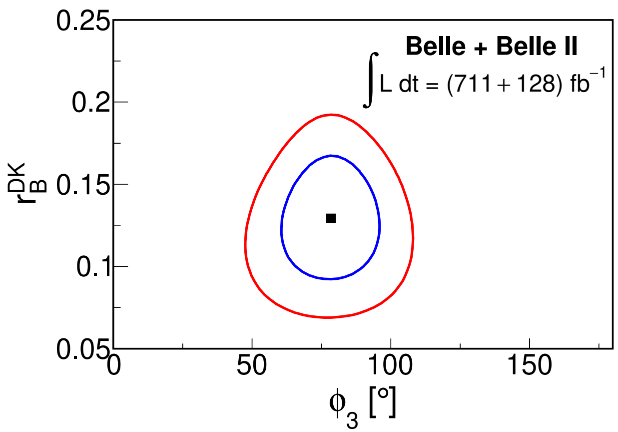
$$\frac{d\Gamma[B^+ \to (m_+^2, m_-^2)]}{d(\text{phase space})} \propto |\mathcal{A}_{\overline{D}^0}|^2 + r_B^2 |\mathcal{A}_{D^0}|^2 + 2r_B |\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D}^0}| \left[\cos\delta_D \cos(\delta_B - \phi_3) - \sin\delta_D \sin(\delta_B - \phi_3)\right]$$

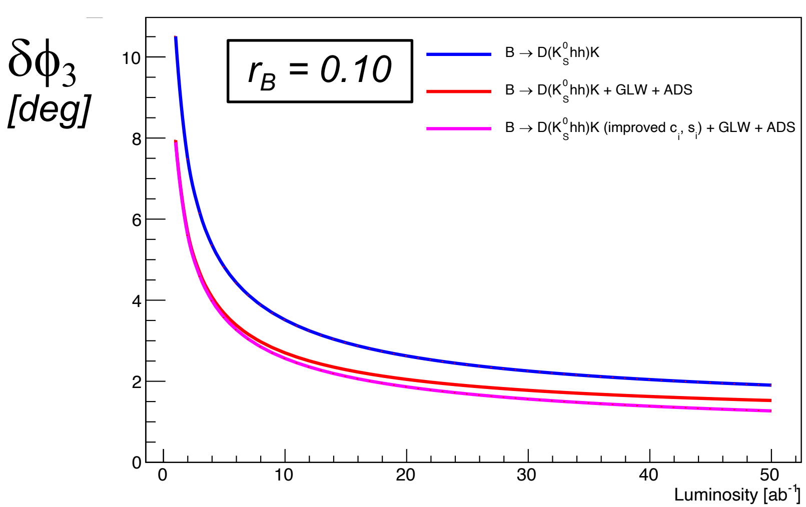
$$\frac{d\Gamma[B^- \to (m_+^2, m_-^2)]}{d(\text{phase space})} \propto |\mathcal{A}_{D^0}|^2 + r_B^2 |\mathcal{A}_{\overline{D}^0}|^2 + 2r_B |\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D}^0}| \left[\cos\delta_D \cos(\delta_B + \phi_3) - \sin\delta_D \sin(\delta_B + \phi_3)\right]$$

Measurement of ϕ_3 with a Dalitz analysis

Results for (711 + 128) fb^{-1}:

$$\phi_3 = (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ$$
$$r_B = 0.129 \pm 0.024 \pm 0.001 \pm 0.002$$
$$\delta_B = (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ$$





Comparison: LHCb 9 fb^{-1}:

[JHEP 02, 169 (2021)]

$$\phi_3 = (68.7\,^{+5.2}_{-5.1})^\circ$$
$$r_B = 0.0904\,^{+0.0077}_{-0.0075}$$
$$\delta_B = (118.3\,^{+5.5}_{-5.6})^\circ$$

Future Belle II:

N_{sig} = 1467 in 711 fb^{-1}

280 in 128 fb^{-1}

⇒ ~75k in 36 ab^{-1}

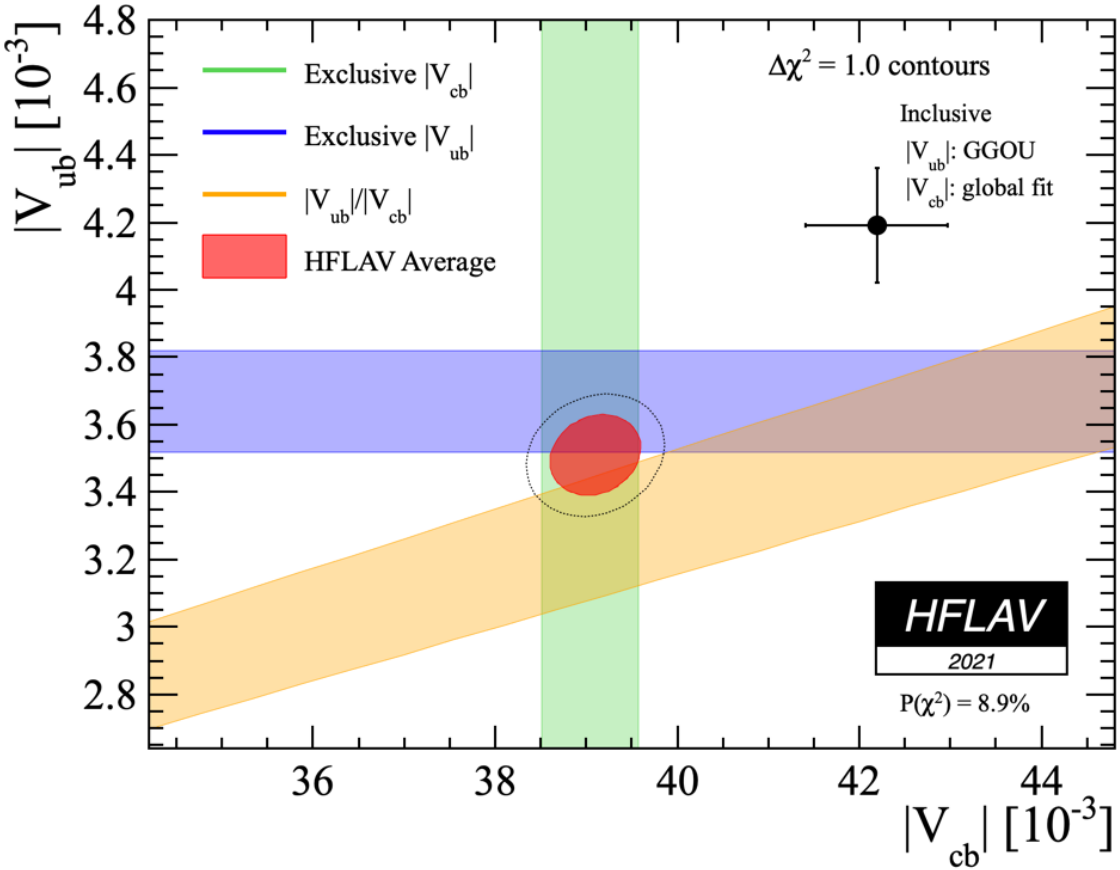
Future LHCb:

