UNIVERSITÄT BONN

Belle II

Bundesministerium für Bildung und Forschung

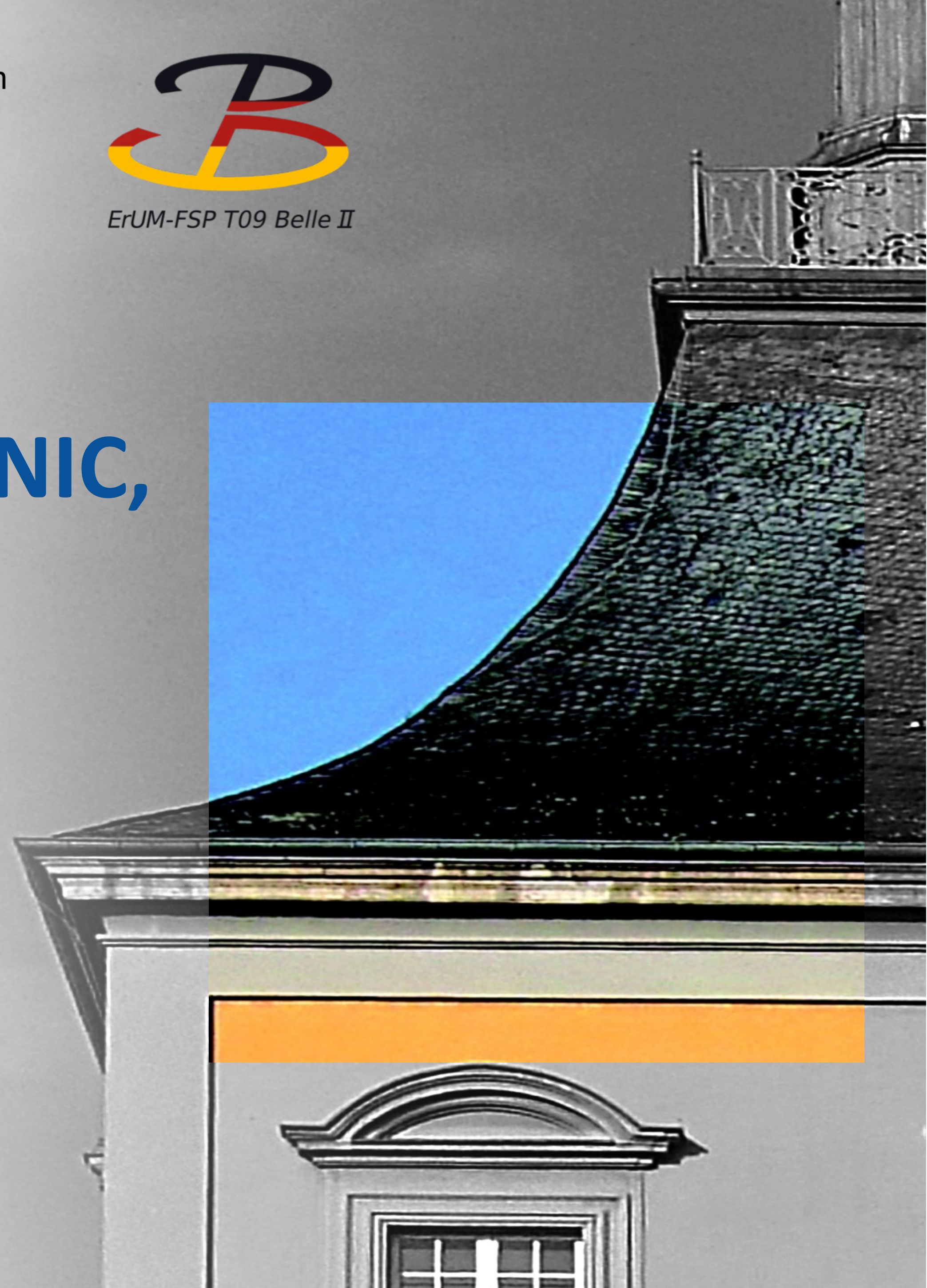
ErUM-FSP T09 Belle II

RECENT RESULTS ON SEMILEPTONIC, RADIATIVE, AND ELECTROWEAK PENGUIN DECAYS AT BELLE II

Svenja Granderath (University of Bonn)

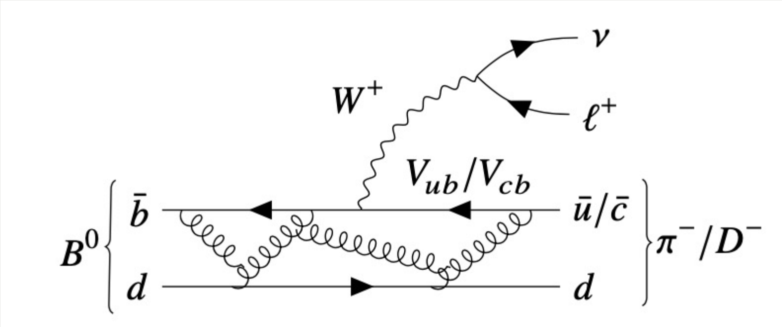
on behalf of the Belle II collaboration

Lake Louise Winter Institute - February 24, 2023



OVERVIEW

SEMILEPTONIC DECAYS



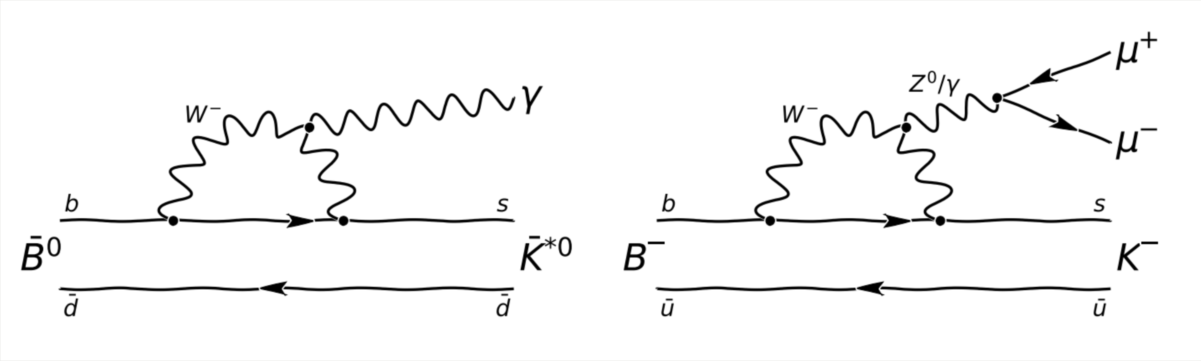
- SM precision measurements

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

- Lepton flavor universality (LFU) tests

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

ELECTROWEAK + RADIATIVE PENGUINS



arXiv: 2205.05222v1

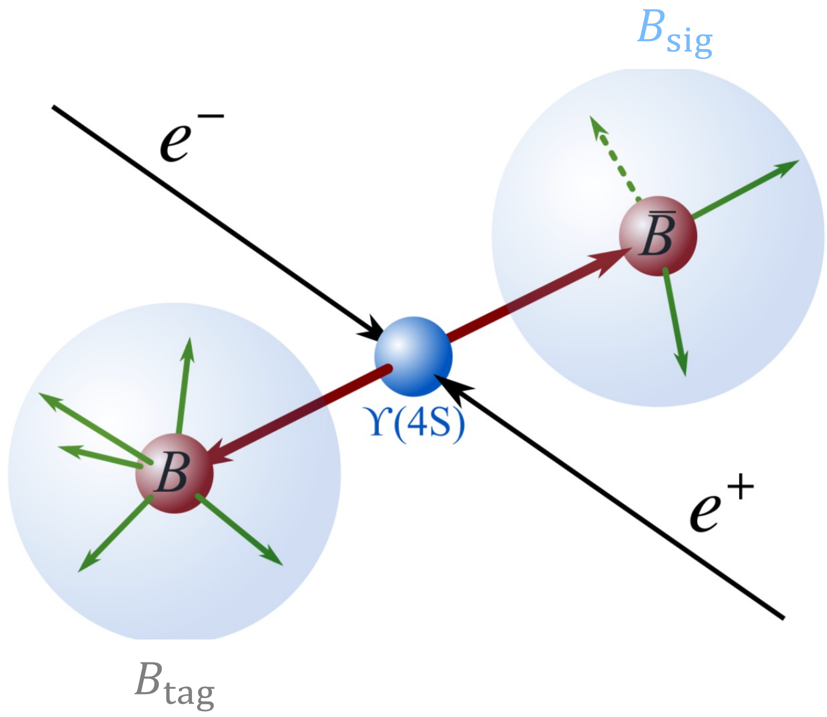
- LFU tests

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

- Non-SM physics probes

RECONSTRUCTION STRATEGIES

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



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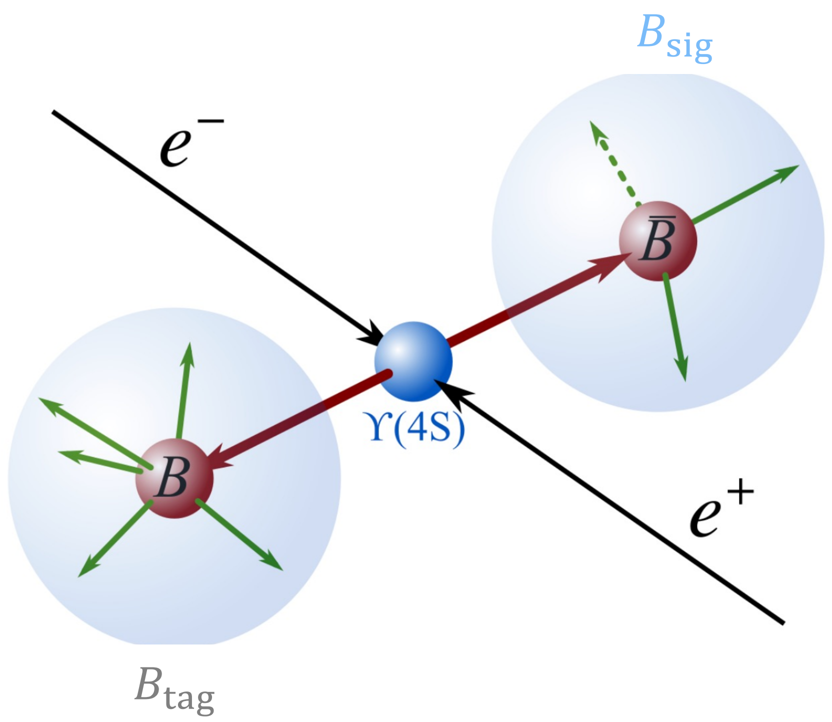

Tagged:

- B_{sig} and B_{tag} reconstructed
- B_{tag} reconstructed using Full Event Interpretation
  Comput Softw Big Sci 3, 6 (2019)

Untagged (inclusive tag):

- Only B_{sig} reconstructed

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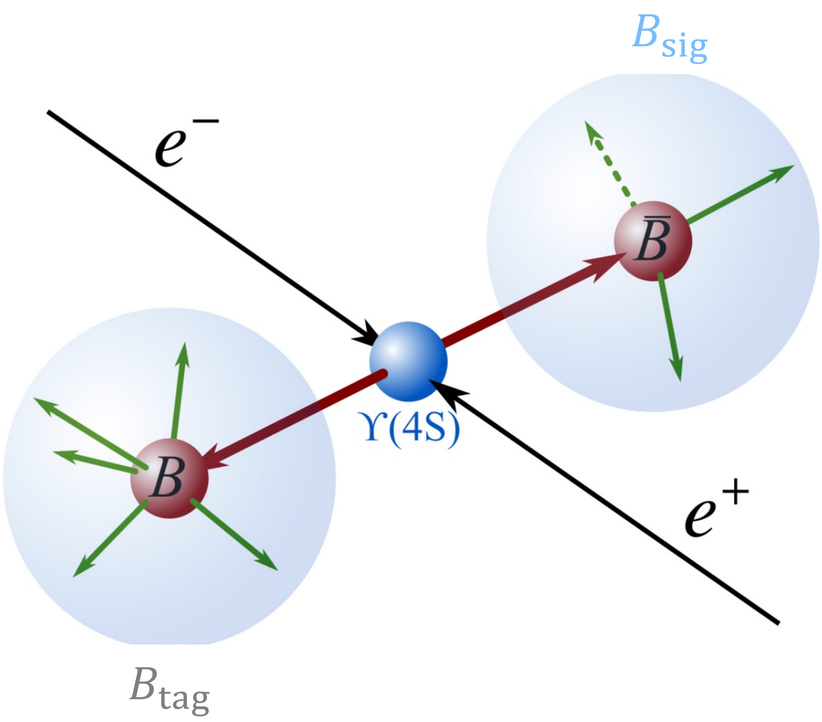

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Low	Efficiency →	High
High	← Purity	Low

