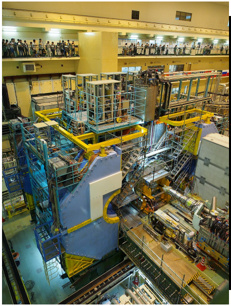
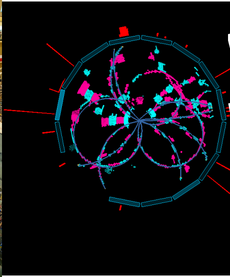
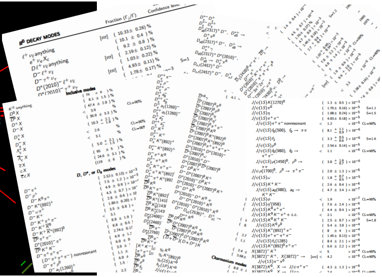
The Belle II Experiment





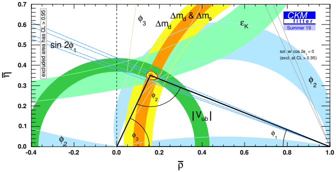


Belle II

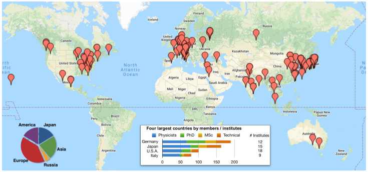
Alexander von Humboldt
Stiftung/Foundation

UNIVERSITÄT BONN

Belle II experiment



- Aim to collect 50 ab^{-1} of e^+e^- collisions at $\sqrt{s} = m_{\Upsilon(4S)}$.
- Wide range of physics: precision CKM measurements, CP violation to new physics searches.

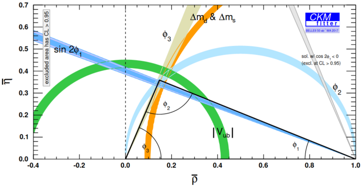


The Belle II Physics Book [arxiv1808.10567]

Observables	Expected the. accuracy	Expected exp. uncertainty	Facility (2025)
UT angles & sides			
ϕ_1 [°]	***	0.4	Belle II
ϕ_2 [°]	**	1.0	Belle II
ϕ_3 [°]	***	1.0	LHCb/Belle II
$\|V_{cb}\|$ incl.	***	1%	Belle II
$\|V_{cb}\|$ excl.	***	1.5%	Belle II
$\|V_{ub}\|$ incl.	**	3%	Belle II
$\|V_{ub}\|$ excl.	**	2%	Belle II/LHCb
CP Violation			
$S(B \to \phi K^0)$	***	0.02	Belle II
$S(B \to \eta' K^0)$	***	0.01	Belle II
$\mathcal{A}(B \to K^0\pi^0)[10^{-2}]$	***	4	Belle II
$\mathcal{A}(B \to K^+\pi^-)$ $[10^{-2}]$	***	0.20	LHCb/Belle II
(Semi-)leptonic			
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	**	3%	Belle II
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	**	7%	Belle II
$R(B \to D\tau\nu)$	***	3%	Belle II
$R(B \to D^*\tau\nu)$	***	2%	Belle II/LHCb
Radiative & EW Penguins			
$\mathcal{B}(B \to X_s\gamma)$	**	4%	Belle II
$A_{CP}(B \to X_{s,d}\gamma)$ $[10^{-2}]$	***	0.005	Belle II
$S(B \to K_S^0\pi^0\gamma)$	***	0.03	Belle II
$S(B \to \rho\gamma)$	**	0.07	Belle II
$\mathcal{B}(B_s \to \gamma\gamma)$ $[10^{-6}]$	**	0.3	Belle II
$\mathcal{B}(B \to K^*\nu\bar{\nu})$ $[10^{-6}]$	***	15%	Belle II
$R(B \to K^*\ell\ell)$	***	0.03	Belle II/LHCb
Charm			
$\mathcal{B}(D_s \to \mu\nu)$	***	0.9%	Belle II
$\mathcal{B}(D_s \to \tau\nu)$	***	2%	Belle II
$A_{CP}(D^0 \to K_S^0\pi^0)$ $[10^{-2}]$	**	0.03	Belle II
$\|q/p\|(D^0 \to K_S^0\pi^+\pi^-)$	***	0.03	Belle II
$A_{CP}(D^+ \to \pi^+\pi^0)$ $[10^{-2}]$	**	0.17	Belle II
Tau			
$\tau \to \mu\gamma$ $[10^{-10}]$	***	< 50	Belle II
$\tau \to e\gamma$ $[10^{-10}]$	***	< 100	Belle II
$\tau \to \mu\mu\mu$ $[10^{-10}]$	***	< 3	Belle II/LHCb

- Belle II Collaboration: 1050 members, 120 institutes, 26 countries

Belle II experiment



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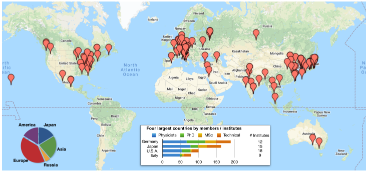

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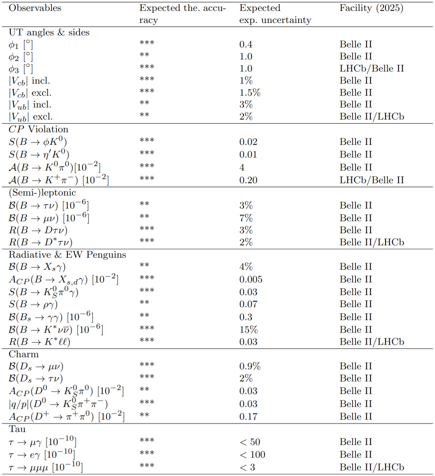

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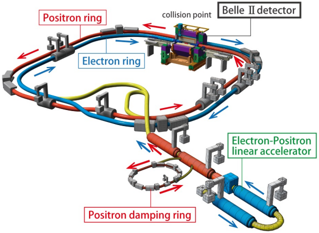
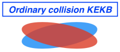
SuperKEKB

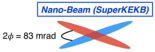
- Upgrade of KEKB with original aim $x40\mathcal{L}$



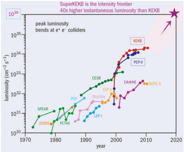
$$L = \frac{\gamma_{e\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

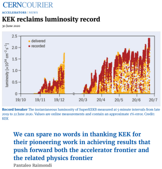
- beam current, $I_{e+/-}$ $\times 1.5$
- Reduction in beam size, β_y, by factor 20





- New aim $x30\mathcal{L}$

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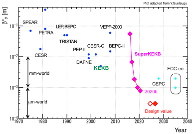
KEK reclaims luminosity record

