Status And Prospects For $|V_{ub}|$ At LHCb


Image credit: R. Matev

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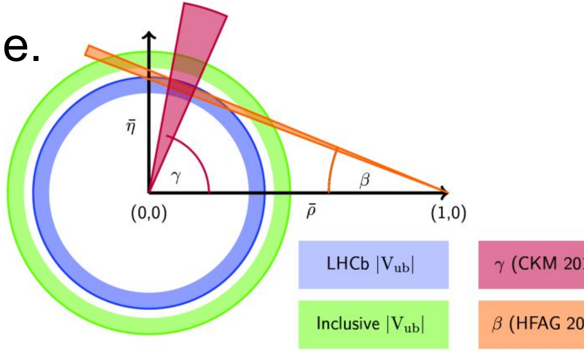
The CKM Matrix and $|V_{ub}|$

- $|V_{ij}|$ describes the amplitude of quark i transitioning to quark j via charged weak current.
- $|V_{ub}|$ has the largest relative uncertainty.

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.00065 & 0.00351^{+0.00015}_{-0.00014} \\ 0.22520 \pm 0.00065 & 0.97344 \pm 0.00016 & 0.0412^{+0.0011}_{-0.0005} \\ 0.00867^{+0.00029}_{-0.00031} & 0.0404^{+0.0011}_{-0.0005} & 0.999146^{+0.000021}_{-0.000046} \end{bmatrix}.$$

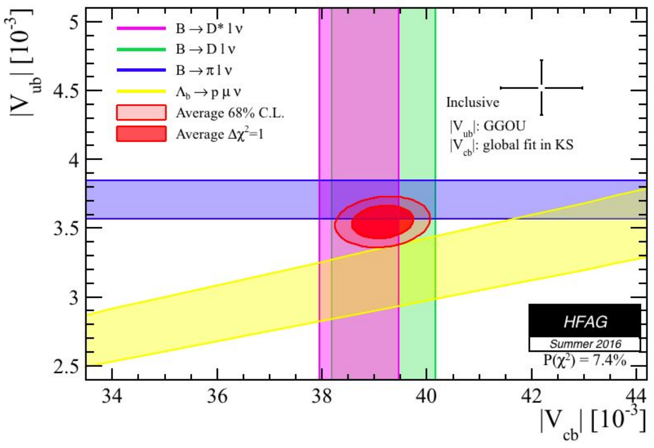
An improved measurement of $|V_{ub}|$ will:

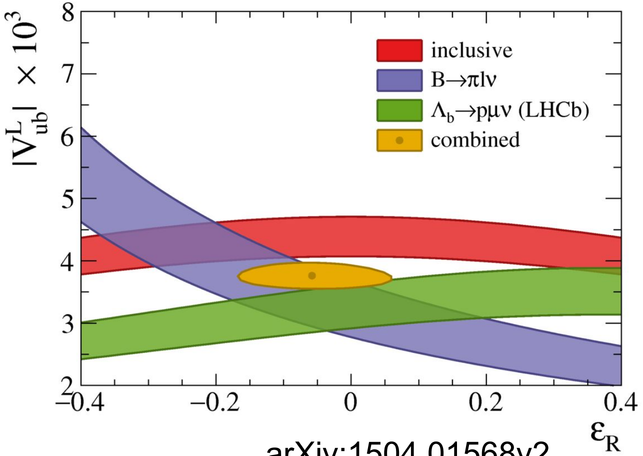
- Improve precision of apex of unitary triangle.
  - Could indicate new physics in sin(2β).
- Test non-perturbative QCD.
- Help predict $\mathcal{B}(B^+ \to \tau\nu)$.



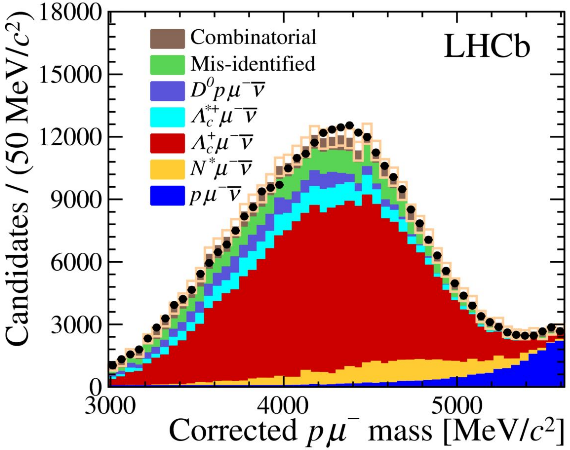
Current Status of $|V_{ub}|$

- Most recent $|V_{ub}|$ measurement comes from LHCb: $\Lambda_b \to p\mu\nu$
  - $|V_{ub}|$ = (3.27 ± 0.15 (exp.) ± 0.16 (theor.) ± 0.06 ($|V_{cb}|$)
- Tension between inclusive and exclusive measurements. ~3σ
- Right handed currents could explain the tension.
  - Less convincingly after $\Lambda_b \to p\mu\nu$.
- Aim is to improve precision of $|V_{ub}|$ (≃ 12% error). $|V_{cb}|$ (≃ 3%)





