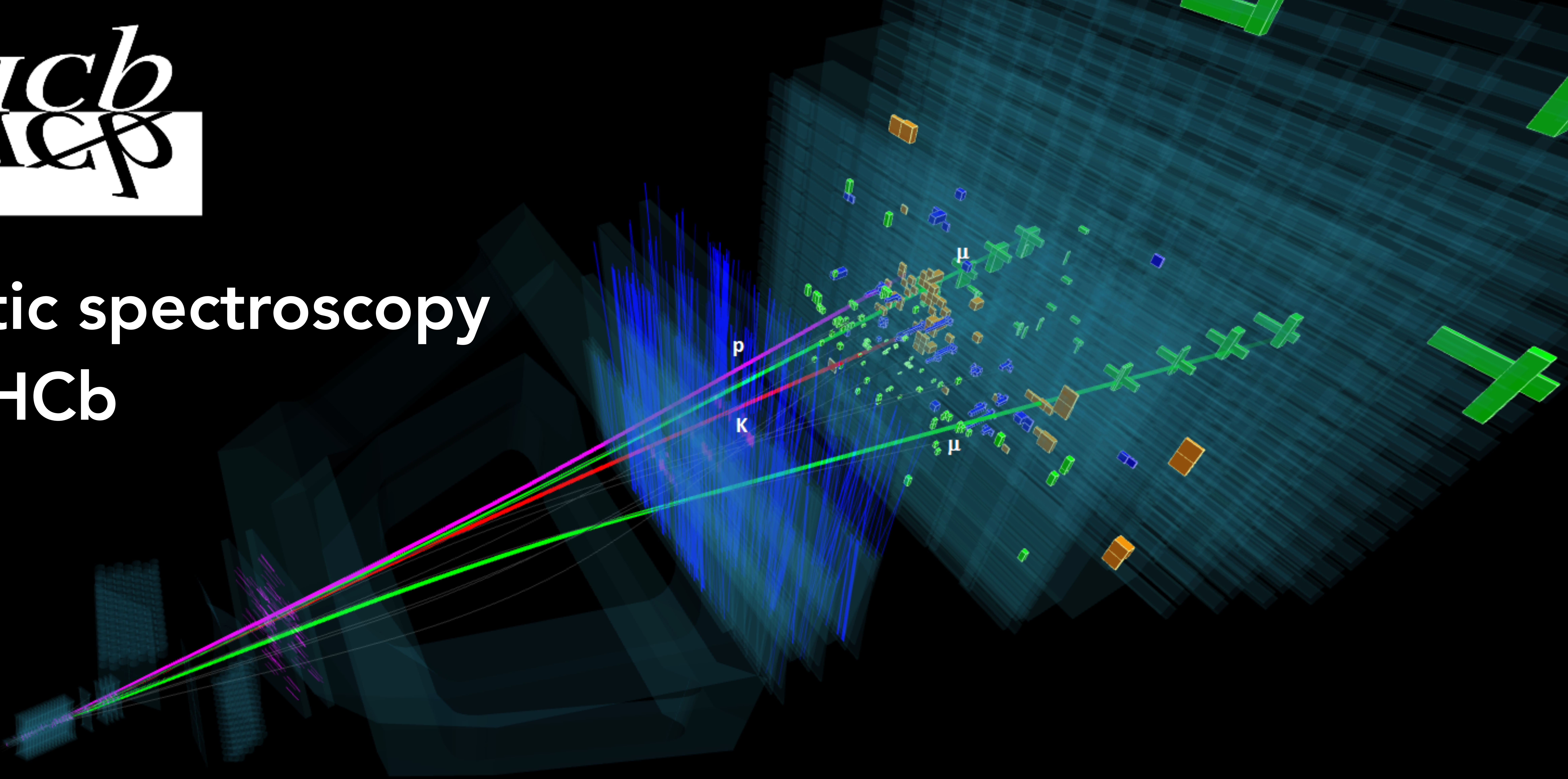
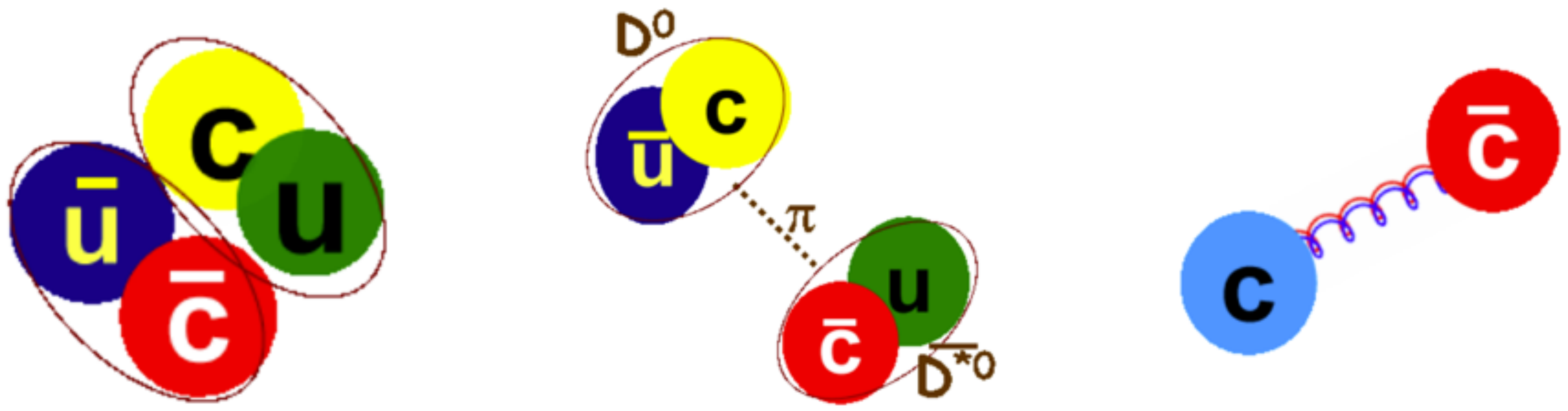
Exotic spectroscopy at LHCb



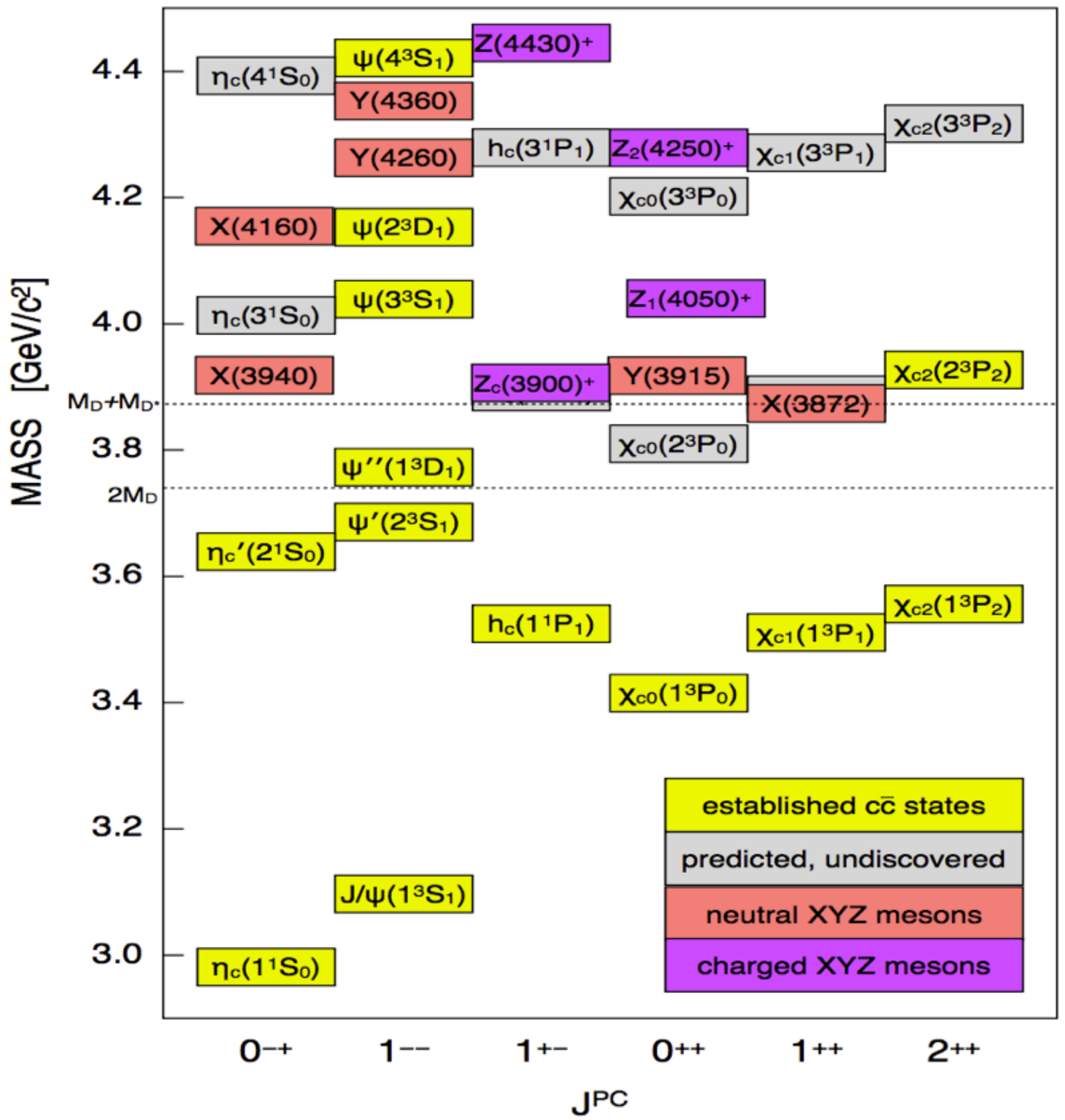
@GreigCowan (Edinburgh)
Rencontres de Blois
31st May 2016

Exotic charmonium spectroscopy ($c\bar{c}$)

- Many different exotic (XYZ) states have been seen since ~2003.
- BESIII, Belle/BaBar, CDF/D0, LHC.
- Are these $[QQ][\bar{q}\bar{q}]$ (tetraquarks), mesonic molecules, hybrids, threshold effects…?
- **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]



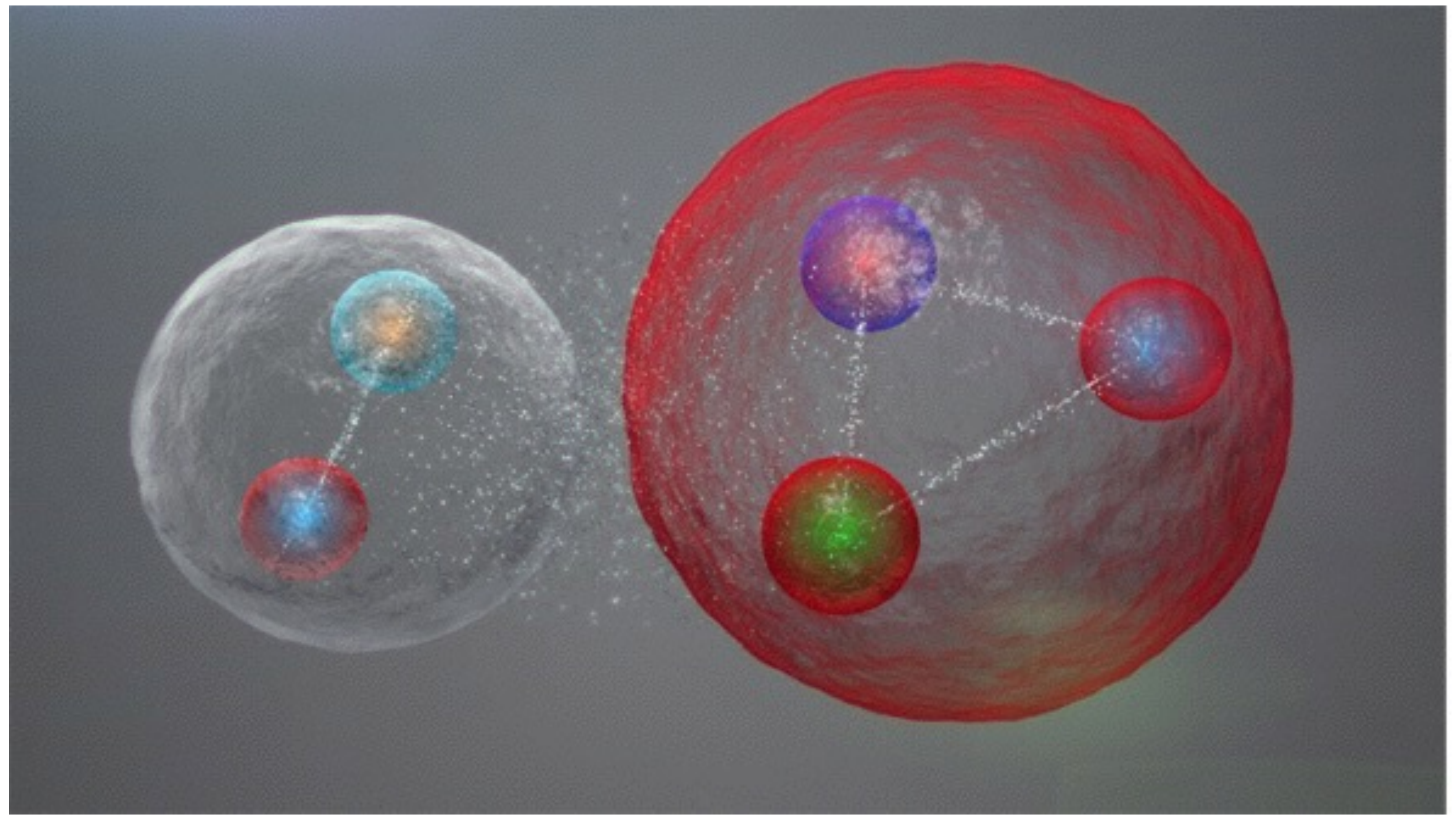
[Olsen arXiv:1403.1254]

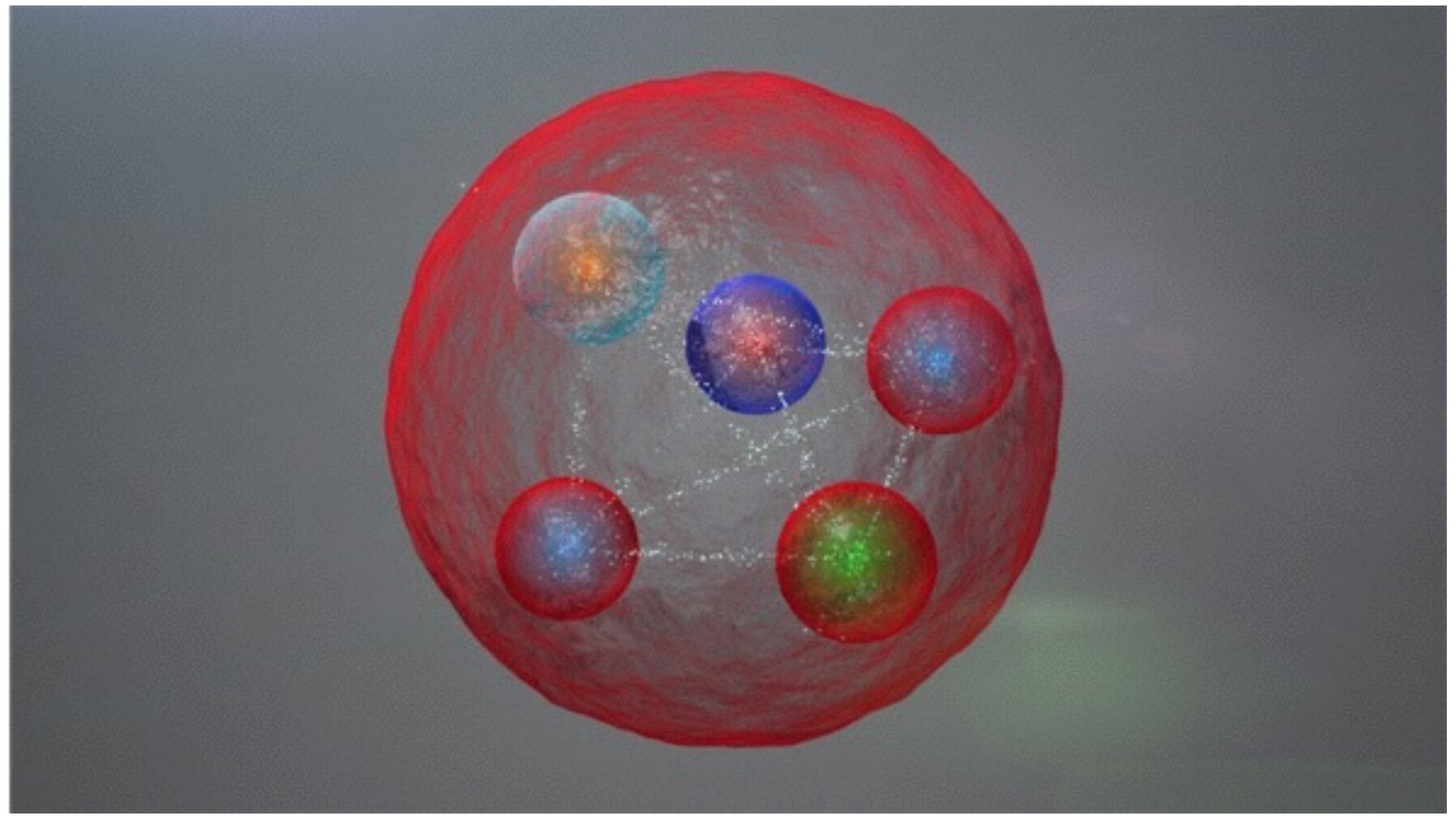
Lattice calculations being done to look for exotic states e.g., [TWQCD PLB 646 (2007) 95–99]

Results discussed today

- Pentaquark observation + model-independent evidence ($\Lambda_b \to J/\psi pK$)
  [PRL 115 (2015) 072001] [arXiv:1604.05708]
- Evidence for exotic structures in $\Lambda_b \to J/\psi p\pi$ decays
  [LHCb-PAPER-2016-015]
- LHCb non-confirmation of D0 tetraquark
  [LHCb-CONF-2016-004]

NEW!





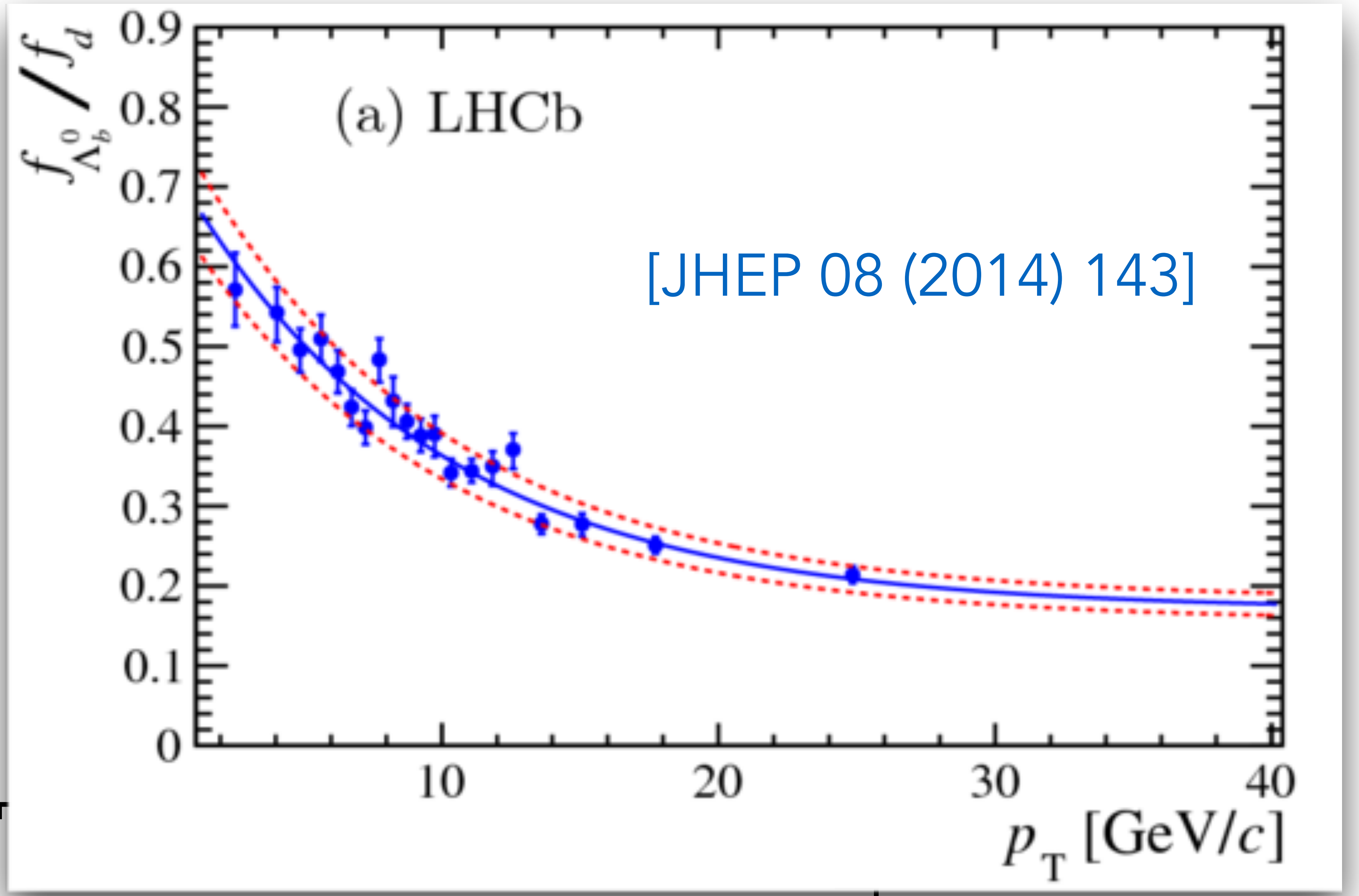
NEW!

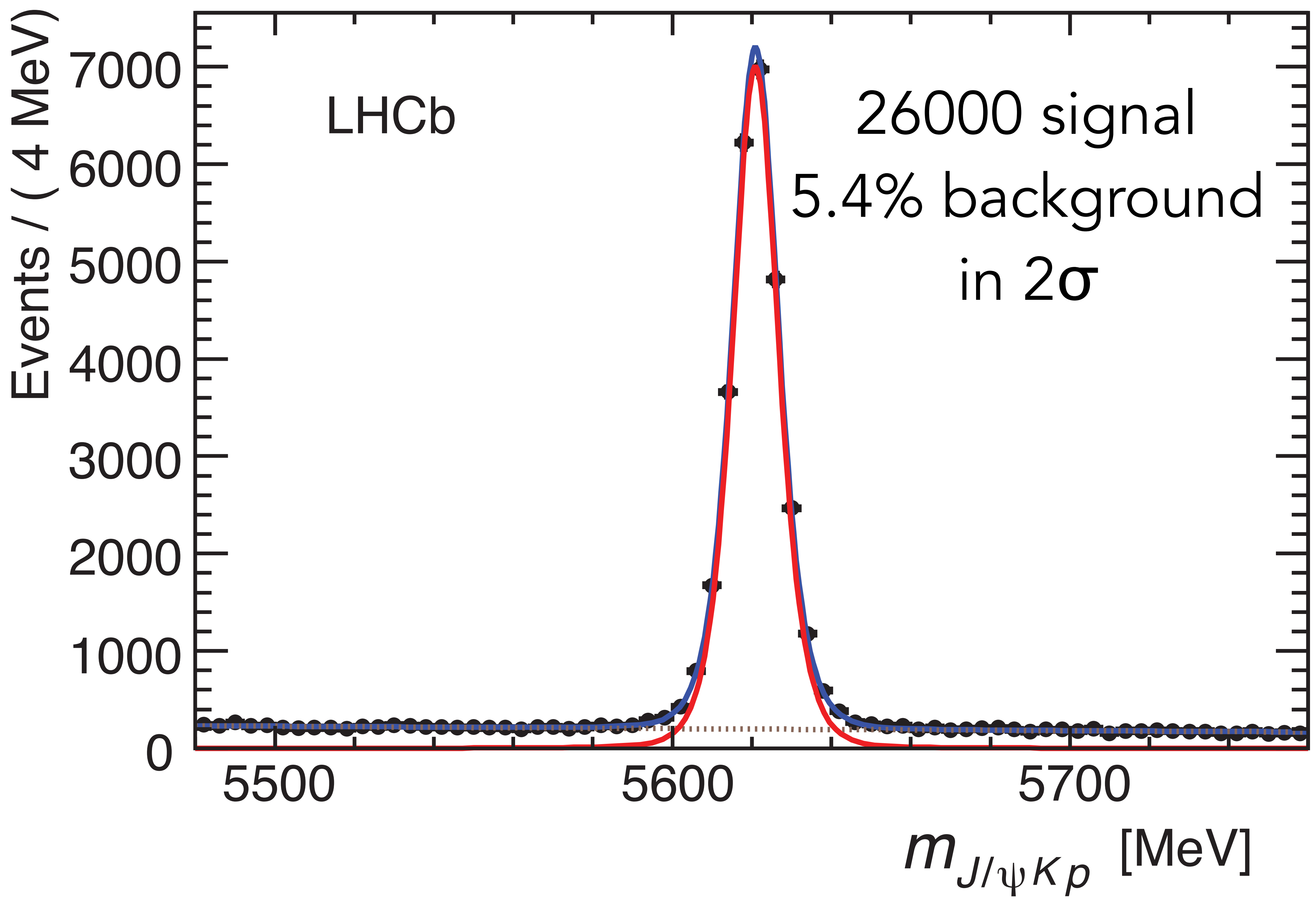
See S. Stone's talk on 2nd June for X(4140) results

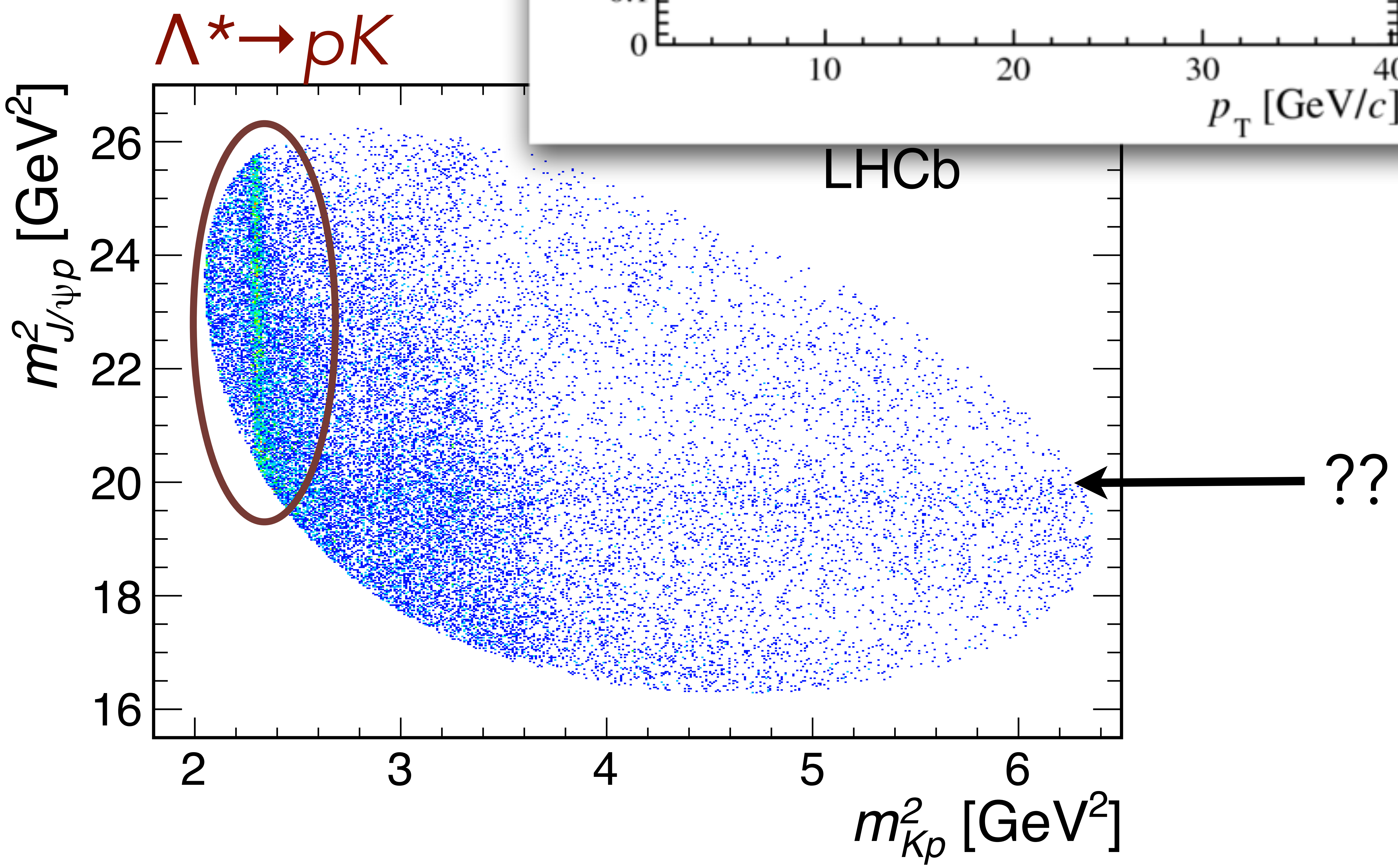
Pentaquark observation [PRL 115 (2015) 072001]

- Take advantage of large production of b-baryons at LHC

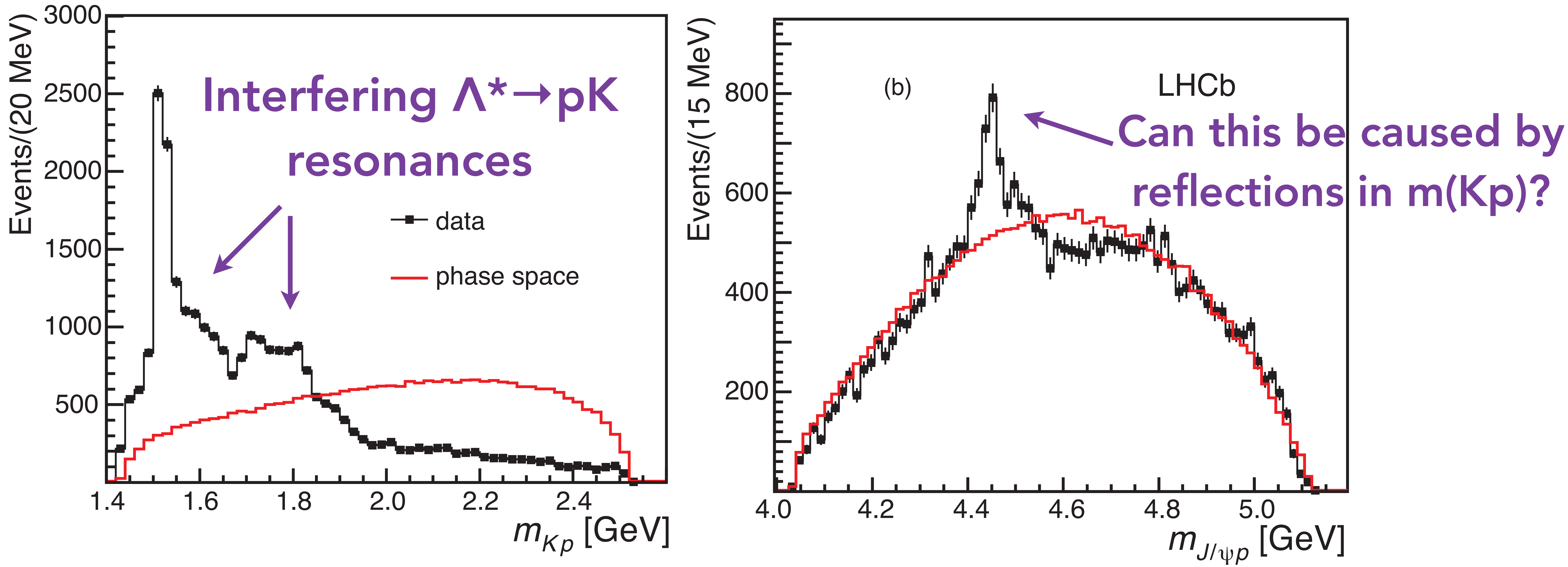
$$\Lambda_b^0 \to J/\psi p K^-$$

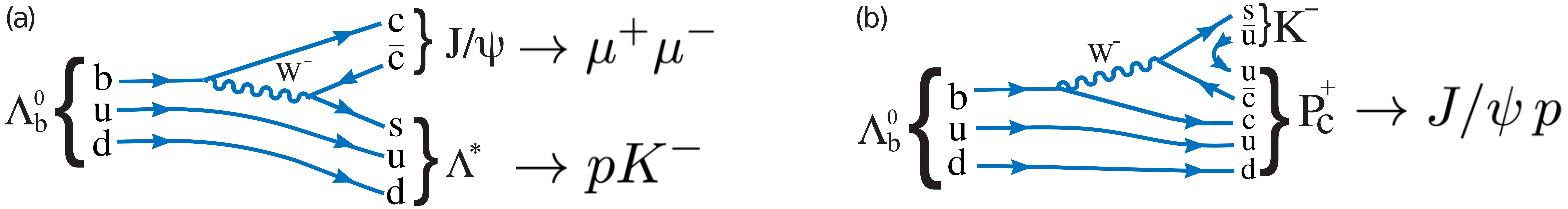




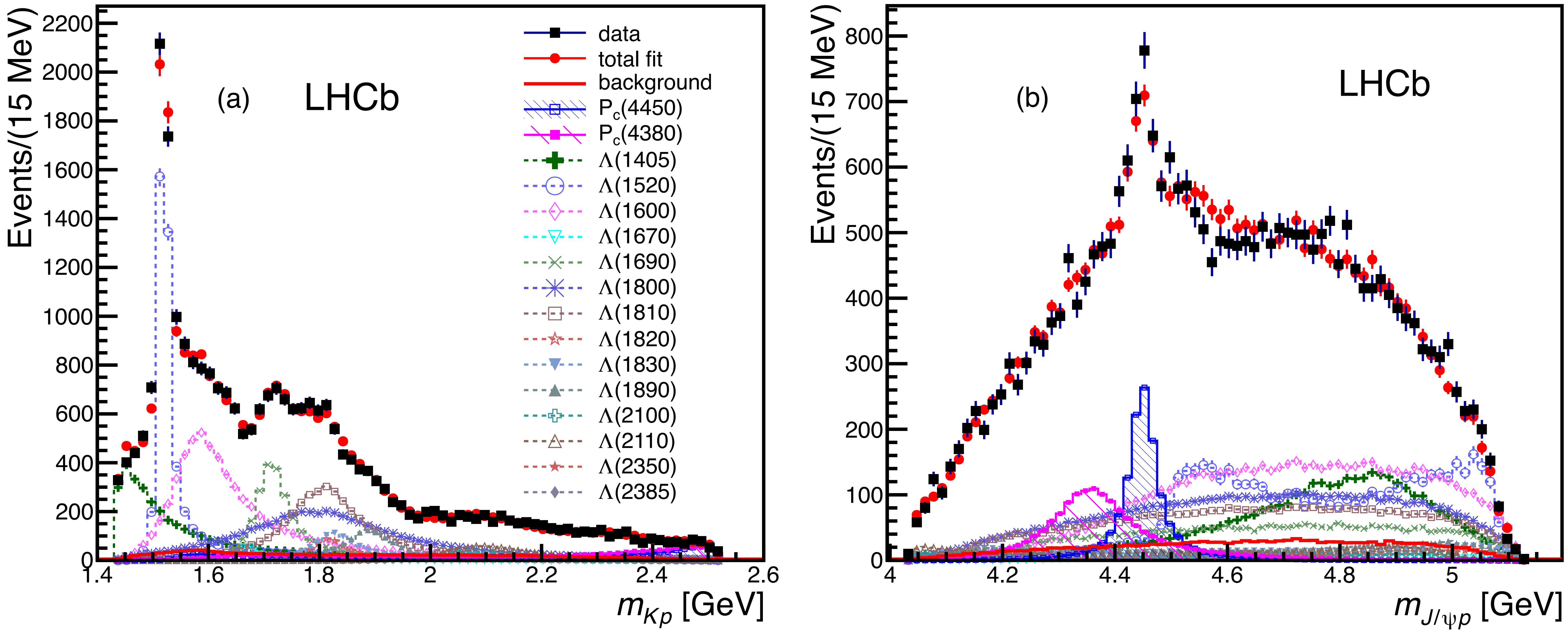


Pentaquark observation [PRL 115 (2015) 072001]





Amplitude model [PRL 115 (2015) 072001]



$uud c\bar{c}$

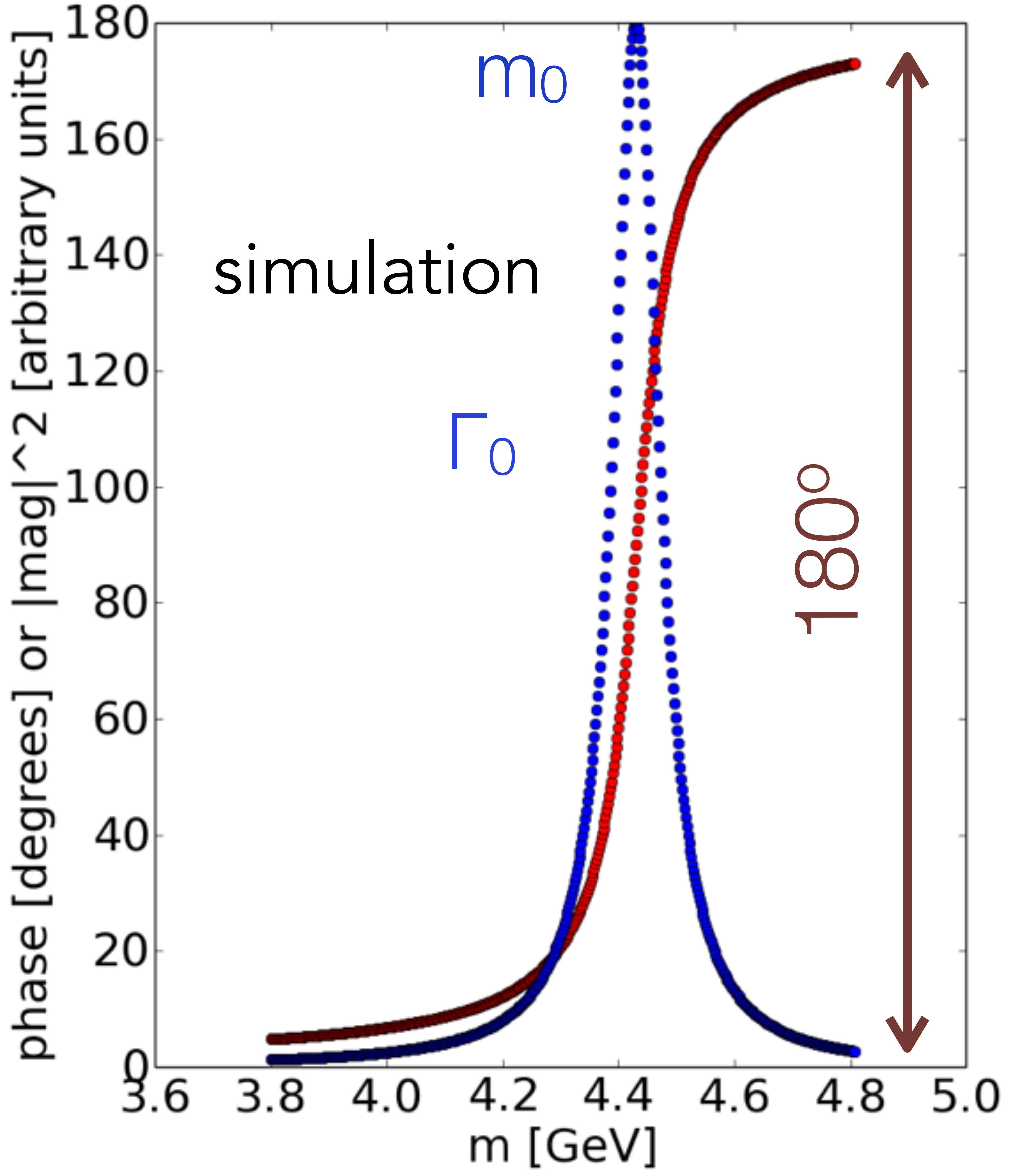
\+ good fit in angular dimensions

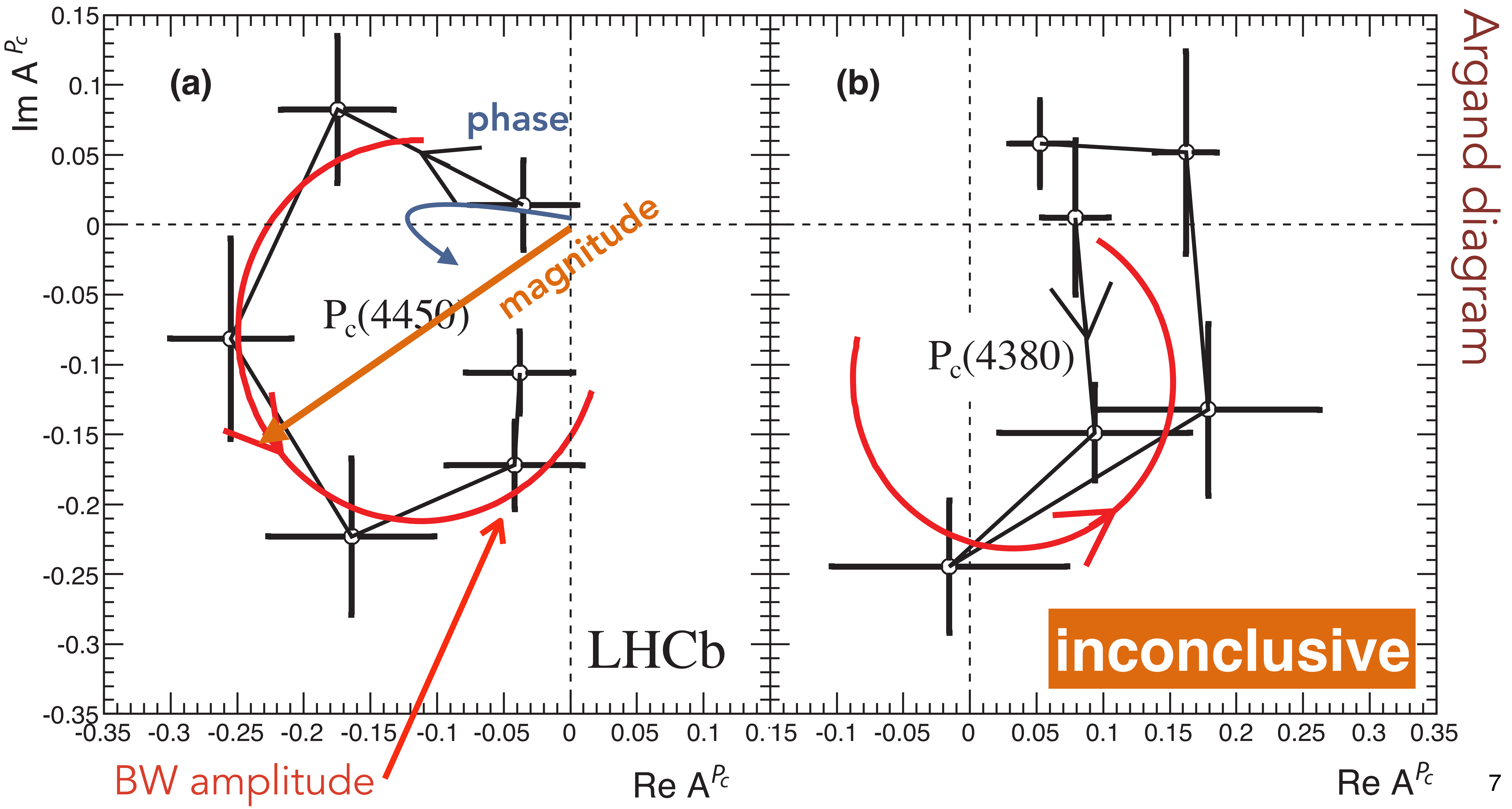
- J^P = ($3/2^+$, $5/2^-$) and ($5/2^+$, $3/2^-$) also give good fits: **need more data.**
- Addition of other resonances does not give improvement.
- Significance evaluated using toy simulation, including systematics.

	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

Resonant behaviour - a bound state?

- Replace BW amplitude with 6 independent complex numbers in 6 bins of *m(J/ψp)* in region of P_c^+ mass peak.
- Allows P_c^+ shape to be constrained only by amplitudes in Kp sector.
- Observe rapid change of phase near maximum of magnitude ⇒ **resonance!**

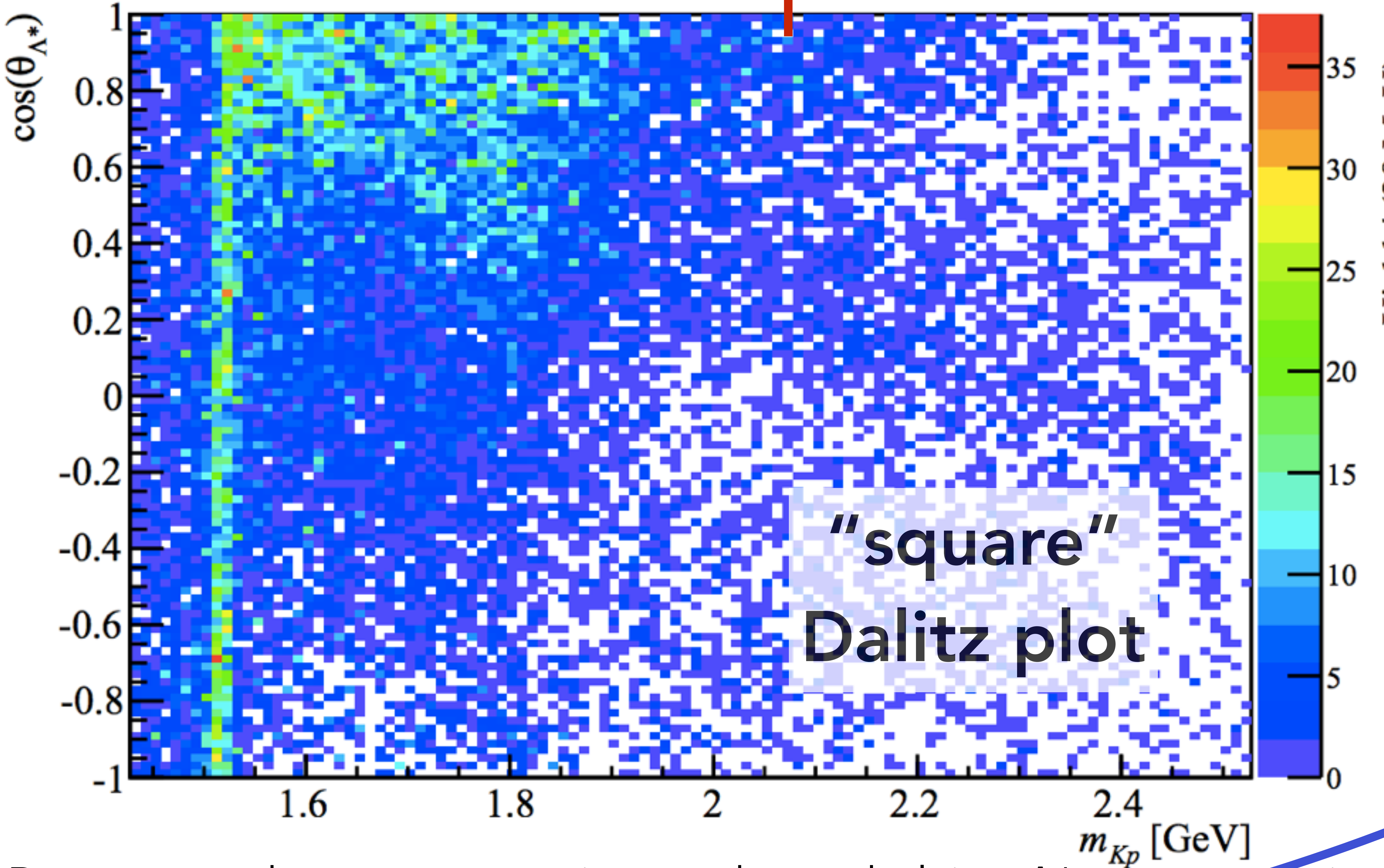


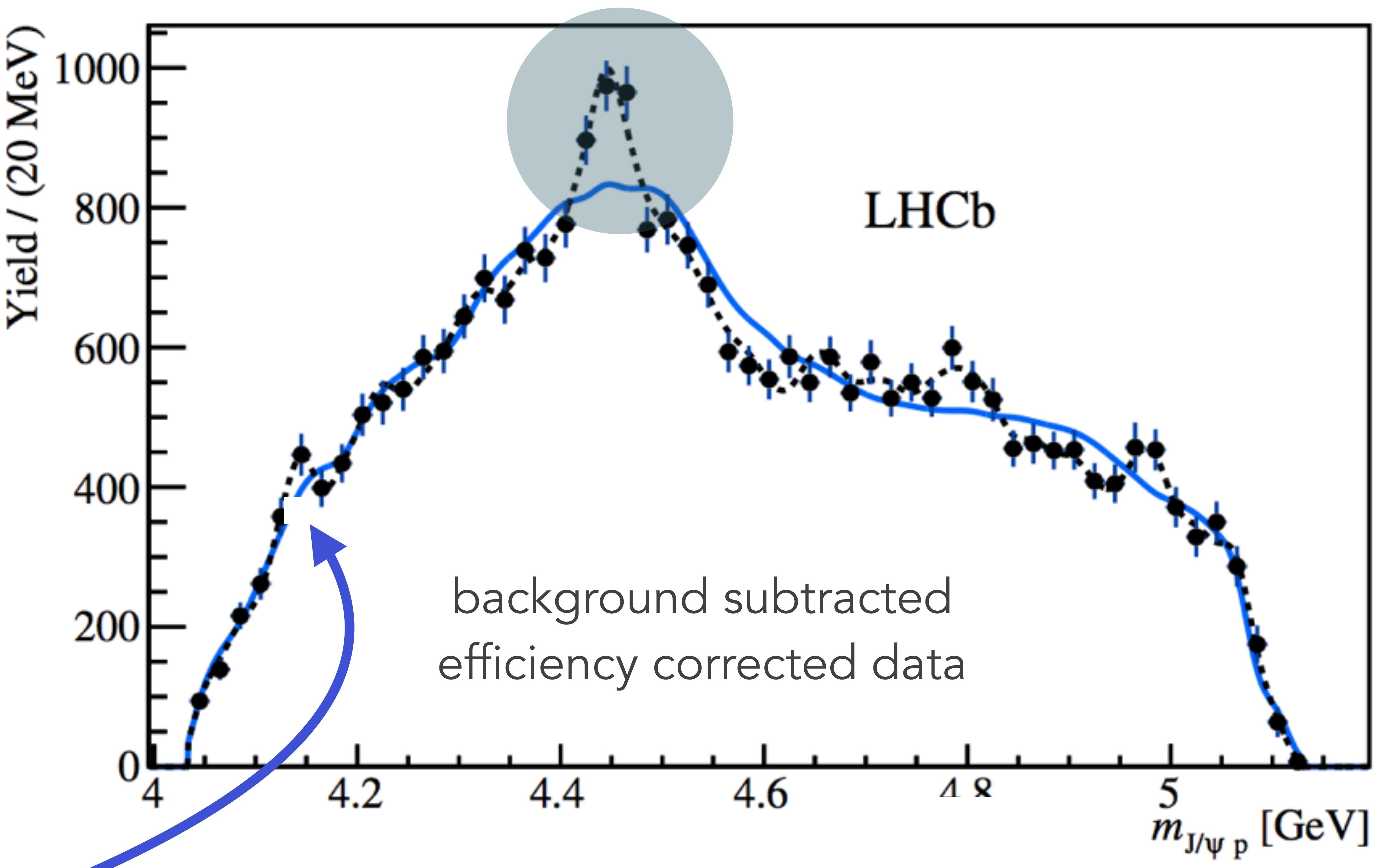


Model independent analysis [PRL arXiv:1604.05708]

Can reflection of the structures in *m(Kp)* and $\cos\theta_\Lambda$ reproduce the *m(J/ψp)* distribution? → **NO!**

[Extension of BaBar PRD 79 (2009) 112001]





- Does not make any assumption on the underlying Λ* resonances in the system, only restricts their maximal spin.
- Weight phase space **simulated $\Lambda_b \to J/\psi pK$ events** with data *m(Kp)* and the spherical harmonic moments of $\cos\theta_\Lambda$.
- Use likelihood ratio to test various hypotheses - **Null hypothesis (Λ* only) rejected at 9σ.**

Evidence for exotics in $\Lambda_b \to J/\psi p \pi^{\pm}$ [LHCb-PAPER-2016-015]

NEW!

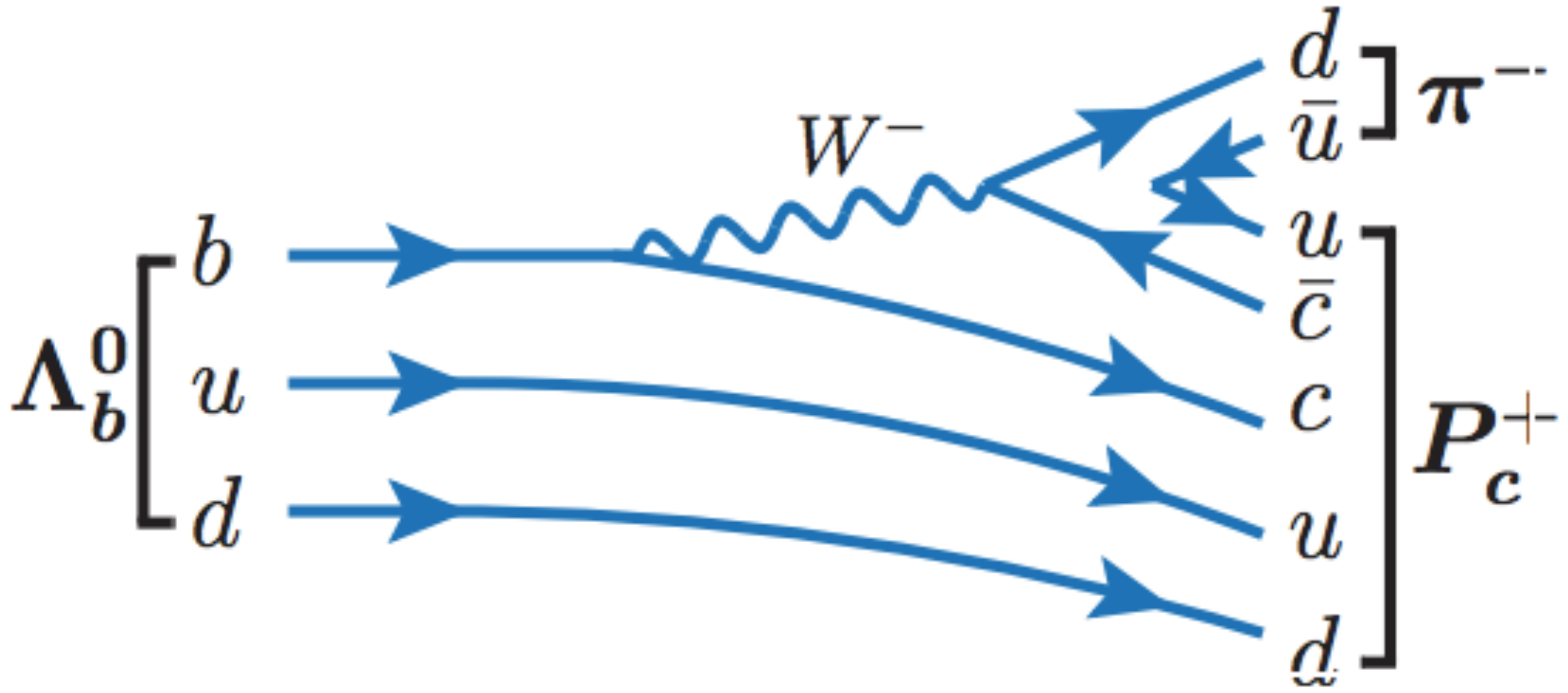
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.0824 \pm 0.0025\,(\text{stat}) \pm 0.0042\,(\text{syst})$$

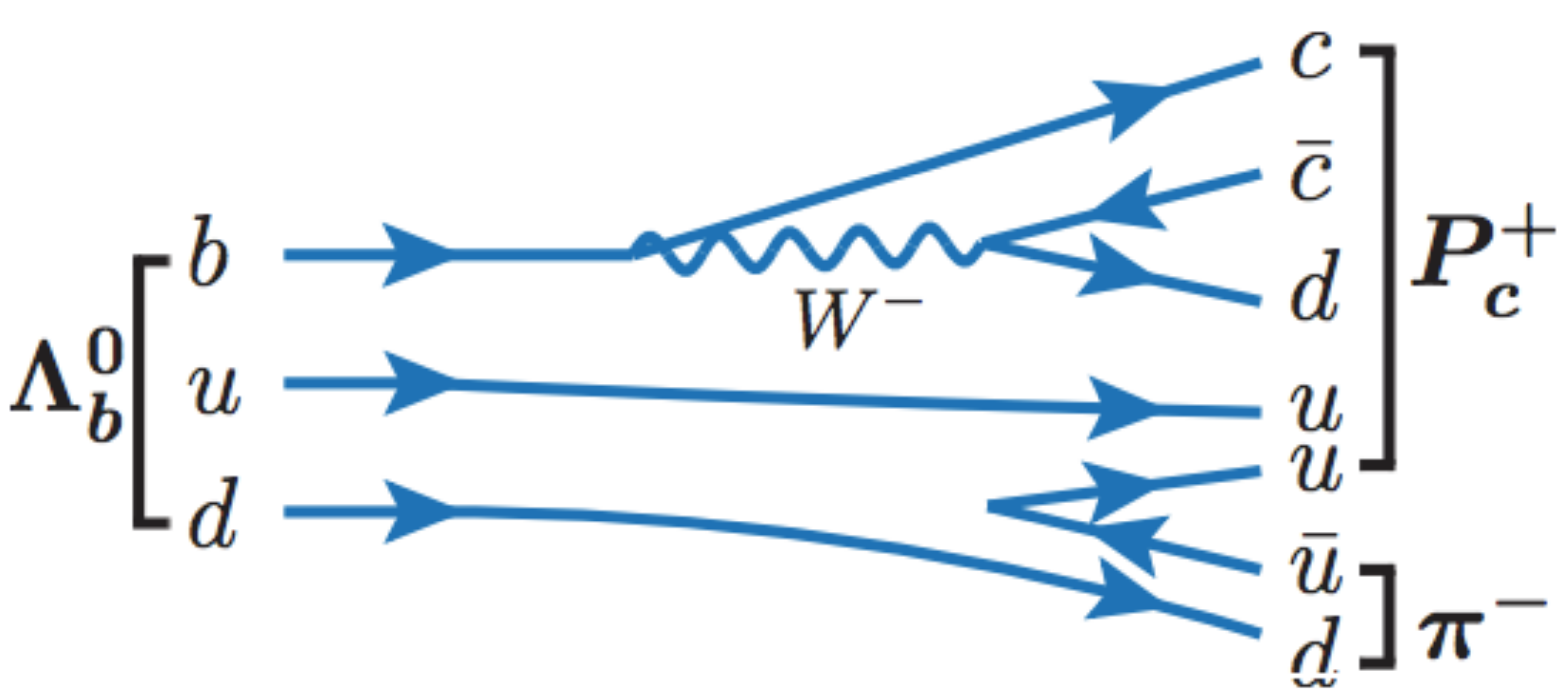
[LHCb JHEP 1407, 103 (2014)]

- Observations of the same two P_c^+ states in another decay could imply they are genuine exotic baryonic states, other than kinematical effects, e.g. so-called triangle singularity. [arXiv:1512.01959]

$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08$$

[Cheng et al. PRD 92, 096009 (2015)]



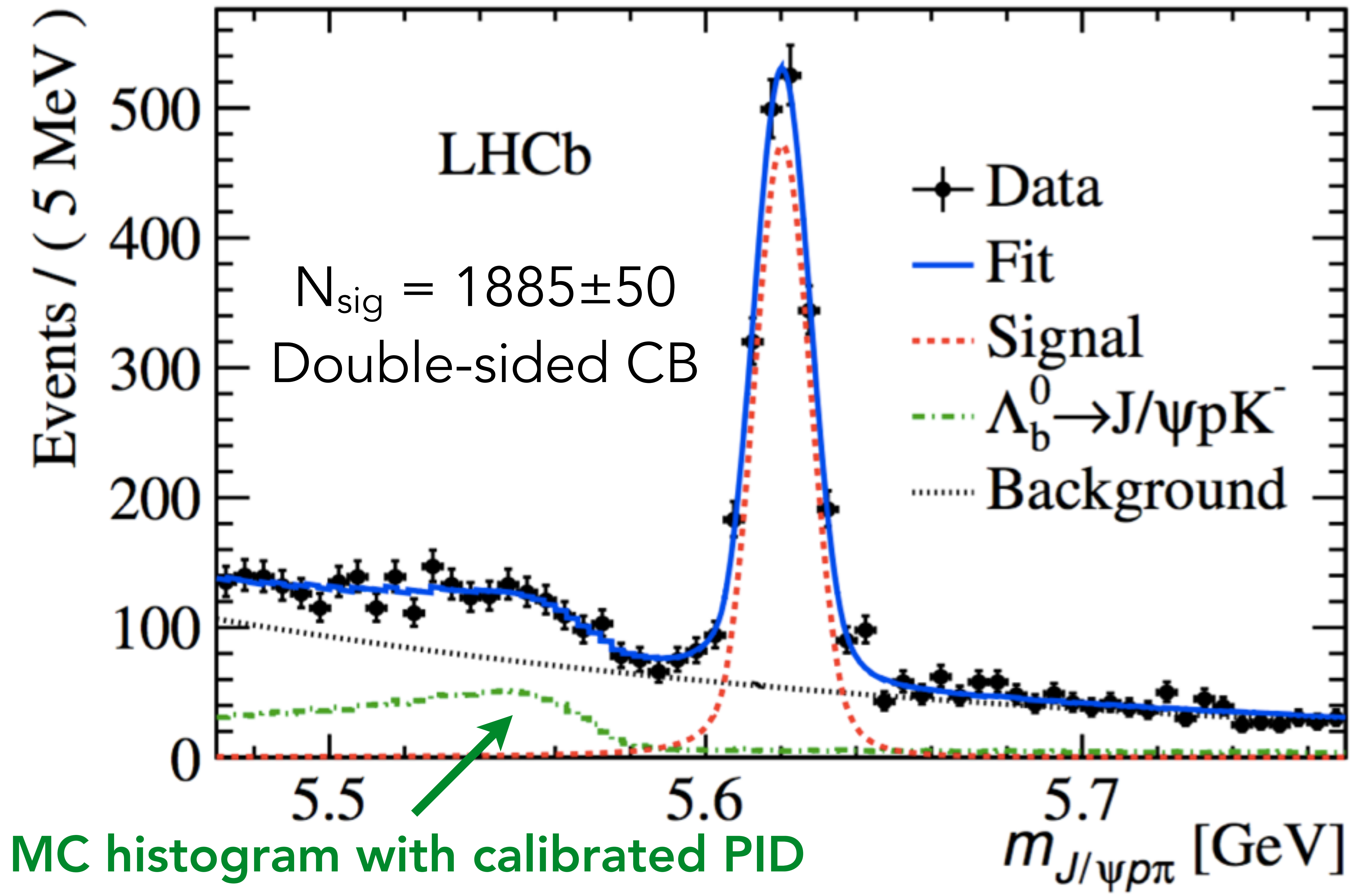


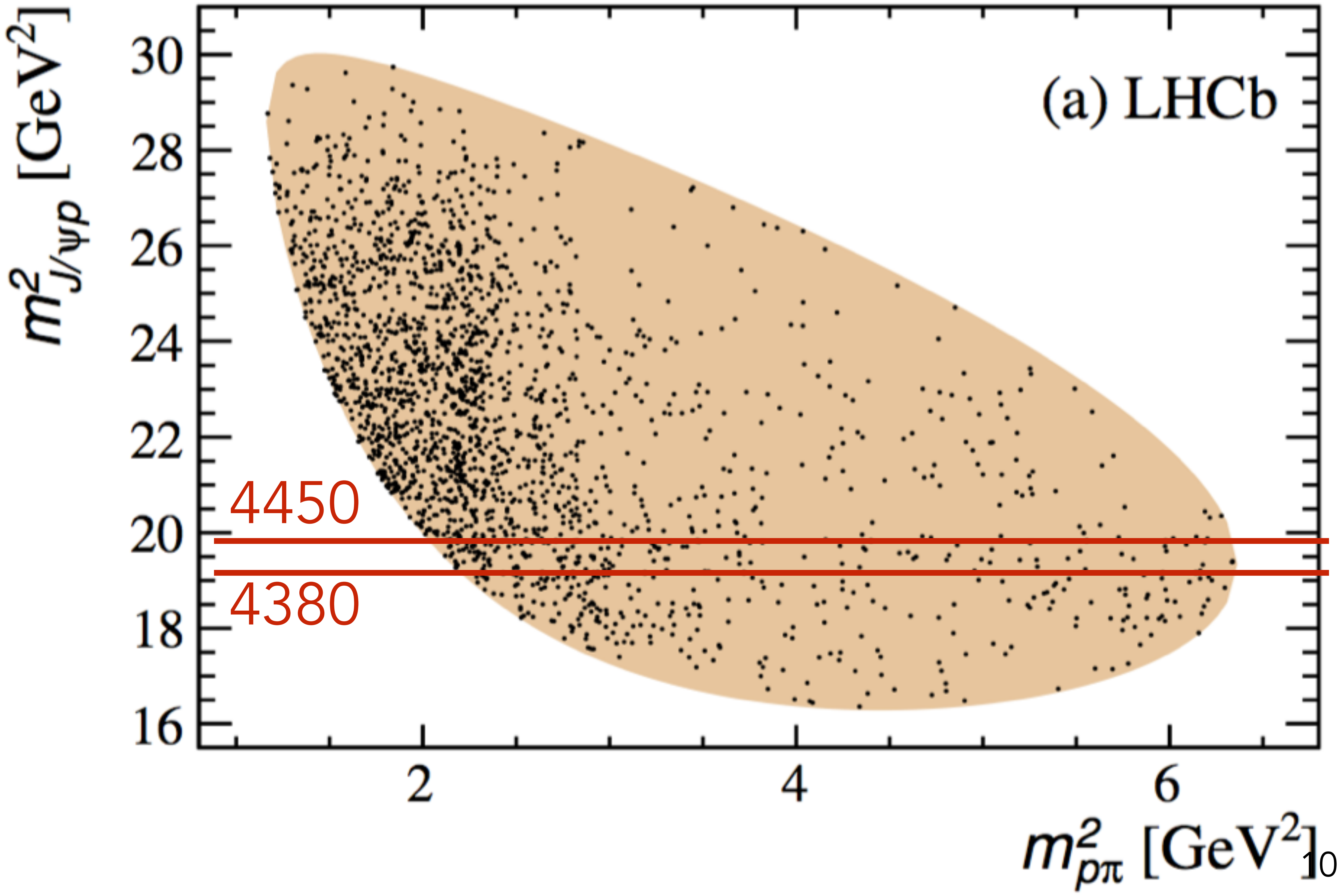
$\Lambda_b \to J/\psi p \pi^-$ data sample [LHCb-PAPER-2016-015]

NEW!

