LHCb and Tetra- and Penta-Quark candidates

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Syracuse University

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Modern Exotic Hadrons
(INT 15-60W)
Outline

• LHCb present and future capabilities in exotic hadron spectroscopy
• LHCb results on exotic hadrons and some near future projects
LHCb detector

- pp collider experiment with “fix target layout”
Typical hadronic collider experiment optimized for high-$p_T$ physics:

- CMS and ATLAS at LHC, CDF and D0 at Tevatron
- “central detector” (less bkg from beam fragments)
- run at highest luminosity available: high $p_T$ thresholds in trigger, not efficient for b decays
- large detector volume: $$$$, large events size $\rightarrow$ limited trigger bandwidth to storage ($\sim 500$ Hz in Run I)
- b triggers via dimuon pairs (e.g. $b \rightarrow J/\psi X$, $J/\psi \rightarrow \mu^+ \mu^-$)
- heavy flavor physics is a very low priority; very low trigger bandwidth allocation ($\sim 5$ Hz)
- no hadron ID (no K,p identification), large backgrounds in exclusive b-hadron decays

LHCb:

- First of a kind
- “forward detector” (can catch b and b in small-volume detector)
- run at diluted luminosity: low $p_T$ thresholds in trigger, efficient for b decays
- hadron ID via RICH detectors; low backgrounds in b-hadron decays
- small detector volume: $\$, small events size $\rightarrow$ large trigger bandwidth to storage (5 kHz in Run I)
- b triggers via dimuon pairs and detached vertices even without muons (trigger on selected c decays too)
- heavy flavor physics is the top priority; takes almost all trigger bandwidth
Colliders and $b\bar{b}$ rates

Previously a lot of results on exotic hadron spectroscopy with heavy quarks came from $e^+e^-$ B-factories (also from $e^+e^-$ charm factory – BES III)

- Tremendous rate potential at hadron colliders
  - physics reach determined by the detector capabilities not by the machine

- Collect all $b$-hadron species at the same time:
  - additional gain by a factor of $\sim 10$-100 in integrated $B_s$ rates at hadronic colliders
  - also get $\Lambda_b$, $B_c$ which are out of reach for the 10 GeV $e^+e^-$ factories

- Charm rates factor of 10 higher than beauty rates:
  - nuisance and physics opportunity at the same time
LHCb luminosity and its upgrade

- Maximal value of luminosity for safe LHCb operations $\sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$
- Beams are intentionally misaligned at LHCb to stay below this limit.
- Luminosity is “leveled” over run duration.

The main luminosity limitation comes from 1MHz L0 bandwidth imposed by the readout speed.

**upgrade: (2020-)** instantaneous luminosity up to $\sim 20 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$

- Readout all detectors at 40 MHz. Do all triggering in the computer farm. Increase output bandwidth to 20-30 kHz to cope with the increased physics rate
- Factor of $\sim 2$ improvement in hadronic trigger efficiencies. Muon trigger efficiencies stay the same.
LHCb present and future data samples

**Increase in data statistics by a factor of:**
- ~3 by 2018
- ~10 by 2026 (with a new detector)
- ~17 by 2030

LHCb Integrated luminosities profile:
- RUN I: ~3 fb\(^{-1}\)
- RUN II: ≥ 5 fb\(^{-1}\)
- Upgrade: ≥ 50 fb\(^{-1}\)
Triggering in LHCb

- Collision rate at LHC is up to 40 MHz, our trigger rate to storage was 5 kHz in Run I (20 kHz in Run II): live or die by trigger performance
- Tons of particles coming out of PV i.e. primary pp interaction point (mostly $\pi$, some K, p, very little $\mu$)
- Most of our triggers rely on long visible lifetime of the lightest b- (and c-) hadrons: weak decays, lifetime prolonged by significant forward momentum
- Reconstruction of b or c decay vertex, detached from PV, also important for suppression of backgrounds in offline analysis (eliminate combinatorics from PV)

- Most efficient triggers (the lowest $p_T$ thresholds) on dimuon pairs e.g. $J/\psi \rightarrow \mu^+\mu^-$, $\psi' \rightarrow \mu^+\mu^-$, ...
- We do trigger on purely hadronic detached vertices, but with lower efficiency (higher $p_T$ thresholds) – unique feature at LHC!
- We have $J/\psi \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow \mu^+\mu^-$ triggers with no detached vertex requirement; we can do promptly produced channels with them

Attention: lots of other tracks from PV not shown!
Rare but typical LHCb event

Contains $B_s \rightarrow \mu^+ \mu^-$
Efficiencies and backgrounds in LHCb

- Assuming the final state is triggered on!
- **The detector works the best for all-charged final states** \((\pi^\pm,K^\pm,p,\bar{p},\mu^\pm)\):
  - absolute reconstruction efficiency per track lower than at \(e^+e^-\) B-factories; lose efficiency faster when increasing final state multiplicity
  - channels with dimuons cleaner than without them
  - channels with kaons (to lesser extent with protons) cleaner than without them
- **Efficiency penalty for** \(K^0_s\rightarrow\pi^+\pi^-\) and \(\Lambda\rightarrow p\pi^-\):
  - forward boost is not helping in detecting them; they live too long:
  - once they decay beyond the vertex detector, momentum resolution is poor, combinatorics larger
  - we reconstruct only a fraction of them, \(K^0_s/K^\pm\) penalty is \(\sim 1/10\) (much smaller penalty at \(e^+e^-\) B-factories)
  - can’t trigger on them
- **Efficiency & background penalty for** \(\gamma,\pi^0,\eta\):
  - we do have electromagnetic calorimeter, but its granularity is very coarse for busy forward direction at a hadronic collider, energy resolution not great (cheap technology, lots of radiation length in front of it)
  - efficiency drops quickly with energy (difficult to do \(\pi^0\) from high multiplicity decay)
  - difficult to detect more than one
  - \(\pi^0/\pi^\pm\) efficiency penalty \(\sim 1/10\) or more
  - backgrounds are high and increase with decreasing energy
- No \(K^0_L, n\):
  - we do have a very crude hadron calorimeter, but used only in low level trigger, no hadronic clusters in offline
  - perhaps could do them as a “missing particle”, reconstruction ambiguities and large backgrounds
- **\(e\) not as useful as \(\mu\)** (lose them to bremsstrahlung in the tracker)
Data mining

