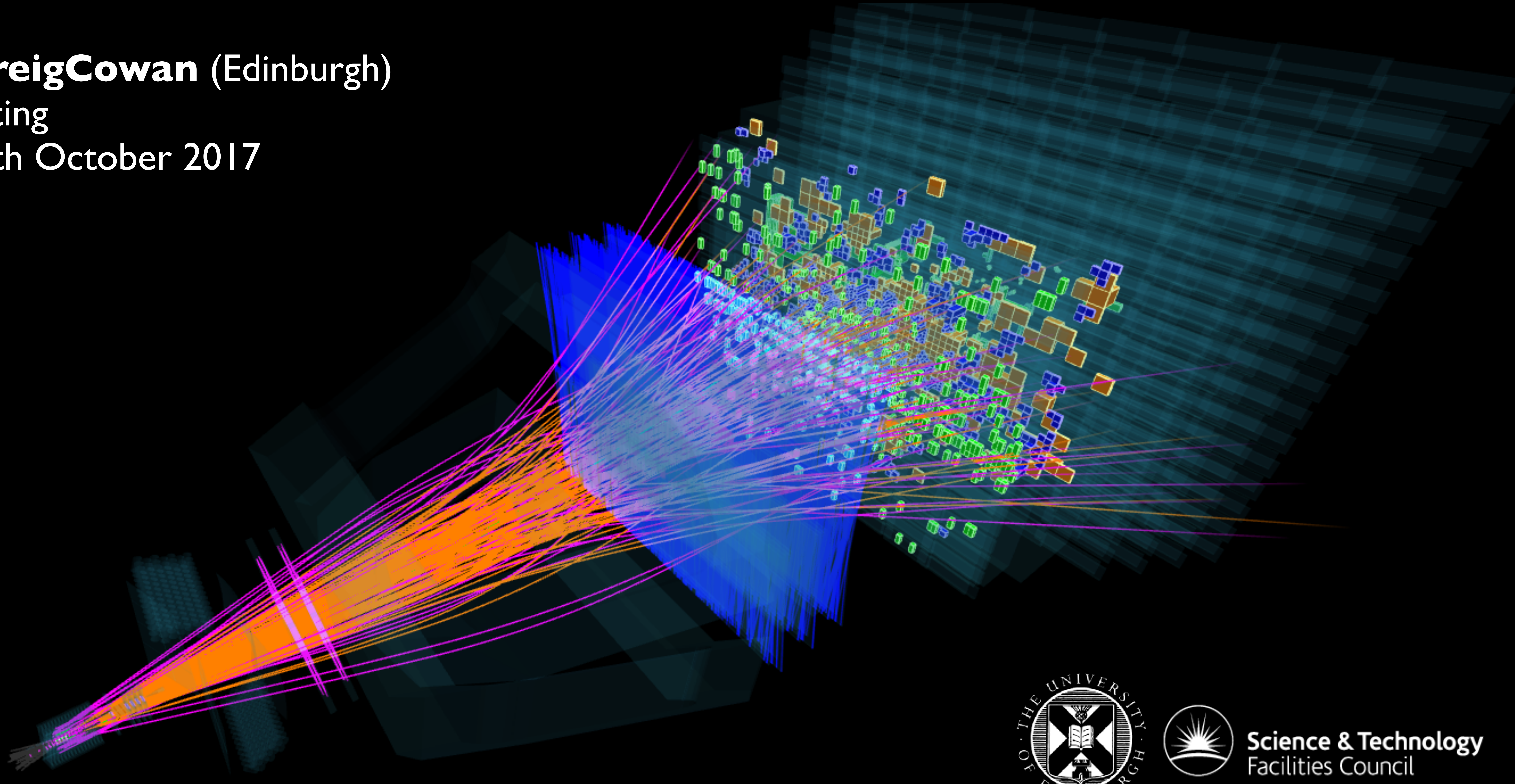
(Exotic) Hadron physics at LHCb

@GreigCowan (Edinburgh)

FSP meeting

Siegen, 5th October 2017



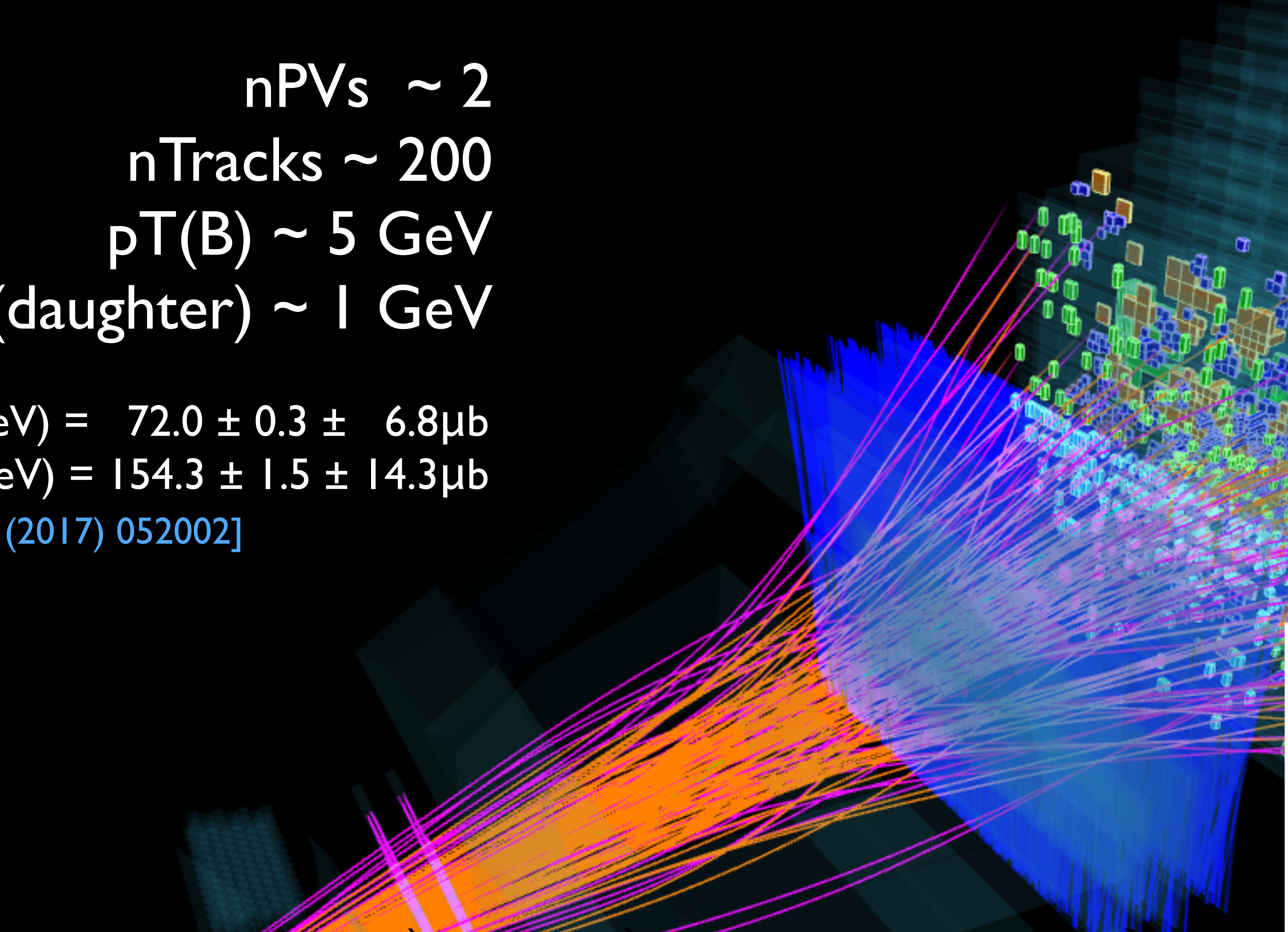
THE UNIVERSITY OF EDINBURGH

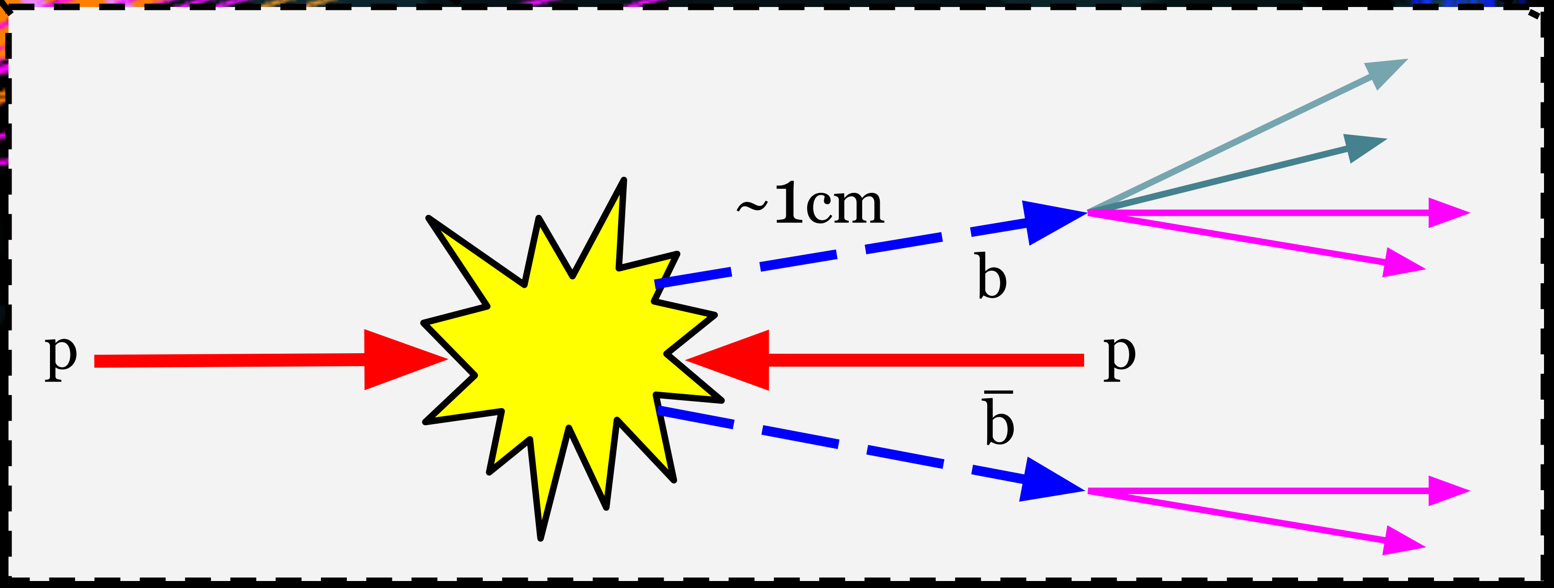
Science & Technology Facilities Council

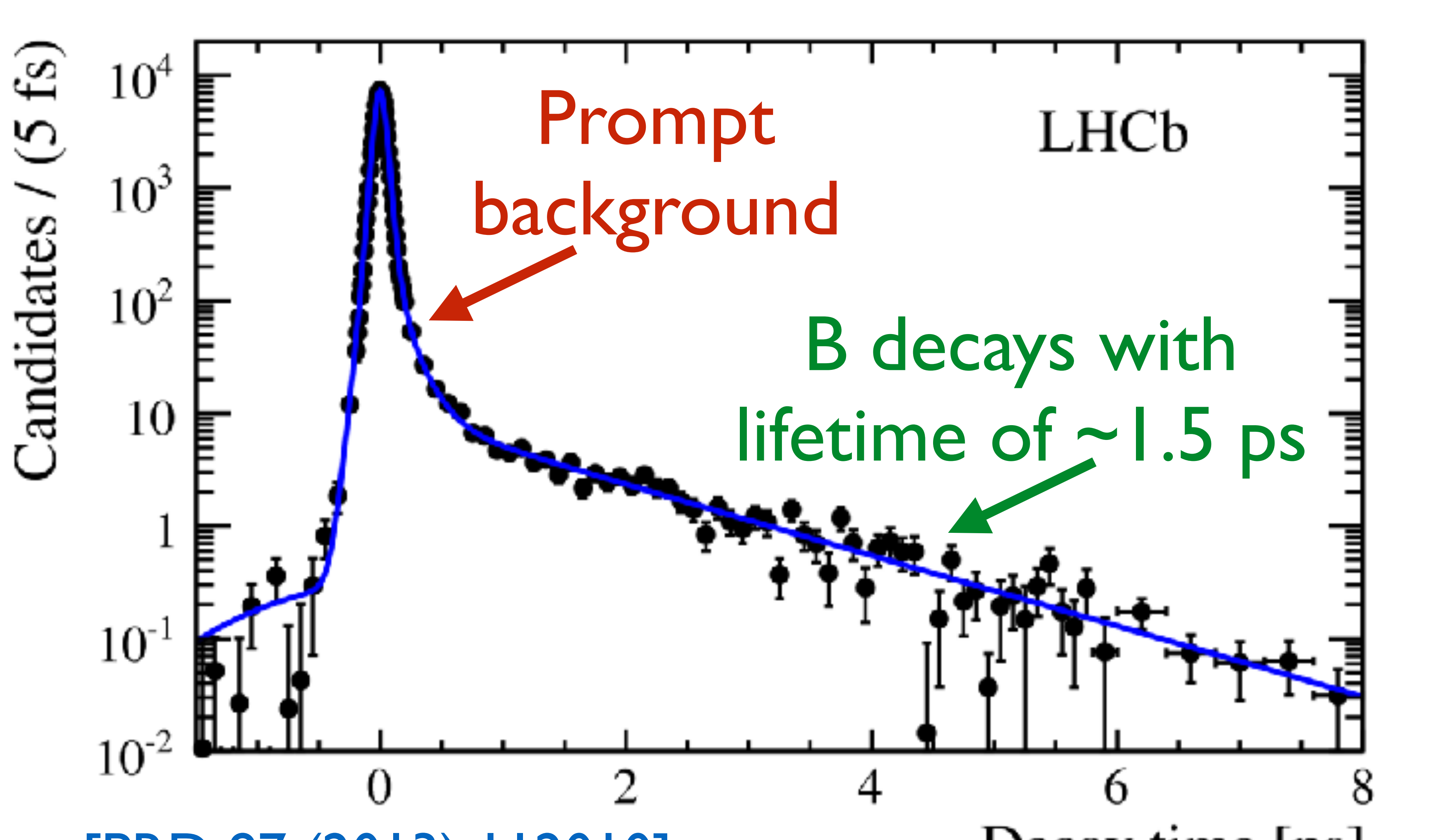
(Exotic) Hadron physics at LHCb

nPVs ~ 2
nTracks ~ 200
pT(B) ~ 5 GeV
pT(daughter) ~ 1 GeV

σ_{bb}(7 TeV) = 72.0 ± 0.3 ± 6.8μb
σ_{bb}(13 TeV) = 154.3 ± 1.5 ± 14.3μb
[PRL 118 (2017) 052002]

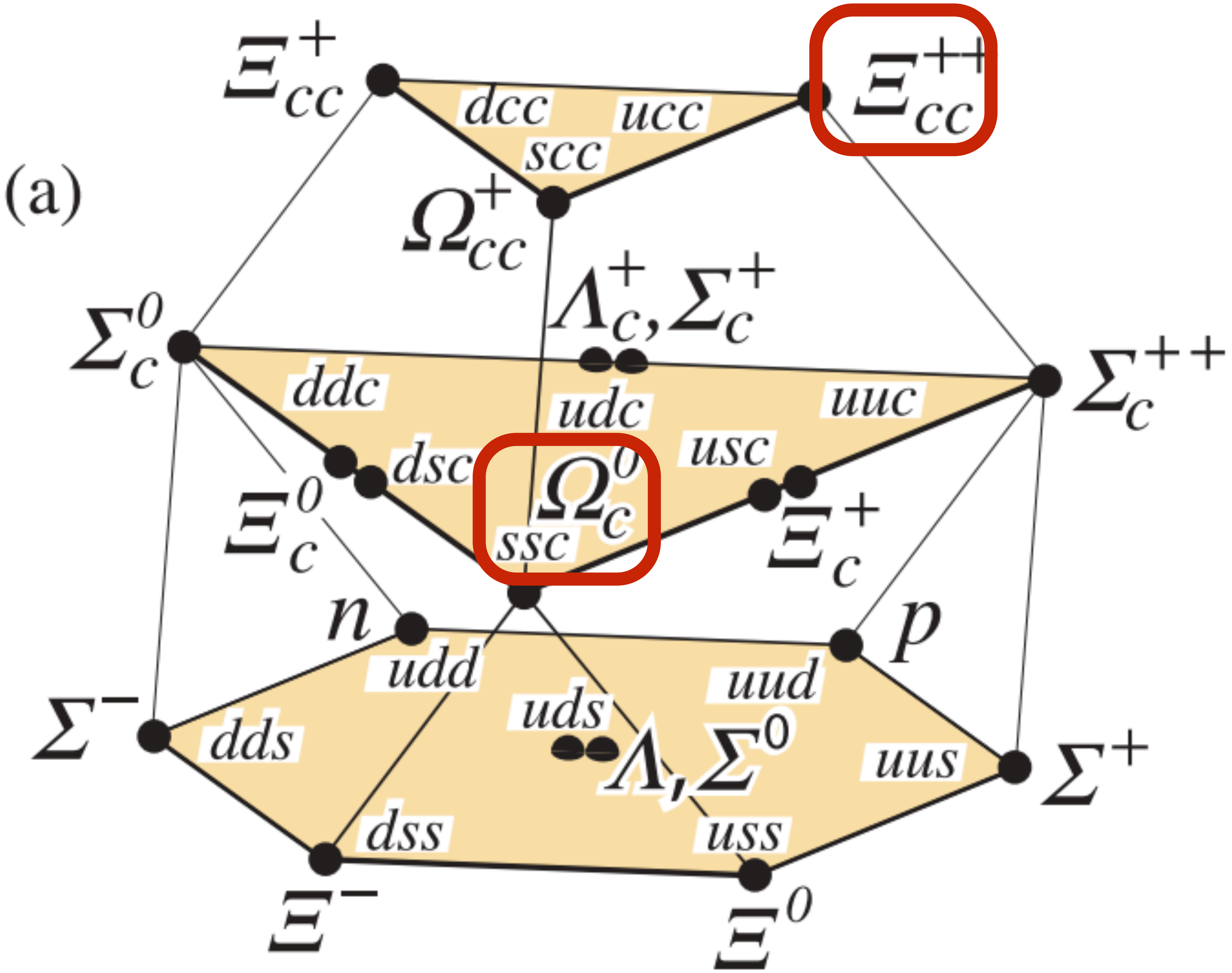






[PRD 87 (2013) 112010]

Recent news on charm baryons



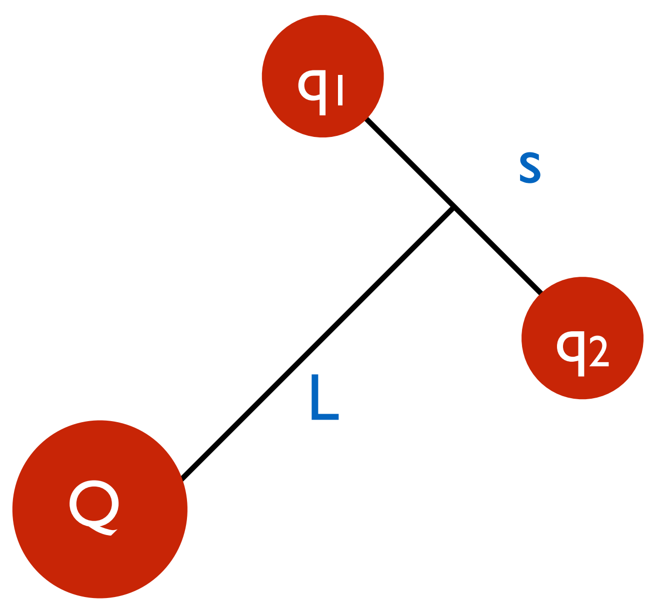
Strange-charm baryons

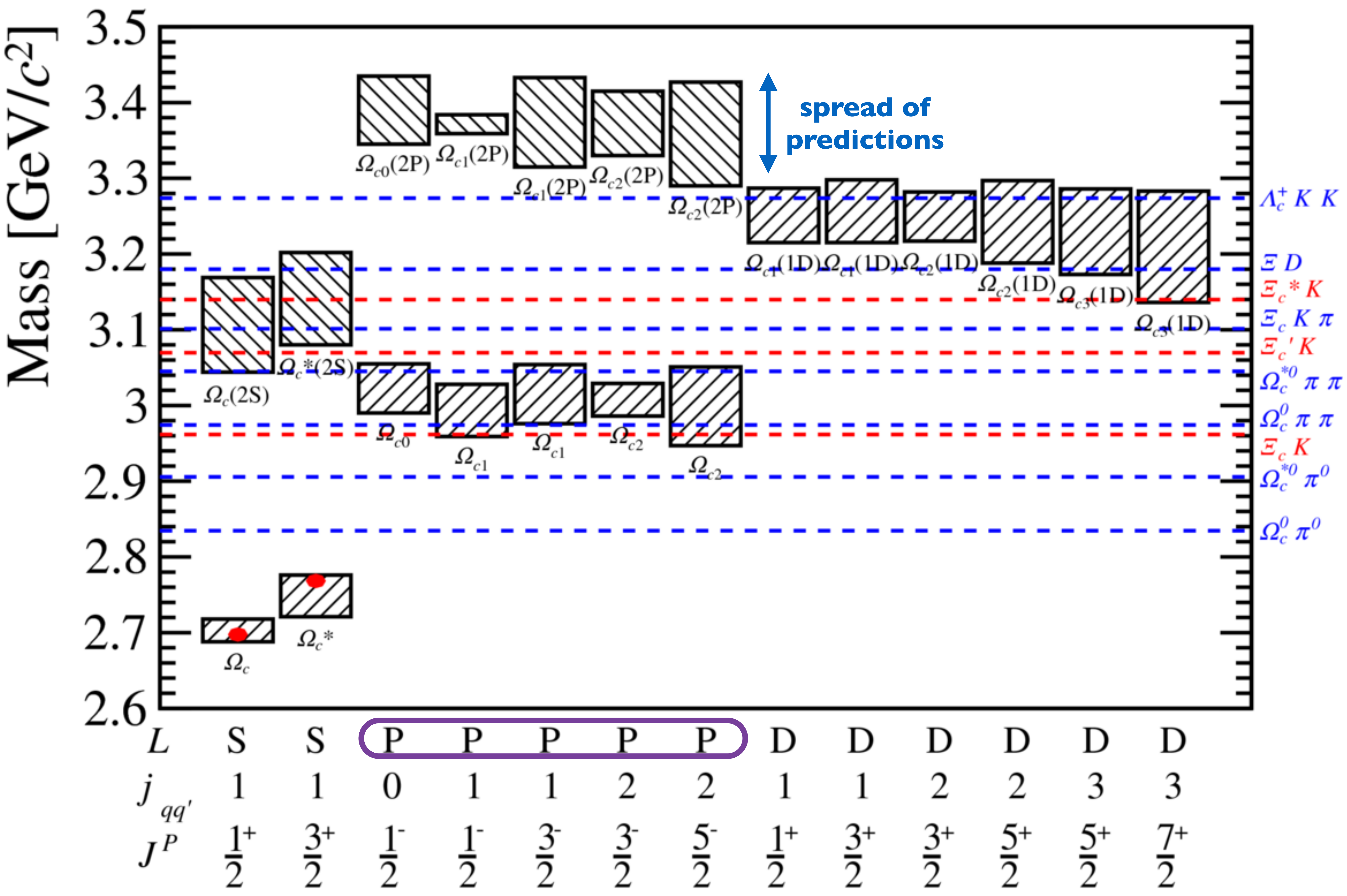
[PRL 118 (2017) 182001]

The **css** system can be used to test HQET and Lattice, as many states expected

Heavy quark + light **ss** diquark

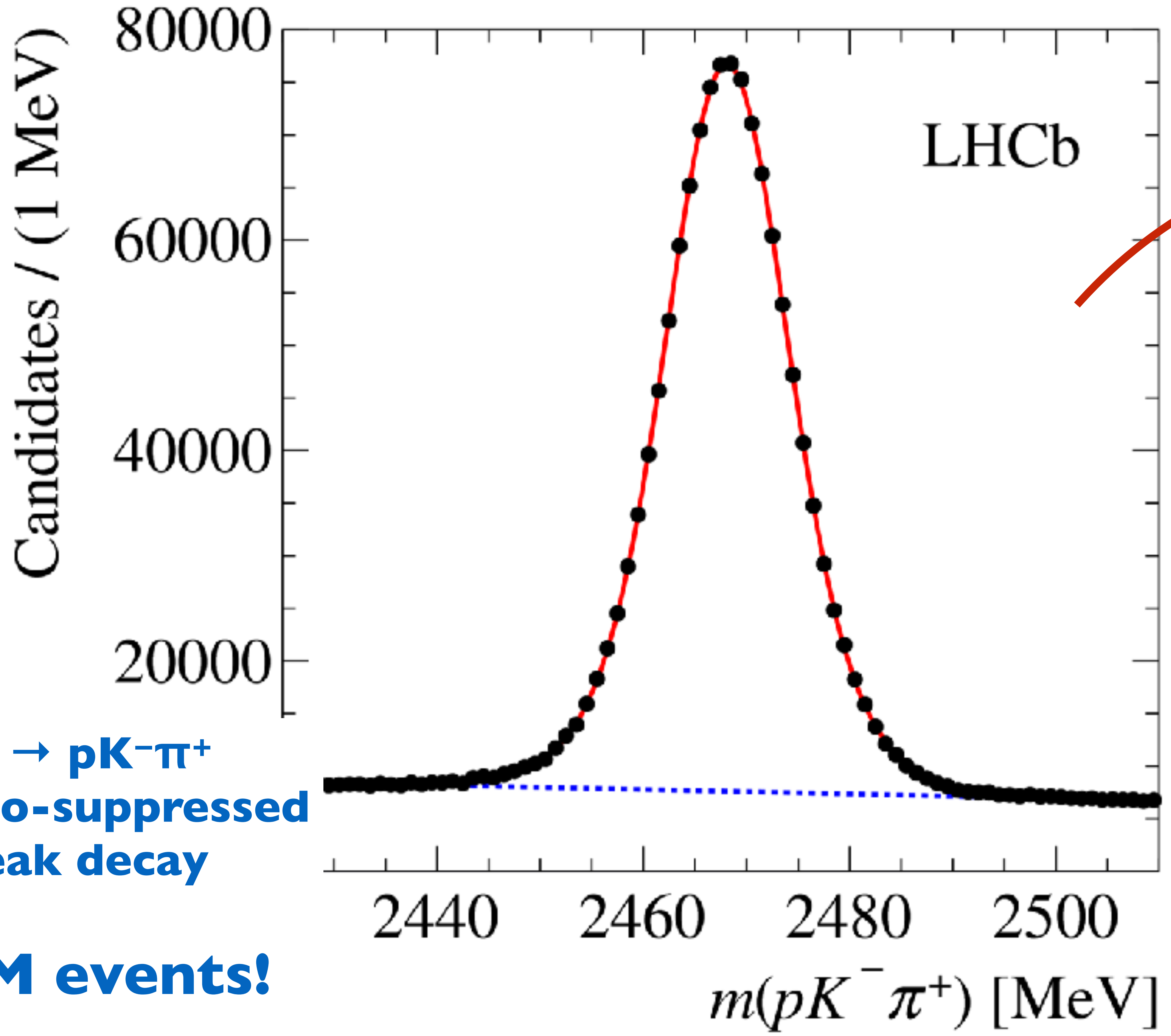
5 P-wave states predicted





Strange-charm baryons

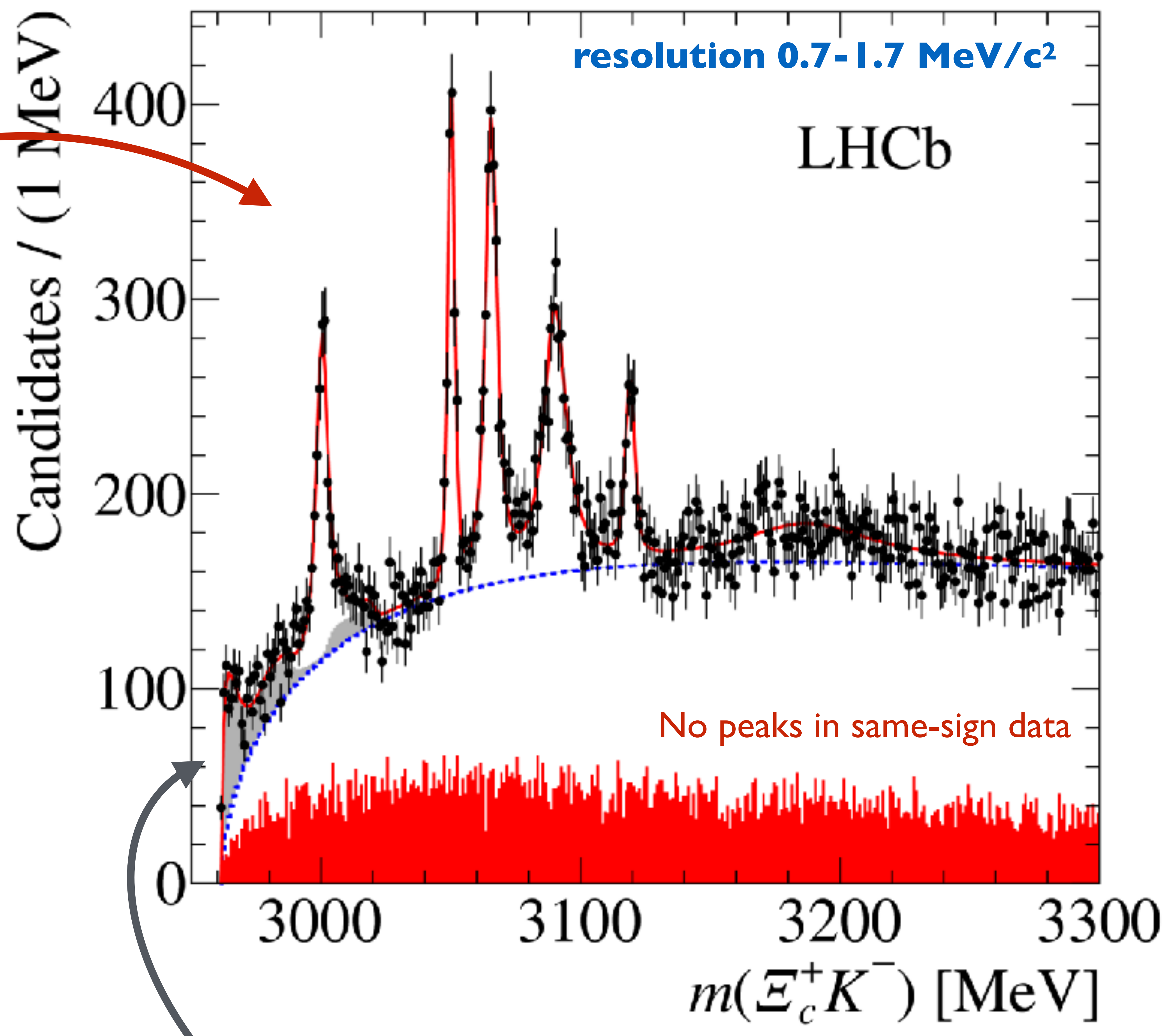
[PRL 118 (2017) 182001]



$\Xi_c^+ \rightarrow pK^-\pi^+$
Cabibbo-suppressed weak decay

0.9 M events!

Add a kaon



Threshold enhancement consistent with $\Omega_c(3066)^0 \rightarrow \Xi_c'^+ K^-$

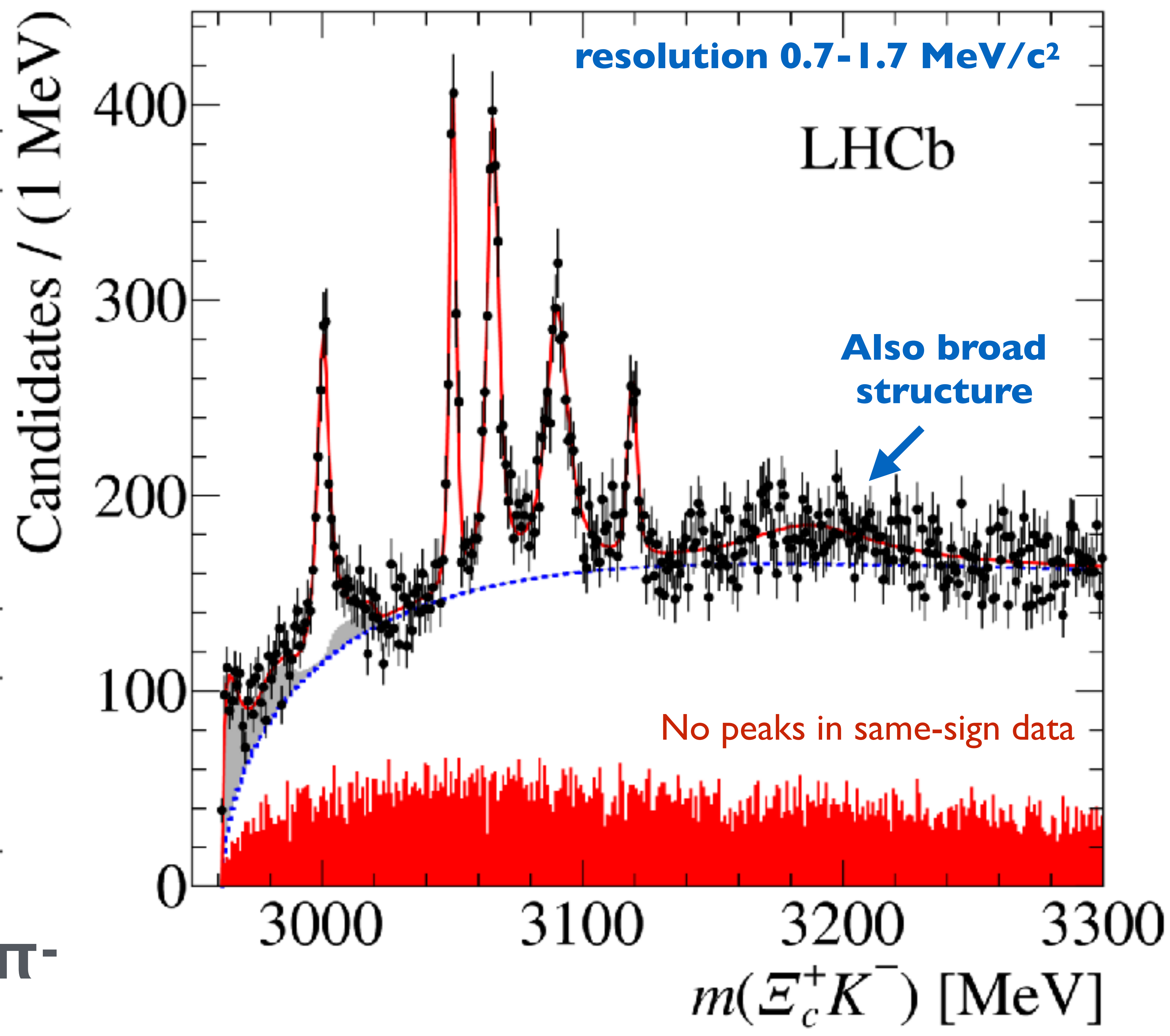
Ξ_c^+ detached from, but pointing back to, the primary pp vertex

LHCb-RICH system to identify particle type of daughter tracks

Strange-charm baryons

[PRL 118 (2017) 182001]

Resonance	Mass (MeV)	Γ (MeV)	Yield	N_σ
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$	20.4
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$	20.4
		$< 1.2\,\mathrm{MeV}, 95\%$ CL	**Very narrow!**	
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$	23.9
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$	21.1
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$	10.4
		$< 2.6\,\mathrm{MeV}, 95\%$ CL	**Very narrow!**	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\mathrm{fd}}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\mathrm{fd}}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\mathrm{fd}}$			$190 \pm 70 \pm 20$	



What are the quantum numbers? Use $\Omega_b^- \rightarrow (\Xi_c^+ K^-)\pi^-$

Why are they so narrow?

Are the narrowest states pentaquark candidates?

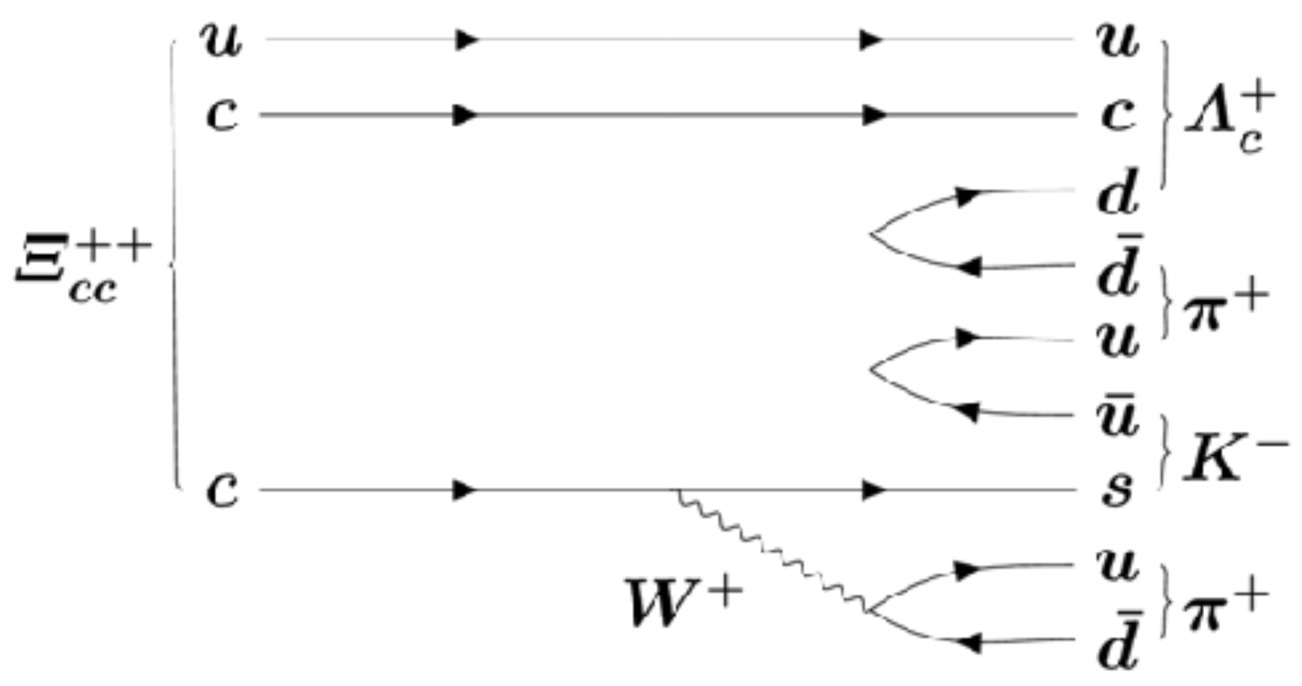
Which are orbital/radial excitations?

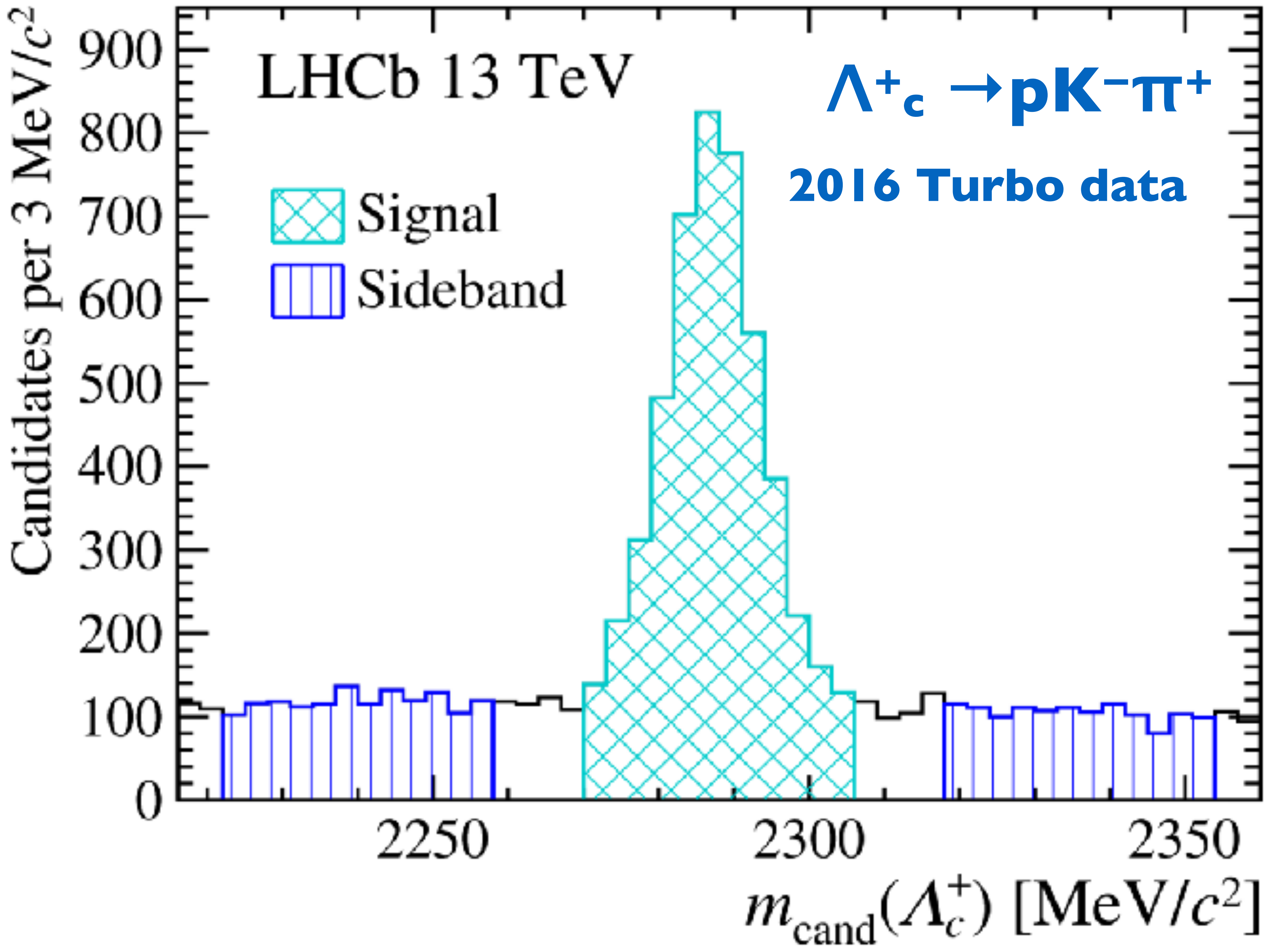
Do they have isospin partners?

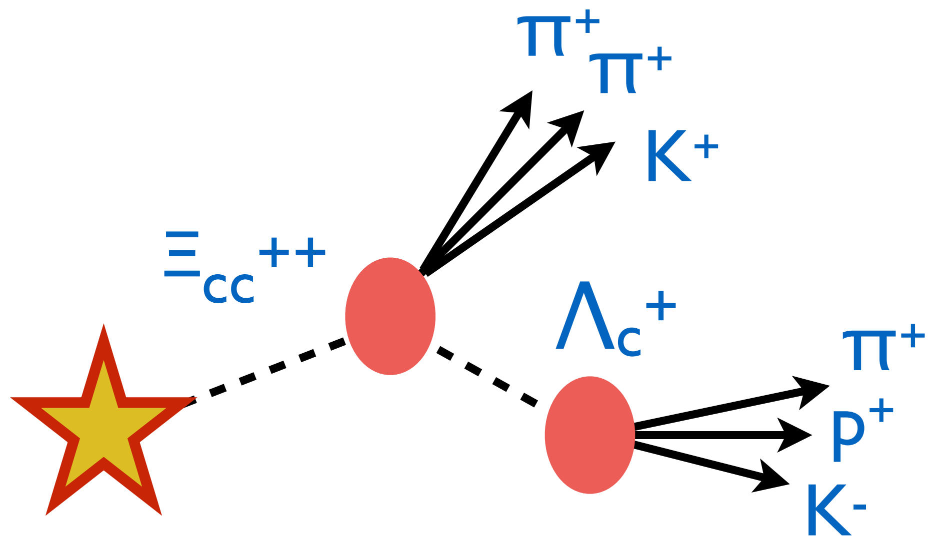
[Karliner, Rosner, PRD 95 (2017) 114012]
[Kim et al., PRD 96 (2017) 014009]

Doubly-charmed baryon

[PRL 119 (2017) 112001]







Novel online data processing → Turbo!

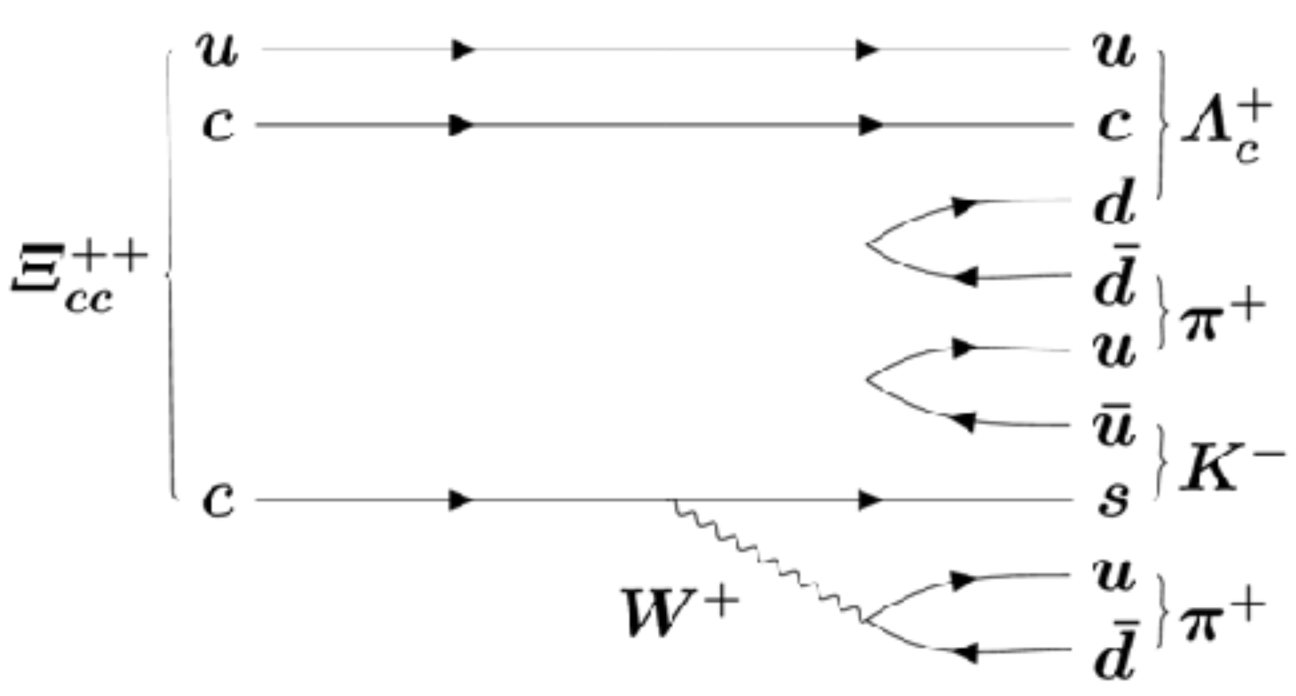
Full event reconstruction used in trigger (exploiting real-time alignment capabilities of LHCb in Run 2)

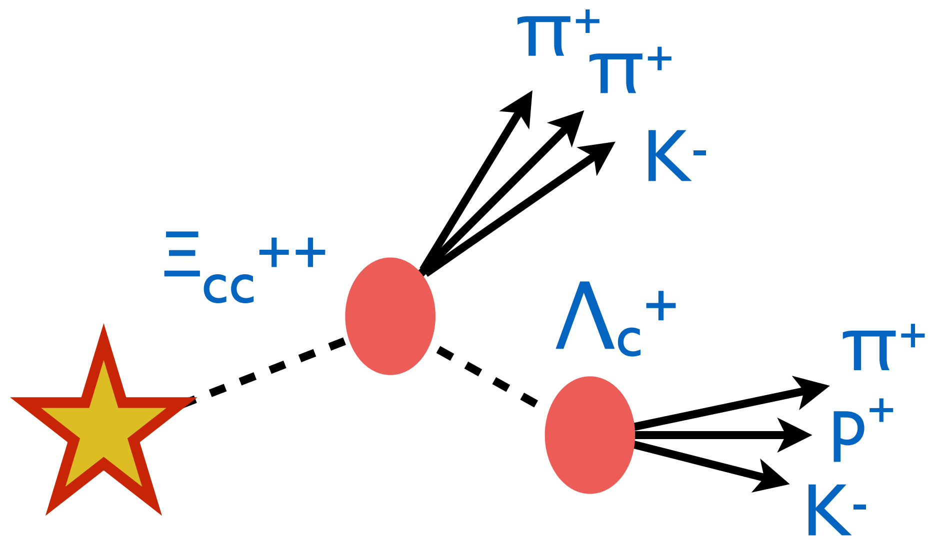
Write out events in ready-to-analyse format ⇒ no need for additional offline processing.

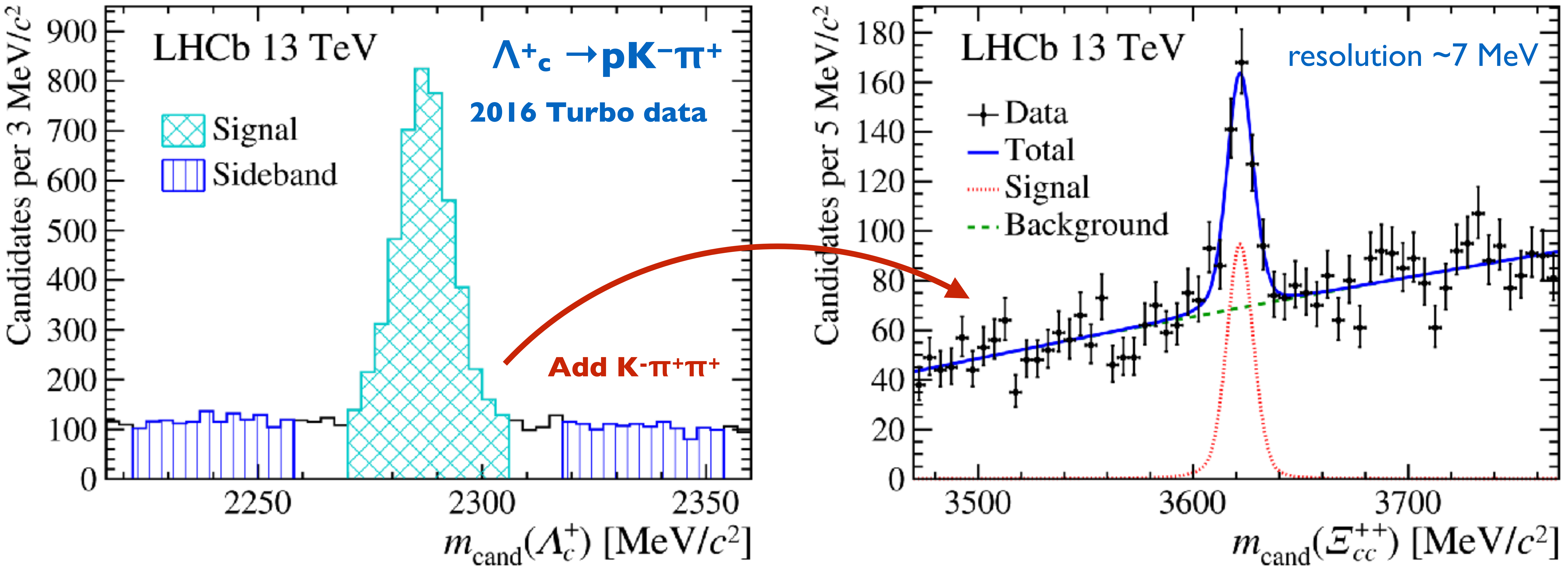
Only save part of the event that is needed → less disk space, crucial for states with large production cross-sections

Doubly-charmed baryon

[PRL 119 (2017) 112001]







>12σ significant signal observed consistent with a **weakly** decaying state

$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\ (\text{stat}) \pm 0.27\ (\text{syst}) \pm 0.14\ (\Lambda_c^+)$ MeV

consistent with many theory predictions
e.g. Lattice [Alexandrou PRD 96 (2017) 034511]

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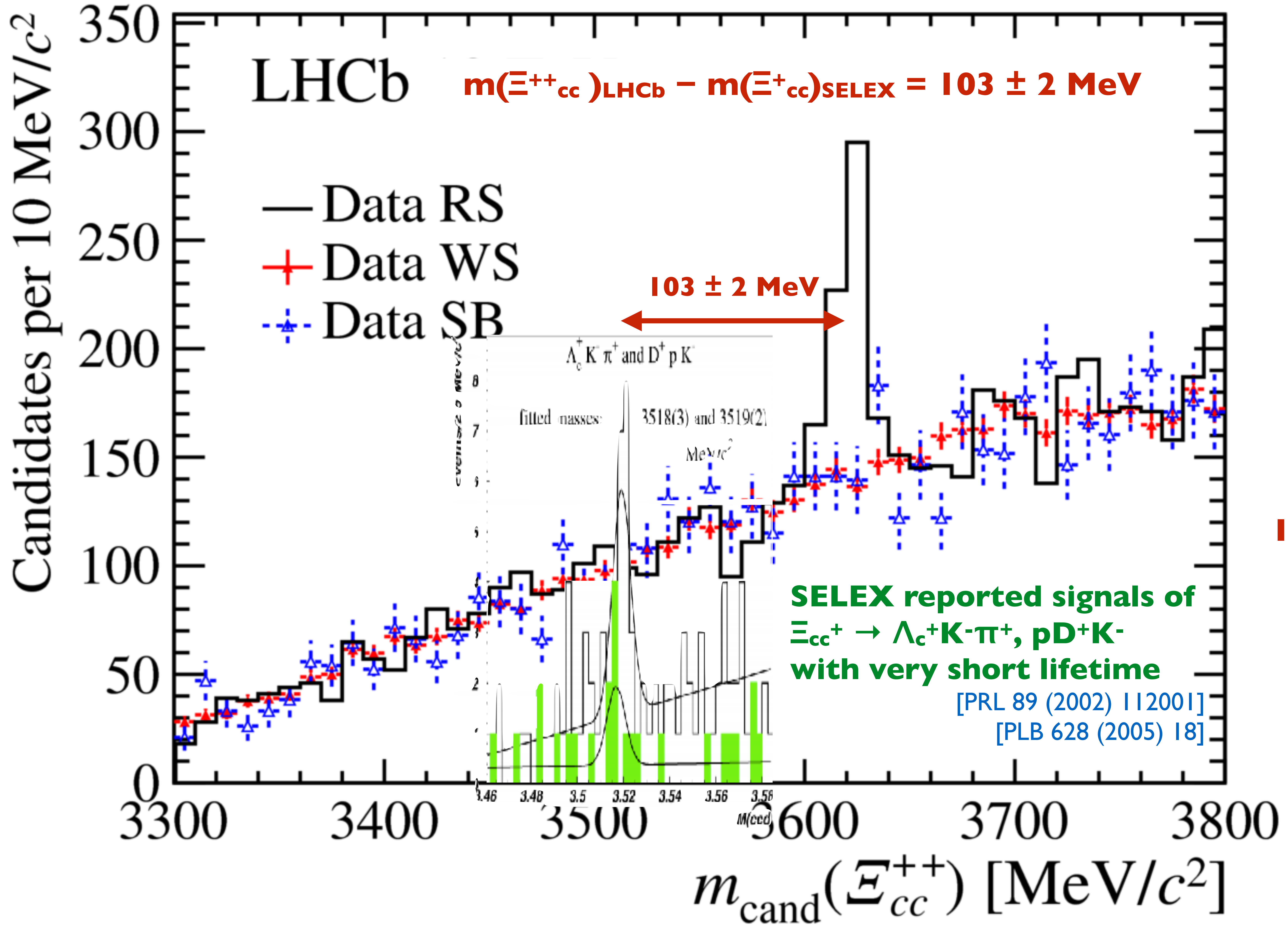
Comparison with SELEX

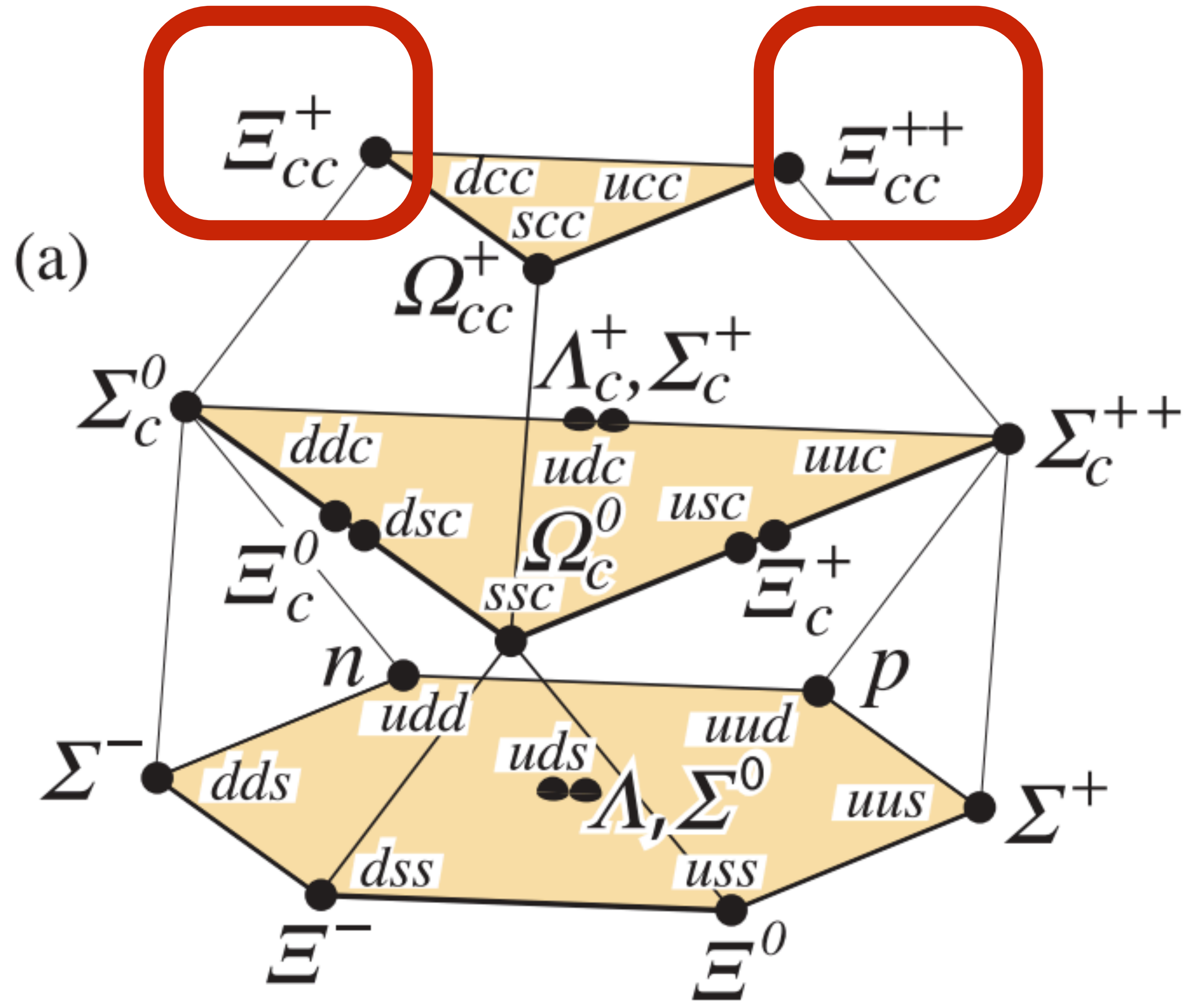
[PRL 119 (2017) 112001]



SELEX reported signals of $\Xi_{cc}^+ \to \Lambda_c^+K^-\pi^+$, pD^+K^- with very short lifetime

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

isospin partners

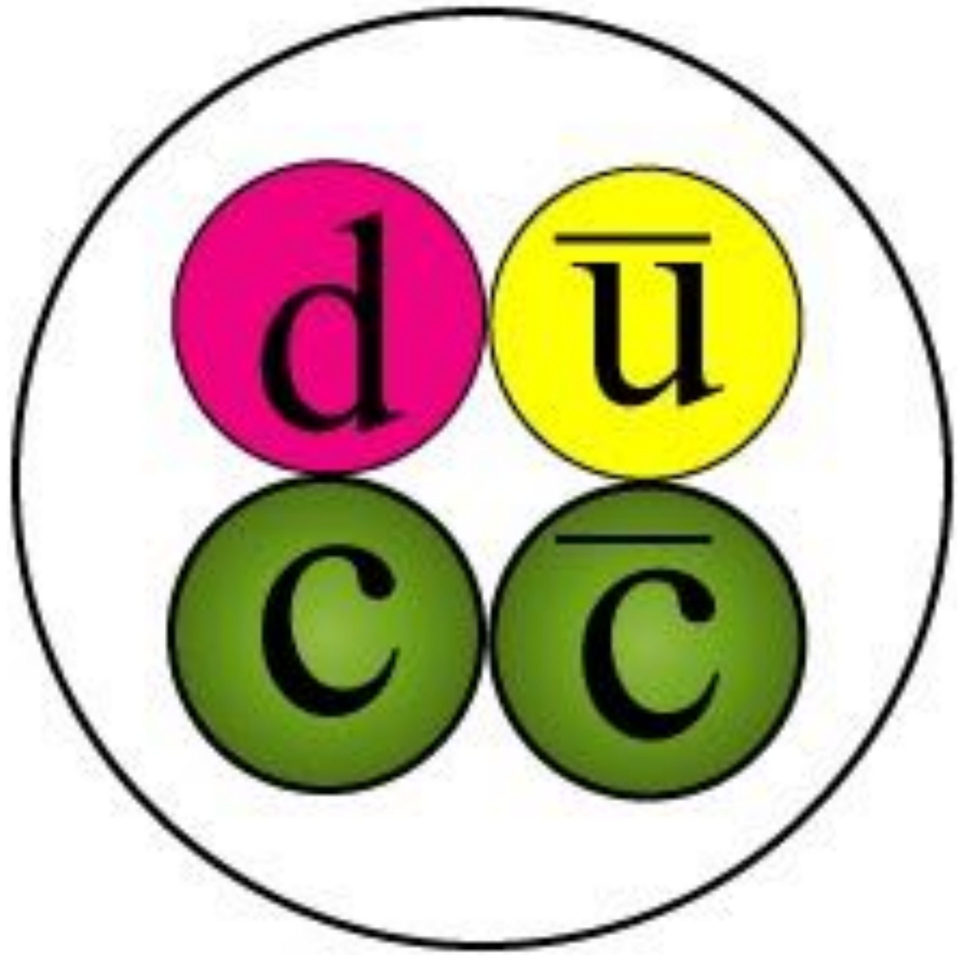


Inconsistent with being isospin partners

[Brodsky at al., PLB 698 (2011) 251]
[Karliner, Rosner, PRD 96 (2017) 033004]

Next steps: measure lifetime, new decay modes and search for other **double-heavies** Ξ_{cc}^+ , Ω_{cc}^+ , Ξ_{bc}, Ω_{bb} and Ξ_{bb}

Exotic mesons and baryons



The quark model

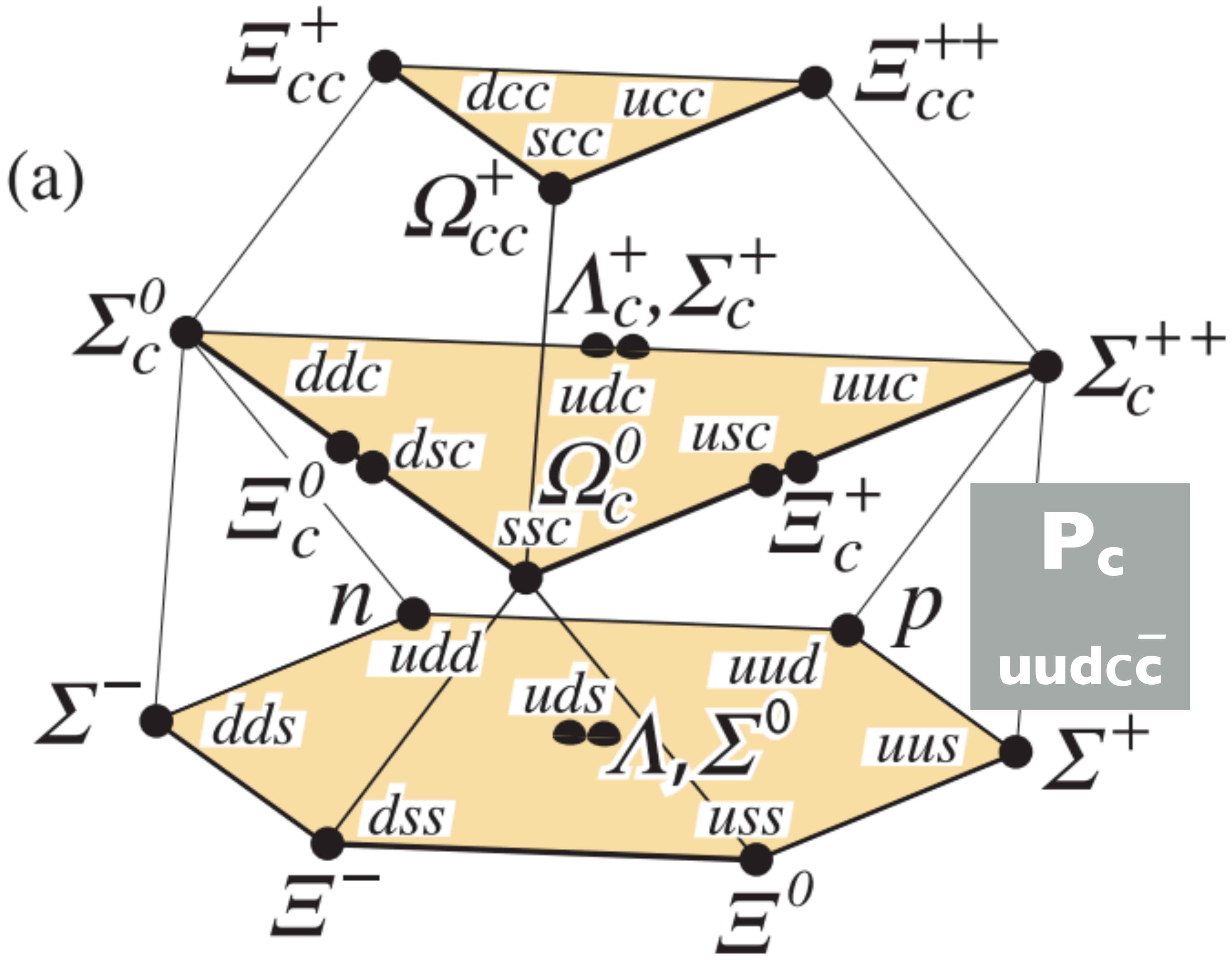
Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

Received 4 January 1964

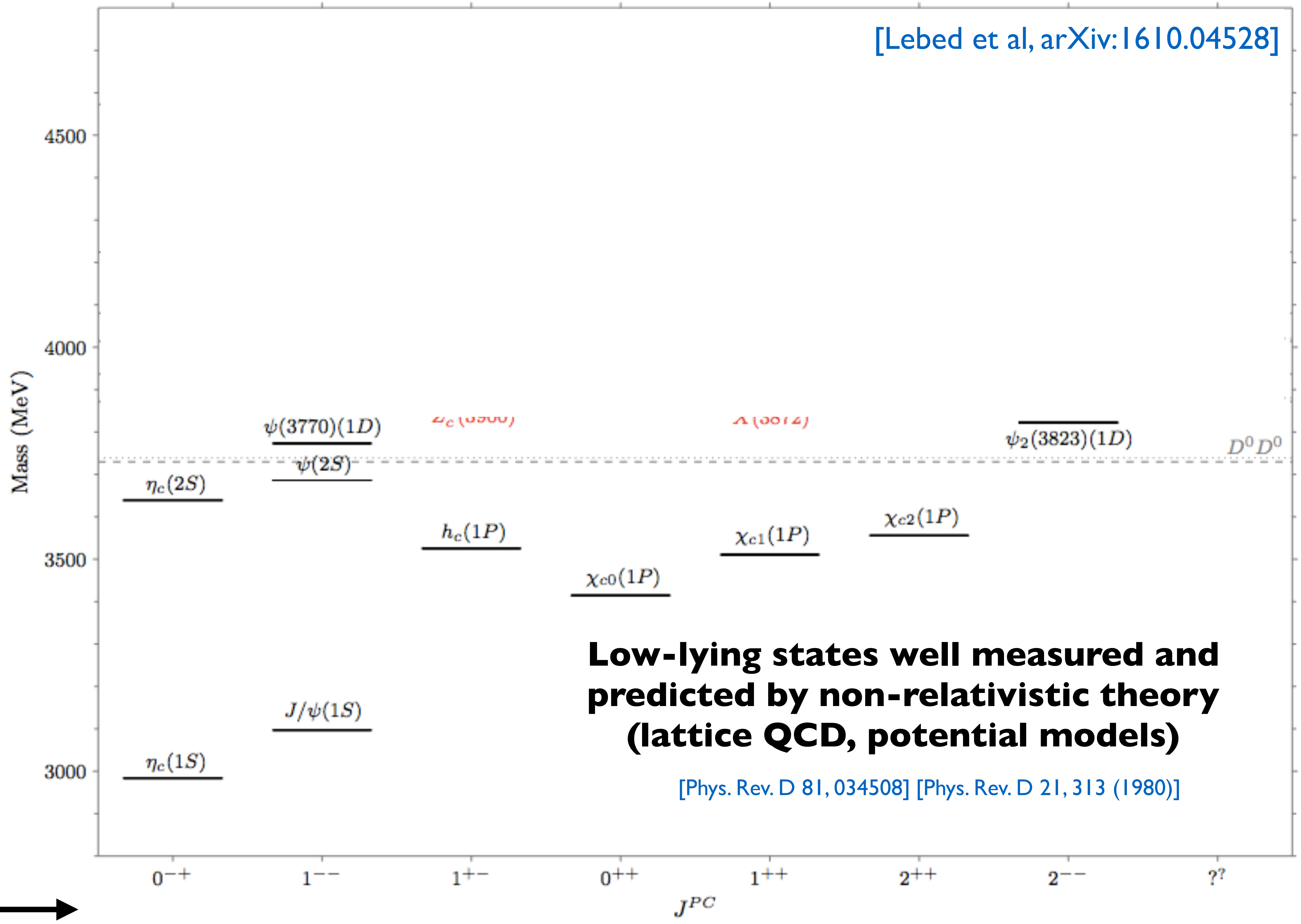
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while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



Quarks as the building blocks of mesons and baryons was first proposed in 1964 by Gell-Mann and Zweig

Charmonium spectroscopy

[Lebed et al, arXiv:1610.04528]



Low-lying states well measured and predicted by non-relativistic theory (lattice QCD, potential models)

[Phys. Rev. D 81, 034508] [Phys. Rev. D 21, 313 (1980)]

Classify using J^{PC}

$J = L \oplus S$

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

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

$n^{2S+1}L_J$ ⟶

Charmonium spectroscopy

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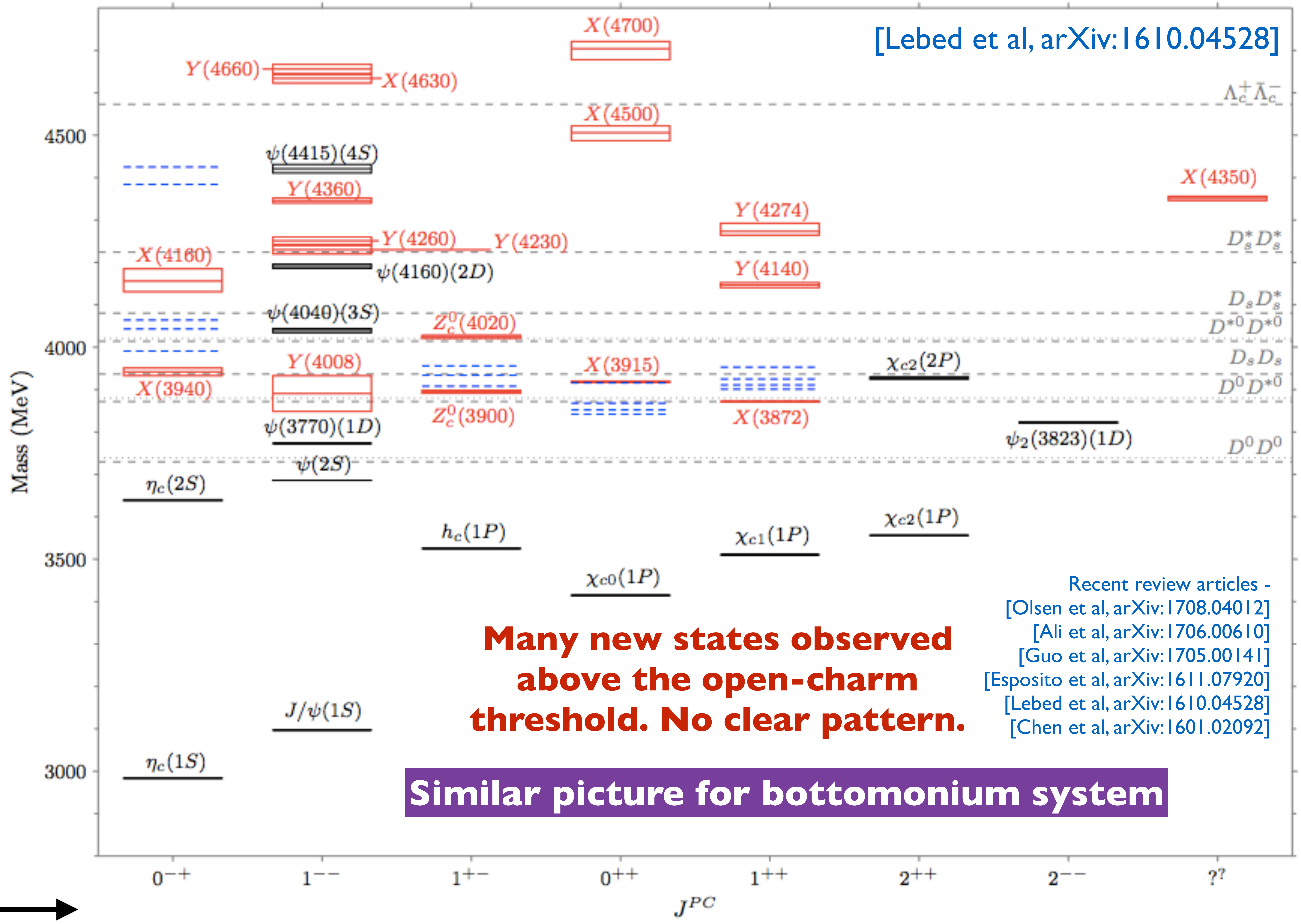


Many new states observed above the open-charm threshold. No clear pattern.

Recent review articles -
[Olsen et al, arXiv:1708.04012]
[Ali et al, arXiv:1706.00610]
[Guo et al, arXiv:1705.00141]
[Esposito et al, arXiv:1611.07920]
[Lebed et al, arXiv:1610.04528]
[Chen et al, arXiv:1601.02092]

Similar picture for bottomonium system

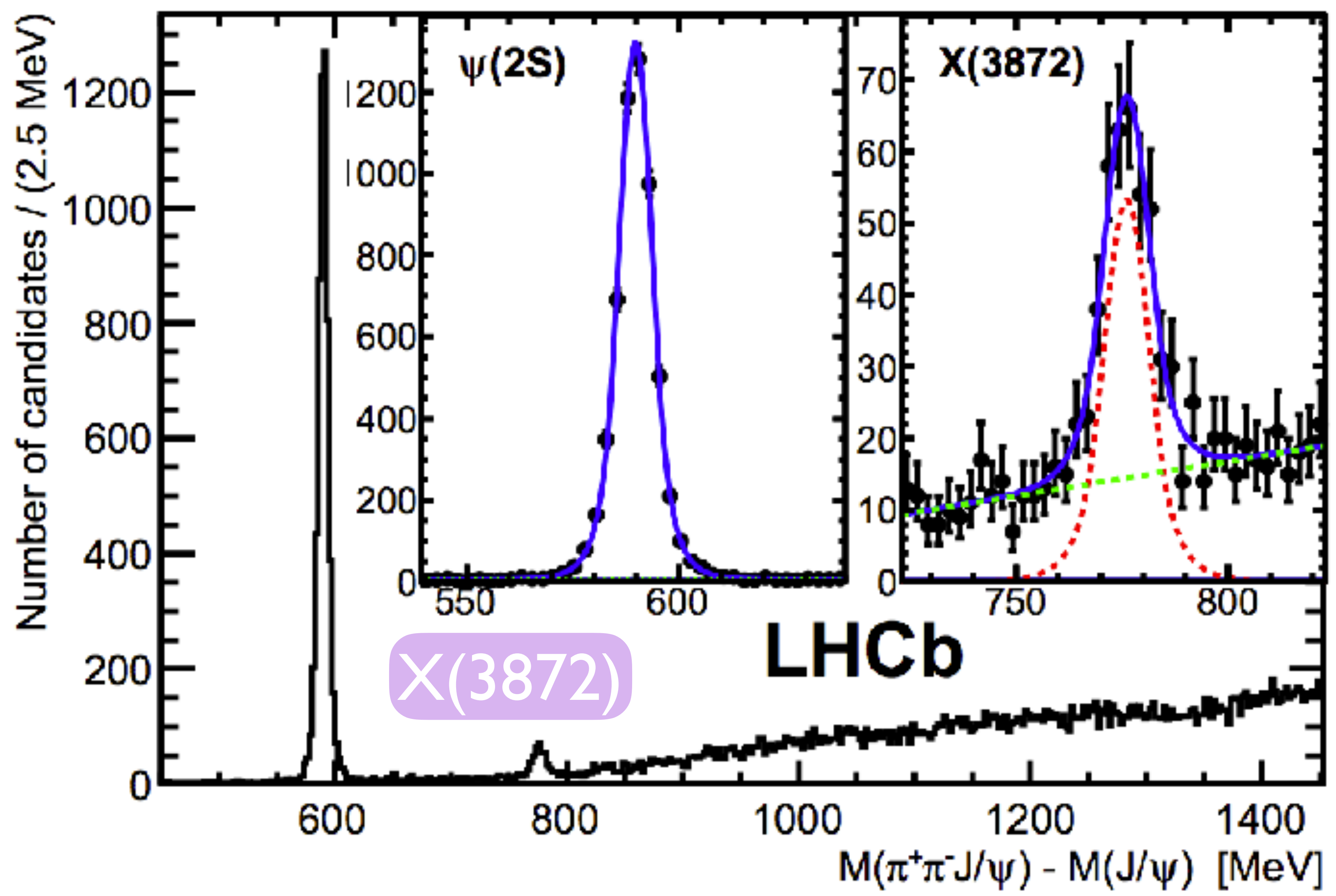
The X(3872) revolution

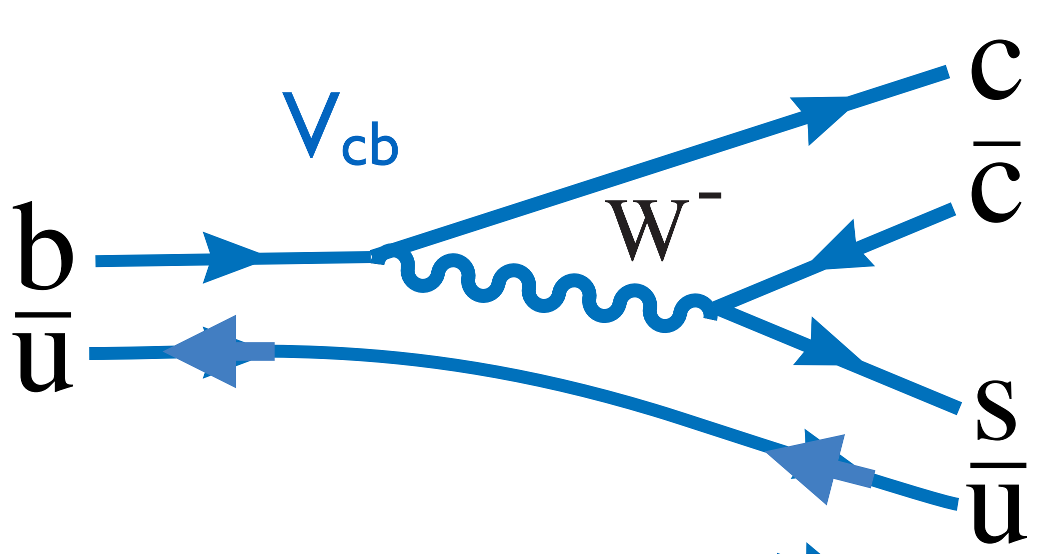
Observation in 2003 by Belle has led to a revolution in exotic hadron spectroscopy [PRL 91 (2003) 262001 with >1100 citations!]