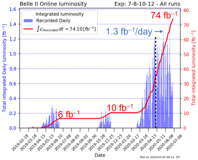
30 June 2020

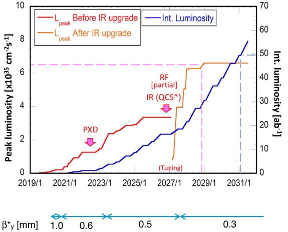
Record breaker The instantaneous luminosity of SuperKEKB measured at 5-minute intervals from late 2019 to 22 June 2020. Values are online measurements and contain an approximate 1% error. Credit: KEK

We can spare no words in thanking KEK for their pioneering work in achieving results that push forward both the accelerator frontier and the related physics frontier

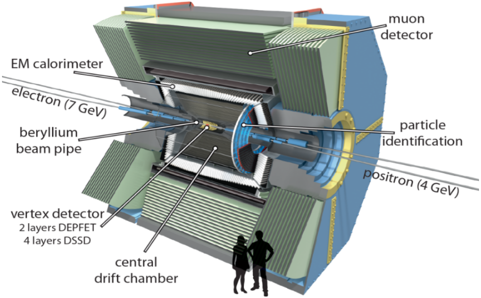
Pantaleo Raimondi

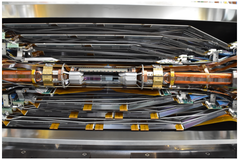


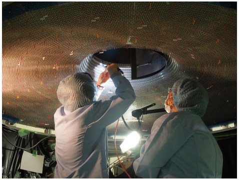




The Belle II Detector

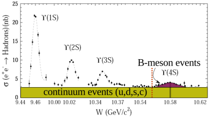


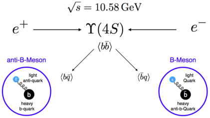


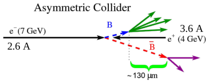


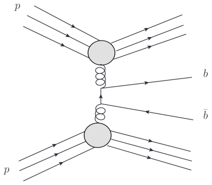
- Inner vertex detector:
  - PXD: 2 layers of DEPFET pixels
  - SVD: 4 layers of DSSD
- Central Drift Chamber for tracking.
- 1.5 T Superconducting solenoid
- Excellent tracking and vertexing down to $p_{\mathrm{T}} \sim 100$ MeV
- Impact parameter resolution in z ~ 20 μm
- PID provided by Time of propagation (TOP) counter and a aerogel RICH
- Outer muon and K_{L} detector

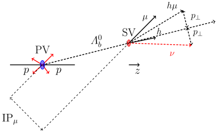
Belle II and LHCb







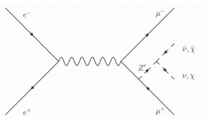


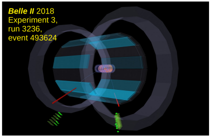


- Event topology:
  - $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^+B^-, B^0\overline{B}^0$
  - $\sigma(e^+e^- \rightarrow \Upsilon(4S))$ small
  - Clean environment $\implies$ great for missing energy
- Detector:
  - Fully hermetic
  - Great performance for electrons, γs and neutrals

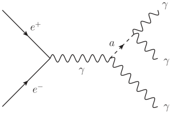
- Event topology:
  - $pp \rightarrow b\bar{b}$
  - $\sigma(pp \rightarrow b\bar{b})$ much larger
  - Events less clean and less constraints as partons interact
  - Λ_b, B_s through fragmentation
- Detector:
  - Forward spectrometer
  - Electrons and π^0s challenging due to ECAL

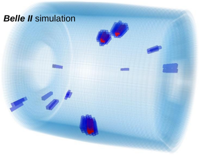
Hidden sector searches - the first Belle II papers



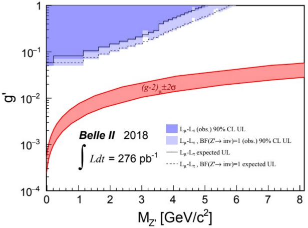


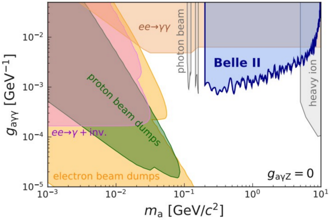
- Search for a $e^+e^- \to \ell^+\ell^-(Z' \to \text{invisible})$
- Limit in the plane of $M_{Z'}$ and g'
- Published in PhysRevLett.124.141801





- Search for a $e^+e^- \to (A \to \gamma\gamma)\gamma$
- Bump hunt in the diphoton mass
- Submitted to PRL arXiv:2007.13071

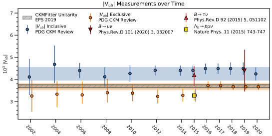


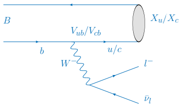


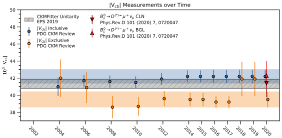
- More searches to follow (e.g dark photon via $e^+e^- \to \gamma_{\text{ISR}}(A' \to \chi\bar{\chi})$)

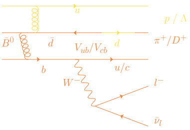
Semileptonic B decays motivation

- Longstanding exclusive/inclusive $|V_{u/cb}|$ puzzle.

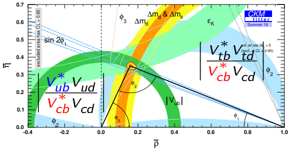






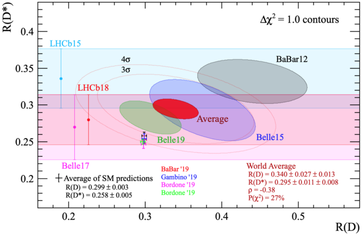


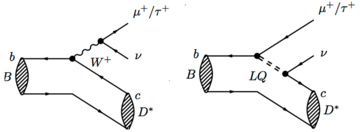
- $|V_{ub}|/|V_{cb}|$ constrains UT length opposite ϕ_1



- Potentially new physics in $B \to D^{(*)}\tau\nu$.

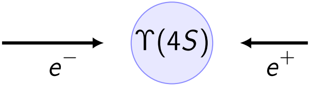
$$R\left(D^{(*)}\right) = \frac{\mathcal{B}(B \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(B \to D^{(*)}\mu^-\bar{\nu}_\mu)}$$





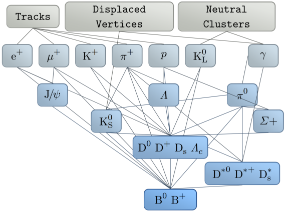
Full Event Interpretation at Belle II

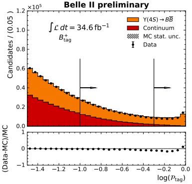
- Collide e^+e^- to make $\Upsilon(4S)$ particles.

