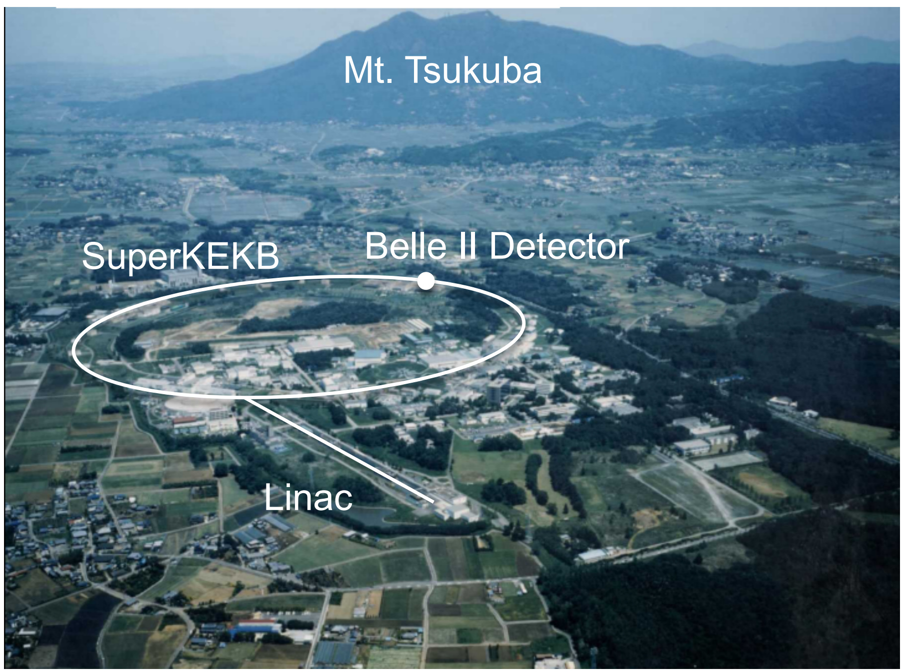
Towards first CKM measurements at Belle II

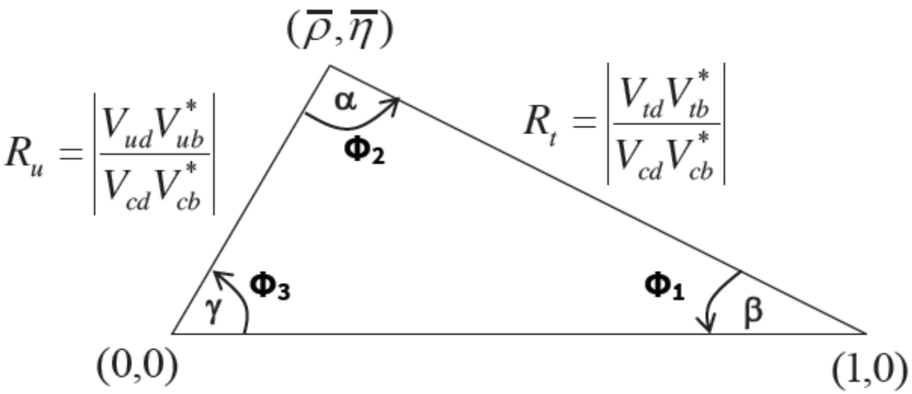
Mario Merola (Università di Napoli Federico II and INFN)

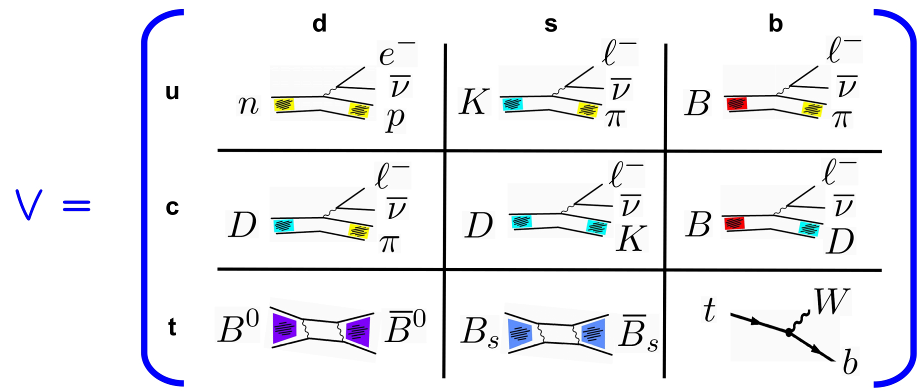
On behalf of the Belle II Collaboration

FPCP2020, 8-12 June 2020



‘Standard’ Unitarity Triangle: sides and angles





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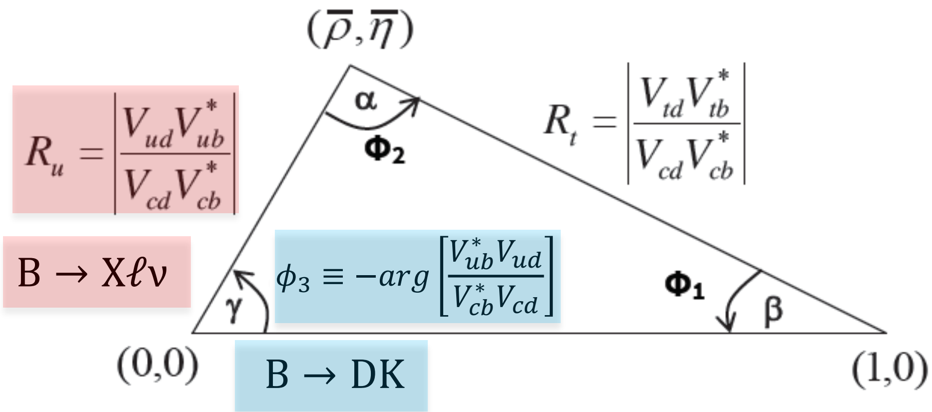
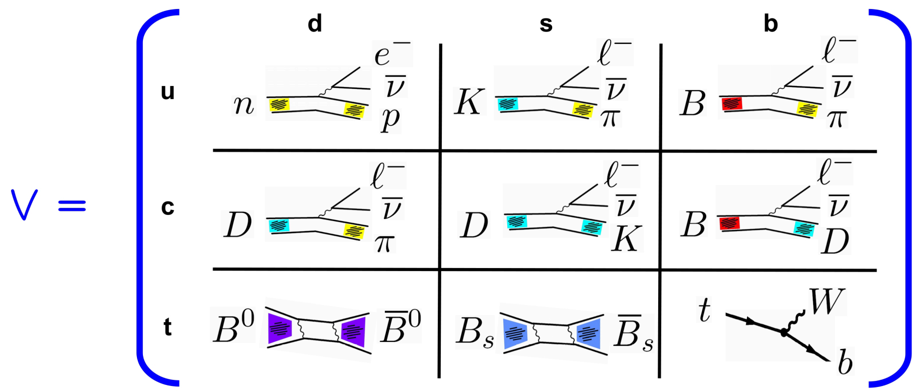




In this talk will focus on $R_u \sim |V_{ub}|/[V_{cb}]$ and ϕ_3:

- Semileptonic B decays with missing energy $B \rightarrow X_{u(c)}\ell\nu$
- Hadronic B decays into charm $B \rightarrow DK$

For ϕ_1, ϕ_2 measurements see Fernando Abudinén’s talk today

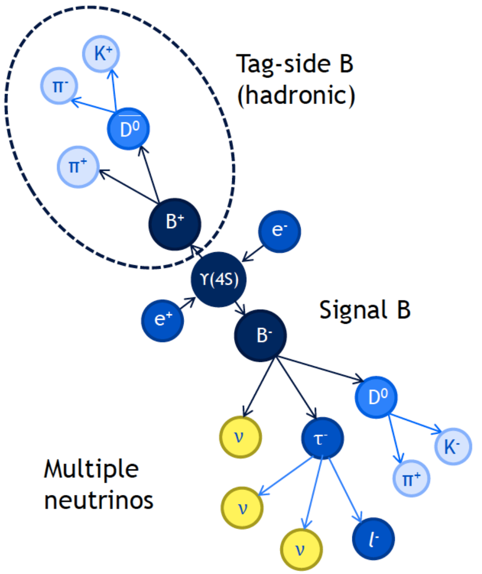
Belle II physics reach projections summarized in the Belle II Physics Book (PTEP 2019 (2019) 12, 123C01, https://doi.org/10.1093/ptep/ptaa008)