• Offline analysis includes “stripping”:
  – large reduction in data volume before accessible for physics analysis.
  – essentially a software trigger run in offline:
    • however, unlike online trigger it can be redone.
    • occasional restriping with refined offline software and possibly new stripping criteria
  – inclusive “stripping lines” $J/\psi \rightarrow \mu^+ \mu^-$, $\psi' \rightarrow \mu^+ \mu^-$, $Y^{(n)} \rightarrow \mu^+ \mu^-$
    • when $J/\psi$, $\psi'$ are detached then much lower $p_T$ cut-offs (better efficiency)
    • all event info (all particles) in the event accessible in offline analysis (“full DST”)
    • we can easily mine $\mu^+ \mu^-$ + hadrons final states
  – exclusive “stripping lines” for everything else:
    • only selected final state particles are accessible in offline analysis (“micro DST”)
    • pretty tight “bandwidth” limitations per channel: have to decide on most important cuts based on simulations and small test samples (for bkgds)
    • to select a new channel, must write a new stripping line, test it, get it approved by Working Group, wait for next stripping campaign (often many months)
Prompt signals

- Prompt signal are hard at LHC:
  - we only trigger on prompt \( J/\psi \rightarrow \mu^+\mu^- \), \( \psi' \rightarrow \mu^+\mu^- \), \( \Upsilon \rightarrow \mu^+\mu^- \), \( \Upsilon' \rightarrow \mu^+\mu^- \)
  - Combinatorial background from \( \pi^\pm, K^\pm, p \) produced at PV is huge
    - the only exotic candidate we have been able to see in prompt production so far is \( X(3872) \rightarrow \pi^+\pi^- J/\psi \)
    - backgrounds are much higher for \( \pi^+\pi^- \Upsilon \); even \( \Upsilon' \rightarrow \pi^+\pi^- \Upsilon \) is barely doable (\( \Upsilon \)'s are heavier \( \rightarrow \) softer transition pions \( \rightarrow \) higher backgrounds)
    - we have tried and failed to see any \( Z_{b^+} \) states
  - D0 has recently claimed observation of prompt production of \( X(4140) \rightarrow \phi J/\psi \) at Tevatron. This is very doable in LHCb.


\( \sqrt{s} = 7 \) TeV

- 0.035 fb\(^{-1}\) (2010 data)

\( \psi(2S) \)

- 565\( \pm \)62 events

\( \sigma_M = 3.3 \) MeV

\( X(3872) \)

(same sign \( \pi\pi \))
Central Exclusive Production

- Various types of pp collisions at LHC:

  - Normal data
  - Single Diffraction
  - Double Diffraction
  - Central Exclusive (elastic)
  - Central Exclusive (inelastic)
  - Elastic Scattering

LHCb coverage (approximate)

<table>
<thead>
<tr>
<th>No magnetic field</th>
<th>CEP events: Trigger on and reconstruct a handful of particles (muons, hadrons, photons..)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>CEP backgrounds: reject events with additional particles, usually very forward</td>
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</table>
CEP triggers

Di-μ triggered events

• Special low-multiplicity no-backwards-tracks dimuon triggers were deployed for part of Run I
  - Can do exclusive $\pi^+\pi^- J/\psi$, look e.g. for $X(3872)$
• Later also extended to dihadron lines ($\chi_{c0} \to K^+K^-,\pi^+\pi^-$)
  - Plan to study charmonia decays to 2-4 body final states
• More opportunities in Run II (but not after the upgrade; too many pp interactions per crossing)
Heavy ions in LHCb

- In early 2013 LHCb collected 1.6 nb\(^{-1}\) of pPb and Pbp data \((s_{NN}^{1/2} = 5\text{ TeV})\)

- Plan to take peripheral Pb+Pb collision data (multiplicity too high in head-on)
- Not clear if have any potential for exotics?
X(3872) – discovered in 2003

\[ \Gamma_{X(3872)} < 1.2 \text{ MeV} \]

very narrow

\[ 2^+ \quad (\text{CL}=68\%) \]

\[ 1^+ \quad (\text{CL}=7\%) \]

BaBar data preferred \( J^P=2^+ \) (without ruling out \( 1^{++} \)) from the shape of \( m_{3\pi} \) distribution \( \rightarrow \eta(1^{1D_2}) \) \( cc \) state?

Mass indistinguishable from \( D_0 \bar{D}^{*0} \) thresholds

\[ M_{X(3872)} - [M_{D_0} + M_{D^{*0}}] = -0.11 \pm 0.19 \text{ MeV} \]
Helicity amplitudes for $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi \rho$, $J/\psi \rightarrow \mu^+\mu^-$, $\rho \rightarrow \pi^+\pi^-$

$\lambda$ – particle helicity (spin projection onto its momentum)

Helicity couplings:

nuisance parameters

$$\left| M(\Omega | J_x, A^J_x) \right|^2 = \sum_{\Delta \lambda_x = -1, 1} \left| M^{X \rightarrow \psi \rho}_{\Delta \lambda_x} \right|^2$$

5D analysis

$$\Omega \equiv (\theta_x, \theta_\psi, \theta_\rho, \Delta \phi_{\psi,x}, \Delta \phi_{\rho,x})$$

Number of $B_{LS}$ coupling equals number of independent $A^J_{\lambda_\psi, \lambda_\rho}$ couplings (1-5 depending on $J_x$) – no gain, unless high $L$ values neglected
Determination of $J^{PC}$ for $X(3872)$

1++: no $B_{LS}$ couplings to fit

3 x 1D $\chi^2$ analysis

$$L = L_{\text{min}}$$

$2^+$: $\alpha_{2^+} = B_{2^+} / (B_{1^+} + B_{2^+}) = (0.64, 0.27)$

$\sqrt{313/173} = 1.3$ small gain is statistical errors

5D unbinned likelihood ratio analysis

173±16 events

PRD84(2011)052004

Very clear separation between 1++ and 2−

The data choose 1++

- It is important to analyze data in all sensitive dimensions simultaneously. Angular correlations by far more powerful than 1D projections.
2015 update to X(3872) $J^{PC}$ determination
(all $L$ values allowed)

$J^{PC} = 1^{++}$ at $16\sigma$

<4% at 95% CL

LHCb Tetra- and Penta-quarks, T. Skwarnicki INT, Nov 2015

LHCb 3 fb$^{-1}$ (2011+2012 data)
1011±38 events

PRD92, 011102 (2015)

Many more amplitudes to fit

LHCb 2015

CDF 2007

LHCb 2013

Bin Gui
PhD
Syracuse 2014
Radiative decays of $X(3872)$ in LHCb


$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \psi(2S)\gamma$

$B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi\gamma$

$36.4 \pm 9.0$ events $4.4\sigma$ $X(3872)$

$591 \pm 48$ events $12\sigma$ $X(3872)$

The most significant evidence for $X(3872) \rightarrow \psi(2S)\gamma$ to date!

