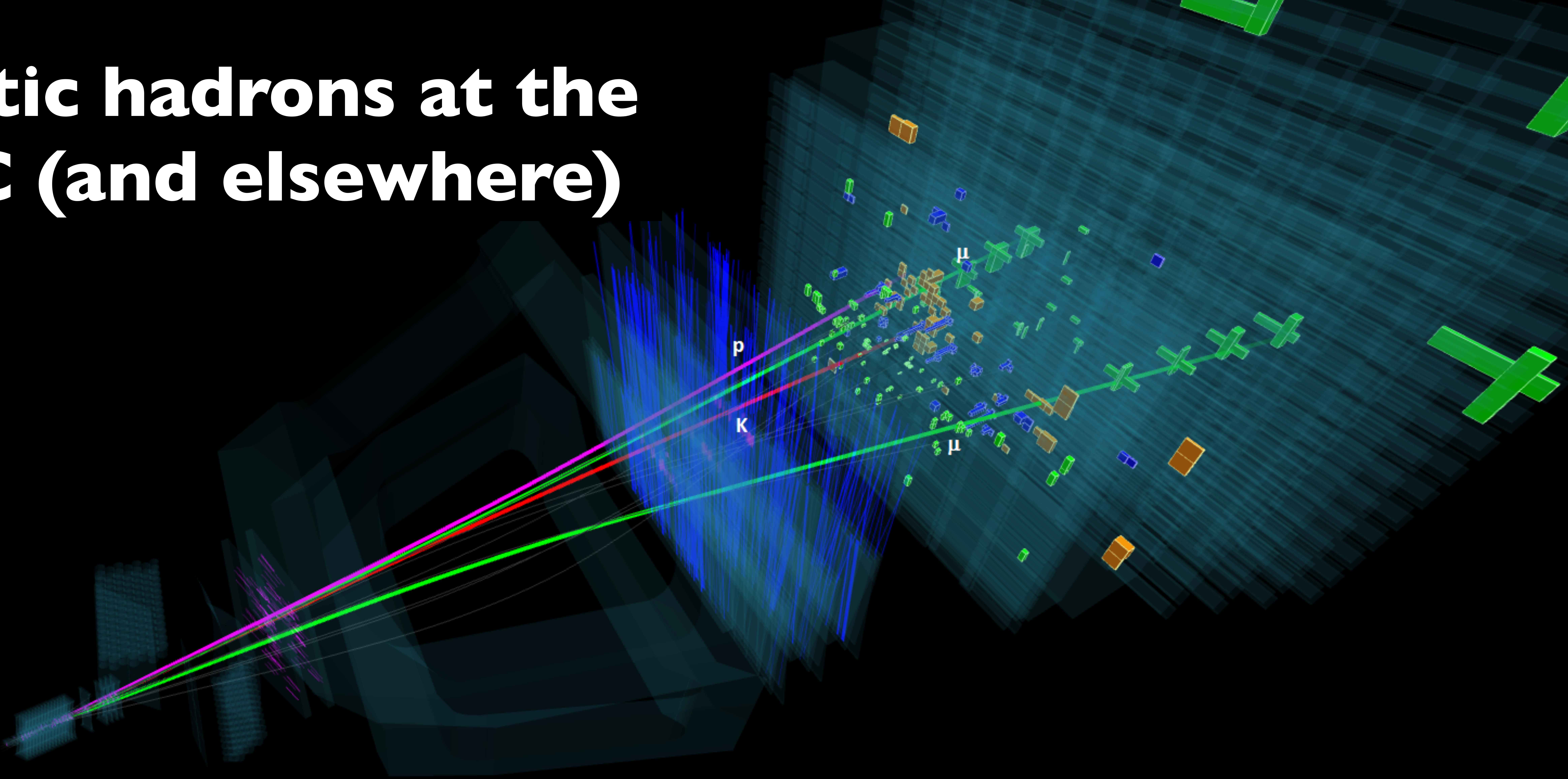
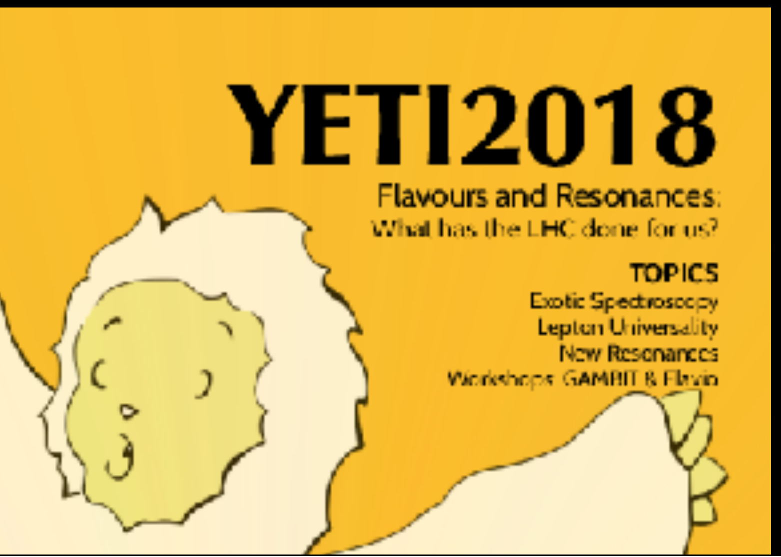
Exotic hadrons at the LHC (and elsewhere)





@GreigCowan (Edinburgh)

YETI 2018

IPPP Durham

The University of Edinburgh

Science & Technology Facilities Council

Rough outline

See lecture from A. Alves for details on many experimental analysis methods

1. Experimental facilities

2. The quark model → new results about "conventional" baryons

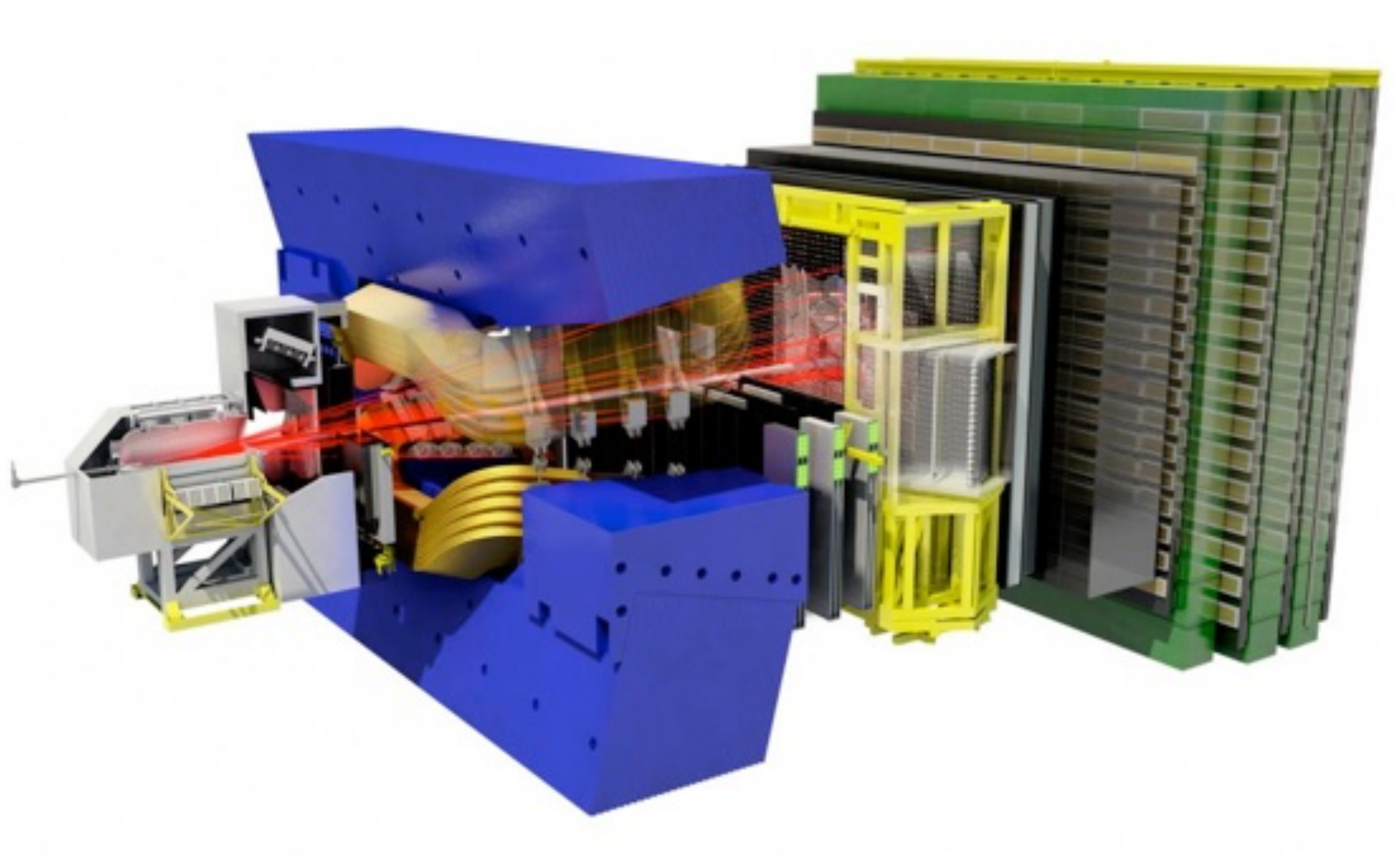
3. The charmonium system as a portal to exotic hadrons

    a. Tetraquarks

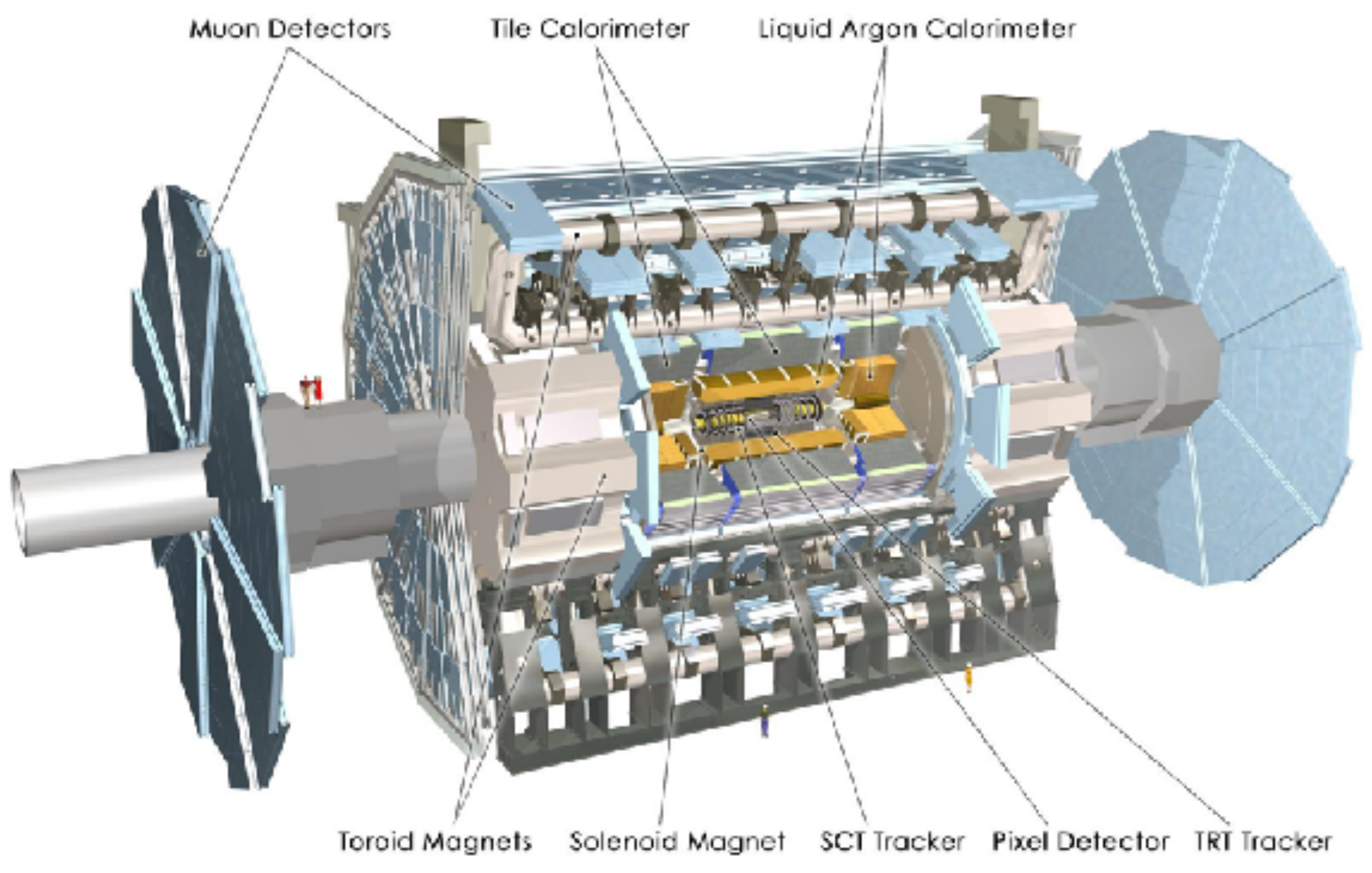
    b. Pentaquarks

Experimental facilities

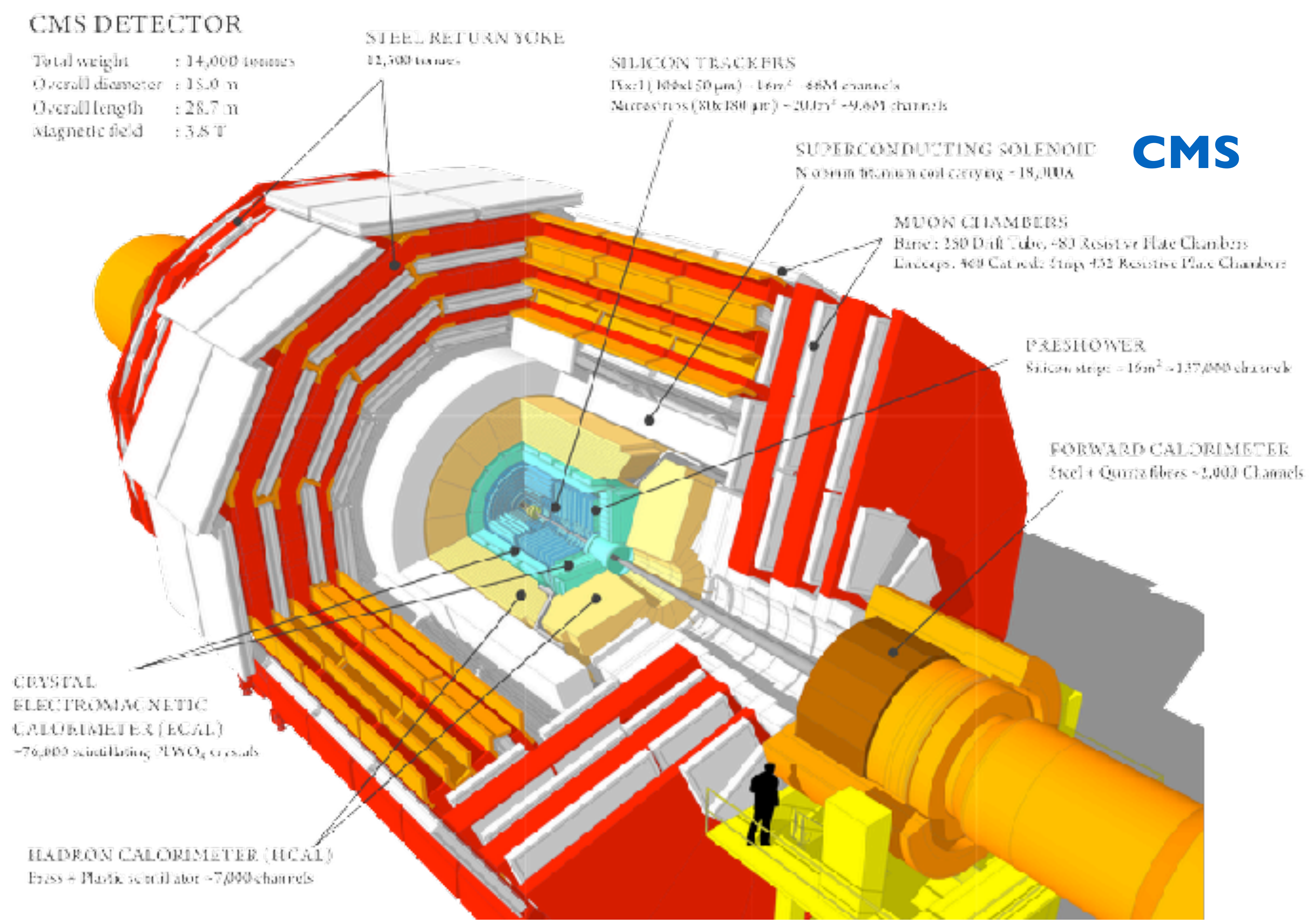
LHCb



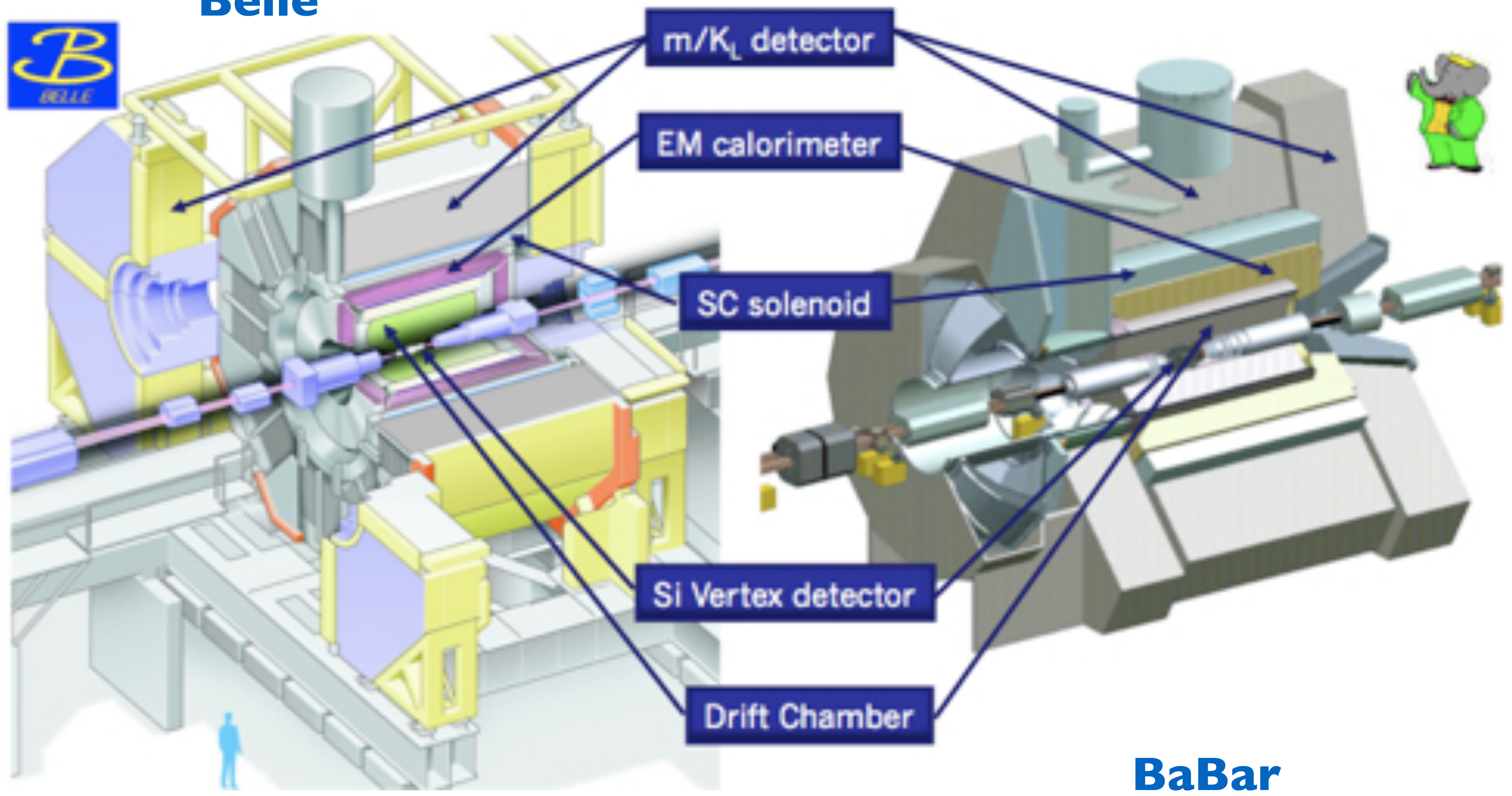
ATLAS



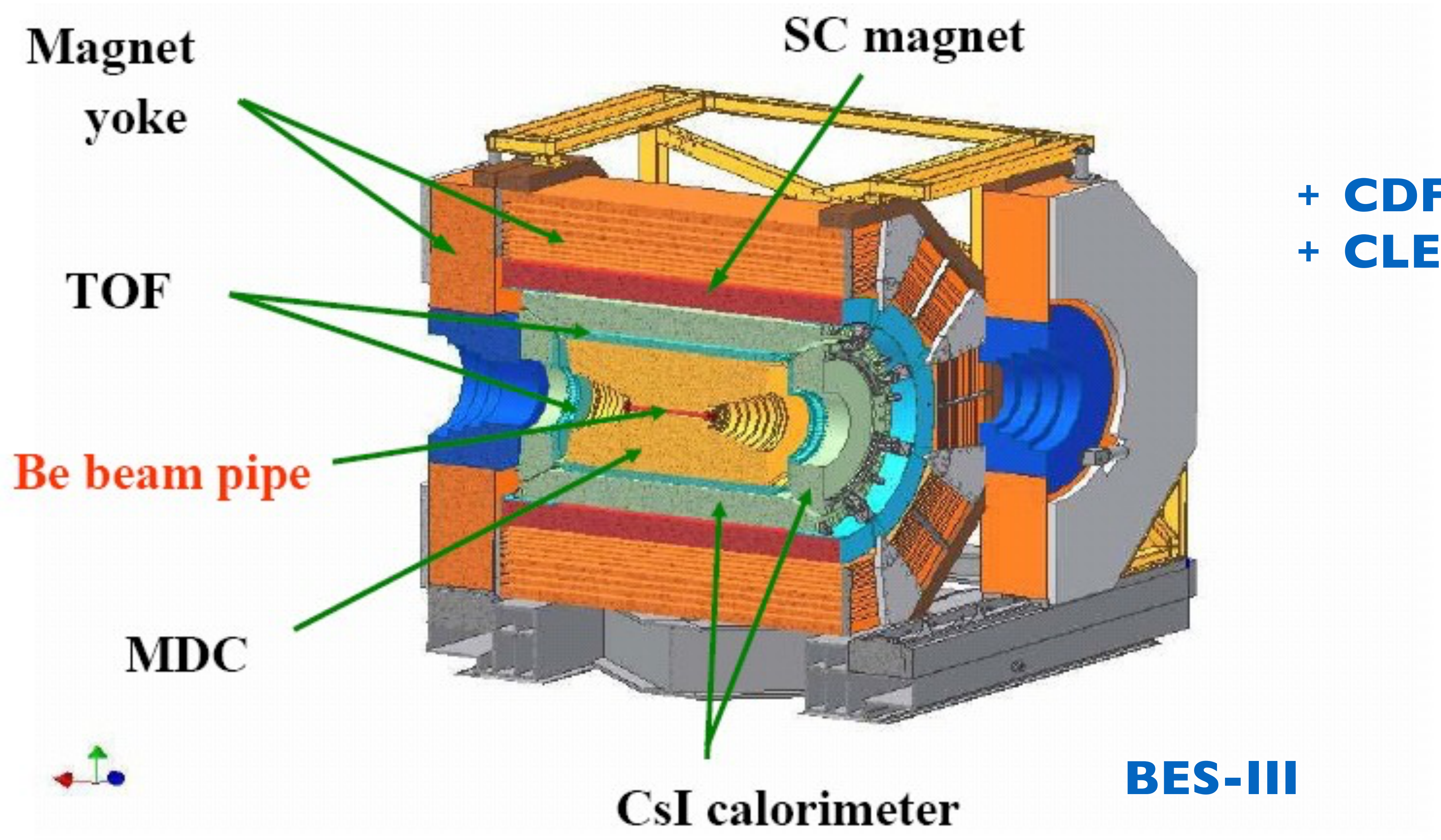
CMS



Belle



BaBar



BES-III

+ **CDF, D0 @ Tevatron**
+ **CLEO**

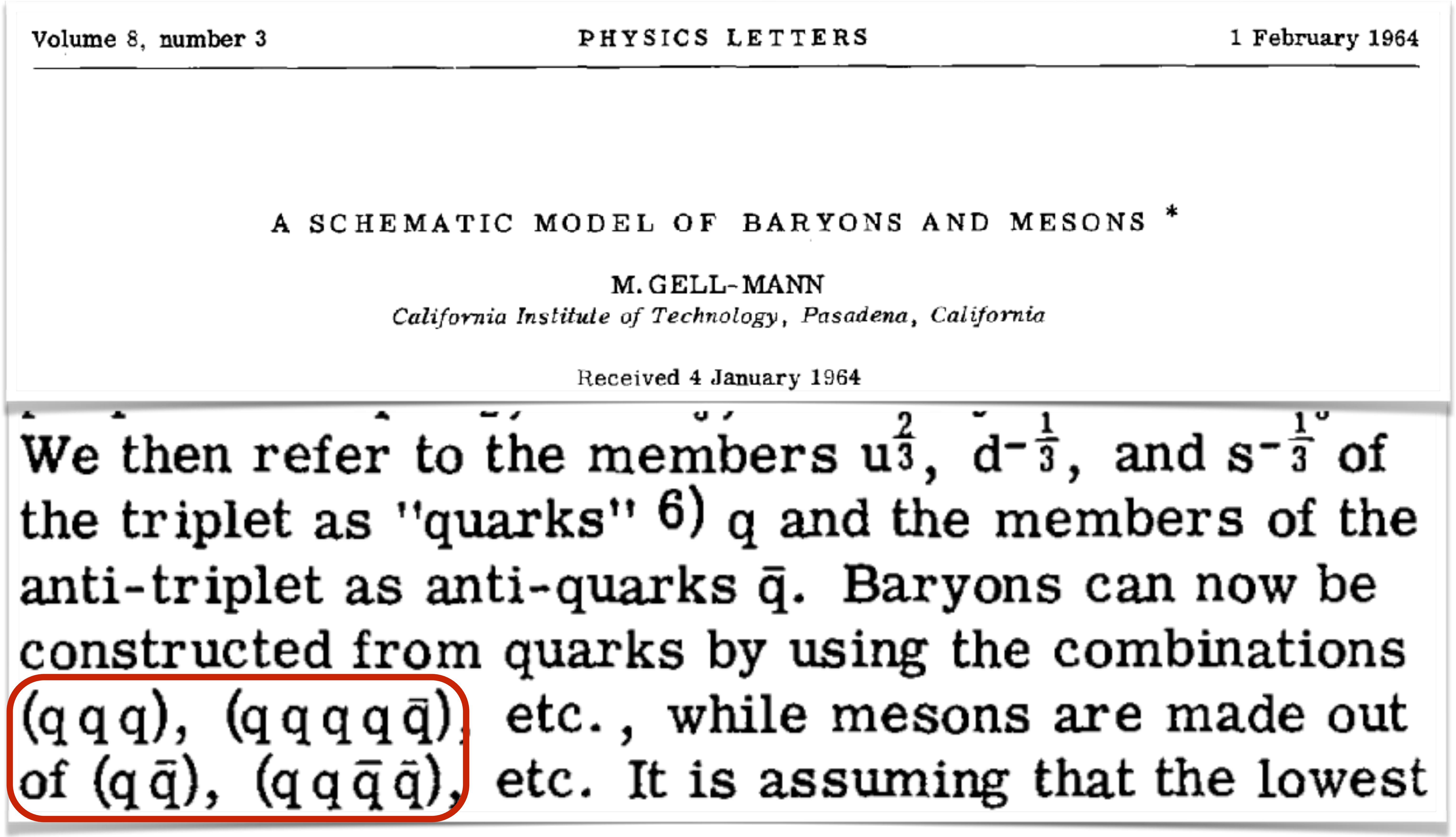
Experimental facilities

B-factories

Experiments	**Laboratory**	**Collider**	**Production environment**	**Approximate operational period**
Belle/Belle-II	KEK, Japan	KEKB	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	1999-2010 (2018-2025)
BaBar	SLAC, USA	PEP-II	$e^+e^- \to \Upsilon(4S) \to B\bar{B}$	1999-2008
CDF/D0	Fermilab, USA	Tevatron	$p\bar{p} \to b\bar{b}X$ (2 TeV)	1987-2011
BES-III	IHEP, China	BEPC	$e^+e^- \to \psi(3770) \to D\bar{D}$	2008-present
CLEO	Cornell, USA	CESR	$e^+e^- \to \psi(3770) \to D\bar{D}$	~2000
ATLAS/CMS/LHCb	CERN, Switzerland	LHC	$pp \to b\bar{b}\,X$ (7-13 TeV)	2011-present

+ **COMPASS (CERN) and CLAS/GlueX (Jefferson Lab) fixed target experiments**

The birth of the quark model

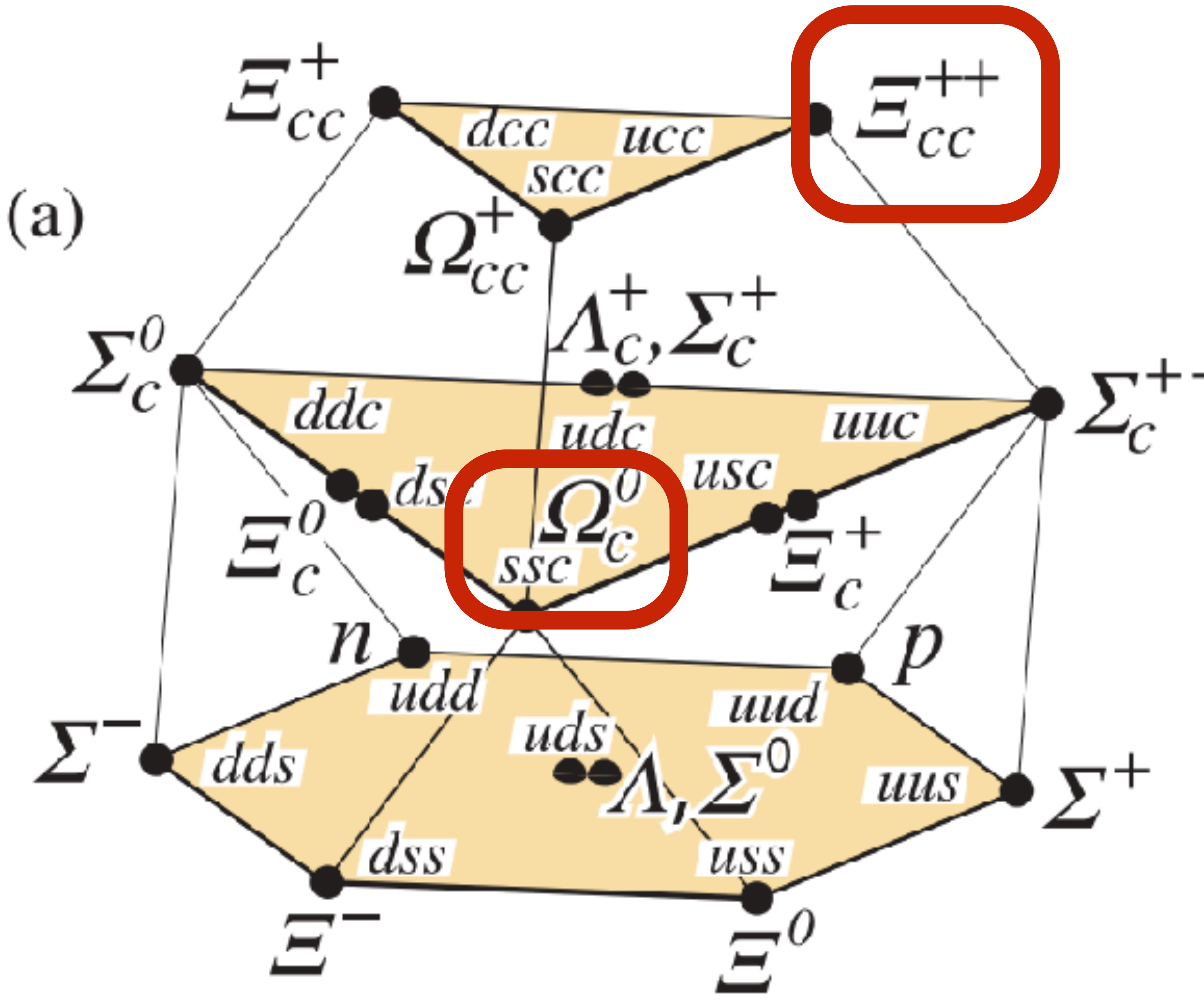

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

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



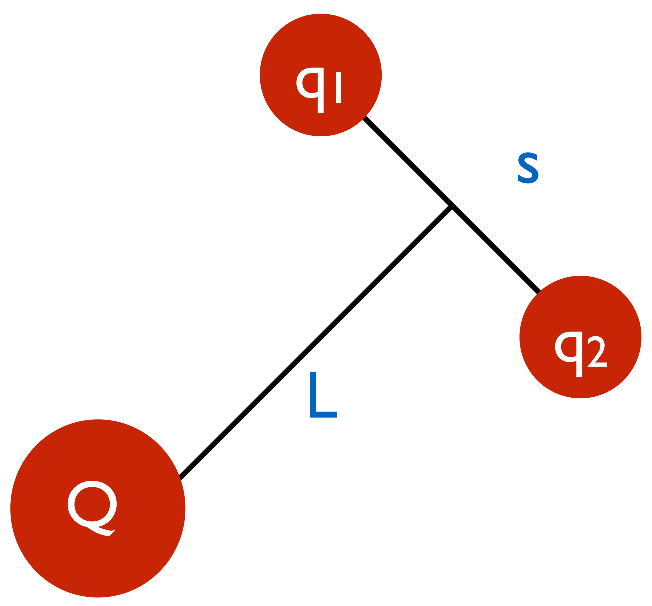
Quarks as the building blocks of mesons and baryons was first proposed in 1964 by Gell-Mann and Zweig

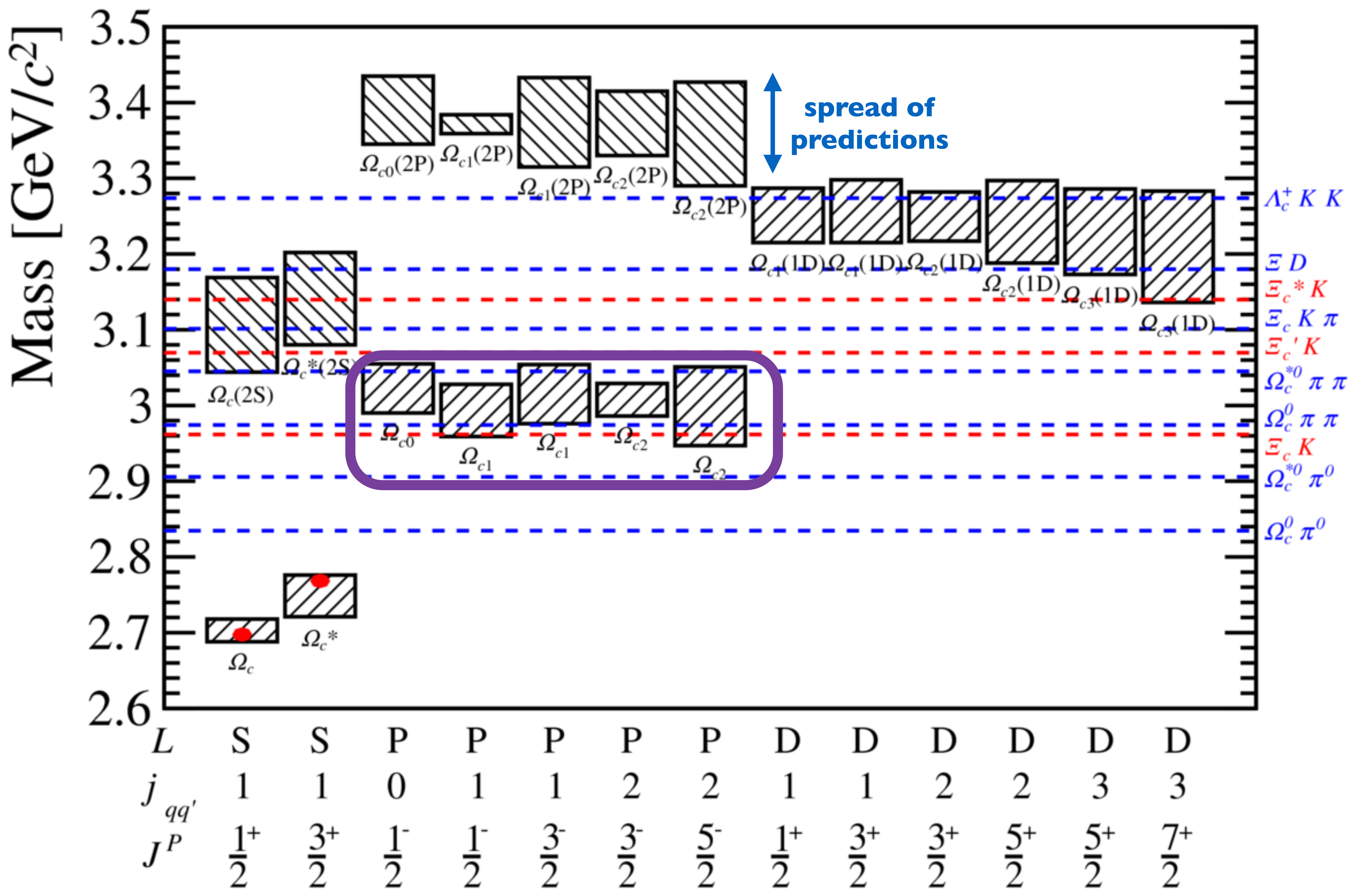
Strange-charm baryons

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

Static heavy quark (Q) + light **ss** diquark

5 P-wave states predicted (*)

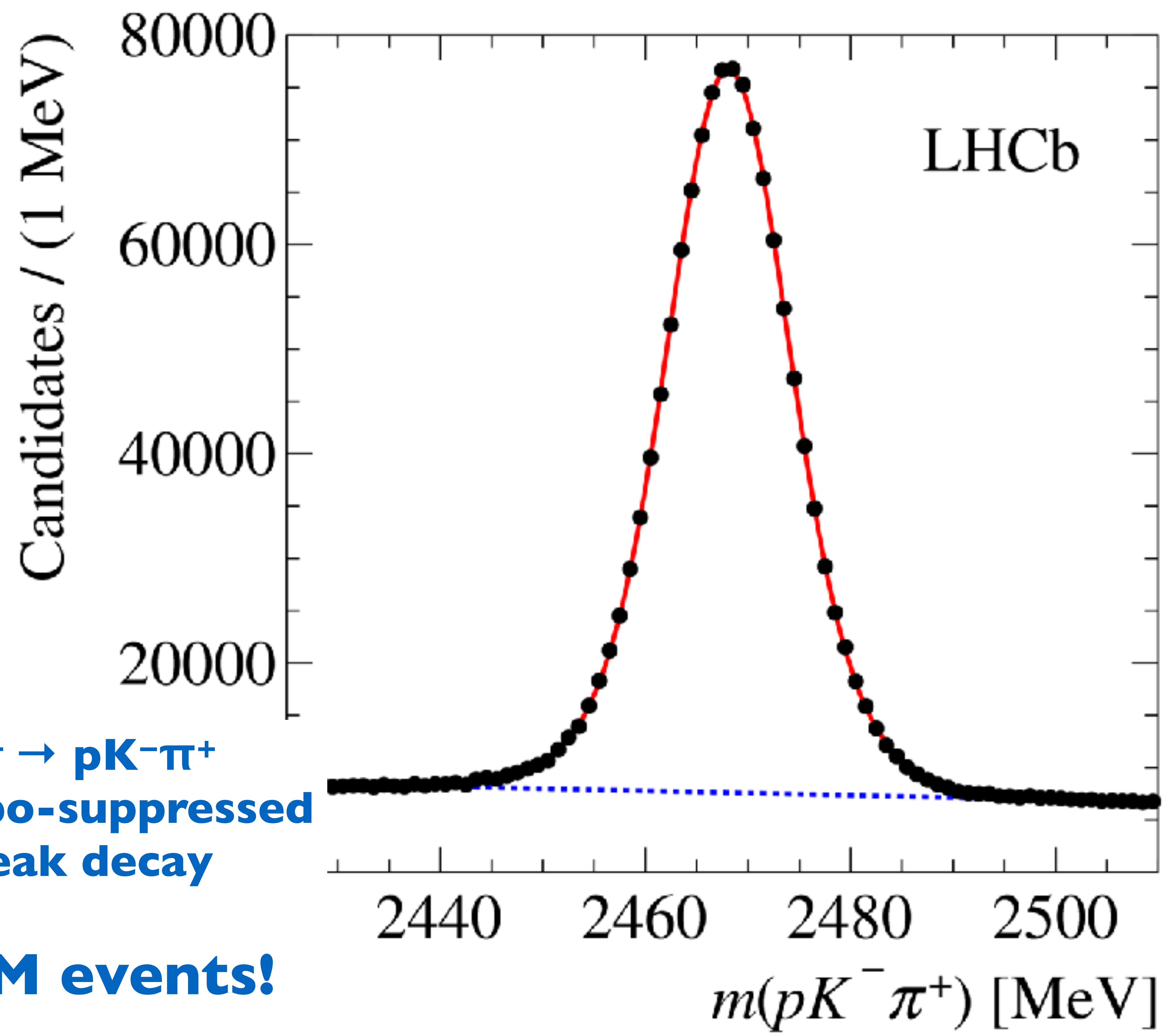




(*) 7 if you include possible excitations between the quarks in the diquark

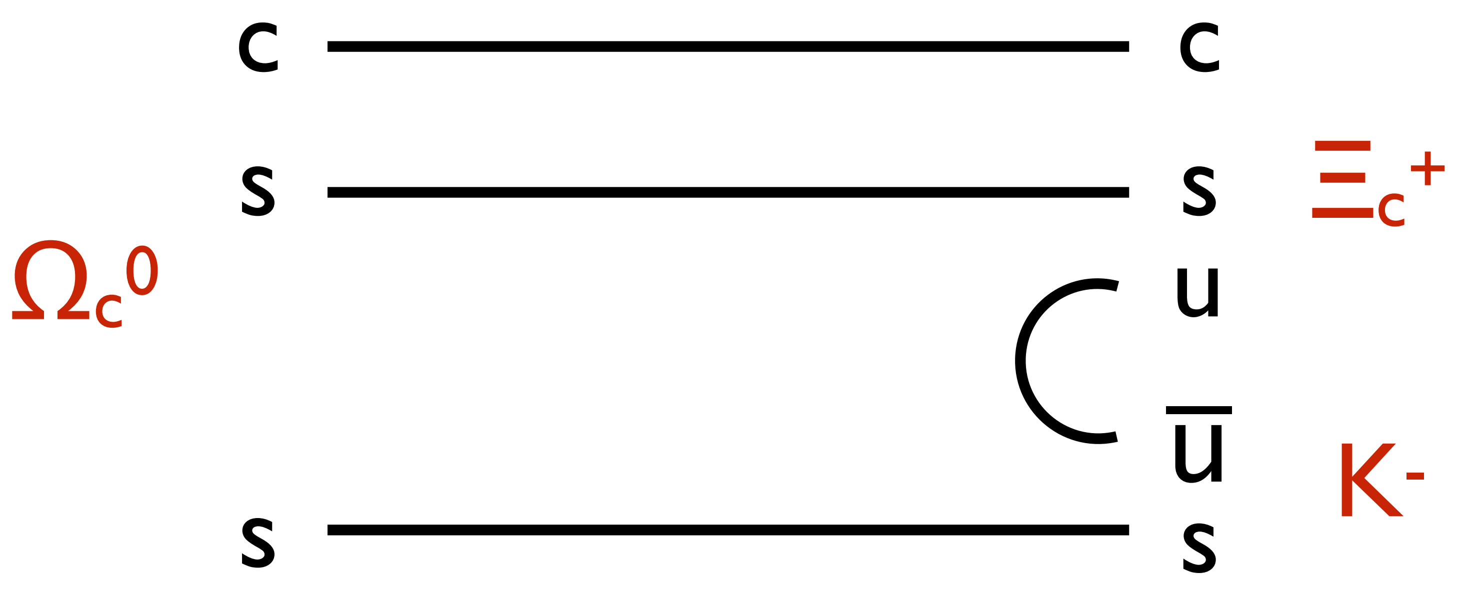
Strange-charm baryons

[PRL 118 (2017) 182001]



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

0.9 M events!

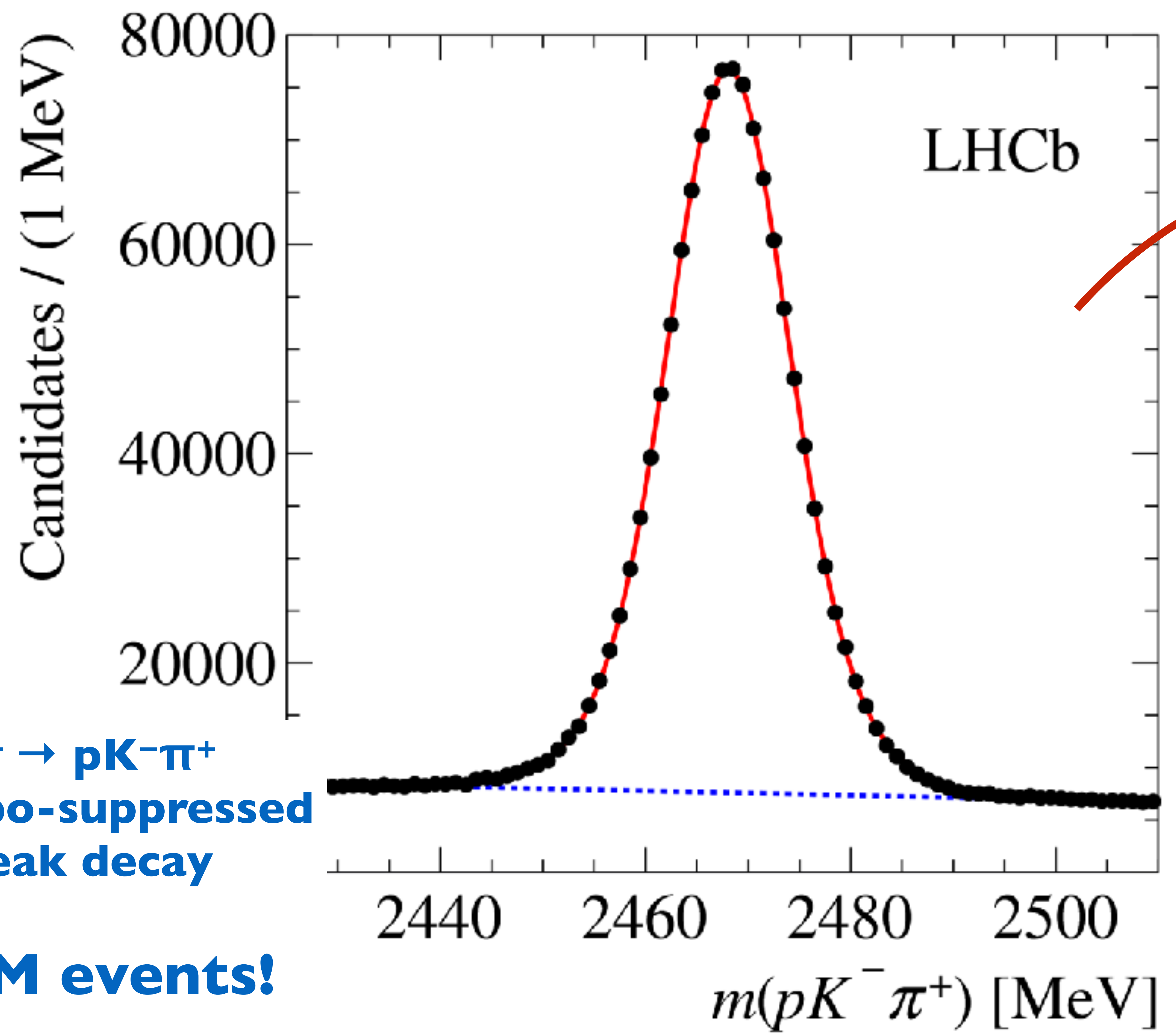


Ξ_c^+ detached from, but pointing back to, the primary pp vertex

LHCb-RICH system to identify particle type of daughter tracks

Strange-charm baryons

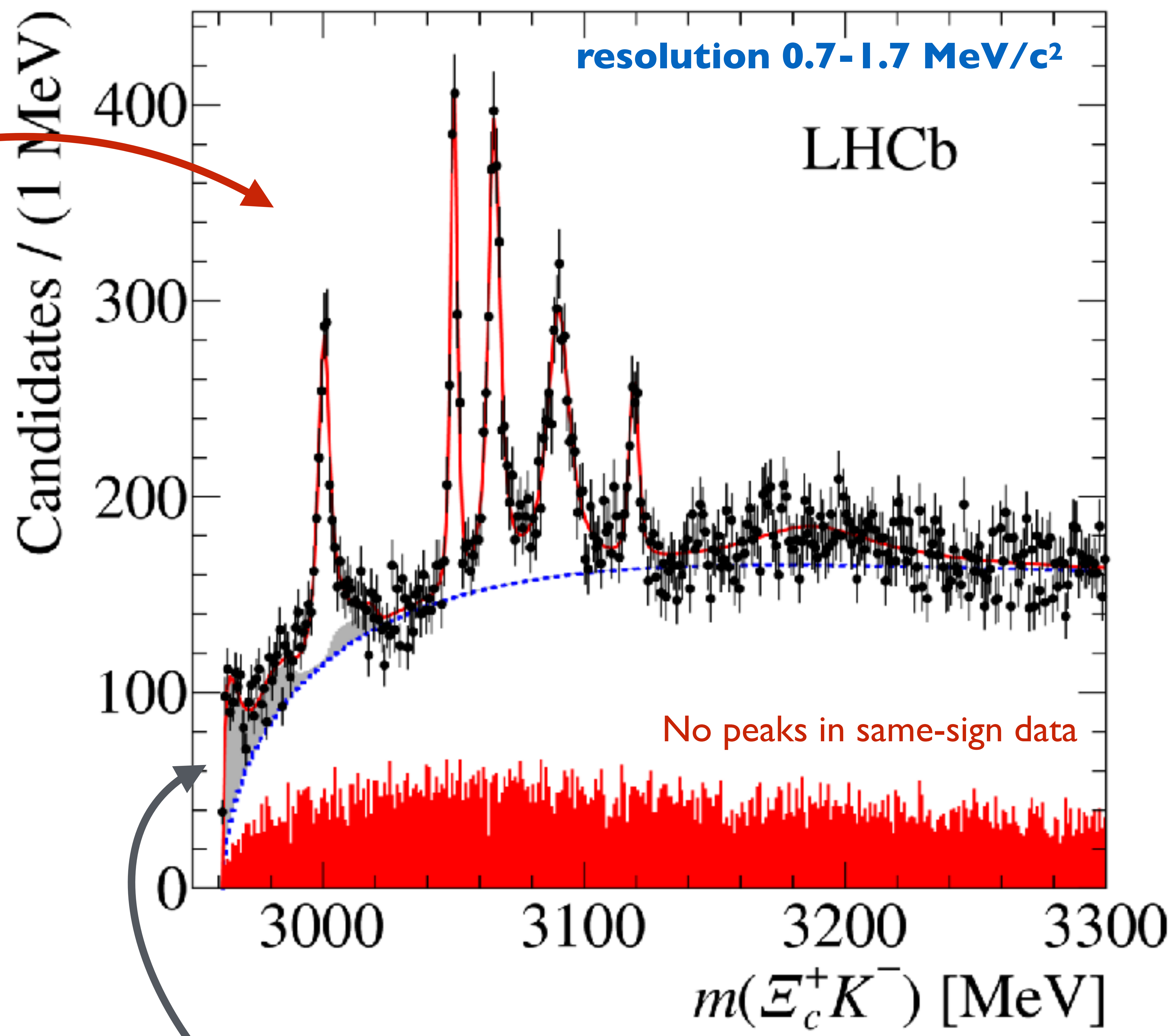
[PRL 118 (2017) 182001]



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

0.9 M events!

Add a kaon



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

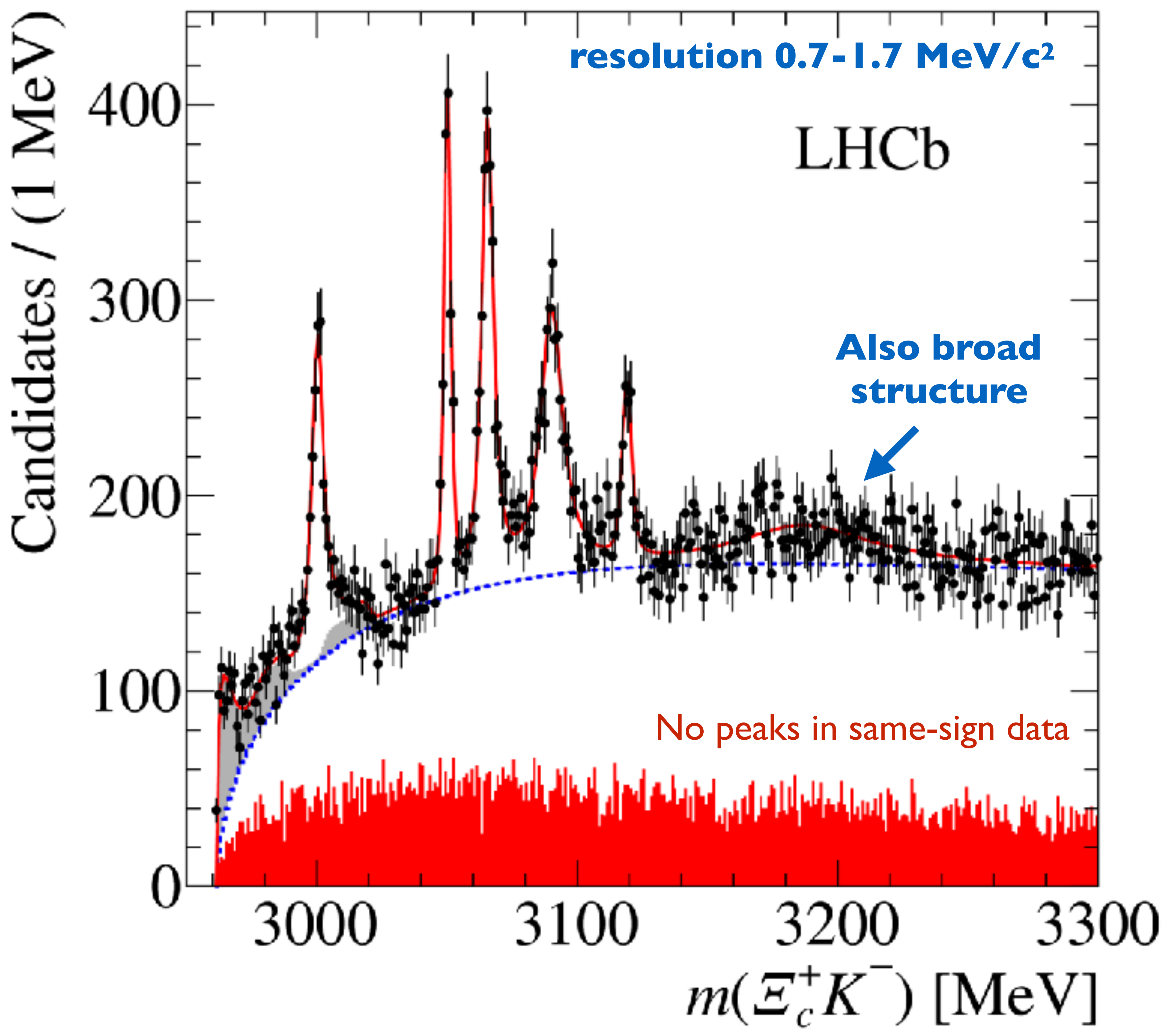
Ξ_c^+ detached from, but pointing back to, the primary pp vertex

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
		$< 1.2\,\text{MeV}, 95\%\ \text{CL}$	**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
		$< 2.6\,\text{MeV}, 95\%\ \text{CL}$	**Very narrow!**	
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$	$1670 \pm 450 \pm 360$	
$\Omega_c(3066)^0_{\rm fd}$			$700 \pm 40 \pm 140$	
$\Omega_c(3090)^0_{\rm fd}$			$220 \pm 60 \pm 90$	
$\Omega_c(3119)^0_{\rm fd}$			$190 \pm 70 \pm 20$	



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

Why are they so narrow?