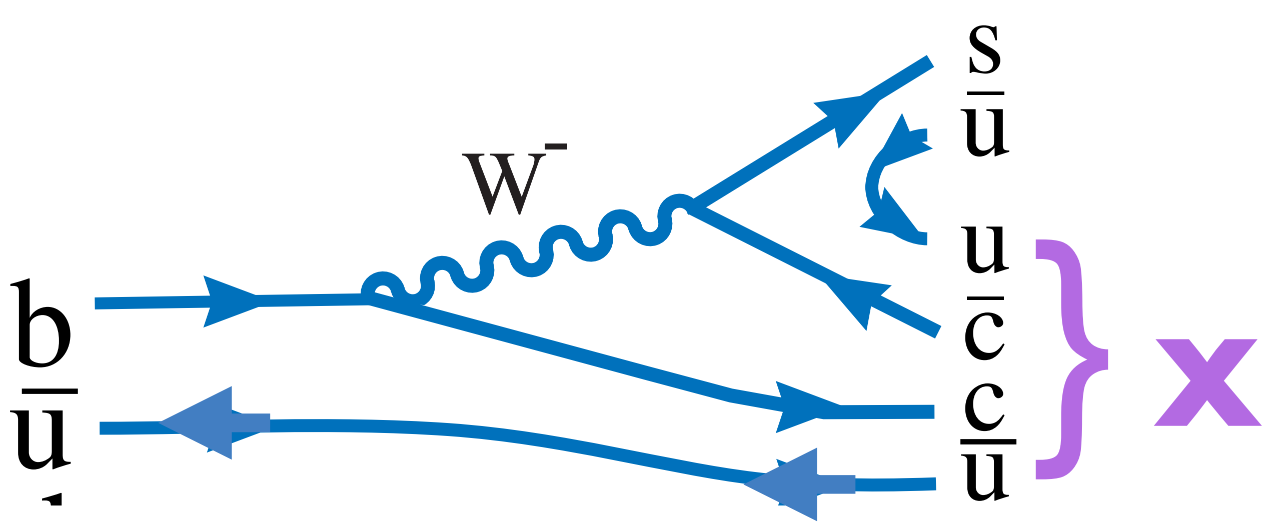
Many phenomenological models: $[c\bar{u}][\bar{c}u]$ tetraquark, D^0D^{*0} molecule, $c\bar{c}g$ hybrid, hadro-charmonium…

$J^{PC} = 1^{++}$ from LHCb [PRD 92 (2015) 011102]

[PRL 110 (2013) 222001]







$$B^+ \to \psi(2S)K^+ \hookrightarrow J/\psi\pi^+\pi^-$$

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

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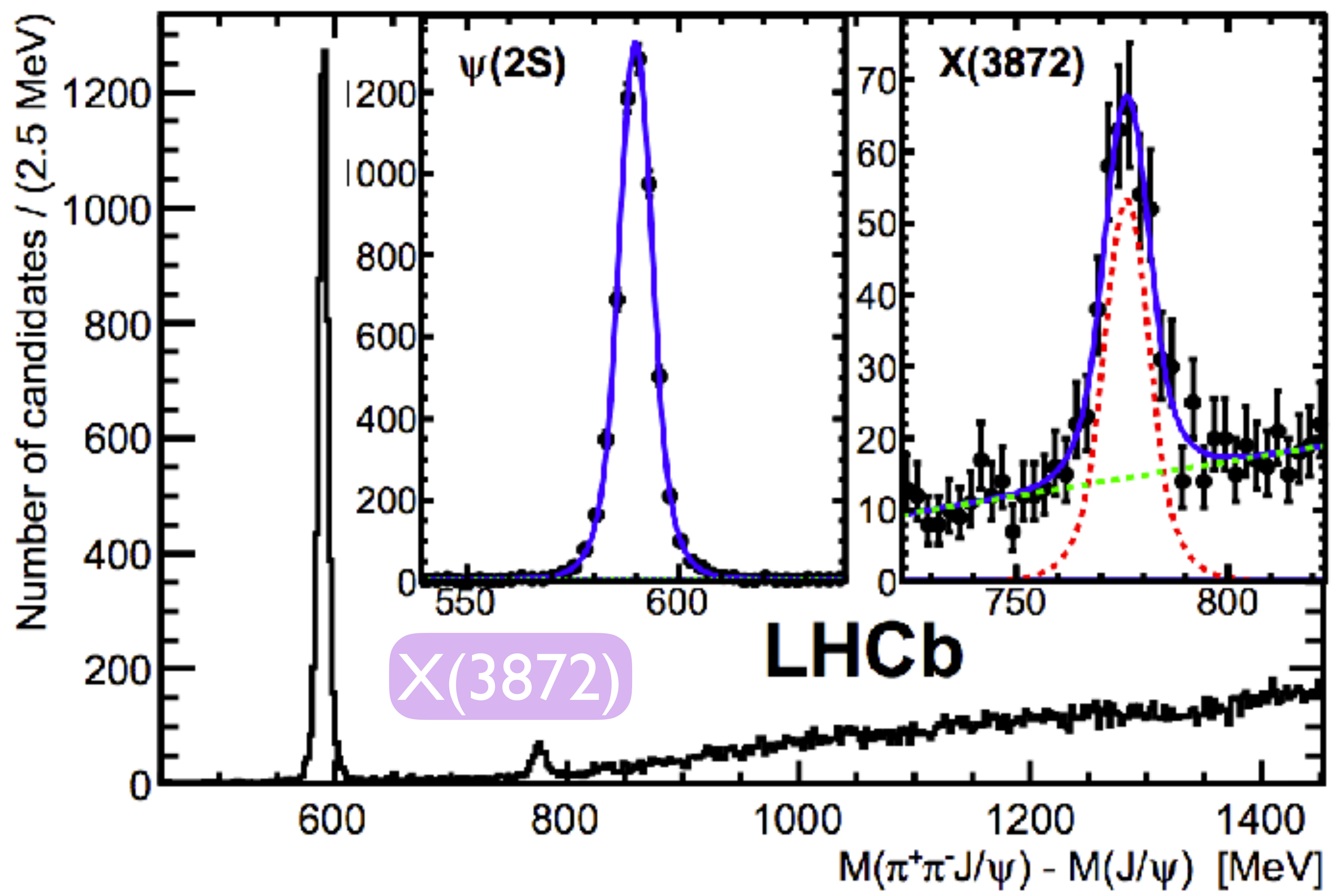
$J^{PC} = 1^{++}$ from LHCb [PRD 92 (2015) 011102]

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]

[PRL 110 (2013) 222001]



Most studied state, but many open questions

$$\Gamma_{X(3872)} < 1.2\ \text{MeV}/c^2$$

$$M_{X(3872)} = 3871.69 \pm 0.17\ \text{MeV}/c^2$$

$$M_{D^0} + M_{D^{*0}} = 3871.81 \pm 0.09\ \text{MeV}/c^2$$

[PDG]

Loosely bound in the molecule scenario

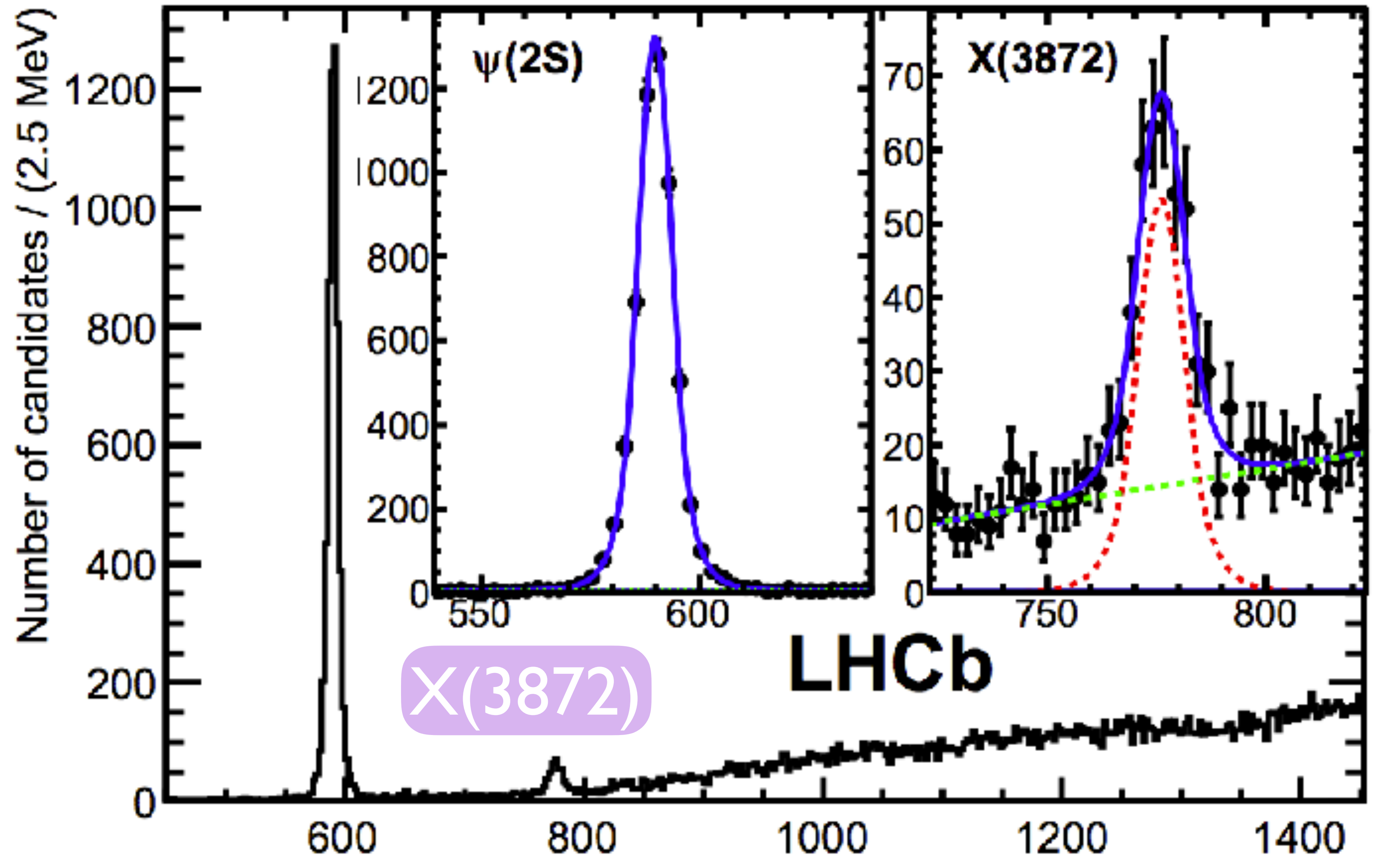
Amplitude analyses

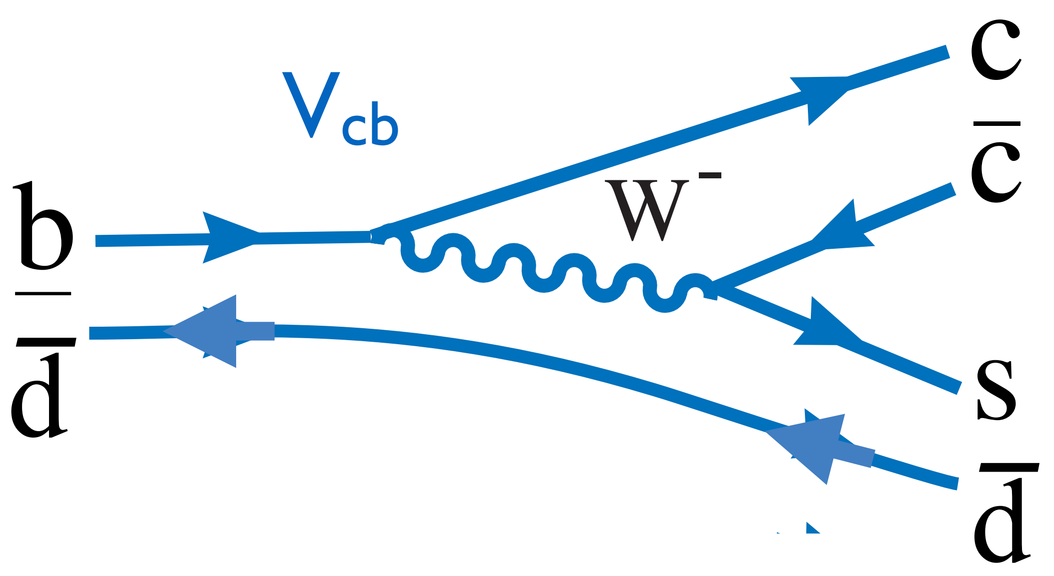
Both decay chains have the same particles in the final state.

Mass fit is sufficient to separate if state isolated and narrow, otherwise need an **amplitude analysis** to disentangle interfering contributions and to measure quantum numbers.

B hadrons provide well-defined state of known spin.

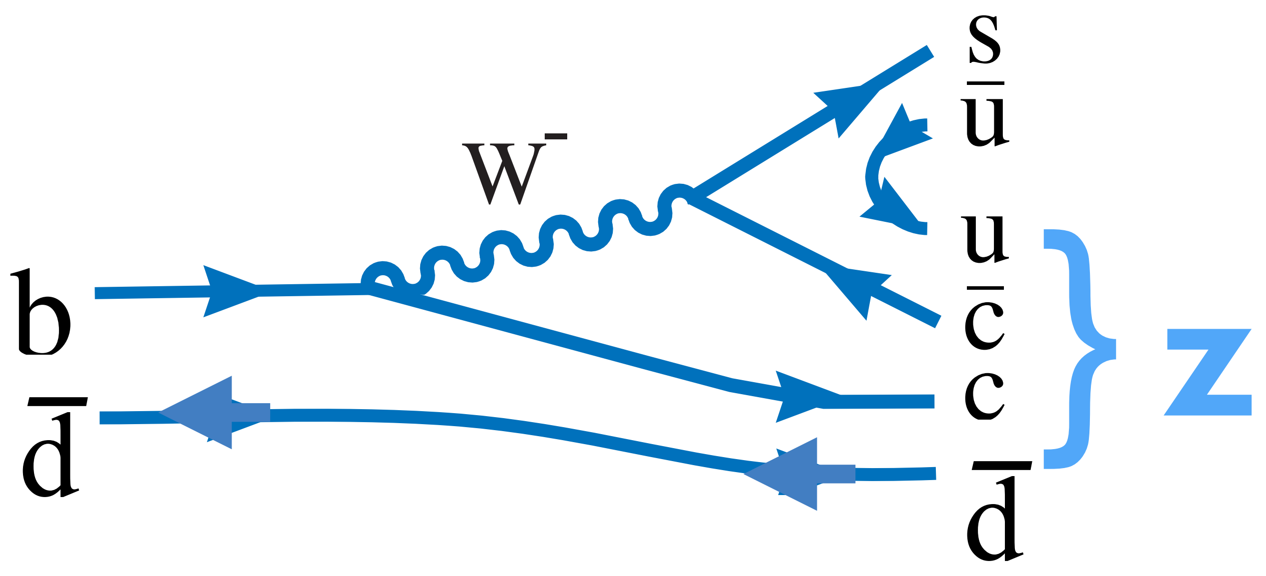
[PRL 110 (2013) 222001]





$B^0 \to \psi(2S) K^+ \pi^-$

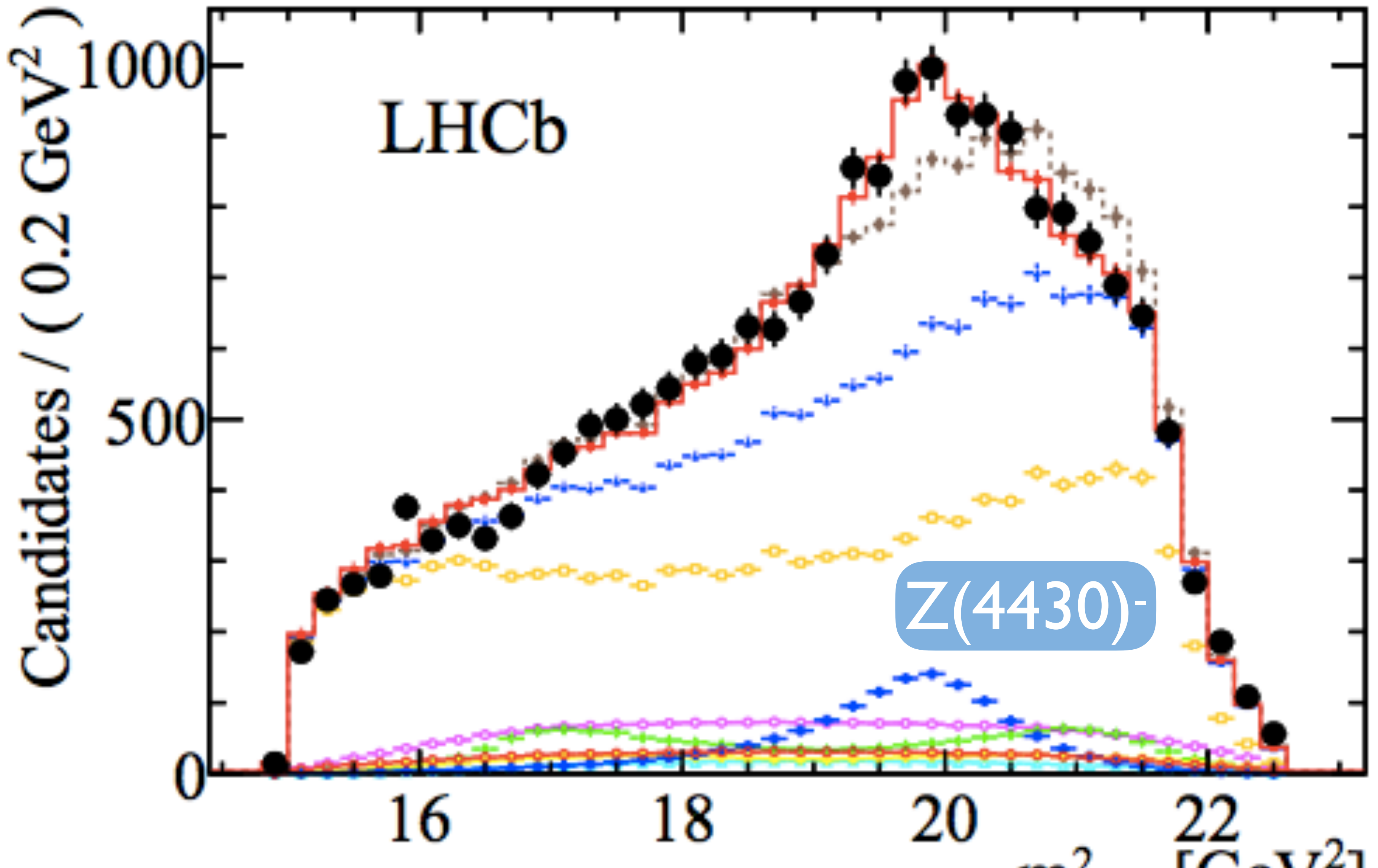
$\hookrightarrow J/\psi \pi^+ \pi^-$



$B^0 \to Z(4430)^- K^+$

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

$\hookrightarrow J/\psi \pi^+ \pi^-$



[PRL 112 (2014) 222002]

$X(4140) \to J/\psi\phi$: some history

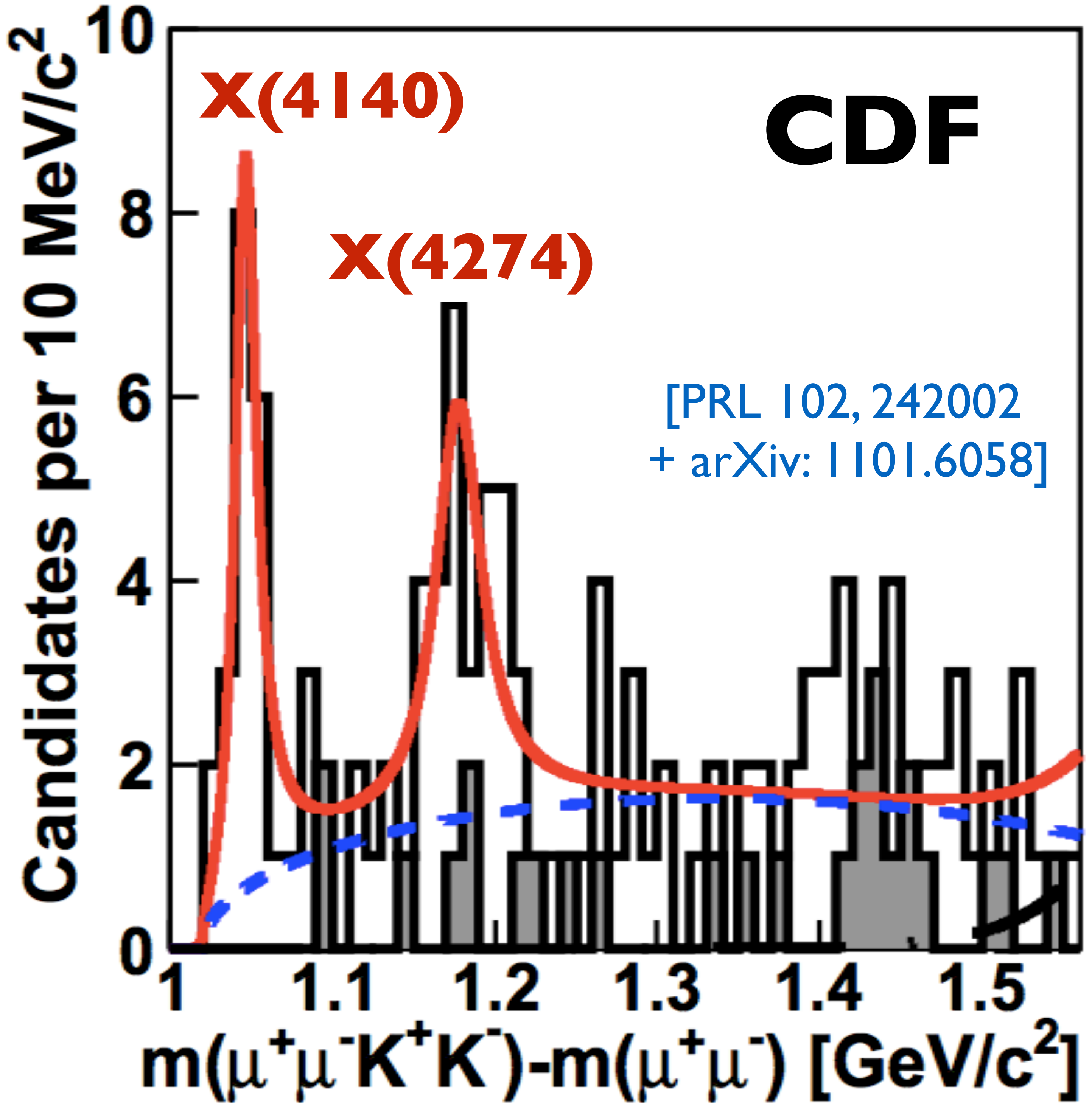
Seen by CDF, D0 and CMS in $B^+ \to J/\psi\phi K^+$ decays
No evidence from LHCb, BaBar, BES-III, Belle.

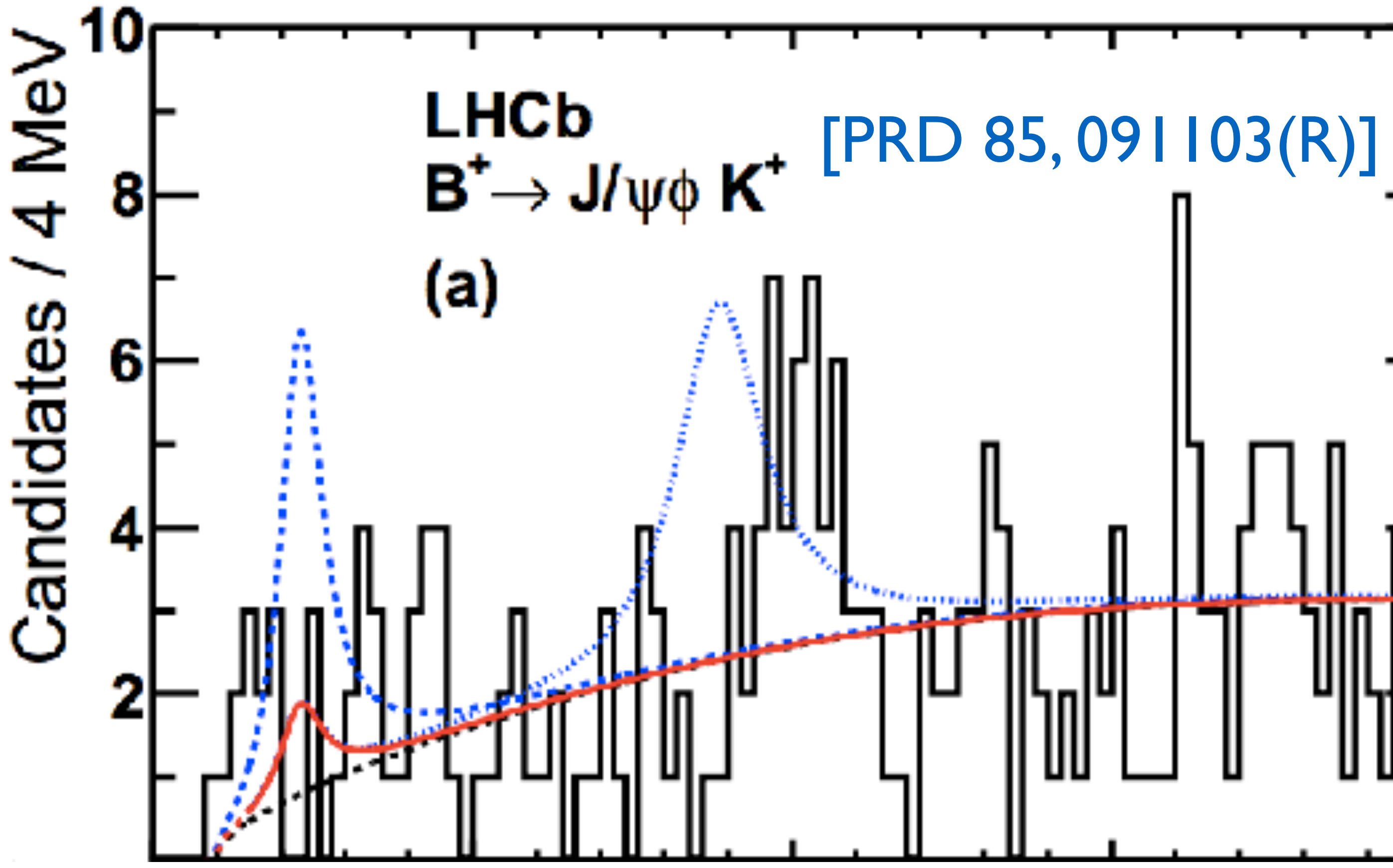
Well above open-charm threshold but has **narrow width** → not conventional $c\bar{c}$.

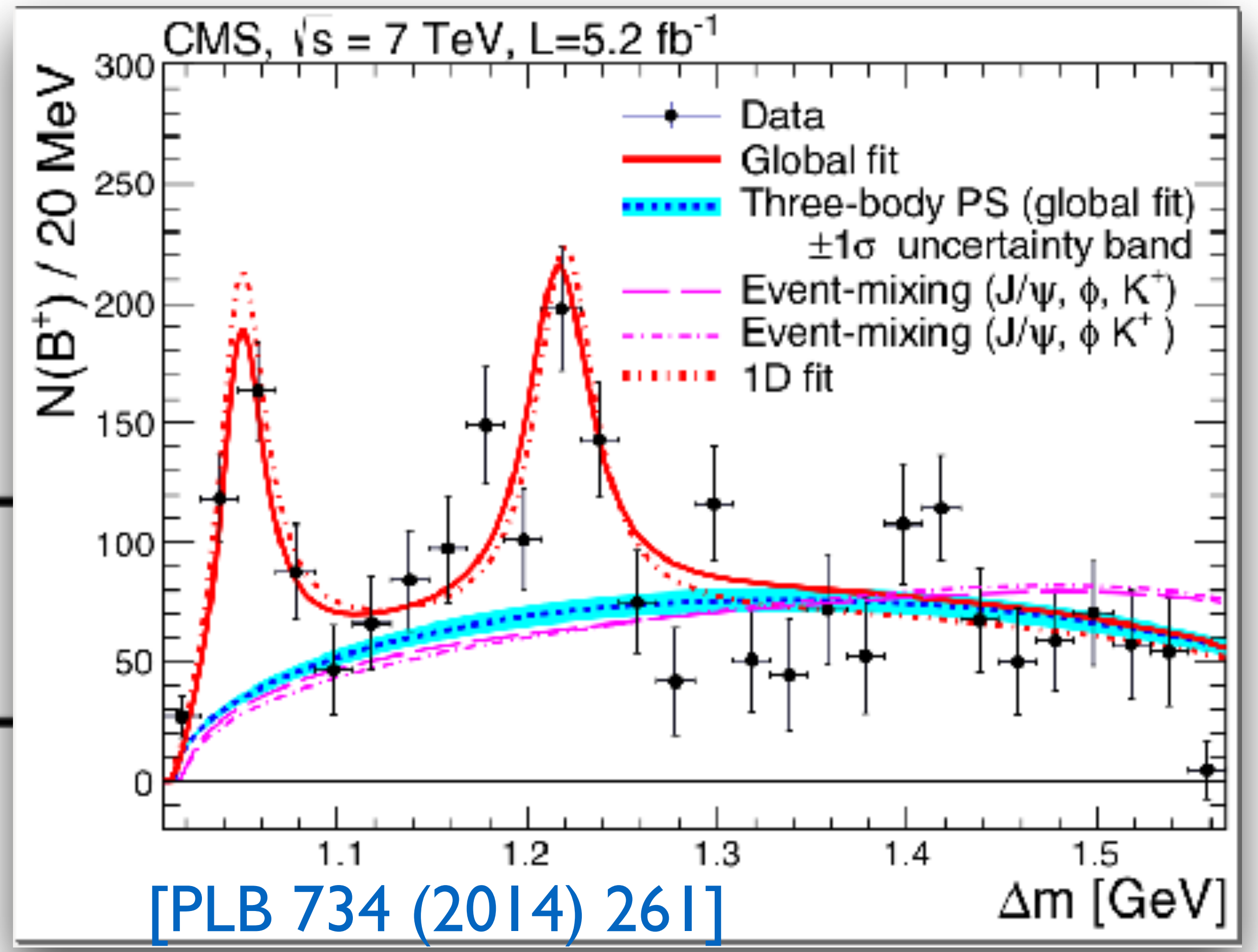
Also second state at higher mass…

Full amplitude analysis of decay is essential!

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







Experiment	X(4140)	X(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]	$M = 4148.0 \pm 2.4 \pm 6.3$, $\Gamma = 28^{+15}_{-11} \pm 19$	$M = 4313.8 \pm 5.3 \pm 7.3$, $\Gamma = 38^{+30}_{-15} \pm 16$

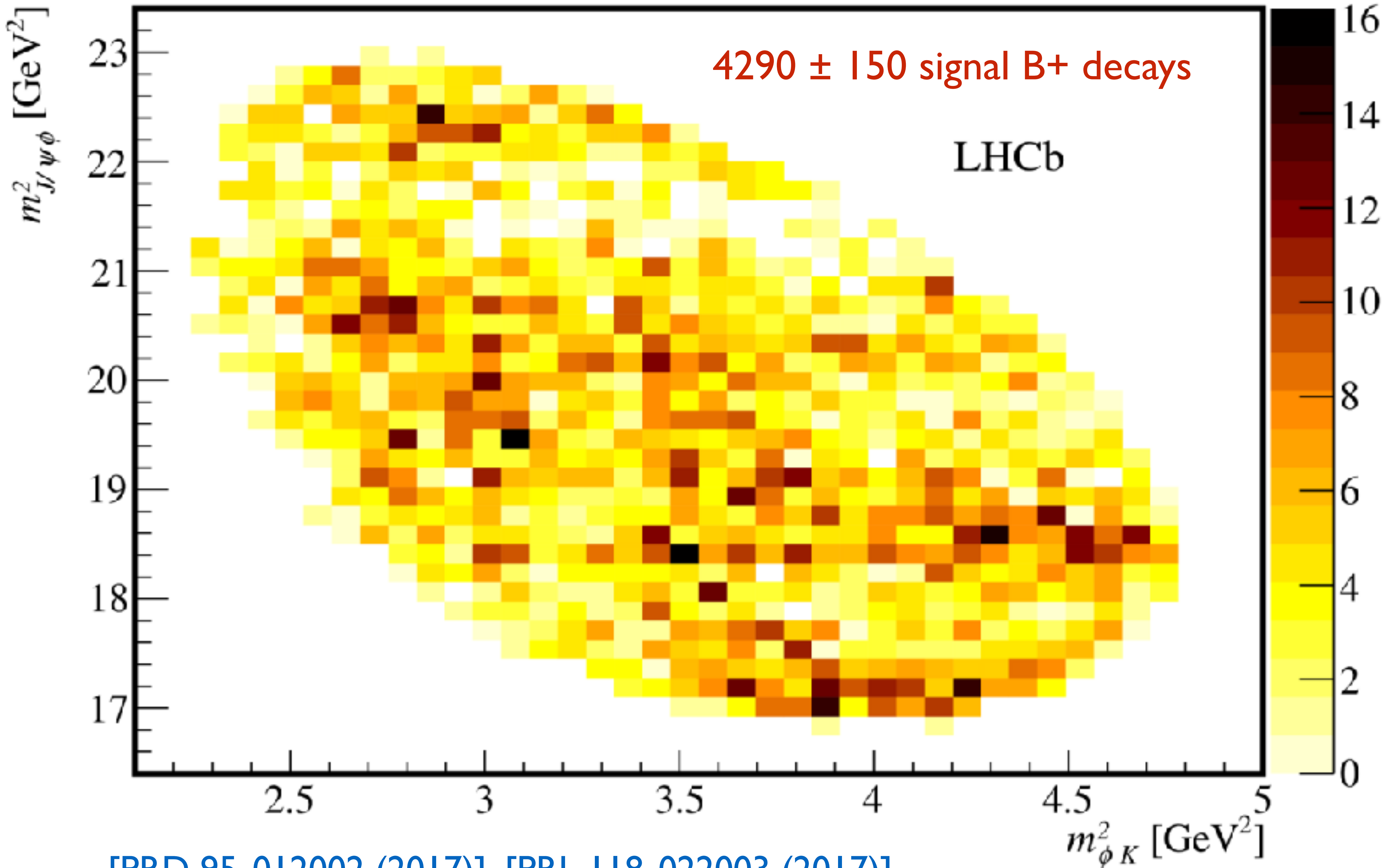
[D0 PRD 89, 012004]
[Belle PRL 104, 112004]
[BES-III PRD 91 (2015) 032002]

$B^+ \to J/\psi\phi K^+$ @ LHCb

Are reflections from K^* system causing structure in $J/\psi\phi$?

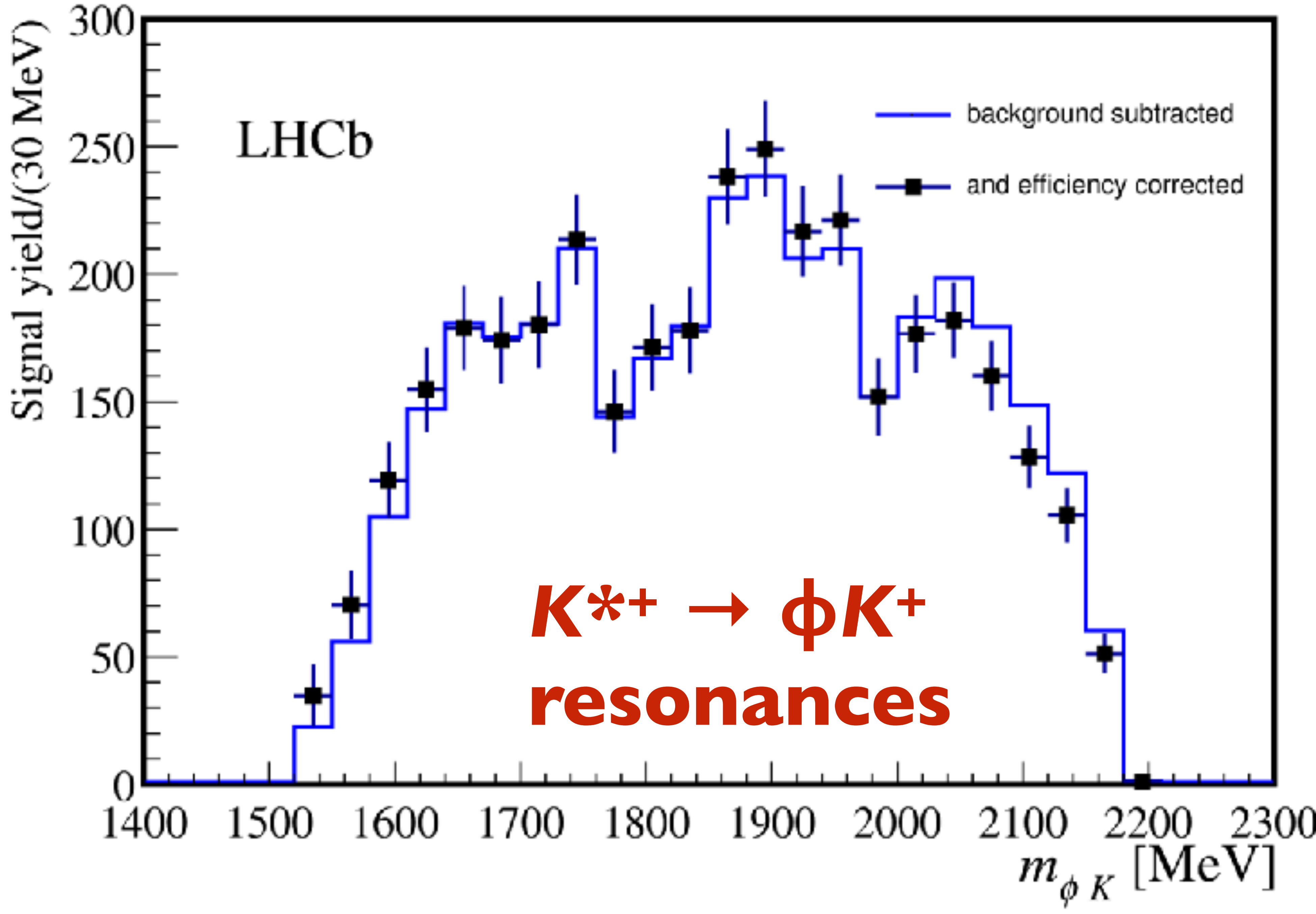
Not sufficient to just fit 1D mass distributions with ad-hoc assumptions about K* contributions

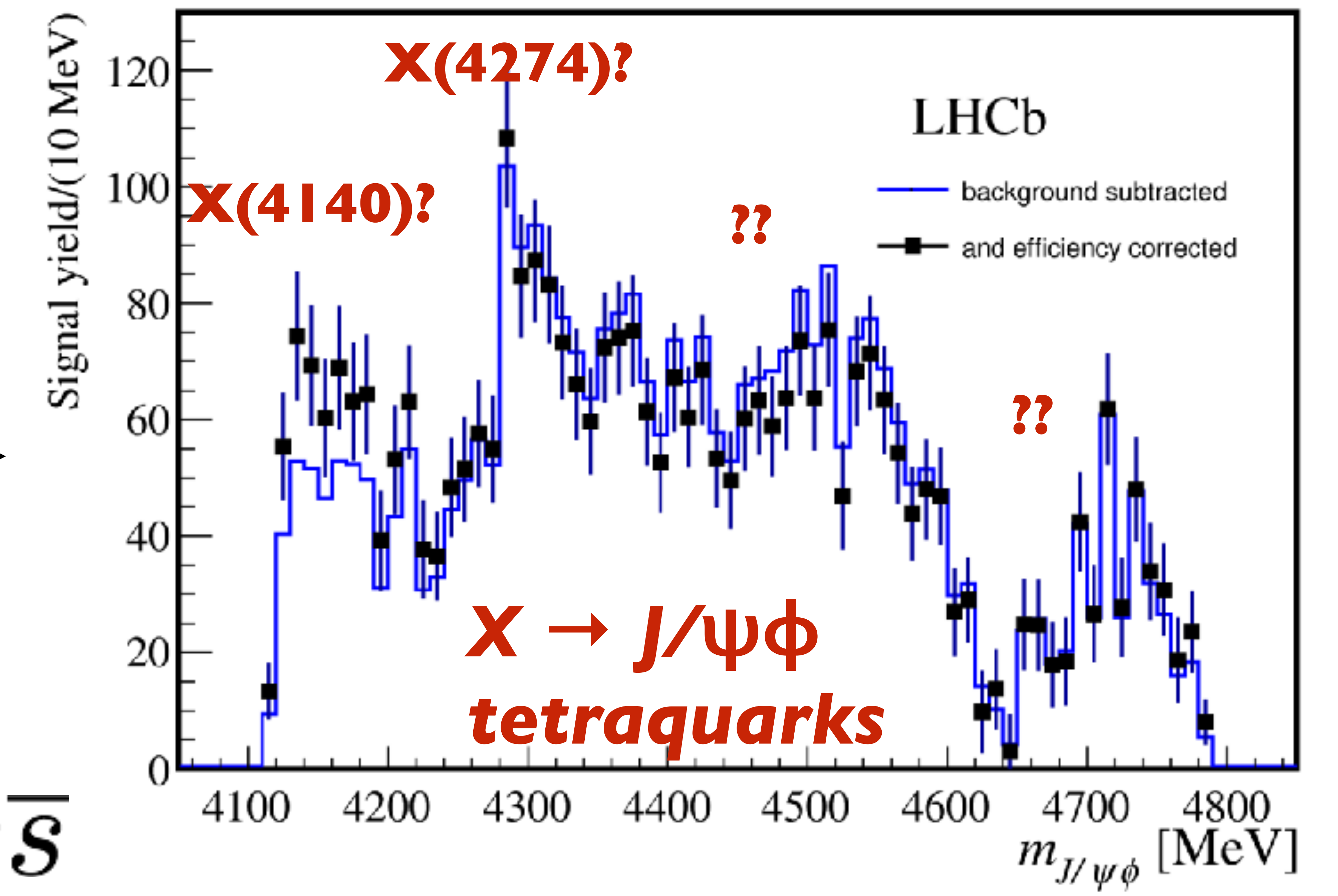
$K^{*+} \to \phi K^+$ resonances expected to be broad (scattering expts)



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

1D projection





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

$B^+ \to J/\psi\phi K^+$ @ LHCb

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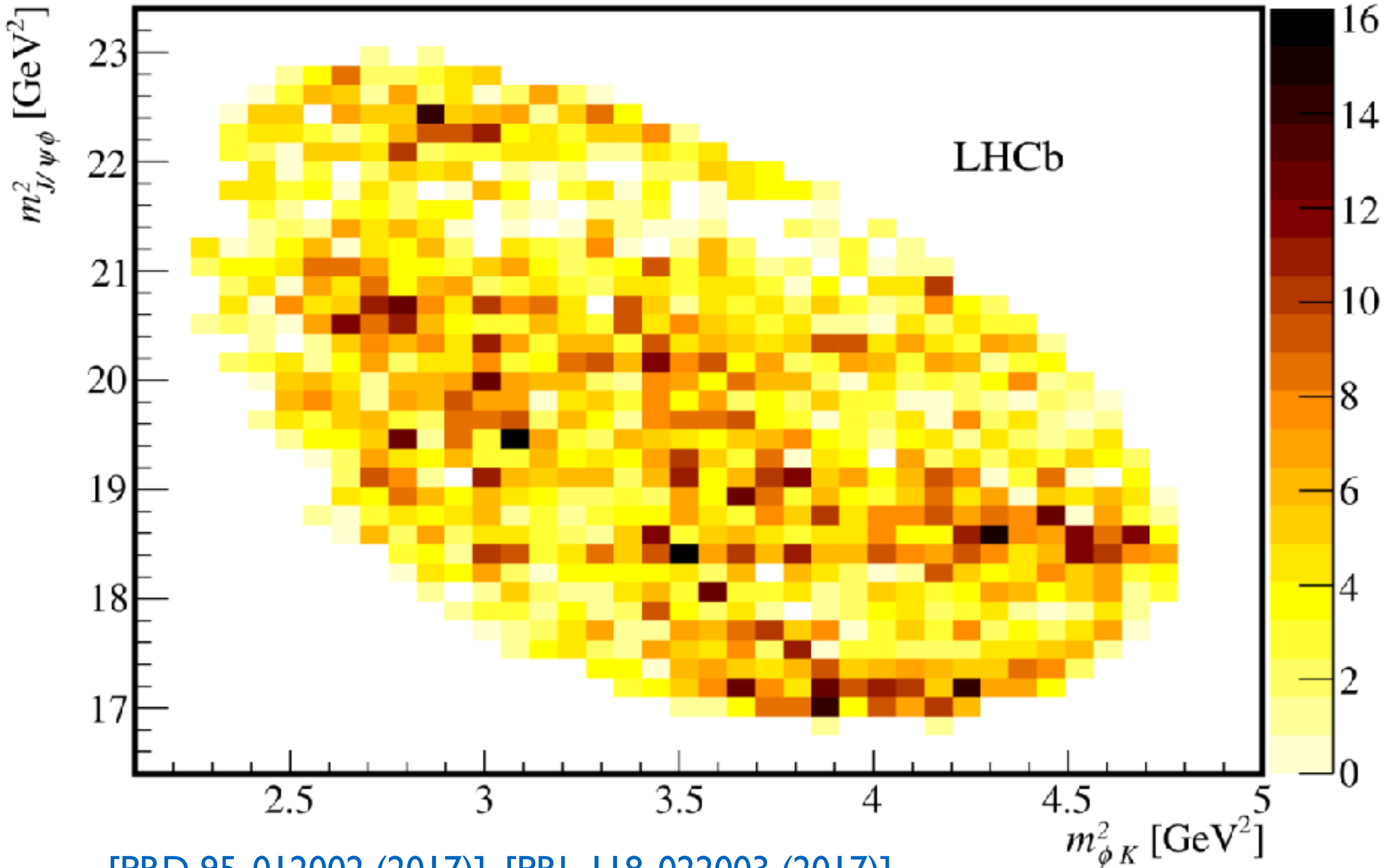
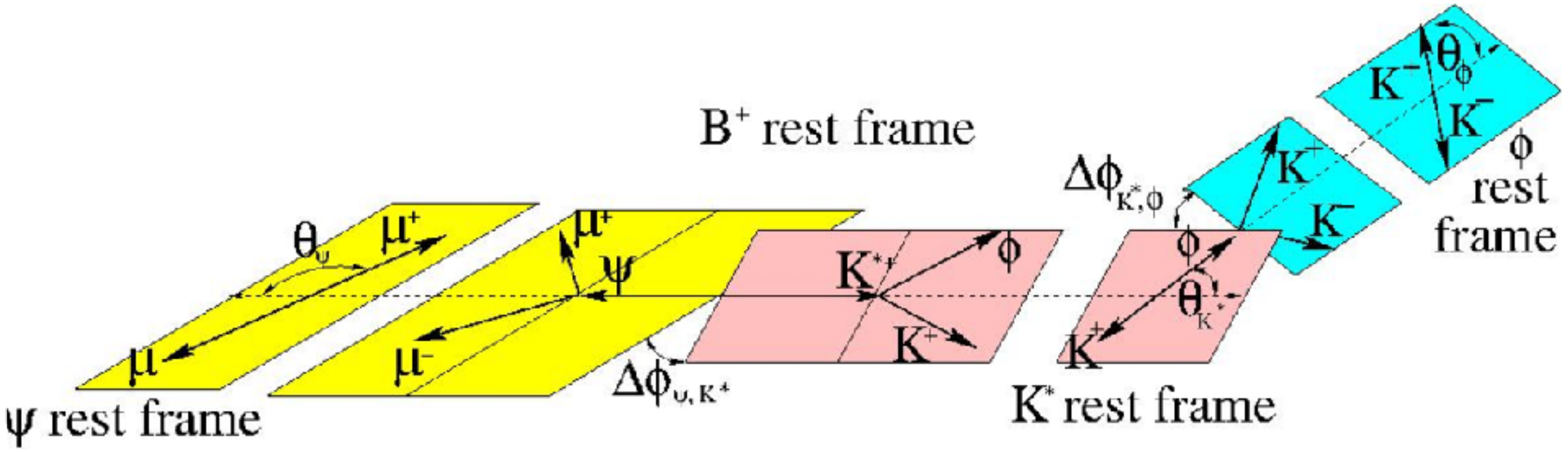
6D amplitude analysis to understand resonant structure

Three **interfering** decay chains (same particles in final state but different intermediate resonances):

1. $B^+ \to K^{*+} J/\psi, \;\; K^{*+} \to \varphi K^+$
2. $B^+ \to X K^+, \;\; X \to J/\psi \varphi$
3. $B^+ \to Z^+ \varphi, \;\; Z^+ \to J/\psi K^+$

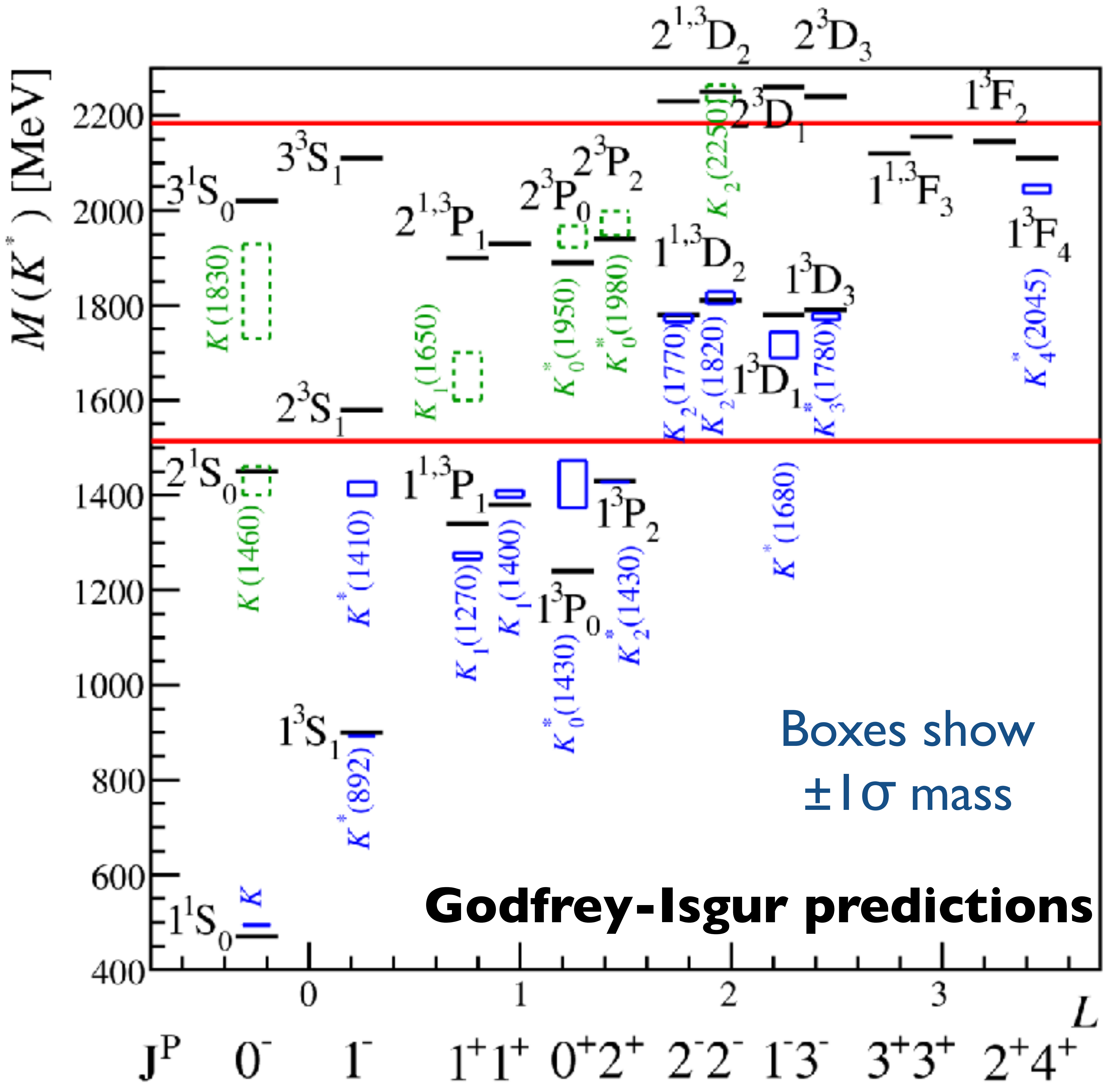




$$\Omega \equiv (\theta_{K^*}, \theta_{\psi}, \Delta\phi_{\psi,K^*}, \theta_{\phi}, \Delta\phi_{K^*,\phi})$$

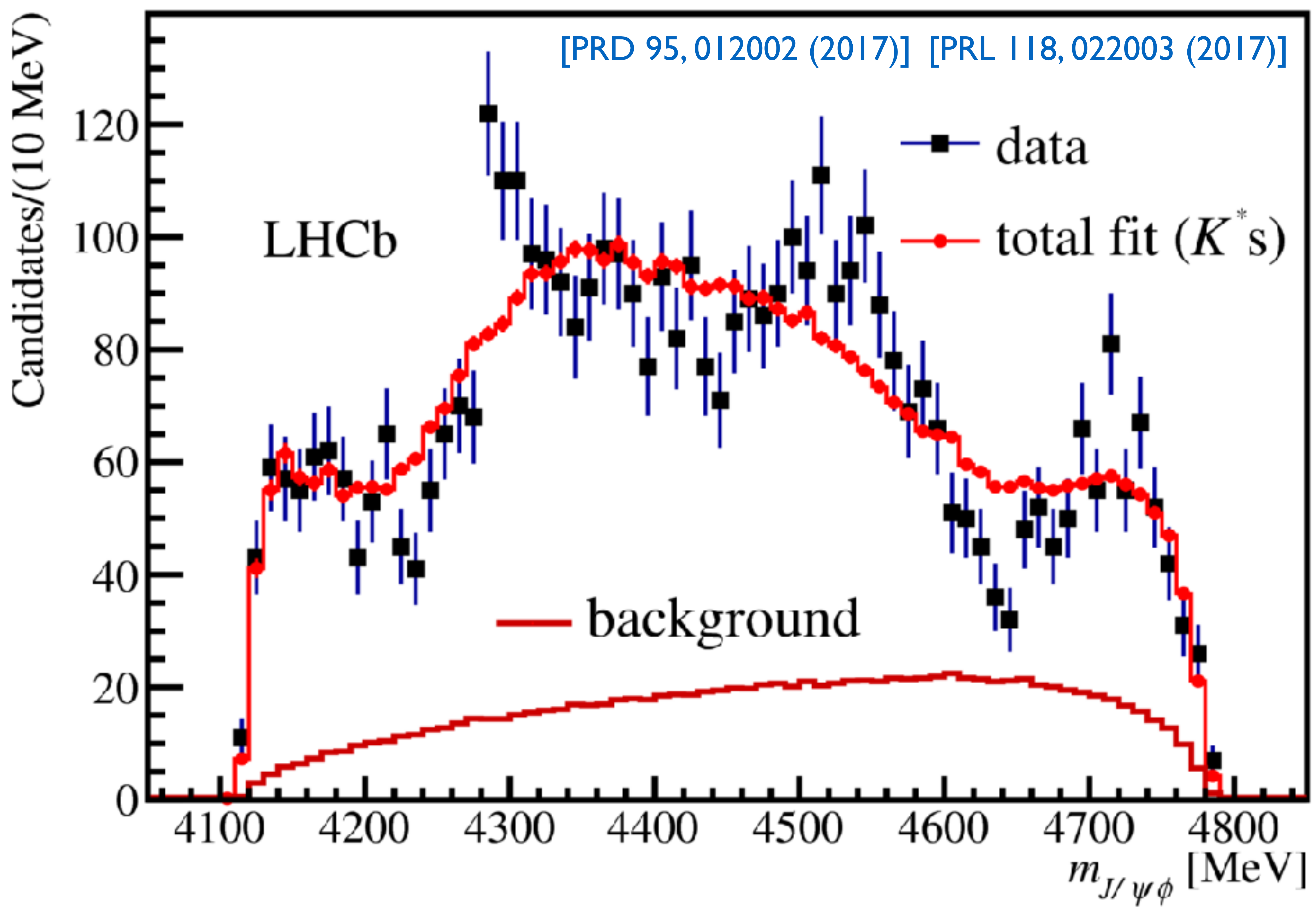
[PRD 95, 012002 (2017)] [PRL 118, 022003 (2017)]

Which *K** resonances to include?



Experimental measurements of **well-established** and **unconfirmed** K* resonances

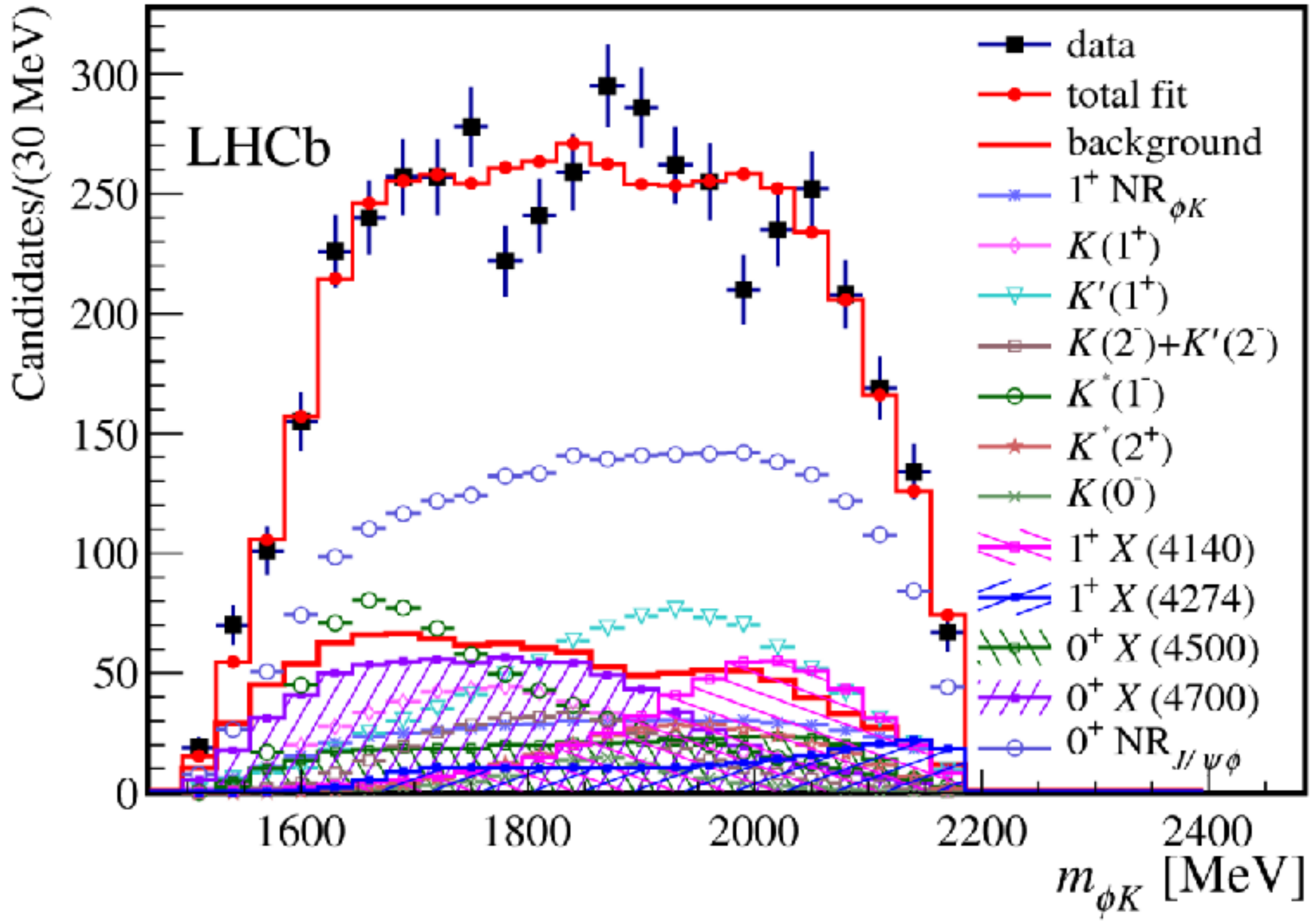
Higher spin states expected to be suppressed in B decays due to orbital angular momentum required to produce them

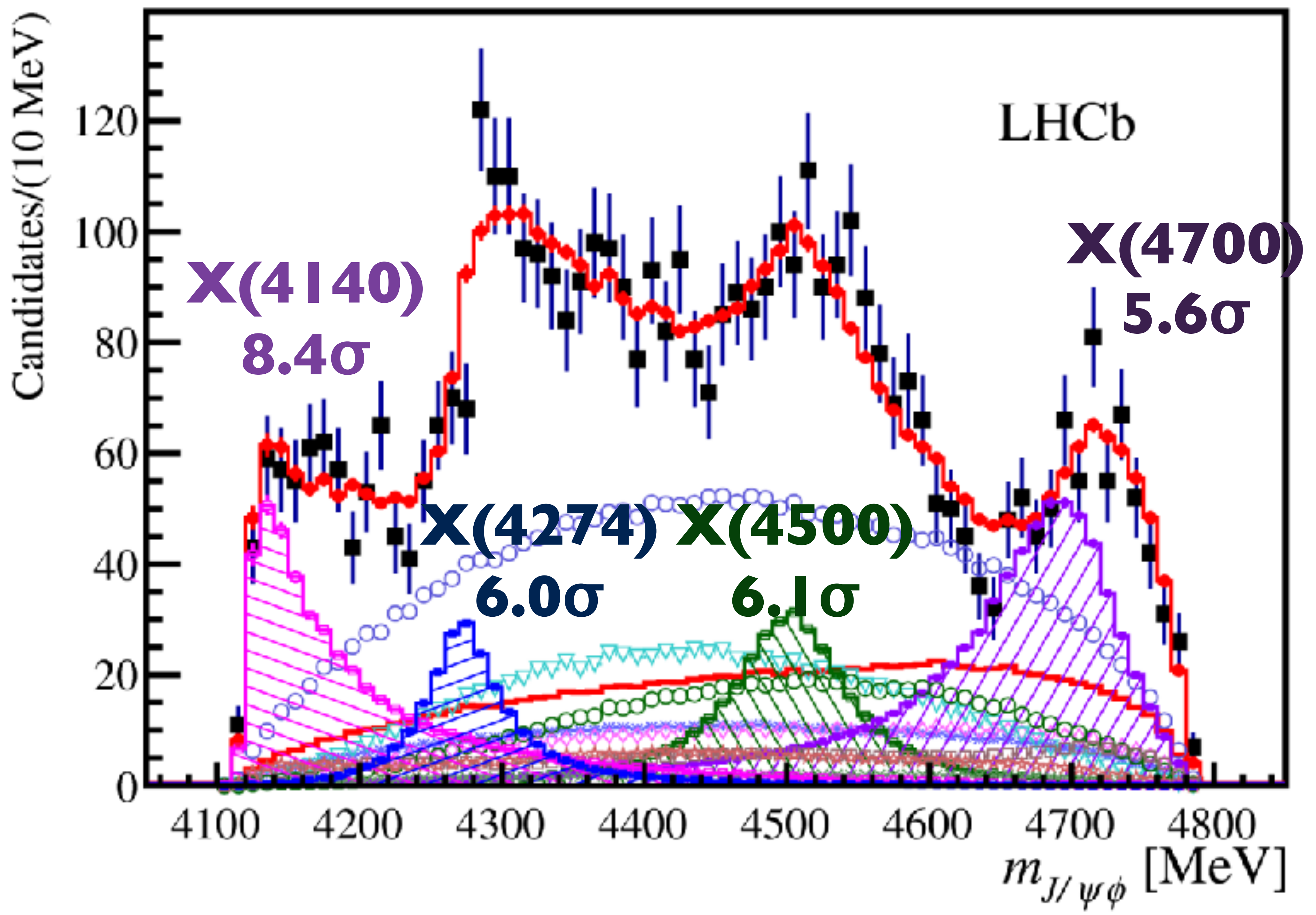


104 free parameters in fit

p-value H_0 (only K* resonances) < 10^{-4}

Results including $X \to J/\psi\phi$ states





7 K^* states, 4 exotic X states and NR $J/\psi\phi$ and ϕK^* components.

Inclusion of exotic Z states does not improve fit.

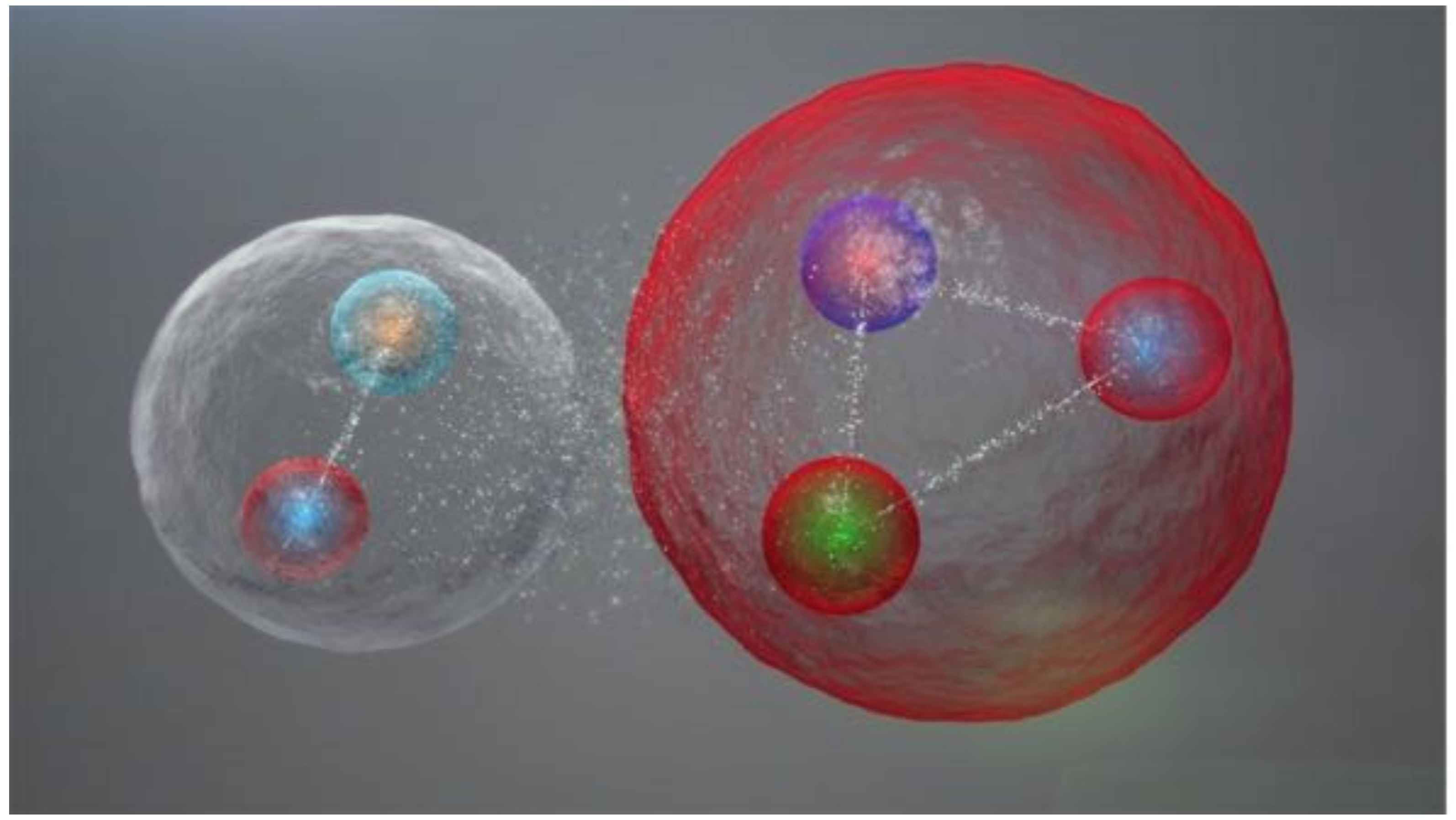
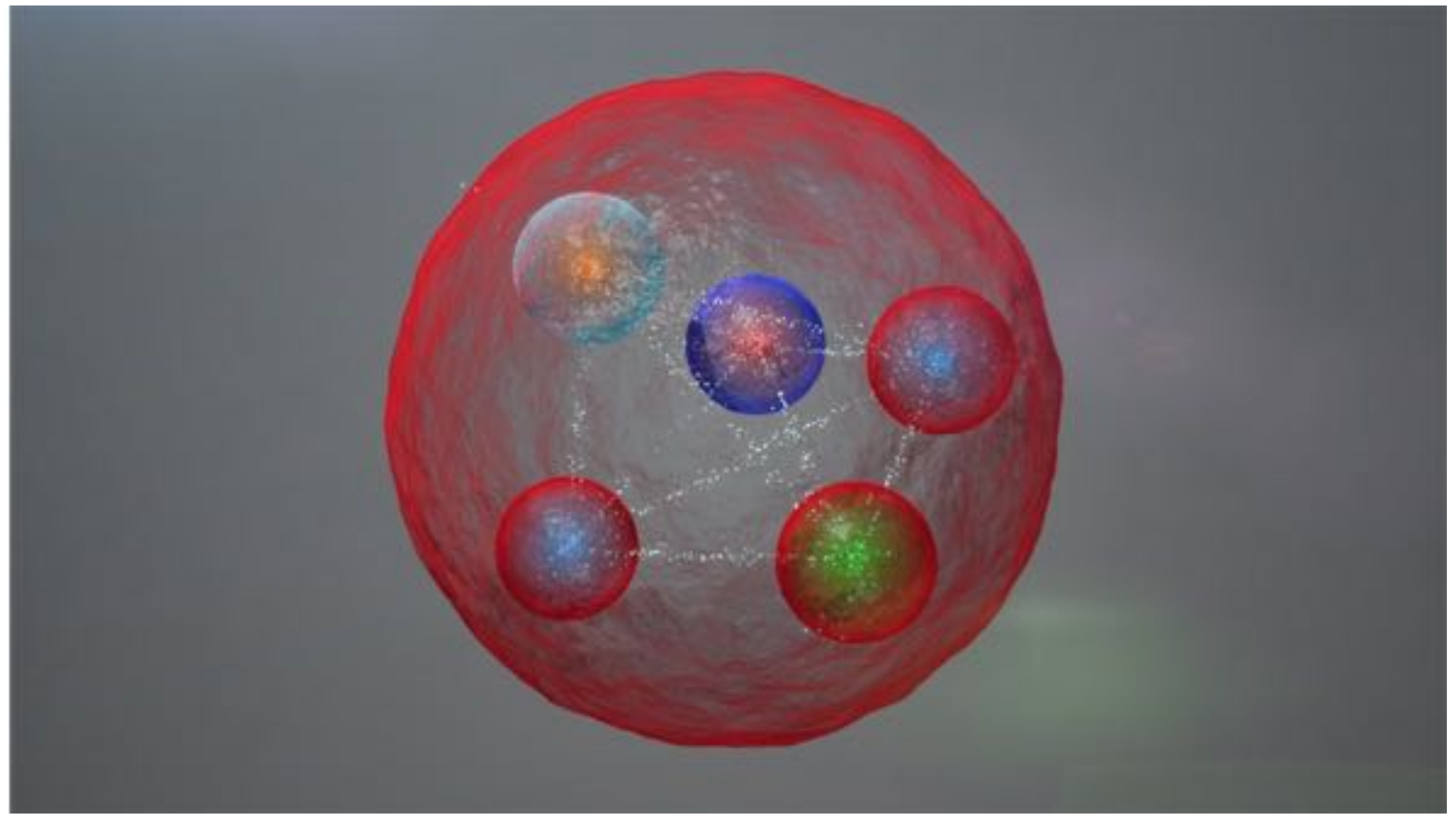
98 free parameters in fit
p-value = 22%

Contri- bution	sign. or Ref.	M_0 [MeV]	Γ_0 [MeV]	Fit results FF %
All $X(1^+)$				$16\pm3\ ^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13\pm3.2\ ^{+4.8}_{-2.0}$
ave.	Table 1	4143.4 ± 1.9	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\ ^{+17.2}_{-3.6}$	$56\pm11\ ^{+8}_{-11}$	$7.1\pm2.5\ ^{+3.5}_{-2.4}$
CDF	[28]	$4274.4\ ^{+8.4}_{-6.7}\pm1.9$	$32\ ^{+22}_{-15}\pm8$	
CMS	[25]	$4313.8\pm5.3\pm7.3$	$38\ ^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm5\pm7$
$NR_{J/\psi\phi}$	6.4σ			$46\pm11\ ^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\ ^{+12}_{-15}$	$92\pm21\ ^{+21}_{-20}$	$6.6\pm2.4\ ^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm5\ ^{+9}_{-5}$

first observation

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

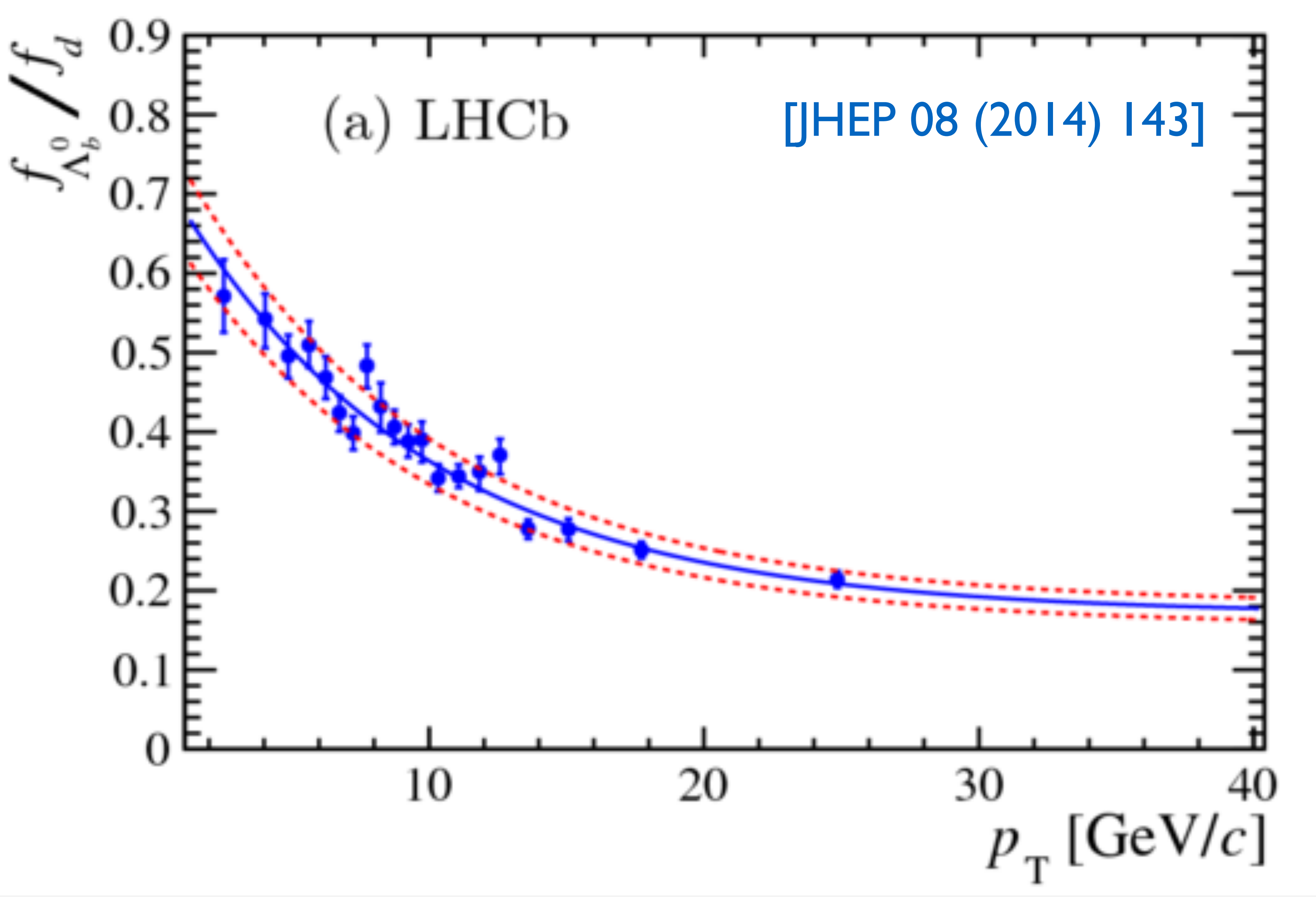
Exotic baryons

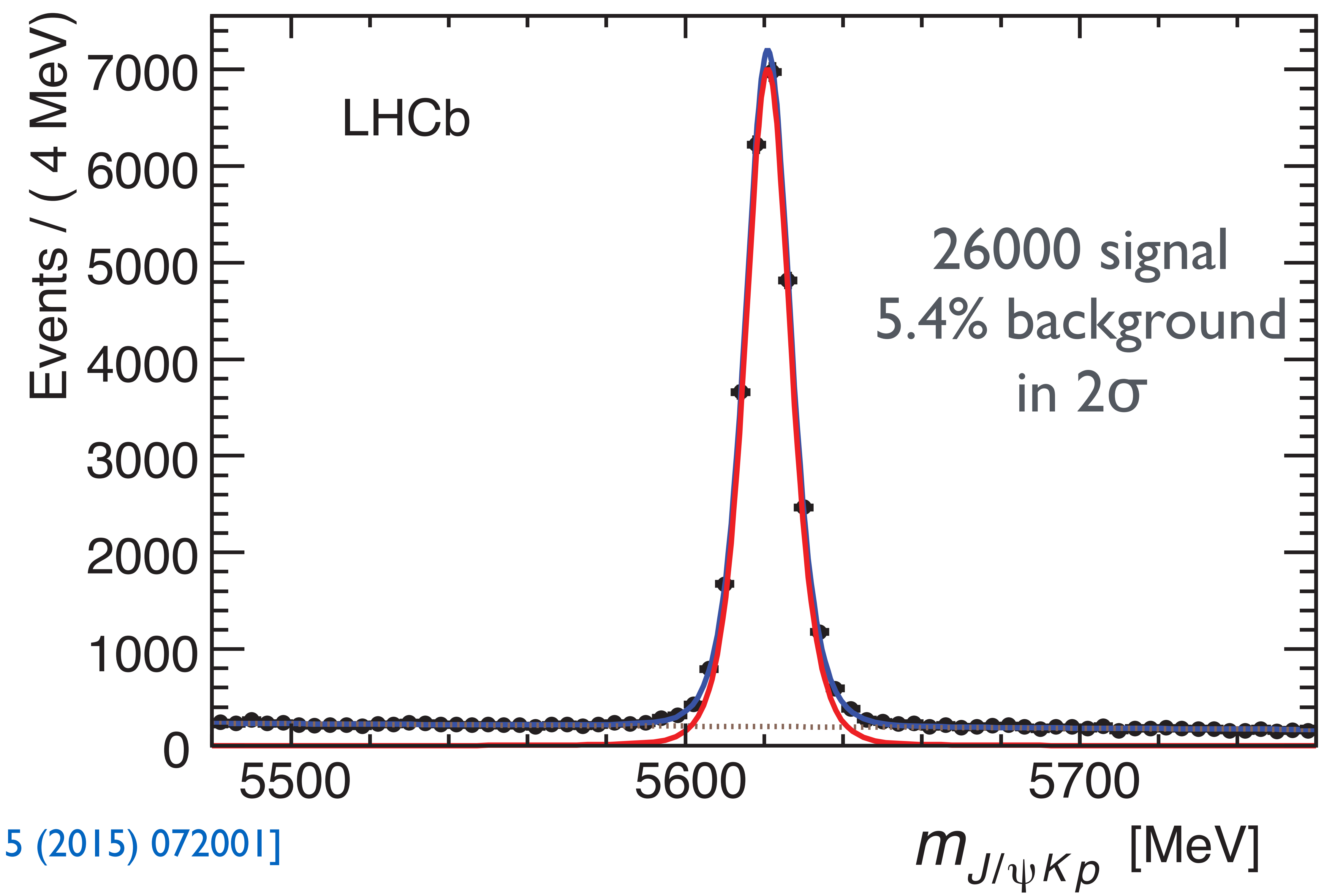
Pentaquark observation

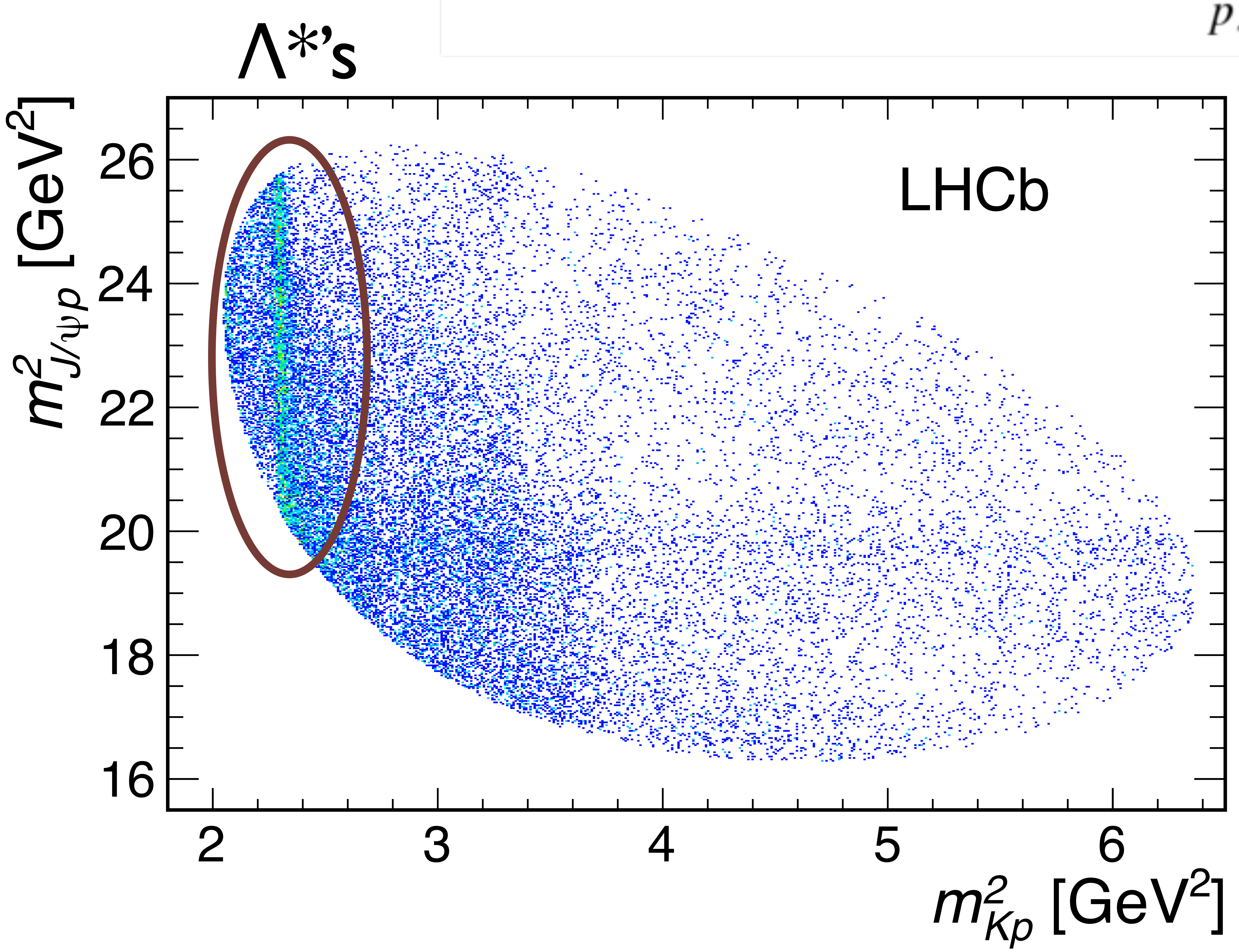
Large production of b-baryons at LHC.

Many more Λ_b in LHCb than central detectors.



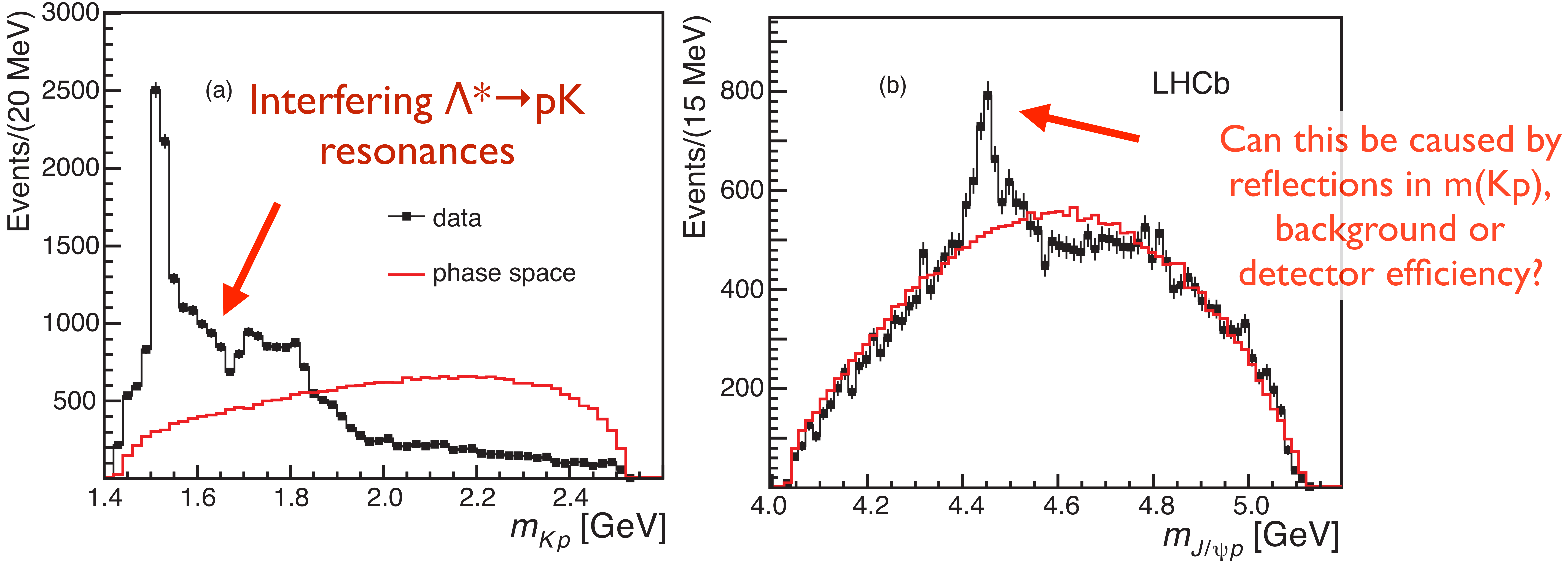
$\Lambda_b^0 \to J/\psi p K^-$

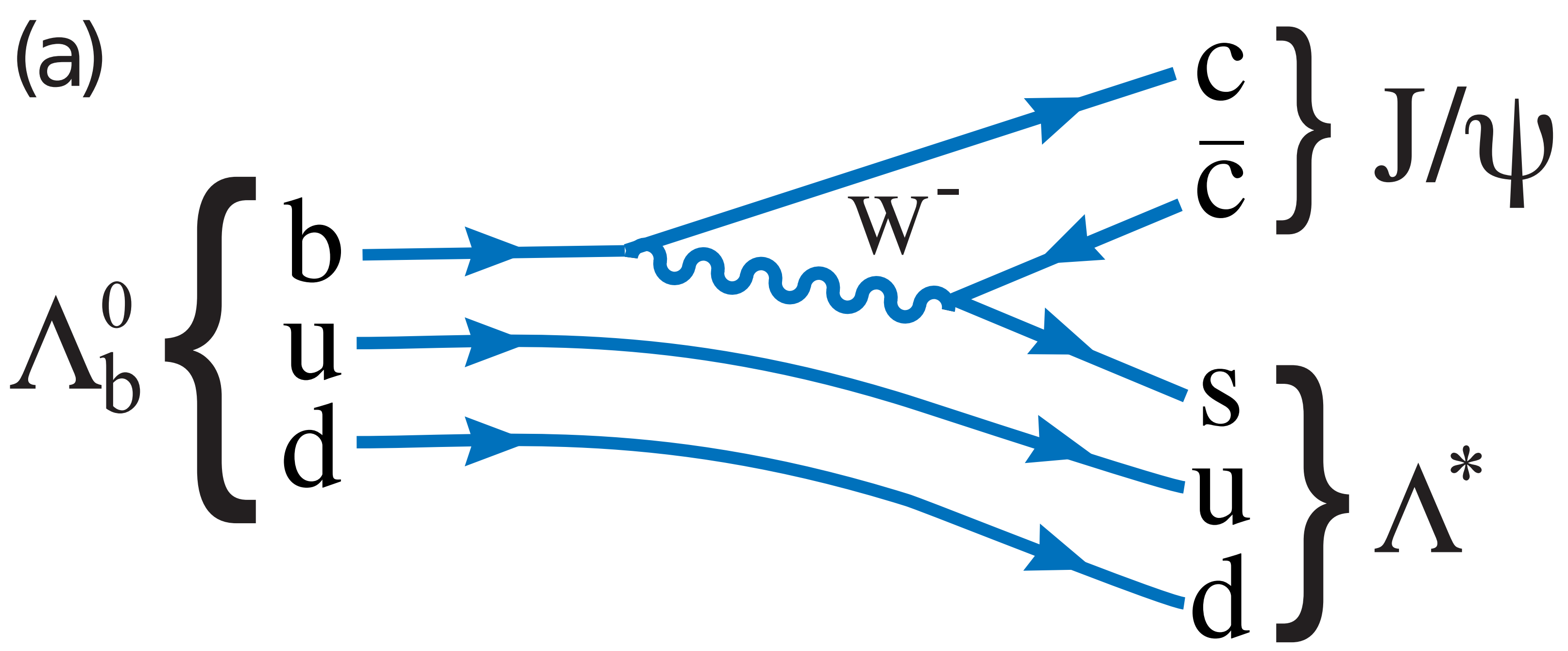




[PRL 115 (2015) 072001]

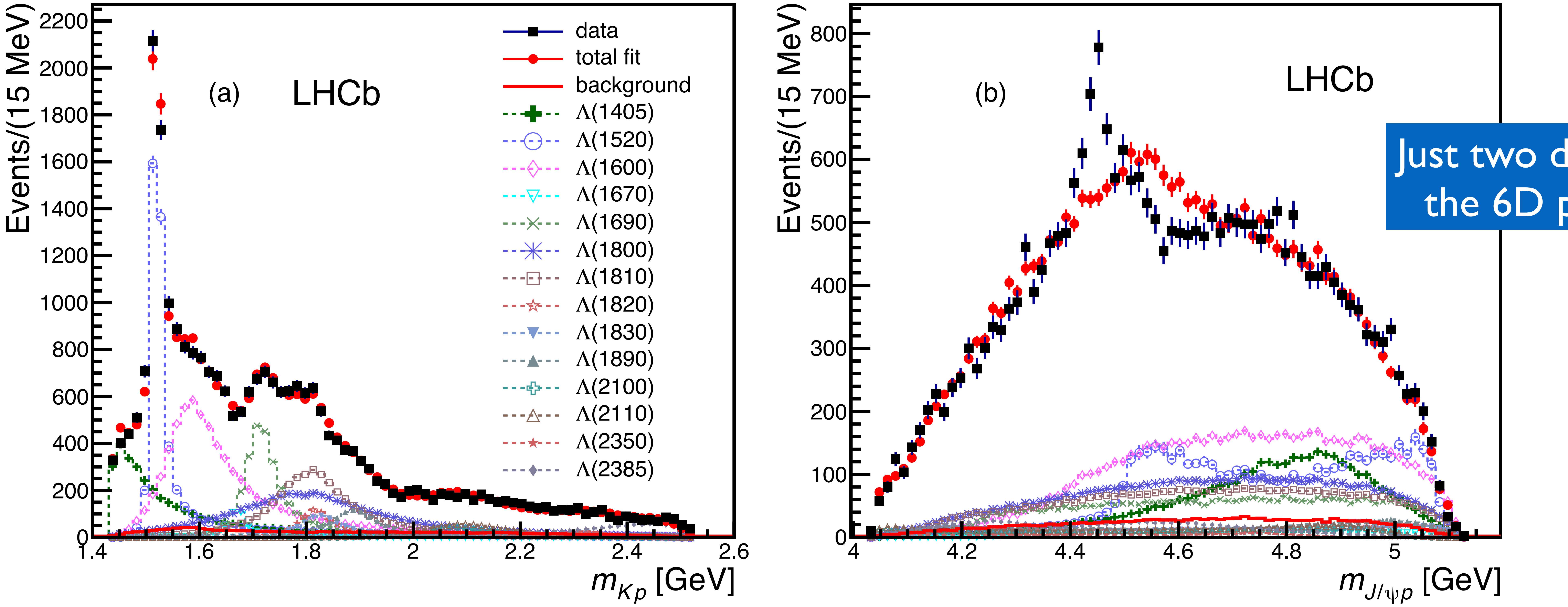
Pentaquark observation





[PRL 115 (2015) 072001]

Results without P_c states



Just two dimensions of the 6D phase space

Using full set of Λ*'s the m(Kp) distribution looks good but not m(J/ψp).