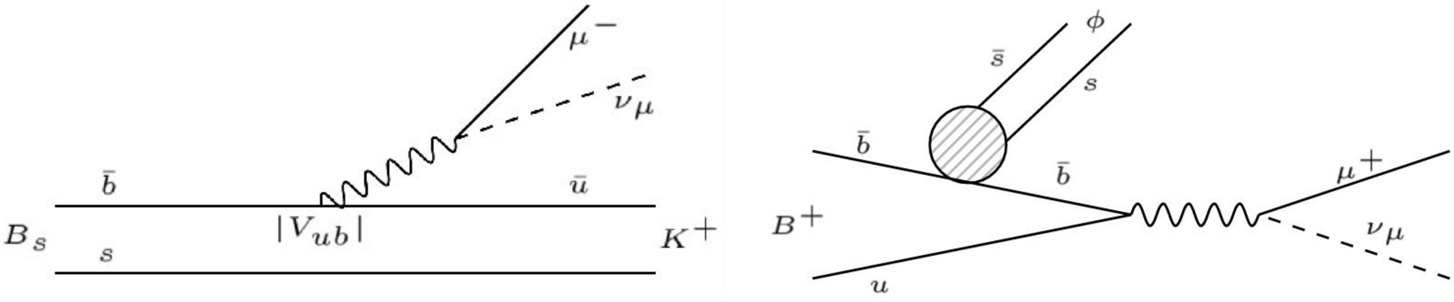
arXiv:1504.01568v2



How To Measure $|V_{ub}|$

How V_{ub} is measured:

- Use exclusive decays:
  - $B \to \pi^{\pm}\mu^{\mp}\nu,\ \ B_s \to K^{\pm}\mu^{\mp}\nu,\ \ \Lambda_b \to p\mu\nu$
- Inclusive decays (Very difficult with LHCb)
  - $B^+ \to \tau^+\nu$X
- Annihilation decays:
  - $B^+ \to \mu^+\mu^-\mu^+\nu\,,\ \ B^+ \to \phi\mu^+\nu$

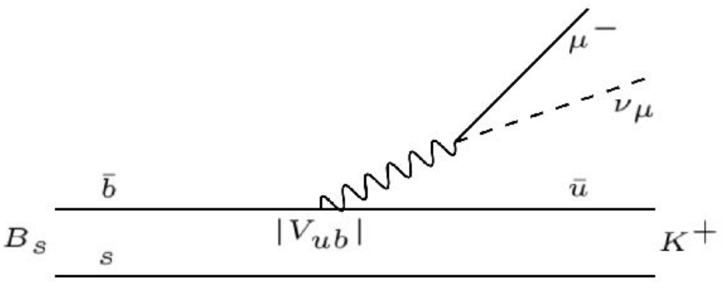


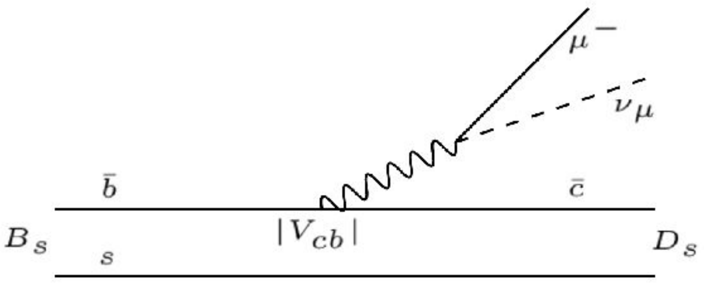
Exclusive type decay (left) and annihilation type (right).

How To Measure $|V_{ub}|$ at LHCb

- Measure $|V_{ub}|$ relative to $|V_{cb}|$:
    - Take the ratio of branching fractions, and combine with a theoretical input

$$\underbrace{\frac{\mathcal{B}(B_s^0 \to K^- \mu^+ \nu_\mu)}{\mathcal{B}(B_s^0 \to D_s^- \mu^+ \nu_\mu)}}_{\textbf{experimental measurement}} = \underbrace{R_{\mathrm{FF}}}_{\textbf{theoretical calculations}} \times \frac{|V_{ub}|^2}{|V_{cb}|^2}$$





Feynman diagram for the signal (left) and normalisation (right).

