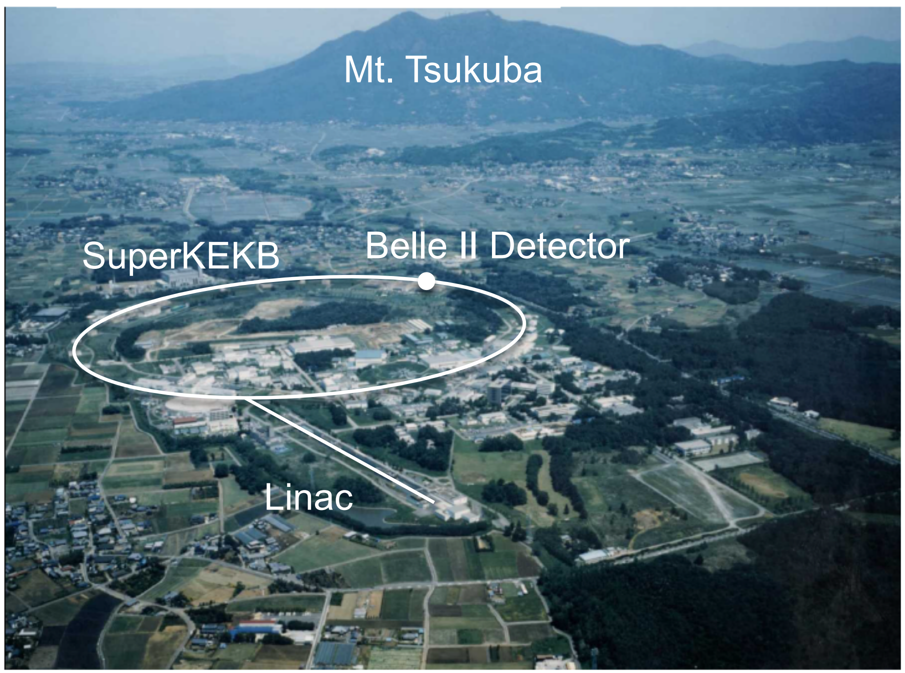
Missing Energy B Decays at the Belle II Experiment

Mario Merola (Università di Napoli Federico II and INFN)

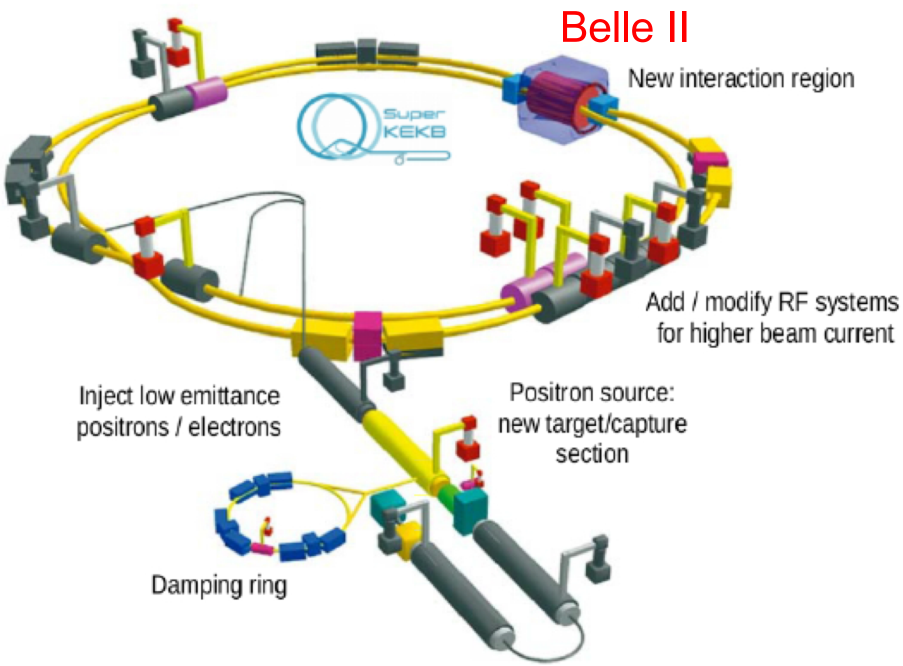
On behalf of the Belle II Collaboration

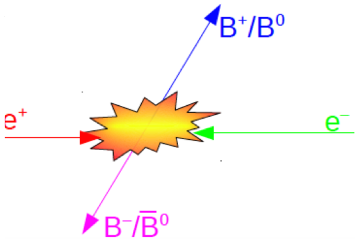
Beauty 2018, 10 May, Isola d'Elba



SuperKEKB

- **Electron-positron collider** situated at KEK (Tsukuba, Japan), upgrade of KEKB
- **e^+e^-** (4 GeV + 7 GeV) **→ $B\bar{B}$** mainly at $\sqrt{s^{cm}}$=10.58 GeV (peak of ϒ(4S) resonance)
- **First collisions recorded on 26 April** (see more in the talk tomorrow "Phase II running of SuperKEKB and Belle II" – Carlos Marinas)





10^{10} BB pairs per year @ full luminosity

Cross sections at Y(4S)

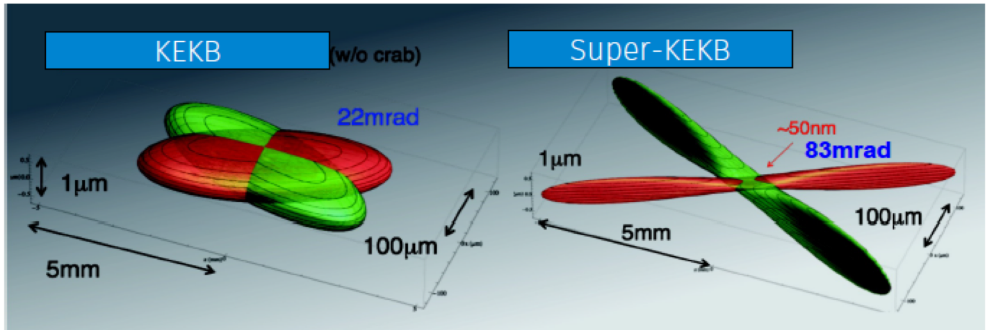
Physics process	Cross section (nb)
$\Upsilon(4S) \rightarrow B\bar{B}$	1.2
$e^+e^- \rightarrow$ continuum	2.8
$\mu^+\mu^-$	0.8
$\tau^+\tau^-$	0.8
Bhabha ($\theta_{lab} \geq 17°$)	44
$\gamma\gamma$ ($\theta_{lab} \geq 17°$)	2.4
2γ processes [b]	~ 80
Total	~ 130

[a] The rate is pre-scaled by a factor of 1/100.

[b] $\theta_{lab} \geq 17°$, $p_t \geq 0.1 \mathrm{GeV}/c$

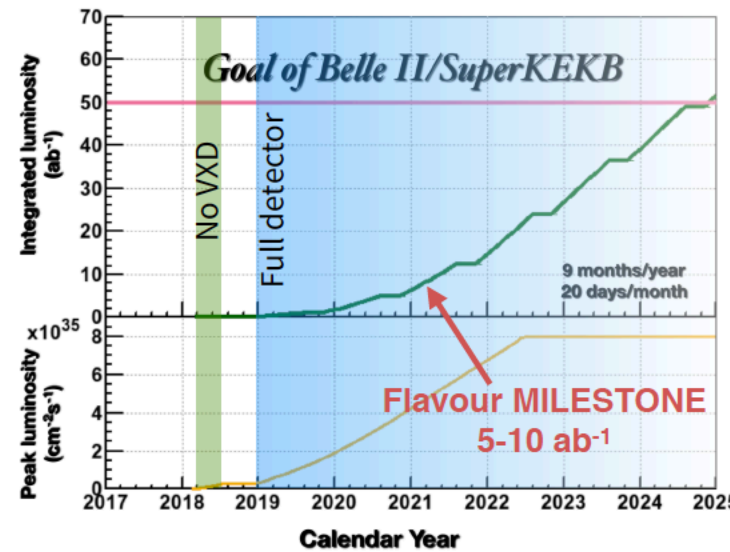
From KEKB to SuperKEKB

Nano-beam scheme firstly proposed by P. Raimondi for SuperB



	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	2.1×10^{34}
SuperKEKB	4.0/7.0	0.27/0.30	3.2/2.5	41.5	3.6/2.6	80×10^{34}

factor 20 factor 2-3



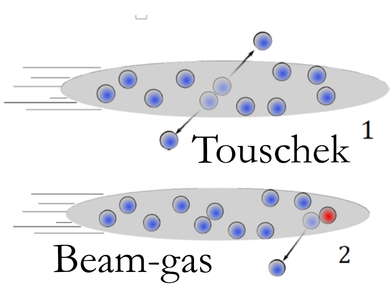
Factor ~ 40-50 in the luminosity

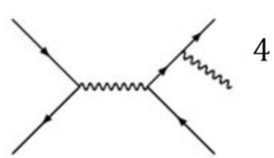
beam current

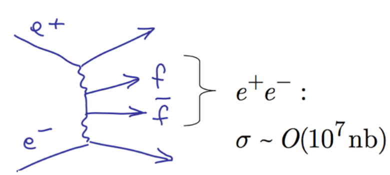
$$L = \frac{\gamma_\pm}{2 e r_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}}\frac{R_L}{R_{\xi_y}}$$

vertical beta function at IP

Higher backgrounds







- Radiation damage
- Occupancy in inner detectors
- Fake hits and pile-up

From Belle to Belle II

Belle Upgrade:

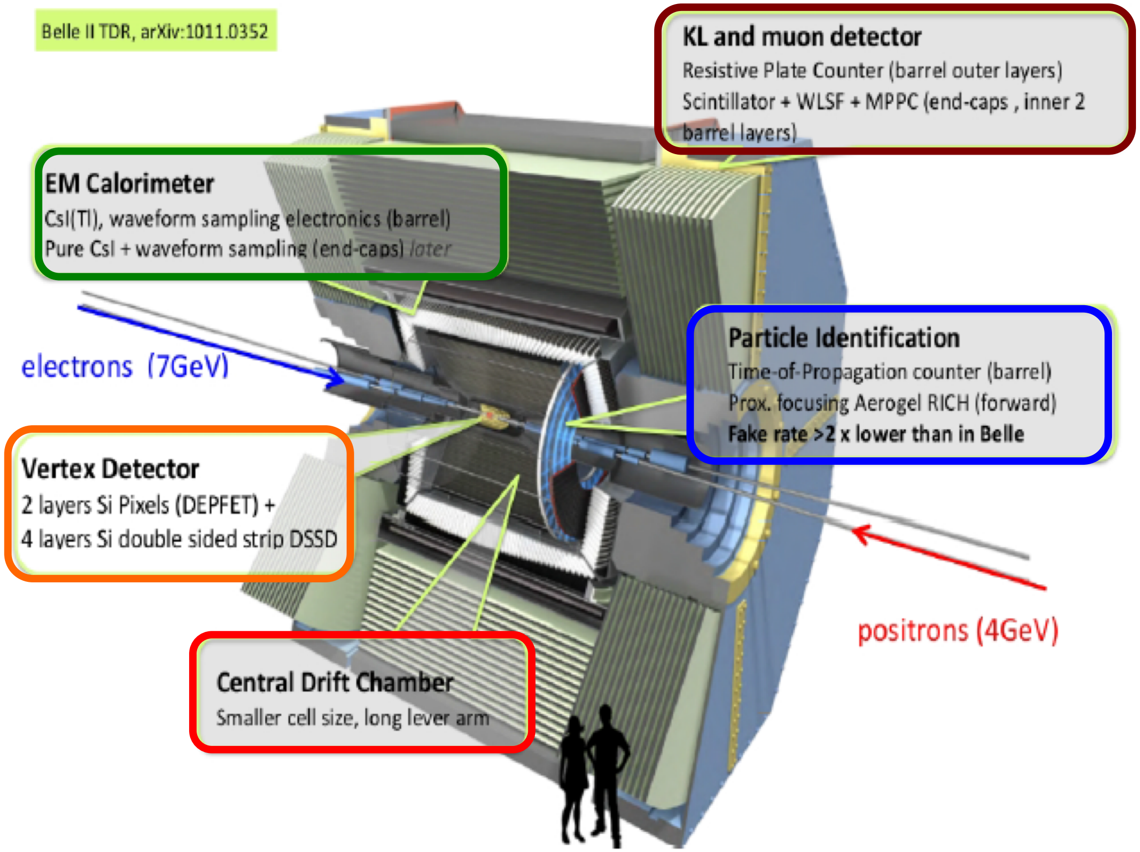
- **Extended VXD region** (added pixel detector)

- **Extended Drift Chamber region**

- **New ECL electronics** (waveform sampling and fitting)

- **Better hermeticity: new PID detector** in the forward region

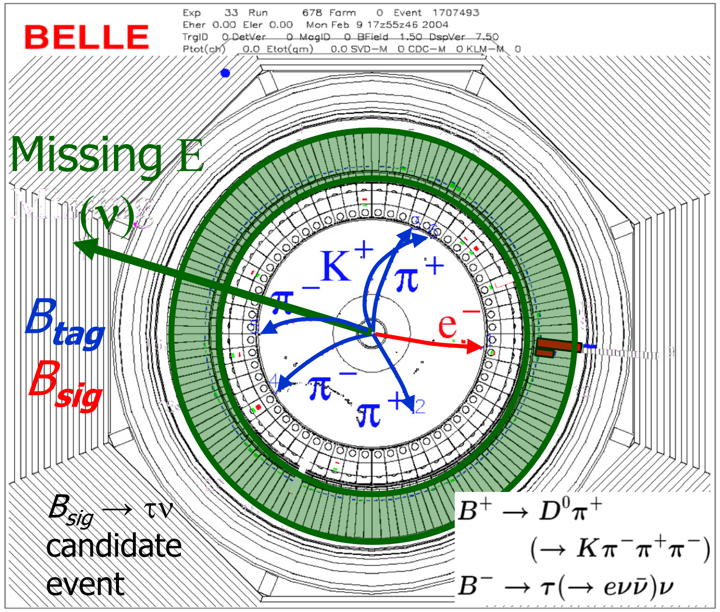
- **High efficiency KLM detector** (some RPCs layers substituted with scintillators to resist neutron background)



- improved IP and secondary vertex resolution
- better K/π separation and flavor tagging
- robust against machine background
- higher K_S, π^0 and slow pions reconstruction efficiency

Unique capabilities of e^+e^- B factories - Belle II

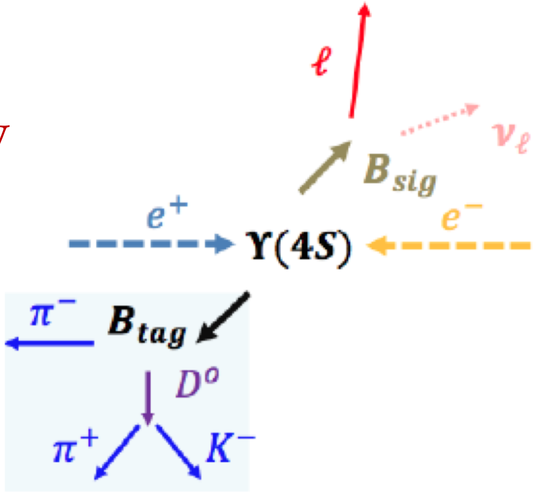
- **Beam energy constraint** and adjusted for different resonances Υ(nS)
- **Clean experimental environment:** high B, D, K, τ lepton reconstruction efficiency
- **Excellent EM calorimetry performance:** high reconstruction efficiency of neutral final states too



The **full reconstruction of one B (B_{tag})** constraints the 4-momentum of the other (B_{sig})

Reconstruction of **channels with missing energy**

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



B tag reconstruction strategy

- **Hadronic tagging**
  - \- Low efficiency
  - \+ B tag completely reconstructed
- **Semileptonic tagging**
  - \- More backgrounds, B momentum unmeasured
  - \+ Higher efficiency
- **Inclusive tagging (no tagging)**
  - B-tag not explicitly reconstructed
  - Reconstruct the signal and then use the Rest of Event (ROE) to constrain the neutrino momentum

Efficiency ↓ Purity ↑

$\varepsilon = \mathcal{O}(0.5\%)$

$\varepsilon = \mathcal{O}(1\%)$

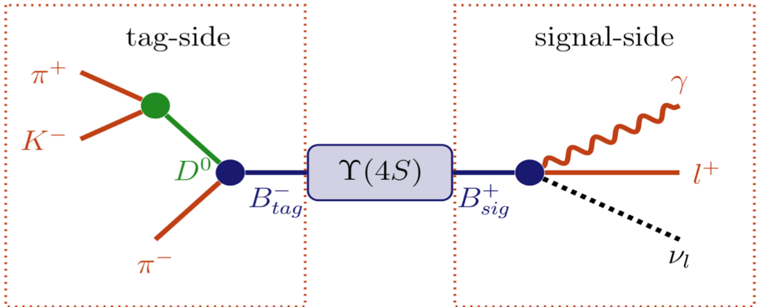
$\varepsilon = \mathcal{O}(100\%)$

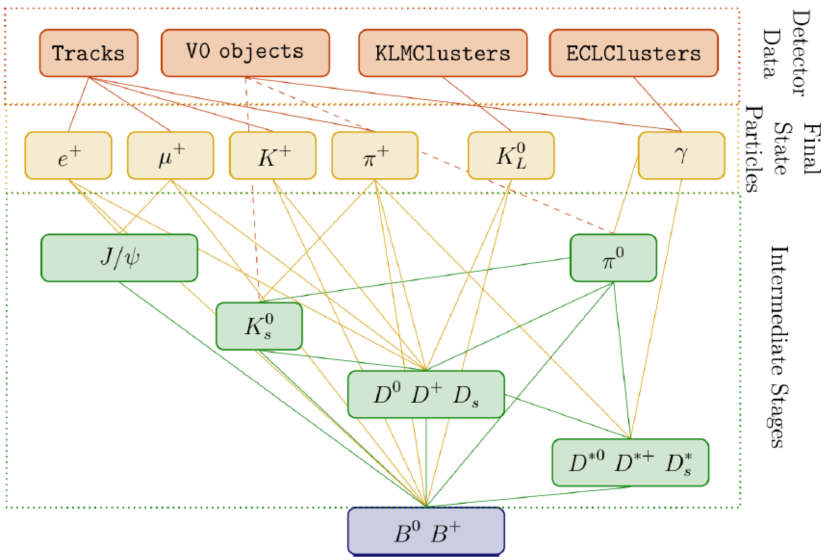
Tag side reconstruction: Full Event Interpretation (FEI)

- It is an extension of the Full Reconstruction (FR) used in Belle, and uses a multivariate technique to reconstruct the B-tag side through O(10^3) decay modes in a Υ(4S) decay.