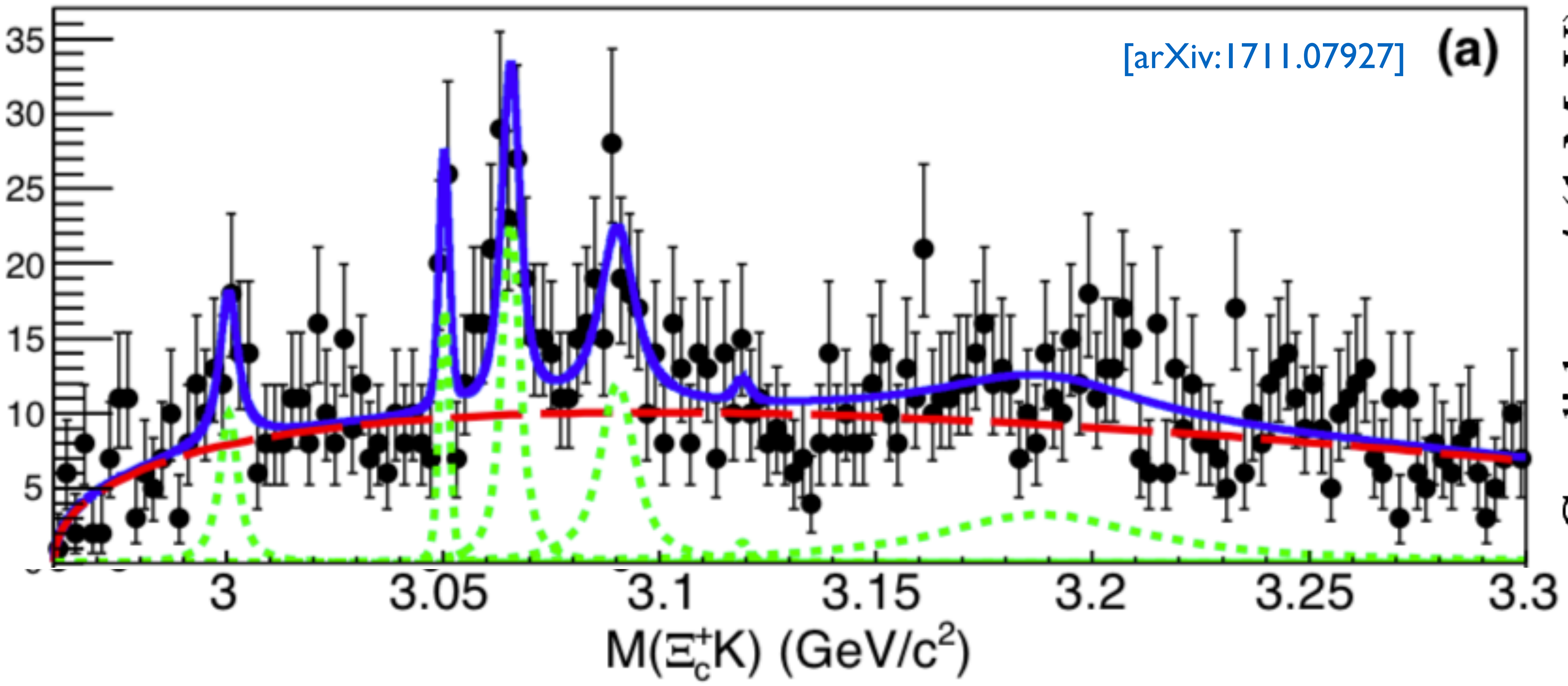
Are the narrowest states pentaquark candidates ($cs\bar{s}u\bar{u}$)?

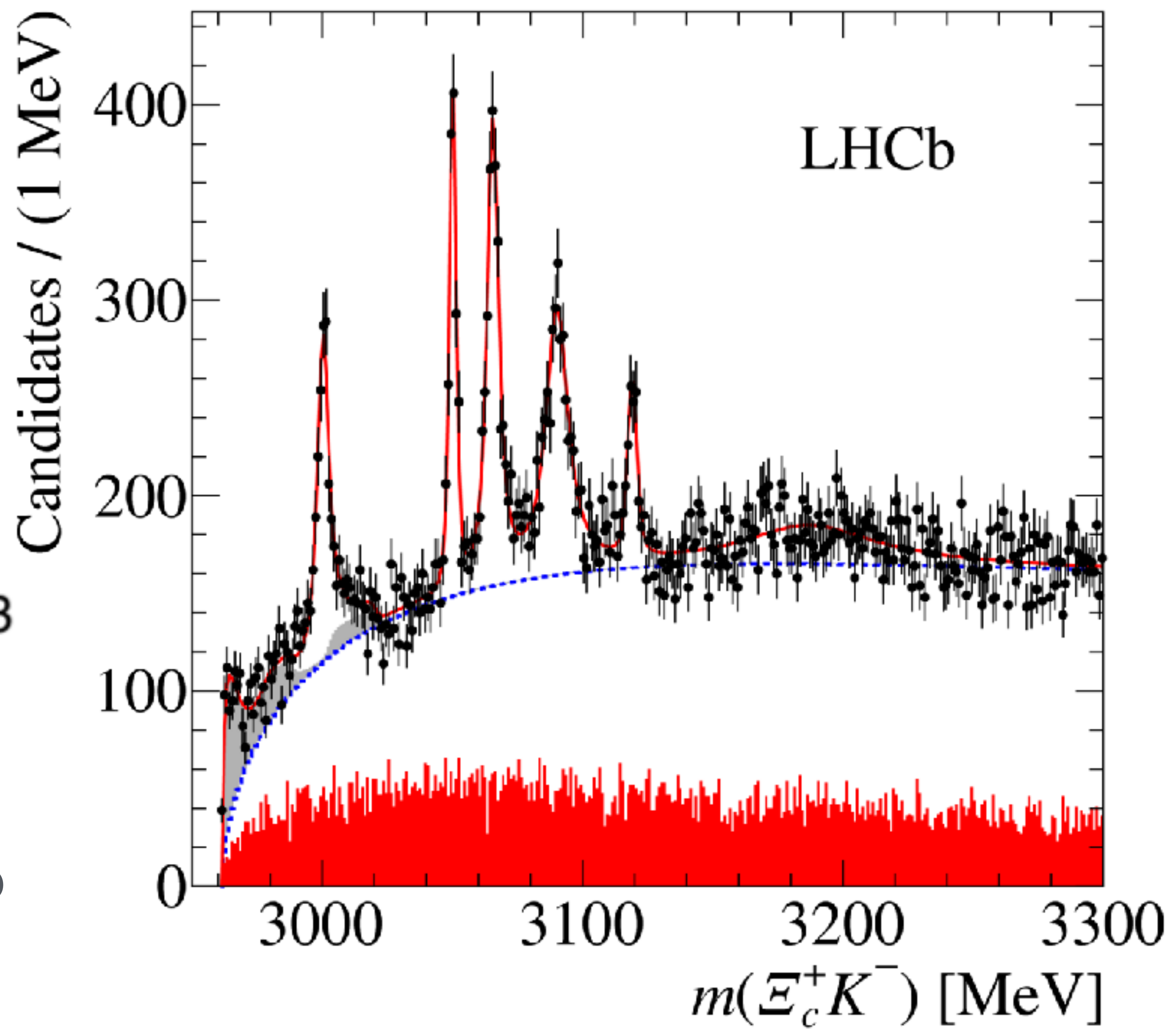
Which are orbital ($L=1$) or radial ($\Omega_c(2S)$) excitations?

Do they have isospin partners?

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

Confirmation by Belle

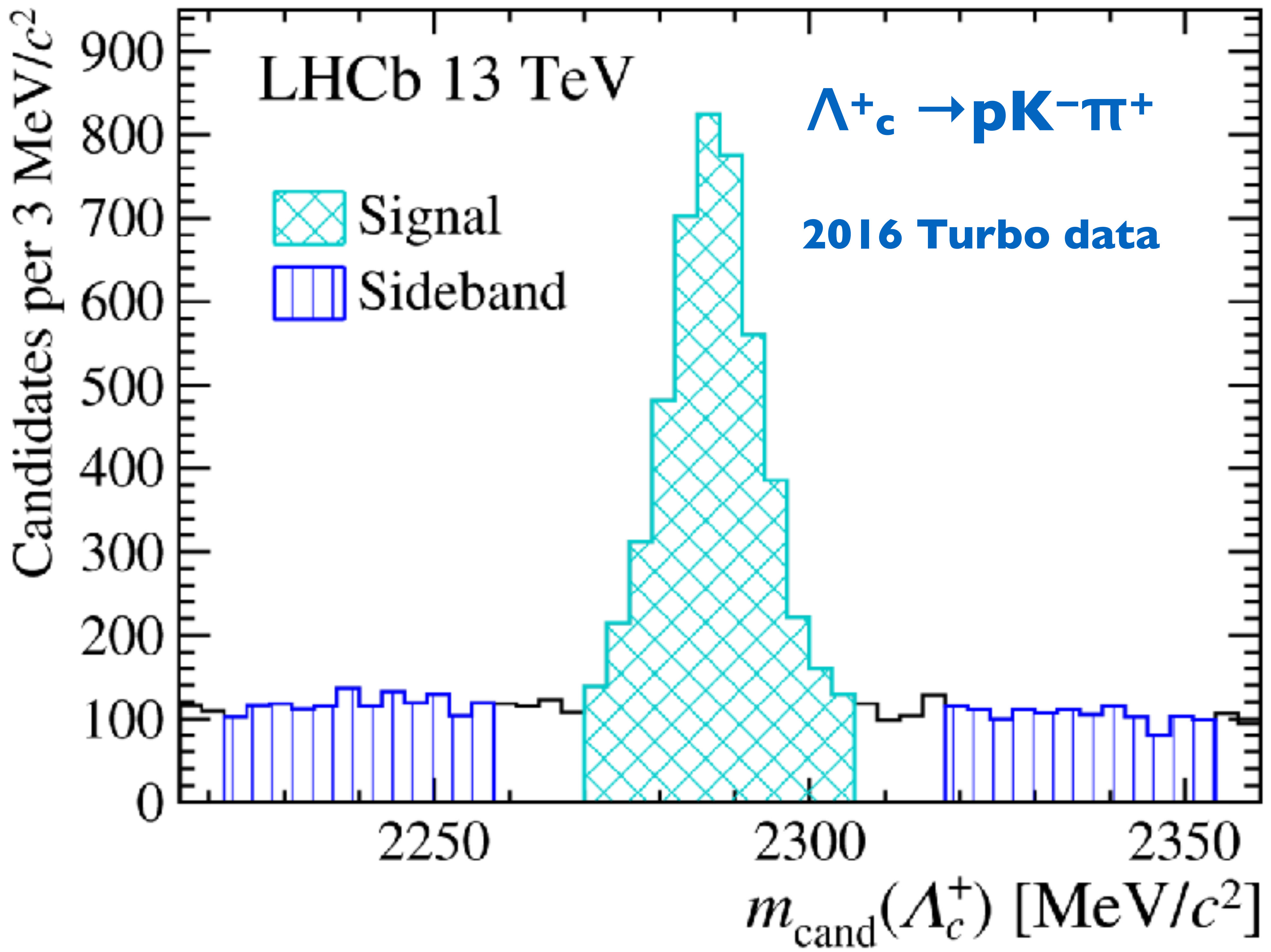


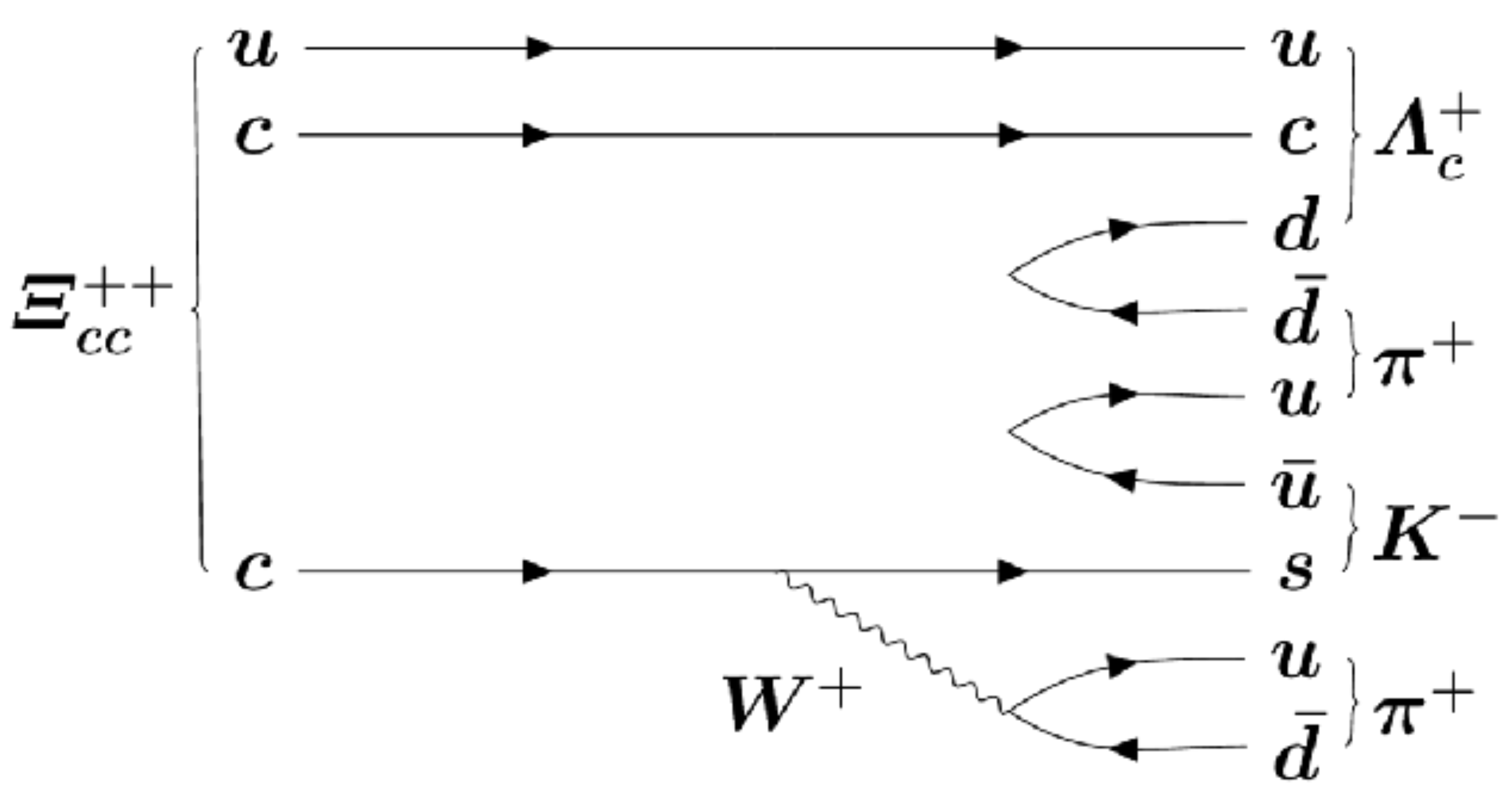


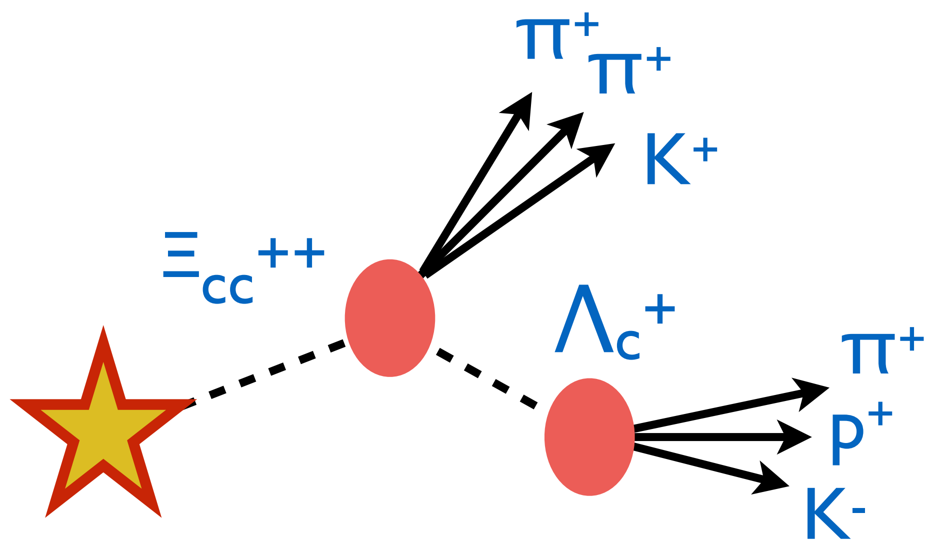
Higher state appears to be suppressed relative to LHCb data. May indicate that it is a pentaquark state that had suppressed production in e^+e^- collisions at Belle.

Doubly-charmed baryon

[PRL 119 (2017) 112001]







Novel online data processing → Turbo!

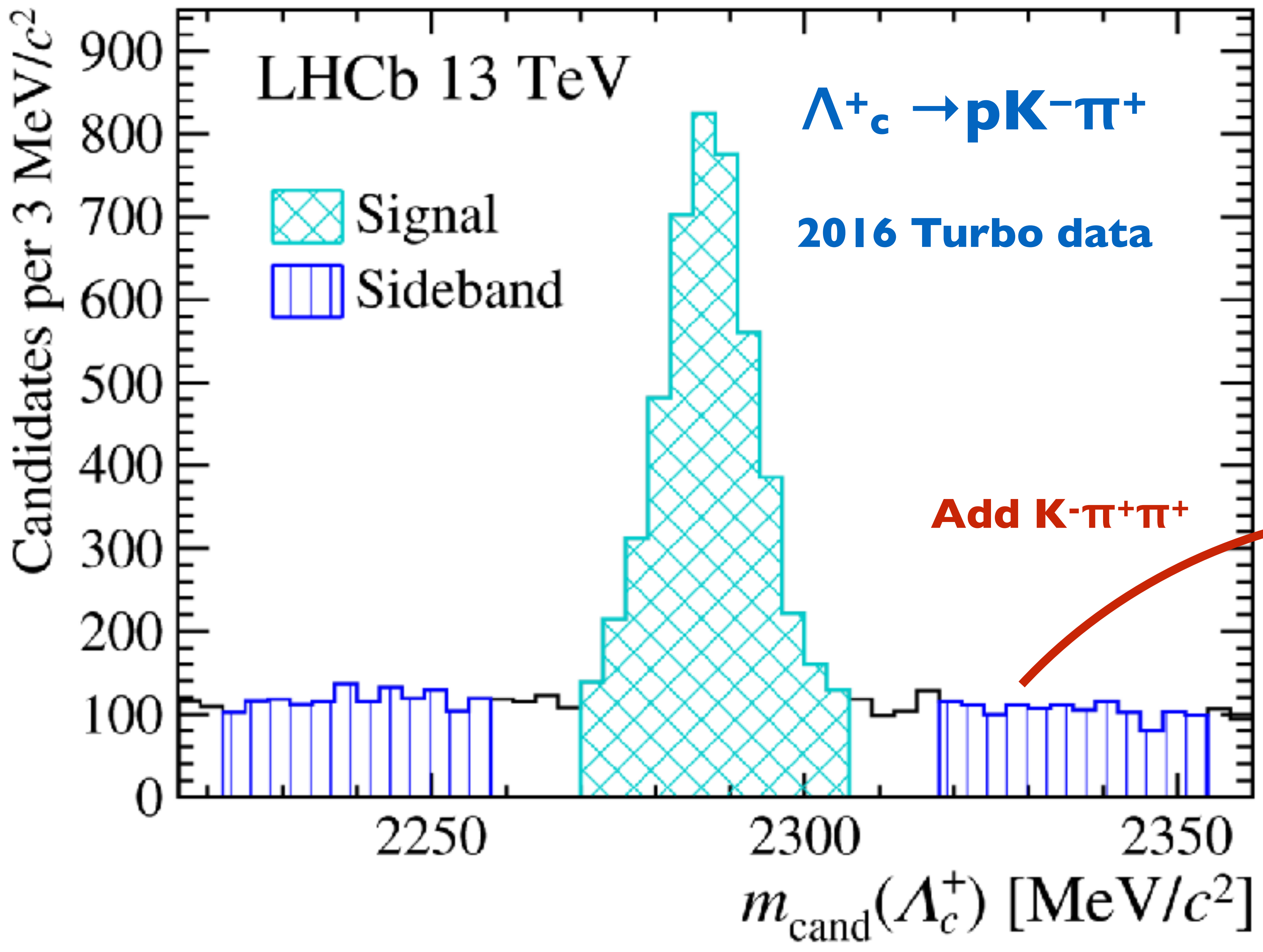
Full event reconstruction used in trigger (exploiting real-time alignment capabilities of LHCb in Run 2)

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

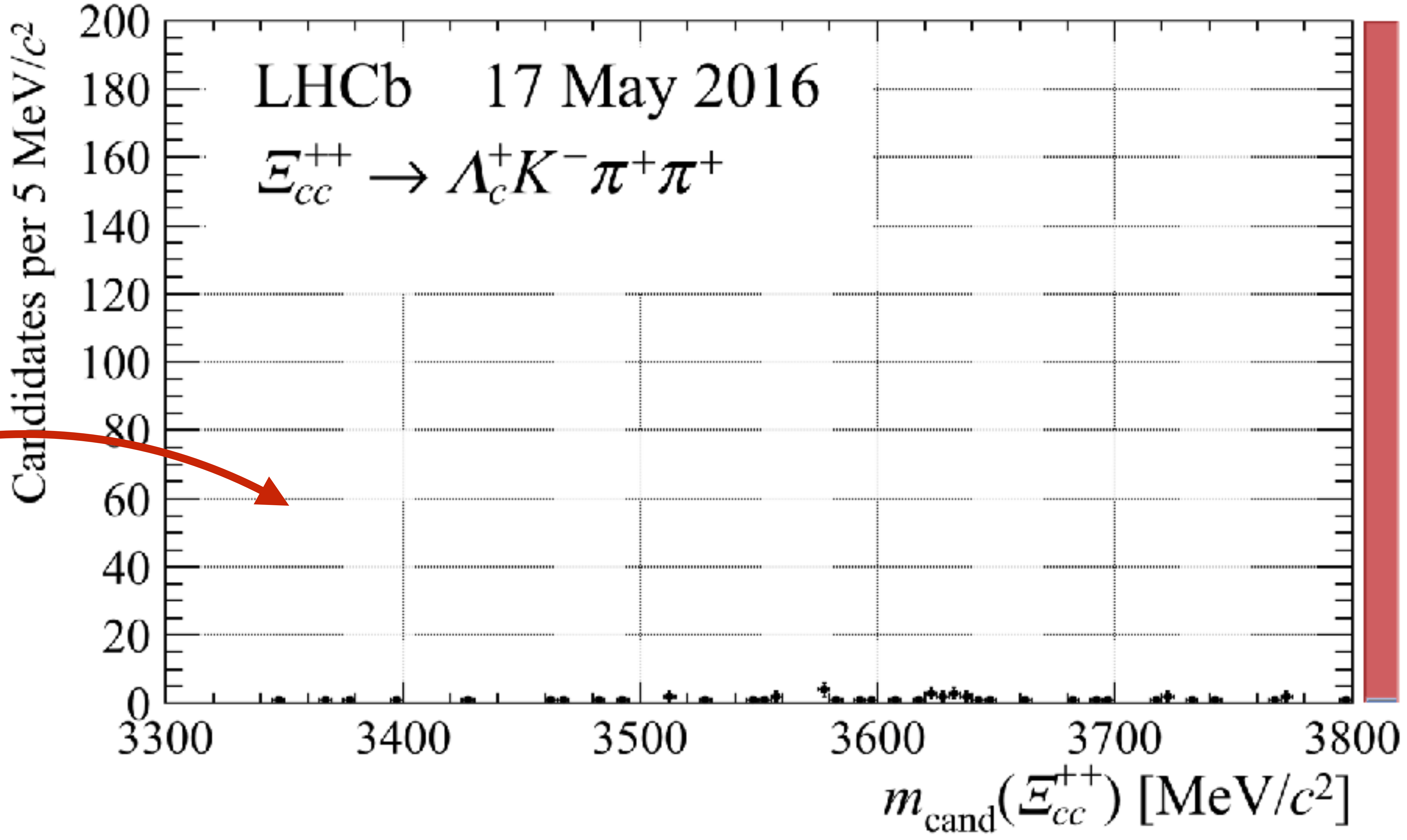
Only save part of the event that is needed → less disk space, crucial for states with large production cross-sections

Doubly-charmed baryon

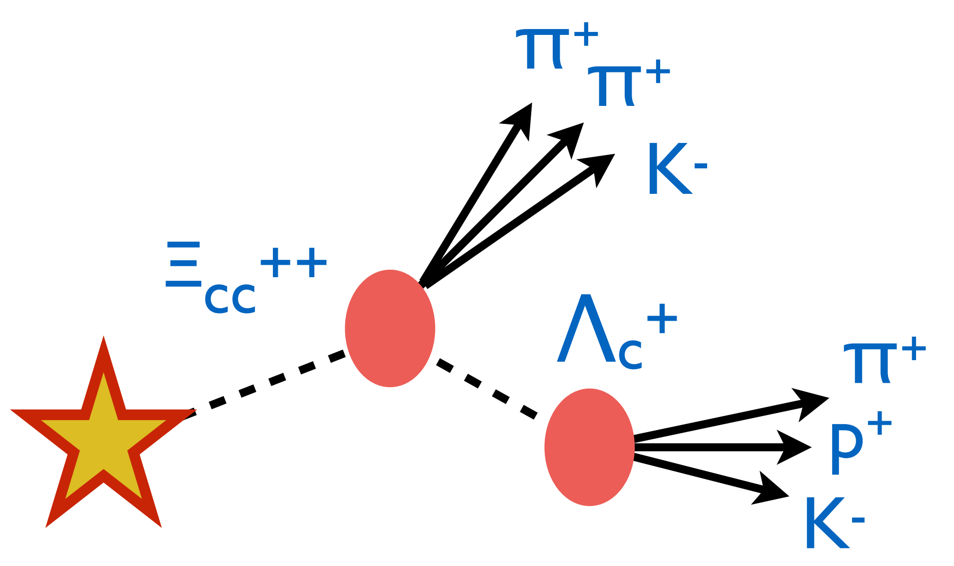
[PRL 119 (2017) 112001]



resolution ~7 MeV



link



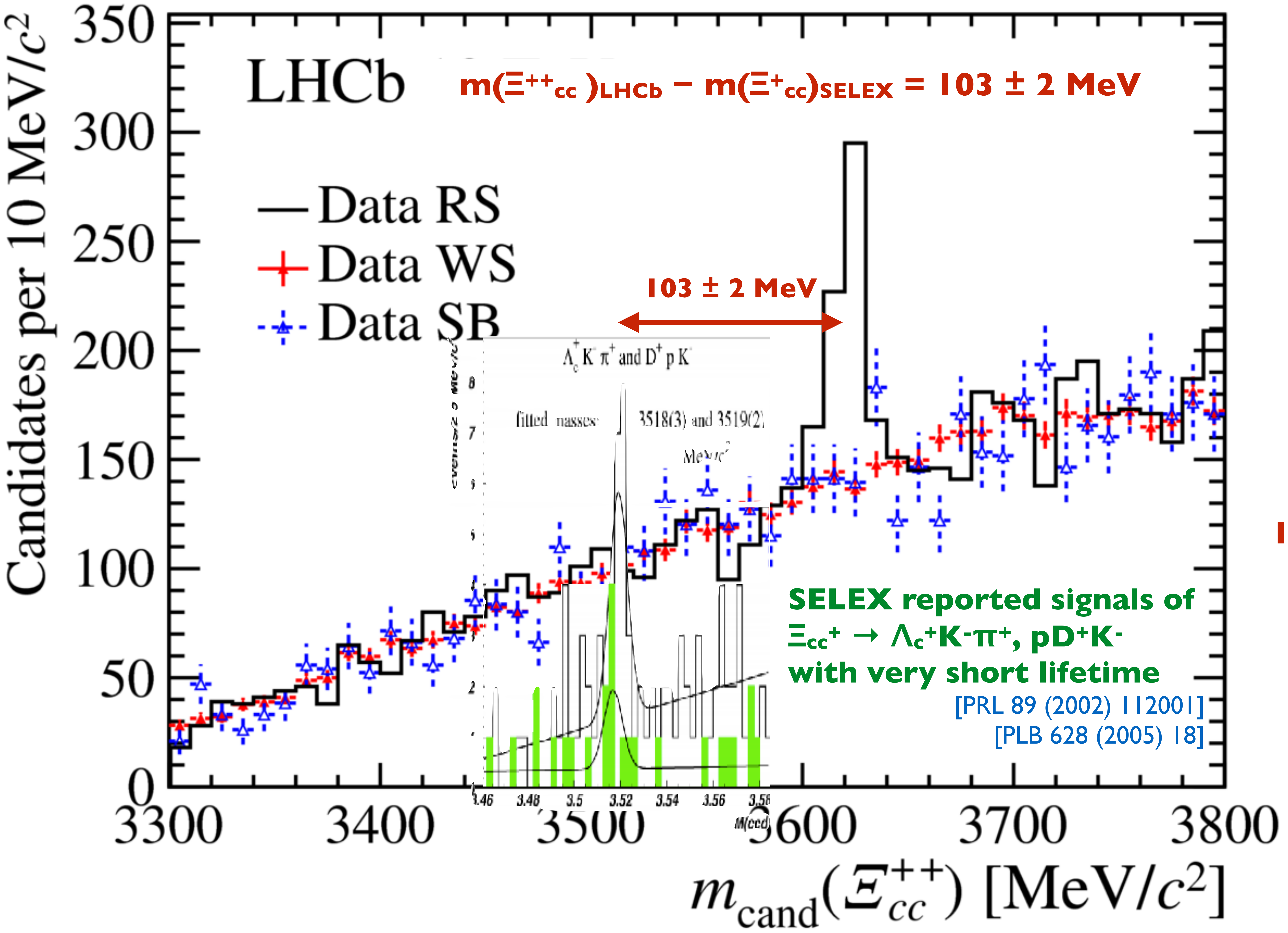
>12σ significant signal observed consistent with a **weakly** decaying state

$m(\Xi_{cc}^{++})$ = 3621.40 ± 0.72 (stat) ± 0.27 (syst) ± 0.14 (Λ_c^+) MeV

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

Comparison with SELEX

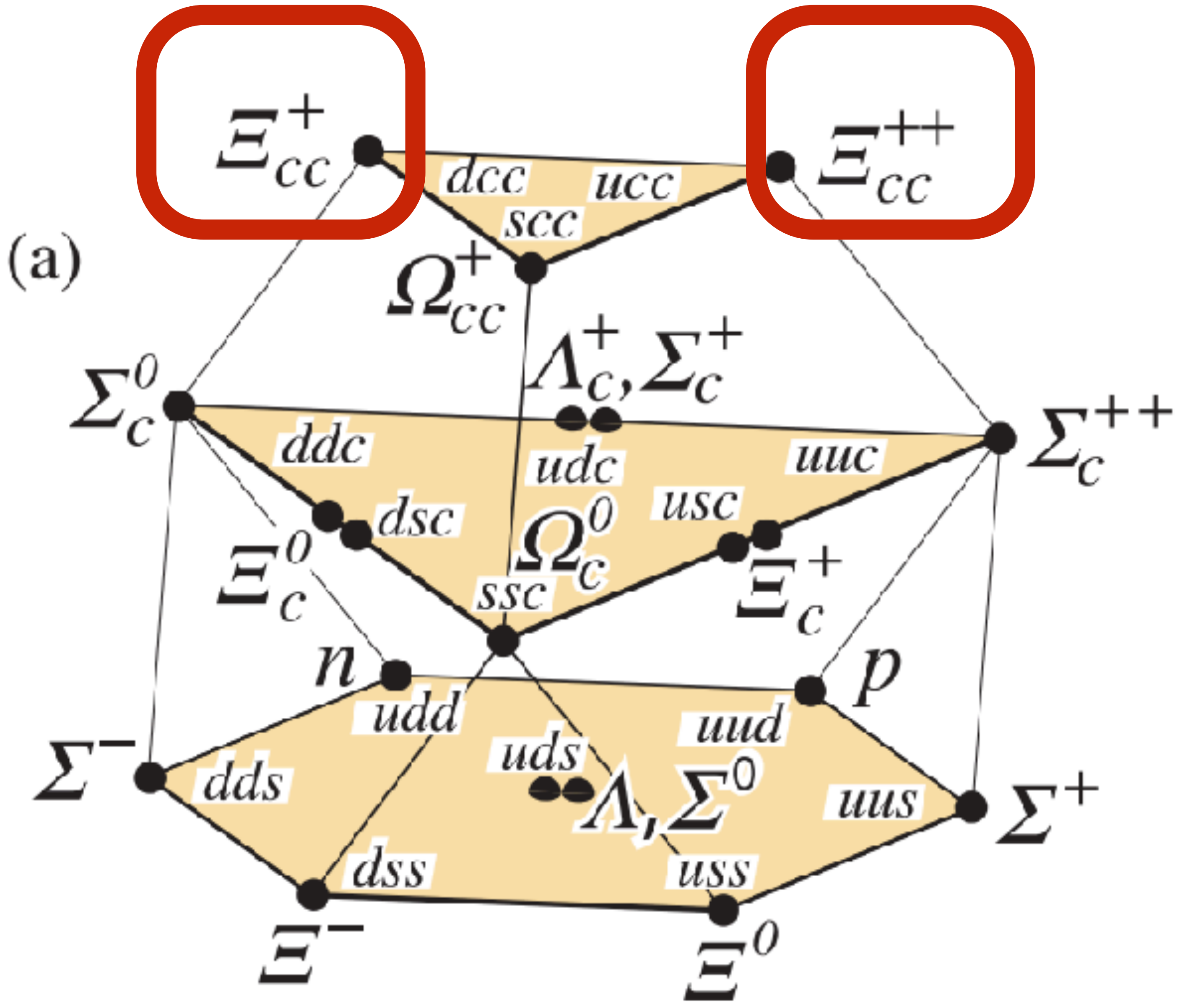
[PRL 119 (2017) 112001]



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

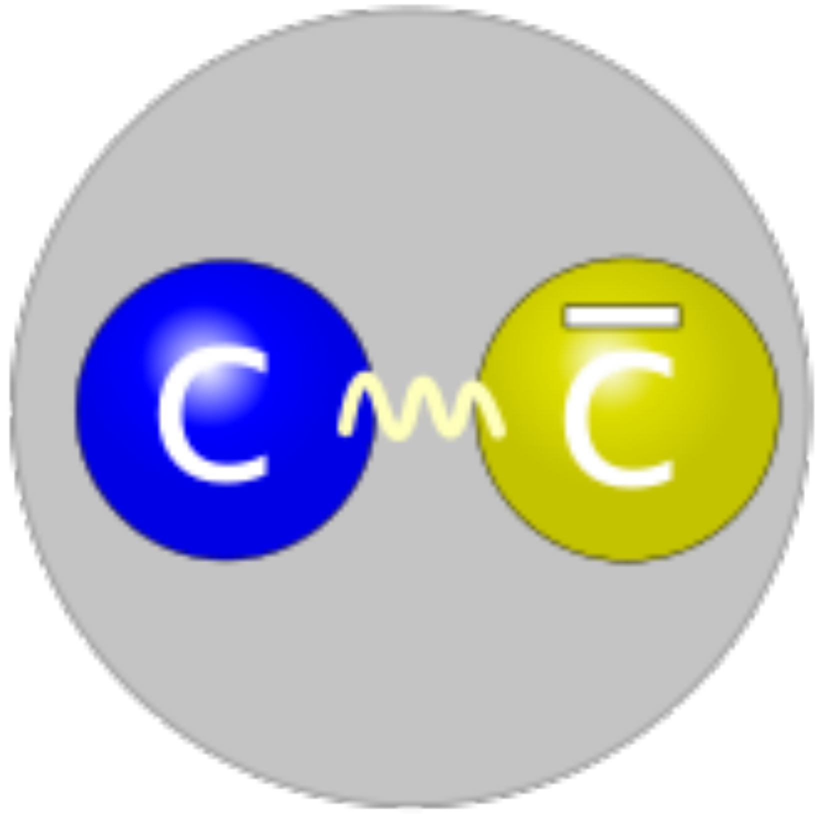


Inconsistent with being isospin partners

[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}

Quarkonium

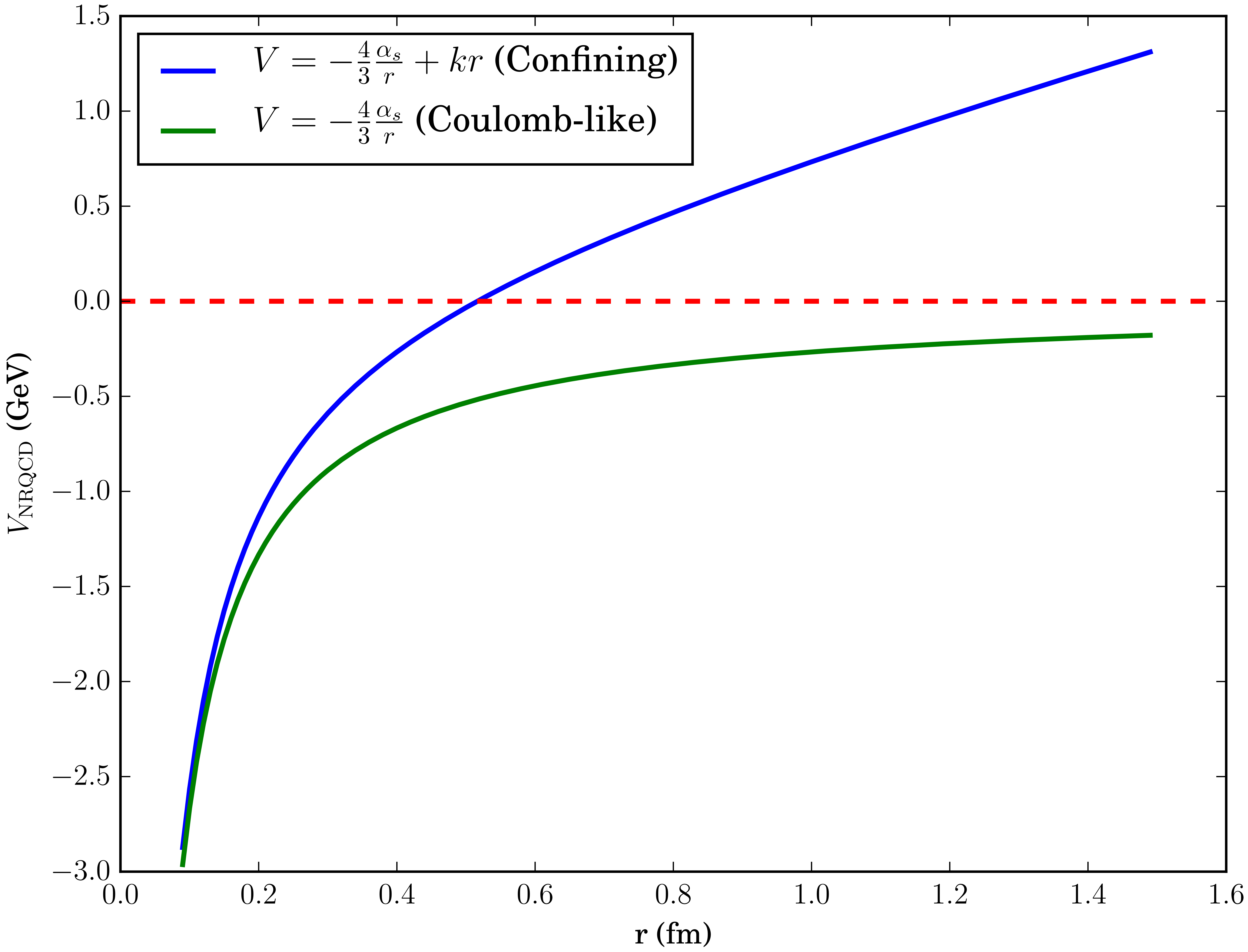


m(bottom) ~ 5000 MeV
m(charm) ~ 1500 MeV
Λ_{QCD} ~ 100 MeV
α_s ~ 0.3

Velocities of heavy-quarks are low so can use V_{NRQCD} to predict spectrum of $c\bar{c}$ and $b\bar{b}$ states

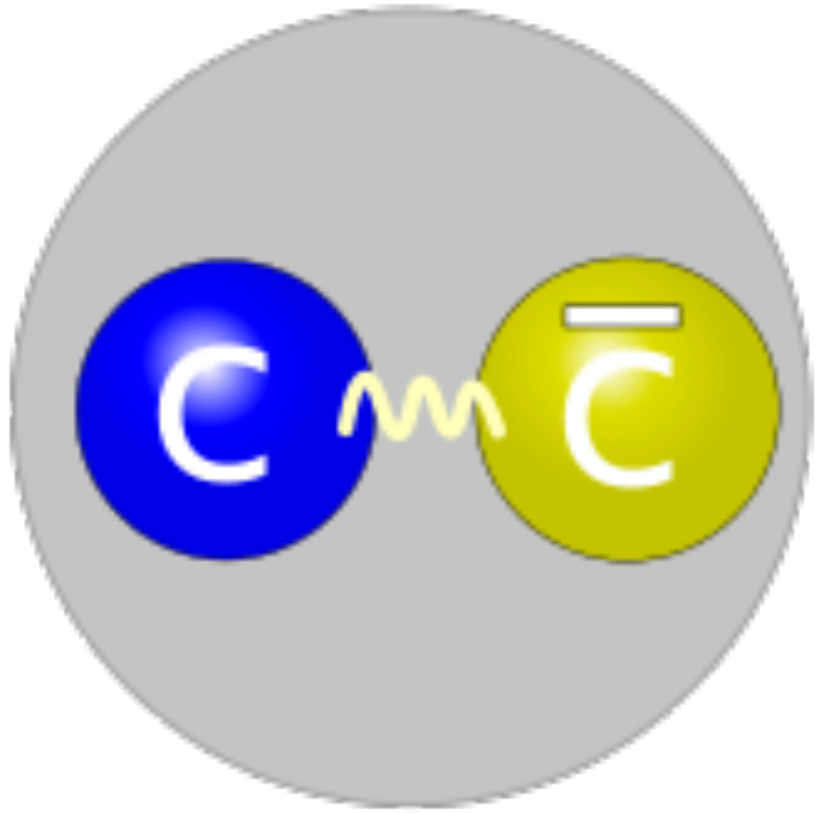
Potential model:
[Radford and Repko, PRD 75 (2007) 074031]

gluon self-interaction gives linear (confining) term at large distances



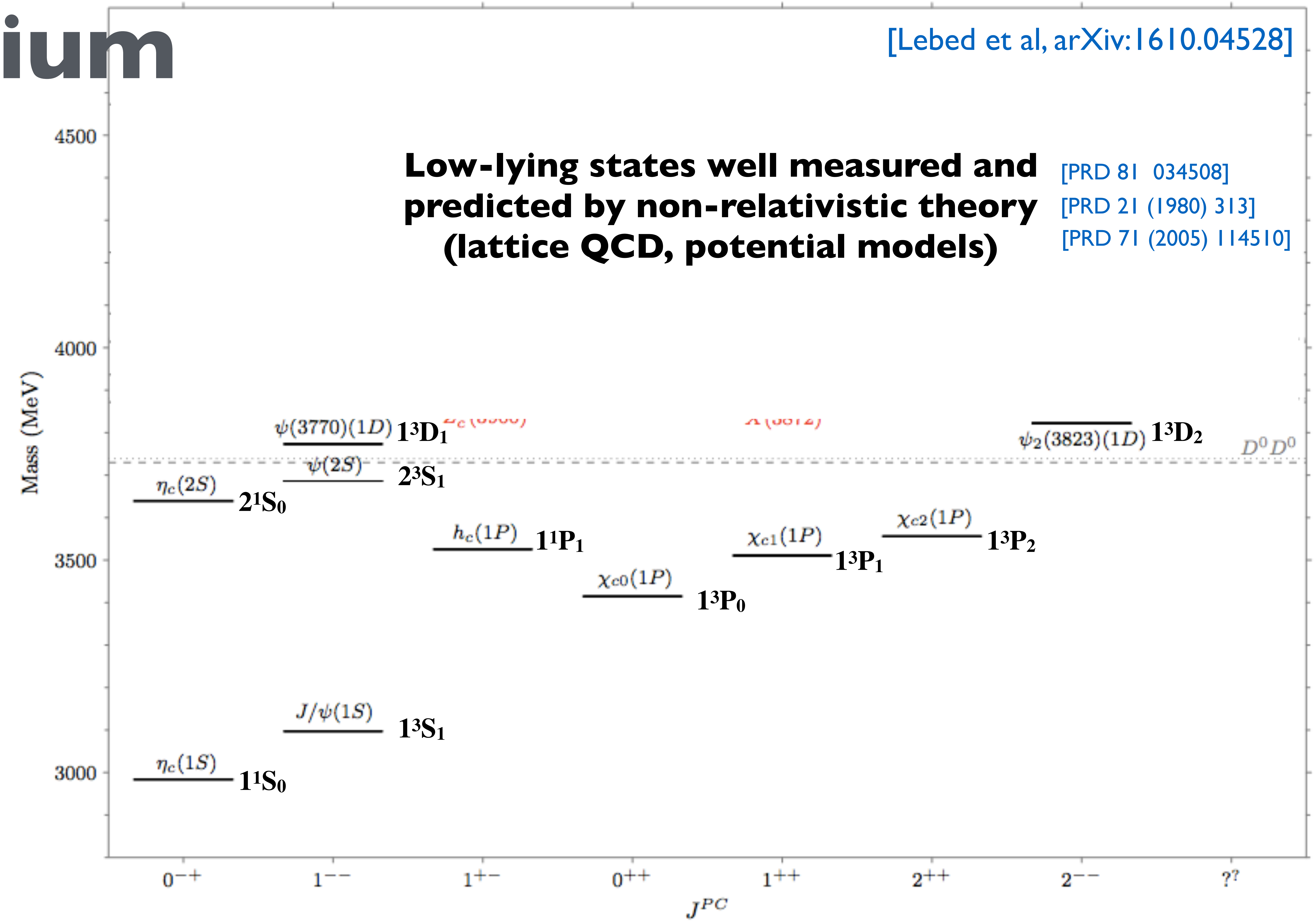
Charmonium

[Lebed et al, arXiv:1610.04528]



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

[PRD 81 034508]
[PRD 21 (1980) 313]
[PRD 71 (2005) 114510]



Classify using J^{PC}

$J = L \oplus S$

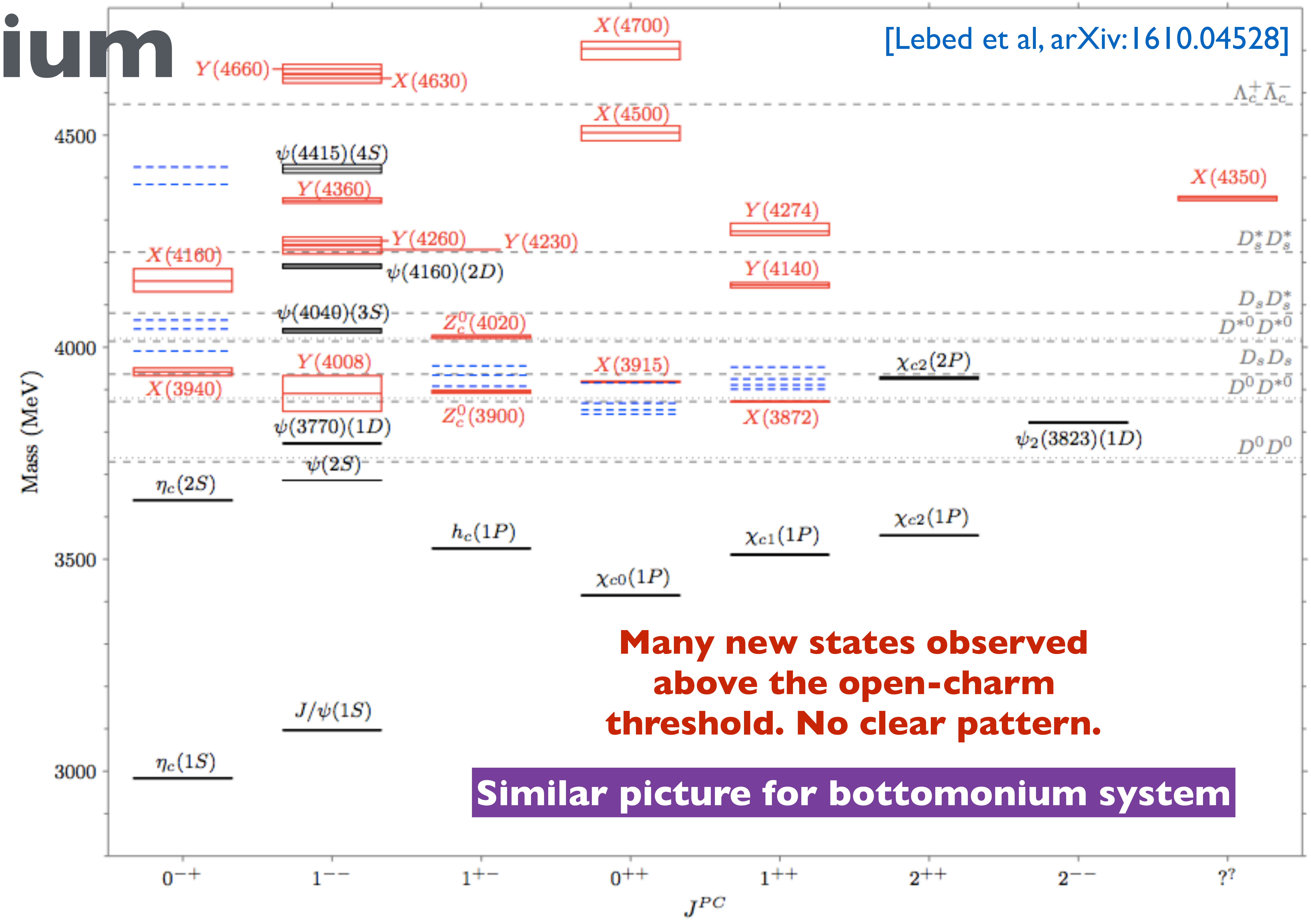
$P = (-1)^{L+1}$

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

$n^{2S+1}L_J$

Charmonium

[Lebed et al, arXiv:1610.04528]



Classify using J^{PC}

$J = L \oplus S$

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

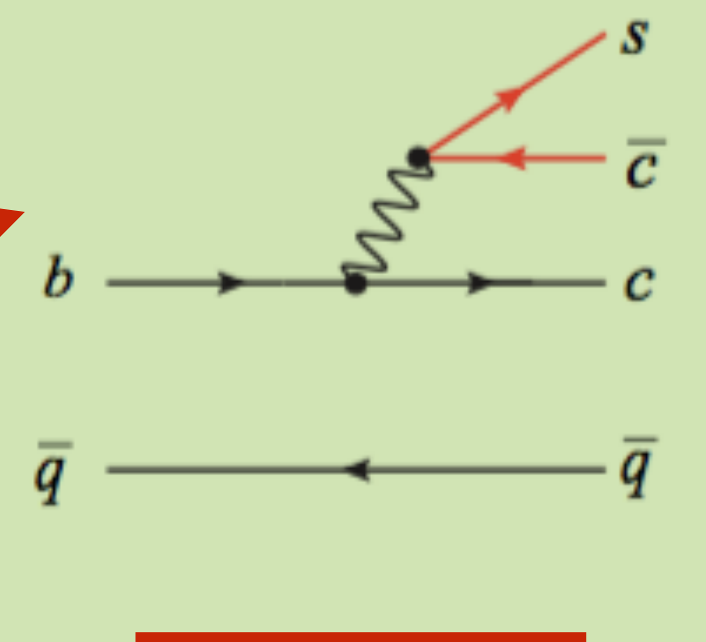
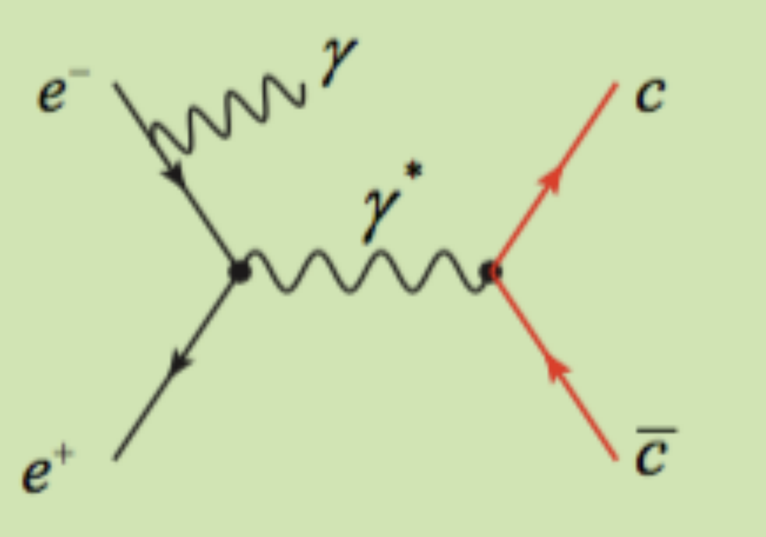
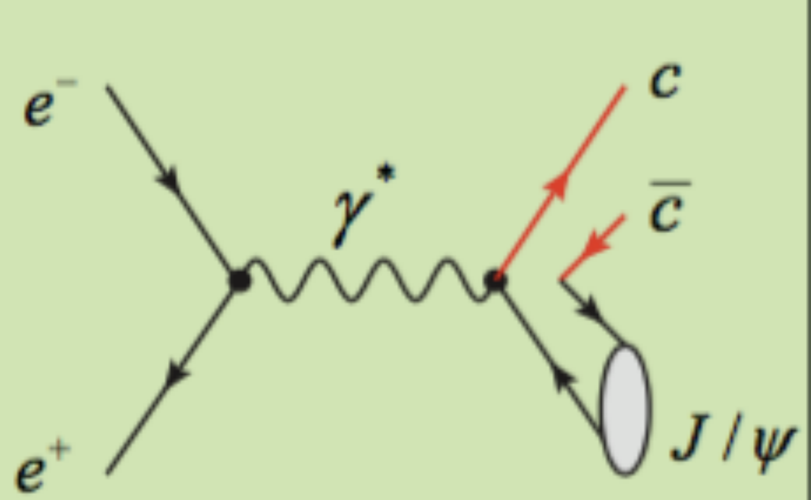
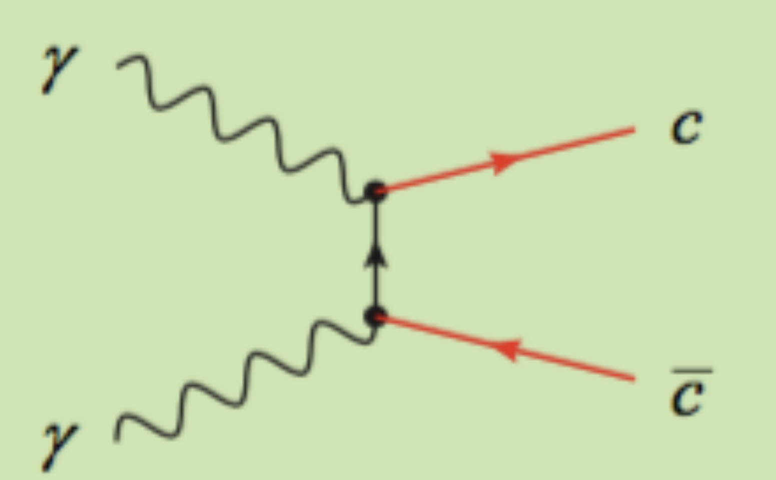
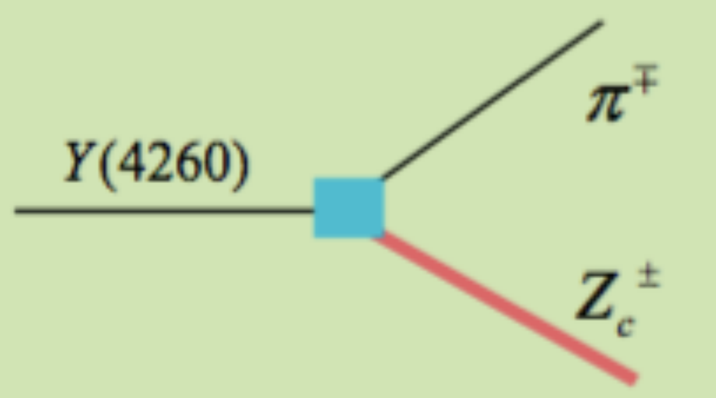
$C = (-1)^{L+S}$

