LHCb status and prospects

Anton Poluektov

University of Warwick, UK

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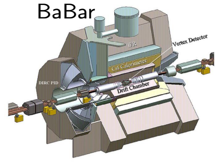
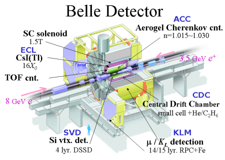
LHCb collaboration

Flavour physics at colliders

e^+e^- machines





Production of $b\bar{b}$ pairs at threshold.

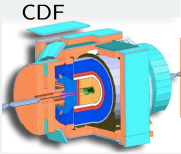
Pros:

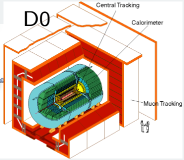
- Clean environment
- Efficient reconstruction of neutral modes
- Efficient flavour tagging

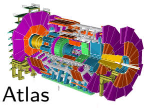
Contras:

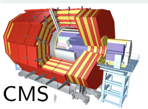
- Low production cross-section (especially B_s^0 and heavier)
- Small boost (artificially by asymmetric energies) $\Rightarrow$ low decay time resolution

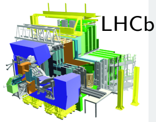
Hadron machines











Production of $b\bar{b}$ pairs in pp ($p\bar{p}$) collisions:

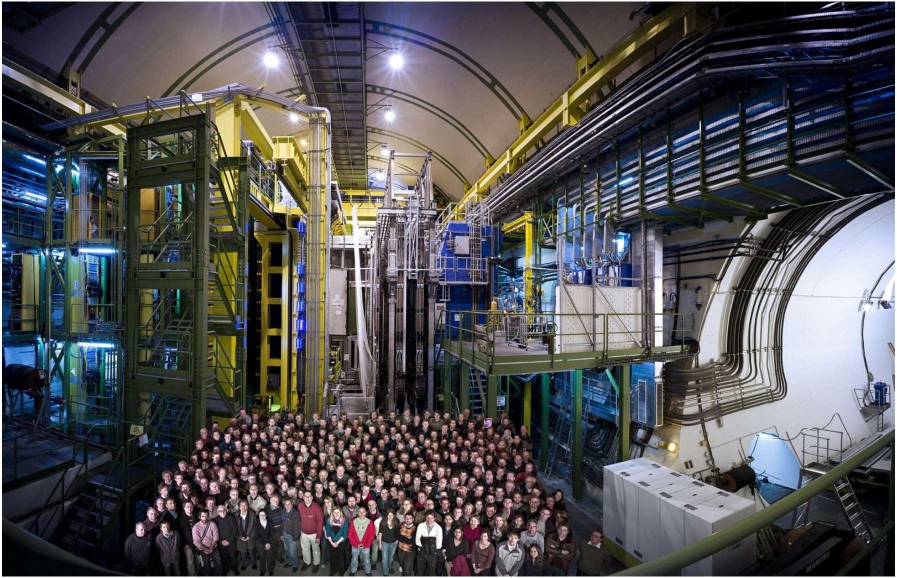
Pros:

- Forward production, large boost
- All sorts of b hadrons produced ($B^0, B^+, B_s^0, B_c^+, \Lambda_b^0, \Xi_b, B^*, \ldots$)
- Large production cross-section

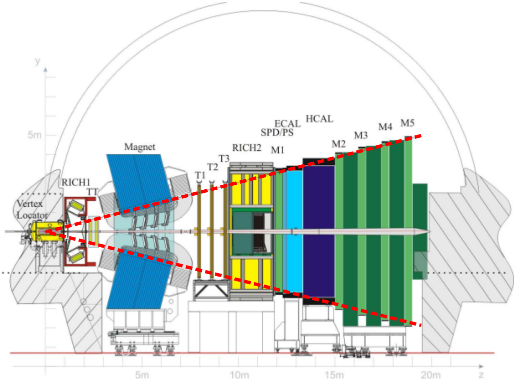
Contras:

- Busy events, hard to reconstruct neutral modes.
- Lower flavour tagging power

LHCb experiment

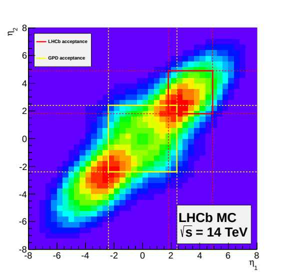


One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Rapidity coverage

$$2 < \eta < 5$$



- Covers forward region (maximum of c and b production)

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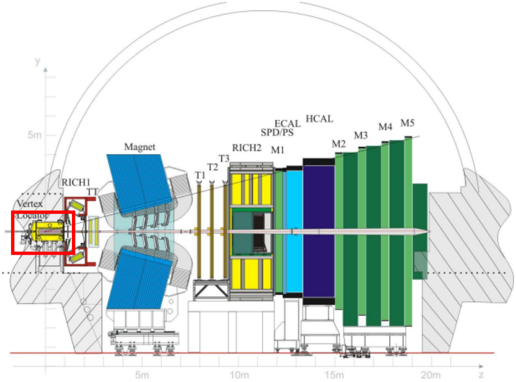
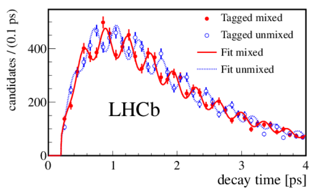


Vertexing

B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background

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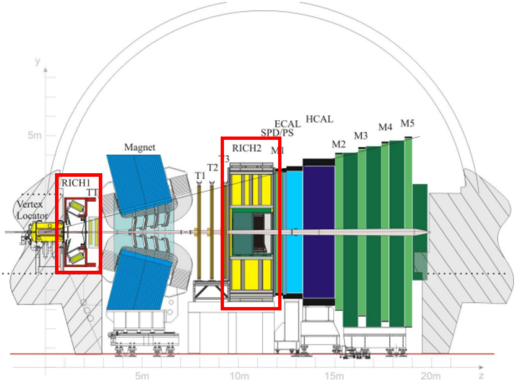
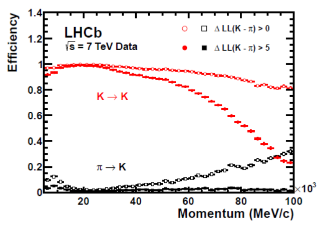


PID

K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background

LHCb

[JINST 3 (2008) S08005]

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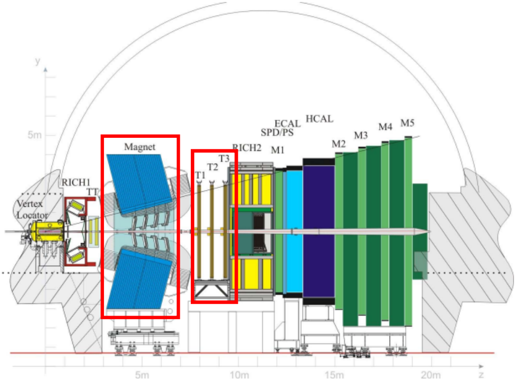
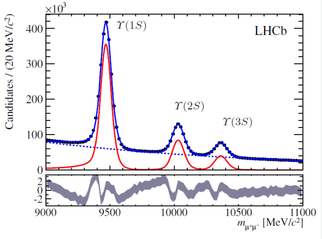


Tracking

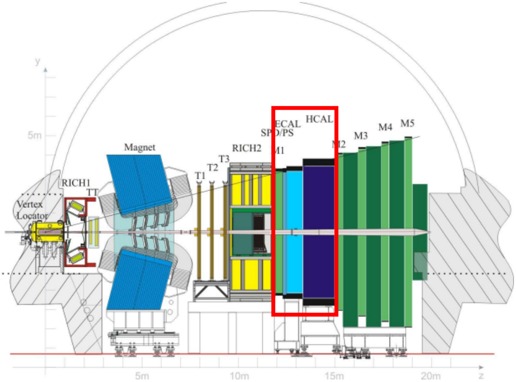
$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

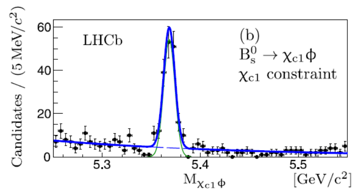
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B^0_s oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Calorimetry

$B_s^0 \to \chi_{c1}\phi$, $\chi_{c1} \to J/\psi\gamma$



[Nucl. Phys. B874 (2013) 663]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking
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[JINST 3 (2008) S08005]

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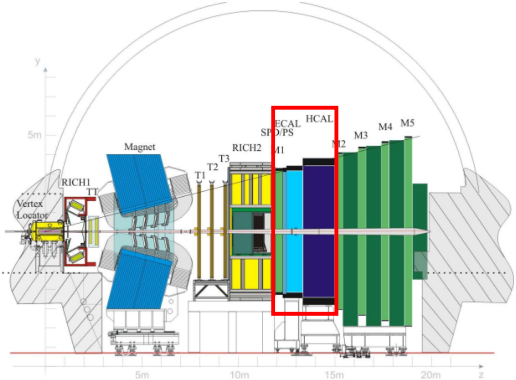

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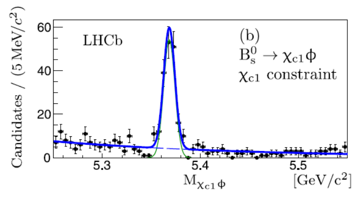

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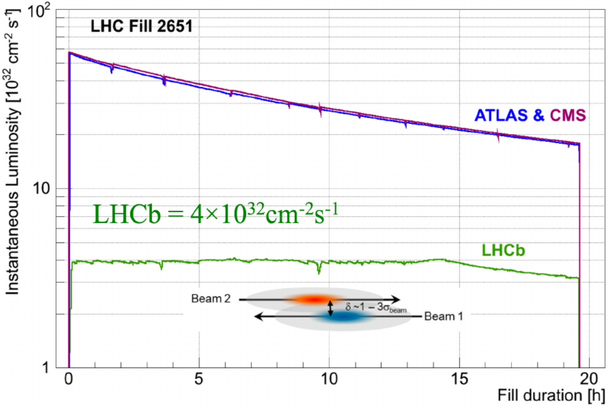
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state
- Efficient trigger, including fully hadronic modes

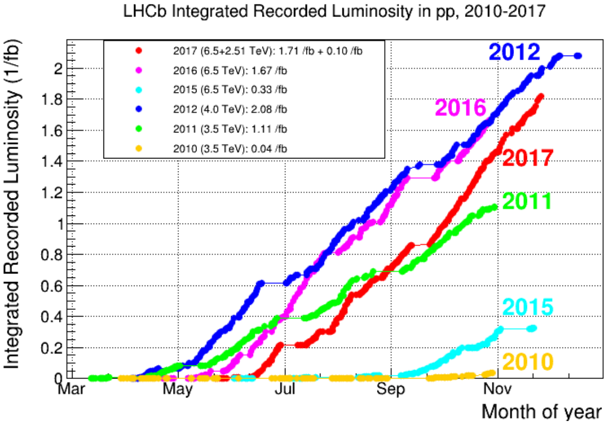
LHCb operation



$3\,\text{fb}^{-1}$ in 2011 and 2012 (Run 1, $\sqrt{s} = 7, 8\,\text{TeV}$): Most of results in this talk

$2\,\text{fb}^{-1}$ in 2015 and 2016 (Run 2, $\sqrt{s} = 13\,\text{TeV}$, higher b CS): Analyses ongoing

$1.7\,\text{fb}^{-1}$ in 2017 at $13\,\text{TeV}$



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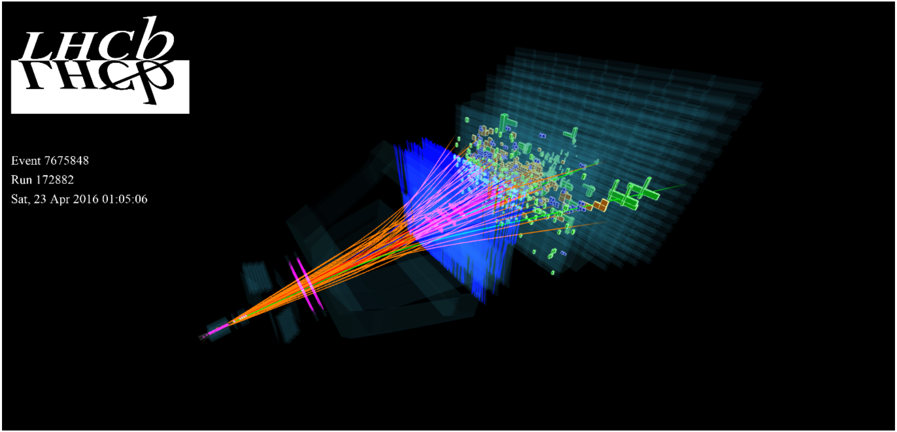
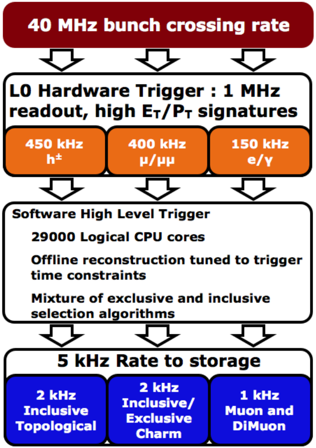
Proton-proton collision



LHCb trigger

Trigger is a crucial elements in experiments at hadron machines. Need to work in a very difficult environment with hundreds of tracks in each beam crossing.



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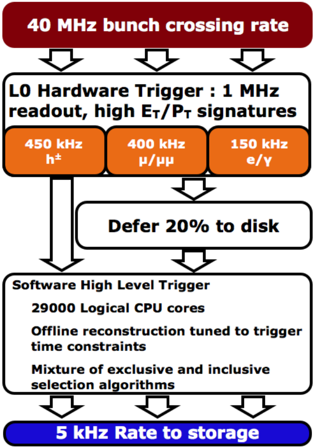

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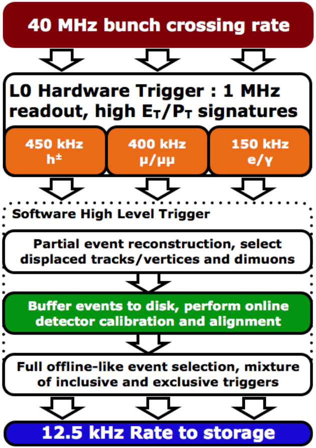


- 2011 and early 2012: increased trigger bandwidth (compared to design 2 kHz) to accommodate charm
- 2012: *deferred trigger* configuration: keep the trigger farm busy between fills
- Since 2015: *split trigger*
  - All 1st stage (HLT1) output stored on disk
  - Used for real-time calibration and alignment
  - 2nd stage (HLT2) uses offline-quality calibration
  - 5 kHz of 12 kHz to Turbo stream:
    - Candidates produced by trigger are stored
    - No raw event ⇒ smaller event size
    - Used for high-yield channels (charm, J/ψ, . . .)

