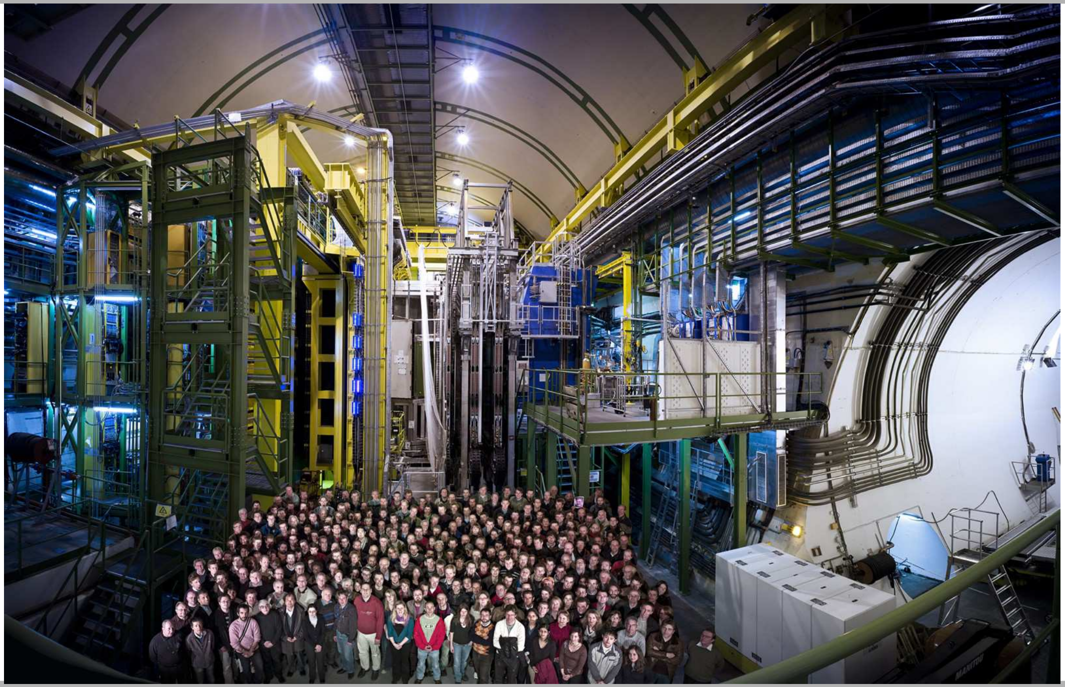
Hadron spectroscopy at LHCb

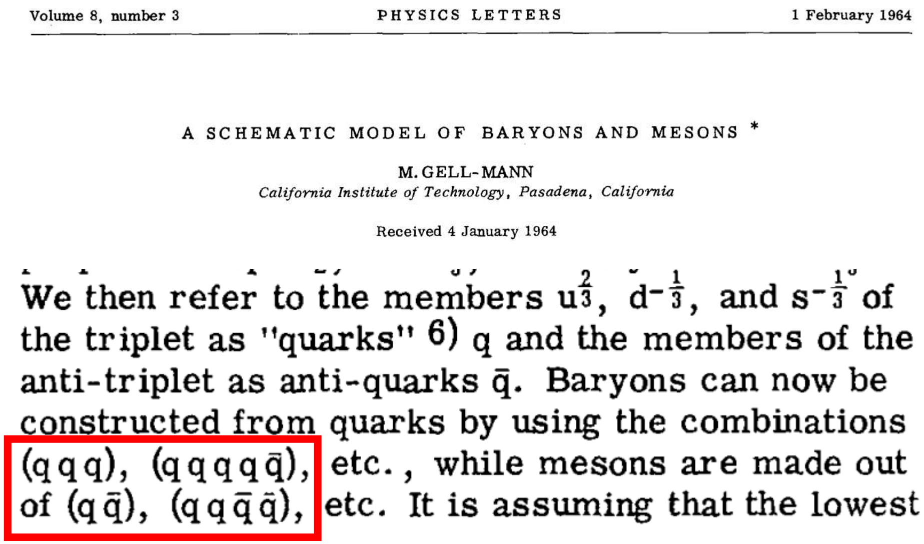
M. Kreps on behalf of the LHCb Collaboration

ICNPF, Kolymbari, Crete, Greece, 2014

Physics Department



Introduction



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

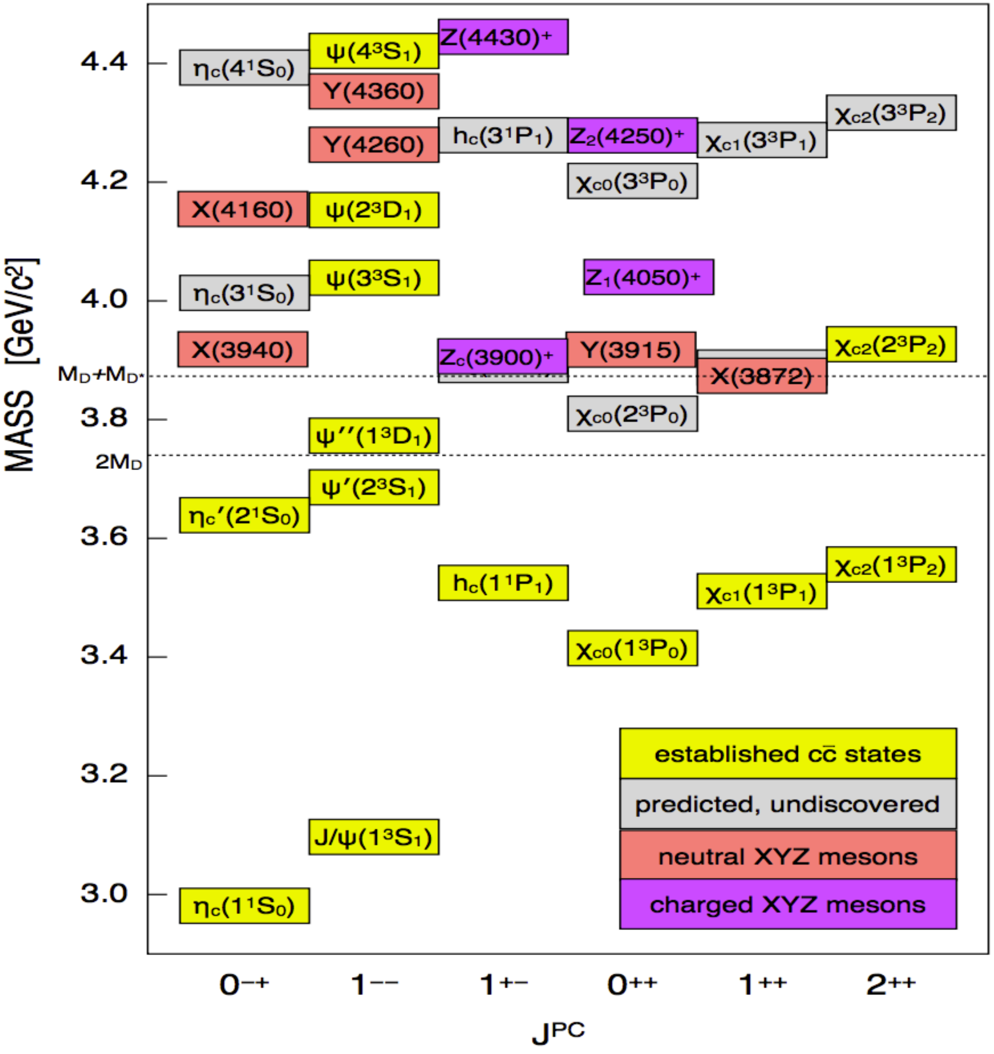
M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

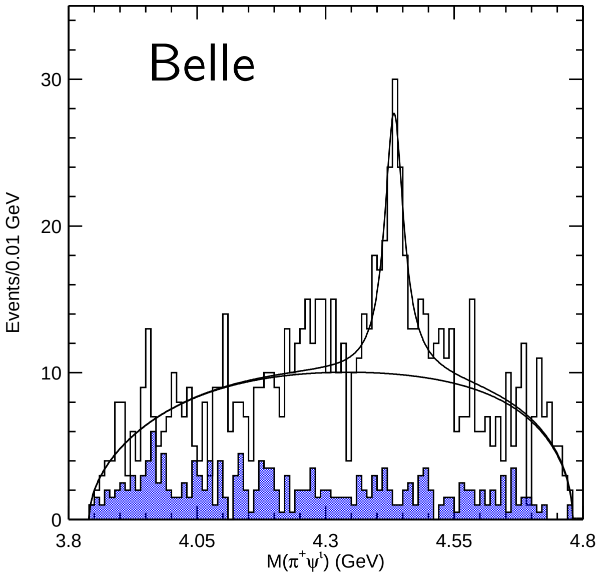
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

- We think of hadrons as $q\bar{q}$ or qqq
- But there is nothing preventing other combinations
- Can we find
    - molecule
    - tetraquark
    - your other favourite choice

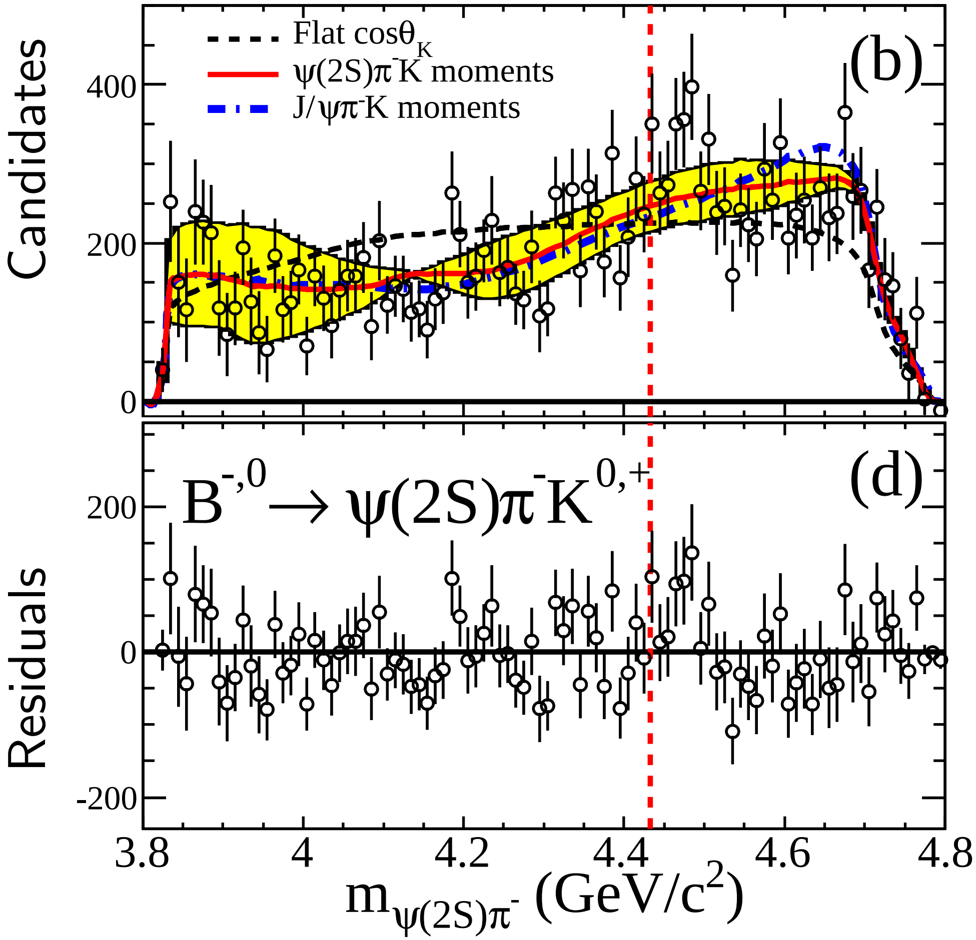
arXiv:1403.1254



$Z(4430)^+$ history



PRL 100, 142001



PRD 79, 112001

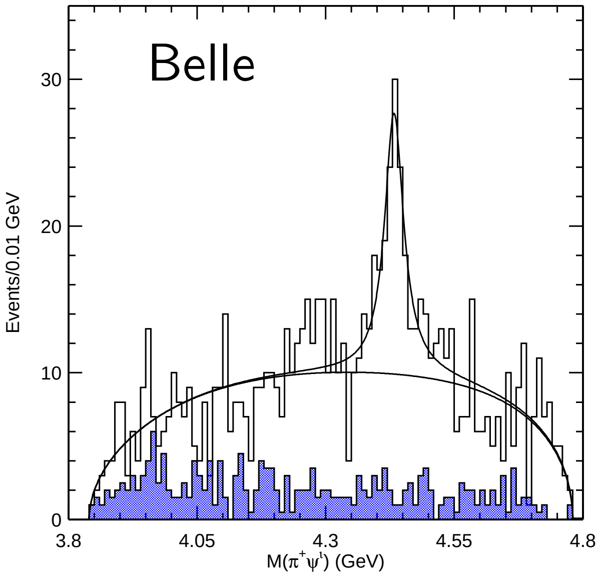
- Seen by Belle, but not Babar
- Data consistent
- Charged state

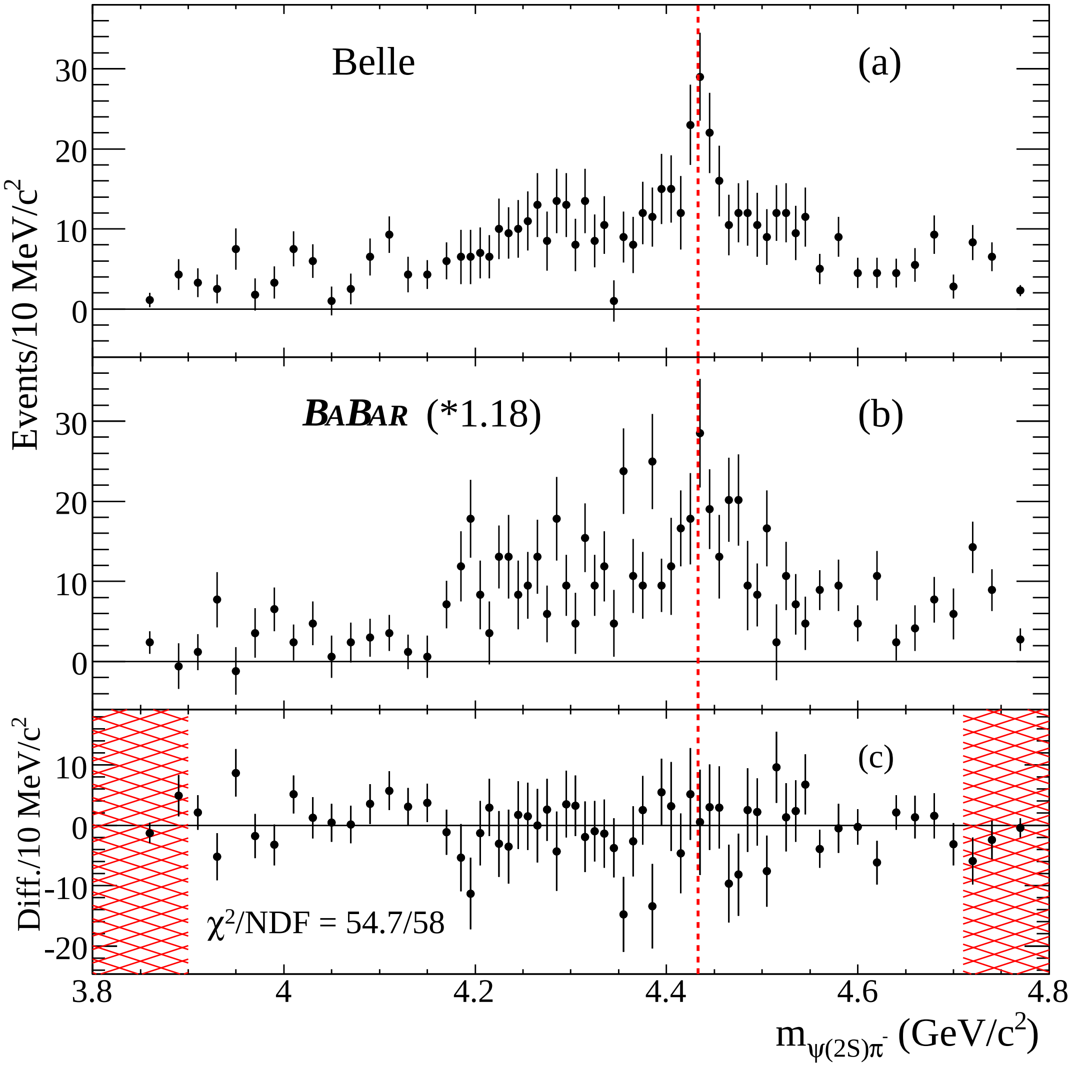
→ Cannot be $c\bar{c}$

- Latest Belle result uses 4D analysis
- Is it real and if yes, is it resonance?

