SEMILEPTONIC B DECAYS AT BELLE AND BELLE II

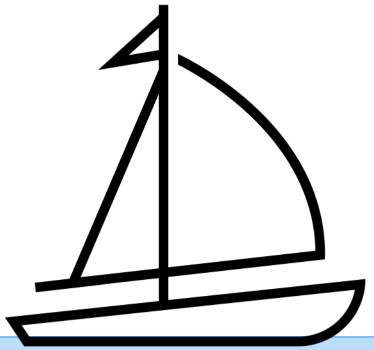
Svenja Granderath (University of Bonn)

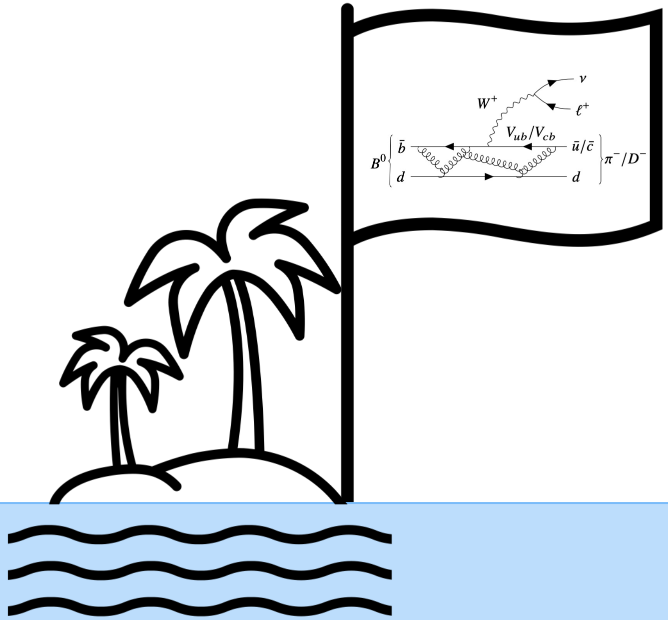
on behalf of the Belle II collaboration

(with material from the Belle collaboration)

Moriond QCD - La Thuile - April 2, 2024

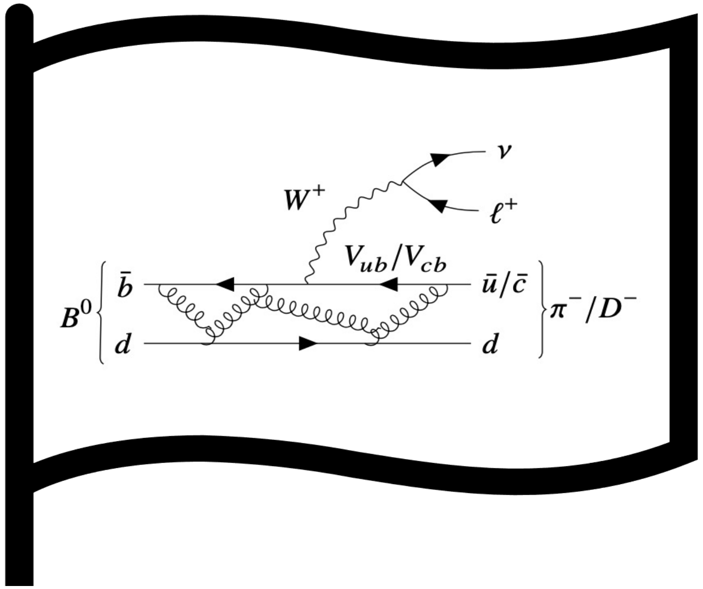
SEMILEPTONIC B DECAYS



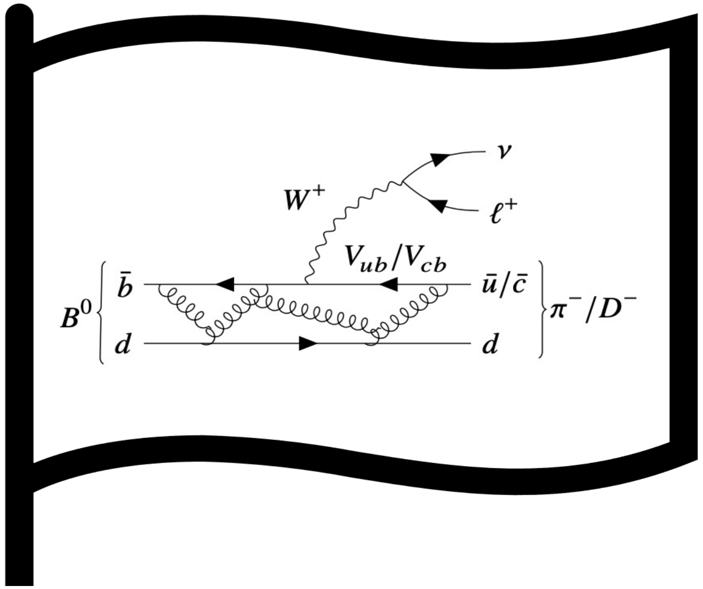


Land of semileptonic B decays

SEMILEPTONIC B DECAYS



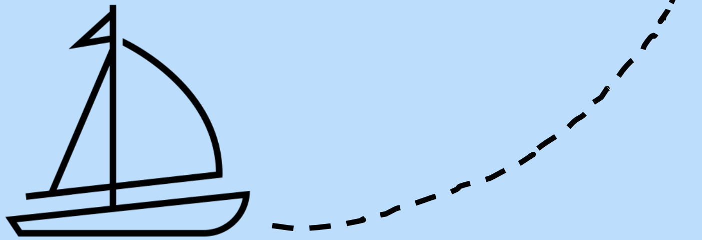
SEMILEPTONIC B DECAYS



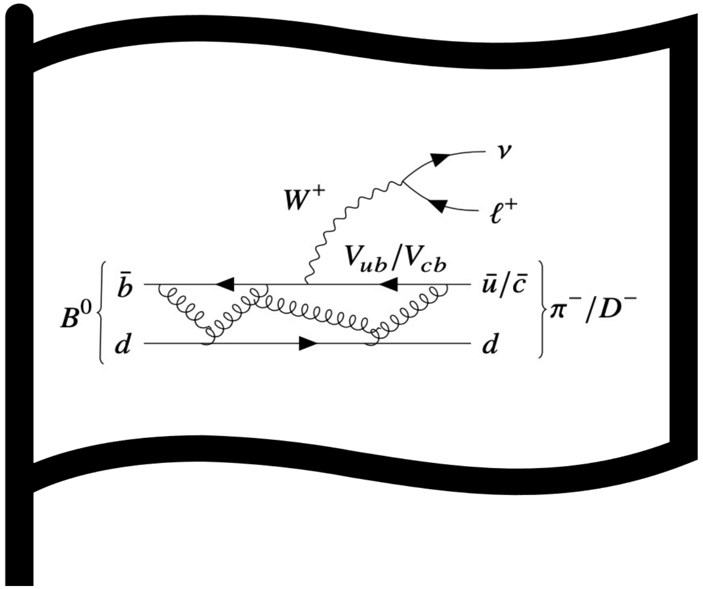
$$\underbrace{\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}}_{\text{CKM Matrix}}$$

Form-factor measurements

SM precision measurements



SEMILEPTONIC B DECAYS



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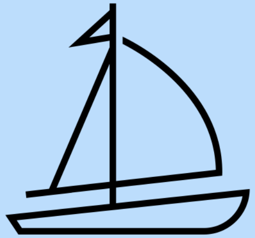
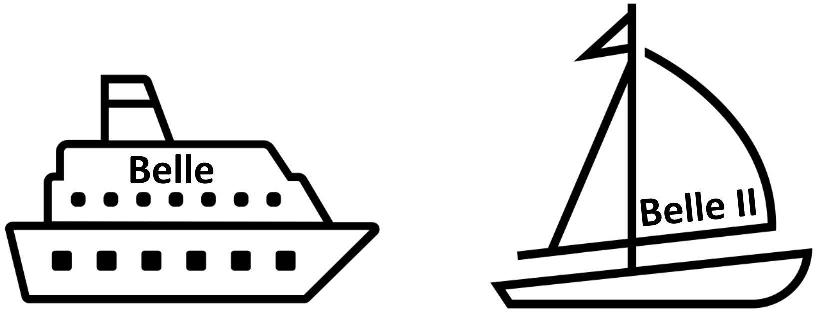


Lepton universality violation (LUV) tests

Angular observables

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

BELLE AND BELLE II

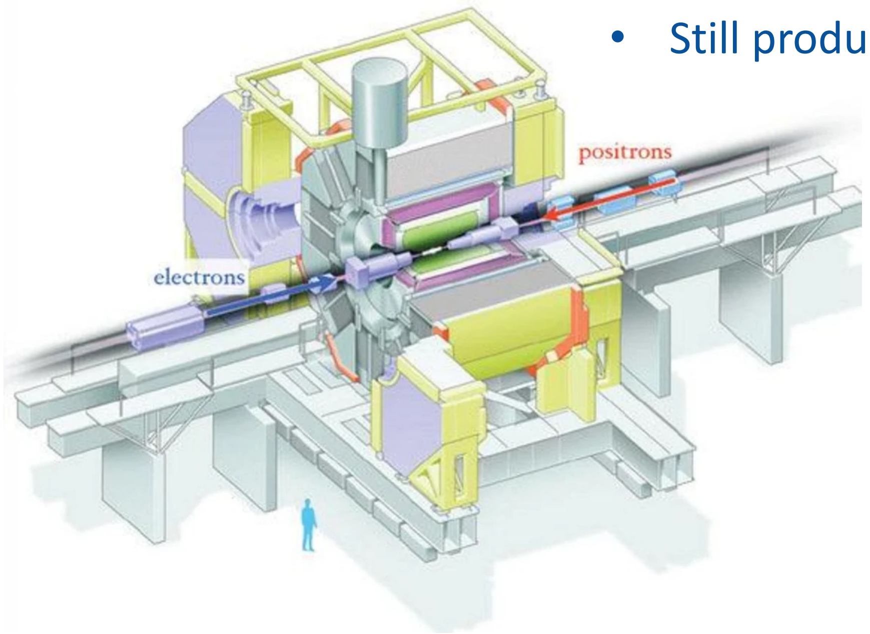


- Detectors located at the interaction points of electron-positron colliders
- Center-of-mass energy corresponding to $\Upsilon(4S)$ resonance

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

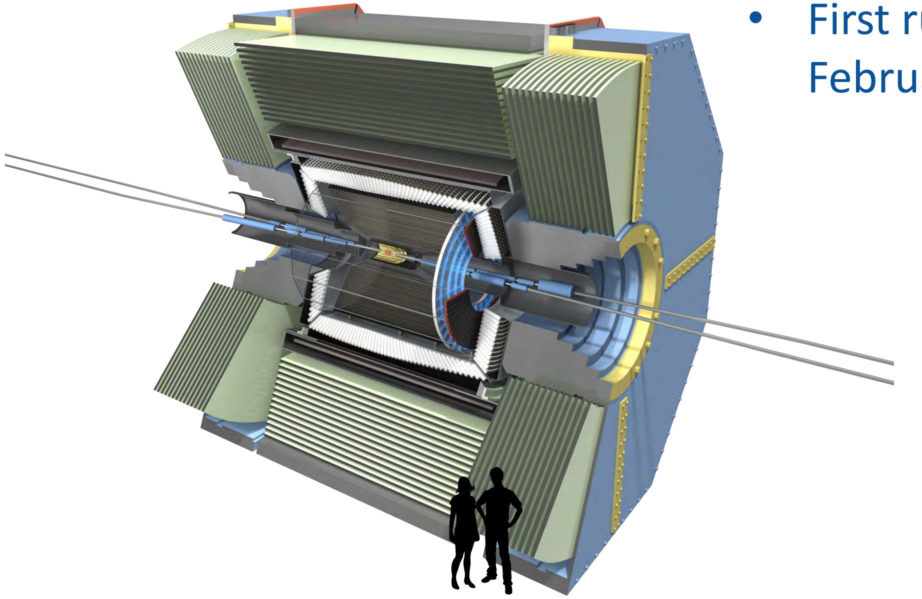
Belle:

- 1999-2010
- $\mathcal{L}_{\text{int}} = 711\text{fb}^{-1}$
- Still produces results



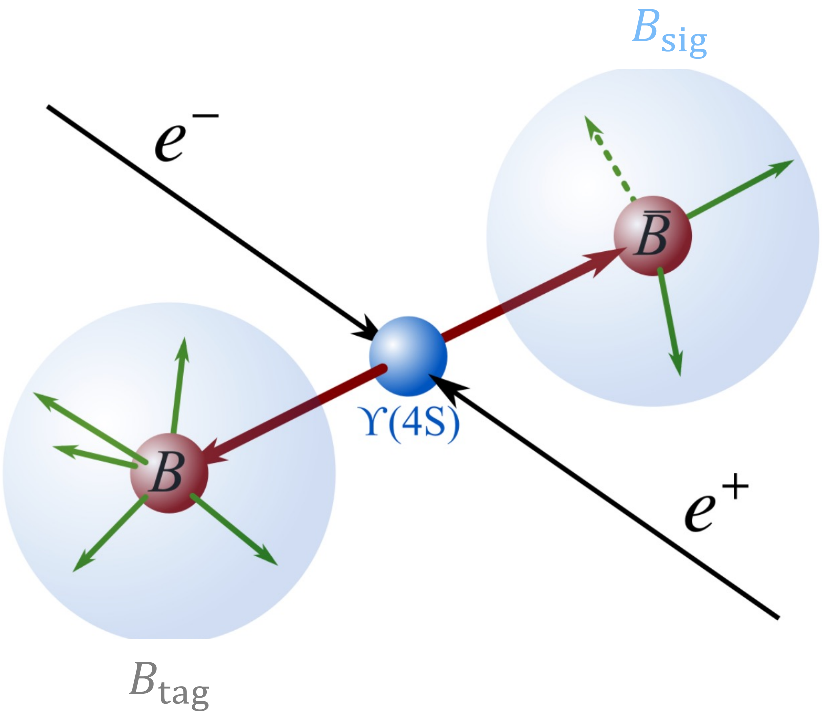
Belle II:

- Operating since 2019
- $\mathcal{L}_{\text{int}} = 364\text{fb}^{-1}$
- First run 2 collisions on February 20th 2024



RECONSTRUCTION

$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B_{\text{sig}} B_{\text{tag}}$$



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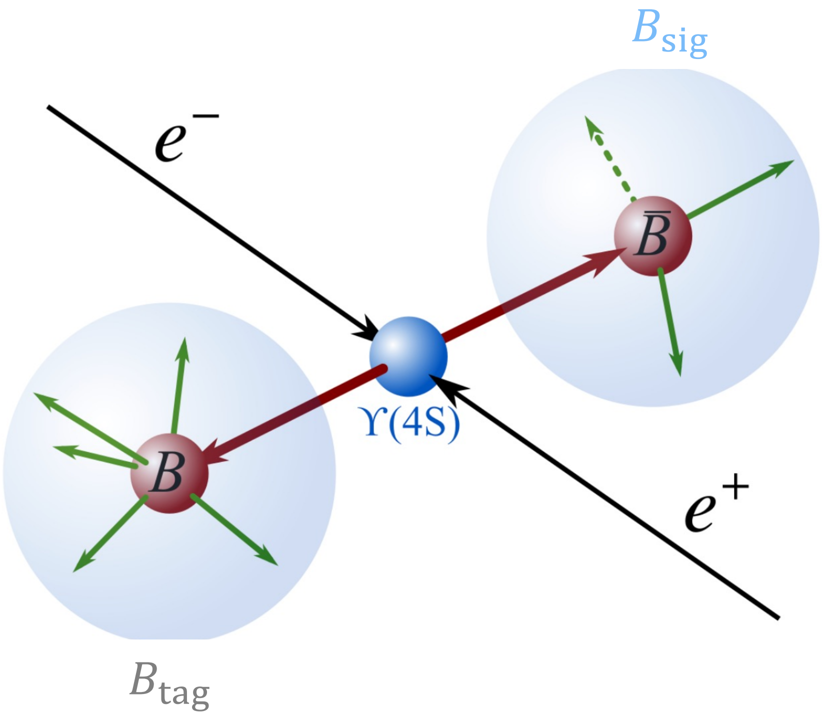

Tagged:

- B_{sig} and B_{tag} reconstructed
- Reconstruct B_{tag} in hadronic or semileptonic modes using multivariate methods

Untagged (inclusive tag):

