UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

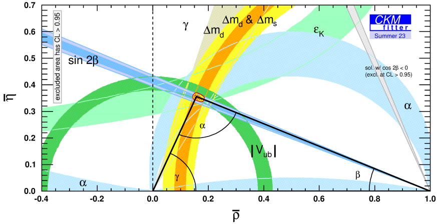
Inclusive semileptonic B_s^0 meson decays via a sum-of-exclusive modes technique

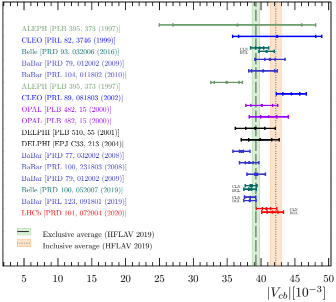
Based on M. De Cian, N. Feliks, M. Rotondo, K. Vos, JHEP06(2024)158

Wien, September 23 - 27, 2024

Michel De Cian, Heidelberg

$|V_{cb}|$ - Inclusive and exclusive





- B-factories can measure $|V_{cb}|$ inclusively and exclusively. The inclusive measurement is made possible by fully reconstructing the other B mesons in the event.
- Detectors at hadron machines (=LHCb) so far measured $|V_{cb}|$ only exclusively, but also have large samples of B_s^0 and Λ_b^0 hadrons. No full event reconstruction possible.
- Can we combine the two?

[Phys.Rev.D 107 (2023) 7, 072002]

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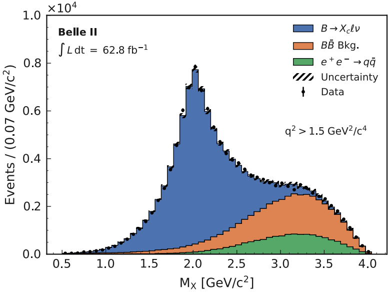
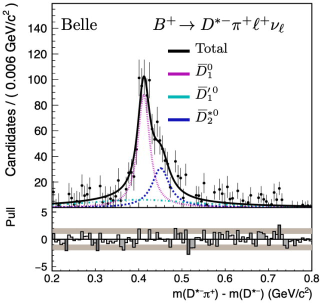
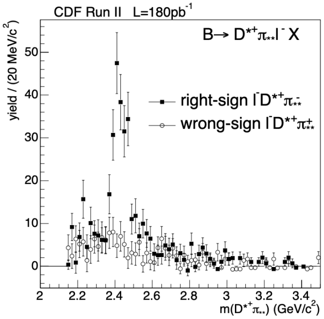


- Measuring $|V_{cb}|$: Determine the statistical moments of the $m(X_c)$, q^2 or E_ℓ^* distributions.
- From this information, determine the non-perturbative parameters of the Heavy Quark Expansion.
- Will only talk about $m(X_c)$, it's the only precisely reconstructible quantity at a hadron collider.

[Phys.Rev.D 107 (2023) 9, 092003]
[Phys.Rev.D 71 (2005) 051103]

"Das Ganze ist mehr als die Summe seiner Teile"





- The full $m(X_c)$ spectrum can only be reconstructed as a sum-of-exclusives (at a hadron collider).
- A pioneering measurement was done by CDF using $B^+ \to D^{(*)-}\pi^+\ell\nu$ decays.
- However, this works best if there are many non-overlapping resonances, avoiding interference.
- This is (mostly) the case for $B_s^0 \to X_{cs}\ell\nu$ decays, but much less for $B^0/B^+ \to X_c\ell\nu$ decays.
- The task then is: Measure all exclusive branching fractions of the $B_s^0 \to X_{cs}\ell\nu$ spectrum.