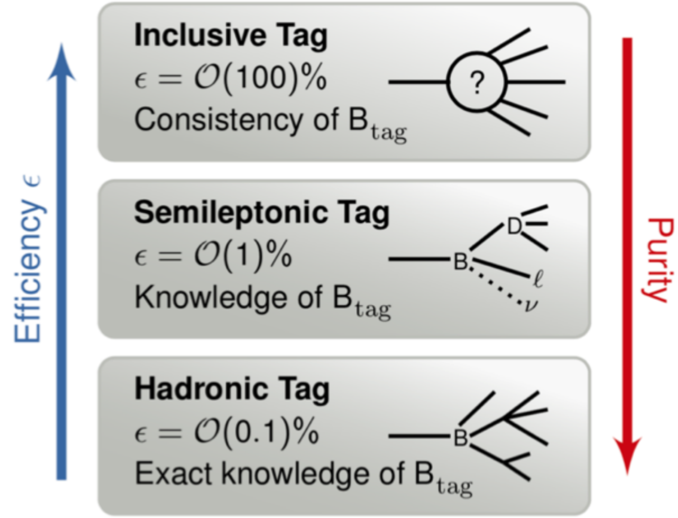
Reconstruction of events with missing energy: Full Event Interpretation (FEI)

- Reconstruct one B ($\mathbf{B_{tag}}$) and constrain the 4-momentum of the other ($\mathbf{B_{sig}}$)

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

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



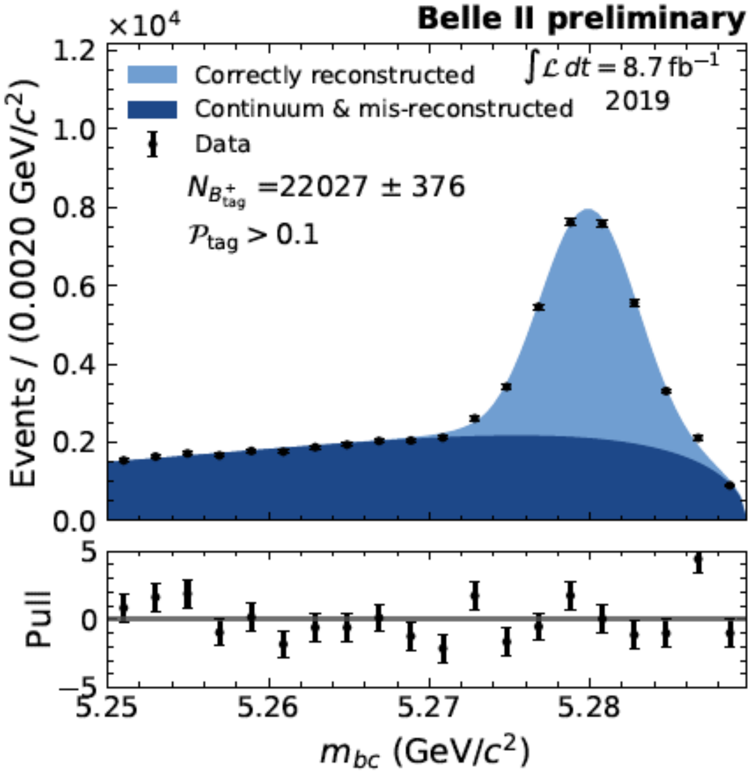


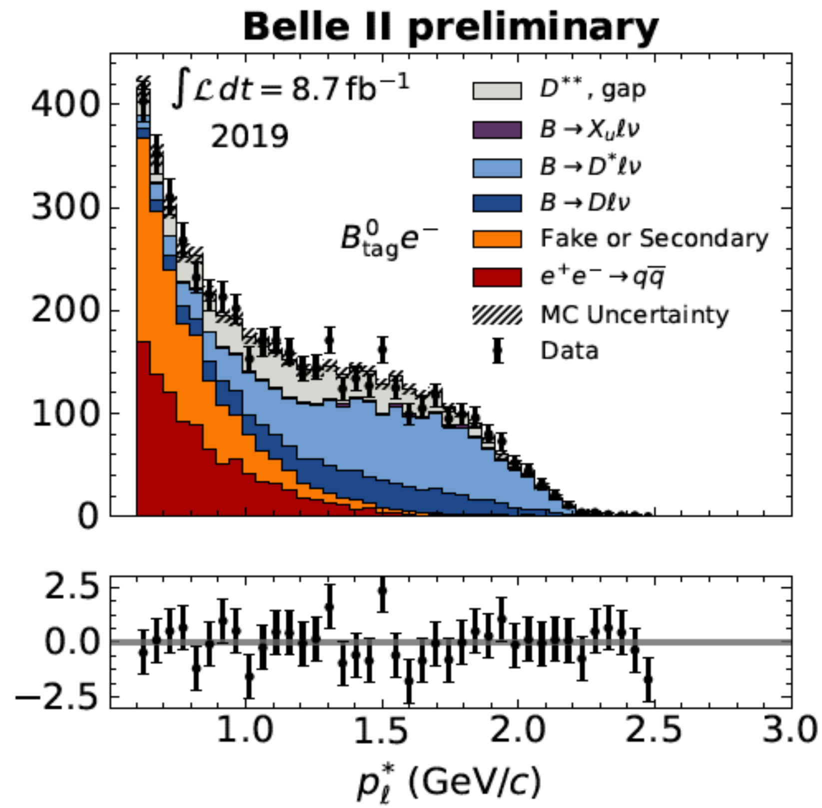
Performances on Belle MC with hadronic tag @10% purity

Tag algorithm	Efficiency $B^{\pm}/B^0$ (%)
Belle algorithm	0.28/0.18
Belle II FEI	0.76/0.46

Belle algorithm: NIM A 654, 432-440 (2011)
Belle II FEI: Keck, T., Abudinén, F., Bernlochner, F.U. et al. Comput Softw Big Sci (2019) 3: 6. https://doi.org/10.1007/s41781-019-0021-8

FEI on Belle II data





- **Tag side** reconstructed in hadronic modes

$$M_{bc} = \sqrt{s/4 - (p^*_B)^2}$$

- Select a lepton and sum the remaining particles' kinematics on the signal side
- Check consistency with the well-known **$B \to X\ell\nu$**
- Also used to calibrate FEI

Details in the talk by Slavomira Stefkova on Thursday

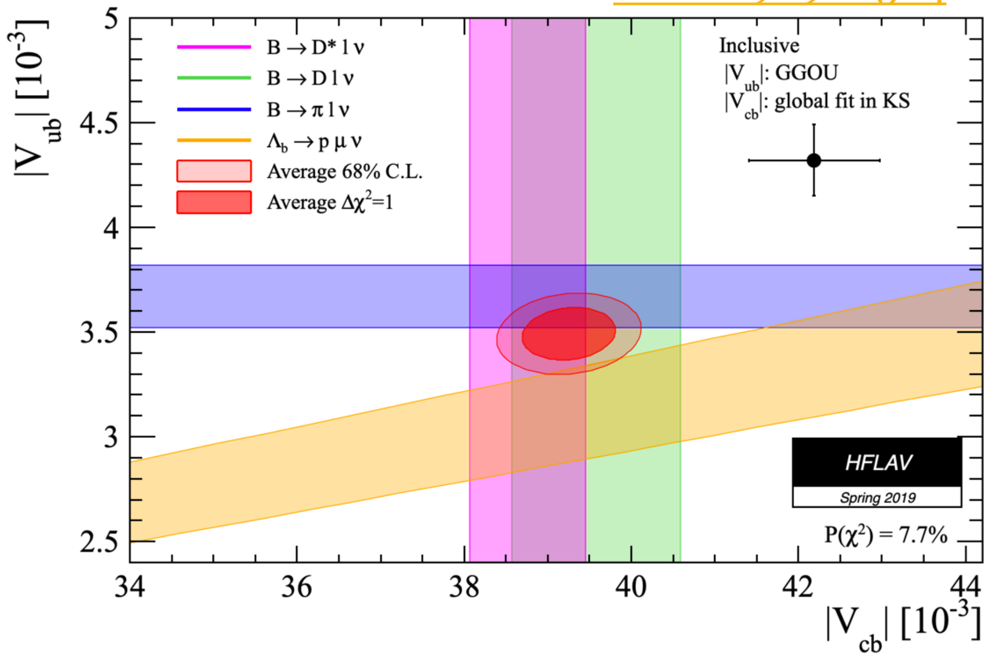
Semileptonic decays: $B \to X\ell\nu$

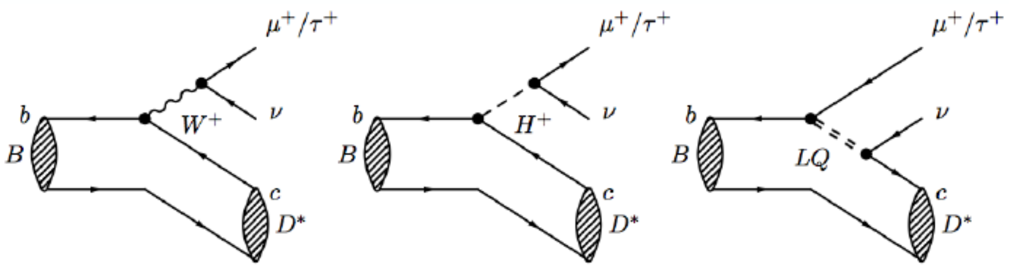
- Current precision is **2% on $|V_{cb}|$** and **5-6% on $|V_{ub}|$**

