Recent results on $R(D^*)$ and $|V_{ub}|$ using semileptonic decays at LHCb.

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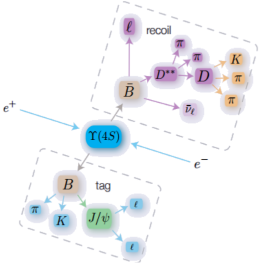
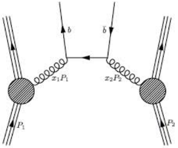
The challenge of studying semileptonic B decays at LHCb

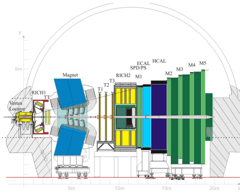
Missing neutrinos $\Rightarrow$ partial reconstruction

- At the e^+e^- B factories:
  - interacting e^+e^- energies known.
  - hermetic detector $\Rightarrow$ tag other B
  - access to missing mass variables

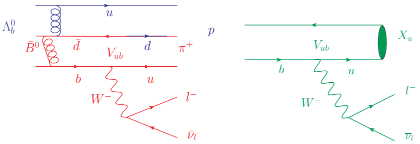


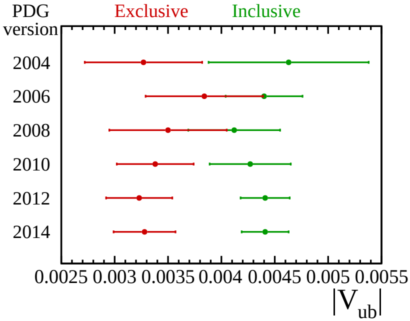
- At LHCb:
  - interacting parton energies unkown
  - B hadron fractions unkown
  - forward acceptance
  - can access the B flight direction



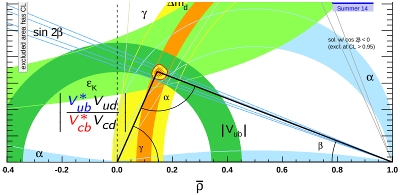


The $|V_{ub}|$ puzzle





- Longstanding discrepancy between exclusive and inclusive $|V_{ub}|$.
- $|V_{ub}|/|V_{cb}|$ constrains the length of the unitarity triangle opposite the angle β.



$|\mathrm{V}_{\mathrm{ub}}|$ from $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays

- Normalise $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ to $\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu$ in the high q^2 $(= m^2_{\mu\nu})$ region where theory uncertainty is lowest:

$$R_{theory}(|\mathrm{V}_{\mathrm{ub}}|^2/|\mathrm{V}_{\mathrm{cb}}|^2) = \frac{N(\Lambda_b \to p\mu^-\overline{\nu}_\mu)}{N(\Lambda_b \to (\Lambda_c \to pK\pi)\mu^-\overline{\nu}_\mu)} \times \frac{\mathcal{B}(\Lambda_c \to pK\pi)}{\epsilon_{rel}}$$

- 2012 Dataset ($\sim$ 2fb^{-1})
- Relative efficiency $\epsilon_{rel} = 3.52 \pm 0.20$ determined from simulation.
- Branching fraction $\mathcal{B}(\Lambda_c \to pK\pi)$ from Belle PRL 113, 042002 (2014)

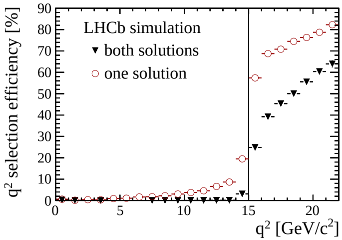
$$R_{theory} = \frac{\int_{15\,\mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{7\,\mathrm{GeV}^2/c^4}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{cb}|^2 dq^2} = 1.471 \pm 0.095(stat) \pm 0.109(syst)$$

W. Detmold, C. Lehner and S. Meinel [Phys.Rev. D92 (2015) 3, 034503]

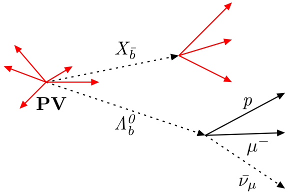
See next talk by Stefan Meinel.

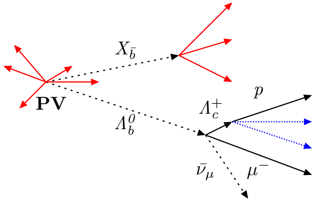
Selection

- Reconstruct q^2 up to a 2-fold ambiguity.
- Require both solutions $> q^2_{cut}$.



