Beauty decays as a probe of fundamental physics: the synergy between LHCb & lattice QCD

A blueprint for discussion
Marina Artuso
based on results by the LHCb collaboration
Some “case studies” will be presented to motivate brainstorming on future opportunities.

Experimental details on the measurements presented will be uneven.

This talk is not meant as a compendium of LHCb contributions to flavor physics!
LATTICE INPUT TO MEASURE QUARK MIXING PARAMETERS $V_{ub}$ AND $V_{cb}$
$V_{xb}$ and semileptonic $b$ decays

Illustration focused on $V_{ub}$, change $u \rightarrow c$ for $V_{cb}$.

What we want to know

Experimental observables

Lattice QCD, LC sum rules, HQE...

\[ |V_{ub}|^2 \times \text{Hadronic matrix element} \times \text{(known factors)} \]

$q^2 = m^2(\mu \nu)$

"exclusive" study a specific final state

"inclusive" study an inclusive property of the decay ($E_\mu$, $M_{\text{had}}$, $q^2$)
Tension between inclusive and exclusive determinations of $V_{xb}$

<table>
<thead>
<tr>
<th></th>
<th>Inclusive</th>
<th>Exclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{cb}$</td>
<td>$(42.2\pm0.6)\times10^{-3}$</td>
<td>$(39.5\pm0.8)\times10^{-3}$</td>
</tr>
<tr>
<td>$V_{ub}$</td>
<td>$(4.41\pm0.15^{+0.15}_{-0.17})\times10^{-3}$</td>
<td>$(3.28\pm0.29)\times10^{-3}$</td>
</tr>
</tbody>
</table>

- Failure LQCD & Sum rules to predicted exclusive form-factors correctly?
- Failure of the HQE to evaluate the hadronic matrix element correctly?
- New physics?

*Additional information needed!*
Why $\Lambda_b$ semileptonic decays?

- Use of $b$-baryon decays provides complementary information to $B$ mesons.
- At LHCb $\Lambda_b$ are produced copiously.

$\Lambda_b^0$ decays:

$$W^- \rightarrow \mu^- + \bar{v}_\mu$$

$\Lambda_b$ decay:

$$W^- \rightarrow \mu^- + \bar{v}_\mu$$
1) Kinematic constraints allow determination of magnitude of $\Lambda_b$ momentum (modulo 2-fold ambiguity)

2) LHCb determines the ratio $\Lambda_b \rightarrow p\mu\nu/\Lambda_b \rightarrow \Lambda_c\mu\nu$ in high $q^2$ region
   $\Rightarrow$ Minimize background from Cabibbo favored decays in $\Lambda_b \rightarrow p\mu\nu$
   $\Rightarrow$ Use region where lattice predictions are expected to be more reliable

3) Use normalization factor derived from Lattice QCD calculation to extract $|V_{ub}/V_{cb}|^2$
Cabibbo favored decays typically have additional tracks forming a good secondary vertex with the proton emitted in the semileptonic decay $\Rightarrow$ train multivariate classifier to distinguish between these two configurations, get 90% rejection & 80% efficiency.
Displaced vertex information allow to define the corrected mass

\[ M_{\text{corr}} = \sqrt{M_{\mu\nu}^2 + p_{\perp}^2 + p_{\perp}^2} \]

\( M_{\text{corr}} \) is used to disentangle different fit components

Uncertainty in \( M_{\text{corr}} \) is used to discriminate between signal and background

\[ M_{\text{corr}} \text{ peaks at } \Lambda_b \text{ mass!} \]
The signal fits

\[ N(\Lambda_b \rightarrow p\mu\nu) = 17687 \pm 733 \]

\[ N(\Lambda_b \rightarrow \Lambda_c\mu\nu) = 34255 \pm 571 \]

Candidates / (50 MeV/c^2)

Corrected \( p\mu^- \) mass [MeV/c^2]

Candidates / (40 MeV/c^2)

