Second Italian Workshop on the Physics at High Intensity

Rome,
8–10 November 2023

Overview of CKM metrology from semileptonic B decays

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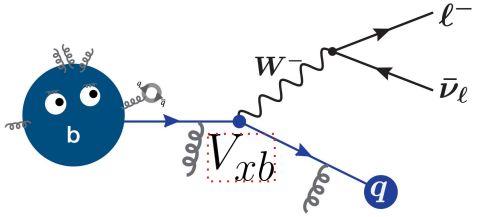
on behalf of the Belle II Collaboration

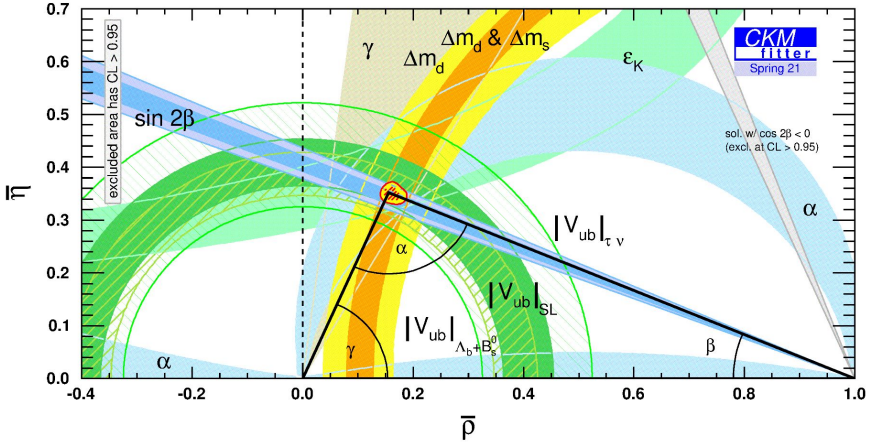
Semileptonic b decays

- **Tree level** process → only Standard Model contributions
- Only one hadronic current with heavy hadrons → **theoretically clean**



Probe the CKM model determining $|V_{ub}|$ and $|V_{cb}|$

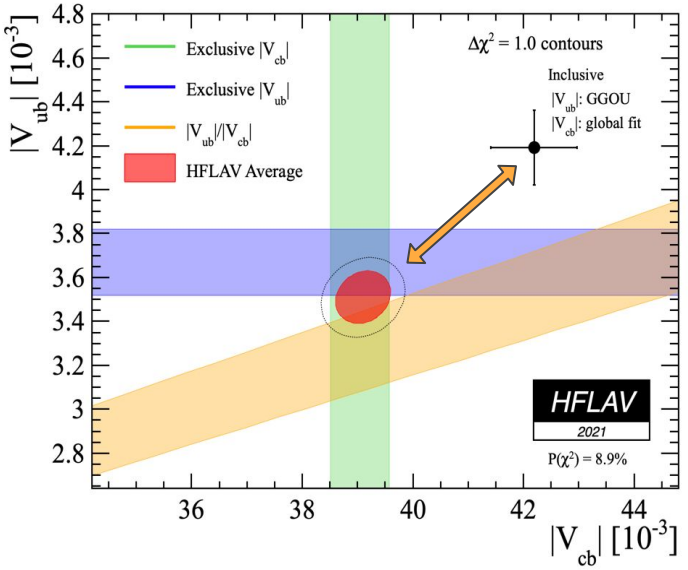
- **Limiting constraint** on the unitarity triangle
- Important input for other observables, e.g. $K \to \pi\nu\nu$



$|V_{xb}|$ measurements

$$\mathcal{B}(b \to Wx) \propto |V_{xb}|^2 \qquad (x = u, c)$$

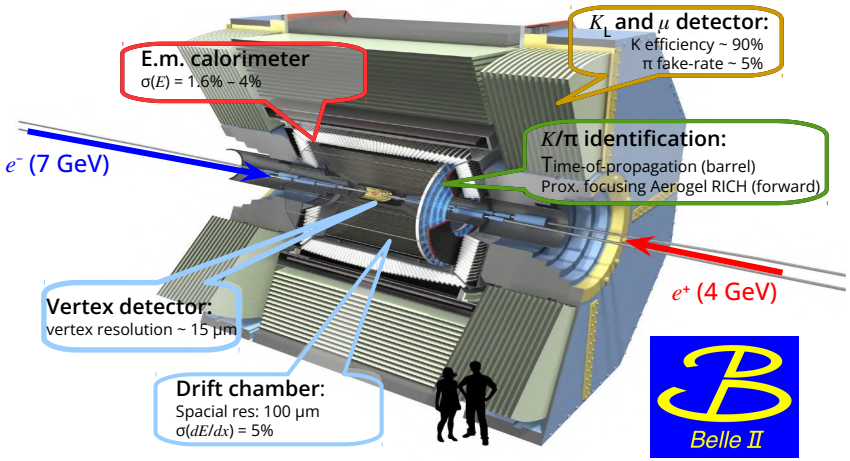
- **Exclusive**: $B \to (\pi, \varrho, \ldots)\, \ell\nu$, $B \to (D, D^*, \ldots)\, \ell\nu$+
  - Many channels **accessible** from experiments
  - Need form factors from theory → rely on lattice QCD (**LQCD**)
- **Inclusive** $B \to X_q\, \ell\nu \quad q = u, c$
  - Experimentally **harder**
  - Use Operator Product Expansion (OPE) and shape functions (non-perturbative for $|V_{ub}|$)

