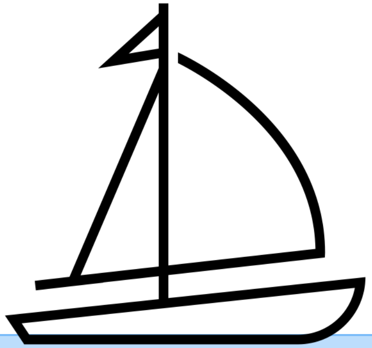
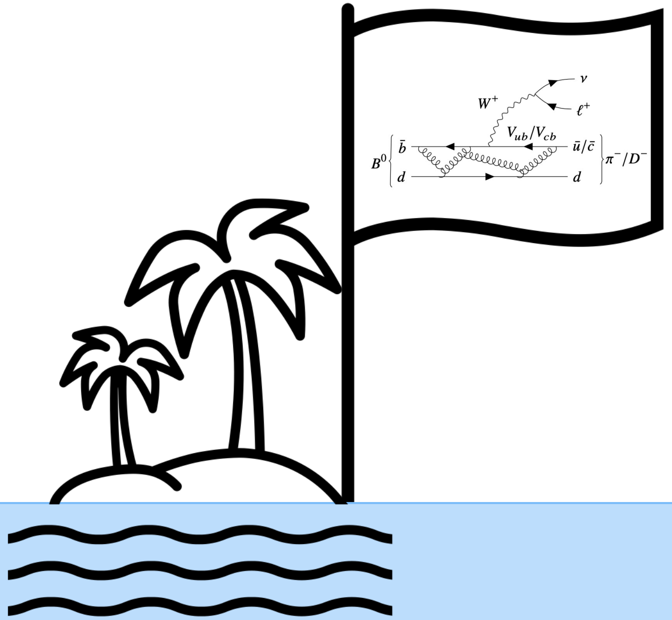
SEMILEPTONIC DECAYS AT BELLE AND BELLE II

Svenja Granderath (University of Bonn)
on behalf of the Belle II collaboration
(with material from the Belle collaboration)

Moriond QCD 2024 – La Thuile - April 2, 2024

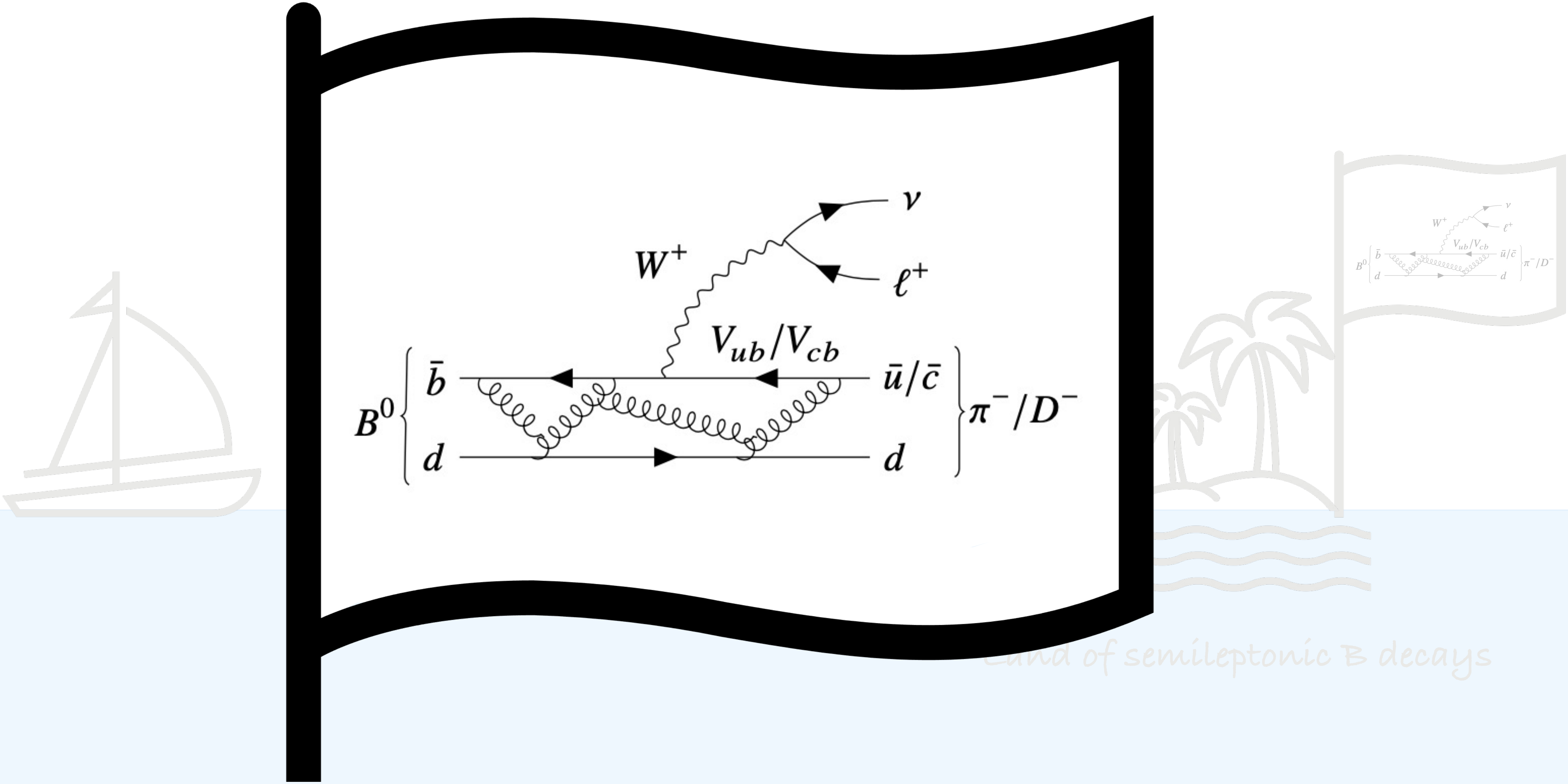
SEMILEPTONIC B DECAYS





Land of semileptonic B decays

SEMILEPTONIC B DECAYS



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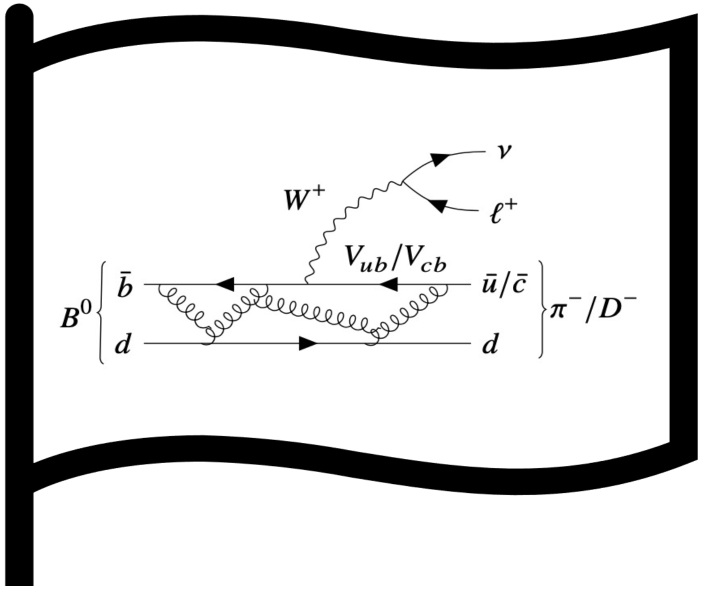

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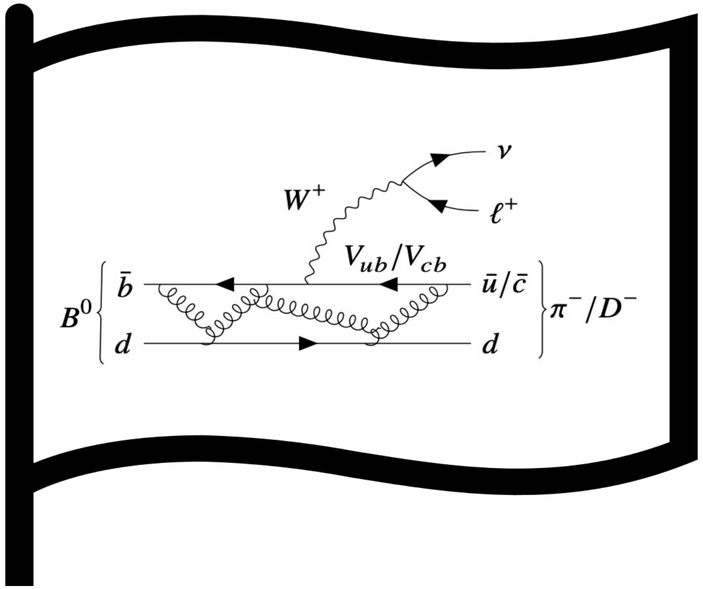
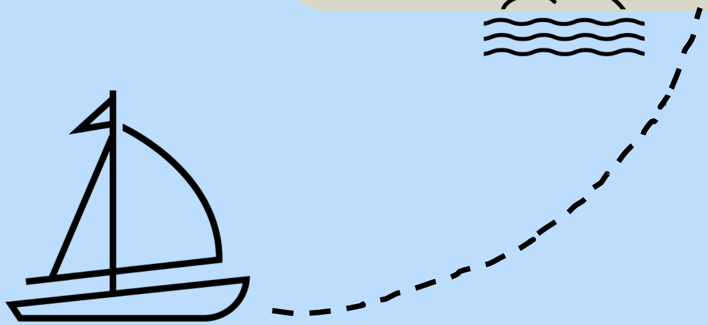


$$\underbrace{\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}}_{\text{CKM Matrix}}$$

Form-factor measurements

SM precision measurements



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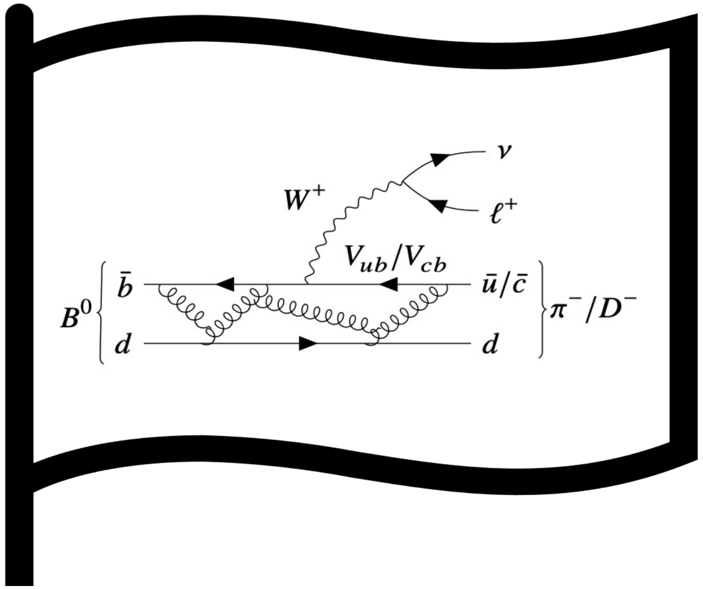

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Form-factor measurements

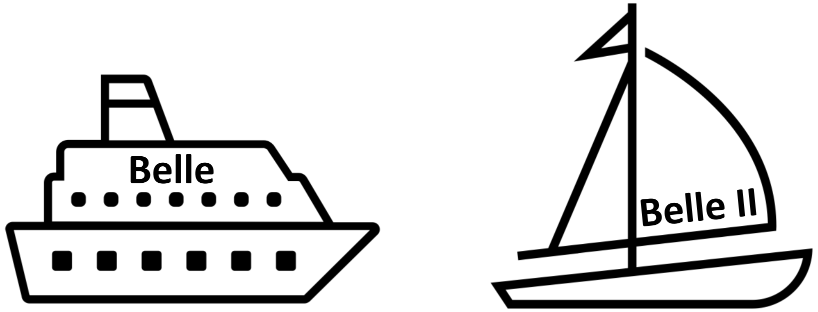
SM precision measurements

Lepton universality violation (LUV) tests

Angular observables

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

BELLE AND BELLE II

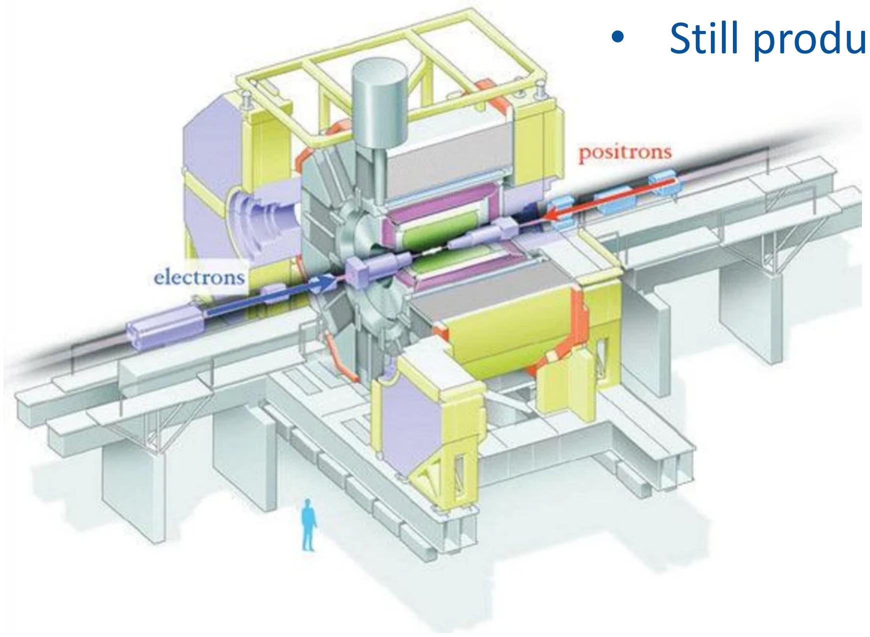


- Detectors located at the interaction points of electron-positron colliders
- Center-of-mass energy corresponding to $\Upsilon(4S)$ resonance

