Semileptonic measurements overview and prospects, with a focus on $|V_{ub}|$ and $|V_{cb}|$

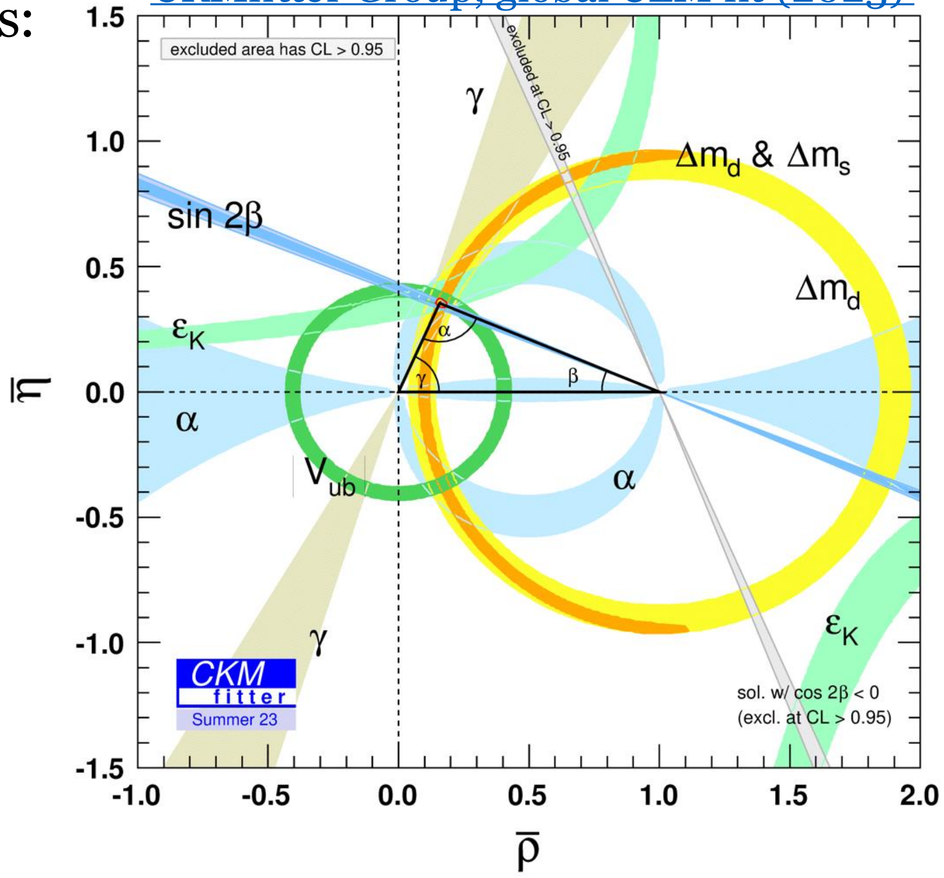
Alexandre Brea, on behalf of the LHCb collaboration

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

- CKM Matrix elements are **fundamental** SM parameters:
Precise determinations are important

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

CKMfitter Group, global CLM fit (2023)



- $|V_{ub}|$ and $|V_{cb}|$ represent a long-standing puzzle.
- Complementary methods yield **inconsistent results**.
- Limits their precision.

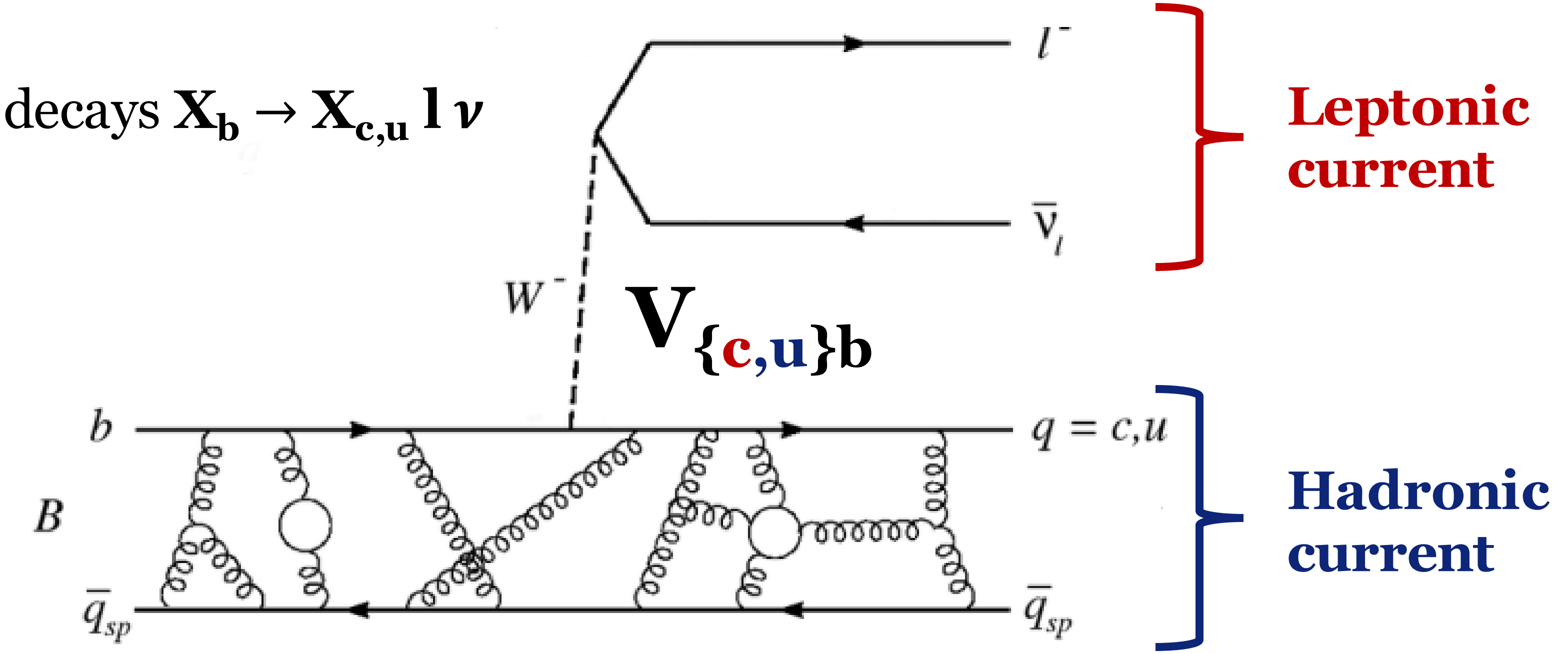
- We need to know $|V_{ub}|$ and $|V_{cb}|$ precisely to constraint the Unitary Triangle of the CKM matrix.

Determining the $|V_{ub}|$ and $|V_{cb}|$ matrix elements

- Usually, done with semileptonic decays $\mathbf{X_b \to X_{c,u}\, l\, \nu}$

- **Theoretically clean**
 (only one hadronic current).

- **Experimentally feasible**
 (large enough BFs).



- Leptonic B -> l ν decays are theoretically simpler, but **experimentally much harder**.

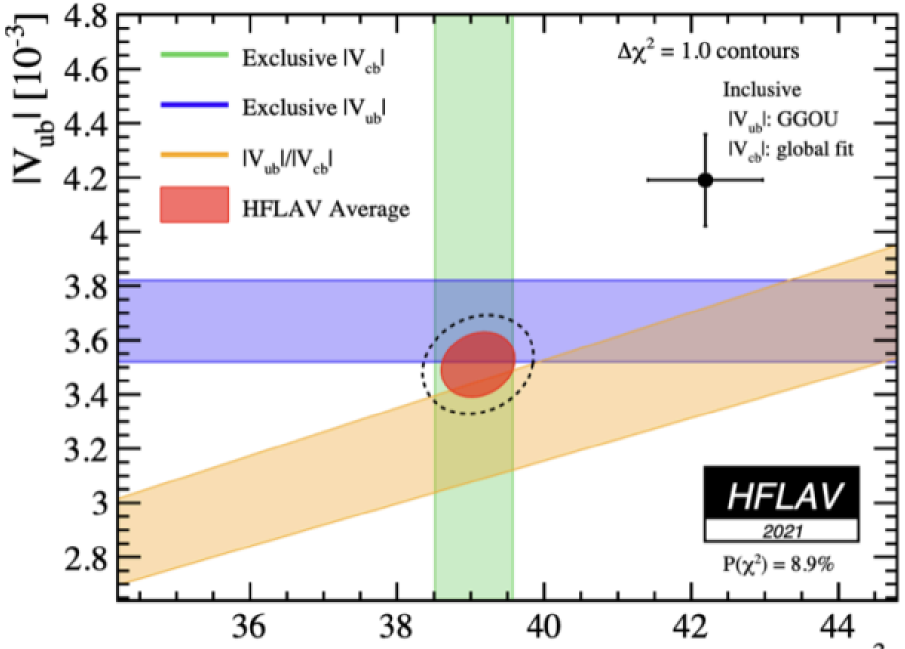
- Only one signal track (or τ decay) and small BFs.

- Described by **form factors** (FFs):

- Functions of $q^2 = (p_\mu + p_\nu)^2$
- Calculated with num-methods:
LCSR (small q^2) or LQCD (high q^2)

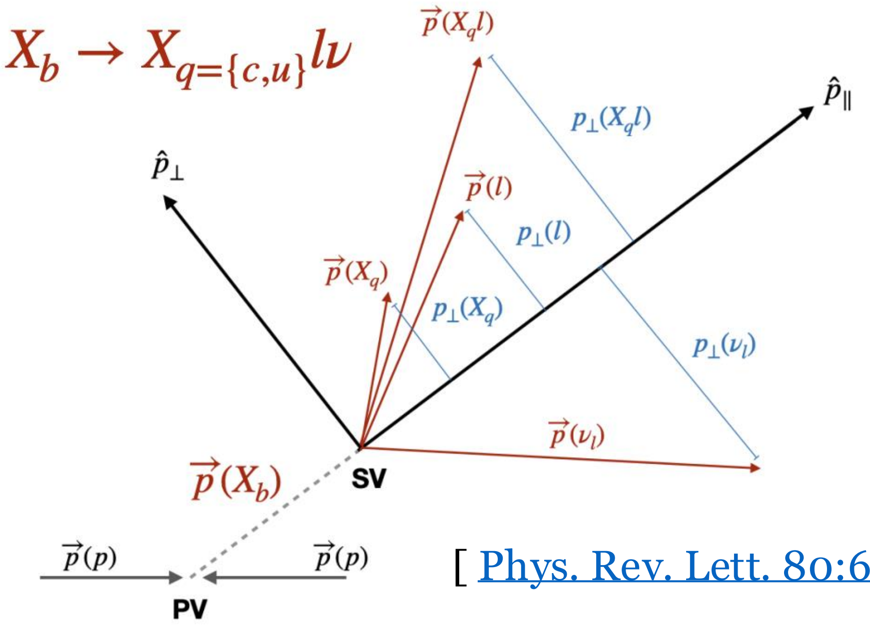
Two complementary methods to determine $|V_{ub}|$ and $|V_{cb}|$

- **Exclusive** and **inclusive** semileptonic $X_b \to X_{c,u}\, l\, \nu$ decays.
- ➢ Largely theoretically and experimentally **independent**.
  - Long-standing tension **(~3 σ)**.
  - **Limits** the precision of SM tests and sensitivity to NP.



[Phys. Rev. D 107, 052008 (2023)]

Semileptonic Decays: Some Ingredients



[Phys. Rev. Lett. 80:660-665,(1998)]

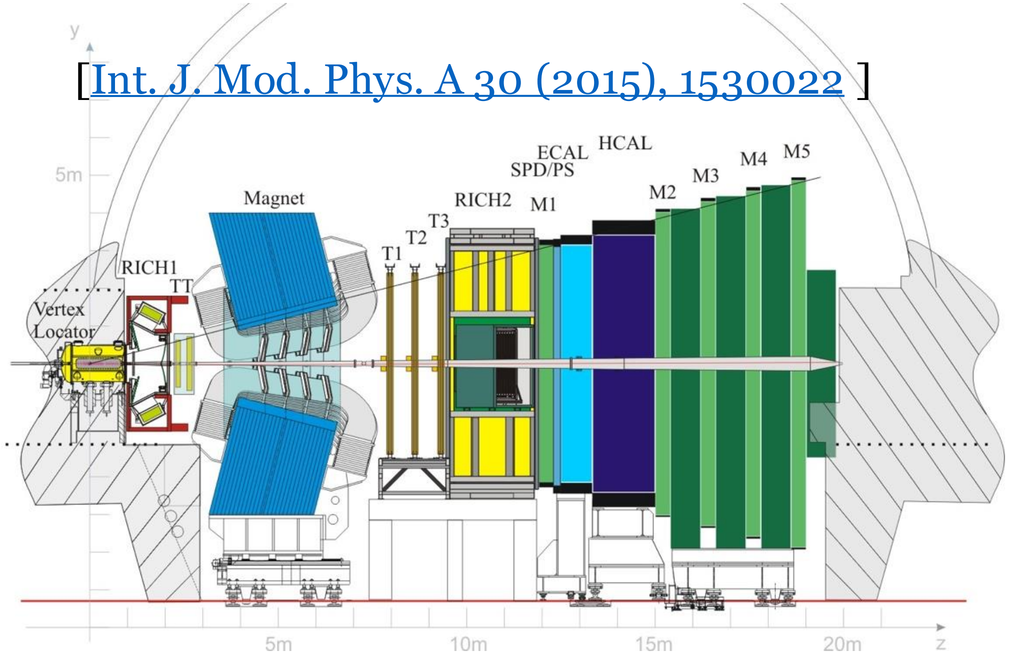
$$m_{corr}(X_b) = \sqrt{m(X_q l)^2 + p_\perp(X_q l)^2} + p_\perp(X_q l)$$

- Determining q^2 up to a two-fold ambiguity.
- Degraded q^2 resolution.
- Unfolding required to obtain the true q^2.