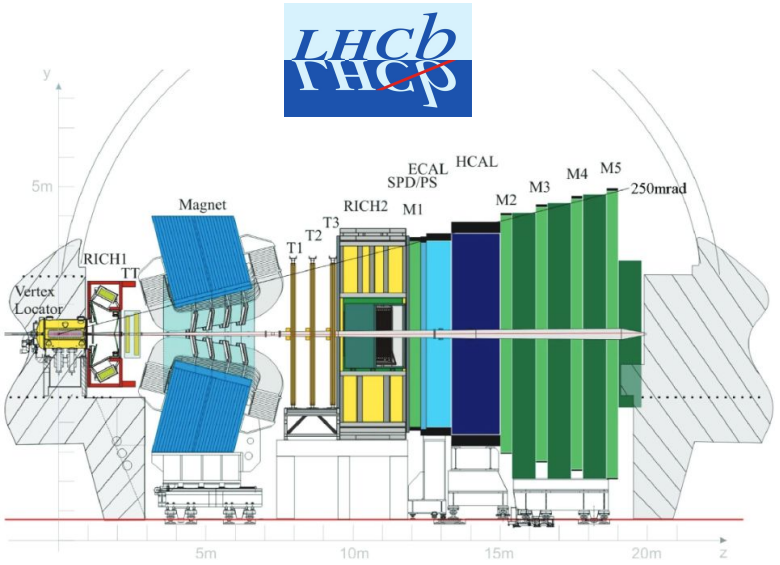


Long-standing discrepancy between exclusive and inclusive determination

- Belle (II) and LHCb will help towards a better understanding

Belle II and LHCb experiments

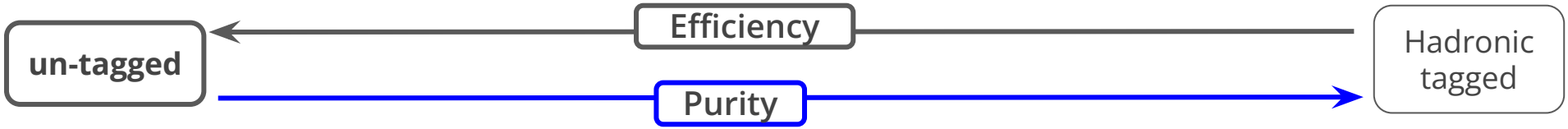




- e^+e^- collisions @ $\Upsilon(4S)$, ~**390 M $B\bar{B}$** pairs produced
- **Clean** environment
- High **hermeticity** (~ 4π acceptance)
- Better **neutral reconstruction**

- pp collisions, **very large b-hadrons sample**, >10^{12} including barions
- **High background** environment
- Better **charged reconstruction**

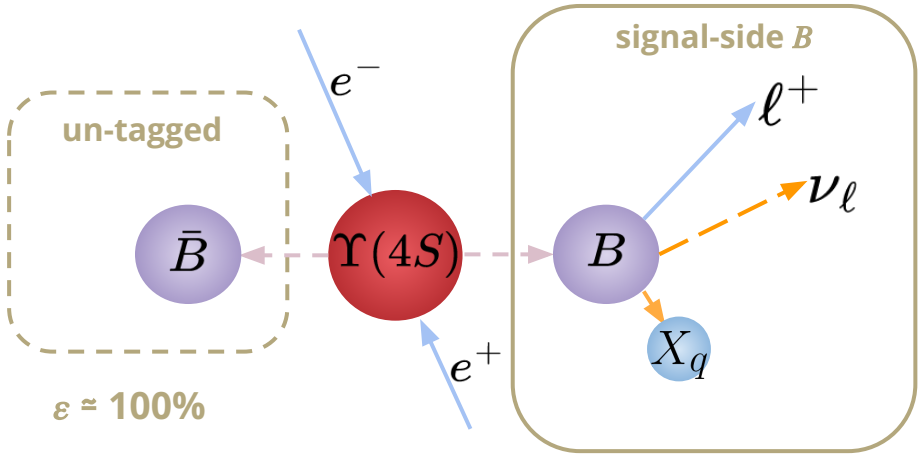
B-meson reconstruction at B-factories



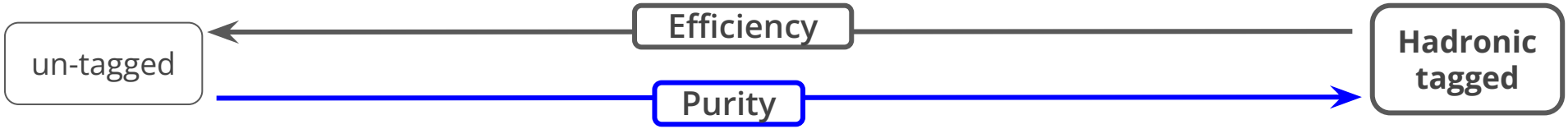
Select only B-signal candidates, ignoring the partner B