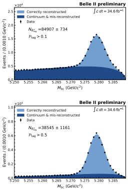


- FEI: employs over 200 BDTs to reconstruct 10000 B decay chains.

Comput Softw Big Sci (2019) 3: 6.







$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{\mathrm{tag}}}^{\mathrm{cm}})^2}$$

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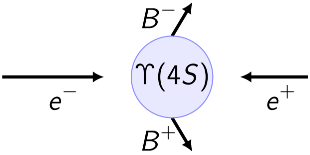

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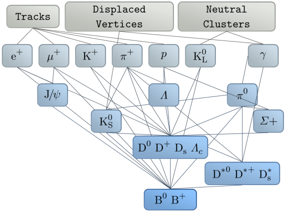

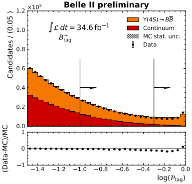

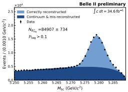

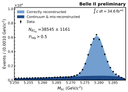

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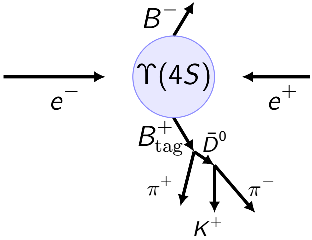
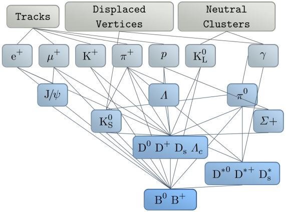
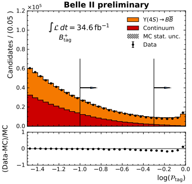


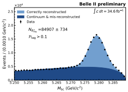
- Reconstruct tag-side (B_{tag}).

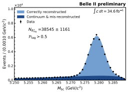
- FEI: employs over 200 BDTs to reconstruct 10000 B decay chains.

Comput Softw Big Sci (2019) 3: 6.





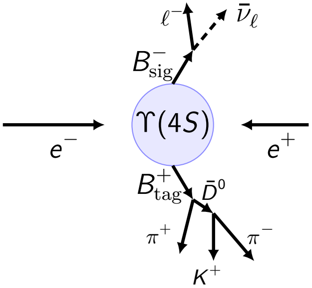




$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{\text{tag}}}^{\text{cm}})^2}$$

Full Event Interpretation at Belle II

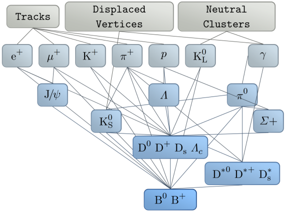
- Collide e^+e^- to make $\Upsilon(4S)$ particles.

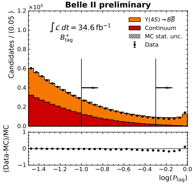


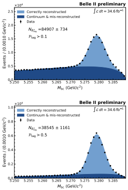
- Reconstruct tag-side (B_{tag}).
- Study remaining B as signal (B_{sig}).

- FEI: employs over 200 BDTs to reconstruct 10000 B decay chains.

Comput Softw Big Sci (2019) 3: 6.







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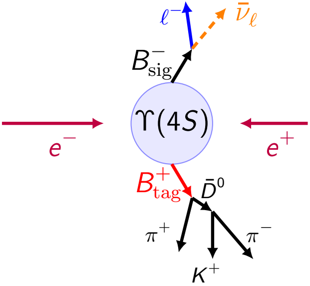
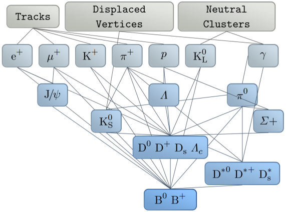
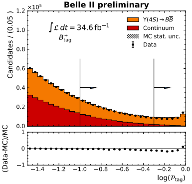


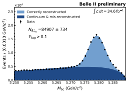
- Reconstruct tag-side ($B_{\rm tag}$).
- Study remaining B as signal ($B_{\rm sig}$).
- Flavour constraints: $B^+_{\rm tag} \implies B^-_{\rm sig}$
  Kinematic constraints:
  $p_\nu = p_{e^+e^-} - p_{\ell^-} - p_{B^+}$

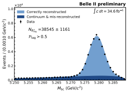
- FEI: employs over 200 BDTs to reconstruct 10000 B decay chains.

Comput Softw Big Sci (2019) 3: 6.





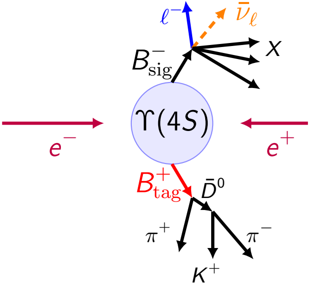




$$M_{bc} = \sqrt{E_{beam}^2/4 - (p_{B_{\rm tag}}^{\rm cm})^2}$$

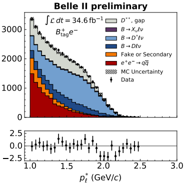
$B \to X\ell\nu$ decays

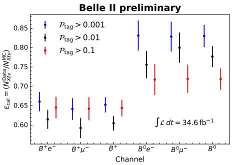
- Crucial for inclusive $|V_{ub}|$ and $|V_{cb}|$
- Large branching fraction ($\sim$20%).
- FEI calibrated by measuring $X\ell\nu$ [arxiv2008.06096]



- Measurement of the M_X moments [arxiv2009.04493]

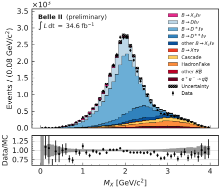
- Calibration factor, $\epsilon_{cal} = N^{X\ell\nu}_{Data} / N^{X\ell\nu}_{MC}$

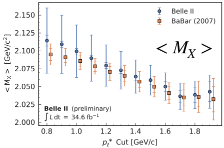




$* \implies B$ Rest Frame

- Fit M_X functional form after a background subtraction.