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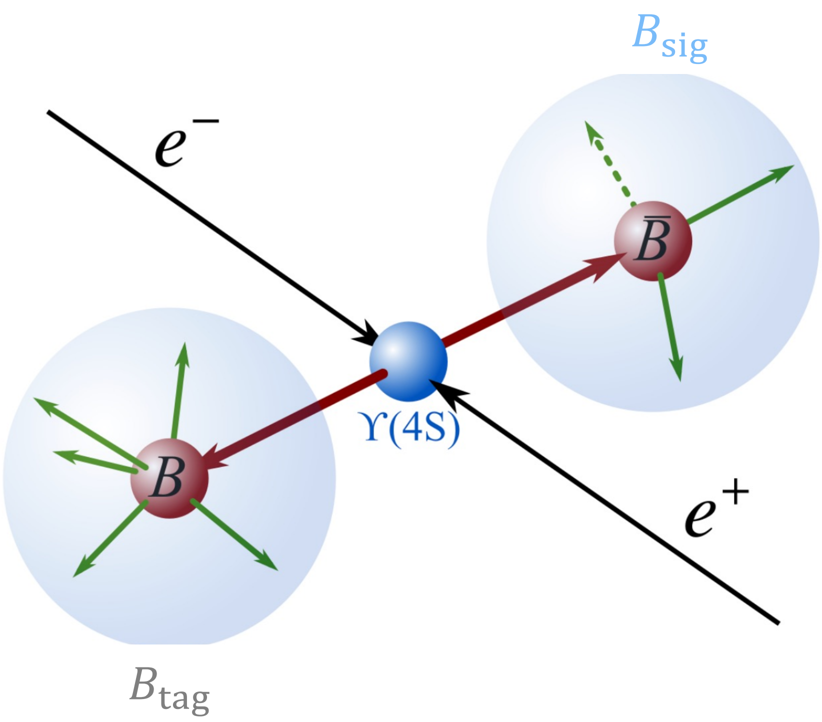

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Low — Efficiency → High

High ← Purity — Low

Exclusive:

- B_{sig} reconstructed as specific final state

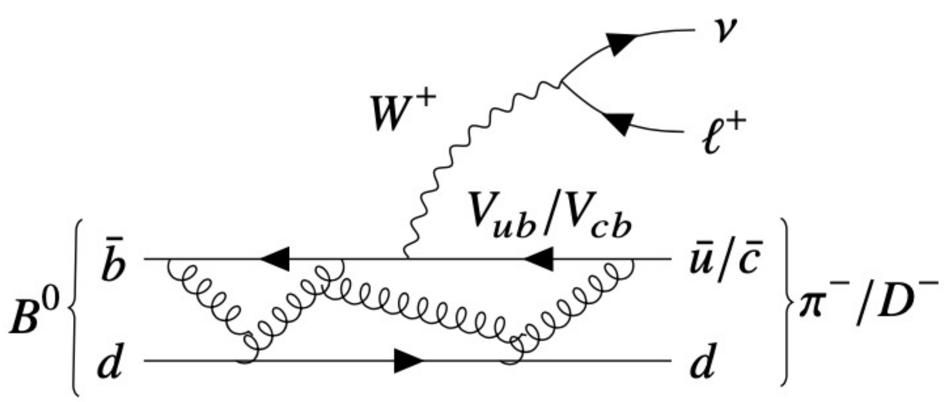
Inclusive:

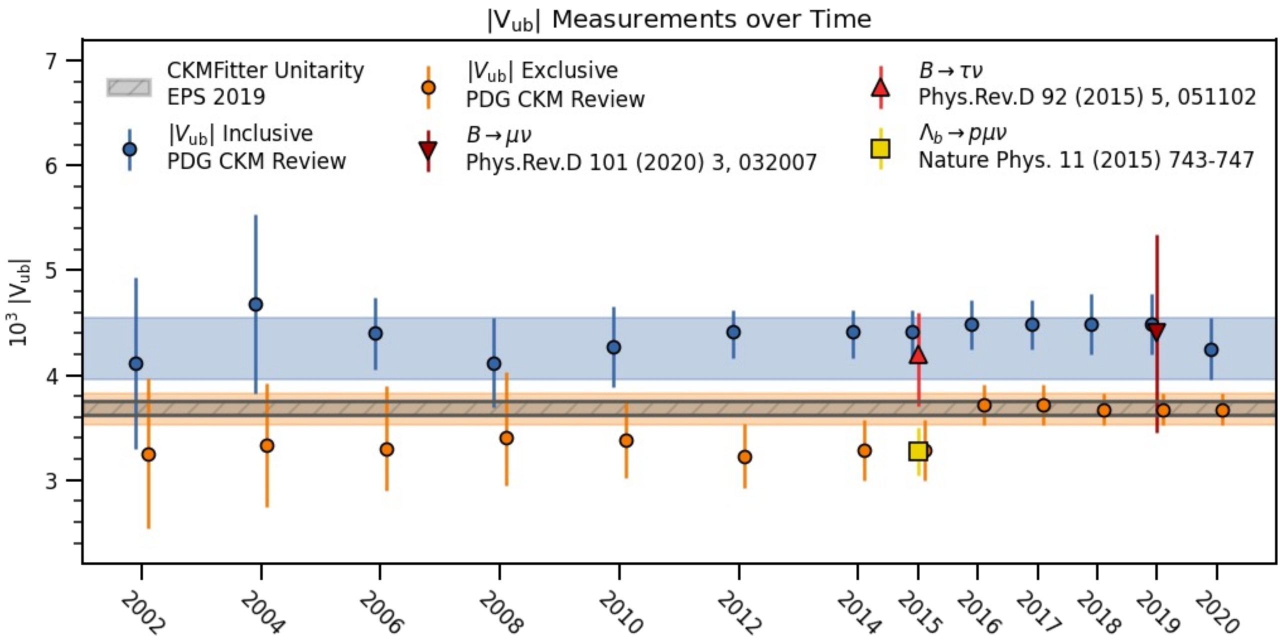
- B_{sig} reconstructed as sum of modes

Approaches are theoretically and experimentally independent

MOTIVATION: CKM MATRIX ELEMENTS

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





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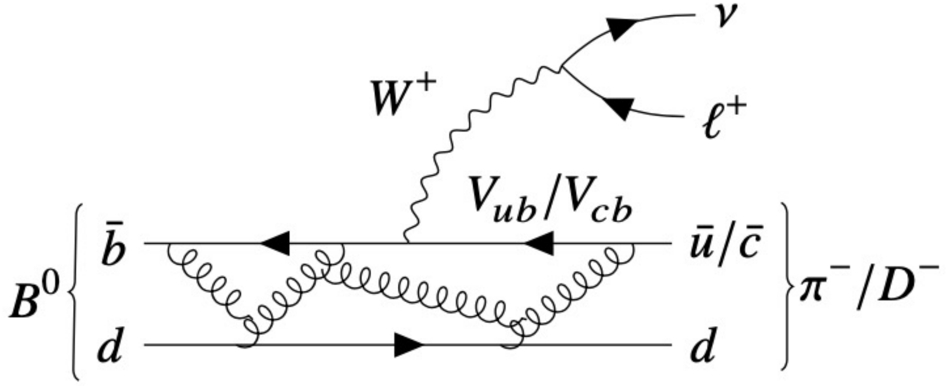

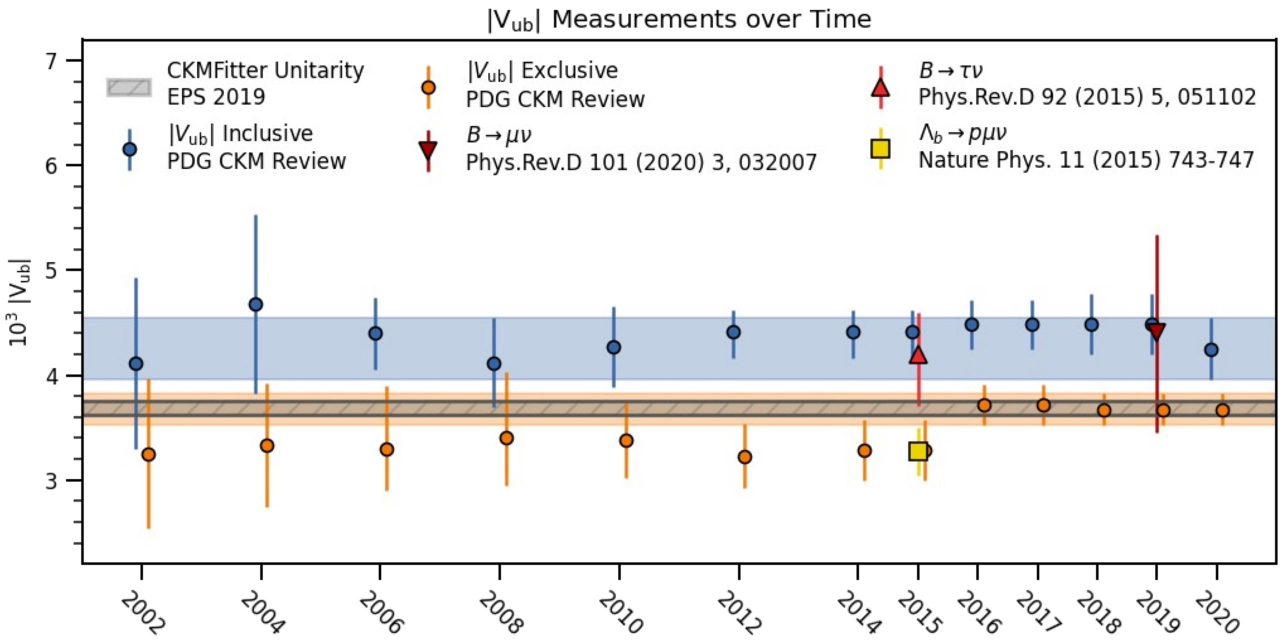

Measure decay rates:

$$\frac{d\Gamma}{dq^2} \propto |V_{ub}|^2 \times |FF(q^2)|^2$$

Momentum transfer squared:
$q^2 = (p_B - p_X)^2$

$$\frac{d\Gamma}{dw} \propto |V_{cb}|^2 \times |FF(w)|^2$$

Hadronic recoil:
$w = \frac{p_B \cdot p_X}{m_B m_X}$

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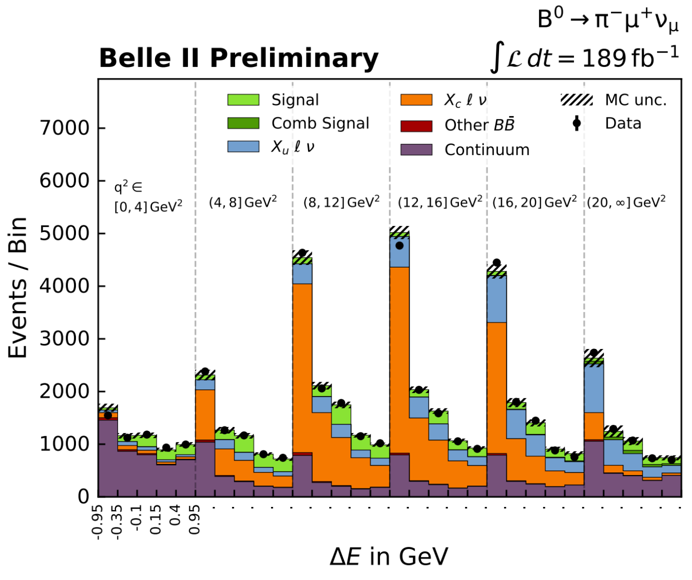
$|V_{UB}|$

