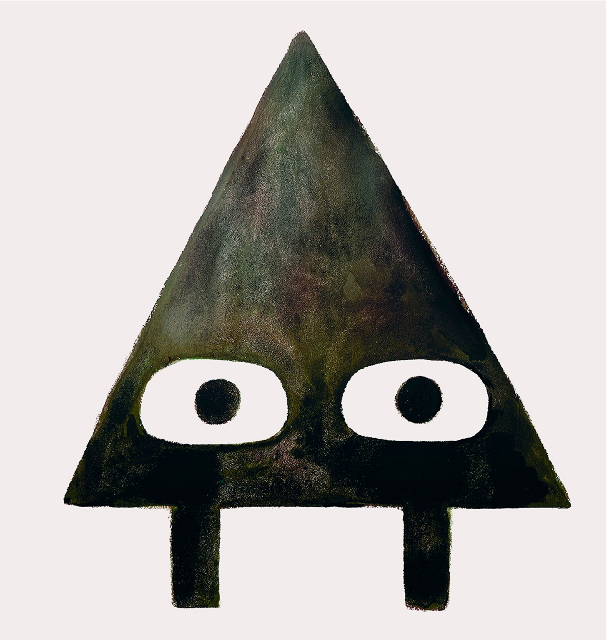
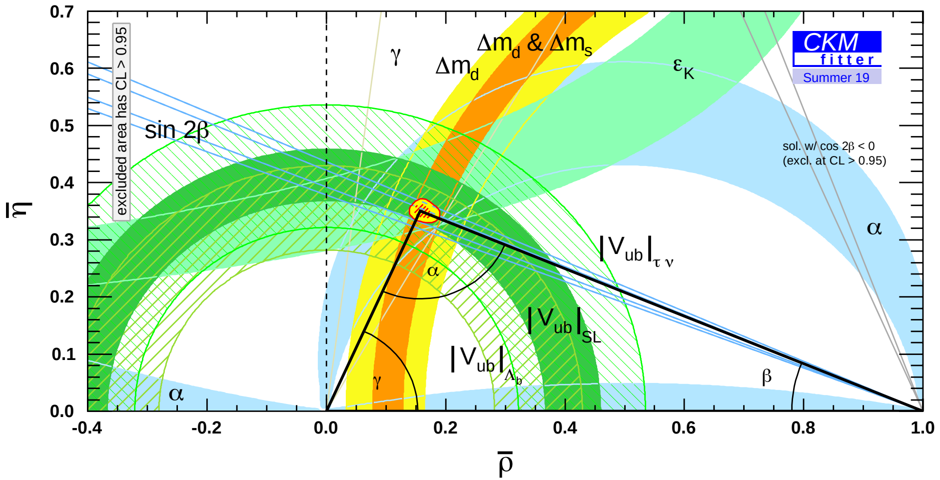
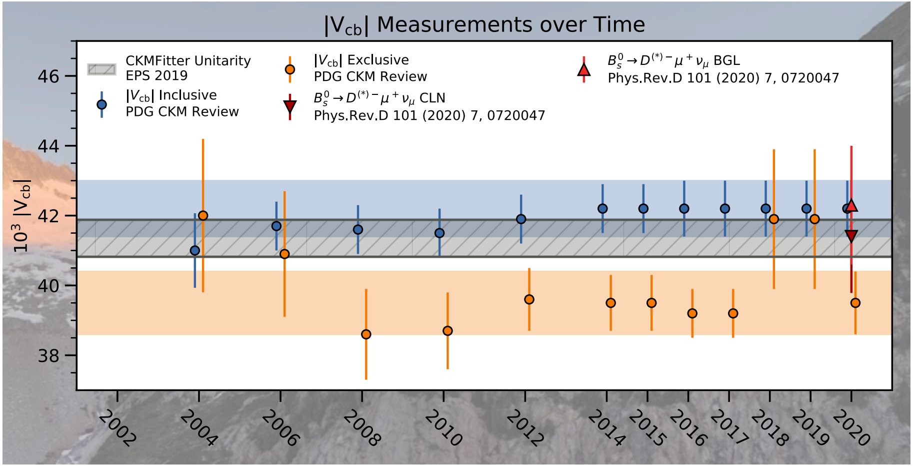


[source]

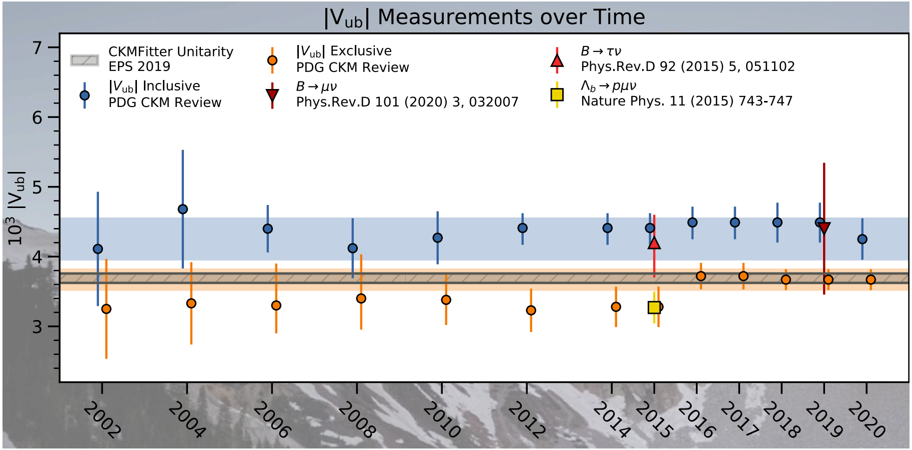


CKM fitter
Summer 19
excluded area has CL > 0.95
sin 2β
γ
Δm_d & Δm_s
Δm_d
ε_K
sol. w/ cos 2β < 0
(excl. at CL > 0.95)
α
$|V_{ub}|_{\tau\nu}$
$|V_{ub}|_{SL}$
$|V_{ub}|_{\Lambda_b}$
β
$\bar{\eta}$
$\bar{\rho}$