- Boosted decision tree removes backgrounds with additional charged tracks that could vertex with $p\mu$ candidate.



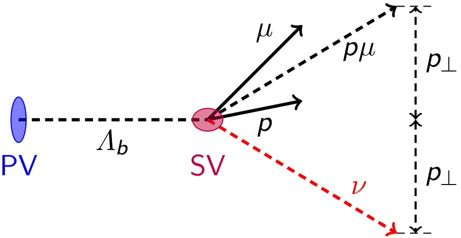


The corrected mass

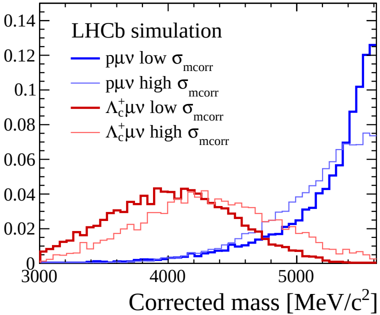
- Fit the corrected mass:

$$M_{corr} = \sqrt{p_\perp^2 + M_{p\mu}^2} + p_\perp$$

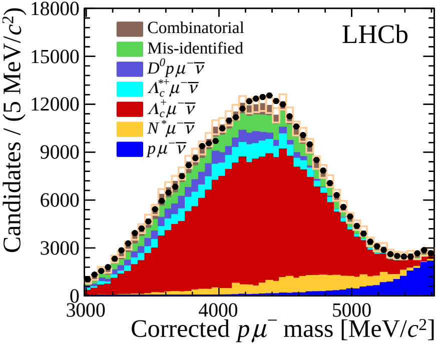
- Determine its uncertainty.
- Reject candidates if: $\sigma_{M_{corr}} > 100\,\mathrm{MeV}/c^2$

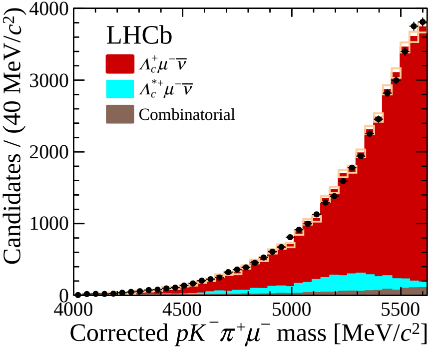


- Compare simulated signal and background shapes for low and high $\sigma_{M_{corr}}$
- Truncation at m_{Λ_b} due to q^2 cut.



Signal and normalisation fits

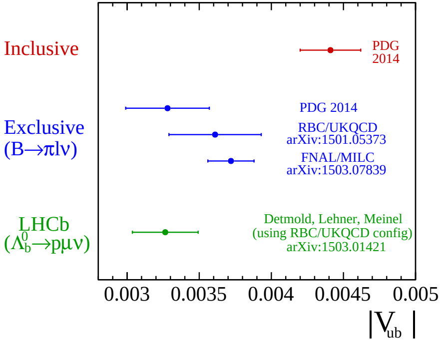


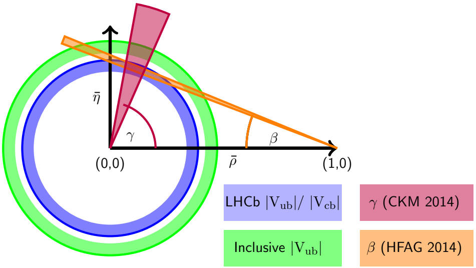


- $N(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = 17687 \pm 733$ Nature Physics 11, 743-747 (2015)
- $N(\Lambda_b \to (\Lambda_c \to pK\pi)\mu^-\overline{\nu}_\mu) = 34255 \pm 571.$
- First observation of $\Lambda_b \to p\mu^-\overline{\nu}_\mu$ decays:
  $\mathcal{B}(\Lambda_b \to p\mu^-\overline{\nu}_\mu) = (4.1 \pm 1.0) \times 10^{-4}.$

The first $|V_{ub}|$ determination from a hadron collider

$$|V_{ub}| = (3.27 \pm 0.15(exp) \pm 0.16(theory) \pm 0.06(|\mathrm{V_{cb}}|)) \times 10^{-3}$$



