Measuring $|V_{ub}|$ at LHCb

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RTG Students Lecture

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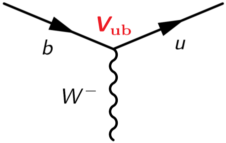
Outline

1. Lecture
   - CKM Mechanism
   - How to measure CKM matrix elements in general?
2. Lecture Today: How to measure CKM matrix elements in B-decays?
   - Differences between B-factories and Hadron colliders
   - $|V_{cb}|$
   - $|V_{ub}|$
3. Lecture: Specific LHCb measurements
   - $\Lambda_b \to p\mu\nu$
   - $B_s^0 \to K^- \mu^+ \nu_\mu$

Recap of the first two lectures

Why is $|V_{ub}|$ important?

- Quarks change their flavour in the SM by the emission of a W-Boson
- The rate is proportional to the coupling strength $|V_{ub}|^2$



- These 9 different couplings form the CKM matrix:

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}, \frac{\sigma(V_{CKM})}{|V_{CKM}|} = \begin{pmatrix} 0.02\% & 0.3\% & 12\% \\ 4\% & 2\% & 2\% \\ 7\% & 7\% & 3\% \end{pmatrix} \quad \text{[PDG 2014]}$$

$\rightarrow |V_{ub}|$ is least well known element of the CKM matrix

Recap of the first two lectures

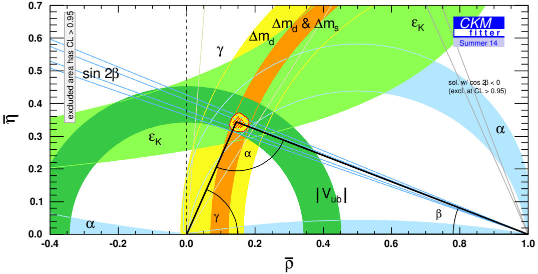
CKM unitarity

- In the SM the CKM matrix is unitary
- Leads to several unitarity equations, e.g.:

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$

- Precision limited by magnitude and phase of $|V_{ub}|$

$\rightarrow$ If it is no triangle $\rightarrow$ New Physics

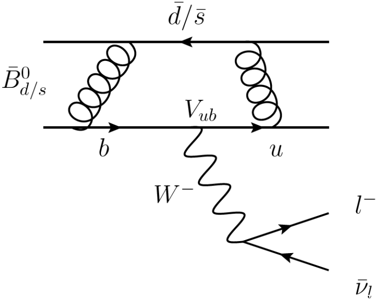


Recap of the first two lectures

Measuring $|V_{ub}|$

- $|V_{ub}|$ measured using (semi-)leptonic decays
- 3 different strategies:
  - **exclusive**: semileptonic decays such as $\bar{B}^0 \to \pi^+ l^- \bar{\nu}$
  - **inclusive**: all semileptonic $B \to X_u l^- \bar{\nu}$ transitions
  - measure pure leptonic decay $B^+ \to \tau\nu$
- Factorise electroweak and strong parts of the decay: $\frac{d\Gamma}{dq^2} \propto G_F^2 |V_{ub}|^2 |f^+(q^2)|^2$

  $\to$ Semileptonic decays rely on non-perturbative FF calculations from LQCD or QCD sum rules



Recap of the first two lectures

Hadron colliders

Advantages

- **large production cross section** of beauty quarks: $\sigma(pp \to b\bar{b}X) = 284 \pm 20 \pm 49\mu b$ at 7 TeV
- Millions of B candidates available, **all b-hadrons produced**: $B^0, B^+, B_s, B_c, \Lambda_b, \ldots$
- Excellent vertex separation, tracking and PID systems

Disadvantages

- but **dirty environment**: many other particles produced in pp collisions
  $\rightarrow$ No possibility to use beam energy constraints
- No kinematic constraints from other (tagging) B, also b-hadron production fractions poorly known
- **unknown initial state** which makes reconstruction of neutrino challenging
- must trigger on **specific exclusive decay modes** and typically charged hadrons in final state
  $\rightarrow$ no inclusive measurements possible, hard to reconstruct neutrals

The $|V_{ub}|$ puzzle - Status of 2014

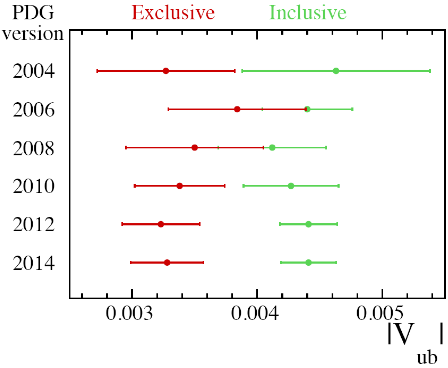
- **Discrepancy between exclusive vs. inclusive measurement**:

  excl.: $(3.28 \pm 0.29) \times 10^{-3}$ [PDG 2014]

  incl.: $(4.14 \pm 0.15^{+0.15}_{-0.19}) \times 10^{-3}$

  $\rightarrow$ **~3σ** deviation
- Leptonic measurements not precise enough, favours inclusive results