UNTAGGED $B^0 \to \pi^- l\nu$ arxiv: 2210.04224

- Large backgrounds suppressed using BDTs

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

- Binned fit of ΔE and M_{bc} in six q^2 bins



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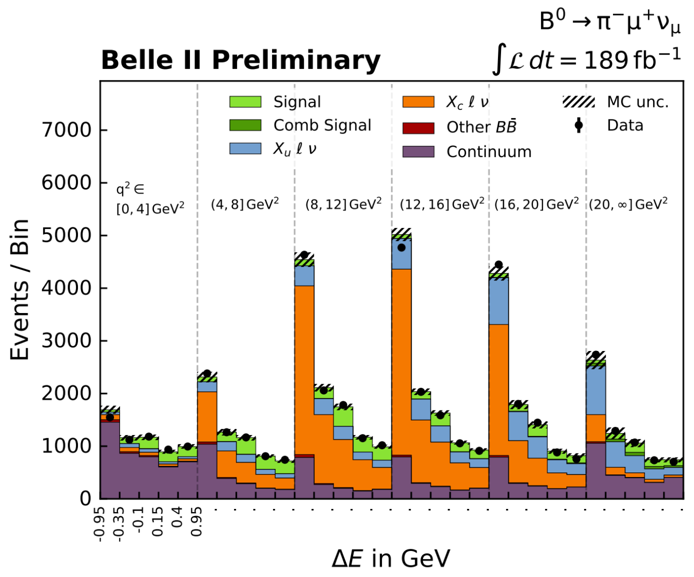
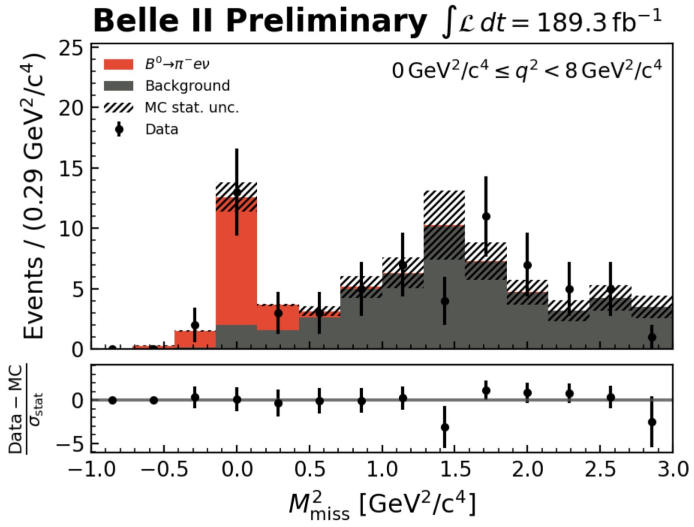
TAGGED $B \to \pi e \nu$ arxiv:2206.08102

$$M_{miss}^2 = p_{e^+e^-} - p_{B_{tag}} - p_\pi - p_e$$

- Binned fit of M_{miss}^2 in three q^2 bins





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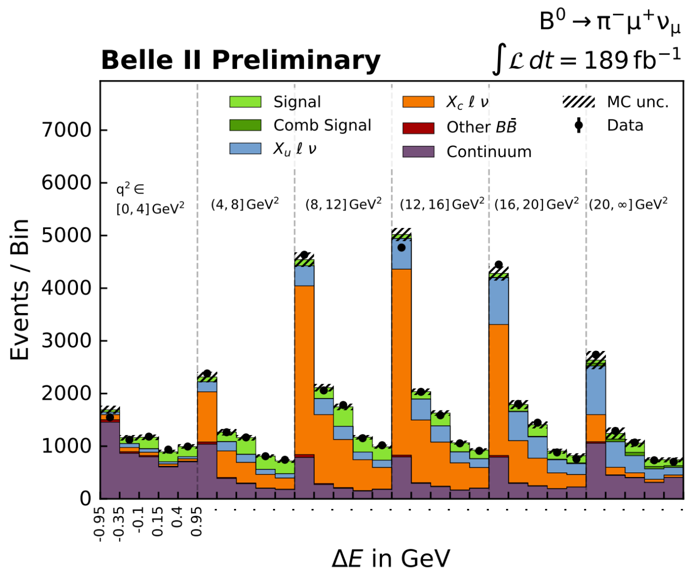
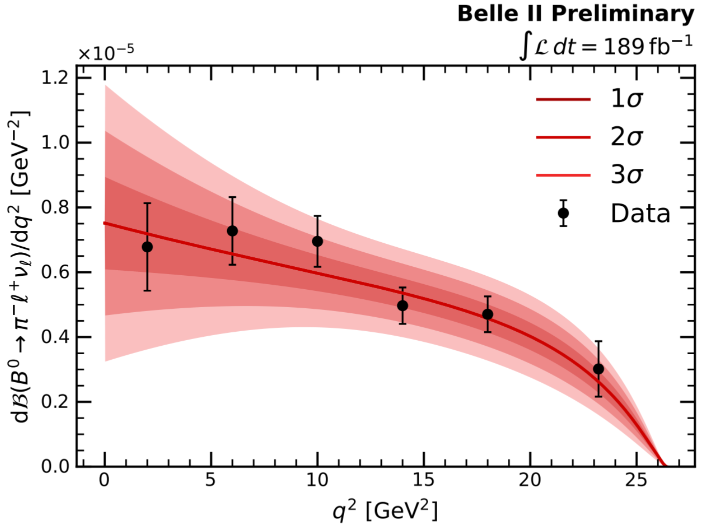
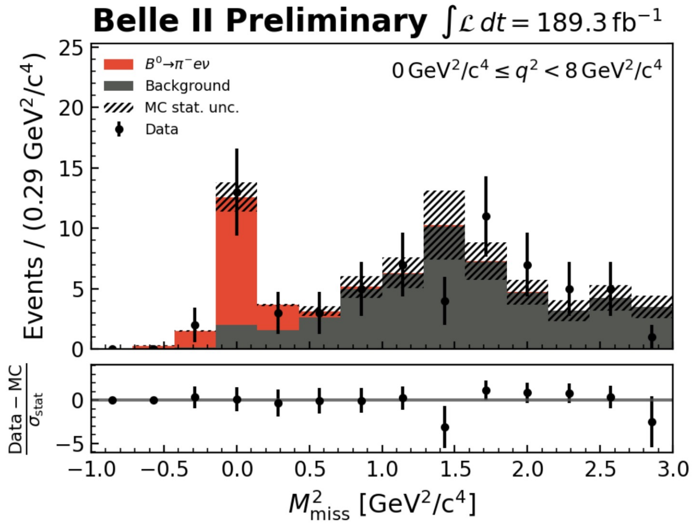
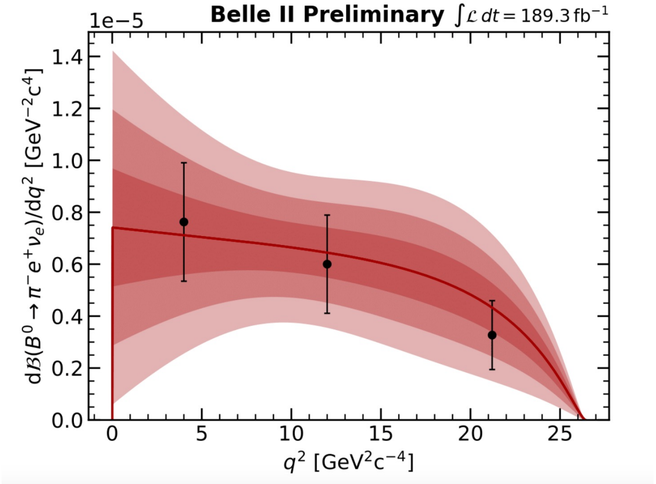








- Combined fit to BCL expansion and form-factor LQCD constraints

Phys. Rev. D 82, 099902
Phys. Rev. D 92, 014024

$$|V_{ub}| = (3.55 \pm 0.12_{stat} \pm 0.13_{syst} \pm 0.17_{theo}) \times 10^{-3}$$

$$|V_{ub}| = (3.88 \pm 0.45_{tot}) \times 10^{-3}$$

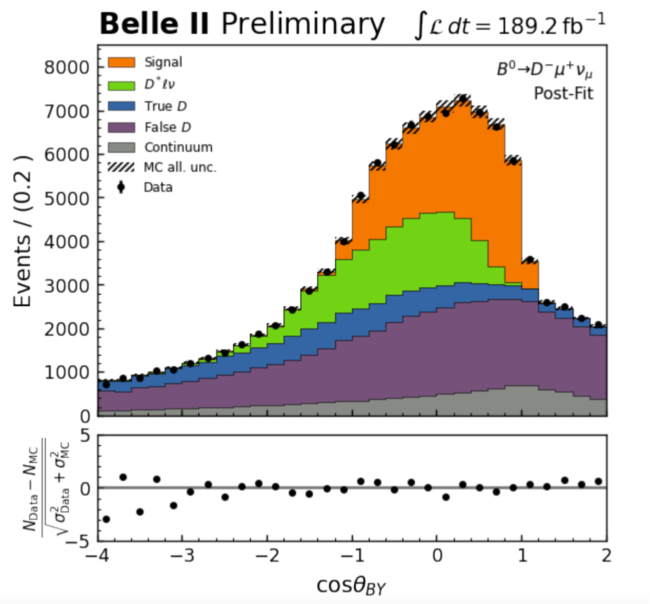
|V_{CB}|

UNTAGGED $B \to Dlv$ arxiv: 2210.13143

- Large backgrounds from B $\to D^{*}lv$

$$\cos\theta_{BY} = \frac{2E_B E_Y - m_B^2 - m_Y^2}{2p_B p_Y} \qquad Y = Dl$$

- Binned fit of $\cos\theta_{BY}$ in ten w bins



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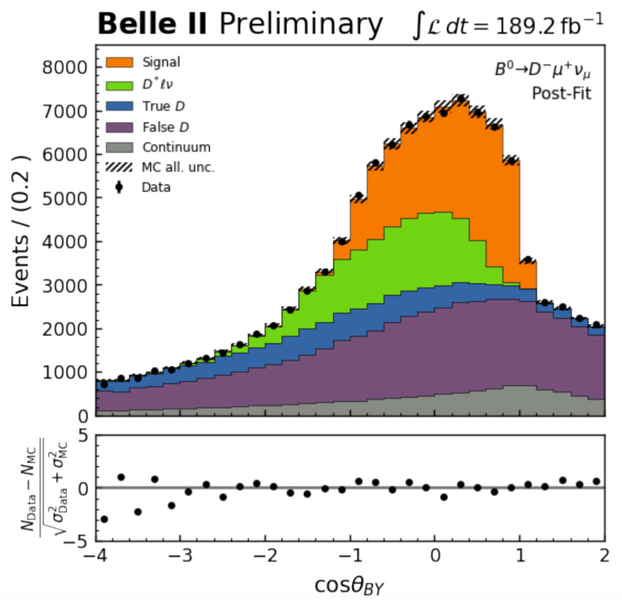