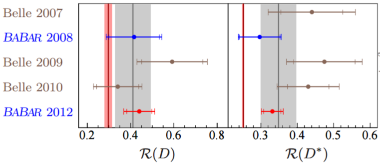


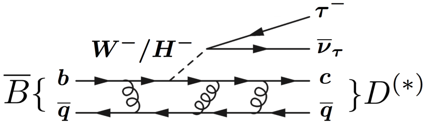
Nature Physics 11, 743-747 (2015)

The $R(D^*)$ Anomaly

- The Standard Model exhibits lepton universality.
  - electoweak couplings are equivalent for the three flavours.
  - amplitudes for processes with e, μ, τ identical up to effects depending on lepton mass.
- A violation of this is a clear sign of new physics.
- The massive τ gives sensistivity to a charged higgs contribution.

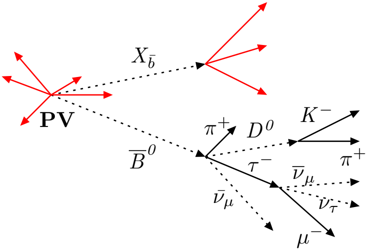
$$R(D^*) = \frac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)} = 0.252 \pm 0.003$$



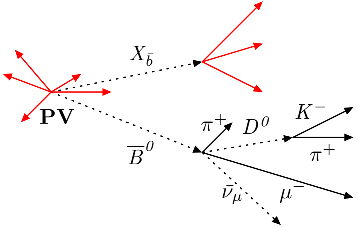


$R(D^*)$ selection

Signal ($B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$)

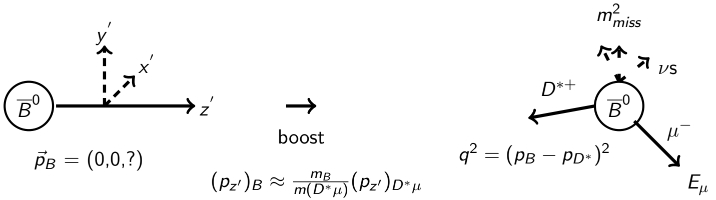


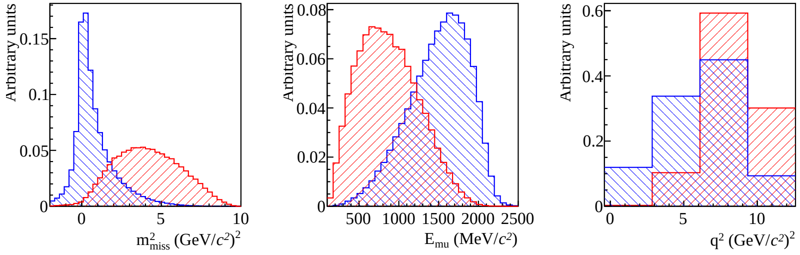
Normalisation ($B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$)



- Take $\tau^- \to \mu^-\nu_\tau\bar{\nu}_\mu$.
- Reconstruct $D^{*+} \to \pi^+(D^0 \to K^-\pi^+)$
- Boosted decision tree removes backgrounds with additional charged tracks originating from the $D^*\mu$ vertex.

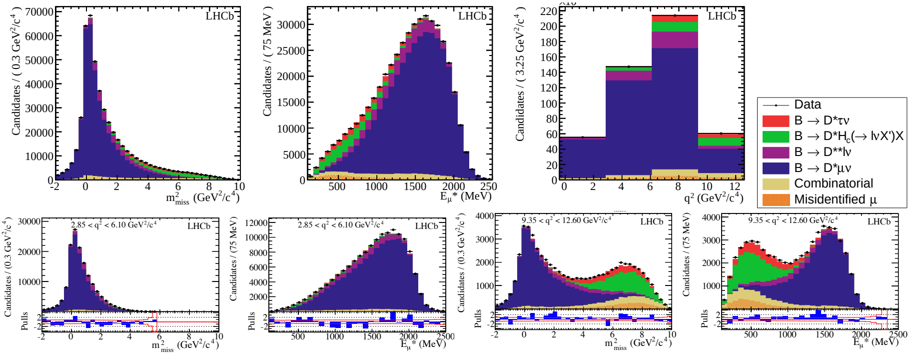
Finding an approximate B rest frame





$B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ $\quad$ $B^0 \to D^{*+}\mu^-\overline{\nu}_\mu$