$Z(4430)^+$ history

PRL 100, 142001





PRD 79, 112001

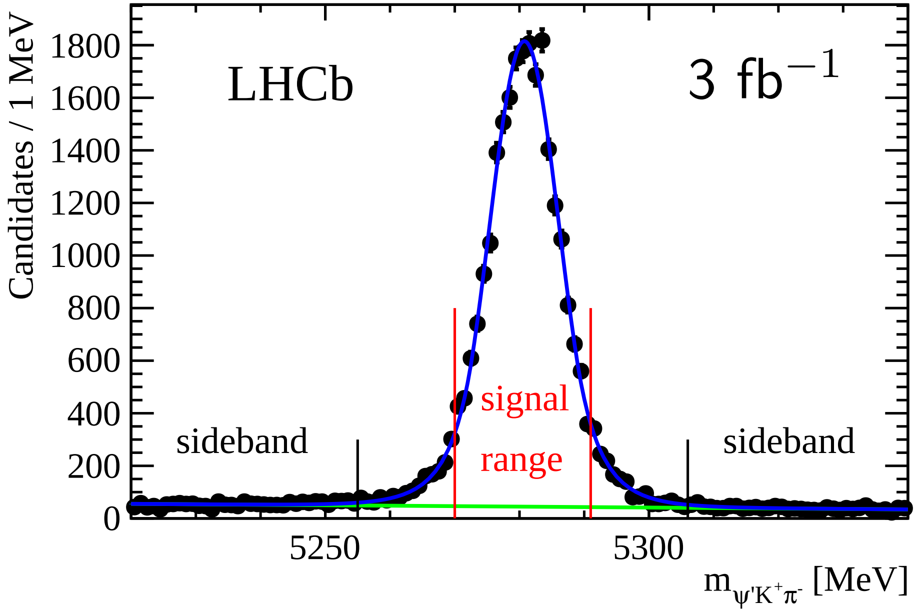
- Seen by Belle, but not Babar
- Data consistent
- Charged state

→ Cannot be $c\bar{c}$

- Latest Belle result uses 4D analysis
- Is it real and if yes, is it resonance?

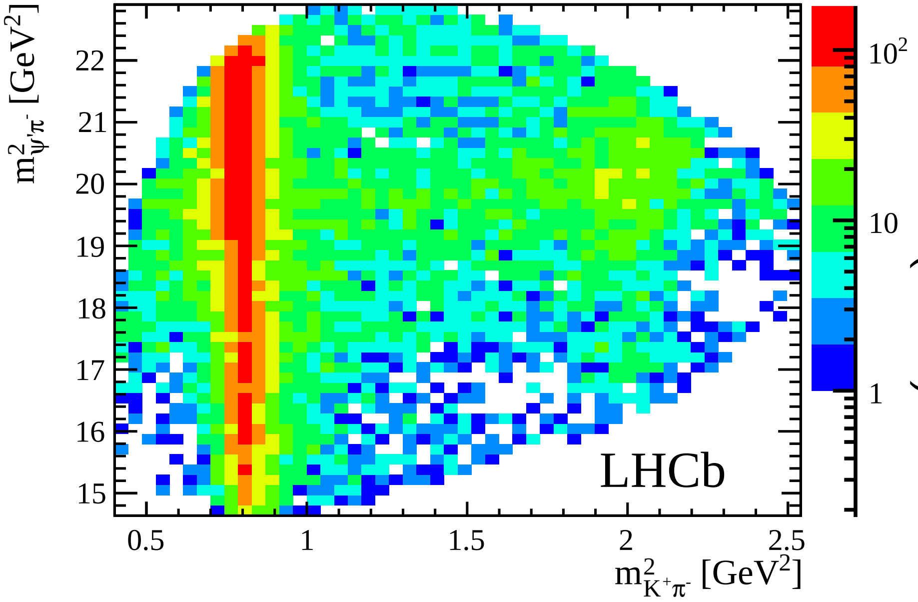
Data sample

- Use $B^0 \to \psi(2S)K\pi$ decays
- Large statistics (> 25k), about 10 times what B-factories had
- Very clean signal, background $4\,\%$ of events (about 8% at B-factories)
- Perform both model-independent analysis (BABAR) and amplitude fit (Belle)



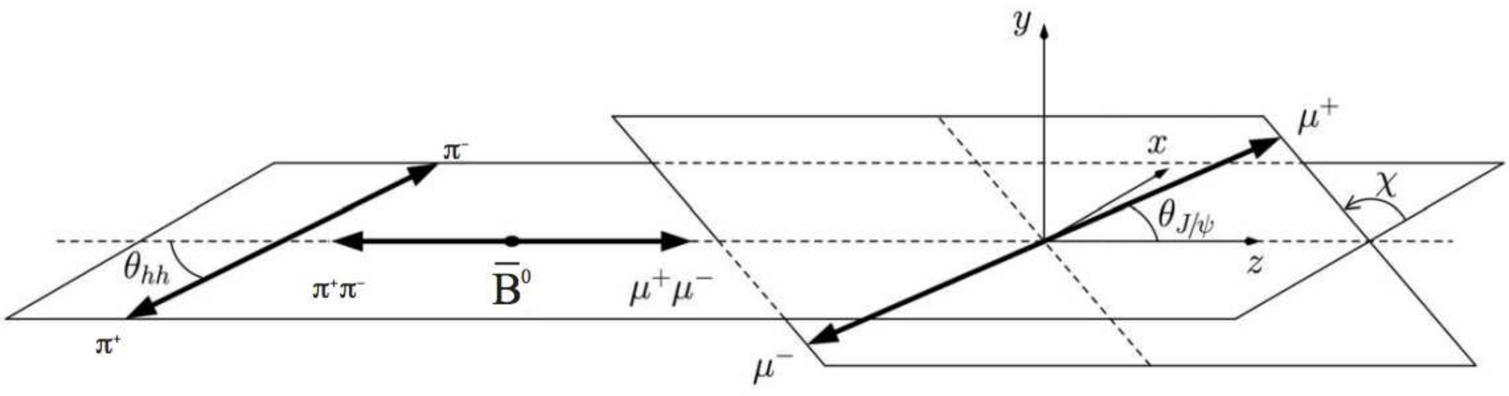
Only 2 out of 4 dimensions

$K^*(892)$ $K_J^*(1430)$



PRL 112 (2014) 222002

Amplitude analysis



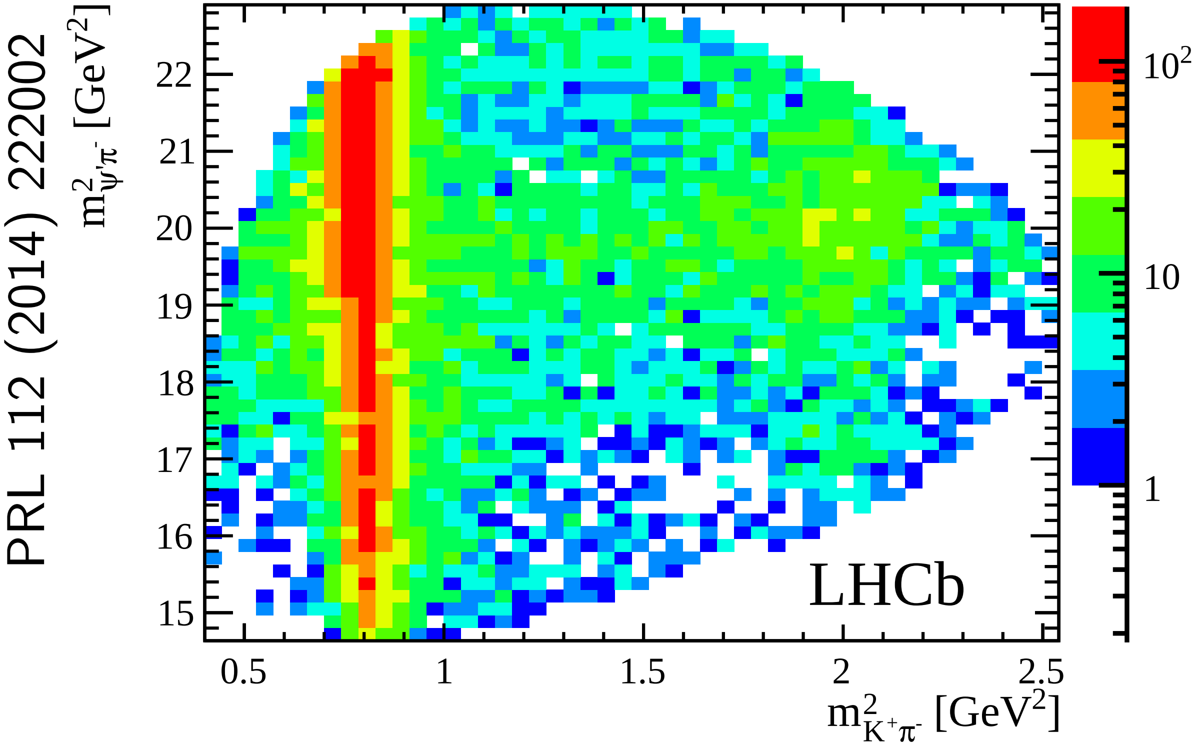
- Full 4D amplitude analysis
- Amplitude

Rotation between helicity frames

$$|M|^2 = \sum_{\Delta\lambda_\mu} \left| \sum_{\lambda_\psi} \sum_{k} A_{k,\lambda_\psi}(\Omega|m_{0k},\Gamma_{0k}) + \sum_{\lambda_\psi^Z} A_{Z,\lambda_\psi^Z}(\Omega^Z|m_{0Z},\Gamma_{0Z}) e^{i\Delta_\mu \alpha} \right|^2$$

- Mass described by relativistic Breit-Wigner
- Angular part using helicity formalism
- Imposes model how invariant mass distribution should look like

Model independent method



- Look to $\cos(\theta_K)$ in bins of $K\pi$ mass
- Allows to find out which spins contribute

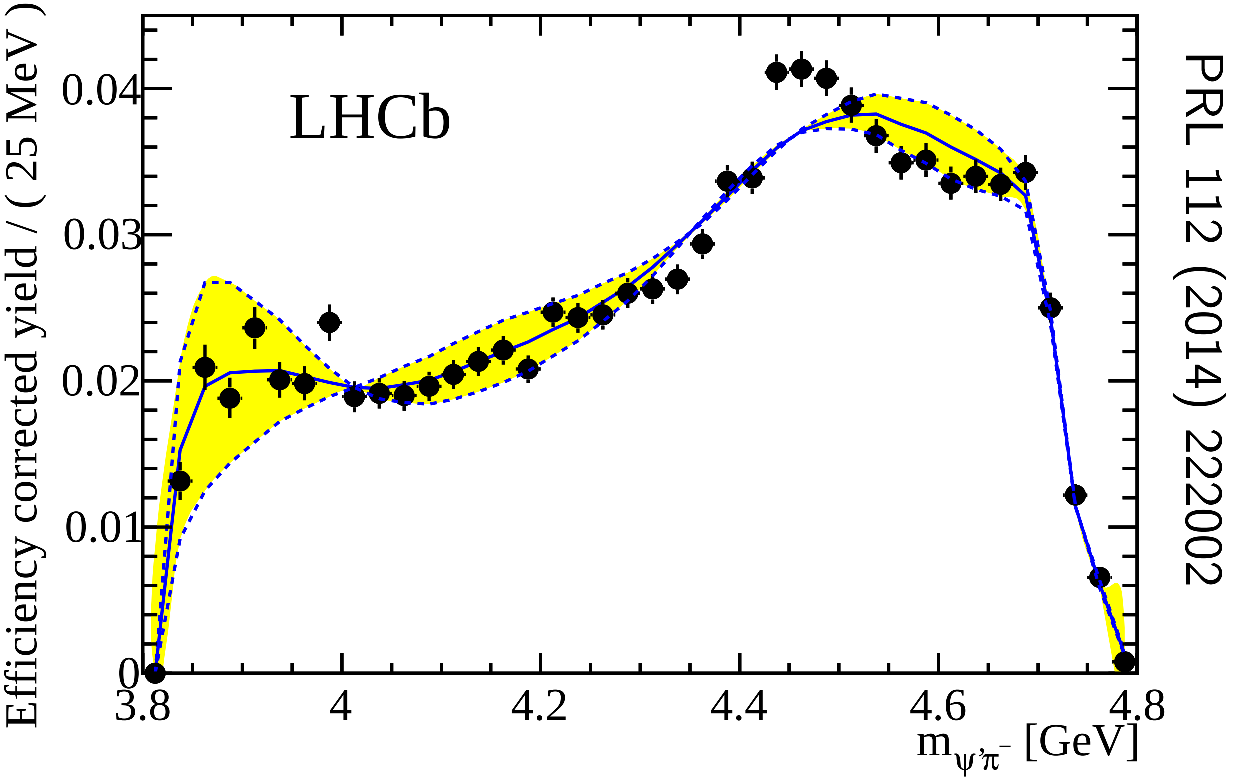
$$\sum_i \frac{1}{\epsilon_i} P_l(\cos\theta_{Ki})$$

- Take only moments corresponding to $J \leq 2$
- Construct Dalitz plot and project on $\psi(2S)\pi$ axis

- Test whether contributions in $K\pi$ system can describe data
- Do not impose specific model for resonances

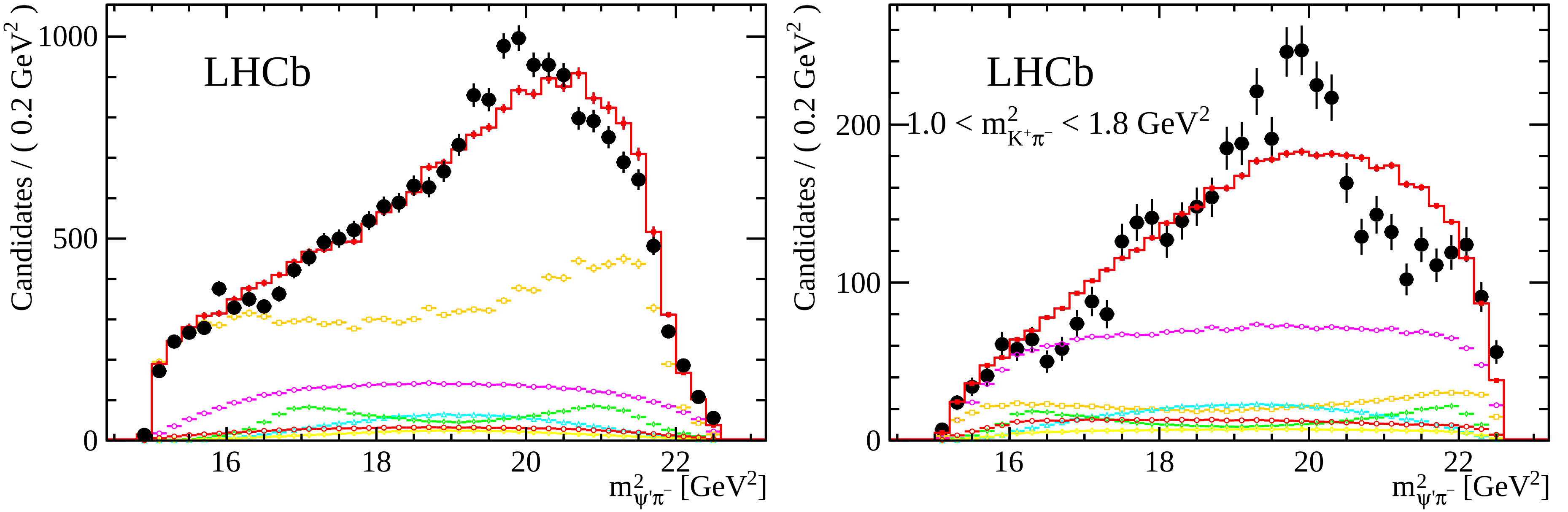
→ Model independent test

Model independent result



- Clearly, pure kaon resonances cannot explain $M(\psi(2S)\pi)$ spectrum
- Understanding details difficult
  - Resonances in $\psi(2S)\pi$ will contribute to $K\pi$ and its moments
  - Any fit to $\psi(2S)\pi$ on top of reflections neglects interference between two axes

Only K^* resonances



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Resonance	J^P	Likely $n^{2S+1}L_J$	Mass (MeV)	Width (MeV)	$\mathcal{B}(K^{*0} \to K^+\pi^-)$
$K_0^*(800)^0$ (κ)	0^+	—	682 ± 29	547 ± 24	$\sim 100\%$
$K^*(892)^0$	1^-	1^3S_1	895.94 ± 0.26	48.7 ± 0.7	$\sim 100\%$
$K_0^*(1430)^0$	0^+	1^3P_0	1425 ± 50	270 ± 80	$(93 \pm 10)\%$
$K_1^*(1410)^0$	1^-	2^3S_1	1414 ± 15	232 ± 21	$(6.6 \pm 1.3)\%$
$K_2^*(1430)^0$	2^+	1^3P_2	1432.4 ± 1.3	109 ± 5	$(49.9 \pm 1.2)\%$
$B^0 \to \psi(2S)K^+\pi^-$ phase space limit			1593		
$K_1^*(1680)^0$	1^-	1^3D_1	1717 ± 27	322 ± 110	$(38.7 \pm 2.5)\%$
$K_3^*(1780)^0$	3^-	1^3D_3	1776 ± 7	159 ± 21	$(18.8 \pm 1.0)\%$
$K_0^*(1950)^0$	0^+	2^3P_0	1945 ± 22	201 ± 78	$(52 \pm 14)\%$
$K_4^*(2045)^0$	4^+	1^3F_4	2045 ± 9	198 ± 30	$(9.9 \pm 1.2)\%$
$B^0 \to J/\psi K^+\pi^-$ phase space limit			2183		
$K_5^*(2380)^0$	5^-	1^3G_5	2382 ± 9	178 ± 32	$(6.1 \pm 1.2)\%$