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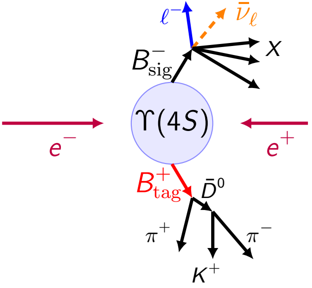

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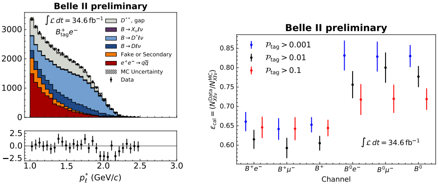

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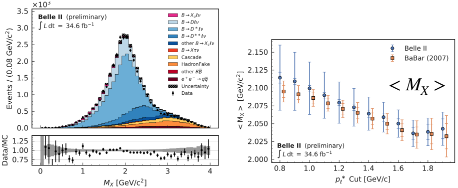

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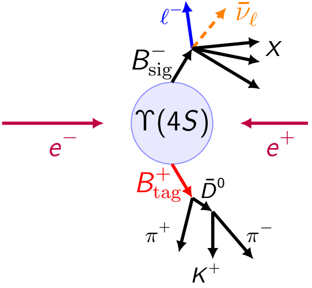

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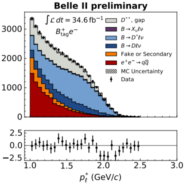

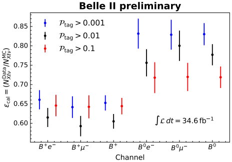

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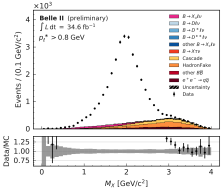

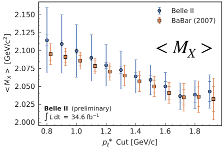

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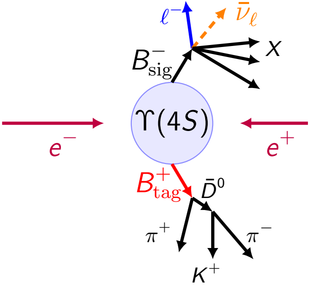

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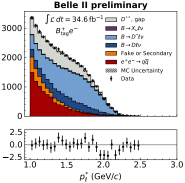

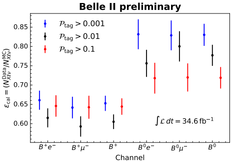

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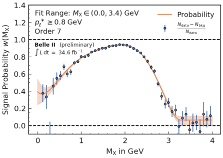
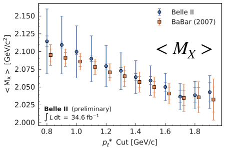
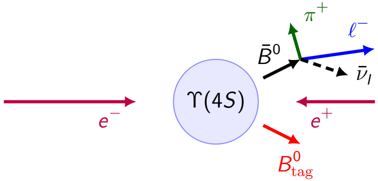
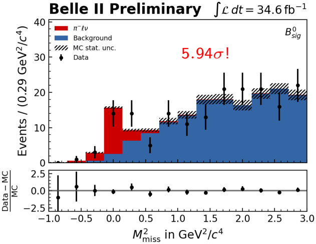




Rediscovering $B \to \pi\ell\nu$ and $B \to D^*\ell\nu$ with tagging

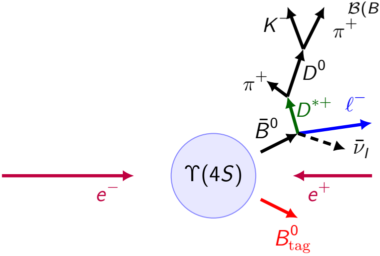
$$\mathcal{B}(B \to \pi\ell\nu) = (1.62 \pm 0.42(\text{stat}) \pm 0.07(\text{sys})) \times 10^{-4}$$

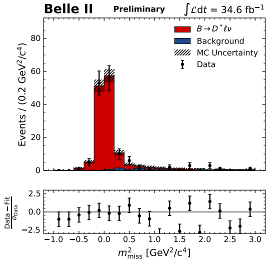




$$m^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_\ell - p_{\pi/D^*})^2$$

$$\mathcal{B}(B^0 \to D^{*+}\ell\nu) = (4.45 \pm 0.41(\text{stat}) \pm 0.27(\text{sys}) \pm 0.45(\pi_s)) \times 10^{-2}$$

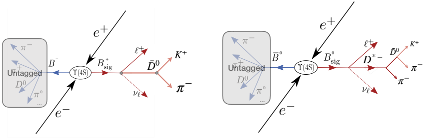




$\pi\ell\nu$: arxiv2008.08819 $D^*\ell\nu$: arxiv2008.10299

Untagged $B \to D^{(*)}\ell\nu$

- Key modes for exclusive $|V_{cb}|$.



Starting from

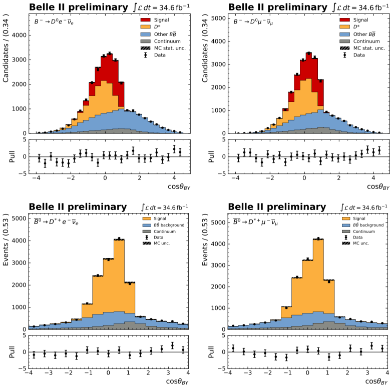
$$0 = p_\nu^2 = (p_B^* - p_Y^*)^2$$

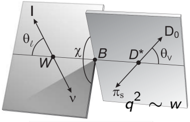
one can derive:

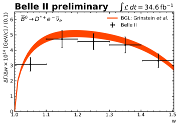
$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - m_B^2 - m_Y^2}{2|\vec{p}_B^*||\vec{p}_Y^*|}$$

- Differential measurements allow a determination of the form factors, $f(q^2)_i$ [arxiv2008.07198]

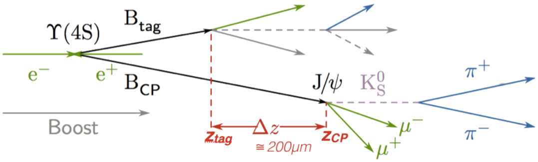
$$\mathcal{B}(B^0 \to D^{*+}\ell\nu) =$$
$$(4.60 \pm 0.05(\mathrm{stat}) \pm 0.17(\mathrm{sys}) \pm 0.45(\pi_s)) \times 10^{-2}$$







$\sin 2\phi_1$ from $B^0 \to J/\psi K_s^0$



$$\begin{tikzcd}
B^0 \arrow[rr] \arrow[dr] & {} \arrow[d, dashed, leftrightarrow, "2\phi_1"] & J/\psi K_S^0 \\
& \overline{B}^0 \arrow[ur] &
\end{tikzcd}$$

$$a_{CP}(t) = \frac{\mathcal{B}(\overline{B}^0 \to K_s^0 J/\psi) - \mathcal{B}(B^0 \to K_s^0 J/\psi)}{\mathcal{B}(\overline{B}^0 \to K_s^0 J/\psi) + \mathcal{B}(B^0 \to K_s^0 J/\psi)}$$

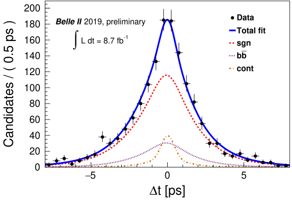
$$= \mathcal{S}_{CP}^{K_s^0 J/\psi} \sin(\Delta m_d t) + \mathcal{A}_{\mathrm{CP}}^{K_s^0 J/\psi} \cos(\Delta m_d t)$$

$$\sim \sin(2\phi_1) \sin(\Delta m_d t) \text{ as} \mathcal{A}_{\mathrm{CP}}^{K_s^0 J/\psi} \sim 0$$