  $\rightarrow$ More precise measurements needed

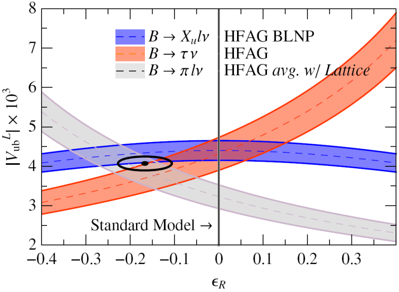


The $|V_{ub}|$ puzzle - Tension be due to New Physics?

Idea: add right-handed charged current to SM [Phys. Rev. D 90, 094003 (2014)]

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

- $B \to \pi l \nu$ is purely a vector current whereas $B \to X_u l \nu$ is a V-A
- Adding right-handed current (V+A), increases vector current $V \to (1+\epsilon_R)V$ but decreases axial-vector current $A \to (1-\epsilon_R)A$



⇒ negative right-handed can reduce tension between inclusive and exclusive result

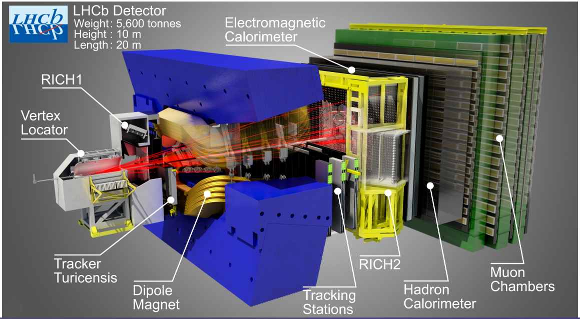
⇒ new measurement with different sensitivity needed

Is it possible to measure $|V_{ub}|$ at LHCb ?

- Long thought that measuring $|V_{ub}|$ is impossible at hadron colliders
- Lack the beam energy constraints of e^+e^- colliders

> “It is particularly important to stress that many of the measurements that constitute the primary physics motivation for Super$B$ cannot be performed in the hadronic environment. For example, modes with missing energy, such as $B^+ \to \ell^+\nu_\ell$ and $B^+ \to K^+\nu\bar{\nu}$, measurements of the CKM matrix elements $|V_{cb}|$ and $|V_{ub}|$, and inclusive analyses of processes such as $b \to s\gamma$ are unique to Super$B$.”

CDR, SuperB factory, arXiv 0709.0451



LHCb

- forward spectrometer covering pseudorapidity $2 < \eta < 5$
- 26 x 10^{10} $b\bar{b}$ pairs

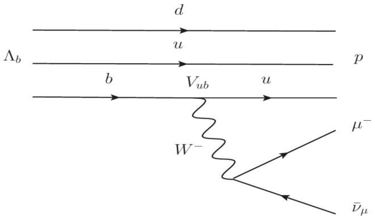
First LHCb measurement on exclusive $|V_{ub}|$: $\Lambda_b \to p\mu^-\nu_\mu$

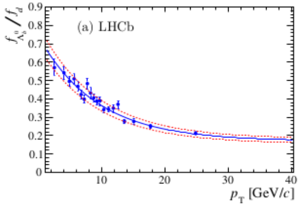
Experimental Challenge at LHCb

- Missing neutrino momentum $\rightarrow$ B not fully reconstructed
- Generally affected by much higher (x10) $X_b \rightarrow X_c \mu \nu$ backgrounds
- "Golden channel" $\bar{B}^0 \rightarrow \pi^+ l^- \bar{\nu}$ suffers from high pion background at LHC

BUT: use $\boldsymbol{\Lambda_b \rightarrow p \mu^- \nu_\mu}$

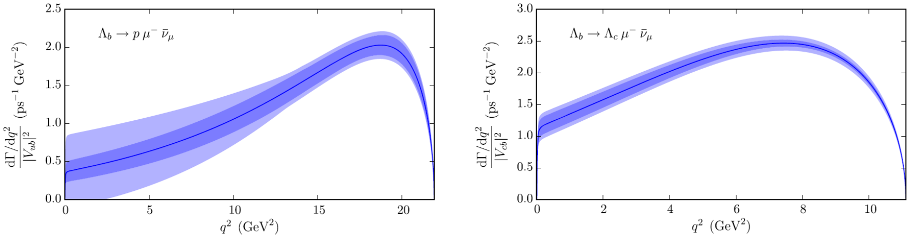
- Excellent μ and p PID at LHCb from RICH/Muon systems
- precision vertexing and tracking used
  $\rightarrow$ displaced $p\mu$ vertex as signature in detector
- High production fraction of Λ_b: ~20% of b-hadrons [JHEP08(2014)143]





