Confirmation of the exotic $Z(4430)^{\pm}$ resonance at LHCb

Greig Cowan (Edinburgh)
on behalf of the LHCb collaboration

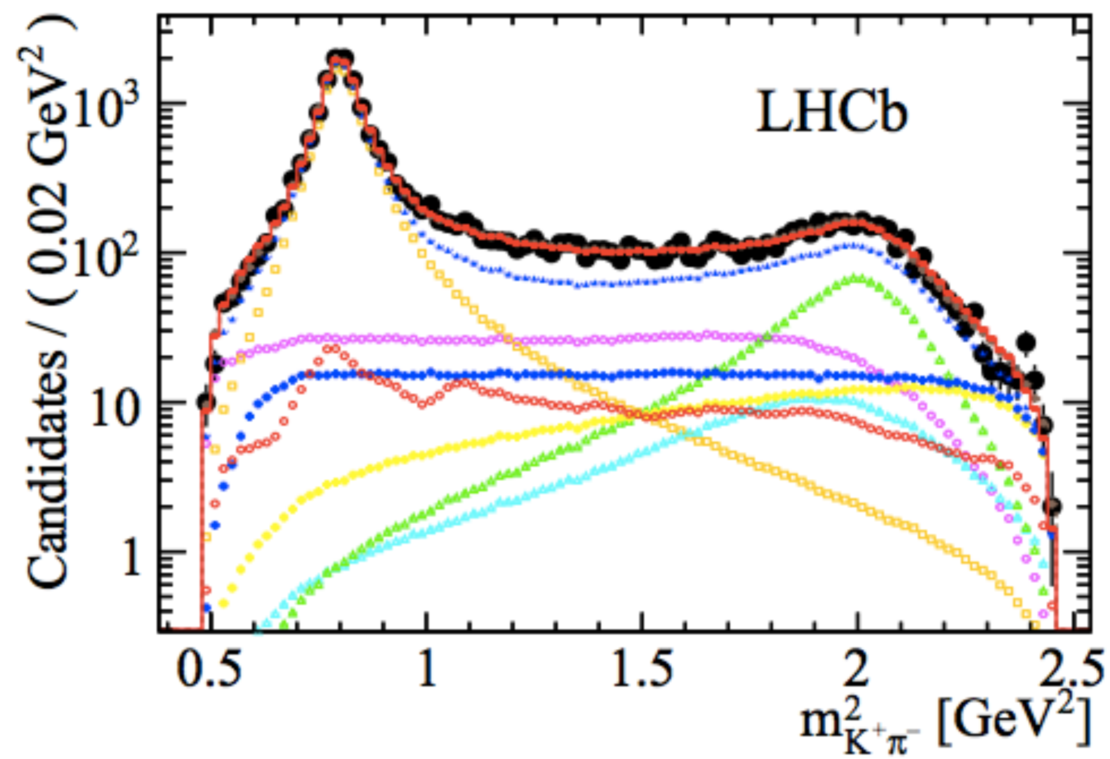
CERN, 3rd June 2014

Science & Technology Facilities Council

Overview

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

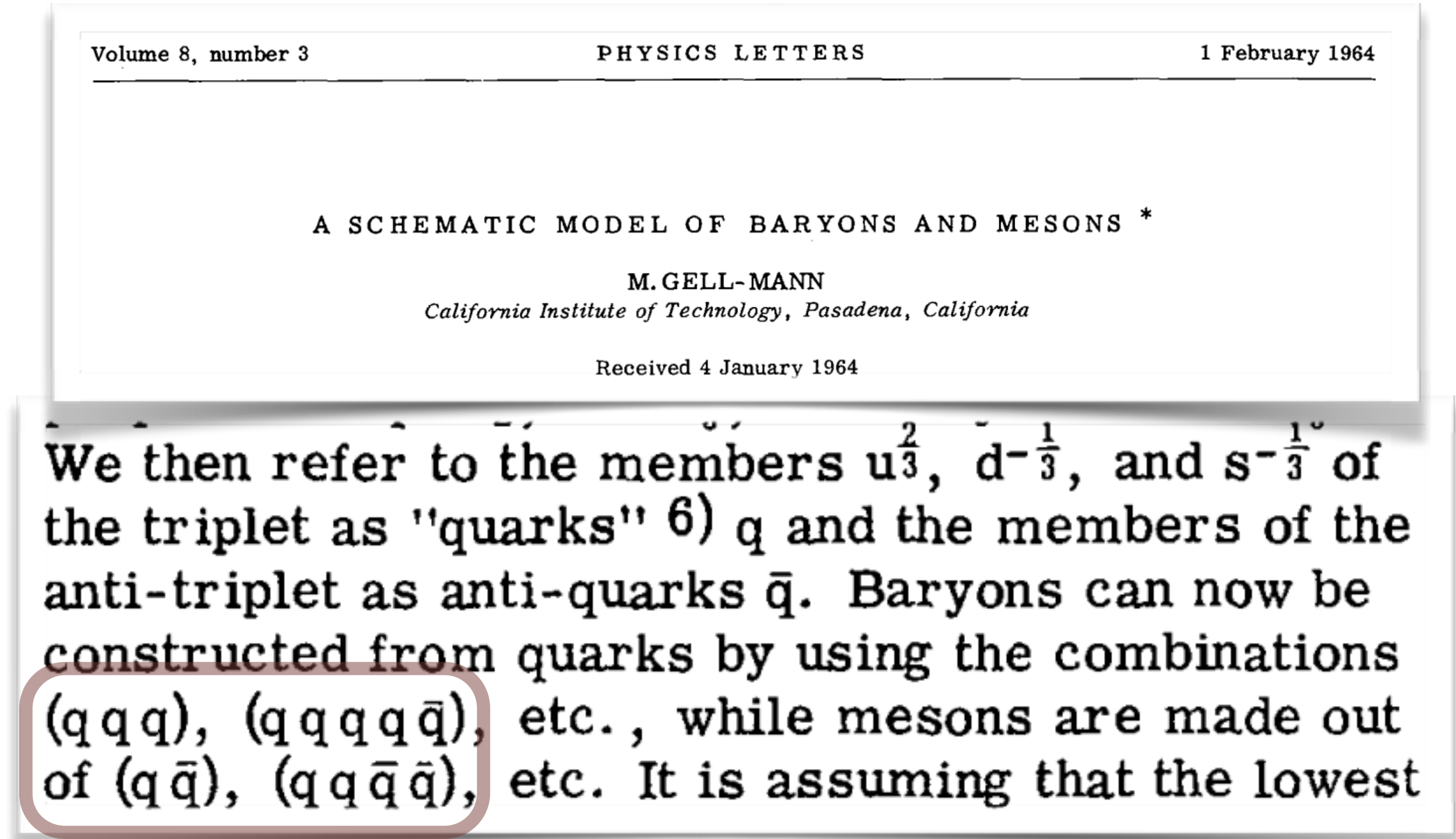
Will give some technical details to explain plots like this



[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.
- **qqq̄q̄** 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) make theoretical predictions difficult.
- What about heavier quarks?

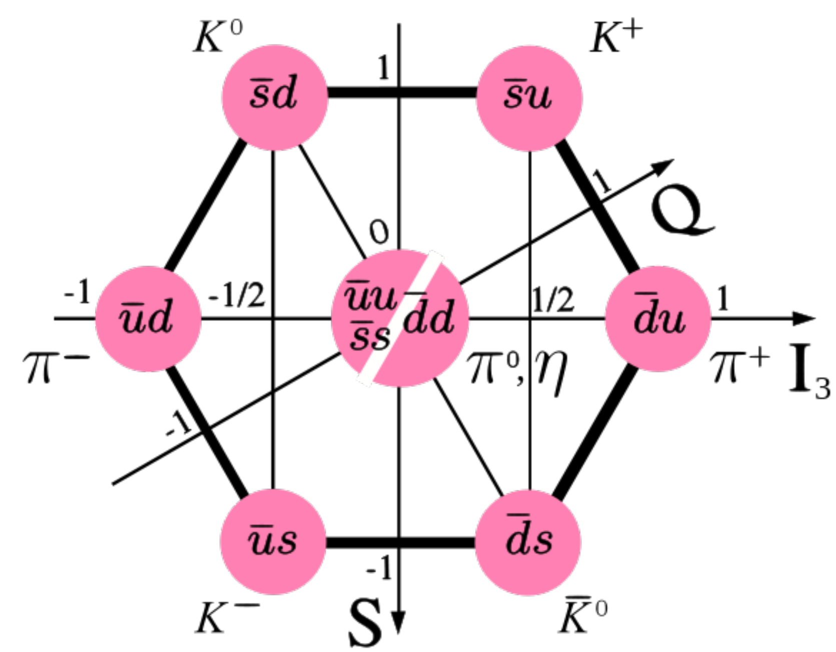

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

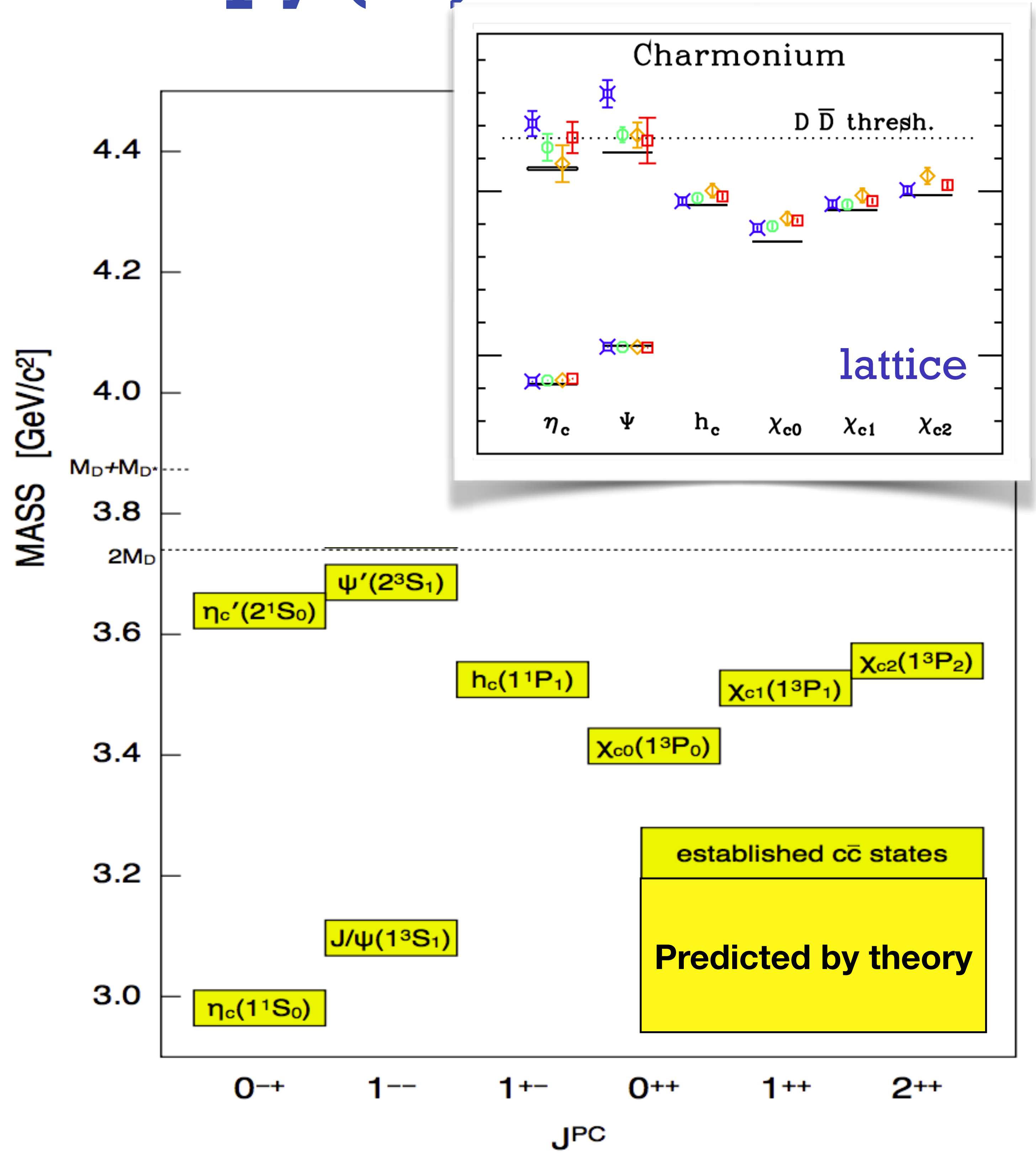
Received 4 January 1964

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$\bar{\text{D}}$ threshold**
  - no mixing of **$c\bar{c}$** with lighter **$q\bar{q}$** states.



[Phys. Rev. D 81, 034508]

[Olsen arXiv:1403.1254]

Classify using J^{PC}

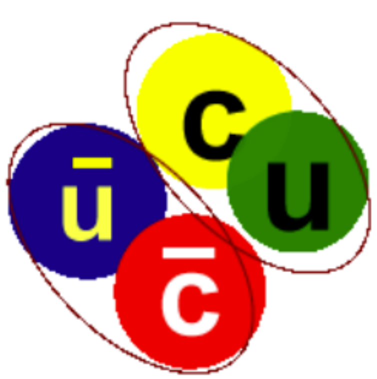
$J = L \oplus S$

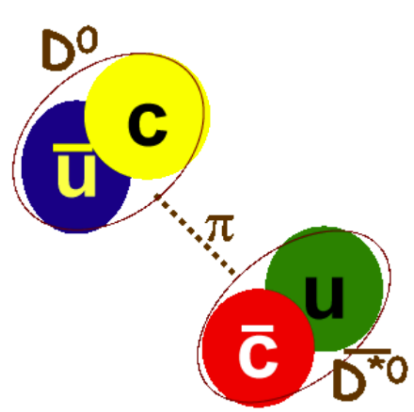
$P = (-1)^{L+1}$

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

Exotic charmonium spectroscopy

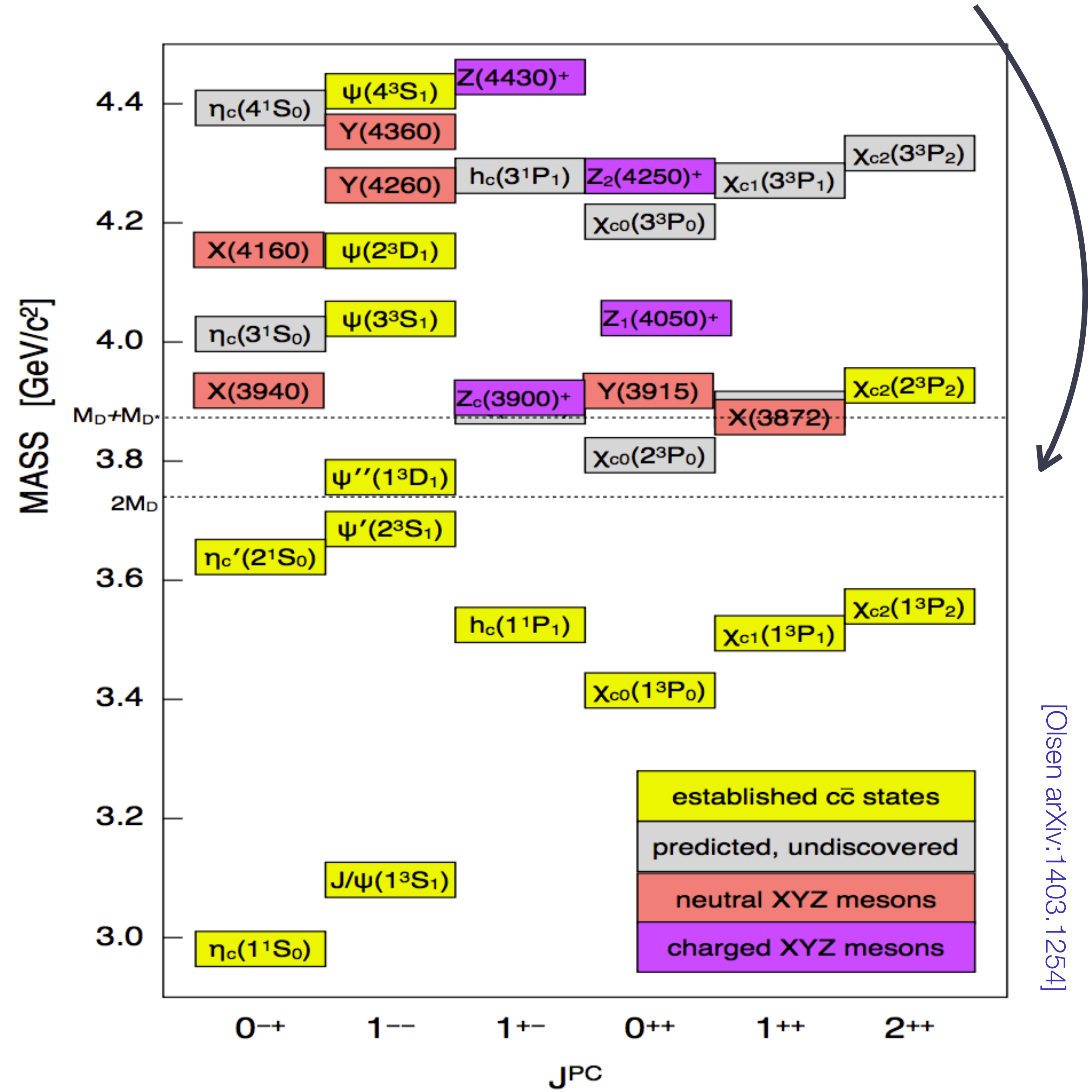
- Many different exotic **(XYZ)** states have been seen.
  - BESIII, Belle/BaBar, CDF/D0
  - mass/width, decay, J^{PC}
- Are these [**QQ**][$\bar{q}\bar{q}$] (tetraquarks), mesonic molecules, threshold effects, hybrids…?
- No clear pattern: need experimental, theoretical study to understand strong interaction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





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

open charm thresholds



[Olsen arXiv:1403.1254]

Lattice calculations begin to support existence of exotic charged states [arXiv:1405.7623v1]

The LHCb experiment

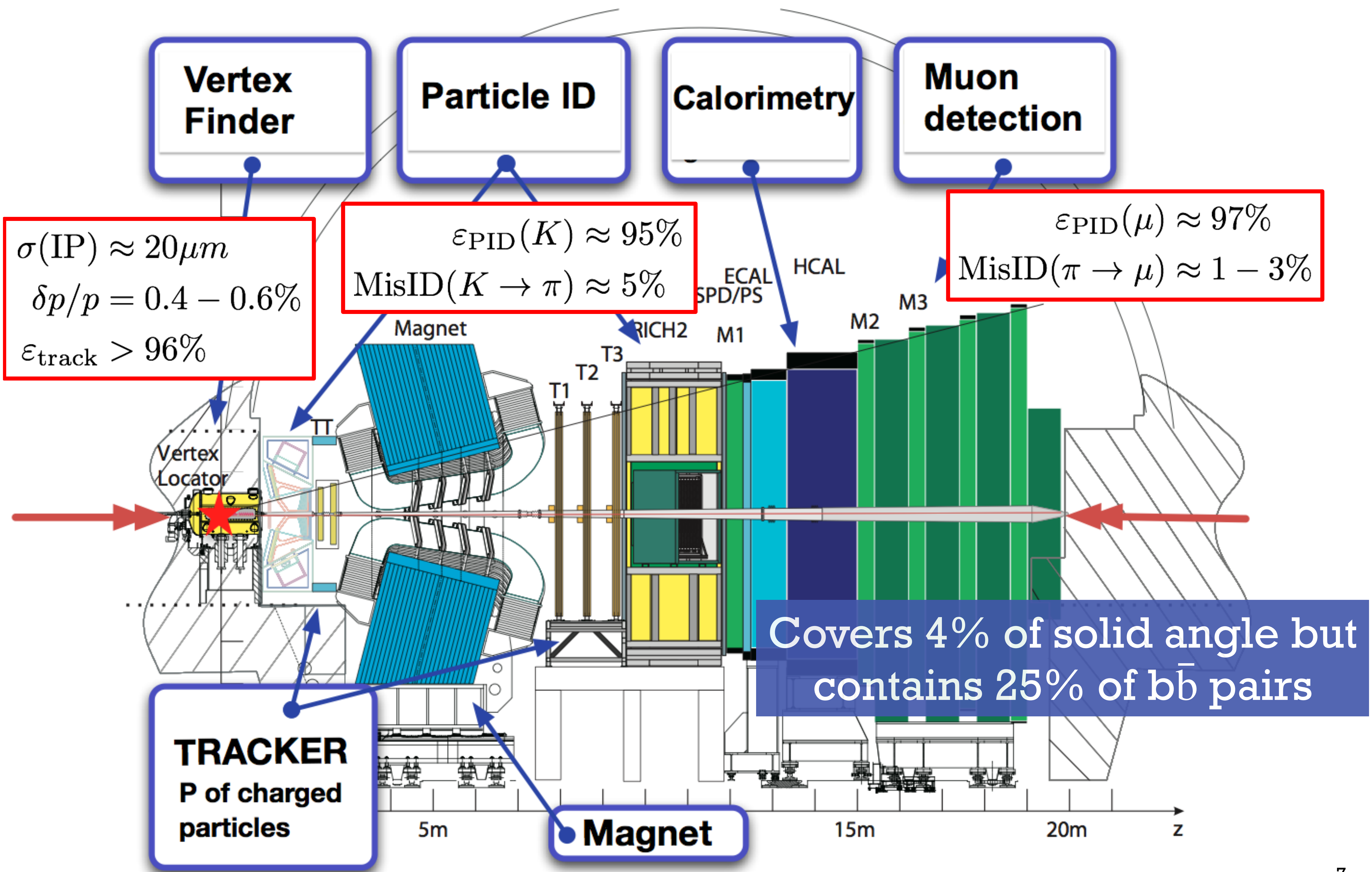
- Rare B decays
- CP violation
- Charm physics
- (Exotic) spectroscopy
- QCD and electroweak

- ~900 physicists from 64 universities/labs in 16 countries.
- Running since 2010, **188 papers published**.
- O(100k) $\mathbf{b\bar{b}}$ pairs produced/sec.

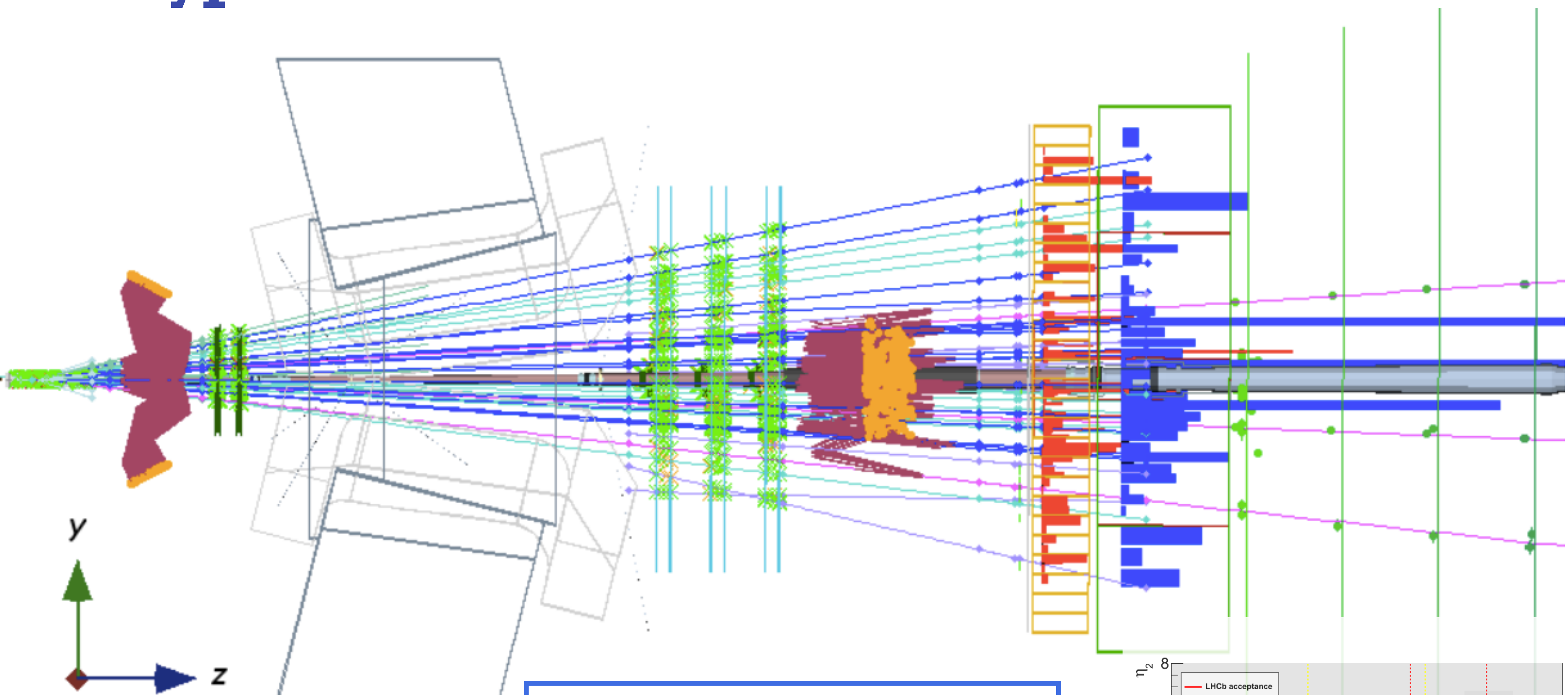
http://cdsweb.cern.ch/collection/LHCb%20Papers?ln=en

The LHCb detector

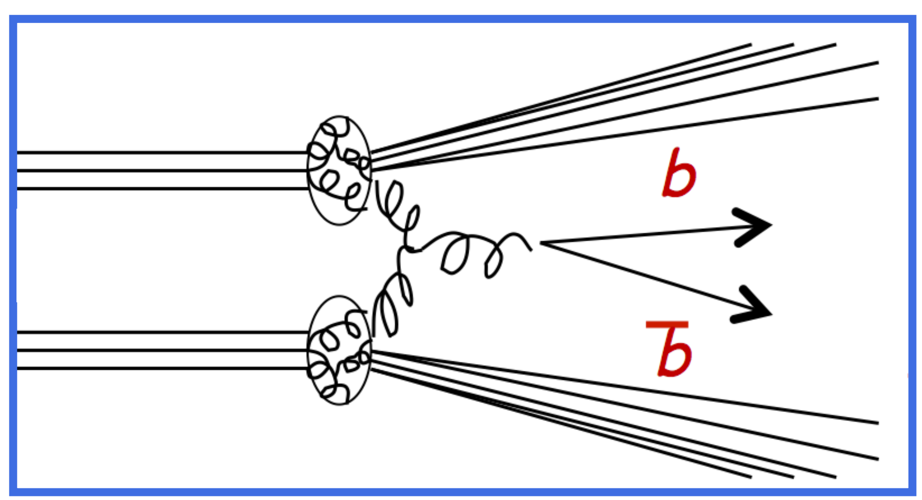
[2008 JINST 3 S08005]

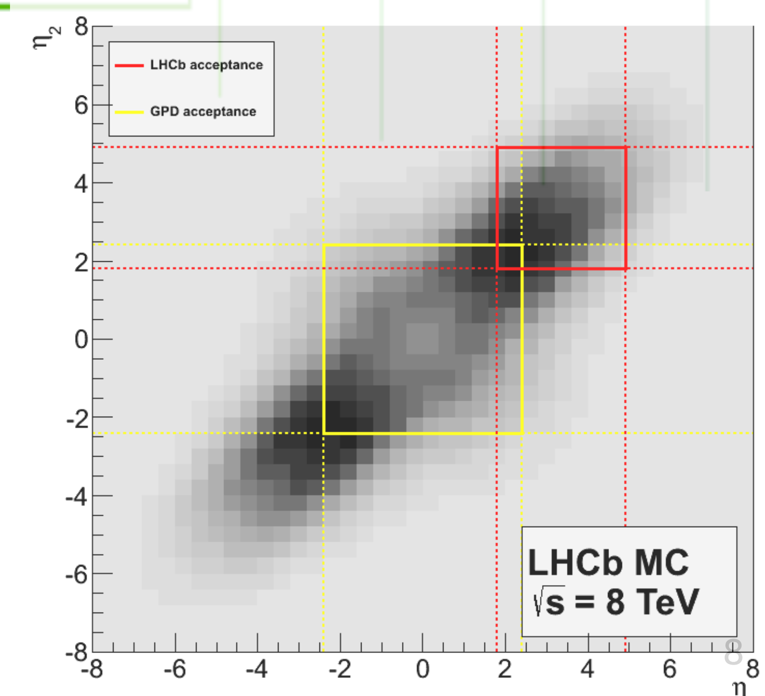


A typical LHCb event



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





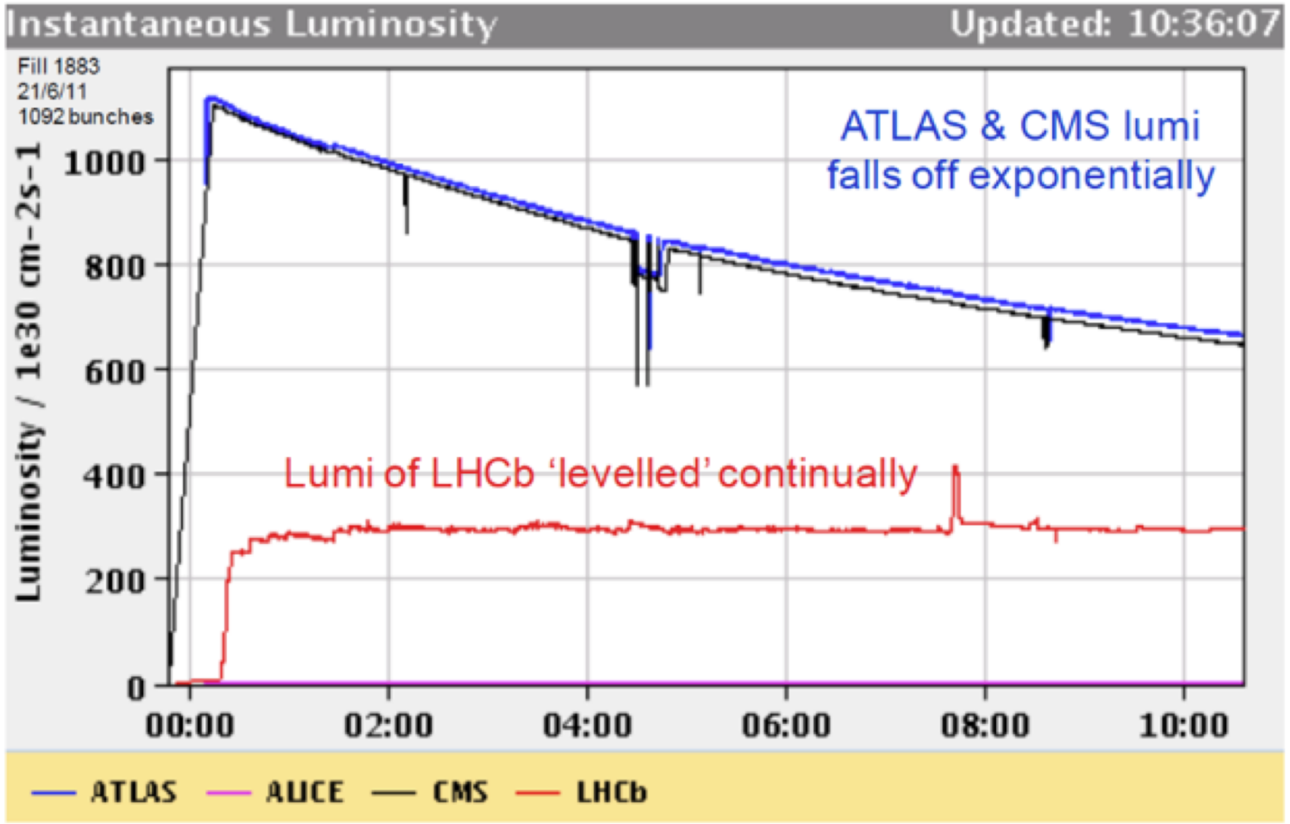
$$\sigma(p\bar{p} \to b\bar{b}X) \sim 80\mu b$$
$$\sigma(c\bar{c}) \quad \sim 1500\mu b$$

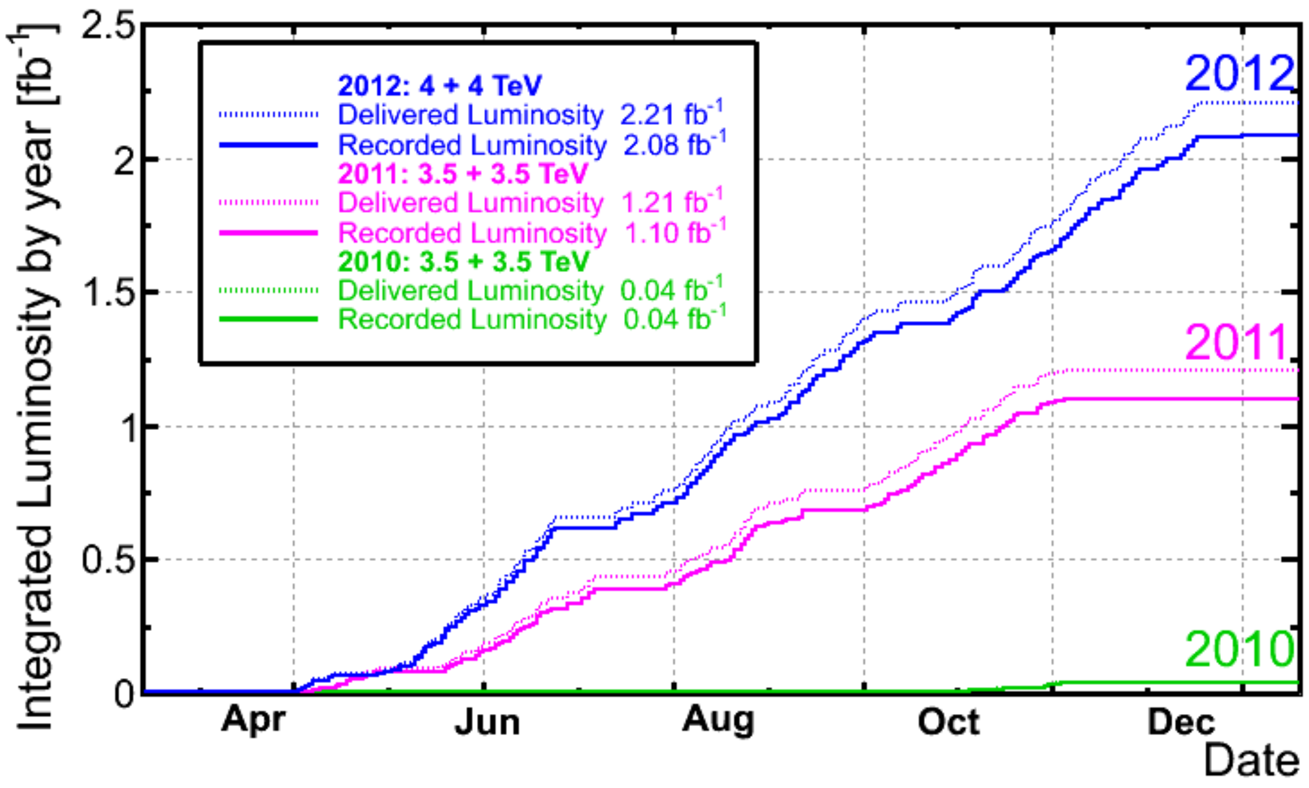
B hadrons fly ~1cm in the detector

Luminosity

$\langle L \rangle_{2011} = 2.7 \times 10^{32}\ \mathrm{Hz/cm^2}$

$\langle L \rangle_{2012} = 4.0 \times 10^{32}\ \mathrm{Hz/cm^2}$





- 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.

