UNIVERSITÄT
HEIDELBERG
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SEIT 1386

Semileptonic charged-current b-hadron decays at LHCb

Neckarzimmern,
March 16, 2023

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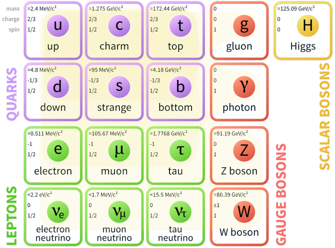
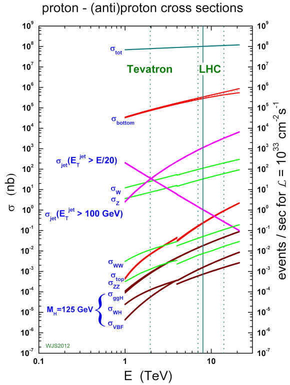
B physics

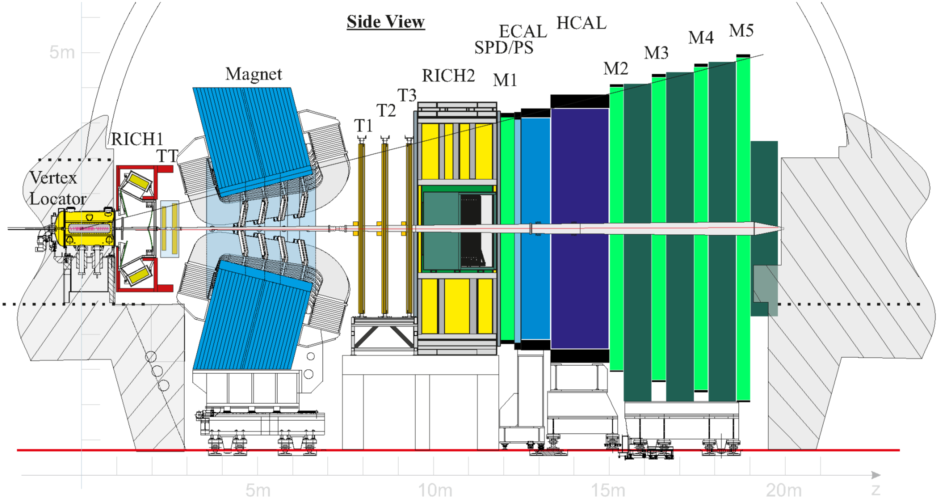


$$B^0 = |d\bar{b}\rangle, B^+ = |u\bar{b}\rangle, B^0_s = |s\bar{b}\rangle, \Lambda^0_b = |udb\rangle, B^+_c = |c\bar{b}\rangle$$

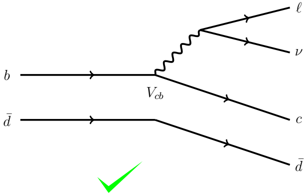


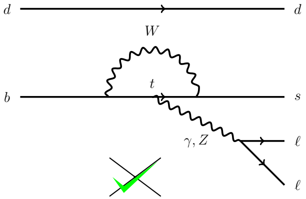
- B physics is the study of bound states containing one b quark and their decays / dynamics.
- They decay in a multitude of final states, allowing the study of a wide range of physics.
- They are copiously produced at the LHC: $10^{11} b\bar{b}$ pairs produced per fb^{-1}
- Non-B physics is great, too (but I had to restrict the topic a bit).

The LHCb detector (Run 1+2)



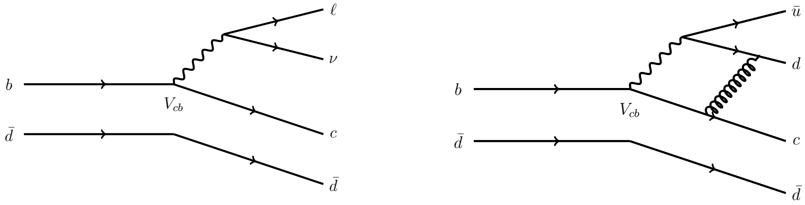
Linguistics





- ”Semileptonic decay” just refers to a final state with leptons and hadrons.
- Except for LHCb people where ”semileptonic B decay” stands for $b \to c$ and $b \to u$ transitions with charged and neutral leptons in the final state.
- *i.e.* no $b \to s\ell^+\ell^-$ transitions like $B^0 \to K^{*0}\ell^+\ell^-$ (they are still great...)

Motivation



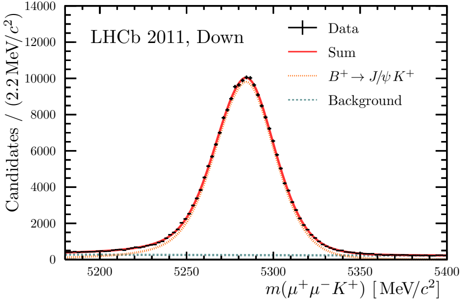
- The fundamental (theoretical) advantage of semi-leptonic decays is the non-coupling of the leptonic system to the outgoing hadron.
- The fundamental (experimental) disadvantage of semi-leptonic decays is the non-reconstructible neutrino.
- Experimental advantage: About 10% of all b-hadron decays: Very large samples, allows for many precision tests of the Standard Model.

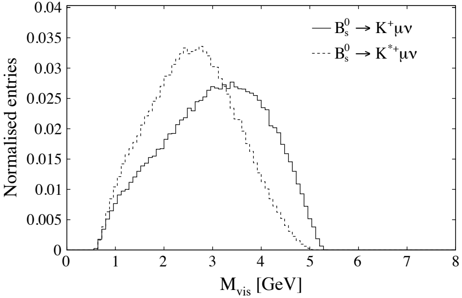
The CKM matrix

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Techniques for semileptonic decays (at LHCb)

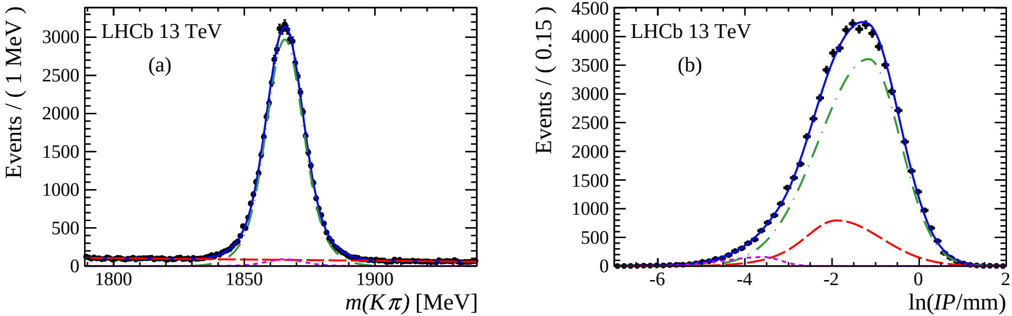
The fundamental experimental problem





- The fundamental experimental problem with semileptonic decays (at LHCb) is the missing neutrino.
- Cannot construct a B meson / baryon invariant mass.
- ”Visible mass”, *i.e.* invariant mass of all remaining particles has poor discrimination power.
- Need smarter approaches.