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

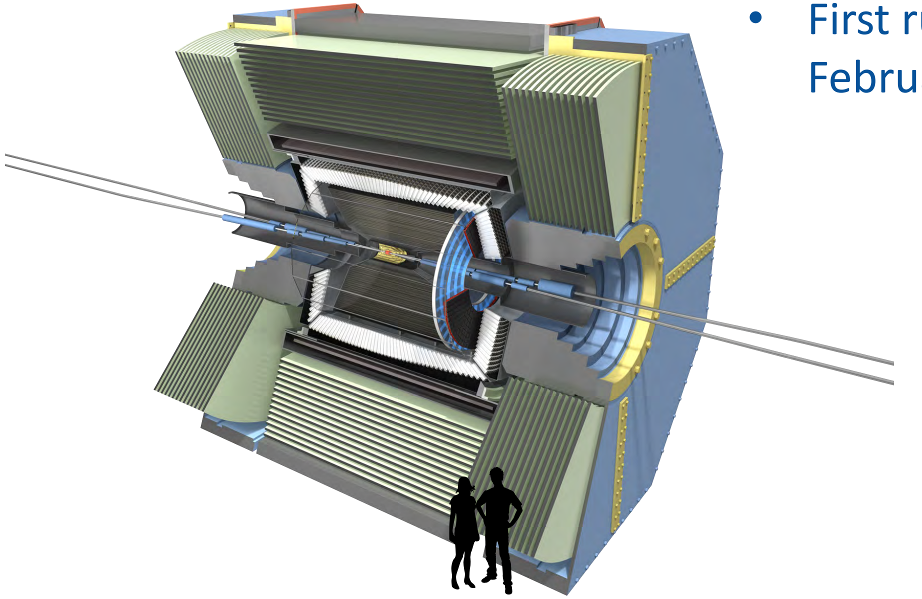
Belle:

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



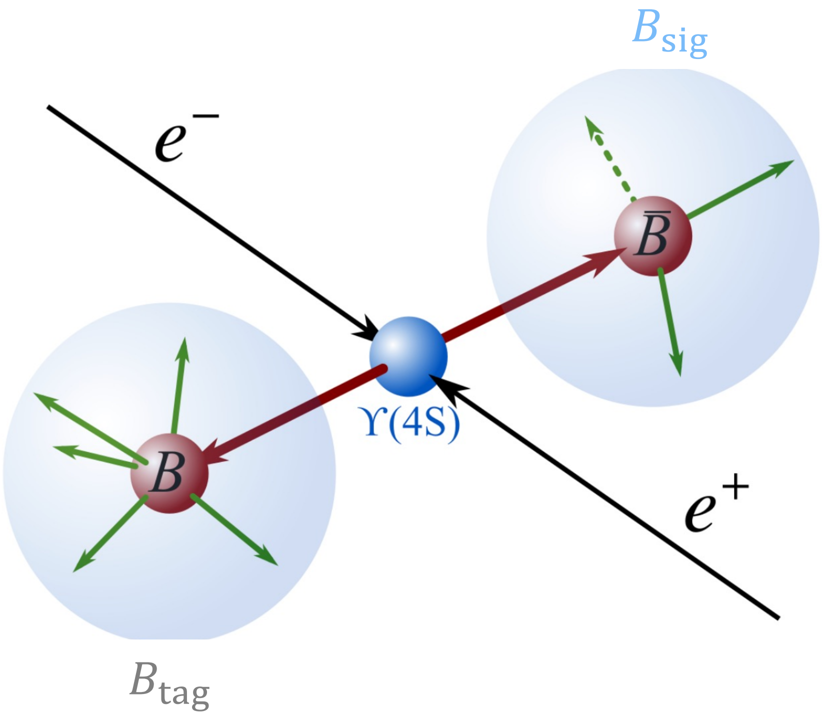
Belle II:

- 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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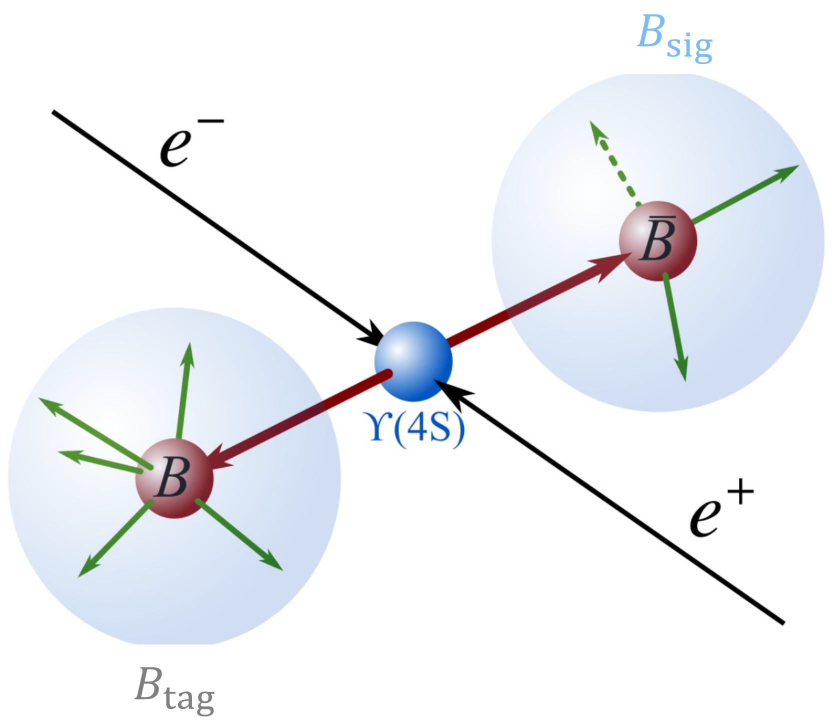


Tagged:

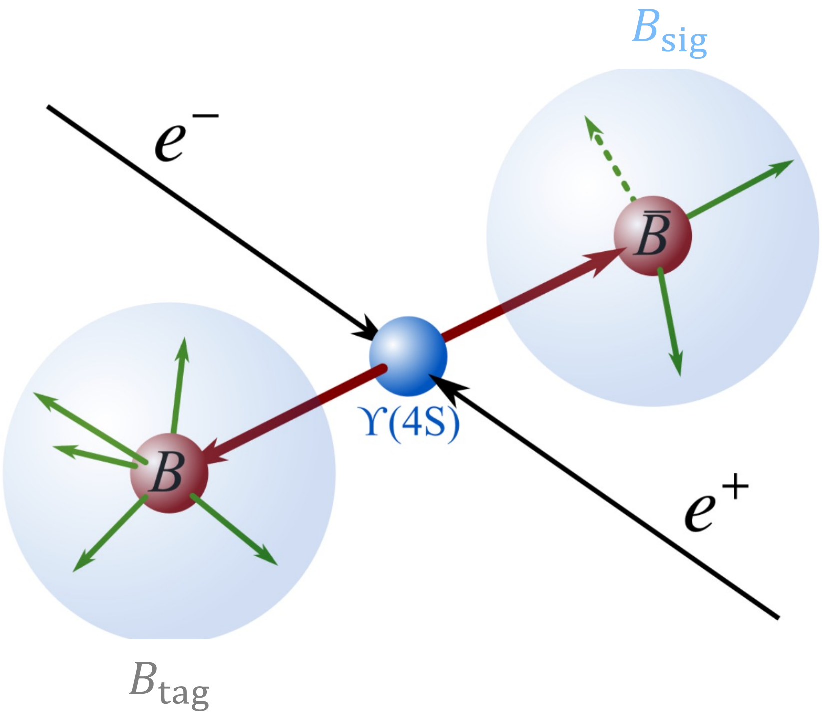
- B_{sig} and B_{tag} reconstructed
- Reconstruct B_{tag} in hadronic or semileptonic modes using multivariate methods

Untagged (inclusive tag):

- Only B_{sig} reconstructed

RECONSTRUCTION

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



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Low → Efficiency → High

High ← Purity ← Low

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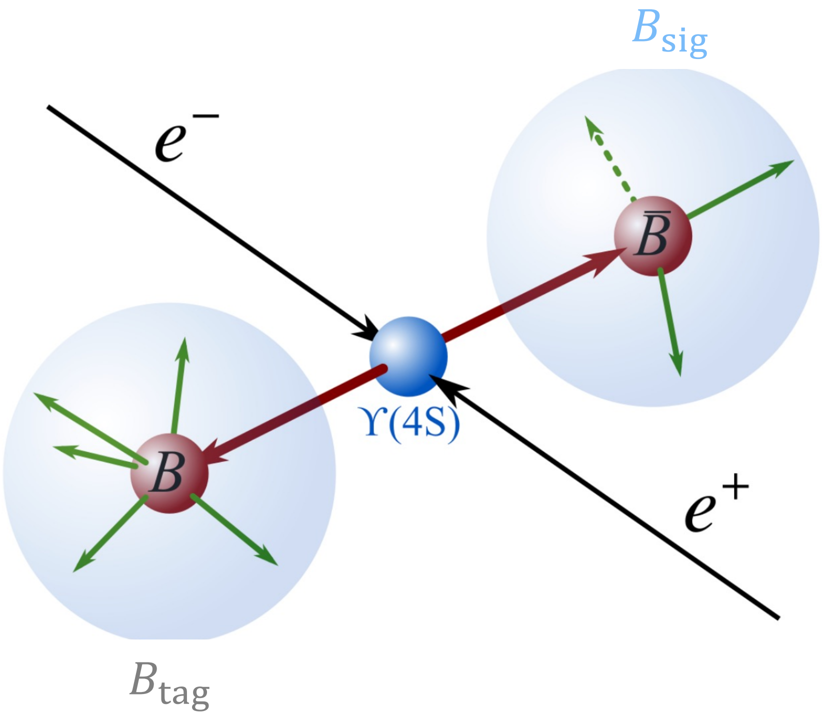

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Low — Efficiency → High

High ← Purity — Low

Exclusive:

- B_{sig} reconstructed as specific final state

Inclusive:

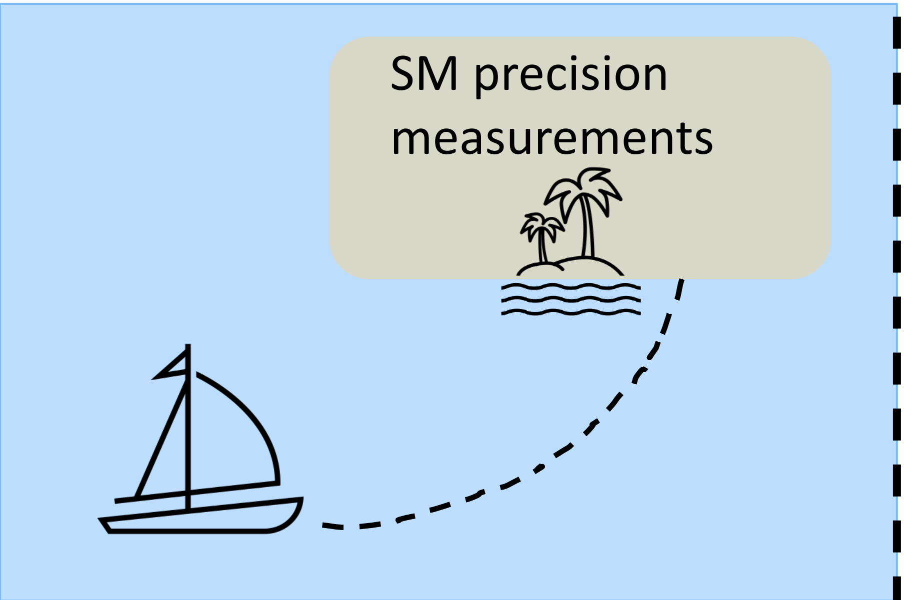
- B_{sig} reconstructed as sum of modes

Approaches are theoretically and experimentally independent

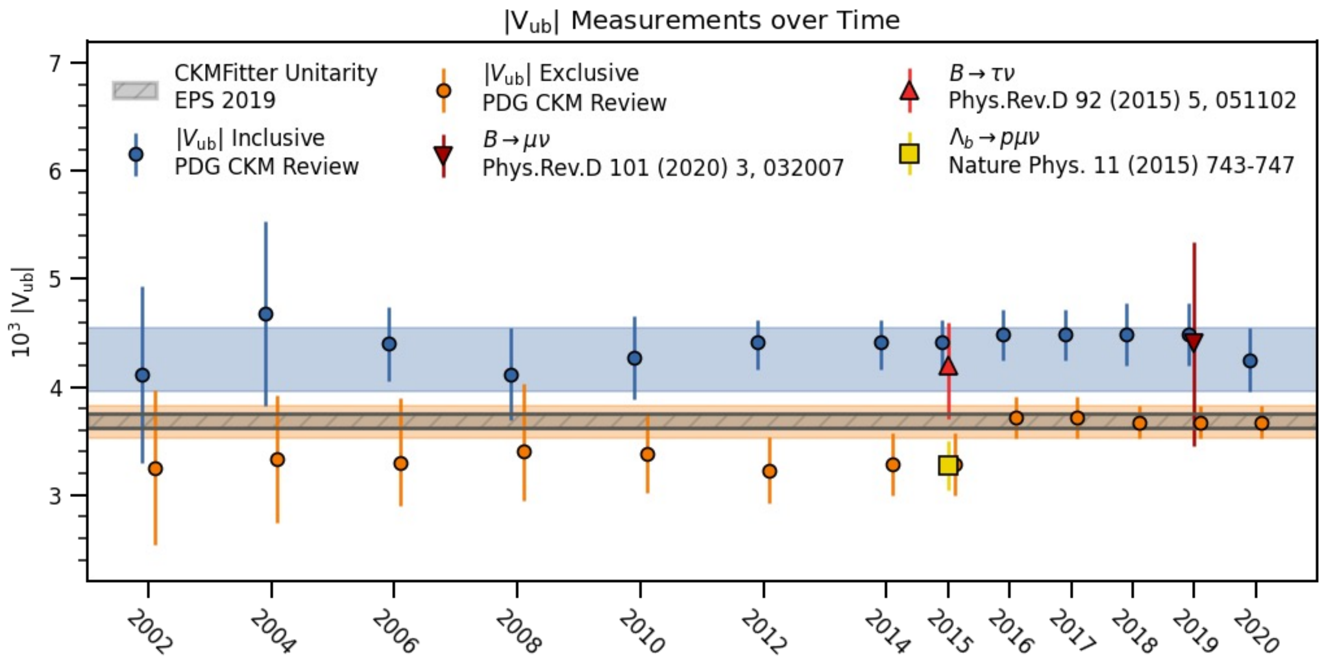
SM PRECISION MEASUREMENTS

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

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



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$|V_{xb}|$ FROM SEMILEPTONIC DECAYS