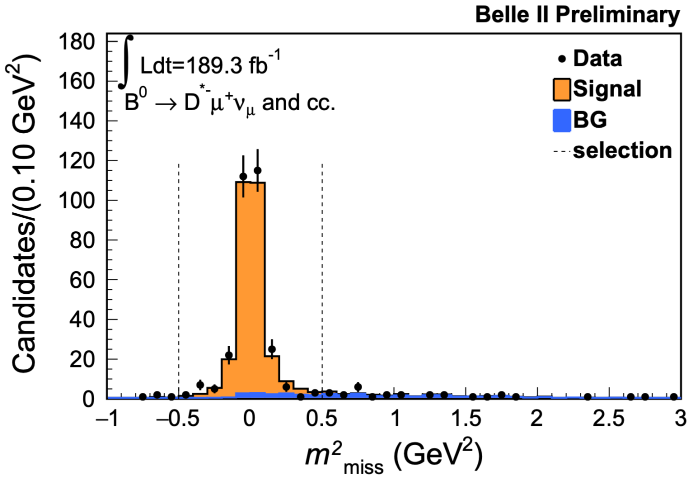

TAGGED $B^0 \to D^{*-}lv$ arxiv: 2301.04716

- Binned fit of M^2_{miss} in ten w bins

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$|V_{CB}|$

UNTAGGED $B \rightarrow Dlv$ arxiv: 2210.13143

- Large backgrounds from B $\rightarrow D^{*}lv$

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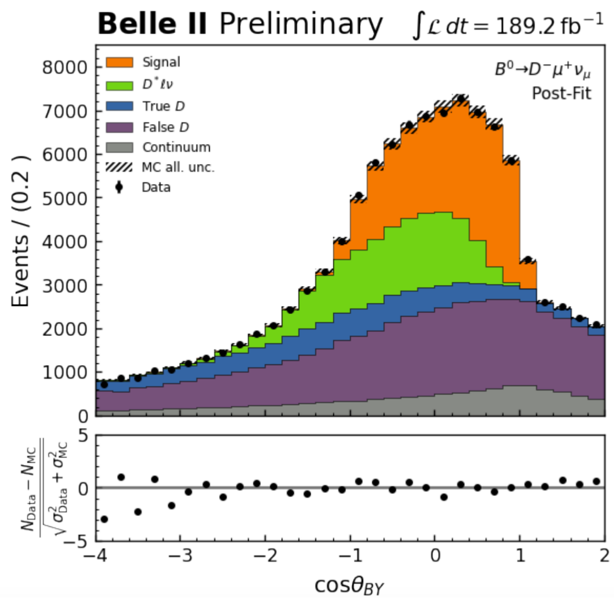
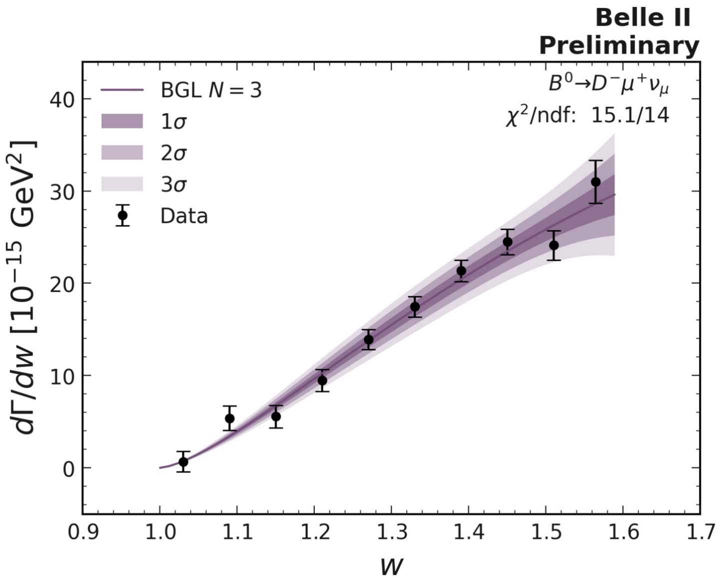
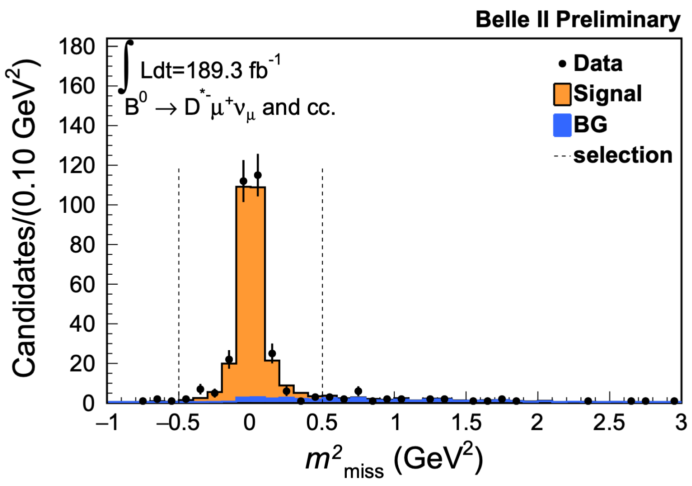
- Combined fit to BGL expansion and form-factor LQCD constraints Phys. Rev. D 56, 6895 Phys. Rev. D 92, 034506 Phys. Rev. D 92, 054510

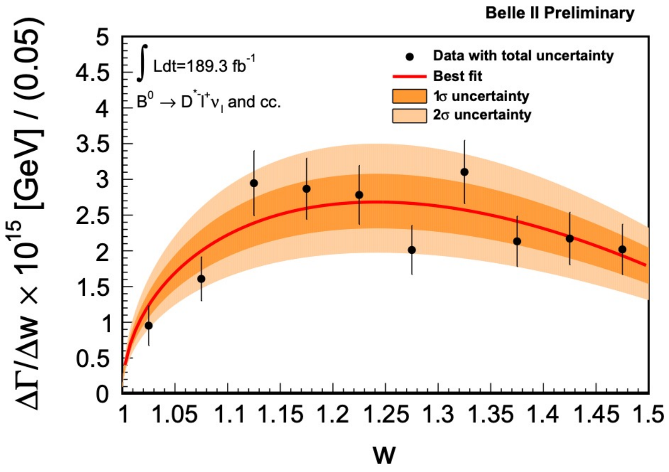
TAGGED $B^0 \rightarrow D^{*-}lv$ arxiv: 2301.04716

- Binned fit of M^2_{miss} in ten w bins
- Fit CLN parametrized form factor to differential decay rates NPB530, 153 (1998))









$$|V_{cb}| = (38.3 \pm 1.2_{tot}) \times 10^{-3}$$

$$|V_{cb}| = (37.9 \pm 2.7_{tot}) \times 10^{-3}$$

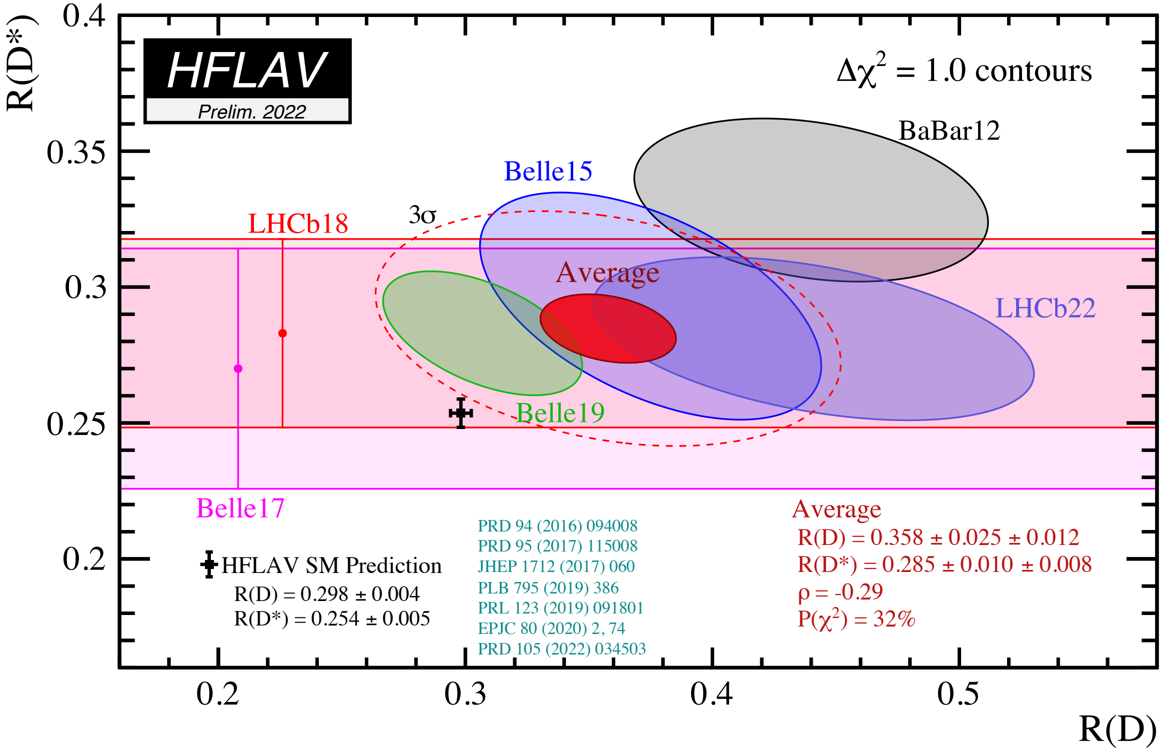
MOTIVATION: LFU TESTS AND EW PENGUINS

– Test LFU in semileptonic decays and electroweak penguins

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

Tension with SM at ≈ 3σ

arXiv:2206.07501



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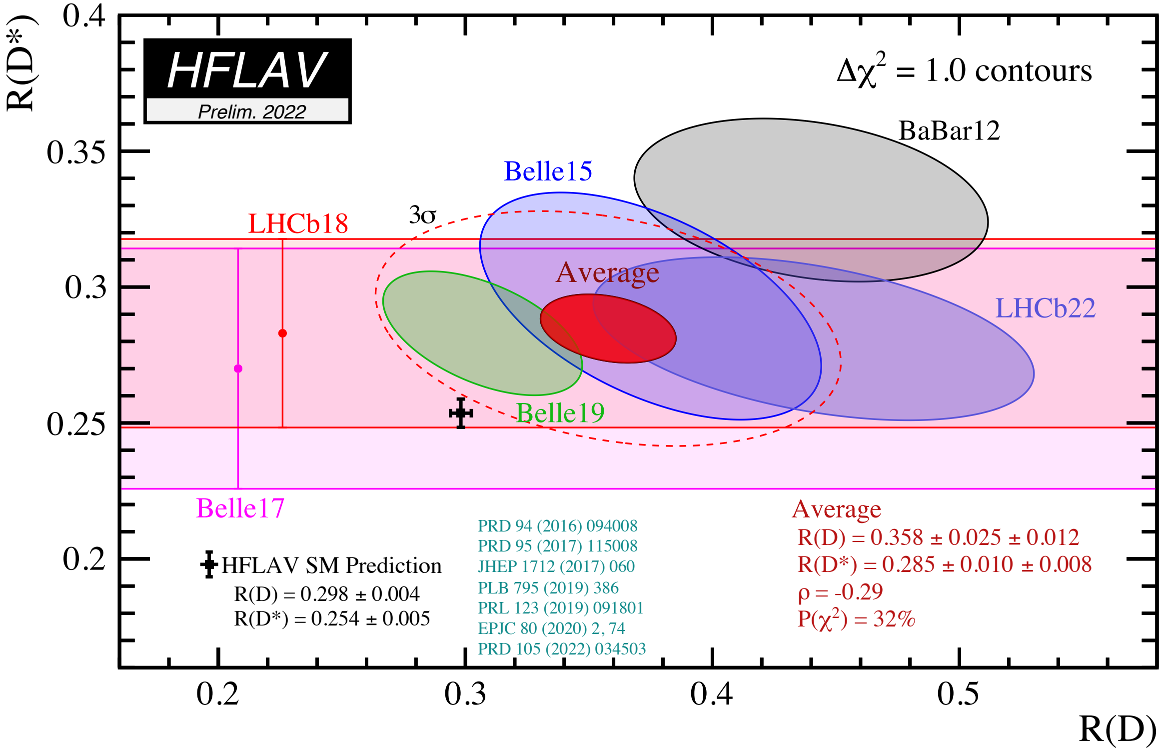
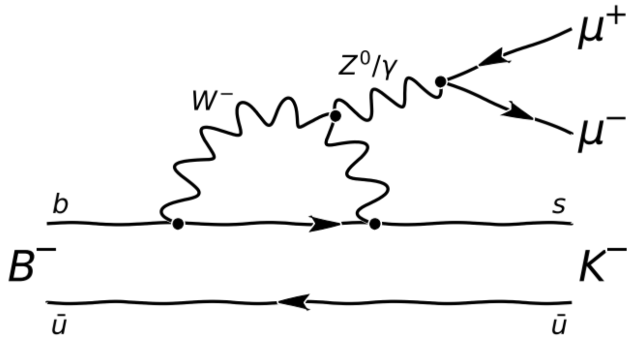




arXiv: 2205.05222v1

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

- Flavor changing neutral current suppressed at tree level
- But allowed in SM through loops
- Sensitive to non-SM contributions