Measuring |V$_{ub}$| and |V$_{cb}$| at LHCb

- At **LHCb**, **exclusive semileptonic decays** can be measured (inclusive semileptonic decays are measured at the B factories) → Largely theoretically and experimentally independent.

[Int. J. Mod. Phys. A 30 (2015), 1530022]



- Normalisation decays used to cancel $b\bar{b}$ - production uncertainties → External inputs: e.g. normalization BFs, fragmentation fractions etc.

PROS

- **Large samples** of B mesons, as well as heavier b hadrons, including $\boldsymbol{B_s^0}$, $\boldsymbol{B_c^+}$ and $\boldsymbol{\Lambda_b^0}$.

CONS

- Hadronic environment, unreconstructed ν → **Large backgrounds**.
- The $\boldsymbol{b\bar{b}}$ production rate cannot be determined precisely -> large uncertainty of measured BFs.

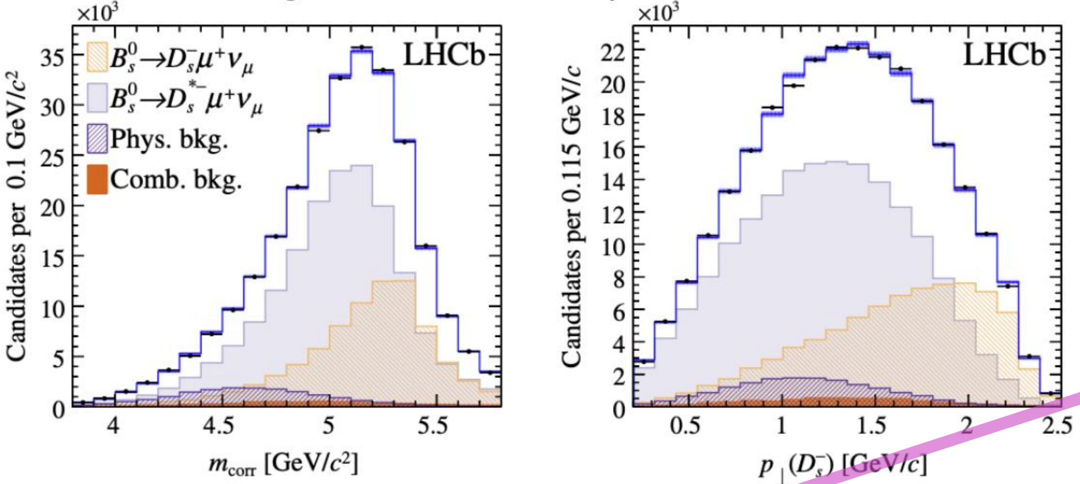
LHCb Results

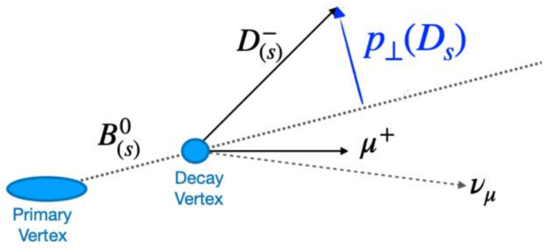
Measurement of $|V_{cb}|$ from the $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$

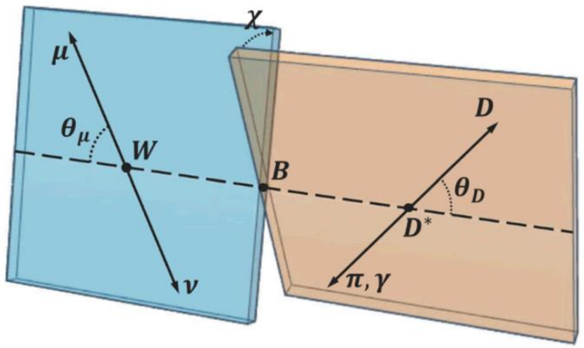
[Phys. Rev. D 101 (2020)]

- **First** $|V_{cb}|$ extraction from a B_s^0 decay.
- **Dataset**: 1 fb^{-1} @ $\sqrt{s}$ = 7 TeV and 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV (Run1), **Normalisation**: $B^0 \to D^{(*)-}\mu^+\nu_\mu$

Signal fit with the **CLN** parameterisation







Normalisation BFs
[PRD 98 (2018)]
Product derived from LHCb measurement
[PRD 100 (2019)]

$$N_{sig}^{(*)} = \frac{N_{norm}^{(*)}}{BF_{norm}} \times \frac{f_s}{f_d} \times BF(D_s^- \to K^+K^-\pi^-) \times \tau_{B_s^0} \times R_\epsilon \times \int \frac{d\Gamma\left(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu\right)}{dx} dx$$

→ $|V_{cb}|$ and FFs

x = [w] for $B_s^0 \to D_s^- \mu^+\nu_\mu$
x = [w, θ_D, θ_μ, χ] for $B_s^0 \to D_s^{*-} \mu^+\nu_\mu$

- $|V_{cb}|_{CLN}$ = (41.4 ± 0.6 (stat) ± 0.9 (syst) ± 1.2 (ext)) x 10^{-3}
- $|V_{cb}|_{BGL}$ = (42.3 ± 0.8 (stat) ± 0.9 (syst) ± 1.2 (ext)) x 10^{-3}

- CLN and BGL extraction compatible
- **Agree** with previous exclusive and inclusive determinations

Measurement of $|V_{ub}|$ from the $\Lambda_b^0 \to p\,\mu^-\bar{\nu}_\mu$

[Nature Physics 11 (2015)]

- First $\Lambda_b^0 \to p\,\mu^-\bar{\nu}_\mu$ observation and $|V_{ub}|$ extraction from baryonic decay.

Dataset: 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV (Run1, 2012), Norm: $\Lambda_b^0 \to \Lambda_c^+\,\mu^-\bar{\nu}_\mu$ ($\Lambda_c^+ \to p\,K^-\pi^+$)

Extracting $|V_{ub}|$ from the BF ratio: -> Measured in the **high q^2 region**

$|V_{ub}|$=(3.27±0.15 (stat)±0.16 (LQCD)±0.06 ($|V_{cb}|$)) x 10^{-3}

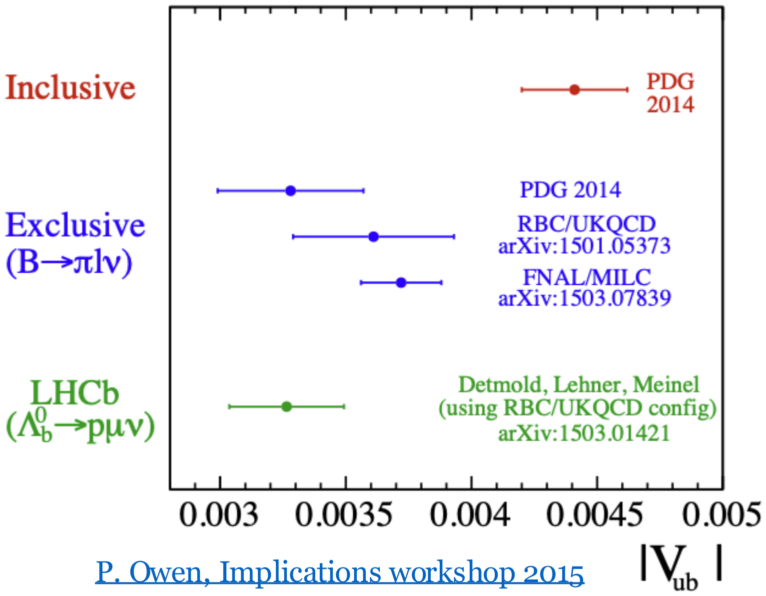
Agrees with exclusively measured average [arXiv:1412.7515]

Disagrees (3.5 σ) with inclusively measured average

FFs with LQCD @ high q^2

Exclusive $|V_{cb}|$ world average

BF $\Lambda_c^+ \to p\ K^-\pi^+$ by Belle



P. Owen, Implications workshop 2015

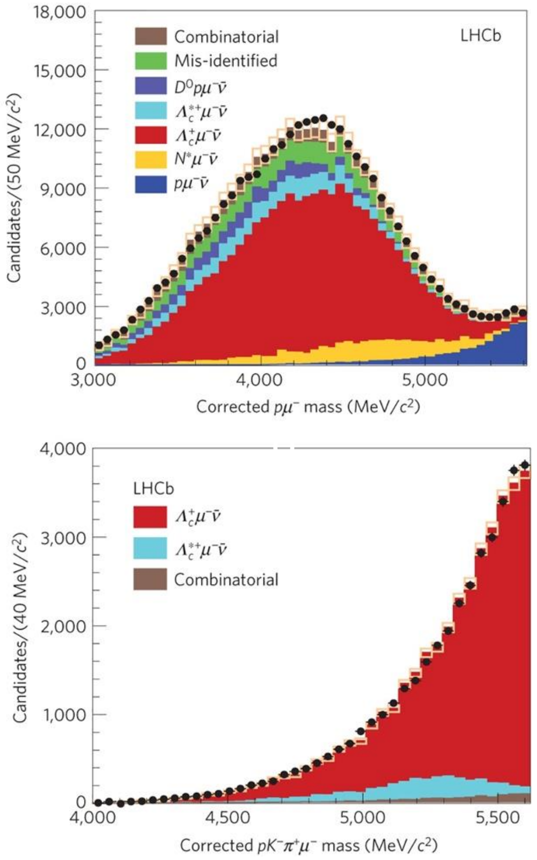
[Phys. Rev. D 92 (2015)]

Largest uncertainty from LQCD calculations ($\sigma_{FF}/|V_{ub}|$) ~5%

Largest external uncertainty from $BF_{\Lambda_c^+ \to pK^-\pi^+}$ ~5%

[Phys. Rev. Lett. 113 (2014)]

Signal Fit



Normalisation Fit

Measurement of $|V_{ub}|/|V_{cb}|$ from the $B_s^0 \to K^-\mu^+\nu_\mu$

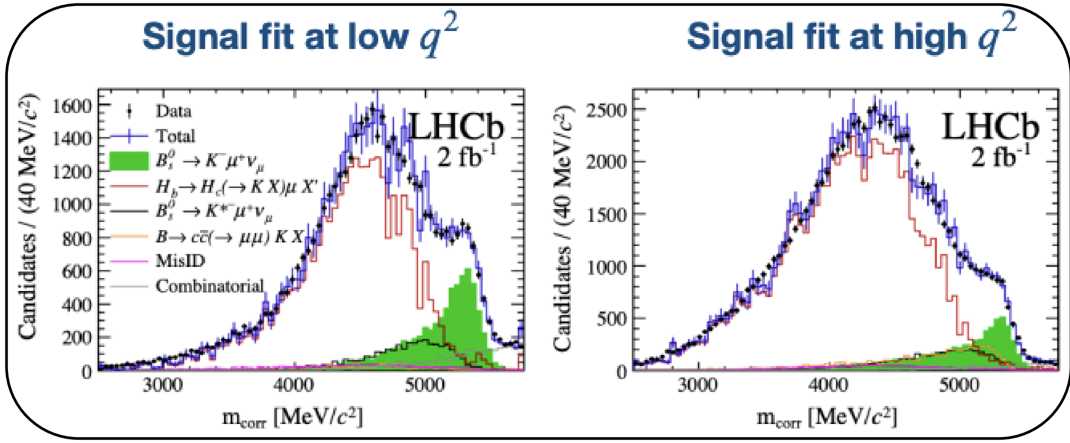
[Phys. Rev. Lett. 126 (2021)]

First $B_s^0 \to K^-\mu^+\nu_\mu$ observation, $|V_{ub}|$ extraction from a B_s^0 decay

Dataset: 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV Run1 (2012)

Normalisation: $B_s^0 \to D_s^- \mu^+\nu_\mu$ with $D_s^- \to K^+K^-\pi^-$ [External BF measurement]

Extracting $|V_{ub}|/|V_{cb}|$ from the BF ratio (measured in two q^2 bins)



