Confirmation of the exotic Z(4430)$^-$ resonance at LHCb

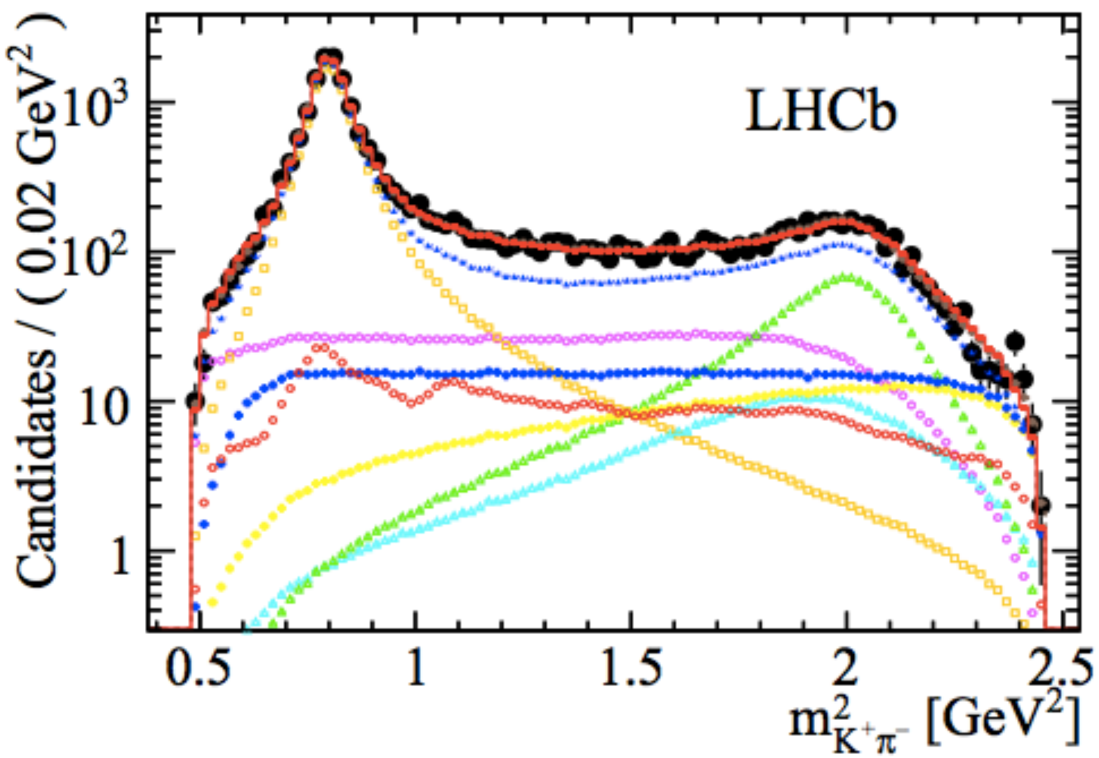
Greig Cowan (Edinburgh)

Edinburgh, 16th May 2014

Overview

1. Exotic spectroscopy: motivation
2. Introduction to the LHCb experiment
3. Reminder of Dalitz plots and amplitude analyses
4. The $Z(4430)^-$
    - History
    - Searching for the $Z(4430)^-$ in $B^0 \rightarrow \psi(2S) K^+ \pi^-$ decays
    - Determining the quantum numbers (J^P)
5. Other exotic spectroscopy results
    - X(3872)
    - The scalar mesons, $f_0(500)$ and $f_0(980)$

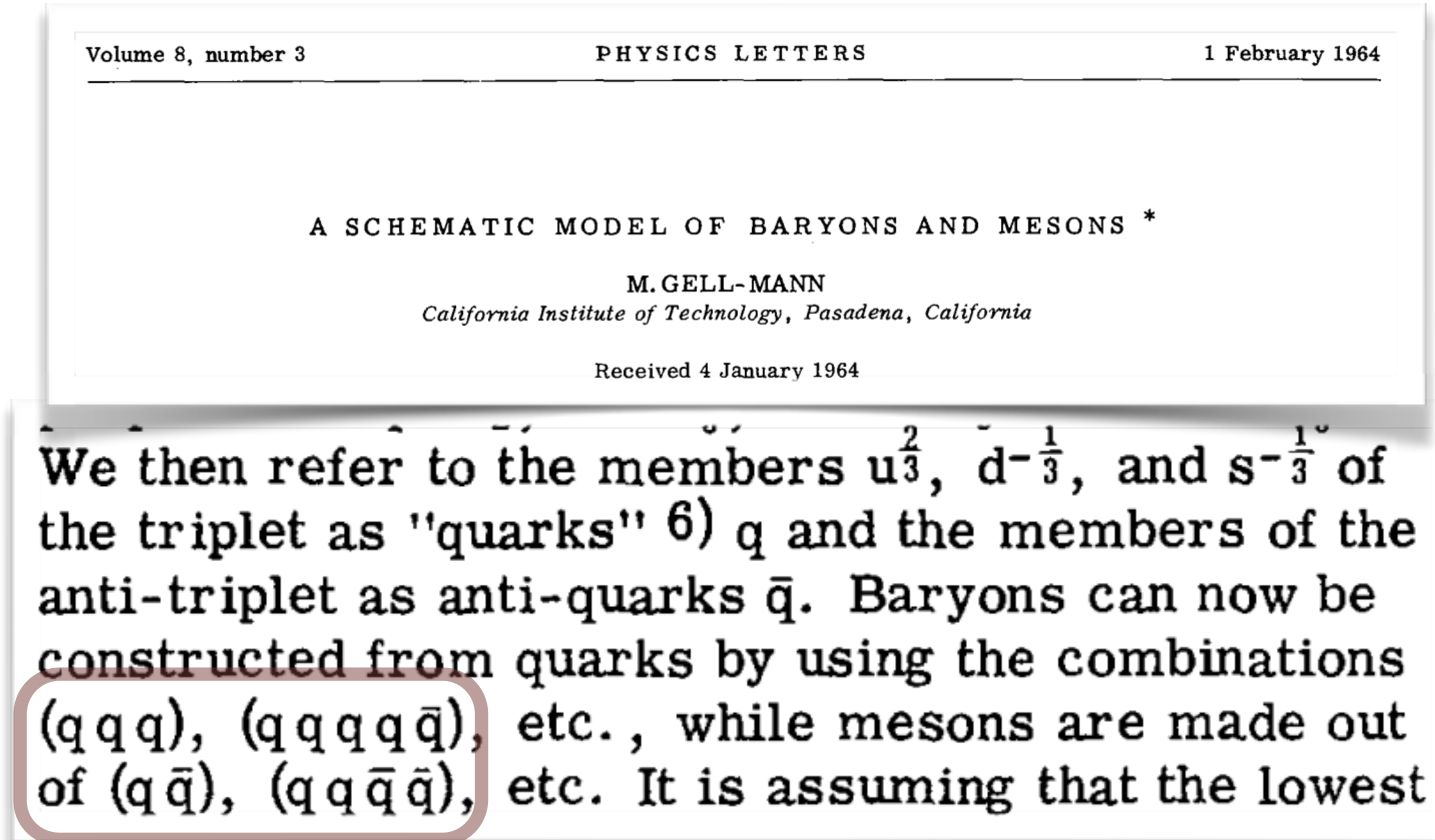
Will give some technical details to explain plots like this



arXiv:1404.1903
accepted by PRL

“Three quarks for Muster Mark!”

- Bound states of quarks to form mesons and baryons were first proposed in 1964 by Gell-Mann and Zweig.
- **$qq\bar{q}\bar{q}$** states are not *a priori* excluded.
- Light quark **spectroscopy** used to understand structure of these states.
  - Difficult due to wide overlapping states, background.
  - Highly relativistic constituents (u, d and s quarks).
- What about heavier quarks?

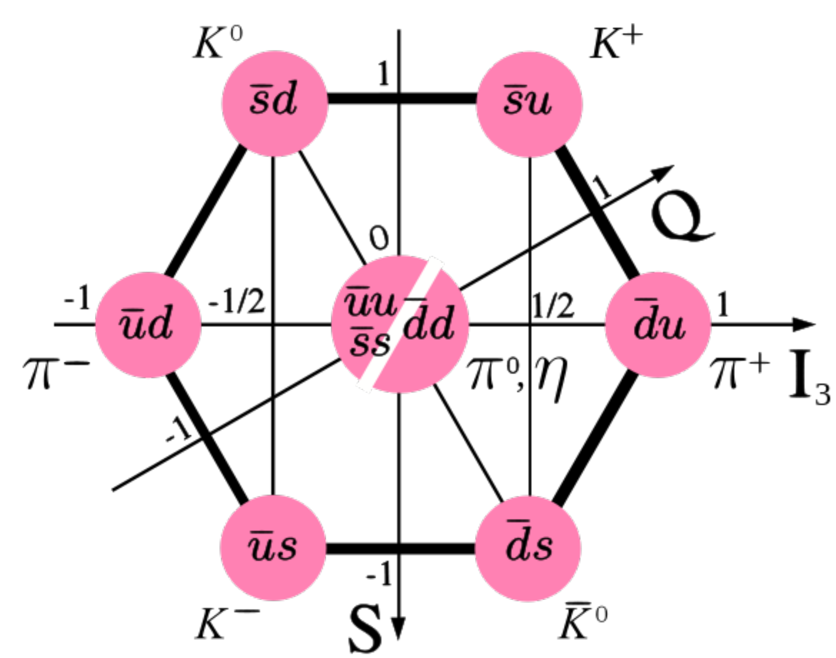

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest



Charmonium spectroscopy ($c\bar{c}$)

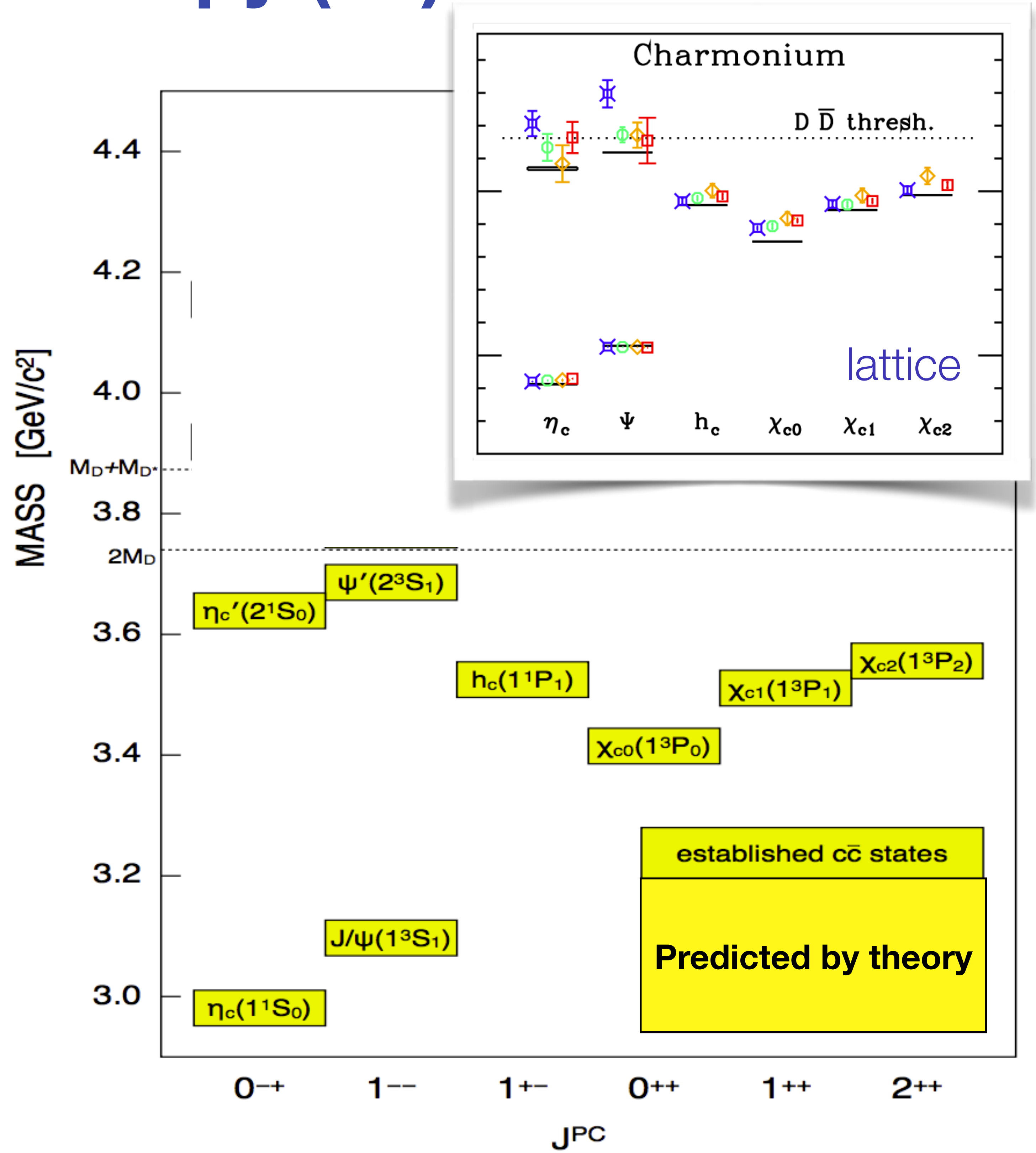
- Simpler system to analyse since **c** quark is heavier
    - non-relativistic calculations
        - potential models
        - lattice QCD
    - narrow, non-overlapping states below **$D\bar{D}$** threshold
    - no mixing of **$c\bar{c}$** with lighter **$q\bar{q}$** states.

Classify using J^{PC}

$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

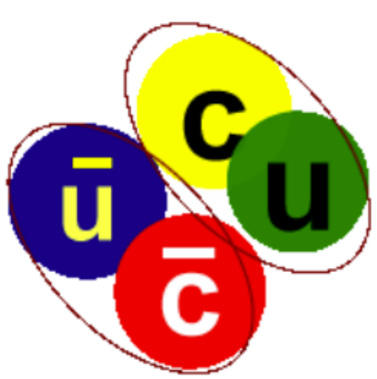


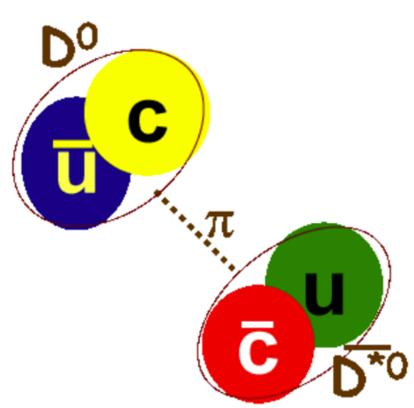
Phys. Rev. D 81, 034508

Olsen arXiv:1403.1254

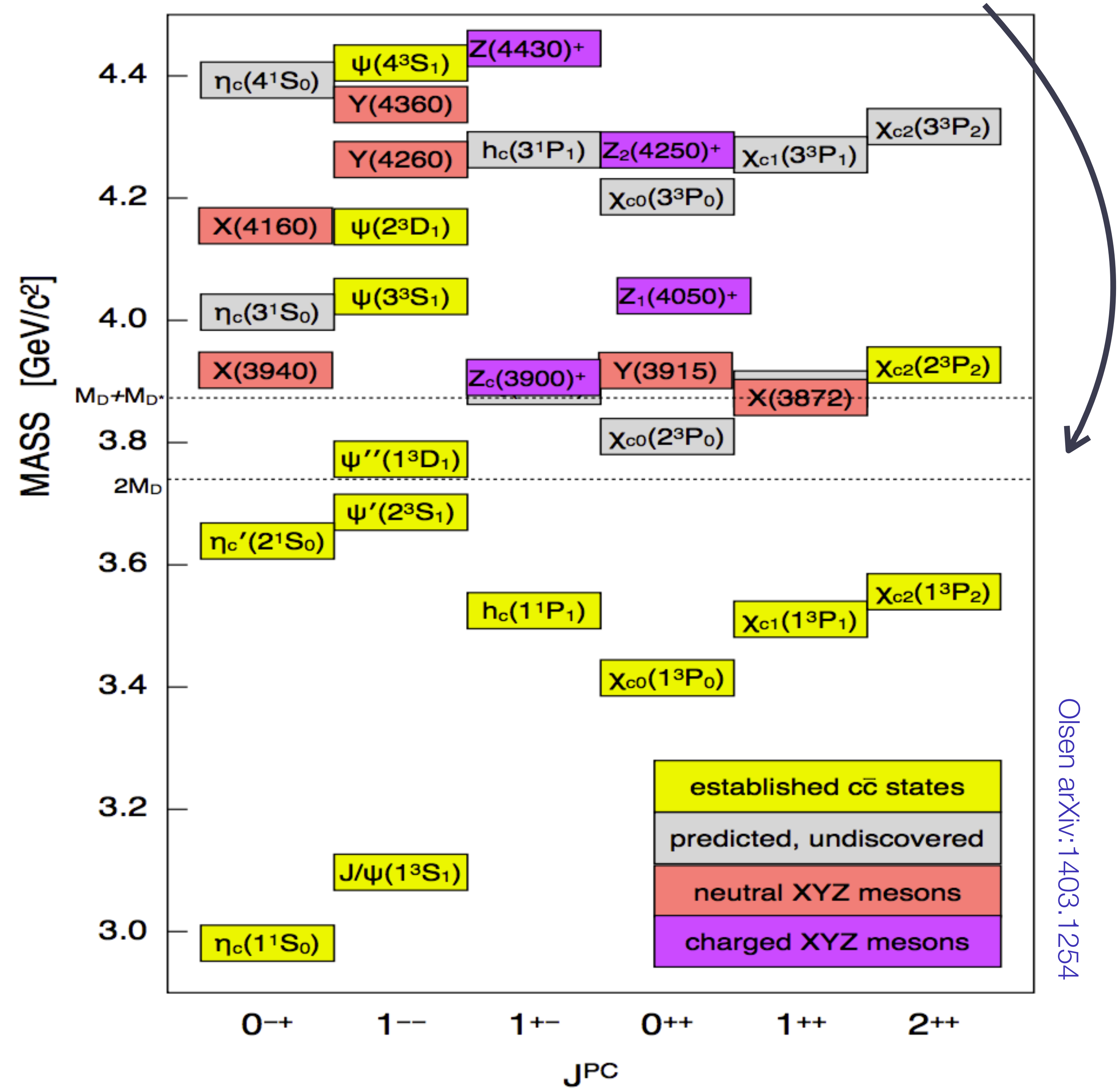
Exotic charmonium spectroscopy

- Many different exotic **(XYZ)** states have been seen.
  - BESIII, Belle/BaBar, CDF/D0
  - mass/width, decay, J^{PC}
- Are these [**qq**][**$\bar{q}\bar{q}$**] (tetraquarks), mesonic molecules, threshold effects, hybrids…?
- No clear pattern: need experimental and theoretical study to understand strong interaction dynamics that can cause their production and structure.





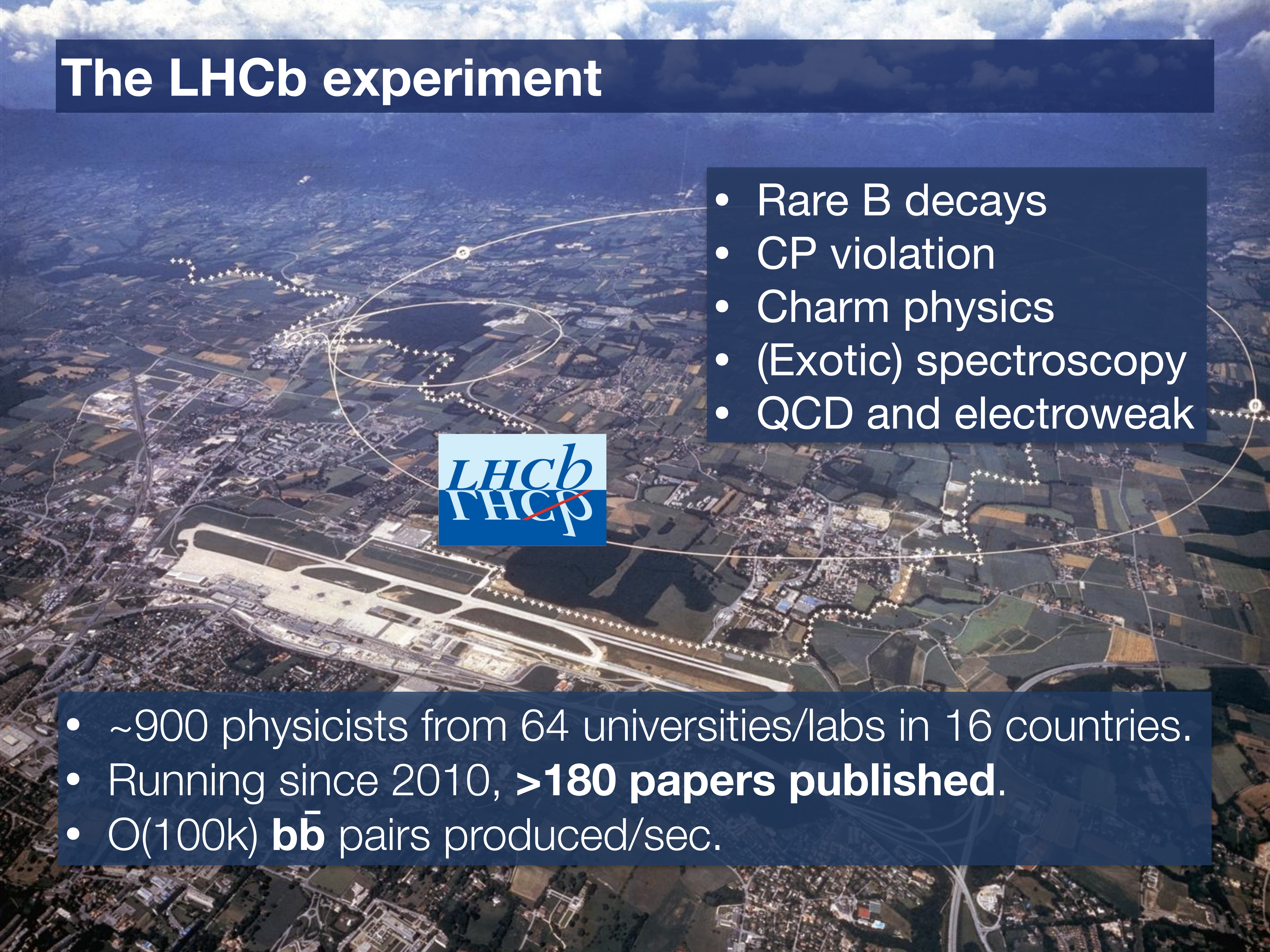
Thresholds



Olsen arXiv:1403.1254

Godfrey, Olsen, Ann.Rev.Nucl.Part.Sci.58:51-73,2008

The LHCb experiment

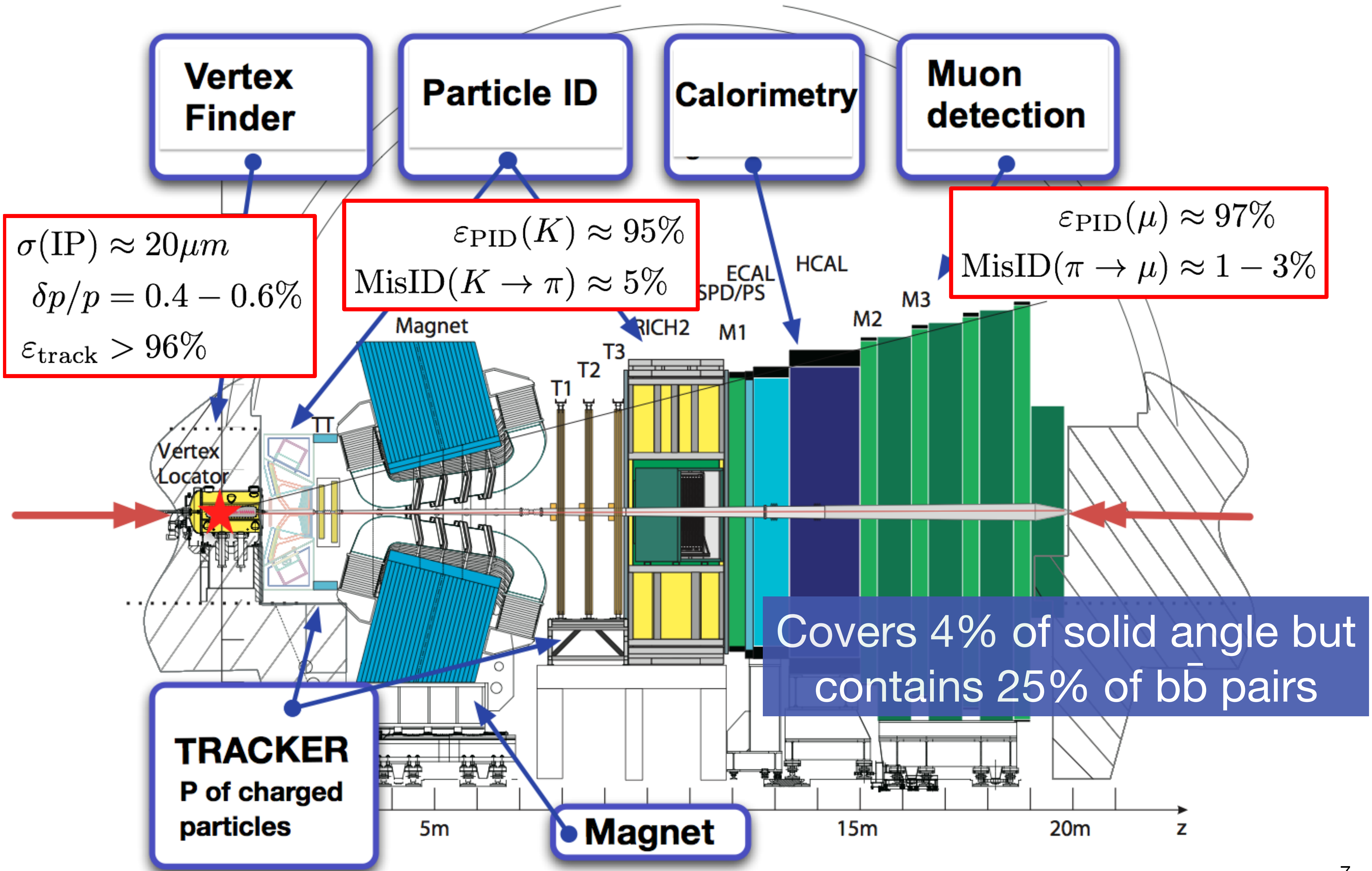


- Rare B decays
- CP violation
- Charm physics
- (Exotic) spectroscopy
- QCD and electroweak

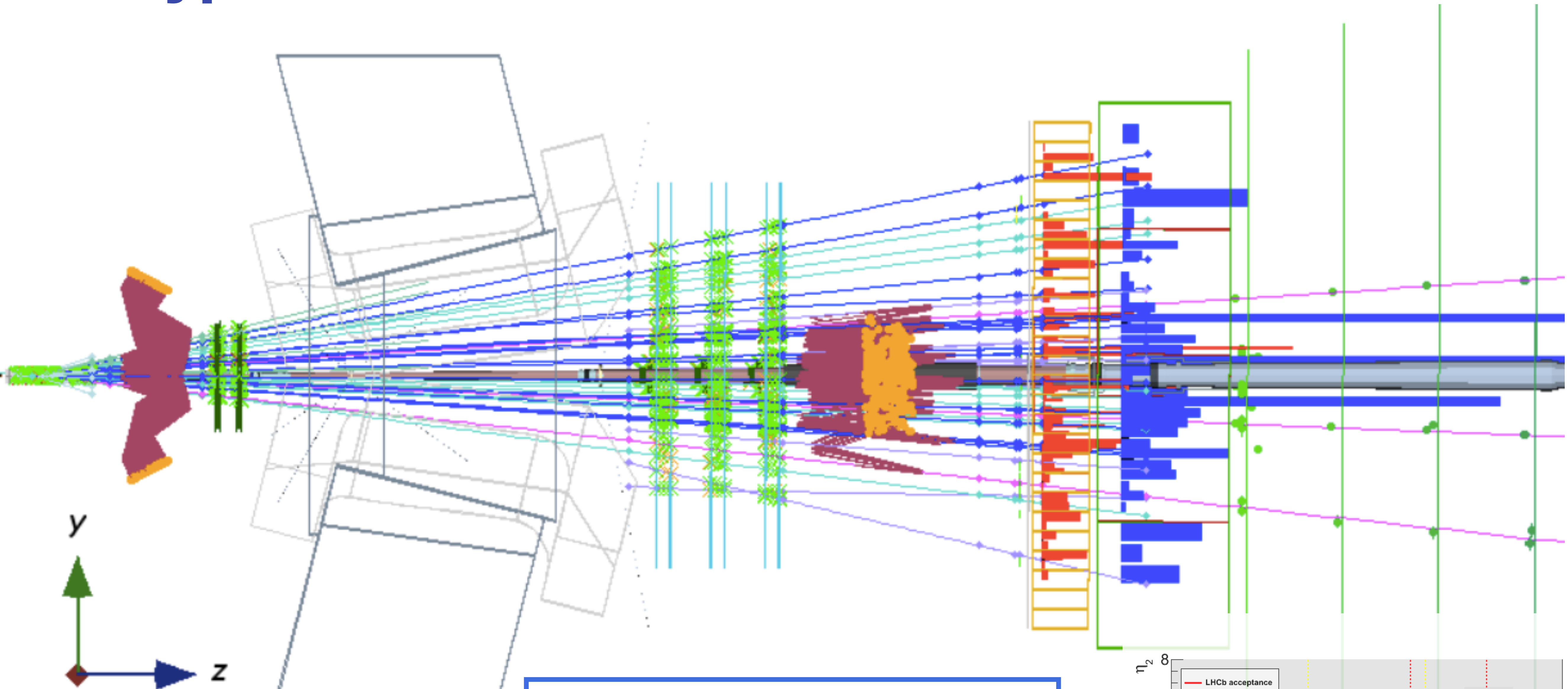
- ~900 physicists from 64 universities/labs in 16 countries.
- Running since 2010, **>180 papers published**.
- O(100k) $\mathbf{b\bar{b}}$ pairs produced/sec.