●— **data**

🟥— **total fit**

🟨— **$K^*(892)$**

🟪— **K^* S-wave**

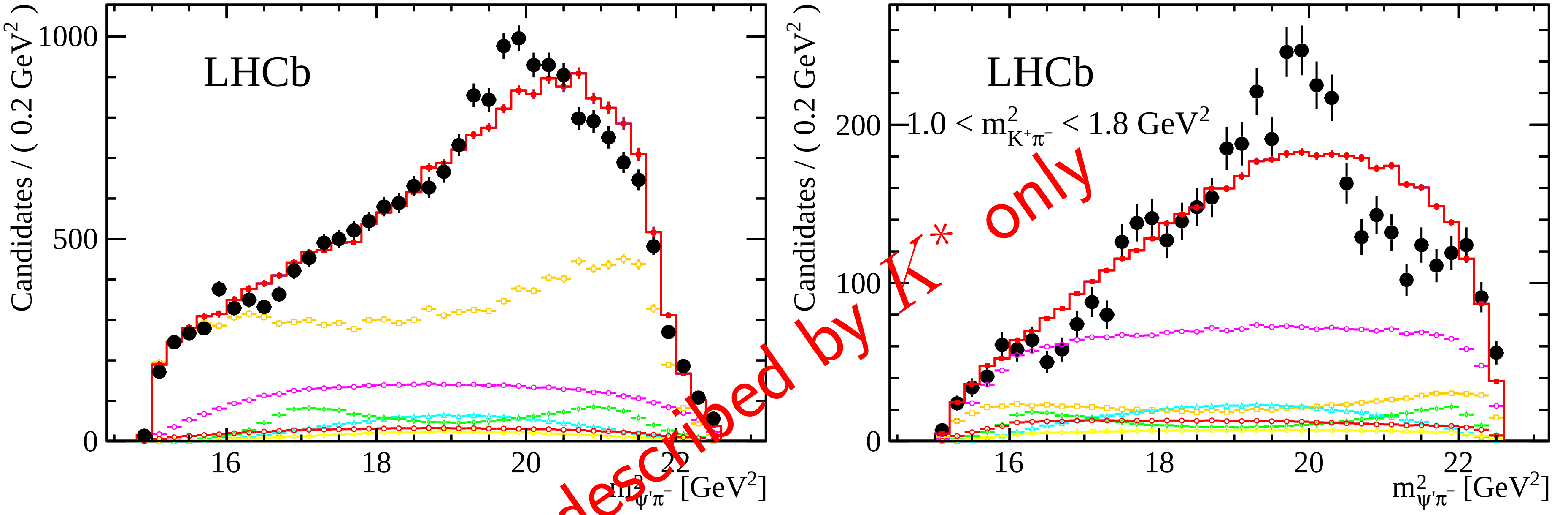
🟩— **$K^*_2(1430)$**

🟥— **background**

🟨— **$K^*(1680)$**

🟦— **$K^*(1410)$**

Only K* resonances



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Data cannot be described by K^* only

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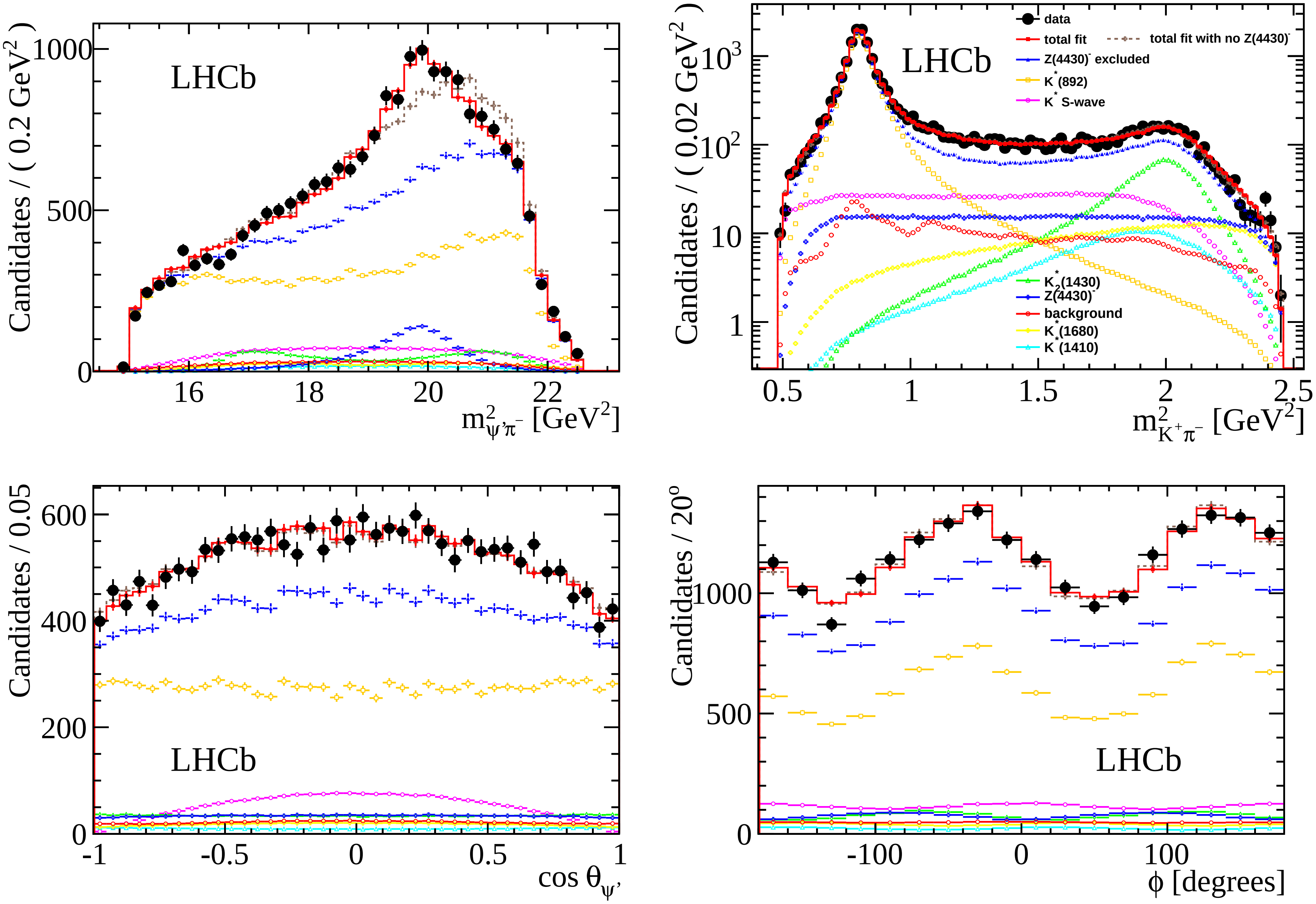
Adding Z^+



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Results

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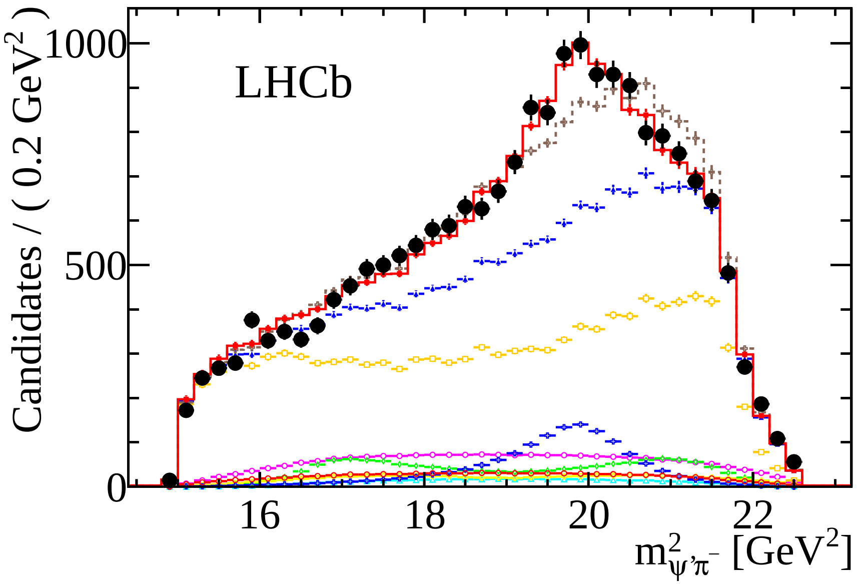

$M(Z)$	$4475 \pm 7^{+15}_{-25}$ MeV
$\Gamma(Z)$	$172 \pm 13^{+37}_{-34}$ MeV
f_Z	$5.9 \pm 0.9^{+1.5}_{-3.3}$ %
f_Z^I	$16.7 \pm 1.6^{+2.6}_{-5.2}$ %
Significance	$> 13.9\sigma$

- Data are described well with 1^+ $Z(4430)^+$ contribution (χ^2 p-value 12%)
- Parameters extracted consistent with Belle
- Large interference effects seen
- Adding additional K^* resonances to model does not alter conclusion

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$$f_Z = \frac{\int A_Z(\Omega)d\Omega}{\int A(\Omega)d\Omega} \qquad f_Z^I = 1 - \frac{\int A_{\mathrm{no}Z}(\Omega)d\Omega}{\int A(\Omega)d\Omega}$$

$Z(4430)^+$ spin

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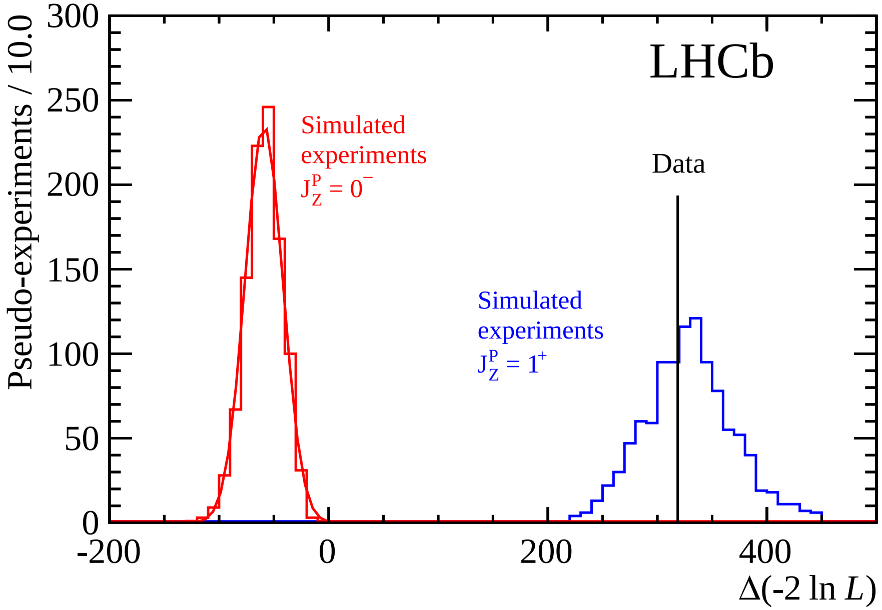
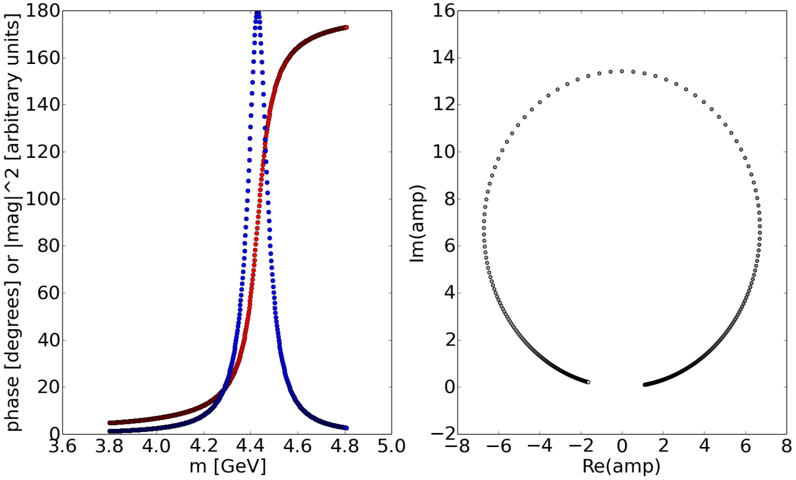


Hypothesis	Rejection
0^-	$9.7\,\sigma$
1^-	$15.8\,\sigma$
2^+	$16.1\,\sigma$
2^-	$14.6\,\sigma$

- As we use full kinematic information, we have sensitivity to quantum numbers
- Test spins 0,1 and 2 with both parities
- Based on likelihood ratio
- Quote exclusion based on asymptotic formula (lower bound)
- Verified by simulation
- All rejections relative to 1^+
- $Z(4430)^+$ is 1^+ state without any doubts

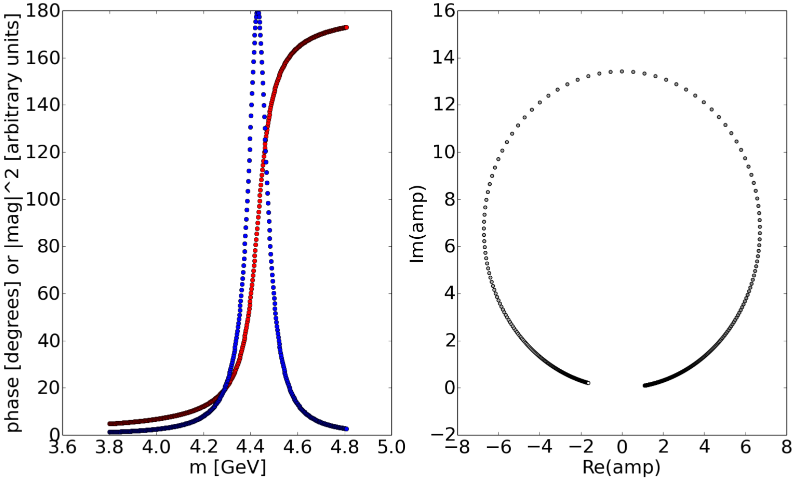
Is $\mathbf{Z(4430)^+}$ resonance?



$$\frac{1}{m_R^2 - m^2 - i m_R \Gamma(m, \Gamma_R)}$$

- Data are consistent with BW for $Z(4430)^+$
- But will they follow if BW is not imposed?
- Change BW in $Z(4430)^+$ amplitude to 6 complex numbers in 6 $M(\psi(2S)\pi)$ bins
- Plot resulting amplitude on Argand plot

Is $\mathbf{Z(4430)^+}$ resonance?



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- Data are consistent with BW for $Z(4430)^+$
- But will they follow if BW is not imposed?
- Change BW in $Z(4430)^+$ amplitude to 6 complex numbers in 6 $M(\psi(2S)\pi)$ bins
- Plot resulting amplitude on Argand plot

⇒ It shows resonance behaviour without imposing it

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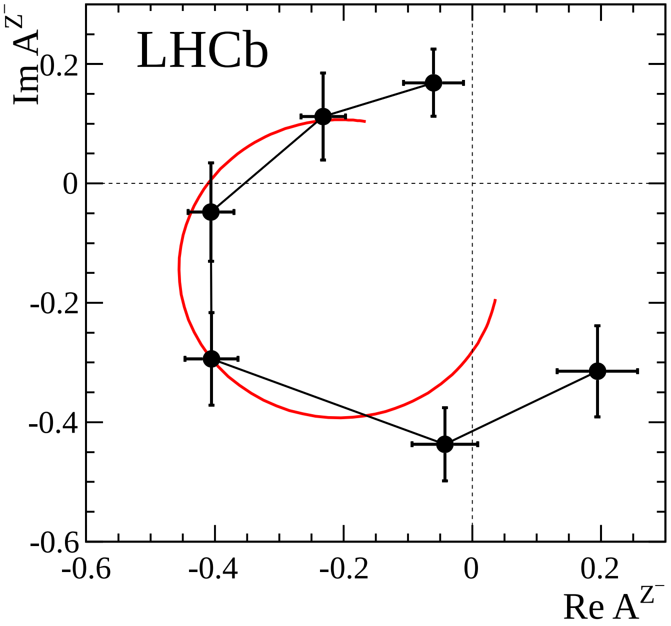
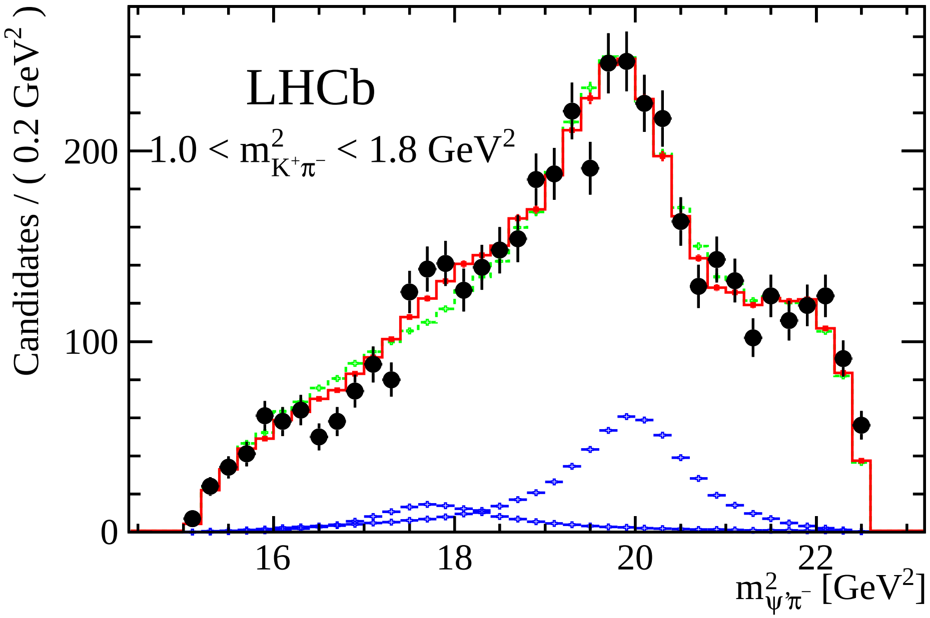