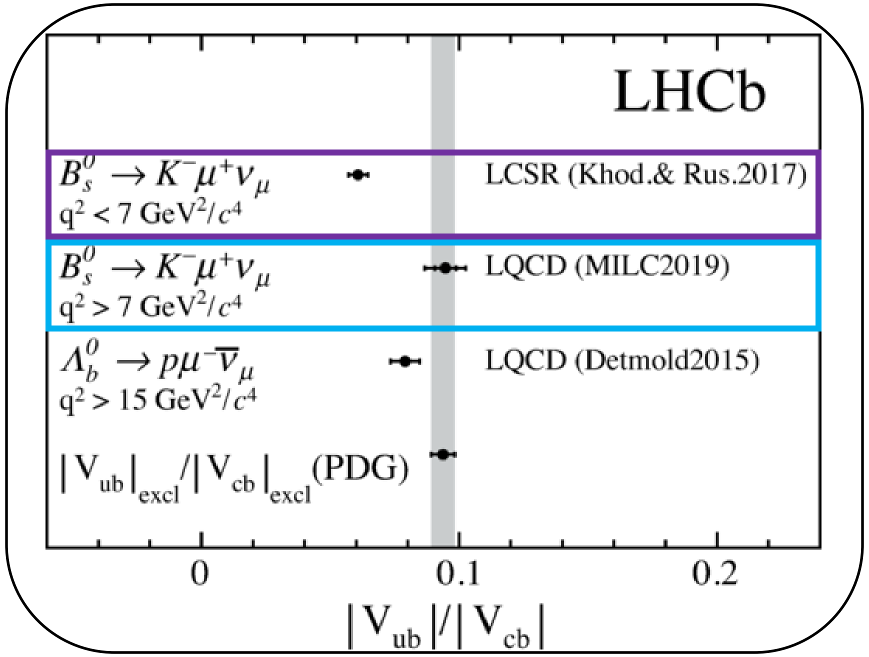
$q^2 < 7$ GeV²/c⁴ :

$|V_{ub}|/|V_{cb}| = 0.0607 \pm 0.015$ (stat) ± 0.0012 (syst) ± 0.0008 (Ds) ± 0.0030 (FF)

$q^2 > 7$ GeV²/c⁴ :

$|V_{ub}|/|V_{cb}| = 0.0946 \pm 0.030$ (stat) $^{+0.0024}_{-0.0025}$ (syst) ± 0.0013 (Ds) ± 0.0068 (FF)

Tension driven by the difference in the FF calculations

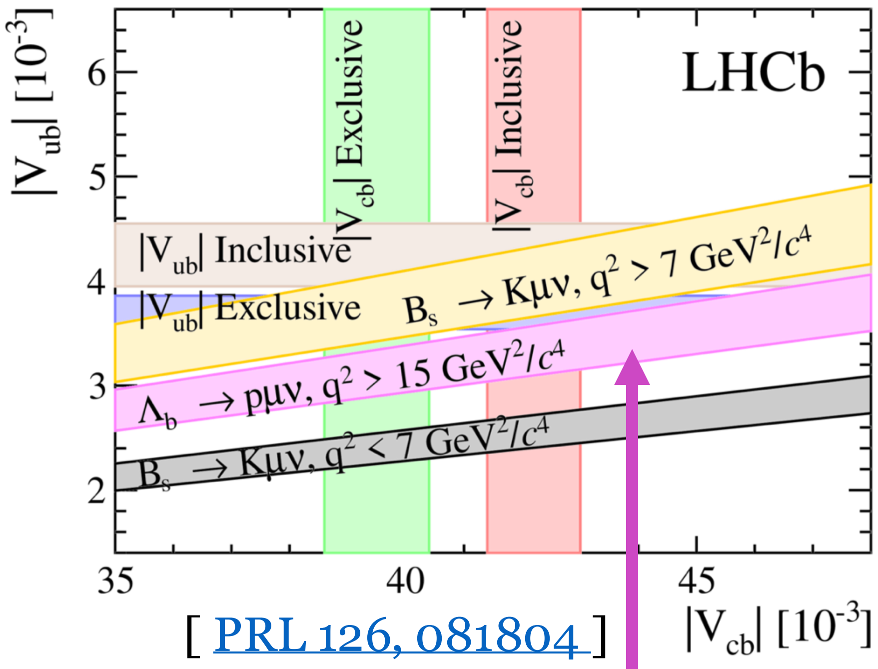


Dominant **uncertainties from FF** calculations:

- Low q^2: $\sigma/(|V_{ub}|/|V_{cb}|) \sim 5$ % [JHEP 2017, 112 (2017)]
- High q^2: $\sigma/(|V_{ub}|/|V_{cb}|) \sim 7$ % [Phys. Rev. D 100, 034501 (2019)]

Summary of LHCb $|V_{ub}|$ and $|V_{cb}|$ results

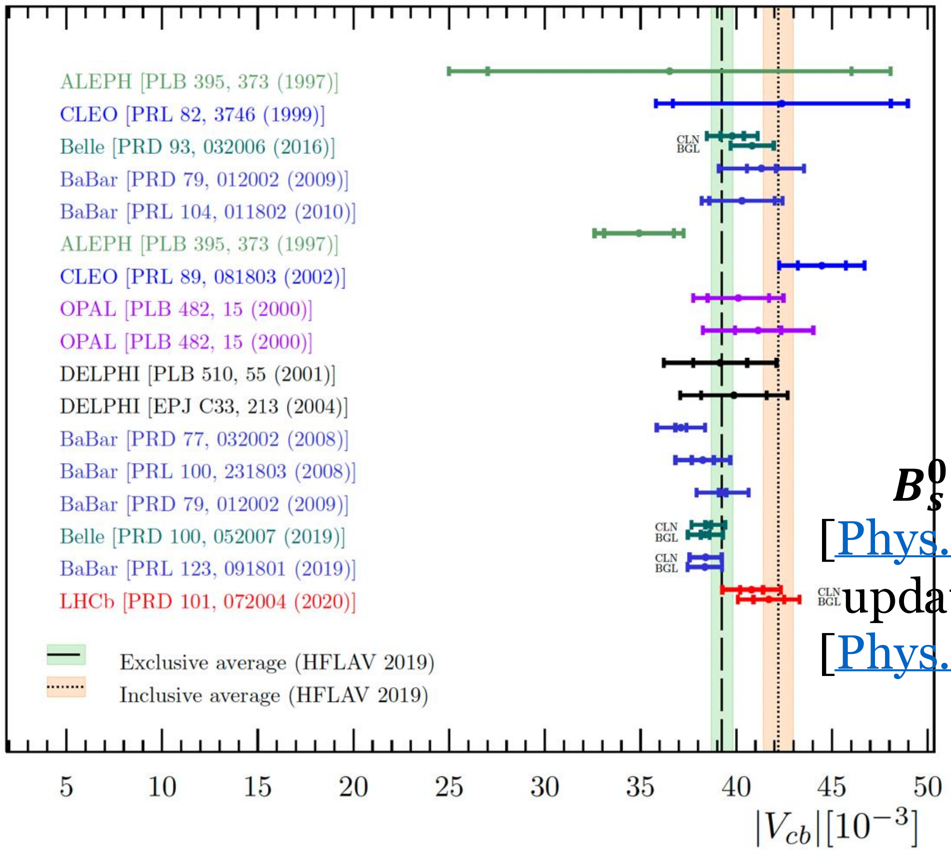
Exclusive & inclusive measurements in the ($|V_{cb}|$, $|V_{ub}|$) plane



[PRL 126, 081804]

[Nature Physics 11 (2015)]
Updated with average BF ($\Lambda_c^+ \to p\, K^- \pi^+$)
[arXiv:1909.12524, (2021)]

Exclusive & inclusive V_{cb}



$B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$
[Phys. Rev. D 101 (2020)]
updated with latest f_s / f_d
[Phys. Rev. D 104 (2021)]

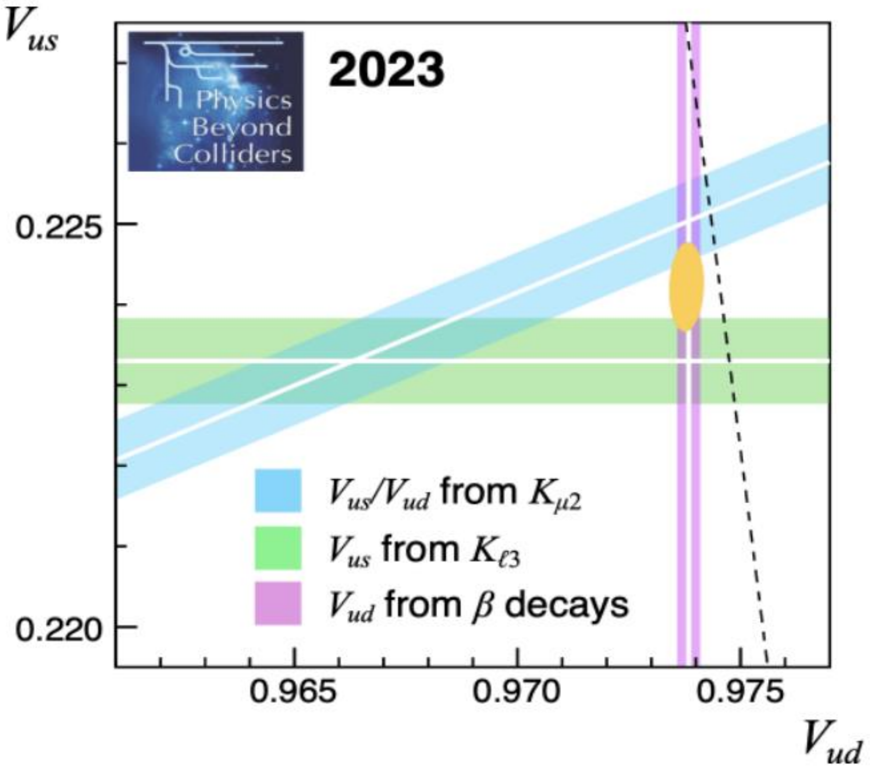
Plot taken from this talk by M. de Cian, FPCP (2021)

LHCb Prospects

Future measurements at LHCb

Observable	Decay Channel	Tentative publication date
$\|V_{us}\|$	$\Lambda \to p\,\mu^- \overline{\nu}_\mu$	Early next year
$\|V_{ub}\|$	$B^+ \to \rho^0 \mu^+ \nu_\mu$	Early next year
→ Expecting > 50 times higher signal yield wrt. to Belle		
$\|V_{ub}\|$	$B_s^0 \to K^- \mu^+ \nu_\mu$	Late next year
→ Expecting a ~ 5-6 times higher signal yield wrt. to Run 1		
$\|V_{cb}\|$	$\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu$	Late next year
→ First determination of the $\|V_{cb}\|$ from a baryonic semileptonic decay		
$\|V_{ub}\|/\|V_{cb}\|$	$B_c^+ \to D^{(*)0} \mu^+ \nu_\mu$	Late next year
→ First CKM matrix element determined from B_c^+ system		
$\|V_{ub}\|$, $\|V_{cb}\|$	$B_{(c)}^+ \to \tau^+ \nu_\tau$	-

V_{us} (Cabbibo Anomaly)



- Strangeness changing SL decays can provide the **most sensitive** test of the unitarity of the CKM matrix (since $|V_{ub}|^2$ is almost negligible) through the relation

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- The experimental result is:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0007$$

Showing a **2.2σ tension with the expected unitarity** in the first CKM row.

- **3σ discrepancy in V_{us}** measurements **in leptonic ($K\mu 2$) and semileptonic ($Kl3$)** kaon decays.

Can hint towards two potential scenarios:

- Existence of physics beyond the SM
- Significant, yet unidentified, systematic effect within the SM itself.

[Phys. Rev. Lett. 114 no. 16, (2015)]

$\Lambda \to p\, \mu^- \bar{\nu}_\mu$

[J. High Energ. Phys. 2019, 48 (2019)]
[J. Phys. Conf. Ser. 1526 012022 (2020)]

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)} \qquad R^{\mu e}_{\rm SM} = \sqrt{1-\frac{m_\mu^2}{\Delta^2}}\left(1-\frac{9}{2}\frac{m_\mu^2}{\Delta^2}-4\frac{m_\mu^4}{\Delta^4}\right)+\frac{15}{2}\frac{m_\mu^4}{\Delta^4}\mathrm{arctanh}\left(\sqrt{1-\frac{m_\mu^2}{\Delta^2}}\right) = 0.153 \pm 0.008$$

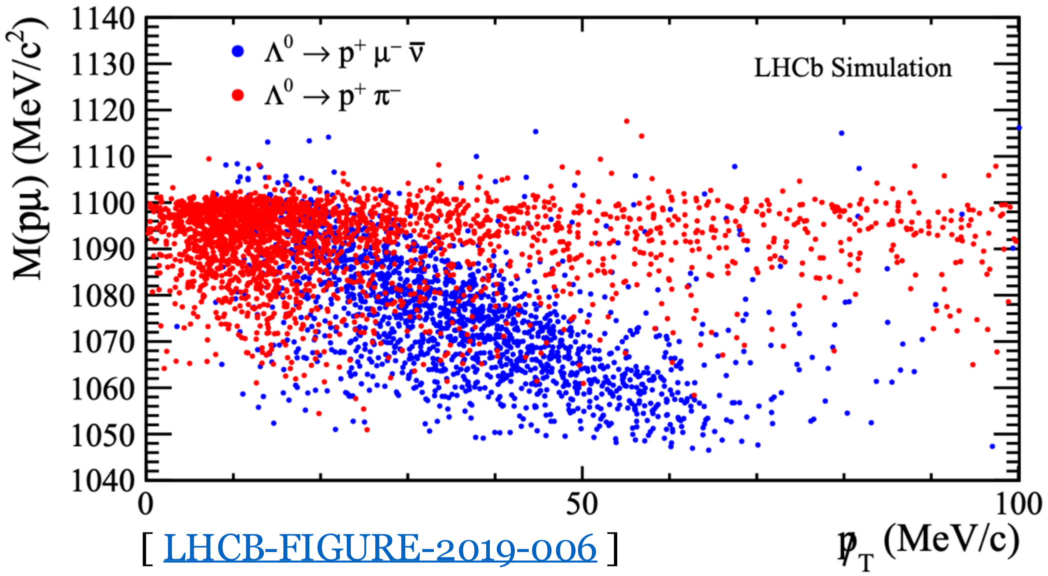
- **Clean theoretical prediction** for the decay rate (going to order δ^2)