$n^{2S+1}L_J$

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

Similar picture for bottomonium system

Production mechanisms

b hadrons	Initial state radiation	double charmonium	γγ collisions ($e^+e^- \to e^+e^- X$)	ISR → Y(4260)
		 C=+	 $J^{PC}=1^{--}$	
$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$Z^+(4248)$	$Y(4660)$			
$Y(4140)$				
$Y(4274)$				
$Z_c^+(4200)$				
$Z^+(4240)$				
$X(3823)$ ← 1^3D_2 $c\bar{c}$				

Relevant for LHC

See backup

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]

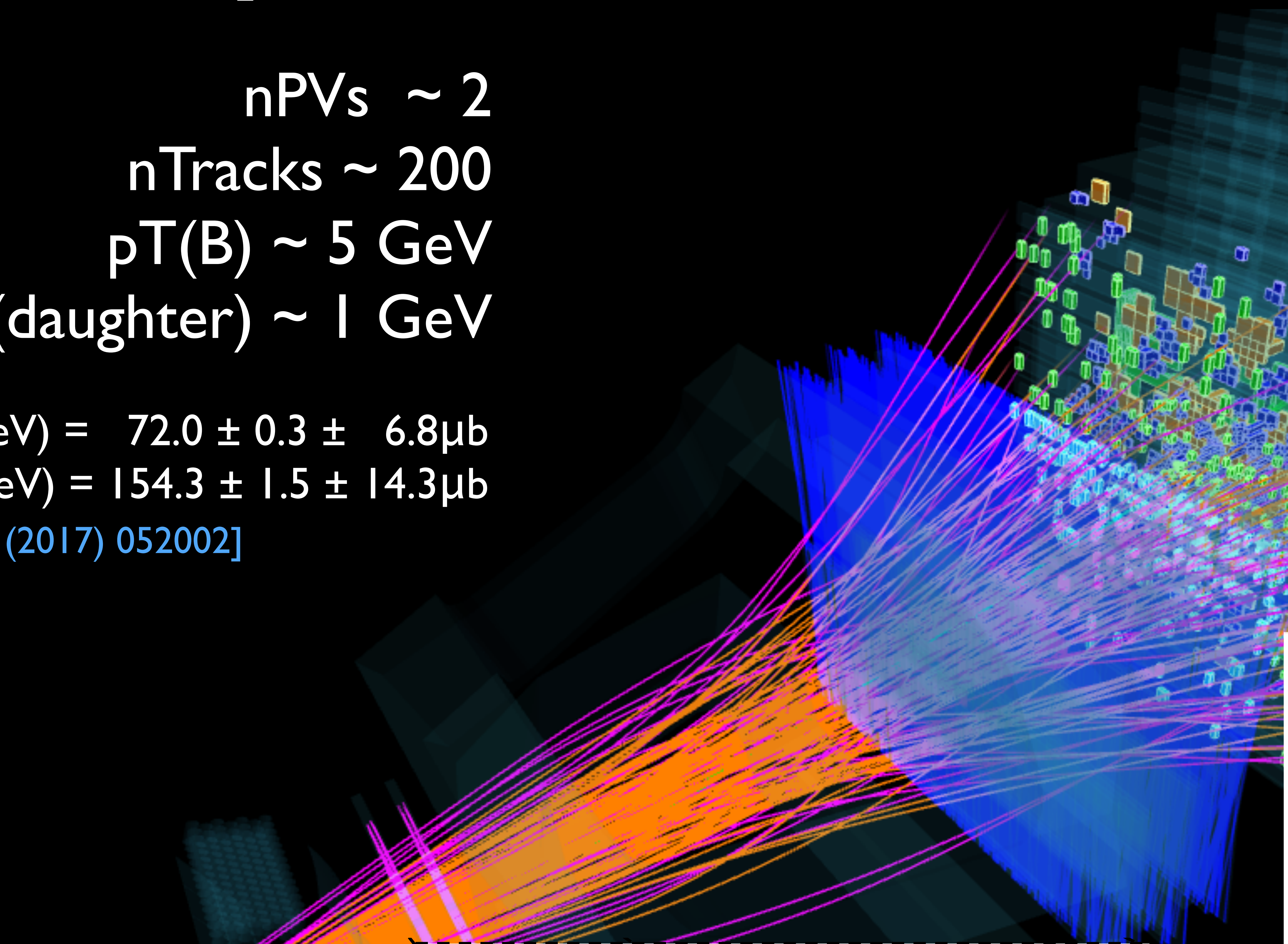
$P_c(4380)$
$P_c(4450)$

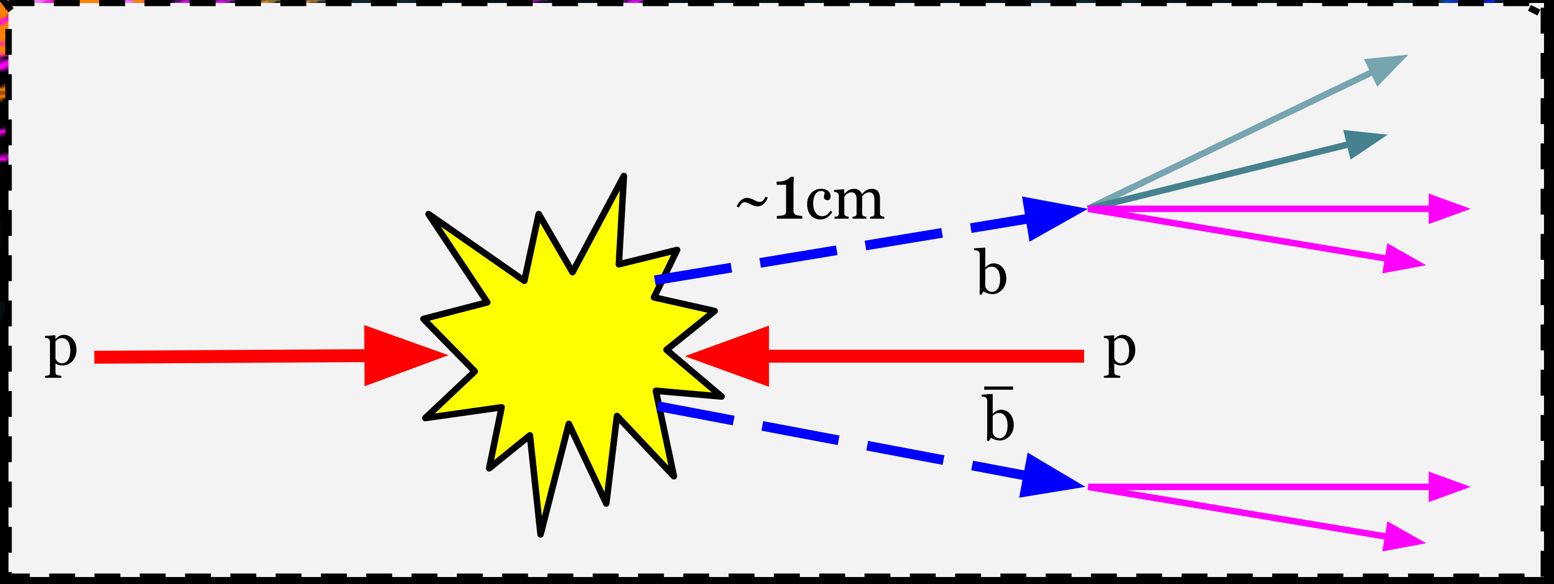
X(3872) also observed in prompt pp, $p\bar{p}$ collisions and ISR

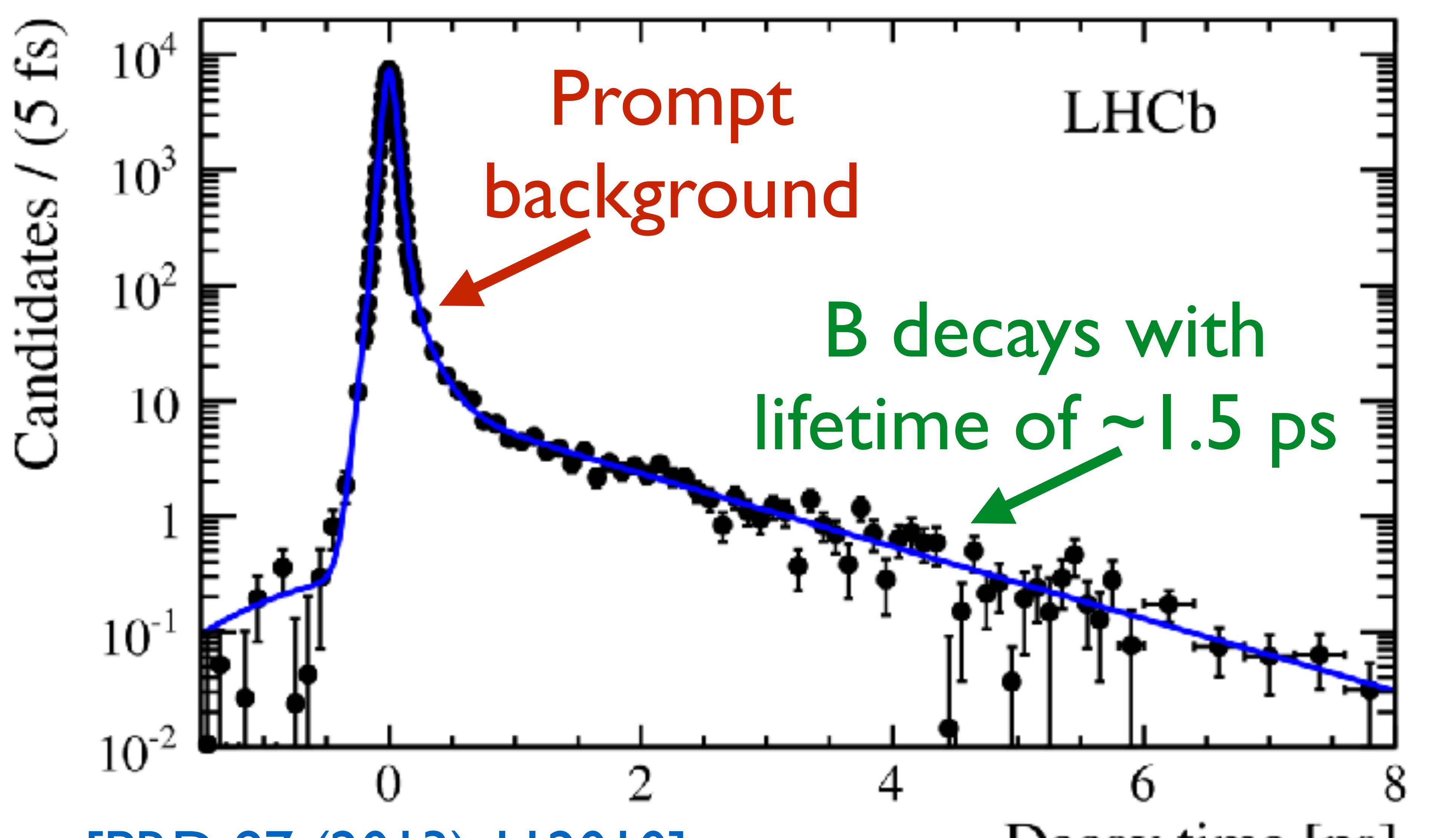
(Exotic) Hadron physics at LHCb

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]



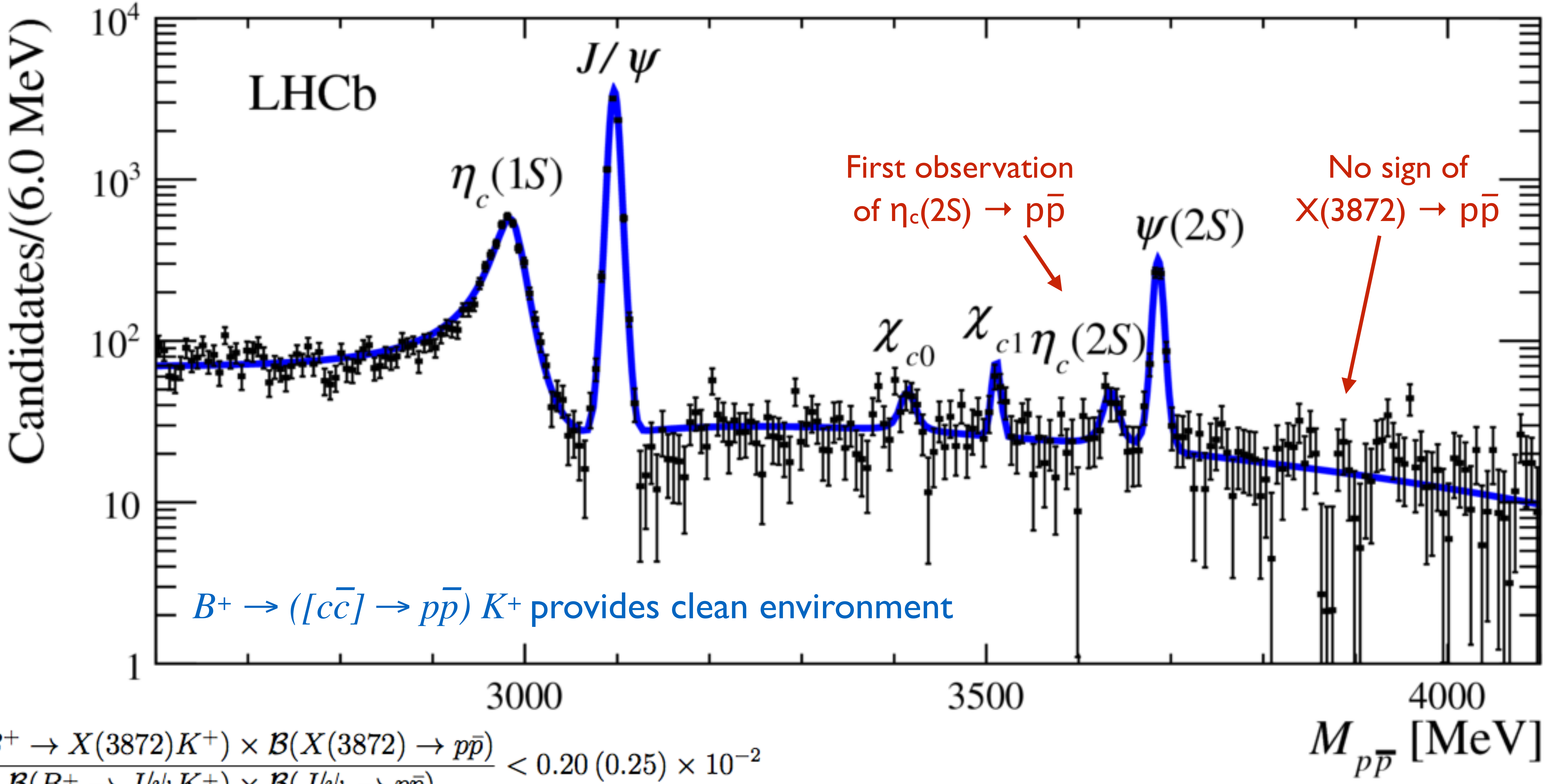




[PRD 87 (2013) 112010]

Charmonium production in b-hadron decays

[PLB 769 (2016) 305-313]



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

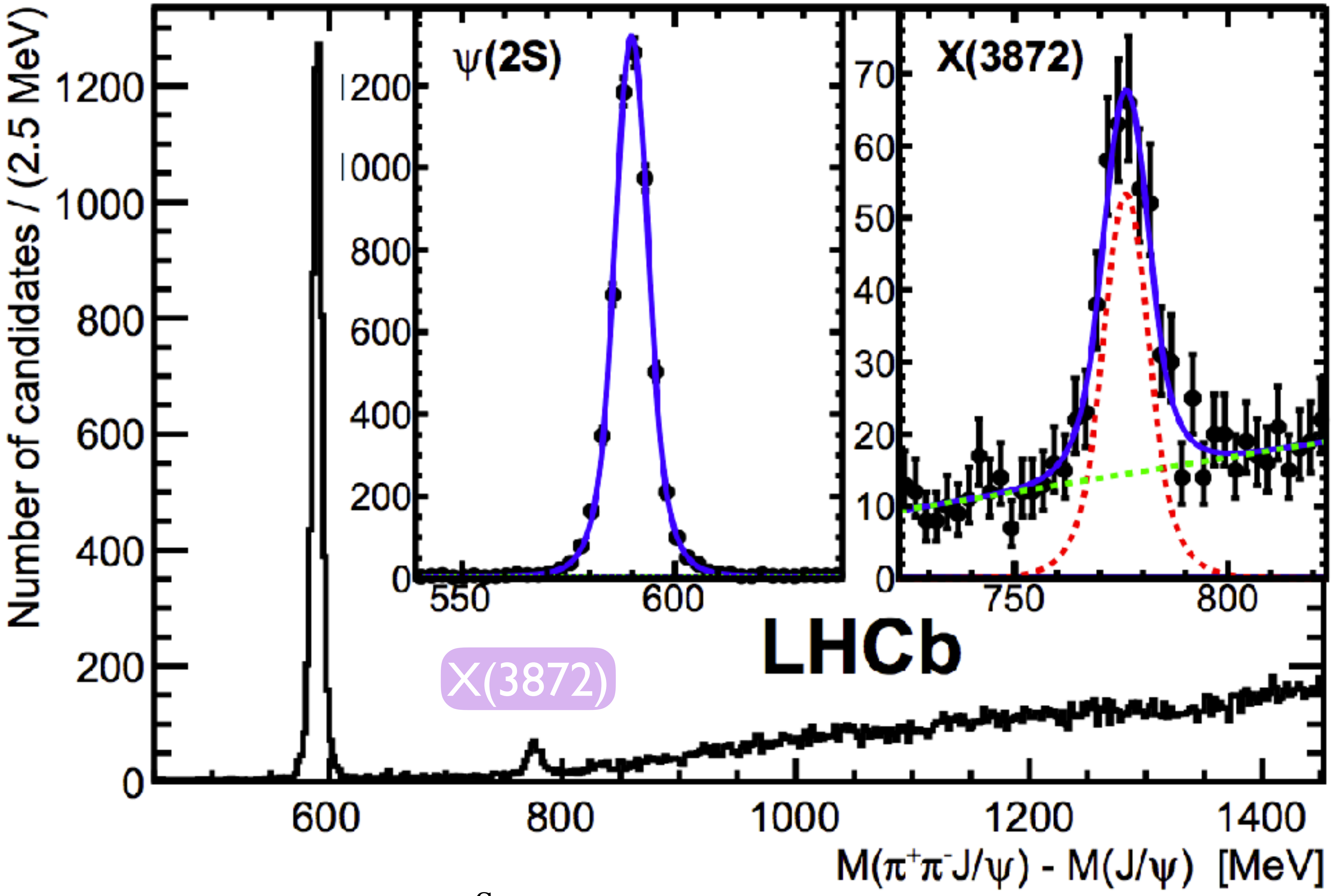
Exotic charmonium production

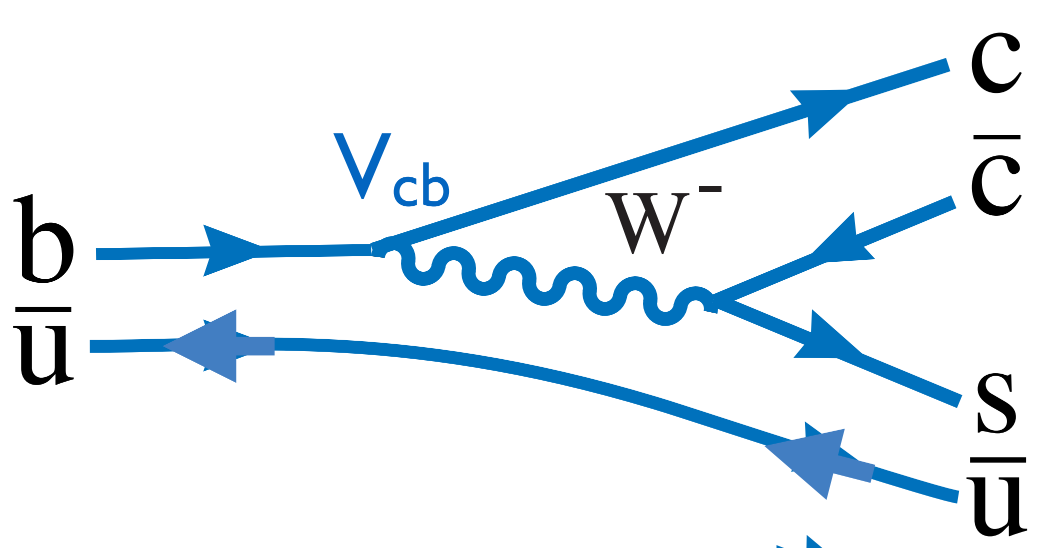
[PRL 110 (2013) 222001]

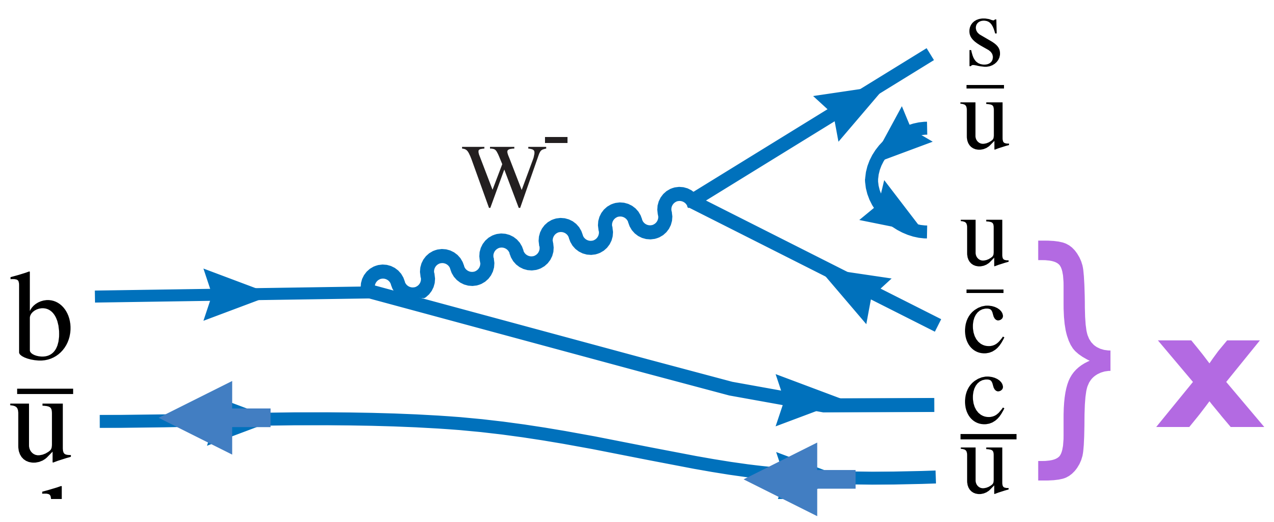
Charmonium in the final state is experimentally useful for triggering, particularly using muon/electron decay modes of J/ψ or ψ(2S)

Both decay chains lead to the same particles in the final state

Mass fit is sufficient to identify exotic if state isolated and narrow, otherwise need **Dalitz or amplitude analysis**







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

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

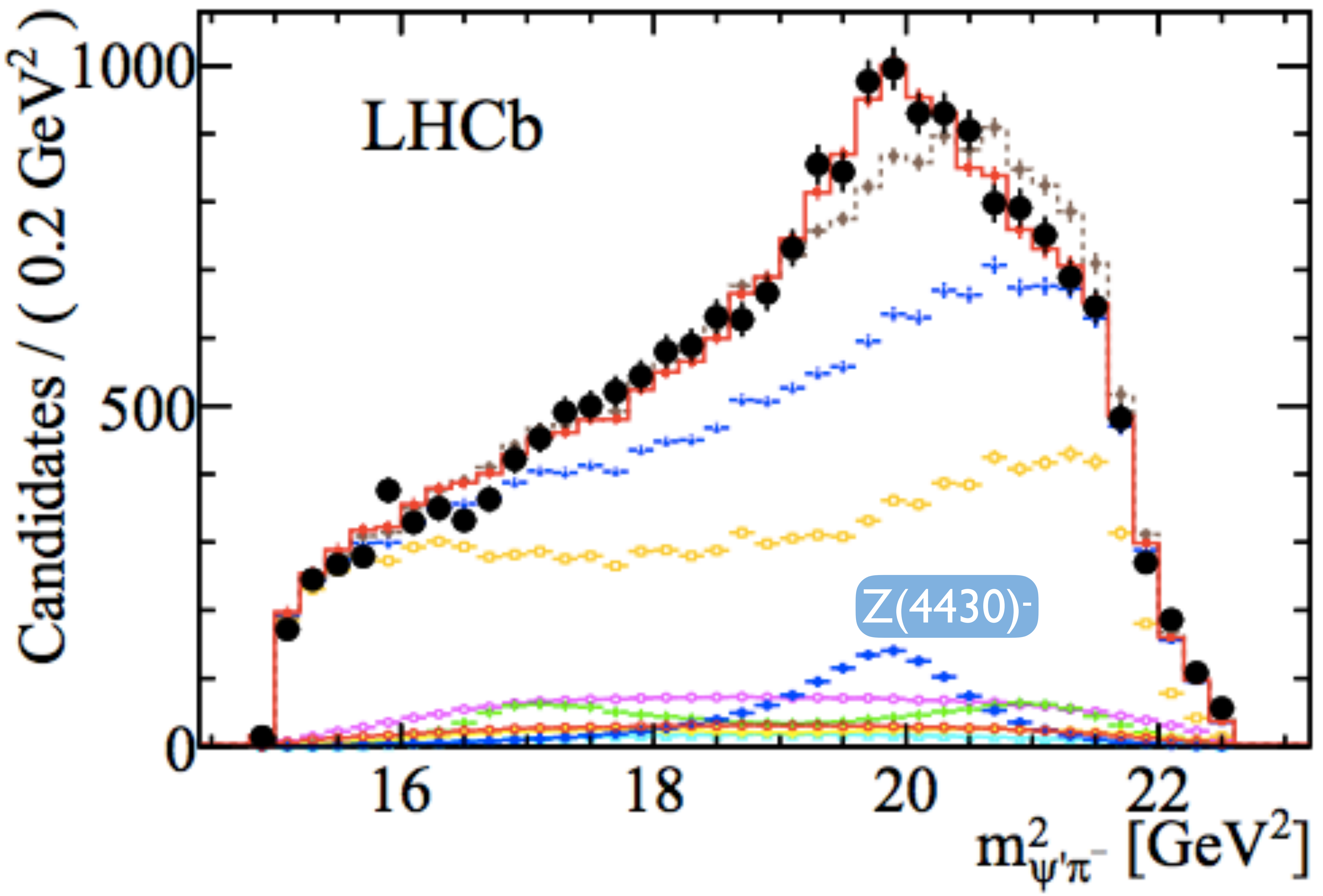
Exotic charmonium production

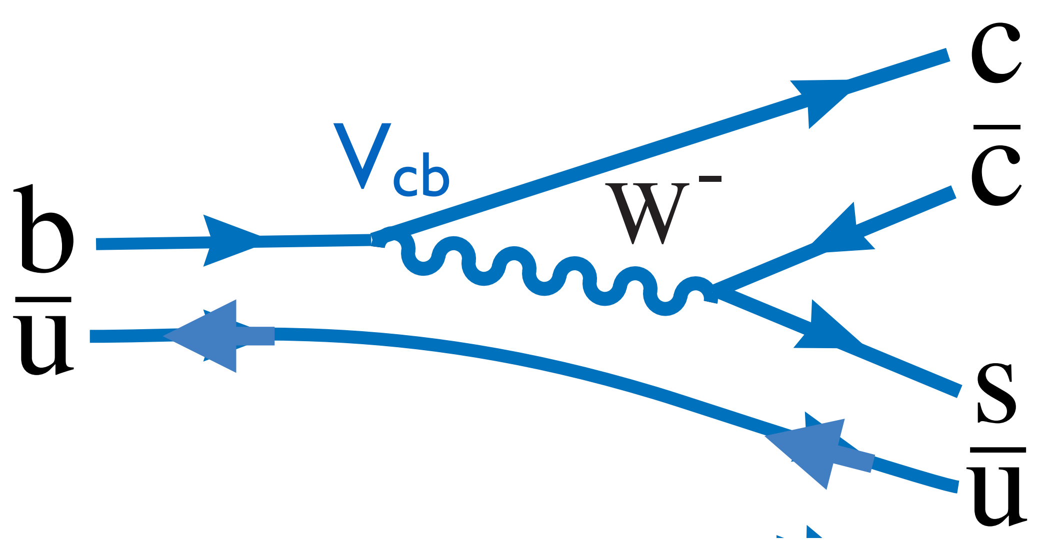
[PRL 112 (2014) 222002]

Charmonium in the final state is experimentally useful for triggering, particularly using muon/electron decay modes of J/ψ or ψ(2S)

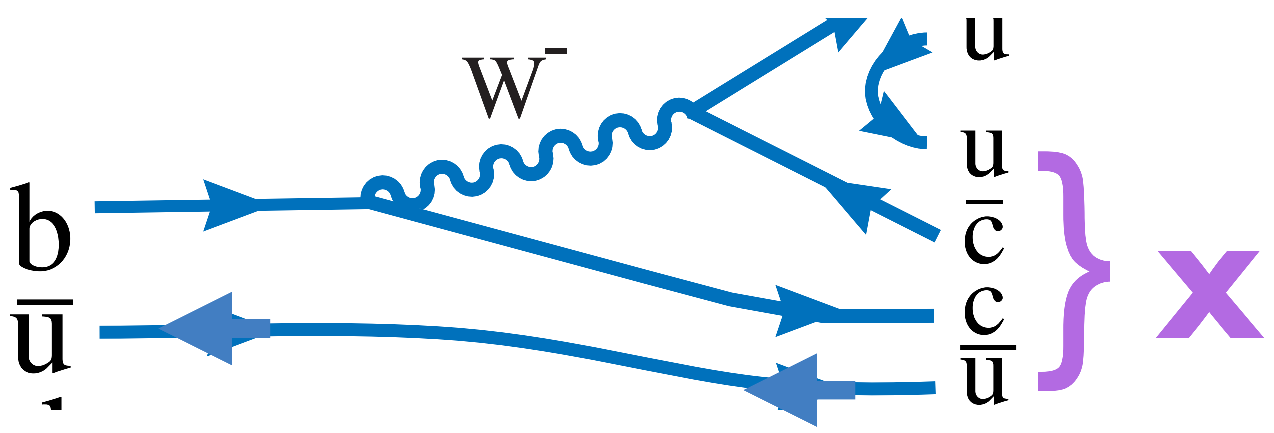
Both decay chains lead to the same particles in the final state

Mass fit is sufficient to identify exotic if state isolated and narrow, otherwise need **Dalitz or amplitude analysis**





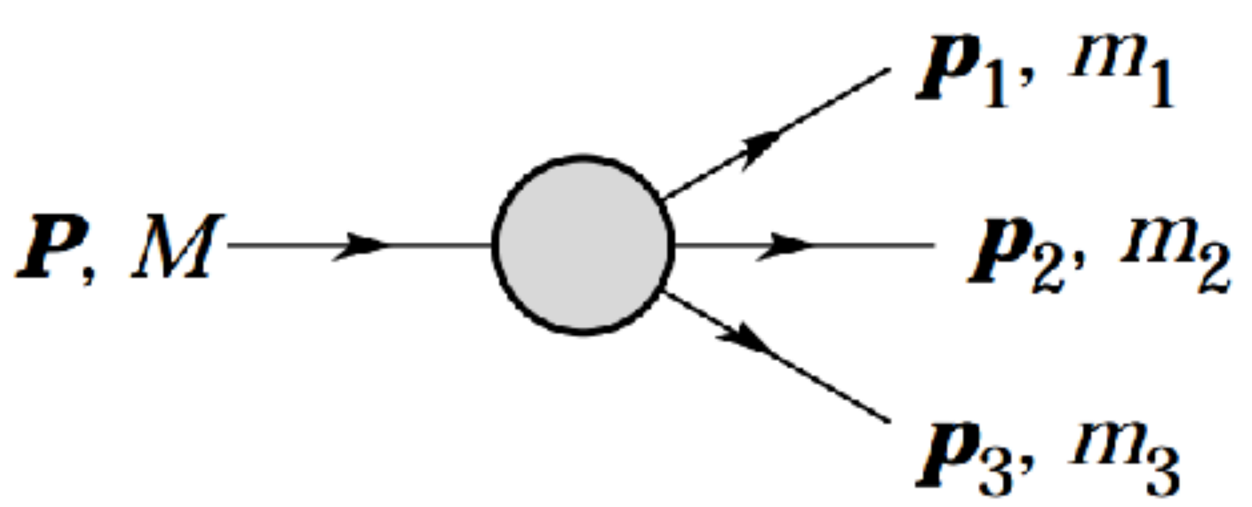
$B^+ \to \psi(2S)K^+, \psi(2S) \to J/\psi\pi^+\pi^-$



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

Reminder about Dalitz plots

scalar → 3 scalars



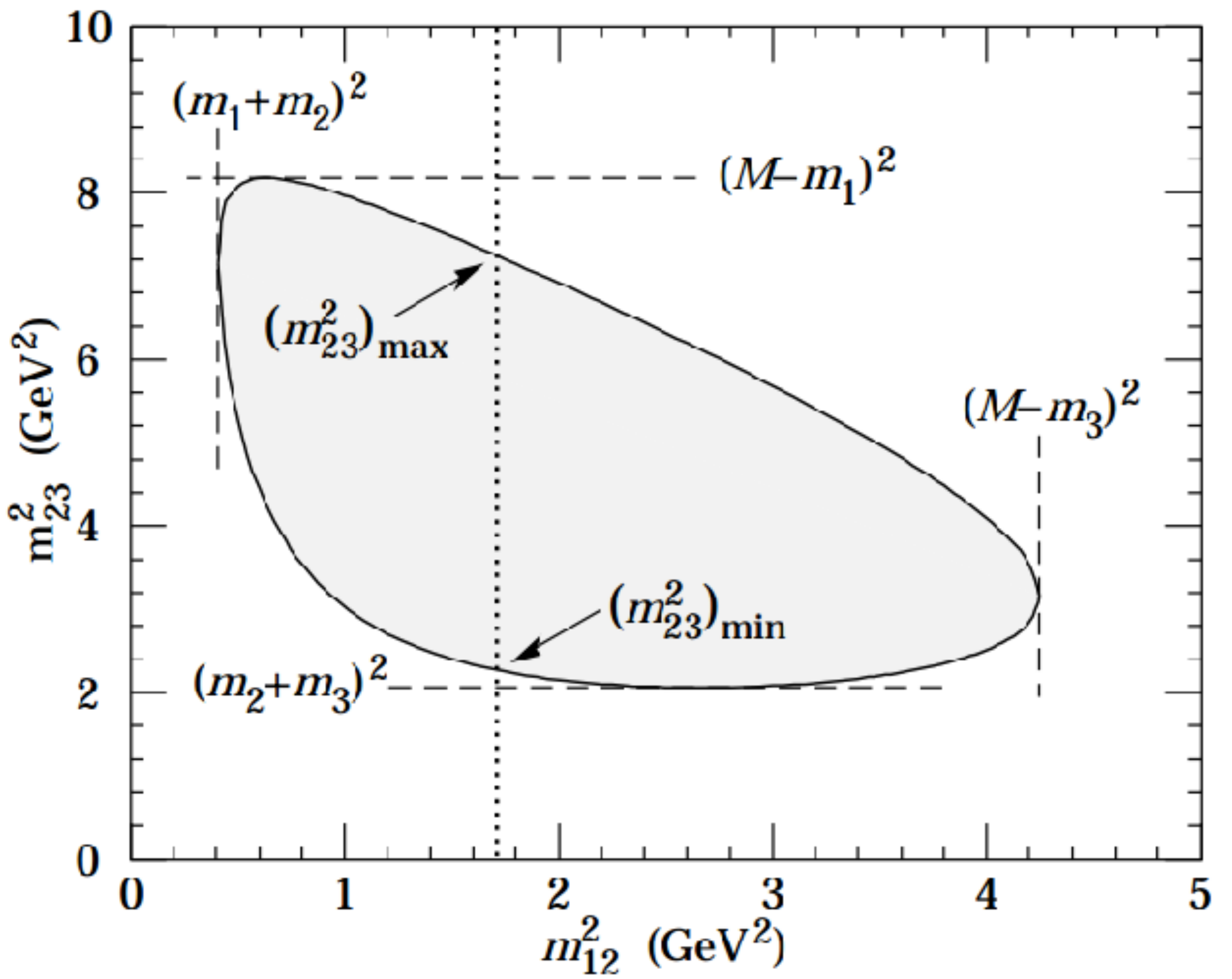
$$d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}\overline{|\mathscr{M}|^2}\, dm_{12}^2\, dm_{23}^2$$

Configuration of parent particle decay depends on angular momentum of decay products

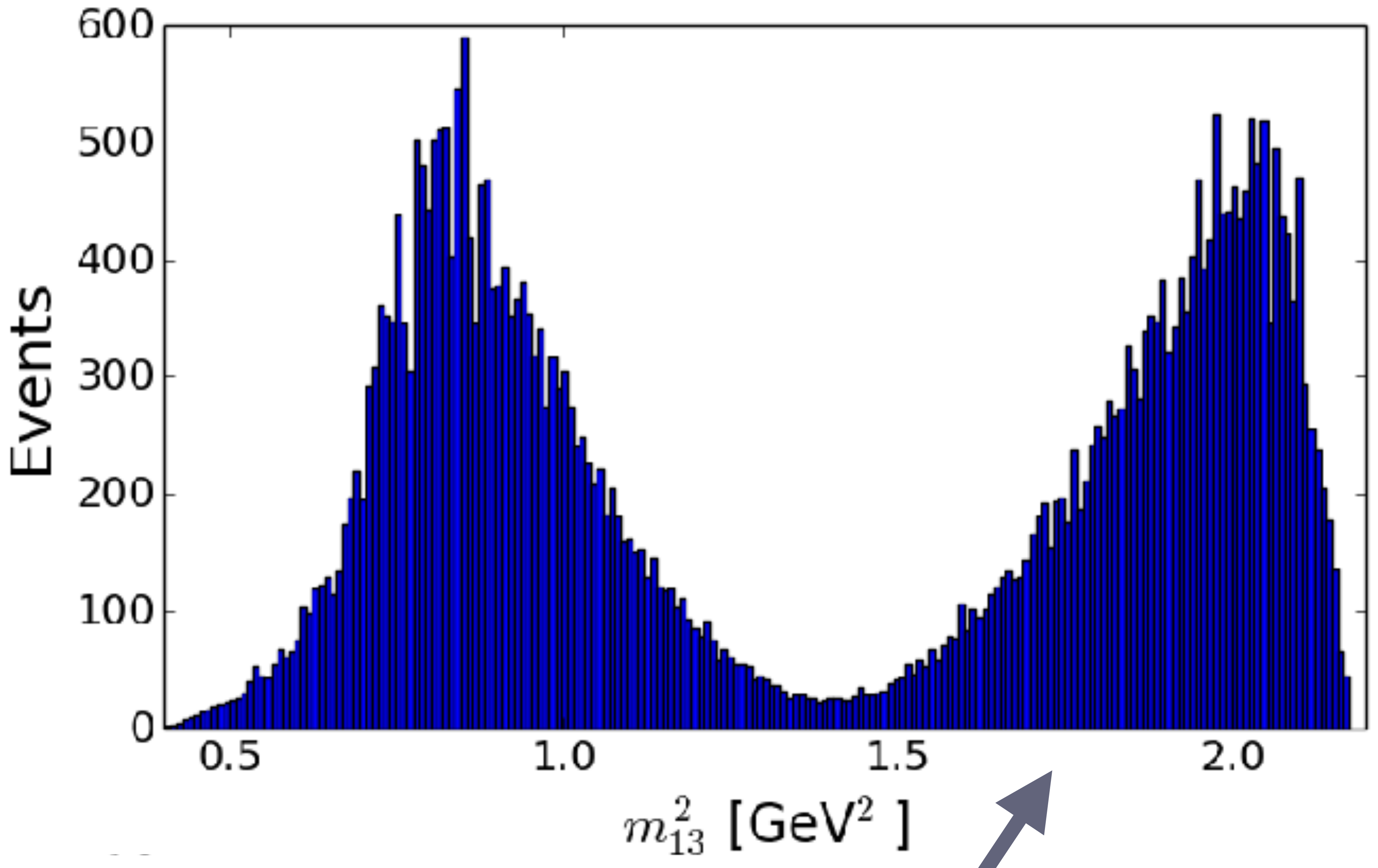
All dynamical information contained in $|M|^2$

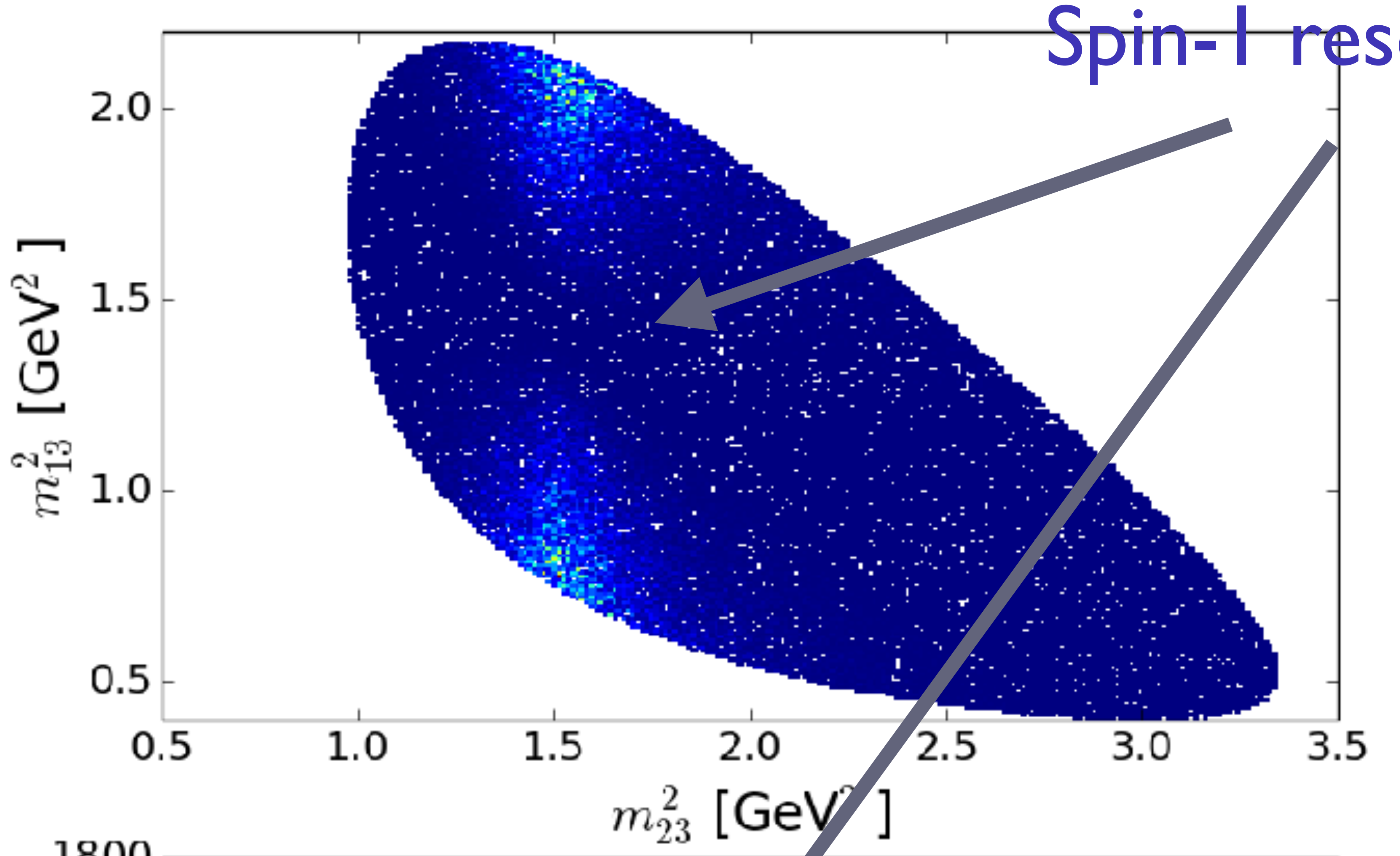
Density plot of m_{12}^2 vs. m_{23}^2 to infer information on $|M|^2$

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



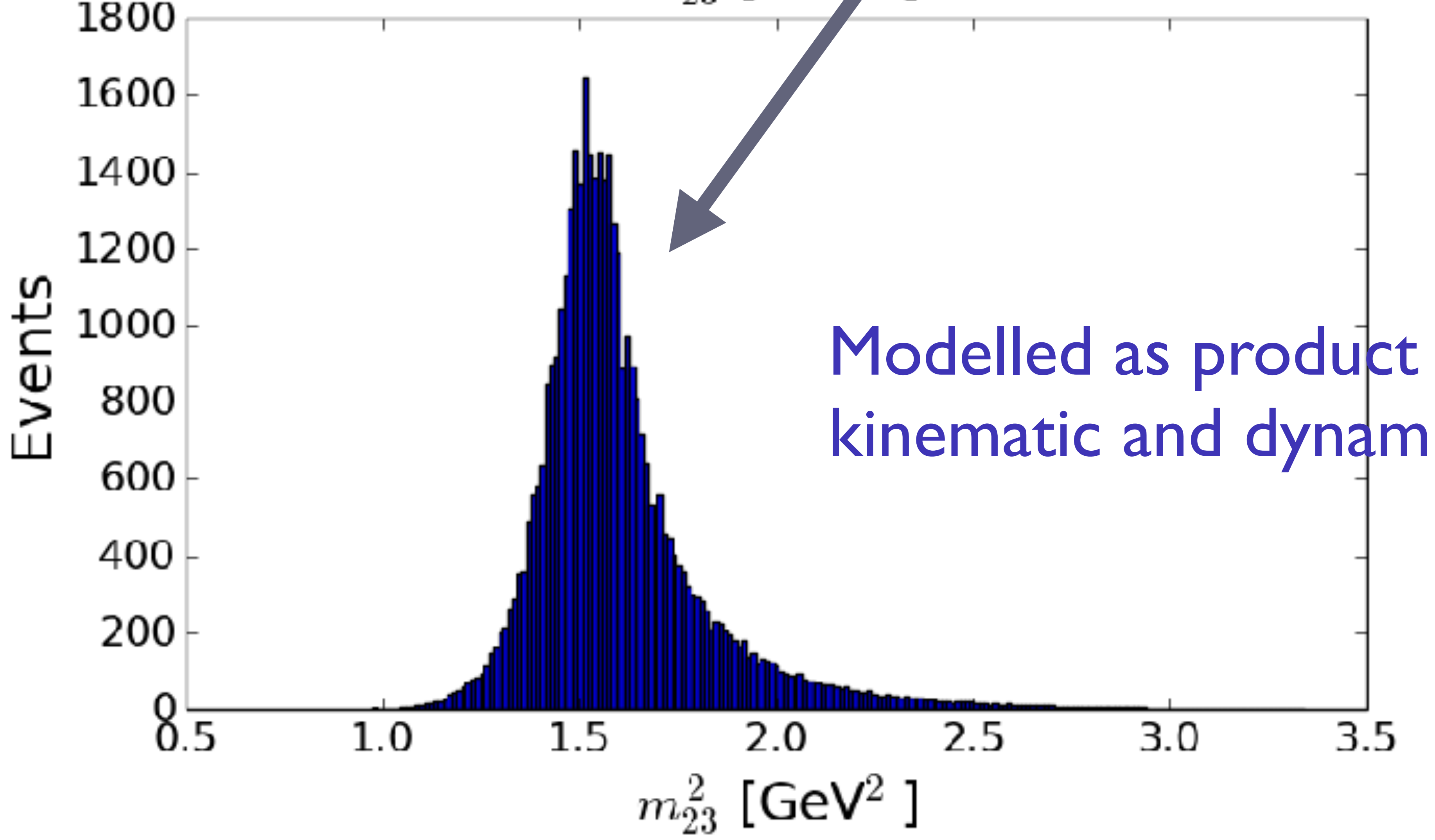
Reminder about Dalitz plots



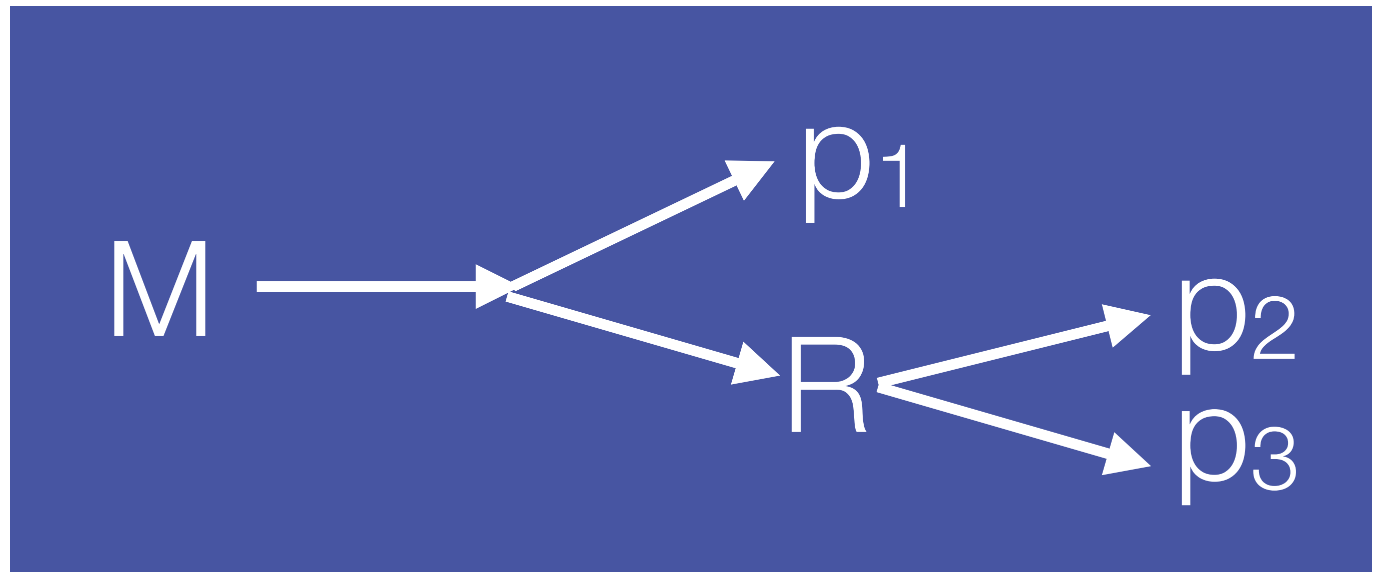


Spin-1 resonance

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

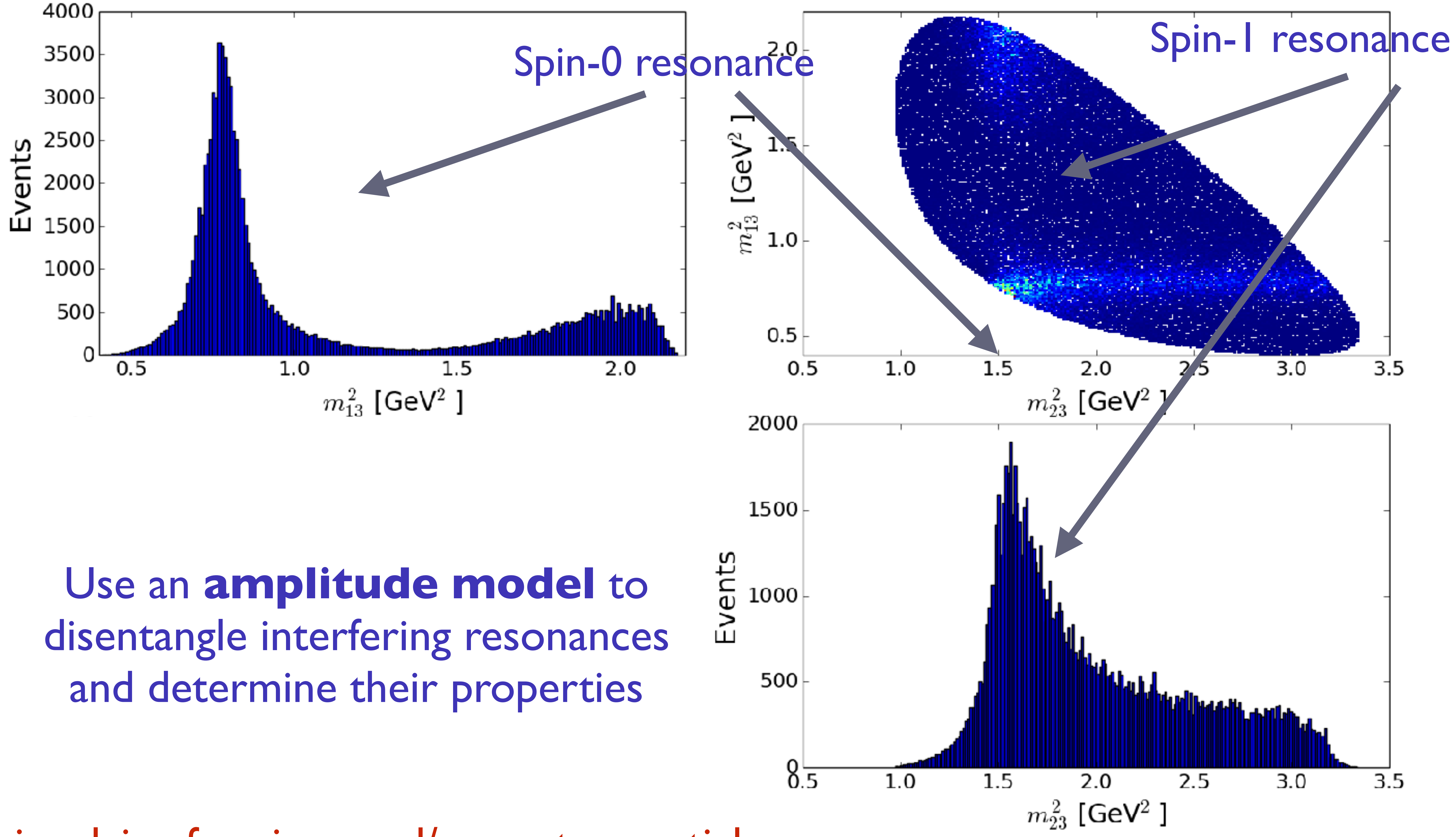


Modelled as product of Breit-Wigner, kinematic and dynamic factors



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

Reminder about Dalitz plots

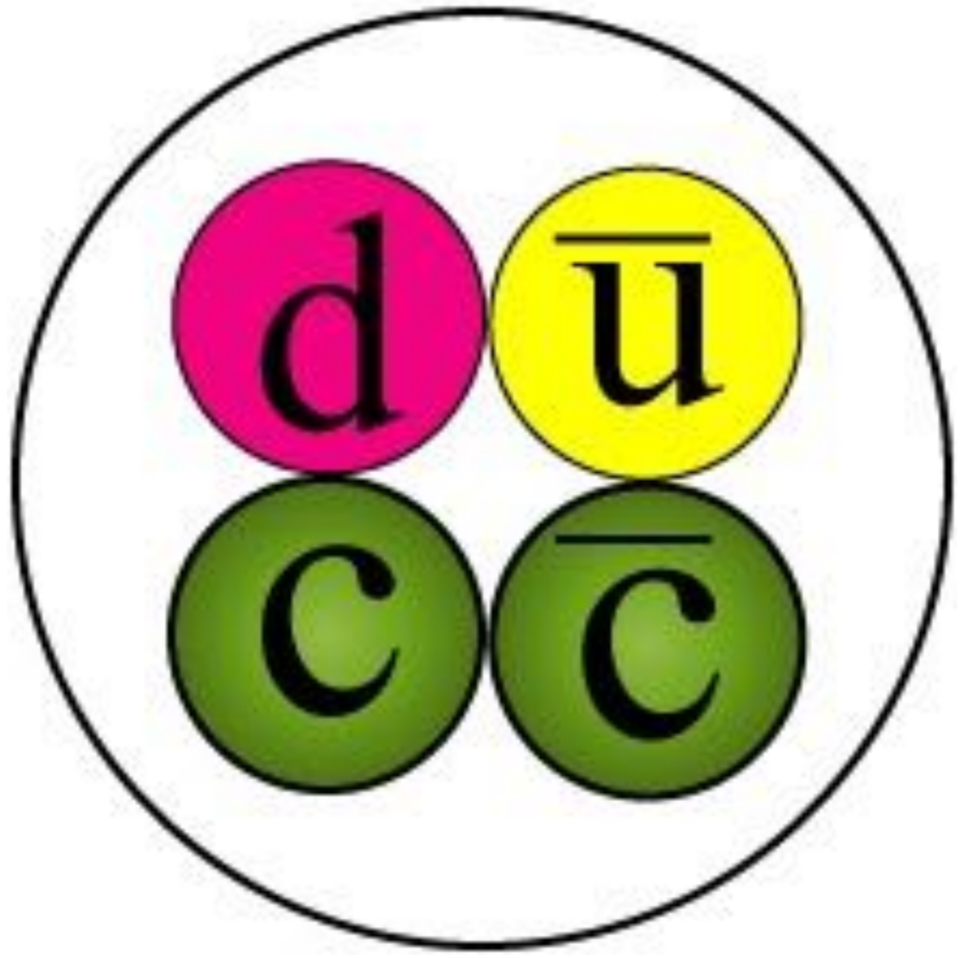


Use an **amplitude model** to disentangle interfering resonances and determine their properties