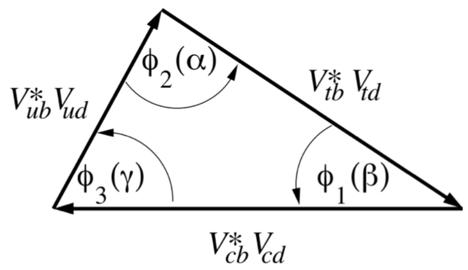
N_{sig} = 13600 in 9 fb^{-1}

⇒ ~75k in 50 fb^{-1}

(similar-sized event samples)

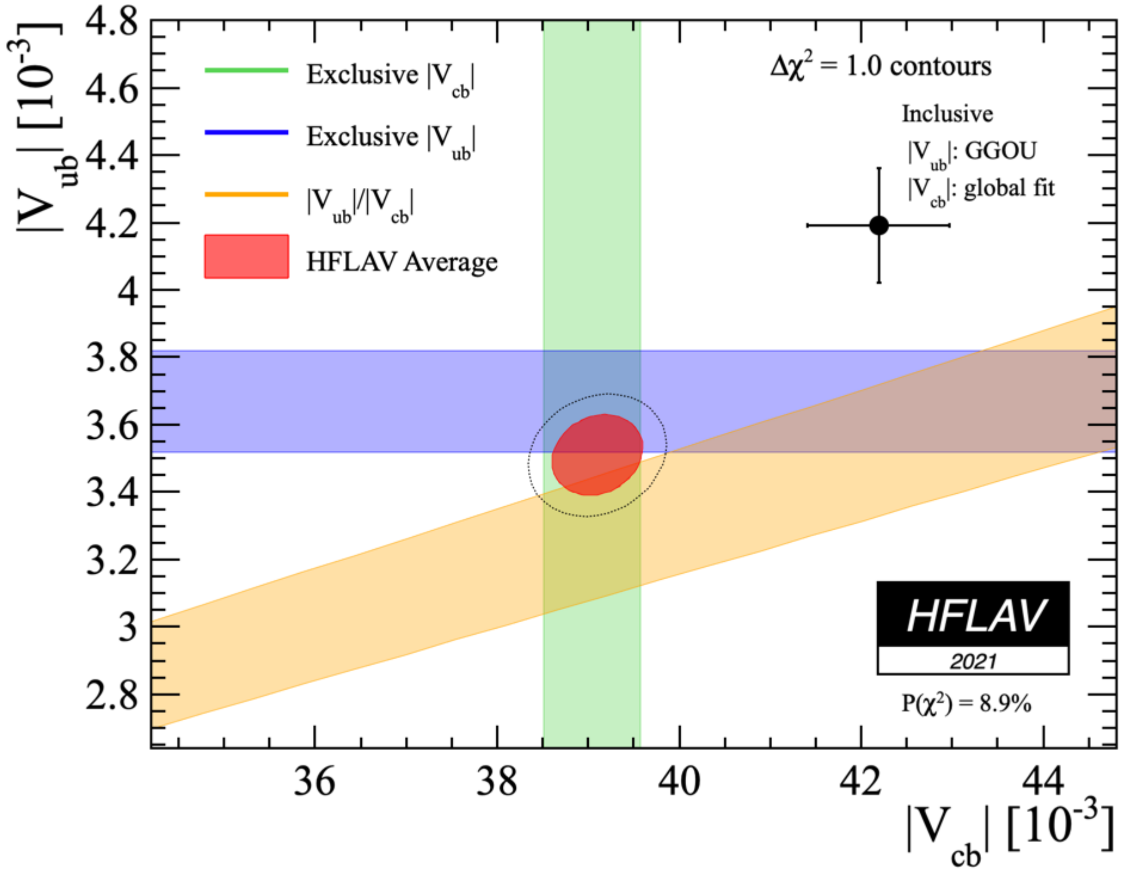
Inclusive vs. Exclusive $|V_{cb}|$, $|V_{ub}|$

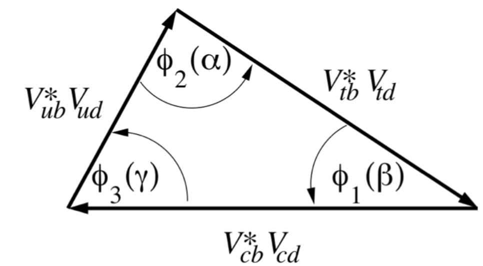




	Exclusive (x 10^{-3})	Inclusive (x 10^{-3})	Difference
$\|V_{cb}\|$	38.46 ± 0.40 (exp) ± 0.55 (th) ($D^*\ell\nu$) 39.14 ± 0.92 (exp) ± 0.36 (th) ($D\ell\nu$)	42.19 ± 0.78 (kinetic scheme) 41.98 ± 0.45 (1S scheme)	2.6–3.6 σ
$\|V_{ub}\|$	$3.67 \pm 0.09 \pm 0.12$ ($\pi\ell\nu$)	$4.62 \pm 0.20 \pm 0.29$ (BLL)	2.5 σ

Inclusive vs. Exclusive $|V_{cb}|$, $|V_{ub}|$





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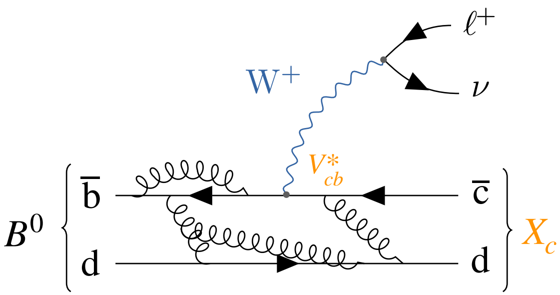
$\|V_{ub}\|$	3.67 ± 0.09 ± 0.12 ($\pi\ell\nu$)	4.62 ± 0.20 ± 0.29 (BLL)	2.5 σ

Inclusive $|V_{cb}|$

Gambino, Schwanda, PRD 89, 014022 (2014)
HFLAV, EPJC 81, 226 (2021)

Fael, Mannel, and Vos, JHEP 02, 177 (2019)
Bernlochner et al., arXiv:2205.10274 (2022)



$B \to X_c\, l\nu$, where X_c denotes final state hadrons containing charm

- *Experimentally, no specific final state is reconstructed. Statistics are high, but backgrounds are high*
- *Theoretically, one calculate a b $\to$ c transition, not a $<D^*|\mathcal{H}|B>$ matrix element (parameterized by form factors).*

Strategy: *the inclusive b $\to$ clv decay rate is calculated via the Heavy Quark Expansion. This is a double expansion in α_s and (Λ_{QCD}/m_b). The expansion depends on unknown B matrix elements of local operators. However, these matrix elements also determine moments of the lepton energy and recoil hadronic mass M_X in $B \to X\, l\nu$. These moments have been measured (Belle, BaBar, others), and thus one can fit the moments and the measured width for $B \to X\, l\nu$ to extract $|V_{cb}|$.To order $(1/m_b)^3$, there are 4 hadronic parameters (~matrix elements) fitted for. [To $(1/m_b)^4$, there would be 13.]*

New Strategy:
Instead of lepton energy and recoil hadronic mass M_X moments, use q^2 moments (mass squared of $\ell\nu$ system). These moments are "re-parameterization invariant," and thus depend on a reduced set of nonperturbative HQE parameters. To order $(1/m_b)^4$, there are only 8. There are two recent measurements of q^2 moments, by Belle (711 fb^{-1}) and Belle II (63 fb^{-1}). [Previously there were none.] Both sets have now been fitted for $|V_{cb}|$.