Analysis strategy

- 2012 Dataset (~2 fb^{-1})
- Normalise signal yield to a $|V_{cb}|$ decay: $\Lambda_b \to \Lambda_c^+ \mu^- \nu_\mu$
  - cancels many systematic uncertainties
  - especially the production rate of Λ_b baryons
- Improved FF calculations from theory for $\Lambda_b \to p\mu^-\nu_\mu$ and $\Lambda_b \to \Lambda_c^+ \mu^- \nu_\mu$ in high q^2 region
  $\to$ there FF calculations from theory are most precise



[Phys. Rev. D 92, 034503 (2015)]

How to extract $|V_{ub}|$?

$$\underbrace{\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}}_{\textbf{experimental measurement}} = \underbrace{R_{\text{FF}}}_{\textbf{theoretical calculations}} \times \frac{|V_{ub}|^2}{|V_{cb}|^2}$$

- Reduce systematic uncertainties by restricting measurement to $q^2 > 15(7)\,\mathrm{GeV}^2$
  $\rightarrow$ LQCD here most precise
- $R_{\text{FF}} = \frac{(\Lambda_b \to p\mu^-\nu_\mu)_{q^2>15\,\mathrm{GeV}^2}}{(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)_{q^2>7\,\mathrm{GeV}^2}} = 0.68 \pm 0.07$ [Phys. Rev. D 92, 034503 (2015)]

  $\rightarrow$ 5% uncertainty on $|V_{ub}|$ from theory

Analysis strategy

$$\frac{\mathcal{B}(\Lambda_b\to p\mu^-\nu_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b\to(\Lambda_c^+\mu^-\nu_\mu)_{q^2>7\,\mathrm{GeV}^2}} = \frac{N(\Lambda_b\to p\mu^-\nu_\mu)}{N(\Lambda_b\to(\Lambda_c^+\to pK^-\pi^+)\mu^-\nu_\mu)} \times \frac{\epsilon(\Lambda_b\to(\Lambda_c^+\to pK^-\pi^+)\mu^-\nu_\mu)}{\epsilon(\Lambda_b\to p\mu^-\nu_\mu)} \times\mathcal{B}(\Lambda_c^+\to pK^-\pi^+)$$

- Determine yields of $\Lambda_b \to p\mu^-\nu_\mu$ and $\Lambda_b \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\nu_\mu$
- Estimate relative experimental efficiency with high precision
- Use $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ from Belle [PRL 113,042002(2014)]
- even tough $\Lambda_b \to p\mu^-\nu_\mu$ is supressed, not rare:
  - expect 500,000 signal decays after trigger and pre-selection
  - Only need ∼10000 to get good enough statistical uncertainty
    → very tight selection to control background and systematic effects

Selection

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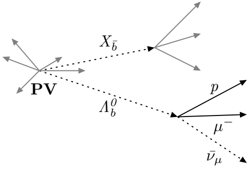
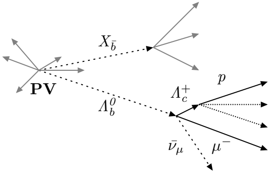
Main bkg comes from $|V_{cb}|$ decays:

- Charm has significant lifetime: cut on vertex quality
- apply tight PID cuts on the proton
- Dedicated MVA classifier used to remove backgrounds with additional charged tracks that vertex with $p\mu$ candidate
  $\rightarrow$ track isolation: 90% rejection with 80% efficiency



signal



background

- Very difficult to isolate against neutral particles

Selection

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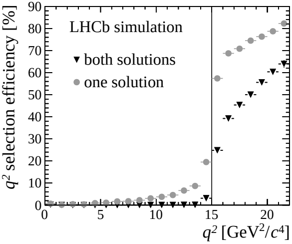
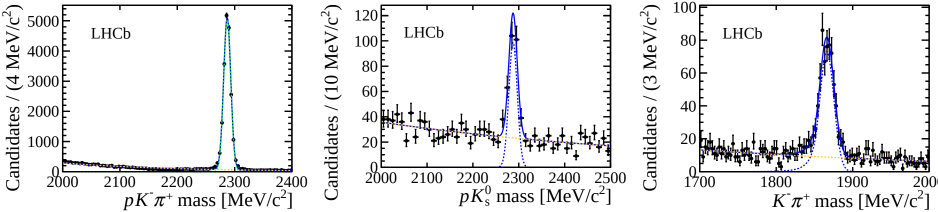
- Difficult to calculate q^2 with missing neutrino
- Use pointing and Λ_b mass constraints to solve for q^2 up to a two-fold ambiguity
- Correct solution has a resolution of 1 GeV^2/c^4 whereas incorrect is $4 GeV^2/c^4$
- Require both solutions to full fill $> q^2_{cut}$ to minimise migration from low q^2



- reconstruct additional tracks to determine background yields:



Selection

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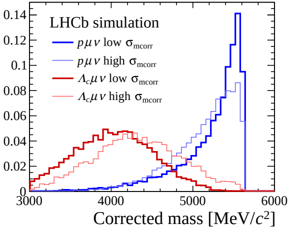
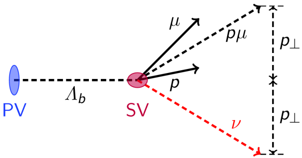
- Corrected mass resolution $\sim$10 times worse than for fully reconstructed decays
- Uncertainty dominated by resolution of PV and Λ_b vertex
- Calculate uncertainty for each event and reject candidates if $\sigma_{m_{corr}} > 100\,\mathrm{MeV}/c^2$ ($\sim$23% survive) to increase separation to background in signal fit



- Fit to corrected mass
  $m_{corr} = \sqrt{m_{h\mu}^2 + p_\perp^2} + p_\perp$, $h = p, \Lambda_c$
  $\rightarrow$ peaks at Λ_b mass if only neutrino is missing



Extracting Yields

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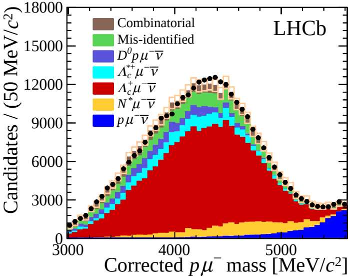
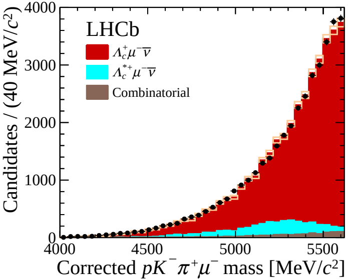
template fit is performed for signal and normalisation separately:



$N(\Lambda_b \to p\mu^-\nu_\mu) = 17687 \pm 733$



$N(\Lambda_b \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\nu_\mu) = 34255 \pm 571$

$\to$ First observation of the decay $\Lambda_b \to p\mu^-\nu_\mu$

$\to$ Separate ground state and excited modes from fit to corrected mass in normalisation channel

Relative efficiencies

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- Relative efficiency determined from simulation
- Difference between data and simulation calculated from control sample with data-driven corrections

$$\frac{\epsilon(\Lambda_b \to p\mu^-\nu_\mu)}{\epsilon(\Lambda_b \to (\Lambda_c^+ \to pK^-\pi^+)\mu^-\nu_\mu)} = 3.52 \pm 0.20$$

- Main differences in efficiency due to:
  - Two extra tracks for normalisation
  - Vertex efficiency (Λ_c lifetime)
  - Corrected mass error cut on signal
- Uncertainty of ratio is dominated by systematic uncertainties

Systematic uncertainties

- Dominated by $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$ from Belle [PRL 113,042002(2014)]
- Trigger uncertainties can be further reduced $\to$ size of control sample in data
- Tracking uncertainties dominated by material interaction of kaon and π
- $\Lambda_c^+ \to pK^-\pi^+$ selection efficiency from knowledge on its Dalitz structure
- Fit systematic dominated by form factors of $\Lambda_b \to N^*\mu^-\nu_\mu$ decays

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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
$\Lambda_b^0 \to N^*\mu^-\overline{\nu}_\mu$ shapes	2.3
Λ_b^0 lifetime	1.5
Isolation	1.4
Form factor	1.0
Λ_b^0 kinematics	0.5
q^2 migration	0.4
PID	0.2
Total	$^{+7.8}_{-8.2}$

Results I

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- Measure the relative branching fraction:

$$\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)_{q^2>15\,\mathrm{GeV}^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)_{q^2>7\,\mathrm{GeV}^2}} = (1.00 \pm 0.04(stat) \pm 0.08(syst)) \times 10^{-2}$$

- Including $\frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)} = R_{\mathrm{FF}} \times \frac{|V_{ub}|^2}{|V_{cb}|^2}$ with $R_{\mathrm{FF}} = 0.68 \pm 0.07$ [Phys. Rev. D 92, 034503 (2015)] gives

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004(exp.) \pm 0.004(theo.) \tag{1}$$

- Use world average for exclusive $|V_{cb}| = (39.5 \pm 0.8) \times 10^{-3}$ measurements [PDG 2014]

exclusive $|V_{ub}|$ LHCb result

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

Results II

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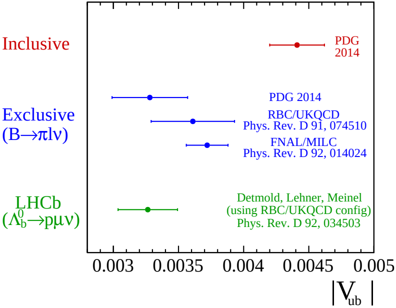
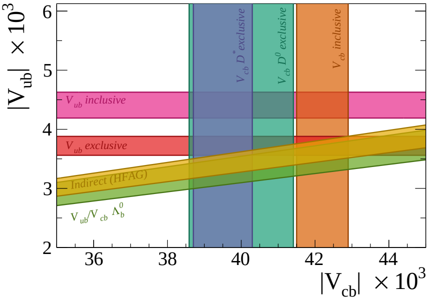
- LHCb is 3.5σ away from inclusive measurement of $|V_{ub}|$
- Consistent with other exclusive measurements