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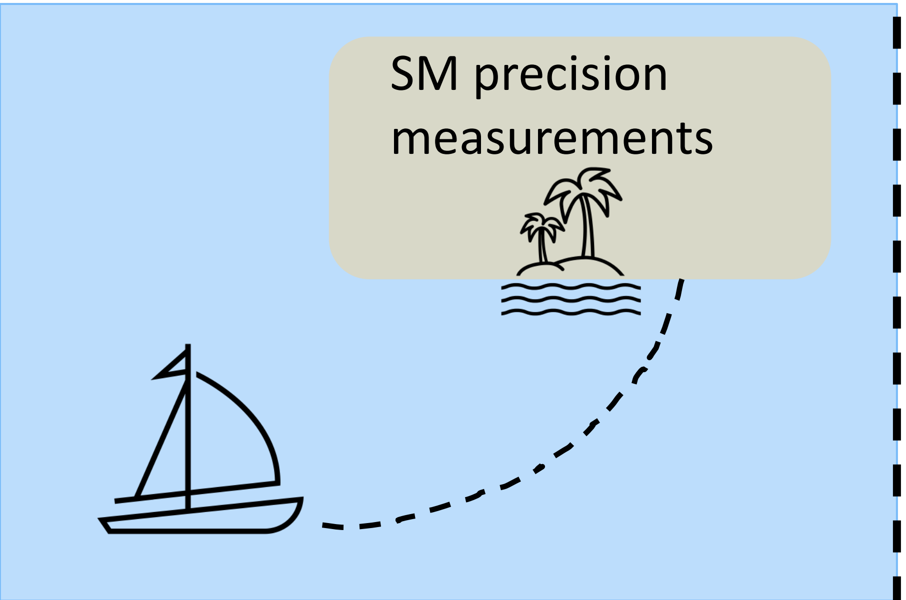

- $B \to Xl\nu$: leptonic and hadronic currents factorize
- Describe kinematics using momentum transfer squared: $q^2 = (p_B - p_X)^2$
- Exclusive: $\frac{d\mathcal{B}}{dq^2} \propto |V_{xb}|^2 \times |FF(q^2)|^2$

Form factors parametrize non-perturbative physics

- Inclusive:

Operator product expansion

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

$|V_{xb}|$ FROM SEMILEPTONIC DECAYS

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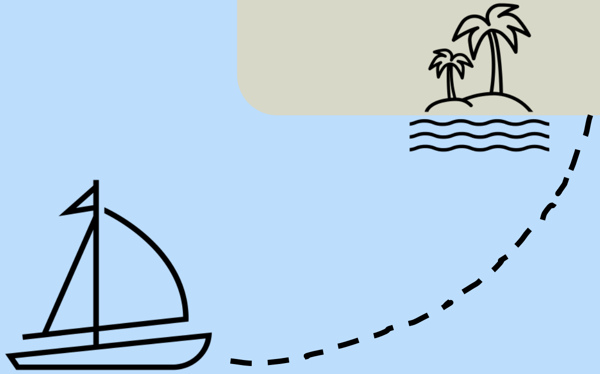
Form-factor measurements

SM precision measurements



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- Inclusive: → Operator product expansion

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

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

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

New for Moriond

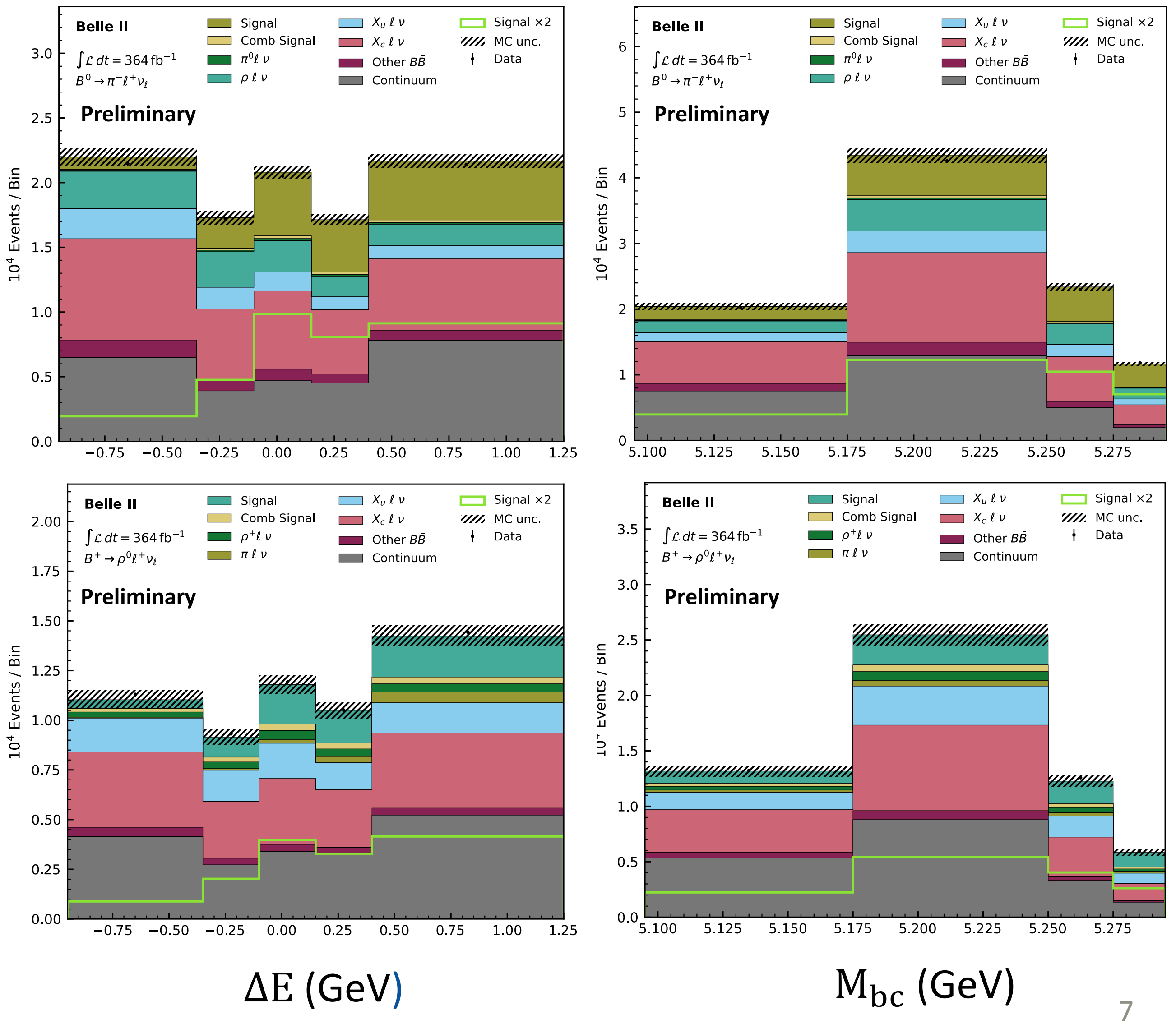
UNTAGGED $B \to \pi/\rho l\nu$ AT BELLE II

- Untagged reconstruction of $B^0 \to \pi^+ l^- \bar{\nu}_l$ and $B^- \to \rho^0 l^- \bar{\nu}_l$
- Main challenge: modes suffer from large $B \to X_c l\nu$ and continuum backgrounds
  - Suppressed using BDTs
- Discriminating variables:

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

$$M_{bc} = \sqrt{E_{beam}^2 - |\overrightarrow{p_B}|^2}$$

- Simultaneously extract signal yields in 13(10) bins of true q^2

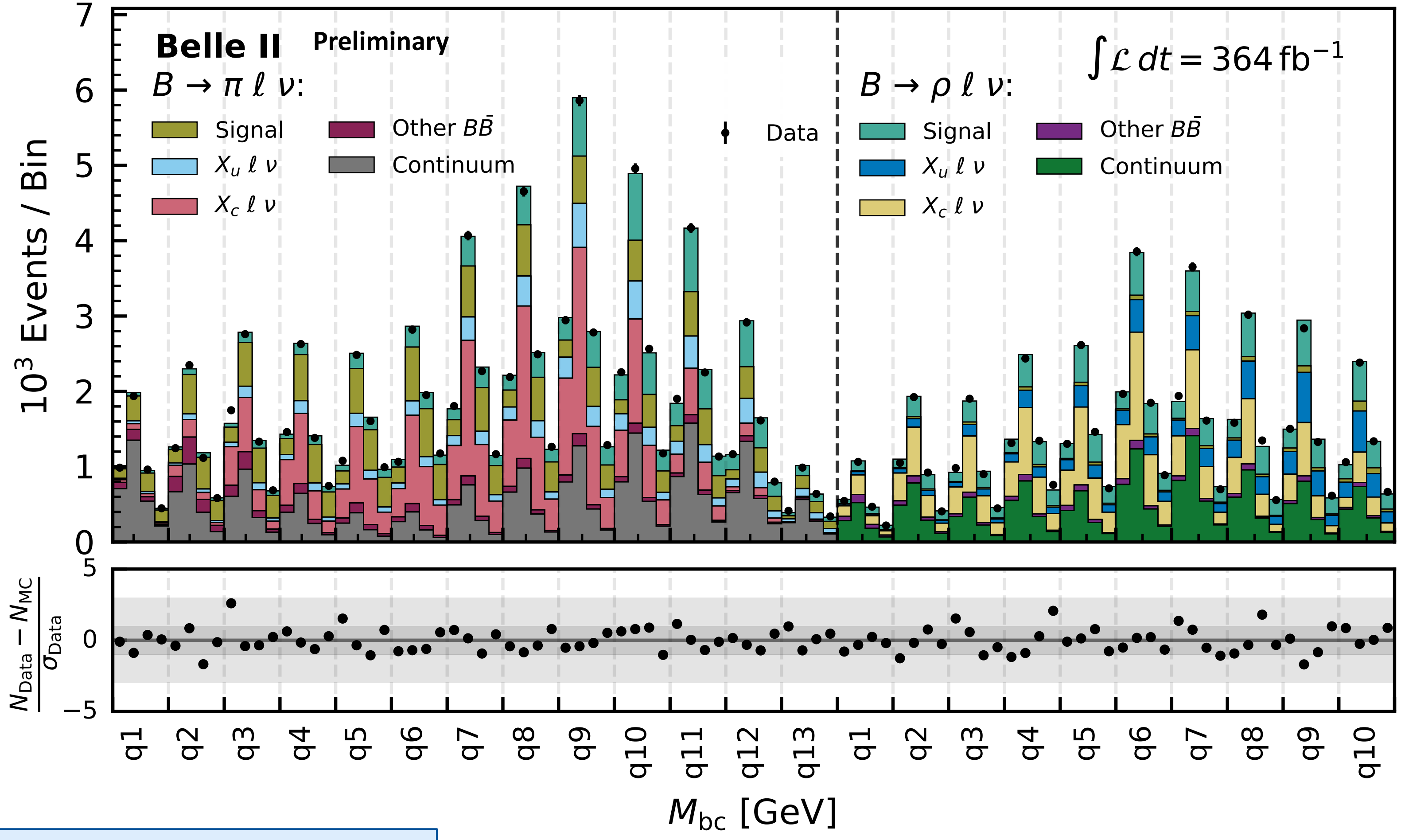


To be submitted to PRD

New for Moriond

UNTAGGED $B \to \pi/\rho l \nu$ AT BELLE II

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



$\mathcal{B}(B^0 \to \pi^+ l^- \bar{\nu}_l) = (1.516 \pm 0.027_{stat} \pm 0.035_{syst}) \times 10^{-4}$

$\mathcal{B}(B^- \to \rho^0 l^- \bar{\nu}_l) = (1.625 \pm 0.063_{stat} \pm 0.088_{syst}) \times 10^{-4}$

