The Future of Flavour Physics

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BSM Forum

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Take home messages

Take Home Message 1:

Flavour physics is interesting!

Take Home Message 2:

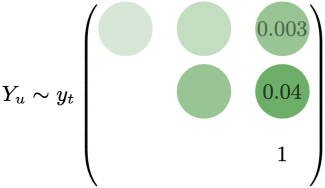
Despite some drawbacks, we can make
good progress in the next few years!

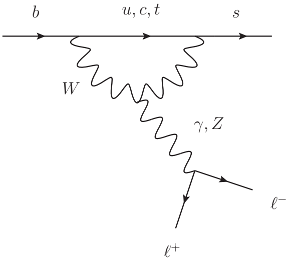
Why flavour?

$$Y_u \sim y_t \begin{pmatrix} & & 0.003 \\ & & 0.04 \\ & & 1 \end{pmatrix}$$

- The origin of the Yukawa patterns is unknown
  - Yukawa couplings are free parameters in the SM and they have to be extracted from data

Why flavour?





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  - Yukawa couplings are free parameters in the SM and they have to be extracted from data
- CKM and/or loop-suppressed decays have a small signal that should make new physics visible
  - We need to control SM predictions at high accuracy

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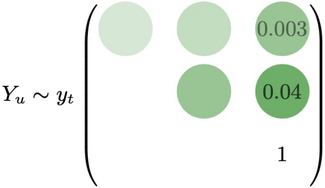
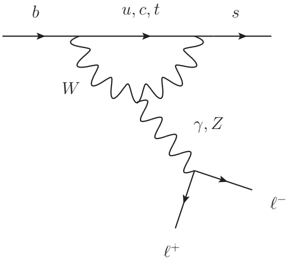




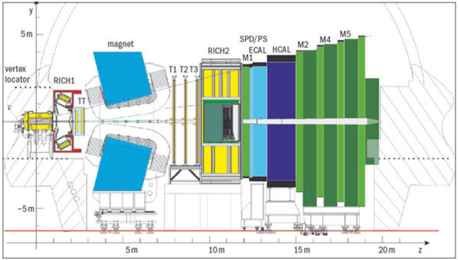
- The origin of the Yukawa patterns is unknown
  - Yukawa couplings are free parameters in the SM and they have to be extracted from data
- CKM and/or loop-suppressed decays have a small signal that should make new physics visible
  - We need to control SM predictions at high accuracy
  - Indirect searches: no energy limitation

$$\mathcal{O}_{\rm th}(y_{ij}) = \mathcal{O}_{\rm exp}$$

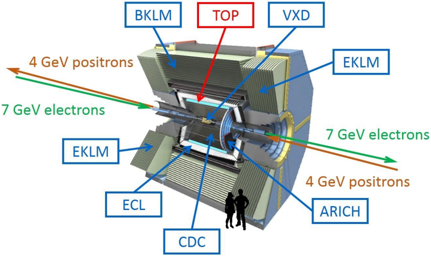
- Control theoretical accuracy
  - ⇒ Predict with high accuracy non-perturbative quantities e.g. decay constants, form factors, etc.
  - ⇒ Need to develop non-perturbative methods
- Control experimental error
  - ⇒ For statistically limited modes we only need to wait
  - ⇒ For systematically limited modes we need more statistics and better techniques

B-physics: LHCb and Belle II

LHCb



Belle/Belle II



- Hadronic machine (pp-collisions)
- Forward detector
- The momentum of the b-hadrons is not known

- e^+e^- collisions at $\sqrt{s} = m(\Upsilon(4S))$
- 4π detector
- The momentum of the b-hadrons is known

Current Experimental Status

Channel	Belle I	Belle II (current)	LHCb Run I+II
B^0, $\bar{B}^0$	$\sim 8 \times 10^8$	$\sim 4 \times 10^8$	$\sim 2 \times 10^{12}$
$B^\pm$	$\sim 8 \times 10^8$	$\sim 4 \times 10^8$	$\sim 2 \times 10^{12}$
B_s^0, $\bar{B}_s^0$	$\sim 6 \times 10^8$		$\sim 0.5 \times 10^{12}$
$B_c^\pm$	–		$\sim 8 \times 10^8$
Λ_b, $\bar{\Lambda}_b$	–		$\sim 1 \times 10^{12}$

- Belle II data are currently analysed and many interesting results are out

  $\Rightarrow$ New analysis techniques help in exploiting the current (low) statistics and achieving remarkable results