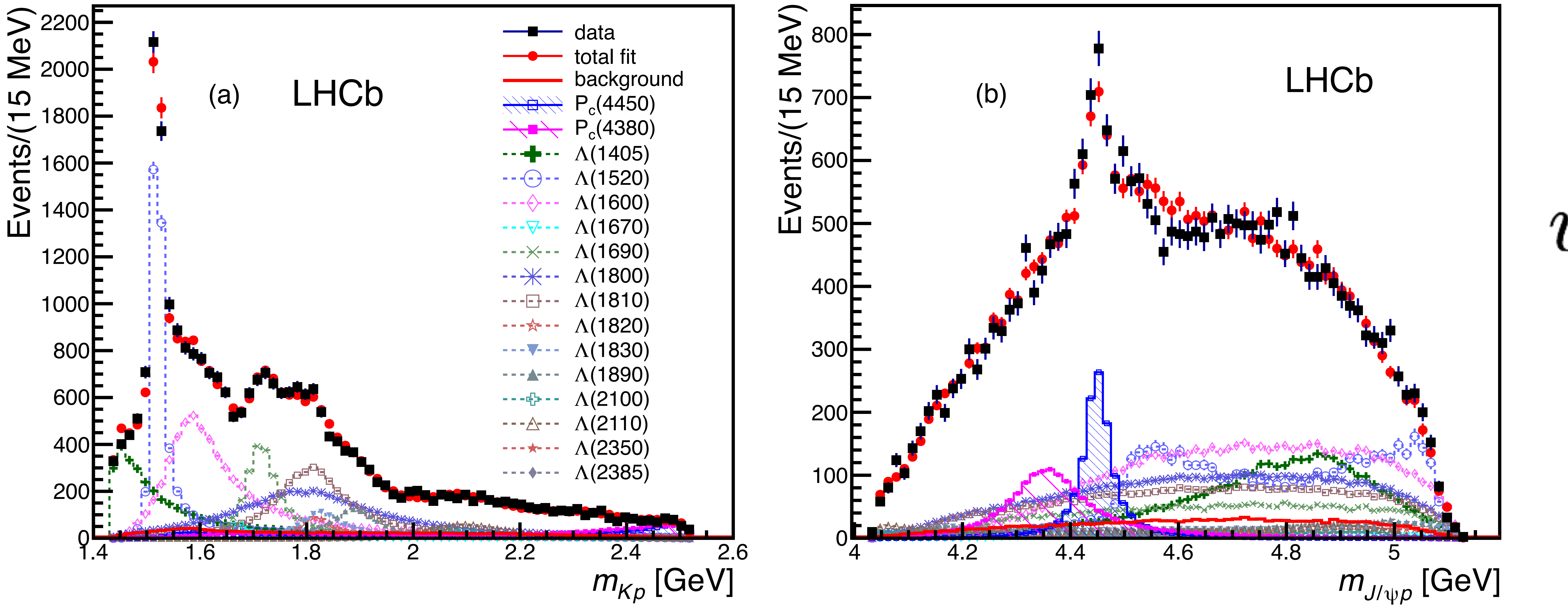
Addition of non-resonant, extra Λ*'s, all Σ* (isospin violating process) does not help.

Also: model independent approach (Legendre moments) excludes the Λ*-only hypothesis at 9σ

[PRL 117 (2016) 082002]

[PRL 115 (2015) 072001]

Reduced model with two P_c's



$uudc\bar{c}$

J^P = ($3/2^+$, $5/2^-$) and ($5/2^+$, $3/2^-$) also give good fits: **need more data.**

No improvement with addition of other resonances

Significance evaluated using toy simulation

Need opposite parity to explain the data

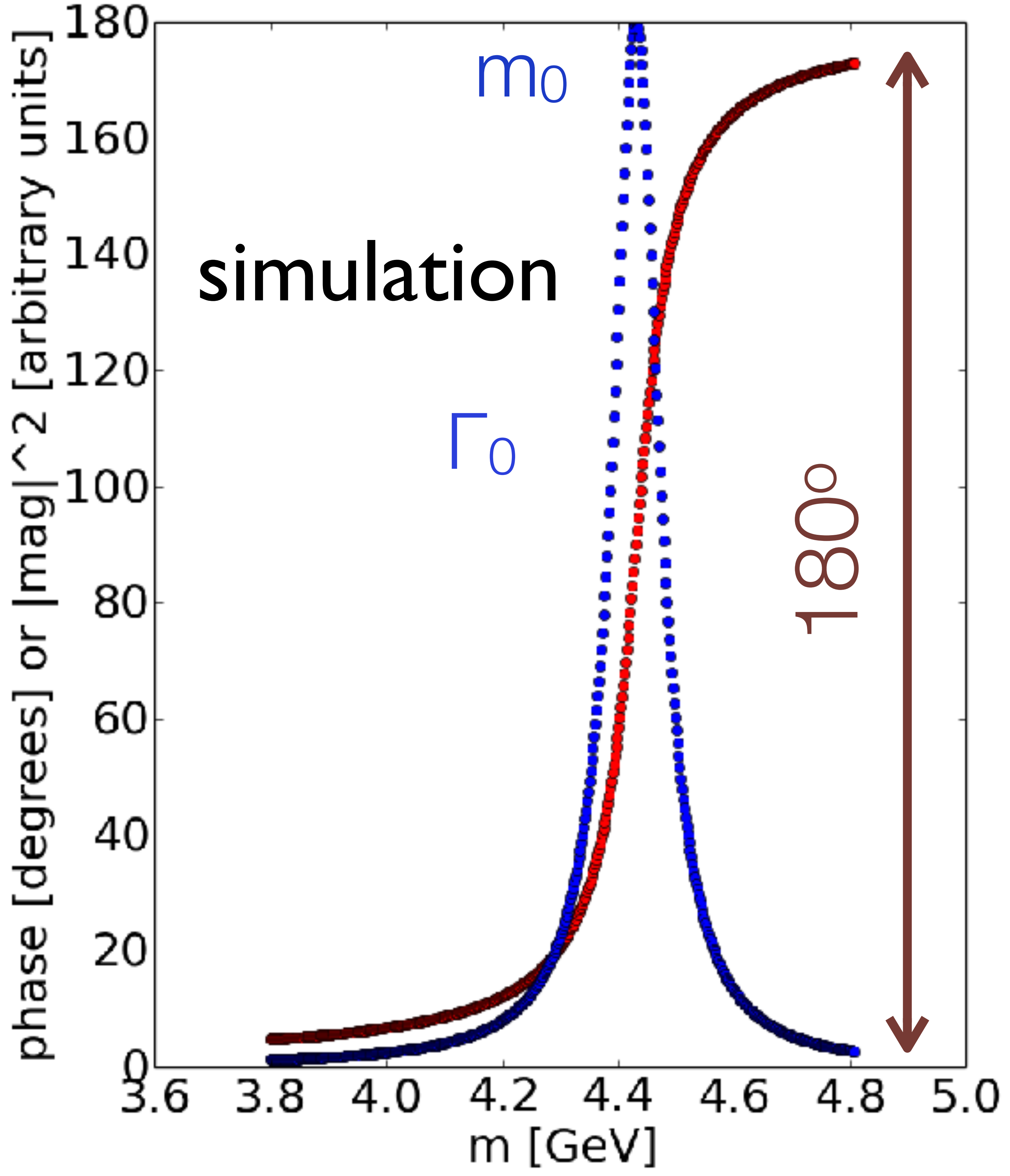
	$P_c(4380)^+$	$P_c(4450)^+$
J^P	$\frac{3}{2}^-$	$\frac{5}{2}^+$
Mass [MeV/c^2]	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Width [MeV/c^2]	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
Fit fraction [%]	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$
Significance	9σ	12σ

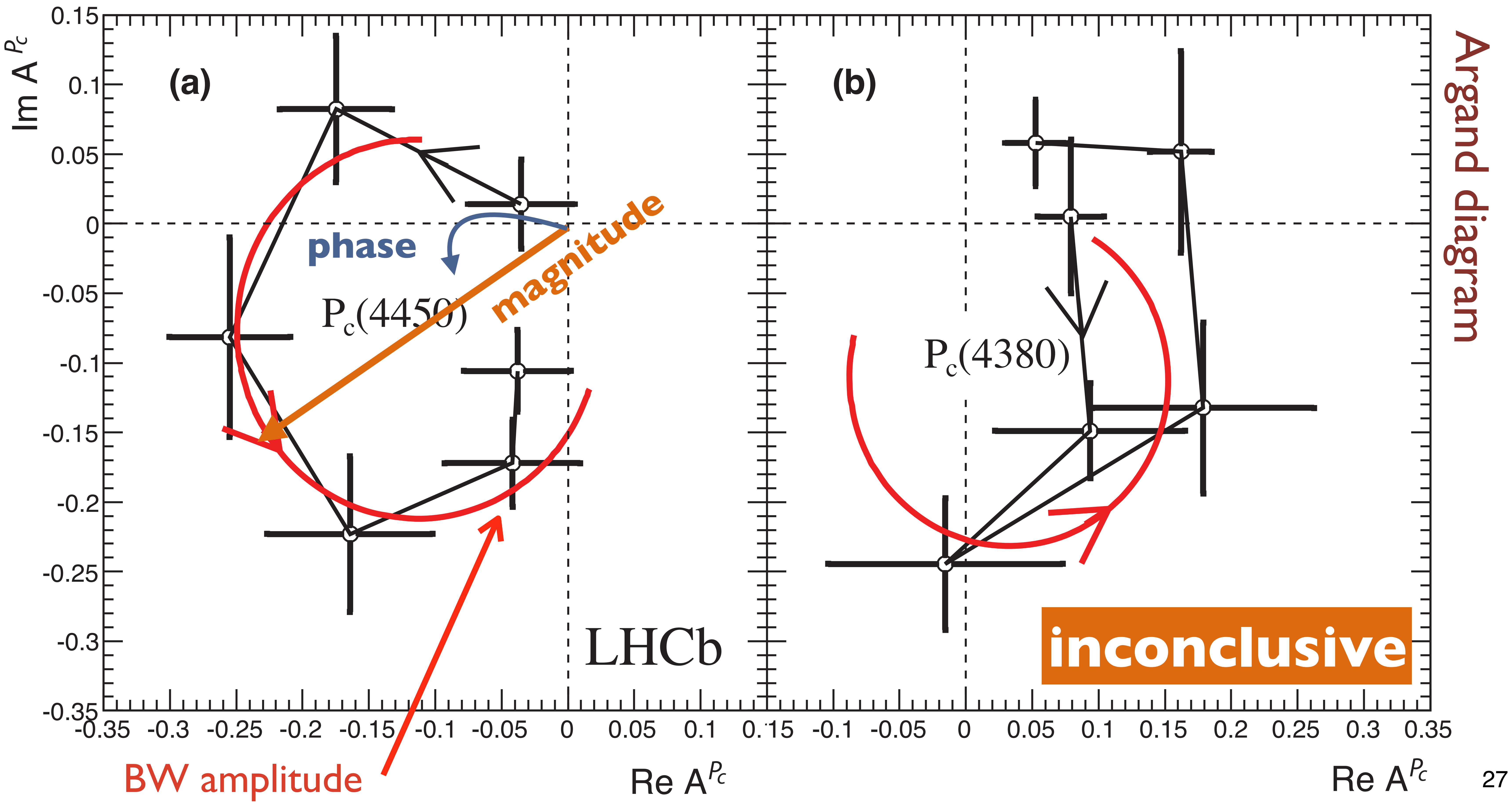
[PRL 115 (2015) 072001]

Resonant behaviour - a bound state?

Observe rapid change of phase near maximum of magnitude ⇒ **resonance!**

[PRL 115 (2015) 072001]

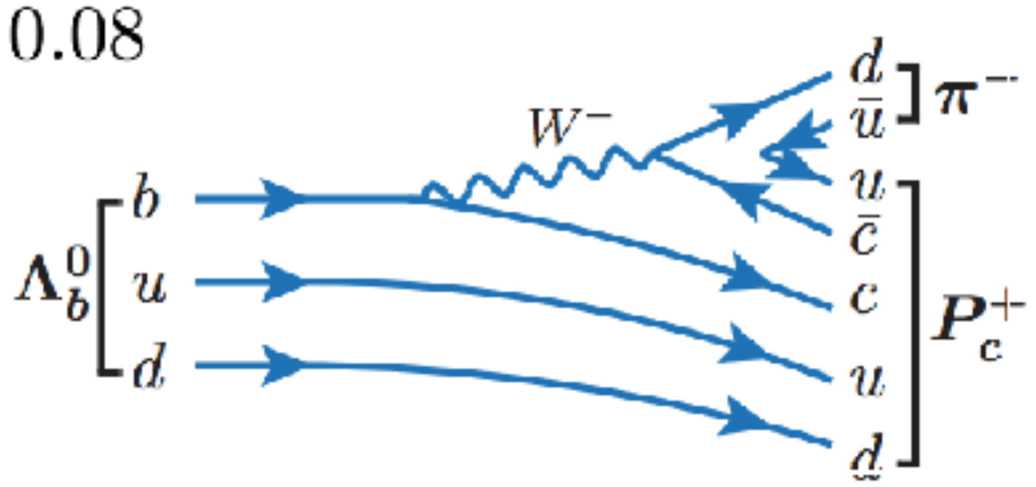




$\Lambda_b \to J/\psi p \pi^-$ pentaquark search

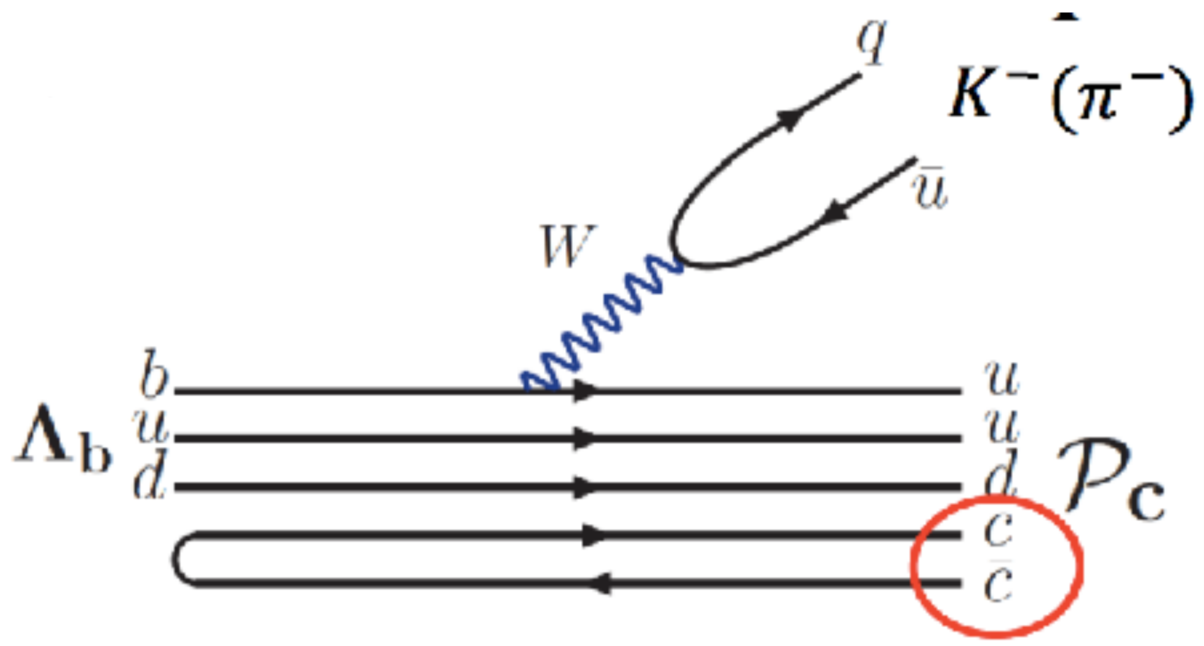
$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08$$

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

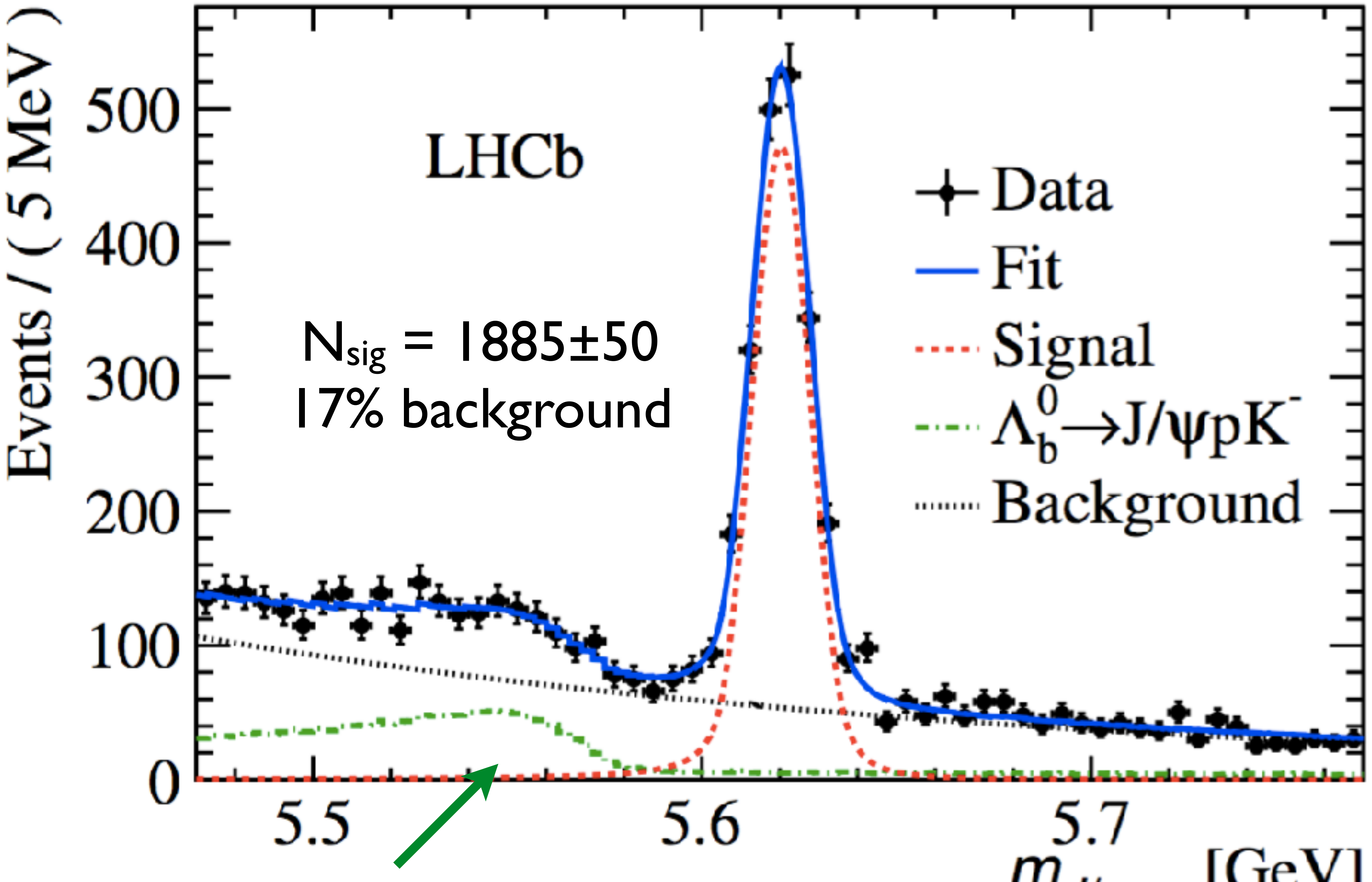


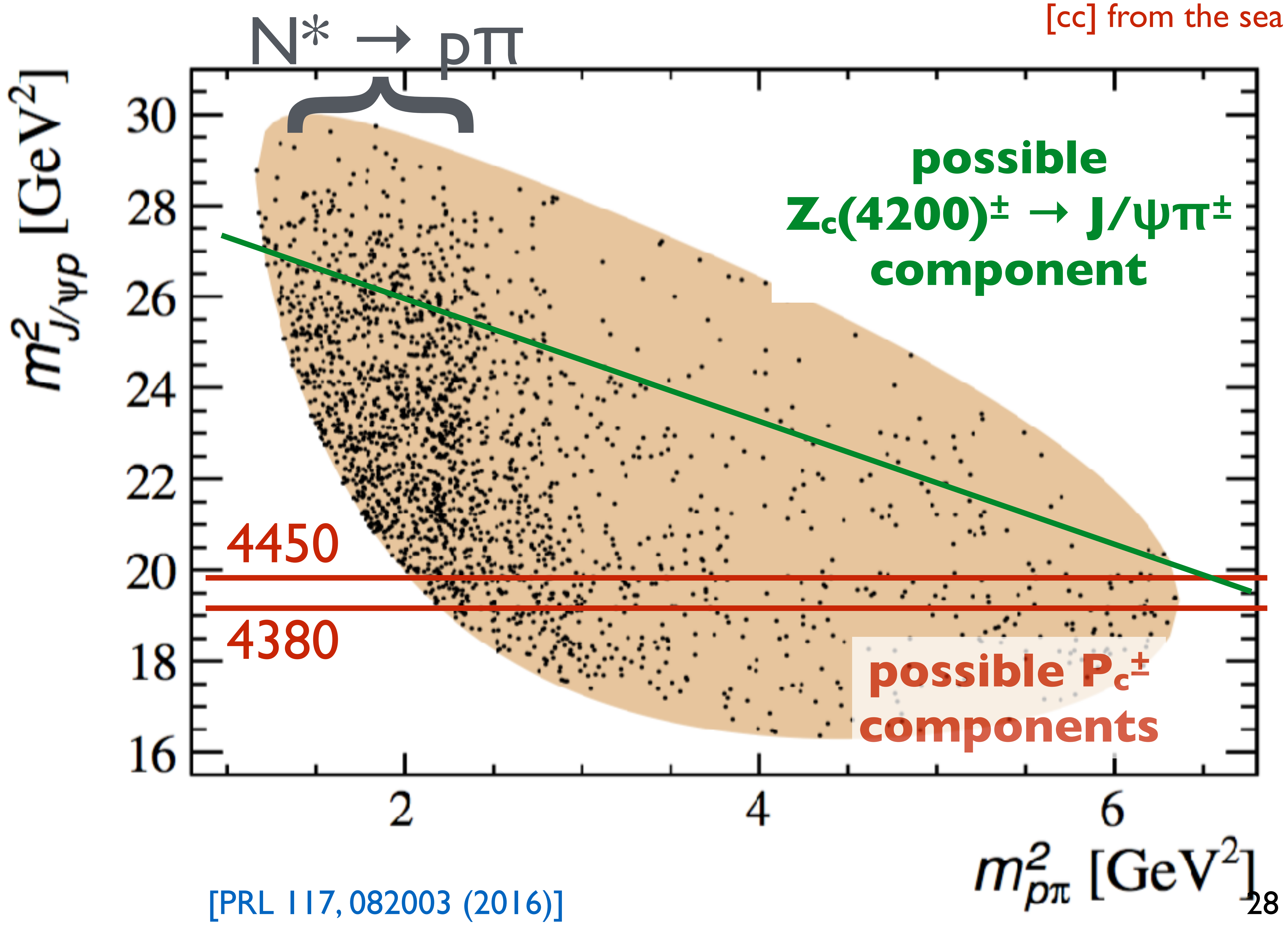
$$R_{\pi^-/K^-} = 0.58 \pm 0.05$$

[Hsiao, PLB 751, 572 (2015)]



[cc] from the sea





[PRL 117, 082003 (2016)]

$\Lambda_b \to J/\psi p \pi^-$ pentaquark search

[PRL 117, 082003 (2016)]

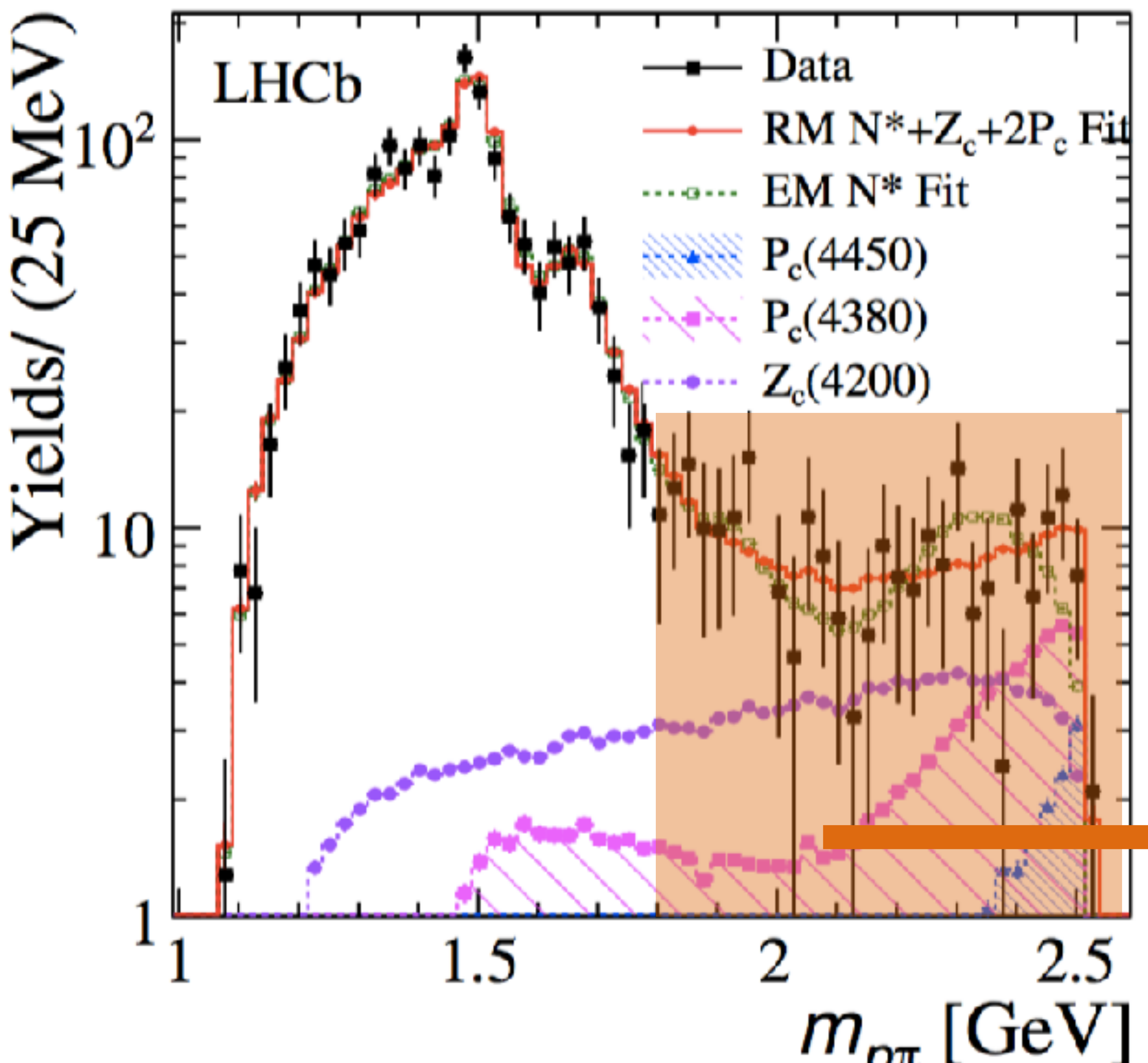
N*-only model not a good fit

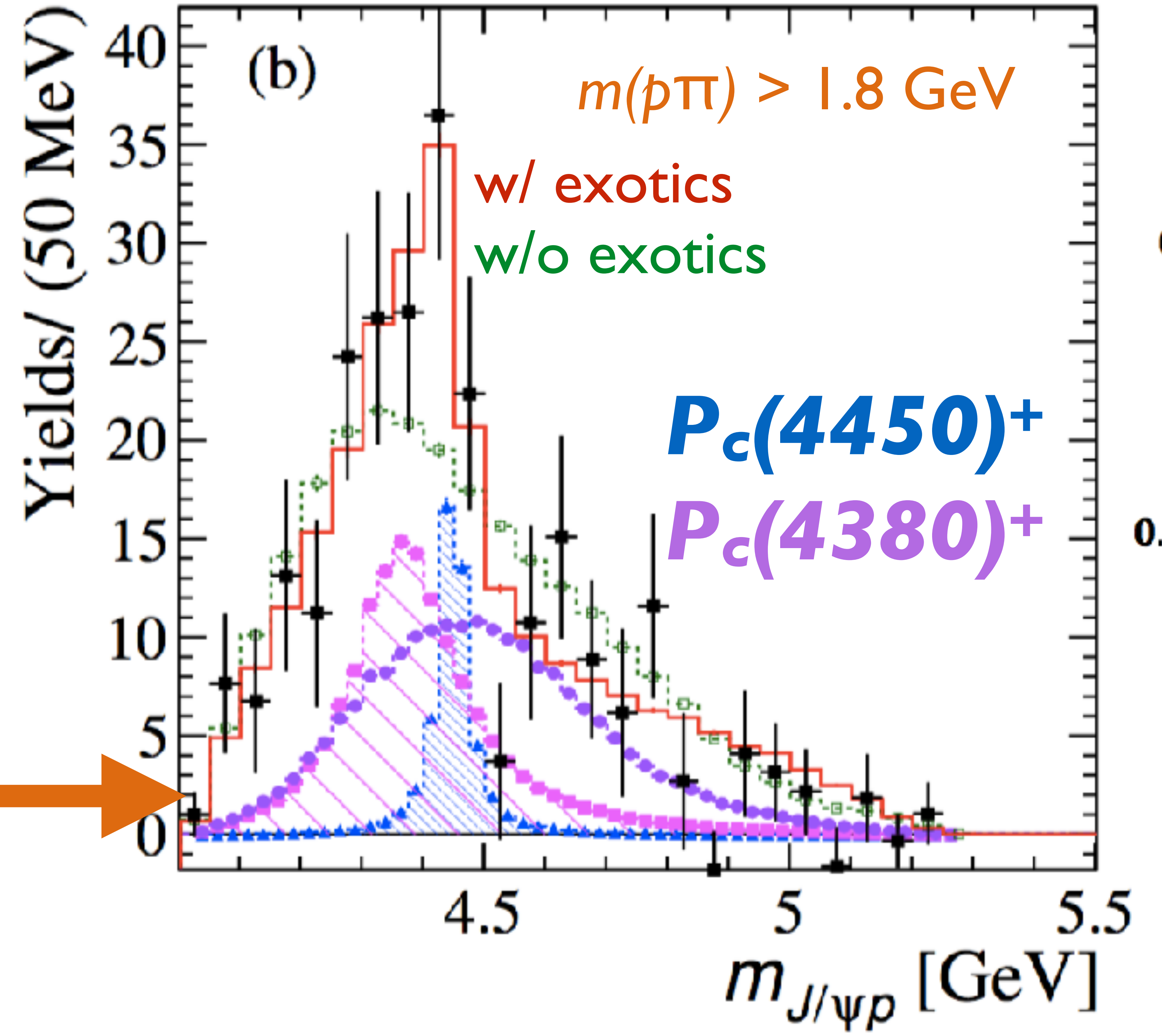
Good fit using 15 N* states + exotic components

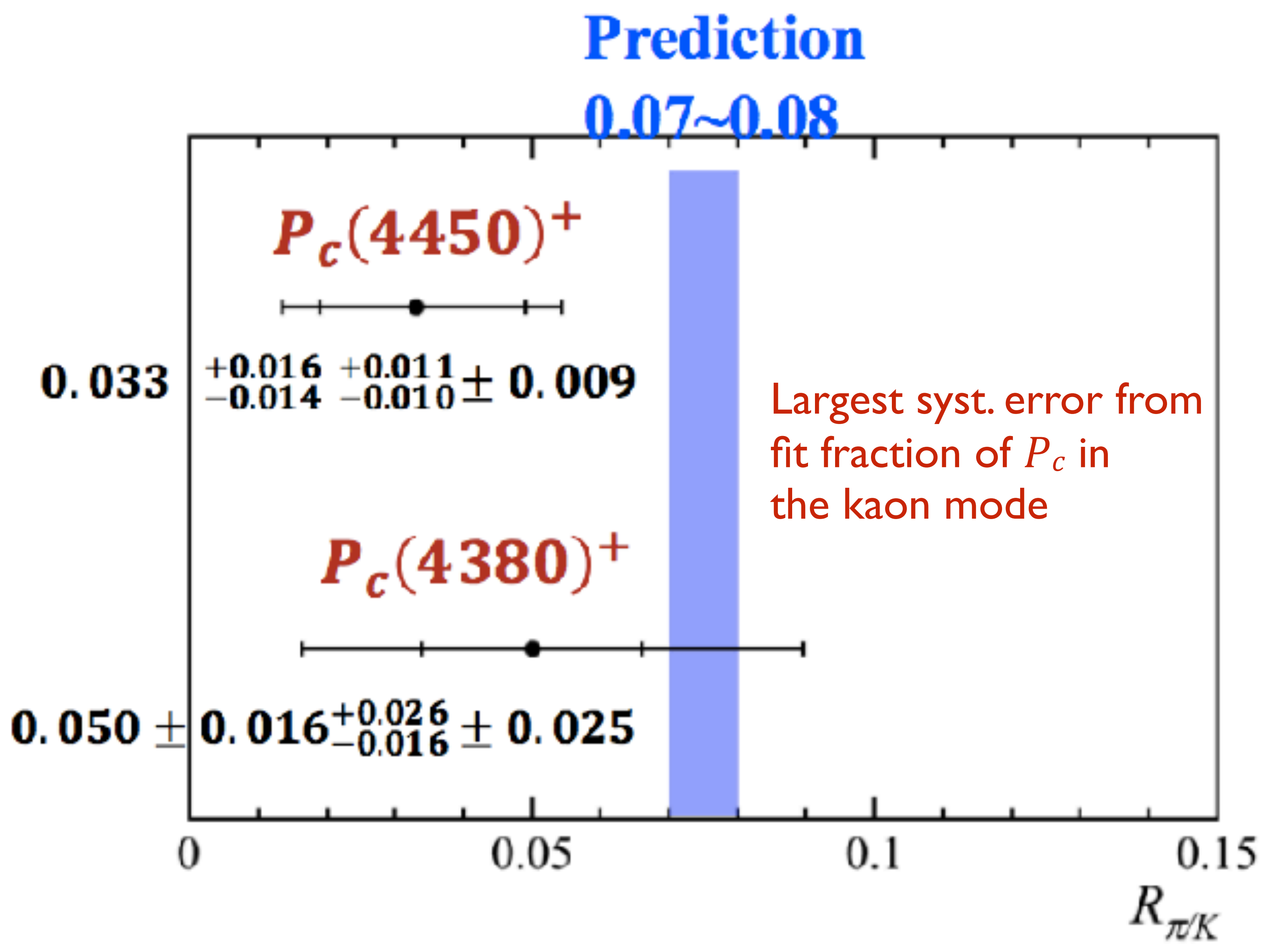
3.1σ for (2 P_c + Z_c) or 3.3σ for 2 P_c states

Main systematics from fixed P_c/Z_c mass/width parameters, N* model and unknown P_c spin

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







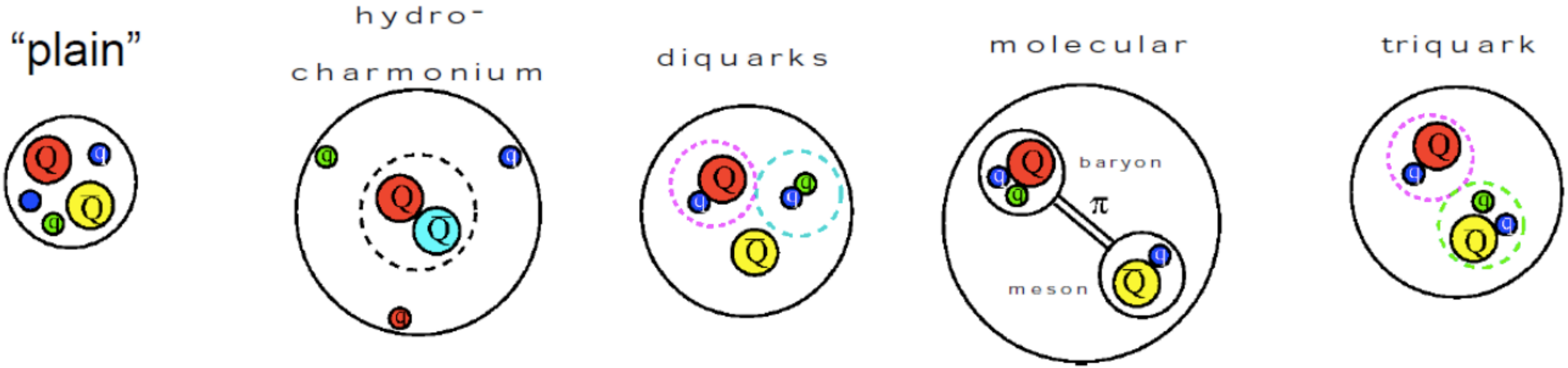
rules out

[Hsiao, PLB 751, 572 (2015)]

Phenomenological models

[Maiani et al arXiv:1507.04980]
[Lebed arXiv:1507.05867]
[Zhu arXiv:1510.08693]
[Roca et al, PRD 92 (2015) 094003]
++++++

Many phenomenological models on the market, e.g., $D^*\Sigma_c$−$D^*\Sigma^*_c$ molecular state, tightly bound di-quarks, hadro-charmonium?



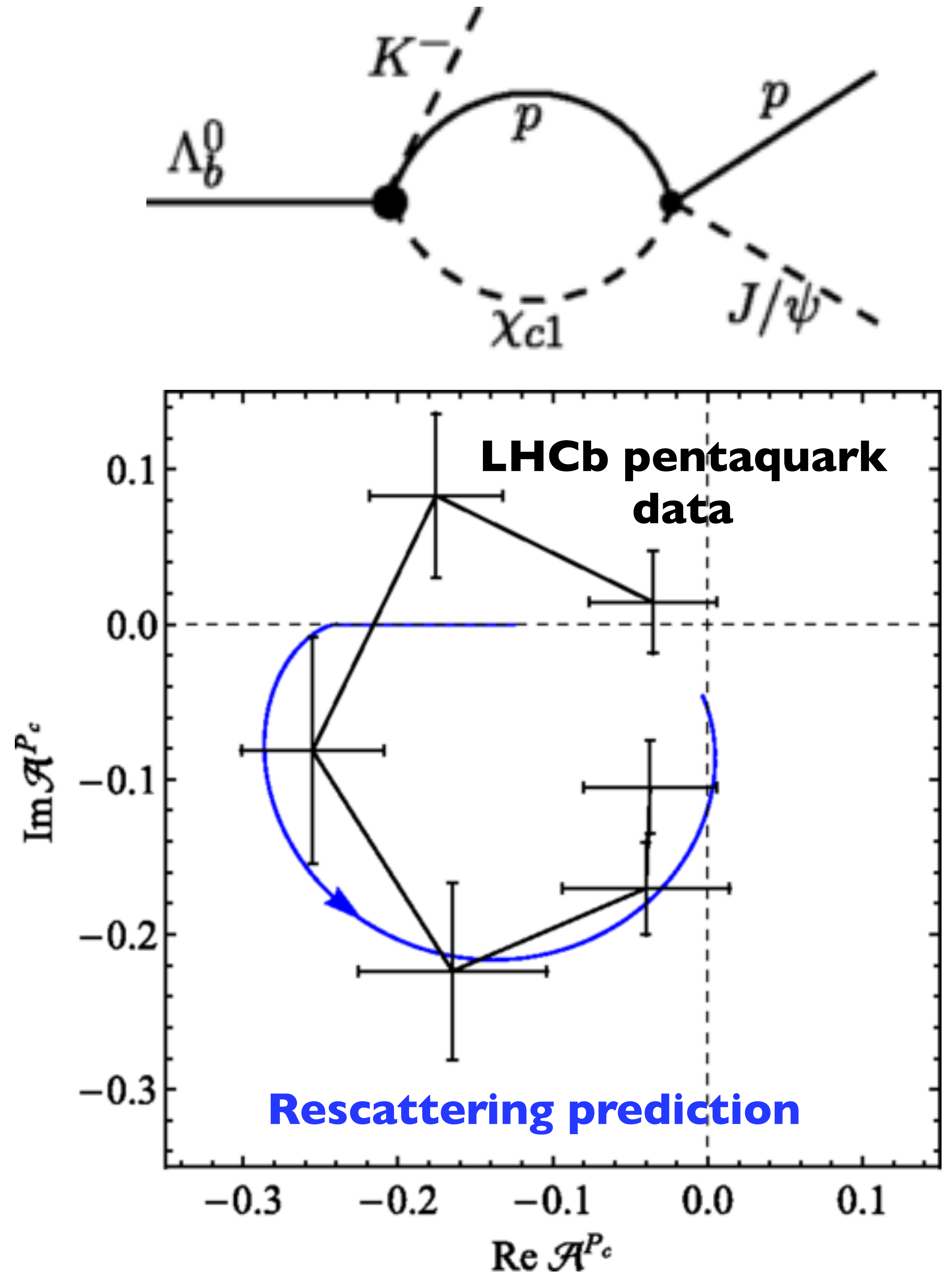
Not all of them can explain all of the observed exotic states, so may need several of them to explain observations.

Another option - rescattering

$P_c(4450)^+$ has mass just above $\chi_{c1}p$ threshold so could be $J/\psi p \to \chi_{c1}p$ kinematic **rescattering** effect.

Reproduces phase motion of $P_c(4450)^+$, but what about $P_c(4380)^+$?

Rescattering would not explain narrow enhancement/deficit above $\chi_{c1}p$ threshold.



[Guo et al, PRD 92 (2015) 071502(R)]
[Bayar at al, PRD 94 (2016) 074039]
[Meißner et al, PLB 751 (2015) 59]

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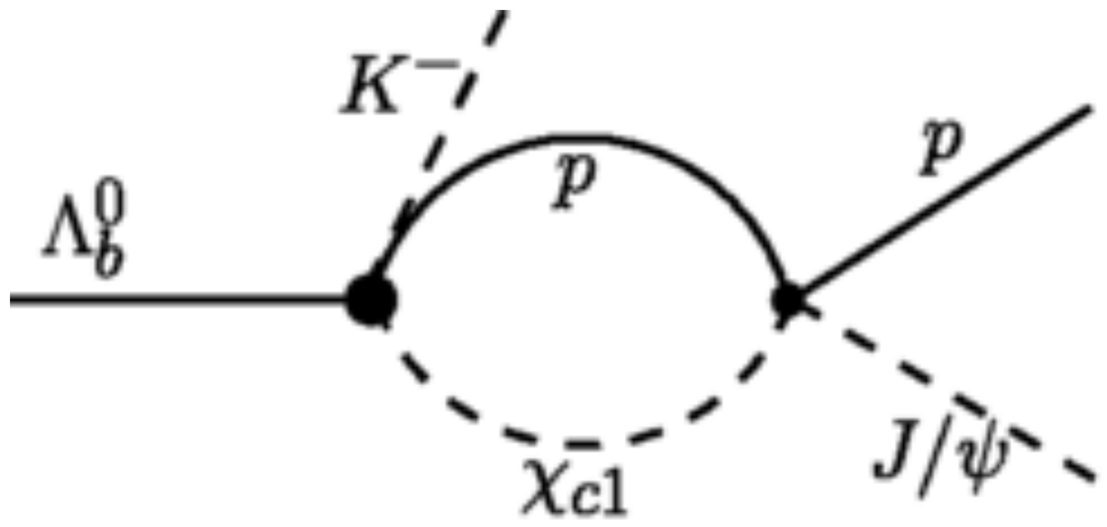

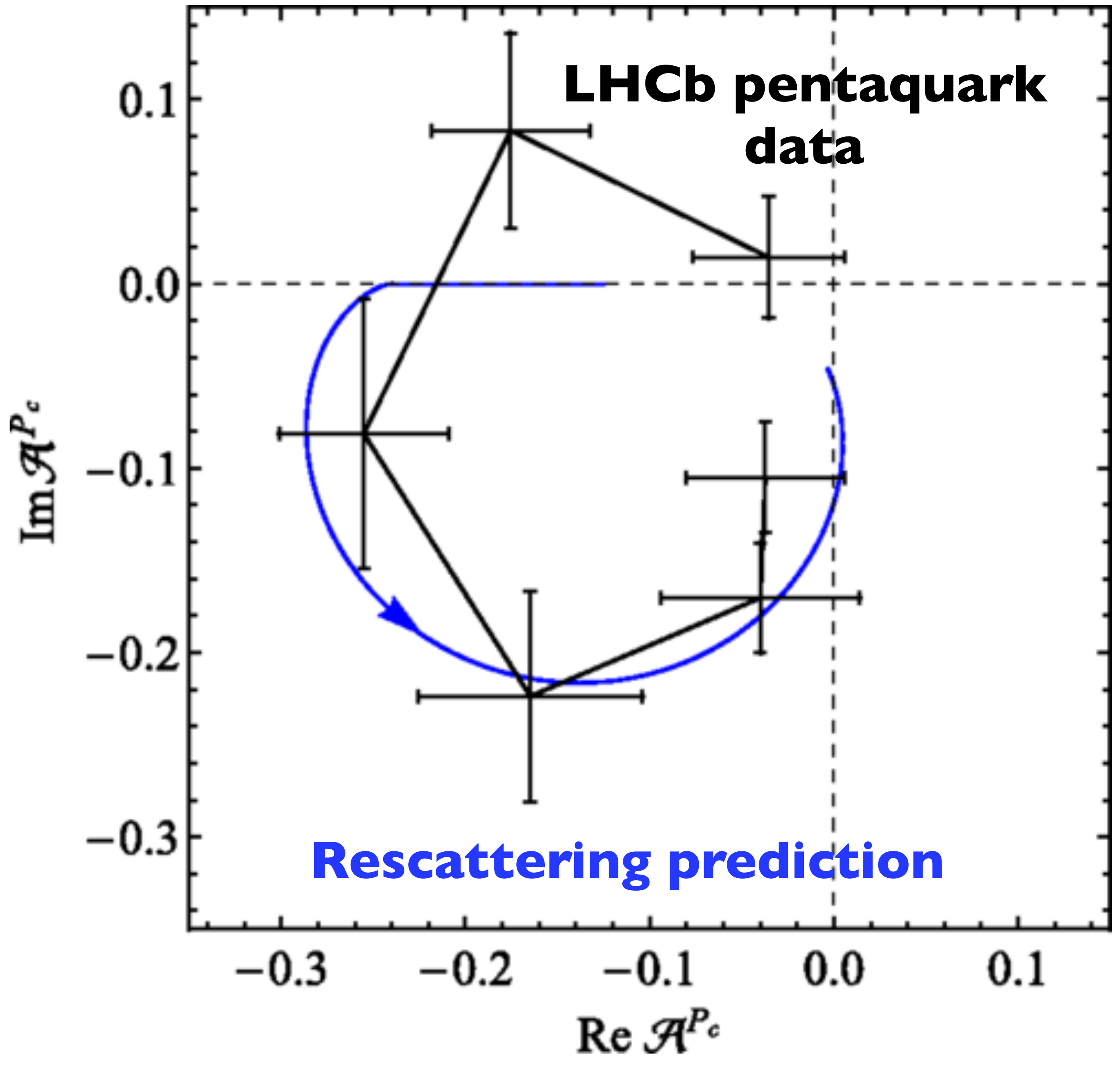

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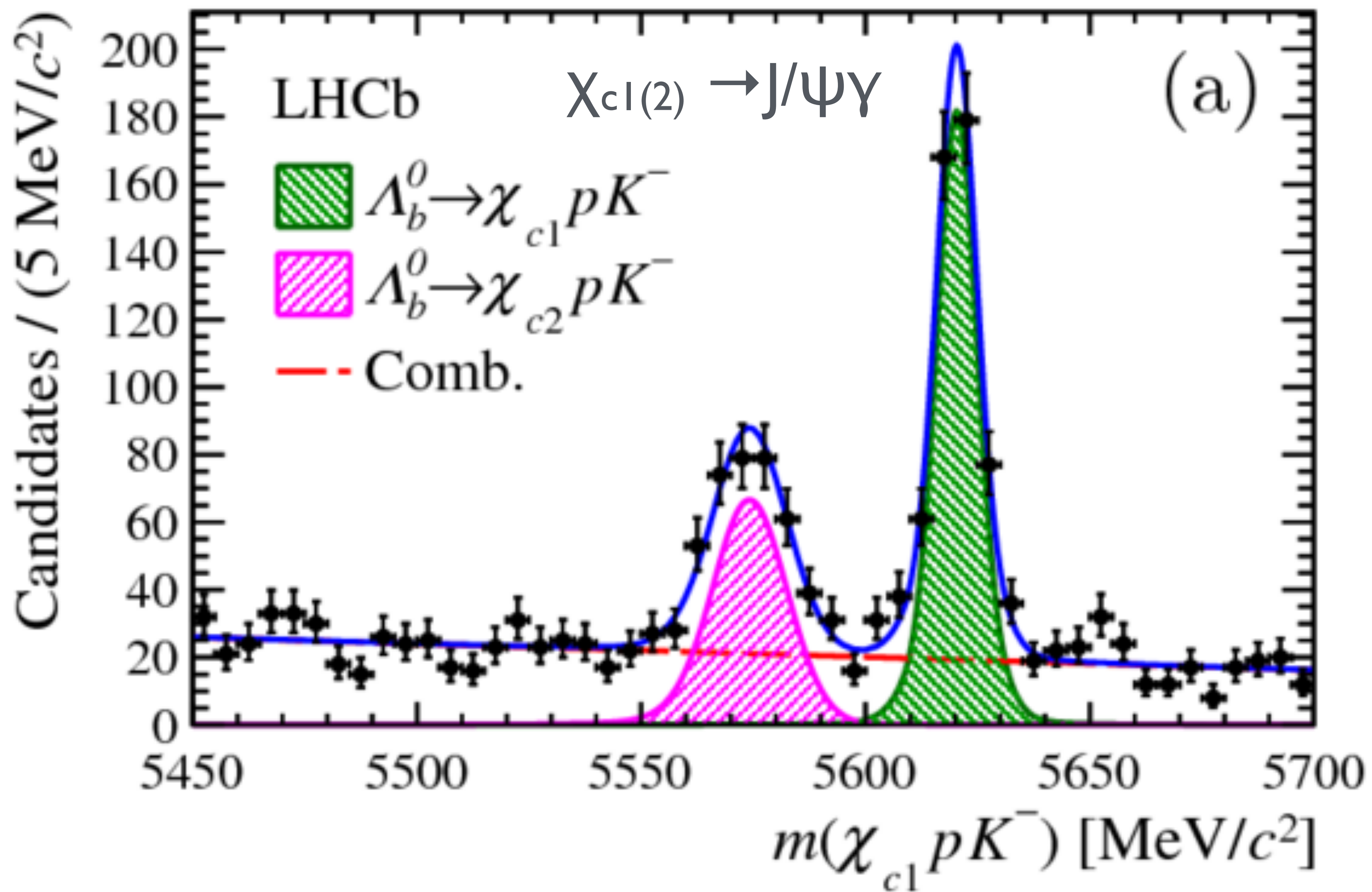


$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

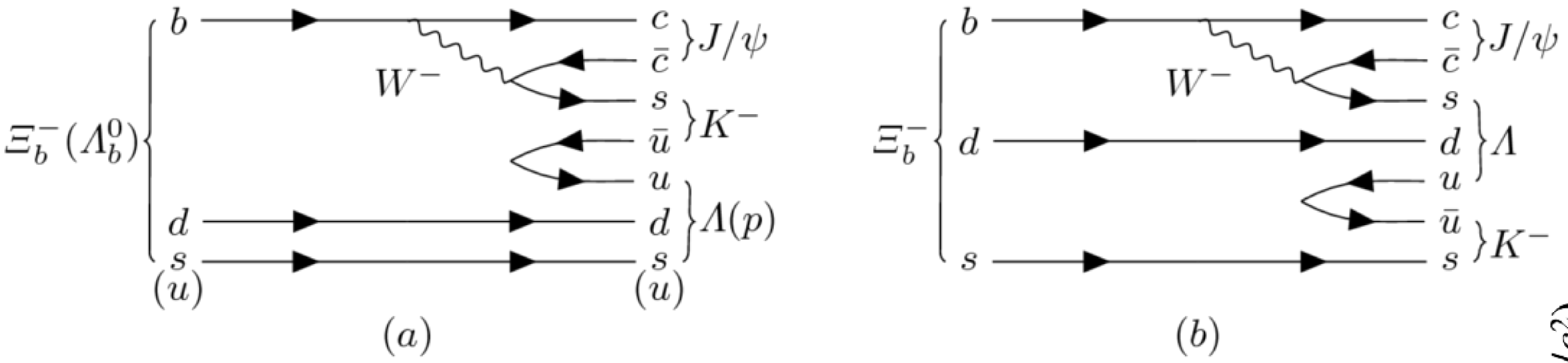
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

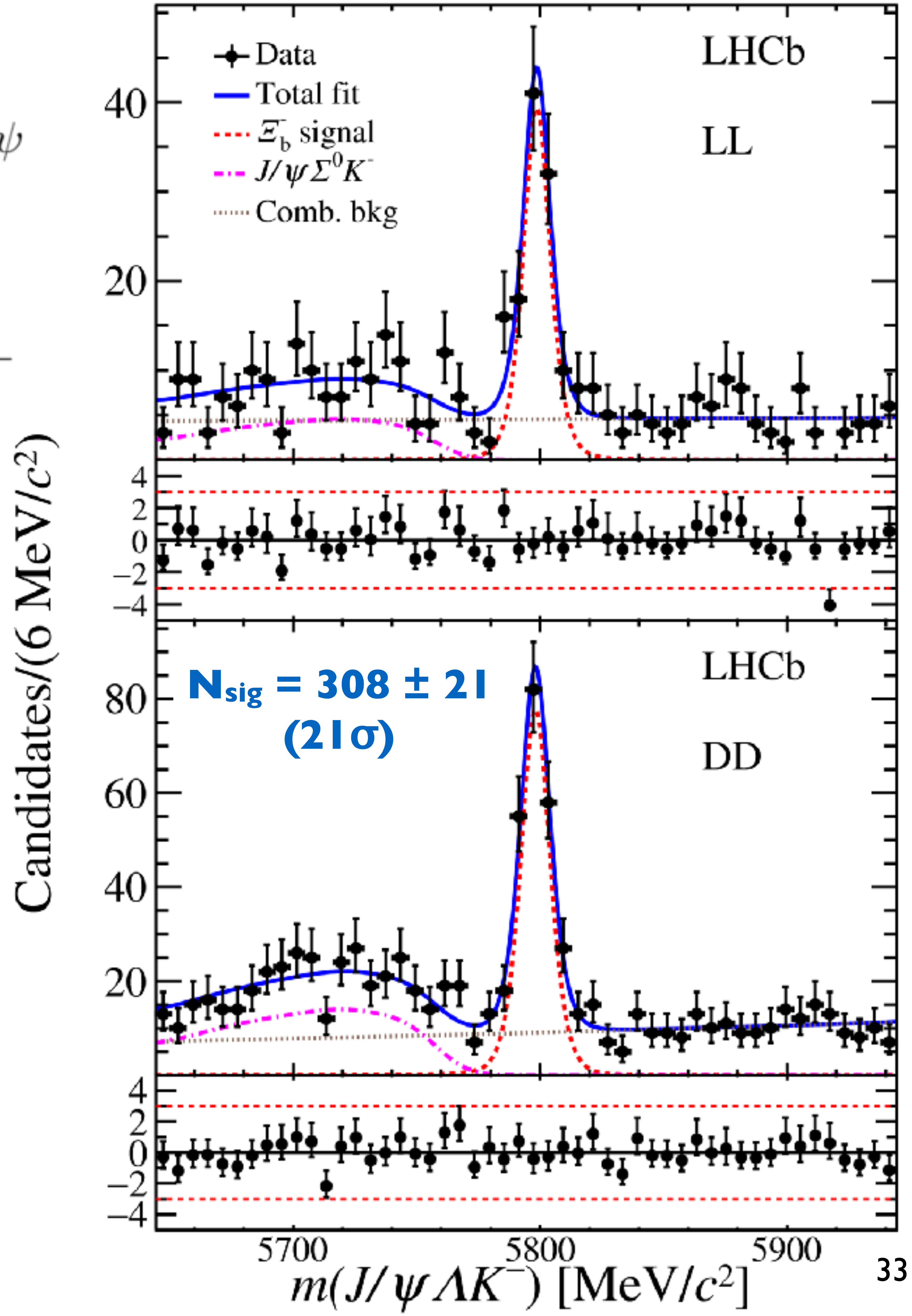
$\mathcal{B}(\chi_{cJ})$

[PRL 119, 062001 (2017)]

Strange pentaquarks?

[PLB 772 (2017) 265-273]





Strange pentaquark (**udscc̄**) predicted with mass ~4.65 GeV and width ~ 10 MeV [PRL 105, 232001 (2010)] [PRC 93, 065203 (2016)]

First observation of the $\Xi^-_b \to J/\psi \Lambda K^-$ decay.

Next steps:

Expect ~1500 signal events after 2018 → amplitude analysis to look for exotics in $m(J/\psi\Lambda)$

Also look for $\Lambda_b \to J/\psi \Lambda \varphi$ decay

Future experimental programme

1. Observe states in different **production** mechanisms

   e.g., prompt production of pentaquark direct from LHC pp collisions

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   Search for $c\bar{c}$, open-charm and charm-less modes using all flavours of b-hadron

   Transitions between exotic states (e.g., Y(4260) → X(3872)γ)

   Publish **non-observations**!

$$\Lambda_b^0 \to \Sigma_c^+ D^-$$
$$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{*0} K$$

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

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$$\Lambda_b^0 \to P_{cs}^0 \phi \to J/\psi \Lambda \phi$$

[PRL 105, 232001 (2010)]

3. Look for **isospin** (ccudd), **strangeness** (ccuds), **bottom** (bbuud) partners

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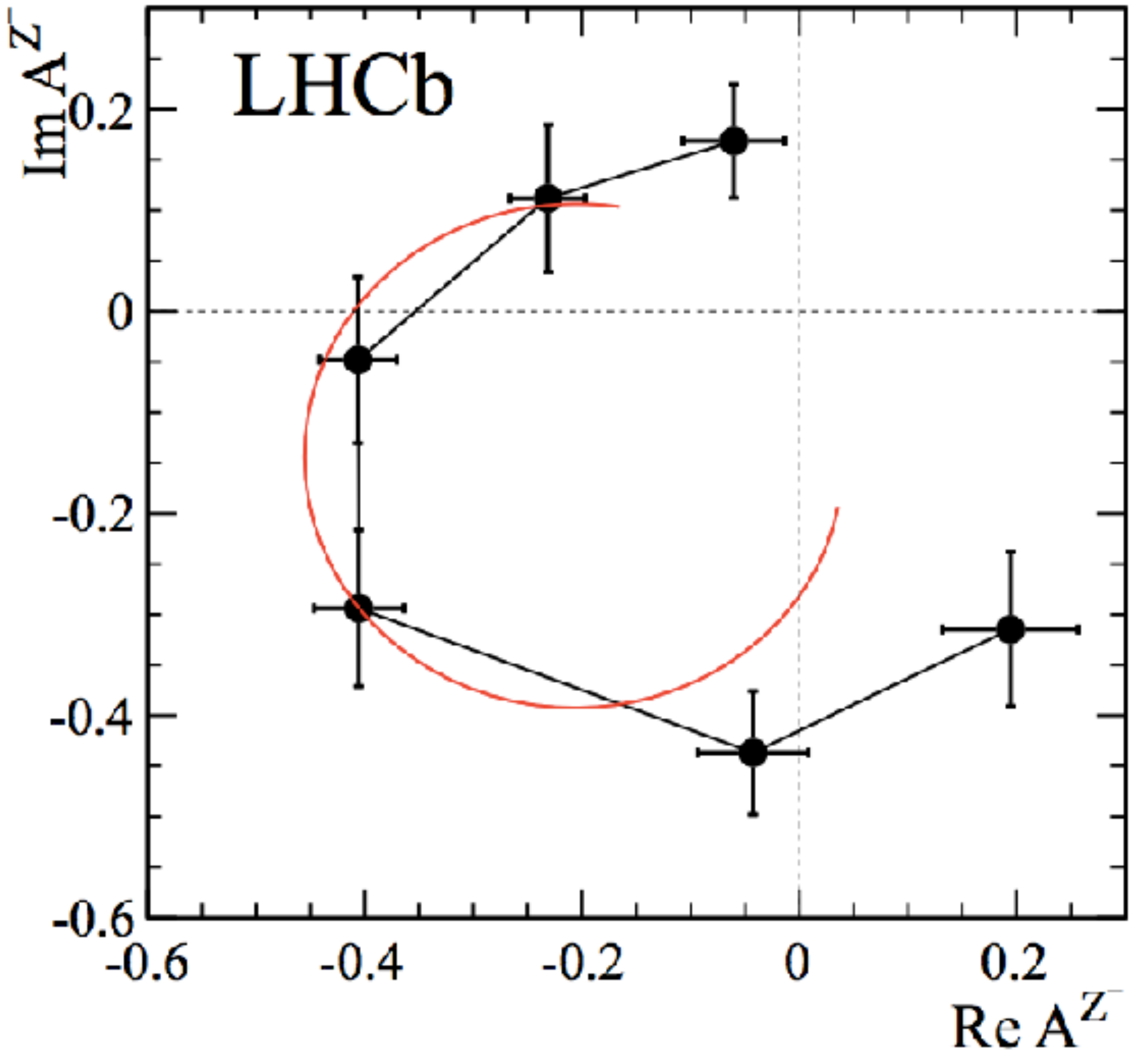


[PRL 105, 232001 (2010)]

3. Look for **isospin** (ccudd), **strangeness** (ccuds), **bottom** (bbuud)

4. Measure angular distributions and **quantum numbers**

   Amplitude (partial wave) analyses are crucial, as are accounting for threshold effects

   Publish experimental efficiencies to allow others to better use results

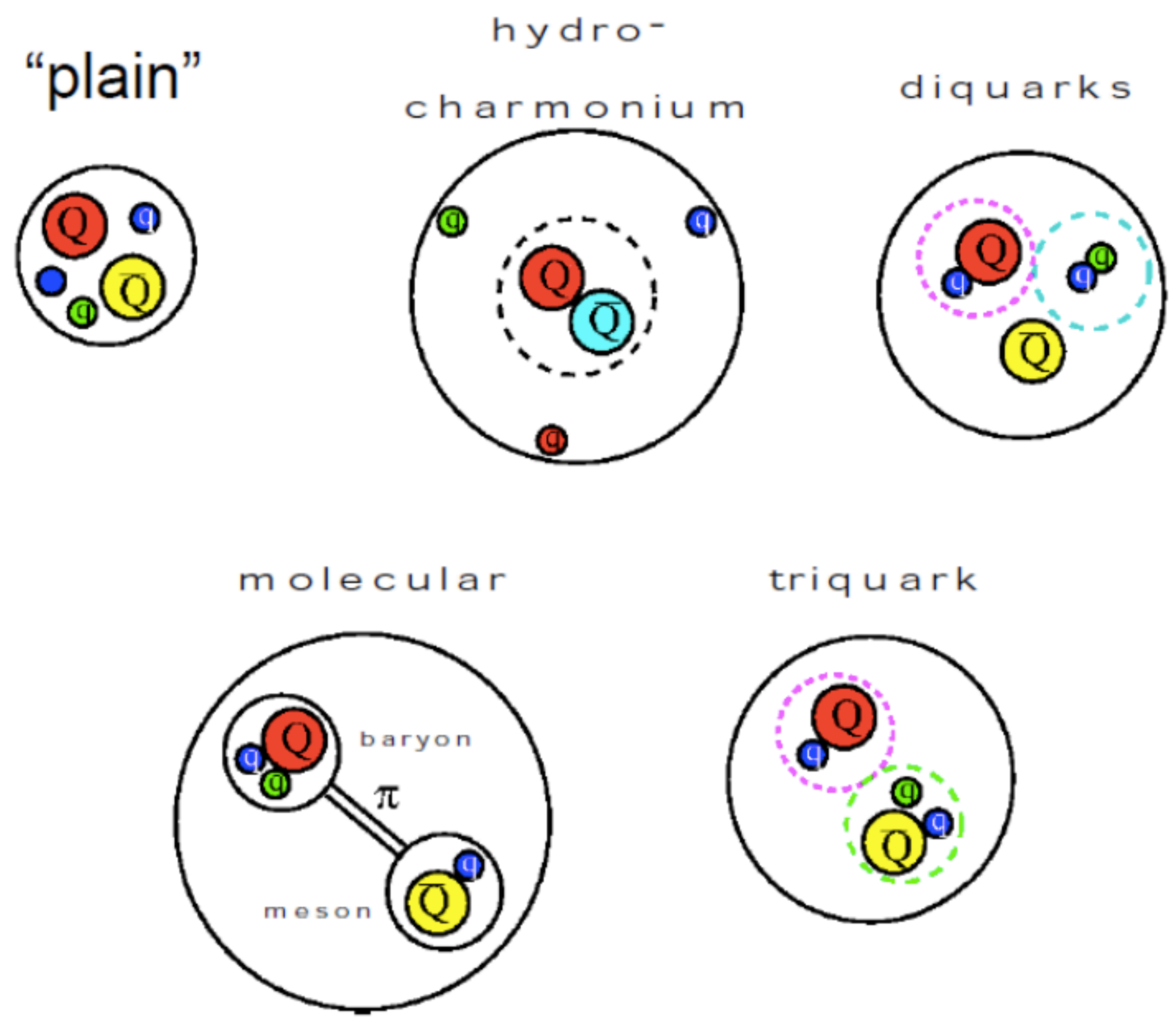
LHC, Belle-II, BES-III, COMPASS, JLab and PANDA all have role to play!

Summary

LHCb provides ideal laboratory for (exotic) hadron spectroscopy due to large heavy quark production cross-sections, efficient triggers and low backgrounds.

New conventional/exotic states now being discovered and their properties measured with unprecedented precision, allowing us to better understand non-perturbative QCD.

Crucial to confirm observations where possible and use state-of-the-art **amplitude analyses** and collaboration with theorists to understand observed states.



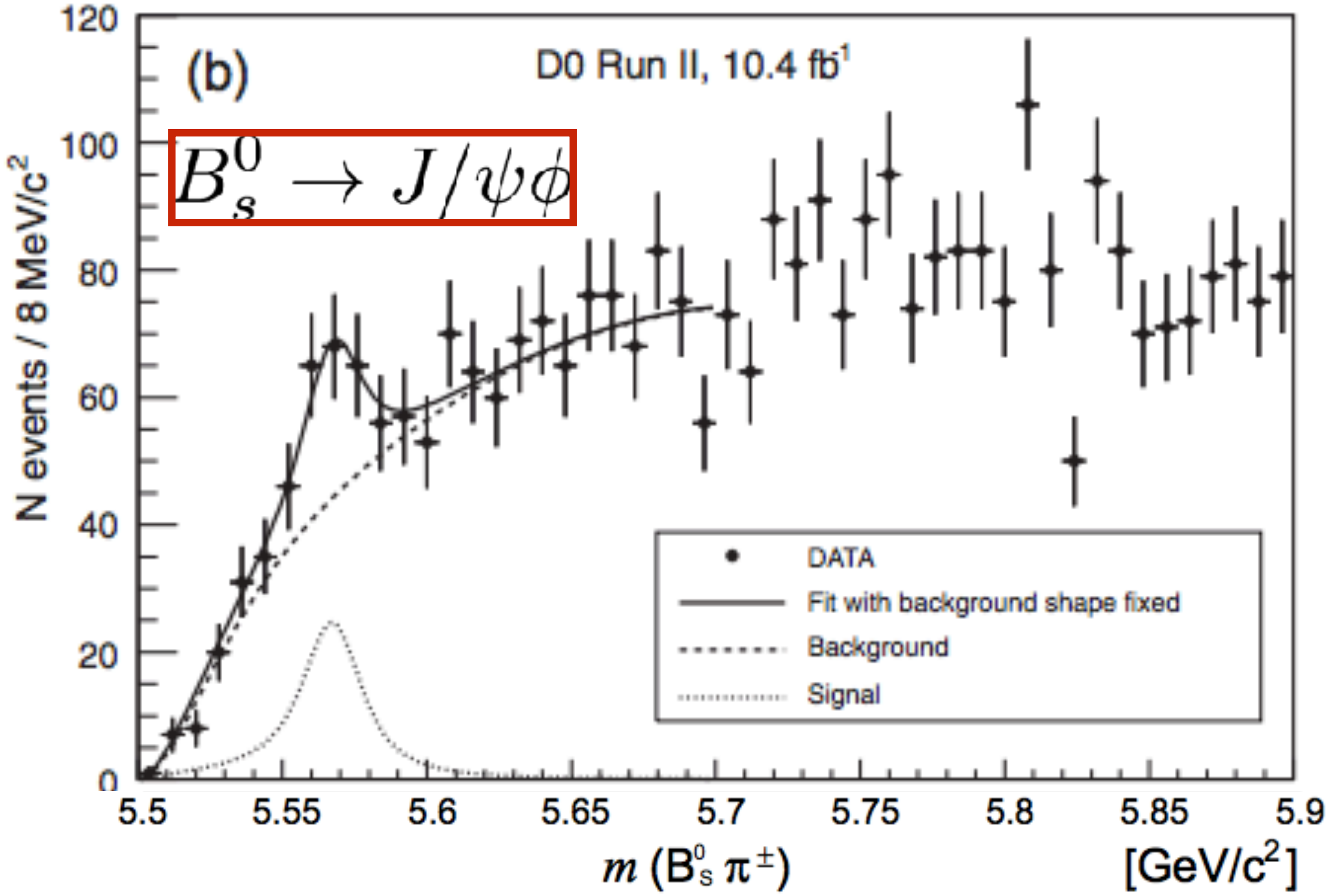
http://higgs.ph.ed.ac.uk/workshops/exotic-hadron-spectroscopy-2017

11-13th December 2017

Backup

The X(5568)$^\pm$ → $B_s\pi^\pm$?

[D0 PRL 117, 022003 (2016)]

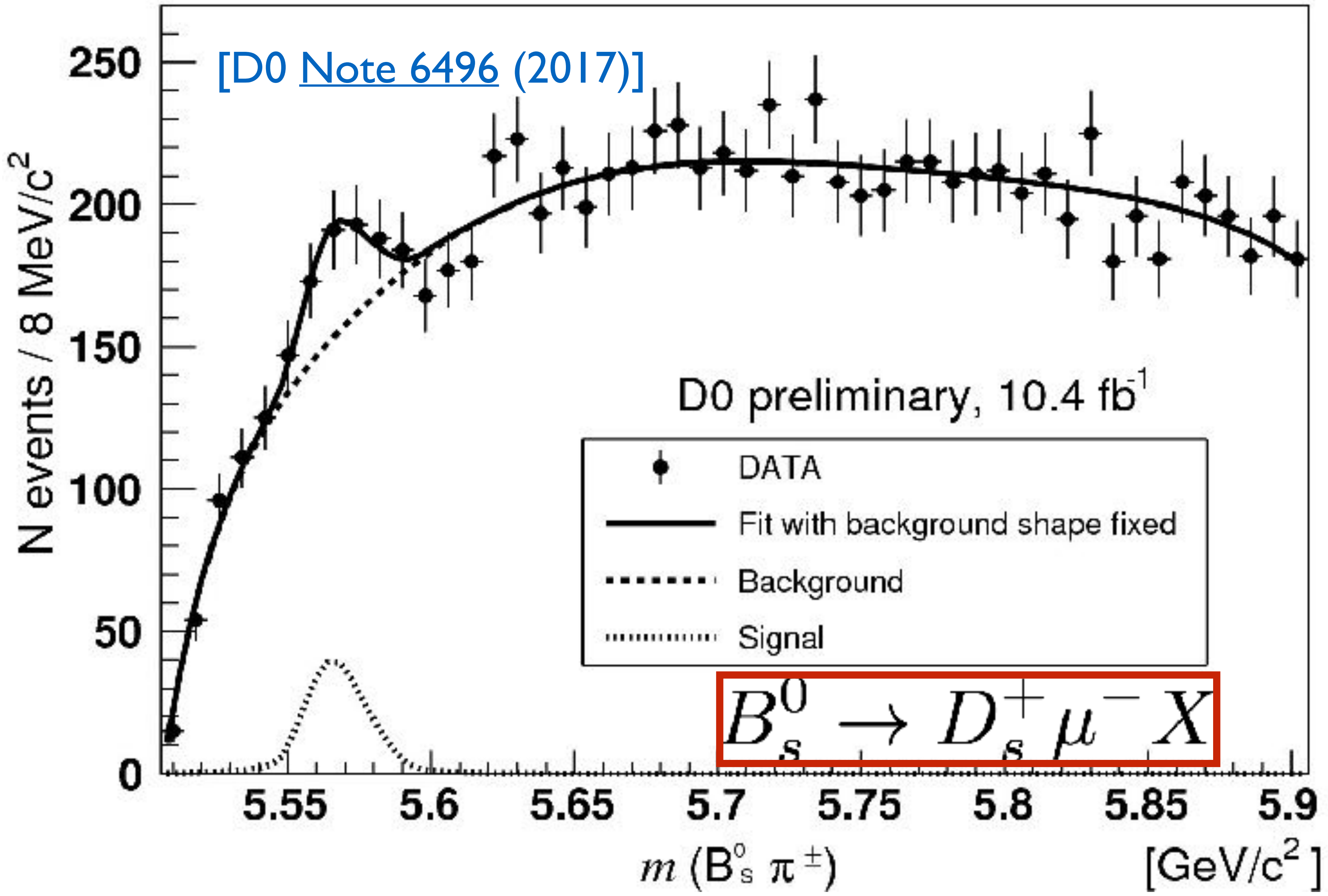


3.9σ evidence for exotic state

Large B_s production fraction: ρ_X = (8.6 ± 1.9 ± 1.4)%

Not due to reflections from kaons/pions

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\mathrm{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\mathrm{MeV}/c^2$$



Possible $\bar{b}s\bar{u}d$ tetraquark/molecule but difficult to explain when considering QCD chiral symmetry, heavy quark symmetry and threshold effects.

[Burns, Swanson, arXiv:1603.04366]
[Guo et al, arXiv:1603.06316]
[Liu, Li, arXiv:1603.04366]

No sign on the lattice [Lang et al., arXiv:1607.03185]

LHC searches for X(5568)$^{\pm}$

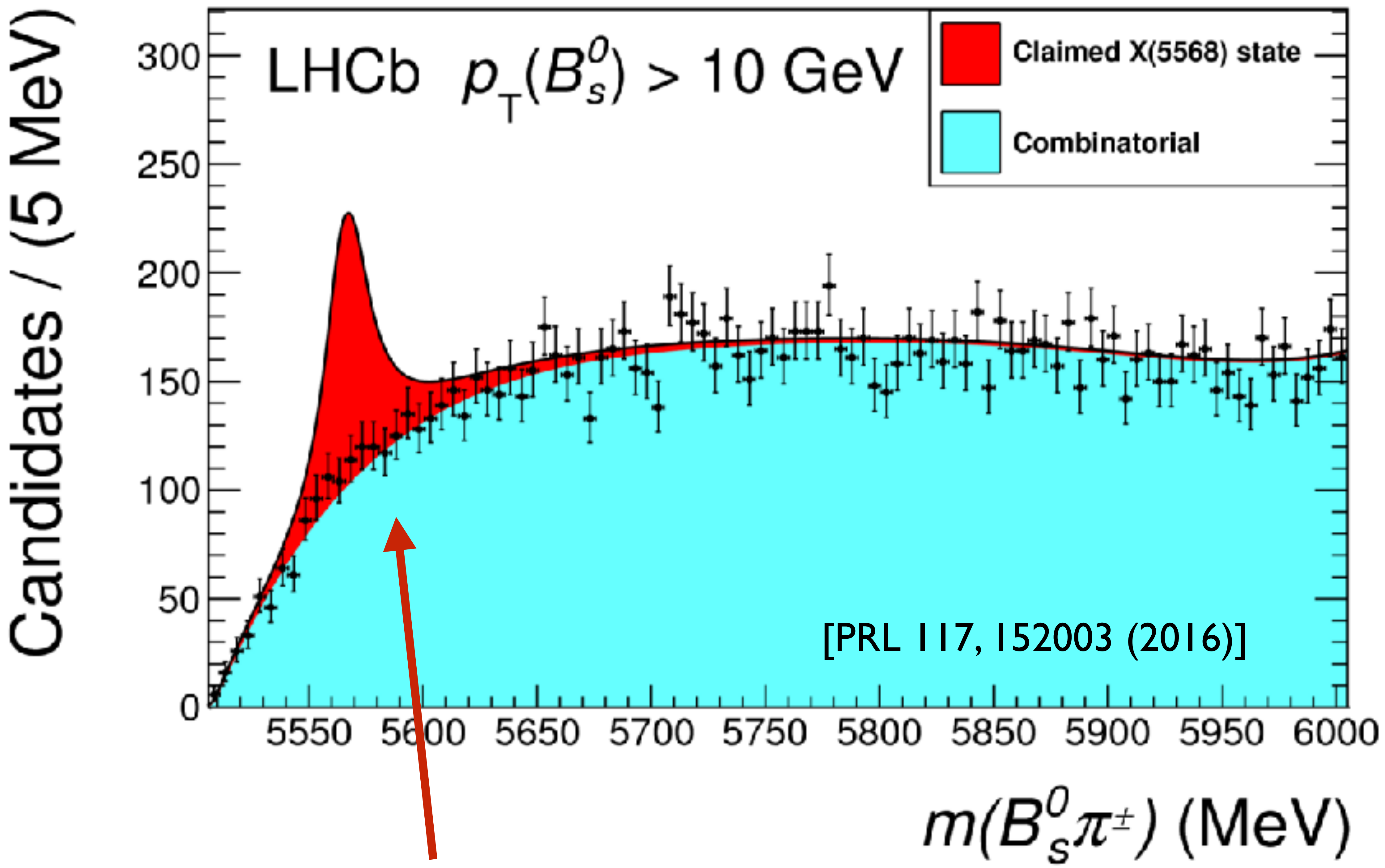
LHCb use >100k B_s mesons and combine with $\pi^{\pm}$. Sample **20x larger** than D0 and much less background.

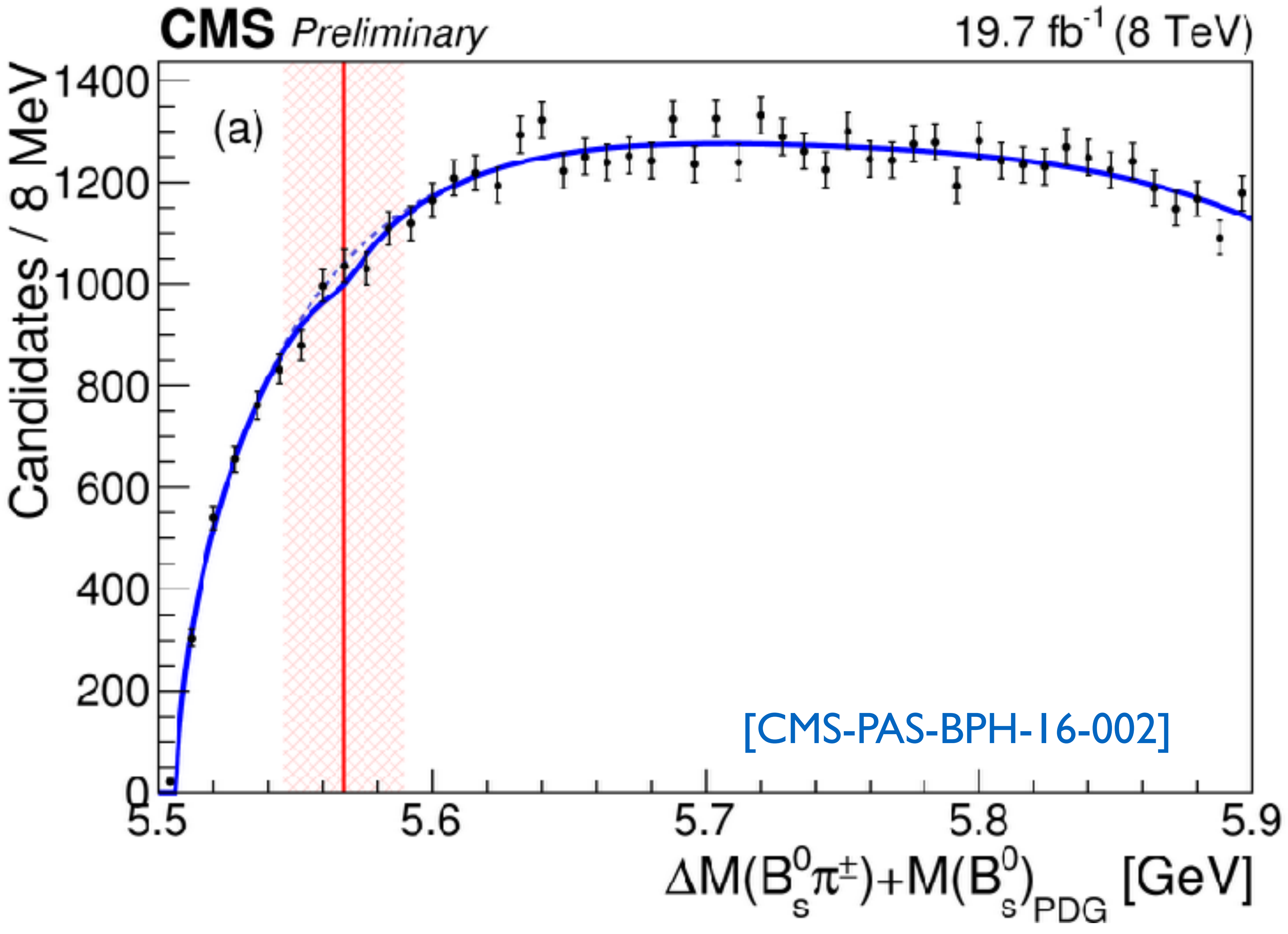
B_s and $\pi^{\pm}$ required to come from same PV.