Corrected \( pK^-\pi^+\mu^- \) mass [MeV/c^2]
Experimental result

$$R_{\text{exp}} \equiv \frac{B(\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu)_{q^2 > 15 \text{ GeV}^2}}{B(\Lambda_b^0 \rightarrow \Lambda_c^+\mu^-\bar{\nu}_\mu)_{q^2 > 7 \text{ GeV}^2}} = \left(1.0 \pm 0.04(\text{stat}) \pm 0.08(\text{syst}) \right) \times 10^{-2}$$

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B(\Lambda_c^+ \rightarrow pK^+\pi^-)$</td>
<td>+4.7</td>
</tr>
<tr>
<td>Trigger</td>
<td>-5.3</td>
</tr>
<tr>
<td>Tracking</td>
<td>3.2</td>
</tr>
<tr>
<td>$\Lambda_c^+$ selection efficiency</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Lambda_b^0 \rightarrow N^*\mu^-\bar{\nu}_\mu$ shapes</td>
<td>2.3</td>
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<tr>
<td>$\Lambda_b^0$ lifetime</td>
<td>1.5</td>
</tr>
<tr>
<td>Isolation</td>
<td>1.0</td>
</tr>
<tr>
<td>Form factors</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Lambda_b^0$ kinematics</td>
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<tr>
<td>$q^2$ migration</td>
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<tr>
<td>Particle Identification Efficiency</td>
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<tr>
<td>Total</td>
<td>+7.8</td>
</tr>
<tr>
<td></td>
<td>-8.2</td>
</tr>
</tbody>
</table>

arXiv:1504:01568
Most recent calculation uses 2+1 flavors of dynamical domain-wall fermions, RBC & UKQCD configurations & $q^2$ dependence parameterized with $z$-expansion

- LHCb uses $q^2 > 15$ GeV$^2$ for $\Lambda_b \rightarrow p \mu^+ \bar{\nu}_\mu$ and $q^2 > 7$ GeV$^2$ for $\Lambda_b \rightarrow \Lambda_c \mu^+ \bar{\nu}_\mu$

⇒ Most reliable theory prediction
\[ R_{TH} \equiv \frac{1}{|V_{ub}|^2} \int_{q_{\text{max}}^2}^{15 \text{GeV}^2} \frac{d\Gamma(\Lambda_b^0 \rightarrow p\mu\bar{\nu}_\mu)}{dq^2} = \frac{1}{|V_{cb}|^2} \int_{q_{\text{max}}^2}^{7 \text{GeV}^2} \frac{d\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^0\mu\bar{\nu}_\mu)}{dq^2} = \frac{(12.31 \pm 0.76 \pm 0.77) \text{ps}^{-1}}{(8.37 \pm 0.16 \pm 0.34) \text{ps}^{-1}} = 1.471 \pm 0.095 \pm 0.110 \]

4.9% theoretical error on \(|V_{ub}/V_{cb}|\)

\[ \frac{\Gamma(\Lambda_b^0 \rightarrow p\mu\bar{\nu}_\mu)}{|V_{ub}^2|} = (25.7 \pm 2.6 \pm 4.6) \text{ps}^{-1} \]

\[ \frac{\Gamma(\Lambda_b^0 \rightarrow \Lambda_c^0\mu\bar{\nu}_\mu)}{|V_{cb}^2|} = (21.5 \pm 0.8 \pm 1.1) \text{ps}^{-1} \]

Using the full \(\Gamma_c\) width, theoretical error on \(|V_{cb}| 3.2\%, \) using \(\Gamma_c\) in \(q^2 \geq 7 \text{GeV}^2\) region, theoretical error 2.2%
Using:

\[ V_{ub} = V_{cb}^{\text{excl}} \sqrt{R_{\text{exp}} / R_{TH}} = V_{cb}^{\text{excl}} \sqrt{(1.0 \pm 0.04 \pm 0.08) \times 10^{-2}} \]

\[ \frac{1.471 \pm 0.095 \pm 0.110}{V_{cb}^{\text{norm.}}} \]

and

\[ |V_{cb}^{\text{excl}}| = (39.5 \pm 0.8) \times 10^{-3} \quad \text{PDG2014} \]