I: Denial



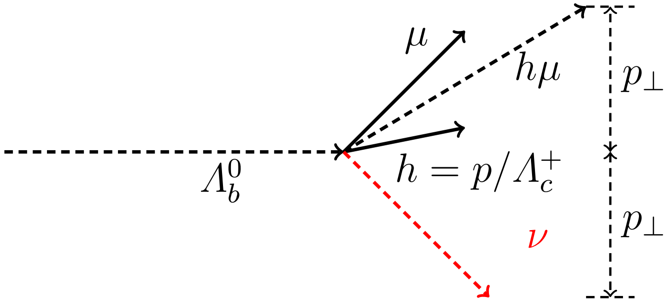
- One might not need a B invariant mass like object at all *e.g.* when studying $B \to D\mu\nu X$.
  - $\mathcal{B}(B \to D\mu\nu X) \approx$ 10% (it's $|V_{cb}|$)
  - Displaced muon
  - D resonance clean to select
- Fit $m(K^{+}\pi^{-})$ and $\log(\mathrm{IP_D})$ simultaneously to select the decay (and separate from prompt charm).

II: Anger

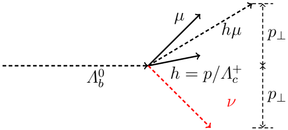
V_{cb} Vs V_{ub}

- The method on the last slide only really works well for abundant (Cabbibo favoured) signals with a clean resonance, and where you do not care about additional particles.
- For decays such as $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ and $B_s^0 \to K^-\mu^+\nu_\mu$, this does not work so well.
- And neither for decays with τ leptons in the final state, such as $B^0 \to D^{*+}\tau^-\nu$
- Let's see if we can't make up an invariant mass variable that is as close as possible to the "standard" one.

III: Bargaining (I)



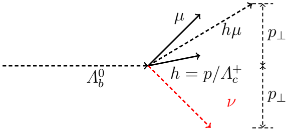
III: Bargaining (II)



$$
\begin{aligned}
m_B^2 &= (p_{vis} + p_\nu)^2 \\
&= m_{vis}^2 + \cancel{m_\nu^2} + 2 \cdot p_{vis} p_\nu \\
p_{vis} \cdot p_\nu &= E_{vis} E_\nu - p_{\parallel vis} p_{\parallel,\nu} - p_{\mathrm{T}vis} p_{\mathrm{T}\nu} \\
&\overset{p_{\mathrm{T}vis} = -p_{\mathrm{T}\nu}}{=} E_{vis} E_\nu - p_{\parallel vis} p_{\parallel,\nu} + {p_\mathrm{T}}^2
\end{aligned}
$$

- *Assume*: $p_{\parallel vis} = p_{\parallel,\nu}$
- $p_{vis} \cdot p_\nu$ is Lorentz invariant. One can always boost along the flight direction in a system where $p_{\parallel vis}$ vanishes.
- $p_{vis} \cdot p_\nu = \sqrt{m_{vis}^2 + {p_\mathrm{T}}^2} \cdot p_\mathrm{T} + {p_\mathrm{T}}^2$

III: Bargaining (III)



- *Assume*: $p_{\parallel vis} = p_{\parallel,\nu}$
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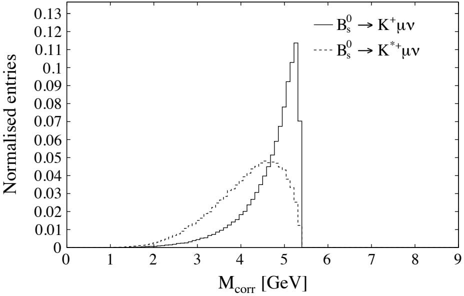
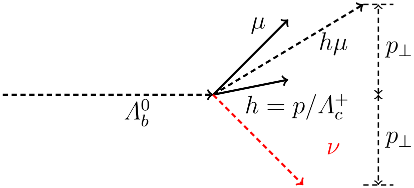
- $p_{vis} \cdot p_\nu = \sqrt{m_{vis}^2 + {p_\mathrm{T}}^2} \cdot p_\mathrm{T} + {p_\mathrm{T}}^2$

$$\begin{aligned} m_{B,corr}^2 &= m_{vis}^2 + 2 \cdot \sqrt{m_{vis}^2 + {p_\mathrm{T}}^2} \cdot p_\mathrm{T} + 2 \cdot {p_\mathrm{T}}^2 \\ &= \left(\sqrt{m_{vis}^2 + {p_\mathrm{T}}^2} + p_\mathrm{T} \right)^2 \\ \therefore m_{B,corr} &= \sqrt{m_{vis}^2 + {p_\mathrm{T}}^2} + p_\mathrm{T} \end{aligned}$$

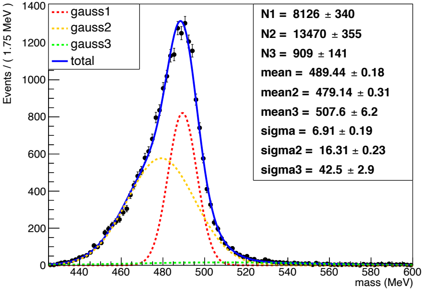
IV: Depression





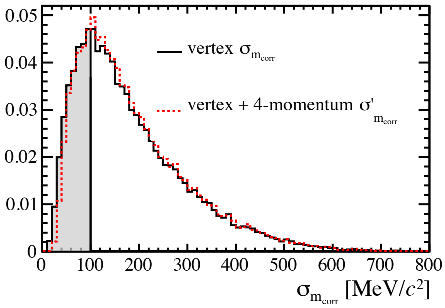
- m_{corr} peaks at the nominal B mass (the case where, in the rest frame of the B, the visible particles and the neutrino fly perpendicular to the flight direction).
- But it has a very long tail to lower masses.
- This is a consequence of the assumption we made.
- Still: One can show that the corrected mass is the best possible variable one can construct (lacking additional information) (arxiv:2108.13820)

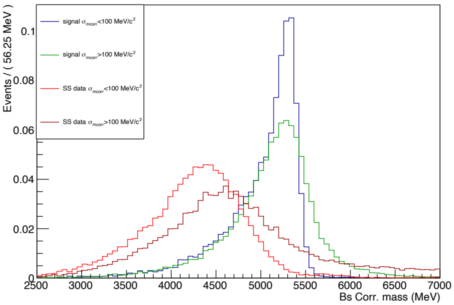
V: Acceptance



- There are some points to consider:
  - In an experimental setup, the upper end of the distribution is broadened due to resolution effects.
  - One can also construct m_{corr} for a missing particle with non-zero mass, *e.g.* one can reconstruct $K^+ \to \pi^+\pi^-\pi^+$ with a missing π^-.
  - $m_{K,corr} = \sqrt{m_{vis}^2 + {p_\mathrm{T}}^2} + \sqrt{m_\pi^2 + {p_\mathrm{T}}^2}$
  - The width of the peak depends on the available phase space.

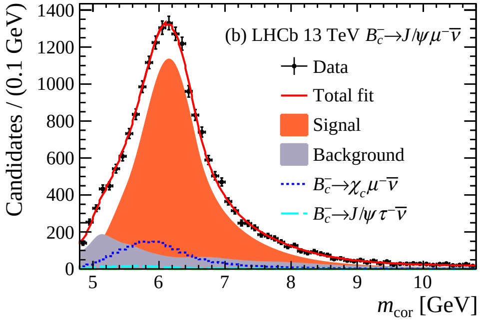
$\sigma(m_{corr})$

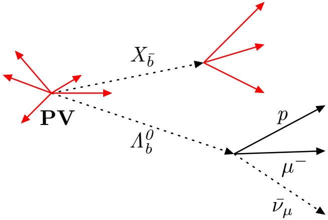




- Can calculate expected error of m_{corr} (have fun with Jacobians...)
  - As expected, error on secondary vertex dominates.
- And then cut on it.
- Improves separation between signal and background, but greatly reduces event yield.

