# $V_{ub}$ measurements at LHCb

**Marta Calvi**

Università di Milano Bicocca and INFN, Milano

on behalf of the LHCb Collaboration

***Challenges in Semileptonic B Decays*. Mitp, Mainz 9-13 April 2018**

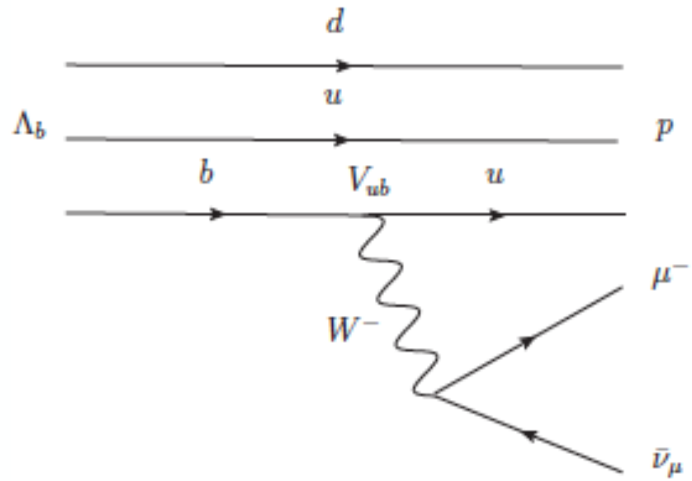
# Outline

- $V_{ub}$ from $\Lambda_b \to p\mu^- \nu$
- $V_{ub}$ from $B_s \to K^+\mu^- \nu$
- $V_{ub}$ from other modes
- Conclusion

# First b→u at LHCb

Nature Physics 10 (2015) 1038

- Approximately 10% of b-hadrons produced at LHC are $\Lambda_b$ .
- Access b→u from $\Lambda_b \to p\mu\nu$.
- First $V_{ub}$ measurement at an hadron collider and first with a baryon.
  - Use 2 $fb^{-1}$ Run1 data (8TeV).



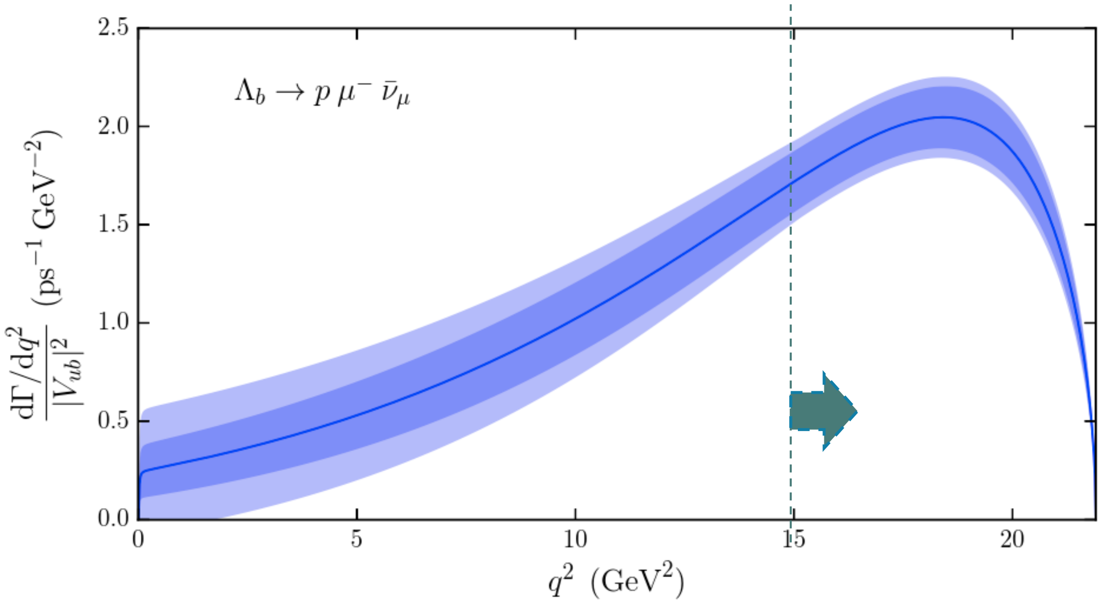

- Normalize to $\Lambda_b \to \Lambda_c \mu\nu$ ($\Lambda_c \to p K \pi$) to cancel experimental uncertainties, including production fraction of $\Lambda_b$ baryons.

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)} R_{FF}$$

$R_{FF}$ = ratio of form factors

# $\Lambda_b \rightarrow p$ Form Factors

- Use LQCD calculation from W. Detmold, C. Lehner, and S. Meinel, *Phys. Rev. D 92, 034503 (2015),arXiv:1503.011421*
- LQCD most accurate at high $q^2$.
- Cut at $q^2 > 15$ (7) GeV$^2$ most appropriate for $\Lambda_b \rightarrow p\mu\nu$ ($\Lambda_b \rightarrow \Lambda_c \mu\nu$ ). Small migration of events from lower reconstructed $q^2$ .
- Theory uncertainty on $|V_{ub}/V_{cb}|$ in that region is 4.9%