LHCb gets:

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

Next: study different \( q^2 \) regions
Compilation and fit
by A. Kronfeld

\[ |V_{tb}| \text{ current status} \]

\[ 10^3 |V_{ub}| \]

\[ 10^3 |V_{cb}| \]

- \( |V_{ub}|, |V_{cb}| \) (latQCD + LHCb)
- \( |V_{ub}| \) (latQCD + BaBar + Belle)
- \( |V_{cb}| \) (latQCD + BaBar + Belle)
- \( |V_{cb}| \) (latQCD + HFAG, \( w = 1 \))
- \( p = 0.19 \)
- \( \Delta \chi^2 = 1 \)
- \( \Delta \chi^2 = 2 \)
- inclusive \( |V_{tb}| \)

predictions w/o \( V_{ub} \) & \( V_{cb} \)
Utfit eps2015
THEORY VALIDATION
Quoting A. Kronfeld “Any large scale computer endeavor is a bit inscrutable, so it becomes more persuasive if the code’s combination of principle and pragmatism can make predictions”

How can we do more?
Remembering the good old times

Predictions with Lattice QCD

Fermilab Lattice, MILC, and HPQCD Collaborations

Semileptonic D Decays
(Fermilab Lattice, MILC, and HPQCD Collaborations)

When our paper was posted on the arXiv, we knew the normalization of the $D \to \pi\nu$ and $D \to K\nu$ form factors agreed with measurements from the BES Collaboration and the CLEO Collaboration. This agreement had been seen throughout the cycle of conference proceedings and journal publications. So this is almost, but not quite, a prediction.

More spectacularly, two months after our paper was posted on the arXiv, the FOCUS Collaboration finished a measurement of the shape of the $D \to K\nu$ form factor. Their data are plotted over our curve (with 1 and 2σ bands) and agree excellently.

Leptonic D Decays
(Fermilab Lattice, MILC, and HPQCD Collaborations)

QCD’s influence on the leptonic decay $D_{(s)} \to K\nu$ is parameterized by decay constants $f_D$ and $f_{D_s}$. Until 2005, the only measurements were based on only a few events and had, hence, uncertainties of 20–60%.

For the 2005 Lepton-Photon Symposium, CLEO-c planned to announce a measurement of $f_D$ with 5–10% uncertainty. The challenge to (lattice) QCD was set.

We took up the challenge, finding [hep-lat/0506030]

$$f_D = 201 \pm 3 \pm 17 \text{ MeV},$$
$$f_{D_s} = 249 \pm 3 \pm 16 \text{ MeV}.$$

Afterwards, CLEO-c showed its new result. With 47 ± 8 events [hep-ex/0508057]

$$f_D = 223 \pm 17 \pm 3 \text{ MeV}.$$

At this year’s Moriond Winter Conference, the BaBar Collaboration showed a nice measurement of $f_{D_s}$ [http://moriond.in2p3.fr/EW2006/Transparencies/], W. Berryhill.pdf:

$$f_{D_s} = 279 \pm 17 \pm 20 \text{ MeV}.$$

Mass of $B_c$ Meson
Ian F. Allison, Christine T.H. Davies, Alan Gray, Andreas S. Kronfeld, Paul B. Mackenzie, James N. Simone
(H PQCD and Fermilab Lattice Collaborations)

The $B_c$ meson consists of a bottom quark and a charmed antiquark. It was first observed by CDF during Run I of the Tevatron. The decay mode was $B_c \to J/\psi K^*$, the neutrino was missed, so the mass resolution was ± 400 MeV. D0 confirmed the observation in Run 2, also in semileptonic decay.

From B Physics at the Tevatron: Run II and Beyond [hep-ph/0201071], it was clear that nonleptonic modes would be much, much better.