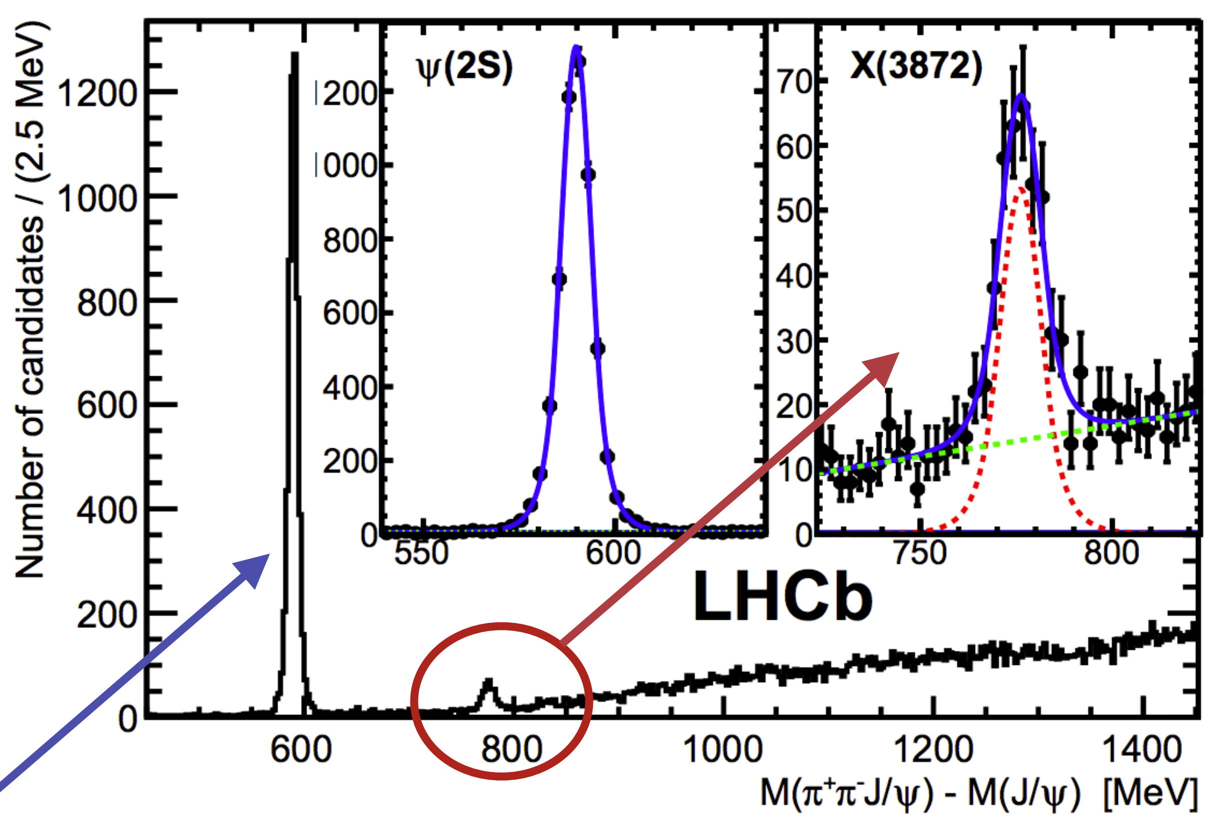
A well known exotic meson: X(3872)

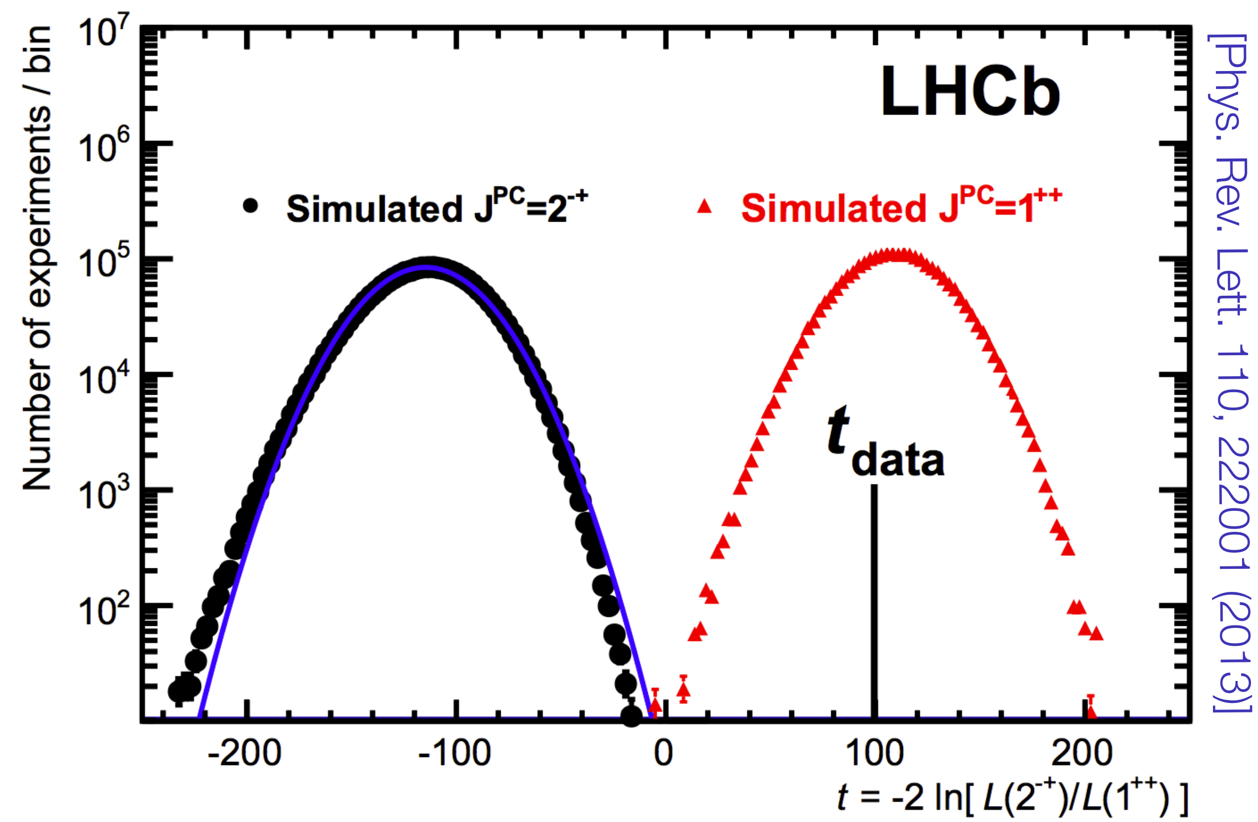
- Observed by 6 experiments, first by Belle
  [PRL 91 (2003) 262001 - 894 citations!]

PDG

$\Gamma_{X(3872)} < 1.2$ MeV
$M_{X(3872)} = 3871.68 \pm 0.17$ MeV
$M_{D0} + M_{D^{*0}} = 3871.85 \pm 0.20$ MeV

- $B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow J/\psi\pi^+\pi^-$
- Measured $J^{PC} = 1^{++} \Rightarrow$ unlikely to be conventional charmonium
- Exotic interpretation: **$c\bar{c}u\bar{u}$** tetraquark, **$D^0D^{*0} = (c\bar{u})(\bar{c}u)$ molecule, $c\bar{c}g$**

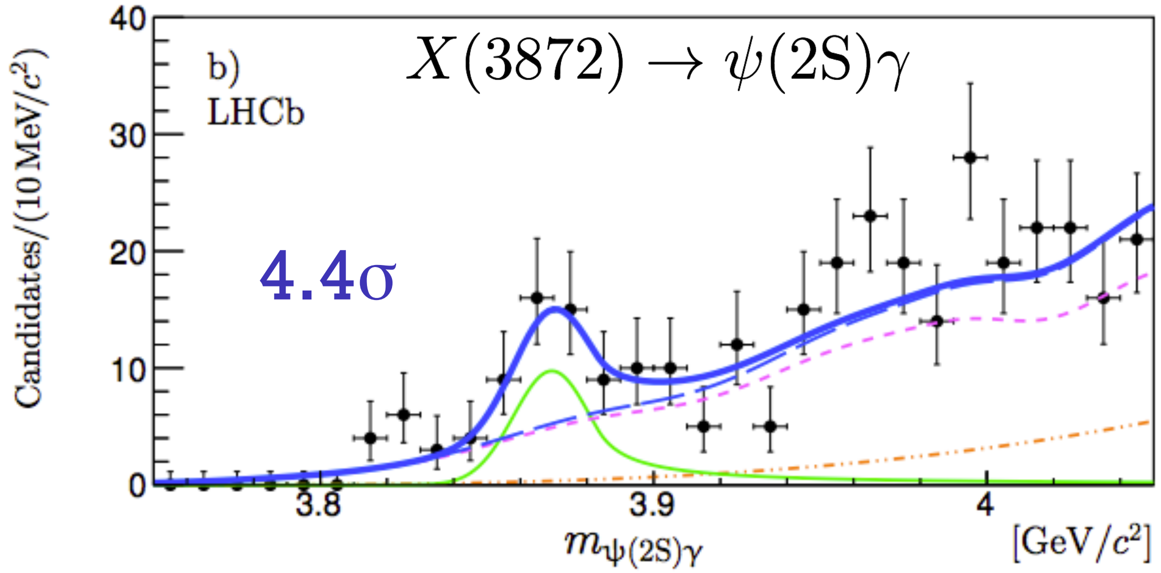


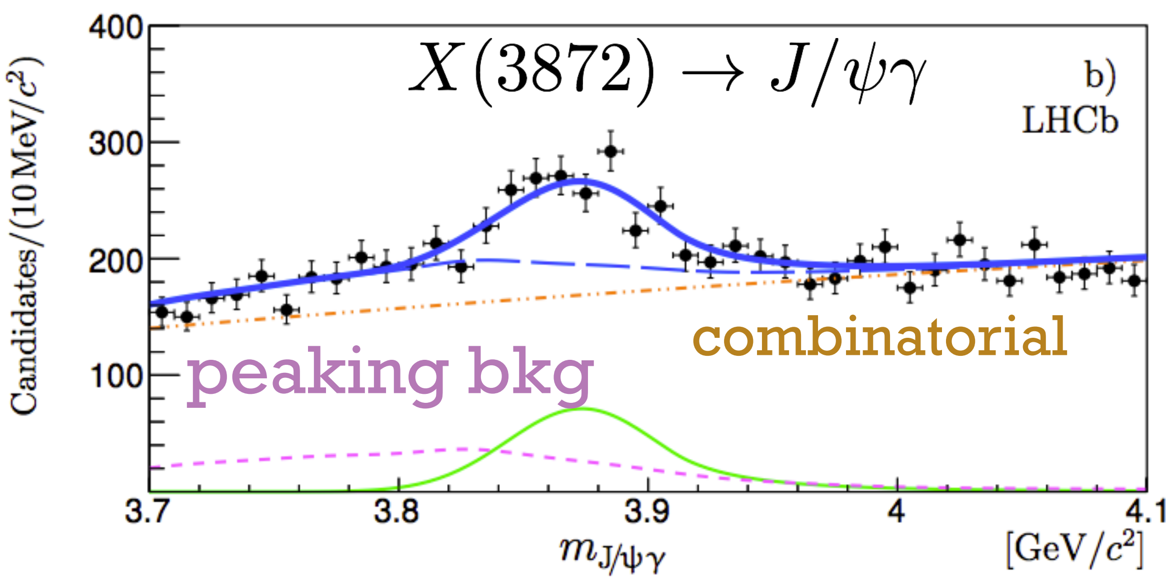


Calibrate using well-known ψ(2S)

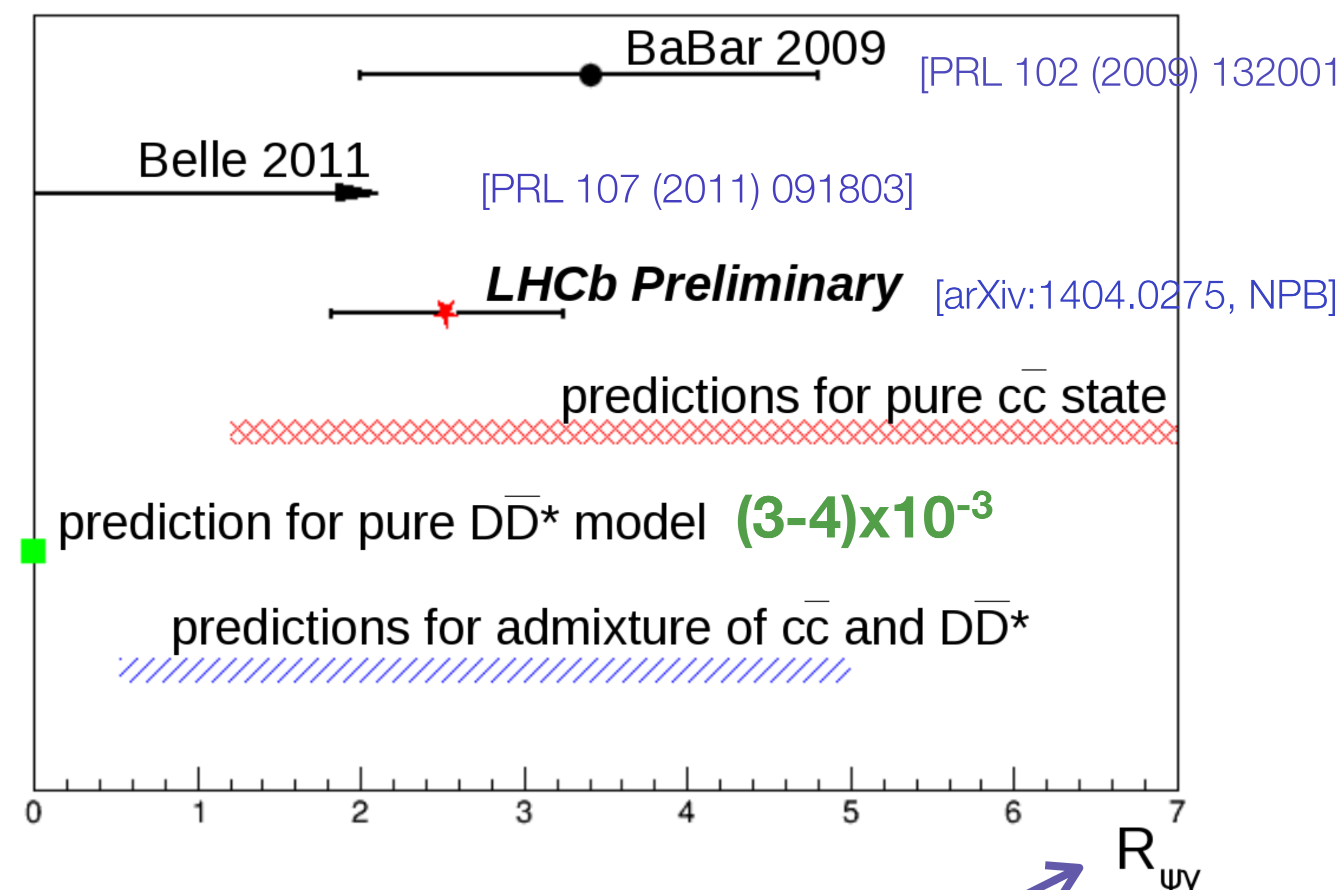
X(3872) seen in B decays and **pp**, **$p\bar{p}$** prompt production

A well known exotic meson: X(3872)





- LHCb has evidence for X(3872) in decays of $B^+ \to \psi\gamma K^+$, $\psi \to \mu^+\mu^-$
- Efficiency($\psi(2S)\gamma$) / Efficiency($J/\psi\gamma$) ~ 0.2
- Detecting soft photons at hadronic collider is hard.
- Pure DD* molecule interpretation disfavoured.



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

Probe of internal structure of X(3872)

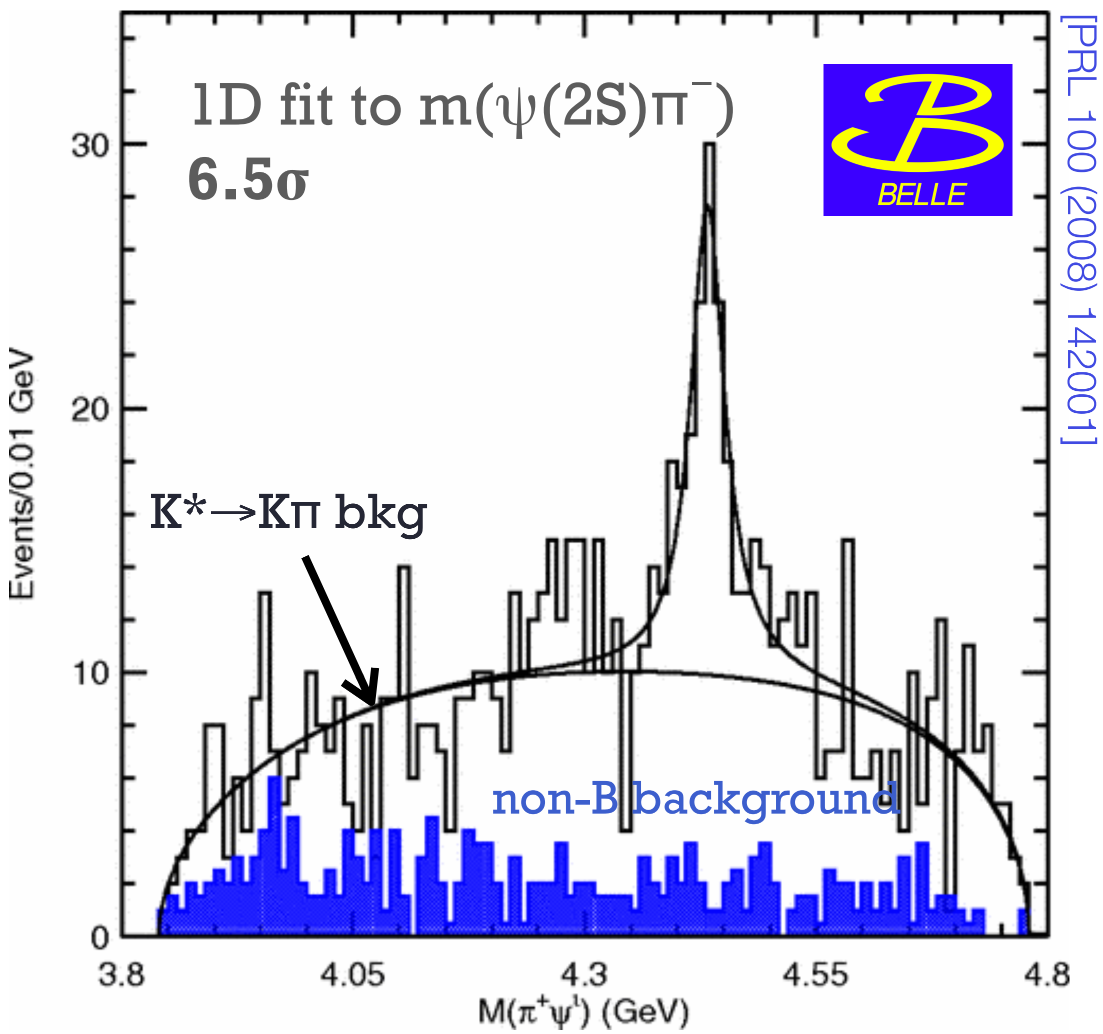
History of the Z(4430)$^\pm$

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

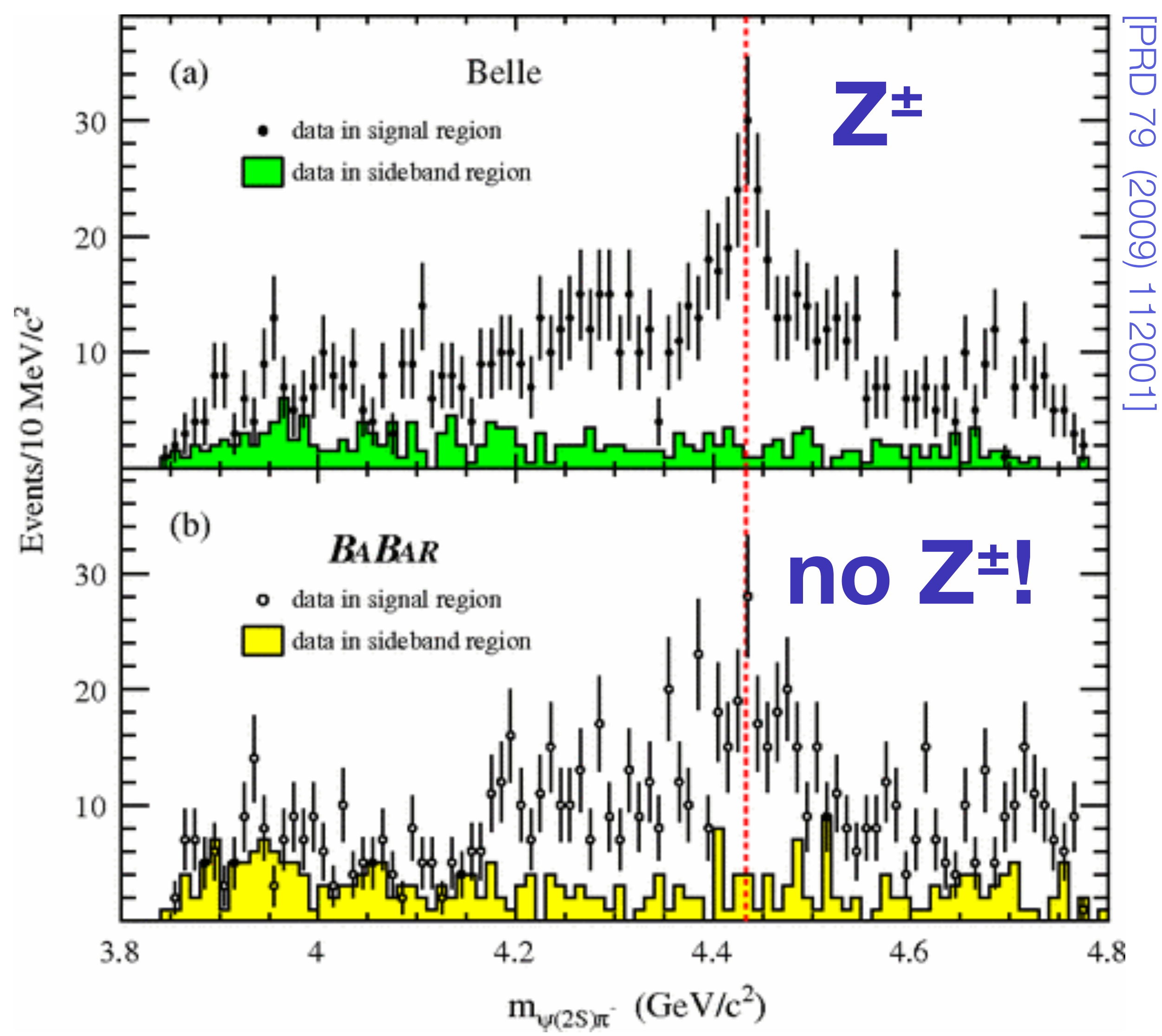
$B^{+,0} \longrightarrow Z(4430)^- K^{+,0}$, with $Z(4430)^- \rightarrow \psi(2S)\pi^-$ and $\psi(2S) \rightarrow \mu^+\mu^-, J/\psi\pi^+\pi^-$

+ charge conjugate

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



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



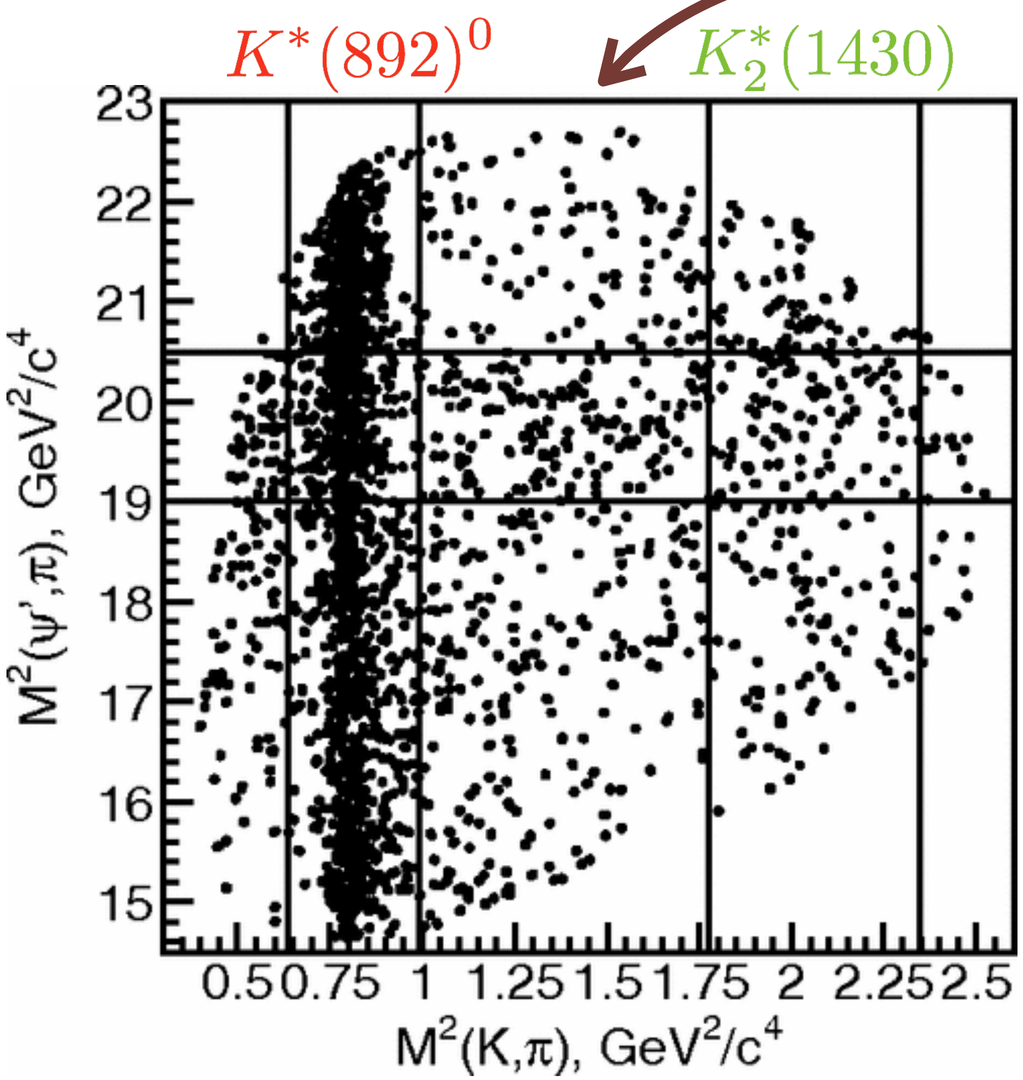
Not observed by BaBar!

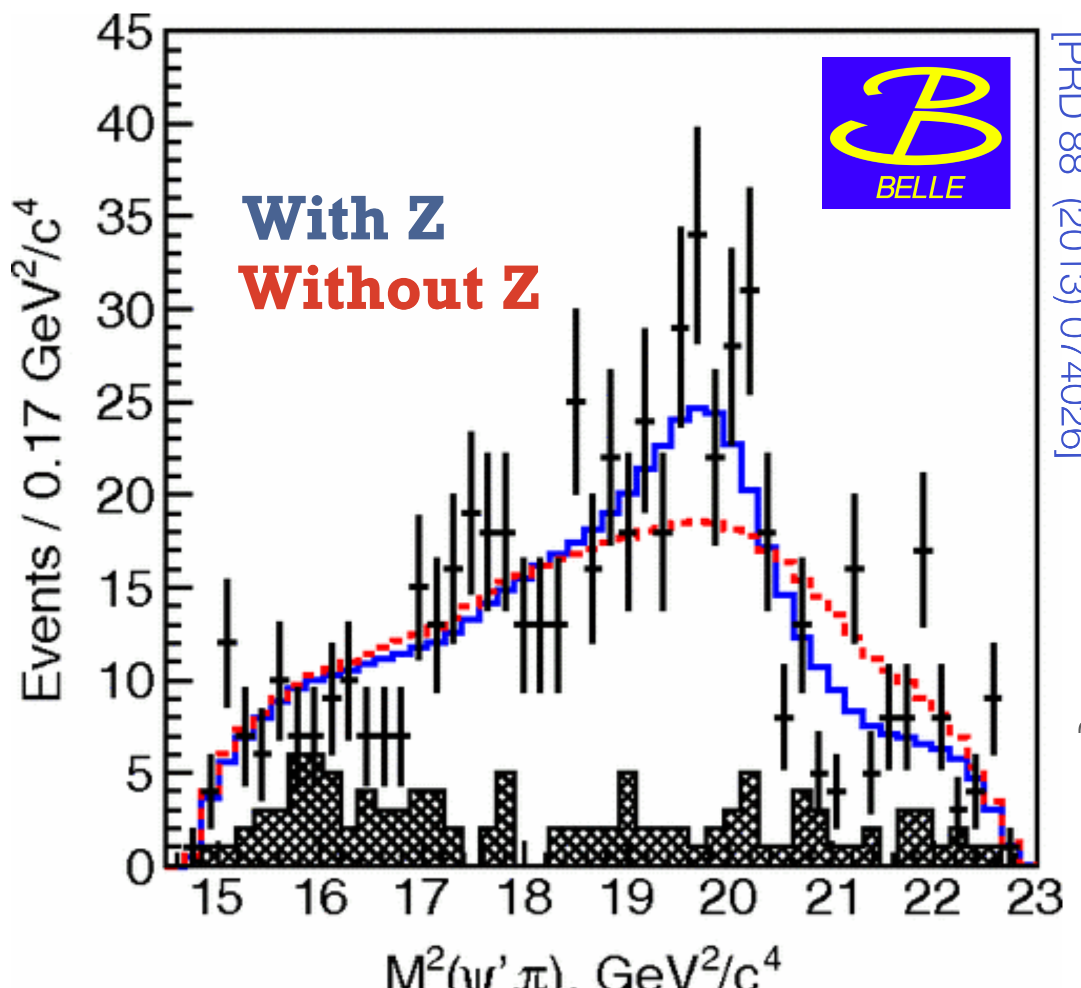
History of the Z(4430)$^-$

M(D*)+M(D**)=4472 MeV

- Belle **[PRL 100 (2008) 142001]** 1D fit to $m(\psi'\pi^-)$ **6.5σ**
- BaBar **[PRD 79 (2009) 112001]** **Not observed but does not contradict Belle!**
- Belle **[PRD 80 (2009) 031104]** 2D amplitude fit to $m(\psi'\pi^-)$ vs $m(K^+\pi^-)$ **6.4σ**
- Belle **[PRD 88 (2013) 074026]** 4D amplitude fit **6.4σ**

K* veto region



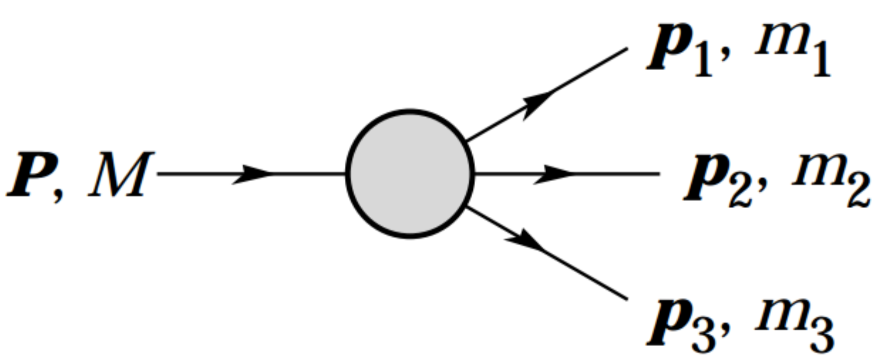


ψ' = ψ(2S)

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

Reminder about Dalitz plots - 3 body decay

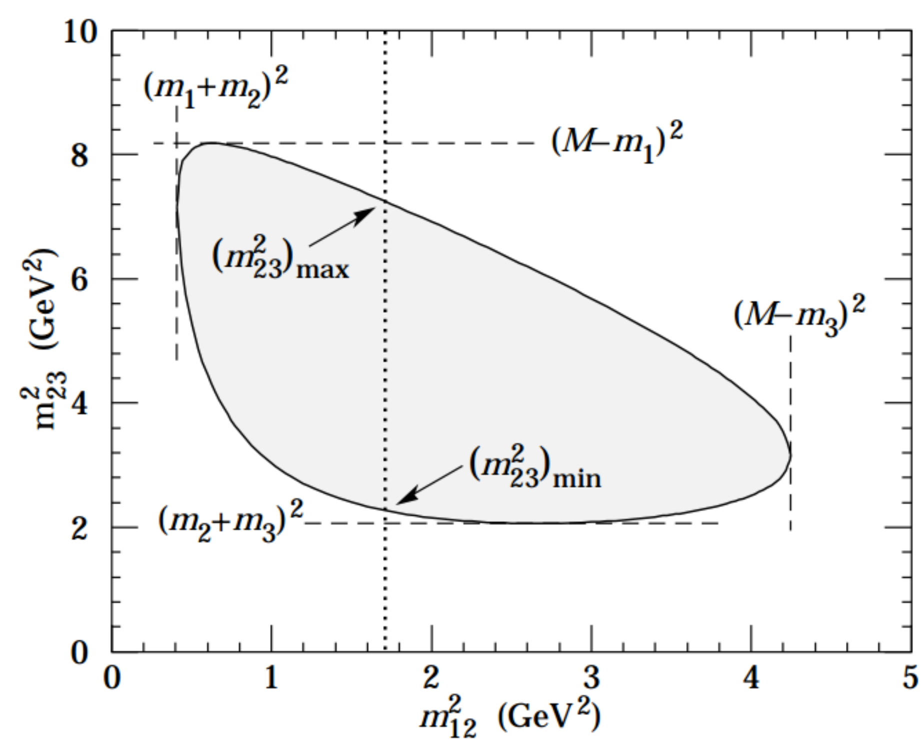
scalar ⟶ 3 scalars



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

Constraints	Degrees of freedom
3 four-vectors	+12
All decay in same plane ($p_{i,z} = 0$)	−3
$E_i^2 = m_i^2 + p_i^2$	−3
Energy + momentum conservation	−3
Rotate system in plane	−1
Total	+2

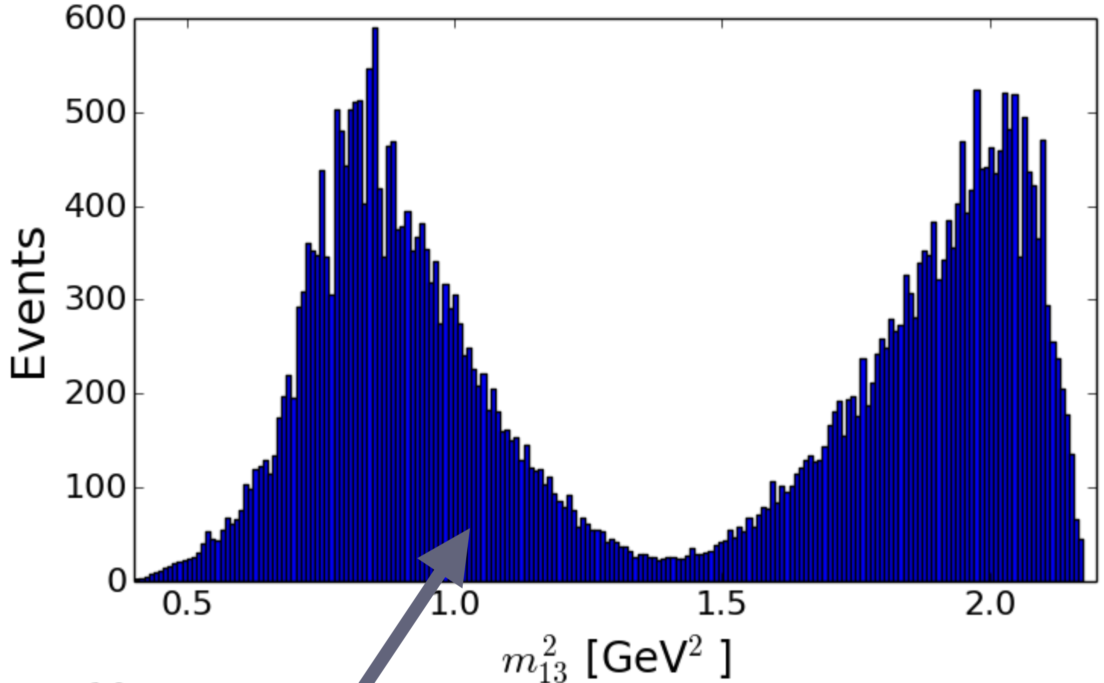
- Configuration of decay depends on angular momentum of decay products.
- All dynamical information contained in $|\mathcal{M}|^2$.
- Density plot of m_{12}^2 vs. m_{23}^2 to infer information on $|\mathcal{M}|^2$.