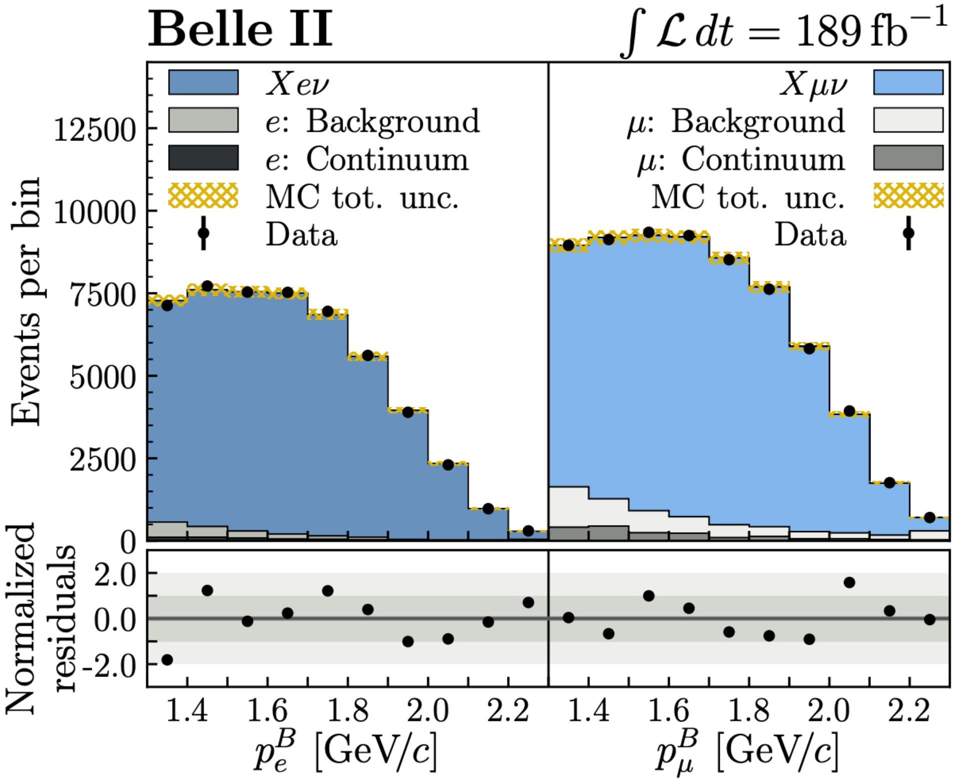
LFU TEST IN $B \to Xl\nu$

arXiv: 2301.08266, submitted to PRL

- Inclusive test in tagged semileptonic decays

$$R(X_{e/\mu}) = \frac{\mathcal{B}(B \to Xe\nu)}{\mathcal{B}(B \to X\mu\nu)}$$

- Fit lepton momentum ($p_l^* > 1.3$ GeV/c) in B frame



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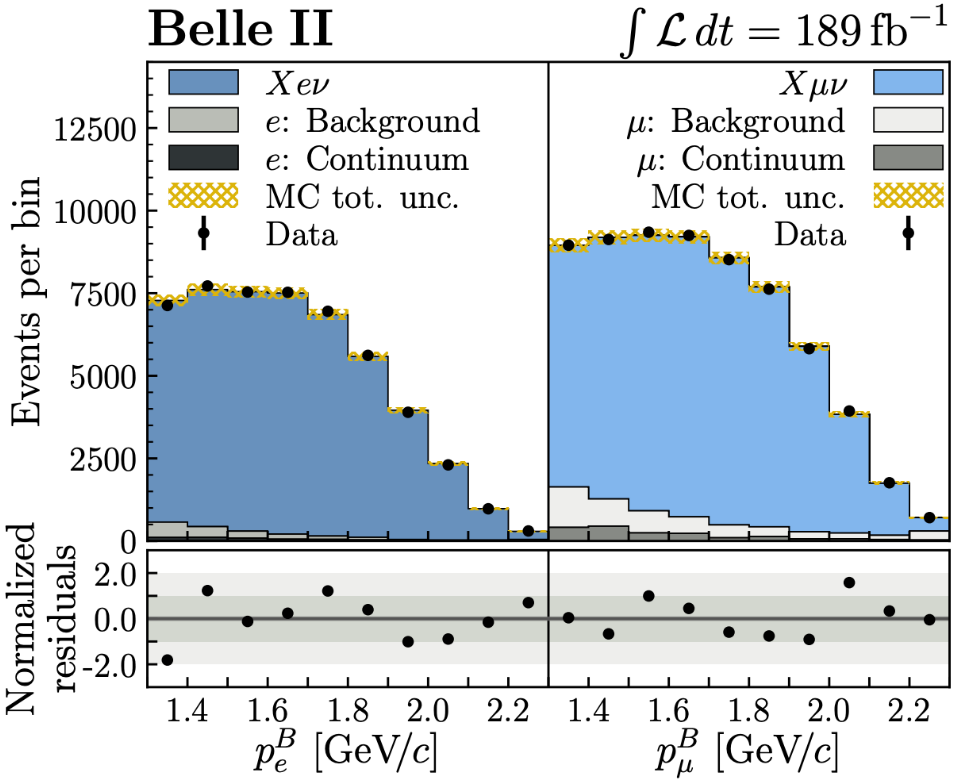
$$\mathrm{R}(\mathrm{X}_{e/\mu}) = 1.033 \pm 0.010_{\text{stat}} \pm 0.019_{\text{syst}}$$

– Compatible with SM prediction arxiv:2207.03432

– Most precise BF-based LFU test with semileptonic decays

– Next: measurement of $R(X_{\tau/l})$

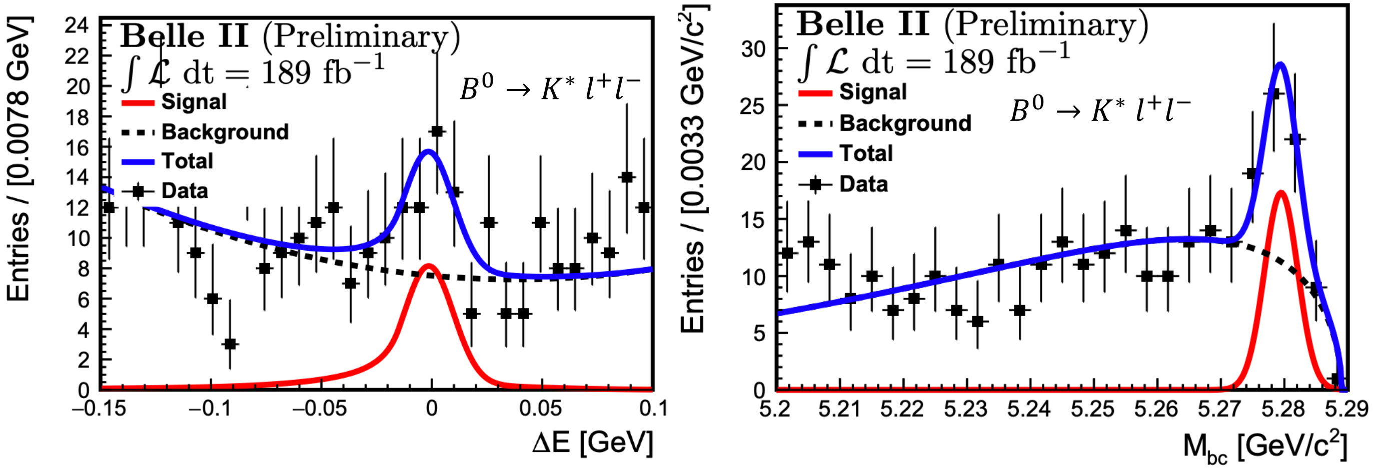


Source	Uncertainty [%]
Sample size	1.0
Lepton identification	1.9
$X_c \ell \nu$ branching fractions	0.1
$X_c \ell \nu$ form factors	0.2
Total	2.2

PREPARATION FOR R(K(*))

$B \rightarrow K^* l^+ l^-$ arxiv:2206.05946

- Suppress background using dilepton mass and BDT
- Unbinned fit of ΔE and M_{bc}



$\mathrm{B}(B \rightarrow K^* l^+ l^-) = (1.25 \pm 0.30_{\mathrm{stat}}{}^{+0.08}_{-0.07}{}_{\mathrm{syst}}) \times 10^{-6}$

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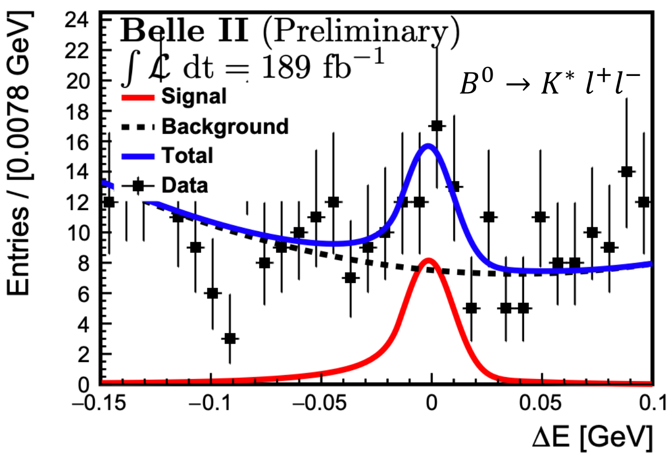
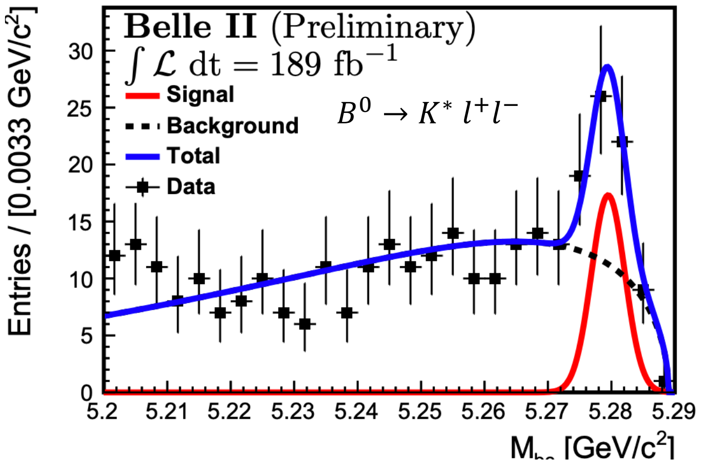
$B \to J/\psi K$ arxiv: 2207.11275

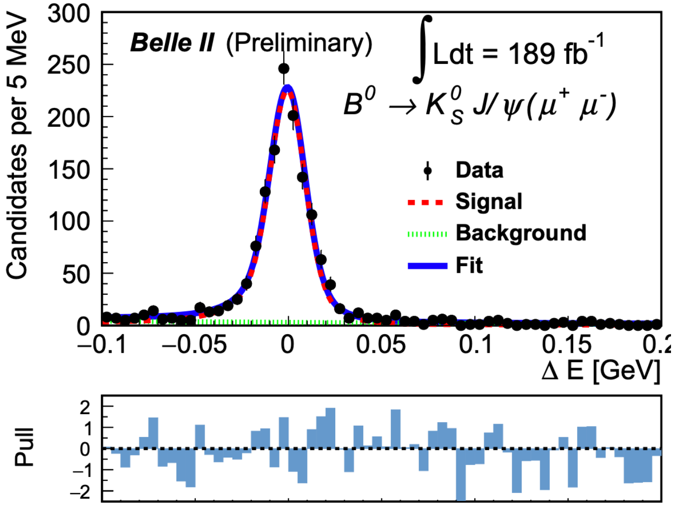
- No $b \to s$ transition
- Important control channel → very pure

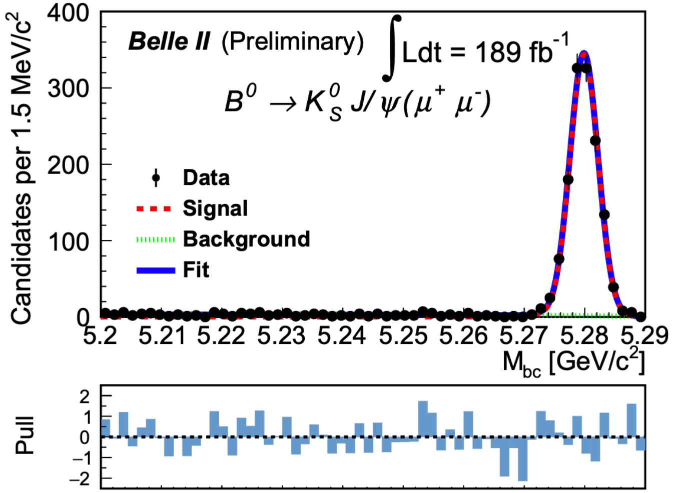
$$R_K(J/\psi) = \frac{B(B \to J/\psi[\mu^+\mu^-]K)}{B(B \to J/\psi[e^+e^-]K)}$$

- Unbinned fit of ΔE and M_{bc}









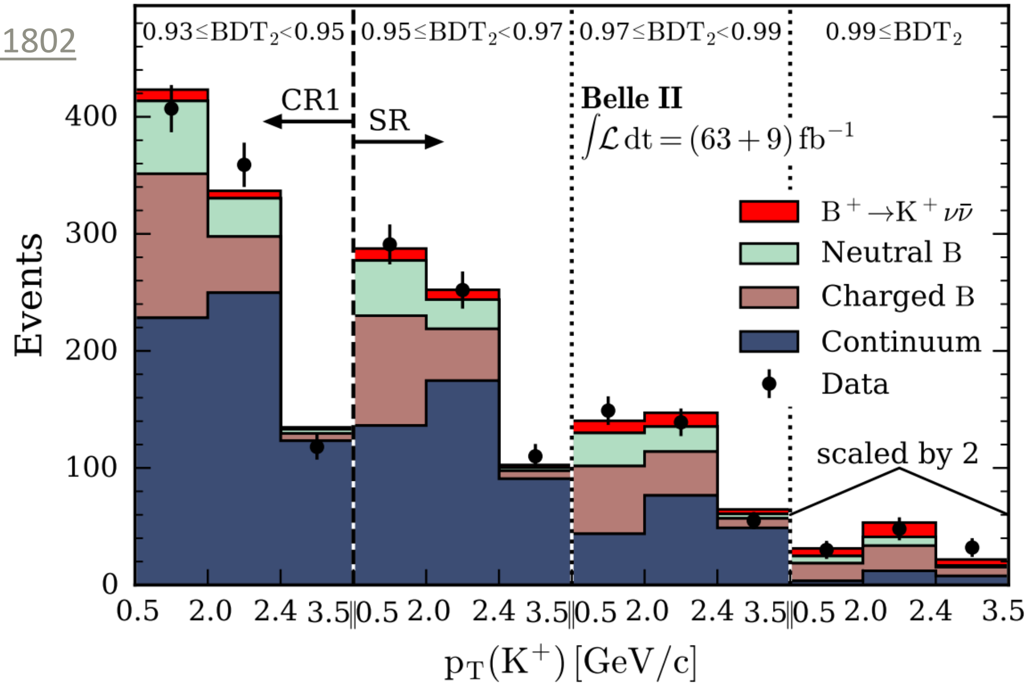
$$R_{K^+}(J/\psi) = 1.009 \pm 0.022_{stat} \pm 0.008_{syst}$$
$$R_{K^0}(J/\psi) = 1.042 \pm 0.042_{stat} \pm 0.008_{syst}$$