- Hierarchical approach: train multivariate classifiers (MVC) on FSP, then reconstruct intermediate particles and build new dedicated MVC. For each candidate a signal probability is defined, which represents the "goodness" of its reconstruction. It uses:

- PID, tracks momenta, impact parameters;
- Cluster info, energy and direction;
- Invariant masses, daughter momenta, vertex quality;
- Classifier output of the daughters



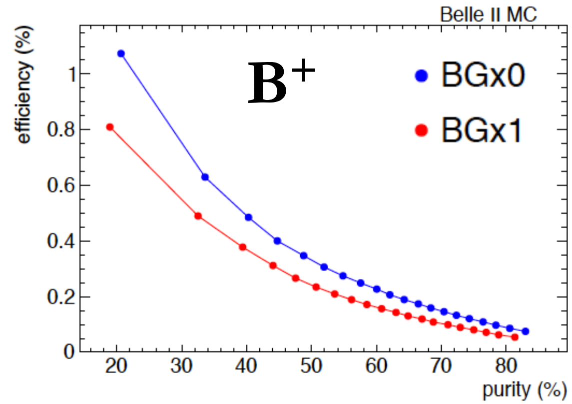


Belle FR: NIM A 654, 432-440 (2011)
Belle II FEI: https://ekp-invenio.physik.uni-karlsruhe.de/record/48602/files/EKP-2015-00001.pdf

Improvement in Belle II algorithms: background rejection

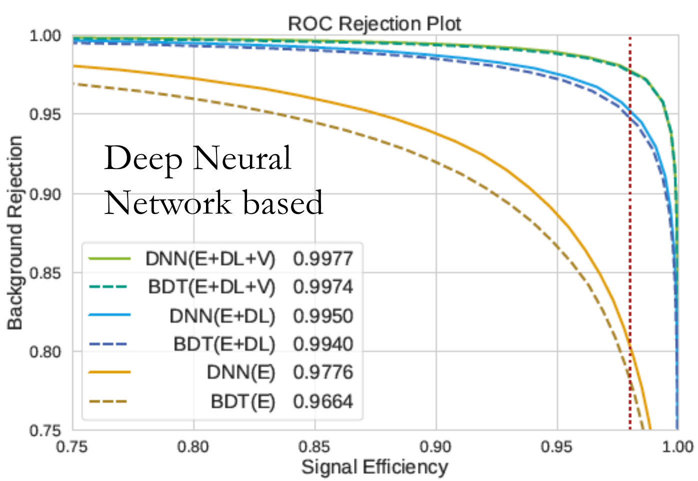
FEI performance with hadronic B-tag reconstruction

Tag algorithm date	MVA	Efficiency	Purity
Belle (2007)	Cut-based	0.1	0.25
Belle FR (2011)	Neurobayes	0.2	0.25
Belle II FEI (2017)	Boosted Decision Trees	0.5	0.25

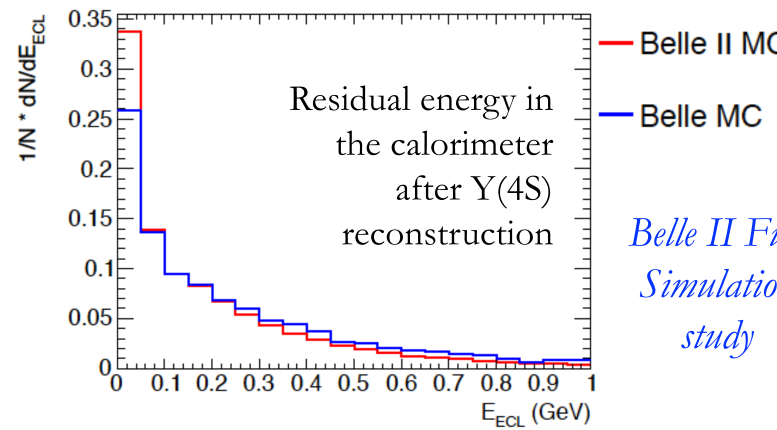


Belle II Full Simulation study

Rejection of the continuum $e^+e^- \to q\bar{q}$ background



Beam background rejection MVA using ECL clusters info



Belle II Full Simulation study

Missing energy B meson decays

- Inclusive semileptonic decays ($B \rightarrow Xl\nu$)
- Semileptonic decays with tau ($B \rightarrow D^{(*)}\tau\nu$)
- Leptonic decay to tau leptons ($B \rightarrow \tau\nu$)
- Penguin electroweak decays ($B \rightarrow K^{(*)}\nu\nu$)
- Leptonic decays to muon, electron, neutrinos and radiative ($B \rightarrow \mu\nu$, $e\nu$, $\nu\nu$, $l\nu\gamma$)

BR ~22%

branching ratio

BR $\sim 10^{-7} \div 10^{-20}$

Belle II Physics Book to be published in 2018

Missing energy B meson decays

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branching ratio

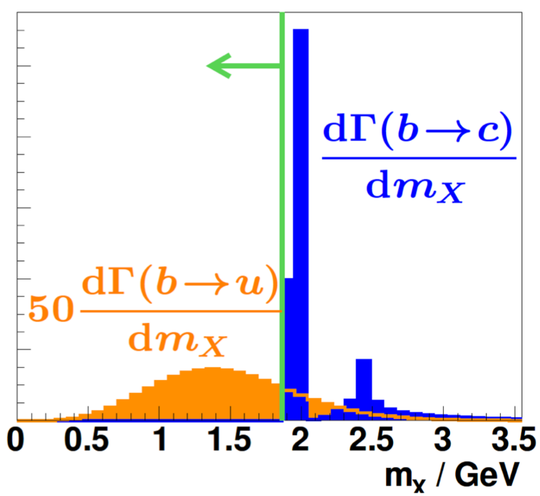
BR ~$10^{-7} \div 10^{-20}$

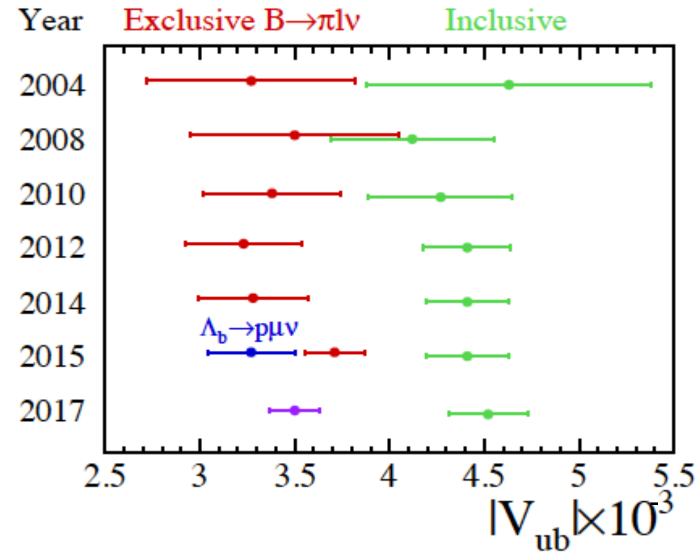
Updates expected by the next Beauty Conference !

Semileptonic decays: $B \rightarrow X_u l \nu$

Measurement of $|V_{ub}|$ from inclusive and exclusive B decays

- **Inclusive decays measurement**
  - Hadronic tag
  - Exploit kinematic endpoints to reduce $B \rightarrow X_c l \nu$ bkg