- Total **kinematic unknown**
- Large combinatorial **background**

Suitable for **exclusive $|V_{xb}|$**



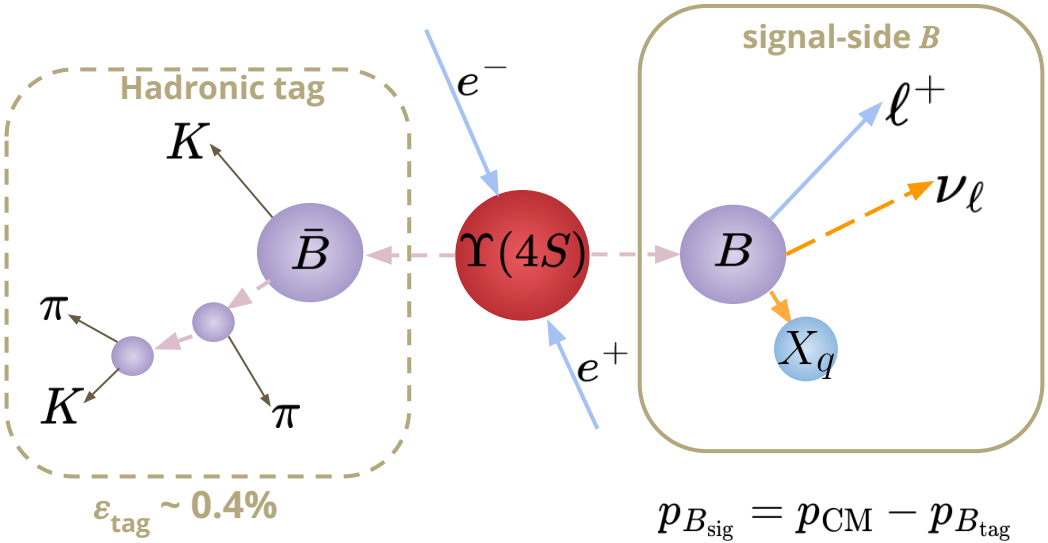
B-meson reconstruction at B-factories



Full reconstruction of the partner B (**tag**) in hadronic decay

- The ***B*-signal kinematic** can be derived precisely → missing mass constraint on the signal-side
- Systematics from B-tag **calibration**

Inclusive $|V_{xb}|$ is possible



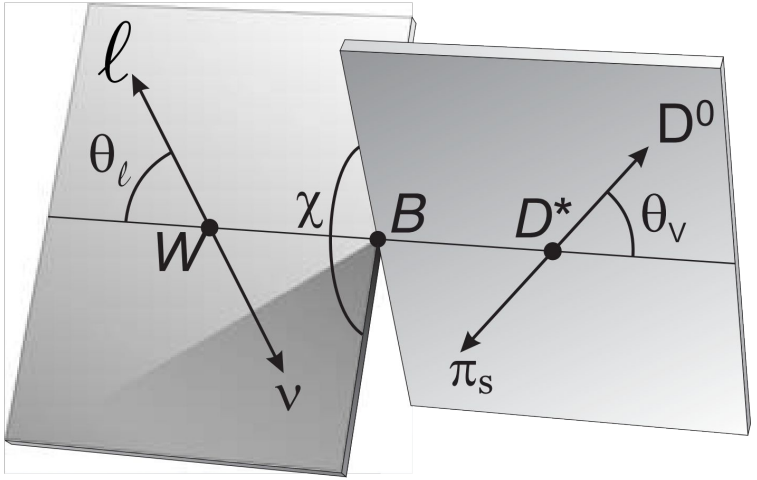
Comput Softw Big Sci 3, 6 (2019)

$|V_{cb}|$ with $B^0 \to D^* \ell \nu$

- Half of available statistics: **~200 $B\bar{B}$** pairs
- Explore both **tagged** and **untagged** approach

Fully differential rate with $D^* \to D^0 \pi_s$, over 4 kinematic parameters:

- D^* recoil parameter: w (prop. to $-q^2$)
  - $w = v_B \cdot v_{D^*}$
- Elicity **angles**:
  - $\theta_\ell, \theta_V, \chi$



$$\frac{d\Gamma}{dw\, d\cos\theta_\ell\, d\cos\theta_V\, d\chi} \propto |V_{cb}|^2\, |F(w,\, \cos\theta_\ell,\, \cos\theta_V,\, \chi)|^2$$

Differential decay rate

Differential form factor

$|V_{cb}|$ with *untagged* $B^0 \to D^* \ell \nu$

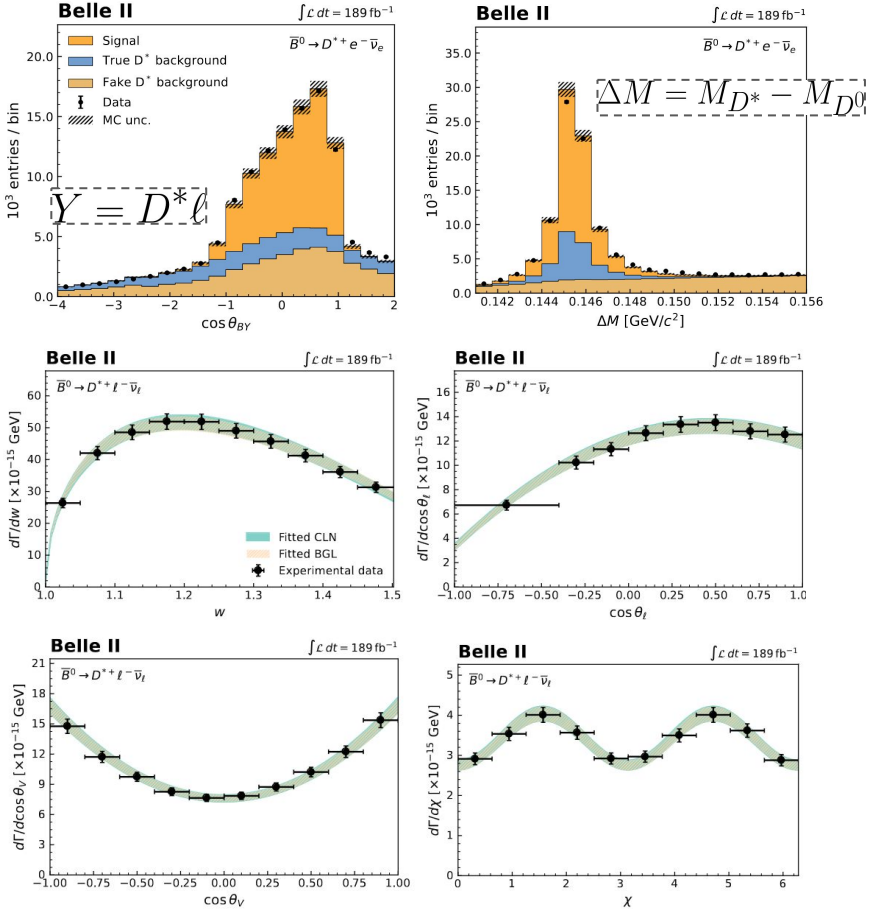
arXiv:2310.01170, PRD accepted

- Estimate the flight direction of signal-B
  - exploit decay kinematic and the rest of event → **improved resolution** w.r.t. Belle and BaBar
- Signal yield extracted on each bin with a **2D fit**
  - $\cos\theta_{BY}$ (cosine of signal-B and reconstructed $D^*\ell$)
  - ΔM (mass different btw D^* and D^0)
- Extract $|V_{cb}|$ with **BGL form factors**:

Use LQCD for low w
PRD 89, 114504 (2014)

$$|V_{cb}|_{\mathrm{BGL}} = (40.9 \pm 0.3_{\mathrm{stat}} \pm 1.0_{\mathrm{sist}} \pm 0.6_{\mathrm{teor}}) \times 10^{-3}$$

- Systematics dominated by **slow pion** efficiency
- In **agreement** with both inclusive and exclusive HFLAV averages



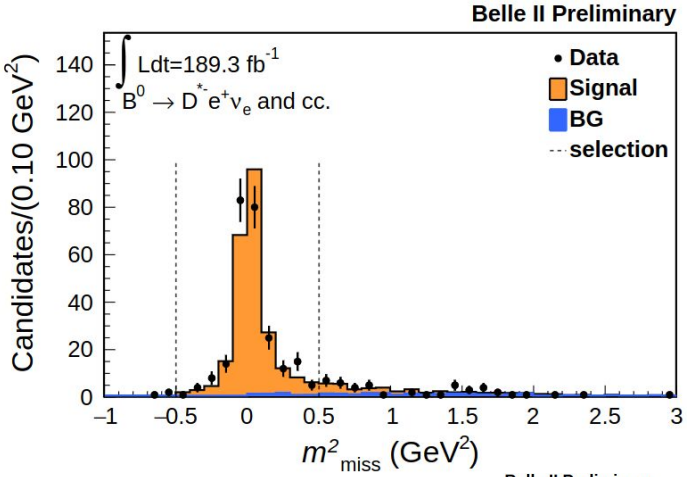
$|V_{cb}|$ with *tagged* $B^0 \to D^* \ell \nu$

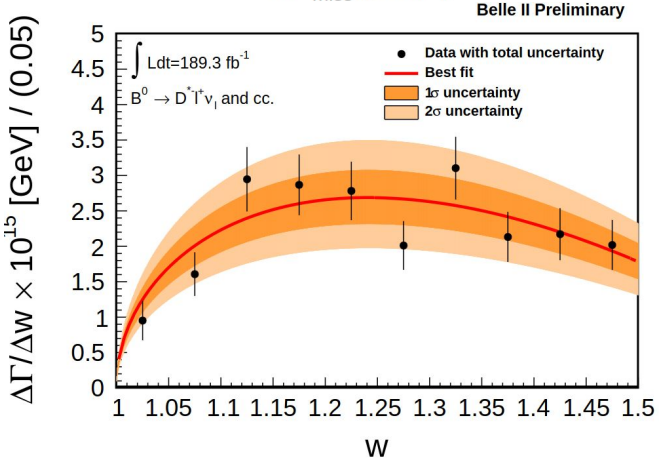
arXiv:2301.04716

- ***B*-signal momentum** inferred exploiting the reconstructed B-tag
- **Small backgrounds**, but **lower statistics** w.r.t. untagged analysis → differentiate only in w
- Extract signal yields from fit on **missing mass squared**
- $|V_{cb}|$ determined in **CLN** parameterization (Caprini, Lellouch, Neubert) from the differential decay rate $\Delta\Gamma/\Delta w$

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

- Dominant **systematics** are **slow pion** efficiency and calibration of the ***B*-tag** efficiency (both ~4%)

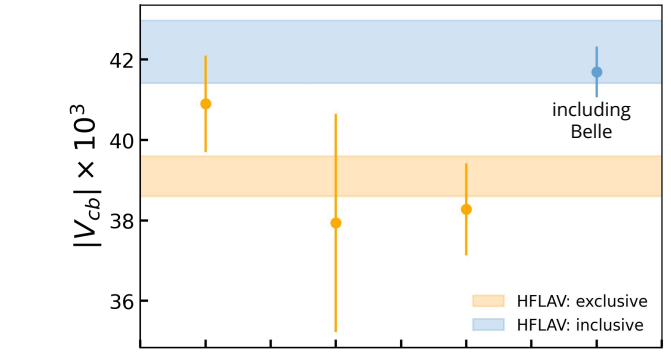




Summary and prospects: $|V_{cb}|$ @Belle II

- First **exclusive** measurements at Belle II
  - exploit statistical power of ***untagged*** measurements
- **Inclusive** effort started with measurement of q^2 **moments** in $B \to X_c \ell \nu$ (arXiv:220506372)
- Fairly new detector → room for performance optimization
  - Reduce systematics, e.g. lepton identification, slow pions, B-tagging
- Aim to measure $|V_{cb}|$ at **~1% precision** with larger dataset (Snowmass White Paper)