# $\Lambda_b \rightarrow p\mu\nu$ at LHCb

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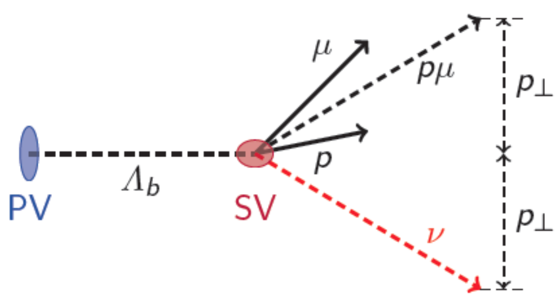
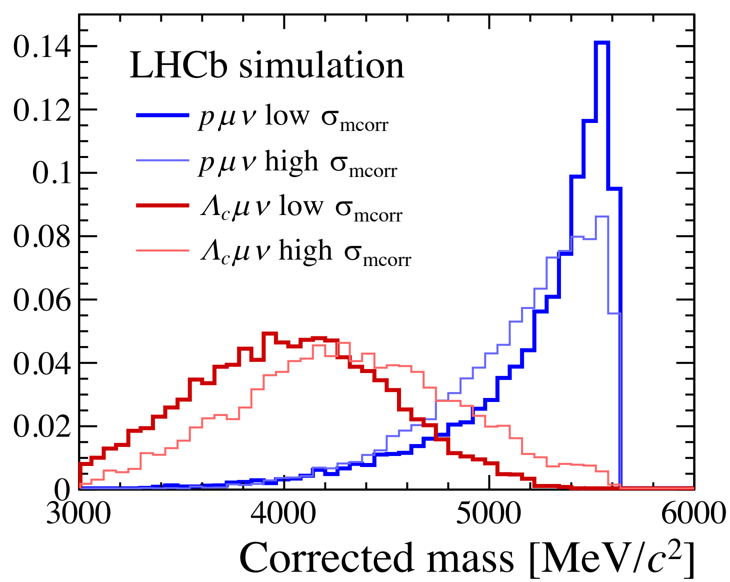
- Signal identification imposing strong proton identification requirements and topological constraints.
- $q^2$ determined using $\Lambda_b$ flight direction and $\Lambda_b$ mass, with two-fold ambiguity. Both solutions required to be above minimum $q^2$.
- Signal yields determined from $\chi^2$ fit to $m_{corr}$ distributions of $\Lambda_b \rightarrow p\mu\nu$ and $\Lambda_b \rightarrow \Lambda_c\mu\nu$ candidates.

$$m_{\mathrm{corr}} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$$




- $p_\perp$ is the $h\mu$ momentum transverse to the $\Lambda_b$ flight direction.

# $\Lambda_b \to p\mu\nu$ at LHCb

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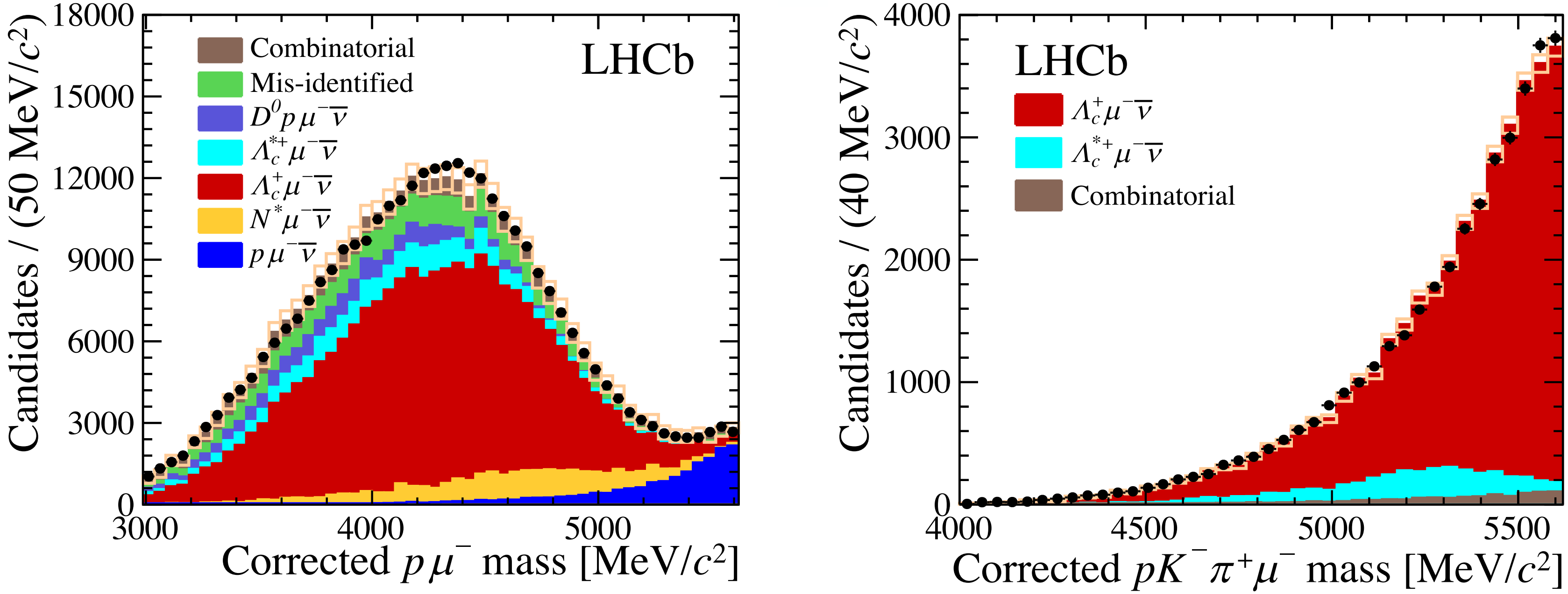
$N(\Lambda_b^0 \to p\mu\nu) = 17,687 \pm 733$ $N(\Lambda_b^0 \to (\Lambda_c^+ \to pK^-\pi^+)\mu\nu) = 34,255 \pm 571$




- Ratio of BFs from ratio of yields and ratio of efficiencies

$$\frac{\mathcal{B}(\Lambda_b \to p\mu\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c\mu\nu_\mu)} = \frac{\mathrm{N}(\Lambda_b \to p\mu\nu_\mu)}{\mathrm{N}(\Lambda_b \to \Lambda_c\mu\nu_\mu)} \frac{\epsilon_{\Lambda_c\mu\nu}}{\epsilon_{p\mu\nu}} \mathcal{B}(\Lambda_c \to pK\pi)$$