Results III

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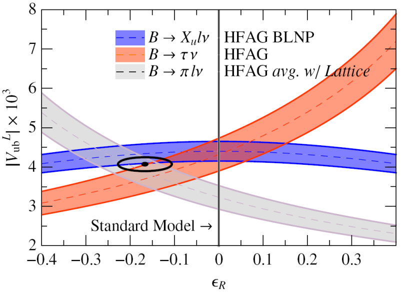
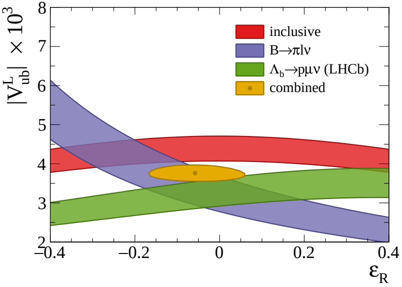
- $|V_{ub}|$ measurement depends on possible right-handed current in SM [Phys. Rev. D 81, 031301 (2010)]
- Previously exclusive/inclusive discrepancy suggested significant right-handed coupling fraction (ϵ_R) $\rightarrow$ solution to $|V_{ub}|$ puzzle?





[Phys. Rev. D 90, 094003 (2014)]

$\rightarrow$ LHCb results does not support that

exclusive $|V_{ub}|$: $B_s^0 \to K^- \mu^+ \nu_\mu$

Introduction

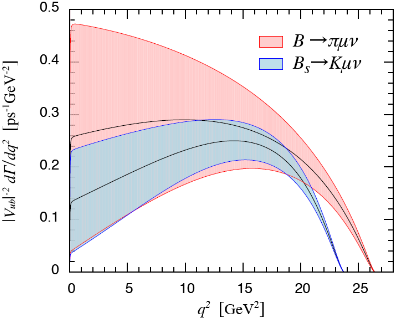
- first $|V_{ub}|$ measurement from a B_s^0 decay
- $B_s^0 \to K^-\mu^+\nu_\mu$ has been never measured before
- comparison with $\Lambda_b^0 \to p\mu^-\nu_\mu$:

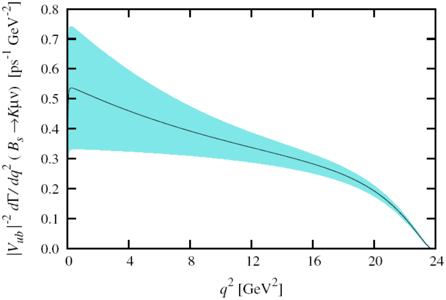
Decay	$\Lambda_b \to p\mu^-\nu_\mu$	$B_s^0 \to K^-\mu^+\nu_\mu$
Production fraction	20%	10%
Branching fraction	4x 10^{-4}	1x 10^{-4} (expected)
Source of backgrounds	Λ_c^+	Λ_c^+, D_s, D^+, D^0,...
$\mathcal{B}(X_c)$ error	3.72%	3.9%
Form factor error	5%	$\sim$3%

- expect smaller FF uncertainties
- many more challenging bkgs
  $\Rightarrow$ clearly more difficult due to many more contributing bkgs, but might have better ultimate precision

$B_s^0 \to K^- \mu^+ \nu_\mu$ Form factor calculations

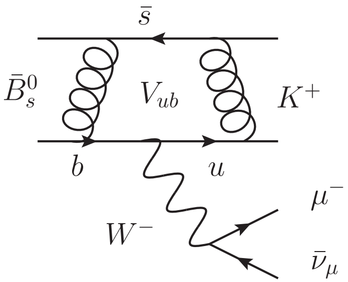
- Form factor calculations available from Lattice for $q^2 \geq 12\,\mathrm{GeV}^2$
  - Flynn et al. Phys. Rev. D 91, 074510 (2015)
  - Bouchard et al., Phys. Rev. D 90, 054506 (2014)
- LCSR predictions at low q^2: arXiv 1703.04765
- perform measurements in both q^2 bin





Analysis Strategy

- normalise wrt. $|V_{cb}|$ decay mode: $B_s^0 \to D_s^- \mu^+ \nu_\mu$
  $\to$ very well understood
- use full Run-I statistics: $3 fb^{-1}$
- look for displaced $K\mu$ vertex
- apply tight PID constraints to select K and suppress high π background
- remove background with add. charged tracks with isolation variables