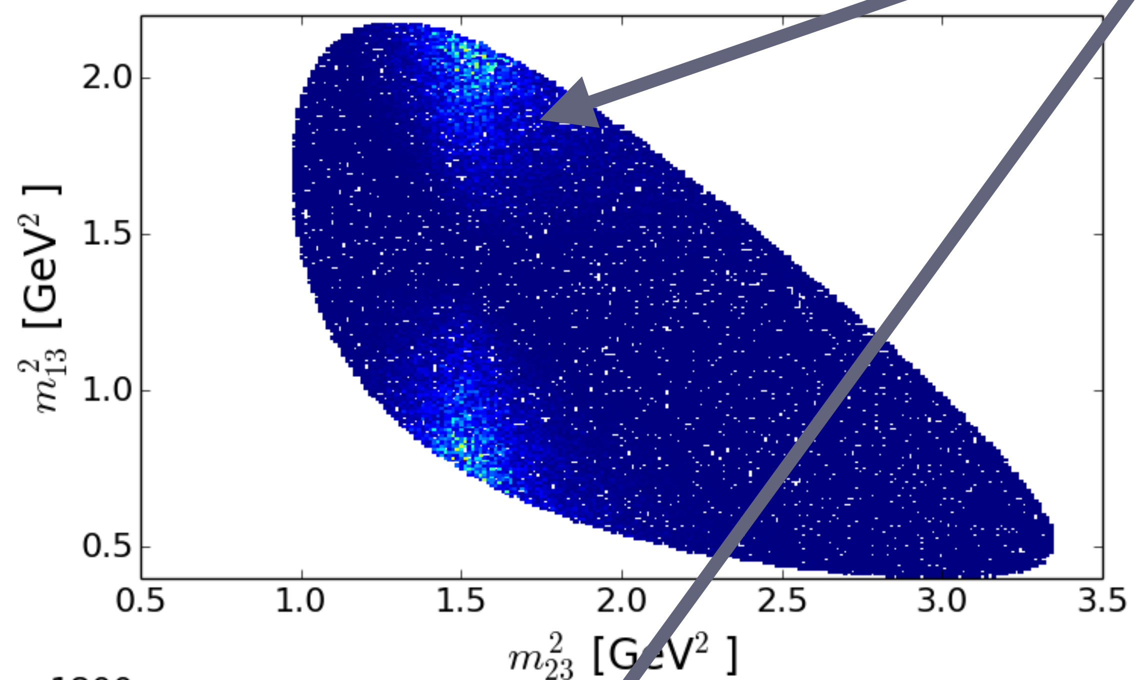


Reminder about Dalitz plots

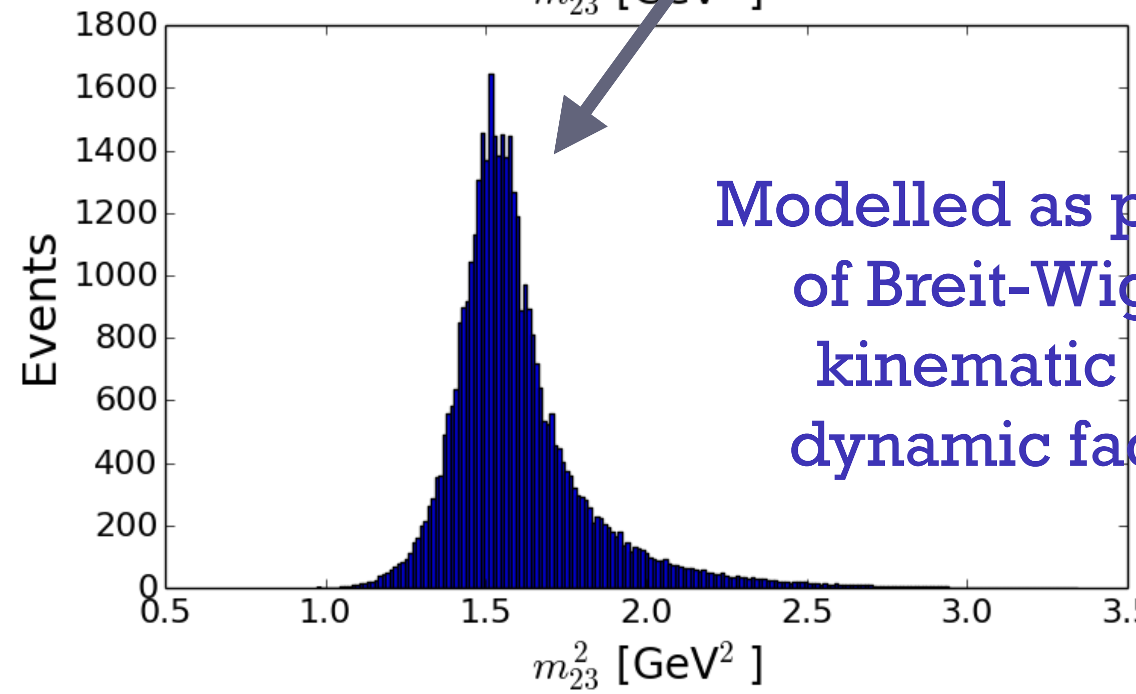
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\,dm_{12}^2\,dm_{23}^2$$

Spin-1 resonance

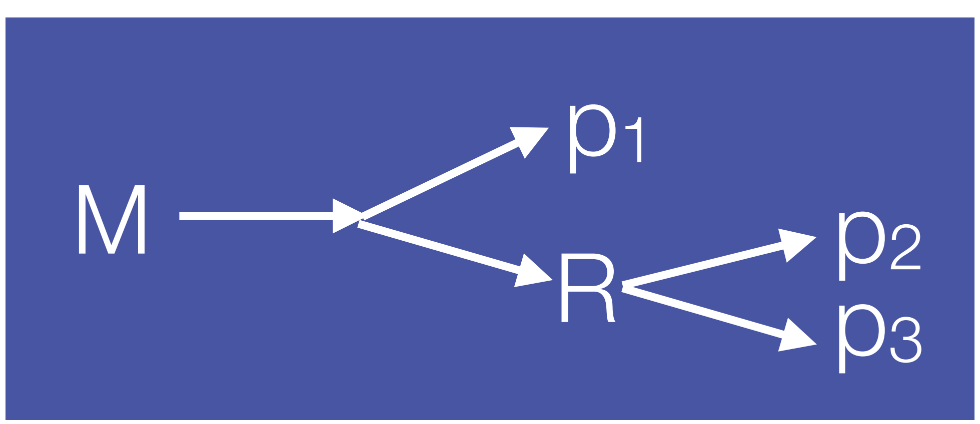




Peaks in distribution do not correspond to a real resonance - just a shadow/reflection

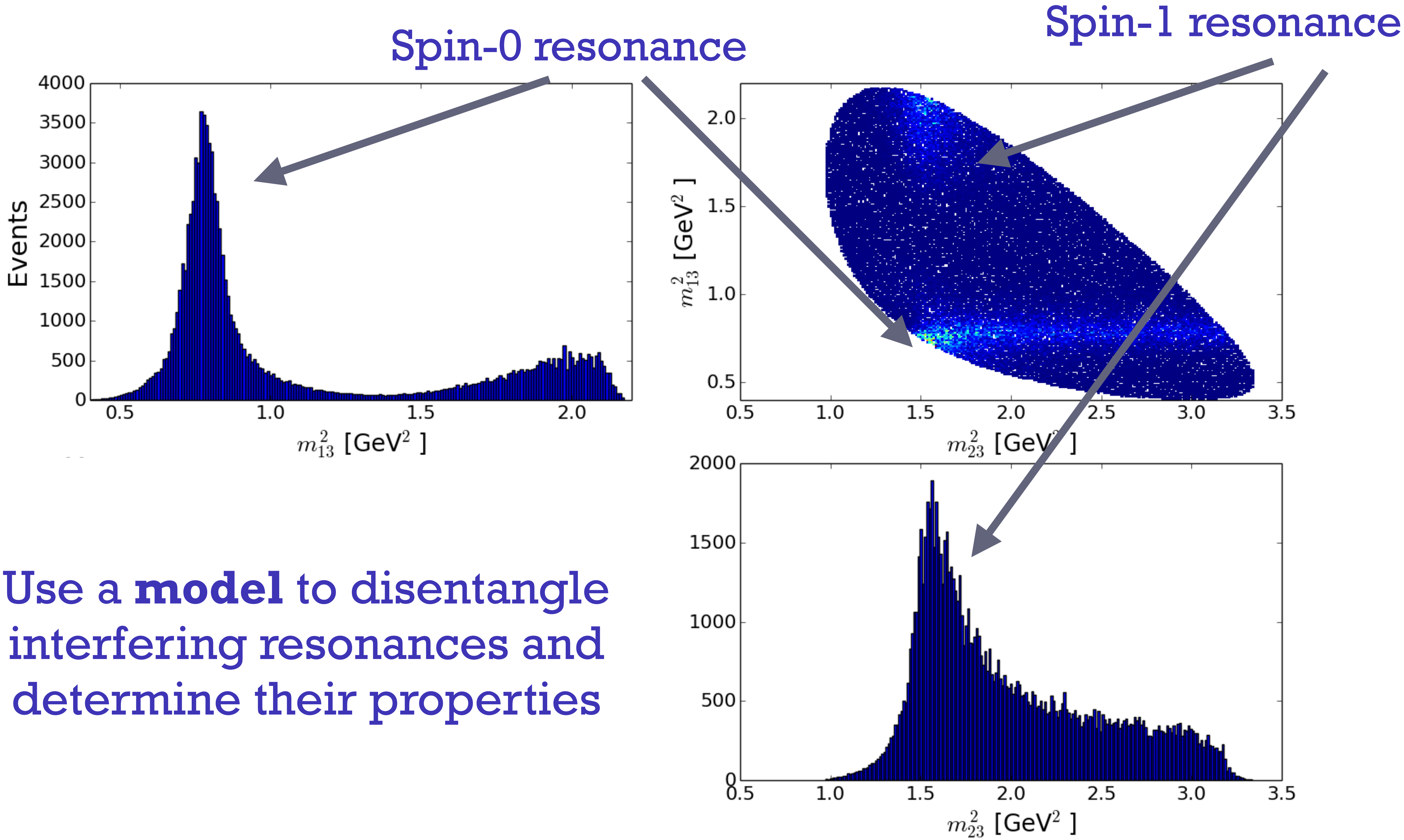


Modelled as product of Breit-Wigner, kinematic and dynamic factors



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

Breit-Wigner amplitude

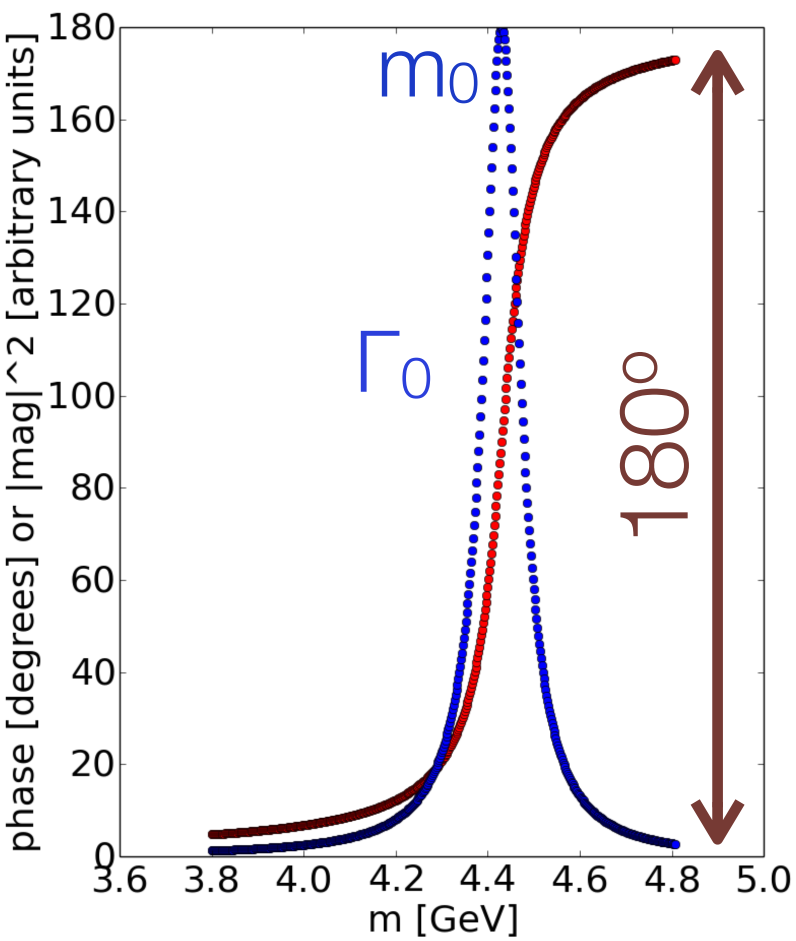
R⟶ab

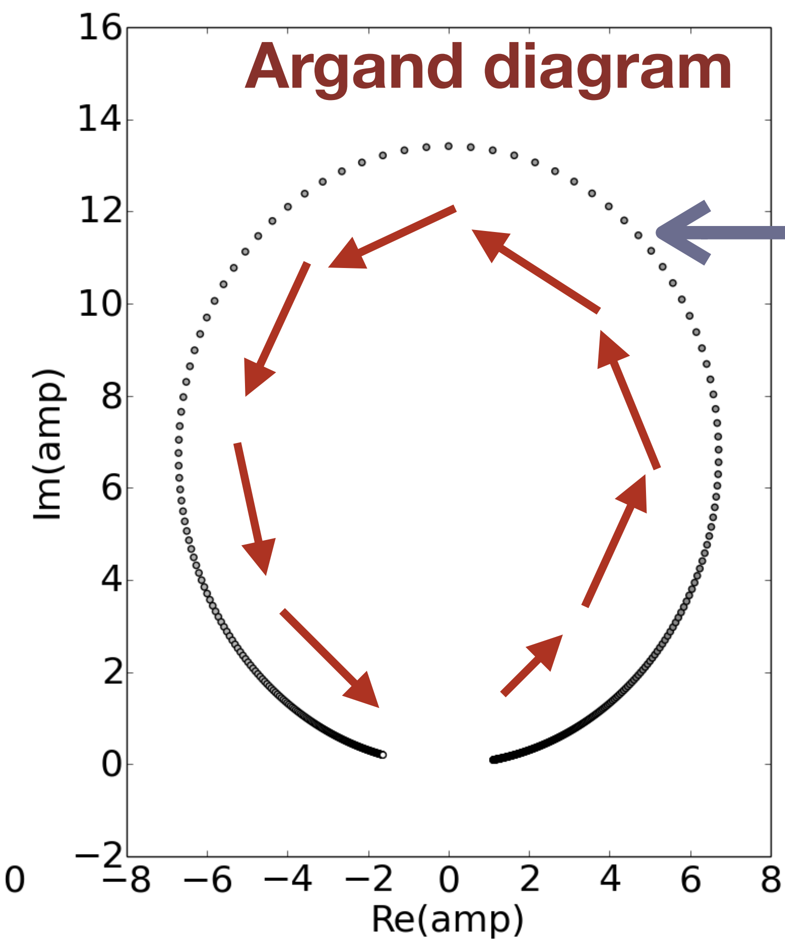
- Often model resonances with pole mass (m_0), width (Γ_0) using a relativistic Breit-Wigner function.
- q is daughter particle momentum in rest frame of resonance.
- B_L' are Blatt-Weisskopf functions for the orbital angular momentum (L) barrier factors.
- Amplitude = $|BW|^2$

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

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

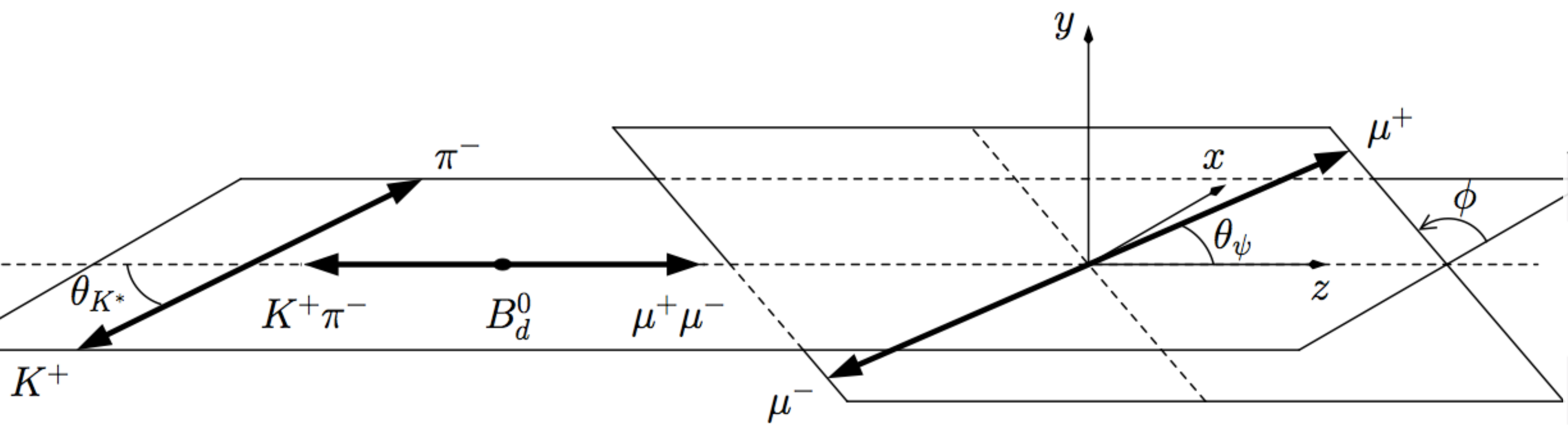
size of the decaying particle (1.6/GeV)





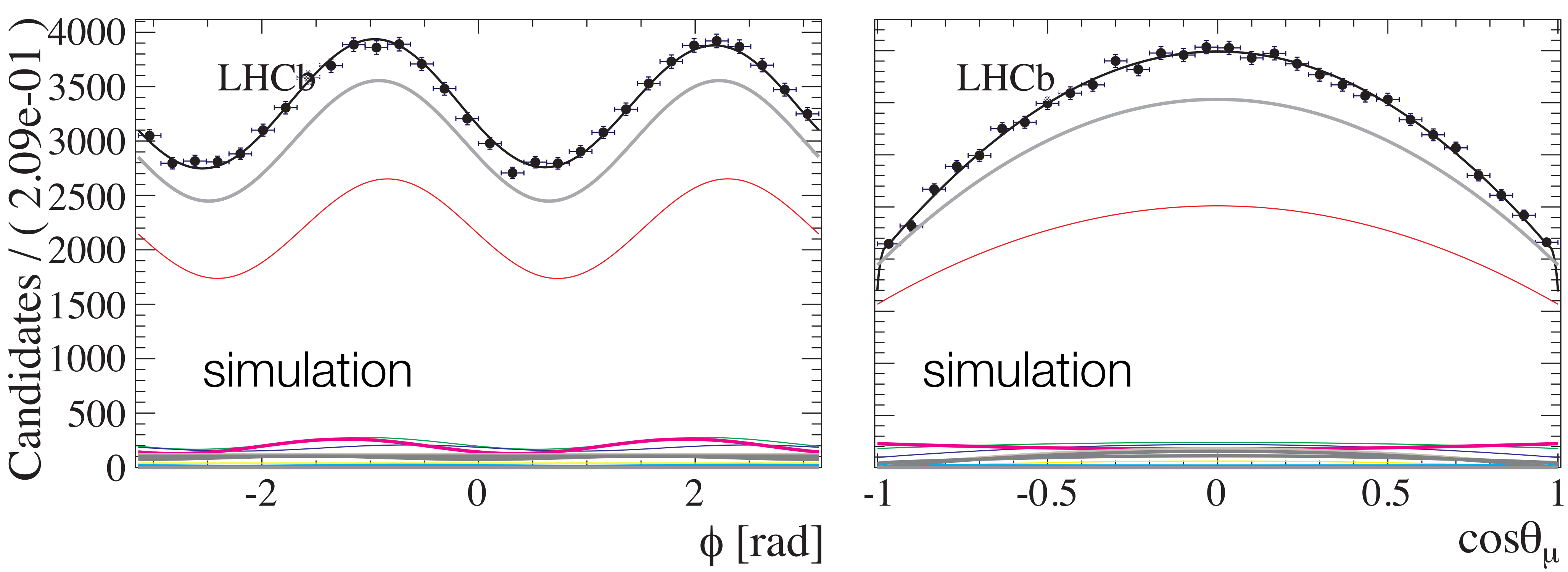
- Circular trajectory in complex plane is characteristic of resonance
- Circle can be rotated by arbitrary phase
- Phase change of 180° across the pole

4D “Dalitz plot” (scalar ⟶ vector scalar scalar)



Constraints	Degrees of freedom
3 four-vectors	+12
All decay in same plane ($p_{i,z} = 0$)	−3
$E_i^2 = m_i^2 + p_i^2$	−3
Energy + momentum conservation	−3
Rotate system in plane	−1
Vector helicity	+2
Total	+4

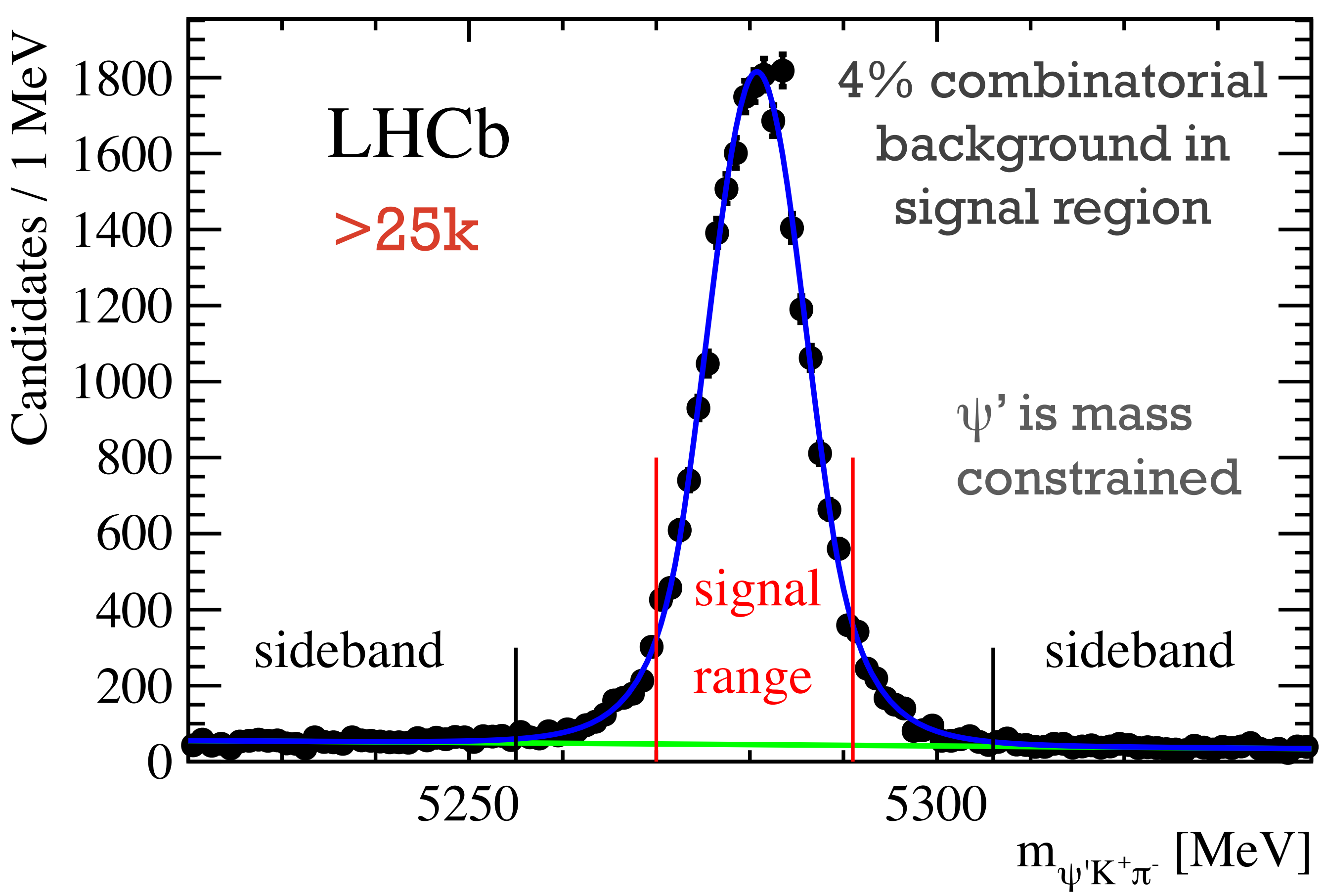
- $B^0 \rightarrow \psi' K^+ \pi^-$, $\psi' \rightarrow \mu^+ \mu^-$
- Must use the angular information, in addition to $m(\psi'\pi^-)^2$ vs $m(K^+\pi^-)^2$, to understand $|\mathcal{M}|^2$.

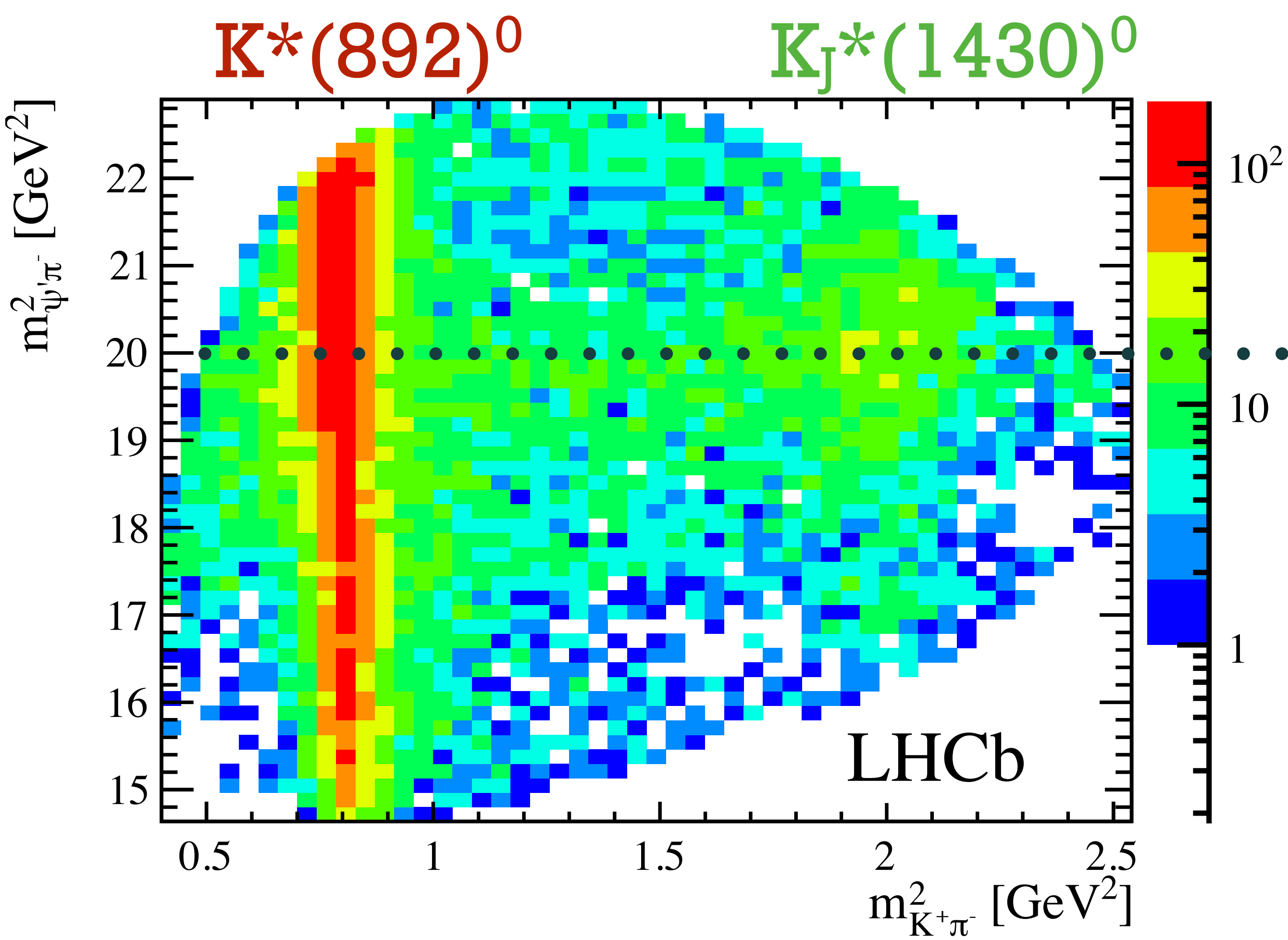


Confirmation of the $Z(4430)^{\pm}$

[arXiv:1404.1903 accepted by PRL]

- LHCb has sample of >25k $B^0 \longrightarrow \psi' K^+ \pi^-$ candidates (x10 Belle/BaBar).
- Selection: most events come through dimuon trigger (eff~90%) $\psi' \longrightarrow \mu^+ \mu^-$
- Typical B^0 pT ~6GeV, μ^+ pT ~ 2GeV, K^+ pT ~1GeV.
- Use sidebands to build 4D model of combinatorial background.
  - Bkgs from mis-ID physics decays is small - **excellent LHCb vertexing, PID!**



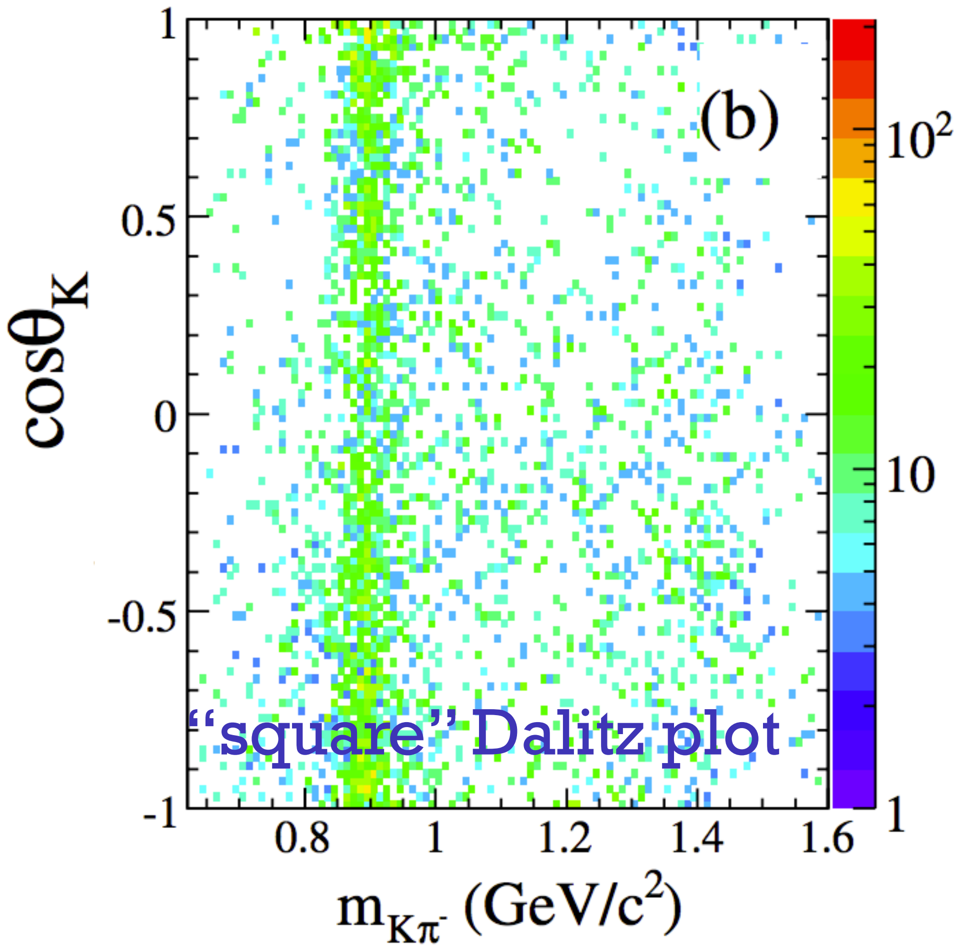


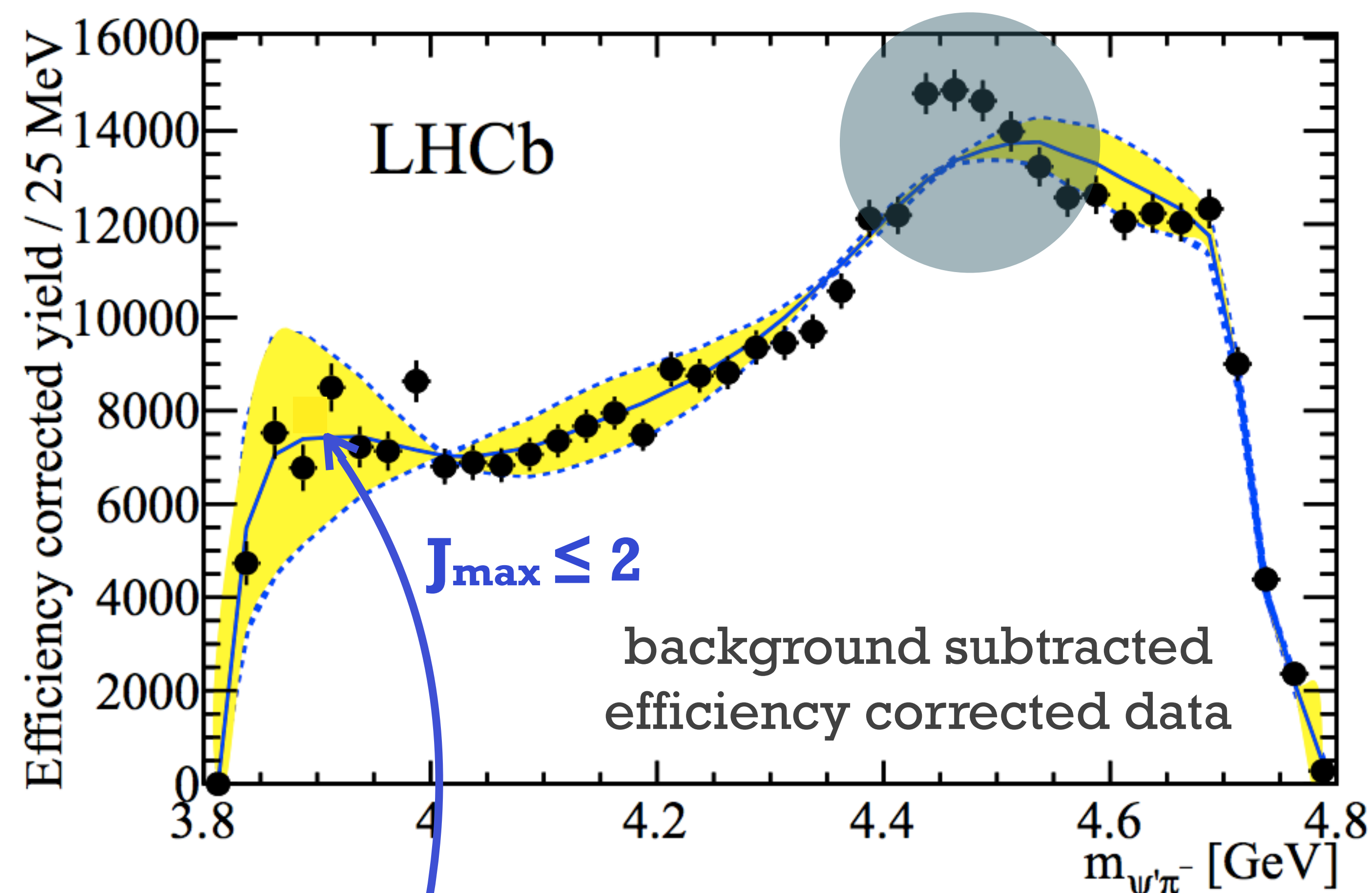
Only 2 of the 4 dimensions…

Model independent analysis - qualitative check

Can reflection of the structures in m(Kπ) and cosθ reproduce the m(ψ'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** $B^0 \to \psi' K^+ \pi^-$ **events** with the spherical harmonic moments of $\cos\theta_K$.
- Moments of K* resonances are **unable** to explain observed distribution.