The Theory

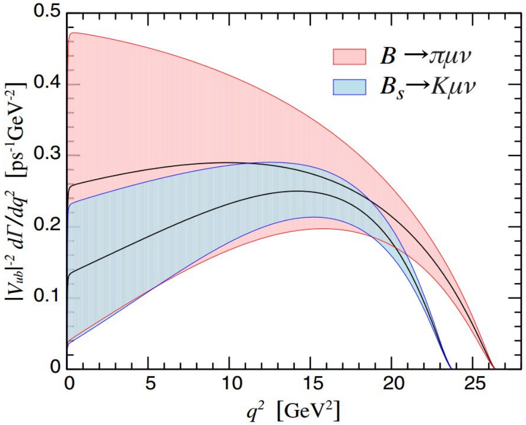
Theorists give us the form factors as a function of q^2.

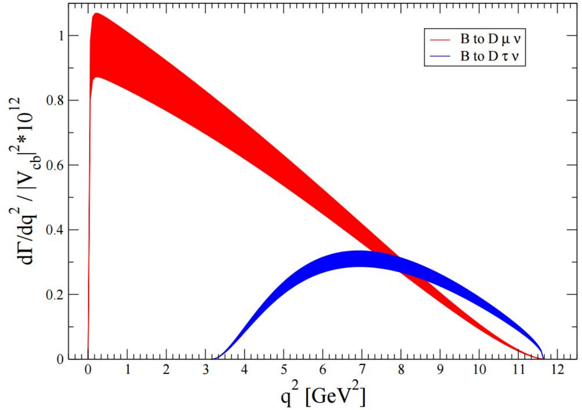
- $q^2 = (E_l + E_\nu)^2$

We measure this. → *We want this.* → *Theorists give us this.*

$$\frac{d\Gamma(B_{(s)}\to P\ell\nu)}{dq^2} = \frac{G_F^2|V_{ub}|^2}{24\pi^3}\frac{(q^2-m_\ell^2)^2\sqrt{E_P^2-M_P^2}}{q^4 M_{B_{(s)}}^2}\left[\left(1+\frac{m_\ell^2}{2q^2}\right)M_{B_{(s)}}^2(E_P^2-M_P^2)|f_+(q^2)|^2 + \frac{3m_\ell^2}{8q^2}(M_{B_{(s)}}^2-M_P^2)^2|f_0(q^2)|^2\right],$$

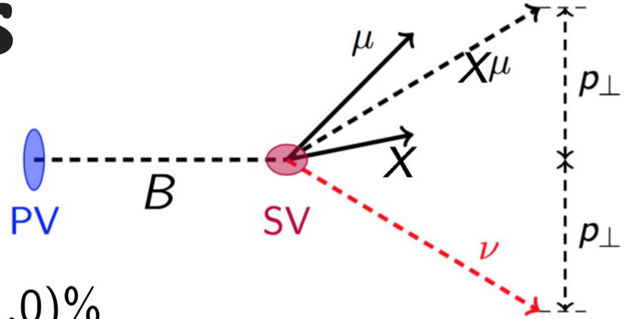
$0\ (m_\mu^2 \ll q^2)$





Theory form factor prediction for the signal (left, PhysRevD.91.07451) and control (right, PhysRevD.92.054510)

Semileptonic Decays

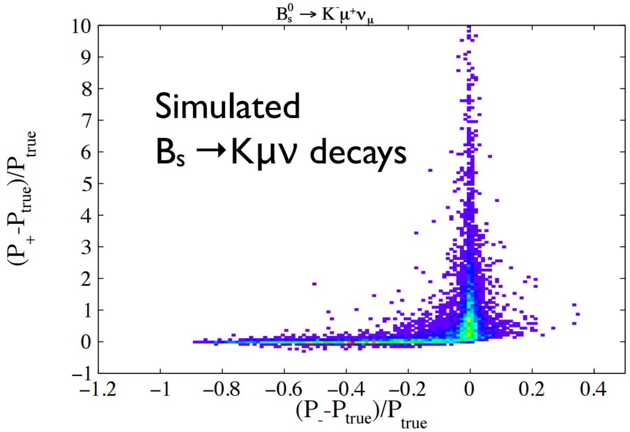


Semileptonic Decays

- B decays into $l\nu X$
- High statistics: $\mathcal{B}(B \to \mu\nu_\mu X) = (10.2 \pm 1.0)\%$
- Events are always partially reconstructed