At Lattice 2004, we presented results that were in almost final form. By mid-November, we posted our paper on the arXiv:

$$m_{B_c} = 6304 \pm 12 \pm 18 \pm 0 \text{ MeV}.$$

Later, CDF presented evidence for $B_c \to J/\psi K^*$ decay, reconstructing a mass [hep-ex/0505076]

$$m_{B_c} = 6287 \pm 5 \text{ MeV}.$$

Our result is based on computing the mass splitting $\Delta q \gamma = m_{B_c} - \left( m_{J/\psi} + m_K \right)/2$, which is astonishingly flat as a function of lattice spacing.
Examples on where we can follow this path

Placeholder for $\Lambda_b \rightarrow \Lambda_c \mu^- \bar{\nu}_\mu$

Study currently under review within the collaboration:

- note access to full $q^2$ (w) region
- Final result with 3fb-1
- With normalization mode & lattice input $|V_{cb}|$

arXiv:1503.01421v3 Detmold, Lehner, Meinel

arXiv:1111.2357 $L=3\text{pb}^{-1}$
HADRONIC MATRIX ELEMENT AND NEW PHYSICS
In B rest frame, three key kinematic variables:

- \( m_{\text{miss}}^2 \)
- \( q^2 = (p_\ell + p_\nu)^2 = m_{W^*}^2 \)
- \( E_\ell^*/|p_\ell^*| \)

\( B^0 \rightarrow D^{*+} \tau^- \nu \)

\[ m_{\text{miss}}^2 > 0 \]
\[ m_{\text{miss}}^2 = 0 \]

\( E_\ell^* \) spectrum is soft
\( E_\ell^* \) spectrum is hard

\[ m_\ell^2 \leq q^2 \leq 10.6 \text{ GeV}^2 \]
\[ \approx 0 \leq q^2 \leq 10.6 \text{ GeV}^2 \]

- Approximation to determine B momentum \((\gamma \beta_z)_B \sim (\gamma \beta_z)_{D^*\mu}\)
  (18% B momentum resolution, moderate effect on relevant kinematic variables)

- Use isolation TMVA to discriminate between signals and variety of backgrounds
B momentum approximation

MC B momentum

Approximate B momentum

\[ \mu \]

\[ \tau \]

\[ m^2_{\text{miss}}(GeV^2) \]

\[ E^\mu_{CM}(MeV) \]

\[ q^2(GeV^2) \]
**B → D*τν fit**

Fit in 4 $q^2$ bins: fit variables $E_m$(CM) & $m_{miss}^2$:
- templates for each component using approximate B momentum

LHCb-PAPER-2015-025
arXiv:1506.08614
# Systematic uncertainties

<table>
<thead>
<tr>
<th>Model uncertainties</th>
<th>Absolute size ( \times 10^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>2.0</td>
</tr>
<tr>
<td>Misidentified ( \mu ) template shape</td>
<td>1.6</td>
</tr>
<tr>
<td>( \overline{B}^0 \to D^{*+}(\tau^-/\mu^-)\overline{\nu} ) form factors</td>
<td>0.6</td>
</tr>
<tr>
<td>( \overline{B} \to D^{*+}H_c(\to \mu\nu X')X ) shape corrections</td>
<td>0.5</td>
</tr>
<tr>
<td>( \mathcal{B}(\overline{B} \to D^{<strong>}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B} \to D^{</strong>}\mu^-\overline{\nu}_\mu) )</td>
<td>0.5</td>
</tr>
<tr>
<td>( \overline{B} \to D^{**}(\to D^{*\pi\pi})\mu\nu ) shape corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Corrections to simulation</td>
<td>0.4</td>
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<tr>
<td>Combinatorial background shape</td>
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<tr>
<td>( \overline{B} \to D^{**}(\to D^{*\pi})\mu^-\overline{\nu}_\mu ) form factors</td>
<td>0.3</td>
</tr>
<tr>
<td>( \overline{B} \to D^{*+}(D_s \to \tau\nu)X ) fraction</td>
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<tr>
<td><strong>Total model uncertainty</strong></td>
<td>2.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalization uncertainties</th>
<th>Absolute size ( \times 10^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated sample size</td>
<td>0.6</td>
</tr>
<tr>
<td>Hardware trigger efficiency</td>
<td>0.6</td>
</tr>
<tr>
<td>Particle identification efficiencies</td>
<td>0.3</td>
</tr>
<tr>
<td>Form-factors</td>
<td>0.2</td>
</tr>
<tr>
<td>( \mathcal{B}(\tau^- \to \mu^-\overline{\nu}<em>\mu\nu</em>\tau) )</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td><strong>Total normalization uncertainty</strong></td>
<td>0.9</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>3.0</td>
</tr>
</tbody>
</table>
In progress at LHCb $B \rightarrow D^{(*)}\tau\nu$, with $\tau \rightarrow 3\pi(\pi^0)$
Combined R(D*) data