Similar selection to $\Lambda_b \to J/\psi p K$ and BDT to suppress background

No prominent $P_c^+(4450)$ peak

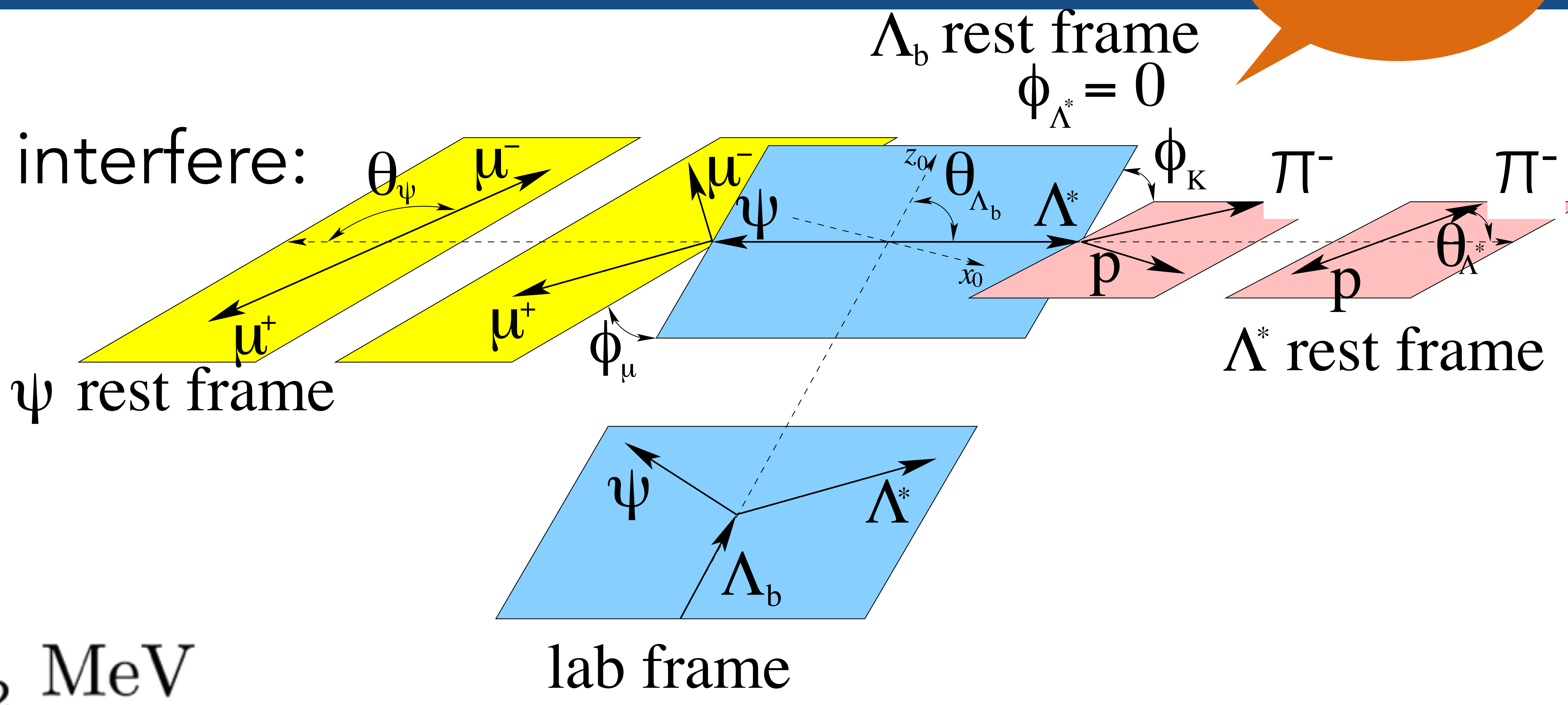




Amplitude model [LHCb-PAPER-2016-015]

NEW!

- Consider three decay chains that mutually interfere:
  - $\Lambda_b^0 \to J/\psi N^*,\ N^* \to p\pi^-$
  - $\Lambda_b^0 \to P_c^+\pi^-,\ P_c^+ \to J/\psi p$
  - $\Lambda_b^0 \to Z_c^- p,\ Z_c^- \to J/\psi\pi^-$



$$m_0 = 4196^{+31+17}_{-29-13}\ \mathrm{MeV},\ \Gamma_0 = 370 \pm 70^{+70}_{-132}\ \mathrm{MeV}$$

$B^0 \to J/\psi K\pi$ [Belle, PRD 90 (2014) 112009]

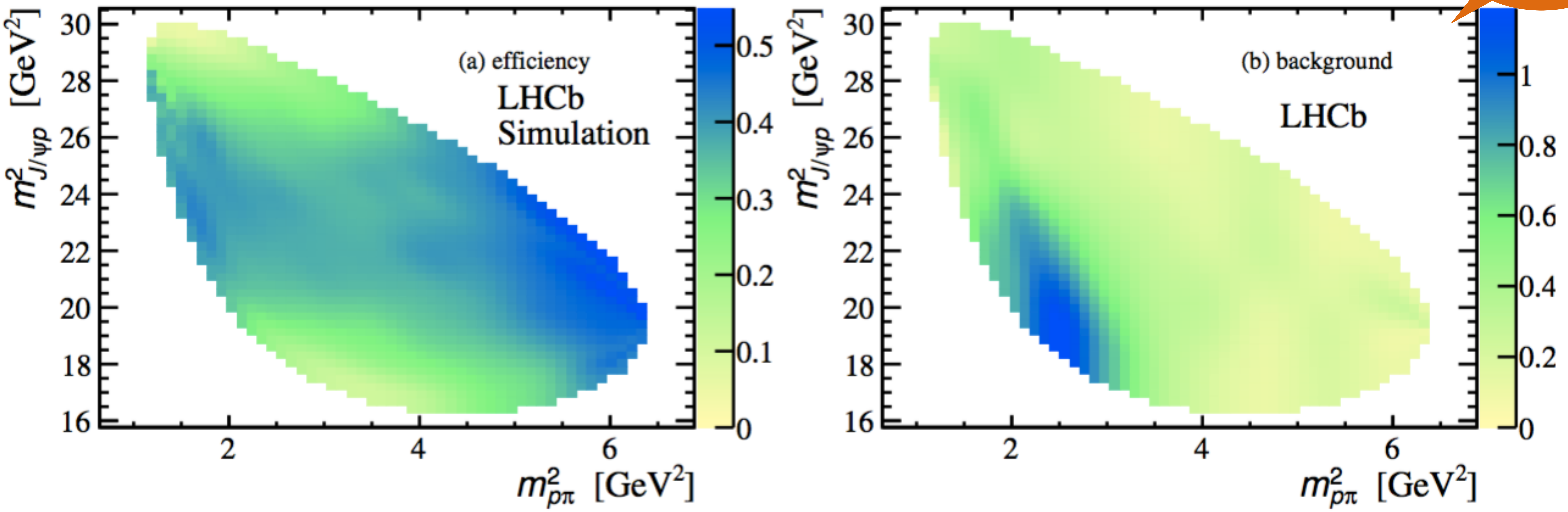
- **Additional angles** to align muon and proton helicity frames between each decay chain

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}=\pm\frac{1}{2}} \sum_{\lambda_p=\pm\frac{1}{2}} \sum_{\Delta\lambda_\mu=\pm 1} \Bigg| \mathcal{M}^{N^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu}$$

$$+ e^{i\,\Delta\lambda_\mu \alpha_\mu^{Z_c}} \sum_{\lambda_p^{Z_c}} e^{i\lambda_p^{Z_c}\alpha_p^{Z_c}} d^{\frac{1}{2}}_{\lambda_p^{Z_c},\lambda_p}(\theta_p^{Z_c})\, \mathcal{M}^{Z_c}_{\lambda_{\Lambda_b^0},\lambda_p^{Z_c},\Delta\lambda_\mu} \Bigg|^2 .$$

Amplitude model [LHCb-PAPER-2016-015]

NEW!



- 6D background subtracted using weighted fit.
- Integrate matrix element by summing over fully-simulated events (accounts for 6D efficiency automatically).

Amplitude model [LHCb-PAPER-2016-015]

NEW!

- Limited statistics, so aim is to check that the data is consistent with that found in $\Lambda_b \to J/\psi pK$
- Parameters of P_c states fixed to those from $\Lambda_b \to J/\psi pK$
- Different combinations of N* resonances considered for systematic uncertainties.
- Default fit: $3/2^-$ $P_c(4380)$, $5/2^+$ $P_c(4450)$, 1^+ $Z_c(4200)$

$Z_c(4430)$ is checked as systematic uncertainty

Well-established N* states

State	J^P	M_0 (MeV)	Γ_0 (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	100	-	4
$N(1720)$	$3/2^+$	1720	250	3	5
$N(1875)$	$3/2^-$	1875	250	-	3
$N(1900)$	$3/2^+$	1900	200	-	3
$N(2190)$	$7/2^-$	2190	500	-	3
$N(2220)$	$9/2^+$	2250	400	-	-
$N(2250)$	$9/2^-$	2275	500	-	-
$N(2600)$	$11/2^-$	2600	650	-	-
$N(2300)$	$1/2^+$	2300	340	-	3
$N(2570)$	$5/2^-$	2570	250	-	3
Free parameters				40	106

Fit results [LHCb-PAPER-2016-015]

NEW!

- **N* only model** not a good fit. **RM model + 2xP_c or Z_c or both gives good fit**.
- **3.3σ** evidence for both P_c states. 3.1σ if 2xP_c + Z_c in fit.
- Main systematics from fixed P_c/Z_c mass/width parameters, N* model and Pc spin.

States	Fit fraction (%)
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.1}_{-1.6}$
$P_c(4450)^+$	$1.6^{+0.8+0.6}_{-0.6-0.5}$
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$

Fit results [LHCb-PAPER-2016-015]

NEW!

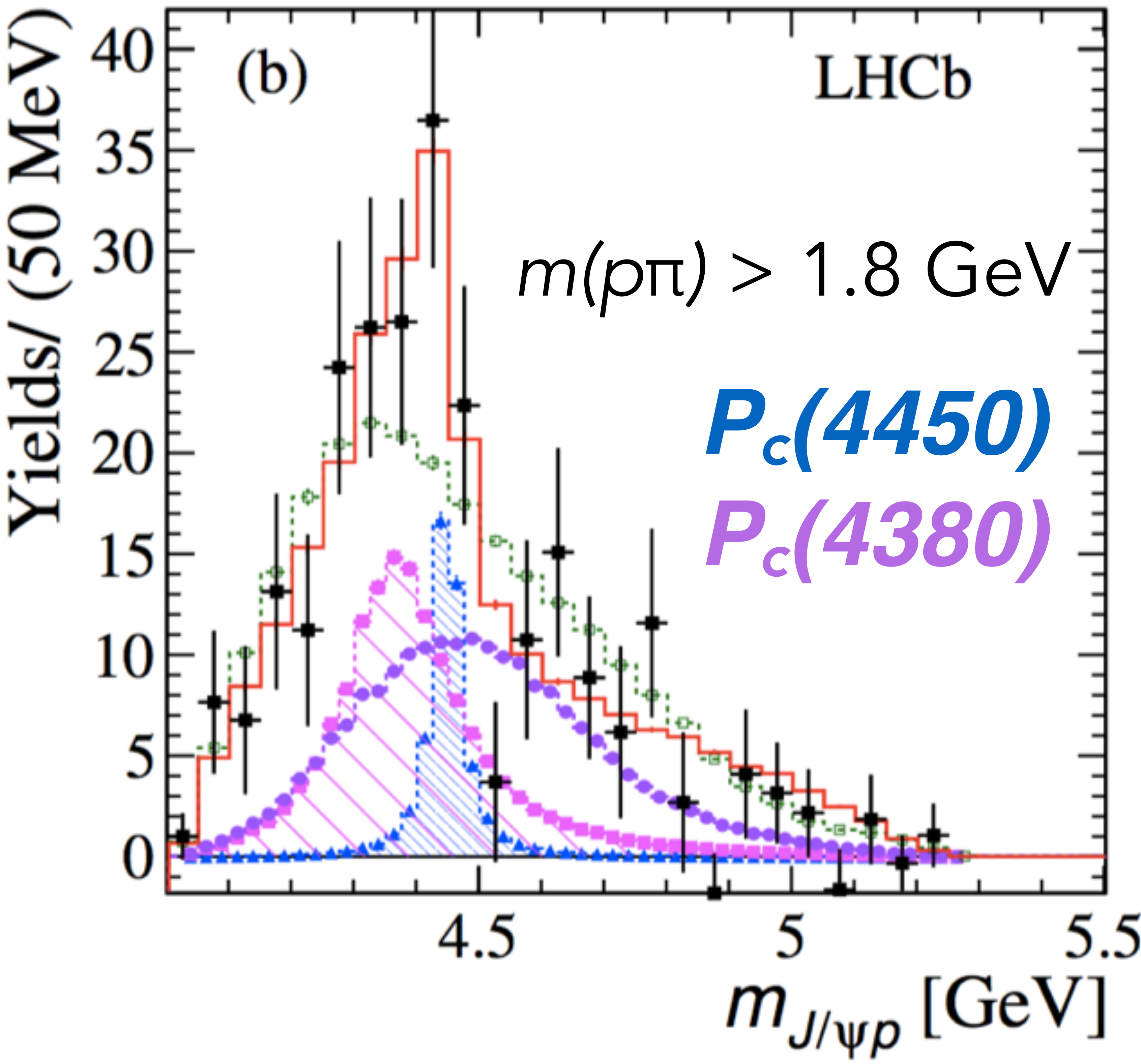
Due to syst. error of fit fraction of P_c in the kaon mode

$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)}$$

$$R_{\pi^-/K^-}(4380) = 0.050 \pm 0.016^{+0.020}_{-0.016} \pm 0.025$$

$$R_{\pi^-/K^-}(4450) = 0.033^{+0.016+0.011}_{-0.014-0.009} \pm 0.009$$

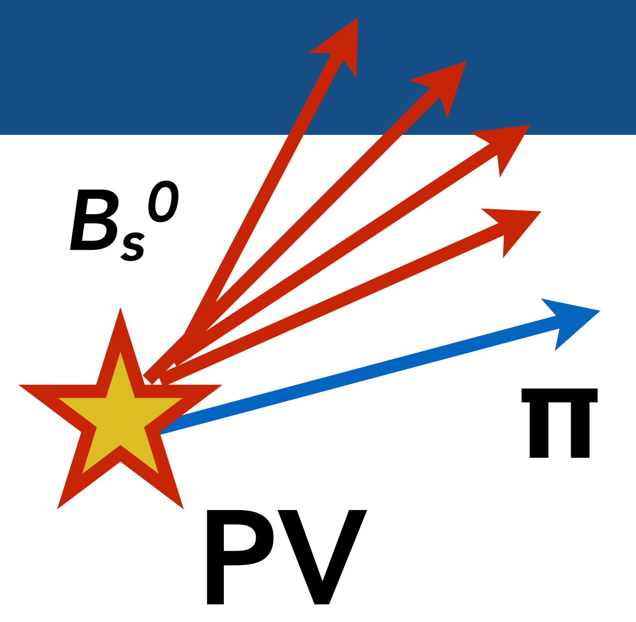
- Ratios consistent with ~0.08 expectation from Cabibbo suppression. [Cheng et al. PRD 92, 096009 (2015)]
- Data consistent with pentaquark observation, but need more data.
- LHC Run-2 well on it's way!



The X(5568)? [D∅ arXiv:1602.07588v2]

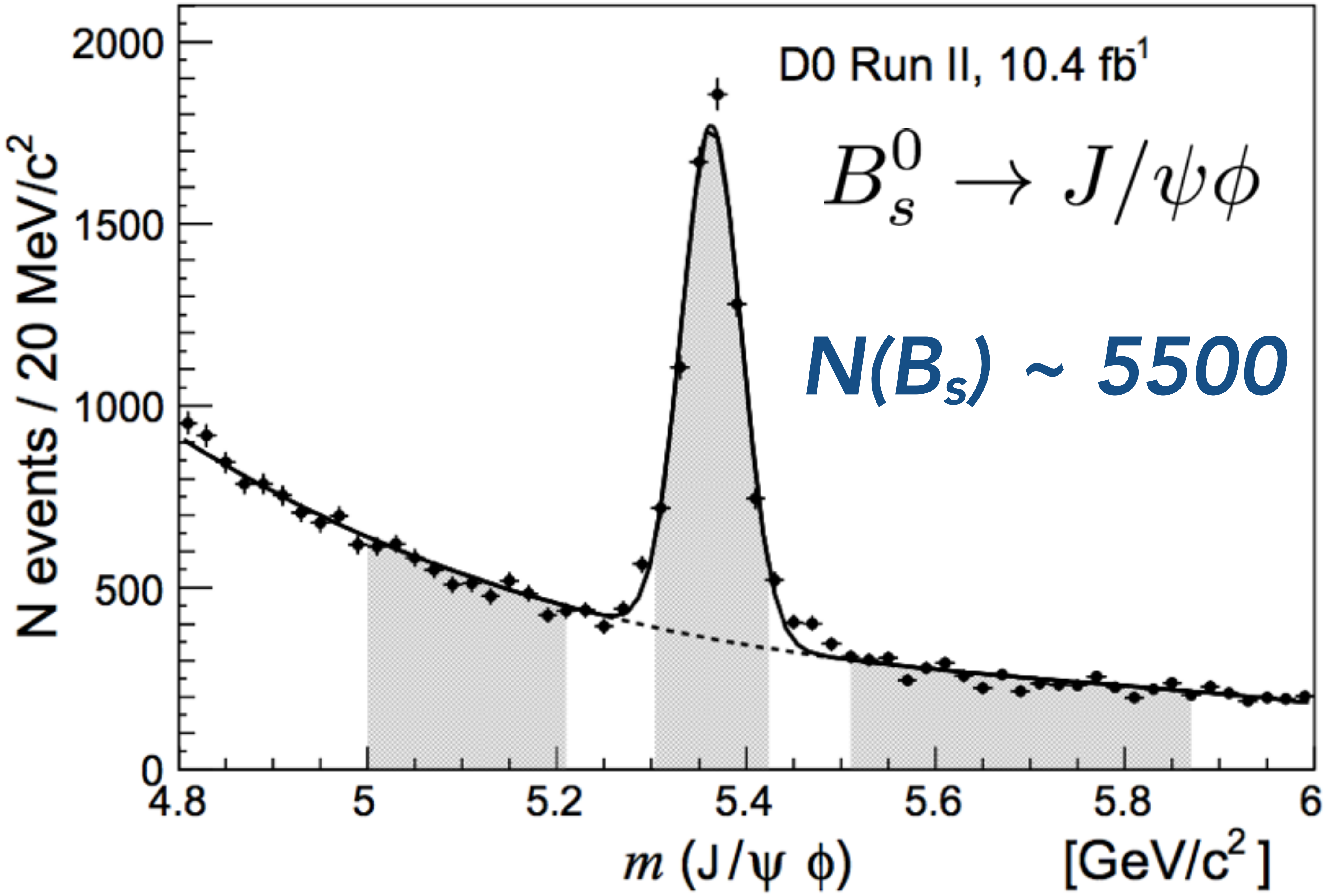
- 5.1σ claim for exotic state $X(5568) \to B_s^0 \pi^+$
- Large B_s^0 production fraction: ρ_X^{D0} = (8.6±1.9±1.4)%

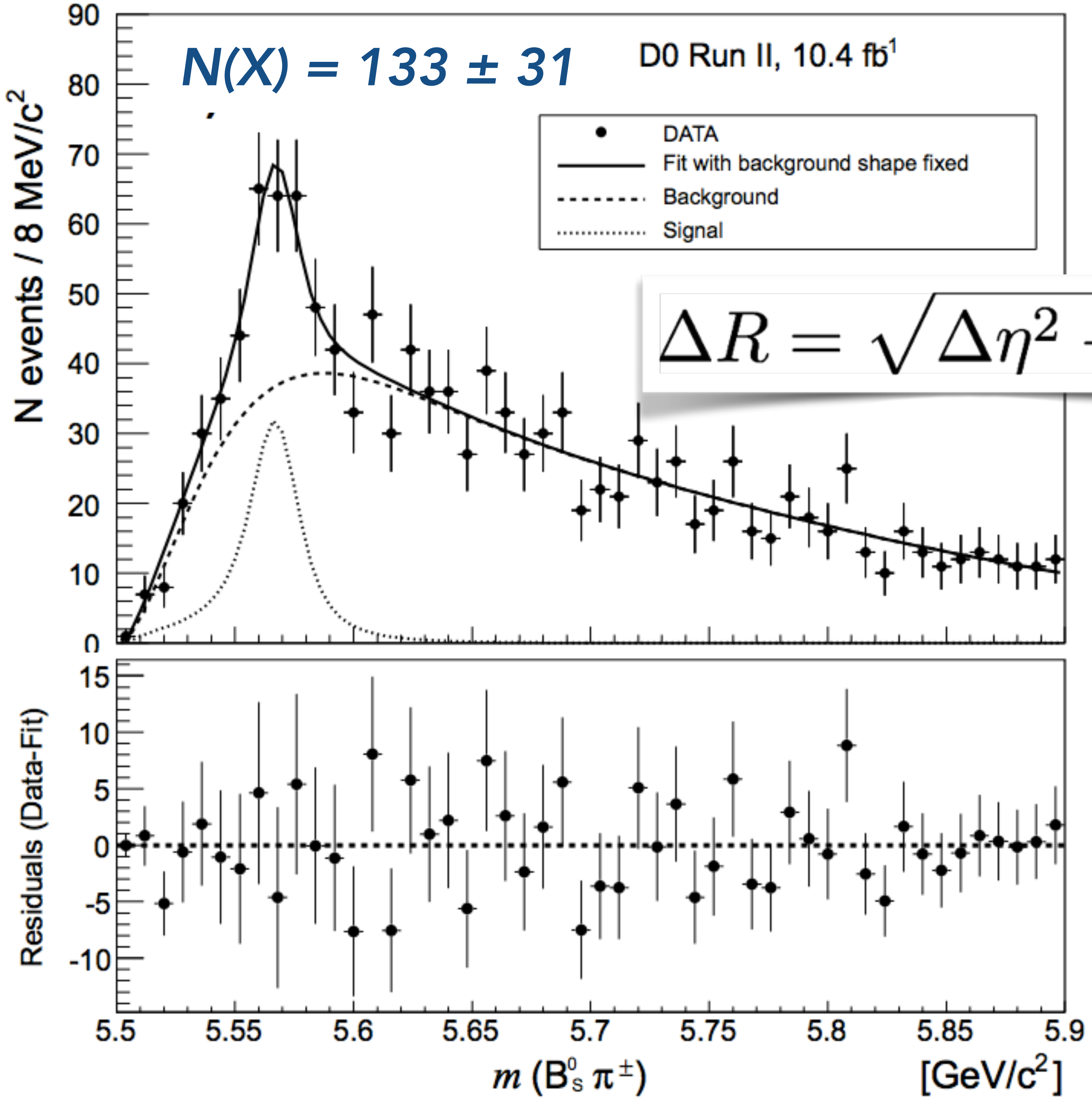
$$\bar{b} s u \bar{d}$$



$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9} \mathrm{MeV}/c^2$$

$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5} \mathrm{MeV}/c^2$$



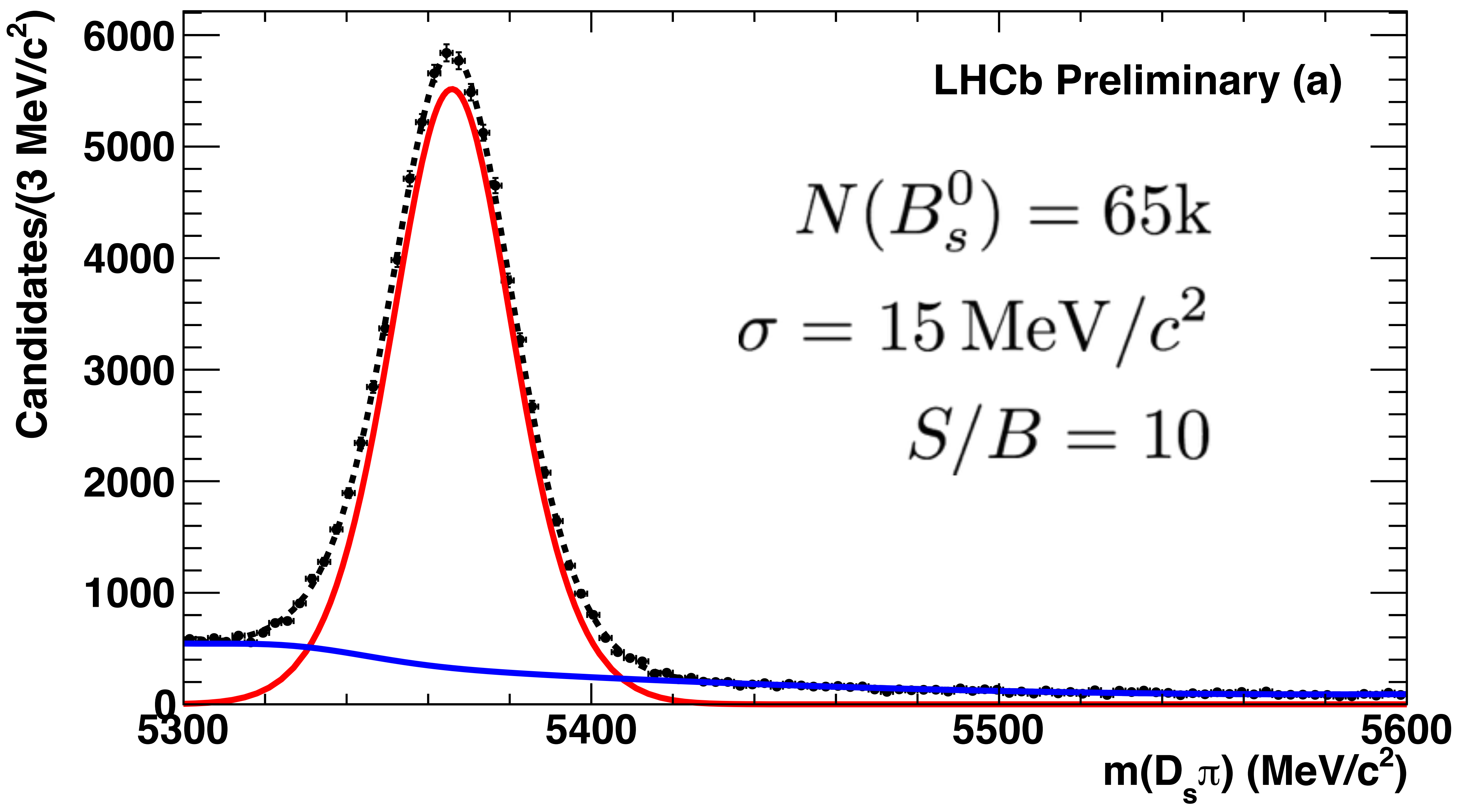


$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

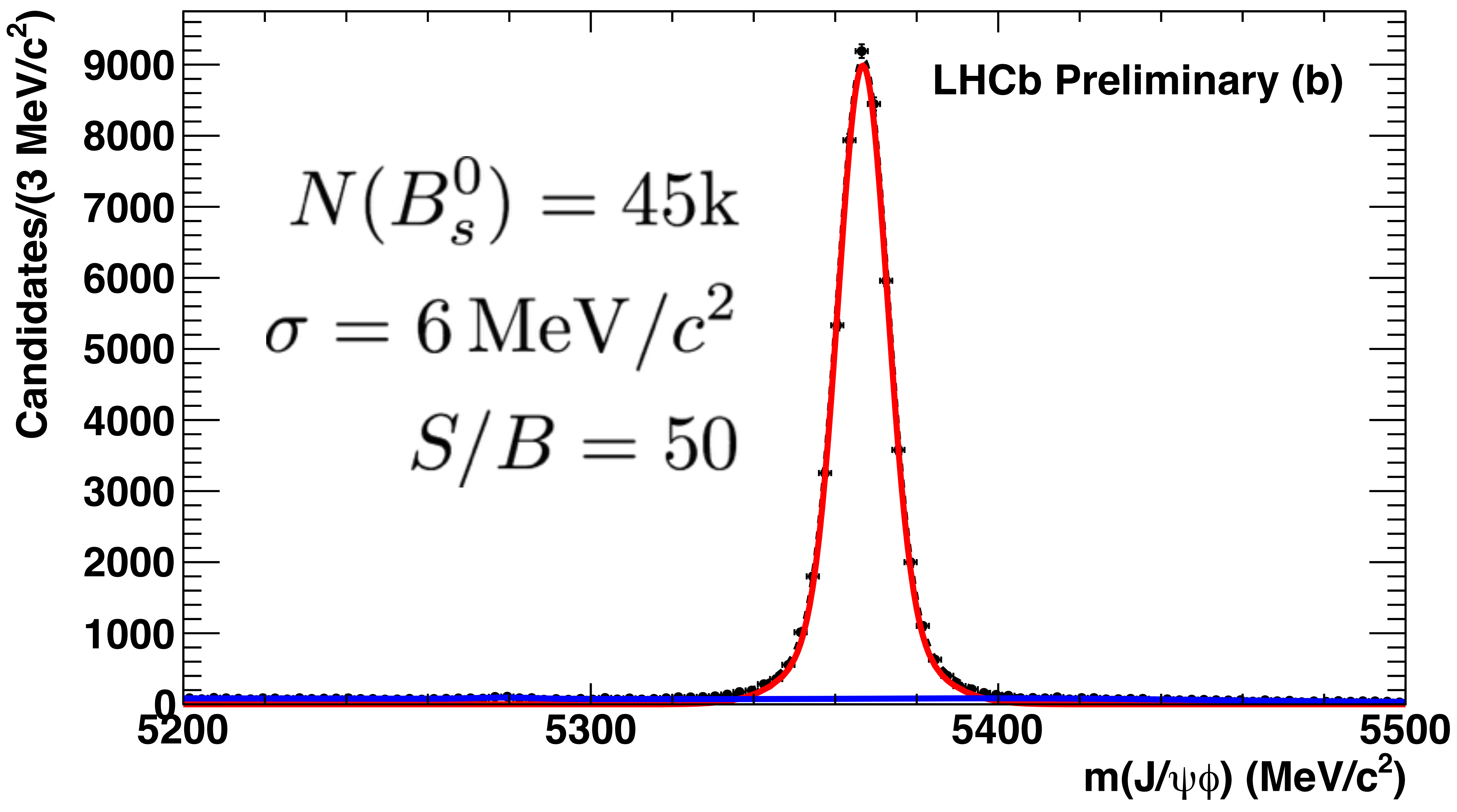
LHCb data sample, B_s^0 [LHCb-CONF-2016-004]

- Cut-based selection for clean B_s^0 samples.
- Mass constraints on J/ψ and D_s^- to improve mass resolution (c.f. DØ 30MeV)
- **Sample 20x that of D0, and much less background.**

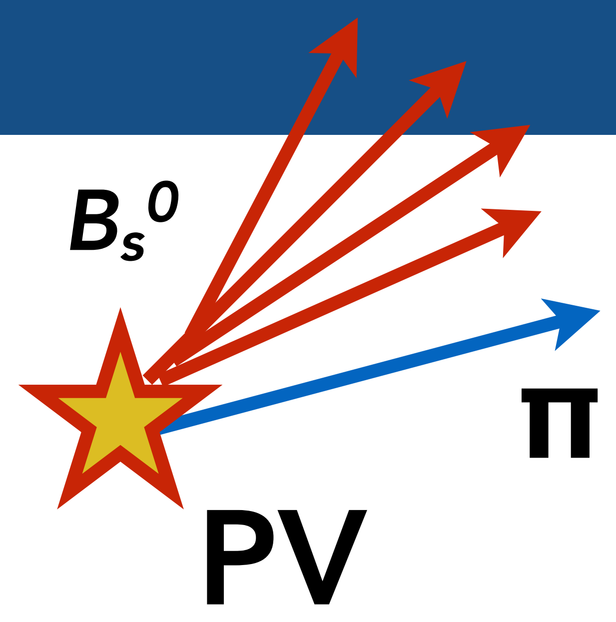
$B_s^0 \to D_s^- \pi^+$



$B_s^0 \to J/\psi\phi$



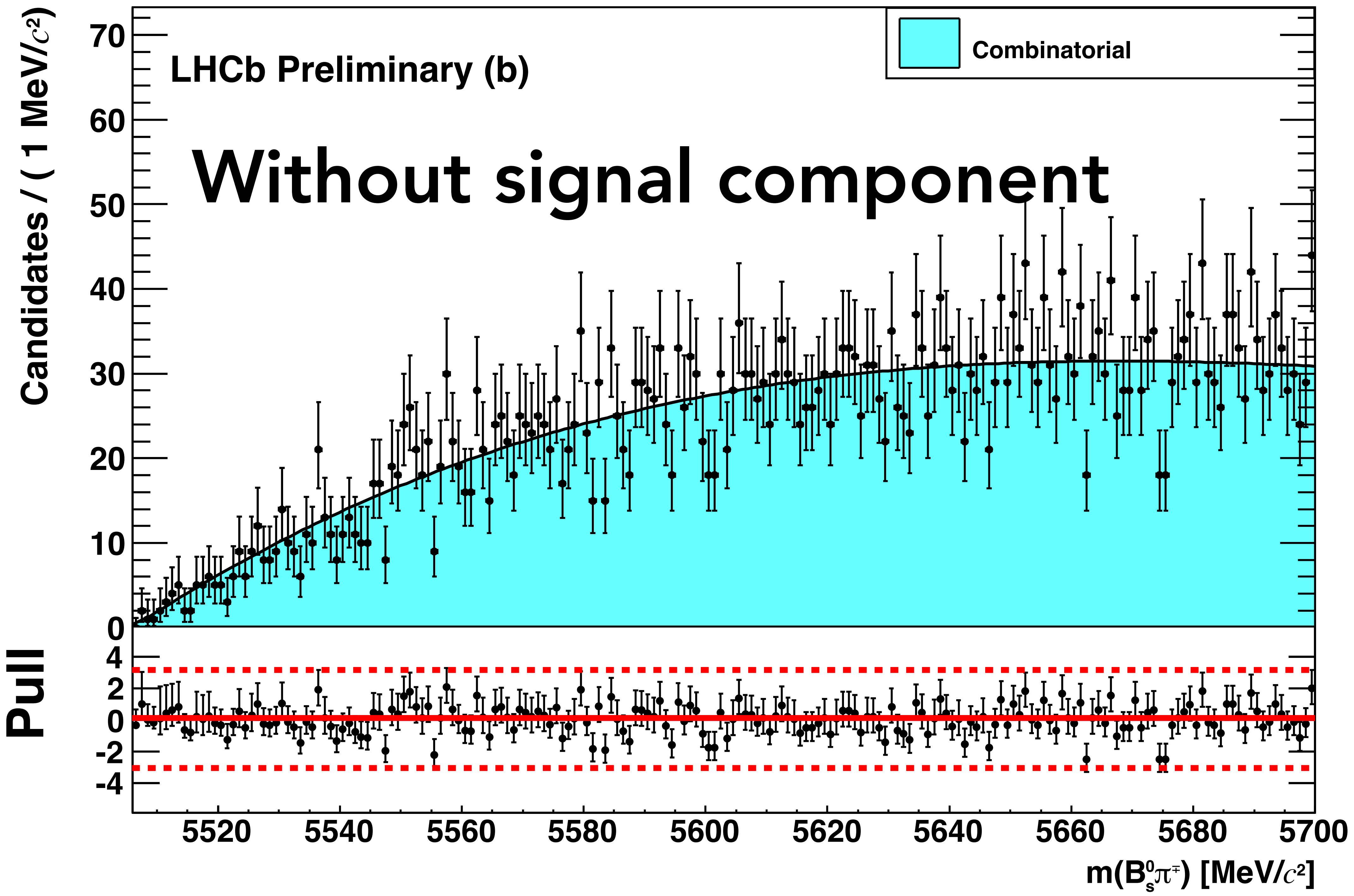
LHCb data sample, $B_s^0\pi^\pm$ [LHCb-CONF-2016-004]

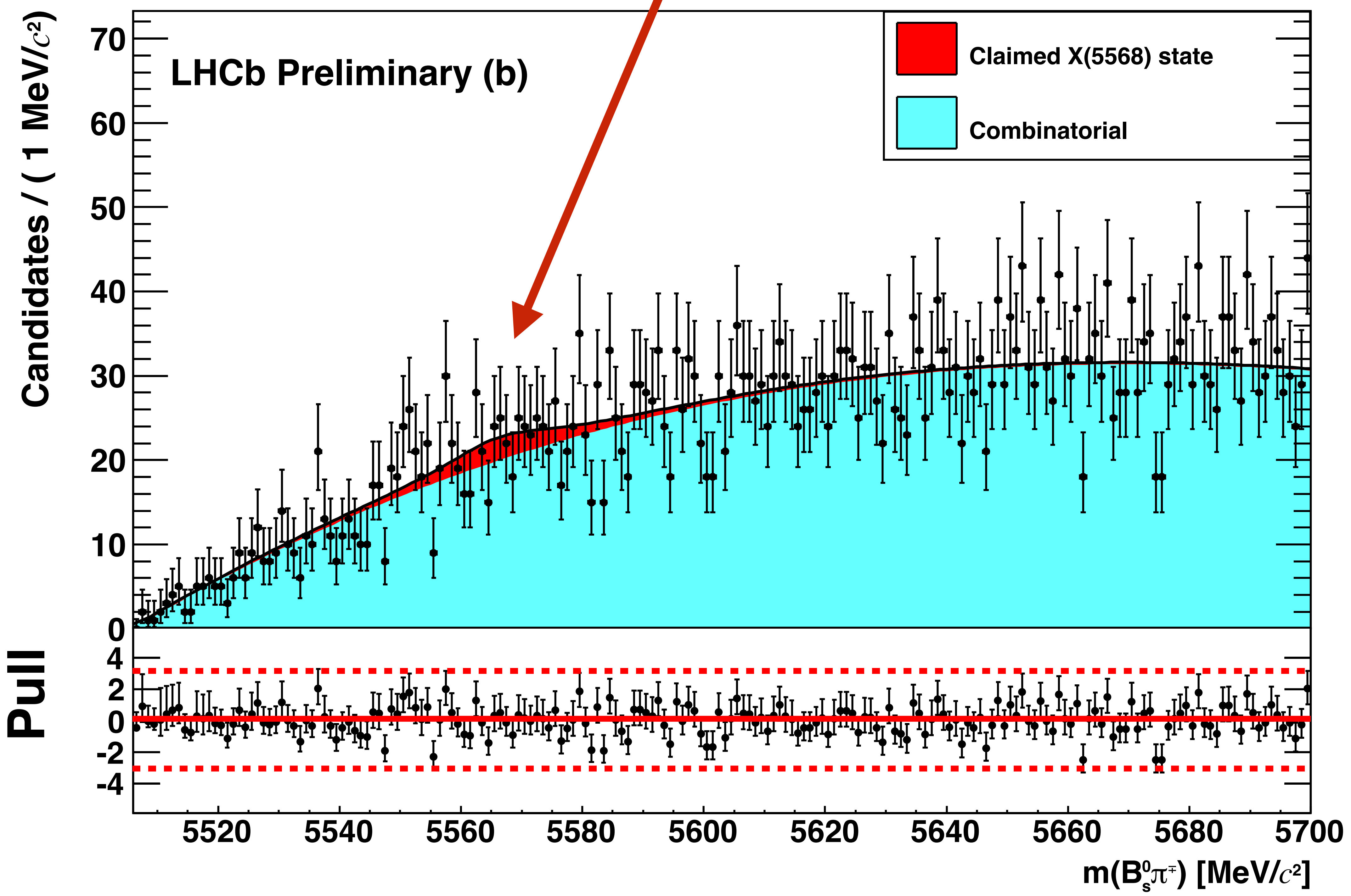


- B_s^0 and $\pi^\pm$ required to come from same PV.
- Fit signal using S-wave Breit-Wigner with mass and width of claimed DØ signal.
- Polynomial for background (comes from random combinations of pions with true or fake B_s^0 candidates.

$p_T(B_s^0) > 10\,\mathrm{GeV}/c$

No significant signal

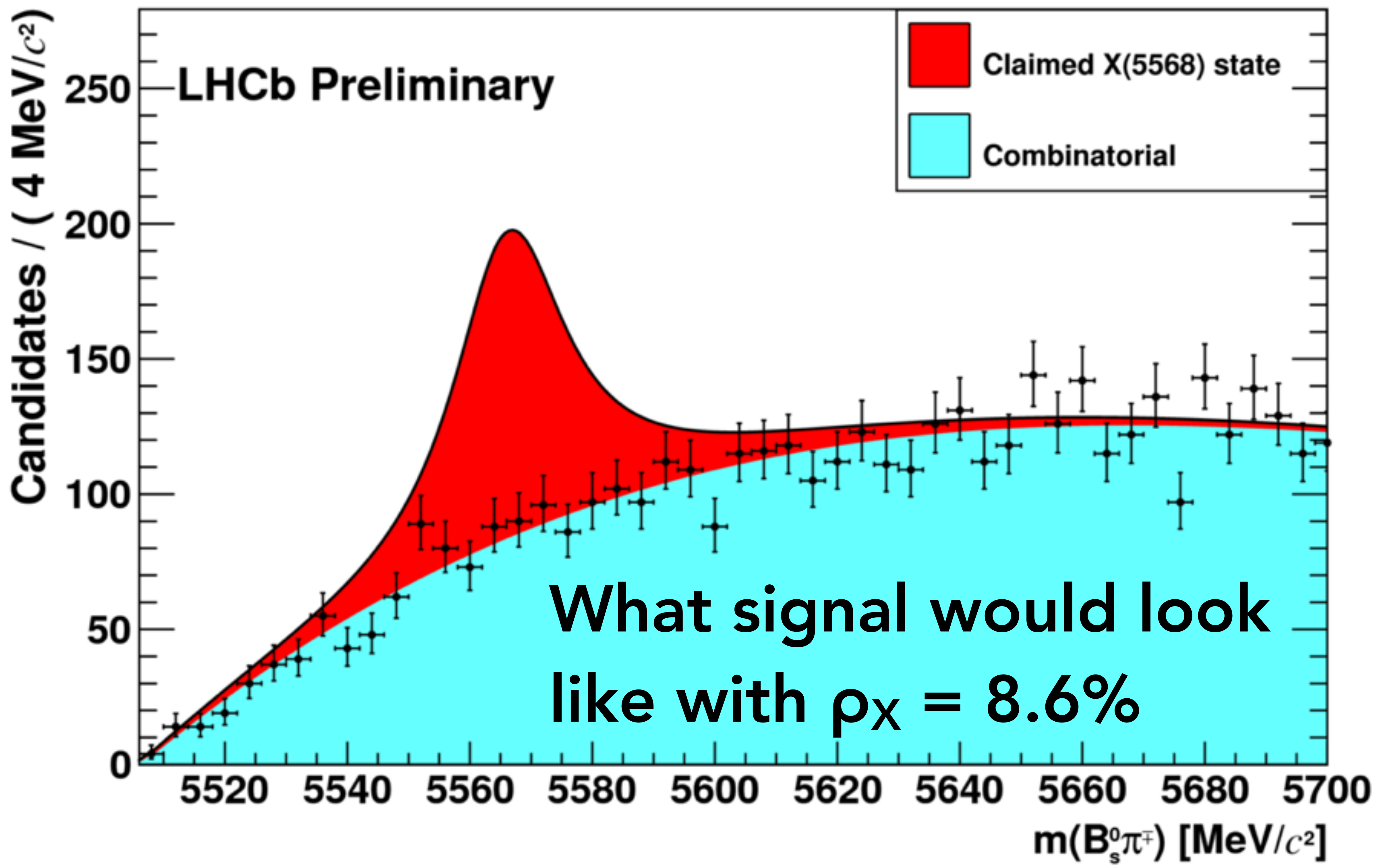




Upper limits on X(5568) production [LHCb-CONF-2016-004]

- No significant signal seen so upper limit set by integrating likelihood in physical (non-negative ρ) region.

$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 5\,\mathrm{GeV}/c) < 0.009\,(0.010)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 10\,\mathrm{GeV}/c) < 0.016\,(0.018)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$

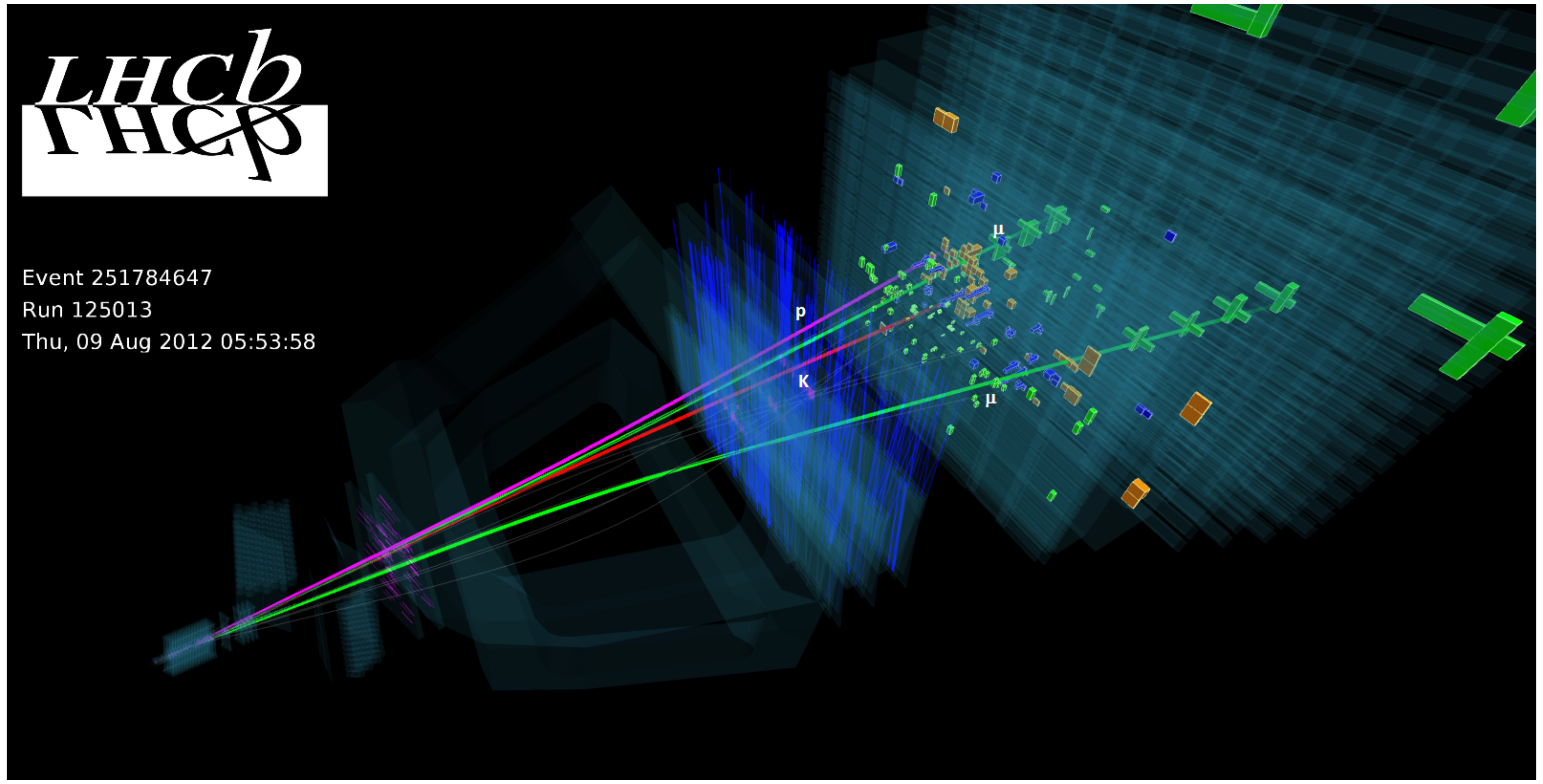


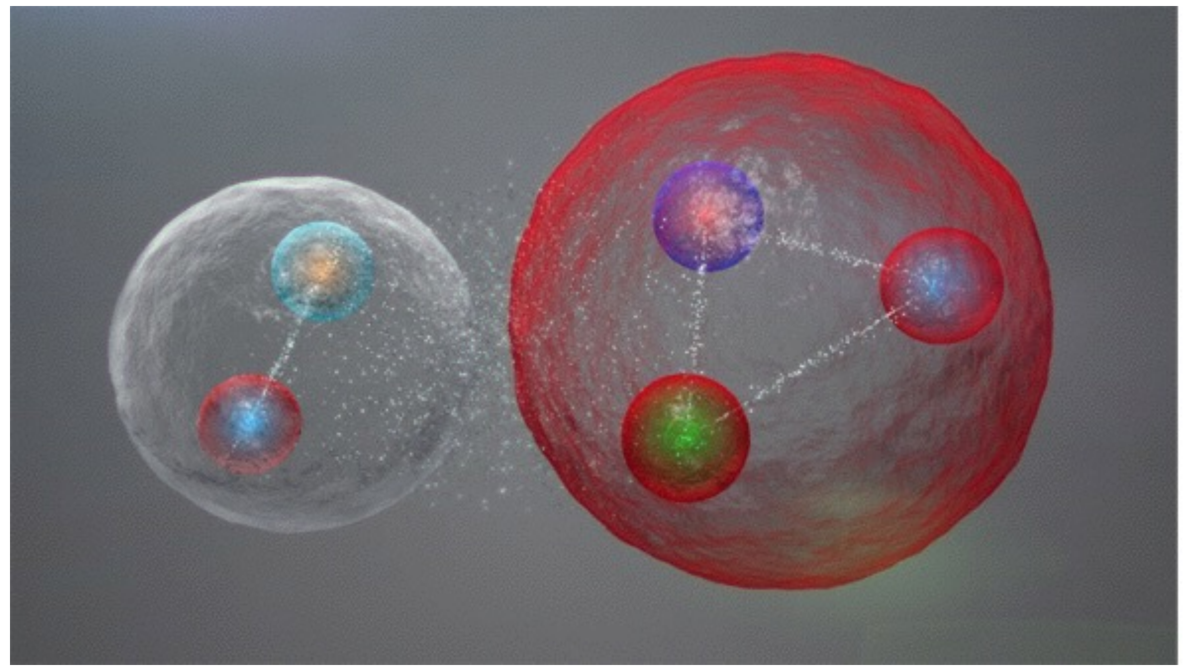
- Dominant systematic from changing D0 mass parameters and efficiency shape.
- Cross-checks show no dependence on rapidity.

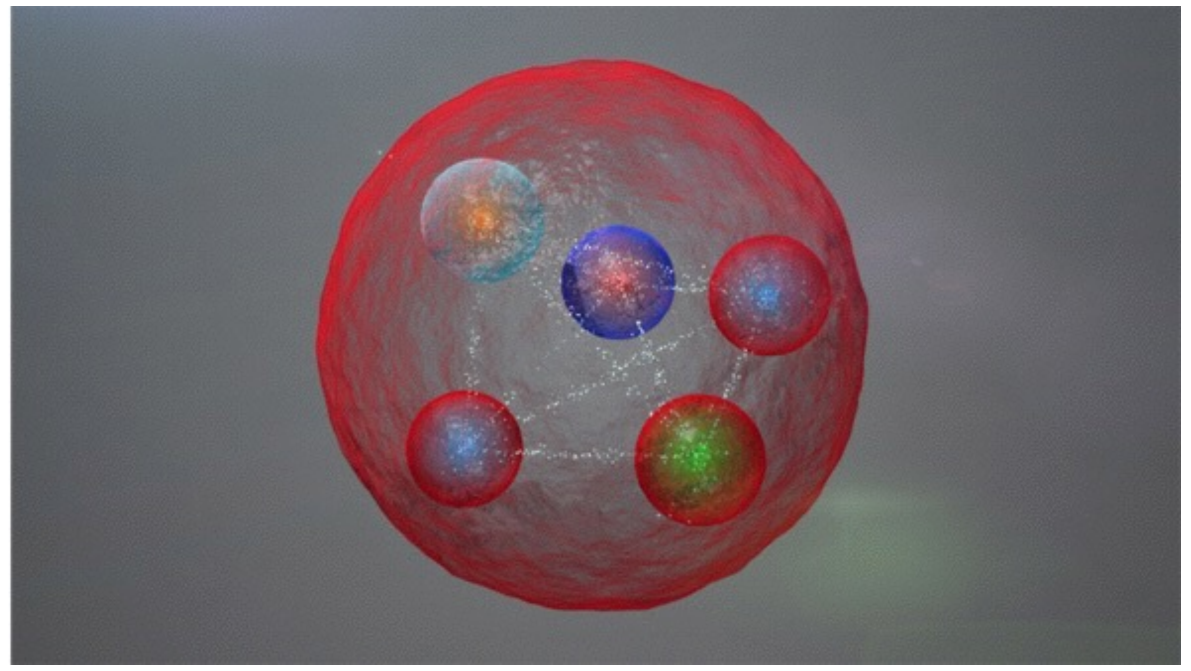
Summary

- **Quantum Chromodynamics** continues to reveal new properties, decades after idea of quarks first proposed.
- **LHCb experiment** observed two pentaquark states ($\Lambda_b \to J/\psi p K$), now with evidence from second channel ($\Lambda_b \to J/\psi p \pi$).
- **No evidence** for D0 tetraquark ($B_s \pi$).
- More **exciting results** expected soon (Run-2 of LHC just starting).

See Sheldon Stone's talk on 2nd June



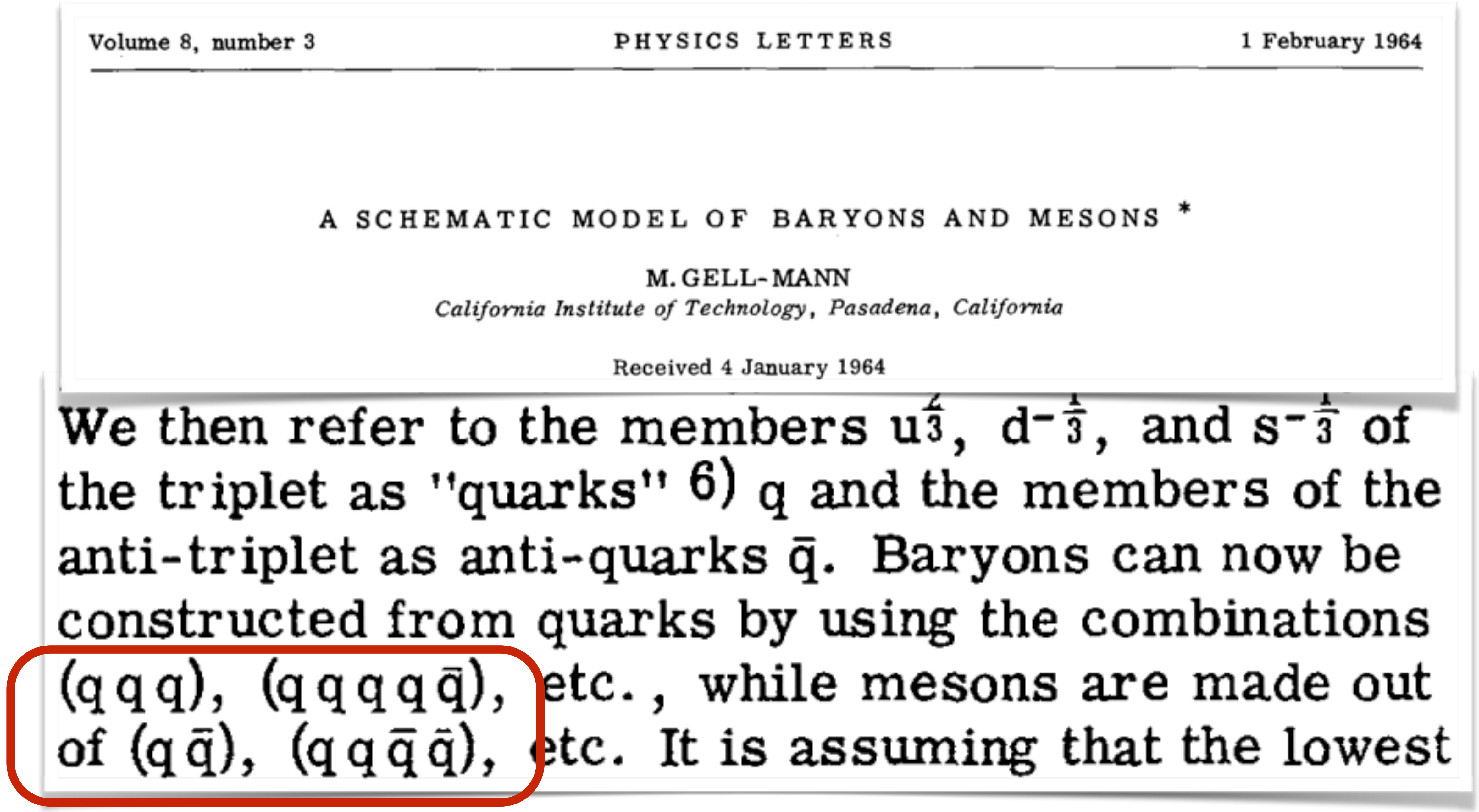




Backup

Three quarks for Muster Mark!

- Bound states of quarks that form mesons and baryons were first proposed in 1964 by Gell-Mann and Zweig.
- Light quark spectroscopy used to understand structure of these states…
- …but, difficult due to wide overlapping states and background.
- Highly relativistic constituents (u, d and s quarks) make theoretical predictions difficult.
- What about heavier quarks?