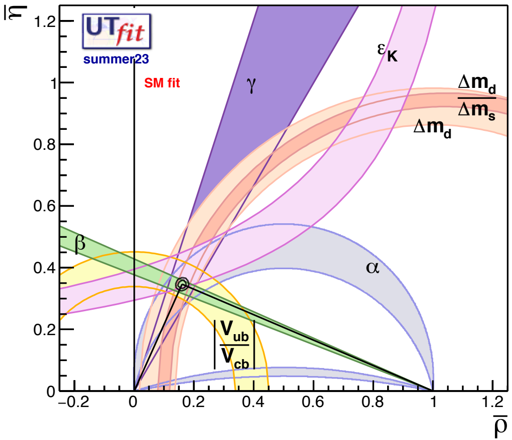
- Many LHCb results are still based on Run I + half of Run II datasets

  $\Rightarrow$ Still room for improvement before Run 3 results

Current Experimental Status

- Data taking is not going as smoothly as foreseen
- LHCb suffered from delays due to problems during the 2023 Run
- Belle II resumed operation this year but they are also under luminosity target
- Recently, CMS has started producing very interesting results in rare decays
- The key forward is the complementarity of these three experiments

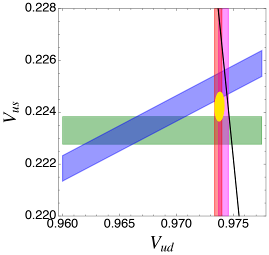
Where are we?

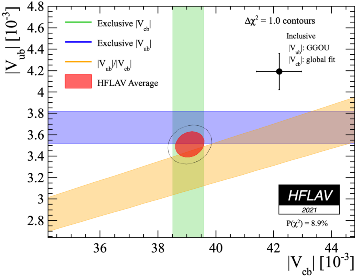


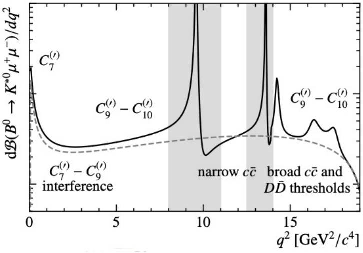
"...there is a general consistency, at the percent level, between the SM predictions and the experimental measurements. Thus in order to discover new physics effects a further effort in theoretical and experimental accuracy is required."

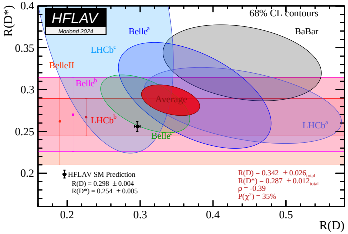
[2212.03894]

However, there are a lot of puzzles that involve single measurements/theoretical predictions:









How do we make progress?

We need a **physics plan**

- Joint between theory and experiment
- Concrete, exploiting what can be measured and predicted with high accuracy

What are the goals?

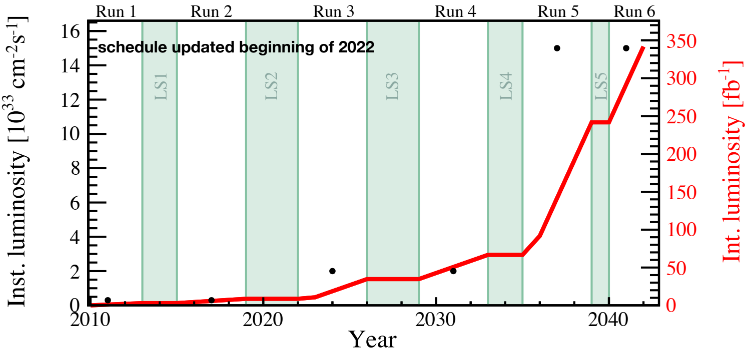
- Understand the SM at high accuracy

  ⇒ With or without the help of experimental data

- Look for hints of NP

  ⇒ Identify processes that are signatures for classes of models

The LHCb case



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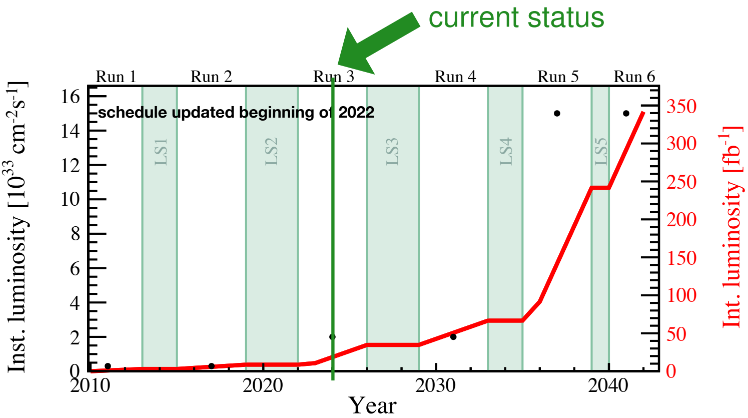