\[ \rho = -0.29 \]

\[ R_{D^*}^{\text{ave}} = 0.322 \pm 0.022 \]

\[ R_{D}^{\text{ave}} = 0.391 \pm 0.050 \]

Plot and average from HFAG

SM p-value \(1.1 \times 10^{-4} \sim 3.9\sigma\)
Lepton flavor violation in $B \rightarrow K^{(*)}\ell\bar{\ell}$? 

$$R_K = \frac{B(B^0 \rightarrow K^{*0} \mu^+\mu^-)}{B(B^0 \rightarrow K^{*0} e^+e^-)}$$

LHCb

(Left: electron triggered category)

PRL 113 (2014) 151601
Similar to $K^*\gamma$, but more decay paths

Several variables can be examined, e.g. muon forward-backward asymmetry, $A_{FB}$ is well predicted in SM

Not all the variables are equal! The never ending struggle to tame strong interaction effects!
New observables in $B \to K^{(*)} \pi^+ \pi^-$

Goal: express differential decay rate in terms of parameters that are less sensitive to the hadronic matrix element uncertainty $\Leftrightarrow$ prevent NP from hiding under strong interaction effects
The $P'_5$ anomaly in the decay $B \to K^{(*)} \mu^+ \mu^-$

- $3.7\sigma$ discrepancy with respect to the Standard Model in the region $4.3 < q^2 < 8.68 \text{ GeV}^2$

Input from lattice:
- Form factors from first principles
- “Understanding non-factorizable contributions is probably the most important open issue which theoretical predictions must conform” Horgan et al, arXiv:1501.00367
theory perspective:

- lattice QCD is poised to predict mass and decay properties of ordinary hadrons, but also exotica (glueballs, tetraquarks, pentaquarks…)

“Multiquark correlations inside hadrons can have a significant and in some cases even striking impact on the hadron spectrum. We show how such correlations in general, and mesons with a dominant tetraquark content in particular, emerge holographically in the AdS/QCD framework.” Forkel arXiv:1206.5745

experimental perspective:

- Nature of scalar nonet still a mystery
- zoo of exotic X,Y,Z particles containing b and c quarks are being discovered
- the new kid on the block!
$P_c$ states in $\Lambda_b \rightarrow J/\psi K^- p$

- Dalitz plot shows an unusual feature
  [arXiv:1507.03414]
Are there “artifacts” that can produce a peak?

- Many checks done that shows this is not the case:
  - e.g. changing p to K, or \( \pi \) to K allows us to veto misidentified \( B_s \rightarrow J/\psi K^- K^+ \) & \( B^0 \rightarrow J/\psi K^- \pi^+ \)
  - Clones & ghost tracks eliminated
  - \( \Xi_b \) decays checked as a source

Can interferences between \( \Lambda^* \) resonances generate a peak in the \( J/\psi p \) mass spectra?

