Measurement of the Shape of the $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$ Differential Decay Rate

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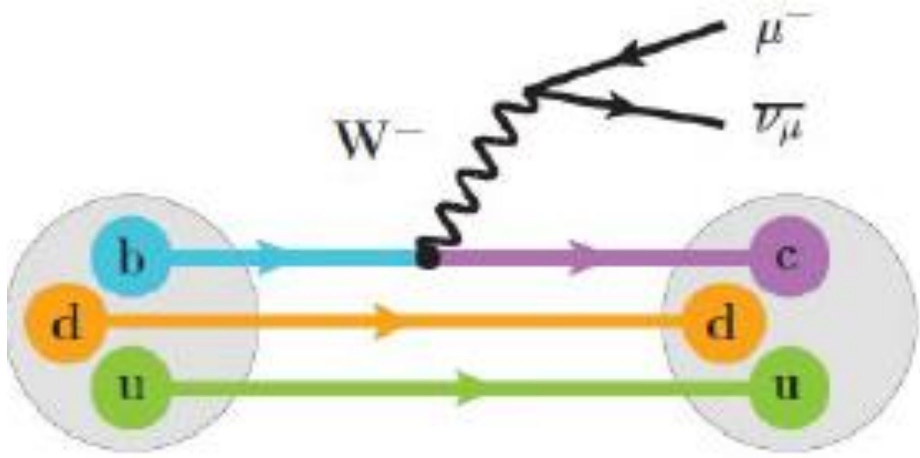
Motivation

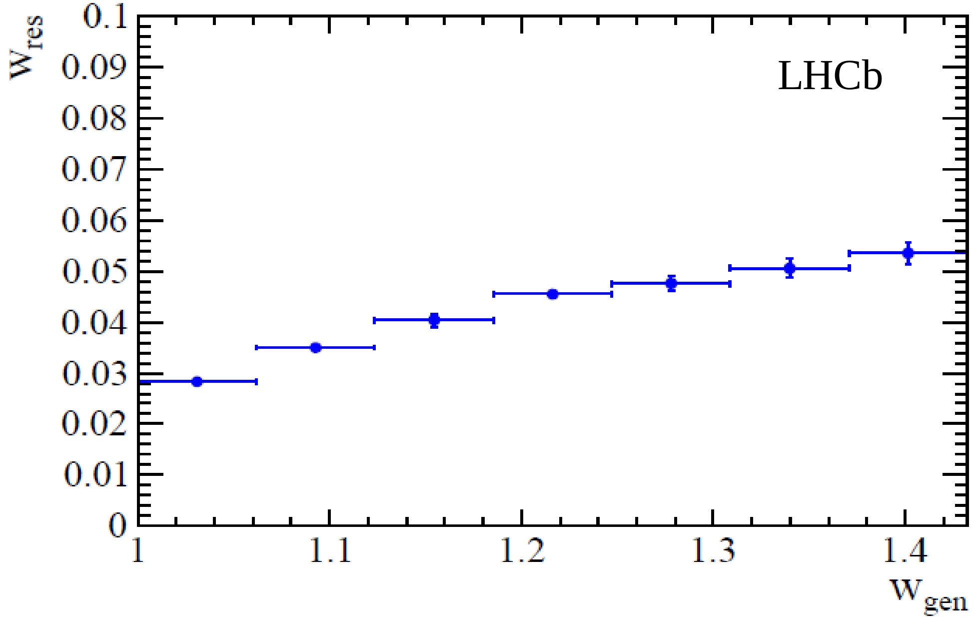
- Studies of semileptonic baryon decays such as $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$ can be used to make precision tests of the Standard model and possibly find evidence for new physics.
  - Heavy-flavored S.L. baryon decays are well suited to study CKM parameters, such as $|V_{cb}|$ and $|V_{ub}|$
- Isgur and Wise[1] provided the framework of Heavy Quark Effective Theory:
  - S.L. baryonic decays are generally described by 6 individual form factors
- In the "static approximation" $m_b, m_c \to \infty$, form factors can be described by a single function $\xi(w)$ [1].
- Recent Lattice-QCD calculations[2] predict dN/dq^2 which can aid in a precise determination of $|V_{cb}|$



$$w = v_{\Lambda_b} \cdot v_{\Lambda_c}$$
$$= (m^2_{\Lambda_b^0} + m^2_{\Lambda_c^+} - q^2)/(2m^2_{\Lambda_b^0} m^2_{\Lambda_c^+})$$

Neutrino Reconstruction

- Missing neutrino track requires special treatment: Λ_b^0 momentum can be calculated up to quadratic uncertainty by using vertex information and conservation of energy and momentum
- Lowest value solution of $\vec{p}_{\Lambda_b^0}$ is the correct solution for a majority of events
  - Differences in w_{meas} and w_{true} arise from limited detector resolution and choosing the incorrect $\vec{p}_{\Lambda_b^0}$ solution.
- $w_{res} = w_{meas} - w_{gen}$, fit with Crystal Ball function for each bin in w.