5% uncertainty

# $|V_{ub}|$ result

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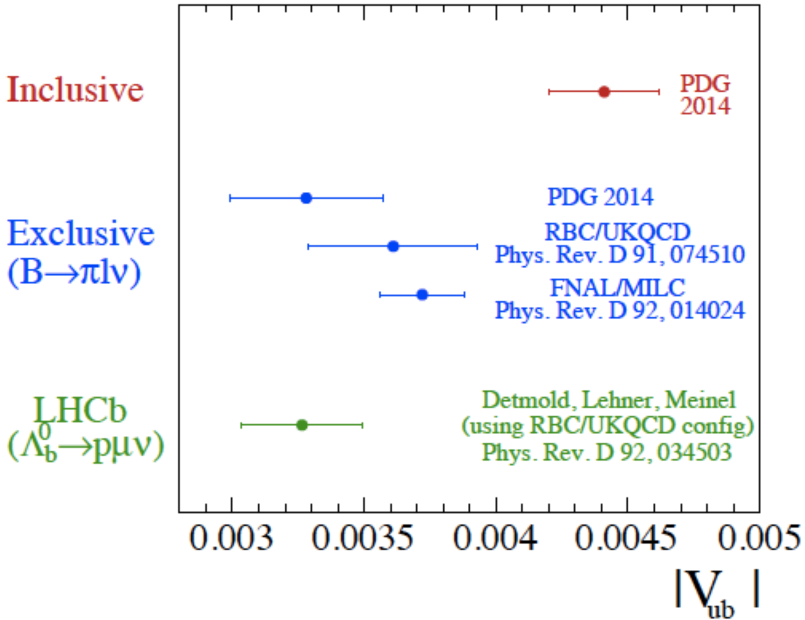
- Measure $$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}$$
- Use $R_{\mathrm{FF}} = 0.68 \pm 0.07$ calculated in the same restricted region
- To determine $$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004$$

and using exclusive

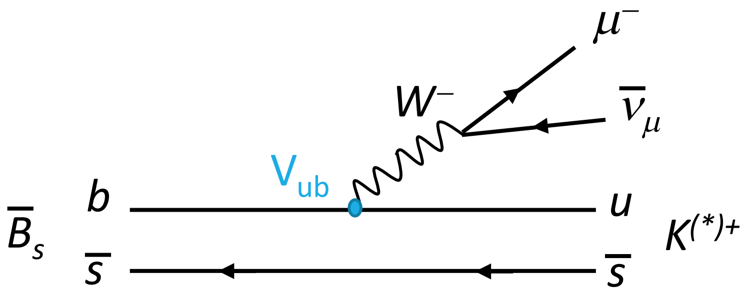
$$|V_{ub}| = (3.27 \pm 0.15 \pm 0.16 \pm 0.06) \times 10^{-3}$$

$$|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$$



# $B_s \rightarrow K^+\mu^-\nu$

- Approximately 10% of b-hadrons produced at LHC are $B_s$
- First measurement of $|V_{ub}|$ from a $B_s$ decay
  - Uncorrelated systematic uncertainties when compared to other measurements
- Use 3 $fb^{-1}$ Run1 data (7,8 TeV).




- Normalization mode $B_s \rightarrow D_s^+\mu^-\nu$ ($D_s^+ \rightarrow KK\pi$) to cancel experimental uncertainties, including production fraction of $B_s$ mesons.

$$\frac{|V_{ub}|^2}{|V_{cb}|^2} = \frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)} R_{\mathrm{FF}}$$

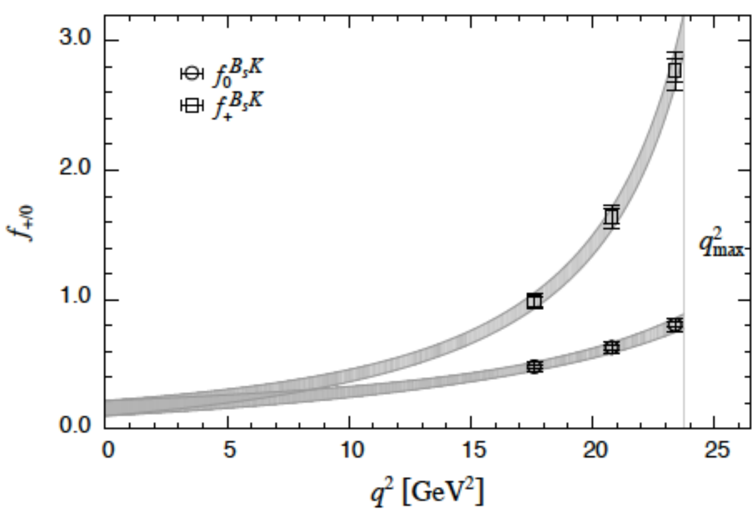
$R_{\mathrm{FF}}$ = ratio of form factors

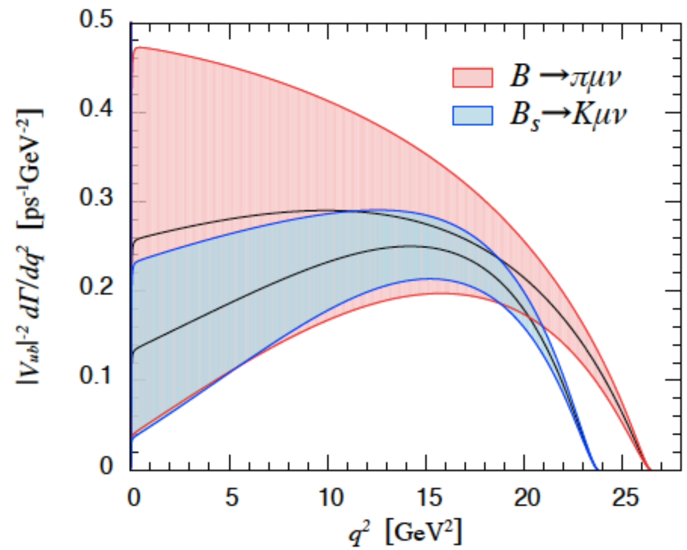
# $B_s \rightarrow K^+\mu^-\nu$

- $B(B_s \rightarrow K^+\mu^-\nu) \sim 10^{-4}$
- Good efficiency/purity at LHCb for kaon and muon identification.
- Large backgrounds but $K\mu$ vertex well separated from primary vertex.
- Normalization mode $B_s \rightarrow D_s^+\mu^-\nu$
  - Small (3.1%) uncertainty in $B(D_s^+ \rightarrow KK\pi)$.
  - Large feed-down from $B_s$ decays to excited $D_s$ mesons with un-reconstructed neutral particles.
  - Good signal identification already proved in LHCb measurement of $B_s$ lifetime (PRL 119, 101801(2017) )