- **Tension** between inclusive and exclusive determinations: ~3σ for $|V_{cb}|$ and ~3.5σ for $|V_{ub}|$

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

arXiv:1909.12524





- Complementary to the R(D)/R(D*) measurements which factor out the $|V_{cb}|$ and form factor uncertainties

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

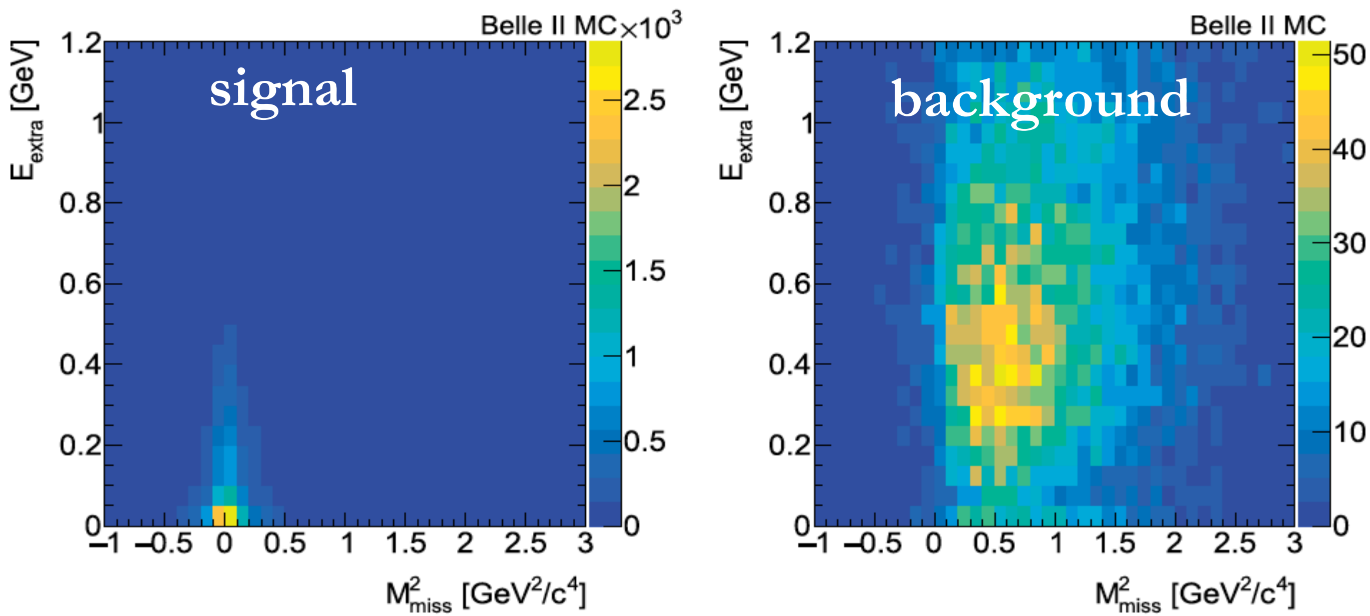
Talk by Saurabh Sandilya on LFU tomorrow

Semileptonic decays: $B \to X_u \ell \nu$ (I)

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

Exclusive: $\mathbf{B^0 \to \pi \ell \nu}$ decay

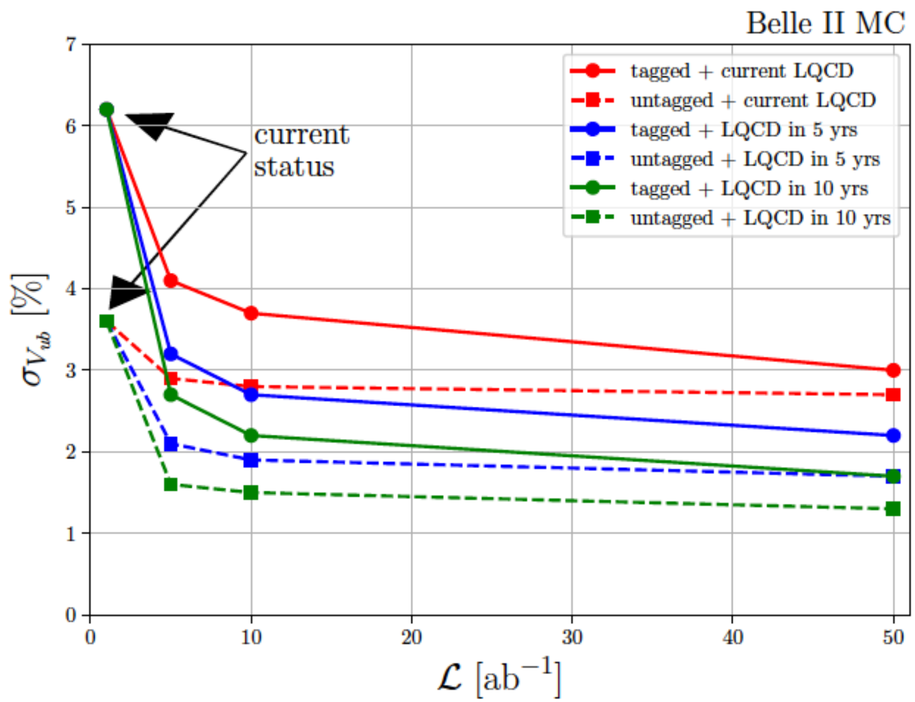
- Exploit **missing mass** and **extra energy** in the calorimeter
- $\mathcal{B} \sim f_i |V_{ub}|^2$. Form factors f_i computed with LQCD*



$$M_{miss}^2 = \left(p_{\Upsilon(4S)} - p_{B_{tag}} - p_\pi - p_\ell\right)^2$$

* PRD 91, 074510 (2015)

Semileptonic decays: $B \to X_u \ell \nu$ (II)



- Projection of $|V_{ub}|$ uncertainies from $B^0 \to \pi \ell \nu$ decay
- Takes advantage from improvements in LQCD

- Precision of ~1% with full Belle II dataset

|Vub| uncert.	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
Exclusive	$(1.2 \oplus 1.7)\%$	$(0.9 \oplus 0.9)\%$
Inclusive	$(2.3 \oplus 2.5\text{-}4.5)\%$	$(1.7 \oplus 2.5\text{-}4.5)\%$

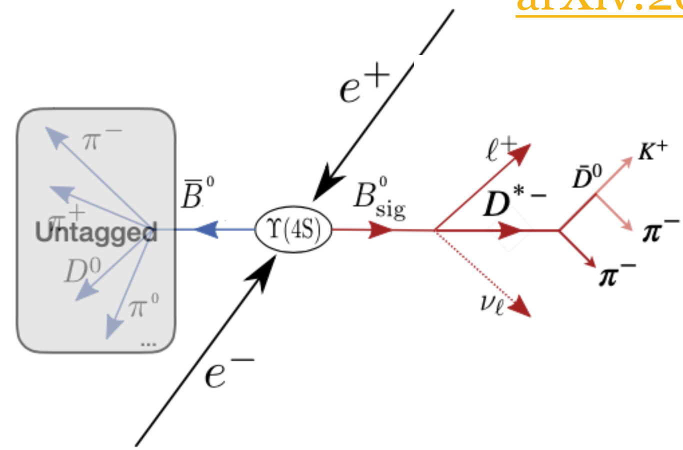
Projected errors: (experiment $\oplus$ theory)