For decays involving fermions and/or vector particles then need to extend to more than 2 dimensions

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

Exotic mesons

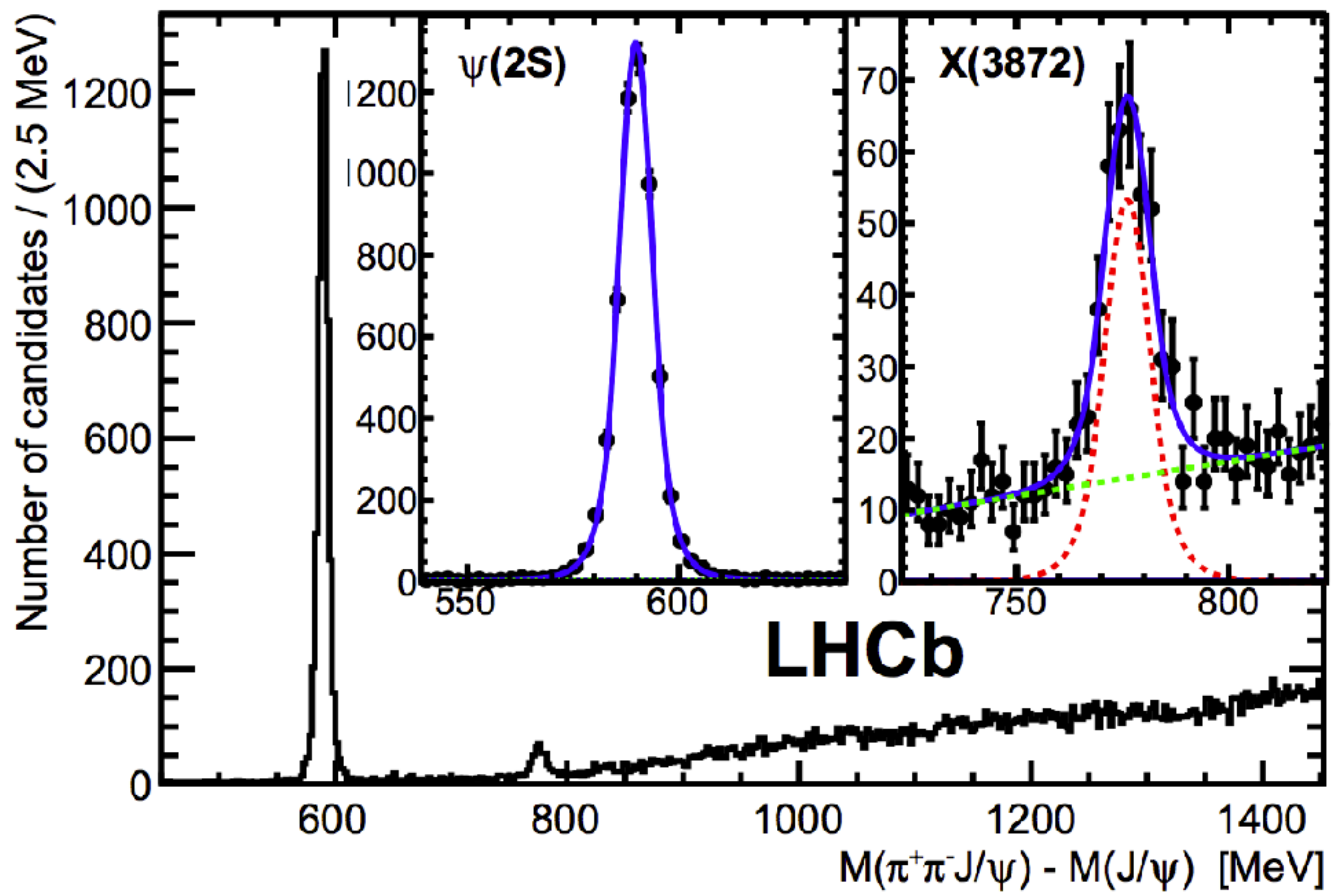


The X(3872) revolution

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, $D^0\bar{D}^{*0} = (c\bar{u})(\bar{c}u)$ molecule, $c\bar{c}g$ hybrid, hadrocharmonium…

[PRL 110 (2013) 222001]



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]

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]

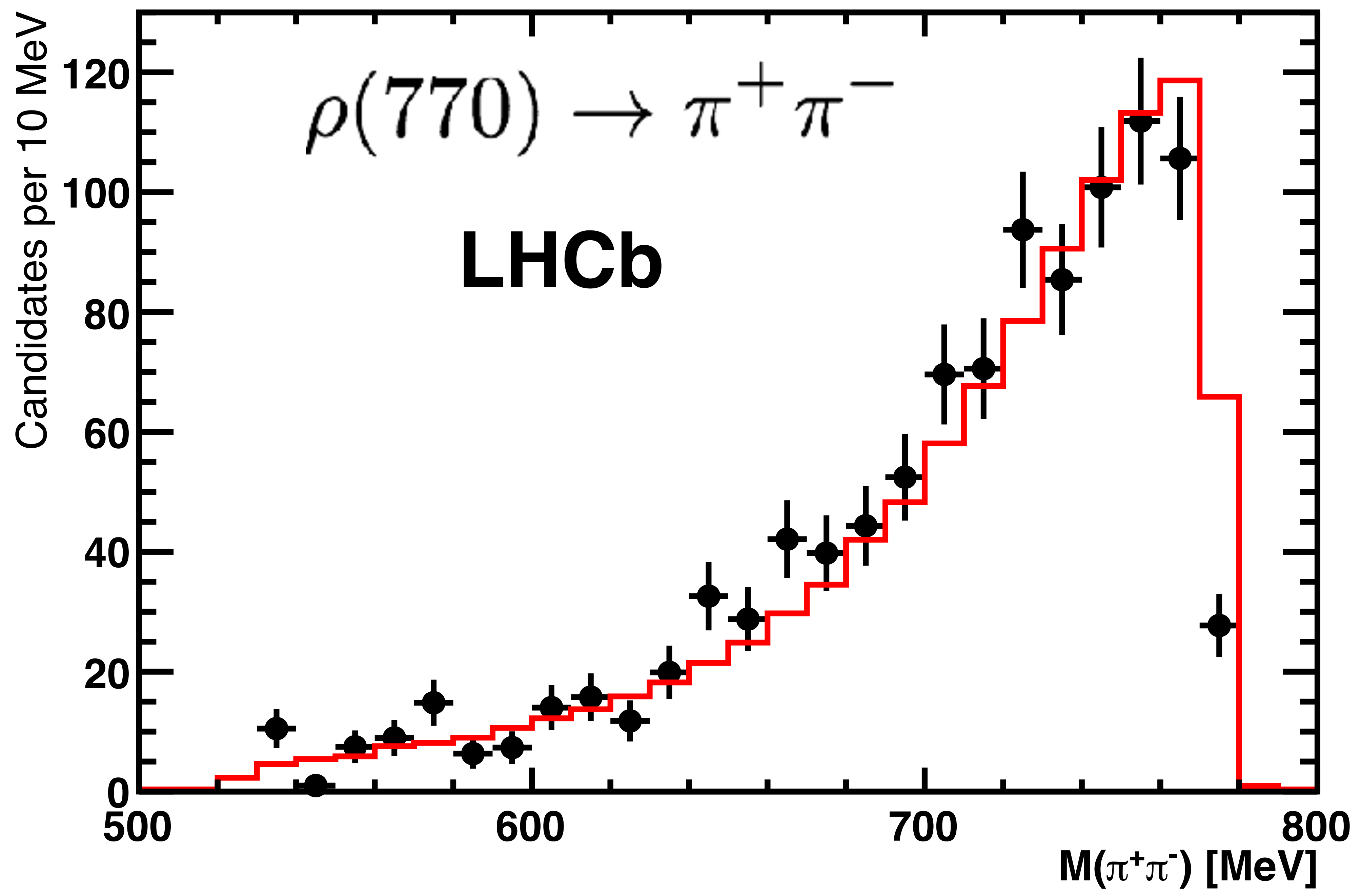
X(3872) quantum numbers

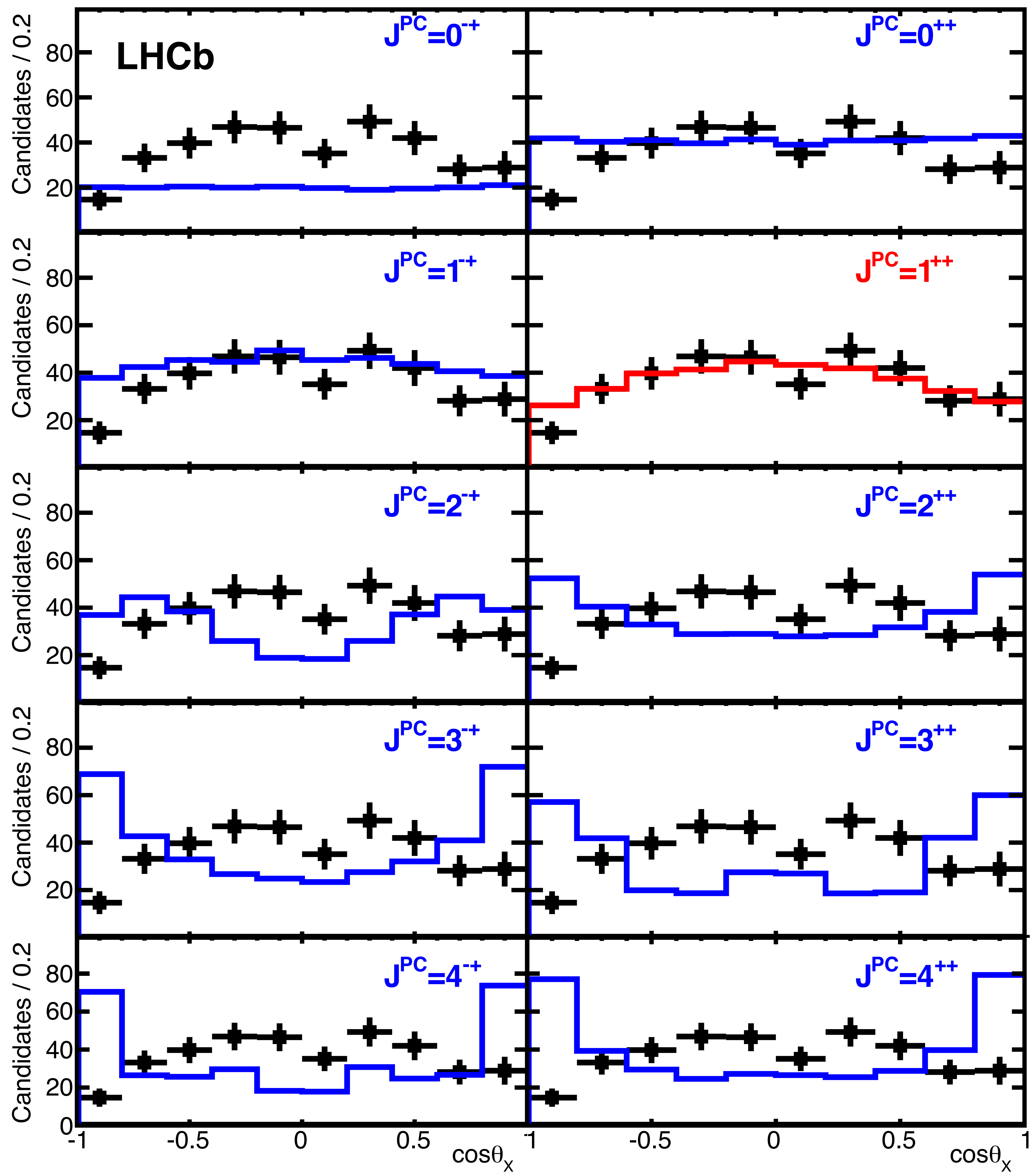
[PRD 92 (2015) 011102]

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

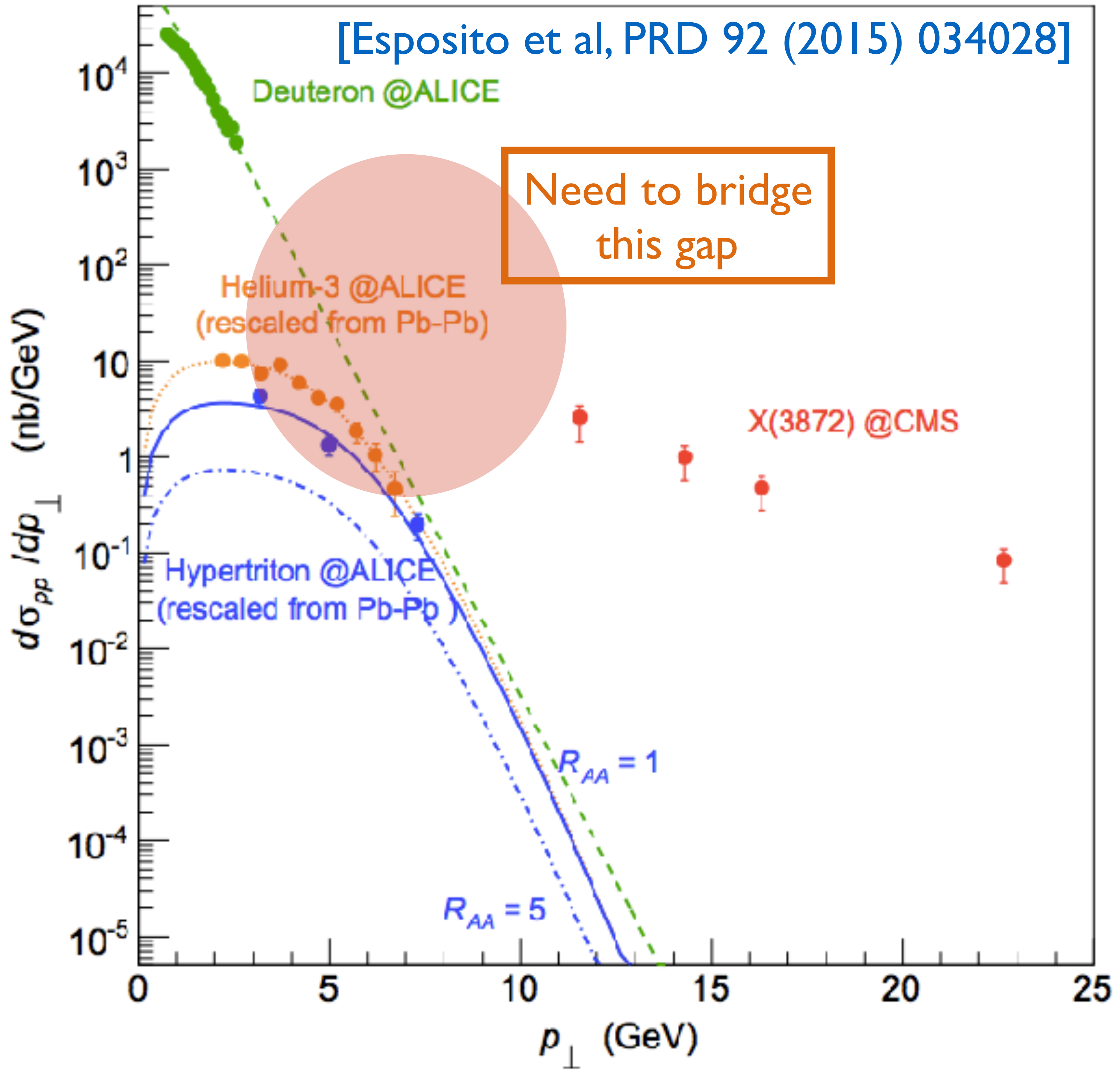
D-wave < 4% @ 95% CL (i.e., negligible)

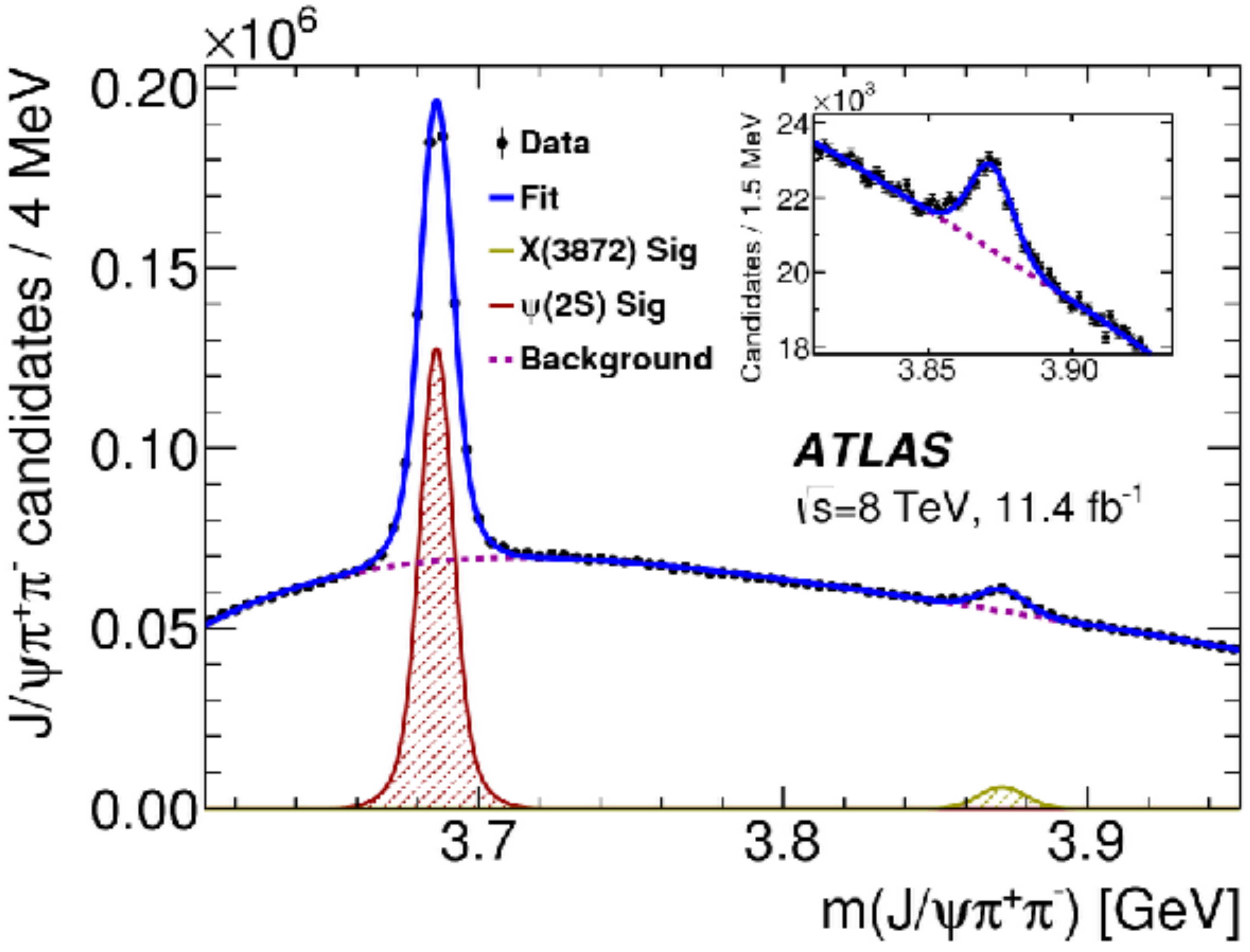
ρ(770) dominates → decay violates isospin so unlikely to be conventional $c\bar{c}$

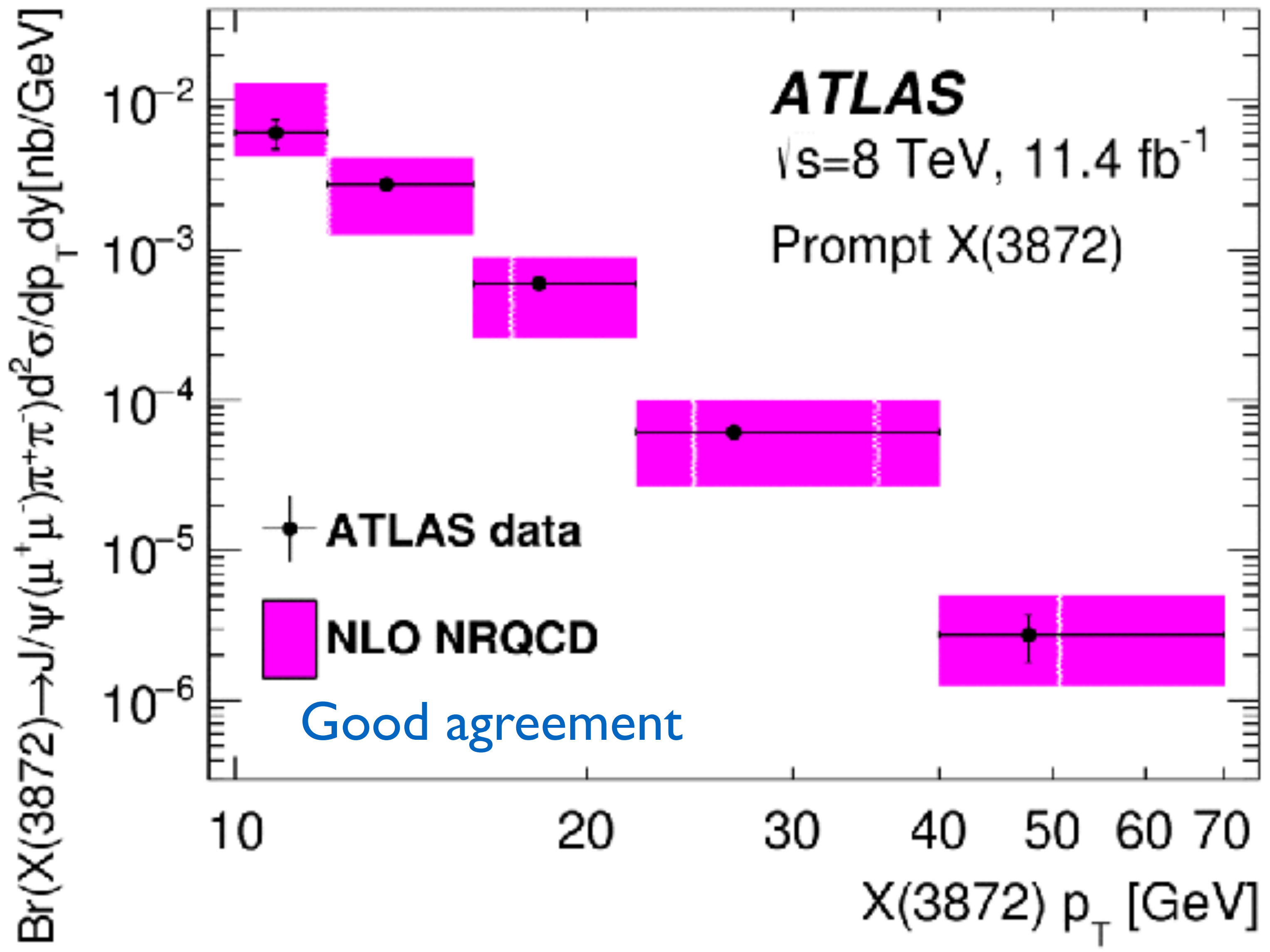




X(3872) production







X(3872) seen in pp and and $p\bar{p}$ collisions. [D0, PRL 103 (2009)152001] [CDF, PRL 103 (2009)152001] [ATLAS, JHEP 01 (2017) 117] [CMS, JHEP 04 (2013) 154] [LHCb, JHEP 04 (2013) 154]

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 $D^0\bar{D}^{*0}$ 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]

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**

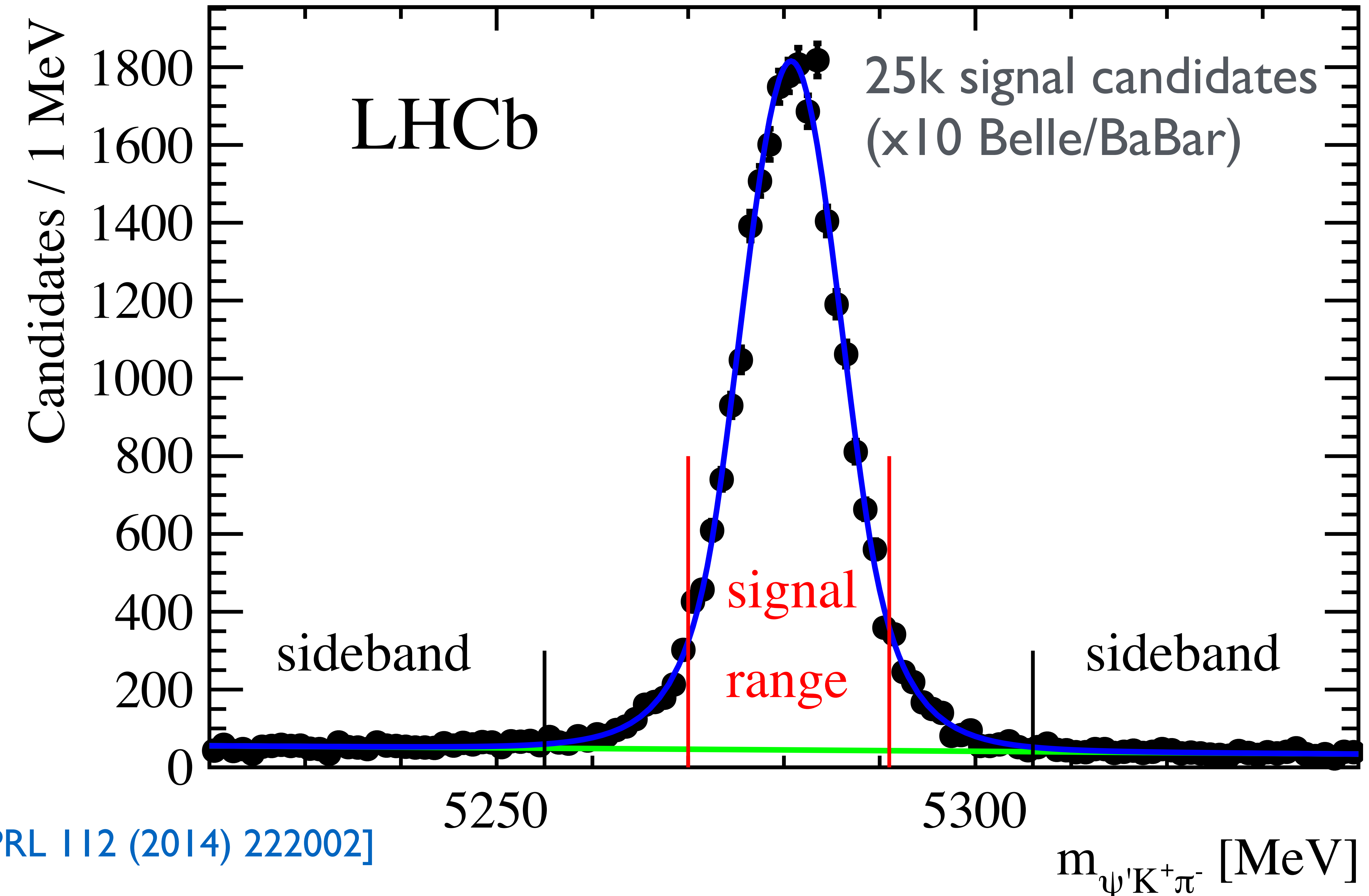
[Belle, PRD 88 (2013) 074026] 4D amplitude fit **6.4σ**

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

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

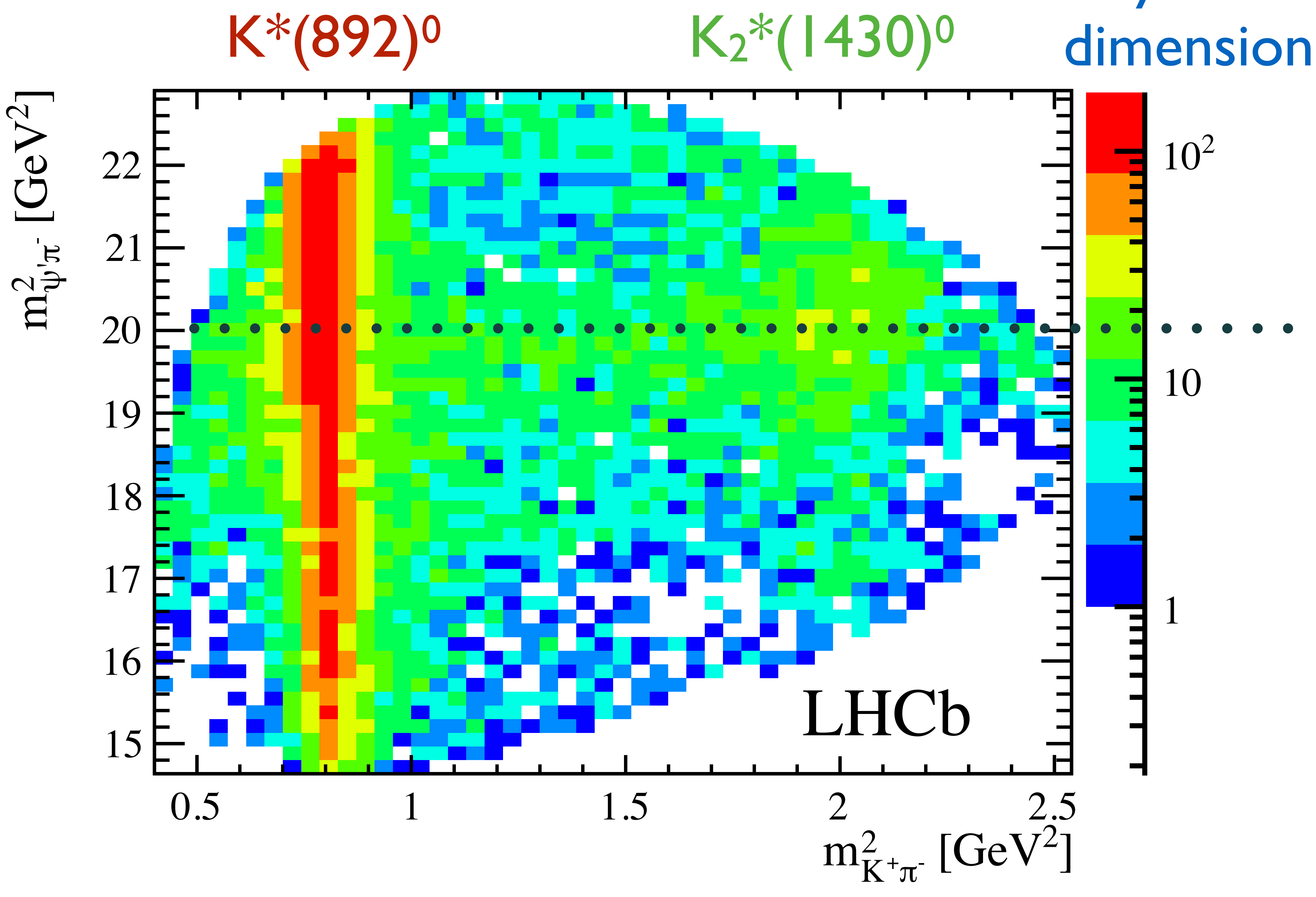
- dimuon in final state → highly efficient for triggering

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



[PRL 112 (2014) 222002]

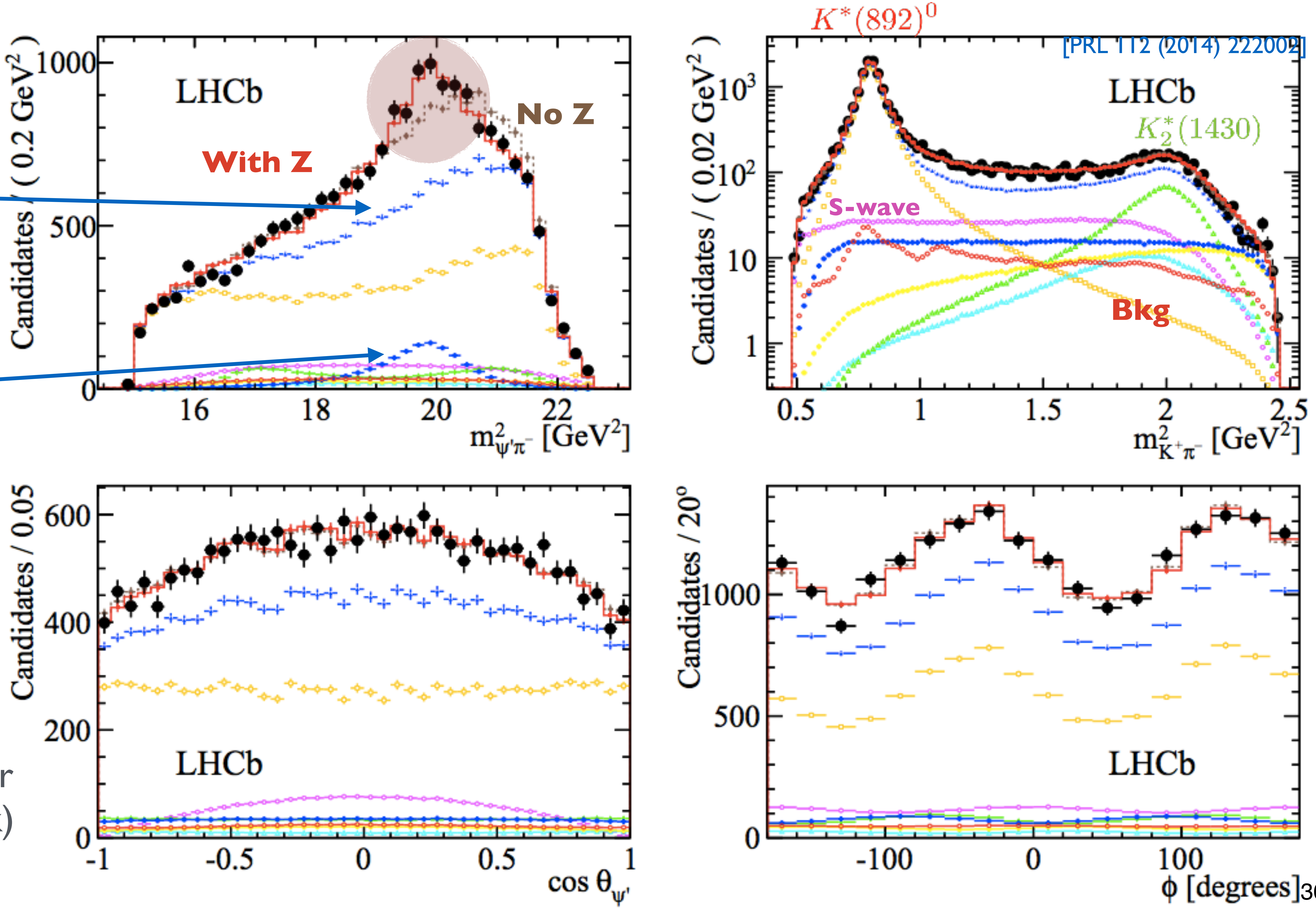
Only 2 of the 4 dimensions…



Confirmation of the Z(4430)$^-$

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

Z$^-$ component $J^P = 1^+$



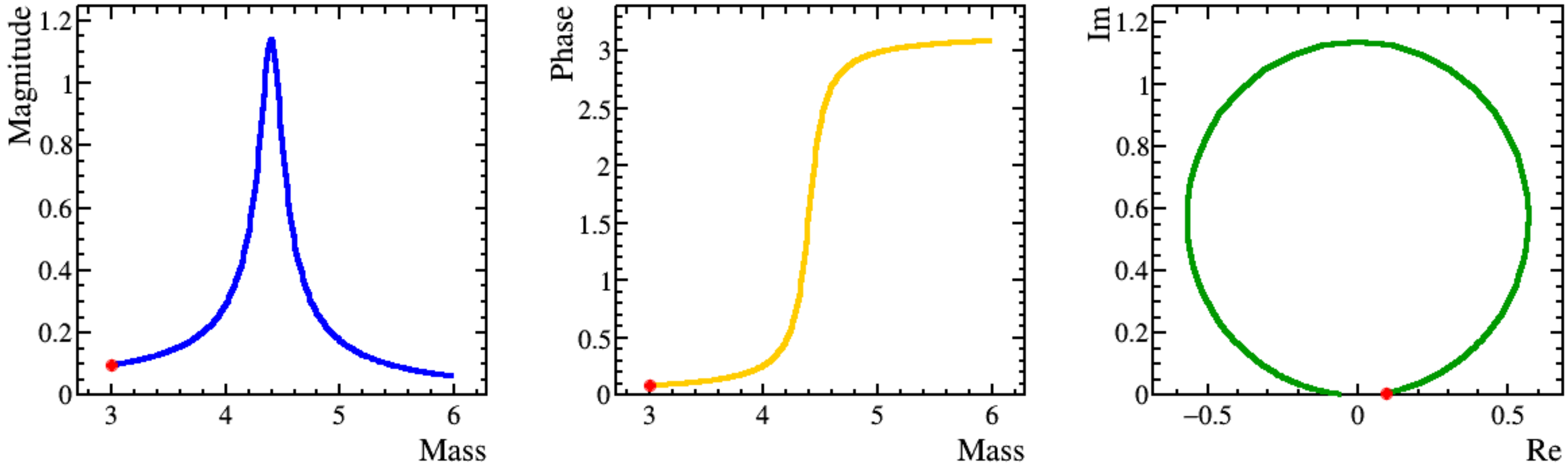
4D amplitude analysis used to measure Z$^-$ parameters (BW mass and width) and J^P

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

[PRD 92 (2015) 112009]

Resonant behaviour

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



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

Argand diagram

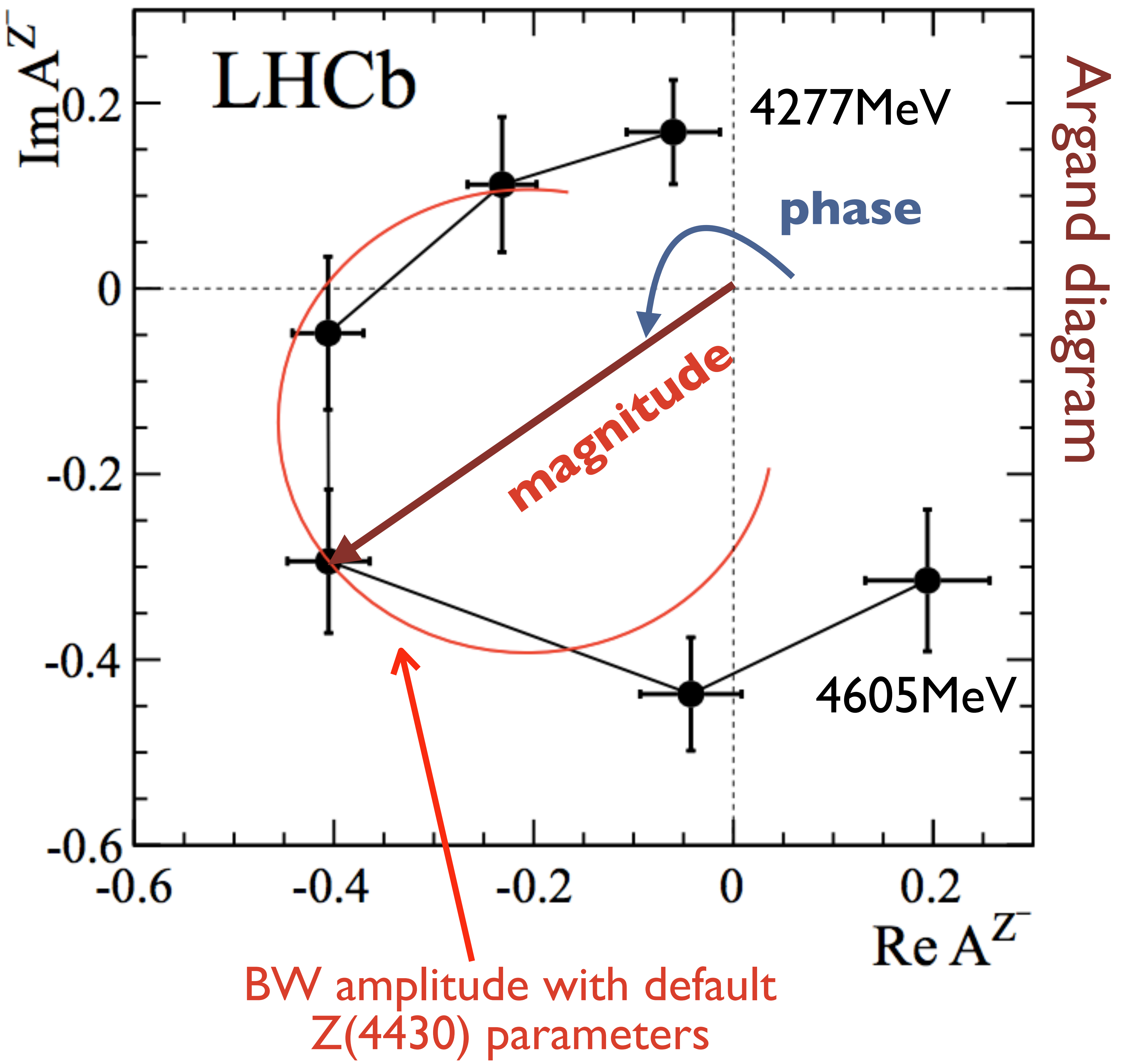
Breit-Wigner resonance parameterisation

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

link

Resonant behaviour

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



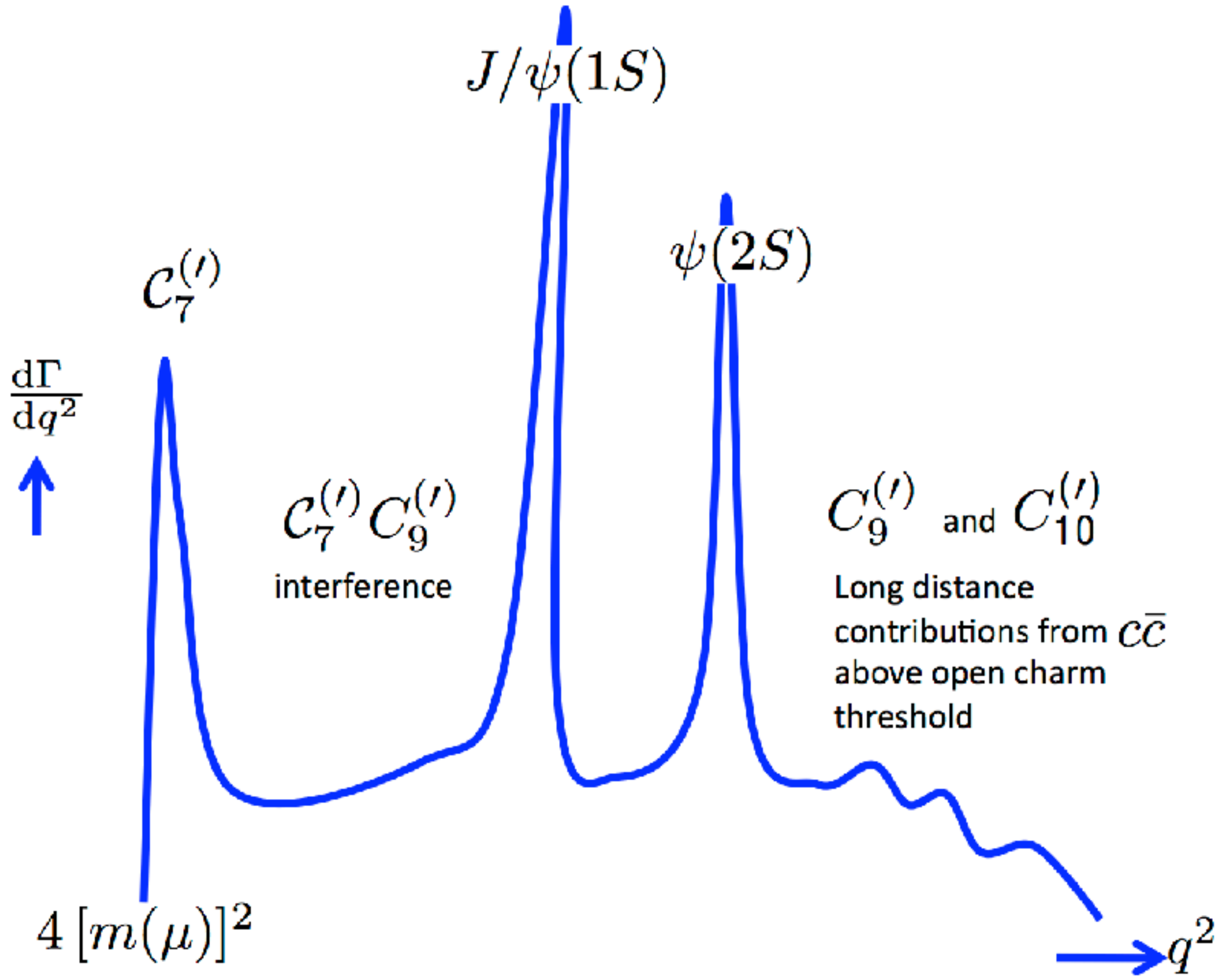
Excellent agreement between LHCb and Belle.

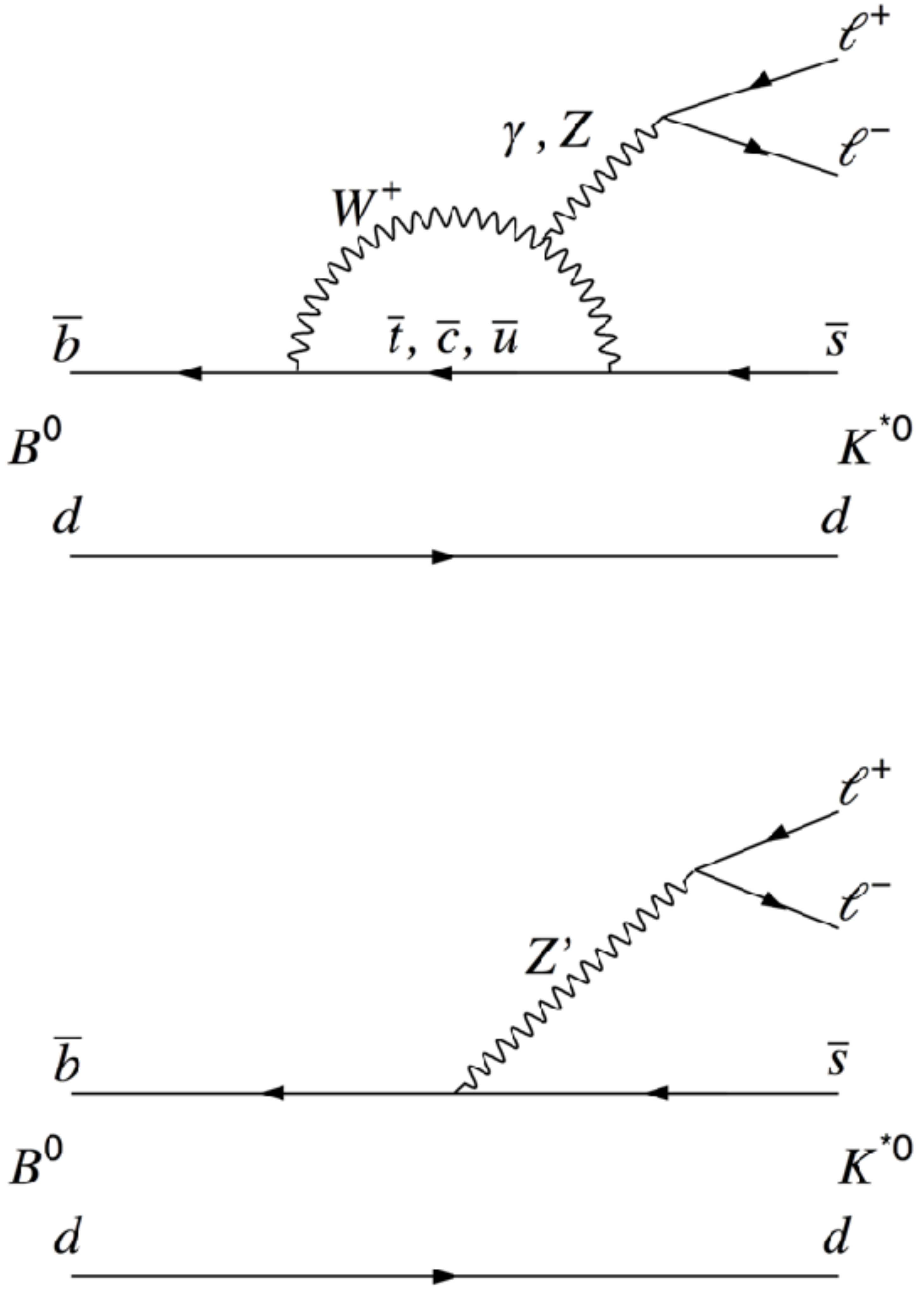
Belle evidence for $Z(4430)^{\pm} \rightarrow J/\psi\pi^{\pm}$ and observation of a new resonant state $Z(4200)^{\pm} \rightarrow J/\psi\pi^{\pm}$ [PRD 90 (2014) 112009]

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

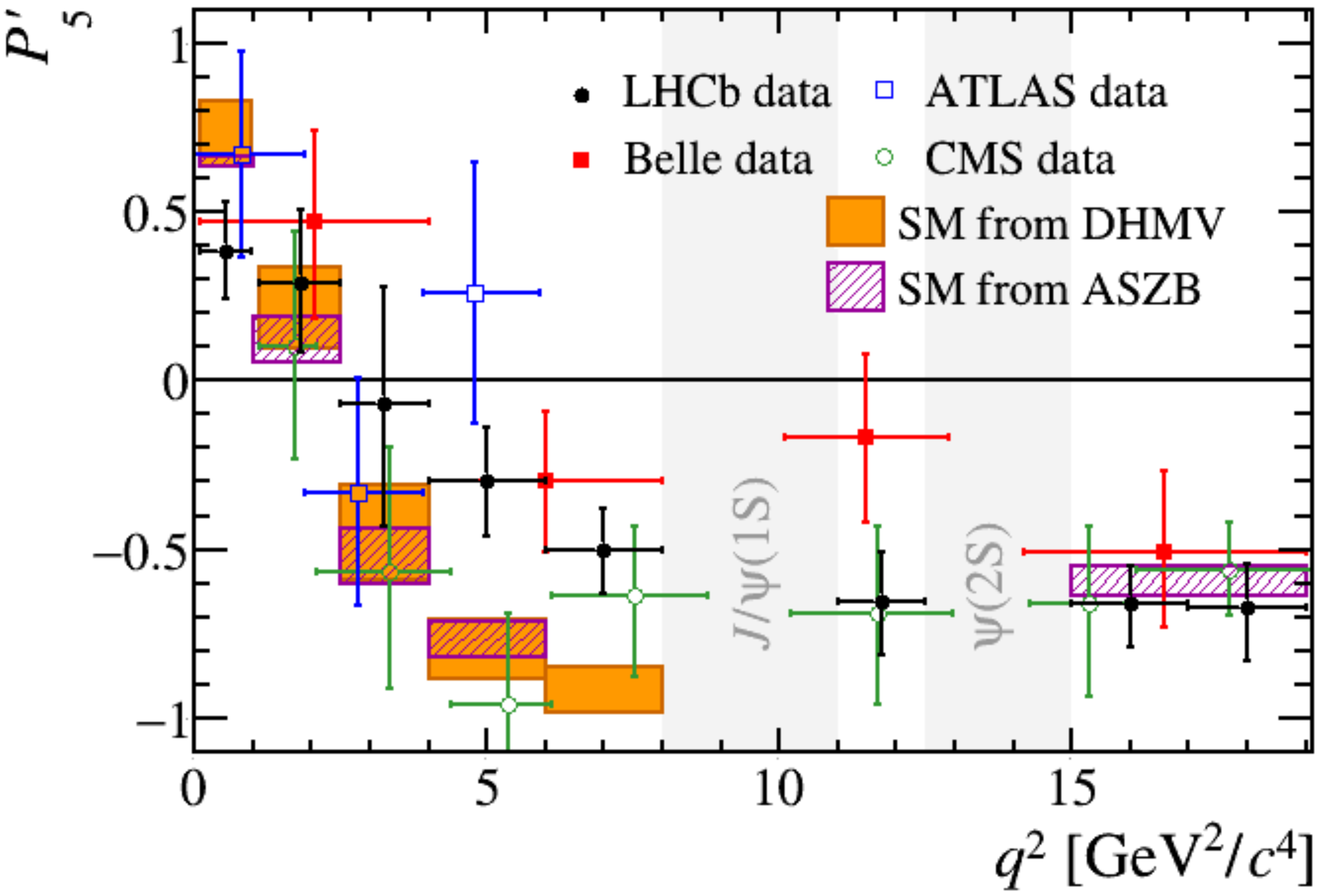
Link to new physics searches with B → K*μ+μ-

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i [\underbrace{C_i(\mu)O_i(\mu)}_{\text{left-handed part}} + \underbrace{C_i'(\mu)O_i'(\mu)}_{\text{right-handed part}}]$$





Link to new physics searches with B → K*μ⁺μ⁻



[JHEP 02 (2016) 104, ATLAS-CONF-2017-023, CMS-PAS-BPH-15-008, PRL 118 (2017) 111801]

Theory uncertainty from hadronic contributions in the $c\bar{c}$ regions

Theoretical attempts to cross the charmonium region use inputs from B → K*(→ Kπ)ψ decays, but currently ignore exotic ψπ resonance contributions

[Bobeth et al., arXiv:1707.07305]
[Blake et al., arXiv:1709.03921]

This will be important to control in the future!

X(4140) → J/ψϕ : some history

Seen by CDF, D0 and CMS

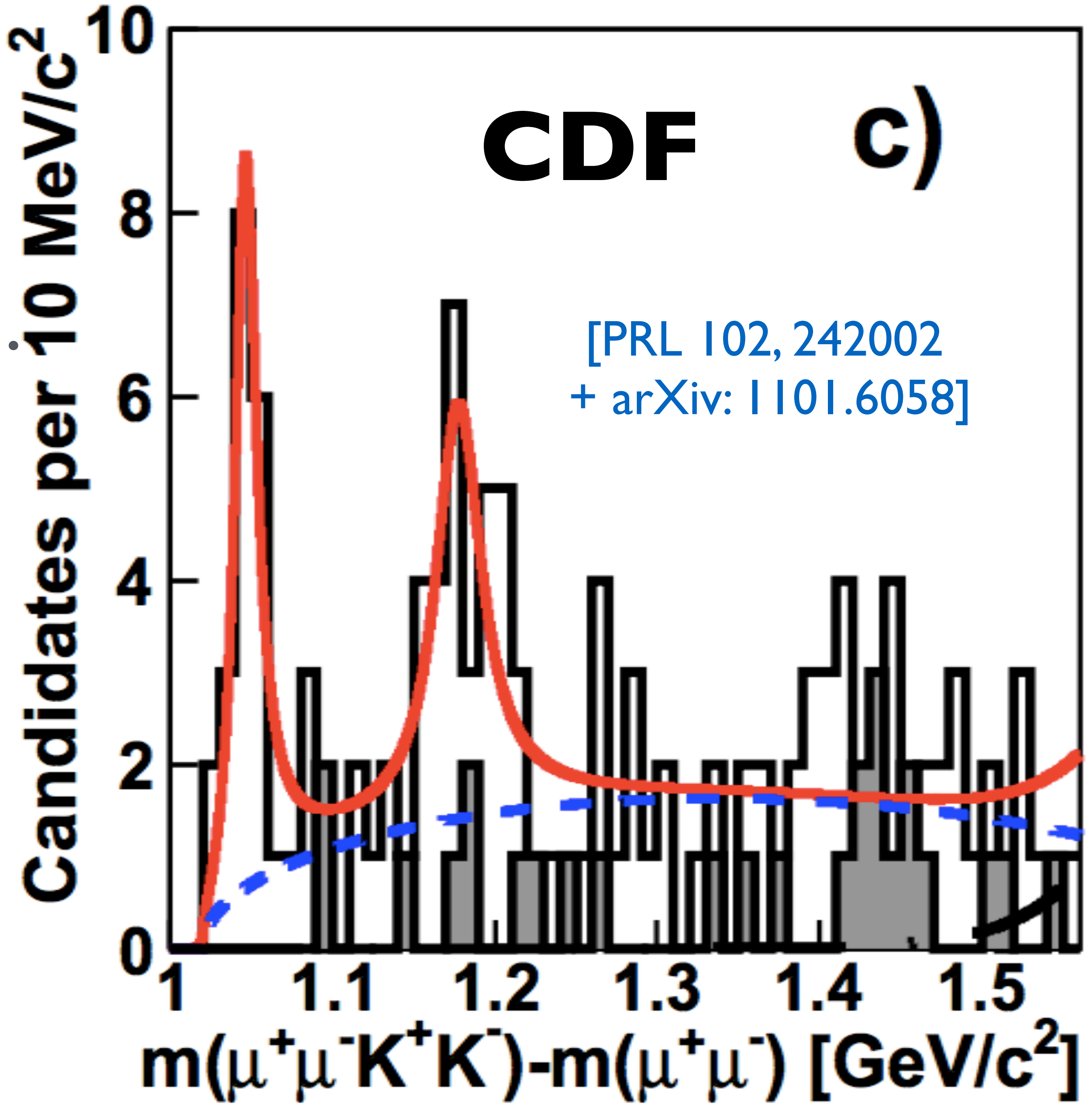
Not seen by LHCb, BaBar, BES-III, Belle (γγ fusion).