Fit signal using S-wave Breit-Wigner with mass and width of claimed D0 signal.

$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 10\,\mathrm{GeV}/c) < 2.1\,(2.4)\%\ @\ 90\ (95)\%\mathrm{CL}$$

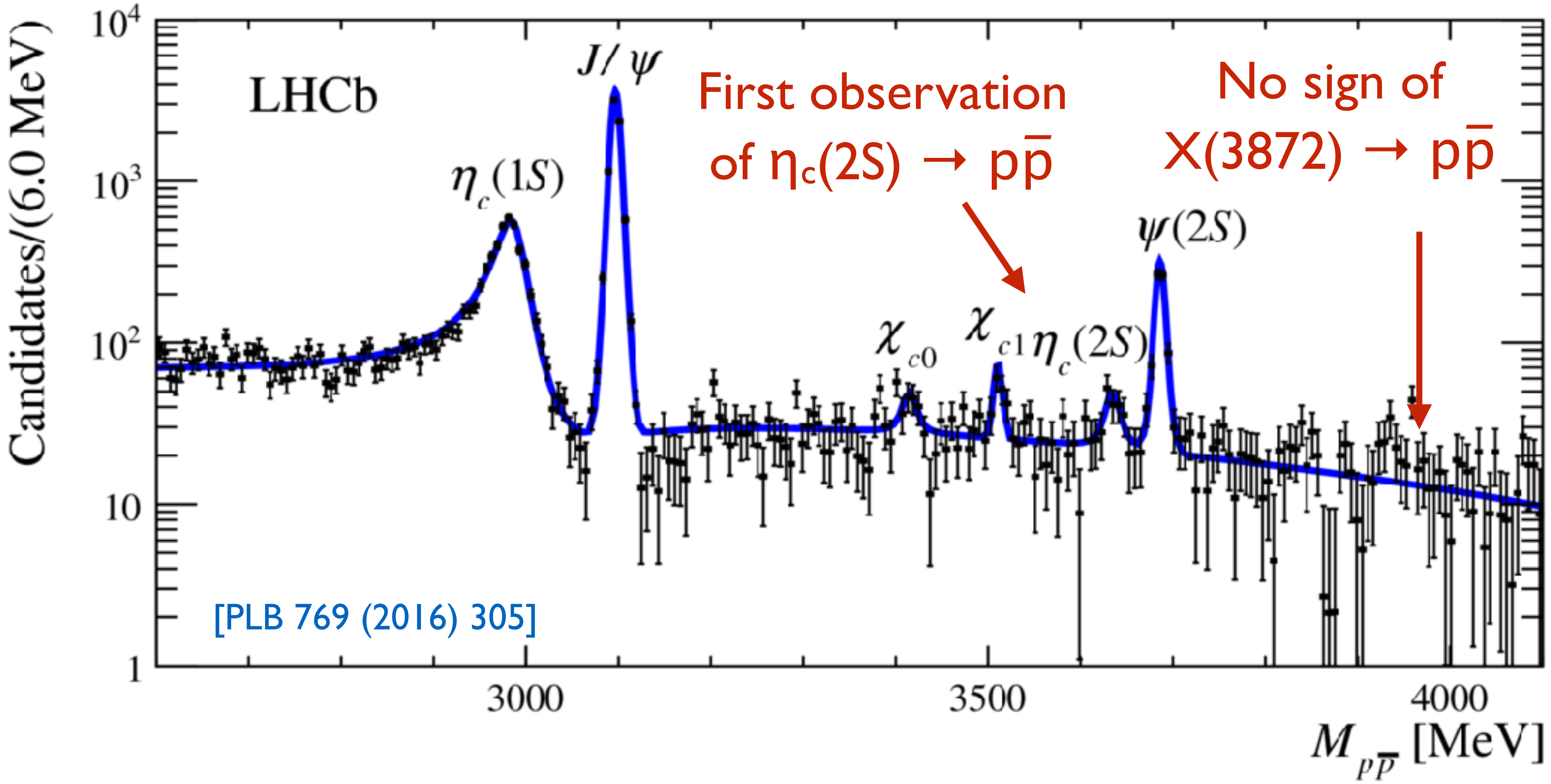
Set limits as a function of X mass and width

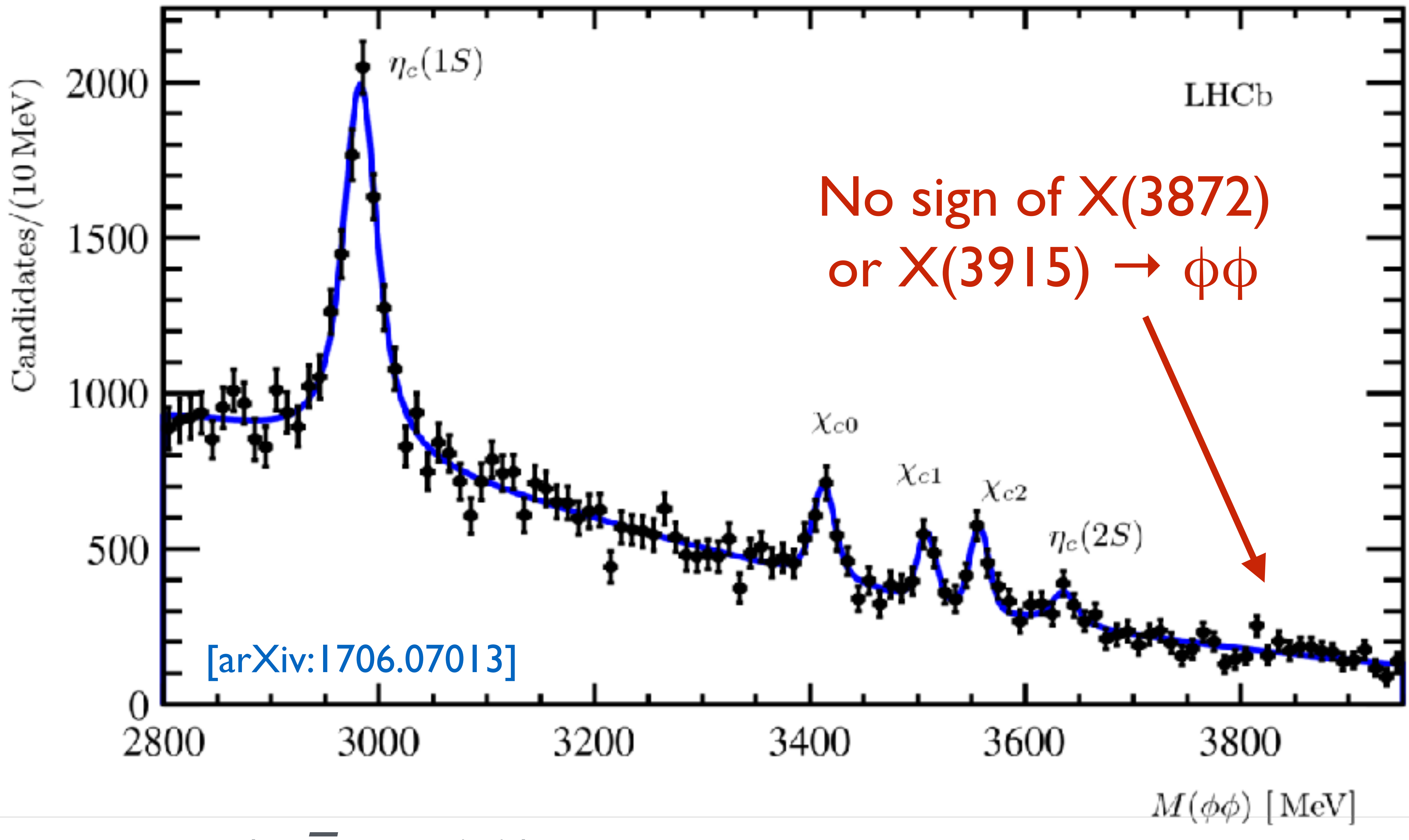




How signal would look according to D0 result for ρ_X

Charmonium production in b-hadron decays





$B^+ \to ([c\bar{c}] \to p\bar{p})\, K^+$ provides clean environment

$b \to ([c\bar{c}] \to \phi\phi)\, X$

require separation between PV and secondary vertices

$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.20\,(0.25) \times 10^{-2}$$

$$R^{X(3872)}_{\chi_{c1}} < 0.39\ (0.34)$$
$$R^{X(3915)}_{\chi_{c0}} < 0.14\ (0.12)$$
$$R^{\chi_{c2}(2P)}_{\chi_{c2}} < 0.20\ (0.16)$$

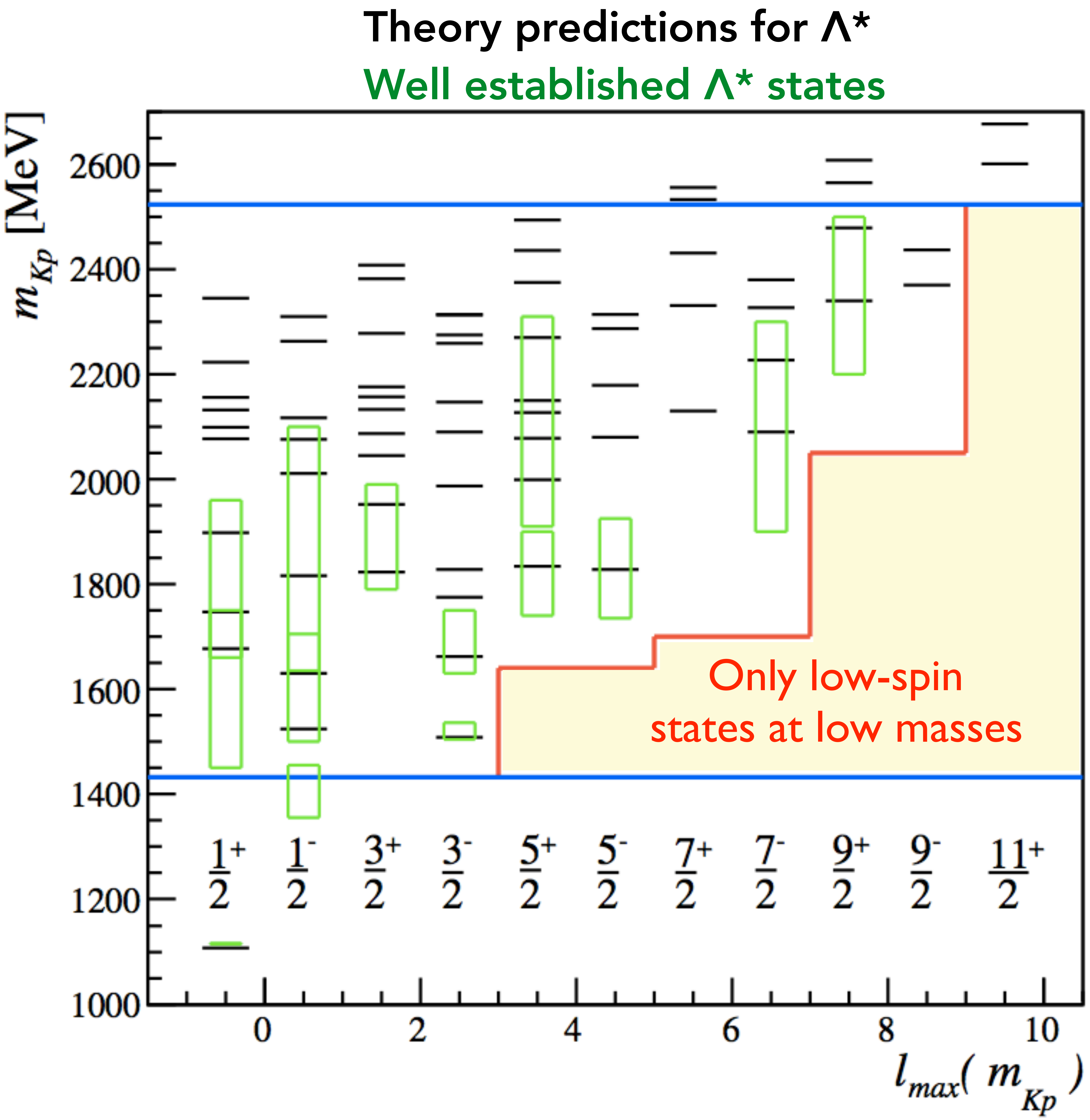
95% (90%) CL upper limit on BR relative to conventional $[c\bar{c}]$ with same J^{PC}

Pentaquark model-independent

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.

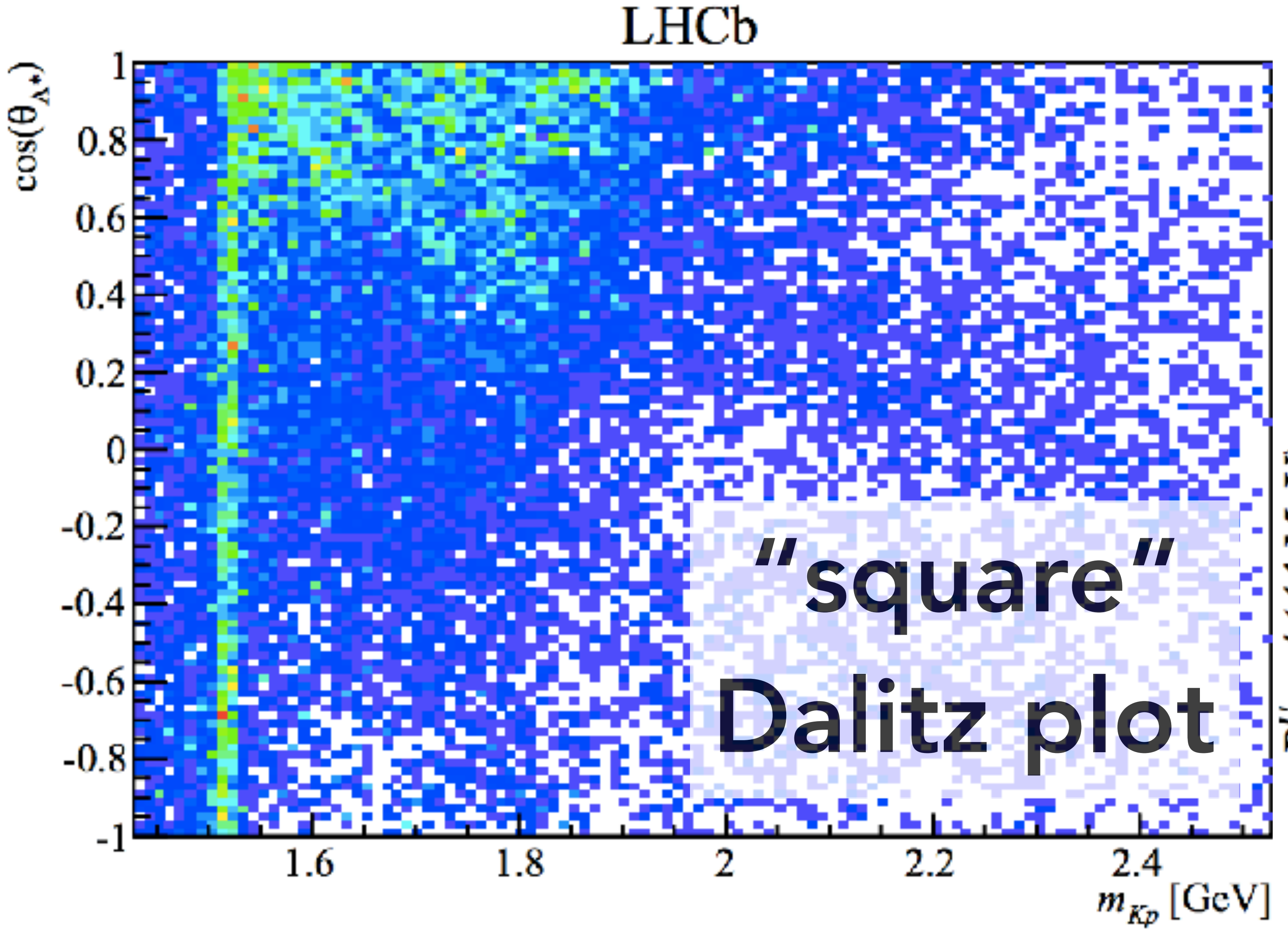
Only restrict the maximal spin of allowed Λ* components at given m(Kp).



Extension of [BaBar PRD 79 (2009) 112001]

[PRL 117 (2016) 082002]

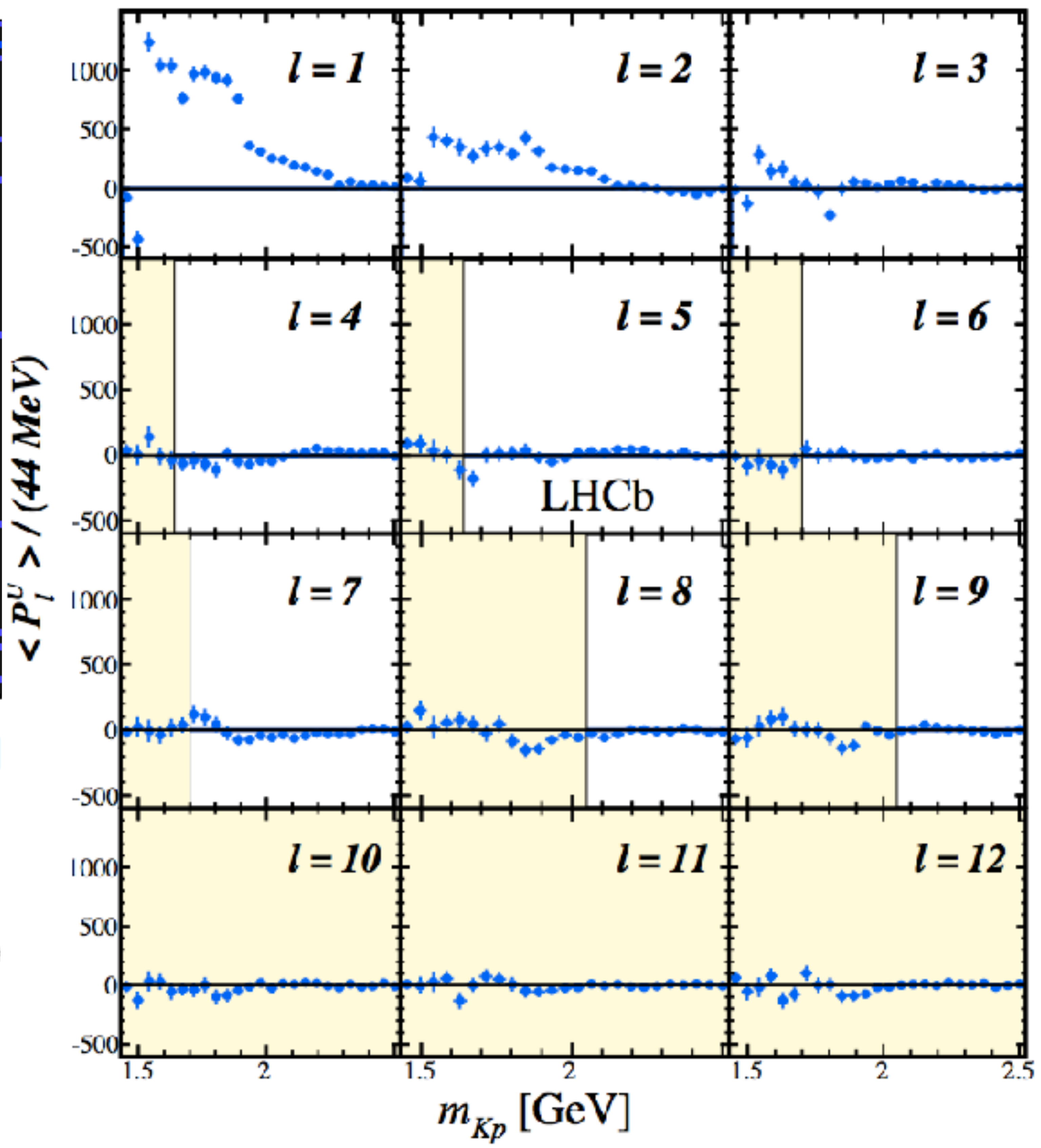
Pentaquark model-independent



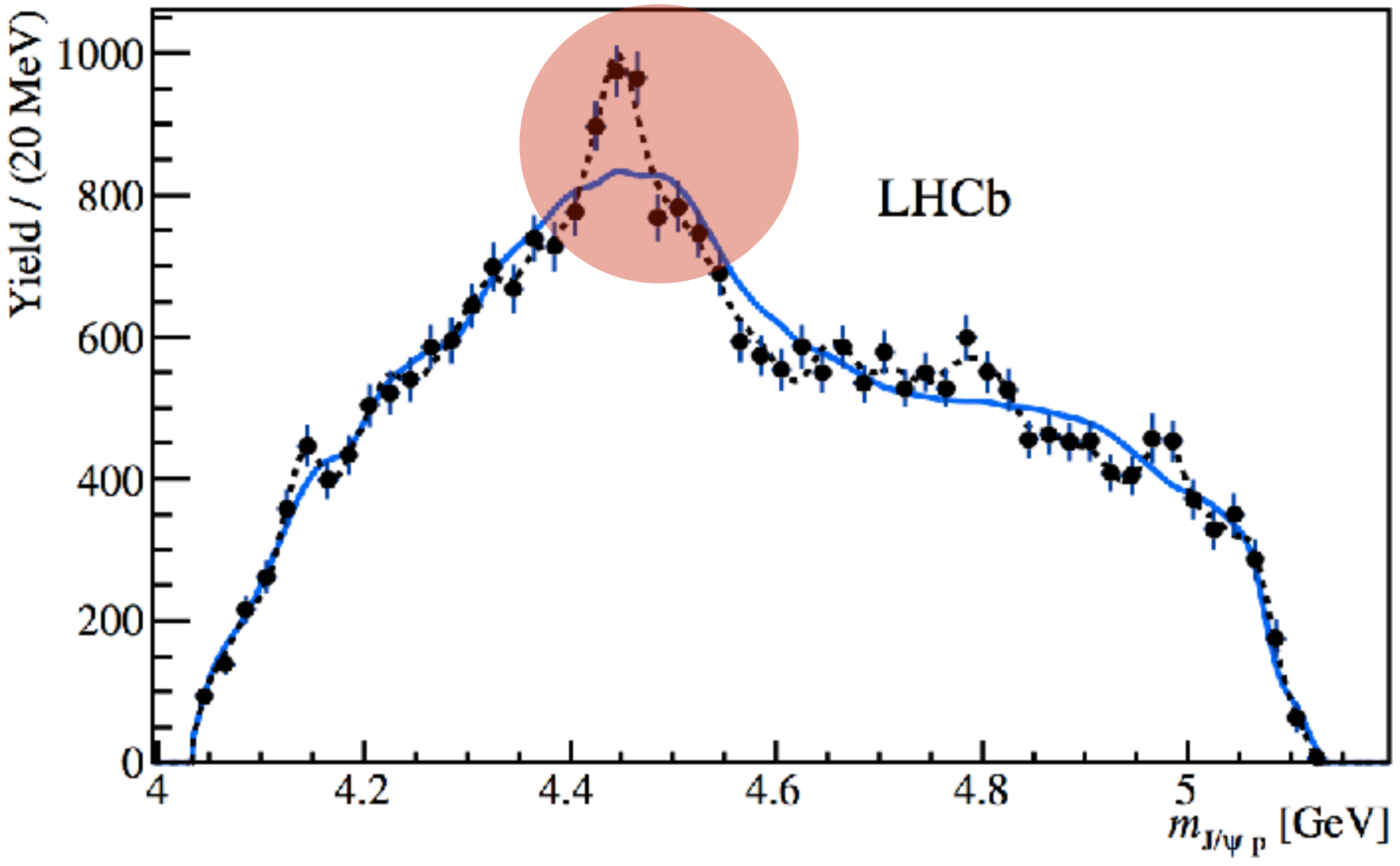
$$\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

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

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



filter out maximum spin for each m(Kp)



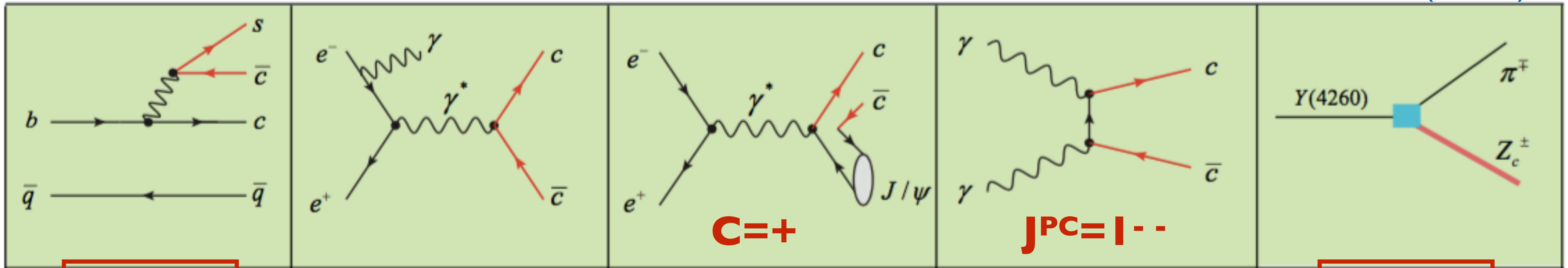
Null hypothesis (Λ* only) rejected at **9σ**

Working with JPAC to use better models of Λ* resonances in future amplitude fits

[PRL 117 (2016) 082002]

Meet the family

Production mechanism



b hadrons	ISR	double charmonium	γγ collisions ($e^+e^- \to e^+e^-X$)	ISR → Y(4260)
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 cc				

See backup (→ $Z_c(3900)$)

Recent review articles -
[Olsen et al, arXiv:1708.04012]
[Ali et al, arXiv:1706.00610]
[Guo et al, arXiv:1705.00141]
[Esposito et al, arXiv:1611.07920]
[Lebed et al, arXiv:1610.04528]
[Chen et al, arXiv:1601.02092]

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

X(3872) also observed in prompt pp, $p\bar{p}$ collisions and ISR

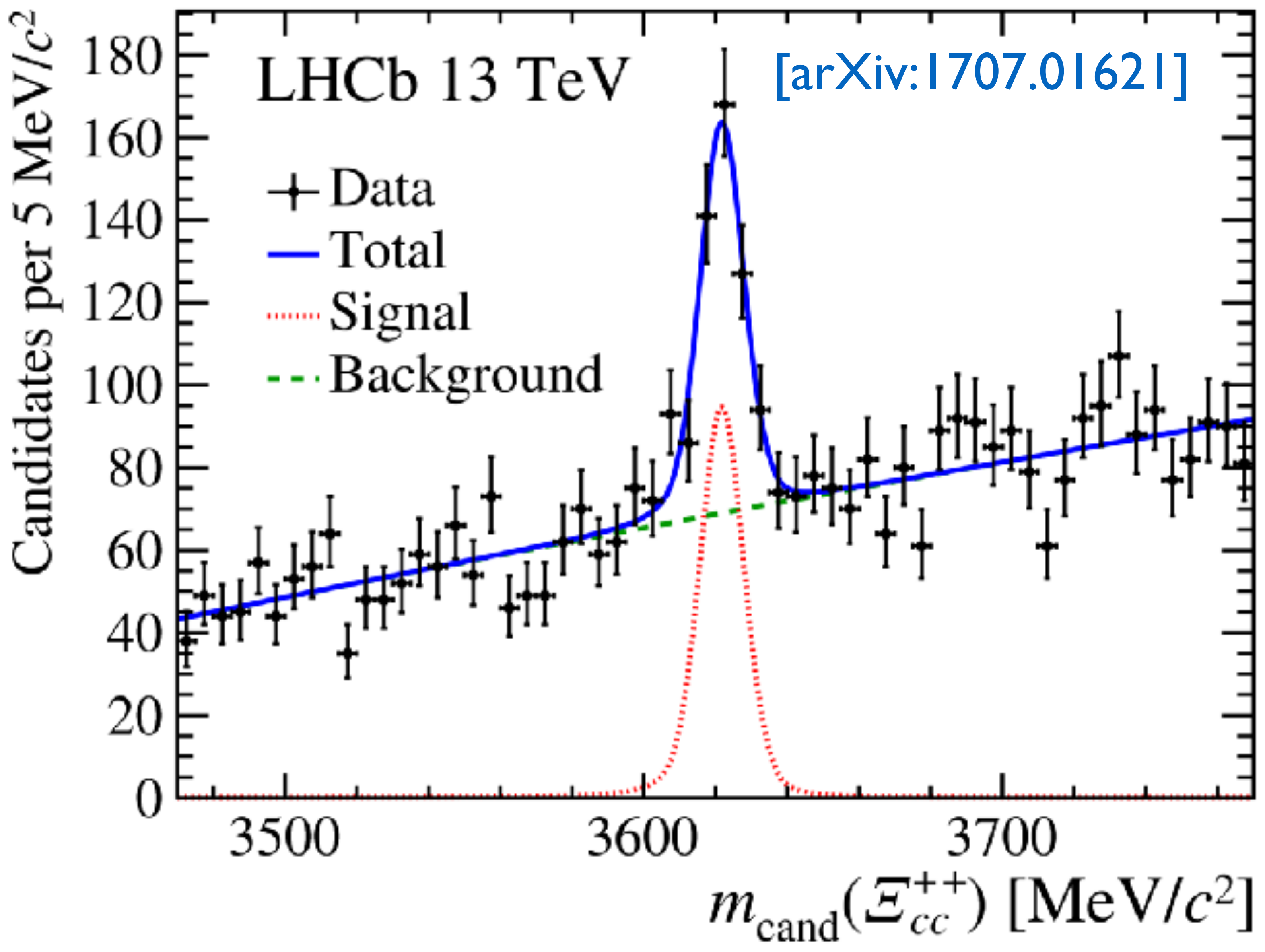
Connections with “conventional” spectroscopy

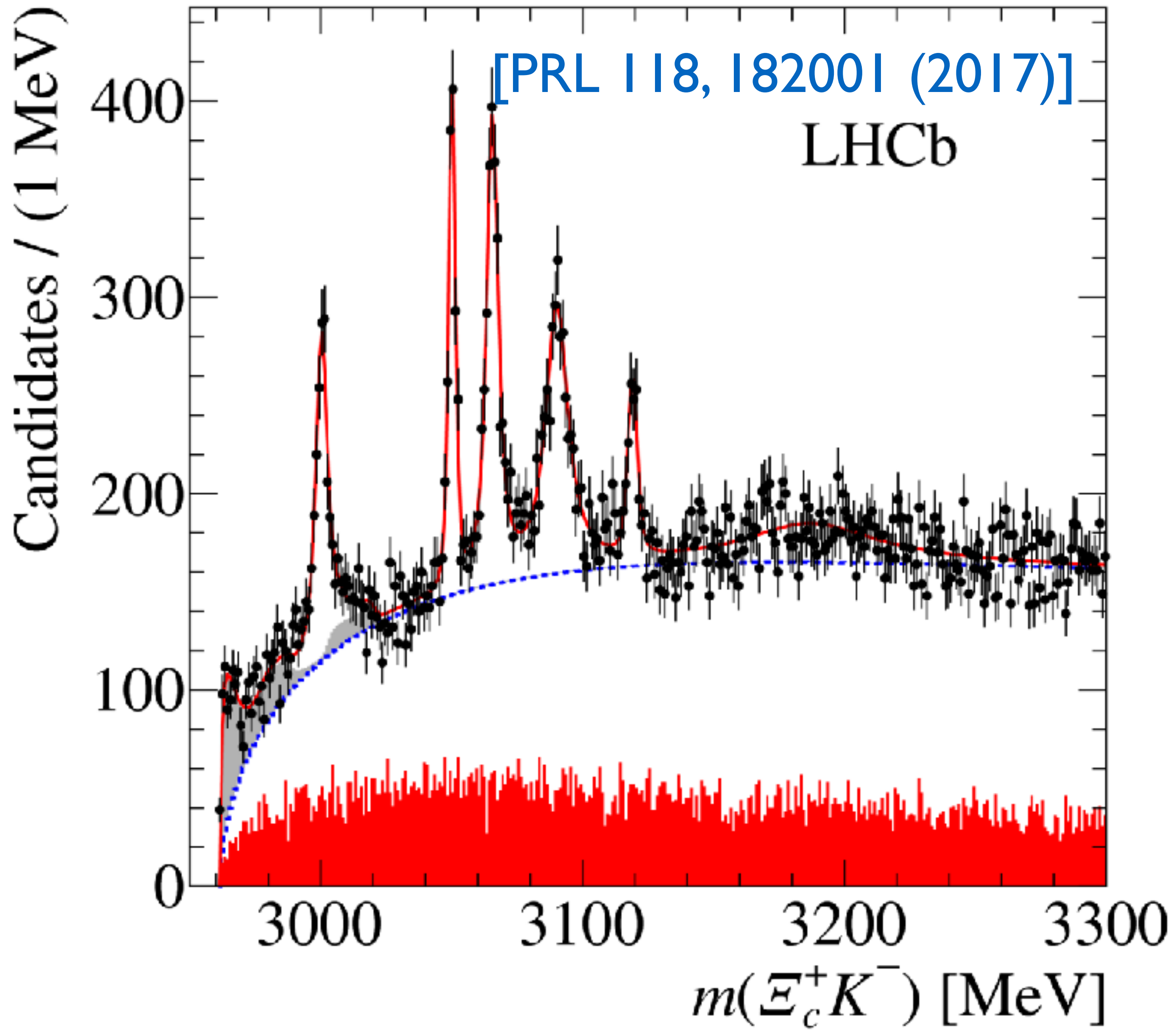
Discovery of Ω_c^{**} and Xi_{cc}^{++} have spurred theoretical investigations, motivated by the calibration of the binding energy of their constituent **diquarks**.

Calibrating diquark model parameters from Ω_c^{**}, treating them as [ss]c diquark-quark objects. Can then use this to make predictions about the Y states. [Ali et al., arXiv:1708.04650]

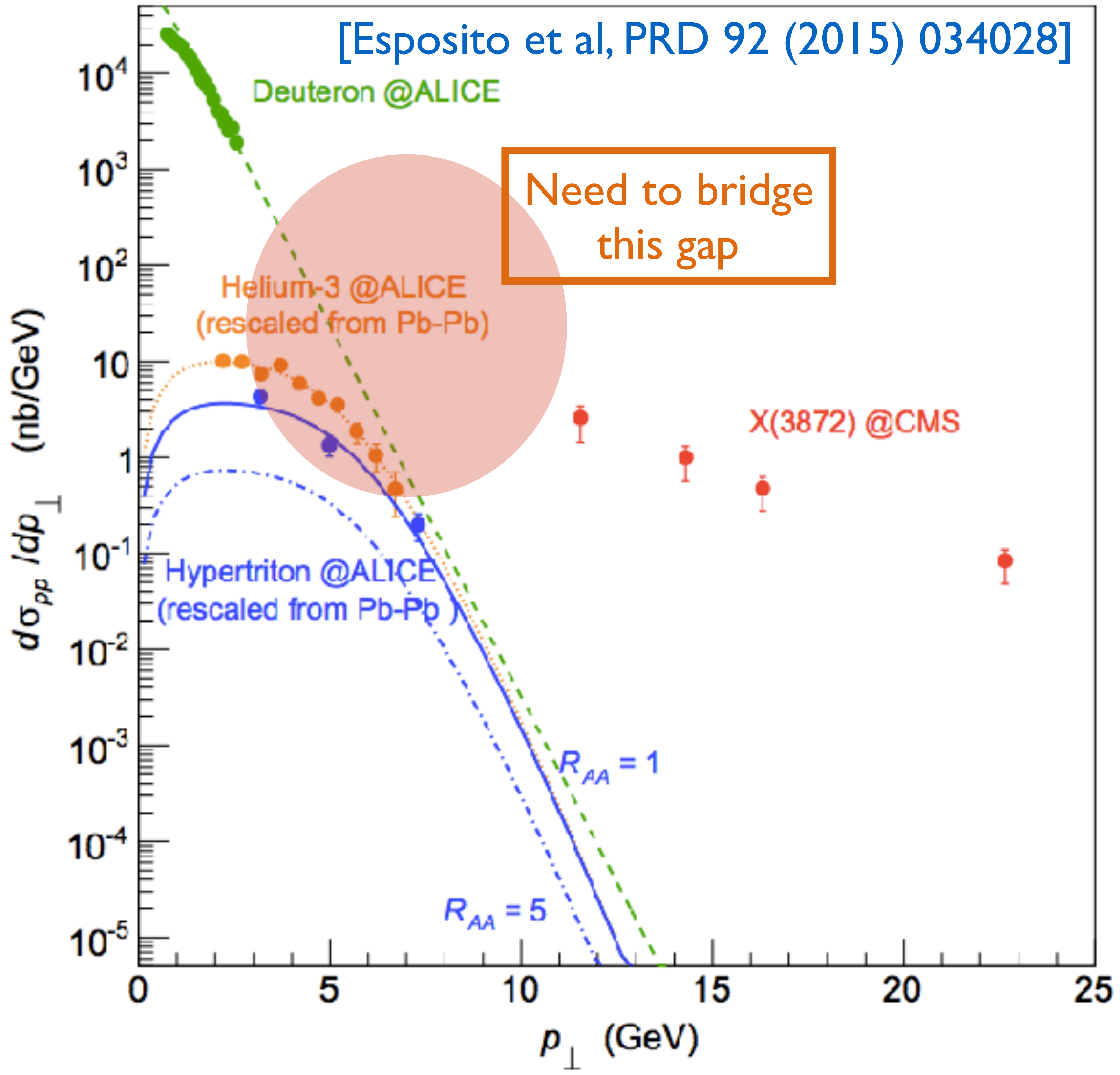
Not only are some of the Ω_c^{**} states now thought of as potential pentaquarks, but theorists are using these as a basis to propose other candidates. [Mehen arXiv:1708.05020] [Karliner and Rosner arXiv:1707.07666]

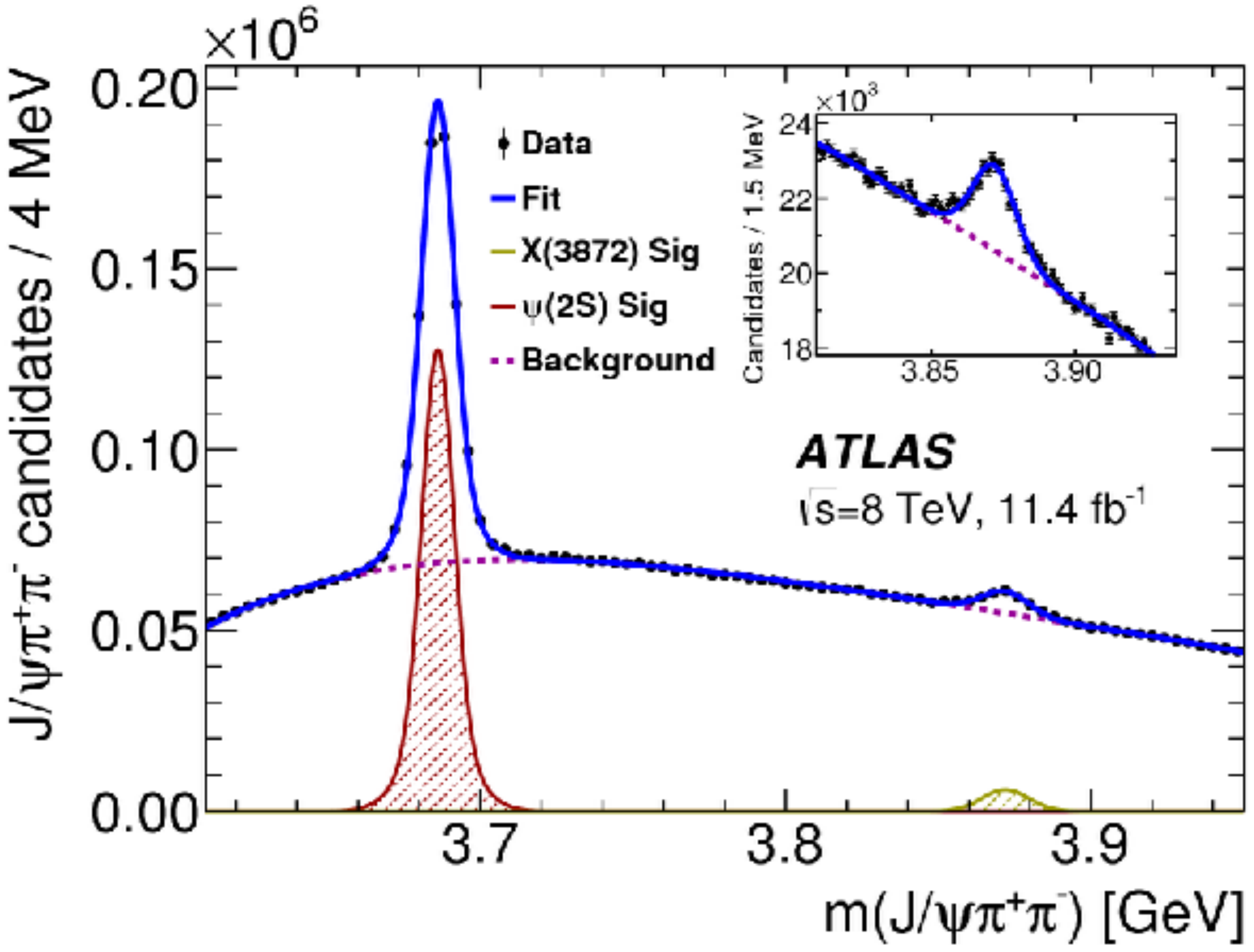
e.g., doubly-bottom tetraquark (~10.4 GeV) that is stable to EM/strong interactions, potentially narrow, with very interesting decay modes (B, D, double-J/ψ …)

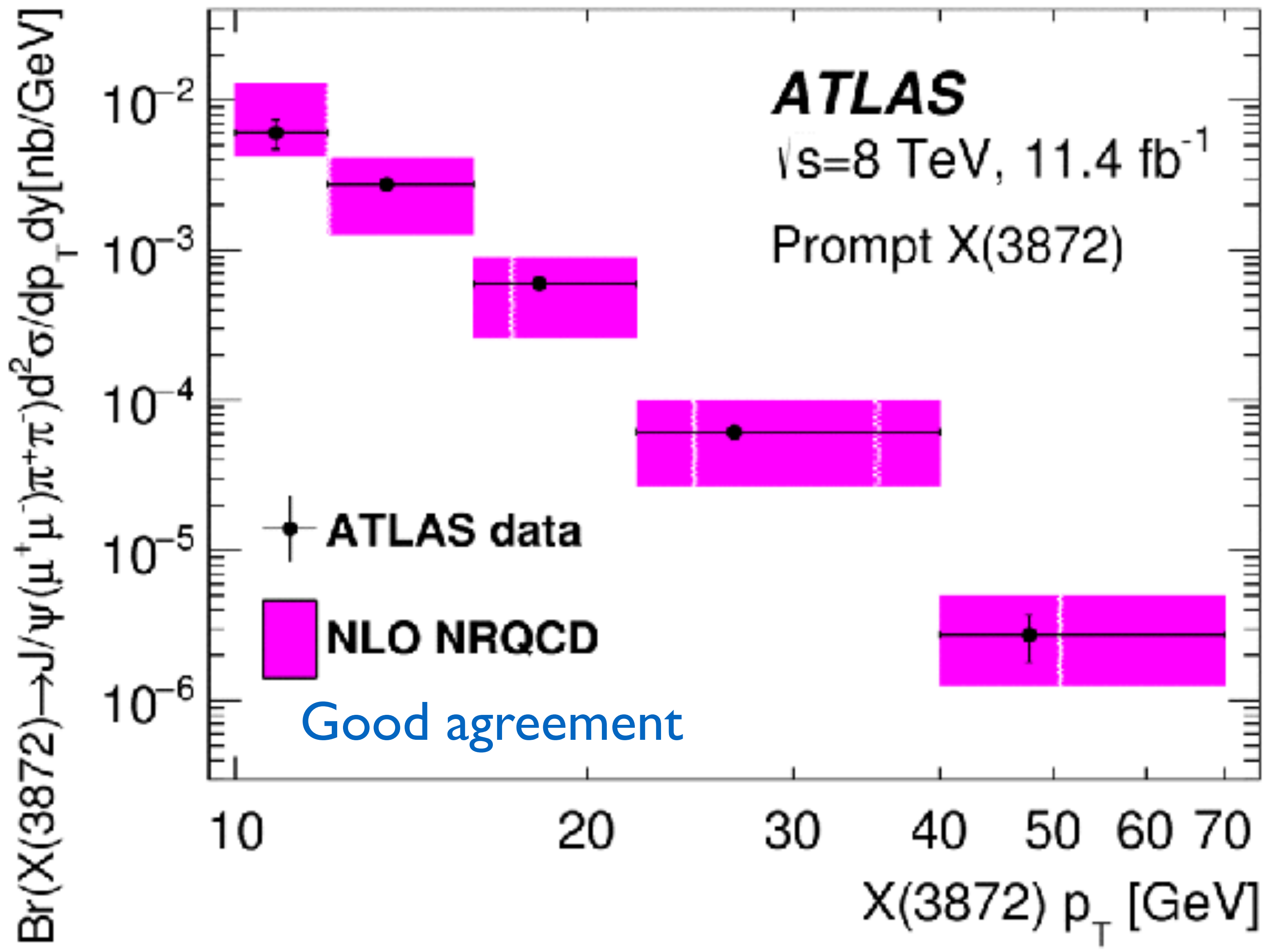




X(3872) production







[D0, PRL 103 (2009)152001] [ATLAS, JHEP 01 (2017) 117]
[CDF, PRL 103 (2009)152001] [CMS, JHEP 04 (2013) 154]
[LHCb, JHEP 04 (2013) 154]

X(3872) seen in pp and and $p\bar{p}$ collisions.

Compare cross-section with that of known molecules to understand X(3872) nature.

NLO NRQCD considers X(3872) to be a mixture of $\chi_{c1}(2P)$ and a D^0D^{*0} molecular state, with the production dominated by the $\chi_{c1}(2P)$ part
[Artoisenet and Braaten, PRD 81 (2010) 114018]

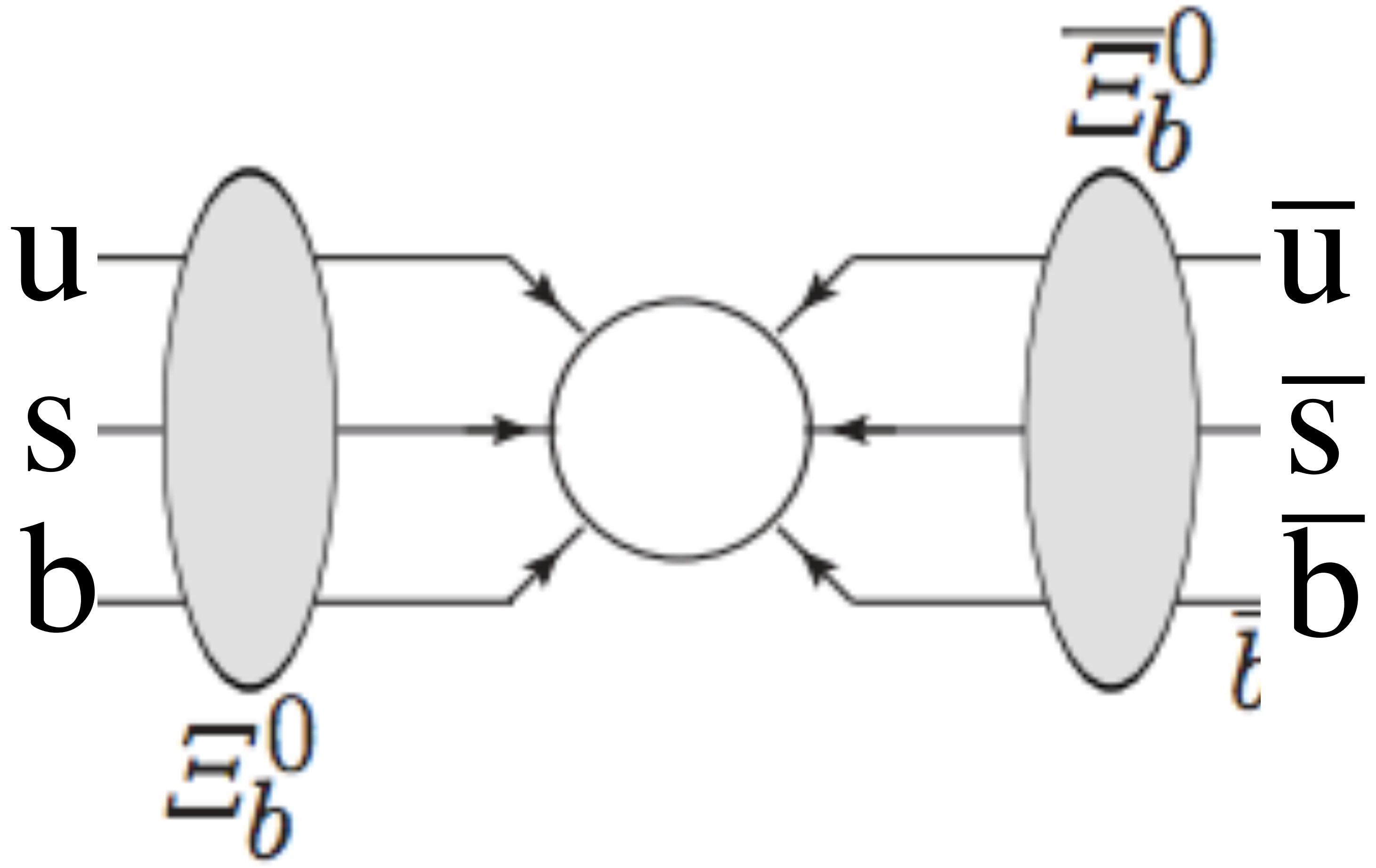
Supported by BR of X(3872) → $[c\bar{c}]\gamma$ decays
[NPB 886 (2014) 665]

Baryon-number violation

BNV never been seen experimentally → strong constraints from proton lifetime.

BSM models with flavour-diagonal six fermion vertices allow BNV without violating constraints.
[PRD 85, 036005 (2012), PLB 721 82 (2013)]

Unambiguous experimental evidence:
baryon-antibaryon oscillations of hadrons that contain quarks of all three generations (usb).

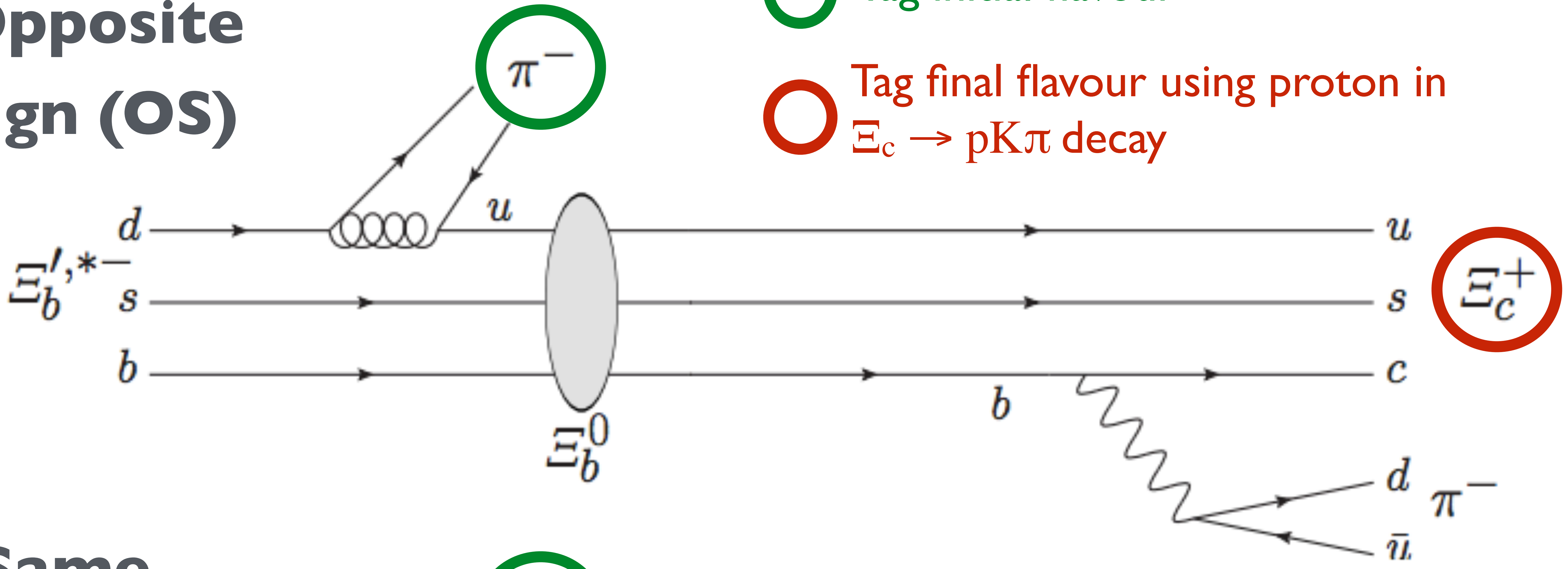


Baryon-number violation @ LHCb

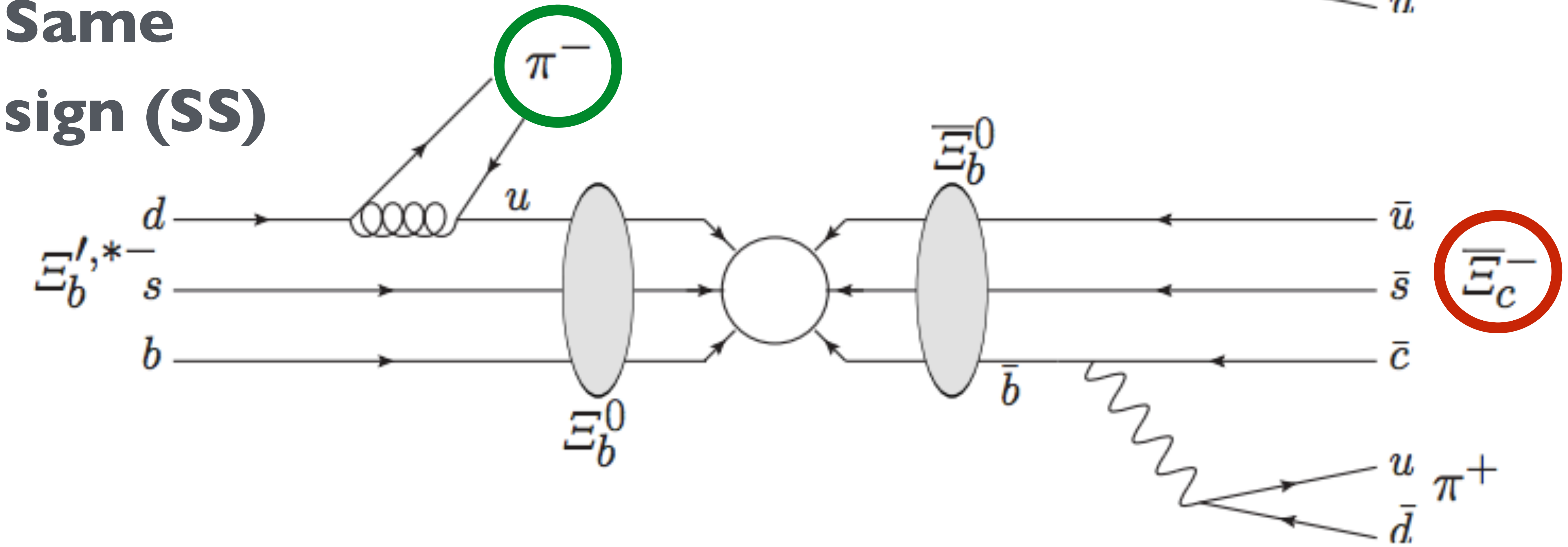
Tag initial flavour

Tag final flavour using proton in $\Xi_c \rightarrow pK\pi$ decay

Opposite sign (OS)



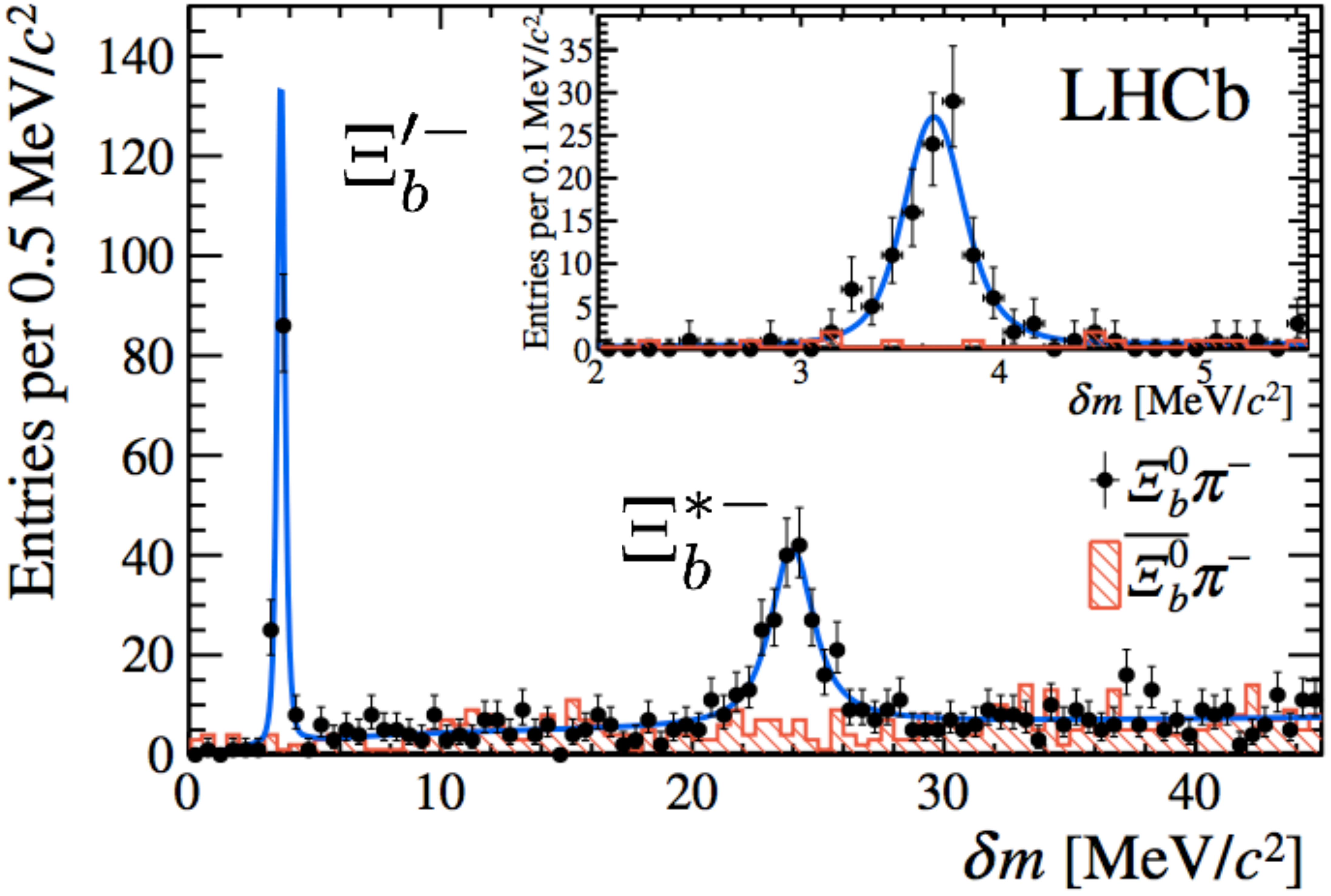
Same sign (SS)



Similar method for measuring charm mixing

$$R(t) = \frac{\Gamma(\Xi_b^0 \rightarrow \overline{\Xi}_c^- \pi^+)}{\Gamma(\Xi_b^0 \rightarrow \Xi_c^+ \pi^-)} \approx \omega t^2$$

[Preliminary LHCb-PAPER-2017-023]



No evidence of BNV oscillations.

$\omega < 0.08$ ps^{-1} @95% CL (using likelihood ratio test and CL$_s$ method)

$\omega = 1/\tau^2_{mix}$ → mixing lifetime > 13 ps.

Future X(3872) measurements

Charged partners of X(3872) predicted by some tetraquark models [Maiani et al]

Partners not observed in B decays and limits below what would be expected for isospin conservation → X(3872) is iso-singlet?

Alternatively, the partners may be **broad** due to presence of thresholds, so may have evaded detection → **amplitude analysis**

Make more precise width and mass measurement

[Belle PRD 84 (2011) 052004]
[BaBar PRD 71 (2005) 031501]

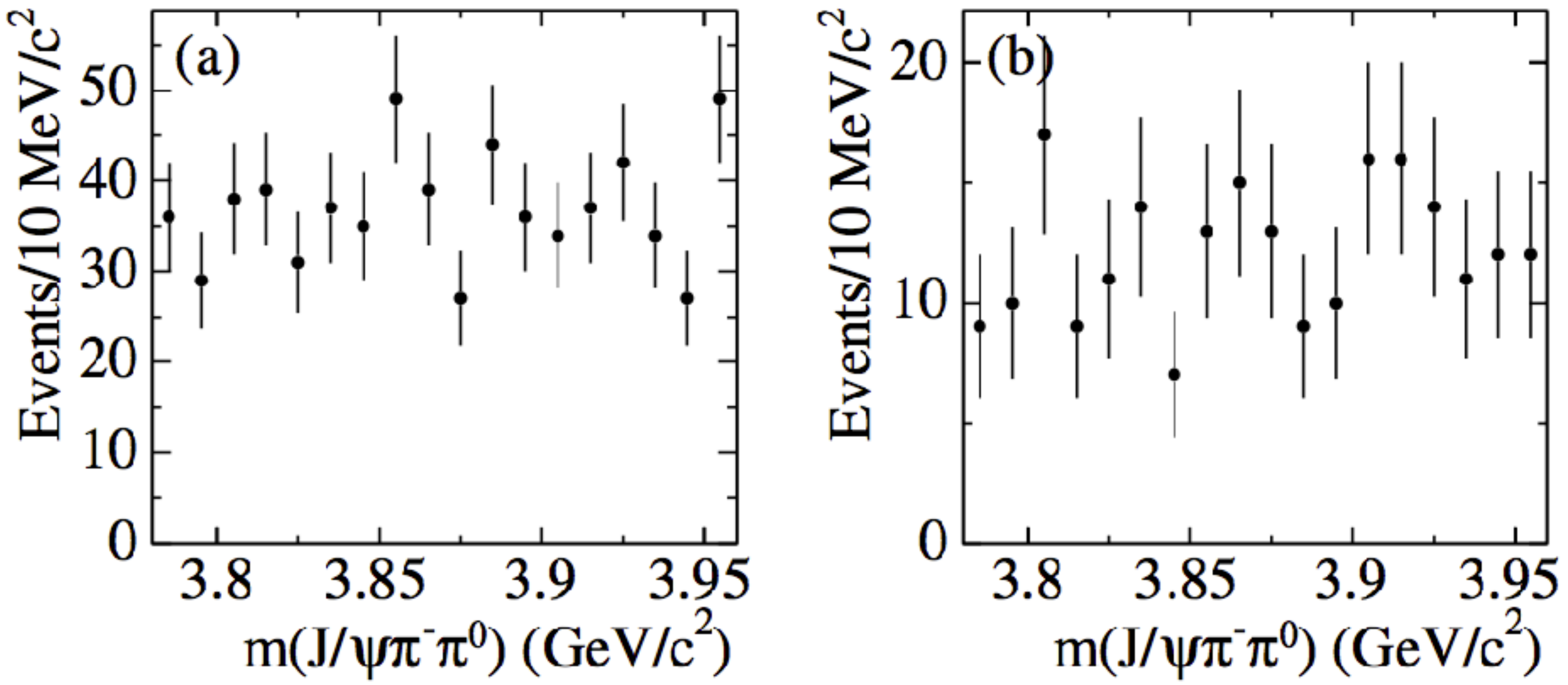


FIG. 3. The $J/\psi\pi^-\pi^0$ invariant mass in 10 MeV/c^2 bins for (a) $B^0 \to J/\psi\pi^-\pi^0K^+$ and (b) for $B^- \to J/\psi\pi^-\pi^0K^0_S$. No indication for the decay $X^- \to J/\psi\pi^-\pi^0$ can be found.

$$\mathcal{B}(\bar{B}^0 \to K^- X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 4.2 \times 10^{-6},$$

$$\mathcal{B}(B^+ \to K^0 X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 6.1 \times 10^{-6},$$

Evidence for exotics in $\Lambda_b \to J/\psi p \pi^-$

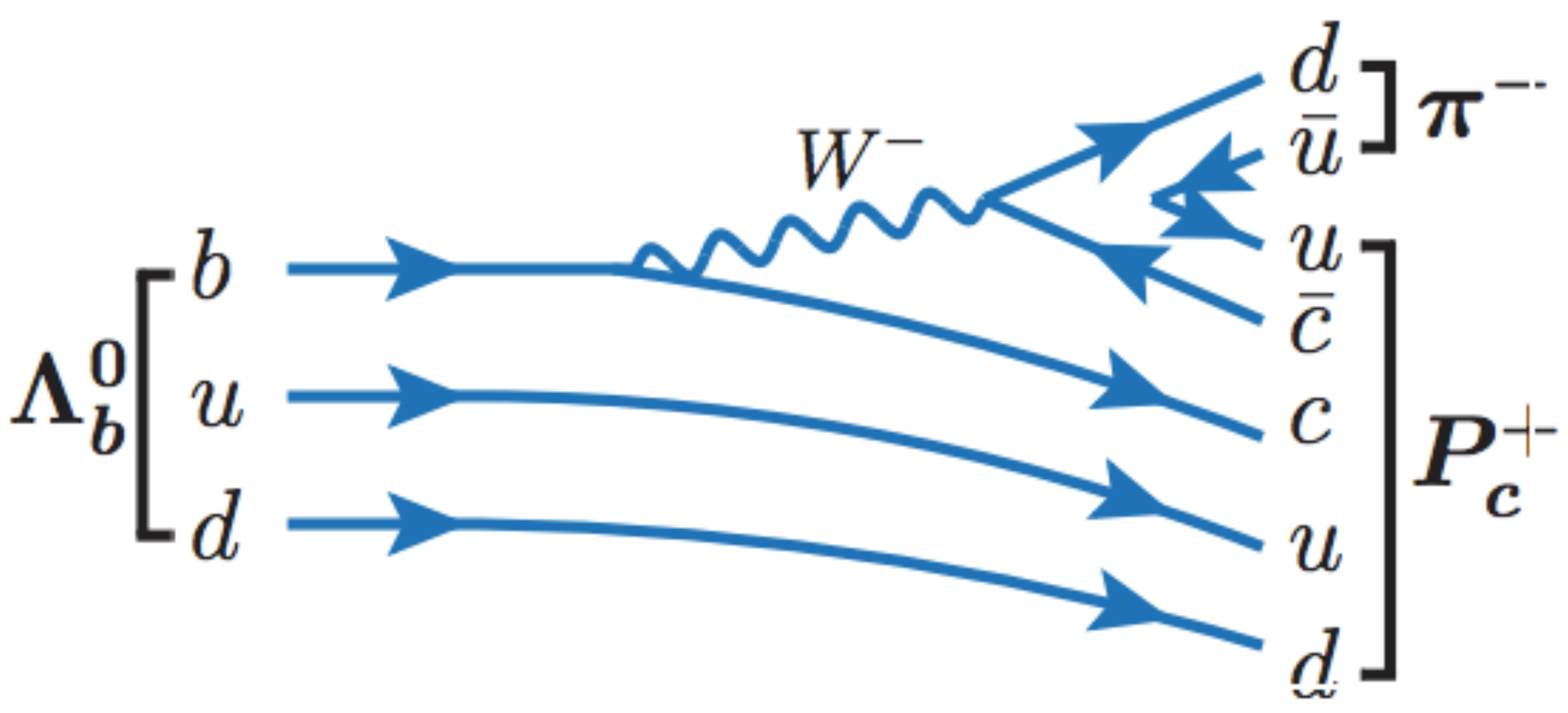
$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.0824 \pm 0.0025\,(\text{stat}) \pm 0.0042\,(\text{syst})$$

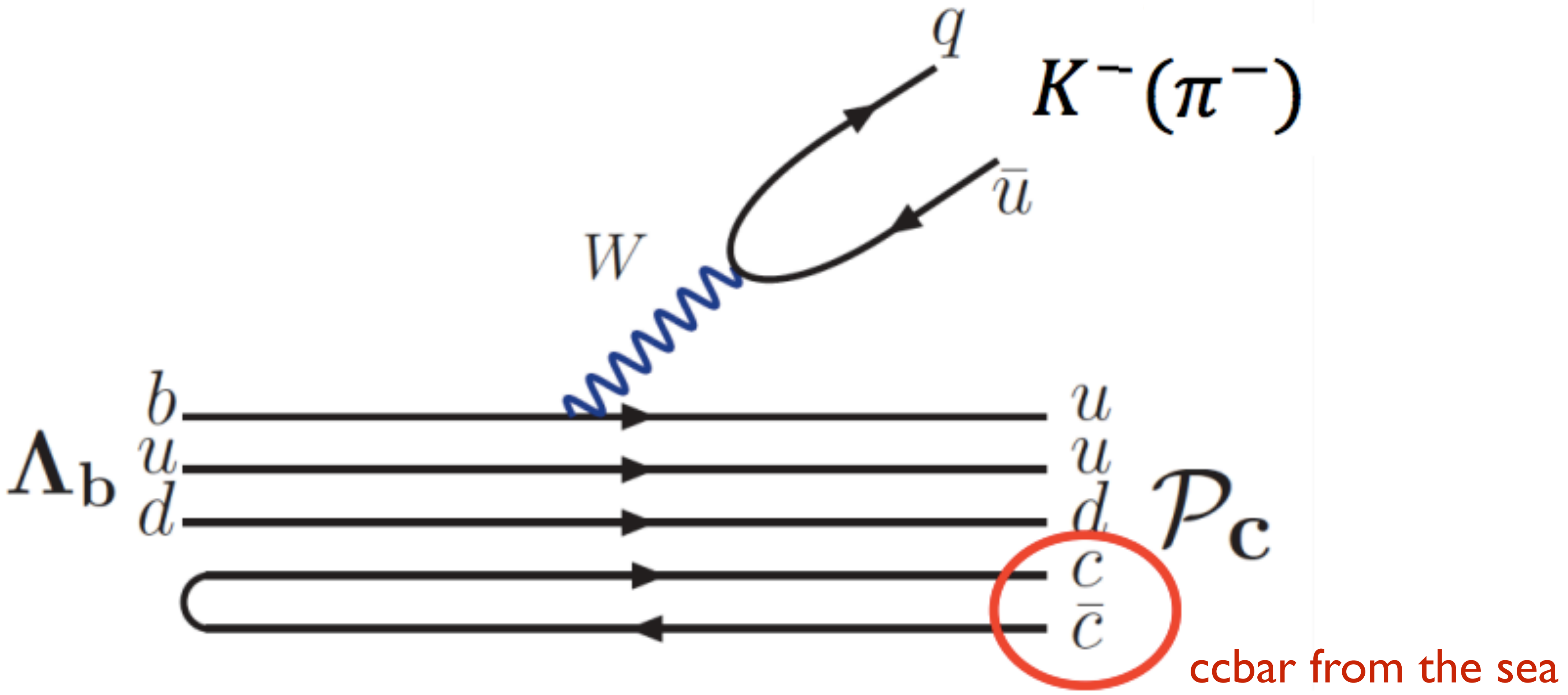
[LHCb JHEP 1407, 103 (2014)]

Observations of the $P_c{}^+$ 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]

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

$$R_{\pi^-/K^-} = 0.58 \pm 0.05$$



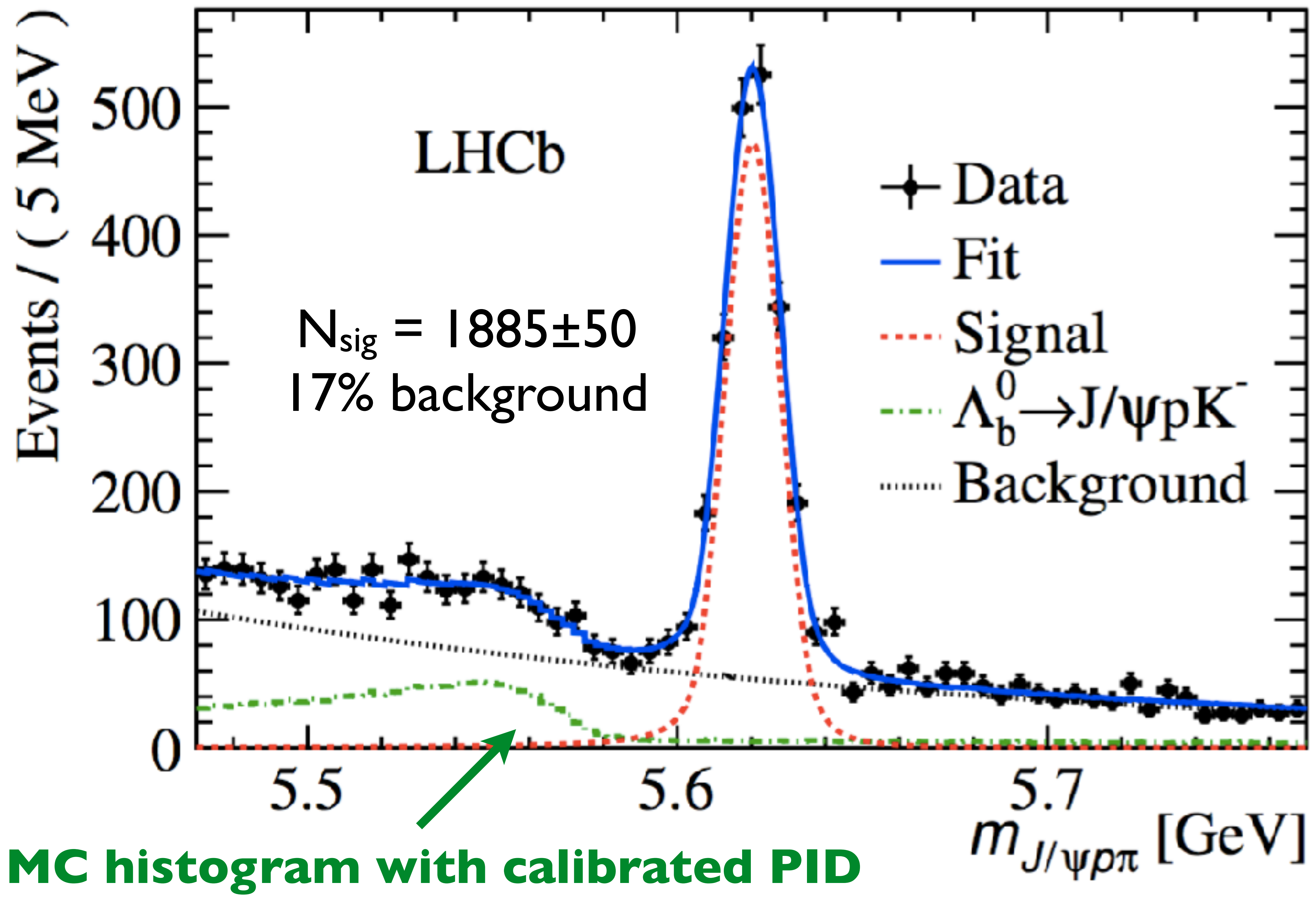


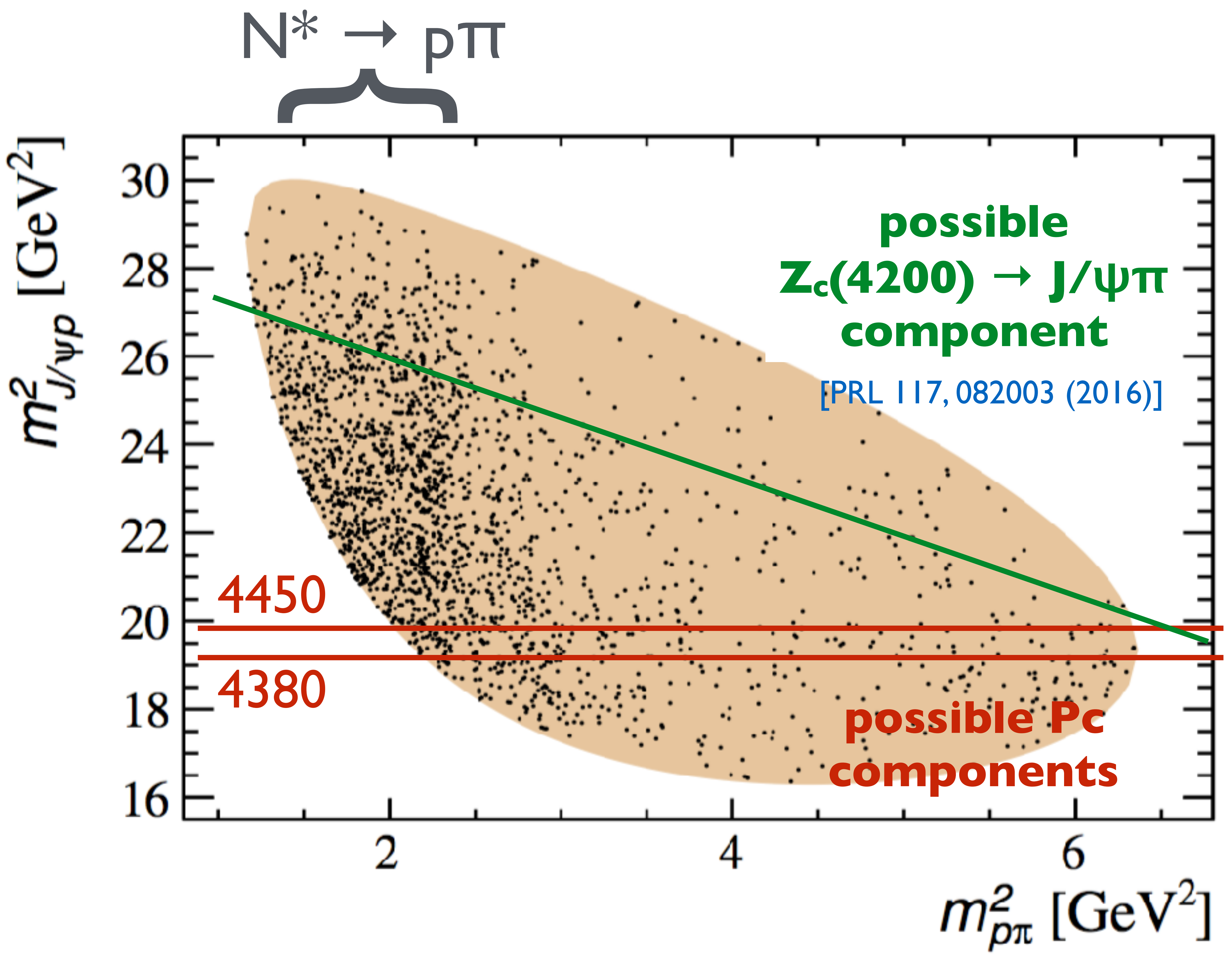
[Cheng et al. PRD 92, 096009 (2015)]

[Hsiao, Phys. Lett. B 751, 572 (2015)]

$\Lambda_b \to J/\psi p \pi^-$ pentaquark search

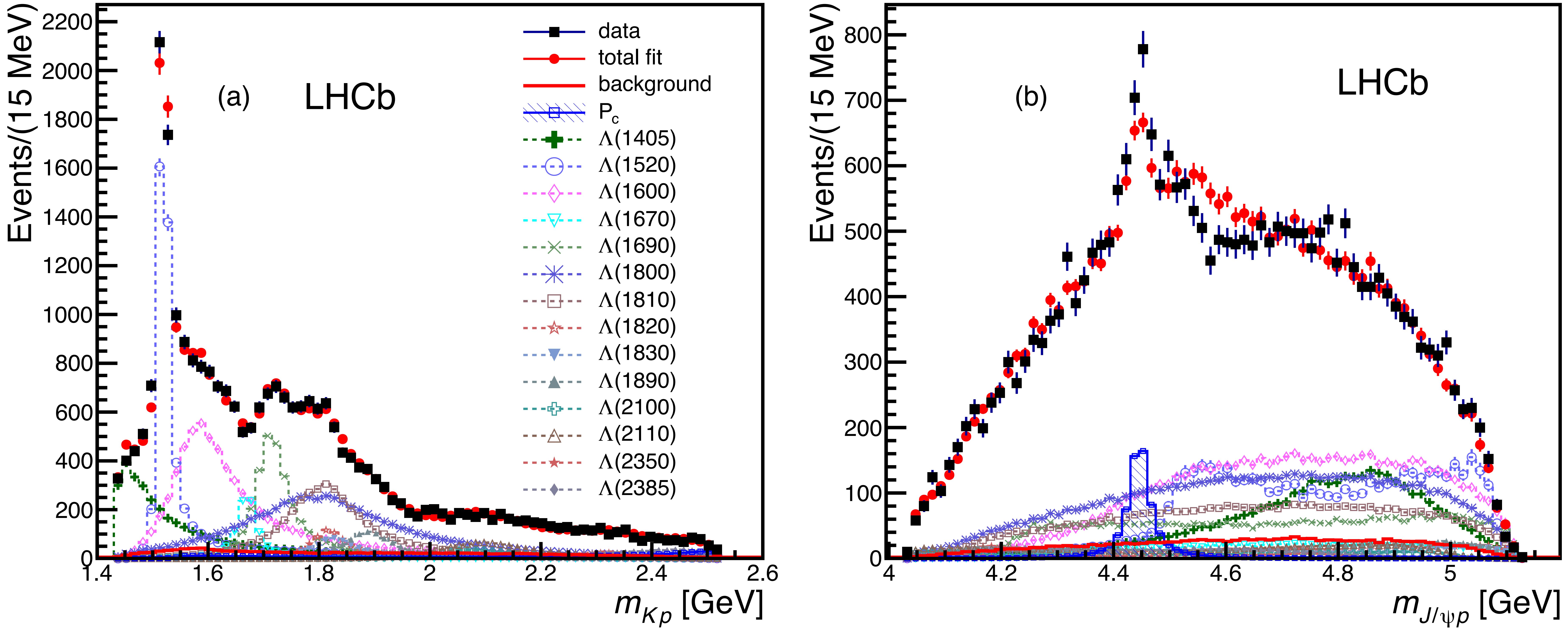
[PRL 117, 082003 (2016)]