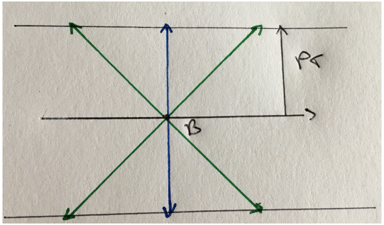
More resolutions

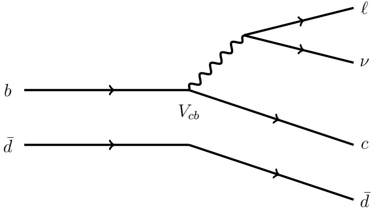




- As seen, there is a long tail to lower masses, bound by the available phase space.
- On top of that, there are resolution effects.
- Upper tail can be longer than lower tail, *e.g.* typically for B_c^+ decays.
- Main reason is the "precision of the lever arm" given by the precision of the secondary vertex.

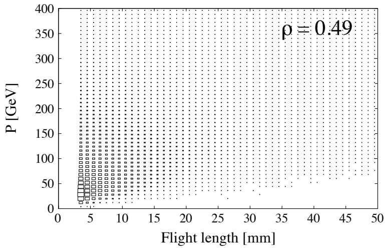
q^2 (I): How

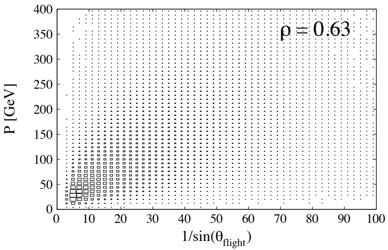




- The corrected mass was constructed by assuming $p_{\|,vis} = p_{\|,\nu}$, *i.e.* only one quantity was fixed.
- If we assume that the mother particle is a b hadron with the known mass, one can obtain $p_{\|,\nu}$
- And calculate q^2 = squared invariant mass of the dilepton system = squared invariant mass of the virtual W.
- Downside: The mass is a squared quantitiy, one obtains two solutions (and only one is correct).

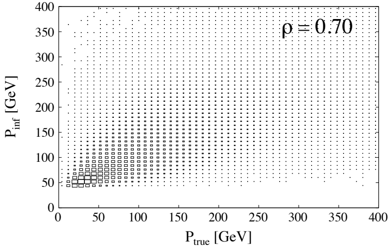
q^2 (II): Which solution to choose

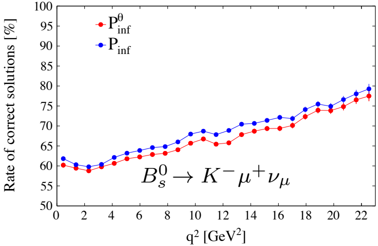




- Experimentally, one solution most often occurs more frequently than the other (due to acceptance of the subdetectors, selection cuts in the analysis, etc...). Can choose this one.
- Or: Try to get an independent measure of the B momentum, and compare with the two solutions: Pick the closer one.
- B momentum is correlated with flight length and angle wrt to beam axis.

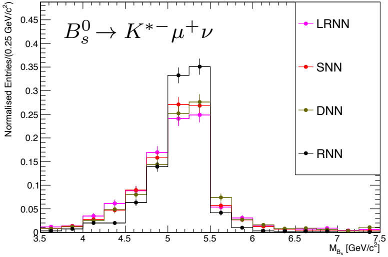
q^2 (III): Which solution to choose

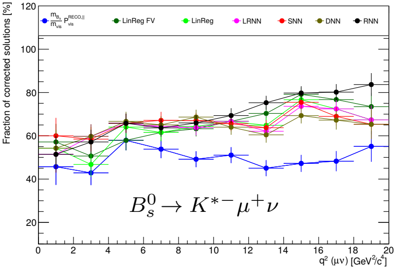


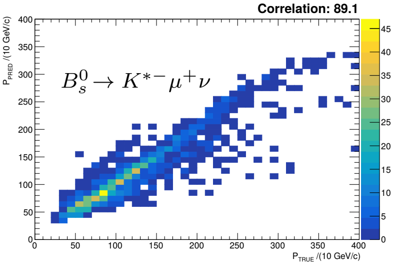


- Use a linear regression with flight length and angle wrt to beam axis to predict B momentum.
- Pick solution which is closer to predicted momentum: Significantly better than random choice.
- Depends on the decay in question.

q^2 (IV): Bring on DNNs!

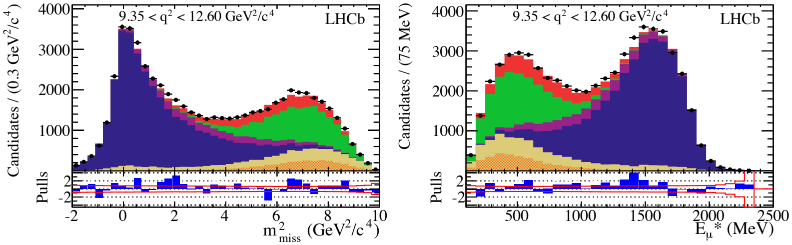






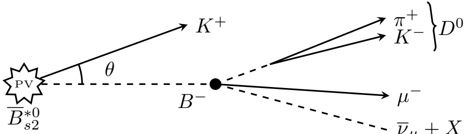
- Using DNNs and training on a specific decay channel performs a bit better.
- No magic bullet though

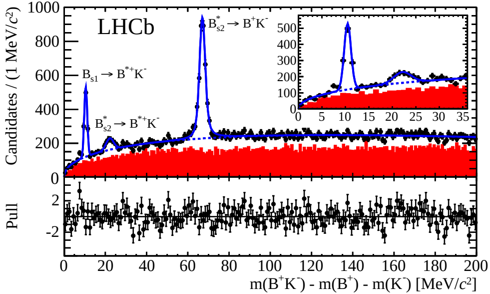
Other approaches: Collinear approximation



- One can use other discriminating variables than m_{corr}, *e.g.* m_{miss}^2
- Approximate the B momentum with $p_{z,B} = \frac{m_B}{m_{vis}} \cdot p_{z,vis}$
- $p_\nu = (p_B - p_{vis})$, *i.e.* m_{miss} is mass of neutrino.
- If only one neutrino missing: Signal peaks at 0, rest higher.
- Also energy of muon in B rest frame is discriminating.
- Note: m_{corr} and m_{miss}^2 are strongly correlated.

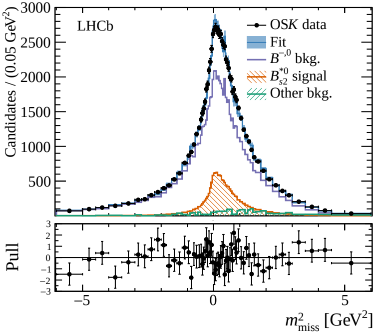
Other approaches: Using $B^*_{s2} \to B^+K^-$ (I)

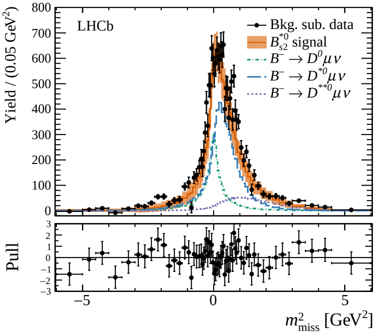




- Use the decay $B^*_{s2} \to B^+K^-$
- This adds another (narrow) resonance to the decay chain.
- Remember: only one component, $p_{\parallel,\nu}$ missing.
- Constrain to B^+ mass, fit in B^*_{s2} mass, or constrain to B^*_{s2} mass, calculate m^2_{miss} (=m^2_ν)

