Some Recent Results from LHCb

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University of Cincinnati
on behalf of the LHCb Collaboration

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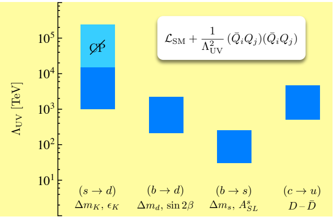
Why Flavor Physics?

- Search for manifestations of **New Physics at the highest energy scales** by studying rare and forbidden decays and and searching for CP violation beyond that described by the Kobayashi-Maskawa phase of the CKM matrix.
  - CP violation in D^0 mixing
  - CP violation in B_s mixing
  - direct CP violation in four-body Λ_b decay
- Better understand strong interactions in the **Standard Model**, especially its non-perturbative aspects.
  - study $K^{*+} \to \phi K^+$ and $X^0 \to J/\psi\phi$ structures in $B^+ \to J/\psi\phi K^+$
  - study character of $Z(4430)^-$ observed in $B^0 \to \psi(2S)K^+\pi^-$
- Use cross-section measurements to probe the structure of the proton
- Probe the “hidden sector” searching for rare decays producing low mass particles with very small couplings to ordinary matter.

Flavor Constrains BSM Physics

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert_D$, ϕ_D
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $\sin(2\beta)$ from $B_d\to\psi K$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $\sin(\phi_s)$ from $B_s\to\psi\phi$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	

Flavor Structure in the SM and Beyond



Generic bounds without a flavor symmetry

- Table above from Isidori and Teubert, Eur.Phys.J.Plus **129**, 40 (2014). Bounds on representative dimension-six $\Delta F = 2$ operators.
- Image to the left from M. Neubert, EPS-HEP-2011.

No-So-Exotic Hadrons

A SCHEMATIC MODEL OF BARYONS AND MESONS *

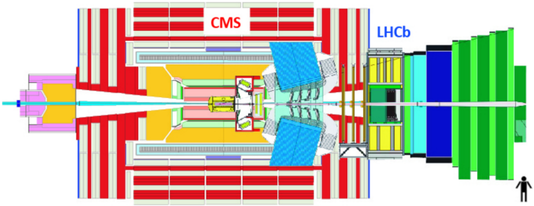
M. GELL-MANN
California Institute of Technology, Pasadena, California

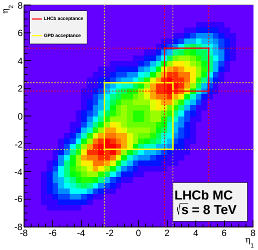
Received 4 January 1964

Gell-Mann's original discussion of hadron properties in terms of quarks also *explicitly* suggested tetra-quark states ($qq\overline{q}\overline{q}$) and penta-quark state ($qqqq\overline{q}$) as well as "ordinary" mesons ($q\overline{q}$) and baryons (qqq).

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" [6] q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

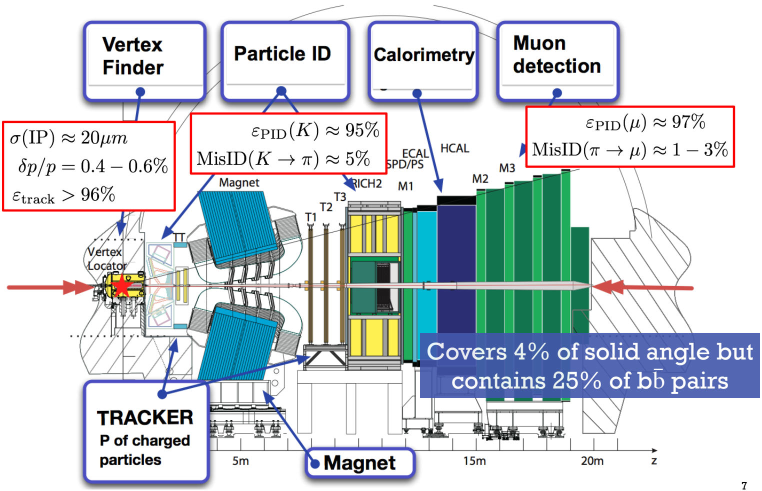
LHC Detector Acceptances for $b\bar{b}$ Production