- Most precise single measurements
- In agreement with world averages

To be submitted to PRD

UNTAGGED $B \to \pi/\rho l\nu$ AT BELLE II

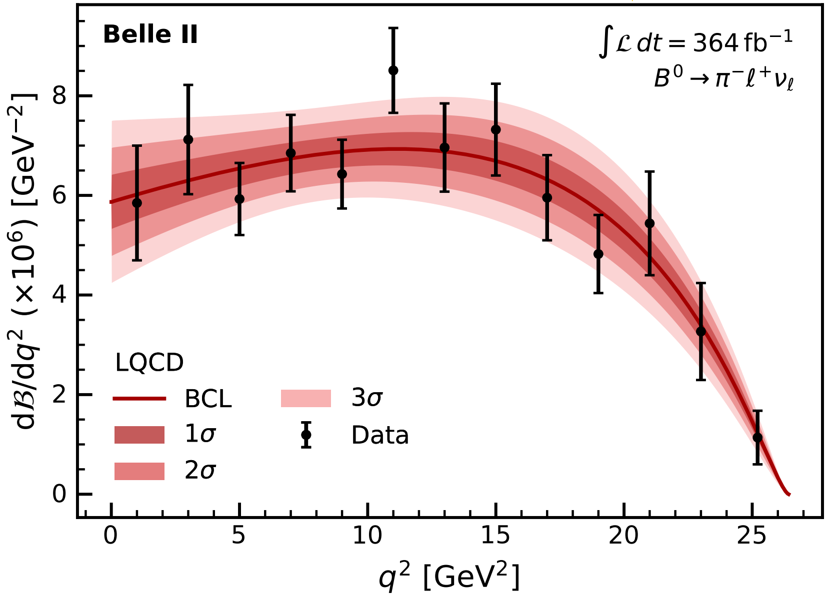
New for Moriond

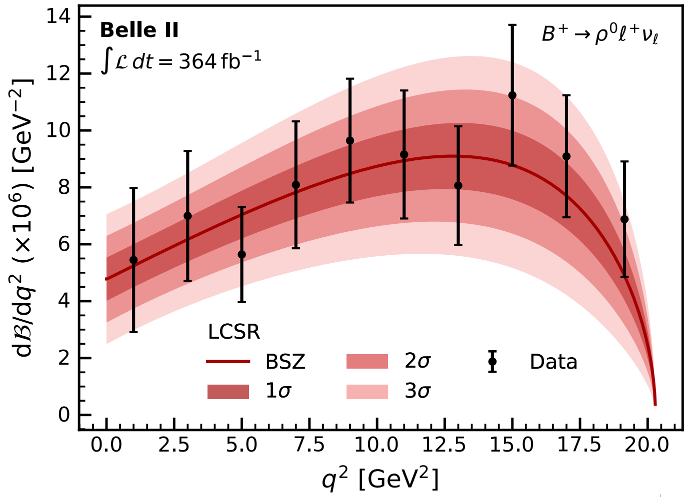
Determine $|V_{ub}|$ by minimising χ^2:

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

- 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) J. High Energ. Phys. **2016**, 98
Theory input	LQCD Eur. Phys. J. C 82 (2022) 869	LCSR J. High Energ. Phys. **2016**, 98
	LQCD + LCSR J. High Energ. Phys. **2021**, 36	





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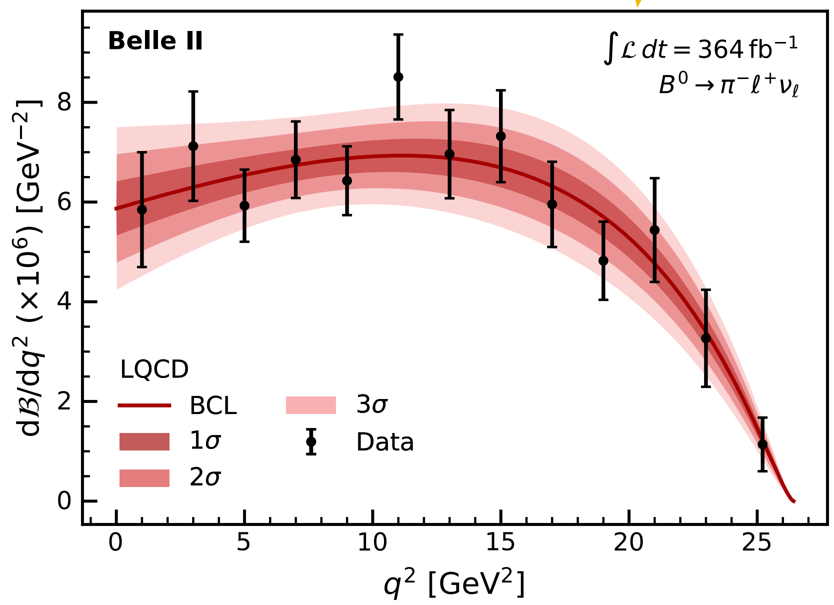
$B^0 \rightarrow \pi^+ l^- \bar{\nu}_l$:

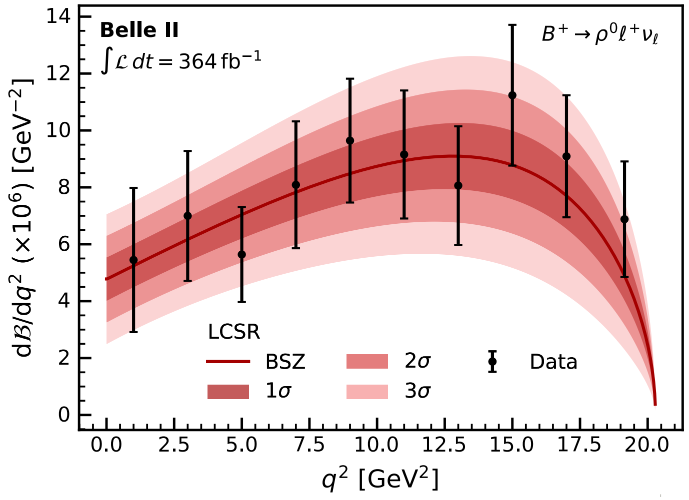
$$|V_{ub}|_{\text{LQCD}} = (3.93 \pm 0.09_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.19_{\text{theo}}) \times 10^{-3}$$
$$|V_{ub}|_{\text{+LCSR}} = (3.73 \pm 0.07_{\text{stat}} \pm 0.07_{\text{syst}} \pm 0.16_{\text{theo}}) \times 10^{-3}$$

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

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

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





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

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:
  - $N_{\pi^+} = 0$ — $B \to \pi^0 l\nu$
  - $N_{\pi^+} = 1$ — $B \to \pi^+ l\nu$
  - $N_{\pi^+} = 2$ — other $B \to X_u l\nu$
  - $N_{\pi^+} \geq 3$

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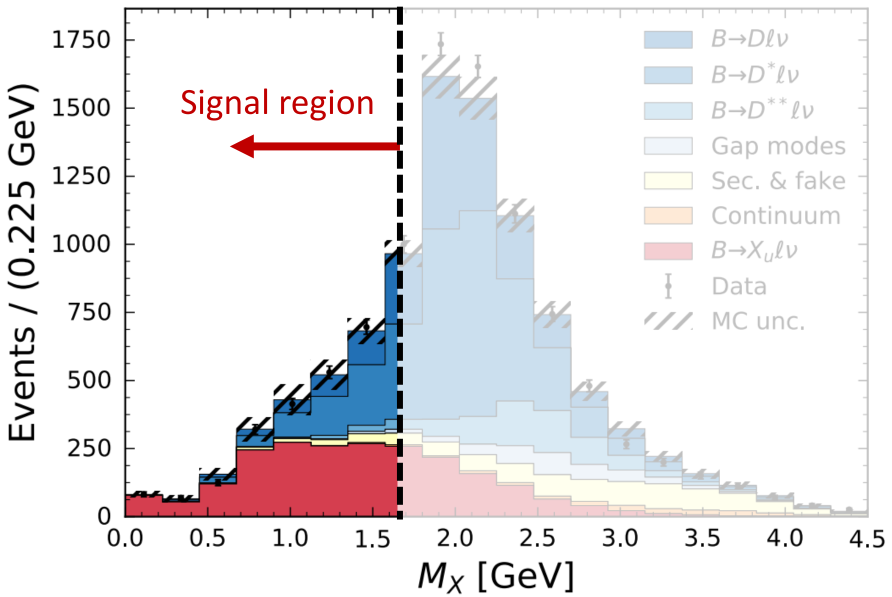
$N_{\pi^+} \geq 3$

other $B \rightarrow X_u l\nu$



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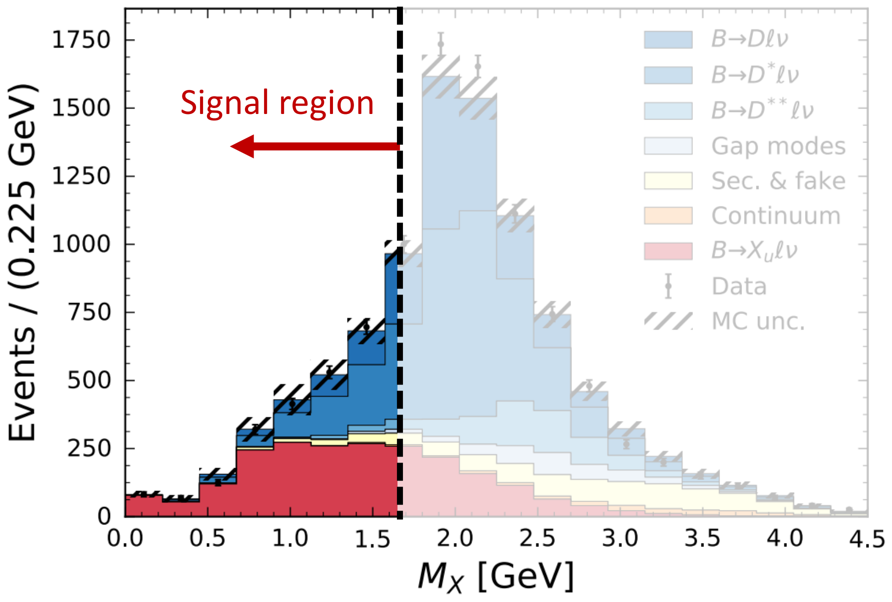
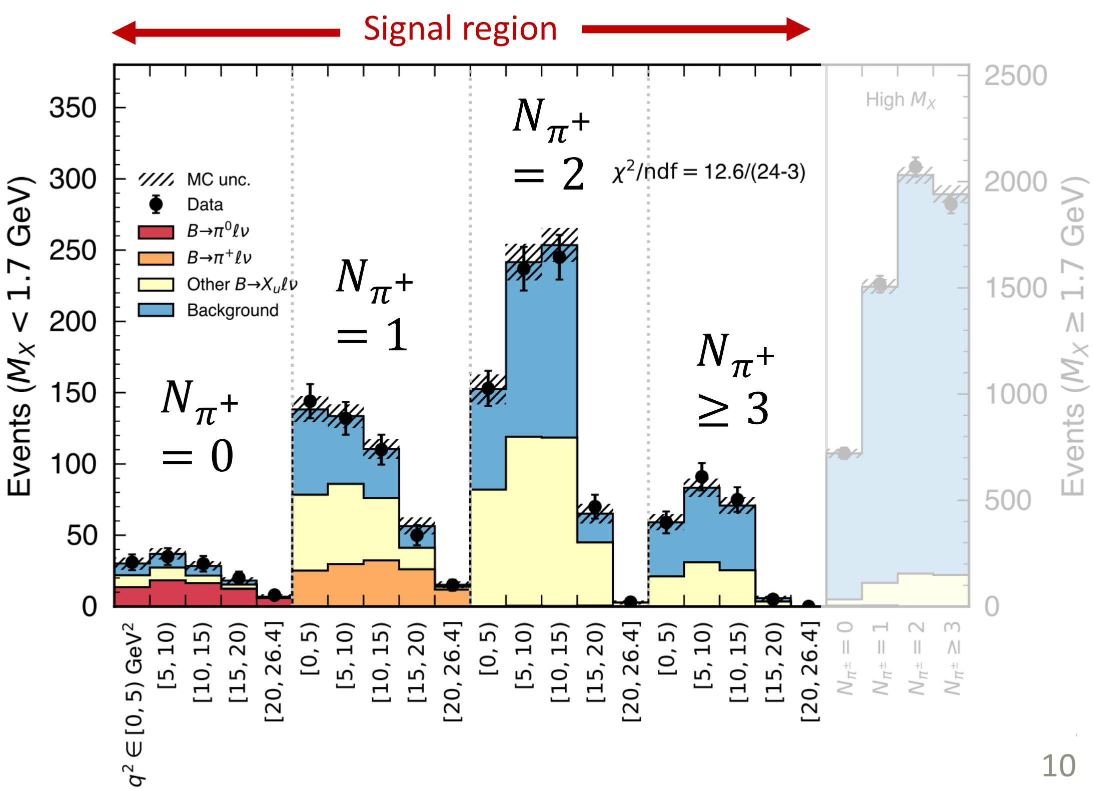
  - $N_{\pi^+} \geq 3$
- Signal region selected in hadronic mass: M_X
- Extract signal yields in 2D fit of q^2 and N_{π^+}