$\text{efficiency}(\psi(2S)\gamma) / \text{efficiency}(J/\psi\gamma) \sim 0.2$

Detecting soft photons at hadronic collider is hard.
Radiative decays of X(3872) in LHCb

Signal events:
- $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow \psi(2S)\gamma$, $J/\psi\gamma$
- $\psi(2S)\gamma$, $J/\psi\gamma$

Signal significance:
- $25.4 \pm 7.3$, $23.0 \pm 6.4$ $3.6\sigma$, $3.5\sigma$
- $5.0^{+11.9}_{-11.0}$, $30.0^{+8.2}_{-7.4}$ $0.4\sigma$, $4.9\sigma$

LHCb $36.4 \pm 9.0$, $591.0 \pm 48.0$ $4.4\sigma$, $12\sigma$

$\text{BR}(X(3872) \rightarrow \psi(2S)\gamma)/\text{BR}(X(3872) \rightarrow J/\psi\gamma)$

$= 2.48 \pm 0.64 \pm 0.29$

- The LHCb results are consistent with, but more precise than, the BaBar and Belle results:
  - LHCb can be competitive on simple final states with neutrals in spite of large backgrounds
- Consistent with the expectations for $\chi_{c1}(2^{3}P_{1})$ state
**X(3872) interpretation**

\[ \chi_c(2^3P_1) \text{ “attracted” by } D^0\bar{D}^*0 \text{ threshold?} \]

\[ M_{X(3872)} - [M_{D^0} + M_{D^*0}] = -0.11 \pm 0.19 \text{ MeV} \]

\[ [cu]_{S=1} [\bar{c}\bar{u}]_{S=0} + [cu]_{S=0} [\bar{c}\bar{u}]_{S=1} \]

**Meson-meson molecule? essentially no binding energy?**

**L=0 mixture?**

**tightly bound tetraquark “attracted” by } D\bar{D}^* \text{ threshold?} \]

e.g. L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, PRD 89 (2014) 114010
Future studies related to X(3872)

- We can have the best measurement of its mass, possibly the best limit on its width.
- Other modes with $B \to X(3872)^+ \ldots$, $X(3872) \to \pi^+\pi^- J/\psi$. Some may be worth amplitude analysis to see if contain exotic candidates decaying to $X(3872)$.
- Other decay modes of $X(3872)$ e.g. $\omega J/\psi$, $D\bar{D}^*$ (hard!)
- Production in CEP or heavy-ion data?
$X(4140)$ in $B^+ \rightarrow J/\psi \phi K^+$

CDF

PRL 102, 242002 (2009)

$\Gamma = 15 \pm 10$ MeV

$4143 \pm 3 \pm 1$ MeV

No evidence for the narrow $X(4140)$ in early LHCb data ($1/10^{th}$ of our data)

All these naïve analyses assume that non-X events conform to 3-body phase-space and do not study systematics of this assumption.
$B^+ \rightarrow J/\psi \phi K^+$

- 6D amplitude analysis of $4289 \pm 151$ events $3 \text{ fb}^{-1}$ in progress
- Difficulty: dealing with high mass region of $K^*$ resonances

<table>
<thead>
<tr>
<th>$^{nS_{1/2}}L_J$</th>
<th>$J^P$</th>
<th>$M_{ch}$</th>
<th>Candidate PDG state</th>
<th>$\Delta M = M_{exp} - M_{th}$</th>
<th>$\phi K$ decay?</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^1S_0$</td>
<td>0+</td>
<td>470</td>
<td>$K^+$</td>
<td>$494$</td>
<td>$+24 \pm 5$</td>
</tr>
<tr>
<td>$1^1S_1$</td>
<td>1-</td>
<td>900</td>
<td>$K^*(892)^+$</td>
<td>$802 \pm 0.3$</td>
<td>$51 \pm 1$</td>
</tr>
<tr>
<td>$1^3P_0$</td>
<td>0+</td>
<td>1240</td>
<td>$K_0(1430)^+$</td>
<td>$1425 \pm 50$</td>
<td>$270 \pm 80$</td>
</tr>
<tr>
<td>$1^3P_1$</td>
<td>1+</td>
<td>1340</td>
<td>$K_1(1270)^+$</td>
<td>$1272 \pm 7$</td>
<td>$90 \pm 20$</td>
</tr>
<tr>
<td>$1^3P_2$</td>
<td>2+</td>
<td>1380</td>
<td>$K_2(1400)^+$</td>
<td>$1403 \pm 7$</td>
<td>$174 \pm 13$</td>
</tr>
<tr>
<td>$2^1S_0$</td>
<td>0-</td>
<td>1450</td>
<td>$K(1460)^+$</td>
<td>$1426 \pm 1$</td>
<td>$98 \pm 3$</td>
</tr>
<tr>
<td>$2^3S_1$</td>
<td>1-</td>
<td>1580</td>
<td>$K(1410)^+$</td>
<td>$1414 \pm 15$</td>
<td>$232 \pm 16$</td>
</tr>
</tbody>
</table>

(bold font – well established PDG states)
$Z(4430)^+$ discovery and its importance


Observation of a resonance-like structure in the $\pi^\pm \psi'$ mass distribution in exclusive $B \to K\pi^\pm \psi'$ decays
Z(4430)$^{-}$ previous measurements

**Belle 2008**

1D $M(\psi'\pi^-)$ mass fit

("K* veto region")

PRL 100, 142001 (2008)

$$M(Z) = 4433 \pm 4 \pm 2 \text{ MeV}$$

$$\Gamma(Z) = 45^{+18}_{-13}^{+30}_{-13} \text{ MeV}$$

significance $6.5\sigma$

**BaBar 2009**

Harmonic moments of K*’s (2D) reflected to $M(\psi'\pi^-)$

Belle 1D 4D

PRL 100, 142001 (2008)

$$M(Z) = 4485^{+22}_{-22}^{+28}_{-11} \text{ MeV}$$

$$\Gamma(Z) = 200^{+41}_{-46}^{+26}_{-35} \text{ MeV}$$

6.4$\sigma$ (5.6$\sigma$ with sys.)

**Belle 2013**

(2D amplitude fit in 2009)

4D amplitude fit

(subsample with $\psi \rightarrow \psi'(\pi^-)$)

PRD 88, 074026 (2013)

With Z(4430)$^{-}$

No Z

$$M(Z) = 4485^{+22}_{-22}^{+28}_{-11} \text{ MeV}$$

$$\Gamma(Z) = 200^{+41}_{-46}^{+26}_{-35} \text{ MeV}$$

6.4$\sigma$ (5.6$\sigma$ with sys.)

**Ad hoc assumption about the K$^* \rightarrow K\pi^-$ background shape.**

Almost **model independent** approach to K$^* \rightarrow K\pi^-$ backgrounds.