No prominent pentaquark-like peaks

Extended model with one P_c



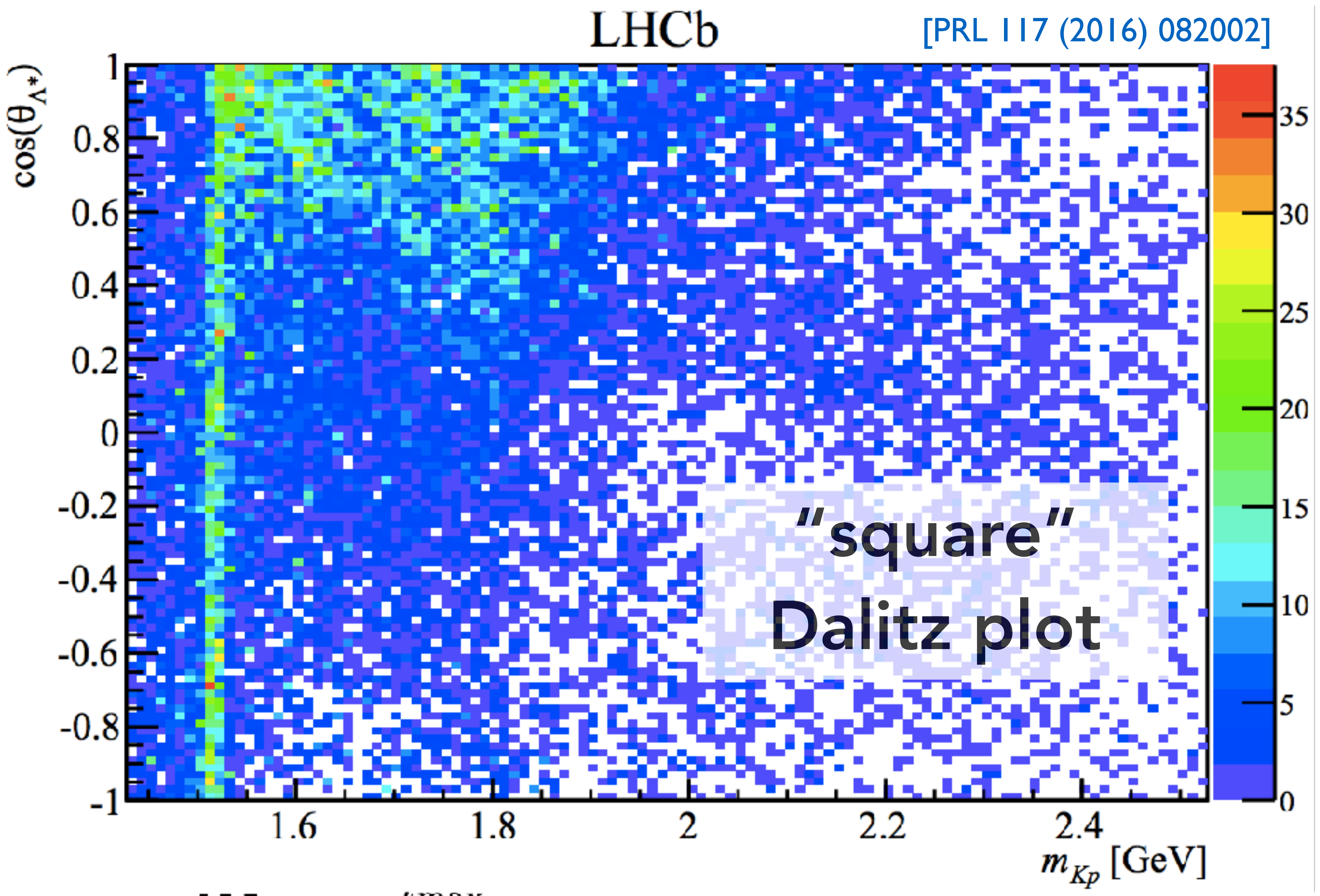
Try all Λ*'s with J^P up to $7/2^{\pm}$

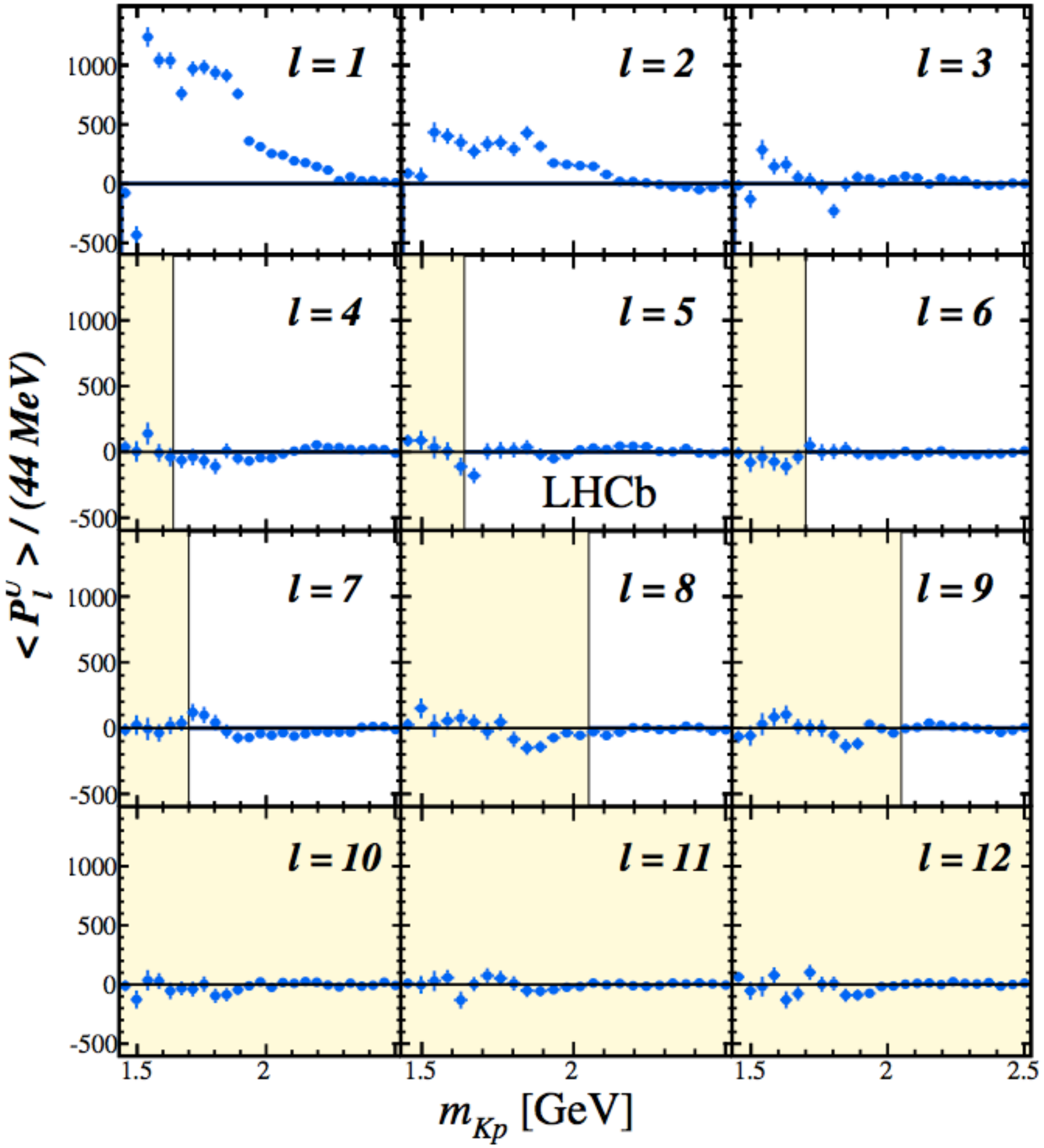
Best fit with a **$J^P = 5/2^{\pm}$** pentaquark gives improvement, but m(J/ψp) still not good

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

[PRL 115 (2015) 072001]

Pentaquark model-independent





filter out maximum spin for each m(Kp)

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

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

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

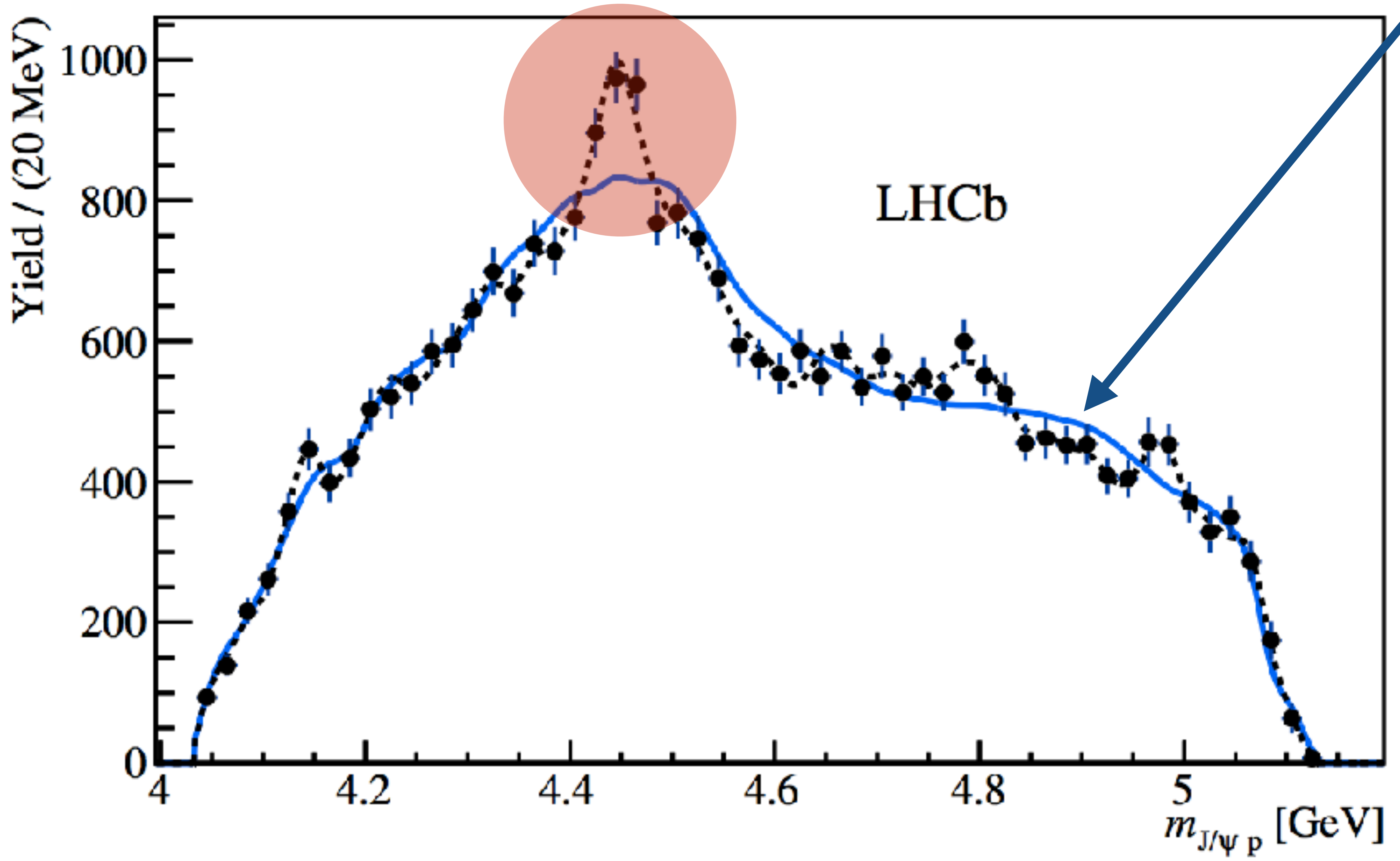
Pentaquark model-independent

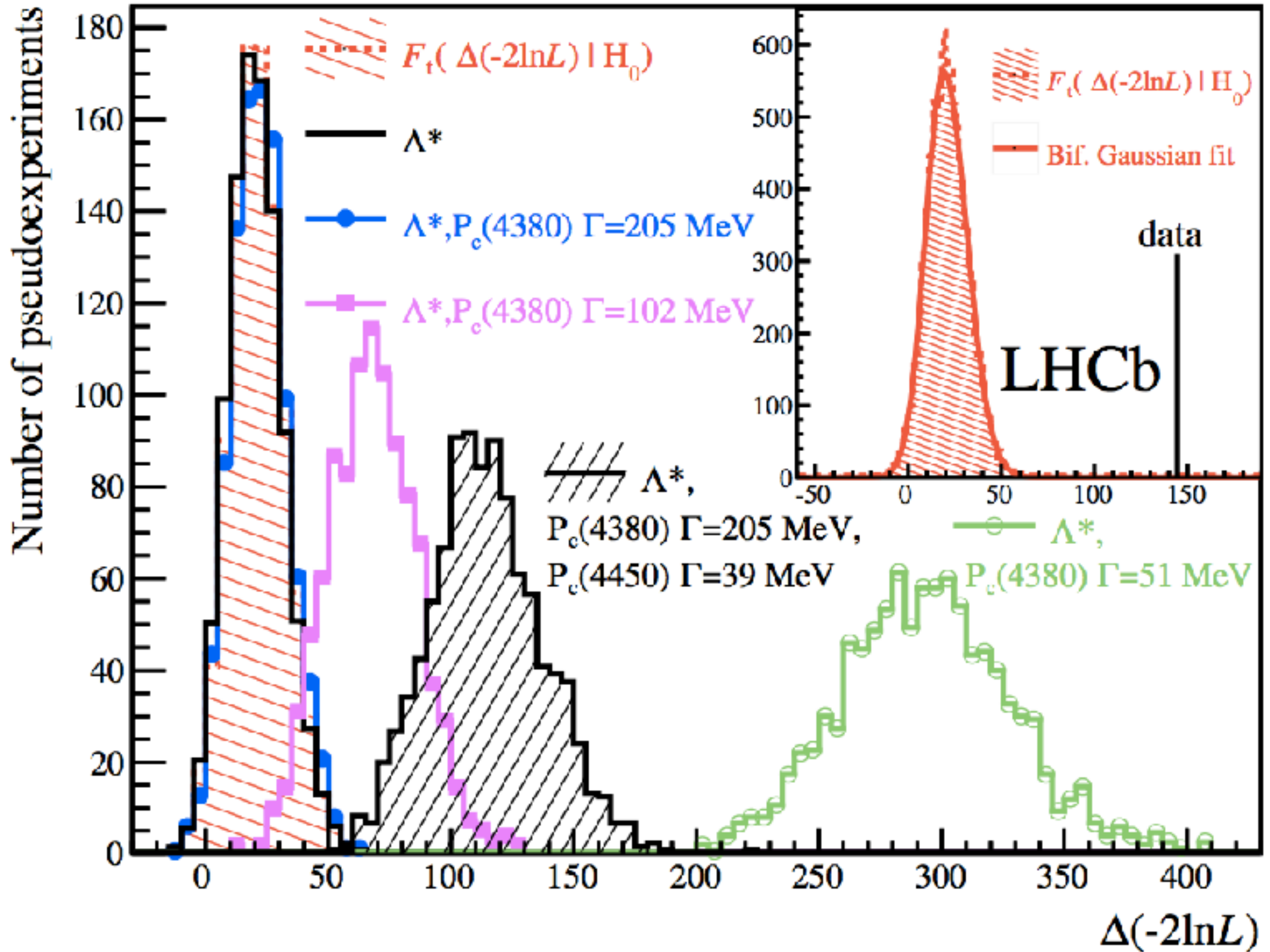
Simulate phase-space decays of $\Lambda_b^0 \to J/\psi p K^-$ [PRL 117 (2016) 082002]

Weight according to m(Kp) and the moments (with l_{max}-filter applied)

Look at reflections of the pK system into the J/ψp system → **pK reflections cannot explain narrow structure!**

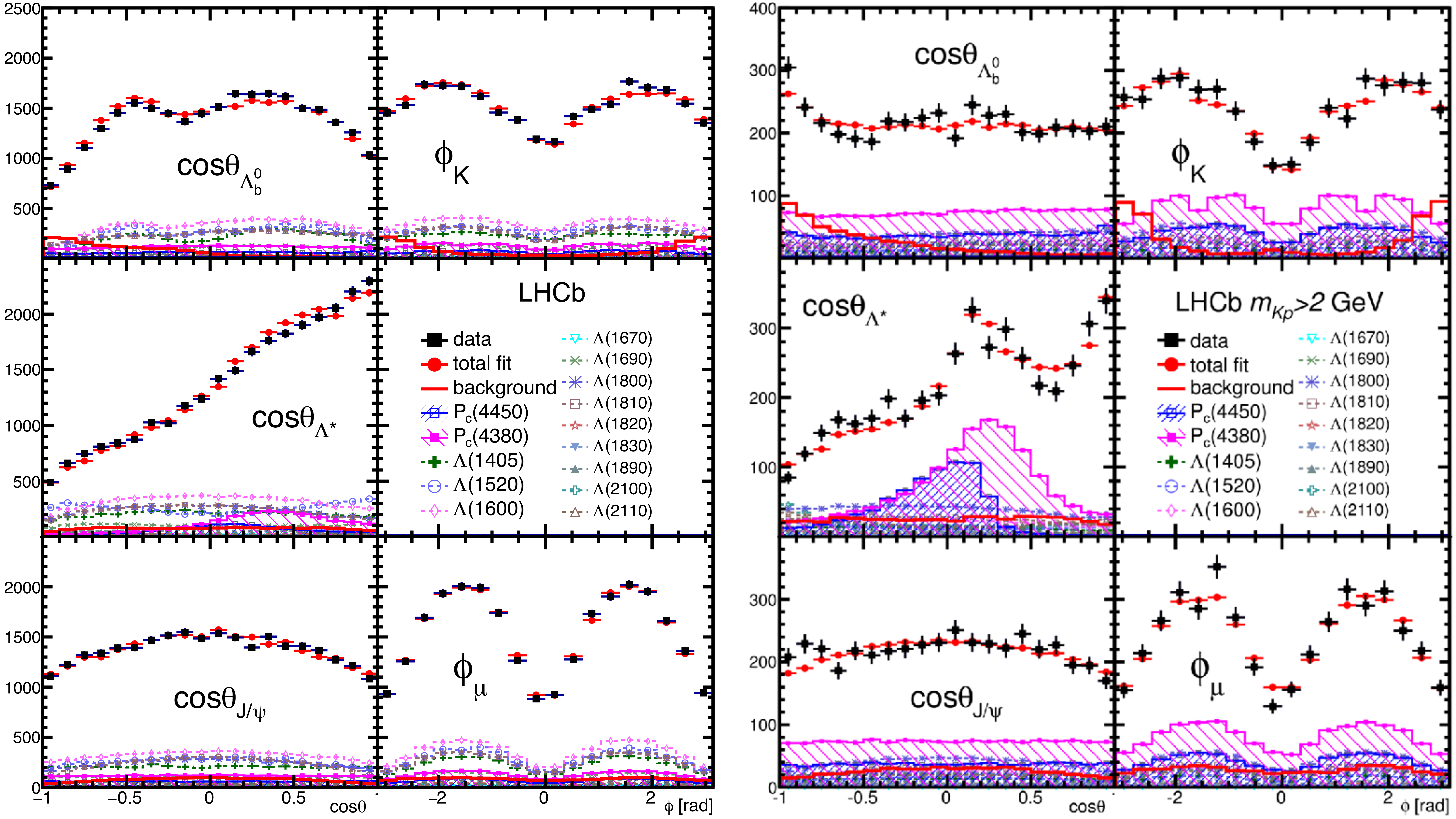
Use likelihood ratio to test various hypotheses - **Null hypothesis (Λ* only)** rejected at **9σ**





Angular distributions

Good fit to the angular observables



[PRL 115 (2015) 072001]

For the future: $B_s^0 \to J/\psi\phi\phi$

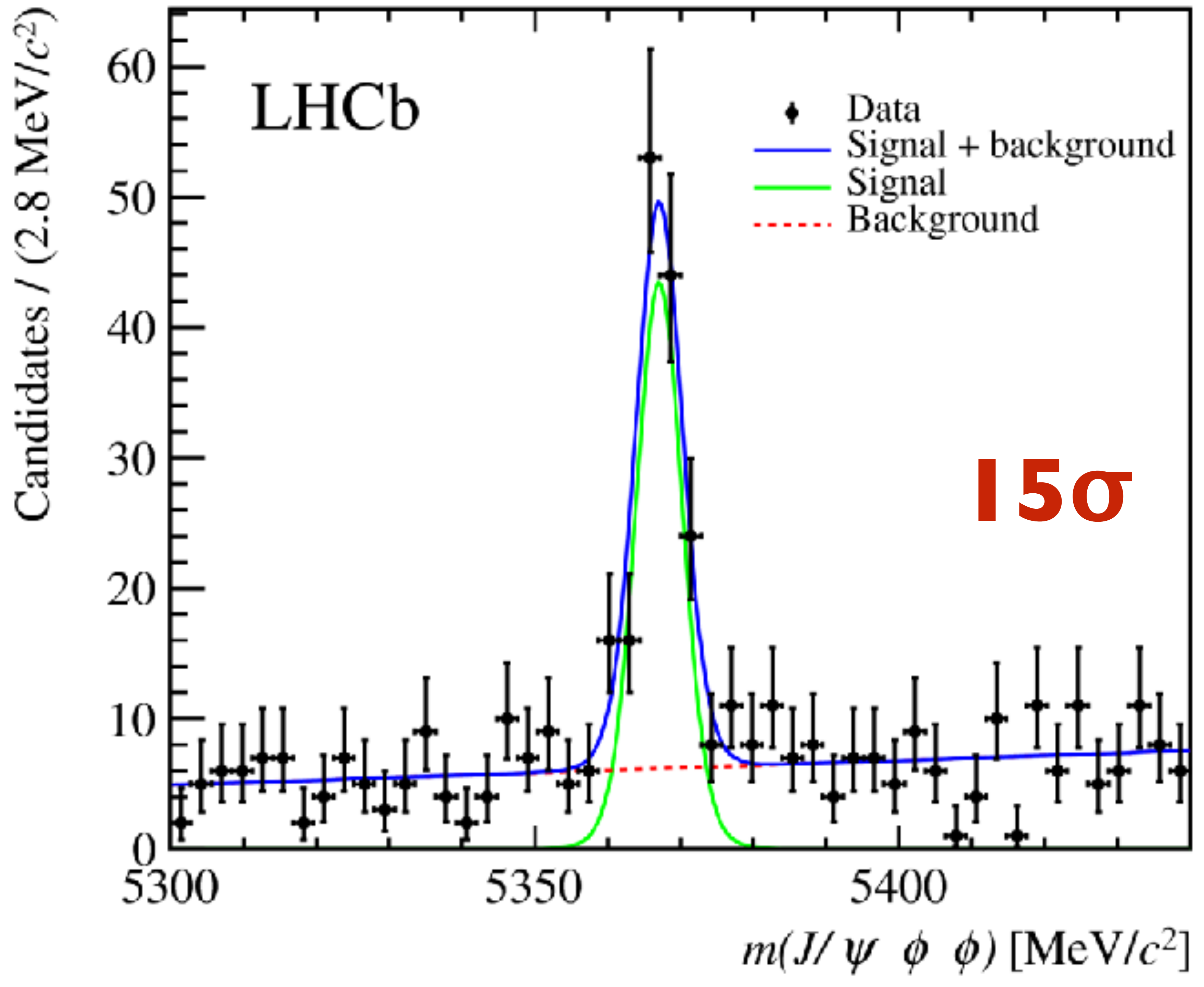
Possible threshold effects in $B_s^0 \to J/\psi\phi\phi$ and other modes [Swanson PRD 91 (2015) 034009]

Simplified phase-space simulation inadequate to describe structure

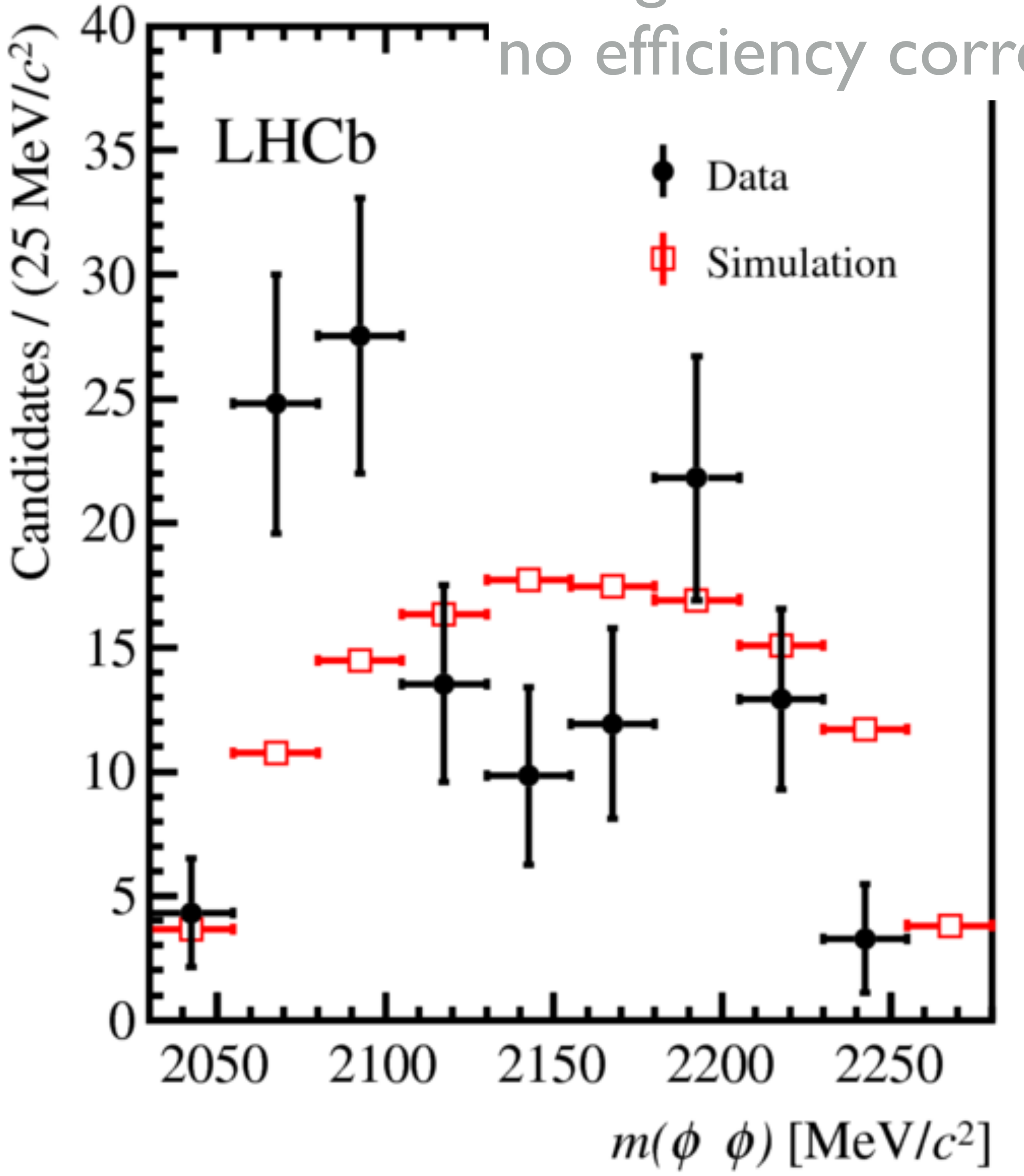
Looking forward to more data in Run-2 of LHCb

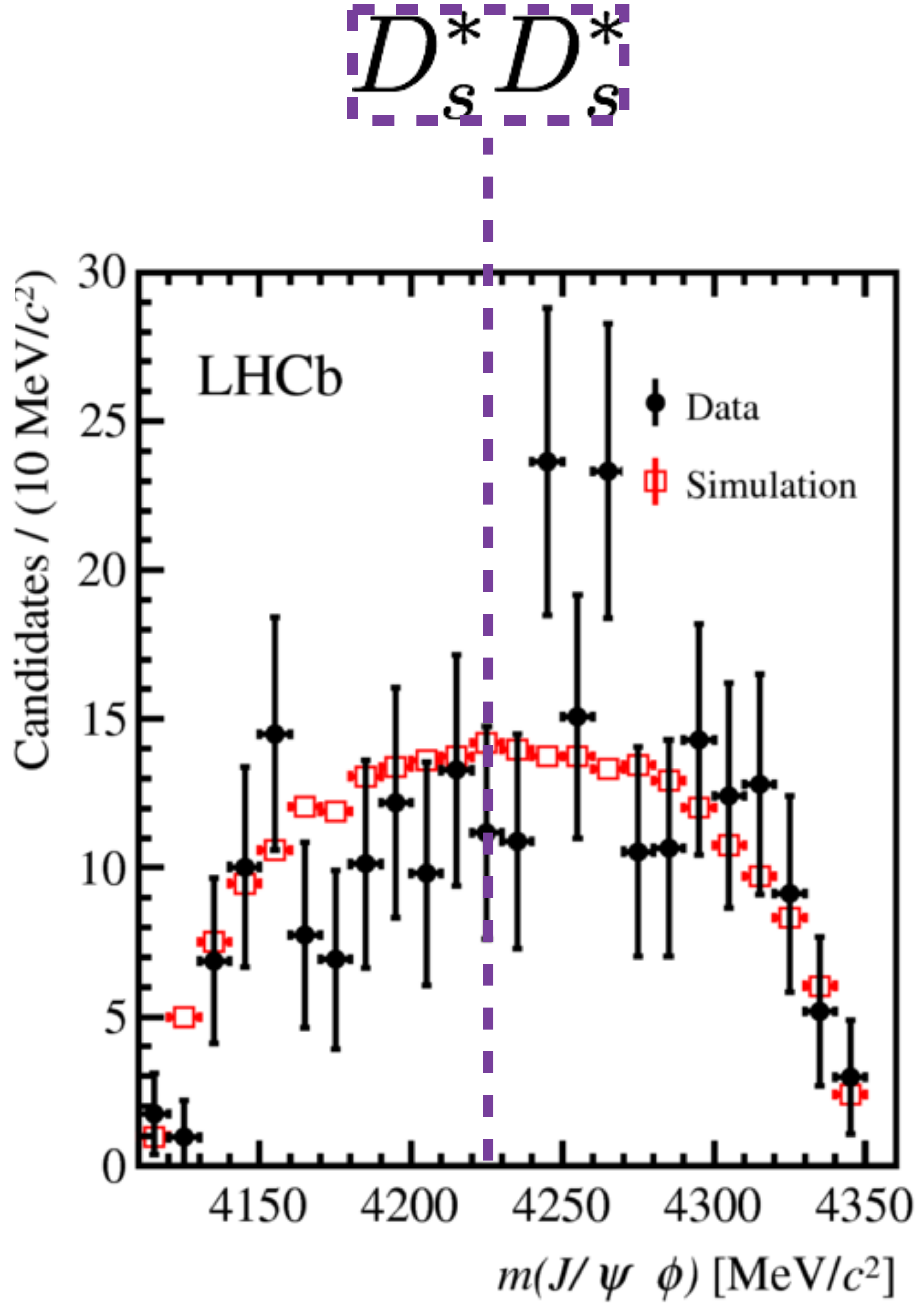
Contamination from non-res decays

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



Background subtracted
no efficiency correction





[JHEP 1603 (2016) 040]

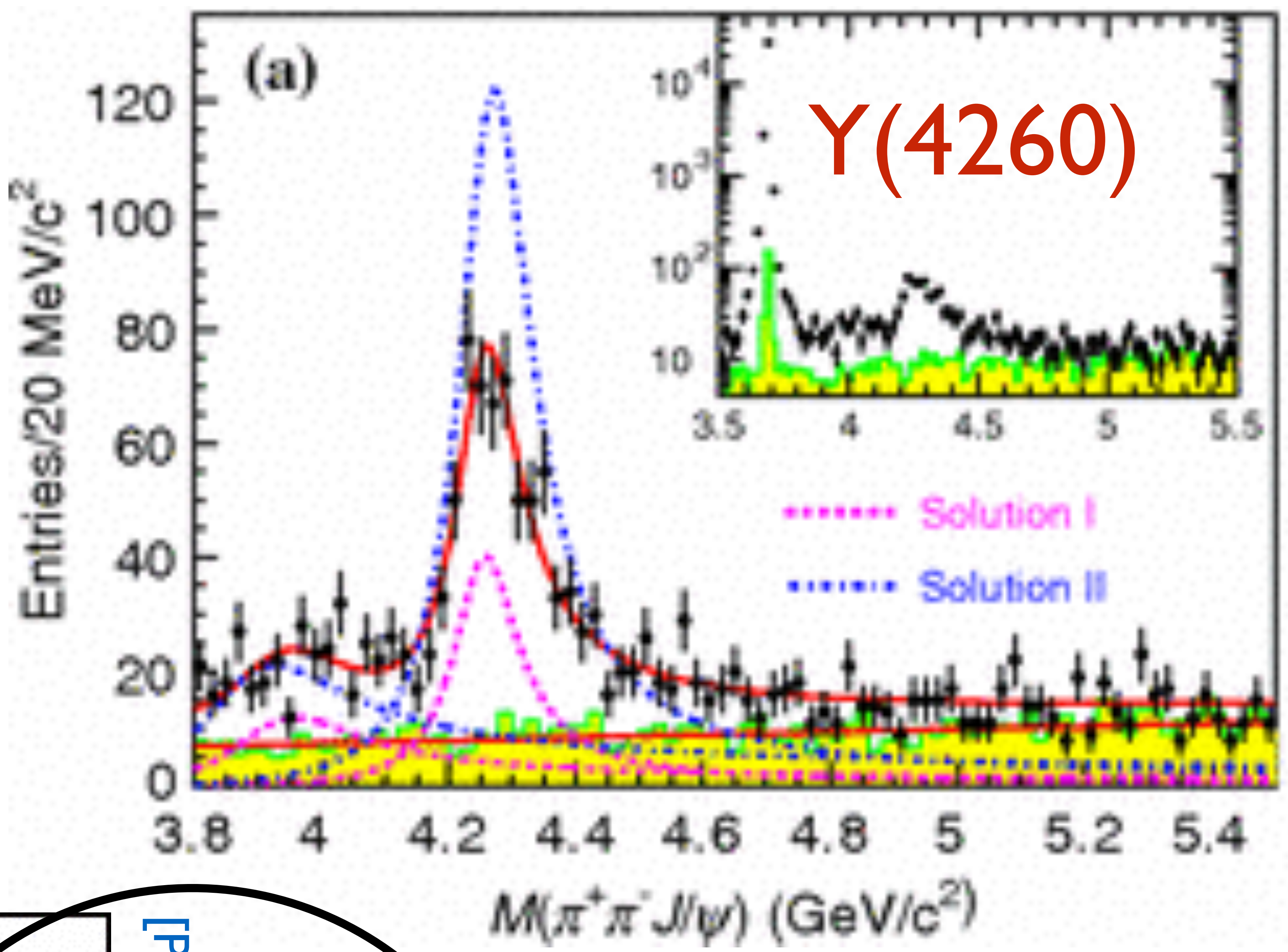
$Z_c(3900)^{\pm}$ in $e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

Observation of another possible **exotic charged state.**

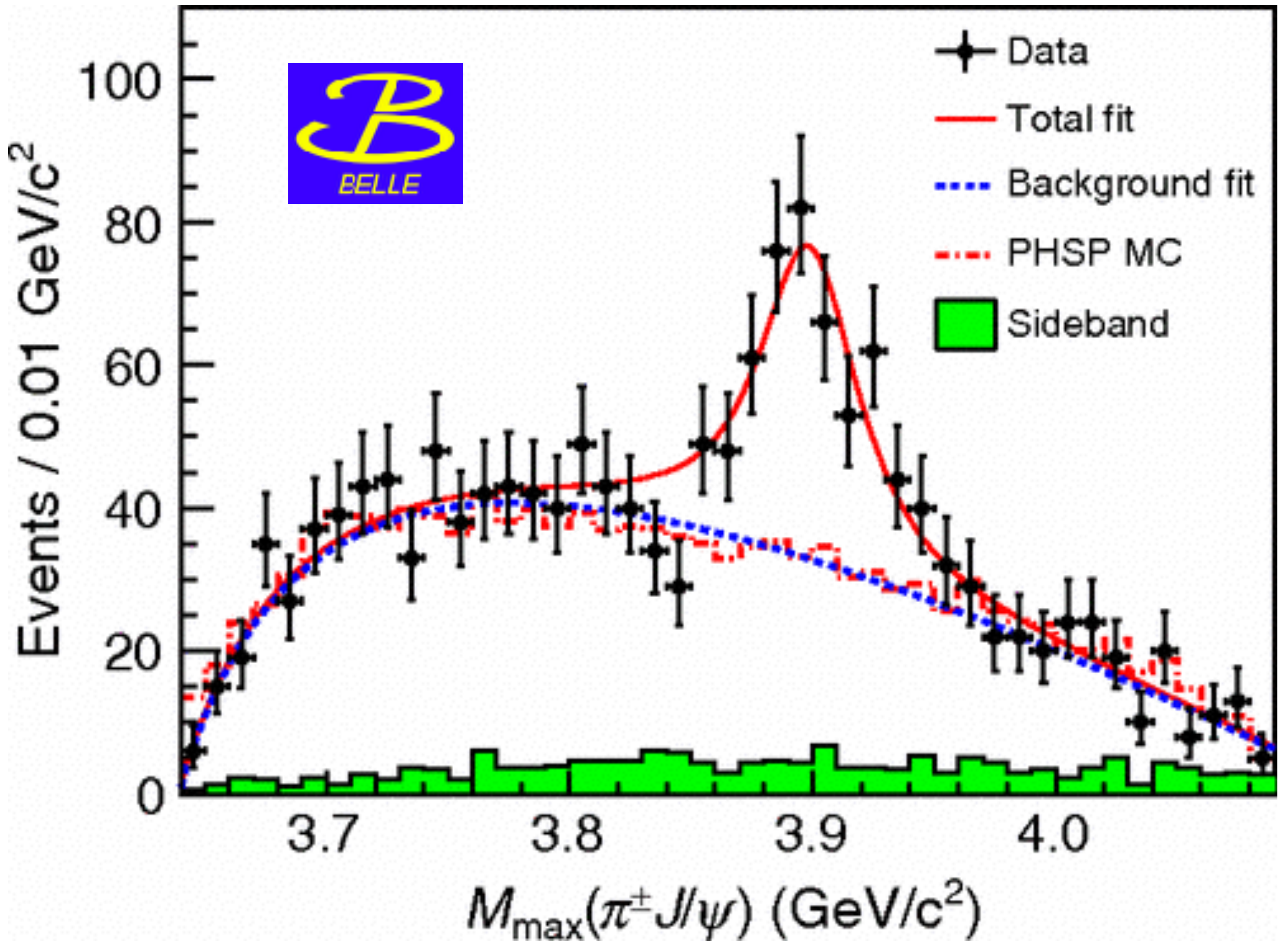
Is $Z(4430)^{\pm}$ a radial excitation of $Z_c(3900)^{\pm}$? [Maiani et al, NJP 10 (2008) 073004] [Wang, arXiv:1405.3581] [Agaev et al, arXiv:1706.01216]

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]

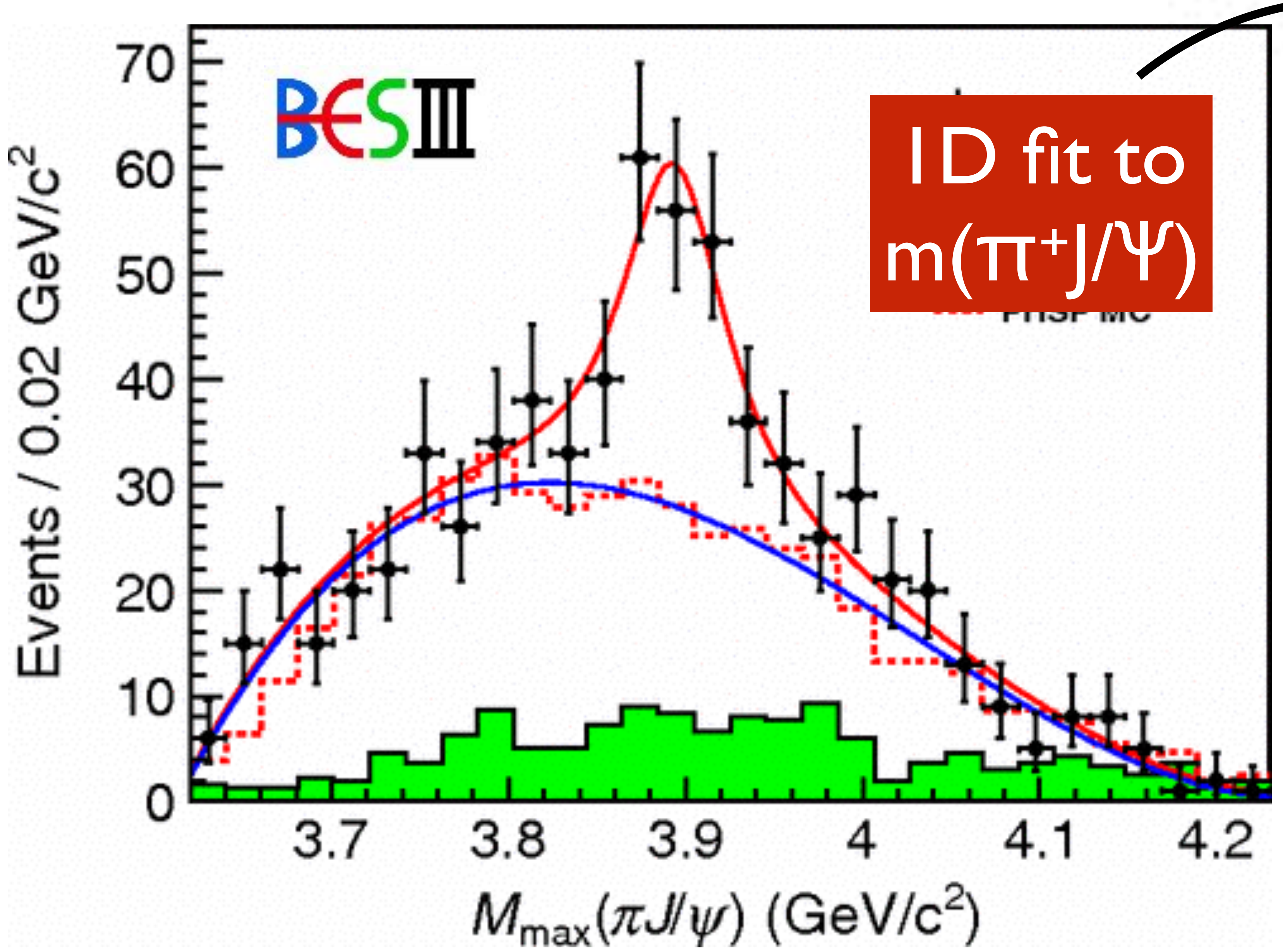
Also appears in $D^{\pm}D^*$ decay mode ($Z_c(3885)^{\pm}$)



[PRL 110 () 252002]



[PRL 110 (2013) 252001]



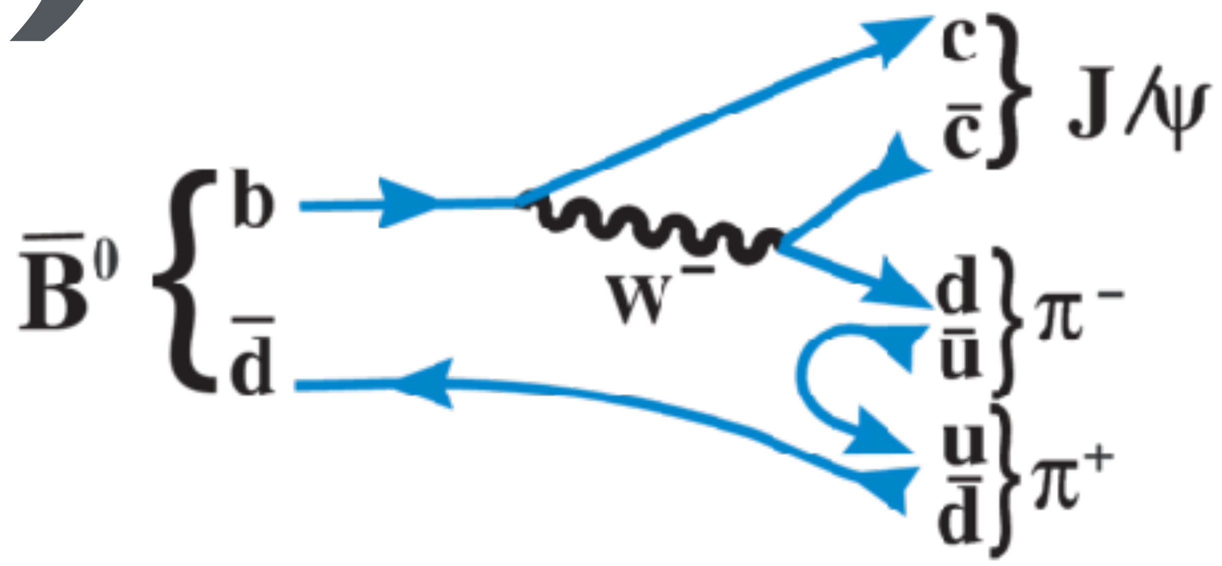
[PRL 110 (2013) 252002]

Brand-new amplitude analysis [PRL 119, 072001 (2017)]

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

$\Gamma = (63 \pm 24 \pm 26)$ MeV

Understanding the $Z_c(3900)^{\pm}$

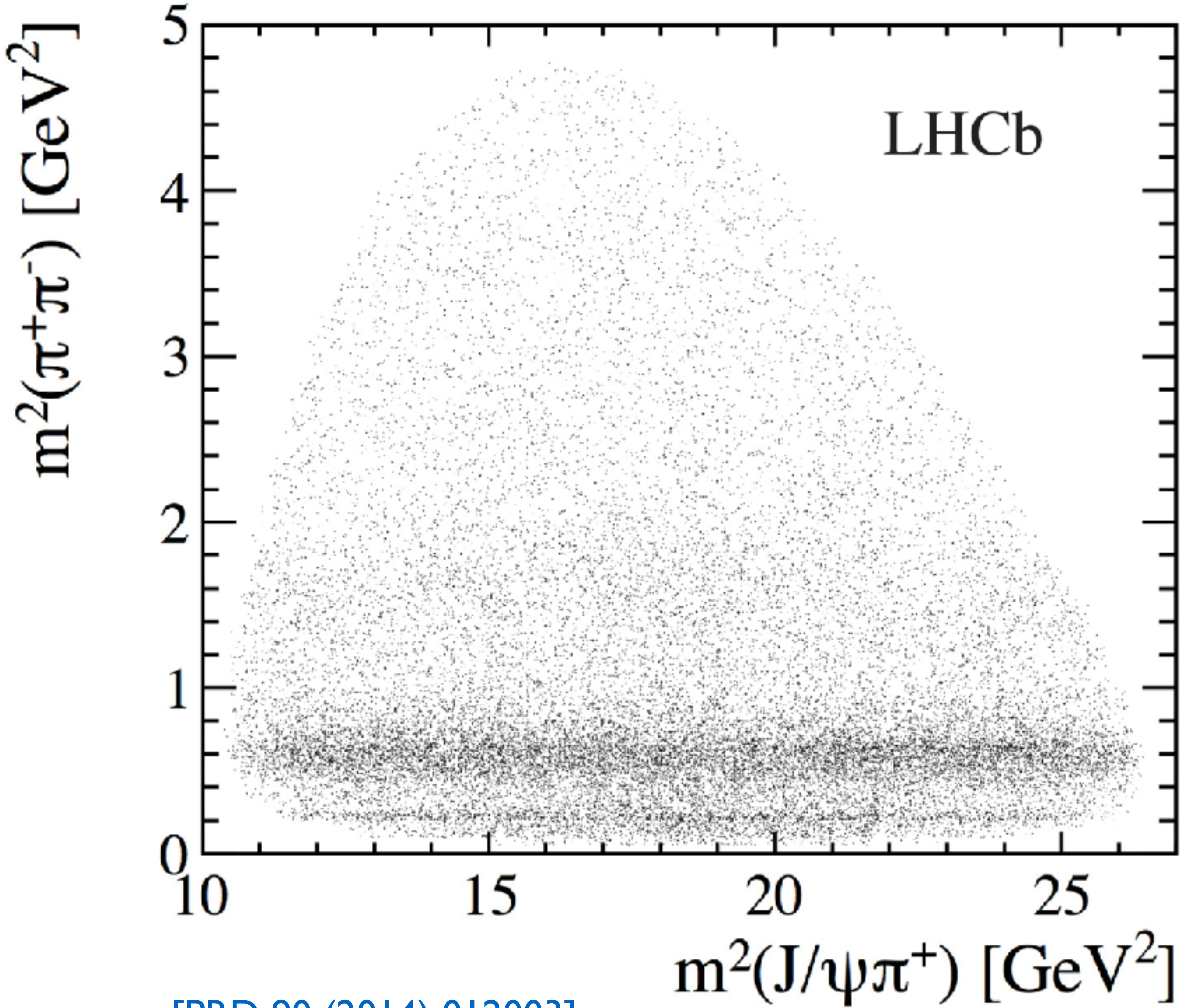


Some lattice QCD calculations do not support existence of $Z_c(3900)^{\pm}$ [Prelovsek et al PRD 91 (2015) 014504]

No sign of $Z_c(3900)^{\pm} \rightarrow J/\psi\pi^{\pm}$ in B decays 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]



[PRD 90 (2014) 012003]

Open questions

We know a lot about some states as they have been seen in multiple production and decay modes by many experiments (i.e., X(3872), Y(4260)) but there are still things we don't know, such as the natural width of the X(3872) or if it is above or below the D^0D^{*0} threshold, or phase motion of the Y(4260) (although we now think it is two peaks!).

[BES-III PRL 118 (2017) 092001]

Lots of useful information from B meson decays (they act as an excellent filter and a well-defined initial state for spectroscopy), ISR but only a few states have been produced in pp, ppbar collisions.

Some states have only been seen by a single experiment in a single production/decay mode. Quantum numbers remain unknown and states need confirmation.

History of this field is one of surprises, driven by experimental results.

Experimentally, focussed on modes containing psi('), but now need to look at pairs of open-charm and open-beauty, which may reveal new surprises.

Why don't we see evidence for Z(3900) and Y(4260) in B decays? Need larger data samples to investigate properly.

Future experimental programme

All LHCb results so far using Run 1.

Total Run 2 (ending in 2018) data will equal ~5/fb at 13 TeV, equivalent to x3 the Run 1 dataset, so prospects are good for more discoveries and more precise measurements.

Beyond this, the LHCb upgrade will run in 2021, when it is possible to accumulate even higher luminosities, leading to around 50/fb total lumi.

ATLAS/CMS will have even higher luminosity, so can contribute.

BES-III will study Y(4260) and Z(3900) in more detail.

Belle-II should have ~x50 larger dataset than Belle. Complementary strengths will be in modes with neutral particles. → look for isospin partners of many of the states that have been observed and useful for D(*)(s)D(*)(s) decay modes due to higher efficiency.

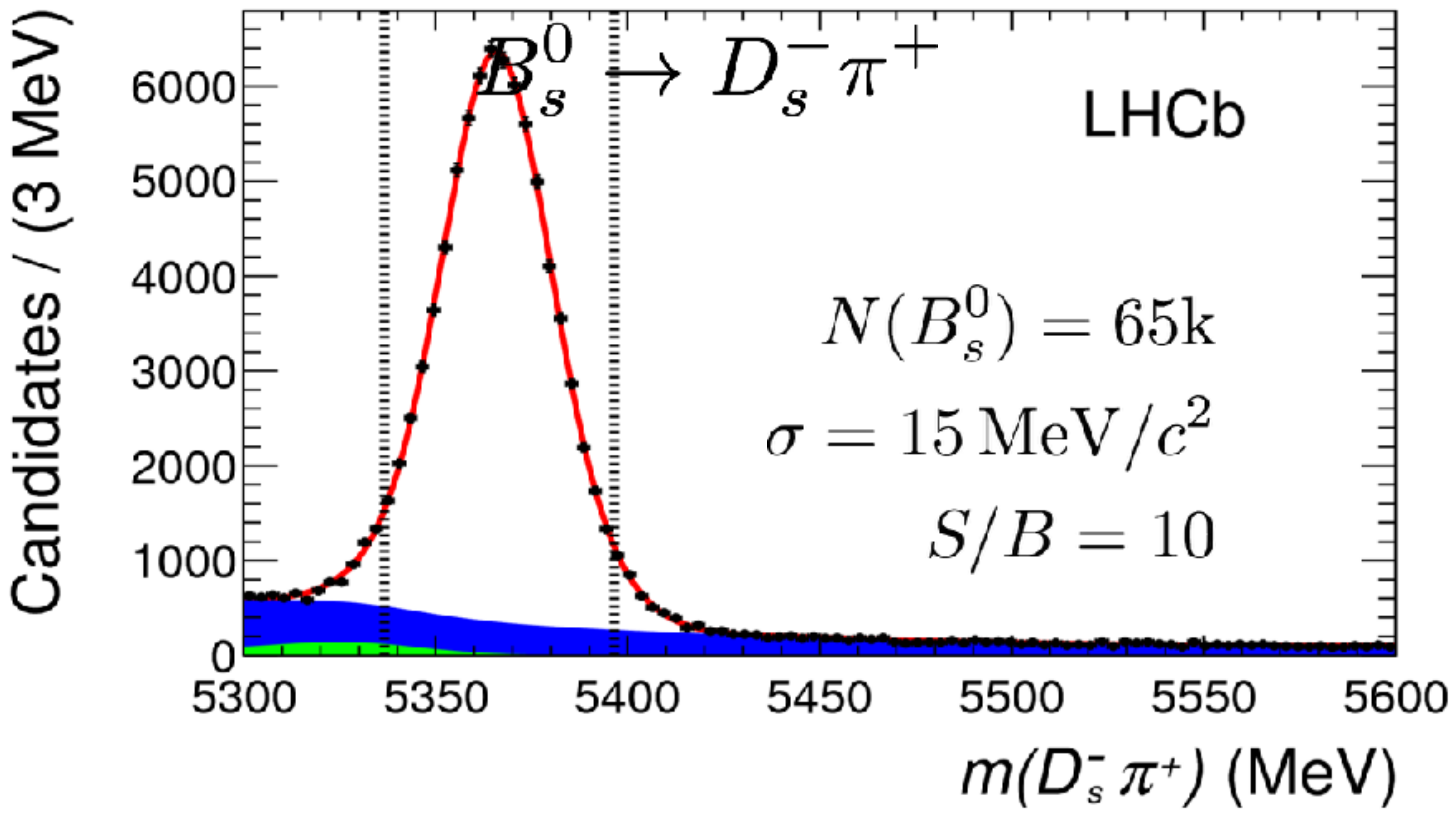
PANDA @ FAIR (2022) X(3872) line shape via energy scan (and width measurement at O(10) keV and D*s0(2317)

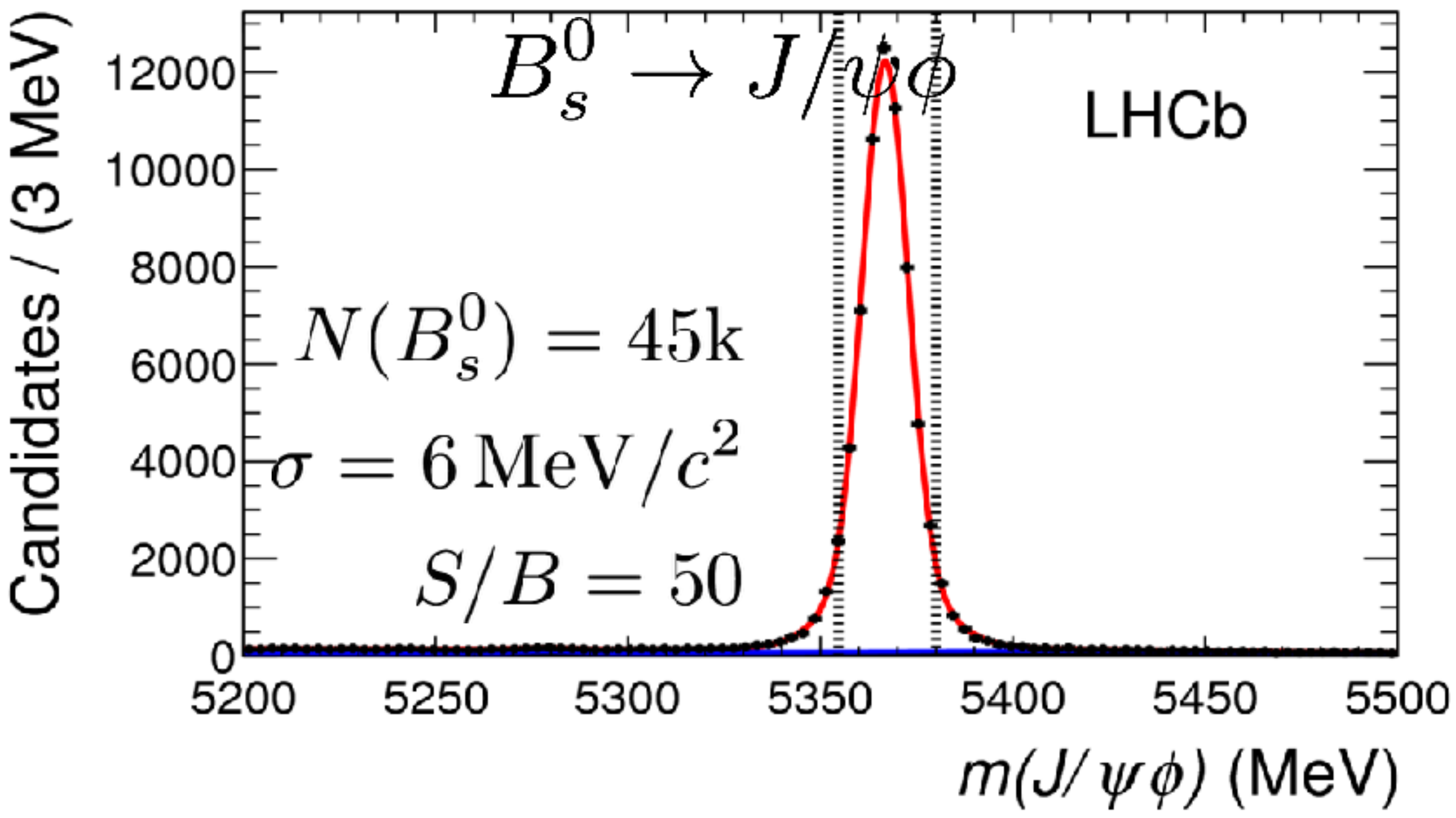
GlueX and CLAS12 photo-production for studies of hybrid mesons and Pc production

LHCb search for X(5568)$^{\pm}$

[PRL 117, 152003 (2016)]

Use 112 000 B_s mesons and combine with $\pi^{\pm}$ → sample 20x that of D0, and much less background.





Z(4430)± charged charmonium exotic

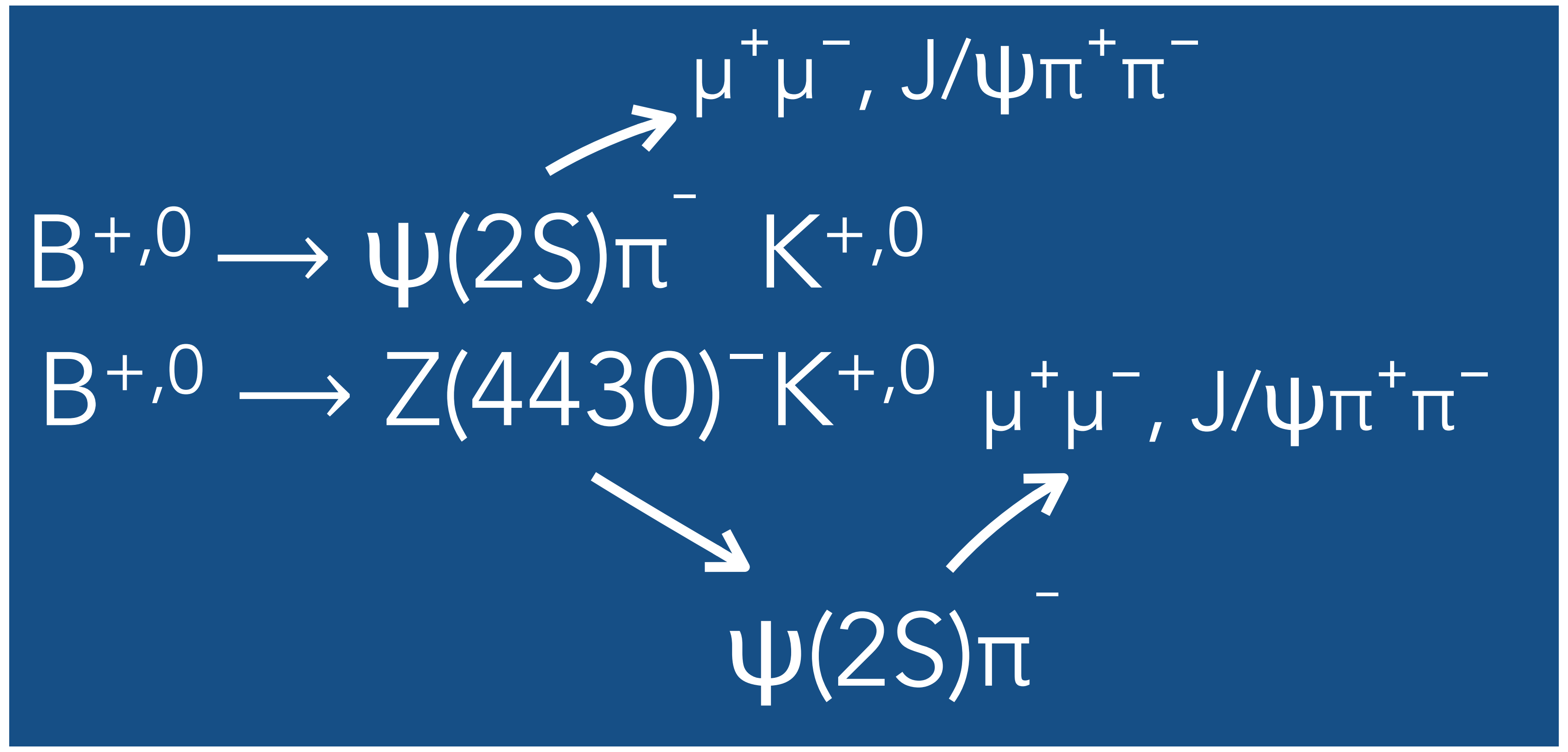
[Belle, PRL 100 (2008) 142001] 1D fit to m(ψ'π⁻) **6.5σ**

[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**

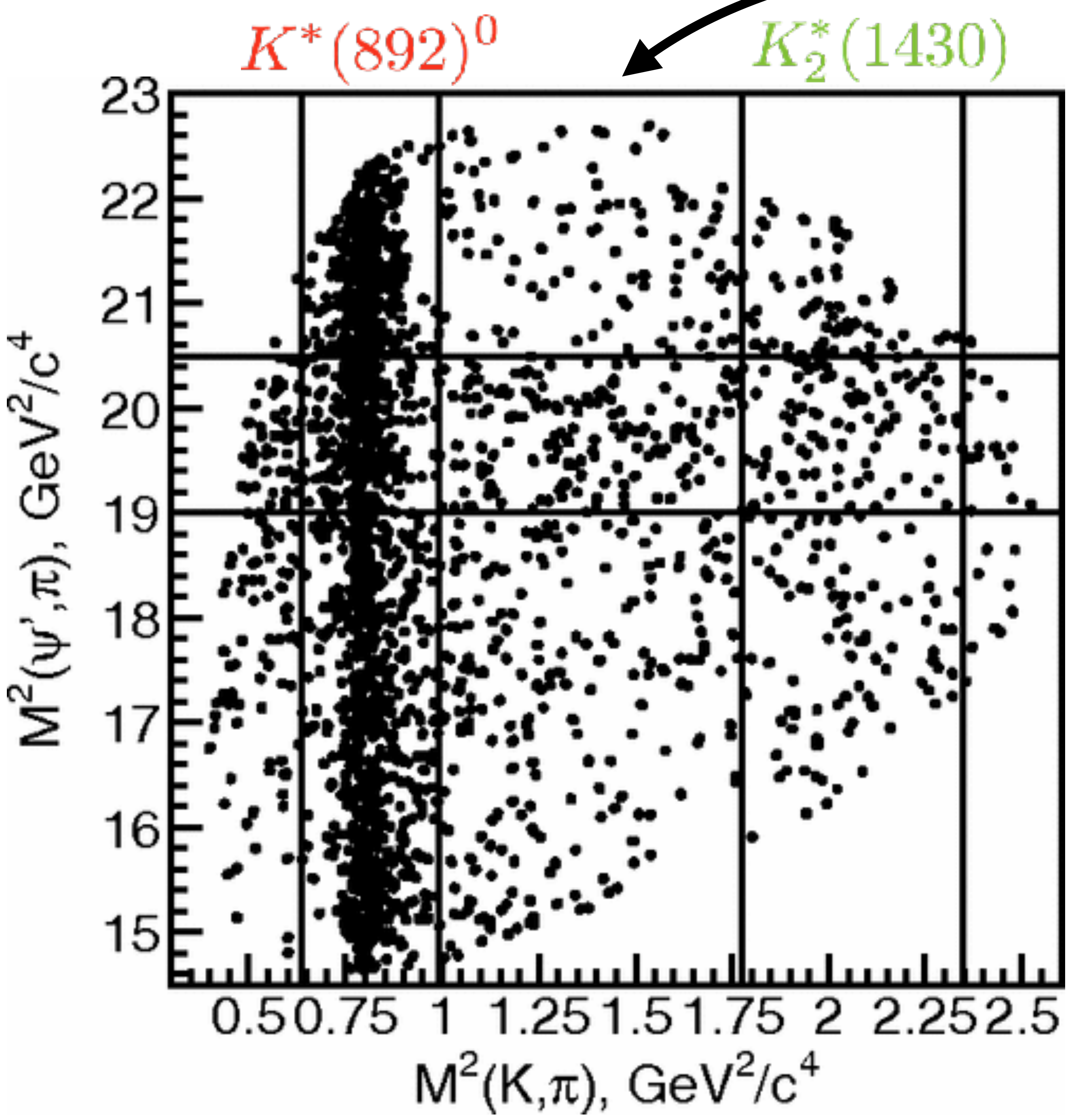
[Belle, PRD 88 (2013) 074026] 4D amplitude fit **6.4σ**

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

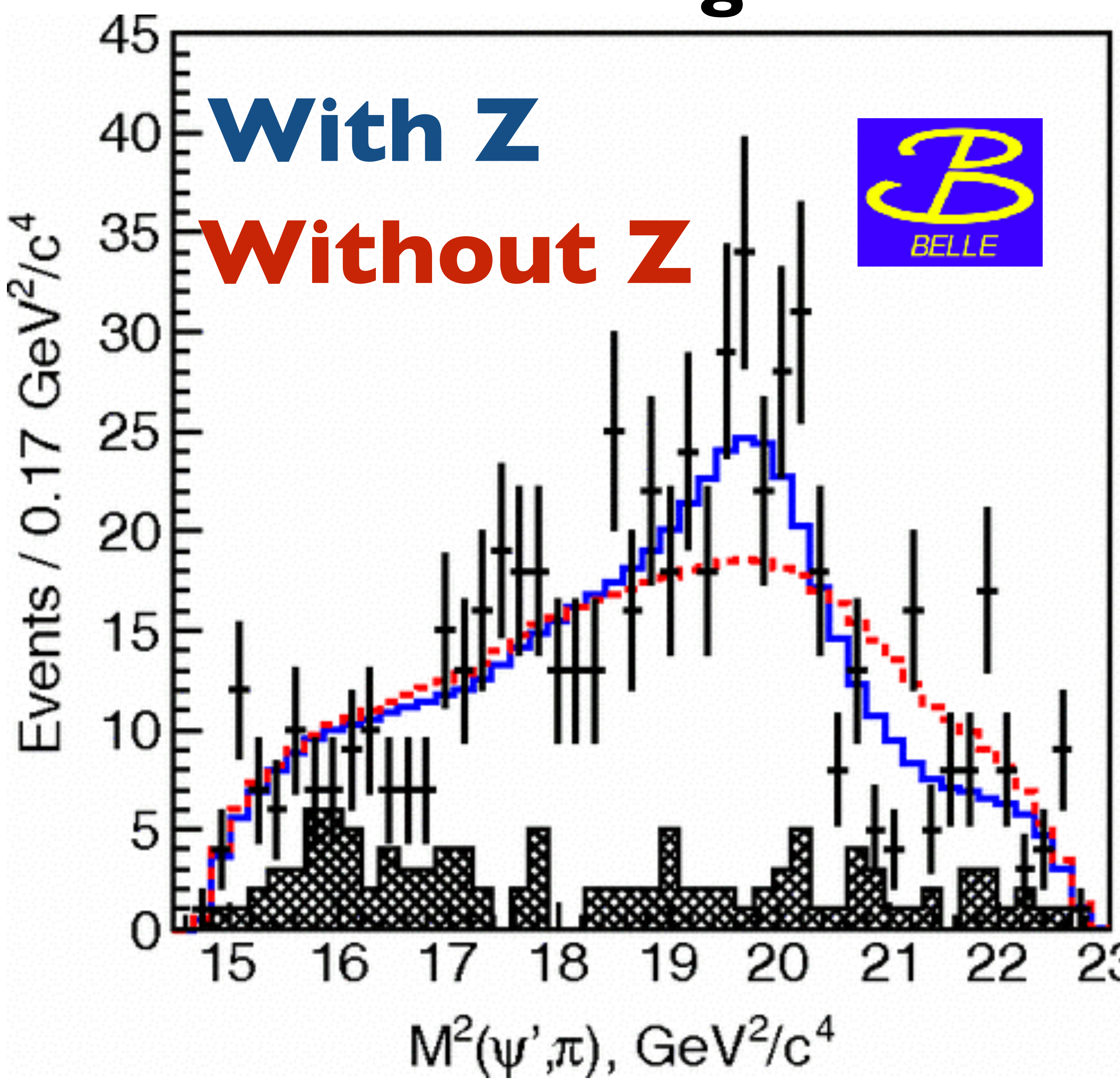


$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV/c^2}$$

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



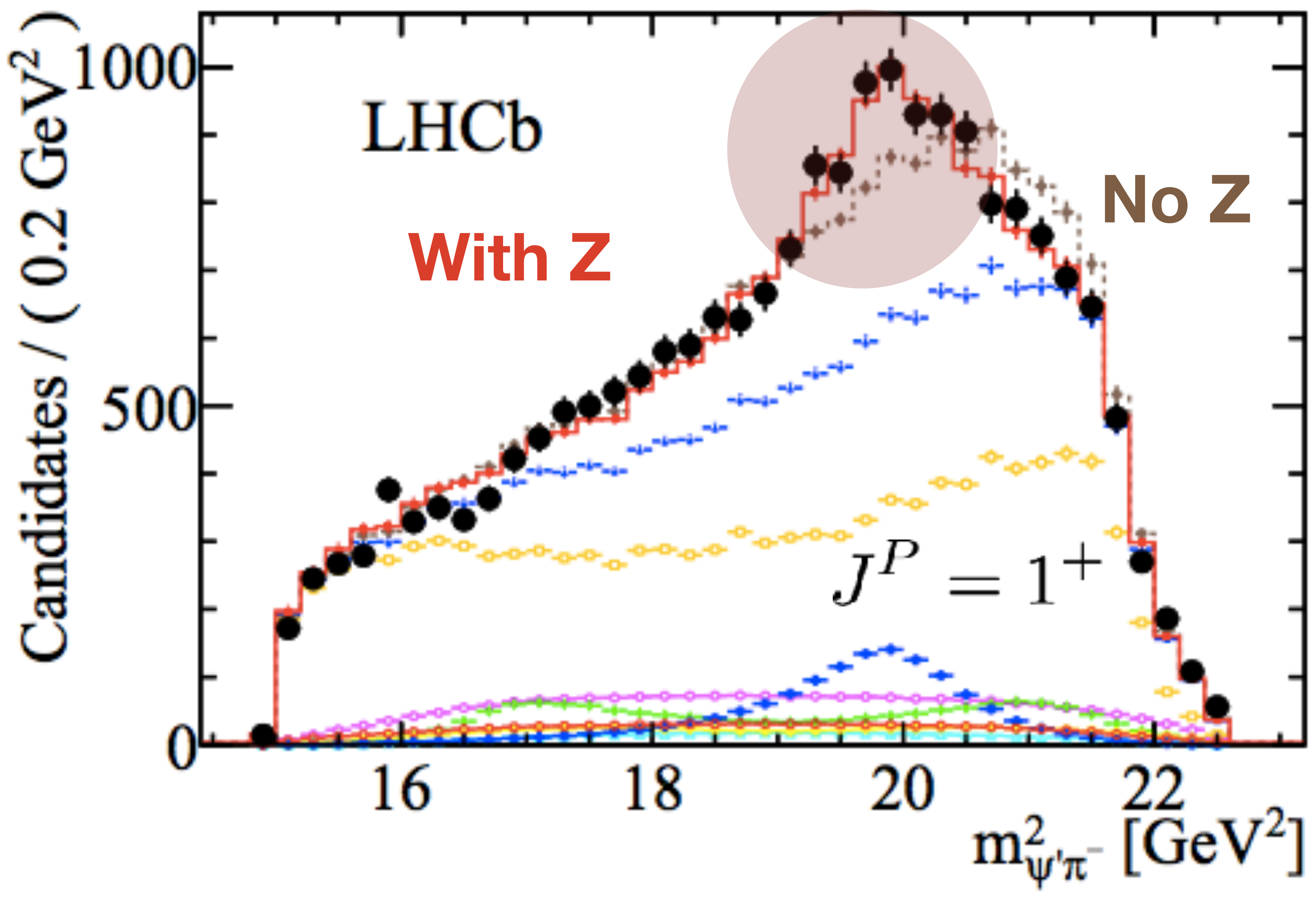
K* veto region

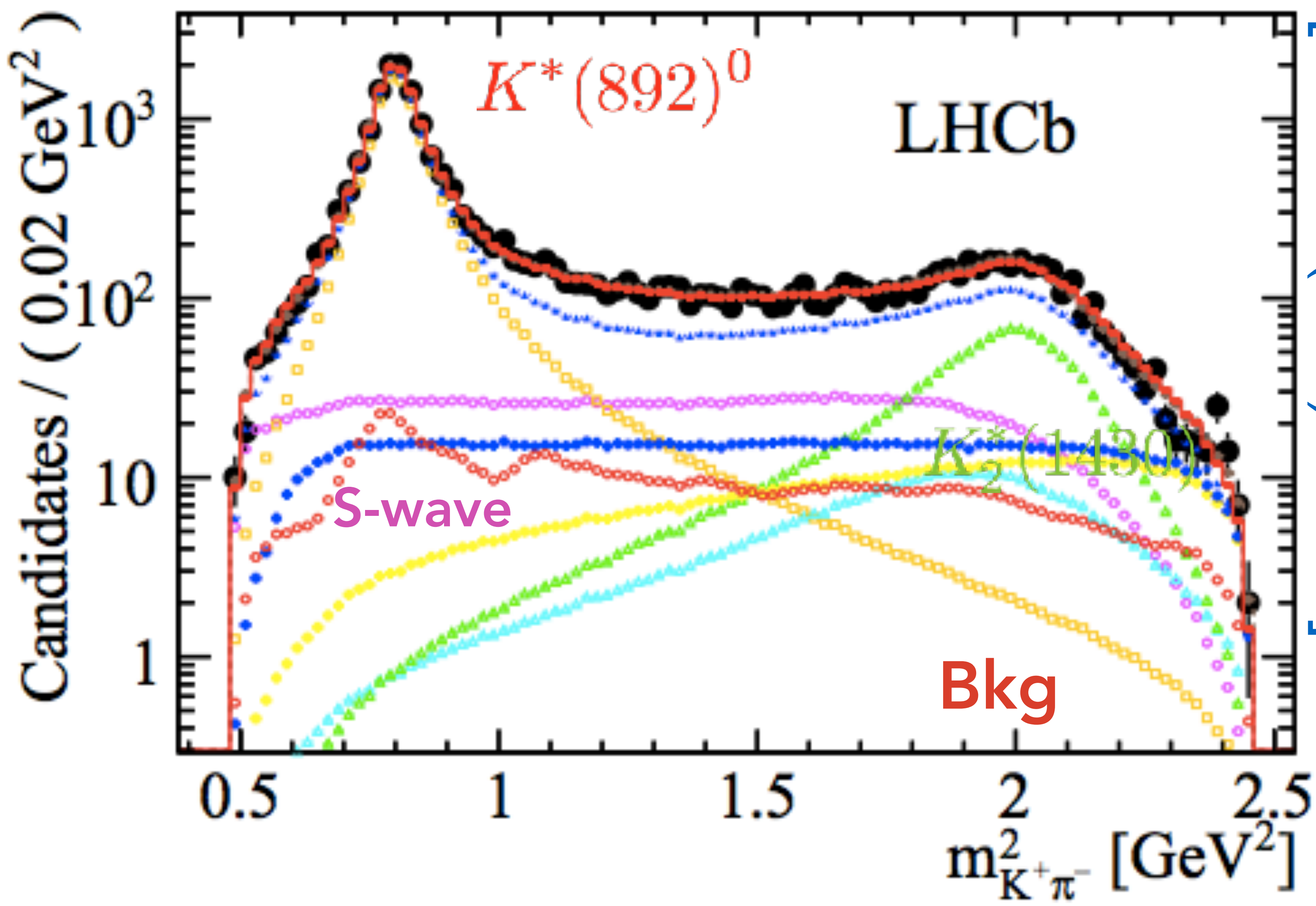


[PRD 88 (2013) 074026]

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

LHCb has >25k $B^0 \rightarrow \psi(2S)K^+\pi^-$ candidates (x10 Belle/BaBar) with 3% background

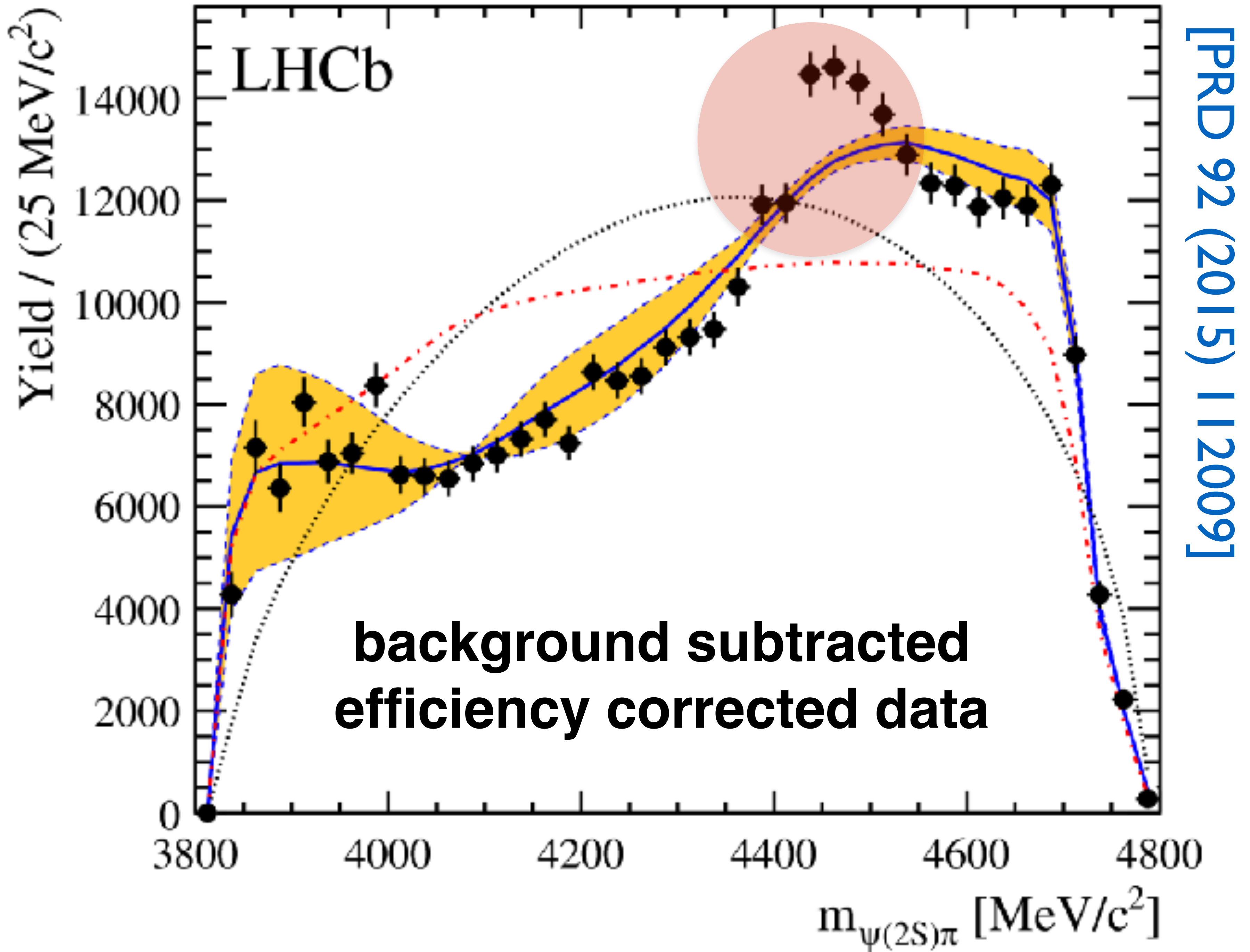




Two analysis methods:

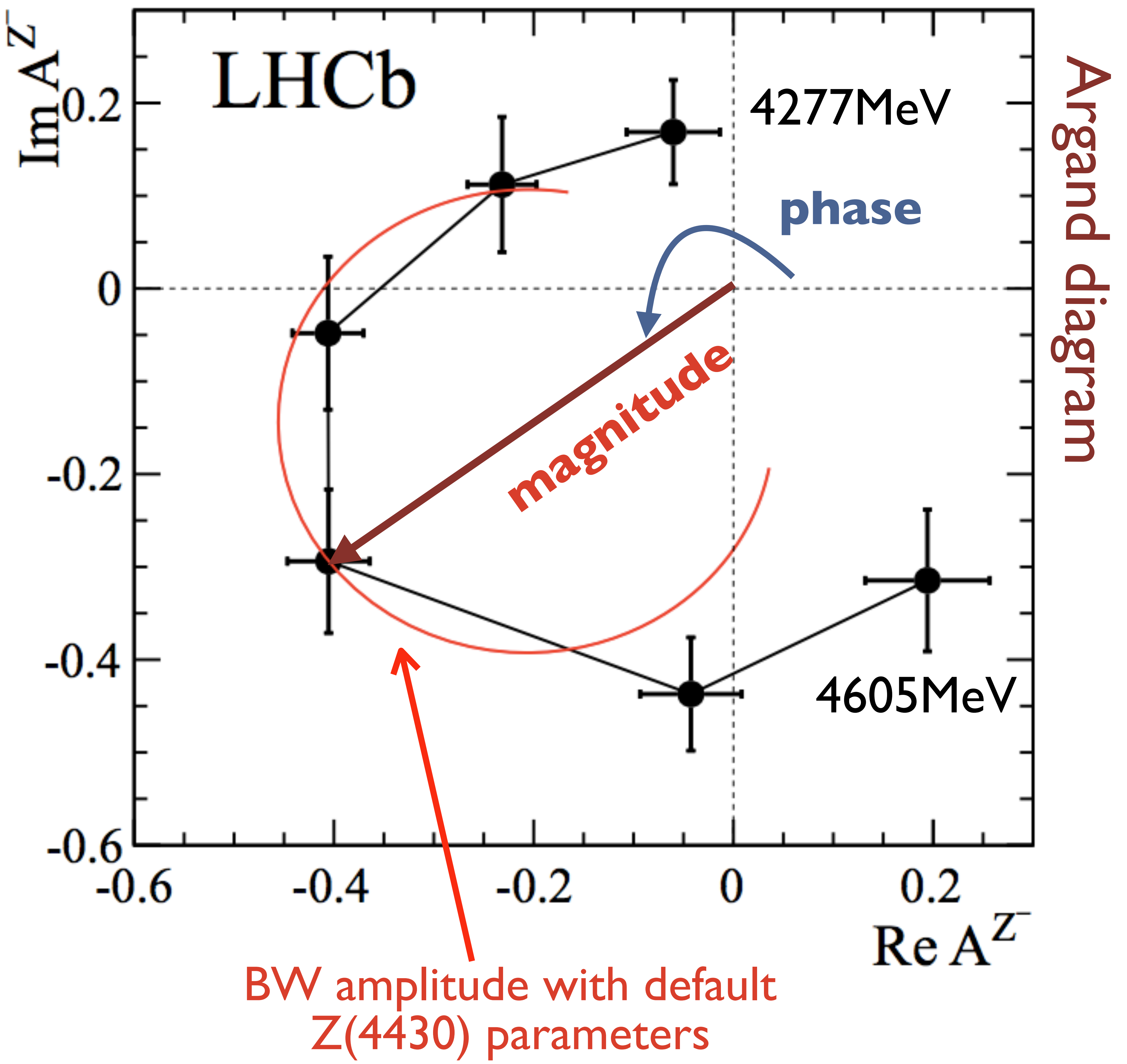
4D amplitude analysis used to measure resonance parameters and J^P.

Study angular moments in model-independent way (similar to what was done for pentaquark).



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)± → J/ψπ± and observation of a new resonant state Z(4200)± → J/ψπ± [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

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?