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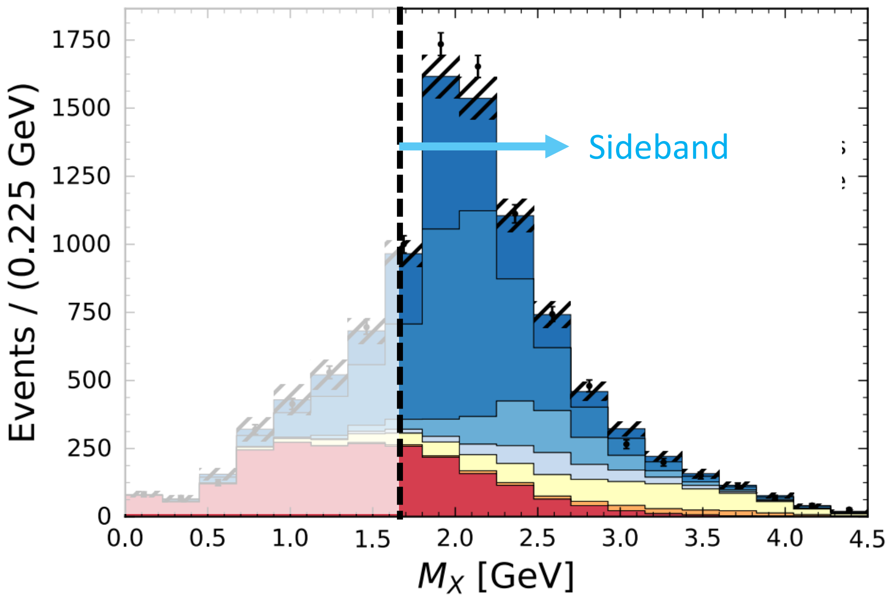
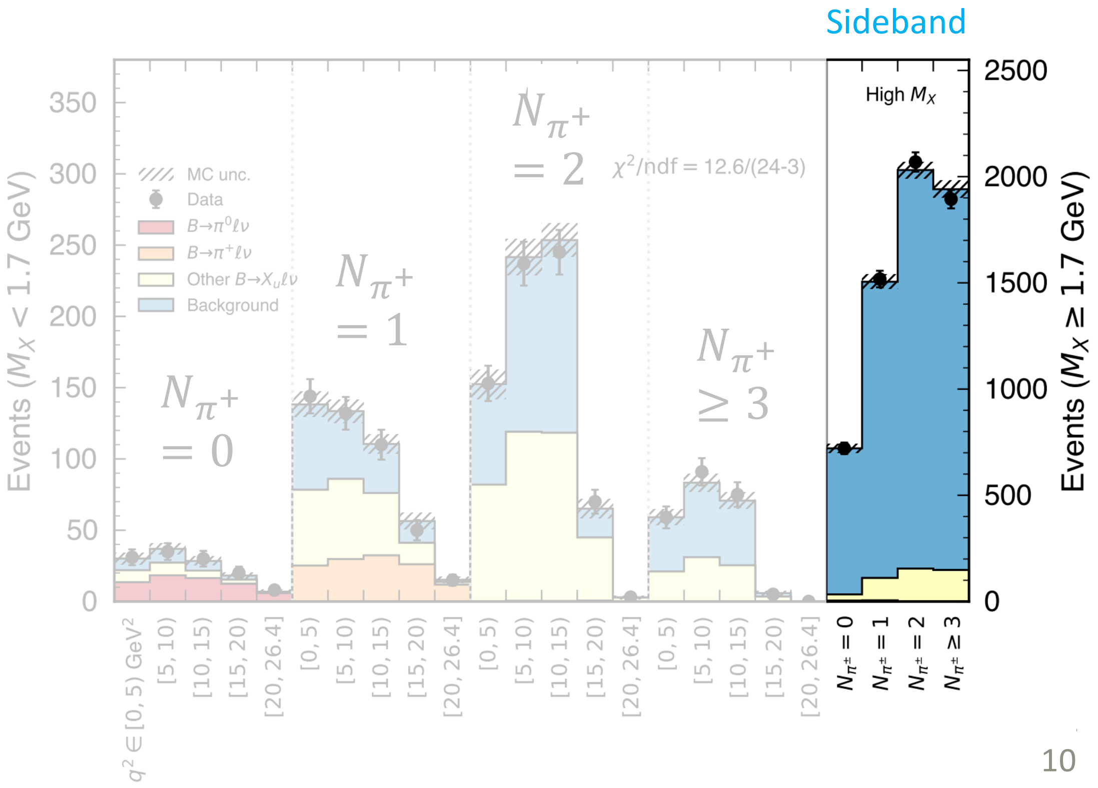


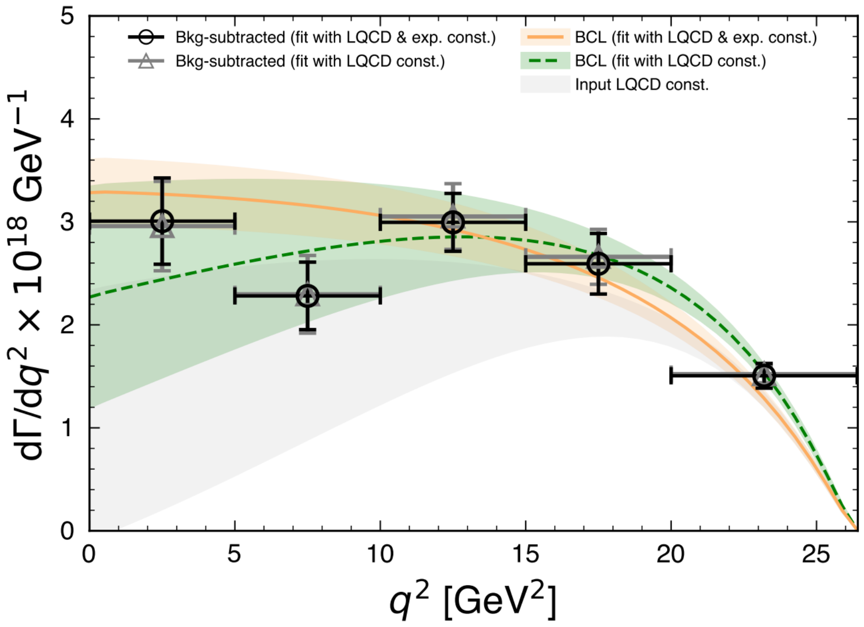
Use high M_X sideband to constrain background



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

Exclusive $|V_{ub}|$:

- Float BCL $B \to \pi l \nu$ FF parameters in fit with two constraining options:
  - FLAG lattice QCD Eur. Phys. J. C 82 (2022) 869
  - FLAG + experimental information



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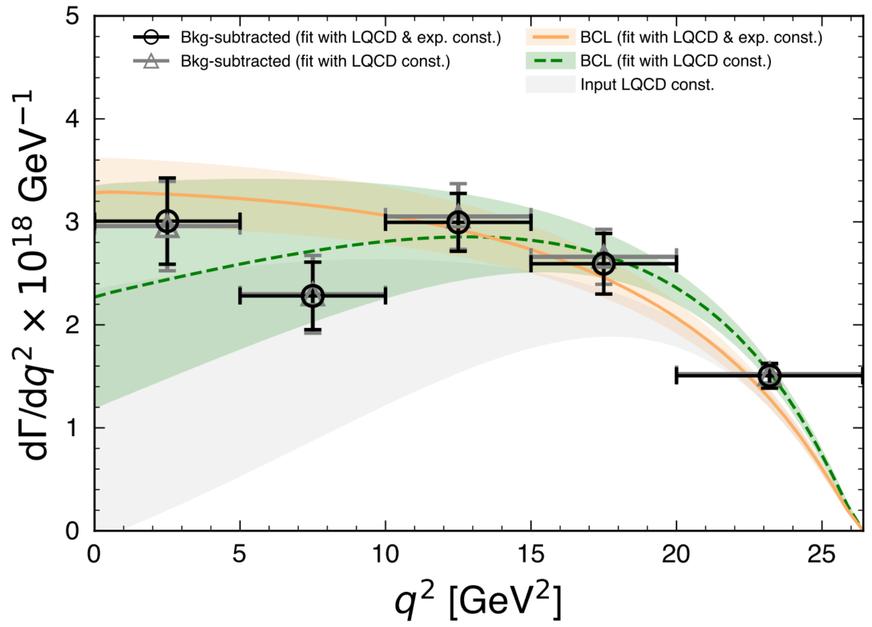

Inclusive $|V_{ub}|$:

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

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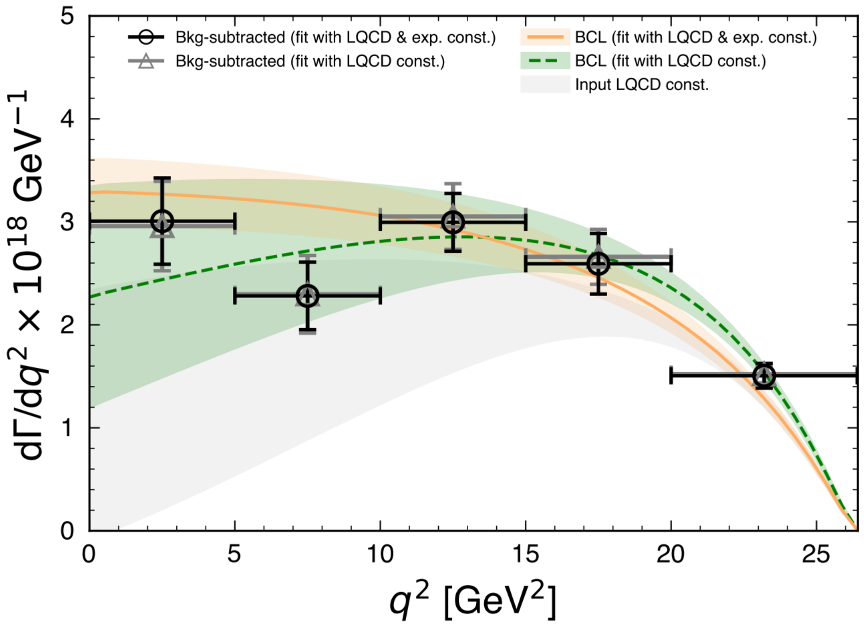

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$$|V_{ub}^{excl}| = (3.78 \pm 0.23_{stat} \pm 0.16_{syst} \pm 0.14_{theo})\times 10^{-3}$$
$$|V_{ub}^{incl}| = (3.90 \pm 0.20_{stat} \pm 0.32_{syst} \pm 0.09_{theo})\times 10^{-3}$$

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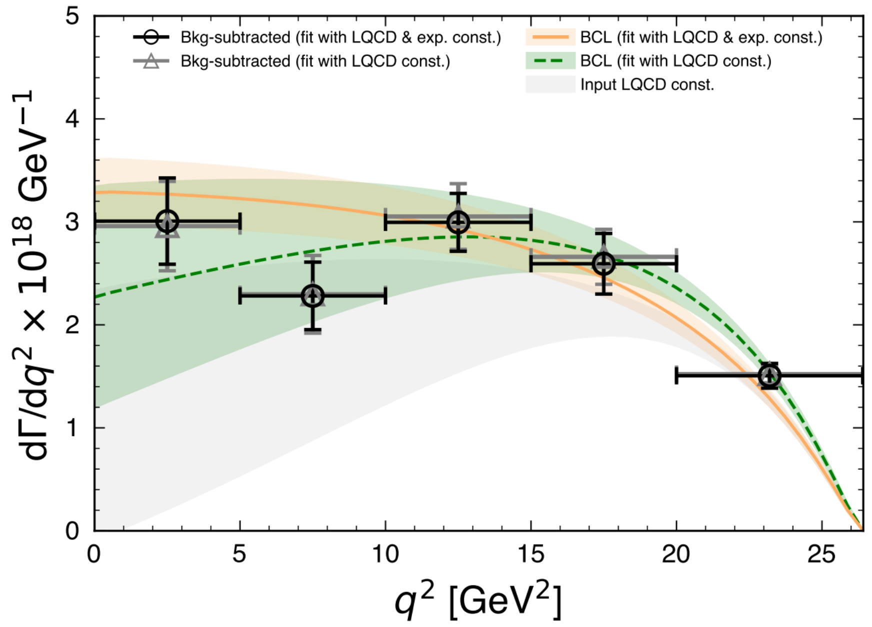
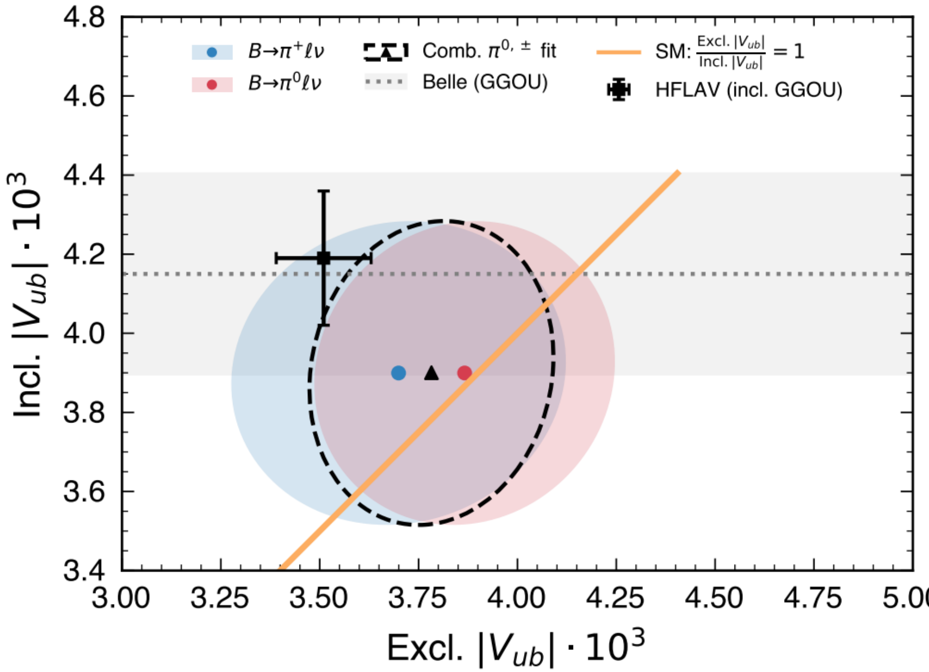