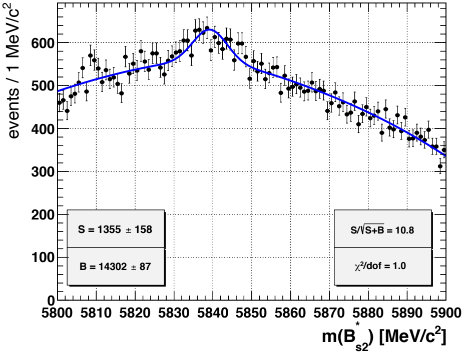
Other approaches: Using $B_{s2}^{*} \to B^{+}K^{-}$ (II)





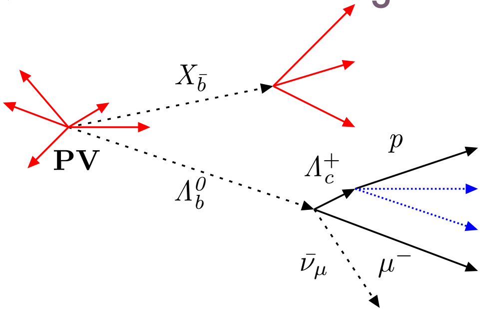
- Constrain to B_{s2}^{*}, calculate m_{miss}^{2}.
- Can be used to *e.g.* calculate $B \to D, D^{*}, D^{**}\mu\nu$ fraction.
- Can be useful for certain decays, but not applicable to all problems.
- Downside: Number of B^{+} reduced by about factor of 100 when requiring B_{s2}^{*} resonance.

Other approaches: Using $B_{s2}^{*} \to B^{+}K^{-}$ (III)



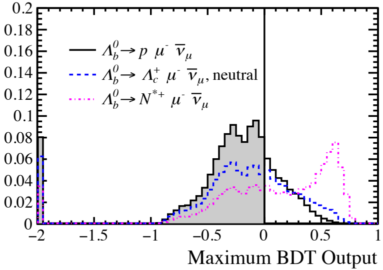
- Constrain to B^{+}, fit in B_{s2}^{*}
- Also works for *e.g.* $B^{+} \to \rho\mu^{+}\nu$, but very little signal yield.
- At some point using the corrected mass becomes more advantageous compared to using B_{s2}^{*}: Bigger signal yield compensates for broad signal distribution.

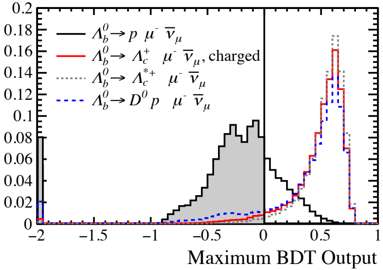
Vertex isolation: charged isolation



- When looking at Cabibbo-supressed semileptonic decays ($|V_{ub}|$), need to fight $|V_{cb}|$ background.
- Two handles: c hadron flies a few mm and decays (mostly) into more tracks than signal.
  - vertex - χ^2 is poor for $|V_{cb}|$ background
  - vertex-χ^2 increases only little by adding closest track.
- In reality: Use as much information as possible and construct a multivariate classifier

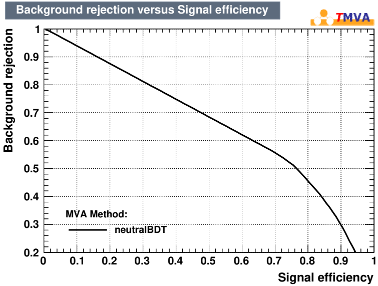
Vertex isolation: charged isolation





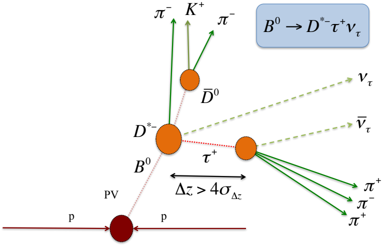
- Run over all tracks in the event which are ”close” to the $p\mu$ vertex, evaluate BDT for them.
- As expected performs better for channels with at least one more track than on channels with neutral particles.
- Different analyses use different techniques, but idea is always the same
- Charged vertex isolation usually most powerful (high-level) variable to extract signal in semileptonic decays.

Vertex isolation: neutral isolation



- Main problem with neutral particles: One does not know their point of origin *i.e.* PV or SV.
- Neutral isolation mostly much less powerful than charged one.
- But similar strategy as charged one: See if you find neutral objects in vicinity of signal decay.

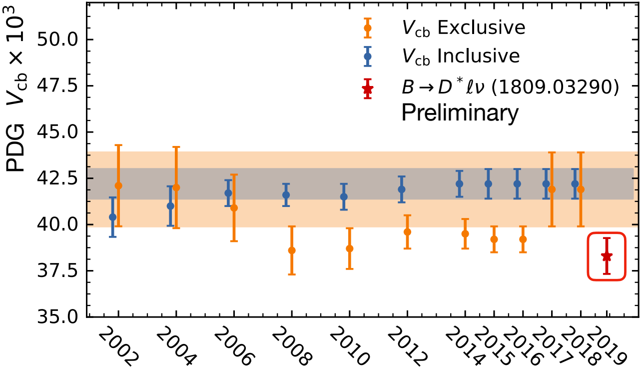
Vertex isolation: "τ isolation"



- With τ in the final state, can reconstruct them as $\tau^+ \to \pi^+\pi^-\pi^+\nu_\tau$.
- The 3 pions form a vertex which has to be displaced from other vertices.
- Depends strongly on the resolution of the τ vertex, as $c\tau \approx 87\ \mu\text{m}$

Some semileptonic measurements at LHCb

Measuring V_{cb}



Measuring V_{cb}

- How do you measure $|V_{cb}|$?
- $\mathcal{B}$ is proportional to $|V_{cb}|^2$, just count the events!
- Or almost...

Measuring V_{cb}

- Let's consider the decay of a pion: $\pi^+ \to \mu^+ \nu_\mu$
- $\Gamma(\pi^+ \to \mu^+ \nu_\mu) = \frac{G_F^2 |V_{ud}|^2 f_\pi^2}{8\pi} m_\pi m_\mu^2 \left(1 - \frac{m_\mu^2}{m_\pi^2}\right)^2$
- Helicity suppressed and non-fundamental parameter f_π (*i.e.* the decay constant).
- f_π takes into account that the pion is a composite object.

- Find a composite particle with b and c quarks: the B_c^+
- $\therefore$ Could measure $B_c^+ \to \mu^+ \nu$. Well, good luck...

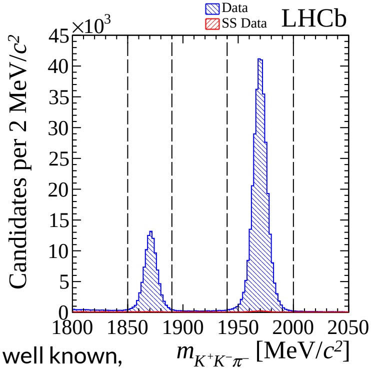
Measuring V_{cb}

- More promising: $B_s^0 \to D_s^{(*)+}\mu\nu$: no helicity suppression.
- $\frac{d\Gamma(B_s^0 \to D_s^+ \mu\nu)}{dw} = \frac{G_F^2 m_D^3}{48\pi^3}(m_B + m_D)^2 \eta_{EW}^2 |V_{cb}|^2 (w^2 - 1)^{3/2} |\mathcal{G}(w)|^2$
- With $w = \frac{m_B^2 + m_D^2 - q^2}{2 m_B m_D}$ and $\mathcal{G}$ a form-factor (only one assuming massless leptons).
- More complicated in case of D_s^{*+} compared to D_s^+ (= more form factors)

- That means: In order to measure $|V_{cb}|$, we need to know (or measure) the form factors.
- Important point: $|V_{cb}|$ does *not* depend on w, but $\mathcal{G}$ does.