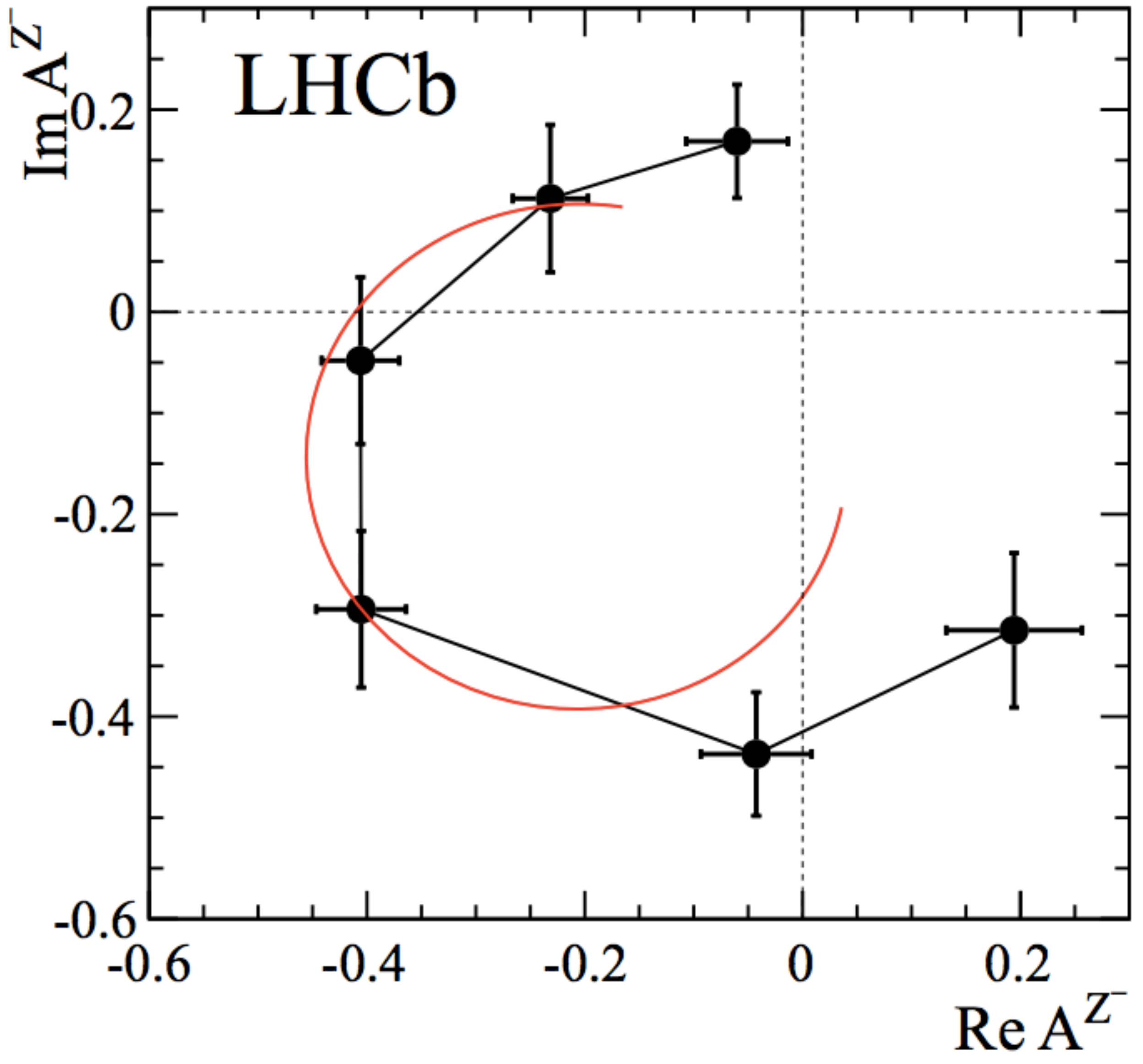
P=+ rules out interpretation in terms of **$\bar{D}$*(2010)D*$_1$(2420)** molecule or threshold effect (cusp).
[Rosner, PRD 76 (2007) 114002] [Bugg, J. Phys. G35 (2008) 075005]

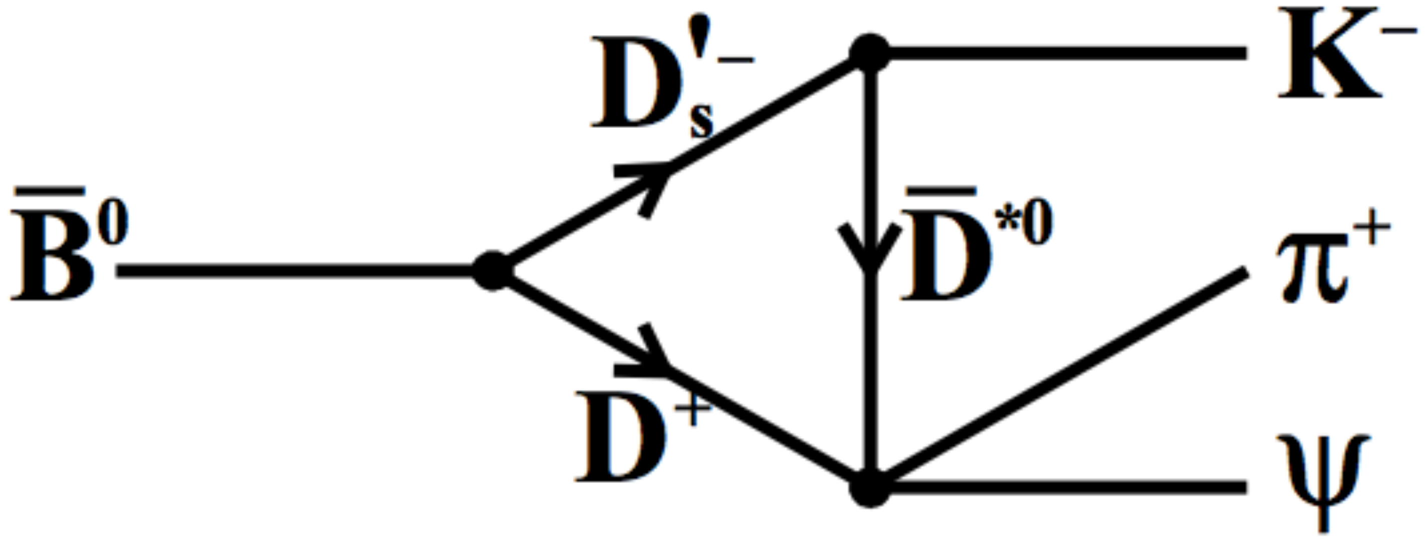
Rescattering effect proposed, but phase motion in wrong direction?
[Pakhov, Uglov PLB748 (2015) 183]

Diquark-antidiquark bound state is an explanation. [Maiani et al, PRD 89 114010]

Potential neutral **isospin partner?**

Z(4430)^0 in $B^+ \to \psi(2S)\pi^0K^+$





Building the log-likelihood

Use **Isobar** approach - matrix element from **coherent sum** of two-body resonances.

$$\frac{d\mathcal{P}}{dm_{\phi K}\, d\Omega} \equiv \mathcal{P}_{\rm sig}(m_{\phi K}, \Omega|\overrightarrow{\omega}) = \frac{1}{I(\overrightarrow{\omega})} |\mathcal{M}(m_{\phi K}, \Omega|\overrightarrow{\omega})|^2 \, \Phi(m_{\phi K})\epsilon(m_{\phi K}, \Omega)$$

Masses, widths, helicity couplings

Phase space = pq

Efficiency

Integral from sum over fully simulated phase space MC

$$I(\overrightarrow{\omega}) \equiv \int \mathcal{P}_{\rm sig}(m_{\phi K}, \Omega)\, dm_{\phi K}\, d\Omega \propto \frac{\Sigma_j w_j^{\rm MC} |\mathcal{M}(m_{Kp\ j}, \Omega_j|\overrightarrow{\omega})|^2}{\Sigma_j w_j^{\rm MC}}$$

MC correction weights

Background

$$-\ln L(\overrightarrow{\omega}) = -\Sigma_i \ln \left[|\mathcal{M}(m_{\phi K\ i}, \Omega_i|\overrightarrow{\omega})|^2 + \frac{\beta\, I(\overrightarrow{\omega})}{(1-\beta) I_{\rm bkg}} \frac{\mathcal{P}^u_{\rm bkg}(m_{\phi K\ i}, \Omega_i)}{\Phi(m_{\phi K\ i})\epsilon(m_{\phi K\ i}, \Omega_i)} \right] + N \ln I(\overrightarrow{\omega})$$

Matrix element for $K^{*+} \to \phi K^+$ contributions

Sum over K* resonances (usually BW)

Sum over J/ψ and φ helicitites

Helicity couplings

$$\mathcal{M}^{K^*}_{\Delta\lambda_\mu} \equiv \sum_j R_j(m_{\phi K}) \sum_{\lambda_{J/\psi}=-1,0,1} \sum_{\lambda_\phi=-1,0,1} A^{B\to J/\psi\, K^*\, j}_{\lambda_{J/\psi}} A^{K^*\to\phi K\, j}_{\lambda_\phi} \times$$

$$d^{J_{K^*}\, j}_{\lambda_{J/\psi},\lambda_\phi}(\theta_{K^*})\, d^1_{\lambda_\phi,0}(\theta_\phi)\, e^{i\lambda_\phi \Delta\phi_{K^*,\phi}}\, d^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\theta_{J/\psi})\, e^{i\lambda_{J/\psi}\Delta\phi_{K^*,J/\psi}}$$

Wigner d-matrices

$$|\mathcal{M}^{K^*}|^2 = \sum_{\Delta\lambda_\mu=\pm1} \left|\mathcal{M}^{K^*}_{\Delta\lambda_\mu}\right|^2$$

In-coherent sum over difference between muon helicitites

$$A_{\lambda_\phi} = P_{K^*}(-1)^{J_{K^*}+1} A_{-\lambda_\phi}$$

Parity conservation in strong decay of K* limits number of couplings

Now include the X → J/ψϕ components

$$\mathcal{M}^{X}_{\Delta\lambda_\mu} \equiv \sum_j R_j(m_{J/\psi\,\phi}) \sum_{\lambda_{J/\psi}=-1,0,1} \sum_{\lambda_\phi=-1,0,1} A^{X\to J/\psi\,\phi\,j}_{\lambda_{J/\psi},\lambda_\phi} \times$$
$$d^{J_X\,j}_{0,\lambda_{J/\psi}-\lambda_\phi}(\theta_X)\, d^1_{\lambda_\phi,0}(\theta^X_\phi)\, e^{i\lambda_\phi\Delta\phi_{X,\phi}}\, d^1_{\lambda_{J/\psi},\Delta\lambda_\mu}(\theta^X_{J/\psi})\, e^{i\lambda_{J/\psi}\Delta\phi_{X,J/\psi}}$$

$J^P{}_X$	Num independent X helicity couplings
0^-	1
0^+	2
1^+	3
1^-, 2^-	4
2^+	5

from parity conservation

Angle to align coordinate axes in the X and K* decay chains

$$|\mathcal{M}^{K^*+X}|^2 = \sum_{\Delta\lambda_\mu=\pm1} \left| \mathcal{M}^{K^*}_{\Delta\lambda_\mu} + e^{i\alpha^X\Delta\lambda_\mu}\mathcal{M}^{X}_{\Delta\lambda_\mu} \right|^2$$

Similar matrix element for the $Z^+ \to J/\psi K^+$ decay chain

Mass dependence

Sum of overlapping Breit-Wigners and mass-independent non-resonant components

$$R(m|M_0,\Gamma_0) = B'_{L_B}(p,p_0,d)\left(\frac{p}{p_0}\right)^{L_B} BW(m|M_0,\Gamma_0)\, B'_{L_A}(q,q_0,d)\left(\frac{q}{q_0}\right)^{L_A}$$

orbital momentum of *B* meson

Blatt-Weisskopf barrier factors

orbital momentum of resonance *A*

$$BW(m|M_0,\Gamma_0) = \frac{1}{M_0^2 - m^2 - iM_0\Gamma(m)}$$

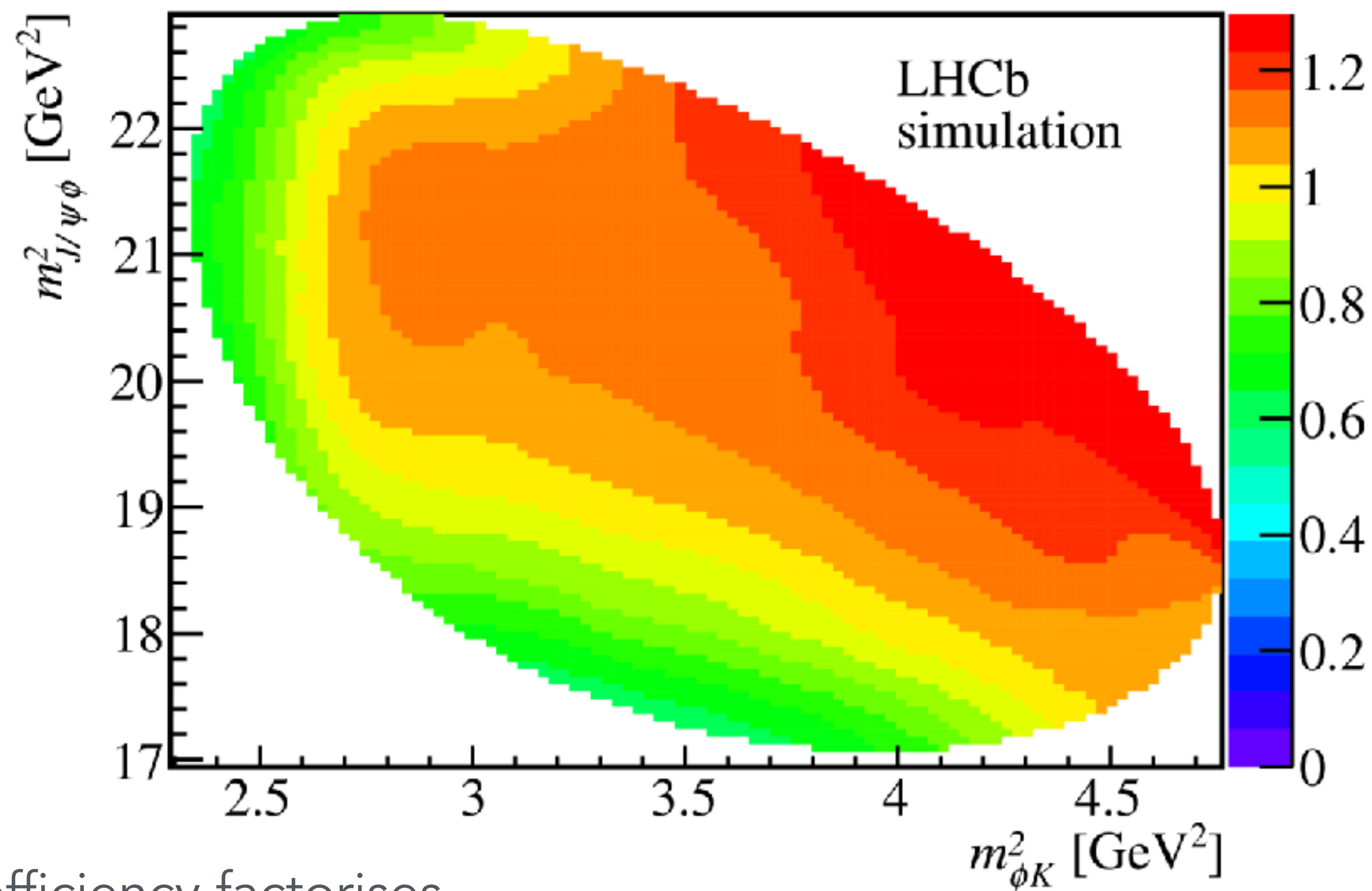
$$\Gamma(m) = \Gamma_0\left(\frac{q}{q_0}\right)^{2L_A+1}\frac{M_0}{m}B'_{L_A}(q,q_0,d)^2$$

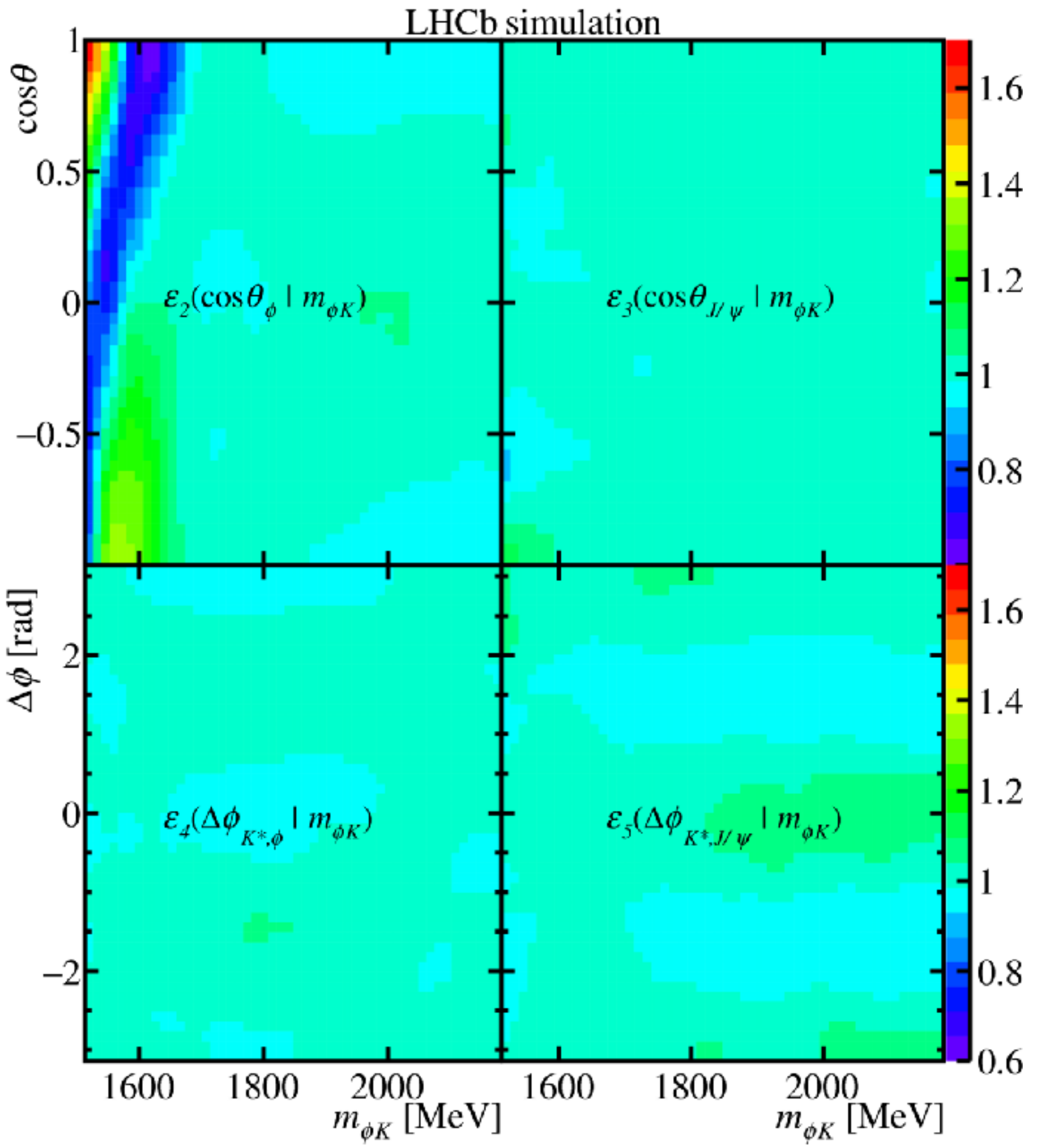
Use minimum allowed value of L_B and L_A

Systematic uncertainty to allow larger values

Efficiency

$$\epsilon(m_{\phi K},\Omega) = \epsilon_1(m_{\phi K},\cos\theta_{K^*})\cdot\epsilon_2(\cos\theta_\phi|m_{\phi K})\cdot\epsilon_3(\cos\theta_{J/\psi}|m_{\phi K})\cdot\epsilon_4(\Delta\phi_{K^*,\phi}|m_{\phi K})\cdot\epsilon_5(\Delta\phi_{K^*,J/\psi}|m_{\phi K})$$





Assume efficiency factorises.

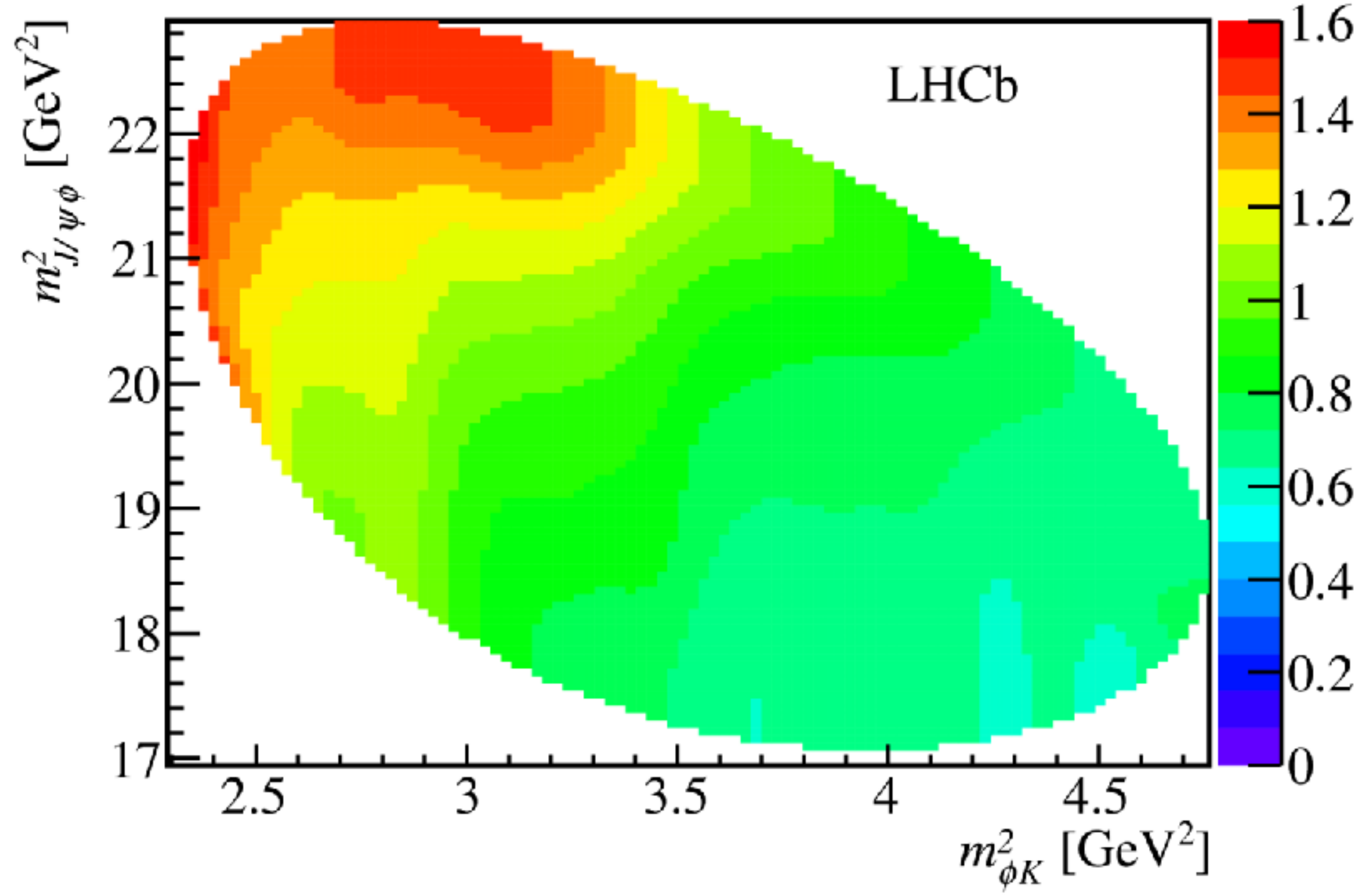
Fully simulated signal decay used to get parameterisation (bi-cubic interpolation between bin centres).

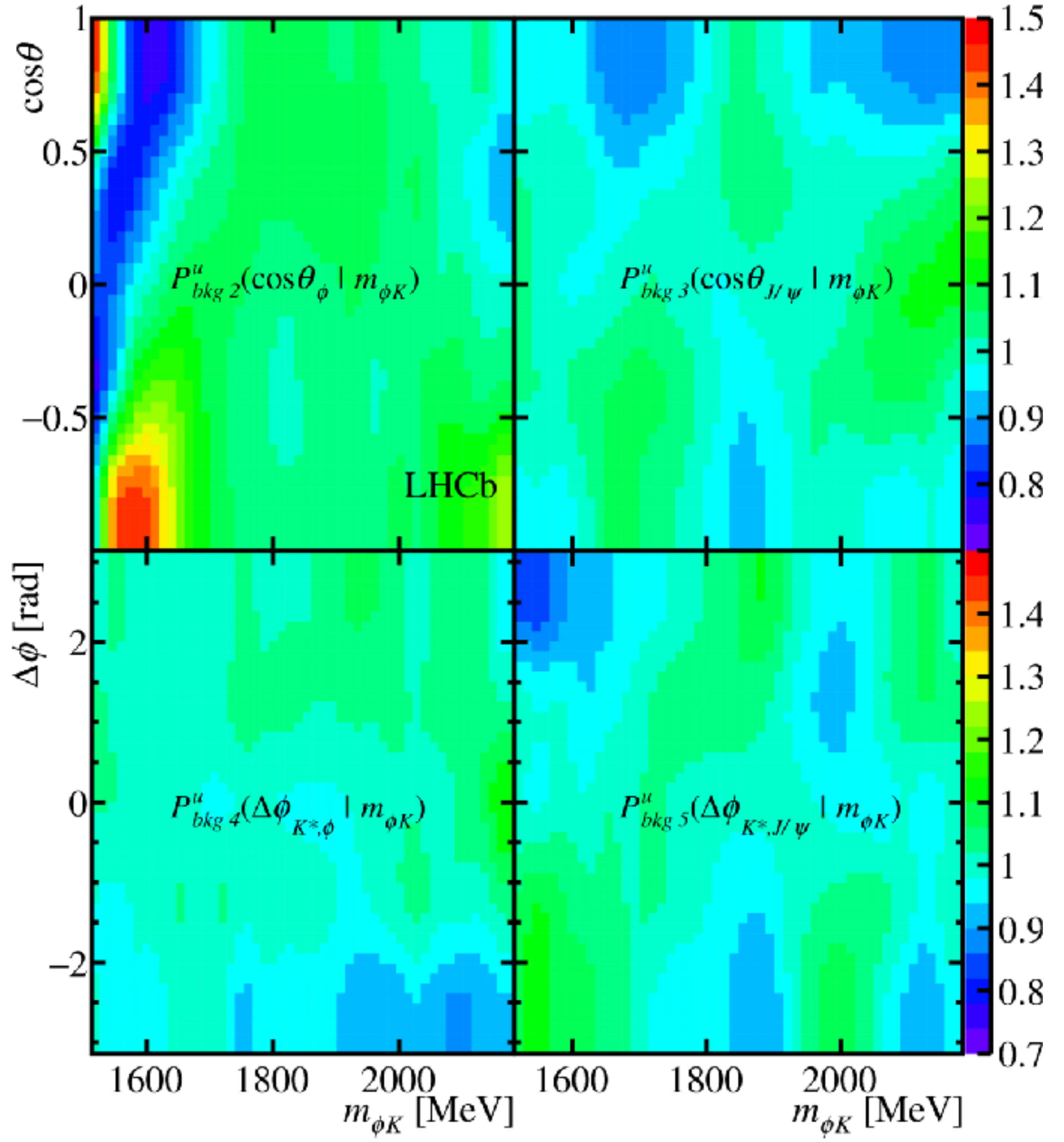
Simulation is weighted to match *p(K)*, *pT(B)* and nTracks distributions in dat

Band in ε_2 from veto on double $\varphi \to K^+K^-$.

Background

$$\frac{\mathcal{P}^u_{\rm bkg}(m_{\phi K},\Omega)}{\Phi(m_{\phi K})} = P_{\rm bkg_1}(m_{\phi K},\cos\theta_{K^*})\cdot P_{\rm bkg_2}(\cos\theta_\phi|m_{\phi K})\cdot P_{\rm bkg_3}(\cos\theta_{J/\psi}|m_{\phi K})\cdot P_{\rm bkg_4}(\Delta\phi_{K^*,\phi}|m_{\phi K})\cdot P_{\rm bkg_5}(\Delta\phi_{K^*,J/\psi}|m_{\phi K}).$$





Same factorisation method as for efficiency.
Use sidebands of the B mass to get distribution.

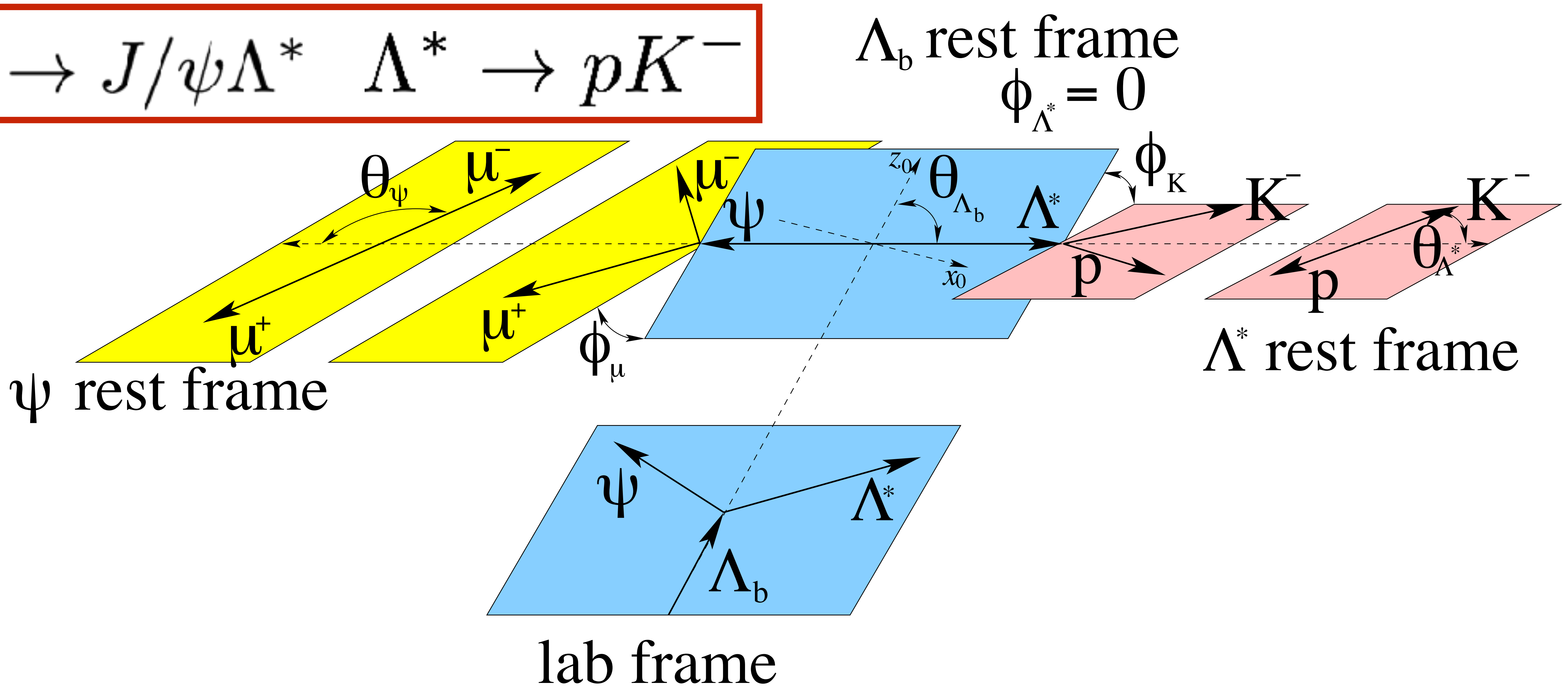
Amplitude model

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

[PRL 115 (2015) 072001]

Amplitude model

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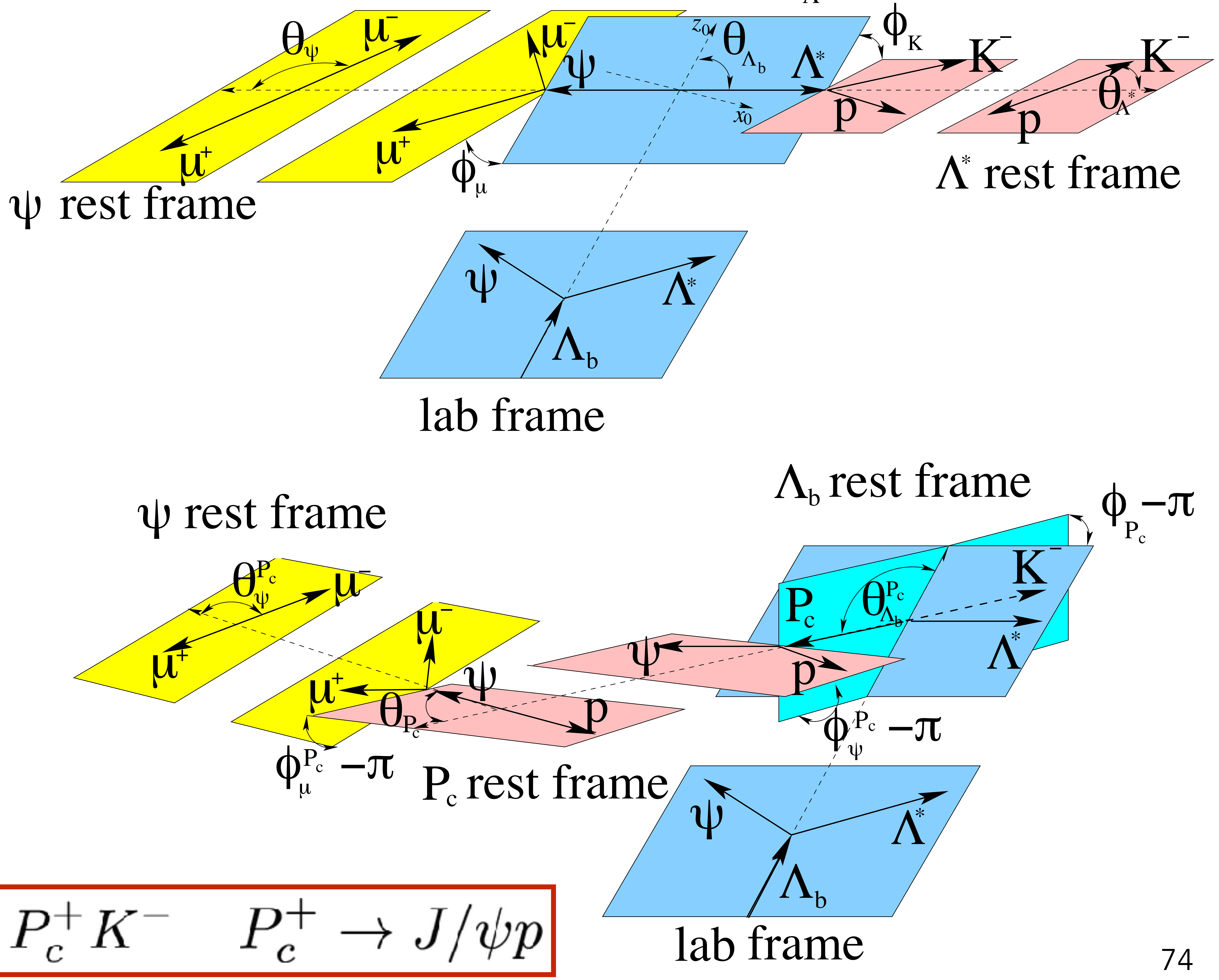
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0
$\Lambda(1600)$	$1/2^+$	1600	150
$\Lambda(1670)$	$1/2^-$	1670	35
$\Lambda(1690)$	$3/2^-$	1690	60
$\Lambda(1800)$	$1/2^-$	1800	300
$\Lambda(1810)$	$1/2^+$	1810	150
$\Lambda(1820)$	$5/2^+$	1820	80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

[PRL 115 (2015) 072001]

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



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

Amplitude model

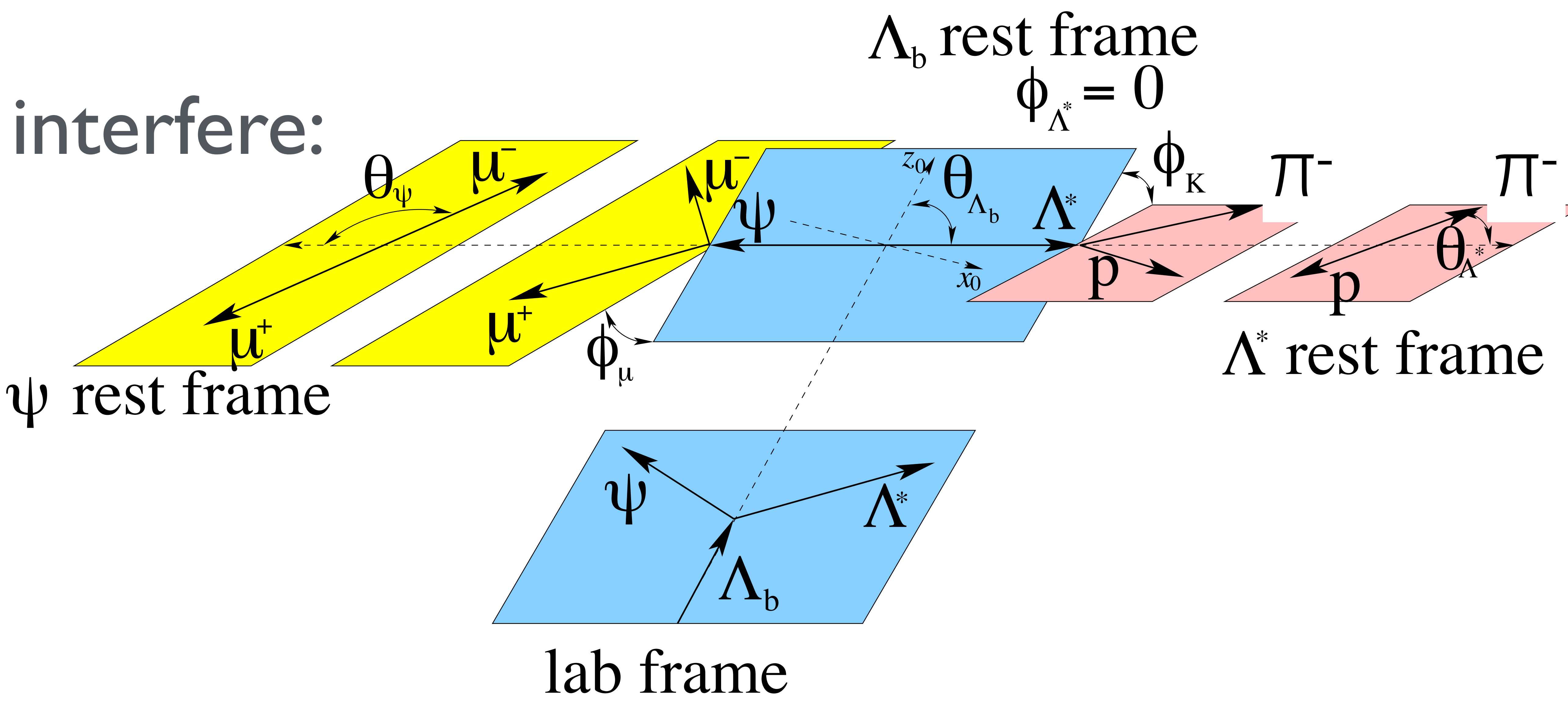
[LHCb-PAPER-2016-015]

Consider three decay chains that mutually interfere:

$\Lambda_b{}^0 \to J/\psi N^*, N^* \to p\pi^-$

$\Lambda_b{}^0 \to P_c{}^+\pi^-, P_c{}^+ \to J/\psi p$

$\Lambda_b{}^0 \to Z_c{}^-p, Z_c{}^- \to J/\psi\pi^-$



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

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

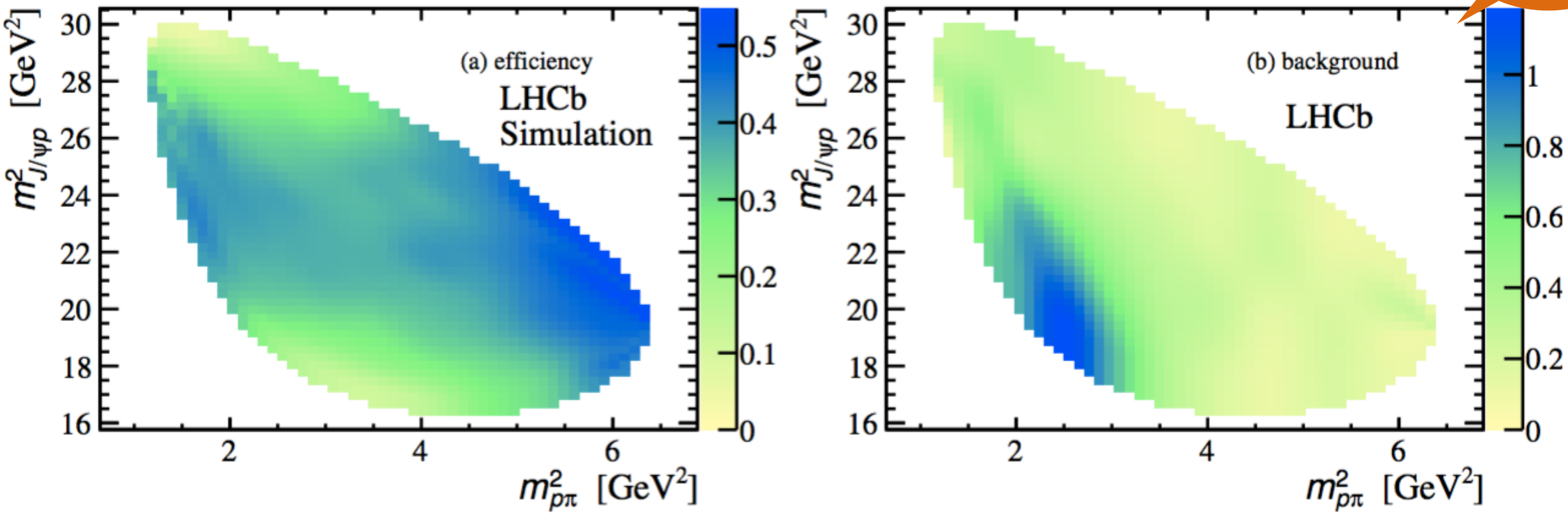
Additional angles to align muon and proton helicity frames between each decay chain

$$|\mathcal{M}|^2 = \sum_{\lambda_{\Lambda_b^0}=\pm\frac{1}{2}} \sum_{\lambda_p=\pm\frac{1}{2}} \sum_{\Delta\lambda_\mu=\pm1} \left| \mathcal{M}^{N^*}_{\lambda_{\Lambda_b^0},\lambda_p,\Delta\lambda_\mu} + e^{i\,\Delta\lambda_\mu \alpha_\mu} \sum_{\lambda_p^{P_c}} d^{\frac{1}{2}}_{\lambda_p^{P_c},\lambda_p}(\theta_p)\, \mathcal{M}^{P_c}_{\lambda_{\Lambda_b^0},\lambda_p^{P_c},\Delta\lambda_\mu} \right.$$

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

Amplitude model [LHCb-PAPER-2016-015]

NEW!



for 6D efficiency automatically).

Amplitude model [LHCb-PAPER-2016-015]

NEW!

Limited statistics, so aim is to check that the c
found in $\Lambda_b \to J/\psi pK$

Parameters of P_c states fixed to those from Λ_b

Different combinations of N* resonances cons
uncertainties.

$Z_c(4430)$ is checked as systematic uncertainty

Default fit: $3/2^-$ $P_c(4380)$, $5/2^+$ $P_c(4450)$, 1^+ $Z_c($

Well-established N* states

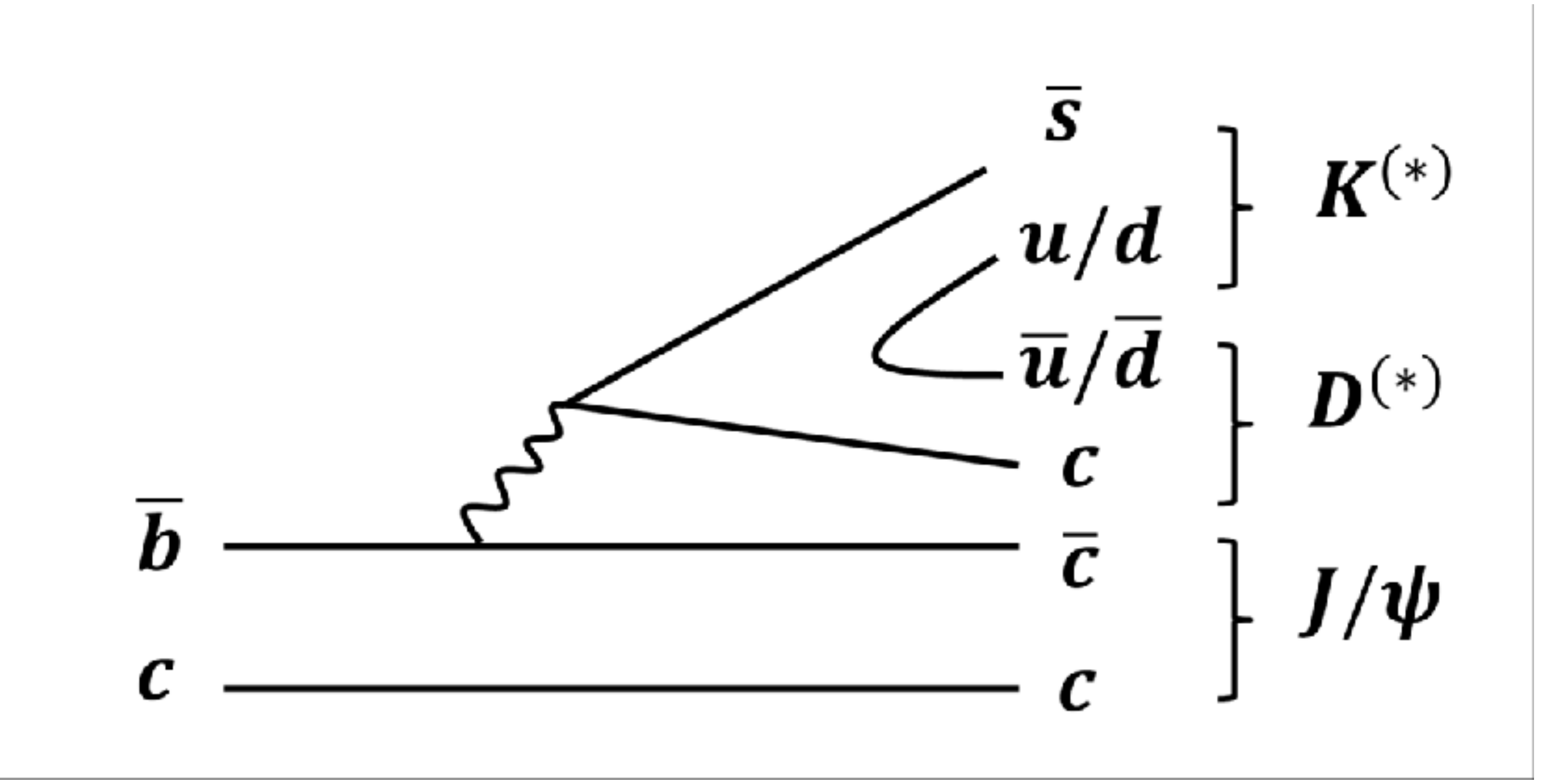
State	J^P	M_0 (MeV)	Γ_0 (MeV)	RM	EM
NR $p\pi$	$1/2^-$	-	-	4	4
$N(1440)$	$1/2^+$	1430	350	3	4
$N(1520)$	$3/2^-$	1515	115	3	3
$N(1535)$	$1/2^-$	1535	150	4	4
$N(1650)$	$1/2^-$	1655	140	1	4
$N(1675)$	$5/2^-$	1675	150	3	5
$N(1680)$	$5/2^+$	1685	130	-	3
$N(1700)$	$3/2^-$	1700	150	-	3
$N(1710)$	$1/2^+$	1710	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

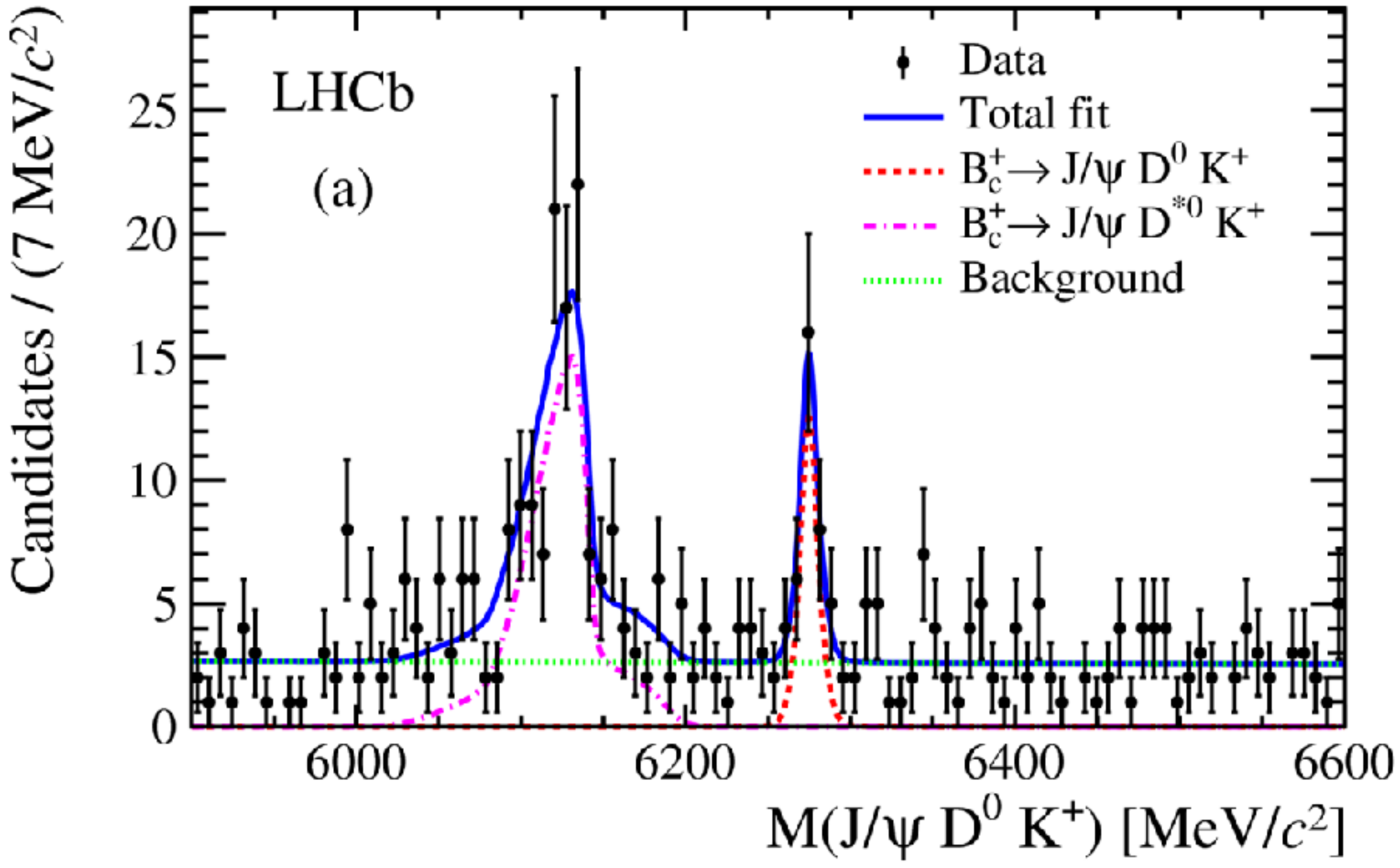
- Z(3900) most probably a threshold cusp []
- Z(3900) been looked for on the lattice, but not found [Prevlosek]
- Candidates for the X(3872) has been seen by multiple groups on the lattice
- Exploratory studies of Z(4430) and Z(4025) (D1barD*)+- threshold but no conclusions yet. Positive parity of Z(4430) means that it can’t be D1barD* threshold

Observation of $B^+_c \to J/\psi D^{(*)} K^{(*)}$ decays

[Phys. Rev. D 95, 032005 (2017)]

part-redo signal due to missing Γ or π0 from D* decays



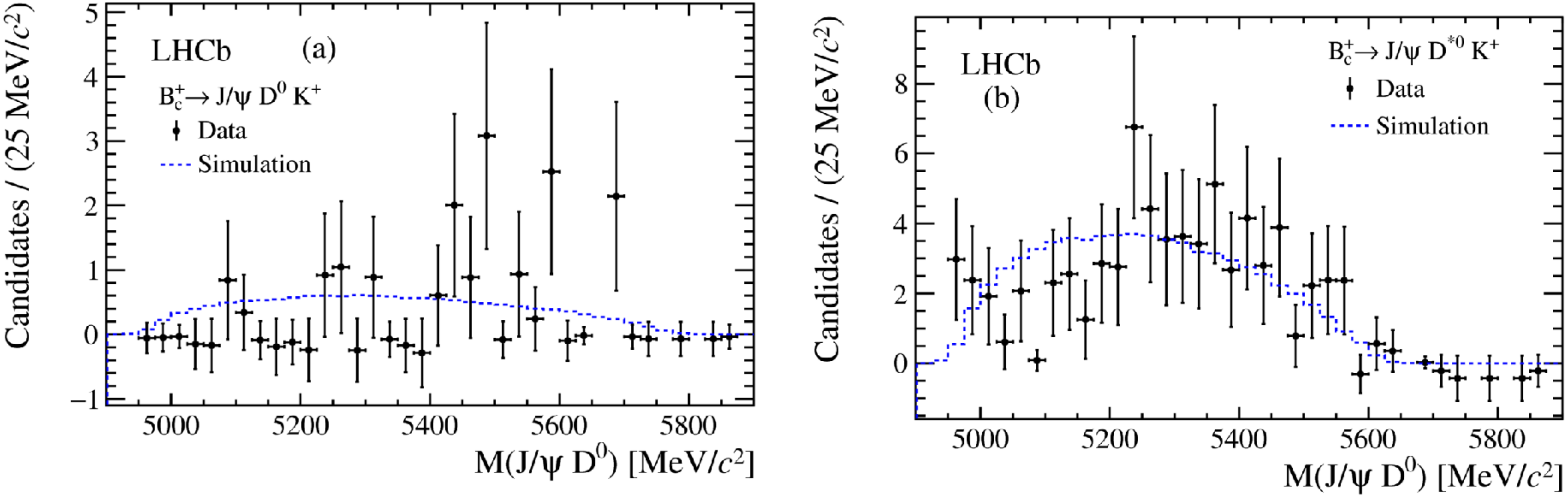


Make most precise B_c^+ mass measurement due to small Q-value in decay

6274.28 ± 1.40 ± 0.32 MeV

Observation of $B^+_c \to J/\psi D^{(*)} K^{(*)}$ decays

[Phys. Rev. D 95, 032005 (2017)]



Good candidates for exotics. Need more statistics.

Also useful for studying excited D_{sJ} meson spectroscopy.

X(3872) quantum numbers

[PRD 92 (2015) 011102]

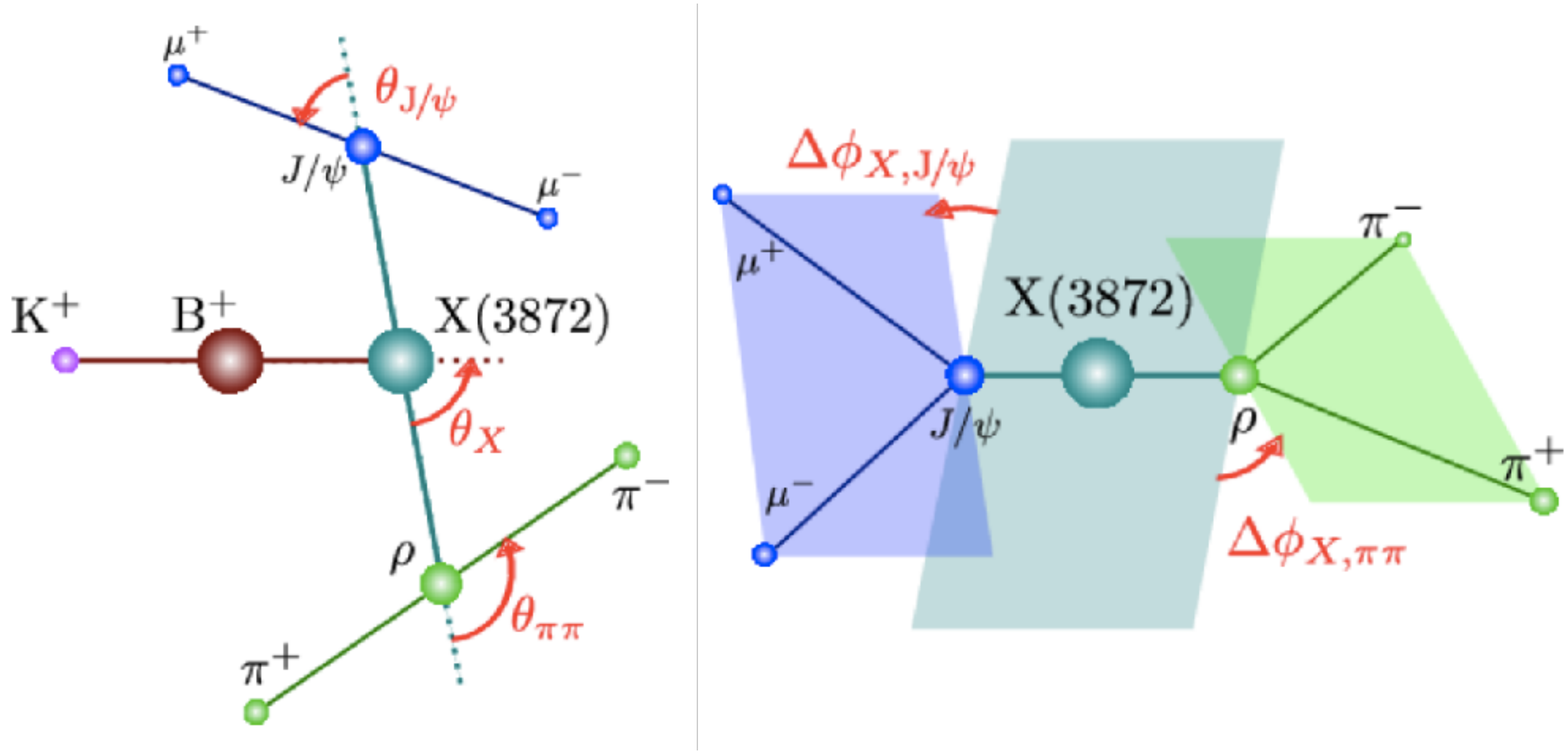
C = +1 since $X(3872) \to J/\psi\gamma$ $B^+ \to X(3872)K^+, X(3872) \to J/\psi\pi^+\pi^-$

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



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

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

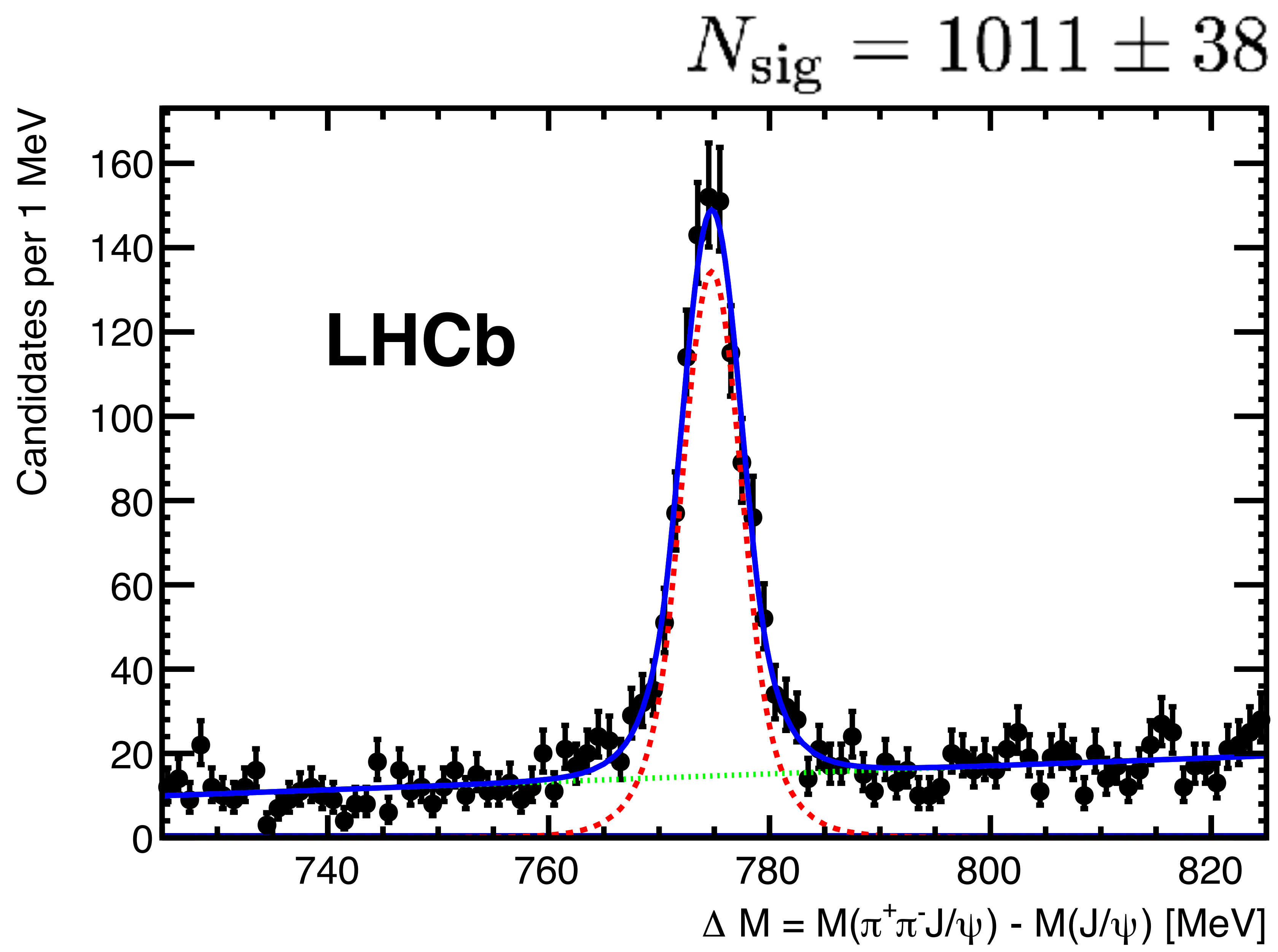
X(3872) quantum numbers

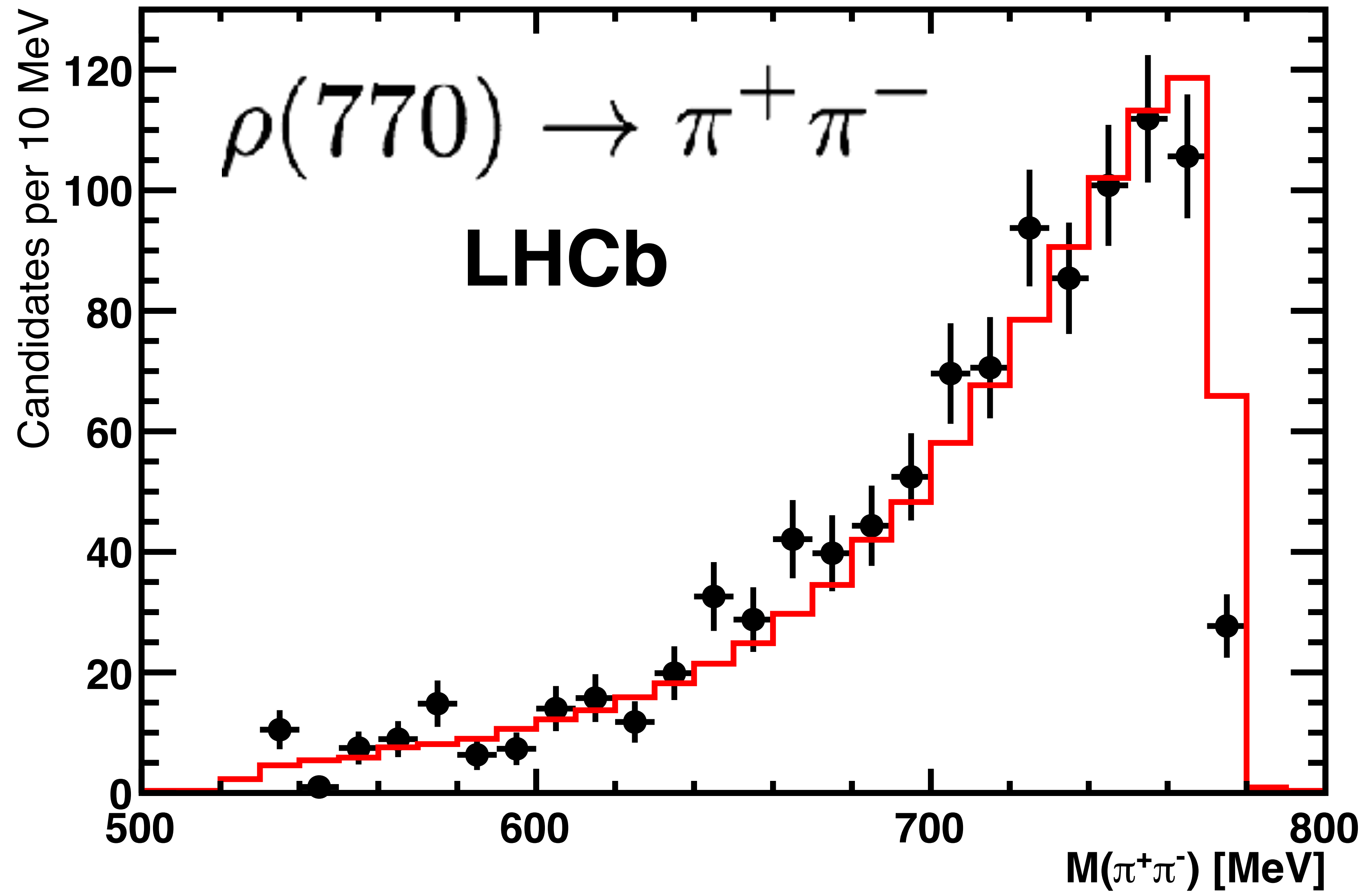
$J^{PC} = 1^{++}$ confirmed!

3x larger sample than previous result

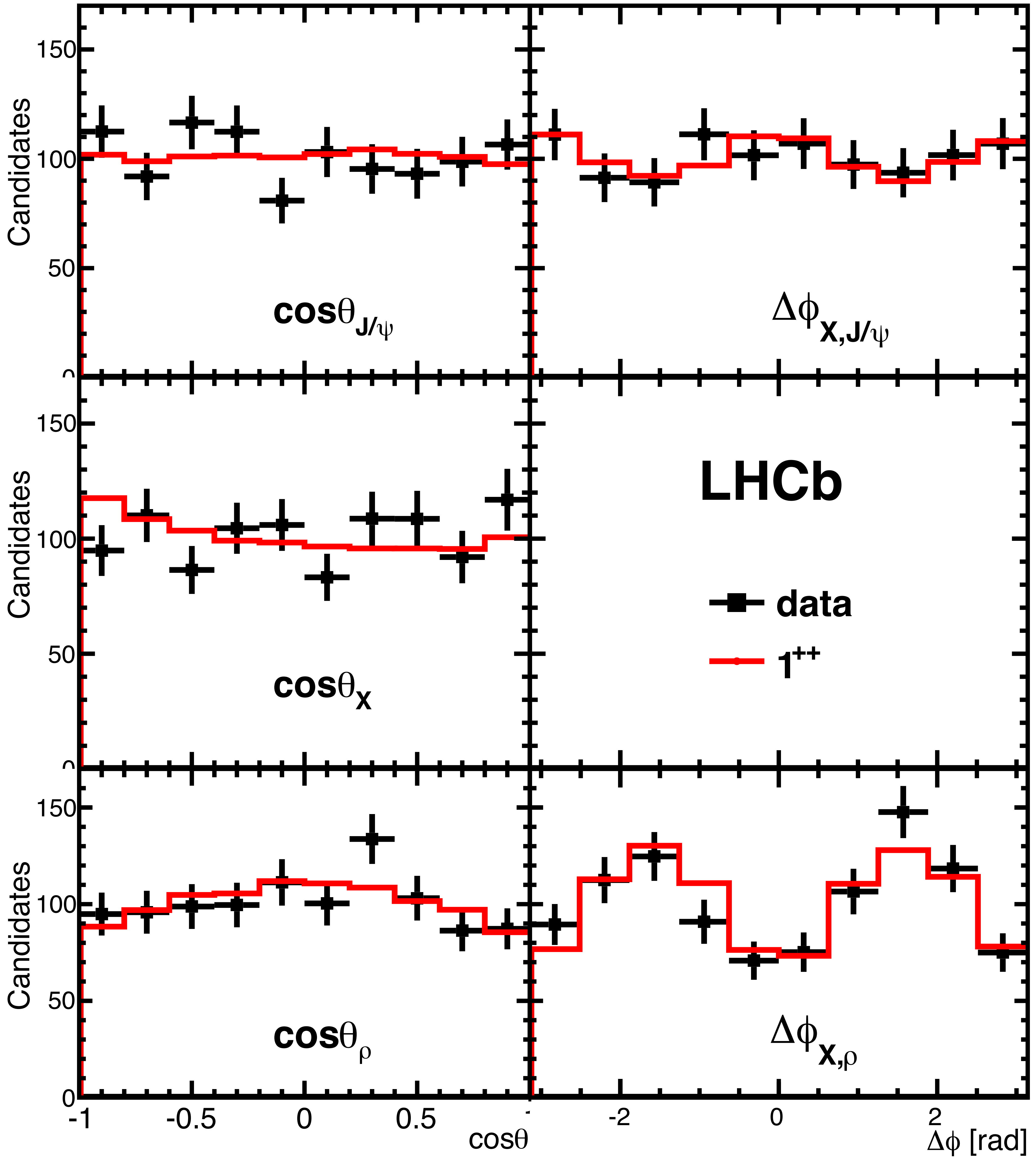
D-wave < 4% @ 95% CL

ρ(770) dominates → decay violates isospin so unlikely to be conventional $c\bar{c}$





[PRD 92 (2015) 011102]



$Z_c(3900)^{\pm}$ amplitude analysis

Original 1D fits from BES
3899.0 +- 3.6 +- 4.9 MeV
46 +- 10 +- 20 MeV

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

1+ state preferred. [PRL 119, 072001 (2017)]

Large systematic from knowledge about σ and f0(980) and f0(1370) lineshapes

$M_{pole} = (3881.2 \pm 4.2 \text{ stat} \pm 52.7 \text{ syst})$ MeV/c^2, $\Gamma_{pole} = (51.8 \pm 4.6 \text{ stat} \pm 36.0 \text{ syst})$ MeV

$M_{pole} = (3883.9 \pm 1.5 \text{ stat} \pm 4.2 \text{ syst})$ MeV/c^2, $\Gamma_{pole} = (24.8 \pm 3.3 \text{ stat} \pm 11.0 \text{ syst})$ MeV

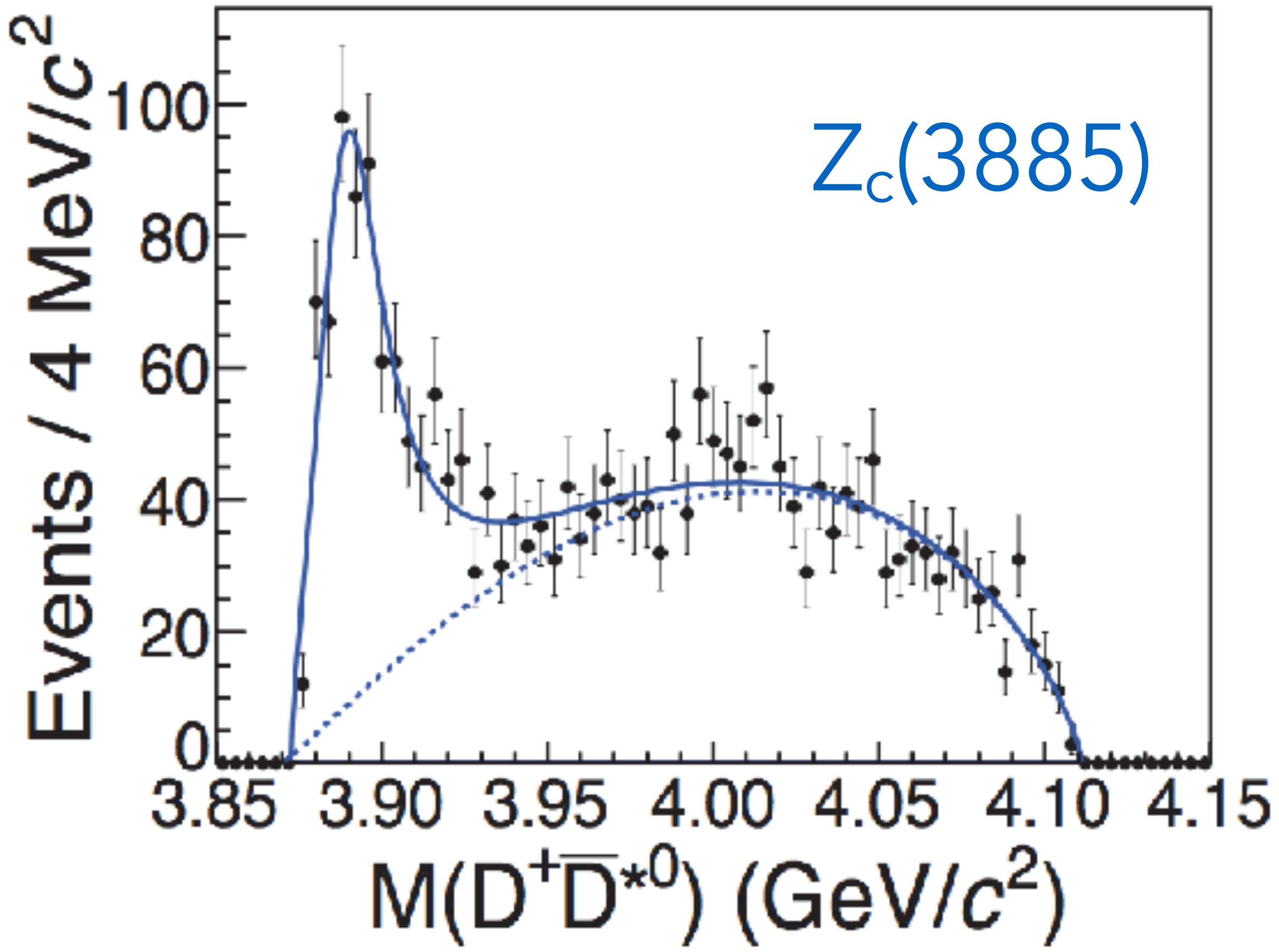
Does $D^{*-}D^0$ analysis use full amplitude fit?

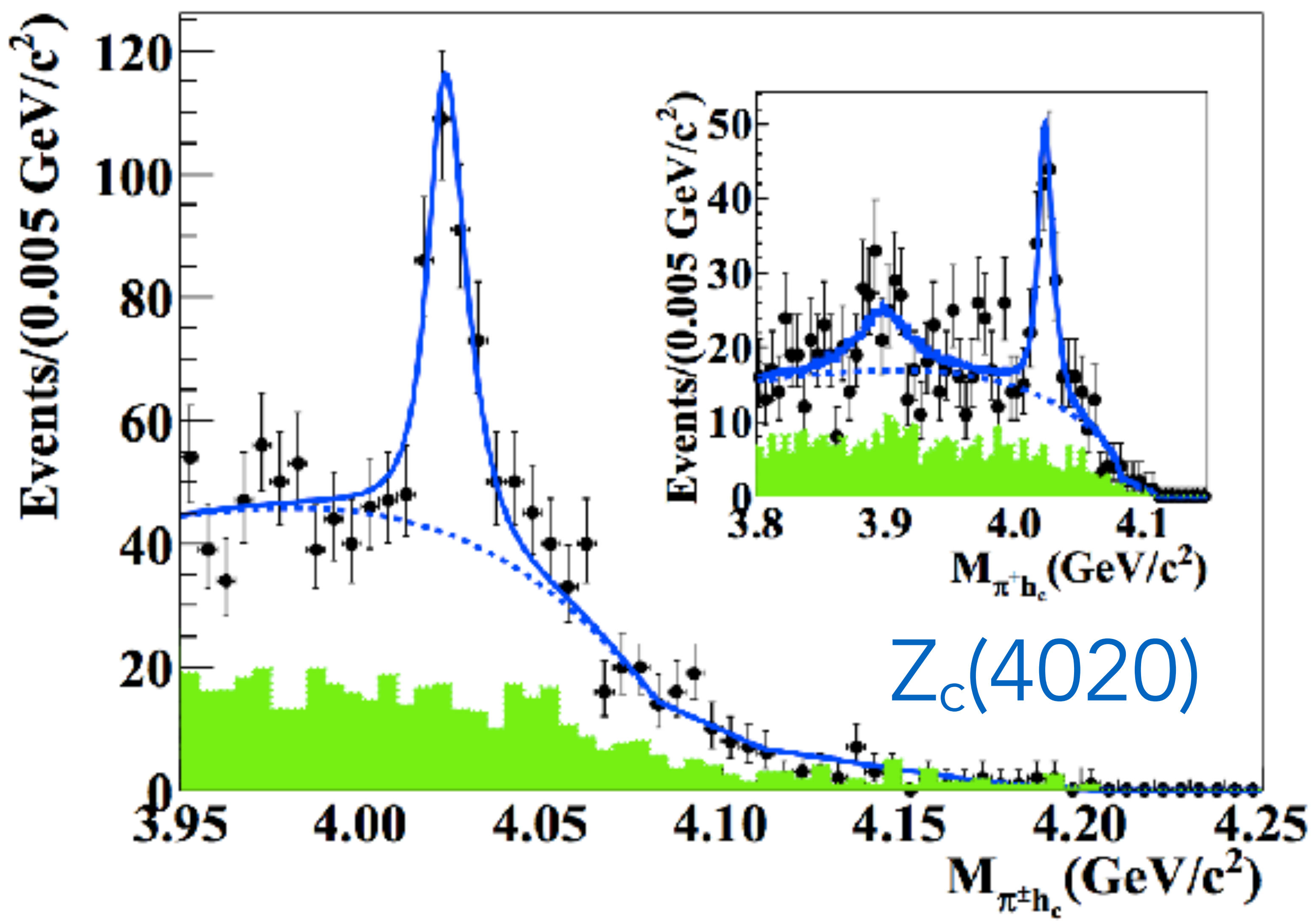
Other exotic states

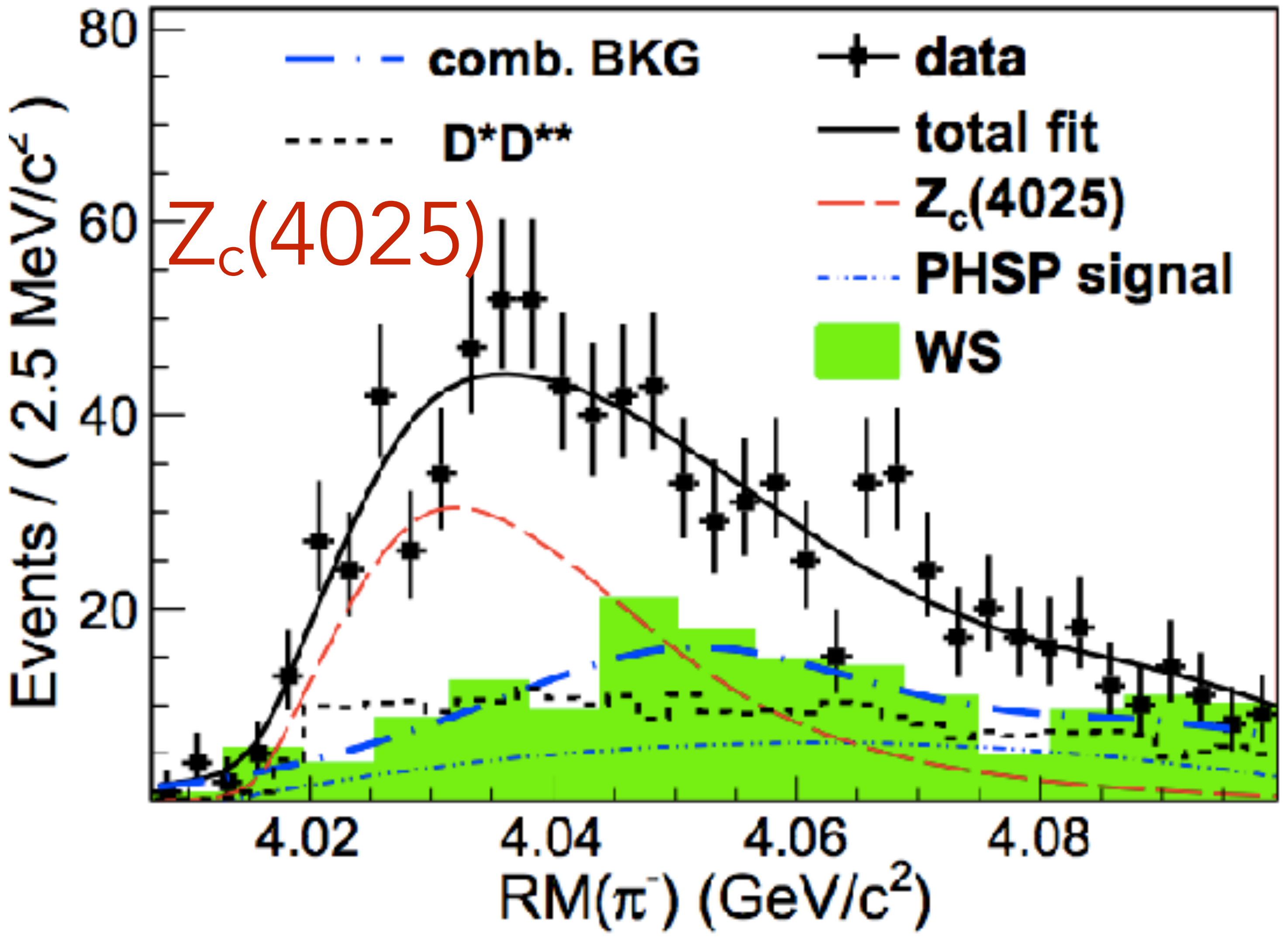
$Z_c(3900)^+$ seen in $J/\psi\pi^+$. Also have $Z_c(3885)^+$ in $(D\bar{D}^*)^+$, showing a dramatic near threshold peak. These could be the same state. Need partial wave analysis of $J/\psi\pi\pi$ final state to determine this.

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

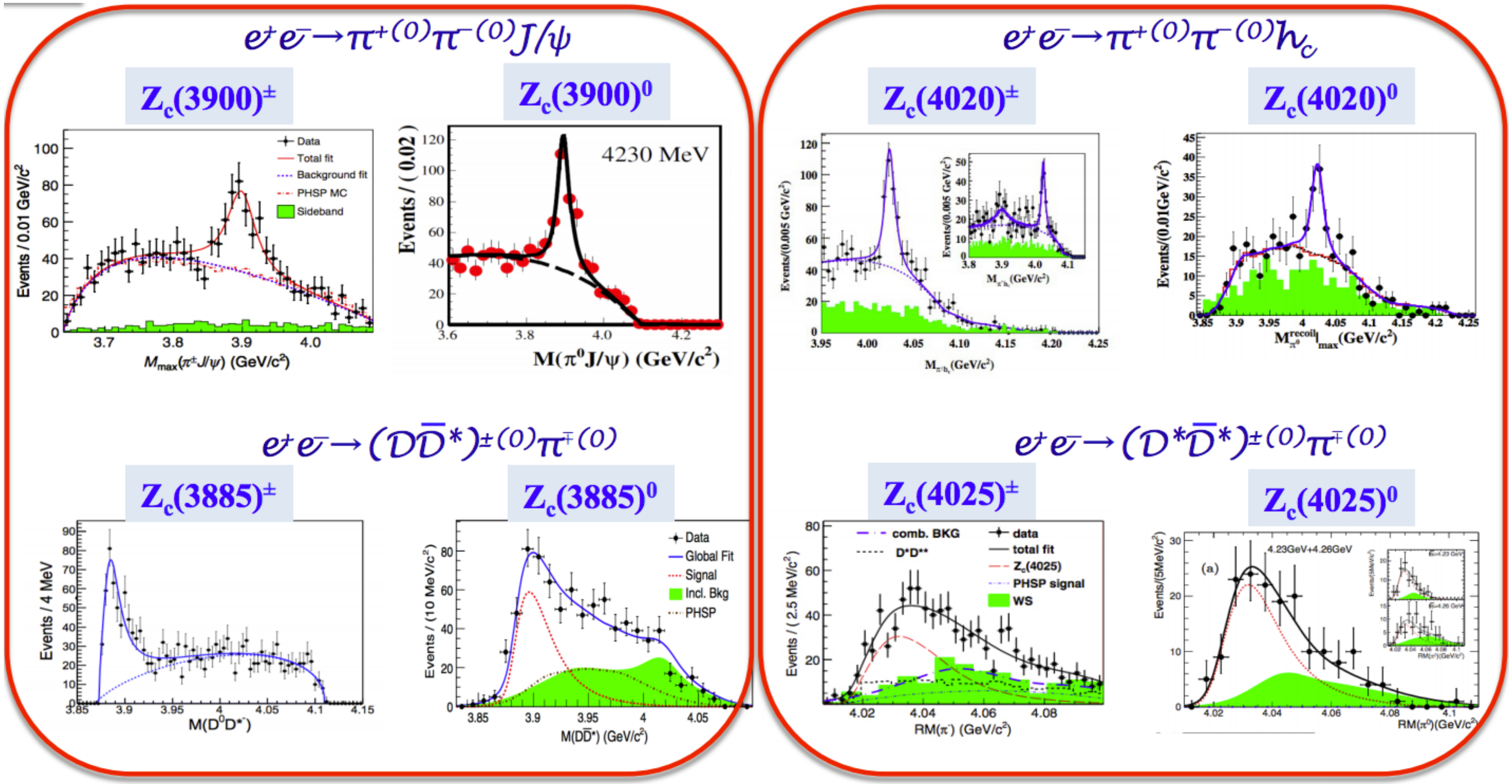
$Z_c(4025)^+$ seen recently by BESIII just above $(D^*\bar{D}^*)^+$ threshold. $m(D^*\bar{D}^*)$ distribution not described by phase space. This could be same state as $Z_c(4020)^+$.