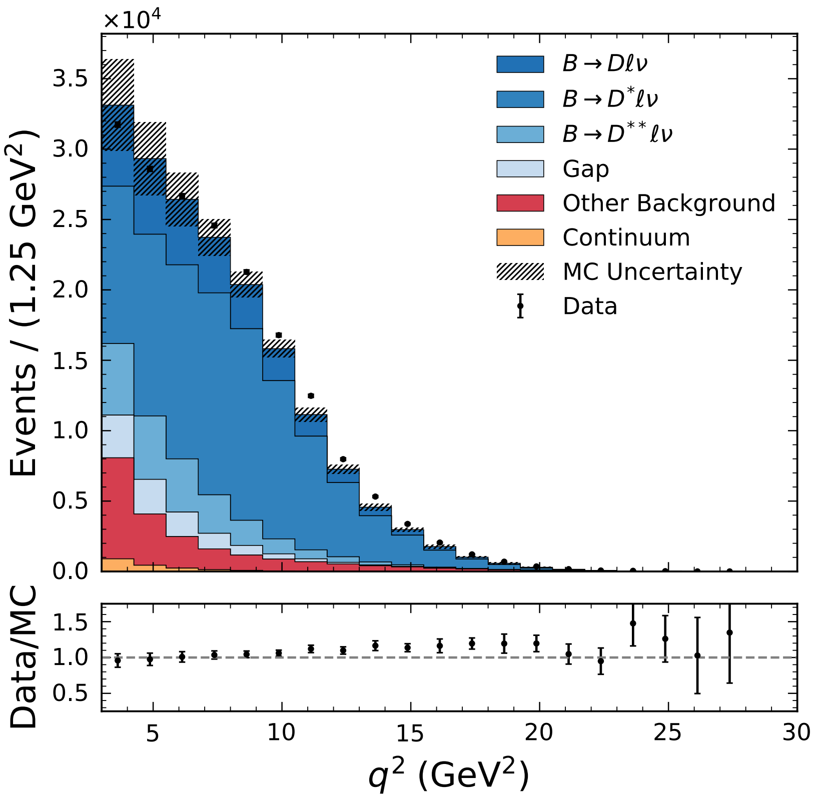
$$\langle (q^2)^n \rangle = \frac{1}{\Gamma_0} \int_{q^2_{\rm cut}}^{q^2_{\rm max}} dq^2\, (q^2)^n \frac{d\Gamma}{dq^2} \qquad \left(\Gamma_0 = \frac{G_F^2\, |V_{cb}|^2\, m_b^5\, A_{EW}}{192\pi^3} \right)$$

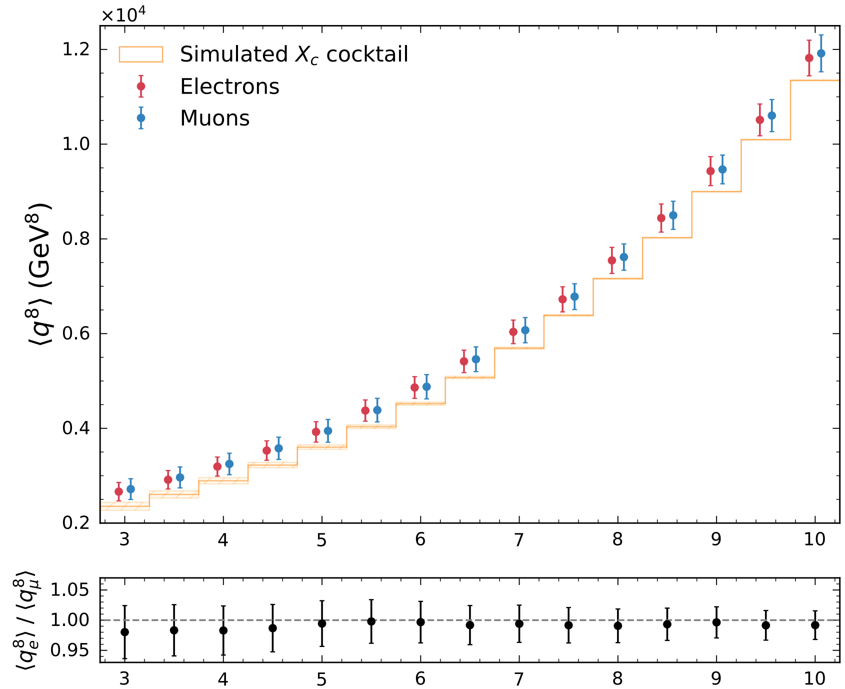
Inclusive $|V_{cb}|$ via q^2 moments: 2 measurements

$B \to X_c \ell \nu$:

711 fb^{-1}:
[PRD 104, 112011 (2021)]

- *to reconstruct $q^2 = (P_\ell + P_\nu)^2$ moments, need P_ν ⇒ must fully reconstruct tag side. To achieve this, use 4 stages of neural networks (output classifier of one stage → input layer of next stage). In total, 1104 decay chains considered, effic. = 0.2–0.3%.*
  [details: Feindt et al., NIM A 654, 432 (2011)]
- *identify μ or e on signal side. Instead of lower p cut (needed to well-identify leptons), impose lower q^2 cut (to preserve re-parameterization invariance).*





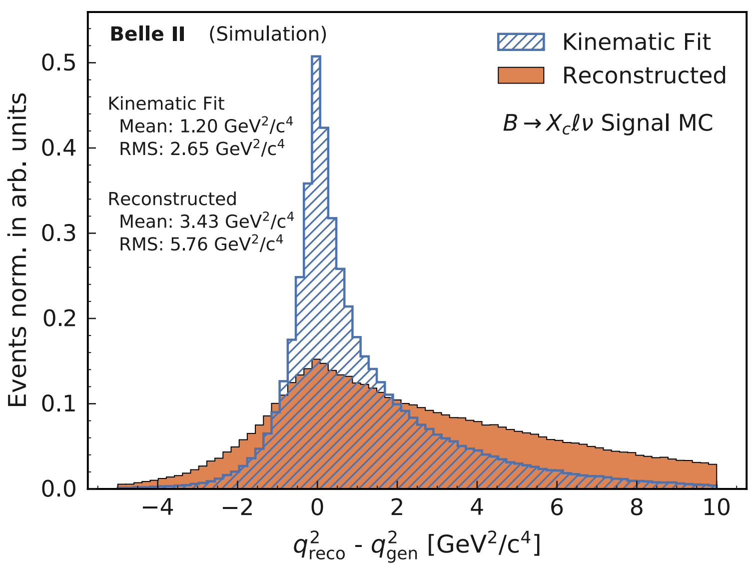
(Lepton flavor universality conserved, but notable systematic from MC simulation (used to apportion background among q^2 bins)