Second Z^+ state



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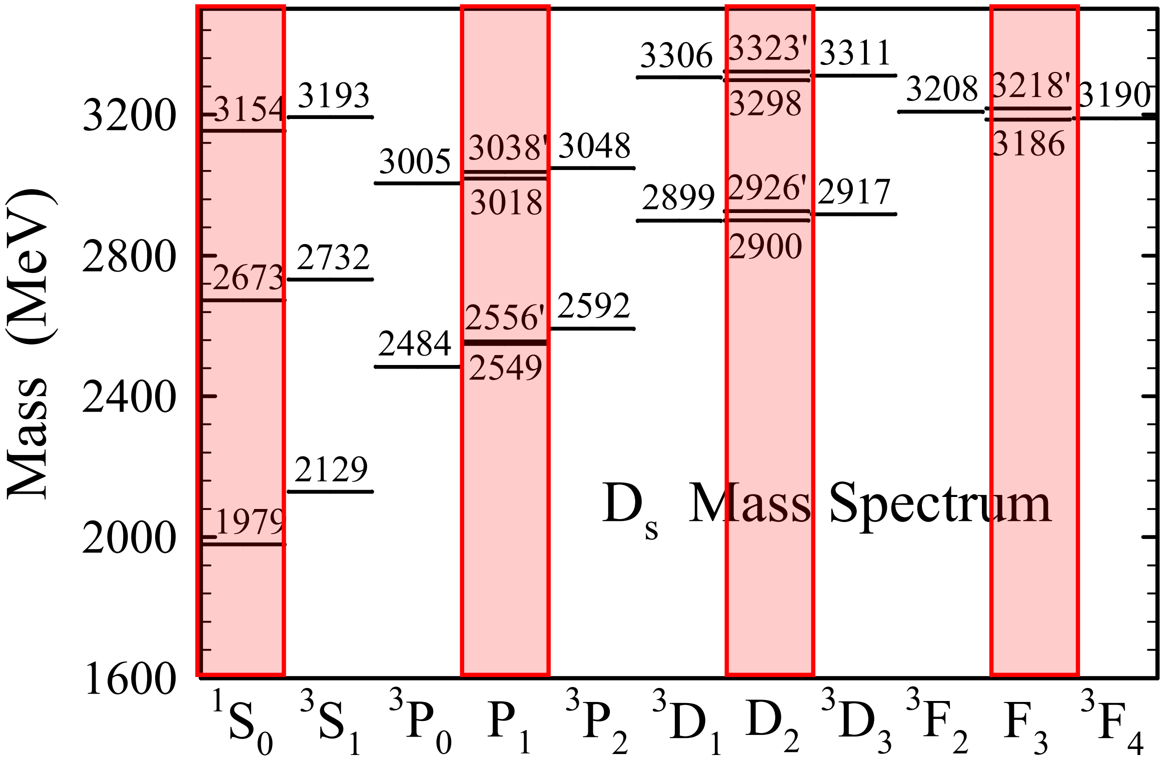
$M(Z_0)$	$4239 \pm 18^{+45}_{-10}$ MeV
$\Gamma(Z_0)$	$220 \pm 47^{+108}_{-74}$ MeV
f_{Z_0}	$1.6 \pm 0.5^{+1.9}_{-0.4}$ %
$f^I_{Z_0}$	$2.4 \pm 1.1^{+1.7}_{-0.2}$ %
Significance	6σ

- Data can be described even better by adding second $\psi(2S)\pi$ state
- On its own, it is significant
- Preferred 0^- (but 660 ± 150 MeV wide 1^+ option cannot be ruled out)

- Argand diagram is inconclusive
- No evidence in model-independent approach
- Will need more data to clarify situation

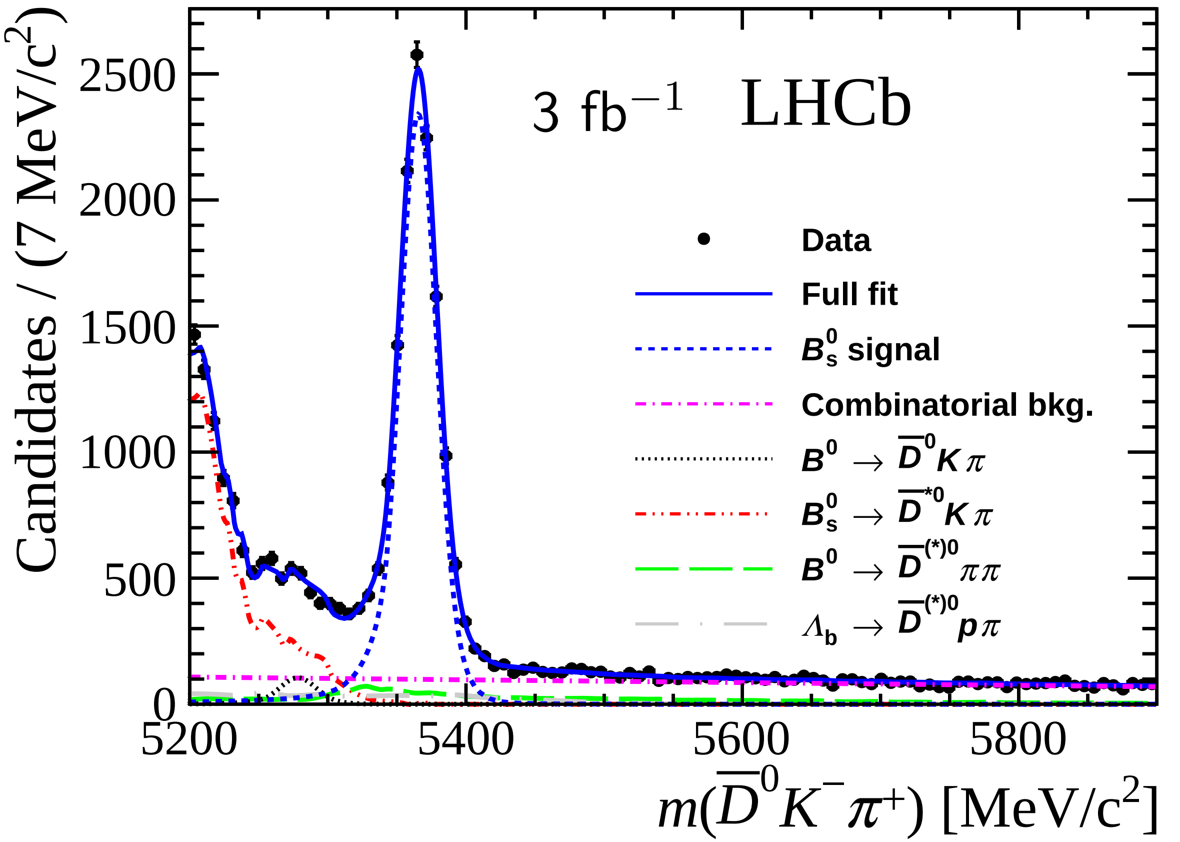
D_{sJ} spectroscopy



PRD 89 (2014) 074023

- Lowest lying D_s and D_s^* well established
- $D_{s1}(2536)$, $D_{s2}^*(2573)$ reasonably studied, "narrow" $L = 1$ states
- $D_{s0}^*(2317)$ and $D_{s1}(2460)$ interpreted as "wide" $L = 1$ states, lower than expected
- States with unnatural spin parity ($J^P = 0^-, 1^+, 2^-, ...$) cannot decay to DK
- $D_{s1}^*(2700)$, $D_{sJ}^*(2860)$ and $D_{sJ}(3040)$ seen by Babar and LHCb in inclusive production

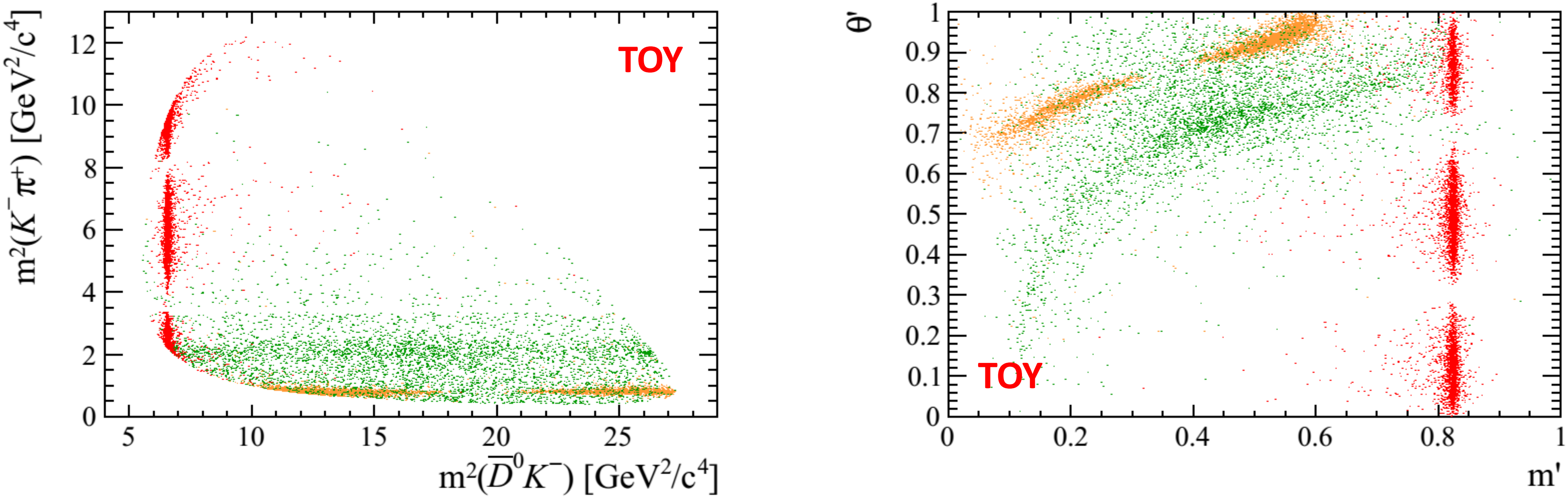
$B_s \to \overline{D}^0 K^- \pi^+$ decay



arXiv:1407.7574,arXiv:1407.7712

- Decay $B_s \to \overline{D}^0 K^- \pi^+$ allows to study D_{sJ} states in $\overline{D}^0 K^-$
- Clean sample of about 11k signal decay (87% purity)
- Dalitz plot analysis allows to access also spin

(Square) Dalitz plot



- Contributions in $\overline{D}K^-$ and $K^-\pi^+$
- D_J^+ would decay to $D^0\pi^+$, so would contribute only through doubly Cabibbo suppressed D^0 decay
- As most activity in corners and around boundary, transform to square Dalitz plot
- m' is effectively $m(DK)$ and θ' is the DK helicity angle

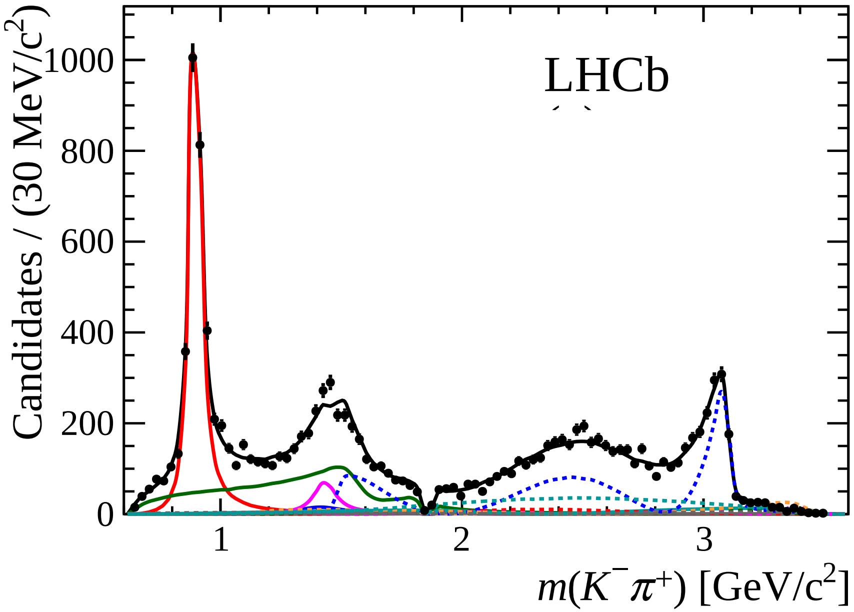
Dalitz model

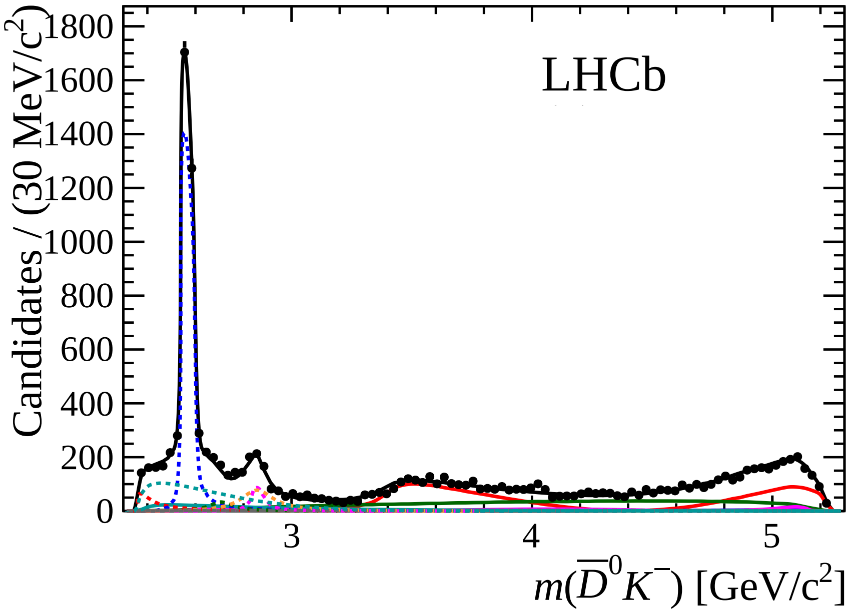
Resonance	Spin	Dalitz plot axis	Model	Parameters (MeV/c^2)
$\overline{K}^*(892)^0$	1	$m^2(K^-\pi^+)$	RBW	$m_0 = 895.81 \pm 0.19,\ \Gamma_0 = 47.4 \pm 0.6$
$\overline{K}^*(1410)^0$	1	$m^2(K^-\pi^+)$	RBW	$m_0 = 1414 \pm 15,\ \Gamma_0 = 232 \pm 21$
$\overline{K}^*_0(1430)^0$	0	$m^2(K^-\pi^+)$	LASS	Parameters floated
$\overline{K}^*_2(1430)^0$	2	$m^2(K^-\pi^+)$	RBW	$m_0 = 1432.4 \pm 1.3,\ \Gamma_0 = 109 \pm 5$
$\overline{K}^*(1680)^0$	1	$m^2(K^-\pi^+)$	RBW	$m_0 = 1717 \pm 27,\ \Gamma_0 = 322 \pm 110$
$\overline{K}^*_0(1950)^0$	0	$m^2(K^-\pi^+)$	RBW	$m_0 = 1945 \pm 22,\ \Gamma_0 = 201 \pm 90$
$D^*_{s2}(2573)^-$	2	$m^2(\overline{D}^0 K^-)$	RBW	Parameters floated
$D^*_{s1}(2700)^-$	1	$m^2(\overline{D}^0 K^-)$	RBW	$m_0 = 2709 \pm 4,\ \Gamma_0 = 117 \pm 13$
$D^*_{sJ}(2860)^-$	?	$m^2(\overline{D}^0 K^-)$	RBW	Parameters floated Multiple spin hypotheses tested
Nonresonant		$m^2(\overline{D}^0 K^-)$	EFF	Parameters floated
$D^{*-}_{s\,v}$	1	$m^2(\overline{D}^0 K^-)$	RBW	$m_0 = 2112.3 \pm 0.5$
$D^*_{s0\,v}(2317)^-$	0	$m^2(\overline{D}^0 K^-)$	RBW	$m_0 = 2317.8 \pm 0.6$
B^{*+}_v	1	$m^2(\overline{D}^0 \pi^+)$	RBW	$m_0 = 5325.2 \pm 0.4$

RBW = Relativistic Breit-Wigner, LASS = LASS $K\pi$ S-wave parameterisation, EFF = exponential form factor