[F. Bernlochner, Snowmass]



[F. Bernlochner, Snowmass]

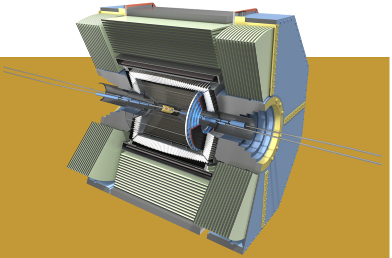


$|V_{cb}|$ and $|V_{ub}|$ measurements at LHCb and Belle (II)

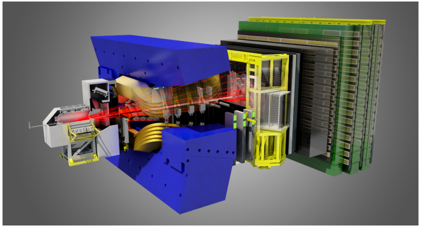
Conference on Flavor Physics and CP Violation (FPCP2021)
(virtual) Shanghai, June 7 - 11, 2021

Michel De Cian, EPFL
on behalf of the LHCb and Belle (II) collaborations

in the main roles:



The Belle (II) experiment
at the e^+e^- SuperKEK B accelerator.



and: The LHCb experiment
at the pp accelerator LHC.

Measuring $|V_{cb}|$ and $|V_{ub}|$ at LHCb and Belle (II)

- Two main ways to measure $|V_{ub}|$ and $|V_{cb}|$
- Exclusive:
  - Focus on a single final state, *e.g.* $B^+ \to \pi^+\mu^-\overline{\nu}_\mu$ or $B^0 \to D^{*-}\mu^+\nu_\mu$.
  - Challenges: Possibly small signal yield, knowledge of hadronic form factors.
- Inclusive:
  - Consider "all" final states, *e.g.* $B^+ \to X_c\mu^-\overline{\nu}_\mu$ or $B^0 \to X_u\mu^+\nu_\mu$.
  - Challenges: Background contamination, shape functions, ...

Table: Matrix of success

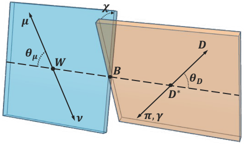
	Belle (II)	LHCb
exclusive	$\|V_{cb}\|$ 🙂 $\|V_{ub}\|$ 🙂	$\|V_{cb}\|$ 🙂 $\|V_{ub}\|$ 🙂
inclusive	$\|V_{cb}\|$ 🙂 $\|V_{ub}\|$ 🙂	$\|V_{cb}\|$ 😐 * $\|V_{ub}\|$ 🙁 *

*not performed yet

total slides

current slide

Exclusive measurements – $|V_{cb}|$



- $\frac{d^4\Gamma(B\to D^{*0}\mu\nu)}{dw d\Omega} = \frac{3m_B^3 m_{D^{*0}}^2 G_F^2}{16(4\pi)^4}\eta_{EW}^2 |V_{cb}|^2 |\mathcal{A}(w,\Omega)|^2, w = \frac{m_B^2+m_{D^*}^2-q^2}{2m_B m_{D^{*0}}}$
- Helicity amplitudes in $\mathcal{A}(w,\Omega)$ depend on 3 form factors: $h_{A_1}(w), R_1(w), R_2(w)$
- External input: $\eta_{EW} = 1.0066$

CLN parametrisation $\rightarrow$ 4 free parameters: $\rho^2, h_{A_1}, R_1(1), R_2(1)$ [Nucl. Phys. B530, 153 (1998)]

$$
\begin{aligned}
h_{A_1}(w) &= h_{A_1}(1)\left(1-8\rho^2 z+(53\rho^2-15)z^2-(231\rho^2-91)z^3\right)\\
R_1(w) &= R_1(1)-0.12(w-1)+0.05(w-1)^2\\
R_2(w) &= R_2(1)-0.11(w-1)-0.06(w-1)^2
\end{aligned}
$$

Similar, but simpler for $B^+ \to D^0\mu^+\nu_\mu$

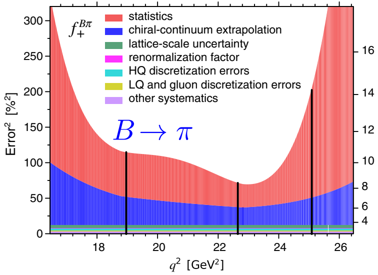
BGL parametrisation $\rightarrow$ Converging series [PRL 74, 4603 (1995)]

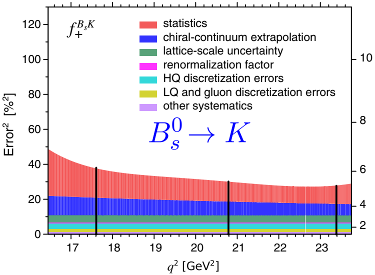
$$
\begin{aligned}
f(z) &= \frac{1}{P_{1^+}(z)\phi_f(z)}\sum_{n=0}^{\infty} b_n z^n \qquad z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}\\
g(z) &= \frac{1}{P_{1^-}(z)\phi_g(z)}\sum_{n=0}^{\infty} a_n z^n\\
\mathcal{F}_1(z) &= \frac{1}{P_{1^+}(z)\phi_{\mathcal{F}_1}(z)}\sum_{n=0}^{\infty} c_n z^n
\end{aligned}
$$

[PRD 91 074510 (2015)]

Exclusive measurements – $|V_{ub}|$

- $\frac{d\Gamma(B\to\pi\ell\nu)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{14\pi^3}|p_\pi|^3|f_+(q^2)|^2$
- Less data available than for exclusive $|V_{cb}|$ measurements: Use theoretical input for form factors (and use different parametrisations), often a mix of LQCD (high q^2) and LCSR (low q^2).
- Different $b \to u$ transitions have different FF uncertainties and experimental challenges.