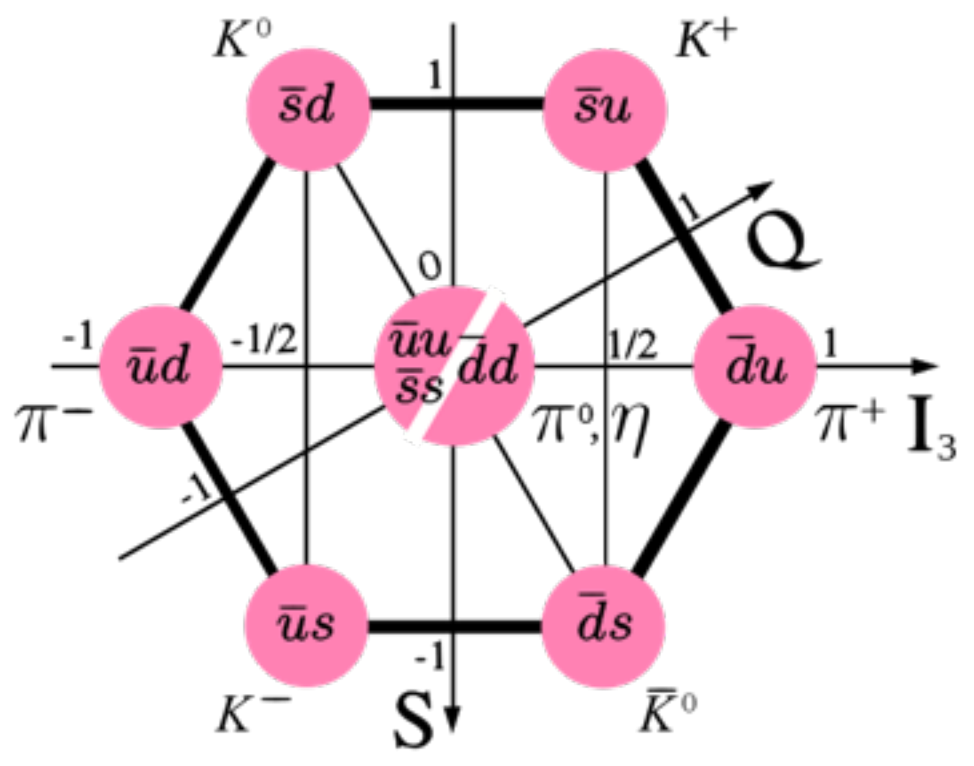

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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

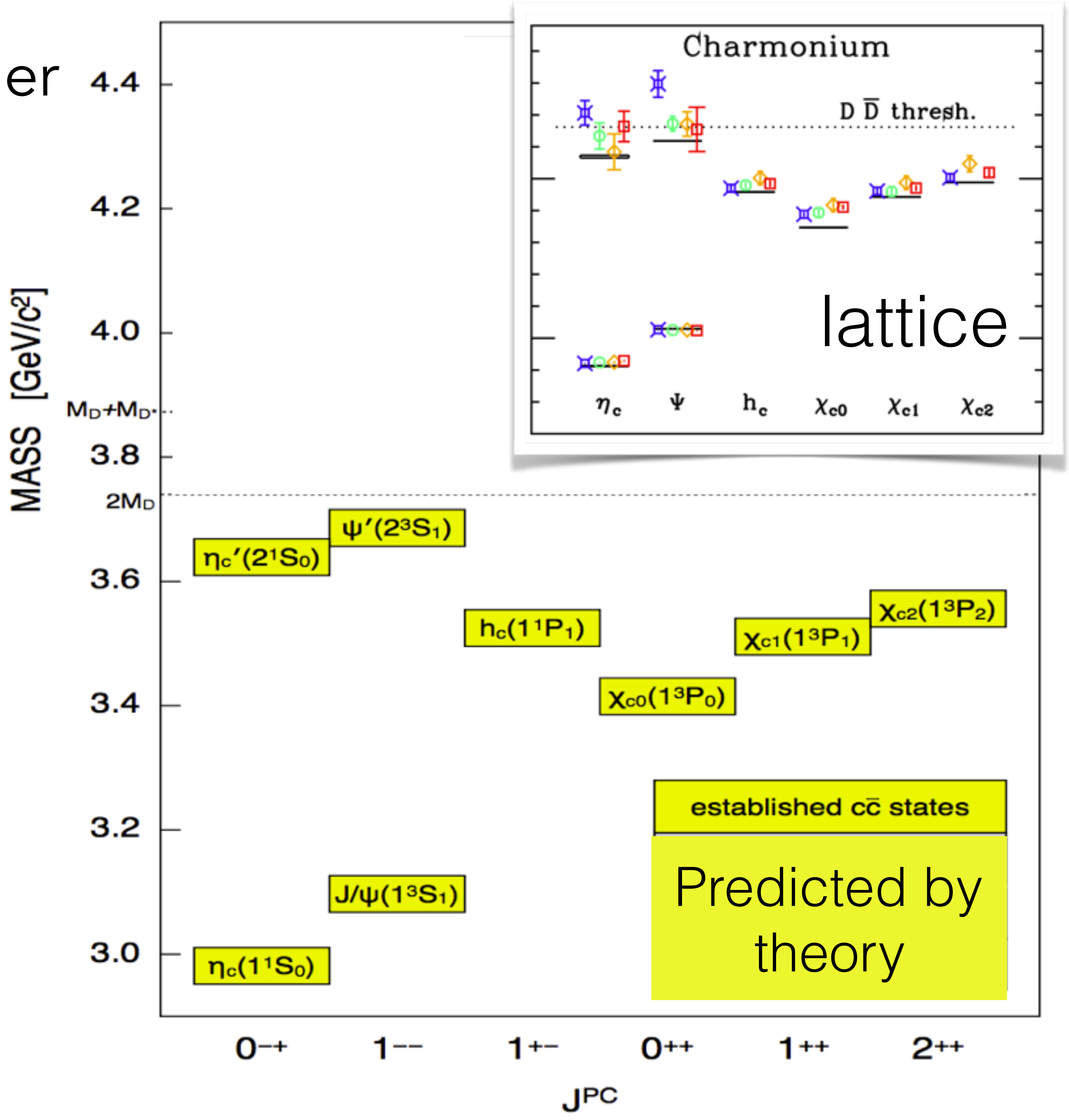


Charmonium spectroscopy ($c\bar{c}$)

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

Classify using JPC
$J = L \oplus S$
$P = (-1)^{L+1}$
$C = (-1)^{L+S}$

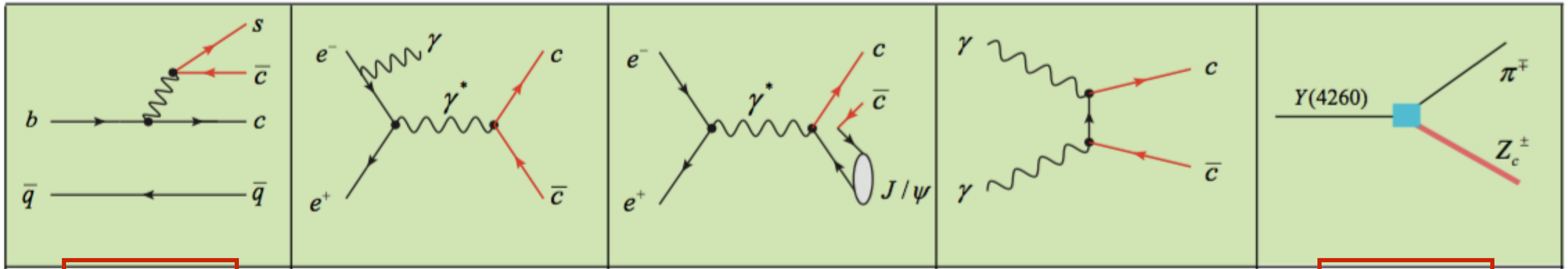
$n^{2S+1}L_J$



[Phys. Rev. D 81, 034508]
[Olsen arXiv:1403.1254]

See backup for bottomonium system

Meet the family



$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$Z^+(4248)$	$Y(4660)$			
$Y(4140)$				
$Y(4274)$				
$Z_c^+(4200)$				
$Z^+(4240)$				
$X(3823)$ ← 1^3D_2 ccbar				

See backup

Recent review articles -
[Chen et al arXiv:1601.02092]
[Olsen arXiv:1511.01589]
[Brambilla arXiv:1010.5827]

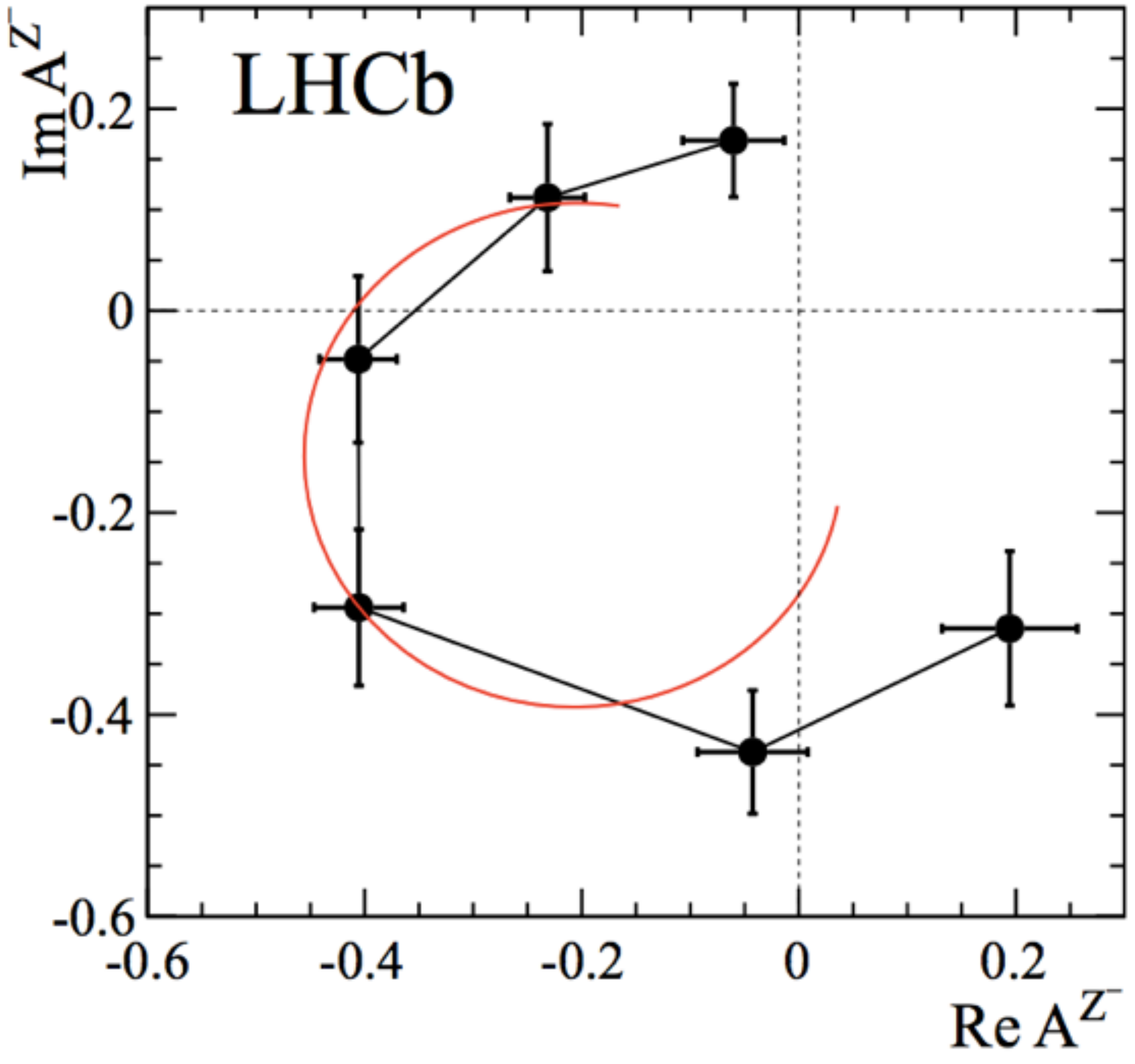
$P_c(4380)$
$P_c(4450)$

X(3872) also observed in prompt pp, ppbar collisions and ISR

Future experimental programme

If P_c states are molecules then their open-charm decays may be dominant

1. Observe states in different **production** and **decay** modes
   - Need to look for $c\bar{c}$ decay modes as-well as open-charm (e.g., B → KDD*) and charm-less.
   - Look at all flavours of B-hadrons
   - Transitions between exotic states (e.g., Y(4260) -> X(3872)γ)
   - Publish **non-observations**!
2. Look for **isospin/charged** partners
3. Measure **branching ratios**
4. Measure angular distributions and **quantum numbers**
   - **Angular** (partial wave) analyses will be crucial, as will accounting for threshold effects
   - Publish efficiencies to allow others to better use results

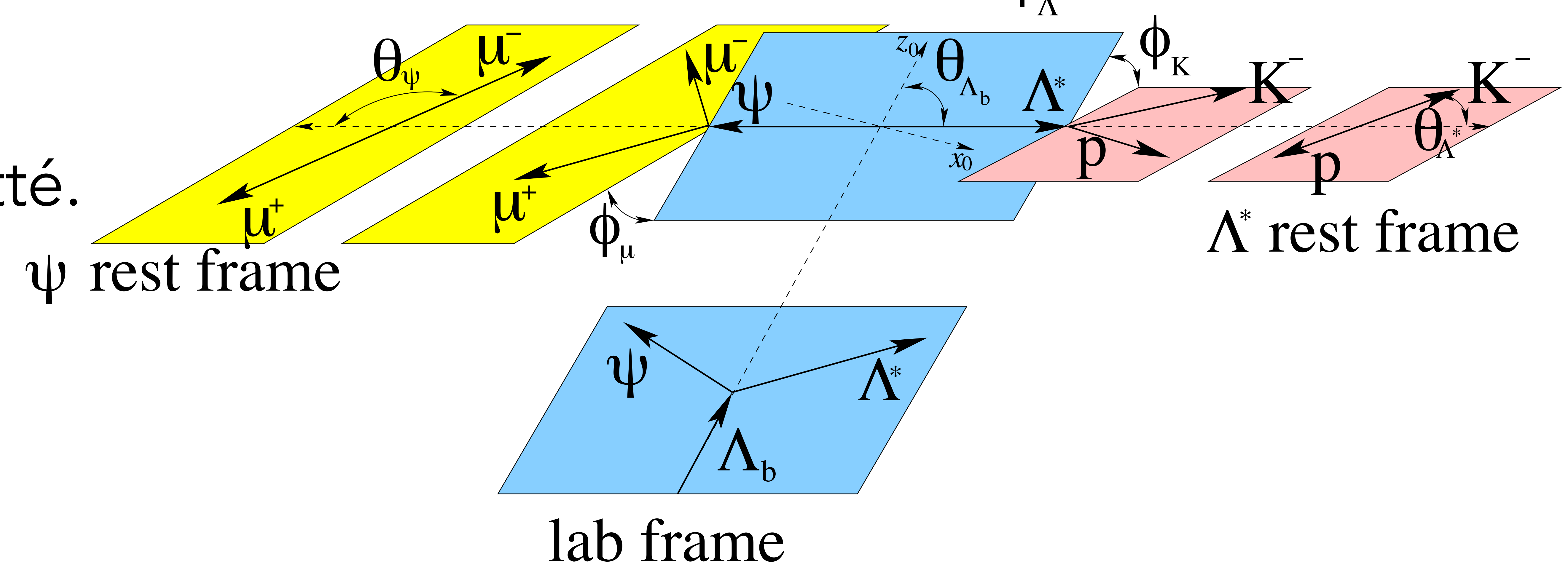


LHCb, CMS, ATLAS, Belle-II, BES-III, COMPASS and PANDA all have role to play!

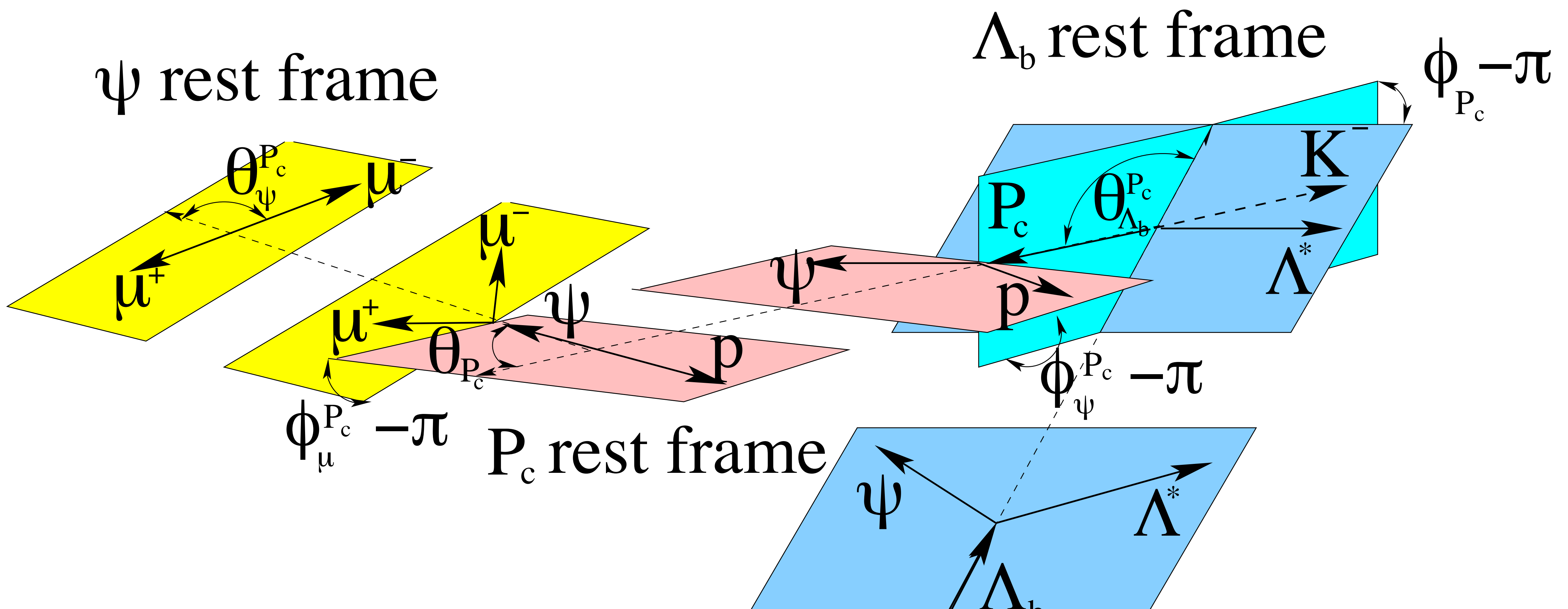
Amplitude model [PRL 115 (2015) 072001]

- Two interfering channels.
- Use 5 angles and *m(Kp)* as fit observables.
- Resonance mass-shapes: Breit-Wigner or Flatté.

$\Lambda_b^0 \to J/\psi \Lambda^* \quad \Lambda^* \to pK^-$

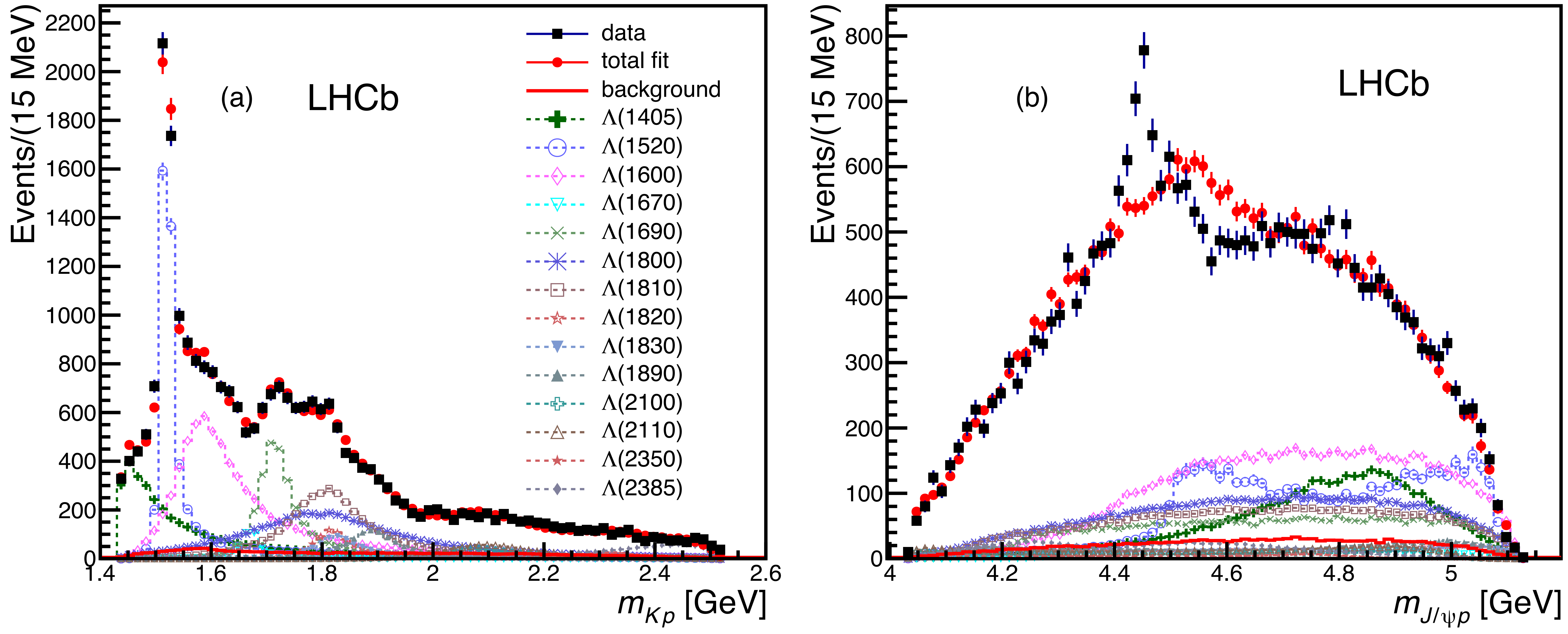


State	J^P	M_0 (MeV)	Γ_0 (MeV)
Λ(1405)	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0
Λ(1520)	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0
Λ(1600)	$1/2^+$	1600	150
Λ(1670)	$1/2^-$	1670	35
Λ(1690)	$3/2^-$	1690	60
Λ(1800)	$1/2^-$	1800	300
Λ(1810)	$1/2^+$	1810	150
Λ(1820)	$5/2^+$	1820	80
Λ(1830)	$5/2^-$	1830	95
Λ(1890)	$3/2^+$	1890	100
Λ(2100)	$7/2^-$	2100	200
Λ(2110)	$5/2^+$	2110	200
Λ(2350)	$9/2^+$	2350	150
Λ(2585)	?	≈2585	200



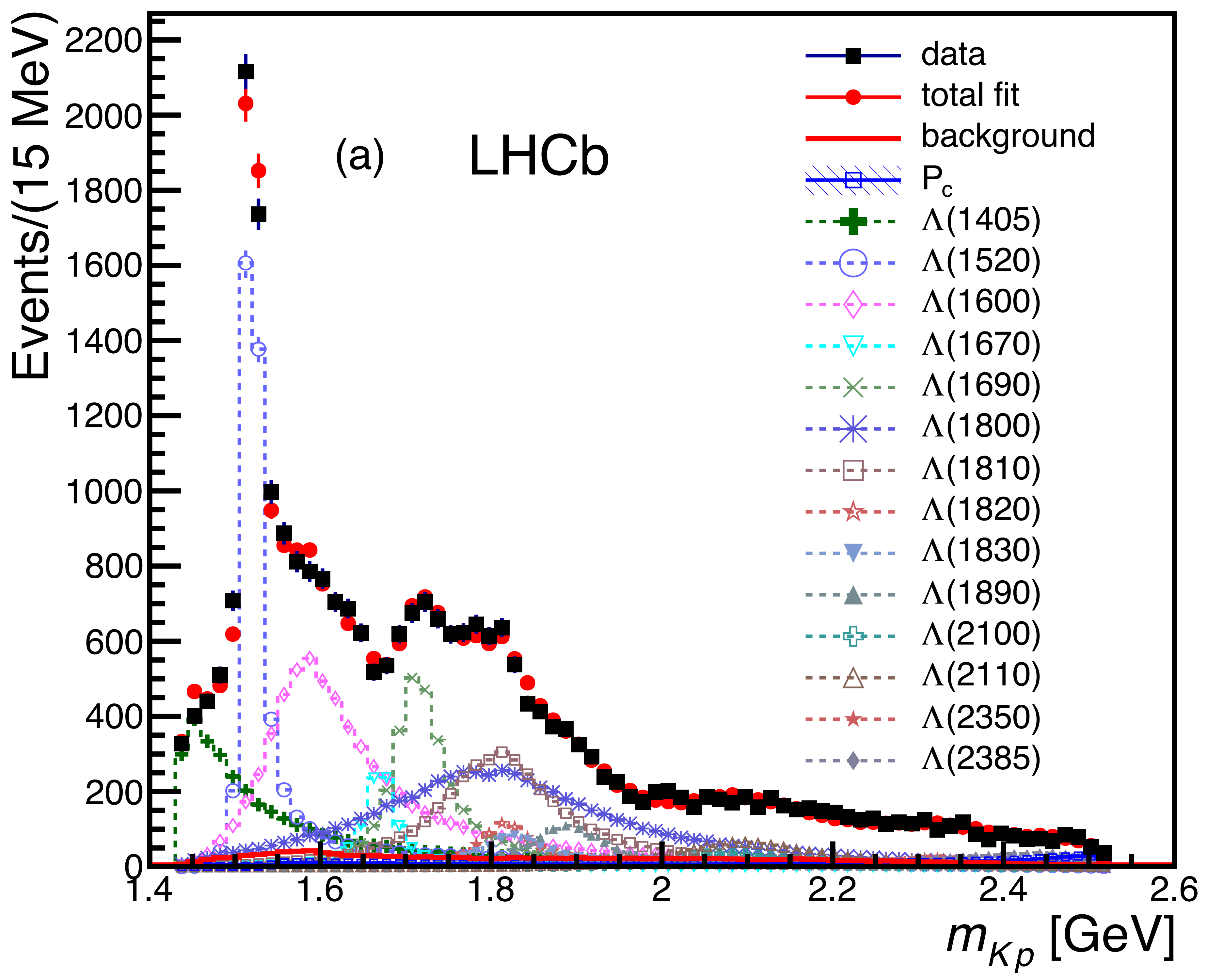
$\Lambda_b^0 \to P_c^+ K^- \quad P_c^+ \to J/\psi p$

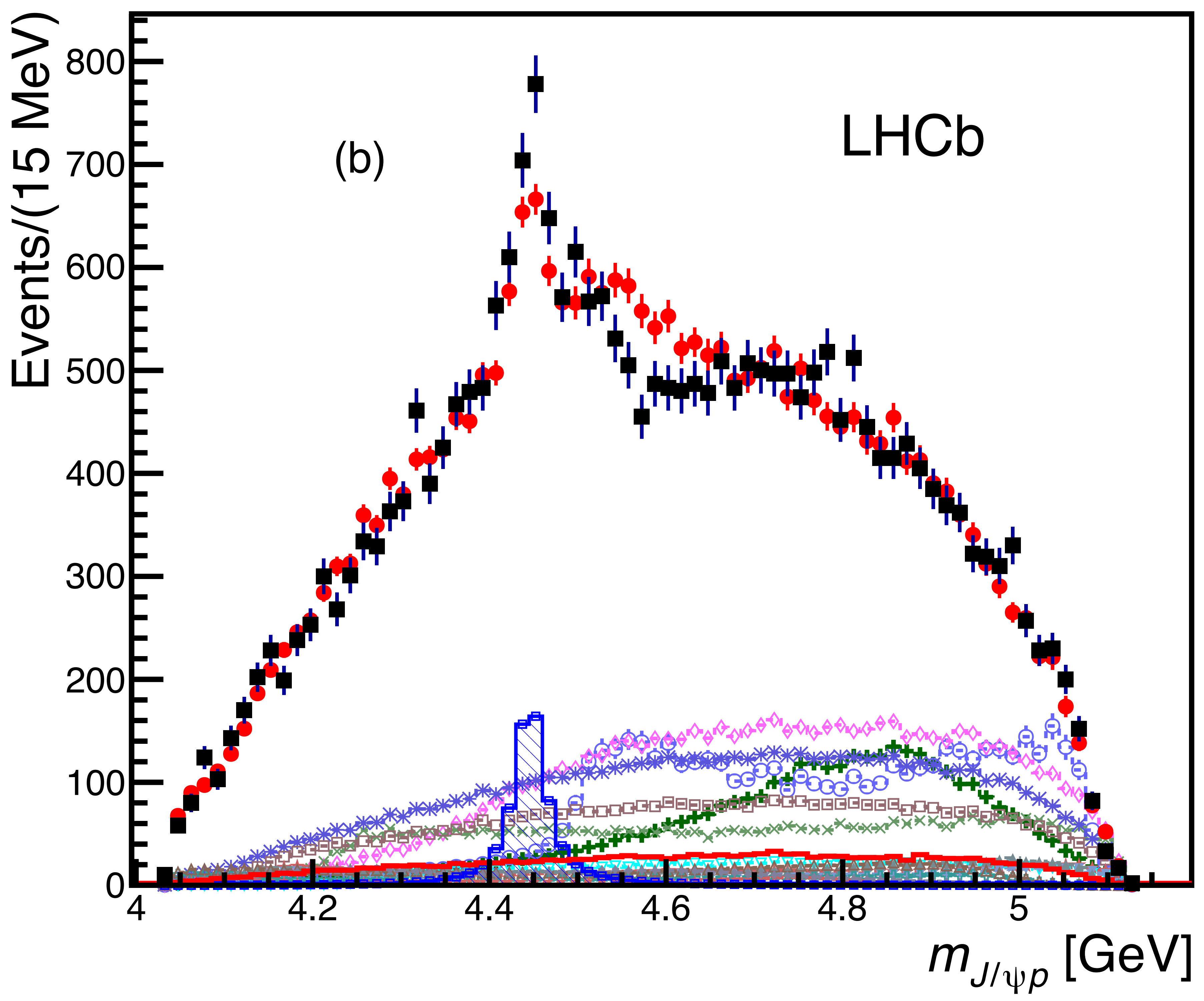
Results without P_c states [PRL 115 (2015) 072001]



- Using full set of Λ*'s m(Kp) looks good but not m(Jpsi p).

Extended model with one P_c [PRL 115 (2015) 072001]





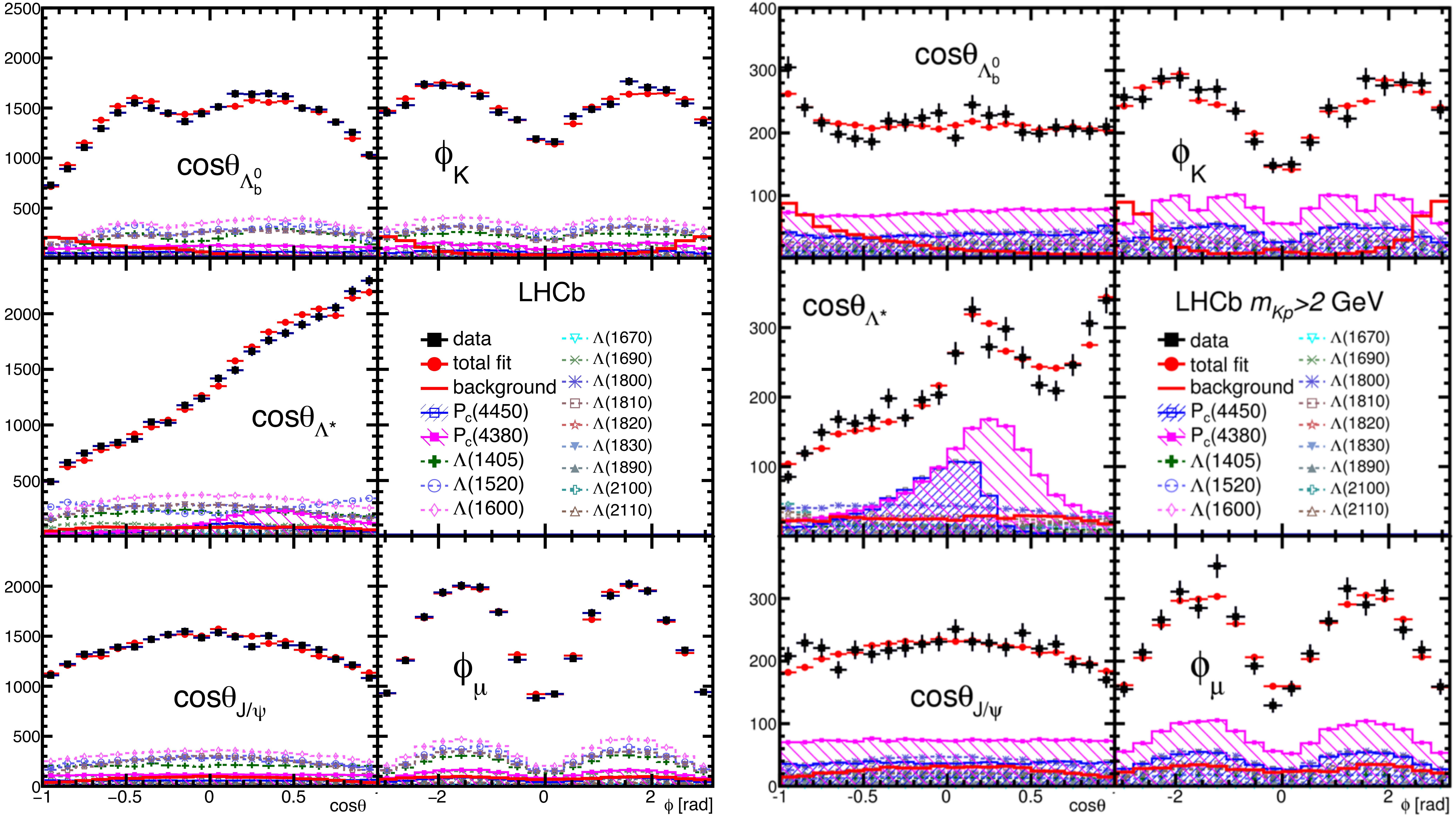
- Try all Λ*'s with J^P up to $7/2^{+/-}$

$$\sqrt{\Delta 2\mathcal{L}} = 14.7\sigma$$

- Best fit with a $J^P = 5/2^+$ pentaquark gives improvement, but m(Jpsi p) still not good.

Angular distributions [PRL 115 (2015) 072001]

Good fit to the angular observables



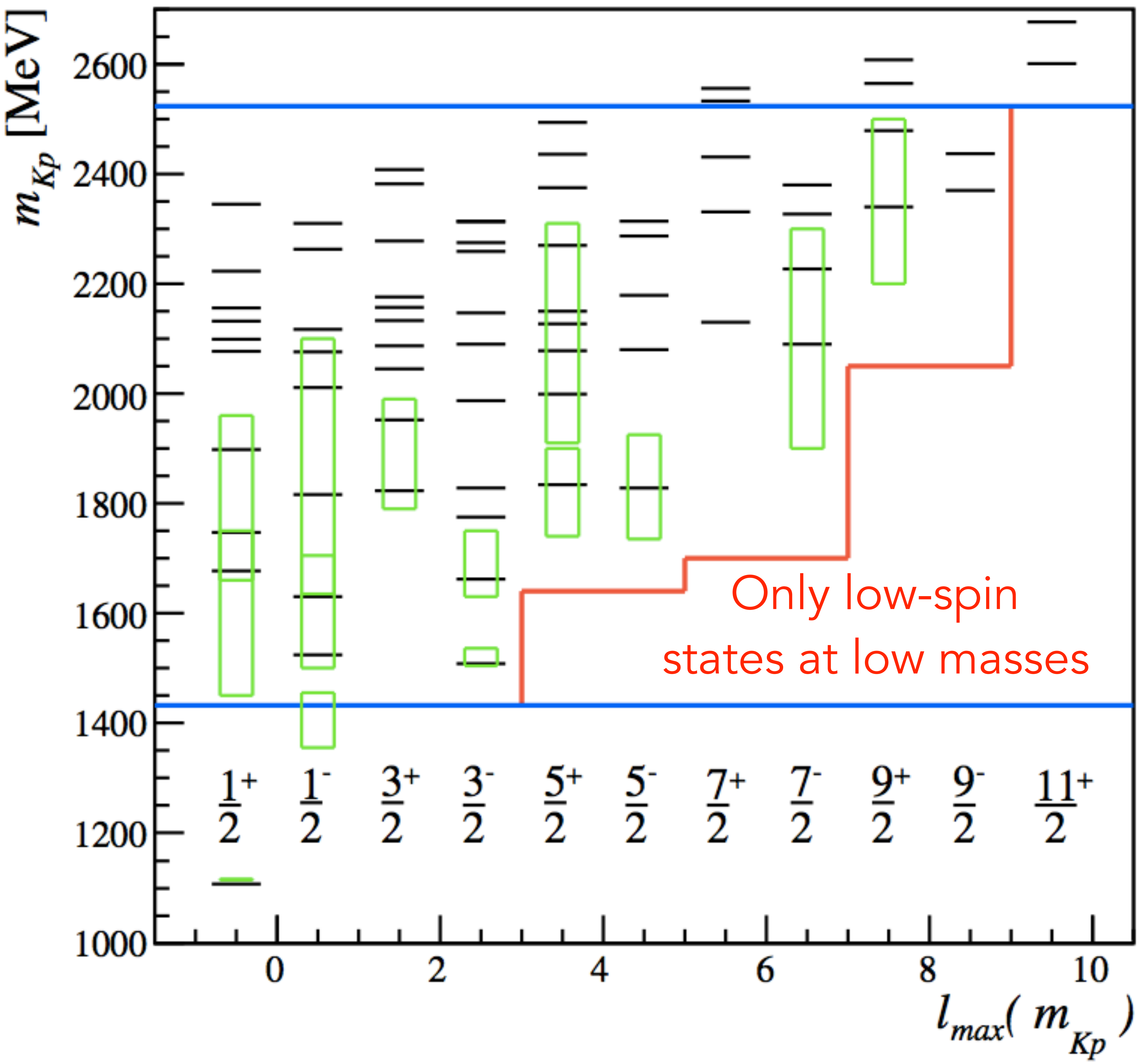
Pentaquark: model-independent [LHCb-PAPER-2016-009]

- Λ^* spectrum is largest systematic uncertainty in observation of P_c^+ states.

- Model-independent approach: do not assume anything about Λ^*, Σ^* or NR composition, spin, masses, widths or mass-shape.

- Only restrict the maximal spin of allowed Λ^* components at given m(Kp).

Theory predictions for Λ*
Well established Λ* states



[Extension of BaBar PRD 79 (2009) 112001]

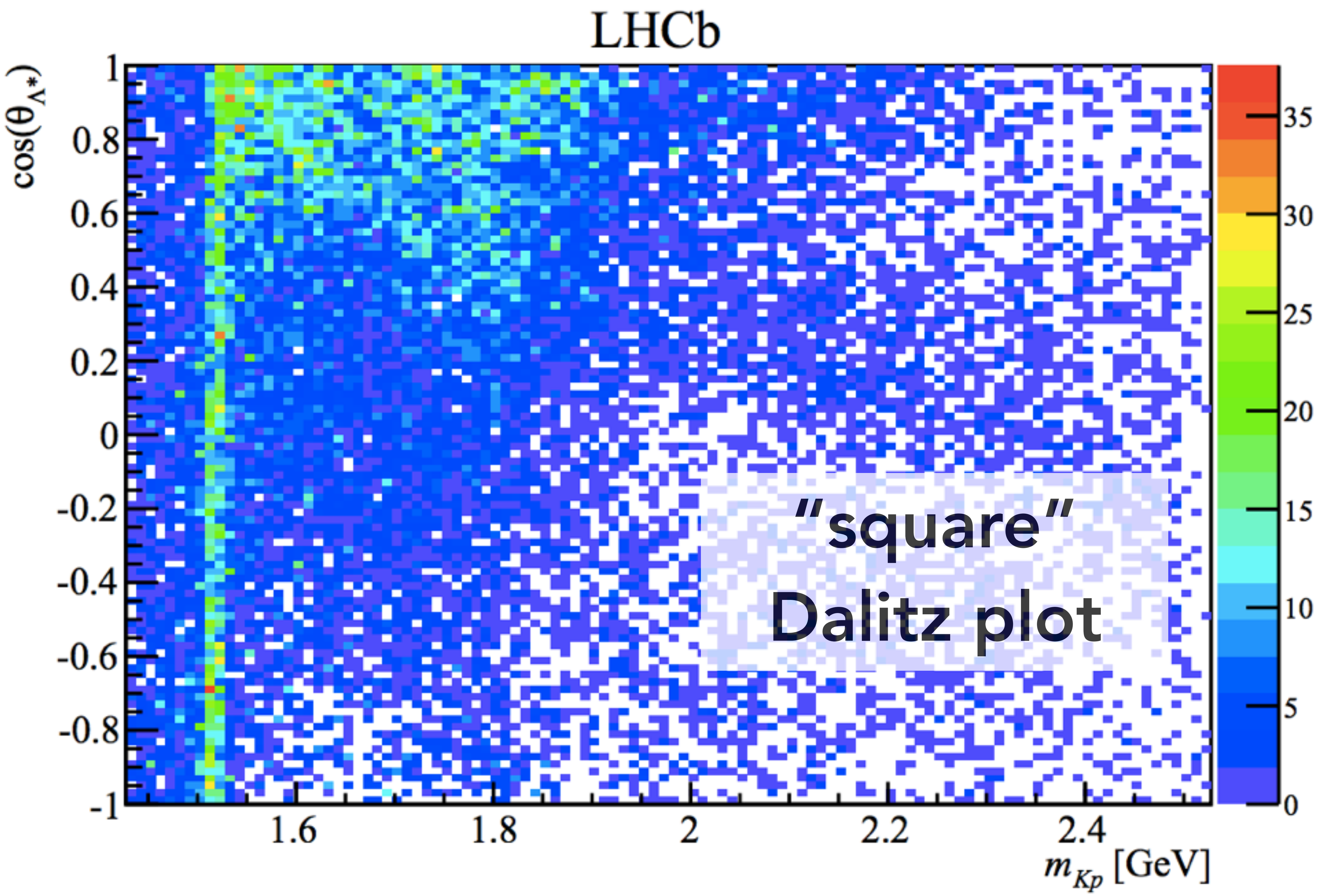
Pentaquark model-independent [LHCb-PAPER-2016-009]

- Expand $\cos\theta_{\Lambda^*}$ distribution in Legendre polynomials.

$$\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

- Moments obtained from the data in bins of m(Kp):

$$\langle P_l^U \rangle^k = \sum_{i=1}^{{n_{\mathrm{cand}}}^k} (w_i/\epsilon_i) P_l(\cos\theta^i_{\Lambda^*})$$



- Maximal rank of the Legendre polynomial $l_{\max}$ cannot be higher than $2J_{\max}$, where $J_{\max}$ is twice the highest (Kp) spin which is present in the data at a given m(Kp) value.

Pentaquark model-independent [LHCb-PAPER-2016-009]

- Expand $\cos\theta_{\Lambda^*}$ distribution in Legendre polynomials.

$$\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

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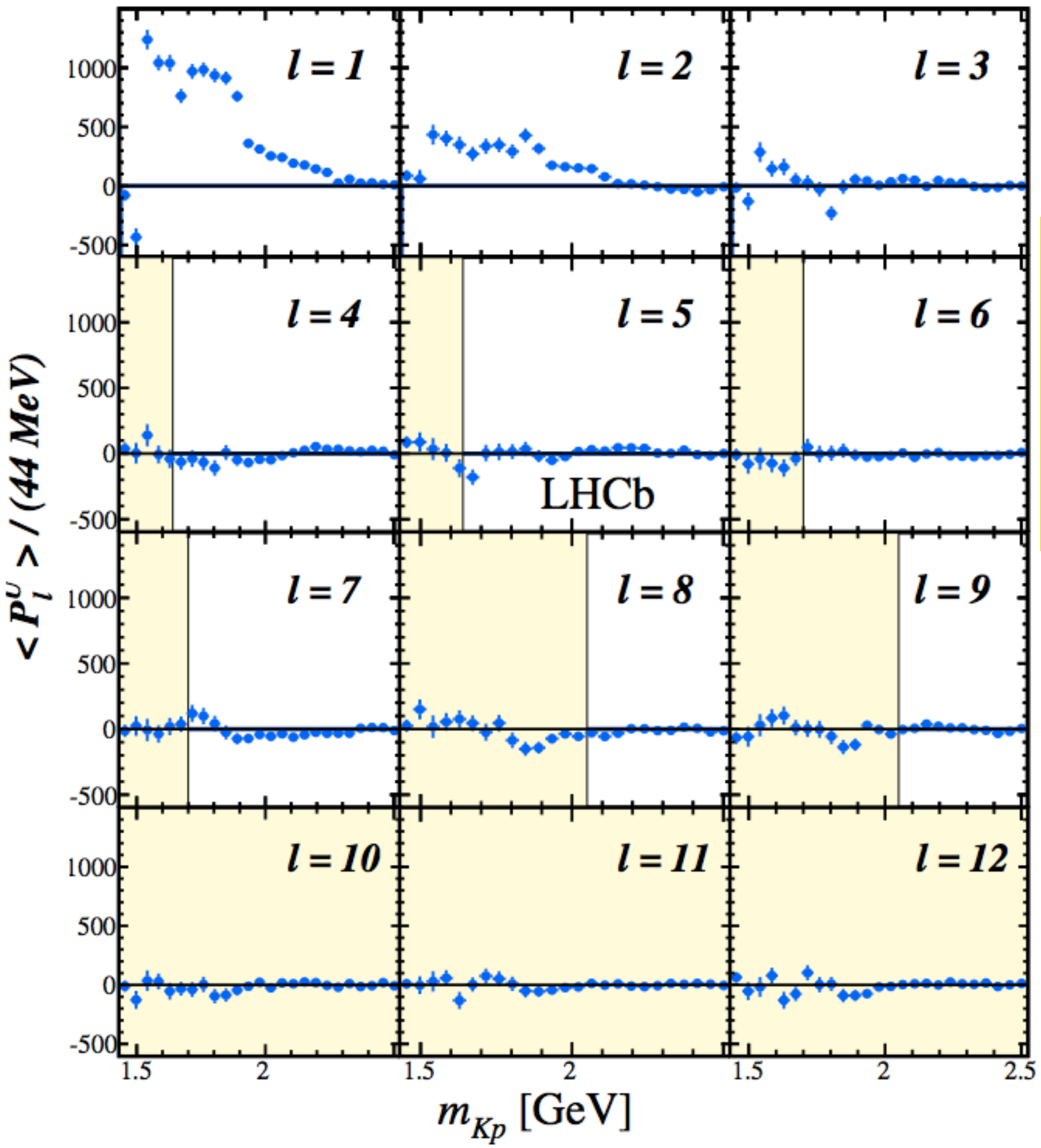
$$\langle P_l^U \rangle^k = \sum_{i=1}^{{n_{\rm cand}}^k} (w_i/\epsilon_i) P_l(\cos\theta^i_{\Lambda^*})$$

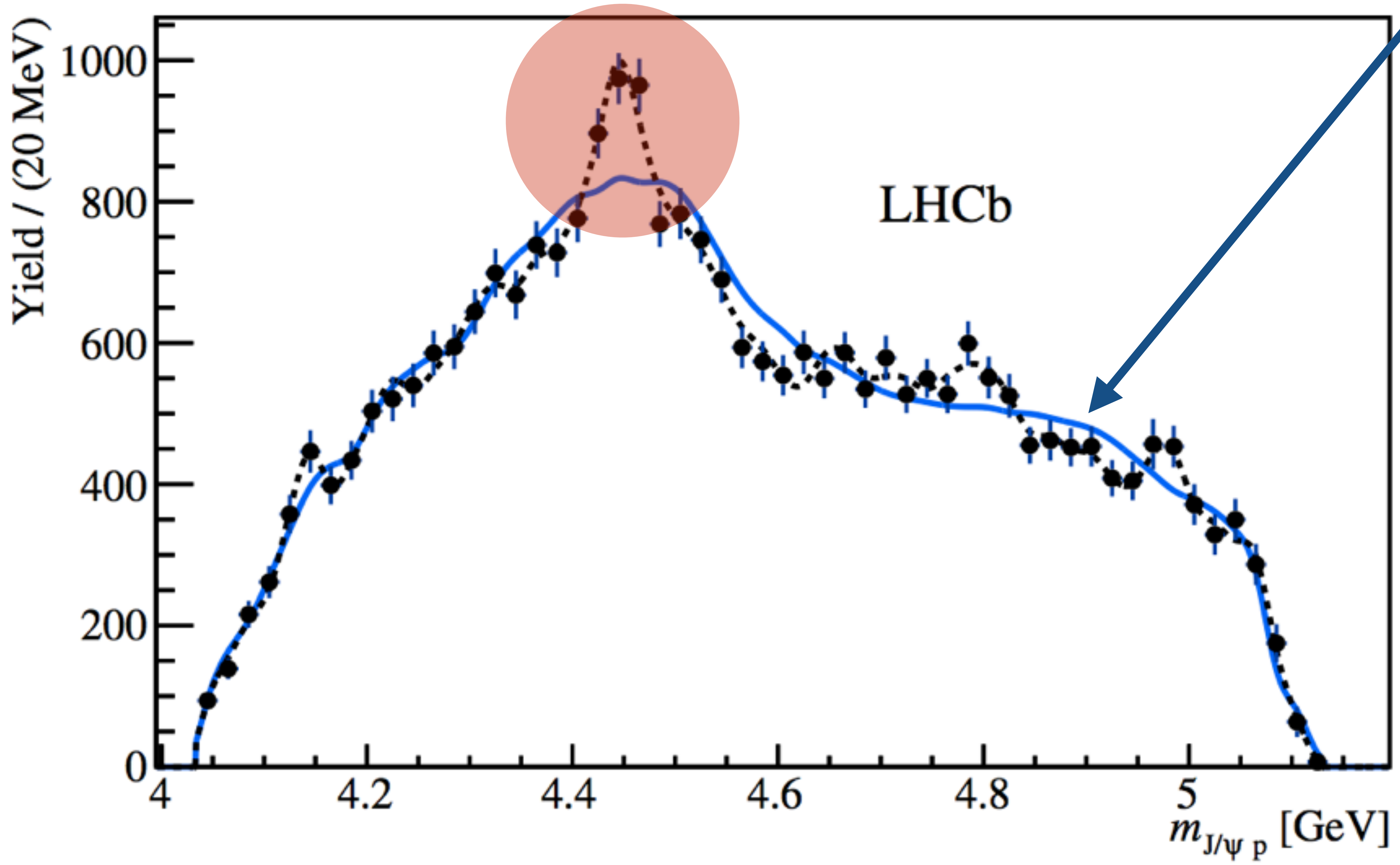


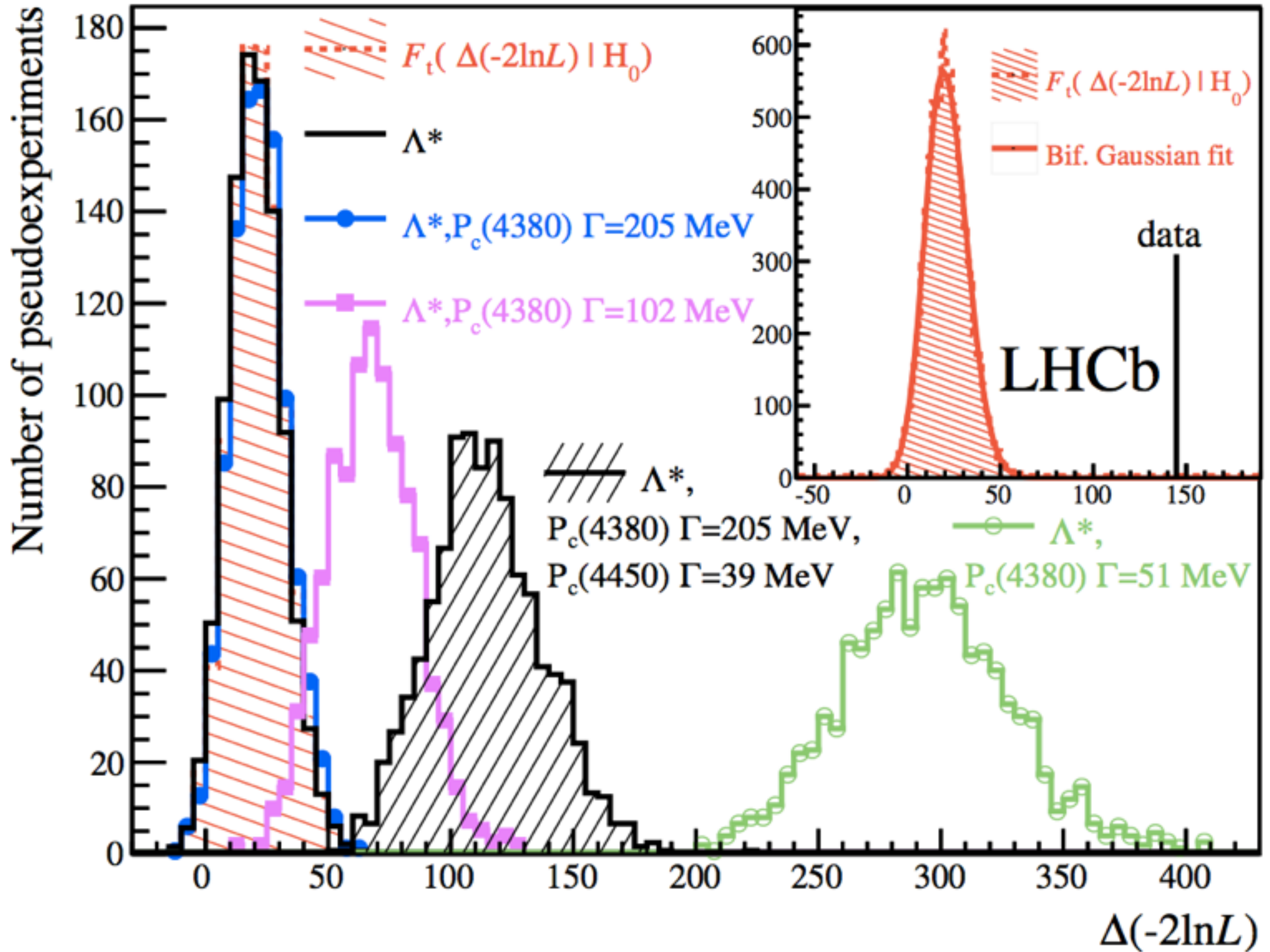
filter out maximum spin for each m(Kp)

- Maximal rank of the Legendre polynomial $l_{\max}$ cannot be higher than $2J_{\max}$, where $J_{\max}$ is twice the highest (Kp) spin which is present in the data at a given m(Kp) value.

Pentaquark model-independent [LHCb-PAPER-2016-009]

- Simulate phase-space decays of $\Lambda_b^0 \rightarrow J/\psi p K^-$
- Weight according to m(Kp) and the moments (with l_{max}-filter applied)
- Look at reflections of the Kp system into the J/ψp system → **pK reflections cannot explain narrow structure!**
- Use likelihood ratio to test various hypotheses - **Null hypothesis (Λ* only)** rejected at **9σ**

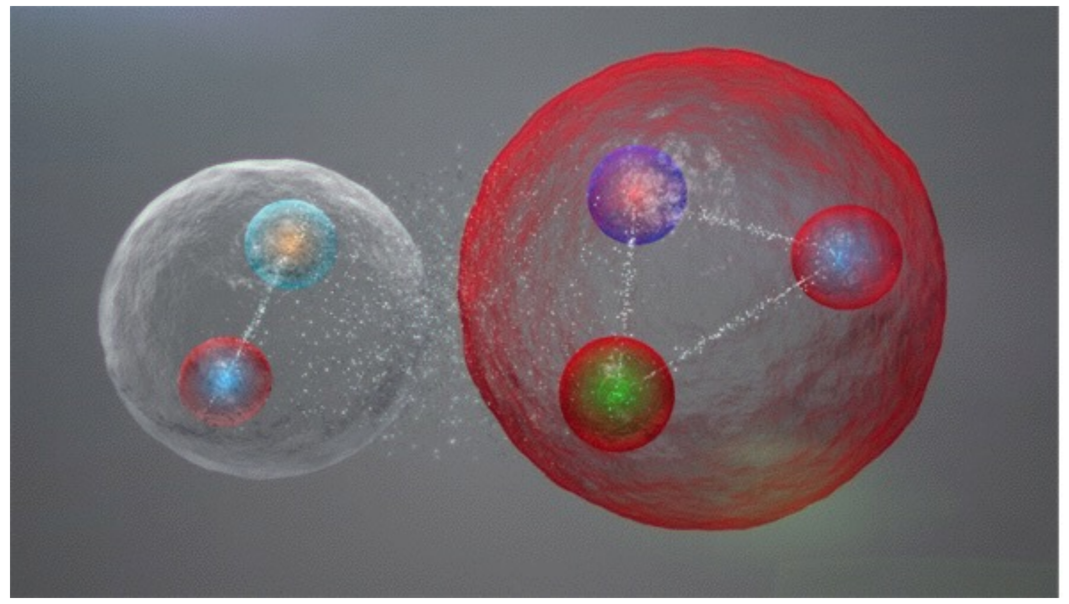


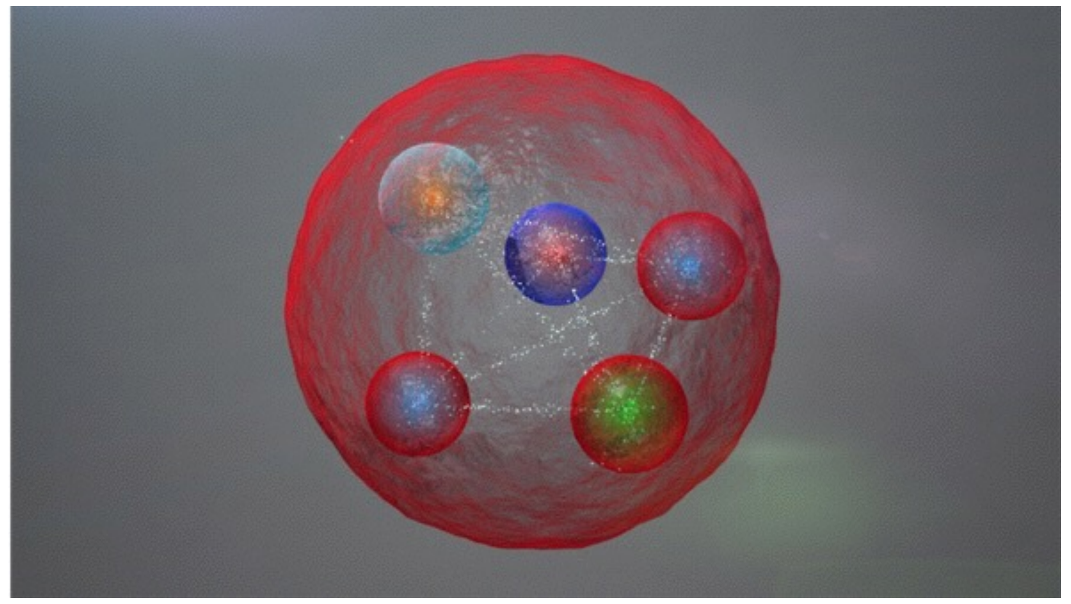


Pentaquark interpretations

- May be molecular or tightly bound pentaquark or some hybrid (see talks after coffee)

  [Maiani et al arXiv:1507.04980] [Lebed arXiv:1507.05867] [Zhu arXiv:1510.08693]





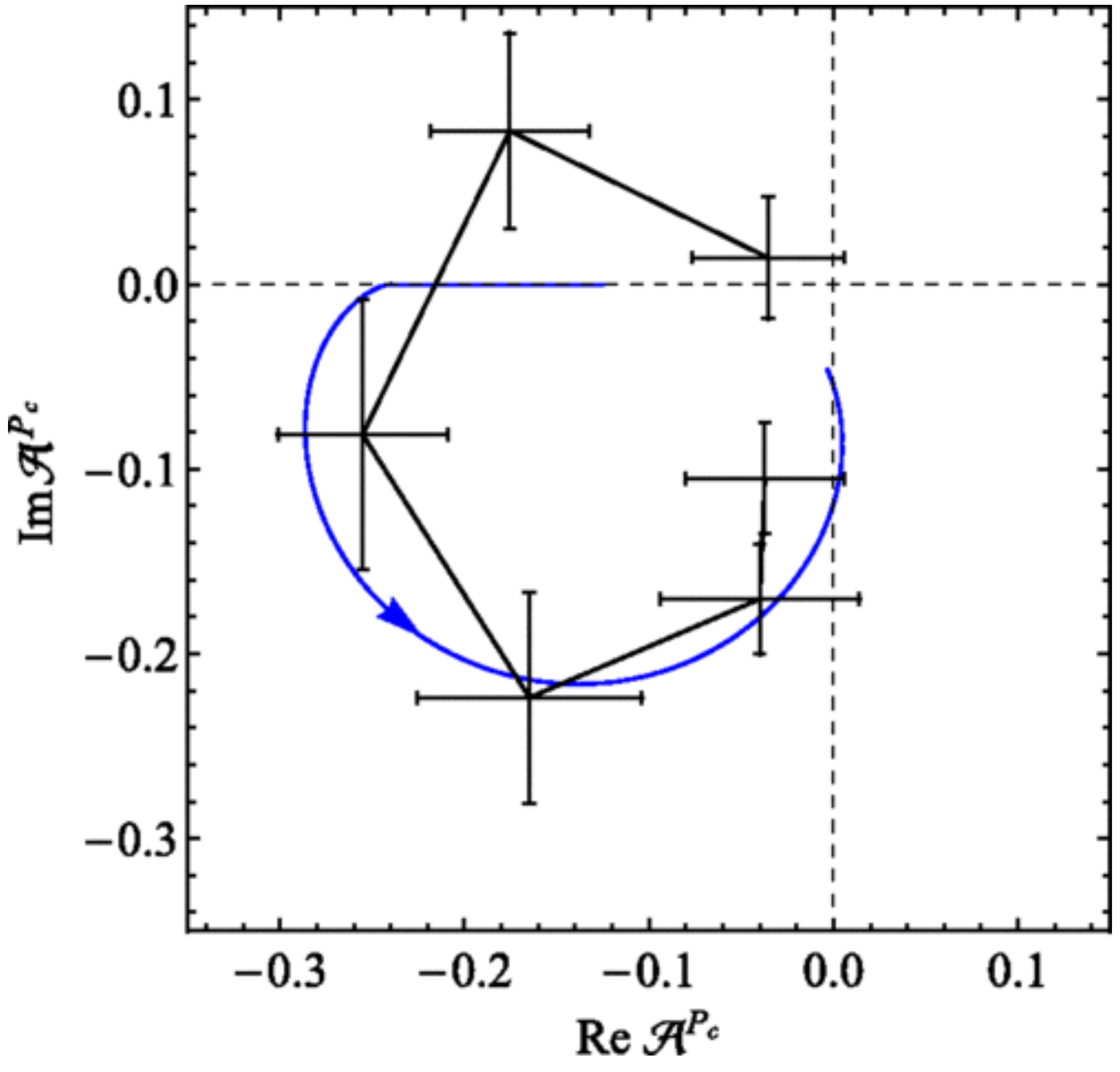
- Experimental programme: look for new decay modes and production mechanisms
- Look for partner states:

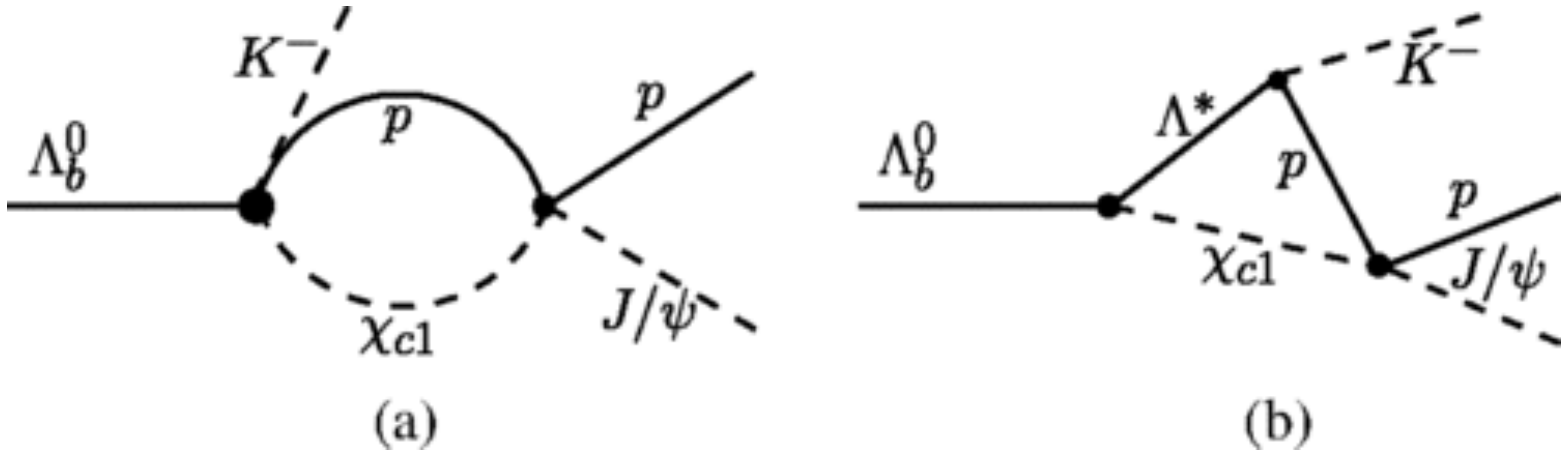
  $$\Lambda_b^0 \to P_c^0 K^0 \to J/\psi n K^0 \text{ or } J/\psi p \pi^- K^0$$
  $$\Lambda_b^0 \to P_{cs}^0 \phi \to J/\psi \Lambda \phi$$