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

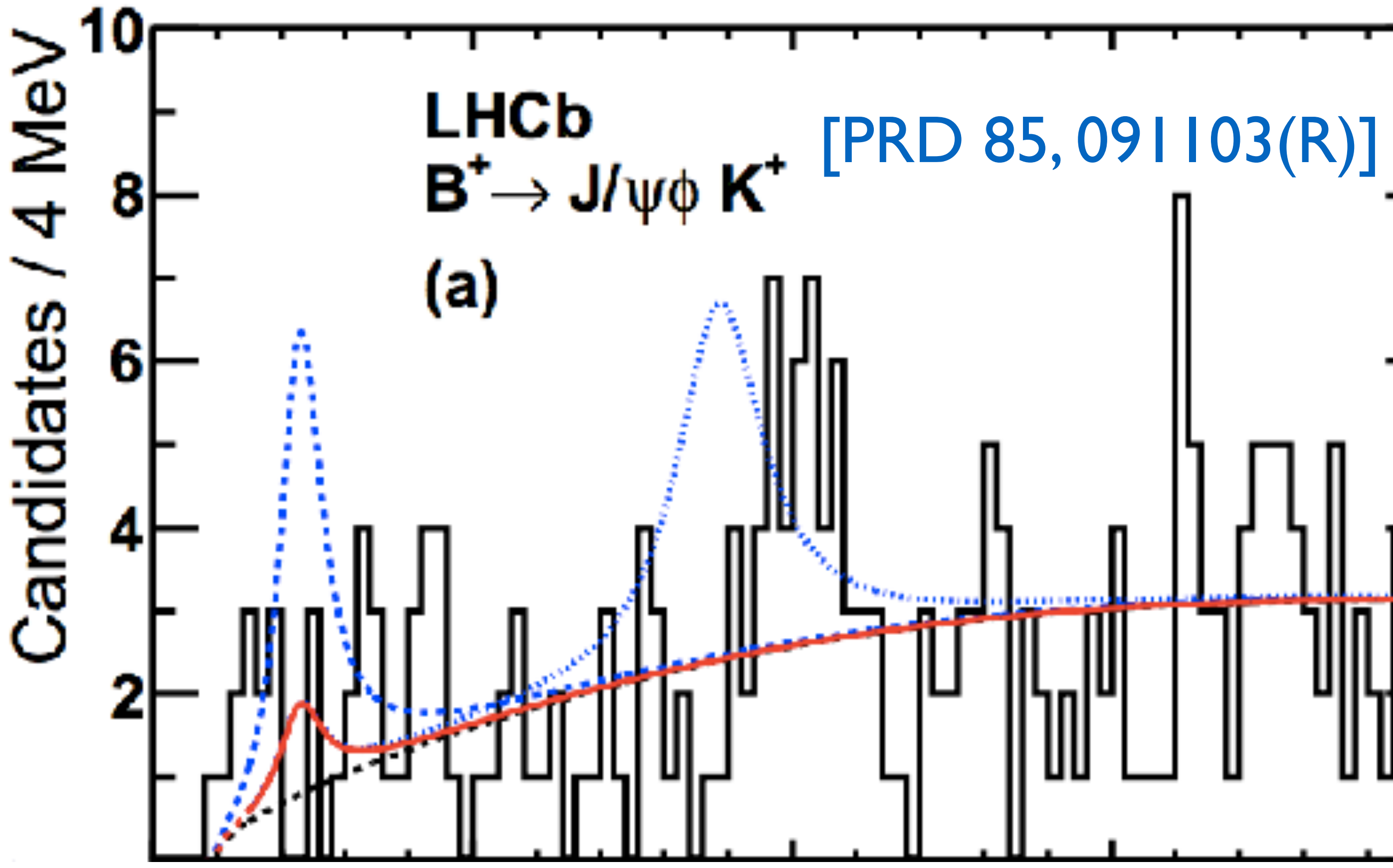
Also second state at higher mass…

Full amplitude analysis of decay is essential!

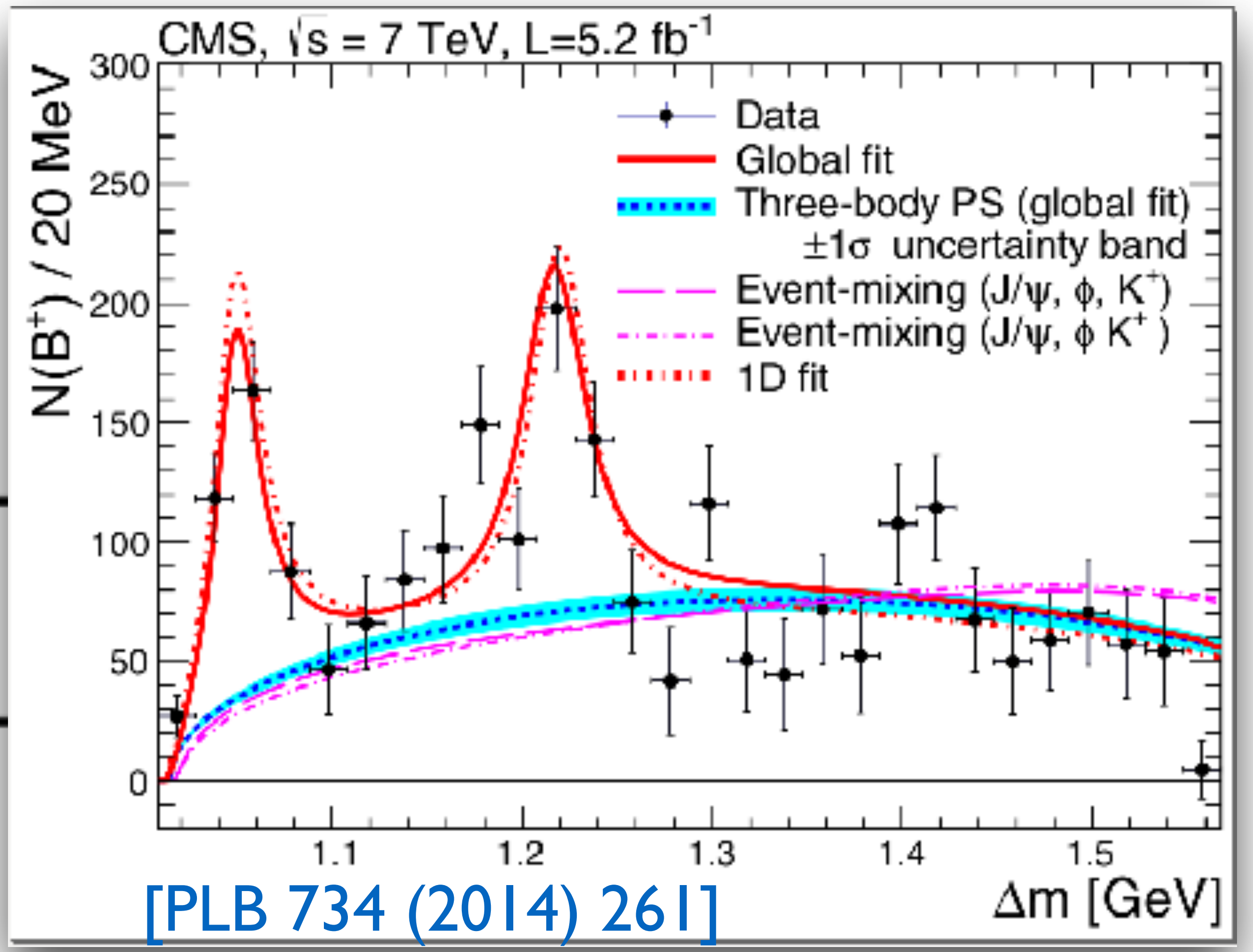
$$c\bar{c}s\bar{s}$$



[PRL 102, 242002 + arXiv: 1101.6058]



[PRD 85, 091103(R)]



[PLB 734 (2014) 261]

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

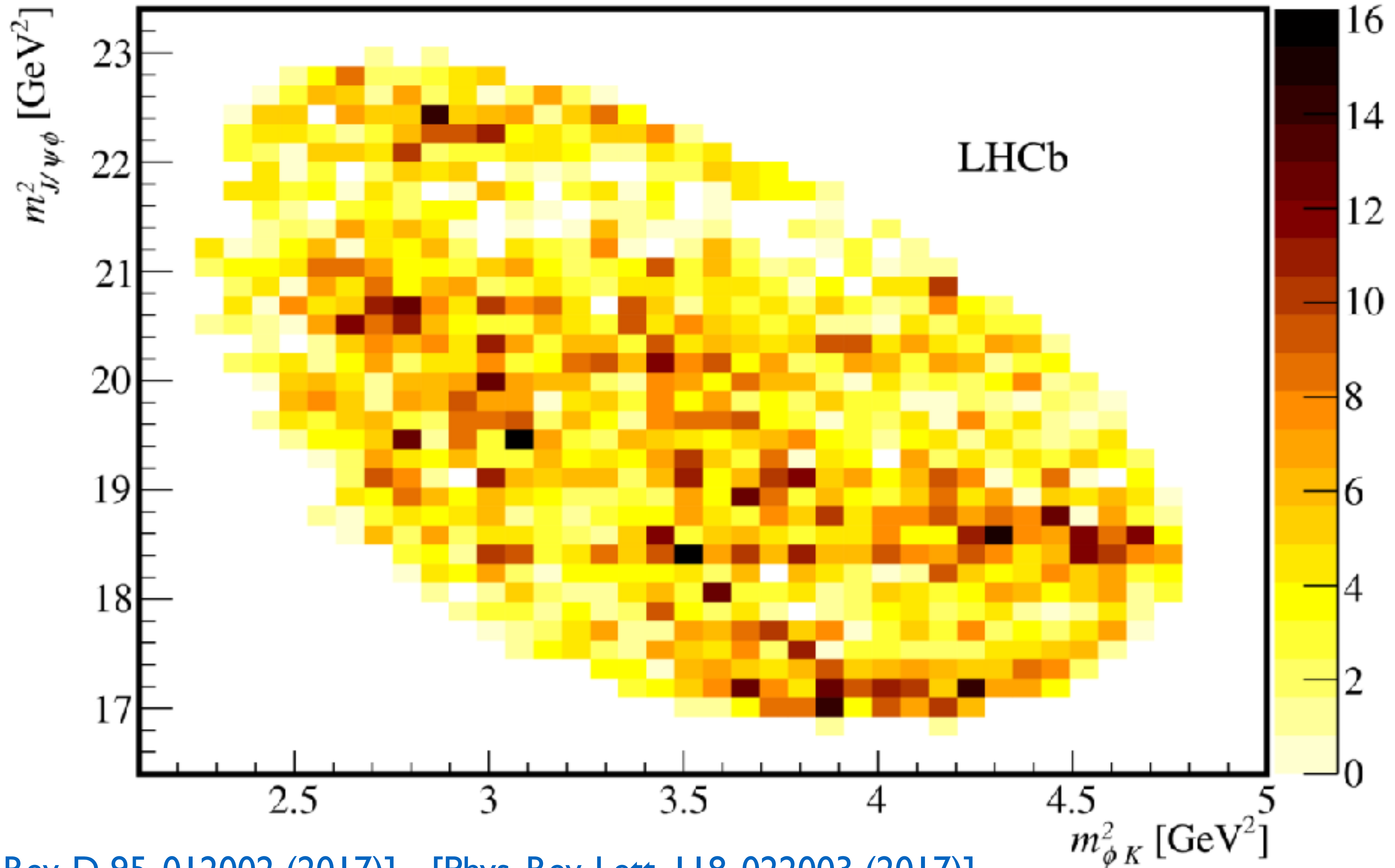
[D0 PRD 89, 012004]
[Belle PRL 104, 112004]
[BES-III PRD 91 (2015) 032002]

$B^+ \to J/\psi\phi K^+$ data sample

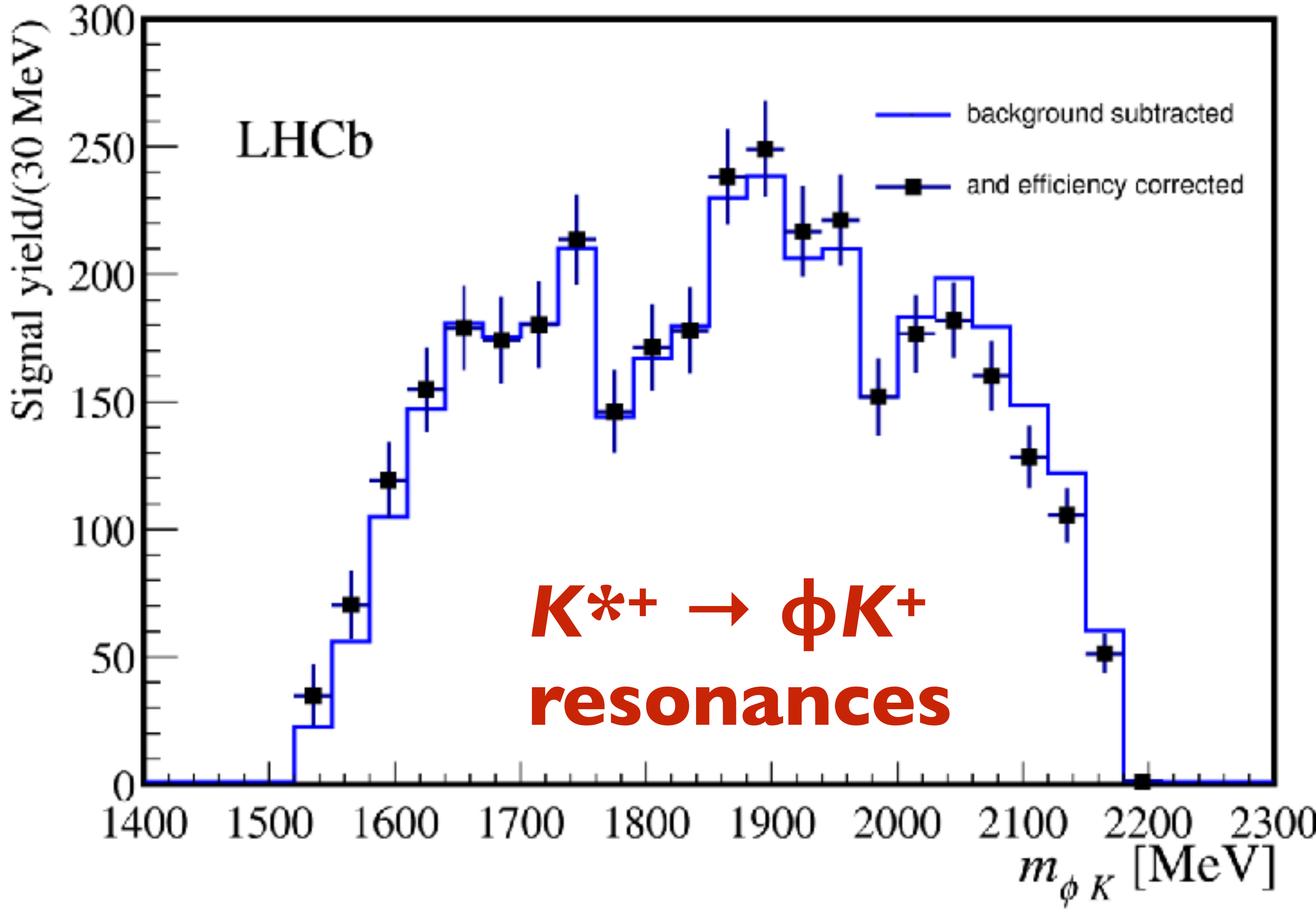
Are reflections from K^* system causing structure in $J/\psi\phi$?

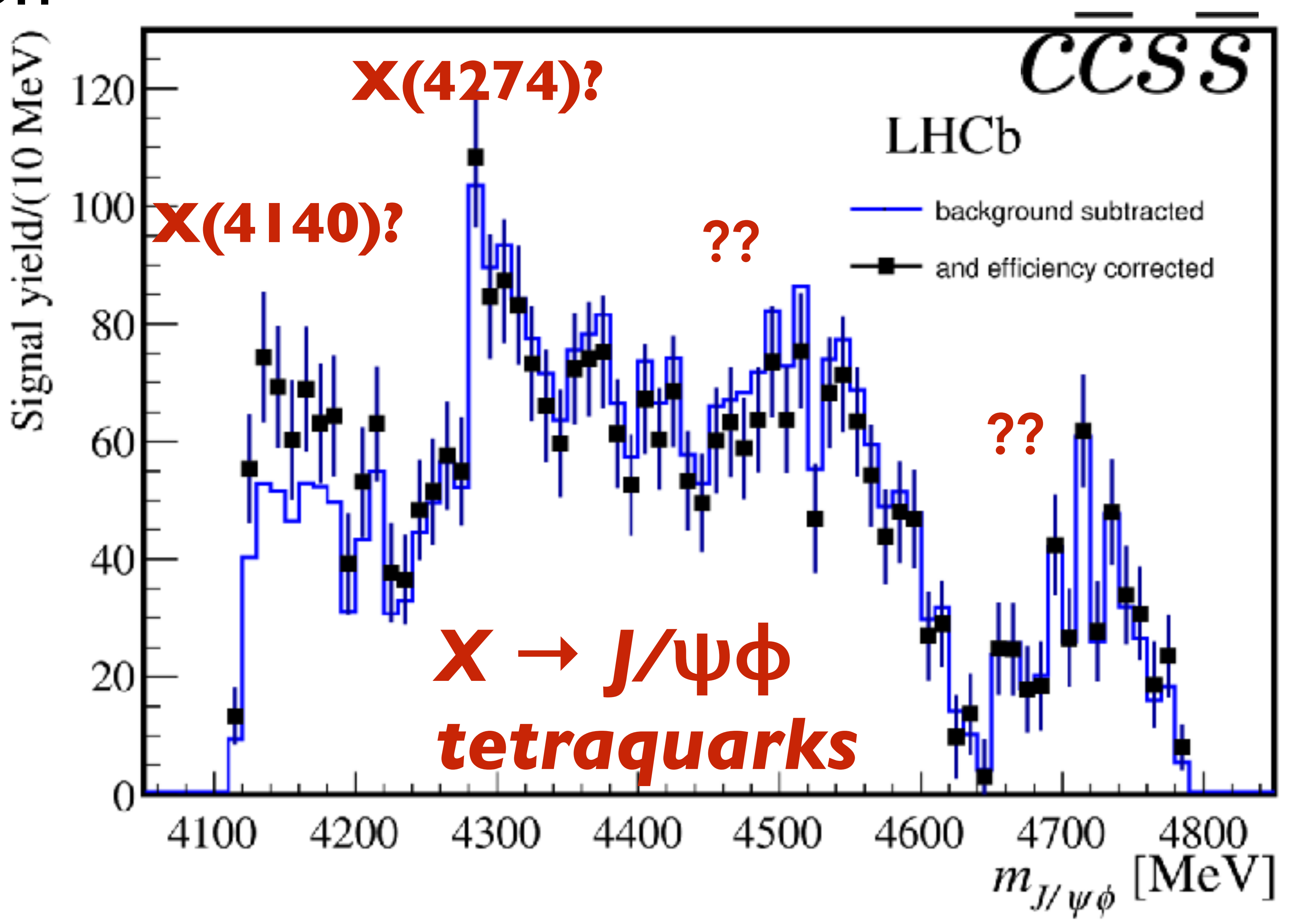
Not sufficient to just fit 1D mass distributions with ad-hoc assumptions about K* contributions

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



1D projection





[Phys. Rev. D 95, 012002 (2017)] [Phys. Rev. Lett. 118, 022003 (2017)]

$B^+ \to J/\psi\phi K^+$ data sample

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

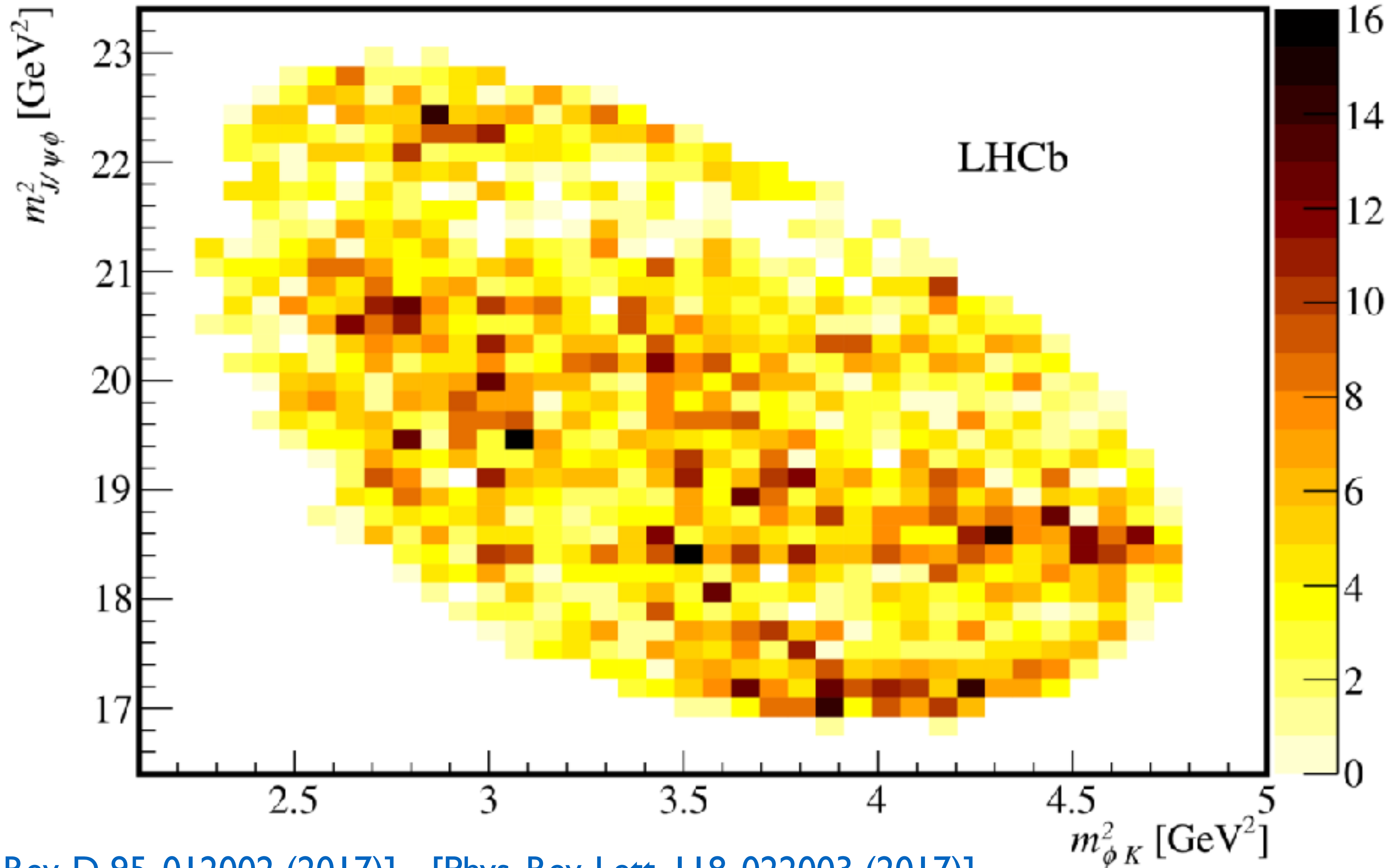
Not sufficient to just fit 1D mass distributions with ad-hoc assumptions about K* contributions

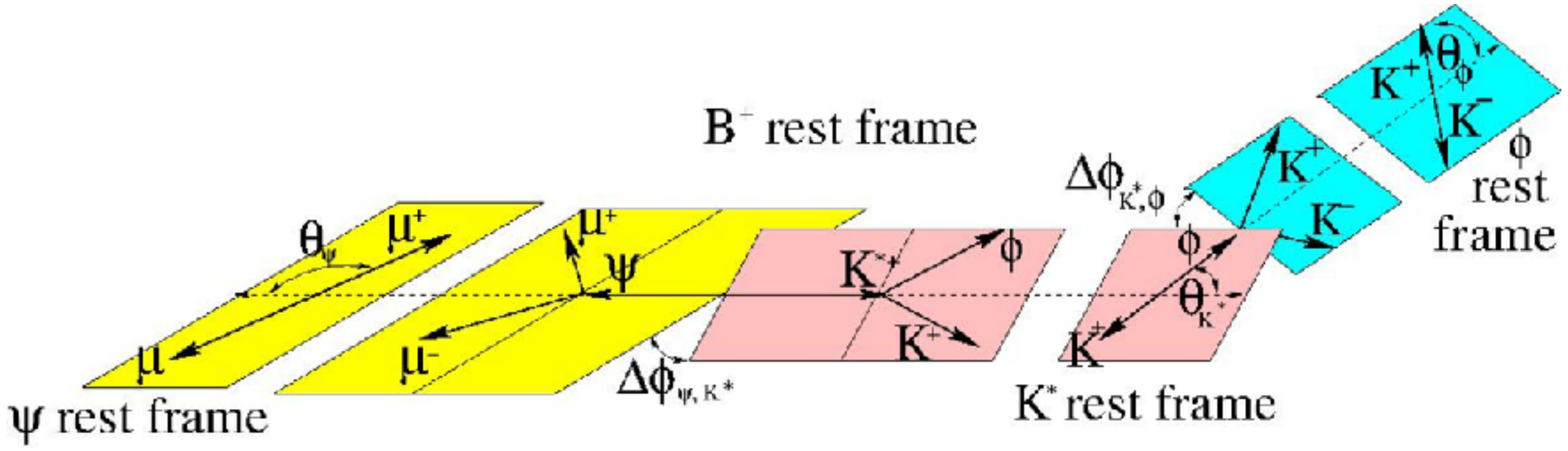
K^{*+} resonances expected to be broad (scattering expts)

6D amplitude analysis to understand structure in final state

Three interfering decay chains:

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

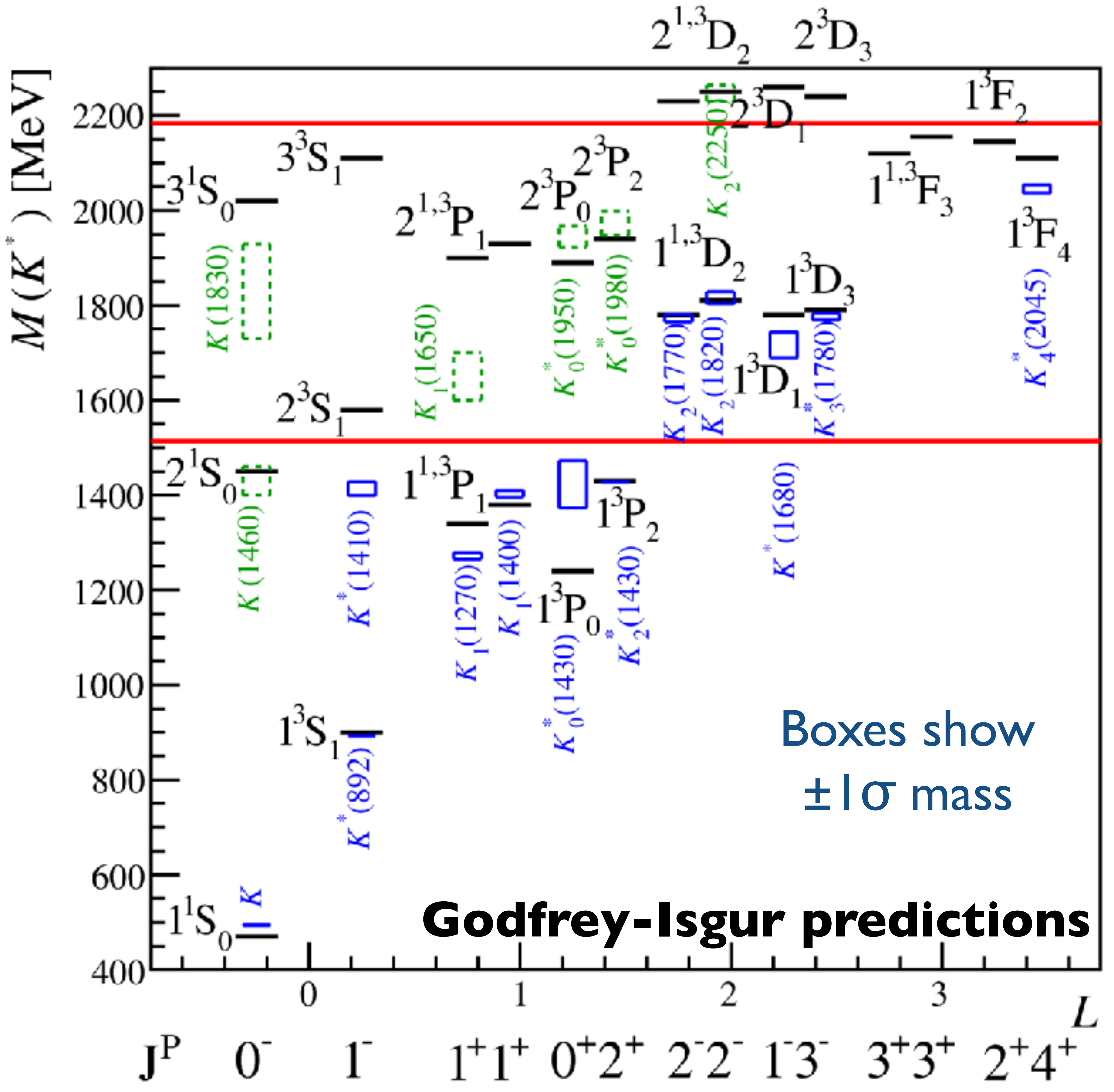




$$\Omega \equiv (\theta_{K^*}, \theta_\psi, \Delta\phi_{\psi,K^*}, \theta_\phi, \Delta\phi_{K^*,\phi})$$

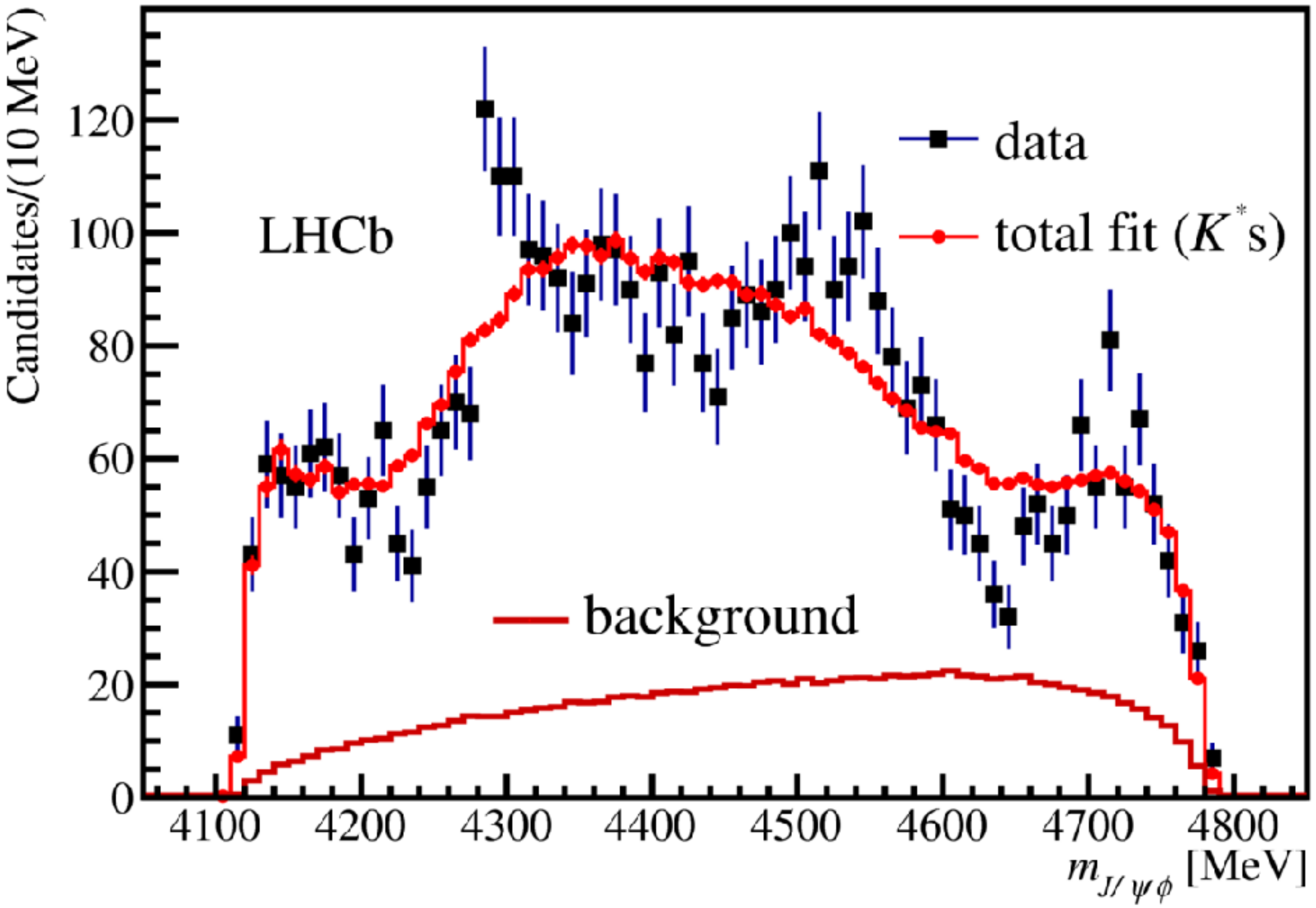
[Phys. Rev. D 95, 012002 (2017)] [Phys. Rev. Lett. 118, 022003 (2017)]

Which *K** resonances to include?



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

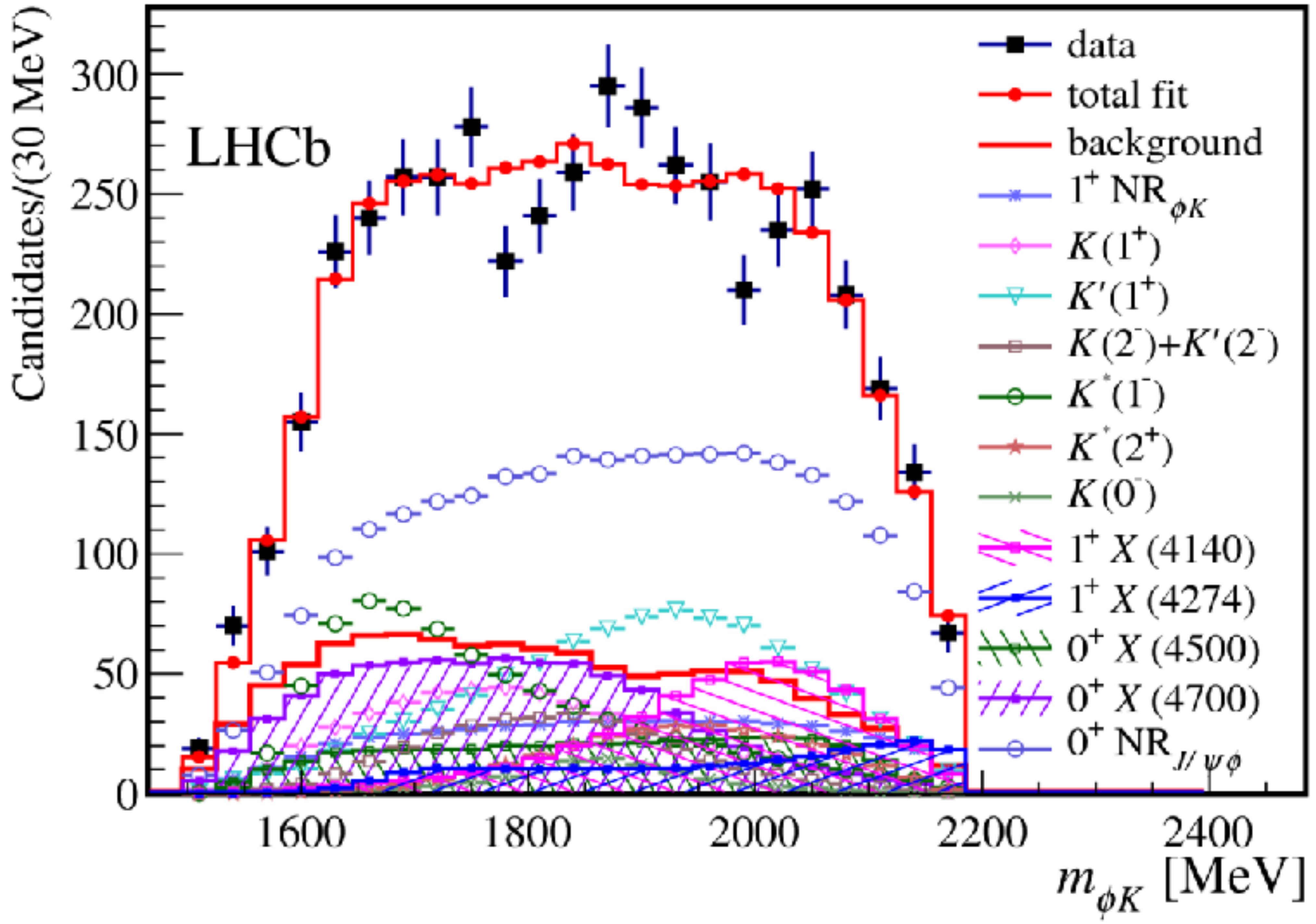
Higher spin states expected to be suppressed in B decays due to orbital angular momentum required to produce them

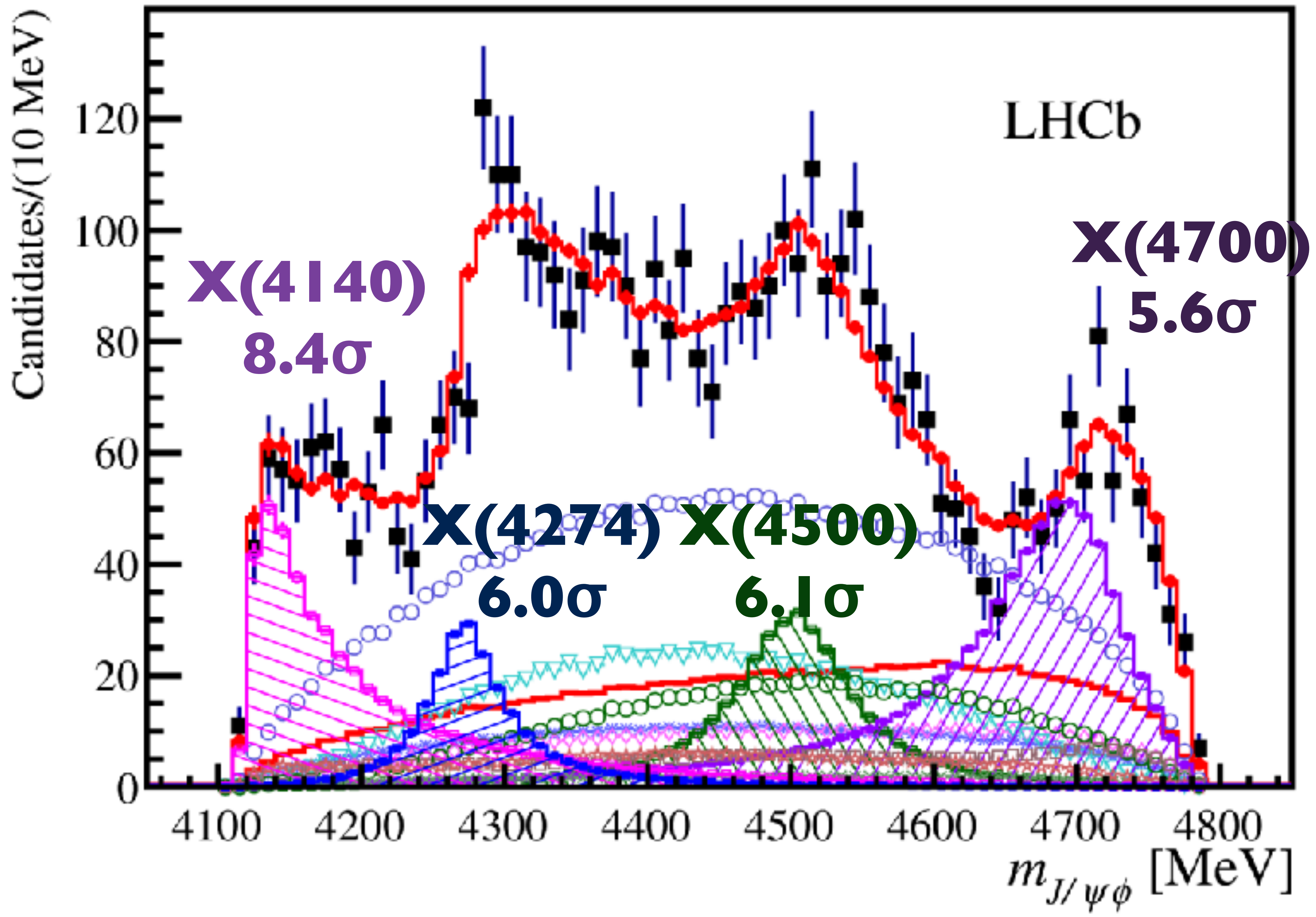


104 free parameters in fit

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

Fit 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 $X(0^+)$				$28\pm\ 5\pm\ 7$
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	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$

first observation

The X(5568)$^{\pm}$ → $B_s\pi^{\pm}$?

[PRL 117, 022003 (2016)]

~5σ claim for exotic state

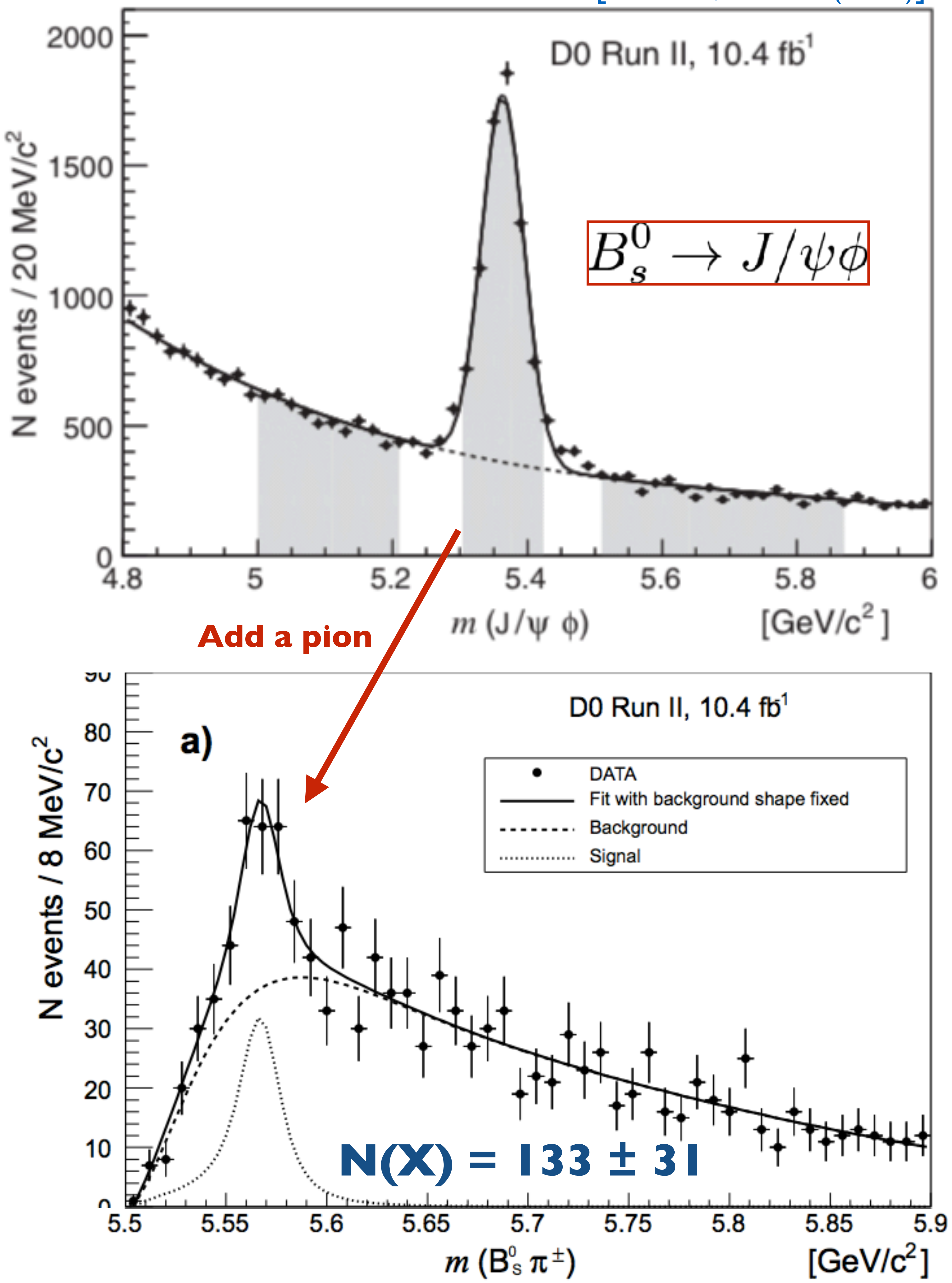
Large B_s production fraction: $\rho_X = (8.6 \pm 1.9 \pm 1.4)\%$

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 *bsud* 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., PRD 94 074509 (2016)]

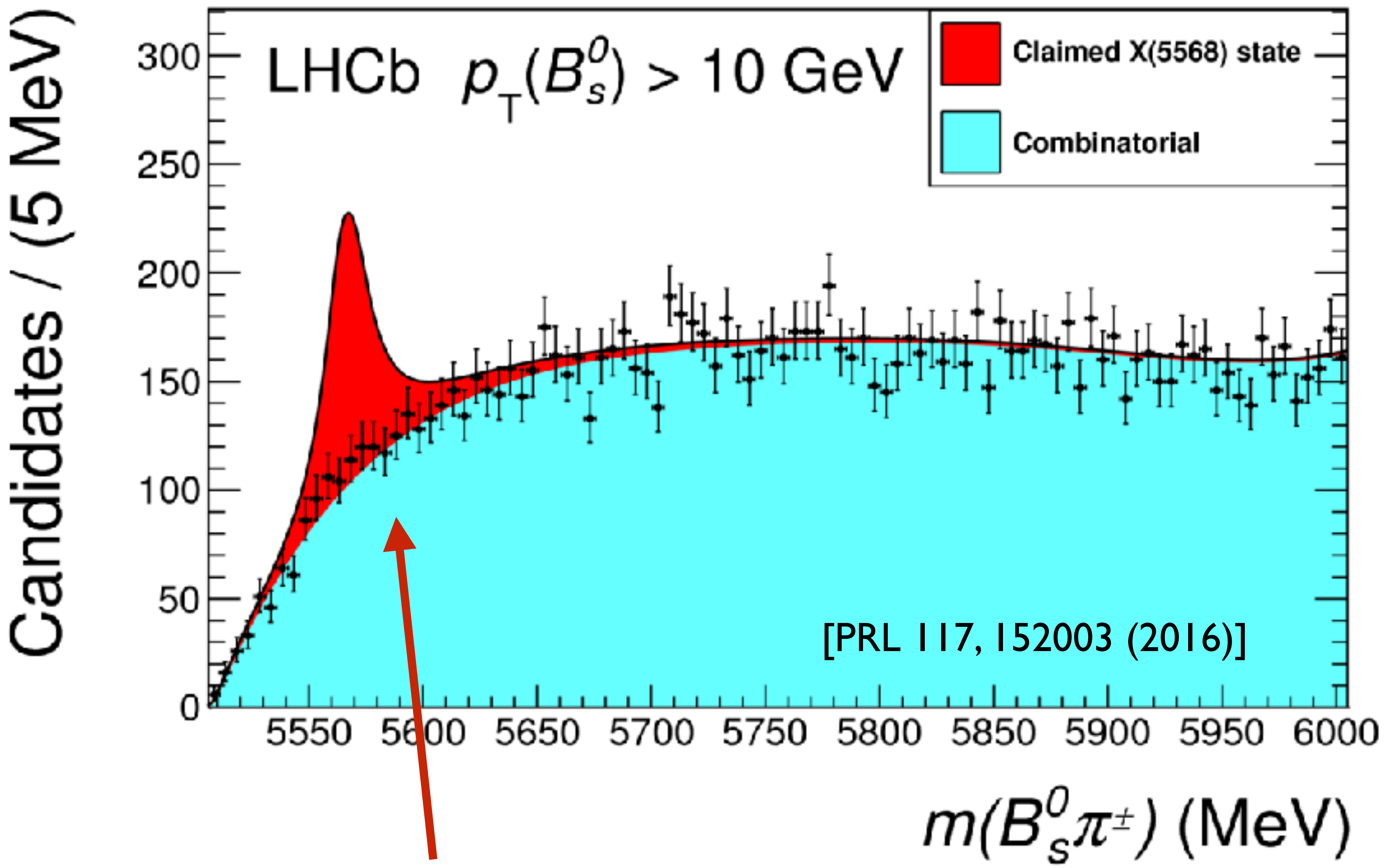
LHC searches for X(5568)$^{\pm}$

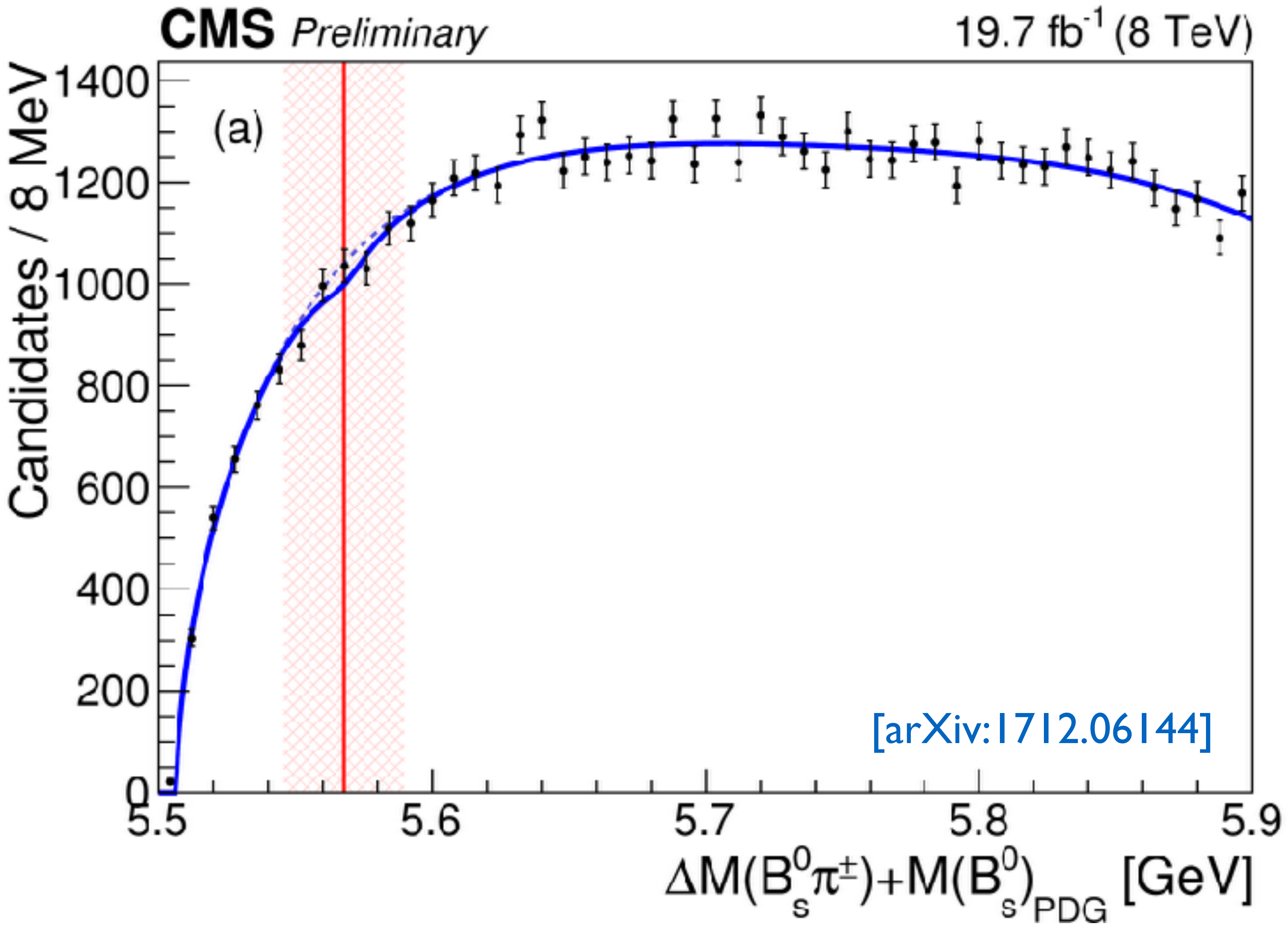
LHCb use >100k B_s mesons and combine with $\pi^{\pm}$.
Sample 20x larger than D0 and much less background.

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.