- Not discussing purely leptonic decays

q^2 = (di-lepton invariant mass)^2

Inclusive measurements of $|V_{ub}|$ and $|V_{cb}|$

$|V_{cb}|$

- $\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \left(1 + \frac{c_5(\mu)\langle O_5(\mu)\rangle}{m_b^2} + \frac{c_6(\mu)\langle O_6(\mu)\rangle}{m_b^3} + \mathcal{O}\left(\frac{1}{m_b^4}\right)\right)$
- HQE with non-perturbative coefficients, determined with moments of the lepton energy / q^2/ the hadronic mass of $B \to X_c \ell \nu$

$|V_{ub}|$

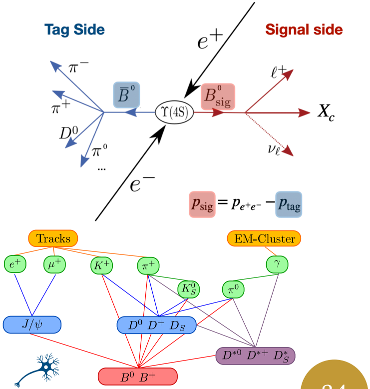
- Dominated by feed-down from X_c: Select region in lepton energy / m_u inaccessible to $B \to X_c \ell \nu$ decays.
- Use "shape-functions" to describe dynamics of the b quark inside the hadron: Different models used with different uncertainties in the perturbative and non-perturbative parameters.

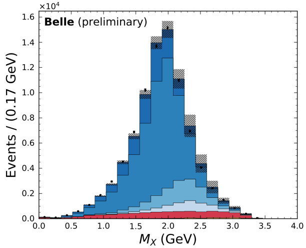
$$|V_{cb}|$$

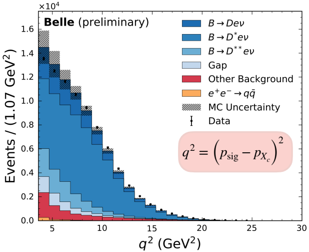
[j.nima.2011.06.008] [arXiv:2105.08001]

Inclusive $|V_{cb}|$ using higher-order terms

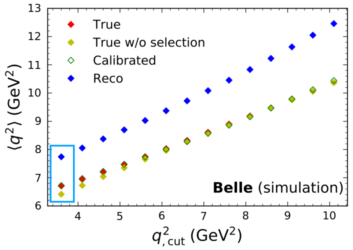
- Use a novel strategy to measure $|V_{cb}|$ with higher-order terms: Exploit parametrization invariance to reduce number of non-perturbative elements in the expansion. [JHEP 02 (2019) 177]
  - Holds only for some observables, *e.g.* $\langle q^2 \rangle$ (but not for $\langle M_X \rangle$
  - Reduces # parameters at order 4 from 13 $\rightarrow$ 8.
- $\therefore$ Measure $\langle q^2 \rangle^{1\ldots4}$ with Belle data
- Use hadronic tagging to fully reconstruct tag-side kinematics, using Full Reconstruction (FR).

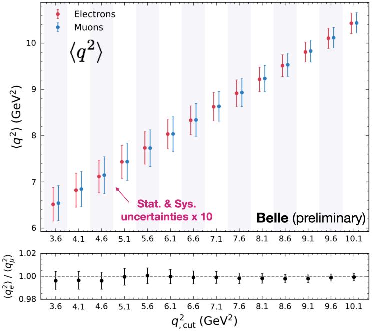






Inclusive $|V_{cb}|$ using higher-order terms

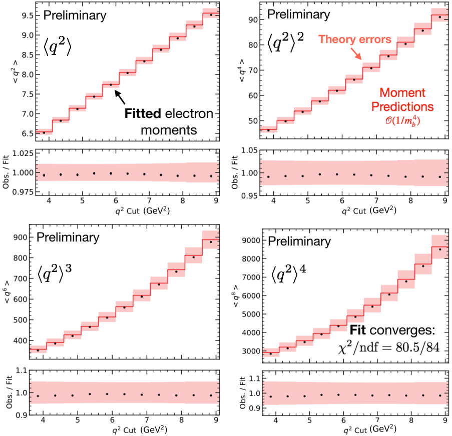


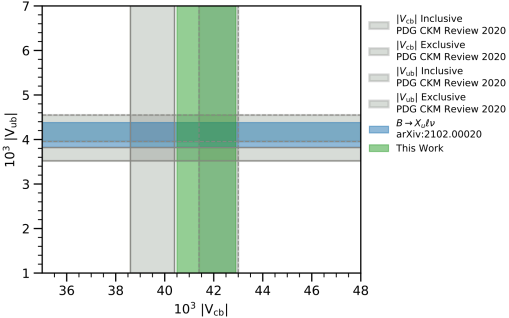


- Using simulation, correct for:
  - Difference between true and reconstructed $\langle q^2 \rangle$
  - Biases from the calibration procedure
  - Biases from the reconstruction.
- as a function of the q^2_{cut} value.
- Good agreement between electron and muon results
  $\longrightarrow$ Combine for the moments determination.

Inclusive $|V_{cb}|$ using higher-order terms

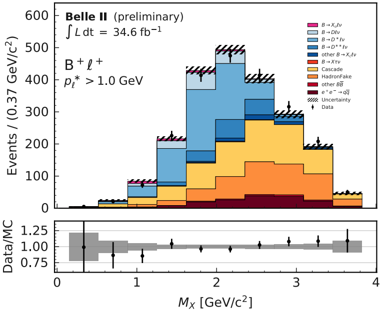
In collaboration with M. Fael, K. Olschewsky, K. Vos

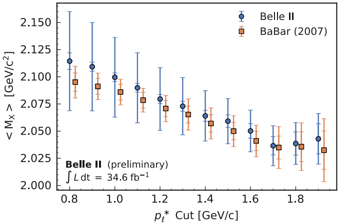


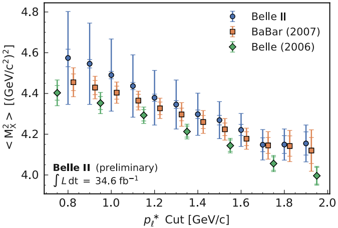


- $|V_{cb}| = (41.7 \pm 1.2) \cdot 10^{-3}$ (preliminary)