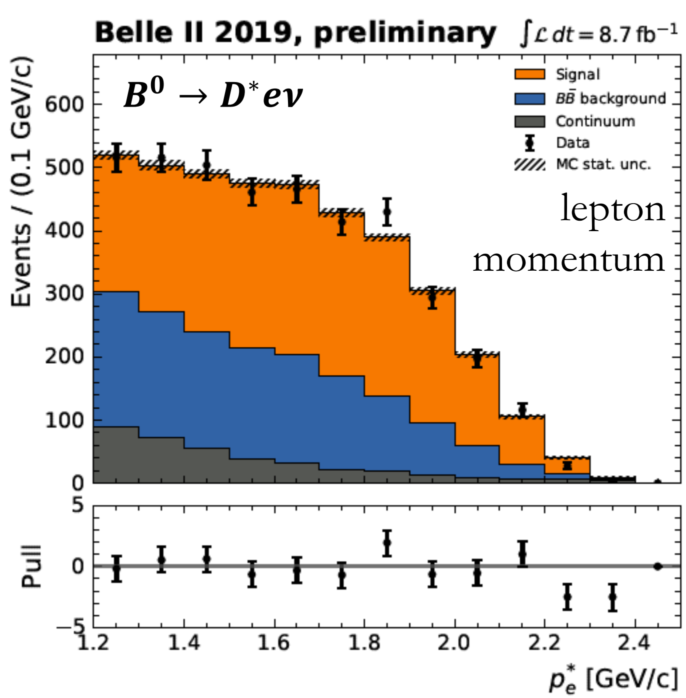
Belle II Physics Book

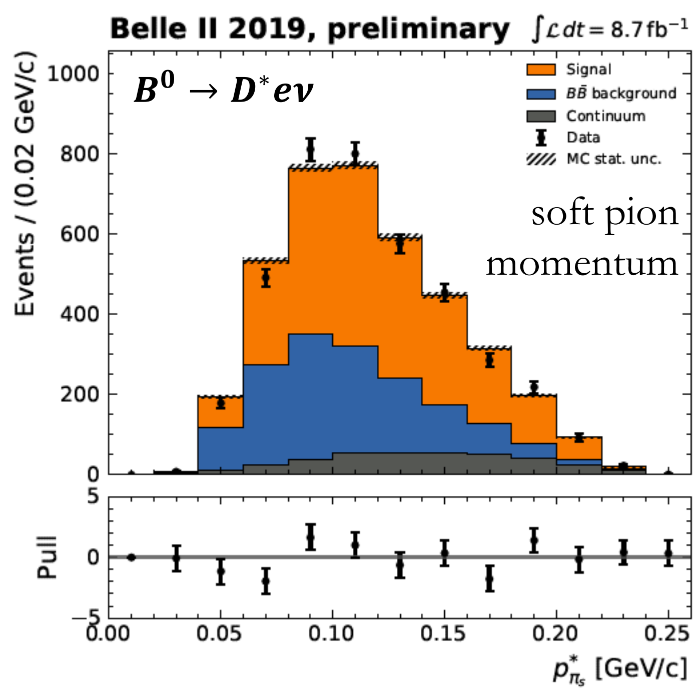
Untagged $B^0 \to D^* \ell \nu$ (I)

arXiv:2004.09066

- Flagship decay for the measurement of $|V_{cb}|$
- Inclusive tagging
- $D^* \to D^0 \pi_s, D^0 \to K\pi$





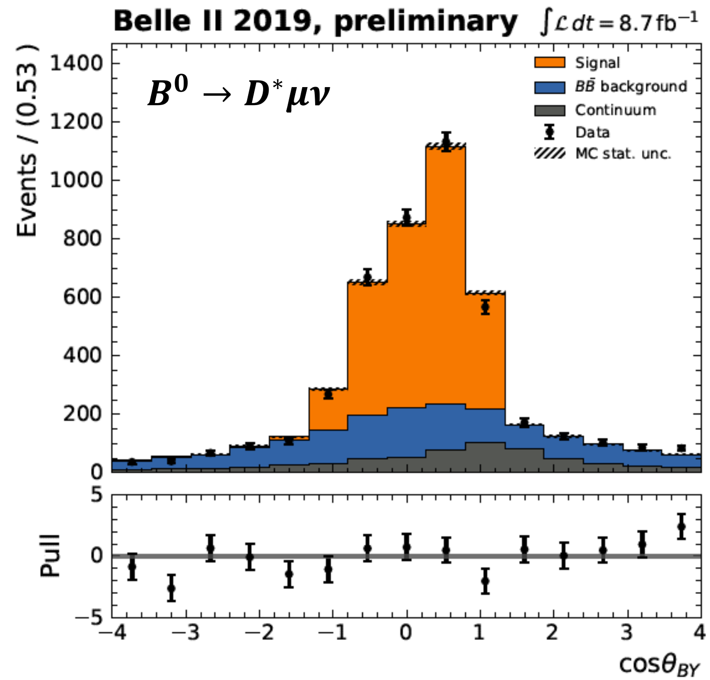


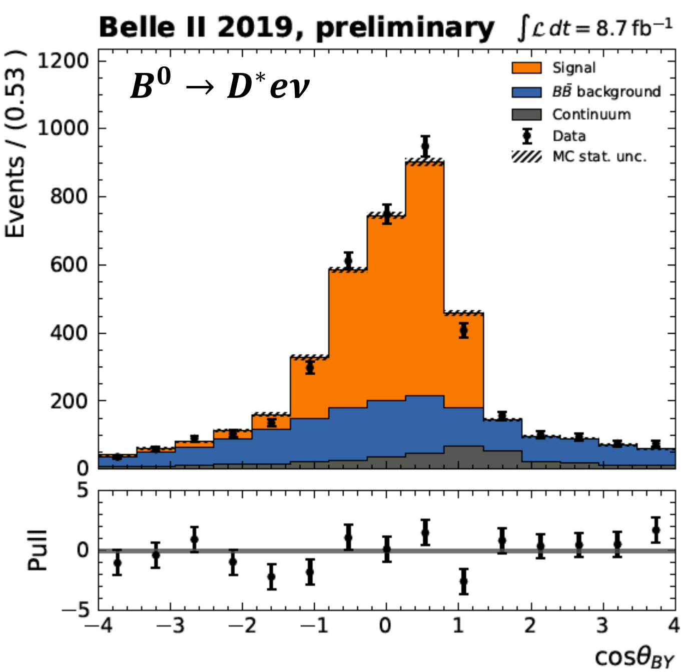
Untagged $B^0 \rightarrow D^*\ell\nu$ (II)

- Angle between the B flight direction and the direction of the ($D^*\ell$) system (Y):

$$\cos\theta_{BY} = \frac{2E_B^* E_Y^* - M_B^2 - m_Y^2}{2p_B^* p_Y^*}$$

- Fit to $\cos\theta_{BY}$ distribution in data to measure the branching ratio





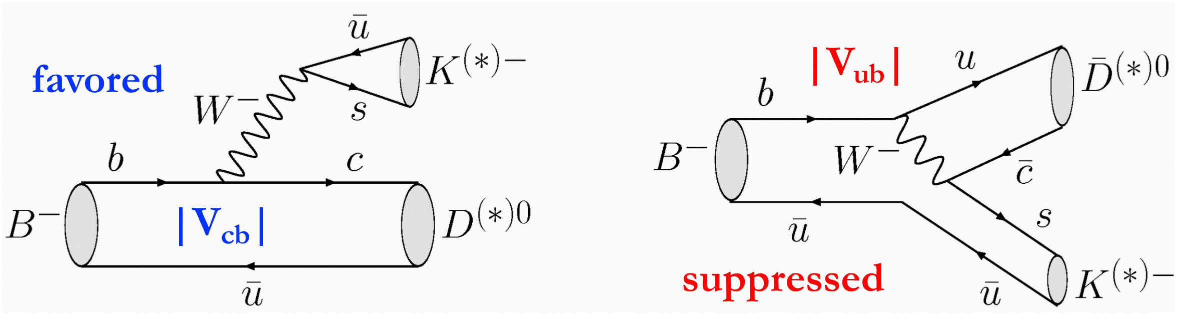
$$\mathcal{B}(\overline{B}^0 \rightarrow D^{*+}e^-\overline{\nu}_e) = (4.55 \pm 0.14(\mathrm{stat}) \pm 0.35(\mathrm{sys}))\%\,,$$
$$\mathcal{B}(\overline{B}^0 \rightarrow D^{*+}\mu^-\overline{\nu}_\mu) = (4.84 \pm 0.13(\mathrm{stat}) \pm 0.37(\mathrm{sys}))\%\,.$$

consistent with the SM within 1σ

|Vcb| uncert.	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
Exclusive	1.8%	1.4%

ϕ_3 angle

- ϕ_3 is accessible at tree level: **theoretically very clean, $\delta\phi_3/\phi_3 \sim 10^{-7}$ ***
- Measured via the interference between $B^- \to D^0 K^-$ and $B^- \to \overline{D}^0 K^-$



$$\frac{A^{suppr.}}{A^{favor.}} = r_B e^{i(\delta_B - \phi_3)}$$

δ_B strong CP conserving phase

* J. Brod, J. Zupan, JHEP 01 (2014) 051

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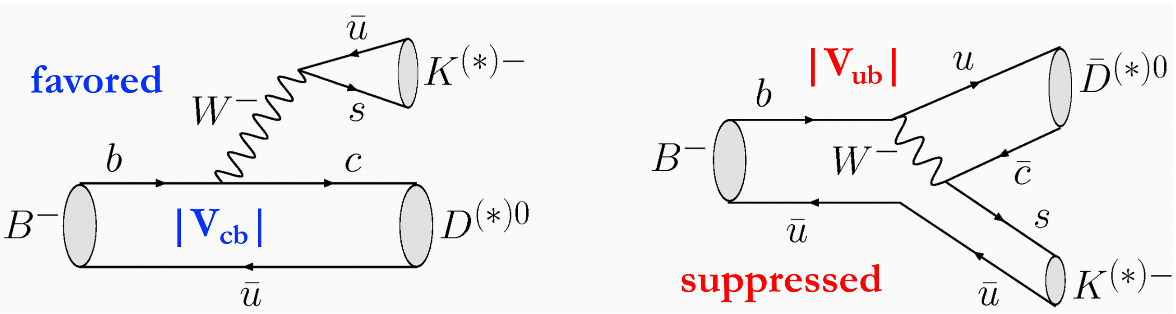
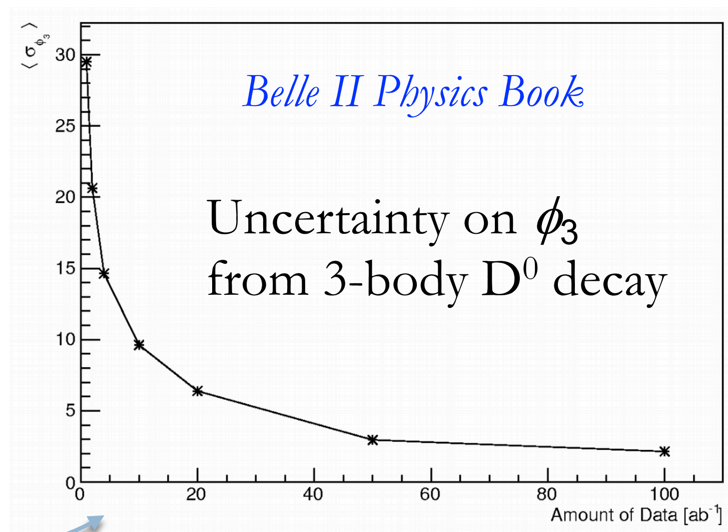