Analysis techniques

Time-dependent measurements

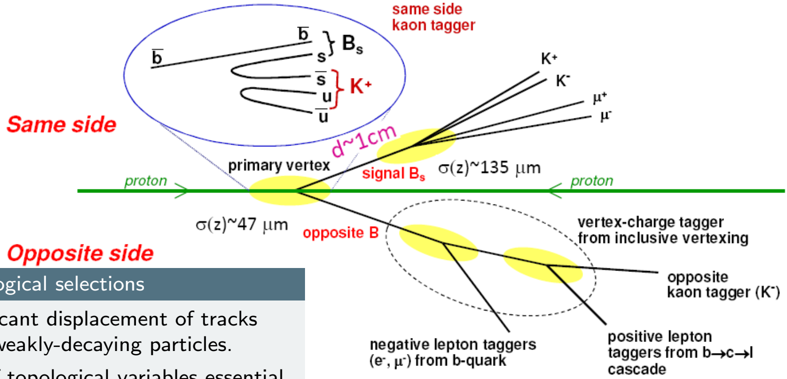
Measure lifetime based on vertex displacement from the primary vertex of pp interaction.

Large boost provides excellent time resolution ($\sigma_t \simeq 45$ fs)

Flavor tagging

Need to identify B flavour *at production time* (different from flavour at decay time due to oscillations).
Use decay products of the opposite-side B (OS) and π, K associated with same-side B (SS).

Effective tagging power $\epsilon_{\mathrm{tag}} D^2 = 3.7\%$.



Topological selections

Significant displacement of tracks from weakly-decaying particles.

Use of topological variables essential to reduce combinatorial background.

CKM measurements

$\mathcal{CP}$ violation in hadrons (difference of decay probabilities for particle and antiparticle) is described by Cabibbo-Kobayashi-Maskawa model

- Few parameters can explain a vast amount of experimental data
- A single weak phase responsible for $\mathcal{CP}$ violation
- Need *interference* of several amplitudes for $\mathcal{CP}$ violation to occur

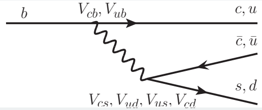
Cabibbo-Kobayashi-Maskawa matrix

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \simeq$$

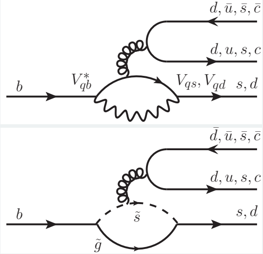
$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

($\lambda \simeq 0.22$ is a small parameter, $A, \rho, \eta \sim \mathcal{O}(1)$)

Tree: SM only



Loop: possible NP



Tree-only quantities: γ, $|V_{ub}|$. SM references, compare with loop-based parameters.

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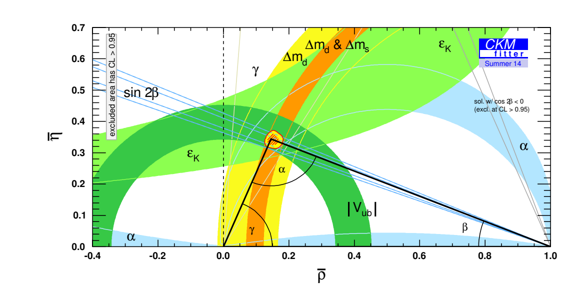
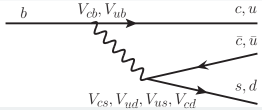
Graphical CKM representation: Unitarity Triangle



Tree: SM only



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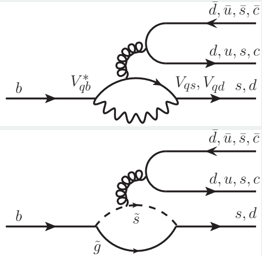


Tree-only quantities: γ, $|V_{ub}|$. SM references, compare with loop-based parameters.

$\mathcal{CP}$ violation phenomenology

B meson system as an example.

Direct $\mathcal{CP}$ violation

Asymmetry in decay amplitudes:
$|\mathcal{A}_f/\overline{\mathcal{A}}_f| \neq 1$

$$A_{\pm} = \frac{\Gamma(B^- \to f^-) - \Gamma(B^+ \to f^+)}{\Gamma(B^- \to f^-) + \Gamma(B^+ \to f^+)}$$

The only possibility for charged mesons.

$\mathcal{CP}$ violation in mixing

If transitions $B^0 \leftrightarrow \overline{B}^0$ are allowed:

$$|B_L\rangle = p|B^0\rangle + q|\overline{B}^0\rangle$$
$$|B_H\rangle = p|B^0\rangle - q|\overline{B}^0\rangle$$

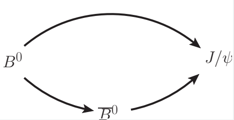
$\mathcal{CP}$ violation if $|q/p| \neq 1$
Can be observed in the asymmetry of "wrong-sign" decays ($\mu^\pm\mu^\pm$)

$$A_{SL} = \frac{1-|q/p|^4}{1+|q/p|^4}$$

Indirect $\mathcal{CP}$ violation (in interference)

Interference between $B^0 \to f$ and $B^0 \to \overline{B}^0 \to f$
Even if $|\mathcal{A}_f/\overline{\mathcal{A}}_f| = 1$ and $|q/p| = 1$, $\mathcal{CP}$ is violated if

$$\mathcal{I}m\left(\frac{q}{p}\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f}\right) \neq 0$$



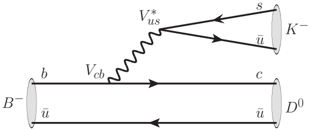
Can be measured in the time-dependent asymmetry:

$$\frac{\Gamma(\overline{B}^0 \to f_{CP}) - \Gamma(B^0 \to f_{CP})}{\Gamma(\overline{B}^0 \to f_{CP}) + \Gamma(B^0 \to f_{CP})}(\Delta t) = S_{f_{CP}} \sin(\Delta m_d \Delta t) + A_{f_{CP}} \cos(\Delta m_d \Delta t)$$

Direct $\mathcal{CP}$ violation in $B \to DK$

Measures CKM phase γ at tree level, $\Rightarrow$ SM reference point.

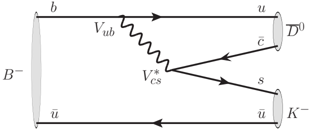
$B^- \to D^0 K^-$:



$A \sim V_{cb}V_{us}^* \sim A\lambda^3$

$+$

$B^- \to \overline{D}^0 K^-$:



$A \sim V_{ub}V_{cs}^* \sim A\lambda^3(\rho - i\eta)$

If D^0 and $\overline{D}^0$ decay into the same final state: $|\tilde{D}\rangle = |D^0\rangle + r_B e^{\pm i\gamma + i\delta_B}|\overline{D}^0\rangle$ for $B^\pm$

Ratio of two amplitudes: $r_B = \left|\frac{A(B^- \to \overline{D}^0 K^-)}{A(B^- \to D^0 K^-)}\right| = \left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \times$ [Color supp] ~ 0.1

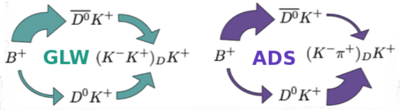
Measurement techniques:

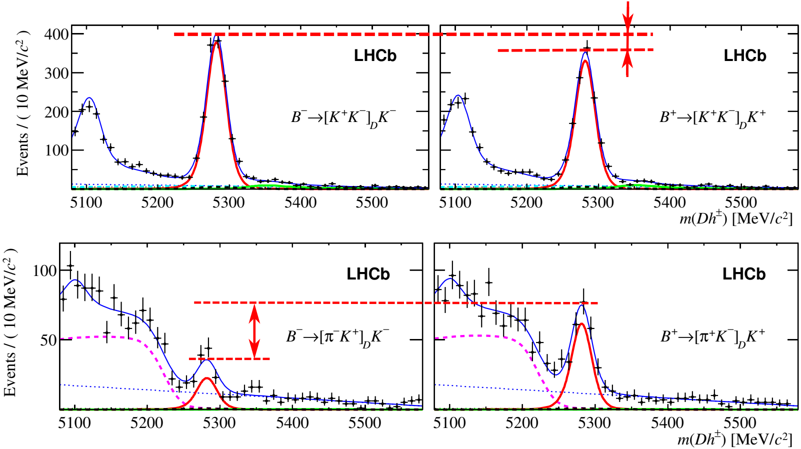
- Measure asymmetry of **rates** with D decaying to $\mathcal{CP}$-eigenstates ($D \to KK$, $\pi\pi$) or suppressed $D^0 \to K^+\pi^-$ states
- Measure asymmetry in **kinematic distributions** for multibody D decays. "Golden mode": $D \to K_S\pi^+\pi^-$.

Extremely clean theoretically, limiting accuracy $< 10^{-7}$

[Phys. Lett. B 760 (2016) 117]

$B^{\pm} \to DK^{\pm}$ with:
suppressed $D \to K^{-}\pi^{+}$ (ADS),
CP-eigenstate $D \to hh$ (GLW)



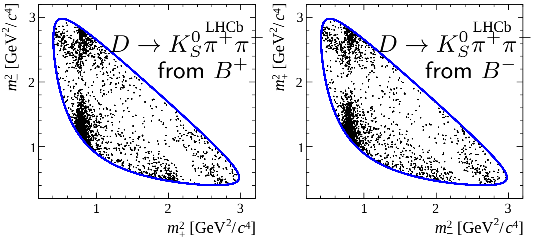


Measure asymmetry of decay probabilities for B^+ and B^-

Direct $\mathcal{CP}$ violation in $B \to DK$: $D \to K^0_S h^+ h^-$ modes

$B^\pm \to DK^\pm$, $D \to K^0_S\pi^+\pi^-$: amplitude analysis

[Phys. Lett. B 718 (2012) 43-55]



2D kinematic distribution of $D \to K^0_S\pi^+\pi^-$ from $B^\pm \to DK^\pm$

$$p_\pm(m^2_+, m^2_-) = |A_D + r_B e^{\pm i\gamma + i\delta}\,\overline{A}_D|^2$$

where A_D is known from flavour-specific $D^* \to D^0\pi$ decays

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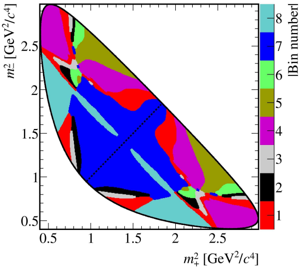
Model-independent analysis: remove dependence on A_D modelling (and hard-to-quantify model uncertainty) by binning the $D \to K^0_S\pi^+\pi^-$ phase space and counting events in bins.

$$N_i = h[K_i + r_B^2 K_{-i} + 2\sqrt{K_i K_{-i}}(xc_i - ys_i)]$$

where $x = r_B\cos(\delta_B \pm \gamma)$, $y = r_B\sin(\delta_B \pm \gamma)$,

$c_i = \langle\cos\Delta\delta_D\rangle_i$, $s_i = \langle\sin\Delta\delta_D\rangle_i$ are obtained from $e^+e^- \to D\overline{D}$

K_i are yields in flavour D^0 decay, from D^* tags



Direct $\mathcal{CP}$ violation in $B \to DK$: charm inputs

Measured asymmetries with ADS/GLW provide constraints on γ, e.g.:

Inputs related to D decays are provided by external measurements:

- r_D, δ_D are ratio and phase difference between $A(D^0 \to K^+\pi^-)$ and $A(D^0 \to K^-\pi^+)$. Extracted from charm mixing analyses or from $e^+e^- \to D\overline{D}$ data.
- Multibody ADS modes e.g. $D \to K^-\pi^+\pi^-\pi^+$: additional coherence factor κ, from $e^+e^- \to D\overline{D}$.
- Quasi-CP-eigenstates as $D \to \pi^+\pi^-\pi^+\pi^-$: CP content F_+, from $e^+e^- \to D\overline{D}$.

$D \to K^0_S\pi^+\pi^-$: average strong phase differences c_i, s_i are external charm input.

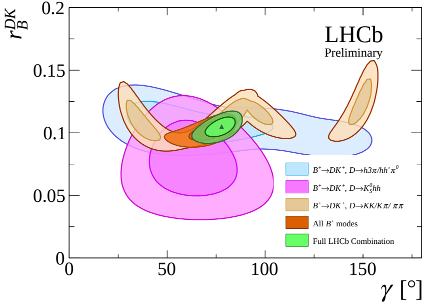
- Currenly from CLEO: contribution to $\sigma(\gamma) \sim 2^\circ$.
- BES-III: ~ 4 times more stats $\Rightarrow$ potentially $\sigma(\gamma) \sim 1^\circ$
- For γ precision $< 1^\circ$ (LHCb upgrade) need more charm data.
- Alternatively, can constrain from charm mixing or other B decays ($B^0 \to DK\pi$ with large r_B).

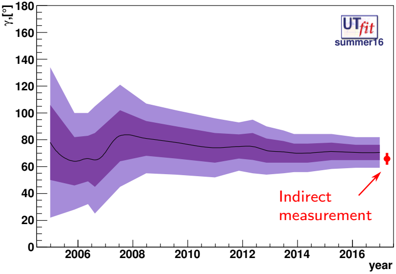
Why $e^+e^- \to D\overline{D}$? Because D mesons are produced in quantum-correlated state $|A(D\overline{D})|^2 = |A(D_1)A(\overline{D}_2) - A(\overline{D}_1)A(D_2)|^2$.
Correlated densities provide relative phase information not observable otherwise.