$B^+ \to K^+ \nu \bar{\nu}$ Phys. Rev. Lett. 127, 181802

- Complementary to $B \to K^{(*)} l^+ l^-$
  - Best upper limit: $1.6{\times}10^{-5}$ at 90% CL by BaBar

Phys. Rev. D 87, 112005

- First attempt using inclusive reconstruction of B_{tag}
- Reduce backgrounds using nested BDTs
- Signal strength from simultaneous fit of p_T in different classifier regions



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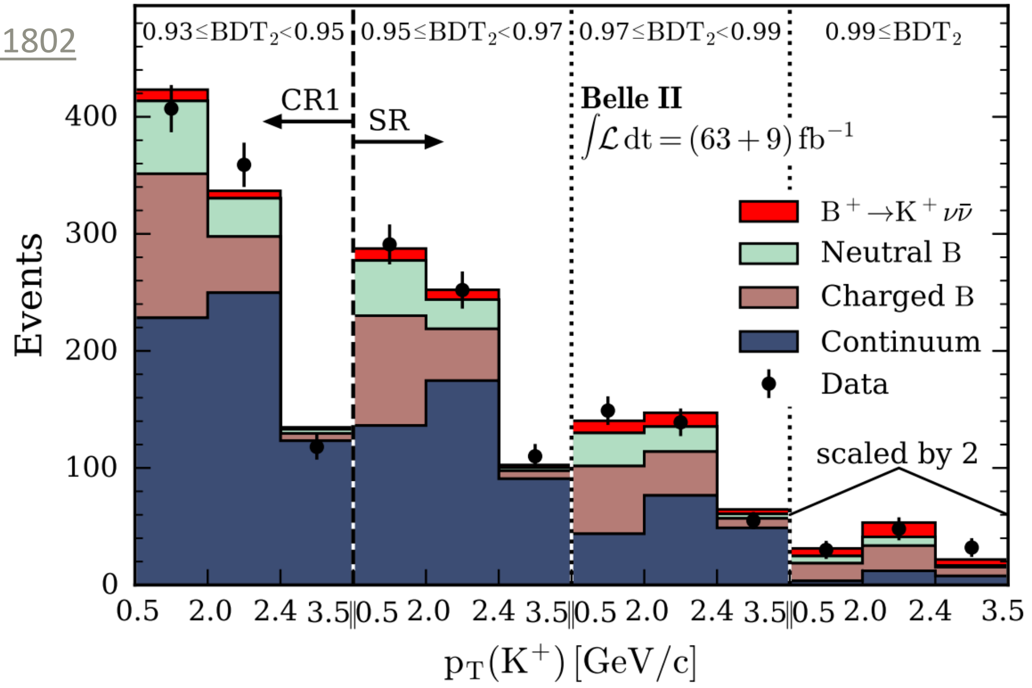
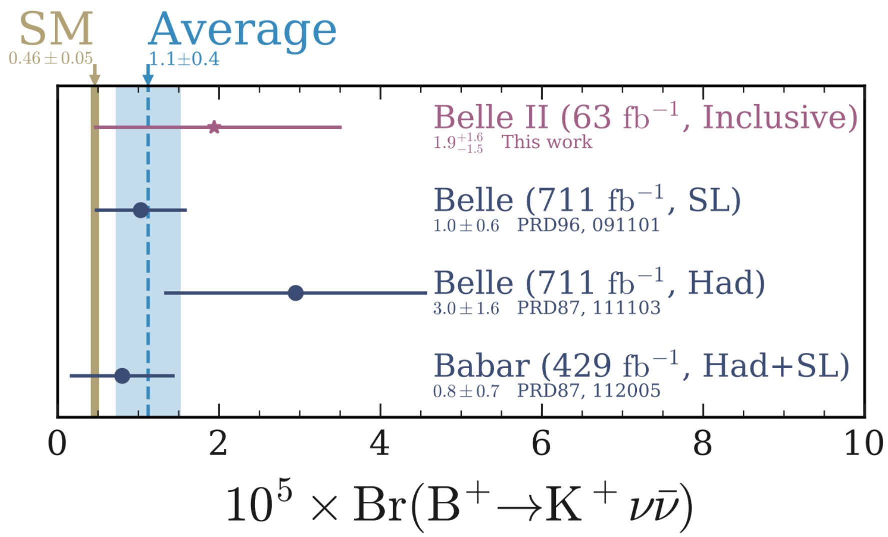
Limit of $4.1{\times}10^{-5}$ at 90% CL

- Soon: Update with data set 6 times as large





$B \to X_s\gamma$

- Higher rates and sensitive to non-SM physics in different ways
- Can extract shape function parameters describing motion of b-quark inside B meson

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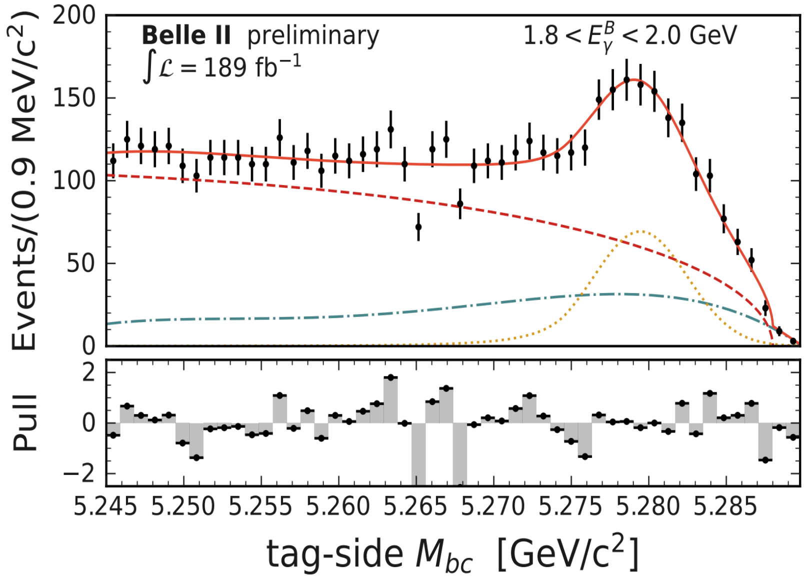
Inclusive $B \to X_s\gamma$:

arxiv: 2210.10220

- Tagged measurement: direct access to E_γ^B
- Extract good B_{tag} events by fitting $\mathrm{M_{bc}}$ in 11 bins of E_γ^B



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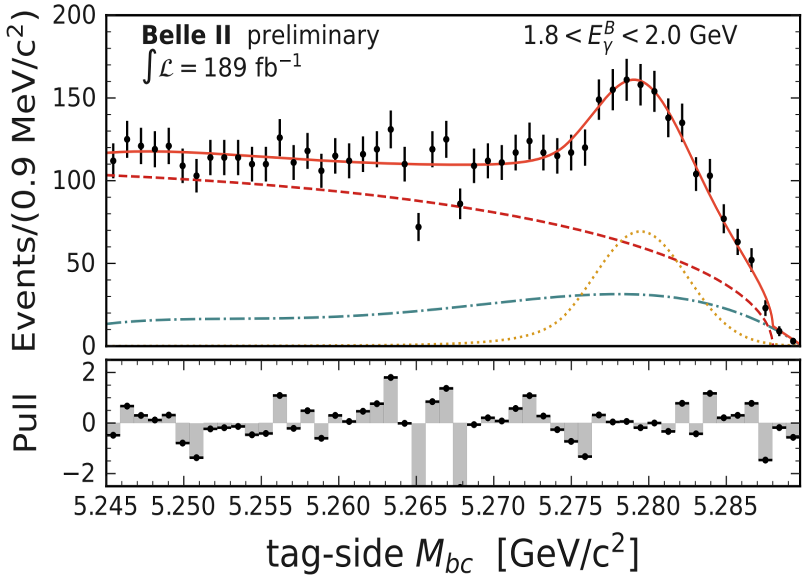

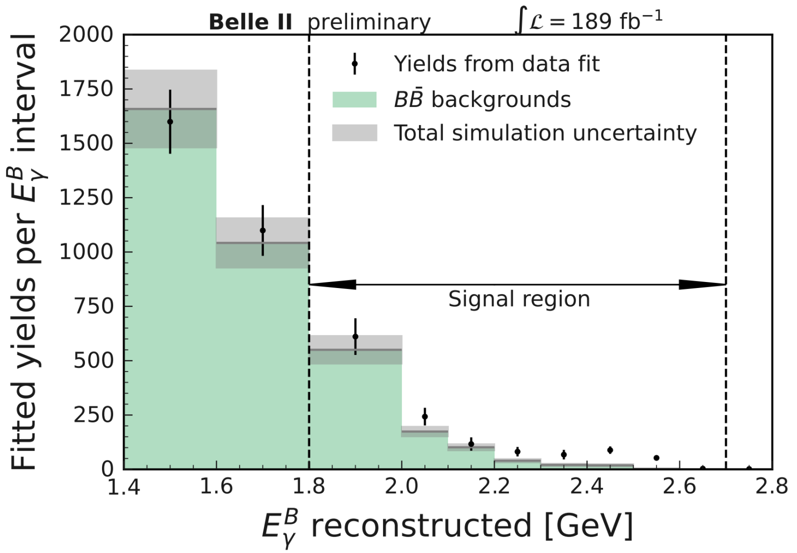

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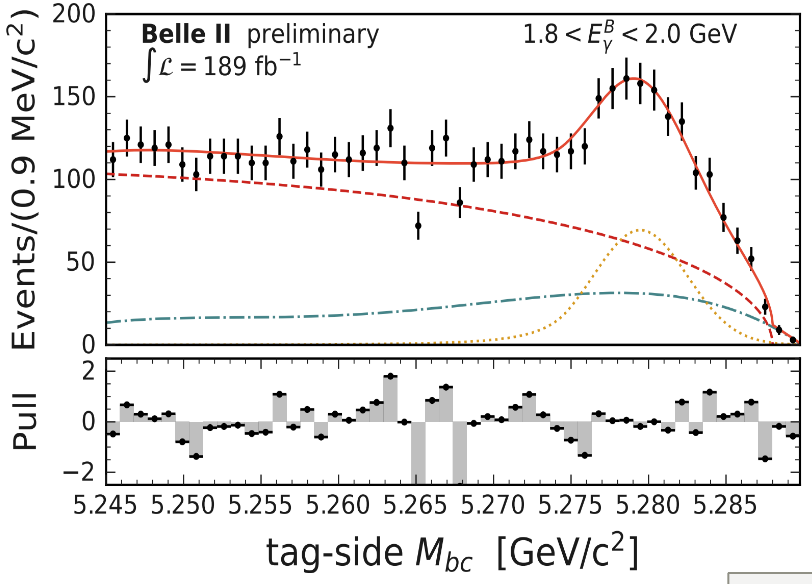
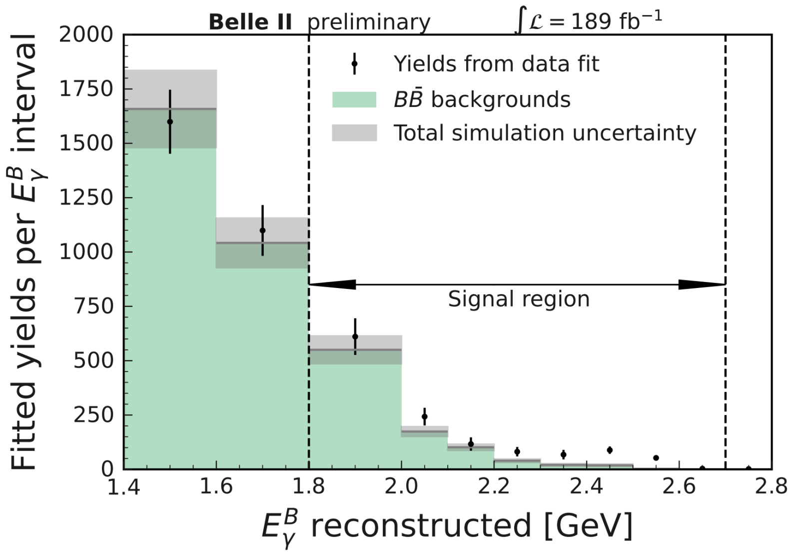
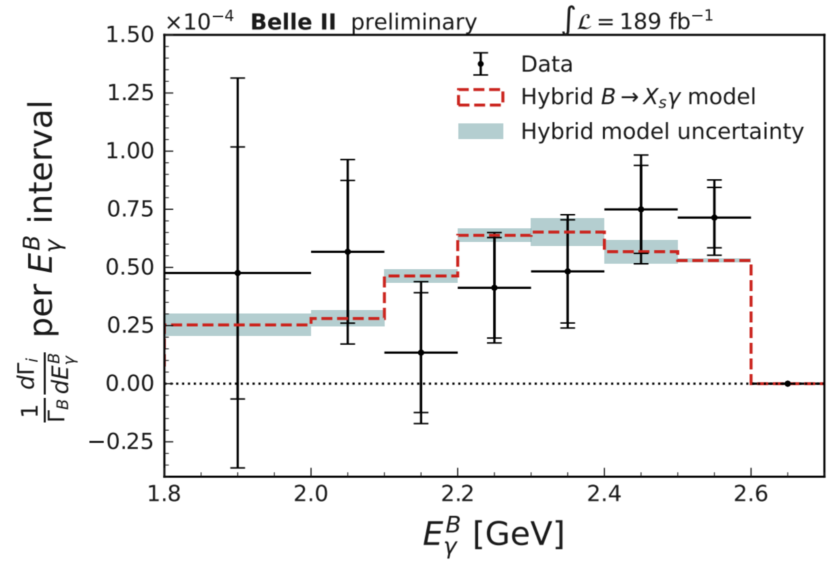
- Subtract background using simulation







$$\mathrm{B}(B \to X_s\gamma)^{E_\gamma^B > 1.8\text{GeV}} = (3.54 \pm 0.78_{\text{stat}} \pm 0.83_{\text{syst}}) \times 10^{-4}$$