# $B_s \rightarrow K^+\mu^-\nu$ Form Factors from LQCD (1)

- Latest results from J.M.Flynn et al (RBC and UKQCD Collaborations) aXiv:1501.05373 Phys.Rev D91.0704510
- Calculations for $q^2 > 17$ GeV$^2$. Extrapolation parametrizing the $q^2$ dependence using BGL or BCL $z$-expansions.
- $\Gamma(B_s \rightarrow K^+\mu^-\nu)/|V_{ub}|^2 = 4.55(1.08)$ ps$^{-1}$

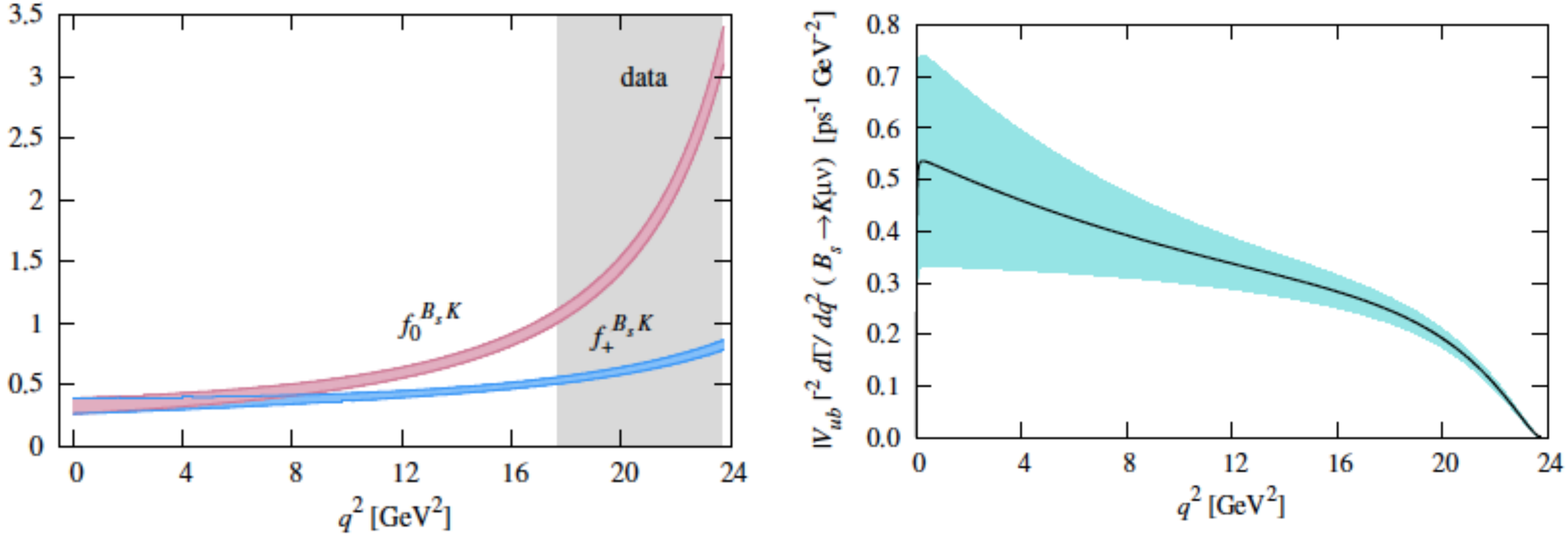



- Uncertainty strongly dependent on $q^2$.
- Lower at high $q^2$ where experimental measurement is more difficult (large background)

# $B_s \to K^+\mu^-\nu$ Form Factors from LQCD (2)

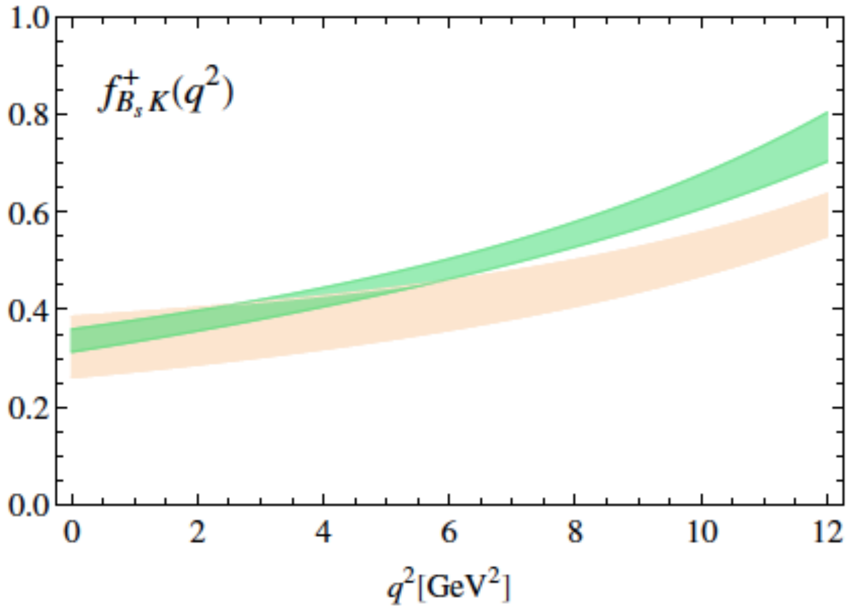
- Previous calculation from. C.M.Bouchard et al (HPQCD Collaboration) aXiv:1406.2279 Phys.Rev D90.054506
- Calculations for $q^2$ > 17 GeV$^2$. Extrapolation to low $q^2$ with BCL *z*-expansion.
- $\Gamma(B_s \to K^+\mu^-\nu)/|V_{ub}|^2$ = 7.75(1.52) ps $^{-1}$




- $f_+(0)$ = 0.323 (63) about the double than in J.M.Flynn et al.
- Also quite different $d\Gamma/dq^2$ shape.