Direct $\mathcal{CP}$ violation in $B \to DK$

- Combination of many different modes sensitive to γ:
  - Time-integrated asymmetries in $B \to DK$, $B \to DK^*$, $B \to DK\pi$ with $D \to hh, hhhh$
  - Dalitz-plot analysis of $D^0 \to K^0_S h^+ h^-$ from $B \to DK$, $B \to DK^*$
  - Time-dependent analysis of $B_s \to D_s K$
- Experimentally, just entering precision measurement regime ($< 10\%$)

[LHCb-CONF-2017-004, EPS 2017]





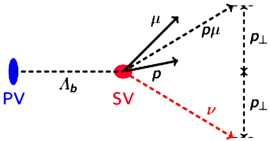
Combination of all LHCb results: $\gamma = (76.8^{+5.1}_{-5.7})^\circ$ (LHCb preliminary)

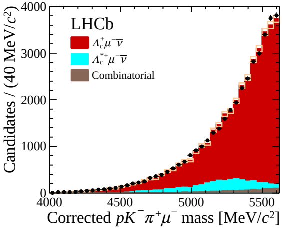
Indirect: $\gamma = (65.3^{+1.0}_{-2.5})^\circ$ [CKMFitter 2016]

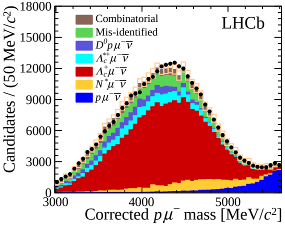
SM reference CKM measurements: $|V_{ub}|$ from semileptonic decays

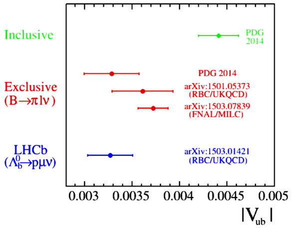
[LHCb, Nature Phys. 11 (2015) 743]

- Use Λ_b^0 sample for $|V_{ub}|$ measurement, cleaner final state
- Measure $|V_{ub}|/|V_{cb}|$ from
  $$|V_{ub}/V_{cb}|^2 = \frac{\mathcal{B}(\Lambda_b^0 \to p\mu\nu)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \mu\nu)} R_{FF}$$
- Fit corrected mass $M_{\rm corr} = \sqrt{p_T^2 + M_{p\mu}^2} + p_T$
- $|V_{ub}| = [3.27 \pm 0.15 \pm 0.16(\text{LQCD}) \pm 0.06(V_{cb})] \times 10^{-3}$
- Dominant uncertainty: absolute $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$. Potential $c\tau$ input.







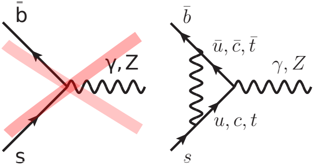


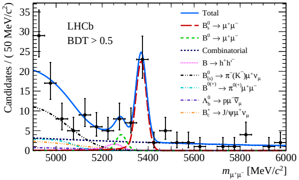
Rare decays

What kinds of rare decays are we studying?

- **Flavour changing neutral currents**.
  In the SM, these are suppressed by weak loop:
  Typical signatures:
  - lepton pair (with $\gamma^*, Z^0 \to \mu^+\mu^-$)
  - hard photon ($B \to K^*\gamma$)

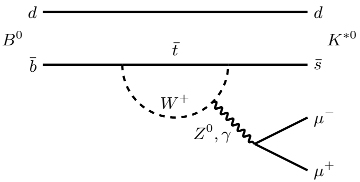
  Search for deviations from SM expectation in probabilities, angular distributions *etc.*

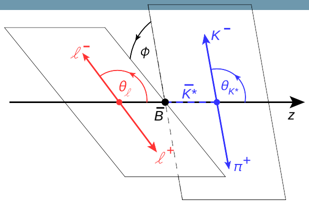




- **Lepton flavour violating decays**
  E.g. $B \to e^\pm\mu^\mp$. Strongly forbidden in the SM.

- **Flavour (non-)universality**
  Lepton couplings in SM are the same for three generations of leptons (e, μ, τ).
  Possible NP if deviations *e.g.* in $B \to K e^+e^-$ and $B \to K\mu^+\mu^-$.



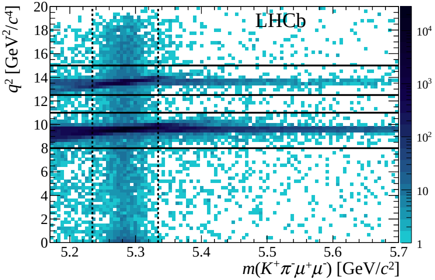


- Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_\mathrm{L})\sin^2\theta_K + F_\mathrm{L}\cos^2\theta_K + \tfrac{1}{4}(1-F_\mathrm{L})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_\mathrm{L}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_\mathrm{FB}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

- $F_\mathrm{L}, A_\mathrm{FB}, S_i$ combinations of K^{*0} spin amplitudes depending on Wilson coefficients $C_7^{(\prime)}$, $C_9^{(\prime)}$, $C_{10}^{(\prime)}$ and form factors
- Relative sign between B^0 and $\overline{B}^0$ → access to CP asymmetries $A_{3,\ldots,9}$
- Alternative: ratios of angular observables where form factors cancel at leading order, e.g. $P_5' = \frac{S_5}{\sqrt{F_\mathrm{L}(1-F_\mathrm{L})}}$ [S. Descotes-Genon *et al.*, JHEP, 05 (2013) 137]

$B^0 \to K^{*0}\mu^+\mu^-$ results

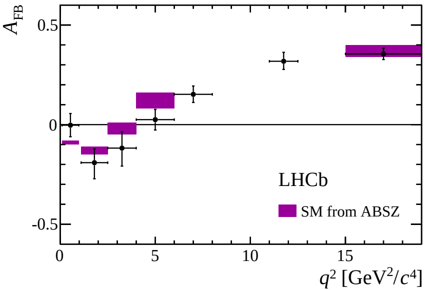


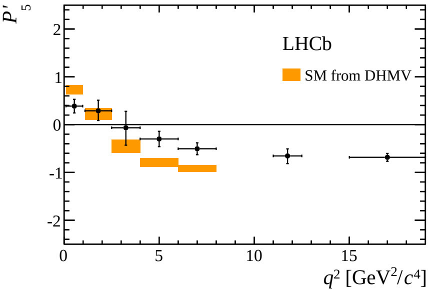
[LHCb, JHEP 02 (2016) 104]

Measure angular observables $F_L, A_{FB}, S_{3...9}$ in bins of q^2.

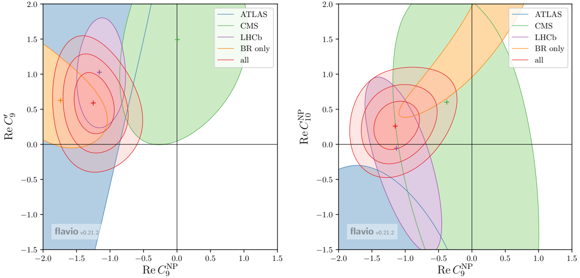
P_5': 3.7σ tension in $q^2 \in (4, 8)\,\mathrm{GeV}^2$

A_{FB}: mild tension in low-q^2 region





Global fits to $b \to s$ data [W. Altmannshofer et al. EPJC 77 (2017) 377]



In general, consistent pattern: modified vector coupling $C_9^{NP} \neq 0$ at 4-5σ level.

- New tree-level contribution from e.g. Z' with a mass of a few TeV
- Problem in our understanding of QCD contributions?

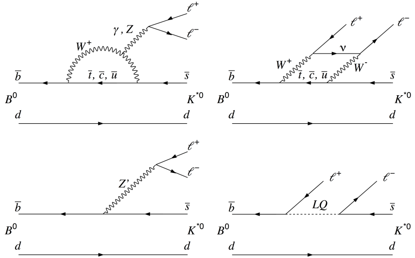
Could be understood by looking at C_9 trend as a function of q^2 $\Rightarrow$ need more data

Lepton universality in $b \to s\ell^+\ell^-$

Lepton universality: electroweak interaction is the same for all three generations of leptons.

$b \to s\ell^+\ell^-$ decyas ($\ell = e, \mu$): good probe of lepton universality.

After a small phase space correction, $\mathcal{B}$ to $\mu^+\mu^-$ and e^+e^- should be equal in SM.



Measure double ratio to cancel systematic uncertainties:

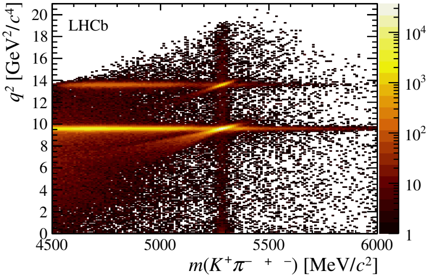
$$R(K^*) = \frac{\mathcal{B}(B^0 \to K^*\mu^+\mu^-)/\mathcal{B}(B^0 \to J/\psi(\mu^+\mu^-)K^*)}{\mathcal{B}(B^0 \to K^*e^+e^-)/\mathcal{B}(B^0 \to J/\psi(e^+e^-)K^*)}$$

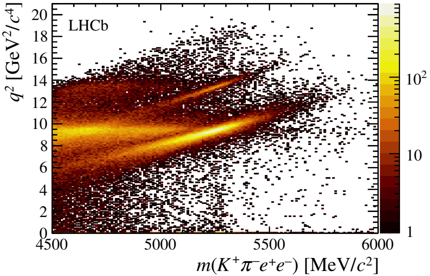
as a function of $q^2 = m^2(\ell^+\ell^-)$.

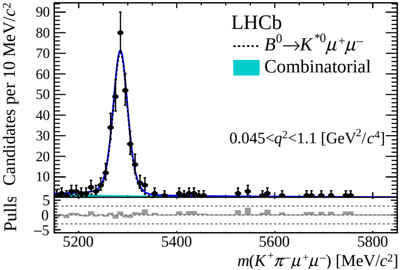
This implies that $\mathcal{B}(J/\psi(\mu^+\mu^-)/\mathcal{B}(J/\psi(e^+e^-) = 1$, an assumption that is tested at e^+e^- machines (in particular, KEDR).

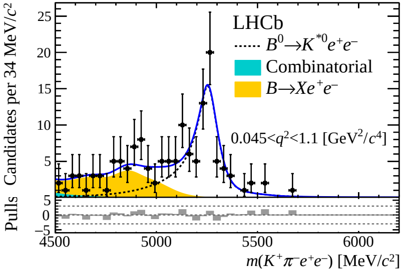
$R(K^*) \neq 1$ could be generated by a contribution of new gauge bosons or leptoquarks.

[arXiv:1705.05802]



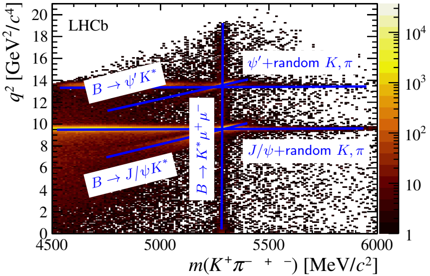


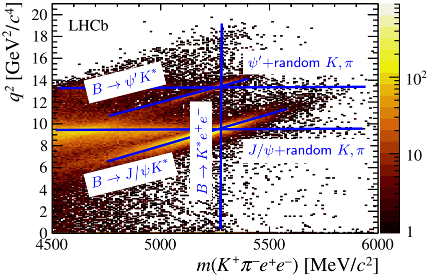


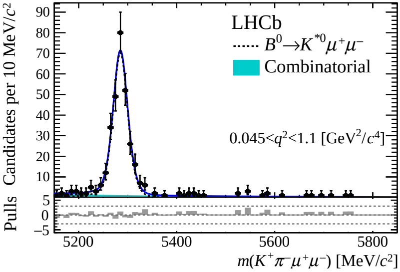


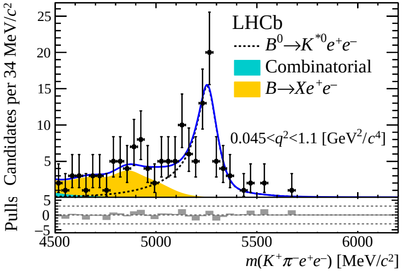
Lepton universality in $b \to s\ell^+\ell^-$

[arXiv:1705.05802]

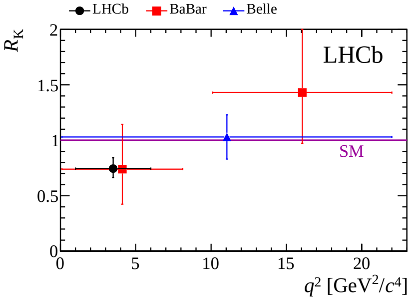




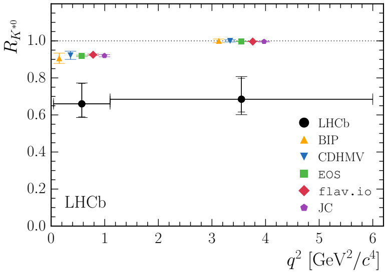




[PRL 113, 151601 (2014)]



[arXiv:1705.05802]



Consistent $R < 1$ pattern in both $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^{*0}\ell^+\ell^-$:

$R_K = 0.745^{+0.090}_{-0.074}\,(\text{stat}) \pm 0.036\,(\text{syst})$ for $1 < q^2 < 6\,\text{GeV}^2/c^4$ (2.6σ from SM)

$R_{K^{*0}} = 0.66^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.03\,(\text{syst})$ for $0.045 < q^2 < 1.1\,\text{GeV}^2/c^4$

$R_{K^{*0}} = 0.69^{+0.11}_{-0.07}\,(\text{stat}) \pm 0.05\,(\text{syst})$ for $1.1 < q^2 < 6.0\,\text{GeV}^2/c^4$ (2.5σ from SM)

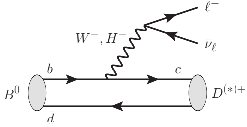
$R \simeq 0.8$ is predicted in some Z' models, see e.g. [W. Altmannshofer et al., PRD 89 (2014) 095033]

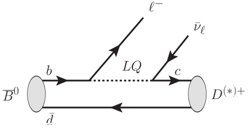
Lepton universality in semileptonic B decays

Another class of decays where hints of lepton non-universality is seen: $B \to D^{(*)}\ell\bar{\nu}_\ell$ ($\ell = (\mu, \tau)$).

Previously studied by B factories and by LHCb with $\tau \to \mu\nu_\tau\bar{\nu}_\mu$.

SM contribution could be modified by charged Higgs or leptoquarks





Observables: yield, $q^2 = (p_B - p_D)^2$, angular distributions.