The LHCb detector

2008 JINST 3 S08005

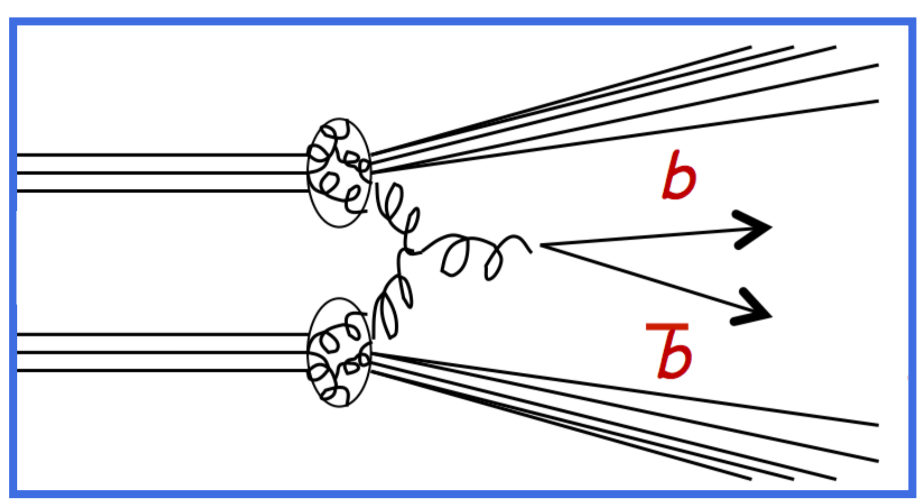


A typical LHCb event

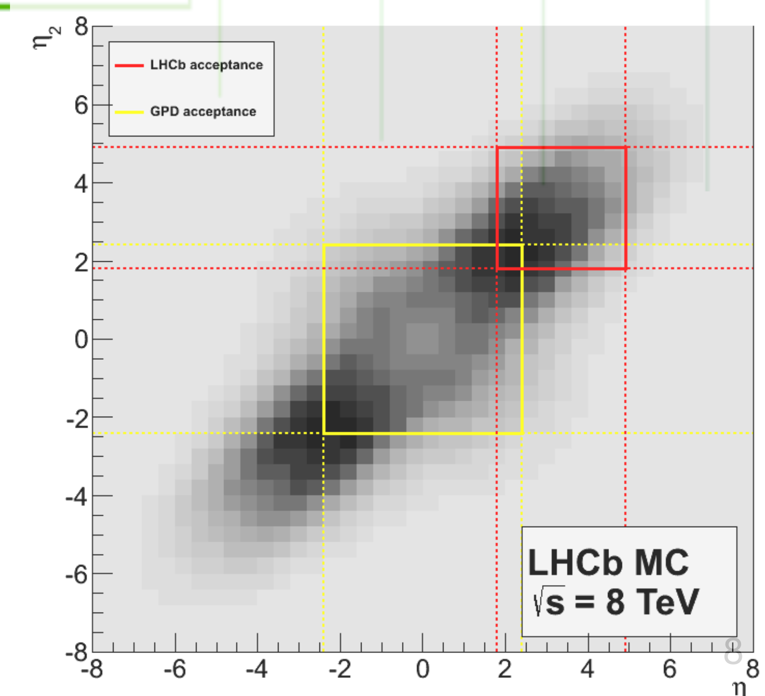


$$\langle nPVs \rangle \sim 2.0$$
$$\langle nTracks \rangle \sim 200$$

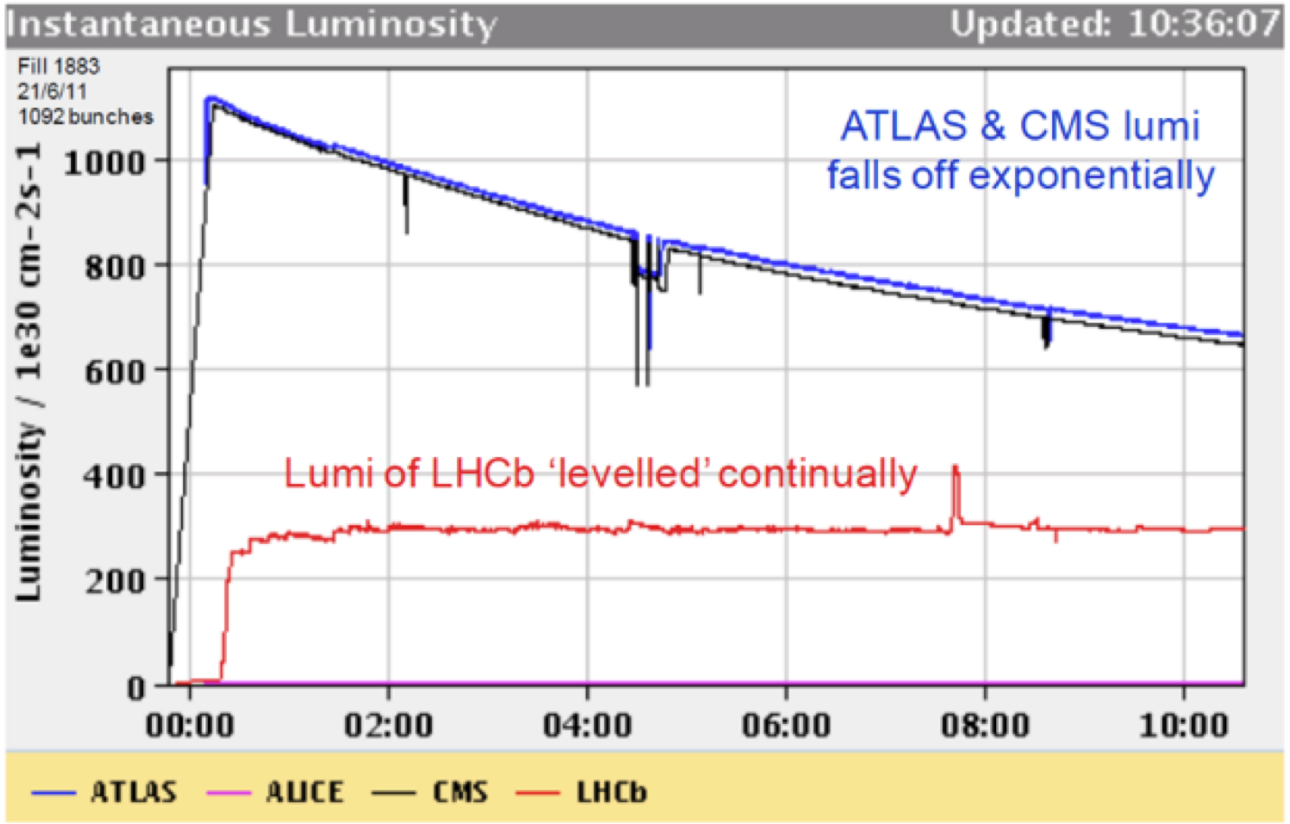
$$\sigma(p\bar{p} \to b\bar{b}X) \sim 80\mu b$$
$$\sigma(c\bar{c}) \quad \sim 1500\mu b$$

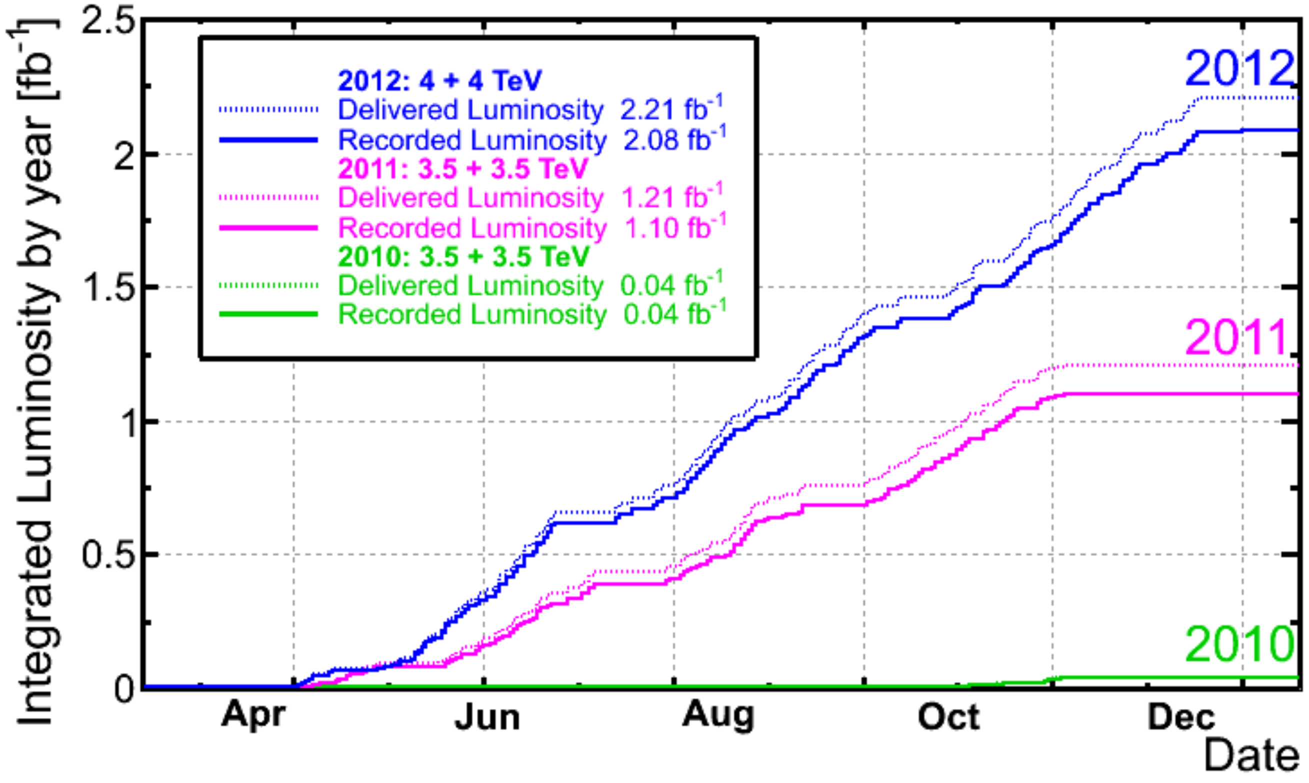


B hadrons fly ~1cm in the detector



Luminosity





- LHCb designed to run at lower luminosity than ATLAS/CMS.
  - LHCb tracking is sensitive to pile-up.
- LHC pp beams are displaced to reduce instantaneous luminosity.
  - Stable running conditions.

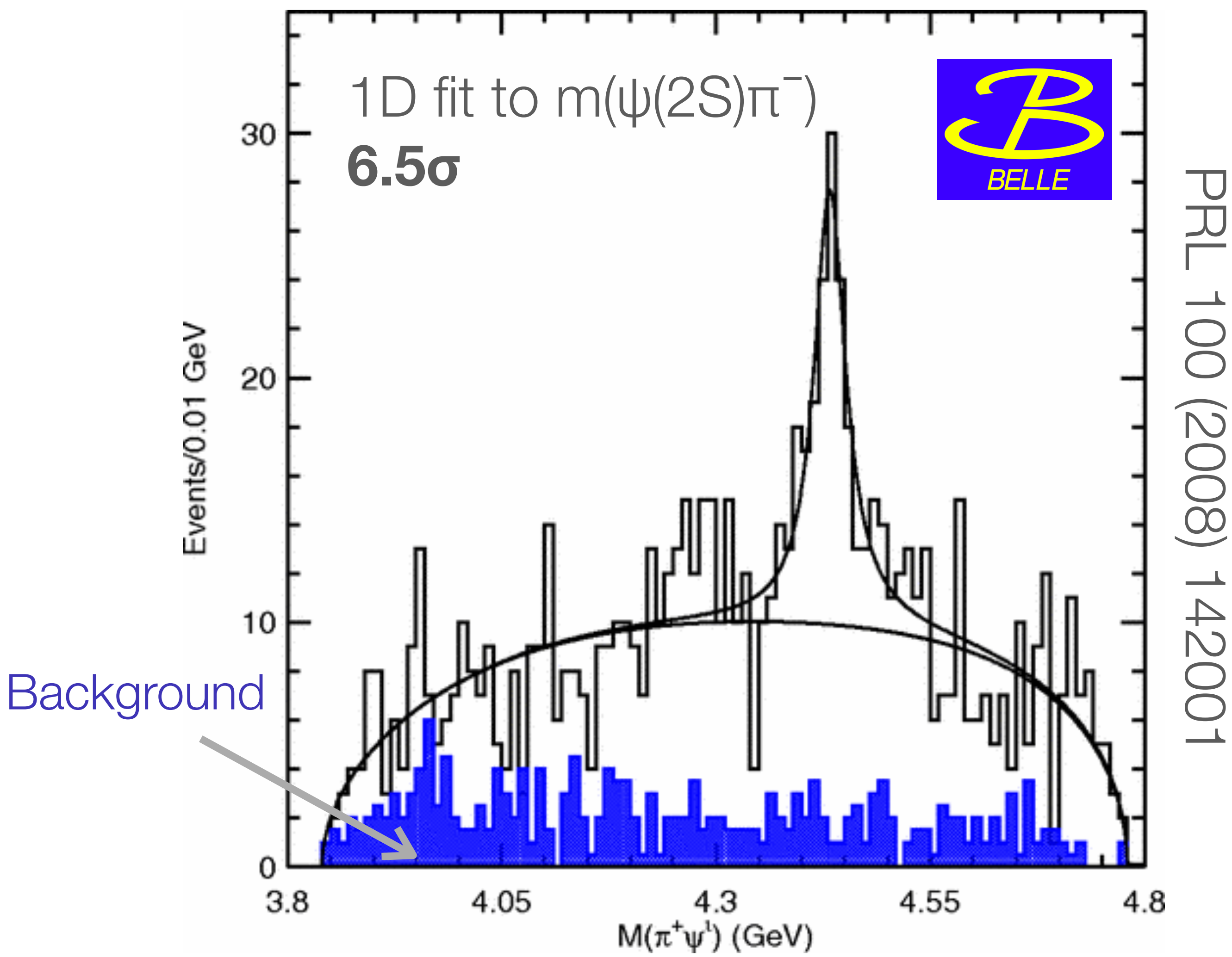
$\langle L \rangle_{2011} = 2.7\times10^{32}$ Hz/cm^2 $\langle L \rangle_{2012} = 4.0\times10^{32}$ Hz/cm^2

History of the Z(4430)$^-$

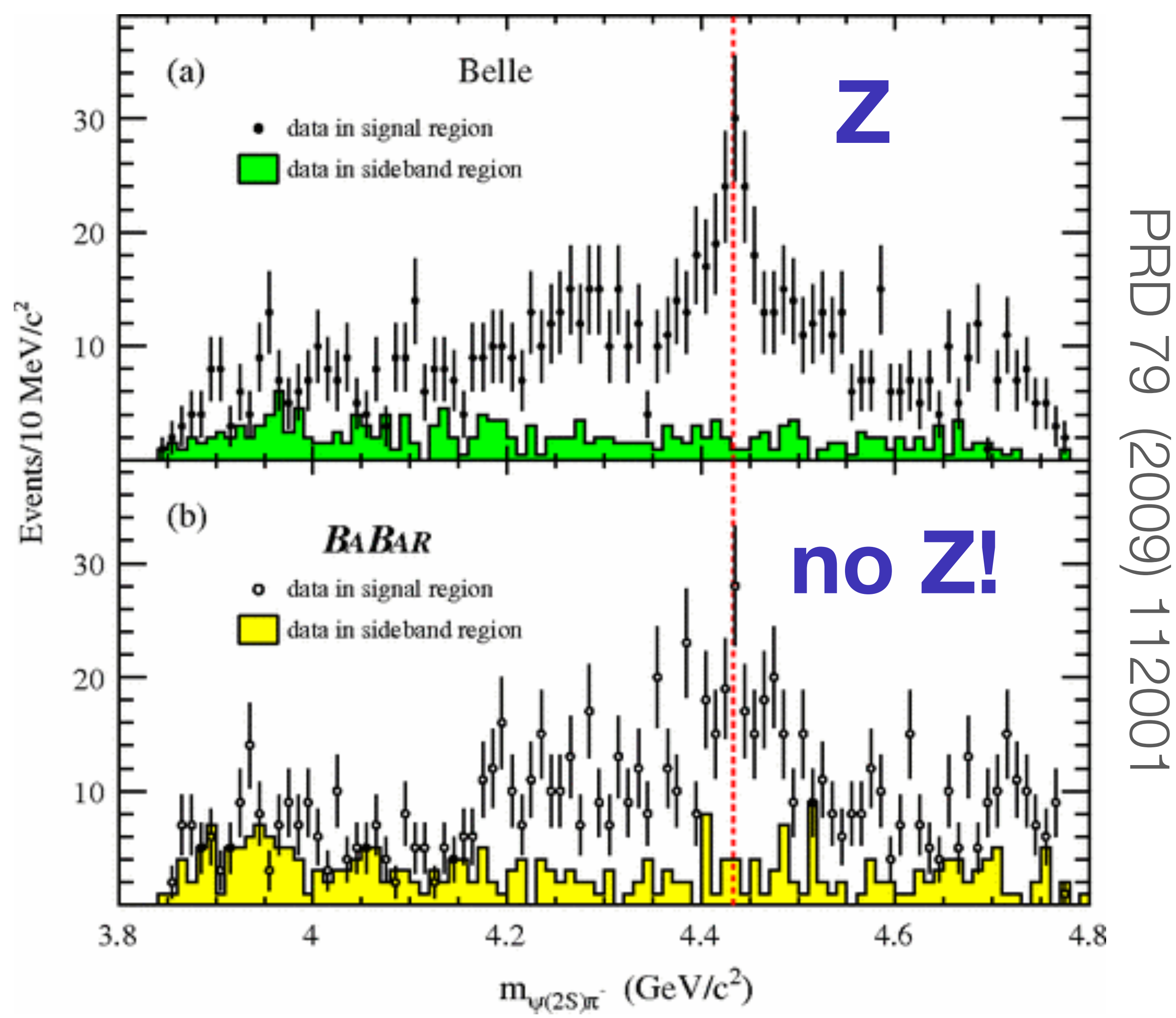
- Belle observed Z(4430)$^-$ from sample of ~2k $B^0 \longrightarrow \psi(2S)K^{+,0}\pi^-$
- Charged state ⇒ minimal quark content of **$c\bar{c}u\bar{d}$**

$B^0 \longrightarrow \psi(2S)K^{+,0}\pi^-$, with $\psi(2S) \to \mu^+\mu^-, J/\Psi\pi^+\pi^-$

$B^0 \longrightarrow Z(4430)^- K^{+,0}$, with $Z(4430)^- \to \psi(2S)\pi^-$, $\psi(2S) \to \mu^+\mu^-, J/\Psi\pi^+\pi^-$



$$M = 4433 \pm 4 \pm 2\ \mathrm{MeV}/c^2$$
$$\Gamma = 45^{+18+30}_{-13-13}\ \mathrm{MeV}/c^2$$

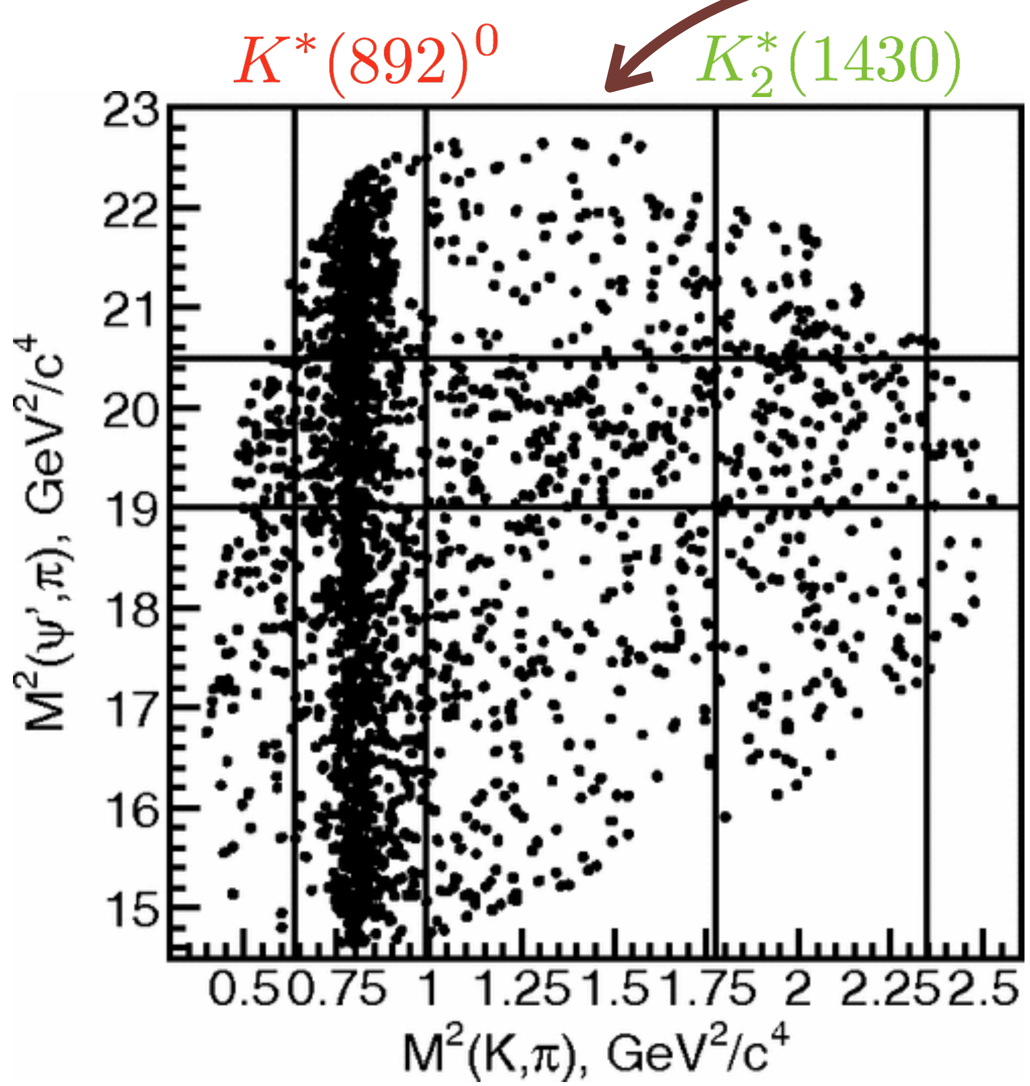


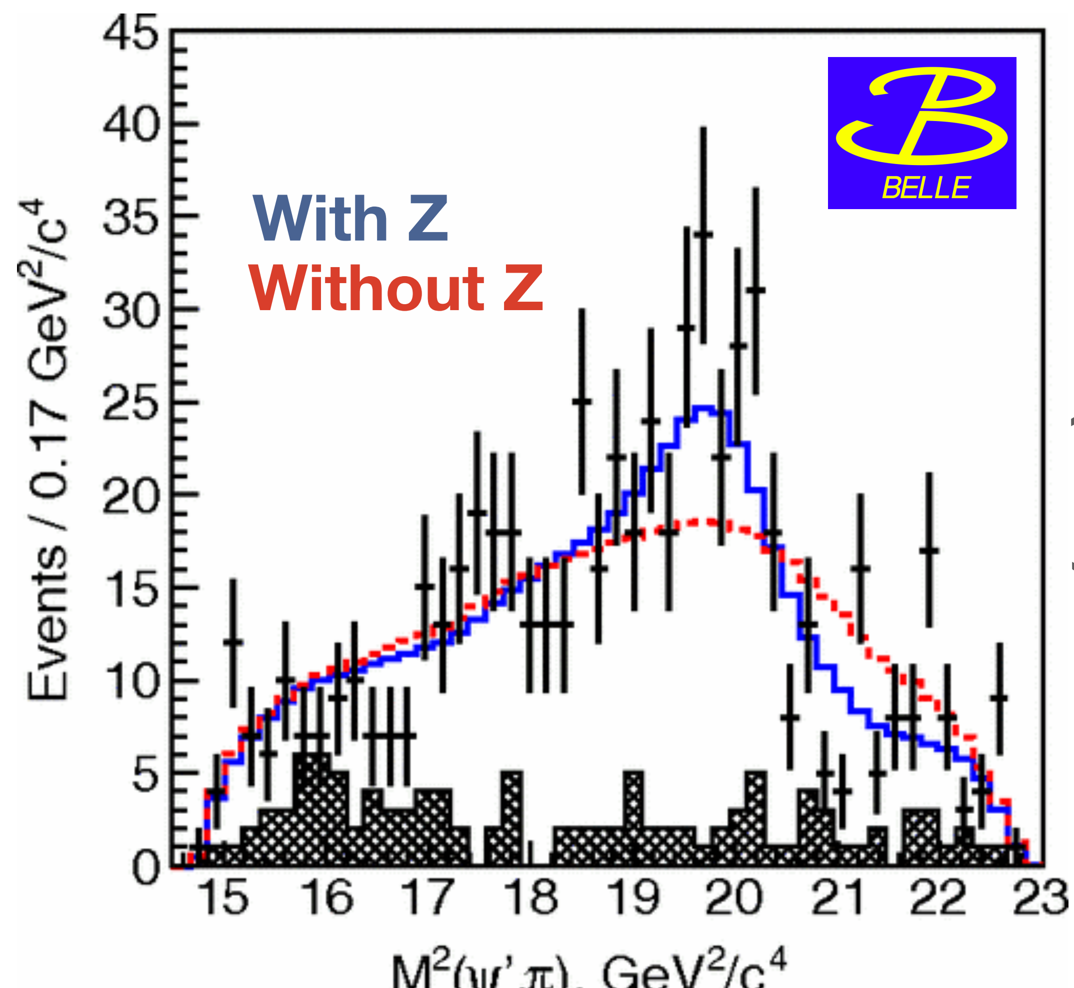
Not observed by BaBar!