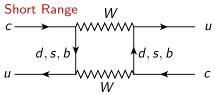


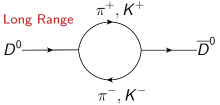
- LHCb is a forward spectrometer, optimized for accepting both B and $\overline{B}$ hadrons in an event;
- accepts about $10\times$ as many triggers as ATLAS or CMS;
- $\sigma(c\,\bar{c}) \sim 20 \times \sigma(b\,\bar{b})$;
- acceptance in η complements ATLAS and CMS for many electro-weak studies.

LHCb Detector [2008 JINST 3 S08005]



Neutral Meson Oscillation and *CP* Violation in Mixing





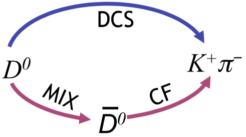
$$|P_{1,2}\rangle = p|P^0\rangle \pm q|\overline{P}^0\rangle \,; \qquad p^2 + q^2 = 1$$

$$x \equiv \frac{\Delta m}{\Gamma} \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

$$|\mathcal{M}|^2 \quad \propto \quad \frac{1}{2}\, e^{-\Gamma t} \Bigg\{ |\mathcal{A}_\alpha|^2 \Big(\cosh y\,\Gamma t + \cos x\,\Gamma t \Big)$$

$$+ \, |\overline{\mathcal{A}}_\alpha|^2 \, |\frac{q}{p}|^2 \Big(\cosh y\,\Gamma t - \cos x\,\Gamma t \Big)$$

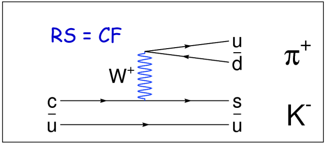
$$+ \, 2 \left[\Re\left(\left(\frac{q}{p}\right)^* \mathcal{A}_\alpha \overline{\mathcal{A}}^*_\alpha \right) \sinh y\,\Gamma t - \Im\left(\left(\frac{q}{p}\right)^* \mathcal{A}_\alpha \overline{\mathcal{A}}^*_\alpha \right) \sin x\,\Gamma t \right] \Bigg\} \,.$$

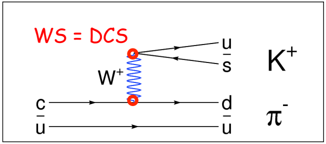


for $x,\, y \ll 1$ (valid for D^0, not for B_s):

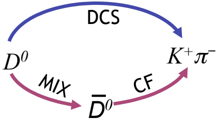
- **doubly Cabibbo-Suppressed (DCS) $\approx \propto e^{-\Gamma t}$;**
- **pure mixing $\propto e^{-\Gamma t} \times (\Gamma t)^2$**
- **interference $\approx \propto e^{-\Gamma t} \times \Gamma t$**

Time Evolution of $D^0 \to K\pi$





DCS and mixing amplitudes interfere to give a "quadratic" WS decay rate (x, y << 1):



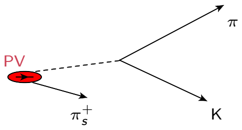
$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D} y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right) \left(\frac{t}{\tau}\right)^2$$

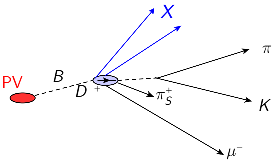
where $x' = x\cos\delta + y\sin\delta$ $\quad y' = y\cos\delta - x\sin\delta$

and δ is the phase difference between DCS and CF decays.