- Only B_{sig} reconstructed

Low → Efficiency → High

High ← Purity ← Low

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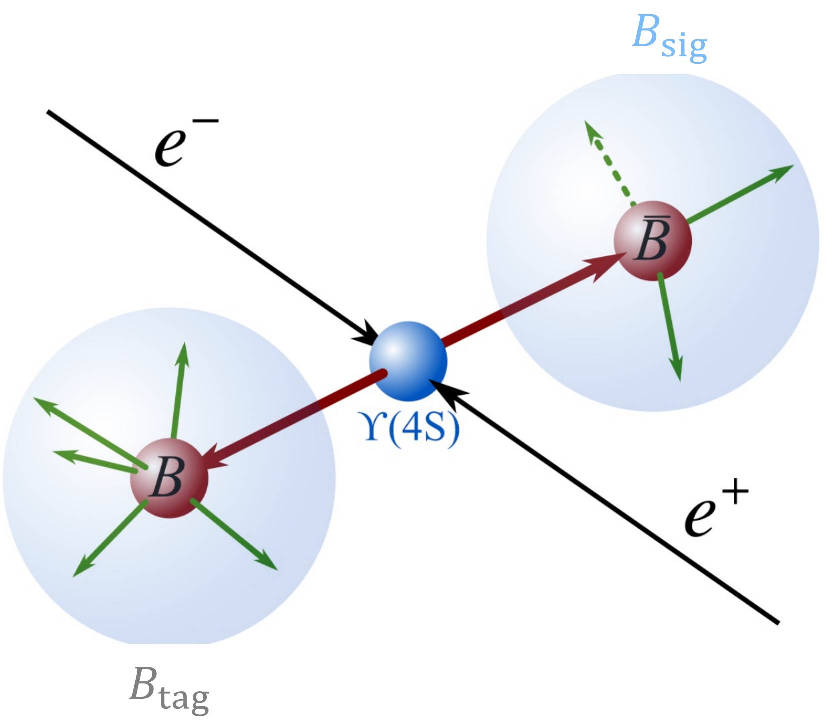

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Low — Efficiency → High

High ← Purity — Low

Exclusive:

- B_{sig} reconstructed as specific final state

Inclusive:

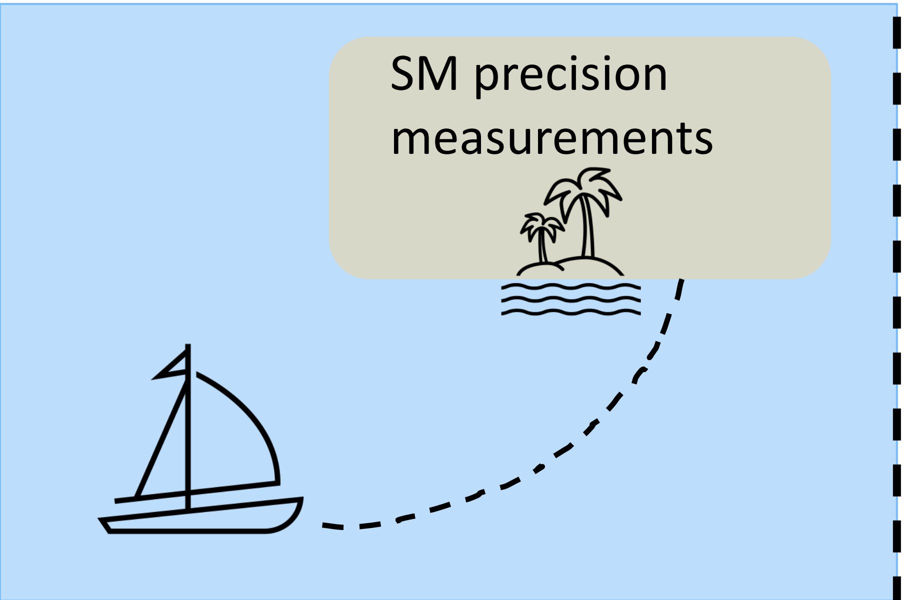
- B_{sig} reconstructed as sum of modes

Approaches are theoretically and experimentally independent

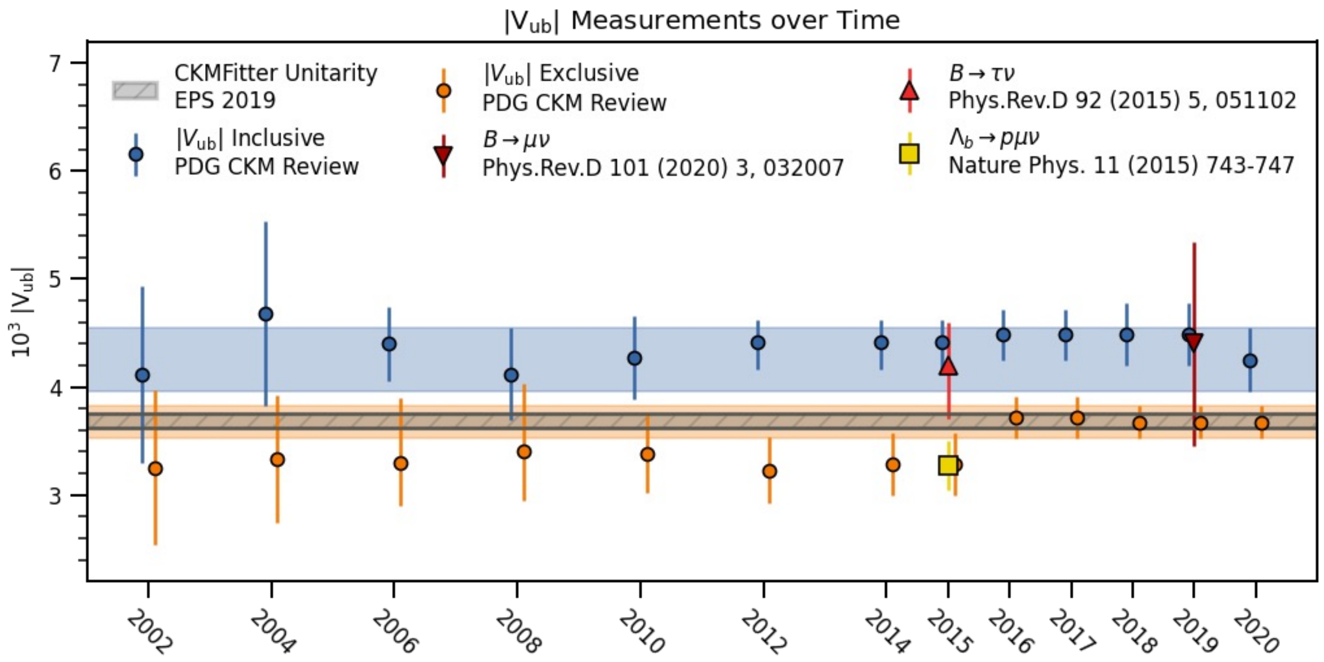
CKM MATRIX ELEMENT MEASUREMENTS

$$\underbrace{\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}}_{\text{CKM Matrix}}$$

Form-factor measurements



- Test SM by over-constraining unitarity triangle
- Important inputs to SM rates of ultra rare decays
- Tension between exclusive and inclusive $|V_{xb}|$ measurements at level of 2-3σ



$|V_{xb}|$ FROM SEMILEPTONIC DECAYS

$$\underbrace{\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}}_{\text{CKM Matrix}}$$

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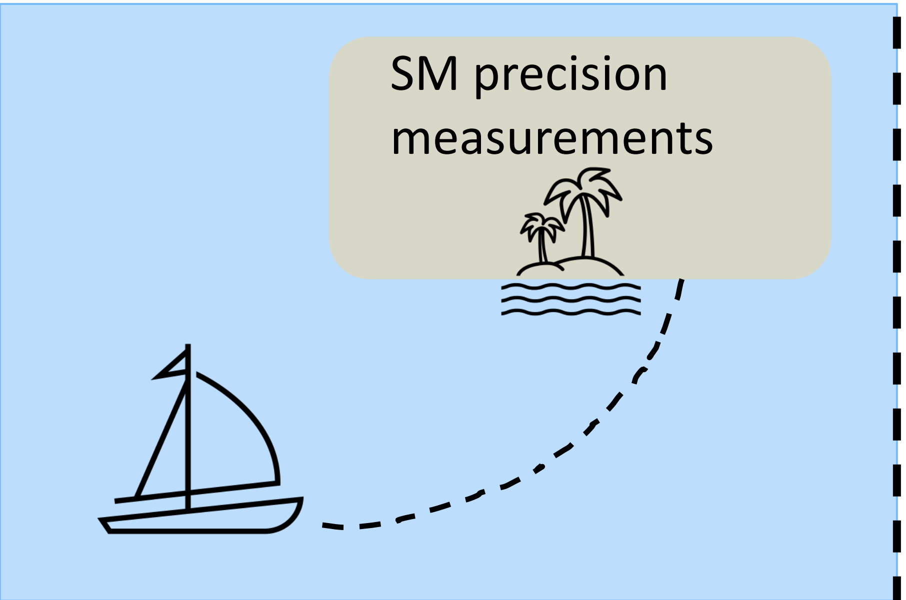

- $B \to Xl\nu$: leptonic and hadronic currents factorize
- Describe kinematics using momentum transfer squared: $\mathrm{q}^2 = (\mathrm{p_B} - \mathrm{p_X})^2$
- Exclusive: $\frac{d\mathcal{B}}{d\mathrm{q}^2} \propto |\mathrm{V_{xb}}|^2 \times |\mathrm{FF}(\mathrm{q}^2)|^2$

Form factors parametrize non-perturbative physics

- Inclusive:

Operator product expansion

$$\mathcal{B} \propto |\mathrm{V_{xb}}|^2 \times \left[\Gamma(b \to q l \bar{\nu}_l) + \frac{1}{m_b} + \alpha_s + \cdots\right]$$

$|V_{xb}|$ FROM SEMILEPTONIC DECAYS

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

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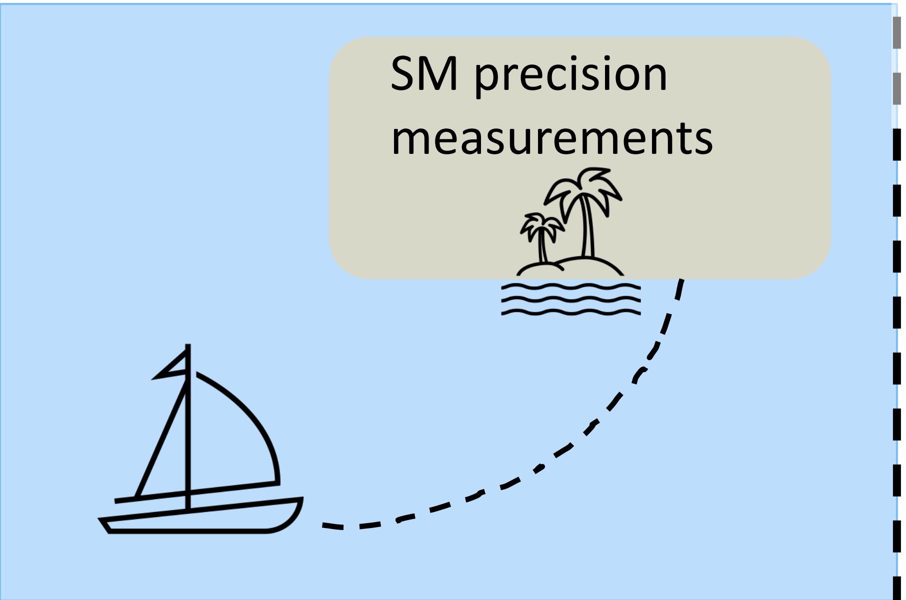
Form-factor measurements



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- Describe kinematics using momentum transfer squared: $q^2 = (p_B - p_X)^2$

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Form factors parametrize non-perturbative physics

- Inclusive:

$$\mathcal{B} \propto |V_{xb}|^2 \times \left[\Gamma(b \to ql\bar{\nu}_l) + \frac{1}{m_b} + \alpha_s + \cdots \right]$$

Operator product expansion

Untagged $B \to \pi/\rho l\nu$ at Belle II — New for Moriond

Tagged simultaneous exclusive and inclusive measurement of $|V_{ub}|$ at Belle

$|V_{ub}|$

Tagged inclusive $B \to Xl\nu$ at Belle

$|V_{ub}|/|V_{cb}|$

To be submitted to PRD

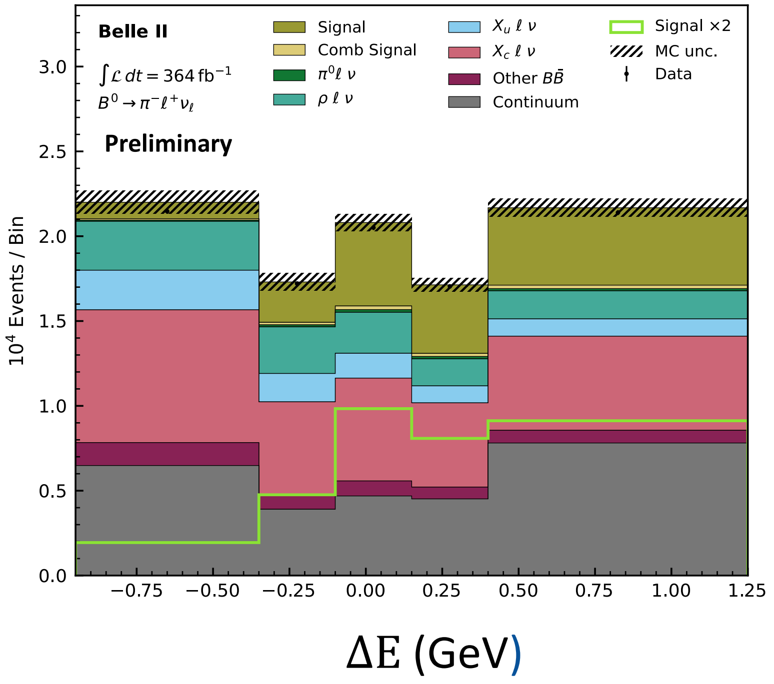
$|V_{ub}|$ FROM $B \to \pi/\rho l\nu$ AT BELLE II

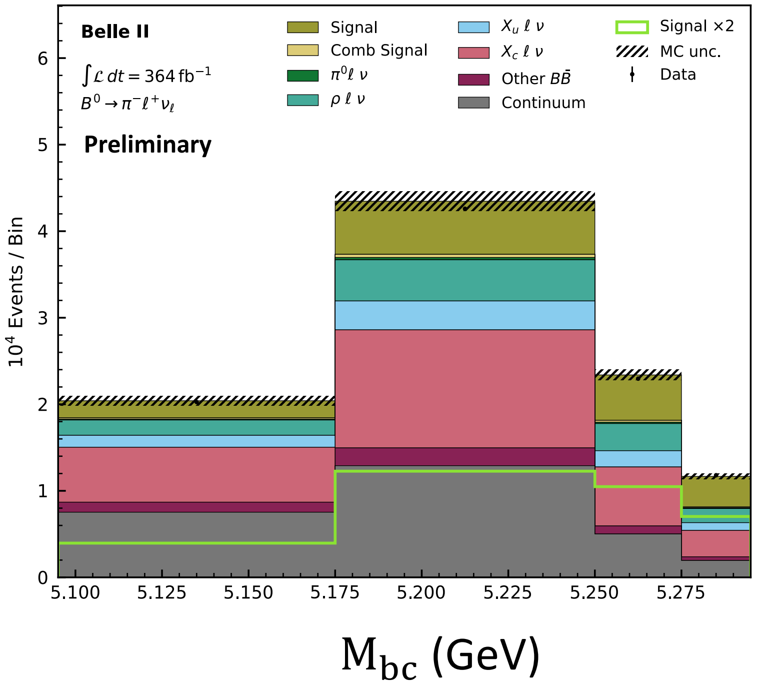
New for Moriond

- Untagged reconstruction of $B^0 \to \pi^+ l^- \bar{\nu}_l$ and $B^- \to \rho^0 l^- \bar{\nu}_l$
- New idea: simultaneously extract signal yields in 13(10) bins of *true* q^2 → Implicit unfolding
- Main challenge: modes suffer from large $B \to X_c l\nu$ and continuum backgrounds
  - Suppressed using BDTs
- Use discriminating variables:

$$\Delta E = E_B - E_{beam}$$

$$M_{bc} = \sqrt{E_{beam}^2 - |\vec{p}_B|^2}$$



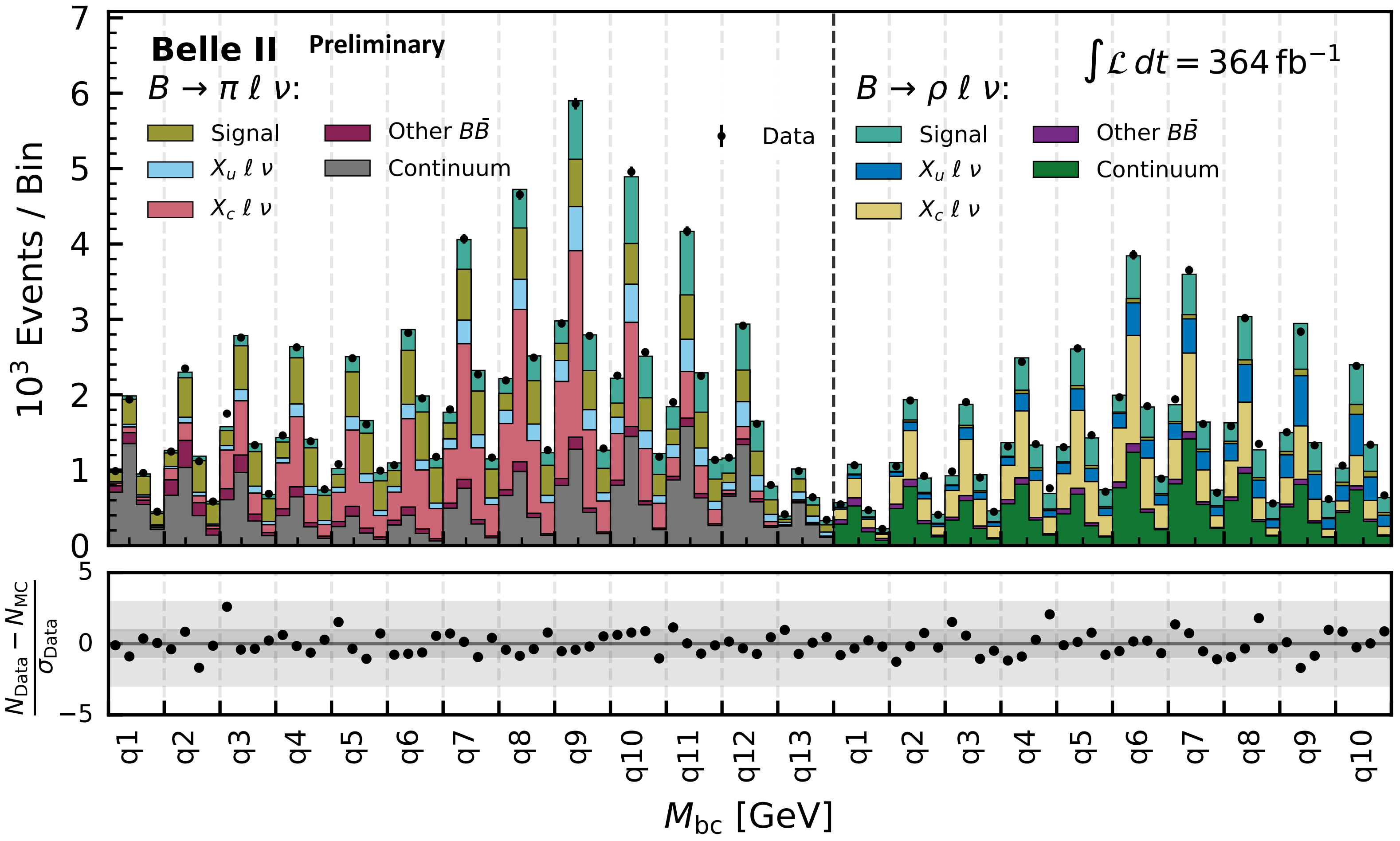


To be submitted to PRD

New for Moriond

$|V_{ub}|$ FROM $B \to \pi/\rho l \nu$ AT BELLE II

- Perform 3D fits to reconstructed q^2, ΔE and M_{bc}
  - Link yields of cross-feed signal components



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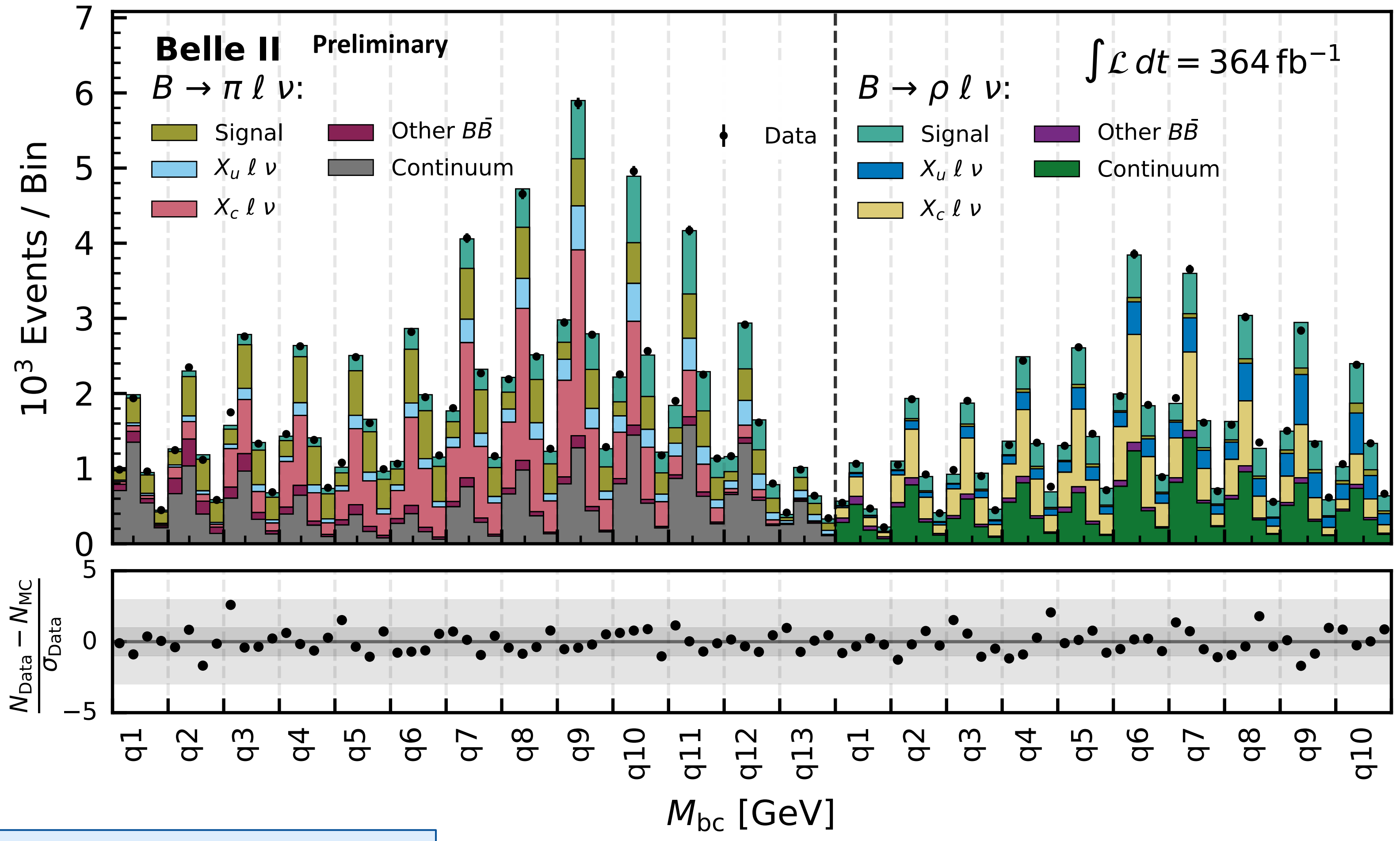
- Perform 3D fits to reconstructed q^2, ΔE and M_{bc}
  - Link yields of cross-feed signal components
- Convert to partial branching fractions $\Delta\mathcal{B}_i$ using reconstruction efficiencies
- Determine total branching fractions:



$$\mathcal{B}(B^0 \to \pi^+ l^- \bar{\nu}_l) = (1.516 \pm 0.042_{stat} \pm 0.059_{syst}) \times 10^{-4}$$
$$\mathcal{B}(B^- \to \rho^0 l^- \bar{\nu}_l) = (1.625 \pm 0.079_{stat} \pm 0.180_{syst}) \times 10^{-4}$$

- In agreement with world averages
- Largest systematic: continuum modelling

To be submitted to PRD

$|V_{ub}|$ FROM $B \to \pi/\rho l\nu$ AT BELLE II

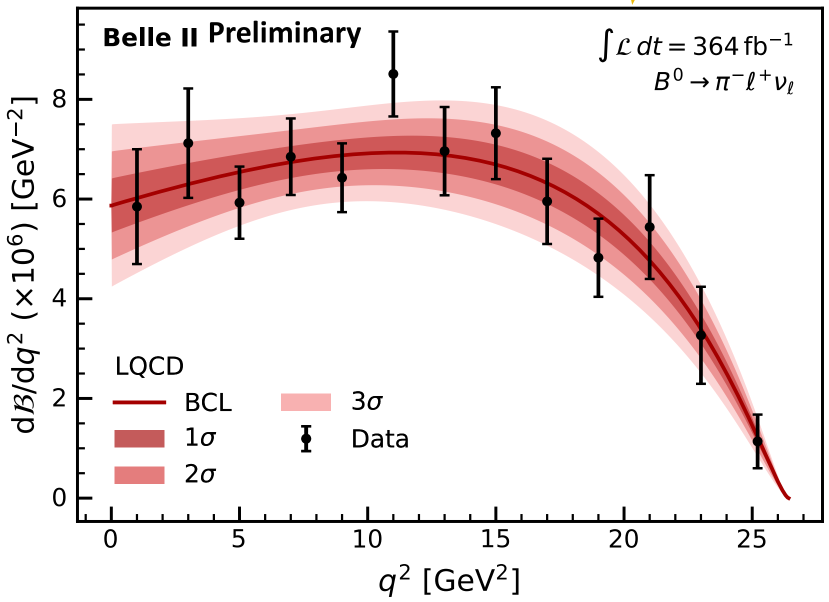
New for Moriond

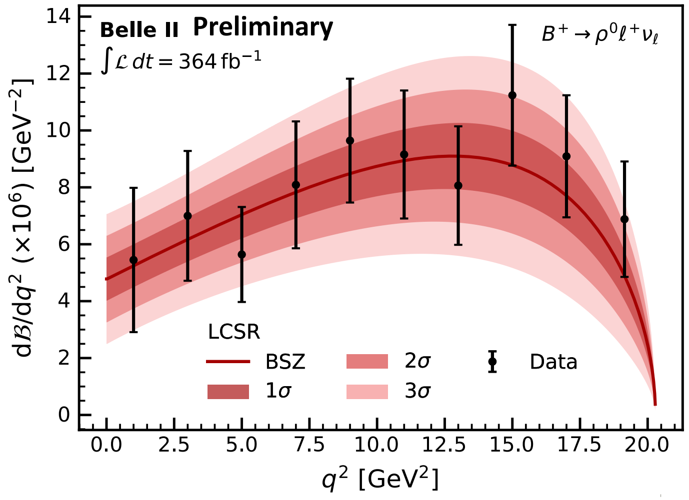
Determine $|V_{ub}|$ by minimising χ^2:

$$\chi^2 = \sum_{i,j}^{N} (\Delta B_i - \Delta\Gamma_i \tau) C_{ij}^{-1} (\Delta B_j - \Delta\Gamma_j \tau) + \chi^2_{\text{Theory}}$$

- Experimental observation
- Experimental covariance
- Theoretical prediction

	$B^0 \to \pi^+ l^- \bar{\nu}_l$	$B^- \to \rho^0 l^- \bar{\nu}_l$
Form factor param.	Bourrely-Caprini-Lellouch (BCL) Phys. Rev. D **82**, 099902	Bharucha-Straub-Zwicky (BSZ) JHEP (2016) 98
Theory prediction	LQCD Eur. Phys. J. C **82** (2022) 869	LCSR JHEP (2016) 98
	LQCD + LCSR JHEP (2021) 36	





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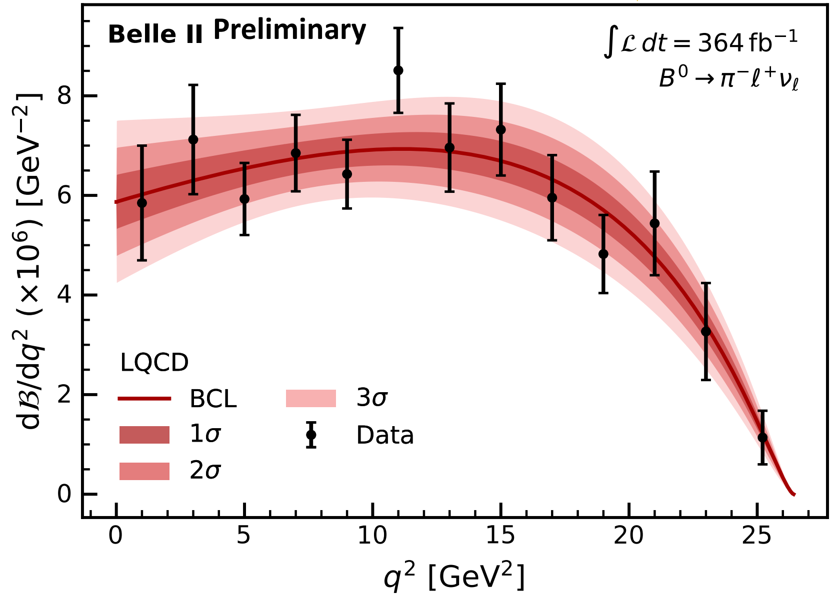
$B^0 \to \pi^+ l^- \bar{\nu}_l$:

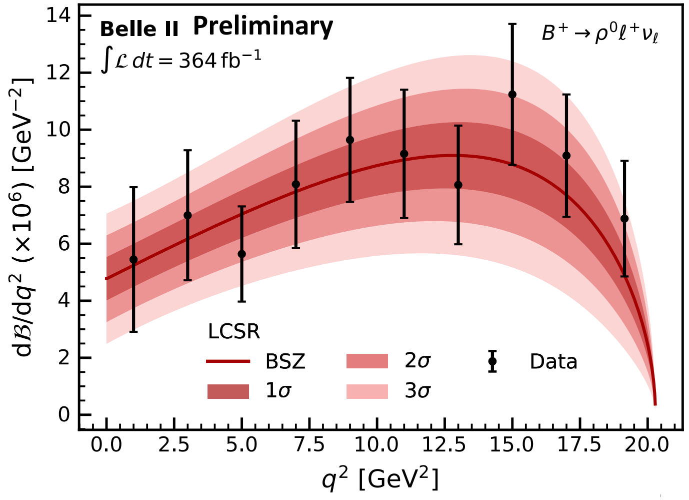
$$|V_{ub}|_{\text{LQCD}} = (3.93 \pm 0.09_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.19_{\text{theo}}) \times 10^{-3}$$
$$|V_{ub}|_{\text{+LCSR}} = (3.73 \pm 0.07_{\text{stat}} \pm 0.07_{\text{syst}} \pm 0.16_{\text{theo}}) \times 10^{-3}$$

$B^- \to \rho^0 l^- \bar{\nu}_l$:

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

- In agreement with exclusive world-average
- Shifts exclusive toward inclusive average





Phys. Rev. Lett. **131**, 211801

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TAGGED SIMULTANEOUS EXCL. AND INCL. $|V_{ub}|$ AT BELLE

- Tagged inclusive reconstruction of $B \to X_u l\nu$
- New idea: bin events by number of charged pions:
  - $N_{\pi^+} = 0$ → $B \to \pi^0 l\nu$
  - $N_{\pi^+} = 1$ → $B \to \pi^+ l\nu$
  - $N_{\pi^+} = 2$
  - $N_{\pi^+} \geq 3$

other $B \to X_u l\nu$

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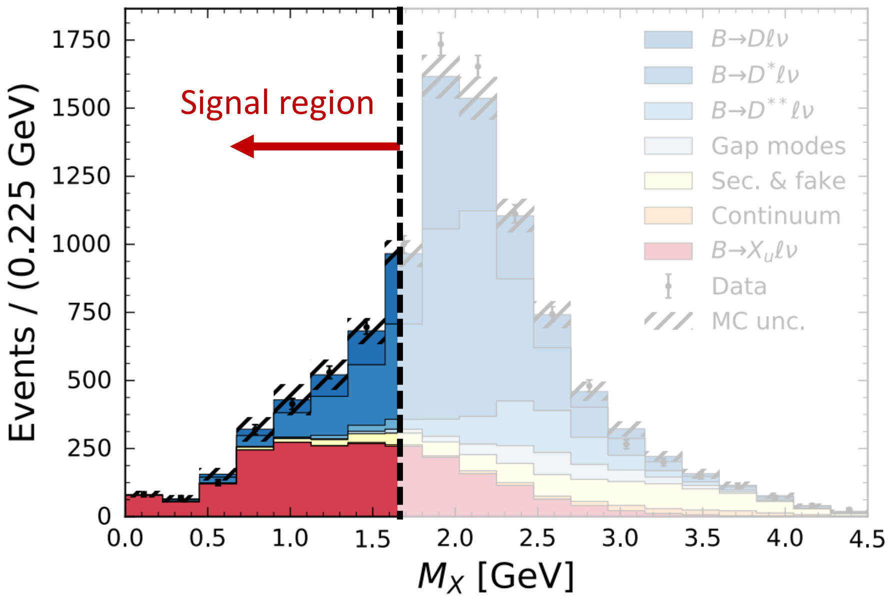