History of the Z(4430)$^-$

- Belle **PRL 100 (2008) 142001** 1D fit to m(ψ(2S)π$^-$) **6.5σ**
- BaBar **PRD 79 (2009) 112001** **Not observed!**
- Belle **PRD 80 (2009) 031104** 2D Dalitz fit to m(ψ(2S)π$^-$) vs m(K$^+$π$^-$) **6.4σ**
- Belle **PRD 88 (2013) 074026** 4D Dalitz fit **6.4σ**

K* veto region

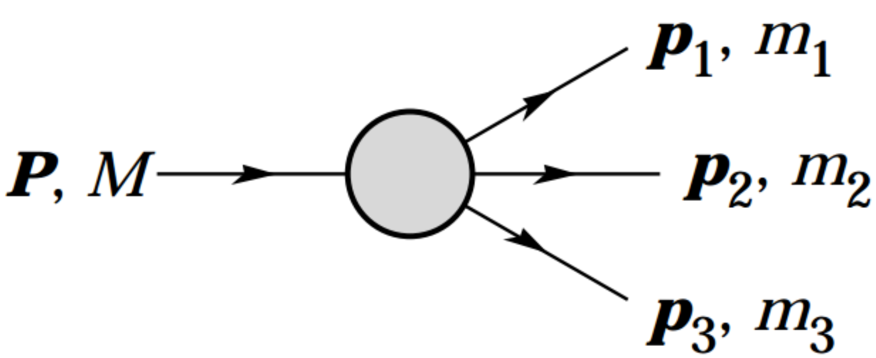




PRD 88 (2013) 074026

$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV/c^2} \qquad \Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}/c^2$$

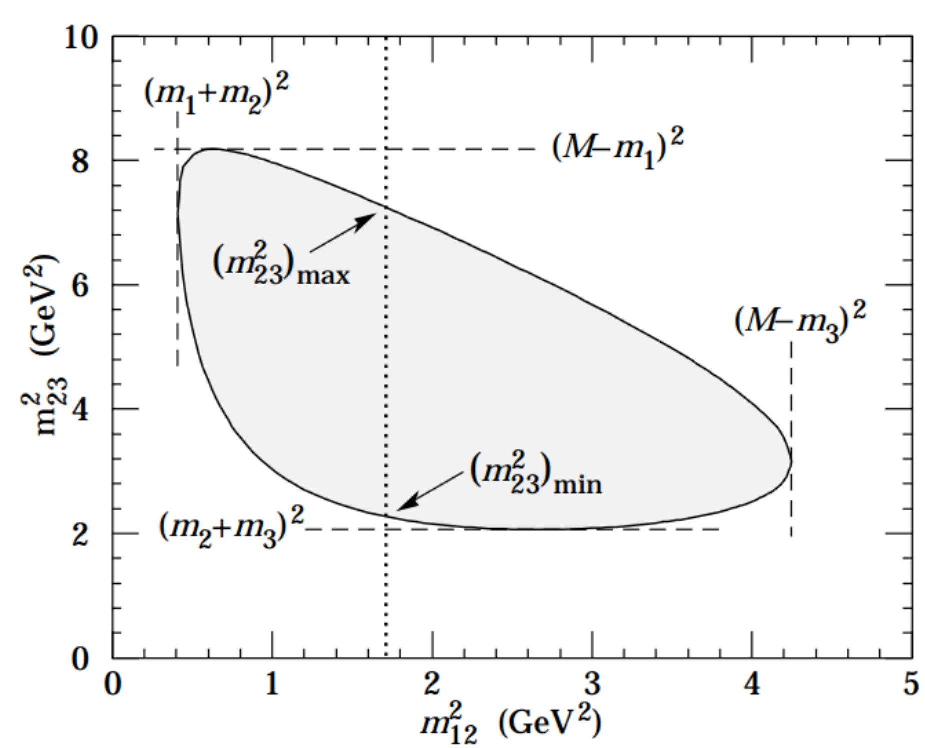
Reminder about Dalitz plots - 3 body decay



Constraints	Degrees of freedom
3 four-vectors	+12
All decay in same plane (p	-3
E	-3
Energy + momentum conservation	-3
Rotate system in plane	-1
Total	**+2**

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\, dm_{12}^2\, dm_{23}^2$$

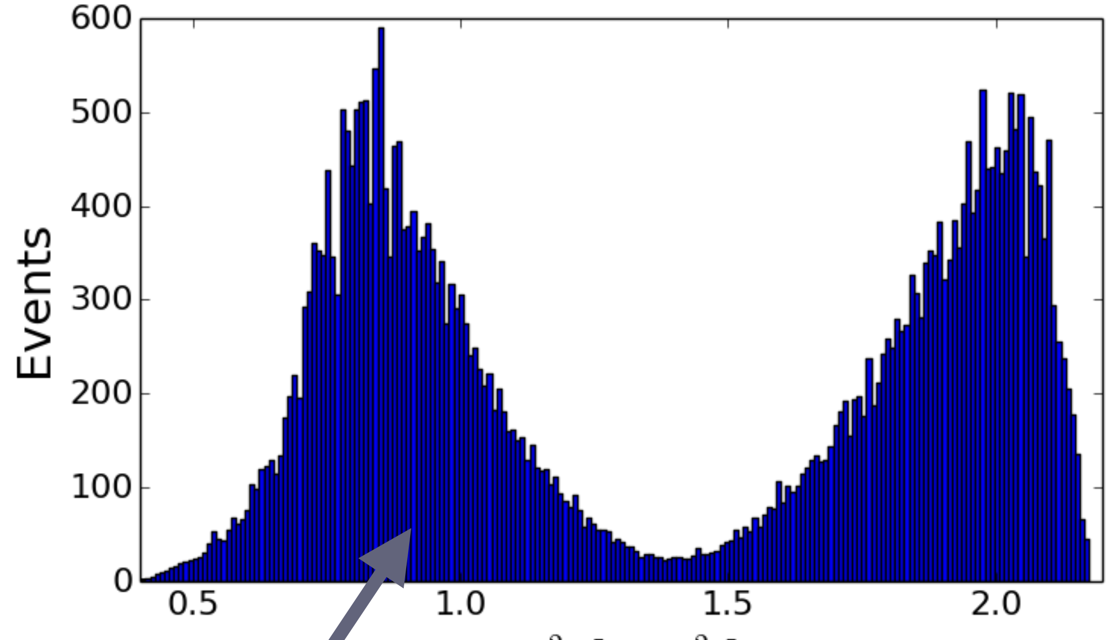
- Configuration of decay depends on ang. mom. of decay products.
- All dynamical information contained in $|\mathcal{M}|^2$.
- Density plot of m_{12}^2 vs. m_{23}^2 to infer information on $|\mathcal{M}|^2$.

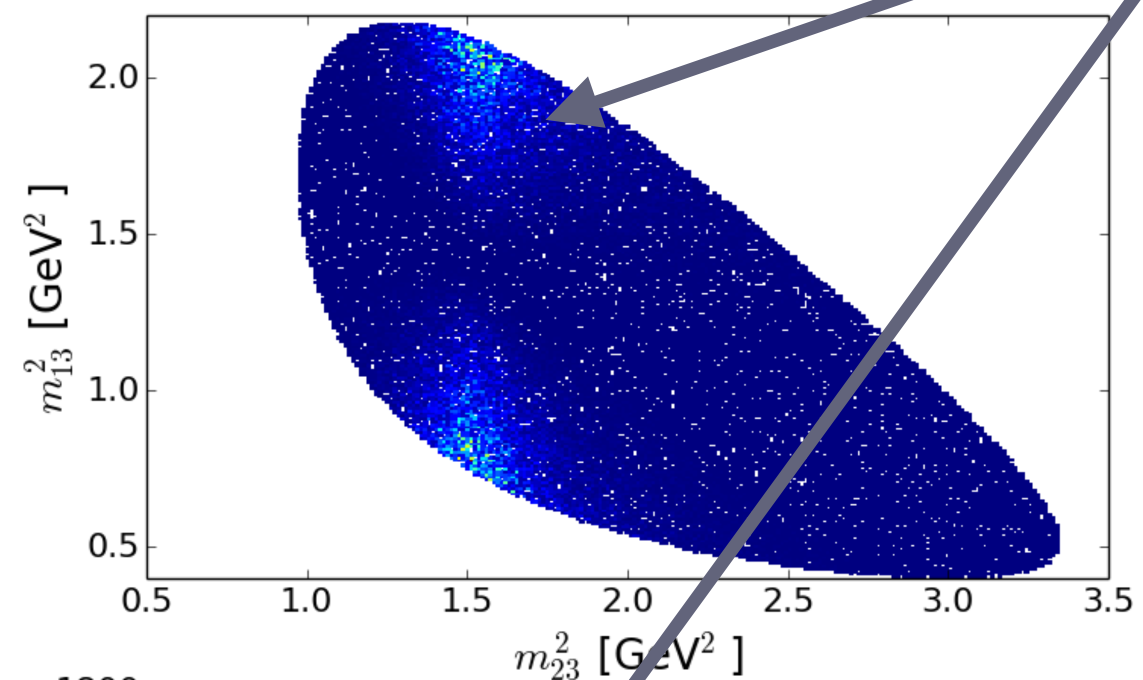


Reminder about Dalitz plots

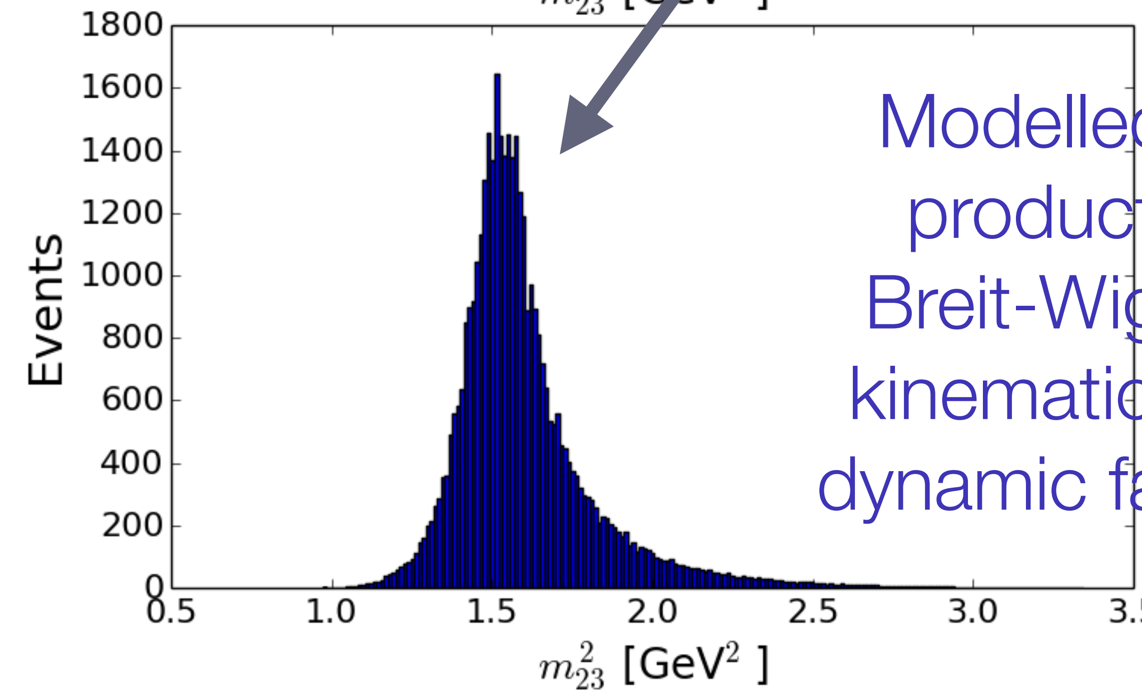
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\,dm_{12}^2\,dm_{23}^2$$

Spin-1 resonance

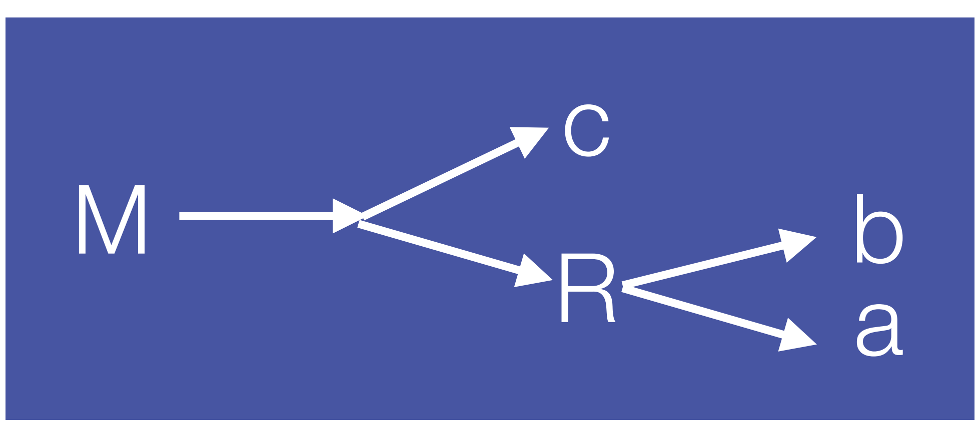




Peaks in distribution
do not correspond to a
real resonance - just a reflection



Modelled as
product of
Breit-Wigner,
kinematic and
dynamic factors



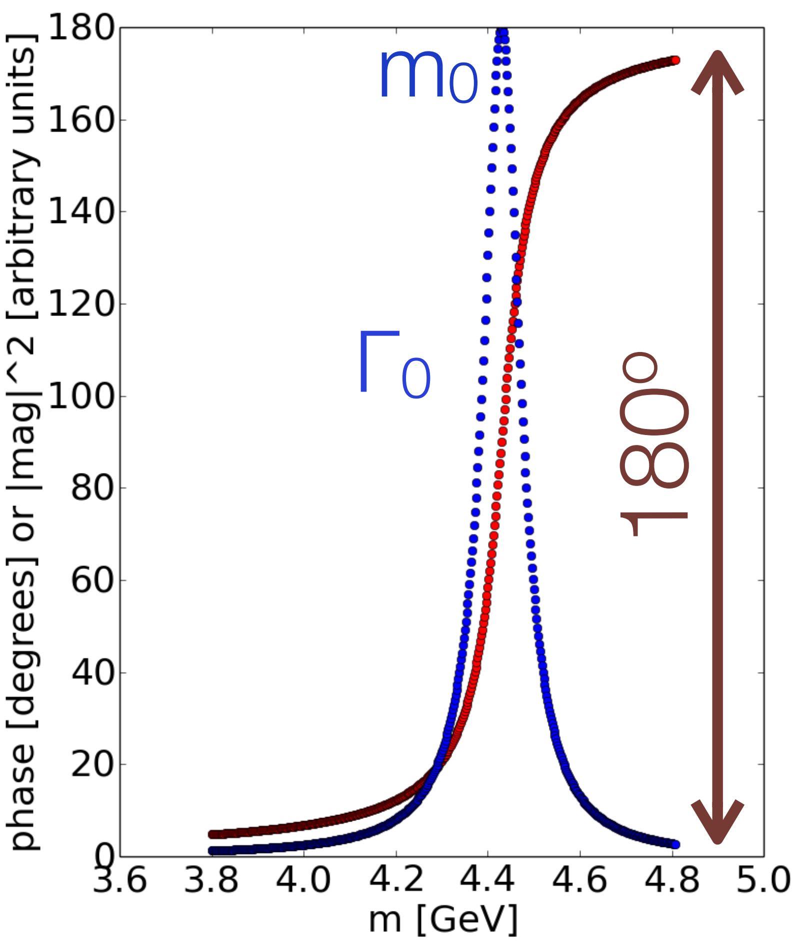
Breit-Wigner amplitude

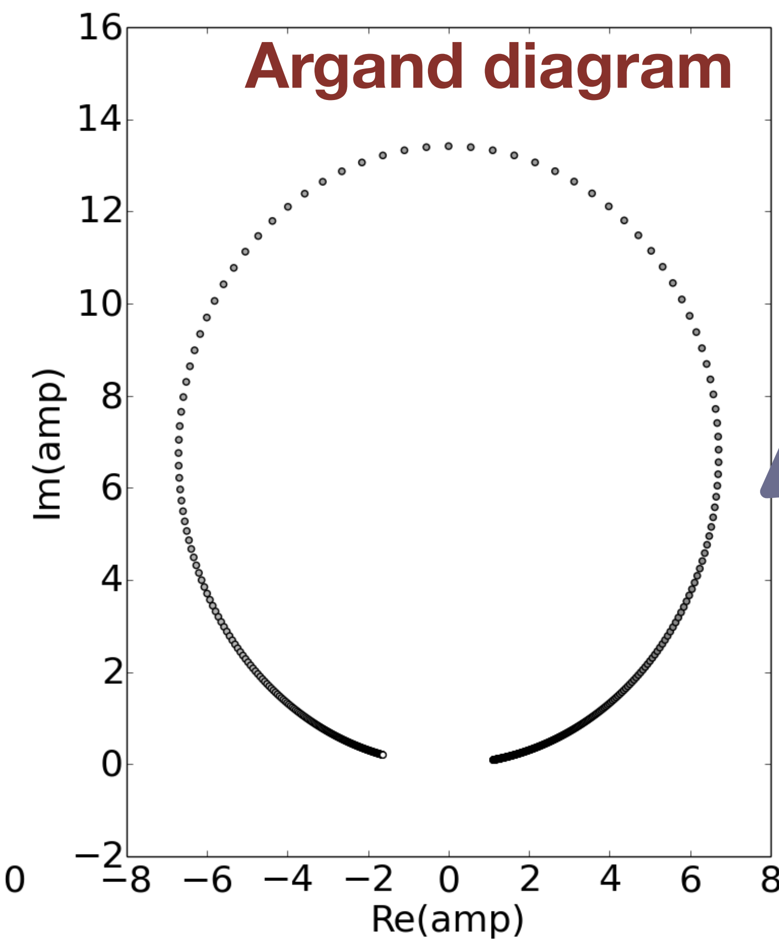
R⟶ab

- Often model resonances with mass (m_0), width (Γ_0) using a relativistic Breit-Wigner function.
- q is daughter particle momentum in rest frame of resonance.
- B_L' are Blatt-Weisskopf functions for the orbital angular momentum (L) barrier factors.
- Amplitude = $|BW|^2$

$$BW(m|m_0,\Gamma_0) = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma(m)}$$

$$\Gamma(m) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2L_{K^*}+1} \frac{m_0}{m} B'_{L_{K^*}}(q,q_0,d)^2$$



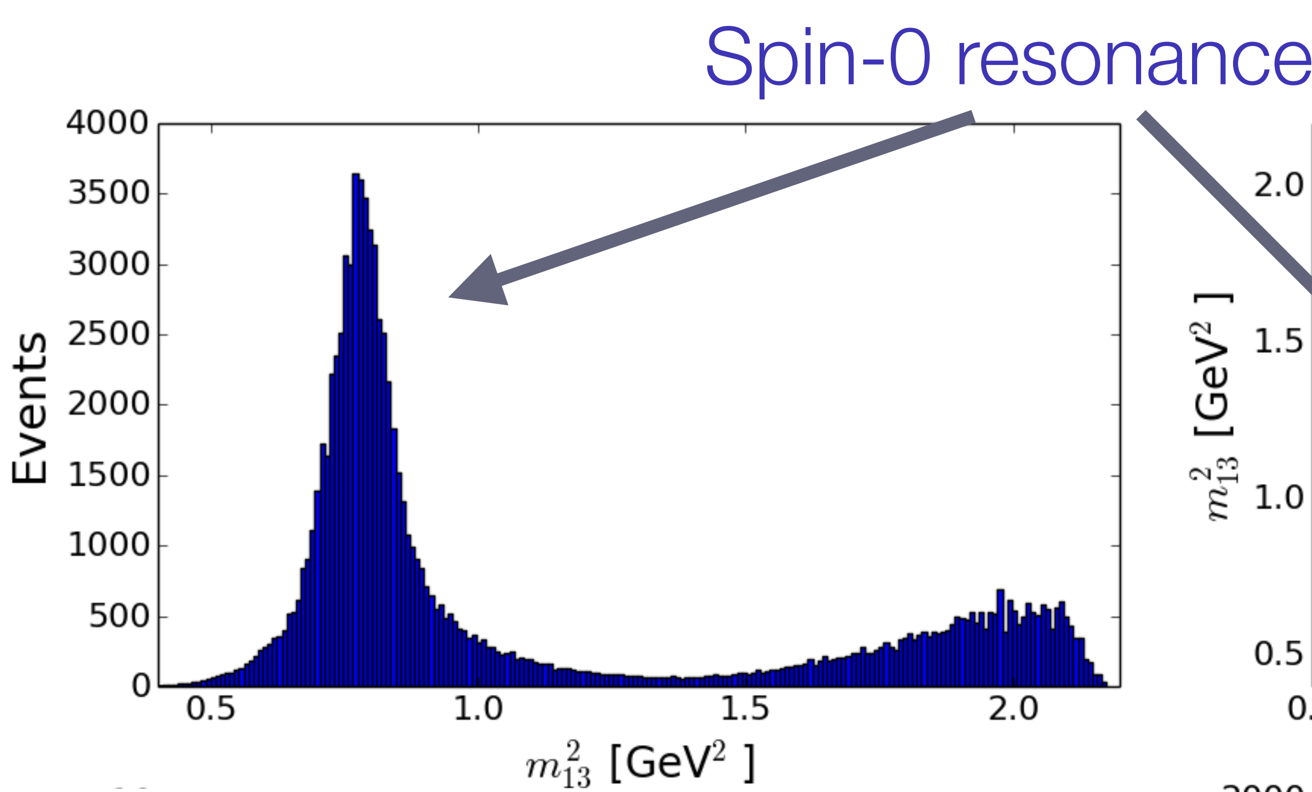


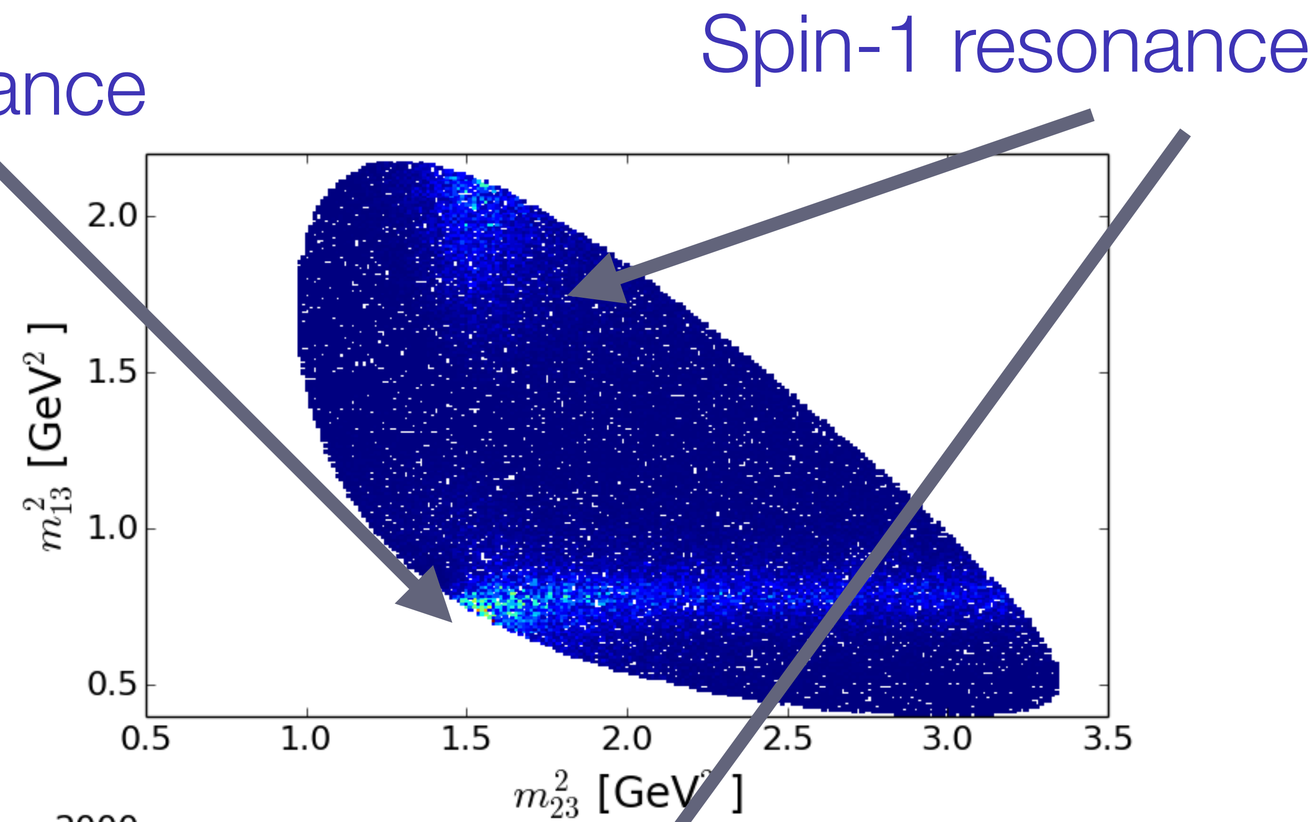
Circular trajectory in complex plane is characteristic of resonance

Phase change of 180º across the pole

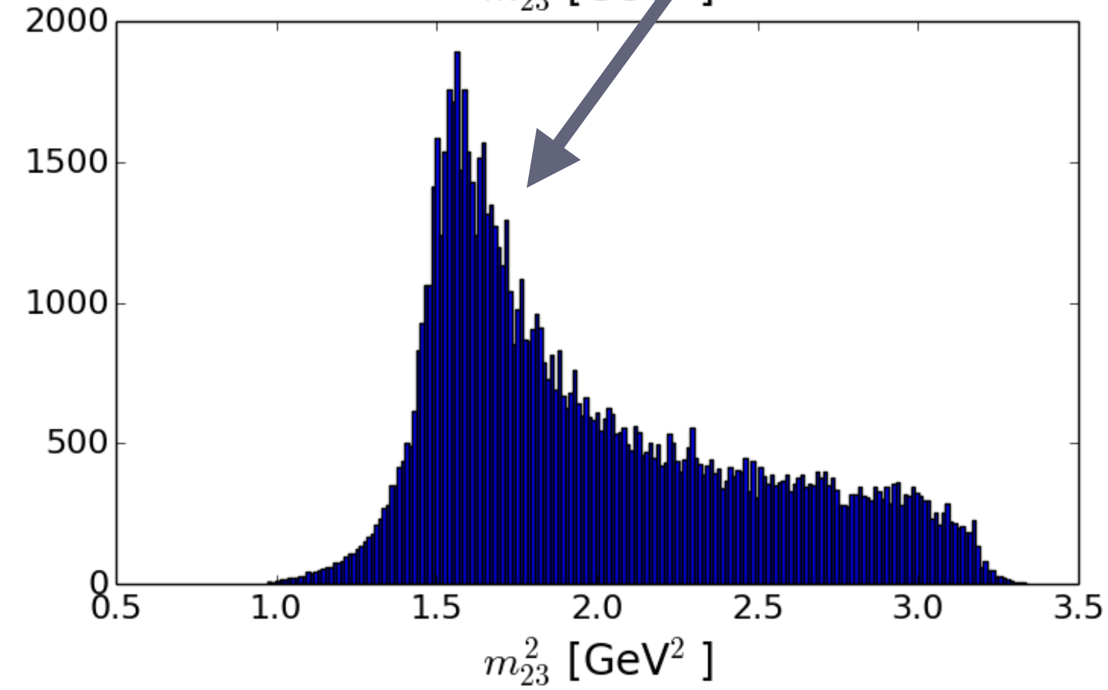
Reminder about Dalitz plots

$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\,dm_{12}^2\,dm_{23}^2$$





Use a **model** to disentangle interfering resonances and determine their properties

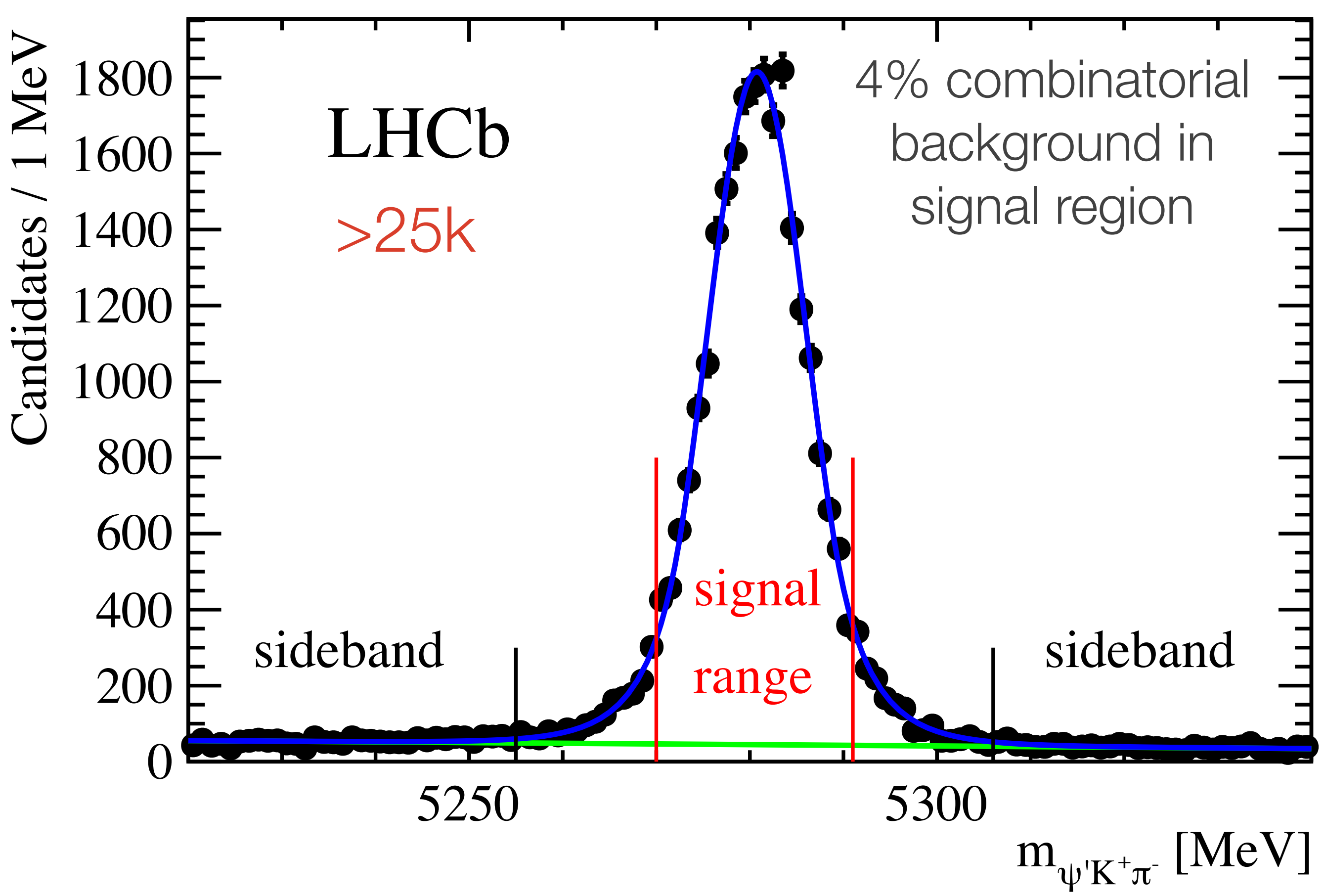


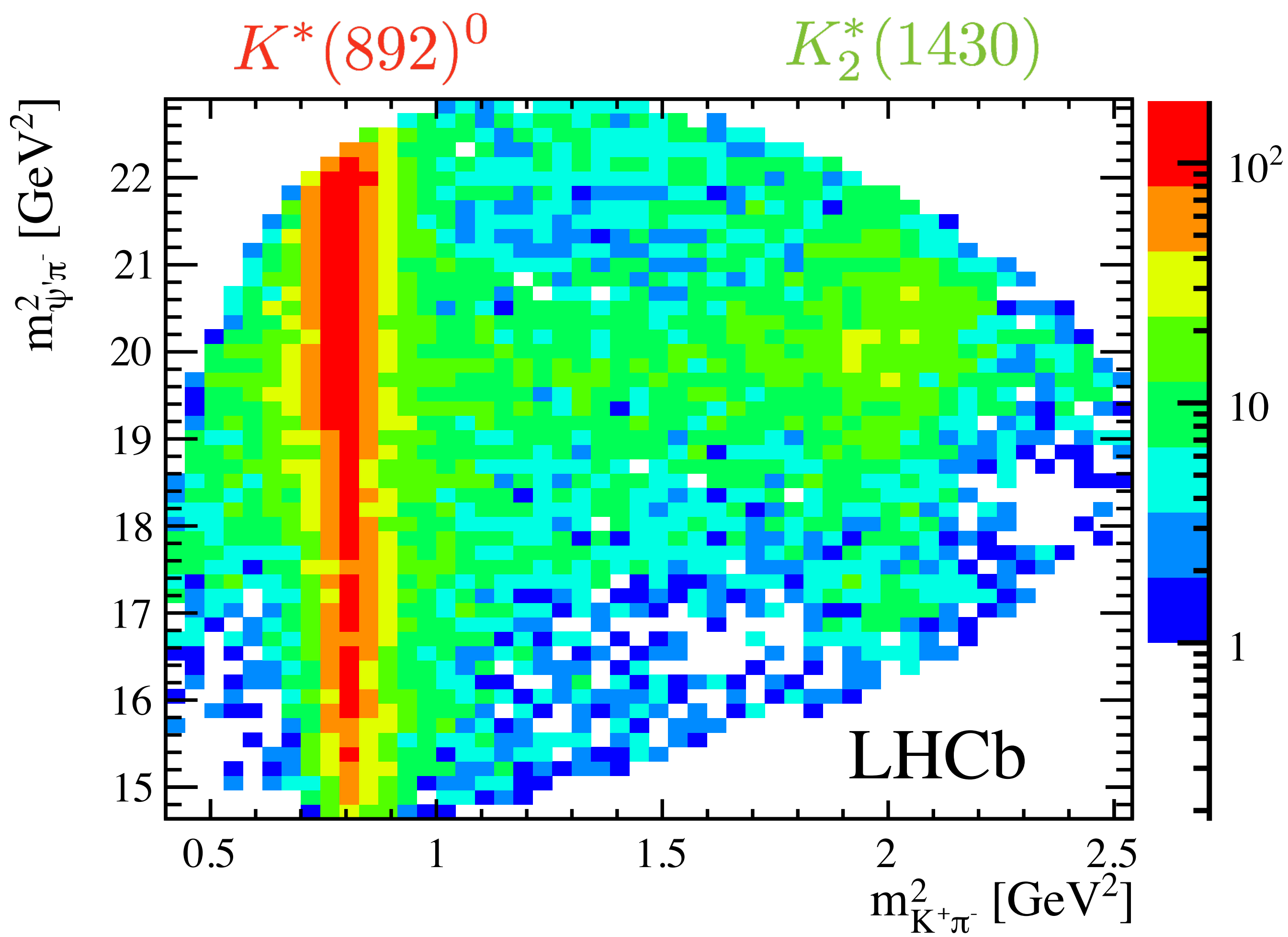
Confirmation of the Z(4430)$^-$

arXiv:1404.1903
accepted by PRL

- LHCb has sample of >25k $B^0 \longrightarrow \psi(2S)K^+\pi^-$ candidates.
  - Factor 10 more than Belle/BaBar.
- Selection: most events come through dimuon trigger (eff~90%)
- Typical B pT ~6GeV, μ pT ~ 2GeV, K pT ~1GeV
- Use sidebands to build 4D model of combinatorial background.
  - Backgrounds from mis-ID physics decays is small - excellent LHCb PID!