**Model dependent** approach to K$^* \rightarrow K\pi^-$ backgrounds.

Higher statistical sensitivity.
Z(4430)$^+$ in LHCb

LHCb-PAPER-2014-014 PRL 112, 22002 (2014)

- $B^0 \rightarrow \psi'K^+\pi^-$, $\psi' \rightarrow \mu^+\mu^-$ (3 fb$^{-1}$)

An order of magnitude larger signal statistics than in Belle or BaBar thanks to hadronic production of b-quarks at LHC.
Even smaller non-B background than at the $e^+e^-$ experiments thanks to excellent performance of the LHCb detector (vertexing, PID)
$B^0 \rightarrow \psi'\pi^+K^-$

Kaon excitations

Is it a reflection of interfering $K^*$$'s \rightarrow \pi^+K^-$?
Proper amplitude analysis necessary to check
Amplitude Analysis of $B^0 \to \psi' \pi^+ K^-$, $\psi' \to \mu^+ \mu^-$

$$\left| M \left( m_{K\pi}, \Omega \mid A_{\psi}^{B \to \psi K^*_n} \right) \right|^2 = \sum_{\Delta \lambda_{\mu} = -1, 1} \left| M_{\Delta \lambda_{\mu}}^{K^*_n} \right|^2$$

$$\Omega \equiv (\theta_{K^n}, \theta_{\psi}, \Delta \phi_{\psi,K^n})$$

4D analysis

1 mass, 3 angles

$M_{\Delta \lambda_{\mu}}^{K^*_n} = \sum_{n} \sum_{\lambda_{\psi} = -1, 0, 1} A_{\psi}^{B \to \psi K^*_n} D_{\psi,0}^{J_{K^*_n}}(0, \theta_{K^n}, 0)^* R(m_{K\pi} \mid M_{K^*_n}, \Gamma_{K^*_n}) D_{\lambda_{\psi}, \Delta \lambda_{\mu}}^{1}(\Delta \phi_{\psi,K^*_n}, \theta_{\psi}, 0)^*$

Breit-Wigner amplitude: $R(m \mid M_x, \Gamma_x) = \frac{B_{\psi}^{'}(p, p_0, d) \left( \frac{p}{M_y} \right)^{\frac{1}{2}} B_{\psi}^{''}(q, q_0, d) \left( \frac{q}{m} \right)^{\frac{1}{2}}}{M_x^2 - m^2 - iM_x \Gamma(m)}$  

Blatt-Weisskopf functions

$\Gamma(m) = \Gamma_x \left( \frac{q}{q_0} \right)^{2l_x + 1} \frac{M_x B_{\psi}^{''}(q, q_0, d)}{m}$

$n = 0^+ : K_0^*(800), K_0^*(1430), NR; \quad 1^- : K^*(892), K^*(1410), K^*(1680) \quad 2^+ : K_2^*(1430) \quad (3^- : K_3^*(1780))$

# of fit parameters: 32
Amplitude fits without $Z(4430)^-$

$\chi^2$ p-value $< 2 \times 10^{-6}$

The data cannot be adequately described with the $J \leq 3$ $K^*$ contributions alone
Amplitude Analysis of $B^0 \rightarrow \psi'\pi^+K^-$, $\psi' \rightarrow \mu^+\mu^-$

\[
\left| M \left( m_{K\pi}, \Omega \mid M_Z, \Gamma_Z, J_Z, A^{Z \rightarrow \psi\pi}_{\lambda_{\psi}}, A^{B \rightarrow \psi K_n^*}_{\lambda_{\psi}} \right) \right|^2 = \sum_{\Delta \lambda_{\mu}=-1,1} \left| M^K_{\Delta \lambda_{\mu}} + e^{i\lambda_{\mu}\alpha_{\mu}} M^Z_{\Delta \lambda_{\mu}} \right|^2
\]

4D analysis

1 mass, 3 angles all derivable from the $K^*$ variables

\[
M^Z_{\Delta \lambda_{\mu}} = \sum_{\lambda_{\psi}=-1,0,1} A^{Z \rightarrow \psi\pi}_{\lambda_{\psi}} D^J_{\lambda_{\psi}, \lambda_{\psi}} (0, \theta_0, 0)^* R(m_{\psi\pi} \mid M_Z, \Gamma_Z) D^{1}_{\lambda_{\psi}, \Delta \lambda_{\mu}} (\Delta \phi_{\psi, Z}, \theta_{\psi}^Z, 0)^*
\]

1 independent complex helicity coupling after $L = L_{\text{min}}$

# of fit parameters: $32 + 4 = 36$
Amplitude fits with $J^P=1^+ Z(4430)^+$

# of fit parameters: $32 + 4 = 36$

- The $\chi^2$ p-value = 12%

- The data are well described when $J^P=1^+ Z(4430)^+$ is included in the fit
- $Z(4430)^+$ significances from $\Delta(-2\ln L)$ is $18.7\sigma$ ($13.9\sigma$ with systematic variations)
Amplitude fits with $J^P=1^+$ $Z(4430)^-$

1. $m_{K\pi}^2 < 0.7$ GeV$^2$
   - Below $K^*(892)^+$

2. $0.7 < m_{K\pi}^2 < 1.0$ GeV$^2$
   - "$K^*(892)^+$ region"

3. $1.0 < m_{K\pi}^2 < 1.8$ GeV$^2$
   - "$K^*$ veto region"
   - Including interferences

4. $m_{K\pi}^2 > 1.8$ GeV$^2$
   - "$K^*_2(1430)^+$ and above"
### $Z(4430)^-$ parameters: LHCb vs Belle

#### Amplitude fractions [%] (statistical errors only)

<table>
<thead>
<tr>
<th>Contribution</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$-wave total</td>
<td>$10.8 \pm 1.3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$NR$</td>
<td>$0.3 \pm 0.8$</td>
</tr>
<tr>
<td>$K_0^*(800)$</td>
<td>$3.2 \pm 2.2$</td>
<td>$5.8 \pm 2.1$</td>
</tr>
<tr>
<td>$K_0^*(1430)$</td>
<td>$3.6 \pm 1.1$</td>
<td>$1.1 \pm 1.4$</td>
</tr>
<tr>
<td>$K^*(892)$</td>
<td>$59.1 \pm 0.9$</td>
<td>$63.8 \pm 2.6$</td>
</tr>
<tr>
<td>$K_2^*(1430)$</td>
<td>$7.0 \pm 0.4$</td>
<td>$4.5 \pm 1.0$</td>
</tr>
<tr>
<td>$K_1^*(1410)$</td>
<td>$1.7 \pm 0.8$</td>
<td>$4.3 \pm 2.3$</td>
</tr>
<tr>
<td>$K_1^*(1680)$</td>
<td>$4.0 \pm 1.5$</td>
<td>$4.4 \pm 1.9$</td>
</tr>
<tr>
<td>$Z(4430)^-$</td>
<td>$5.9 \pm 0.9$</td>
<td>$10.3^{+3.0}_{-3.5}$</td>
</tr>
</tbody>
</table>