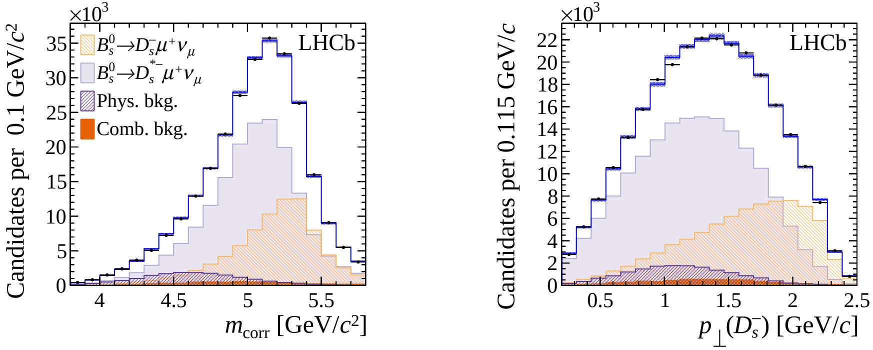
[Phys. Rev. D101 (2020) 072004]

Measuring V_{cb} using B_s^0 decays



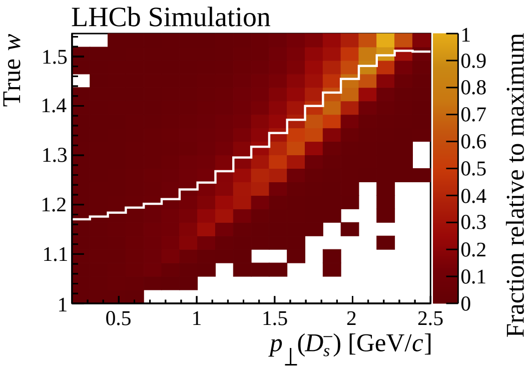
- $N_{B_s^0\to D_s^+\mu\nu} = \mathcal{L}\cdot\sigma_{b\bar{b}}\cdot 2\cdot f_s\cdot\mathcal{B}(B_s^0\to D_s^+\mu\nu)$
- Absolute branching fractions are hard to measure at LHCb: Luminosity $\mathcal{L}$ not well known, $b\bar{b}$ production cross section not well known, f_s not well known
- Perform relative measurement: $\frac{\mathcal{B}(B_s^0\to D_s^+\mu\nu)}{\mathcal{B}(B^0\to D^-\mu\nu)} = \frac{N_{B_s^0\to D_s^+\mu\nu}}{N_{B^0\to D^-\mu\nu}}\cdot R$
- R accounts for different efficiencies, etc.
- Use $D^-\to K^+K^-\pi^-$ and $D_s^-\to K^+K^-\pi^-$: Signal and normalization channel have identical final state, many uncertainties cancel in ratio.

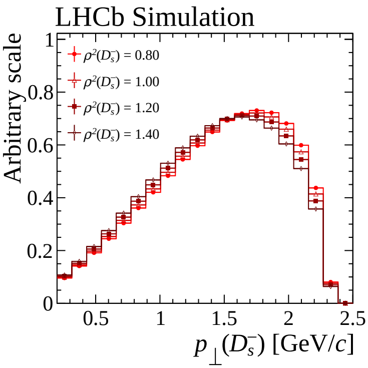
Measuring V_{cb} using B_s^0 decays



- Given that these are $|V_{cb}|$ decays, the sample is dominated by signal events.
- $D_s^{*+} \to D_s^+ \gamma$ or $D_s^{*+} \to D_s^+ \pi^0$: Neutral objects with low $p_{\rm T}$ are hard to reconstruct, so only D_s^+ is measured, and excited states are separated in m_{corr}.
- But why not measure q^2 to obtain w?

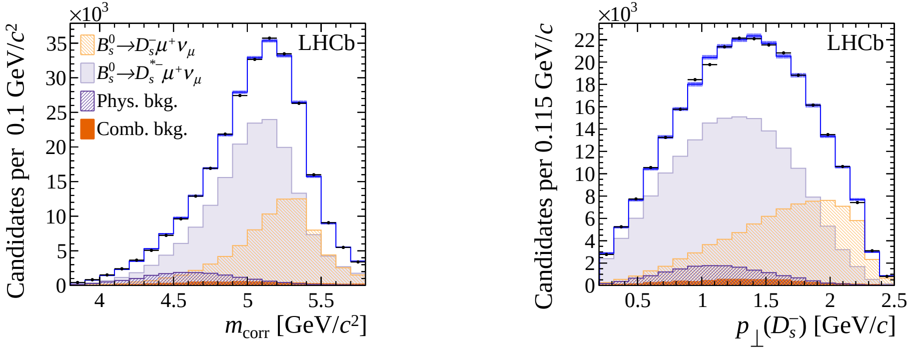
Measuring V_{cb} using B_s^0 decays





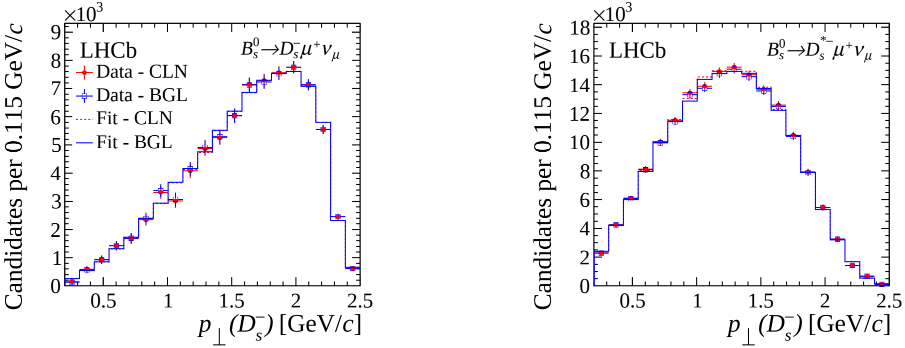
- As seen before, q^2 can only be computed up to a two-fold solution.
- But q^2 is correlated with the p_{T} of the D_s^+ wrt to the B_s^0 flight direction.
- Use this correlation to determine form factor parameters.

Measuring V_{cb} using B_s^0 decays



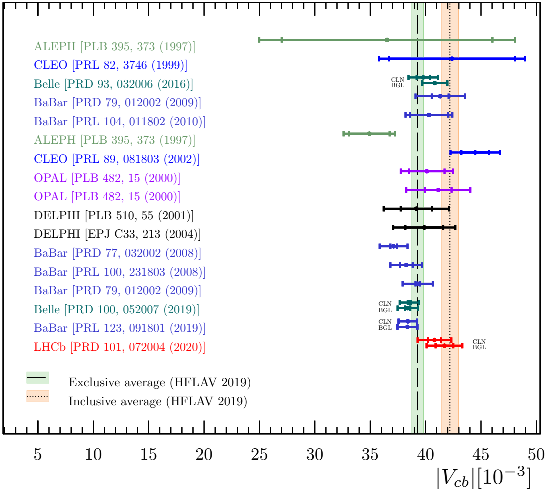
- Need to measure the amount of signal events to determine $|V_{cb}|$.
- Fit the two variables with templates: Histograms from MC that can be scaled up or down until the overall shape fits.
- Take limited number of simulated events into account by allowing for fluctuations in each bin.