$R(D^*)$ fit

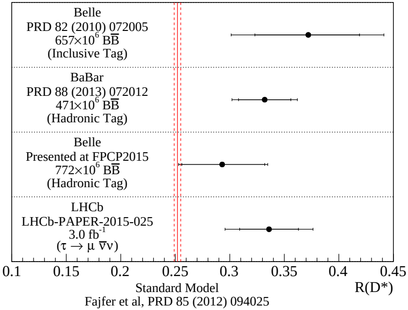


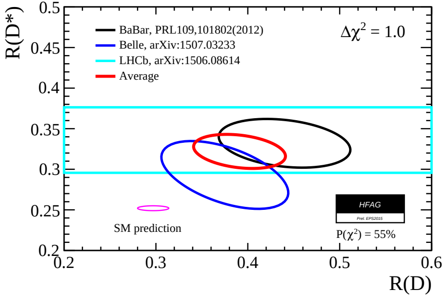
- Three dimensional fit to m^2_{miss}, q^2 and E_μ.
- $B^0 \to D^{*+}\tau^-\overline{\nu}_\tau$ contribution most prominent at high q^2.
- Control various backgrounds using control samples in data.

The first $R(D^*)$ from a hadron collider

$$R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$$

PRL 115, 111803 (2015)





- Combining results for $R(D^*)$ from Belle, BaBar and LHCb gives a 3.9σ discrepancy with the Standard Model.

Conclusion

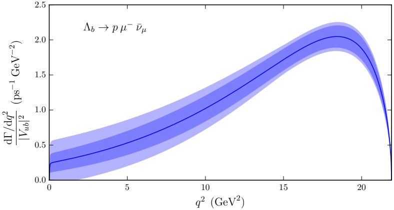
LHCb has peformed two measurements using semileptonic decays which were unexpected from a hadron collider:

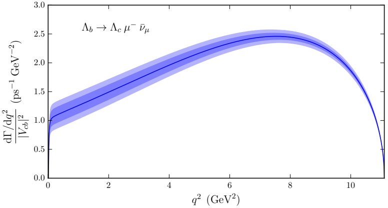
- $|V_{ub}| = (3.27 \pm 0.23) \times 10^{-3}$.
  This measurement is 3.5σ below the inclusive measurement but agrees well with current exclusive average using $B \to \pi l \nu$ decays.
- $R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$
  Together with measurements from the B factories this may be an exciting hint of lepton flavour universality violation and hence new physics.

Theory ratio

- Use the latest Lattice QCD results for these decays to calculate:

$$R_{theory} = \frac{\int_{15\ \mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{7\ \mathrm{GeV}^2/c^4}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c\mu^-\overline{\nu}_\mu)}{dq^2} / |V_{cb}|^2 dq^2}$$





$$R_{theory} = 1.471 \pm 0.095(stat) \pm 0.106(syst)$$

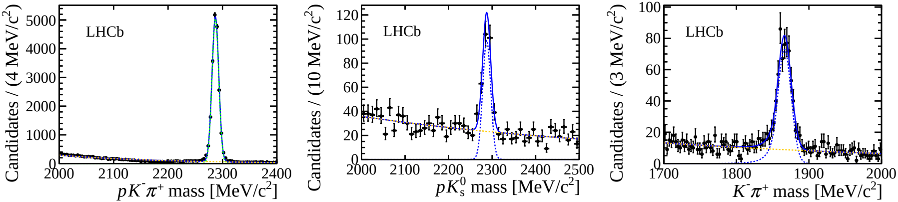
W. Detmold, C. Lehner and S. Meinel [Phys.Rev. D92 (2015) 3, 034503]

Systematic uncertainties for $|V_{ub}|$

Source	Relative uncertainty (%)
$\mathcal{B}(\Lambda_c \to pK^+\pi^-)$	$^{+4.7}_{-5.3}$
Trigger	3.2
Tracking	3.0
Λ_c selection efficiency	3.0
N^* shapes	2.3
Λ_b lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b production	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