- Overall excellent consistency between LHCb and Belle
- Errors substantially improved
Z(4430)\(^+\) spin-parity analysis

**Including systematic variations:**

<table>
<thead>
<tr>
<th>Disfavored J(^p)</th>
<th>Rejection level relative to 1(^+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>Belle</td>
</tr>
<tr>
<td>0⁻</td>
<td>9.7σ</td>
</tr>
<tr>
<td>1⁻</td>
<td>15.8σ</td>
</tr>
<tr>
<td>2⁺</td>
<td>16.1σ</td>
</tr>
<tr>
<td>2⁻</td>
<td>14.6σ</td>
</tr>
</tbody>
</table>

- J\(^p\)=1\(^+\) now established beyond any doubt

**Belle**

PRD 88, 074026 (2013)

**Value in data**

- \(0^+\)
- \(1^+\)

**Toy MC experiments**

- \(\bar{D}_1^0,(\bar{D}_2^{0*})\)
- \(\psi'\)
- \(\pi^+\)
Hadronic resonances – Argand diagram

Forced harmonic oscillator:
\[
m \frac{d}{dt} \left( \frac{dx}{dt} \right) = -k \, x
\]
Restoring force
\[
- b \frac{dx}{dt}
\]
Damping force
\[
-F_0 \cos(\omega_{\text{ext}} t)
\]
Driving force
\[
\omega_0 = \sqrt{\frac{k}{m}}
\]
resonant frequency
\[
\gamma = \frac{b}{2m}
\]
dumping factor
\[
x(t) \rightarrow \frac{F_0 / m}{\sqrt{(\omega_0^2 - \omega_{\text{ext}}^2)^2 + (2 \gamma \omega_{\text{ext}})^2}} \cos(\omega_{\text{ext}} t + \phi)
\]
\[
\phi = \arctan \left( \frac{2 \gamma \omega_{\text{ext}}}{\omega_0^2 - \omega_{\text{ext}}^2} \right)
\]

Breit-Wigner amplitude
\[
|A^Z(m_{\psi\pi})|^2 \sim \frac{1}{M_Z^2 - m_{\psi\pi}^2 - i M_Z \Gamma_Z} = |A^Z(m_{\psi\pi})| e^{i \varphi(m_{\psi\pi})}
\]

\[
|A^Z(m_{\psi\pi})|^2 \sim \frac{1}{(M_Z^2 - m_{\psi\pi}^2)^2 + (M_Z \Gamma_Z)^2}
\]

\[
\varphi(m_{\psi\pi}) = \arctan \left( \frac{M_Z \Gamma_Z}{M_Z^2 - m_{\psi\pi}^2} \right)
\]

- \( m_{\psi\pi} \sim \omega_{\text{ext}} \) driving frequency
- \( M_Z \sim \omega_0 \) resonance frequency
- \( \Gamma_Z = \hbar / \tau_Z \sim \gamma / 2 \) damping factor (mass indeterminacy)

DEMO
Argand diagram of $Z(4430)^+$

- Thanks to the large data statistics LHCb has been able to extract Argand diagram of $Z(4430)^+$ amplitude from its interference with the $K^*$ amplitudes:

$$M^2 - m_{\psi'\pi^+}^2 - i M \Gamma$$

Breit-Wigner amplitude

- Breit-Wigner model rules out rescattering model

$M_{\psi'\pi^+} = 4277$ MeV

$M_Z = 4477$ MeV

P. Pakhlov, T. Uglov
PL B748, 183 (2015)
More than one $Z^\rightarrow \psi'\pi^-$?

- Argand diagram for the $Z_0$ is inconclusive
- No evidence for the $Z_0$ in the model independent approach
- Need more data to clarify!

$M(Z_0) = 4239 \pm 18^{+45}_{-10}$ MeV
$\Gamma(Z_0) = 220 \pm 47^{+108}_{-74}$ MeV
$f_{Z_0} = 1.6 \pm 0.5^{+1.9}_{-0.4}$ %
$f_{Z_0}^{I} = 2.4 \pm 1.1^{+1.7}_{-0.2}$ %

6\sigma significance (with systematics)
Previously confirmed $Z_c^+$ state: $Z_c(3900)^+$
$e^+e^- \rightarrow Y(4260) \rightarrow \pi^-(\pi^+J/\psi)$

BESIII: 525pb$^{-1}$ at 4.26 GeV
Significance $>8\sigma$

BESIII: PRL110, 252001 (2013)
- $M = 3899.0 \pm 3.6 \pm 4.9$ MeV
- $\Gamma = 46 \pm 10 \pm 20$ MeV
- $307 \pm 48$ events

(no Argand diagram analysis)

24$\pm$6 MeV above the DD$^*$ threshold
Z(4430)$^+$ and other $Z_c^+$ states

- The only threshold still at play for Z(4430)$^+$: DD(2600) if D(2600) exists (needs confirmation!) and if it is 1$^-$ states ($2^3S_1$)
- Other charged $Z_c^+,$ $Z_b^+$ states are near $D(^*\overline{D}(^*)$, $B(^*\overline{B}(^*)$ thresholds

Radial excitation of tightly bound tetraquark

Diquark states can be “attracted” towards the mesonic-pair threshold masses

$Z_c(3900)^+$ is 24$^{+6}_{-5}$ MeV above the $D\overline{D}^*$ threshold (favors tetraquark picture)
Belle 4D fits to $B^0 \rightarrow J/\psi \pi^+ K^-$ Z(4430)$^+$ companion : Z(4200)$^+$

Belle

[Graphs and data points showing events vs. $M^2(J/\psi \pi)$]

$Z_c(4200)^+$ (0.5$^{+0.4}_{-0.1}$)

$Z_c(4200)^+$ (1.9$^{+0.7}_{-0.5}$)

$J^P(4200) = 1^+$ preferred by $>8.6\sigma$

$M(4200) = 4196^{+31}_{-29} +17_{-13}$ MeV

$\Gamma(4200) = 370^{+70}_{-70} + 70_{-132}$ MeV

Observation of Z(4430)$^+$ in the 2nd B decay!