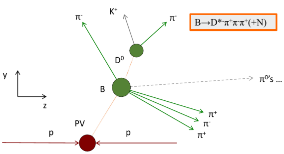
[LHCb-PAPER-2017-017, EPS 2017]

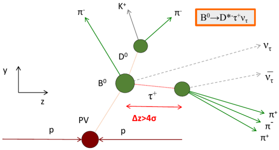
Now: measure $R(D^*) = \dfrac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu)}$ with $\tau \to 3\pi(\pi^0)\bar{\nu}_\tau$ decays.

Technically, measure $K(D^*) = \dfrac{\mathcal{B}(\overline{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\overline{B}^0 \to D^{*+}3\pi)}$

Employ decay topology for background suppression.

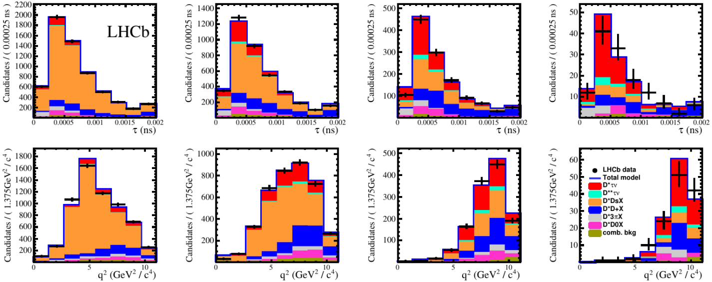
Multivariate discriminant (BDT) to suppress $B \to D^* D_s$





3D fit in τ_B, q^2, BDT response. [LHCb-PAPER-2017-017, EPS 2017]

Fit results in q^2 and τ_B projections (4 BDT bins):



This analysis:

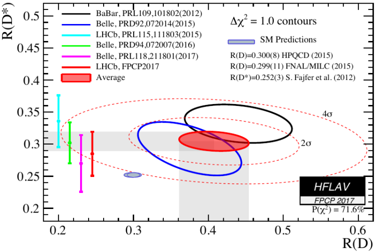
$R(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021(\text{ext})$

External systematics from $\mathcal{B}(D_s^+)$ for backgrounds: potential $c\tau$ input

New WA: $R(D^*) = 0.304 \pm 0.015$

3.4σ above SM prediction

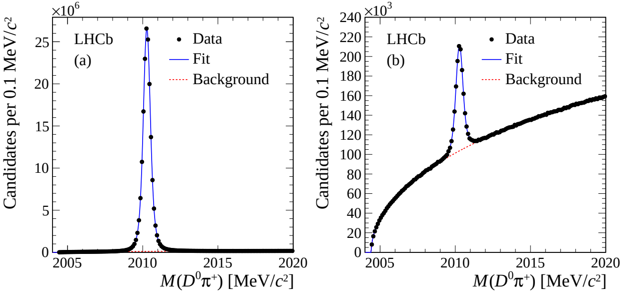
Combined with $R(D)$: 4.1σ from SM

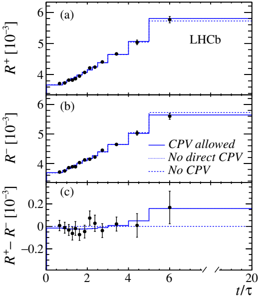


Charm physics

Charm mixing with $D^0 \to K\pi$

$D^{*+} \to D^0\pi^+$ signals: favoured $D^0 \to K^-\pi^+$ (177M evt), suppressed $D^0 \to K^+\pi^-$ (722k evt)





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

Measure y' and x'^2, related to mixing parameters x, y via rotation by strong phase difference δ_D.

Additionally, fits allowing CP violation (direct and in mixing).

$x'^2 = (3.9 \pm 2.7) \times 10^{-5}$, $y' = (5.28 \pm 0.52) \times 10^{-3}$, $R_D = (3.454 \pm 0.031) \times 10^{-3}$

Charm mixing with $D^0 \to K\pi$

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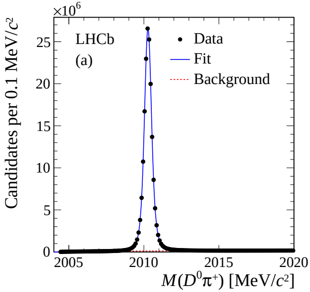
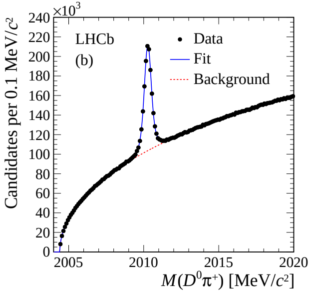
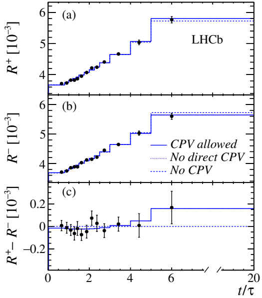
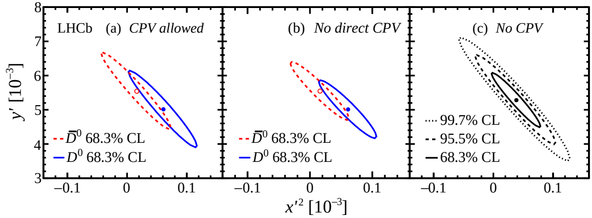




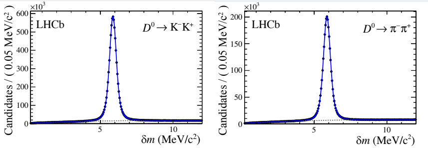


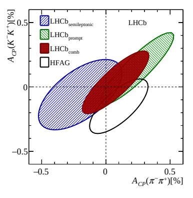


Time-dependent $\mathcal{CP}$ violation in charm

Direct $\mathcal{CP}$ violation in $D^0 \to hh$

[PRL 116, 191601 (2016); PLB 767 (2017) 177-187]





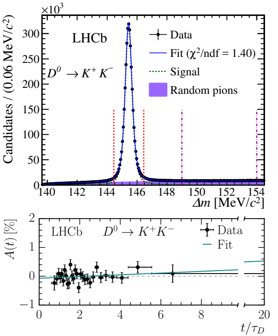
$$\Delta A_{CP}(K^+K^-, \pi^+\pi^-) = (-0.10 \pm 0.08 \pm 0.03)\%$$

$$A_{CP}(K^+K^-) = (+0.04 \pm 0.12 \pm 0.10)\%$$

$$A_{CP}(\pi^+\pi^-) = (+0.07 \pm 0.14 \pm 0.11)\%$$

Indirect $\mathcal{CP}$ violation in $D^0 \to hh$

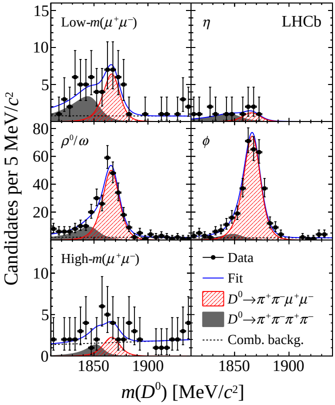
[PRL 118 (2017) 261803]

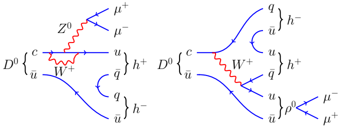


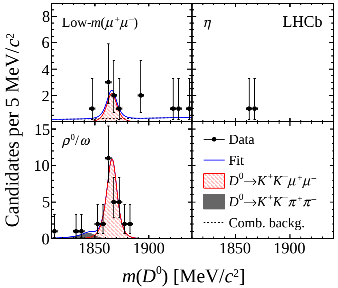
$$A_\Gamma(D^0 \to K^+K^-) = (-0.30 \pm 0.32 \pm 0.14) \times 10^{-3}$$

$$A_\Gamma(D^0 \to \pi^+\pi^-) = (+0.46 \pm 0.58 \pm 0.16) \times 10^{-3}$$

Can proceed via short- ($c \to u\mu^+\mu^-$) or long-distance (via ρ^0, ω *etc.*) contributions







Measured using $D^0 \to K^-\pi^+(\mu^+\mu^-)_{\rho^0,\omega}$ as normalisation

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51(\mathrm{syst}) \pm 0.97(\mathrm{norm})) \times 10^7$$

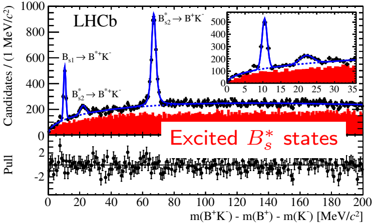
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09(\mathrm{syst}) \pm 0.16(\mathrm{norm})) \times 10^7$$

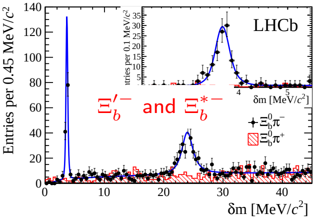
Rarest charm decays ever observed. $\mathcal{B}$'s consistent with SM.

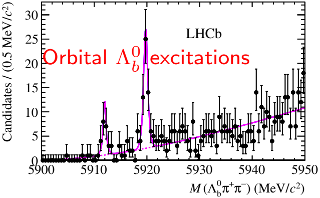
Hadron spectroscopy

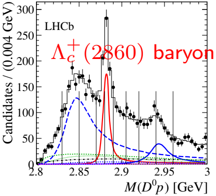
Many disoveries in conventional spectroscopy (b and c states, baryons and mesons)

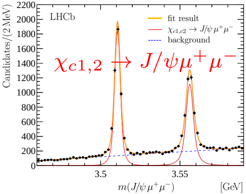
- Test theory approaches to low-energy QCD
- Hadronic input for NP-sensitive measurements
- Because it's awesome!







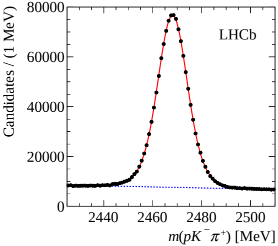


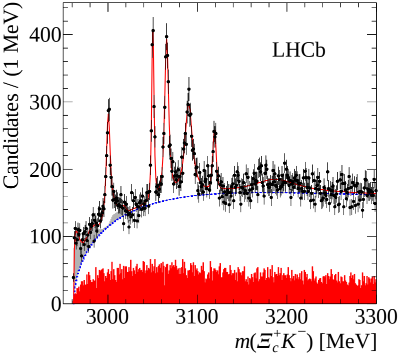


Observation of five new Ω_c states

[PRL 118, 182001 (2017)]

Search for $\Omega_c^{*0} \to \Xi_c^+ K^-$
Large sample of $\Xi_c^+ \to pK^-\pi^+$ decays, combine with a K^-



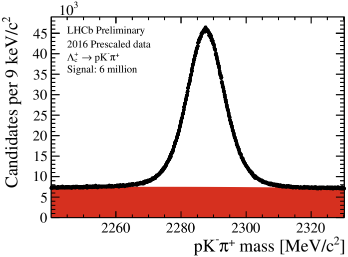


State	Mass, MeV	Width, MeV	Yield
$\Omega_c^0(3000)$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$
$\Omega_c^0(3050)$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$
$\Omega_c^0(3066)$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$
$\Omega_c^0(3090)$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$
$\Omega_c^0(3119)$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$

Two states extremely narrow (3050 and 3119), exotic?

Observation of doubly-charmed state

Search for $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$ [arXiv: 1707.01621]



10% of our $\Lambda_c \to pK^-\pi^+$ sample.

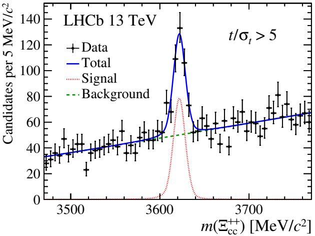
Combine it with K^- and two π^+.

$$M = 3621.40 \pm 0.72 \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\,\text{MeV}$$

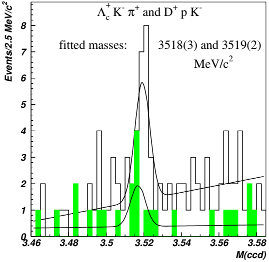
Mass $\sim 100\,\text{MeV}$ away from SELEX, clearly not an isospin partner.

No lifetime measurement yet, but significant displacement $> 5\sigma_\tau \Rightarrow$ weakly decaying.

Observed in Run 2 data (2016)



SELEX signal



Pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$

Most of charm and charmonium spectroscopy is done in decays of b hadrons:

- Clean signal, small background due to well-separated vertex
- Well-defined initial state allows for determination of quantum numbers in amplitude analysis

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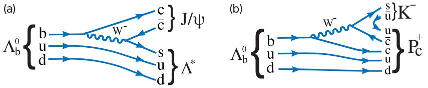
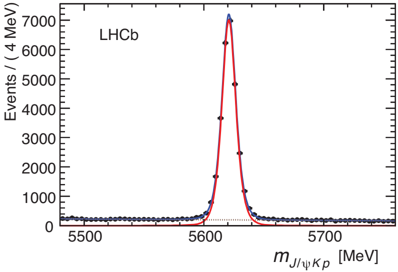
$\Lambda_b^0 \to J/\psi(\mu^+\mu^-)pK^-$ decay

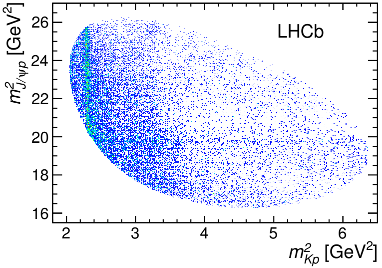
[PRL 115 (2015) 072001]

Conventional contributions only in pK^- spectrum (Λ^* states).





Event yield: 26007 ± 166 events
Low background (5.4%)



Dalitz distribution shows an unexpected narrow feature in $J/\psi p$ mass.