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

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

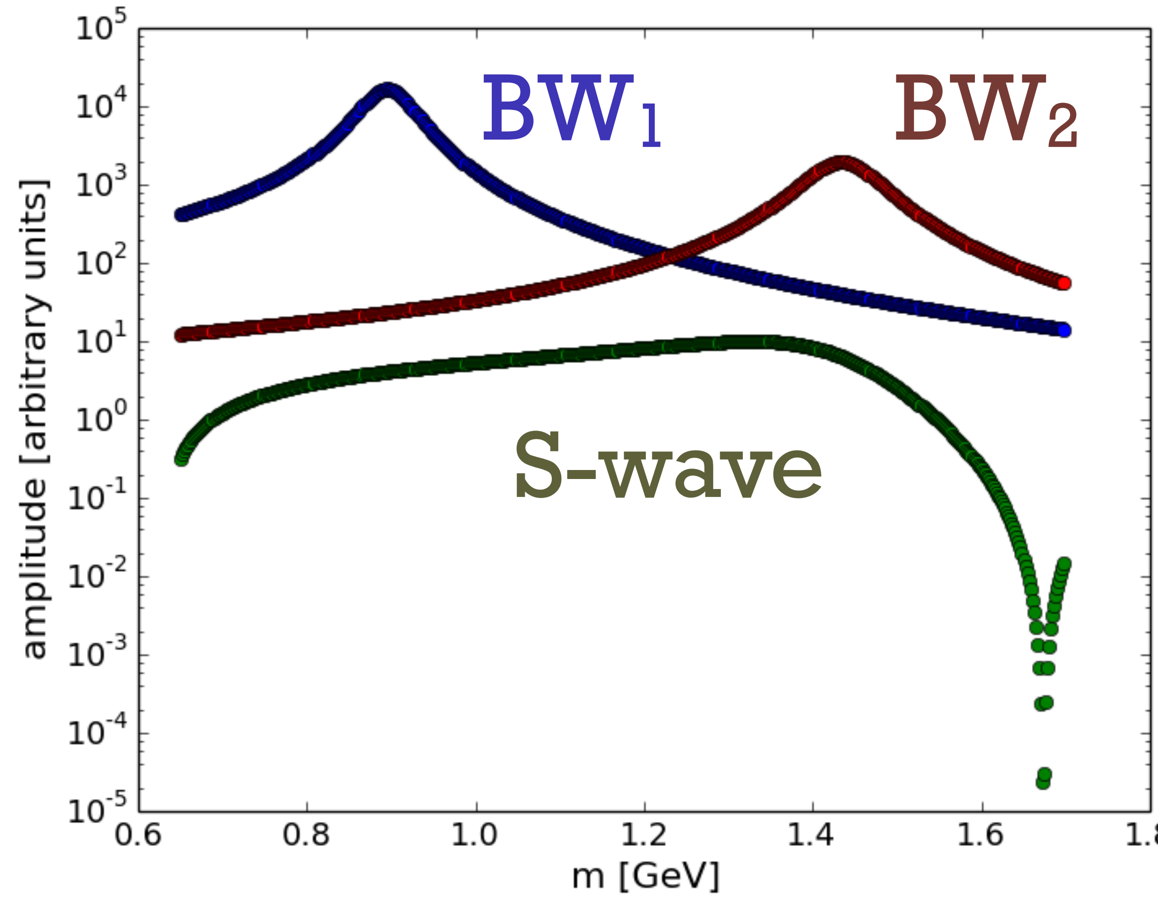
$$Y_2^0 = \sqrt{\frac{5}{4\pi}} \left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$

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

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

Amplitude model

- Use the **Isobar** approach.
- Build amplitude from sum of two-body decays: $B^0 \longrightarrow \psi' \pi^- K^+$ and $B^0 \longrightarrow Z(4430)^- K^+$
- Overlapping and interfering Breit-Wigner resonances.



Sum over the k resonances

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

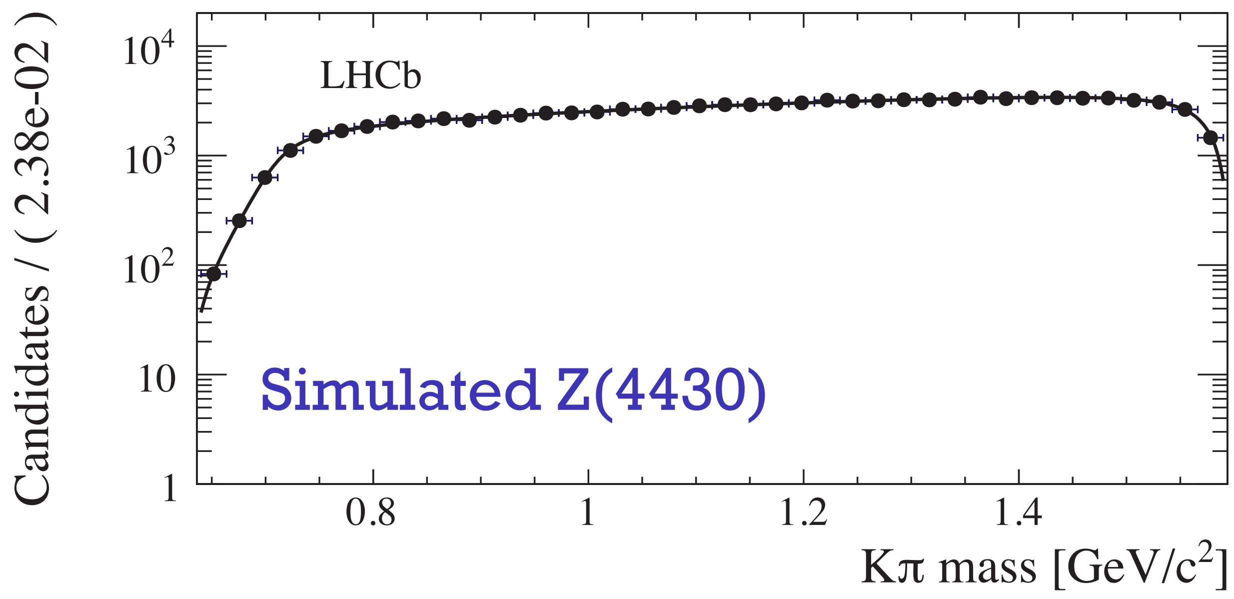
In 4D fit, $\mu^+\mu^-$ are final state particles so different dimuon helicity amplitudes are incoherent (cannot interfere)

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 more difficult since it has different helicity frame compared to $K^+\pi^-$ resonances.
- It is has a BW shape in $m(\Psi'\pi^-)$ mass, but is basically flat in $m(K^+\pi^-)$.
- Low Q-value in Z decay, so ignore D-wave contribution $\Rightarrow A_{Z,-1} = A_{Z,0} = A_{Z,+1}$

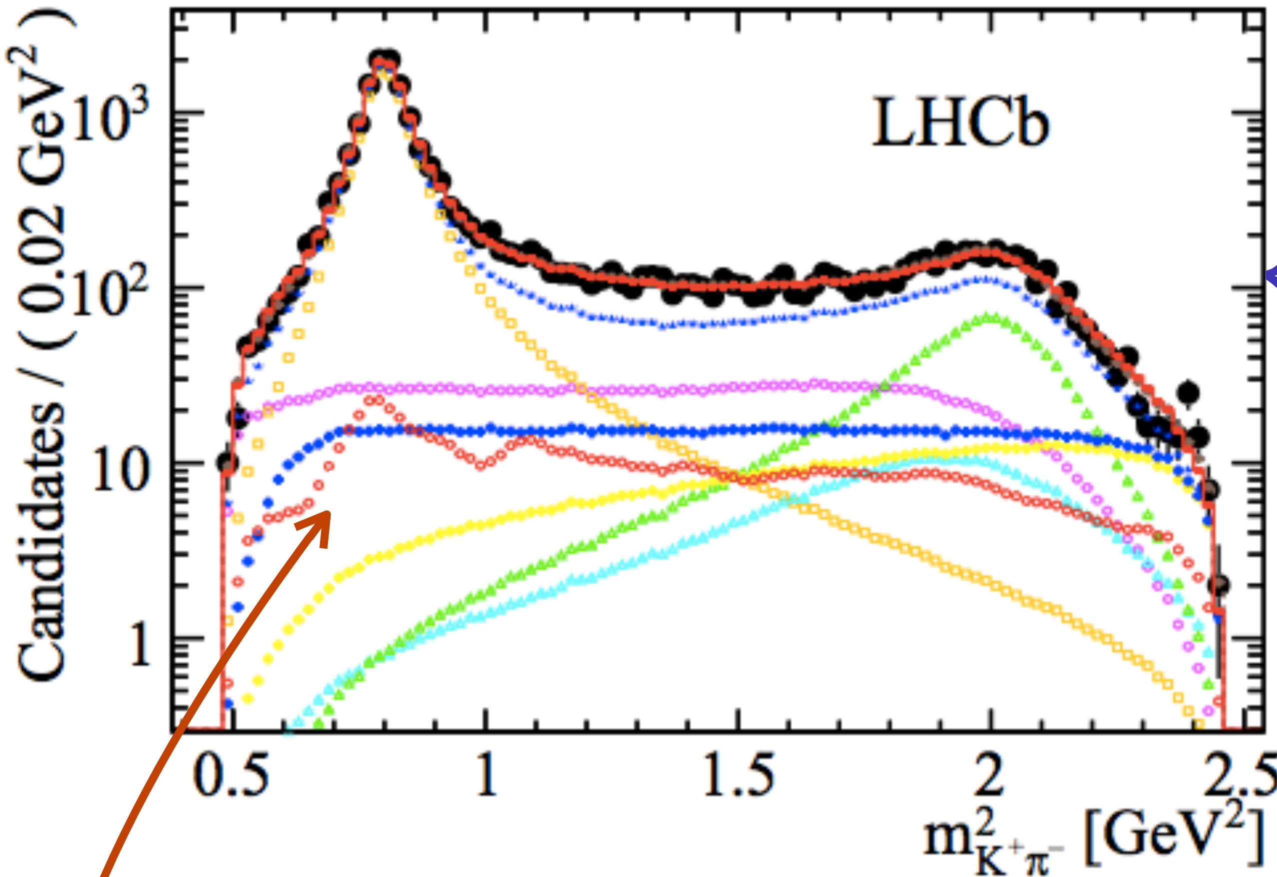


$$|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega | m_{0\,k}, \Gamma_{0\,k}) + \sum_{\lambda_\psi^Z=-1,0,1} A_{Z,\lambda_\psi^Z}(m_{\psi\pi}, \Omega^Z | m_{0\,Z}, \Gamma_{0\,Z}) e^{i\Delta\lambda_\mu \alpha} \right|^2$$

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.
  - Measure all amplitudes relative to K*(892) helicity-0 component.

- Default result includes all resonances up to $K^*_1(1680)$ (**$J \leq 2$**).
- Main source of **systematic uncertainties** comes from varying model to include higher $K^+\pi^-$ spin-states (J = 3, 4, 5).

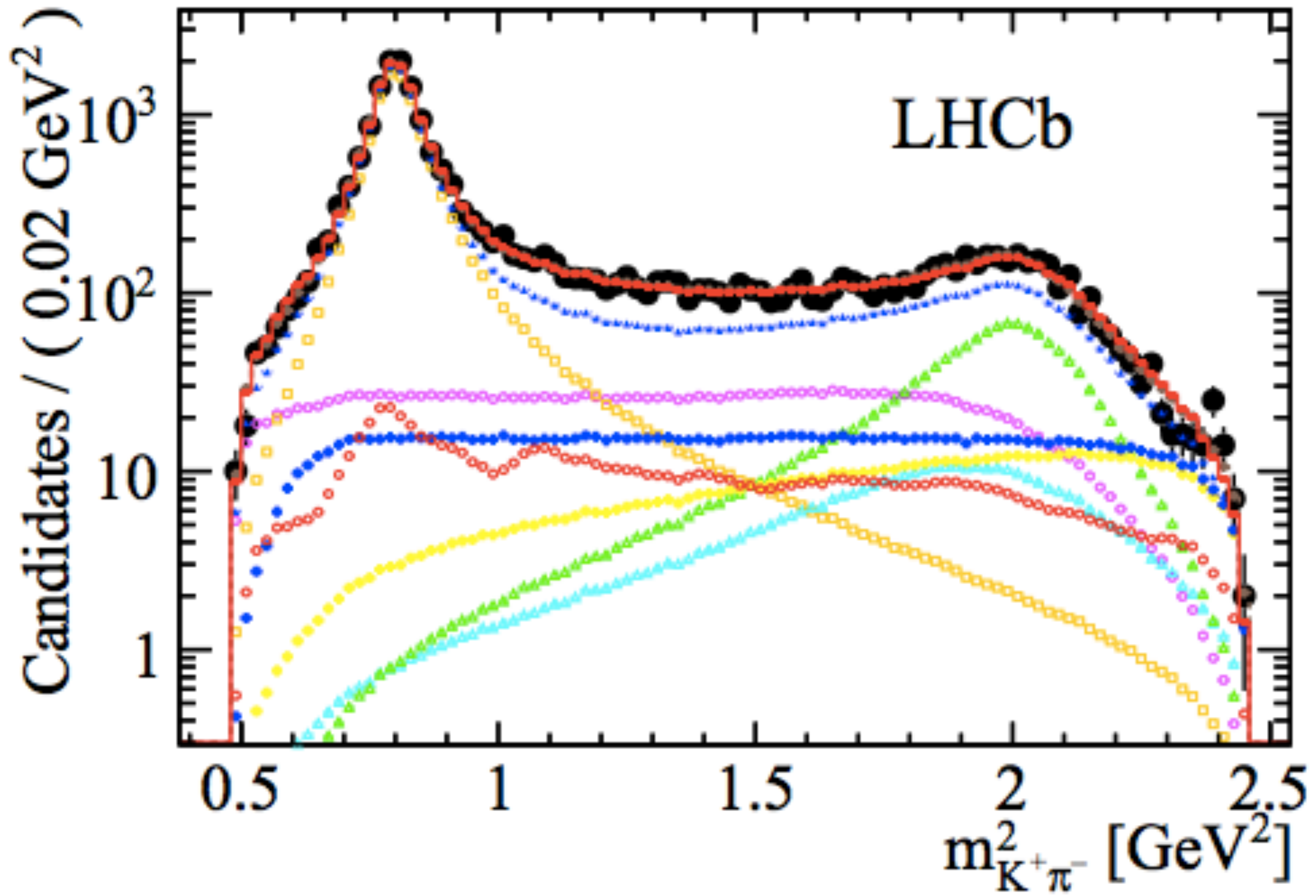
Background from sidebands of B mass

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 $K^{*0}(1430)+K^{*0}(800)$
  - Non-resonant contribution

- LASS model as cross-check [Nucl. Phys. B296 (1988) 493]
  - Does not violate unitarity
  - Sum of elastic scattering, destructively interfering with K*(1430)

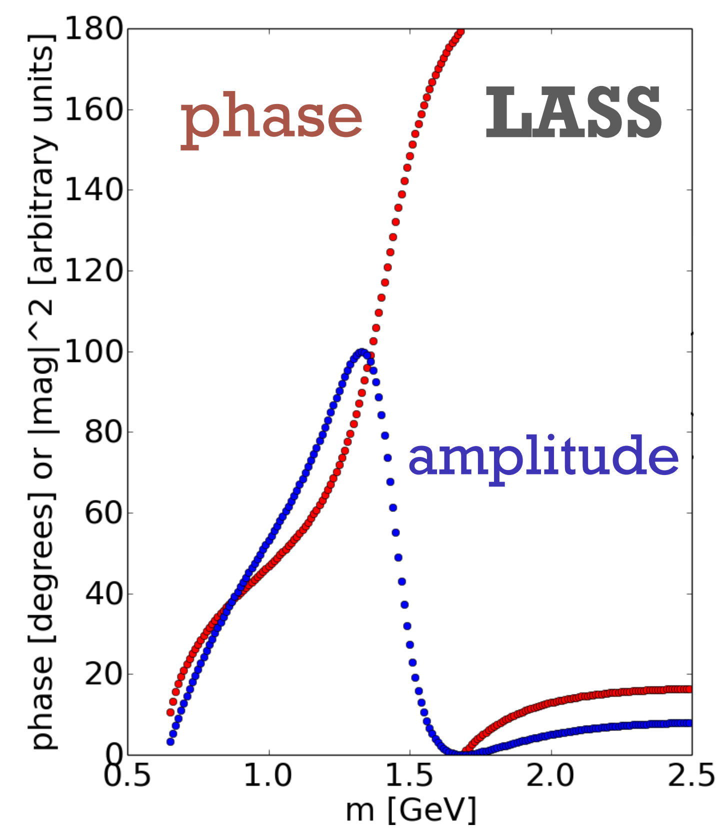


Slowly varying NR contribution

BW amplitude for K(1430)

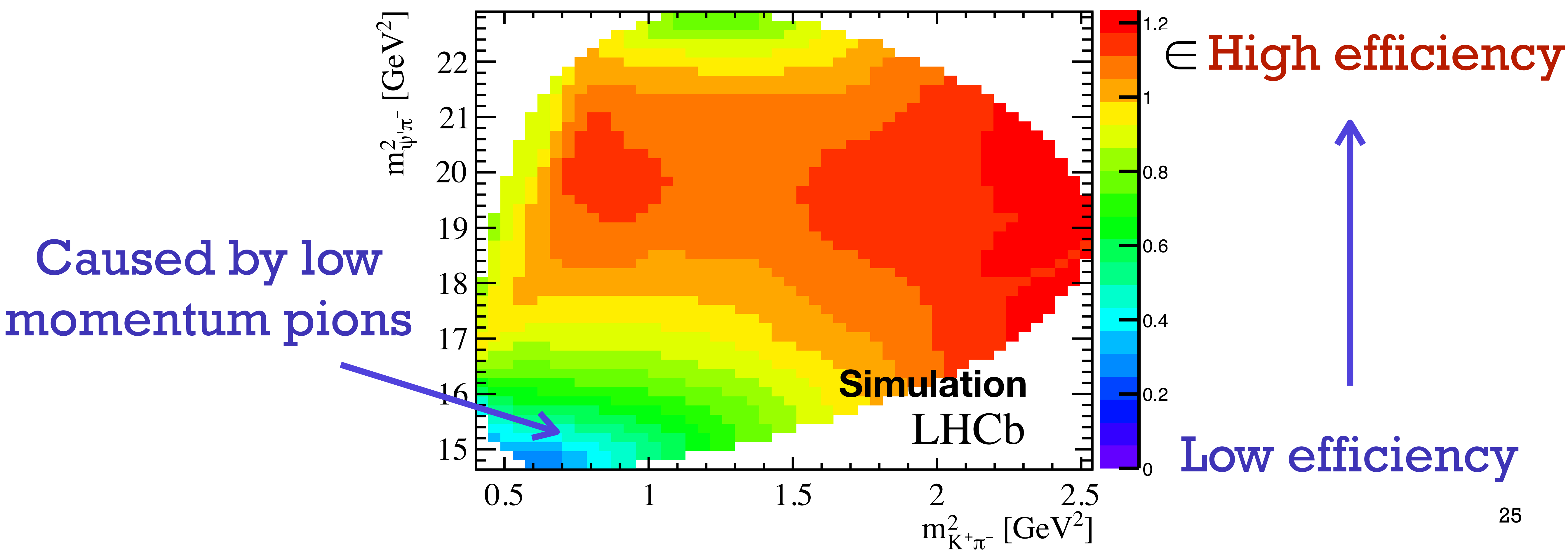
$$\frac{1}{\cot\delta_B(m_{K\pi})-i}+e^{2i\delta_B(m_{K\pi})}\frac{1}{\cot\delta_R(m_{K\pi})-i}$$

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



Reconstruction and selection efficiency

- LHCb < 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 (~12%) near edge of kinematic boundary since efficiency not well modelled there.
- 2D representation…



Fitting the model to the data

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

Observables (mass, angles)

PDF

Parameters

Efficiency drops out

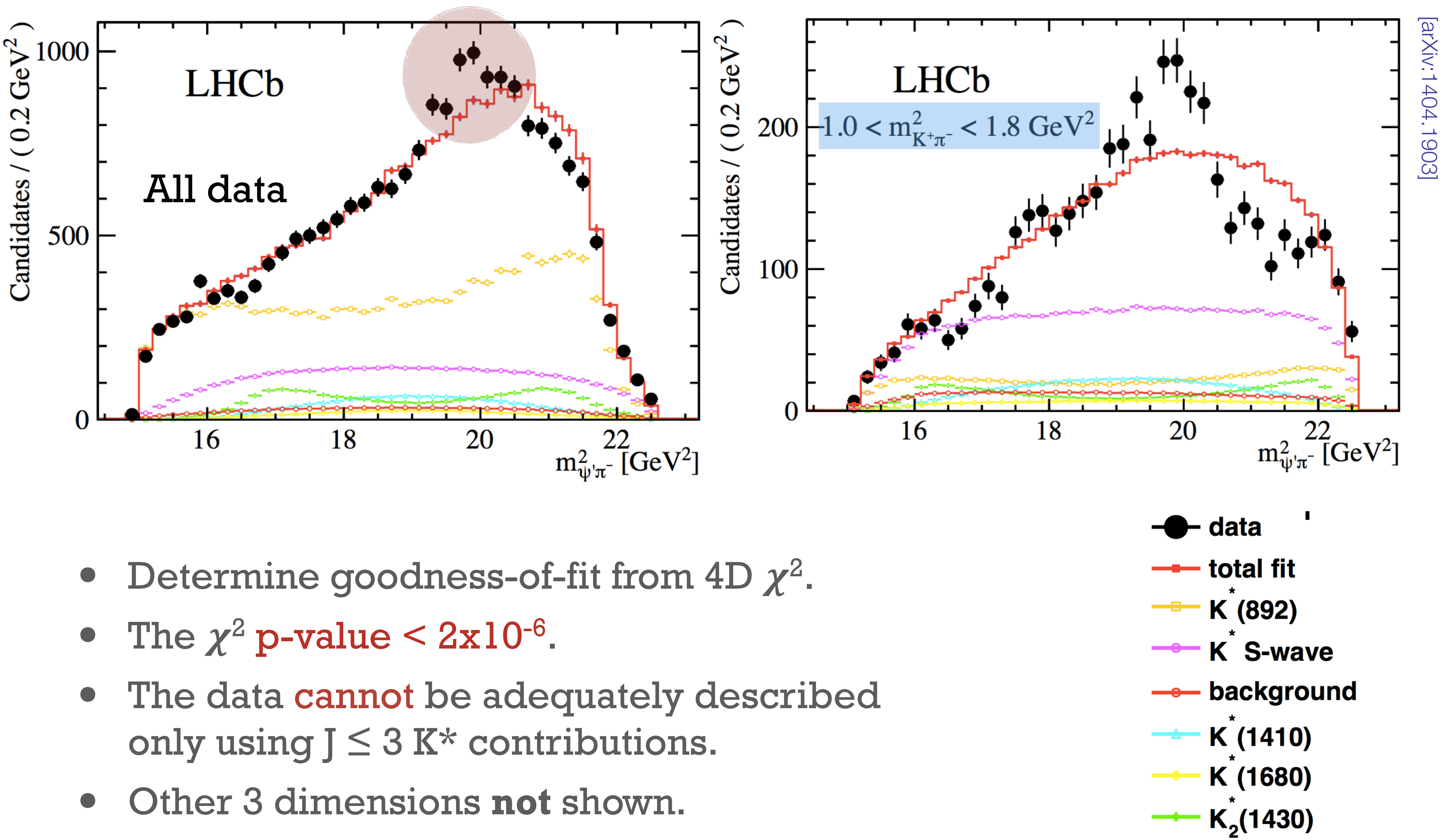
$$-\ln L(\vec{\omega}) = -\sum_{i}^{N_{\text{data}}} \ln P^{u}_{\text{tot}}(\vec{v}_i|\vec{\omega}) = -\sum_{i}^{N_{\text{data}}} \ln\left(|\mathcal{M}(\vec{v}_i|\vec{\omega})|^2 \epsilon(\vec{v}_i)/I(\vec{\omega})\right)$$

- 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 normalisation.
  - Alternative approach explicitly parameterises the 4D efficiency.

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

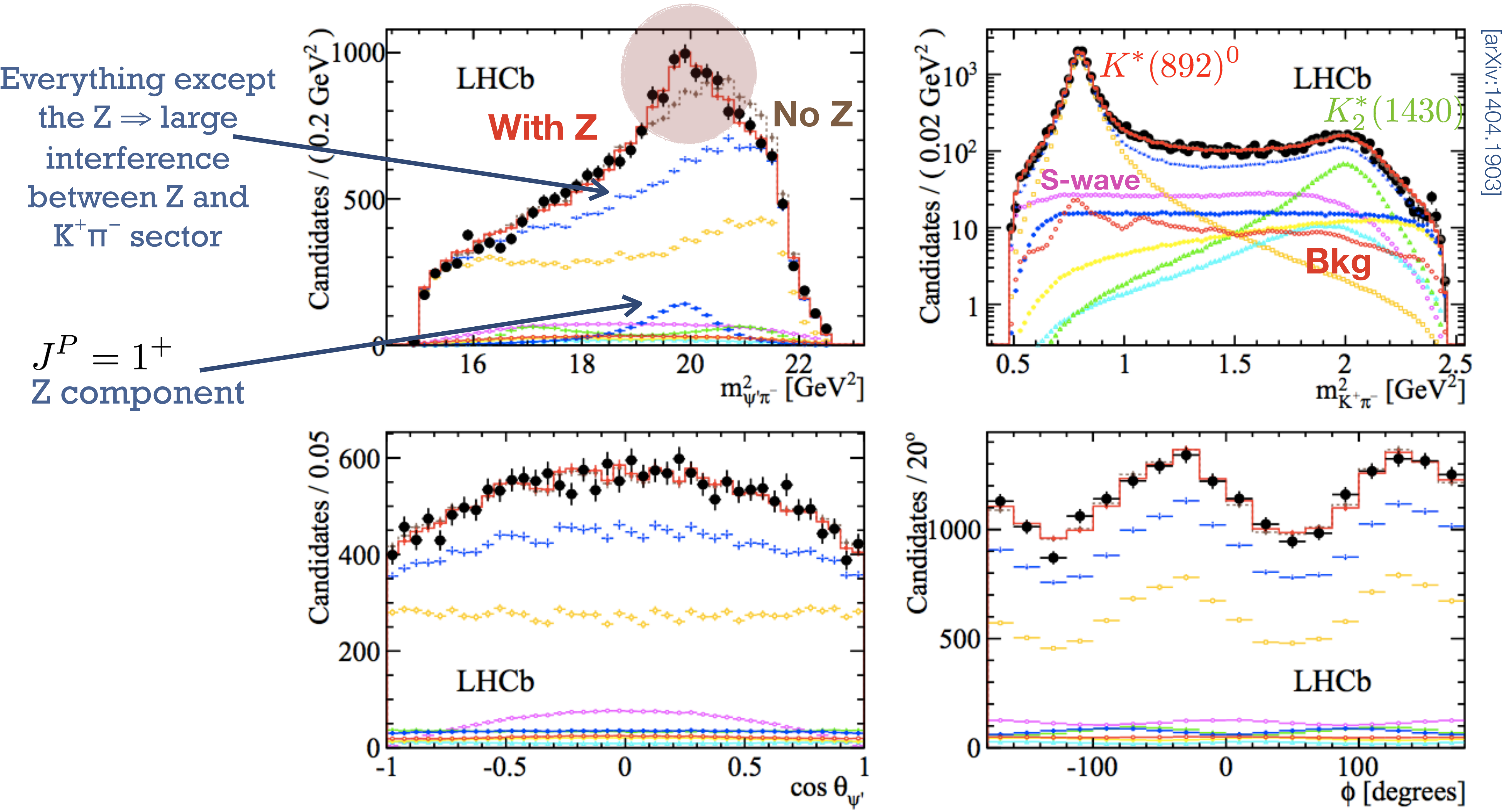
Try different models for $K^+\pi^-$ and Z(4430), compare values of L.

Projections of 4D amplitude fit without Z(4430)



- Determine goodness-of-fit from 4D χ^2.
- The χ^2 p-value < $2\text{x}10^{-6}$.
- The data cannot be adequately described only using $J \leq 3$ K* contributions.
- Other 3 dimensions **not** shown.

Projections of 4D amplitude fit <u>with</u> Z(4430)



- The 4D χ^2 p-value = 12%.
  - 4% with no K_1*(1410), 12% with K_3*(1780)
- The data are well described when including a $J^P=1^+$ Z(4430) in the fit.