$\Delta = M_1 - M_2$ $\quad f_1(0) = \textit{hyperon vector charge}$

$\delta = \frac{M_1 - M_2}{M_1}$ $\quad g_1(0) = \textit{hyperon axial charge}$

- $|\mathbf{V_{us}}|$ can be extracted from the BF
- Adding **hyperons** results to the puzzle

$$|V_{us}|^2 \simeq \frac{\Gamma^{\rm SM}(B_1 \to B_2 \mu^- \bar{\nu}_\mu)\, 60\pi^3}{R^{\mu e} G_F^2\, f_1(0)^2 \Delta^5 \left[\left(1-\frac{3}{2}\delta\right)+3\left(1-\frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}\right]}$$

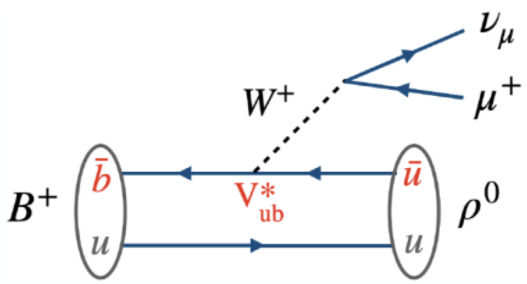


[LHCB-FIGURE-2019-006]

- Best branching ratio measurement from BESIII (2021):
$\mathcal{B}(\Lambda \to p\, \mu^- \bar{\nu}_\mu) = (1.48 \pm 0.21) \times 10^{-4}$ (**14.19 % Uncertainty**)

Dataset: 5.4 fb^{-1} @ $\sqrt{s}$ = 13 TeV (Run2), Norm. : $\boldsymbol{\Lambda \to p\, \pi^-}$
44K pre-selected signal events → **~1.5 % stat. unc.**
Dominated by systematic uncertainties
Publication expected **early next year**

$\boldsymbol{\Xi^- \to \Lambda\, \mu^- \bar{\nu}_\mu}$ proposed as the next natural step



$B^+ \to \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$

1. [Phys. Rev. D 83, 032007 (2011)]
2. [Phys. Rev. D 88, 032005 (2013)]
3. [arXiv:2407.17403(2024)]

Experiment	**BR** (10^{-4})	**Stat.** (10^{-4})	**Syst.** (10^{-4})
BaBar [1]	1.00	0.10	0.17
Belle [2]	1.83	0.10	0.10
Belle2 [3] 364 fb^{-1} preliminary	1.625	0.079	0.18

- Large discrepancy between BaBar and Belle/Belle2.
- A new, **precise measurement** from LHCb will **help** to solve the tension.
- **Large** LHCb data **sample** → precise determination of the differential decay rate and $|V_{ub}|$.

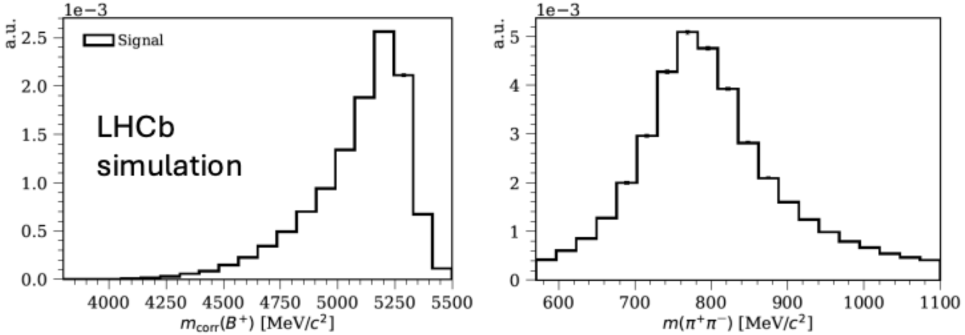
- **Main Backgrounds:**

$B^+ \to \bar{D}^0(\pi^+\pi^- X^0)\mu^+\nu_\mu\ (X)$

$B^{+,0} \to X_u\, \mu^+\nu_\mu$ (varius charmless semileptonic decays)

$B^+ \to \pi^+\pi^-\mu^+\nu_\mu$ (with non-resonant $\pi^+\pi^-$)

- Signal yield extracted from a 2D template fit to m_{corr} and $m_{\pi\pi}$ in O(10) non-uniform q² bins.



[M. Calvi Slides (2024)]

- **Prospects**:
- Expected statistical sensitivity on BF per q² bin **O(5%-6%)**, using 2018 data (~ 2fb-1).
- Systematic uncertainty O(5%-9%), dominated by uncertainty on $m_{\pi\pi}$ shape of the non-resonant component. External systematic uncertainty 4.2%.

$B_s^0 \to K^- \mu^+ \nu_\mu$

[M. Calvi Slides (2024)]

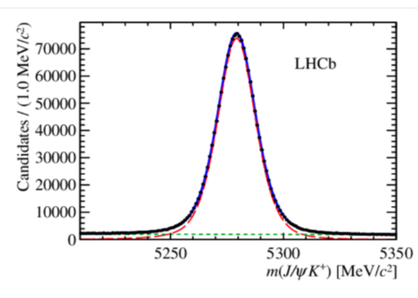
New $\boldsymbol{B_s^0 \to K^- \mu^+ \nu_\mu}$ analysis with **Run2** data ongoing. (2016-2018)
Larger data set (**~5x**) of data → binned BF in **O(10) q² bins**.
Aim a measurement of **|Vub| independent** of |Vcb|.

$$\Delta\mathcal{B}_i = \frac{N_{sig,i}}{N_{norm}} \frac{\epsilon_{norm}}{\epsilon_{sig}} \frac{f_u}{f_s} \mathcal{B}_{norm}$$

Normalisation:

$\boldsymbol{B^- \to J/\Psi(\mu^+\mu^-)\, K^-}$

(well known decay mode)



Eur. Phys. J. C 79,8(2019)706

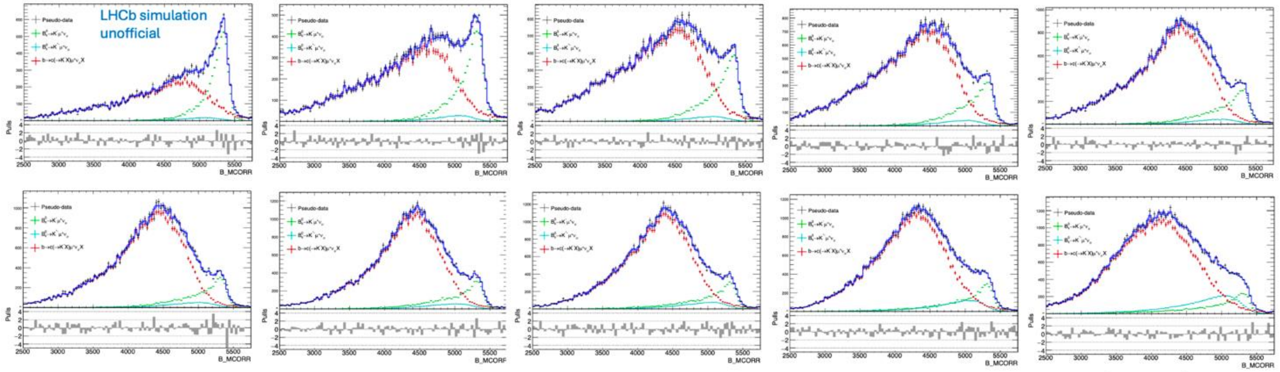
→

f_s/f_d = 0.2539 ± 0.079
1.9 % from Norm BF
3.1 % from f_s/f_d

Signal Fit

Maximum-likelihood fit in HistFactory framework
Simultaneous in O(10) q² bins and three years

Toy MonteCarlo with signal and two physics background contributions

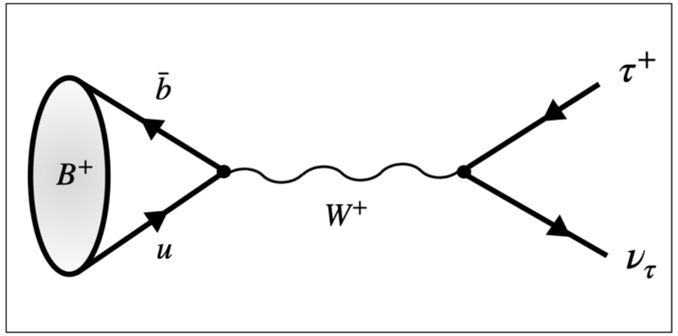


FF determination:

- Several FF schemes available to describe signal shape.
- Baseline FF not defined yet (FLAG24 average?)
  - Could provide results with different options
  - Dependence of fitted signal yields with FF reduced using high number of bins.
  - Dependence of signal eff. per bin on FF to be determined
- Same FF scheme used to fit $\frac{dB}{dq^2}$ and determine $|V_{ub}|$

$$\frac{dB}{dq^2} = \frac{d\Gamma^0_{sig}}{dq^2} |V_{ub}|^2 \tau_B$$

$B_{(c)}^{+} \to \tau^{+}\nu_{\tau}$

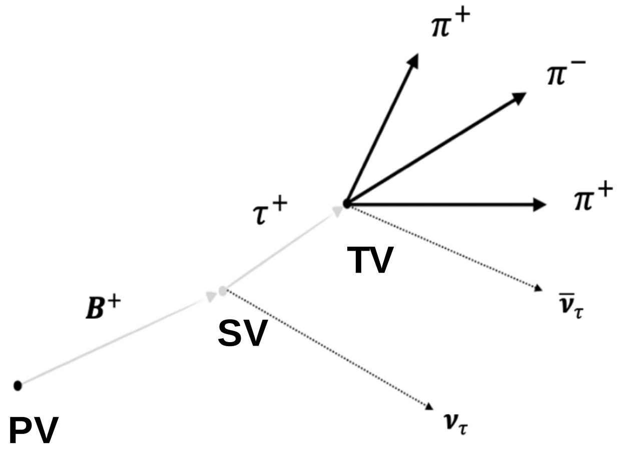


$B^{+} \to \tau^{+}\nu_{\tau}$

- This pure leptonic B decay allows for **precise** SM tests.
- Much larger BF (helicity suppression)
- Clean experimental determination of $\mathbf{V_{ub}}$, test BSM models.

$$\mathcal{B}(B^+ \to \tau^+\nu) = \frac{G_F^2\, m_B}{8\pi} m_\tau^2 \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 f_b^2\, |V_{ub}|^2 \tau_B$$

$$\mathcal{B}(B^+ \to \tau^+\nu) = (1.09 \pm 0.24) \times 10^{-4}$$



$B_c^{+} \to \tau^{+}\nu_{\tau}$

- $\mathbf{b \to c\, \tau\, \nu}$ transition (R_{D}, R_{D^*}, $R_{J/\psi}$), but in annihilation diagram form.
- Fully leptonic final state: Very beneficial for theory predictions, relevant dependence on $\mathbf{V_{cb}}$
- At this moment, **just LHCb can do it**.

Searching for hits in the Vertex Locator (Run 3)

$B^+_{(c)} \to \tau^+ \nu_\tau$

Using heavy flavour tracking

- Look for hits between PV and SV.
- Have better B-hadron direction estimate,
- ➢ better corrected mass.
- Having hits is a distinguishing feature itself.
- Trade efficiency for much-needed purity.

Feasibility in progress

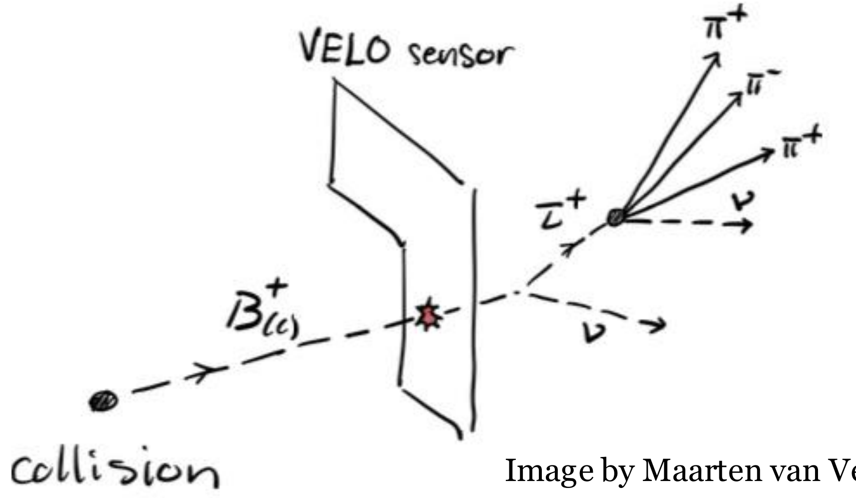
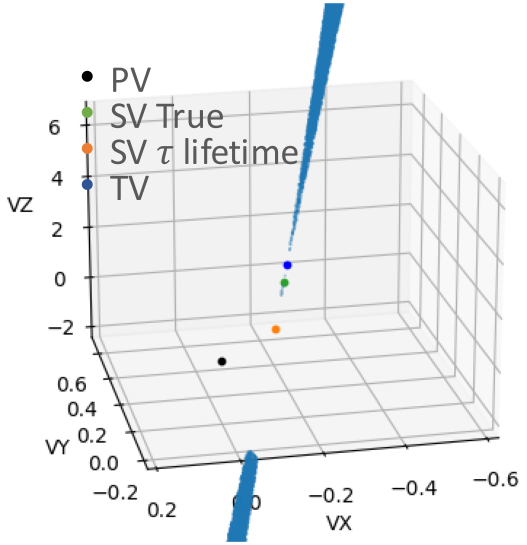
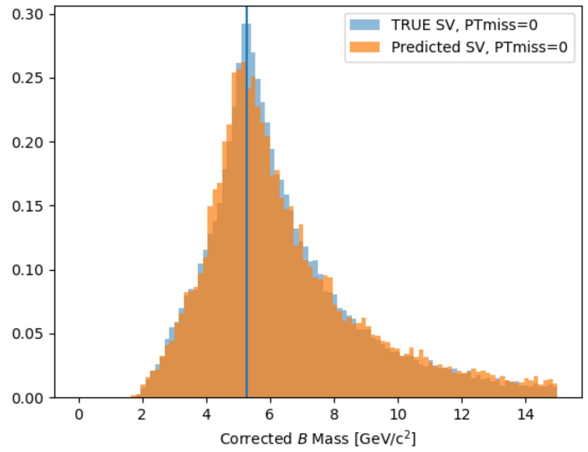


Image by Maarten van Veghel

Kinematic Strategy for predicting SV (Run 2 Data)





- Valid cluster found for **~50%** of events.
- Resolution **comparable** to using TRUE SV
- The main challenge will be the low signal purity
- Currently working on ML to remove comb. Bkg.