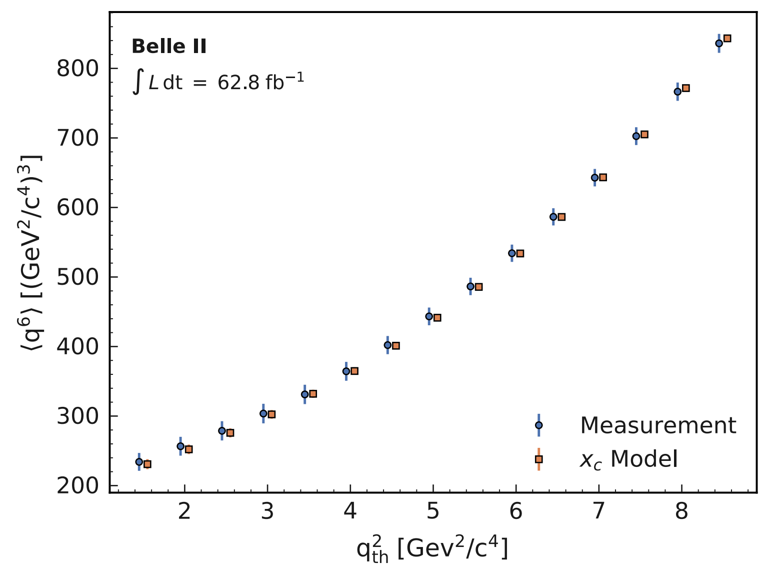
Inclusive $|V_{cb}|$ via q^2 moments: 2 measurements

63 fb^{-1}:
[arXiv:2205.06372]

$B \to X_c \, l\nu$, some improvements w/r/t Belle:

- q^2 threshold is lowered from 3.0 GeV^2 (58% of phase space) to 1.5 GeV^2 (77% of phase space). This introduces some dependence on the moments on modeling $B \to X_c \, l\nu$.
- new algorithm based on boosted decision trees used for full reconstruction of tag side [T. Keck et al., arXiv:1807.08680]. Total of ~10000 decay chains considered. effic. = 0.3-0.4%.
- q^2 resolution is improved by performing a global kinematic fit to the entire decay chain $e^+e^- \to BB \to B_{tag} \, X_c \, \ell \, \nu$, imposing $(P_{tag})2 = m_B^2$, $(P_{sig})^2 = m_B^2$, and overall energy-momentum conservation.





Simultaneous fit of Belle and Belle II q^2 moments:
[Bernlochner et al., arXiv:2205.10274]

$|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$

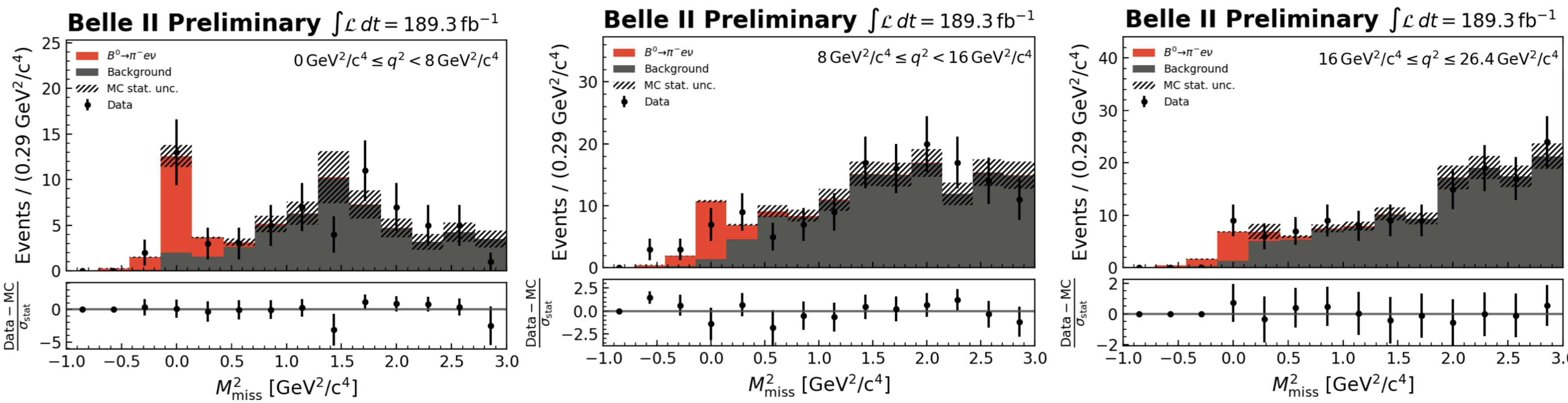
Compare to fit to E_ℓ and M_X moments:
[Bordone et al., PLB 822, 136679 (2021)]

$|V_{cb}| = (42.16 \pm 0.51) \times 10^{-3}$

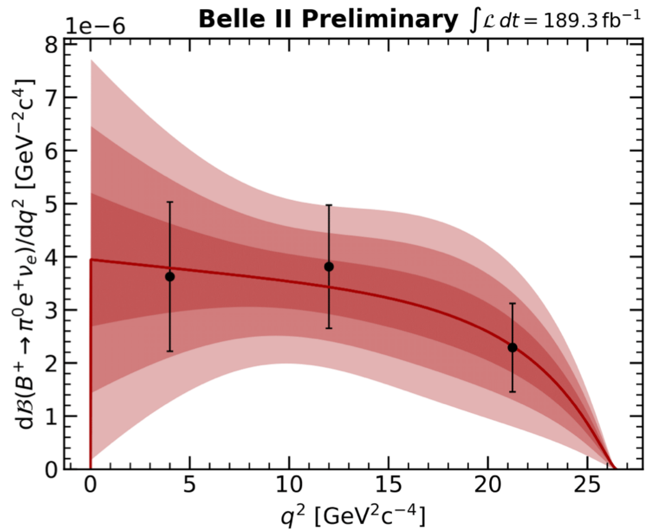
very close (!)
⇒ affirms discrepancy between inclusive and exclusive values of $|V_{cb}|$

Exclusive $|V_{ub}|$ via $B \to \pi e^+ \nu$

189 fb^{-1}:
[arXiv:2206.08102]