$m_i,\ \Gamma_i \Leftrightarrow$ weak eigenstates ; $\quad x \equiv \frac{\Delta m}{\langle\Gamma\rangle}$; $\quad y \equiv \frac{\Delta m}{2\langle\Gamma\rangle}$; $\quad \tau \equiv \frac{1}{\langle\Gamma\rangle}$

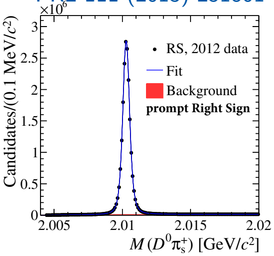
$D^0 \to K\pi$ Samples: Prompt and Doubly-Tagged (DT)



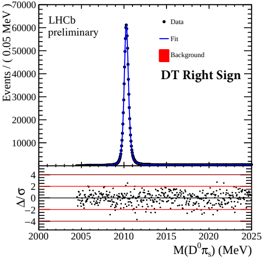


- prompt signal trigger becomes "fully" efficient well above one lifetime;
- doubly-tagged trigger is $\sim$ independent of D^0 decay time;

PRL **111** (2013) 251801



LHCb-PAPER-2016-033



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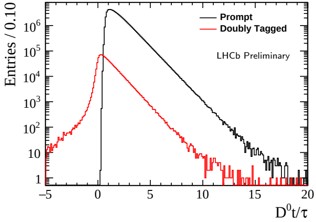
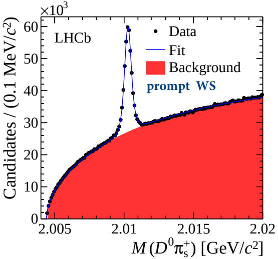
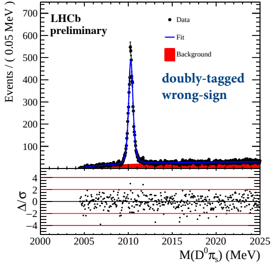


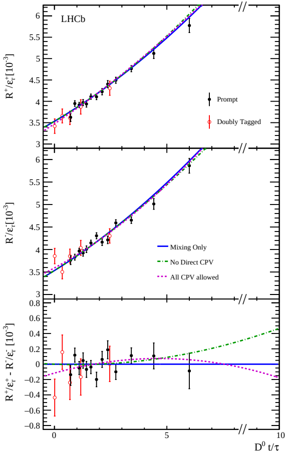
$D^0 \to K\pi$ Mixing and CPV Measurements

$$R^{\pm}(t) = \frac{\mathrm{WS}(t)}{\mathrm{RS}(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

PRL **111** (2013) 251801; LHCB-PAPER-2016-033





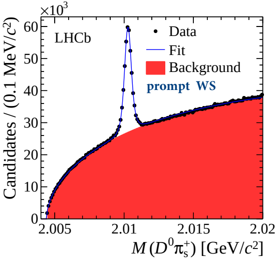


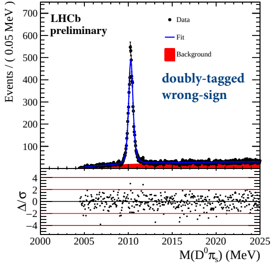
- ~ 54 M prompt RS, ~ 1.7 M DT RS;
- ~ 230 K WS, ~ 6 K WS DT;
- **D^0, $\overline{D}^0$ mixing rates are equal, $\pm 5\%$.**
- adding DT sample [$\mathcal{O}(3\%)$] improves precision by $(10-20)\%$.

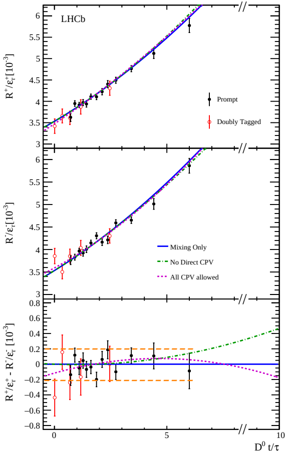
$D^0 \to K\pi$ Mixing and CPV Measurements

$$R^{\pm}(t) = \frac{\mathrm{WS}(t)}{\mathrm{RS}(t)} = R_D^{\pm} + \sqrt{R_D^{\pm}}\,y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^{\pm 2} + y'^{\pm 2}}{4}\right)\left(\frac{t}{\tau}\right)^2$$

PRL **111** (2013) 251801; LHCB-PAPER-2016-033







- $\sim$ 54 M prompt RS, $\sim$ 1.7 M DT RS;
- $\sim$ 230 K WS, $\sim$ 6 K WS DT;
- **D^0, $\overline{D}^0$ mixing rates are equal, $\pm 5\%$.**
- adding DT sample [$\mathcal{O}(3\%)$] improves precision by $(10 - 20)\%$.