Tension between inclusive and exclusive $|V_{ub}|$ measurements

$$|V_{ub}|^2 = \Delta\mathcal{B}_{u\ell\nu}/(\tau_B \Delta\mathcal{R})$$

Measured BR in fiducial phase space region

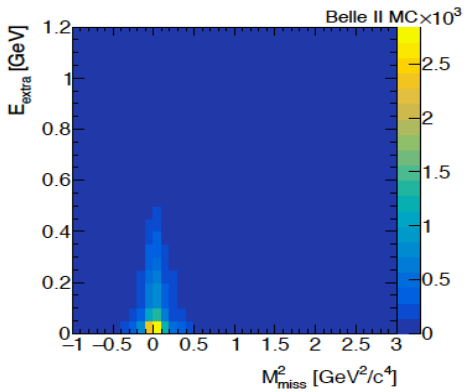
B meson lifetime

Predicted partial decay rate

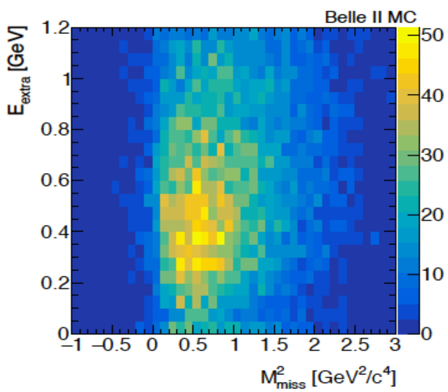
Semileptonic decays: $B \to X_u l \nu$

Belle II Full Simulation study

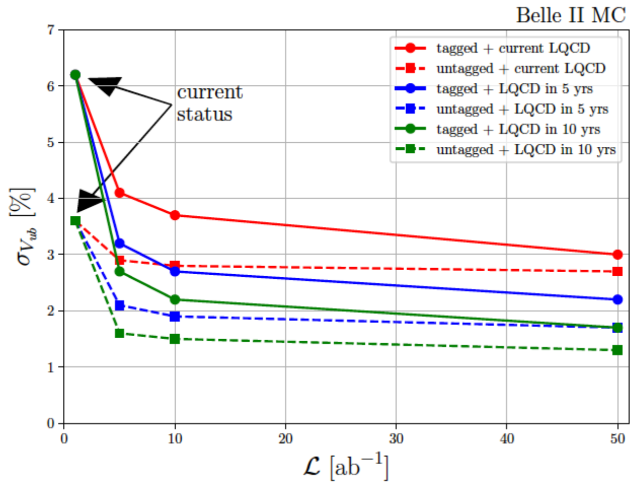
- **$B^0 \to \pi\, l\, \nu$** decay
  - Untagged or tagged (with FEI)
  - Exploit missing mass and extra energy in the calorimeter
  - $\mathcal{B} \sim f_i |V_{ub}|^2$; form factors f_i computed with LQCD (PRD 91, 074510 (2015))



signal



background

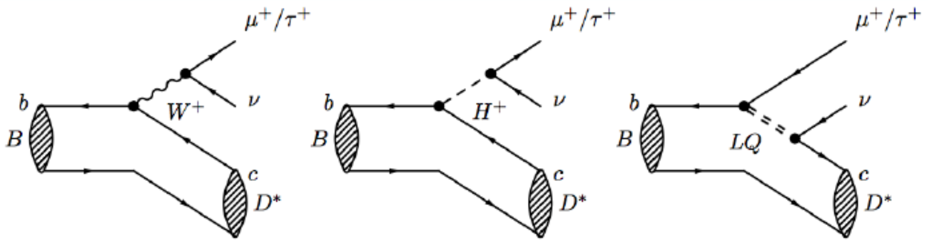


$B \to \pi\, l\, \nu$ projections

Belle II @ 50 ab^{-1}: ~3% (inclusive) / ~2% (exclusive $\pi\, l\, \nu$) uncertainty

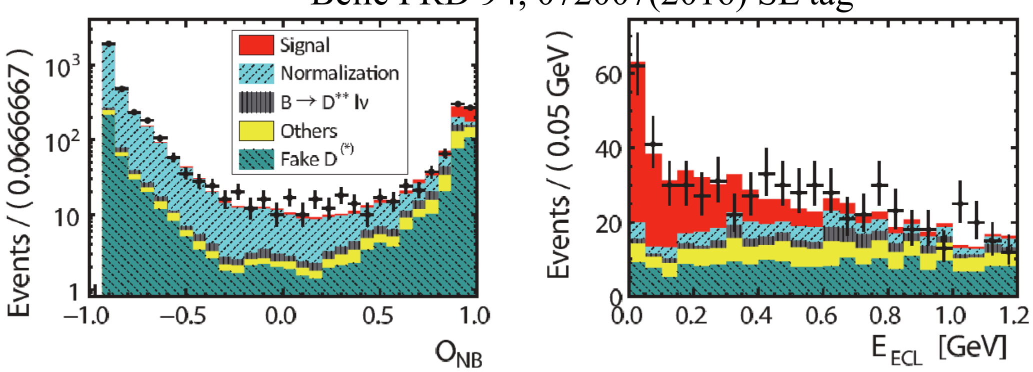
Semileptonic decays: $B \to D^{(*)}\tau\nu$

Clear test of the SM LFU: **NP** (as charged Higgs in 2HDM models or Leptoquarks) **can affect the BR and the tau polarization P_τ**



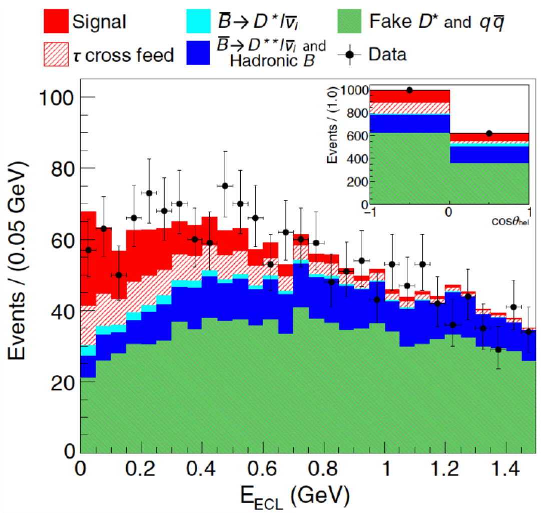
$$\mathcal{R}(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \quad (\ell = e, \mu)$$

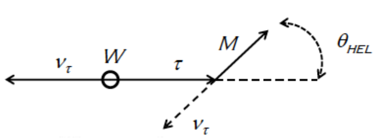
Belle PRD 94, 072007(2016) SL tag



Important background due to D**; not well known, poor modeling –> big uncertainty (1.4% over a total systematic uncertainty of 3.4%)

Belle PRL 118, 211801 (2017) had. tag

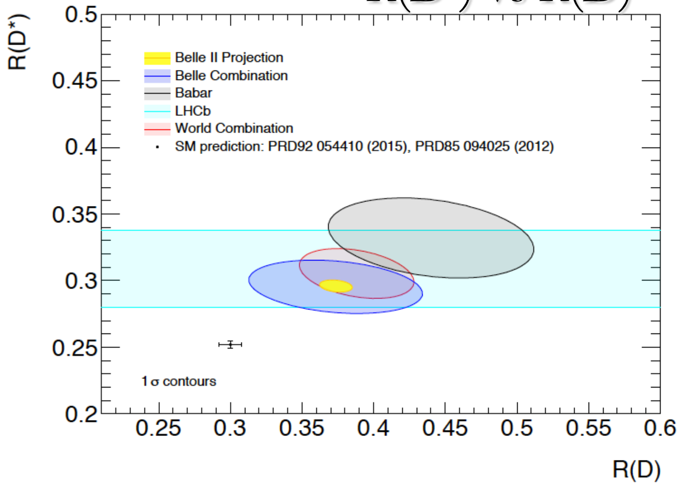




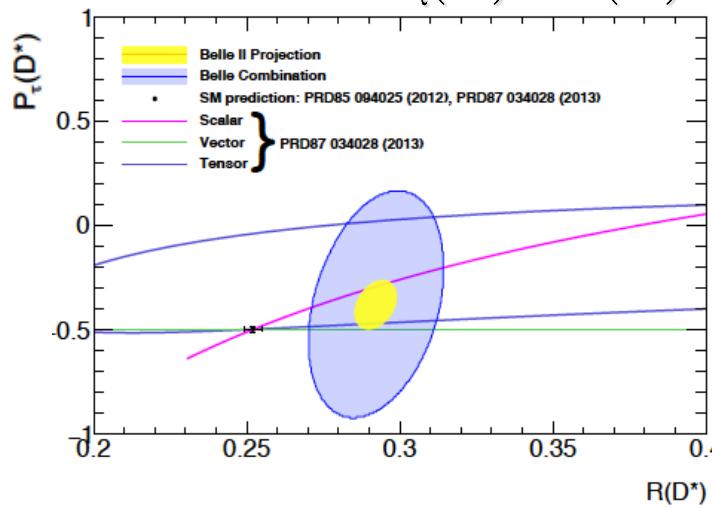
Extract the fractions with positive and negative tau helicity

Semileptonic decays: $B \to D^{(*)}\tau\nu$ Belle II projections

$R(D^*)$ vs $R(D)$



$P_\tau(D^*)$ vs $R(D^*)$

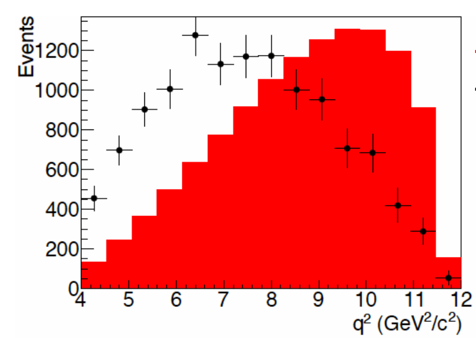


Current combination:
4.1σ from the SM

	ΔR(D) [%]			ΔR(D*) [%]		
	Stat	Sys	Total	Stat	Sys	Total
Belle 0.7 ab^{-1}	14	6	16	6	3	7
Belle II 5 ab^{-1}	5	3	6	2	2	3
Belle II 50 ab^{-1}	2	3	3	1	2	2

Projections based on Belle SL measurement

Belle II full simulation studies in progress



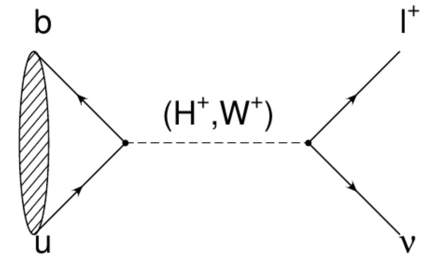
- NP H±
- Pseudo-data SM

50 ab^{-1} projection of subtracted q^2 spectrum in $B \to D^{(*)}\tau\nu$

Leptonic B decays

- Helicity suppressed decays

$$BR_{SM}(B \to \ell\, \nu) = \frac{G_F^2 m_B \tau_B}{8\pi} f_B^2 |V_{ub}|^2 m_\ell^2 \left[1 - \frac{m_\ell^2}{m_B^2}\right]^2$$