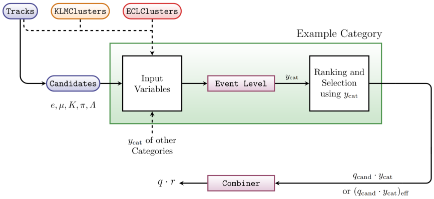
- Measure $a(\Delta t = \Delta z_{\mathrm{boost}}/(\gamma\beta_{\mathrm{boost}} c))$

- One requires:
    - excellent Δz resolution
    - a good flavour tagging performance
    - stats $\mathcal{B}(B^0 \to J/\psi(\ell\ell)K_s^0(\pi^+\pi^-)) \sim 3.6 \times 10^{-5}$

$\tau_{B^0} = 1.48 \pm 0.28(stat) \pm 0.06(sys)$ ps

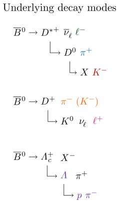


Flavour tagging at Belle II

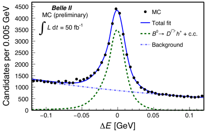


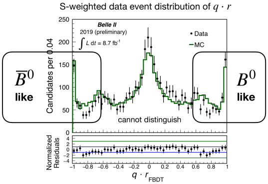
- Performance characterised by:
    - w - wrong tag fraction
    - $\epsilon_{\mathrm{eff}} = \epsilon_{\mathrm{tag}}(1-2w)^2$
- Quantified performance with $B^0 \to D^{(*)-}\pi^+$ [arxiv2008.02707]
- Belle $\epsilon_{\mathrm{eff}} = 30.1 \pm 0.4\%$, Belle II $\epsilon_{\mathrm{eff}} = 33.8 \pm 3.9\%$, LHCb $\epsilon_{\mathrm{eff}} \sim 5\%$

Categories	Targets for $\overline{B}^0$
Electron	e^-
Intermediate Electron	e^+
Muon	μ^-
Intermediate Muon	μ^+
Kinetic Lepton	ℓ^-
Intermediate Kinetic Lepton	ℓ^+
Kaon	K^-
Kaon-Pion	K^-, π^+
Slow Pion	π^+
Maximum p^*	ℓ^-, π^-
Fast-Slow-Correlated (FSC)	ℓ^-, π^+
Fast Hadron	π^-, K^-
Lambda	Λ



- Flavour tagger ouput: $q \cdot r$ where $q = [-1, 1]$ flavour estimate, r = dilution factor$=1-2w$



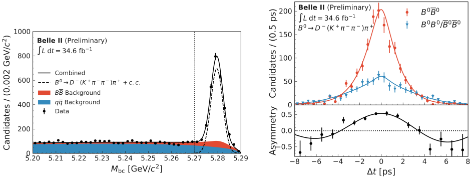


A first time dependent CP measurement at Belle II

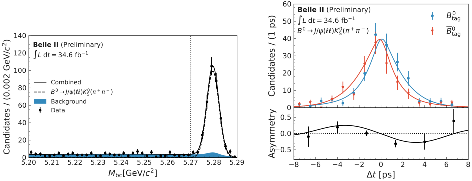
- Experimentally measure

$$a_{CP}(t) = \frac{N(B^0_{\mathrm{tag}}) - N(\overline{B}^0_{\mathrm{tag}})}{N(B^0_{\mathrm{tag}}) + N(\overline{B}^0_{\mathrm{tag}})}(\Delta t)$$
$$= \sin(2\phi_1)\sin(\Delta m_d \Delta t)\times$$
$$(1-2w)\mathcal{R}(\Delta t)$$

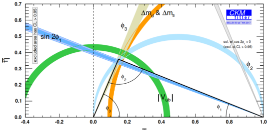
- $\mathcal{R}(\Delta t)$ resolution function.
- w is determined from a time dependent measurement of mixing in $B^0 \to D^-\pi^+$.
- First 2.7 σ evidence of TDCP violation at Belle II!



$$\Delta M_d = 0.531 \pm 0.046(stat) \pm 0.013(sys)$$



$$sin2\phi_1 = 0.55 \pm 0.21(stat) \pm 0.04(sys)$$

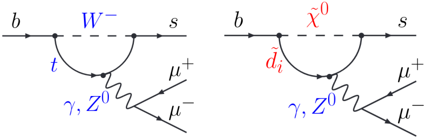


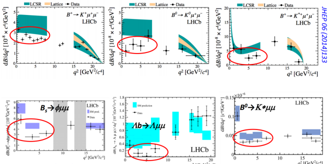
$$\sigma^{BII}_{\phi_1} \sim 0.4^\circ$$

$b \to s\ell\ell$ anomalies

- A wide range of anomalies observed: exclusive $\mathcal{B}$s, angular distribution of $B \to K^*\ell\ell$, $R_{K^{(*)}}$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$





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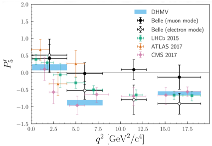
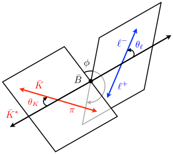
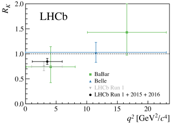
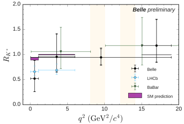
JHEP 06 (2015) 115

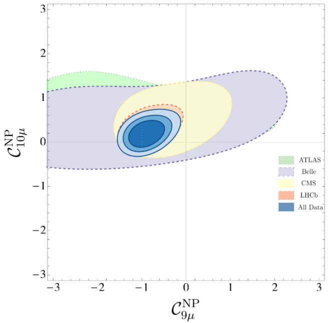
JHEP 11(2016)047
JHEP 04(2017)142





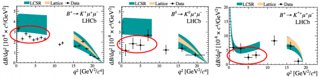




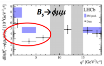


$b \to s\ell\ell$ anomalies

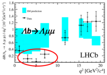
- A wide range of anomalies observed: exclusive $\mathcal{B}$s, angular distribution of $B \to K^*\ell\ell$, $R_{K^{(*)}}$