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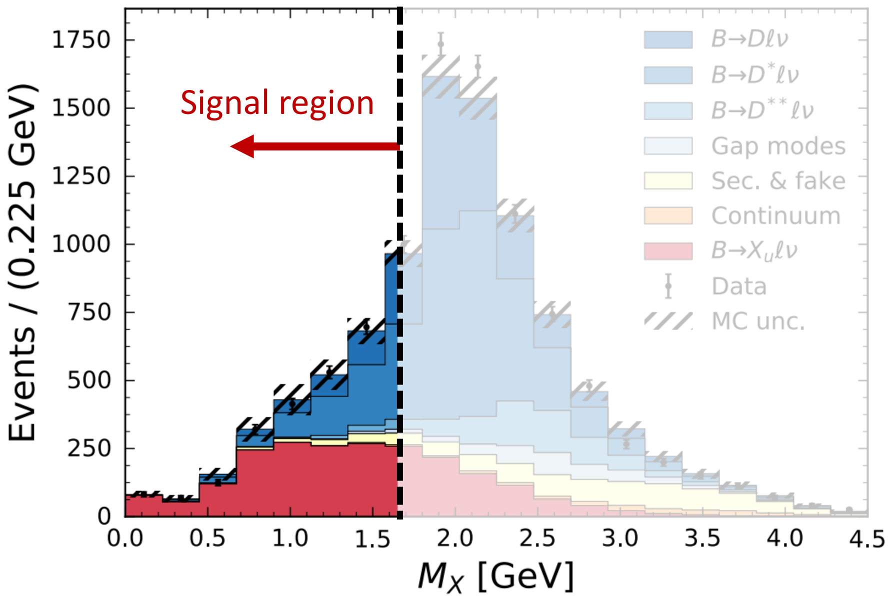
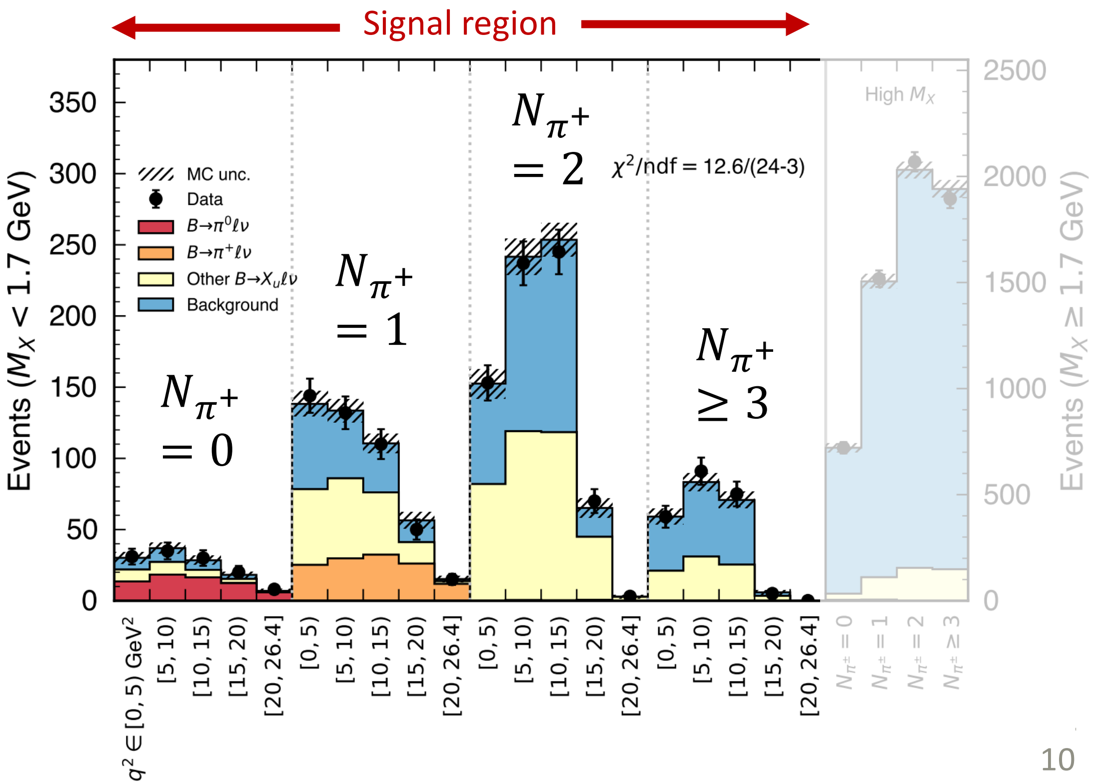
- Signal region selected in hadronic mass: M_X
- Extract signal yields in 2D fit of q^2 and N_{π^+}





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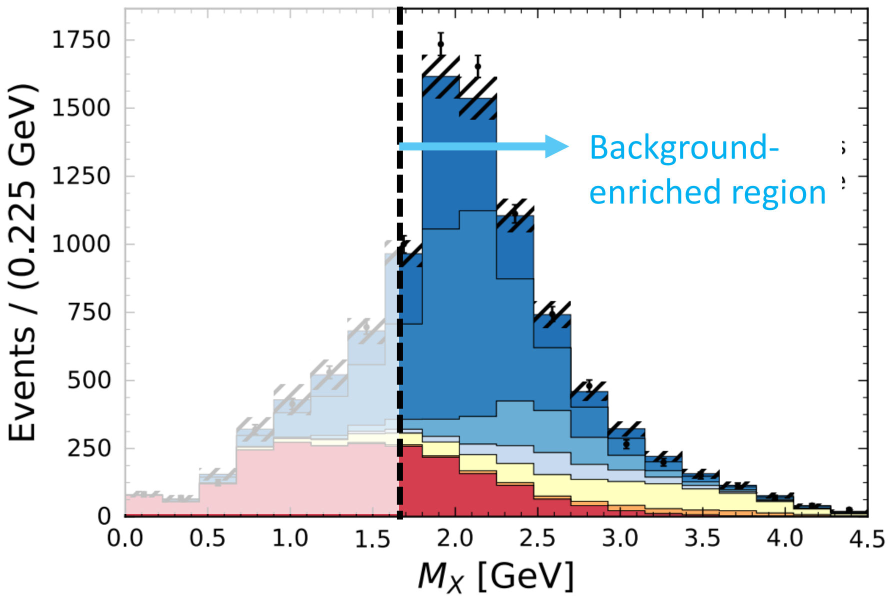
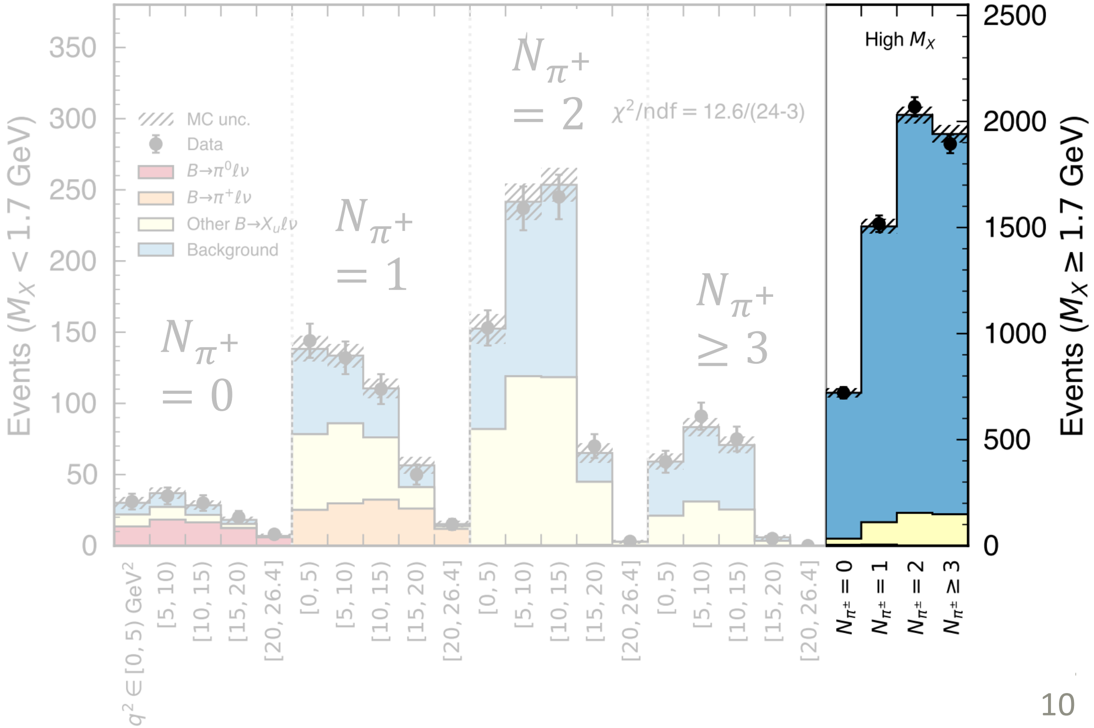


Use high M_X region to constrain background

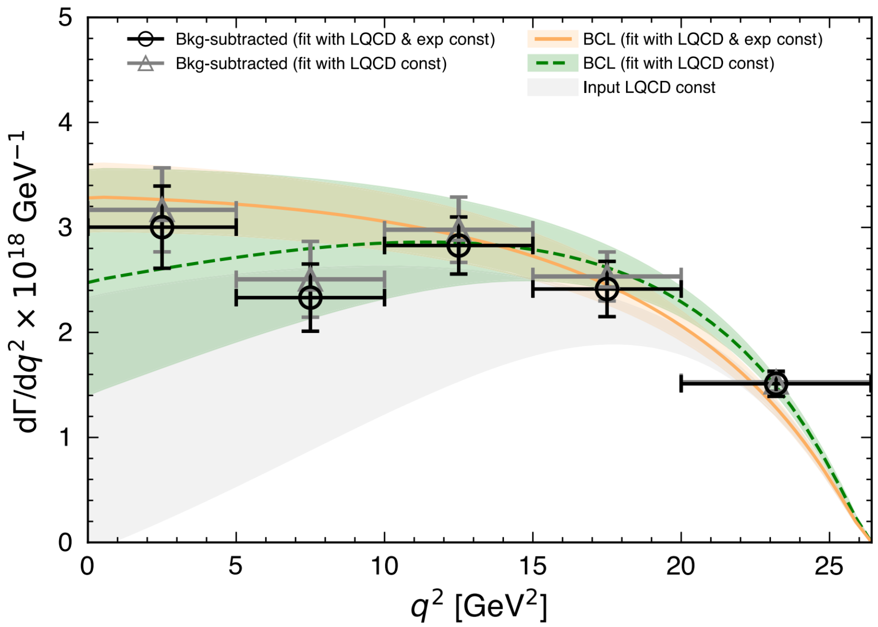
Background-enriched region



TAGGED SIMULTANEOUS EXCL. AND INCL. $|V_{ub}|$ AT BELLE

Exclusive $|V_{ub}|$:

- Fit BCL $B \to \pi l \nu$ FF parameters with two constraining options:
  - LQCD Eur. Phys. J. C **82** (2022) 869
  - LQCD + experimental information



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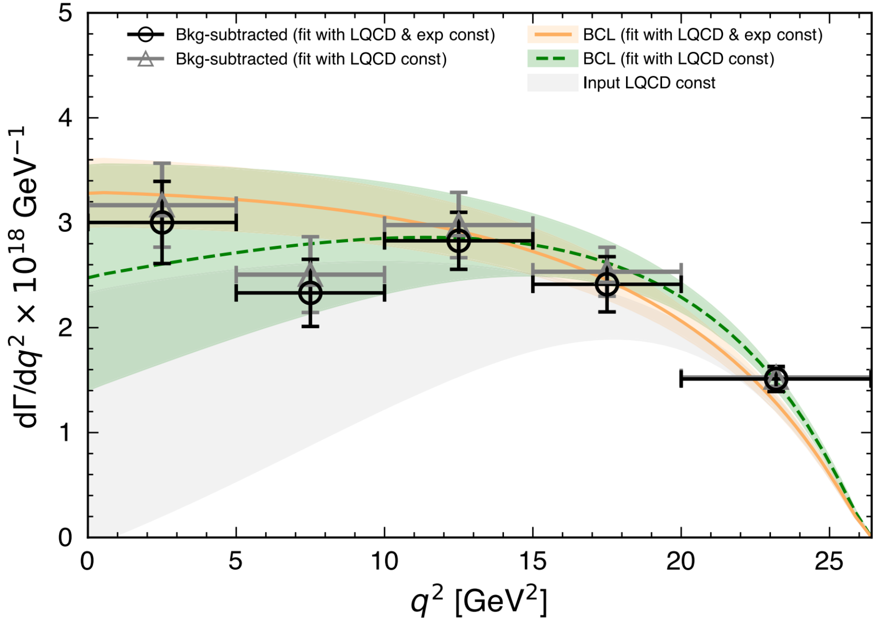

Inclusive $|V_{ub}|$:

- Use theoretical prediction of inclusive partial rate JHEP 10 (2007) 58

$$|V_{ub}^{excl}| = (3.78 \pm 0.23_{stat} \pm 0.16_{syst} \pm 0.14_{theo}) \times 10^{-3}$$
$$|V_{ub}^{incl}| = (3.88 \pm 0.20_{stat} \pm 0.31_{syst} \pm 0.09_{theo}) \times 10^{-3}$$

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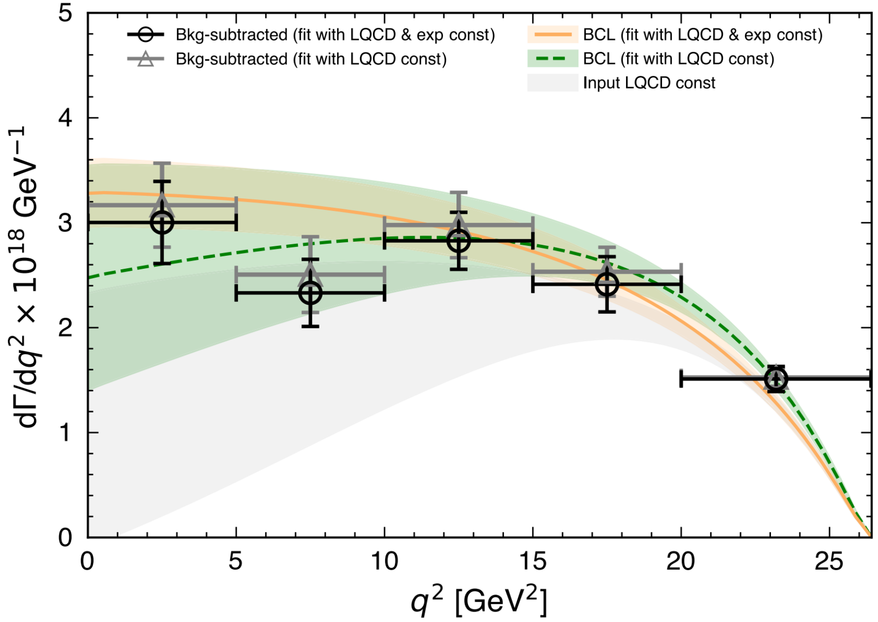

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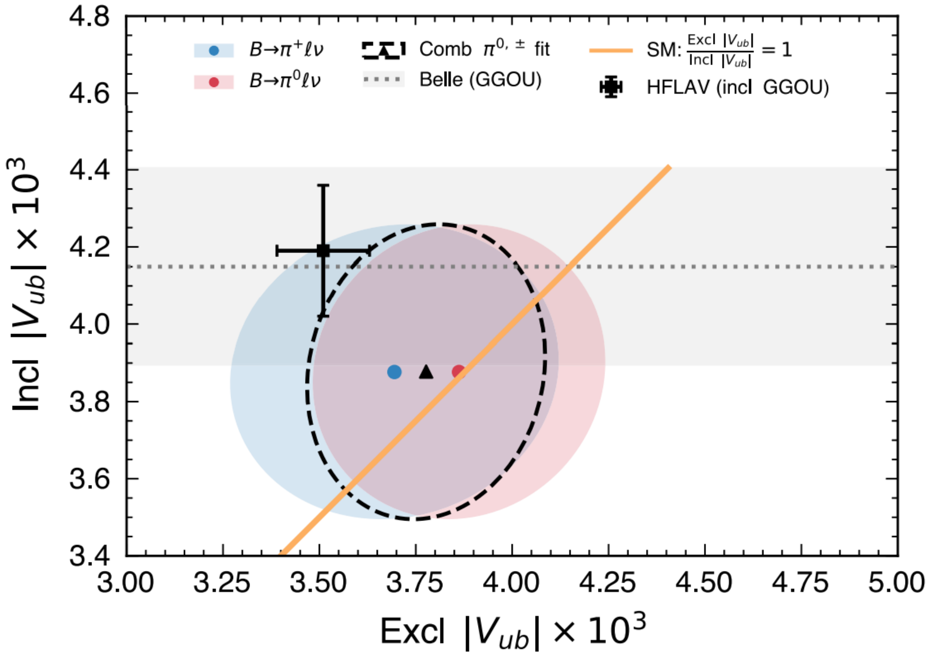
$$|V_{ub}^{excl}| / |V_{ub}^{incl}| = 0.97 \pm 0.12_{tot}$$