$$\frac{A^{suppr.}}{A^{favor.}} = r_B e^{i(\delta_B - \phi_3)}$$

δ_B strong CP conserving phase

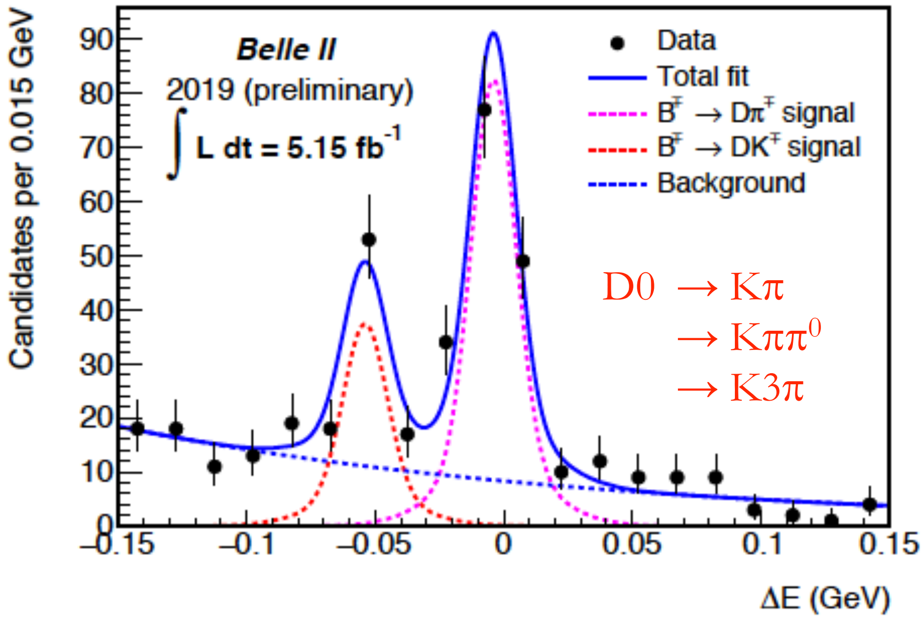
Three approaches depending on **D^0 decay channels**:

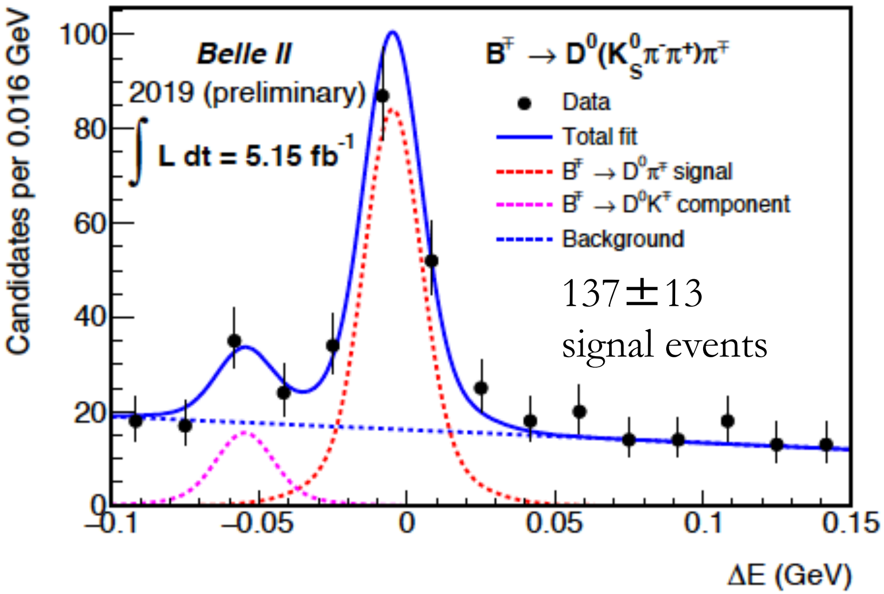
- CP eigenstates: K^+K^-, $\pi^+\pi^-$, etc.
- Doubly Cabibbo suppr.: $K^+\pi^-$
- **Multi-body** (Dalitz analysis): $K_S\pi^+\pi^-$, $K_S\pi^+\pi^-\pi^0$. **Improving precision**: model independent approach and strong phase measurements from BESIII.



* J. Brod, J. Zupan, JHEP 01 (2014) 051

Rediscovery of B → DK at Belle II





- Exploits multivariate techniques to suppress continuum background and good particle identification performances

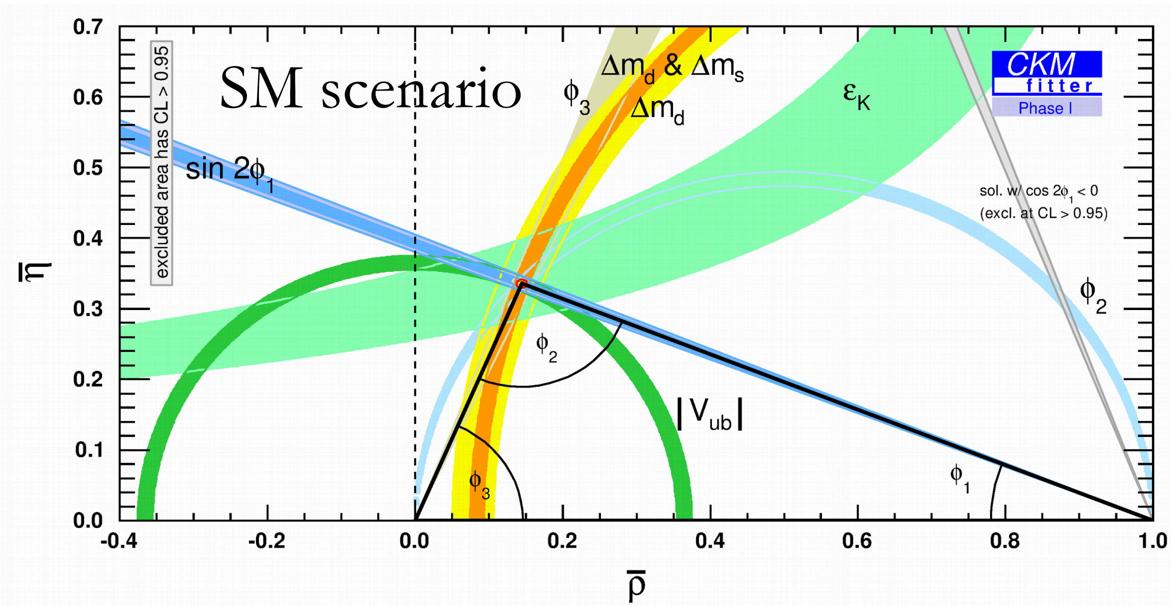
$$\Delta E \equiv E_B^* - \sqrt{s}/2$$

- Observation of the golden 3-body decay as well

Ultimate **Belle II precision on ϕ_3 <1.6°** (combining all the approaches)