$$|V_{ub}^{excl}| / |V_{ub}^{incl}| = 0.97 \pm 0.12_{tot}$$

Agrees with expectation of 1 and within 1.1σ with the world-average

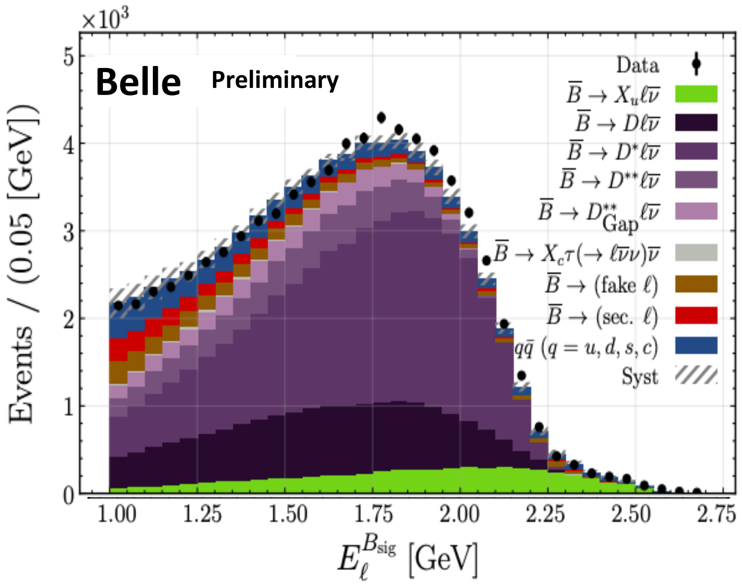


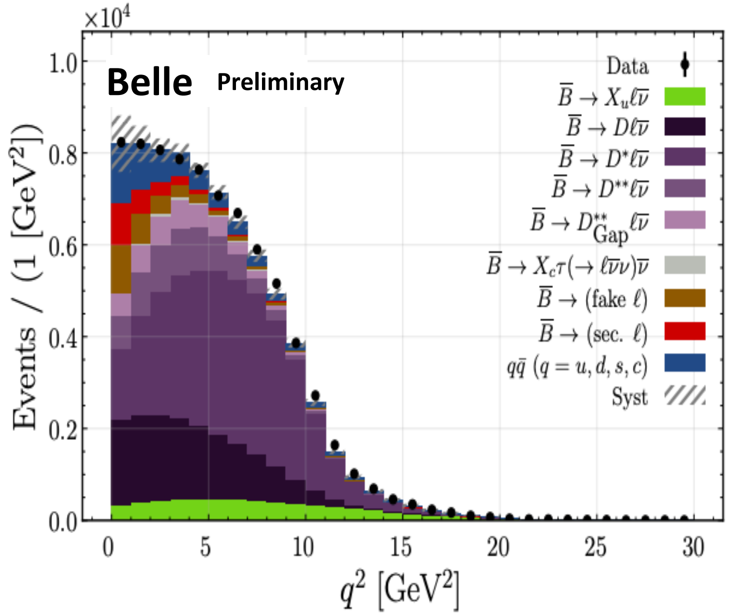
arxiv:2311.00458

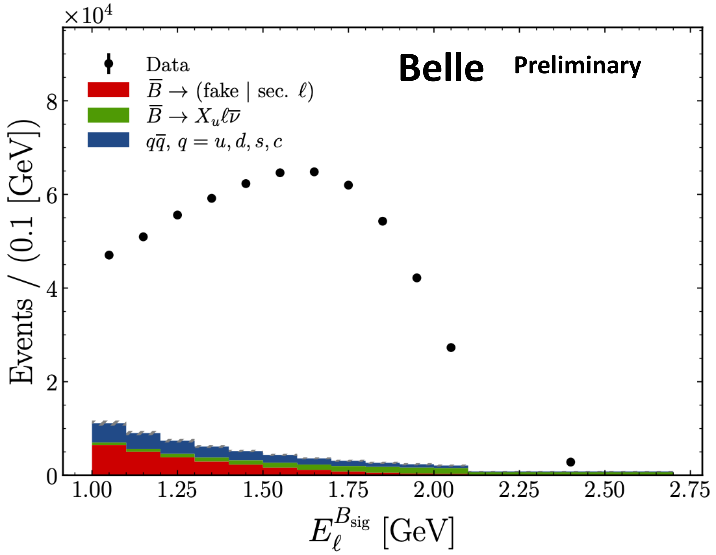
RATIO OF $|V_{ub}| / |V_{cb}|$ AT BELLE

- 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 and q^2
  - $B \to X_c l\nu$ yield via background subtraction
- Obtain (for $E_l > 1.0$ GeV):

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







arxiv:2311.00458

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

- Unfold $B \to X_u l\nu$ and $B \to X_c l\nu$ yields via singular value decomposition (cite)
- Correct for efficiencies and form differential ratios
- Obtain $|V_{ub}|/|V_{cb}|$ using theory input for partial rates

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

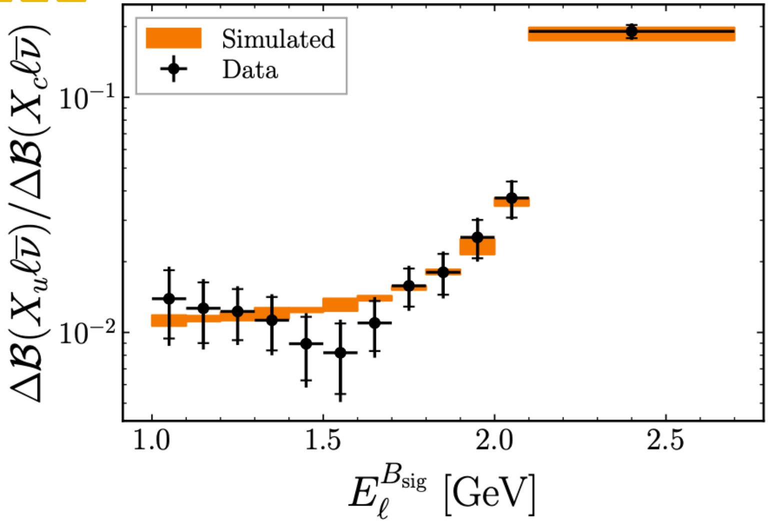
KIN Eur. Phys. J. C **81**, 226

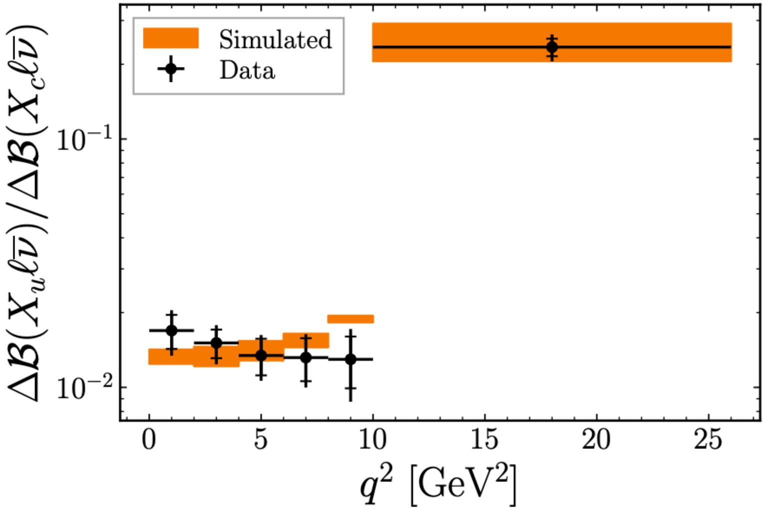
BLNP. Phys. Rev. D **72**, 073006

GGOU. JHEP 10 (2007) 58

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

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



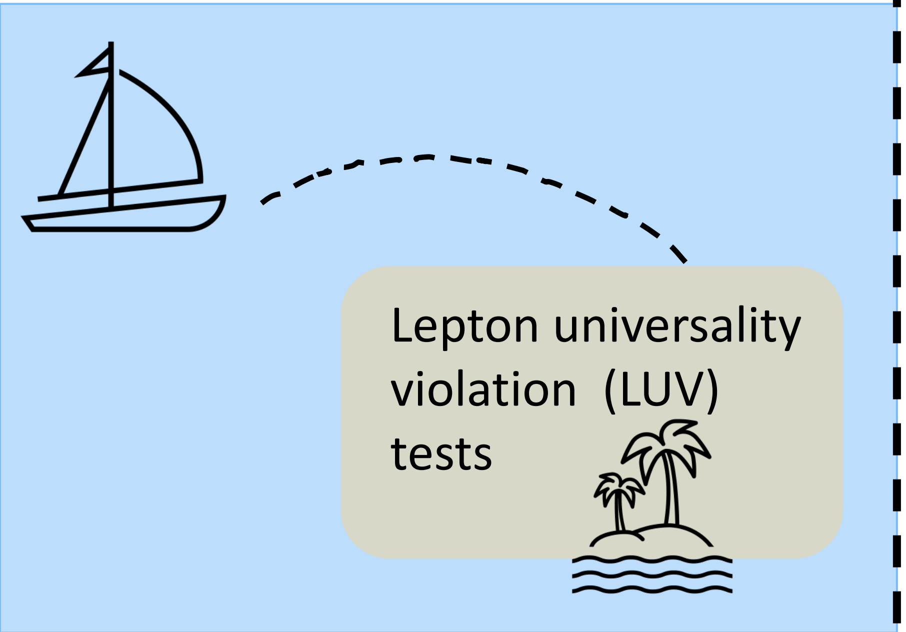


- In agreement with SM prediction

LEPTON UNIVERSALITY VIOLATION (LUV)

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

Angular observables



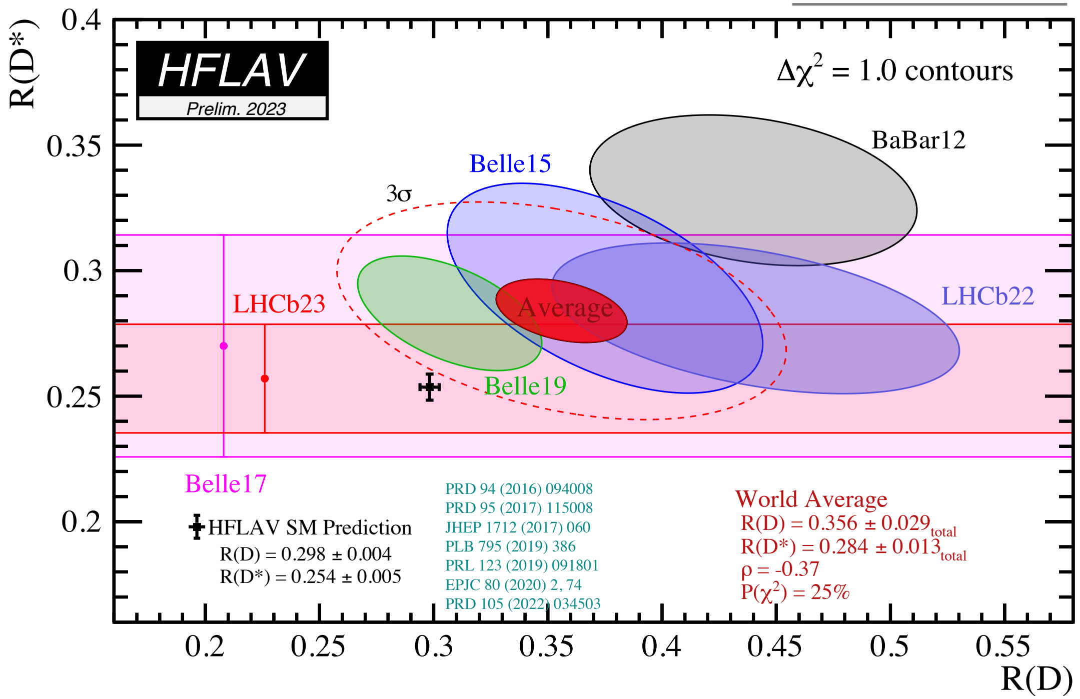
LEPTON UNIVERSALITY VIOLATION (LUV)

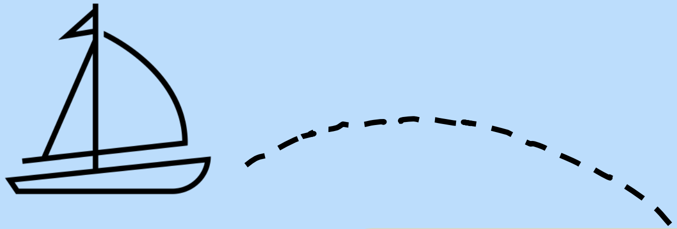
arXiv:2206.07501

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

Angular observables

Tension with SM at ≈ 3σ





Lepton universality violation (LUV) tests

LEPTON UNIVERSALITY VIOLATION (LUV)