	SM Prediction
$\mathcal{B}(B^+ \to e^+\nu_e)$	$(1.09 \pm 0.21) \cdot 10^{-11}$
$\mathcal{B}(B^+ \to \mu^+\nu_\mu)$	$(4.65 \pm 0.91) \cdot 10^{-7}$
$\mathcal{B}(B^+ \to \tau^+\nu_\tau)$	$(1.03 \pm 0.2) \cdot 10^{-4}$

- Sensitive to NP contributions, e.g. type III Higgs doublet model [PhysRevD.86.054014]

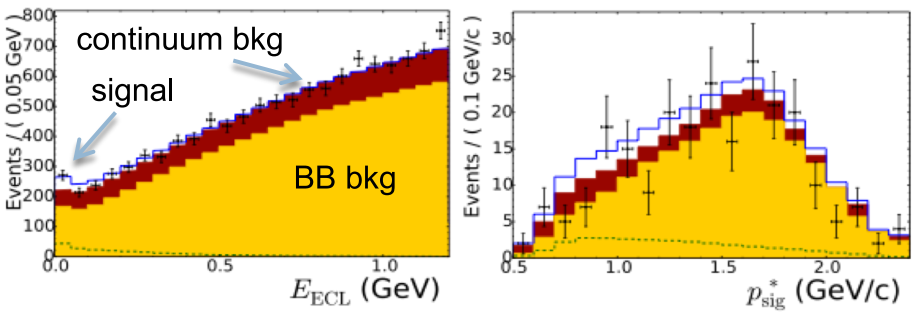
- Clean theoretically, hard experimentally: only $B \to \tau\nu$ has been measured

Belle combination

$$\mathcal{B} = [0.91 \pm 0.19(\text{stat.}) \pm 0.11(\text{syst.})] \times 10^{-4}$$

(evidence at ~4.6 σ level)

Belle PRD 92, 051102 (2015), SL tag

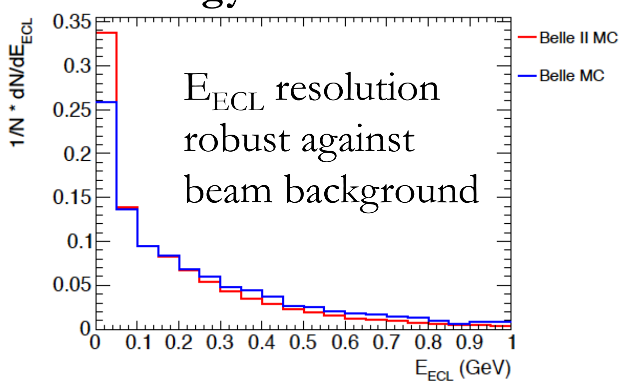


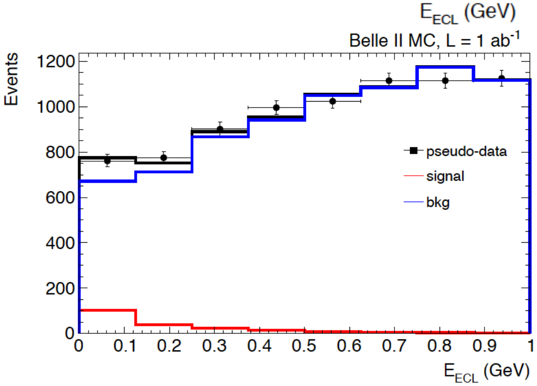
Leptonic B decays: $B \to \tau\nu$

Belle II full simulation study

- Hadronic tag with FEI
- 1-prong τ decays ($\mu\nu\nu$, $e\nu\nu$, $\pi\nu$, $\rho\nu$)
- Dedicated study on machine background impact
- ML fit to extra energy E_{ECL}

Extra energy in the calorimeter





Main systematic uncertainties: background E_{Extra} PDF, branching fractions of the peaking backgrounds, tagging efficiency, and K^0_L veto efficiency

	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29.2	13.0	4.1
	systematic uncertainty (%)	12.6	6.8	4.6
	total uncertainty (%)	31.6	14.7	6.2
semileptonic tag	statistical uncertainty (%)	19.0	8.5	2.7
	systematic uncertainty (%)	17.9	8.7	4.5
	total uncertainty (%)	26.1	12.2	5.3

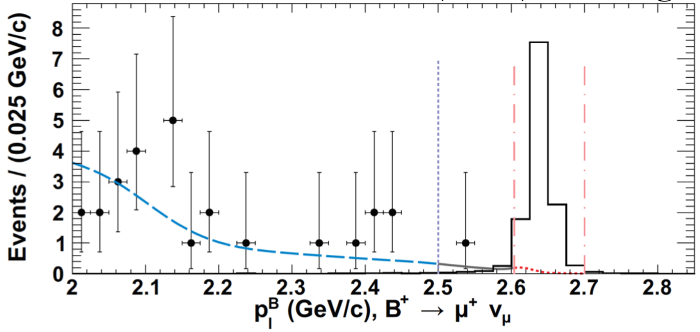
Observation at ~3 ab^{-1}

Leptonic B decays: B → μν and radiative B → lνγ

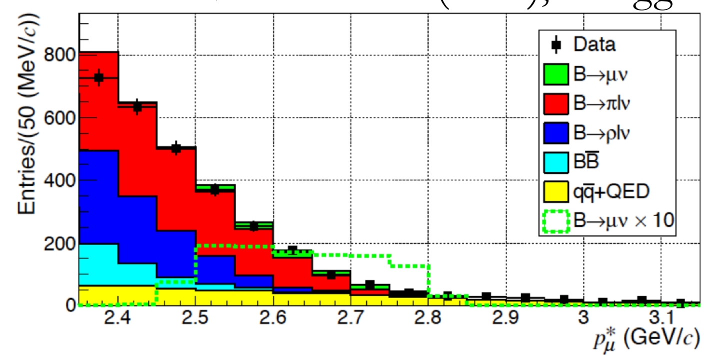
B → μν

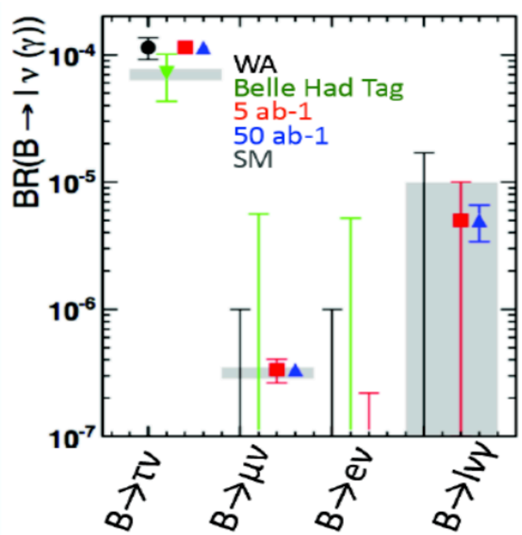
- Two body decay: $p^*_\mu = m_B/2$ in B rest frame
- Tagging → better p^*_μ resolution but small statistics
- ~2.4σ measurement

Belle PRD 91, 052016 (2015), had tag



Belle arXiv:1712.04123 (2018), untagged



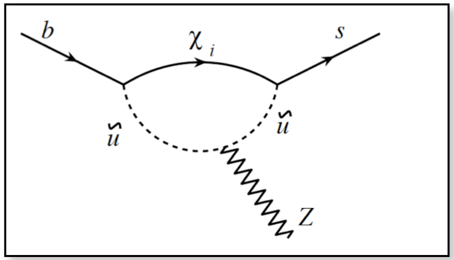


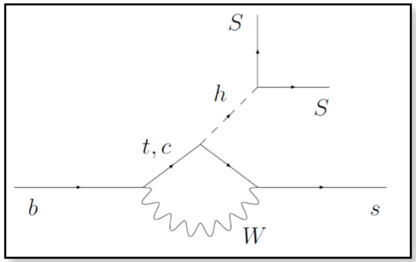
B → lνγ

- Radiative decay lifts the helicity suppression
- Allows a measurement of λ_B → crucial input to QCD factorization predictions of charmless hadronic B decays

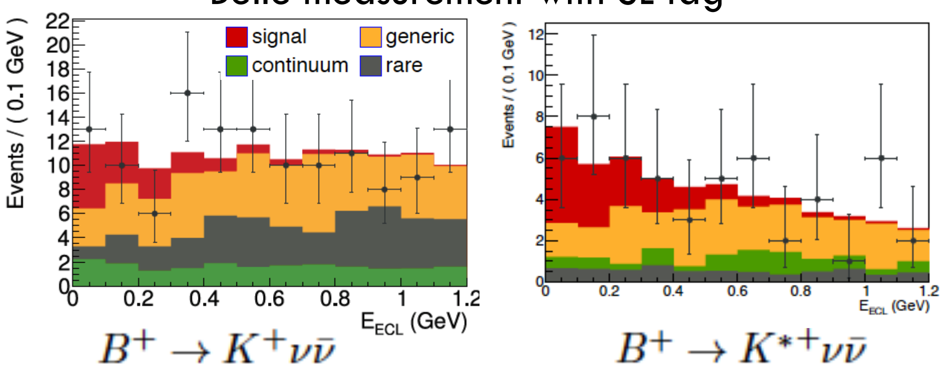
Flavour changing neutral current $B \to K^{(*)}\nu\bar{\nu}$

- Prohibited in the SM at tree level: penguin + box diagrams
- BR ~ $10^{-5} \div 10^{-6}$; NP contribution can increase the BR by factor 50
  - non standard Z-couplings (SUSY)
  - New missing energy sources (DM, extra dim.)