Summary

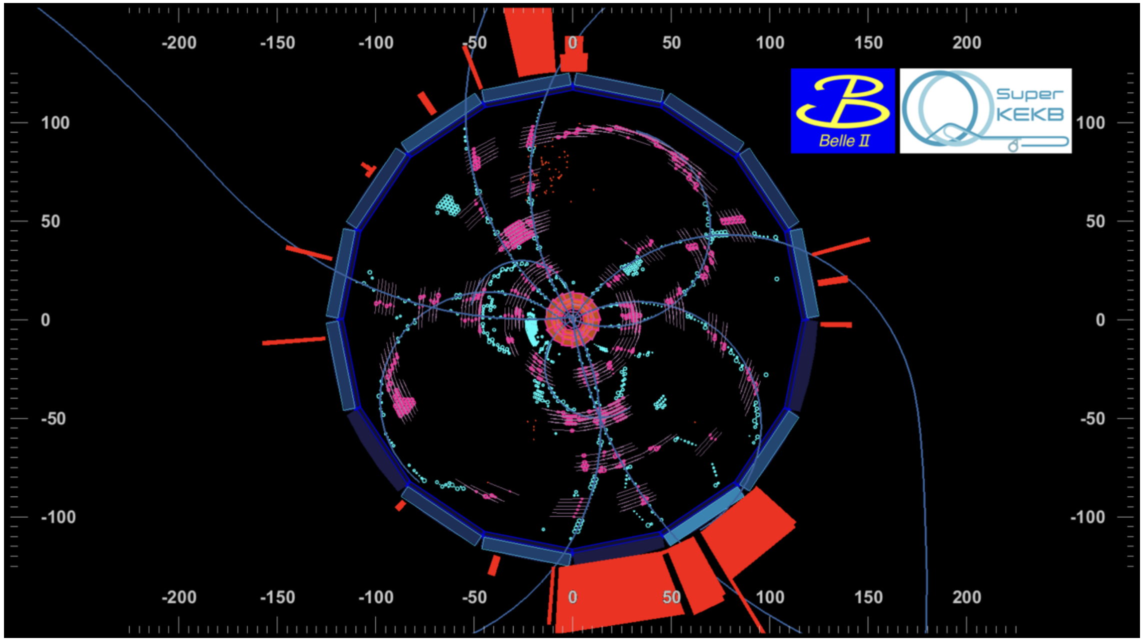
- Within the next years Belle II will be able to address the **inclusive/exclusive $|V_{cb}|/|V_{ub}|$ tension** by measuring semileptonic B decays with missing energy.
- The use of advanced tagging techniques, i.e. FEI, together with untagged analyses will allow to reach a precision of **~1% on $|V_{ub}|$** and **~1.5% on $|V_{cb}|$**.
- Belle II will also deliver a high precision measurement of the ϕ_3 angle, exploiting the Dalitz analysis of **multi-body D^0 decays in the $B \to DK$ process**.



UT in a decade

Assumptions:
Belle II: 50 ab^{-1}
LHCb: 23 fb^{-1}

Thanks !



Summary talk on Belle II status and prospects
by Phillip Urquijo on Friday

Backup

- FEI Calibration (17)
- B –> pilnu decay (18)
- B –> D*lν (19)
- Leptonic B decays (20-23)
- RD/RD* (24)
- B –> sll (25)
- Semileptonic projections (26)
- ϕ_3 angle (27)

FEI Calibration

FEI validated on Belle data

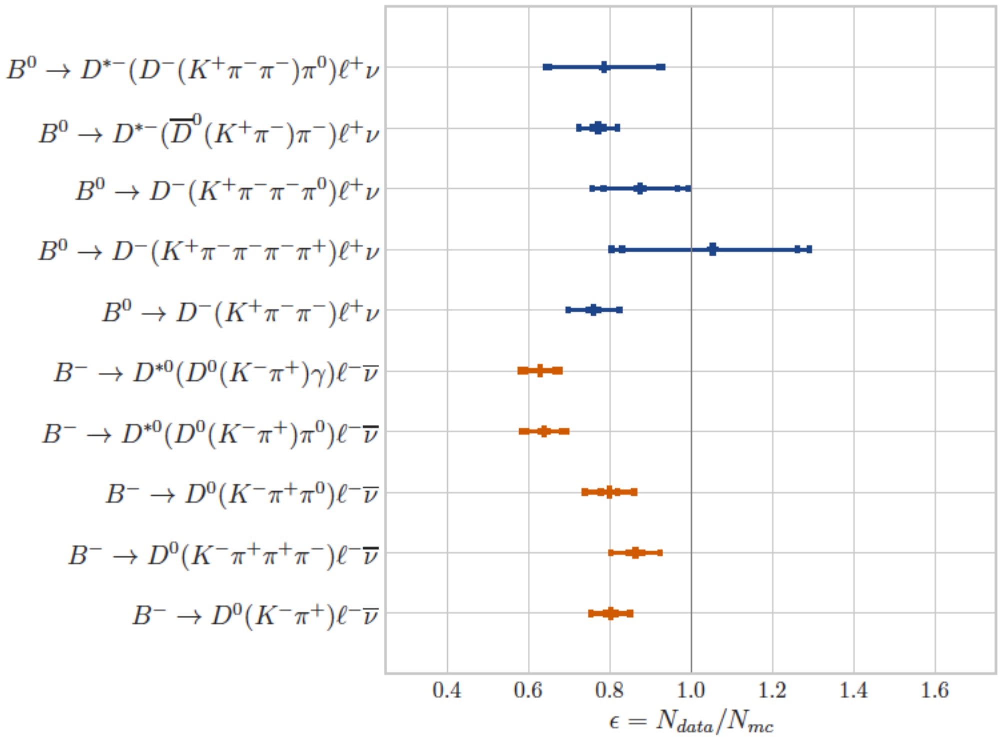
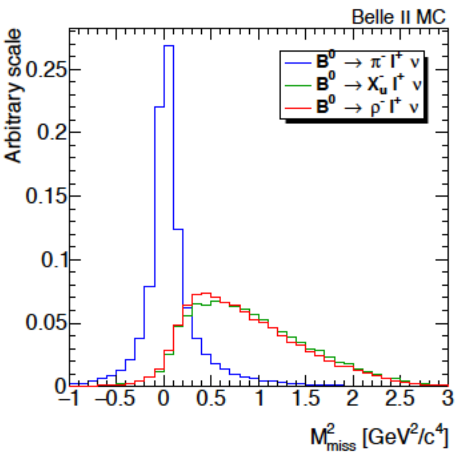


Figure 4.18.: The overall efficiency correction calculated by measuring the known branching fractions of 10 control channels on converted Belle data [76].

Thomas Keck's Master thesis, DOI: http://dx.doi.org/10.5445/IR/1000078149

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



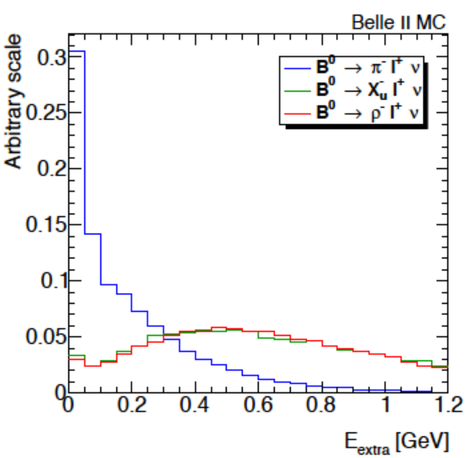


Table 53. Summary of systematic uncertainties on the branching fractions of $B^0 \to \pi^- \ell^+ \nu_\ell$ decays in hadronic tagged and untagged Belle analyses with 711 fb^{-1} [84] and 605 fb^{-1} [299] data samples, respectively. The estimated precision limit for some sources of systematic uncertainties is given in parentheses.

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 five 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 correction.
- 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.

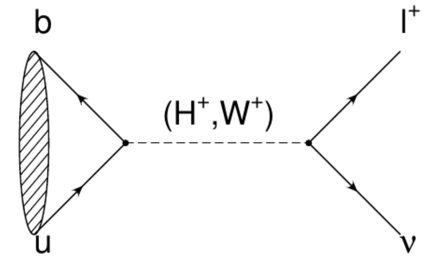
Untagged $B \to D^*l\nu$

Source	Relative uncertainty (%)	
	$\overline{B}^0 \to D^{*+}e^-\overline{\nu}_e$	$\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu$
Lepton-ID, PDF	0.09	0.08
MC statistics, PDF	0.64	0.55
$\mathcal{B}(\bar{B} \to D^{**}\ell\bar{\nu})$	0.18	0.08
Efficiency momentum dependence	0.1	0.1
PDF binning	0.5	0.5
Lepton-ID, efficiency	1.8	2.2
MC statistics, efficiency	0.13	0.13
Tracking of K, π, ℓ	2.5	2.5
Tracking of π_s	6.0	6.0
N_{B^0}	3.3	3.3
Charm branching fractions	1.1	1.1
Total	7.64	7.73

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

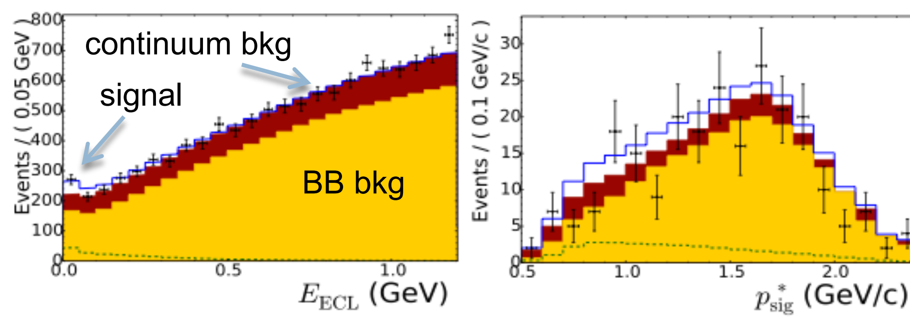
- Sensitive to NP contributions, e.g. type III Higgs doublet model [PhysRevD.86.054014]