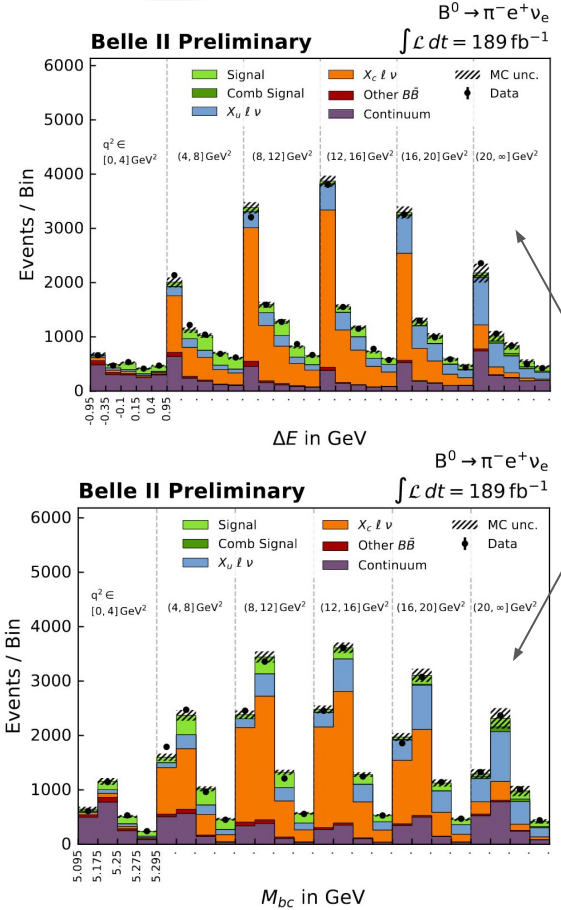
$|V_{cb}|$ measurements at Belle II
(inclusive, exclusive)



arXiv:2310.01170 arXiv:2301.04716 arXiv:2210.13143 PRD 104, 112011 (2021), arXiv:220506372, JHEP 10 (2022) 068

$|V_{ub}|$ with *untagged* $B^0 \to \pi \ell \nu$

arXiv:2210.04224

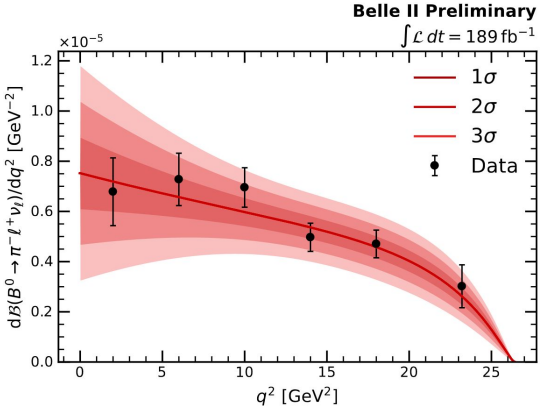


q^2 bin

- Signal yields extracted in 6 q^2 **bins** by a 2D fit on energy difference ΔE and beam-constrained mass M_{bc}

$$\Delta E = E_B - E_{\text{beam}} \qquad M_{bc} = \sqrt{E^2_{\text{beam}} - |\vec{p}_B|^2}$$

- $|V_{ub}|$ determined from the decay rate spectrum using LQCD form factors (FNAL/MILC)

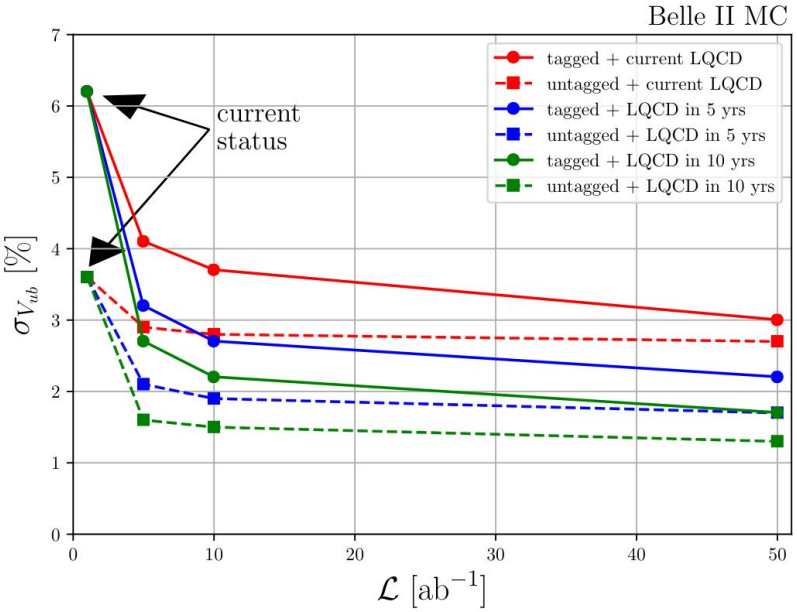


$$|V_{ub}| = (3.55 \pm 0.12_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.17_{\text{theo}}) \times 10^{-3}$$

Prospects: exclusive $|V_{ub}|$ @Belle II

Snowmass White Paper

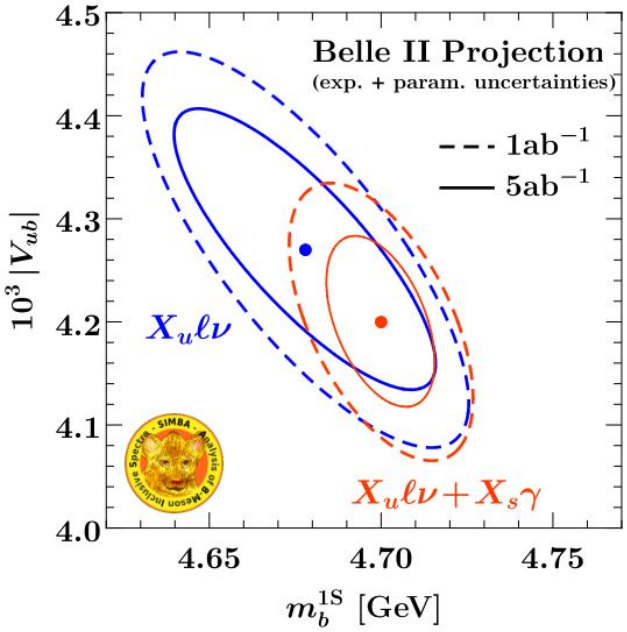
- Belle II will **double the precision** on **exclusive** $|V_{ub}|$ (at least **3%**), even assuming no improvements in form factors uncertainties
- **Untagged** measurements limited by **LQCD inputs**
- **Tagged** measurements limited by the **calibration of *B*-tag efficiency**
    - Improvement of tagging algorithm will be fundamental with higher statistics
- Move towards direct measurements of $|V_{ub}|/|V_{cb}|$