# $B_s \rightarrow K^+\mu^-\nu$ Form Factors from LCSR

- Prediction from A. Khodjamirian and A.V. Rusov
  aXiv:1703.04765 J. High Energ. Phys. (2017) 112
- Predictions in the low $q^2$ range: $0 \leq q^2 \leq 12$ GeV$^2$ (green band).
  - Extrapolation to high $q^2$ with 2 parameters BCL z-expansion available.

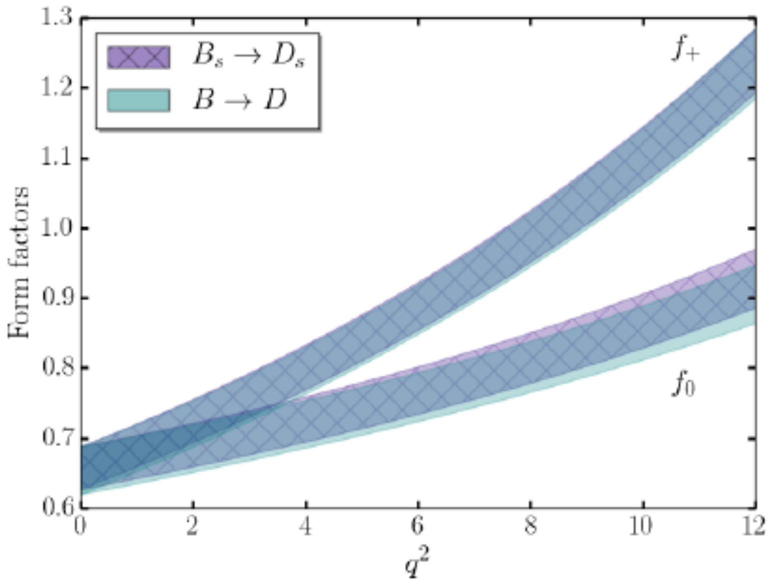


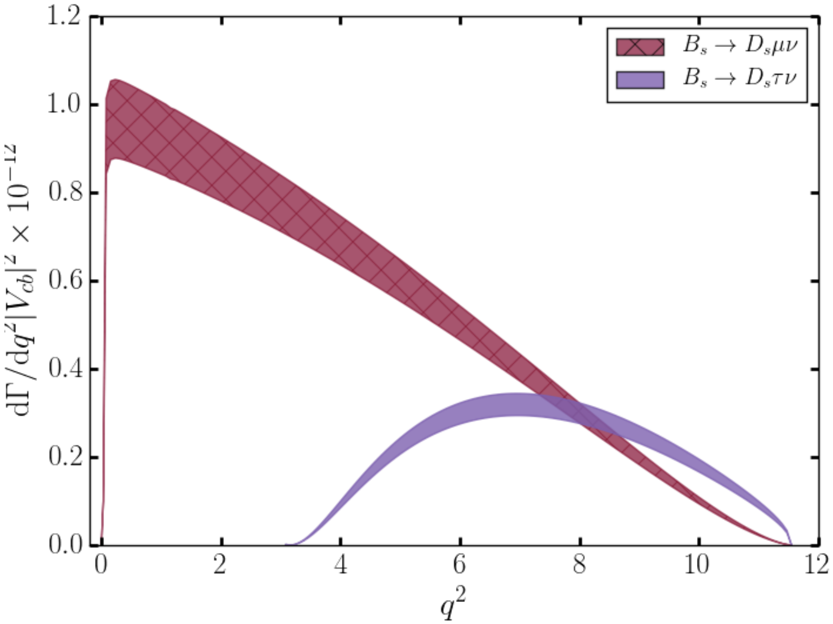

- $f_+(0)$ = 0.336 (23) in good agreement with LQCD C.M. Bouchard (orange).

# $B_s \rightarrow D_s \mu\nu$ Form Factors from LQCD

- Latest from  C.M. Bouchard et al (HPQCD Collaboration)
  arXiv:1703.09728Phys. Rev. D 95, 114506 (2017)

- In agreement with previous prediction from MILC Collaboration
  arXiv:1202.6346 Phys. Rev. D 85, 114502 (2012) Phys. Rev. D 86, 039904




- Low relative uncertainties in the full $q^2$ range.

# $B_s \rightarrow K^+\mu^-\nu$ strategy

- LHCb analysis is still ongoing, I will show some ingredients.
- First result will measure $B_s \rightarrow K^+\mu^-\nu$ yield in two $q^2$ bins and $B_s \rightarrow D_s^+\mu^-\nu$ yield integrated in the full $q^2$ range.
  - Motivated by the different form factor uncertainties
  - Bin optimization ongoing, balancing statistical and systematic uncertainties.
- A $d\Gamma/dq^2$ measurement should follow.

# $B_s \to K^+\mu^-\nu$ Signal selection

$b \to c$ backgrounds

- b-hadron decays to charm and Kaon eg. $B^+ \to J/\psi(\mu\mu)K^+$, $B^0 \to J/\psi(\mu\mu)K^+K^-$
- b-hadron decays to charm semileptonic $b \to cX \to s\mu\nu$ or b-hadron semileptonic decays $b \to c\mu\nu$, with Kaons
- Casual combinations of K and $\mu$ from the decay of same/opposite b -hadron backgrounds
  - Rejected using particle identification and kinematic and topologic variables in multivariate classifiers.
  - Same charge $K^+\mu^+$, $K^-\mu^-$ data sample used as proxy for combinatorial bkgd

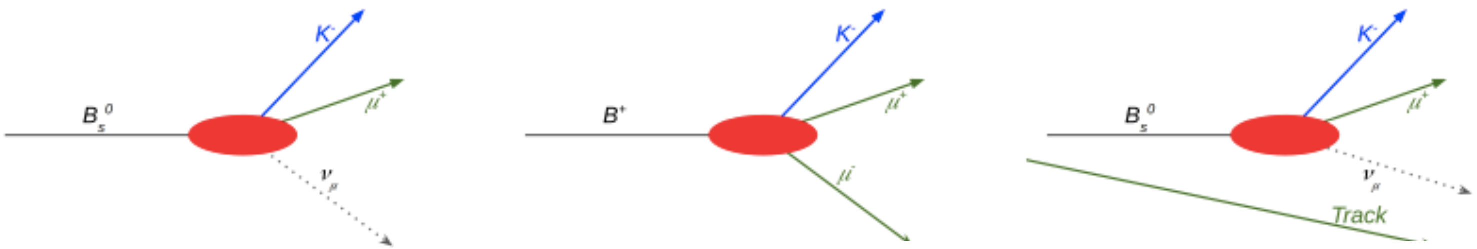
$b \to u$ backgrounds

- $B \to \pi\mu\nu$, $B \to \rho\mu\nu$ etc with (K mis-ID) and decays with muon mis-ID
  - Small after particle identification
- $B_s \to K^{*+}\mu^-\nu$, $K^{*+} \to K^+\pi^0$
  - Reduced with vetos on neutral particles and use of multivariate classifier.