Heavy Quark Expansion

$$\Gamma = |V_{cb}|^2 \frac{G_F^2 m_b^5(\mu)}{192\pi^3} \eta_{ew} \times$$
$$[z_0^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_0^{(1)} + \left(\frac{\alpha_s(\mu)}{\pi}\right)^2 z_0^{(2)}(r) + \dots$$
$$+ \frac{\mu_\pi^2}{m_b^2}\left(z_2^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_2^{(1)}(r) + \dots\right)$$
$$+ \frac{\mu_G^2}{m_b^2}\left(y_2^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} y_2^{(1)}(r) + \dots\right)$$
$$+ \frac{\rho_D^3}{m_b^3}\left(z_3^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} z_3^{(1)}(r) + \dots\right)$$
$$+ \frac{\rho_{LS}^3}{m_b^3}\left(y_3^{(0)}(r) + \frac{\alpha_s(\mu)}{\pi} y_3^{(1)}(r) + \dots\right) + \dots]$$

$$\mathcal{B}(\bar{B}_s^0 \to X_{cs}\ell^-\bar{\nu}_\ell) = 66.85|V_{cb}|^2 \left[\left(1 - \frac{\mu_\pi^2}{2m_b^2}\right) - 0.40\alpha_s^2 - 0.17\alpha_s^3 - 1.91\frac{\mu_G^2}{m_b^2} + \alpha_s\left(-0.39 + 0.36\frac{\mu_\pi^2}{m_b^2}\right) - 16.68\frac{\rho_D^3}{m_b^3} + 1.91\frac{\rho_{LS}^3}{m_b^3}\right]$$

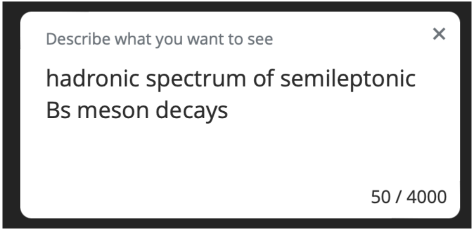
$$M_n = \langle (m_H^2)^n \rangle = \int (m_H^2)^n \frac{1}{\Gamma_{SL}} \frac{d\Gamma_{SL}}{dm_H^2} dm_H^2.$$
$$M_n' = \langle (m_H^2 - \langle m_H^2 \rangle)^n \rangle = \int (m_H^2 - M_1)^n \frac{1}{\Gamma_{SL}} \frac{d\Gamma_{SL}}{dm_H^2} dm_H^2.$$

- $r = \frac{m_c}{m_b}, y_i, z_i$ perturbatively calculable parameters.
- $\mu_\pi^2, \mu_G^2, \rho_D^3, \rho_{LS}^3$ non-perturbative parameters of interest.
- Link non-perturbative parameters to moments of hadronic mass spectrum.

What is the spectrum?

- As said before, all we need to know is the branching fraction of the $B_s^0 \to X_{cs} \ell \nu$ decays.
- And the branching fraction(s) of the $X_{cs} \to XY$ decays.
- And then we can build ourselves as spectrum, measure the moments and determine the HQE parameters

What is the spectrum?



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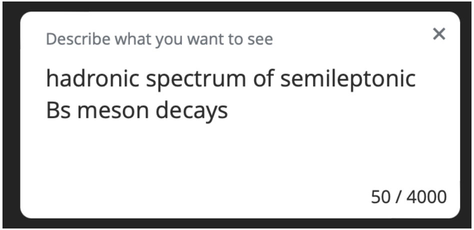
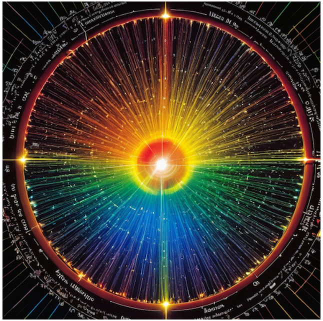


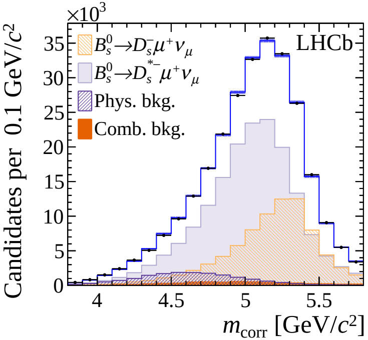


- Well then, let's look at the contributions one-by-one.