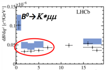
JHEP 06 (2014)133



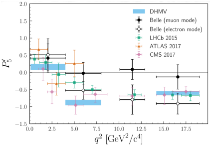
JHEP 09 (2015)179

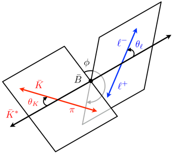


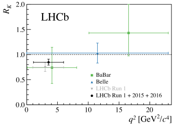
JHEP 06 (2015) 115

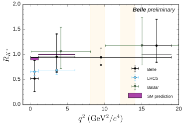


JHEP 11(2016)047
JHEP 04(2017)142

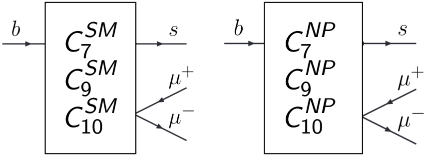


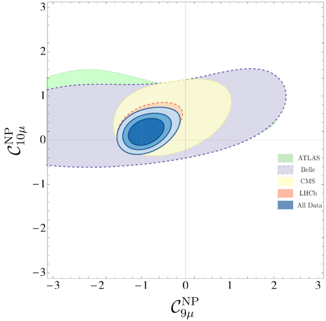




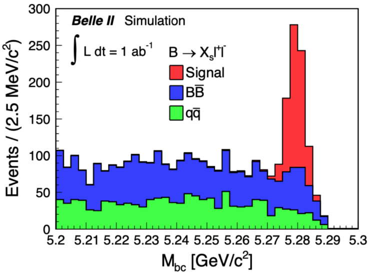


$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2}\sum_i (C_i O_i + C_i' O_i') + \text{h.c.}$$

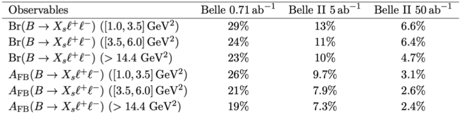




Belle II's orthogonal and complementory role

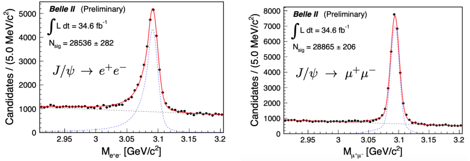


- Soon rediscovery of $B \to X_s \ell\ell$ which has orthogonal OPE theory inputs to $B \to K^{(*)}\ell\ell$

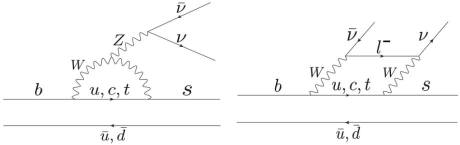


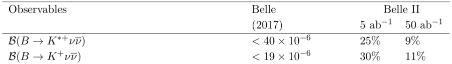
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\text{Br}(B \to X_s \ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	29%	13%	6.6%
$\text{Br}(B \to X_s \ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	24%	11%	6.4%
$\text{Br}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	23%	10%	4.7%
$A_{\text{FB}}(B \to X_s \ell^+\ell^-)$ ($[1.0, 3.5]$ GeV^2)	26%	9.7%	3.1%
$A_{\text{FB}}(B \to X_s \ell^+\ell^-)$ ($[3.5, 6.0]$ GeV^2)	21%	7.9%	2.6%
$A_{\text{FB}}(B \to X_s \ell^+\ell^-)$ (> 14.4 GeV^2)	19%	7.3%	2.4%

- Good performance for both e and μ reconstruction.



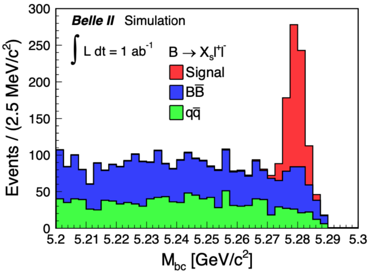
- $b \to s\nu\bar{\nu}$ orthogonal probe without $c\bar{c}$ contributions





Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathcal{B}(B \to K^{*+}\nu\bar{\nu})$	$< 40 \times 10^{-6}$	25%	9%
$\mathcal{B}(B \to K^{+}\nu\bar{\nu})$	$< 19 \times 10^{-6}$	30%	11%

Belle II's orthogonal and complementory role



- Soon rediscovery of $B \to X_s \ell\ell$ which has orthogonal OPE theory inputs to $B \to K^{(*)}\ell\ell$

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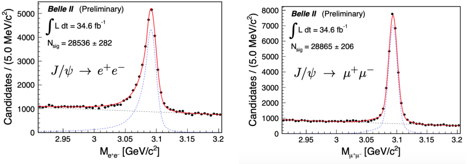
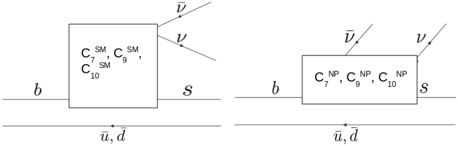


- $b \to s\nu\bar{\nu}$ orthogonal probe without $c\bar{c}$ contributions



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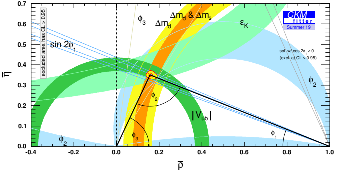
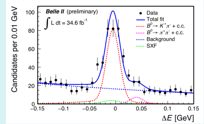
Charmless physics



- ϕ_3 (γ) from $B^\pm \to D^0K^\pm$ $\sigma^{BII}_{\phi_3} \sim 1°$
- ϕ_2 (α) from $B^0 \to \pi^\pm\pi^\mp$ $\sigma^{BII}_{\phi_2} \sim 1°$

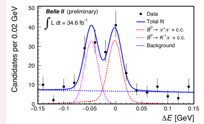


$B^0 \to K^+\pi^-$

N$_{\text{sig}}$	289^{+22}_{-21}
$\mathcal{B}$ [10^{-6}]	18.9 ± 1.4(stat.) ± 1.0(syst.)

PDG

$\mathcal{B}$ [10^{-6}]	19.6 ± 0.5

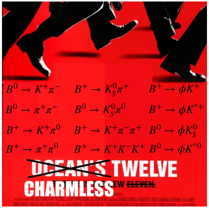


$B^0 \to \pi^+\pi^-$

N$_{\text{sig}}$	61^{+11}_{-10}
$\mathcal{B}$ [10^{-6}]	$5.6^{+1.0}_{-0.9}$(stat.) ± 0.3(syst.)