# $B_s \rightarrow K^+\mu^-\nu$   Charged track isolation

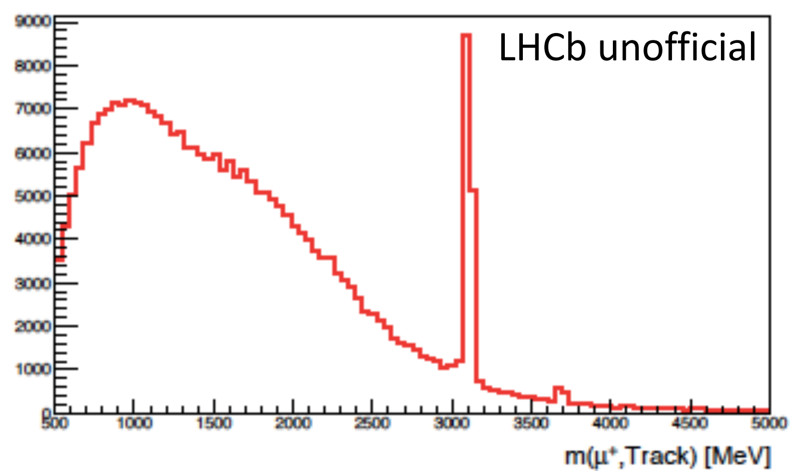
- Partially reconstructed background: same topology of signal but additional missing particles (=tracks).
  - Broad spectrum for visible B mass in semileptonic decays make it difficult to separate.

- $B_s \rightarrow K^+\mu^-\nu$ has no other track sharing the secondary vertex



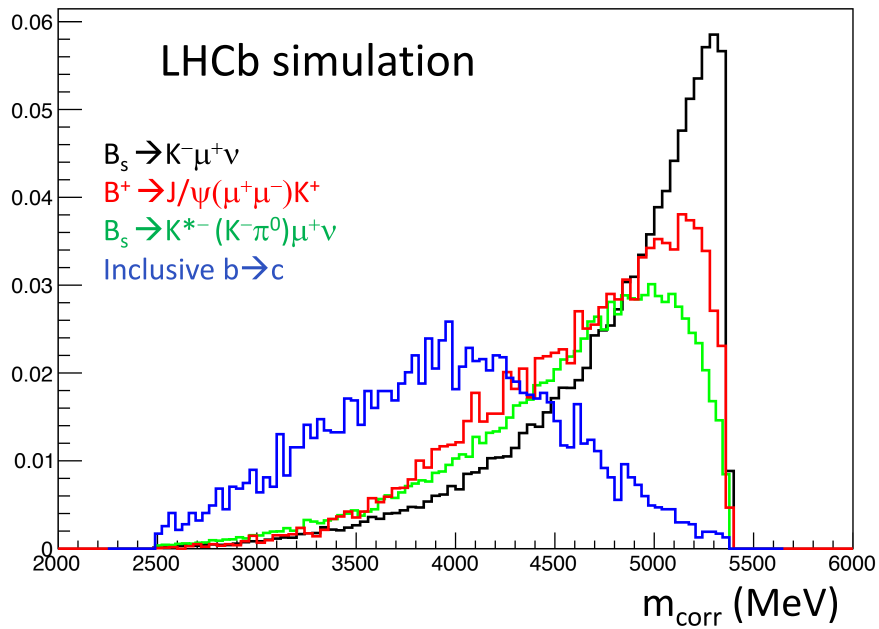

- BDT trained to identify tracks that that are compatible with the same $K\mu$ vertex.

- $m(\mu+\textit{track})$ in data $J/\psi \rightarrow \mu\mu$ and $\psi(2S)$ peaks clearly visible.



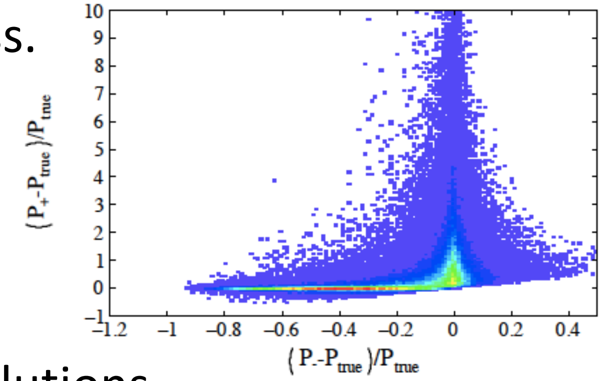
# $B_s \rightarrow K^+\mu^-\nu$ Signal yield

- Determine $B_s \rightarrow K^+\mu^-\nu$ signal yield from a fit to B corrected mass distributions
- Shapes of signal and backgrounds from simulation and data.
- $B^+ \rightarrow J/\psi(\mu\mu)K^+$ used as control channel to test and adjust data/MC agreement