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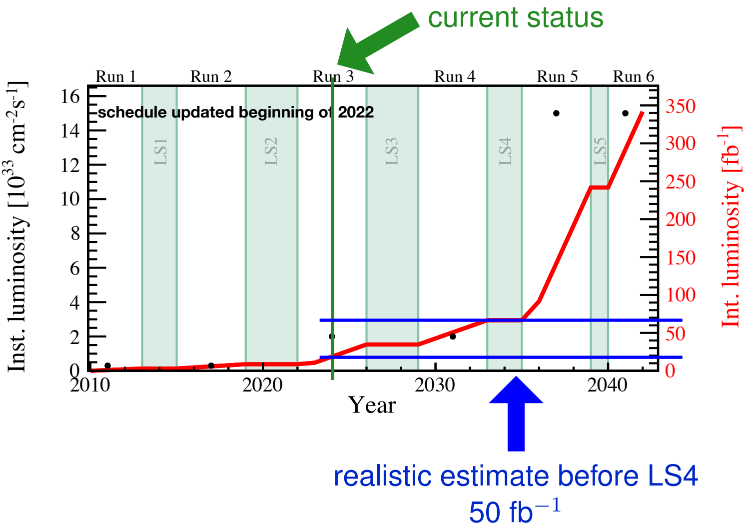
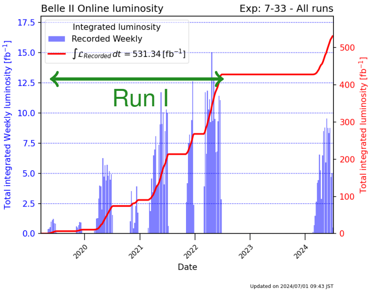
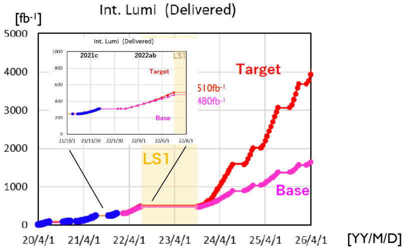


The Belle II case





- Belle II is taking data (will soon end operation for 2024)
- During Run I, they collected 424 fb^{-1}, of which 363 fb^{-1} at the $\Upsilon(4S)$
- From this year's trend, the "Base" luminosity is more realistic

Experimental prospects

- The nominal luminosity targets for Belle II and LHCb are 50 ab^{-1} and 300 fb^{-1}
- Realistically, it is unlikely that they will meet this goal
- In many cases, lower luminosities are anyway enough
- Benchmarks: Belle II with 1 ab^{-1} and LHCb with 100 fb^{-1}

Channel	Belle II	LHCb	FCC-ee
B^0, $\bar{B}^0$	$\sim 1 \times 10^9$	$\sim 2 \times 10^{13}$	$\sim 6.2 \times 10^{11}$
$B^\pm$	$\sim 1 \times 10^9$	$\sim 2 \times 10^{13}$	$\sim 6.2 \times 10^{11}$
B_s^0, $\bar{B}_s^0$	–	$\sim 0.6 \times 10^{13}$	$\sim 1.5 \times 10^{11}$
$B_c^\pm$	–	$\sim 8 \times 10^9$	$\sim 4 \times 10^9$
Λ_b, $\bar{\Lambda}_b$	–	$\sim 1 \times 10^{13}$	$\sim 1.30 \times 10^{11}$

What to expect from Lattice QCD

Input	f_{B_s} $(N_f = 2+1)$	f_{B_s} $(N_f = 2+1+1)$
current	1.8%	0.6%
5 years	0.9%	0.3%
10 years	0.4%	0.11%

- More statistics implies a systematic reduction of uncertainties
- It is expected a reduction of a factor of 2 in 5 years and 5 in 10 years
- However, below the per cent level, QED effects have to be taken into account
  - $\Rightarrow$ Already included in f_K, WIP per heavy mesons
- A conservative 1% error that accounts for QED has to be considered

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Until QED problem is solved, there is no need to improve significantly in statistics

Main references

Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era #1

LHCb Collaboration • Roel Aaij (NIKHEF, Amsterdam) et al. (Aug 27, 2018)

e-Print: 1808.08865 [hep-ex]