PDG

$\mathcal{B}$ [10^{-6}]	5.12 ± 0.19

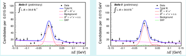


- $\mathcal{B}$s and $\mathcal{A}_{\mathrm{CP}}$s for several modes in [arxiv2009.09452]

$B^0 \to K^+\pi^-$

$A_{CP} = 0.030 \pm 0.064(\text{stat.}) \pm 0.008(\text{syst.})$

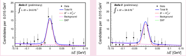
PDG: $A_{CP} = -0.083 \pm 0.004$



$B^+ \to K^0_S\pi^+$

$A_{CP} = -0.072^{+0.109}_{-0.114}(\text{stat.}) \pm 0.024(\text{syst.})$

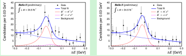
PDG: $A_{CP} = -0.017 \pm 0.016$



$B^+ \to K^+\pi^0$

$A_{CP} = 0.052^{+0.121}_{-0.119}(\text{stat.}) \pm 0.022(\text{syst.})$

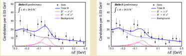
PDG: $A_{CP} = 0.037 \pm 0.021$



$B^+ \to \pi^+\pi^0$

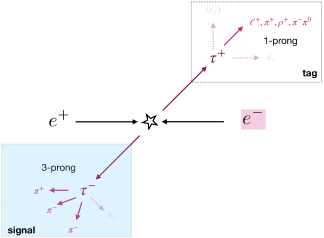
$A_{CP} = -0.268^{+0.249}_{-0.322}(\text{stat.}) \pm 0.123(\text{syst.})$

PDG: $A_{CP} = 0.03 \pm 0.04$



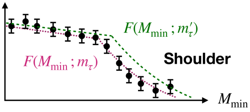
τ physics using $e^+e^- \to \tau^+\tau^-$

- clean e^+e^- enviroment excellent for τ physics

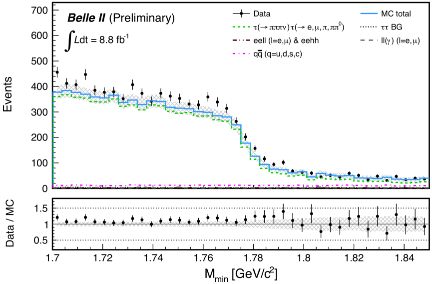


- τ mass recently measured [arxiv2008.04665]

$$M_{\rm min} = \sqrt{M_{3\pi}^2 + 2(E_{\rm beam} - E_{3\pi})(E_{3\pi} - P_{3\pi})} \leq m_\tau,$$



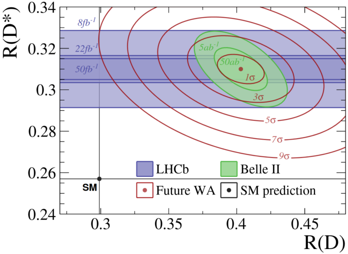
- Precision τ physics (e.g. m_τ, $\mathcal{B}$s)
- Can search for LFV in τs at $\mathcal{O}(10^{-9})$
- $\tau\tau$ events also used to study tracking and PID performance.

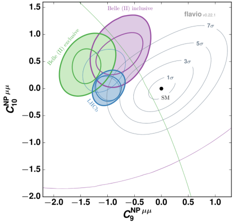


- $m_\tau = 1777.28 \pm 0.75(stat.) \pm 0.33(sys.)$ MeV

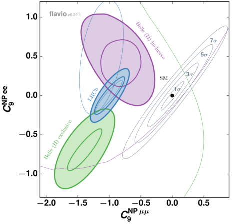
Future prospects

- A joint effort from Belle II and LHCb will be instrumental in resolving the *B* anomalies and finding any inconsistencies in the CKM picture.

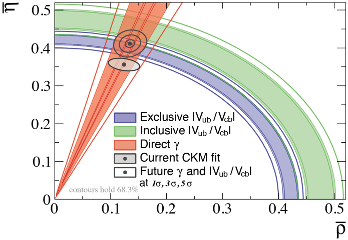




(a) $C_9^{\mathrm{NP}\,\mu\mu}$ versus $C_{10}^{\mathrm{NP}\,\mu\mu}$.



(b) $C_9^{\mathrm{NP}\,\mu\mu}$ versus $C_9^{\mathrm{NP}\,ee}$.



Conclusion

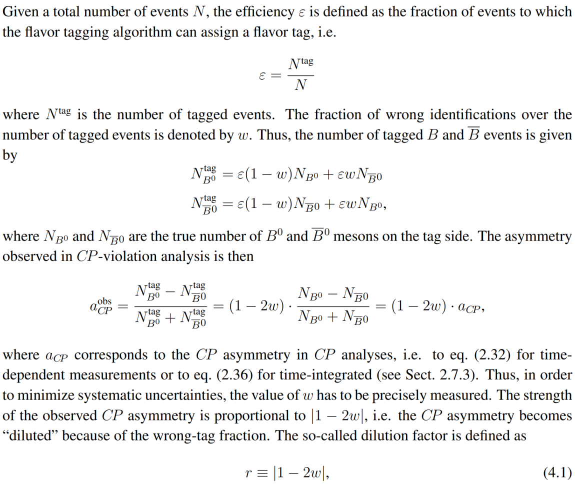
- Belle II will provide precision determinations of the CKM parameters
    - Differential measurement of untagged $D^* \ell \nu$ already $\implies |V_{cb}|$ soon
    - First measurement of $\sin 2\phi_1$ with $B^0 \to J/\psi K_s$
    - Observation of $B \to \pi \ell \nu \implies |V_{ub}|$ soon
    - Measurements of key charmless modes for ϕ_2 and ϕ_3
- Belle II will play a crucial role in the B anomalies
    - $B \to D^* \ell \nu$ observed with tagging in preparation for $R(D^{(*)})$
    - Belle II will provide orthogonal probes of the $b \to s \ell \ell$ anomalies
- While being a B factory Belle II has a diverse physics program.
    - τ mass measurement
    - First papers dark sector searches

m_τ systematics

Systematic uncertainty	MeV/c^2
Momentum shift due to the B-field map	0.29
Estimator bias	0.12
Choice of p.d.f.	0.08
Fit window	0.04
Beam energy shifts	0.03
Mass dependence of bias	0.02
Trigger efficiency	≤ 0.01
Initial parameters	≤ 0.01
Background processes	≤ 0.01
Tracking efficiency	≤ 0.01

Table I. Summary of systematic uncertainties.

Flavour tagging: miss tag fraction



Given a total number of events N, the efficiency ε is defined as the fraction of events to which the flavor tagging algorithm can assign a flavor tag, i.e.

$$\varepsilon = \frac{N^{\text{tag}}}{N}$$

where N^{tag} is the number of tagged events. The fraction of wrong identifications over the number of tagged events is denoted by w. Thus, the number of tagged B and $\overline{B}$ events is given by

$$N^{\text{tag}}_{B^0} = \varepsilon(1-w)N_{B^0} + \varepsilon w N_{\overline{B}^0}$$
$$N^{\text{tag}}_{\overline{B}^0} = \varepsilon(1-w)N_{\overline{B}^0} + \varepsilon w N_{B^0},$$