Tools

- Use corrected mass:
  - $m_{corr} = \sqrt{m^2_{charm+\mu} + p^2_\perp} + p_\perp$
- Reconstruct neutrino momentum from the topology. (2-fold ambiguity)
- Use machine learning to help find the correct solution.



arxiv:1611.08522

Why $B_s \to K^- \mu^+ \nu$

Channel is theoretically very nice:

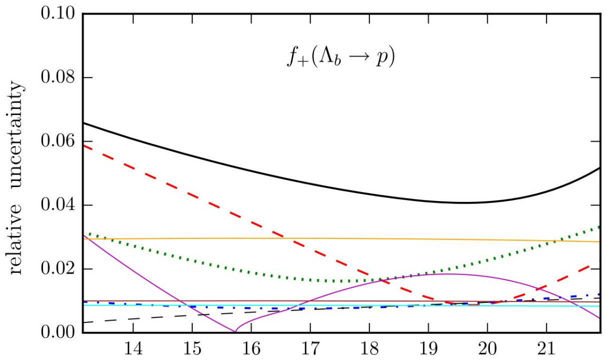
- Good form factor precision
- Control channel is very well understood:
  - $B_s \to D_s \mu^+ \nu$

However:

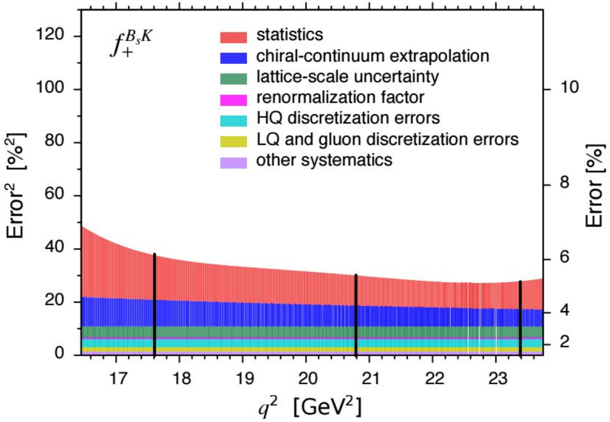
- There are many difficult backgrounds
- Statistics will be lower than $\Lambda_b \to p\mu\nu$

Decay	Λ_b^0	B_s^0
theory error	5%	3%
prod frac	20%	10%
BF	4×10^{-4}	1×10^{-4}
$\mathcal{B}(X_c)$ error	${}^{+5.3}_{-4.7}\%$	$\pm 3.9\%$
background	Λ_c^+	$\Lambda_c^+, D_s, D^+, D^0$