Phenomenology of B_s Mixing and CP Violation

In the special case when the B_s decays semi-leptonically ($\overline{B}_s \to D_s^+ \mu^- X$), there is no DCS amplitude. Thus, the WS rate results from pure mixing.

$$|\mathcal{M}|^2 \quad \propto \quad \frac{1}{2}\, e^{-\Gamma t} \left\{ |\overline{\mathcal{A}}_\alpha|^2 \left|\frac{q}{p}\right|^2 \left(\cosh y\,\Gamma t - \cos x\,\Gamma t \right) \right\}$$

The difference in mixing rates for $B_s \to \overline{B}_s$ and $\overline{B}_s \to B_s$ (as $p \neq q$) produces an asymmetry in the rates to these final states:

$$a_{\rm sl} \equiv \frac{\Gamma(\overline{B}_s \to f) - \Gamma(B_s \to \overline{f})}{\Gamma(\overline{B}_s \to f) + \Gamma(B_s \to \overline{f})} \approx \frac{\Delta\Gamma_s}{\Delta m_s} \tan \phi_{12s} \ ,$$

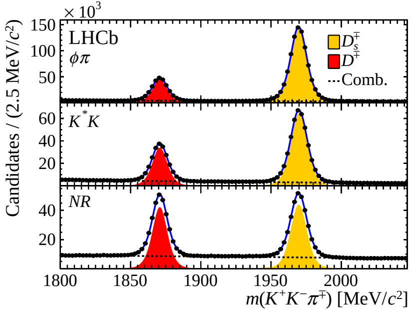
Here, $x_s \equiv \Delta m_s / \Gamma_s \gg 1$ while $y_s \equiv \Delta\Gamma_s / 2\Gamma_s \ll x_s$. As a result, the mixing period is much less than the lifetime. Tagging the flavor of a B_s when it is produced is not efficient, and measuring the time-integrated asymmetry introduces only a factor of 2 dilution in sensitivity. Hence, $a^s_{\rm sl}$ is calculated as

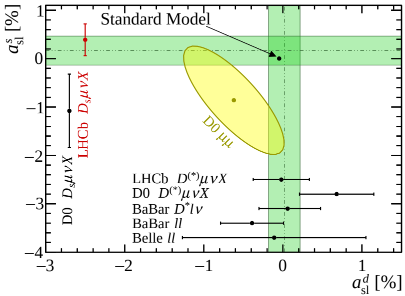
$$a^s_{\rm sl} = \frac{2}{1 - f_{\rm bkg}} (A_{\rm raw} - A_{\rm det} - f_{\rm bkg} A_{\rm bkg}) \ ,$$

where $A_{\rm det}$ is the detection asymmetry, $f_{\rm bkg}$ is the fraction of b-hadron background and $A_{\rm bkg}$ the background asymmetry.

CP Violation in B_s Mixing

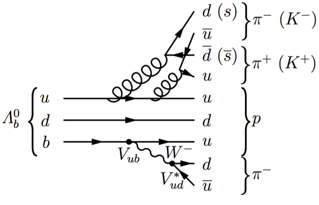
PRL **117** (2016) 061803

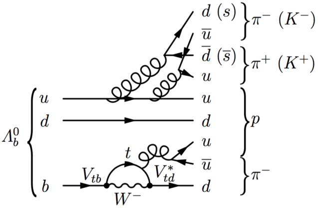




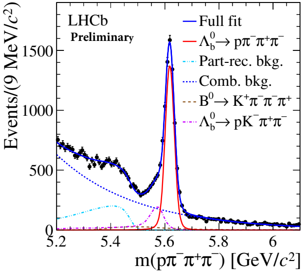
- $B_s \to D_s^{\pm}(\to KK\pi)\mu^{\mp} X$ tags flavor at decay;
- $D_s \to KK\pi$ Dalitz plot divided into three signal regions, $\phi\pi$ (900 K events), K^*K (415 K events), and non-resonant (280 K events);
- **SM $\Rightarrow$ $a_{sl}^s \sim 2 \times 10^{-5}$** [e.g., Lenz and Nierste, JHEP **06** (2007) 072];
- result of this analysis: **$a_{sl}^s = (0.39 \pm 0.26 \pm 0.20)\%$**.