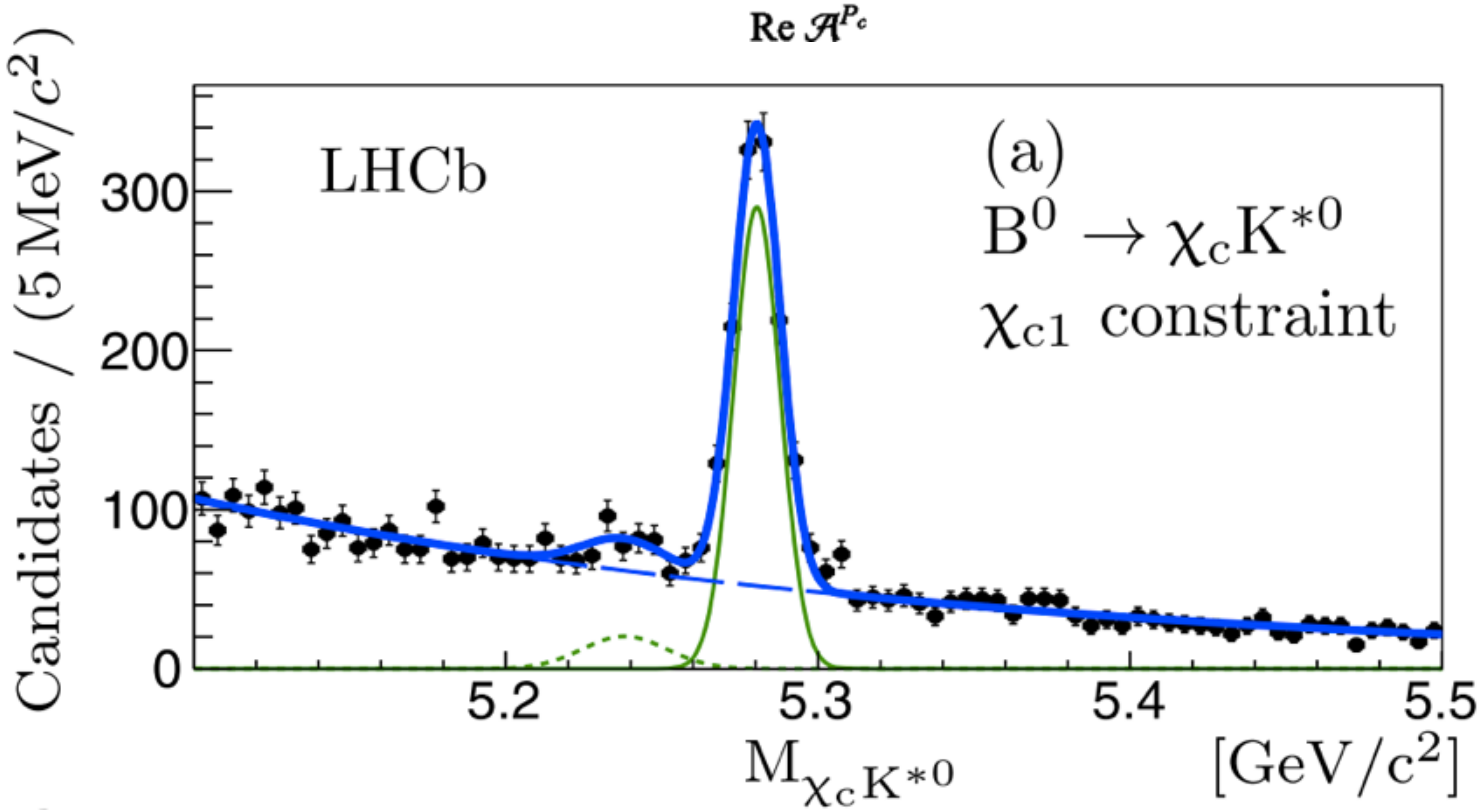
  - **Isospin** (ccudd), **strangeness** (ccuds), **bottom** (bbuud) partners
- Cabibbo-suppressed decays $\Lambda_b^0 \to J/\psi p \pi^-$
- Open-charm and charmless decays $\Lambda_b^0 \to \Sigma_c^+ D^-$ $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0}$

Pentaquark interpretations $\Lambda_b^0 \to \chi_{c1} p K^-$

- $P_c(4450)$ has mass just above threshold of $\chi_{c1} p$
- Maybe due to kinematic rescattering effect?
  [Guo et al PRD 92 (2015) 071502(R)]
- Reproduces phase motion of $P_c(4450)$ but what about $P_c(4380)$?
- Rescattering would not explain narrow enhancement above $\chi_{c1} p$ threshold

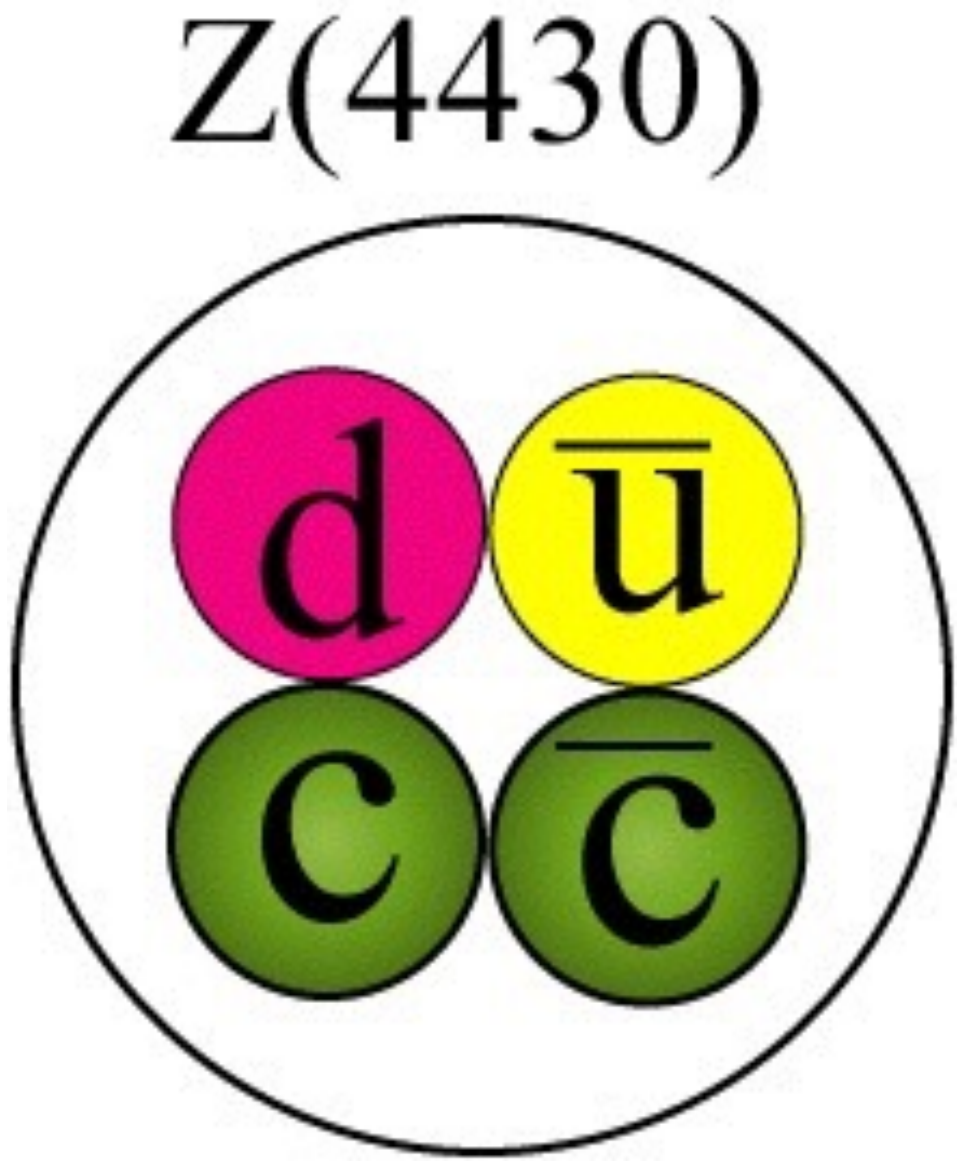






[NPB 874 (2013) 663]

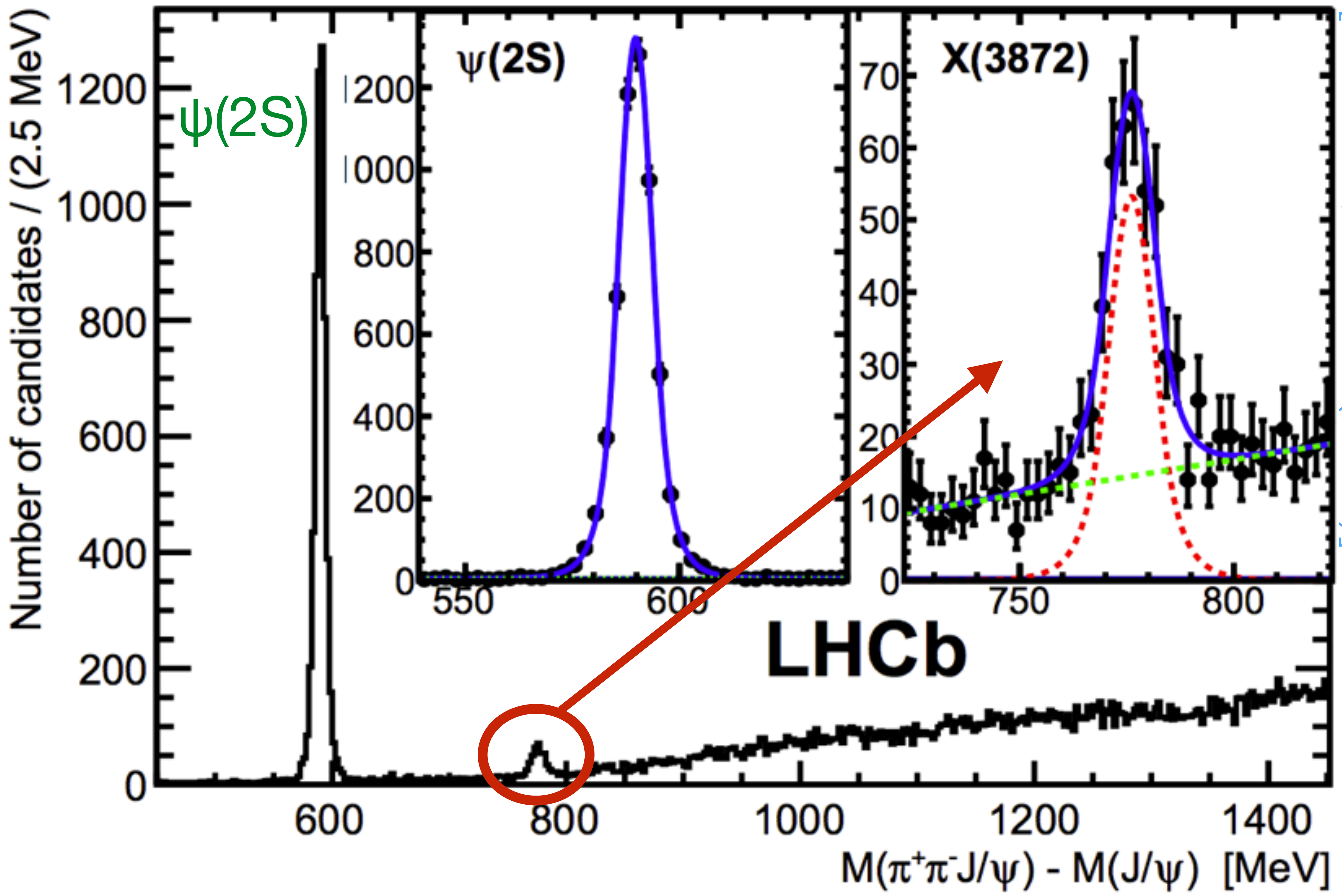
Exotic mesons



The X(3872) revolution

- Observation in 2003 by Belle has led to a revolution in exotic meson/baryon spectroscopy. [PRL 91 (2003) 262001 - 1183 citations!]
- Exotic interpretation: $c\bar{c}u\bar{u}$ tetraquark, $D^0D^{*0} = (c\bar{u})(\bar{c}u)$ molecule, $c\bar{c}g$

$$B^+ \to X(3872)K^+, X(3872) \to J/\psi\pi^+\pi^-$$



[PRL 110, 222001 (2013)]

Observation		Note
$B \to KX(3872)$	$\to J/\psi\rho^0, J/\psi\pi^+\pi^-$	Belle [63], BaBar [84]
	$\to J/\psi\omega(\to \pi^+\pi^-\pi^0)$	Belle [75], BaBar [90]
	$\to D^0\bar{D}^{*0}, D^0\bar{D}^0\pi^0$	Belle [76], BaBar [87]
	$\to \gamma J/\psi, \gamma\psi(3686)$	Belle [75], BaBar [86]
$p\bar{p} \to \cdots + X(3872)(\to J/\psi\pi^+\pi^-)$		CDF [67], D0 [68]
$pp \to \cdots + X(3872)$	$\to J/\psi\pi^+\pi^-$	LHCb [91], CMS [73]
	$\to \gamma J/\psi, \gamma\psi(3686)$	LHCb [92]
$e^+e^-[\to Y(4260)] \to \gamma X(3872)(\to J/\psi\pi^+\pi^-)$		BESIII [93]

$$\Gamma_{X(3872)} < 1.2\ \mathrm{MeV}/c^2$$
$$M_{X(3872)} = 3871.69 \pm 0.17\ \mathrm{MeV}/c^2$$
$$M_{D^0} + M_{D^{*0}} = 3871.81 \pm 0.09\ \mathrm{MeV}/c^2$$

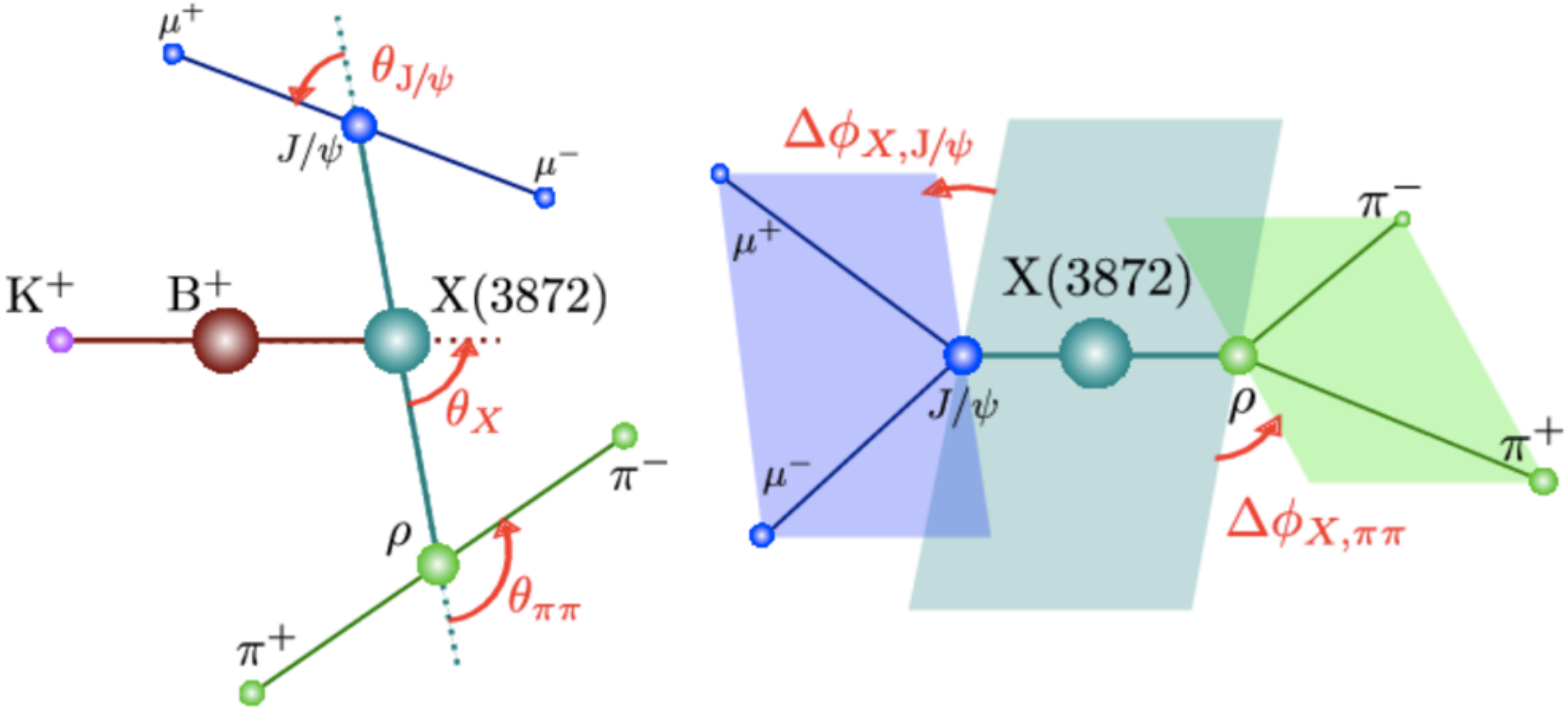
[PDG]

X(3872) quantum numbers [PRD 92 (2015) 011102]

- **C = +1** since $X(3872) \to J/\psi\gamma$

$$B^+ \to X(3872)K^+, X(3872) \to J/\psi\pi^+\pi^-$$

- Pure DD* molecule interpretation disfavoured. [LHCb NPB 886 (2014) 665]
- Analyse 5D angular correlations
- Amplitude model includes D-wave components (previously ignored)
- Use likelihood ratio test to compare J^{PC} hypotheses

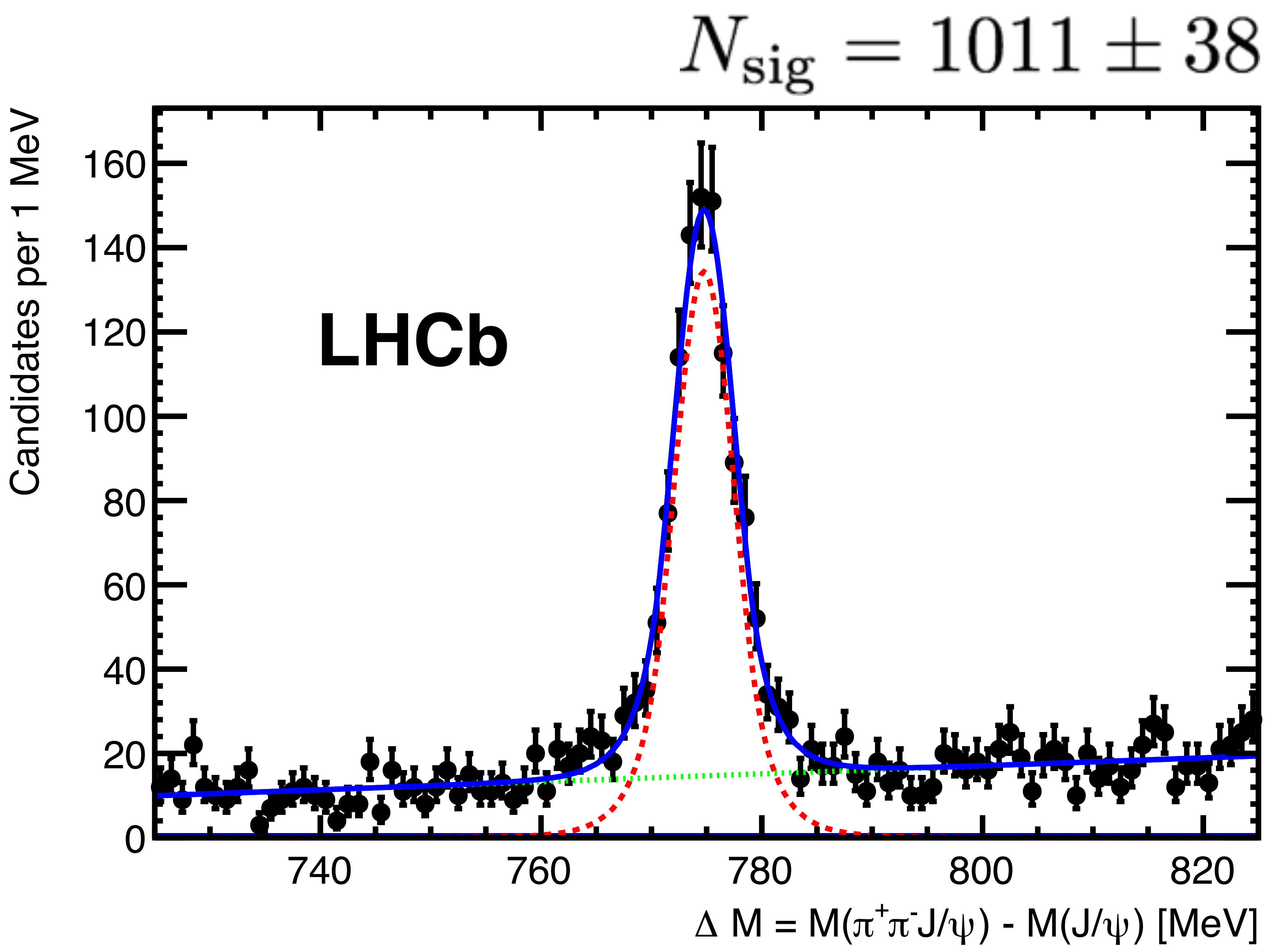


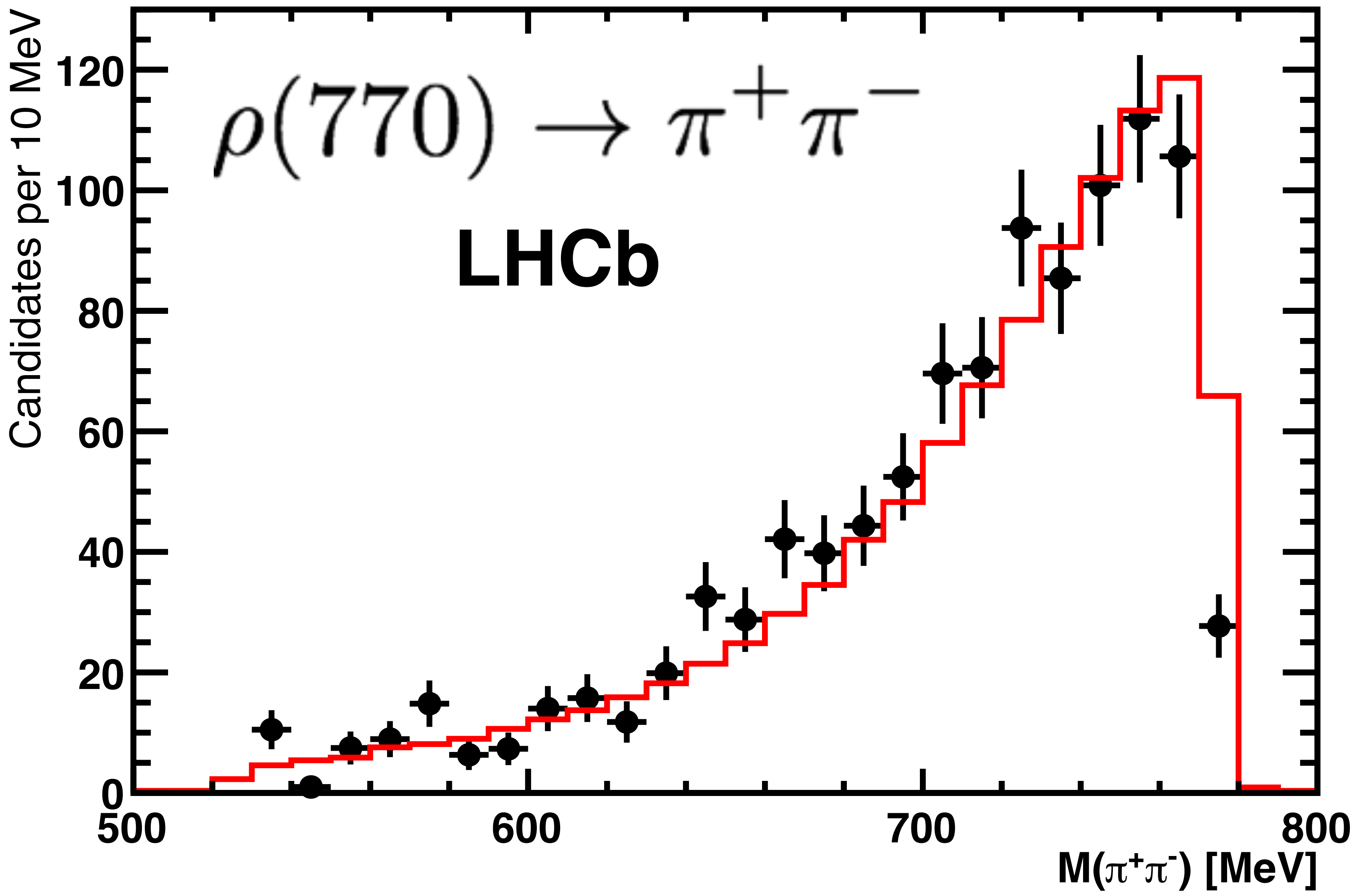
Previously studied by:
[LHCb PRL 110 (2013) 222001]
[Belle PRD 84 (2011) 052004]
[CDF PRL 98 (2007) 132002]

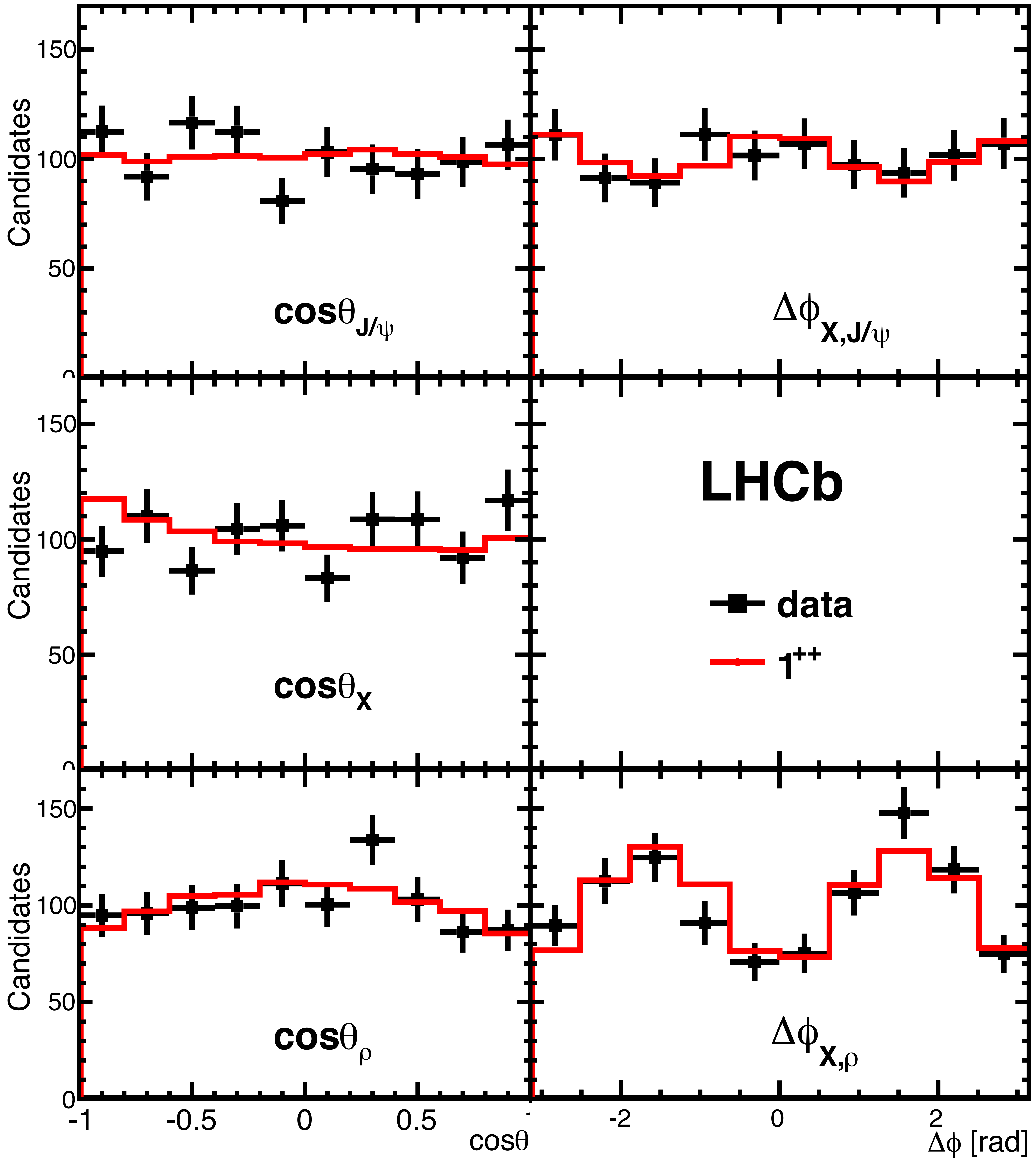
$$|\mathcal{M}(\Omega|J_X)|^2 = \sum_{\Delta\lambda_\mu=-1,+1} \Big| \sum_{\lambda_{J/\psi},\lambda_\rho=-1,0,+1} A_{\lambda_{J/\psi},\lambda_\rho} \; D^{J_X}_{0,\,\lambda_{J/\psi}-\lambda_\rho}(0,\theta_X,0)^* \; D^{1}_{\lambda_\rho,0}(\Delta\phi_{X,\rho},\theta_\rho,0)^* \; D^{1}_{\lambda_{J/\psi},\,\Delta\lambda_\mu}(\Delta\phi_{X,J/\psi},\theta_{J/\psi},0)^* \Big|^2,$$

X(3872) quantum numbers [PRD 92 (2015) 011102]

- $J^{PC} = 1^{++}$ confirmed!
- 3x larger sample than previous result
- D-wave negligible < 4% @ 95% CL
- ρ(770) dominates → decay violates isospin so unlikely to be conventional ccbar







Future X(3872) measurements

- Charged partners of X(3872) predicted by some tetraquark models [Maiani et al]
  - But so far not observed in B decays
  - May be **broad** due to presence of thresholds, so experimental techniques should be aware
- Make more precise width and mass measurement $m_X - m_{\psi(2S)}$

[BaBar PRD 71, 031501 (2005)]

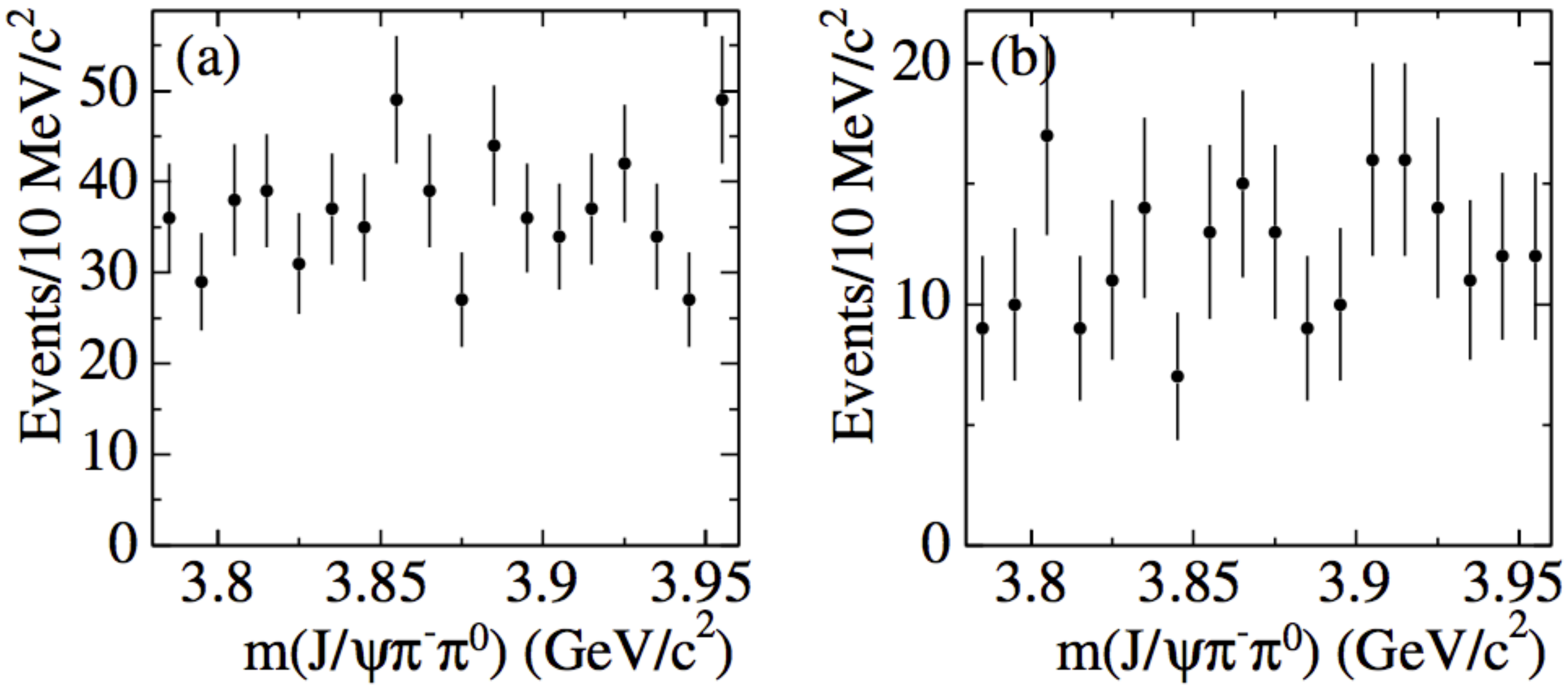
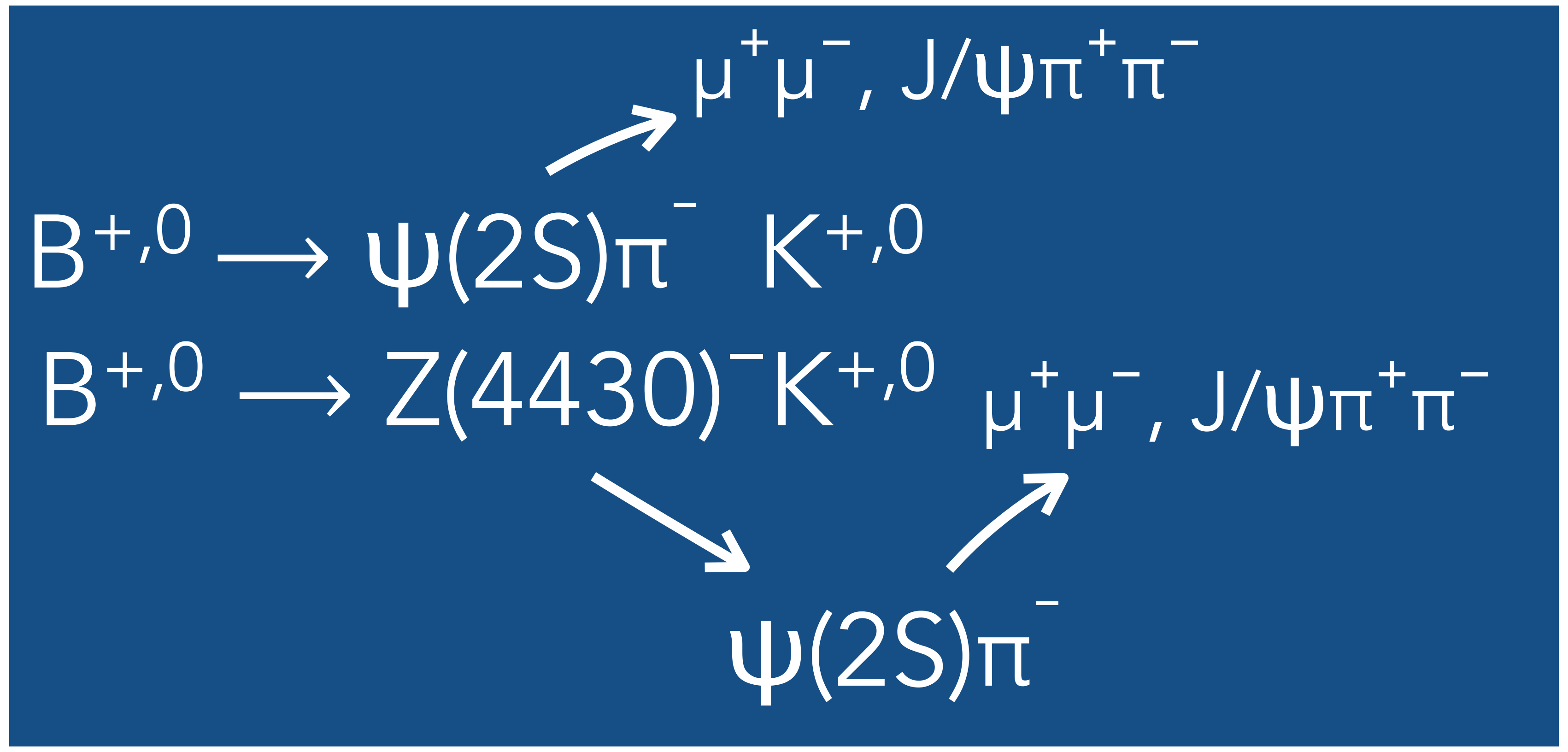


FIG. 3. The $J/\psi\pi^-\pi^0$ invariant mass in 10 MeV/c^2 bins for (a) $B^0 \to J/\psi\pi^-\pi^0 K^+$ and (b) for $B^- \to J/\psi\pi^-\pi^0 K^0_S$. No indication for the decay $X^- \to J/\psi\pi^-\pi^0$ can be found.

$Z(4430)^{\pm}$ charged charmonium exotic

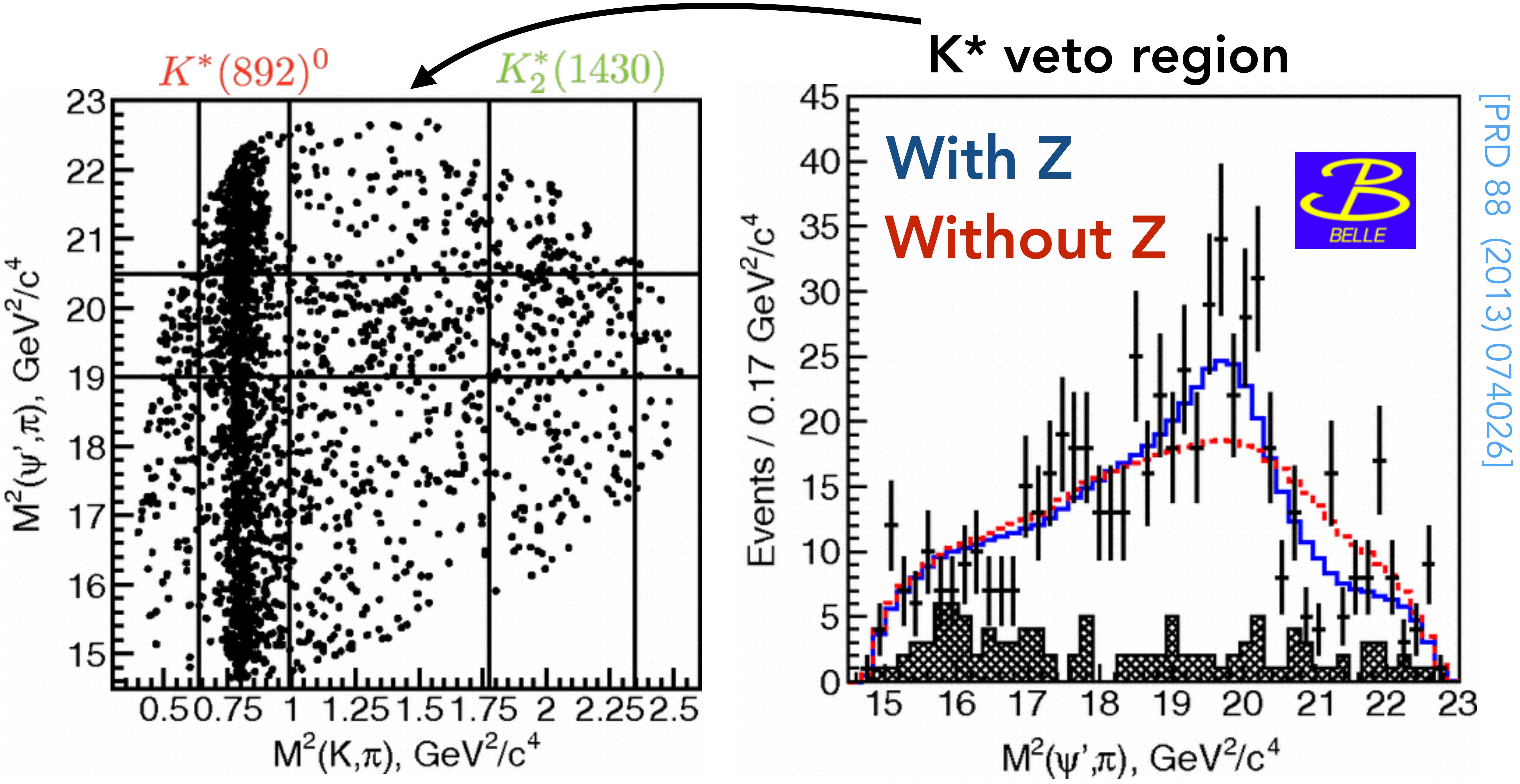
- Belle [PRL 100 (2008) 142001] 1D fit to $m(\psi'\pi^-)$ **6.5σ**
- BaBar [PRD 79 (2009) 112001] Not observed but does not contradict Belle!
- Belle [PRD 80 (2009) 031104] 2D amplitude fit to $m(\psi'\pi^-)$ vs $m(K^+\pi^-)$ **6.4σ**
- Belle [PRD 88 (2013) 074026] 4D amplitude fit **6.4σ**

$c\bar{c}u\bar{d}$



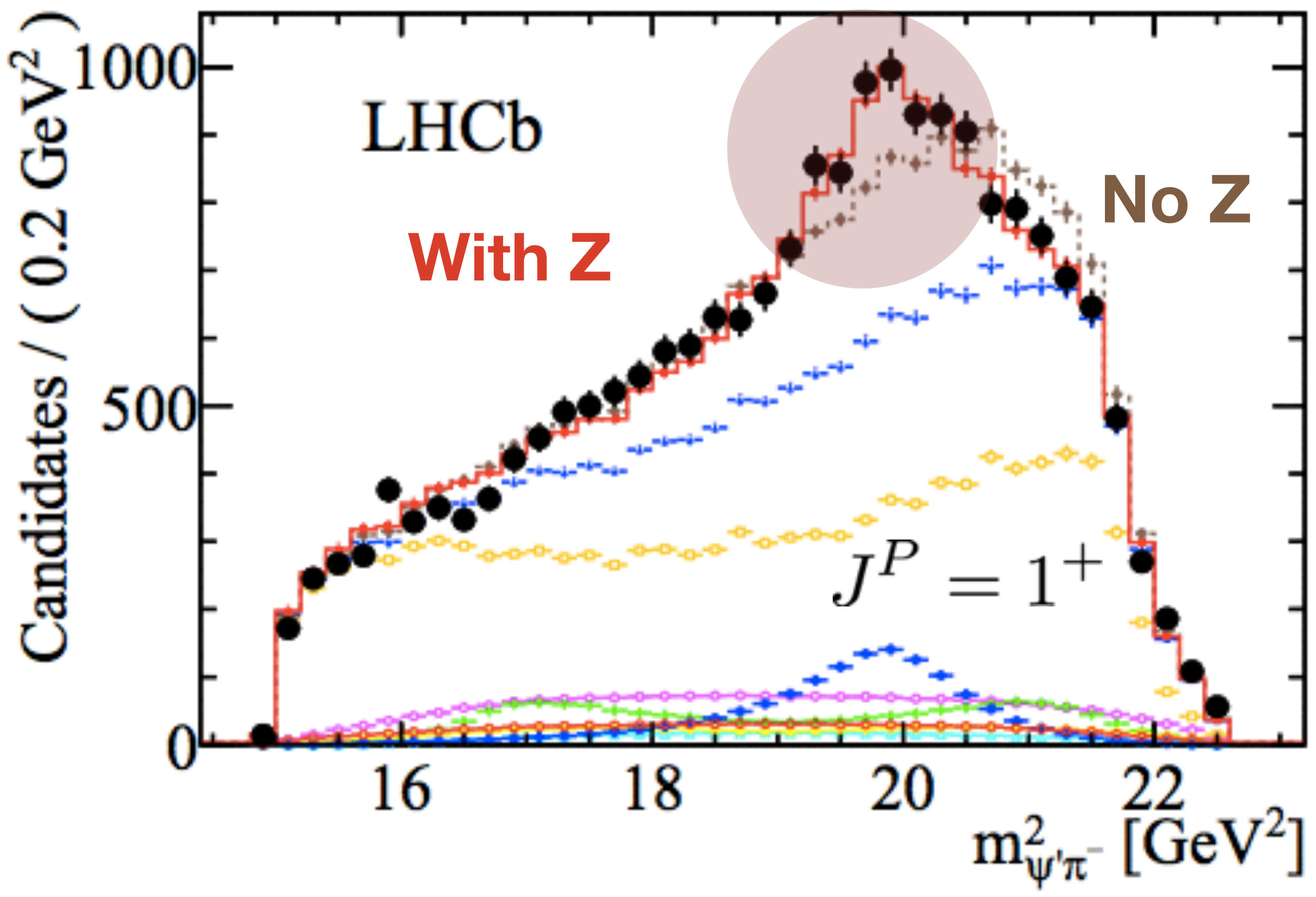
$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV/c^2}$$

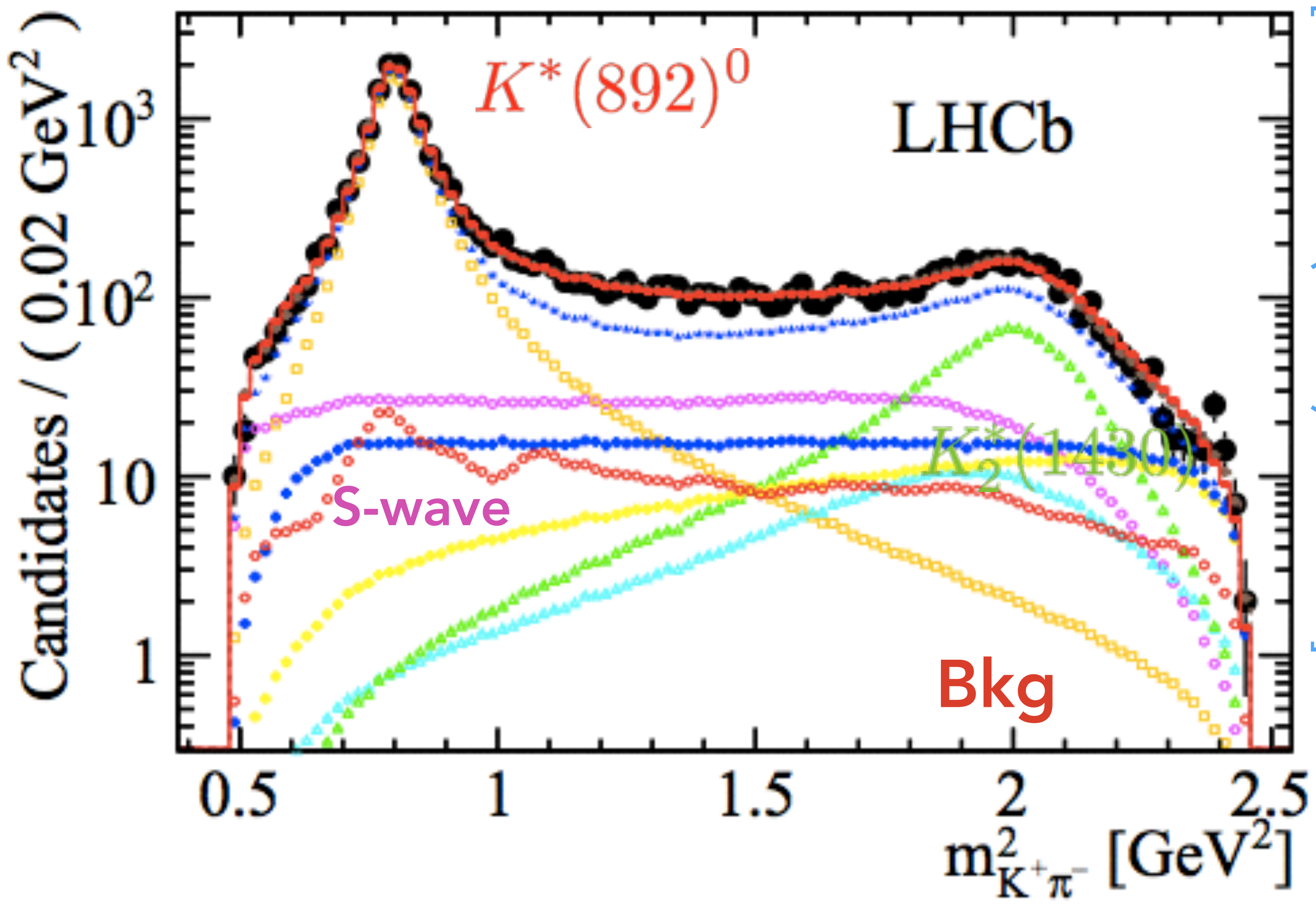
$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}/c^2$$



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

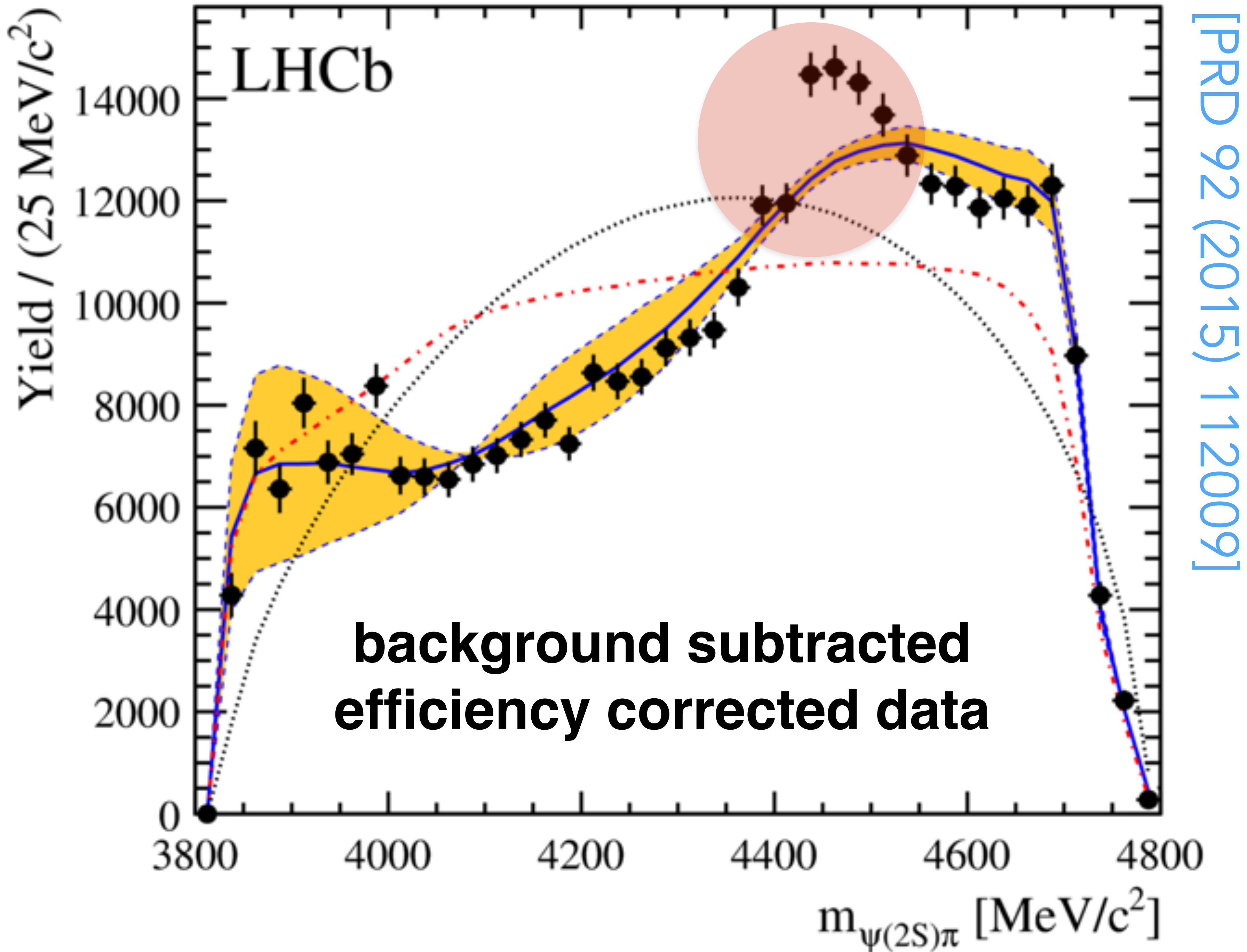
- LHCb has >25k $B0 \longrightarrow \psi' K^+ \pi^-$ candidates (x10 Belle/BaBar) with 3% background.





[PRL 112 (2014) 222002]

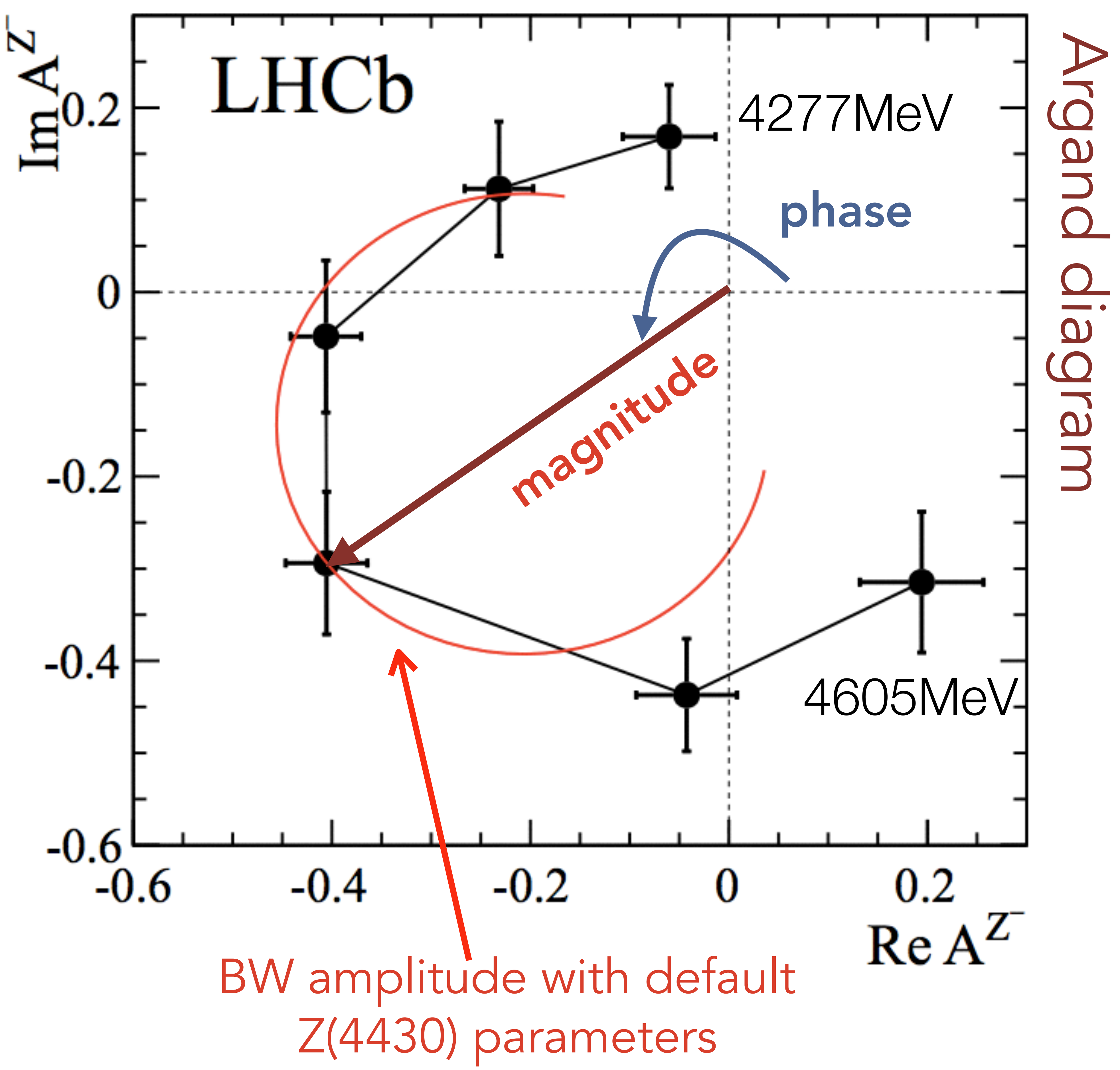
- Two analysis methods:
  - 4D amplitude analysis used to measure resonance parameters and J^P.
  - Study angular moments in model-independent way (similar to what was done for pentaquark).



[PRD 92 (2015) 112009]

Resonant behaviour - a bound state?