$Z(4430)^{\pm}$ parameters from amplitude fit

	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%] (with interference)	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$
J^P	1^+	1^+

New (large) systematic included

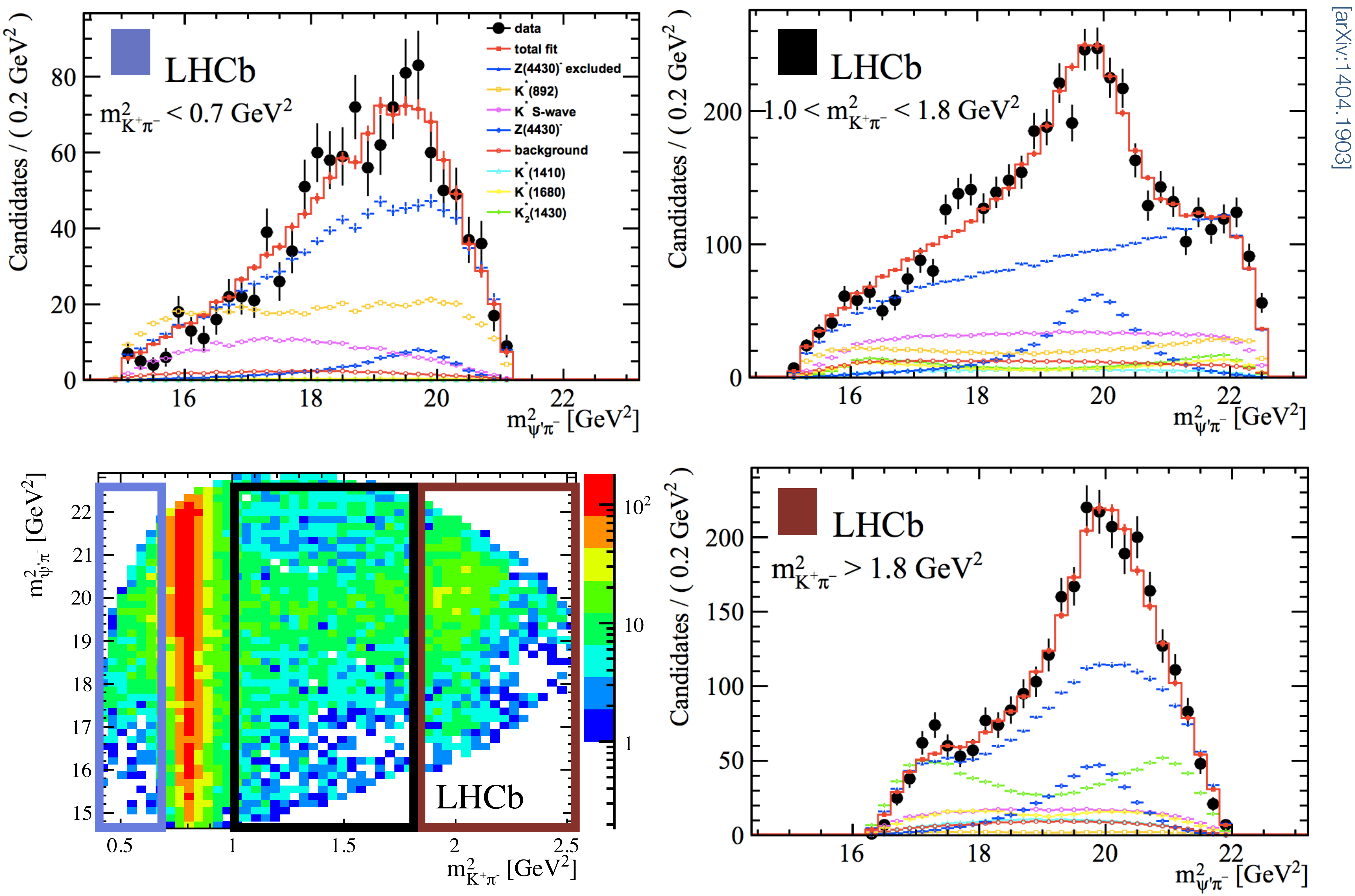
Amplitude fractions [%]

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

- Excellent agreement between LHCb and Belle.
- Large width - unlikely to be molecule?

$$f_i = \frac{\int |A_i(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega}{\int |\sum_k A_k(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega}$$

Fit projections in slices of $m(K^+\pi^-)$

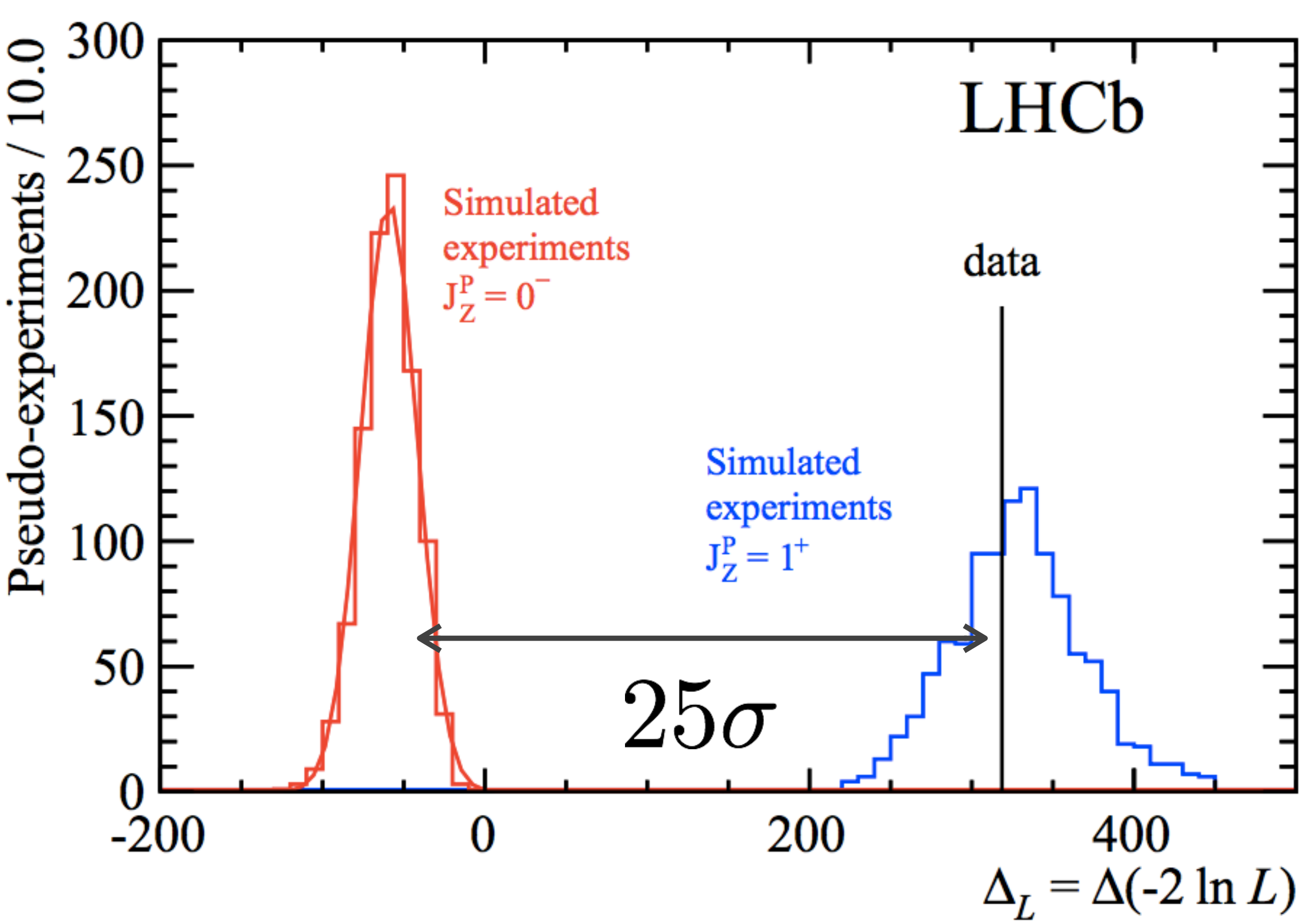


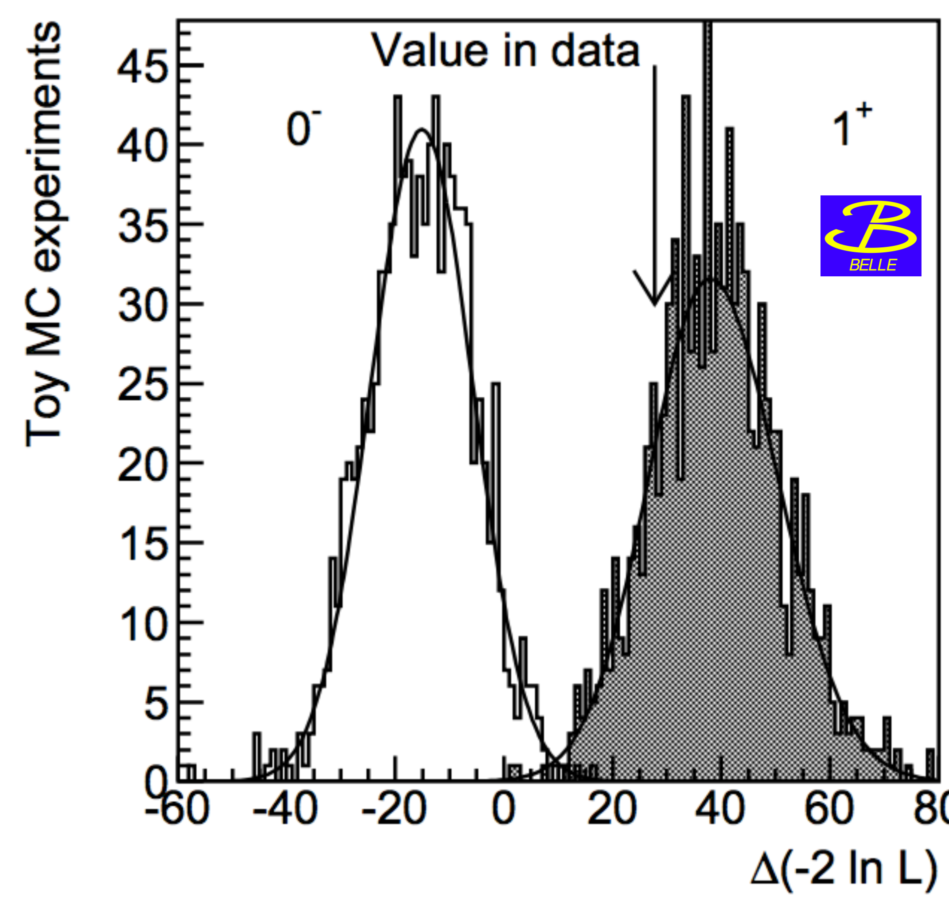
Spin determination

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

- Build different $|M|^2$ corresponding to different J^P values.
- $J^P=1^+$ is favoured (confirms Belle).
- Rule out other J^P with large significance.
- Quote exclusion based on asymptotic formula (lower bound).

Disfavoured J^P	Rejection level relative to 1^+ LHCb	Belle
0^-	9.7σ	3.4σ
1^-	15.8σ	3.7σ
2^+	16.1σ	5.1σ
2^-	14.6σ	4.7σ

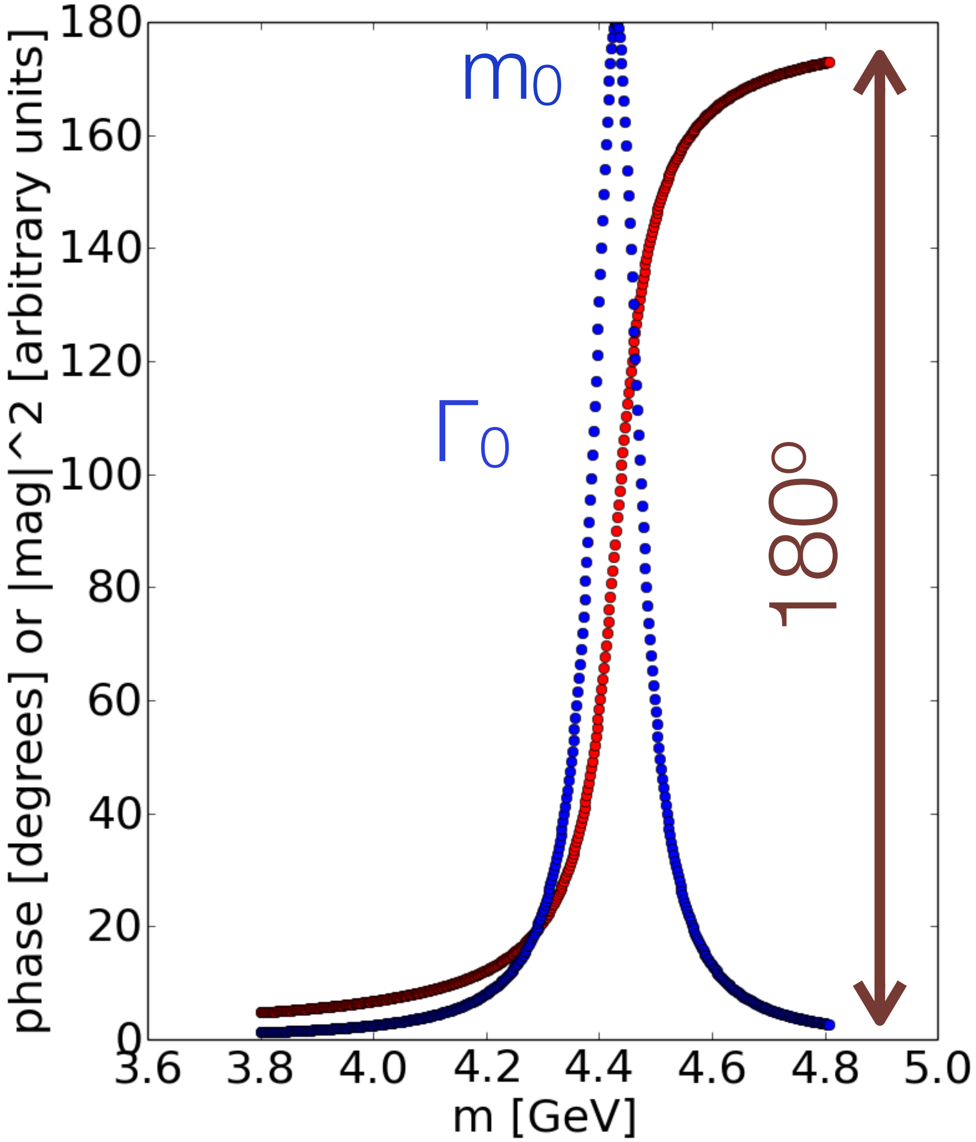


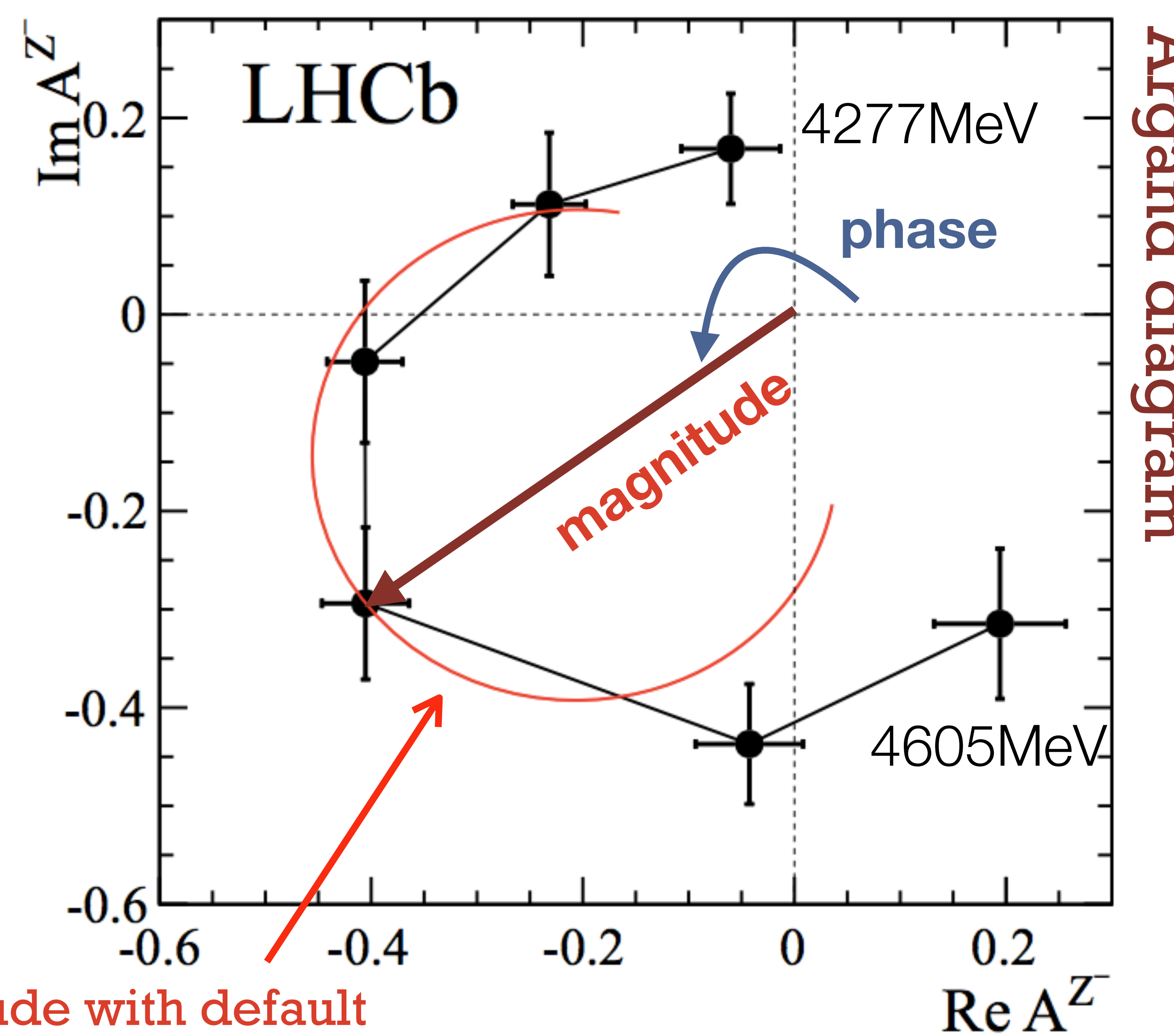


[PRD88 (2013) 074026]

Resonant behaviour - a bound state?

- Replace BW amplitude with 6 independent complex numbers in 6 bins of $m(\psi'\pi)$ in region of Z(4430) mass peak.
- Allows Z(4430) shape to be constrained only by amplitudes in $K\pi$ sector.
- Observe rapid change of phase near maximum of magnitude ⇒ **resonance!**





Systematics: second exotic Z?

- Fit confidence level increases to 26% with a second exotic ($J^P=0^-$) component, but…
  - No evidence for Z_0 in model independent approach.
  - Argand diagram for Z_0 is inconclusive.
- Need larger samples to characterise this state.

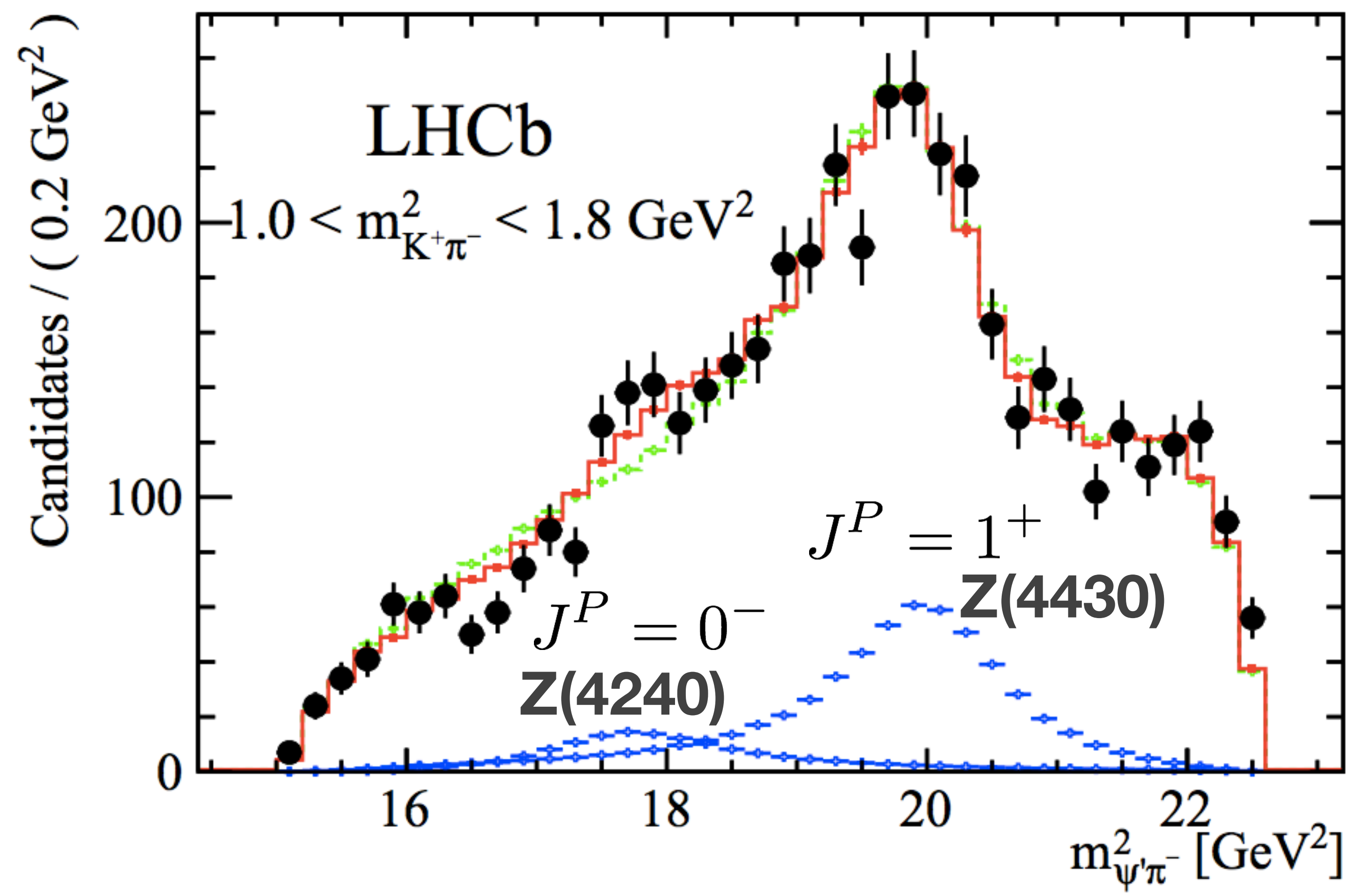
Significance from
$$\Delta(-2\ln L)$$
$$6\sigma$$

Fitted parameters

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

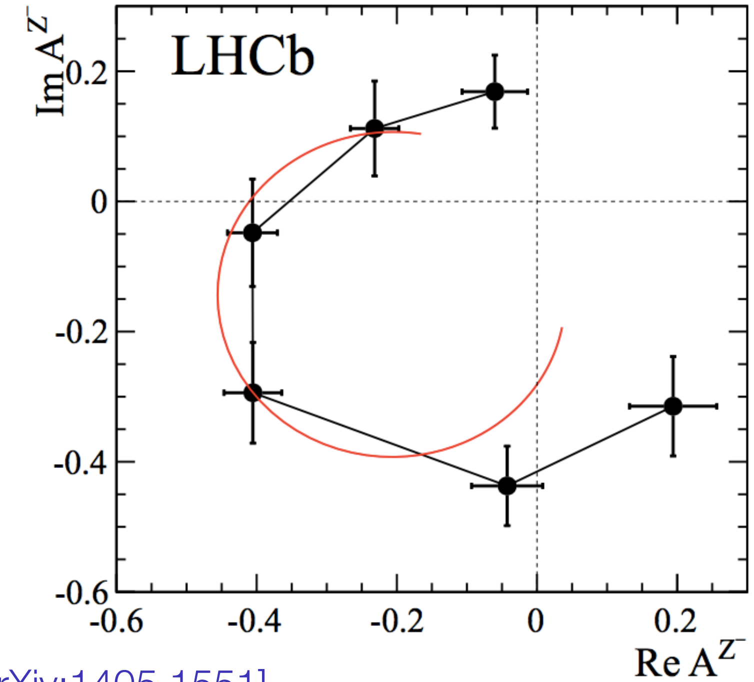
Same mass, width as $Z^- \to \chi_{c1}\pi^-$ seen by Belle, but $J^P=0^-$ can't decay strongly to $\chi_{c1}\pi^-$

[PRD 78 (2008) 072004]



- 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

Implications

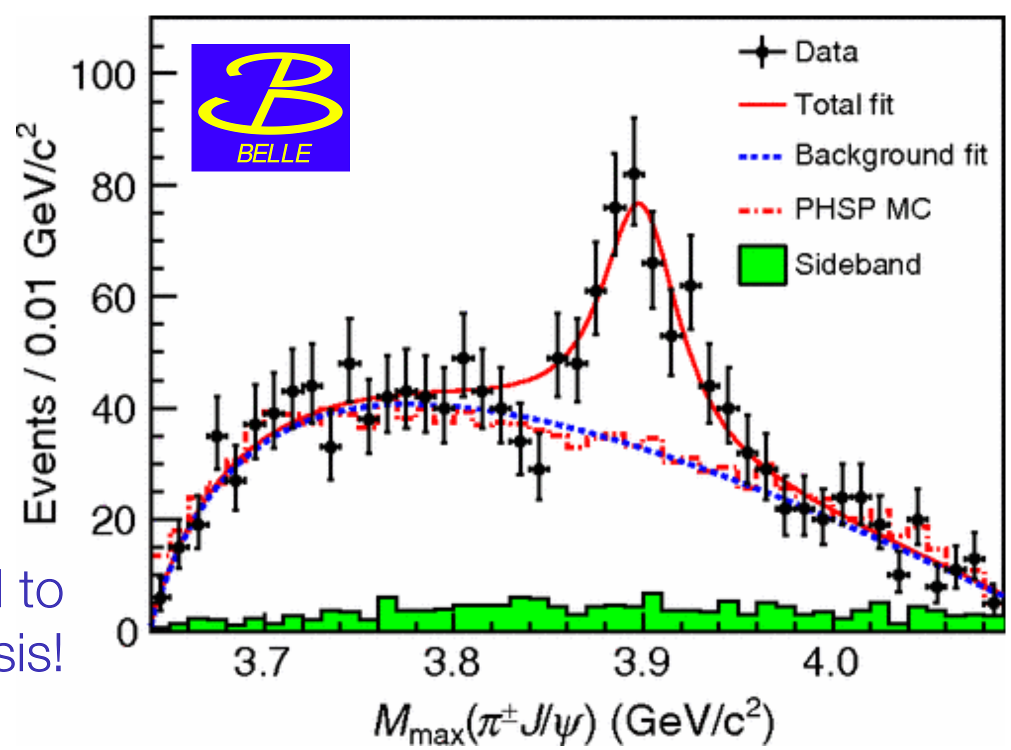


- Result confirms existence of the Z(4430), measures $J^P=1^+$ and, for the first time, demonstrates **resonant behaviour**.
- P=+ rules out interpretation in terms of **$\bar{D}^*(2010)D^*_1(2420)$** molecule or threshold effect (cusp).
  [Rosner, PRD 76 (2007) 114002] [Bugg, J. Phys. G35 (2008) 075005]
- Four-quark bound state is a remaining explanation. [Maiani et al, arXiv:1405.1551]
- Potential neutral **isospin partner?** $Z(4430)^0$ in $B^+ \longrightarrow \psi' \pi^0 K^+$
- 2013: Observation of another **exotic charged state: $Z_c(3900)^\pm$** in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
- Is $Z(4430)^\pm$ a radial excitation of $Z_c(3900)^\pm$?
  [Wang, arXiv:1405.3581]

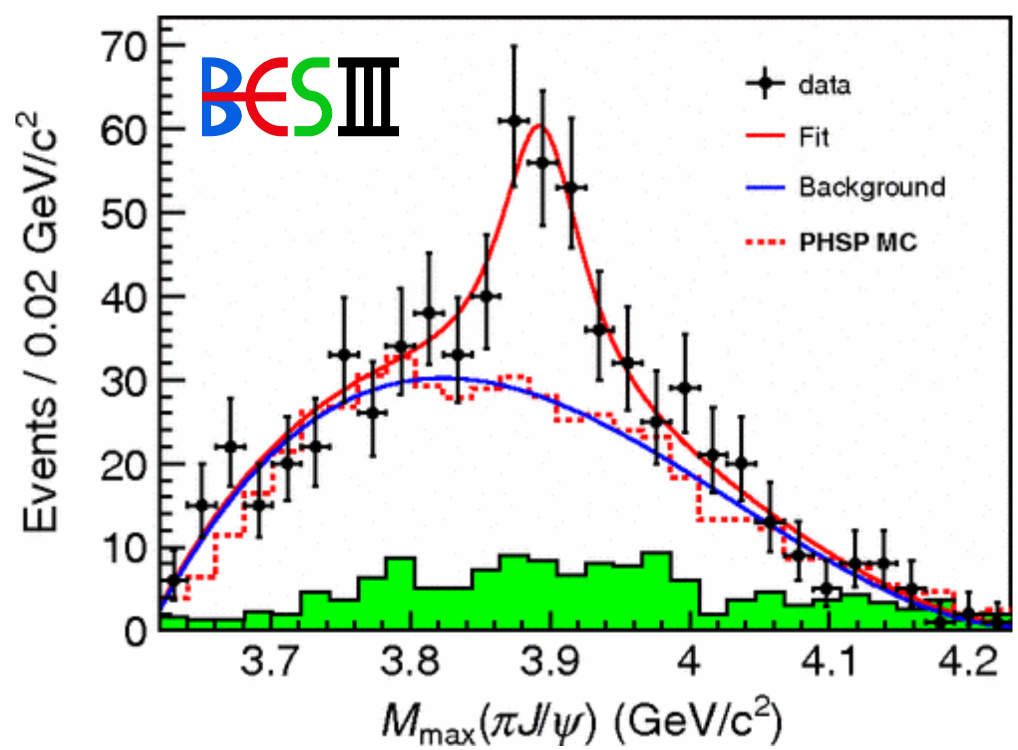
$M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2
$\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2

1D fit to m(πJ/Ψ)

Looking forward to amplitude analysis!

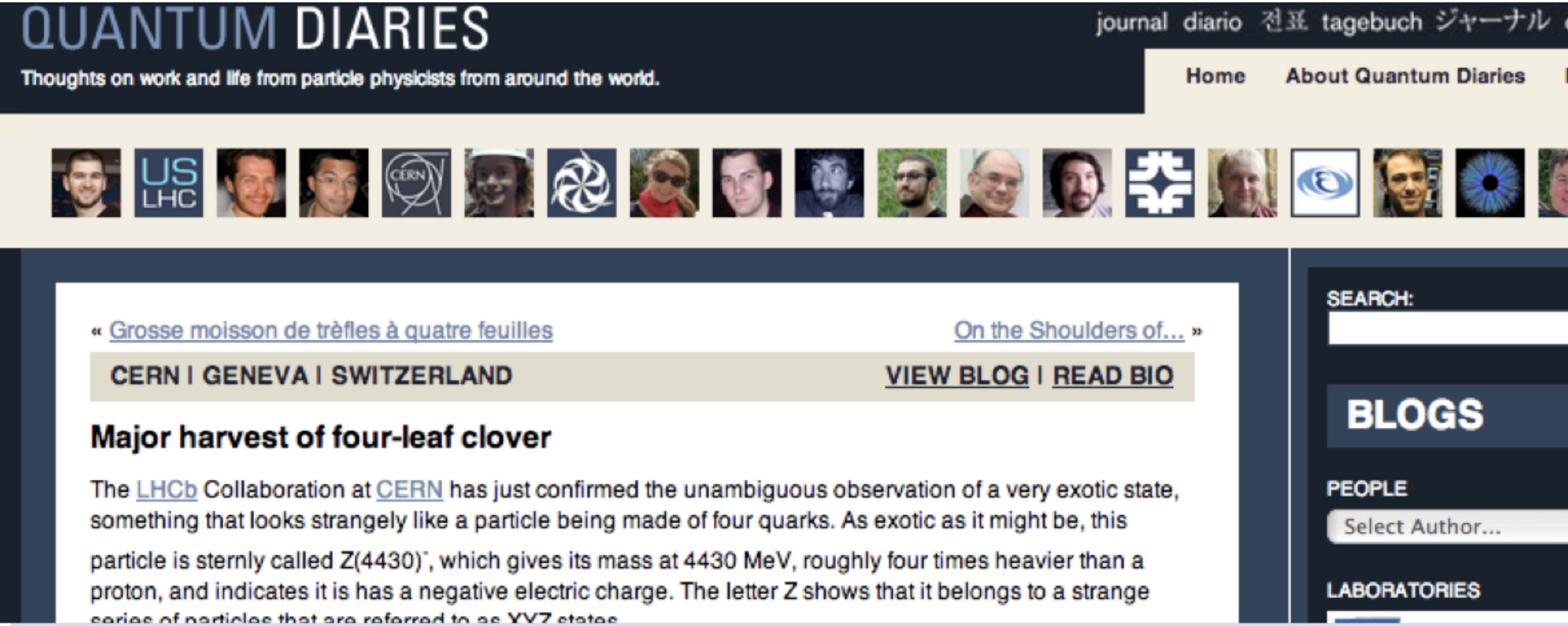


[PRL 110, 252001]



[PRL 110, 252002]

[CLEO-c, PLB 727 (2013) 366-370]



QUANTUM DIARIES

Thoughts on work and life from particle physicists from around the world.

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« Grosse moisson de trèfles à quatre feuilles

On the Shoulders of... »

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Major harvest of four-leaf clover

The LHCb Collaboration at CERN has just confirmed the unambiguous observation of a very exotic state, something that looks strangely like a particle being made of four quarks. As exotic as it might be, this particle is sternly called Z(4430)⁻, which gives its mass at 4430 MeV, roughly four times heavier than a proton, and indicates it is has a negative electric charge. The letter Z shows that it belongs to a strange series of particles that are referred to as XYZ states.

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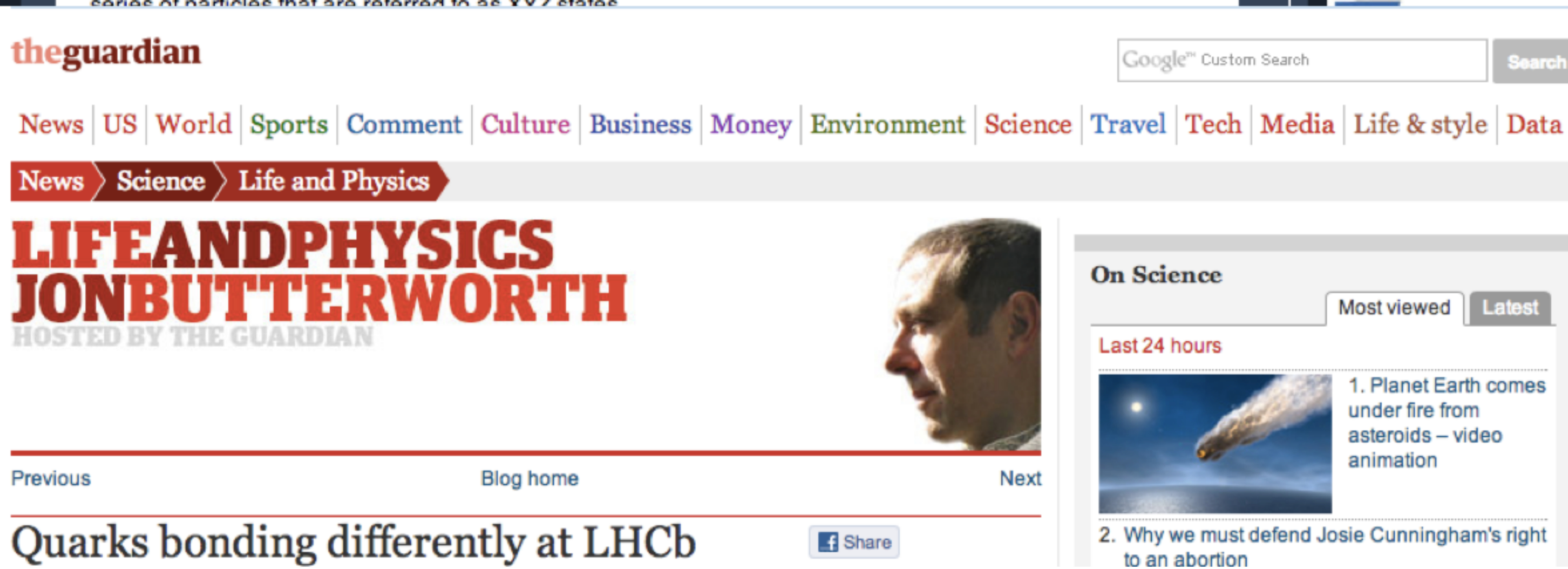

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Time To Open the Gates of Hell? CERN: Large Hadron Collider Discovers 'Very Exotic Matter' That Challenges Traditional Physics! (Must-See Videos)

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The Large Hadron Collider beauty collaboration has confirmed the existence of exotic hadron with two quarks, two anti-quarks.

"The last time they fired it up, it was almost openining dimensional portals like a stargate! There were reports that people were seen coming in and out of different dimensions!" —Hagmann and Hagmann Report

ISNA
خبرگزاری دانشجویان ایران، ایسنا
Iranian Students' News Agency

تعداد کل اخبار: 289

پنجشنبه ۴ اردیبهشت ۱۳۹۳ / Apr 24 2014

بازنویسی فیزیک نوین با کشف ذره جدید چهار کوارکی

» سرويس: علمي و فناوري - علم و فناوري جهان

کد خبر: 93012911697
جمعه ۲۹ فروردین ۱۳۹۳ - ۰۹:۰۸

دانشمندان مرکز سرن در سوئیس با استفاده از آشکارساز زیبایی برخورددهنده بزرگ هادرونی(LHCb) وجود یک ذره عجیب را تائید کرده‌اند.

به گزارش سرویس علمی خبرگزاری دانشجویان ایران(ایسنا)، این ذره ملقب به Z(4430) ابتدا در سال 2007 کشف شده بود، اما

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

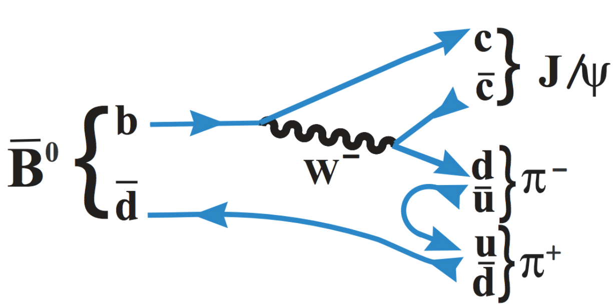
- Study substructure of light mesons that decay to $\pi^+\pi^-$.
- Mass ordering is reversed between the scalar and vector mesons nonets.