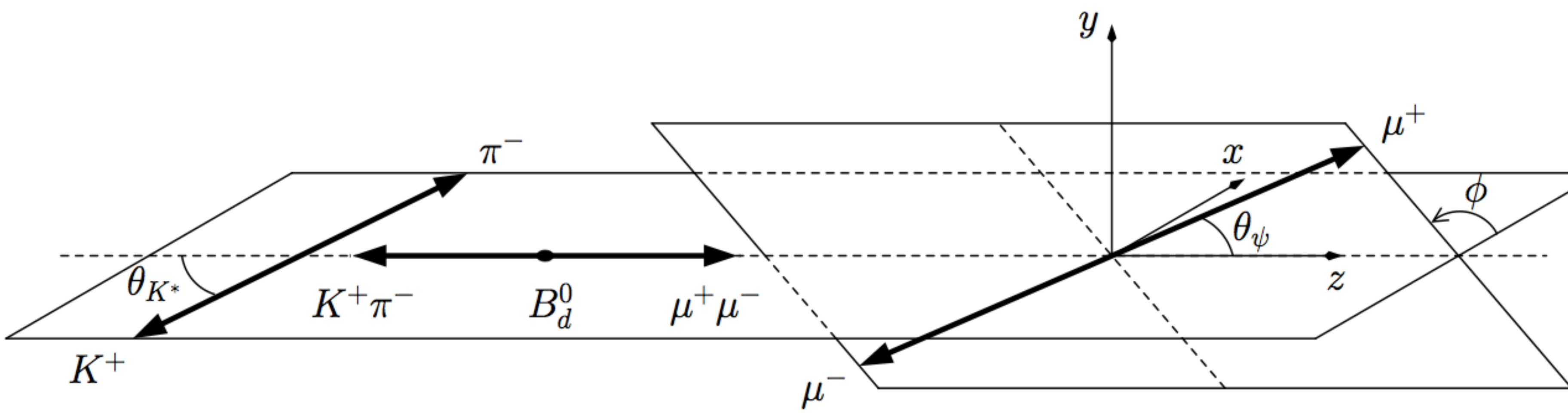
$\psi(2S) \longrightarrow \mu^+\mu^-$





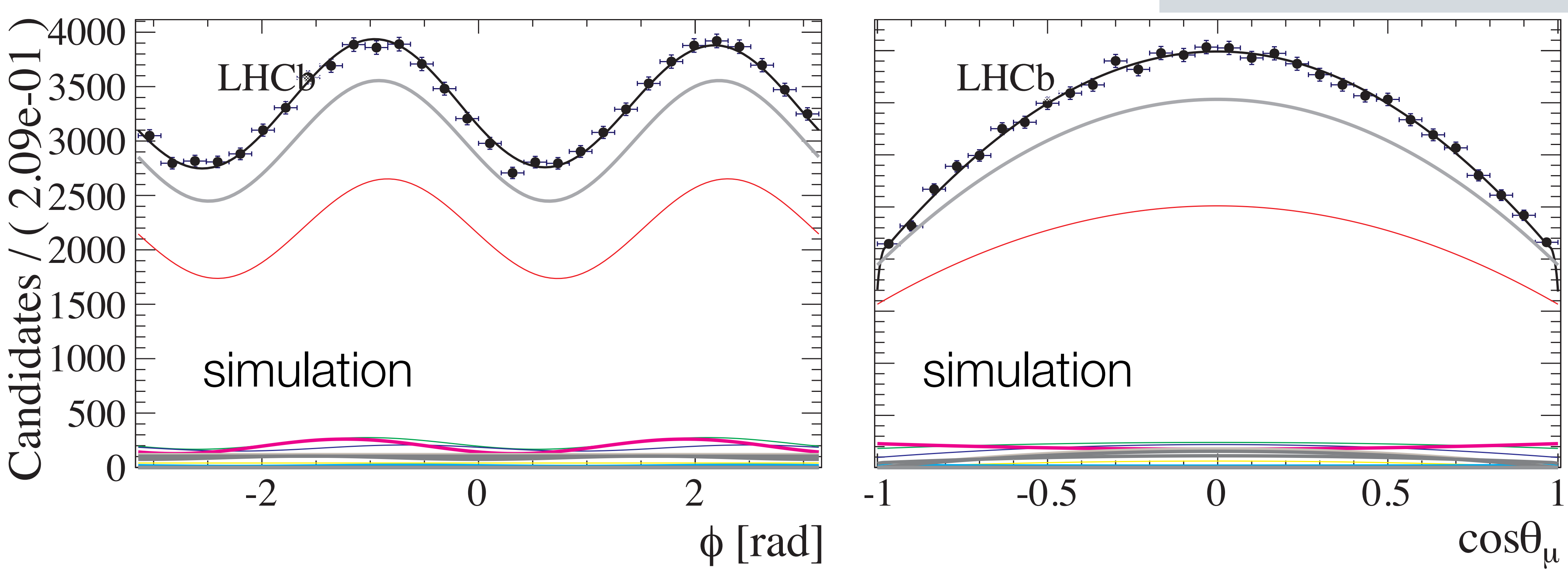
Only 2 of the 4 dimensions…

4D Dalitz plot (scalar ⟶ vector scalar scalar)



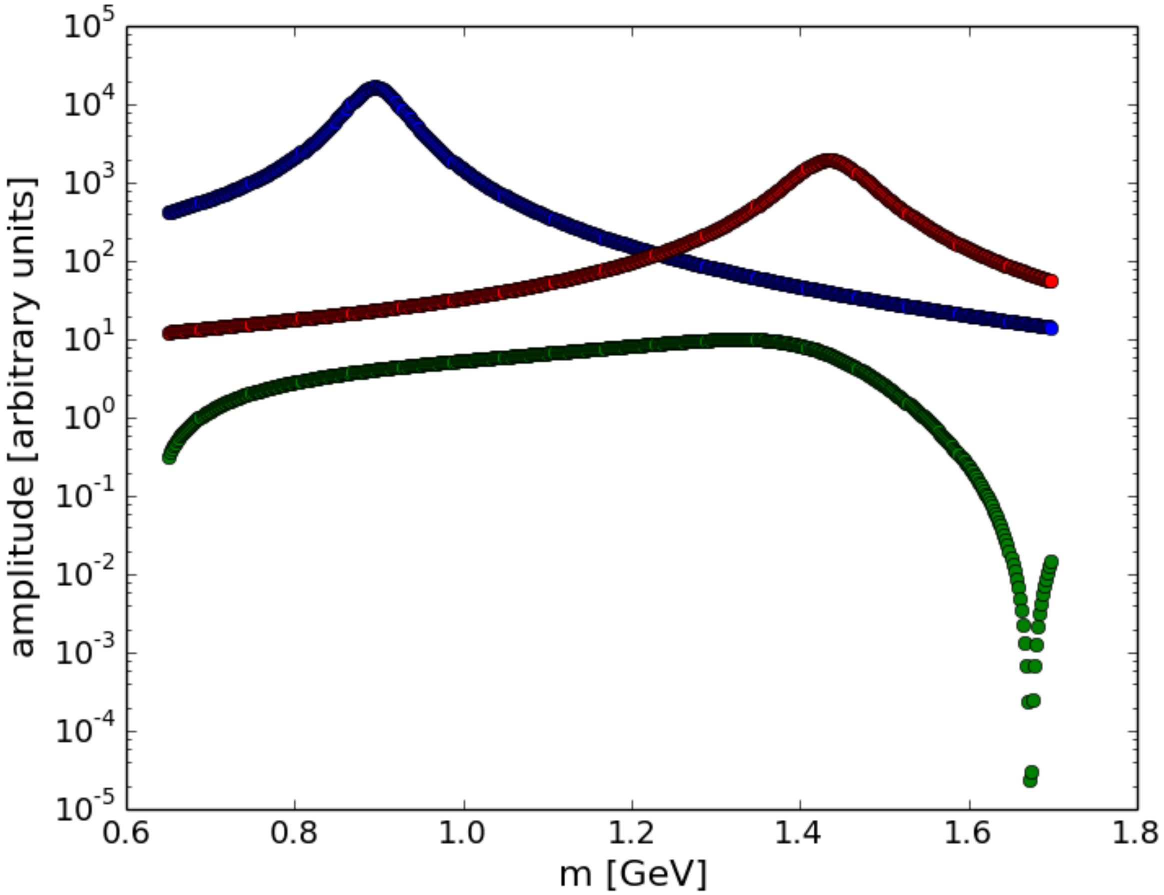
Constraints	Degrees of freedom
3 four-vectors	+12
All decay in same plane (p	-3
E	-3
Energy + momentum conservation	-3
Rotate system in plane	-1
Vector helicity	+2
Total	**+4**

- $B^0 \longrightarrow \psi(2S)K^+\pi^-$, $\psi(2S) \longrightarrow \mu^+\mu^-$
- Need to use the angular information, in addition to $m(\psi(2S)\pi^-)^2$ vs $m(K^+\pi^-)^2$, to understand $|\mathcal{M}|^2$.



Amplitude model

- Use the Isobar approach, build amplitude from sum of overlapping and interfering Breit-Wigner resonances.



Sum over the k resonances

$$|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega | m_{0\,k}, \Gamma_{0\,k}) \right|^2$$

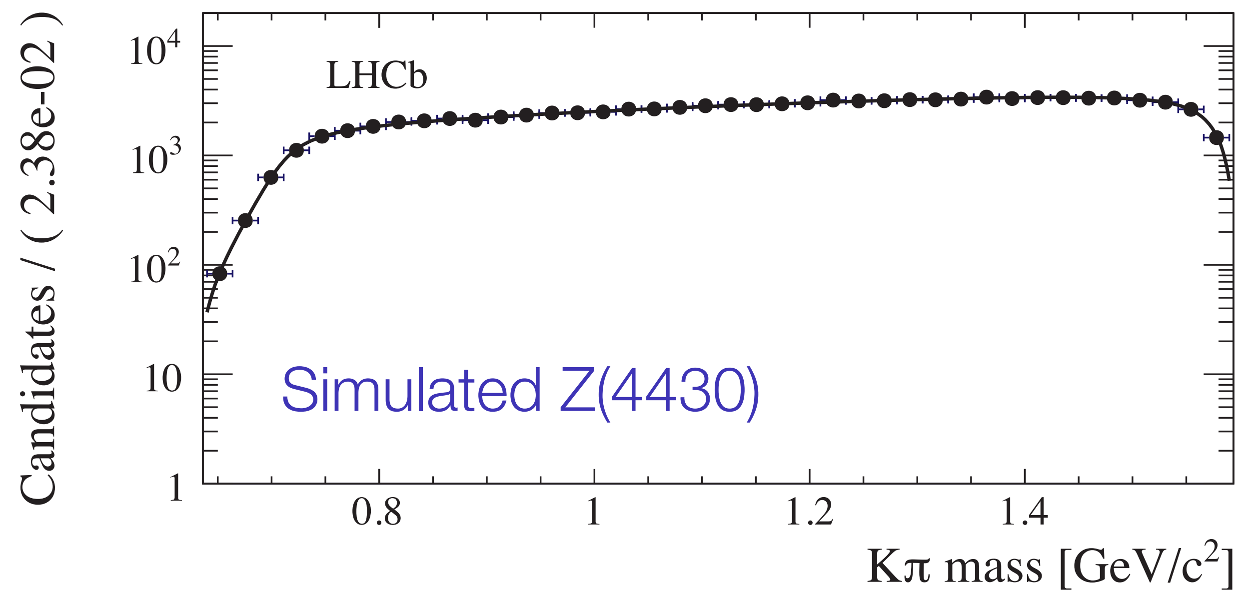
In 4D fit, $\mu^+\mu^-$ are final state particles: thus different dimuon helicity amplitudes are incoherent (cannot interfere)

Now different ψ helicity amplitudes interfere

Complex amplitude that encodes the mass and angular dependence

Amplitude model - adding in the Z(4430)

- Adding the Z(4430) component is a bit more difficult since it has different helicity frame compared to $K^+\pi^-$ resonances.
- It is has a BW shape in $m_{\psi(2S)\pi^-}$ mass, but is basically flat in $m_{K^+\pi^-}$.
- Low Q-value in decay, so ignore D-wave contribution ⇒ $A_{Z,-1} = A_{Z,0} = A_{Z,+1}$

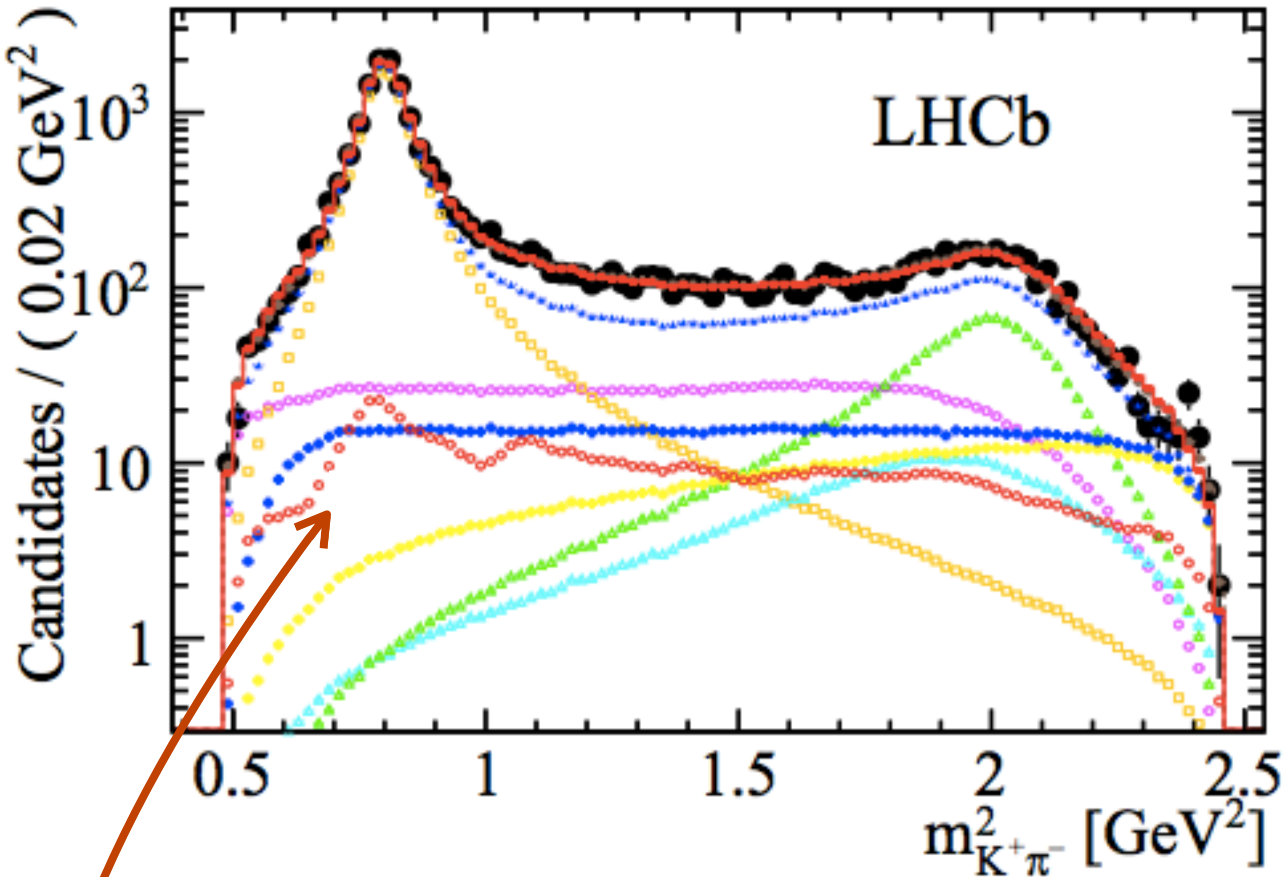


$$|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega | m_{0\,k}, \Gamma_{0\,k}) + \sum_{\lambda_\psi^Z=-1,0,1} A_{Z,\lambda_\psi^Z}(m_{\psi\pi}, \Omega^Z | m_{0\,Z}, \Gamma_{0\,Z}) e^{i\Delta\lambda_\mu \alpha} \right|^2$$

Z(4430) component interferes with the $K^+\pi^-$ sector

Rotation by α to different helicity frame

Which resonances should we add?



From PDG

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

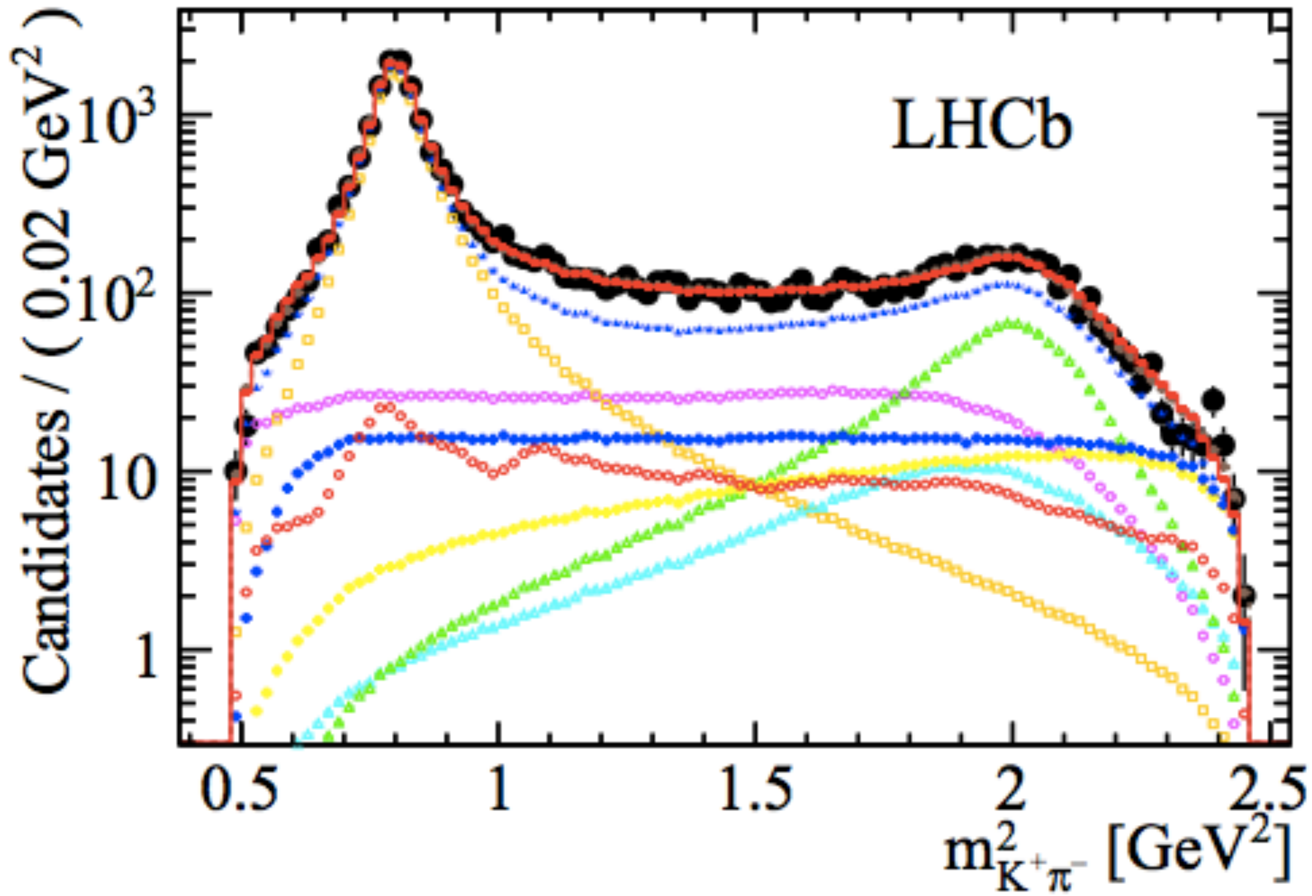
- $K^+\pi^-$ spectrum contains many overlapping resonances.
  - Each resonance has a complex amplitude for **each** helicity component, this impacts the $m_{\psi(2S)\pi^-}$ distribution.
  - Measure all amplitudes relative to K*(892) helicity-0 component.
- Nominal result includes all resonances up to $K^*_1(1680)$.
- Main source of **systematic uncertainties** comes from varying model to include higher $K^+\pi^-$ spin-states.

Background from sidebands of B mass

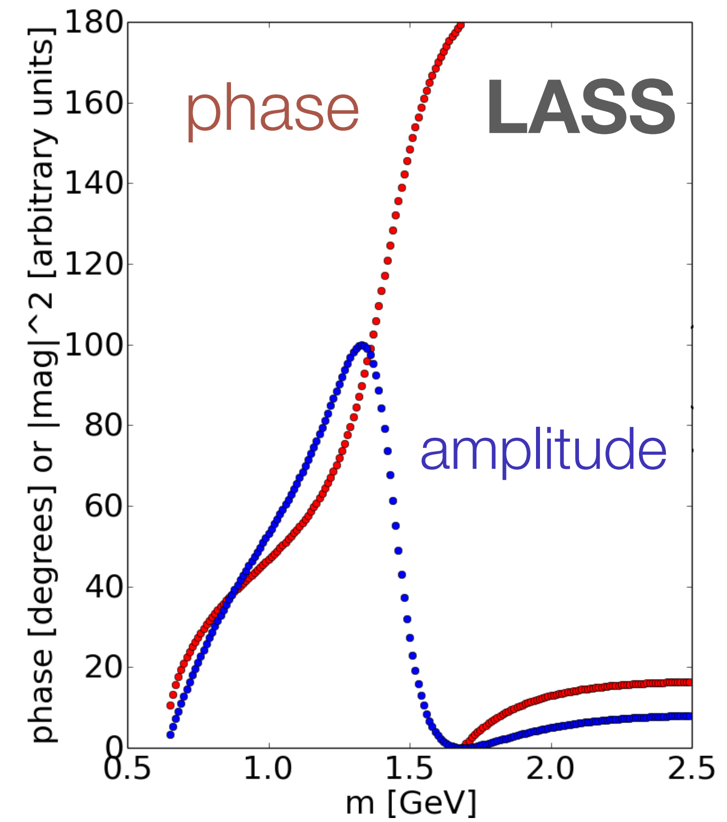
S-wave parameterisation

- Z(4430) has largest effect ~1.5GeV
- Important to understand the **Kπ S-wave** in this region

- **Isobar model** is default
  - BW amplitude for K*(1430)+K_0(800)
  - Non-resonant contribution



- LASS model as cross-check
  - Does not violate unitarity
  - Sum of elastic scattering, destructively interfering with K*(1430).