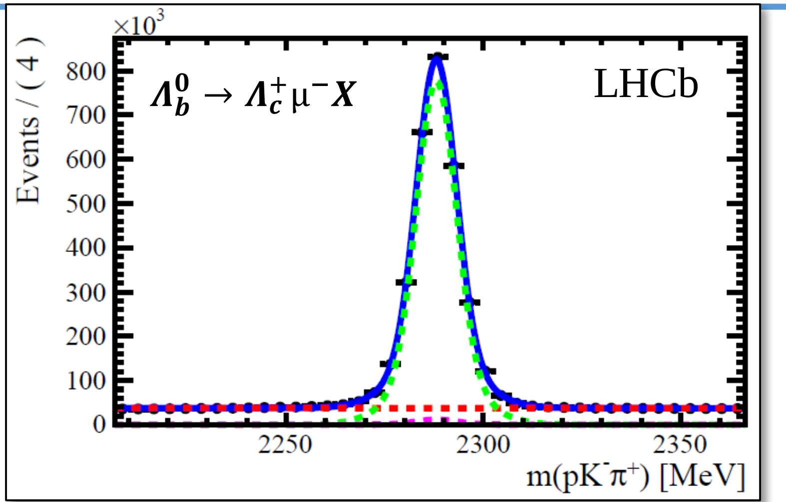


Analysis Strategy

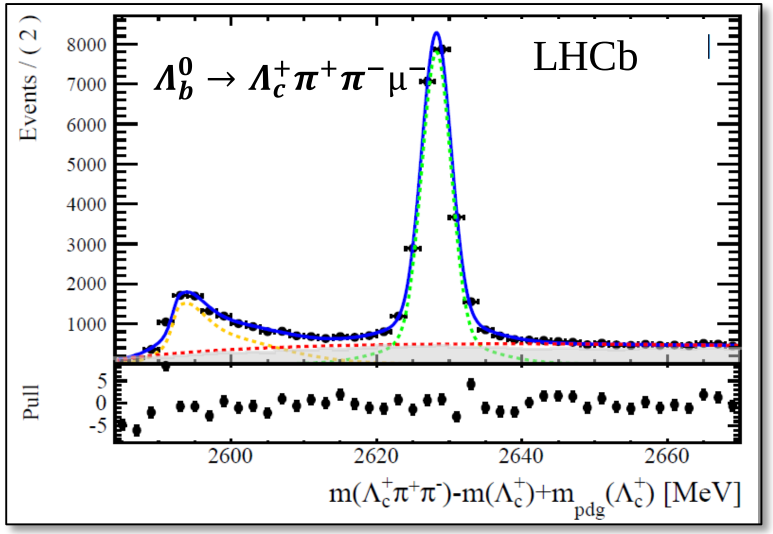
- Measure the raw inclusive yield $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu X$ with $\Lambda_c^+ \to pK^-\pi^+$, and subtract contributions from Λ_c^{*+} modes to get the exclusive yield.
  - Correct the exclusive $\Lambda_b^0 \to \Lambda_c^+ \mu^- \bar{\nu}_\mu$ yield for selection efficiencies using simulation
- Do the neutrino reconstruction
- Unfold the spectrum ${}^{dN}/_{dw}$ to the true distribution
- Fit the spectrum ${}^{dN}/_{dw}$ using HQET prediction for $\xi(w)$
- Repeat the procedure binning in q^2 to compare with Lattice-QCD calculations