Towards inclusive $|V_{cb}|$ with Belle II

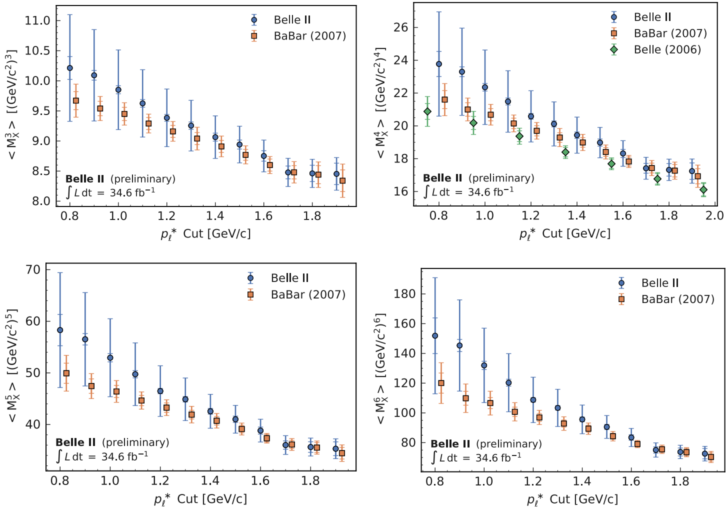






- Similar strategy as in the Belle measurement, but much smaller dataset: Measure $\langle M_X^{1..6} \rangle$.
- Use hadronic tagging with Full Event Interpretation (FEI), reconstruct a high-momentum lepton and use the rest of the event to construct M_X.
- Similar correction procedure as for the Belle measurement.

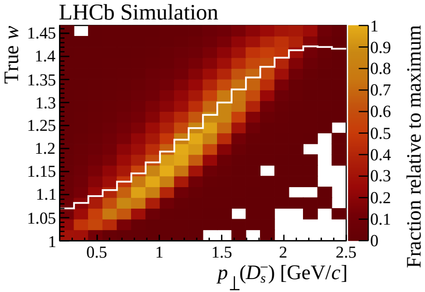
Towards inclusive $|V_{cb}|$ with Belle II

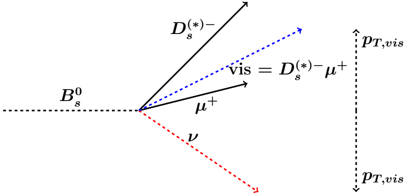


Results in agreement with earlier measurements but not competitive yet

[Phys. Rev. D101 (2020) 072004]

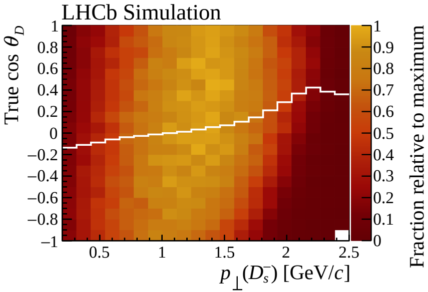
Exclusive $|V_{cb}|$ using B_s^0 decays

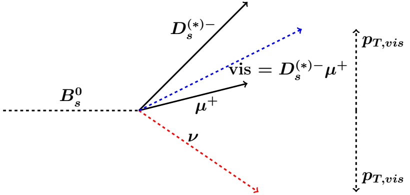




- Use the decay $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu, D_s^- \to K^+K^-\pi^-$ to measure $|V_{cb}|$ exclusively.
  - Normalize to $B^0 \to D^{(*)-}\mu^+\nu_\mu, D^- \to K^+K^-\pi^-$
- B_s^0 mesons abundantly produced at LHCb.
- Use the corrected mass variable $m_{\text{corr}} = \sqrt{m_{vis}^2 + p_{\mathrm{T}}{}_{vis}^2} + p_{\mathrm{T}vis}$ to distinguish signal and background
- and the correlation between $p_{\mathrm{T}rel}$ and w, $\cos\theta_D$ and $\cos\theta_\mu$ to determine the angular shape.

Exclusive $|V_{cb}|$ using B_s^0 decays

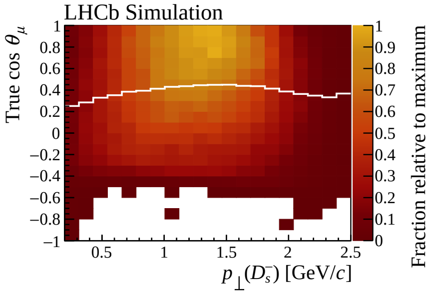


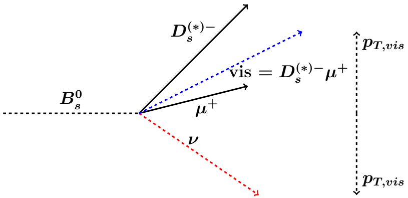


- Use the decay $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu, D_s^- \to K^+K^-\pi^-$ to measure $|V_{cb}|$ exclusively.
  - Normalize to $B^0 \to D^{(*)-}\mu^+\nu_\mu, D^- \to K^+K^-\pi^-$
- B_s^0 mesons abundantly produced at LHCb.
- Use the corrected mass variable $m_{\text{corr}} = \sqrt{m_{vis}^2 + p_{\mathrm{T}\,vis}^2} + p_{\mathrm{T}\,vis}$ to distinguish signal and background
- and the correlation between $p_{\mathrm{T}rel}$ and w, cos θ_D and cos θ_μ to determine the angular shape.