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

X(3872) radiative decays

LHCb has evidence for X(3872) in $B^+ \rightarrow \psi\gamma K^+$, $\psi \rightarrow \mu^+\mu^-$

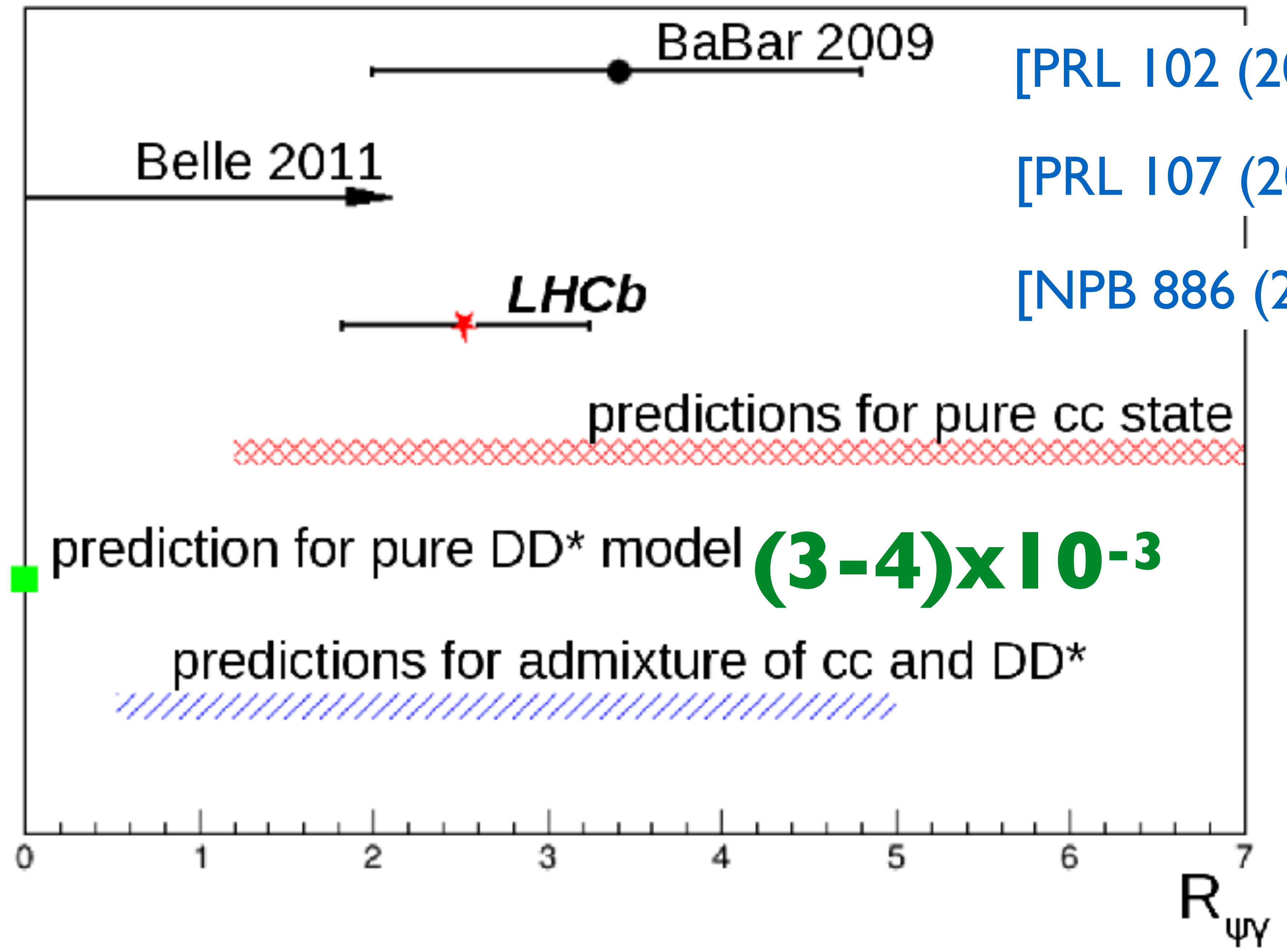
Efficiency(ψ(2S)γ) / Efficiency(J/ψγ) ~ 0.2

Detecting soft photons at hadronic collider is hard.

Pure DD* molecule interpretation disfavoured.

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

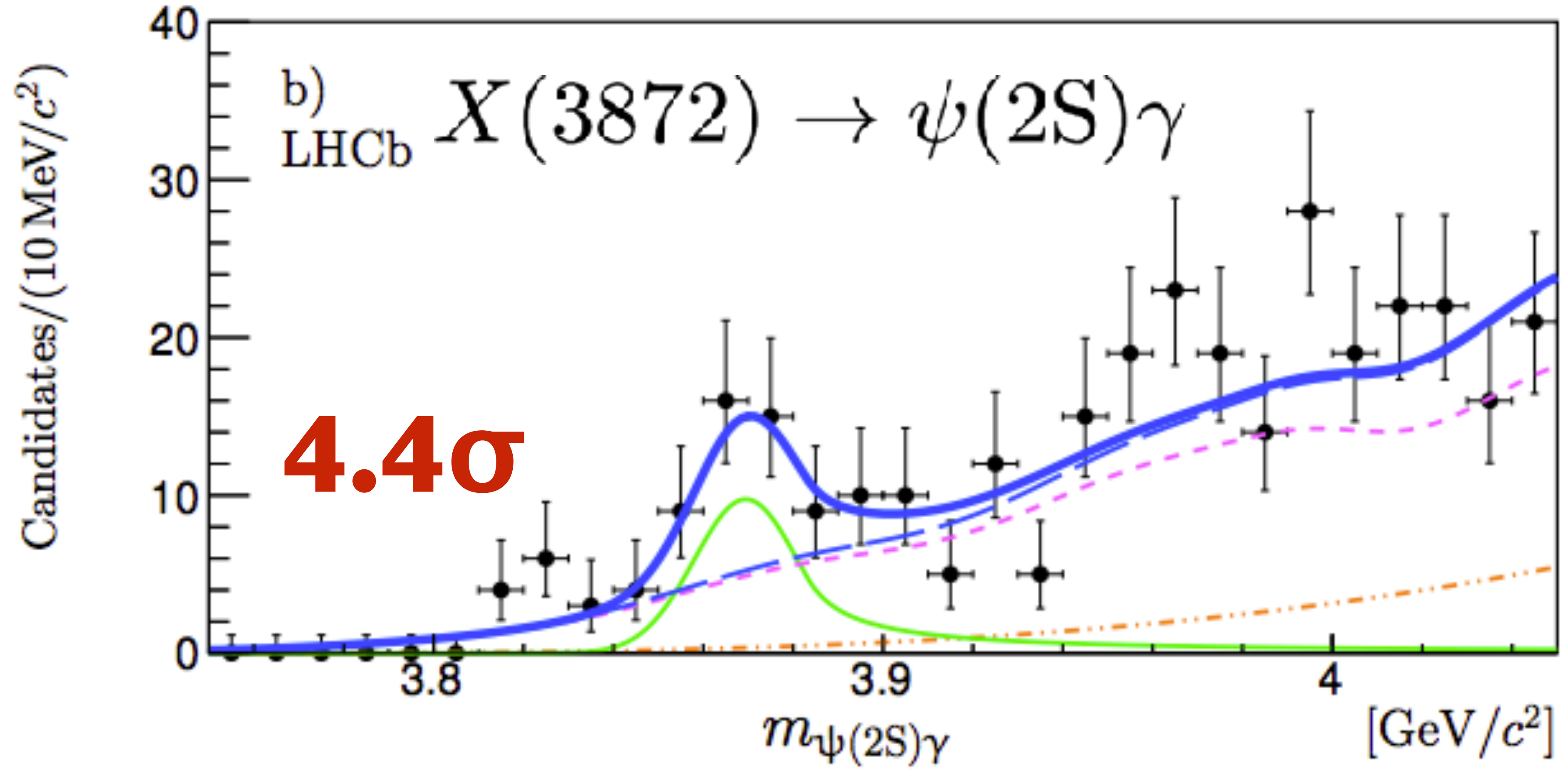
Probe of internal structure of X(3872)

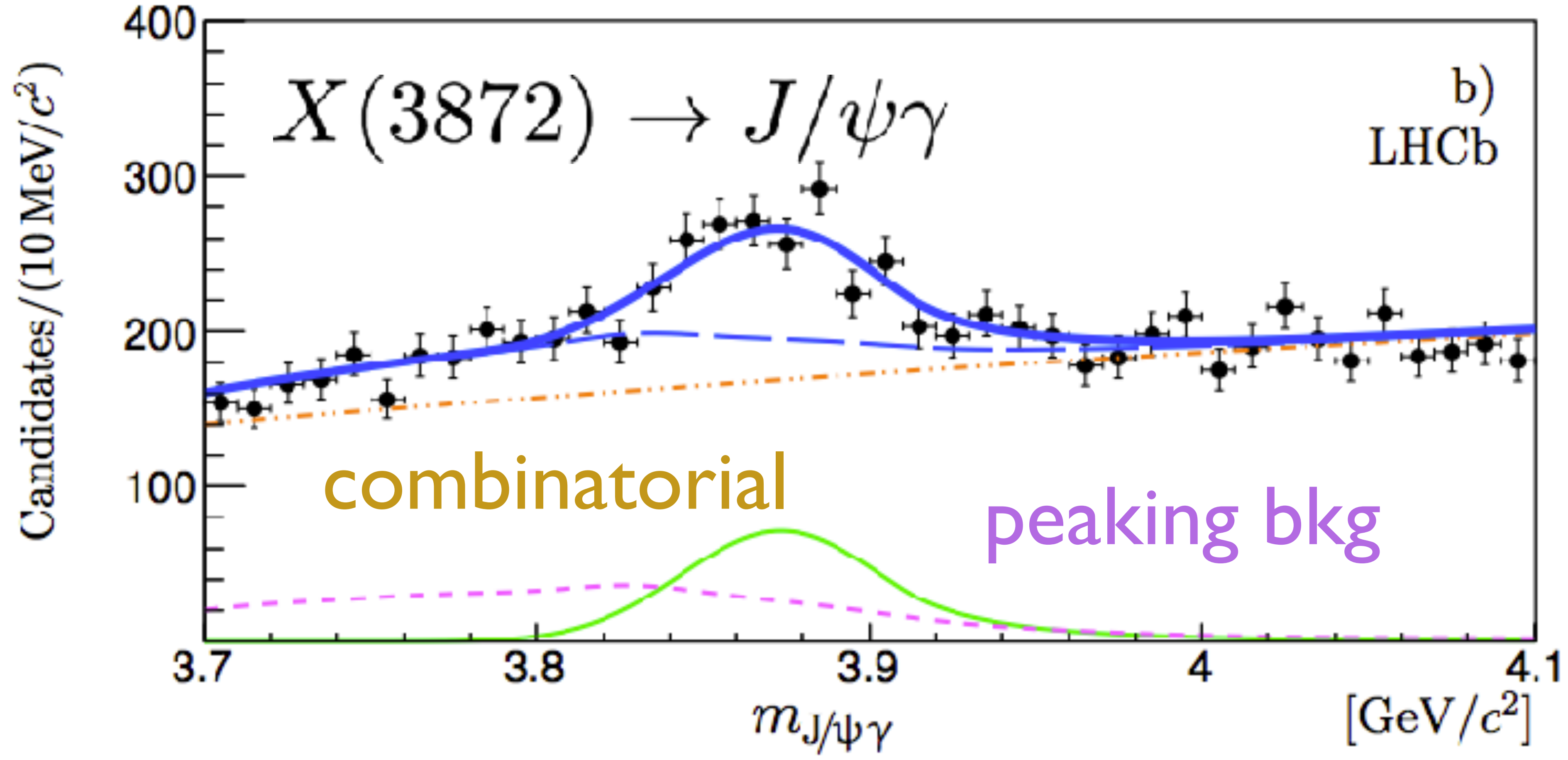


[PRL 102 (2009) 132001]

[PRL 107 (2011) 091803]

[NPB 886 (2014) 665]





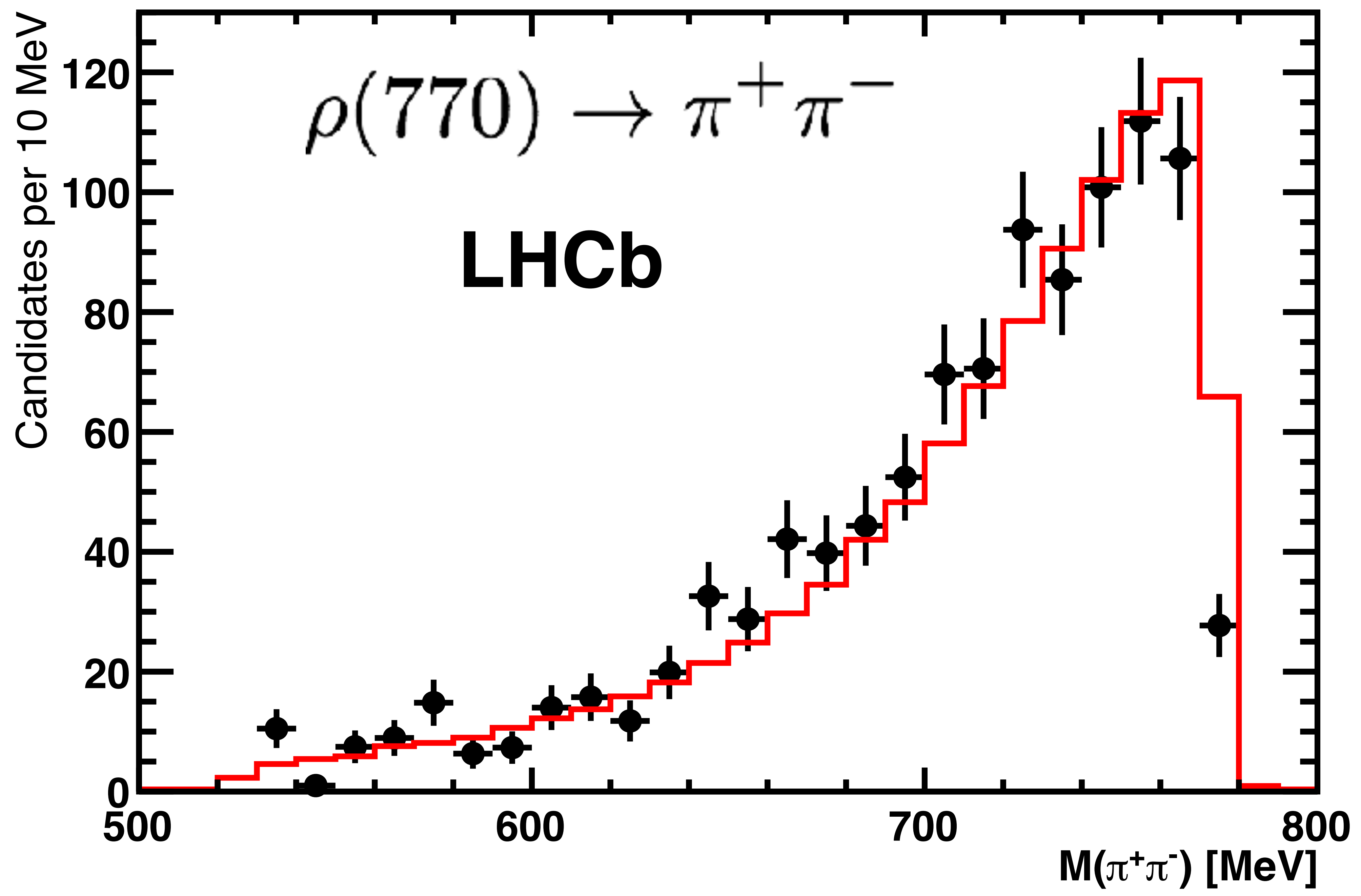
X(3872) quantum numbers

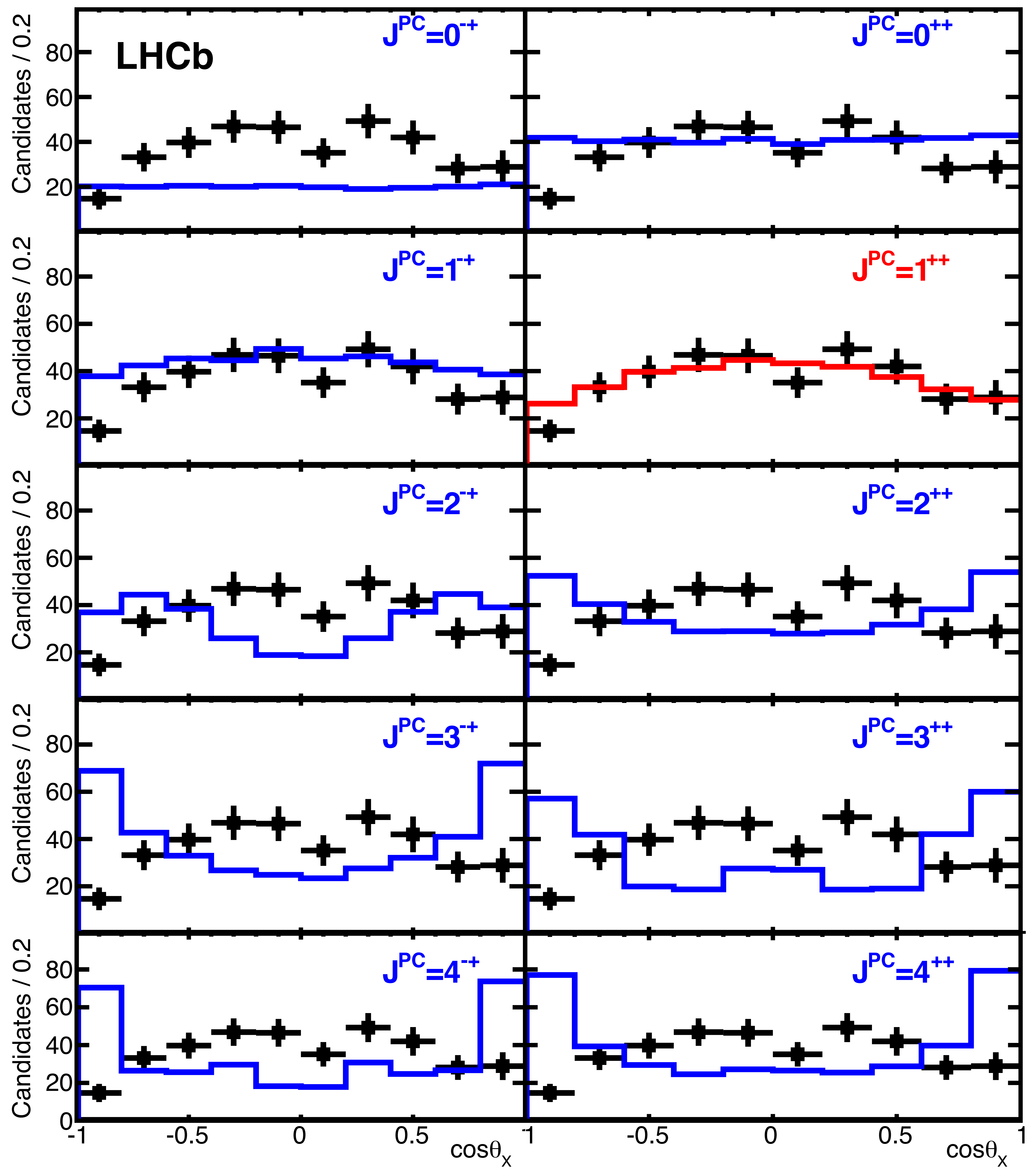
[PRD 92 (2015) 011102]

$J^{PC} = 1^{++}$ confirmed!

D-wave < 4% @ 95% CL (i.e., negligible)

ρ(770) dominates → decay violates isospin so unlikely to be conventional ccbar





Other exotic states in quarkonium spectra

Belle have evidence for $Z_1(4050)^-$ and $Z_2(4250)^-$ states in $B^0 \to Z^- K^+$, $Z^- \to \chi_{c1}\pi^-$. [PRD 78 (2008) 072004]

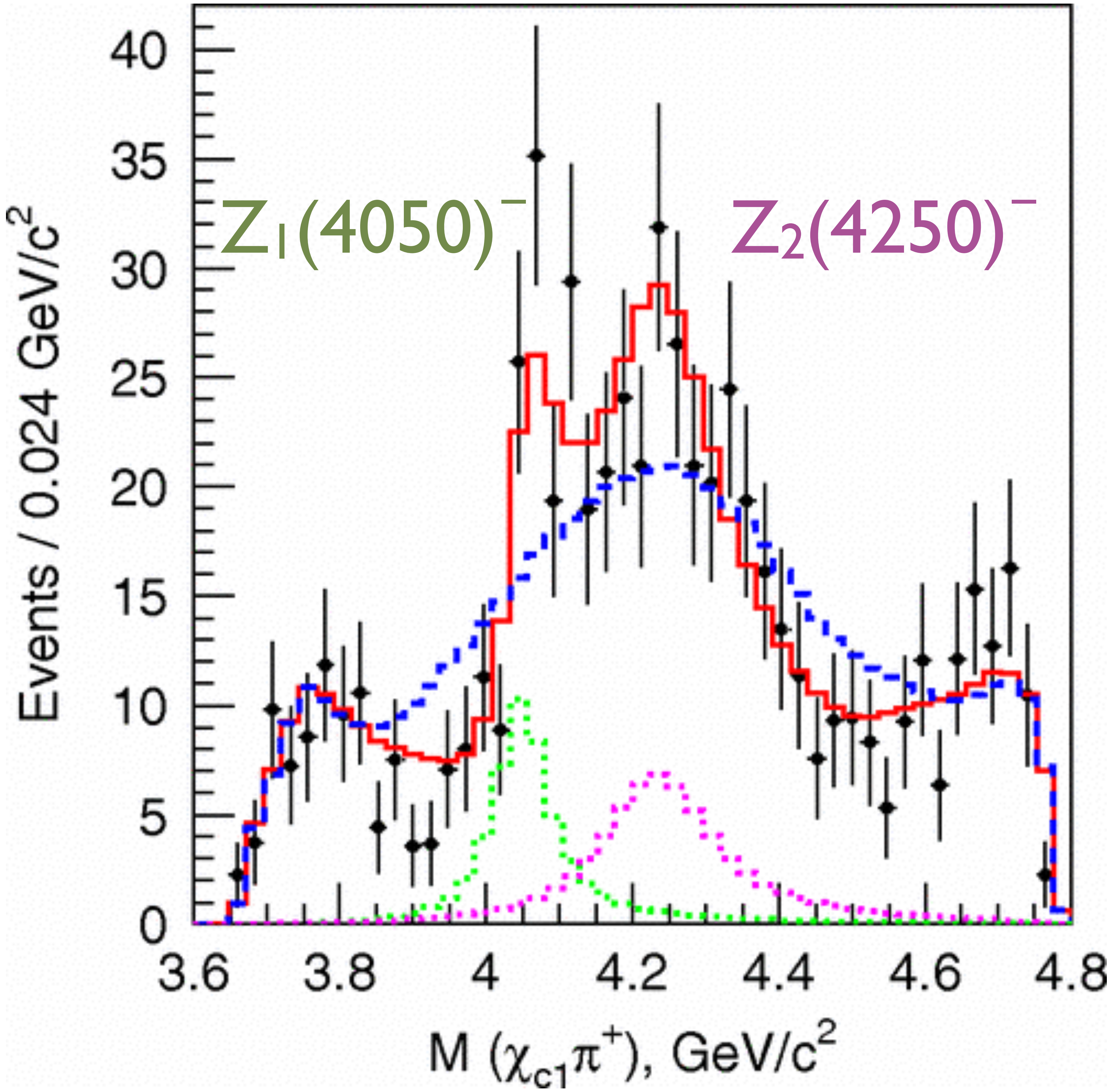
But only uses a simplified 2D Dalitz fit to the phase space. Quantum numbers undetermined.

BaBar have not confirmed. [PRD 85 (2012) 052003]

LHCb should be able to do something here in future

Expect x10 larger sample than Belle

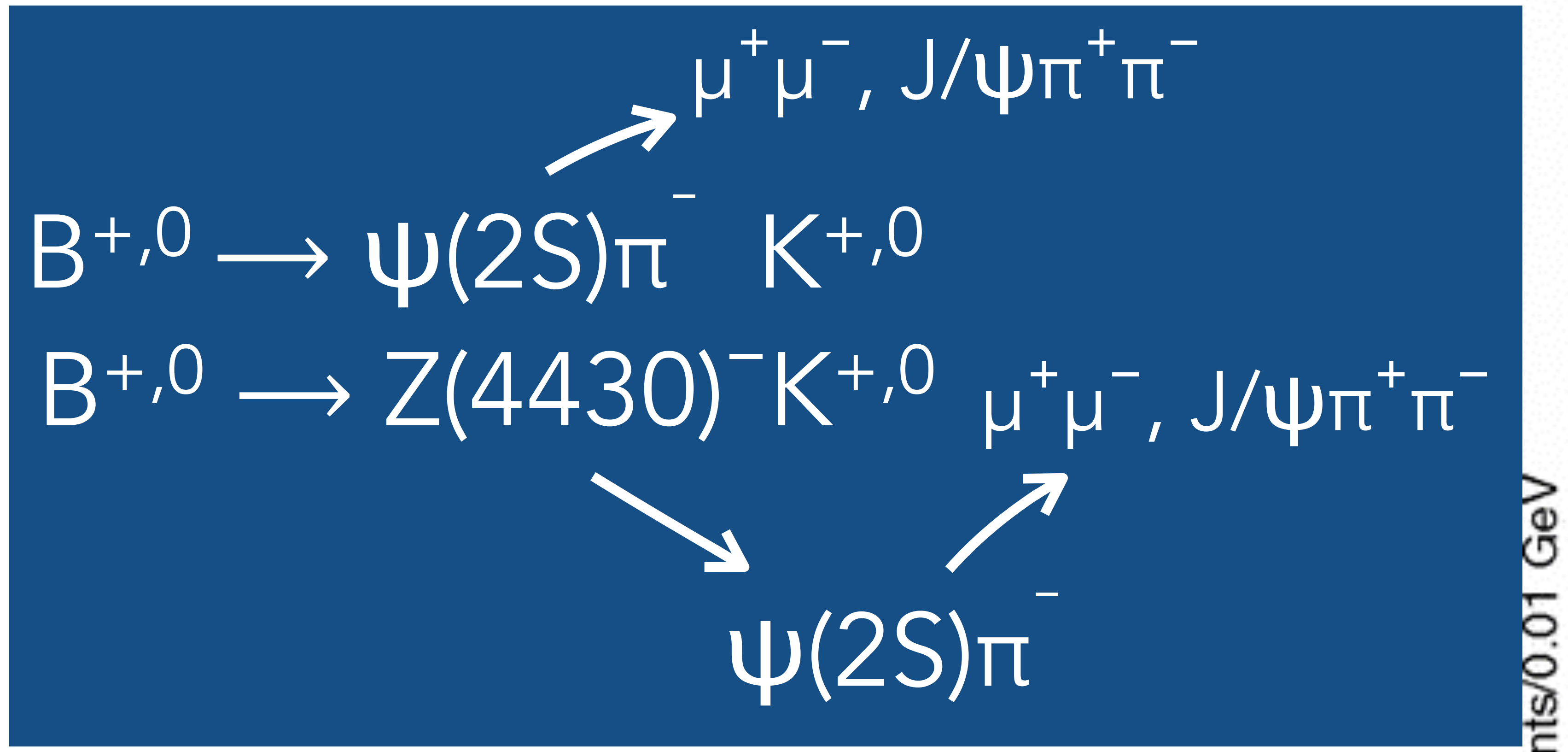
Requires description of 6D phase space



Z(4430)± charged charmonium exotic

- 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**

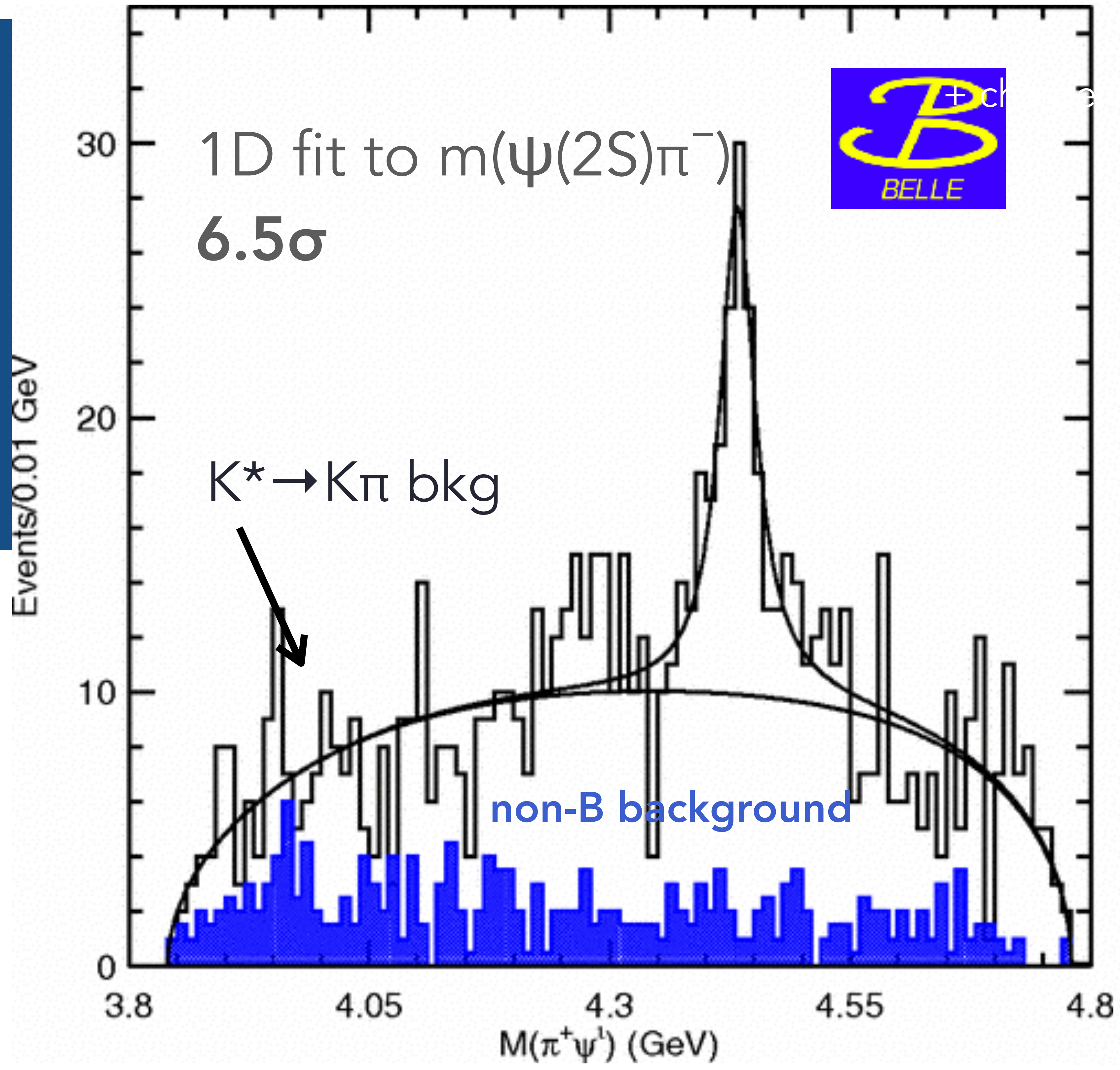
$$c\bar{c}u\bar{d}$$



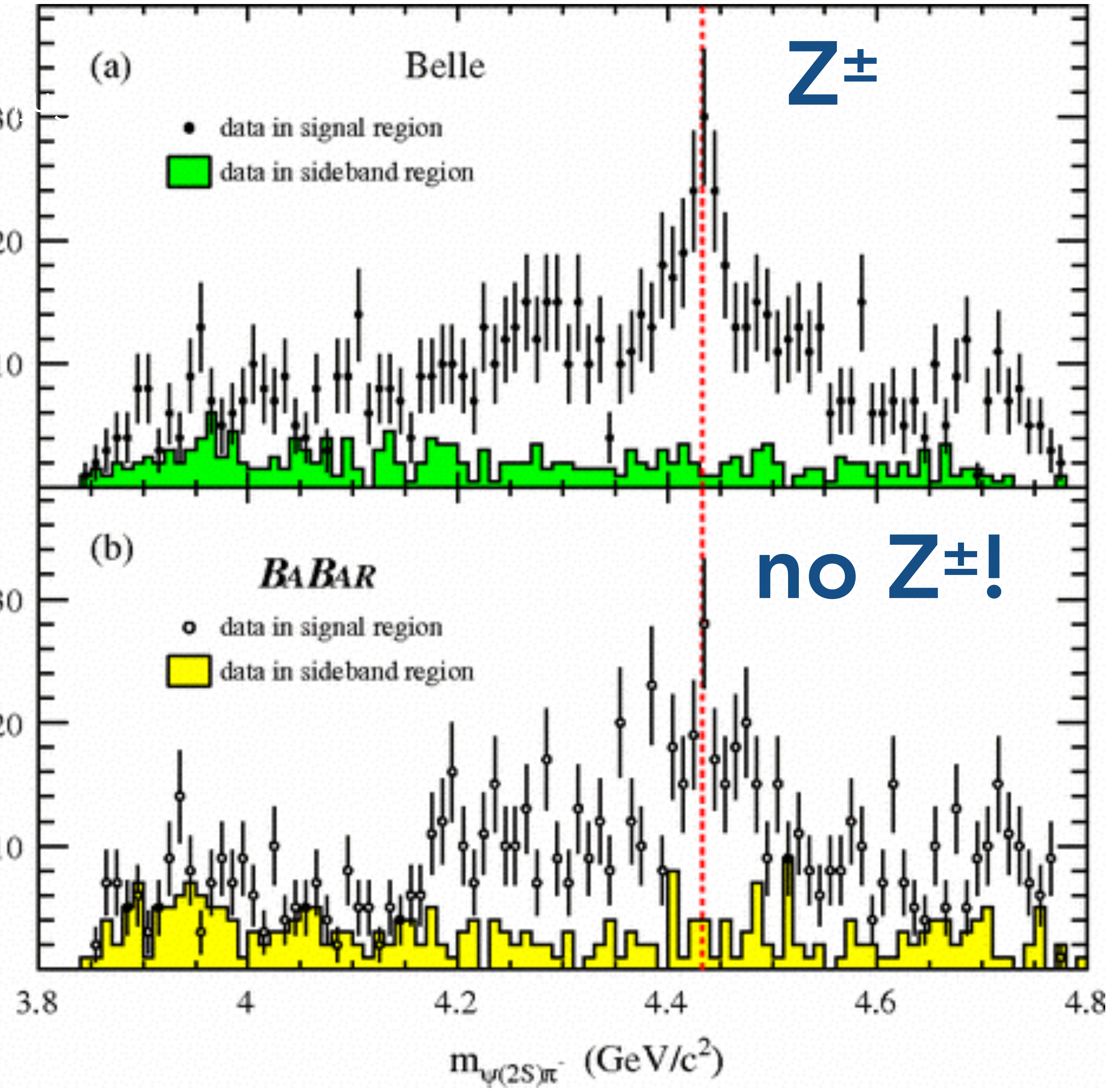
$$M = 4433 \pm 4 \pm 2 \text{ MeV}/c^2$$

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

[PRL 100 (2008) 142001]



[PRD 79 (2009) 112001]



Not observed by BaBar!

History of the Z(4430)$^-$

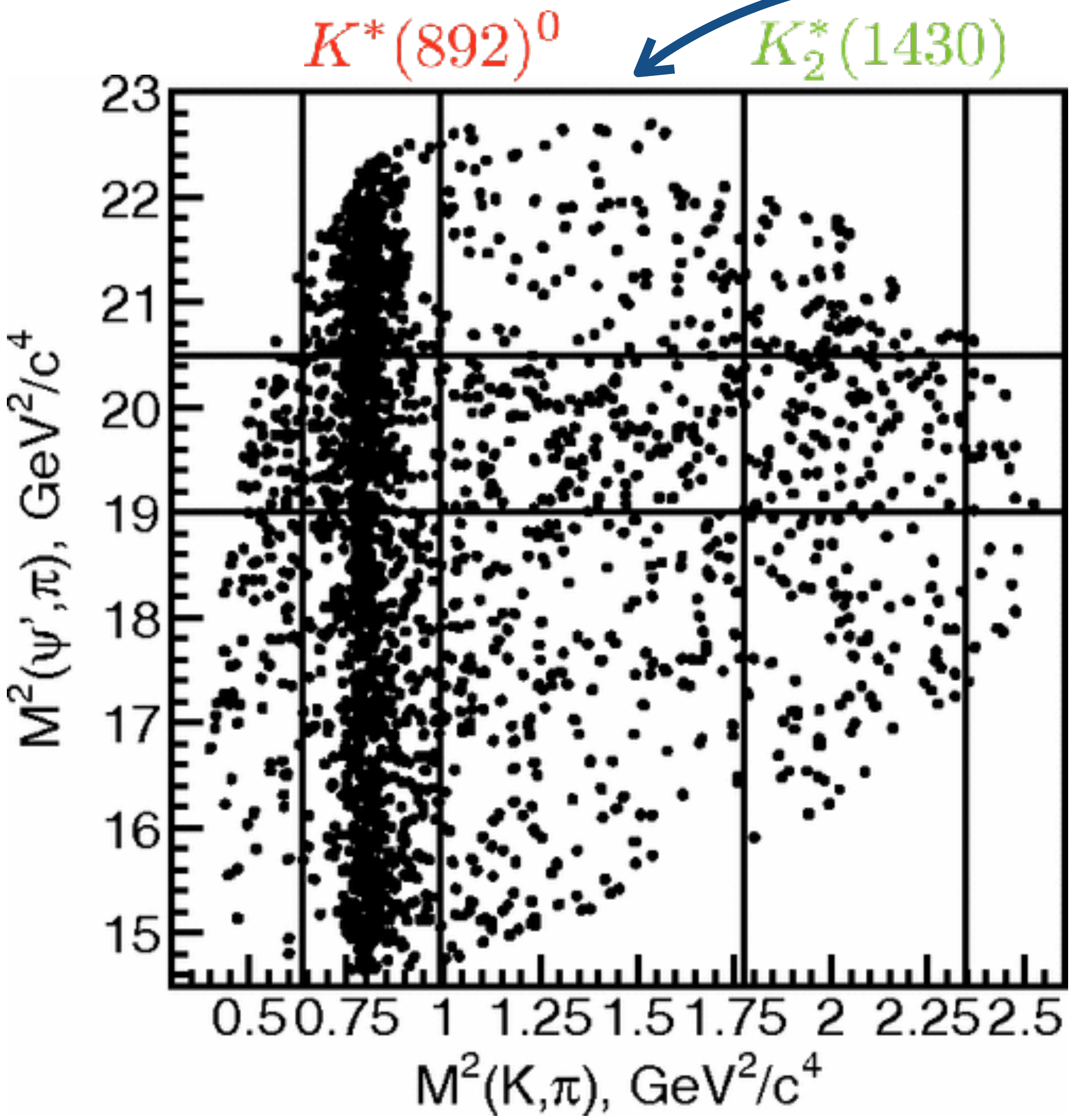
M(D*)+M(D**)=4472 MeV

- 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**

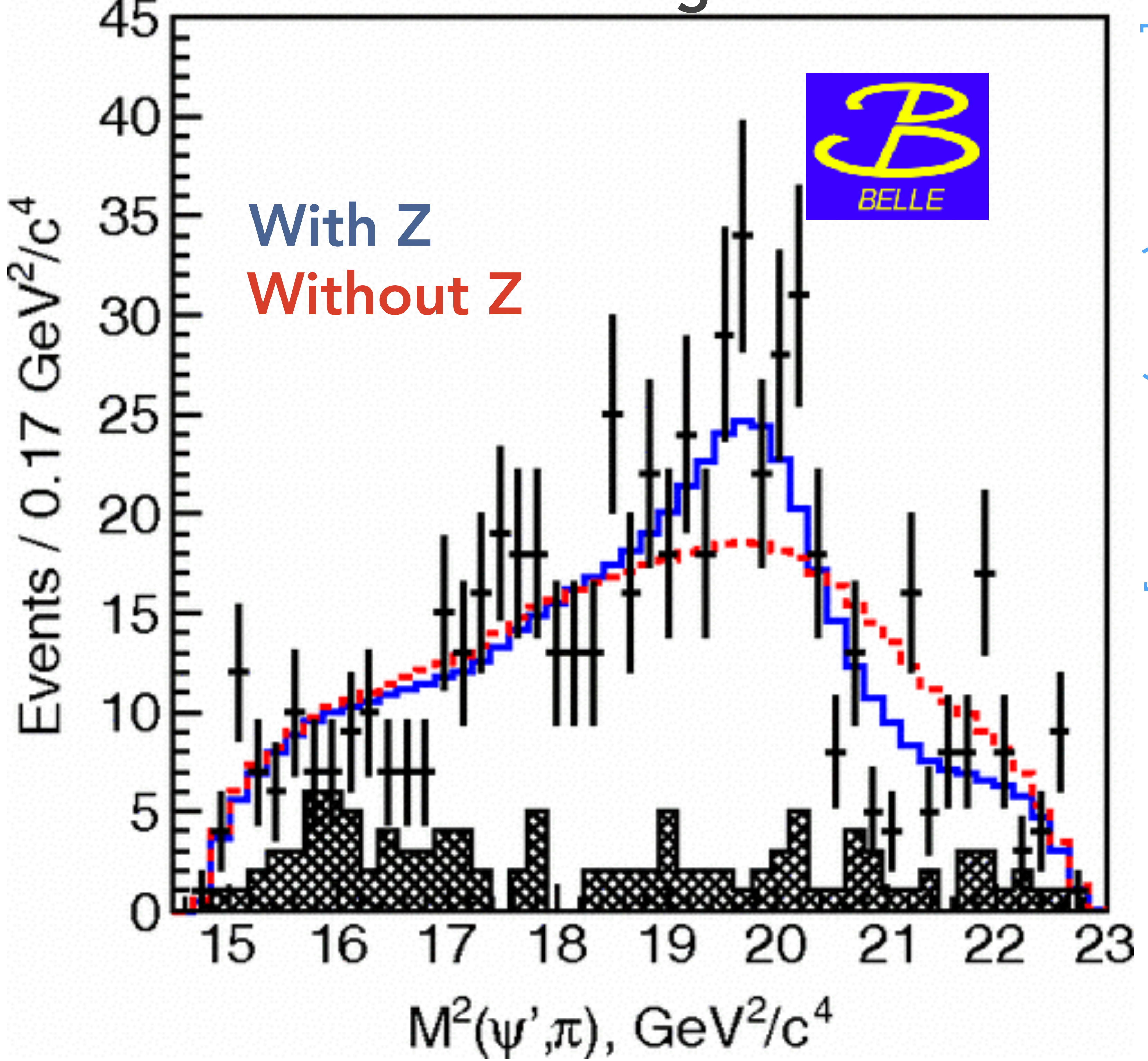
ψ′ = ψ(2S)

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

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



K* veto region



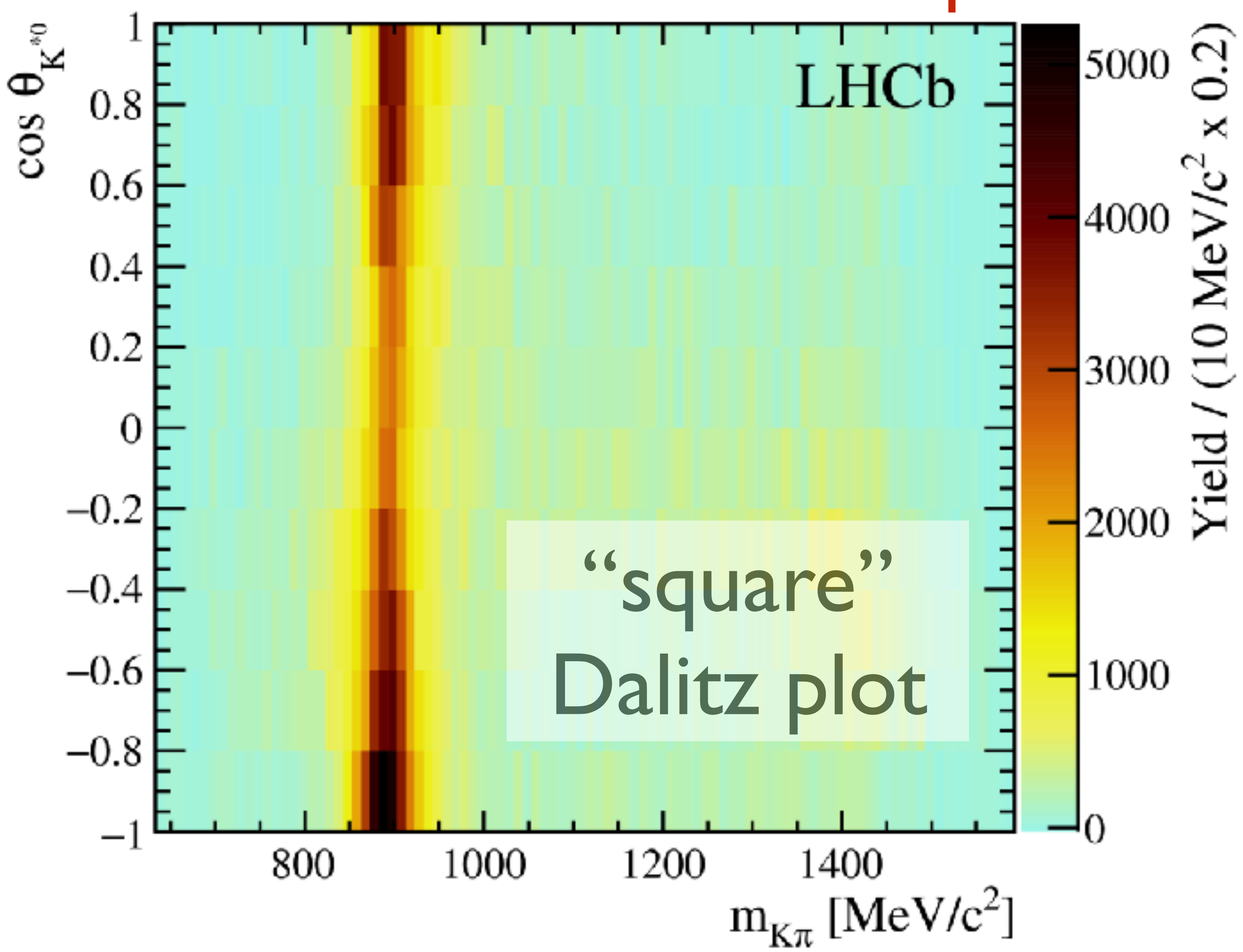
[PRD 88 (2013) 074026]

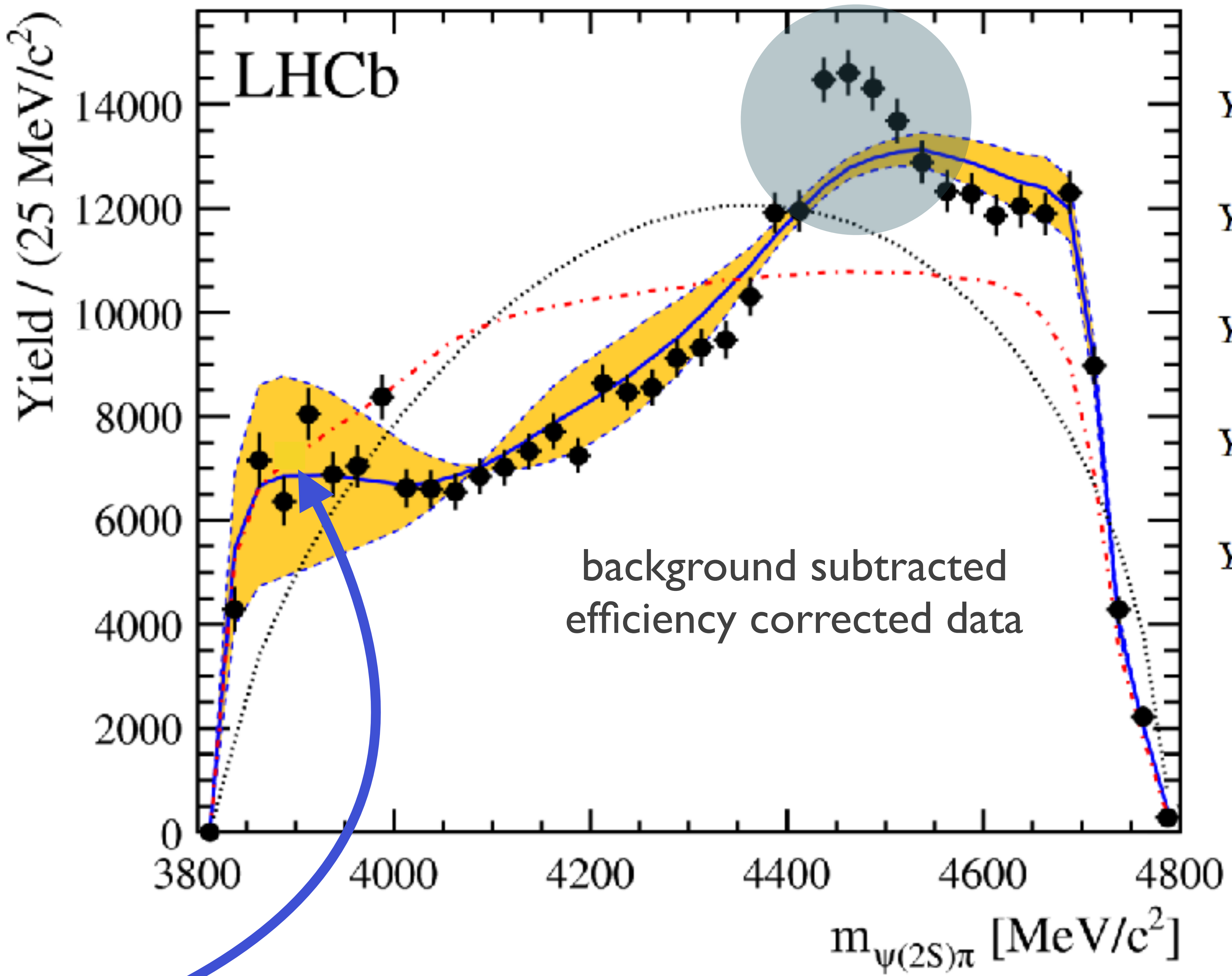
Model independent analysis

Can reflection of the structures in m(Kπ) and cosθ reproduce the m(ψ’π) distribution? → **NO!**

[PRD 92 (2015) 112009]

Extension of [BaBar PRD 79 (2009) 112001]





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

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

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

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

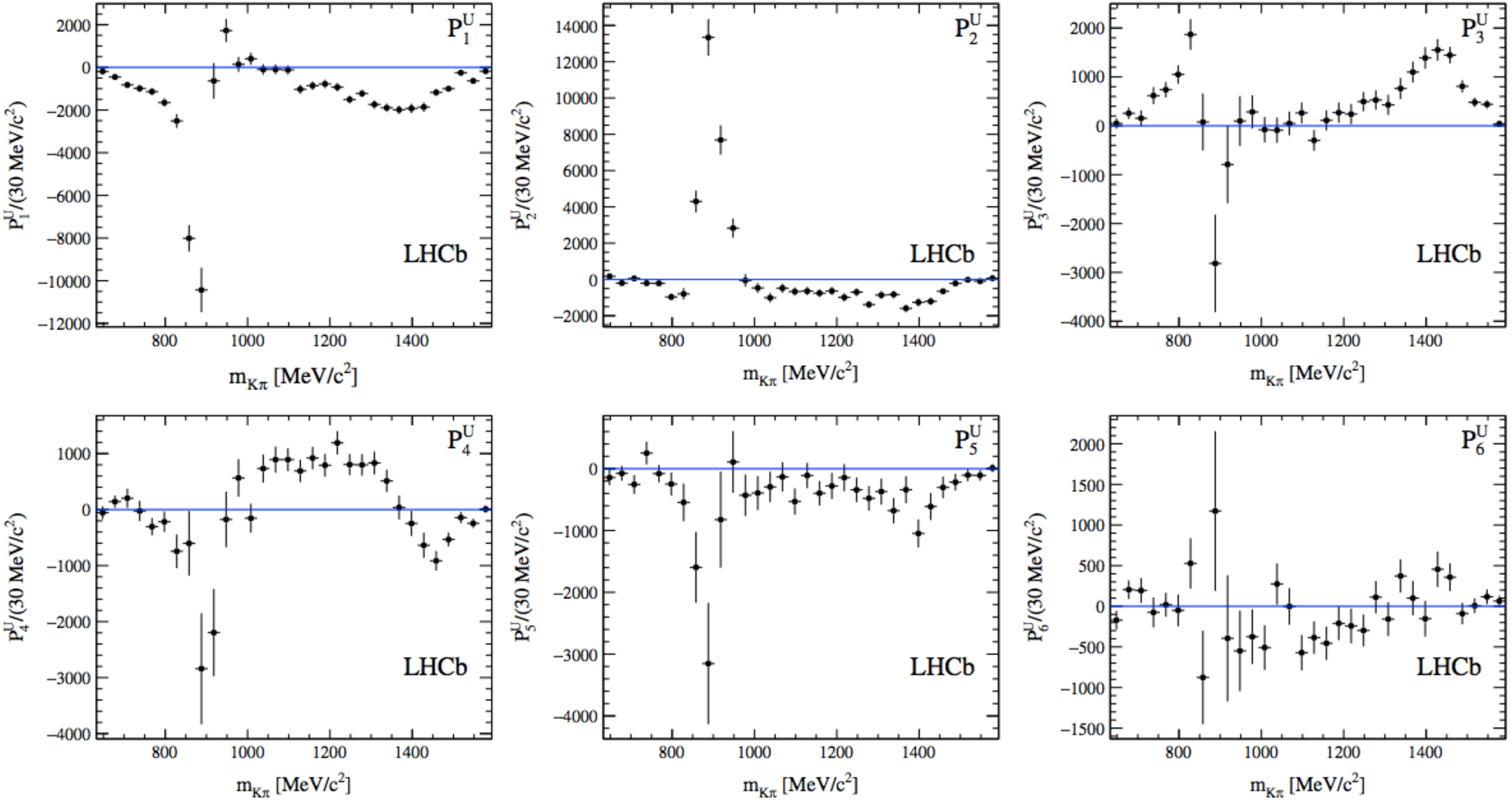
$$Y_2^2 = \frac{1}{4}\sqrt{\frac{15}{2\pi}}\sin^2\theta\, e^{2i\phi}$$

Does not make any assumption on the underlying K* resonances in the system, only restricts their maximal spin.

Weight phase space **simulated** $B^0 \rightarrow \psi' K^+ \pi^-$ **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)

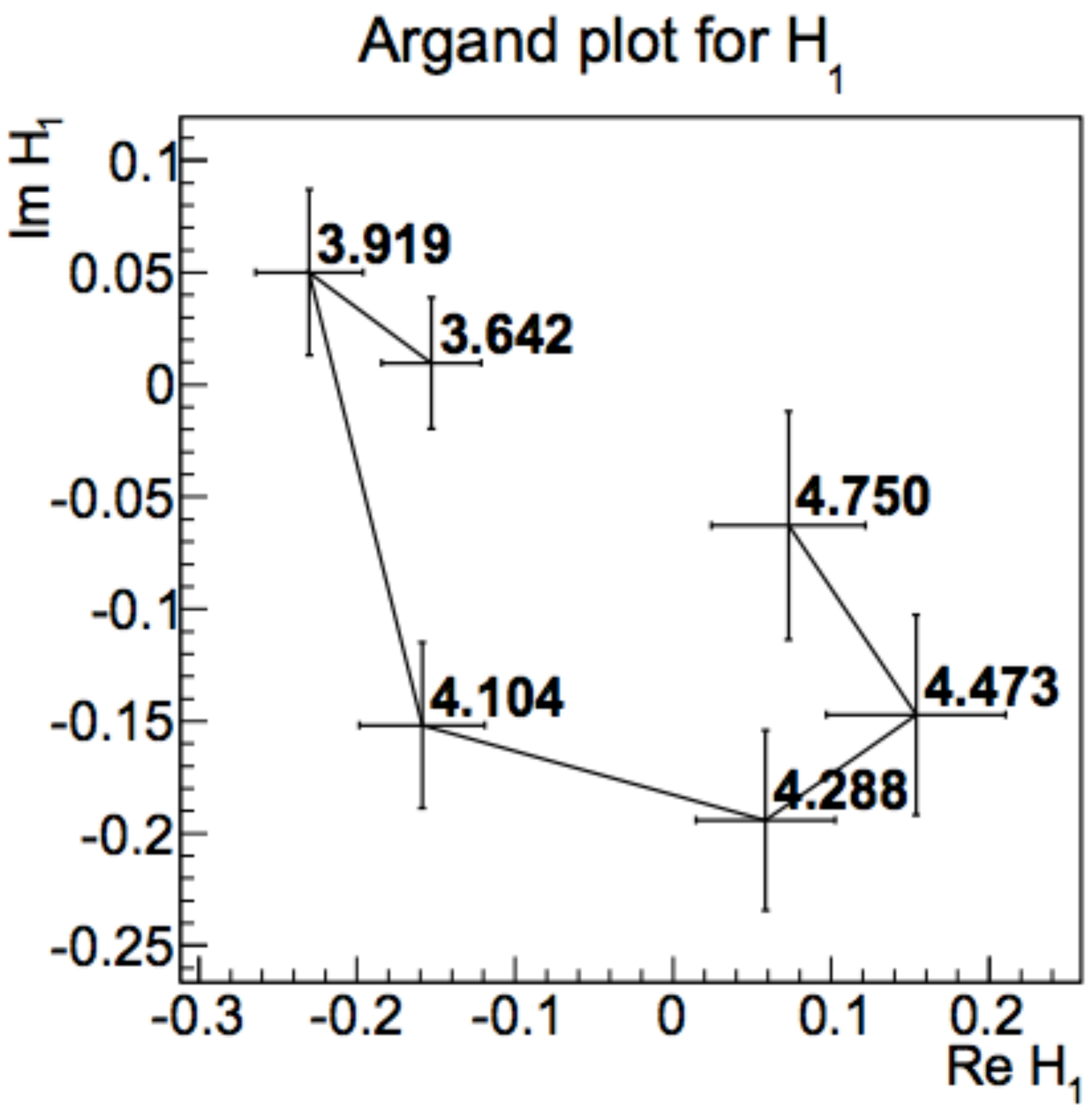
[PRD 90 (2014) 112009]

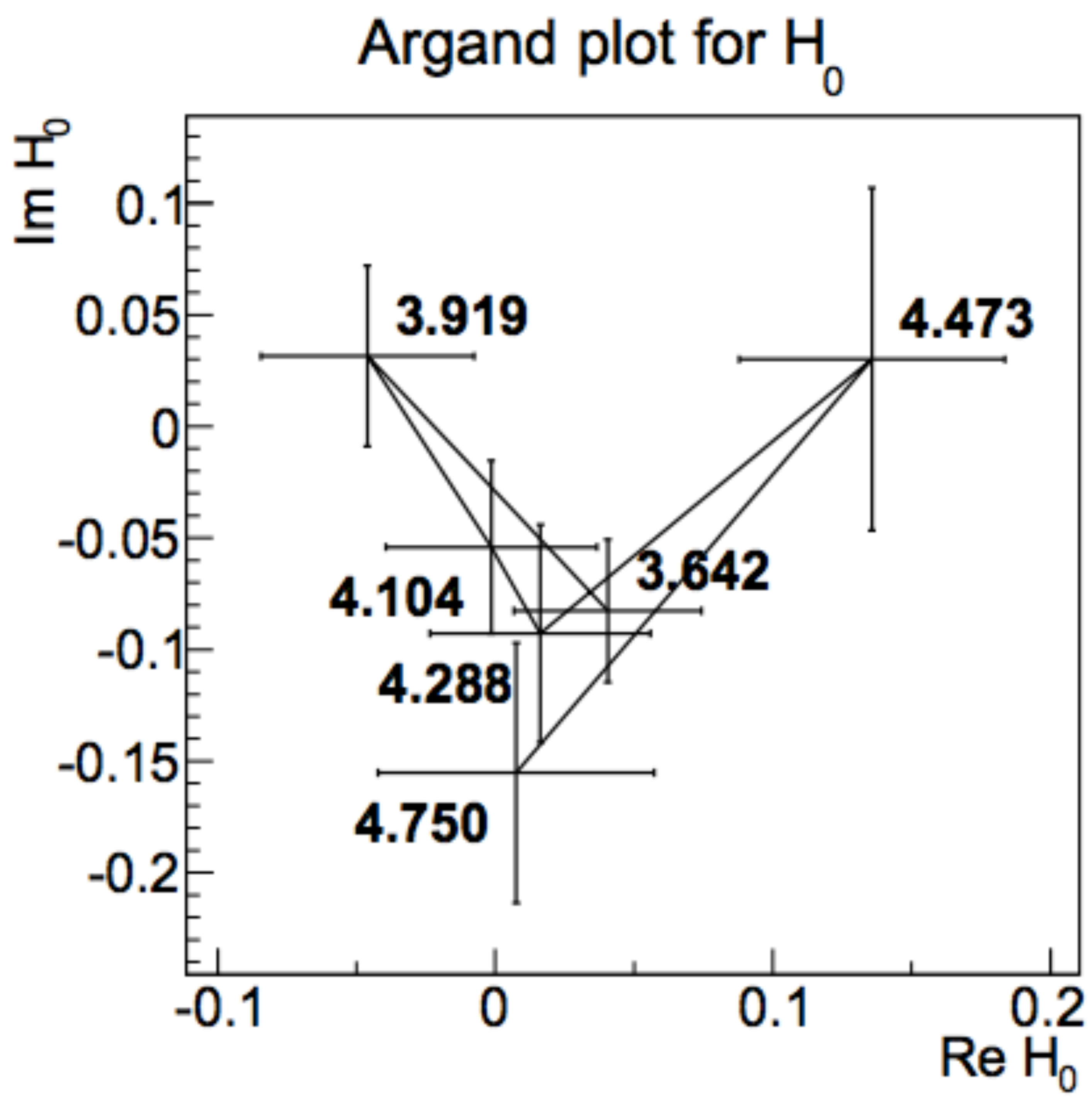
Belle 4D amplitude fit of $B^0 \to J/\psi\pi^- K^+$.

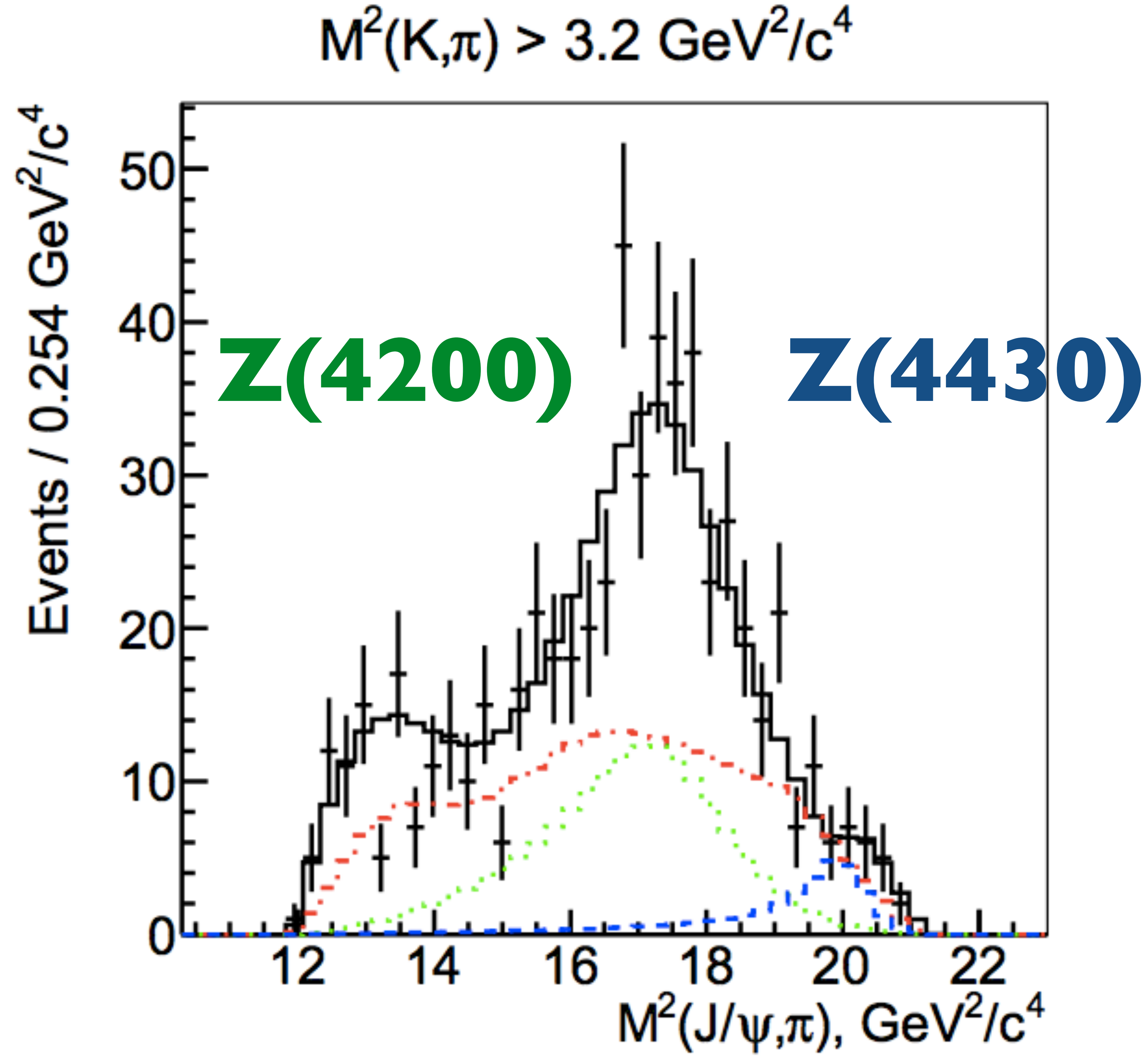
$Z(4200)^+$ at 7.2σ with systematics ($J^P = 1^+$). Width ~370MeV.

$Z(4430)^+$ at 4.0σ → evidence for **new decay mode!**

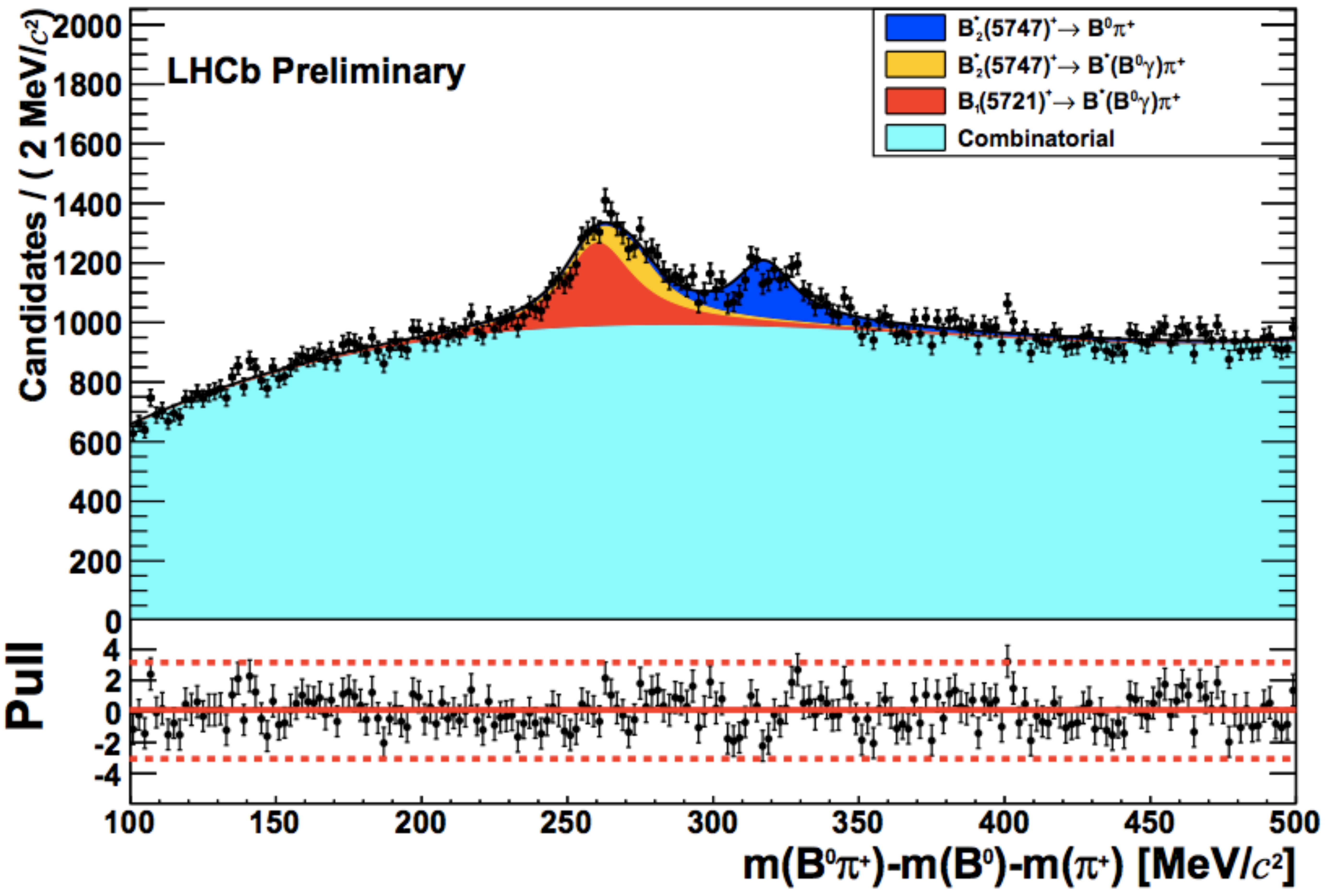
Expect smaller BR if Z has large radius, with larger overlap with ψ(2S).







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



Well known excited B states found using same analysis techniques

Light meson exotics

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

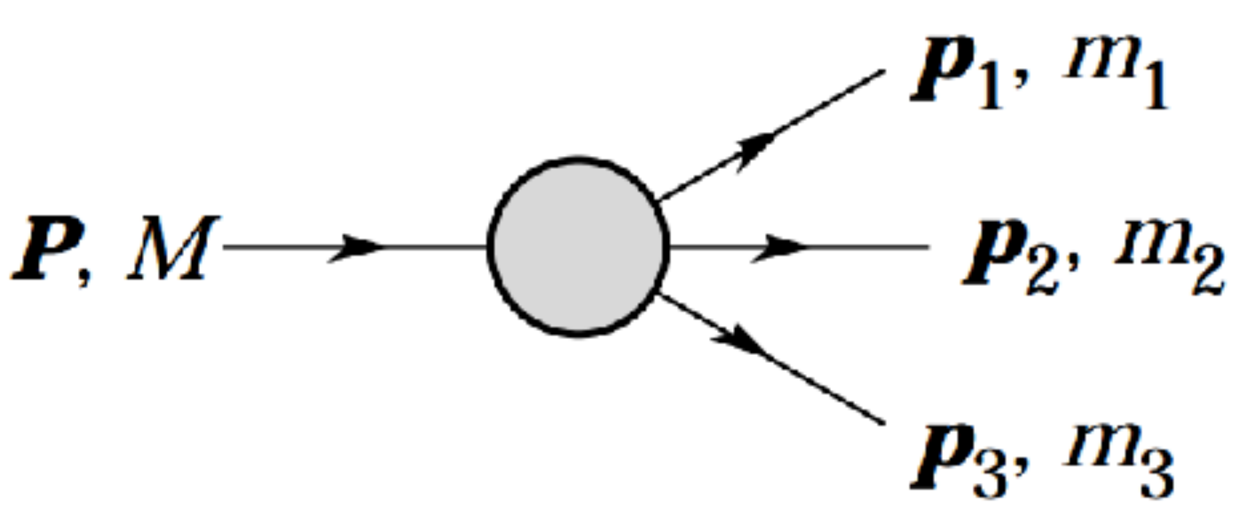
BES-III observes number of light quark exotics.

X(1835) threshold enhancement in $J/\psi \rightarrow \gamma$ppbar .

ppbar bound state or glueball?

Reminder about Dalitz plots - 3 body decay

scalar → 3 scalars



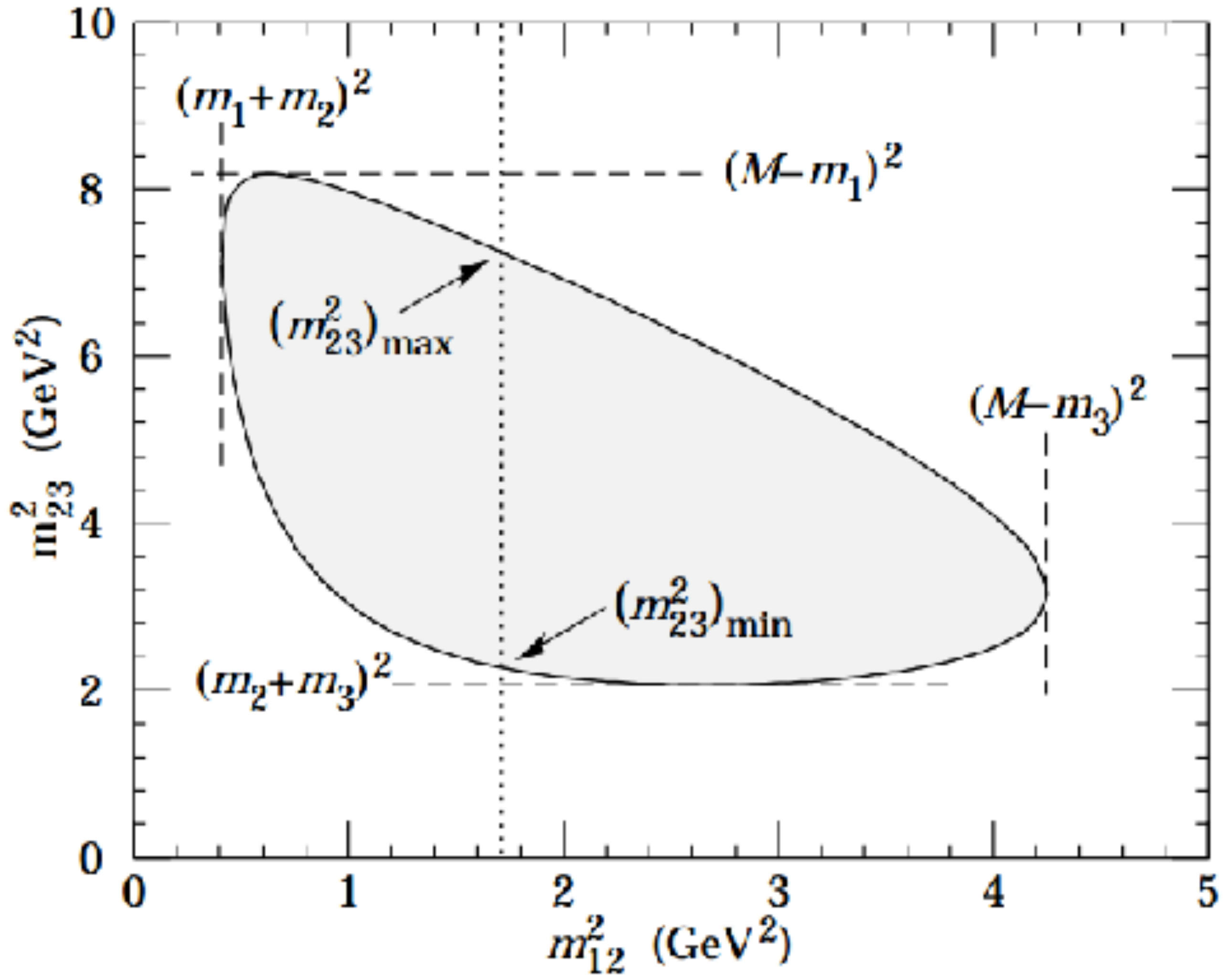
$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathscr{M}|^2}\, dm_{12}^2\, dm_{23}^2$$

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.

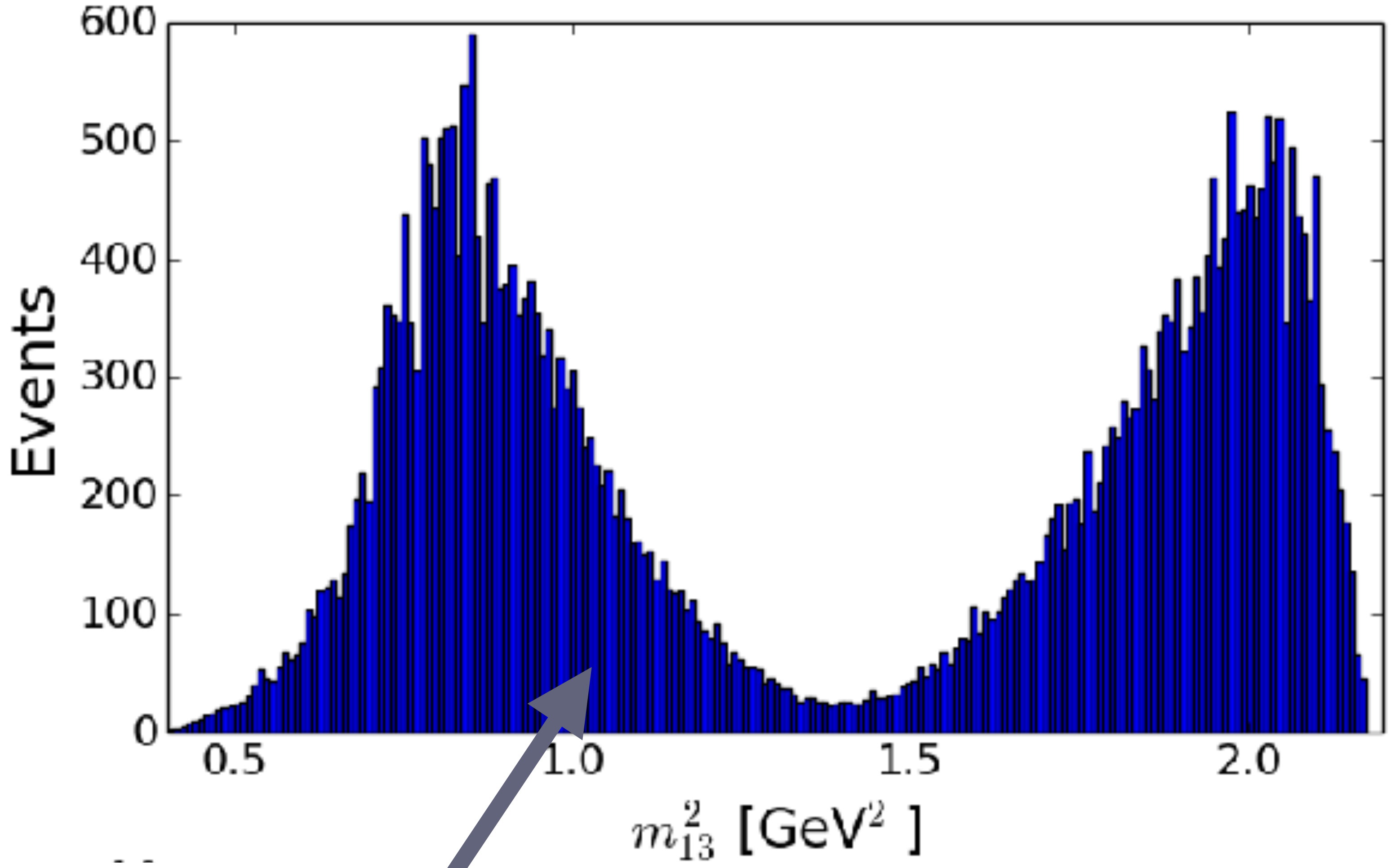
All dynamical information contained in $|\mathcal{M}|^2$.

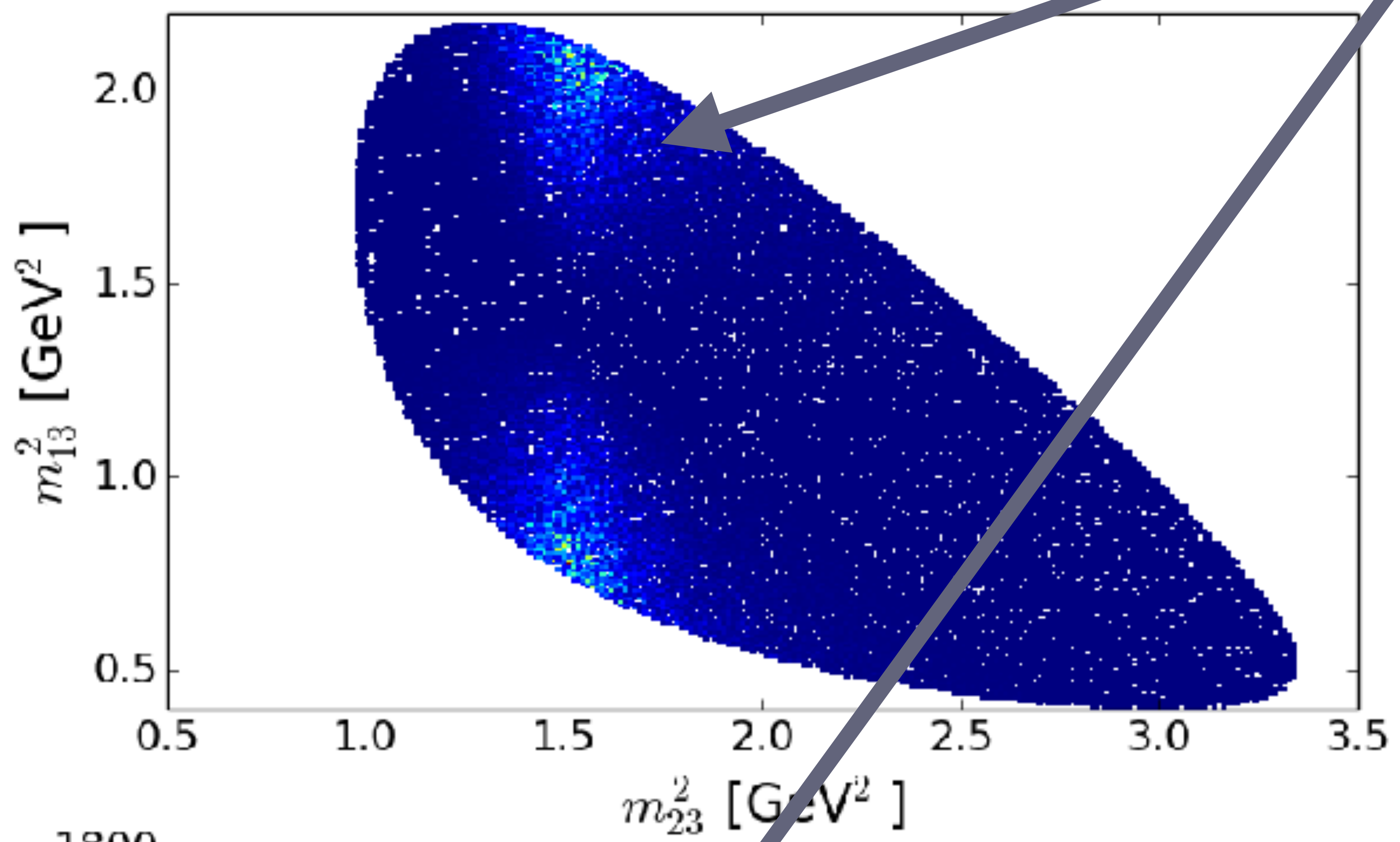
Density plot of m_{12}^2 vs. m_{23}^2 to infer information on $|\mathcal{M}|^2$.