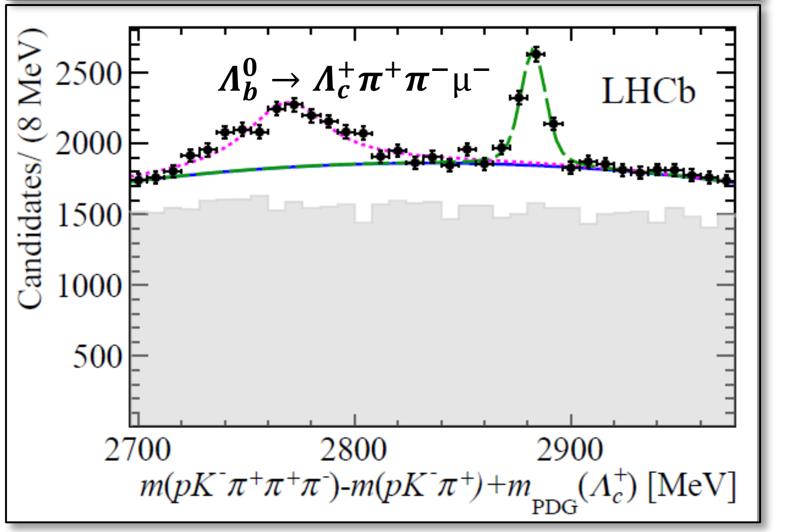
Mass Spectra

- Full 2011 + 2012 datasets corresponding to 3fb^{-1} integrated luminosity
- Simultaneous fit to $m(pK^-\pi^+)$ and ln(IP/mm) to determine the **inclusive** $\boldsymbol{\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu X}$ **yield**, including prompt & combinatoric backgrounds.
- Λ_c^+ candidates within ±20MeV of $m_{PDG}(\Lambda_c^+)$ are combined $\pi^+\pi^-$ tracks to determine yields from Λ_c^{*+} modes
- Subtract Λ_c^{*+} yields to obtain the exclusive $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu$ yield, binned in w.



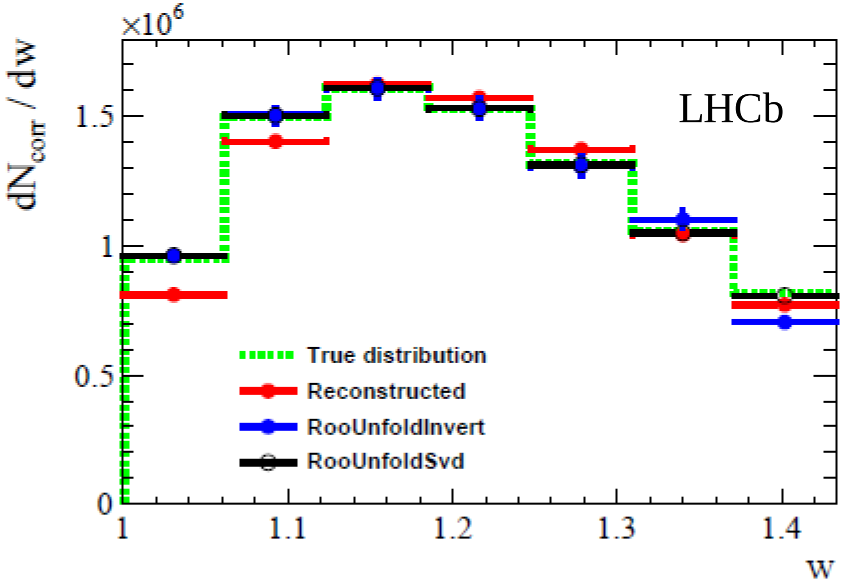
Final state	Yield
$\Lambda_c(2595)^+\mu^-\overline{\nu}_\mu$	8569 ± 144
$\Lambda_c(2625)^+\mu^-\overline{\nu}_\mu$	22965 ± 266
$\Lambda_c(2765)^+\mu^-\overline{\nu}_\mu$	2975 ± 225
$\Lambda_c(2880)^+\mu^-\overline{\nu}_\mu$	1602 ± 95
$\Lambda_c^+\mu^-\overline{\nu}_\mu X$	$(2.74\pm0.02)\times10^6$