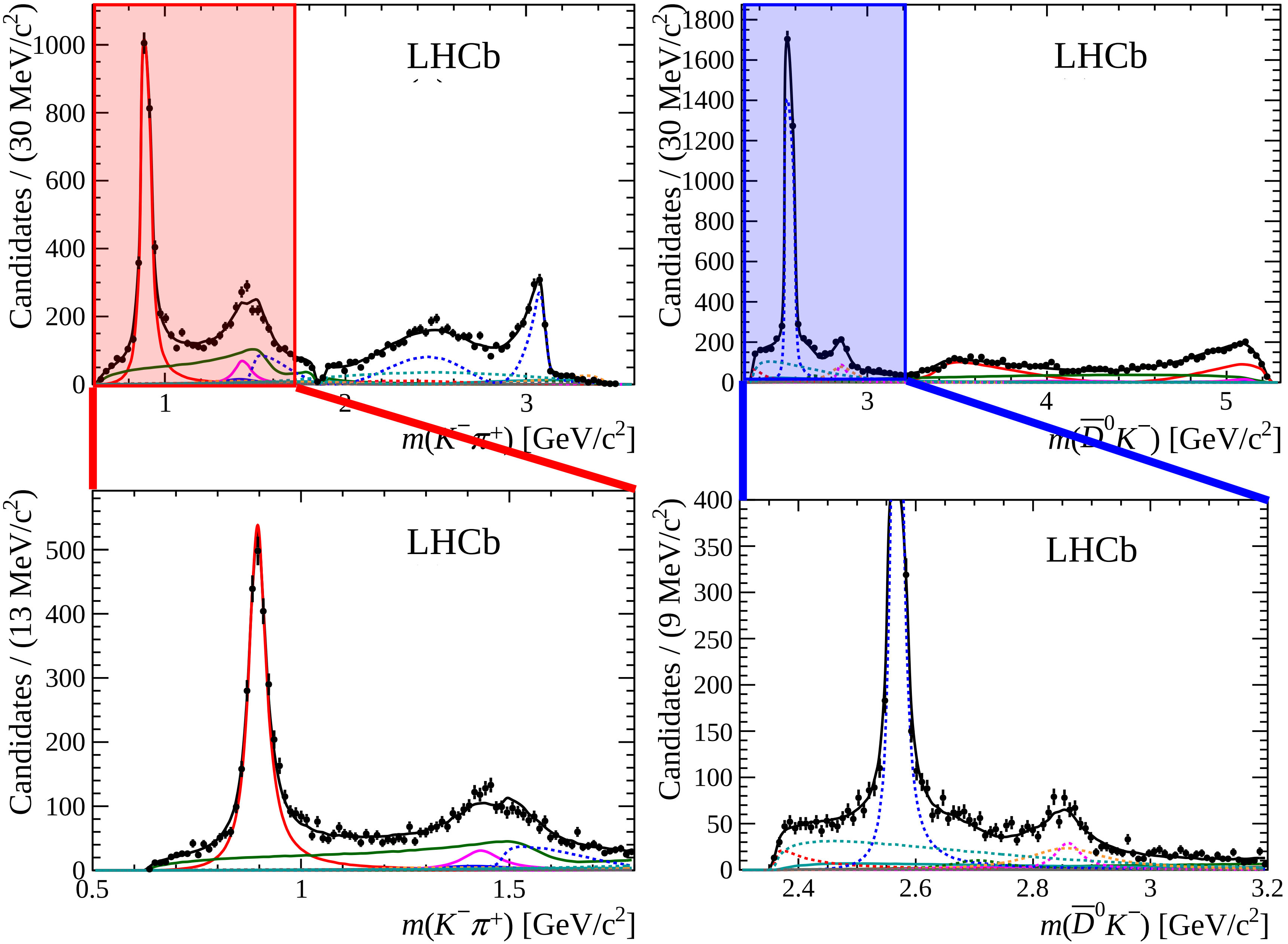
Dalitz plot fit

arXiv:1407.7574,arXiv:1407.7712





Dalitz plot fit



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Dalitz plot fit

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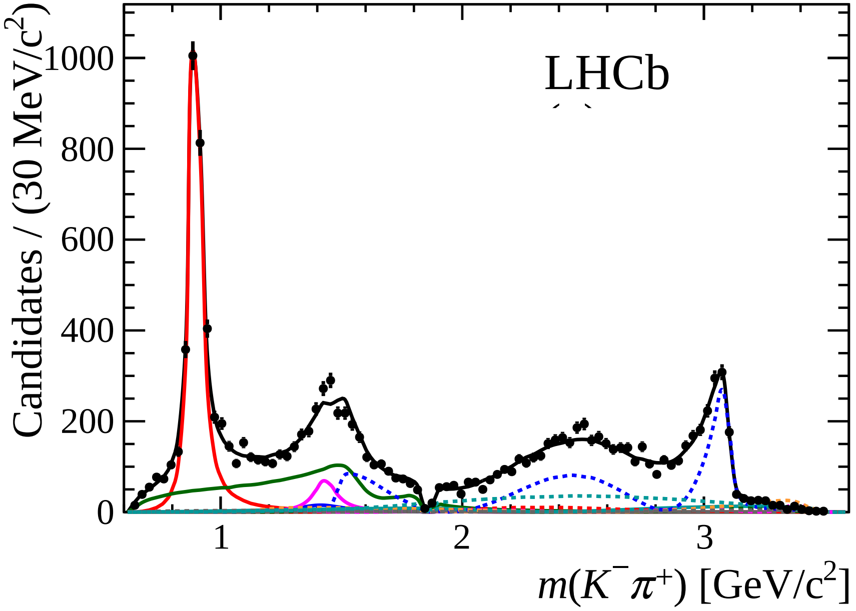
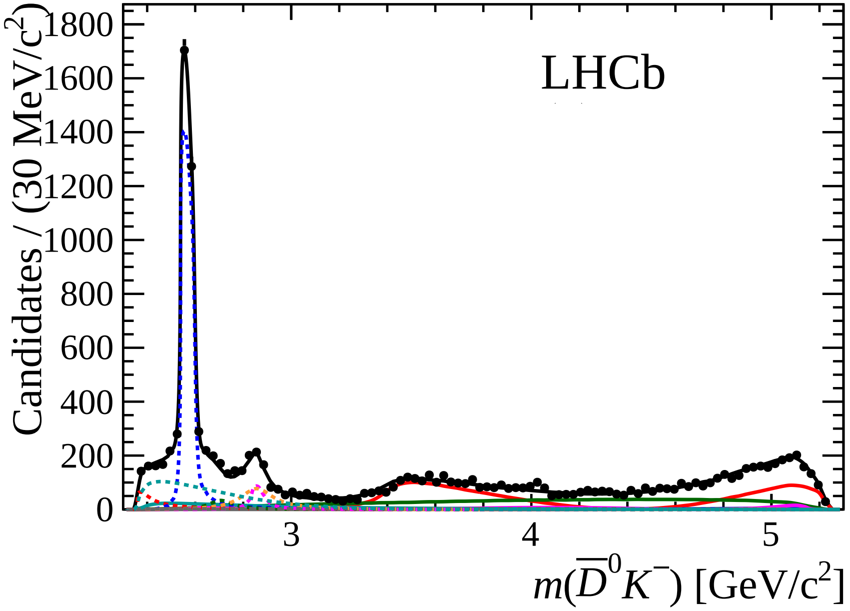
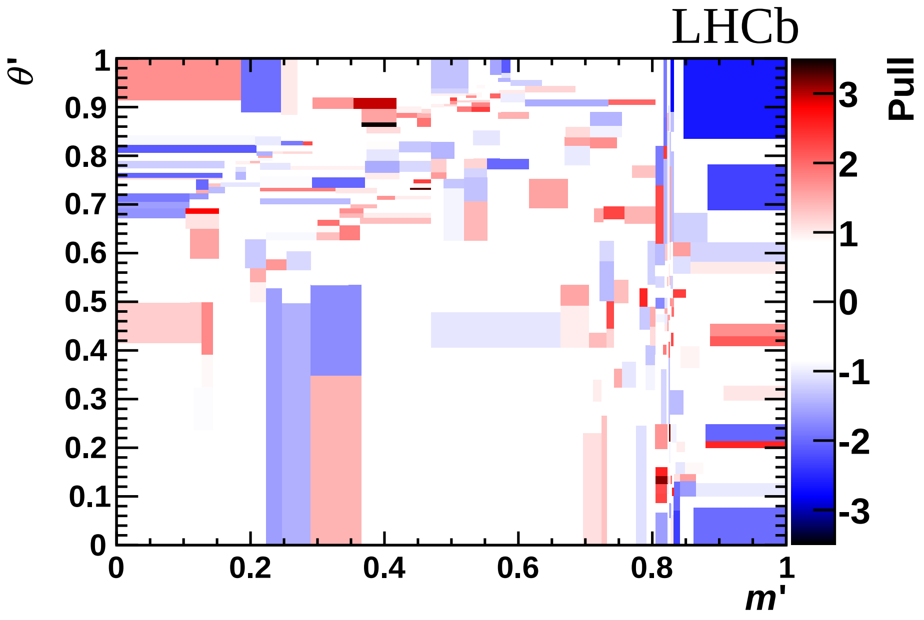
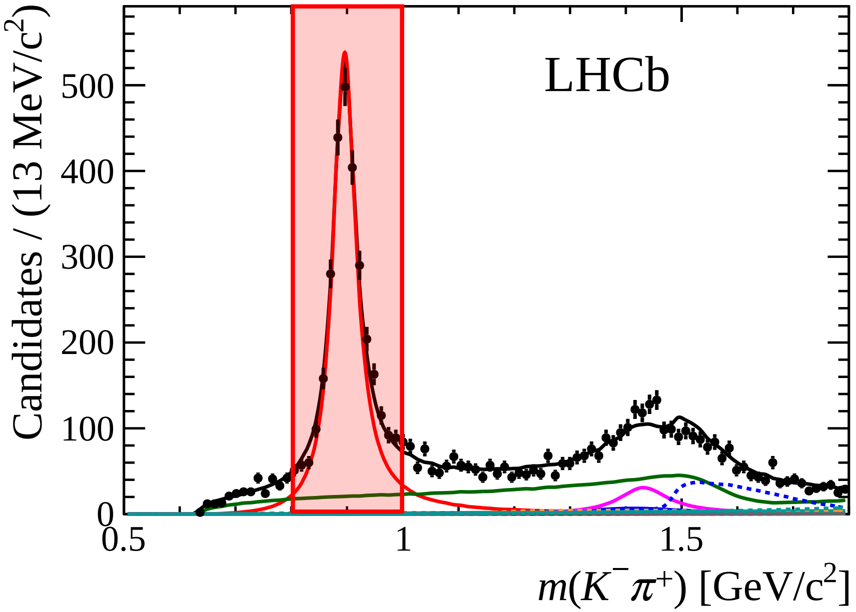


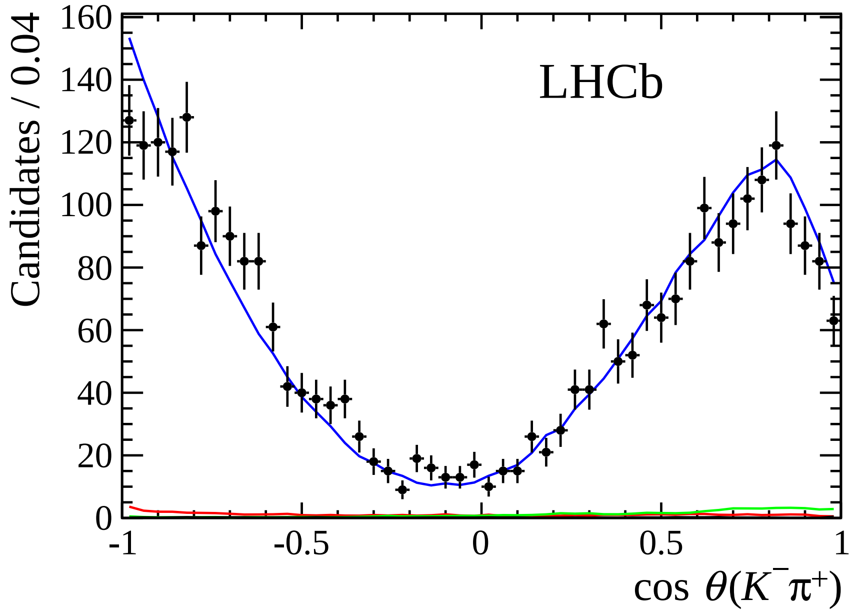




Helicity angle projections

arXiv:1407.7574,arXiv:1407.7712





- Angular distribution depends on spin of the resonance
- Spin 1: $\cos^2\theta$

Helicity angle projections

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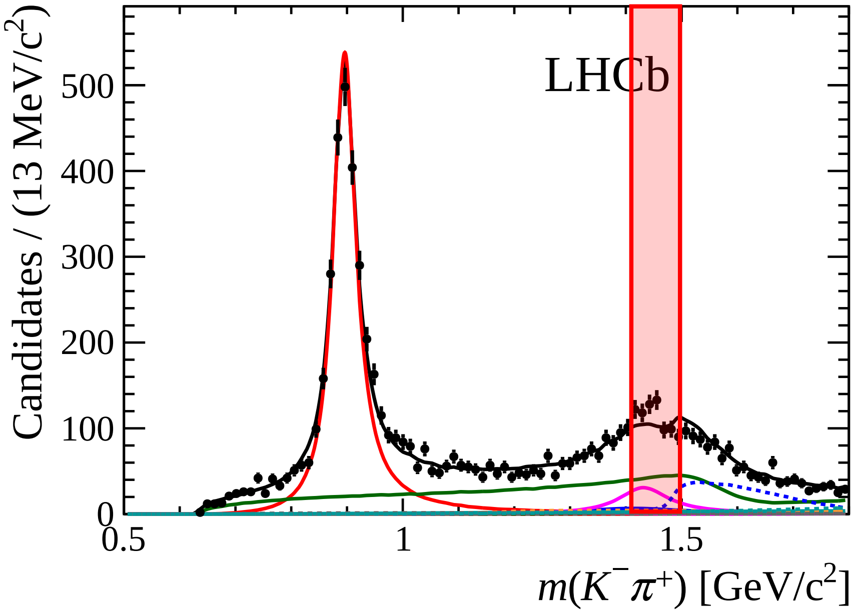

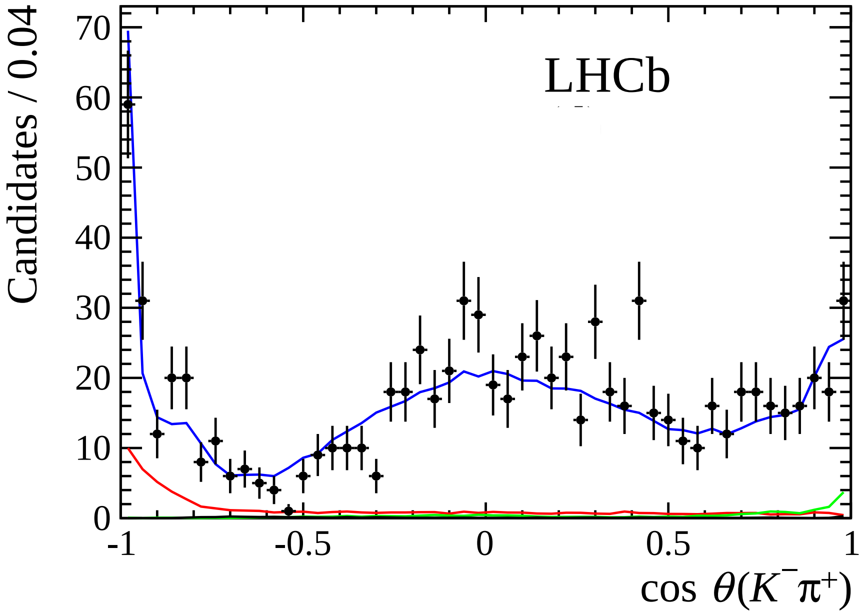

- Angular distribution depends on spin of the resonance
- Spin 1: $\cos^2\theta$
- Spin 0: Flat
- Spin 2: $(\frac{3}{2}\cos^2\theta - \frac{1}{2})^2$
- Spin 3: $(-\frac{3}{2}\cos\theta + \frac{5}{2}\cos^3\theta)^2$

Helicity angle projections

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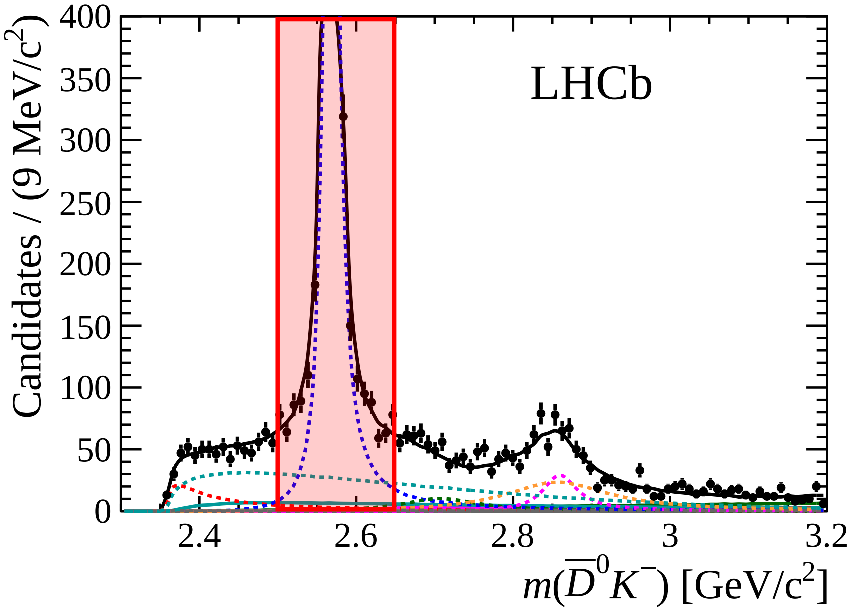