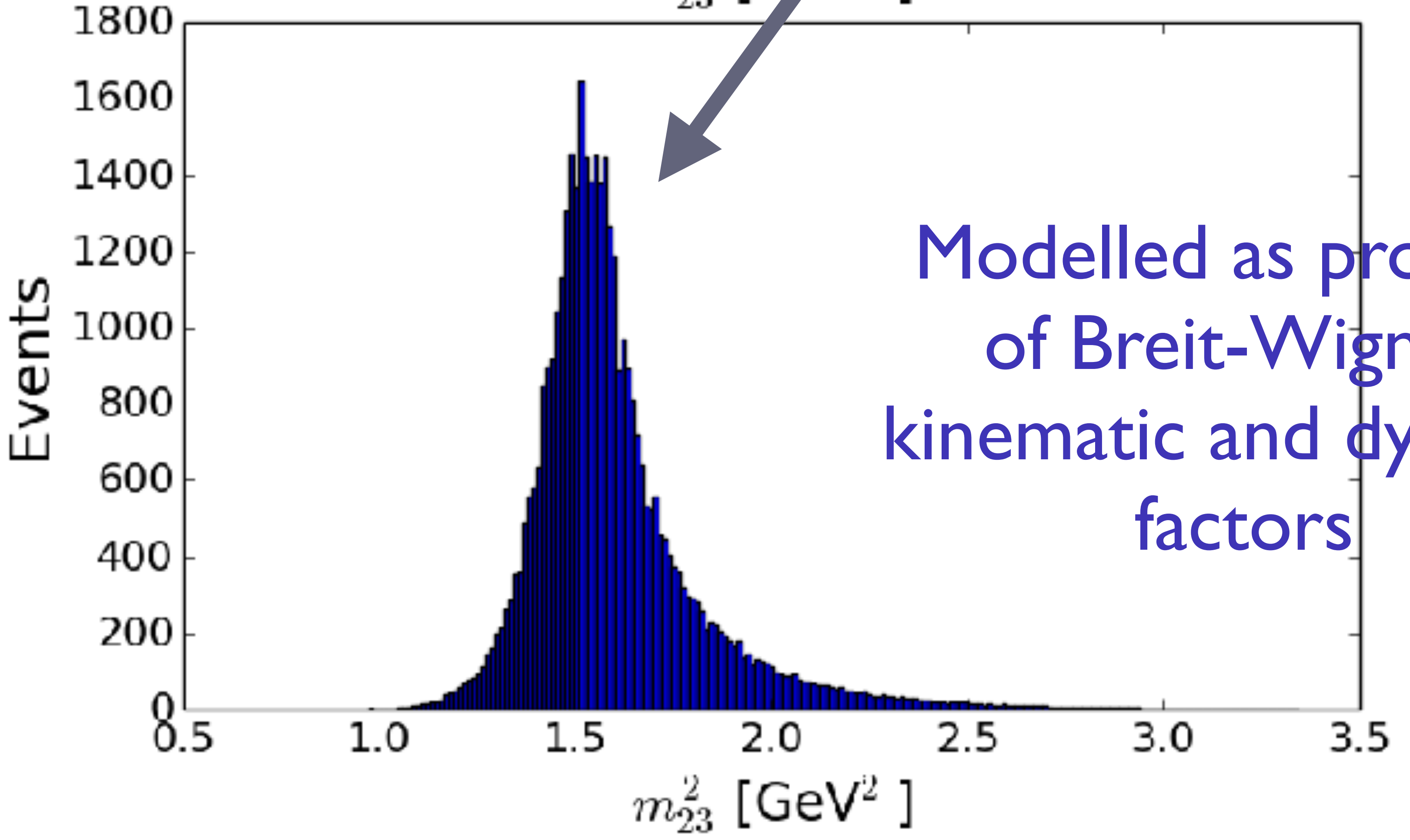
Reminder about Dalitz plots

Spin-1 resonance

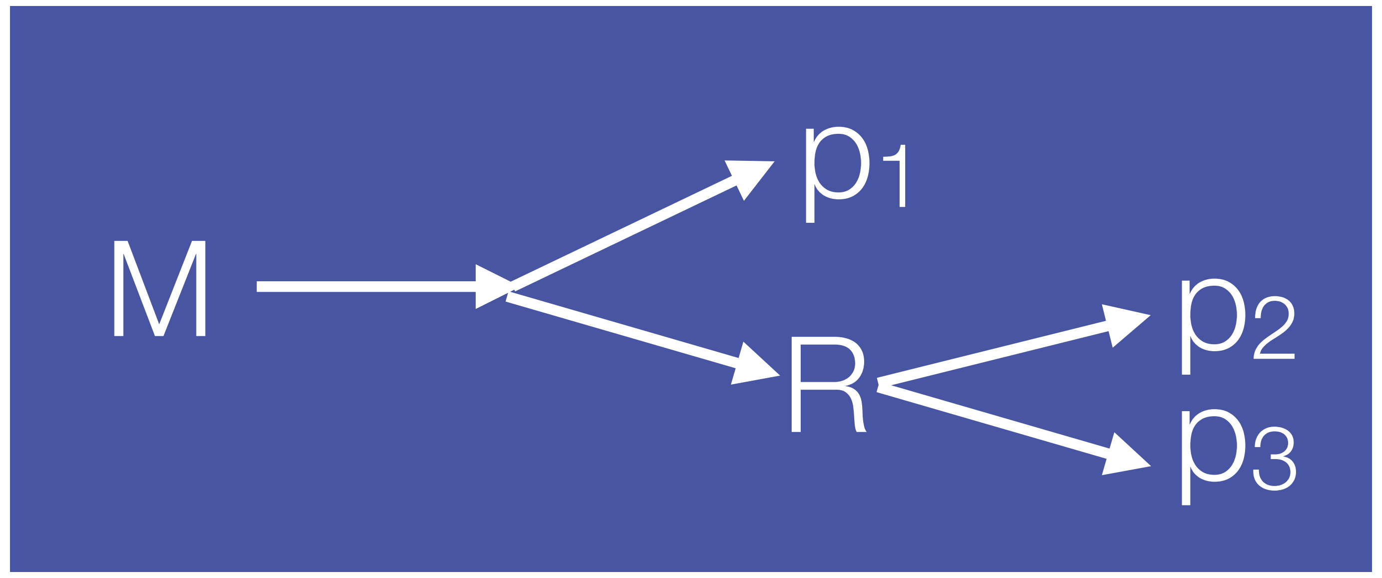




Peaks in distribution do not correspond to a real resonance - just a shadow/reflection



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

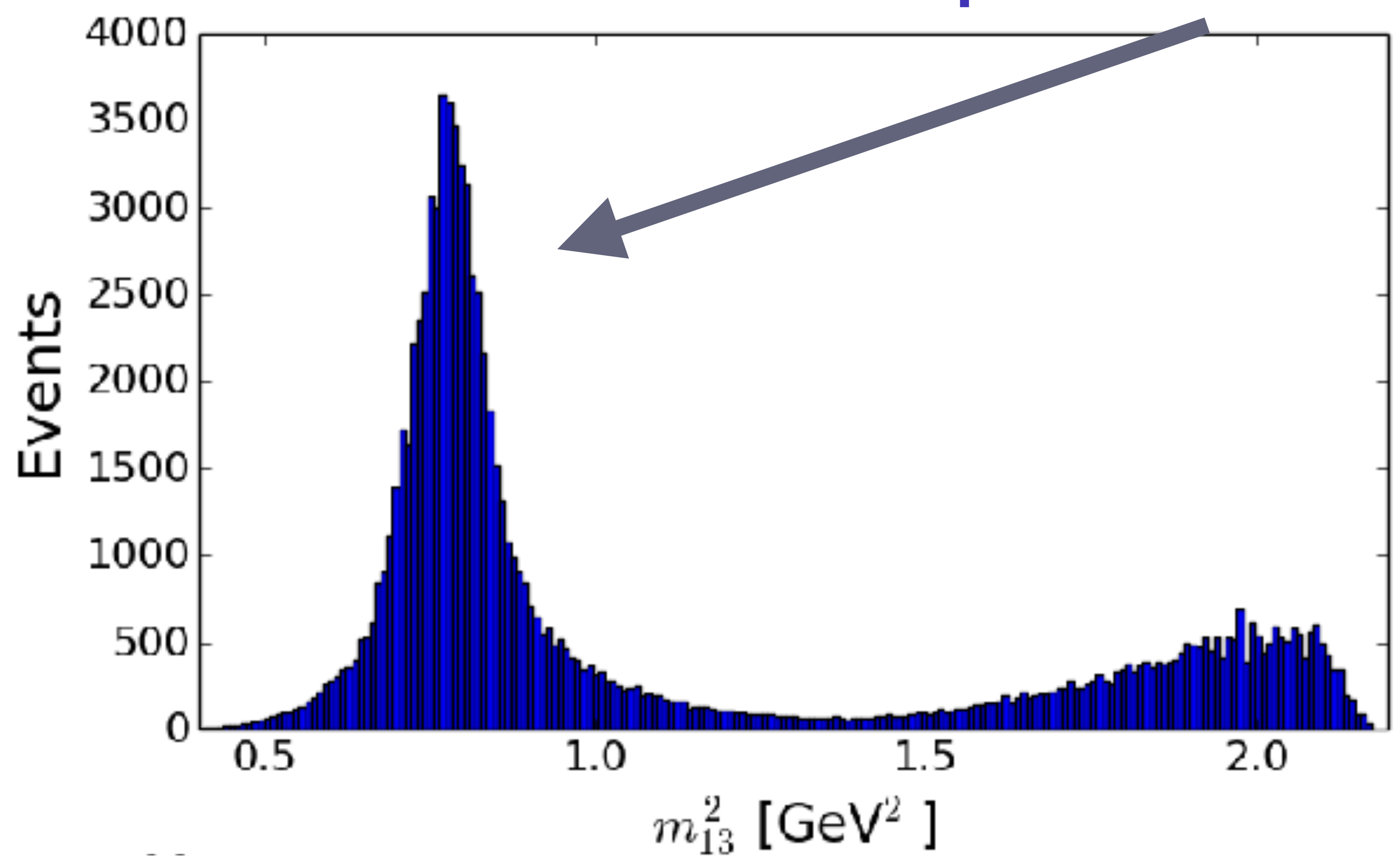


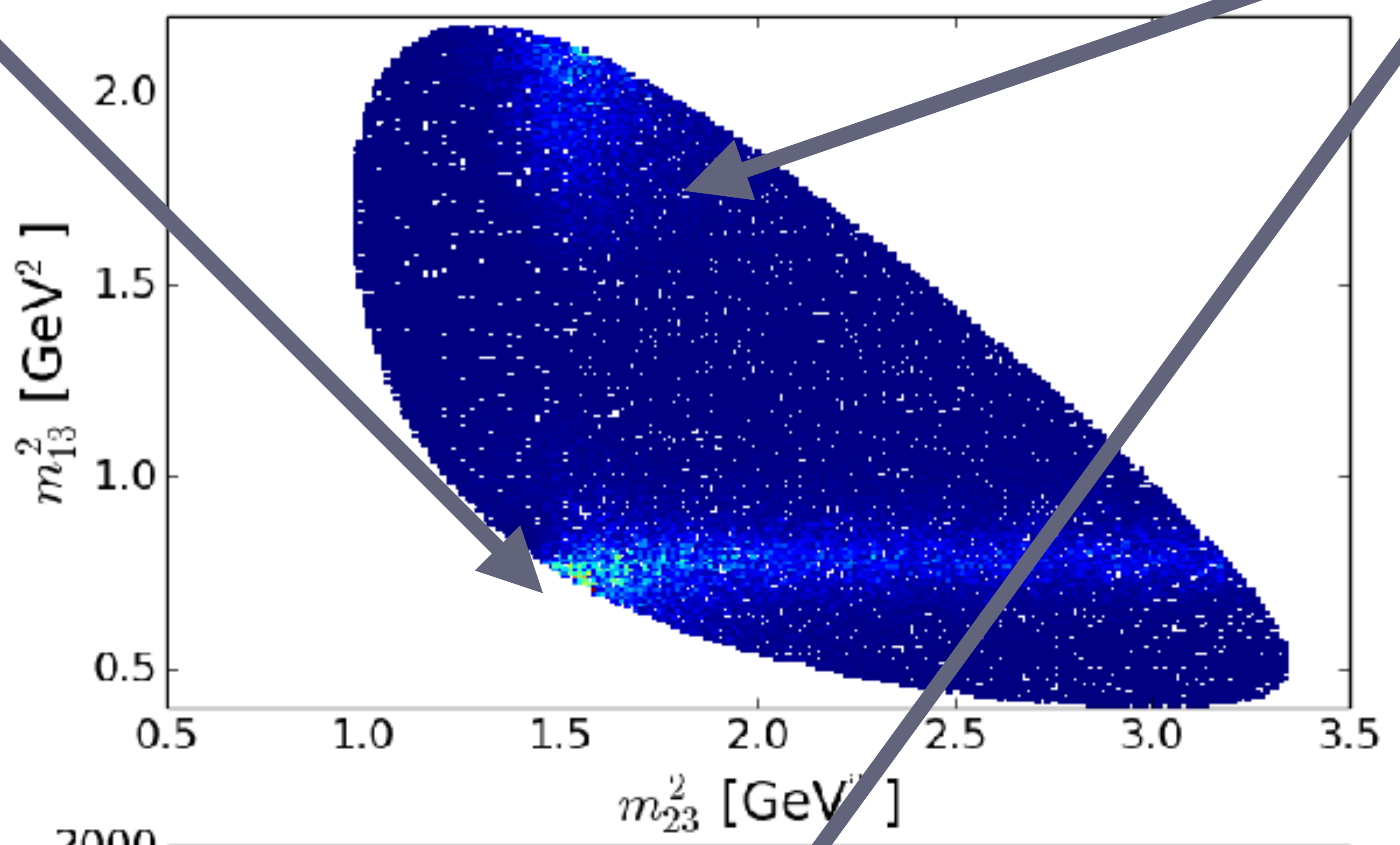
$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} \overline{|\mathscr{M}|^2} \, dm_{12}^2 \, dm_{23}^2$$

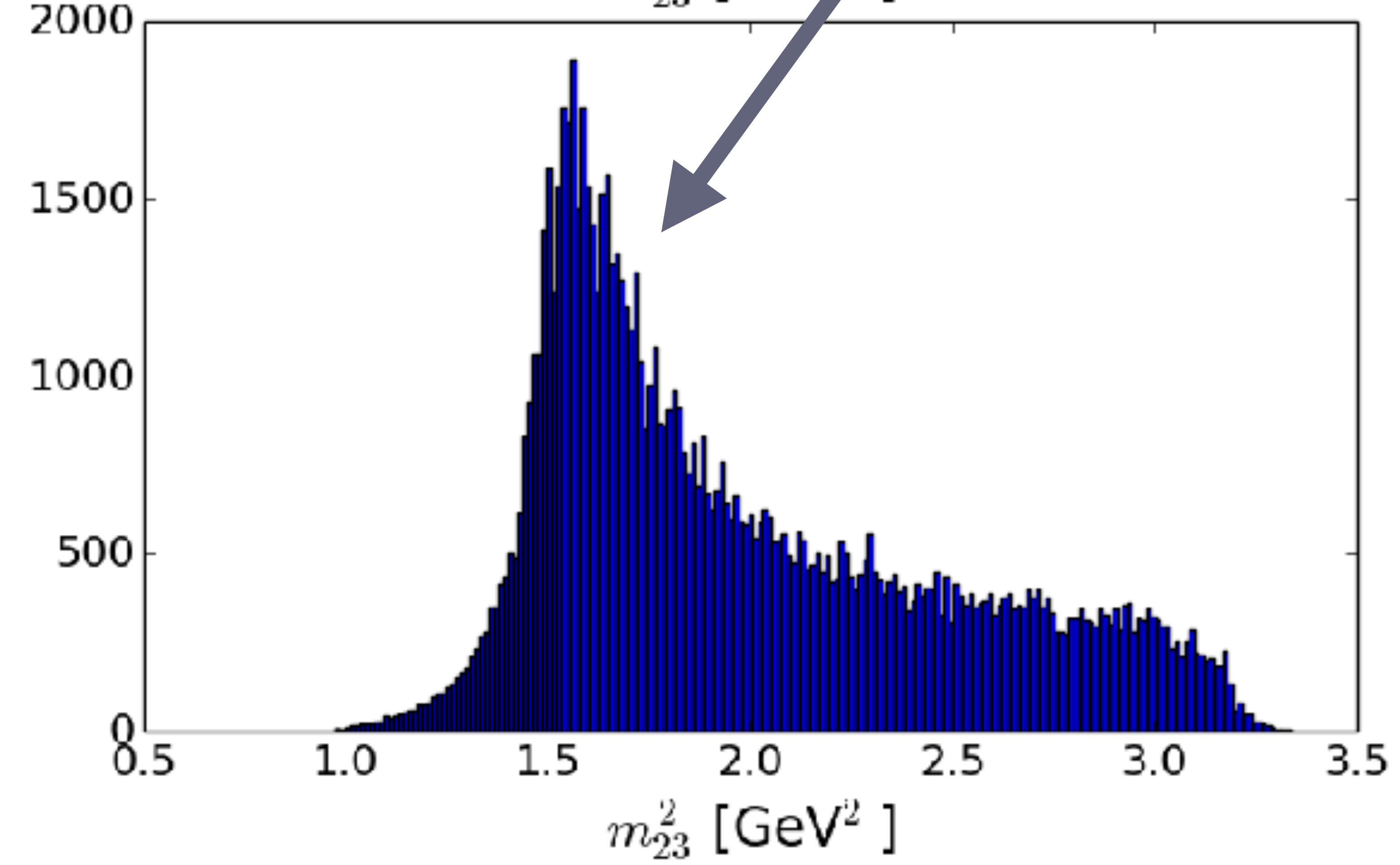
Reminder about Dalitz plots

Spin-0 resonance

Spin-1 resonance







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.

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

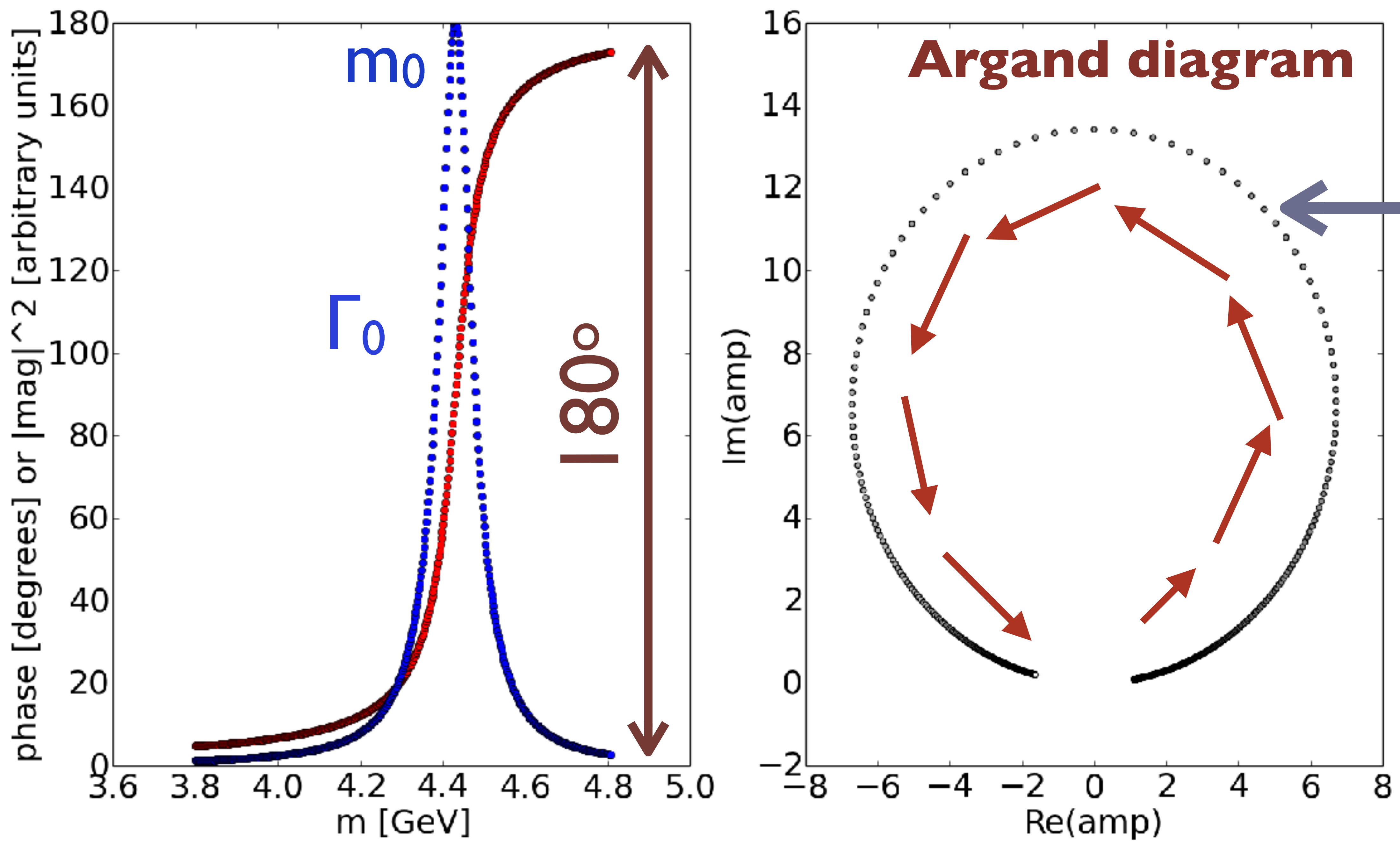
q is daughter particle momentum in rest frame of resonance.

B_L' are Blatt-Weisskopf functions for the orbital angular momentum (L) barrier factors.

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

size of the decaying particle (1.6/GeV)

Amplitude = $|BW|^2$

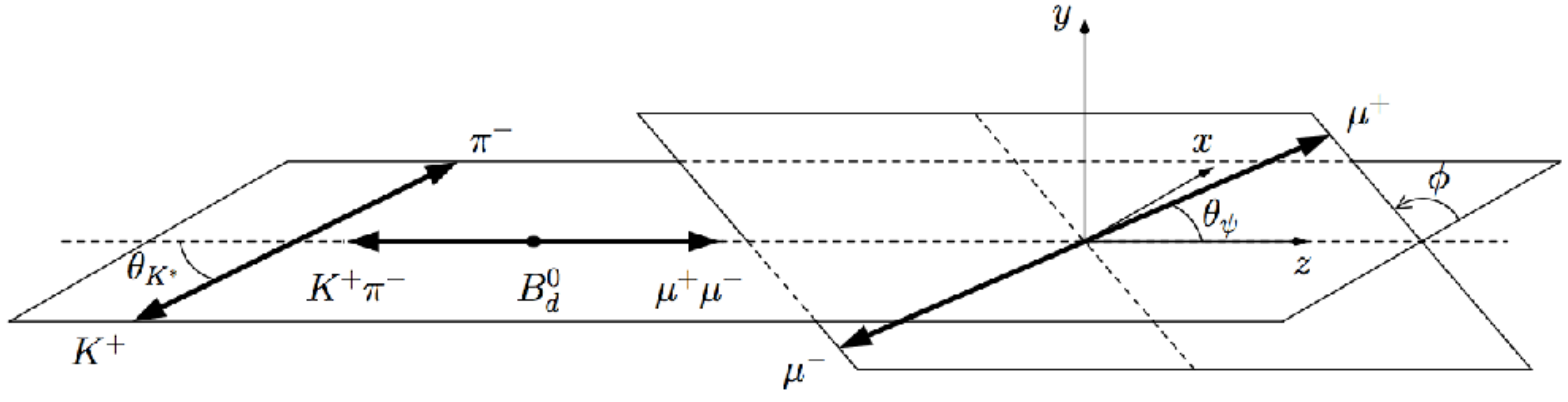


Circular trajectory in complex plane is characteristic of resonance

Circle can be rotated by arbitrary phase

Phase change of 180° across the pole

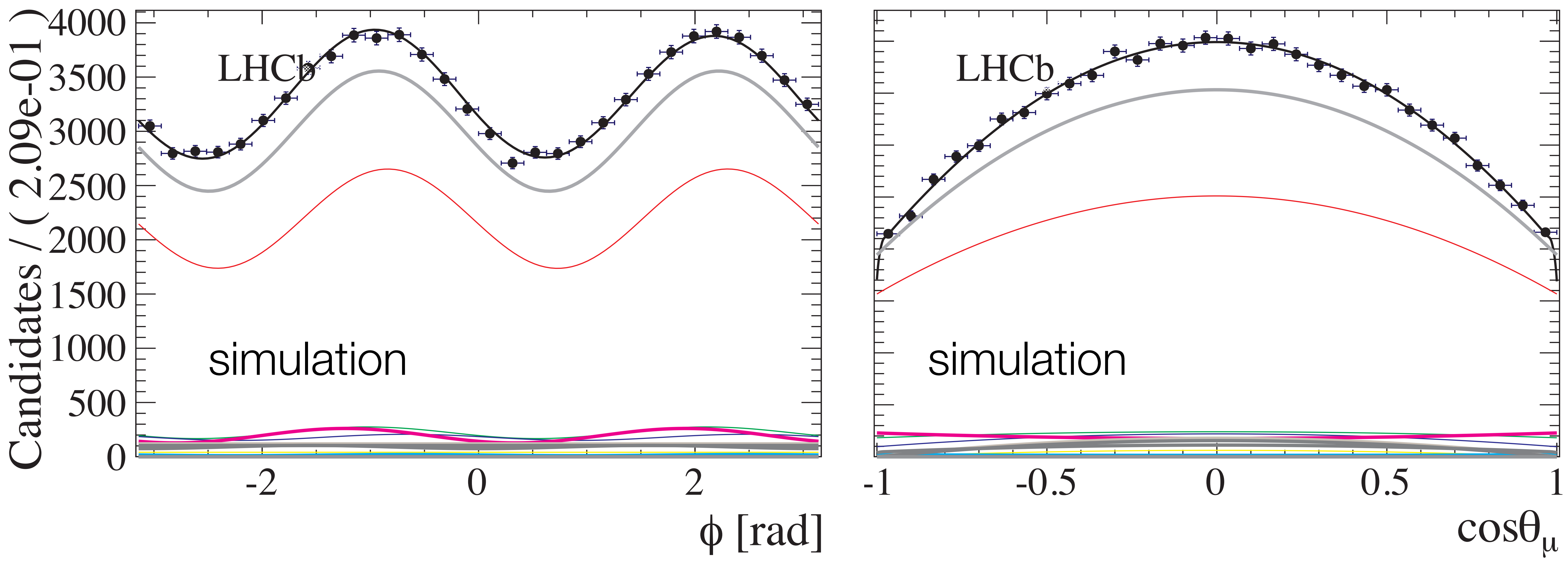
4D "Dalitz plot" (scalar ⟶ vector scalar scalar)



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 $|\mathcal{M}|^2$.

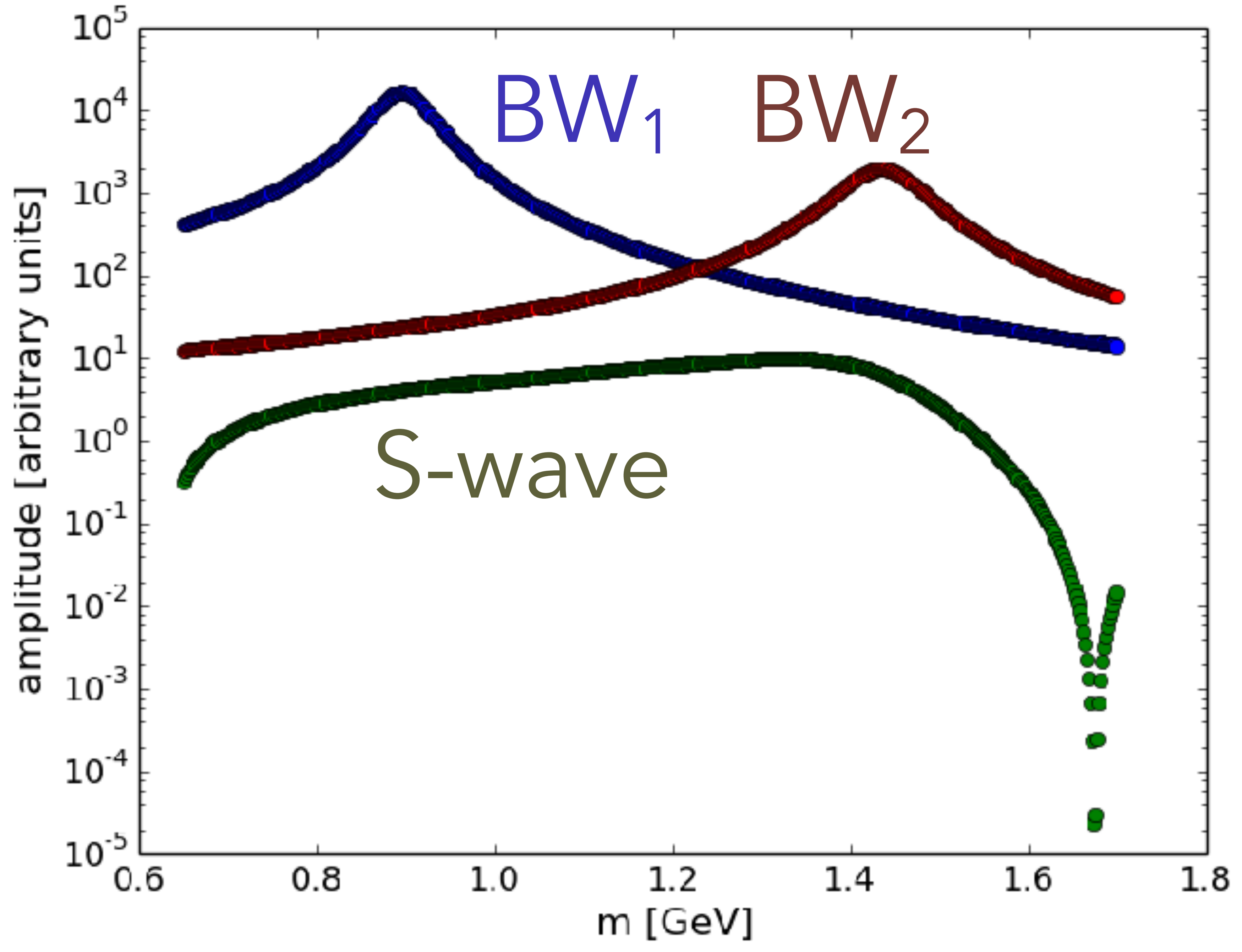


Amplitude model

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

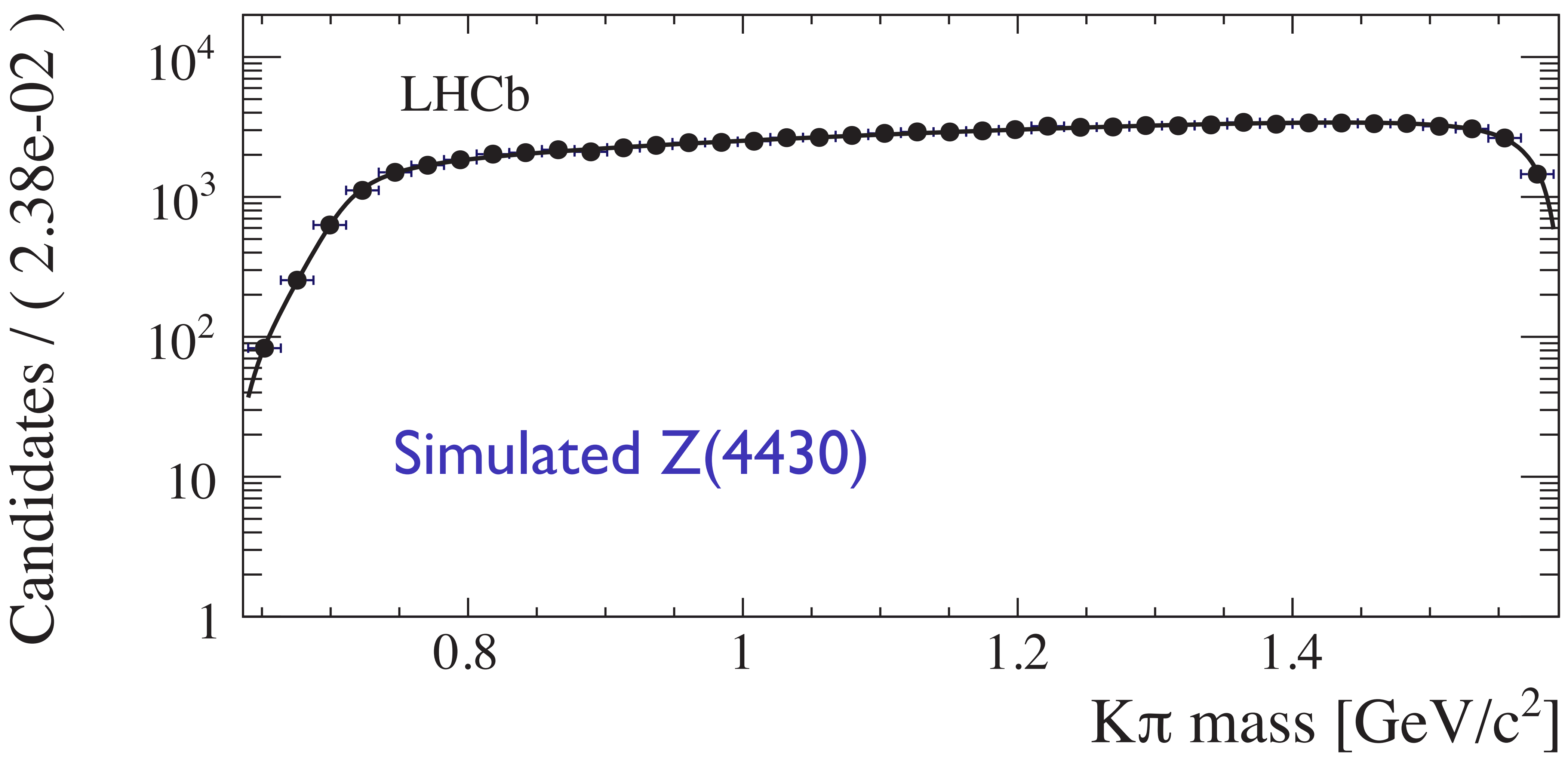
Amplitude model - adding in the Z(4430)

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 ⇒

$A_{Z,-1} = A_{Z,0} = A_{Z,+1}$

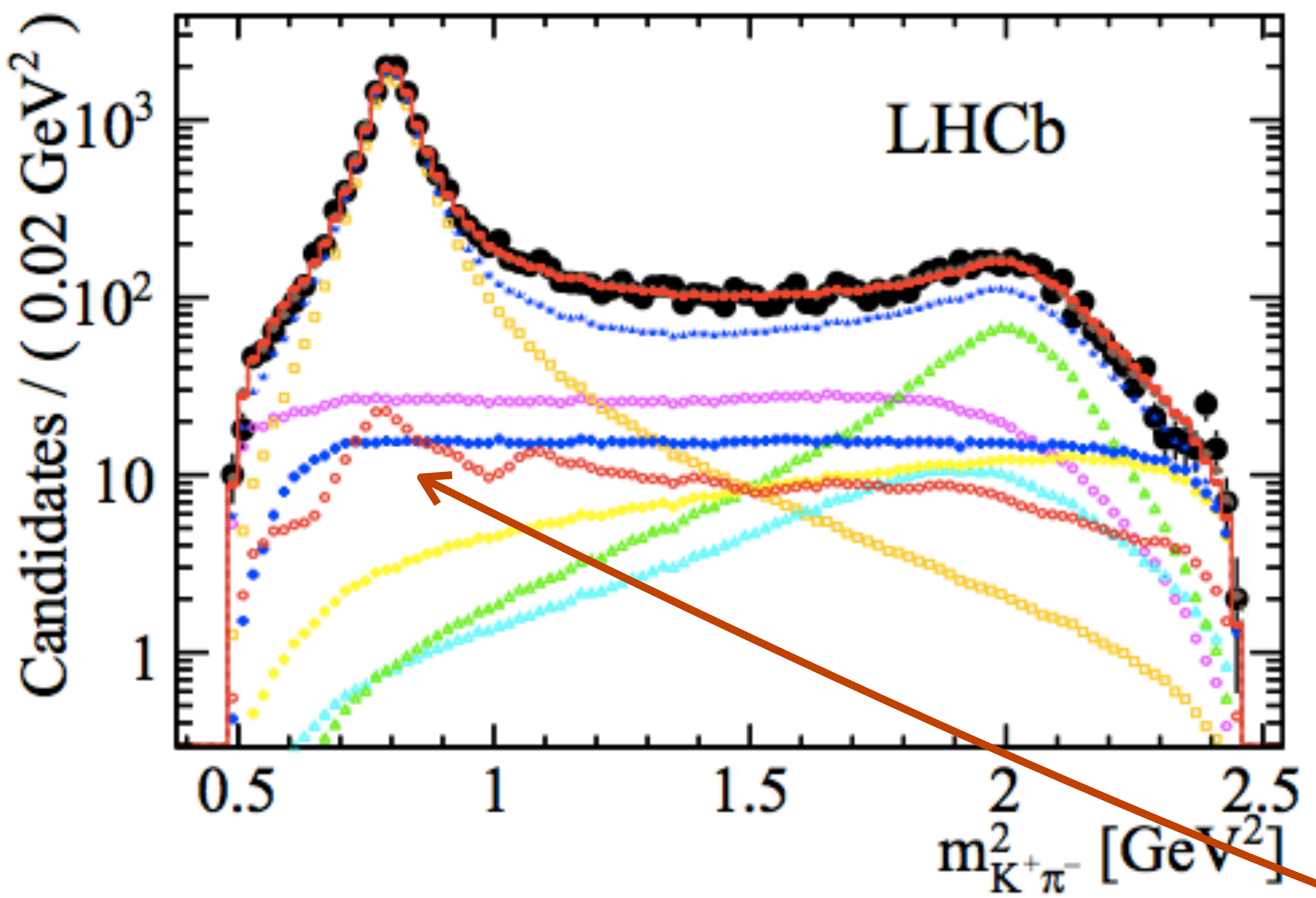


$$|\mathcal{M}|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega | m_{0\,k}, \Gamma_{0\,k}) + \sum_{\lambda_\psi^Z=-1,0,1} A_{Z,\lambda_\psi^Z}(m_{\psi\pi}, \Omega^Z | m_{0\,Z}, \Gamma_{0\,Z}) e^{i\Delta\lambda_\mu \alpha} \right|^2$$

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	$(6.1 \pm 1.2)\%$

Background from sidebands of B mass

$K^+\pi^-$ 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 **systematic uncertainty** 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

Does not violate unitarity

Sum of elastic scattering, destructively interfering with K*(1430)

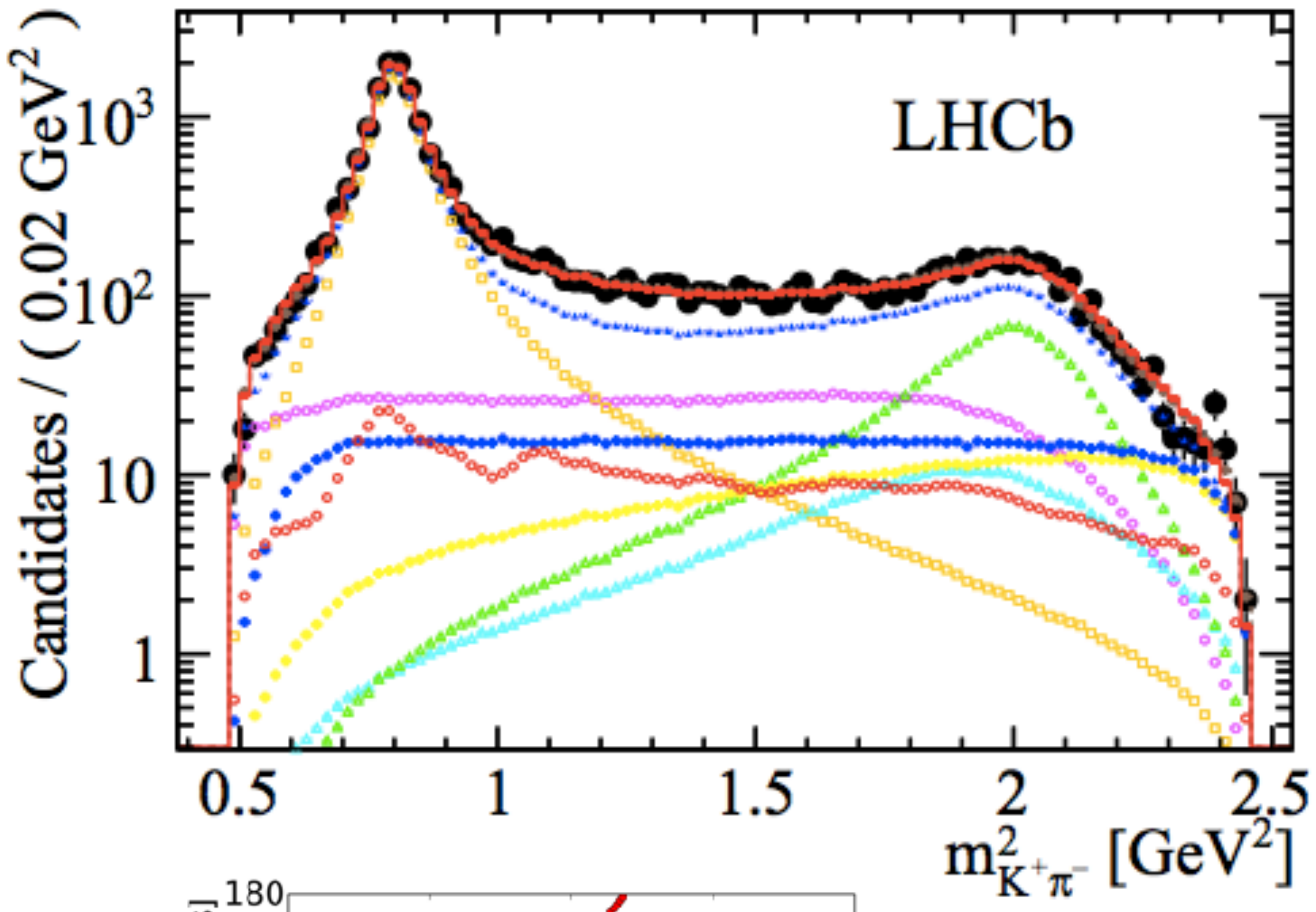
[Nucl. Phys. B296 (1988) 493]

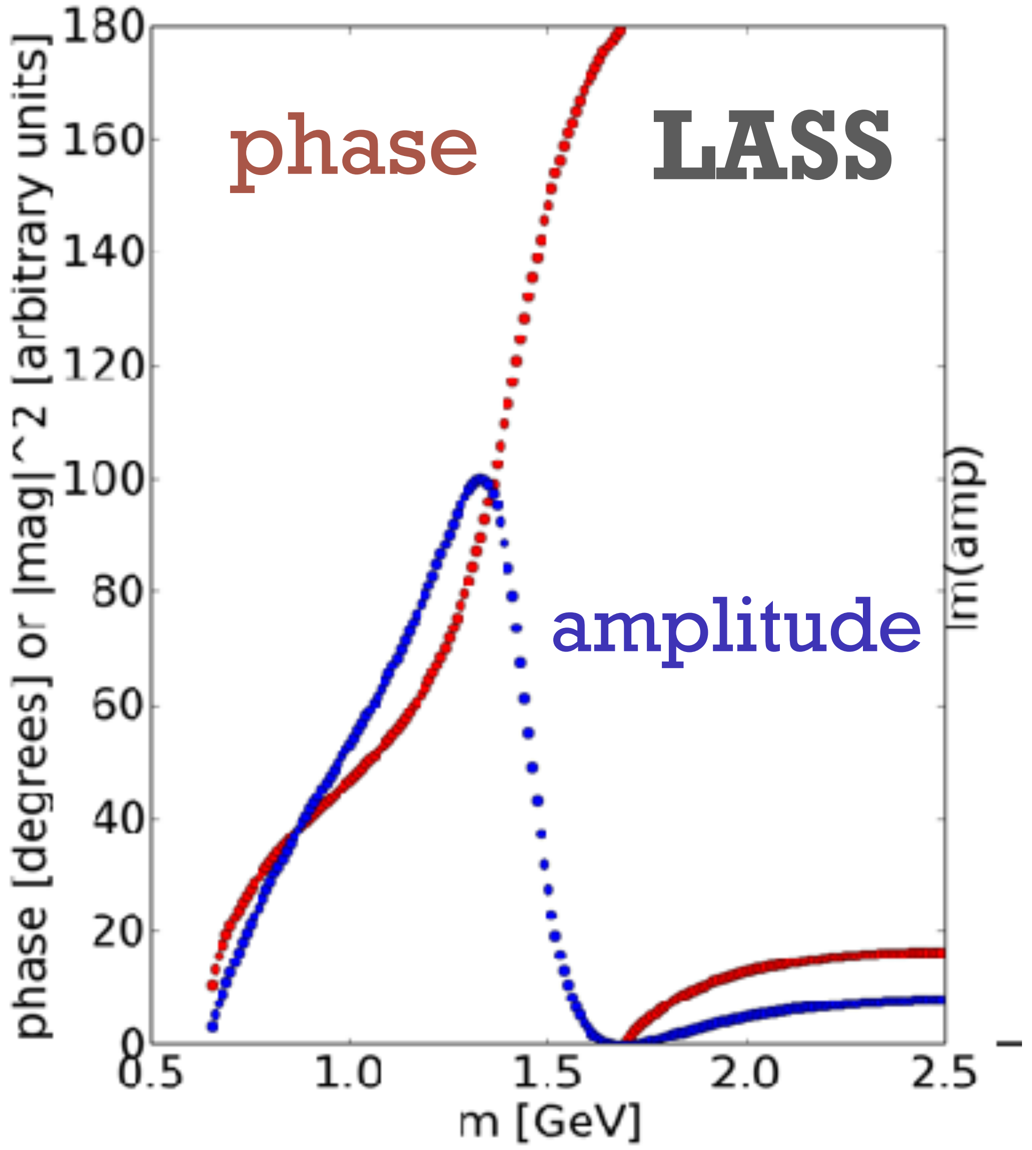
Slowly varying NR contribution

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 $B^0 \rightarrow \psi' K^+ \pi^-$ candidates (x10 Belle/BaBar). $\psi' \rightarrow \mu^+ \mu^-$

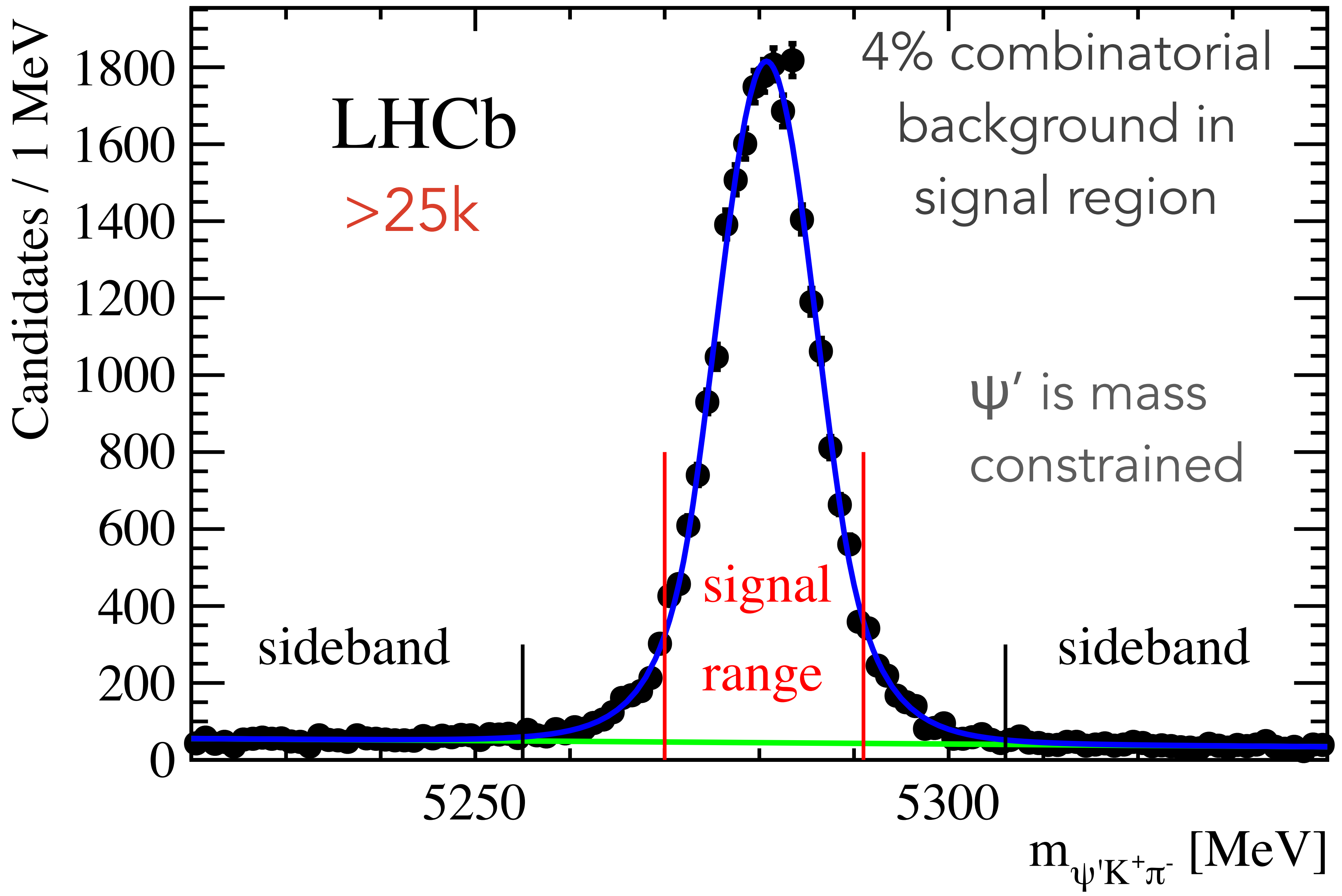
Selection: most events come through dimuon trigger (eff~90%)

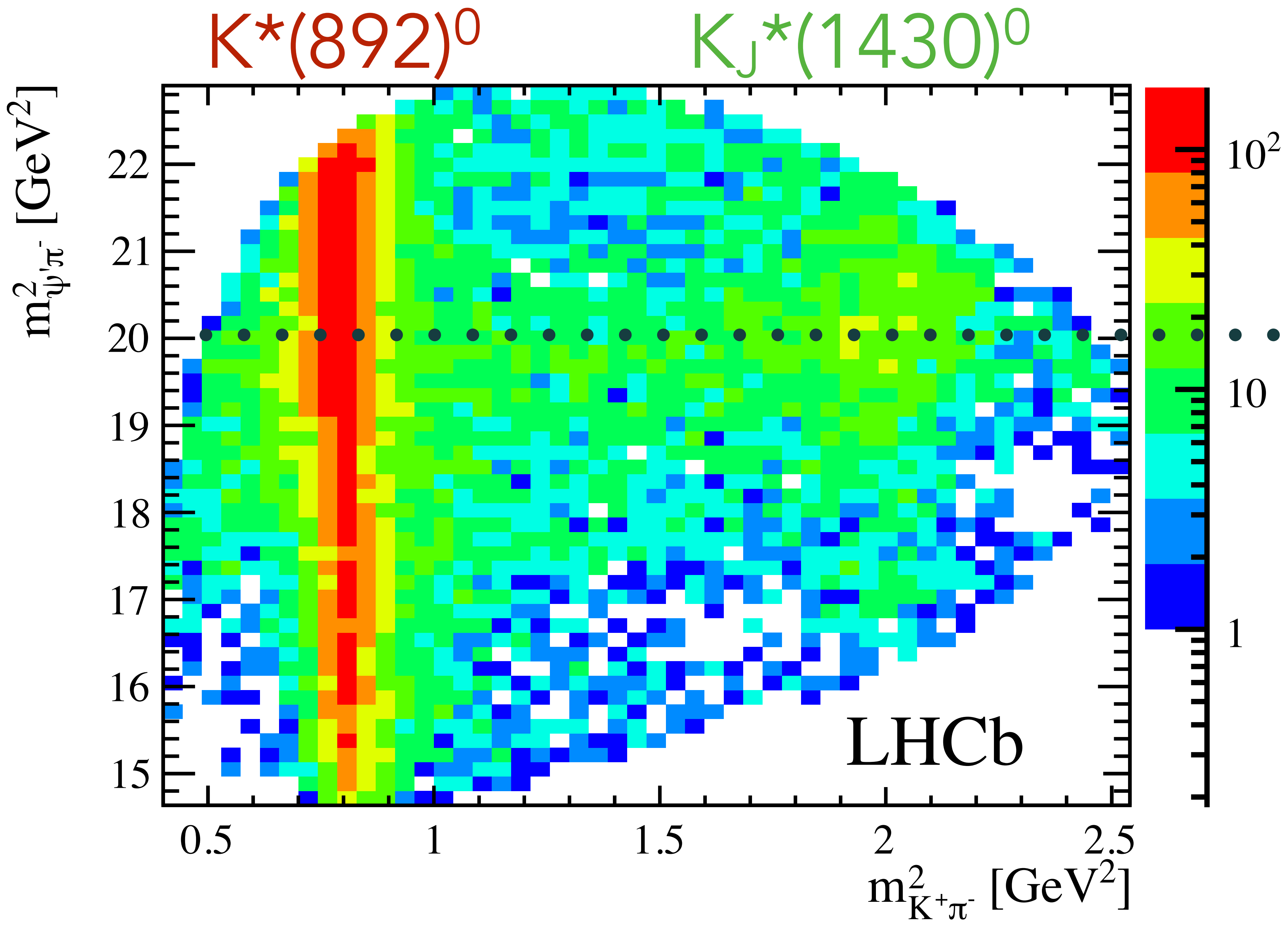
Typical B^0 p_T ~6GeV, μ^+ p_T ~ 2GeV, K^+ p_T ~1GeV.

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…





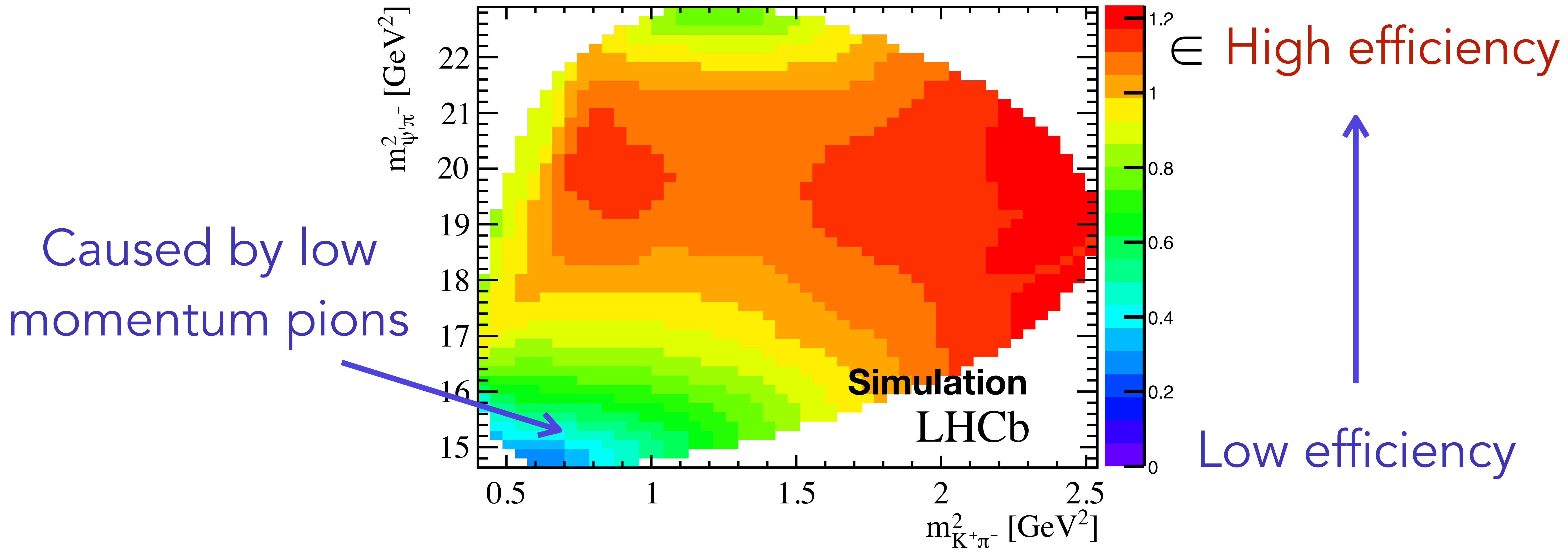
Reconstruction and selection efficiency

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	$10.3^{+3.0}_{-3.5}$

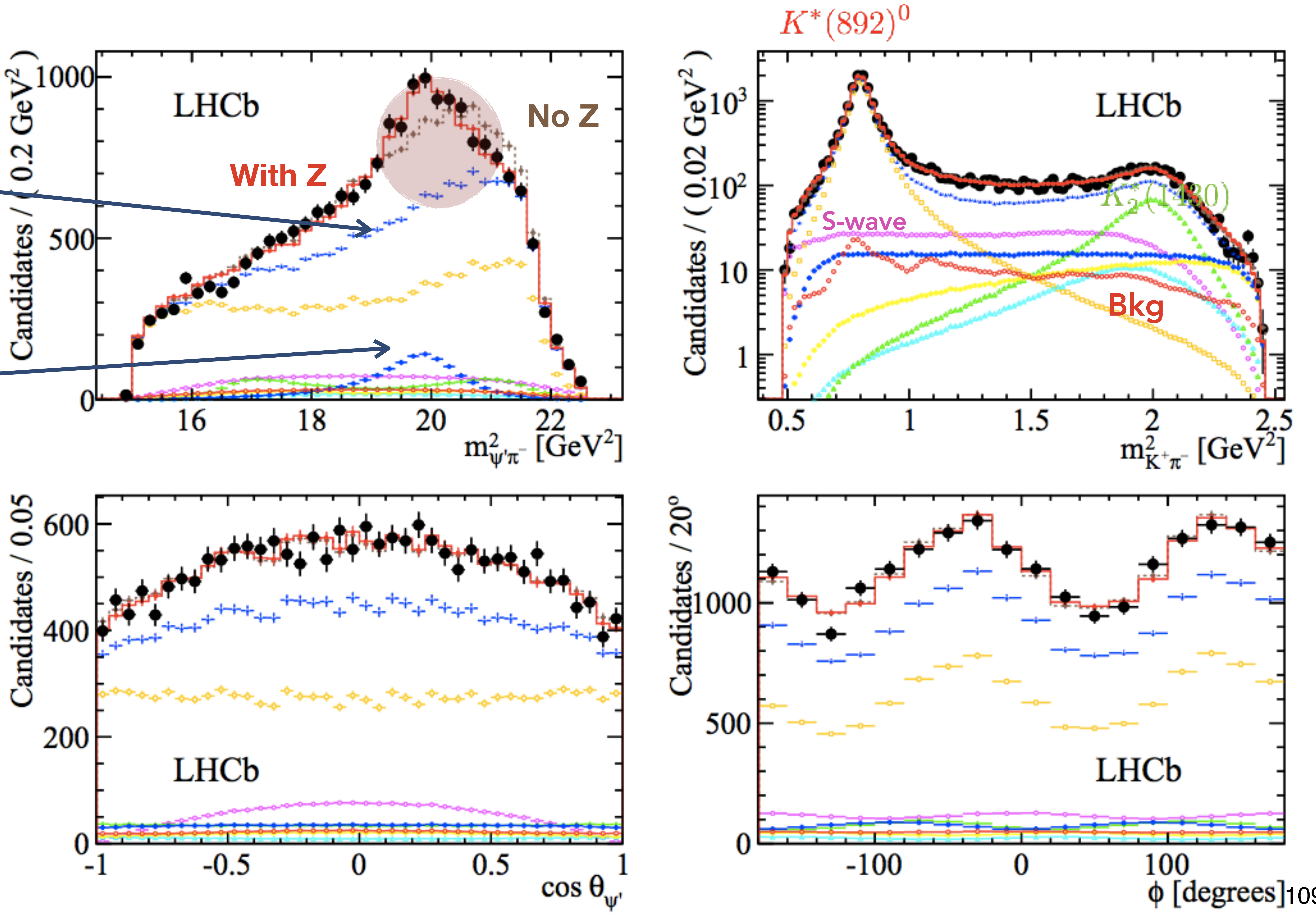
- Excellent agreement between LHCb and Belle.
- Large width - unlikely to be molecule?

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

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

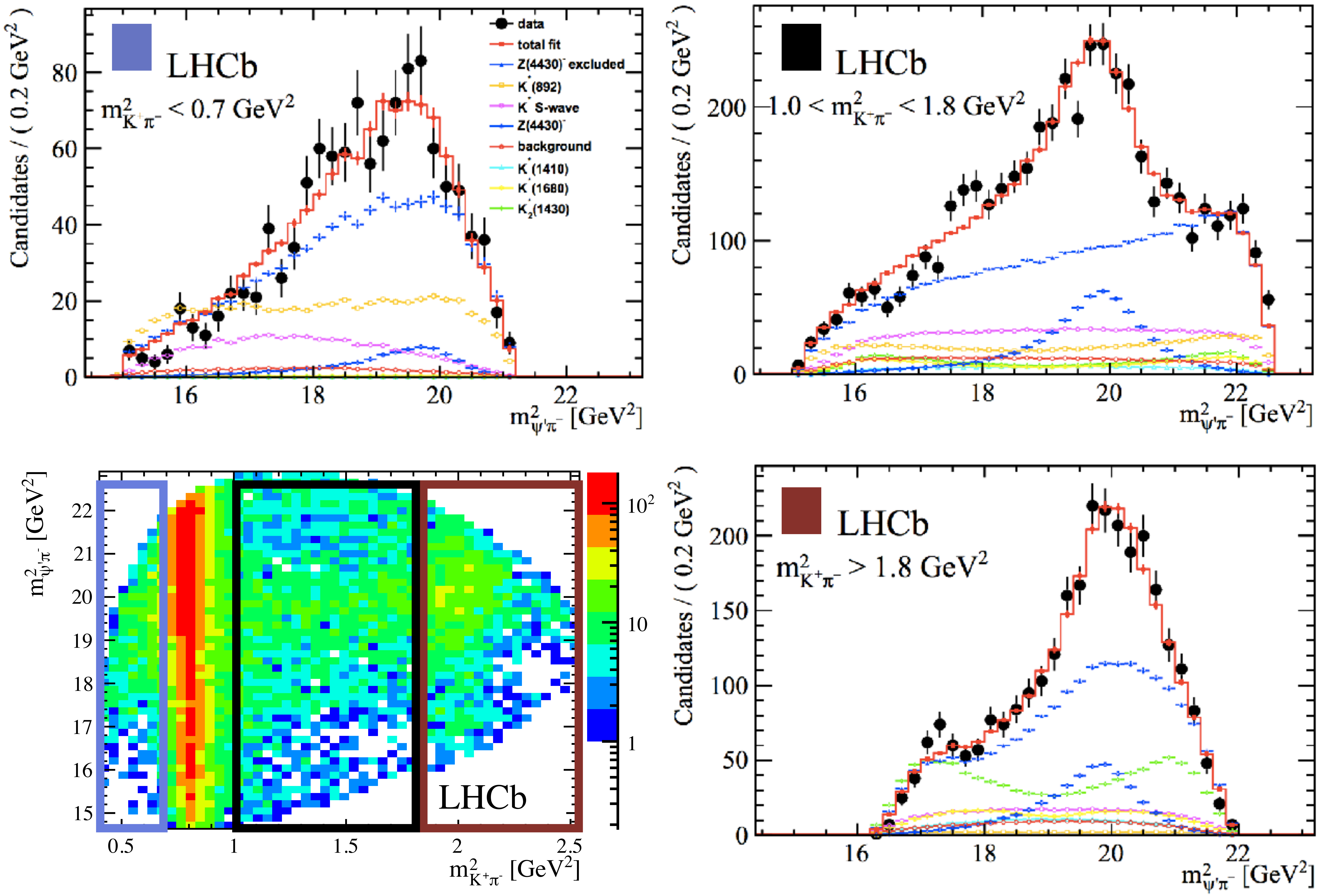
Everything except the Z ⇒ large interference between Z and $K^+\pi^-$ sector

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 $m(K^+\pi^-)$

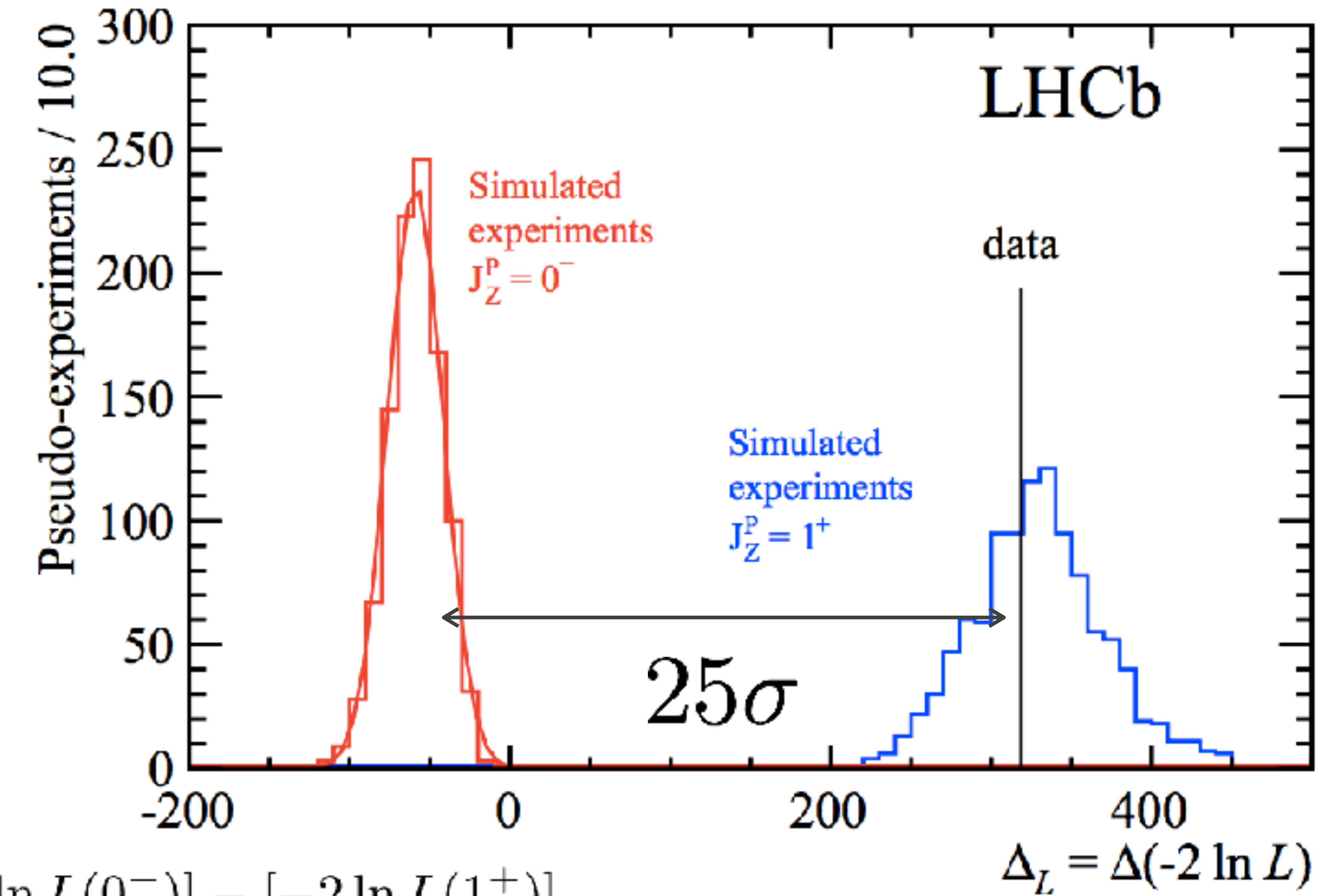


[PRL 112 (2014) 222002]

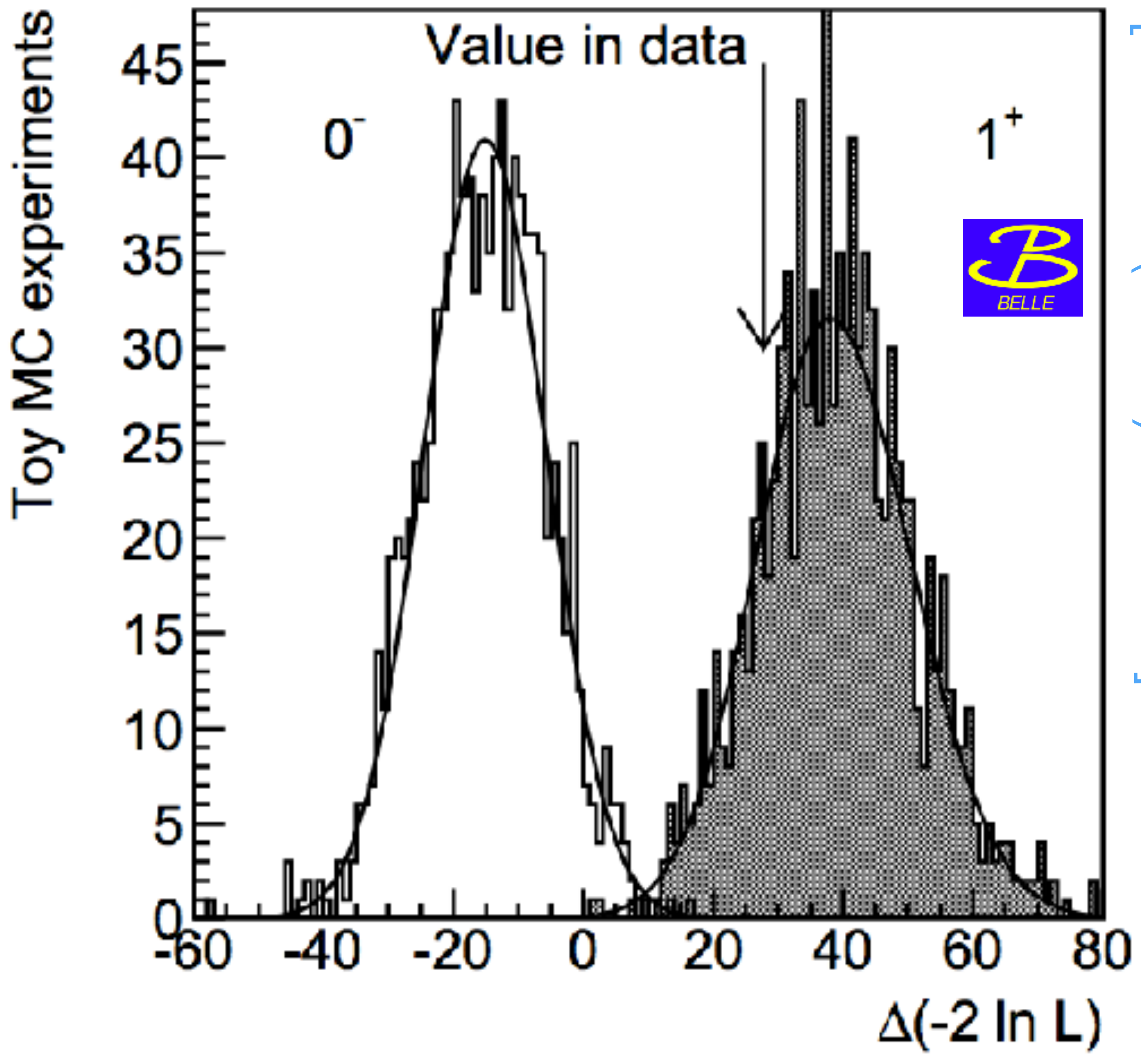
Spin determination

- 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]

111

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.

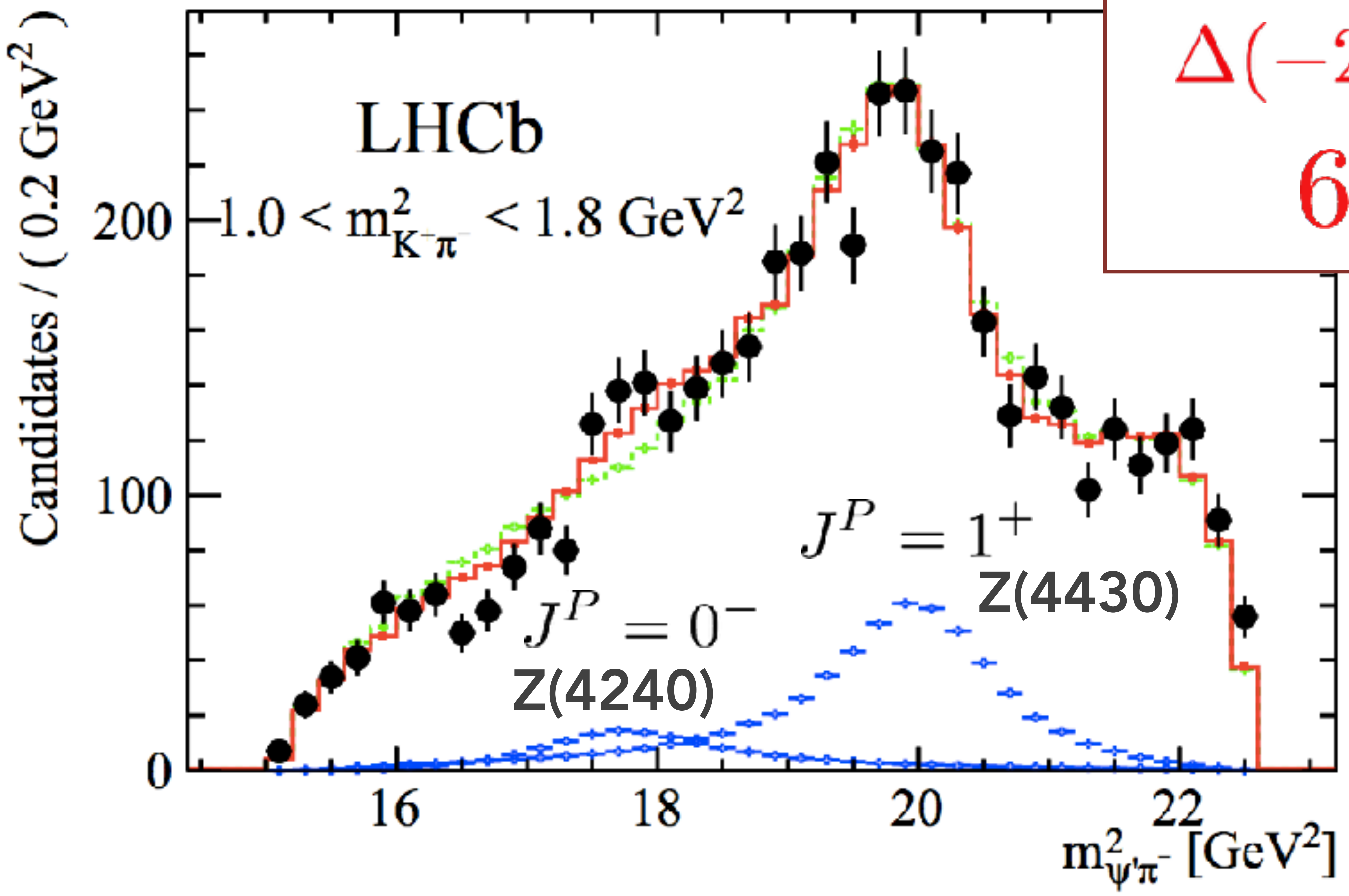
Need larger samples to characterise this state.

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]

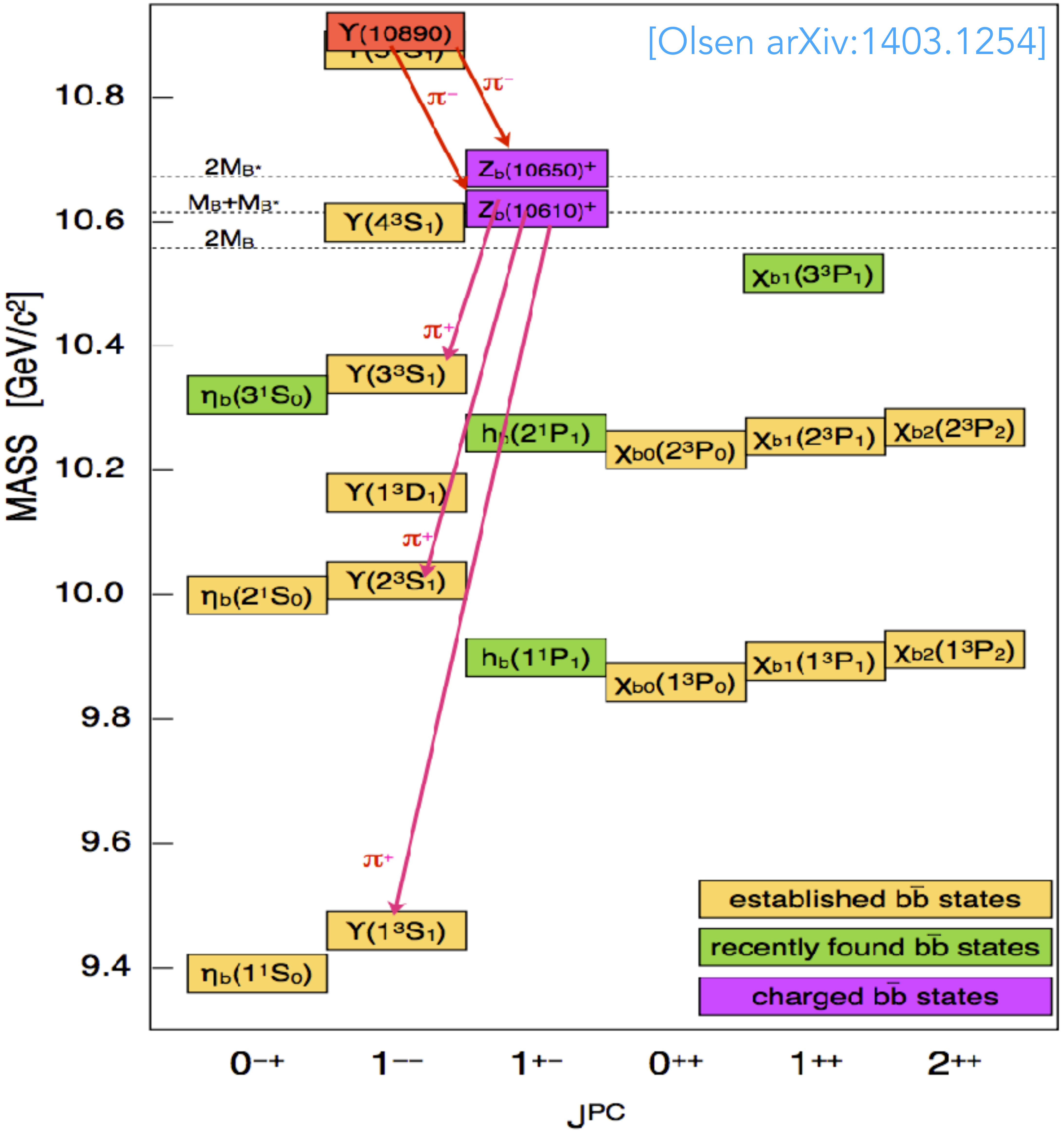


Significance from $\Delta(-2\ln L)$

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

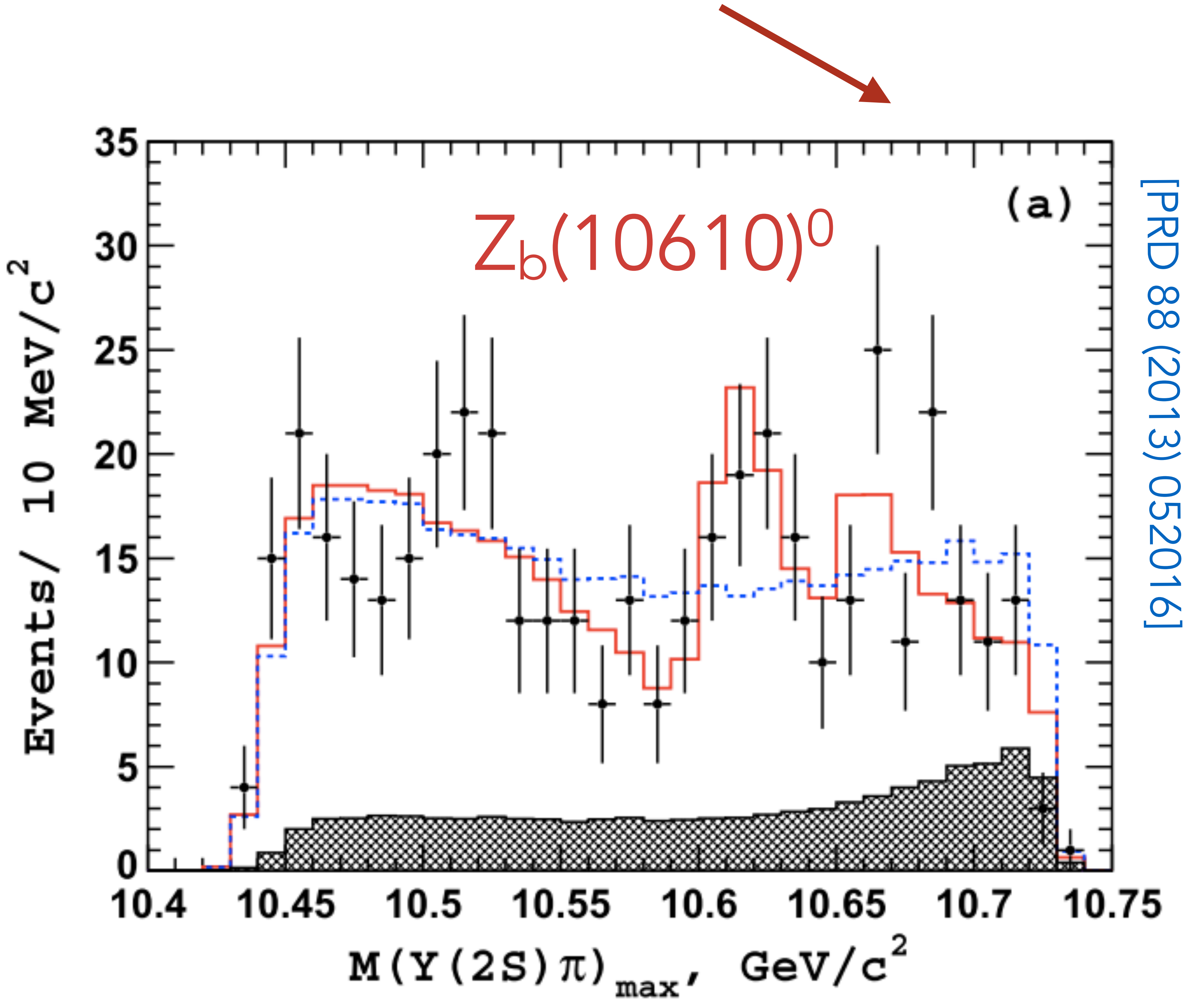


Bottomonium-like states

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?

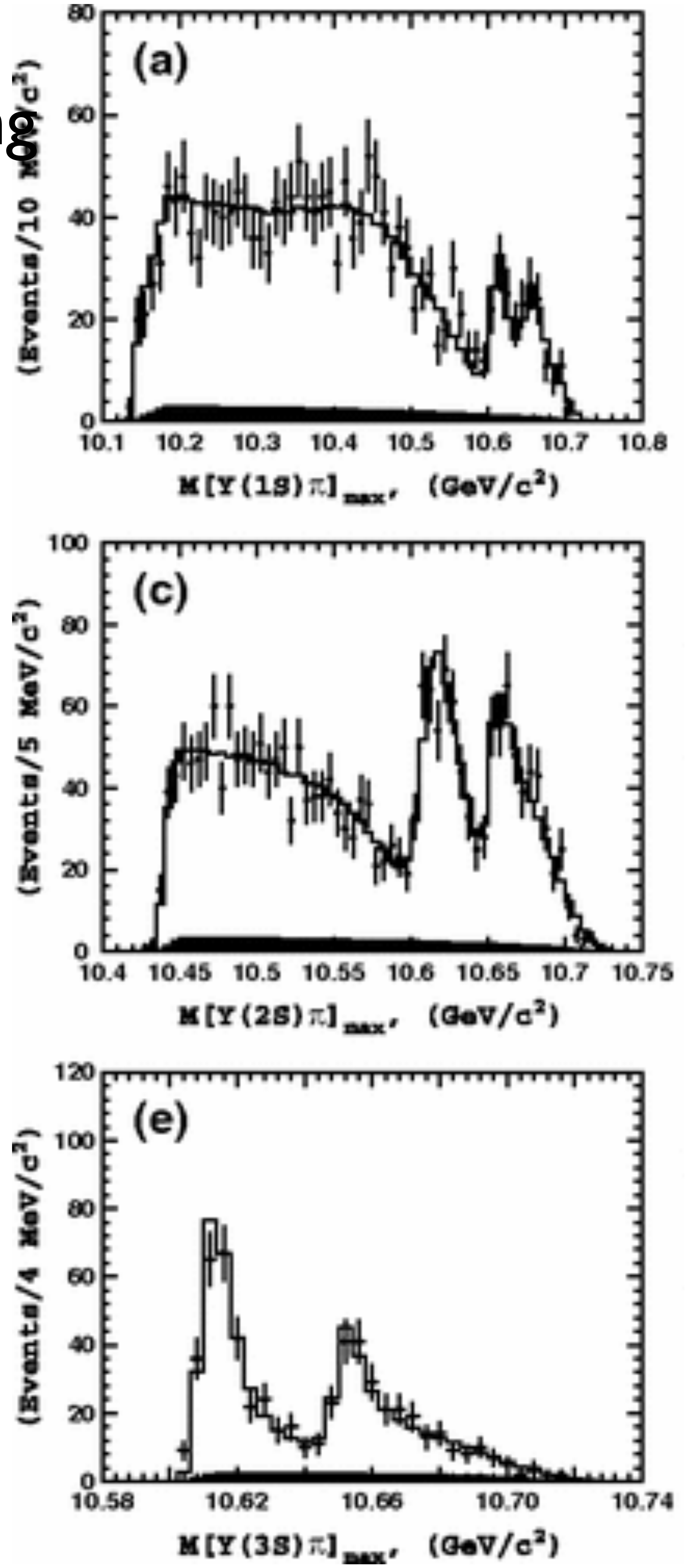
Also first evidence for neutral isospin partners in $\pi^0\pi^0\Upsilon(2S)$ amplitude fit.



[PRD 88 (2013) 052016]

Projections of Dalitz plots

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



[PRL 108 (2012) 122001]

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

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?