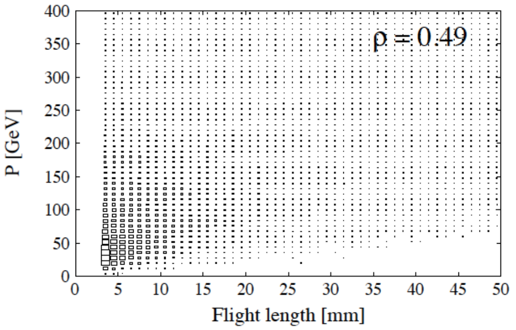


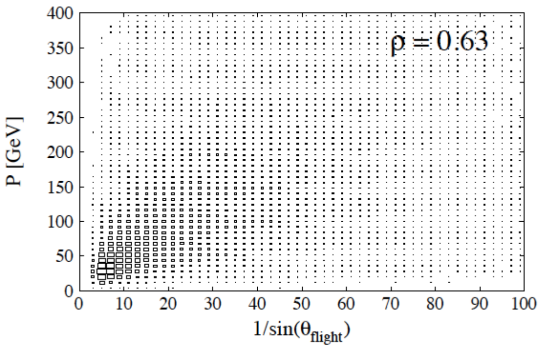
# $q^2$ reconstruction

- No beam energy constrain available at LHC.
- $q^2$ determined using $B_s$ flight direction and $B_s$ mass. Quadratic constrain imply two-fold ambiguity.
  - Imperfect reconstruction of vertices positions leads to ~20% unphysical solutions (candidates rejected)

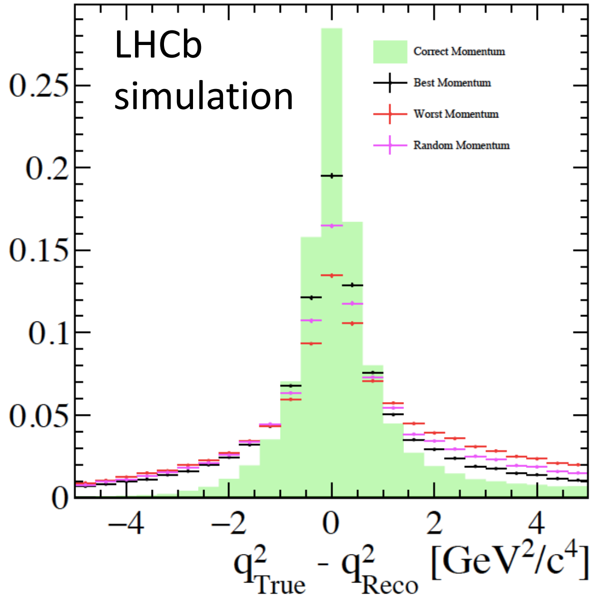



- Use linear regression to choose among the two solutions (arXiv: 1611.08522)
  - Correlation with $B_s$ flight distance and polar angle
  - Correct solution chosen 70% of the time.



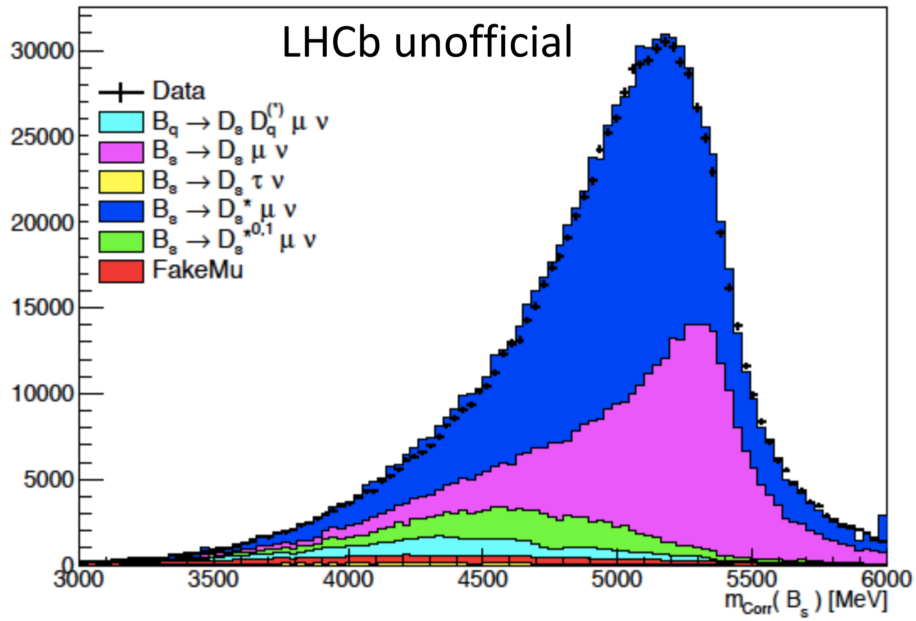

arXiv: 1611.08522




arXiv: 1611.08522

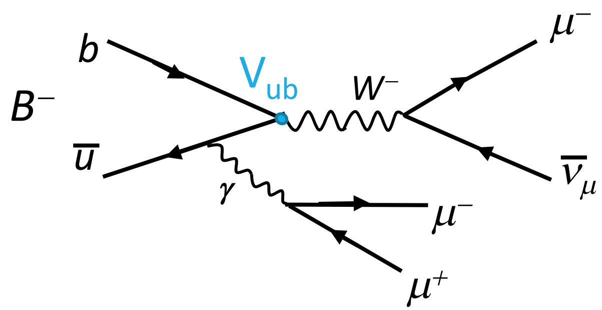
# Normalization $B_s \rightarrow D_s^+\mu^-\nu$

- Large $B_s \rightarrow D_s^+\mu^-\nu$ yield but large feed-down from excited D mesons decays with neutrals: $D_s^* \rightarrow D_s\gamma$, $D^{**} \rightarrow D^*\pi^0$, …
- Determine signal yield from a fit to $m_{corr}$ distribution.
  - Other backgrounds: double charm decays, tauonic decays, muon mis-id
- Each entry in $m_{corr}$ distribution comes from a fit to $KK\pi$ mass to subtract non-$D_s$ background.



# Leptonic modes to $V_{ub}$

- $B^- \rightarrow \mu^- \nu$ purely leptonic decay too hard at LHCb.
- Hard initial state photon might help.




$B^- \rightarrow \mu^- \bar{\nu}\, \mu^+ \mu^-$

- No helicity suppression. Virtual photon materialization adds more particles in the final state.
- Not yet observed, expect $\mathcal{B}(B^- \rightarrow \mu^- \bar{\nu} \mu^+ \mu^-) \sim 10^{-8}$
- Analysis of Run1 + 2016 data ongoing: follow Sally's talk tomorrow.