	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 [%]	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$
J^P	1^+	1^+



- Excellent agreement between LHCb and Belle.
- Belle evidence for Z(4430)$^{\pm}$ → J/ψπ$^{\pm}$ and observation of a new resonant state Z(4200)$^{\pm}$ → J/ψπ$^{\pm}$

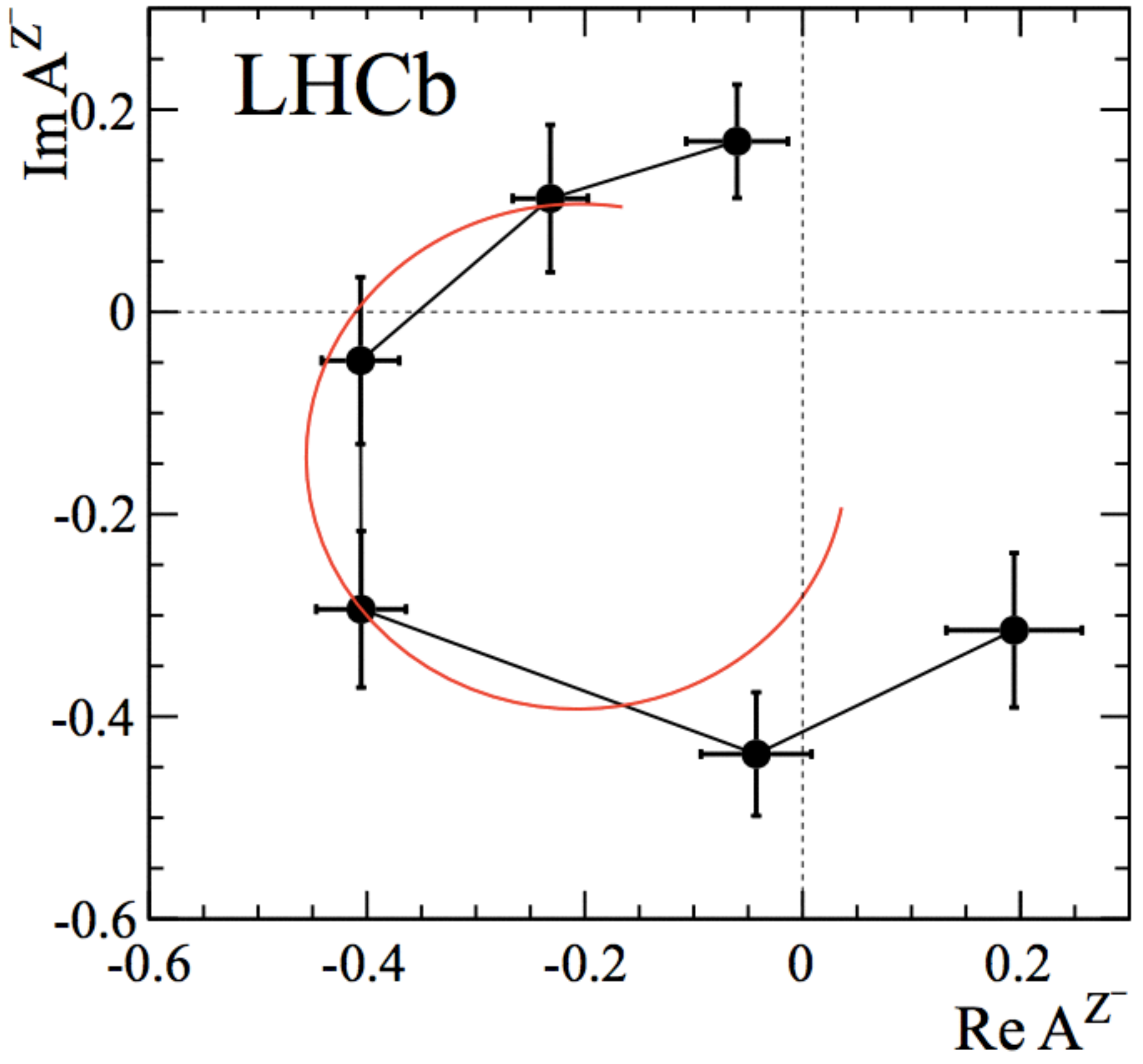
[PRD 90 (2014) 112009]

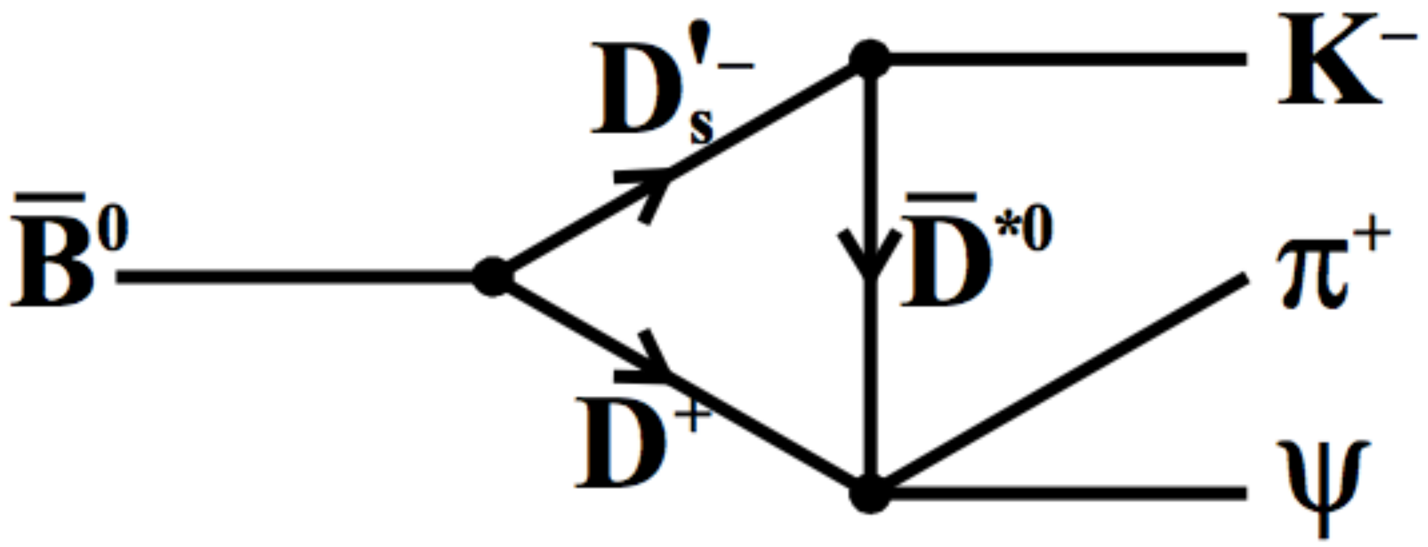
$$\frac{\mathcal{B}(Z(4430)^+ \to \psi(2S)\pi^+)}{\mathcal{B}(Z(4430)^+ \to J/\psi\pi^+)} \approx 10$$

Z(4430) interpretations (see talks after coffee)

- Result confirms existence of the Z(4430), measures **J^P=1⁺** and, for the first time, demonstrates **resonant behaviour**.
- Mass close to DD* thresholds - perhaps this is the organising principle of these exotic states?
- Large width - unlikely to be molecule?
- **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]
- Rescattering effect proposed, but phase motion in wrong direction?
  [Pakhov, Uglov PLB748 (2015) 183]
- Diquark-antidiquark bound state is an explanation.
  [Maiani et al, PRD 89 114010]
- Potential neutral **isospin partner?**

Z(4430)⁰ in $B^+ \longrightarrow \psi'\pi^0K^+$

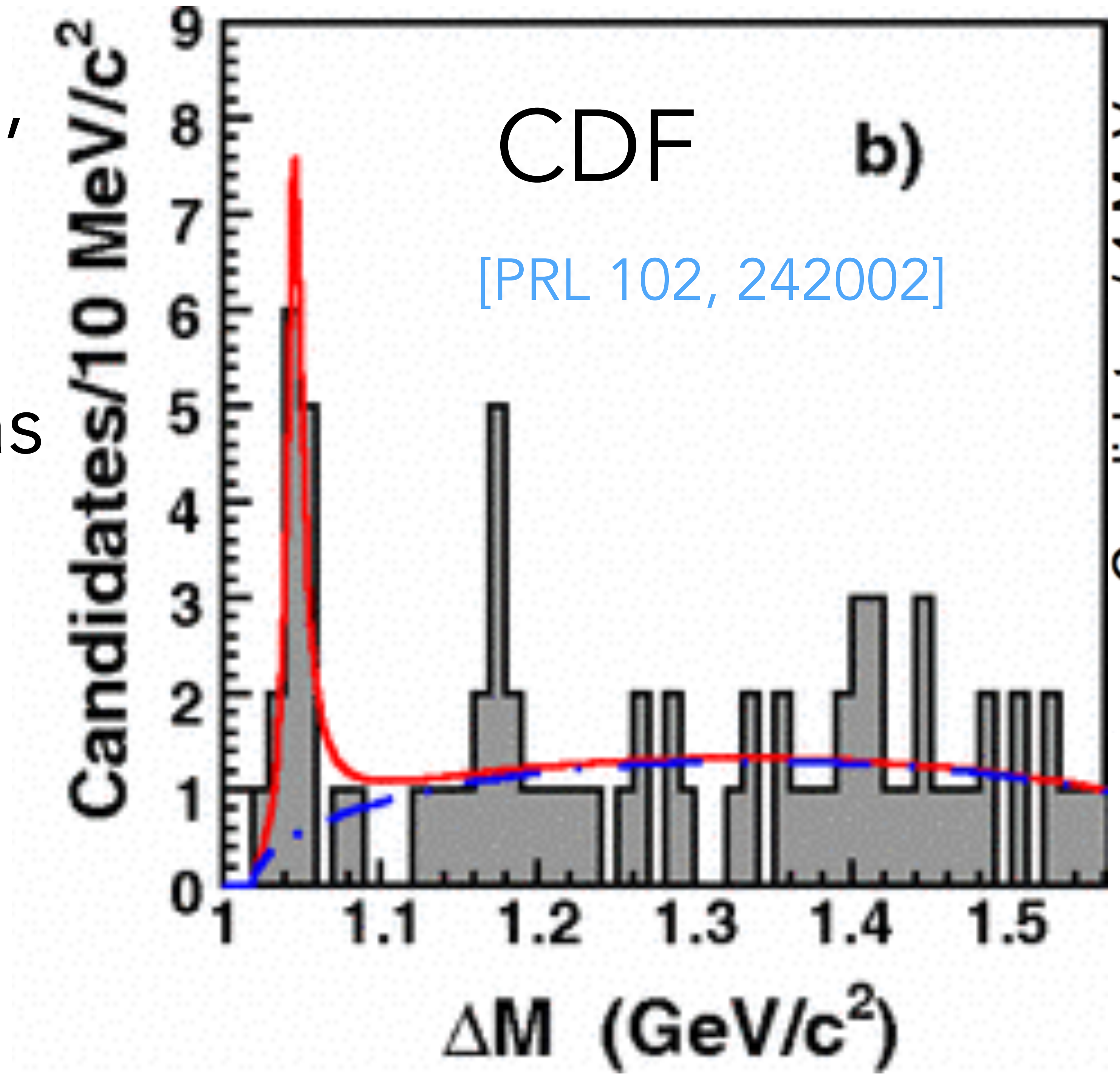


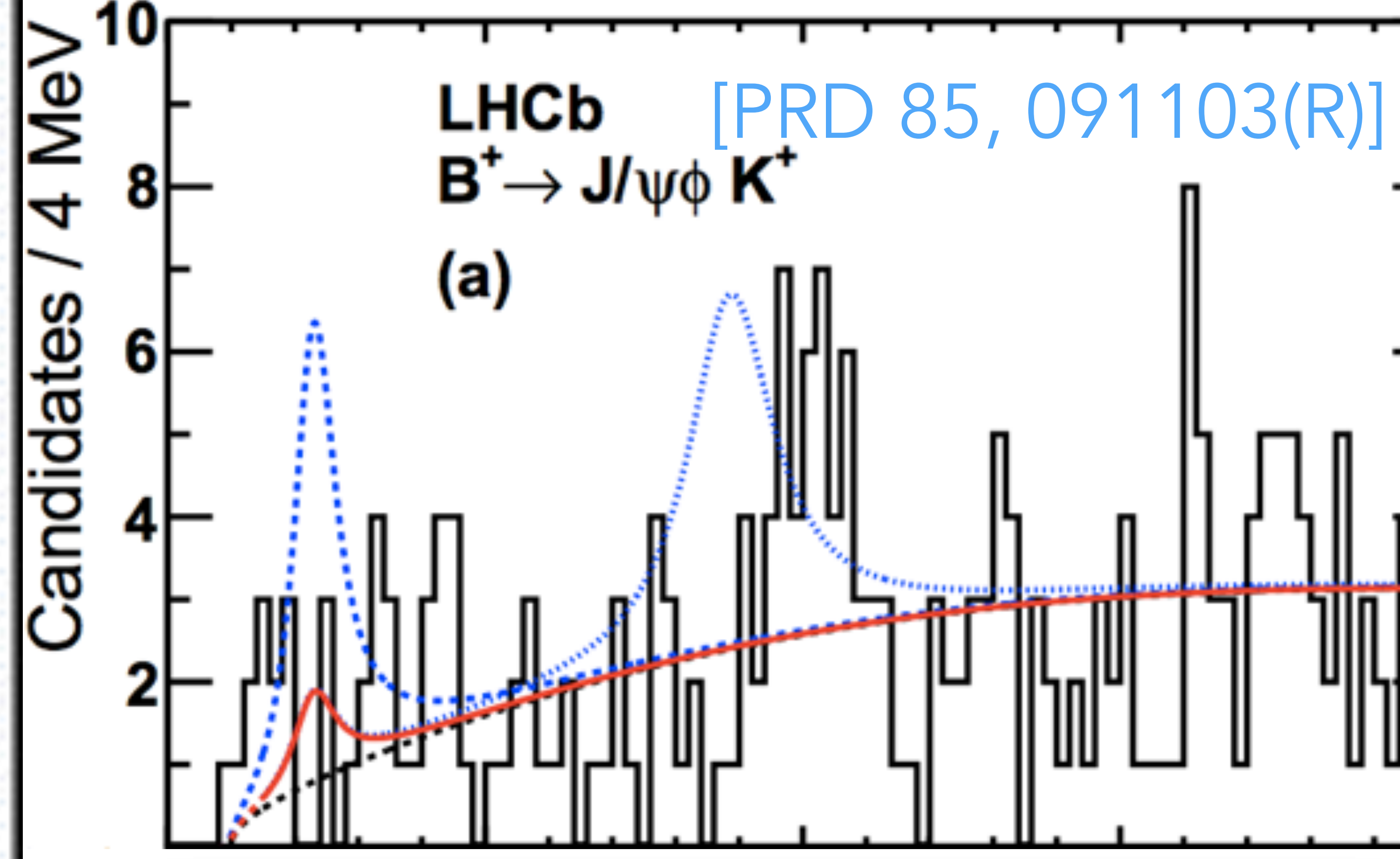


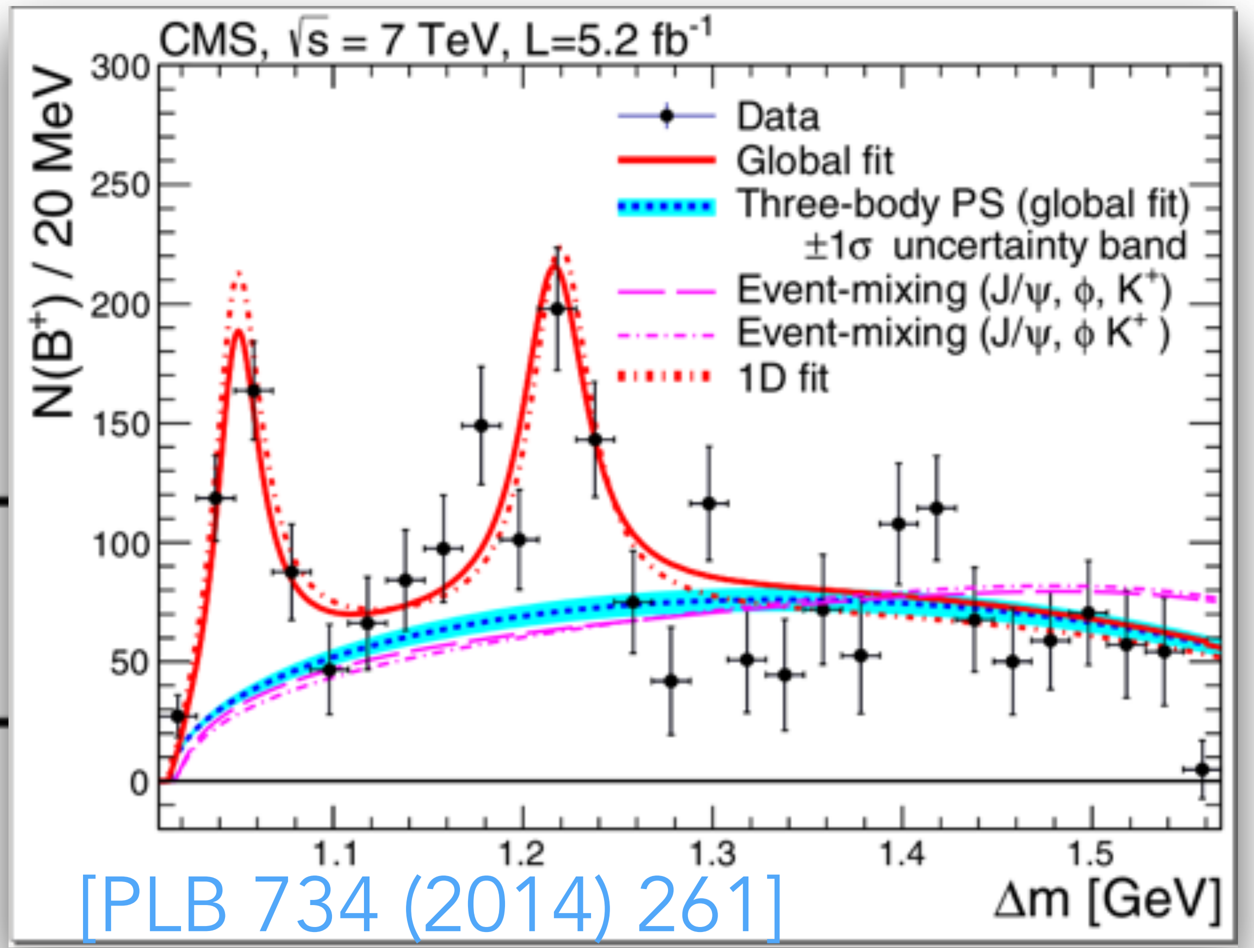
X(4140) and X(4274) $B^{\pm/0} \to X K^{\pm/0}, X \to J/\psi\phi$

- Seen by CDF, D0 and CMS, not by LHCb, BaBar, BES-III or Belle (in γγ fusion).
- Well above open-charm threshold but has narrow width → not conventional $c\bar{c}$.
- **Full amplitude analysis of decay is essential!**

$$c\bar{c}s\bar{s}$$







Experiment	$Y(4140)$	$Y(4274)$
CDF [69]	$M = 4143.0 \pm 2.9 \pm 1.2$, $\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7$	–
CDF [100]	$M = 4143.4^{+2.9}_{-3.0} \pm 0.6$, $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5$	$M = 4274.4^{+8.4}_{-6.7} \pm 1.9$, $\Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6$
DØ [102]	$M = 4159.0 \pm 4.3 \pm 6.6$, $\Gamma = 19.9 \pm 12.6^{+1.0}_{-8.0}$	–
CMS [74]	$M = 4148.0 \pm 2.4 \pm 6.3$, $\Gamma = 28^{+15}_{-11} \pm 19$	$M = 4313.8 \pm 5.3 \pm 7.3$, $\Gamma = 38^{+30}_{-15} \pm 16$

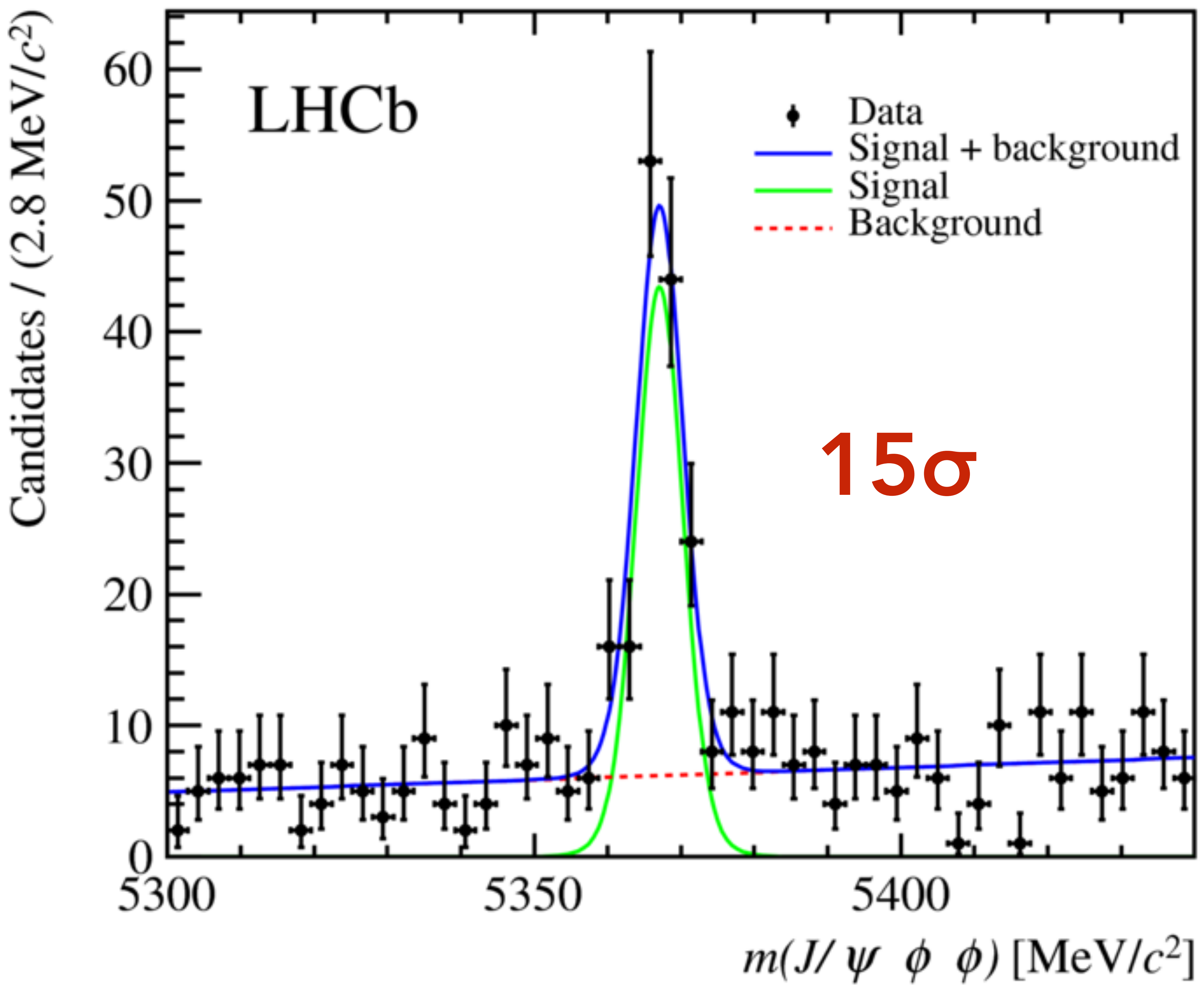
[D0 PRD 89, 012004]
[Belle PRL 104, 112004]
[BES-III PRD 91 (2015) 032002]

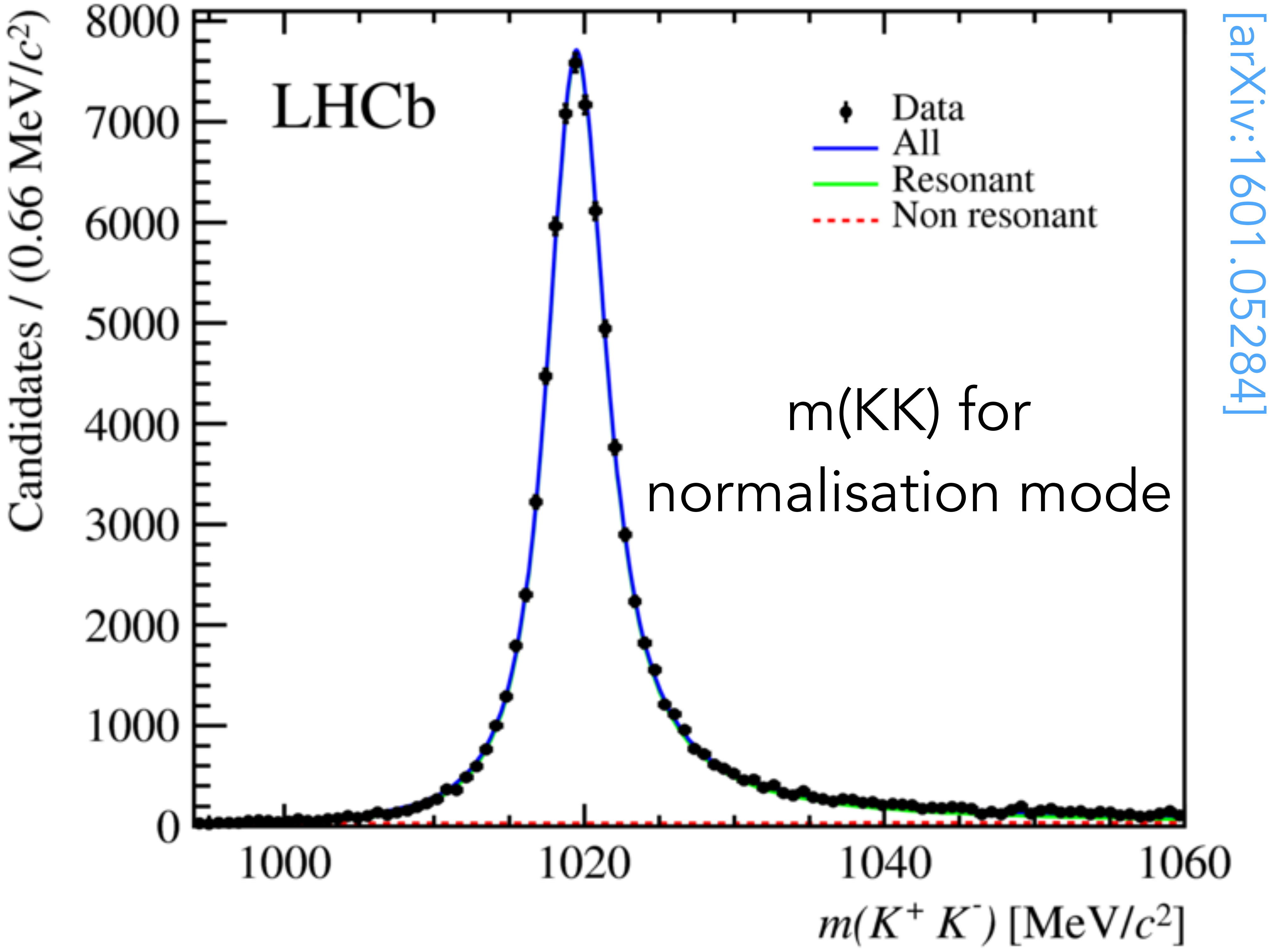
$B_s^0 \rightarrow J/\psi\phi\phi$

- [Swanson PRD 91 (2015) 034009] predicts threshold effects in $B_s^0 \rightarrow J/\psi\phi\phi$ and other modes.
- LHCb recently observed this decay (resonant decay dominates).

$$\frac{B(B_s^0 \to J/\psi\phi\phi)}{B(B_s^0 \to J/\psi\phi)} = 0.0115 \pm 0.0012^{+0.0005}_{-0.0009}$$

Contamination from non-res decays



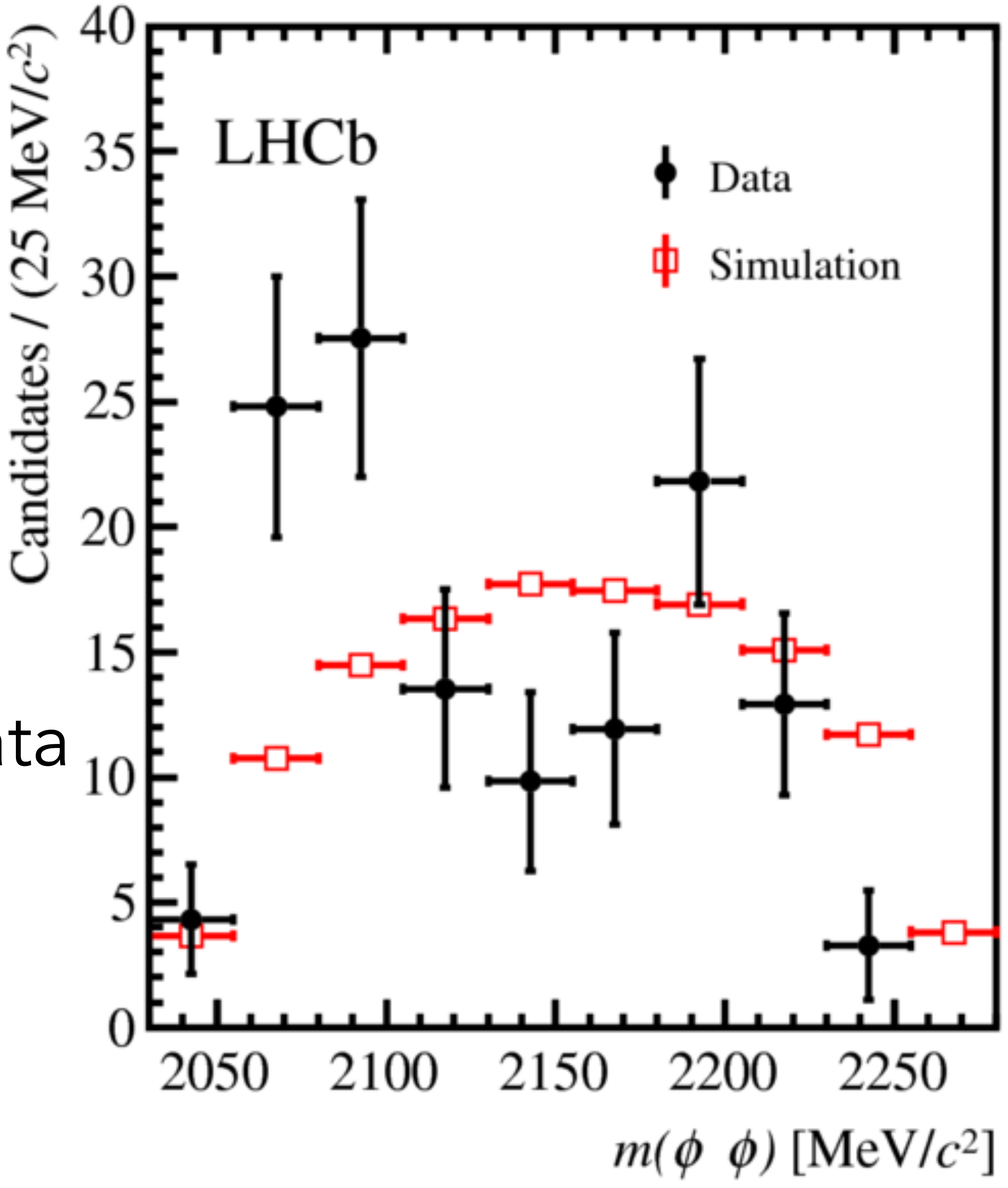


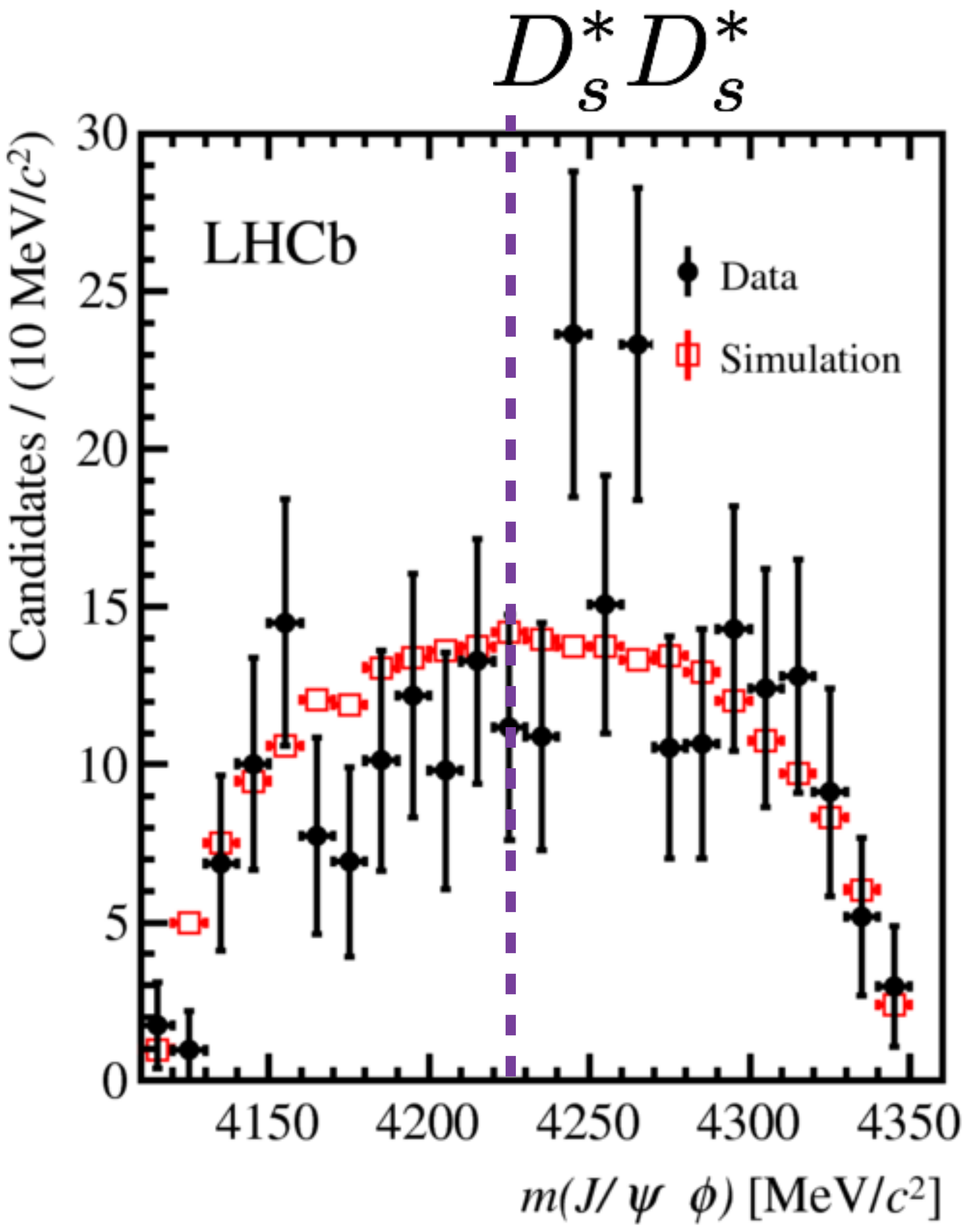
[arXiv:1601.05284]

$B_s^0 \to J/\psi\phi\phi$

- [Swanson PRD 91 (2015) 034009] predicts threshold effects in $B_s^0 \to J/\psi\phi\phi$ and other modes.
- LHCb recently observed this decay (resonant decay dominates).

- Background subtracted no efficiency correction.
- Simplified phase-space simulation inadequate to describe structure
- Looking forward to more data in Run-2 of LHCb…

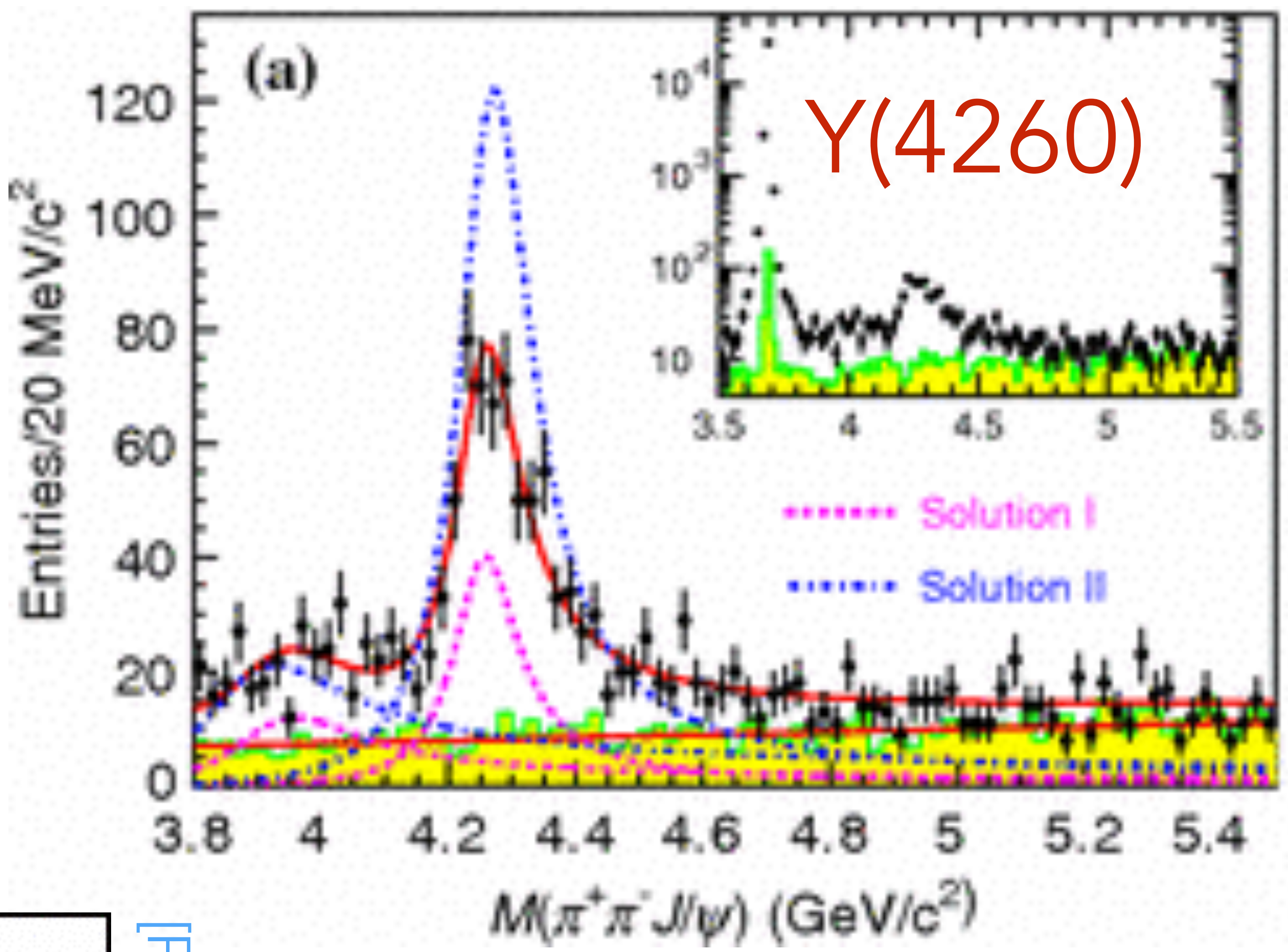




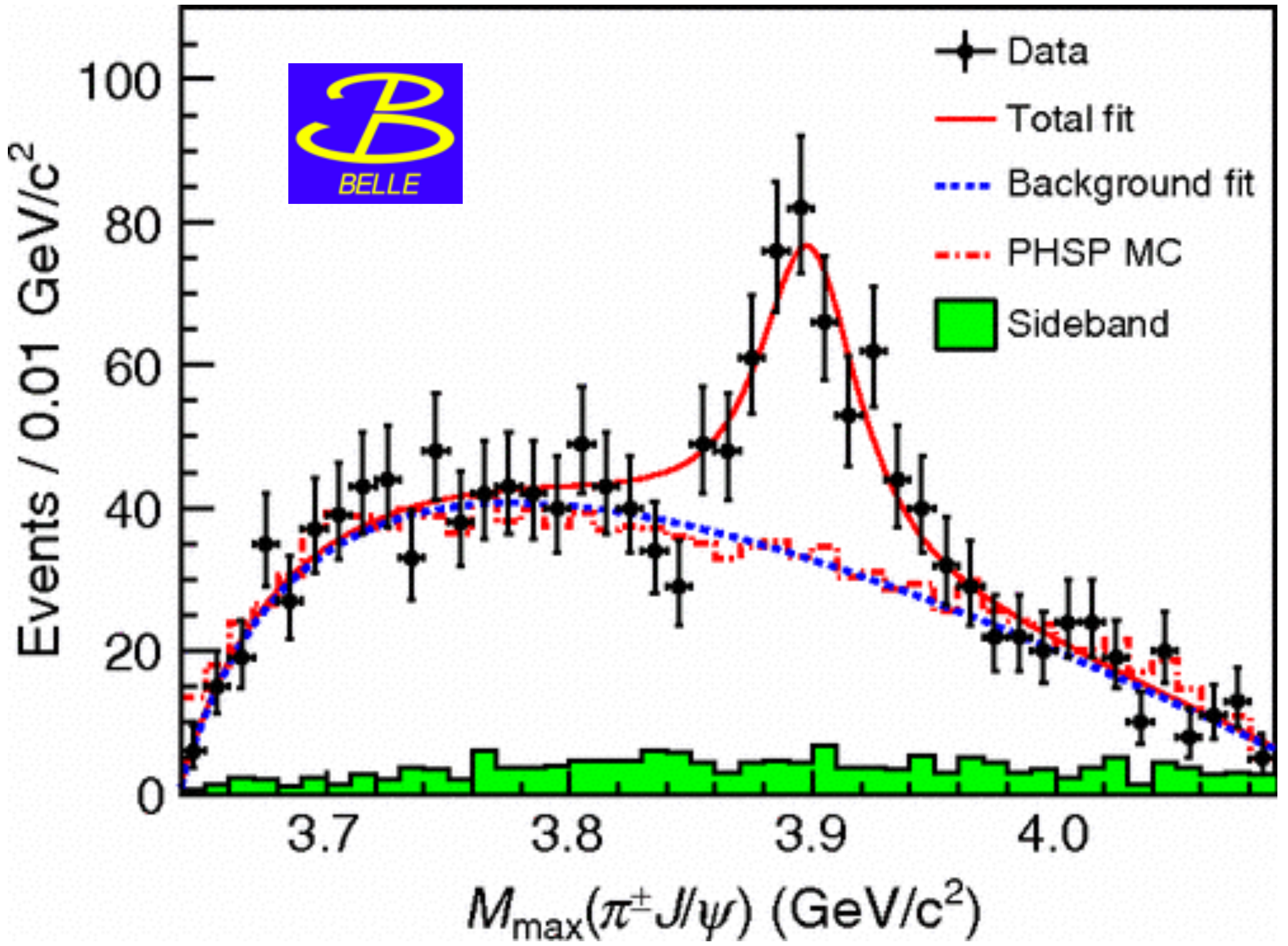
[arXiv:1601.05284]

$Z_c(3900)^{\pm}$ in $e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

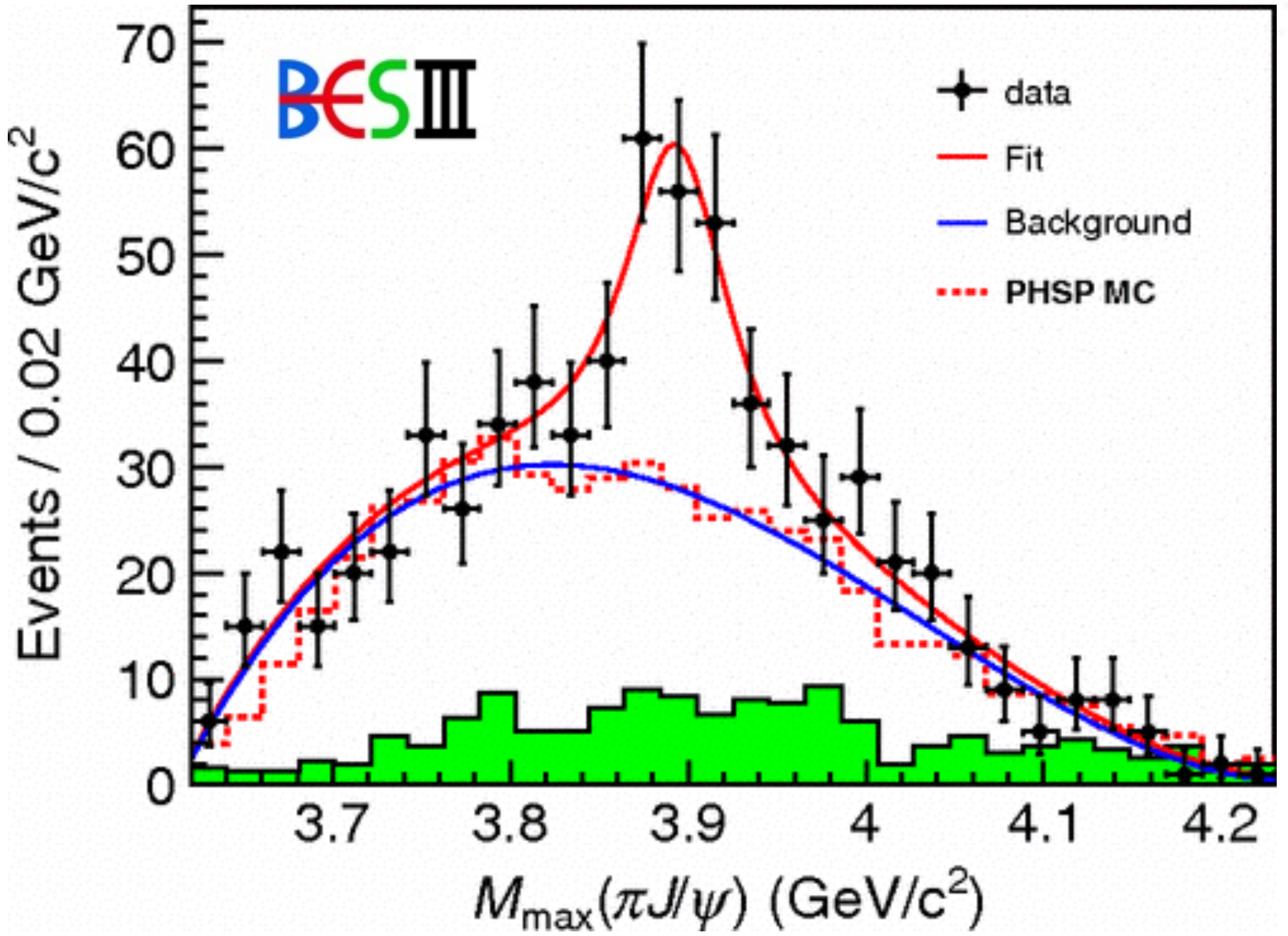
- Observation of another possible **exotic charged state.**
- Is $Z(4430)^{\pm}$ a radial excitation of $Z_c(3900)^{\pm}$?
  [Maiani et al, NJP 10 (2008) 073004] [Wang, arXiv:1405.3581]
- CLEO-c and BES-III have evidence/observation for neutral member of **isospin triplet** decaying to $\pi^0 J/\psi$.
  [PLB 727 (2013) 366] [PRL 115 (2015) 112003]
- Also appears in D^+D^* decay modes [see backup]



[PRL 110 () 252002]



[PRL 110 (2013) 252001]



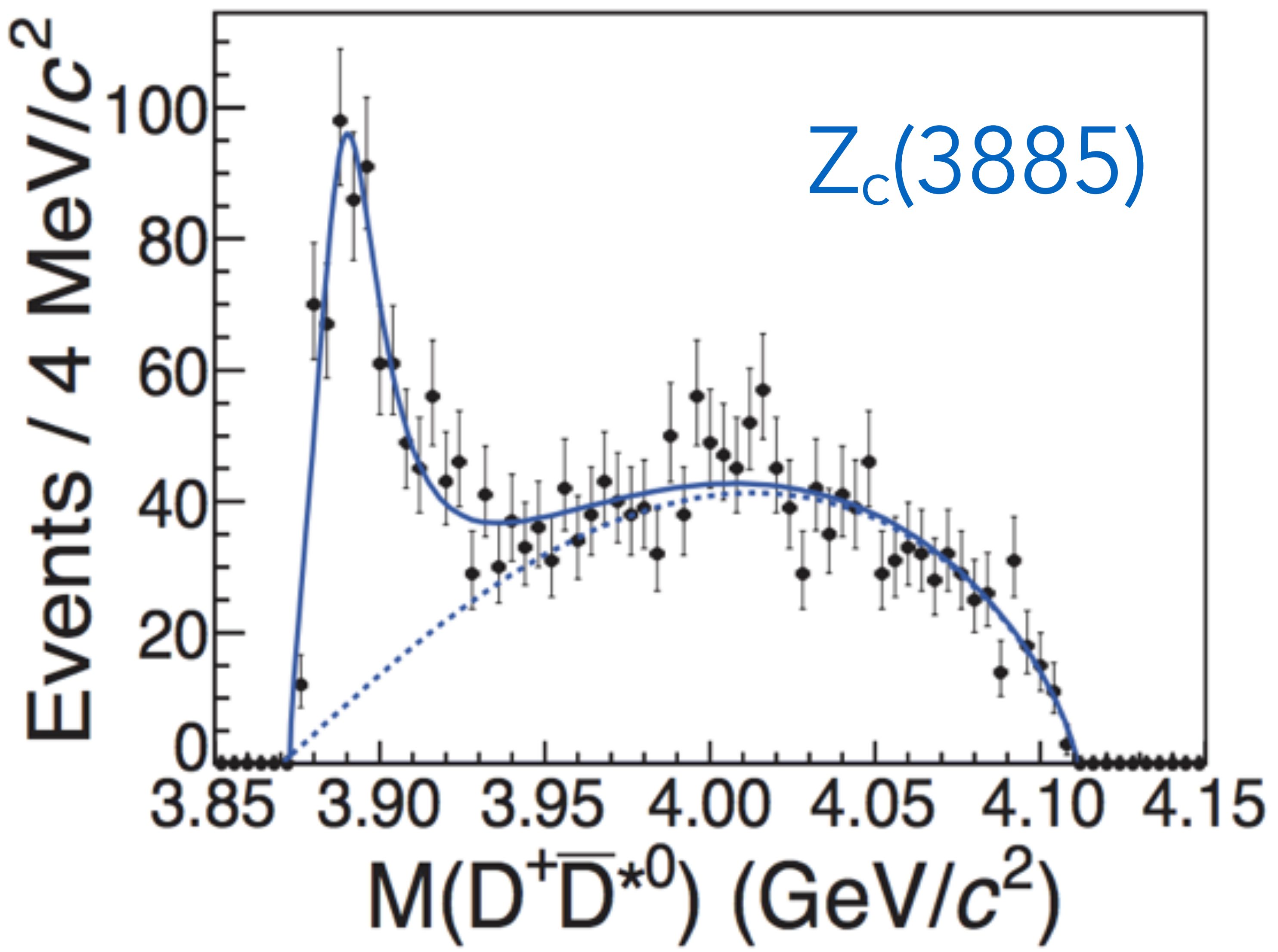
[PRL 110 (2013) 252002]

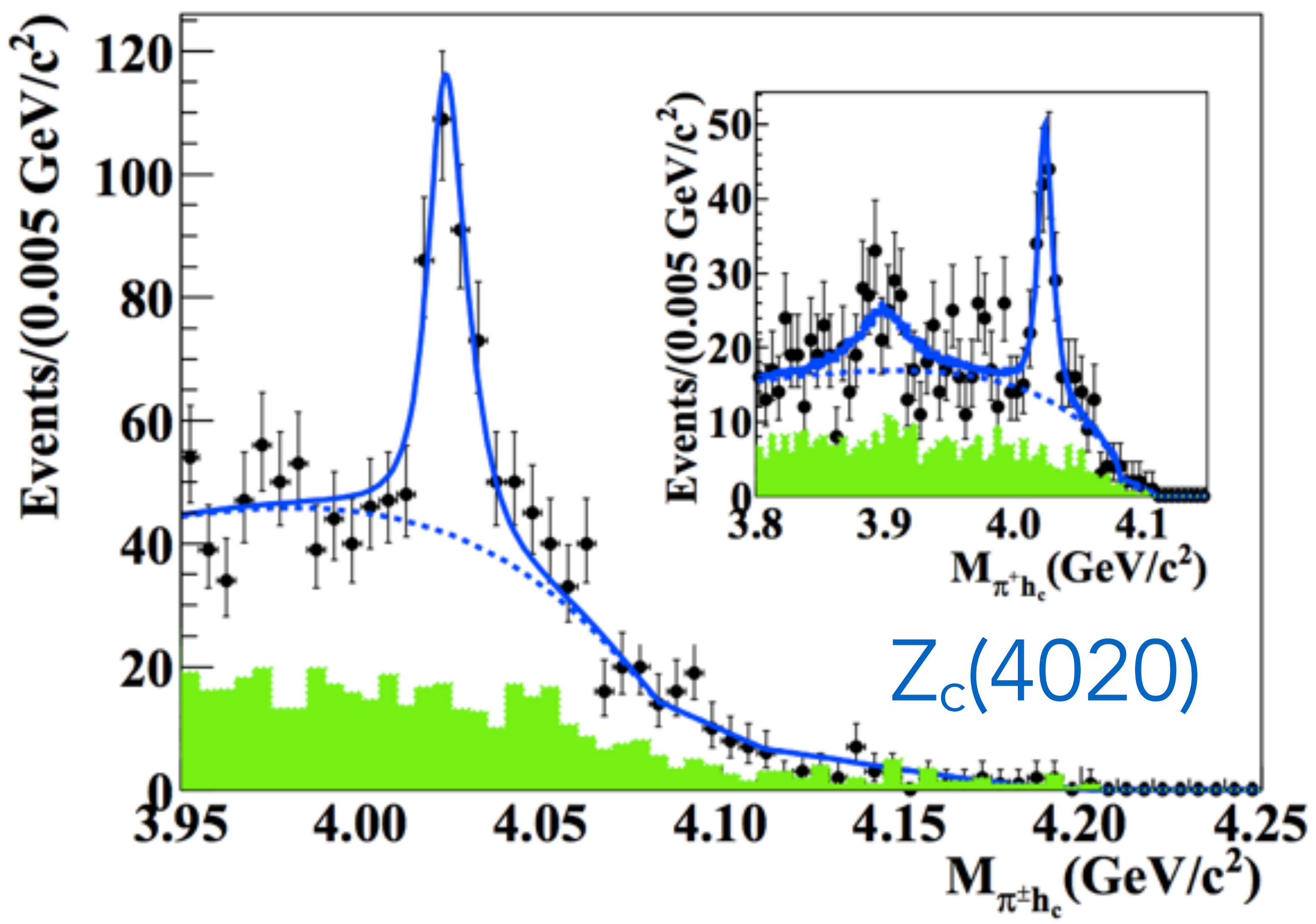
1D fit to $m(\pi^+ J/\Psi)$ ← Looking forward to amplitude analysis!

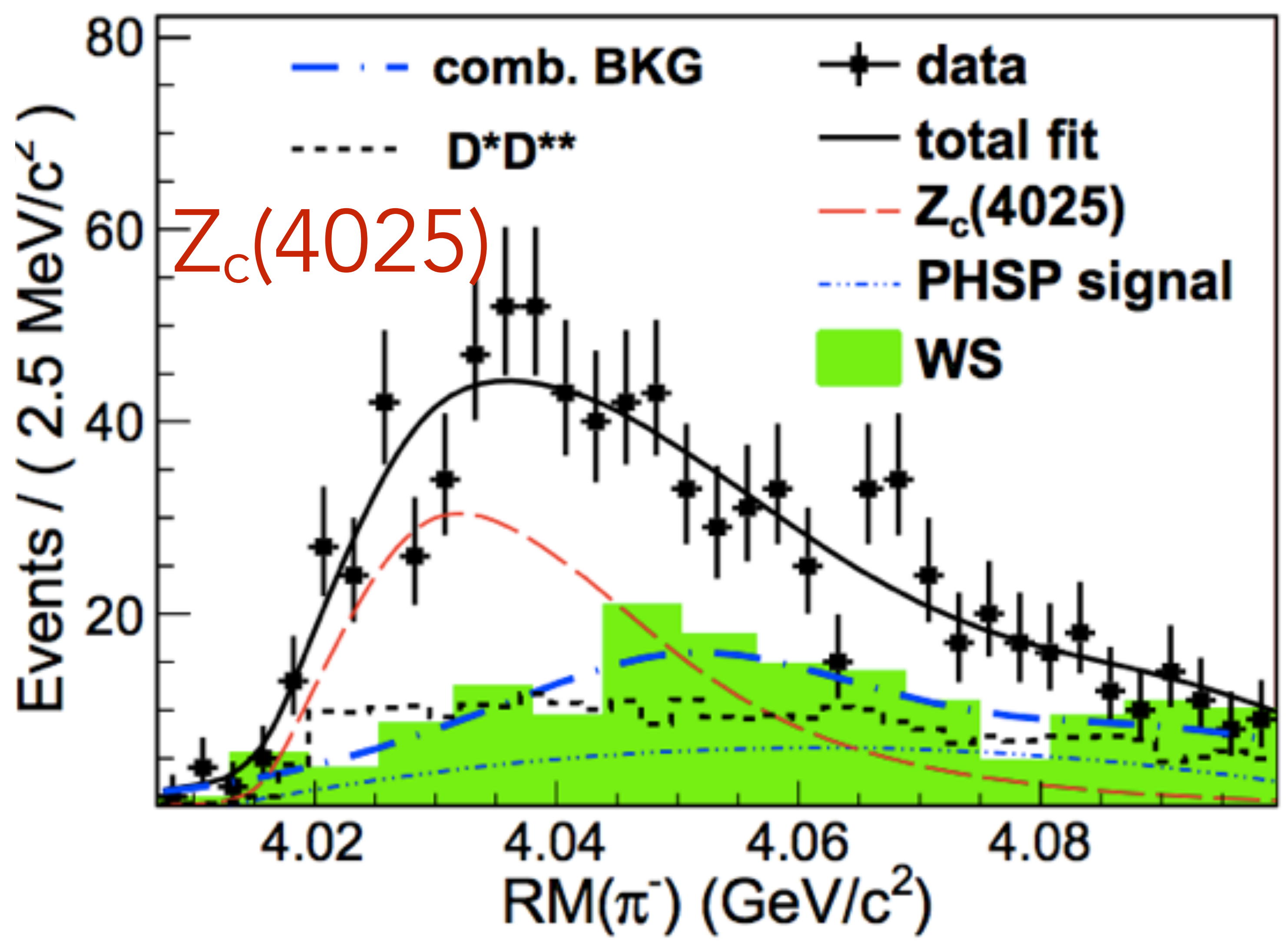
$M = (3894.5 \pm 6.6 \pm 4.5)$ MeV/c^2
$\Gamma = (63 \pm 24 \pm 26)$ MeV/c^2

Other exotic states

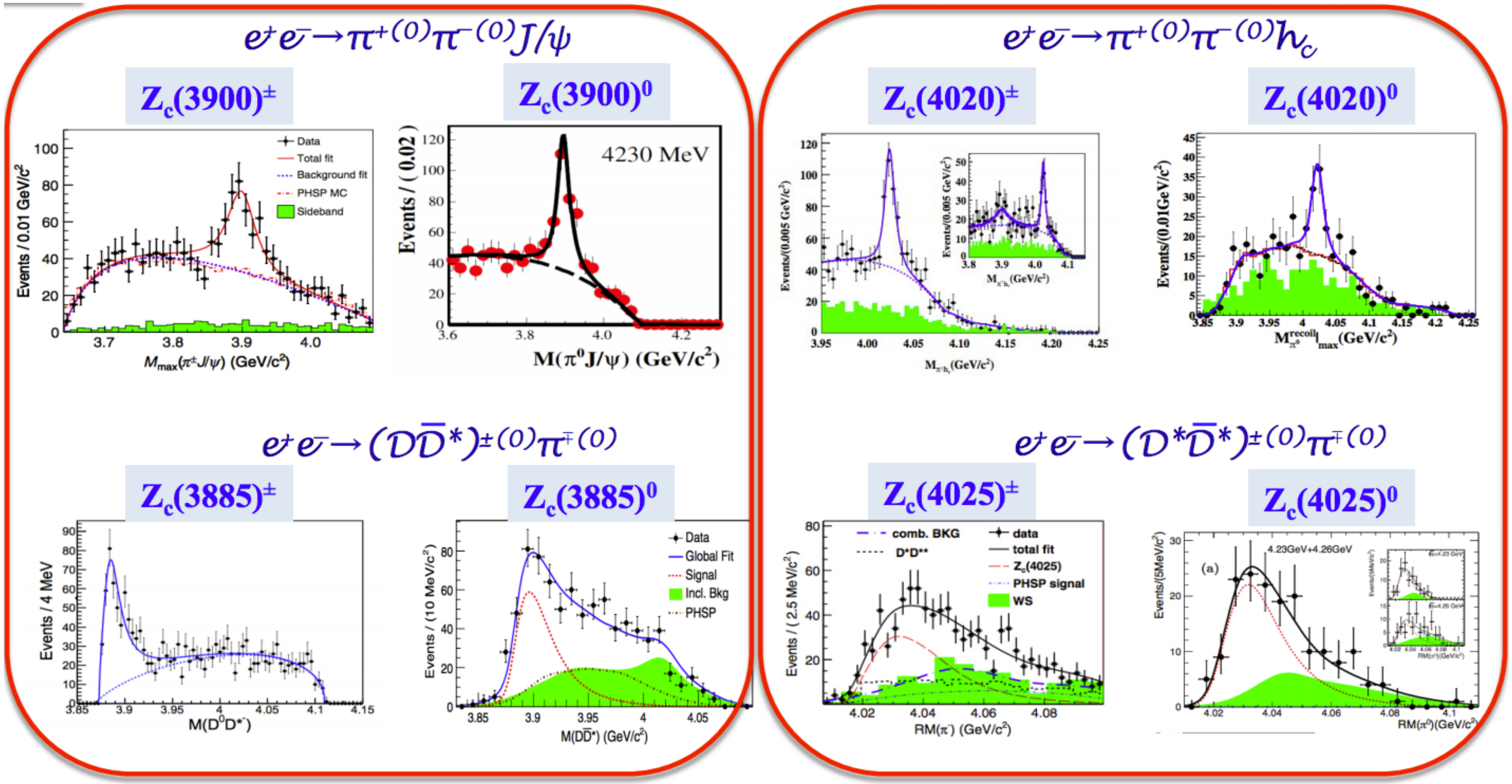
- $Z_c(3900)^+$ seen in $J/\psi\pi^+$. Also have $Z_c(3885)^+$ in $(D\bar{D}^*)^+$, showing a dramatic near threshold peak. These could be the same state. Need partial wave analysis of $J/\psi\pi\pi$ final state to determine this.
- $Z_c(4020)^+$ seen in $h_c(1P)\pi^+$ by BESIII. Very narrow width. This 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 $Z_c(4020)^+$.