[Phys. Rev. D101 (2020) 072004]

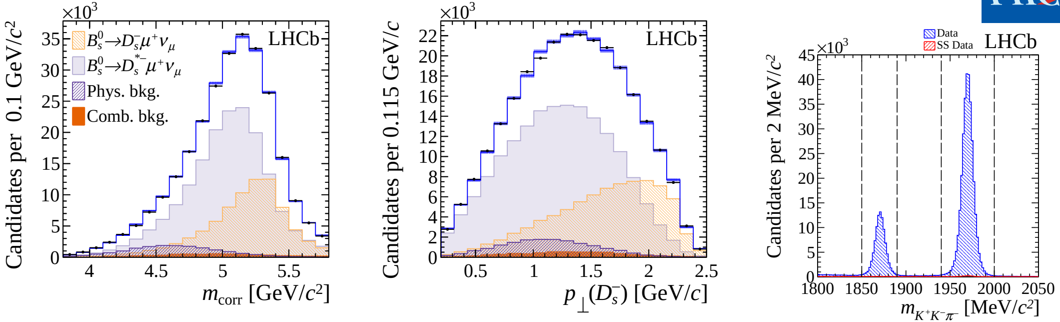
Exclusive $|V_{cb}|$ using B_s^0 decays





- Use the decay $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu, D_s^- \to K^+K^-\pi^-$ to measure $|V_{cb}|$ exclusively.
  - Normalize to $B^0 \to D^{(*)-}\mu^+\nu_\mu, D^- \to K^+K^-\pi^-$
- B_s^0 mesons abundantly produced at LHCb.
- Use the corrected mass variable $m_{\text{corr}} = \sqrt{m_{vis}^2 + p_{\text{T}}{}_{vis}^2} + p_{\text{T}}{}_{vis}$ to distinguish signal and background
- and the correlation between $p_{\text{T}}{}_{rel}$ and w, $\cos\theta_D$ and $\cos\theta_\mu$ to determine the angular shape.

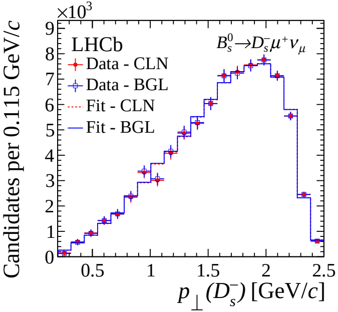
Exclusive $|V_{cb}|$ using B_s^0 decays

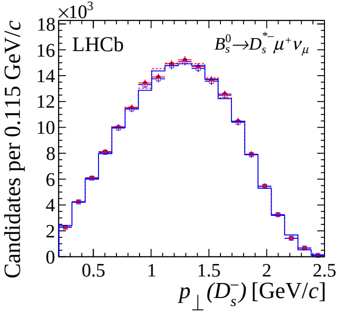


- Clean signal and normalization samples
- $D_s^{*+} \to D_s^+ \gamma/\pi^0$: Neutral objects with low p_{T} have a low reconstruction efficiency in LHCb, so only D_s^+ is reconstructed.
- Similar for $D^{*-} \to D^- \gamma/\pi^0$

[Phys. Rev. D101 (2020) 072004]

Exclusive $|V_{cb}|$ using B_s^0 decays

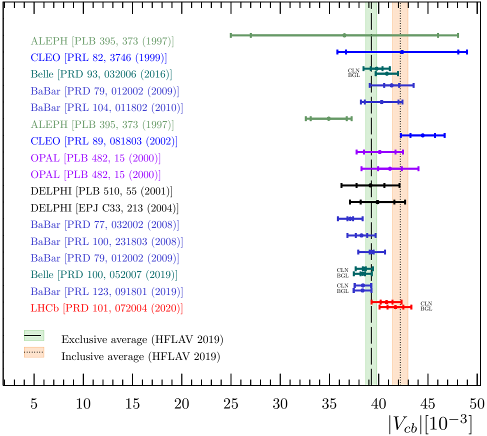




- Perform fit using both, CLN and BGL, parametrisation.
- Leading to:
  - $|V_{cb}|_{\text{CLN}} = (40.8 \pm 0.6 \pm 0.9 \pm 1.1) \cdot 10^{-3}$
  - $|V_{cb}|_{\text{BGL}} = (41.7 \pm 0.8 \pm 0.9 \pm 1.1) \cdot 10^{-3}$
- Updated results wrt to [Phys. Rev. D101 (2020) 072004] due to new value of f_s / f_d from [LHCb-PAPER-2020-046].

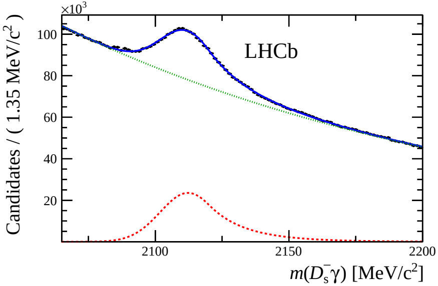
[Phys. Rev. D101 (2020) 072004]

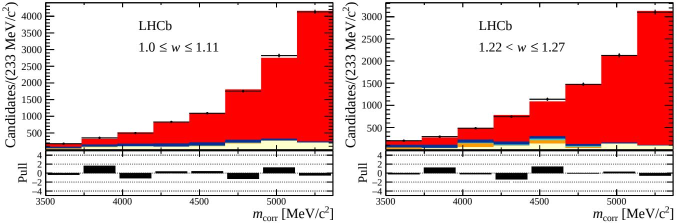
Exclusive $|V_{cb}|$ using B_s^0 decays



- Used the latest average of f_s/f_d from [LHCb-PAPER-2020-046] for the LHCb numbers.