Ground and first excited state

$\mathcal{B}(B_s^0 \to D_s^+ \ell \nu)$

- Known with about 10% relative precision.
  Possibility for a further reduction (?)
- $\mathcal{B}(D_s^+ \to K^+ K^- \pi^+)$ known to about 2% relative precision.
- Could use different D_s^+ final state for less model dependence on $K^+ K^- \pi^+$ spectrum



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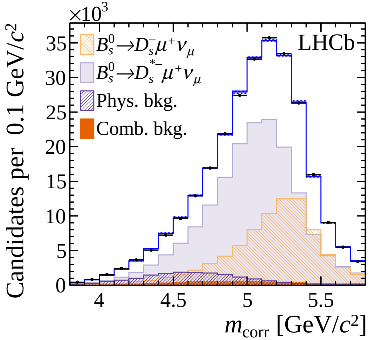

$$\mathcal{B}(B_s^0 \to D_s^{*+} \ell \nu)$$

- Known with about 10% relative precision.
  Possibility for a further reduction (?)
- $\mathcal{B}(D_s^{*+} \to D_s^+ \gamma)$ known to about 0.5% relative precision.

First two higher excited states

- The first two higher resonances are below the DK threshold, so exclusively decay to D_s^+ mesons.

$$\mathcal{B}(B_s^0 \to D_{s0}^{*+} \ell \nu)$$

- No measurement has been published. We assume $(0.3 \pm 0.3)\%$ BR
- $\mathcal{B}(D_{s0}^{*+} \to D_s^+ \pi^0)$ known to about 20% relative (and absolute) precision (measured by BESIII).
- The π^0 is very soft, resulting in a small reconstruction efficiency, but clearly doable.

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$\mathcal{B}(B_s^0 \to D_{s1}'^{+} \ell\nu)$

- No measurement has been published. We assume $(0.3 \pm 0.3)\%$ BR
- $\mathcal{B}(D_{s1}'^{+} \to D_s^{*+} \pi^0)$ known to about 20% relative (and absolute) precision.
- The π^0 is very soft, resulting in a small reconstruction efficiency, but clearly doable.
- The decay $D_{s1}'^{+} \to D_s^+ \gamma$ also exists, with 18% BR.

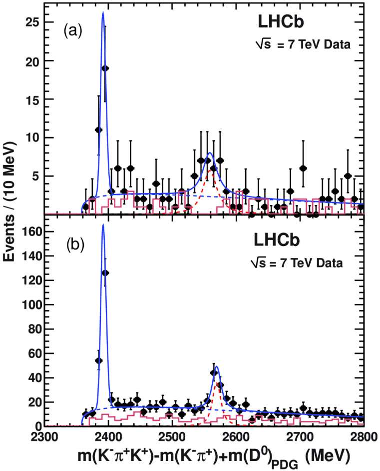
[Phys.Lett.B 698 (2011) 14-20]

Second two higher excited states

- The second two higher resonances are above the DK threshold.

$$\mathcal{B}(B_s^0 \to D_{s1}^+ \ell\nu)$$

- DØ and LHCb, ≈20% relative uncertainty. Easy to improve.
- $\mathcal{B}(D_{s1}^+ \to D^{*0} K^+)$ about 15% rel. uncertainty (new BES result).
- Experimentally "easy", D^{*0} can be reconstructed as D^0



[Phys.Lett.B 698 (2011) 14-20]

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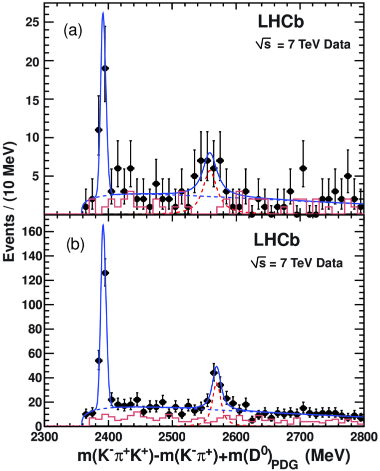
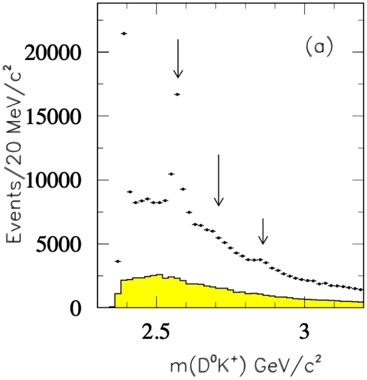
$$\mathcal{B}(B_s^0 \to D_{s2}^{*+} \ell\nu)$$