Slowly varying NR contribution

BW amplitude for K(1430)

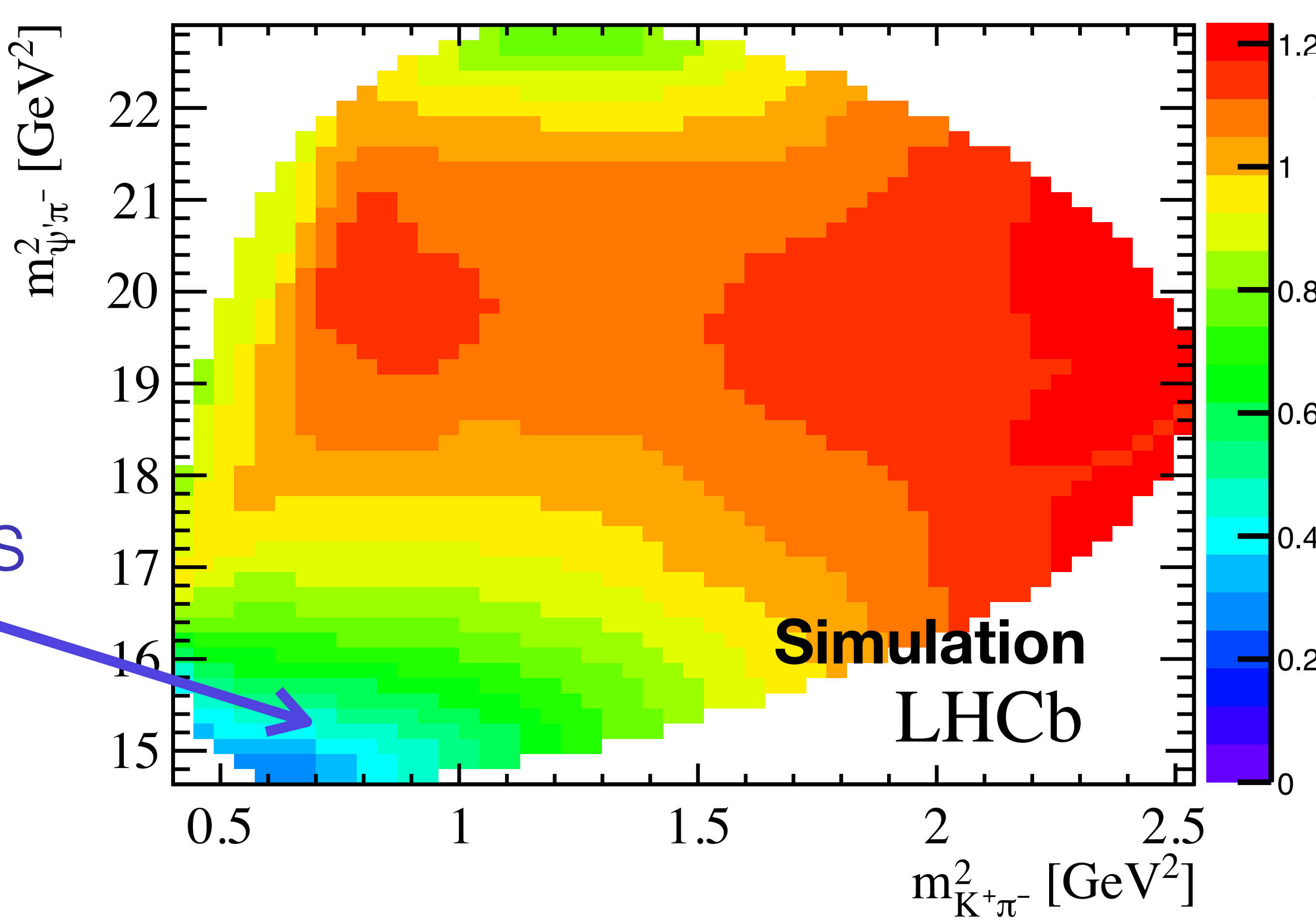
$$\frac{1}{\cot\delta_B(m_{K\pi}) - i} + e^{2i\delta_B(m_{K\pi})}\frac{1}{\cot\delta_R(m_{K\pi}) - i}$$

$$\cot\delta_B(m_{K\pi}) = \frac{1}{a\,q} + \frac{1}{2}r\,q \qquad \cot\delta_R(m_{K\pi}) = \frac{m_0^2 - m_{K\pi}^2}{m_0\Gamma(m_{K\pi})}$$

Reconstruction and selection efficiency

- Unfortunately, LHCb is not 100% efficient at reconstructing the decay particles in 4D space.
- Extract efficiency model from events simulated uniformly in phase space and passed through detector reconstruction.
- Also, remove events near edge of Dalitz boundary since efficiency not well modelled there.
- 2D representation…

Caused by low momentum pions



∈ High efficiency

Low efficiency

Fitting the model to the data

- Likelihood fit to measure **~50** free parameters: amplitudes, phases, resonance mass/widths.

Observables (mass, angles)

PDF

Parameters

Efficiency

$$-\ln L(\vec{\omega}) = -\sum_{i}^{N_{\text{data}}} \ln P^{u}_{\text{tot}}(\vec{v}_i|\vec{\omega}) = -\sum_{i}^{N_{\text{data}}} \ln\left(|\mathcal{M}(\vec{v}_i|\vec{\omega})|^2 \epsilon(\vec{v}_i)/I(\vec{\omega})\right)$$

- In any amplitude fit, difficulty comes from **integrating** the matrix element.
- Solution: sum over fully simulated, reconstructed phase space MC.
  - This automatically includes the efficiency in the calculation.
  - Alternative approach that explicitly parameterises the 4D efficiency.

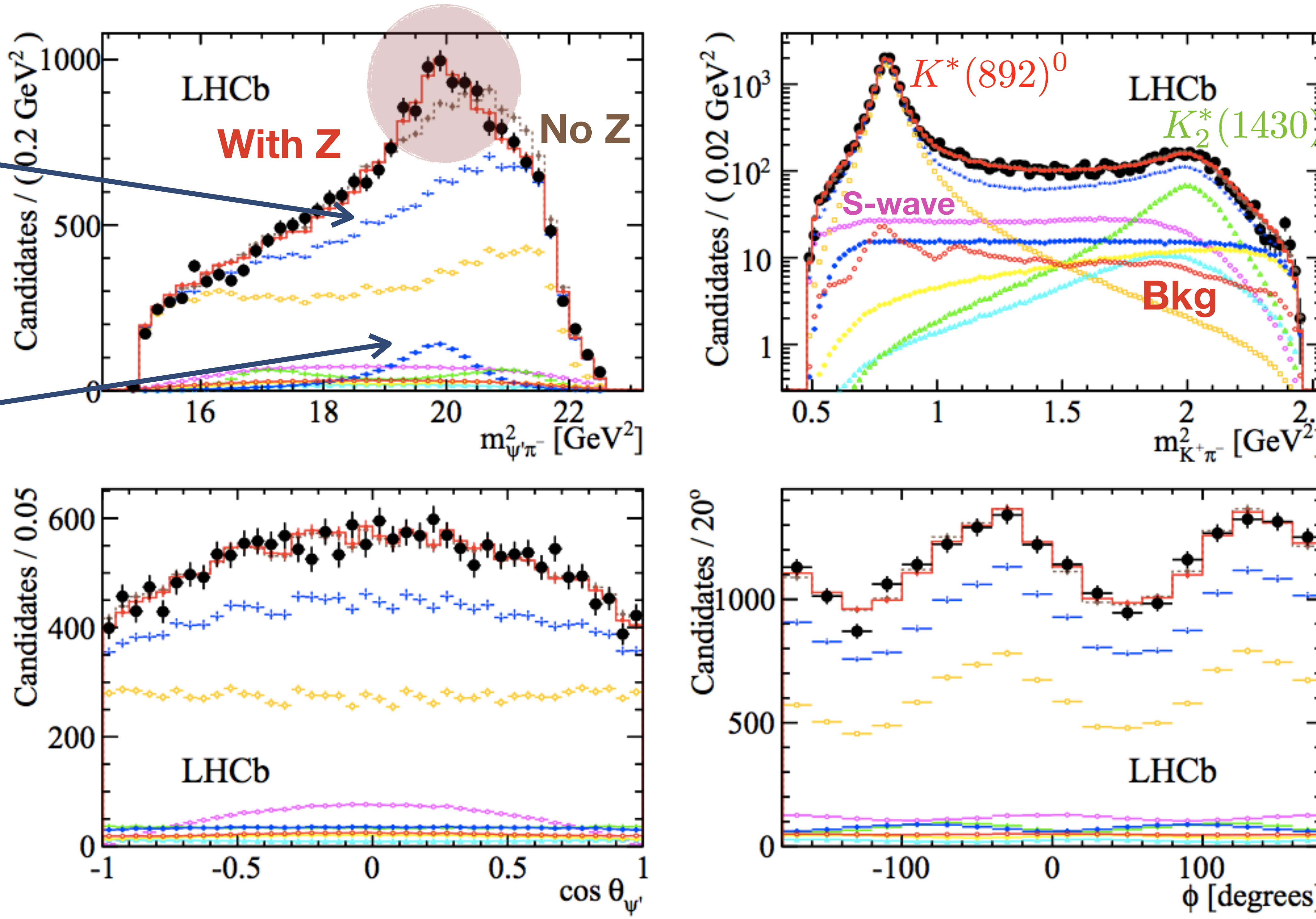
$$I(\vec{\omega}) = \sum_{i}^{N_{\text{MC}}} |\mathcal{M}(\vec{v}_i|\vec{\omega})|^2$$

Try different models for $K^+\pi^-$ and Z(4430), compare values of $\mathcal{L}$.

Projections of 4D amplitude fit

Everything except the Z ⇒ large interference between Z and $K^+\pi^-$ sector

$J^P = 1^+$ Z component

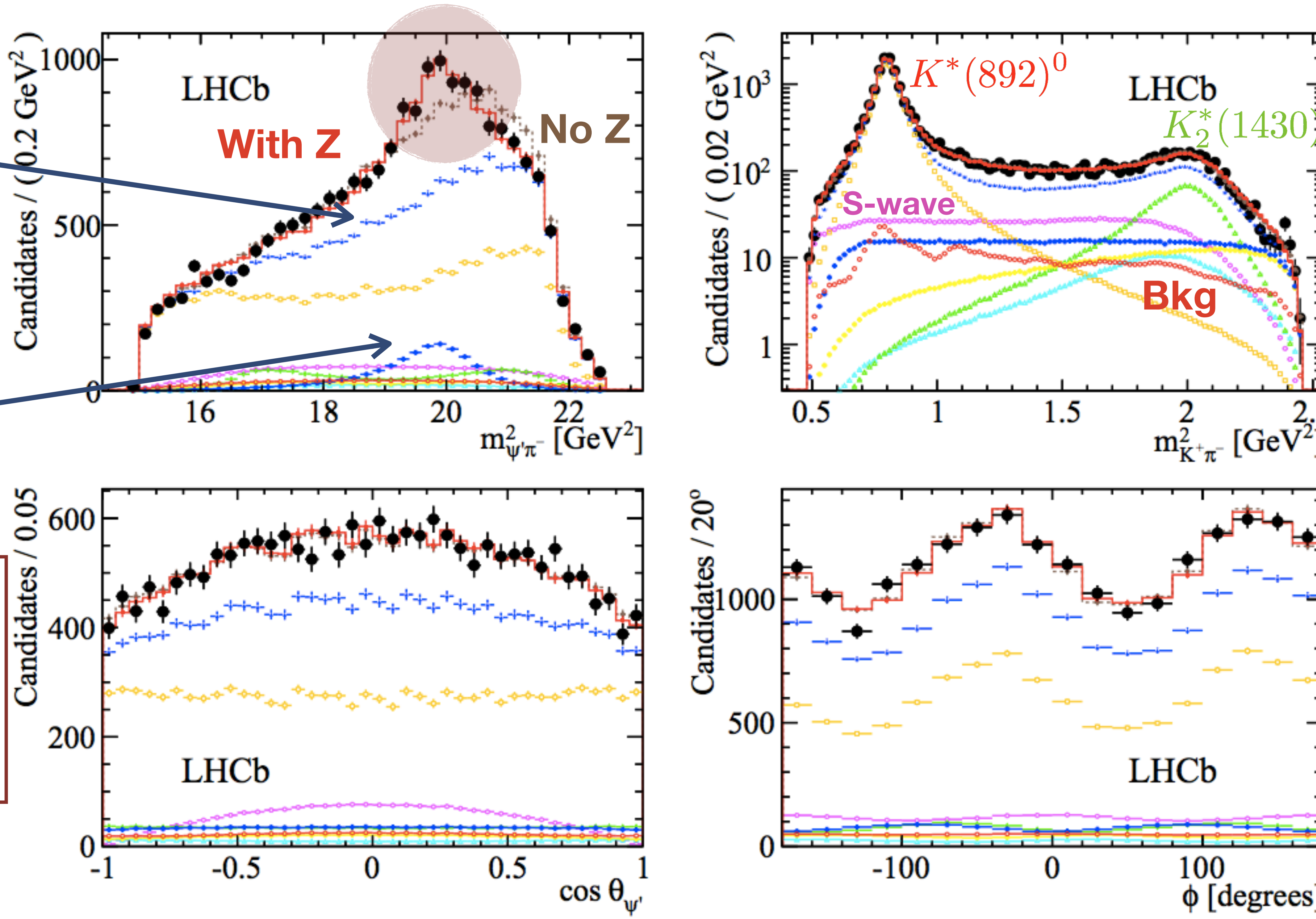


arXiv:1404.1903

Projections of 4D amplitude fit

Everything except the Z ⇒ large interference between Z and $K^+\pi^-$ sector

$J^P = 1^+$ Z component



arXiv:1404.1903

Significance from

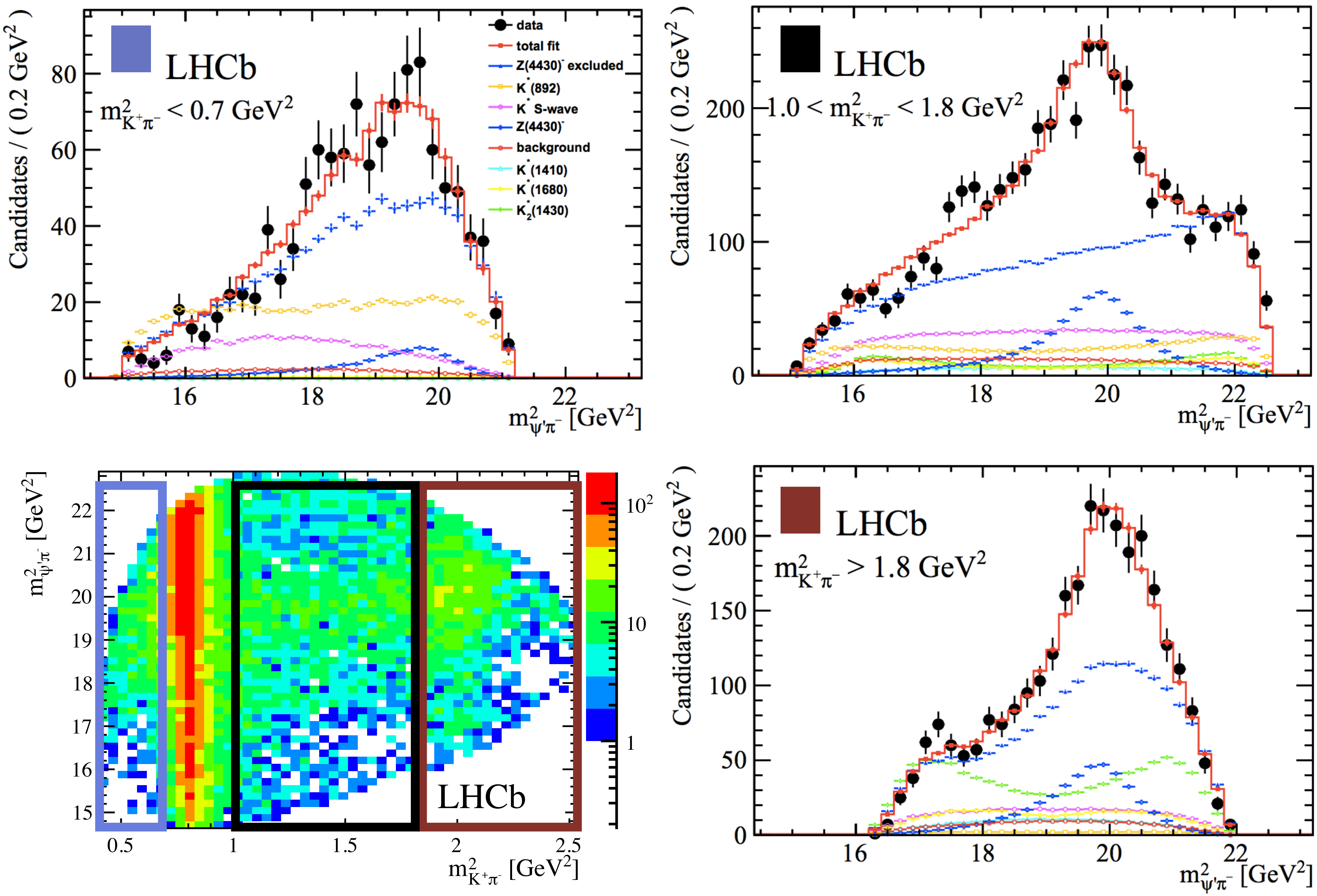
$$\Delta(-2\ln L) > 13.9\sigma$$

Fitted parameters

$$M_Z = 4475 \pm 7\ ^{+15}_{-25}\ \text{MeV}$$
$$\Gamma_Z = 172 \pm 13\ ^{+37}_{-34}\ \text{MeV}$$
$$f_Z = (5.9 \pm 0.9\ ^{+1.5}_{-3.3})\%$$

- Goodness of fit confidence level = 12%
  - 4% with no $K_1^*(1410)$, 12% with $K_3^*(1780)$

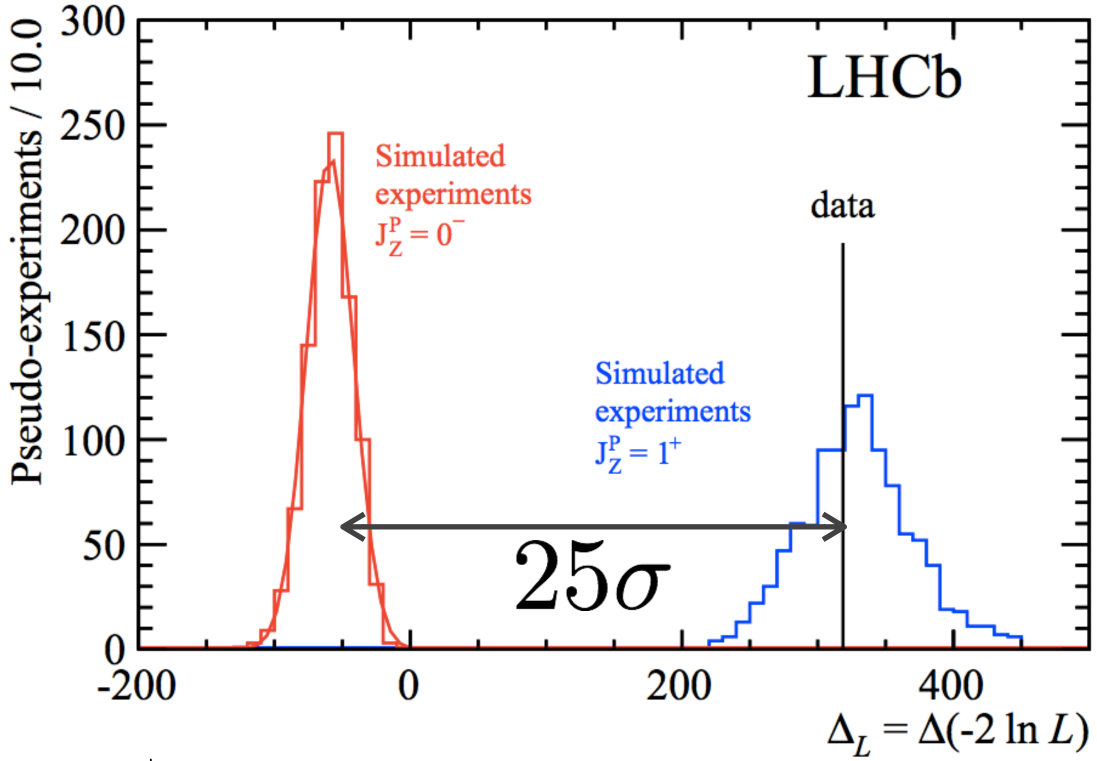
Fit projections in slices of $m_{K^+\pi^-}$

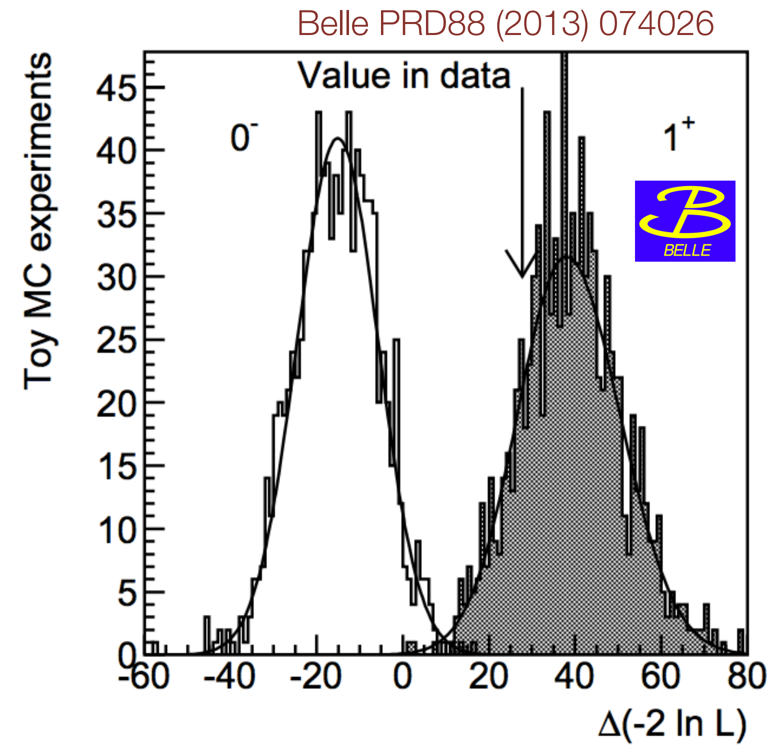


arXiv:1404.1903

Spin determination and resonant behaviour

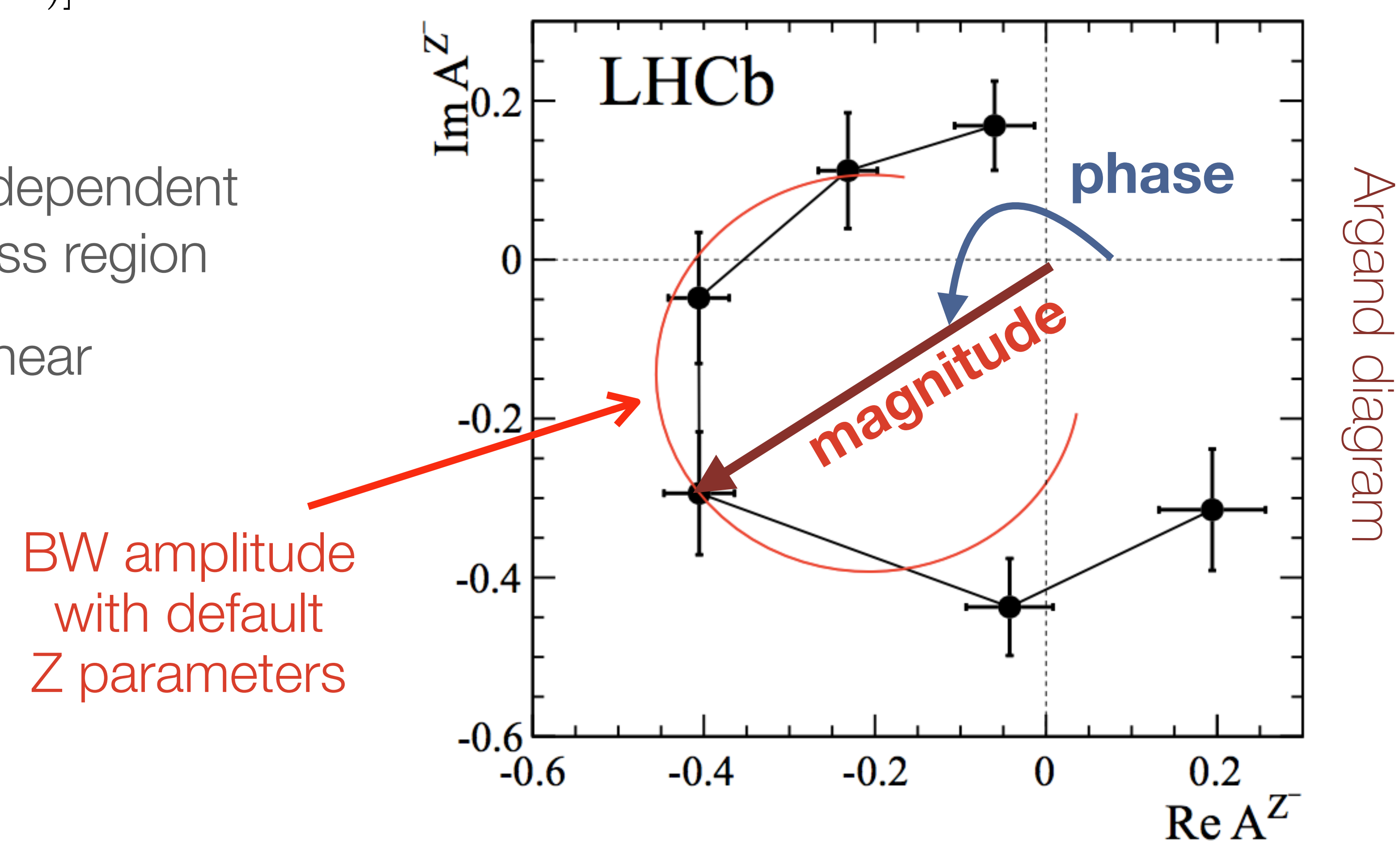
- Build different $|M|^2$ corresponding to different JP values.
- $J^P=1^+$ assignment favoured (confirms Belle)
- Rule out other J^P with large significance ($> 9\sigma$ after systematics)





$$\Delta(-2\ln L) = [-2\ln L(0^-)] - [-2\ln L(1^+)]$$

- Replace BW amplitude with 6 independent complex numbers in Z(4430) mass region
- Observe rapid change of phase near maximum of magnitude
- Resonance!



arXiv:1404.1903
accepted by PRL

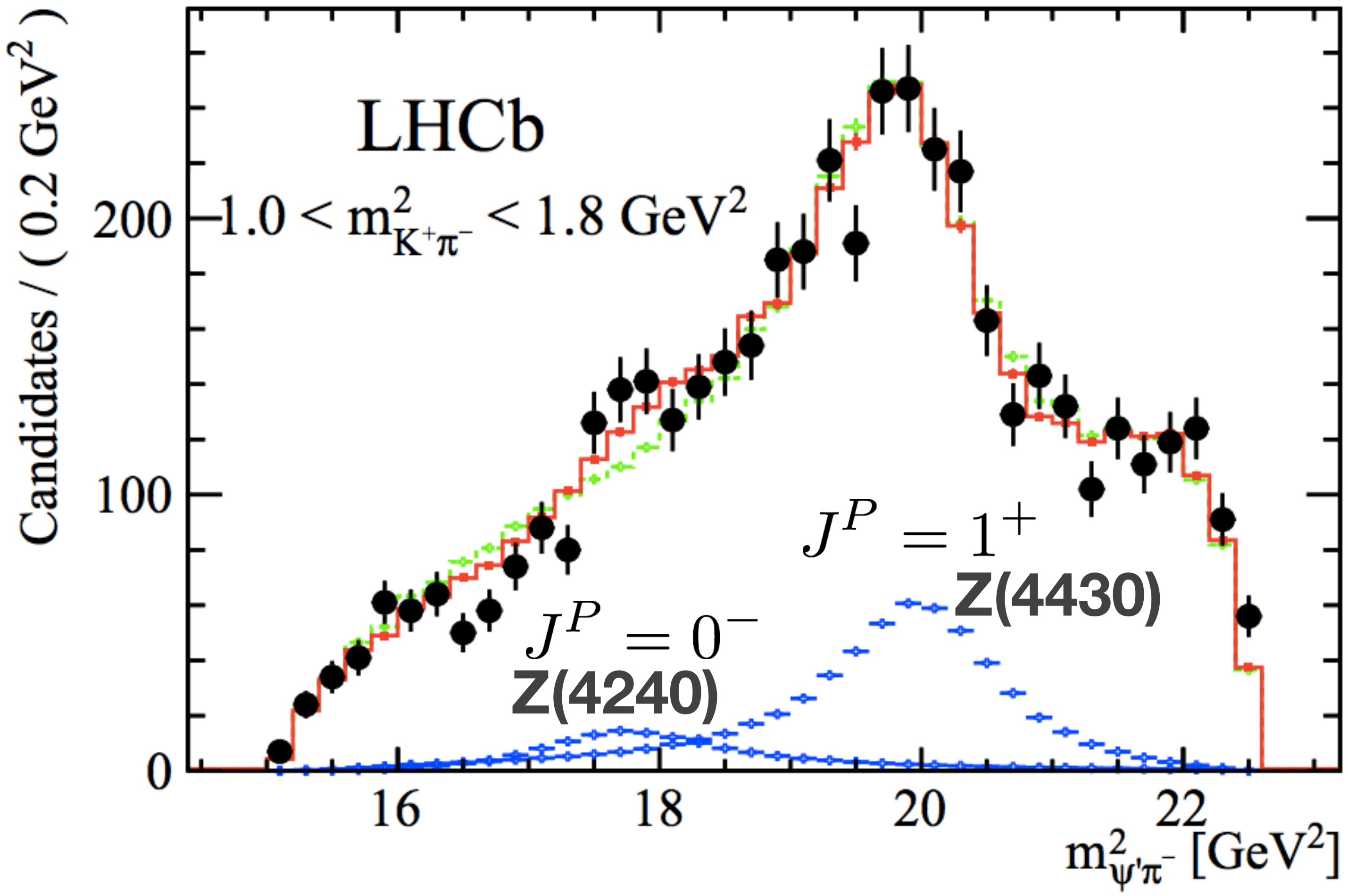
Systematics: second exotic Z?

- Investigated the possibility of a second exotic component.
- Fit confidence level increases to 26%.
- Need larger samples to characterise this state.