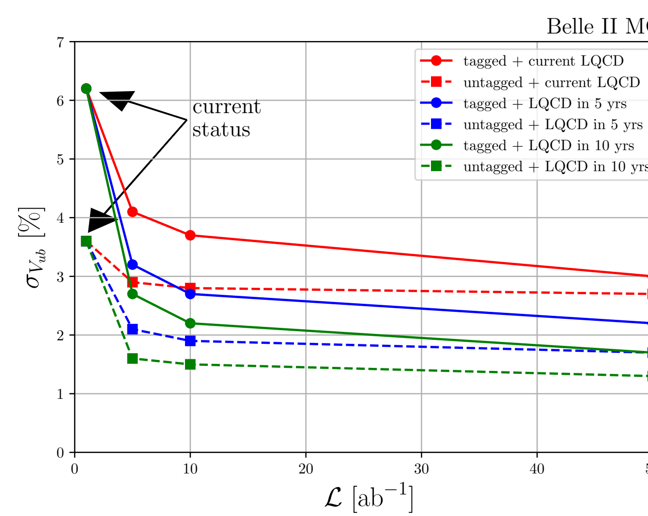


- *same tag-side reconstruction as used for inclusive $|V_{cb}|$*
- *BCL parametrization of form factors*
  [Bourrely et al., PRD 79, 013008 (2009)]
- *normalization from LQCD*
  [FNAL/MILC, PRD 92, 014024 (2015)]



$|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$

HFLAV fit: $(3.51 \pm 0.12) \times 10^{-3}$



$a_\mu = (g-2)/2$

[Aoyama et al., Phys. Rep. 887, 1 (2020)]

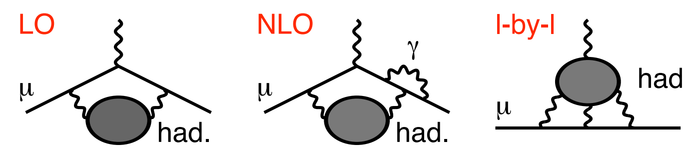
Discrepancy:
a_μ *[Experiment – Theory]* = $(279 \pm 76) \times 10^{-11}$

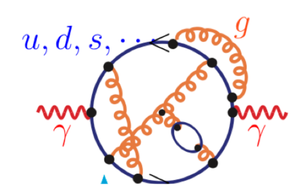
Experimental uncertainty:
$\delta a_\mu = 63 \times 10^{-11} \rightarrow \sim 16 \times 10^{-11}$
E-989

Theoretical uncertainty:

Contribution	Magnitude (10^{-11})	Uncertainty (10^{-11})
QED	116584718.931	0.104
electroweak	153.6	1.0
NLO hadronic	-98.3	0.7
NNLO hadronic	12.4	0.1
light-by-light hadronic	92	18
LO hadronic	6931	40

Hadronic contributions:





$a_\mu = (g\text{-}2)/2$

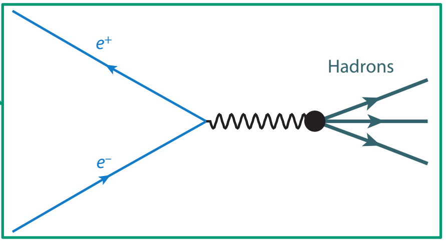
Aoyama et al., Phys. Rep. 887, 1 (2020)
Lees et al. (BaBar), PRD 104, 112003 (2021)
Fabio Anulli, ICHEP 2022

Leading order hadronic contribution is calculated using a dispersion relation:

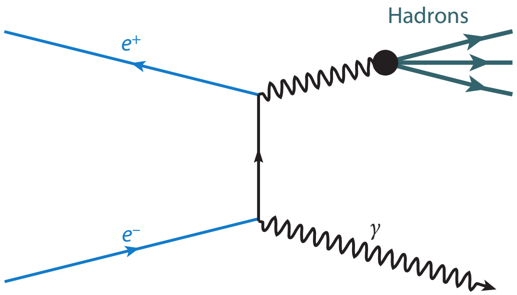
$$a_\mu^{\rm LO} = \frac{\alpha^2}{3\pi^3}\int_{M_\pi^2}^{\infty}\left(\frac{K(s)}{s}\right)\frac{\sigma_0(e^+e^-\to \text{hadrons})}{\sigma_{\rm pt}}\,ds$$

kernel function: $K(s)/s \approx 1/s^2$

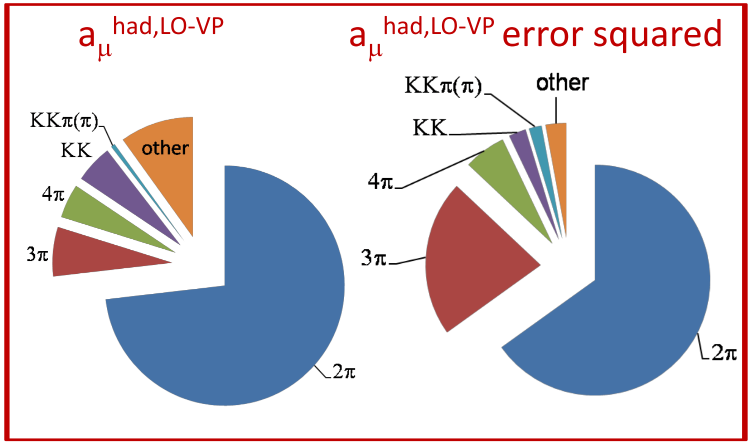
$$\sigma_{\rm pt} = \left(\frac{4}{3}\right)\frac{\pi\alpha^2}{s}$$



$\sigma(e^+e^-\to$ hadrons) can be measured at an e^+e^- collider via "initial-state-radiation" events:



$\sigma(e^+e^-\to$ hadrons) dominated by $e^+e^-\to\pi\pi$, but significant uncertainty arises from $e^+e^-\to\pi^+\pi^-\pi^0$