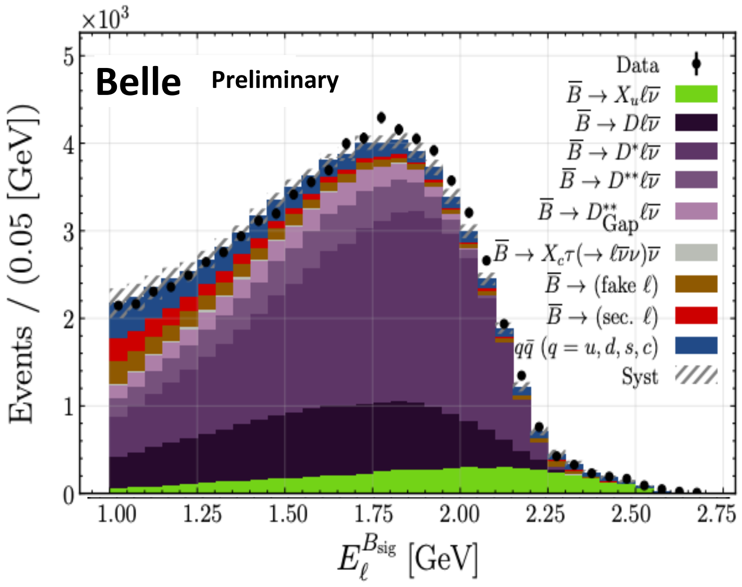
Agrees with expectation of 1 and within 1.2σ with the world-average

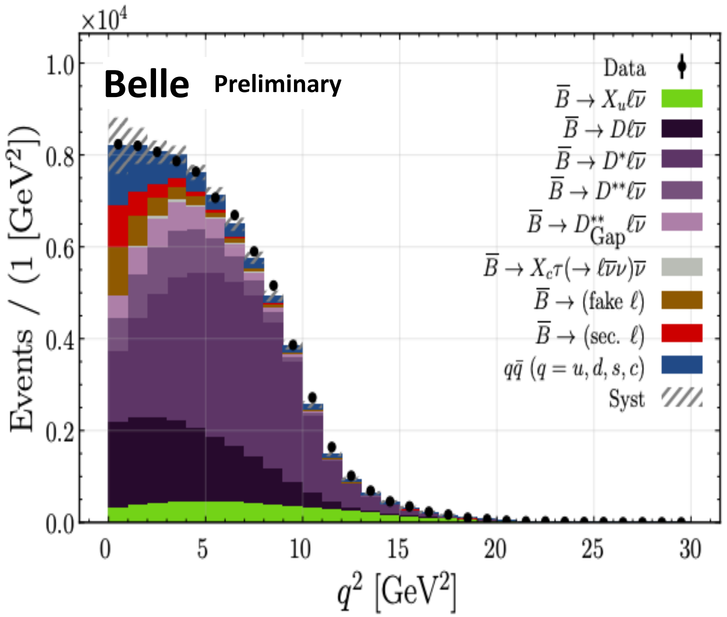


arxiv:2311.00458

RATIO OF $|V_{ub}|/|V_{cb}|$ AT BELLE

- Inclusive reconstruction of $B \to Xl\nu$ using the Belle II hadronic tagging algorithm
- Main challenge: modelling of inclusive background
- Extraction:
  - $B \to X_u l\nu$ yield from 2D fit to lepton energy E_l^B and q^2





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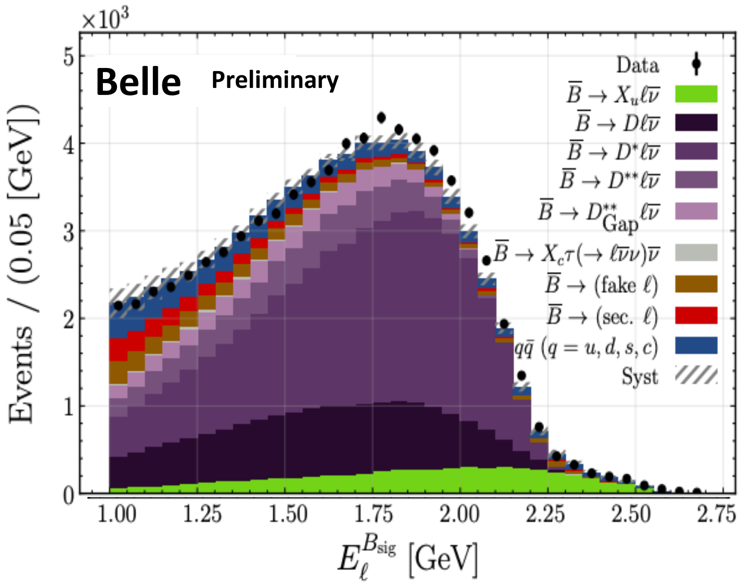
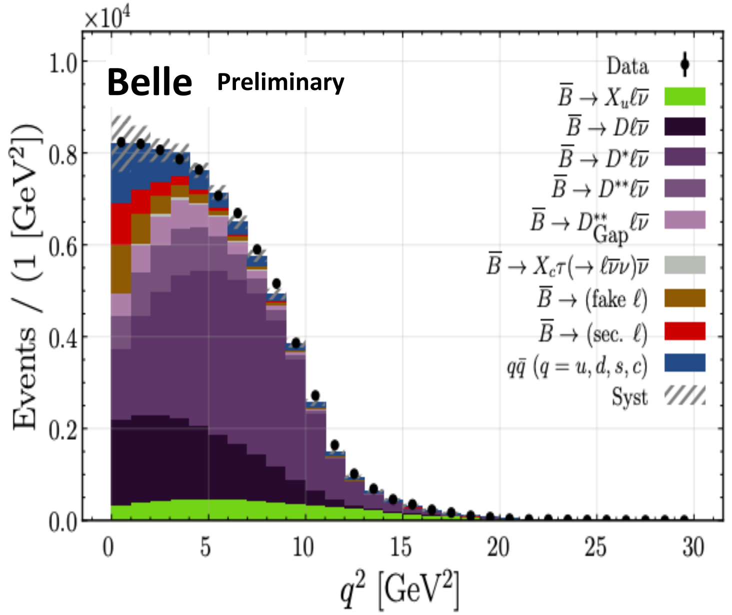
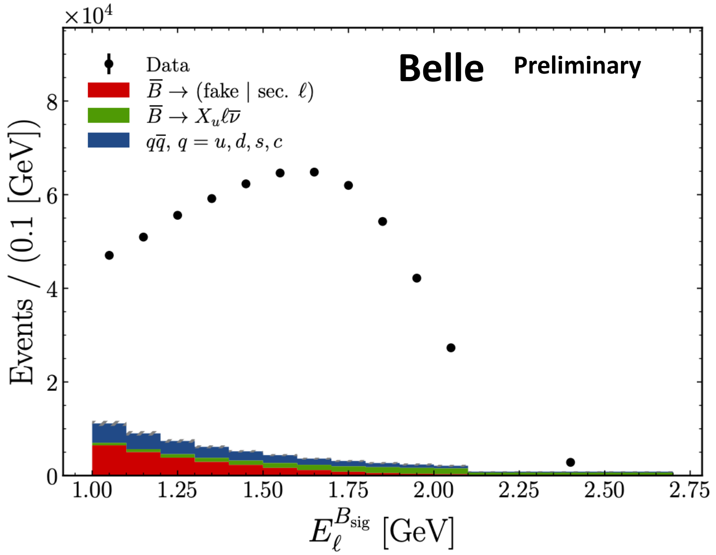
- Extraction:
  - $B \to X_u l\nu$ yield from 2D fit to lepton energy E_l^B and q^2
  - $B \to X_c l\nu$ yield via background subtraction in E_l^B
- Obtain (for $E_l^B > 1.0$ GeV):

$$\frac{\Delta\mathcal{B}(B \to X_u l\nu)}{\Delta\mathcal{B}(B \to X_c l\nu)} = 1.96(1 \pm 8.4\%_{\text{stat}} \pm 7.9\%_{\text{syst}})\times 10^{-2}$$







UNIVERSITÄT BONN

RATIO OF $|V_{ub}|/|V_{cb}|$ AT BELLE

– Obtain $|V_{ub}|/|V_{cb}|$ using theory input for partial rates

$$\frac{|V_{ub}|}{|V_{cb}|} = \sqrt{\frac{\Delta\mathcal{B}(B \to X_u l\nu)}{\Delta\mathcal{B}(B \to X_c l\nu)} \frac{\Delta\Gamma(B \to X_c l\nu)}{\Delta\Gamma(B \to X_u l\nu)}}$$

KIN Eur. Phys. J. C **81**, 226

BLNP Phys. Rev. D **72**, 073006

GGOU JHEP 10 (2007) 58

$$\frac{|V_{ub}|}{|V_{cb}|}^{\mathrm{BLNP}} = 0.0972(1 \pm 4.2\%_{\mathrm{stat}} \pm 3.9\%_{\mathrm{syst}} \pm 5.6\%_{\mathrm{theo}})$$

$$\frac{|V_{ub}|}{|V_{cb}|}^{\mathrm{GGOU}} = 0.0996(1 \pm 4.2\%_{\mathrm{stat}} \pm 3.9\%_{\mathrm{syst}} \pm 3.0\%_{\mathrm{theo}})$$

- In agreement with world averages of inclusive results

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→ KIN Eur. Phys. J. C **81**, 226

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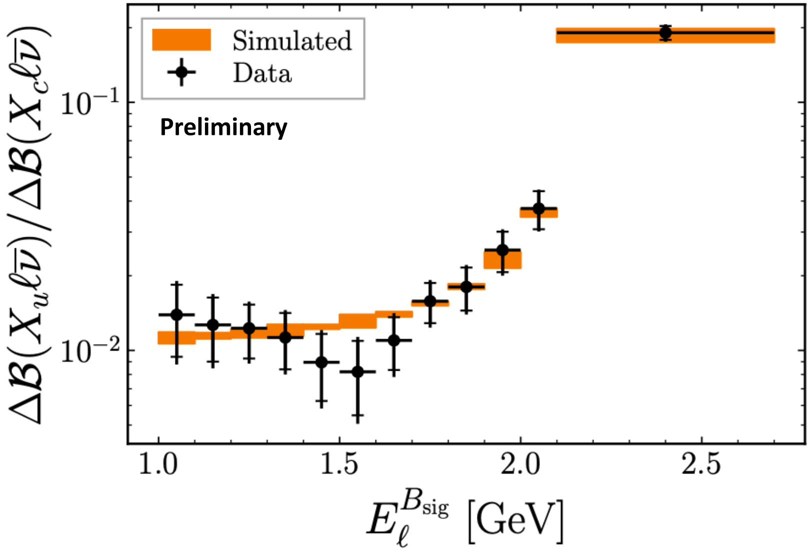
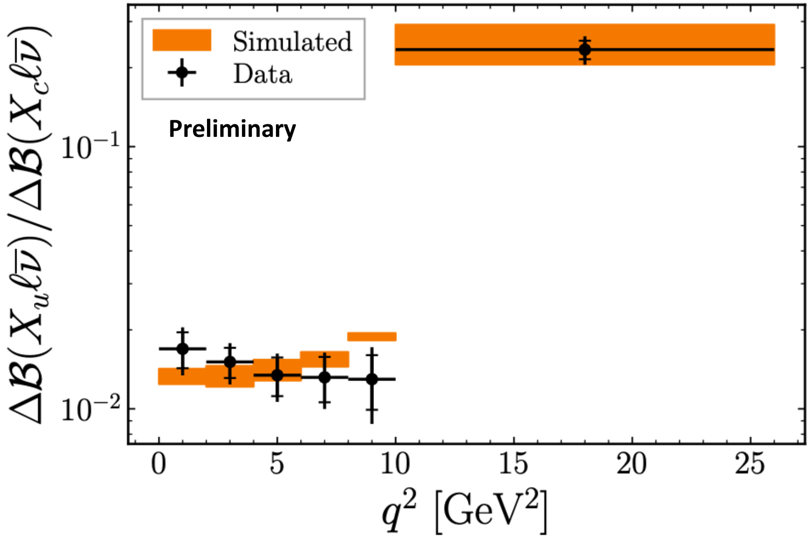
$$\frac{|V_{ub}|}{|V_{cb}|}^{\mathrm{BLNP}} = 0.0972(1 \pm 4.2\%_{\mathrm{stat}} \pm 3.9\%_{\mathrm{syst}} \pm 5.6\%_{\mathrm{theo}})$$

$$\frac{|V_{ub}|}{|V_{cb}|}^{\mathrm{GGOU}} = 0.0996(1 \pm 4.2\%_{\mathrm{stat}} \pm 3.9\%_{\mathrm{syst}} \pm 3.0\%_{\mathrm{theo}})$$

- In agreement with world averages of inclusive results

- Additionally provides differential ratios:
  - After unfolding $B \to X_u l\nu$ and $B \to X_c l\nu$ yields and correcting for efficiencies

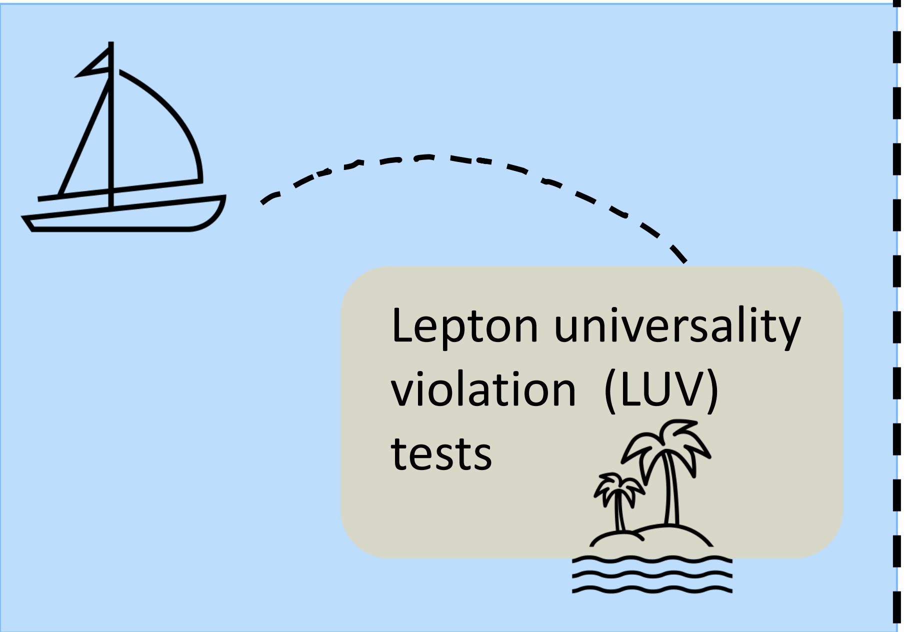




LEPTON UNIVERSALITY VIOLATION (LUV)

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

Angular observables



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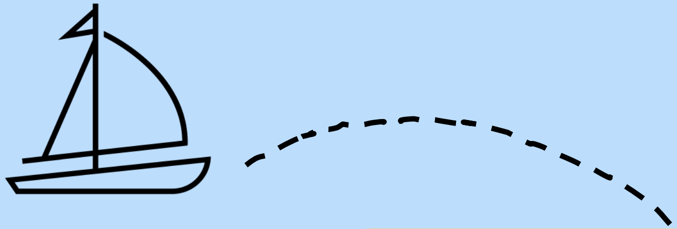
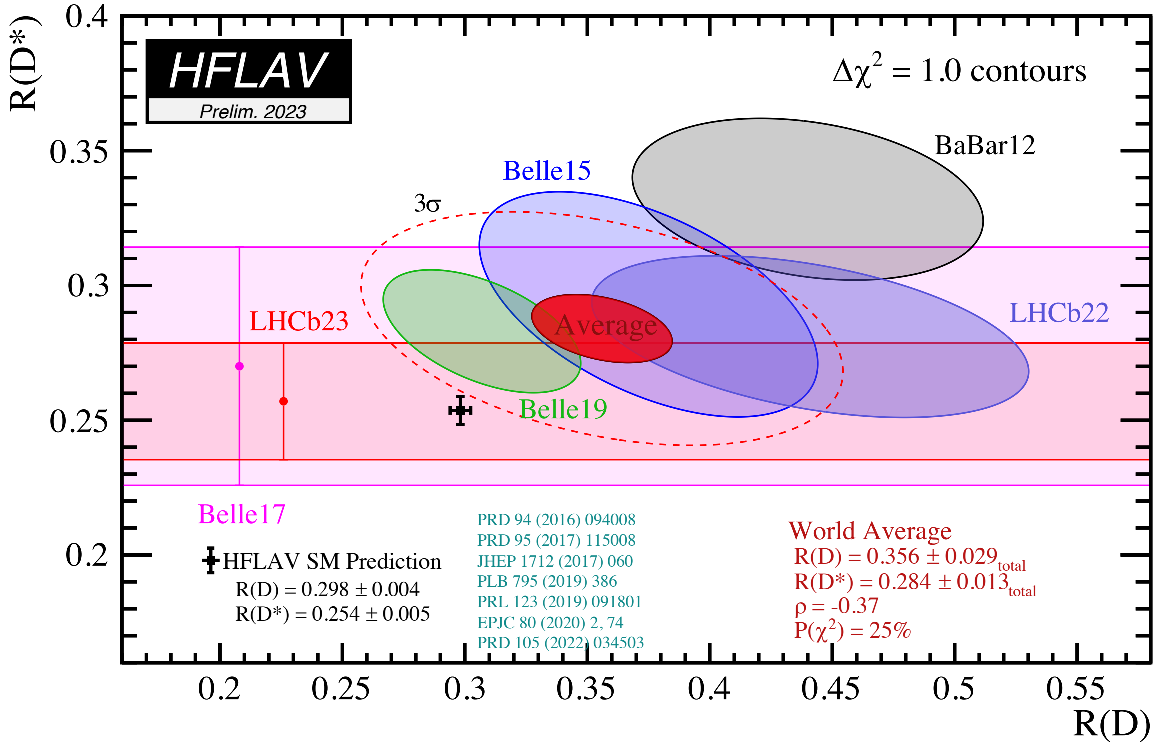