Prospects: inclusive $|V_{ub}|$ @Belle II

Snowmass White Paper

- **Inclusive $|V_{ub}|$** is very challenging, **unique** to Belle (II)
- With larger sample size and improved B-tag, expected to reach **~3% precision**
    - Further improvements with a **global fit** including the shape-function from $B \to X_s \gamma$
- Explore **simultaneous determination of incl. and excl. $|V_{ub}|$**, first measurement by Belle arxiv: 2303.17309
- Improve **shape-function** knowledge via **differential** measurement of inclusive BR as done by Belle PRL 127, 261801 (2021)

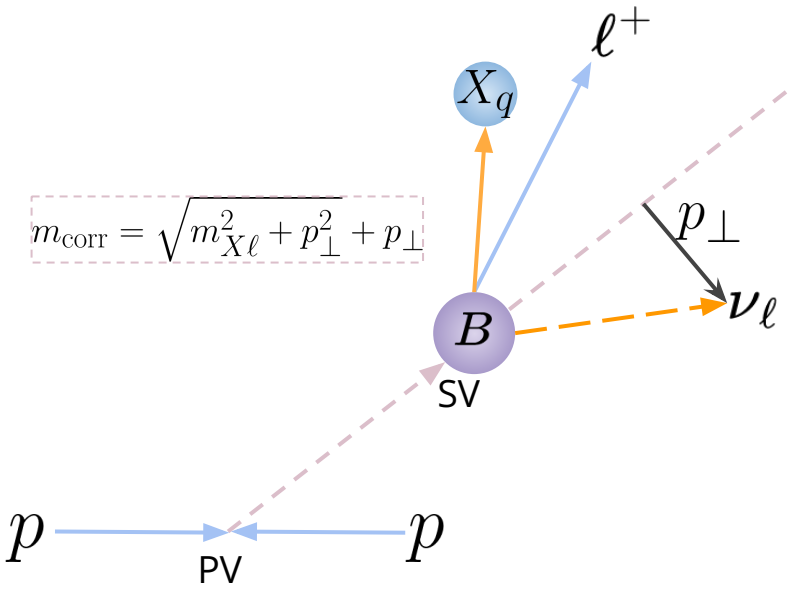


B-meson reconstruction at hadron colliders

The B-meson **direction** is derived from **vertex reconstruction**, however its energy is unknown

- Determine **neutrino** direction with a 2-fold ambiguity (to compute q^2)
- Use "$p_\perp$-corrected" mass (m_{corr}) to approximate B mass
- Need a **normalization channel** to measure BR (critical for systematics)

Focus on **exclusive $|V_{xb}|$**



$|V_{ub}|$ / $|V_{cb}|$ with $B^0_s \to K \mu \nu$

PRL 126, 081804 (2021)

LHCb can exploit a huge B_s sample → **theoretically cleaner** than B_u and B_d (heavier spectator quark)

- Run1 dataset (2 fb^{-1}@ 8 TeV)
- **Normalization** channel
  - $B^0_s \to D^-_s \mu^+ \nu_\mu$ with $D^-_s \to K^+K^-\pi^-$

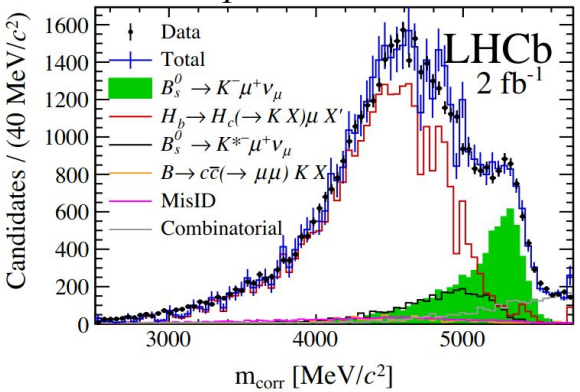
Extract $|V_{ub}|$ / $|V_{cb}|$ from the **BR ratio** into **two q^2 bins:**

$$\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} = \frac{N_K}{N_{D_s}} \frac{\epsilon_{D_s}}{\epsilon_K} \times \mathcal{B}(D_s^- \to K^+ K^- \pi^-)$$