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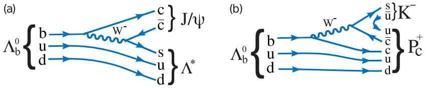

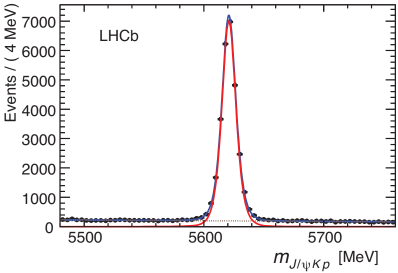

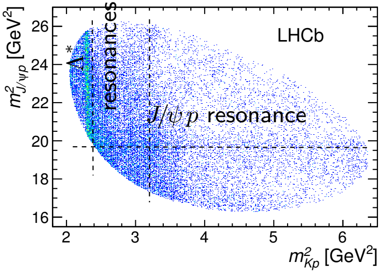

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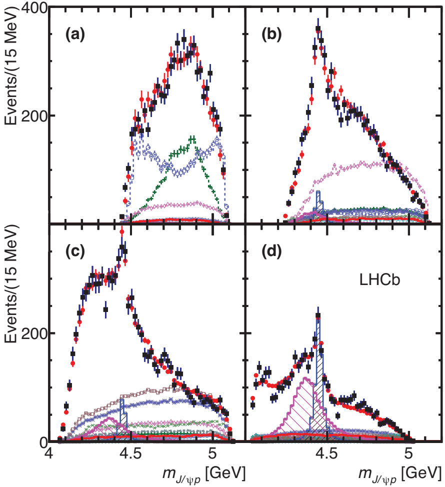
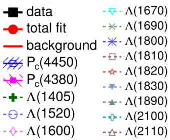
Pentaquark states in $\Lambda_b^0 \to J/\psi p K^-$



Two $J/\psi p$ states give the best fit,
$J = 3/2$ and $5/2$ with opposite parities

PRL 115, 072001 (2015),



Parameters of the pentaquark states

$P_c(4380)$:

$M = 4380 \pm 8 \pm 29\,\text{MeV}$,

$\Gamma = 205 \pm 18 \pm 86\,\text{MeV}$

$\mathcal{F} = (8.4 \pm 0.7 \pm 4.2(\text{syst}))\%$

$P_c(4450)$:

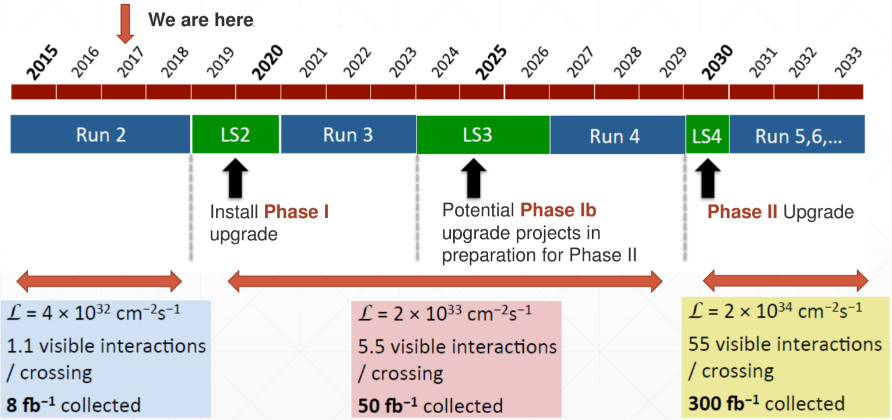
$M = 4449.8 \pm 1.7 \pm 2.5\,\text{MeV}$

$\Gamma = 39 \pm 5 \pm 19\,\text{MeV}$

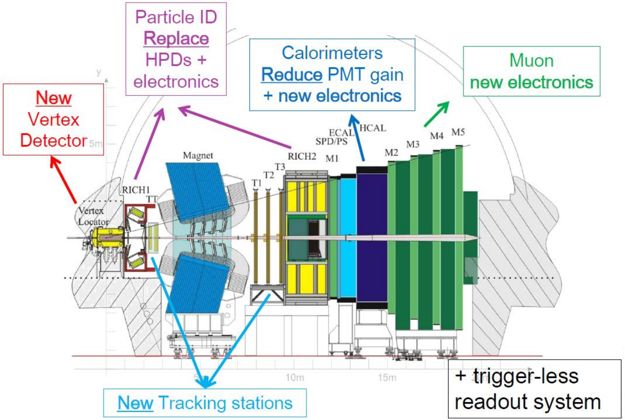
$\mathcal{F} = (4.1 \pm 0.5 \pm 1.1(\text{syst}))\%$

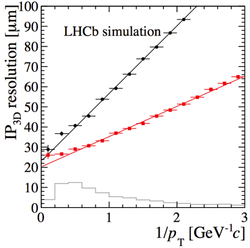
Significance (stat+syst) is overwhelming: 9σ and 12σ

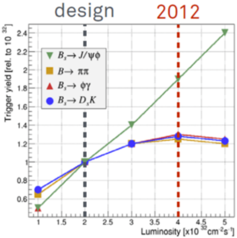
LHCb: upgrade and future plans



LHCb: upgrade and future plans







Hardware L0 trigger becomes bottleneck at high luminosities
Readout at 40 MHz will allow to keep high efficiency for hadronic channels.

Summary

LHCb: flavour physics in proton-proton collisions. Extremely successfull so far.

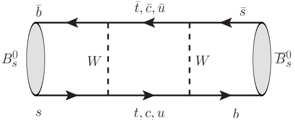
- Entering precision phase of $\mathcal{CP}$ violation measurements.
  - Looks SM-like yet.
- Interesting hints in rare decays. Stay cautiously optimistic, need more data.
  - Angular observables in $b \to s$ transitions.
  - Flavour universality.
- Broad charm physics programme
  - Thanks to innovations in trigger
- A flood of discoveries in charm and beauty spectroscopy.
  - Conventional ans exotic
- Many interesting topics I could not cover: EW physics, soft QCD, fixed-target programme (gaseous target), etc.
- Upgrade: Phase I approved and on track.
  - Start data taking in 2021, aim 50 fb^{-1} ($\times 60$ Run 1 stats for hadronic modes) by 2029
- Further upgrades being discussed
  - Up to 300 fb^{-1}, 2031 and beyond

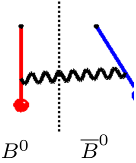
Backup

Oscillations of neutral mesons

Weakly decaying neutral mesons (K^0, D^0, B^0, B^0_s) are known to *oscillate*.

Weak loop connects states of opposite flavour: *mixing*





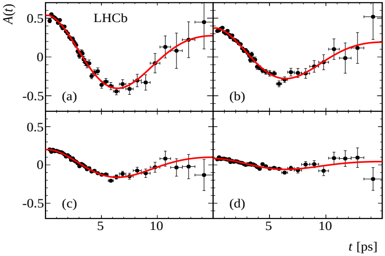
Two mass eigenstates, mass difference ΔM

$$|B_L\rangle = |B^0\rangle + |\overline{B}^0\rangle$$
$$|B_H\rangle = |B^0\rangle - |\overline{B}^0\rangle$$

In general, width difference $\Delta\Gamma$

For B^0 mesons, oscillation period is $\sim$ lifetime.

[LHCb, New J. Phys. 15 (2013) 053021]

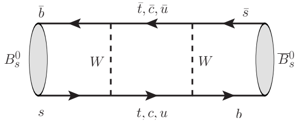


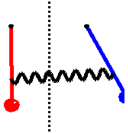
Many $\mathcal{CP}$ violation measurements involve oscillations.
That's why we want B mesons to be *boosted*
(e^+e^- machines: artificial boost by asymmetric beam energies)

Oscillations of neutral mesons

Weakly decaying neutral mesons (K^0, D^0, B^0, B_s^0) are known to *oscillate*.

Weak loop connects states of opposite flavour: *mixing*





B_s^0 $\overline{B}_s^0$

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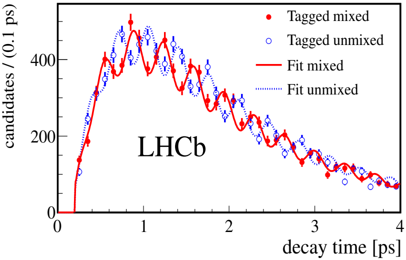
In general, width difference $\Delta\Gamma$

B_s^0 mesons oscillate many times during their lifetime.

[LHCb, Eur. Phys. J. C (2016) 76:412]



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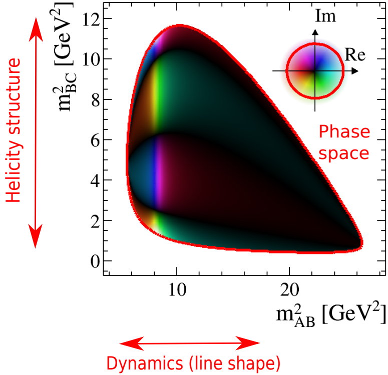
Amplitude analyses

Another tool to measure phases: *amplitude analysis* technique.

Perform fits of the amplitude as a function of phase space variables

- Three-body decays $D \to ABC$: two kinematic variables m^2_{AB}, m^2_{BC} (*Dalitz plot*)
- Add angular variables if initial/final state not scalar



- Absolute phase not visible, but *relative* phases of components can be accessed though interference
- Typically, use *isobar model*. E.g. for a resonance in AB:
  - Line shape (*Breit-Wigner* etc.) in m^2_{AB}
  - Helicity structure (depending on spin of resonance) in m^2_{BC}
- In addition, there exist model-independent techniques for amplitude analyses.

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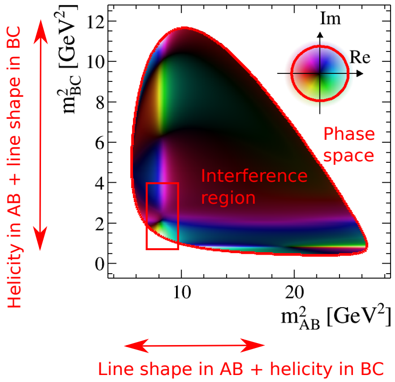

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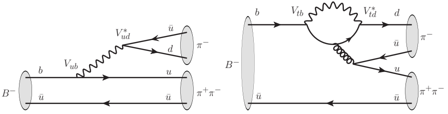
- In addition, there exist model-independent techniques for amplitude analyses.

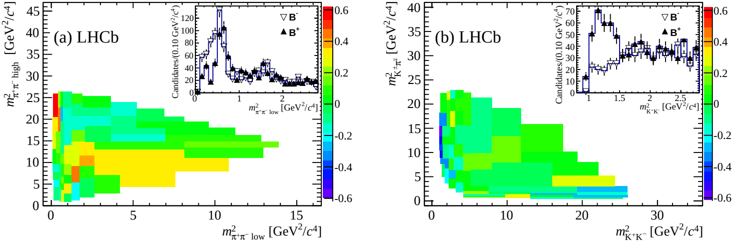
Charmless B decays, in principle, also give access to the value of γ, although they can be affected by the New Physics due to penguin contribution:



$B^\pm \to \pi^\pm\pi^+\pi^-$, $B^\pm \to \pi^\pm K^+K^-$

Study integrated $\mathcal{CP}$ asymmetries, as well as local asymmetries over the phase space.

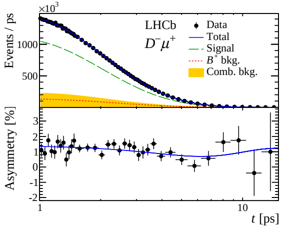
$$A_{CP} = \frac{\Gamma(B^-) - \Gamma(B^+)}{\Gamma(B^-) + \Gamma(B^+)}$$



Huge asymmetries in certain regions of phase space. Amplitude analyses ongoing to understand their nature.

Use semileptonic $B^0_{(s)} \to D_{(s)}\mu\bar{\nu}_\mu$ decays. [LHCb, PRL 114 (2015) 041601, PRL 117 (2016) 061803]

$$A_{CP} \equiv a_{sl} = \frac{\Gamma(\overline{B} \to B \to f) - \Gamma(B \to \overline{B} \to \overline{f})}{\Gamma(\overline{B} \to B \to f) + \Gamma(B \to \overline{B} \to \overline{f})}$$



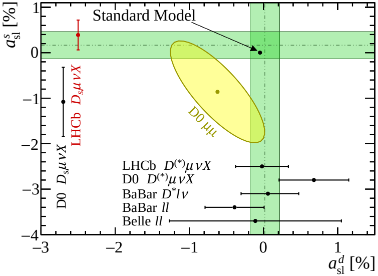
Standard Model predictions: [A. Lenz, arXiv:1205.1444]

$a^d_{sl} = (-4.1 \pm 0.6) \times 10^{-4}$
$a^s_{sl} = (+1.9 \pm 0.3) \times 10^{-5}$

Production asymmetry can be $A_P \neq 0$ in pp collisions.

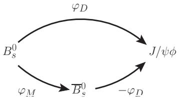
- For B^0_s: smeared by fast B^0_s oscillations, not an issue
- For B^0, can be accounted for by measuring time-dependent asymmetry:

$$A_{\mathrm{raw}}(t) = A_D + \frac{a_{sl}}{2} - \left(A_P + \frac{a_{sl}}{2}\right)\cos\Delta m t$$

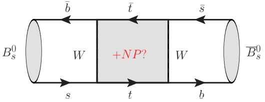


3.6σ tension with SM from $D0$, but not confirmed by LHCb measurements

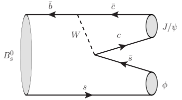
Measure $\mathcal{CP}$ violation in the interference of decays with and w/o mixing
"Golden mode": $B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$



φ_M:



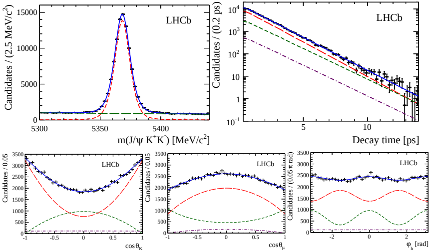
φ_D:



$\mathcal{CP}$ violating phase $\varphi_s = \varphi_M - 2\varphi_D$; $\varphi_s^{SM} \simeq -2\beta_s = 0.0376 \pm 0.0008$ rad [CKMFitter]

- Time-dependent flavor-tagged decay rate
- K^+K^- can be in P wave (ϕ) or S wave
- 3 P waves ($\mathcal{CP}$-odd or $\mathcal{CP}$-even), angular analysis to distinguish them

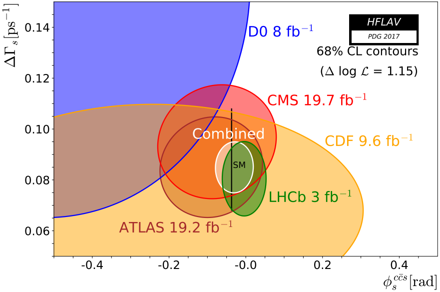
[PRL 114 (2015) 041801]



6D fit! (m_{KK}, t, mistag rate, 3 angles), bins in m_{KK} and B tag.