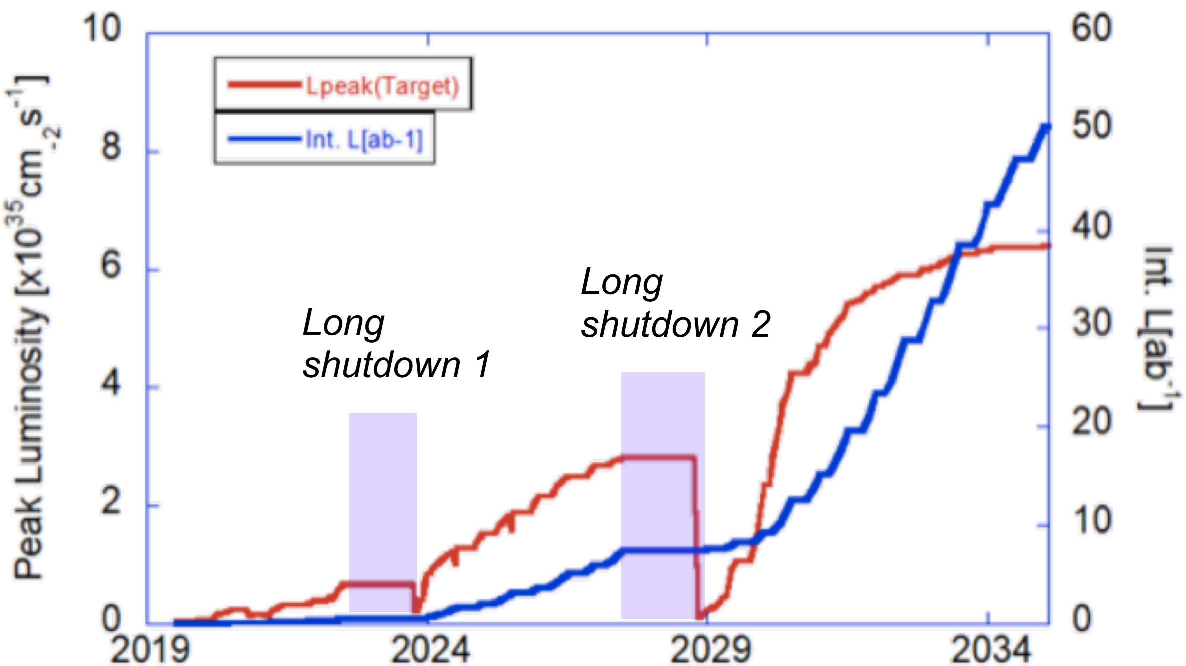


new measurement of $\sigma(e^+e^-\to\pi^+\pi^-\pi^0)$ from BaBar reduces uncertainty by ~factor of 2:

$\Rightarrow a_\mu^{\rm LO}(\pi^+\pi^-\pi^0) = (45.86 \pm 0.14 \pm 0.58) \times 10^{-10}$

[**Note:** 2.9σ discrepancy between BaBar and KLOE for $a_\mu^{\rm LO}(\pi^+\pi^-)$ should be resolved by Belle II]

Running Plan



we are here

Long shutdown #1

Detector upgrades:

- PXD (pixel) detector: complete 2nd layer
- TOP (particle ID) detector: exchange "conventional" PMTs for life-extended PMTs
- upgrade of back-end readout (COPPER-> PCIe40)

Accelerator upgrades:

- shielding of QCS (final focusing) bellows
- additional neutron shielding
- installation of nonlinear collimator
- enlarged beampipe for HER injection
- pulse-by-pulse beam control for LINAC

Summary

- Belle II has taken 423 fb^{-1} of data, ~equaling the BaBar sample. The only missing element is the second layer of the PXD (to be installed this year during LS1).

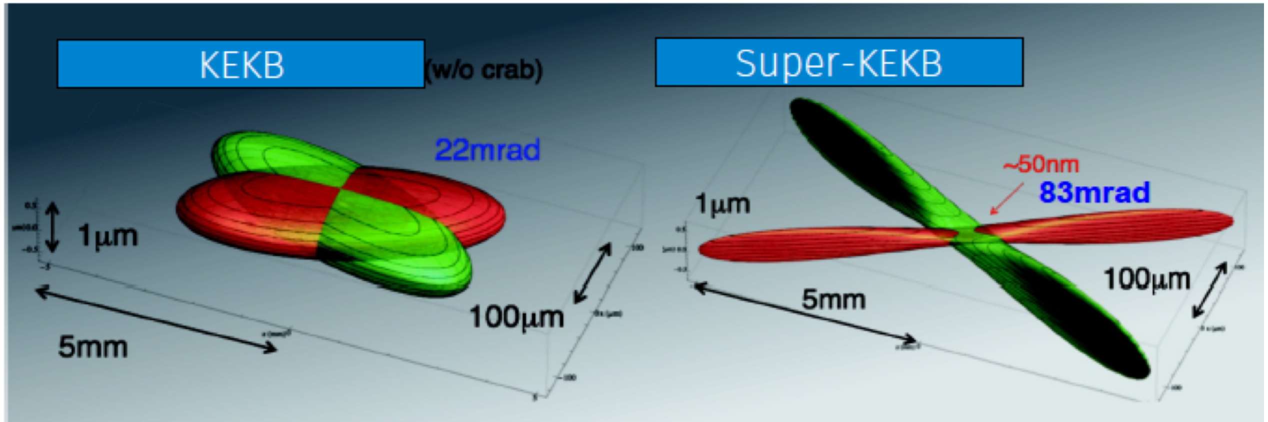
- Detector works well, many analyses in progress. A dozen new results presented at Moriond 2022, another ~dozen at ICHEP22.

- Accelerator commissioning is proceeding, but there are challenges (as expected) for this machine: background is higher than expected, dominated by beam gas, Touschek. β_y^* is slowly being reduced. Both instantaneous luminosity and specific luminosity significantly higher than Belle (& BaBar), but still have a ways to go. We are 2-3 years behind in luminosity profile/data.

- Physics potential is large: there is much better vertexing (⇒ 2x better decay time resolution) and (in principle) better particle ID than in Belle. Full reconstruction on tag side is much improved over Belle/BaBar. Improved triggering (relevant for DM searches).

Extras

How to get 40x instantaneous luminosity?



	E (GeV) LER/HER	β*$_y$ (mm) LER/HER	β*$_x$ (cm) LER/HER	φ (mrad)	I (A) LER/HER	L (cm^{-2}s^{-1})
KEKB	3.5/8.0	5.9/5.9	120/120	11	1.6/1.2	2.1 x 10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80 x 10^{34}

factor 20   factor 2-3

beam size:
100 μm(H) x 2 μm(V)
→ 10 μm(H) x 59 nm(V)

Belle-II Goal:
40 x Belle = 8 x 10^{35}

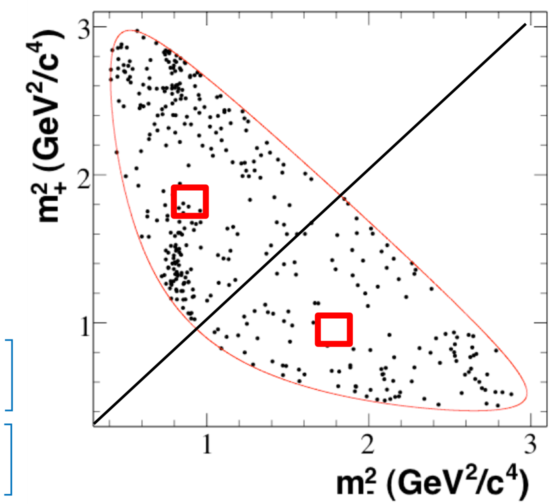
Final focus quadrupole being inserted:

Measurement of ϕ_3 with a Dalitz analysis

$$\frac{d\Gamma[B^+ \to (m_+^2, m_-^2)]}{d(\text{phase space})} \propto |\mathcal{A}_{\overline{D}^0}|^2 + r_B^2|\mathcal{A}_{D^0}|^2 + 2r_B|\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D}^0}|\left[\cos\delta_D\cos(\delta_B - \phi_3) - \sin\delta_D\sin(\delta_B - \phi_3)\right]$$

$$\frac{d\Gamma[B^- \to (m_+^2, m_-^2)]}{d(\text{phase space})} \propto |\mathcal{A}_{D^0}|^2 + r_B^2|\mathcal{A}_{\overline{D}^0}|^2 + 2r_B|\mathcal{A}_{D^0}||\mathcal{A}_{\overline{D}^0}|\left[\cos\delta_D\cos(\delta_B + \phi_3) - \sin\delta_D\sin(\delta_B + \phi_3)\right]$$