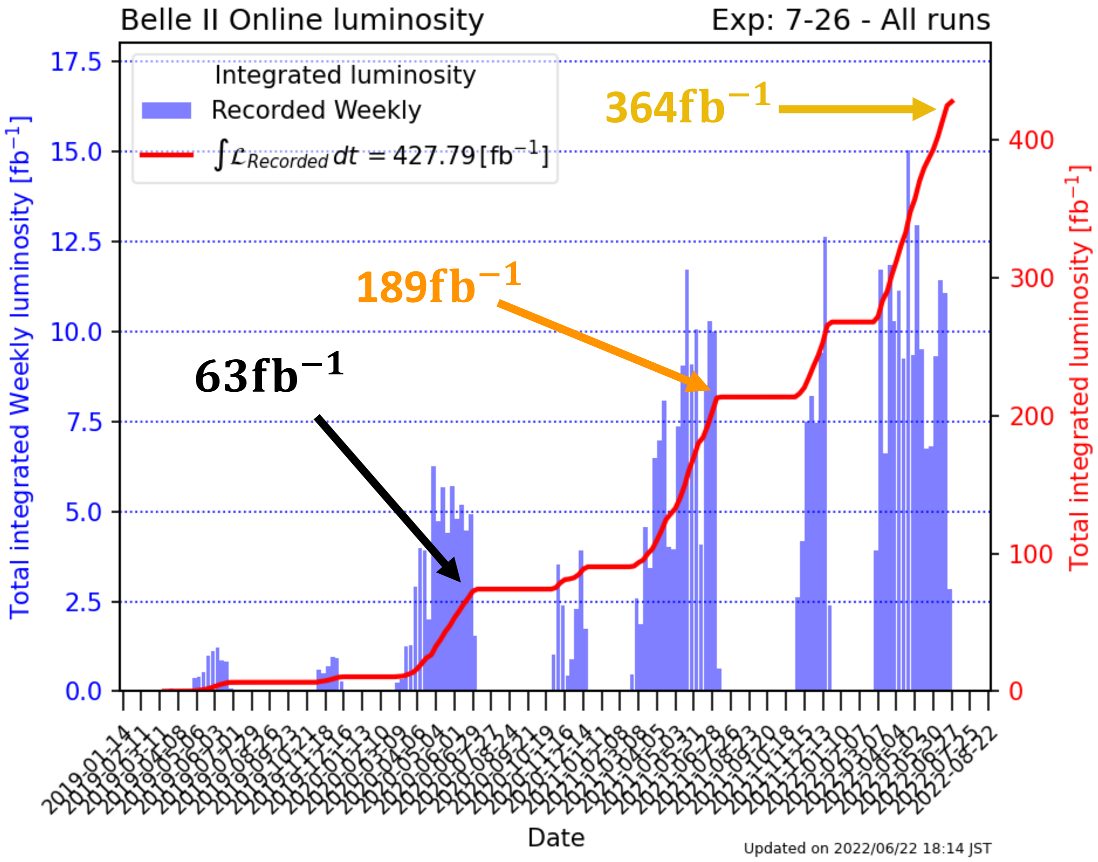
SUMMARY

- First results with data set smaller than data set of BaBar and Belle
  - Only presented a subset of results
  - Already produce highly competitive results:

$$R(X_{e/\mu}), \mathrm{B}(B^+ \to K^+ \nu\bar{\nu}), \ldots$$

- Soon results with data set 2 (to 6) times larger!

Tagged $B \to \rho l\nu$: arXiv:2211.15270
Lepton mass squared moments: arXiv:2205.06372 (submitted to PRD)
Untagged $B \to X_c l\nu$: arXiv:2111.09405
Untagged $B \to K^*\gamma$: arxiv: 2110.08219
Mixing probability: arXiv:2106.00482
…

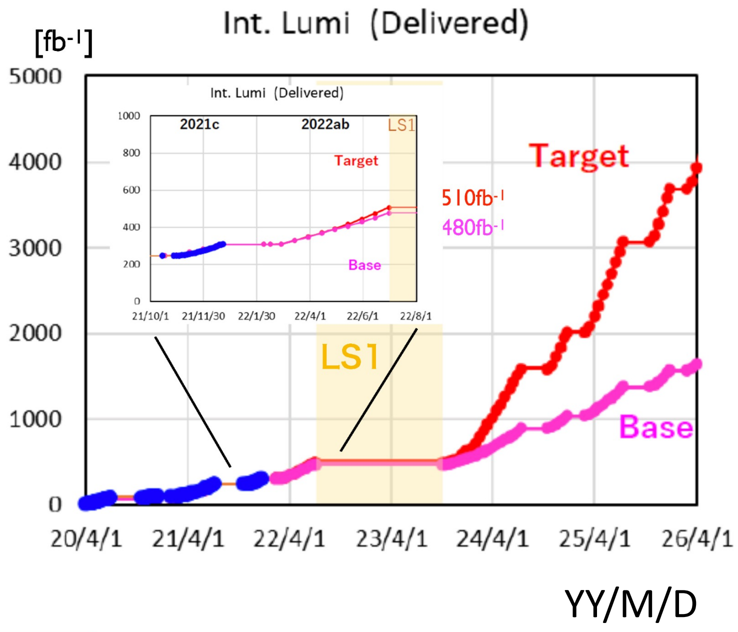


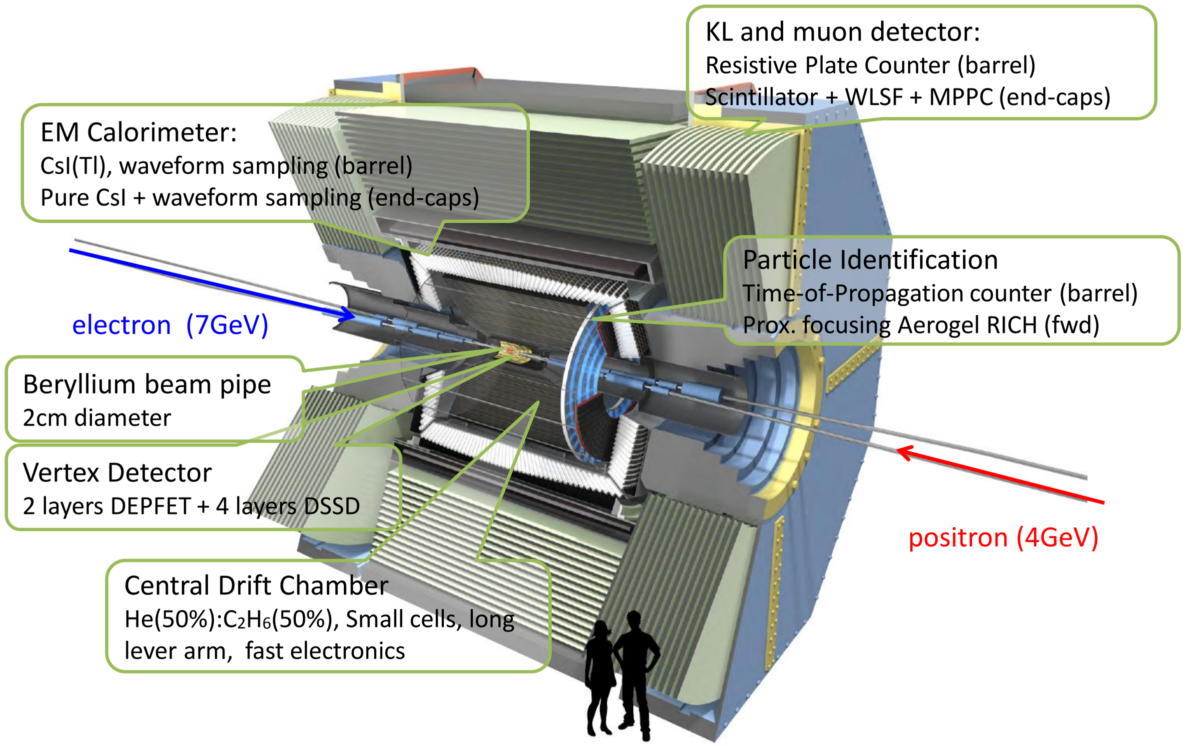
Thank you for your attention!

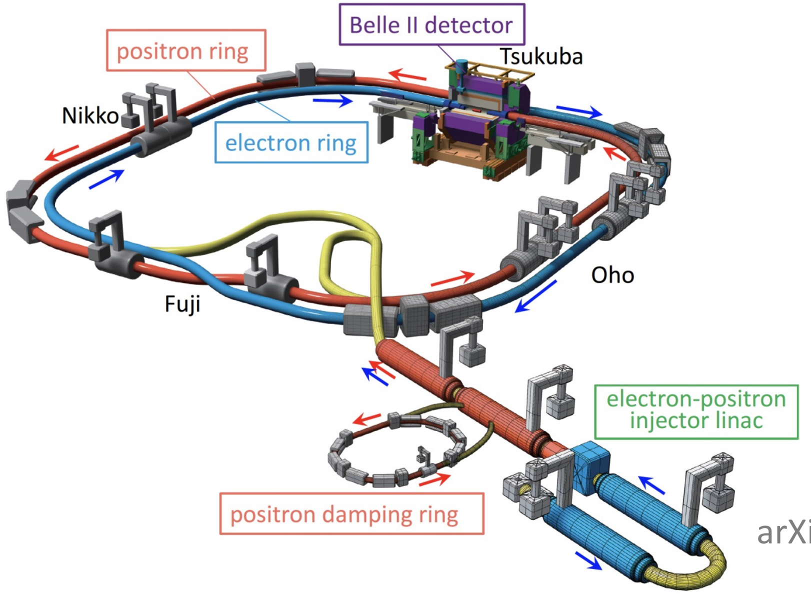
Backup

SUPERKEKB, BELLE II DETECTOR

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





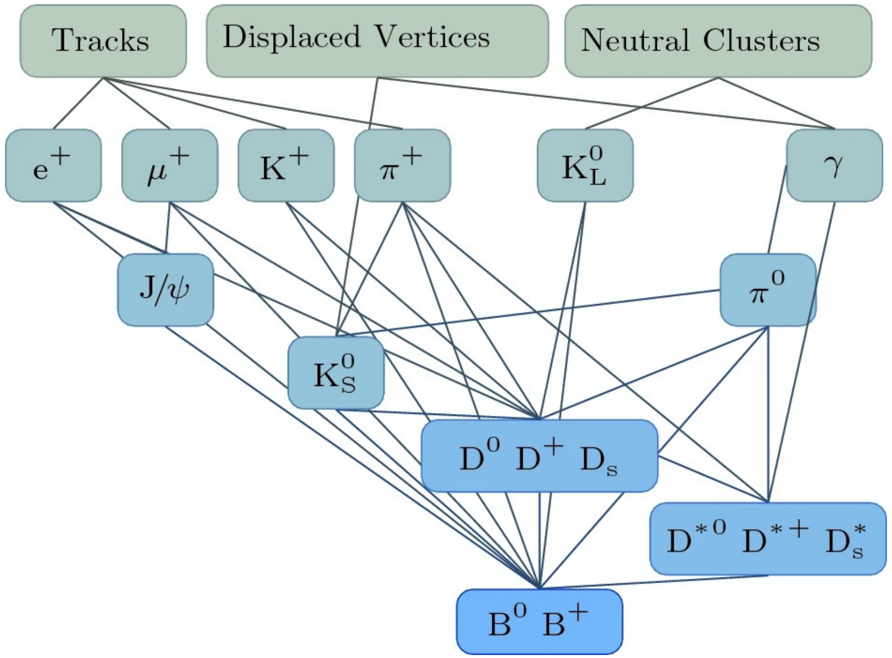


arXiv:1809.01958

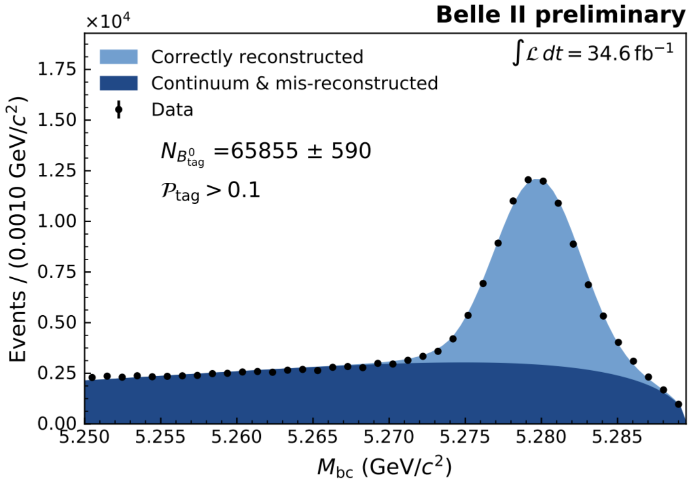
FULL EVENT INTERPRETATION (FEI)