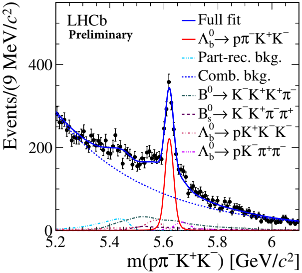
$\Lambda_b^0 \to p\pi^+\pi^-\pi^-$, $\Lambda_b^0 \to p\pi^- K^+ K^-$: Physics & Signals





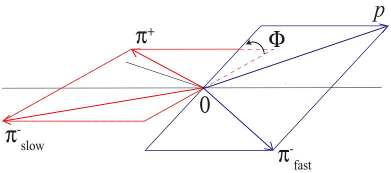
LHCb-PAPER-2016-030





Triple Product Asymmetry Math

Example: $\Lambda_b^0 \to p\pi^+\pi^-\pi^- + \text{cc}$



- $C_{\widehat{T}} = \vec{p}_p \cdot (\vec{p}_{h_1^-} \times \vec{p}_{h_2^+})\ [\Lambda_b^0]$
- $\overline{C}_{\widehat{T}} = \vec{p}_{\overline{p}} \cdot (\vec{p}_{h_1^+} \times \vec{p}_{h_2^-})\ [\overline{\Lambda}_b^0]$

$$A_{\widehat{T}}(C_{\widehat{T}}) = \frac{N(C_{\widehat{T}} > 0) - N(C_{\widehat{T}} < 0)}{N(C_{\widehat{T}} > 0) + N(C_{\widehat{T}} < 0)}$$

$$\overline{A}_{\widehat{T}}(\overline{C}_{\widehat{T}}) = \frac{\overline{N}(-\overline{C}_{\widehat{T}} > 0) - \overline{N}(-\overline{C}_{\widehat{T}} < 0)}{\overline{N}(-\overline{C}_{\widehat{T}} > 0) + \overline{N}(-\overline{C}_{\widehat{T}} < 0)}$$

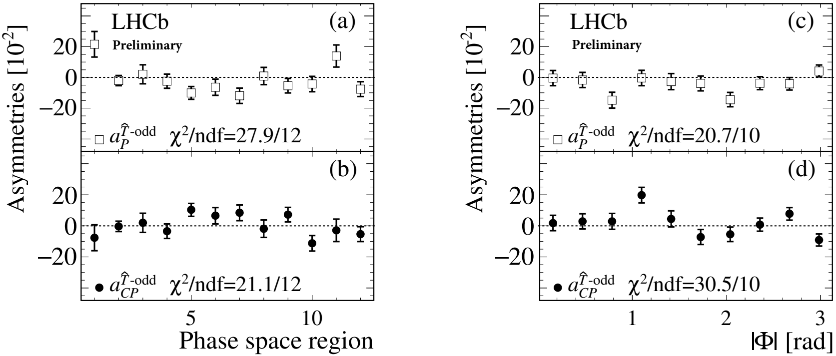
$$a_P^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} + \overline{A}_{\widehat{T}}\right) \qquad a_{CP}^{\widehat{T}\text{-odd}} = \frac{1}{2}\left(A_{\widehat{T}} - \overline{A}_{\widehat{T}}\right)$$