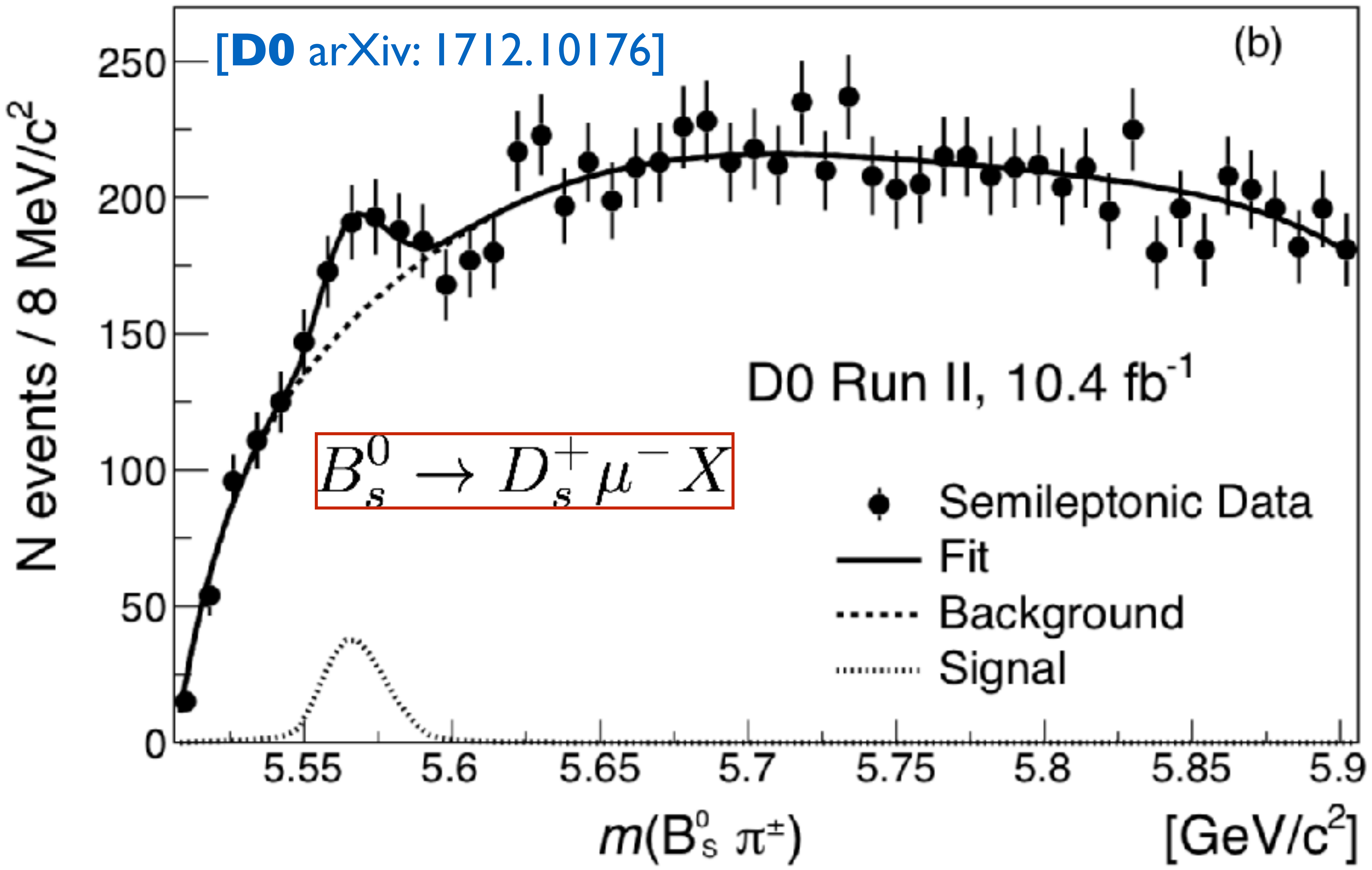
$$\rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 5\,{\rm GeV}/c) < 0.009\,(0.010)\ @\ 90\,(95)\,\%\ {\rm CL}$$
$$\rho_X^{\rm LHCb}(B_s^0\ p_{\rm T} > 10\,{\rm GeV}/c) < 0.016\,(0.018)\ @\ 90\,(95)\,\%\ {\rm CL}$$



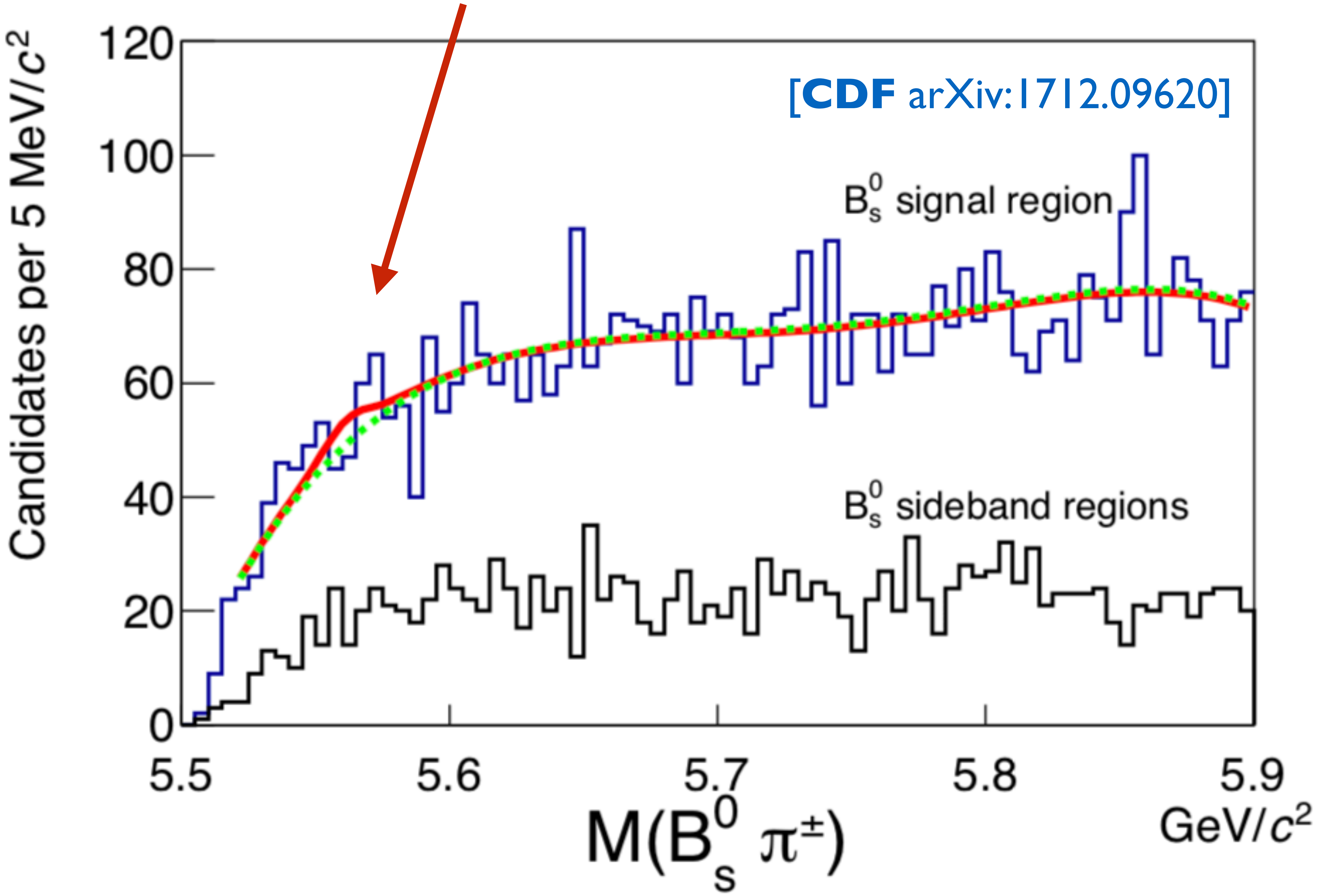


How signal would look according to D0 result

Hot off the press!



No significant signal

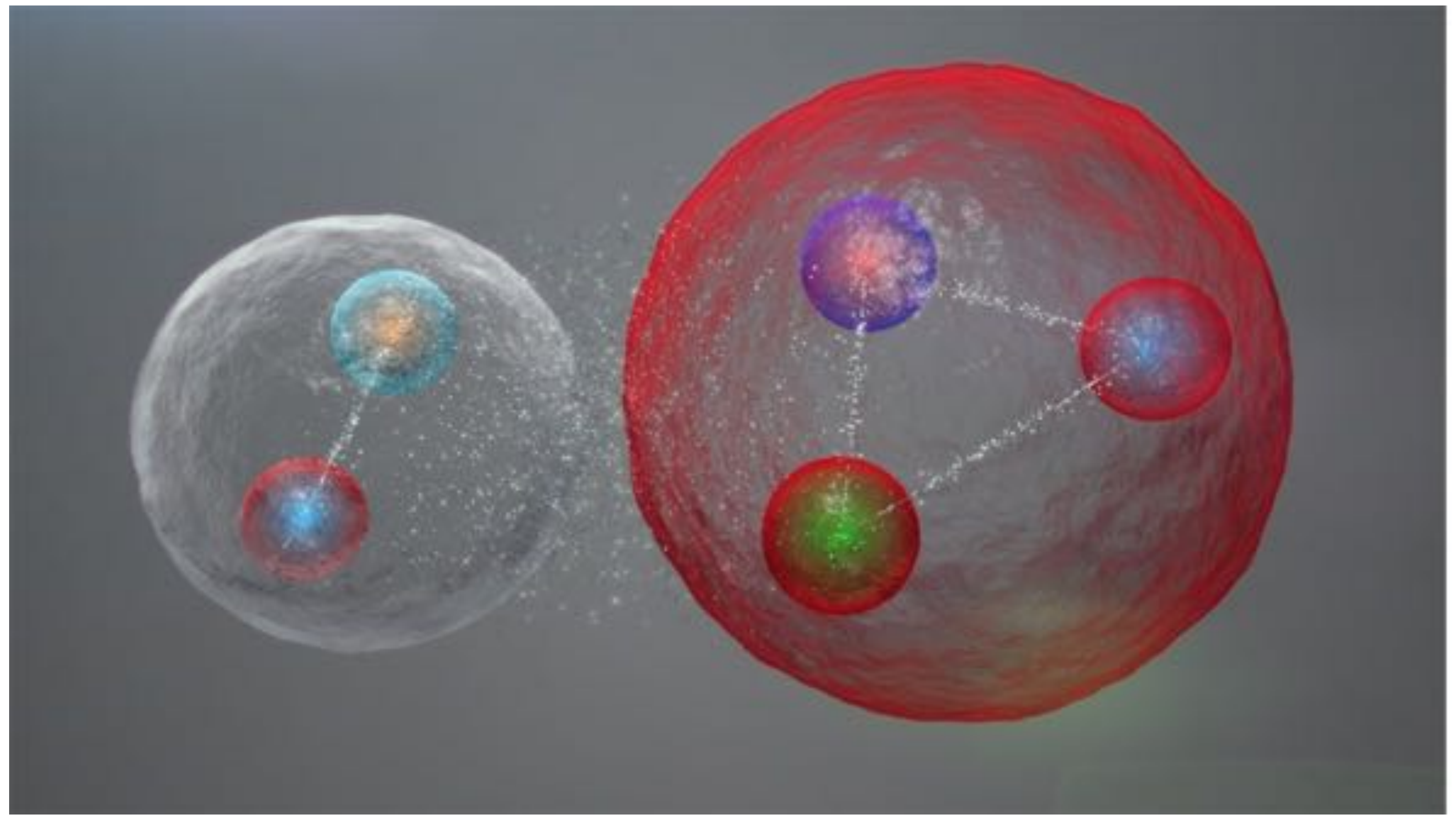


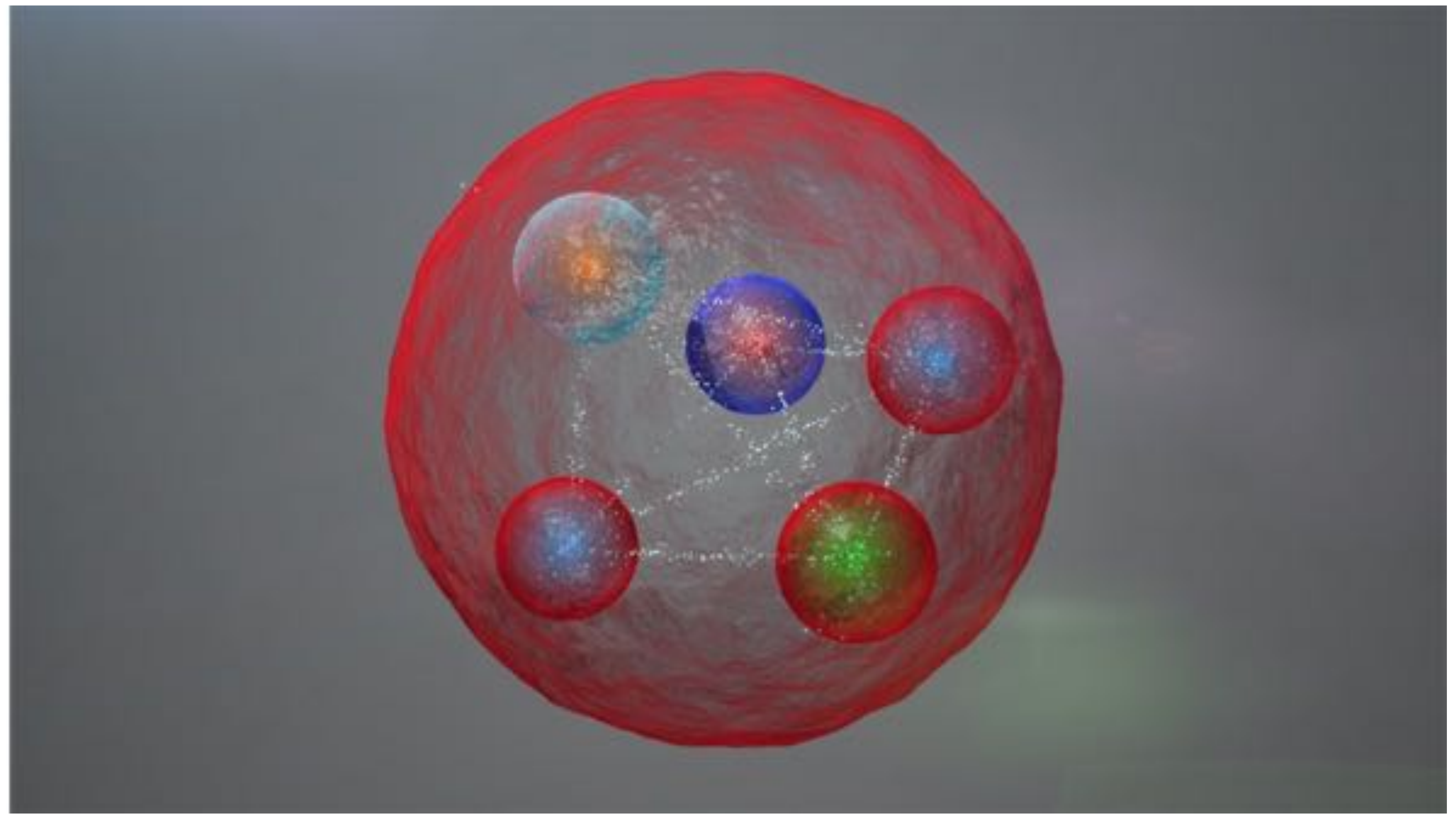
Over Christmas D0 published result showing the X(5568) signal using a different Bs decay mode while CDF show data consistent with background only.

Could D0 "signal" be due to some underestimated background? → **more work needed**

CDF result removes possibility that X(5568) is predominately produced at in $p\bar{p}$ collisions.

Exotic baryons

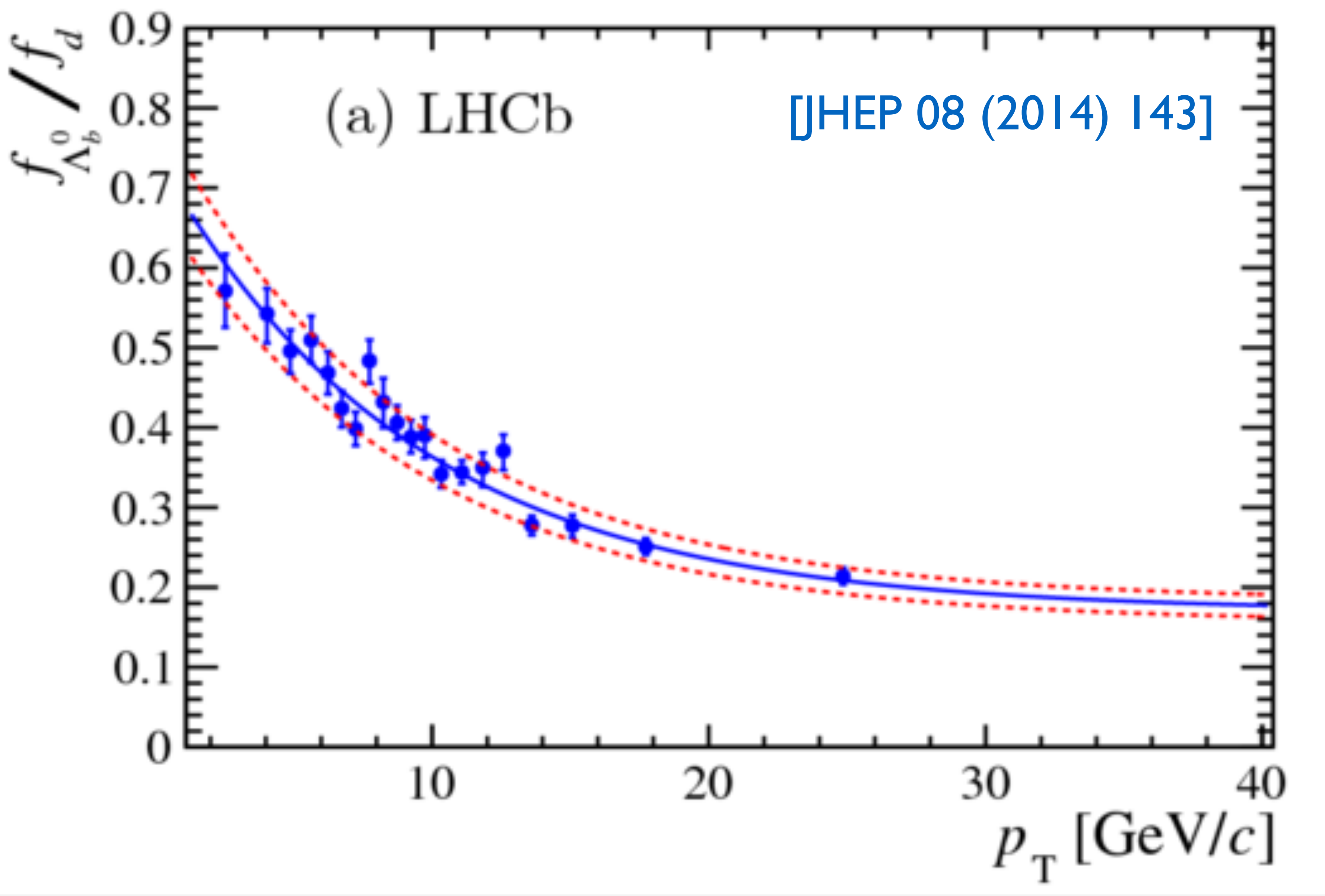




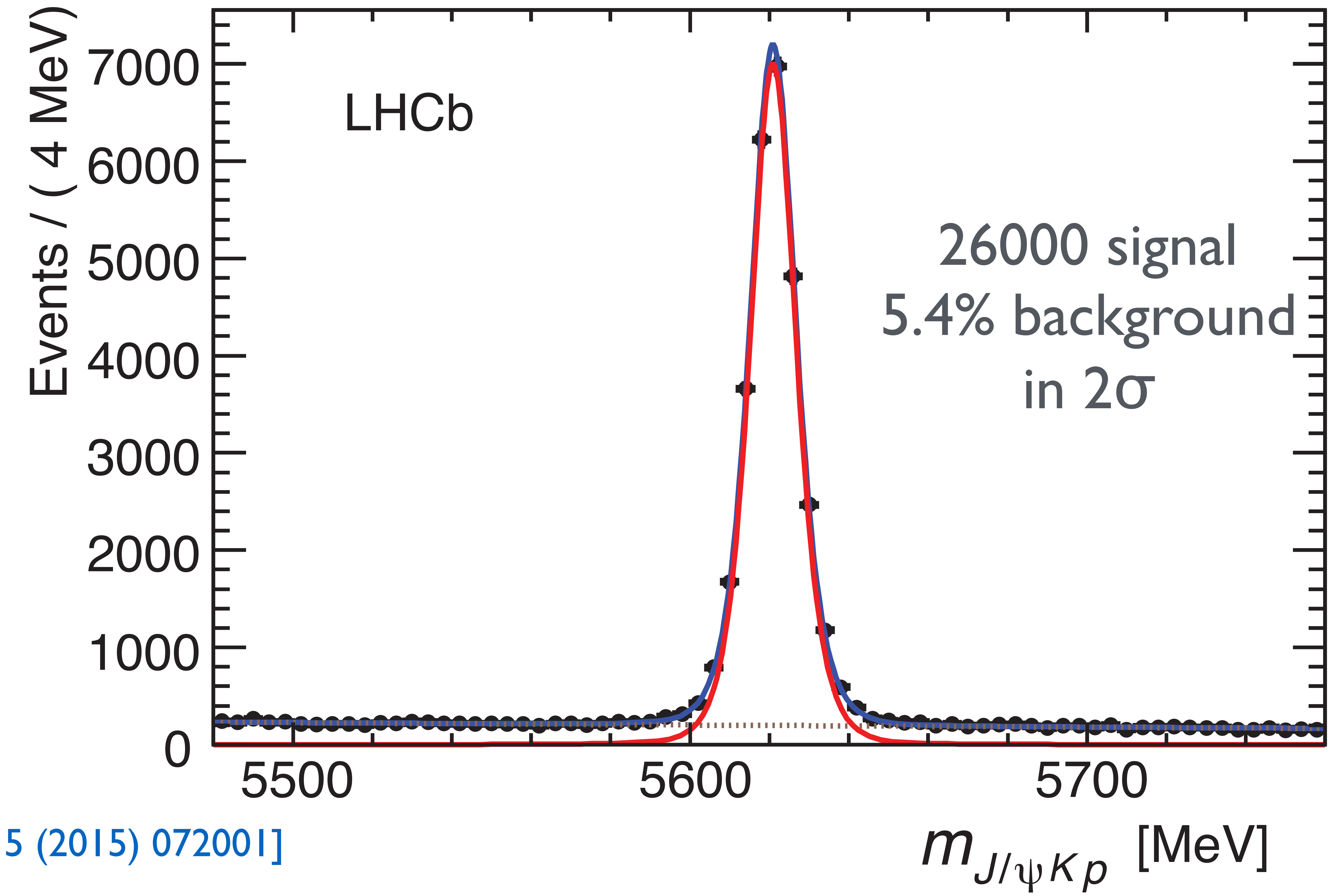
Pentaquark observation

Large production of b-baryons at LHC.

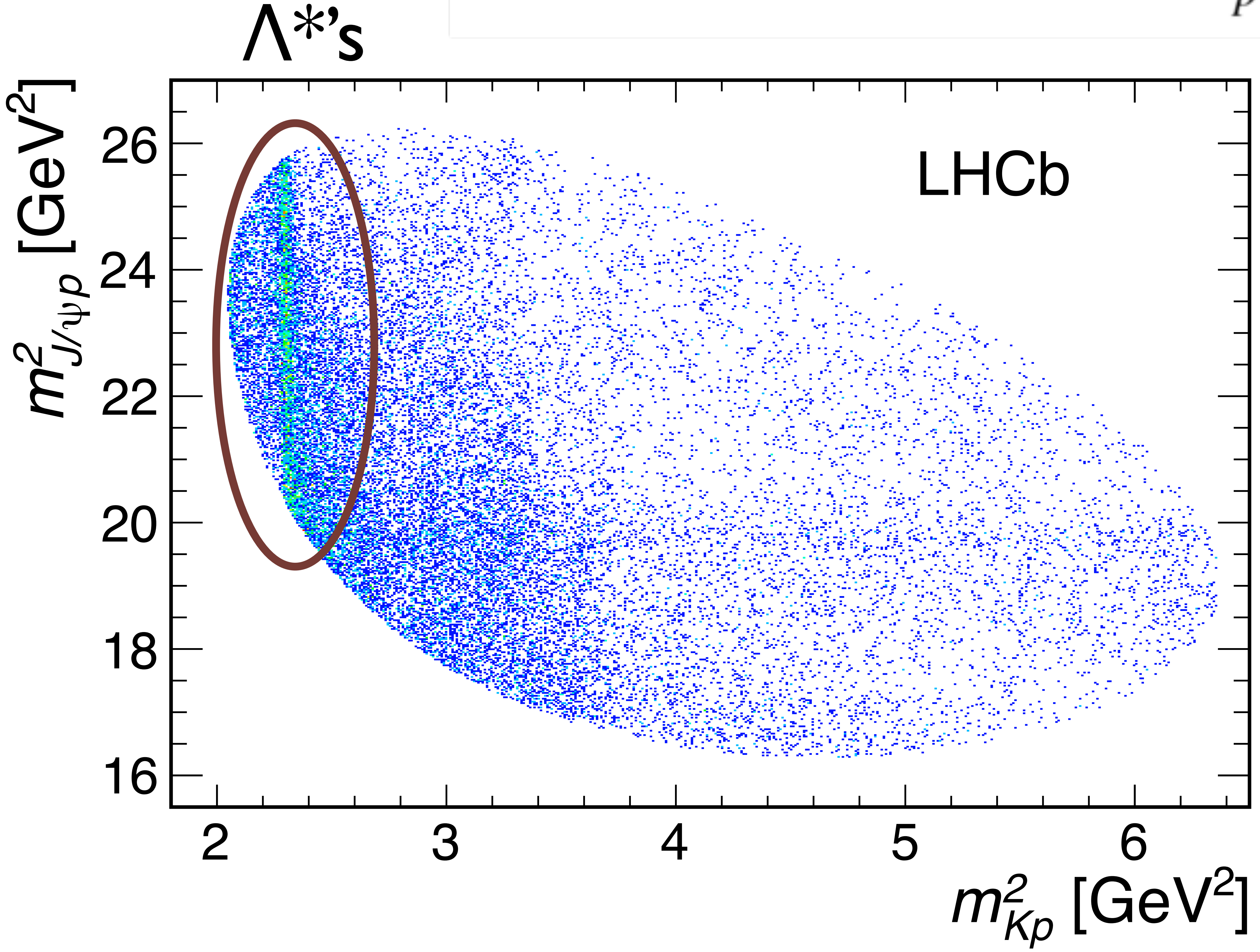
Many more Λb in LHCb than central detectors.



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



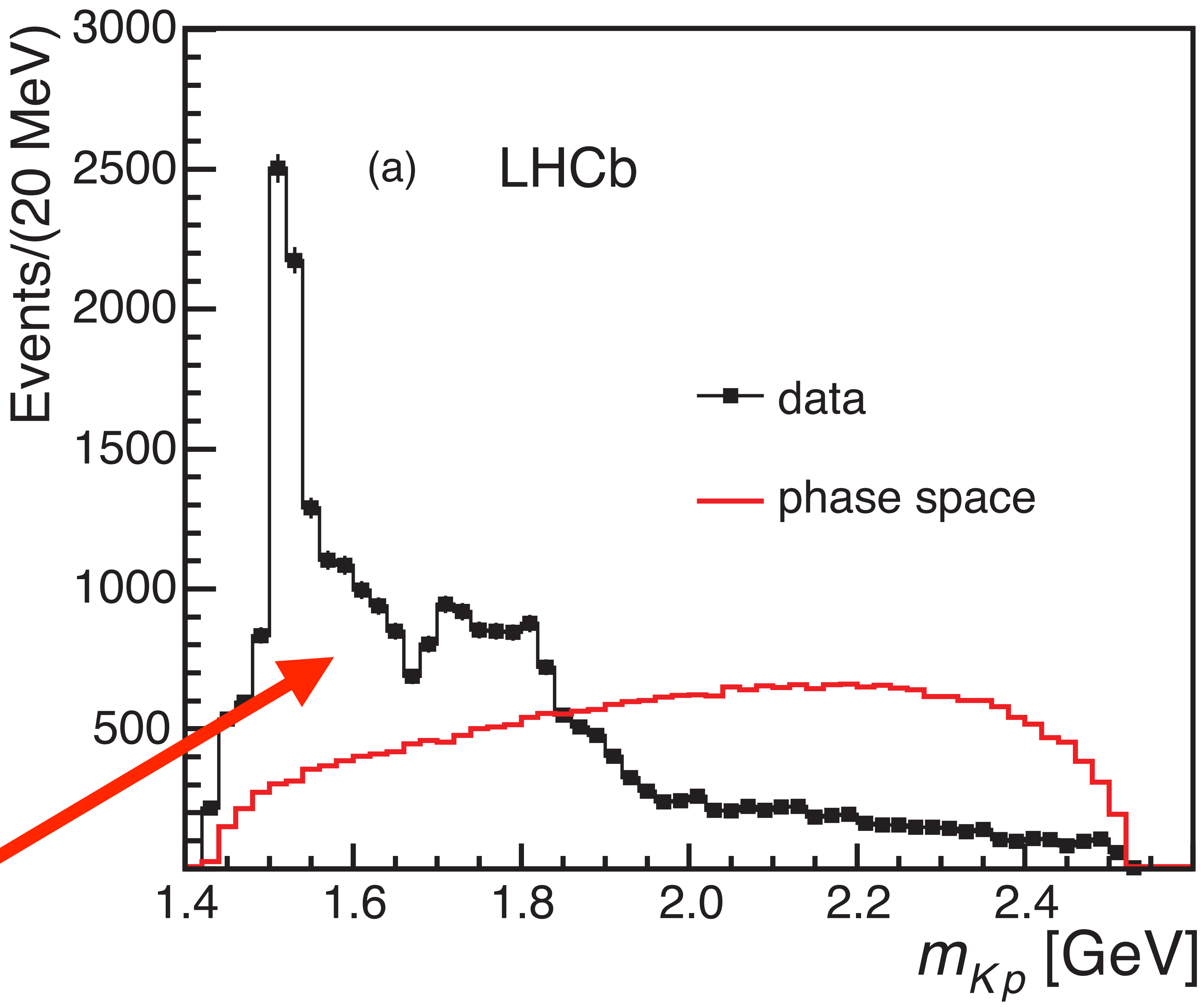
[PRL 115 (2015) 072001]

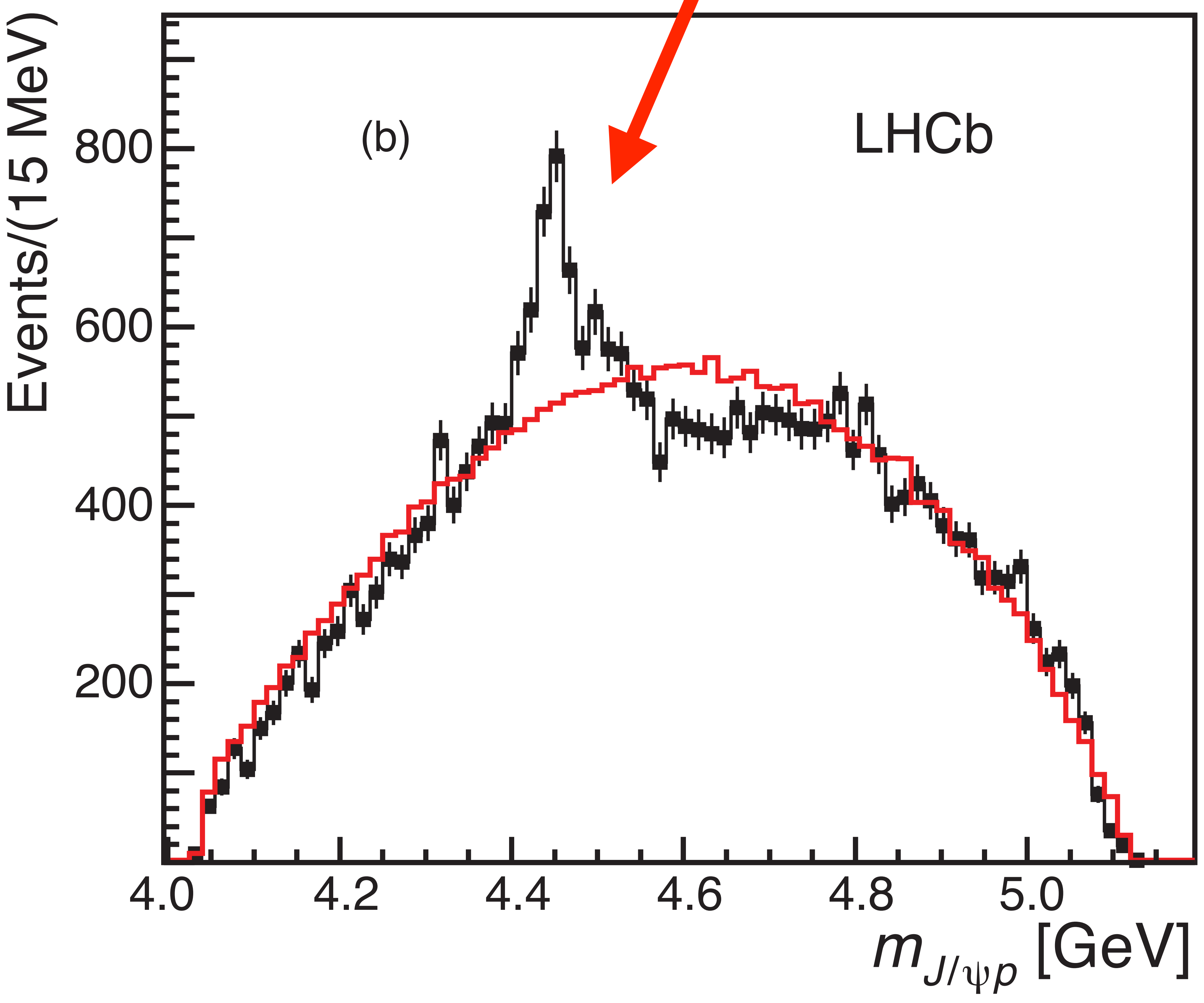


Pentaquark observation

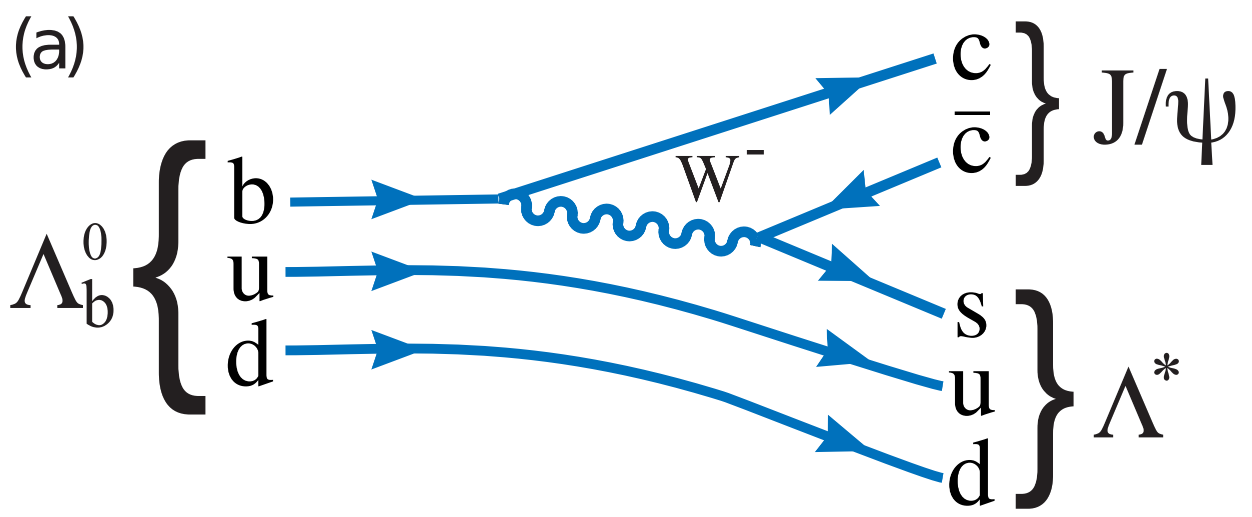
Can this be caused by reflections in m(Kp), background or detector efficiency?

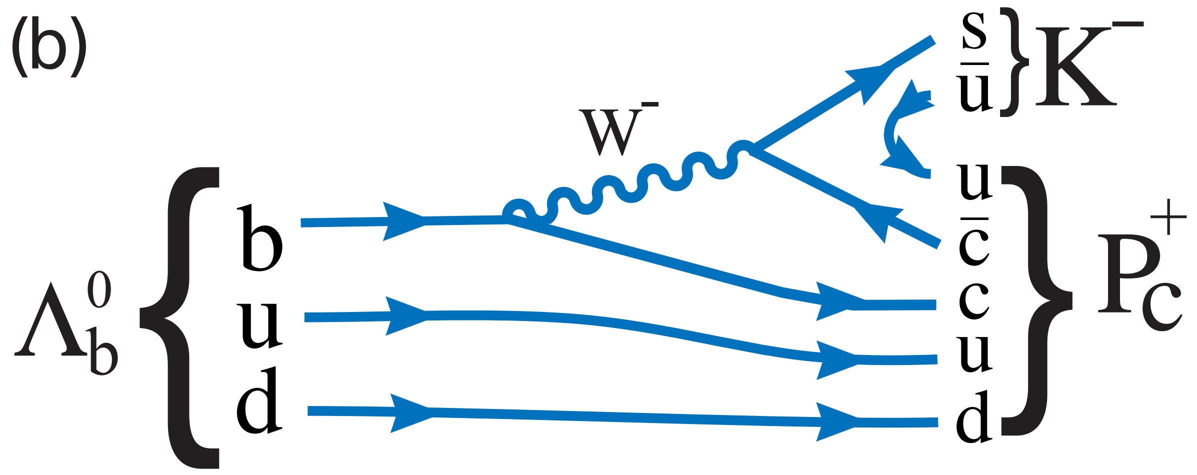
State	J^P	M_0 (MeV)	Γ_0 (MeV)
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0
$\Lambda(1600)$	$1/2^+$	1600	150
$\Lambda(1670)$	$1/2^-$	1670	35
$\Lambda(1690)$	$3/2^-$	1690	60
$\Lambda(1800)$	$1/2^-$	1800	300
$\Lambda(1810)$	$1/2^+$	1810	150
$\Lambda(1820)$	$5/2^+$	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





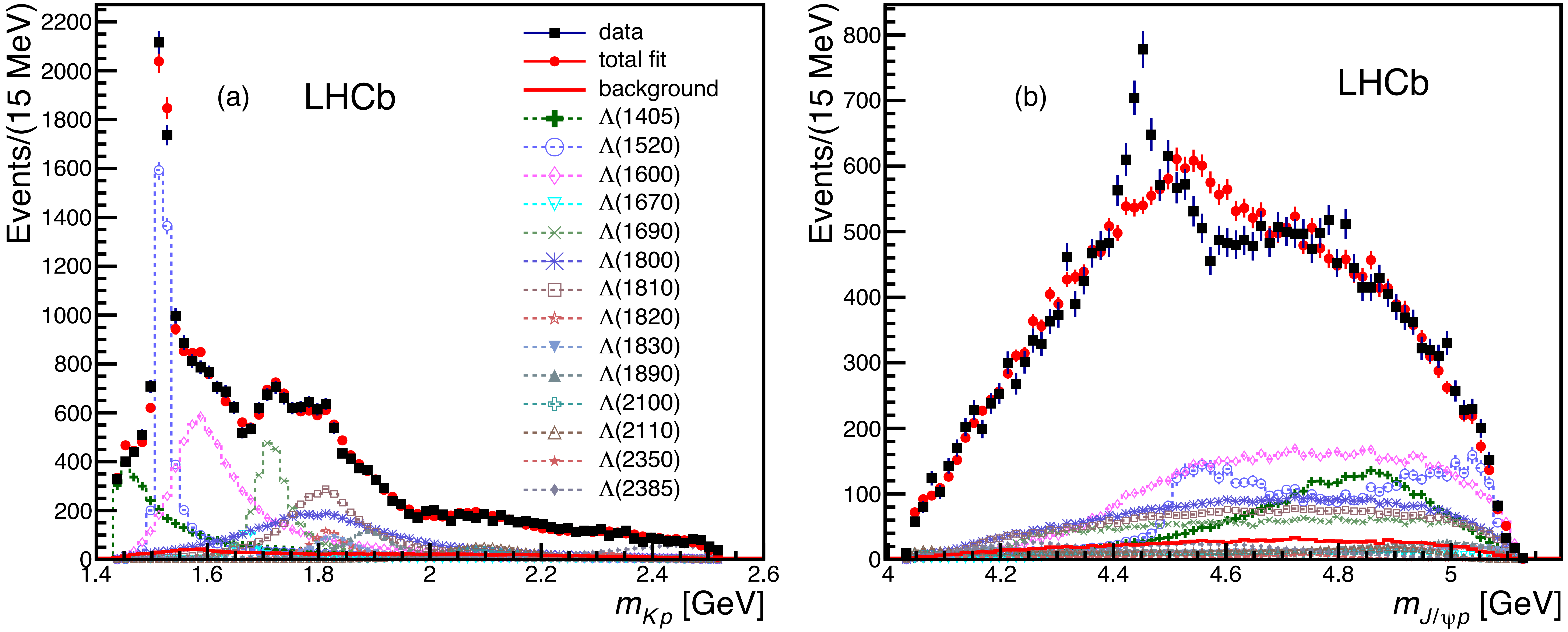
Interfering $\Lambda^* \rightarrow pK$ resonances





[PRL 115 (2015) 072001]

Results without P_c states

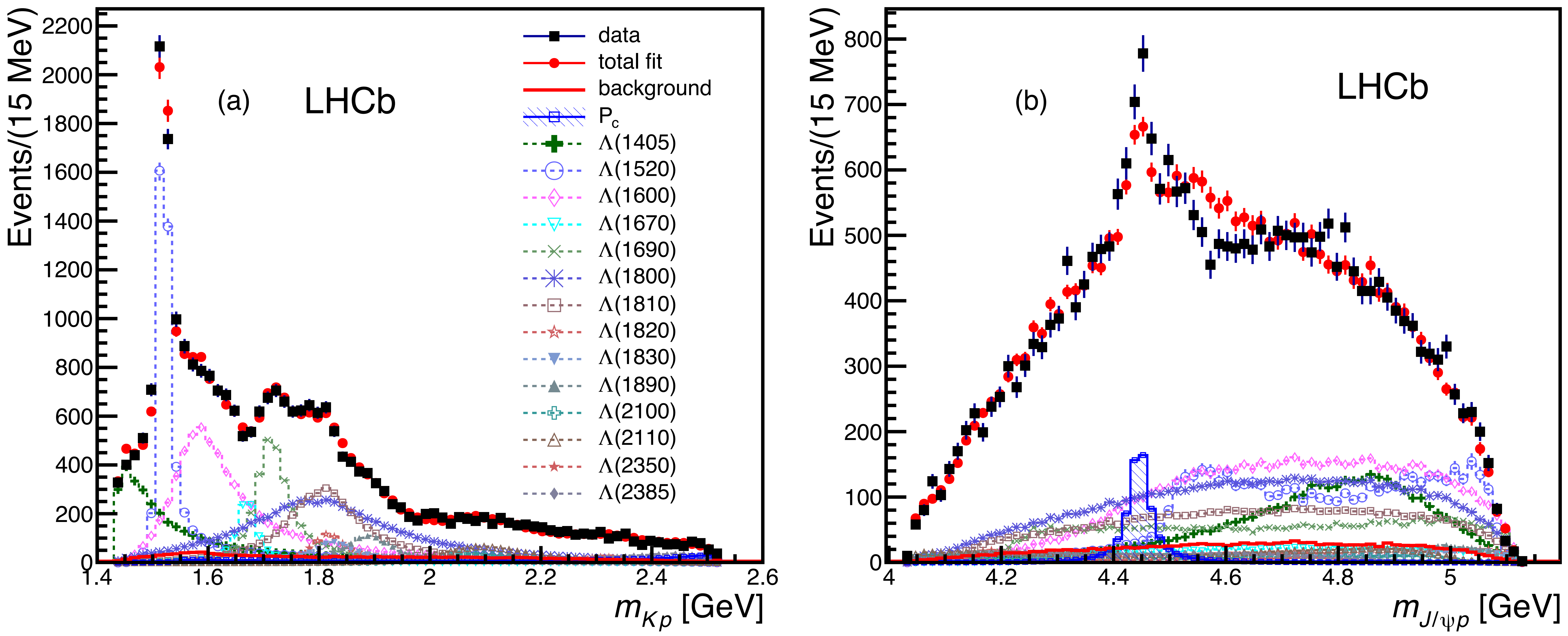


Using full set of Λ*'s the m(Kp) distribution looks good but not m(J/ψp).

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

[PRL 115 (2015) 072001]

Extended model with one P_c



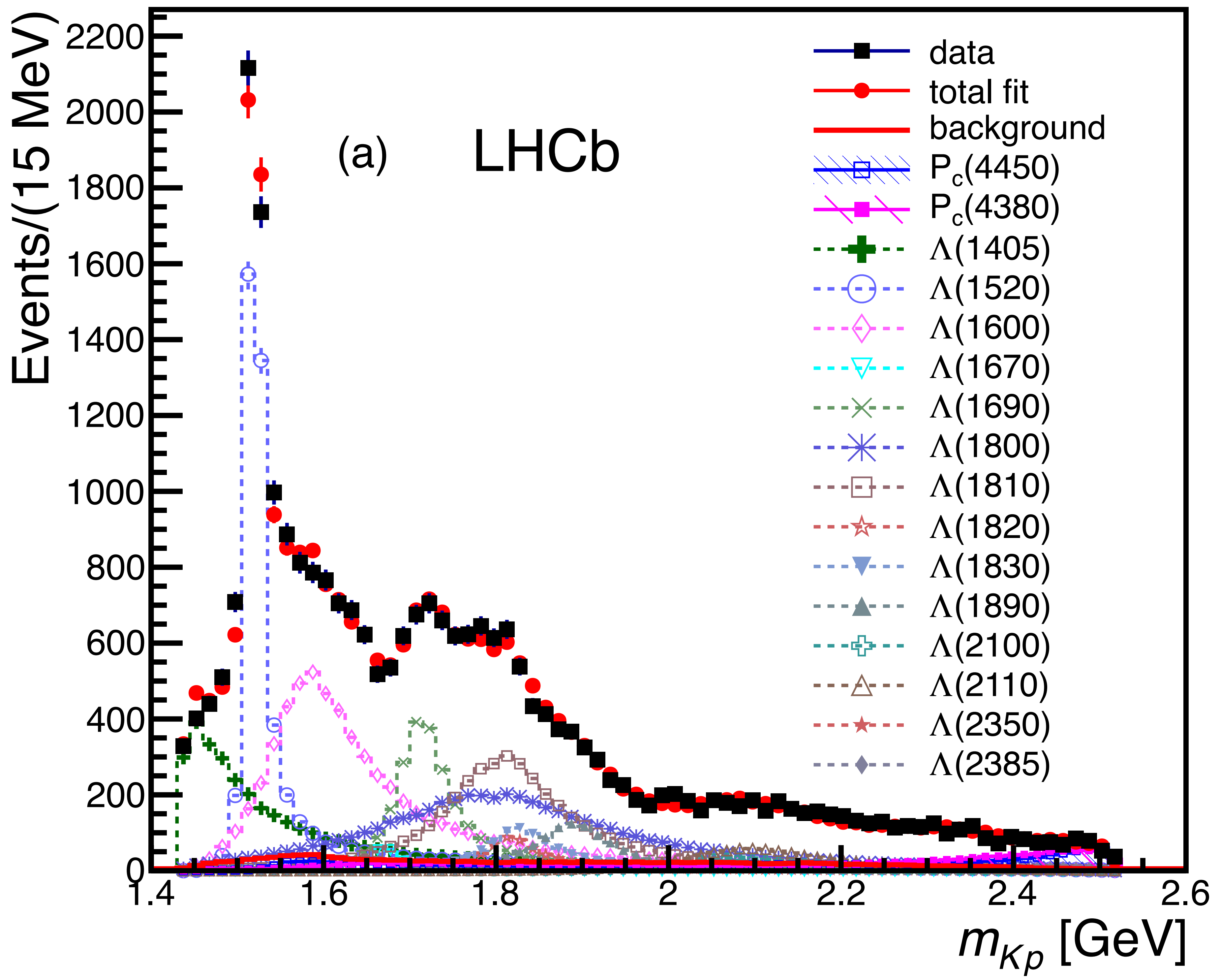
Try all Λ*'s with J^P up to $7/2^{\pm}$

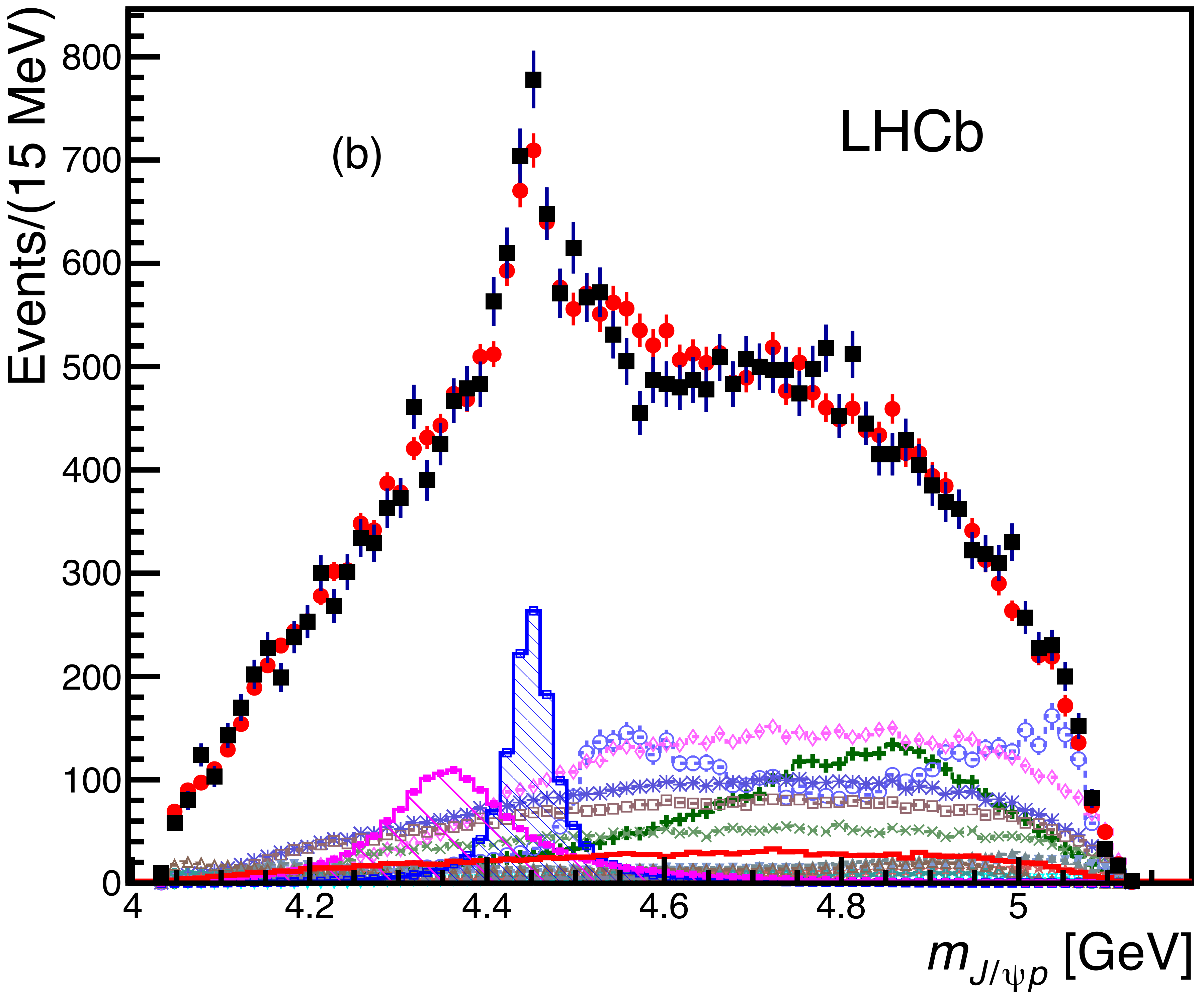
Best fit with a $J^P = 5/2^{\pm}$ pentaquark gives improvement, but m(J/ψp) still not good

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

[PRL 115 (2015) 072001]

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

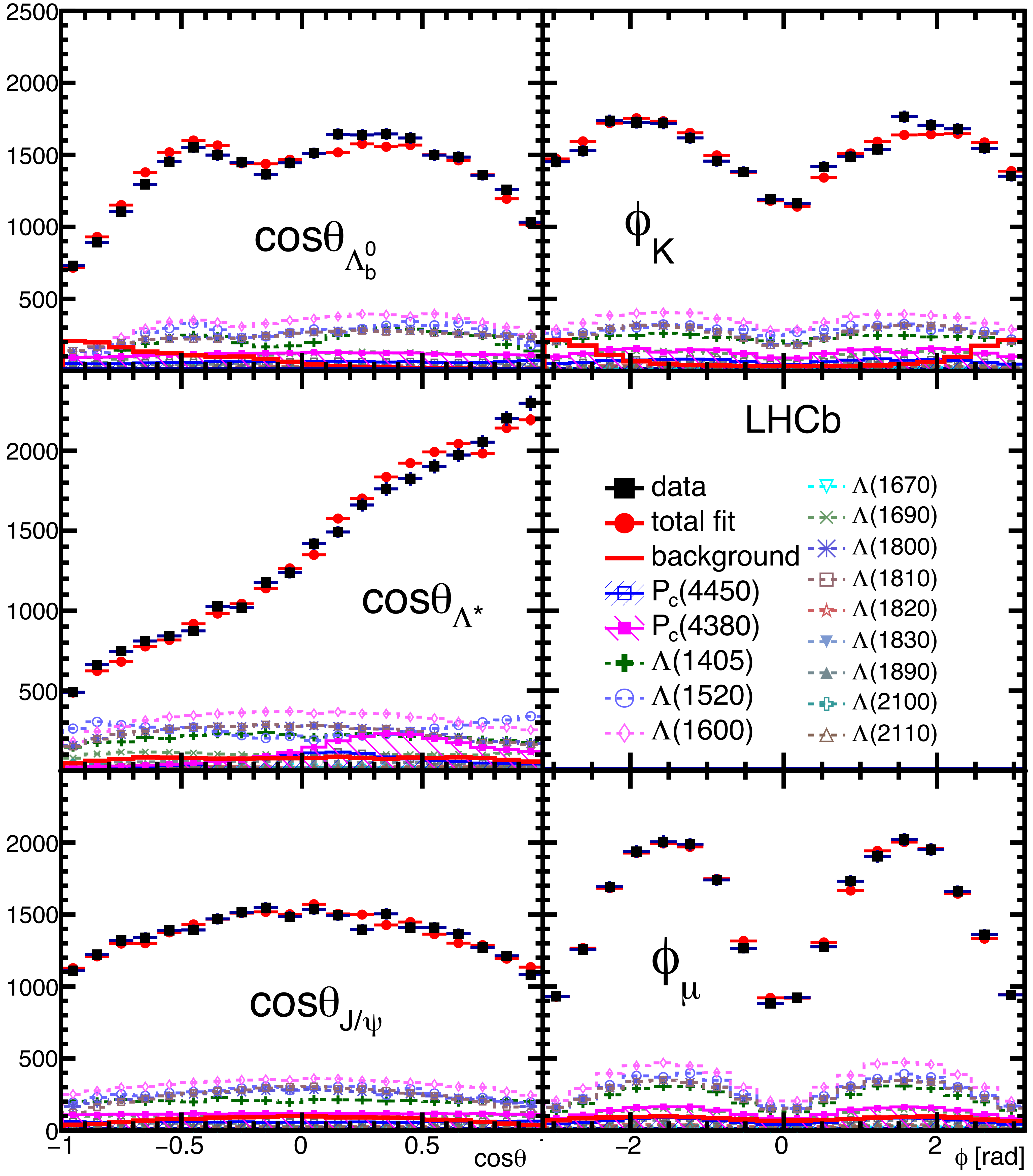
Significance evaluated using toy simulation