Significance from
$\Delta(-2\ln L)$
6σ

Fitted parameters

$$M_{Z_0} = 4239 \pm 18 \; ^{+45}_{-10} \text{ MeV}$$
$$\Gamma_{Z_0} = 220 \pm 47 \; ^{+108}_{-\;\;74} \text{ MeV}$$
$$f_{Z_0} = (1.6 \pm 0.5 \; ^{+1.9}_{-0.4})\%$$

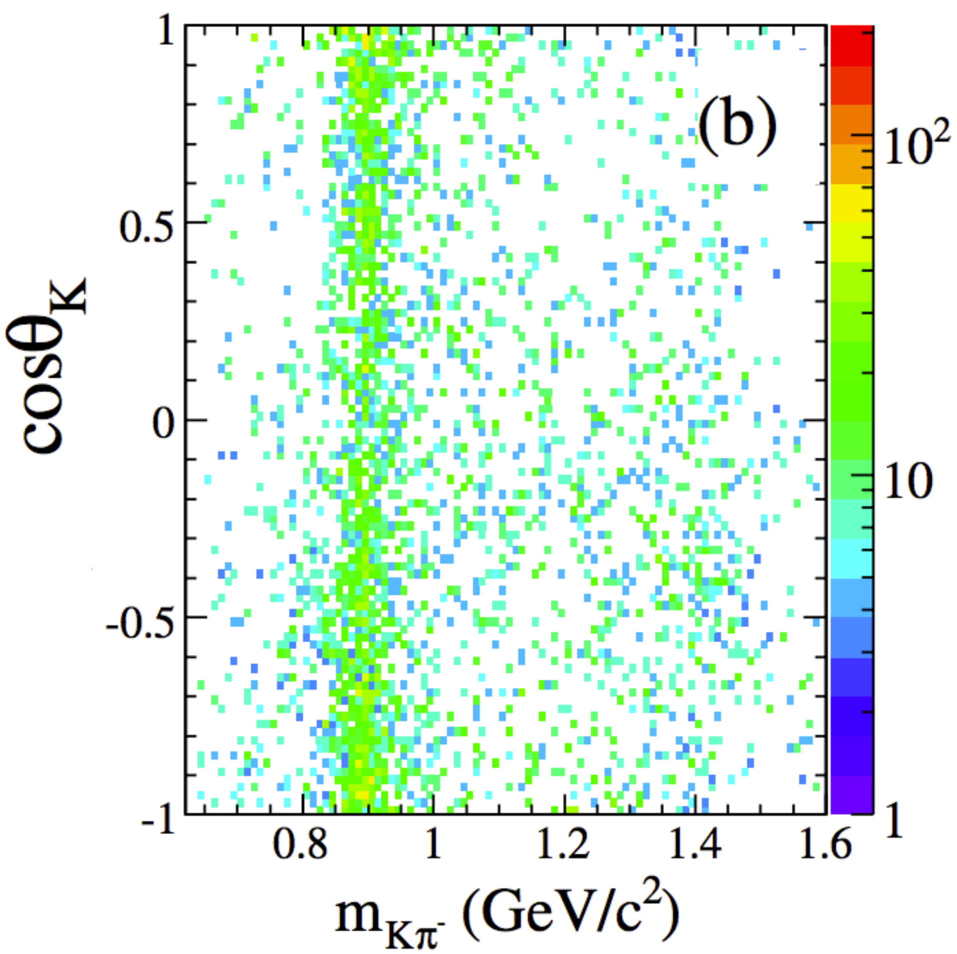


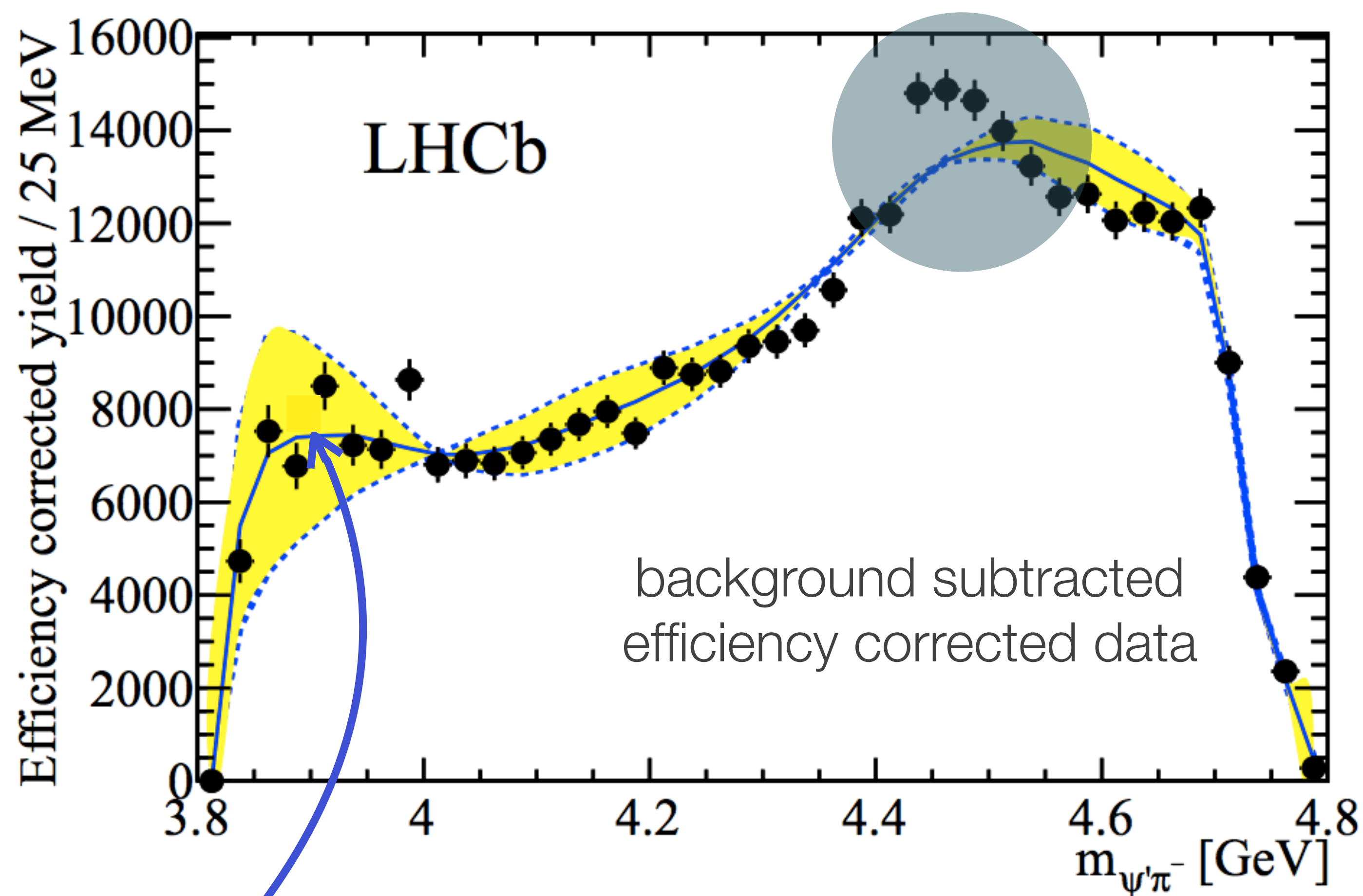
- Many checks performed to determine stability of the result and evaluate systematic errors on m_Z, Γ_Z, f_Z.
- Main systematics come from assumption on $K^+\pi^-$ Isobar model, efficiency and $(q/m_{K^+\pi^-})^L$ vs. q^L

Model independent analysis

Can reflection of the structures in m(Kπ) and cos reproduce the m(Ψ(2S)π) distribution? → **NO!**

BaBar data for $B^0 \to \psi(2S) K \pi^-$
PRD 79 (2009) 112001





- Does not make any assumption on the underlying K* resonances in the system, only restricts their maximal spin (J ≤ 2).
- Weight phase space **simulated events** with the spherical harmonic moments of $\cos\theta_K$
- Moments of K* resonances are unable to explain observed distribution.

$$Y_1^0 = \sqrt{\frac{3}{4\pi}} \cos\theta$$

$$Y_1^1 = -\sqrt{\frac{3}{8\pi}} \sin\theta\, e^{i\phi}$$

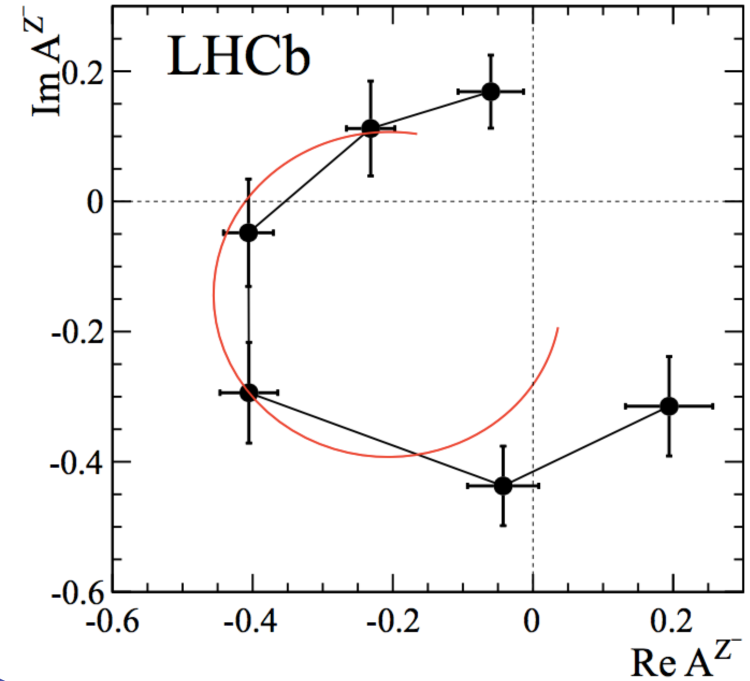
$$Y_2^0 = \sqrt{\frac{5}{4\pi}} \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

$$Y_2^1 = -\sqrt{\frac{15}{8\pi}} \sin\theta\cos\theta\, e^{i\phi}$$

$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}} \sin^2\theta\, e^{2i\phi}$$

A bit more context…

- This result confirms the existence of the Z(4430), measures $J^P=1^+$ and, for the first time, demonstrates the **resonant behaviour**.
- P=+ rules out interpretation in terms of **$\bar{D}^*(2007)D^*_2(2460)$** molecule or threshold effect.
- Four quark bound state is a remaining explanation.



Rosner, Phys. Rev. D76 (2007) 114002

Bugg, J. Phys. G35 (2008) 075005

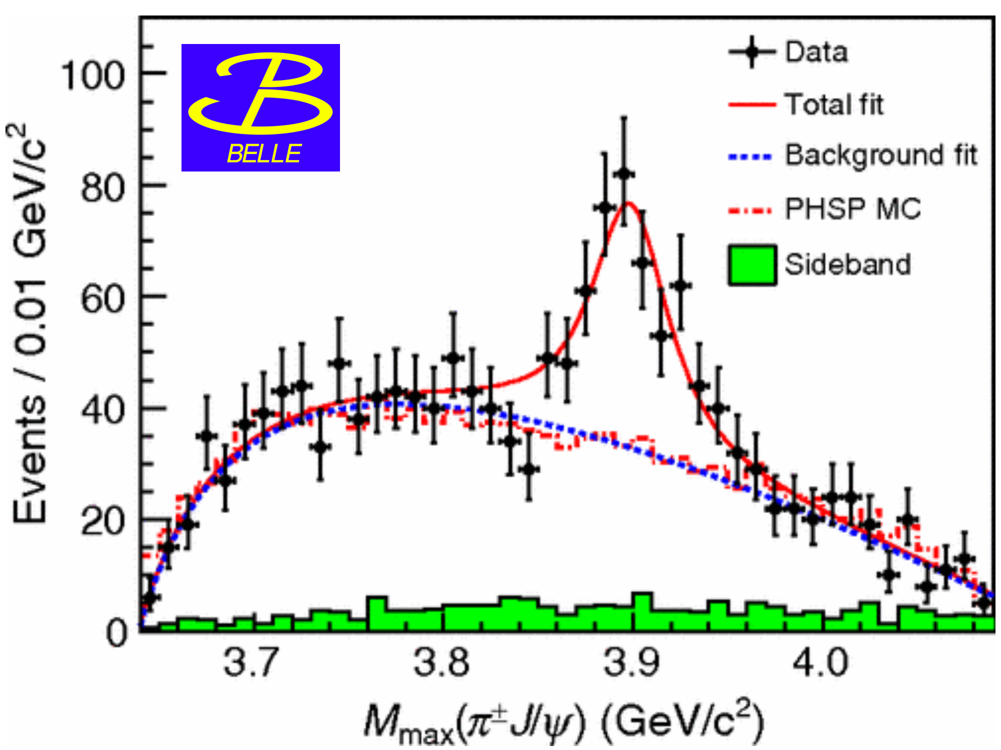
- Last year BESIII and Belle observed another **exotic charged** state.

$Z_c(3900)$ in $e^+e^- \to \pi^+\pi^- J/\psi$

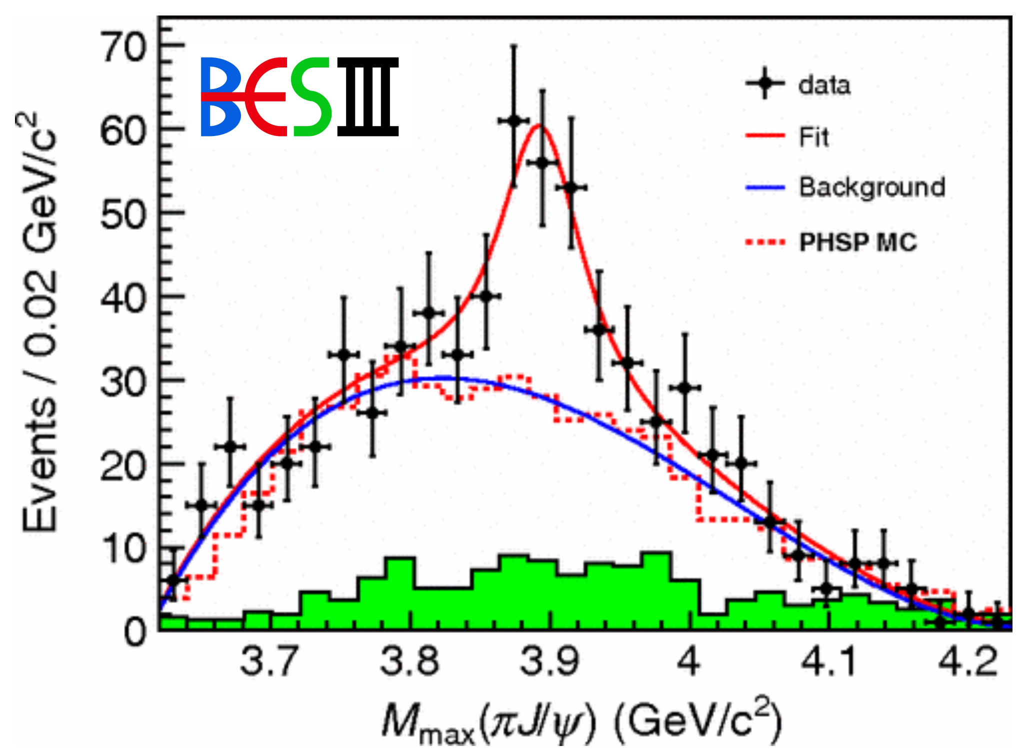
$M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2

$\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2

1D fit to m(πJ/Ψ) only



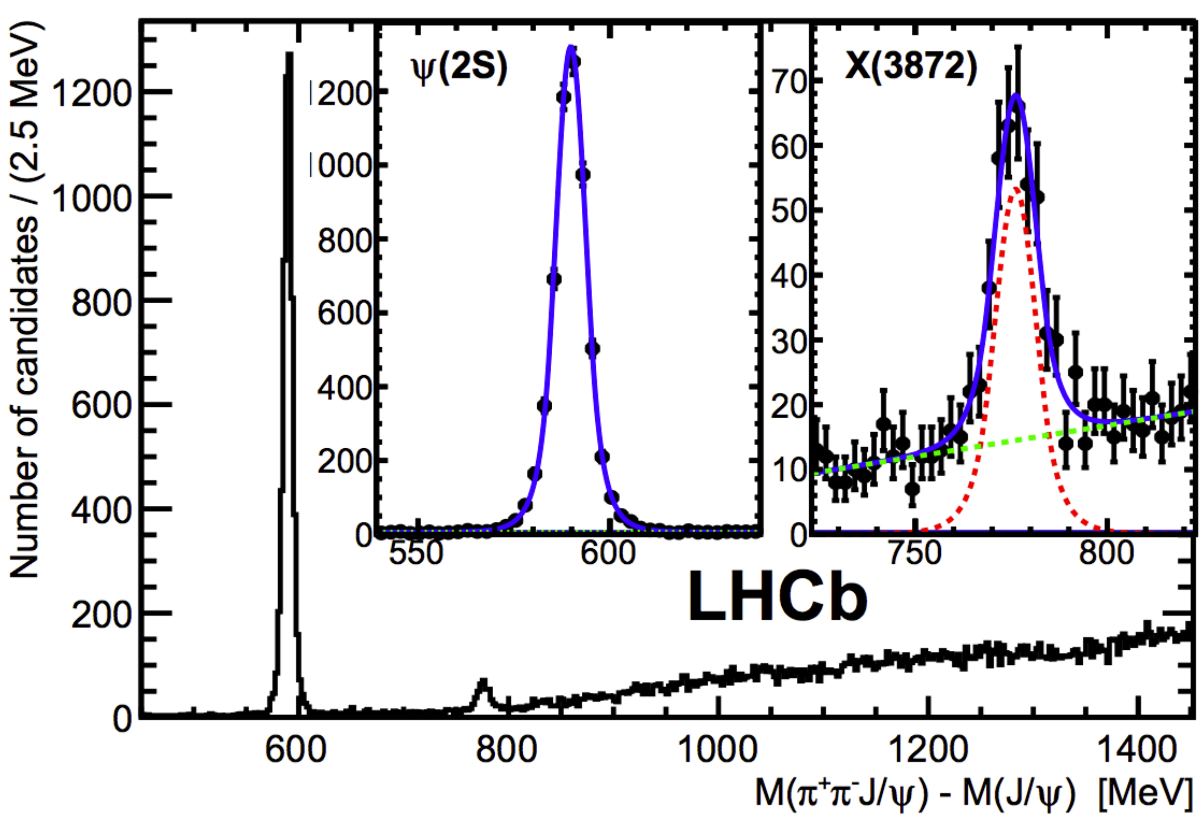
Phys. Rev. Lett. 110, 252001

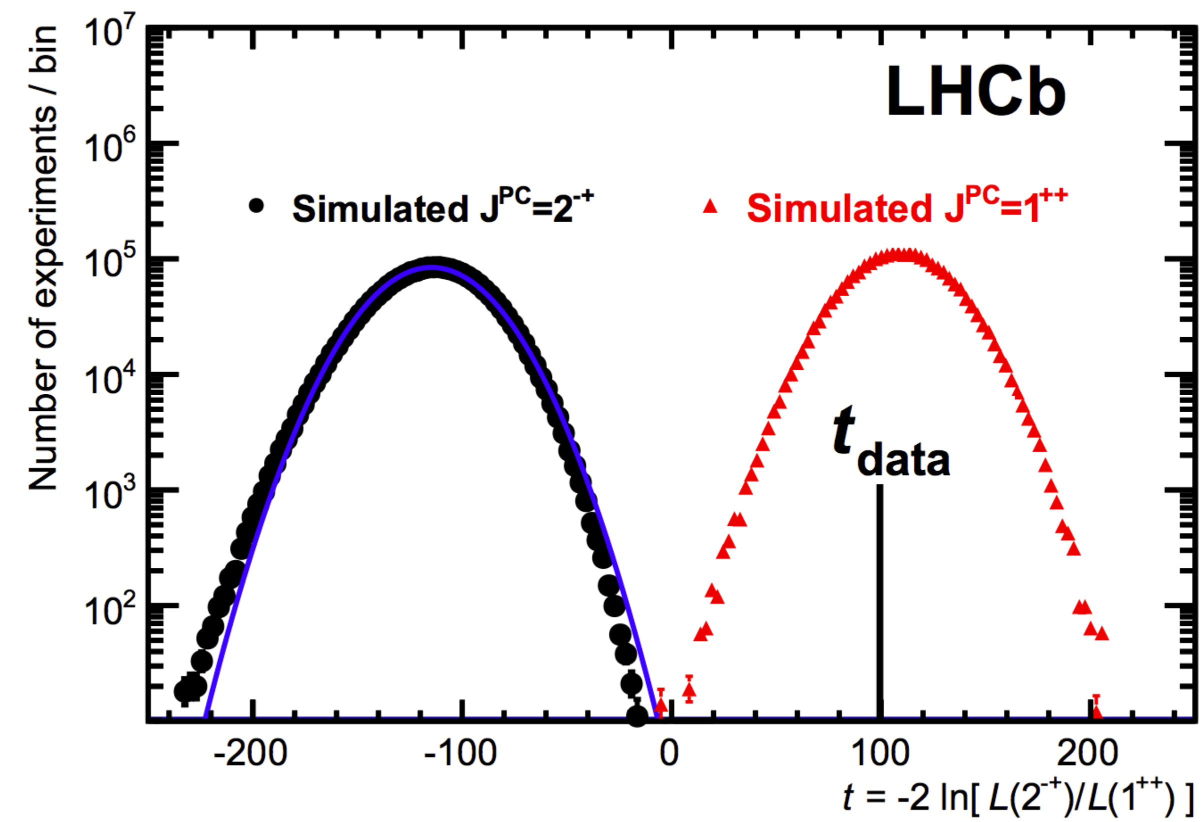


Phys. Rev. Lett. 110, 252002

A well known exotic meson: X(3872)

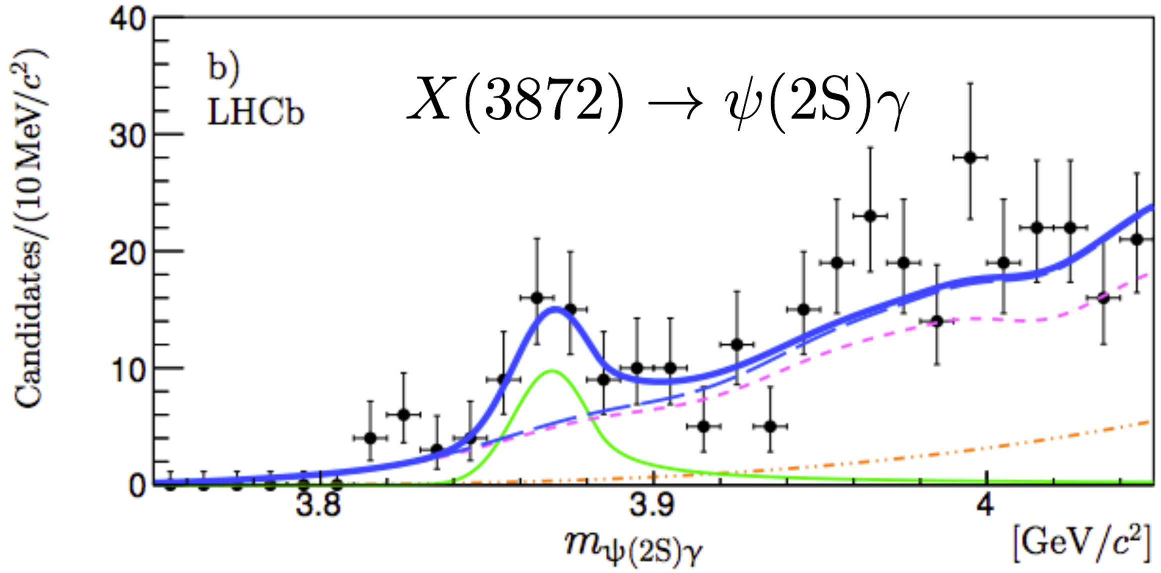
- Observed by many experiments, first by Belle (PRL 91 (2003) 262001 - 894 citations!)
- $B^+ \rightarrow X(3872)K^+$, $X(3872) \rightarrow J/\psi\pi^+\pi^-$
- Use well-known ψ(2S) resonance to calibrate
- Measure $J^{PC} = 1^{++}$ - favours exotic interpretation
- Could be some combination of **$c\bar{c}u\bar{u}$** quarks or **DD* molecule**

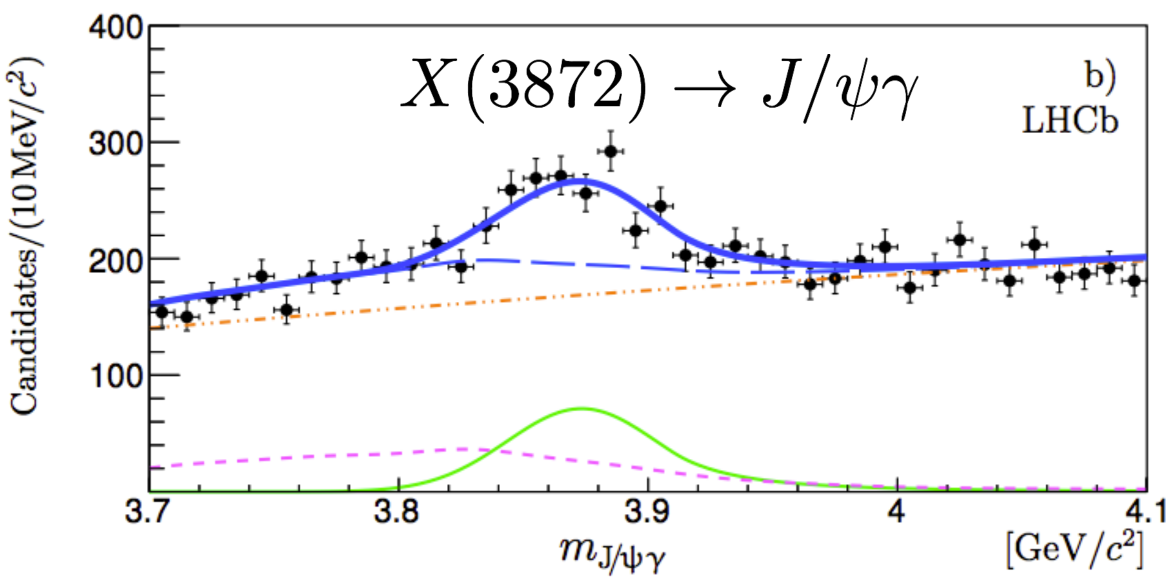




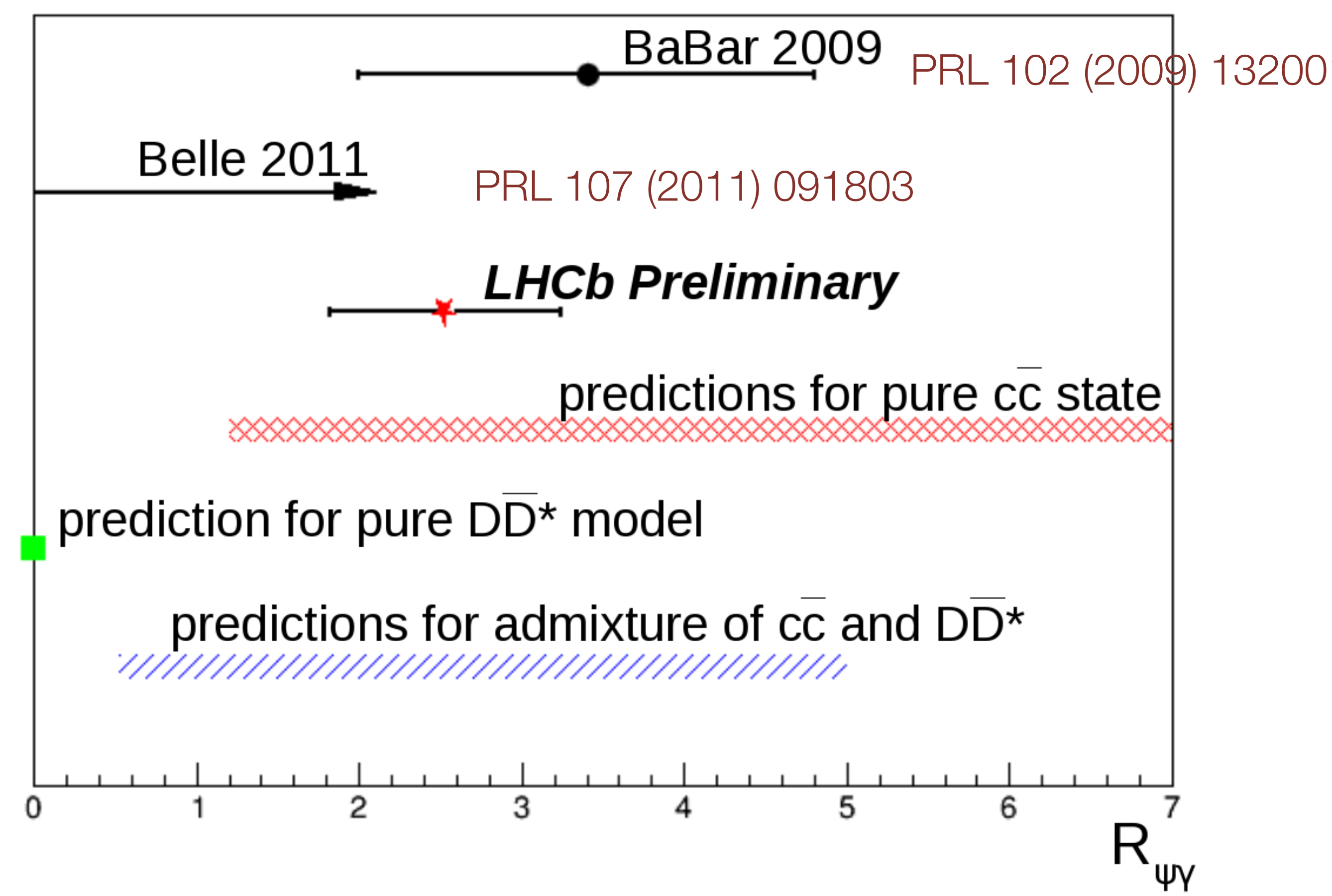
Phys. Rev. Lett. 110, 222001 (2013)