- 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

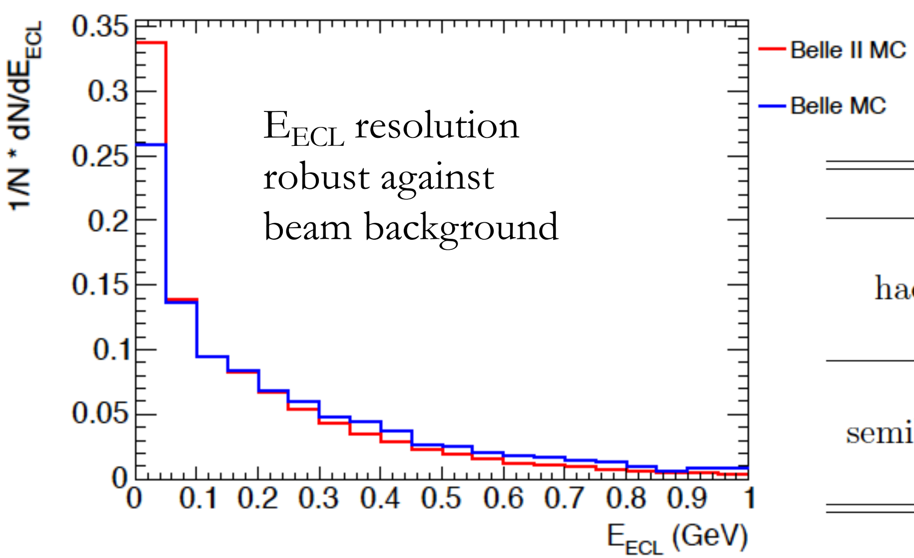


Leptonic B decays: $B \to \tau\nu$

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

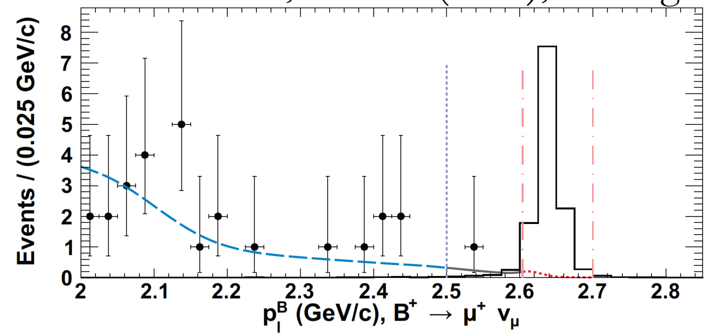
	Integrated Luminosity (ab^{-1})	1	5	50
hadronic tag	statistical uncertainty (%)	29.2	13.0	4.1
	systematic uncertainty (%)	12.6	6.8	4.6
	total uncertainty (%)	31.6	14.7	6.2
semileptonic tag	statistical uncertainty (%)	19.0	8.5	2.7
	systematic uncertainty (%)	17.9	8.7	4.5
	total uncertainty (%)	26.1	12.2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

Observation at ~3 ab^{-1}

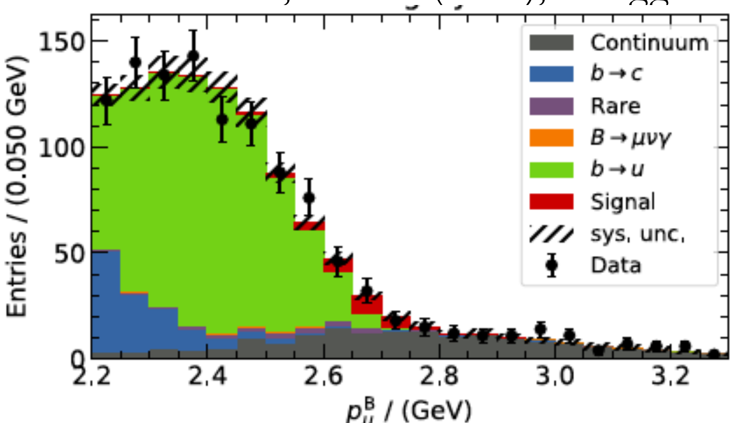
Leptonic B decays: B → μν

- Two body decay: $p_\mu^* = m_B/2$ in B rest frame
- Tagging → better p_μ^* resolution but small statistics
- Untagged measurement (2020):
  - 2.8σ precision on the BR
  - 20% uncertainty on $|V_{ub}|$

Belle PRD **91**, 052016 (2015), had tag

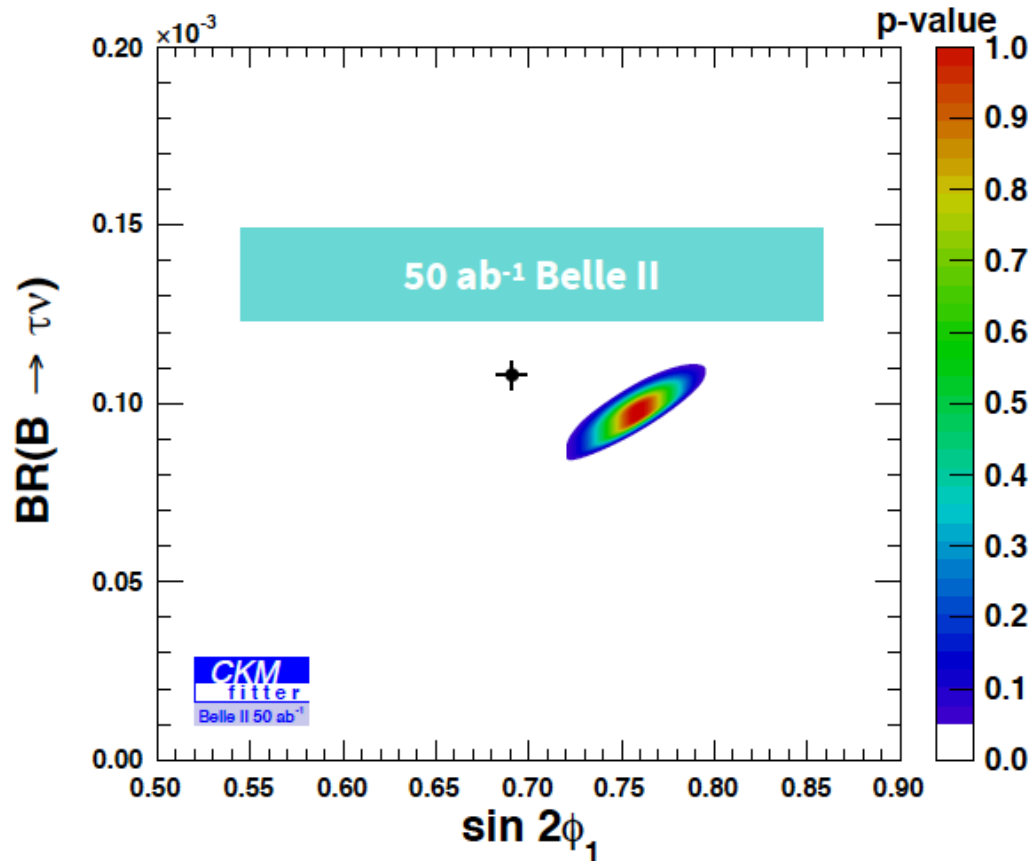


Belle PRD **101**, 032007 (2020), untagged



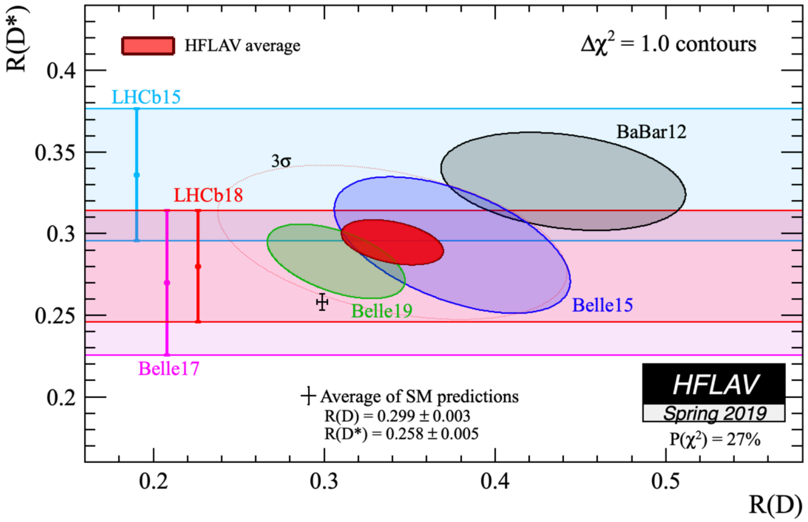
Unc. on $|V_{ub}|$	Belle II @5ab^{-1}	Belle II @50 ab^{-1}
B → τν	5%	1.5 - 2 %
B → μν	10%	5%