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

Angular distributions

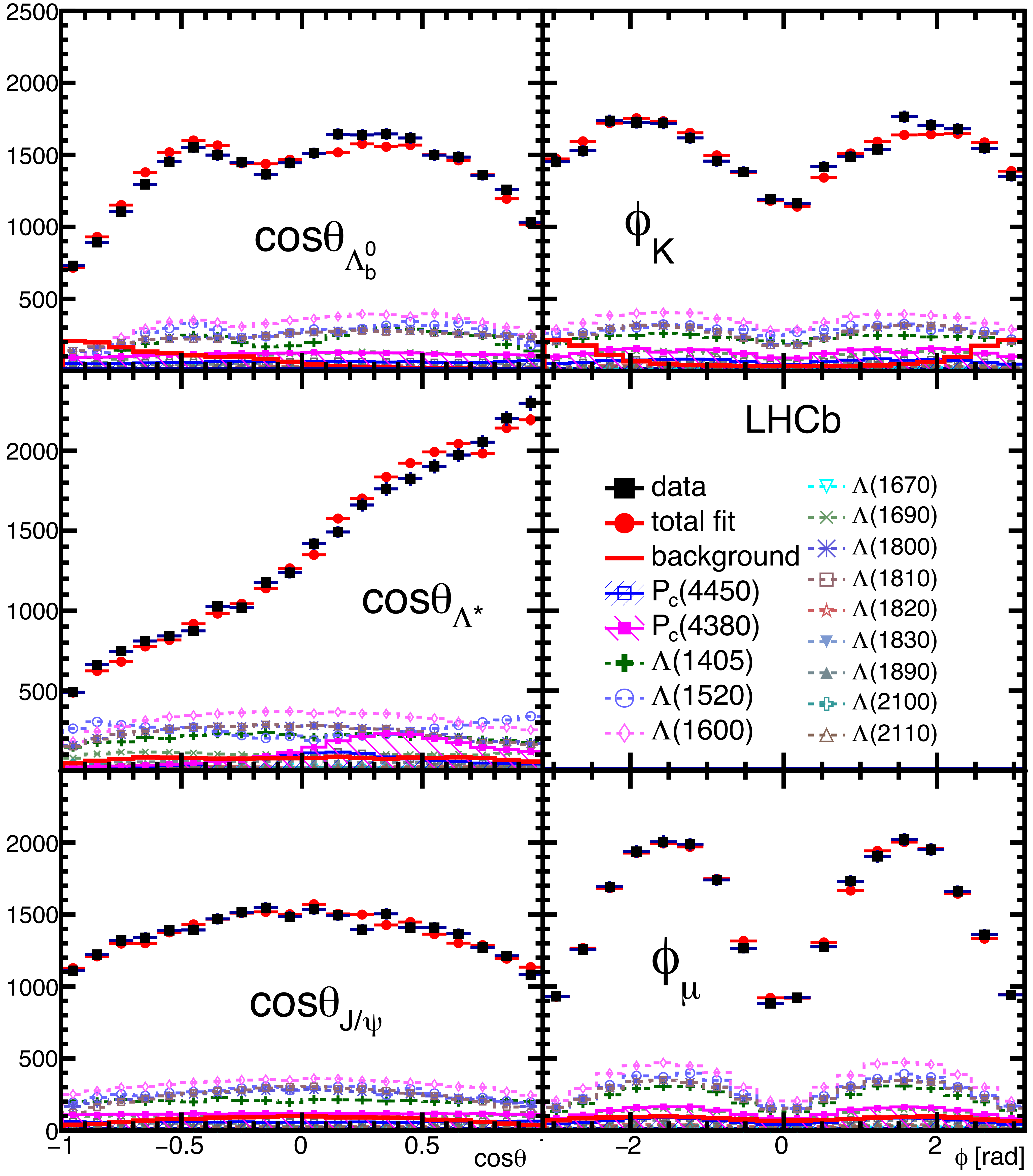
Good fit to the angular observables



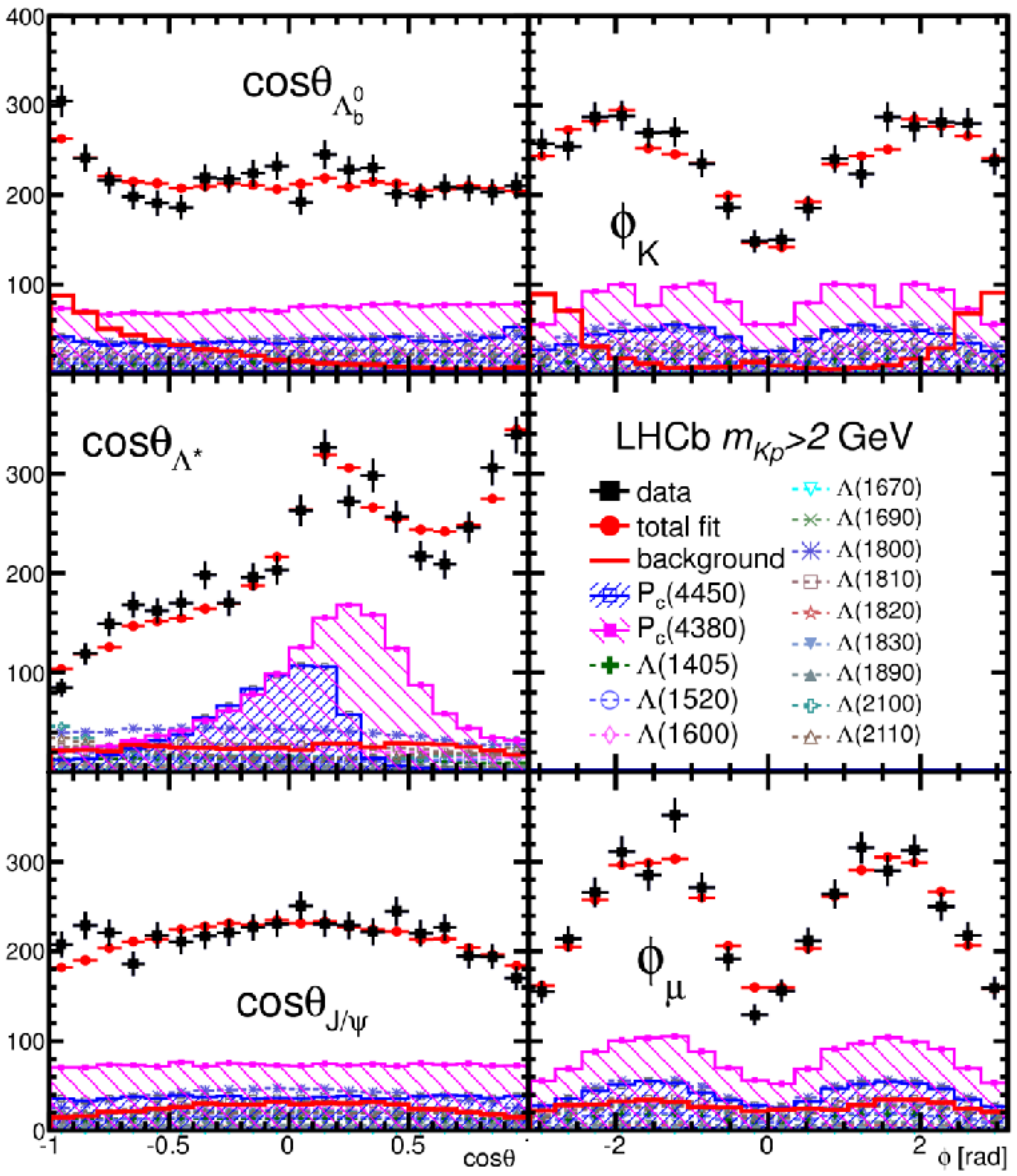
[PRL 115 (2015) 072001]

Angular distributions

Good fit to the angular observables

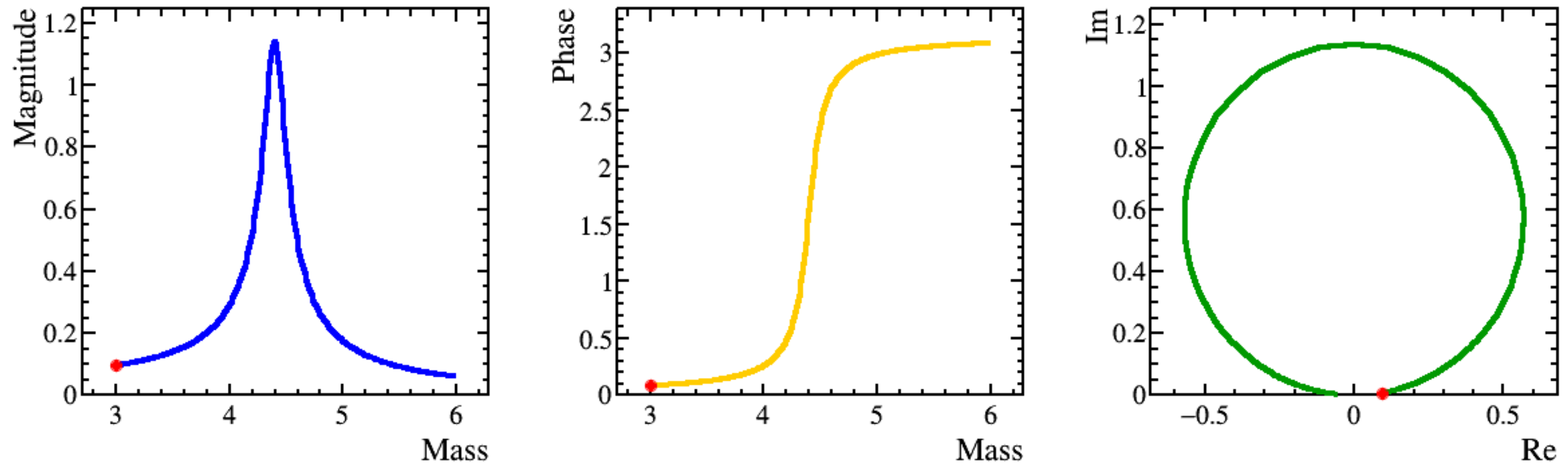


High m(Kp) region > 2 GeV

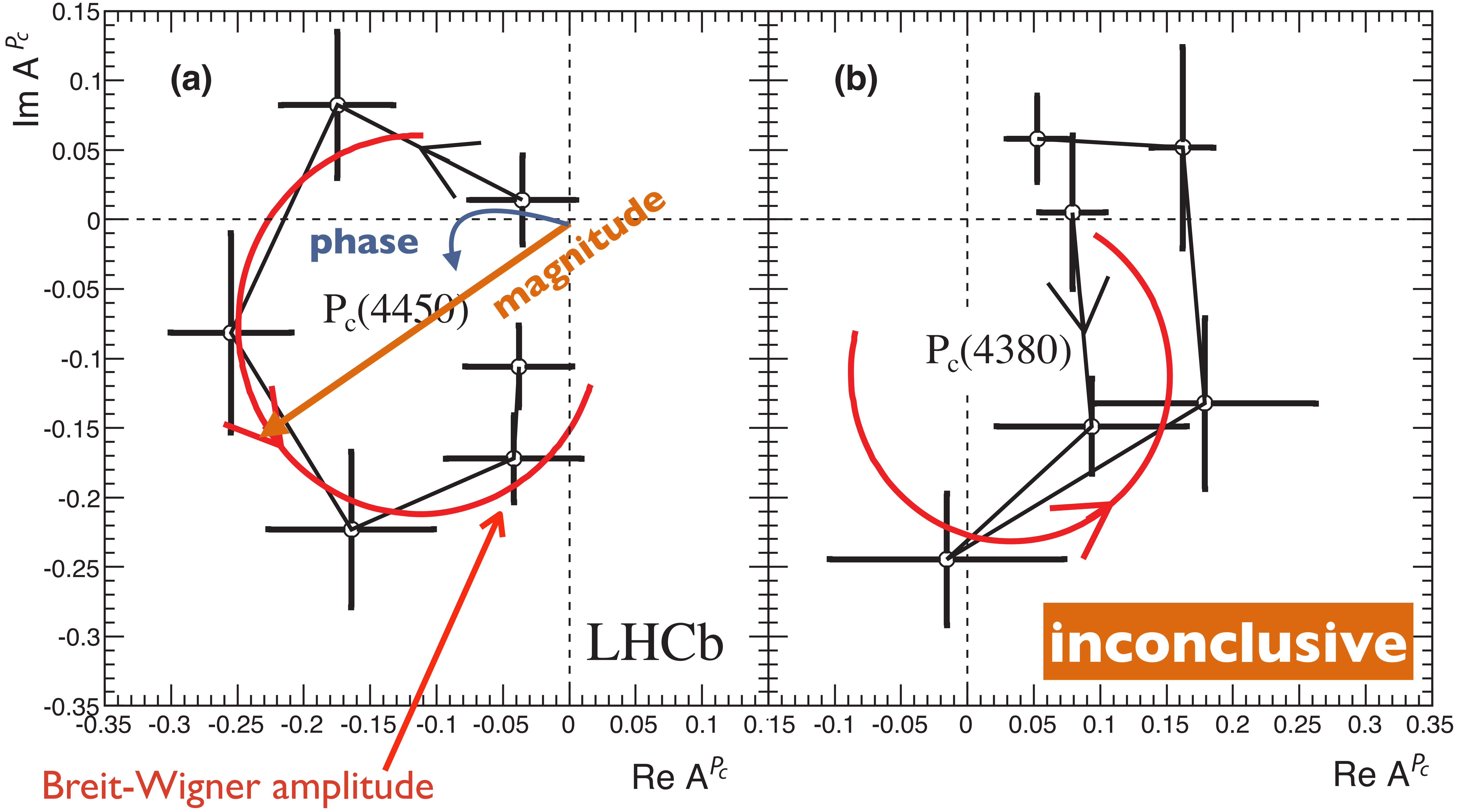


[PRL 115 (2015) 072001]

Resonant behaviour



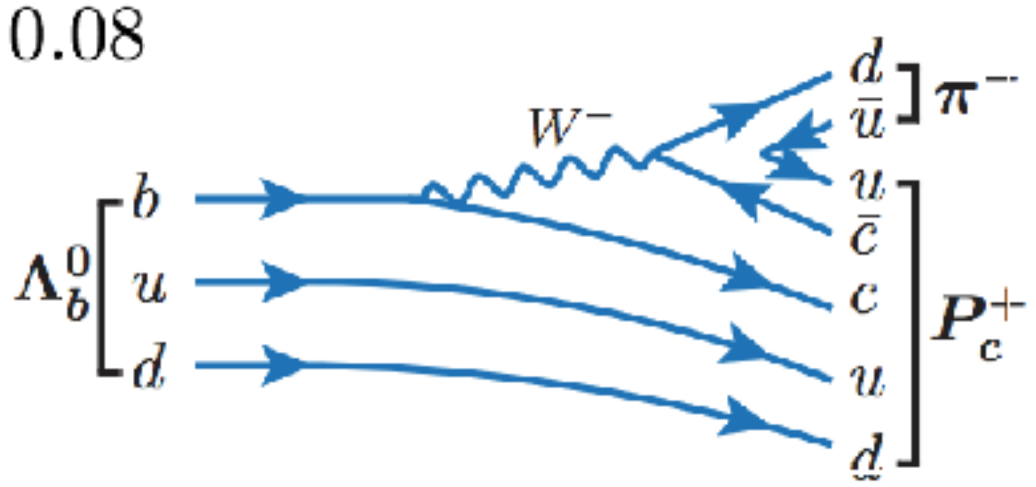
Observe rapid change of phase near maximum of magnitude ⇒ **resonance!**



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

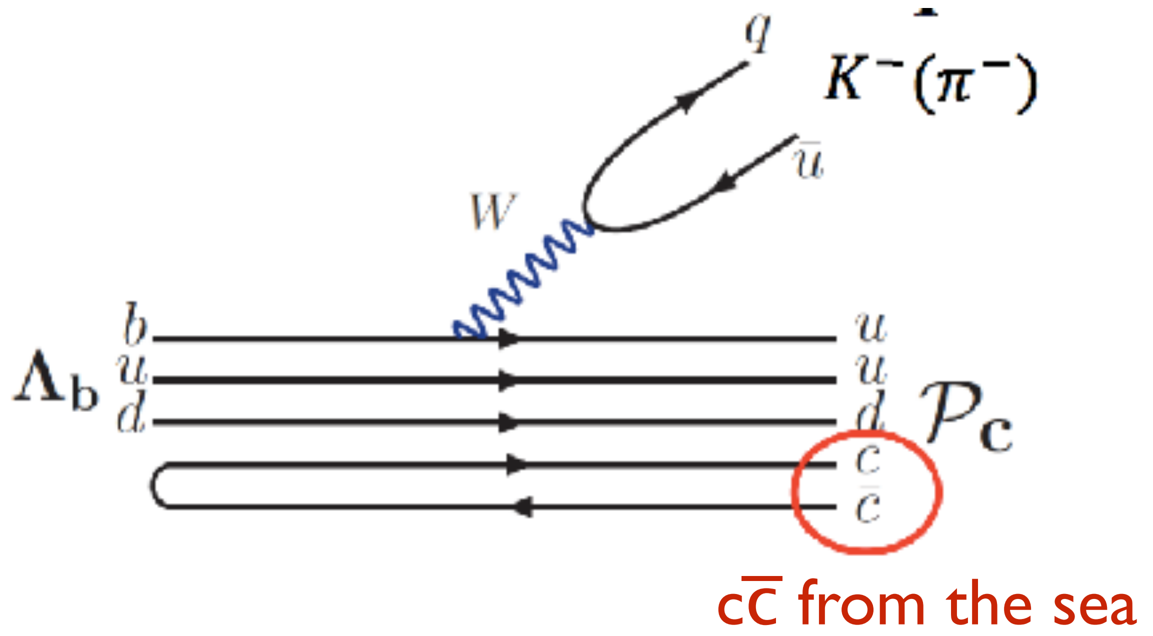
$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08$$

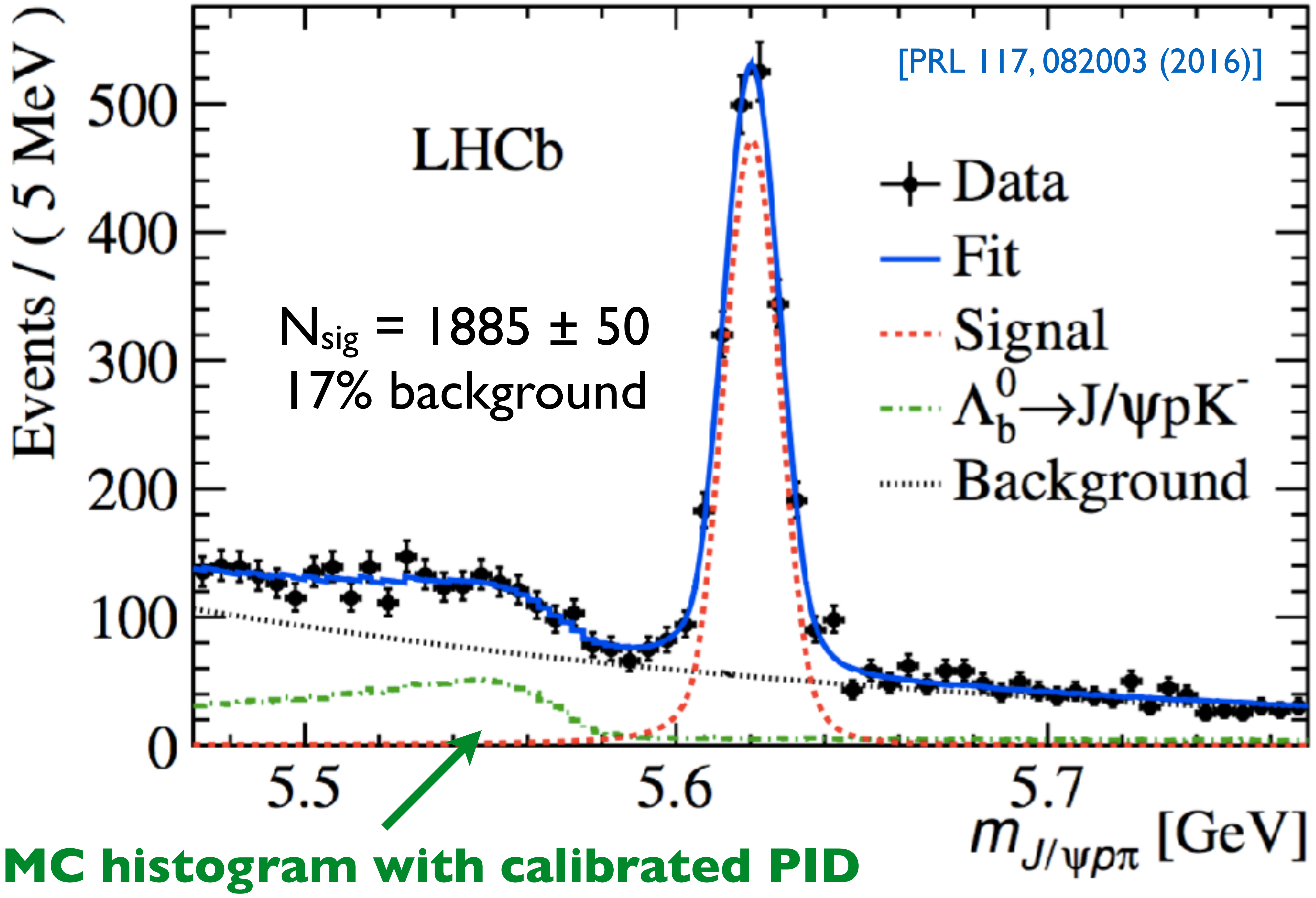
[Cheng et al. PRD 92, 096009 (2015)]

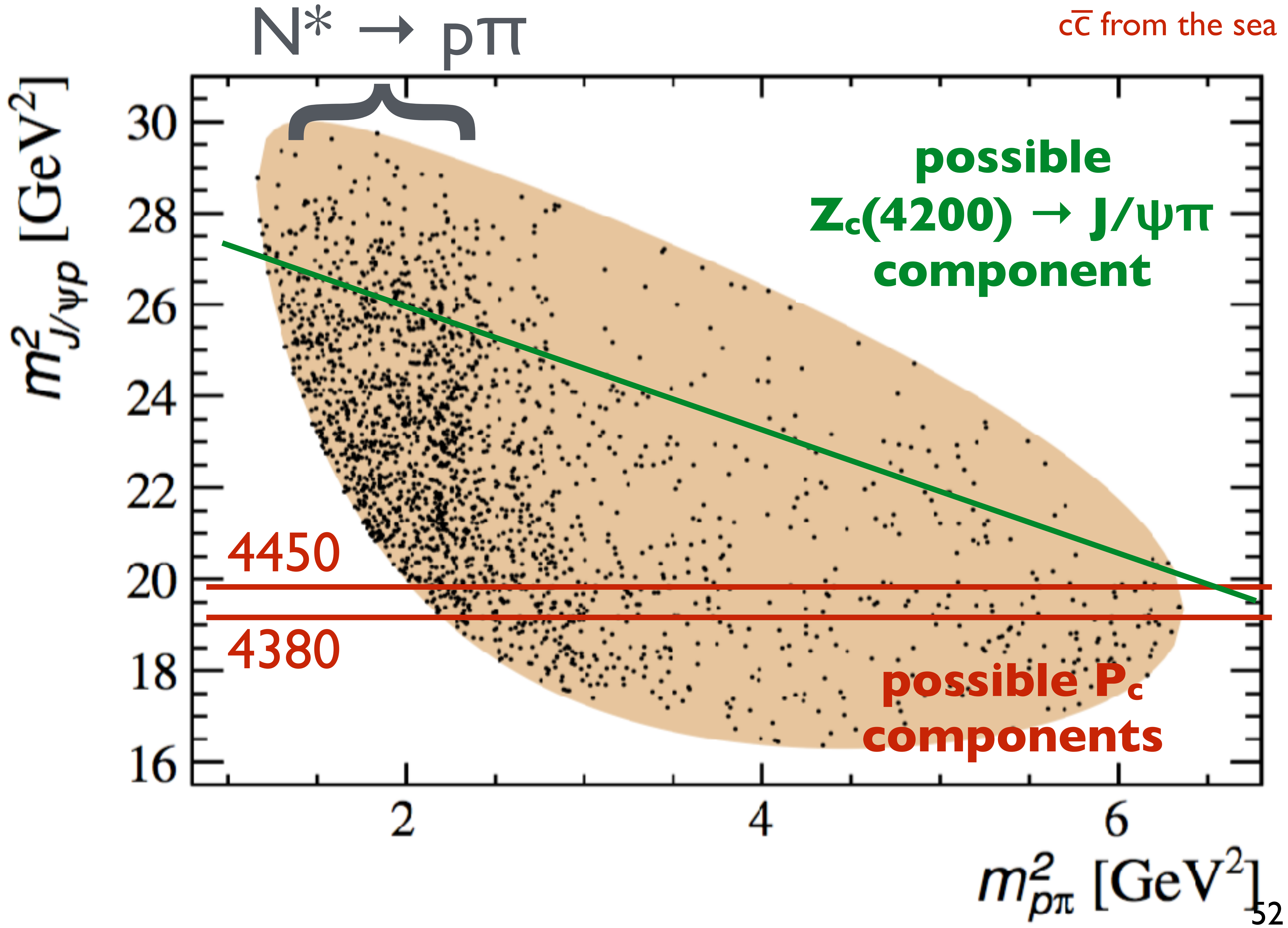


$$R_{\pi^-/K^-} = 0.58 \pm 0.05$$

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







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

[PRL 117, 082003 (2016)]

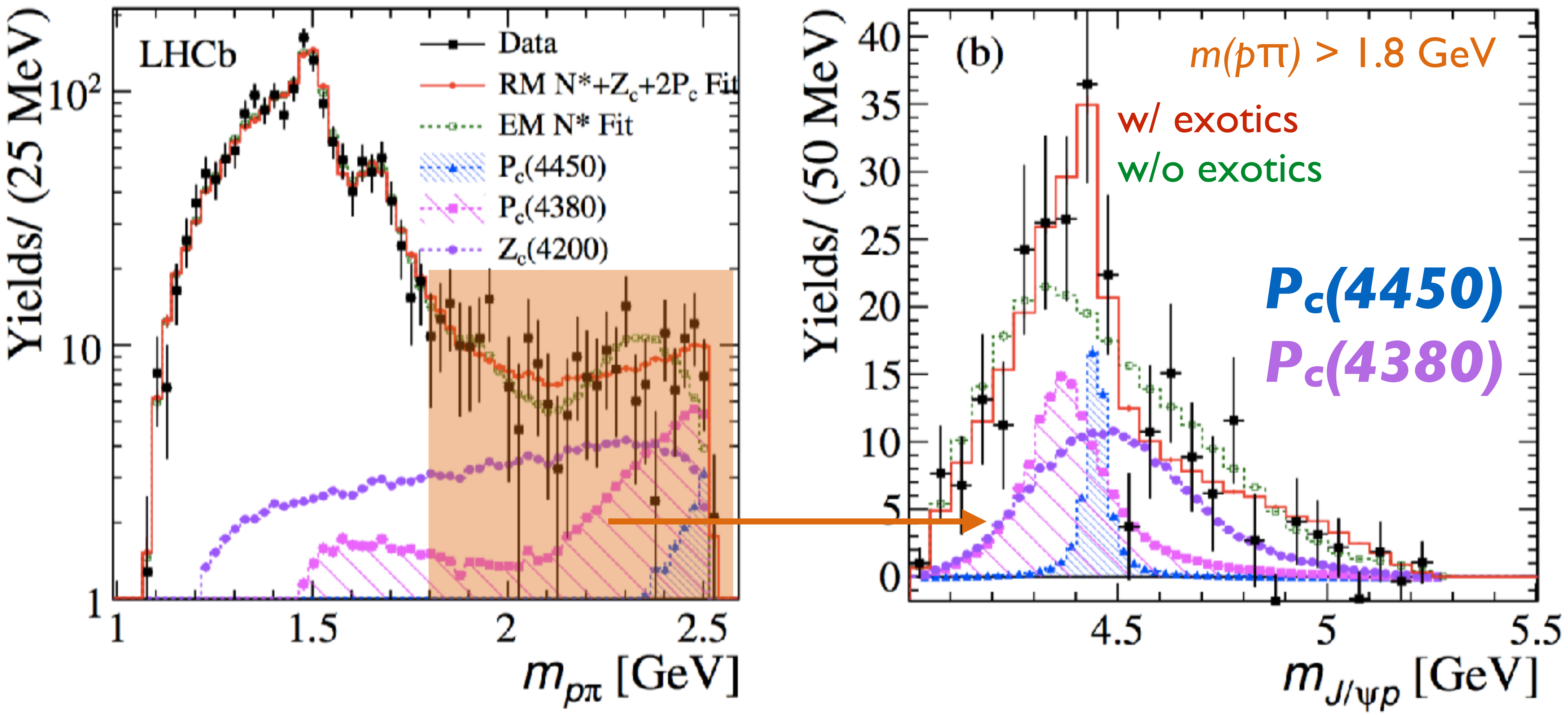
N*-only model not a good fit

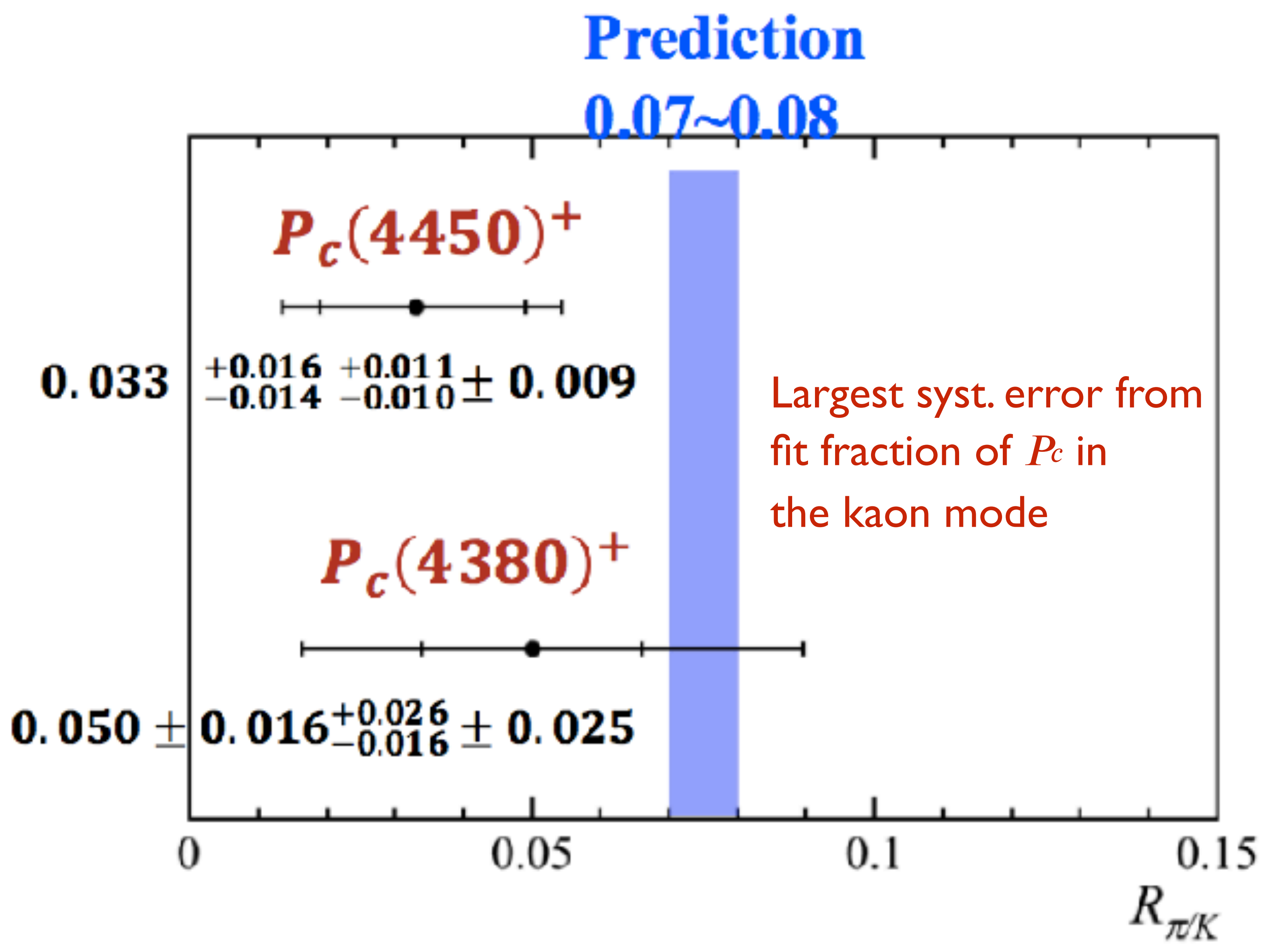
Good fit using 15 N* components + exotic components

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 P_c spin

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



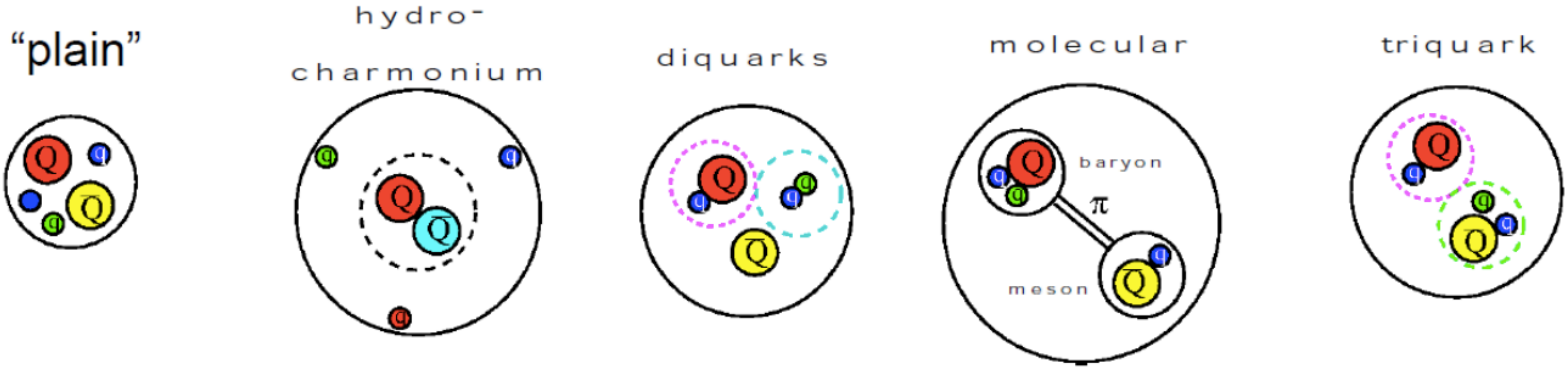


rules out [Hsiao, Phys. Lett. B 751, 572 (2015)]

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?



None of them can explain all observed exotic states, so may need several models to describe everything we see.

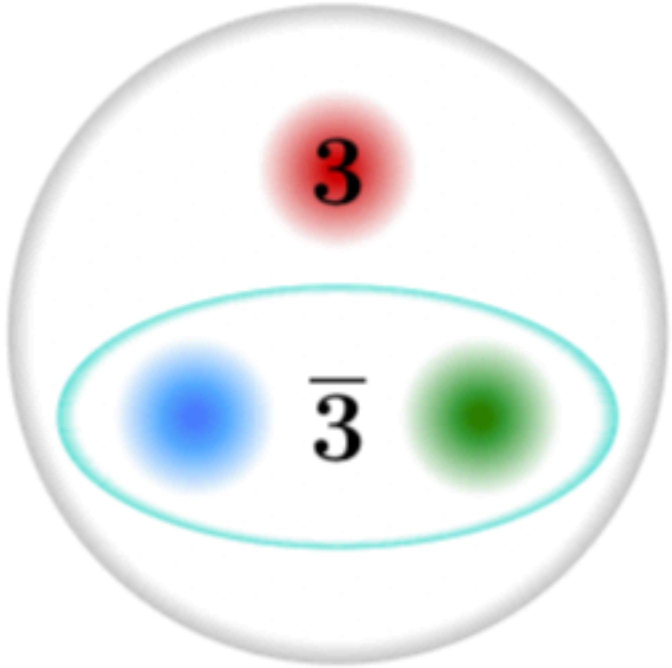
The di-quark model

Can build colour-neutral objects from coloured constituents

Meson

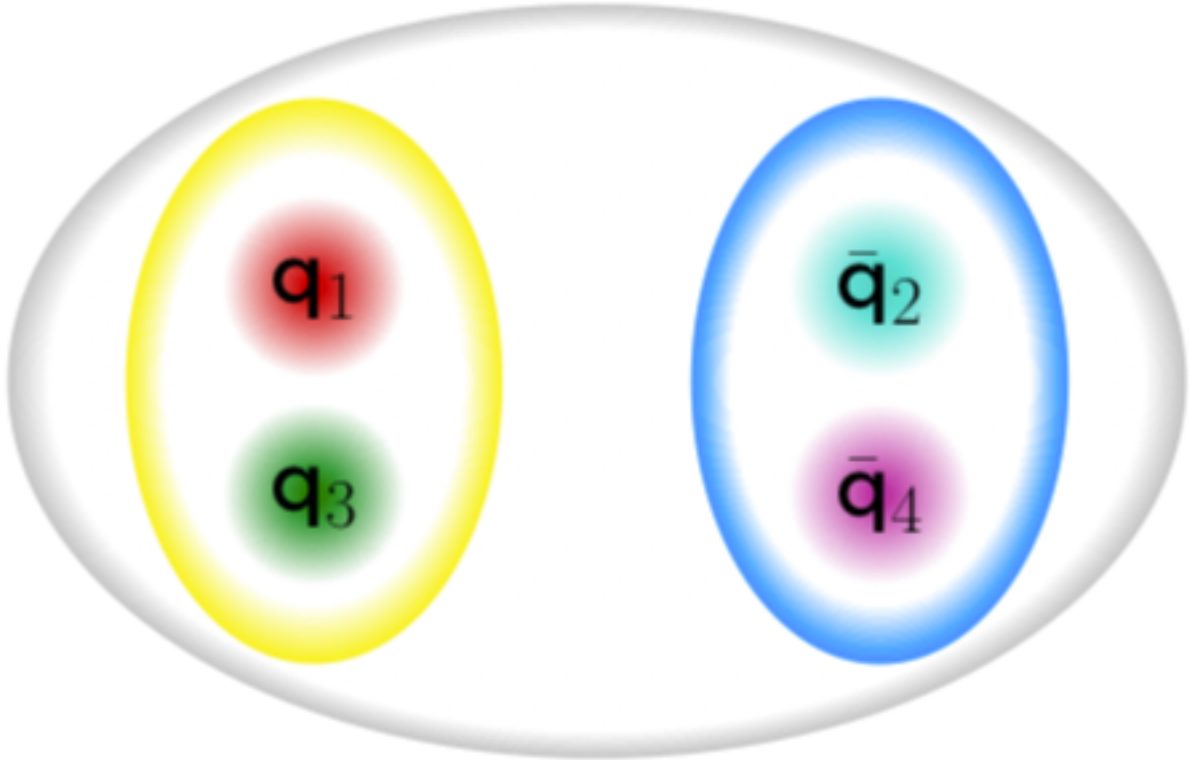
Mesons are bound through attractive $3\overline{3}$ colour coupling

Baryon



$3\otimes3 \rightarrow \overline{3}$, allowing for qq diquark to bind with the other quark to make the baryon

Tetraquark



Bind two diquarks together

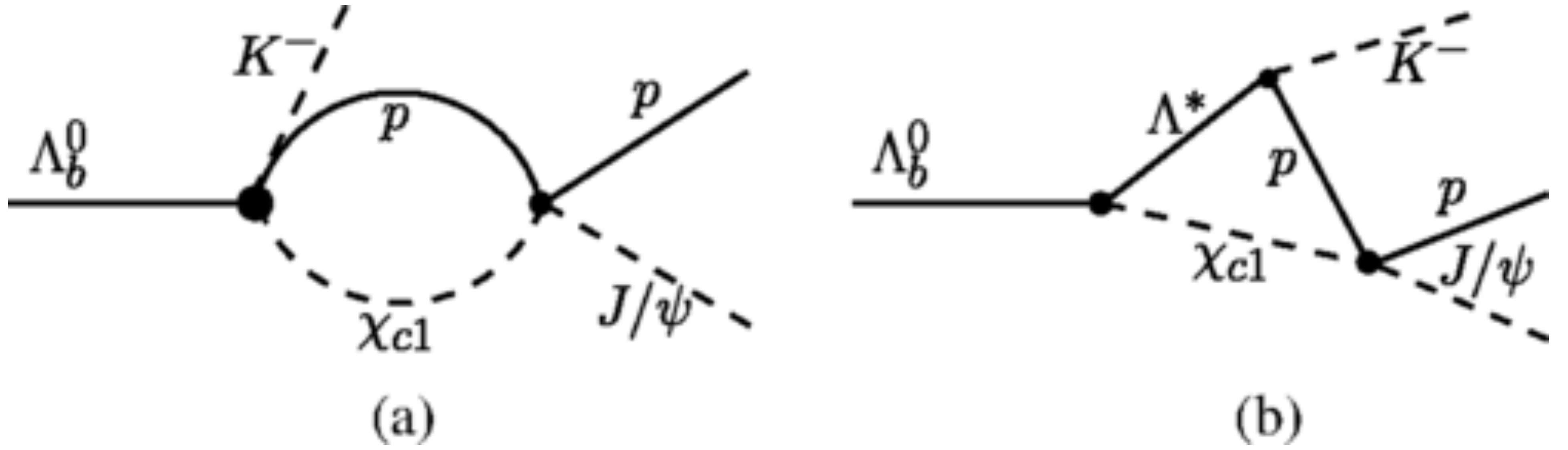
[Thanks to S. Neubert for images]

Could rescattering explain exotics?

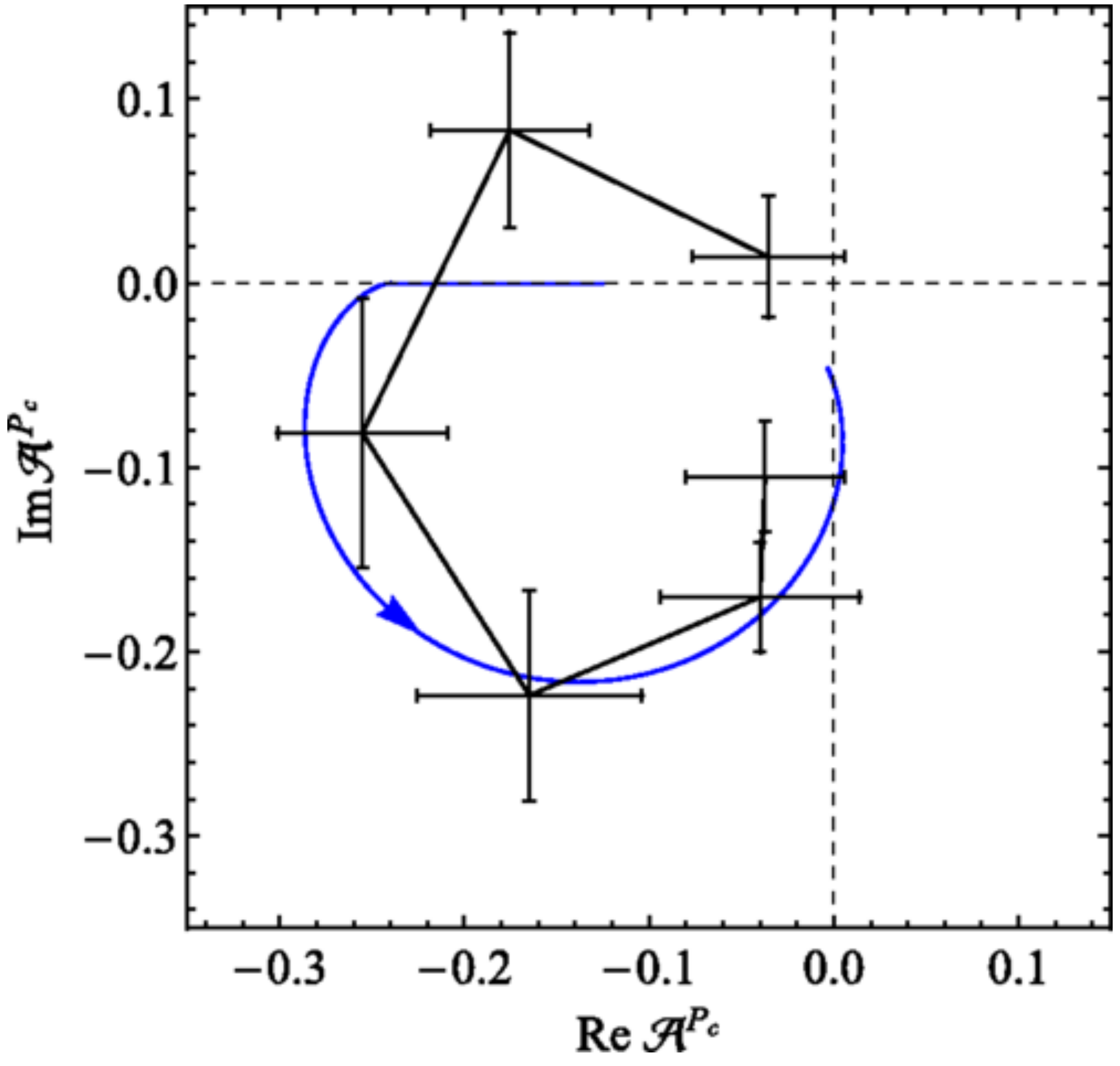
$P_c(4450)$ has mass at threshold of $\chi_{c1}p$ so could be due to $J/\psi p \rightarrow \chi_{c1}p$ kinematic rescattering

Reproduces $P_c(4450)$ phase motion but what about $P_c(4380)$?

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



[Guo et al., PRD 91 (2015) 051504]
[Guo et al, PRD 92 (2015) 071502(R)]
[Bayer et al., PRD 94 (2016) 074039]

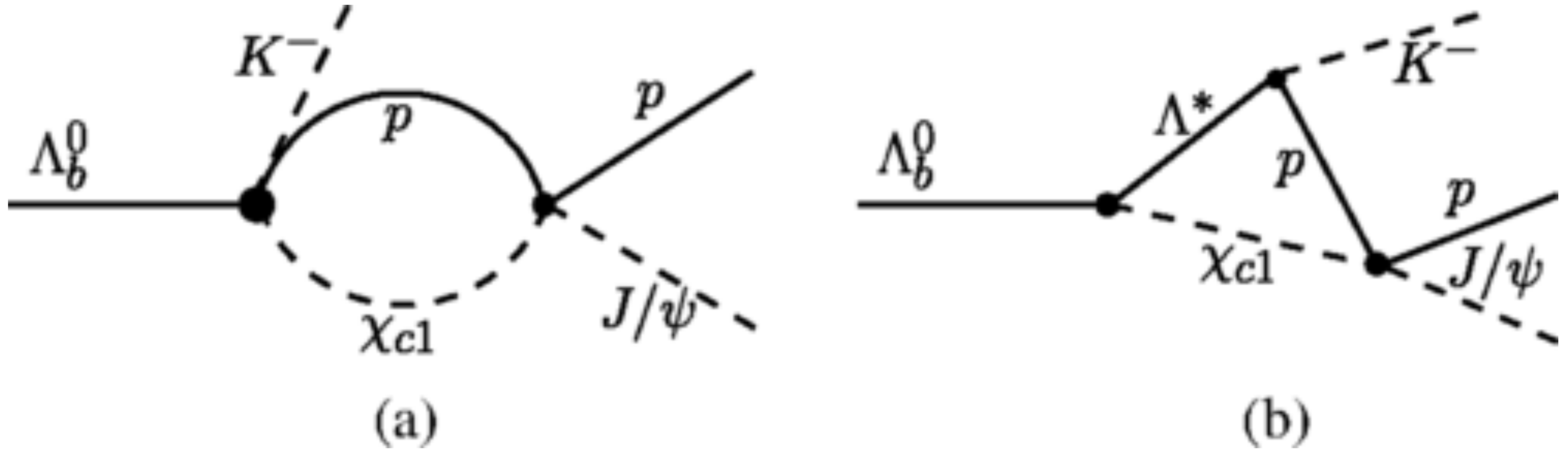


Could rescattering explain exotics?

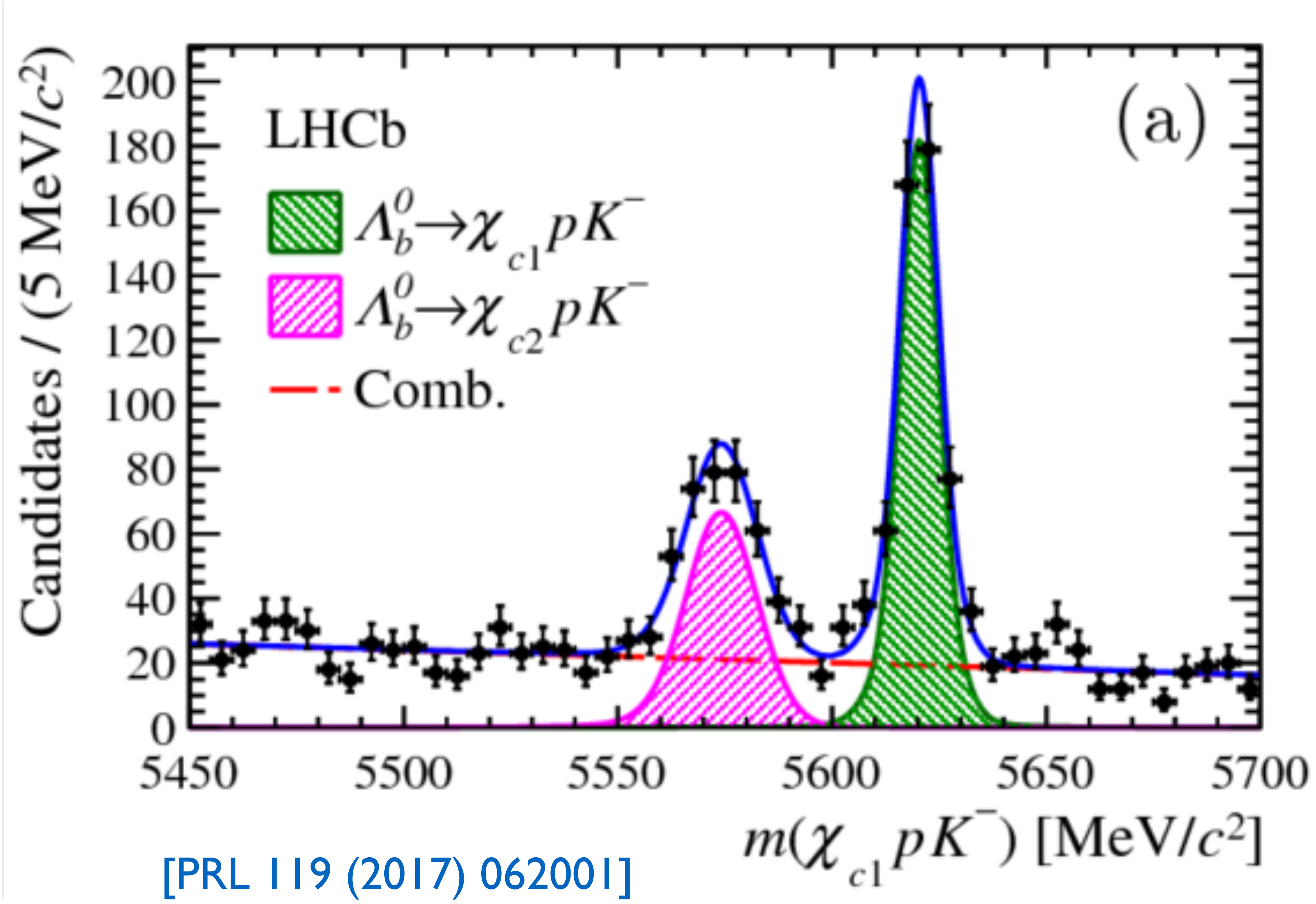
$P_c(4450)$ has mass at threshold of $\chi_{c1}p$ so could be due to $J/\psi p \to \chi_{c1}p$ kinematic rescattering

Reproduces $P_c(4450)$ phase motion but what about $P_c(4380)$?

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



[Guo et al., PRD 91 (2015) 051504]
[Guo et al, PRD 92 (2015) 071502(R)]
[Bayer et al., PRD 94 (2016) 074039]

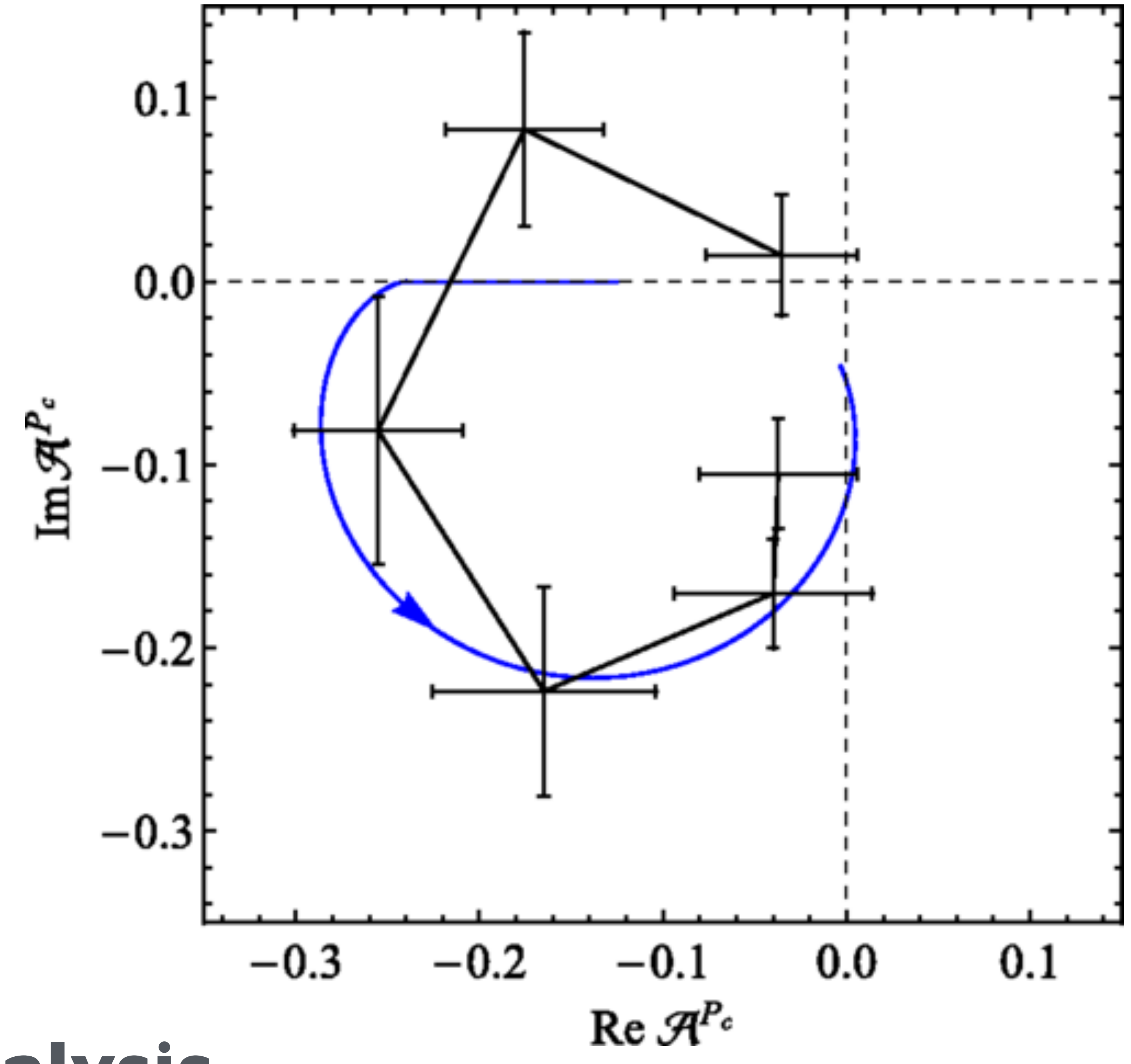


[PRL 119 (2017) 062001]

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

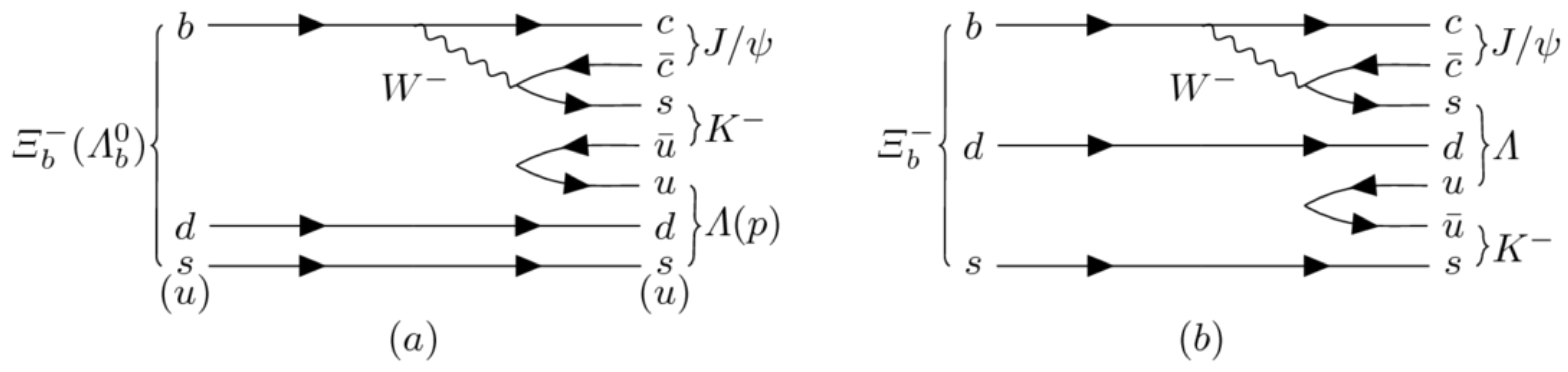
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$

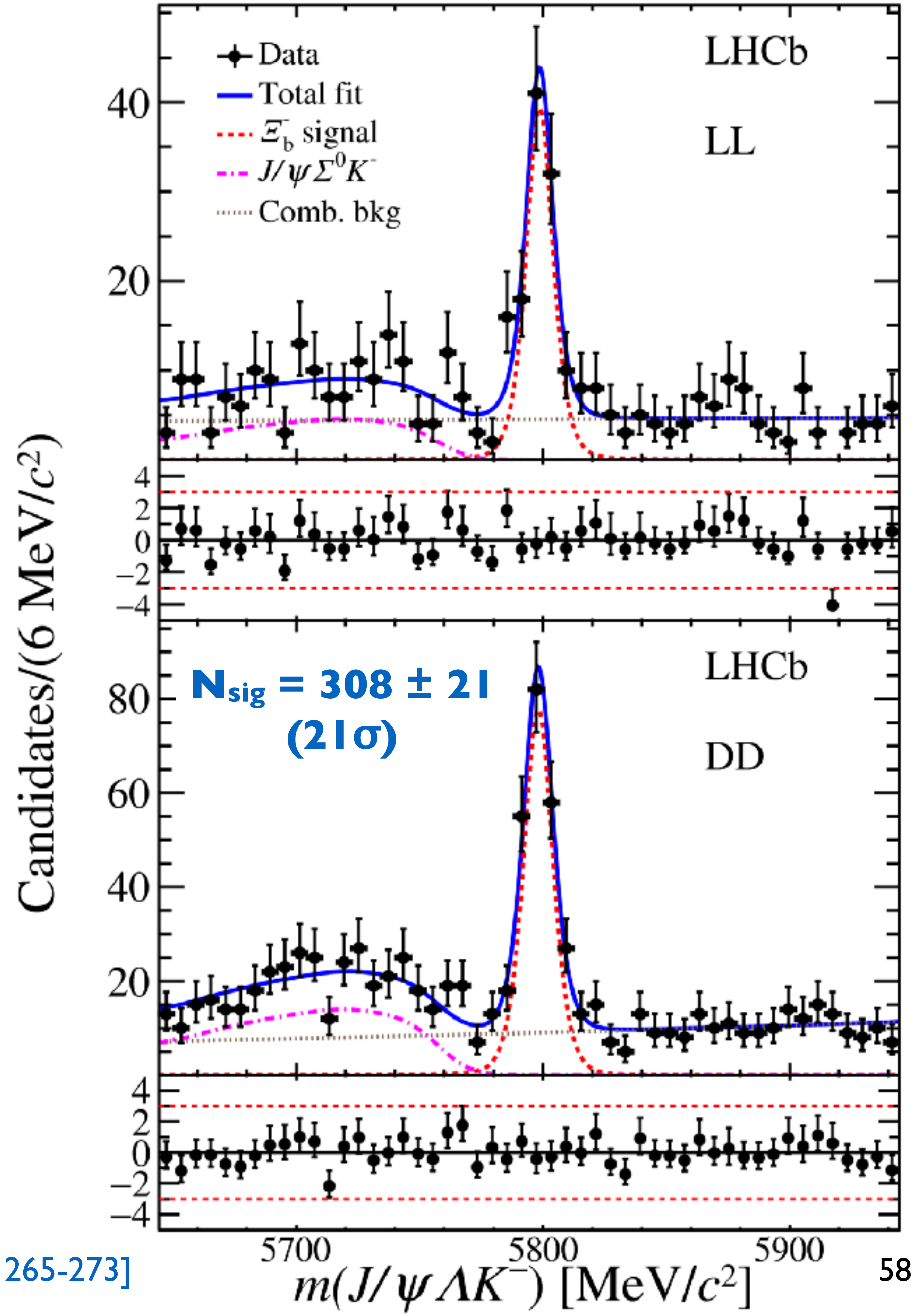
$\mathcal{B}(\chi_{cJ})$



Next step: amplitude analysis

Observation of the $\Xi^-_b \to J/\psi \Lambda K^-$ decay





Strange pentaquark ($udsc\bar{c}$) predicted [PRL 105, 232001 (2010)]

Can be searched for in the Ξ_b decay [PRC 93, 065203 (2016)]

Expect ~1500 signal events after 2018
→ amplitude analysis

[Phys. Lett. B 772 (2017) 265-273]

Connections with "conventional" spectroscopy

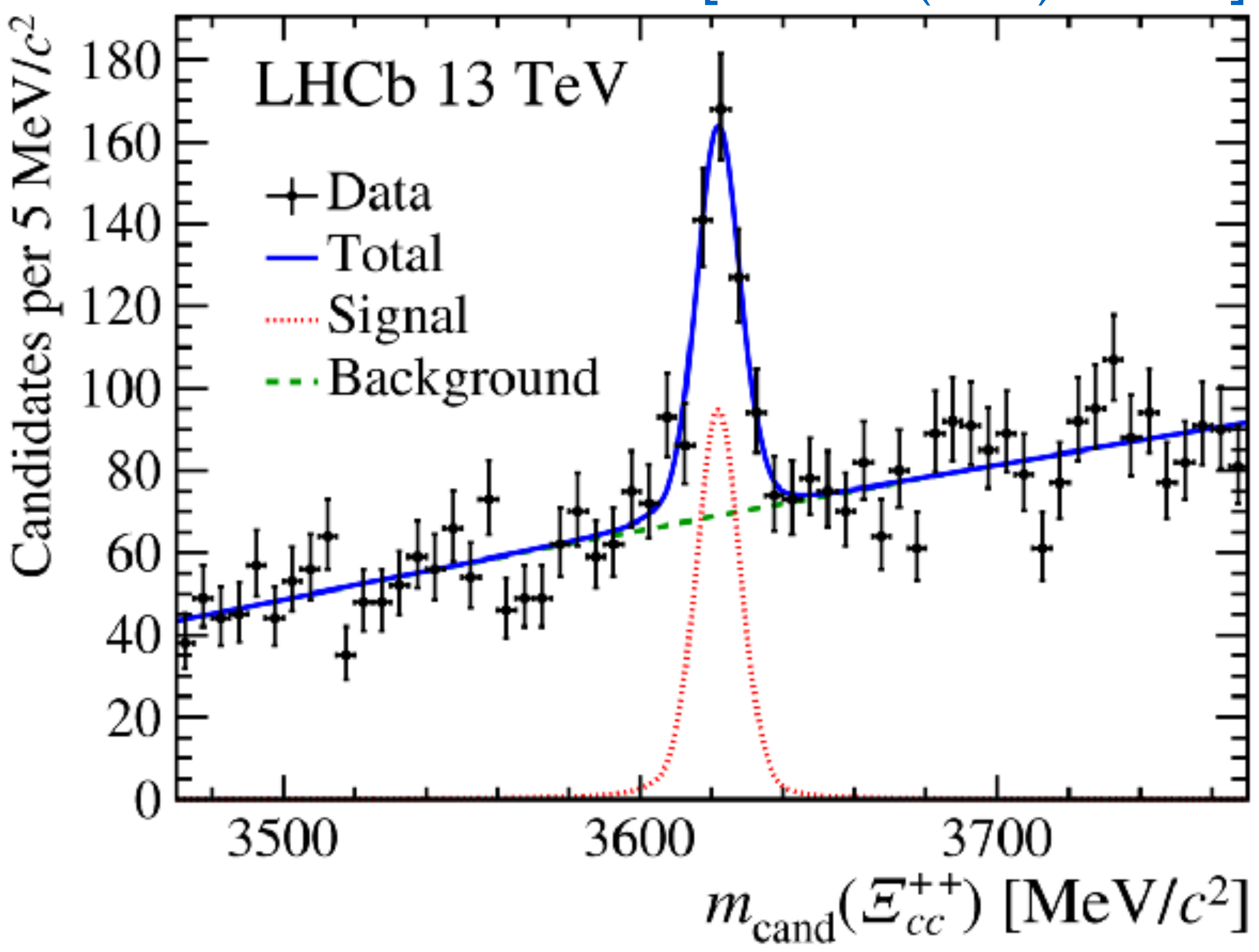
Discovery of Ω_c^{**} and Ξ_{cc}^{++} have spurred theoretical investigations, motivated by the calibration of the binding energy of their constituent **diquarks**.