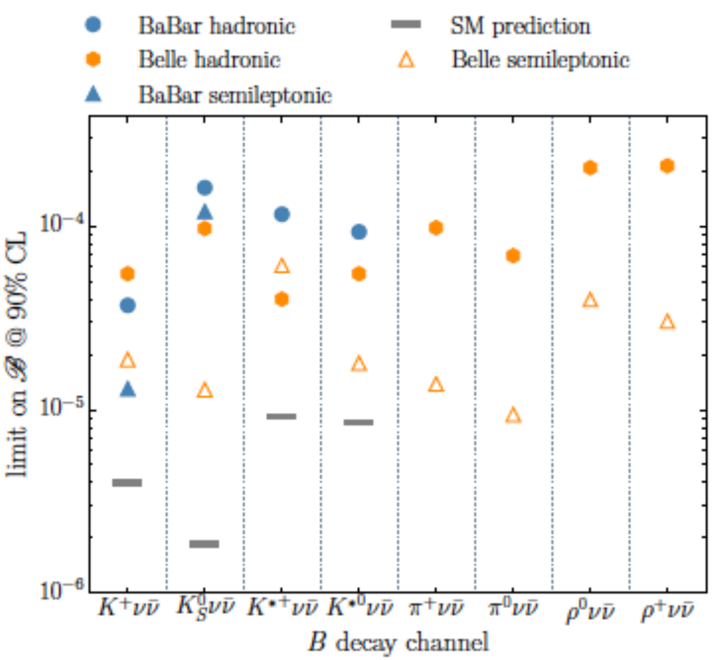




Belle measurement with SL tag



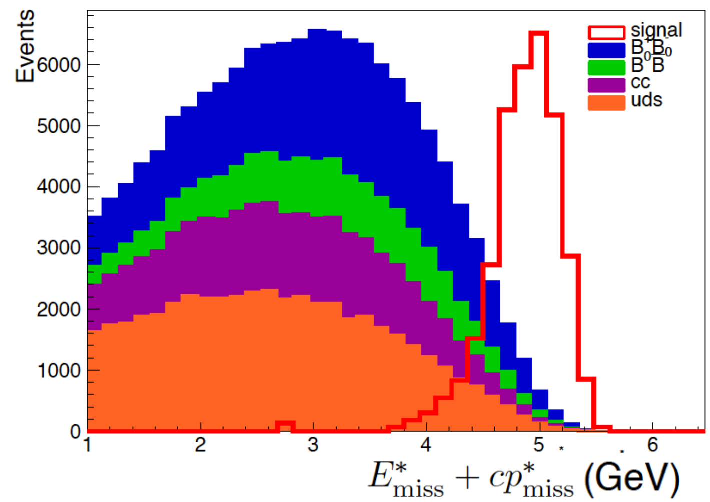
Belle PRD(R) 96, 091101 (2017)

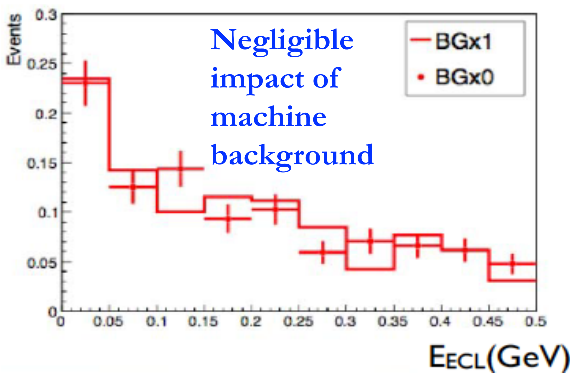


Flavour changing neutral current $B \to K^{(*)}\nu\bar{\nu}$

Belle II full simulation study

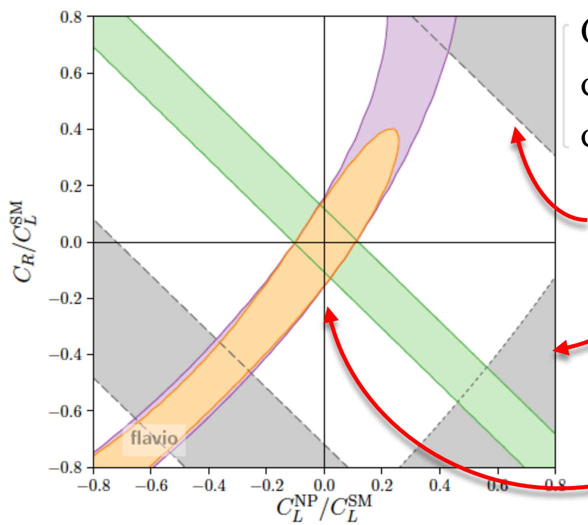
- Hadronic tag with FEI
- $K^* \to K\pi^0$
- Cut and count in extra energy signal window





Observables	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B^+ \to K^+\nu\bar{\nu})$	30%	11%
$Br(B^0 \to K^{*0}\nu\bar{\nu})$	26%	9.6%
$Br(B^+ \to K^{*+}\nu\bar{\nu})$	25%	9.3%

Observation at ~18 ab^{-1}



Constraints on new physics contributions to Wilson coefficients C_L, C_R

90% CL excluded by Belle and Babar

68% CL allowed by Belle II at 50 ab^{-1}

Conclusions

- Unique capabilities of Belle II to study **B decays with missing energy in the final state**

- Within the first **two years of data taking** Belle II will collect **5 to 10 ab^{-1}** and will be able to
  - address the Lepton Flavour Universality Violation by precisely measuring **R(D) / R(D*)**
  - address the **$|V_{ub}|$ puzzle** from inclusive and exclusive semileptonic decays

- Discovery potential also in rare processes suppressed in the SM ($B \to \tau\nu$, $B \to l\nu\gamma$, $B \to K^{(*)}\nu\nu$, $B \to \mu\nu$, $B \to \nu\nu$)

Thanks !

Backup

Belle II Detector

Component	Type	Configuration	Readout	Performance
Beam pipe	Beryllium double-wall	Cylindrical, inner radius 10 mm, 10 μm Au, 0.6 mm Be, 1 mm coolant (paraffin), 0.4 mm Be		
PXD	Silicon pixel (DEPFET)	Sensor size: 15×100 (120) mm^2 pixel size: 50×50 (75) μm^2 2 layers: 8 (12) sensors	10 M	impact parameter resolution $\sigma_{z_0} \sim 20\ \mu$m (PXD and SVD)
SVD	Double sided Silicon strip	Sensors: rectangular and trapezoidal Strip pitch: 50(p)/160(n) - 75(p)/240(n) μm 4 layers: 16/30/56/85 sensors	245 k	
CDC	Small cell drift chamber	56 layers, 32 axial, 24 stereo r = 16 - 112 cm - 83 $\leq z \leq$ 159 cm	14 k	$\sigma_{r\phi} = 100\ \mu$m, $\sigma_z = 2$ mm $\sigma_{p_t}/p_t = \sqrt{(0.2\%p_t)^2 + (0.3\%/\beta)^2}$ $\sigma_{p_t}/p_t = \sqrt{(0.1\%p_t)^2 + (0.3\%/\beta)^2}$ (with SVD)

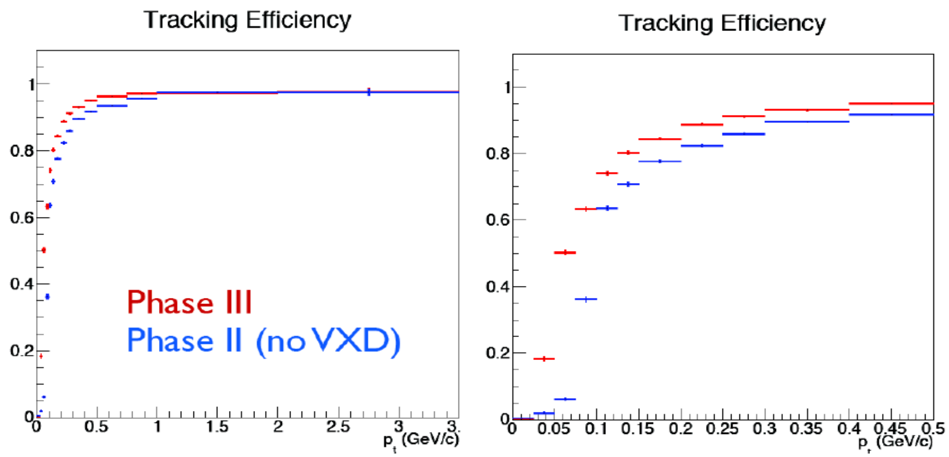
component	background	generic $B\overline{B}$
PXD	10000 (580)*	23
SVD	284 (134)	108
CDC	654	810
TOP	150	205
ARICH	191	188
ECL	3470	510
BKLM	484	33
EKLM	142	34

* in parentheses numbers without 2-γ QED

Total number of hits per event in each subdetector

Phase II

Tracking without VXD



What can we do with phase II data ?