Feasibility in progress

Conclusion and outlook

- LHCb has measured $|\mathbf{V_{ub}}|$ **and** $|\mathbf{V_{cb}}|$ from new **exclusive** channels involving $\boldsymbol{\Lambda_b^0}$ baryons and $\boldsymbol{B_s^0}$ mesons

• Constraining the Unitary Triangle of the CKM matrix.
• Providing complementary information to understand the long-standing tension between the exclusive and inclusive determinations.

- More LHCb measurements next year:

• Larger signal samples (reducing statistical and systematic uncertainties)
• Measuring new semileptonic channels
• Improving $|\mathbf{V_{ub}}|$ precision from $\boldsymbol{B_s^0 \to K^- \mu^+ \nu_\mu}$ through a differential measurement.
• Addressing the Cabibbo anomaly with a SHD ($|\mathbf{V_{us}}|$) measurement.

- Exciting ideas for the future:

• Aiming to measure $\boldsymbol{B_c^+ \to \tau^+ \nu_\tau}$ for the first time and also $\boldsymbol{B^+ \to \tau^+ \nu_\tau}$

Thank you!

Back Up

Measurement of $|V_{cb}|$ from the $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$

Measurement of $|V_{cb}|$ from the $B_s^0 \to D_s^{(*)-} \mu^+ \nu_\mu$

[Phys. Rev. D 101 (2020)]

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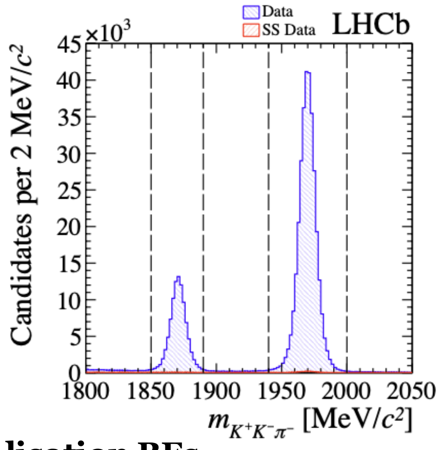
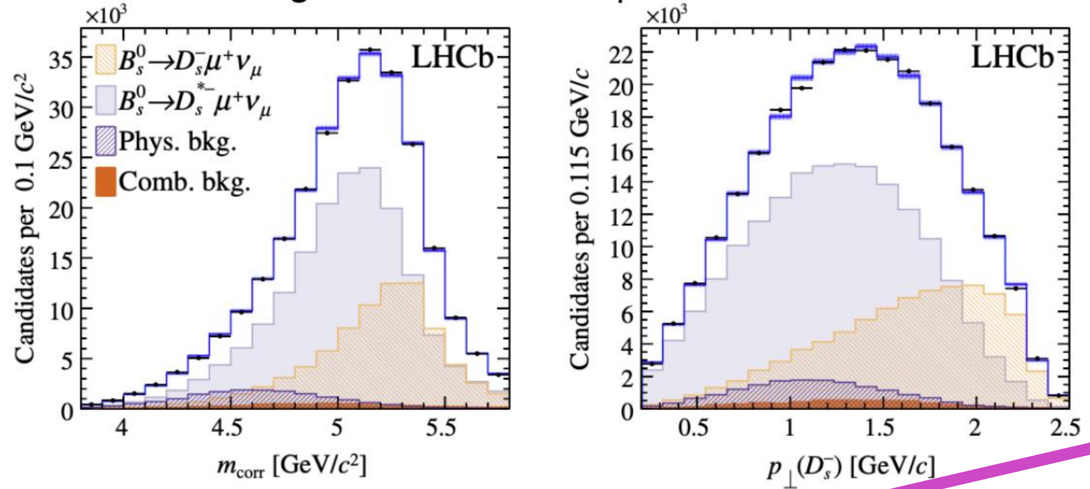
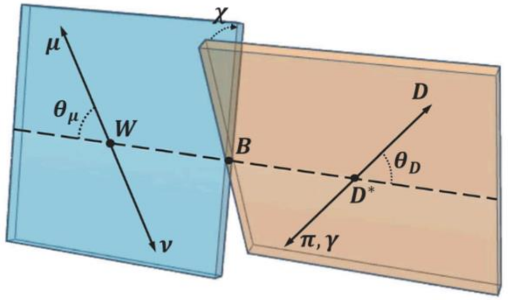


Signal fit with the **CLN** parameterisation





Normalisation BFs

[PRD 98 (2018)]

Product derived from LHCb measurement [PRD 100 (2019)]

$|V_{cb}|$ and FFs

$$N_{sig}^{(*)} = \frac{N_{norm}^{(*)}}{BF_{norm}} \times \frac{f_s}{f_d} \times BF(D_s^- \to K^+K^-\pi^-) \times \tau_{B_s^0} \times R_\epsilon \times \int \frac{d\Gamma\left(B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu\right)}{dx} dx$$

x = [w] for $B_s^0 \to D_s^- \mu^+ \nu_\mu$

x = [w, θ_D, θ_μ, χ] for $B_s^0 \to D_s^{*-} \mu^+ \nu_\mu$

- $|V_{cb}|_{CLN}$ = (41.4 ± 0.6 (stat) ± 0.9 (syst) ± 1.2 (ext)) x 10^{-3}
- $|V_{cb}|_{BGL}$ = (42.3 ± 0.8 (stat) ± 0.9 (syst) ± 1.2 (ext)) x 10^{-3}

- CLN and BGL extraction compatible
- Agree with previous exclusive and inclusive determinations

Measurement of |V$_{cb}$| from the $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

- Differential decay rates ($m_\mu \approx 0$):

$$\frac{d\Gamma(B_s^0 \to D_s^-\mu^+\nu_\mu)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D^2)^2\eta_{EW}^2 \times |V_{cb}|^2 (w^2-1)^{3/2}|G(w)|^2$$

One FF

$$\frac{d^4\Gamma(B_s^0 \to D_s^{*-}\mu^+\nu_\mu)}{dw\, d\cos\theta_\mu\, d\cos\theta_D\, d\chi} = \frac{3G_F^2 m_{B_s^0}^3 m_{D_s^*}^2}{16(4\pi)^4}\eta_{EW}^2 \times |V_{cb}|^2 |A(w,\theta_\mu,\theta_D,\chi)|^2$$

Three FFs

Where $w = v_{B_s^0} \times v_{D_s^{(*)-}}$ is the hadronic recoil variable that depends on q^2 and θ_D, θ_μ and χ are the three helicity angles: 7

>> Alternative method to infer FFs.

FFs can be modelled with the parameterisations:

CLN: Caprini, Lellouch and Neubert [Nucl. Phys. B530 (1998) 153]

BGL: Boyd, Grinstein and Lebed [Phys. Rev. Lett. 74 (1995) 4603]

→ Differential measurements allow us to extract information on the FFs.

Limitations on the $|V_{cb}|$ precision:

- **Uncertainty is dominated by external inputs:**

  → $f_s/f_d \times BF(D_s^- \to K^+K^-\pi^-)(\times\tau_{B_s})$ with $\sigma/|V_{cb}| \sim 2\,\%$.
  [Phys. Rev.D 100, 031102 (2019), Phys. Rev. Lett. 124, 122002 (2020)].

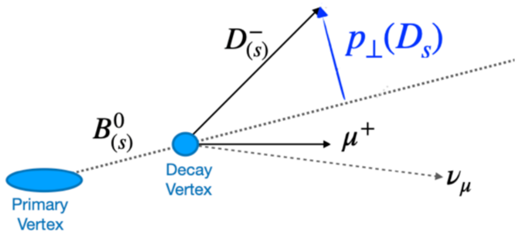
  → Normalisation BFs with $\sigma/|V_{cb}| \sim 2\,\%$.
  [Phys. Rev. D 98, 030001 (2018)].

- **Largest systematic uncertainty:**

  → $D_{(s)} \to K^+K^-\pi^-$ modelling with $\sigma/|V_{cb}| \sim 2\,\%$.

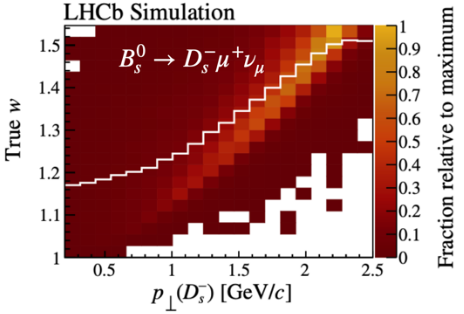
- Usually, FFs are extracted by measuring the decay distribution wrt. q^2 or $w = w(q^2)$.

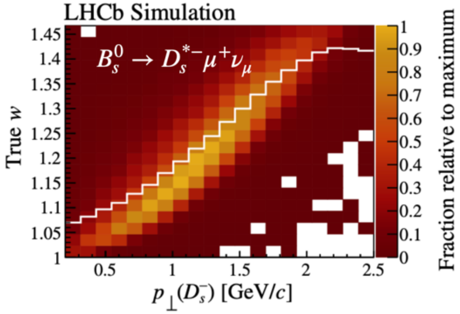
- This analysis exploits a new variable, $p_\perp(D_s^-)$, which is an approximation of w.



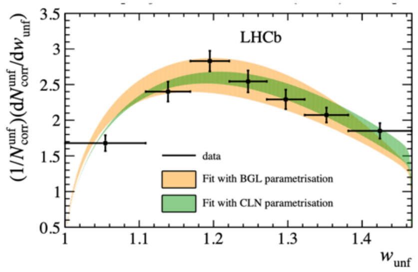
→ **Strongly correlated with** w, and thus, with the FFs.

→ Can be **fully reconstructed.**





Measurement of the shape of the $B_s^0 \to D_s^{*-}\mu^+\nu_\mu$ differential decay rate [J. High Energ. Phys. 144 (2020)]

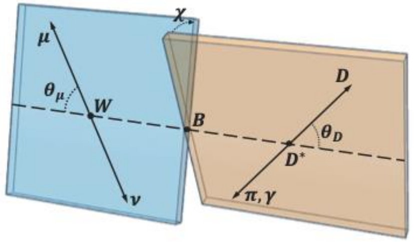


→ Both fits **give consistent results** and **describe the measured spectrum well.**

→ Results allows to **constrain FF parameterisations.**

Measurement of |V$_{cb}$| from the $B_s^0 \to D_s^{(*)-}\mu^+\nu_\mu$

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 $\to$ 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 $\to$ Converging series [PRL 74, 4603 (1995)]

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

$$z = \frac{\sqrt{w+1}-\sqrt{2}}{\sqrt{w+1}+\sqrt{2}}$$

From this talk by M. de Cian, FPCP (2021)

Measurement of $|V_{ub}|$ from the $\Lambda_b^0 \to p\, \mu^- \bar{\nu}_\mu$

Measurement of $|V_{ub}|$ from the $\Lambda_b^0 \to p\,\mu^-\bar{\nu}_\mu$

[Nature Physics 11 (2015)]

- First $\Lambda_b^0 \to p\,\mu^-\bar{\nu}_\mu$ observation and $|V_{ub}|$ extraction from baryonic decay.