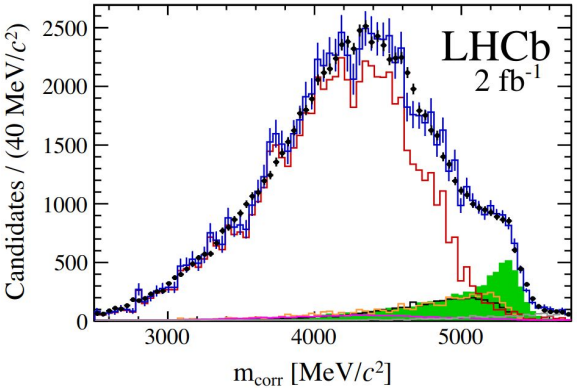
Extract from ML fit on m_{corr}

External measurement

$q^2 < 7$ GeV$^2/c^4$



$q^2 > 7$ GeV$^2/c^4$



$|V_{ub}|$ / $|V_{cb}|$ with $B^0_s \to K \mu \nu$

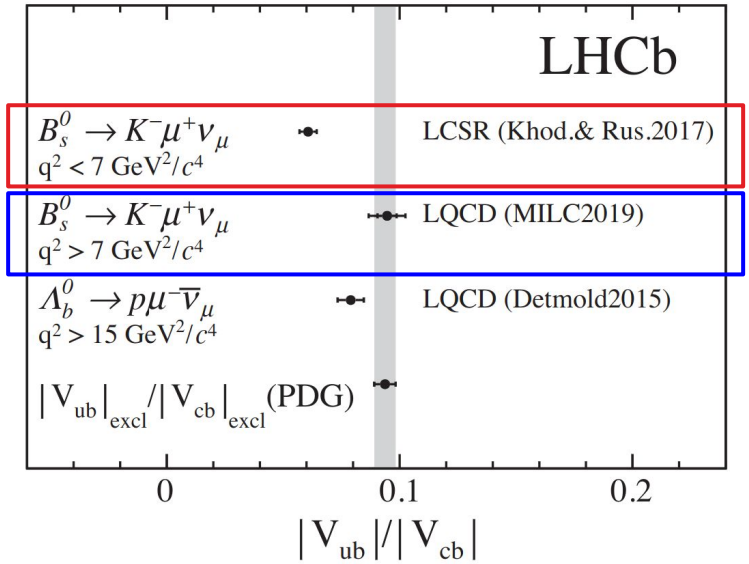
PRL 126, 081804 (2021)

Use different **form factors** for $B^0_s \to K\mu\nu$ (*), to maximize theoretical input precision:

- **Low q^2** : **LCSR** (light cone sum rule)
- **High q^2** : **LQCD** (lattice QCD)

- **Discrepancy** in the two q^2 regions driven by **different FF** (dominant systematics)

→ **Investigate finer q^2 bins with the full LHCb dataset**

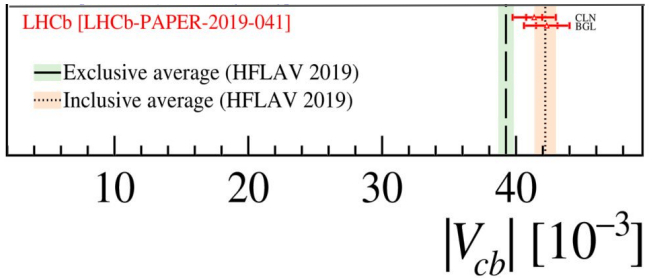


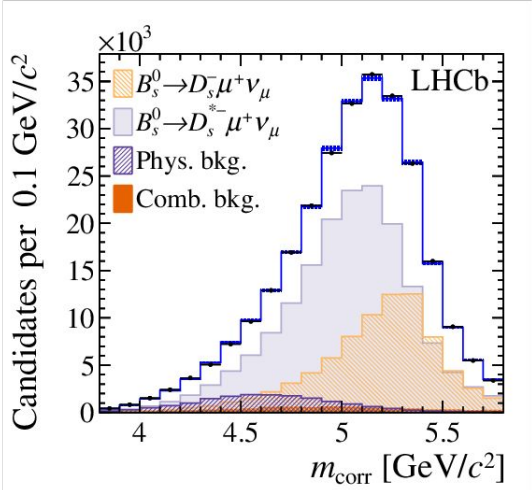
(*) For normalization channel use LQCD in the full q^2.

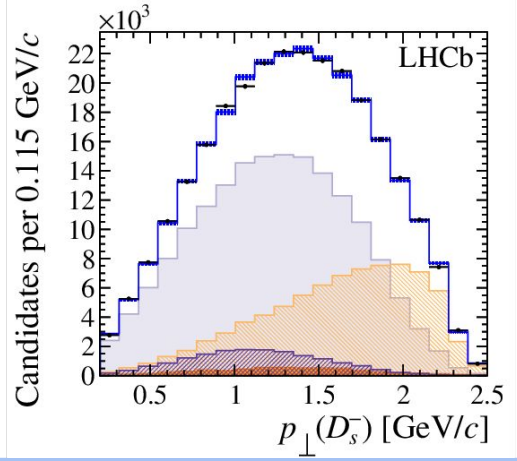
$|V_{cb}|$ with $B^0_s \to D_s^{(*)} \mu\nu$

PRD 101, 072004 (2020)

- Full Run1 dataset (1 fb^{-1}@ 7 TeV + 2 fb^{-1}@ 8 TeV)
- Use the corresponding B^0 mode as a **normalization channel**: $B^0 \to D^{(*)} \mu\nu$
- **Differential** decay rate **in** $w \to$ approximate by (transverse) momentum $p_\perp(D_s)$ of the D_s
- Extract signal in **2D fit** on m_{corr} and $p_\perp(D_s)$
- Extract $|V_{cb}|$ with both CLN and BGL form factors
  - Extracted values compatible with each other







Prospects: exclusive $|V_{xb}|$ @LHCb

arXiv:1808.08865

- Looking for updates with the **Run2** dataset
  - finer **binning in q^2** should be possible
  - **fully differential** measurements to validate FF
- A significant improvement expected in $|V_{ub}|$ precision from differential measurement of exclusive $B^0_s \to K\mu\nu$
- Exploit the **unique Λ_b sample**
  - planned **$|V_{cb}|$** measurement on $\Lambda_b^0 \to \Lambda_c \mu\nu$
  - update on **$|V_{ub}|$** from $\Lambda_b^0 \to p\mu\nu$, last measurement Nature Physics 11 (2015)

Experiment	LHCb			
	Run 1	Run 2	Runs 3–4	Runs 5–6
Completion date	2012	2018	2031	2041
Center-of-mass energy	7/8 TeV	13 TeV	14 TeV	14 TeV
$b\bar{b}$ cross section [nb]	$(3.0/3.4)\times10^5$	5.6×10^5	6.0×10^5	6.0×10^5
Integrated luminosity [fb^{-1}]	3	6	40	300
B^0 mesons [10^9]	100	350	2,500	19,000
B^+ mesons [10^9]	100	350	2,500	19,000
B_s mesons [10^9]	24	84	610	4,600
Λ_b baryons [10^9]	51	180	1,300	9,800
B_c mesons [10^9]	0.8	4.4	19	150

RMP 94, 015003 (2022)

Summary

The tension between different determinations of $|V_{xb}|$ still exists.