The Belle II Physics Book #1

Belle-II Collaboration • E. Kou (Orsay, LAL)(ed.) et al. (Aug 30, 2018)

Published in: *PTEP* 2019 (2019) 12, 123C01, *PTEP* 2020 (2020) 2, 029201 (erratum) • e-Print: 1808.10567 [hep-ex]

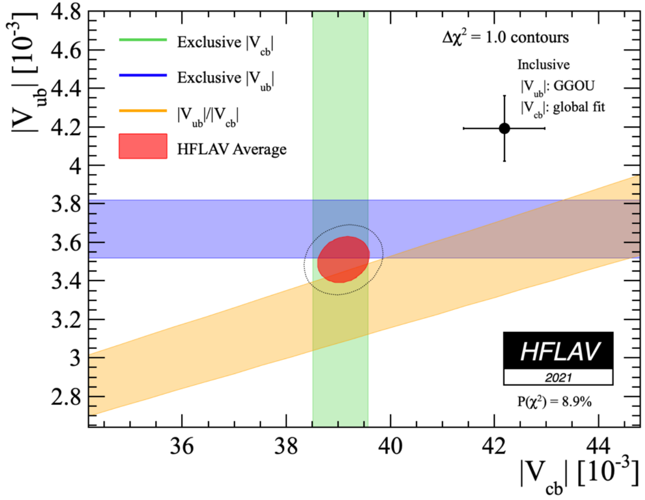
Snowmass White Paper: Belle II physics reach and plans for the next decade and beyond #2

Belle-II Collaboration • Latika Aggarwal et al. (Jul 13, 2022)

e-Print: 2207.06307 [hep-ex]

$|V_{cb}|$ and $|V_{ub}|$

The long-standing $|V_{cb}|/V_{ub}$ puzzle



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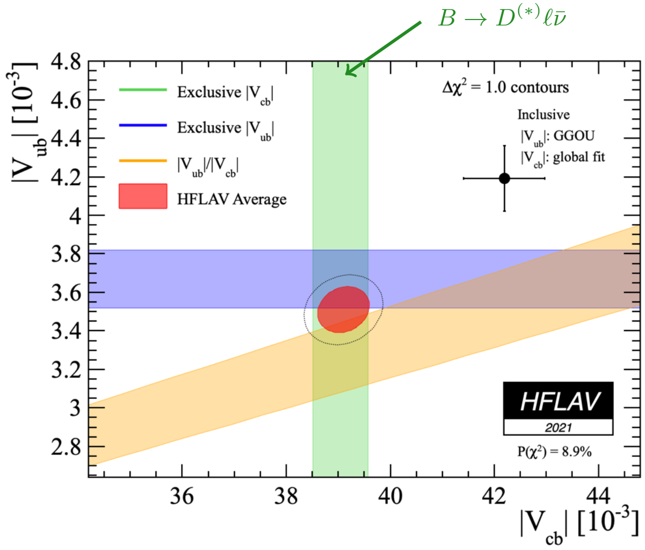

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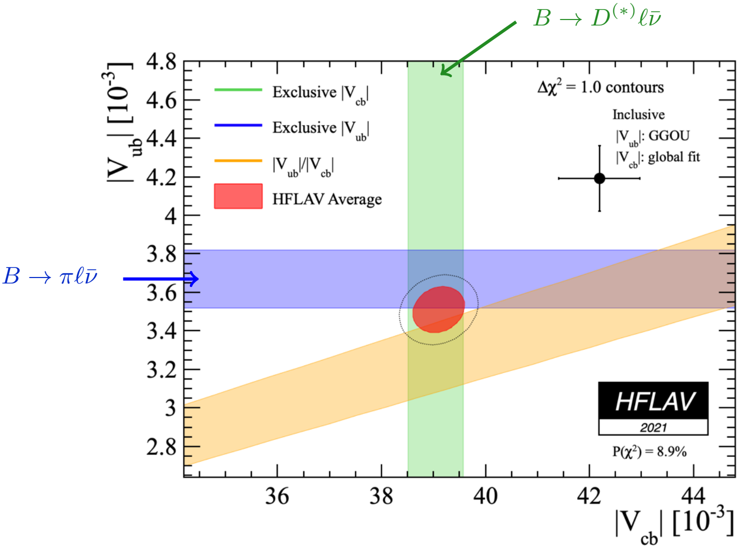