$\Lambda_b^0 \to p\pi^+\pi^-\pi^-$ and $\Lambda_b^0 \to p\pi^-K^+K^-$ TPAs

- $\approx 6000\ \Lambda_b^0 \to p\pi^+\pi^-\pi^-$ and $\approx 1000\ \Lambda_b^0 \to p\pi^-K^+K^-$ studied;
- **Analysis performed blindly**. All event selection criteria *and* all analysis procedures (including division of phase space into bins, defining statistical procedure to be employed, etc.) determined prior to examining data; similarly, all systematic uncertainties were evaluated prior to examining (unblinded) data.
- **globally**, no significant parity or *CP* violation observed in either sample;
- two binning schemes employed; one separates the data into disjoint subsamples according to two-body invariant masses and azimuthal angle; the other separates the data into disjoint samples using only azimuthal angle.
- **locally**, no significant parity or *CP* violation in $\mathbf{\Lambda_b^0 \to p\pi^-K^+K^-}$.

Evidence for parity and CP violation in $\Lambda_b^0 \to p\pi^+\pi^-\pi^-$

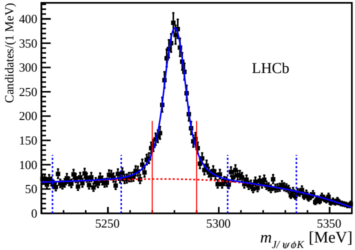
LHCb-PAPER-2016-030, in preparation

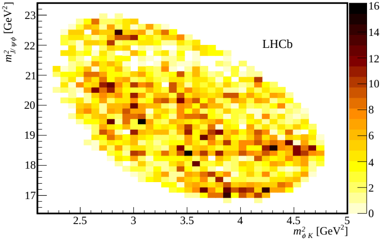


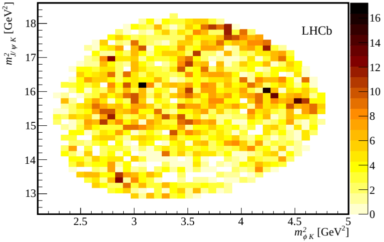
- The consistency of the data with the CP symmetry hypothesis is found to be $\mathbf{p = 9.8 \times 10^{-4}}$ ($3.3\,\sigma$) using a well-established statistical test (R. A. Fisher, *The Design of Experiments* 1935), employing pseudoexperiments based on permuting the real data events to capture correlations.

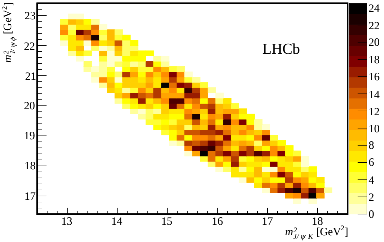
Structure in $B^+ \to J/\psi\phi K^+$ LHCb-PAPER-2016-018 & 2016-019

Dalitz plot distributions are background-subtracted and efficiency-corrected



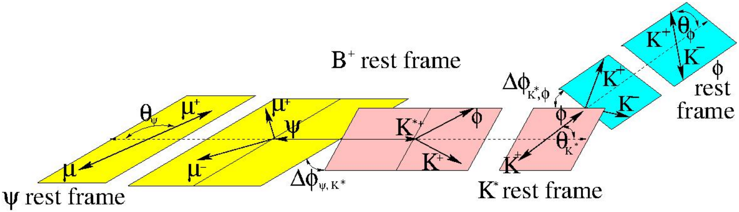


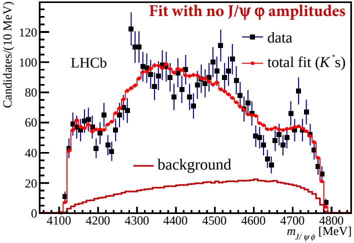


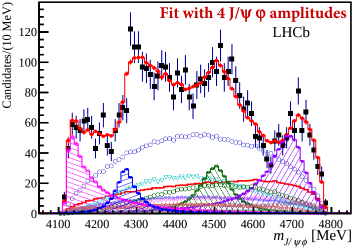


Some Fit Projections for $B^+ \to J/\psi\phi K^+$

LHCb-PAPER-2016-018 & LHCb-PAPER-2016-019







$J/\psi\ \phi$ Amplitudes in the Default Fit Model

LHCb-PAPER-2016-018 & LHCb-PAPER-2016-019

Contri-bution	sign.	Fit results M_0 [MeV]	Γ_0 [MeV]	Fit Fractions%
All $X(1^+)$				$16\pm3\ ^{+\ 6}_{-\ 2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13\pm3.2\ ^{+4.8}_{-2.0}$
ave. prior		4143.4 ± 1.9	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-\ 3.6}$	$56\pm11\ ^{+\ 8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF		$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS		$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm\ 5\pm\ 7$
NR $J/\psi\phi$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