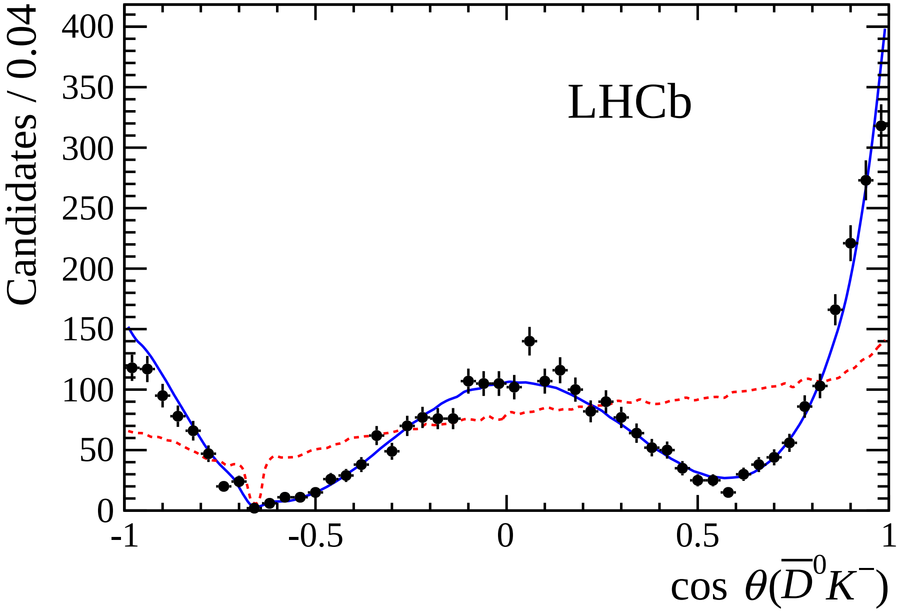

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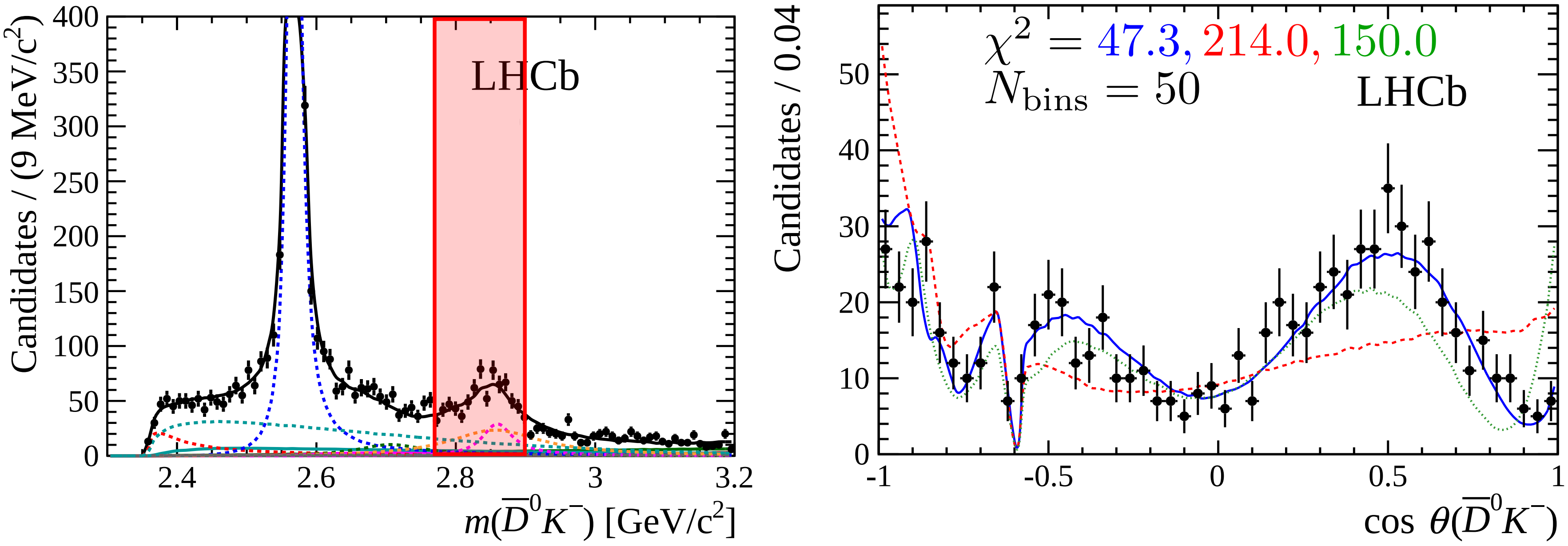
- Spin 0: Flat
- Spin 2: $(\frac{3}{2}\cos^2\theta - \frac{1}{2})^2$
- Spin 3: $(-\frac{3}{2}\cos\theta + \frac{5}{2}\cos^3\theta)^2$
- Spin of $D_{s2}(2573)$ determined as 2 for the first time

2860 MeV region

arXiv:1407.7574,arXiv:1407.7712



Spin hypothesis	ΔNLL	$\sqrt{2\Delta\mathrm{NLL}}$	Masses and widths			
1+3	0	—				
0	141.0	16.8	2862	57		
0+1	113.2	15.0	2446*	250	2855	96
0+2	155.1	17.6	2870	61	2569*	17
0+3	105.1	14.5	2415*	188	2860	52
1	156.8	17.7	2866	92		
1+2	138.6	16.6	2851	99	3134*	174
2	287.9	24.0	3243*	81		
2	365.5	27.0	2569*	17		
2+3	131.2	16.2	2878	12	2860	56
3	136.5	16.5	2860	57		

Results

- Best measurement of mass and width of $D_{s2}^{*}(2573)$
  Uncertainties are statistical, systematic and Dalitz model

$$
\begin{aligned}
m(D_{s2}^{*}(2573)^{-}) &= 2568.39 \pm 0.29 \pm 0.19 \pm 0.18\,\mathrm{MeV}/c^2 \\
\Gamma(D_{s2}^{*}(2573)^{-}) &= 16.9 \pm 0.5 \pm 0.4 \pm 0.4\,\mathrm{MeV}/c^2
\end{aligned}
$$

  - Some tension with world average

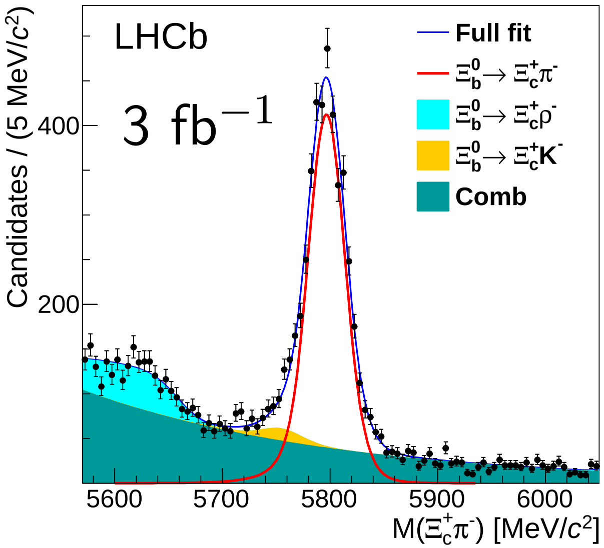
- Confirm spin 2 for $D_{s2}^{*}(2573)$
- With high significance, peak at $m(DK) \approx 2860$ MeV is due to two resonance with spins 1 and 3

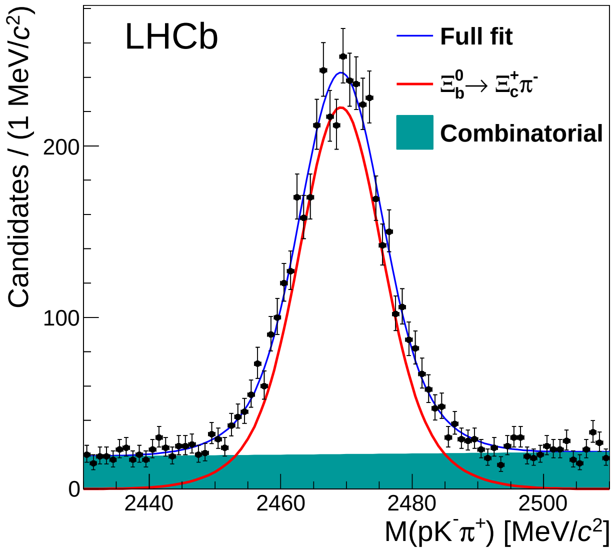
$$
\begin{aligned}
m(D_{s1}^{*}(2860)^{-}) &= 2859 \pm 12 \pm 6 \pm 23\,\mathrm{MeV}/c^2 \\
\Gamma(D_{s1}^{*}(2860)^{-}) &= 159 \pm 23 \pm 27 \pm 72\,\mathrm{MeV}/c^2 \\
m(D_{s3}^{*}(2860)^{-}) &= 2860.5 \pm 2.6 \pm 2.5 \pm 6.0\,\mathrm{MeV}/c^2 \\
\Gamma(D_{s3}^{*}(2860)^{-}) &= 53 \pm 7 \pm 4 \pm 6\,\mathrm{MeV}/c^2
\end{aligned}
$$

- Measured also branching fractions of B_s to several intermediate state, see backup or arXiv:1407.7574,arXiv:1407.7712

Ξ_b^0 Mass

PRL 113 (2014) 032001





- Mass of the Ξ_b^0 difficult to measure as high branching fraction decays are difficult to reconstruct
- At LHCb, data sample allows to exploit more suppressed decays
- Here, we use $\Xi_b^0 \to \Xi_c^+\pi^-$ with $\Xi_c^+ \to pK^-\pi^+$
- Have about 3800 signal decays
- Mass measured

$$M(\Xi_b^0) = 5791.80 \pm 0.39 \pm 0.17 \pm 0.26\ \mathrm{MeV}$$

- In the process we exploit also large sample of Ξ_c baryons to measure

$$M(\Xi_c^+) = 2467.97 \pm 0.14 \pm 0.10 \pm 0.14\ \mathrm{MeV}$$

- The most precise measurements

Uncertainties: statistical, systematic, $\Lambda_{b/c}$ mass

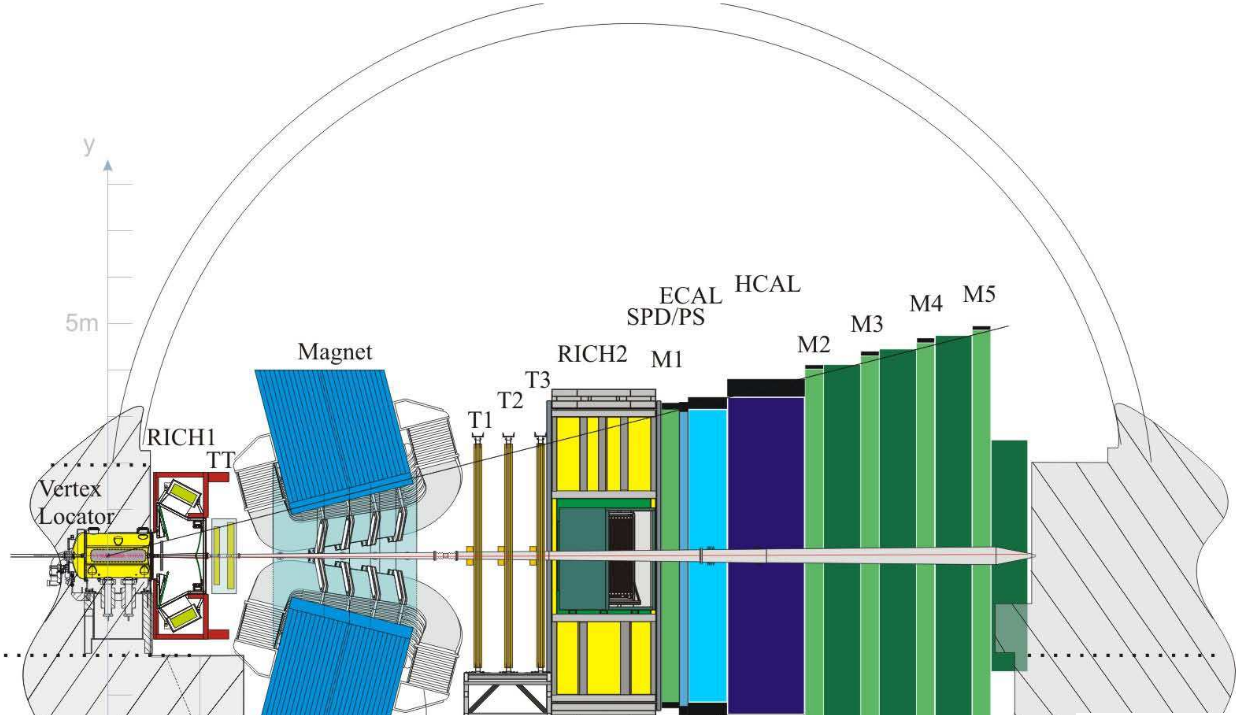
Conclusions

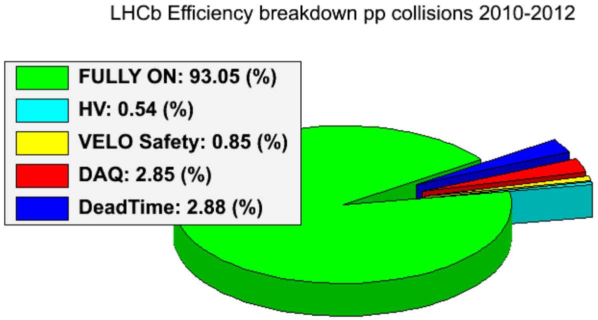
- $Z(4430)^+$ from Belle confirmed and $J^P = 1^+$ without any doubts
- From Argand plot, resonance character of $Z(4430)^+$ is demonstrated
- Charge and quantum numbers rule out conventional explanations
- Confirm spin of $D^*_{s2}(2573)$
- Demonstrated that peak around 2860 MeV is due to two states $D^*_{s1}(2860)$ and $D^*_{s3}(2860)$
- Measured mass and width of $D^*_{s2}(2573)$, $D^*_{s1}(2860)$ and $D^*_{s3}(2860)$
- Amplitude analyses of exclusive B decays good systems for study of charm spectroscopy
- At LHCb, we are effectively only at the beginning of the program
- Much more is possible and much more will come

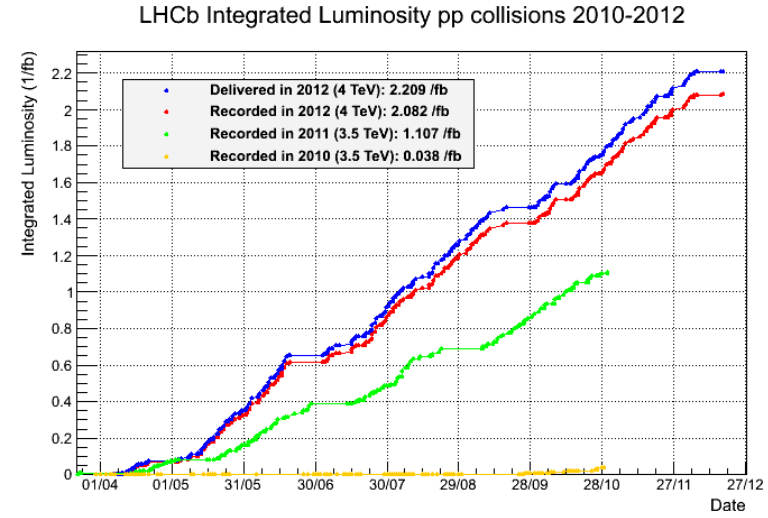
Backup

LHCb detector

- Good mass resolution
- Good time resolution
- High trigger rate on c and b
- Uniform running conditions