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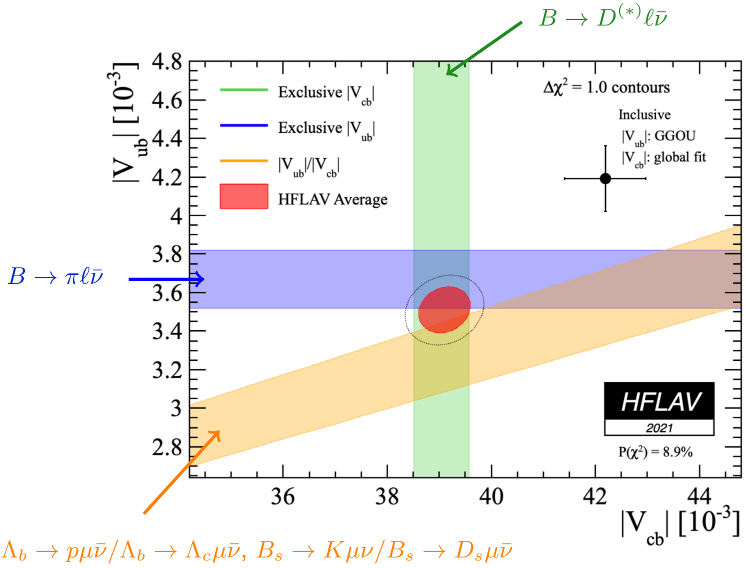
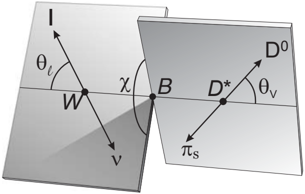


$|V_{cb}|$ and $|V_{ub}|$: current status

- Inclusive V_{cb} is rather stable
- Inclusive V_{ub} is less clean theoretically because cuts used in experiments make the theory prediction less precise
- Exclusive V_{cb} from $B \to D$ is also rather stable
- Exclusive V_{cb} from $B \to D^*$ is still shaky and depends strongly on the experimental dataset used and from theory inputs
- Exclusive V_{ub} from $B \to \pi$ is rather reliable

$B \to D^* \ell \bar{\nu}$



$$\frac{d\Gamma}{dw d\cos(\theta_\ell) d\cos(\theta_v) d\chi} = \frac{3G_F^2}{1024\pi^4}|V_{cb}|^2\eta_{EW}^2 M_B r^2 \sqrt{w^2-1}q^2$$
$$\times \{(1-\cos(\theta_\ell))^2 \sin^2(\theta_v) H_+^2(w) + (1+\cos(\theta_\ell))^2 \sin^2(\theta_v) H_-^2(w)$$
$$+ 4\sin^2(\theta_\ell)\cos^2(\theta_v) H_0^2(w) - 2\sin^2(\theta_\ell)\sin^2(\theta_v)\cos(2\chi) H_+(w) H_-(w)$$
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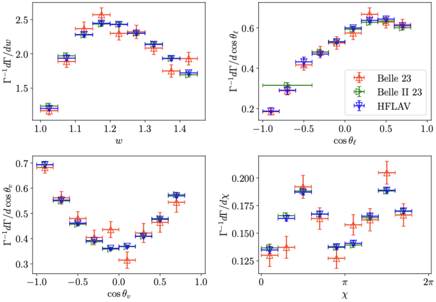
$$+ 4\sin(\theta_\ell)(1+\cos(\theta_\ell))\sin(\theta_v)\cos(\theta_v)\cos(\chi) H_-(w) H_0(w)\}$$



- Belle II with inclusive tag, Belle with hadronic tag
- Belle II w/ 189 fb^{-1} has the same precision as the previous untagged Belle analysis with the full dataset
  - $\Rightarrow$ Success of the inclusive tagging!
- Systematically dominated
  - $\Rightarrow$ Feedown from $B \to D^{**}$ can be reduce with further data

$B \to D^* \ell \bar{\nu}$: theory

$$\frac{d\Gamma}{dw d\cos(\theta_\ell) d\cos(\theta_v) d\chi} = \frac{3G_F^2}{1024\pi^4} |V_{cb}|^2 \eta_{EW}^2 M_B r^2 \sqrt{w^2-1} q^2$$
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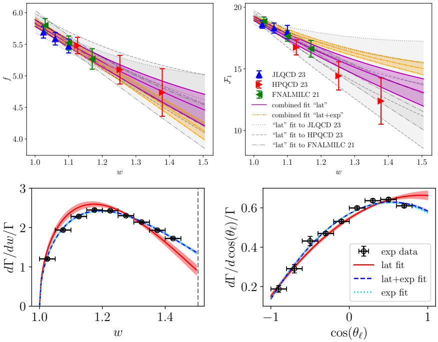
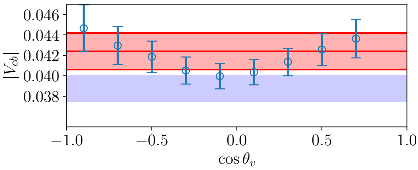
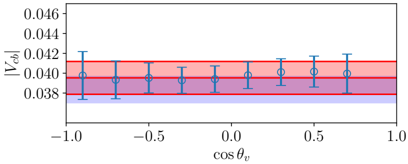
Hadronic form factors