Exotic Z_c states from BES-III

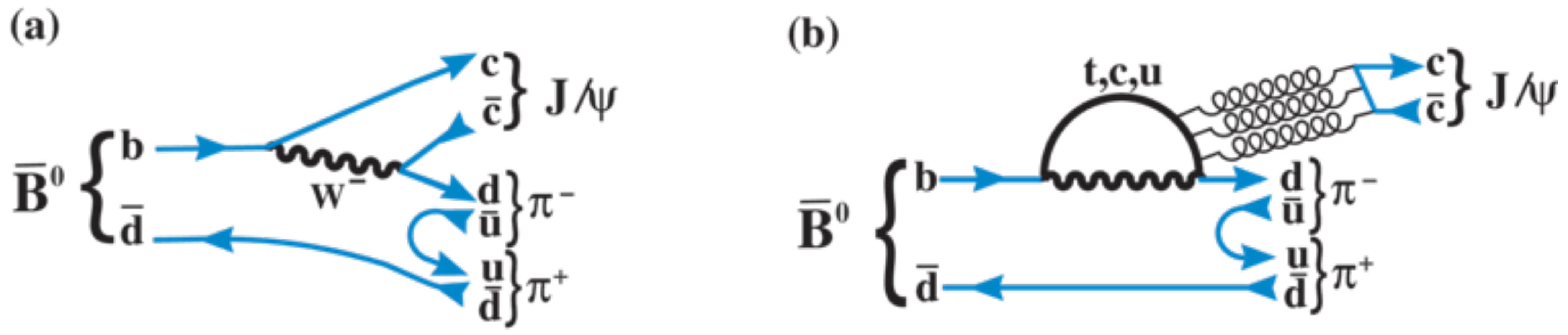


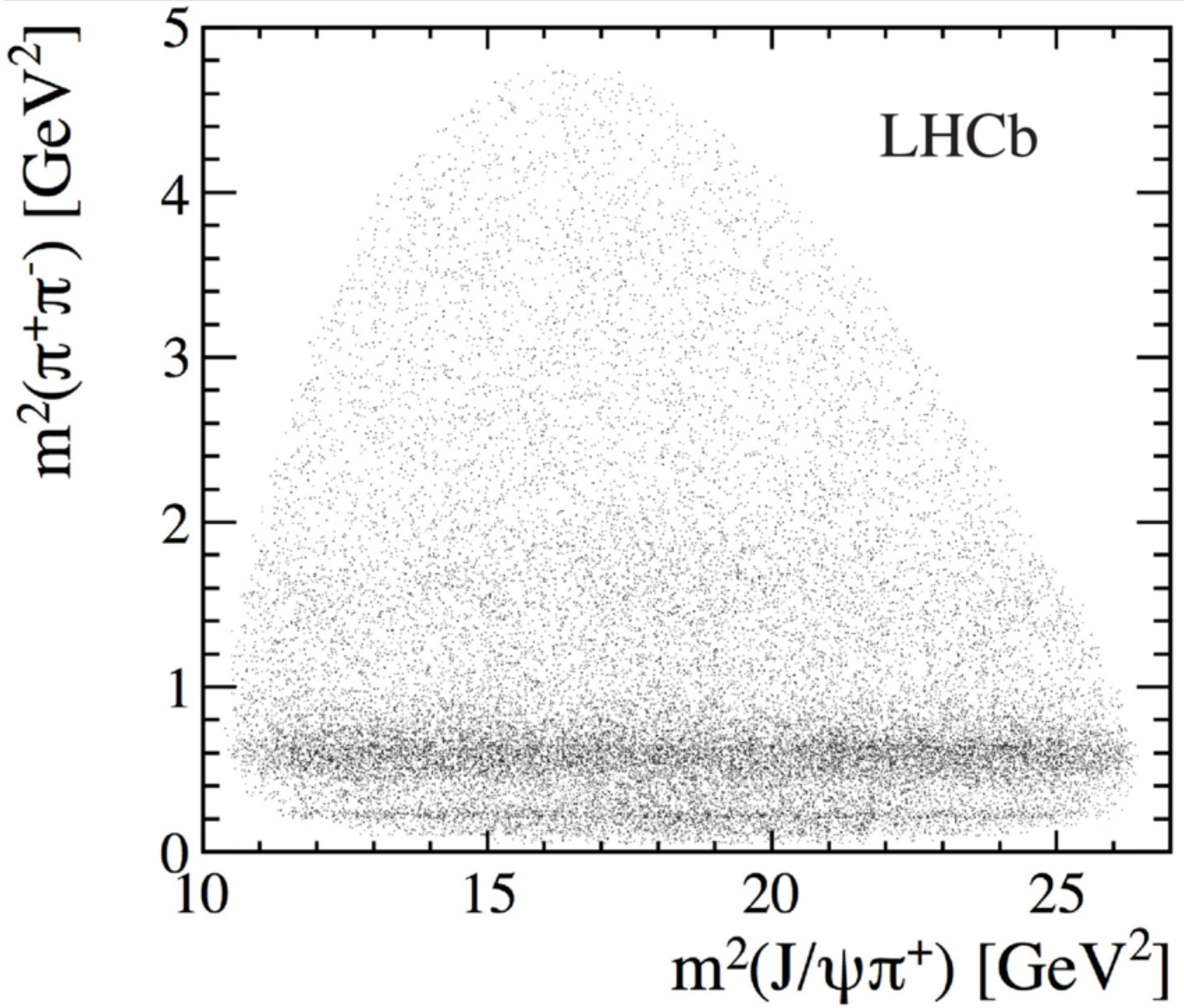
- Nature of these states? Isospin triplets?
- Different decay channels of the same states observed?
- Other decay modes?

http://moriond.in2p3.fr/QCD/2016/WednesdayAfternoon/Garzia.pdf

Understanding $Z_c(3900)^{\pm}$ and $Z_c(4020)^{\pm}$

- Some lattice QCD calculations do not support existence of $Z_c(3900)^{\pm}$ [Prelovsek et al PRD91 (2015) 014504]
- No sign of $Z_c(3900)^{\pm} \rightarrow J/\psi\pi^{\pm}$ in B decays [LHCb, Belle] or photo-production ($\gamma p \rightarrow J/\psi\pi^{\pm}$ n) [COMPASS, PLB 742, 330 (2015)]
- Indicates that $Z_c(3900)^{\pm}$ (and $Z_c(4020)^{\pm}$) may not be dynamical in nature but some kinematic effect (e.g., threshold cusp)?
  [Swanson PRD 91 (2015) 034009] [Ikeda et al arXiv:1602.03465]
  [Szczepaniak PLB 747 (2015) 410]
- Or maybe not? [Cleven et al arXiv:1510.00854]





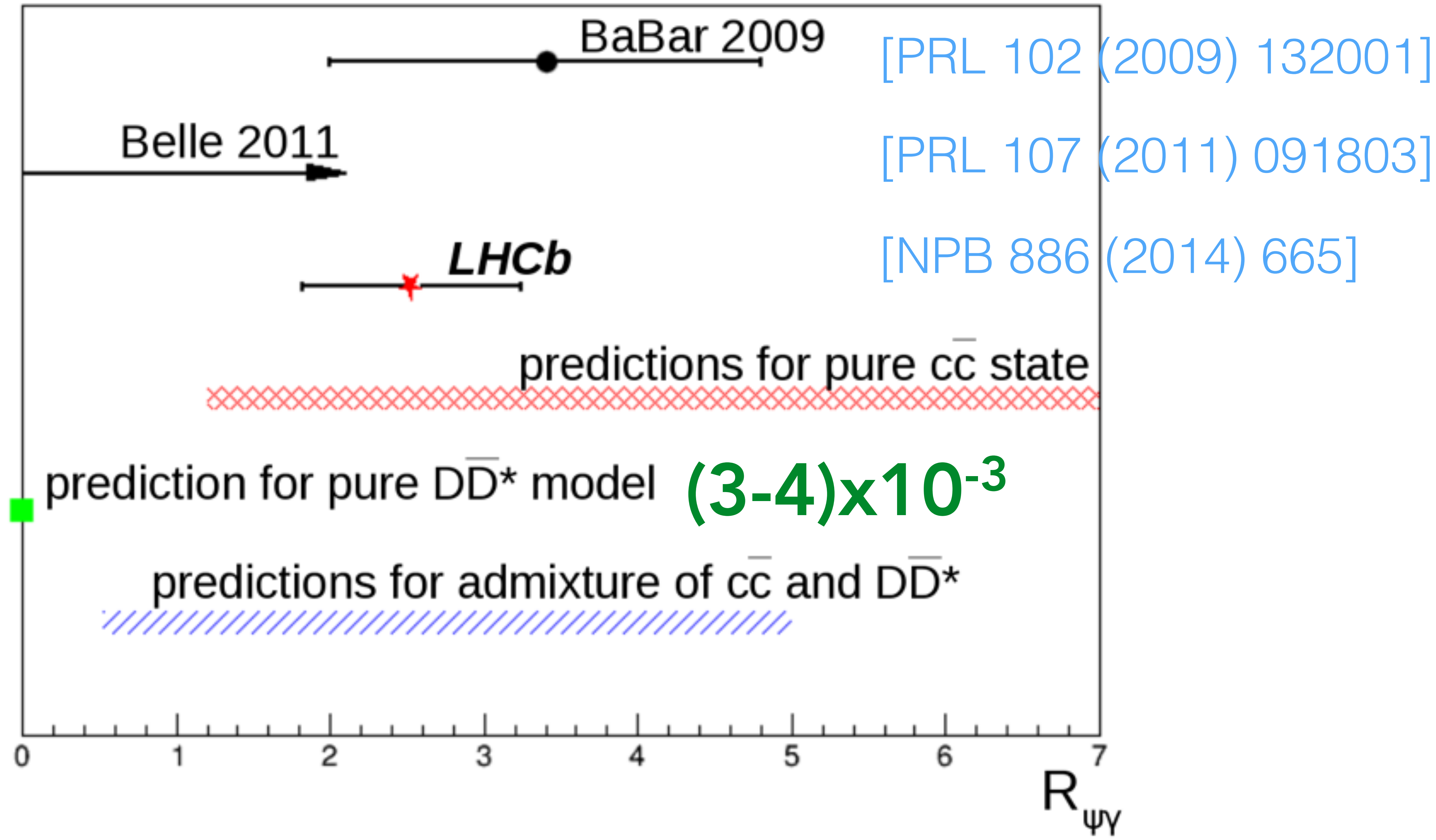
[PRD90 (2014) 012003]

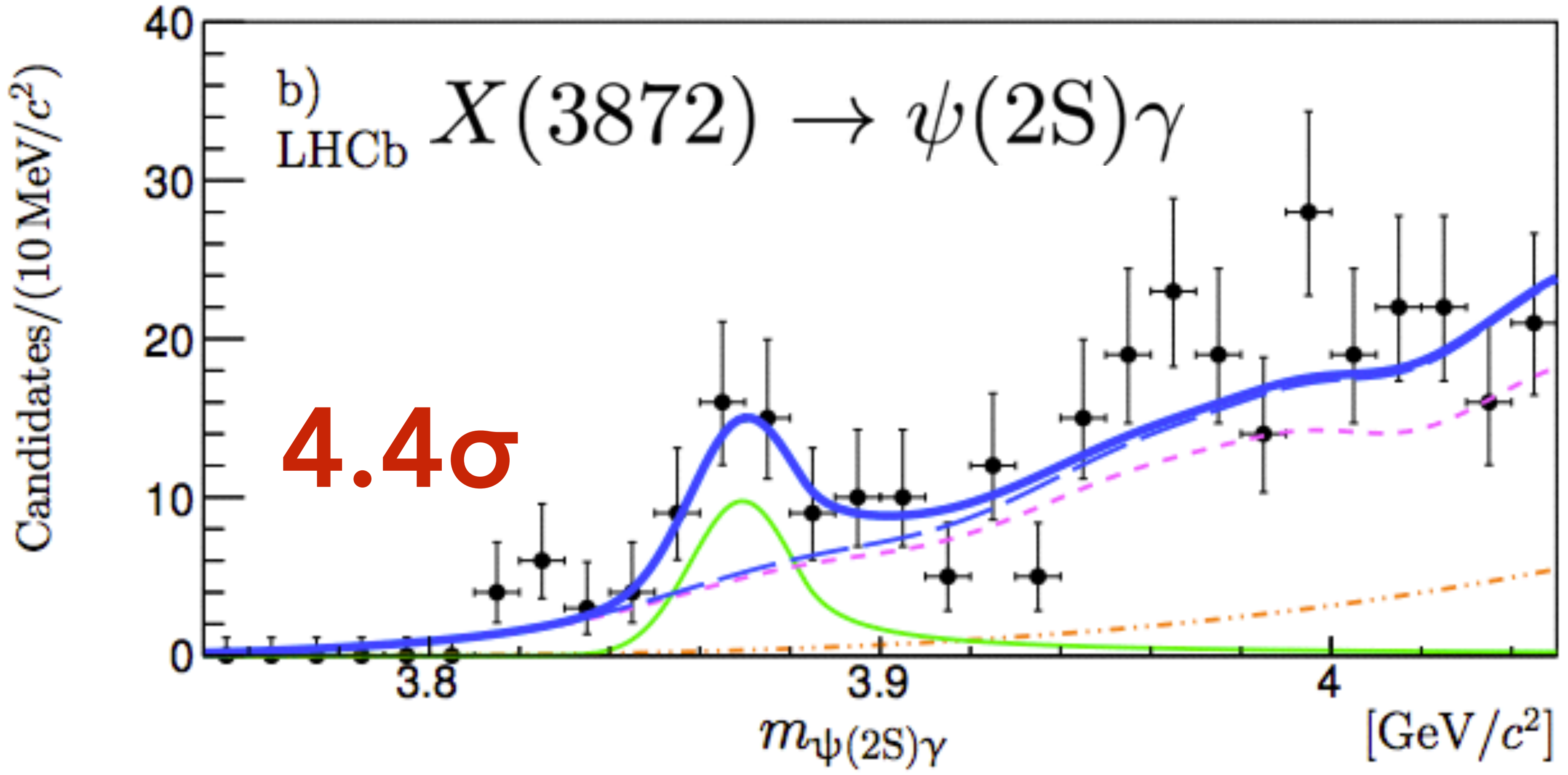
X(3872) radiative decays [NPB 886 (2014) 665]

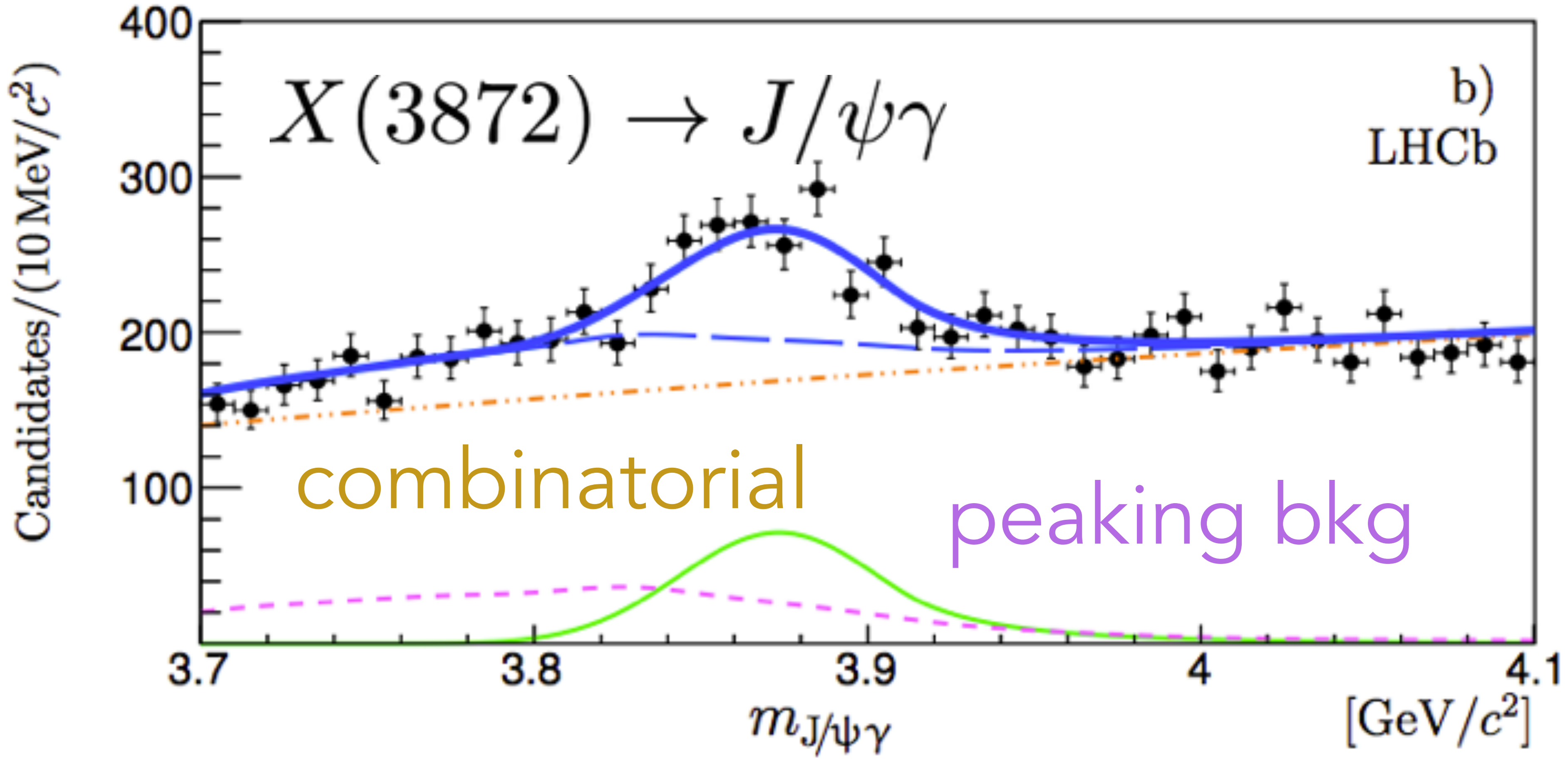
- LHCb has evidence for X(3872) in decays of $B^+ \to \psi\gamma K^+$, $\psi \to \mu^+\mu^-$
- Efficiency($\psi(2S)\gamma$) / Efficiency($J/\psi\gamma$) ~ 0.2
- Detecting soft photons at hadronic collider is hard.
- Pure DD* molecule interpretation disfavoured.

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

Probe of internal structure of X(3872)

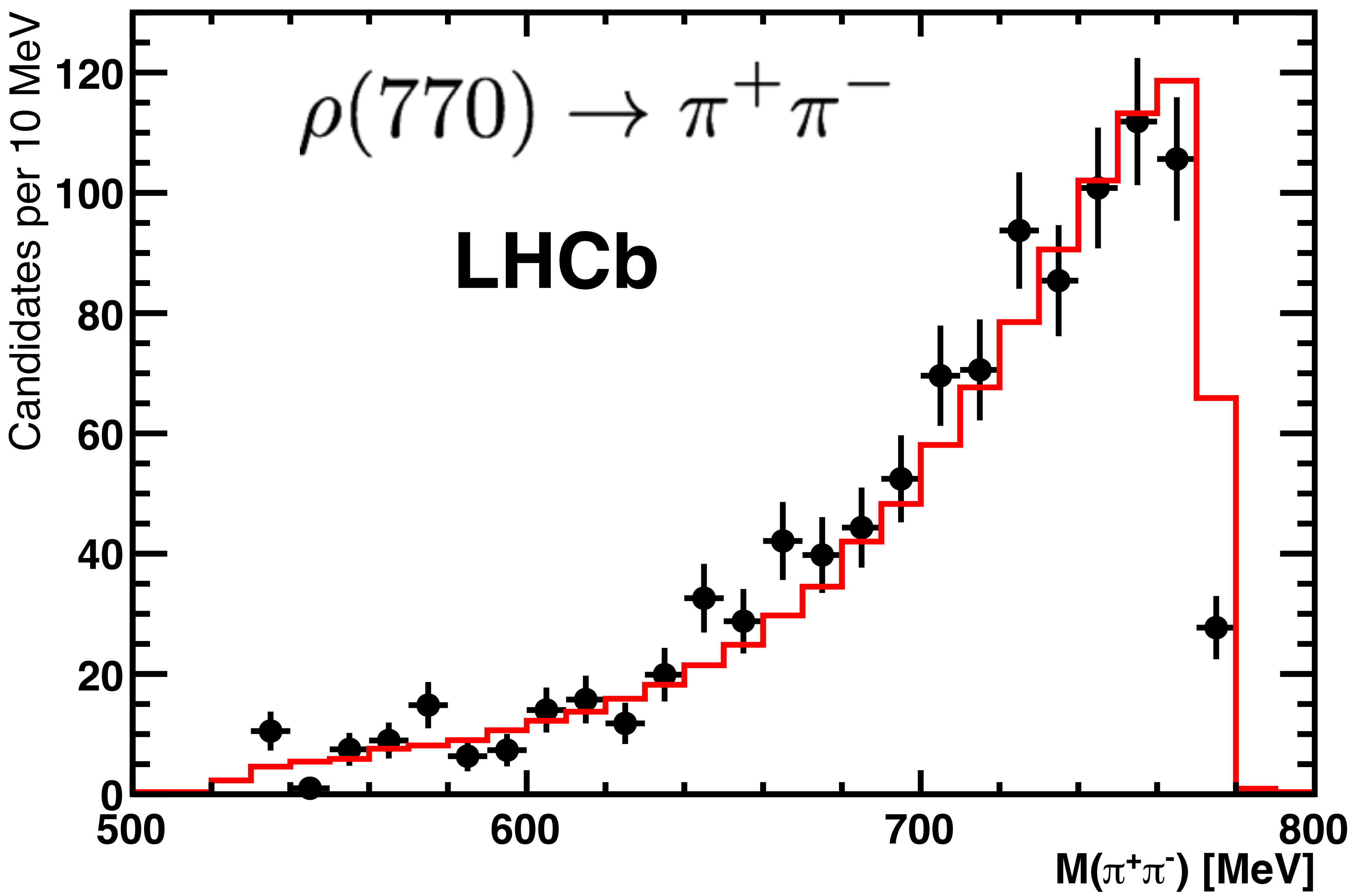


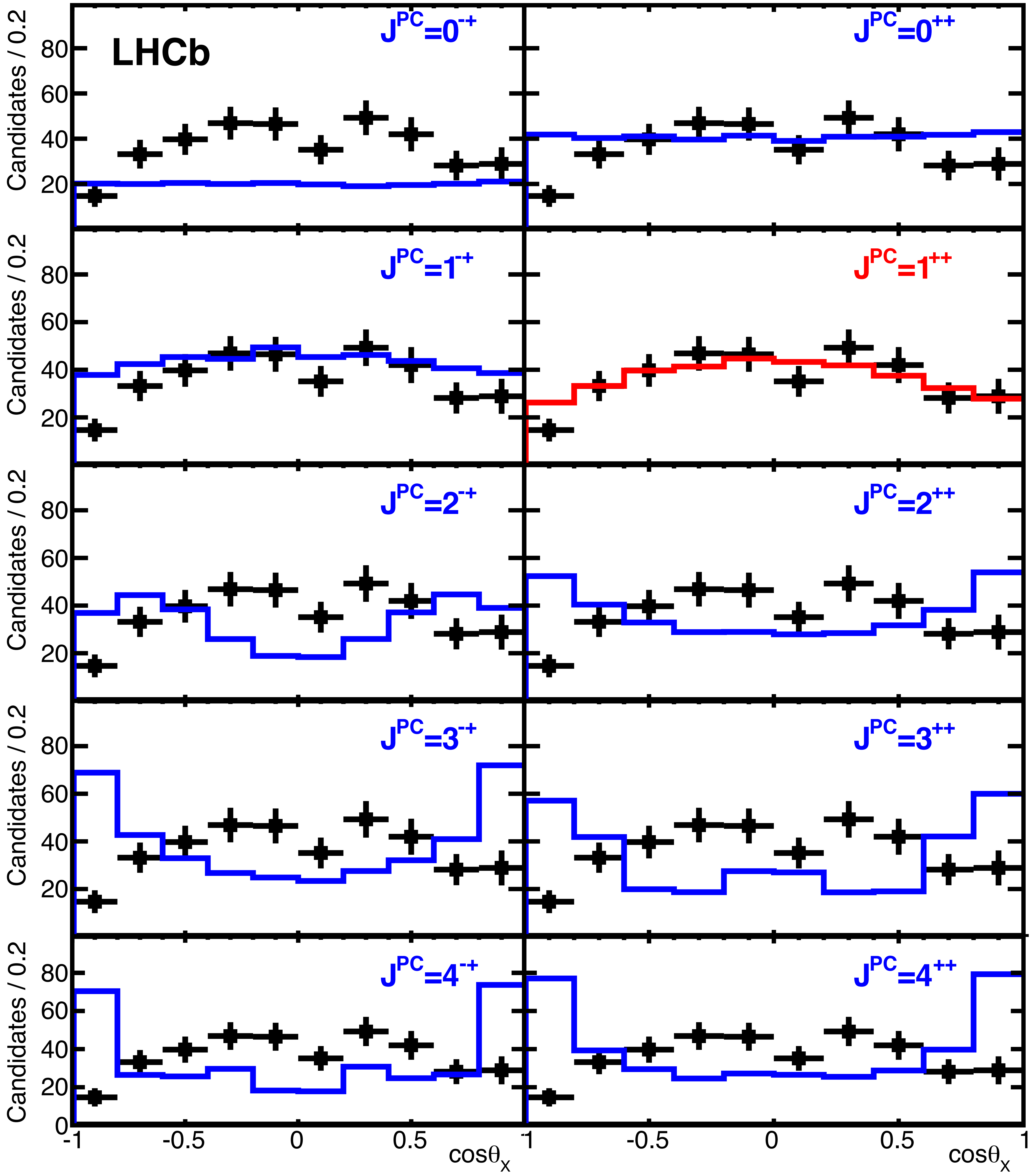




X(3872) quantum numbers [PRD 92 (2015) 011102]

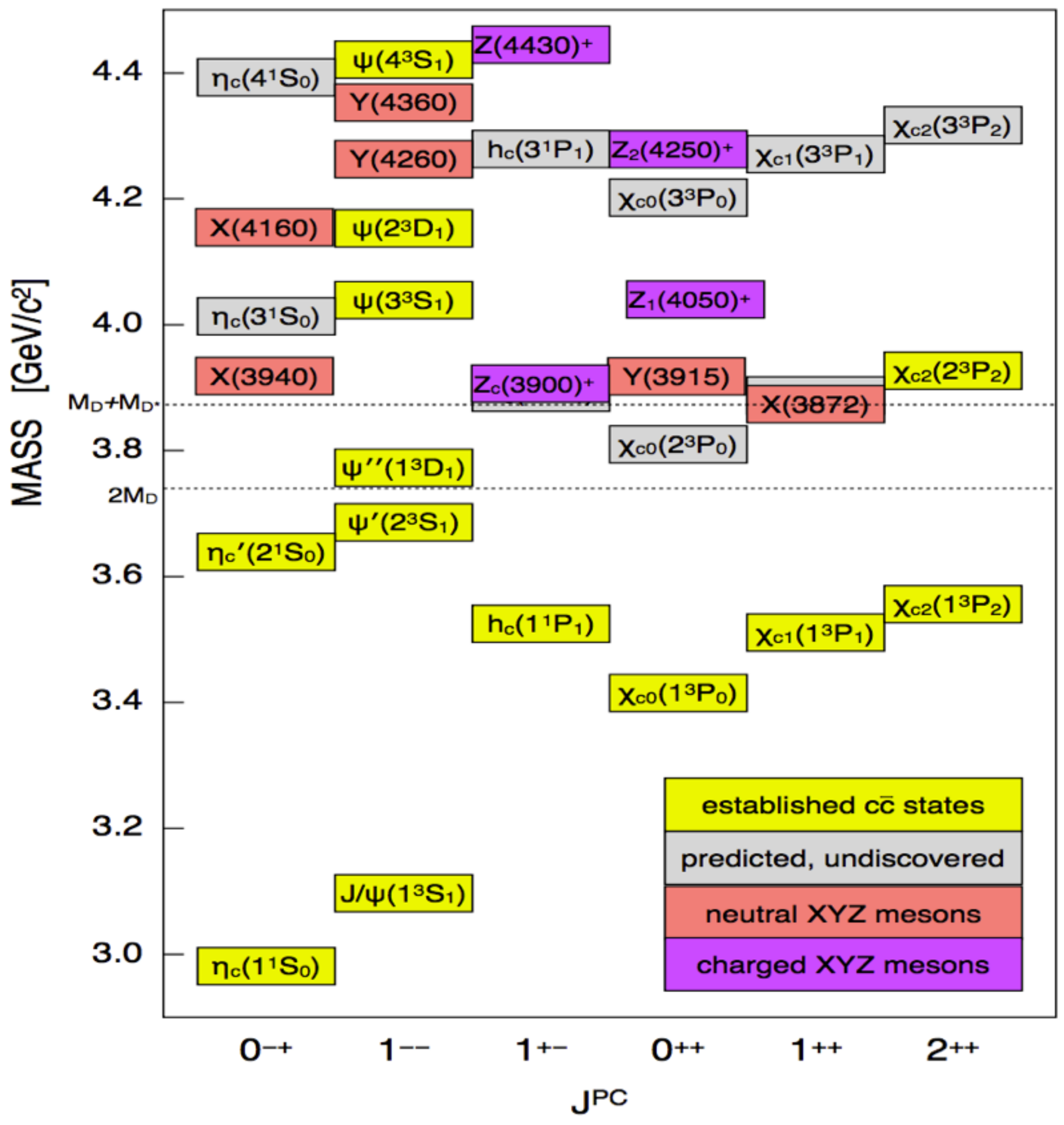
- $J^{PC} = 1^{++}$ confirmed!
- D-wave negligible < 4% @ 95% CL
- ρ(770) dominates -> decay violates isospin so unlikely to be conventional ccbar





Summary

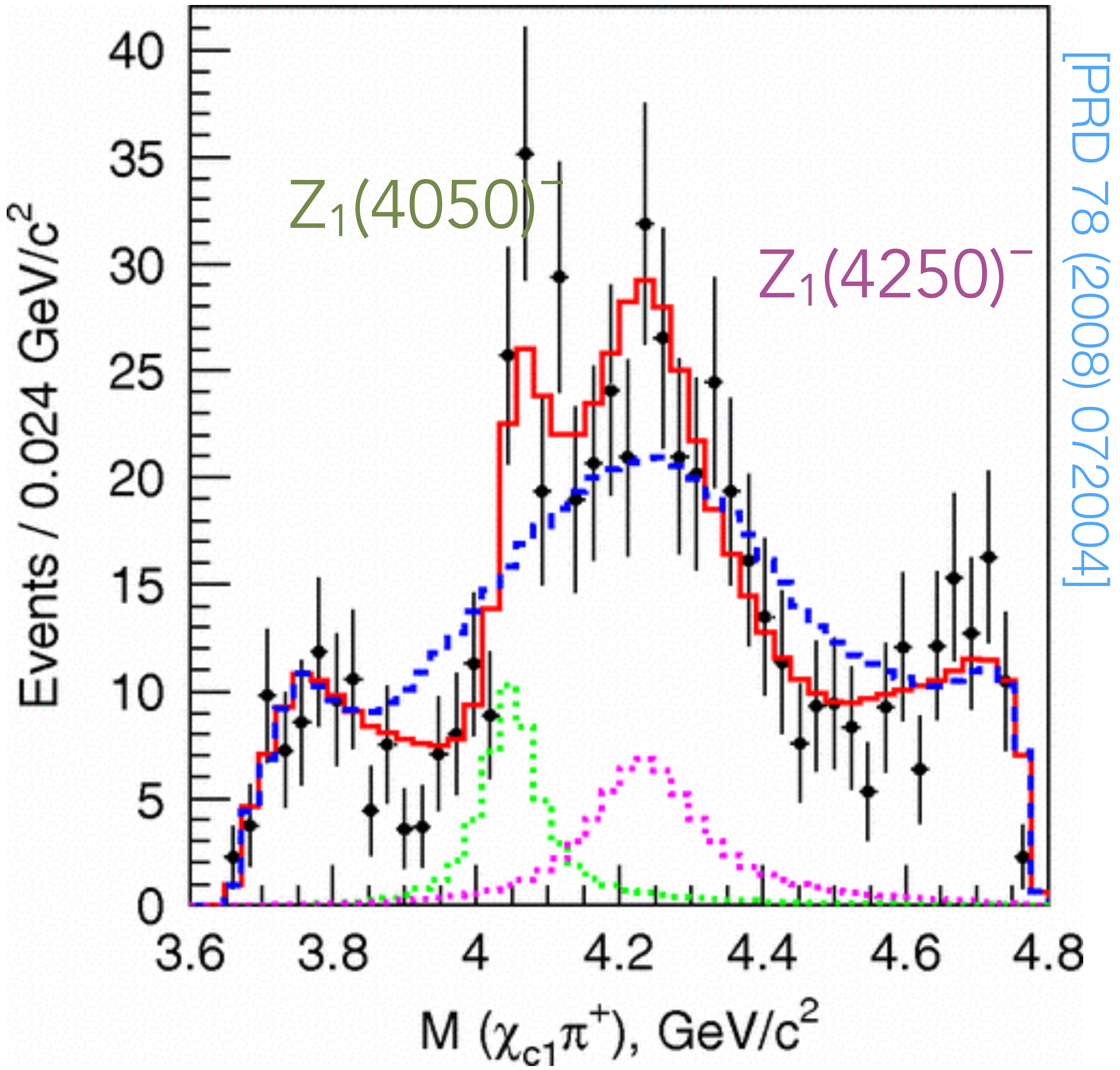
- Revolution in heavy-quark spectroscopy since 2003 discovery of X(3872).
- ~25 XYZ and P_c states observed using different production and decay mechanisms.
- Crucial to confirm observations where possible and use state-of-the-art amplitude analyses to understand observed states (look at phase-motion!)
- Exotic states provide ideal foundation to deepen understanding of non-perturbative QCD.
    - Only by collecting more observations can we hope to piece together the kinematic and dynamical effects that govern these states.



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… [PRD 85 () 052003]



LHCb should be able to do something here in future

$Z(4430)^{\pm}$ charged charmonium exotic

- 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**

$c\bar{c}u\bar{d}$

$\mu^+\mu^-, J/\psi\pi^+\pi^-$

$B^{+,0} \longrightarrow \psi(2S)\pi^- \; K^{+,0}$

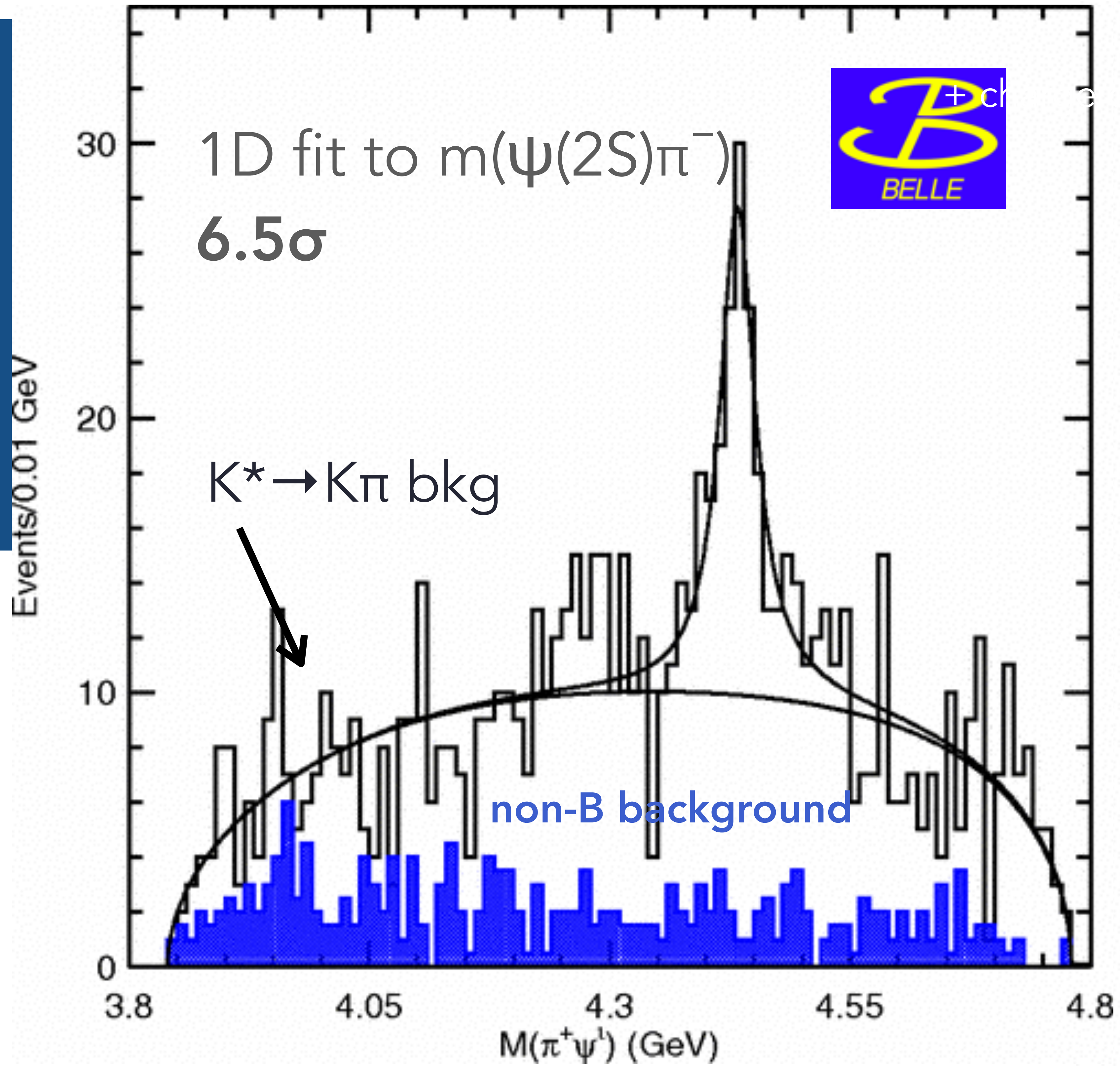
$B^{+,0} \longrightarrow Z(4430)^- K^{+,0}$ $\quad \mu^+\mu^-, J/\psi\pi^+\pi^-$

$\psi(2S)\pi^-$

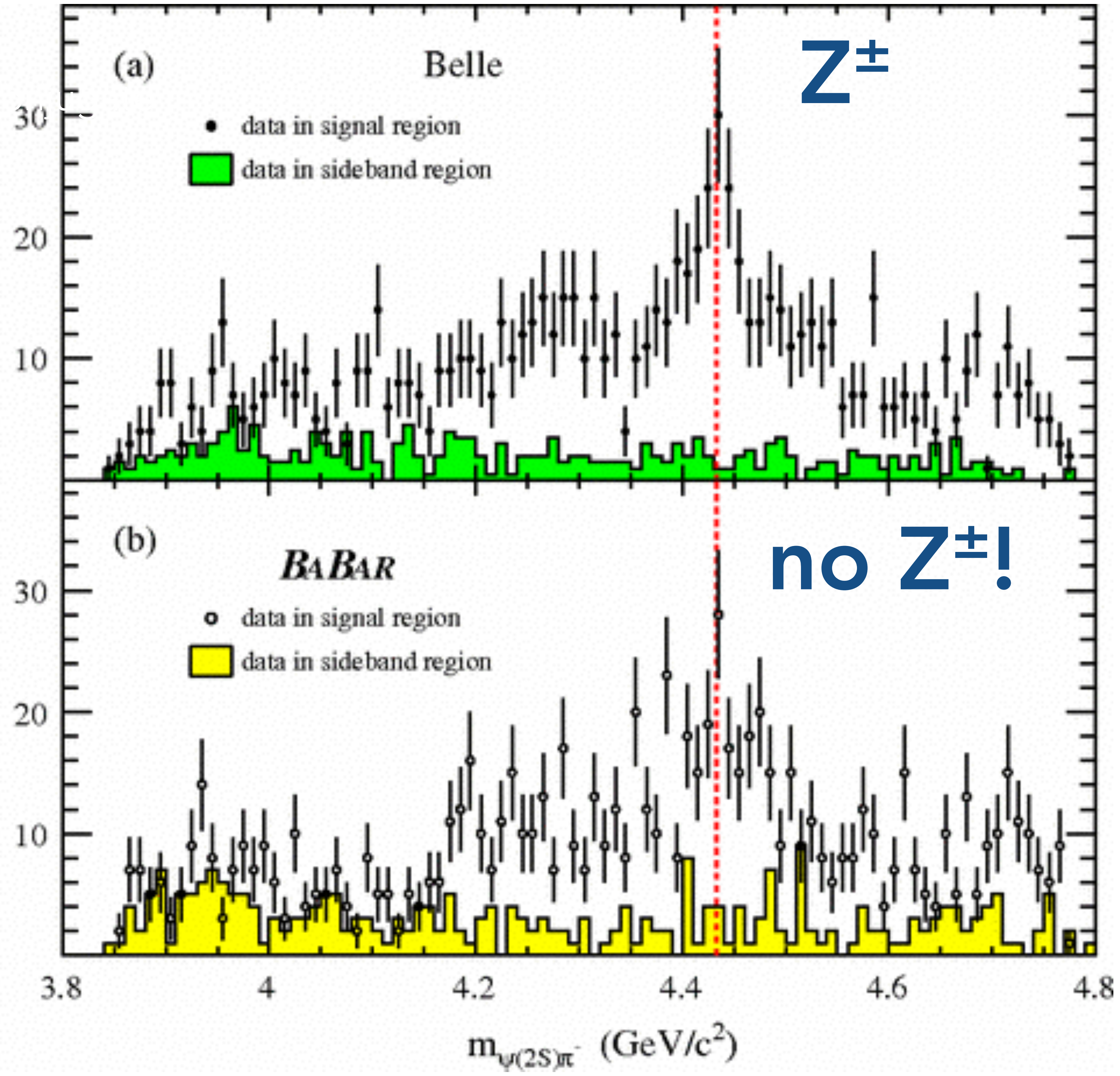
$$M = 4433 \pm 4 \pm 2 \ \mathrm{MeV}/c^2$$

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

[PRL 100 (2008) 142001]



[PRD 79 (2009) 112001]



Not observed by BaBar!

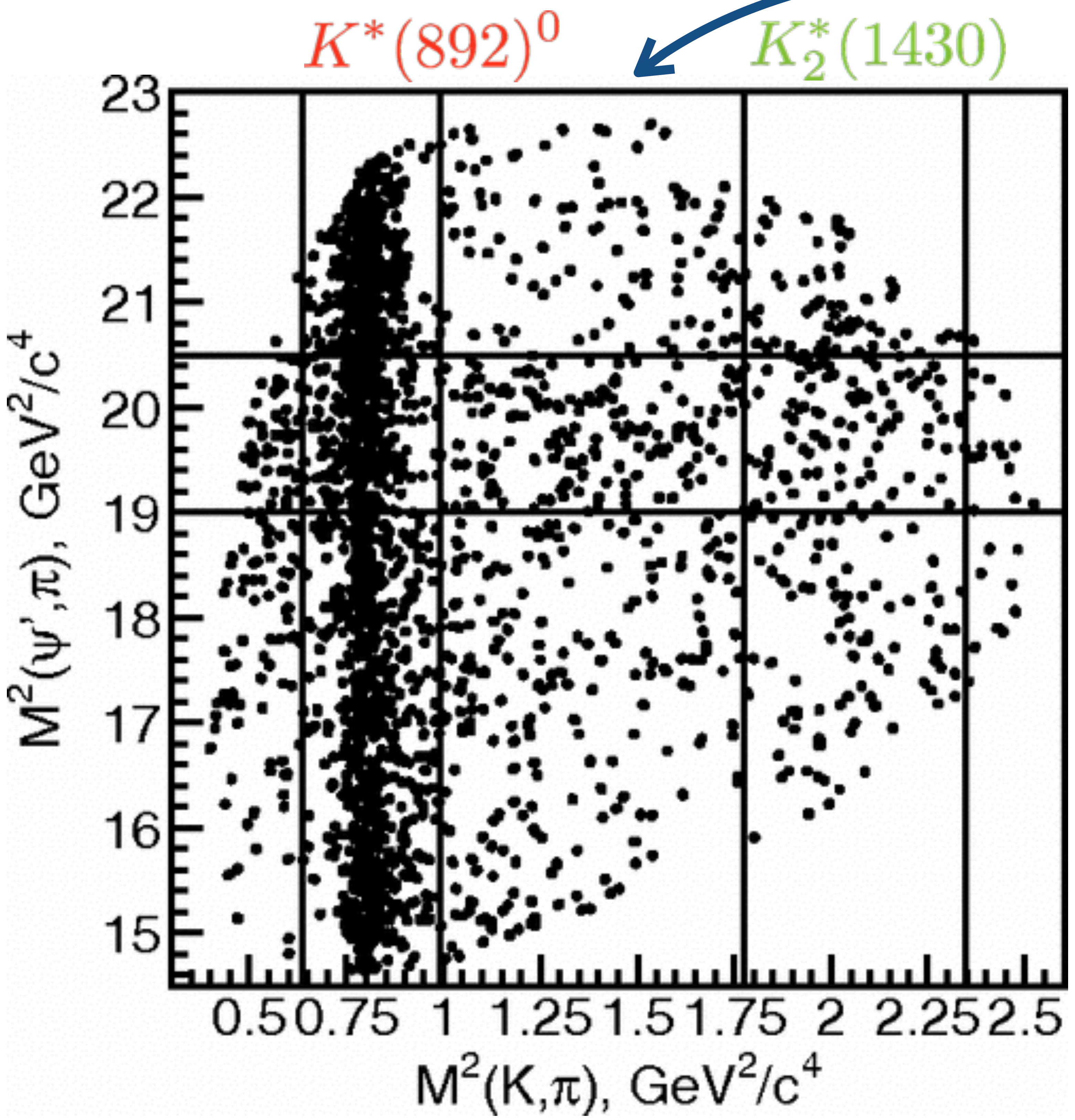
History of the Z(4430)$^-$

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

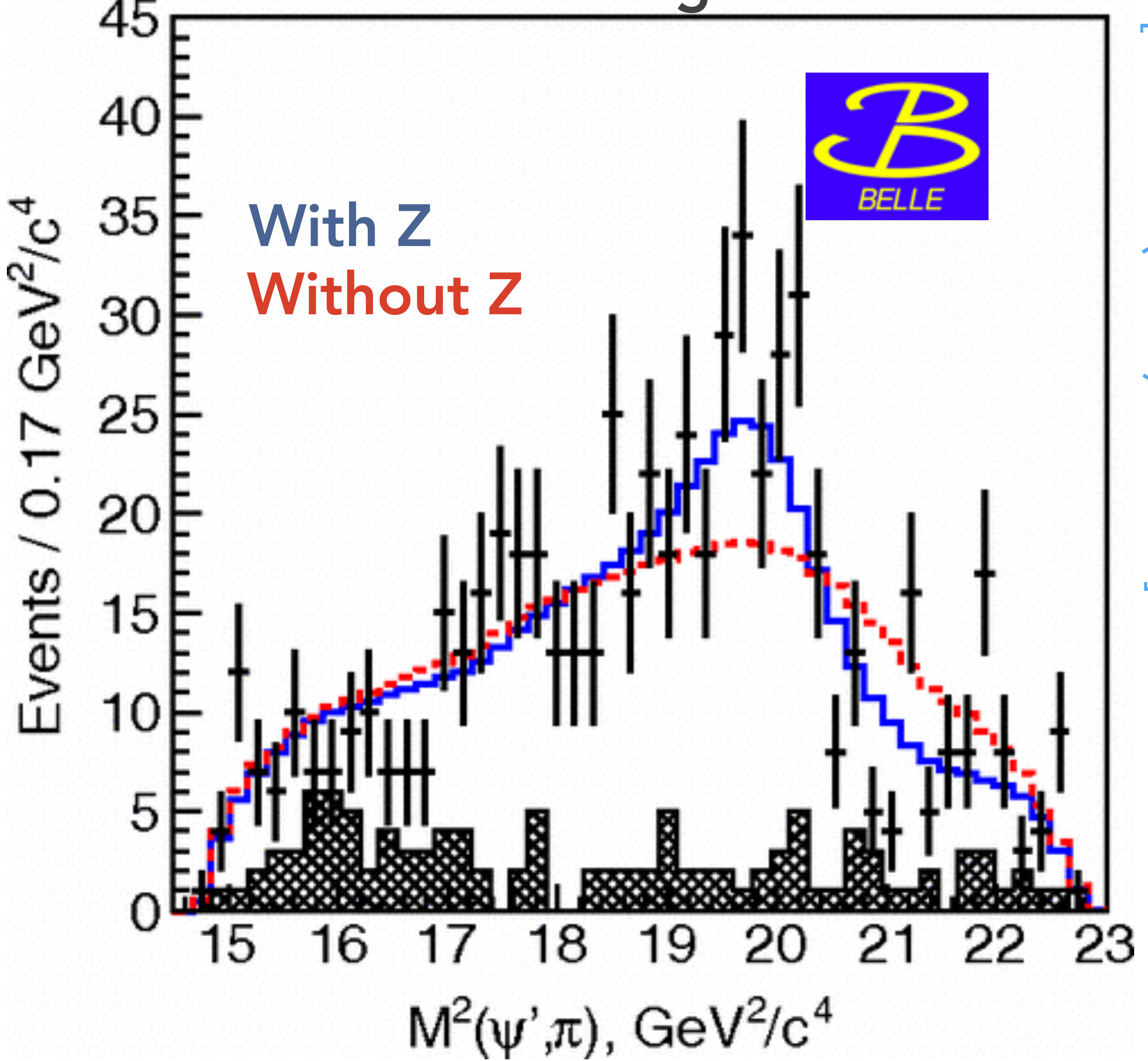
- Belle **[PRL 100 (2008) 142001]** 1D fit to m(ψ′π$^-$) **6.5σ**
- BaBar **[PRD 79 (2009) 112001]** **Not observed but does not contradict Belle!**
- Belle **[PRD 80 (2009) 031104]** 2D amplitude fit to m(ψ′π$^-$) vs m(K$^+$π$^-$) **6.4σ**
- Belle **[PRD 88 (2013) 074026]** 4D amplitude fit **6.4σ**

ψ′ = ψ(2S)

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



K* veto region



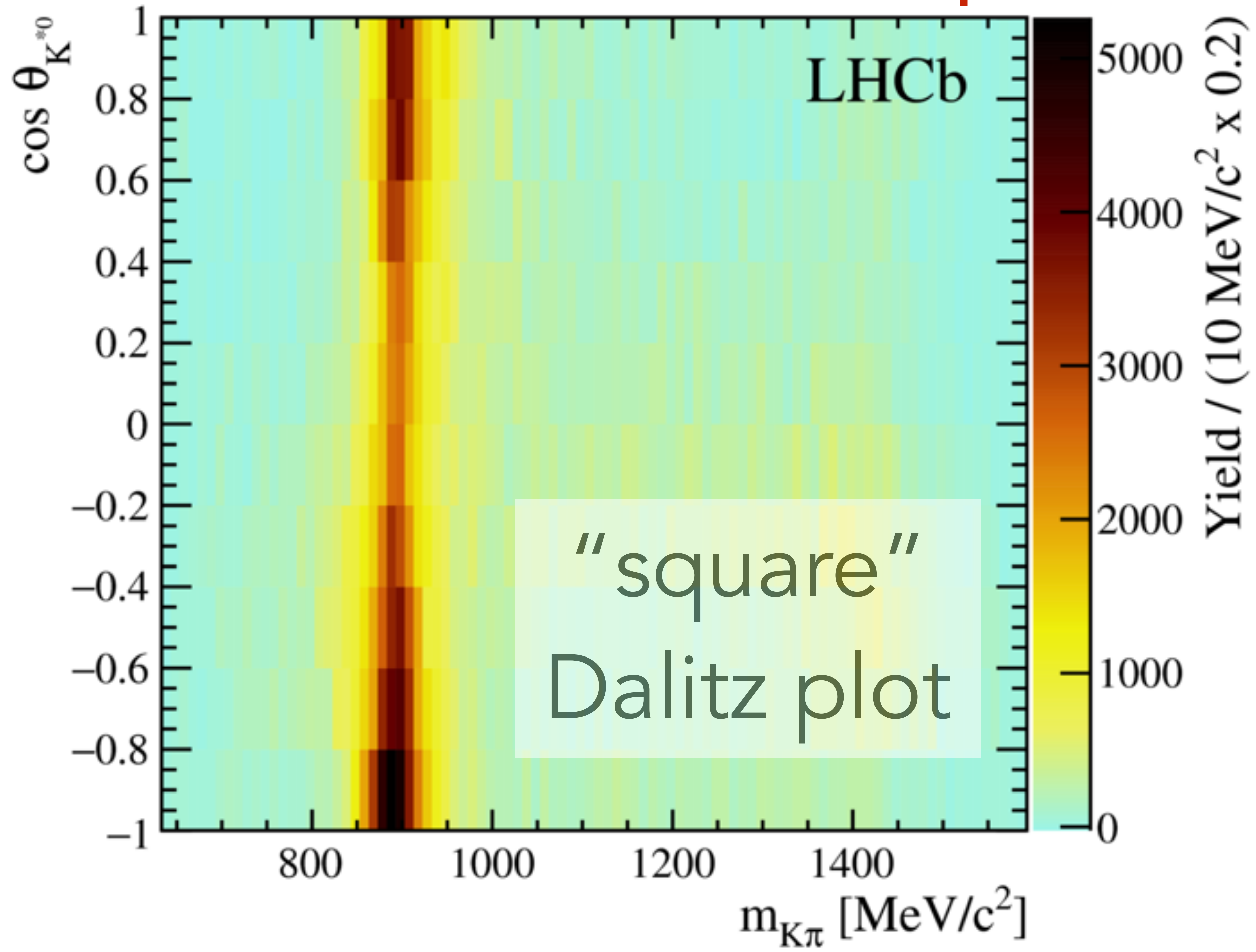
[PRD 88 (2013) 074026]

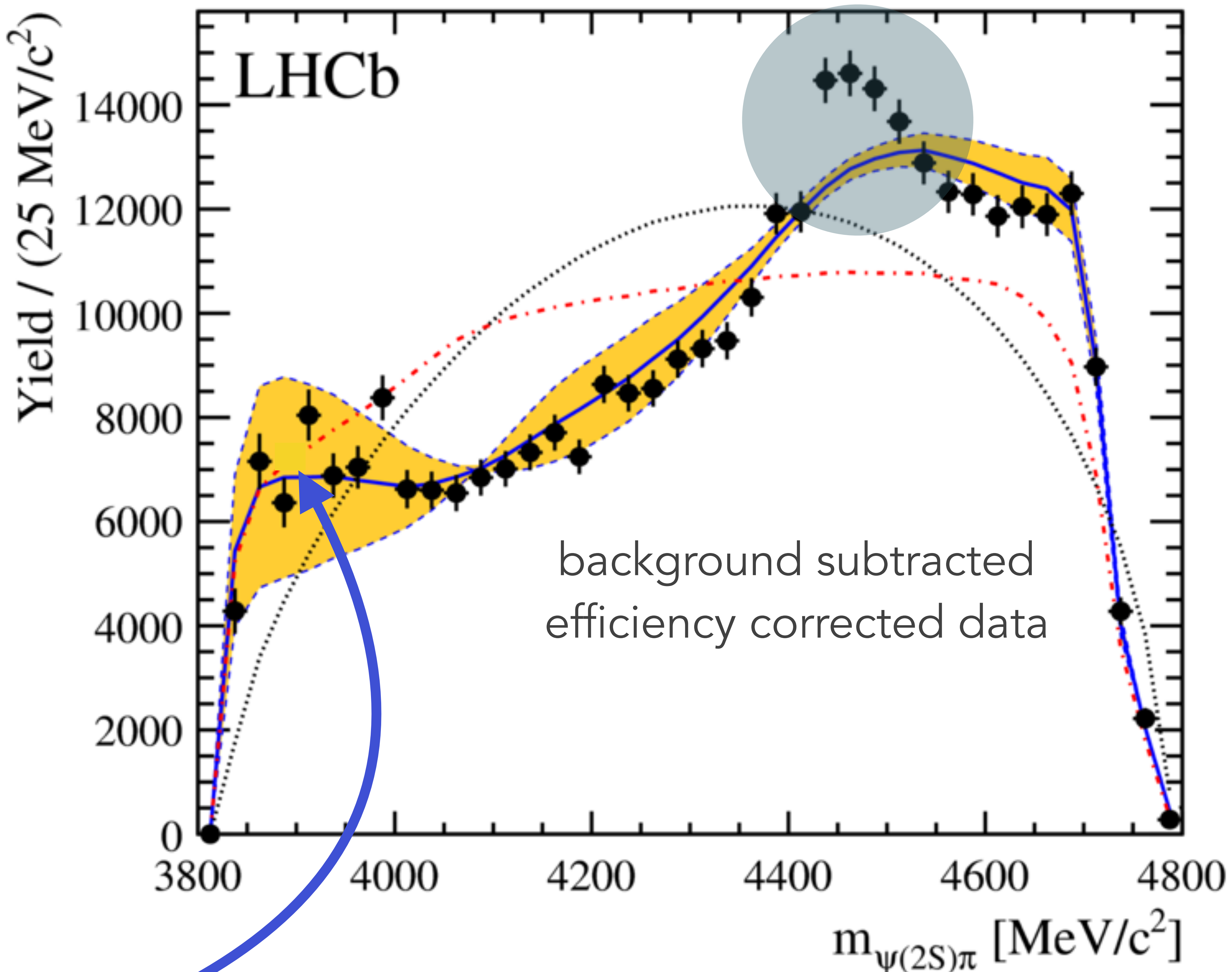
Model independent analysis [PRD 92 (2015) 112009]

[Extension of BaBar PRD 79 (2009) 112001]

Can reflection of the structures in m(Kπ) and cosθ reproduce the m(ψ′π) distribution?

NO!

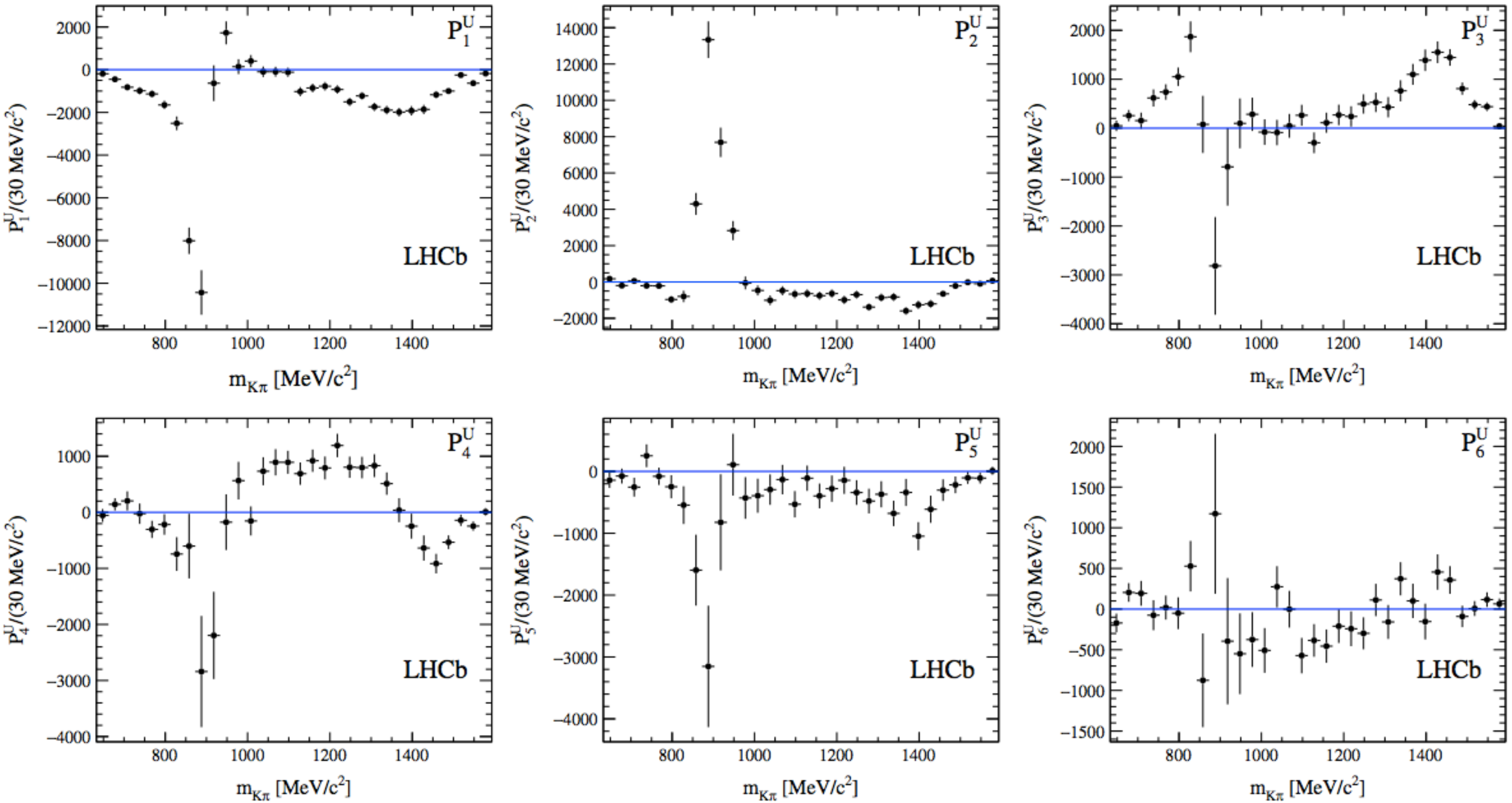




$$Y_1^0 = \sqrt{\frac{3}{4\pi}}\cos\theta$$
$$Y_1^1 = -\sqrt{\frac{3}{8\pi}}\sin\theta\, e^{i\phi}$$
$$Y_2^0 = \sqrt{\frac{5}{4\pi}}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)$$
$$Y_2^1 = -\sqrt{\frac{15}{8\pi}}\sin\theta\cos\theta\, e^{i\phi}$$
$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

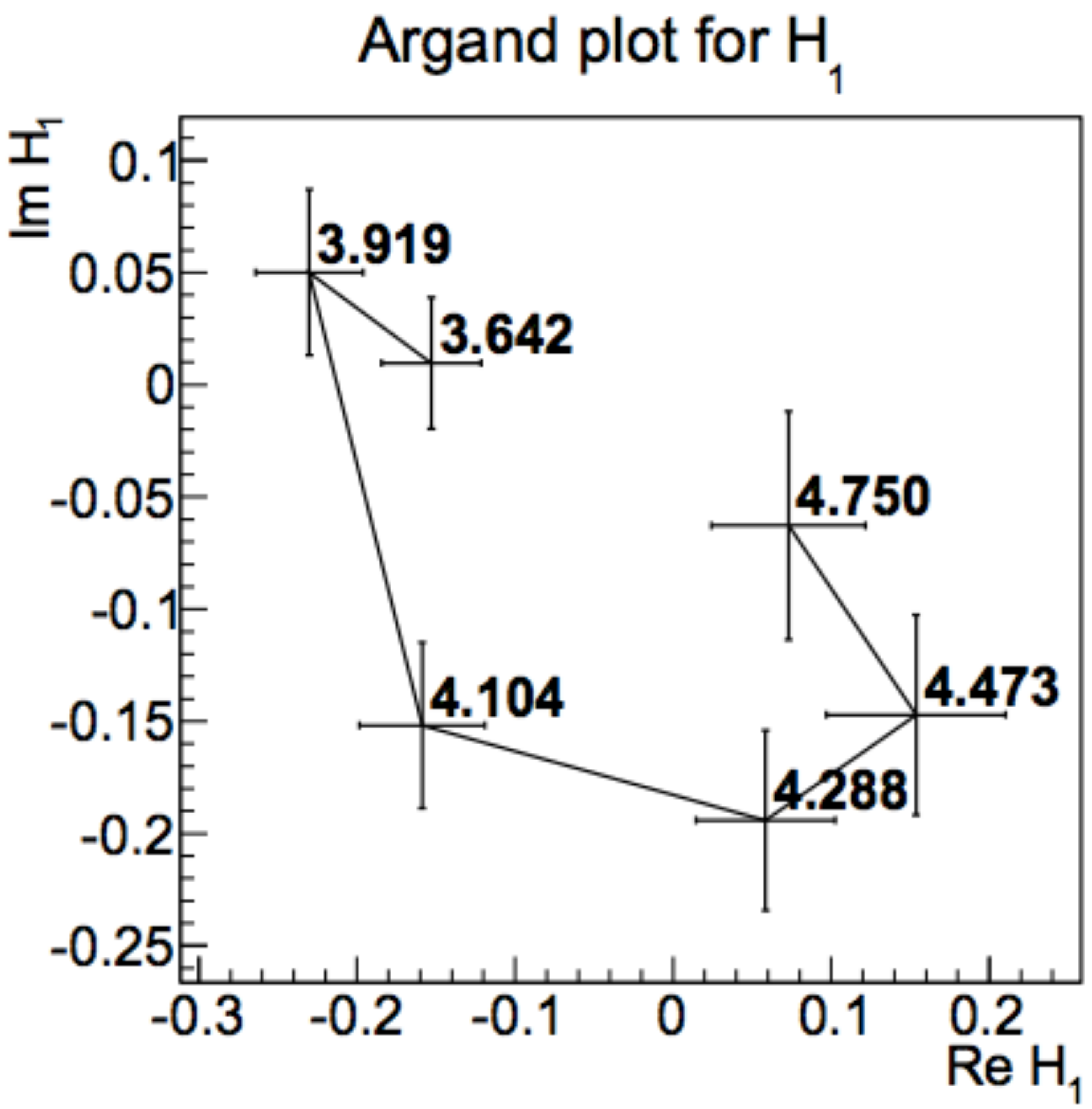
- Does not make any assumption on the underlying K* resonances in the system, only restricts their maximal spin.
- Weight phase space **simulated** $B^0 \to \psi' K^+\pi^-$ **events** with data m(Kpi) and the spherical harmonic moments of $\cos\theta_K$.
- Moments of K* resonances are **unable** to explain observed distribution.