Table from Patrick Owen



$\Lambda_b \to p\mu\nu$ form factor error budget PhysRevD.92.034503



$B_s \to k\mu\nu$ form factor error budget arXiv:1501.05373

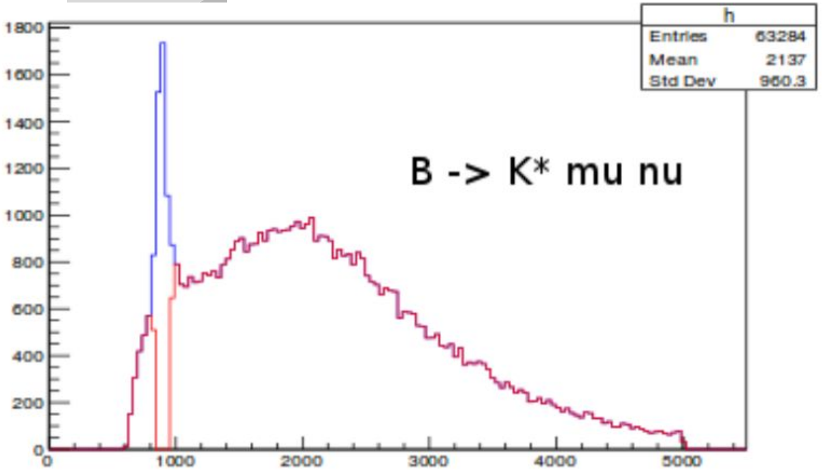
Backgrounds

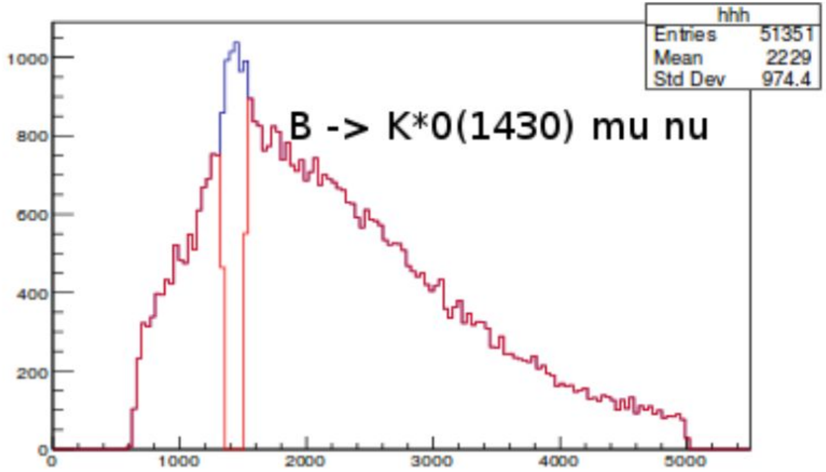
Several Sources of backgrounds:

- Additional charged tracks
  - e.g. $B^+ \to J/\psi K^+$, $B_s \to D_s \mu\nu$
- Additional neutral tracks
  - e.g. $B_s \to K^* \mu\nu (K^* \to K\pi^0)$
- Misidentified particles
  - e.g. $\Lambda_b \to p\mu\nu$, $J/\psi \to \mu^+\mu^-$
- Combinatorial
  - Random combination of kaon and muon.

Additional Neutral Tracks

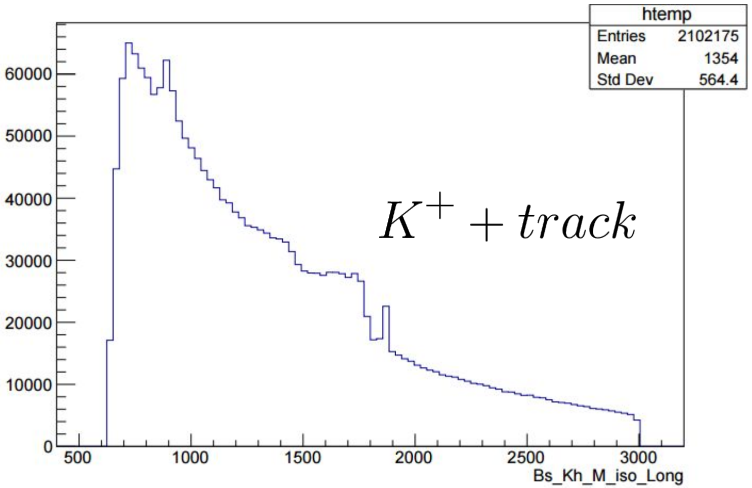
- Draw cones around track in ΔR.
- Search for hits in neutral calorimeters.
- Reconstruct photons or π^0 using existing tools.
- Veto event if high pion likelihood and $m(K^{\pm}\pi^{0}) \approx m(K^{*})$