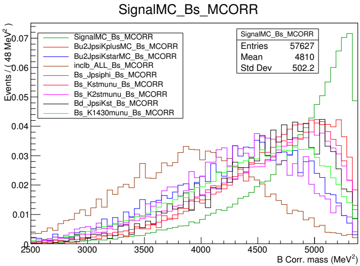
Main Backgrounds to $B_s^0 \to K^- \mu^+ \nu_\mu$

- partially reconstructed background with **additional charged track(s)**:
  $B^+ \to J/\psi K^+$, $B^+ \to J/\psi K^{*+}$, $B_s \to J/\psi \phi$, $B_s \to D_s \mu \nu$, $B_d \to \rho \mu \nu$, ...
  $\to$ use charge track isolation tools $\to$ **isolation BDT**

- **additional neutral particles** from higher excited modes:
  $B_s^0 \to K^* \mu \nu_\mu$, $B_s^0 \to K_2^* \mu \nu_\mu$, $B_s^0 \to K^*(1430) \mu \nu_\mu$
  $\to$ use **neutral isolation** tools: dedicated π^0 reconstruction to veto K^* candidates

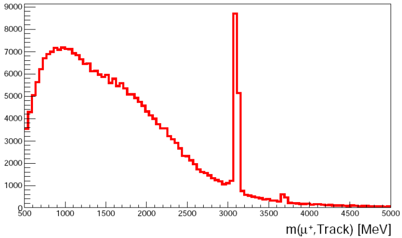
- combinatorial bkg: use SS data as a proxy
  trained dedicated **BDT against SS sample**

- miss-ID bkg



Charged Track Isolation

- Tool developed to compare every track in the event with the signal candidate:
  - Search through every track in event
    - Does the track originate from the same decay? (bad)
    - Or is the track isolated? (good)
- isolation variables as output of tool:

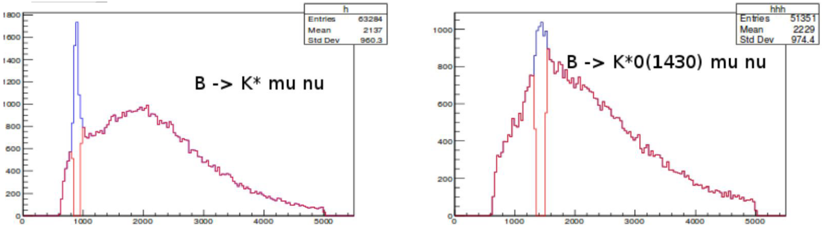


$\longrightarrow$ apply J/ψ veto

- Train BDT to discriminate against charged backgrounds
- Training variables include output of charged isolation tool, kinematics

Neutral Isolation

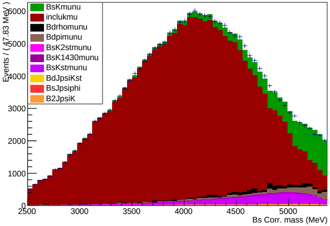
- Draw cones around track in ΔR
- Search for hits in neutral calorimeters
- Reconstruct photons or π^0
- Veto event if high pion likelihood and $m(K^{\pm}\pi^0) \approx m(K^*)$



$\rightarrow$ apply vetos on π^0, K^* and $K^*(1430)$ mass

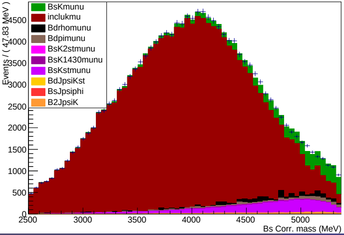
Signal Fit

full q^2

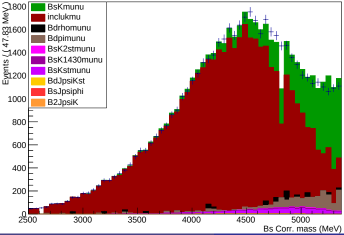


- perform binned template fit to corrected B_s mass
- templates from MC, constrained from data
- not yet all possible backgrounds included
- so far gives $\sim$ 10000 signal events per bin
- needs to be finalised and validated

low q^2



high q^2

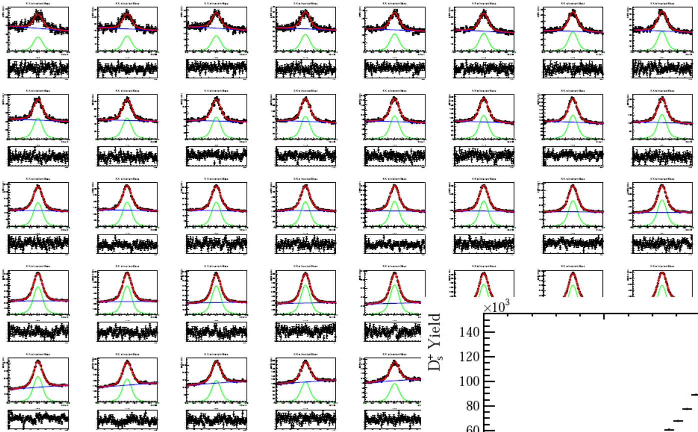


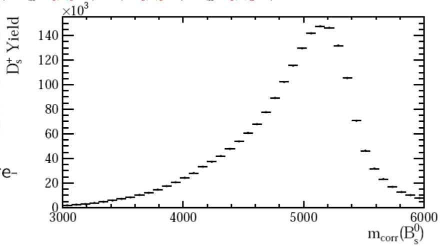
$B_s^0 \to D_s \mu \nu$ Normalisation channel