Leptonic B decays

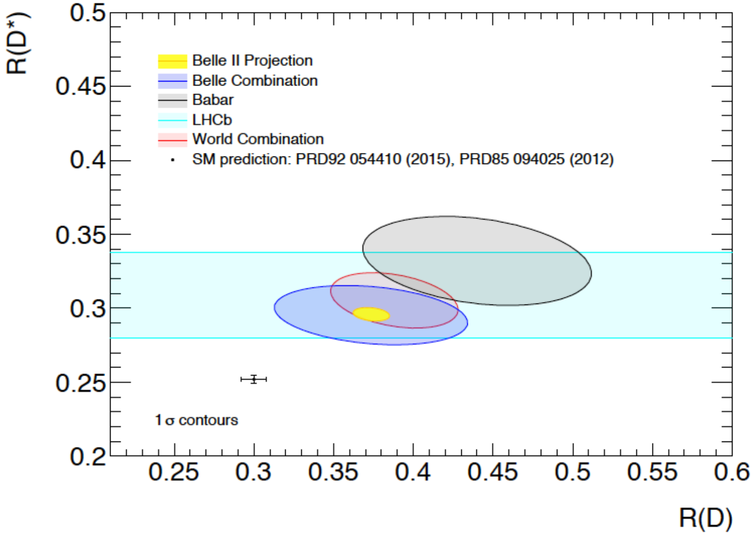


R(D)/R(D*)

World average



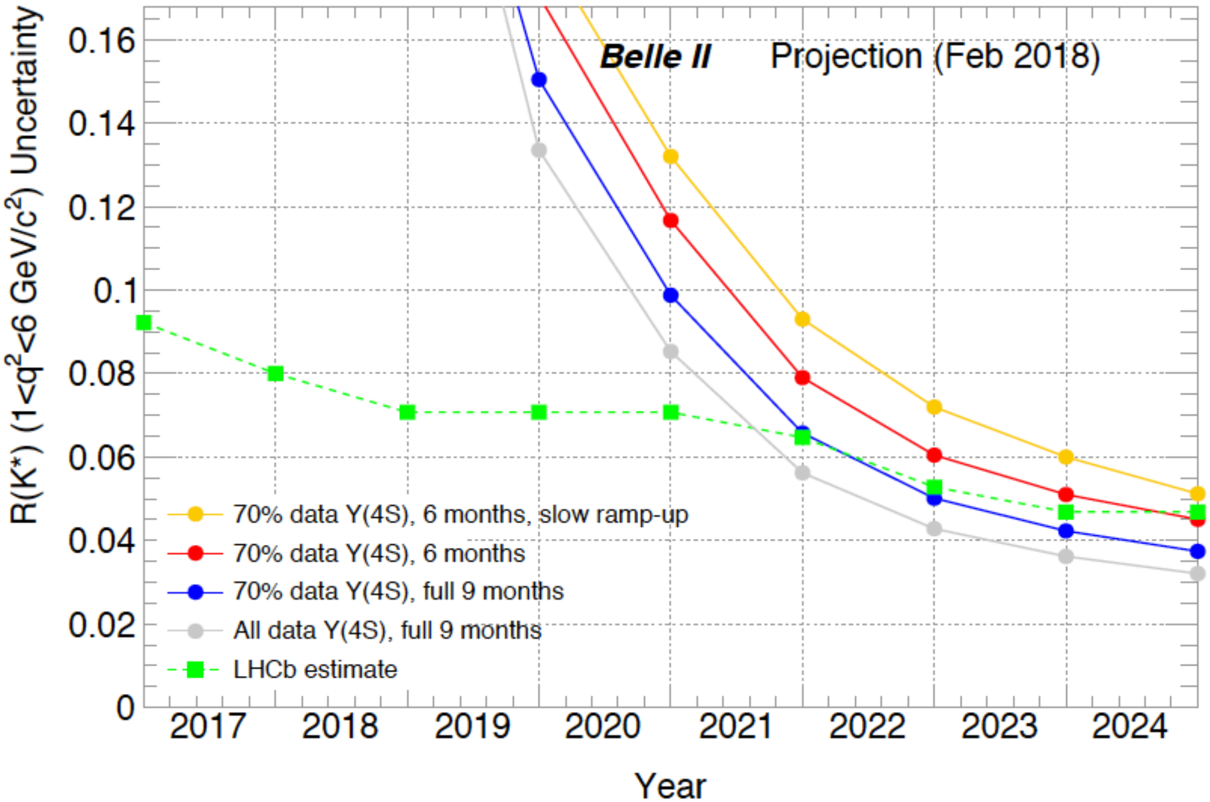
Belle II projection



	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

Main systematics: D** modelling, soft pions, yield of fake D* candidates. **Studies of $B \to D^{**}l\nu$ and $B \to D^{**}\tau\nu$ planned**

$B \to sll$: R(K*)



$$R_K^{(*)} = \frac{\mathfrak{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathfrak{B}(B \to K^{(*)}e^+e^-)}$$

LHCb values based on naive run-1 extrapolation (not official)
Belle II scenarios due to operating conditions at KEK

** Consider it as a sketch to show Belle II can provide confirmation of any persistent anomaly.

Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$Br(B \to X_s \ell^+\ell^-)$ ([1.0, 3.5] GeV^2)	29%	13%	6.6%
$Br(B \to X_s \ell^+\ell^-)$ ([3.5, 6.0] GeV^2)	24%	11%	6.4%
$Br(B \to X_s \ell^+\ell^-)$ ($>$ 14.4 GeV^2)	23%	10%	4.7%

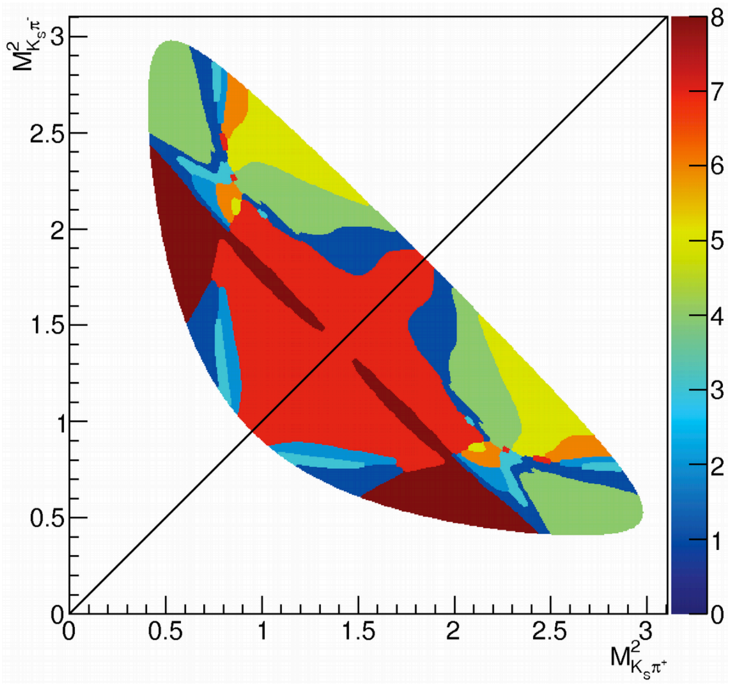
Projections

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.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\mathrm{ex.}} \pm 1.4\%_{\mathrm{th.}})$	1.8%	1.4%
$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\mathrm{ex.}} \pm 2.5\%_{\mathrm{th.}})$	3.4%	3.0%
$\lvert V_{ub}\rvert$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\mathrm{ex.}} \pm 3.0\%_{\mathrm{th.}})$	2.4%	1.2%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	20%	7%
$R(B \to D\tau\nu)$ (Had. tag)	$0.374 \cdot (1 \pm 16.5\%)$	6%	3%
$R(B \to D^*\tau\nu)$ (Had. tag)	$0.296 \cdot (1 \pm 7.4\%)$	3%	2%

Process	Observable	Theory	Sys. dom. (Discovery) $[ab^{-1}]$	vs LHCb	vs Belle	Anomaly	NP
$B \to \pi \ell \nu_\ell$	$\lvert V_{ub}\rvert$	★★★	10-20	★★★	★★★	★★	★
$B \to X_u \ell \nu_\ell$	$\lvert V_{ub}\rvert$	★★	2-10	★★★	★★	★★★	★
$B \to \tau\nu$	$Br.$	★★★	>50 (2)	★★★	★★★	★	★★★
$B \to \mu\nu$	$Br.$	★★★	>50 (5)	★★★	★★★	★	★★★
$B \to D^{(*)} \ell \nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1-10	★★★	★★	★★	★
$B \to X_c \ell \nu_\ell$	$\lvert V_{cb}\rvert$	★★★	1-5	★★★	★★	★★	★★
$B \to D^{(*)} \tau \nu_\tau$	$R(D^{(*)})$	★★★	5-10	★★	★★★	★★★	★★★
$B \to D^{(*)} \tau \nu_\tau$	P_τ	★★★	15-20	★★★	★★★	★★	★★★
$B \to D^{**} \ell \nu_\ell$	$Br.$	★	-	★★	★★★	★★	-

ϕ_3 angle

Dalitz plot of $K_S\pi^+\pi^-$



Combination of measurements