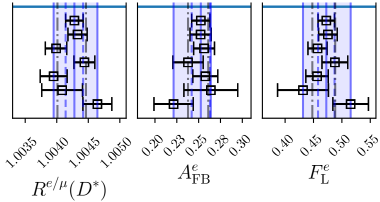
- The $B \to D^*$ case is more complicated because the D^* is unstable
- Recent progress from Lattice QCD: complete calculation away from zero-recoil



- Different lattice results yield different phenomenological consequences
- Understanding the differences among lattice and with experimental data is essential to make any progress

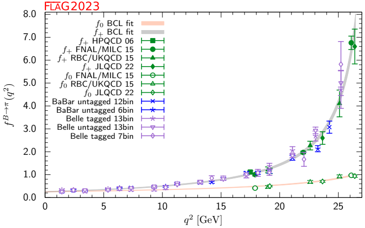


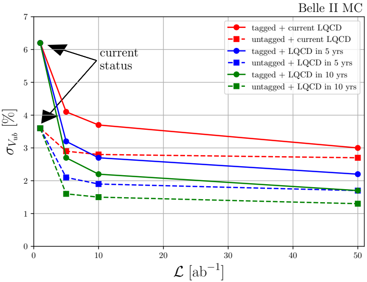




- The spread of the results is worrisome when trying to make precise predictions
- Combining various lattice results reduces uncertainties but renders predictions incompatible with the ones from a single dataset
- It is not clear that more statistics will solve the problem, difficult to give a solid prospect

Exclusive V_{ub} from $B \to \pi \ell \bar{\nu}$

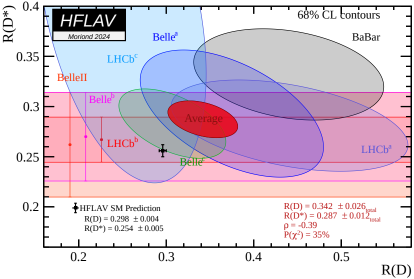




- Predictions for $B \to \pi$ form factors are more stable
- Agreement with experimental data is very good
- With combined progress from theory and experiment, the uncertainty on inclusive V_{ub} reaches 2% with $5\,ab^{-1}$
- Can the inclusive tagging bring to similar results with less statistics?

New physics in $b \to c\ell\bar{\nu}$

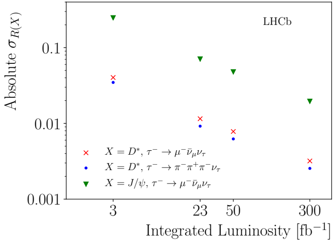
Lepton Flavour universality

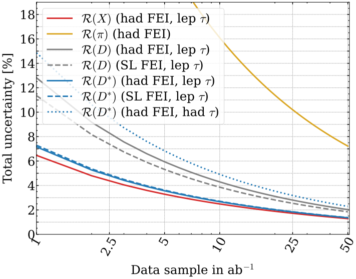


$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

- Test Universality between the 3rd and 2nd lepton families
- Ratios allow cancelling hadronic uncertainties and experimental uncertainties
- The $B \to D^*$ mode is still affected by the same effects discussed before
- The theory prediction of $B \to D$ is much cleaner

Experimental prospects





- Main experimental uncertainties: $B \to D^{**}$ feed down, simulates samples size
  - improvable with data-driven analysis and more efficient simulation software
- Uncertainties should approach the few % level with more statistics
- Current theory uncertainty for R_D is 1%
- No study with the inclusive tagging, ongoing work at Belle II

“Dirty” b-hadron decays

$b \to s e^+ e^-$

Yield	Run 1 result	$9\,\mathrm{fb}^{-1}$	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$
$B^+ \to K^+ e^+ e^-$	254 ± 29 [274]	1 120	3 300	7 500	46 000
$B^0 \to K^{*0} e^+ e^-$	111 ± 14 [275]	490	1 400	3 300	20 000
$B_s^0 \to \phi e^+ e^-$	–	80	230	530	3 300
$\Lambda_b^0 \to p K e^+ e^-$	–	120	360	820	5 000
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at low q^2 probes $b \to s\gamma$