- **Selection** is similar to that of the $K^- \mu^+ \nu_\mu$ mode, in order to try and cancel efficiency ratio systematics
- problem: can't use sPlot technique to remove combinatorial bkg under D_s peak
  $\to$ correlations between $KK\pi$ invariant mass and B_s^0 corrected mass
- split B_s^0 corrected mass range of 3000-6000 MeV into 40 bins
- in each bin perform fit to invariant $KK\pi$ mass to extract the D_s yield

  $\to$ subtract the $KK\pi$ combinatorial component
  $\to$ still remaining $D_s \mu$ combinatorial background

Control Fit templates

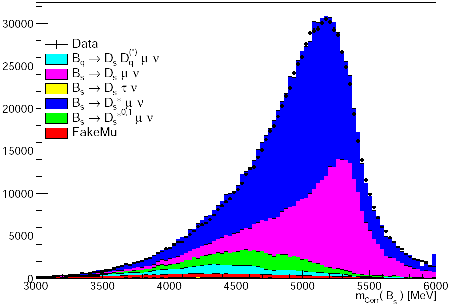




Each point in the data histogram (right) corresponds to a signal yield in the plots (above).

Control Fit Results

- main challenge: separate D_s^* and D_s
- feed down from higher excited D resonances, tauonic modes and double charm modes taken from MC
- combinatorial $D_s\mu$ background obtained from data:
    - SS: Real D_s^+ + μ^+
    - Real D_s^+ + fake μ^- $(DLL_{\mu\pi}(\mu) < 0)$



$\to$ gives $B_s^0 \to D_s\mu\nu \sim 300000$

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

- BDT optimization ongoing
- Signal Fit need to be finalized including all backgrounds, also needs validations
- Efficiency calculations almost done
- Systematic uncertainty evaluation started
- Expect new form factor calculations soon, including ratio $B_s^0 \to K^- \mu^+ \nu_\mu / B_s^0 \to D_s \mu \nu$
- Aiming for publication very soon

$\Rightarrow$ Stay tuned!

Conclusions

- LHCb performed a precise measurement of $|V_{ub}|$ using the decay $\Lambda_b \to p\mu^-\nu_\mu$
- First determination of $|V_{ub}|$ in a hadron collider and in a baryonic decay

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

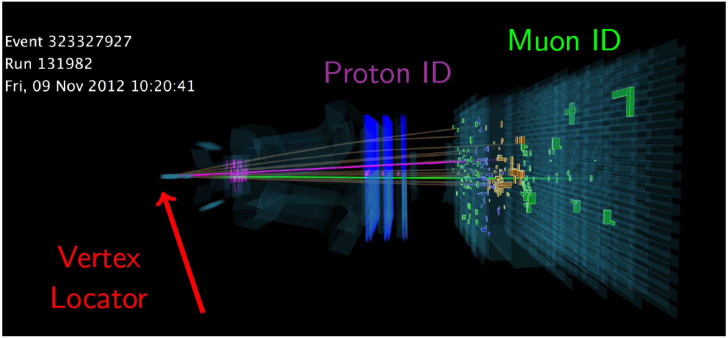
- Consistent with other exclusive $|V_{ub}|$ measurements in $\bar{B}^0 \to \pi^+ l^- \nu_\mu$
- Measurement is 3.5σ below inclusive measurement of $|V_{ub}|$
- Right-handed currents can no longer explain the $|V_{ub}|$ puzzle
- We are in the final months to determine $|V_{ub}|$ in $B_s^0 \to K^-\mu^+\nu_\mu$ decays

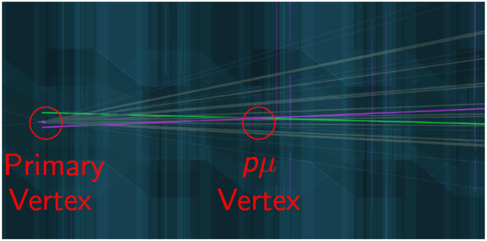
$\Rightarrow$ **Very interesting time ahead of us, also with start of Belle II soon!**

Thanks for your attention!