$Z(4430)^+$ mass and width fixed in these fits to the $B^0 \rightarrow J/\psi \pi^+ K^-$ results

(In the LHCb fits, we neglect D-wave in Z(1$^+$) decays: $H_1 = H_0$)
Future studies of $Z(4430)^+$

- We have 10 times more data than Belle for $B \rightarrow J/\psi \pi^+ K^-$
  - We will analyze it to verify Belle’s results
  - Possibly contribute to $K^*$ spectroscopy at high mass
  - Likely to be published together with reanalysis of $B \rightarrow \psi' \pi^+ K^-$ (lower $\psi' \pi^+$ mass region?)

- We can improve $B \rightarrow \psi' \pi^+ K^-$ results even without new data by adding $\psi' \rightarrow \pi^+ \pi^- J/\psi$ (1/3 of the $\psi' \rightarrow \mu^+ \mu^-$ sample), but is the complication worth the effort?
The decay first observed by LHCb and used to measure $\Lambda_b^0$ lifetime (LHCb-PAPER-2013-032, PRL 111, 102003)

The background is only 5.4% in the signal region!

The sideband distributions are flat → no major reflections from the other b-hadrons after the selection

Assist.Prof. Liming Zhang Tsinghua Univ. (previously at Syracuse)
\( \Lambda_b^0 \rightarrow J/\psi p K^- \): unexpected structure in \( m_{J/\psi p} \)

- Unexpected, narrow peak in \( m_{J/\psi p} \)
- Ignored in LHCb for more than 2 years. We, like almost everybody else, did not believe in pentaquarks:

\( \Lambda_b^0 \rightarrow J/\psi p K^- \) is assumed to be a reflection of interfering \( \Lambda^* \)'s → p K^-?

Proper amplitude analysis absolutely necessary to check.
Amplitude Analysis of $\Lambda_b \rightarrow J/\psi p K^-$, $J/\psi \rightarrow \mu^+ \mu^-$

$$M \left( m_{Kp}, \Omega \mid A_{\Lambda_b \rightarrow J/\psi}^{\Lambda^*}, A_{\Lambda_p \rightarrow p K^*}^{\Lambda^*} \right)^2 = \sum_{\lambda_{\Lambda_b} = -1/2, +1/2} \sum_{\lambda_p = -1/2, +1/2} \sum_{\Delta \lambda_\mu = -1, 1} \left| M_{\Lambda^*_{\lambda_{\Lambda_b}, \lambda_p, \Delta \lambda_\mu}}^{\Lambda} \right|^2$$

$$\Omega \equiv (\theta_{\Lambda_b}, \theta_{\Lambda^*}, \Delta \phi_{\Lambda^*_{\Lambda_b}}, \theta_\psi, \Delta \phi_\psi, \Lambda_b)$$

6D analysis

1 mass, 5 angles

$$M_{\Lambda^*_{\lambda_{\Lambda_b}, \lambda_p, \Delta \lambda_\mu}}^{\Lambda} = \sum_{n} \sum_{\lambda_\Lambda} \sum_{\lambda_\psi} A_{\Lambda_b \rightarrow J/\psi}^{\Lambda^*} D_{\Lambda^*_{\lambda_{\Lambda_b}, \lambda_\psi}, \Lambda_p \rightarrow p K^*}^{\Lambda^*} (0, \theta_{\Lambda_b}^*, 0)^* \text{LAB frame}$$

$$A_{\Lambda_p \rightarrow p K}^{\Lambda^*} D_{\Lambda^*_{\lambda_{\Lambda_b}, \lambda_p}, \theta_{\Lambda_b}^*, 0} \left( \Delta \phi_{\Lambda^*_{\Lambda_b}}, 0 \right)^* R(m_{Kp}, M_{\Lambda^*_{\Lambda_b}, \Gamma_{\Lambda_b}}) D_{\Lambda^*_{\lambda_{\Lambda_b}, \lambda_p}, \Delta \lambda_\mu}^{\Lambda^*} (\Delta \phi_\psi, \Lambda_b, \theta_\psi, 0)^*$$

4-6 independent complex helicity couplings per $\Lambda_n^*$ resonance
### $\Lambda^*$ resonance model

All known $\Lambda^*$ states from KN scattering experiments.

No high-$J^P$ high-mass states limit $L$

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th># Reduced</th>
<th>All states, all $L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda(1405)$</td>
<td>$1/2^-$</td>
<td>$1405.1^{+1.3}_{-1.0}$</td>
<td>$50.5 \pm 2.0$</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>$\Lambda(1520)$</td>
<td>$3/2^-$</td>
<td>$1519.5 \pm 1.0$</td>
<td>$15.6 \pm 1.0$</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>
</tr>
<tr>
<td>$\Lambda(2585)$</td>
<td>$5/2^-$</td>
<td>$\approx2585$</td>
<td>$200$</td>
<td>0</td>
<td>6</td>
</tr>
</tbody>
</table>

# of fit parameters: 64, 146
Fit with $\Lambda^* \rightarrow pK^-$ contributions only

- Include all known $\Lambda$ excitations:
- $m_{Kp}$ looks fine, but not $m_{J/\psi p}$
Amplitude Analysis of $\Lambda_b \rightarrow J/\psi p K^-$, $J/\psi \rightarrow \mu^+ \mu^-$

$$M(m_{Kp}, \Omega | M_{P_c}^{P_c}, \Gamma_{P_c}, J_{P_c}, A_{\Lambda_b \rightarrow P_c^{P_c} K}, A_{\Lambda_b \rightarrow J/\psi \Lambda_n^{*}}, A_{\Lambda_b \rightarrow J/\psi \Lambda_n^{*} p K}^* )^2 =$$

$$\sum_{\lambda_{\Lambda_b} = -1/2, +1/2} \sum_{\lambda_p = -1/2, +1/2} \sum_{\Delta \lambda_{\mu} = -1, 1} M_{\Lambda_{\lambda_{\Lambda_b}}, \lambda_p, \Delta \lambda_{\mu}}^* + e^{i \Delta \lambda_{\mu} \alpha_{\mu}} \sum_{\lambda_p^{P_c} = -1/2, +1/2} d_2^{1/2} \lambda_p^{P_c} \lambda_p (\theta_p) M_{\lambda_{\Lambda_b}, \lambda_p^{P_c}, \Delta \lambda_{\mu}}^{P_c}$$

6D analysis

1 mass, 6+2 angles
all derivable from the $\Lambda^*$ variables

$$M_{\lambda_{\Lambda_b}, \lambda_p, \Delta \lambda_{\mu}}^{P_c} = \sum_{n} \sum_{\lambda_{P_c}} \sum_{\lambda_{\psi} = -1, 0, 1} A_{\Lambda_b \rightarrow P_c^{P_c} K}^* D_{\lambda_{\Lambda_b}, \lambda_p}^{1/2} (\phi_{P_c}, \theta_{\Lambda^*_{P_c}}, 0)^*$$

$$A_{\lambda_{\psi}, \lambda_p}^{P_c \rightarrow \psi p} D_{\lambda_{P_c}, \lambda_{\psi} - \lambda_p} (\Delta \phi_{P_c, \Lambda_b}, \theta_{P_c}, 0)^* R(m_{\psi p} | M_{P_c}^{P_c}, \Gamma_{P_c}) D_{\lambda_{\psi}, \lambda_{\mu}}^{1/2} (\Delta \phi_{\psi P_c}, \theta_{\psi P_c}, 0)^*$$