Dataset: 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV (Run1, 2012), Norm: $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu$ ($\Lambda_c^+ \to p K^-\pi^+$)

Extracting $|V_{ub}|$ from the BF ratio: -> Measured in the high q^2 region

Target

$$\frac{|V_{ub}|^2}{|V_{cb}|^2}\frac{G(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})_{q^2>15\mathrm{GeV}^2/c^4}}{G(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu_\mu})_{q^2>7\mathrm{GeV}^2/c^4}} = \frac{N(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})_{q^2>15\,\mathrm{GeV}^2/c^4}}{N(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})_{q^2>7\,\mathrm{GeV}^2/c^4}}$$

$$\times \frac{\epsilon(\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\mu^-\overline{\nu_\mu})_{q^2>7\,\mathrm{GeV}^2/c^4}}{\epsilon(\Lambda_b^0 \to p\mu^-\overline{\nu_\mu})_{q^2>15\,\mathrm{GeV}}} \times BF(\Lambda_c^+ \to pK^-\pi^+)$$

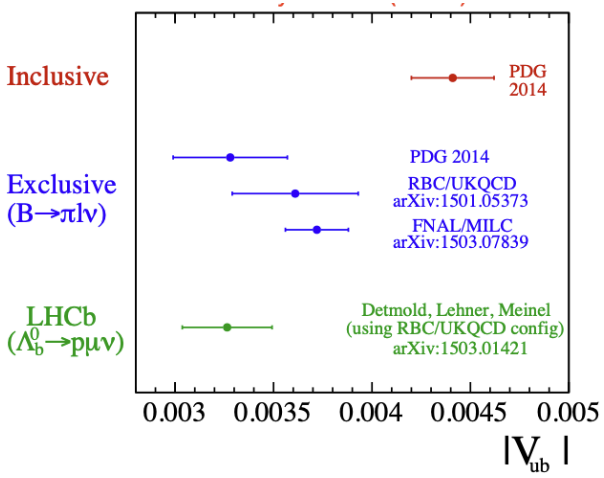
FFs with LQCD @ high q^2
Exclusive $|V_{cb}|$ world average
BF $\Lambda_c^+ \to p\,K^-\pi^+$ by Belle

$|V_{ub}|$=(3.27±0.15 (stat)±0.16 (LQCD)±0.06 ($|V_{cb}|$)) x 10^{-3}

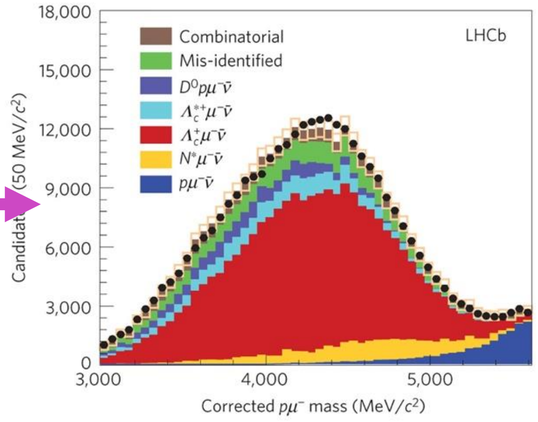
Agrees with exclusively measured average [arXiv:1412.7515]
Disagrees (3.5 σ) with inclusively measured average

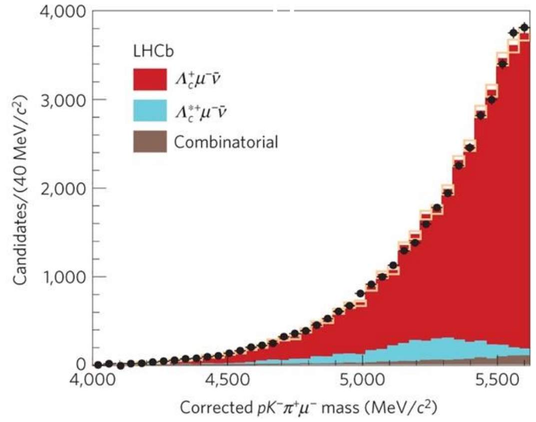
[Phys. Rev. D 92 (2015)]
Largest uncertainty from LQCD calculations ($\sigma_{FF}/|V_{ub}|$) ~5%
Largest external uncertainty from $BF_{\Lambda_c^+ \to pK^-\pi^+}$ ~5%
[Phys. Rev. Lett. 113 (2014)]

P. Owen, Implications workshop 2015



Signal Fit





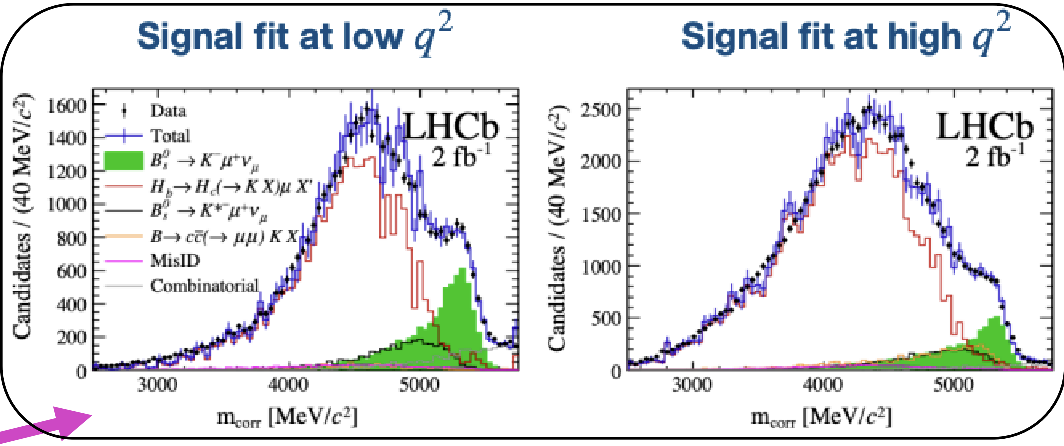
Normalisation Fit

Measurement of $|V_{ub}|/|V_{cb}|$ from the $B_s^0 \to K^- \mu^+ \nu_\mu$

Measurement of $|V_{ub}|/|V_{cb}|$ from the $B_s^0 \to K^- \mu^+ \nu_\mu$

[Phys. Rev. Lett. 126 (2021)]

First $B_s^0 \to K^- \mu^+ \nu_\mu$ observation & $|V_{ub}|$ extraction from a B_s^0 decay
Dataset: 2 fb^{-1} @ $\sqrt{s}$ = 8 TeV Run1 (2012)
Normalisation $B_s^0 \to D_s^- \mu^+ \nu_\mu$ with $D_s^- \to K^+ K^- \pi^-$
Extracting $|V_{ub}|/|V_{cb}|$ from the BF ratio (measured in two q^2 bins):



Target

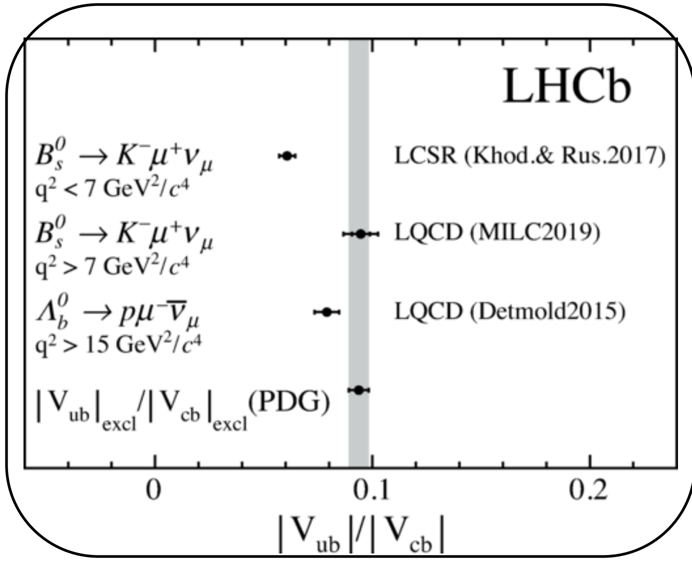
$$\frac{|V_{ub}|^2}{|V_{cb}|^2} \frac{G(B_s^0 \to K^- \mu^+ \nu_\mu)}{G(B_s^0 \to D_s^- \mu^+ \nu_\mu)}^{*} = \frac{N(B_s^0 \to K^- \mu^+ \nu_\mu)}{N(B_s^0 \to D_s^- \mu^+ \nu_\mu)} \times \frac{\epsilon(B_s^0 \to D_s^- (\to K^- K^+ \pi^-) \mu^+ \nu_\mu)}{\epsilon(B_s^0 \to K^- \mu^+ \nu_\mu)} \times BF(D_s^- \to K^- K^+ \pi^-)$$

External BF measurement

$q^2 < 7$ GeV$^2/c^4$: $|V_{ub}|/|V_{cb}|$ = 0.0607 ± 0.015 (stat) ± 0.0012 (syst) ± 0.0008 (Ds) ± 0.0030 (FF)

$q^2 > 7$ GeV$^2/c^4$: $|V_{ub}|/|V_{cb}|$ = 0.0946 ± 0.030 (stat) $^{+0.0024}_{-0.0025}$ (syst) ± 0.0013 (Ds) ± 0.0068 (FF)

Tension driven by the difference in the FF calculations



* Dominant uncertainties from FF calculations:
- Low q^2: $\sigma/(|V_{ub}|/|V_{cb}|)$ ~ 5 % [JHEP 2017, 112 (2017)]
- High q^2: $\sigma/(|V_{ub}|/|V_{cb}|)$ ~ 7 % [Phys. Rev. D 100, 034501 (2019)]

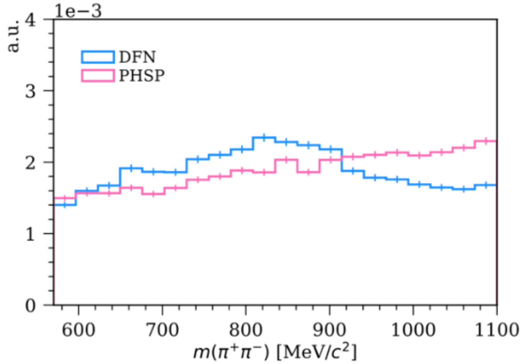
* FFs for normalization:
- Full q^2 LQCD

[Phys. Rev. D 101, 074513 (2020)]

$$B^{+} \to \rho^{0}(\pi^{+}\pi^{-})\mu^{+}\nu_{\mu}$$

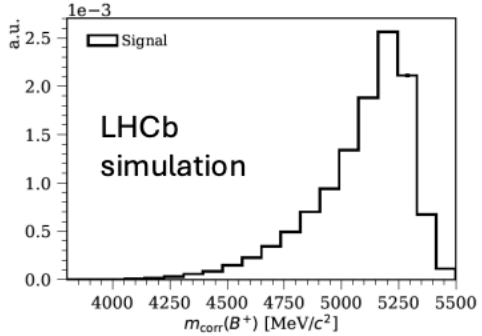
$B^+ \to \rho^0(\pi^+\pi^-)\mu^+\nu_\mu$

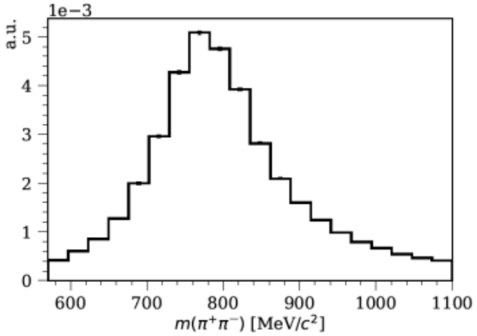
- Goal: measure the differential decay rate in q^2 bins
- The ρ^0 decays exclusively via $\rho^0 \to \pi^+\pi^-$.
- Norm mode: $B^+ \to \bar{D}^0(\pi^+\pi^-)\mu^+\nu_\mu$
- $BF = (3.34 \pm 0.14).10^{-5}$ -> Stat. Unc. ~ 3%



$B^+ \to \pi^+\pi^-\mu^+\nu_\mu$ shapes from
DFN/PYTHIA simulation [JHEP 06 (1999) 017]
Phase-space simulation

Signal simulated with BCL/BSZ FFs [PRD104,034032 (2021)] and mpipi shape reweighted to include ρ –w interference





- **Main Backgrounds:** MVA (Isolation)

$B^+ \to \bar{D}^0(\pi^+\pi^- X^0)\mu^+\nu_\mu\ (X)$

$B^{+,0} \to X_u\,\mu^+\nu_\mu$ (varius charmless semileptonic decays)

$B^+ \to \pi^+\pi^-\mu^+\nu_\mu$ (with non-resonant $\pi^+\pi^-$)

Comb Bkg: modelled with SS data

MisID Bkg: modelled with data-driven methods

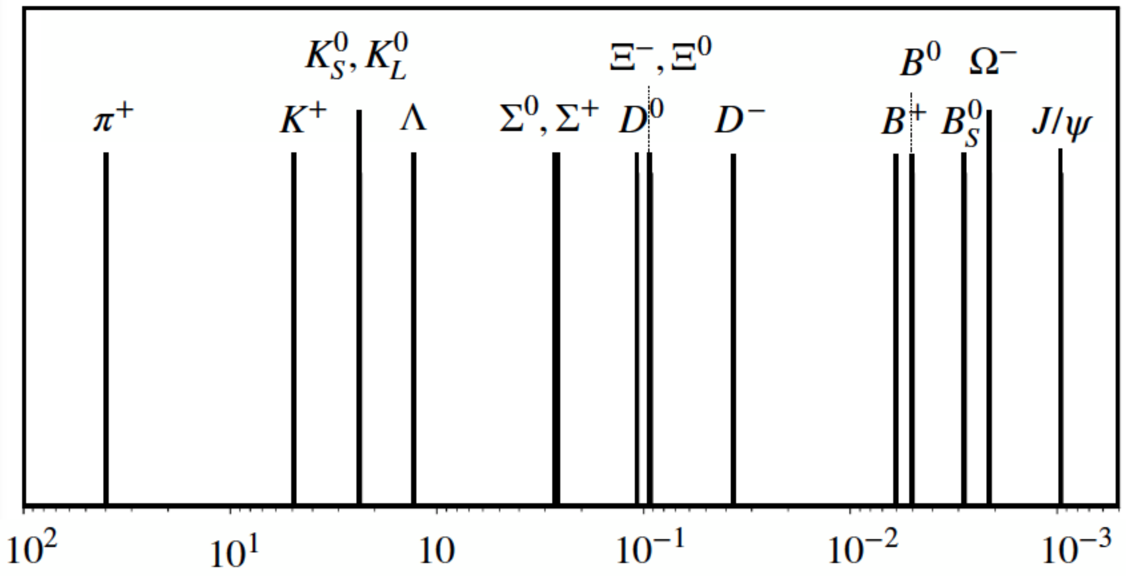
- Measurement of $|V_{ub}|$ and FFs from fit to dB/dq^2, following [PRD 104,034032 (2021)]
- Predictions of the FFs $V(q^2)$, $A_1(q^2)$ and $A_{12}(q^2)$ based on light-cone sum rules (LCSR) calculations valid in $q^2 \lesssim 14\,GeV^2/c^4$ [PRD 79,013008 (2009)].
- BCL/BSZ parametrisations to extrapolate FFs in the full region [JHEP08,098 (2016)]

$|V_{us}|$ from the $\Lambda \rightarrow p\,\mu^{-}\,\bar{\nu}_{\mu}$

Strange physics at LHCb

- LHCb obtained **leading strange physics measurements**, particularly searching for their rare decays, publishing best measurements in $K_S^0 \to \mu^+ \mu^-$, $K_S^0 \to \mu^+ \mu^- \mu^+ \mu^-$, and $\Sigma^+ \to p \mu^+ \mu^-$.