Measuring V_{cb} using B_s^0 decays

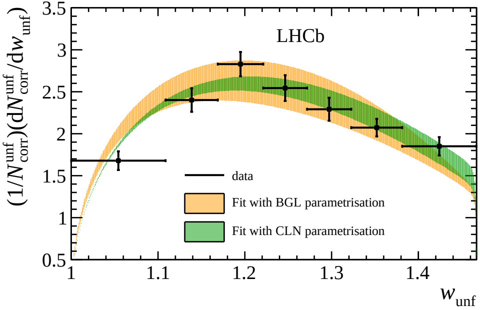


- Several form factor parametrizations exist.
- "Famous" ones: BGL and CLN. Can fit for both parameter sets and extract $|V_{cb}|$ with one or the other.
- Results are fully consistent.

Measuring V_{cb} using B_s^0 decays

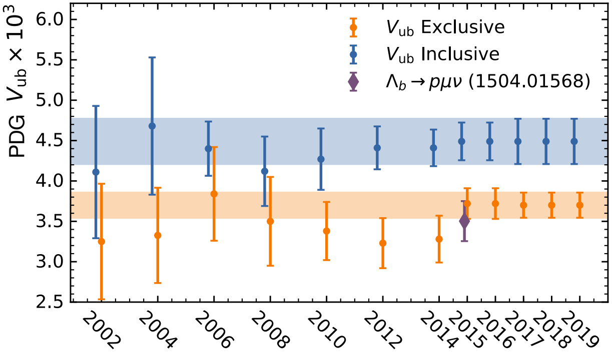


Some comments to $|V_{cb}|$ at LHCb

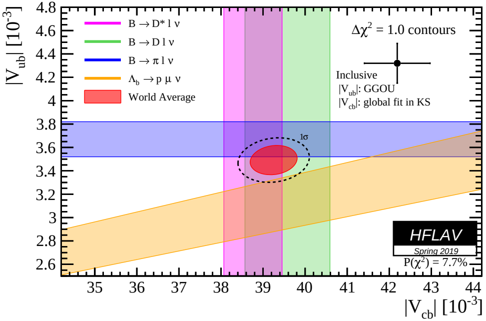


- LHCb was not built to measure $|V_{cb}|$, but achieves a good precision still.
- Always need to rely on precision of normalisation channel (*i.e.* an external measurement). For this measurement also rely on f_s/f_d.
- LHCb also measured shape of differential decay rate of $B_s^0 \to D_s^{*+}\mu^-\nu$ by fully reconstructing $D_s^{*+} \to D_s^+\mu^-$ (without measuring $|V_{cb}|$)
- No inclusive measurement of $|V_{cb}|$ so far at LHCb, but investigations using a sum-of-exclusive approach with B_s^0 decays are ongoing.

Measuring V_{ub}



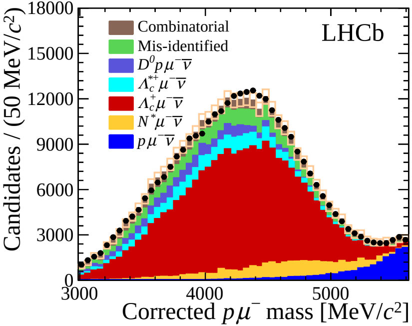
Measuring V_{ub}



- Much more background: $|V_{cb}| \gg |V_{ub}|$
  - Use isolation techniques / machine learning.
- Hadronic system has lower mass (*e.g.* mass of ρ^0 vs mass of D^0), mostly coming with more background.
- Less events: Have not (yet) determined form factors and $|V_{ub}|$ at the same time.
  - Use theoretical predictions for the form factors

[Nature Physics 11 (2015) 743]

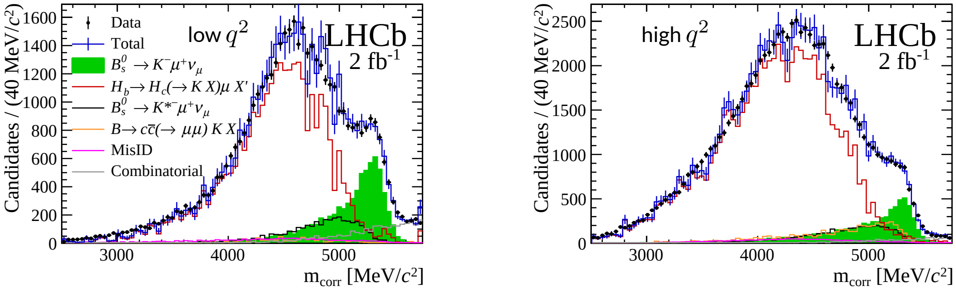
Measuring V_{ub} using Λ_b^0 baryons



- Measure $\frac{|V_{ub}|}{|V_{cb}|} = R_{FF} \cdot \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu^- \overline{\nu}_\mu)}$
- Protons as final states are less abundant than kaons or pions (easier to separate from background).
- Use the corrected mass. Unfortunately not very clean, but not the dominant uncertainty.
- Model all backgrounds with templates: Large contribution from Λ_c^+ decays.
- Normalization to Λ_c^+ decay reduces systematic uncertainties and dependence on $f_{\Lambda_b^0}$.
- First measurement of the decay $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$, about 15'000 events.

[Phys. Rev. Let. 126, 081804]

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

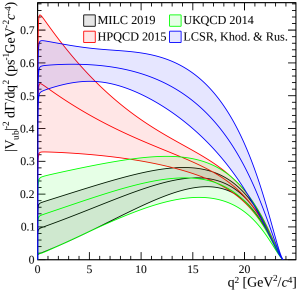


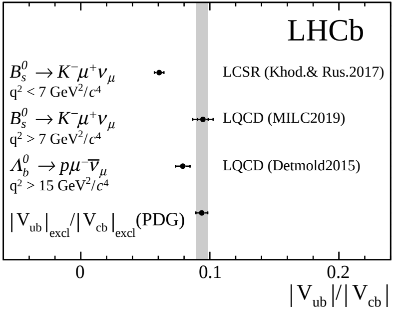
- Use $B_s^0 \to K^- \mu^+ \nu_\mu$ decays to measure $|V_{ub}|$: First observation of $B_s^0 \to K^- \mu^+ \nu_\mu$.
- Measure $\frac{|V_{ub}|}{|V_{cb}|} = R_{FF} \cdot \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^+ \mu \nu)}$, use m_{corr} to discriminate signal and background.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

R_{FF}: form factor ratio

[Phys. Rev. Let. 126, 081804]

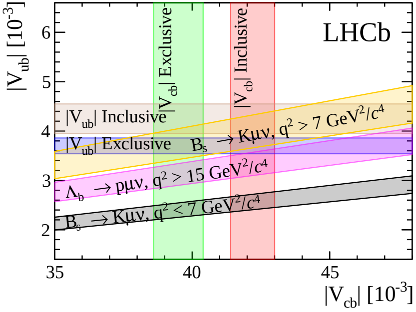
Exclusive $|V_{ub}|$ using B_s^0 mesons





- 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.