- Background studies
- Detector and trigger performance studies
- Simulation validation
- Exercising of calibration and alignment procedures
- Reconstruction algorithm tuning
- Physics measurements

Belle II Physics Book

- B2TiP Report (600p)
  - https://confluence.desy.de/display/BI/B2TiP+ReportStatus
- To be published in PTEP / Oxford University Press & printed.
  - Belle II Detector, Simulation, Reconstruction, Analysis tools
  - Physics working groups
  - New physics prospects and global fit code

PTEP

Prog. Theor. Exp. Phys. **2015**, 00000 (319 pages)
DOI: 10.1093/ptep/0000000000

The Belle II Physics Book

Emi Kou[1], Phillip Urquijo[2], The Belle II collaboration[3], and The B2TiP theory community[4]

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The report of the Belle II Theory Interface Platform is presented in this document.

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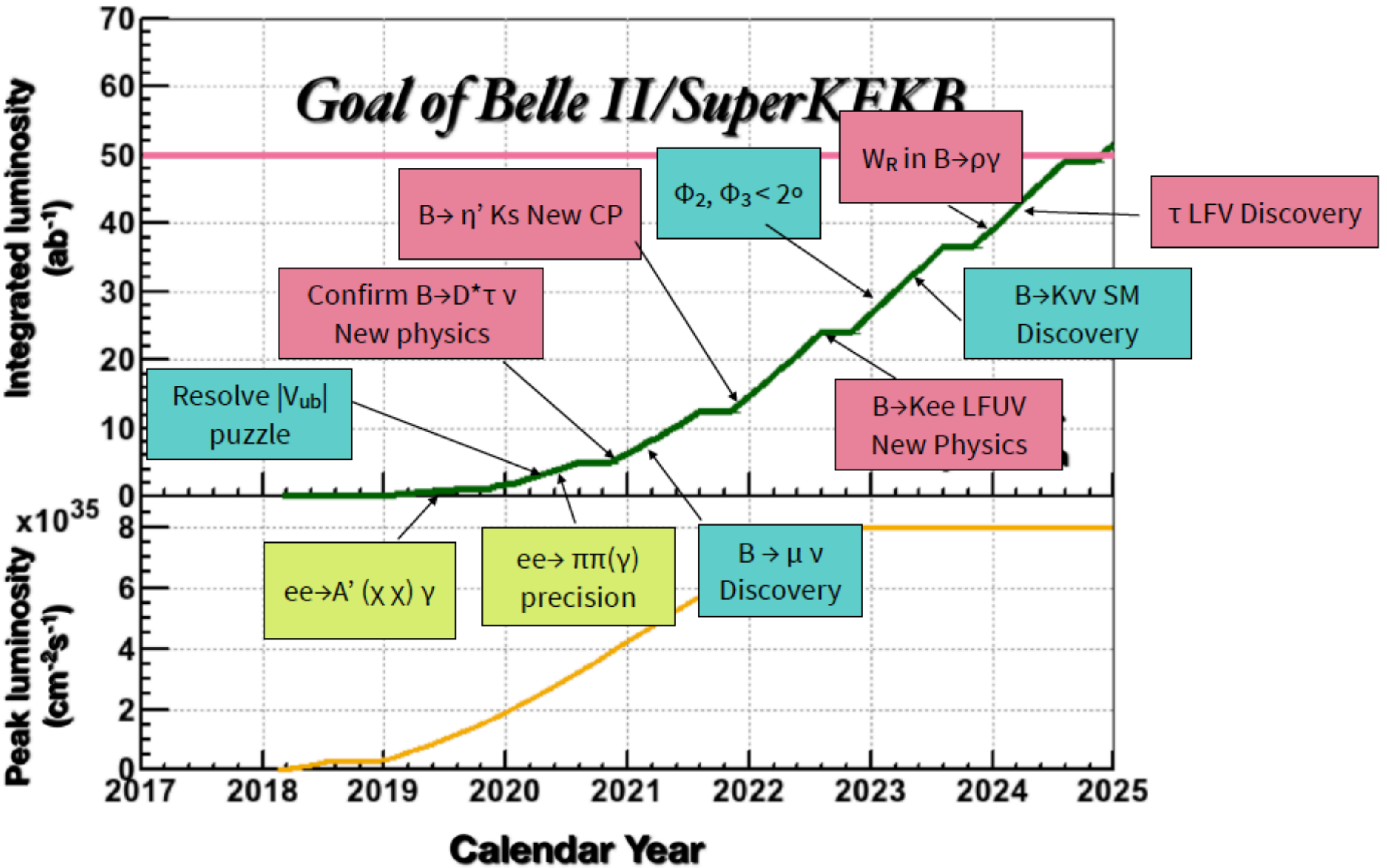
Roadmap



Goal of Belle II/SuperKEKB
Integrated luminosity (ab^{-1})
Peak luminosity (cm^{-2}s^{-1})
x10^{35}
Calendar Year
70
60
50
40
30
20
10
0
8
6
4
2
0
2017
2018
2019
2020
2021
2022
2023
2024
2025
W$_R$ in B→ργ
Φ$_2$, Φ$_3$ < 2°
B→ η' Ks New CP
τ LFV Discovery
Confirm B→D*τ ν New physics
B→Kνν SM Discovery
Resolve |V$_{ub}$| puzzle
B→Kee LFUV New Physics
ee→A' (χ χ) γ
ee→ ππ(γ) precision
B → μ ν Discovery

FEI Calibration

FEI validated on Belle real data

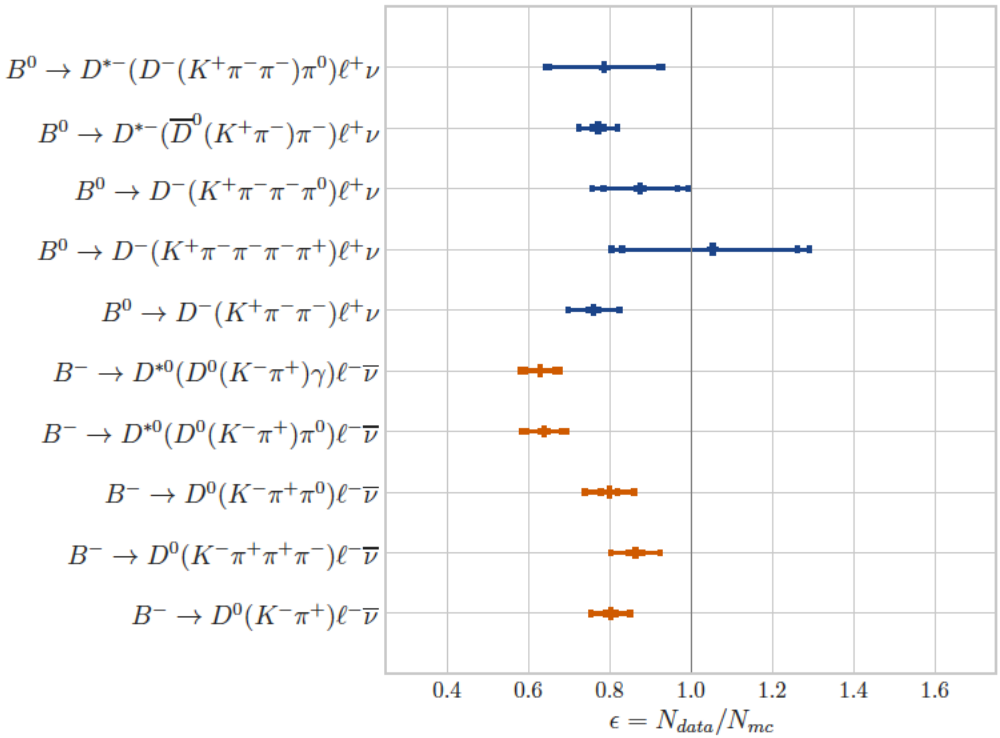


Figure 4.18.: The overall efficiency correction calculated by measuring the known branching fractions of 10 control channels on converted Belle data [76].