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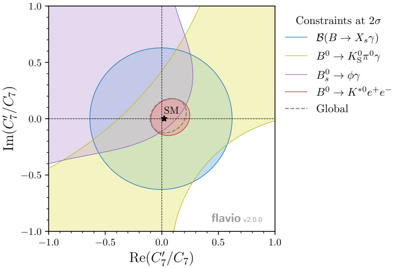

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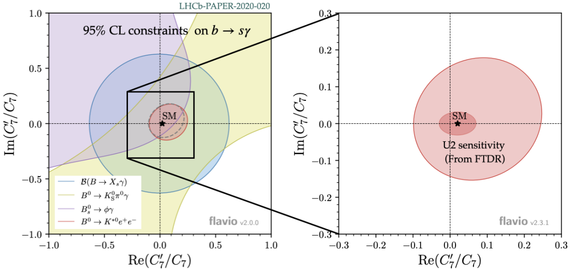


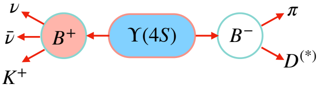
“Clean” b-hadron decays

Belle II

Hadronic tag

$B_{\text{tag}} \to \text{hadrons, e . g } B \to D^{(*)}\text{n}\pi$

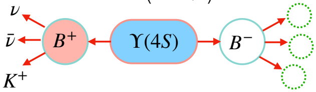
$\epsilon = \mathcal{O}(2\%)$



Inclusive tag

$B_{\text{tag}} \to \text{anything}$

$\epsilon = \mathcal{O}(100\%)$



Full Event Interpretation (FEI)

- Wrt Belle algorithm more decay modes have been added
- Low efficiency but high signal purity

Inclusive tagging

- High efficiency but low purity
- Properties of the Rest-Of-Event (ROE) are used to increase efficiency
- Especially convenient for modes with neutrinos

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

[2311.14647]

Hadronic Tagging

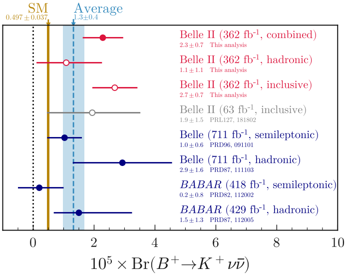
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (1.1^{+0.9+0.8}_{-0.8-0.5}) \times 10^{-5}$$

Inclusive Tagging

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (2.7 \pm 0.5 \pm 0.5) \times 10^{-5}$$

Combined

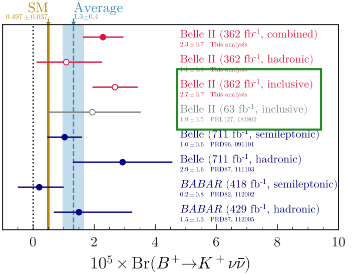
$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (2.7 \pm 0.5^{+0.5}_{-0.4}) \times 10^{-5}$$



$3.5\,\sigma$ evidence wrt background only

$2.7\,\sigma$ tension wrt SM

Prospects



uncertainty scales with luminosity
$\sim$ 26%

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)
$B^0 \to K^0_{\mathrm{S}}\nu\bar{\nu}$	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)

$B^+ \to K^+\nu\bar{\nu}$ @14%

What about theory?

$$\frac{d\mathcal{B}(B \to K\nu\bar{\nu})_{\rm SD}}{dq^2} = \frac{G_F^2 \alpha_{\rm EW}^2(M_Z) X_t^2}{32\pi^5 \sin^4\theta_W} \times \tau_B |V_{tb}V_{ts}^*|^2 |\vec{p}_K|^3 f_+^2(q^2)$$

⟵ Current uncertainties $3-4\%$

- Currently, SM prediction is affected by $\sim 7\%$ uncertainty
- With Lattice QCD projections in 5 years $\sim 2\%$

With Lattice in 5 years + 1 ab^{-1} Belle II
we could see $B^+ \to K^+\nu\bar{\nu}$
at 5σ with same central values