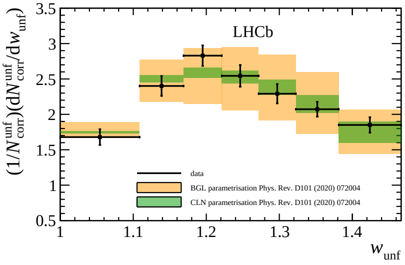
Measuring the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ decay rate

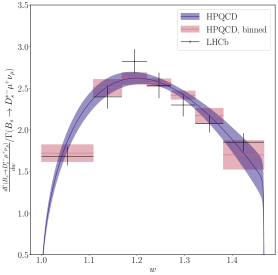




- Determine the FFs of $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ by measuring the shape of its differential decay rate.
- Fully reconstruct D_s^{*-} with (low-p_{T}) photon from $D_s^{*-} \to D_s^-\gamma$
- Use m_{corr} to separate signal from background, determine q^2 (and w) using kinematical constraints.

Measuring the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ decay rate



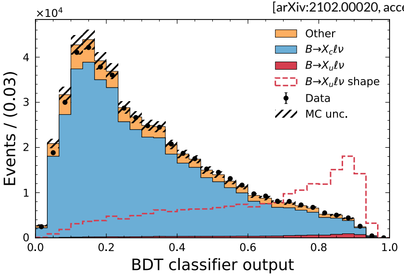


- Provide w data for phenomenological analysis for the first time.
- Good agreement with FFs from [Phys. Rev. D101 (2020) 072004]
- and with recent LQCD calculation from HPQCD [arXiv:2105.11433]

$$|V_{ub}|$$

Partial $\mathcal{B}$ and inclusive $|V_{ub}|$

[arXiv:2102.00020, accepted by PRD]

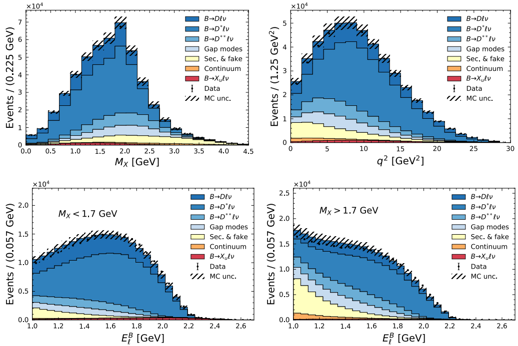


- The dilemma of inclusive $|V_{ub}|$:
  - Want to reduce contributions from $B \to X_c \ell \nu$ as much as possible $\to$ Only consider small phase space.
  - Precision of shape functions decreases for small phase space $\to$ Increase phase space.
- "Resolve" dilemma by enlarging the regions where $\Delta\mathcal{B}(B \to X_u \ell \nu)$ is measured and suppress $B \to X_c \ell \nu$ background using machine learning.
- Use hadronic tagging with FR to constrain the kinematics of B_{sig}
  - Use M^2_{miss}, D^* veto variables, presence of kaons, B_{sig} vertex fit quality and the total net charge of the event to distinguish $B \to X_c \ell \nu$ from $B \to X_u \ell \nu$.

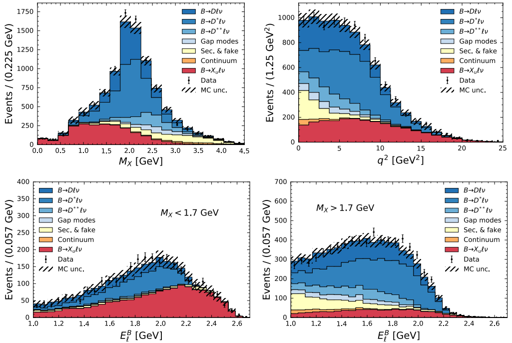
34

[arXiv:2102.00020]

Partial $\mathcal{B}$ and inclusive $|V_{ub}|$



before BDT



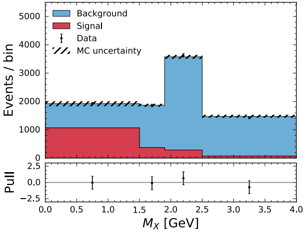
after BDT

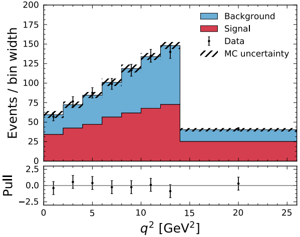
[arXiv:2102.00020]

Partial $\mathcal{B}$ and inclusive $|V_{ub}|$

$$|V_{ub}|\ (\mathrm{BLNP}) = \left(4.05 \pm 0.09^{+0.21}_{-0.22}{}^{+0.18}_{-0.20}\right) \times 10^{-3},$$
$$|V_{ub}|\ (\mathrm{DGE}) = \left(4.16 \pm 0.09^{+0.21}_{-0.22}{}^{+0.11}_{-0.12}\right) \times 10^{-3},$$
$$|V_{ub}|\ (\mathrm{GGOU}) = \left(4.15 \pm 0.09^{+0.21}_{-0.22}{}^{+0.08}_{-0.09}\right) \times 10^{-3},$$
$$|V_{ub}|\ (\mathrm{ADFR}) = \left(4.05 \pm 0.09^{+0.21}_{-0.22} \pm 0.18\right) \times 10^{-3}.$$

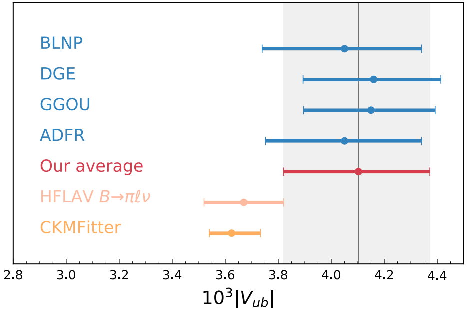
- $|V_{ub}| = \sqrt{\dfrac{\Delta\mathcal{B}(B \to X_u \ell\nu)}{\tau_B \Delta\Gamma(B \to X_u \ell\nu)}}$
- Use 4 different theoretical predictions for $\Delta\Gamma(B \to X_u \ell\nu)$
- Use a 2D fit in M_X and q^2 in the most inclusive sample with $E_\ell^B > 1\ \mathrm{GeV}/c$ to determine $|V_{ub}|$ with the 4 different predictions.