$\Delta \Phi_{P_c, \Lambda_b}, -\pi$

3-4 independent complex helicity couplings per $P_c^n$ resonance
**Λ* Plus P_c^+ Matrix Element**

2 additional angles to align the muon and proton helicity frames between the Λ* and P_c^+ decay chains

also derivable from the Λ* decay variables

\[
\left| M \left( m_{Kp}, \Omega | M_{p_c^n}, \Gamma_{p_c^n}, J, A_{\Lambda_n^{\Lambda_\Lambda \rightarrow \Lambda_n^p}}, A_{p_c^n \rightarrow \Lambda_n^p}, A_{\Lambda_n^{\Lambda_n^p \rightarrow \psi \Lambda_n^p}}, A_{\Lambda_n^{\Lambda_n^p \rightarrow p K}} \right) \right|^2 =
\]

\[
\sum_{\lambda_{\Lambda_b} = -1/2, +1/2} \sum_{\lambda_p = -1/2, +1/2} \sum_{\Delta \lambda_{\mu} = -1, 1} M_{\Lambda_b^{\Lambda_\Lambda}, \lambda_p, \Delta \lambda_{\mu}} + e^{i \Delta \lambda_{\mu} \alpha_{\mu}} \sum_{\lambda_p p_c = -1/2, +1/2} \sum_{\lambda_p} \frac{1}{2} \left( \theta_p \right) M_{p_c}^{p_c, \lambda_p, \lambda_p, \Delta \lambda_{\mu}}
\]

- Without this realignment can’t describe Λ* plus P_c^+ interferences properly
- They integrate out to zero in full phase-space but present in the differential 6D fit-PDF
Fit with $\Lambda^*$'s and one $P_c^+ \rightarrow J/\psi p$ state

# of fit parameters: 146 + 10 = 156

- Try all $J^P$ of $P_c^+$ up to $7/2^\pm$
- Best fit has $J^P = 5/2^\pm$. Still not a good fit
Fit with $\Lambda^*$’s and two $P_{c}^{+} \rightarrow J/\psi p$ states

- Obtain good fits even with the reduced $\Lambda^*$ model

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Fit fraction (%)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{c}(4380)^{+}$</td>
<td>4380 ±8±29</td>
<td>205±18±86</td>
<td>8.4±0.7±4.2</td>
<td>9σ</td>
</tr>
<tr>
<td>$P_{c}(4450)^{+}$</td>
<td>4449.8±1.7±2.5</td>
<td>39±5±19</td>
<td>4.1±0.5±1.1</td>
<td>12σ</td>
</tr>
</tbody>
</table>

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

- Fit improves greatly, for 1 $P_c \Delta(-2\ln \mathcal{L})=14.7^2$, adding the 2nd $P_c$ improves by $11.6^2$, for adding both together $\Delta(-2\ln \mathcal{L})=18.7^2$
- Simulations of pseudoexperiments are used to turn the $\Delta(-2\ln \mathcal{L})$ values to significances:
  - significance of $P_c(4450)^+$ state is $12\sigma$
  - significance of $P_c(4380)^+$ state is $9\sigma$
  - combined significance of the two $P_c^+$ states is $15\sigma$
- This includes the dominant systematic uncertainties, coming from difference between extended and reduced $\Lambda^*$ model results.
Fit with $\Lambda^*$’s and two $P_c^+ \rightarrow J/\psi p$ states

Need for the 2nd broad $P_c^+$ state becomes visually apparent in the region where the $\Lambda^* \rightarrow pK^-$ background is the smallest.
Data preference for opposite parity $P_c^+$ states

- Positive interference between the $P_c$ states
- Negative interference between the $P_c$ states

This interference pattern only for states with opposite parity
Angular distributions

All data

LHCb Tetra- and Penta-quarks, T. Skwarnicki INT, Nov 2015

- Good description of the data in all 6 dimensions!

LHCb all $m_{Kp}$

LHCb $m_{Kp}>2$ GeV

PRL 115, 07201 (2015)
No need for exotic J/ψK⁻ contributions

- J/ψK⁻ system is well described by the Λ* and Pc⁺ reflections.

\[ m_{\text{Kp}} < 1.55 \text{ GeV} \]
\[ 1.55 < m_{\text{Kp}} < 1.70 \text{ GeV} \]
\[ 1.70 < m_{\text{Kp}} < 2.00 \text{ GeV} \]

PRL 115, 07201 (2015)
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$M_0$ (MeV)</th>
<th>$\Gamma_0$ (MeV)</th>
<th>Fit fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>low</td>
<td>high</td>
<td>low</td>
</tr>
<tr>
<td>Extended vs. reduced</td>
<td>21</td>
<td>0.2</td>
<td>54</td>
</tr>
<tr>
<td>$\Lambda^*$ masses &amp; widths</td>
<td>7</td>
<td>0.7</td>
<td>20</td>
</tr>
<tr>
<td>Proton ID</td>
<td>2</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>$10 &lt; p_T &lt; 100$ GeV</td>
<td>0</td>
<td>1.2</td>
<td>1</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>3</td>
<td>0.3</td>
<td>34</td>
</tr>
<tr>
<td>Separate sidebands</td>
<td>0</td>
<td>0</td>
<td>5</td>
</tr>
<tr>
<td>$J^P$ (3/2$^+$, 5/2$^-$) or (5/2$^+$, 3/2$^-$)</td>
<td>10</td>
<td>1.2</td>
<td>34</td>
</tr>
<tr>
<td>$d = 1.5 - 4.5$ GeV$^{-1}$</td>
<td>9</td>
<td>0.6</td>
<td>19</td>
</tr>
<tr>
<td>$L^P_{\Lambda^0_b}$ $\Lambda^0_b \rightarrow P^+_c$ (low/high)$K^-$</td>
<td>6</td>
<td>0.7</td>
<td>4</td>
</tr>
<tr>
<td>$L^P_{\Lambda^0_c}$ $P^+_c$ (low/high) $\rightarrow J/\psi p$</td>
<td>4</td>
<td>0.4</td>
<td>31</td>
</tr>
<tr>
<td>$L^A_{\Lambda^0_b}$ $\Lambda^0_b \rightarrow J/\psi \Lambda^*$</td>
<td>11</td>
<td>0.3</td>
<td>20</td>
</tr>
<tr>
<td>Efficiencies</td>
<td>1</td>
<td>0.4</td>
<td>4</td>
</tr>
<tr>
<td>Change $\Lambda(1405)$ coupling</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Overall</td>
<td>29</td>
<td>2.5</td>
<td>86</td>
</tr>
<tr>
<td>sFit/cFit cross check</td>
<td>5</td>
<td>1.0</td>
<td>11</td>
</tr>
</tbody>
</table>