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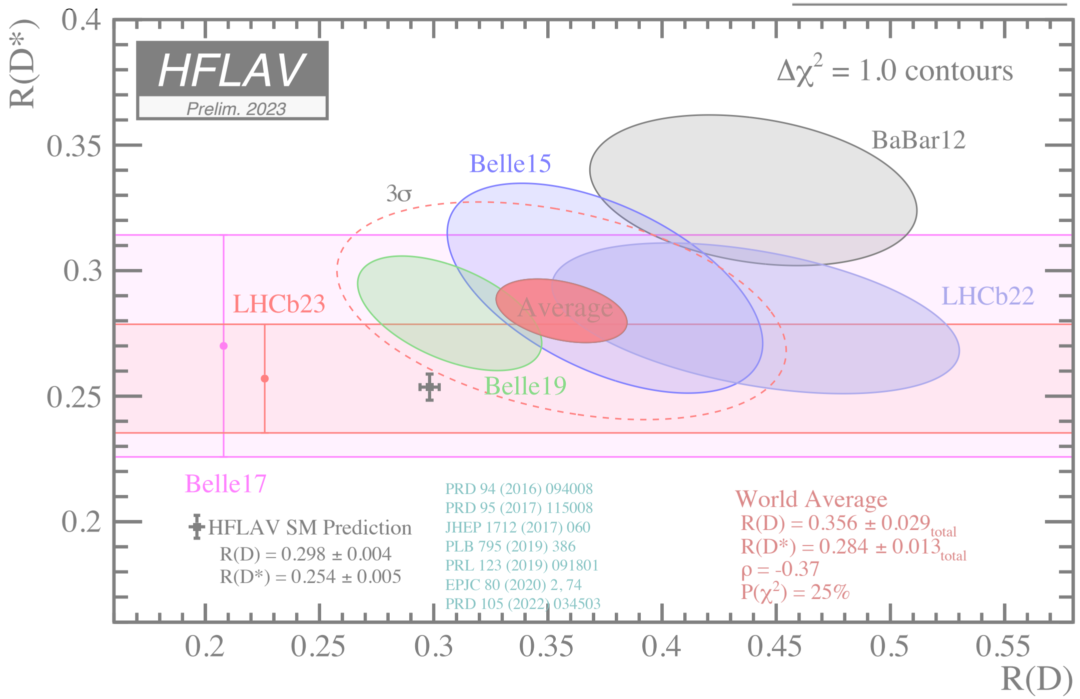
arXiv:2206.07501



Lepton universality violation (LUV) tests

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

Tagged $B \to X l\nu$ at Belle II $R(X)$

arxiv:2401.02840

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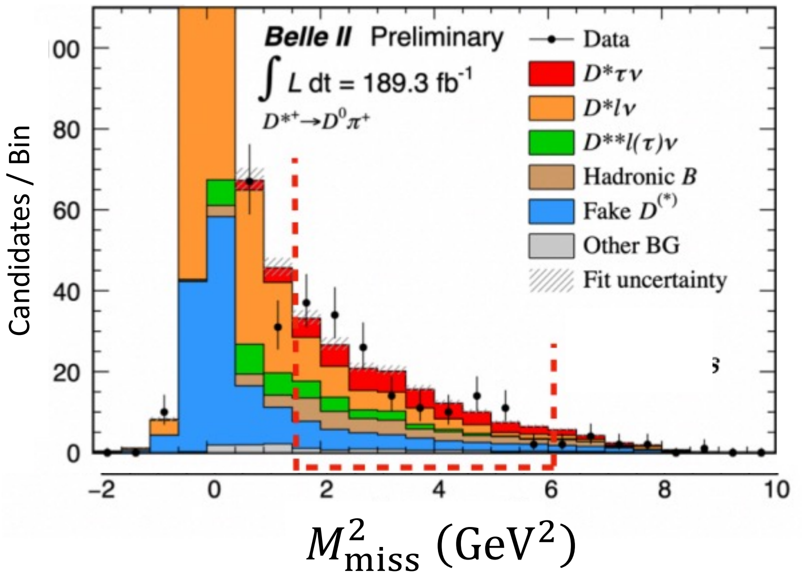
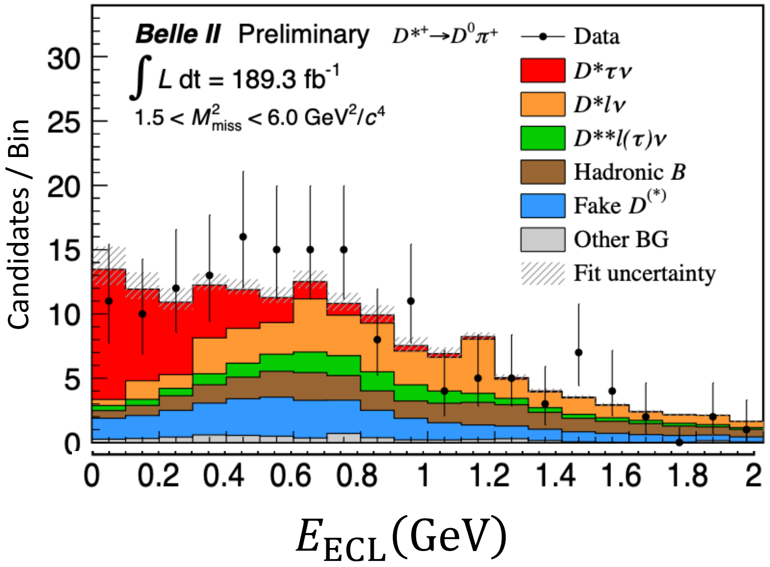
LUV TEST IN $B \to D^* l\nu$ AT BELLE II

- 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 residual energy in the calorimeter E_{ECL} and mass of undetected neutrinos $M^2_{\mathrm{miss}} = (p_{e^+e^-} - p_{B_{\mathrm{tag}}} - p_{D^*} - p_{l/\tau})^2$





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

Consistent with SM prediction and previous measurements

arxiv:2311.07248

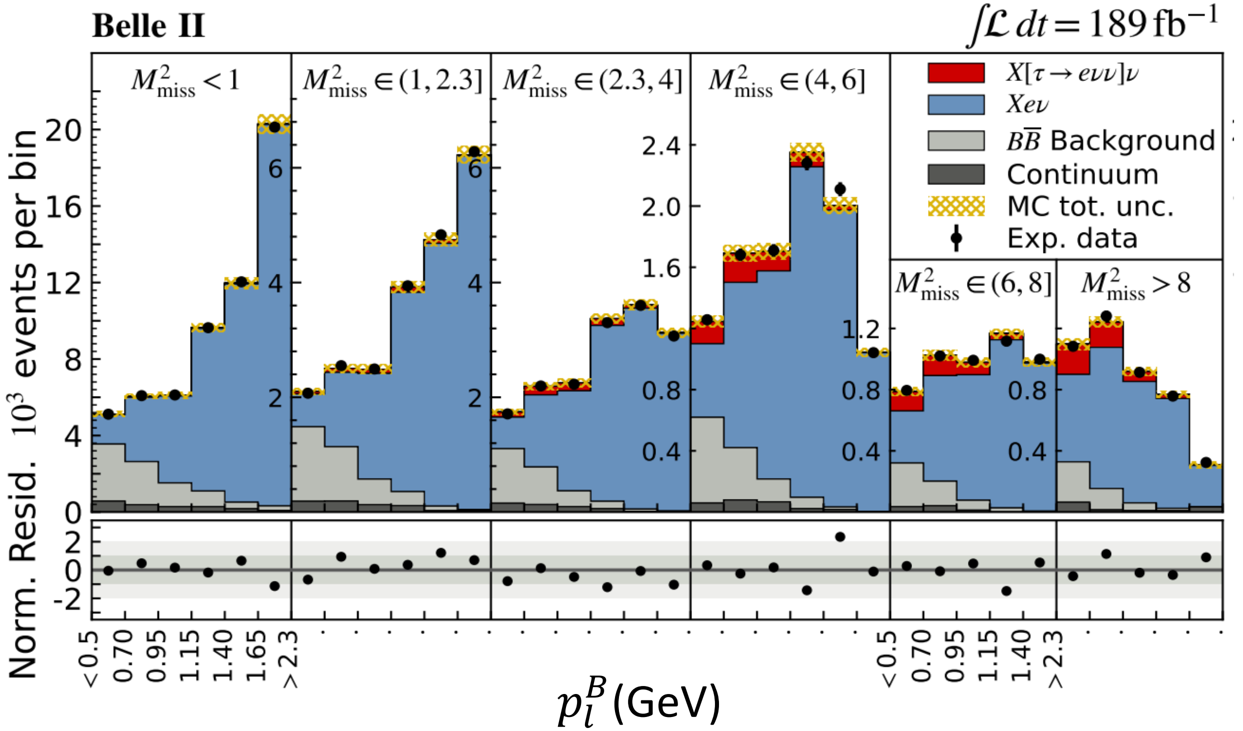
LUV TEST IN $B \to Xl\nu$ AT BELLE II

- Complementary inclusive test of LUV in tagged semileptonic B decays

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

- Main challenge: modelling of backgrounds from $B \to X_c \to l$
  - Use high lepton momentum p_l^B sideband to reweight inclusive $B \to Xl\nu$
- 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 $R(D^{(*)})$

J. High Energ. Phys. **2022**, 7

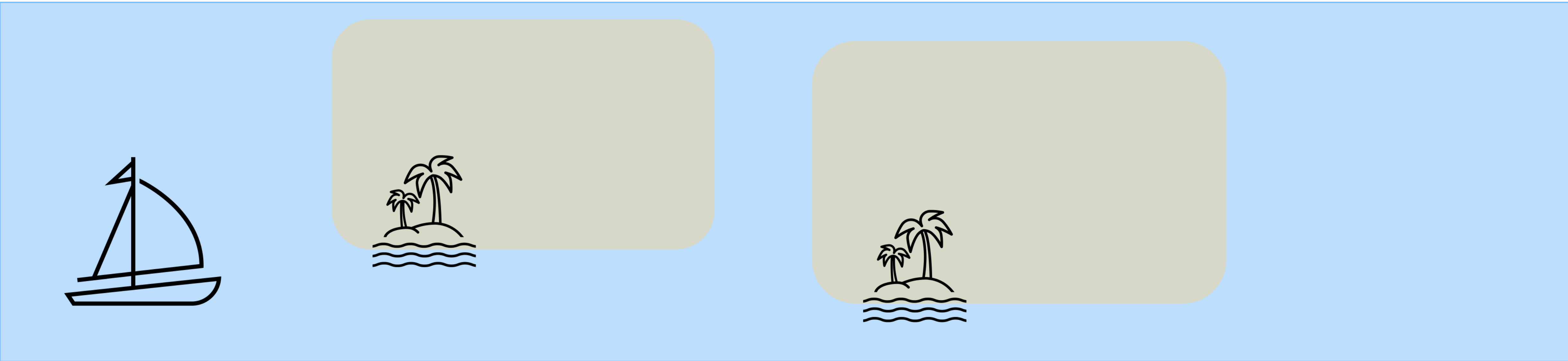
SUMMARY

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



UNIVERSITÄT BONN

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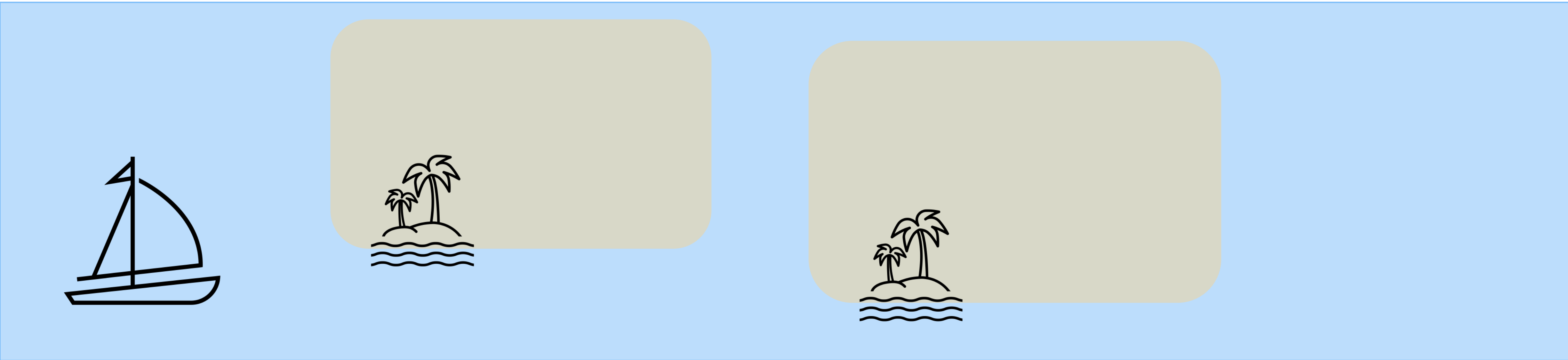

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Many more results:

- Differential distributions of B → D*ℓν
- Angular coefficients of B → D*ℓν
- Branching fractions of B → D(*) π(π)ℓν
- q moments of 2 B → Xcℓν