LHCb detector

- Good mass resolution
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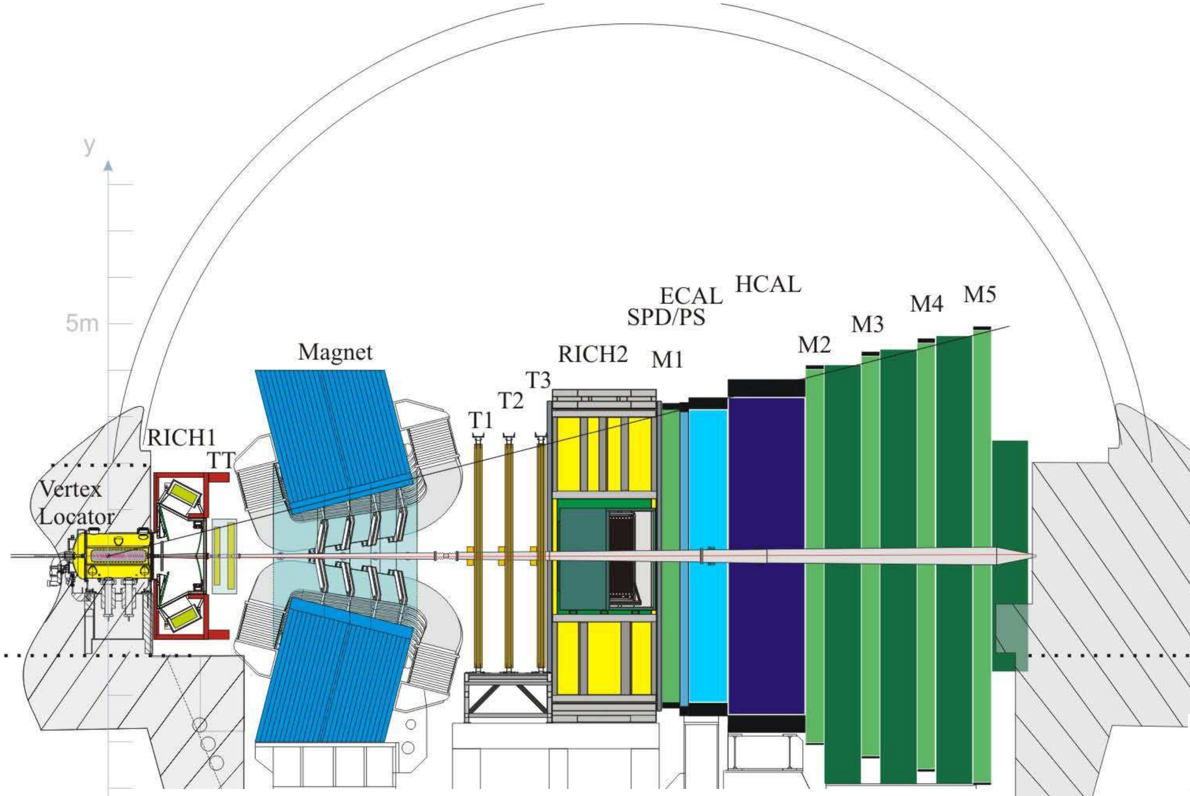
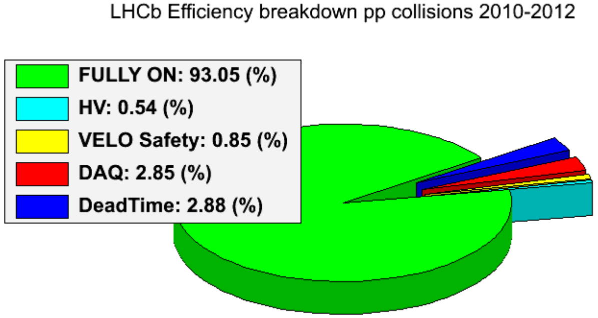
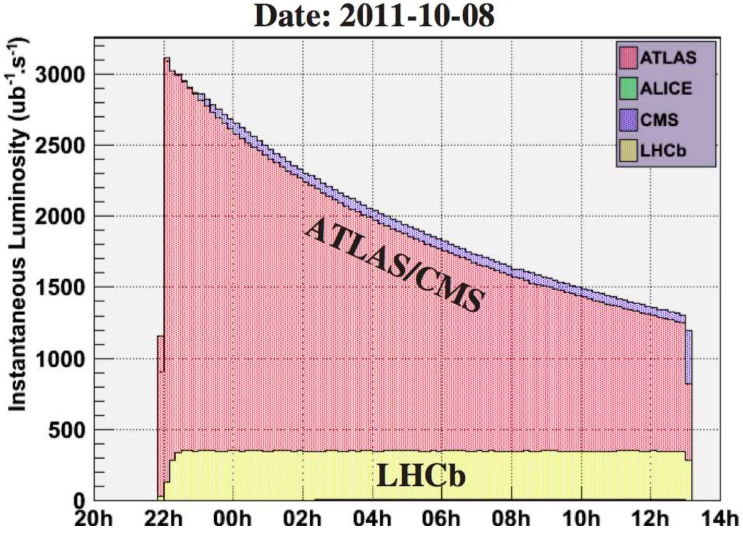
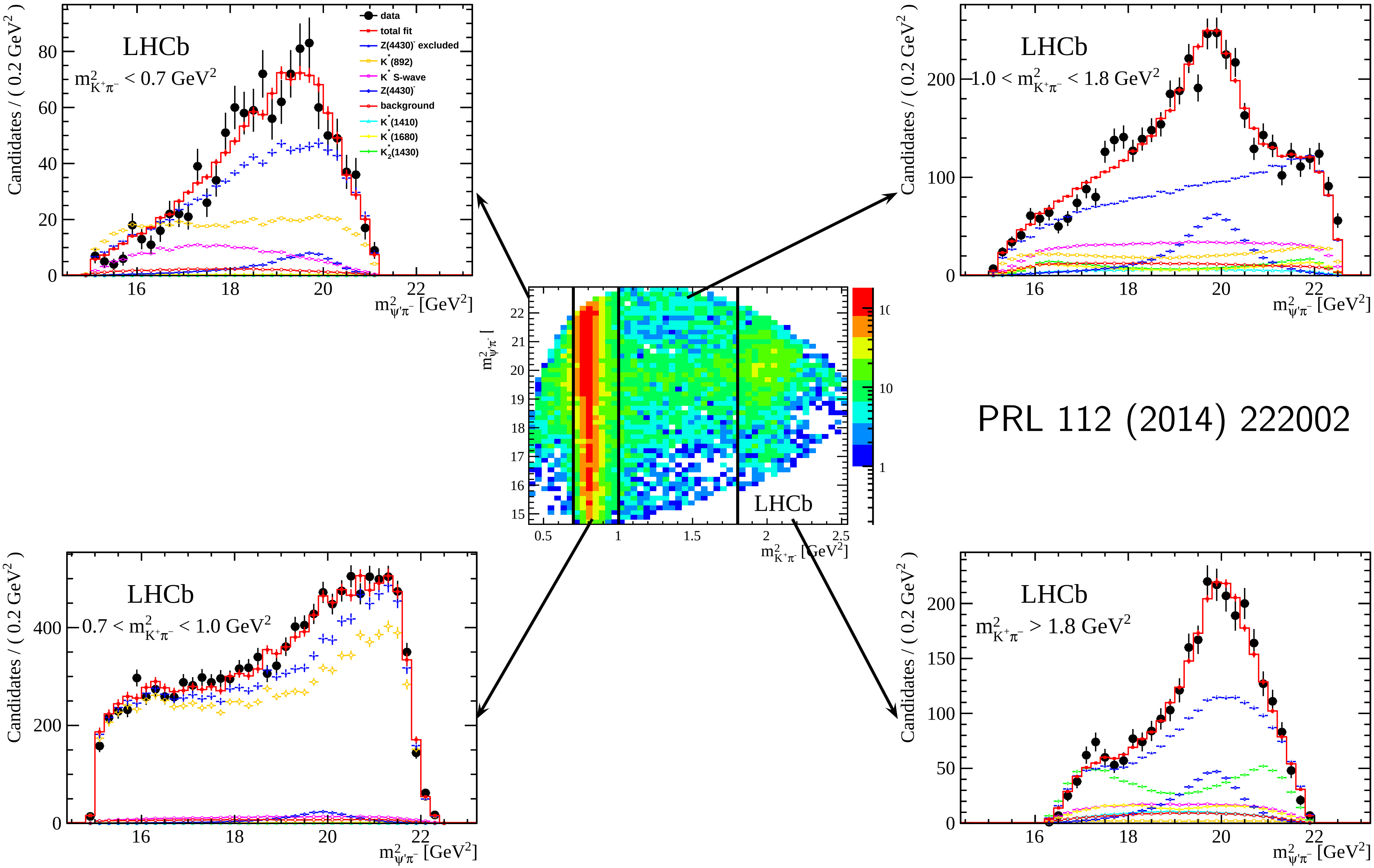






Dalitz plot slices



PRL 112 (2014) 222002

Amplitude analysis

$$|M|^2 = \sum_{\Delta\lambda_\mu} \left| \sum_{\lambda_\psi} \sum_{k} A_{k,\lambda_\psi}(\Omega|m_{0k},\Gamma_{0k}) + \sum_{\lambda_\psi^Z} A_{Z,\lambda_\psi^Z}(\Omega^Z|m_{0Z},\Gamma_{0Z}) e^{i\Delta_\mu \alpha} \right|^2$$

$$A_{k,\lambda_\psi}(\Omega|m_R,\Gamma_R) = F_B^{L_B} \left(\frac{p_B}{m_B}\right)^{L_B} R(m|m_R,\Gamma_R) F_R^{L_R} \left(\frac{p_R}{m_R}\right)^{L_R} Z(\Omega)$$

Blatt-Weisskopf form factor

Angular distribution (Helicity)

Orbital momentum part

$$R(m|m_R,\Gamma_R) = \frac{1}{m_R^2 - m^2 - i m_R \Gamma(m,\Gamma_R)}$$

$$\Gamma(m,\Gamma_R) = \Gamma_R \left(\frac{p_R}{p_{R0}}\right)^{2L_R+1} \frac{m_R}{m} F_R^2$$

Excitement?

LHCb confirms existence of exotic hadrons

How CERN's Discovery of Exotic Particles May Affect Astrophysics

by BRIAN KOBERLEIN *on* APRIL 10, 2014

大型强子对撞机捕获到神秘粒子Z（4430）

或许成为物质形式“四夸克态”存在的有力证据

2014/04/13　15:46

LHCb実験を行っている国際研究チームが、4個のクォークが結合した粒子である「Z(4430)⁻」を合成したと発表した。Z(4430) としては、初発見から7年目にしてようやく別の研究チームが存在を立証した事になる。

นักฟิสิกส์ยืนยันพบฮาดรอนสองคว้ากสองแอนตีคว้าก

WRITTEN BY NATTY_SCI ON APRIL 13, 2014. POSTED IN ฟิสิกส์, วิทยาศาสตร์

ล่าสุด เครื่อง LHCb ได้มีการศึกษาอีกครั้งและใช้ข้อมูลอนุภาคจากเครื่องโดยตรงมาวิเคราะห์ แต่นำเอาเทคนิคการวิเคราะห์ของศูนย์ปฏิบัติการวิจัยเบลล์และ BaBar มาใช้ ศาสตราจารย์ชวาร์นิคกี้และทีมงานได้ยืนยันแล้วว่า Z(4430) นั้นมีอยู่จริง และ exotic hadron ก็มีอยู่จริงด้วย

Nowa forma materii: potwierdzono istnienie egzotycznych hadronów

13-04-2014 13:08 TO TRZECI RODZAJ HADRONÓW, DOTYCHCZAS WYRÓŻNIANO BARIONY I MEZONY

"המובהקות לאותות של Z (4430) מדהימה – לפחות 13.9 סיגמה – דבר המאשר את קיומו של מצב זה" אמר דובר LHCb פיירולואיג'י קמפנה. "ניתוח ה- LHCb חשף את הטבע המהדהד של המבנים הנצפים, והוכיח כי זהו באמת חלקיק, ולא תכונה מיוחדת של הנתונים".

confirmada l´existència d´una nova partícula subatòmica

Эксперимент LHCb окончательно доказал реальность экзотического мезона Z(4430)

PISTOLA FUMANTE DI UNA PARTICELLA A QUATTRO QUARK

Objavili čudnú časticu, urýchľovač ju potvrdil

LHCb kinnitas tetrakvargi olemasolu

LHC Beauty Tangkap Z (4430) Mungkin Tetraquark

Mystisk partikel udfordrer fysikernes kvarkmodel

SPIEGEL ONLINE WISSENSCHAFT

Exotisches Teilchen: Physikern gelingt Nachweis eines Partikels aus vier Quarks

Các nhà nghiên cứu tại LHC xác nhận sự tồn tại của hạt Tetraquark: tổ hợp tạo thành từ 4 quark

Thảo luận trong 'Khoa học' bắt đầu bởi ndminhduc, 15/4/14.

De LHCb heeft 't bevestigd: er bestaan exotische hadronen

10 APRIL 2014 DOOR ARIE NOUWEN • REAGEER

ISNA

خبرگزاری دانشجویان ایران، ایسنا

Iranian Students' News Agency

تاکنون کشف ذره Z(4430) در سال 2007 بشدت جنجال برانگیز بود و فیزیکدانان بر سر موجودیت یا عدم موجودیت آن اختلاف نظر داشتند

تائید کنونی ذره با استفاده از آشکارساز LHCb ماورای هرگونه تردید منطقی موجود است.

LHCb confirma la existencia de la partícula Z(4430) formada por cuatro quarks

Παρασκευή, 11 Απριλίου 2014

Ο LHCb επιβεβαιώνει την ύπαρξη εξωτικού σωματιδίου, LHCb confirms existence of exotic hadrons

Time To Open the Gates of Hell? CERN: Large Hadron Collider Discovers 'Very Exotic Matter' That Challenges Traditional Physics! (Must-See Videos)

Thursday, April 17, 2014 19:57

SAT APR 12, 2014 AT 08:25 PM PDT

Tetra Quark: Not a New Star Trek Character, a New State of Matter.

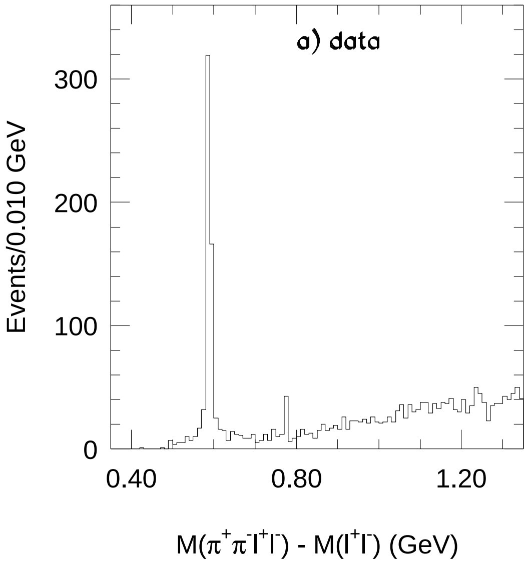
Natuurkunde & wiskunde

CERN-fysici bevestigen bestaan nieuw exotisch deeltje

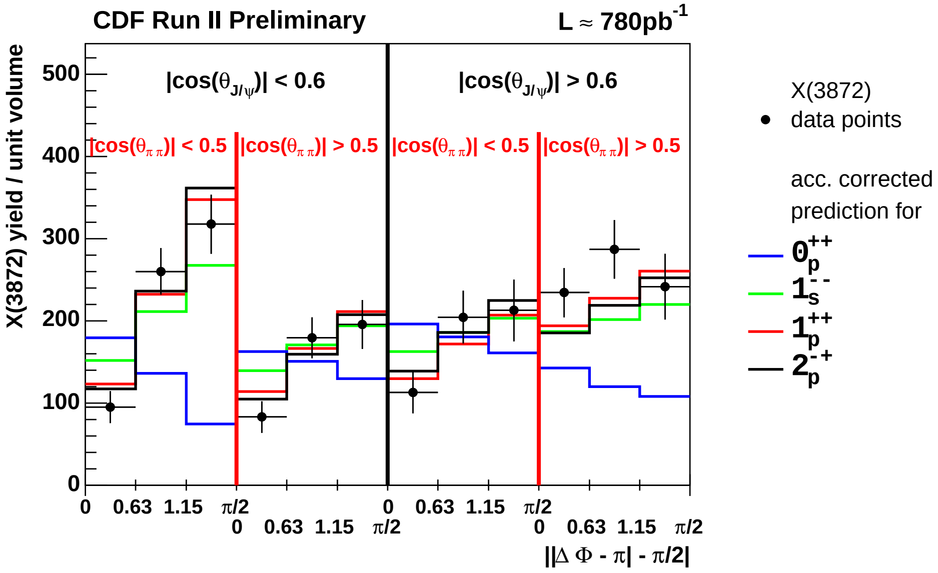
X(3872) enigma

- Discovered in 2003 by Belle
- Huge number of results available
- Quantum numbers $J^{PC} = 1^{++}$
- Nature of $X(3872)$ still unclear
- Today radiative decays