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

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

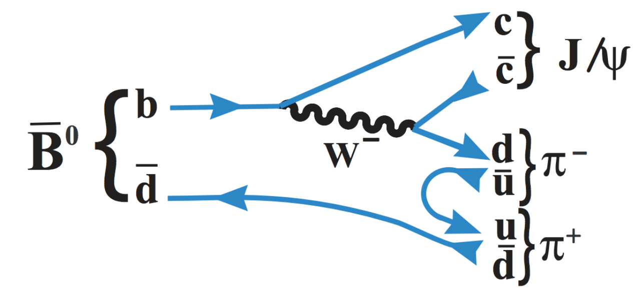


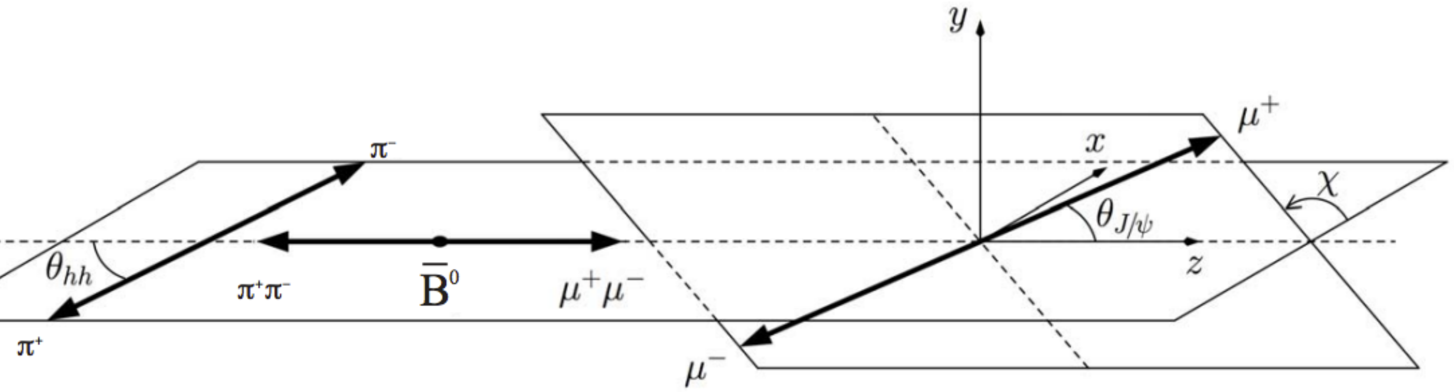
$$\tan^2\varphi_m \equiv r_\sigma^f = \frac{\mathcal{B}\left(\bar{B}^0 \to J/\psi\, f_0(980)\right)}{\mathcal{B}\left(\bar{B}^0 \to J/\psi\, f_0(500)\right)} \frac{\Phi(500)}{\Phi(980)} = 1/2$$

mixing angle — phase space

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

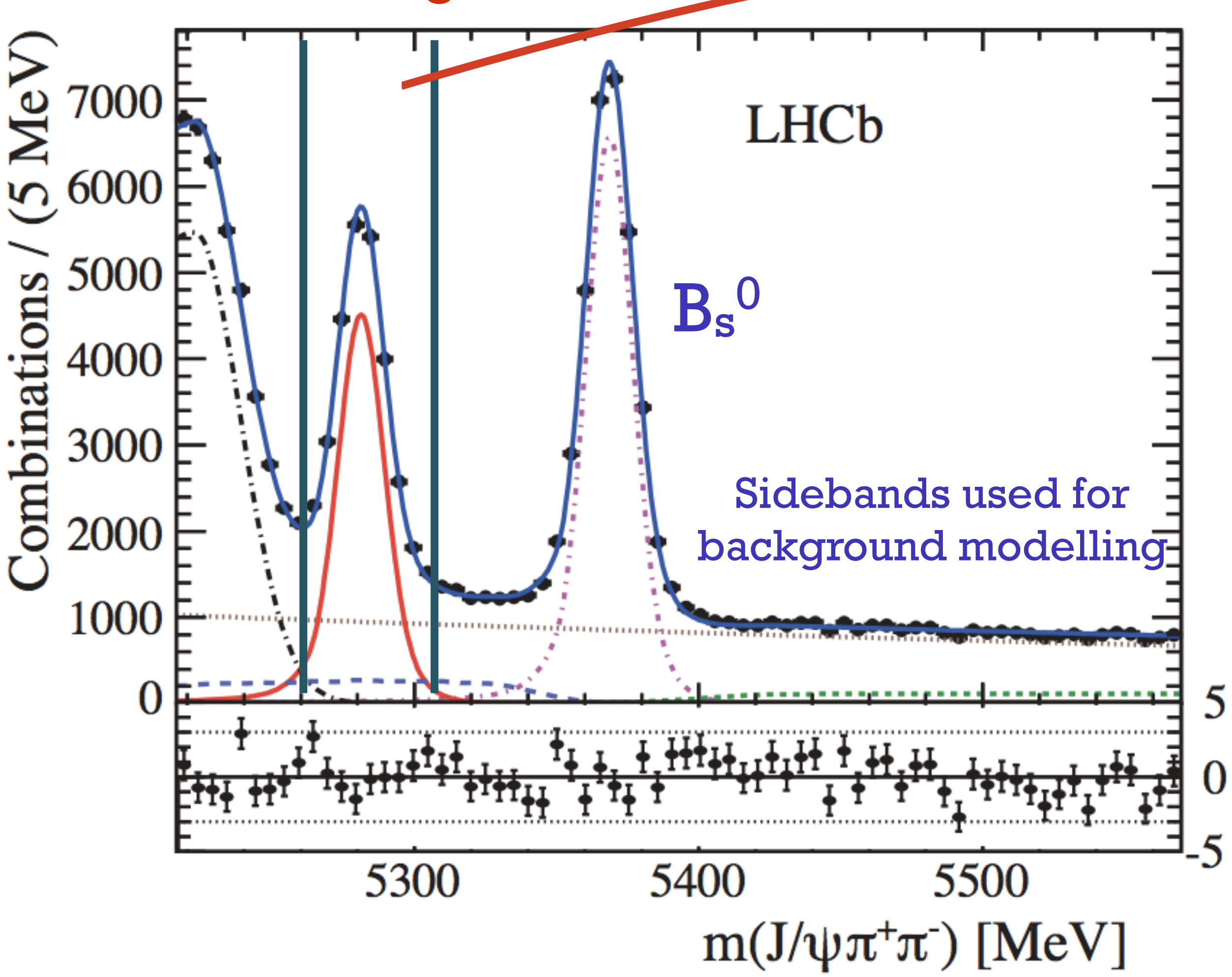
Amplitude analysis of $B^0 \to J/\psi\pi^+\pi^-$

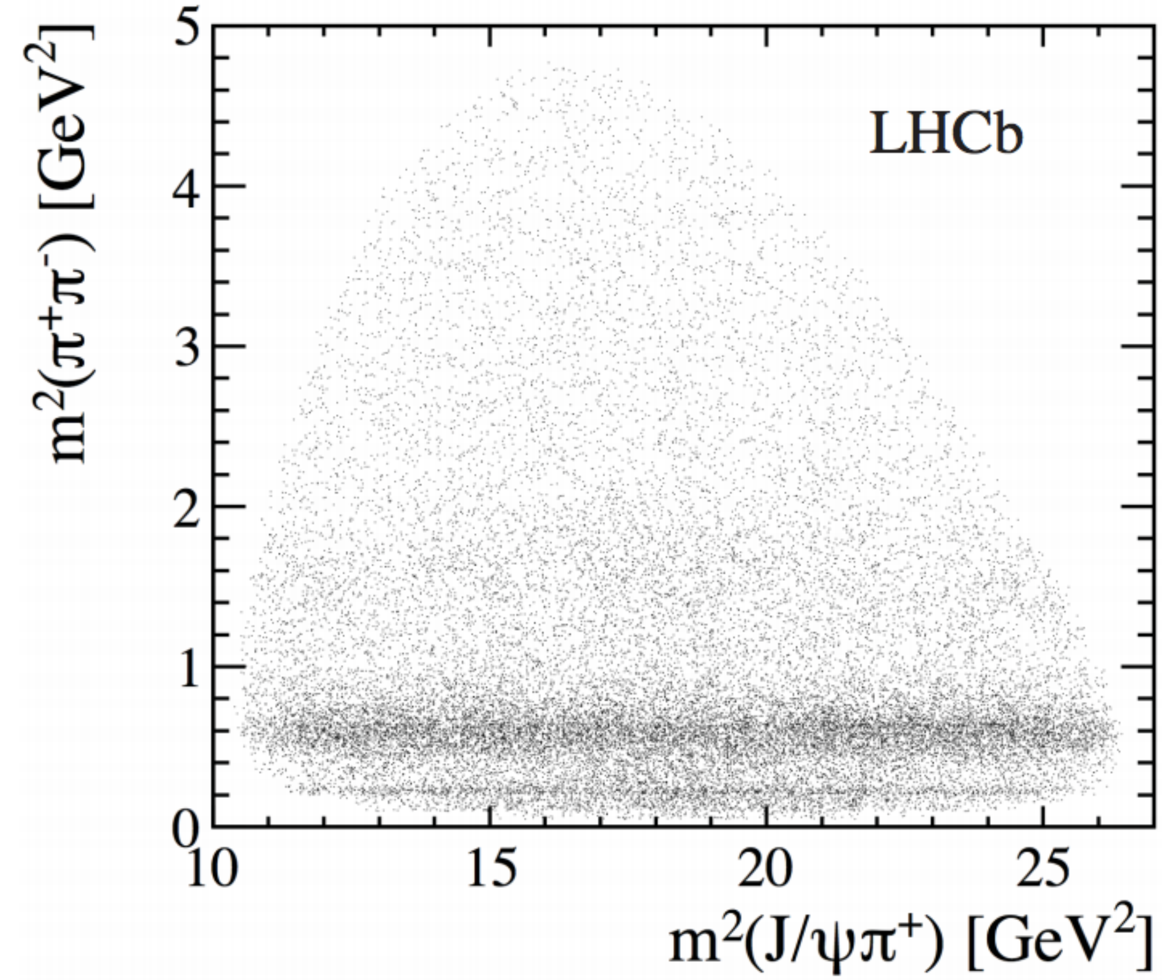




- Similar analysis to Z(4430)
  - Build 4D matrix element from overlapping $\pi^+\pi^-$ resonances.
  - Correct for efficiency.
- No sign of exotic $J/\psi\pi^+$ resonances…

19k $\mathbf{B^0}$ signal



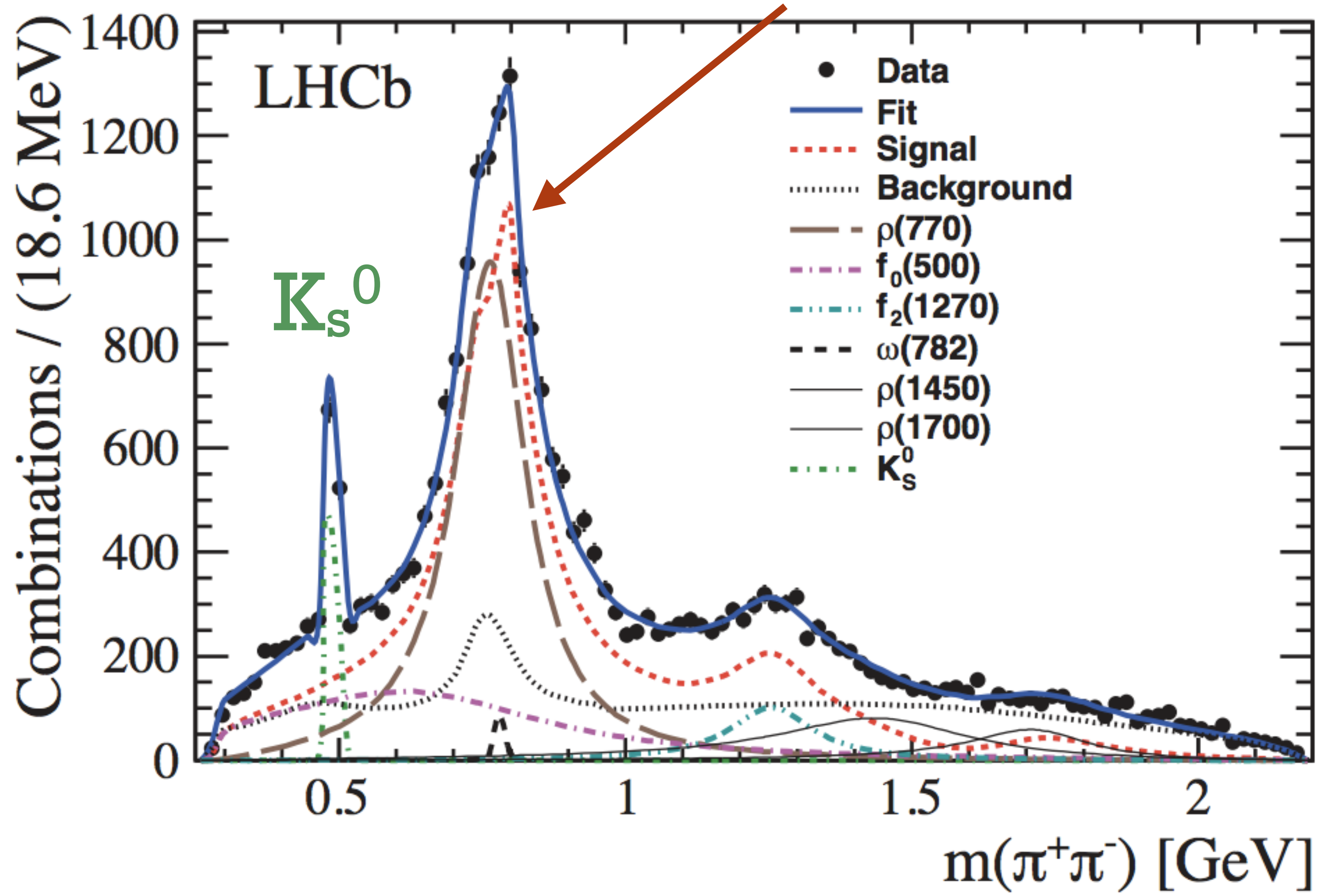


[arXiv:1404.5673, PRD]

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

ρ-ω interference visible

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



[arXiv:1404.5673, PRD]

- BW for $f_0(500)$: mass/width Gaussian constrained to CLEO values.
- Flatté for $f_0(980)$: parameters fixed to those from $B_s^0 \to J/\psi\pi^+\pi^-$ [Phys. Rev. D 89, 092006 (2014)]
- Best fit model does **not** require $f_0(980)$ component ⇒ upper limit for mixing angle:

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

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

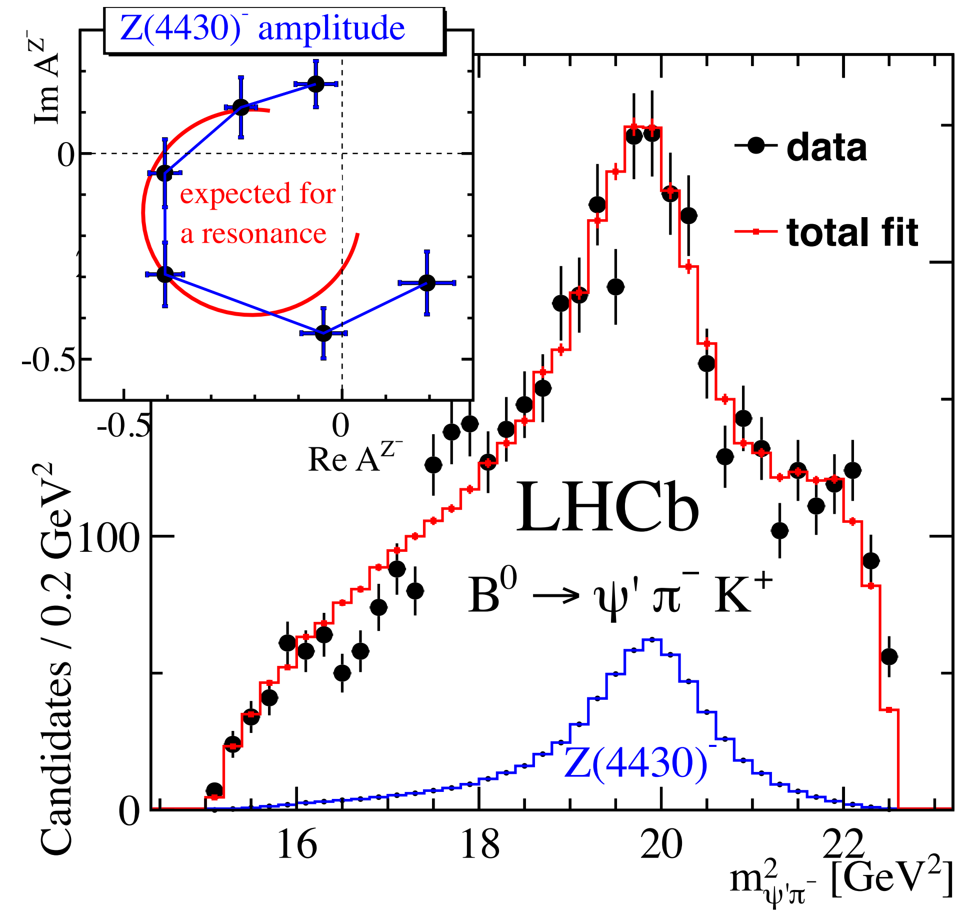
[Stone, Zhang, PRL 111, 062001 (2013)]

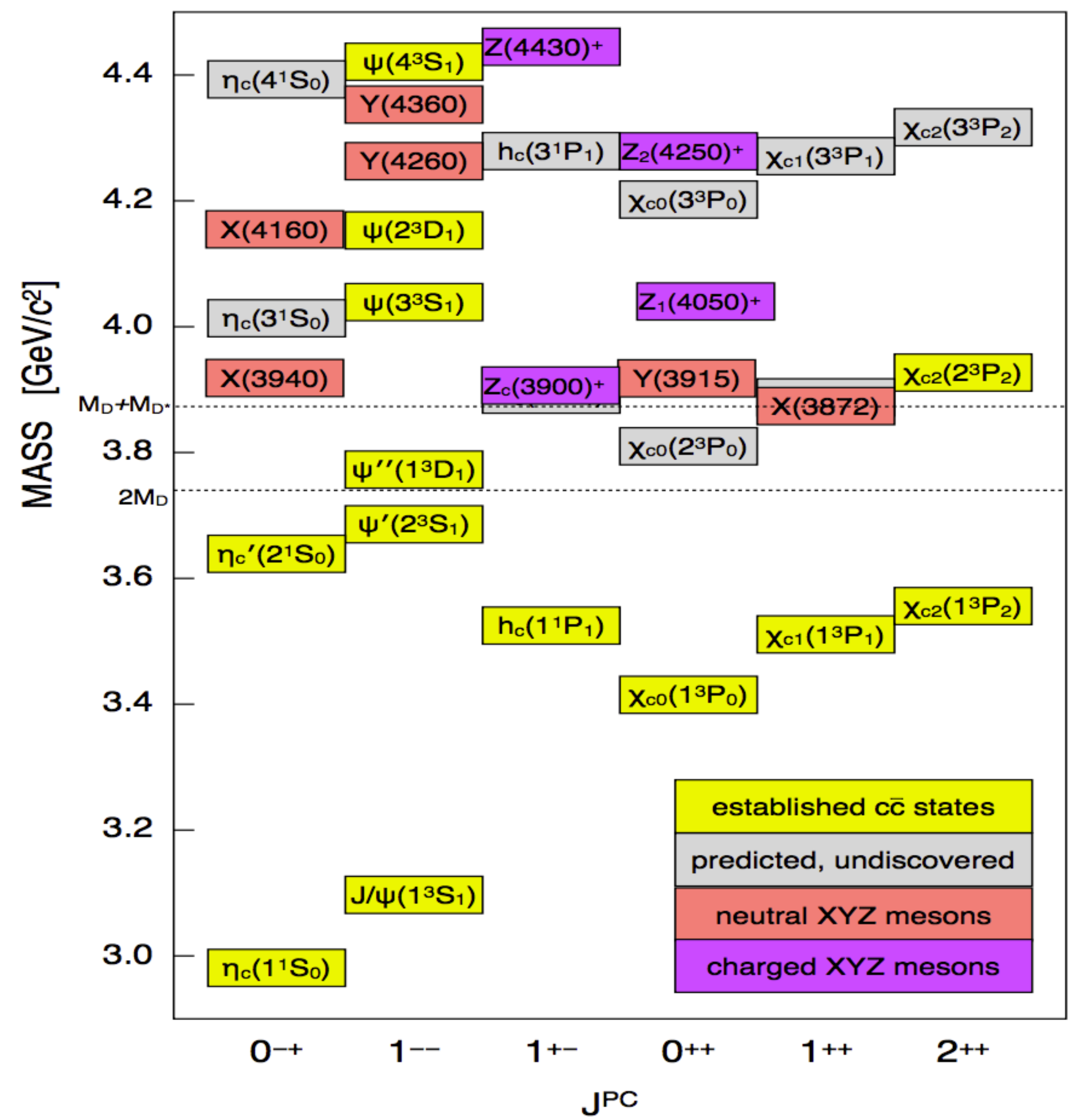
Summary

- LHCb has confirmed this existence and shown the **resonant** behaviour of the Z(4430)$^{\pm}$.
- Minimal quark content of **$c\bar{c}u\bar{d}$**.
- No clear picture of the complex system of charmonium-like exotic resonances.
- Further constraints will come from observing Z(4430)$^{\pm}$ and other exotics in alternative decay modes and/or production mechanisms.

- **Interesting times ahead…**
  - LHCb has large datasets of B decays containing J/ψ, ψ(2S), χ_c… where other exotics could live.
  - Look for synergies with the **$s\bar{s}$** and **$b\bar{b}$** sectors.
  - Data taking starts again in 2015, looking forward to collecting even higher statistics!

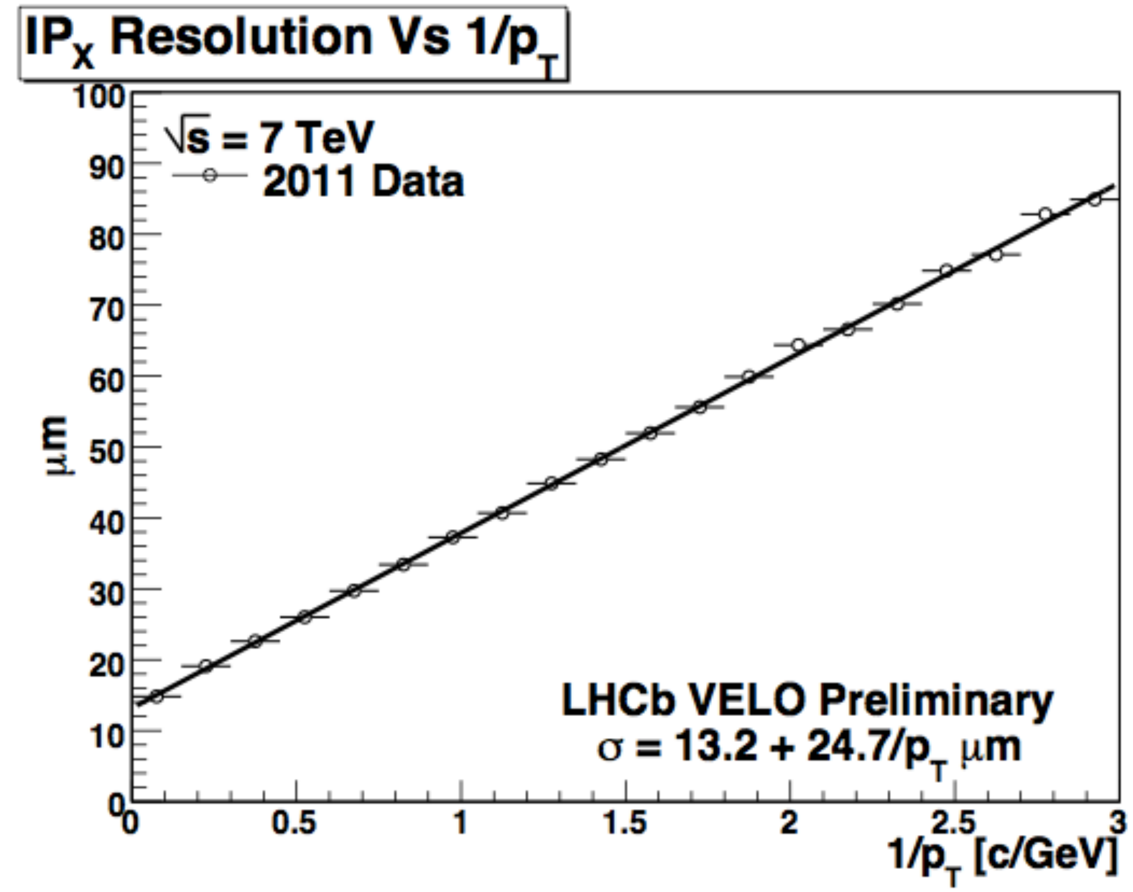
Z(4430) in the media: http://www.phy.syr.edu/~tomasz/z4430.html





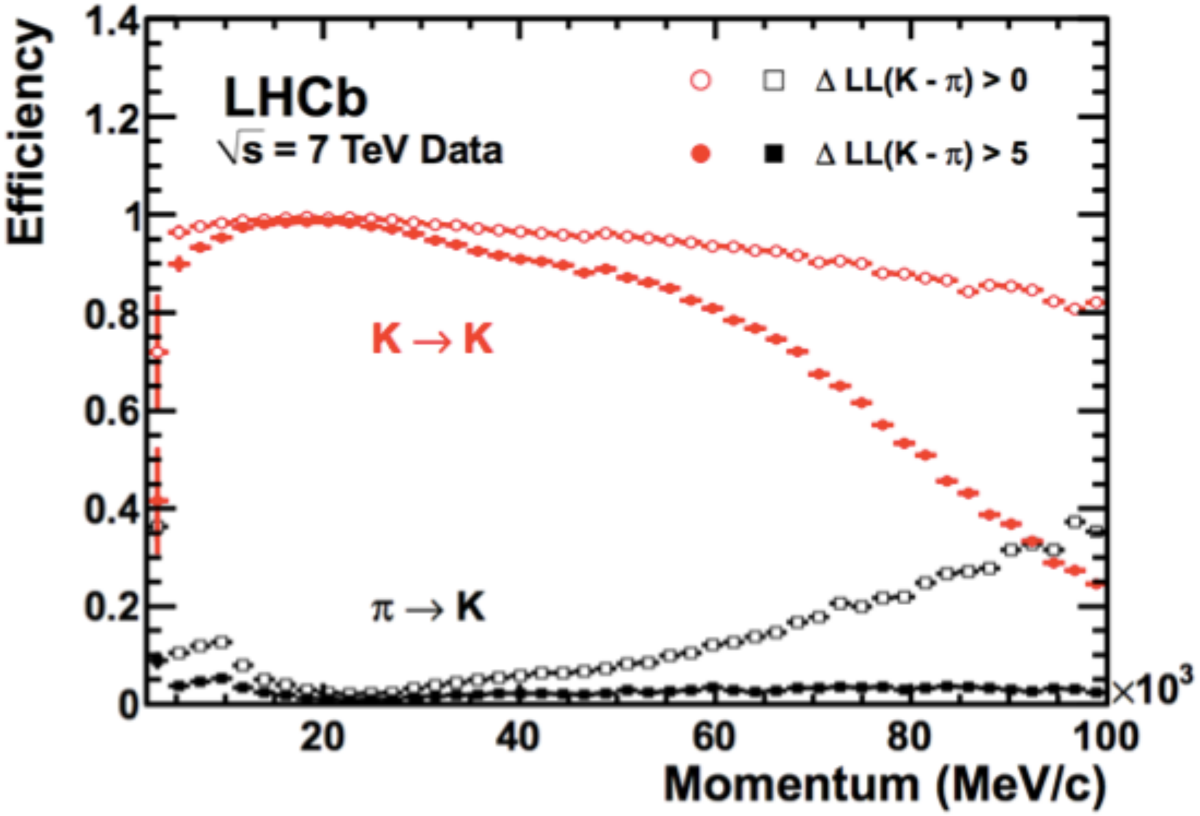
BACKUP

Vertex Locator (VELO)

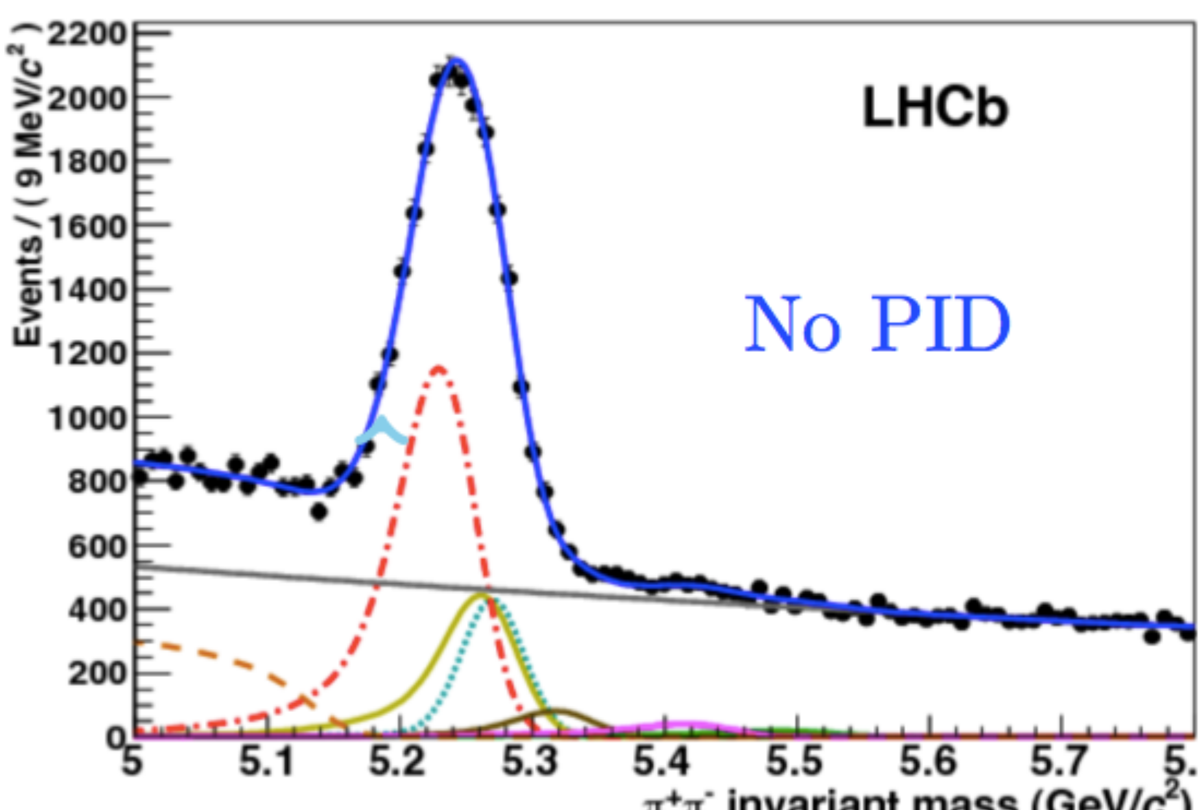


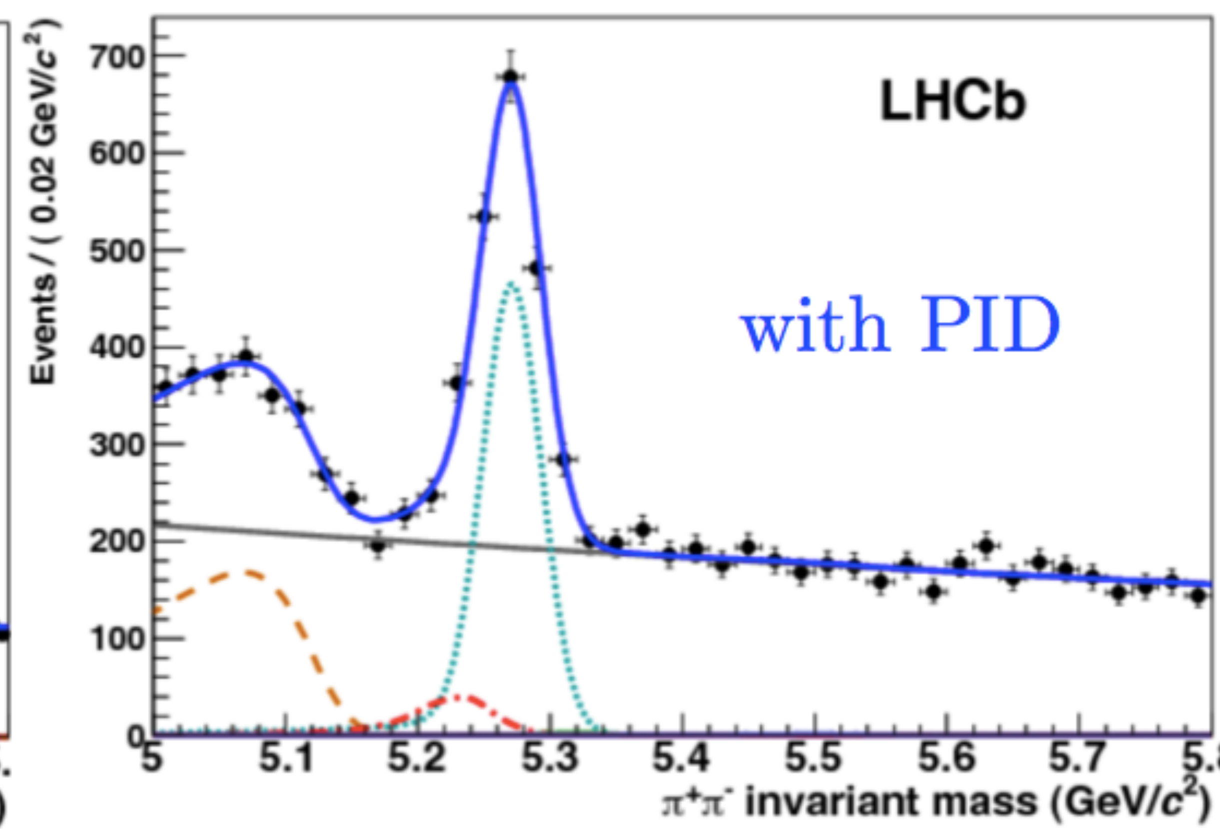
- 21 silicon strip detectors, 8mm from beam line.
- Operates in vacuum, separated from LHC vacuum by $300\mu m$ Al foil.
- Primary vertex resolution $\sim 13, 13, 69\mu$m in x, y, z.
- IP resolution of tracks with $p_T > 2\,\mathrm{GeV/c^2}$ is $\sim 20\mu$m.
- Decay time resolution ~ 45 fs for many B decay channels.