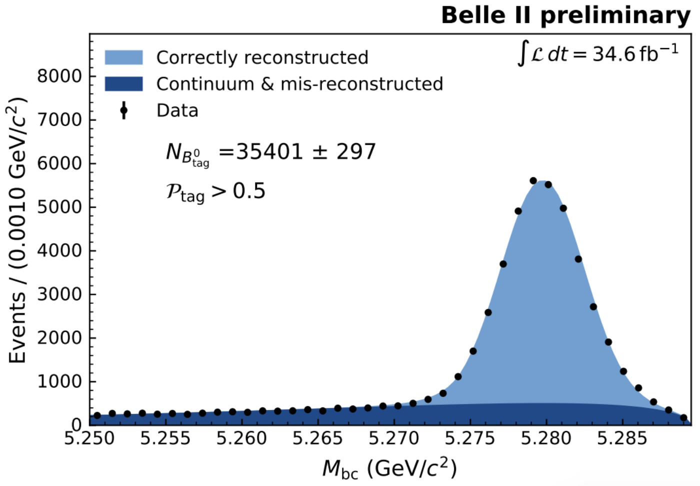
- FEI algorithm used to reconstruct B_{tag}
  - Uses ≈ 200 BDTs to reconstruct O(10000) different B decay chains
  - Assigns signal probability of being correct B_{tag}

Comput Softw Big Sci 3, 6 (2019)



arXiv:2008.060965





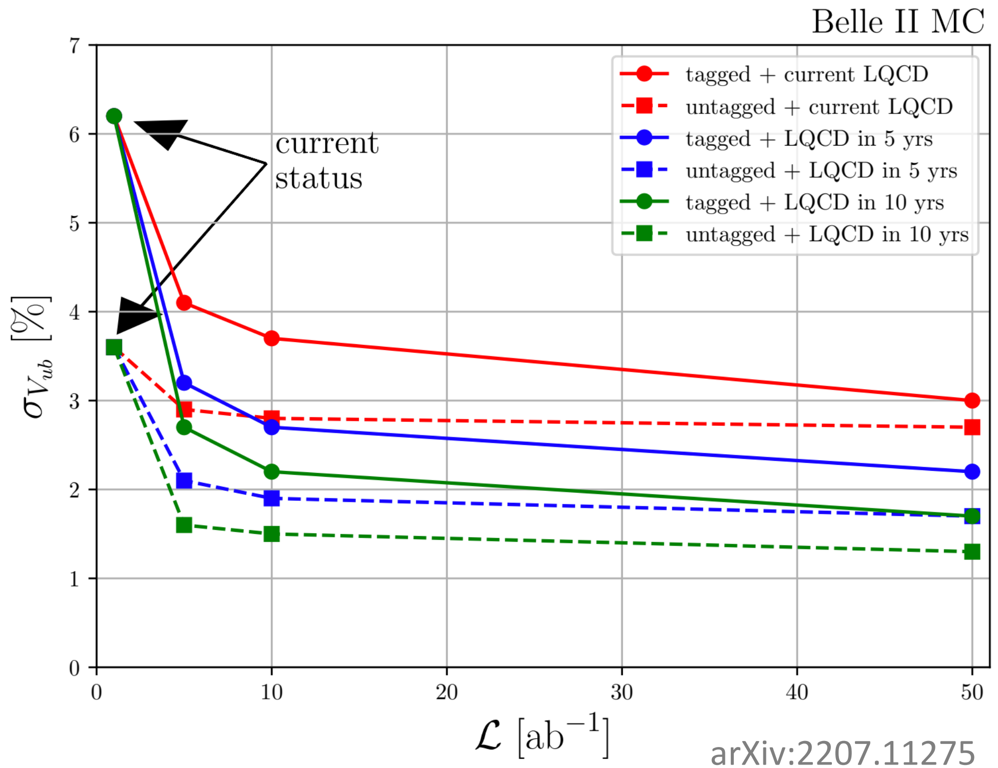
CKM MATRIX ELEMENTS

Tension:

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

– Improvements:

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



arXiv:2207.11275

R(X)

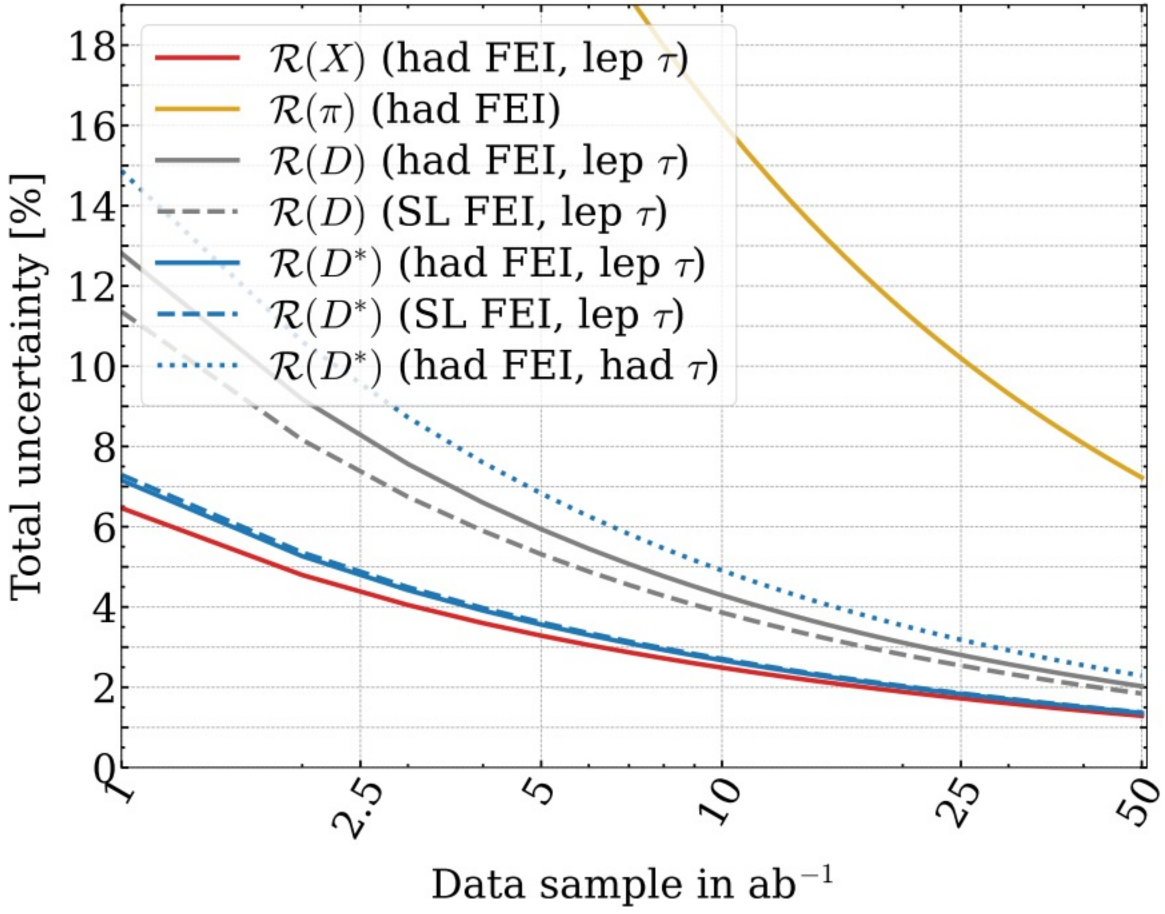
$R(D^{(*)})$:

- Understand B→ $D^{**}l\nu$ downfeed

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

- Control inclusive background composition

arXiv:2207.11275



$B^+ \to K^+\nu\bar{\nu}$

- Reduced theoretical uncertainties compared to $B \to K^* l^+ l^-$
  - No virtual photon contribution

Decay	$1\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$	$10\,\mathrm{ab}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to K^+\nu\bar{\nu}$	0.55 (0.37)	0.28 (0.19)	0.21 (0.14)	0.11 (0.08)
$B^0 \to K_S^0\nu\bar{\nu}$	2.06 (1.37)	1.31 (0.87)	1.05 (0.70)	0.59 (0.40)
$B^+ \to K^{*+}\nu\bar{\nu}$	2.04 (1.45)	1.06 (0.75)	0.83 (0.59)	0.53 (0.38)
$B^0 \to K^{*0}\nu\bar{\nu}$	1.08 (0.72)	0.60 (0.40)	0.49 (0.33)	0.34 (0.23)

arXiv:2207.11275

Baseline: no further improvements

Improved: efficiency increases by 50% at same background level

For the $B^+ \to K^{*+}\nu\bar{\nu}$ decay:

Baseline: 20% efficiency increase

Improved: 70% efficiency increase

$B \to X_s\gamma$

arXiv:2207.11275

Lower E_γ^B threshold	Statistical uncertainty				Baseline (improved) syst. uncertainty
	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}	
1.4 GeV	10.7%	6.4%	4.7%	2.2%	10.3% (5.2%)
1.6 GeV	9.9%	6.1%	4.5%	2.1%	8.5% (4.2%)
1.8 GeV	9.3%	5.7%	4.2%	2.0%	6.5% (3.2%)
2.0 GeV	8.3%	5.1%	3.8%	1.7%	3.7% (1.8%)

Inclusive:

- E_γ^B threshold
  - Lower: higher BB background
  - Higher: larger theoretical uncertainties
- Background from events with energetic $\pi^0 \to \gamma\gamma$ photon
- Systematic limit from $\pi^0 \to \gamma\gamma$ veto modeling

Baseline: Background at 10% level

Improved: Background at 5% level

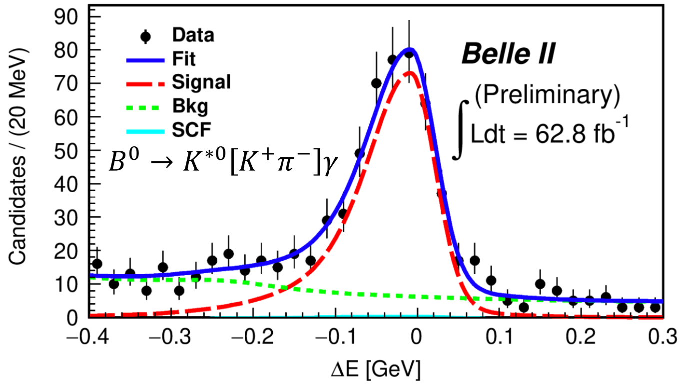
arXiv:2207.11275

Observable	1 ab^{-1}	5 ab^{-1}	10 ab^{-1}	50 ab^{-1}	Systematic uncertainty
$\Delta_{0+}(B \to K^*\gamma)$	1.3%	0.6%	0.4%	0.2%	1.2%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.4%	0.6%	0.5%	0.2%	0.2%
$A_{CP}(B^+ \to K^{*+}\gamma)$	1.9%	0.9%	0.6%	0.3%	0.2%
$\Delta A_{CP}(B \to K^*\gamma)$	2.4%	1.1%	0.7%	0.3%	0.3%

Exclusive: $B \to K^*\gamma$ arxiv: 2110.08219

- Untagged measurement
- Unbinned fit to $\Delta E = E_B - E_{beam}$

- Experimentally more straightforward but larger theoretical uncertainties
- Ratios best → uncertainties related to FF suppressed



Prog. Theor. Exp. Phys. 2020, 083C01

Mode	$\mathcal{B}_{meas}$ $[10^{-5}]$	$\mathcal{B}_{PDG}$ $[10^{-5}]$
$B^0 \to K^{*0}\gamma$	$4.5 \pm 0.3 \pm 0.2$	4.18 ± 0.25
$B^+ \to K^{*+}\gamma$	$5.2 \pm 0.4 \pm 0.3$	3.92 ± 0.22