- Implemented a decay amplitude analysis that incorporates both decay sequences
Two interfering channels:

$\Lambda_b \rightarrow J/\psi \Lambda^*$,  
$\Lambda^* \rightarrow K^- p$

&

$\Lambda_b \rightarrow P_c^+ K^-$,  
$P_c^+ \rightarrow J/\psi p$

Use $m(K^- p)$ & 5 decay $\angle$’s as fit parameters

- Mass shapes: Breit-Wigner or Flatte’
Results without $P_c$ states

- Use extended model, so all possible known $\Lambda^*$ amplitudes. $m_{Kp}$ looks fine, but not $m_{J/\psi p}$
- Additions of non-resonant, extra $\Lambda^*$’s doesn’t help
Extended model with 1 $P_c$

- Try all $J^P$ up to $7/2^\pm$
- Best fit has $J^P = 5/2^\pm$. Still not a good fit
Reduced model with 2 $P_c$'s

Best fit has $J^P = (3/2^-, 5/2^+)$, also $(3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ are preferred.
Argand diagrams

Amplitudes for 6 bins between $+\Gamma$ & $-\Gamma$
☐ New manifestation of QCD (different hadron structure)?
☐ Rescattering effect?
☐ Can lattice predict spectra of more exotic hadronic structures (tetraquarks, pentaquarks, dibaryons, others…)?
Conclusions and outlook

- LHCb is adding a wealth of data that allow to probe in novel ways the Standard Model and offer new insight on new physics model.
- Theoretical input on the hadronic matrix element mediating the decays that we use to probe the fundamental quantities is crucial.
- Testable predictions are critical component to this joint theoretical and experimental effort.
THE END
The LHCb detector
In the forward region at LHC the $b\bar{b}$ production $\sigma$ is large.

The hadrons containing the $b$ & $\bar{b}$ quarks are both likely to be in the acceptance. Essential for “flavor tagging”

LHCb uses the forward direction where the B’s are moving with considerable momentum $\sim 100$ GeV, thus minimizing multiple scattering.

At $\mathcal{L}=4\times10^{32}/\text{cm}^2/\text{s}$, we get $\sim 10^{12}$ B hadrons in $10^7$ sec in the LHCb acceptance.
The two-fold ambiguity

LHCb simulation

- both solutions
- one solution

$q^2$ selection efficiency [%]

$q^2$ [GeV$^2$/c$^4$]

Boosted frame
Conjecture that discrepancy between $|V_{ub}|$ from inclusive and exclusive determinations could be attributed to right-handed currents.

Constraint from this measurement disfavors this solution of the puzzle.
Cross-checks