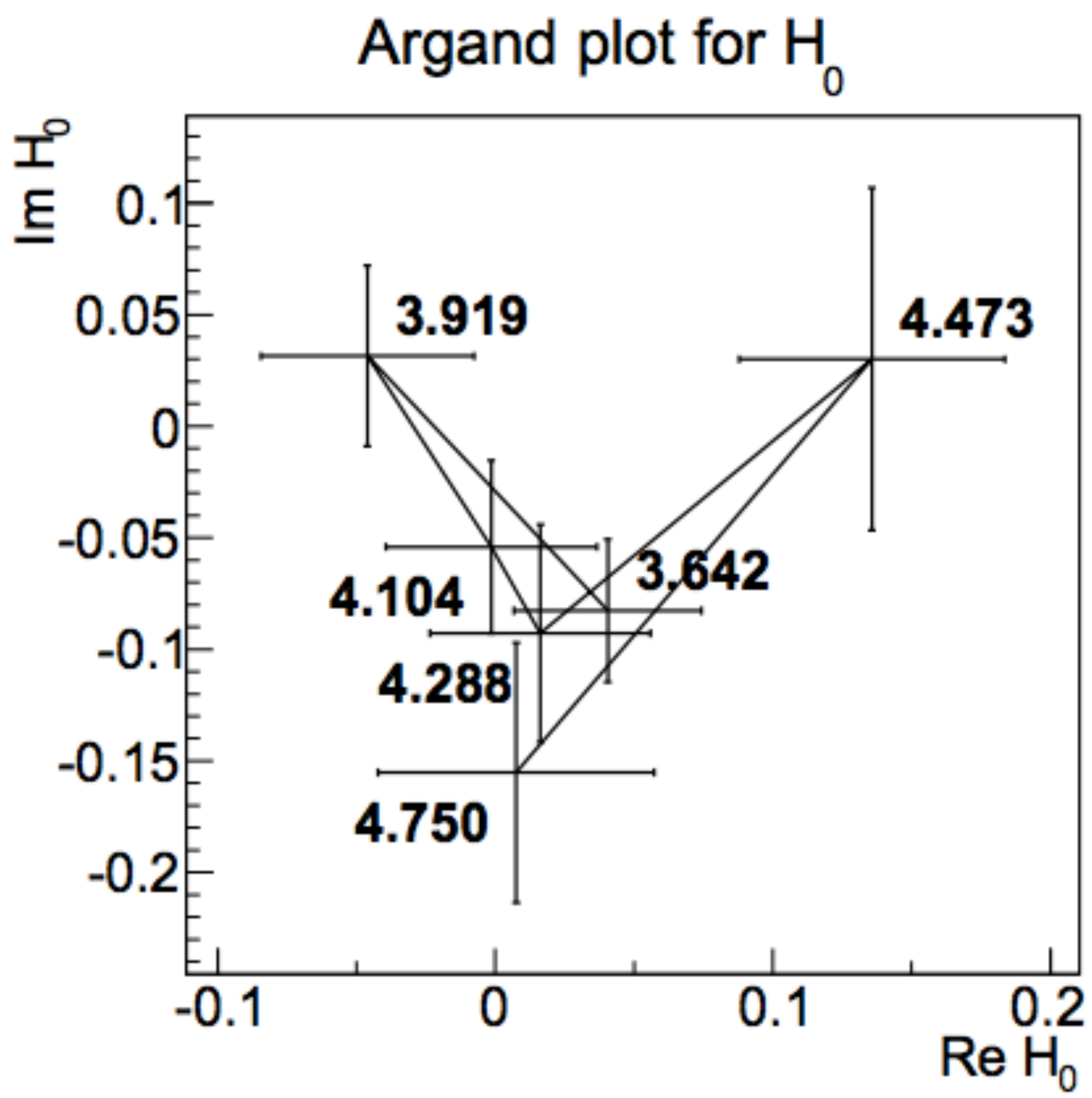
Z(4430) model independent

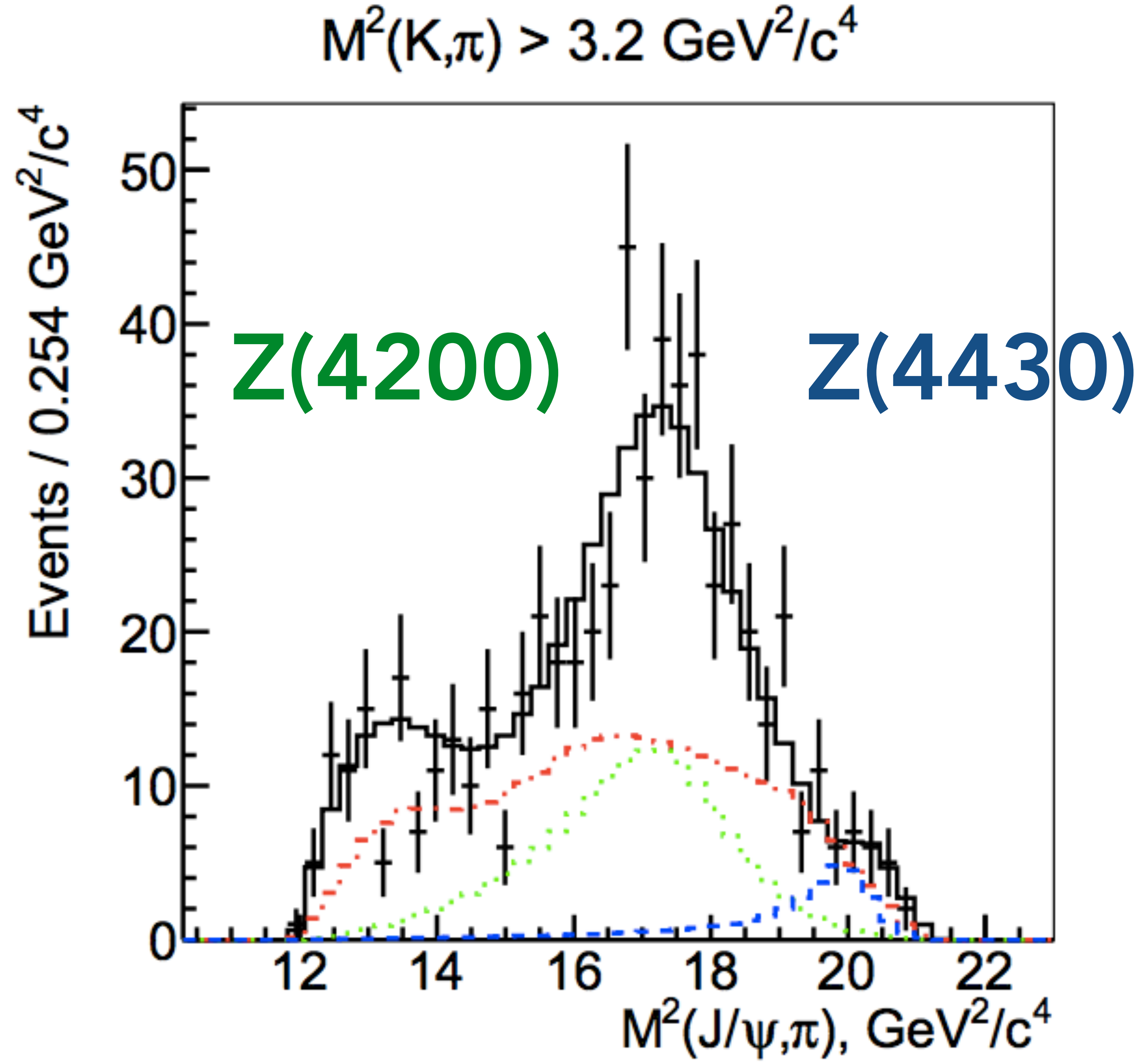


New decay mode of the Z(4430) [PRD 90 (2014) 112009]

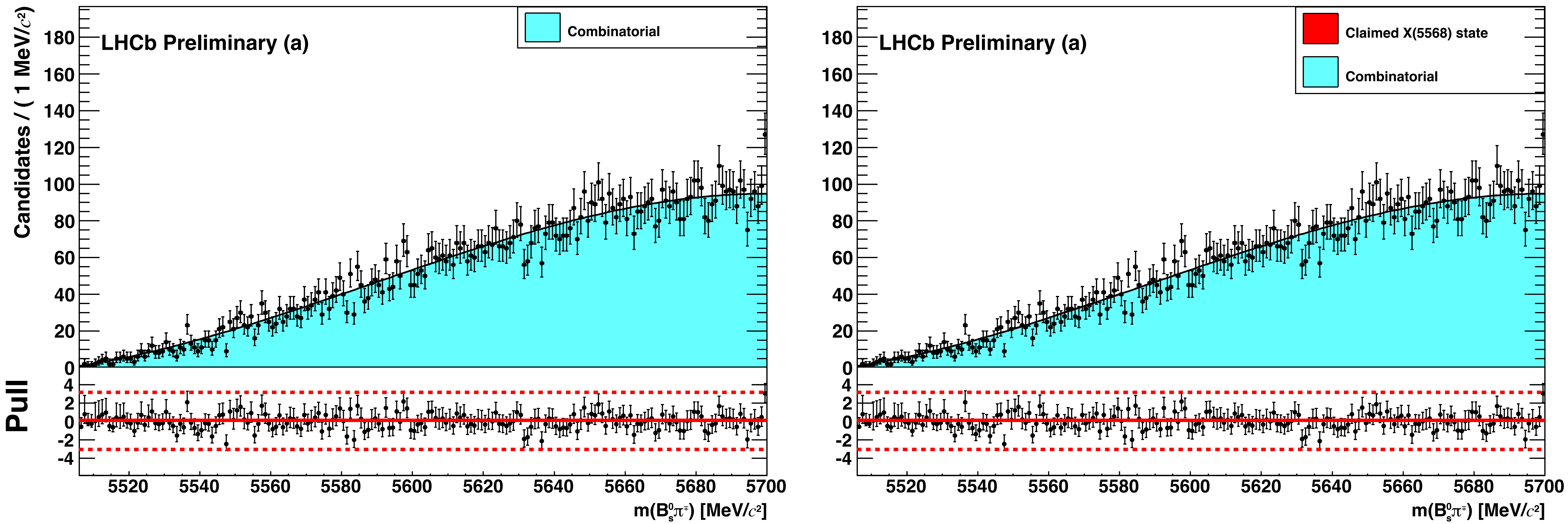
- Belle 4D amplitude fit of $B^0 \longrightarrow J/\psi\pi^- K^+$.
- $Z(4200)^+$ at 7.2sigma with systematics ($J^P = 1^+$). Width ~370MeV.
- $Z(4430)^+$ at 4.0sigma: evidence for **new decay mode!**
  - Expect smaller BR if Z has large radius, with larger overlap with ψ'.





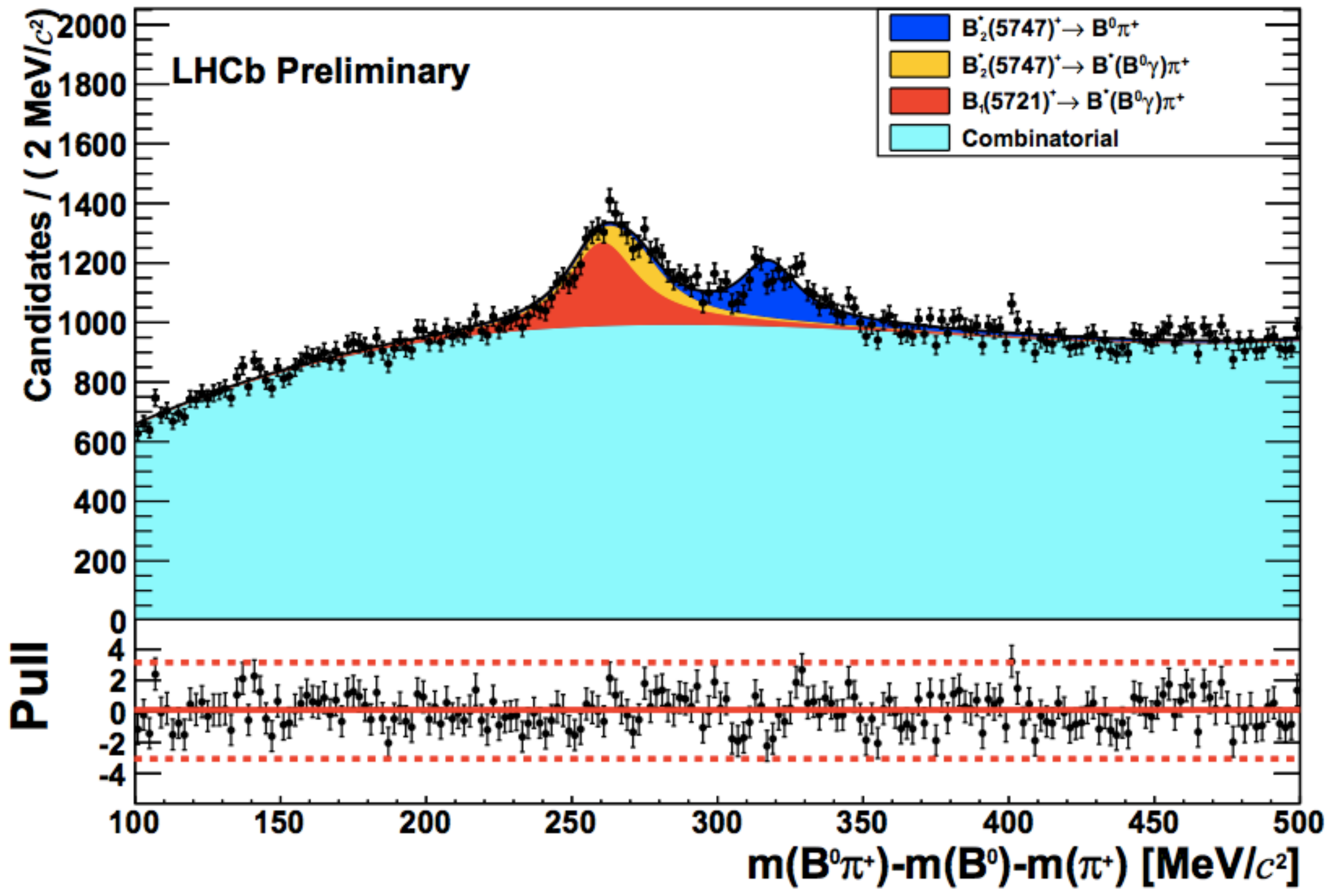


LHCb limits on the X(5568) [LHCb-CONF-2016-004]



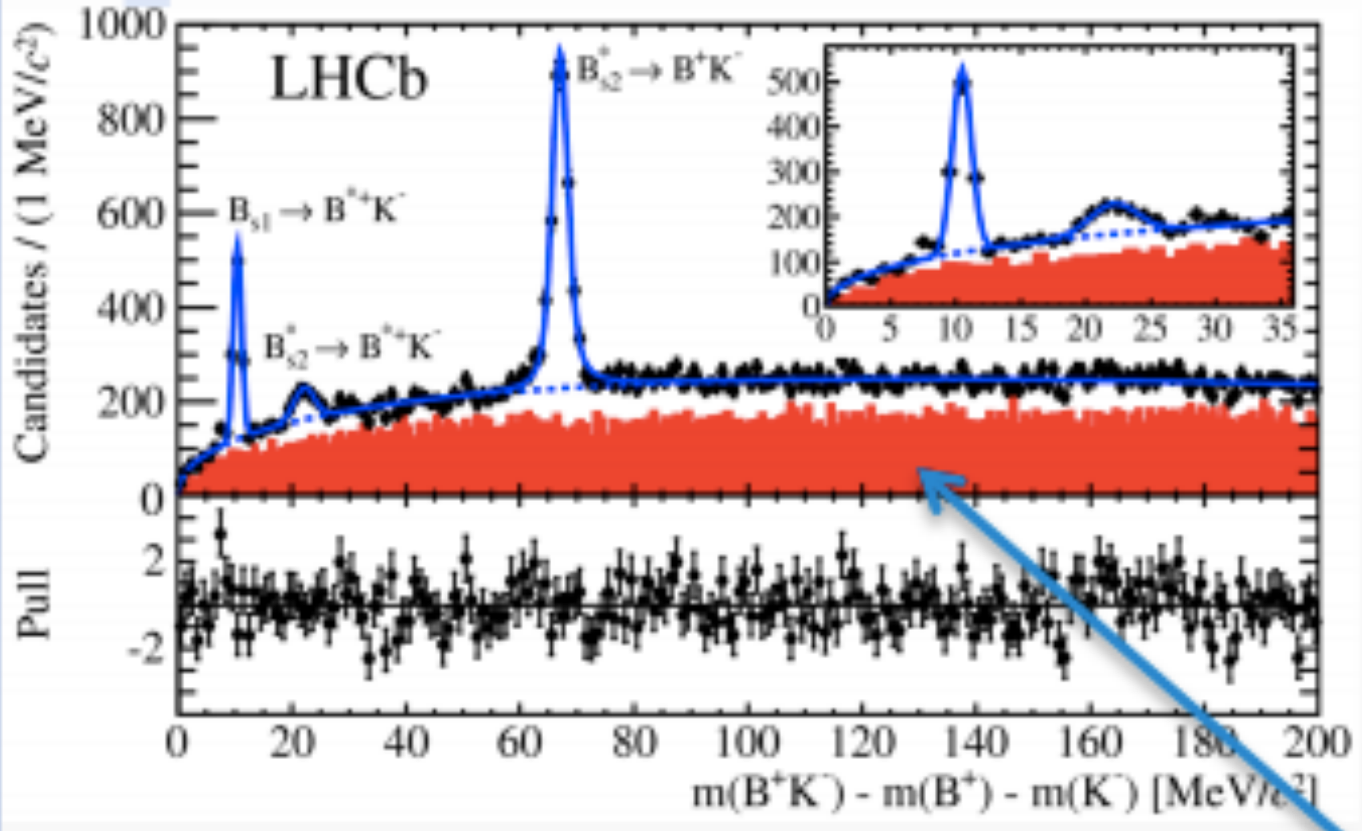
$$p_{\mathrm{T}}(B_s^0) > 5\,\mathrm{GeV}/c$$

LHCb limits on the X(5568) [LHCb-CONF-2016-004]



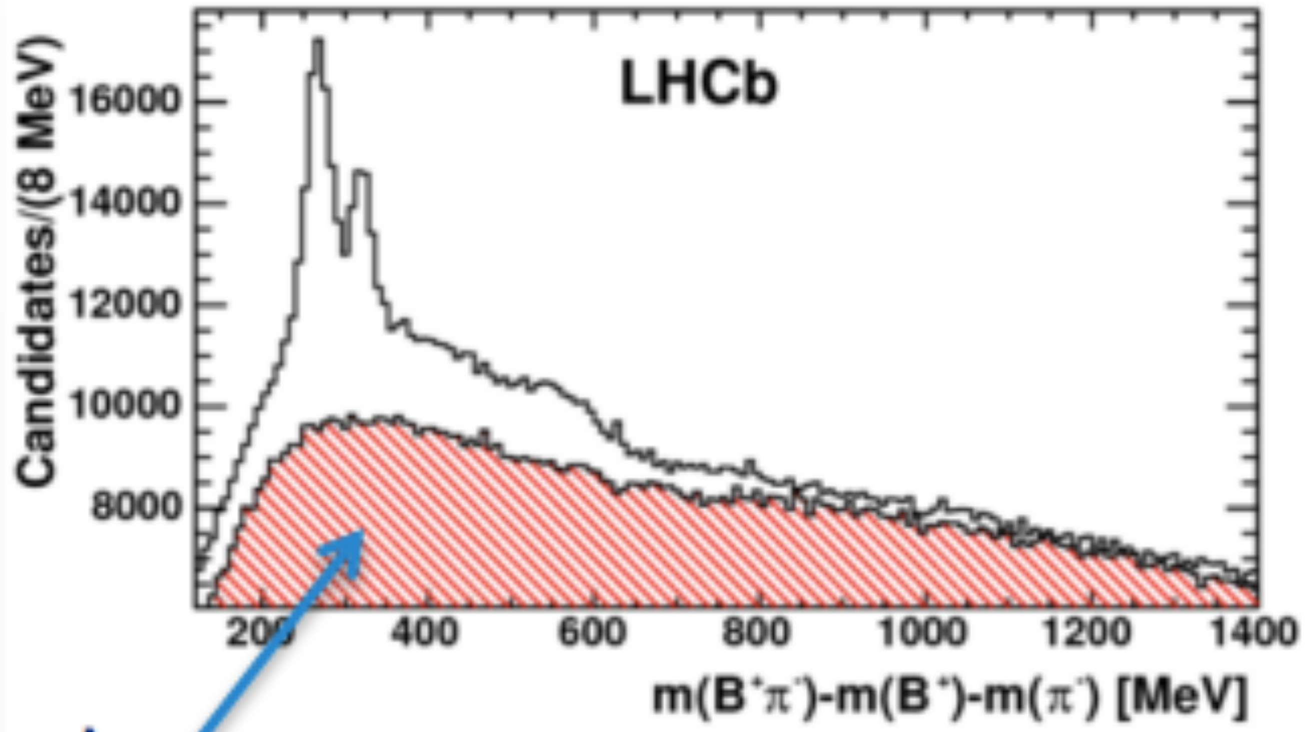
Well known excited B states found using same analysis techniques

OTHER "IMPLICIT" SEARCHES



PRL 110 (2013) 151803

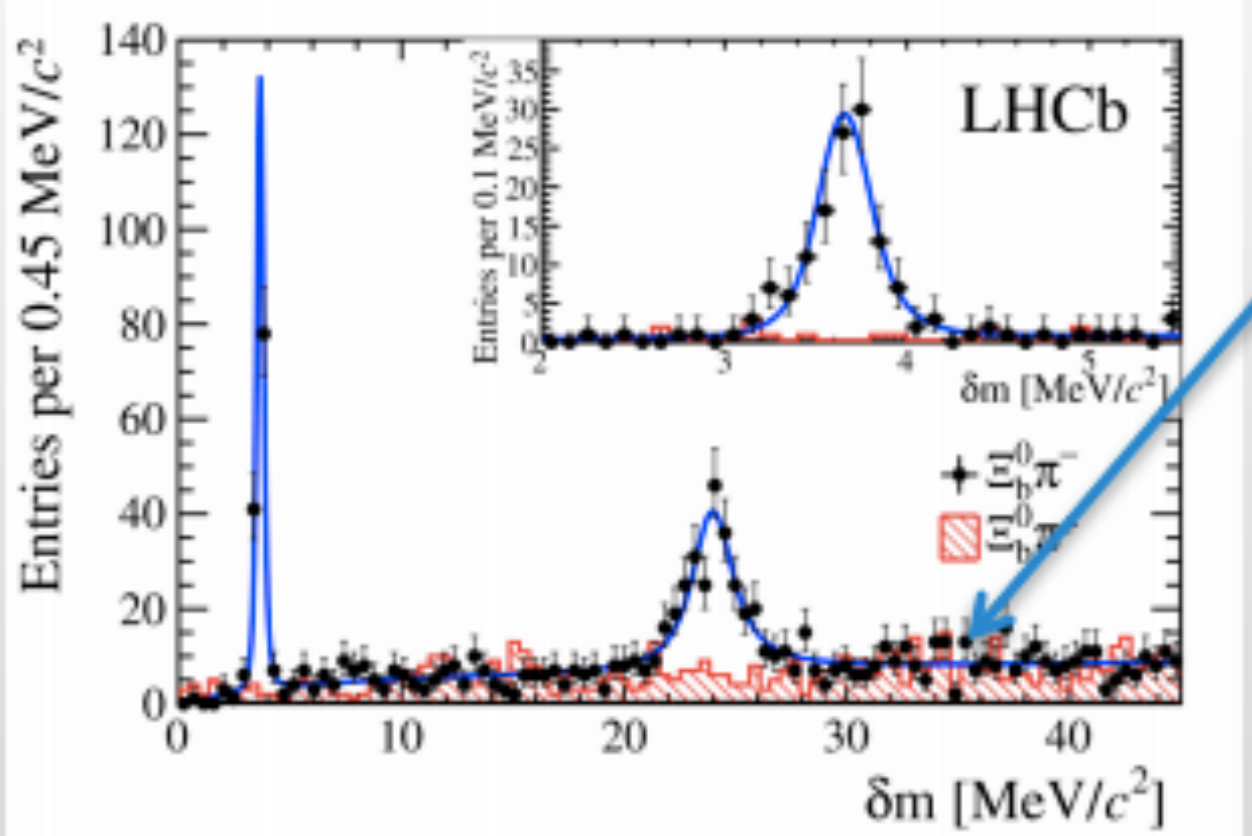
B^+K^+



$B^+\pi^+$

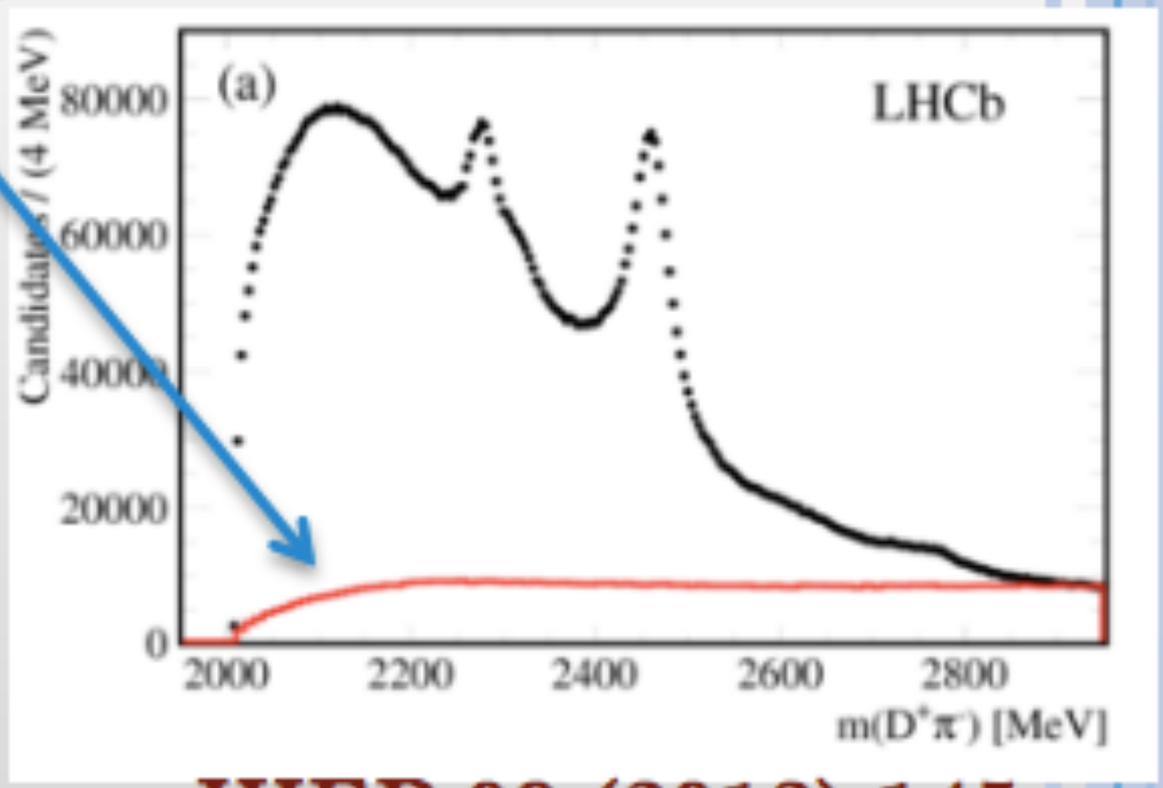
JHEP 1504 (2015) 024

The red histograms, referred as Wrong Sign plots, are implicitly searches for tetra/ pentaquark



$\Xi_b^0\pi^+$

PRL 114 (2015) 062004



$D^+\pi^+$

JHEP 09 (2013) 145

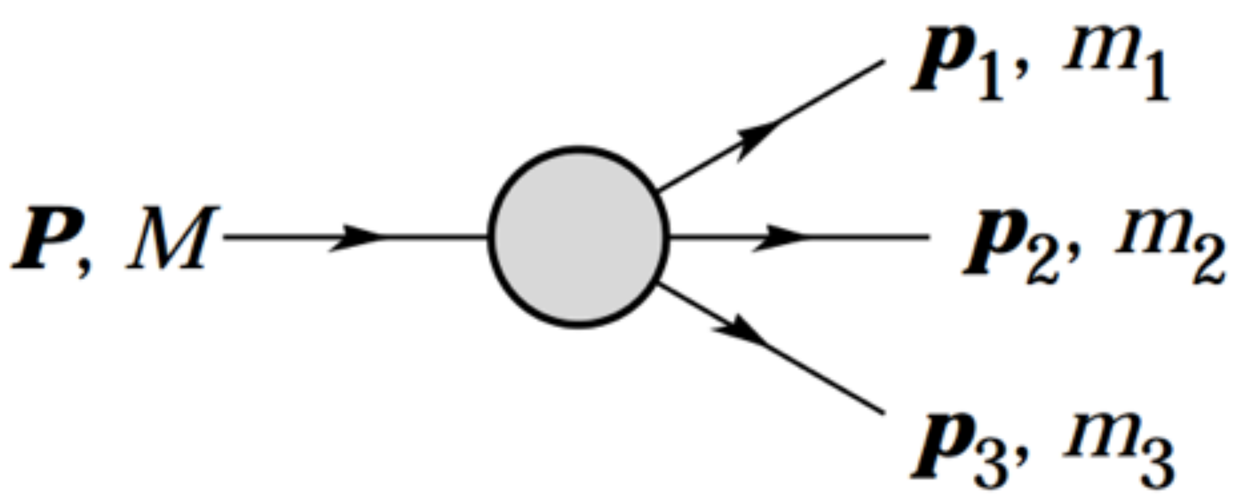
Light meson exotics

[PRL 95 (2003) 262001]
[PRL 108 (2012)112003]
[PRL 106 () 072002]
[PRL 115 () 091803]

- BES-III observes number of light quark exotics.
  - X(1835) threshold enhancement in Jpsi -> gamma ppbar .
  - ppbar bound state or glueball?

Reminder about Dalitz plots - 3 body decay

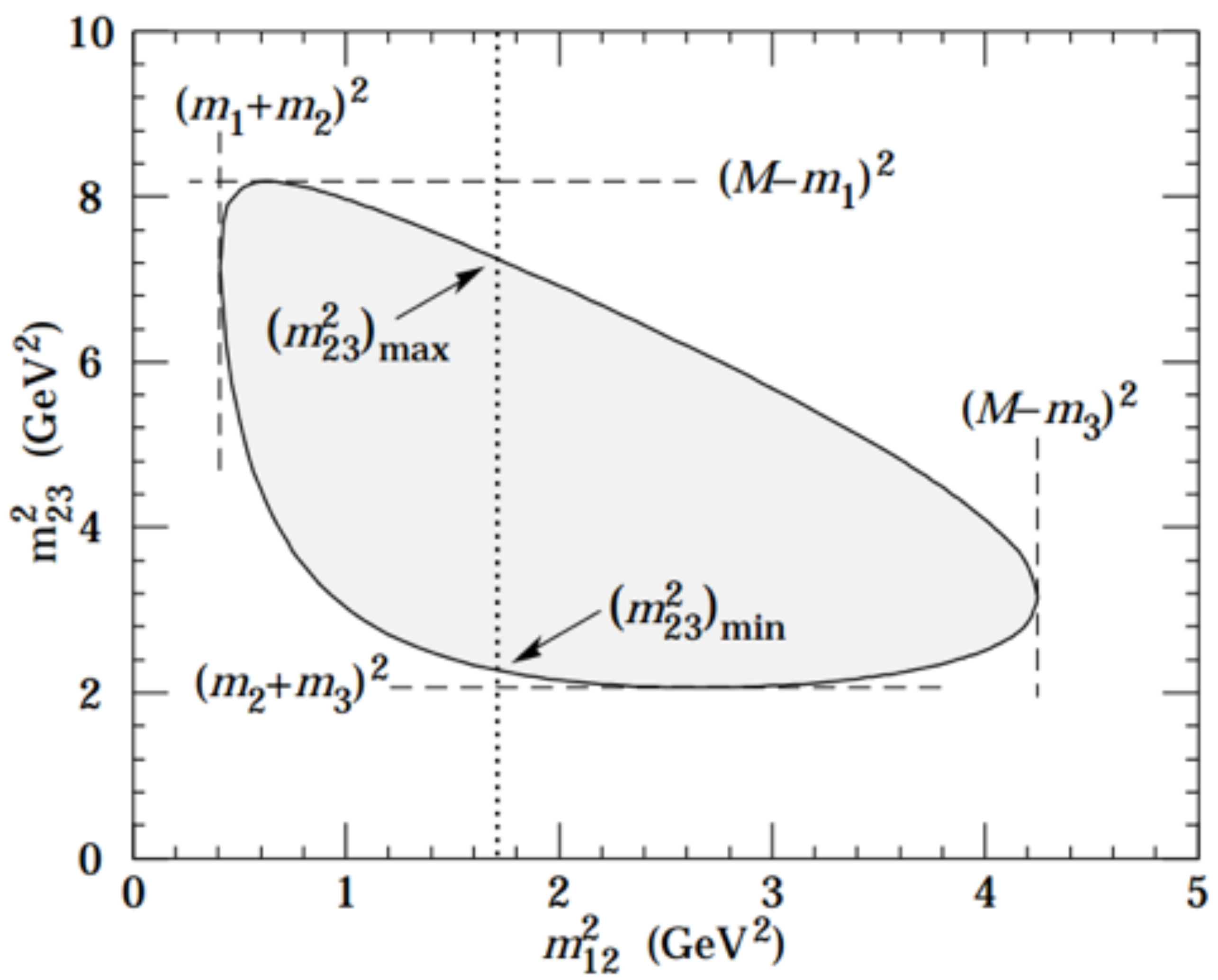
scalar ⟶ 3 scalars



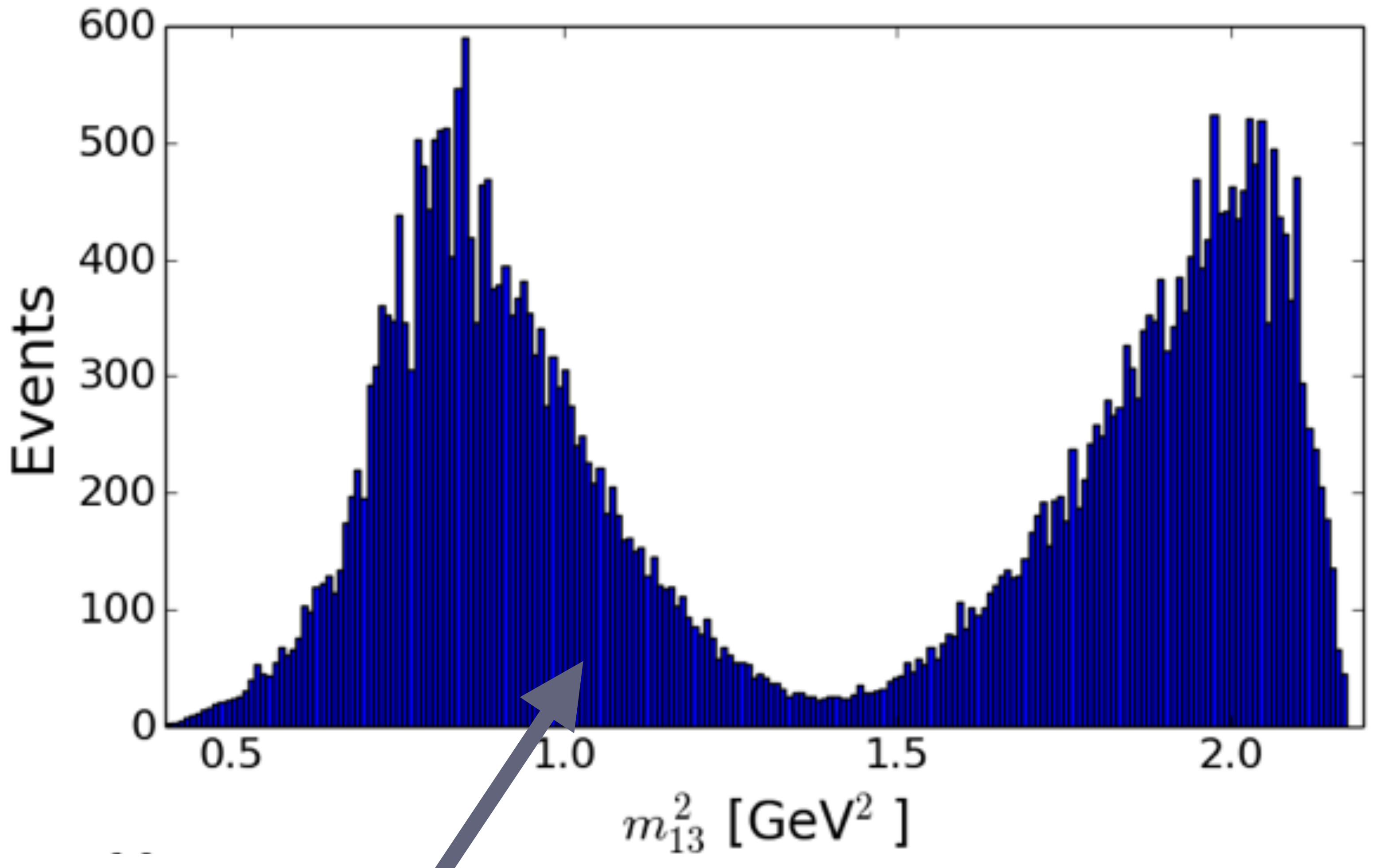
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\, dm_{12}^2\, dm_{23}^2$$

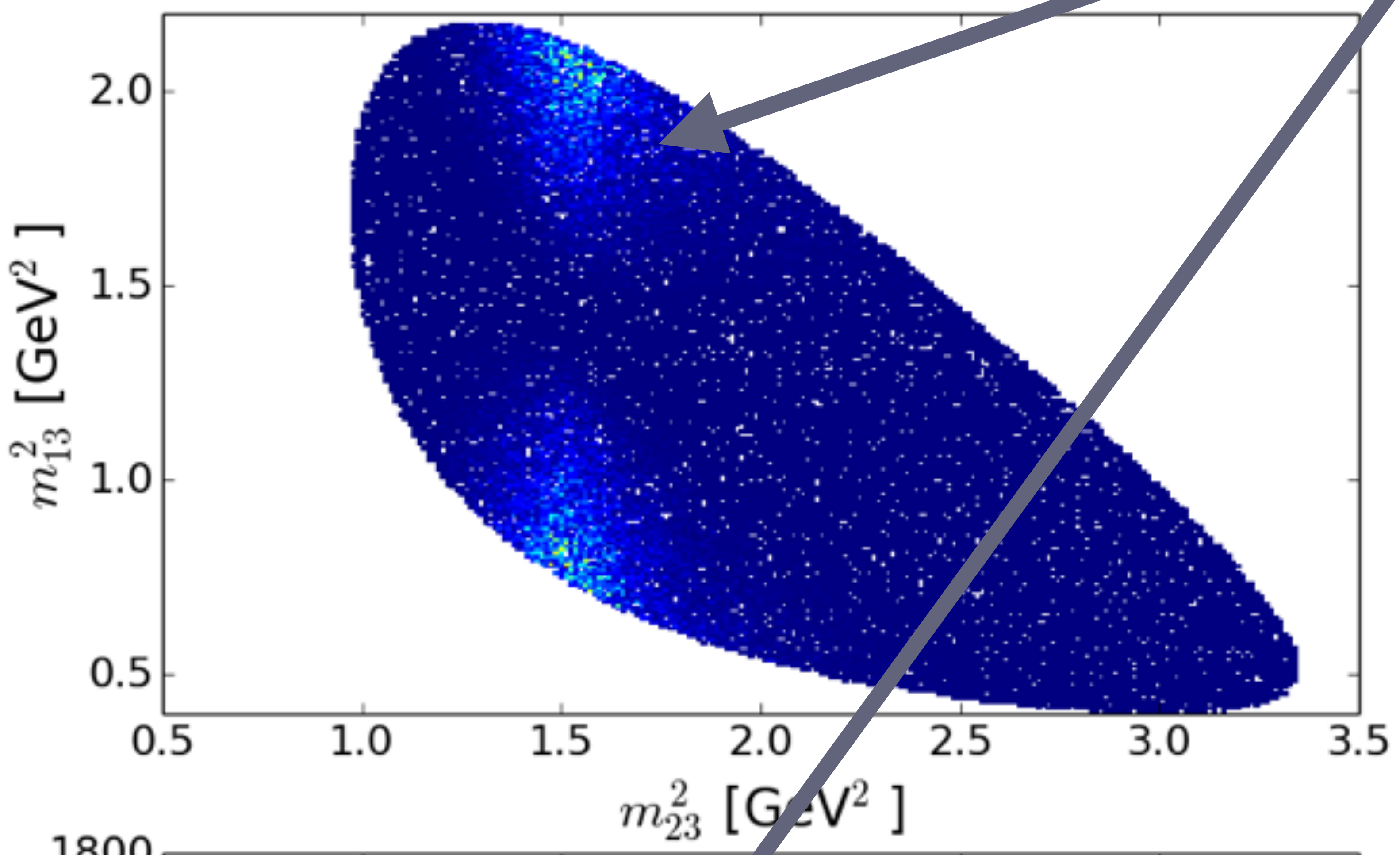
Constraints	Degrees of freedom
3 four-vectors	+12
All decay in same plane ($p_{i,z} = 0$)	−3
$E_i^2 = m_i^2 + p_i^2$	−3
Energy + momentum conservation	−3
Rotate system in plane	−1
Total	+2

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



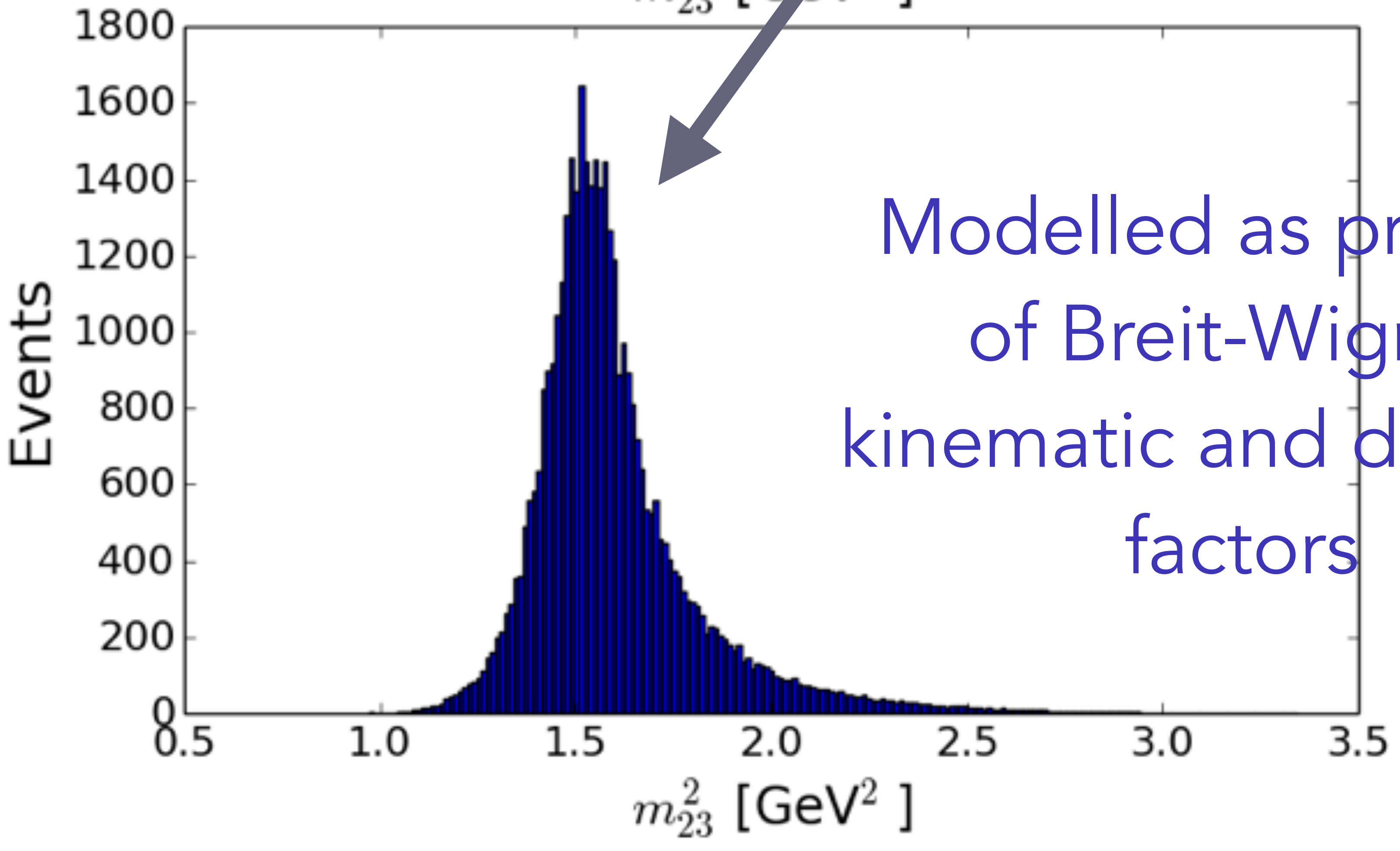
Reminder about Dalitz plots



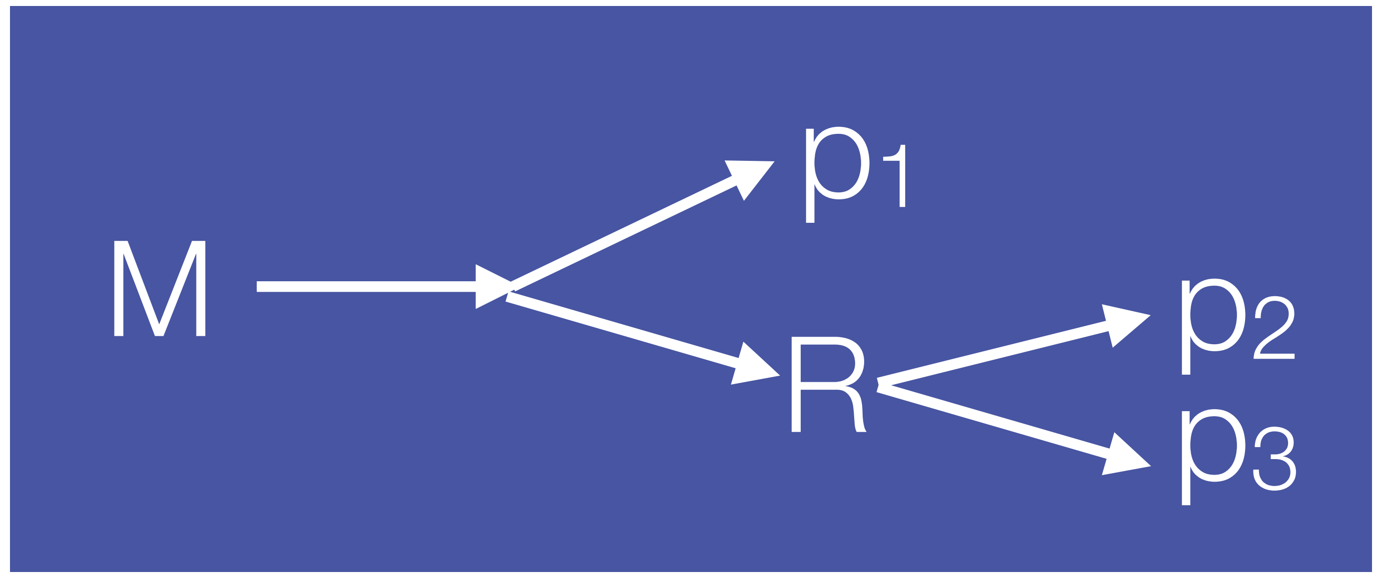


Spin-1 resonance

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

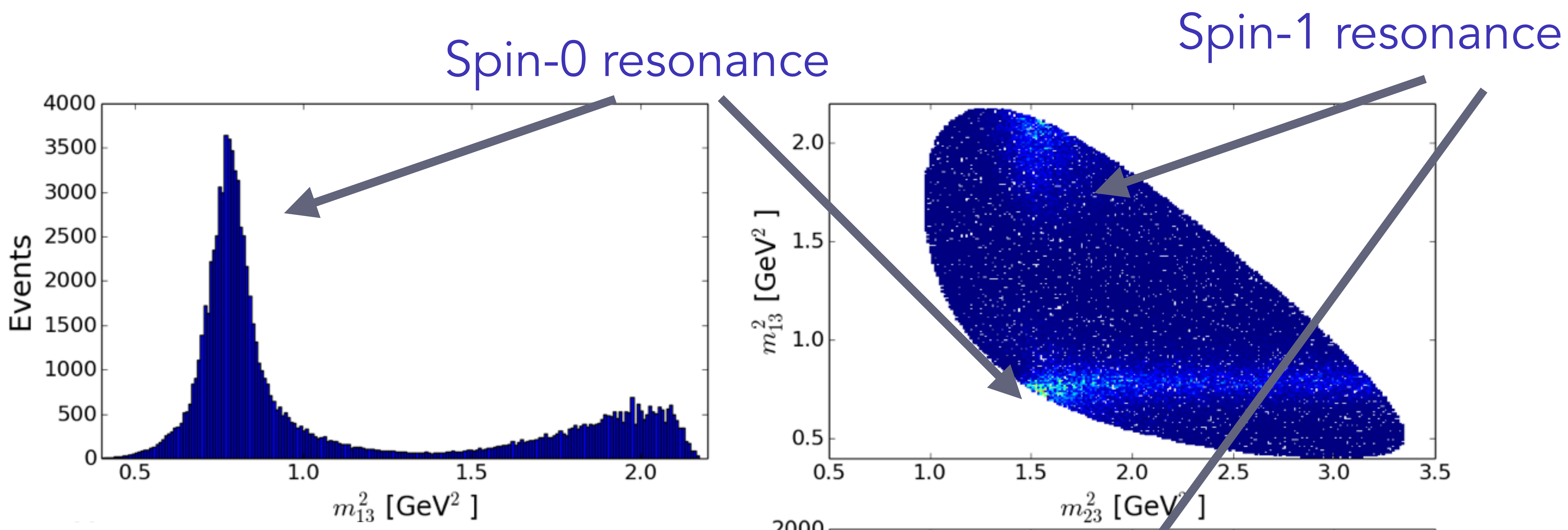


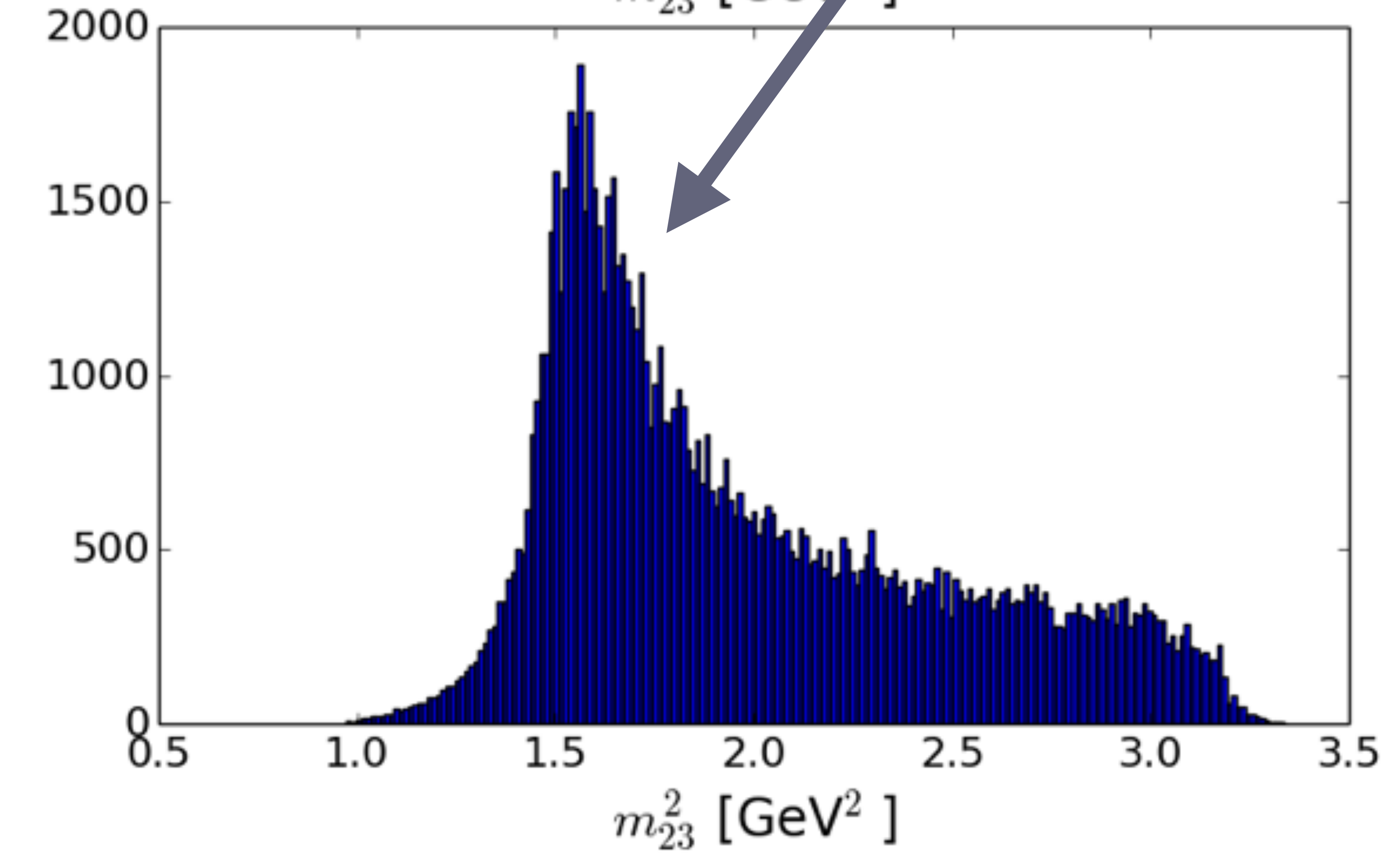
Modelled as product of Breit-Wigner, kinematic and dynamic factors



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

Reminder about Dalitz plots





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

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

Breit-Wigner amplitude

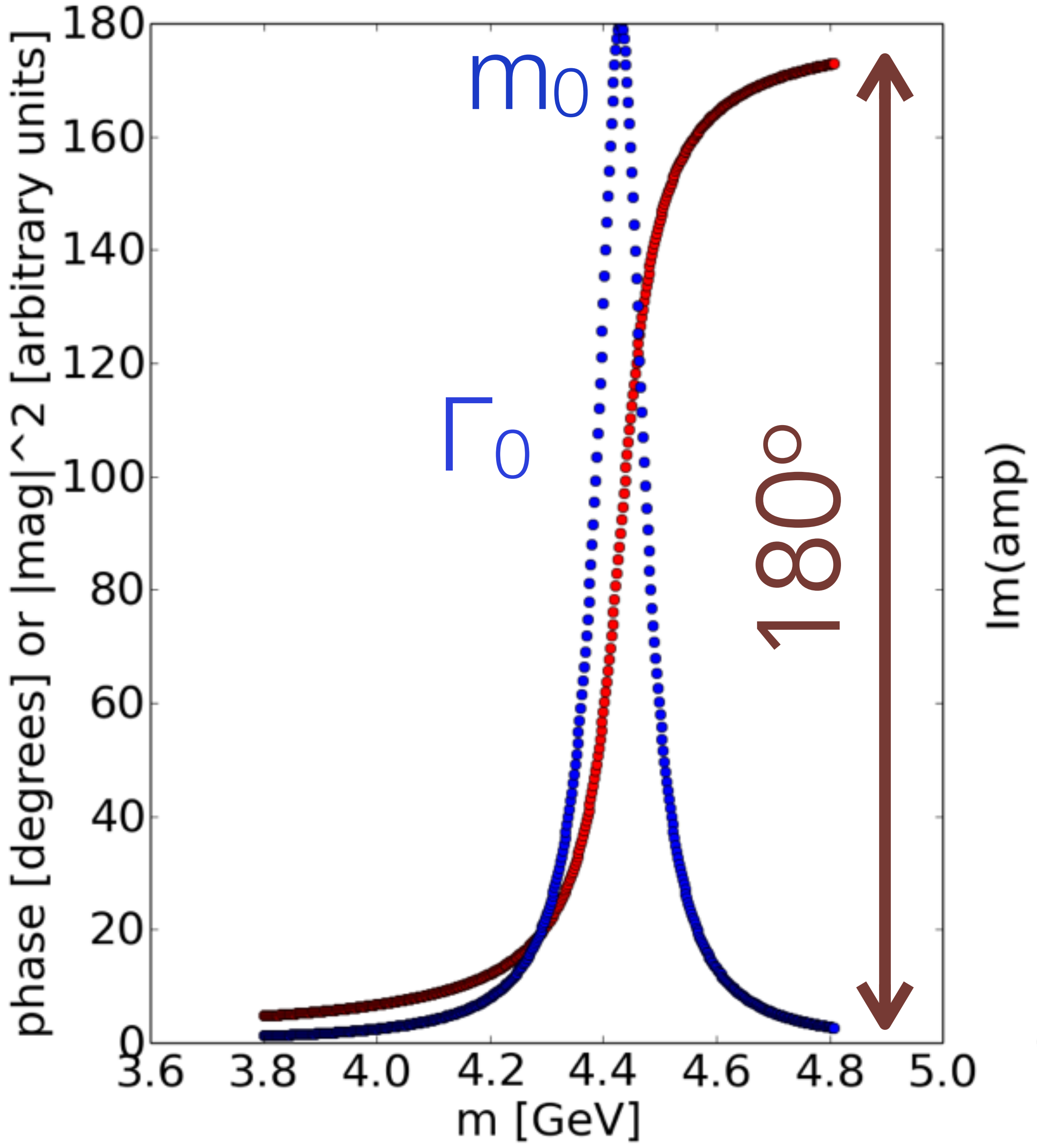
R⟶ab

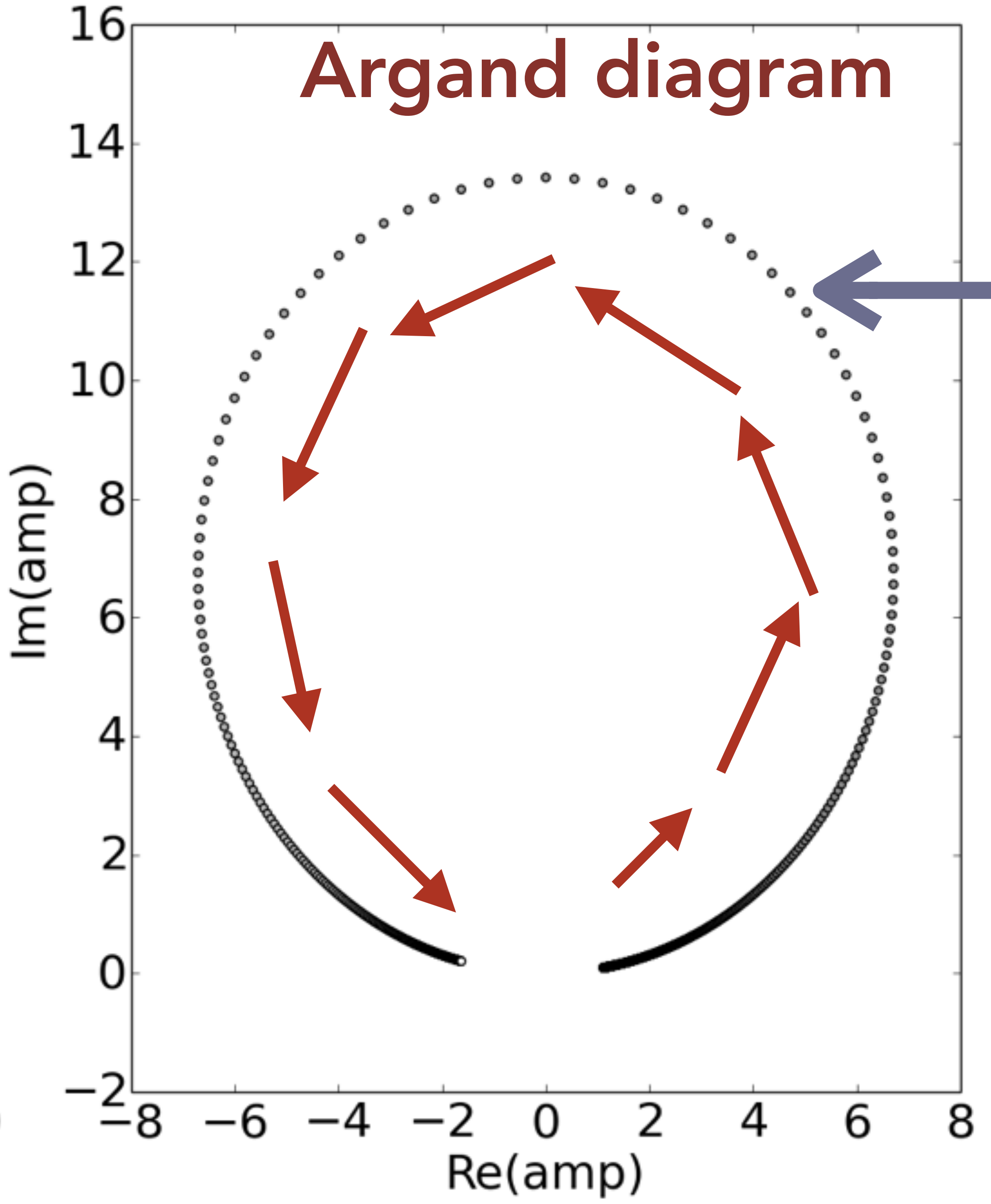
- Often model resonances with pole mass (m_0), width (Γ_0) using a relativistic Breit-Wigner function.
- q is daughter particle momentum in rest frame of resonance.
- B_L' are Blatt-Weisskopf functions for the orbital angular momentum (L) barrier factors.
- Amplitude = $|BW|^2$

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

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

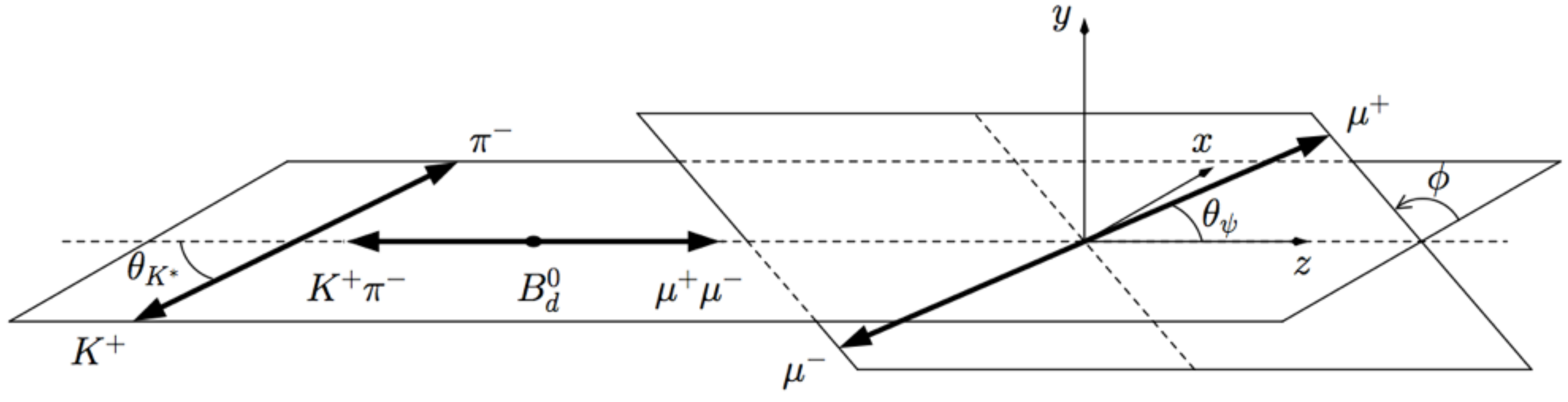
size of the decaying particle (1.6/GeV)





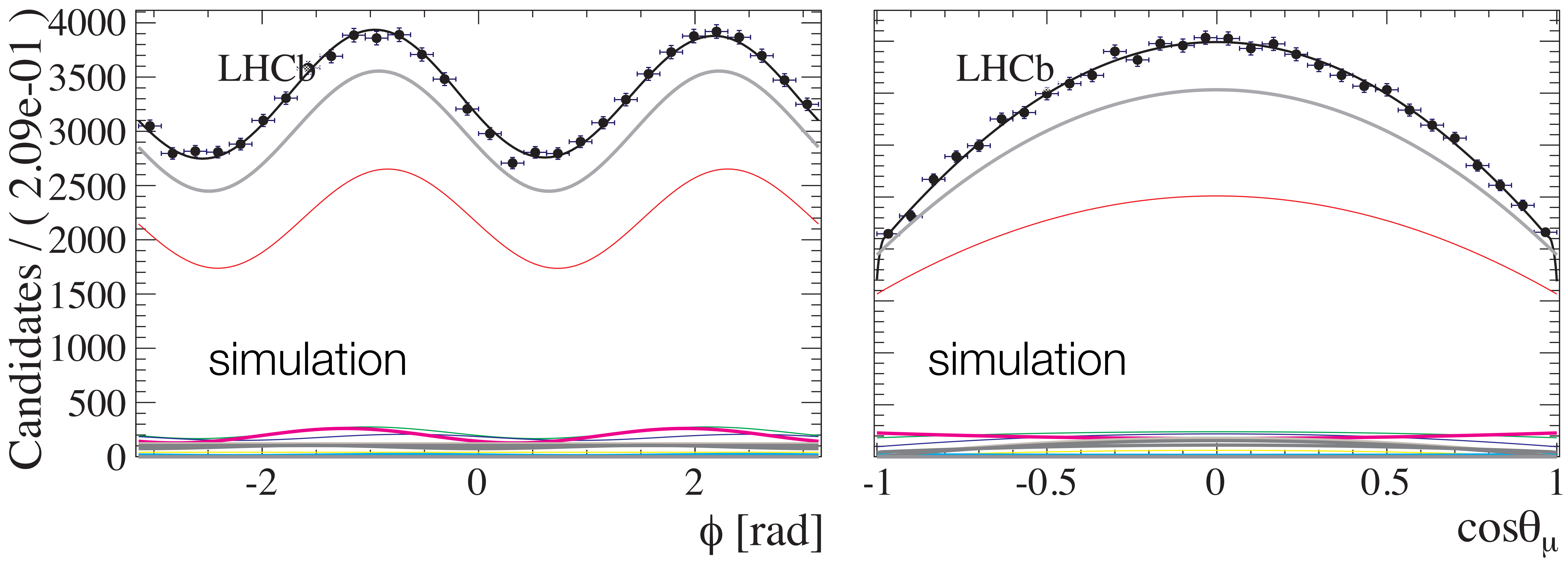
- Circular trajectory in complex plane is characteristic of resonance
- Circle can be rotated by arbitrary phase
- Phase change of 180° across the pole

4D "Dalitz plot" (scalar ⟶ vector scalar scalar)