Backup Slides

Signal Selection





Neutrino reconstruction

due to missing neutrino, events are only partially reconstructed:
$\rightarrow$ use pointing and Λ_b mass to solve for q^2 up to 2-fold ambiguity:
neutrino momentum parallel to flight direction is unknown $p(\nu)_{||}$:

$$(p_\nu + p_{h\mu})^2 = m^2_{\Lambda_b}$$

with $p_\nu = (\sqrt{p^2(\nu)_{||} + p^2_\perp}, 0, -p_\perp, p(\nu)_{||})$ and
$p_{h\mu} = (\sqrt{p^2(h\mu)_{||} + p^2_\perp + m^2_{h\mu}}, 0, p_\perp, p(h\mu)_{||})$
gives

$$p(\nu)_{||} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

with $a = |2p(h\mu)_{||} m_{h\mu}|^2$, $b = 4p(h\mu)(2p_\perp p(h\mu) - m^2_{miss})$,
$c = 4p^2_\perp(p^2(h\mu) + m^2_{\Lambda_b}) - |m^2_{miss}|$, $m^2_{miss} = m^2_{\Lambda_b} - m_{h\mu}$

Lattice Calculations

- Calculate 6 form factors (3 vector, 3 axial) for each decay. Lattice QCD with 2 + 1 dynamical domain-wall fermions.
- Calculation performed with six pion masses and two different lattice spacings.
- b and c quarks implemented with relativistic heavy-quark actions.
- Uses gauge-field configurations generated by the RBV and UKQCD collaborations.
- b $\rightarrow$ u and b $\rightarrow$ c currents renormalised with a mostly non-perturbative method.
- Parametrises the form factor q^2 dependence with a z expansion.
- Systematics include: the continuum extrapolation uncertainty, the kinematic (q2) extrapolation uncertainty, the perturbative matching uncertainty, the uncertainty due to the finite lattice volume and the uncertainty from the missing isospin breaking effects.

W. Detmold, C. Lehner and S. Meinel [Phys. Rev. D 92, 034503 (2015)]

Theory ratio

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

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

Branching fraction extrapolation factor

- convert measured ratio into bf using:

$$\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu) = \tau_{\Lambda_b} \frac{\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} |V_{cb}|^2 R_{FF}$$

$$= \tau_{\Lambda_b} \mathcal{B}_{ratio} \int_{7\,\mathrm{GeV}/c^2}^{q'_{max}} \frac{d\Gamma(\Lambda_b \to \Lambda_c^+\mu^-\nu_\mu)}{dq^2} / |V_{cb}|^2 dq^2$$

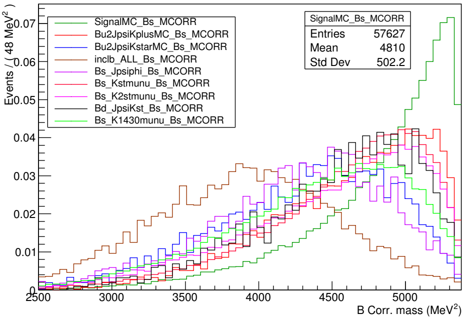
$$\times \frac{\int_{0\,\mathrm{GeV}^2/c^4}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\nu_\mu)}{dq^2} / |V_{ub}|^2 dq^2}{\int_{15\,\mathrm{GeV}/c^2}^{q_{max}} \frac{d\Gamma(\Lambda_b \to p\mu^-\nu_\mu)}{dq^2} / |V_{ub}|^2 dq^2}$$

- results in:

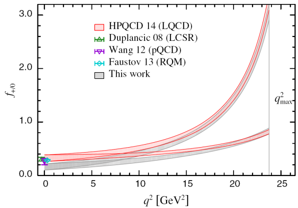
$$\mathcal{B}(\Lambda_b \to p\mu^-\nu_\mu) = (4.1 \pm 1.0) \times 10^{-4}$$

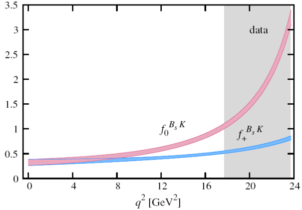
$B_s^0 \to K^- \mu^+ \nu_\mu$ Selection

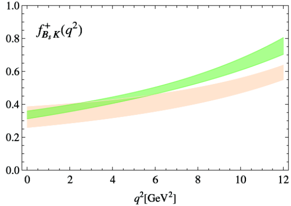
- apply stripping 21r0p1 cuts
- preselection cuts:
  - Bs mass cut = 2500 < Bs_MCORR < 7000
  - Tight kaon PID cuts
  - Trigger: (Bs_Hlt2SingleMuonDecision_TOS ||Bs_Hlt2TopoMu2BodyBBDTDecision_TOS == 1)
- J/ψ misID, π^0 and K^* vetoes
- cut on charged isolation and SS BDT



$B_s^0 \to K^- \mu^+ \nu_\mu$ Form factor calculations







Flynn

Bouchard

$f^+_{B_s K}(0) = 0.323(63)$

LCSR

$f^+_{B_s K}(0) = 0.336 \pm 0.023$

all three contain HPQCD Bouchard et al. prediction (middle)