Channel	$\mathcal{R}$	ϵ_L	ϵ_D	σ_L $\left(\frac{MeV}{c^2}\right)$	σ_D $\left(\frac{MeV}{c^2}\right)$
$K_S^0 \to \mu^+\mu^-$	1	1.0 (1.0)	1.8 (1.8)	~3.0	~8.0
$K_S^0 \to \pi^+\pi^-$	1	1.0 (0.30)	1.9 (0.91)	~2.5	~7.0
$K_S^0 \to \pi^0\mu^+\mu^-$	1	0.93 (0.93)	1.5 (1.5)	~35	~45
$K_S^0 \to \gamma\mu^+\mu^-$	1	0.85 (0.85)	1.4 (1.4)	~60	~60
$K_S^0 \to \mu^+\mu^-\mu^+\mu^-$	1	0.37 (0.37)	1.1 (1.1)	~1.0	~6.0
$K_L^0 \to \mu^+\mu^-$	~1	2.7 (2.7) $\times 10^{-3}$	0.014 (0.014)	~3.0	~7.0
$K^+ \to \pi^+\pi^+\pi^-$	~2	9.0 (0.75) $\times 10^{-3}$	41 (8.6) $\times 10^{-3}$	~1.0	~4.0
$K^+ \to \pi^+\mu^+\mu^-$	~2	6.4 (2.3) $\times 10^{-3}$	0.030 (0.014)	~1.5	~4.5
$\Sigma^+ \to p\mu^+\mu^-$	~0.13	0.28 (0.28)	0.64 (0.64)	~1.0	~3.0
$\Lambda \to p\pi^-$	~0.45	0.41 (0.075)	1.3 (0.39)	~1.5	~5.0
$\Lambda \to p\mu^-\bar{\nu}_\mu$	~0.45	0.32 (0.31)	0.88 (0.86)	-	-
$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	~0.04	39 (5.7) $\times 10^{-3}$	0.27 (0.09)	-	-
$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	~0.04	24 (4.9) $\times 10^{-3}$	0.21 (0.068)	-	-
$\Xi^- \to p\pi^+\pi^-$	~0.04	0.41 (0.05)	0.94 (0.20)	~3.0	~9.0
$\Xi^0 \to p\pi^-$	~0.03	1.0 (0.48)	2.0 (1.3)	~5.0	~10
$\Omega^- \to \Lambda\pi^-$	~10^{-3}	95 (6.7) $\times 10^{-3}$	0.32 (0.10)	~7.0	~20



Multiplicity of particles produced in a single pp interaction at $\sqrt{s}$ = 13 TeV within LHCb acceptance.

A. A. Alves Junior et al. "Prospects for Measurements with Strange Hadrons at LHCb". In: JHEP 05 (2019), p. 048. doi: 10.1007/JHEP05(2019)048. arXiv: 1808.03477 [hep-ex]

Semileptonic Hyperon Decays

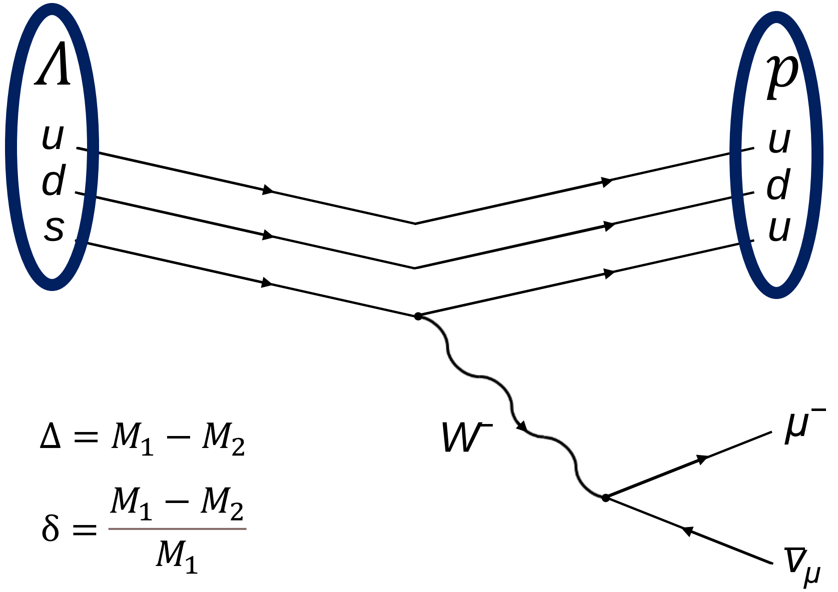
- The **LFU test observable** defined as the ratio between muon and electron modes [Phys. Rev. Lett. 114 no. 16, (2015)]

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2 \mu^- \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2 e^- \bar{\nu}_e)} = 0.153 \pm 0.008$$

is **sensitive** to non standard scalar and tensor contributions.

- In the SM, the **dependence** on the form factors is anticipated to **simplify** when considering the **ratio**.

$$R^{\mu e}_{\rm SM} = \sqrt{1 - \frac{m_\mu^2}{\Delta^2}}\left(1 - \frac{9}{2}\frac{m_\mu^2}{\Delta^2} - 4\frac{m_\mu^4}{\Delta^4}\right) + \frac{15}{2}\frac{m_\mu^4}{\Delta^4}\,\mathrm{arctanh}\left(\sqrt{1 - \frac{m_\mu^2}{\Delta^2}}\right)$$



$\Delta = M_1 - M_2$

$\delta = \frac{M_1 - M_2}{M_1}$

$f_1(0) = hyperon\ vector\ charge$

$g_1(0) = hyperon\ axial\ charge$

- **Clean theoretical prediction** for the decay rate (going to order δ^2)

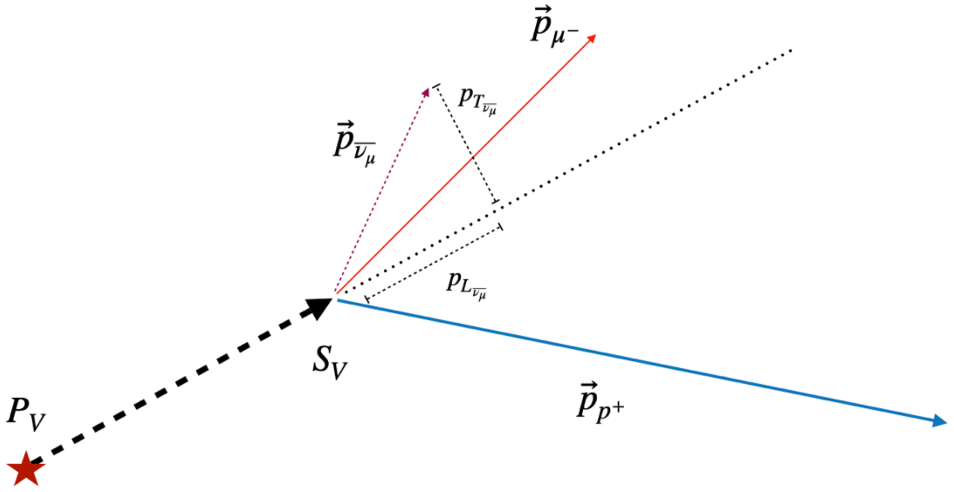
$$\Gamma^{\rm SM}(B_1 \to B_2 e^- \bar{\nu}_e) \simeq \frac{G_F^2 |V_{us}\, f_1(0)|^2 \Delta^5}{60\pi^3}\left[\left(1 - \frac{3}{2}\delta\right) + 3\left(1 - \frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2} - 4\delta\frac{g_2(0)}{f_1(0)}\frac{g_1(0)}{f_1(0)}\right]$$

$$|V_{us}|^2 \simeq \frac{\Gamma^{\rm SM}(B_1 \to B_2 \mu^- \bar{\nu}_\mu)\, 60\pi^3}{R^{\mu e} G_F^2\, f_1(0)^2 \Delta^5 \left[\left(1 - \frac{3}{2}\delta\right) + 3\left(1 - \frac{3}{2}\delta\right)\frac{g_1(0)^2}{f_1(0)^2}\right]}$$

$\Lambda \to p\, \mu^- \bar{\nu}_\mu$

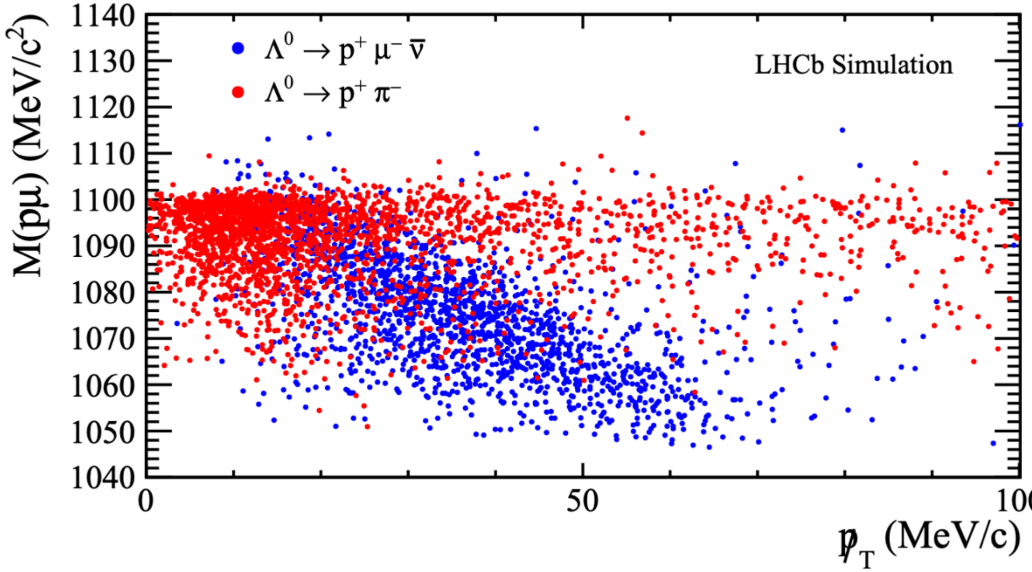
[J. High Energ. Phys. 2019, 48 (2019)]
[LHCB-FIGURE-2019-006]
[J. Phys. Conf. Ser. 1526 012022 (2020)]

- Best branching ratio measurement from BESIII (2021):
  $\mathcal{B}\,(\Lambda \to p\, \mu^- \bar{\nu}_\mu) = (1.48 \pm 0.21) \times 10^{-4}$ **(14.19 % Uncertainty)**



$p_T(\nu_\mu)$: obtained from proton and muon (PTmiss)
$p_L(\nu_\mu)$: obtained by imposing Λ mass
→ **recovered neutrino momentum components**

$$p_L(\nu_\mu) = \frac{E_{p\mu} \cdot \sqrt{A^2 - M_\Lambda^2 \cdot p_T'^2} - A \cdot p'_{p\mu z} + p'_{p\mu z} \cdot p_T'^2}{(p'_{p\mu z})^2 - E_{p\mu}^2} \qquad A = \frac{M_\Lambda^2 - M_{p\mu}^2}{2}$$



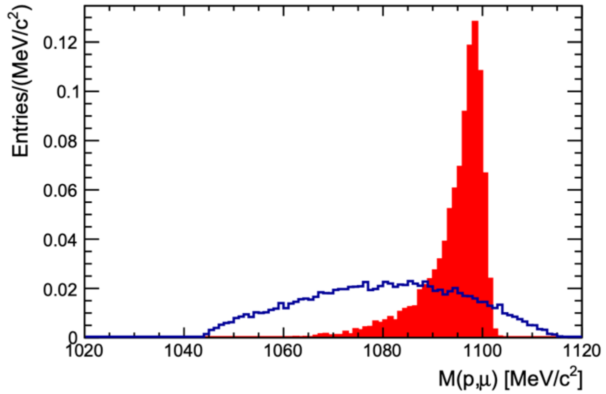
Dataset: 5.4 fb^{-1} @ $\sqrt{s}$ = 13 TeV (Run2),
Normalisation: $\Lambda \to p\, \pi^-$