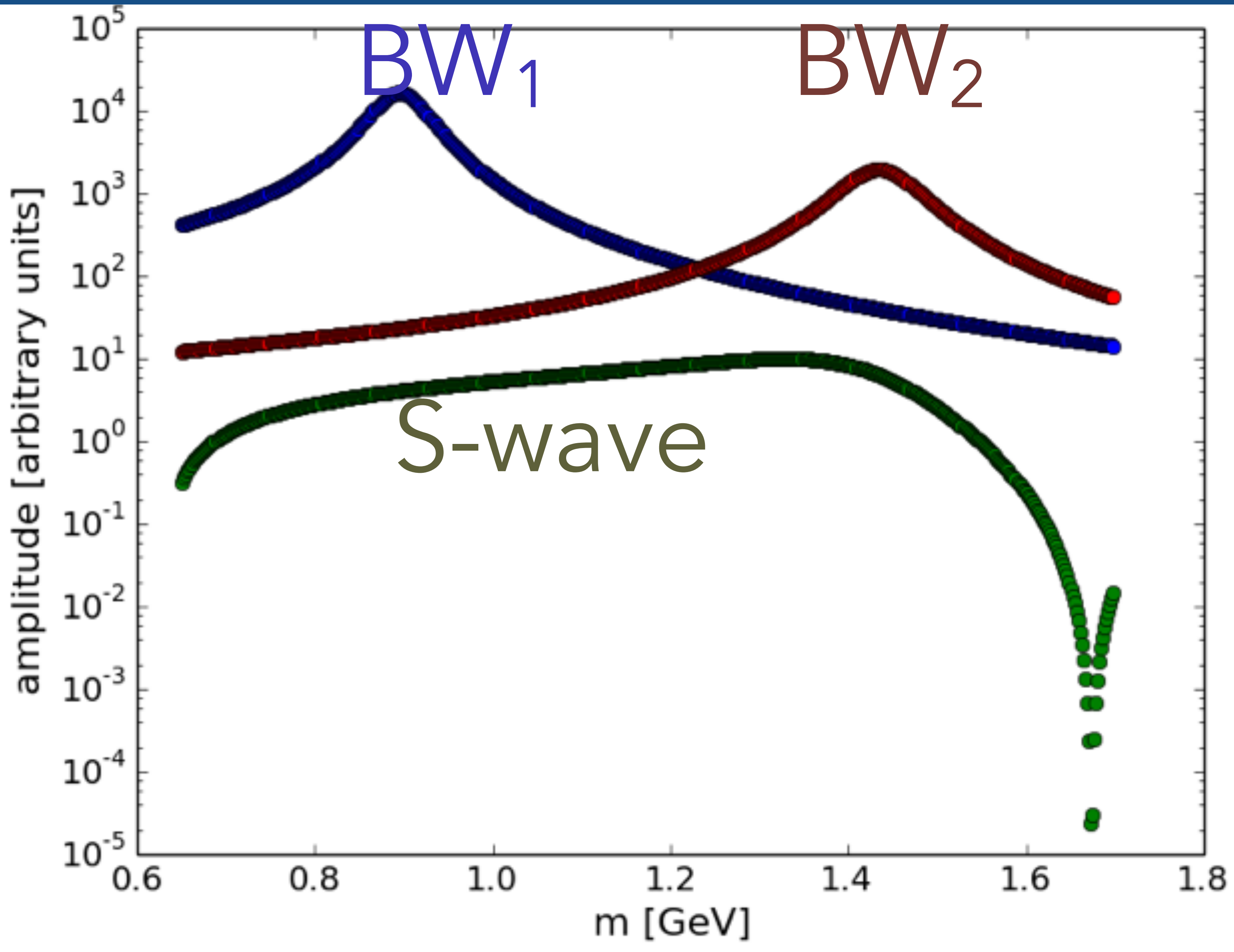
Constraints	Degrees of freedom
3 four-vectors	+12
All decay in same plane ($p_{i,z} = 0$)	−3
$E_i^2 = m_i^2 + p_i^2$	−3
Energy + momentum conservation	−3
Rotate system in plane	−1
Vector helicity	+2
Total	+4

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



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

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

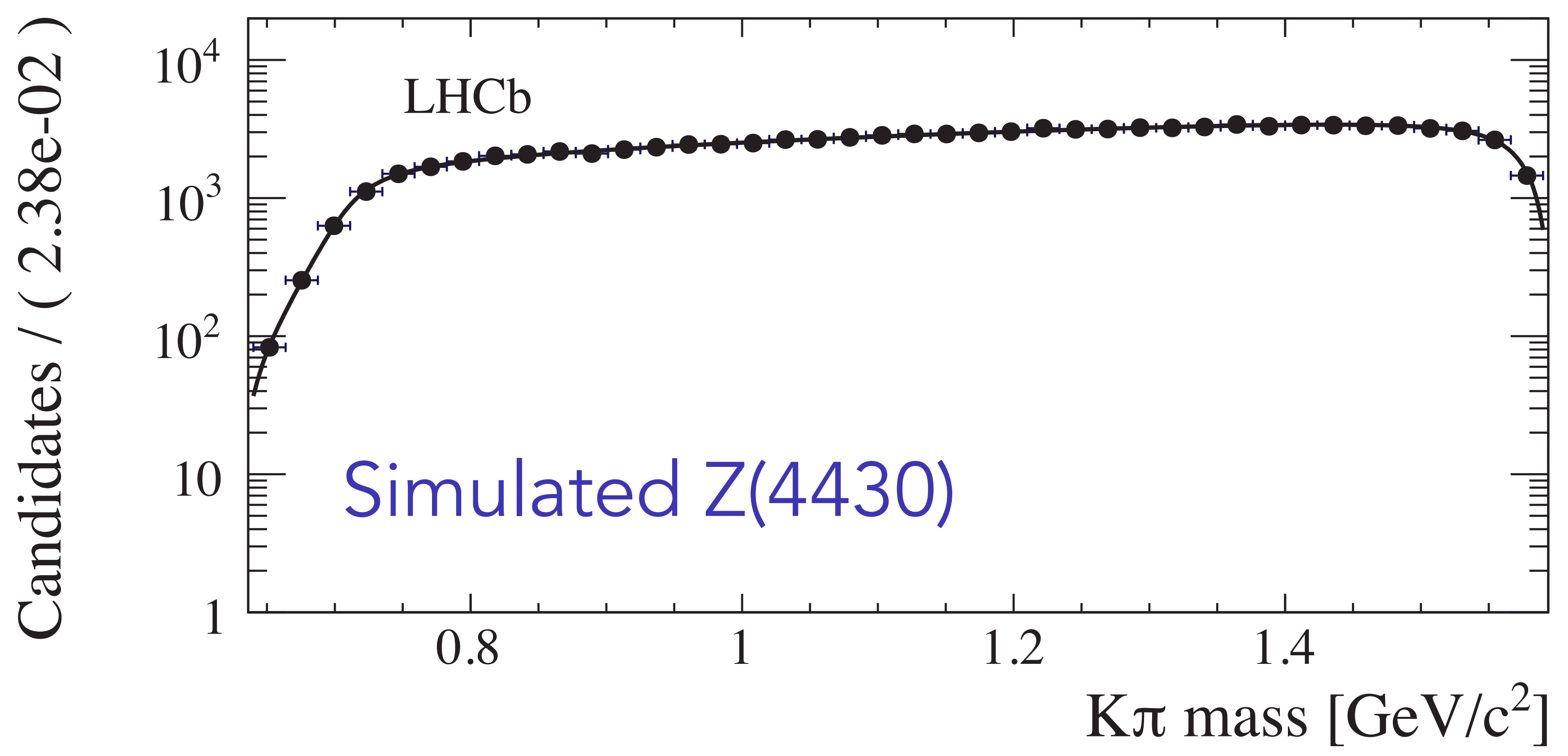
In 4D fit, $\mu^+\mu^-$ are final state particles so different dimuon helicity amplitudes are incoherent (cannot interfere)

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 ⇒ $A_{Z,-1} = A_{Z,0} = A_{Z,+1}$



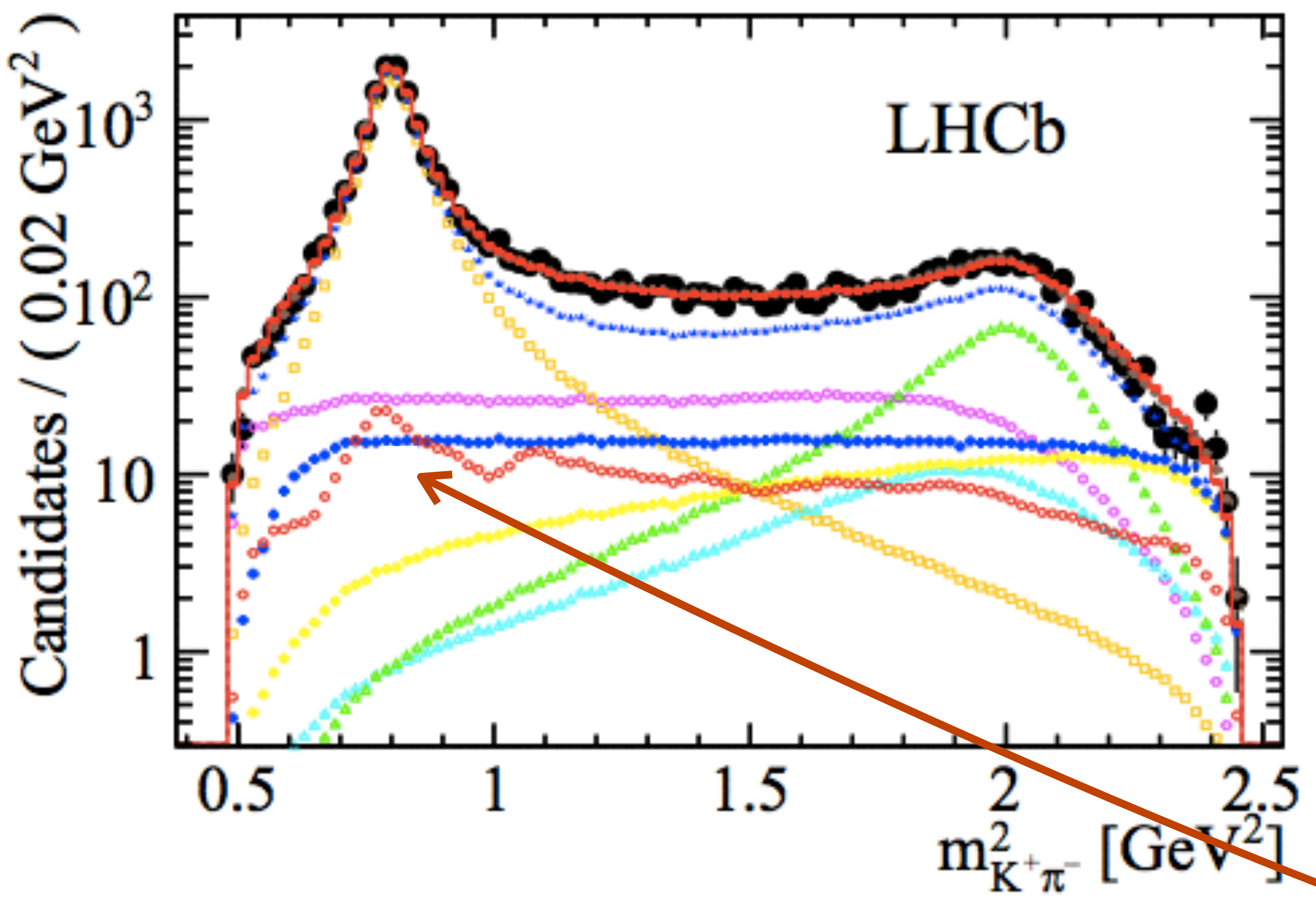
$$|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega | m_{0\,k}, \Gamma_{0\,k}) + \sum_{\lambda_\psi^Z=-1,0,1} A_{Z,\lambda_\psi^Z}(m_{\psi\pi}, \Omega^Z | m_{0\,Z}, \Gamma_{0\,Z}) e^{i\Delta\lambda_\mu \alpha} \right|^2$$

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)	$\mathcal{B}(K^{*0} \to K^+\pi^-)$
$K_0^*(800)^0$ (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	$(6.1 \pm 1.2)\%$

- $K^+\pi^-$ 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.

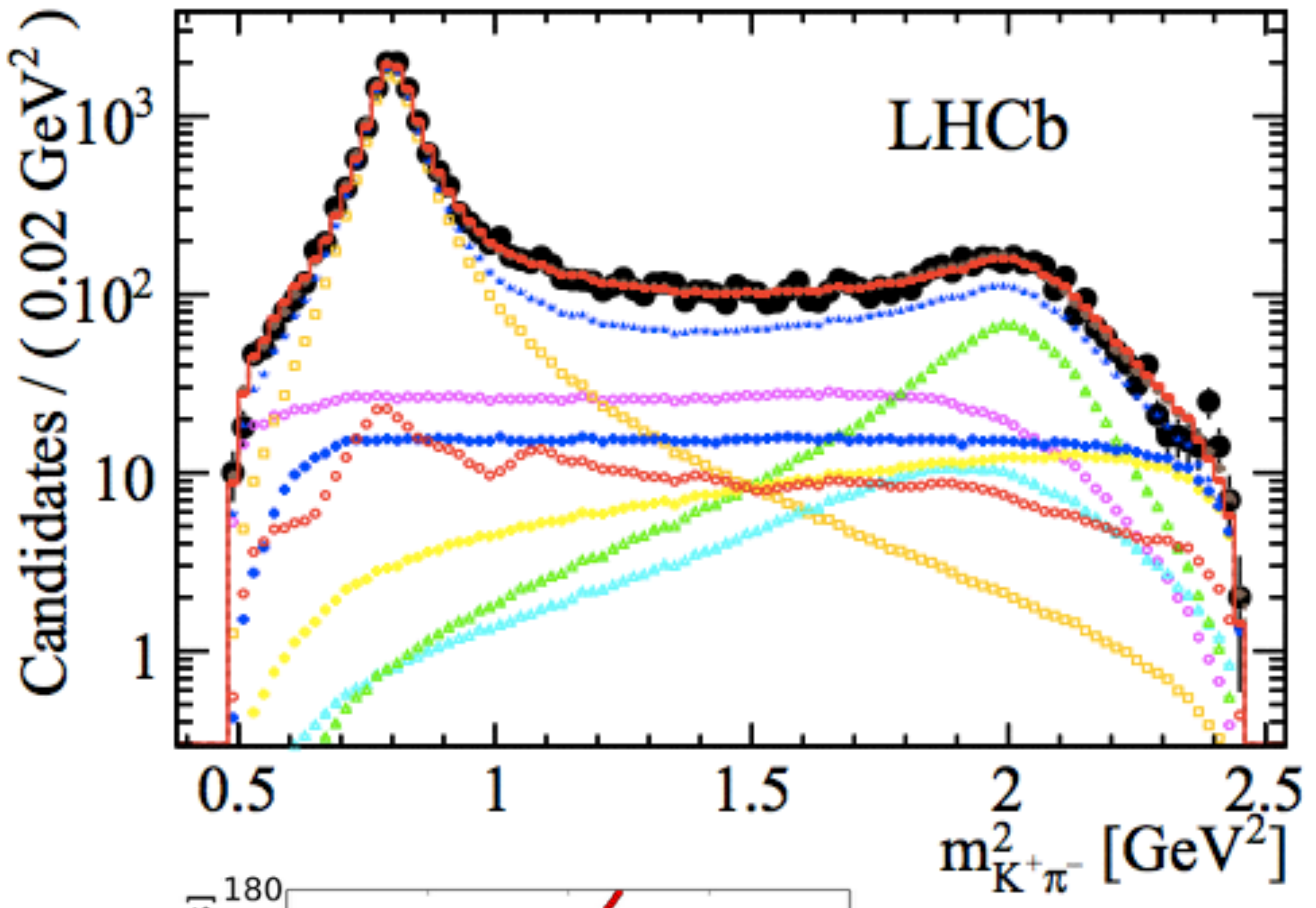
- Default result includes all resonances up to $K^*_1(1680)$ (**J ≤ 2**).
- Main source of **systematic uncertainties** comes from varying model to include higher $K^+\pi^-$ spin-states (J = 3, 4, 5).

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)

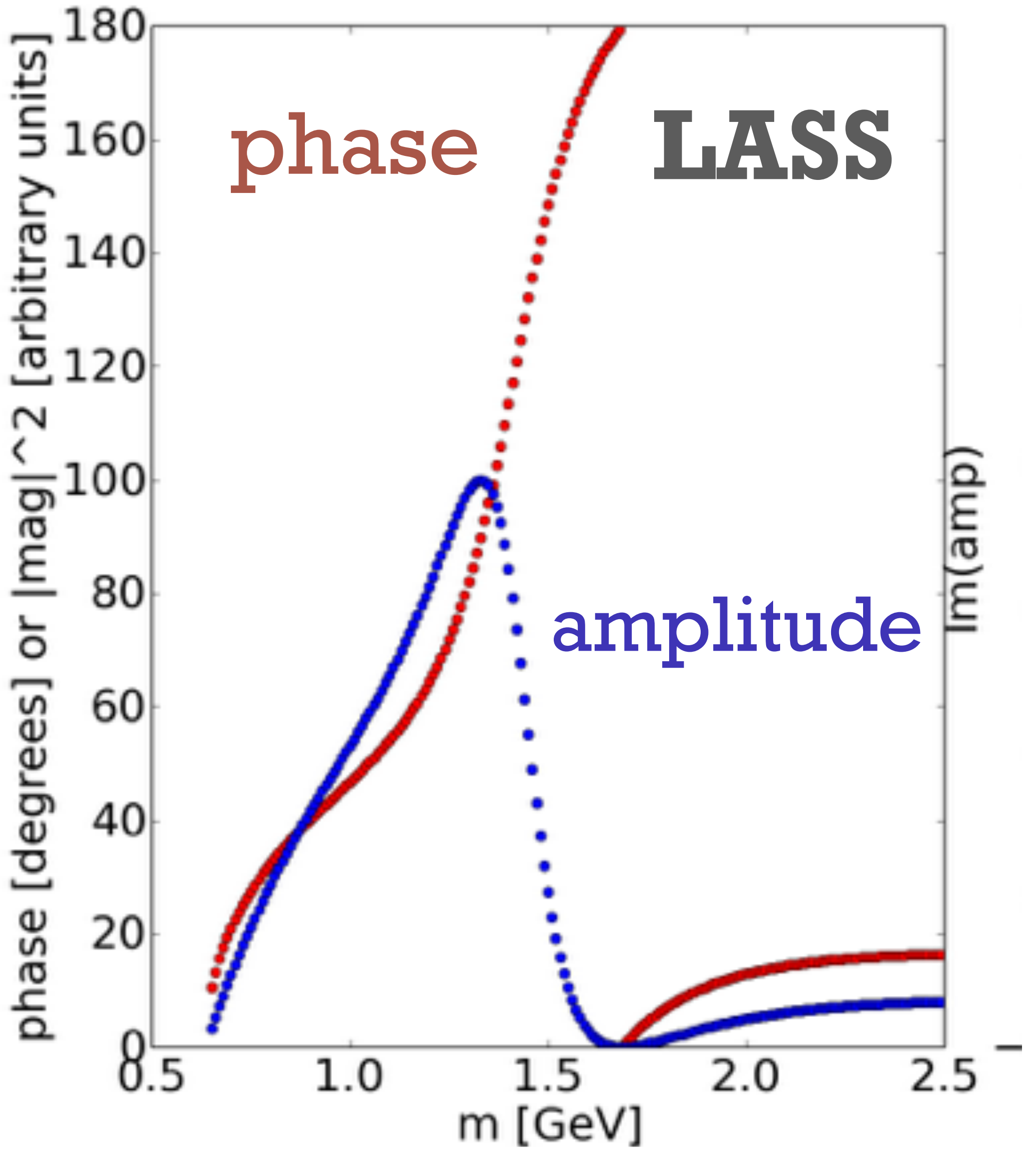


Slowly varying NR contribution

BW amplitude for K(1430)

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

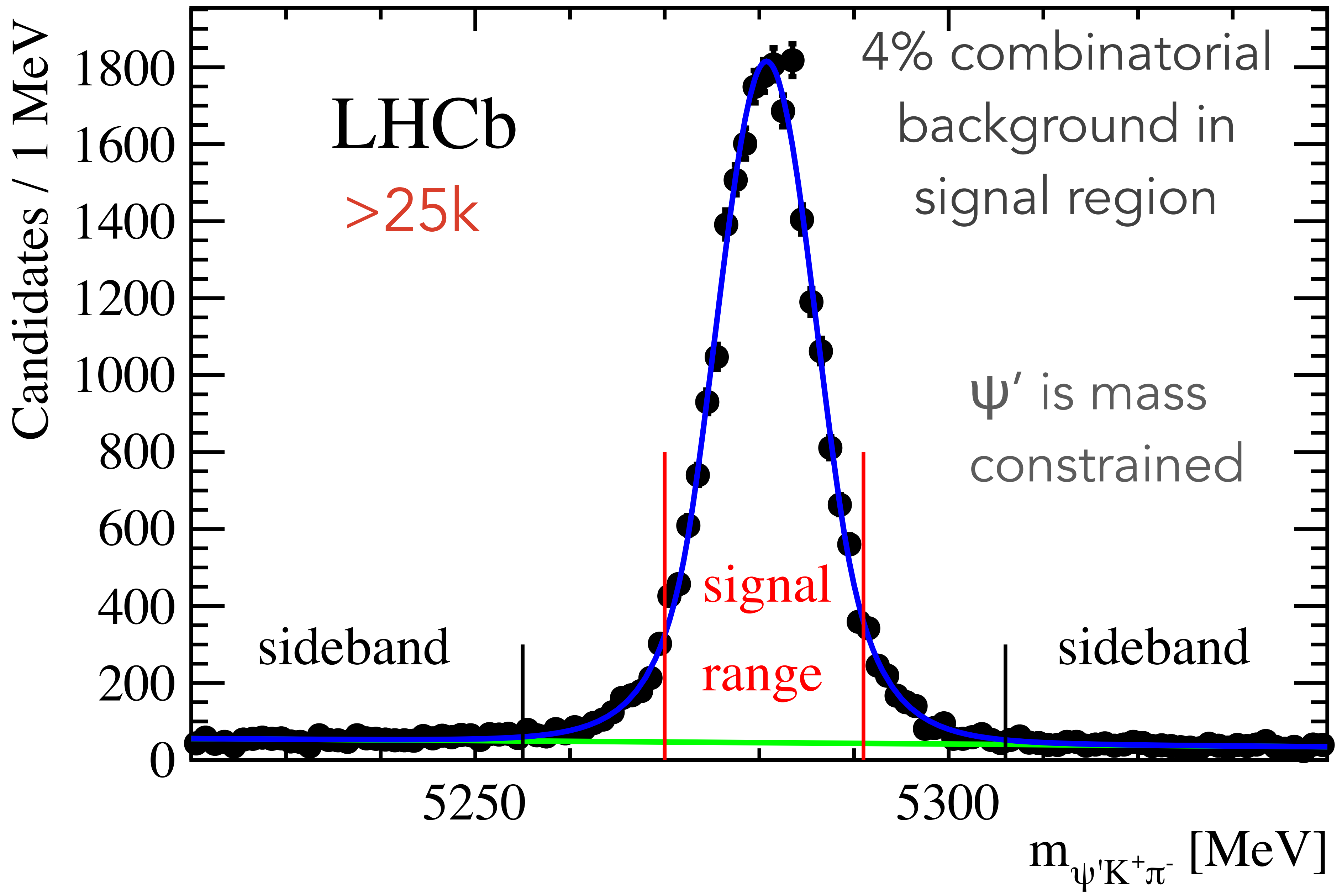
$$\cot\delta_B(m_{K\pi}) = \frac{1}{a\,q} + \frac{1}{2}r\,q \qquad \cot\delta_R(m_{K\pi}) = \frac{m_0^2 - m_{K\pi}^2}{m_0\Gamma(m_{K\pi})}$$

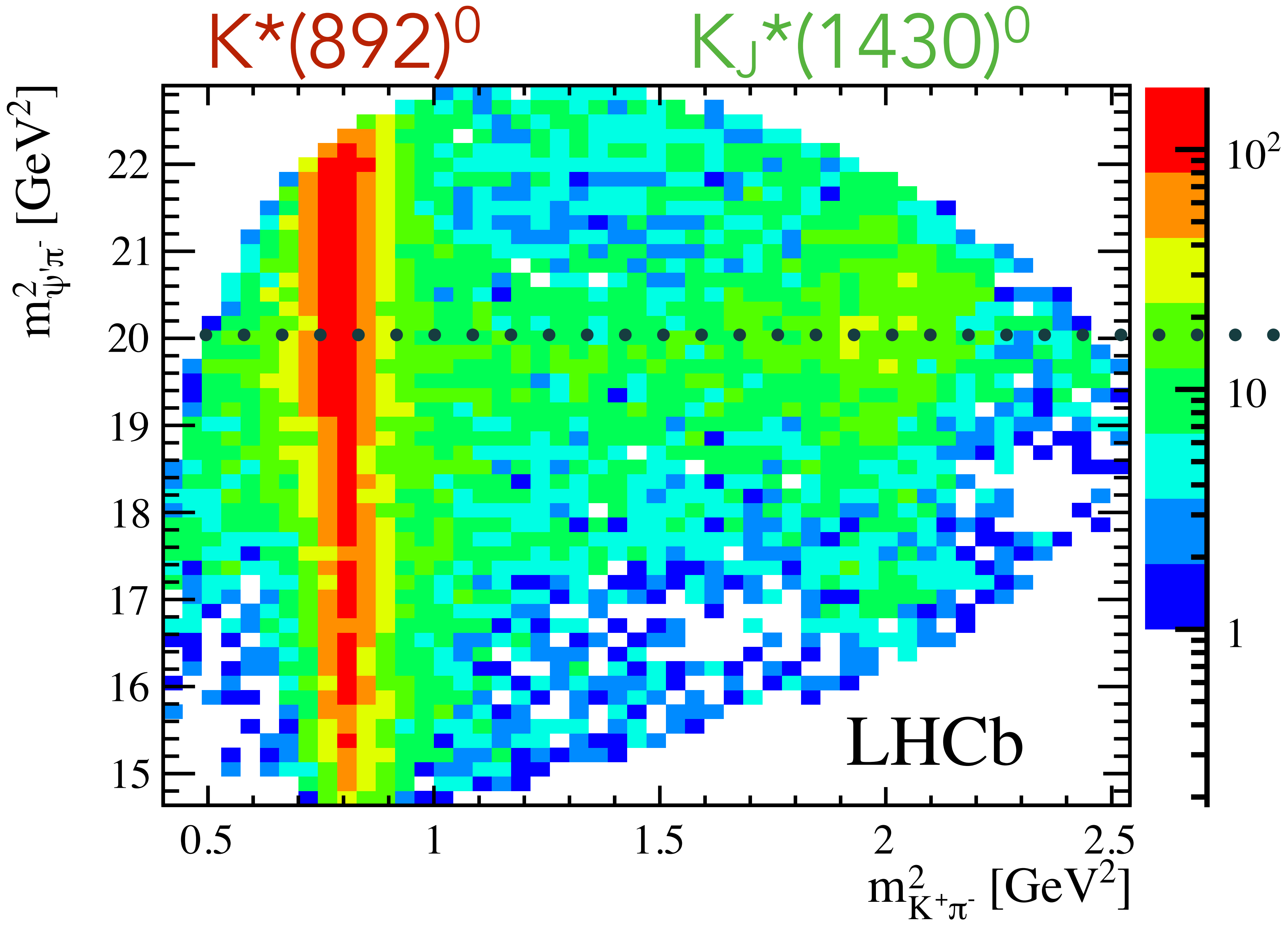


Confirmation of the Z(4430)$^{\pm}$ [PRL 112 (2014) 222002]

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

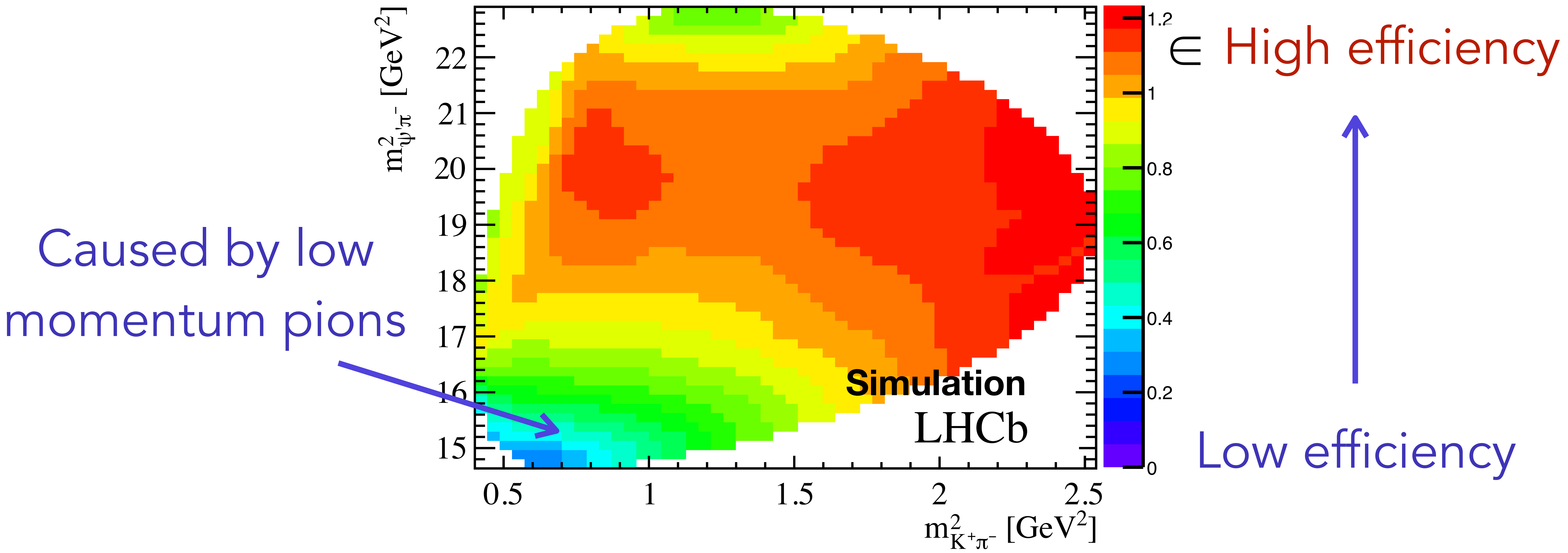
Only 2 of the 4 dimensions…





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

Observables (mass, angles)

PDF

Parameters

Efficiency drops out

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

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

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

- 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.

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

$Z(4430)^{\pm}$ 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	$10.3^{+3.0}_{-3.5}$

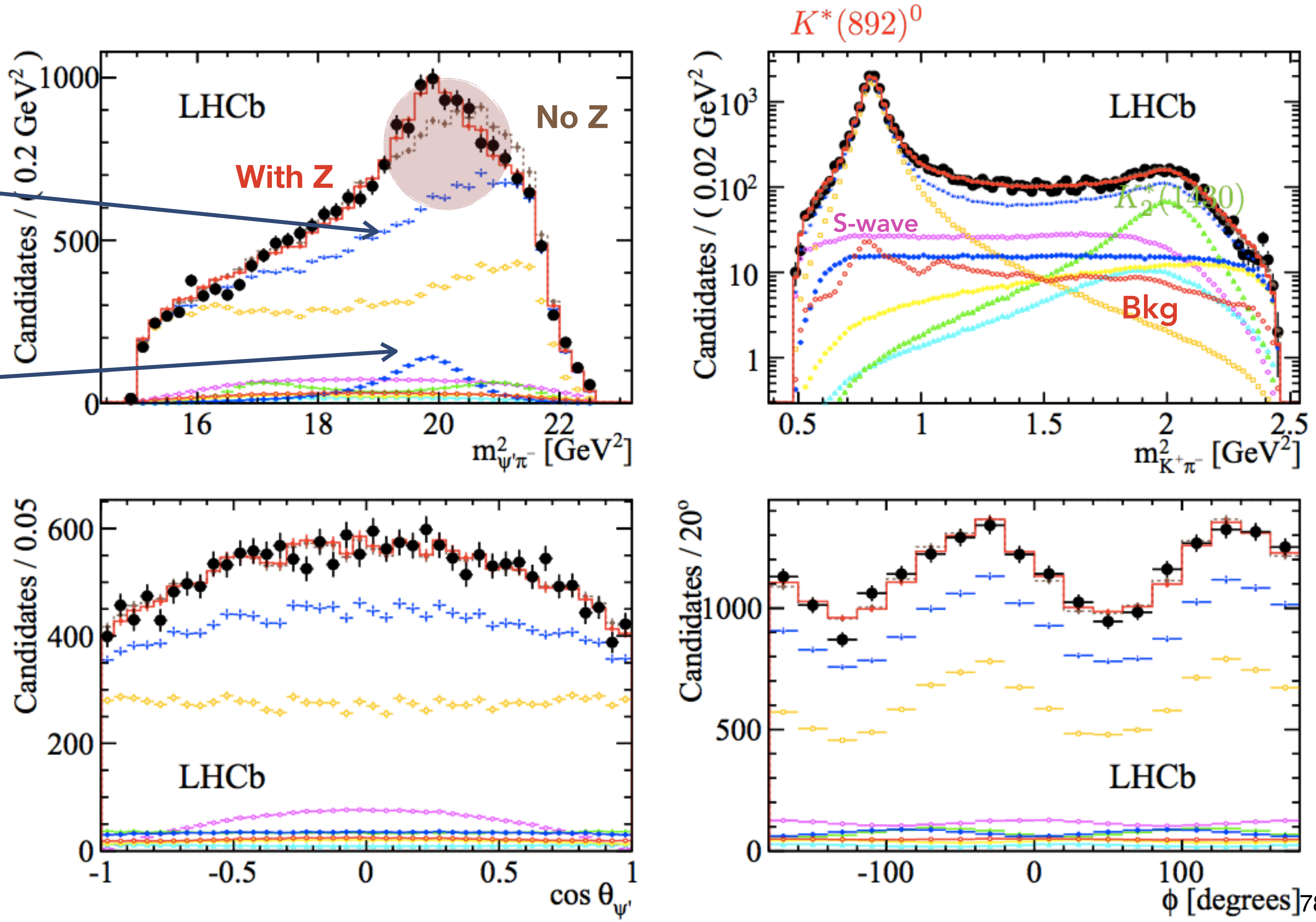
- Excellent agreement between LHCb and Belle.
- Large width - unlikely to be molecule?

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

Confirmation of the Z(4430)$^{\pm}$ [PRL 112 (2014) 222002]

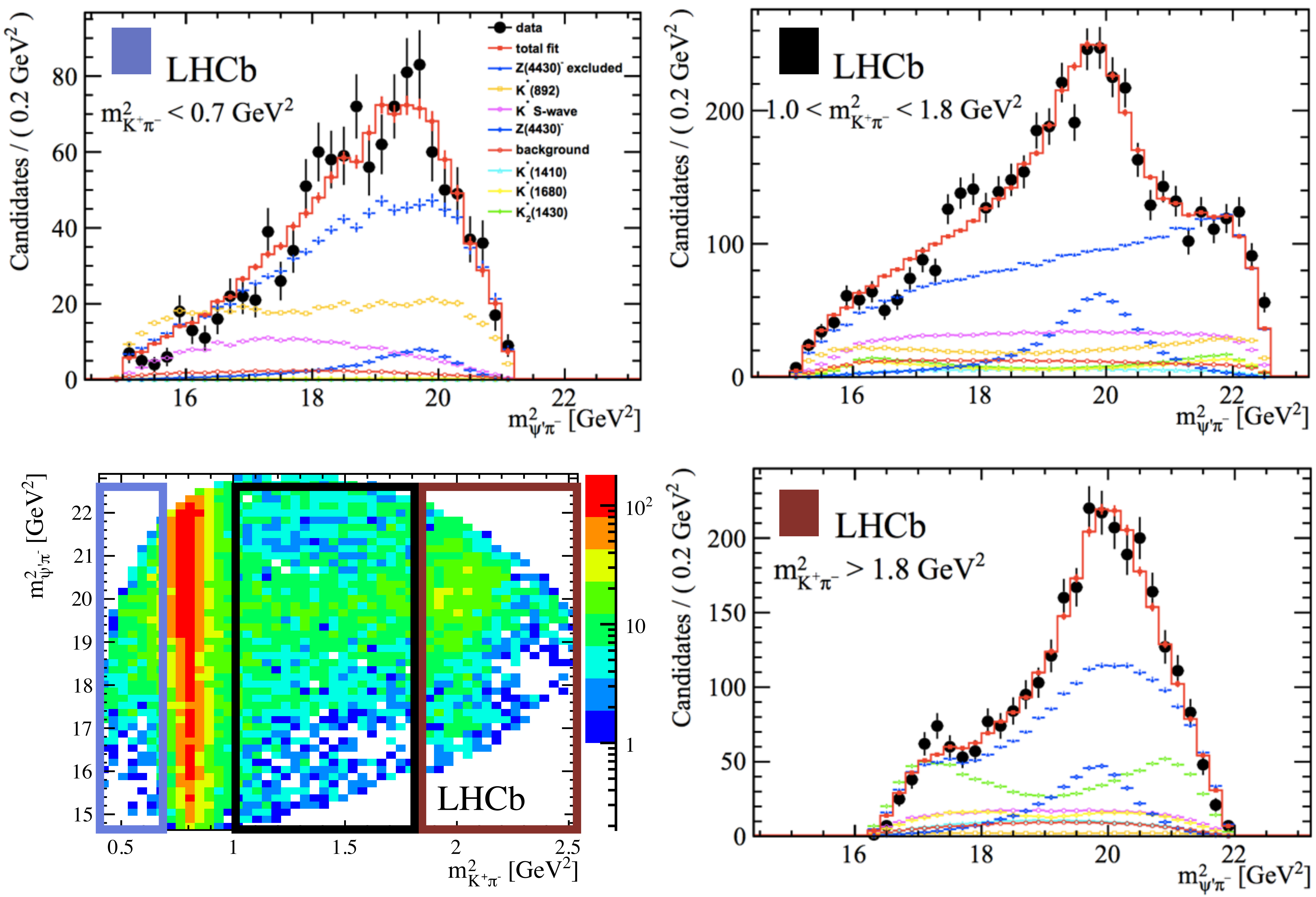
Everything except the Z ⇒ large interference between Z and $K^+\pi^-$ sector

Z component $J^P = 1^+$



- LHCb has sample of >25k B0 ⟶ $\psi' K^+\pi^-$ candidates (x10 Belle/BaBar).
- 4D amplitude analysis performed.

Fit projections in slices of m(K⁺π⁻)

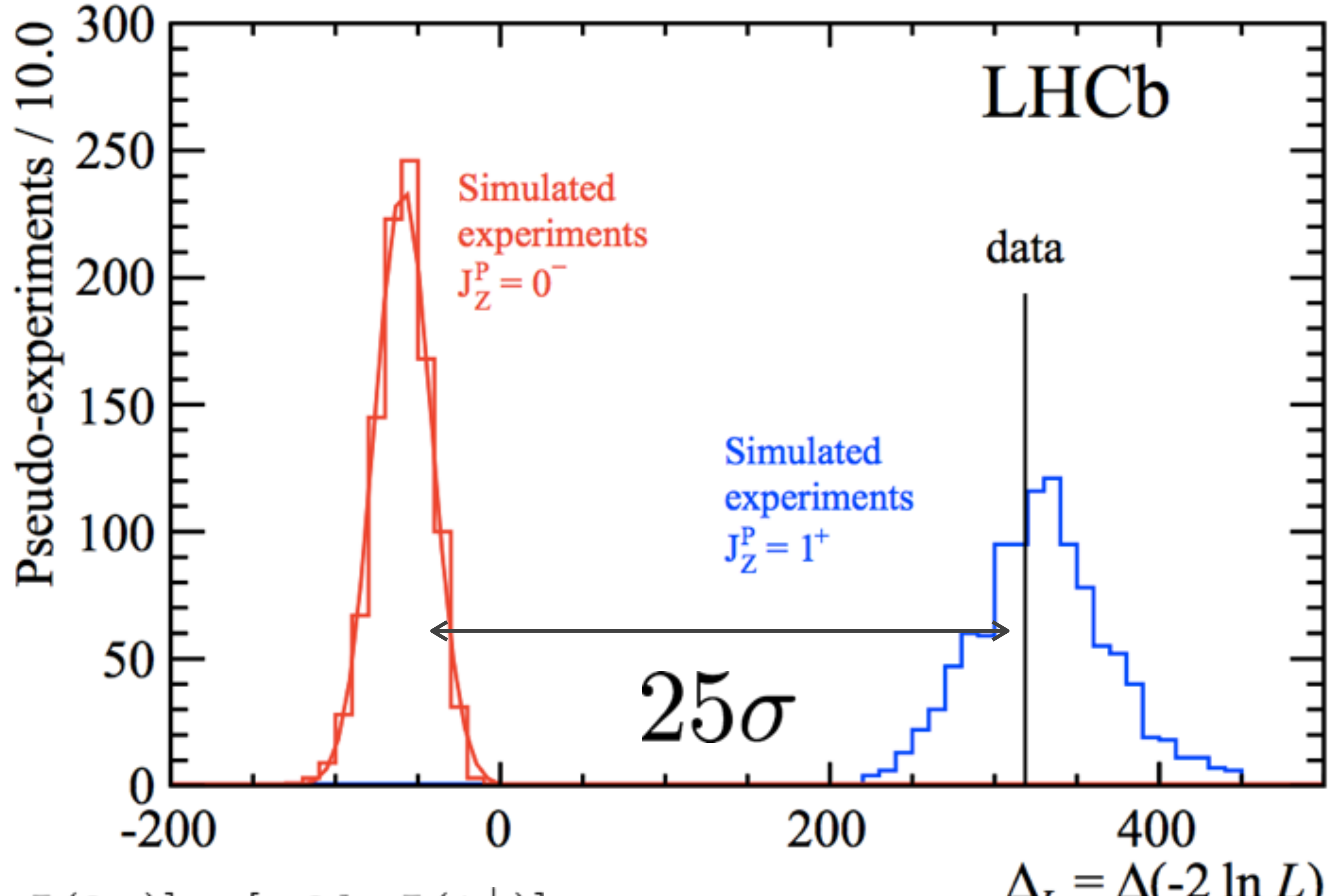


[PRL 112 (2014) 222002]

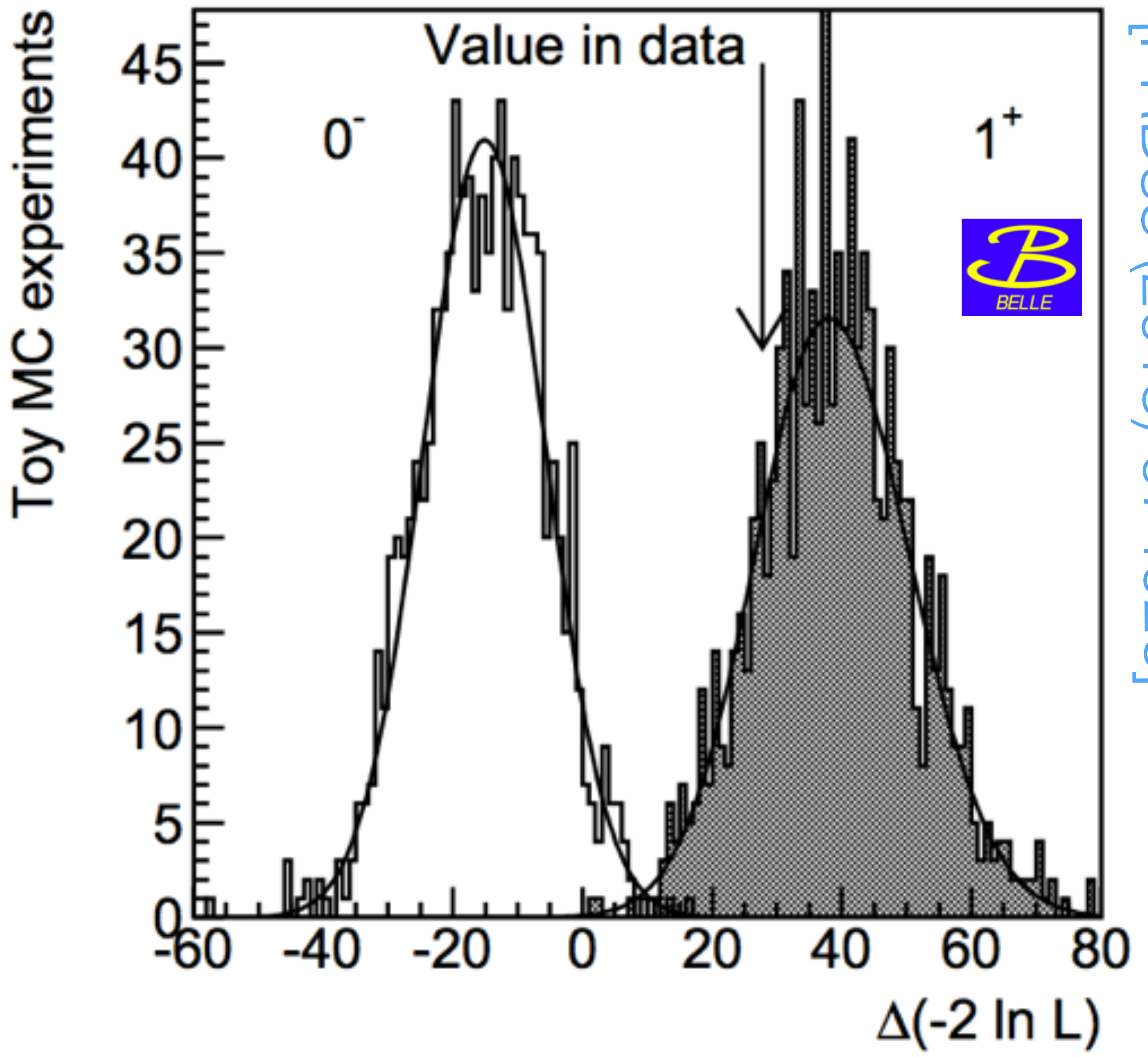
Spin determination

- 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).
- Positive parity rules out Z being $D^*(2007)D_1(2420)$ molecule.

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



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



[PRD88 (2013) 074026]

Systematics: second exotic Z?

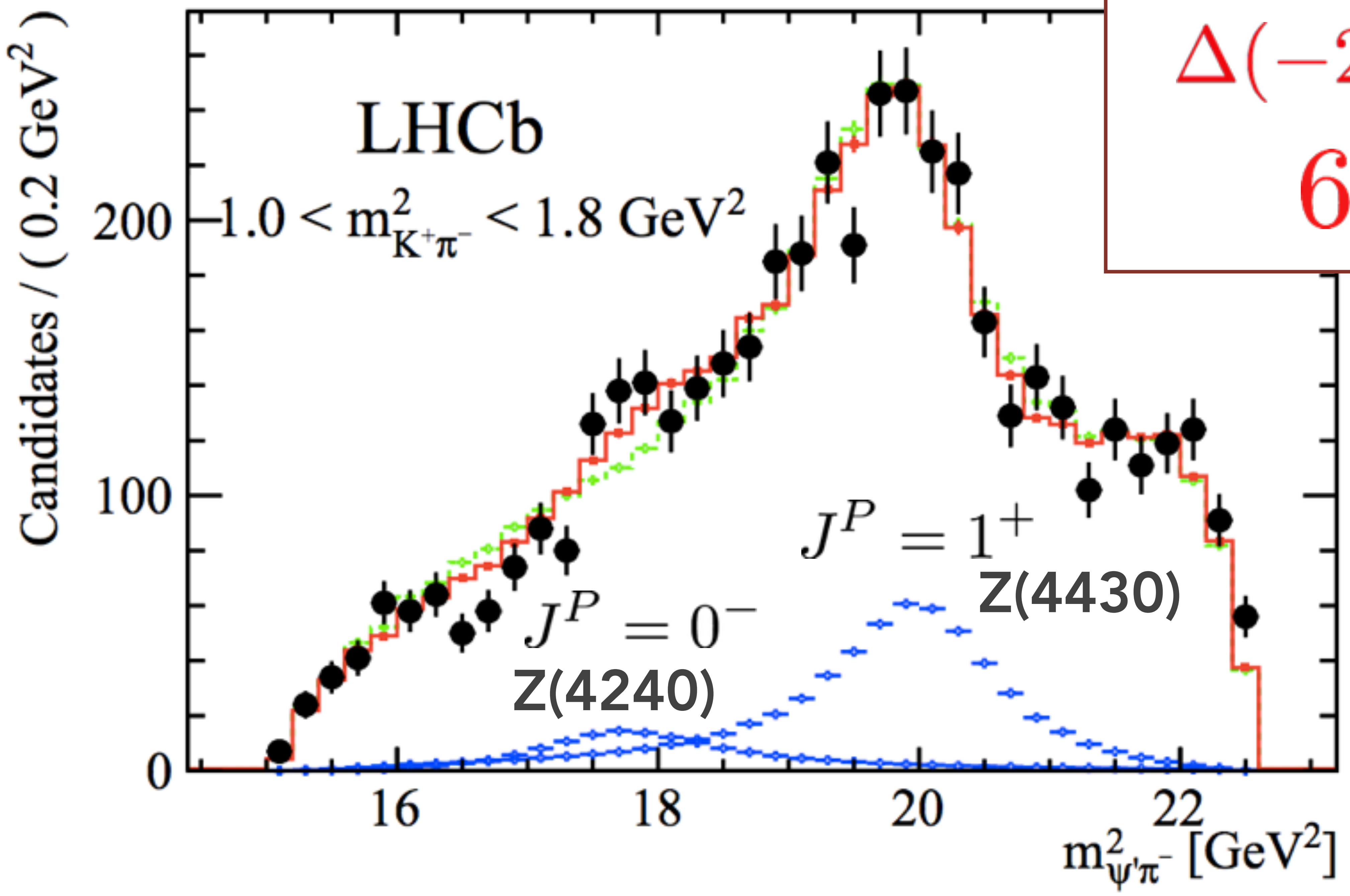
- Fit confidence level increases to 26% with a second exotic ($J^P=0^-$) component, but…
  - No evidence for Z_0 in model independent approach.
  - Argand diagram for Z_0 is inconclusive.
- Need larger samples to characterise this state.

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 $\chi_{c1}\pi^-$

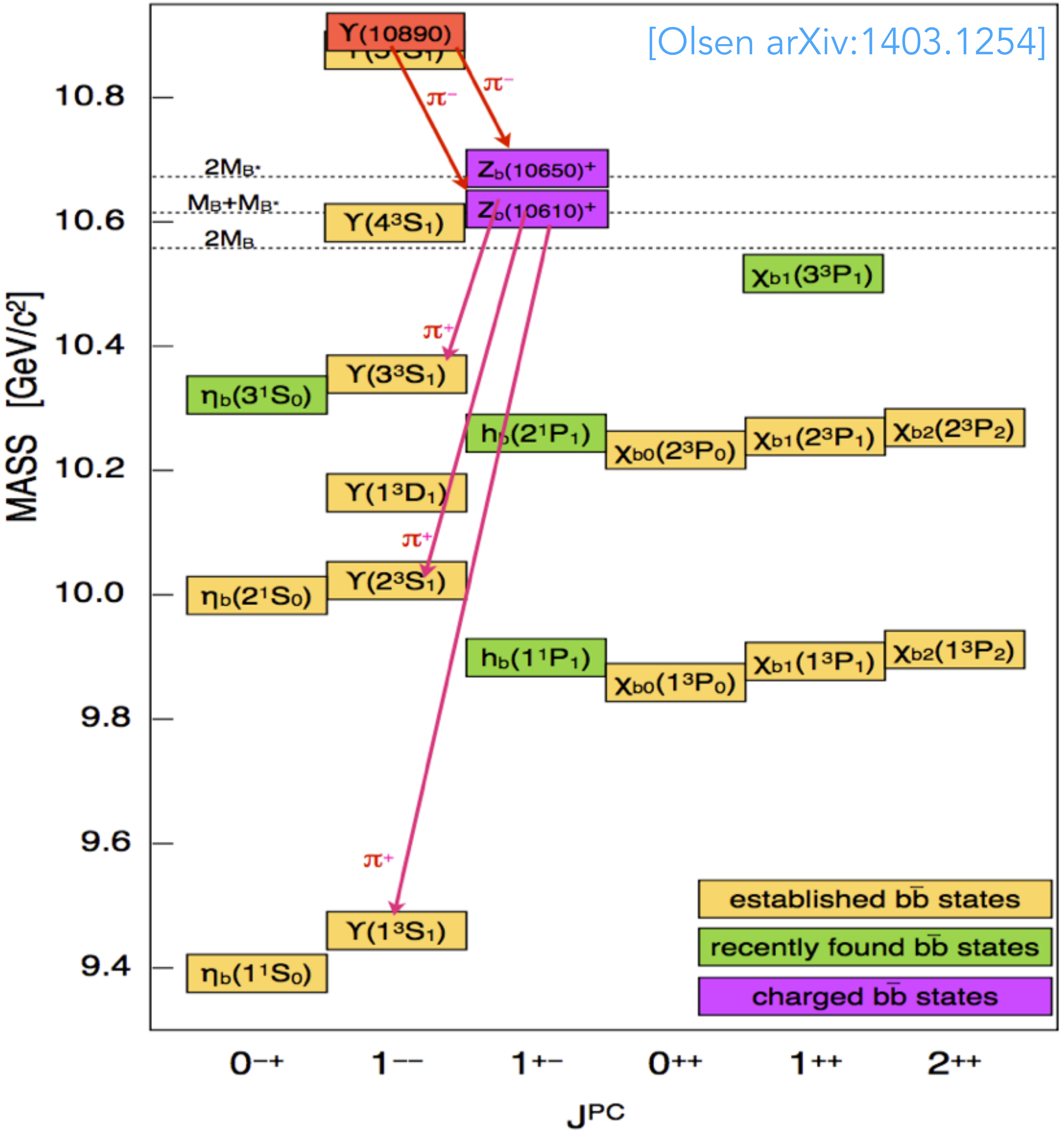
[PRD 78 (2008) 072004]



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

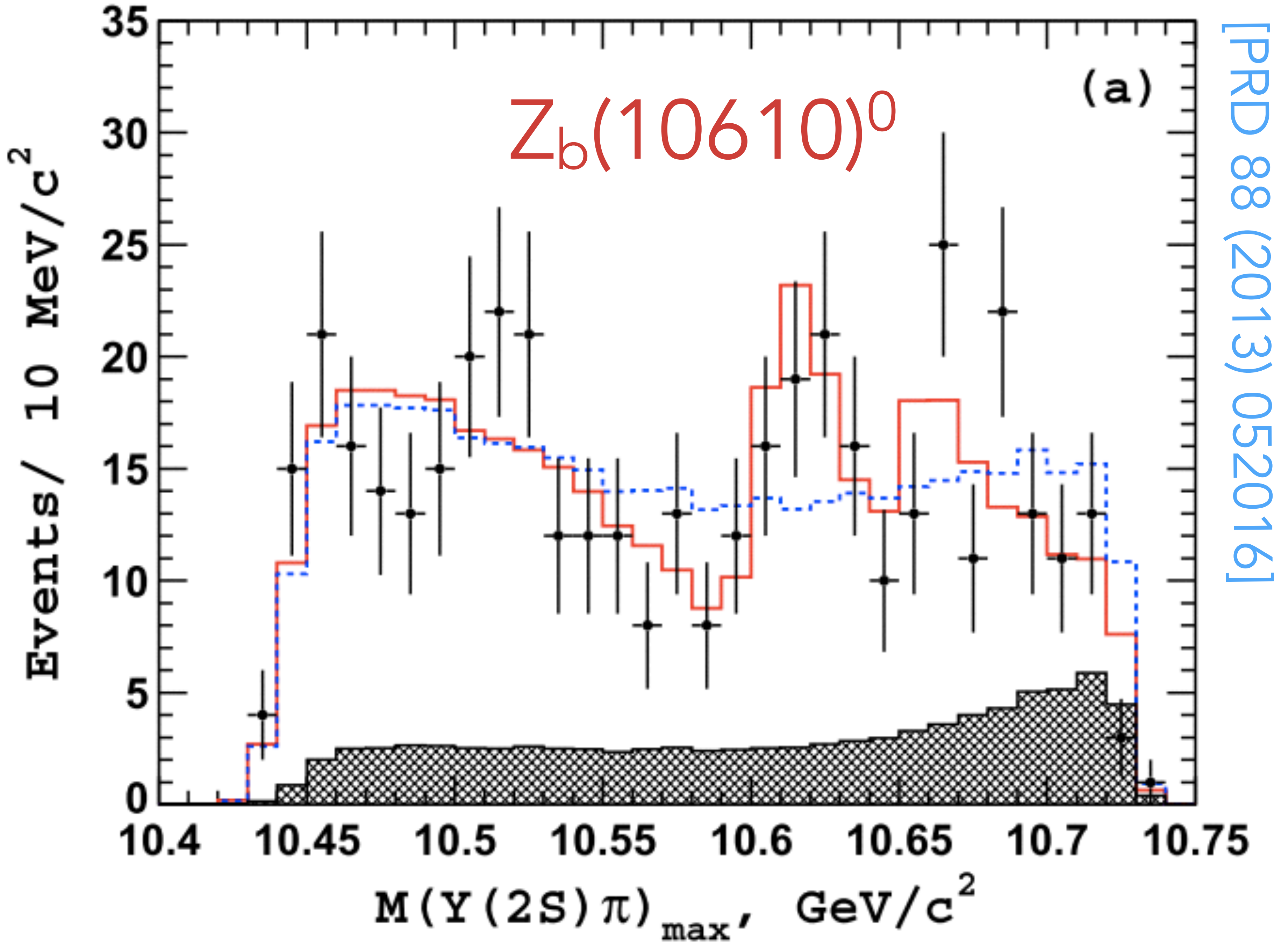
- Many checks performed to determine stability of the result and evaluate systematic errors on m_Z, Γ_Z, f_Z.
- Main systematics come from assumption on $K^+\pi^-$ Isobar model, efficiency and $(q/m_{K^+\pi^-})^L$ vs. q^L

Bottomonium spectrum



Bottomonium-like states

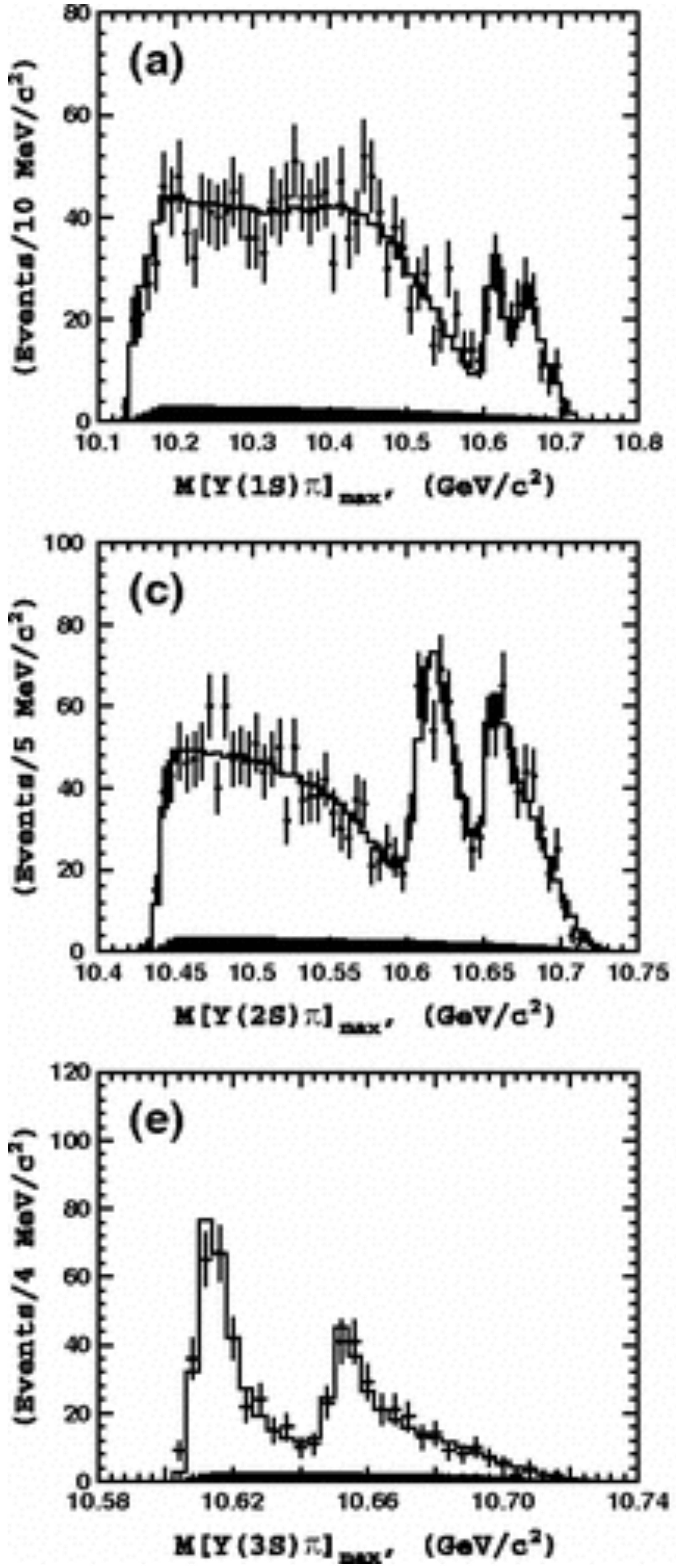
- Belle has evidence for $Z_b(10610)^+$ and $Z_b(10650)^+$ resonances when looking at $\pi^+\pi^-\Upsilon(nS)$ and $\pi^+\pi^- h_b(mP)$. [arXiv:1403.0992v1]
- $I^G(J^P) = 1^+(1^+)$, Virtual $B\bar{B}^*$ and $B^*\bar{B}^*$ S-wave molecule-like states?
- Also first evidence for neutral isospin partners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



[PRD 88 (2013) 052016]

Projections of Dalitz plots

Use Breit-Wigner (without energy dependent width) to model resonances



[PRL 108 (2012) 122001]

References

- Suggestions for how field should progress: http://arxiv.org/pdf/1511.06779.pdf

- Heavy-light diquarks Maini et al Phys.Rev.D71:014028,2005

Pentaquark models (tightly bound)

- All models must explain JP of two states not just one. They also should predict properties of other states: masses, widths, JP. Many models: Lets start with tightly bound quarks ala' Jaffe
- Two colored diquarks plus the anti-quark L.Maiani, et. al, [arXiv:1507.04980], ibid [PRD20(1979) 748]
- Colored diquark + colored triquark, R. Lebed [arXiv:1507.05867], R. Zhu & C-F. Qiao [arXiv:1510.08693]
- Bag model, Jaffe; Strings, Rossi & Veneziano [Nucl. Phys. B123 (1977) 507]

Pentaquark models (molecular)

- Molecular models, generally with meson exchange for binding ala' Törnqvist [Z. Phys. C61 (1994) 525] 10.1007/BF01413192
  - L. Ma et.al, [arXiv:1404.3450] for Z(4430)
  - T. Barnes et.al, [arXiv:1409.6651] for Z(4430)
- π exchange models usually predict only one state, mainly JP=1/2+, but could also include ρ exchange…
- Several authors consider Σc D(*) components (most of these are postdictions)

Implications (see talks after coffee)

- Many states appear to lie just above threshold which indicates experimental enhancements may be due to threshold cusp (the movement of resonant poles due to the proximity of multiparticle thresholds) effects rather than quark binding. [Bugg, Swanson] [Blitz Lebed PRD91 (2015) 094025]
- Zc(3900) DD*
- Zc(4020) D*D*
- Zb(10610) BB*
- Zb(10650) B*B*

What are the degrees of freedom?