- LHCb, about 35% relative uncertainty. Easy to improve.
- $\mathcal{B}(D_{s2}^{*+} \to D^0 K^+)$ about 15% rel. uncertainty (new BES result).
- Experimentally "easy" to reconstruct

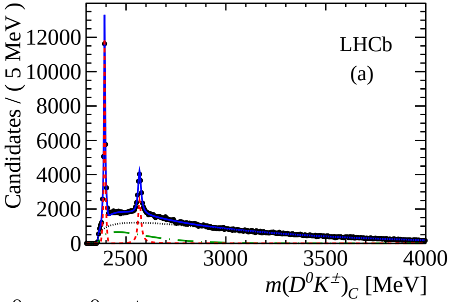


Higher resonances

- Higher resonances exist and have been observed.
- They are not considered for this study.
- Measuring a branching fraction $\mathcal{B}(B_s^0 \to (D_{sJ}^{*+} \to D^0 K^+)\ell\nu)$ is experimentally not difficult, but $\mathcal{B}(D_{sJ}^{*+} \to D^0 K^+)$ is not doable at a hadron machine (or very hard)
- How about Belle 2?



Non-resonant decays



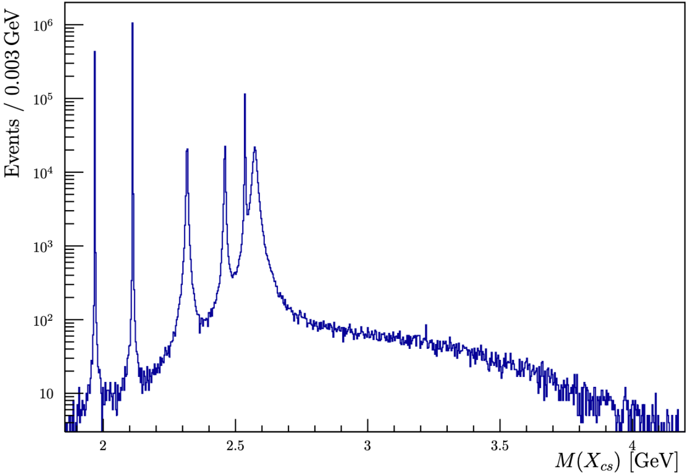
- $B_s^0 \to D^0 K^+ \ell\nu$ has been observed in LHCb, but no branching fraction value has been published.
- We extract the shape from a "modified Goity-Roberts model" (describing $B \to D\pi\ell\nu$ decays), accounting for the K - π difference.
- Lately a new, model-independent approach for $B \to D\pi\ell\nu$ decays was presented - can it be applied to $B_s^0 \to D^0 K^+ \ell\nu$ decays as well? - Yesterday I learned, it will!

Total BR

$$\Gamma_{SL}(B_s^0)/\Gamma_{SL}(B^0) = 1 - (0.018 \pm 0.008).$$
$$\mathcal{B}(\overline{B}_s^0 \to X_c \ell^- \bar{\nu}_\ell) = (10.05 \pm 0.31)\%,$$

- Summing up all individual BRs, including an estimate for the non-resonant contribution from Phys. Rev. D 100 (2019) 3, 031102, and using isospin-arguments, we found the sum larger than the theoretical prediction for the semileptonic BR.
  - This needs to be updated with the BES III measurements for $\mathcal{B}(D_{s1}^+ \to D^{*0} K^+)$ and $\mathcal{B}(D_{s2}^{*+} \to D^0 K^+)$
- What we did instead is to constrain the non-resonant contribution to be the difference between the 6 resonant decays and the theoretical prediction.