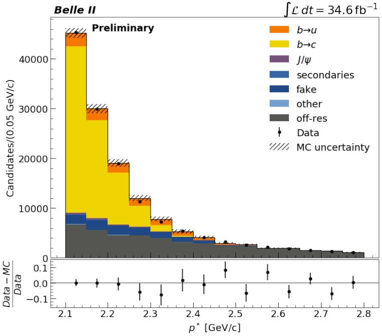
- Average of the most precise ones leads to: $|V_{ub}| = (4.10 \pm 0.09 \pm 0.22 \pm 0.15) \cdot 10^{-3}$

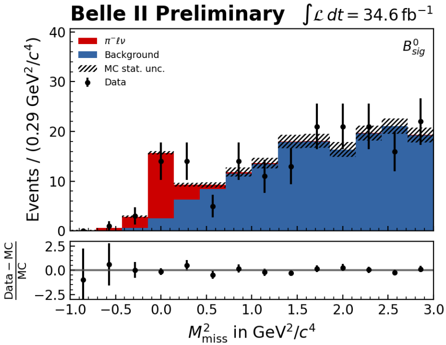
Partial $\mathcal{B}$ and inclusive $|V_{ub}|$



- Obtained result shows a discrepancy with respect to $|V_{ub}|$ exclusive from $B \to \pi\ell\nu$ (1.3σ) and from CKM constraints (1.6σ).

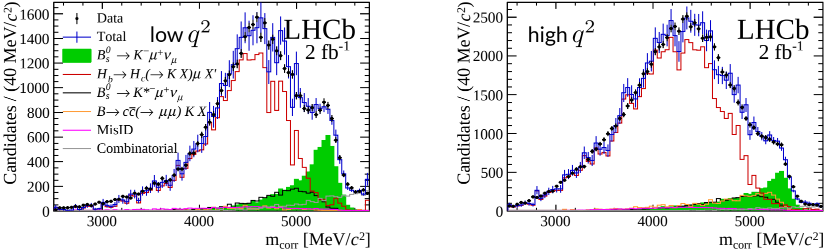
First Belle II results on $B \to X_u \ell \nu$





- Rediscover $B \to X_u \ell \nu$ close to the kinematic endpoint of p^*_ℓ
- And $B^0 \to \pi^- \ell \nu$ using FEI.

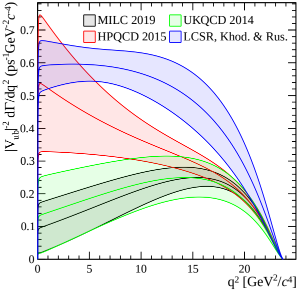
Exclusive $|V_{ub}|$ from B_s^0 mesons

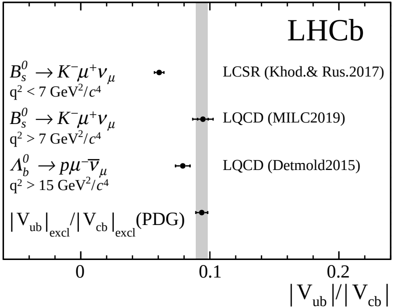


- Use $B_s^0 \to K^- \mu^+ \nu_\mu$ decays to measure $|V_{ub}|$: First observation of $B_s^0 \to K^- \mu^+ \nu_\mu$.
- Measure $\frac{|V_{ub}|}{|V_{cb}|} = R_{FF} \cdot \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}$, use $m_{\rm corr}$ to discriminate signal and background.
- Divide $B_s^0 \to K^- \mu^+ \nu_\mu$ in two bins of q^2 with equal number of signal events.

$R_{\rm FF}$: form factor ratio

Exclusive $|V_{ub}|$ from B_s^0 mesons

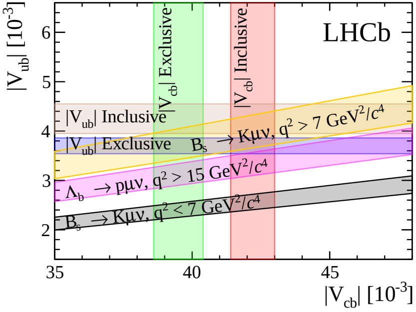




- Two different FF predictions for $B_s^0 \to K^-\mu^+\nu_\mu$ used to extract $|V_{ub}|$:
  - Low q^2: LCSR based on [JHEP 08 112]
  - High q^2: LQCD based on [Phys. Rev. D100, 034501]
- Provide two values of $|V_{ub}|$. Differential rate will help understanding the $B_s^0 \to K^-\mu^+\nu_\mu$ decay better.

[Phys. Rev. Lett. 126, 081804]

Exclusive $|V_{ub}|$ from B_s^0 mesons



Uncertainty	All q^2	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{corr})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	–	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$	$^{+3.0}_{-3.4}$
Total	$^{+4.0}_{-4.3}$	$^{+4.3}_{-4.5}$	$^{+5.0}_{-5.3}$

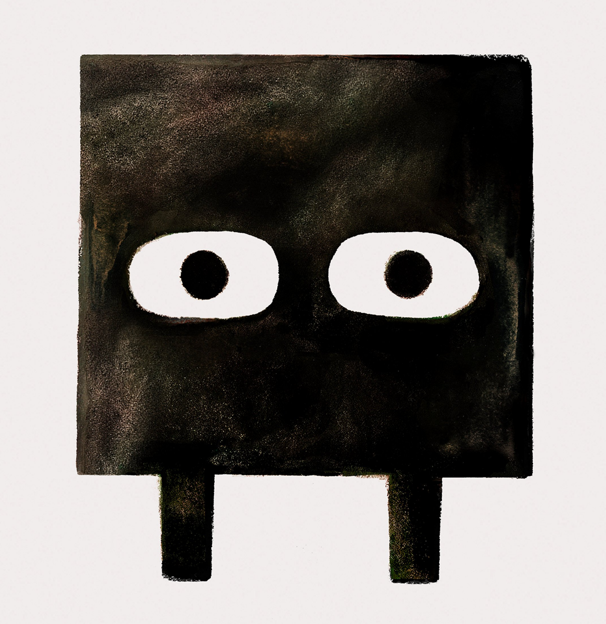
- Measurement (in individual q^2 bins) is systematically limited, many are connected with limited size of simulation sample.
- More q^2 bins will allow for a more precise measurement using the full LHCb data set.