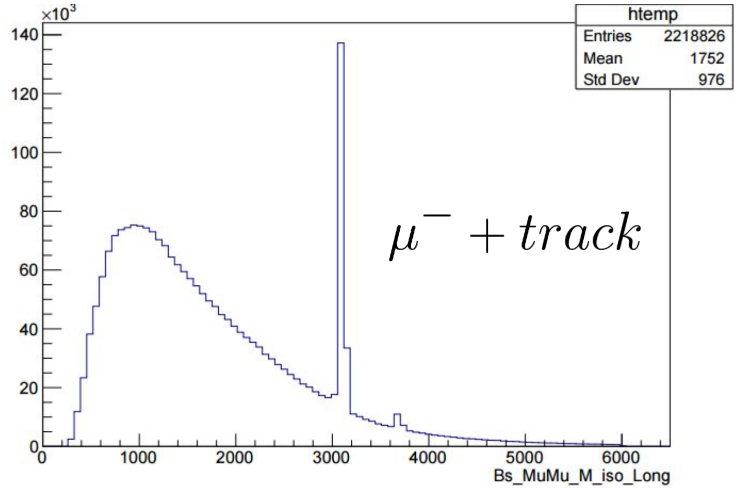




Non Isolated Charged Tracks

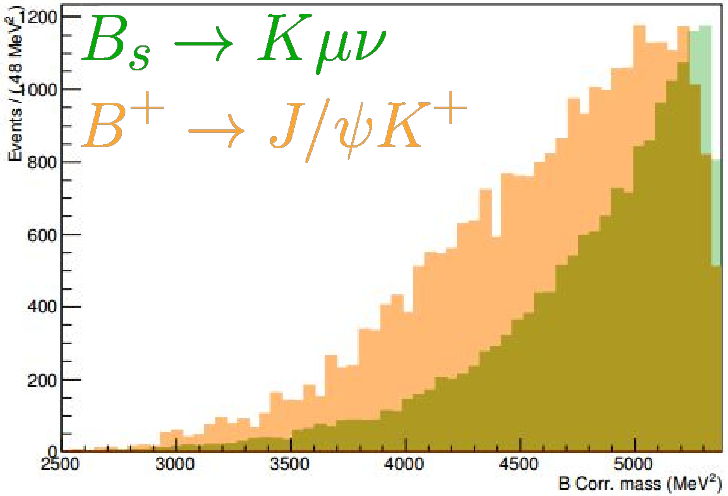
- Search through every track in event
  - Does the track originate from the same decay? (bad)
  - Or is the track isolated? (good)
- Use a previously trained BDT to find these tracks.

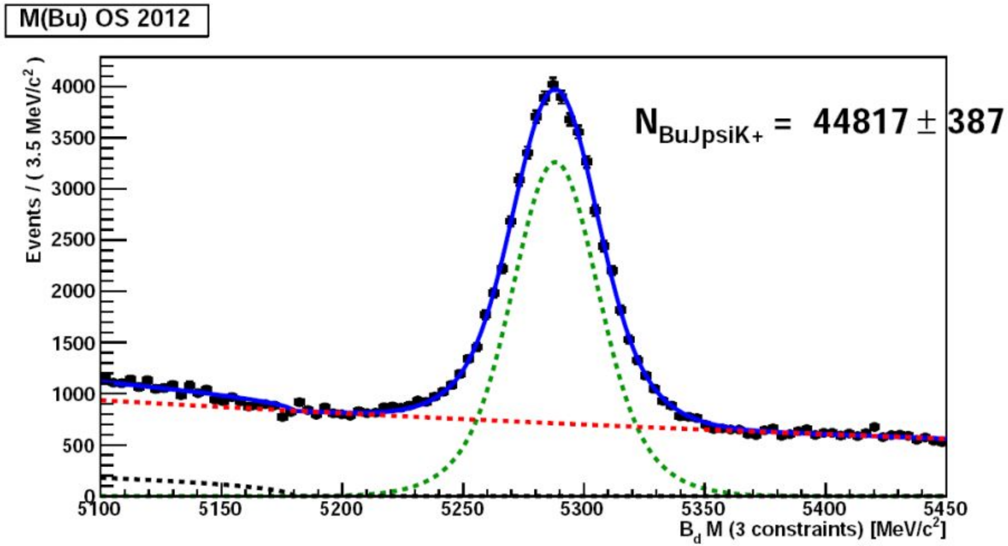




Signal Fit - Constraining Yields

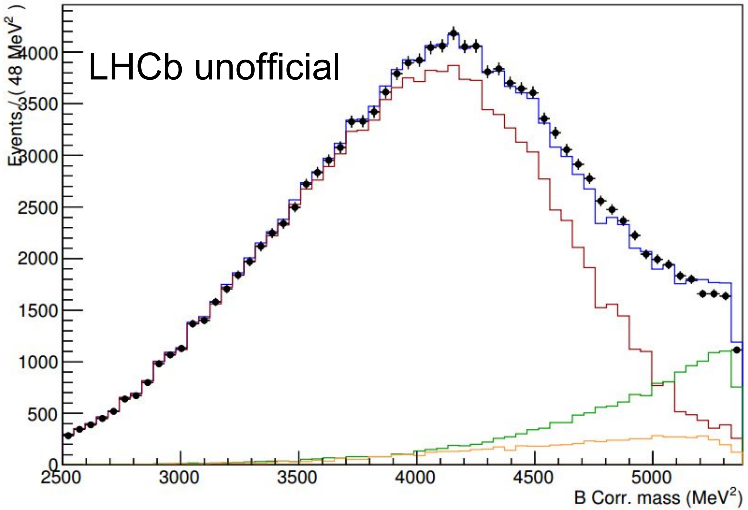
- $B^+ \to J/\psi K^+$ has a very similar shape to signal in corrected mass.
- Reconstruct B+ peak using least isolated track before selection.
- Calibrate B+ yield with efficiencies.
  - Fix $B^+ \to J/\psi K^+$ yield in the fit.