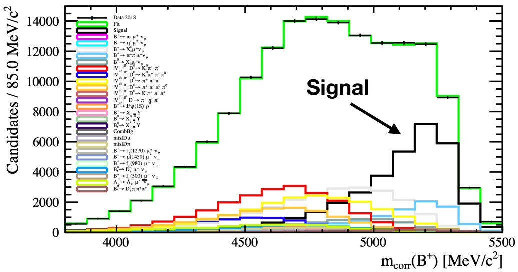
Exclusive $|V_{ub}|$ using B_s^0 mesons

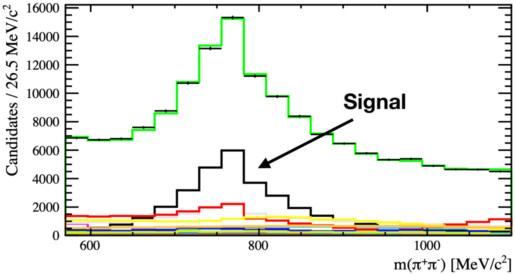


Uncertainty	All q^2	low q^2	high q^2
Tracking	2.0	2.0	2.0
Trigger	1.4	1.2	1.6
Particle identification	1.0	1.0	1.0
$\sigma(m_{corr})$	0.5	0.5	0.5
Isolation	0.2	0.2	0.2
Charged BDT	0.6	0.6	0.6
Neutral BDT	1.1	1.1	1.1
q^2 migration	–	2.0	2.0
Efficiency	1.2	1.6	1.6
Fit template	$^{+2.3}_{-2.9}$	$^{+1.8}_{-2.4}$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

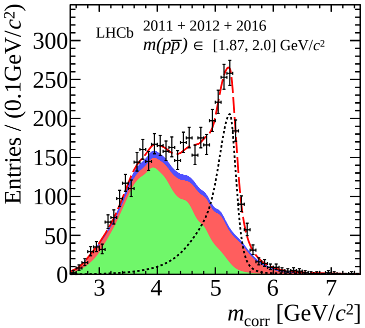
$B^0 \to \rho^0 \mu \nu$





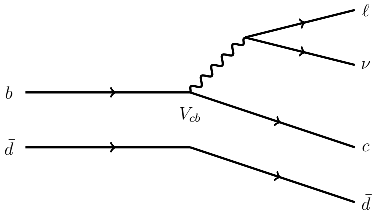
- Broad vector meson in final state, more difficult to describe theoretically an experimentally.
- Simulate many different templates to describe the background ($b \to c, b \to u$) and signal ($B^0 \to \rho^0 \mu\nu, B^0 \to f_2(1270)\mu\nu$, ..., with $\rho^0, f_2(1270), \ldots \to \pi^+\pi^-$) processes.
- Can not just measure $|V_{ub}|$, but probe structure of V-A current.

Some comments to $|V_{ub}|$ at LHCb



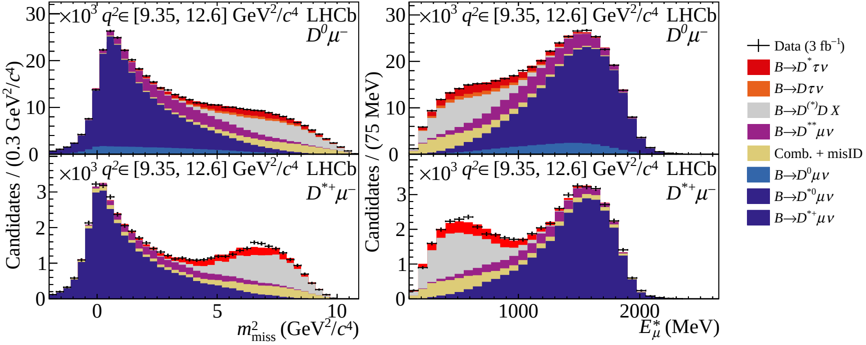
- LHCb was not built to measure $|V_{ub}|$, but achieves a good precision still.
- Much more background than for $|V_{cb}|$, partly compensated by machine learning and very large number of b hadrons produced at LHCb.
- Differential measurements on the way.
- Inclusive $|V_{ub}|$ very hard at LHCb (but who knows if we can do it ☺)

Lepton Flavour Universality (LFU) in $\overline{B}^0 \rightarrow D^* \ell \nu$



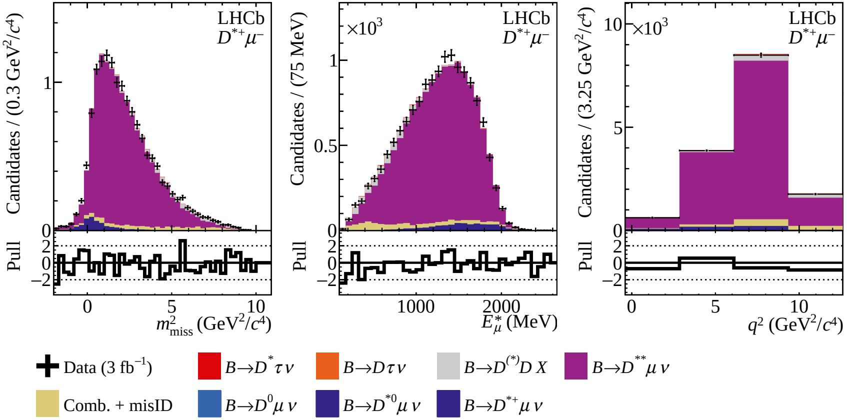
- Measure lepton flavour universality in charged-current (tree) decays.
- Measure $R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \rightarrow D^{*+} \tau^- \nu)}{\mathcal{B}(\overline{B}^0 \rightarrow D^{*+} \mu^- \nu)}$
- Can also measure $R(D^0)$, $R(D_s^+)$, $R(\Lambda_c^+)$, ... with muons and taus.
- Or with muons and electrons (no measurement published by LHCb so far)
- Original motivation was sensitivity for a charged Higgs.
- Now missing (at least) 2 neutrinos in the final state.

LFU in $\overline{B}^0 \to D^*\ell\nu$, muonic mode



- Use $\tau^- \to \mu^-\nu\nu$, *i.e.* τ and μ modes have the same final state.
  - Distinguish with kinematical distributions
- Measure $R(D^*)$ and $R(D^0)$ simultaneously:
  - $R(D^*)$ with $D^{*+}\,\tau^-$, $D^{*+} \to D^0\pi^+$
  - $R(D^*)$ and $R(D^0)$ with $D^0\,\tau^-$ with $D^{*+} \to D^0\pi^+$, $D^{*0} \to D^0\pi^0/\gamma$ and just D^0

LFU in $\overline{B}^0 \to D^* \ell \nu$, muonic mode



- Higher excited states of D meson: $\overline{B}^0 \to D^{**} \ell \nu$ not well known.
- Use control sample where one additional pion is added to $D^{*+}\, \tau^-$ and $D^0\, \tau^-$

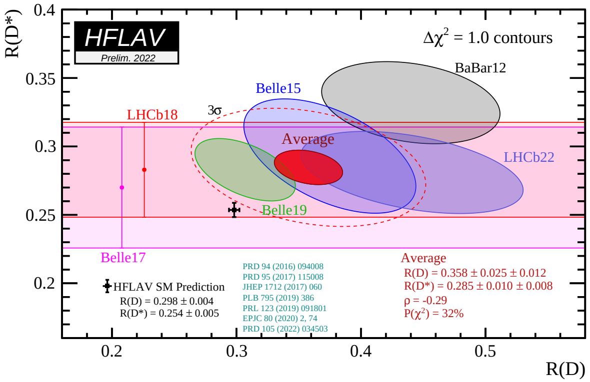
[arxiv:2302.02886]

LFU in $\overline{B}^0 \to D^* \ell \nu$, muonic mode

- Very challenging measurement (at LHCb):
- Soft muons prone to misidentification
- Form-factor uncertainties of $\overline{B}^0 \to D^{*+} \ell \nu$.
- Knowledge on $B \to D^{(*)} D X$ templates.
- Very large simulated samples needed (billions of events).
- etc...