Resulting spectrum



Resulting moments & HQE parameters

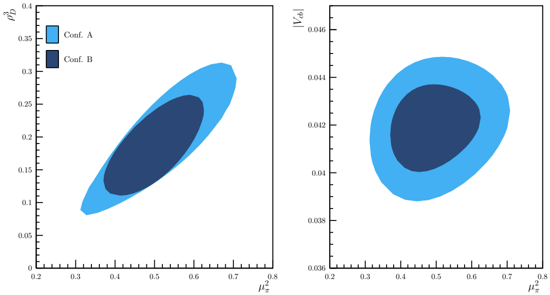
Moments	Conf. A	M'_2	M'_3	Conf. B	M'_2	M'_3	$L=0$ and $L=1$
M_1 [GeV^2]	4.82± 0.08	0.74	0.55	4.78±0.02	0.72	0.45	4.79±0.02
M'_2 [GeV^4]	1.36 ± 0.29		0.96	1.22±0.05		0.90	0.82±0.09
M'_3 [GeV^6]	4.7 ± 1.8			3.86±0.28			1.07±0.11

- Use hyperfine splitting $(m^2_{B_s^{*0}} - m^2_{B_s^0}) = \frac{4}{3} C_{\rm mag} \mu_{G^2}(B_s^0) + \mathcal{O}(1/\,\mathrm{m_b})$ to obtain constraint for $\mu_G^2(B_s^0)$: $\frac{\mu_G^2(B_s^0)}{\mu_G^2(B^0)} = 1.14 \pm 0.10$
- Take ρ^3_{LS} from B^0 decays and increase uncertainty to account for $SU(3)_F$ breaking: $\rho^3_{LS}(B_s^0) \simeq -(0.13 \pm 0.10)\ \mathrm{GeV}^3$
- μ_π^2 and ρ_D^3 are left free in the fit.

Resulting moments & HQE parameters

- We then obtain:
- $\mu_\pi^2 = (0.46 \pm 0.12)\ \mathrm{GeV}^2$ and therefore $\frac{\mu_\pi^2(B_s^0)}{\mu_\pi^2(B^0)} \sim 0.96$
- $\rho_D^3 = (0.16 \pm 0.06)\ \mathrm{GeV}^3$ and therefore $\frac{\rho_D^3(B_s^0)}{\rho_D^3(B^0)} \sim 0.86$
- The (constrained) values of $\mu_G^2(B_s^0)$ and $\rho_{LS}^3(B_s^0)$ are very close to the input constrains.
- The main reason for the low values of μ_π^2 and ρ_D^3 is the small value of M_3' ($4.7\,\mathrm{GeV}^6$) compared to the prediction ($8.8\,\mathrm{GeV}^6$).
- This might be due to an underestimation of higher-mass resonances in the toy model.
  - This needs to be updated with the new results from BES III on the D_{s1}^+ and D_{s2}^{*+} branching fractions.

$|V_{cb}|$ & correlation



- Using the experimentally measured $\mathcal{B}(B_s^0 \to X\ell\nu) = (9.6 \pm 0.8)\%$ we calculate $|V_{cb}|$ to be $(41.8 \pm 2.0) \cdot 10^{-3}$.
- While μ_π^2 and ρ_D^3 are strongly correlated, $|V_{cb}|$ only exhibits a weak correlation to μ_π^2.

What is needed to turn this into a (precise) measurement?

- An improved measurement of the $B_s^0 \to D_s^+ \ell\nu$ and $B_s^0 \to D_s^{*+} \ell\nu$ branching fractions (mostly experimental).
- Measurements of $B_s^0 \to D_{s0}^{*+} \ell\nu$ and $B_s^0 \to D_{s1}^{'+} \ell\nu$ (experimental), including solid predictions (or measurements) for the D_{s0}^{*+} and $D_{s1}^{'+}$ decays (theoretical / experimental).
- Updated measurements for $B_s^0 \to D_{s1}^{+} \ell\nu$ and $B_s^0 \to D_{s2}^{*+} \ell\nu$ (experimental)
- And an improved handling of the non-resonant contribution (theoretical/experimental).