Several different B_s^0 decay modes used by LHCb

Decay mode	Analysis technique	φ_s result	Publicaion
$J/\psi\phi$	angular, bins in m_{KK}	$-0.068 \pm 0.049 \pm 0.006$	[PRL 114, 041801 (2015)]
$J/\psi\pi^+\pi^-$	amplitude, angular	$+0.070 \pm 0.068 \pm 0.008$	[PLB 736 (2014) 186]
$D_s^+ D_s^-$	CP-even	$+0.02 \pm 0.17 \pm 0.02$	[PRL 113, 211801 (2014)]
$\psi(2S)\phi$	angular	$+0.23^{+0.29}_{-0.28} \pm 0.02$	[PLB 762 (2016) 253]
$J/\psi K^+K^-$ above ϕ	amplitude, angular	$+0.119 \pm 0.107 \pm 0.034$	[arXiv:1704.08217]



Measurements are also performed by Atlas, CMS and Tevatron experiments

World-averaged value $\varphi_s(WA) = -0.030 \pm 0.033$ [HFLAV, arXiv:1612.07233]

In excellent agreement with the SM value $\varphi_s^{SM} = 0.0376 \pm 0.0008$

"Golden mode" at B-factories, but LHCb provides competitive measurement after recent flavour-tagging improvements.

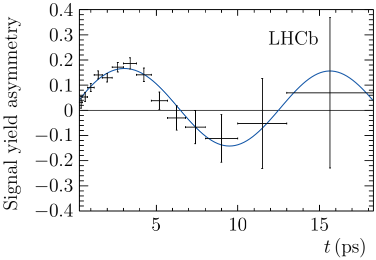
Time-dependent asymmetry:

$$A(t) = \frac{S\sin(\Delta m t) + C\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2) + A_{\Delta\Gamma}\sinh(\Delta\Gamma t/2)}; S = \sin 2\beta$$

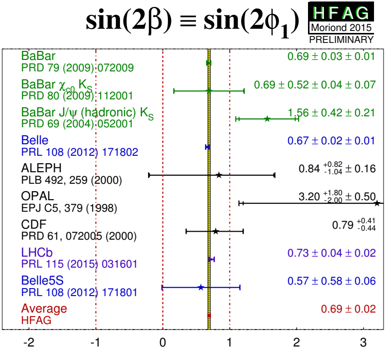
[LHCb, PRL 115, 031601 (2015)]

Effective tagging power

$\varepsilon_{\rm tag}(1-2\omega) = 3.02\%$

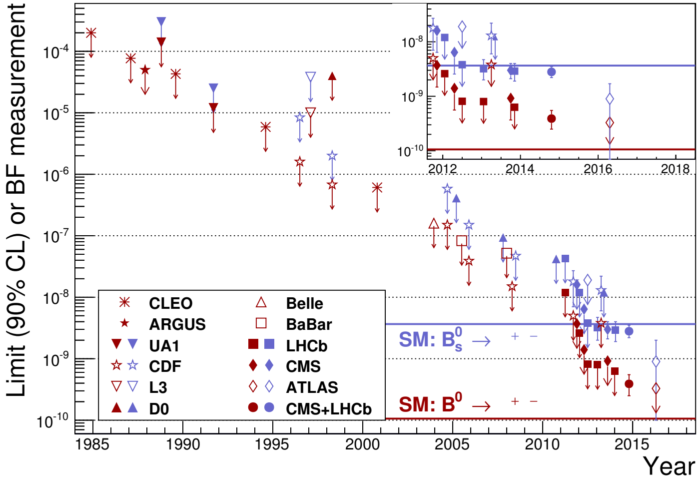


$\sin 2\beta = 0.731 \pm 0.035 \pm 0.020$



$B_{(s)} \to \mu^+\mu^-$: the story so far

SM expectation: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.65 \pm 0.23) \times 10^{-9}$ [C. Bobeth, PRL 112, 101801 (2014)]



- Combination of CMS and LHCb:

  [Nature 522, 68-72]

  - Observation of $B_s^0 \to \mu^+\mu^-$:

    $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 2.8^{+0.7}_{-0.6} \times 10^{-9}$

    6.2σ significance

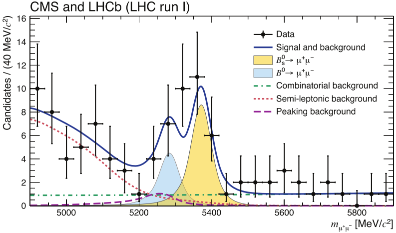
    1.2σ compatibility with SM
  - Evidence of $B^0 \to \mu^+\mu^-$:

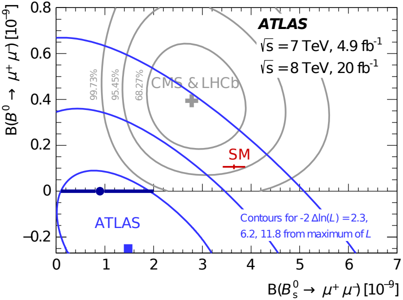
    $\mathcal{B}(B^0 \to \mu^+\mu^-) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$

    3.0σ significance

    2.2σ compatibility with SM
- Atlas [EPJ C76 (2016) 9, 513]
  - $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}$
  - $\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.2 \times 10^{-10}$

    at 95% CL





Effective lifetime of $B_s^0 \to \mu^+\mu^-$

The two mass eigenstates of B_s^0 have significant width difference, $\Delta\Gamma = 0.082 \pm 0.007$ ps^{-1}.

In SM, only heavier mass eigenstate decays to $\mu^+\mu^-$.

Can measure B_s^0 lifetime in $B_s^0 \to \mu^+\mu^-$ decays (*effective lifetime*)

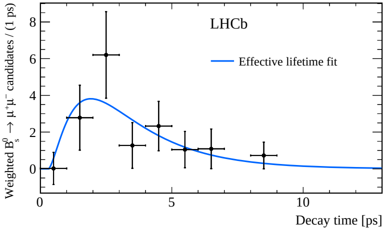
$$\tau_{\mu^+\mu^-} = \frac{\tau_{B_s^0}}{1-y_s^2}\frac{1+2A_{\Delta\Gamma}\,y_s + y_s^2}{1+A_{\Delta\Gamma}\,y_s},$$

$$y_s = \tau_{B_s^0}\frac{\Gamma_s}{2}$$

In SM, $A_{\Delta\Gamma}=1$, while in NP models it could be $A_{\Delta\Gamma} \in [-1,1]$

New independent observable sensitive to NP

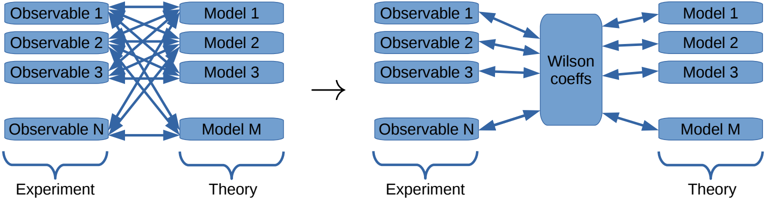
[LHCb, PRL 118, 191801 (2017)]



$\tau_{\mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05$ ps

To be compared to $\tau_{B_s^0} = 1.520 \pm 0.004$ ps

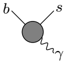
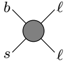
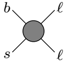
Effective theory



Model-independent description in effective theory:

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{\rm tb} V_{\rm ts}^* \sum_i \underbrace{\mathcal{C}_i \mathcal{O}_i}_{\text{Left-handed}} + \underbrace{\mathcal{C}'_i \mathcal{O}'_i}_{\text{Right-handed, } \frac{m_s}{m_b} \text{ suppressed}}$$

Wilson coefficients $\mathcal{C}_i^{(\prime)}$ encode short-distance physics, $\mathcal{O}_i^{(\prime)}$ corr. operators

		$b \to s\gamma$	$B \to \mu\mu$	$b \to s\ell\ell$
	$\mathcal{O}_7^{(\prime)}$ photon penguin	✓		✓
	$\mathcal{O}_9^{(\prime)}$ vector coupling			✓
	$\mathcal{O}_{10}^{(\prime)}$ axialvector coupling		✓	✓
	$\mathcal{O}_{S,P}^{(\prime)}$ (pseudo)scalar penguin		✓	

[LHCb, PRL 118, 191801 (2017)]

Run 1 + part of Run2, 4.4 fb^{-1} in total.

First observation of $B_s^0 \to \mu^+\mu^-$ in a single experiment

- Observation of $B_s^0 \to \mu^+\mu^-$:

  $$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

  7.8σ significance

- $B^0 \to \mu^+\mu^-$ consistent with no signal:

  $$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.5^{+1.2}_{-1.0}{}^{+0.2}_{-0.1}) \times 10^{-10}$$

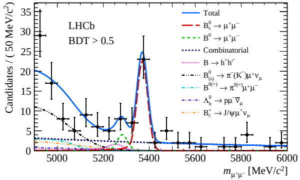
  1.6σ significance

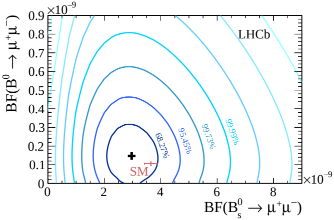
  $$\mathcal{B}(B^0 \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

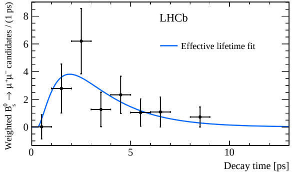
- First measurement of effective B_s^0 lifetime
  New independent observable sensitive to NP

  $$\tau_{\mu^+\mu^-} = 2.04 \pm 0.44 \pm 0.05 \text{ ps}$$

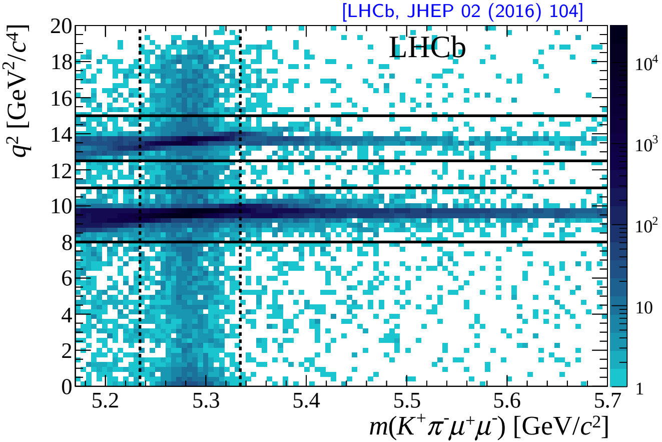
  To be compared to $\tau_{B_s^0} = 1.520 \pm 0.004$ ps



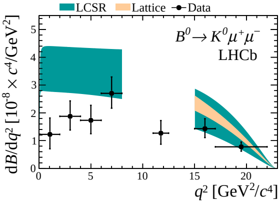


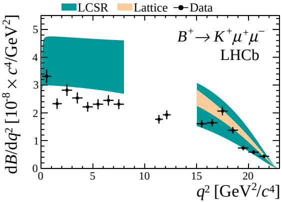


$B^0 \to K^{*0}\mu^+\mu^-$ selection

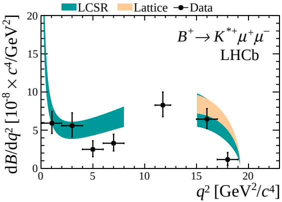


- BDT to suppress combinatorial background
  Input variables: PID, kinematic and geometric quantities, isolation variables
- Veto of $B^0 \to J/\psi\, K^{*0}$ and $B^0 \to \psi(2S)K^{*0}$ (important control decays) and peaking backgrounds using kinematic variables and PID
- Signal clearly visible as vertical band after the full selection

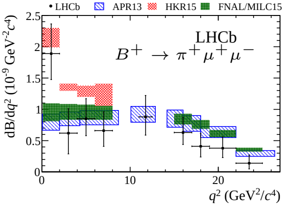




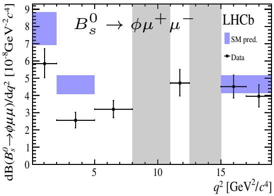
[JHEP 06 (2014) 133]



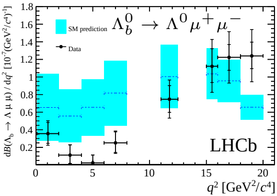
[JHEP 10 (2015) 034]



[JHEP 09 (2015) 179]



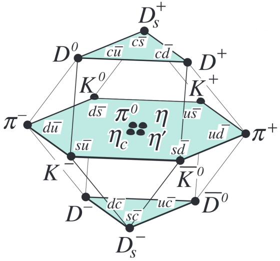
[JHEP 06 (2015) 115]



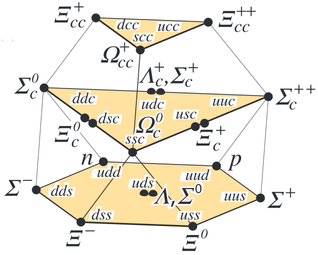
Cross-sections consistently lower than SM in low-q^2 region.

New Physics or larger theory uncertainty?

- No free quarks, held together by strong interaction. Form colourless objects, most simple ones: mesons ($q\bar{q}$) and baryons (qqq)
- Angular, spin and radial excitations $\Rightarrow$ spectroscopy
- Perturbative QCD calculations have limited applicability: phenomenological models (non-relativistic potential), lattice QCD.