☐ Many done, some listed here:
☐ Signal found using different selections by others
☐ Two independently coded fitters using different background subtractions (sFit & cFit)
☐ Split data shows consistency: 2011/2012, magnet up/down, \( \Lambda_b/\bar{\Lambda}_b \), \( \Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high}) \)
☐ Extended model fits tried without \( P_c \) states, but two additional high mass \( \Lambda^* \) resonances allowing masses & widths to vary, or 4 non-resonant terms of J up to 3/2
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>( M_0 ) (MeV)</th>
<th>( \Gamma_0 ) (MeV)</th>
<th>Fit fractions (%)</th>
<th>( \Lambda(1405) )</th>
<th>( \Lambda(1520) )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low</td>
<td>high</td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td><strong>Extended vs. reduced</strong></td>
<td>21</td>
<td>0.2</td>
<td>54</td>
<td>10</td>
<td>3.14</td>
</tr>
<tr>
<td><em><em>( \Lambda^</em> ) masses &amp; widths</em>*</td>
<td>7</td>
<td>0.7</td>
<td>20</td>
<td>4</td>
<td>0.58</td>
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<td><strong>Proton ID</strong></td>
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<tr>
<td><strong>10 &lt; ( p_p ) &lt; 100 GeV</strong></td>
<td>0</td>
<td>1.2</td>
<td>1</td>
<td>1</td>
<td>0.09</td>
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<td><strong>Nonresonant</strong></td>
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<td>34</td>
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<td><strong>Separate sidebands</strong></td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>0.24</td>
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<tr>
<td><strong>( J^P ) (3/2^+, 5/2^-) or (5/2^+, 3/2^-)</strong></td>
<td>10</td>
<td>1.2</td>
<td>34</td>
<td>10</td>
<td>0.76</td>
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<tr>
<td><strong>( d = 1.5 - 4.5 \text{ GeV}^{-1} )</strong></td>
<td>9</td>
<td>0.6</td>
<td>19</td>
<td>3</td>
<td>0.29</td>
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<tr>
<td><strong>( L_{PB}^{P_c} \Lambda_b^0 \rightarrow P_c^+ \text{ (low/high)} K^- )</strong></td>
<td>6</td>
<td>0.7</td>
<td>4</td>
<td>8</td>
<td>0.37</td>
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<td><strong>( L_{PB}^{P_c} \text{ (low/high)} \rightarrow J/\psi p )</strong></td>
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<td>0.4</td>
<td>31</td>
<td>7</td>
<td>0.63</td>
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<tr>
<td><em><em>( L_{PB}^{P_c} \Lambda_b^0 \rightarrow J/\psi \Lambda^</em> )</em>*</td>
<td>11</td>
<td>0.3</td>
<td>20</td>
<td>2</td>
<td>0.81</td>
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<td><strong>Efficiencies</strong></td>
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<td>4</td>
<td>0</td>
<td>0.13</td>
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<tr>
<td><strong>Change ( \Lambda(1405) ) coupling</strong></td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td><strong>Overall</strong></td>
<td>29</td>
<td>2.5</td>
<td>86</td>
<td>19</td>
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<tr>
<td><strong>sFit/cFit cross check</strong></td>
<td>5</td>
<td>1.0</td>
<td>11</td>
<td>3</td>
<td>0.46</td>
</tr>
</tbody>
</table>
## Models: extended & reduced

- Consider all \( \Lambda^* \) states & all allowed \( L \) values

<table>
<thead>
<tr>
<th>State</th>
<th>( J^P )</th>
<th>( M_0 ) (MeV)</th>
<th>( \Gamma_0 ) (MeV)</th>
<th># Reduced</th>
<th># Extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Lambda(1405) )</td>
<td>1/2(^-)</td>
<td>1405.1(^{+1.3}_{-1.0})</td>
<td>50.5 ± 2.0</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1520) )</td>
<td>3/2(^-)</td>
<td>1519.5 ± 1.0</td>
<td>15.6 ± 1.0</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1600) )</td>
<td>1/2(^+)</td>
<td>1600</td>
<td>150</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1670) )</td>
<td>1/2(^-)</td>
<td>1670</td>
<td>35</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1690) )</td>
<td>3/2(^-)</td>
<td>1690</td>
<td>60</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1800) )</td>
<td>1/2(^-)</td>
<td>1800</td>
<td>300</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1810) )</td>
<td>1/2(^+)</td>
<td>1810</td>
<td>150</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>( \Lambda(1820) )</td>
<td>5/2(^+)</td>
<td>1820</td>
<td>80</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1830) )</td>
<td>5/2(^-)</td>
<td>1830</td>
<td>95</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(1890) )</td>
<td>3/2(^+)</td>
<td>1890</td>
<td>100</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(2100) )</td>
<td>7/2(^-)</td>
<td>2100</td>
<td>200</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(2110) )</td>
<td>5/2(^+)</td>
<td>2110</td>
<td>200</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>( \Lambda(2350) )</td>
<td>9/2(^+)</td>
<td>2350</td>
<td>150</td>
<td>0</td>
<td>6</td>
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<tr>
<td>( \Lambda(2585) )</td>
<td>?</td>
<td>( \approx 2585 )</td>
<td>200</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

# parameters: 64 | 146
Data demands 2 states

- Interference between opposite parity states needed to explain $P_c$ decay angular distribution
- Fit projections

![Graph showing corrected events/(0.1) vs. $\cos(\theta_{P_c})$](image)

Large $m(Kp)$ region negative interference

Small $m(Kp)$ region positive interference
Experimental background studies

- After selection reconstruct additional tracks to determine background yields.