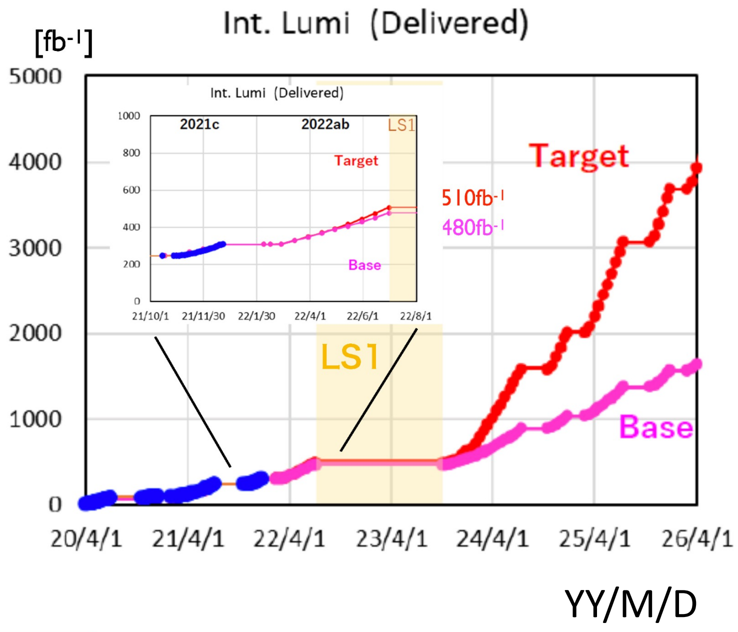
- Test of LFU with inclusive R(Xe/μ)
- |V from untagged cb | B0 → D*+ℓ−ν
- Lepton mass squared moments of B → Xcℓν
- B->D*lnu angular asymmetries

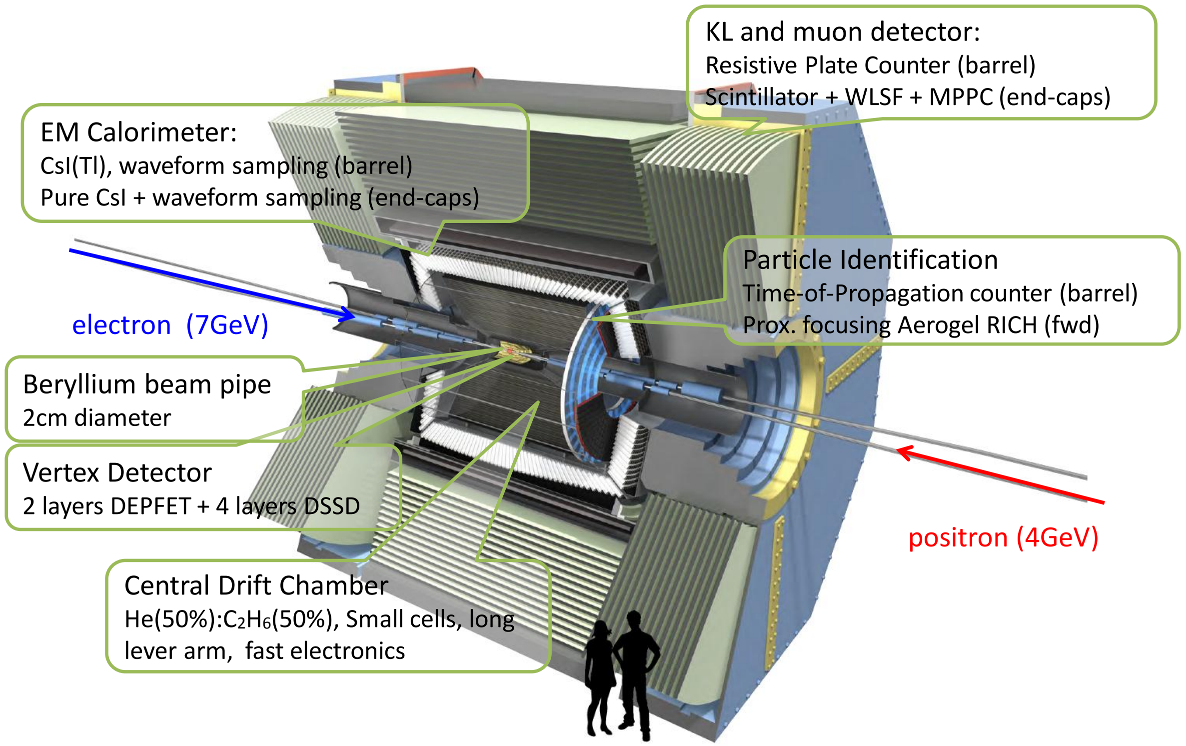
Thank you for your attention!

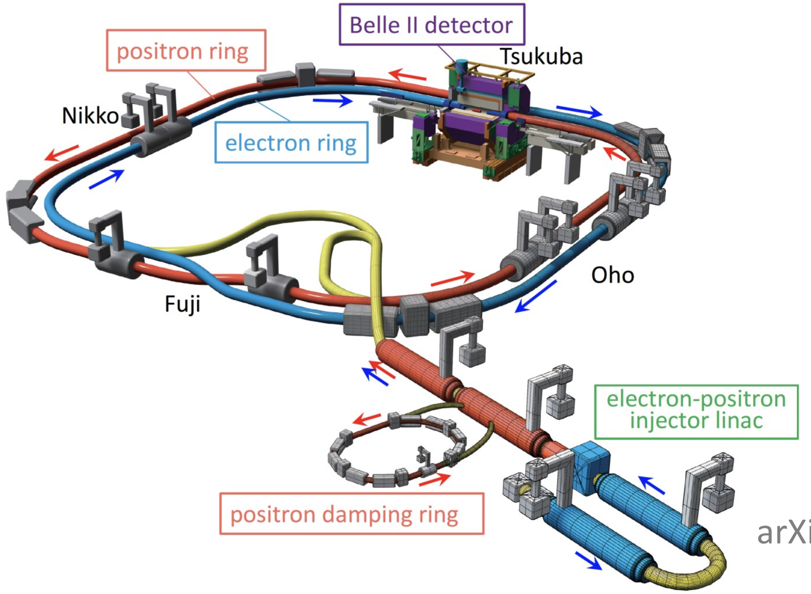
Backup

SUPERKEKB, BELLE II DETECTOR

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





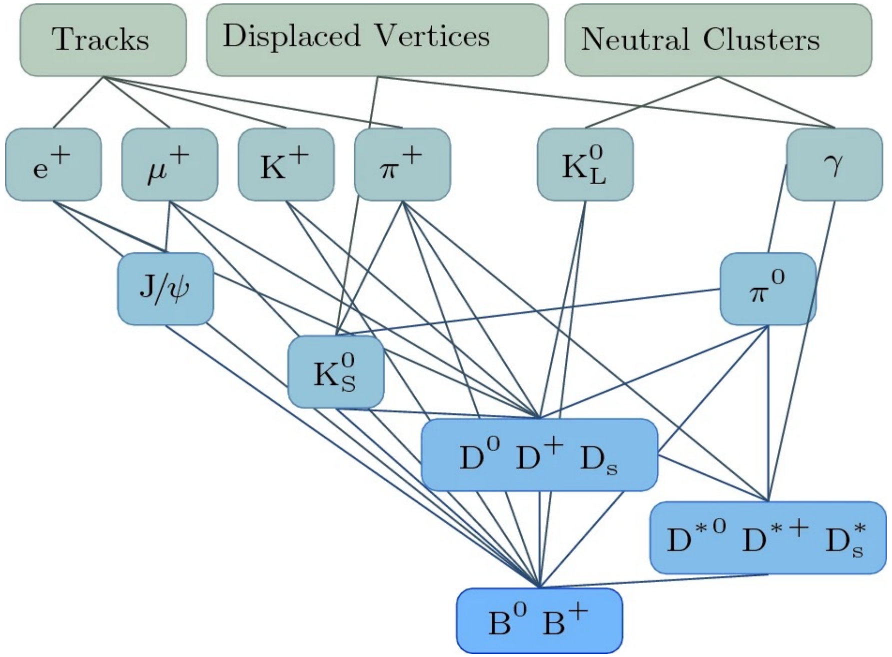


arXiv:1809.01958

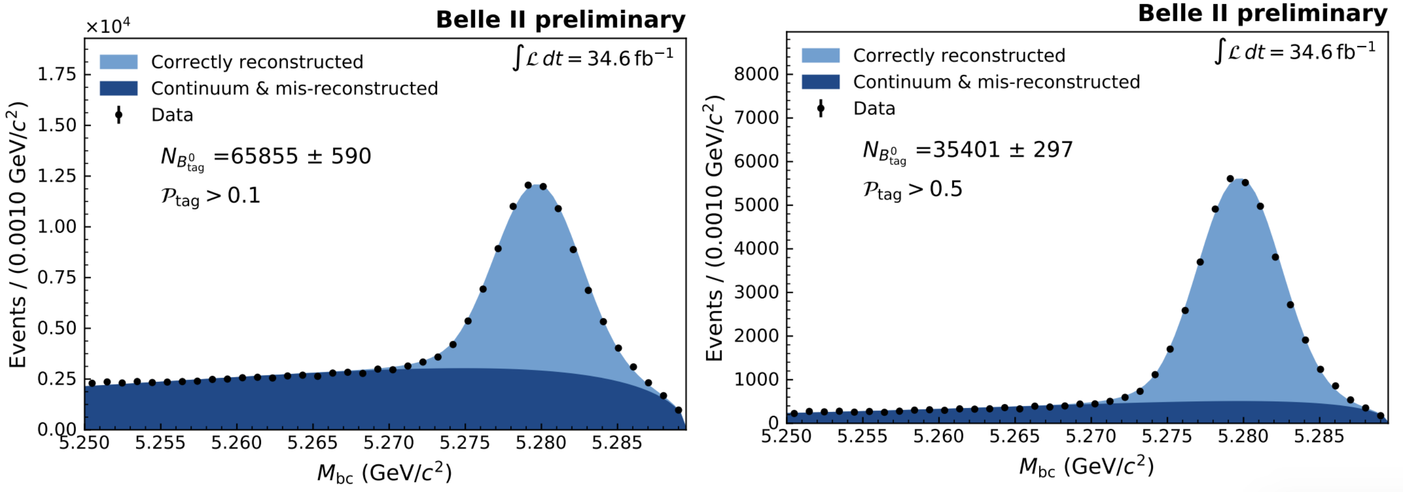
FULL EVENT INTERPRETATION (FEI)

- 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



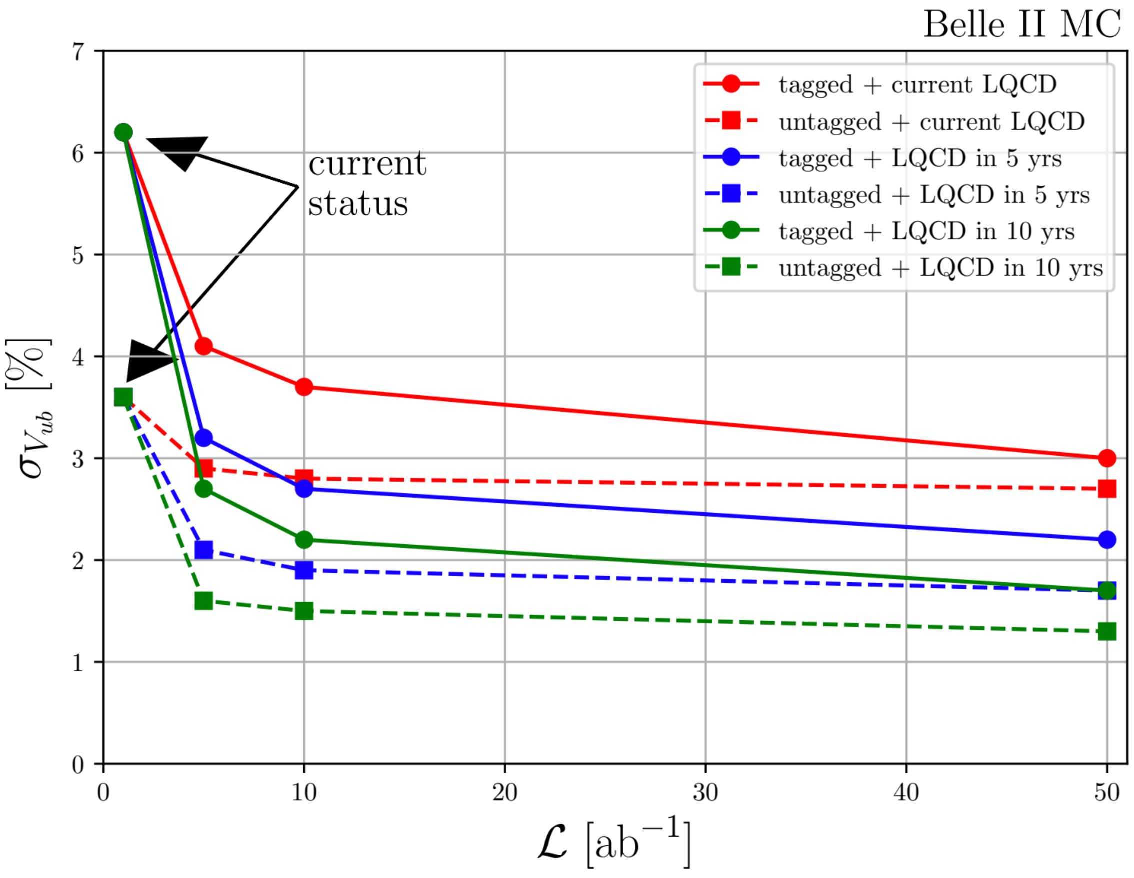
CKM MATRIX ELEMENTS

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

PROJECTION AT BELLE II: R(X)

arXiv:2207.11275

$R(D^{(*)})$:

- Understand B→ $D^{**}l\nu$ downfeed

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

- Control inclusive background composition