ave. prior see Table 1 in LHCb-PAPER-2016-019

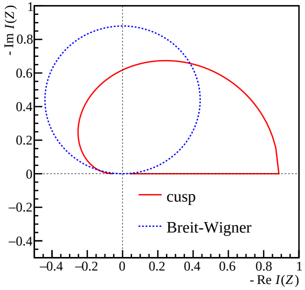
CDF arXiv:1101.6058

CMS Phys. Lett. **B734** (2014) 261

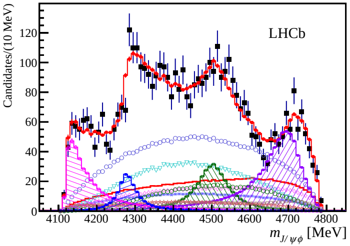
Alternative Model for $X^0(4140)$

LHCb-PAPER-2016-018 & LHCb-PAPER-2016-019

- Our 1^{++} assignment to $X(4140)$ and its large width rule out an interpretation as a 0^{++} or 2^{++} $D_s^{*+}D_s^{*-}$ molecule.
- A threshold cusp parameterization proposed by Swanson [Int. J. Mod. Phys. E **25**, no. 07, 1642010 (2016)], in which an exponential form factor, with a momentum scale (β_0) characterizes the hadron size, makes the cusp peak slightly above the sum of masses of the rescattering mesons.

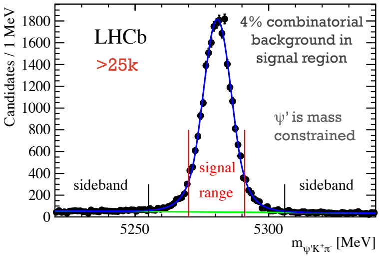


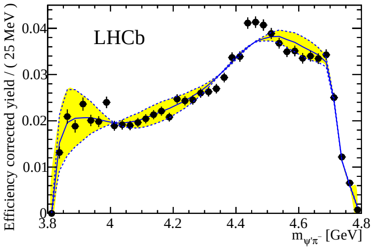
- This model fits the data as well as the default amplitude model.



$B^0 \to Z^-(4430)K^+$; $Z^-(4330) \to \psi'\pi^-$; $|dc\,\overline{cu}\rangle$

PRL **112** (2014) 222002

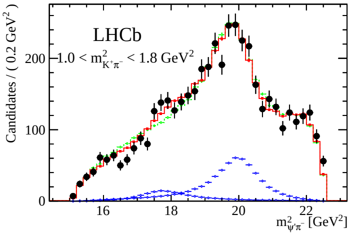


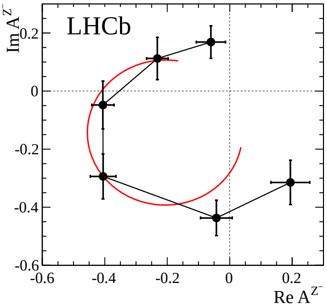


- $B^0 \to \psi' K^+ \pi^-$; $\psi' \to \mu^-\mu^+$
- Amplitude fits plus model-independent analysis
- $Z^-(4430) \to \psi'\pi^-$ first observed by Belle [PRL 100 (2008) 142001]

- Background-subtracted, efficiency-corrected $m(\psi'\pi^-)$ distribution.
- Model projections of $\cos\theta_{K^*}$ moments up to order 4, allows for $J(K^*) \leq 2$, including correlated uncertainties.