Lepton universality violation (LUV) tests

Tension with SM at ≈ 3σ

arXiv:2206.07501



LEPTON UNIVERSALITY VIOLATION (LUV)

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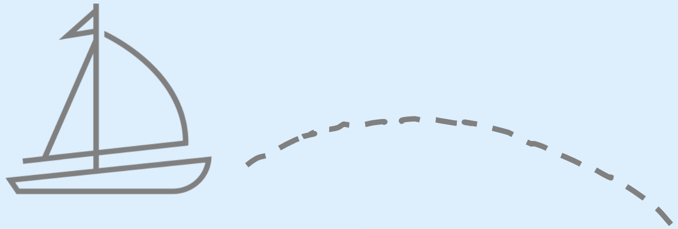

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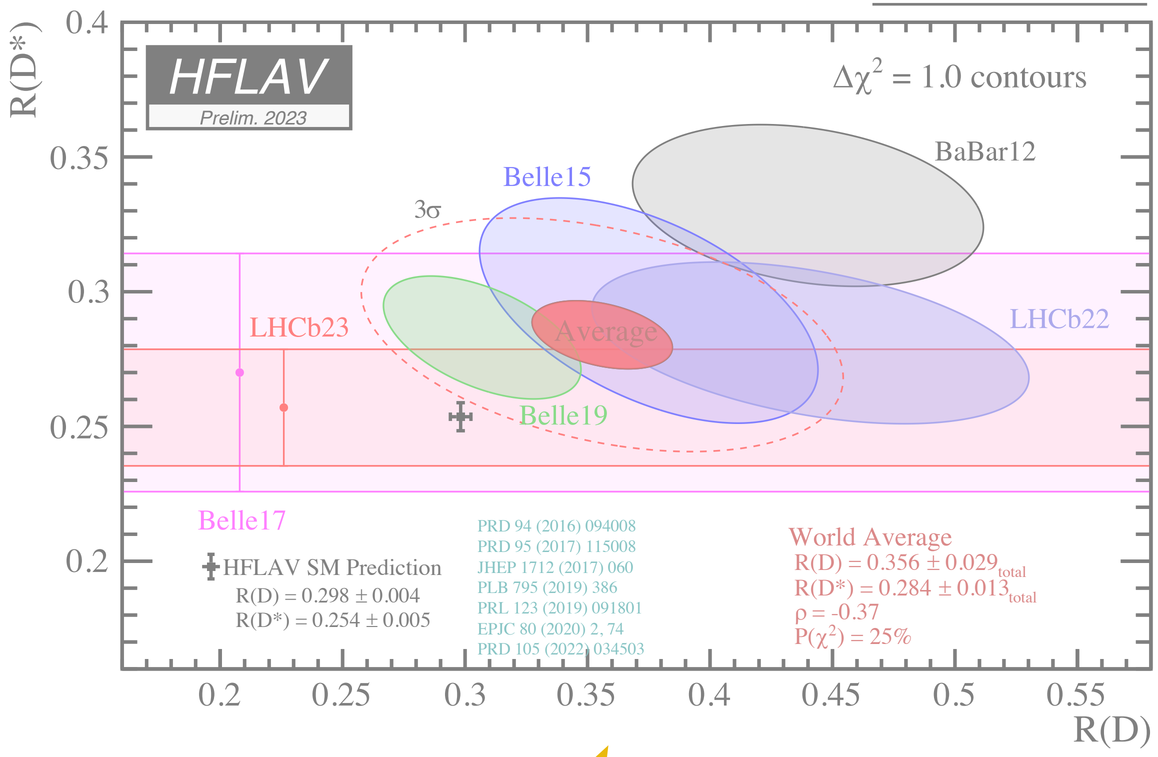


Updated

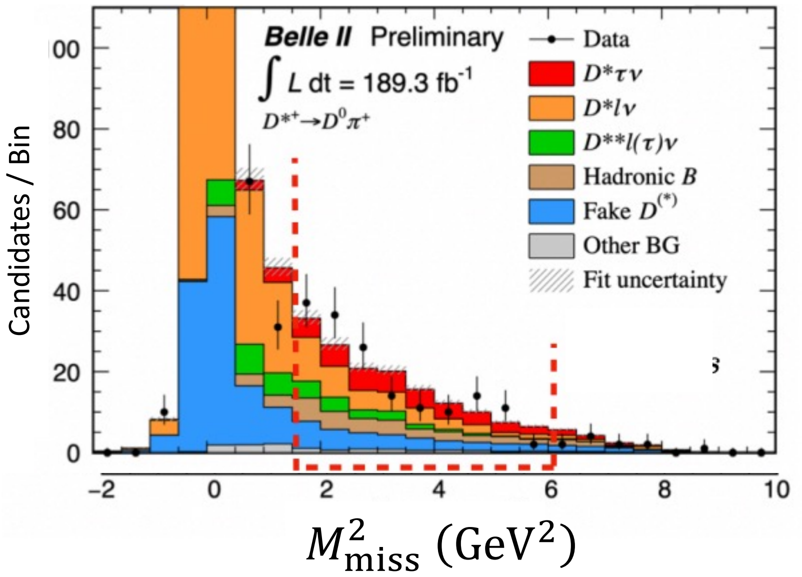
Tagged $B \to D^* l\nu$ at Belle II	$R(D^*)$
Tagged $B \to Xl\nu$ at Belle II	$R(X)$

arxiv:2401.02840, submitted to PRD

Updated

LUV TEST IN $B \to D^* l\nu$ AT BELLE II

- Reconstruct $B \to D^* l\nu$ and $B \to D^* \tau\nu$ to measure: $R(D^*) = \frac{\mathcal{B}(B \to D^* \tau\nu)}{\mathcal{B}(B \to D^* l\nu)}$
  - With $D^{*+} \to D^{0/+}\pi^{+/0}$, $D^{*0} \to D^0\pi^0$ and $\tau \to l\nu\nu$ → Reconstruct D in 11 modes
- Main challenge: significant background from poorly known $B \to D^{**} l\nu$ decays
- Extract signal with 2D fit to mass of undetected neutrinos $M^2_{\text{miss}} = (p_{e^+e^-} - p_{B_{\text{tag}}} - p_{D^*} - p_l)^2$ and residual energy in the calorimeter E_{ECL}



LUV TEST IN $B \to D^* l\nu$ AT BELLE II

Updated

- Reconstruct $B \to D^* l\nu$ and $B \to D^* \tau\nu$ to measure: $R(D^*) = \frac{\mathcal{B}(B \to D^* \tau\nu)}{\mathcal{B}(B \to D^* l\nu)}$
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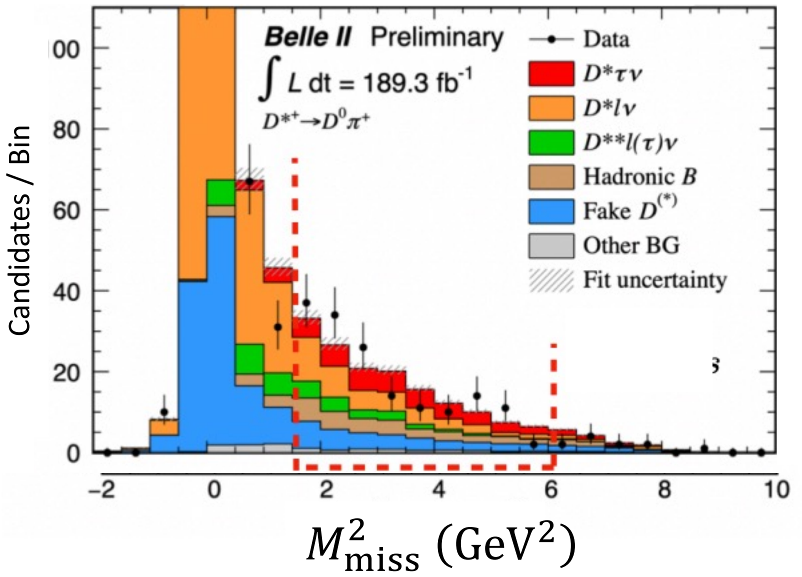
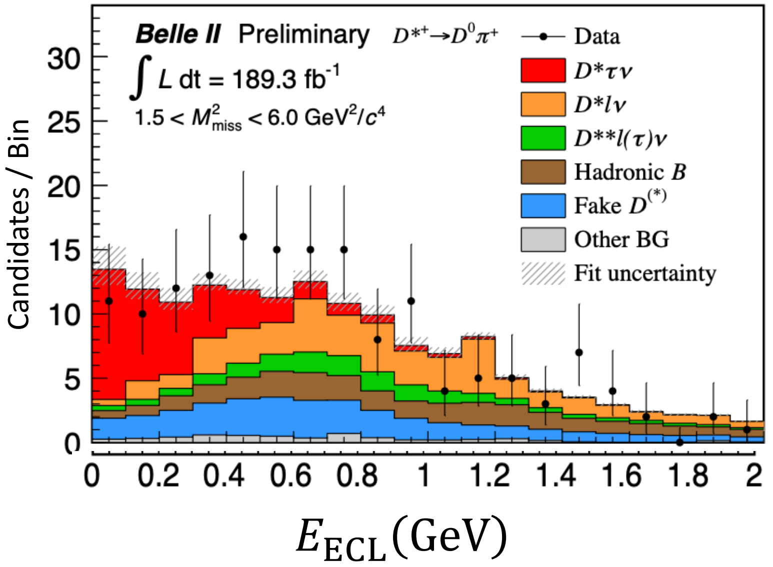




$$R(D^*) = 0.262^{+0.041}_{-0.039}(\text{stat})^{+0.035}_{-0.032}(\text{syst})$$

Consistent with SM prediction and previous measurements arxiv:2401.02840, submitted to PRD

LUV TEST IN $B \rightarrow D^* l\nu$ AT BELLE II

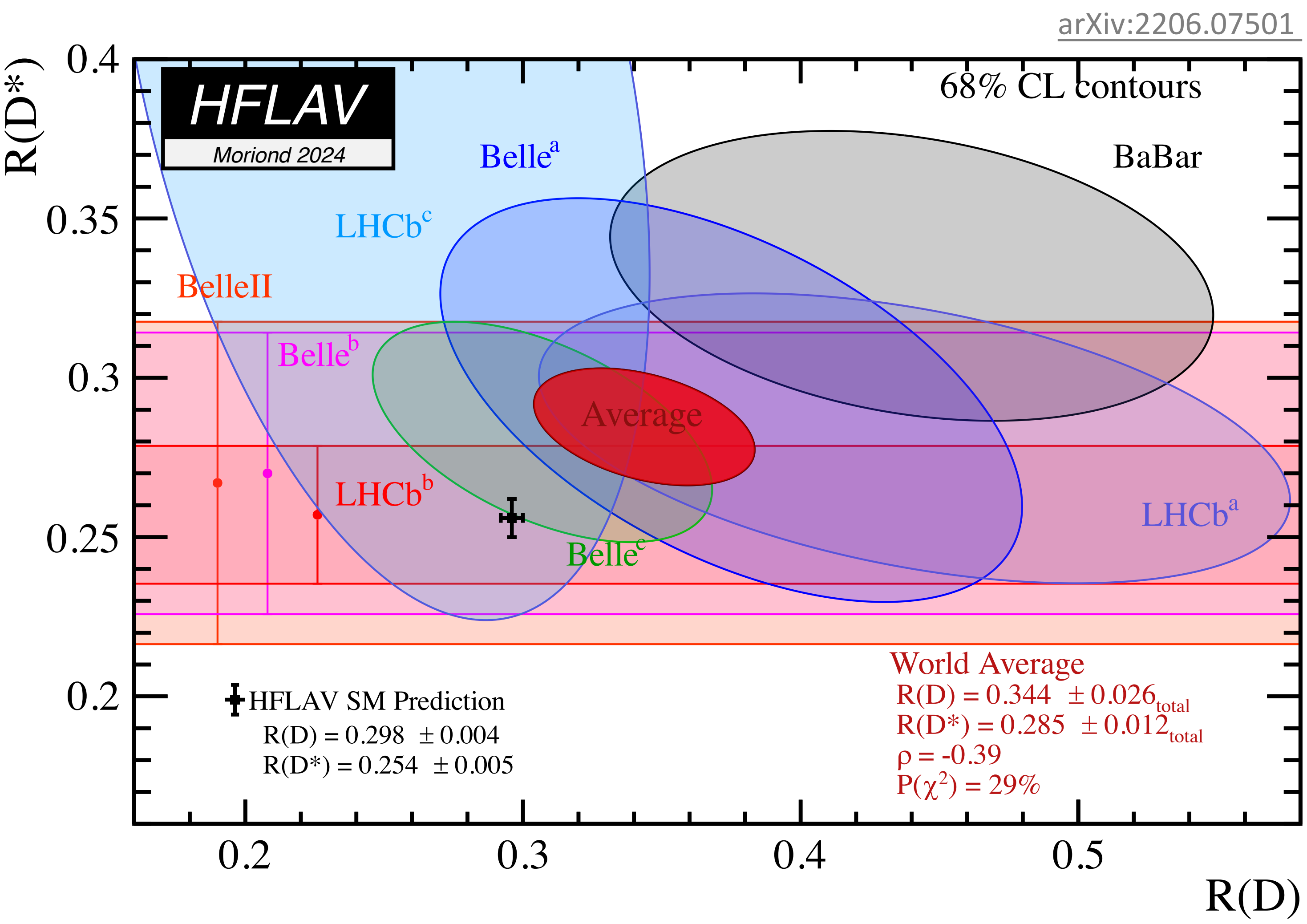
arXiv:2206.07501

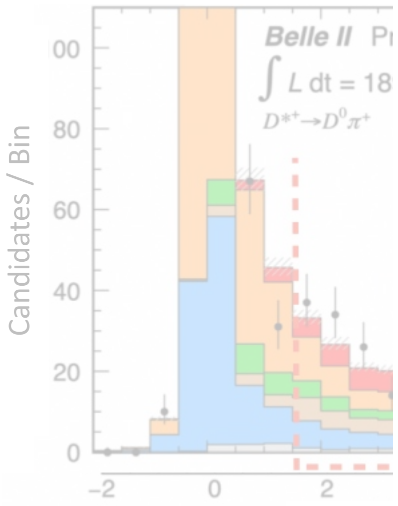
– Reconstru

– With D^{*+}

– Main chall

– Extract sig of undetec





$M^2_{\rm miss}$ (GeV^2)