A well known exotic meson: X(3872)





- LHCb has evidence for X(3872) in decays of $B^+ \to \psi\gamma K^+,\ \psi \to \mu^+\mu^-$
- Pure DD* molecule interpretation disfavoured



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

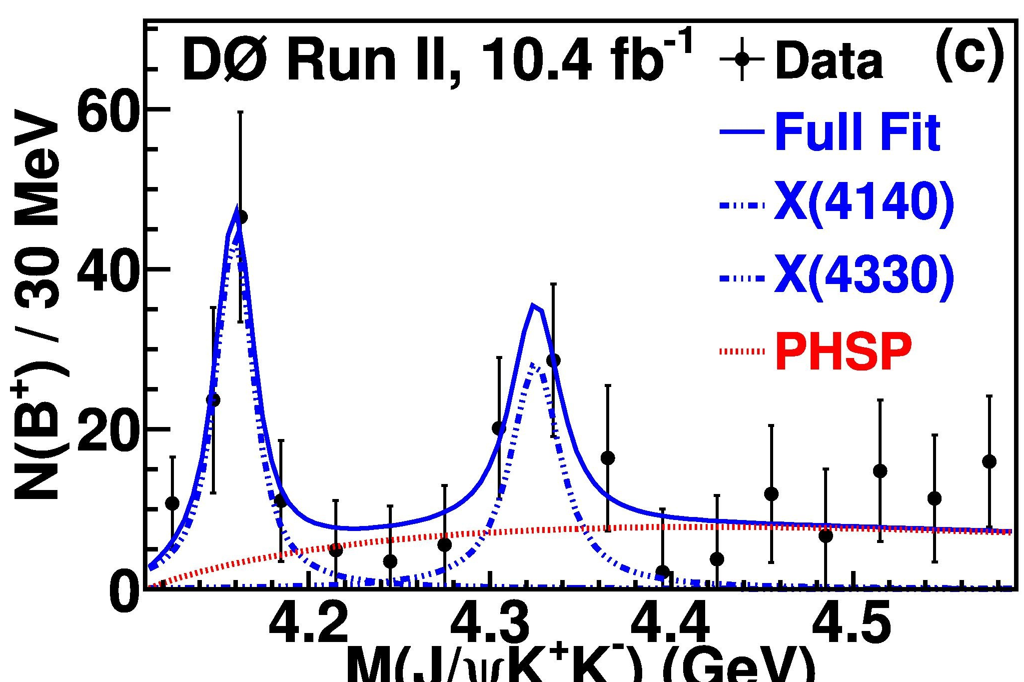
arXiv:1404.0275

An enigma… the X(4140)

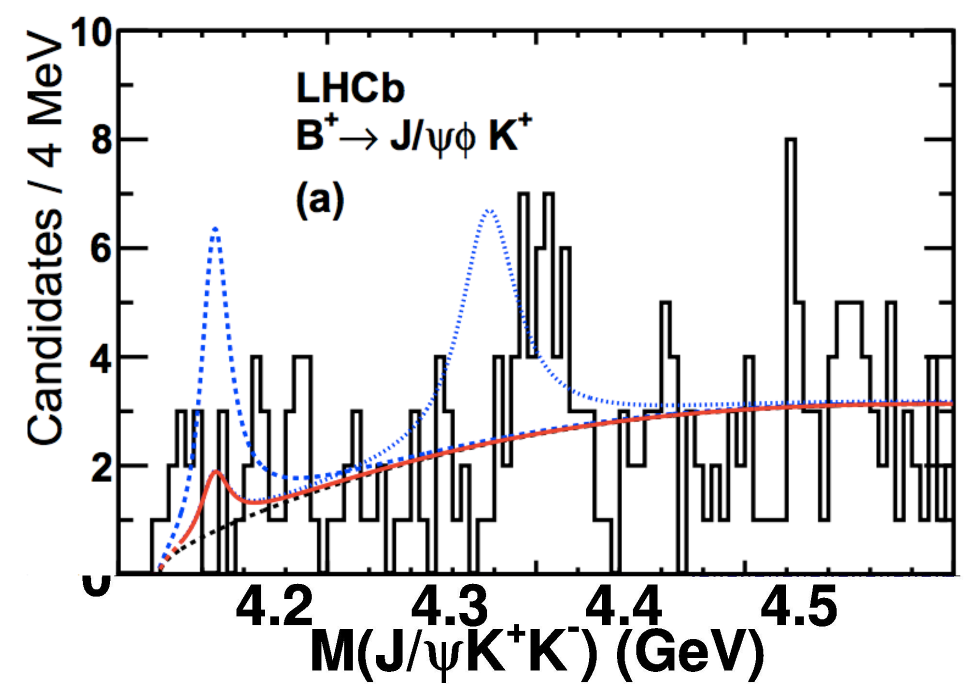
$B^{\pm/0} \to X K^{\pm/0} \quad X \to J/\psi\phi$

Experiment	Mass (MeV)	Width (MeV)	σ	Published?	Ref.
CDF	4143.0±2.9±1.2	11.7	3.8	Y	Phys. Rev. Lett. **102**, 242002
CDF	4143.4	15.3	>5	N	Public Note 10244
D0	4159.0±4.3±6.6	19.9±12.6	3.1	Y	Phys. Rev. D **89**, 012004
CMS	4148.0±2.4±6.3	28	>5	N	arXiv:1309.6920
Belle	-	-	-	Y	Phys. Rev. Lett. 104, 112004
LHCb	-	-	-	Y	Phys. Rev. D 85, 091103(R)
BaBar	-	-	-	N	-

- Could be some hybrid state: $c\bar{c}s\bar{s}$



Phys. Rev. D 89, 012004



Phys. Rev. D 85, 091103(R)

Light quark spectroscopy using $B^0 \to J/\Psi\pi^+\pi^-$

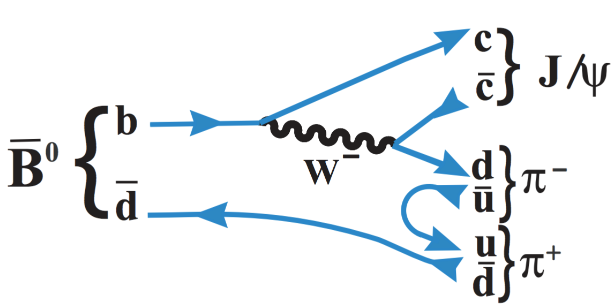
- Study substructure of light mesons that decay to $\pi^+\pi^-$.
- Mass ordering is reversed between the scalar and vector mesons nonets.

Isospin	$I=0$	$I=1/2$	$I=0$	$I=1$
Scalar mesons	$f_0(500)$	$\kappa(800)$	$f_0(980)$	$a_0(980)$
Vector mesons	$\phi(1020)$	$K^*(892)^0$	$\omega(783)$	$\rho(776)$

- Are the scalar mesons ($f_0(500)$, $f_0(980)$) **$q\bar{q}$** or **tetraquarks** or some mixture?

Scalar meson mixing

$$
\begin{aligned}
|f_0(980)\rangle &= \cos\varphi_m |s\bar{s}\rangle + \sin\varphi_m |n\bar{n}\rangle \\
|f_0(500)\rangle &= -\sin\varphi_m |s\bar{s}\rangle + \cos\varphi_m |n\bar{n}\rangle, \\
\text{where } |n\bar{n}\rangle &\equiv \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right).
\end{aligned}
$$

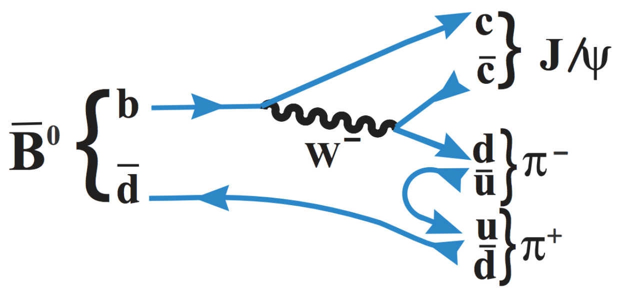


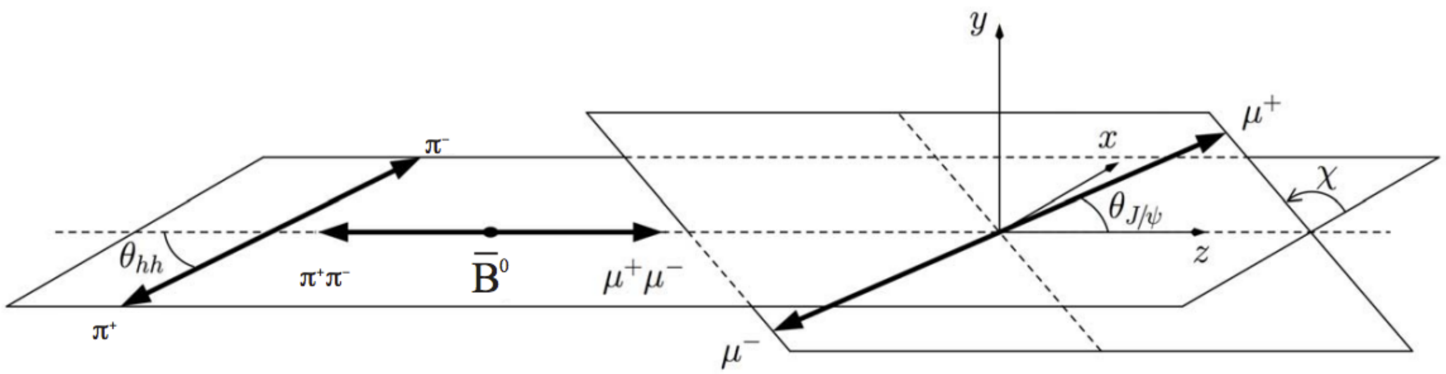
$$
\tan^2\varphi_m \equiv r_\sigma^f = \frac{\mathcal{B}\left(\bar{B}^0 \to J/\psi\, f_0(980)\right)}{\mathcal{B}\left(\bar{B}^0 \to J/\psi\, f_0(500)\right)} \frac{\Phi(500)}{\Phi(980)}, \quad =1/2
$$

phase space

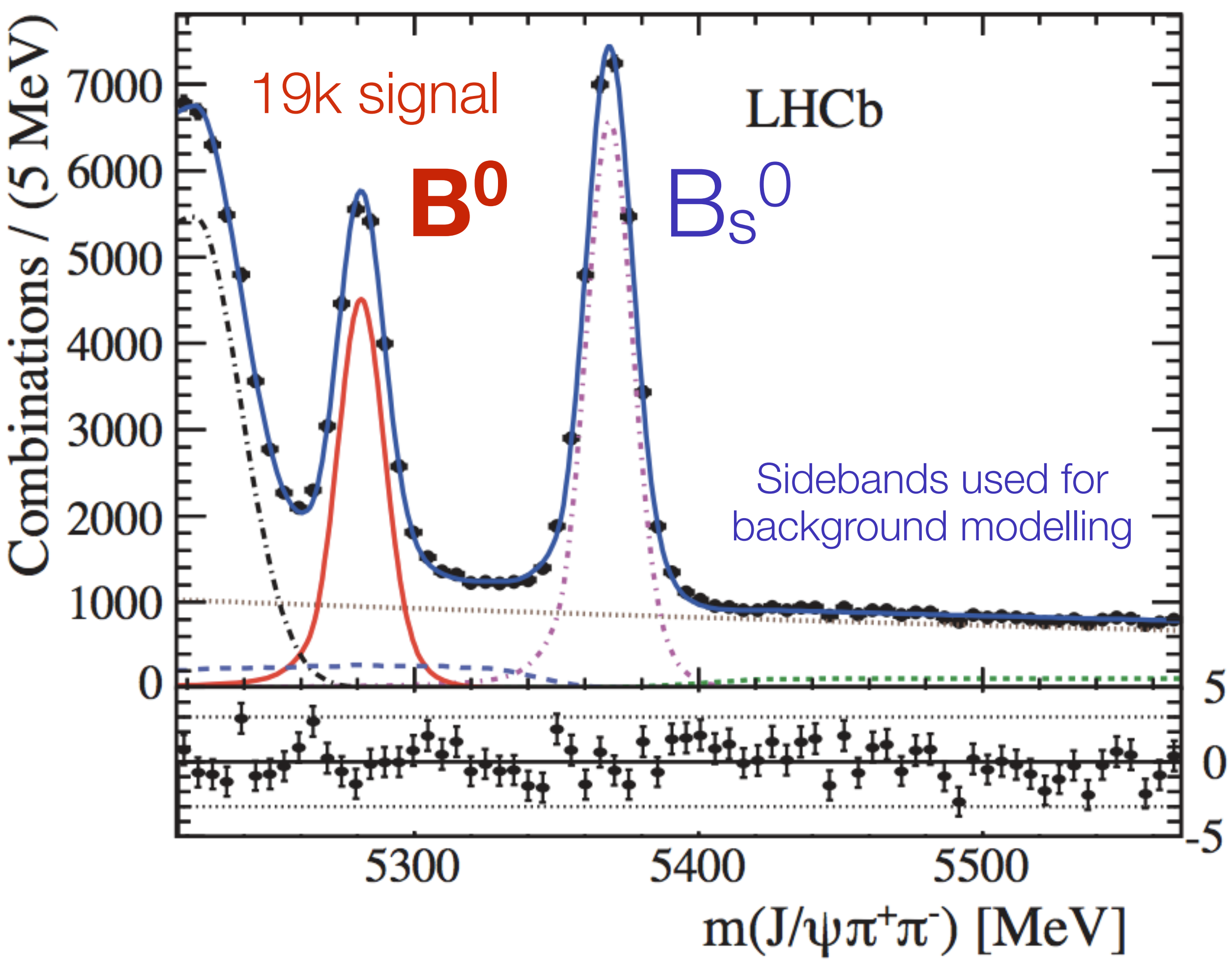
Stone, Zhang, PRL 111, 062001 (2013)
Fleischer, Knegjens Eur.Phys.J. C71 (2011) 1832
PDG review on scalar mesons below 2GeV

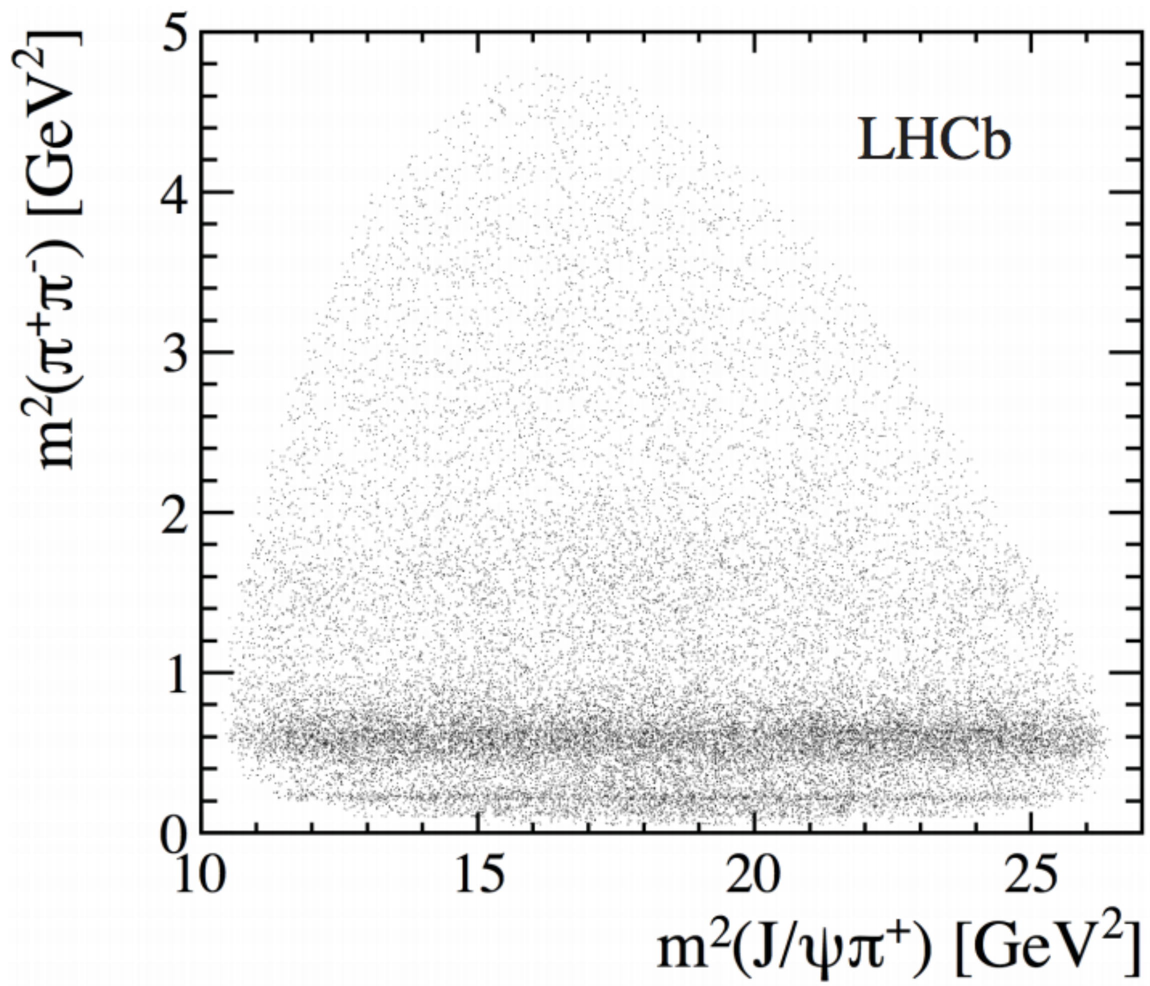
Amplitude analysis of $B^0 \to J/\Psi\pi^+\pi^-$





- Similar analysis to Z(4430)
  - Build 4D matrix element from overlapping $\pi^+\pi^-$ resonances.
  - Correct for efficiency.
- No sign of exotic $J/\psi\pi^+$ resonances…



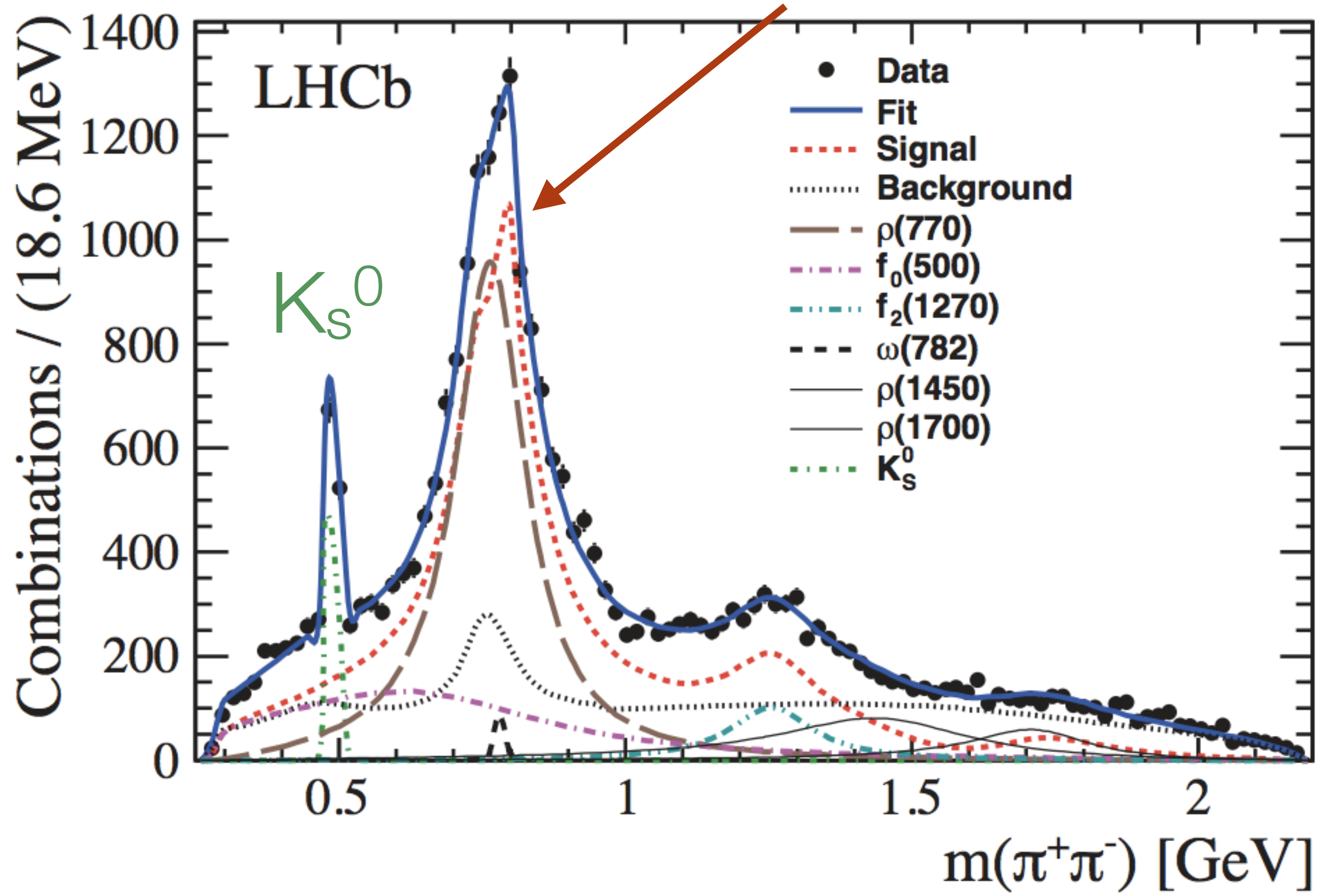


arXiv:1404.5673

Amplitude analysis of $B^0 \to J/\Psi \pi^+ \pi^-$

Component	Fit fraction (%)
$\rho(770)$	$63.1 \pm 2.2^{+3.4}_{-2.2}$
$f_0(500)$	$22.2 \pm 1.2^{+2.6}_{-3.5}$
$f_2(1270)$	$7.5 \pm 0.6^{+0.4}_{-0.6}$
$\omega(782)$	$0.68^{+0.20+0.17}_{-0.14-0.13}$
$\rho(1450)$	$11.6 \pm 2.8 \pm 4.7$
$\rho(1700)$	$5.1 \pm 1.2 \pm 3.0$

ρ-ω interference visible



arXiv:1404.5673

- Best fit model shows does not require $f_0(980)$ component.
- Gives upper limit on the mixing angle between $f_0(500)$ and $f_0(980)$.

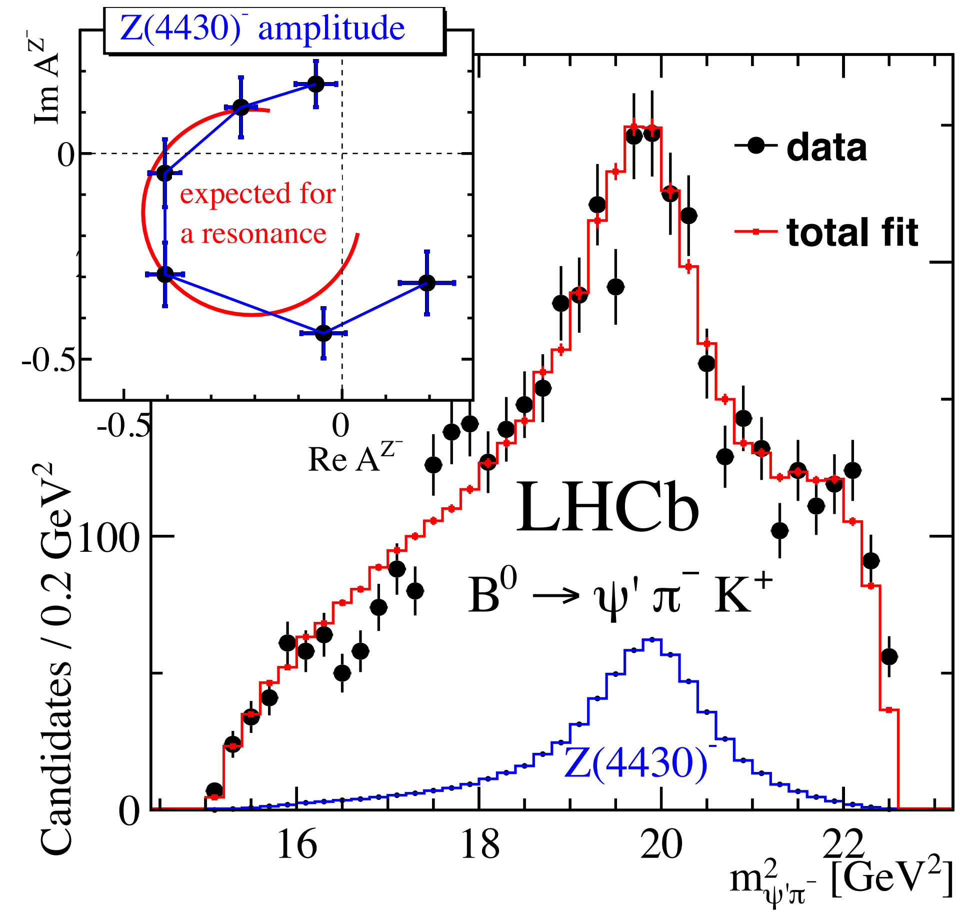
$$\tan^2 \varphi_m \equiv r_\sigma^f = \left(1.1^{+1.2+6.0}_{-0.7-0.7}\right) \times 10^{-2} < 0.098 \text{ at } 90\% \text{ C.L}$$

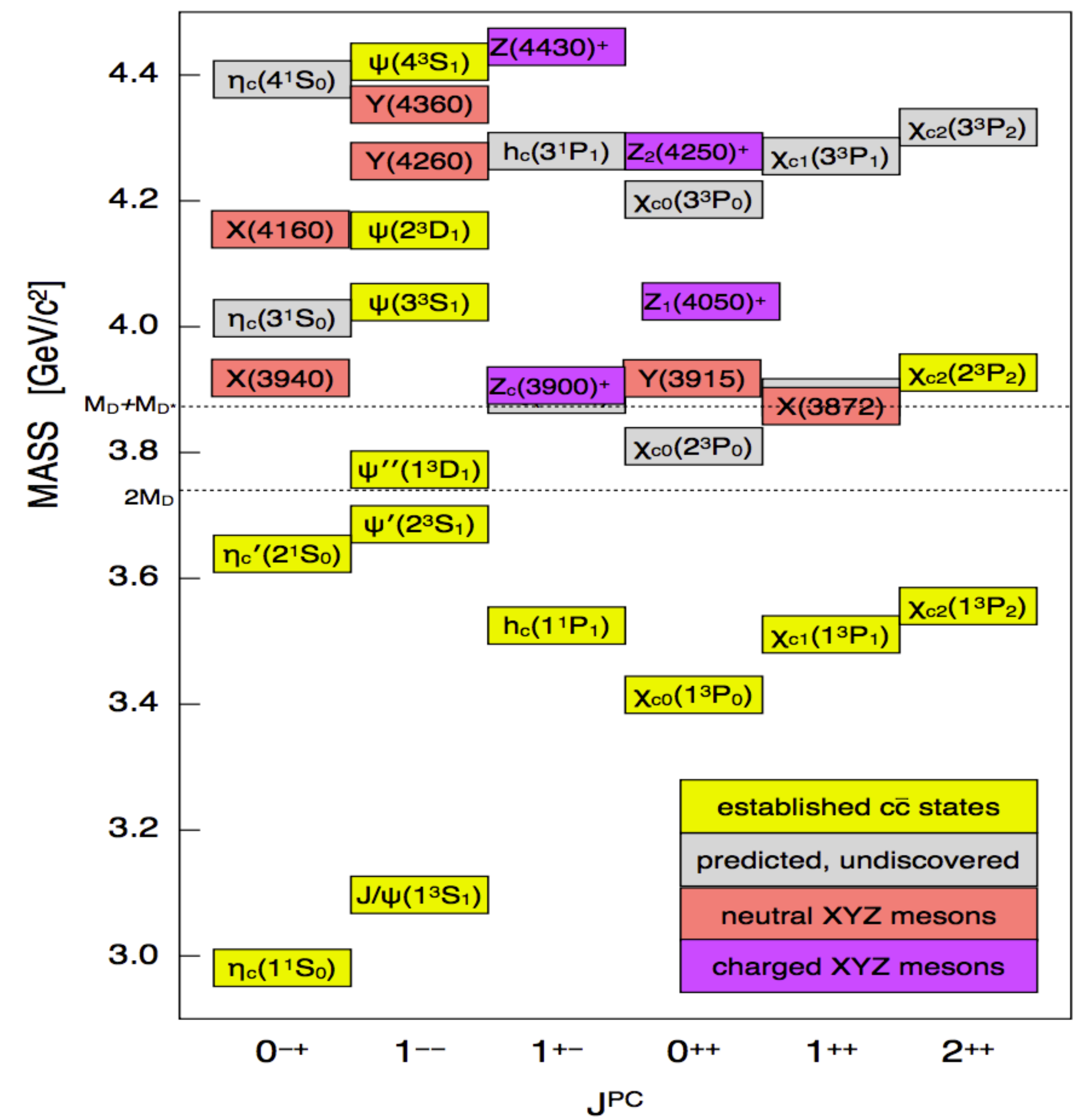
Different from tetraquark prediction (1/2) by 8σ

Summary

- LHCb has confirmed this existence and shown the **resonant** behaviour of the $Z(4430)^{-}$.
- Minimal quark content of **$c\bar{c}u\bar{d}$**.
- No clear picture of the complex system of charmonium-like exotic resonances.
- $Z(4430)^{-}$ should help to improve understanding.
- Further constraints could come from observing this in other decay modes.