Resonant Character of the $Z^{-}(4430)$



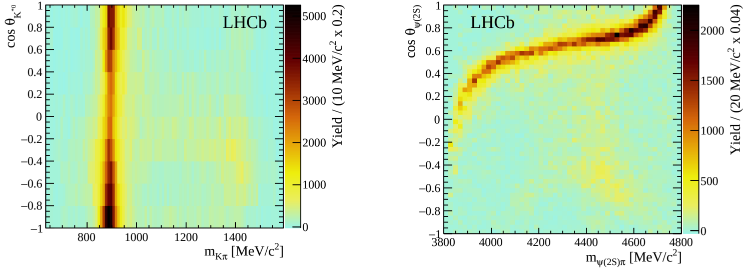


- Amplitude fit including $J^P = 1^+$ $Z^-(4430) \to \psi'\pi^-$ improves overall χ^2 corresponding to $18.7\,\sigma$. [PRL **112** (2014) 222002]
- Relative to $J^P = 1^+$, the 0^-, 1^-, 2^+, and 2^- hypotheses are rejected by at least $9.7\,\sigma$, $15.8\,\sigma$, $16.1\,\sigma$, and $14.6\,\sigma$.
- $\Rightarrow$ **4-quark resonant state**

- **A fit including an additional $J^P = 0^-$ $\psi'\pi^-$ amplitude with $m = (4239 \pm 18^{+45}_{-10})$ MeV and $\Gamma = (220 \pm 47^{+108}_{-74})$ MeV improves overall χ^2 corresponding to $6\,\sigma$.**

Model-Independent Evidence for the $Z^{-}(4430)$ – I

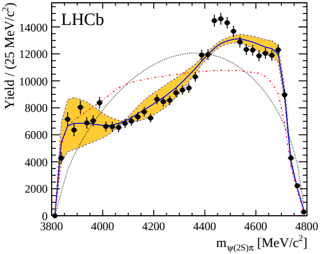
Phys. Rev. **D92** (2015) 112009



- "Square Dalitz plots" expose helicity structures of amplitudes.
- The $K^{*}(892)$ band in the left-hand plot has two lobes produced by the $P \to VP\ cos\theta$ amplitude.
- The left-hand plot also has an accumulation of events near 1400 MeV which might be produced by higher mass K^{*} amplitudes.
- The right-hand plot has an accumulation of events near 4430 MeV. It might be a reflection of features produced by K^{*} amplitudes.

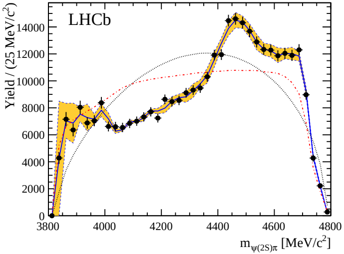
Model-Independent Evidence for the $Z^-(4430)$ – II

Phys. Rev. **D92** (2015) 112009



The $\cos\theta$ distribution in each $m(K\pi)$ bin is described in terms of Legendre polynomials up to order

$$l_{\max} = \begin{cases} 2 & m(K\pi) < 836\,\text{MeV} \\ 3 & 836\,\text{MeV} < m(K\pi) < 1000\,\text{MeV} \\ 4 & m(K\pi) > 1000\,\text{MeV}\,. \end{cases}$$



The $\cos\theta$ distribution in each $m(K\pi)$ bin is described in terms of Legendre polynomials up to order $l_{\max} = 30$.

Using MC experiments, the $m_{\psi(2S)\pi}$ projections of the data prefer this Legendre polynomial weighting at the 15 σ level.

To Take Away

- We are measuring the particle – antiparticle differences in mixing rates at the $\pm 5\%$ level in the D^0 system and at the $\pm 0.35\%$ level in the B_s system. The limits from these measurements constrain BSM physics reach at high mass scales that complement those from direct searches.
- We have observed evidence for (direct) CP violation in Λ_b decays using triple product asymmetries.
- More than 50 years after the prediction of tetra-quark and penta-quark states, we are discovering many of these in the decays of B-hadrons.
- Flavor physics is fun.