Conclusion

- Presence of mostly narrow resonances in hadronic spectrum in $B_s^0 \to X_{cs}\ell\nu$ allow for a sum-of-exclusives approach to an inclusive measurement.
- Performed a proof-of-concept. It shows a significant difference in ρ_D^3 for B_s^0 compared to B^0 and to the prediction, most likely coming from a mismodeling of the X_{cs} spectrum - clearly needs more study.
- Most input measurements can be experimentally and theoretically improved. Most importantly, the decay $B_s^0 \to D^0 K^+ \ell\nu$ needs a better understanding.
- With these improvements, a precise measurement of the HQE parameters in semileptonic B_s^0 decays can be obtained.

b – A – c – K – u – P

D_{s0}^{*+}		$D_{s1}^{\prime +}$		D_{s1}^{+}		D_{s2}^{*+}	
$2317.8 \pm 0.5\,\mathrm{MeV}$		$2459.5 \pm 0.6\,\mathrm{MeV}$		$2535.11 \pm 0.06\,\mathrm{MeV}$		$2569.1 \pm 0.8\,\mathrm{MeV}$	
$< 3.8\,\mathrm{MeV}$		$< 3.5\,\mathrm{MeV}$		$0.92 \pm 0.05\,\mathrm{MeV}$		$16.9 \pm 0.7\,\mathrm{MeV}$	
$D_s^+ \pi^0$	$100^{+0}_{-20}\%$	$D_s^{*+} \pi^0$	$48 \pm 11\%$	$D^{*+} K_\mathrm{S}^0$	$85 \pm 12\%$	$D^0 K^+$	seen
$D_s^+ \gamma$	$< 5\%$	$D_s^+ \gamma$	$18 \pm 4\%$	$D^{*0} K^+$	100%	$D^+ K_\mathrm{S}^0$	seen
$D_s^{*+} \gamma$	$< 6\%$	$D_s^+ \pi^+ \pi^-$	$4.3 \pm 1.3\%$	$D^+ \pi^- K^+$	$2.8 \pm 0.5\%$	$D^{*+} K_\mathrm{S}^0$	seen
$D_s^+ \gamma\gamma$	$< 18\%$	$D_s^{*+} \gamma$	$< 8\%$	$D_s^+ \pi^+ \pi^-$	seen		
		$D_{s0}^{*+} \gamma$	$3.7^{+5.0}_{-2.4}\%$	$D^+ K^0$	$< 34\%$		
				$D^0 K^+$	$< 12\%$		

B_s^0 Decay	$\mathcal{B}$[%] (Conf. A)	$\mathcal{B}$[%] (Conf. B)
$\overline{B}_s^0 \to X_{cs}\ell\bar{\nu}_\ell$	10.05±0.31	10.05±0.31
$\overline{B}_s^0 \to D_s^+\ell^-\bar{\nu}_\ell$ [38]	2.44±0.23	2.44± 0.10
$\overline{B}_s^0 \to D_s^{*+}\ell^-\bar{\nu}_\ell$ [38]	5.3±0.5	5.30 ±0.22
$\overline{B}_s^0 \to D_{s0}^{*+}\ell^-\bar{\nu}_\ell$ (see text)	0.3±0.3	0.30±0.03
$\overline{B}_s^0 \to D_{s1}^{\prime+}\ell^-\bar{\nu}_\ell$ (see text)	0.3±0.3	0.30±0.03
$\overline{B}_s^0 \to D_{s1}^{+}\ell^-\bar{\nu}_\ell$	0.98±0.20	0.98±0.05
$\overline{B}_s^0 \to D_{s2}^{*+}\ell^-\bar{\nu}_\ell$	0.58±0.20	0.58±0.04
$\overline{B}_s^0 \to D^{(*)}K\ell^-\bar{\nu}_\ell$ (see text)	0.15±0.15	0.150±0.015