Particle ID

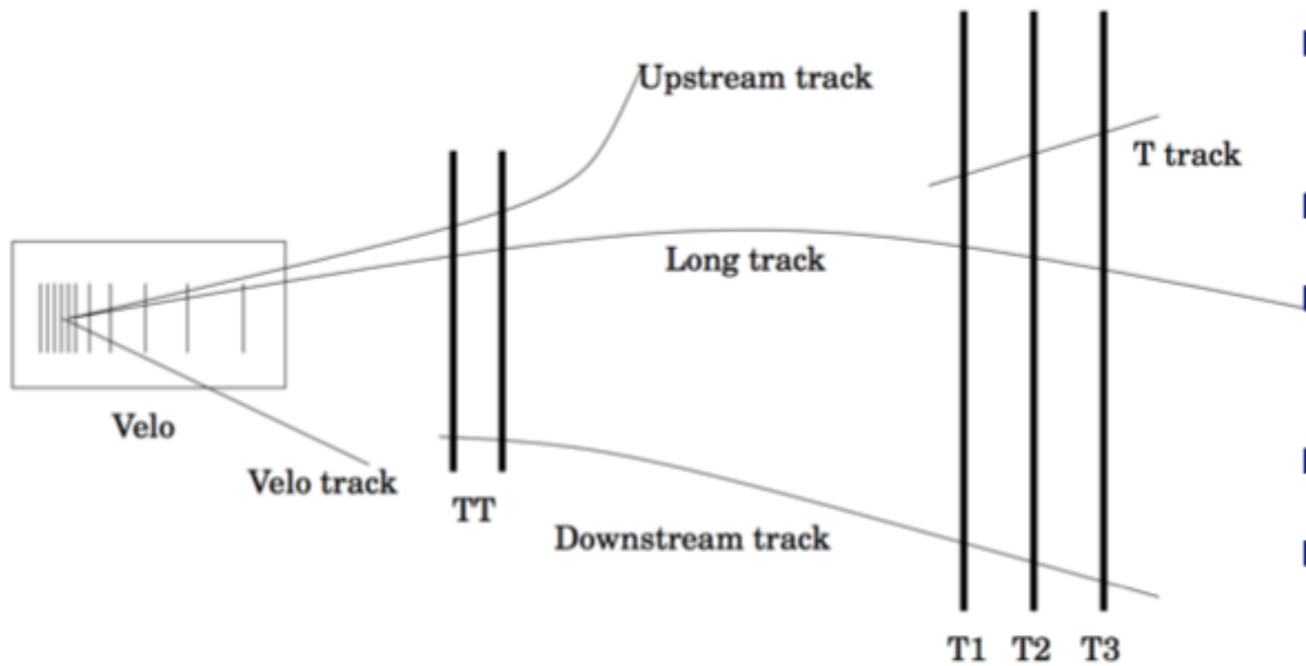


- Gas radiators (C_4F_{10}, CF_4) + aerogel.
- Photomultiplier tubes to detect Cerenkov light.
- Excellent for suppressing backgrounds.
- Muon-ID: $\varepsilon(\mu \to \mu) \sim 97\%, \varepsilon(\pi \to \mu) \sim 1 - 3\%$

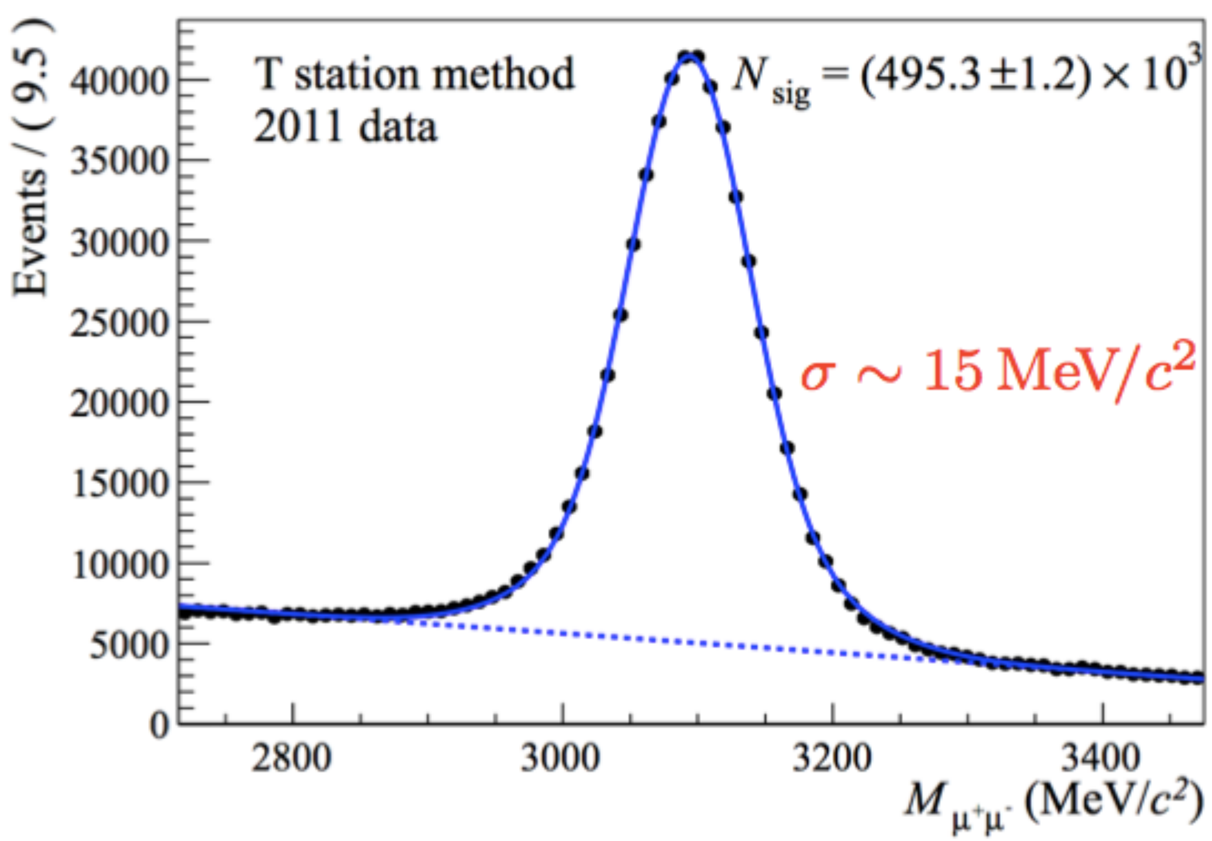


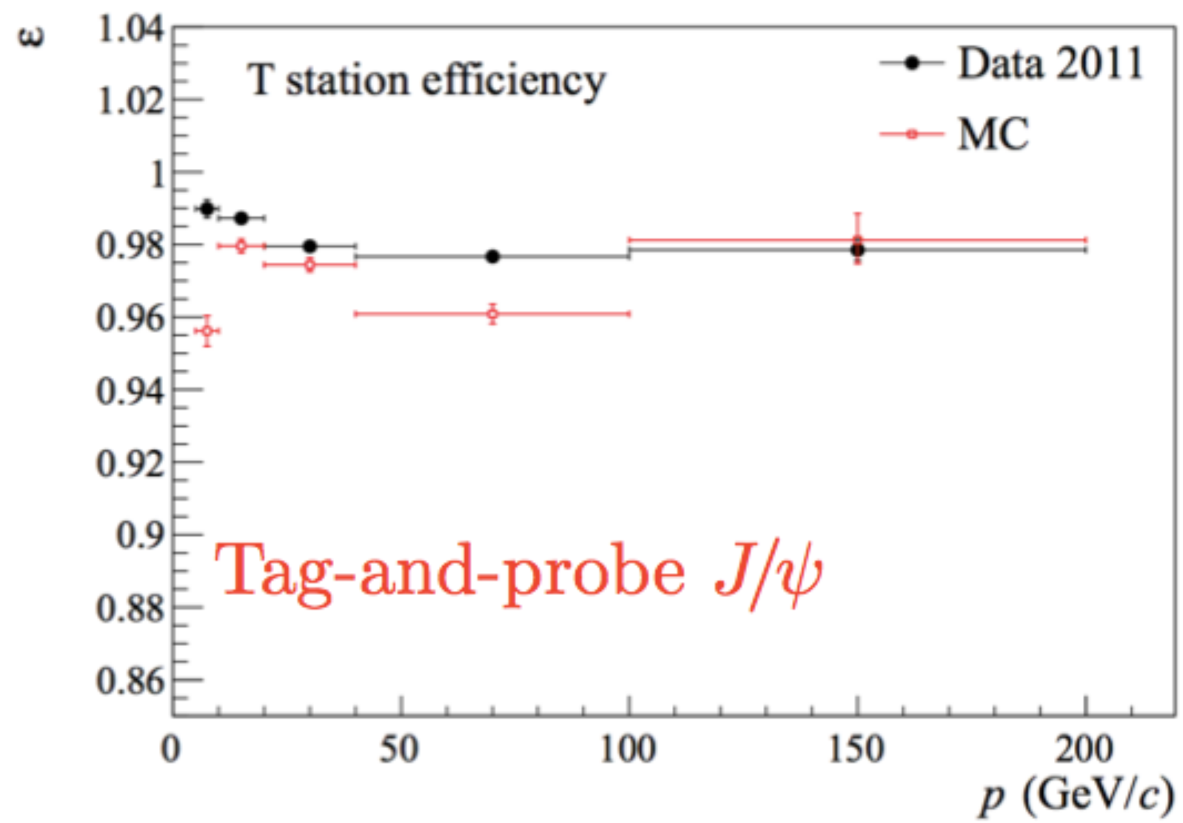


Tracking



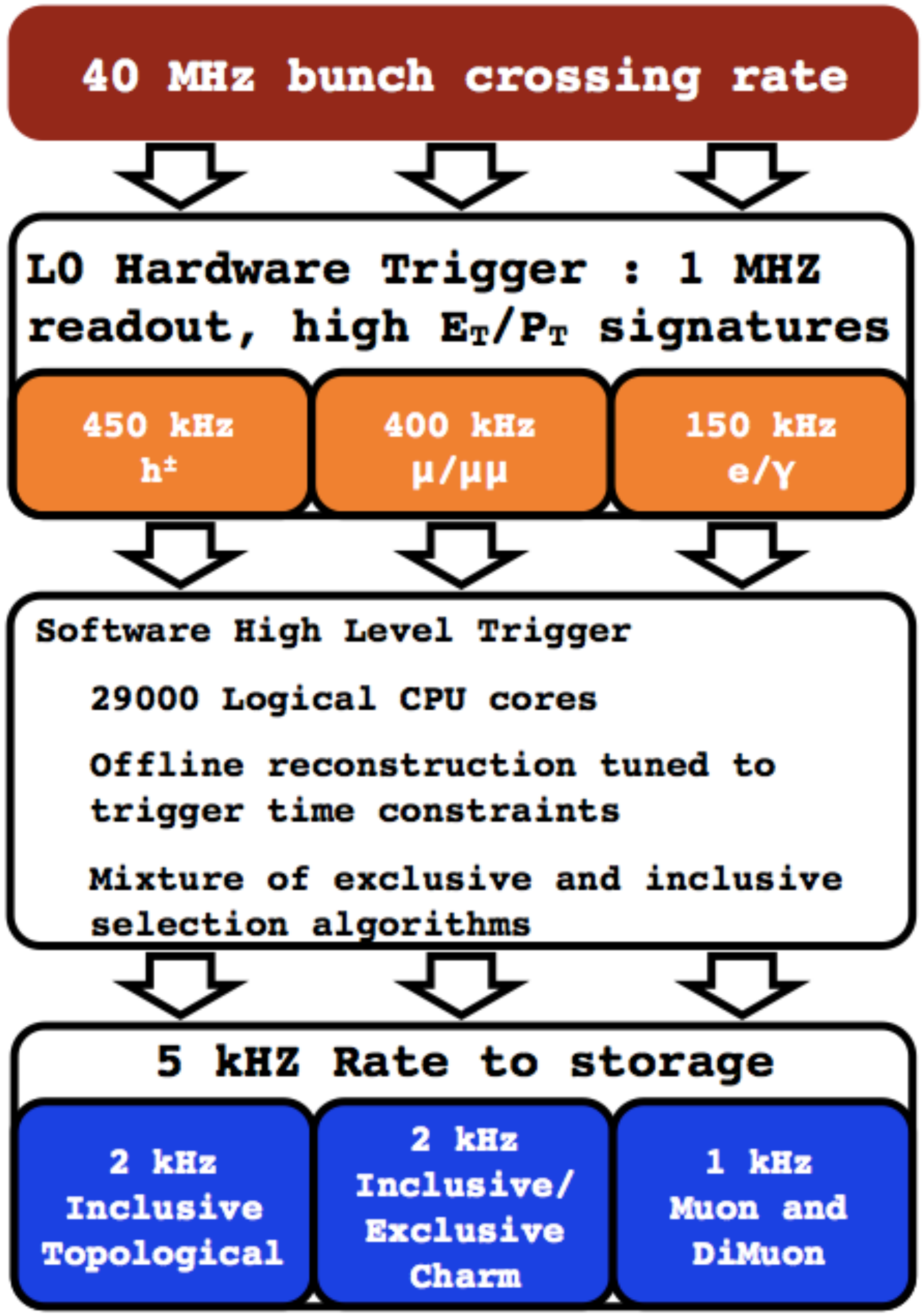
- Silicon microstrip detectors closest to beam pipe.
- Straw tubes cover larger area.
- Aligned to $\sim 14\mu m$ using large samples of $J/\psi \to \mu\mu$, $D^0 \to K\pi$.
- $\Delta p/p \sim 0.5\%$.
- Mass resolution $\sim 8\,\mathrm{MeV}/c^2$ for $b \to J/\psi\, X$ decays.

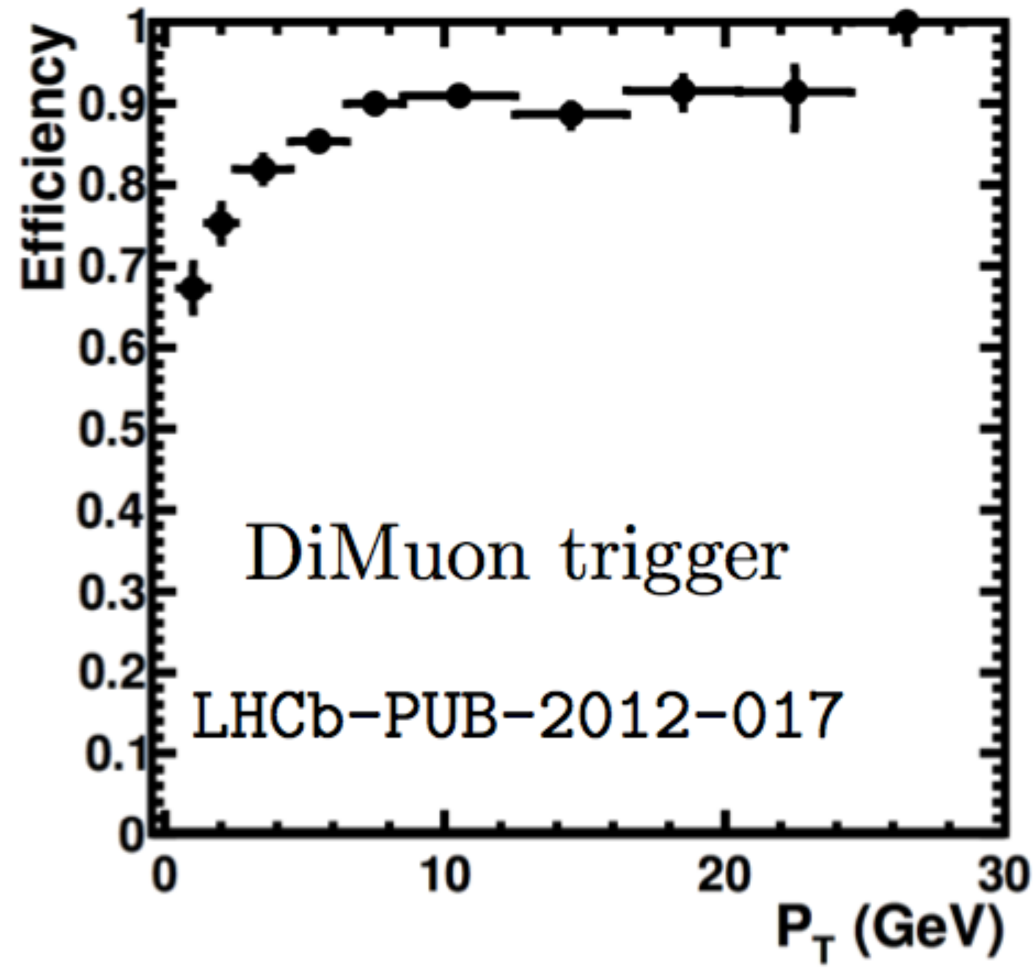




Trigger

- Approach: try to maintain high efficiency for manageable data rates.



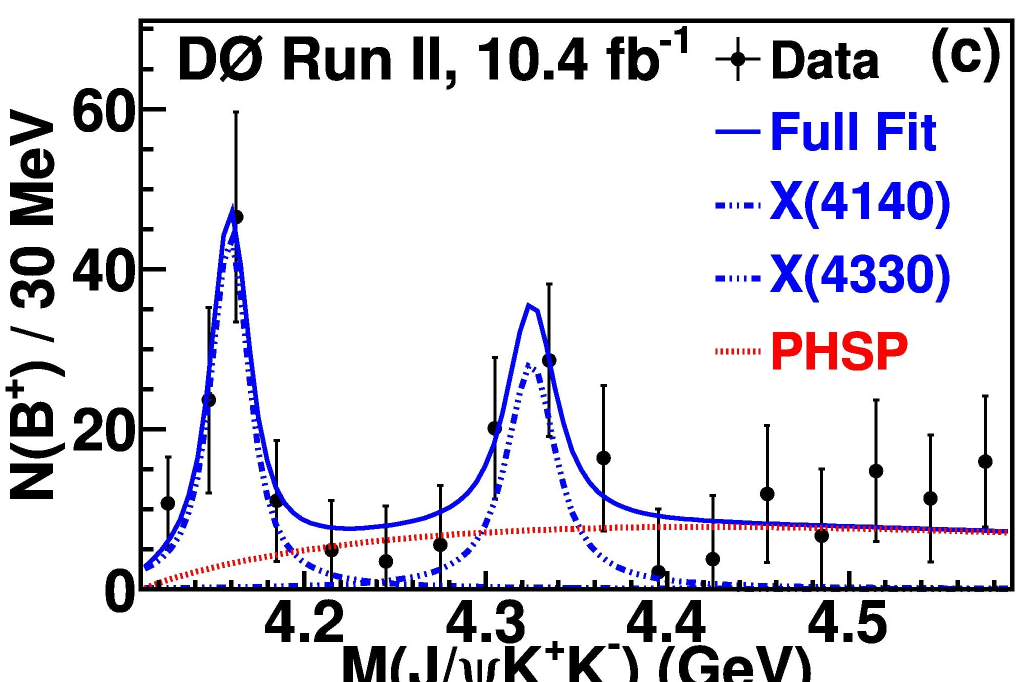


Lower efficiency for multi-body final states

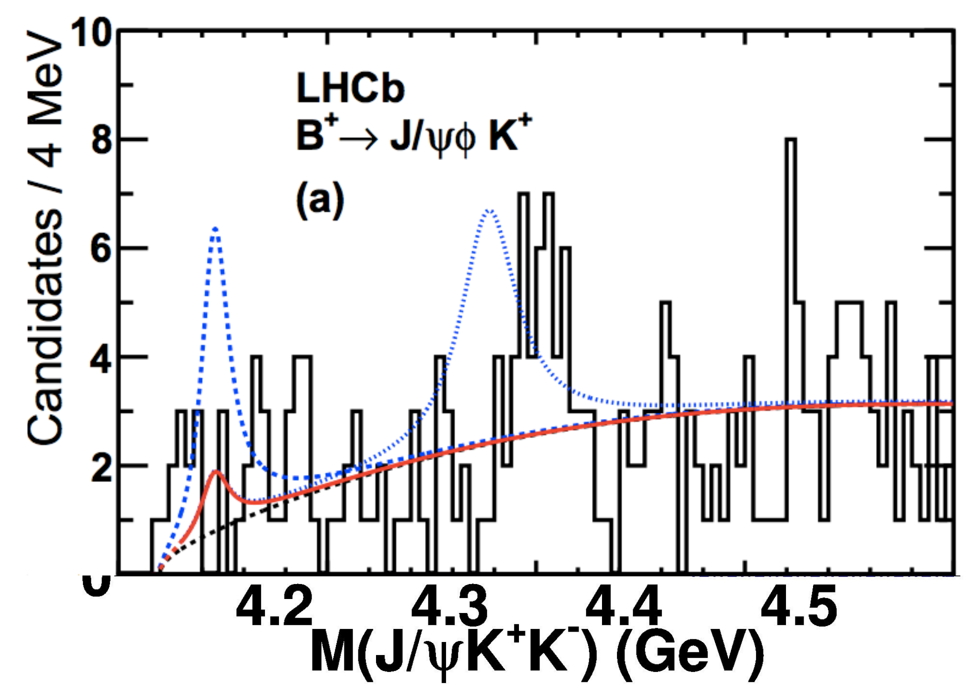
An enigma… the X(4140)

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

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	Conference



[Phys. Rev. D 89, 012004]



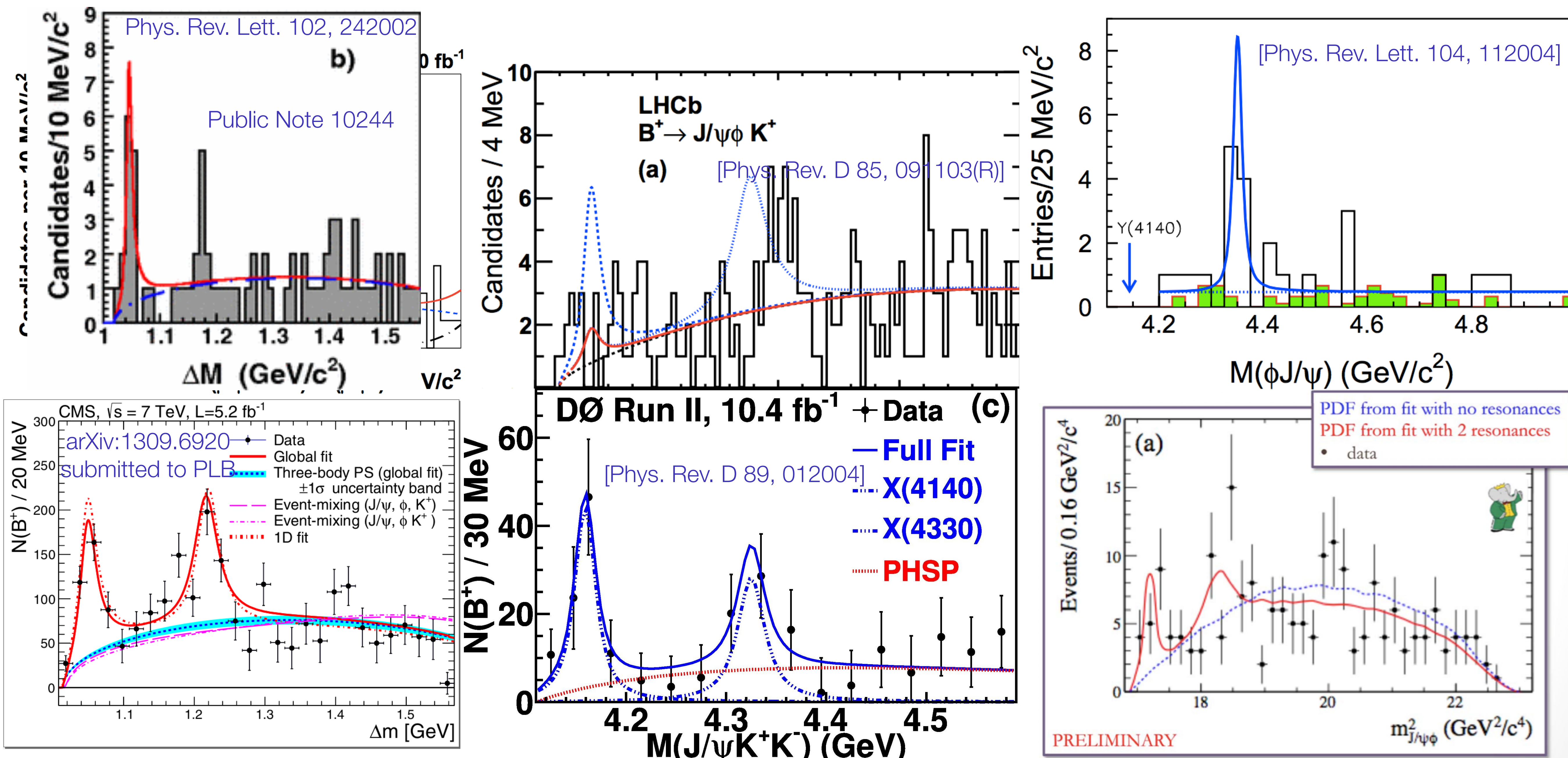
[Phys. Rev. D 85, 091103(R)]

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

An enigma… the X(4140)

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

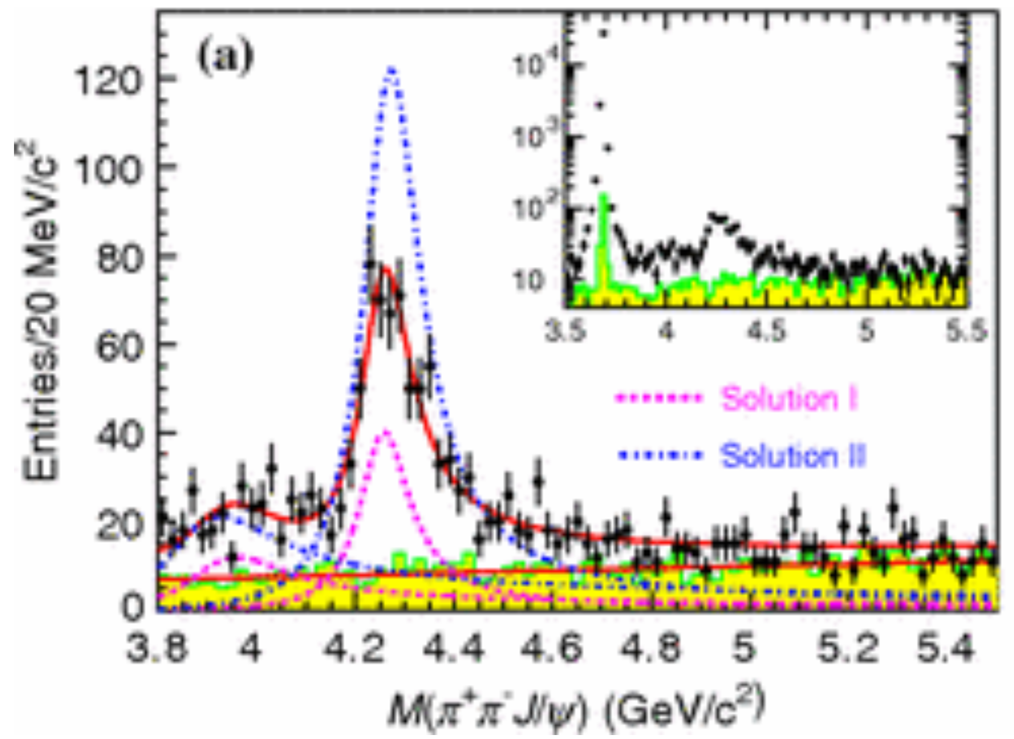
- X(4140) seen by some experiments, not by others in in m(J/ψΦ).
- Could be some hybrid state: **$c\bar{c}s\bar{s}$**



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

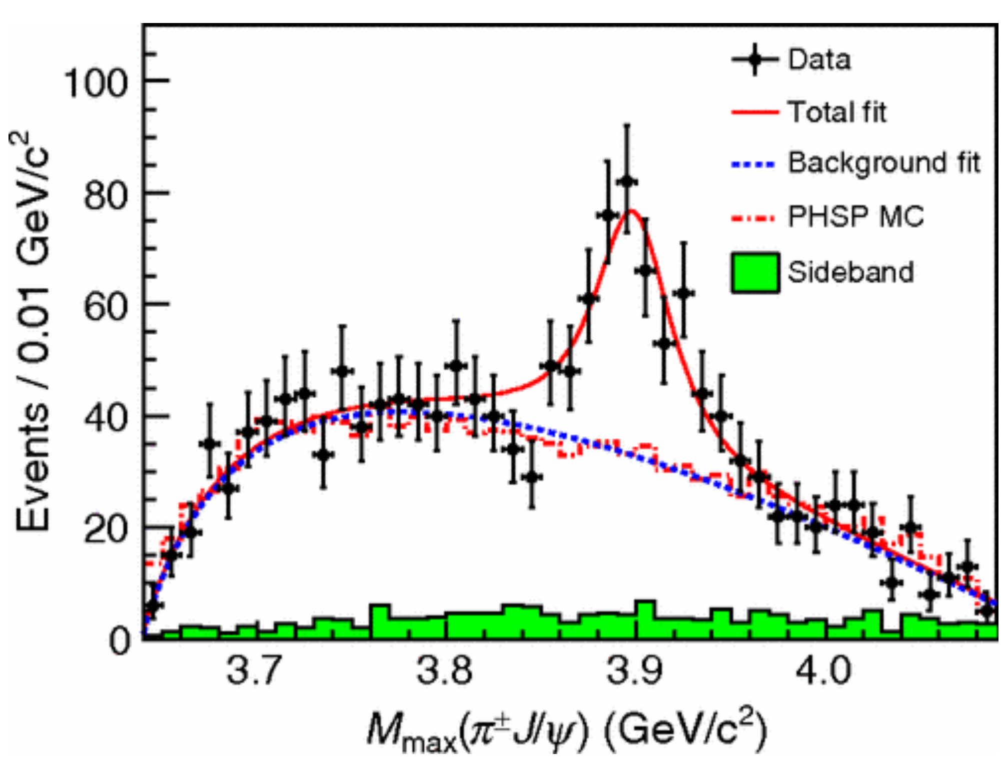
- Other exotic **charged** state observed by BESIII, Belle at the Y(4260) and CLEO-c at Y(4160).
- CLEO-c also have evidence for neutral member of isospin triplet decaying to $\pi^0 J/\psi$.

Y(4260)

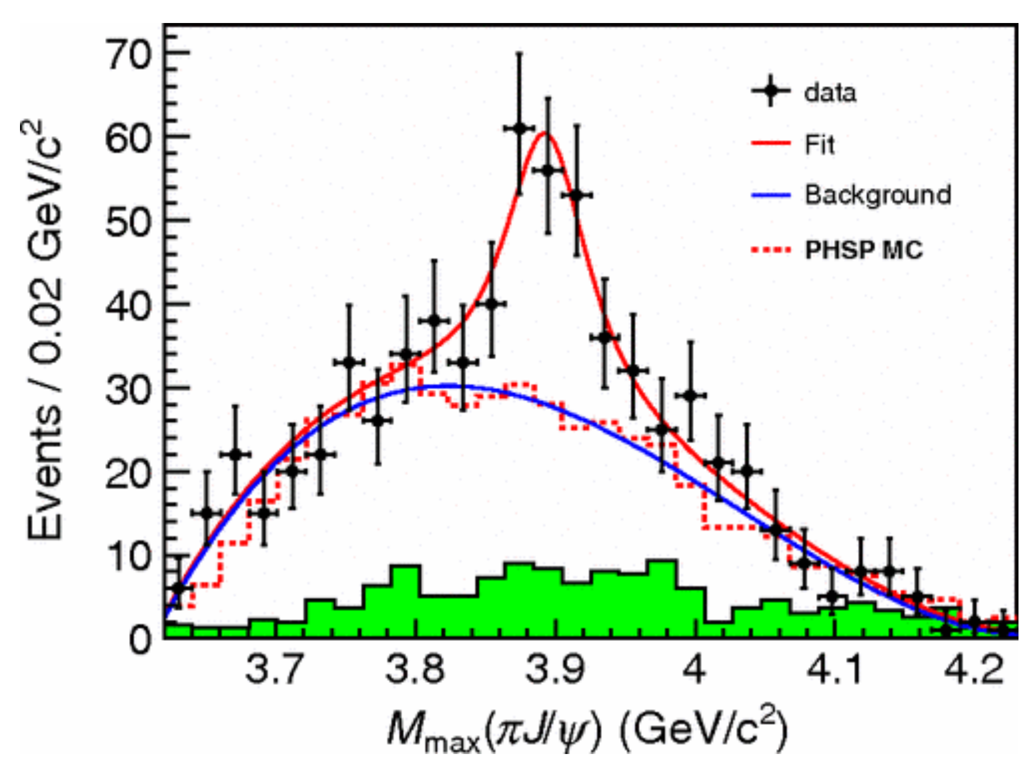


[Phys. Rev. Lett. 110, 252002]

$M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2
$\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2



[Phys. Rev. Lett. 110, 252001]



[Phys. Rev. Lett. 110, 252002]

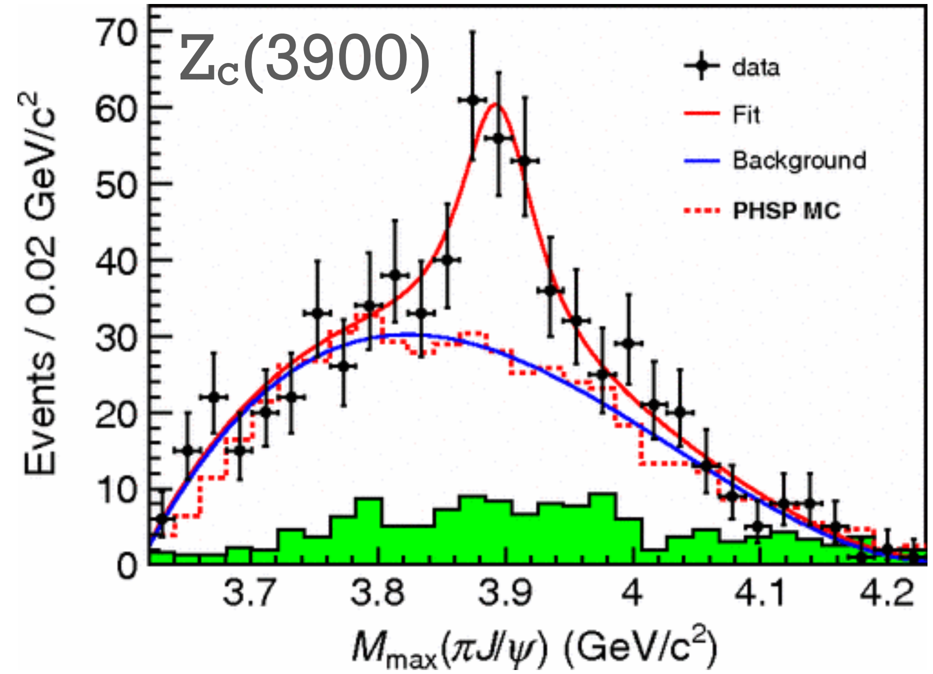
Other exotic states

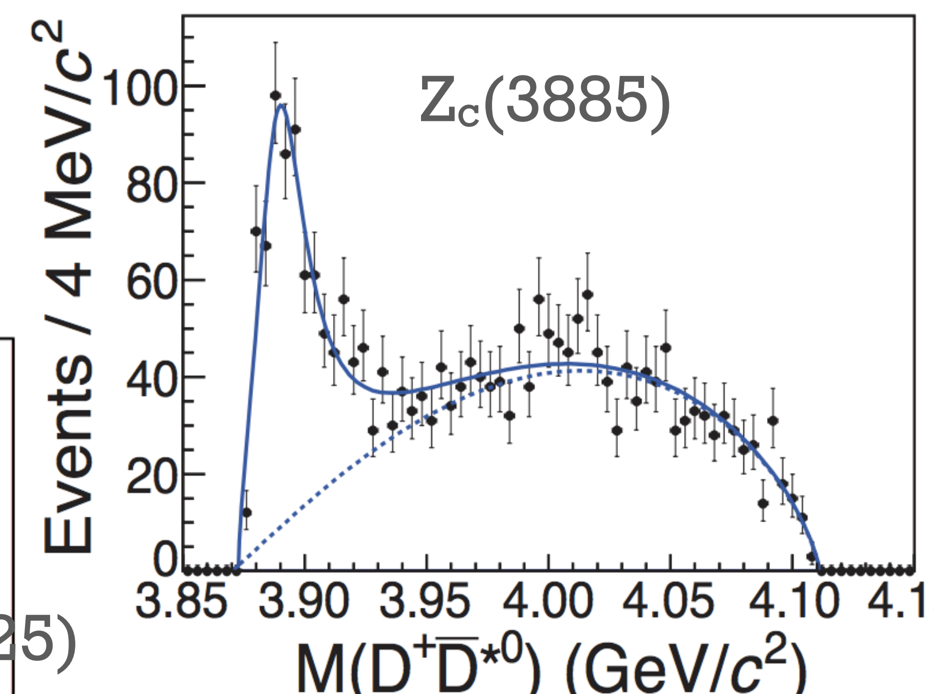
[Phys. Rev. Lett. 111, 242001 (2013)]
[Phys. Rev. Lett. 112, 022001 (2014)]
[Phys. Rev. Lett. 112, 132001 (2014)]

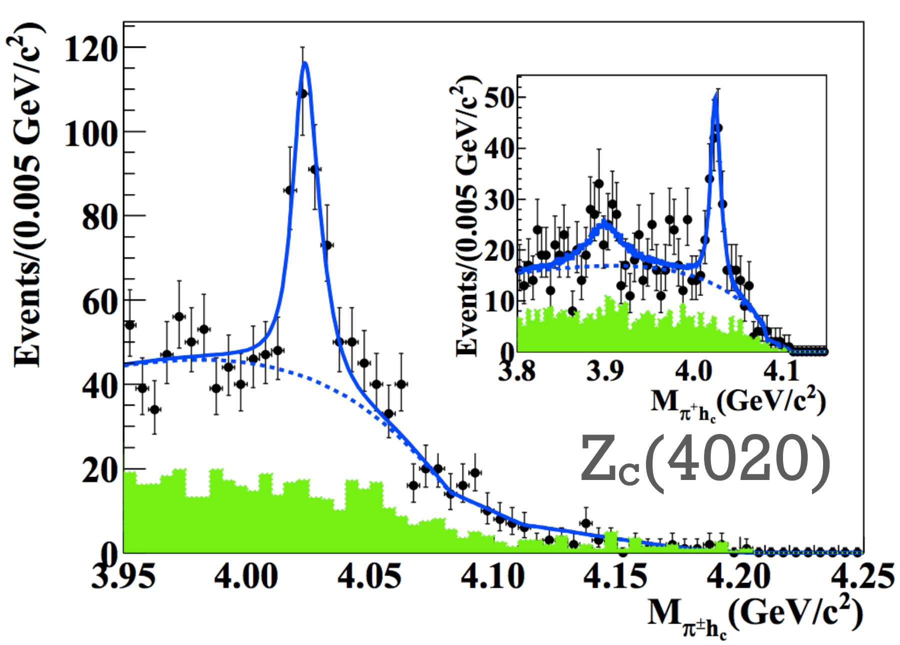
- $Z_c(3900)^+$ seen in $J/\psi\pi^+$. Also have $Z_c(3885)^+$ in $(D\bar{D}^*)^+$, showing a dramatic near threshold peak. These could be the same state. Need partial wave analysis of $J/\psi\pi\pi$ final state to determine this.