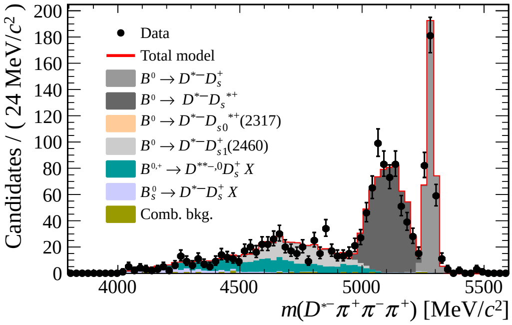
Internal fit uncertainties	$\sigma_{\mathcal{R}(D^*)} (\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)} (\times 10^{-2})$	**Correlation**
Statistical uncertainty	1.8	6.0	-0.49
Simulated sample size	1.5	4.5	
$B \to D^{(*)} D X$ template shape	0.8	3.2	
$\overline{B} \to D^{(*)} \ell^- \overline{\nu}_\ell$ form-factors	0.7	2.1	
$\overline{B} \to D^{**} \mu^- \overline{\nu}_\mu$ form-factors	0.8	1.2	
$\mathcal{B}\ (\overline{B} \to D^* D_s^- (\to \tau^- \overline{\nu}_\tau) X\ )$	0.3	1.2	
MisID template	0.1	0.8	
$\mathcal{B}\ (\overline{B} \to D^{**} \tau^- \overline{\nu}_\tau\ )$	0.5	0.5	
Combinatorial	< 0.1	0.1	
Resolution	< 0.1	0.1	
Additional model uncertainty	$\sigma_{\mathcal{R}(D^*)} (\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)} (\times 10^{-2})$	
$B \to D^{(*)} D X$ model uncertainty	0.6	0.7	
$\overline{B}_s^0 \to D_s^{**} \mu^- \overline{\nu}_\mu$ model uncertainty	0.6	2.4	
Data/simulation corrections	0.4	0.8	
Coulomb correction to $\mathcal{R}(D^{*+})/\mathcal{R}(D^{*0})$	0.2	0.3	
MisID template unfolding	0.7	1.2	
Baryonic backgrounds	0.7	1.2	
Normalization uncertainties	$\sigma_{\mathcal{R}(D^*)} (\times 10^{-2})$	$\sigma_{\mathcal{R}(D^0)} (\times 10^{-2})$	
Data/simulation corrections	$0.4 \times \mathcal{R}(D^*)$	$0.6 \times \mathcal{R}(D^0)$	
$\tau^- \to \mu^- \nu \overline{\nu}$ branching fraction	$0.2 \times \mathcal{R}(D^*)$	$0.2 \times \mathcal{R}(D^0)$	
Total systematic uncertainty	2.4	6.6	-0.39
Total uncertainty	3.0	8.9	-0.43

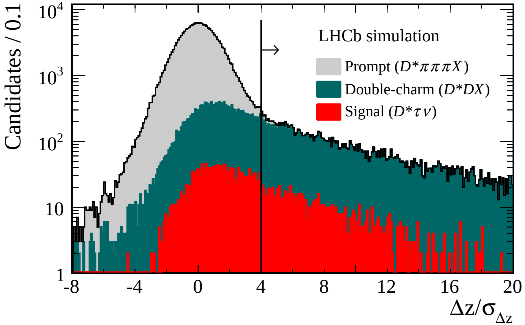
LFU in $\overline{B}^0 \to D^* \ell \nu$, muonic mode



- $R(D^*) = 0.281 \pm 0.018 \pm 0.024$
- $R(D^0) = 0.441 \pm 0.060 \pm 0.066$
- $\rho = -0.43$ (correlation)

LFU in $\overline{B}^0 \to D^{*+}\ell\nu$, 3-prong mode

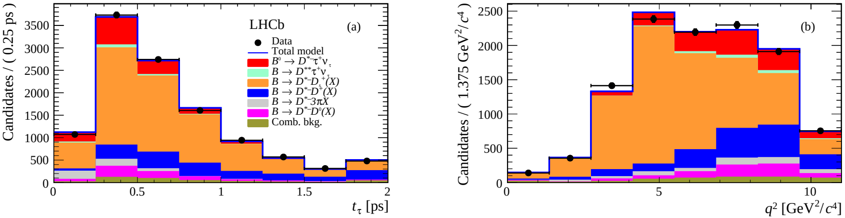




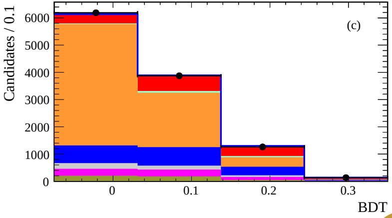
- Use $\tau^- \to \pi^-\pi^+\pi^-\nu$. 3 pions form a vertex that can be used for displacement.
- Use $\overline{B}^0 \to D^{*+}3\pi$ as normalisation channel, and known ratio $\mathcal{B}(\overline{B}^0 \to D^{*+}3\pi)/\mathcal{B}(\overline{B}^0 \to D^{*+}\mu\nu)$ to calculate R_{D^*}
- Despite measuring the same physics, different challenges: Large background from $B \to D^{*-}D_s^+X$ decays, with $D_s^+ \to \pi^+\pi^-\pi^+X$

[Phys Rev D 97 072013]

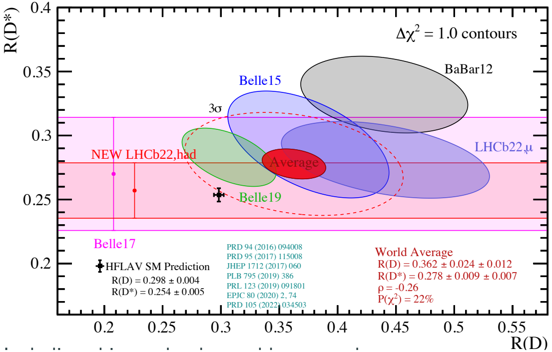
LFU in $\overline{B}^0 \to D^{*+}\ell\nu$, 3-prong mode

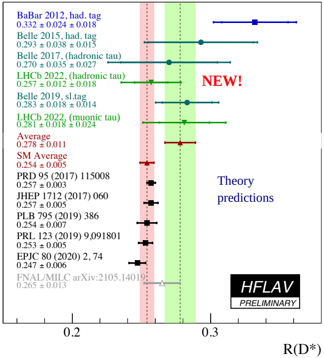


- Fit in τ decay time, q^2 and a BDT variable.
- Obtain about 1300 $\overline{B}^0 \to D^{*+}\tau^-\nu$ events
- New result with 2015 - 2016 data shown last week (with very similar strategy), about 2x as many signal events.



LFU in $\overline{B}^0 \to D^{*+}\ell\nu$, 3-prong mode

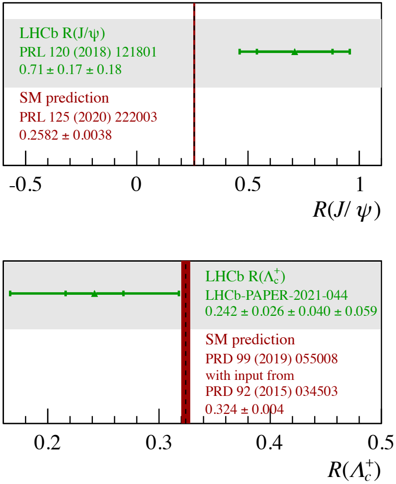




- $\overline{B}^0 \to D^{*+}\ell\nu$ with hadronic τ decays perfectly consistent with SM prediction.
- Precision from LHCb starting to match precision of B factories.

[PRL 128 191803]

LFU in $B_c^+ \to J/\psi\,\ell\nu$ and $\Lambda_b^0 \to \Lambda_c^+\ell\nu$



Conclusions

- Semileptonic decays are a great tool to probe the fundamental structure and parameters of the SM, with controlled theoretical uncertainties.
- Main experimental challenge with semileptonic decays (in LHCb) is the missing neutrino. Have developed ways to mitigate this in the last ~ 10 years.
- Many exciting results published, and more to come.

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