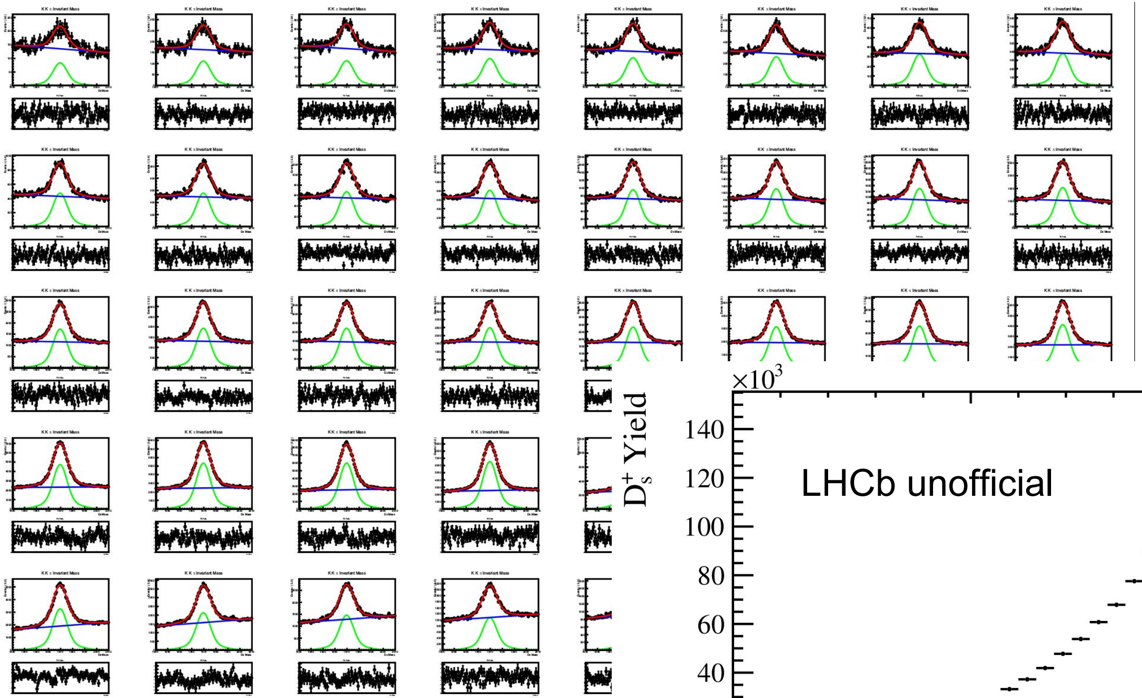
Signal Fit

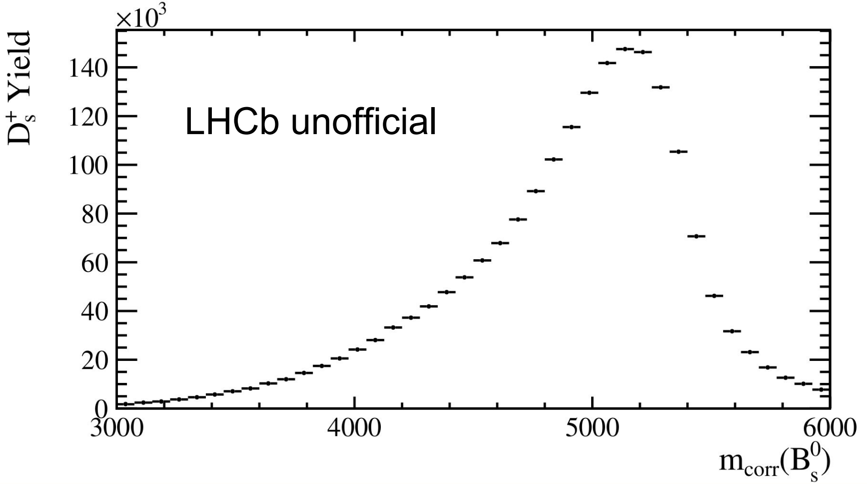
- Use the Beeston-Barlow “lite” template fitter.
  - Sums source templates to match the data.
  - Allows bin contents to vary within uncertainty.
- Templates determined from Monte Carlo.
- More backgrounds to be added.



+ Data
– Signal, $B_s \to K^- \mu^+ \nu$
– $B^+ \to J/\psi K^+$
– Combinatorial
– Model

Control Fit, Background Removal





Every point corresponds to a fit to the KKπ invariant mass.