- Uncertainties in the $\Lambda^*$ model dominate
Additional cross-checks

- Many additional cross-checks have been done. Some are listed here:
  - The same $P_c^+$ structure found using very different selections by different LHCb teams
  - Two independently coded fitters using different background subtractions (cFit & sFit)
  - Split data shows consistency: 2011/2012, magnet up/down, $\Lambda_b/\Lambda_b$, $\Lambda_b(p_T \text{ low})/\Lambda_b(p_T \text{ high})$
  - Extended model fits tried without $P_c$ states, but with two additional high mass $\Lambda^*$ resonances allowing masses & widths to vary, or 4 non-resonant terms of $J$ up to 3/2
Argand diagrams

$P_c^+$ amplitudes for 6 $m_{J/ψp}$ bins between $+Γ$ & $-Γ$ around the resonance mass

- Good evidence for the resonant character of $P_c(4450)^+$
- The errors for $P_c(4380)^+$ are too large to be conclusive
Molecular states?

\[(qqqq) (qqqq)\]
molecule
e.g. deuteron

\[\Lambda_c^+, \Sigma_c^+\]
\[D^0\]
\[I = 1/2 (\Lambda, \Sigma), 3/2 (\Sigma)\]
decay

\[p\]
\[n\]
\[\rho\]
\[J/\psi\]

Difficult to get more than one state \((n=1, l=0)\).

\[M = M_1 + M_2 - (a few \text{ MeV})\]

\[J^P = (J_1 \otimes J_2)^{P1^*P2}\]

\[\Gamma \sim \max(\Gamma_1, \Gamma_2)\]
Baryon-meson molecules?

Binding energy for L=0


\[ \Lambda_c^+ + D^0 \quad \Sigma_c^+ + D^0 \quad \Sigma_c^* + \bar{D}^0 \quad \Sigma^* + \bar{D}^0 \quad \Sigma_c^* + D^0 \quad \Lambda_c^0 + D^0 \]

Rich spectrum of relatively narrow states expected:
all shown + isospin partners + strange partners + b quark + …

Cannot accommodate a \( \frac{5\pm}{2} \) state with a plausible S-wave molecule
L>0 molecules not likely to be bound
Tightly bound pentaquarks?

Maiani, Polosa, Riquer [arXiv:1507.04980],
Anisovich et al [arXiv:1507.07652, 1509.04898],
Li, He, He [arXiv:1507.08252],
Ghosh et al [arXiv:1508.00356]

\[ P_c(4380)^+ \]

\[ P_c(4450)^+ \]

\[ \frac{5}{2}^+ \quad \text{or} \quad \frac{3}{2}^+ \]

Such mass difference and the opposite parity can be explained by \( \Delta l = 1 \)

Can accommodate \( \frac{5}{2}^+ \) when at least one diquark in \( S=1 \) state

Rich spectrum of states expected:
\( S=0 \) (lower \( J \)) + \( l + n + \) isospin partners + strange partners + \( b \) quark + ...

\[
\bar{c}[cu]_{S=1} [ud]_{S=0} (l=1)
\]

\[
\bar{c}[cu]_{S=1} [ud]_{S=1} (l=0)
\]
Conventional hadrons produced and then rescatter (rearrange quarks) to produce a peak in the exotic channel. Peaking structures related to mass thresholds.

Ad hoc parameter values to generate desired structures.

Can sometimes arrange for the resonant-like phase running.

Given proliferation of thresholds, why aren’t they everywhere?

Not clear these models can describe decay angles distributions – predictions and tests on the data are needed.

In the past, many resonances which are well established by now, were proposed to be rescattering effects (e.g. $a_1(1260)$).
Future studies of \( P_c(4380)^+ \), \( P_c(4450)^+ \)

- Nathan has a few months left before he will graduate:
  - We are working on improving \( \Lambda^* \) model in hope that we can improve \( P_c \) \( J^P \) determinations:
    - In present Isobar model:
      - try new states suggested in C. Fernandez-Ramirez et al paper (arxiv:1510.07065 Oct 23), remove \( \Lambda(1800) \)
      - more advanced models of non-resonant contributions than what we have tried so far
      - see if our data can contribute to \( \Lambda^* \) spectroscopy
    - Possibly replace the Isobar approach with C. Fernandez-Ramirez et al approach adopted to our data (with their help!)
      - We are interested in testing rescattering models, but need their 6D formulation!
  - There is a large effort in LHCb to look for these states in other modes and for other pentaquarks with heavy quarks
Outlook to the future

• At present there are many plausible explanations for the observed $P_c^+$ states.
• The main competition is between tightly bound models based on diquark substructure, loosely bound molecules and rescattering effects.
• Clarifying $J^P$ values and resonant nature of the discovered $P_c^+$ states with more statistics will be very important.
• All models predict many other related states to exist. Different models predict different mass spectra. We badly need to discover more elements of future periodic table of such states!
• Interactions forming pentaquark states must also play a role in tetraquark states. It is important to pursue both spectroscopies together!
• Searches for states with even more quarks e.g. sextquarks (i.e. dibaryons) interesting.
• We can do more to test the diquark idea in ordinary baryons! Need experimentalists to do better on identifying all excited baryons.
• So far the most compelling tetraquark and pentaquark candidates have been discovered with hidden charm inside ($c\bar{c}$). The other heavy quark systems should also be creating bound structures ($b\bar{b}, b\bar{c}, c\bar{c}, ...$)
• We are only at the beginning of hopefully very interesting road ahead…
Conclusion

- Two pentaquark candidates decaying to J/ψp observed by LHCb with overwhelming significance in a state of the art amplitude analysis: they will not go away!

Pentaquark candidates rise from the ashes for the 2nd time.
- LHC resurrects them: should not be a surprise given baryon cross-sections.

\[ \text{c\bar{c}} \text{ pair inside:} \]
- Given the history of Quark Model should not be a surprise either.

**Hopefully true July 2015 revolution!**
- The simplicity of lower mass excitations of mesons and baryons, which led us to the discovery of quarks via q\bar{q}, qqq structures, also misled us to believe that we had already understood hadronic structures. Much experimental and theoretical work remains to be done to achieve this goal.