Theory predictions for $\bar{B}_s \to \mu^+\mu^-$

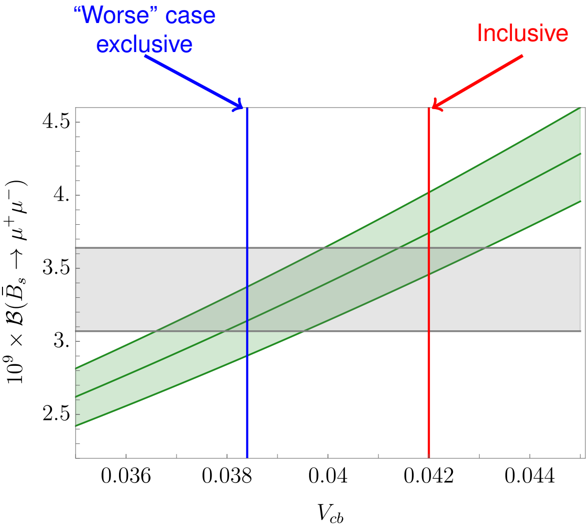
$$\mathcal{B}(B_s \to \mu^+\mu^-) = \frac{\tau_B}{32\pi^2}\frac{\alpha_{\rm EM}^2 G_F^2}{m_{B_s}}|V_{tb}V_{ts}^*|^2 f_{B_s}^2 m_\mu^2 \sqrt{1-\frac{4m_\mu^2}{m_{B_s}^2}}|C_{10}|^2(1+\Delta_{\rm QED})$$

hadronic input

photons probing the B_s structure
[Beneke, Bobeth, Szafro, '19]

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.660 \pm 0.138) \cdot 10^{-9}$$

- Leading uncertainty from $|V_{cb}|$
- Current total uncertainty $\sim 3.8\%$
- No pollution from charm rescattering


"Worse" case
exclusive
Inclusive
4.5
4.
3.5
3.
2.5
$10^9 \times \mathcal{B}(\bar{B}_s \to \mu^+\mu^-)$
0.036
0.038
0.04
0.042
0.044
V_{cb}

Experimental prospects on $\bar{B}_s \to \mu^+\mu^-$

[2108.09283,2108.09284,2212.10311]

$$\mathcal{B}(\bar{B}_s \to \mu^+\mu^-) = (3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$$

- With $100\,\mathrm{fb}^{-1}$, the statistical uncertainty drops to ± 0.14 ($\sim 4.5\%$)
- Leading current systematics is f_s/f_d (3%)
  - Prospects with more luminosity are not clear
  - Interplay with CMS is interesting to validate results
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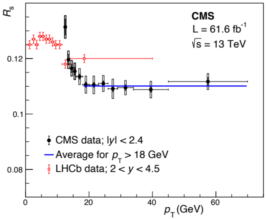
[2212.02309]



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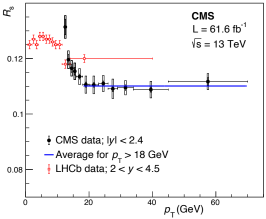
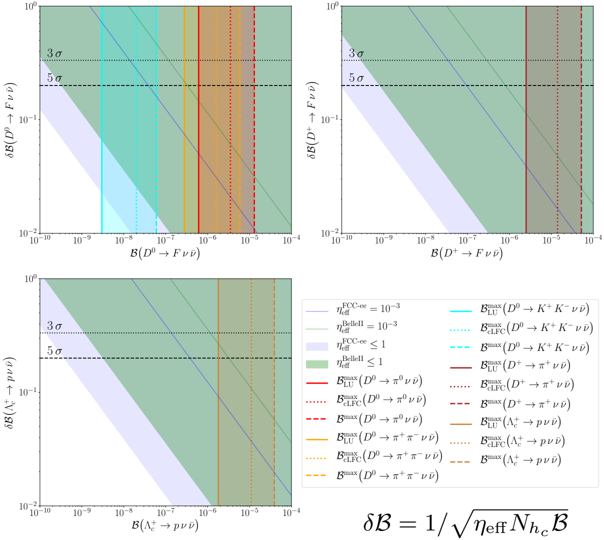


Potential reduction from 16% to 6% with $100\,\mathrm{fb}^{-1}$

Charm is the new beauty

[R. Bause, H. Gisbert, M. Golz, G. Hiller, '21]



$$\delta\mathcal{B} = 1/\sqrt{\eta_{\rm eff}\,N_{h_c}\,\mathcal{B}}$$

- $c \to u\nu\bar\nu$ modes are very suppressed by GIM $\Rightarrow$ SM predictions are zero
- any signal is a clear sign of NP

Take home messages

Take Home Message 1:

Flavour physics is interesting!

Take Home Message 2:

Despite some drawbacks, we can make
good progress in the next few years!

Appendix