- Next steps…
    - LHCb has large datasets of B decays containing J/Ψ, Ψ(2S), χ_{c}… where other exotics could live.
    - Data taking starts again in 2015, looking forward to collecting even higher statistics!



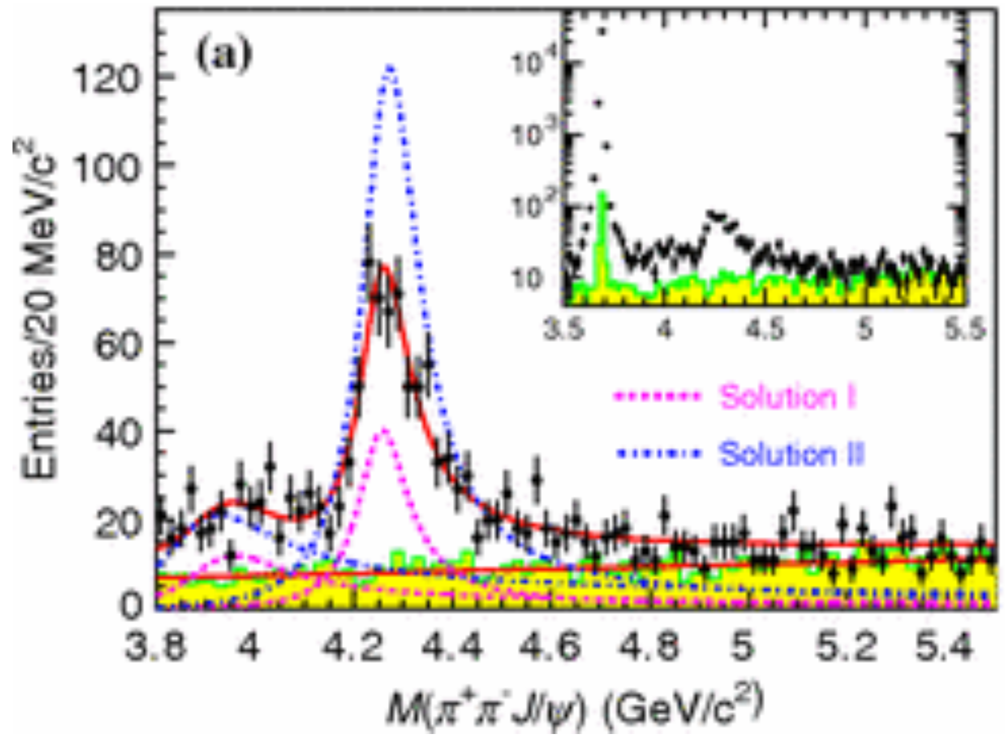


Z(4430) in the media: http://www.phy.syr.edu/~tomasz/z4430.html

BACKUP

$Z_c(3900)$ in $e^+e^- \to \pi^+\pi^- J/\psi$

Y(4260)

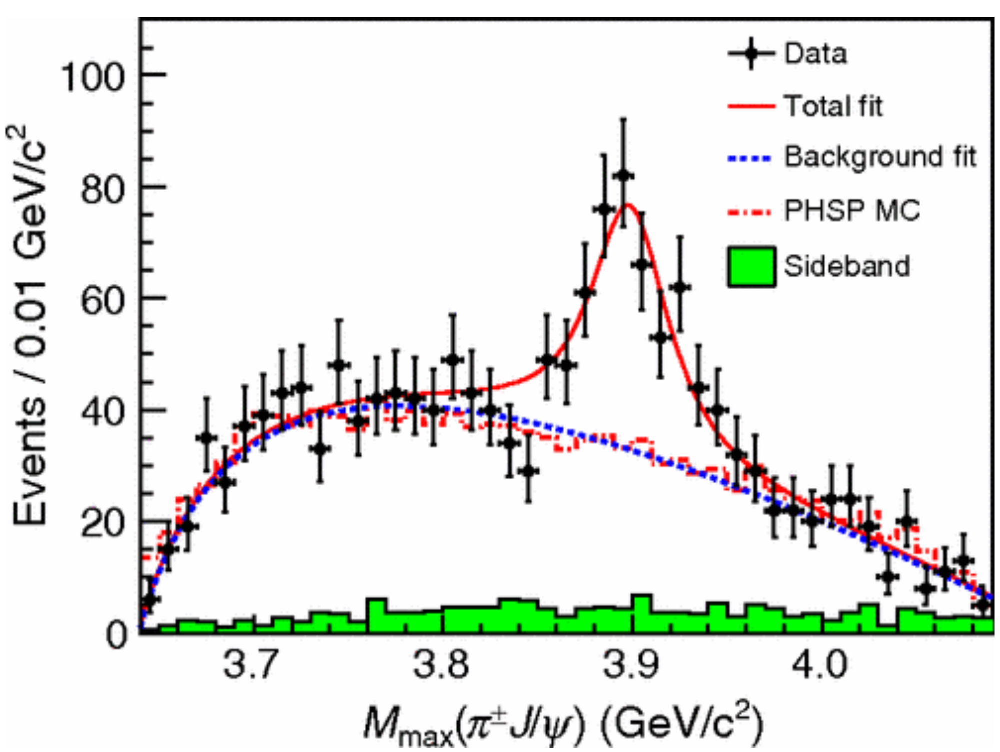


Phys. Rev. Lett. 110, 252002

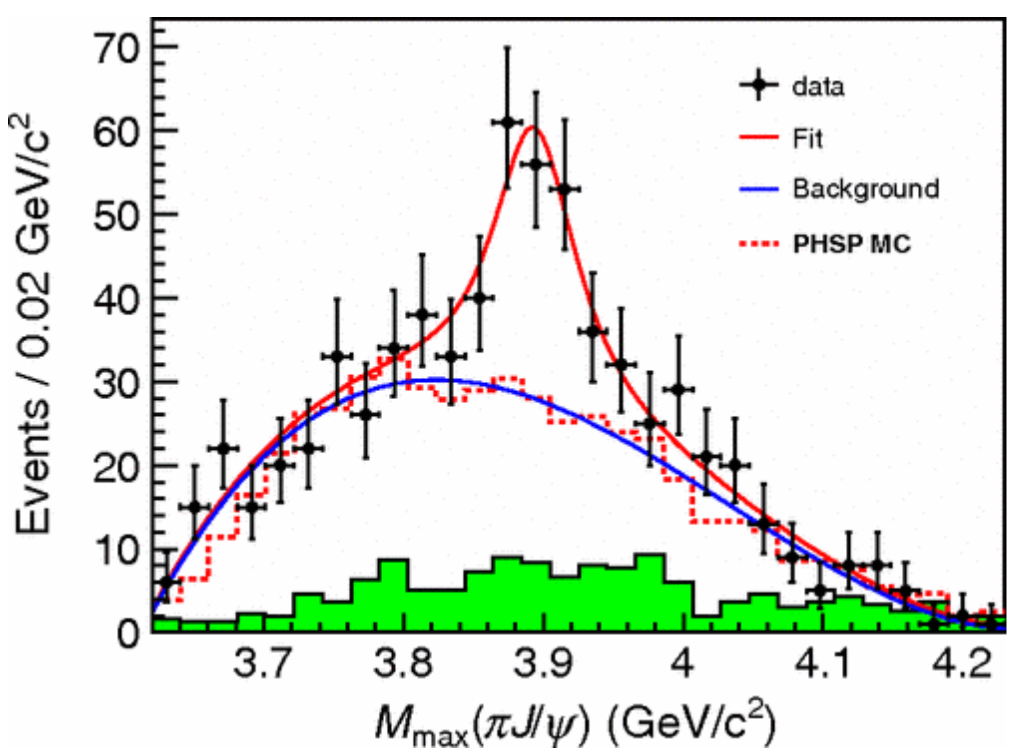
- Other exotic **charged** state observed by BESIII and Belle

$M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2

$\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2



Phys. Rev. Lett. 110, 252001

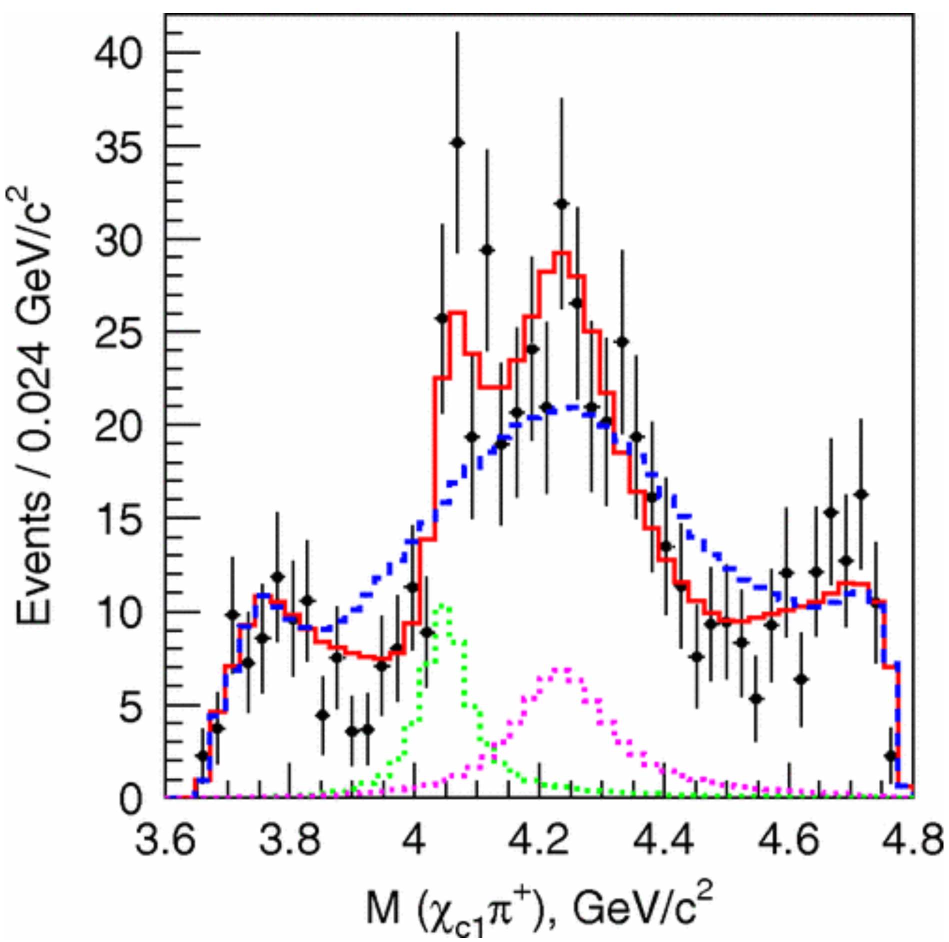


Phys. Rev. Lett. 110, 252002

Other exotic states in quarkonium spectra

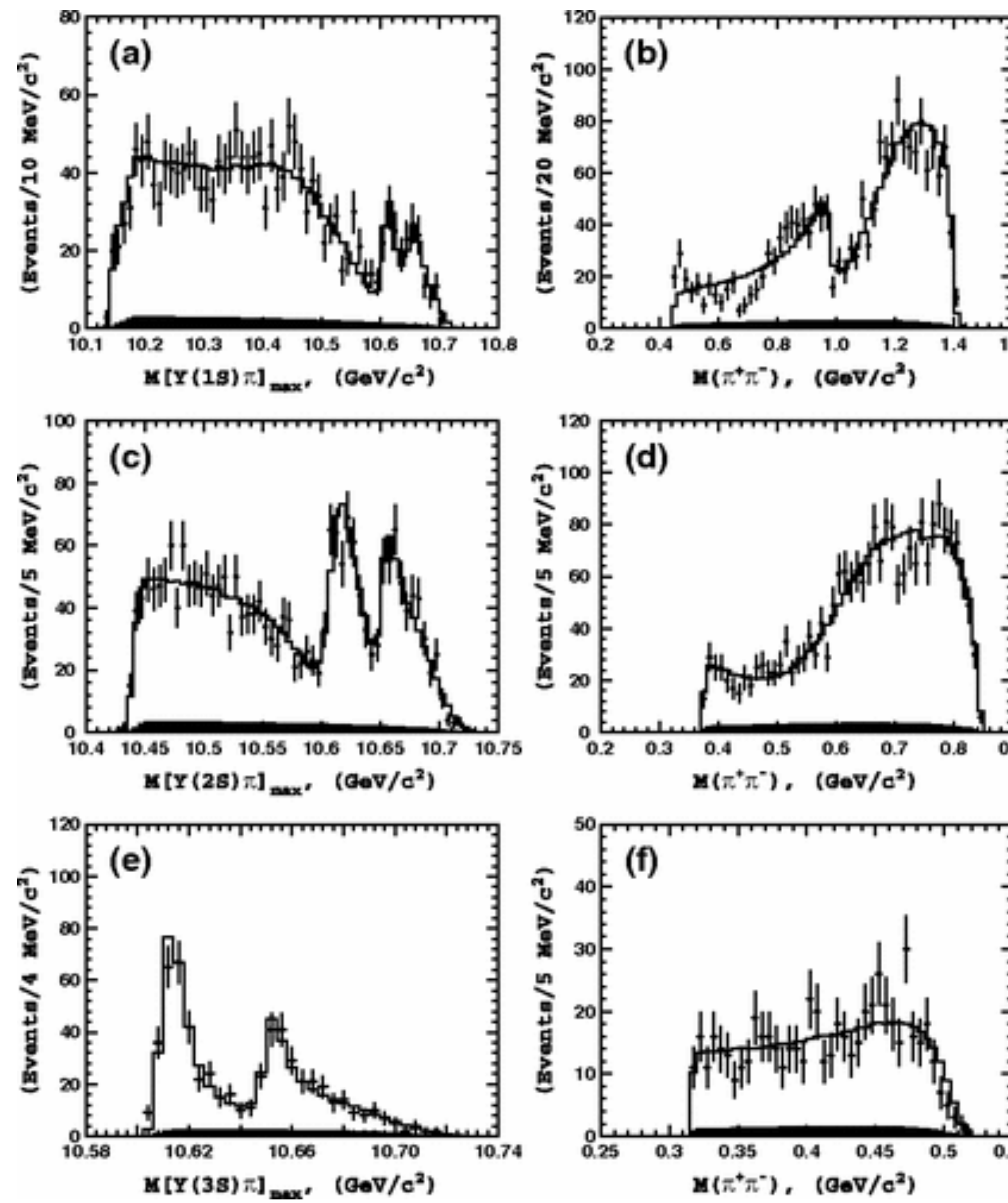
- Belle have evidence for $Z_1(4050)^-$ and $Z_2(4250)^-$ states in $B0 \to Z^- K^+$, $Z^- \to \chi_{c1}\pi^-$.
- BaBar have not confirmed… Phys. Rev. D 85, 052003

- Also Belle has claimed evidence for Z_b resonances when looking at $\mathbf{b\bar{b}}$ spectrum.



PRD 78 (2008) 072004

LHCb should be able to do something here in future

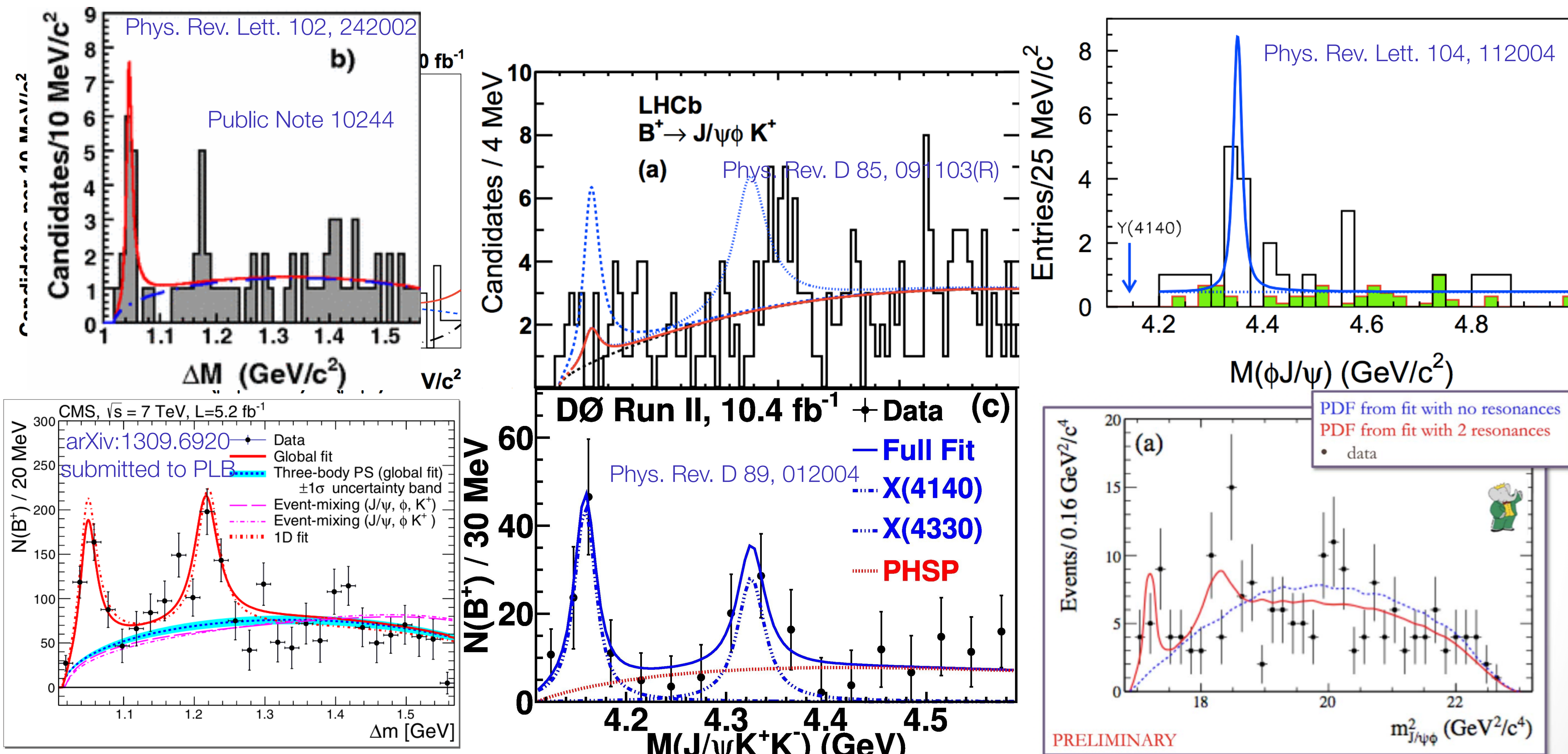


PRL 108 (2012) 122001

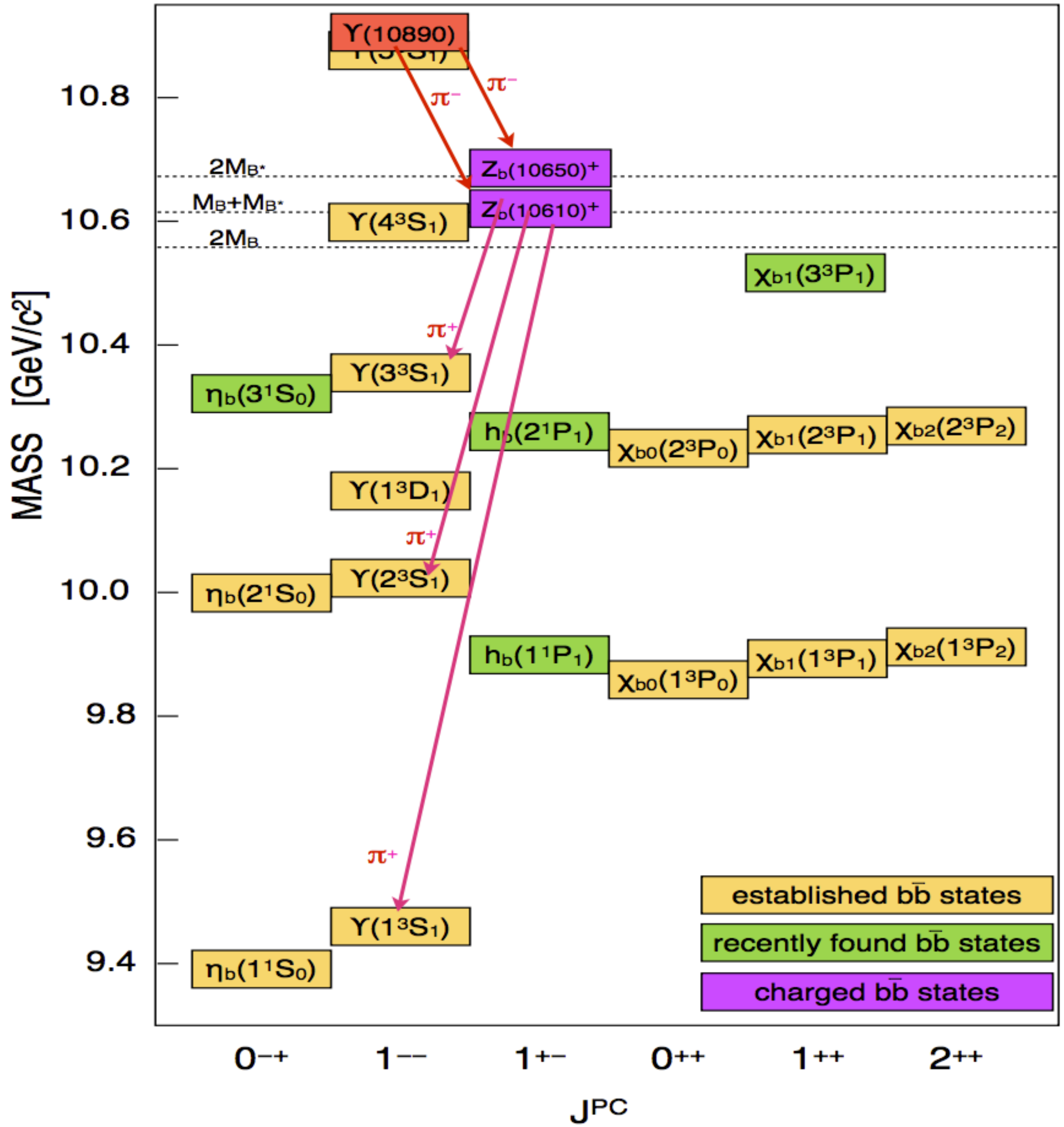
An enigma… the X(4140)

$$B^{\pm/0} \to X K^{\pm/0}$$
$$X \to J/\psi\phi$$

- X(4140) seen by some experiments, not by others in in m(J/ψΦ).
- Could be some hybrid state: **$c\bar{c}s\bar{s}$**



Bottomonium spectrum



Olsen arXiv:1403.1254

Helicity formalism

- Helicity (λ) is projection of $\bar{\mathbf{J}}$ onto $\bar{\mathbf{p}}$ (lambda = -|J|…+|J|)
- a ⟶ bc

$$|\mathcal{M}|^2 \propto \left| A_{\lambda_b,\lambda_c} d^{J_a}_{\lambda_a,\lambda_b-\lambda_c}(\theta) e^{i(\lambda_a-(\lambda_b-\lambda_c))\phi} \right|^2$$

- A is complex helicity coupling
- d are Wigner d-matrices (see tables in PDG)
- θ is helicity angle
- ϕ is azimuthal angle defined by decay plane
  - Dependence drops out unless studying cascade decay like a⟶bc, b⟶de

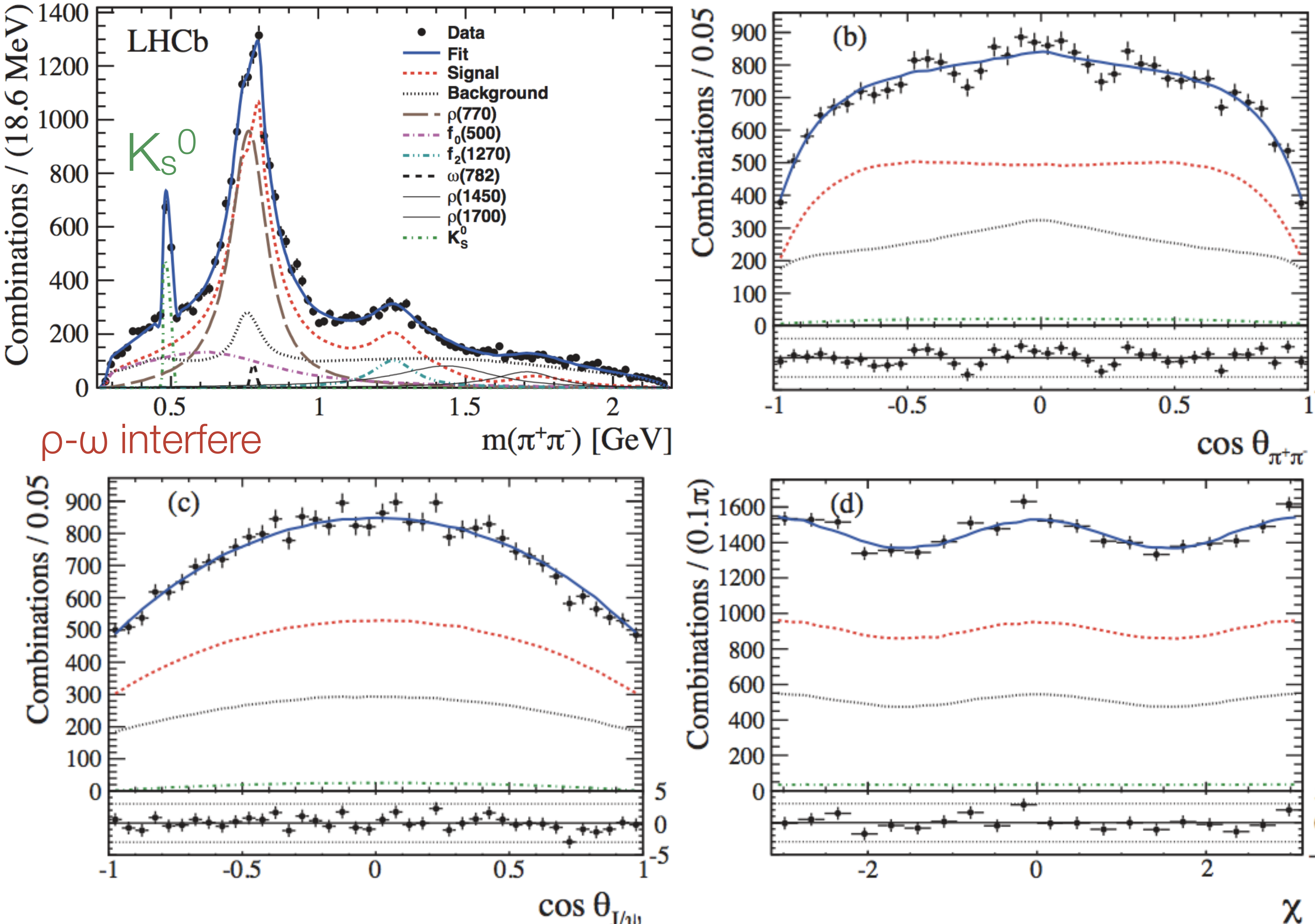
Helicity formalism

- Cascade decays: a⟶bc, b⟶de
- In this case, need to **coherently sum over helicity of intermediate particle**…
- …and **sum incoherently over final state particle helicities**.

$$|\mathcal{M}|^2 \propto \sum_{\lambda_c} \sum_{\lambda_d} \sum_{\lambda_e} \left| \sum_{\lambda_b} A^a_{\lambda_b,\lambda_c} A^b_{\lambda_d,\lambda_e} \cdots \right|^2$$

- For $B^0 \longrightarrow \psi(2S) K^+ \pi^-$
  - B^0 is spin-0, $\lambda_B = 0$
  - $\psi(2S) \longrightarrow \mu^+\mu^-$ is EM decay, $\Delta\lambda_\mu = \pm 1$

Amplitude analysis of $B^0 \longrightarrow J/\Psi\pi^+\pi^-$



arXiv:1404.5673

References

- PDG review on light scalar mesons
- Amsler et al, Physics reports 389 (2004) 61-117
- Close http://arxiv.org/pdf/hep-ph/0204205v3.pdf
- Polosa et al (Z(4430), tetraquark model) http://arxiv.org/pdf/1405.1551.pdf
- Gell-Mann (Schematic model of baryons and mesons) Physics Letters volume 8, number 3 (1964).
- http://pdg.lbl.gov/2011/reviews/rpp2011-rev-clebsch-gordan-coefs.pdf