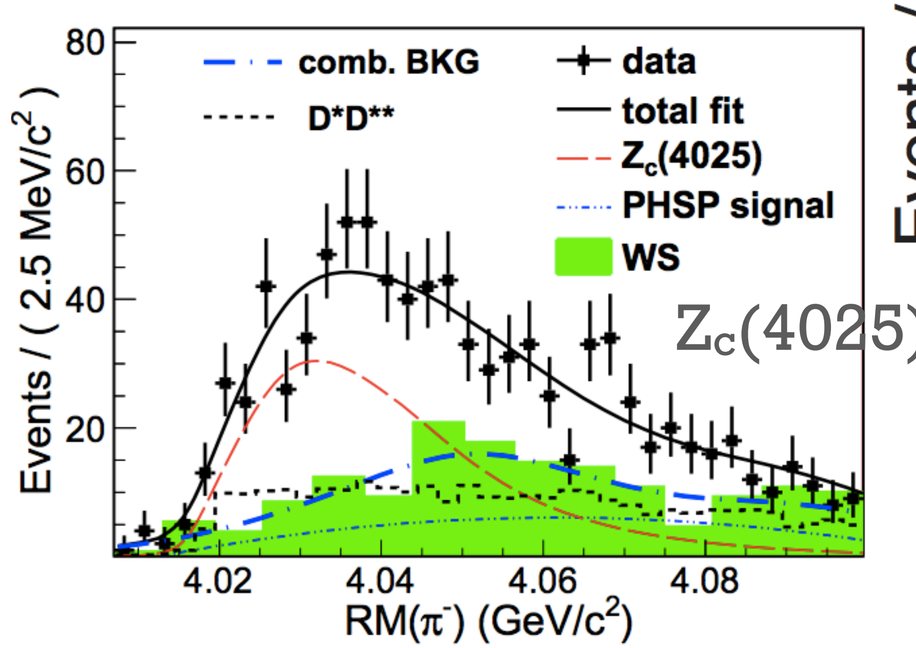
- $Z_c(4020)^+$ seen in $h_c(1P)\pi^+$ by BESIII. Very narrow width. This could be charm-sector equivalent of $Z_b(10650)^+$. Isospin triplet?

- $Z_c(4025)^+$ seen recently by BESIII just above $(D^*\bar{D}^*)^+$ threshold. $m(D^*\bar{D}^*)$ distribution not described by phase space. This could be same state as $Z_c(4020)^+$.



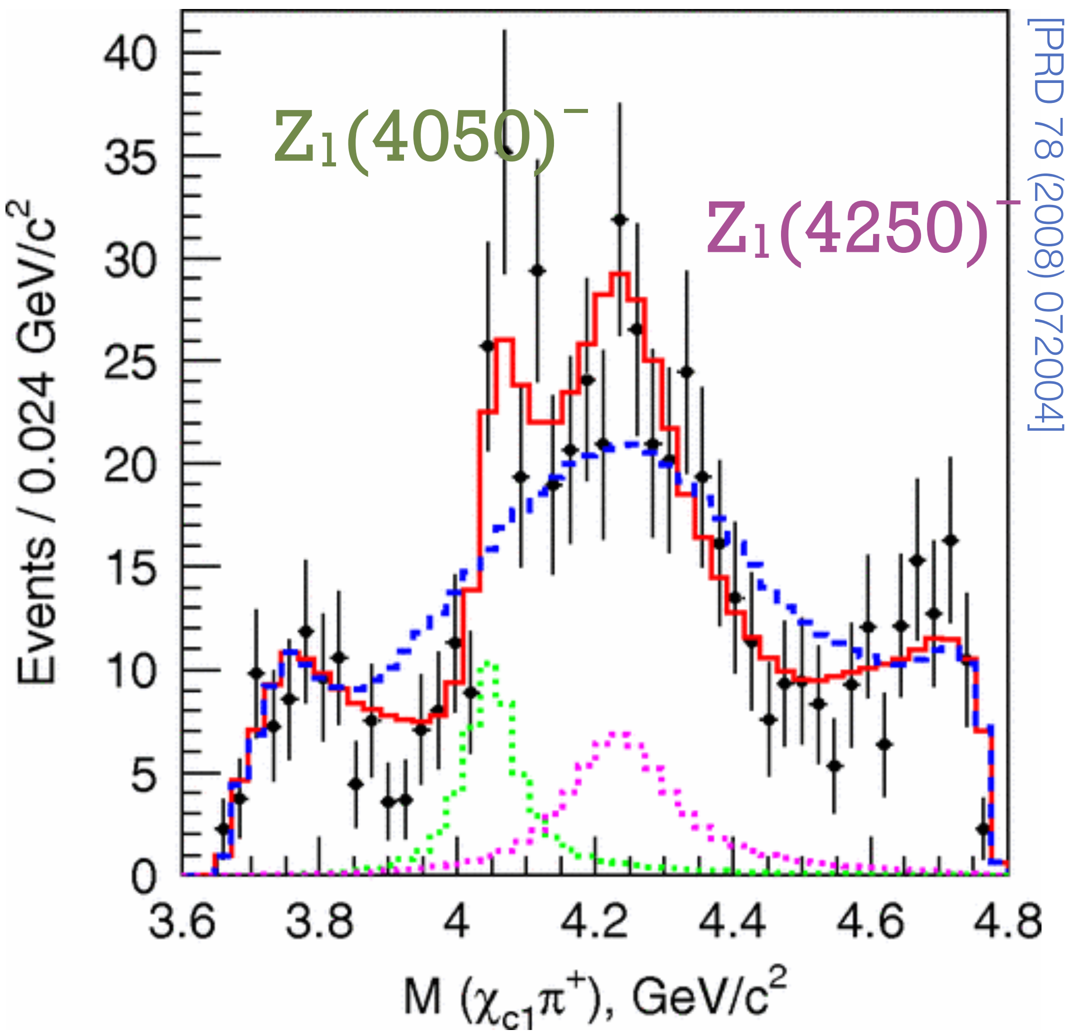






Other exotic states in quarkonium spectra

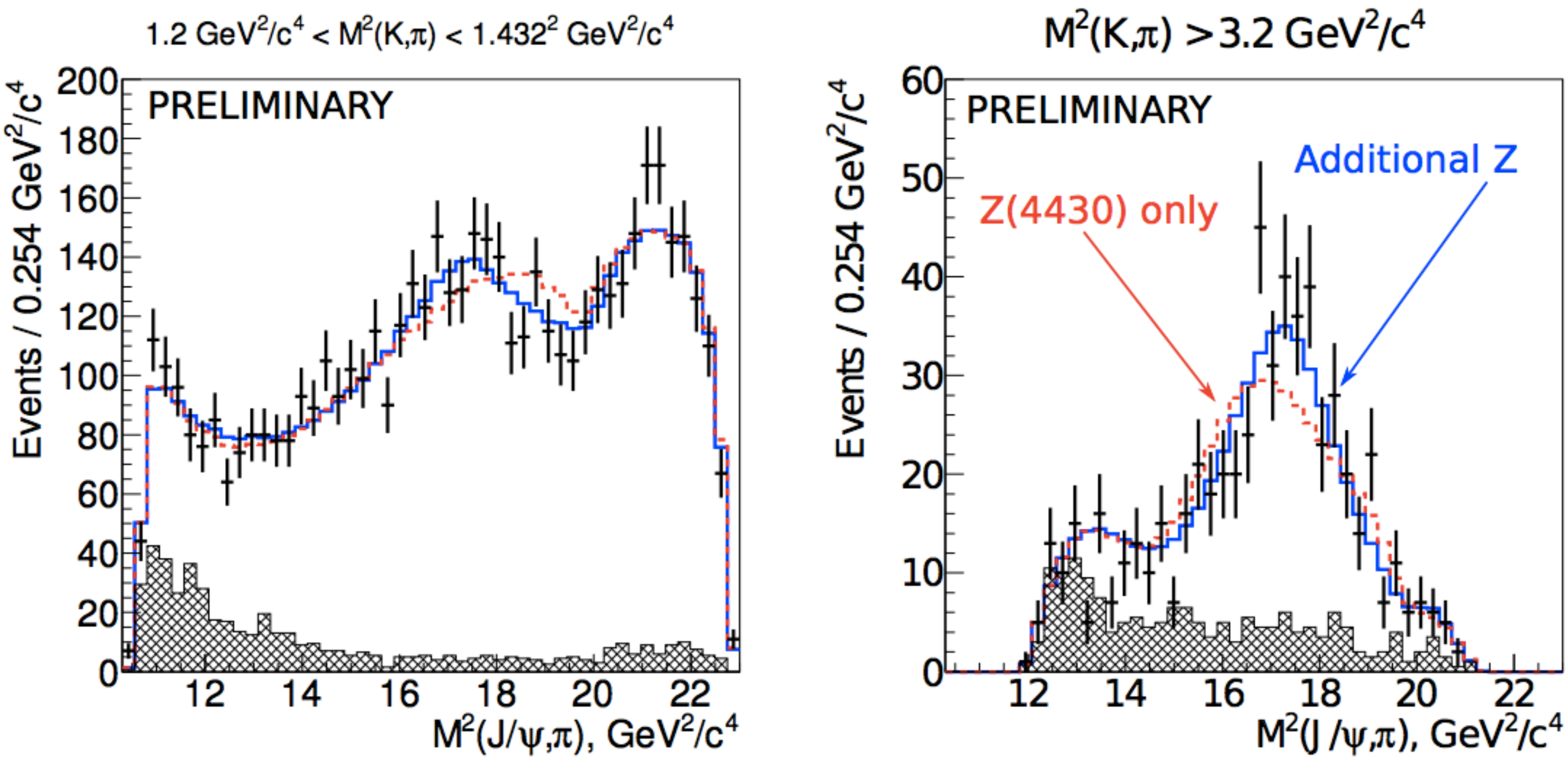
- Belle have evidence for $Z_1(4050)^-$ and $Z_2(4250)^-$ states in $B^0 \rightarrow Z^- K^+, Z^- \rightarrow \chi_{c1}\pi^-$.
- BaBar have not confirmed… [Phys. Rev. D 85, 052003]



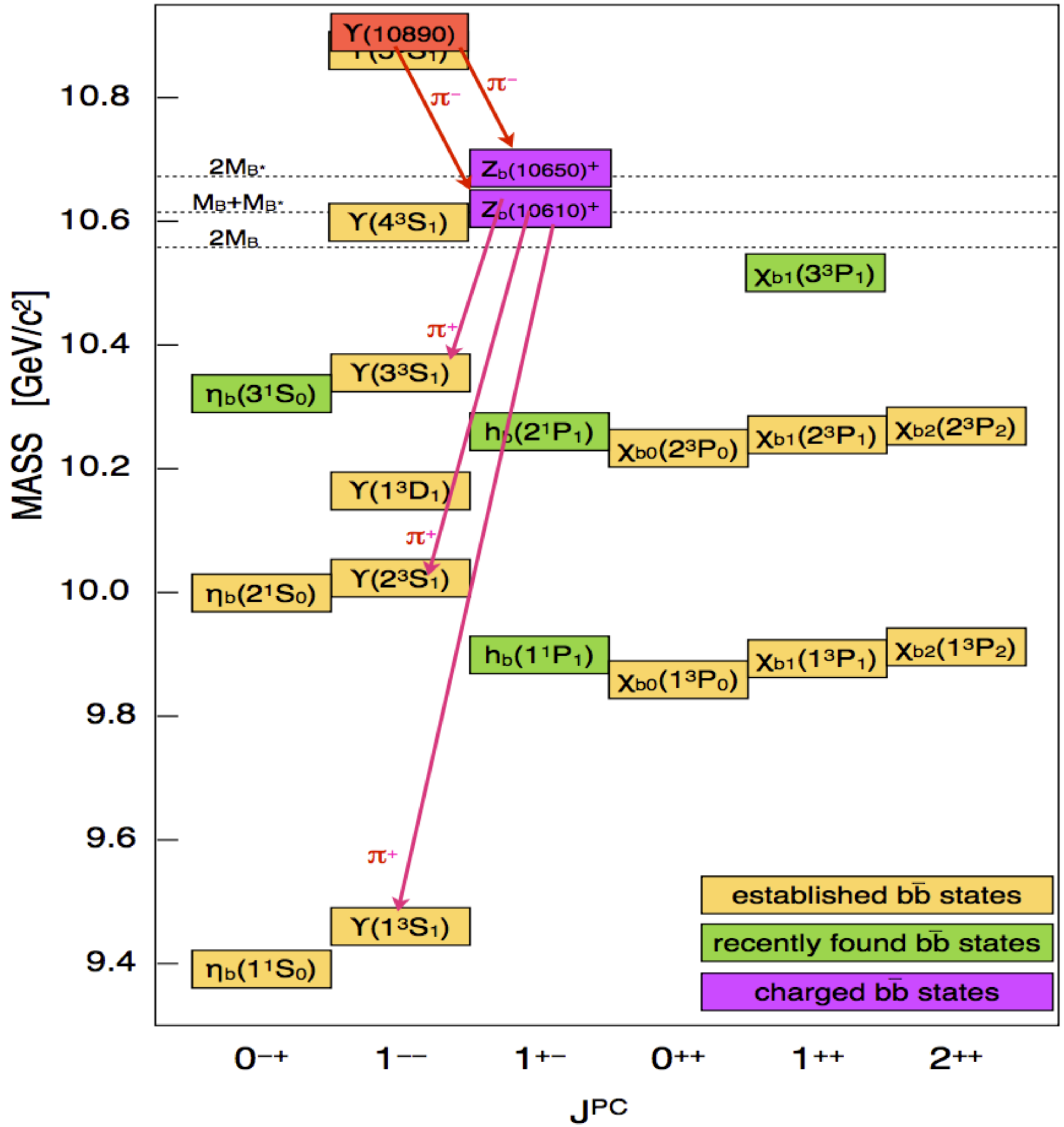
LHCb should be able to do something here in future

Do we see Z(4430) in $B^0 \longrightarrow J/\psi\pi^- K^+$ decays?

- 4D amplitude fit of $B^0 \longrightarrow J/\psi\pi^- K^+$ shown by Belle @ Moriond QCD 2014.
- $Z(4200)^+$ at 7.2sigma with systematics ($J^P = 1^+$). Width ~370MeV.
- $Z(4430)^+$ at 4.0sigma: evidence for **new decay mode.**
    - Expect smaller BR if Z has large radius, with larger overlap with ψ'.



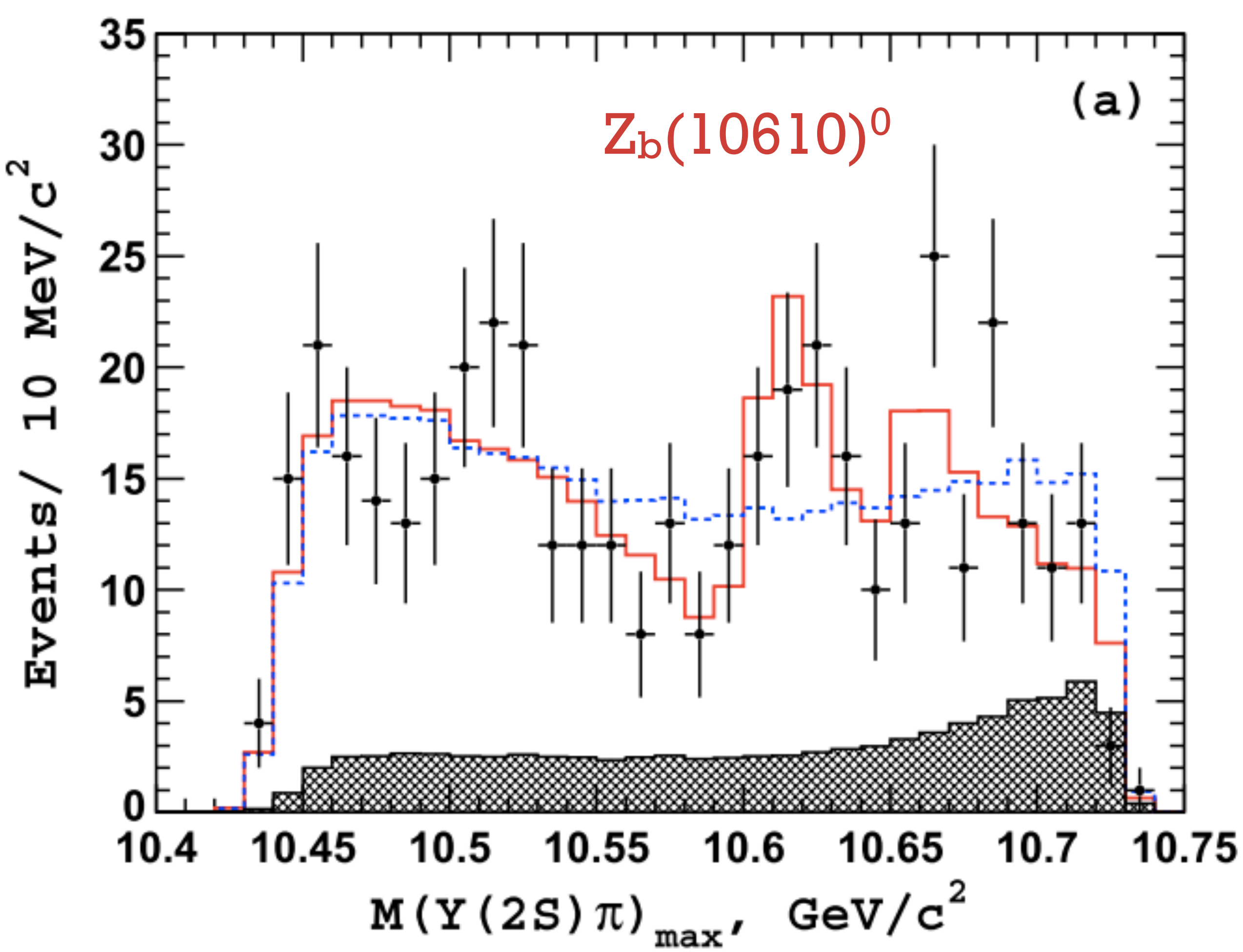
Bottomonium spectrum



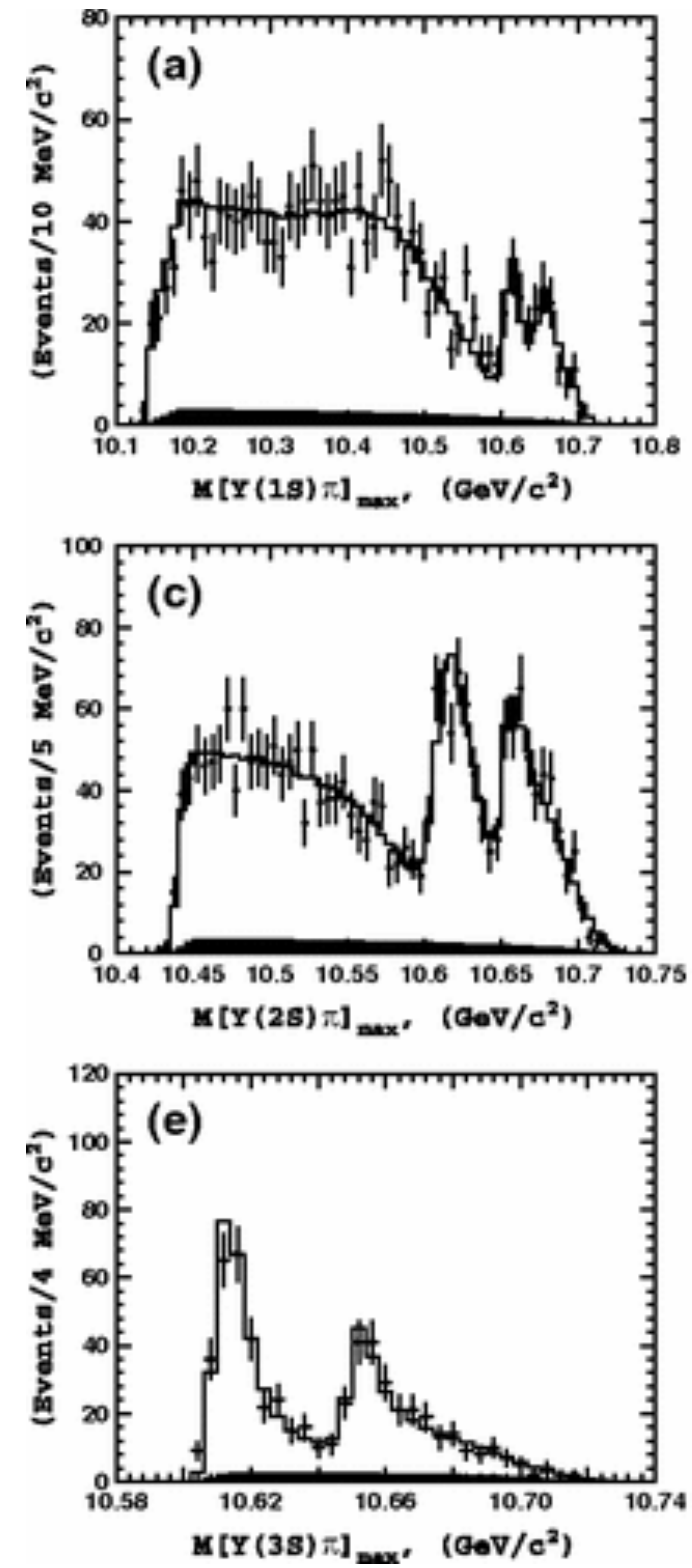
[Olsen arXiv:1403.1254]

Other exotic states in quarkonium spectra

- $\mathbf{b\bar{b}}$ spectrum
- Belle has claimed evidence for $Z_b(10610)^+$ and $Z_b(10650)^+$ resonances when looking at $\pi^+\pi^-\Upsilon(nS)$ and $\pi^+\pi^- h_b(mP)$.
- $I^G(J^P) = 1^+(1^+)$, Virtual $B\bar{B}^*$ and $B^*\bar{B}^*$ S-wave molecule-like states? [arXiv:1403.0992v1]
- Also first evidence for neutral isospin partners in $\pi^0\pi^0\Upsilon(2S)$ amplitude fit.

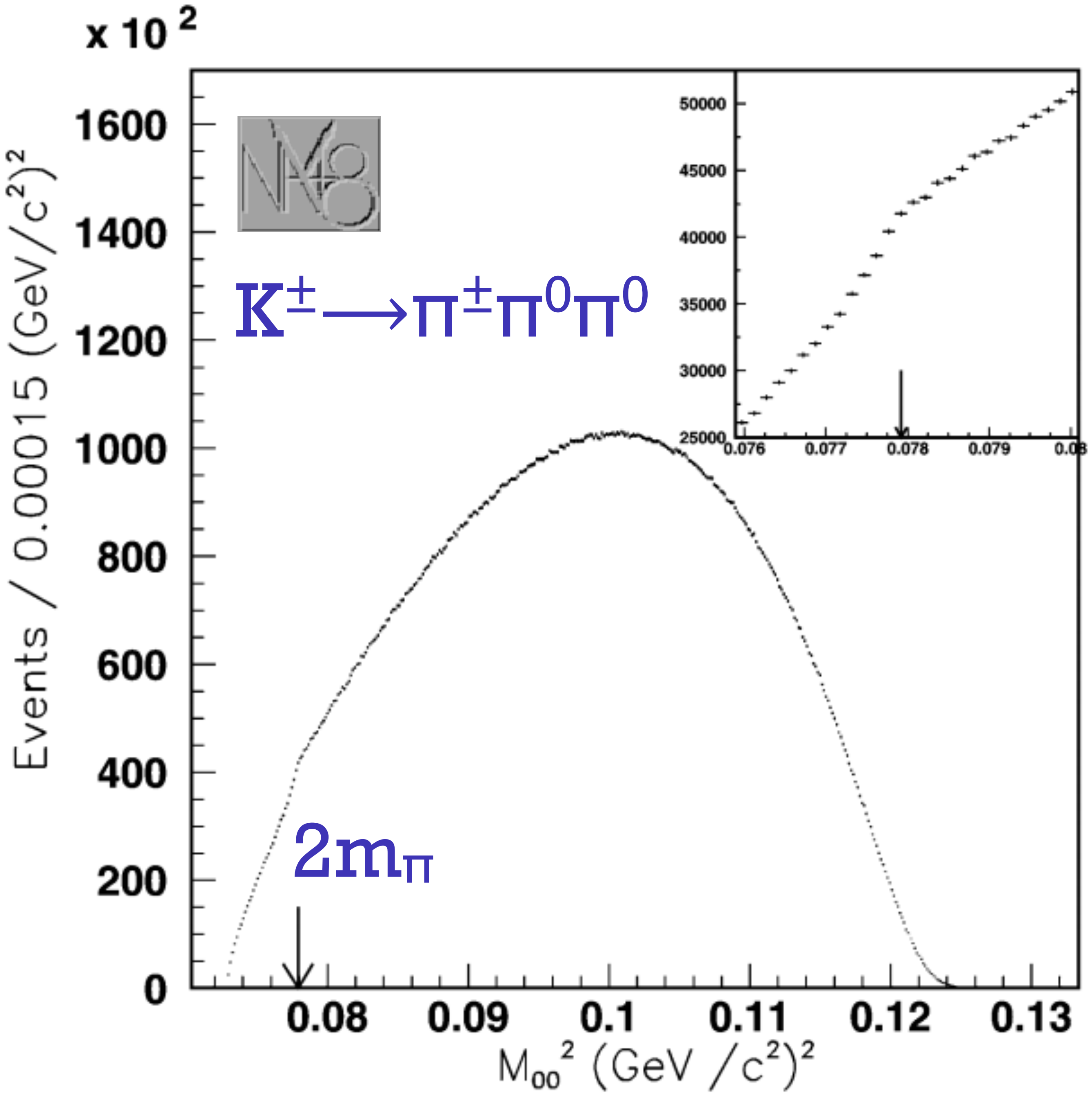


[PRD 88 (2013) 052016]

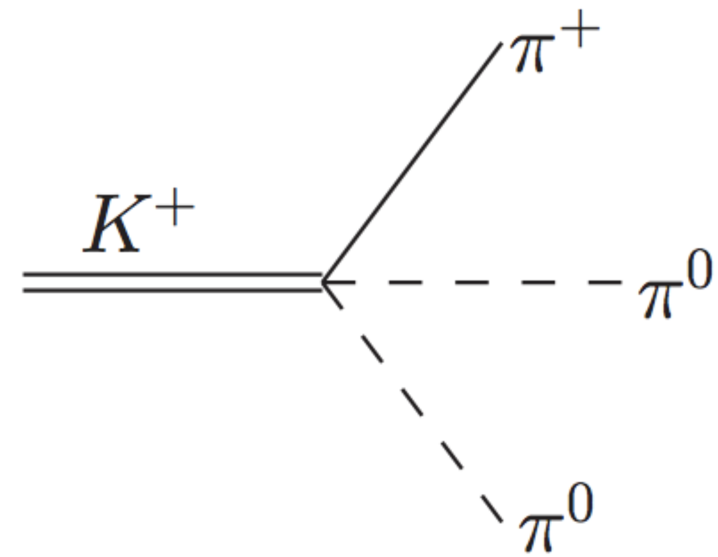


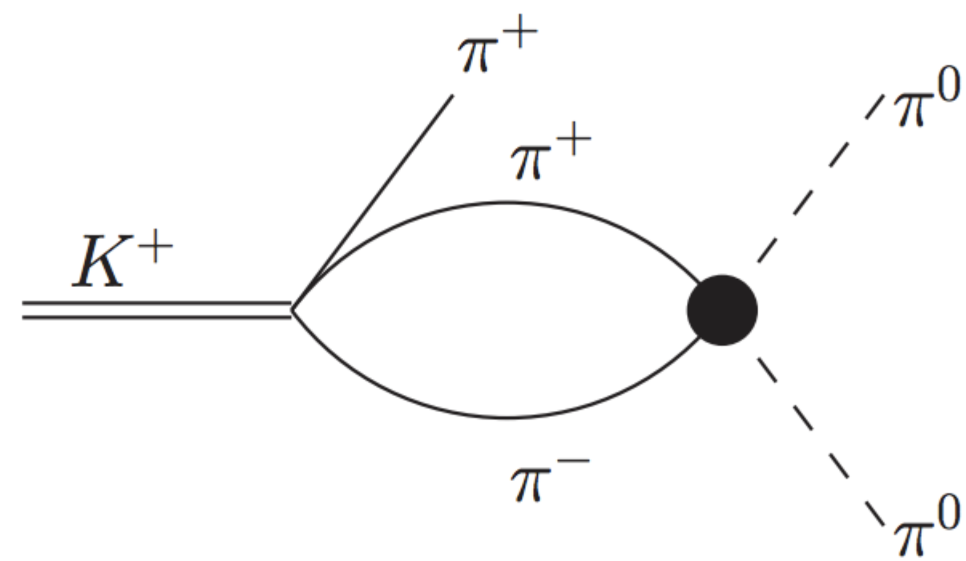
[PRL 108 (2012) 122001]

Cusps, threshold effects, rescattering



[NA48/2 PLB 633 (2006) 173–182]





[N Cabibbo, PRL 93:121801,2004]

Expect $\pi^+\pi^-$ to be in
an S-wave configuration

Helicity formalism

- Helicity (λ) is projection of $\bar{\mathrm{J}}$ onto $\bar{\mathrm{p}}$ (lambda = -|J|...+|J|)
- a $\longrightarrow$ 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$\longrightarrow$bc, b$\longrightarrow$de

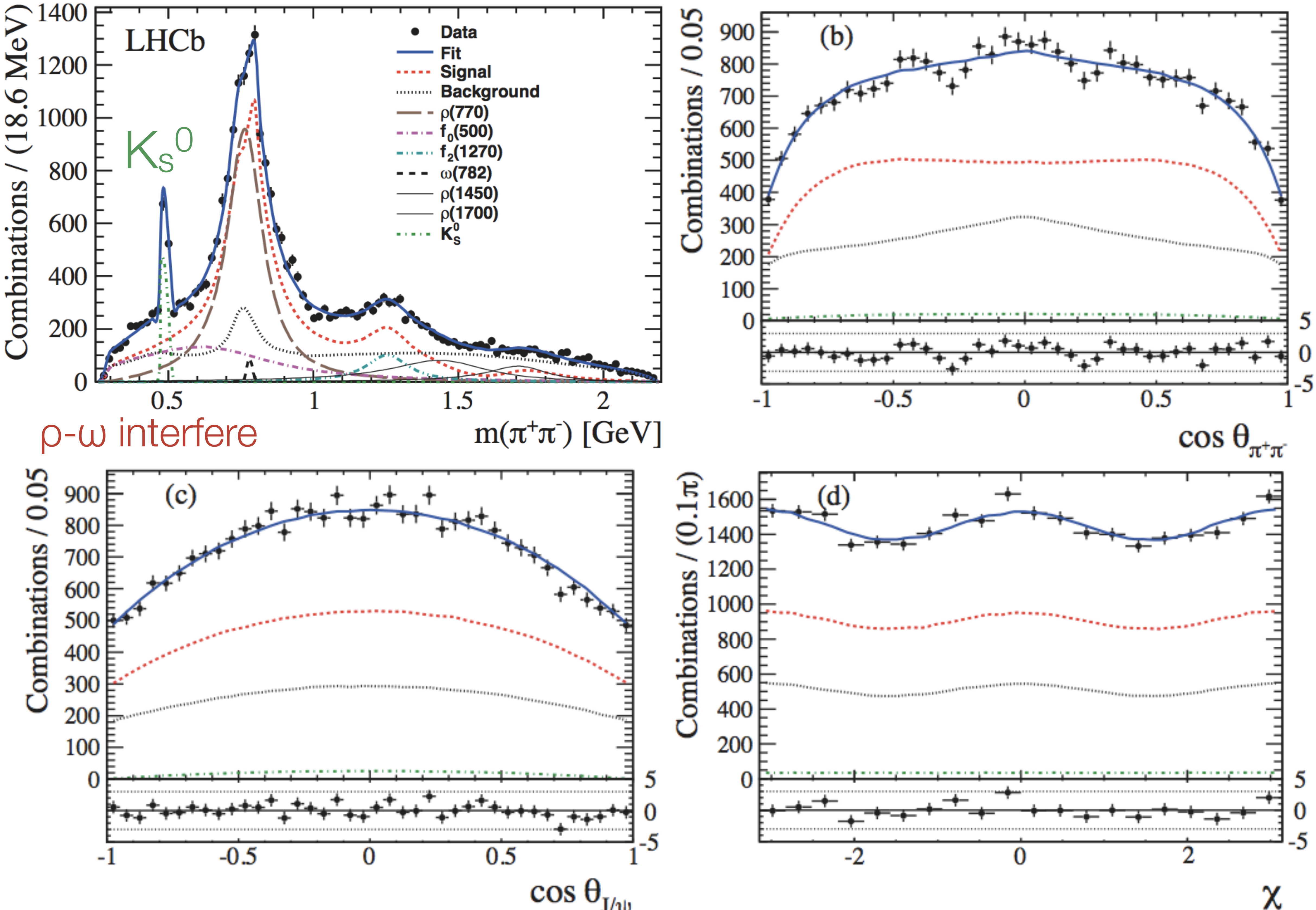
Helicity formalism

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

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



[arXiv:1404.5673]