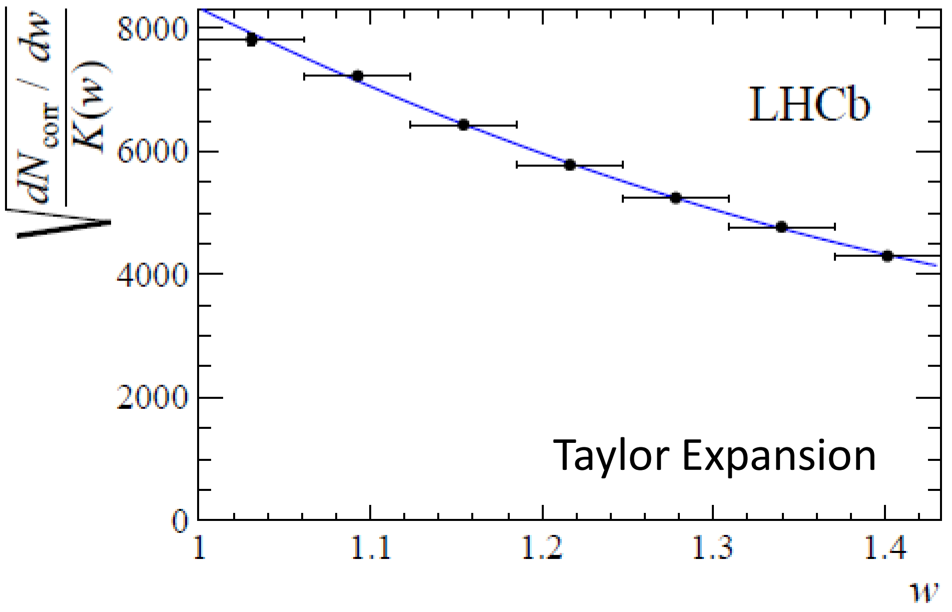
Determining the Unfolded Spectrum

- In order to compare with theoretical models, it is necessary to unfold the w_{meas} to the true distribution to account for smearing induced by the finite resolution.
- Unfolding procedure is based on the SVD regularization method[12], accomplished using the RooUnfold package
  - Full covariance matrix is produced, used in subsequent fit of Isgur-Wise function
  - R_{ij} gives the fraction of events in bin $w_{i,gen}$ that end up in bin $w_{j,meas}$
- Unfold from 14 bins of w_{meas} to 7 bins of w_{gen}



The Isgur-Wise Function Shape

- In the static approximation (m_b & $m_c \rightarrow \infty$), the 6 F.F.'s describing Λ_b^0 decays are characterized by a **single function ξ(w)**[1]
- Function is $\sqrt{{}^{dN}/_{dw}}$ divided by a kinematic factor $K(w)$
- Theory-motivated expressions for $\xi(w)$ are fit to the data to determine slope at zero recoil (ρ^2) and curvature (σ^2): Exponential[3] and Dipole[4]
- Also perform a Taylor expansion to study the kinematic limit ($w = 1$)
    - Only minor corrections in (${}^{1}/_{m_b}, {}^{1}/_{m_c}$) expected[5]



$$\xi_B(w) = 1 - \rho^2(w-1) + \frac{\sigma^2}{2}(w-1)^2$$

Comparison with Theory Predictions

- Taylor expansion is in good agreement with theoretical predictions:

- Bound on $\rho^2 \geq {}^3/_4$ from Ref.9
- Curvature **within uncertainties** consistent with lower bound: $\sigma^2 \geq {}^3/_5\,[\rho^2 + (\rho^2)^2]$ from Ref. 10

Theory Prediction for the slope of $\xi(w)$

ρ^2	Approach	Reference
1.35 ± 0.13	QCD Sum Rules	[6]
$1.2^{+0.8}_{-1.1}$	Lattice-QCD (static approximation)	[7]
1.51	HQET	[8]

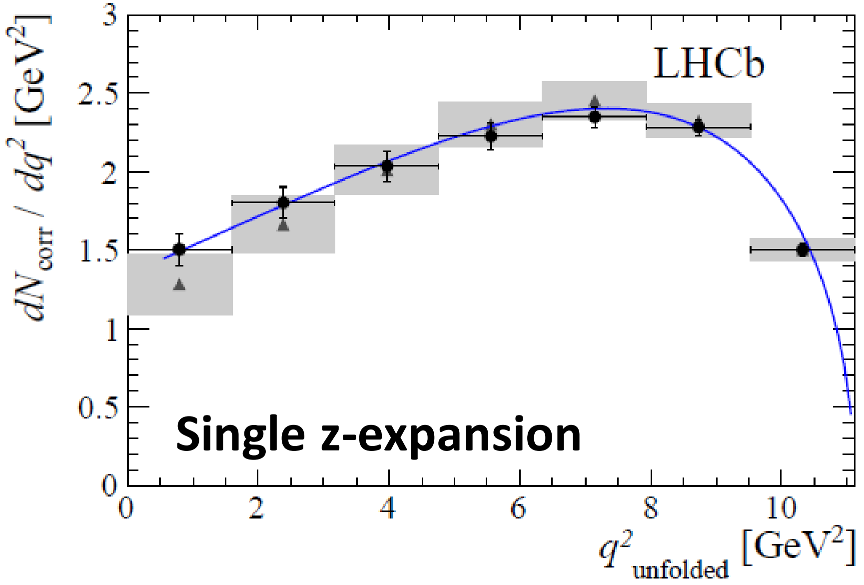
Our Fit Results for the slope and curvature of $\xi(w)$

Fit Shape	ρ^2	σ^2	Correlation Coefficient	χ^2/DOF
Exponential*	1.65 ± 0.03	2.72 ± 0.10	100%	5.3/5
Dipole*	1.82 ± 0.03	4.22 ± 0.12	100%	5.3/5
Taylor Series	1.63 ± 0.07 ± 0.08	2.16 ± 0.34	97%	4.5/4