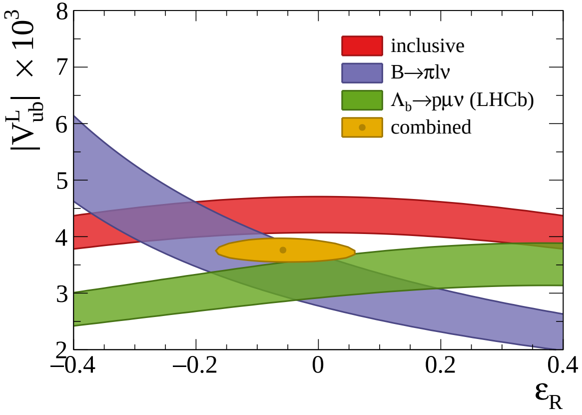
Background reconstruction for $|V_{ub}|$

- Constrain background from $\Lambda_b \to \Lambda_c \mu^- \overline{\nu}_\mu$ and $\Lambda_b^0 \to D^0 p \mu^- \overline{\nu}_\mu$ decays by reconstructing $\Lambda_c^+ \to pK^-\pi^+$, $\Lambda_c^+ \to pK_s^0$ and $D^0 \to K^-\pi^+$.



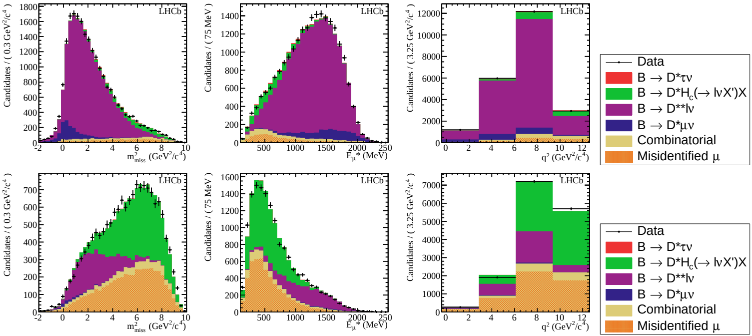
Can new physics explain the puzzle?

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}} V^L_{ub}(\bar{u}\gamma_\mu P_L b + \epsilon_R \bar{u}\gamma_\mu P_R b)(\bar{\nu}\gamma^\mu P_L l) + h.c.$$



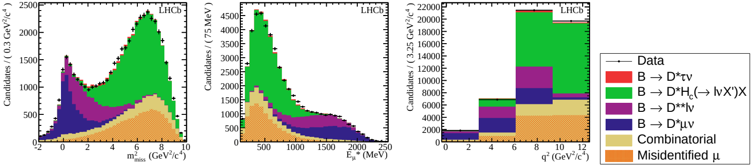
Fits to control samples for $R(D^*)$

- Invert boosted decision tree requirement to select control regions enriched in particular backgrounds.
- Samples selecting $D^{*+}\mu^-\pi^-$ and $D^{*+}\mu^-\pi^-\pi^+$ to control background from $B \to D^{**}\mu\nu$:



Fits to control samples for $R(D^*)$

- Sample selecting $D^{*+}\mu^- K^{+/-}$ to control background from $B \to D^*(H_c \to Kl\nu X')X$:



Systematic uncertainties for $R(D^*)$

TABLE I. Systematic uncertainties in the extraction of $\mathcal{R}(D^*)$.

Model uncertainties	Absolute size ($\times 10^{-2}$)
Simulated sample size	2.0
Misidentified μ template shape	1.6
$\bar{B}^0 \to D^{*+}(\tau^-/\mu^-)\bar{\nu}$ form factors	0.6
$\bar{B} \to D^{*+}H_c(\to \mu\nu X')X$ shape corrections	0.5
$\mathcal{B}(\bar{B} \to D^{**}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{**}\mu^-\bar{\nu}_\mu)$	0.5
$\bar{B} \to D^{**}(\to D^*\pi\pi)\mu\nu$ shape corrections	0.4
Corrections to simulation	0.4
Combinatorial background shape	0.3
$\bar{B} \to D^{**}(\to D^{*+}\pi)\mu^-\bar{\nu}_\mu$ form factors	0.3
$\bar{B} \to D^{*+}(D_s \to \tau\nu)X$ fraction	0.1
Total model uncertainty	**2.8**
Normalization uncertainties	**Absolute size ($\times 10^{-2}$)**
Simulated sample size	0.6
Hardware trigger efficiency	0.6
Particle identification efficiencies	0.3
Form factors	0.2
$\mathcal{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)$	< 0.1
Total normalization uncertainty	**0.9**
Total systematic uncertainty	**3.0**

PRL 115, 111803 (2015)