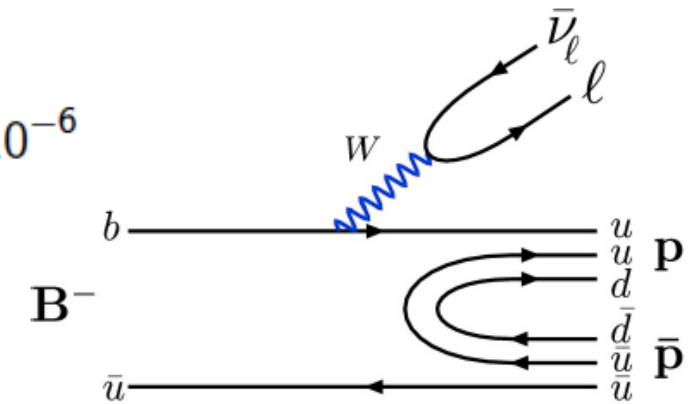
# Other semileptonic modes to $V_{ub}$

- Other b-hadron semileptonic exclusive modes under study.
  - Large b→c $\mu\nu$ X background to be defeated.
  - B→$\pi\mu\nu$, B→$\rho\mu\nu$ … don't seem accessible (yet).
  - Form factors not always available.

- $B^+ \rightarrow p\bar{p}\mu^+\nu$ has signal well recognized thanks to proton identification.
- BR ~ $10^{-4}$ and $q^2$ spectra predicted by C.Q. Geng arXiv:1107.0801 with pQCD
- Evidence from Belle

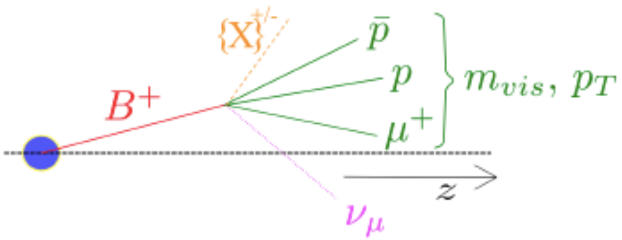
$$\mathcal{B}(B^- \to p\bar{p}\mu^-\bar{\nu}_\mu) = (3.1^{+3.1}_{-2.4} \pm 0.7) \times 10^{-6}$$

PRD 89, 011101 (2014)

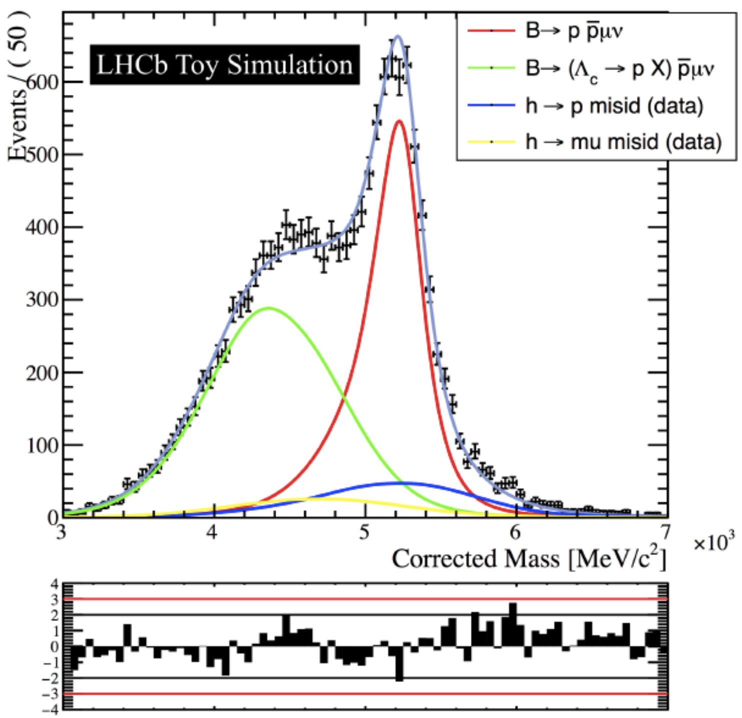


# $B^+ \to p\bar{p}\,\mu^+\nu$

- Particle identification and Isolation tools to reject most backgrounds.
- Fit to B corrected mass distribution to determine signal yield.




- Most of the signal is expected at low $p\bar{p}$ invariant mass, based on Belle observations in $B\to p\bar{p}\pi$, $B\to p\bar{p}K$, $B\to p\bar{p}K^*$ decay modes.
  Pys.Rev. Lett. 92 (2004) 131801
- To reduce the dependence on the $p\bar{p}$ spectra shape, might fit in bins of $p\bar{p}$ invariant mass.



# Conclusion

- LHCb has entered into the game for $V_{ub}$ measurements.
- All b-hadrons produced in pp collisions: can exploit $\Lambda_b$ and $B_s$ semileptonic decays
  - First measurement of $|V_{ub}|/|V_{cb}|$ with $\Lambda_b \to p\mu\nu$, $\Lambda_b \to \Lambda_c\mu\nu$
  - $B_s \to K\mu\nu$ will be the next one.
- Other modes under study.
- Next run with LHCb upgraded will provide more data and new measurements.

# backup

| Source | Relative uncertainty (%) |
|---|---|
| $\mathcal{B}(\Lambda_c^+ \to pK^+\pi^-)$ | $^{+4.7}_{-5.3}$ |
| Trigger | 3.2 |
| Tracking | 3.0 |
| $\Lambda_c^+$ selection efficiency | 3.0 |
| $\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes | 2.3 |
| $\Lambda_b^0$ lifetime | 1.5 |
| Isolation | 1.4 |
| Form factor | 1.0 |
| $\Lambda_b^0$ kinematics | 0.5 |
| $q^2$ migration | 0.4 |
| PID | 0.2 |
| Total | $^{+7.8}_{-8.2}$ |

The table shows the relative systematic uncertainty on the ratio of the $\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu$ and $\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu$ branching fractions broken into its individual contributions. The total is obtained by adding them in quadrature. Uncertainties on the background levels are not listed here as they are incorporated into the fits.