$E_{\rm ECL}$(GeV)

modes

ecays

nass

$.041$(stat)$^{+0.035}_{-0.032}$(syst)

ith SM

nd previous

nts

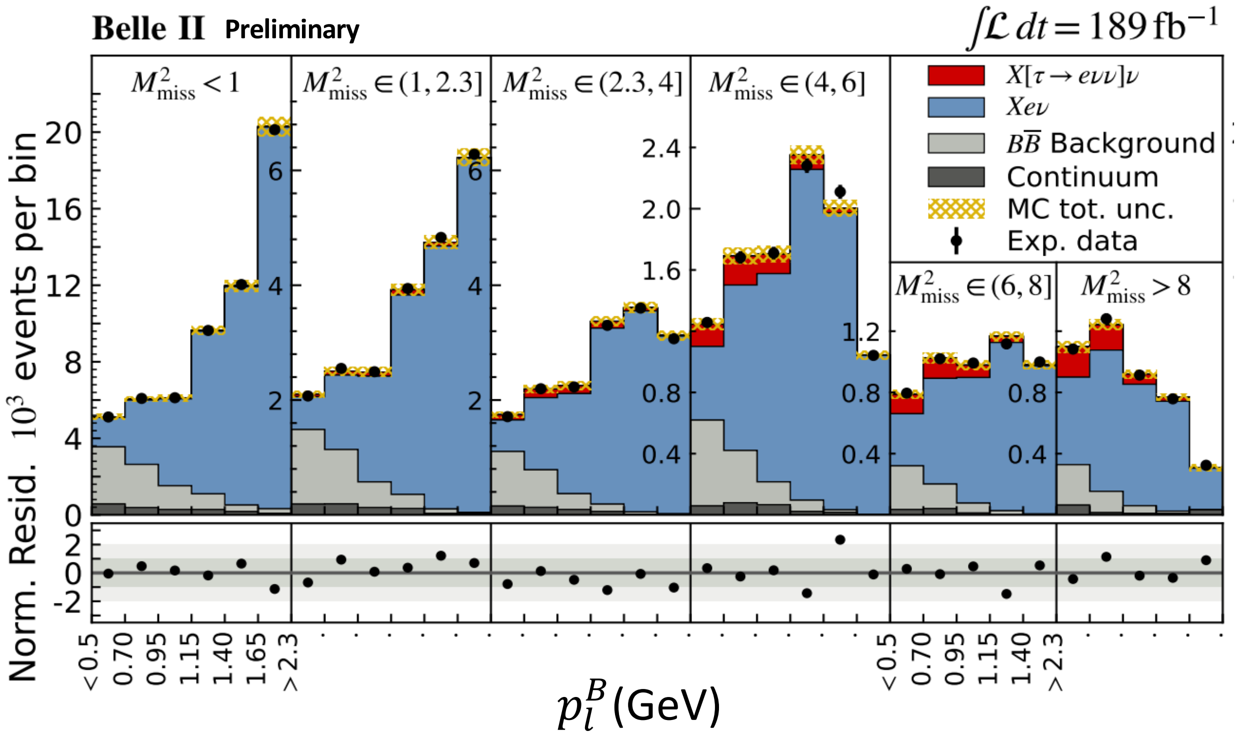
LUV TEST IN $B \rightarrow Xl\nu$ AT BELLE II

- Complementary inclusive test of LUV in tagged semileptonic B decays

$$R(X) = \frac{\mathcal{B}(B \rightarrow X\tau\nu)}{\mathcal{B}(B \rightarrow Xl\nu)}$$

- Main challenge: modelling of backgrounds from $B \rightarrow X_c \rightarrow l$
  - Use high lepton momentum p_l^B sideband to reweight inclusive $B \rightarrow Xl\nu$
- Extract signal from 2D fit to p_l^B and M_{miss}^2

$$\mathrm{R}(X) = 0.228 \pm 0.016_{stat} \pm 0.036_{syst}$$



- First measurement at B-factory with $\Upsilon(4S)$
- Consistent with SM prediction and $R(D^{(*)})$

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SUMMARY

Precision measurements:

- Most recent $|V_{ub}|$ results from $B \to \pi l \nu$ shift exclusive closer to inclusive average
- Very active field, with diverse approaches toward measuring $|V_{ub}|$ and $|V_{cb}|$

LUV measurements:

- LU challenged using exclusive and inclusive modes
- Making advances in understanding backgrounds

Many more results:

Belle

- Differential distributions of $B \to D^* l \nu$
  Phys. Rev. D **108**, 012002
- Angular coefficients of $B \to D^* l \nu$
  arXiv:2310.20286
- BFs of $B \to D^{(*)} \pi (\pi) l \nu$
  Phys. Rev. D **107**, 092003

Belle II

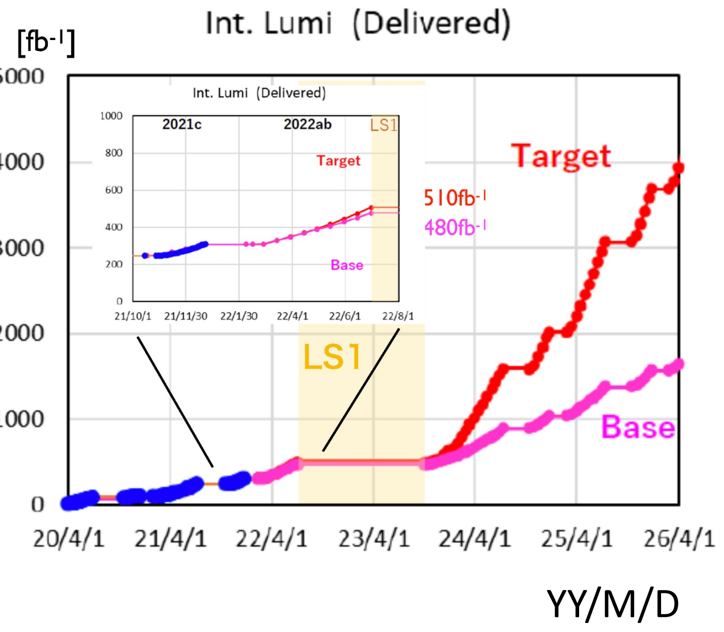
- Test of LFU with inclusive $R(X_{e/\mu})$
  Phys. Rev. Let. **131**, 05184
- $|V_{cb}|$ from untagged $B^0 \to D^* l \nu$
  Phys. Rev. D **108**, 092013
- $B \to D^* l \nu$ angular asymmetries
  Phys. Rev. Let. **131**, 181801

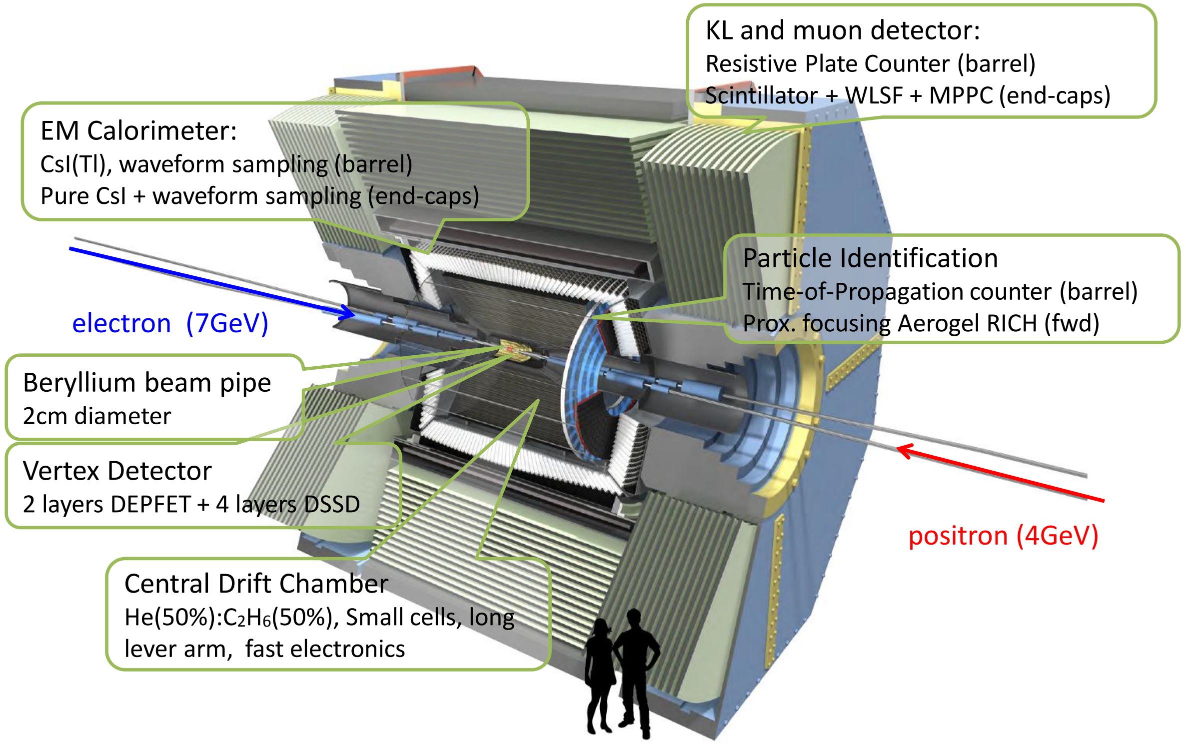
Thank you for your attention!

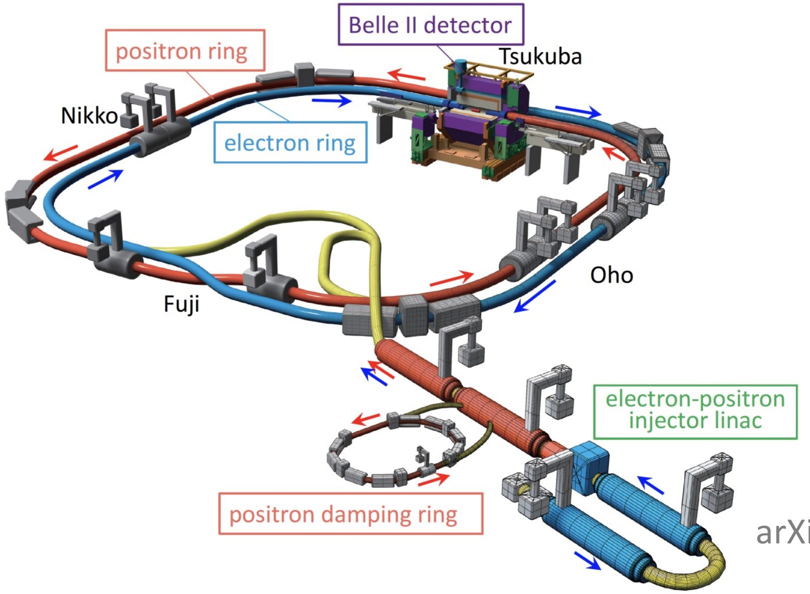
Backup

SUPERKEKB, BELLE II DETECTOR

- Long Shutdown 1 completed (15 months)
  - Detector upgrades and beam-pipe improvement





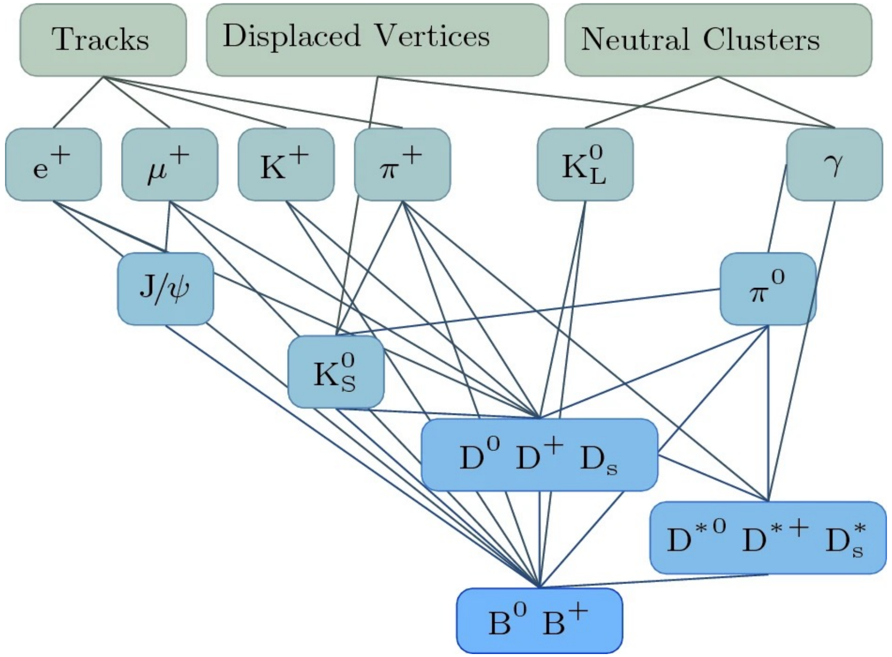


arXiv:1809.01958

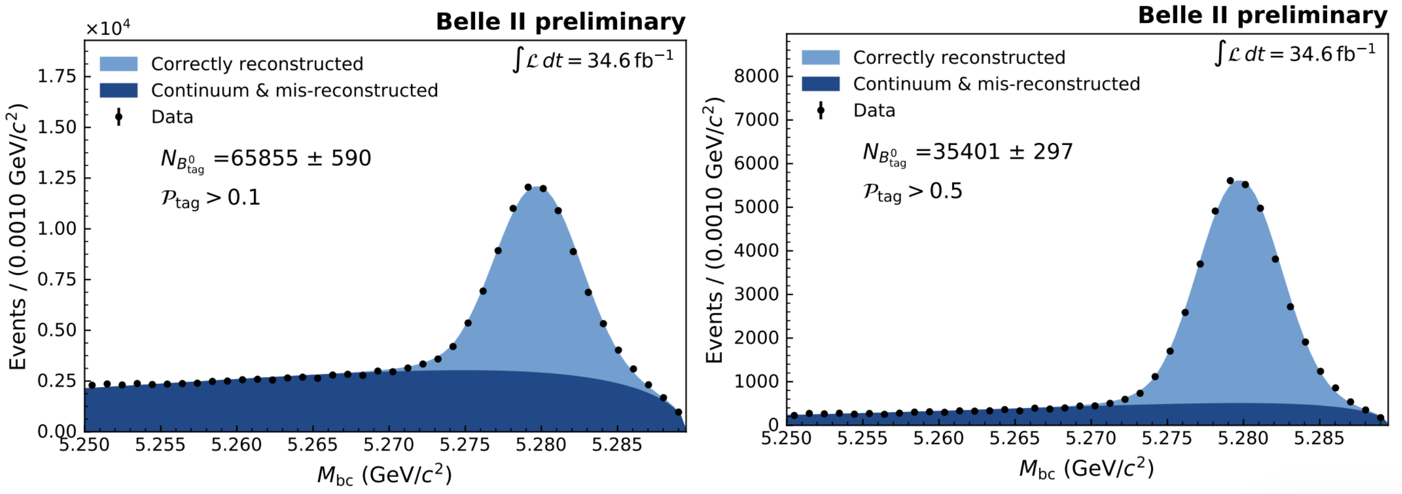
FULL EVENT INTERPRETATION (FEI)

- FEI algorithm used to reconstruct B_{tag}
  - Uses ≈ 200 BDTs to reconstruct O(10000) different B decay chains
  - Assigns signal probability of being correct B_{tag}

Comput Softw Big Sci 3, 6 (2019)



arXiv:2008.060965



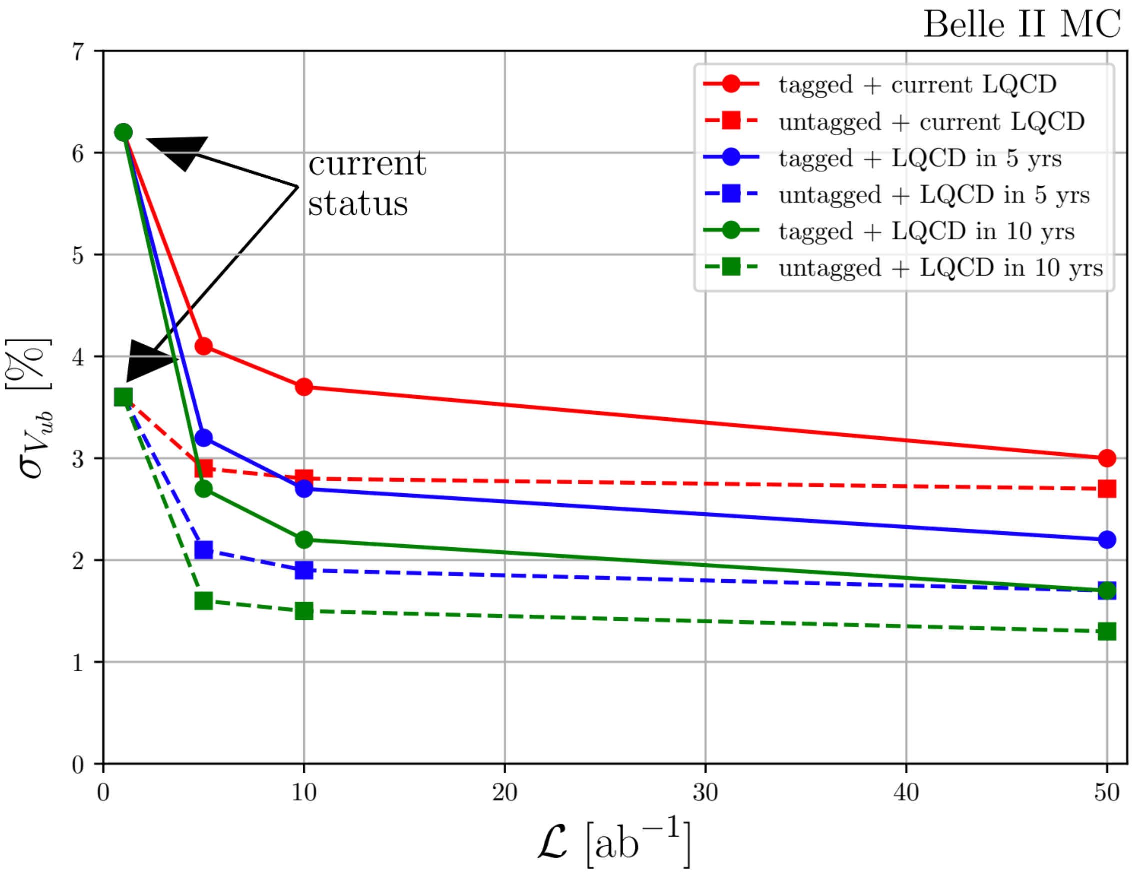
PROJECTION: CKM MATRIX ELEMENTS

Tension:

- Most indications point to inconsistent experimental/theoretical inputs
- Cannot exclude non-SM physics

– Improvements:

- Theoretical understanding
- B→ $Xl\nu$ background modeling
- Calibration of B_{tag} efficiency



arXiv:2207.11275

$B \to \pi/\rho l\nu$ ADDITIONAL INFORMATION

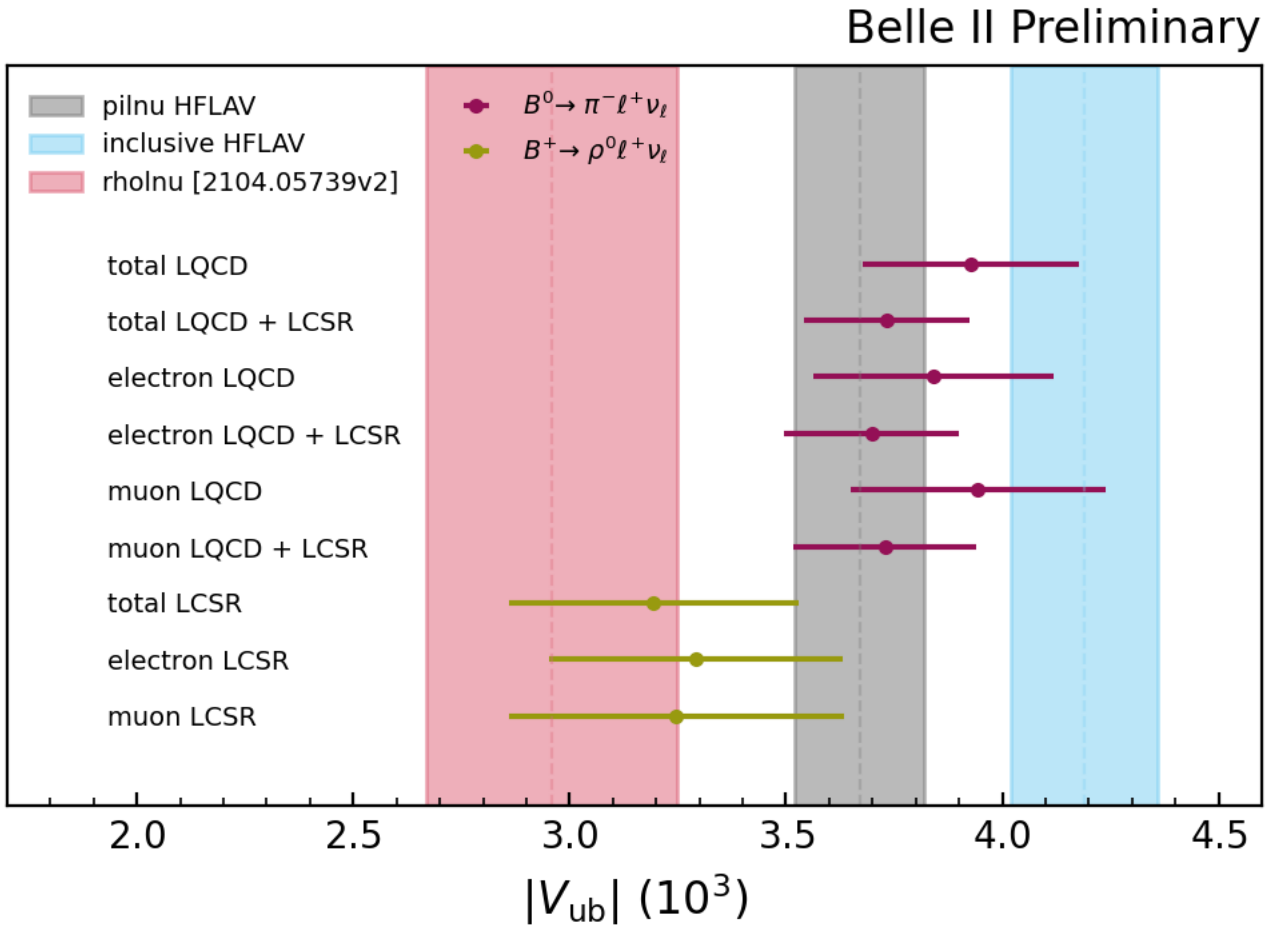


Table VIII: Summary of fractional uncertainties in % on the extracted $|V_{ub}|$ values.

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

$B \to \pi/\rho l\nu$ FORM FACTOR COEFFICIENTS

Table VI: Measured central values of $|V_{ub}|$ and the BCL form-factor coefficients with total uncertainties from the fits to the $B^0 \to \pi^- \ell^+ \nu_\ell$ spectrum.

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

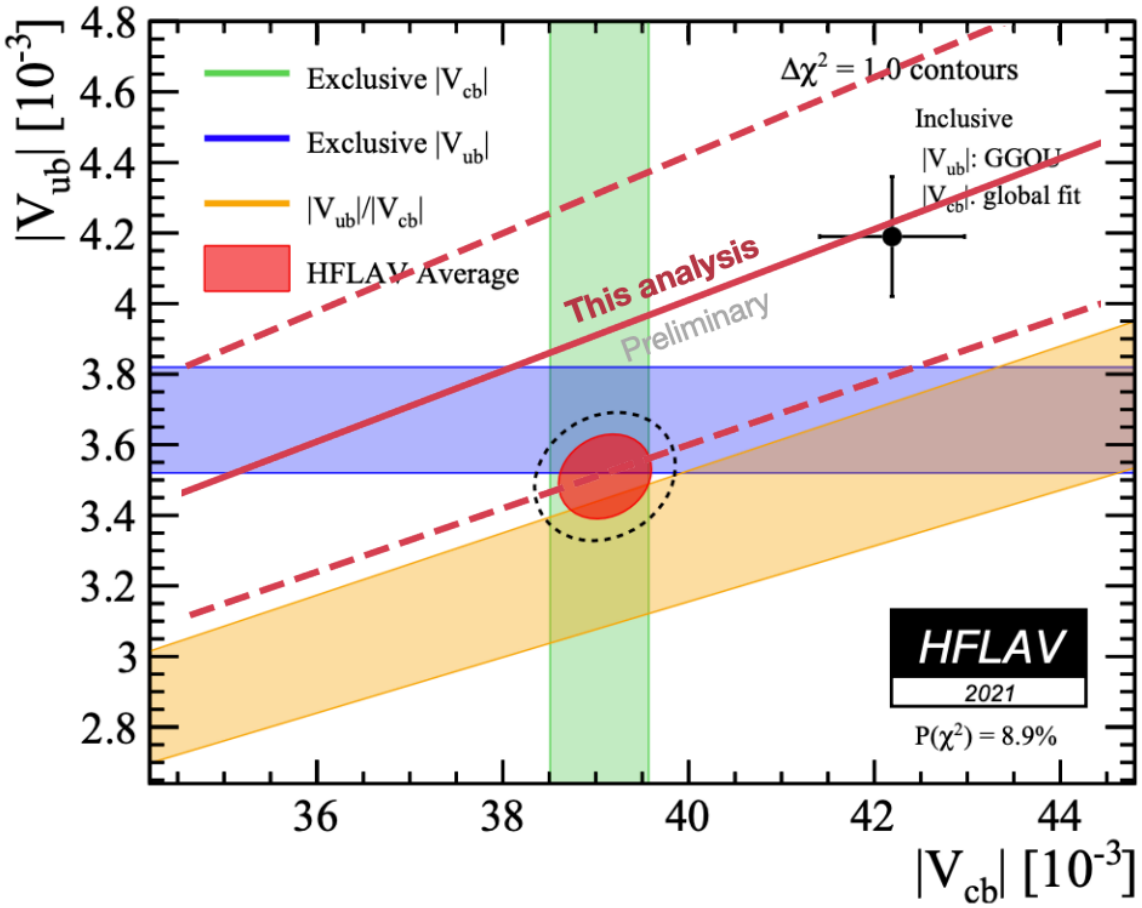
Table VII: Measured central values of $|V_{ub}|$ and the BSZ form-factor coefficients with total uncertainties from the fit to the $B^+ \to \rho^0 \ell^+ \nu_\ell$ spectrum.

		$B^+ \to \rho^0 \ell^+ \nu_\ell$ LCSR
$\lvert V_{ub}\rvert$ (10^{-3})		3.19 ± 0.33
$A_1(q^2)$	$b_0^{A_1}$	0.27 ± 0.03
	$b_1^{A_1}$	0.34 ± 0.13
$A_2(q^2)$	$b_0^{A_2}$	0.29 ± 0.03
	$b_1^{A_2}$	0.66 ± 0.17
$V(q^2)$	b_0^V	0.33 ± 0.03
	b_1^V	-0.93 ± 0.17
χ^2/ndf		$3.85/3$

ADDITIONAL INFORMATION $|V_{ub}|/|V_{cb}|$

TABLE III. Summary of the central value (R), statistical, and systematic uncertainties for the ratio of partial branching fractions. The uncertainties are given as relative values on the central value in percent.

$R \times 100$	1.96
Stat. Error (Data)	8.4
$\mathcal{B}(\bar{B} \to \pi/\eta/\rho/\omega/\eta'\ell\bar{\nu})$	0.2
$\mathcal{FF}(\bar{B} \to \pi/\eta/\rho/\omega/\eta'\ell\bar{\nu})$	0.3
$BF(\bar{B} \to x_u\ell\bar{\nu})$	0.6
Hybrid Model (BLNP)	0.5
DFN ($m_b^{\mathrm{KN}}, a^{\mathrm{KN}}$)	5.0
$N_{g\to s\bar{s}}$	1.3
$\mathcal{B}(\bar{B} \to D\ell\bar{\nu})$	0.1
$\mathcal{B}(\bar{B} \to D^*\ell\bar{\nu})$	0.8
$\mathcal{B}(\bar{B} \to D^{**}\ell\bar{\nu})$	0.3
$\mathcal{B}(\bar{B} \to D^{(*)}\eta\ell\bar{\nu})$	0.2
$\mathcal{B}(\bar{B} \to D^{(*)}\pi\pi\ell\bar{\nu})$	0.2
$\mathcal{FF}(\bar{B} \to D\ell\bar{\nu})$	0.2
$\mathcal{FF}(\bar{B} \to D^*\ell\bar{\nu})$	0.9
$\mathcal{FF}(\bar{B} \to D^{**}\ell\bar{\nu})$	0.4
Sec.Fakes. Composition	3.8
In-situ q^2 Calibration	2.8
ℓID Efficiency	0.1
ℓID Fake Rate	0.3
$K\pi$ID Efficiency	1.1
$K\pi$ID Fake Rate	0.7
K_S^0 Efficiency	0.2
π_{slow} Efficiency	< 0.1
Tracking	0.1
Continuum Calibration	0.4
N_{BB}	< 0.1
$f_{+/0}$	< 0.1
Stat. Error (MC)	2.8
Total Syst.	7.9



SIMULTANEOUS $|V_{ub}|$ SYSTEMATICS

Sources	Relative Syst. Uncertainty
Exclusive mode	$\mathcal{B}(B \to \pi \ell \nu)$
Tagging efficiency	4.1%
$B \to X_u \ell \nu$ modelling	3.5%
$B \to X_c \ell \nu$ modelling	1.2%
Inclusive mode	$\Delta\mathcal{B}(B \to X_u \ell \nu)$
$B \to X_u \ell \nu$ modelling	10.9%
Fragmentation	5.3%
$B \to X_c \ell \nu$ modelling	2.8%

PROJECTION AT BELLE II: $R(D^{(*)})$ R(X)

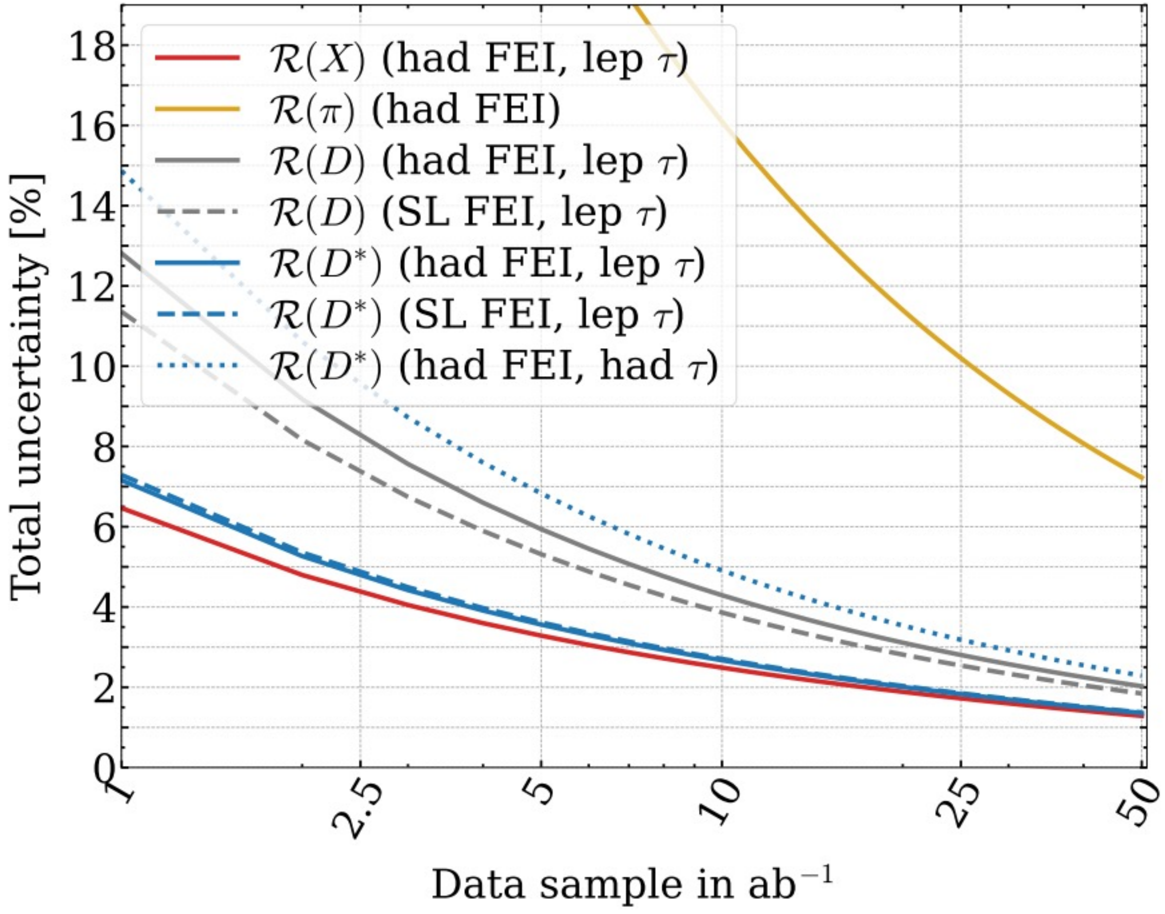
arXiv:2207.11275

$R\left(D^{(*)}\right)$:

- Understand B→ $D^{**}l\nu$ downfeed

$R(X_{\tau/l})$

- Control inclusive background composition



R(D*) SYSTEMATIC UNCERTAINTIES

Table VIII. Summary of systematic uncertainties on $R(D^*)$.

Source	Uncertainty
PDF shapes	$^{+9.1\%}_{-8.3\%}$
Simulation sample size	$^{+7.5\%}_{-7.5\%}$
$\overline{B} \to D^{**}\ell^-\overline{\nu}_\ell$ branching fractions	$^{+4.8\%}_{-3.5\%}$
Fixed backgrounds	$^{+2.7\%}_{-2.3\%}$
Hadronic B decay branching fractions	$^{+2.1\%}_{-2.1\%}$
Reconstruction efficiency	$^{+2.0\%}_{-2.0\%}$
Kernel density estimation	$^{+2.0\%}_{-0.8\%}$
Form factors	$^{+0.5\%}_{-0.1\%}$
Peaking background in ΔM_{D^*}	$^{+0.4\%}_{-0.4\%}$
$\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$ branching fractions	$^{+0.2\%}_{-0.2\%}$
$R(D^*)$ fit method	$^{+0.1\%}_{-0.1\%}$
Total systematic uncertainty	$^{+13.5\%}_{-12.3\%}$

ADDITIONAL INFORMATION R(X)

Table I: Relative statistical and systematic uncertainties on the value of $R(X_{\tau/\ell})$.

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