Step 1: *divide Dalitz plot into symmetric + and – bins:*



Step 2: *define more robust fitting variables:*

$$x^\pm = r_B\cos(\delta_B \pm \phi_3)$$
$$y^\pm = r_B\sin(\delta_B \pm \phi_3)$$

⇒ *equations become:*

$(r_B)^2$

$$N_i^{B+} = N_{B+}\left[F_{-i} + (x_+^2 + y_+^2)F_i + 2\sqrt{F_i F_{-i}}\left(x_+\langle\cos\delta_D\rangle - y_+\langle\sin\delta_D\rangle\right)\right]$$

$$N_{-i}^{B+} = N_{B+}\left[F_i + (x_+^2 + y_+^2)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_+\langle\cos\delta_D\rangle + y_+\langle\sin\delta_D\rangle\right)\right]$$

$$N_i^{B-} = N_{B-}\left[F_i + (x_-^2 + y_-^2)F_{-i} + 2\sqrt{F_i F_{-i}}\left(x_-\langle\cos\delta_D\rangle + y_-\langle\sin\delta_D\rangle\right)\right]$$

$$N_{-i}^{B-} = N_{B-}\left[F_{-i} + (x_-^2 + y_-^2)F_i + 2\sqrt{F_i F_{-i}}\left(x_-\langle\cos\delta_D\rangle - y_-\langle\sin\delta_D\rangle\right)\right]$$

m_{bc} cut + ΔE, C' fit

measured by BESIII

fractions of D^0 decays; determined from $B^- \to D^0\pi^-$ sample

Measurement of ϕ_3 with a Dalitz analysis

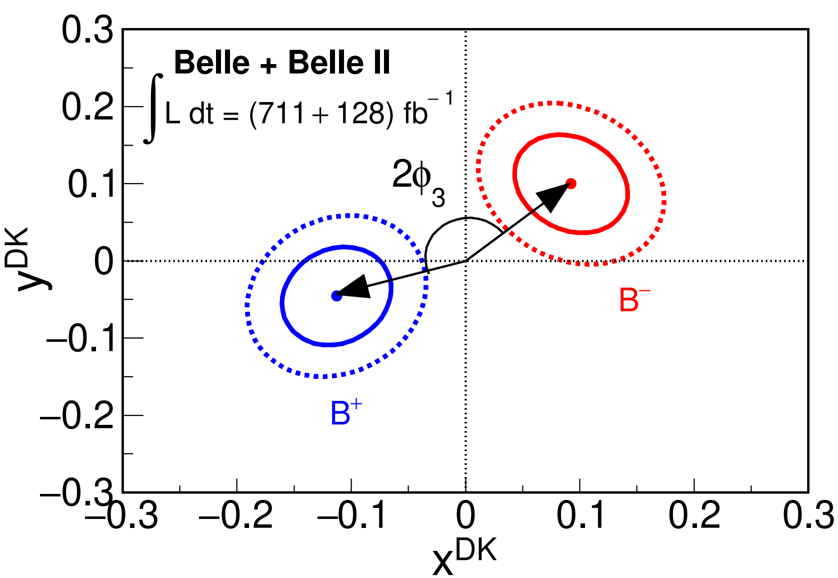
Results for (711 + 128) fb^{-1}:

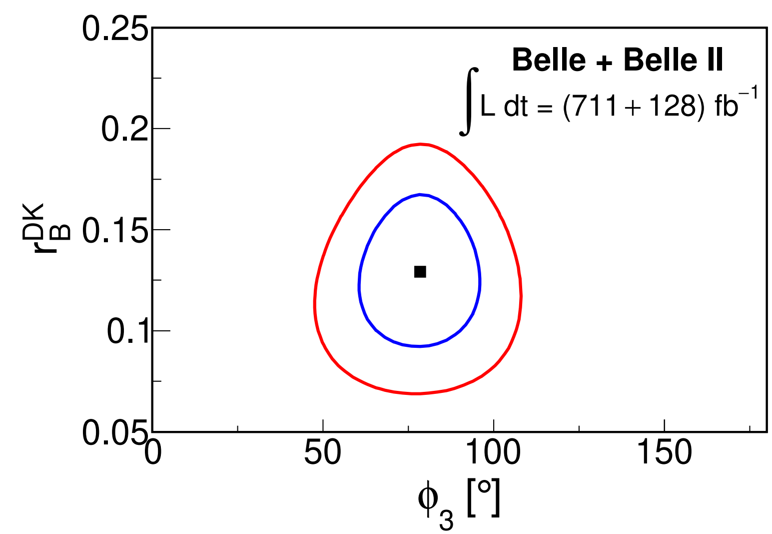
$$\begin{aligned} x^+ &= (-11.28 \pm 3.15 \pm 0.18 \pm 0.22)\% \\ x^- &= (9.24 \pm 3.27 \pm 0.17 \pm 0.23)\% \\ y^+ &= (-4.55 \pm 4.20 \pm 0.11 \pm 0.55)\% \\ y^- &= (10.00 \pm 4.20 \pm 0.23 \pm 0.67)\% \end{aligned}$$

GAMMACOMBO *frequentist procedure*

$$\begin{aligned} \phi_3 &= (78.4 \pm 11.4 \pm 0.5 \pm 1.0)^\circ \\ r_B &= 0.129 \pm 0.024 \pm 0.001 \pm 0.002 \\ \delta_B &= (124.8 \pm 12.9 \pm 0.5 \pm 1.7)^\circ \end{aligned}$$

$$\begin{aligned} x^\pm &= r_B \cos(\delta_B \pm \phi_3) \\ y^\pm &= r_B \sin(\delta_B \pm \phi_3) \end{aligned}$$

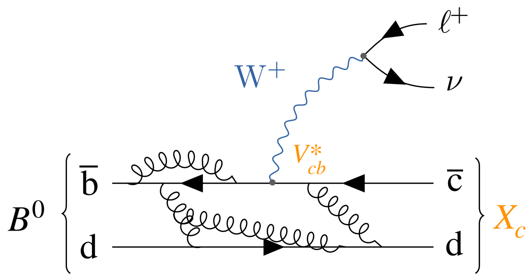




Inclusive $|V_{cb}|$

Gambino and Schwanda, PRD 89, 014022 (2014)