- From **theory**: improved inputs from **LQCD** will be fundamental

Belle (II) is the major actor in the semileptonic $|V_{xb}|$ determination

- **First measurements** exploit the statistical power of **untagged analysis**
- A lot of **different** measurements possible

LHCb can deliver **complementary** tests on **exclusive** measurements exploiting B_s and Λ_b

- First exclusive $|V_{xb}|$ measurements at a **hadron collider**
- Competitive results on **exclusive** $|V_{cb}|$

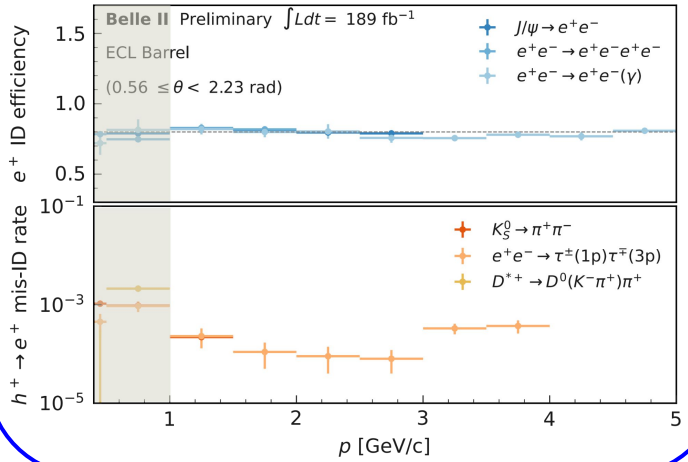
Backup slides

Lepton Identification at Belle II

- **Efficiencies** and **fake rates** measured on different well-known control channels
  BELLE2-CONF-PH-2022-003

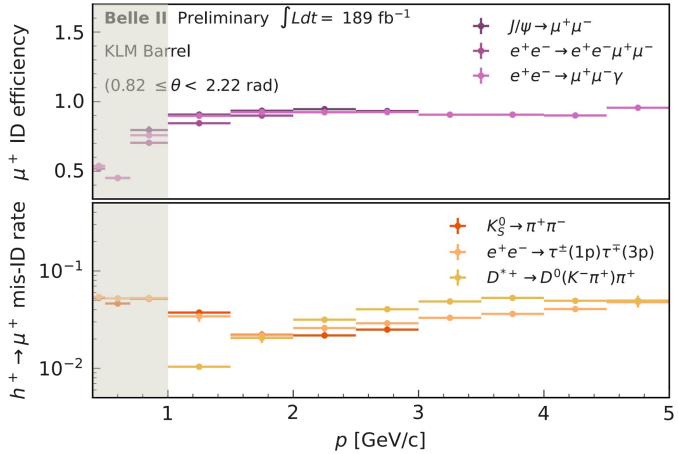
Electron ID

BDT exploiting **calorimeter** information

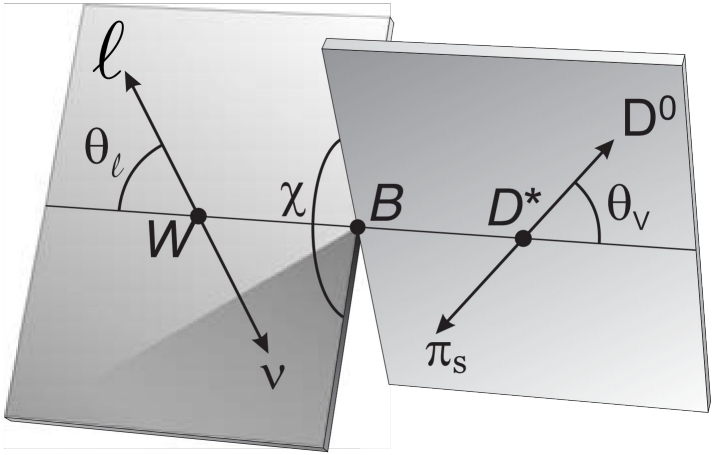


Muon ID

Combine likelihoods from **all sub-detectors** (calorimeter and μ detector are the most important)

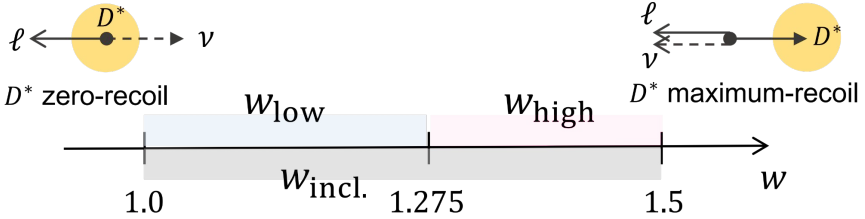


$B^0 \to D^* \ell \nu$ angular variables



Semileptonic B decays to D* vector

- **4 parameters** to fully describe $B \to D^* \ell \nu$ decay:
  - $\ell\nu$ invariant mass $q^2 = (p_B - p_{D^*})^2$
  - 3 helicity angles θ_ℓ, θ_V, χ
- Properties of ***V − A* coupling** and **spin of virtual *W* boson** are encoded in angular distributions
- Use D^* **recoil parameter** w: product of B and D^* four-velocity (it is proportional to $-q^2$)



$$w = \frac{m_B^2 + m_{D_*}^2 - q^2}{2 m_B m_{D^*}}$$