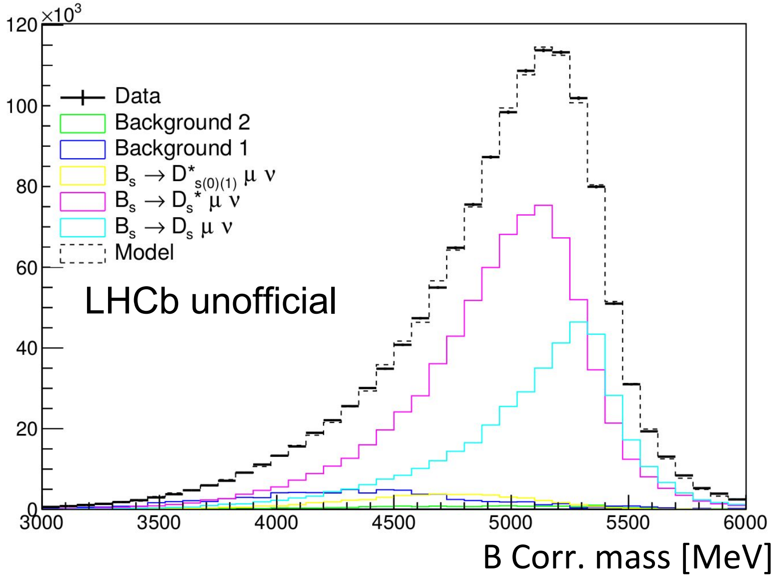
Only remaining combinatorial is D_s+μ.

Control Fit

- Uses the same Beeston-Barlow "lite" fitter.
- Combinatorial background almost entirely eliminated.
- Templates with similar shape are combined.

Backgrounds include:

- Excited D_s modes.
- Tauonic decays.
- B→Double charm.
- Same Sign, Fake μ.



Summary

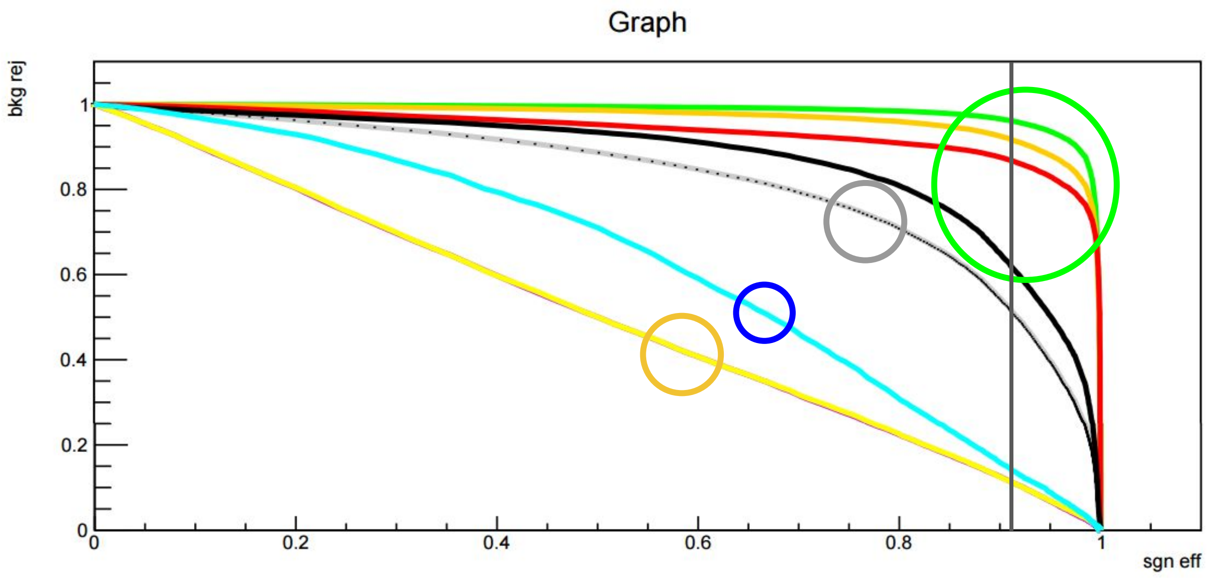
- LHCb has successfully measured $|V_{ub}|$ using $\Lambda_b \to p\mu\nu$
- Research into $|V_{ub}|$ has grown rapidly at LHCb.
- $B_s \to K^-\mu^+\nu$ aims to improve our understanding.
- Aim to have a result ready for summer conferences.

Thank You

Backup

Removing Charged Backgrounds

- Train BDT to discriminate against charged backgrounds
  - Signal: $B_s \to K^- \mu^+ \nu$ Monte Carlo.
  - Background: Weighted sum of MC and Same Sign data.
- Training variables include output of charged isolation tool, kinematics.



- Additional charged tracks
- Combinatorial
- Miss-ID
- Additional neutral track