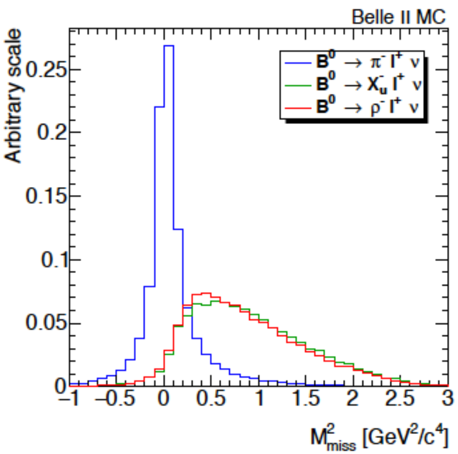
Thomas Keck's master thesis

Physics prospects: Belle II vs LHCb

Observables	Expected th. 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	Belle II/LHCb
$\lvert V_{cb}\rvert$ incl.	***	1%	Belle II
$\lvert V_{cb}\rvert$ excl.	***	1.5%	Belle II
$\lvert V_{ub}\rvert$ incl.	**	3%	Belle II
$\lvert V_{ub}\rvert$ excl.	**	2%	Belle II/LHCb
CPV			
$S(B \to \phi K^0)$	***	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
$S(B \to K^0_S\pi^0\gamma)$	***	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
$\mathcal{B}(B \to K^*\nu\overline{\nu})$ $[10^{-6}]$	***	15%	Belle II
$\mathcal{B}(B \to K\nu\overline{\nu})$ $[10^{-6}]$	***	20%	Belle II
$R(B \to K^*\ell\ell)$	**	0.03	Belle II/LHCb

	Observables	Belle or LHCb* (2014)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}	LHCb 2018	LHCb 50 fb^{-1}
Charm Rare	$\mathcal{B}(D_s \to \mu\nu)$	$5.31 \cdot 10^{-3}(1 \pm 5.3\% \pm 3.8\%)$	2.9%	0.9%		
	$\mathcal{B}(D_s \to \tau\nu)$	$5.70 \cdot 10^{-3}(1 \pm 3.7\% \pm 5.4\%)$	3.5%	2.3%		
	$\mathcal{B}(D^0 \to \gamma\gamma)$ $[10^{-6}]$	< 1.5	30%	25%		
Charm CP	$A_{CP}(D^0 \to K^+K^-)$ $[10^{-4}]$	$-32 \pm 21 \pm 9$	11	6		
	$\Delta A_{CP}(D^0 \to K^+K^-)$ $[10^{-3}]$	3.4*			0.5	0.1
	A_Γ $[10^{-2}]$	0.22	0.1	0.03	0.02	0.005
	$A_{CP}(D^0 \to \pi^0\pi^0)$ $[10^{-2}]$	$-0.03 \pm 0.64 \pm 0.10$	0.29	0.09		
	$A_{CP}(D^0 \to K^0_S\pi^0)$ $[10^{-2}]$	$-0.21 \pm 0.16 \pm 0.09$	0.08	0.03		
Charm Mixing	$x(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-2}]$	$0.56 \pm 0.19 \pm {}^{0.07}_{0.13}$	0.14	0.11		
	$y(D^0 \to K^0_S\pi^+\pi^-)$ $[10^{-2}]$	$0.30 \pm 0.15 \pm {}^{0.05}_{0.08}$	0.08	0.05		
	$\lvert q/p\rvert(D^0 \to K^0_S\pi^+\pi^-)$	$0.90 \pm {}^{0.16}_{0.15} \pm {}^{0.08}_{0.06}$	0.10	0.07		
	$\phi(D^0 \to K^0_S\pi^+\pi^-)$ [°]	$-6 \pm 11 \pm {}^{4}_{5}$	6	4		
Tau	$\tau \to \mu\gamma$ $[10^{-9}]$	< 45	< 14.7	< 4.7		
	$\tau \to e\gamma$ $[10^{-9}]$	< 120	< 39	< 12		
	$\tau \to \mu\mu\mu$ $[10^{-9}]$	< 21.0	< 3.0	< 0.3		

Semileptonic decay: $B^0 \to \pi l \nu$



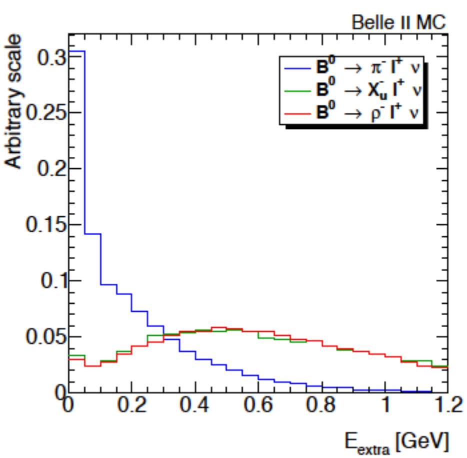


Table 54: Summary of systematic uncertainties on the branching fractions of $B^0 \to \pi^- \ell^+ \nu_\ell$ decays in hadronic tagged and untagged Belle analyses with 711 fb^{-1} [271] and 605 fb^{-1} [269] data samples, respectively. The estimated precision limit for some sources of systematic uncertainties is given in brackets.

Source	Error (Limit) [%] Tagged [%]	Untagged
Tracking efficiency	0.4	2.0
Pion identification	–	1.3
Lepton identification	1.0	2.4
Kaon veto	0.9	–
Continuum description	1.0	1.8
Tag calibration and $N_{B\bar{B}}$	4.5 (2.0)	2.0 (1.0)
$X_u \ell \nu$ cross-feed	0.9	0.5 (0.5)
$X_c \ell \nu$ background	–	0.2 (0.2)
Form factor shapes	1.1	1.0 (1.0)
Form factor background	–	0.4 (0.4)
Total	5.0	4.5
(reducible, irreducible)	(4.6, 2.0)	(4.2, 1.6)

LQCD: current is the world avergage by FLAG group
- 5 yr w/o EM": We assume a factor of 2 reduction of the lattice QCD uncertainty in the next ve years and that the uncertainty of the EM correction is negligible (e.g. for processes insensitive to the EM correction).
- 5 yr w/ EM": The lattice QCD uncertainty is reduced by a factor of 2, but we add in quadrature 1% uncertainty from the EM correction19.
- 10 yr w/o EM": We assume a factor of 5 reduction of the lattice QCD uncertainty in the next ten years. It is also assumed that the EM correction will be under control and its uncertainty is negligible.
- 10 yr w/ EM": We assume lattice QCD uncertainties reduced by a factor of 5, but add in quadrature 1% uncertainty from the EM correction.

R(D*) Belle measurement

Belle PRD 94, 072007(2016) SL tag

	$\mathcal{R}(D^*)$ [%]		
Sources	$\ell^{\rm sig} = e, \mu$	$\ell^{\rm sig} = e$	$\ell^{\rm sig} = \mu$
MC size for each PDF shape	2.2	2.5	3.9
PDF shape of the normalization in $\cos\theta_{B\text{-}D^*\ell}$	$^{+1.1}_{-0.0}$	$^{+2.1}_{-0.0}$	$^{+2.8}_{-0.0}$
PDF shape of $B \to D^{**}\ell\nu_\ell$	$^{+1.0}_{-1.7}$	$^{+0.7}_{-1.3}$	$^{+2.2}_{-3.3}$
PDF shape and yields of fake $D^{(*)}$	1.4	1.6	1.6
PDF shape and yields of $B \to X_c D^*$	1.1	1.2	1.1
Reconstruction efficiency ratio $\varepsilon_{\rm norm}/\varepsilon_{\rm sig}$	1.2	1.5	1.9
Modeling of semileptonic decay	0.2	0.2	0.3
$\mathcal{B}(\tau^- \to \ell^- \bar{\nu}_\ell \nu_\tau)$	0.2	0.2	0.2
Total systematic uncertainty	$^{+3.4}_{-3.5}$	$^{+4.1}_{-3.7}$	$^{+5.9}_{-5.8}$

Leptonic radiative B → lνγ

$$\Gamma = \frac{d\Gamma}{dE_\gamma} = \frac{\alpha_{em} G_F^2 m_B^4 |V_{ub}|^2}{48\pi^2} x_\gamma^3 (1 - x_\gamma)[F_A^2 + F_V^2].$$

$$F_V(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) + \frac{Q_b m_B f_B}{2E_\gamma m_b} + \frac{Q_u m_B f_B}{(2E_\gamma)^2} \right],$$

$$F_A(E_\gamma) = \frac{Q_u m_B f_B}{2E_\gamma \lambda_B} R(E_\gamma, \mu) + \left[\xi(E_\gamma) - \frac{Q_b m_B f_B}{2E_\gamma m_b} - \frac{Q_u m_B f_B}{(2E_\gamma)^2} + \frac{Q_\ell f_B}{E_\gamma} \right],$$

Beneke and Rohrwild, 2011, https://doi.org/10.1140/epjc/s10052-011-1818-8

Flavour changing neutral current
$B \to K^{(*)}\nu\bar{\nu}$

In BSM right handed operator for neutrinos $Q_R^\ell = (\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_{\ell L}\gamma^\mu \nu_{\ell L})$

$$\frac{\mathrm{Br}(B \to K\nu\bar{\nu})}{\mathrm{Br}(B \to K\nu\bar{\nu})_{\mathrm{SM}}} = \frac{1}{3}\sum_\ell (1 - 2\,\eta_\ell)\,\epsilon_\ell^2\,,$$

$$\frac{\mathrm{Br}(B \to K^*\nu\bar{\nu})}{\mathrm{Br}(B \to K^*\nu\bar{\nu})_{\mathrm{SM}}} = \frac{1}{3}\sum_\ell (1 + \kappa_\eta \eta_\ell)\,\epsilon_\ell^2\,,$$

$$\epsilon_\ell = \frac{\sqrt{|C_L^\ell|^2 + |C_R^\ell|^2}}{|C_L^{\mathrm{SM}}|}\,,$$

$$\eta_\ell = \frac{-\mathrm{Re}\left(C_L^\ell C_R^{\ell *}\right)}{|C_L^\ell|^2 + |C_R^\ell|^2}\,.$$