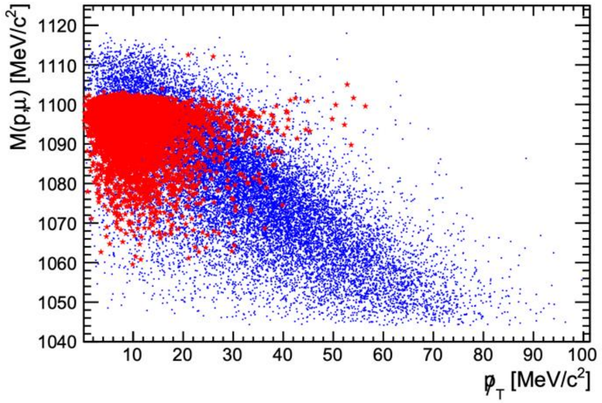
44K selected signal events → **~1.5 % stat. unc.**
Dominated by systematic uncertainties
Publication expected early next year

$\Xi^- \to \Lambda\, \mu^- \bar{\nu}_\mu$ proposed as the next natural step

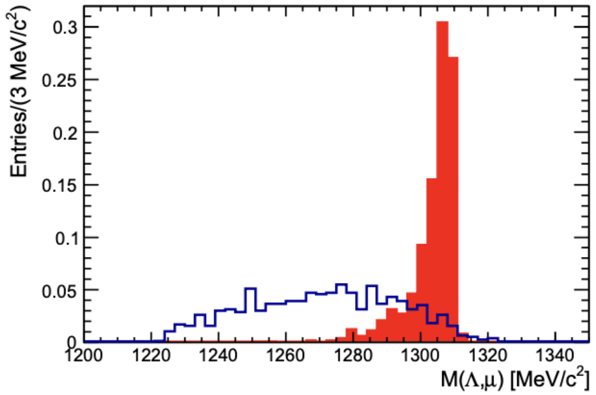
SHD Prospects in LHCb

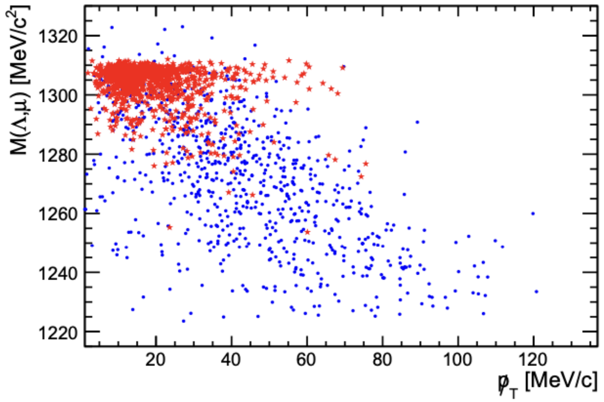
$\Lambda \to p\,\mu^- \bar{\nu}_\mu$ *vs* $\Lambda \to p\,\pi^-$





$\Xi^- \to \Lambda\,\mu^- \bar{\nu}_\mu$ *vs* $\Xi^- \to \Lambda\,\pi^-$





$$B_{(c)}^{+} \to \tau^{+} \nu_{\tau}$$

$B_{(c)}^{+} \to \tau^{+}\nu_{\tau}$

$\hat{f}$: flight direction

$$\hat{f} = \frac{\overrightarrow{TV} - \overrightarrow{SV}}{|\overrightarrow{TV} - \overrightarrow{SV}|}$$

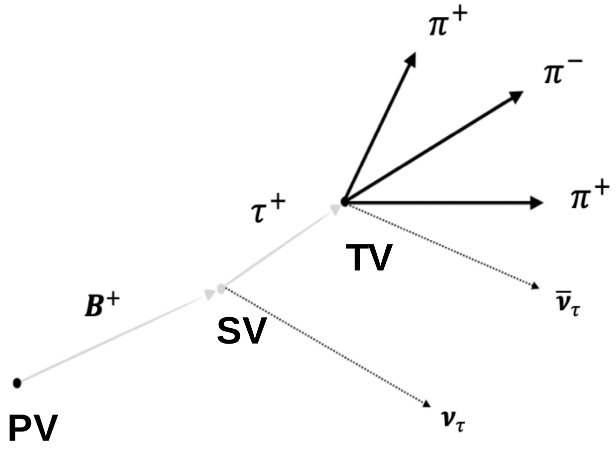
Orthogonal basis

$$\hat{x} = (-\hat{f}_y, \hat{f}_x, 0)$$
$$\hat{y} = \hat{f} \times \hat{x}$$
$$\hat{z} = \hat{f}$$

In this orthogonal basis:

$$\vec{p}'_{3\pi}$$
$$\vec{p}'_{\nu} = (-p'_{3\pi\,x}, -p'_{3\pi\,y}, p'_L)$$

$$\not{p}'_T = \sqrt{p'^{\,2}_{3\pi\,x} + p'^{\,2}_{3\pi\,y}}$$



We constrain the τ mass (M_τ) and use energy conservation:

$$M_\tau^2 = (E_{3\pi} + E_\nu)^2 - |\vec{p}'_{3\pi} - \vec{p}'_\nu|^2$$

$$A = \frac{M_\tau^2 - M_{3\pi}^2}{2}$$

$$p'_L = \frac{p'_{3\pi\,z}\left(A - \not{p}'^{\,2}_T\right) \pm E_{3\pi}\sqrt{A^2 - \not{p}'^{\,2}_T M_\tau^2}}{E_{3\pi}^2 - p'^{2}_{3\pi\,z}}$$

$$A^2 - \not{p}'^{\,2}_T M_\tau^2 > 0$$

$$\not{p}'_T < \frac{M_\tau^2 - M_{3\pi}^2}{2M_\tau}$$

same limit for the first neutrino

$$\not{p}'_T < \frac{M_B^2 - M_\tau^2}{2M_B}$$

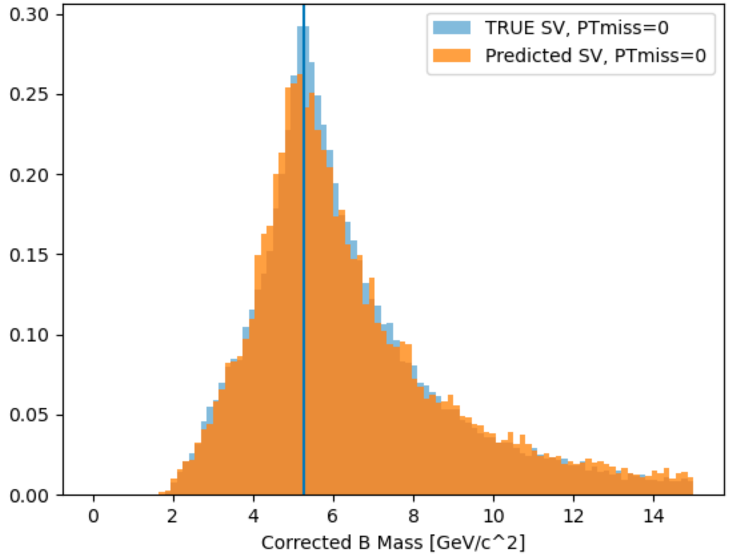
$B_{(c)}^{+} \to \tau^{+}\nu_{\tau}$ with Run 2 Data

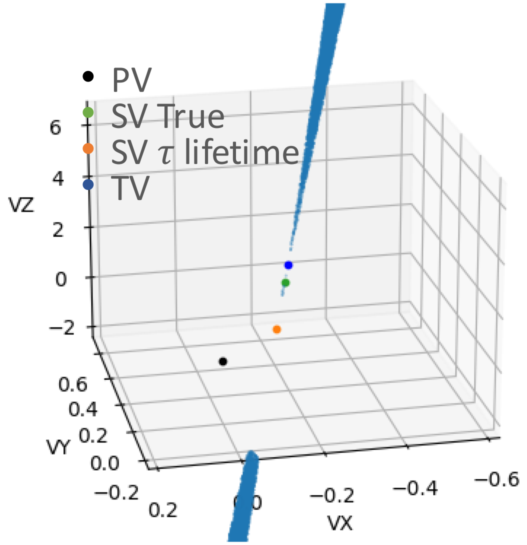
Kinematic Strategy for predicting SV

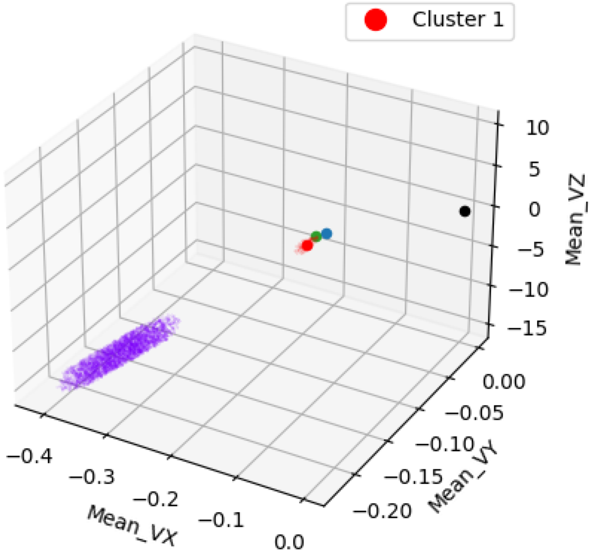
1. Assume $\vec{p}_{\nu}$ is in the same direction as $\vec{p}_{3\pi} \to \ p_{\nu} = \frac{1}{2}\frac{M_{\tau}^{2} - M_{3\pi}^{2}}{E_{3\pi} - p_{3\pi}}$

2. Create a grid of points between PV and TV and check the two $P_L > 0$ conditions for each point (valid SV)

3. Identify cluster of valid SVs and compute centroid







- Valid cluster found for ~50% of events.
- Resolution comparable to the one using TRUE SV
- The main challenge will be the low signal purity
- Currently working on ML to remove comb. Bkg.

Feasibility of analysing these final states in progress

$B_s^0 \to K^- \mu^+ \nu_\mu$

[M. Calvi Slides (2024)]

Prospects on $|V_{ub}|$ and FF determination in $B^0_s \rightarrow K^- \mu^+ \nu_\mu$

- Several FF scheme available to describe signal shape in simulation. Examples:
  - LCSR JHEP 08(2017)112
  - HPQCD 2014 PRD 90(2014)054506
  - RBC/UKQCD PRD 91(2015)074510
  - FNAL/MILC PRD 100(2019)034501

  } Average of 3 LQCD results by FLAG21(Feb 23). BCL extrapolation.
  - RBC/UKQCD update PRD 107 2023)114512 superseeding their previous results, with BGL.
  - Bayesian inference JHEP 12 (2023) 175 with BGL
  - LCSR&LQD combination arXiv:2308.04347, with modified BGL
- Baseline FF to be used not defined yet (FLAG24 average?)
  - Could provide results with different options.
  - Dependence of fitted signal yields on FF reduced using high number of bins (small variation of m_{cor} distribution inside the bin).
  - Dependence of signal efficiency per bin on FF to be detrmined.
- Same FF scheme will be used to fit $\frac{d\mathcal{B}}{dq^2}$ distribution and determine $|V_{ub}|$ via

$$\frac{d\mathcal{B}}{dq^2} = \frac{d\Gamma^0_{sig}}{dq^2} |V_{ub}|^2 \;\tau_B$$

$B_s^0 \to K^- \mu^+ \nu_\mu$

[M. Calvi Slides (2024)]

- Background from physics processes: shape modelled with simulation.
- Main sources are $b \to c$ decays like $H_b \to (H_c \to K^- X)\mu^+\nu_\mu X'$ and $H_b \to c\bar{c}(\mu^+\mu^-)K^- X$ (concentrated in few q^2 bins).
  - Suppressed with multivariate classifier with kinematical and topological variables, trained on simulation.
- Contributions from $B^0_s \to (K^{*-} \to K^- \pi^0)\mu^+\nu_\mu$ with $K^*(892)$, $K^*_0(1430)$, $K^*_2(1430)$ with unreconstructed π^0
  - Unmeasured branching fractions
  - Poor knowledge of the expected q^2 shape, additional input would be useful
  - Some separation from signal due to the missing particle
  - Partially suppressed with neutral isolation criteria
- Smaller contributions from random $K^-\mu^+$ combinations and semileptonic decays with mis-identified K^-.
  - Suppressed with multivariate classifier trained on $K^\pm\mu^\pm$ data and PID cuts. Shape modelled with data-driven methods.

Take into account

- B momentum reconstruction in semileptonic decays challenging at LHCb
  - Main production from gluons at LHC → large variation of B momenta
  - LHCb forward acceptance → partial coverage of the complete $b\bar{b}$ event .

Operation and data

$$\sqrt{s} = 7\,\text{TeV} : \sigma(pp \to b\bar{b}X) = (72.0 \pm 0.3 \pm 6.8)\,\mu b$$

$$\sqrt{s} = 13\,\text{TeV} : \sigma(pp \to b\bar{b}X) = (144 \pm 1 \pm 21)\,\mu b$$