Conclusions

- After 20 years of precision measurements, $|V_{cb}|$ and $|V_{ub}|$ are still an exciting research topic with unresolved puzzles.
- Many recent measurements by Belle (II) and LHCb add precision, but did not resolve all mysteries.
- Belle II and LHCb will continue to show a ”collaborative competition”.
- Exciting new results expected for the future: More exploitation of the Belle data set, new results by Belle II in the following months, start of the LHCb upgrade, results using B_c^+ mesons, $B^+ \to \tau^+/\mu^+\nu$, etc.

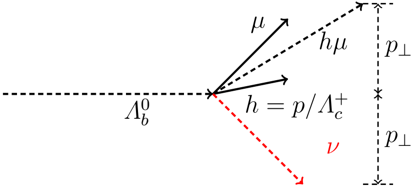
34

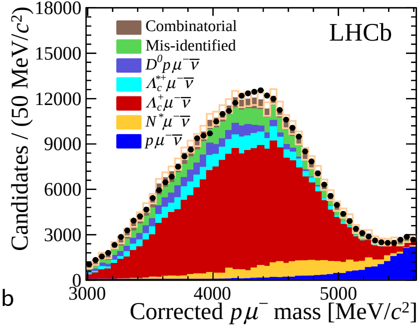
[source]



[Nature Physics 11 (2015) 743]

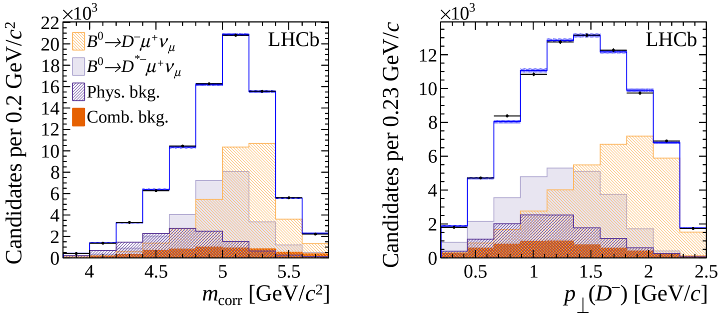
Exclusive $|V_{ub}|$ from Λ_b^0 baryons





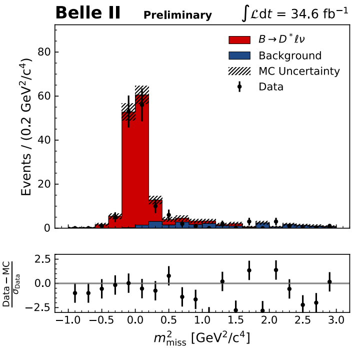
- First measurement of $|V_{ub}|$ (relative to $|V_{cb}|$) at LHCb
- Use the corrected mass variable to separate signal and background.
  - $m_{\text{corr}} = \sqrt{m_{vis}^2 + p_{\text{T}}{}^2} + p_{\text{T}}$
- Yields about 15'000 signal events.
- Measure $|V_{ub}| = R_{FF} \cdot \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^- \overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)} \cdot |V_{cb}|$ in high-q^2 region, using R_{FF} from [Phys Rev D. 92 (2015) 034503]
- $|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \cdot 10^{-3}$. Most precise exclusive result.

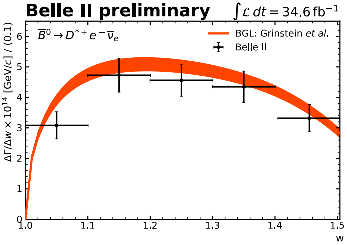
Exclusive $|V_{cb}|$ using B_s^0 decays

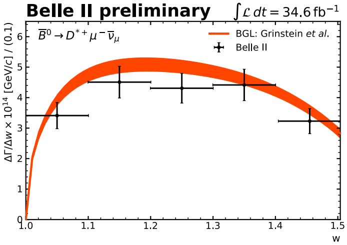


- Clean signal and normalization samples
- $D_s^{*+} \to D_s^+ \gamma/\pi^0$: Neutral objects with low p_{T} have a low reconstruction efficiency in LHCb, so only D_s^+ is reconstructed.
- Similar for $D^{*-} \to D^- \gamma/\pi^0$

$B \to D^{(*)}\ell\nu$ at Belle II

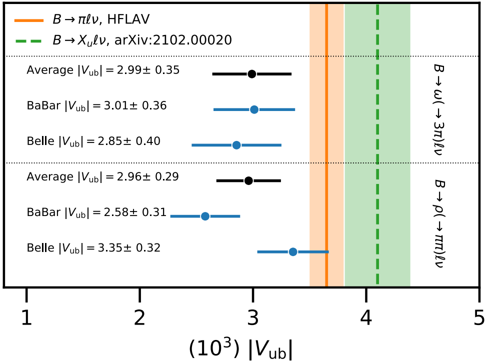






- Reconstruct $B \to D^{*}\ell\nu$ using hadronic tagging and FEI or $B \to D^{(*)}\ell\nu$ without tagging.
- Determine $\mathcal{B}(B^0 \to D^{*-}\ell^+\nu)$ = $(4.51 \pm 0.41 \pm 0.27 \pm 0.45)\%$ with FEI
- and $\mathcal{B}(B^0 \to D^{*-}\ell^+\nu)$ = $(4.60 \pm 0.05 \pm 0.17 \pm 0.45)\%$ without tagging.

$|V_{ub}|$ from $B^+ \to \rho/\omega\ell\nu$



- Large discrepancy between values extracted from $B^+ \to \rho/\omega\ell\nu$ and $B \to \pi\ell\nu$