$SU(4)$ meson multiplets with $S = 1/2$

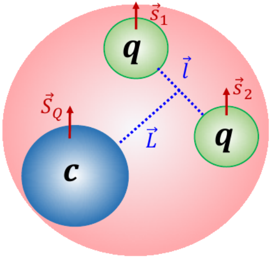


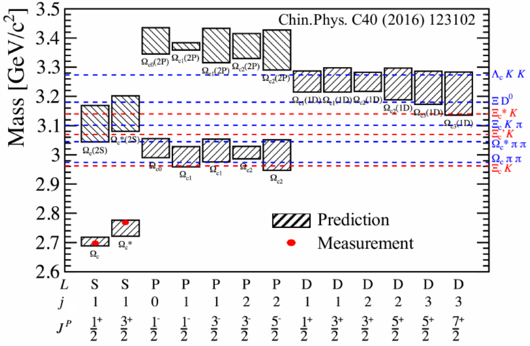
$SU(4)$ baryon multiplets with $S = 1/2$

- Exotic spectroscopy: beyond 2- and 3-quark systems: tetraquarks ($qq\bar{q}\bar{q}$), pentaquarks ($qqqq\bar{q}$)

Baryons with a single heavy quark:

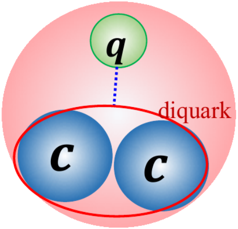
- Heavy quark effective theory: heavy quark as a source of static potential
- Various spin and orbital excitations (L, l, s_Q, s_1, s_2)
- Ground states: $L = l = 0$, spin $S = 1/2$ or $3/2$

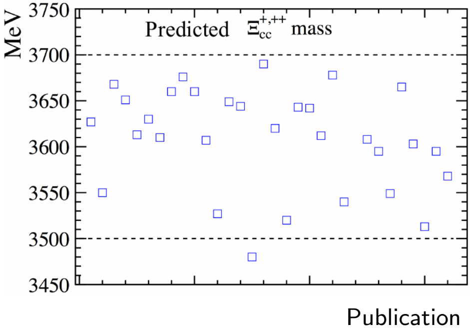




- No orbital excitations in css system (Ω_c^0) seen so far
- Expect many states above $\Xi_c K$ kinematic threshold

- Double heavy quarks have only been seen in mesons: $\psi(c\bar{c})$, $\Upsilon(b\bar{b})$, $B_c^+(\bar{b}c)$.
- Expect three doubly-charmed states: Ξ_{cc}^+ (ccd), Ξ_{cc}^{++} (ccu) and Ω_{cc}^+ (ccs)
- A different system: cc as a heavy diquark; similar to heavy mesons Qq.
- Many theoretical models (relativistic and non-relativistic QCD potential, triple harmonic oscillator, sum rules, bag model etc.), lattice results.

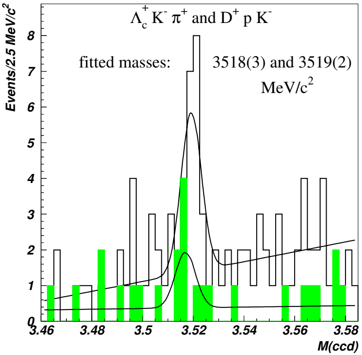




- Ξ_{cc}^+ and Ξ_{cc}^{++} expected to have small mass difference.
- Lifetime $\tau(\Xi_{cc}^{++}) > \tau(\Xi_{cc}^+)$ due to different interference pattern of spectator and exchange diagrams

SELEX collaboration (Fermilab E781) seen a peak in $\Lambda_c^+ K^- \pi^+$ and $D^+ p K^-$ spectra

[PRL 89 (2002) 112001, PLB 628 (2005) 18]

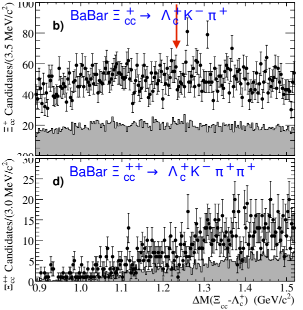


Combined mass:
$M(\Xi_{cc}^+) = 3518.7 \pm 1.7$ MeV

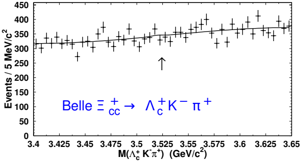
Questions:

- Weakly decaying, but very short lifetime ($\tau(\Xi_{cc}^+) < 33$ fs 90% CL)
- Large production ratio (20% of Λ_c^+ rate through Ξ_{cc}^+)

Not confirmed by other experiments:

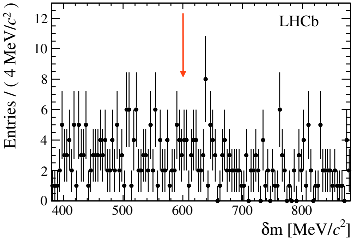


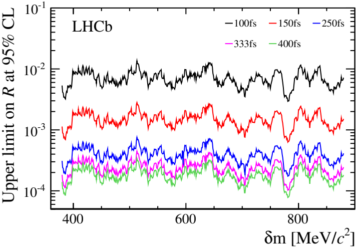
BaBar: Phys.Rev. D74 (2006) 011103



Belle: Phys.Rev.Lett. 97 (2006) 162001

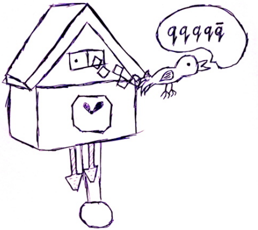
$\delta m \equiv m(\Lambda_c^+ K \pi) - m(\Lambda_c^+) - m(K) - m(\pi)$

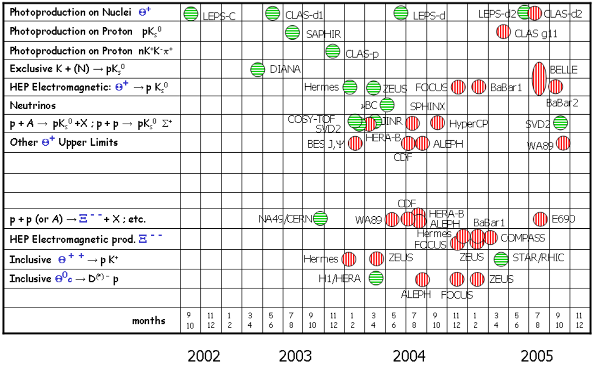




[LHCb, JHEP 12 (2013) 090] (0.65 fb^{-1})

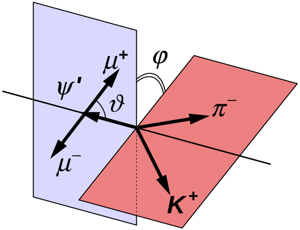
- Theorists have thought about exotic (beyond $q\bar{q}$, qqq) hadrons since the early days of quark model
- Experimental evidence for 4-quark mesons started to appear only recently.
  - $X(3872)$ (Belle, BaBar, CDF)
  - $Z_b(10610)$ and $Z_b(10650)$ (Belle)
  - $Z(4430)$ (Belle, LHCb)
  - $Z_c(3900)$ (BES-III)
- Pentaquarks: discoveries and undiscoveries... [R.A. Schumacher, nucl-ex/0512042]

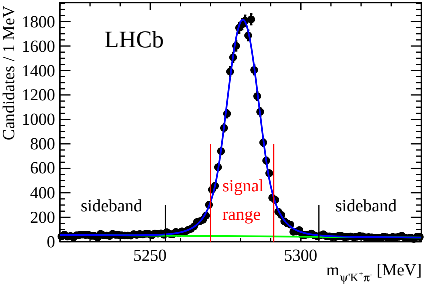


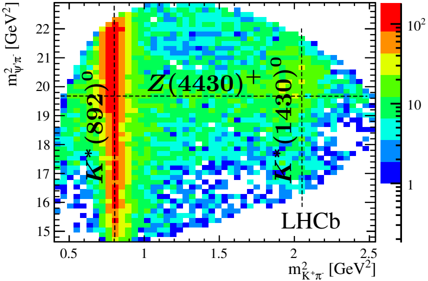


[PRL 112, 222002 (2014)]

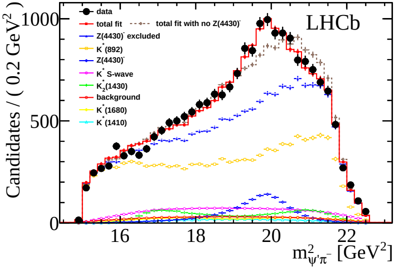
- Decay $B^0 \to \psi(2S)K^+\pi^-$
- Signal yield: 25k events
- Combinatorial background: $\sim 4\%$
- 4D amplitude analysis: $(m^2(K\pi),\ m^2(\psi(2S)\pi),\ \theta_{\psi'},\ \phi_{\psi'})$

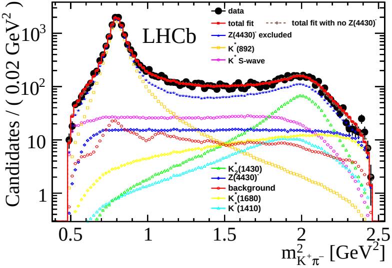






[PRL 112, 222002 (2014)]



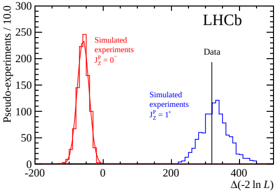


Model-dependent fit prefers resonance-like state with $J^P = 1^+$

$\mathcal{F}(Z(4430)^+) = (5.9 \pm 0.9^{+1.5}_{-3.3}(syst))\%$

Quantum numbers (wrt. favoured $J^P = 1^+$)

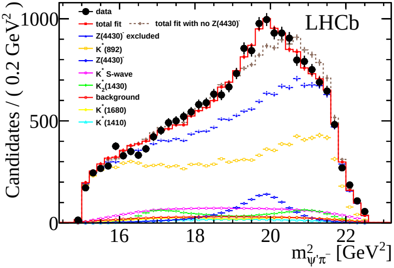
J^P	LHCb	Belle
0^-	9.7	3.4
1^-	15.8	3.7
2^+	16.1	5.1
2^-	14.6	4.7

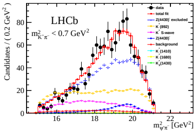


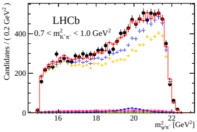
Parameters

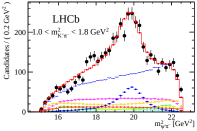
	LHCb	Belle
Mass, MeV	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
Width, MeV	$172 \pm 13^{+27}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$

[PRL 112, 222002 (2014)]









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J^P	LHCb	Belle
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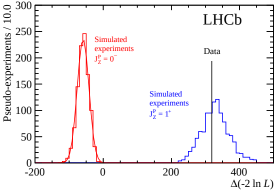

Parameters

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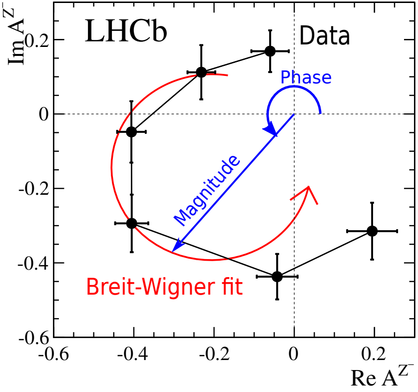
Mass, MeV	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
Width, MeV	$172 \pm 13^{+27}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$

$Z(4430)$: model-independent confirmation

[PRL 112, 222002 (2014)]

Model-independent test of phase rotation. Interference with K^* states provides reference amplitude for phase motion measurement.



- Split $M(\psi'\pi^-)$ (4277–4605 MeV) into 6 bins.
- Fit magnitude and phase independently for each bin.
- Clear phase rotation in counter clockwise direction: characteristic of a resonant behaviour.

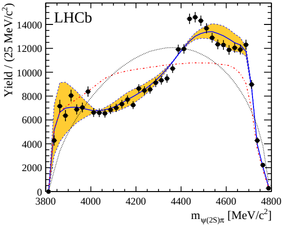
[PRD 92 (2015) 112009]

Model-independent confirmation of a structure in $\psi'\pi^-$.

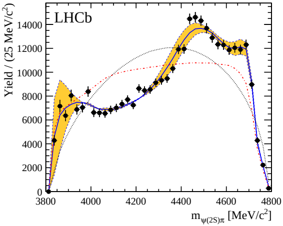
Check that $K^-\pi^+$ amplitude *only* fails to describe the decay.

$K^-\pi^+$ should contribute to reasonably low moments, while exotic $\psi'\pi^-$ contributes to *all* moments.

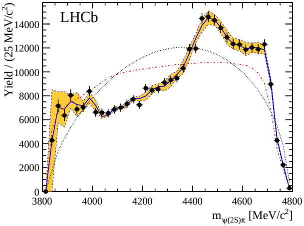
$J_{\max} = 2$
$l_{\max} = 4$
(K^*, K_2^* etc.)



$J_{\max} = 3$
$l_{\max} = 6$
($+K_3^*(1780)$ etc.)



$J_{\max} = 15$
$l_{\max} = 30$
...



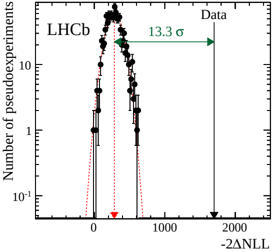
$m_{(\psi(2S)\pi)}$ distribution can only be described by an unreasonable number of Legendre moments.

[PRD 92 (2015) 112009]

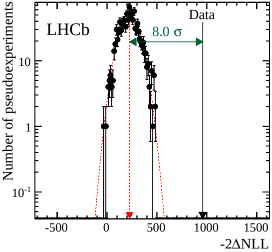
Test statistic:

$$-2\Delta NLL = -2\sum_i \frac{W_i}{\epsilon_i} \log \frac{F_l(m^i_{\psi\pi})}{F_{30}(m^i_{\psi\pi})}$$

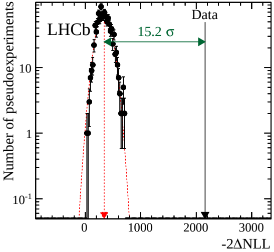
Run toys with $K^+\pi^-$-only model to determine distribution, compare with $-2\Delta NLL$ in data.



$l_{\max} = 4$



$l_{\max} = 6$



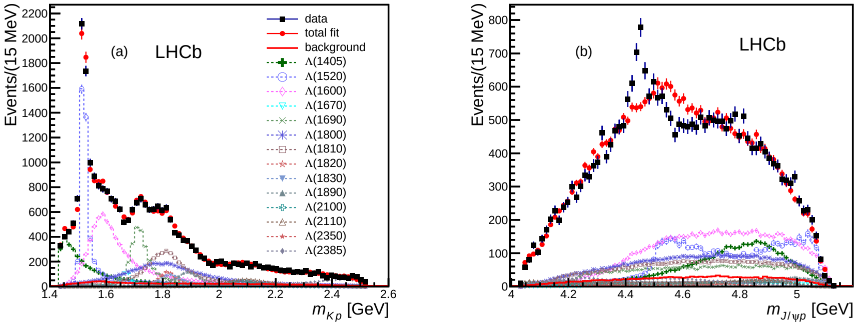
$l_{\max} = 4\dots6$ depending on $m(K^+\pi^-)$

Resonances with spin up to 3 cannot reproduce the features seen in data.

PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \to J/\psi p K^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$



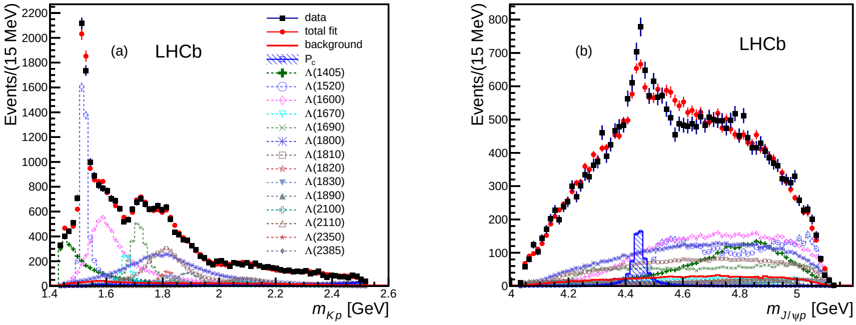
Admixture of all known Λ^* states does not reproduce the peak observed at $m_{J/\psi p} = 4450\,\mathrm{MeV}$.

Pentaquark states in $\Lambda_b^0 \to J/\psi pK^-$

PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \to J/\psi pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$

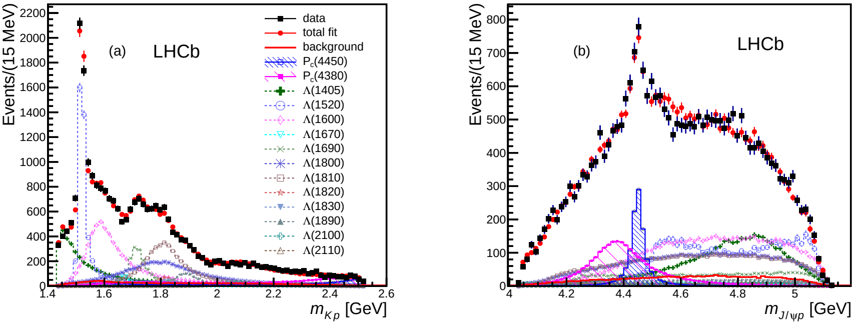


Inclusion of the exotic $J/\psi p$ state improves the fit, best $J^P = 5/2^\pm$

PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \to J/\psi pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$



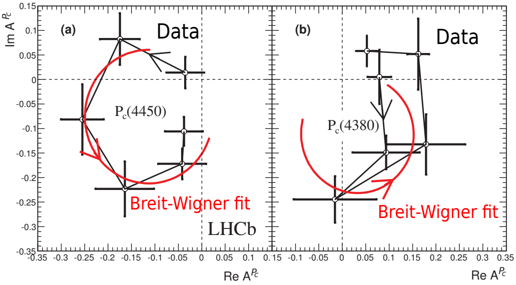
Two $J/\psi p$ states give the best fit, $J = 3/2$ and $5/2$ with opposite parities

Pentaquark states in $\Lambda_b^0 \to J/\psi p K^-$

PRL 115, 072001 (2015),

Argand plots: model-independent confirmation of the resonant character of the exotic states.

Interference with Λ^* states allows to extract the phase in bins of $m_{J/\psi\, p}$.



Clear phase rotation for $P_c(4450)$, direction consistent with Breit-Wigner amplitude

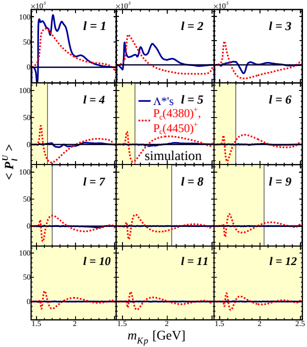
Not conclusive for $P_c(4380)$, need more statistics.

[PRL 117 (2016) 082002]

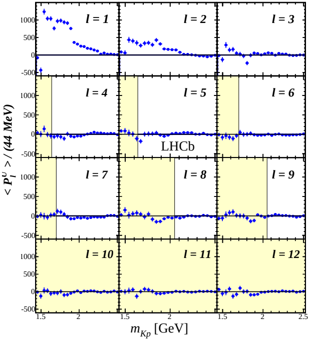
Checking that Λ^* resonances *only* cannot describe the data.

Use Legendre moments in $\cos\theta_{\text{hel}}$ as a function of m_{pK}.

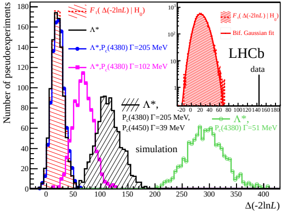
Allow $l_{\max}$ depending on m_{pK}



Moments from model



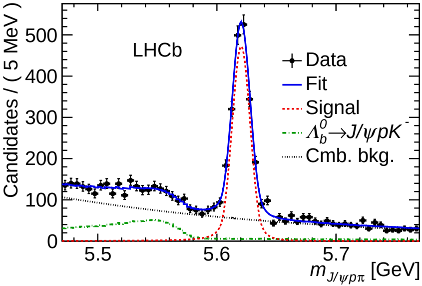
Moments from data



10σ significance

Exotic contributions in $\Lambda_b^0 \to J/\psi\, p\pi^-$

[PRL 117 (2016) 082003]

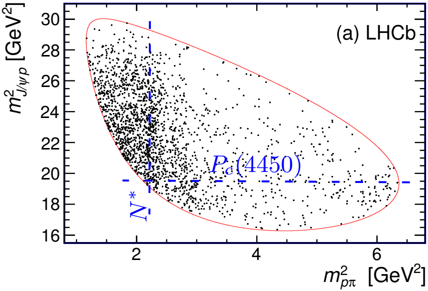


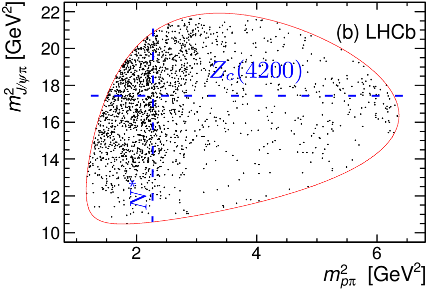
Signal yield: 1885 ± 50 events
Background: $\sim 20\%$

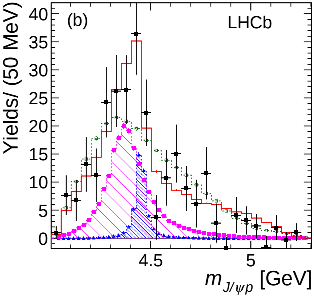
N^* states in $p\pi^-$

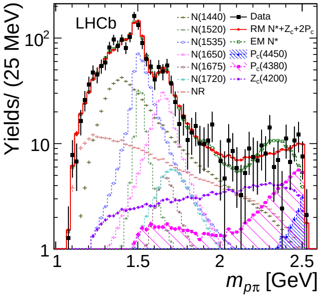
Possible exotic contributions:

- P_c in $J/\psi\, p$
- Z_c in $J/\psi\, \pi^-$ [Belle, PRD 90, 112009 (2014)]
  $M = 4196^{+31}_{-29}{}^{+17}_{-13}$ MeV
  $\Gamma = 370 \pm 70^{+70}_{-132}$ MeV









[PRL 117 (2016) 082003]

$N^* \to p\pi^-$ contributions:

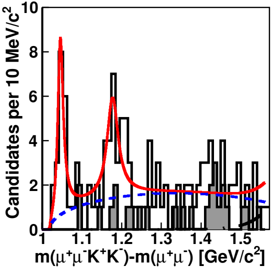
- Baseline: isobar $p\pi^-$ with 7-14 states.
- Tried BW and Flatté for N(1535) (opening of $n\eta$ threshold)
- Cross-check: K-matrix for $1/2^-$ wave using Bonn-Gatchina parametrisation [A. Anisovich et al., arXiv:0911.5277]

Exotic contributions:

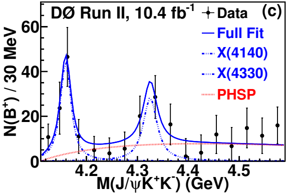
- Considered $P_c(4380)$, $P_c(4450)$ (in $J/\psi\, p$) and $Z_c(4200)$ (in $J/\psi\, \pi^-$).
- Total significance of exotic contributions: 3.1σ.
- Individual contributions are not significant
- Fit fractions:
  - $\mathcal{F}(P_c(4380)) = (5.1 \pm 1.5^{+2.6}_{-1.6})$%
  - $\mathcal{F}(P_c(4450)) = (1.6^{+0.8}_{-0.6}{}^{+0.6}_{-0.5})$%
  - $\mathcal{F}(Z_c(4200)) = (7.7 \pm 2.8^{+3.4}_{-4.0})$%

Peaks in $J/\psi\,\phi$ around 4140 and $4274\,\mathrm{MeV}$ are found by CDF and confirmed by D0 and CMS

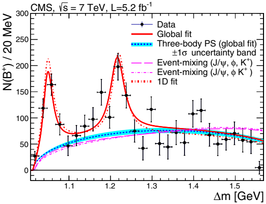
[CDF, PRL 102, 242002 (2009)]



[D0, PRD 89, 012004 (2014)]



[CMS, PLB 734 (2014) 261]



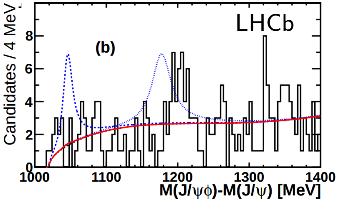
Belle [PRL 104:112004 (2010)]:

no $X(4140)$, but $X(4350)$ in $\gamma\gamma \to J/\psi\,\phi$

no evidence from:

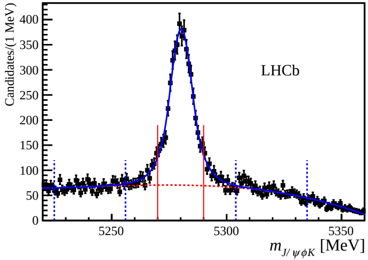
BaBar [PRD 91, 012003 (2015)],

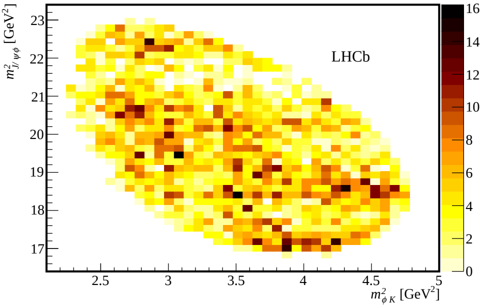
LHCb ($0.37\,\mathrm{fb}^{-1}$) [PRD 85, 091103(R) (2012)]



Exotic states in $B^+ \to J/\psi\,\phi K^+$

[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]

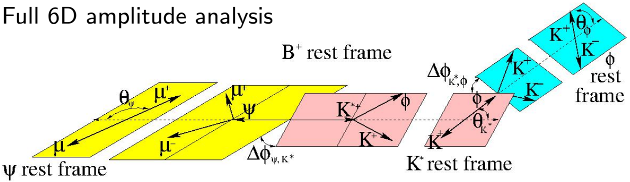




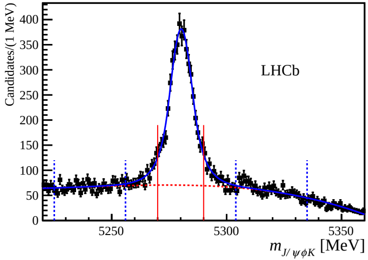
Signal yield: 4289 ± 151 events

Background: $\sim 20\%$

Full 6D amplitude analysis



[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]



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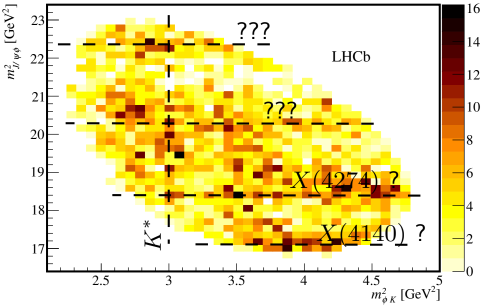
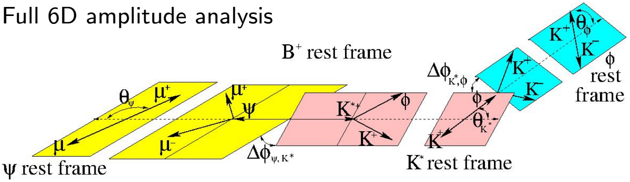
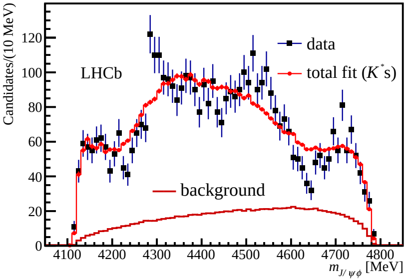


Full 6D amplitude analysis

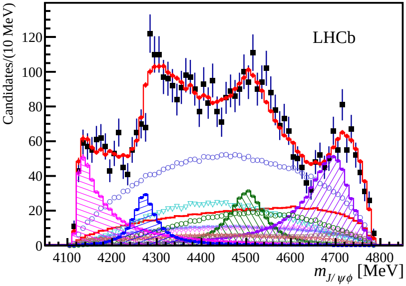


Exotic states in $B^+ \to J/\psi \phi K^+$

[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]



K^* states only



K^* plus 4(!) exotic states in $J/\psi\,\phi$

Contribution	J^{PC}	Significance	M_0 [MeV]	Γ_0 [MeV]	FF %
$X(4140)$	1^{++}	8.4σ	$4146.5 \pm 4.5\,^{+4.6}_{-2.8}$	$83 \pm 21\,^{+21}_{-14}$	$13 \pm 3.2\,^{+4.8}_{-2.0}$
$X(4274)$	1^{++}	6.0σ	$4273.3 \pm 8.3\,^{+17.2}_{-\ 3.6}$	$56 \pm 11\,^{+\ 8}_{-11}$	$7.1 \pm 2.5\,^{+3.5}_{-2.4}$
$X(4500)$	0^{++}	6.1σ	$4506 \pm 11\,^{+12}_{-15}$	$92 \pm 21\,^{+21}_{-20}$	$6.6 \pm 2.4\,^{+3.5}_{-2.3}$
$X(4700)$	0^{++}	5.6σ	$4704 \pm 10\,^{+14}_{-24}$	$120 \pm 31\,^{+42}_{-33}$	$12 \pm\ 5\,^{+\ 9}_{-\ 5}$

Masses for $X(4140)$ and $X(4274)$ are consistent with previous measurements, but widths significantly larger.