Y. Amhis et al. (Heavy Flavor Averaging Group), EPJC 81, 226 (2021) https://hflav.cern.ch/content/semileptonic-b-decays

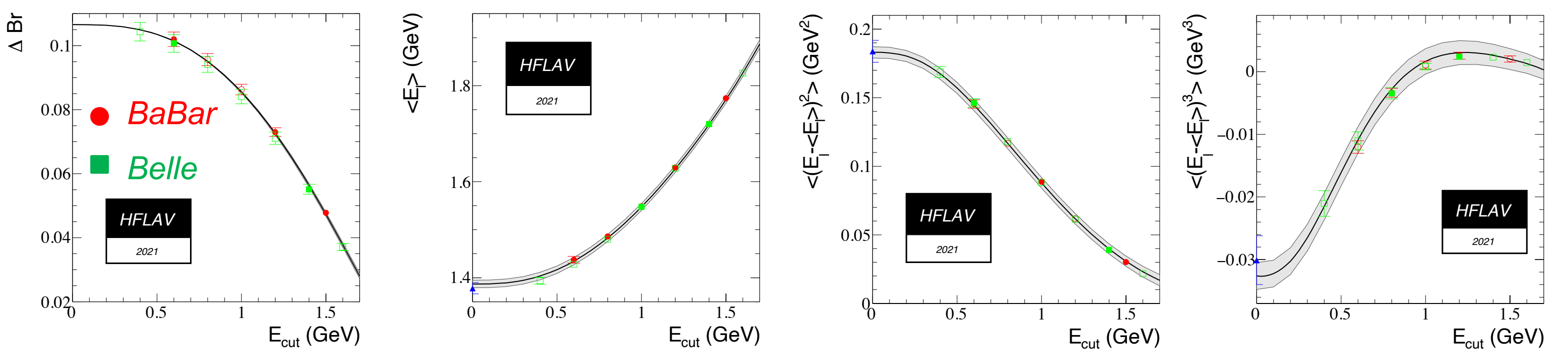


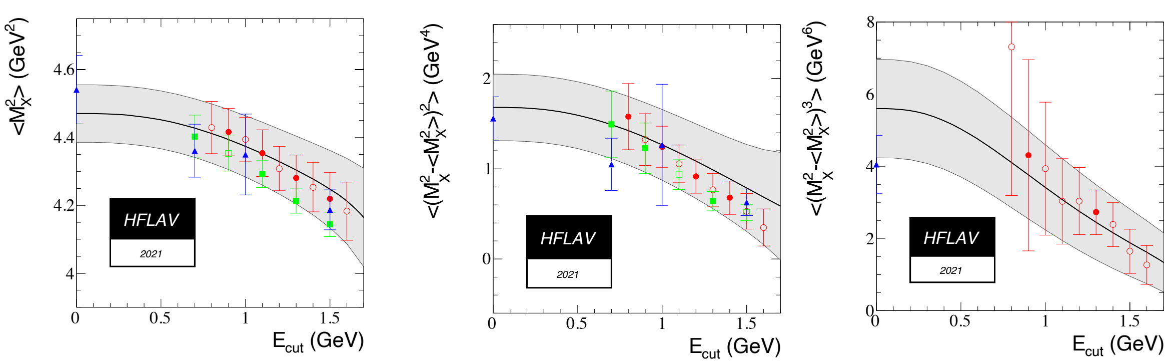
$B \to X_c \, l \nu$, where X_c denotes final state hadrons containing charm

- *Experimentally, no specific final state is reconstructed. Statistics are high, but backgrounds are high*
- *Theoretically, one calculate a b $\to$ c transition, not a $\langle D^* | \mathcal{H} | B \rangle$ matrix element (parameterized by form factors).*

Strategy: *the inclusive b $\to$ clv decay rate is calculated via the Heavy Quark Expansion. This is a double expansion in α_s and (Λ_{QCD}/m_b). The expansion depends on unknown B matrix elements of local operators. However, these matrix elements also determine moments of the lepton energy and recoil hadronic mass M_X in $B \to X \, l \nu$. These moments have been measured (Belle, BaBar, others), and thus one can fit the moments and the measured width for $B \to X \, l \nu$ to extract $|V_{cb}|$. To order $(1/m_b)^3$, there are 4 hadronic parameters (~matrix elements) fitted for. [To $(1/m_b)^4$, there would be 13.]*

$$\langle E_\ell^n \rangle = \frac{\int_{E_{\rm cut}}^{E_{\rm max}} dE_\ell \, (E_\ell)^n \frac{d\Gamma}{dE_\ell}}{\int_{E_{\rm cut}}^{E_{\rm max}} dE_\ell \, \frac{d\Gamma}{dE_\ell}}$$





$|V_{cb}| = (42.19 \pm 0.78) \times 10^{-3}$ *(kinetic scheme)*

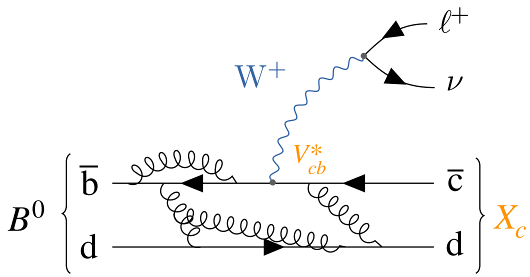
Including recently calculated $(\alpha_s)^3$ corrections:

$|V_{cb}| = (42.16 \pm 0.51) \times 10^{-3}$

[Bordone et al., PLB 822, 136679 (2021)]

Inclusive $|V_{cb}|$ redux

Fael, Mannel, and Vos, JHEP 02, 177 (2019)
Bernlochner et al., arXiv:2205.10274 (2022)



New Strategy:
Instead of lepton energy and recoil hadronic mass M_X moments, use q^2 moments (mass squared of $\ell\nu$ system). These moments are "re-parameterization invariant," and thus depend on a reduced set of nonperturbative HQE parameters. To order $(1/m_b)^4$, there are only 8. There are two recent measurements of q^2 moments, by Belle (711 fb^{-1}) and Belle II (63 fb^{-1}). [Previously there were none.] Both sets have now been fitted for $|V_{cb}|$.

$$\langle (q^2)^n \rangle = \frac{1}{\Gamma_0} \int_{q^2_{\rm cut}}^{q^2_{\rm max}} dq^2\, (q^2)^n \frac{d\Gamma}{dq^2} \qquad \left(\Gamma_0 = \frac{G_F^2\, |V_{cb}|^2\, m_b^5\, A_{EW}}{192\pi^3} \right)$$

Heavy Quark Expansion:

$$\begin{aligned} \langle (q^2)^n \rangle \simeq\ & \mu_3 \left[X_0^{(n)} + \left(\frac{\alpha_s}{\pi}\right) X_1^{(n)} + \ldots \right] + \\ & \frac{\mu_G^2}{m_b^2} \left[g_0^{(n)} + \left(\frac{\alpha_s}{\pi}\right) g_1^{(n)} + \ldots \right] + \\ & \frac{\rho_D^3}{m_b^3} \left[d_0^{(n)} + \left(\frac{\alpha_s}{\pi}\right) d_1^{(n)} + \ldots \right] + \\ & \frac{r_E^4}{m_b^4} l_{r_E}^{(n)} + \frac{r_G^4}{m_b^4} l_{r_G}^{(n)} + \frac{s_B^4}{m_b^4} l_{s_B}^{(n)} + \frac{s_E^4}{m_b^4} l_{s_E}^{(n)} + \frac{s_{qB}^4}{m_b^4} l_{s_{qB}}^{(n)} \end{aligned}$$

non-perturbative hadronic parameters (to be fitted)