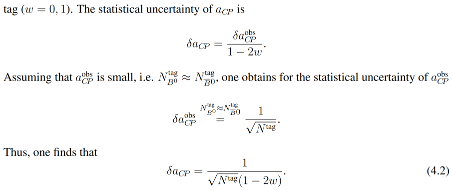
where N_{B^0} and $N_{\overline{B}^0}$ are the true number of B^0 and $\overline{B}^0$ mesons on the tag side. The asymmetry observed in CP-violation analysis is then

$$a^{\text{obs}}_{CP} = \frac{N^{\text{tag}}_{B^0} - N^{\text{tag}}_{\overline{B}^0}}{N^{\text{tag}}_{B^0} + N^{\text{tag}}_{\overline{B}^0}} = (1-2w)\cdot\frac{N_{B^0} - N_{\overline{B}^0}}{N_{B^0} + N_{\overline{B}^0}} = (1-2w)\cdot a_{CP},$$

where a_{CP} corresponds to the CP asymmetry in CP analyses, i.e. to eq. (2.32) for time-dependent measurements or to eq. (2.36) for time-integrated (see Sect. 2.7.3). Thus, in order to minimize systematic uncertainties, the value of w has to be precisely measured. The strength of the observed CP asymmetry is proportional to $|1-2w|$, i.e. the CP asymmetry becomes "diluted" because of the wrong-tag fraction. The so-called dilution factor is defined as

$$r \equiv |1-2w|, \tag{4.1}$$

Effective tagging efficiency



tag ($w = 0, 1$). The statistical uncertainty of a_{CP} is

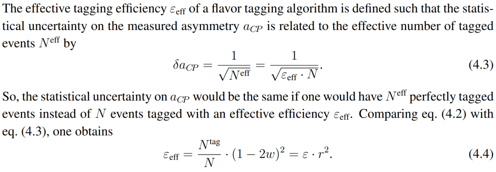
$$\delta a_{CP} = \frac{\delta a_{CP}^{\text{obs}}}{1 - 2w}.$$

Assuming that a_{CP}^{obs} is small, i.e. $N_{B^0}^{\text{tag}} \approx N_{\overline{B}{}^0}^{\text{tag}}$, one obtains for the statistical uncertainty of a_{CP}^{obs}

$$\delta a_{CP}^{\text{obs}} \overset{N_{B^0}^{\text{tag}} \approx N_{\overline{B}{}^0}^{\text{tag}}}{=} \frac{1}{\sqrt{N^{\text{tag}}}}.$$

Thus, one finds that

$$\delta a_{CP} = \frac{1}{\sqrt{N^{\text{tag}}}(1 - 2w)}. \tag{4.2}$$



The effective tagging efficiency ε_{eff} of a flavor tagging algorithm is defined such that the statistical uncertainty on the measured asymmetry a_{CP} is related to the effective number of tagged events N^{eff} by

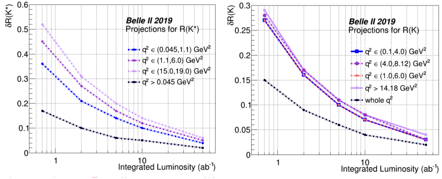
$$\delta a_{CP} = \frac{1}{\sqrt{N^{\text{eff}}}} = \frac{1}{\sqrt{\varepsilon_{\text{eff}} \cdot N}}. \tag{4.3}$$

So, the statistical uncertainty on a_{CP} would be the same if one would have N^{eff} perfectly tagged events instead of N events tagged with an effective efficiency ε_{eff}. Comparing eq. (4.2) with eq. (4.3), one obtains

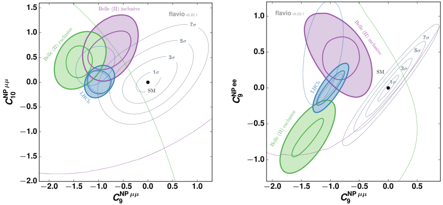
$$\varepsilon_{\text{eff}} = \frac{N^{\text{tag}}}{N} \cdot (1 - 2w)^2 = \varepsilon \cdot r^2. \tag{4.4}$$

Belle II $b \to sll$ and LFV prospects

- Uncertainty on $R(K)$ and $R(K^*)$ of 3-4%



- Complementory constraints on C_9 and C_{10}.



(a) $C_9^{NP\mu\mu}$ versus $C_{10}^{NP\mu\mu}$.

(b) $C_9^{NP\mu\mu}$ versus $C_9^{NP ee}$.

- P_5' projections for $B \to K^* \ell\ell$

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II ab^{-1}
P_5' ([1.0, 2.5] GeV^2)	0.47	0.17	0.054
P_5' ([2.5, 4.0] GeV^2)	0.42	0.15	0.049
P_5' ([4.0, 6.0] GeV^2)	0.34	0.12	0.040
P_5' (> 14.2 GeV^2)	0.23	0.088	0.027

- Clean environment and possibility of tagging essential will allow competive searches for $B \to K^*\tau\tau$ and $B \to K^*\ell\tau$

Observables	Belle 0.71 ab^{-1} (0.12 ab^{-1})	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B^+ \to K^+\tau^+\tau^-) \cdot 10^5$	< 32	< 6.5	< 2.0
$\mathrm{Br}(B^0 \to \tau^+\tau^-) \cdot 10^5$	< 140	< 30	< 9.6
$\mathrm{Br}(B_s^0 \to \tau^+\tau^-) \cdot 10^4$	< 70	< 8.1	–
$\mathrm{Br}(B^+ \to K^+\tau^\pm e^\mp) \cdot 10^6$	–	–	< 2.1
$\mathrm{Br}(B^+ \to K^+\tau^\pm \mu^\mp) \cdot 10^6$	–	–	< 3.3
$\mathrm{Br}(B^0 \to \tau^\pm e^\mp) \cdot 10^5$	–	–	< 1.6
$\mathrm{Br}(B^0 \to \tau^\pm \mu^\mp) \cdot 10^5$	–	–	< 1.3

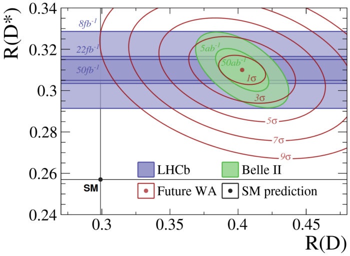
$|V_{xb}|$ and $R(D^*)$ prospects

- Eventually systematically limited by tagging calibration

	5 ab^{-1}	50 ab^{-1}
R_D	$(\pm 6.0 \pm 3.9)\%$	$(\pm 2.0 \pm 2.5)\%$
R_{D^*}	$(\pm 3.0 \pm 2.5)\%$	$(\pm 1.0 \pm 2.0)\%$

stat. sys.

- LHCb and Belle II will resolve $R(D^*)$ anomaly.



- Will achieve 1-2% uncertainty on $|V_{ub}|$ and $|V_{cb}|$

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\lvert V_{cb}\rvert$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\lvert V_{cb}\rvert$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\text{ex.}} \pm 1.4\%_{\text{th.}})$	1.8%	1.4%
$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\text{ex.}} \pm 2.5\%_{\text{th.}})$	3.4%	3.0%
$\lvert V_{ub}\rvert$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\text{ex.}} \pm 3.0\%_{\text{th.}})$	2.4%	1.2%

- $\Longrightarrow$ high precision tree level determination of the UT apex