*Only ρ^2 is floating in the fit, σ^2 determined from the fitted slope

Comparison with Lattice-QCD

- Recent Lattice-QCD calculations[2] predict the 6 F.F.'s for Λ_b^0 decays in terms of q^2
  - Simplest check on the theory: Compare measured $d\Gamma/dq^2$ with predicted spectrum
  - $d\Gamma/dq^2$ related to dN/dq^2 by a constant term including $|V_{cb}|^2$
- We derive dN/dq^2 exactly as we did for w, and perform a χ^2 fit to this distribution using the function described in Ref. 2, with only the overall normalization floating.



- Lattice-QCD calculations do not allow for a simple extrapolation to the static limit:
  - We check the consistency with the static approximation assuming all 6 F.F.'s are proportional to a single z-expansion function[11]
  - Resulting fit yields a P-value = 87%, static appx. is OK

Fit Method	χ^2/DOF
Nominal (normalization floating)	1.32
Single z-expansion	1.85

Conclusions

- A precise measurement of the Isgur-Wise function shape for the decay $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \bar{\nu}_\mu$ has been performed.
- The slope and curvature of $\xi(w)$ are consistent with theory predictions from:
  - QCD sum rules
  - Older Lattice-QCD calculations with large uncertainties
  - HQET
- Study of dN/dq^2 is consistent with Lattice-QCD calculations, which will allow for a precise determination of $|V_{cb}|$

Thank You

References and backup slides follow

References

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Isgur-Wise Shapes

- ıThe differential decay width is related to the IW function ξ(w) by:

  $$\frac{d\Gamma}{dw} = GK(w)\xi_B^2(w),$$

  where G is a constant term including $|V_{cb}|^2$ and K(w) is a kinematic function.

- The IW function is fit parameterized in 3 ways:

  Exponential: $\xi_B(w) = \ \xi_B(1)e^{[-\rho^2(w-1)]}$

  Dipole: $\xi_B(w) = \ \left({}^{2}/_{w+1}\right)^{2\rho^2}$

  Taylor Expansion: $\xi_B(w) = 1 - \rho^2(w-1) + \frac{\sigma^2}{2}(w-1)^2$

- Curvature is a free parameter only in the Taylor expansion. It is extracted by $\xi_B''(w)$ for the Exponential and Dipole fits.

Single z-expansion

- $d\Gamma/dq^2$ is expressed in terms of 6 independent form factors[2]: $f_{+,0,\perp}$ and $g_{+,0,\perp}$
- Form factors are expressed in terms of the z-expansion[11]:

$$f(q^2) = \frac{1}{1 - q^2/(m^f_{pole})^2} \times [a_0^f + a_1^f z^f(q^2)]$$

- a_0^f and a_1^f are allowed to float in our fit.

Nominal Function

$$\begin{aligned}\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} &= \frac{G_F^2|V_{cb}|^2\sqrt{s_+s_-}}{768\pi^3 m^3_{\Lambda_b^0}}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \\ &\times\Big\{4\left(m_\ell^2+2q^2\right)\left(s_+[g_\perp(q^2)]^2+s_-[f_\perp(q^2)]^2\right) \\ &+2\frac{m_\ell^2+2q^2}{q^2}\left(s_+\left[\left(m_{\Lambda_b^0}-m_X\right)g_+(q^2)\right]^2+s_-\left[\left(m_{\Lambda_b^0}+m_X\right)f_+(q^2)\right]^2\right) \\ &+\frac{6m_\ell^2}{q^2}\left(s_+\left[\left(m_{\Lambda_b^0}-m_X\right)f_0(q^2)\right]^2+s_-\left[\left(m_{\Lambda_b^0}+m_X\right)g_0(q^2)\right]^2\right)\Big\},\end{aligned}$$

Reduced Function for single z-expansion

$$\begin{aligned}\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} &= \frac{G_F^2|V_{cb}|^2\sqrt{s_+s_-}}{768\pi^3 m^3_{\Lambda_b^0}}\left(1-\frac{m_\ell^2}{q^2}\right)^2 g_\perp^2(q^2) \\ &\times\Big\{4\left(m_\ell^2+2q^2\right)\left(s_++s_-\right) \\ &+\frac{4}{q^2}\left[s_+\left(m_{\Lambda_b^0}-m_X\right)^2+s_-\left(m_{\Lambda_b^0}+m_X\right)^2\right]\left[2m_\ell^2+q^2\right]\Big\}\end{aligned}$$