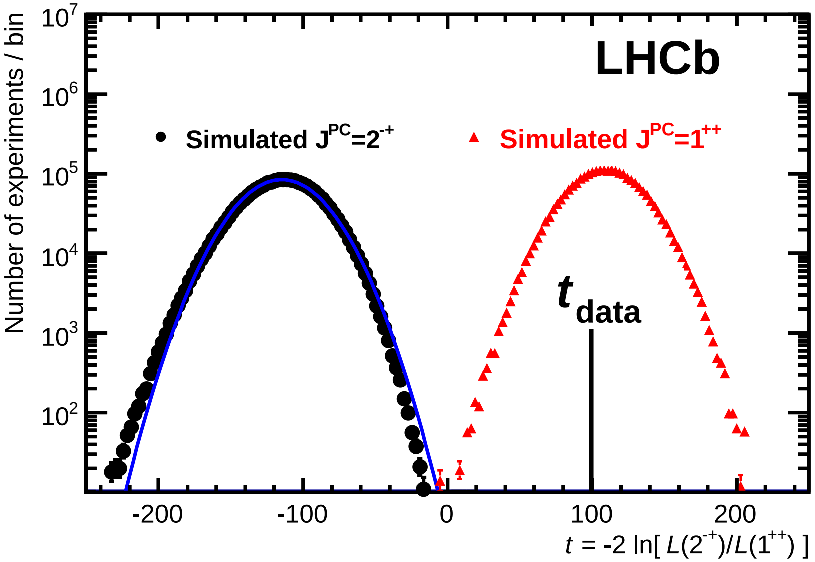
PRL 91, 262001



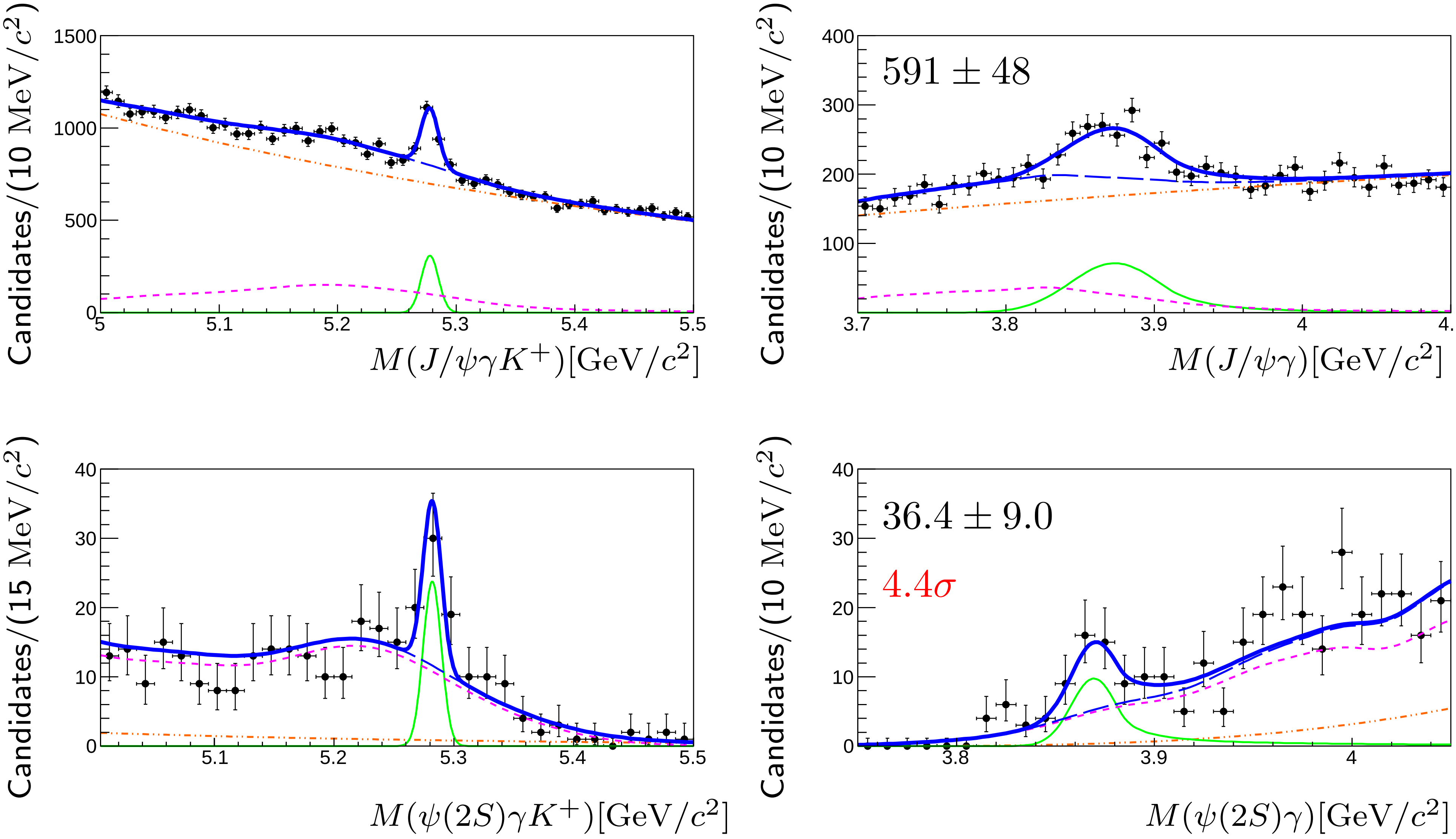
PRL 98, 132002



PRL 110, 222001



$\mathbf{X(3872)} \rightarrow \psi\gamma$



arXiv:1404.0275

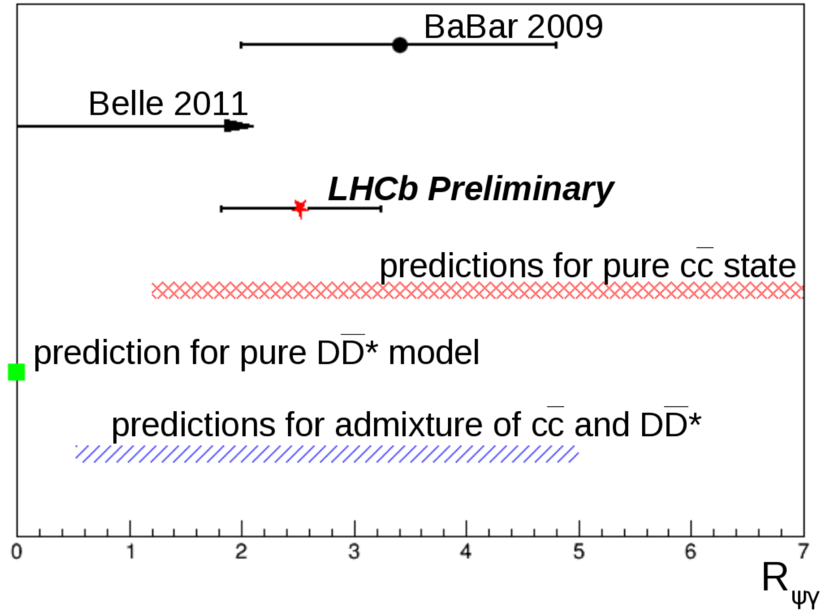
$\mathbf{X(3872)} \rightarrow \psi\mathbf{(2S)}\gamma$

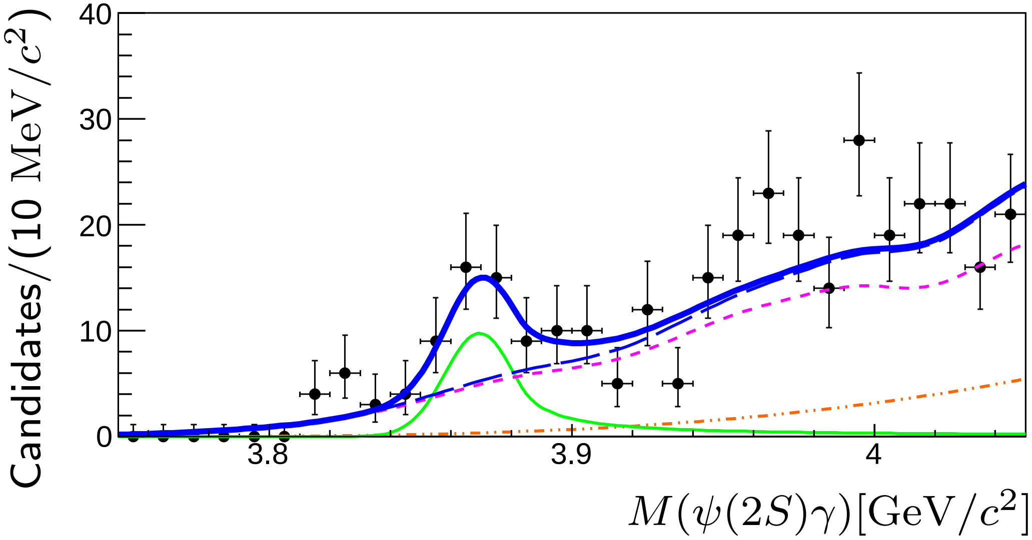
THE UNIVERSITY OF WARWICK

- We measure

$$R = \frac{\mathcal{B}(X(3872) \rightarrow \psi(2S)\gamma)}{\mathcal{B}(X(3872) \rightarrow J/\psi\,\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

- Compare to theory for different interpretations
  - Clear inconsistency with pure molecule
  - Pure $c\bar{c}$ or mixture of molecule with $c\bar{c}$ possible



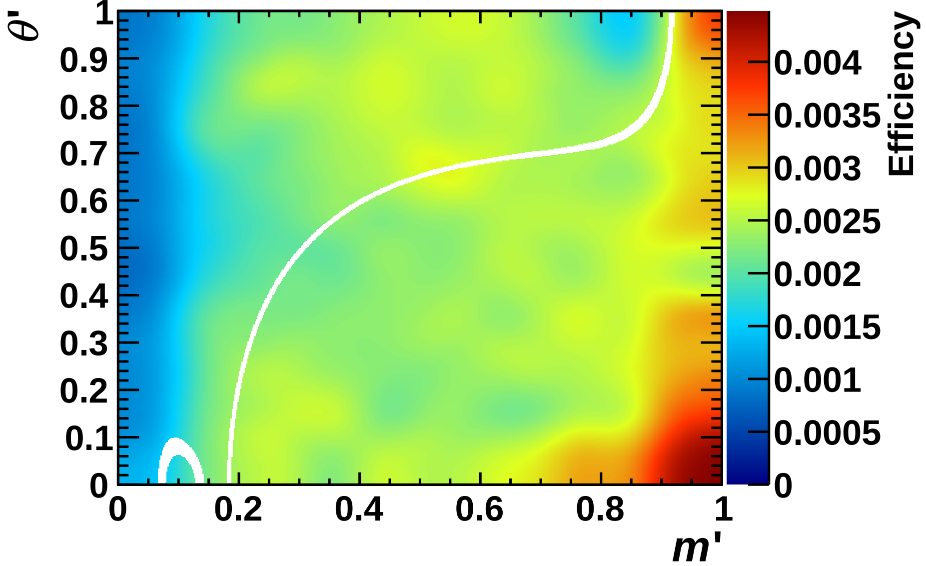


arXiv:1404.0275

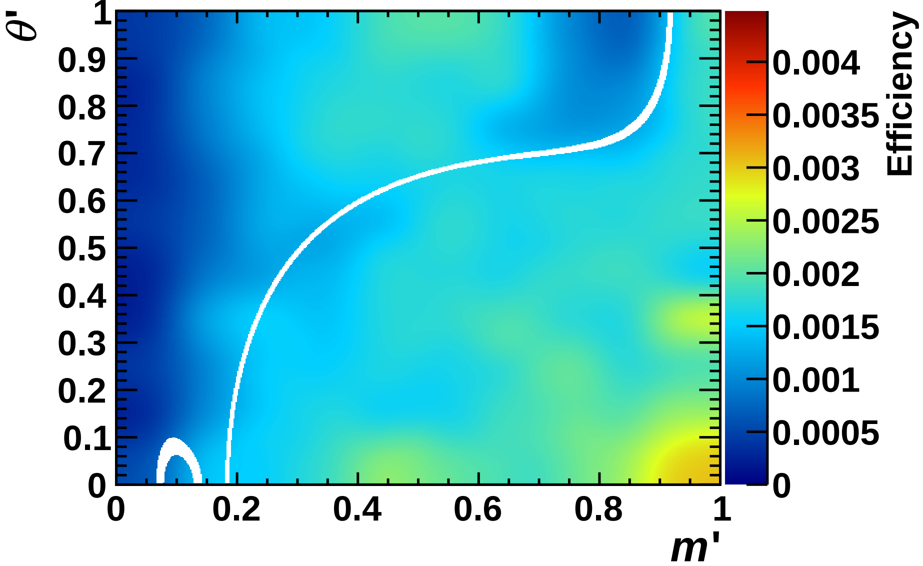
$B_s \to \overline{D}^0 K^- \pi^+$ efficiency, bg

arXiv:1407.7574,arXiv:1407.7712

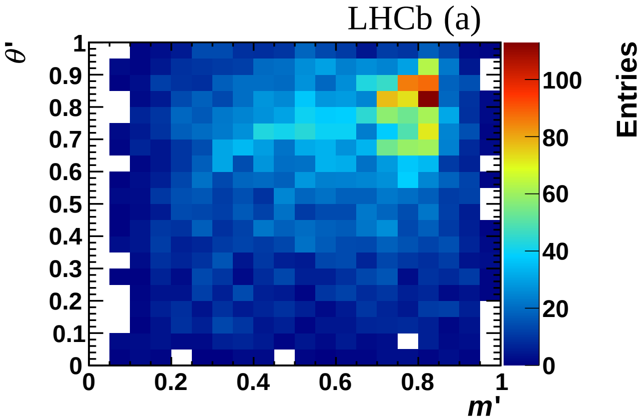
TOS



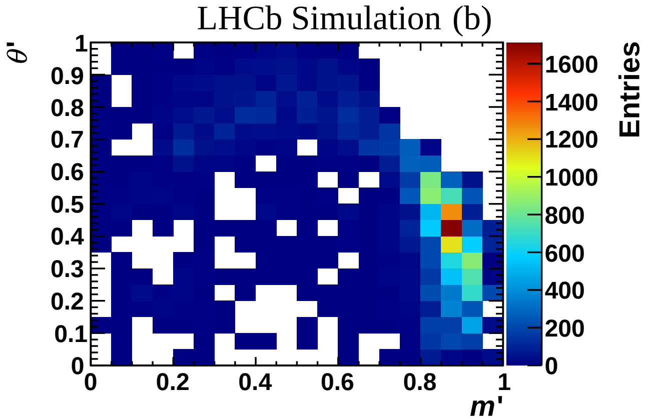
TIS



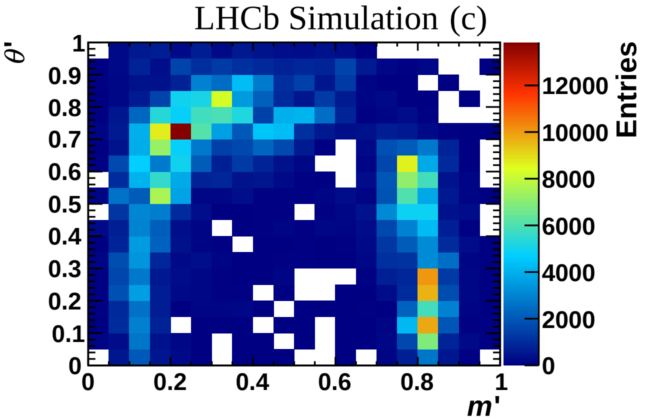
Combinatorial



$\Lambda_b \to D^{(*)} p \pi$



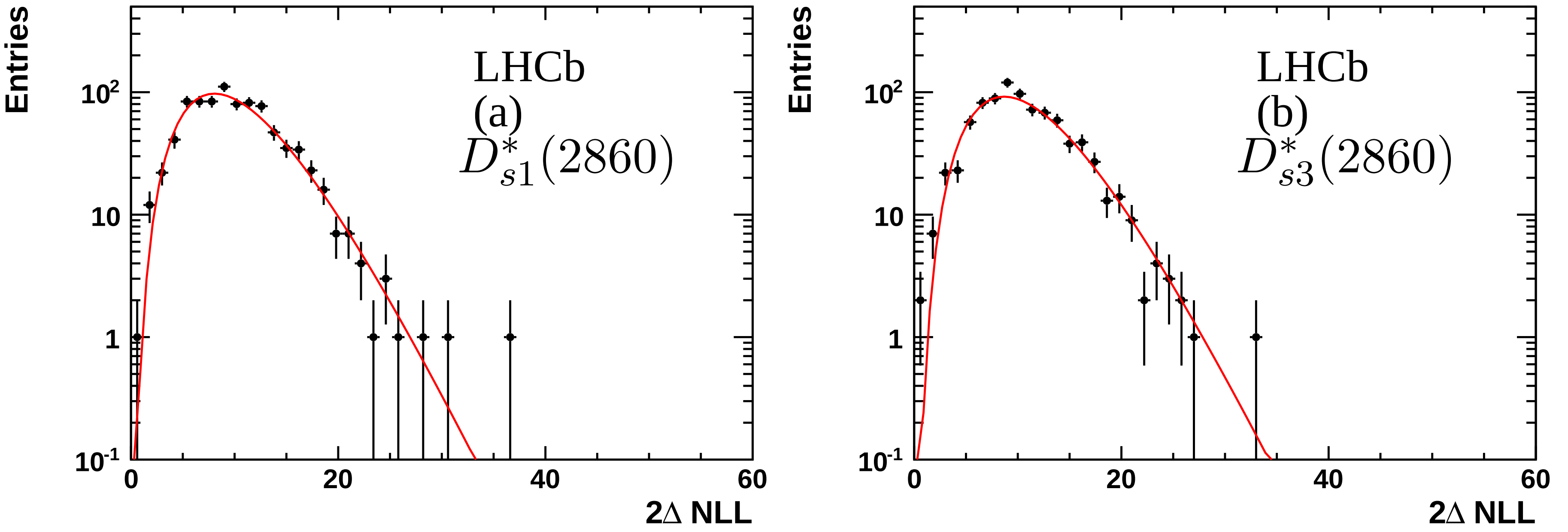
$B^0 \to D^{(*)} \pi\pi$



D_{sJ} spin

- Verify the significance of having two states around 2.86 GeV by simulations
- Generate samples with only single resonance
- Compare likelihood ratios on data to distribution from generated experiments
- In data we have 2ΔNLL of 313.6 and 273

arXiv:1407.7574,arXiv:1407.7712



$B_s \to \overline{D}^0 K^- \pi^+$ BFs

Resonance R	Product branching fraction (10^{-5})	Branching fraction (10^{-4})
$\overline{K}^*(892)^0$	$28.6 \pm 0.6 \pm 0.7 \pm 0.9 \pm 4.2$	$4.29 \pm 0.09 \pm 0.11 \pm 0.14 \pm 0.63$
$\overline{K}^*(1410)^0$	$1.7 \pm 0.5 \pm 0.2 \pm 1.4 \pm 0.2$	$3.86 \pm 1.14 \pm 0.45 \pm 3.18 \pm 0.89$
LASS nonresonant	$13.7 \pm 2.5 \pm 1.5 \pm 4.1 \pm 2.0$	$2.06 \pm 0.38 \pm 0.23 \pm 0.62 \pm 0.30$
$\overline{K}^*_0(1430)^0$	$20.0 \pm 1.6 \pm 0.7 \pm 3.3 \pm 2.9$	$3.00 \pm 0.24 \pm 0.11 \pm 0.50 \pm 0.44$
LASS total	$21.4 \pm 1.4 \pm 1.0 \pm 4.7 \pm 3.1$	$3.21 \pm 0.21 \pm 0.15 \pm 0.71 \pm 0.47$
$\overline{K}^*_2(1430)^0$	$3.7 \pm 0.6 \pm 0.4 \pm 1.1 \pm 0.5$	$1.11 \pm 0.18 \pm 0.12 \pm 0.33 \pm 0.15$
$\overline{K}^*(1680)^0$	$< 2.0\ (2.4)$	$< 0.78\ (0.93)$
$\overline{K}^*_0(1950)^0$	$< 3.7\ (4.1)$	$< 1.1\ (1.2)$
$\overline{K}^*_3(1780)^0$	$< 0.33\ (0.38)$	$< 0.26\ (0.30)$
$\overline{K}^*_4(2045)^0$	$< 0.21\ (0.24)$	$< 0.31\ (0.36)$
$D^*_{s2}(2573)^-$	$25.7 \pm 0.7 \pm 0.8 \pm 1.1 \pm 3.8$	
$D^*_{s1}(2700)^-$	$1.6 \pm 0.4 \pm 0.4 \pm 0.5 \pm 0.2$	
$D^*_{s1}(2860)^-$	$5.0 \pm 1.2 \pm 0.7 \pm 3.3 \pm 0.7$	
$D^*_{s3}(2860)^-$	$2.2 \pm 0.1 \pm 0.3 \pm 0.4 \pm 0.3$	

arXiv:1407.7574,arXiv:1407.7712