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]

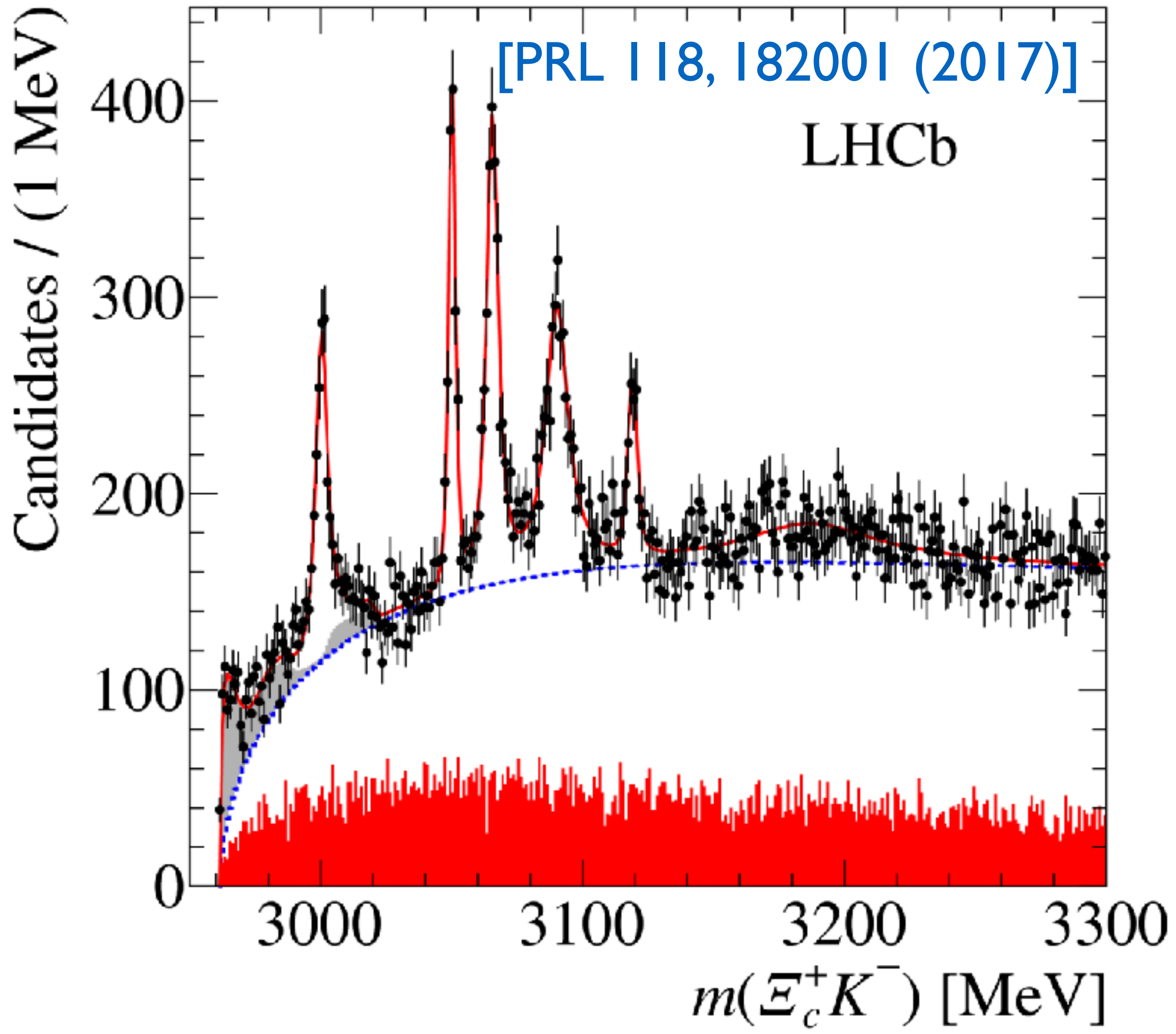
Not only are some of the Ω_c^{**} states now thought of as potential pentaquarks, but theorists are using these as a basis to propose other candidates. [Mehen arXiv:1708.05020] [Karliner and Rosner arXiv:1707.07666]

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 …)

[PRL 119 (2017) 112001]



[PRL 118, 182001 (2017)]



Future experimental programme

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

   e.g. Photo-production $\gamma p \rightarrow J/\psi p$ experiment has been approved at JLab

   [Meziani et al., arXiv:1609.00676]

Future experimental programme

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

   e.g. Photo-production $\gamma p \rightarrow J/\psi p$ experiment has been approved at JLab

   [Meziani et al., arXiv:1609.00676]

2. Observe states in different **decay** modes

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

   Transitions between exotic states (e.g., $Y(4260) \rightarrow X(3872)\gamma$)

   Publish **non-observations**!

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

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

Future experimental programme

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

   e.g. Photo-production $\gamma p \rightarrow J/\psi p$ experiment has been approved at JLab

   [Meziani et al., arXiv:1609.00676]

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

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

2. Observe states in different **decay** modes

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

   Transitions between exotic states (e.g., $Y(4260) \rightarrow X(3872)\gamma$)

   Publish **non-observations**!

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

   [PRL 105, 232001 (2010)]

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

Future experimental programme

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

   e.g. Photo-production $\gamma p \to J/\psi p$ experiment has been approved at JLab

   [Meziani et al., arXiv:1609.00676]

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

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

2. Observe states in different **decay** modes

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

   Transitions between exotic states (e.g., $Y(4260) \to X(3872)\gamma$)

   Publish **non-observations**!

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

   [PRL 105, 232001 (2010)]

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

4. Measure **branching ratios**

Future experimental programme

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

   e.g. Photo-production $\gamma p \rightarrow J/\psi p$ experiment has been approved at JLab

   [Meziani et al., arXiv:1609.00676]

2. Observe states in different **decay** modes

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

   Transitions between exotic states (e.g., Y(4260) $\rightarrow$ X(3872)γ)

   Publish **non-observations**!

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

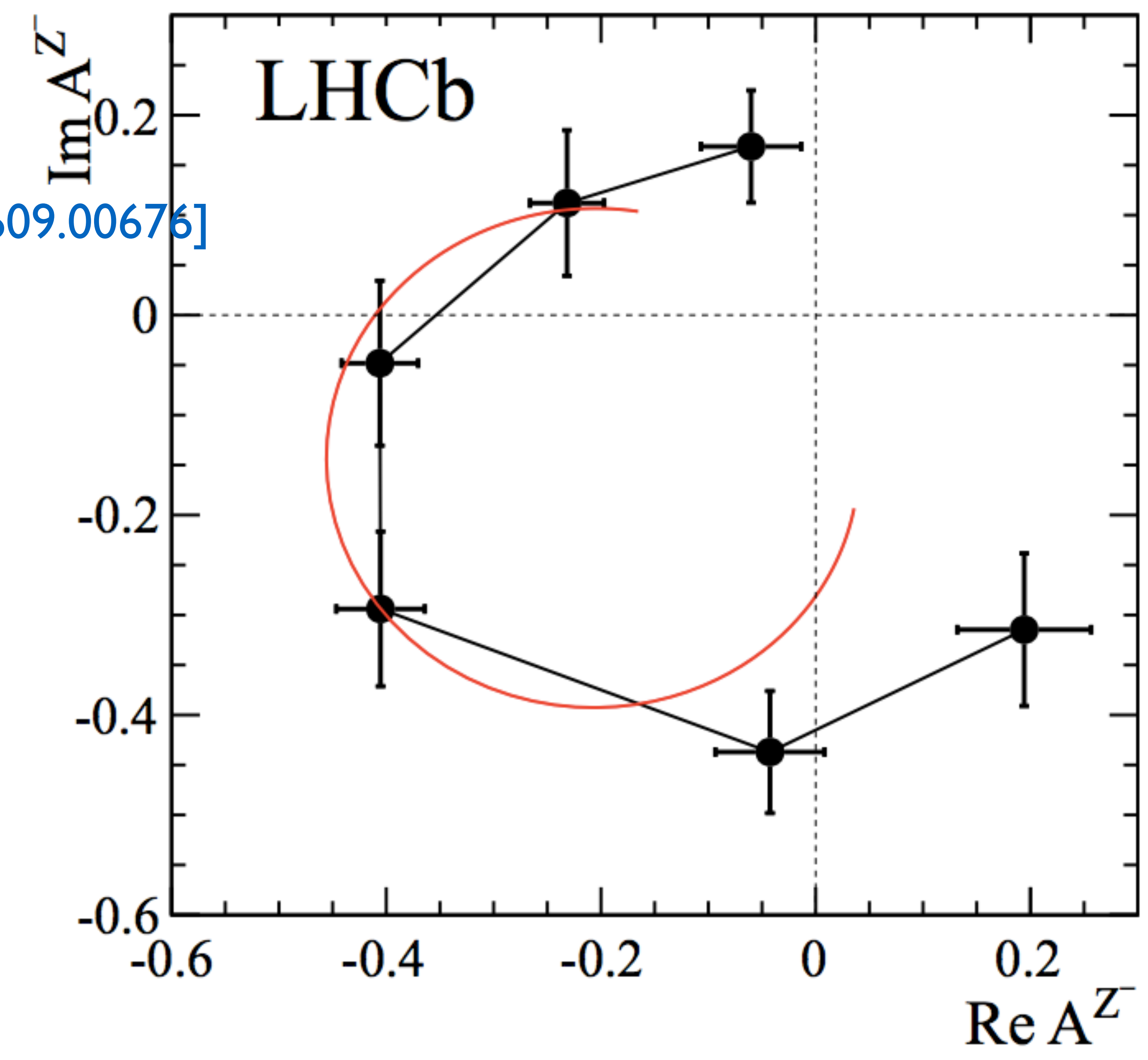
   [PRL 105, 232001 (2010)]

4. Measure **branching ratios**

5. 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!

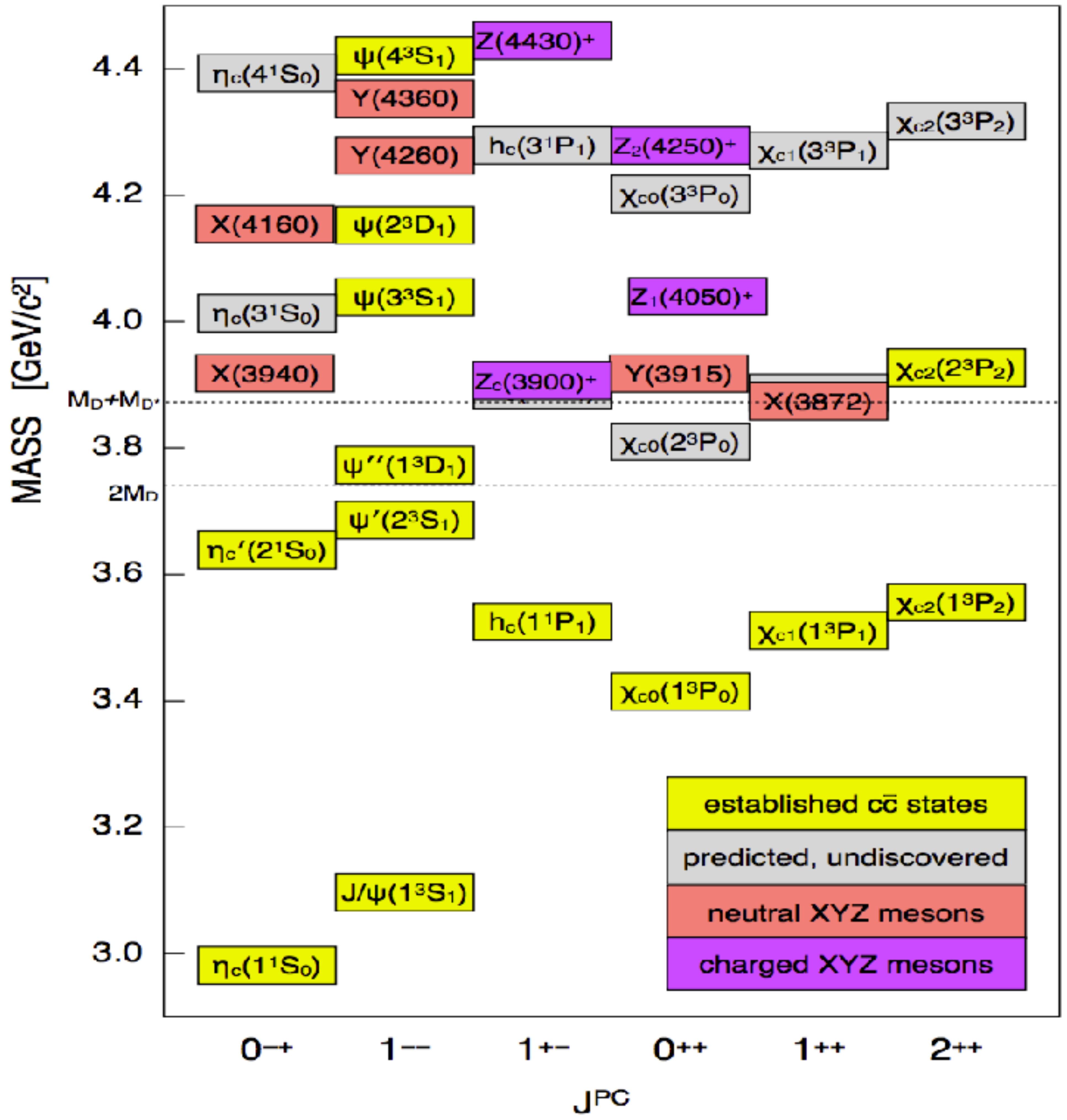
Summary

Revolution in heavy-quark spectroscopy since 2003 discovery of X(3872).

~30 XYZ and P_c states observed using different production and decay mechanisms.

Exotic states provide ideal foundation to deepen understanding of non-perturbative QCD dynamics.

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



Backup

The next ~20 years...

We are here

LHC phase 2 (HL-LHC)

visible int/bunch crossing	~1	~1	~6	~6	~55
inst $\mathcal{L}_{\text{LHCb}}$ cm^{-2}s^{-1}	4×10^{32}	4×10^{32}	2×10^{33}	2×10^{33}	$1\text{-}2\times10^{34}$
$\int dt\, \mathcal{L}_{\text{LHCb}}$	3 fb^{-1}	9 fb^{-1}		50 fb^{-1}	300 fb^{-1}
	2011-2012 Run 1	2015-2018 Run 2	2021-2023 Run 3	2026-2029 Run 4	2031-… Run 5/6

LS2: install LHCb upgrade I

LS3: upgrade I consolidation

LS4: install LHCb upgrade II

Install ATLAS/CMS phase 2 upgrades in LS3
Belle-II finishes at same time (~2025)

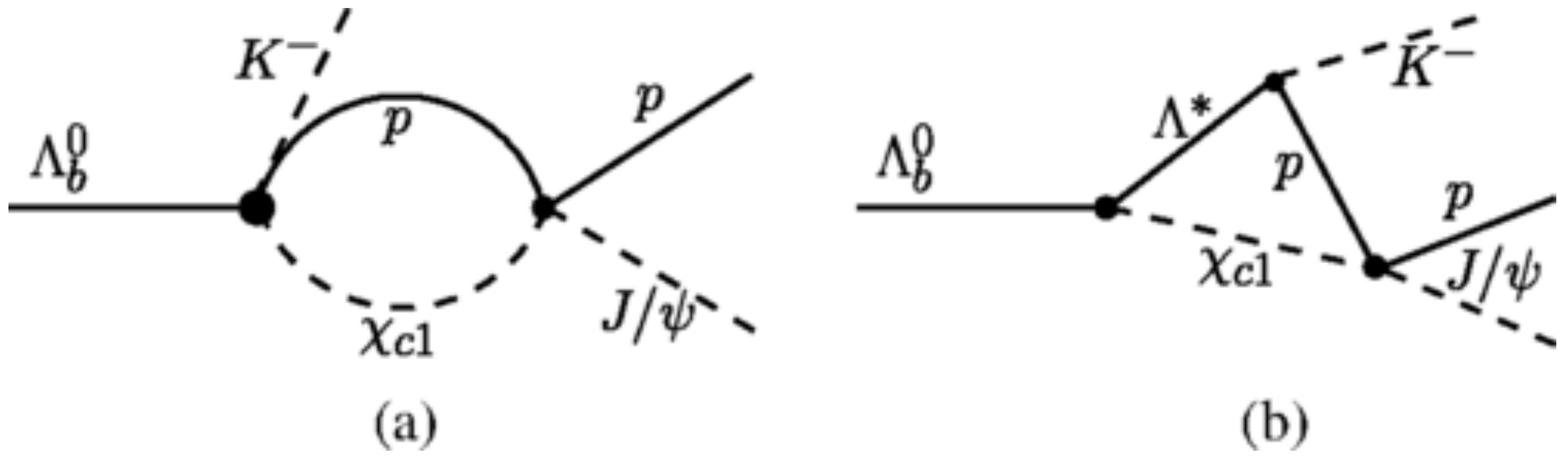
"New" experiments to take advantage of the HL-LHC

What is a resonance?

Formally, taken as meaning a pole in the S-matrix (scattering matrix) of a particular process.

They are dynamical (and non-perturbative) in nature: the interactions between quarks/gluons (or among hadrons) give the poles in the scattering amplitude.

S-matrix can also have "kinematic" singularities, such as at two-body thresholds or the triangle singularity (originating from three on-shell particles)



Important to be able to distinguish the dynamical and kinematics singularities

[Guo, arXiv:1712.10126]

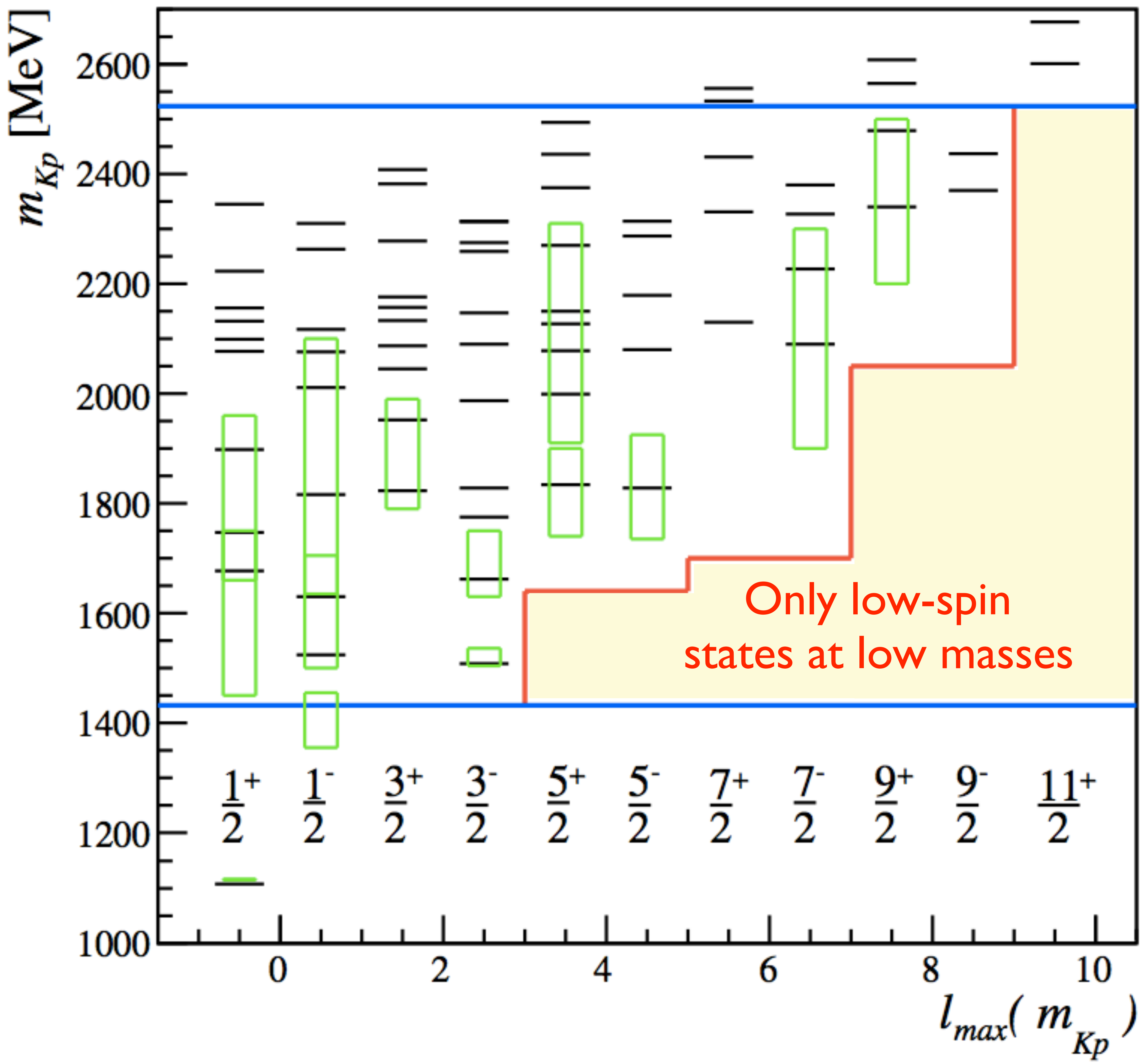
Pentaquark model-independent

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).

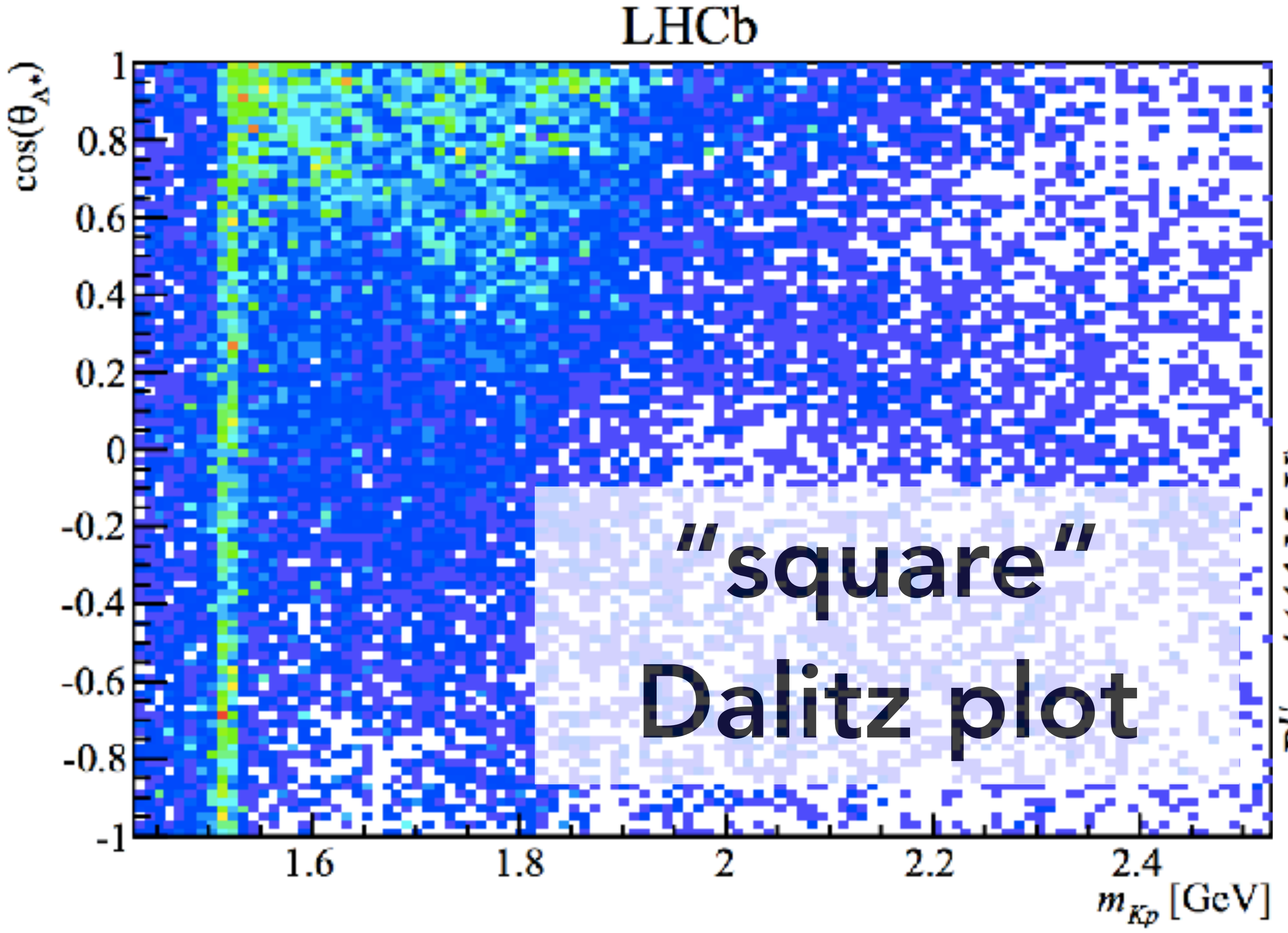
Theory predictions for Λ*
Well established Λ* states

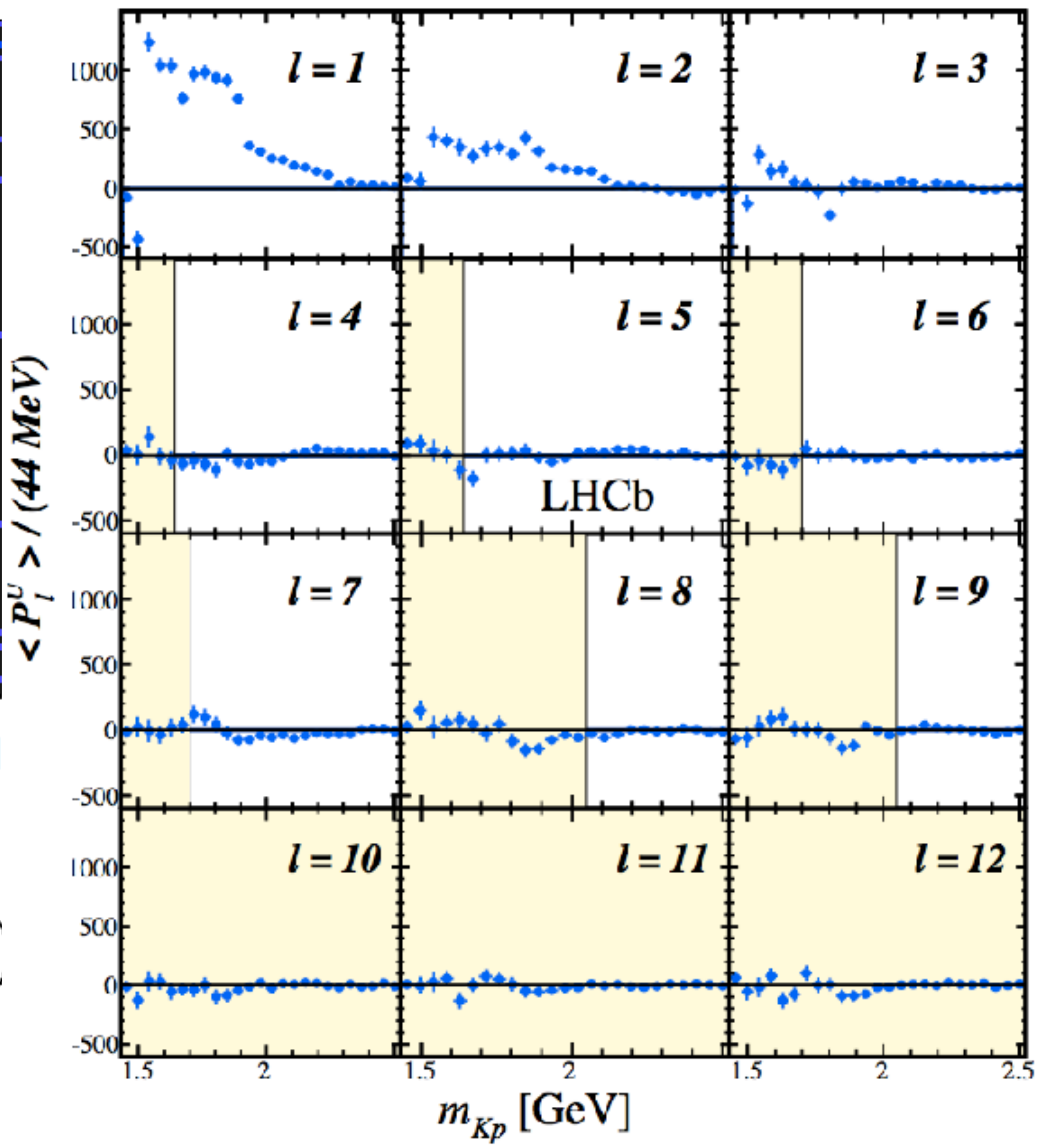


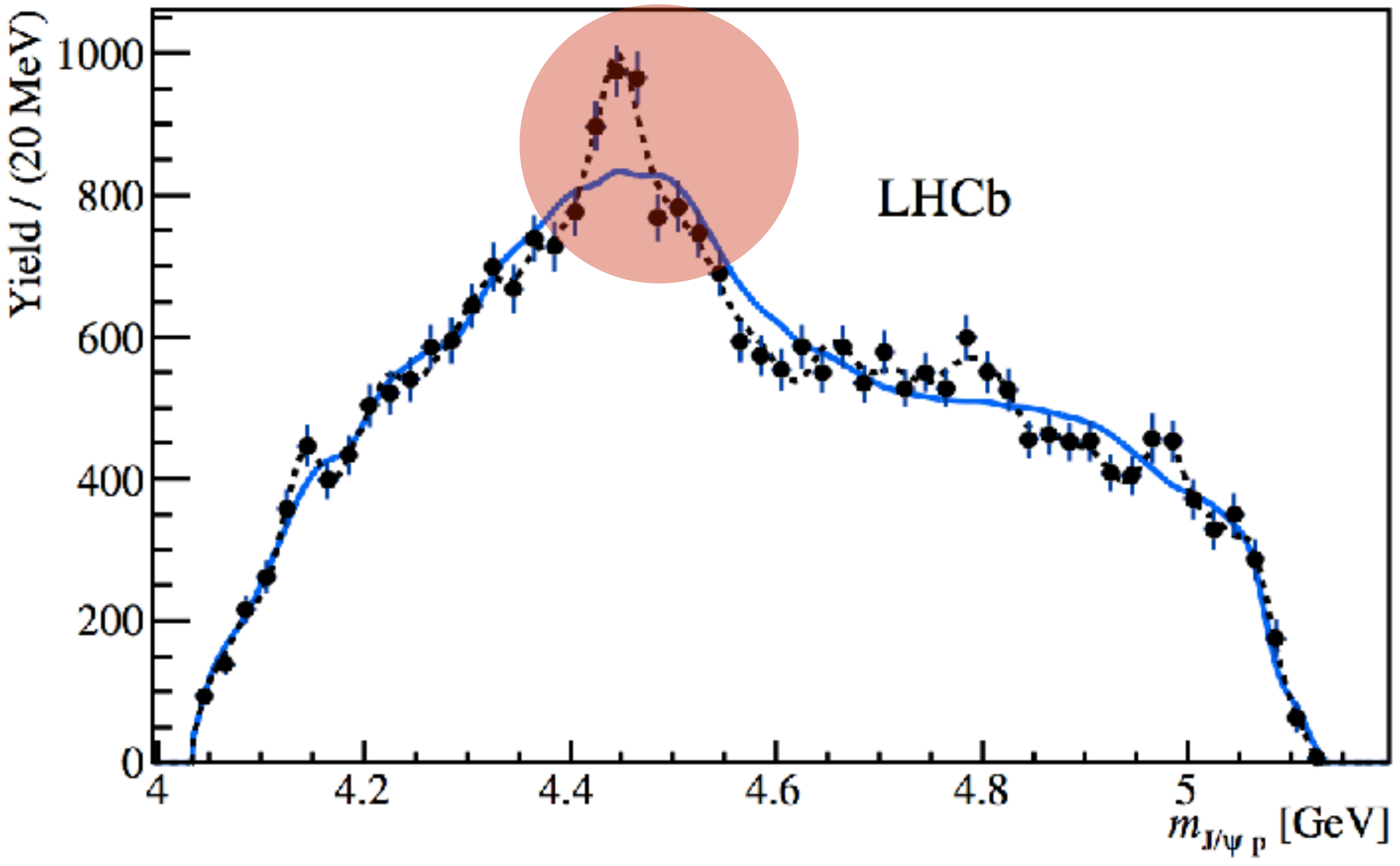
Extension of [BaBar PRD 79 (2009) 112001]

[PRL 117 (2016) 082002]

Pentaquark model-independent [PRL 117 (2016) 082002]







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

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

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

filter out maximum spin for each m$(K\text{p})$

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

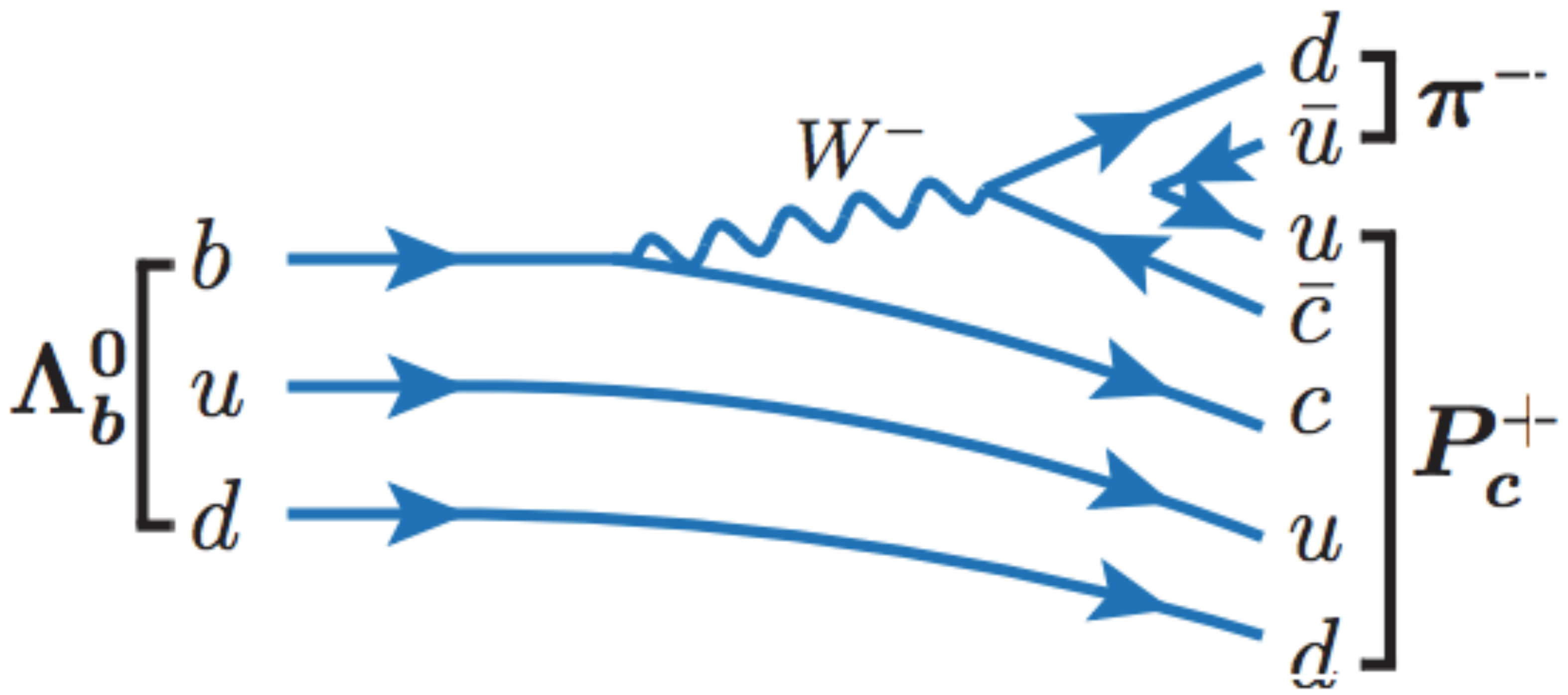
Working with JPAC to use better models of Λ* resonances in future amplitude fits

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

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p\pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.0824 \pm 0.0025\,(\mathrm{stat}) \pm 0.0042\,(\mathrm{syst})$$ [LHCb JHEP 1407, 103 (2014)]

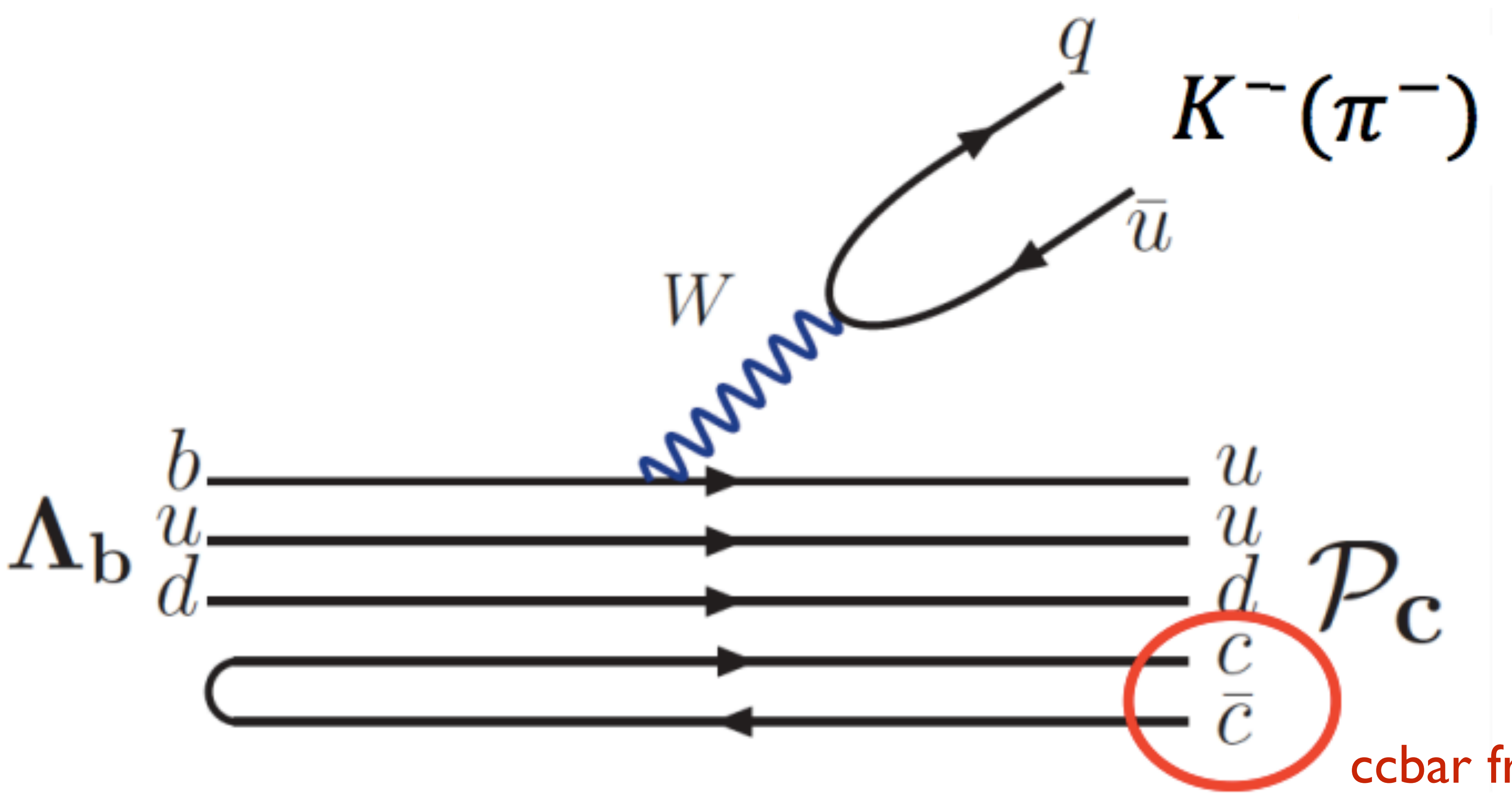
Observations of the P_c^+ states in another decay could imply they are genuine exotic baryonic states, other than kinematical effects, e.g. so-called triangle singularity. [arXiv:1512.01959]

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



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

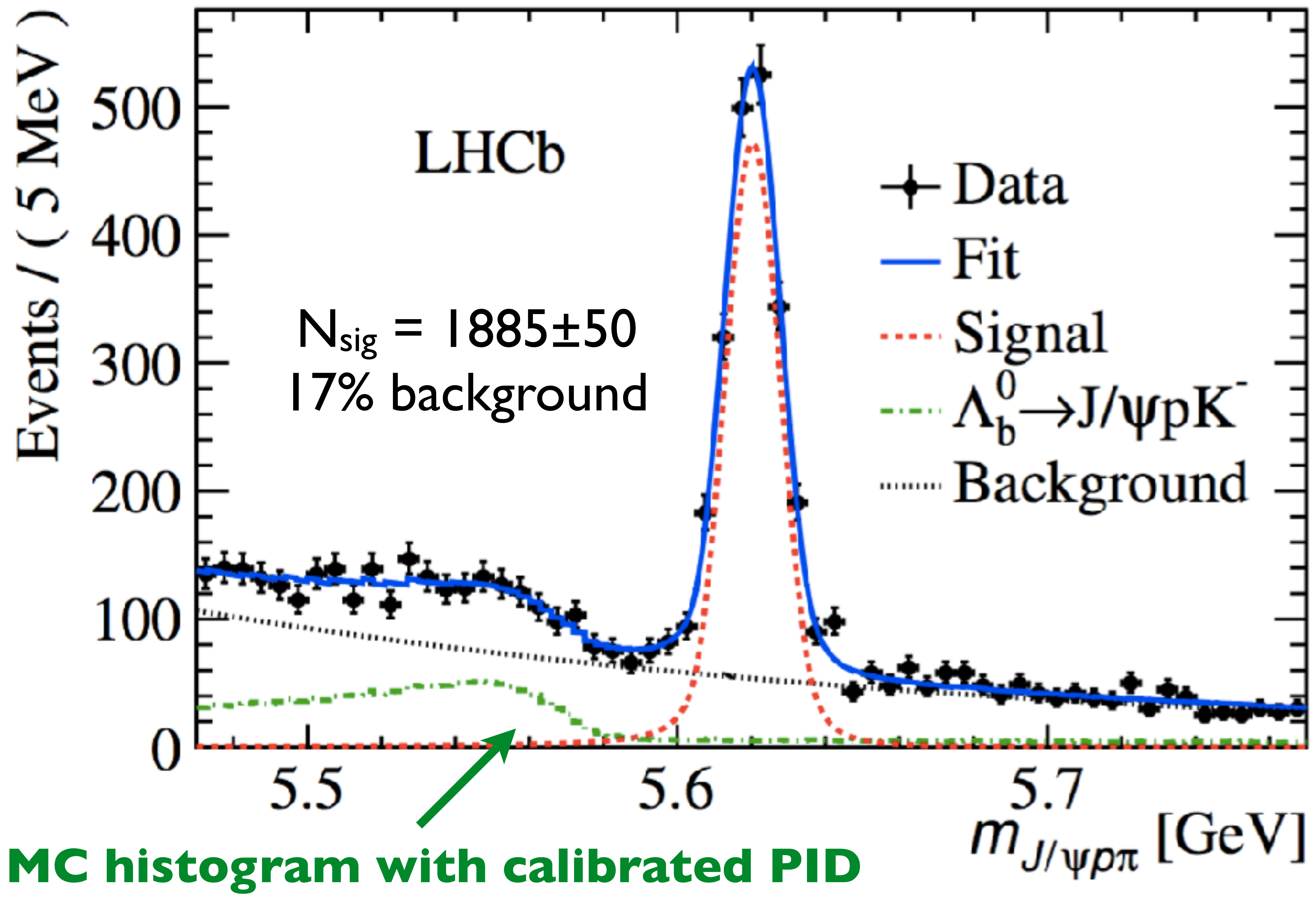
$$R_{\pi^-/K^-} = 0.58 \pm 0.05$$

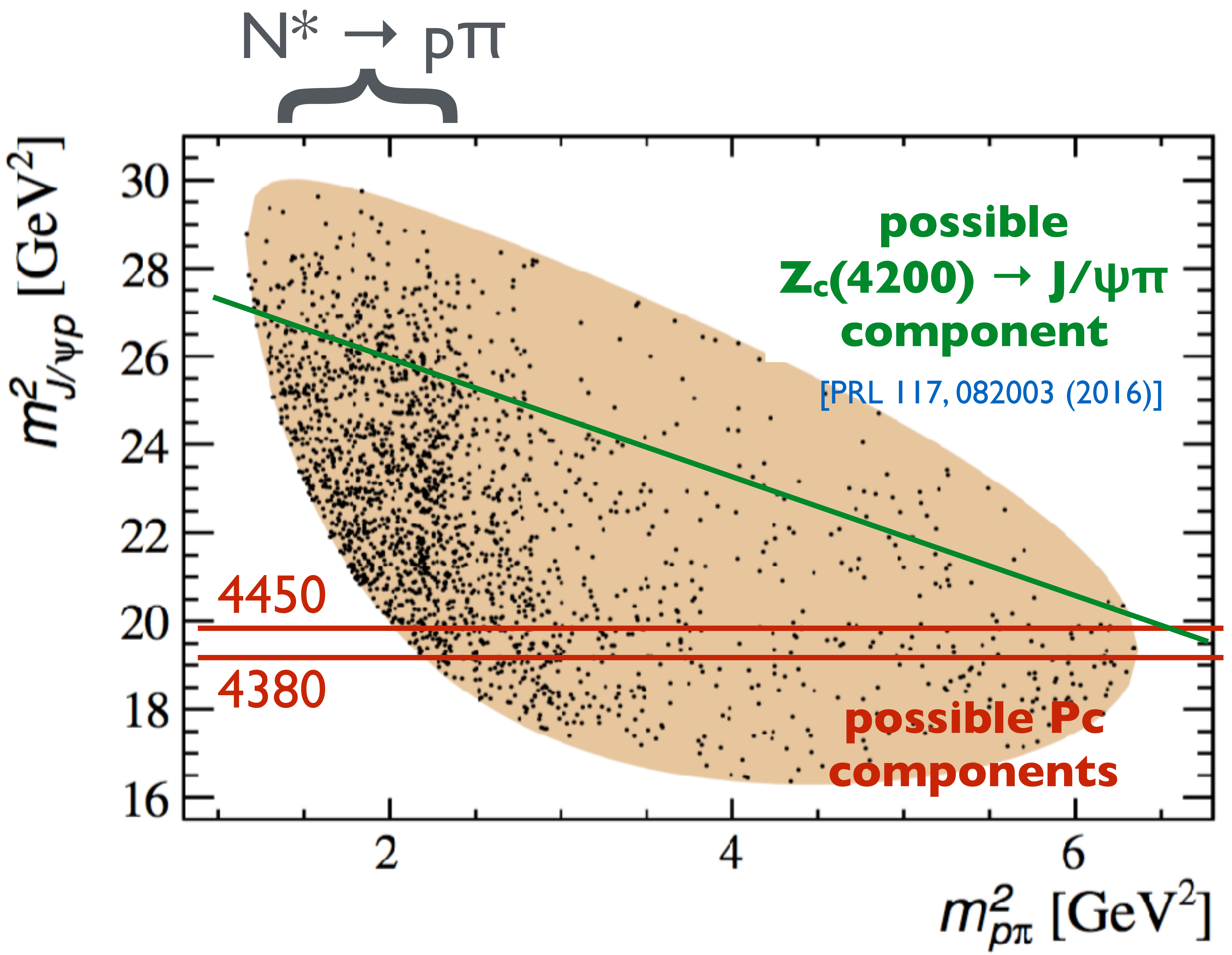


[Hsiao, Phys. Lett. B 751, 572 (2015)]

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

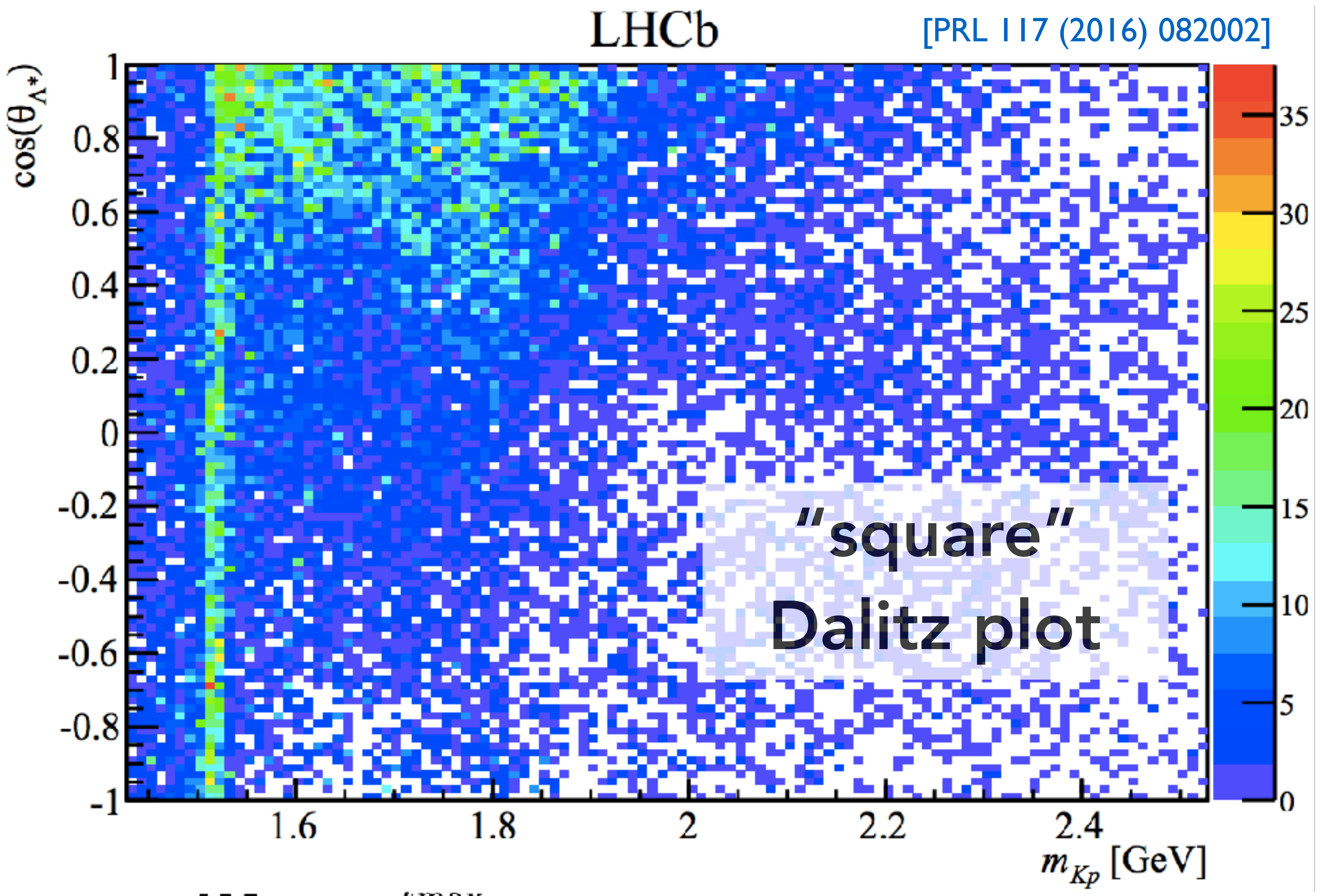
[PRL 117, 082003 (2016)]

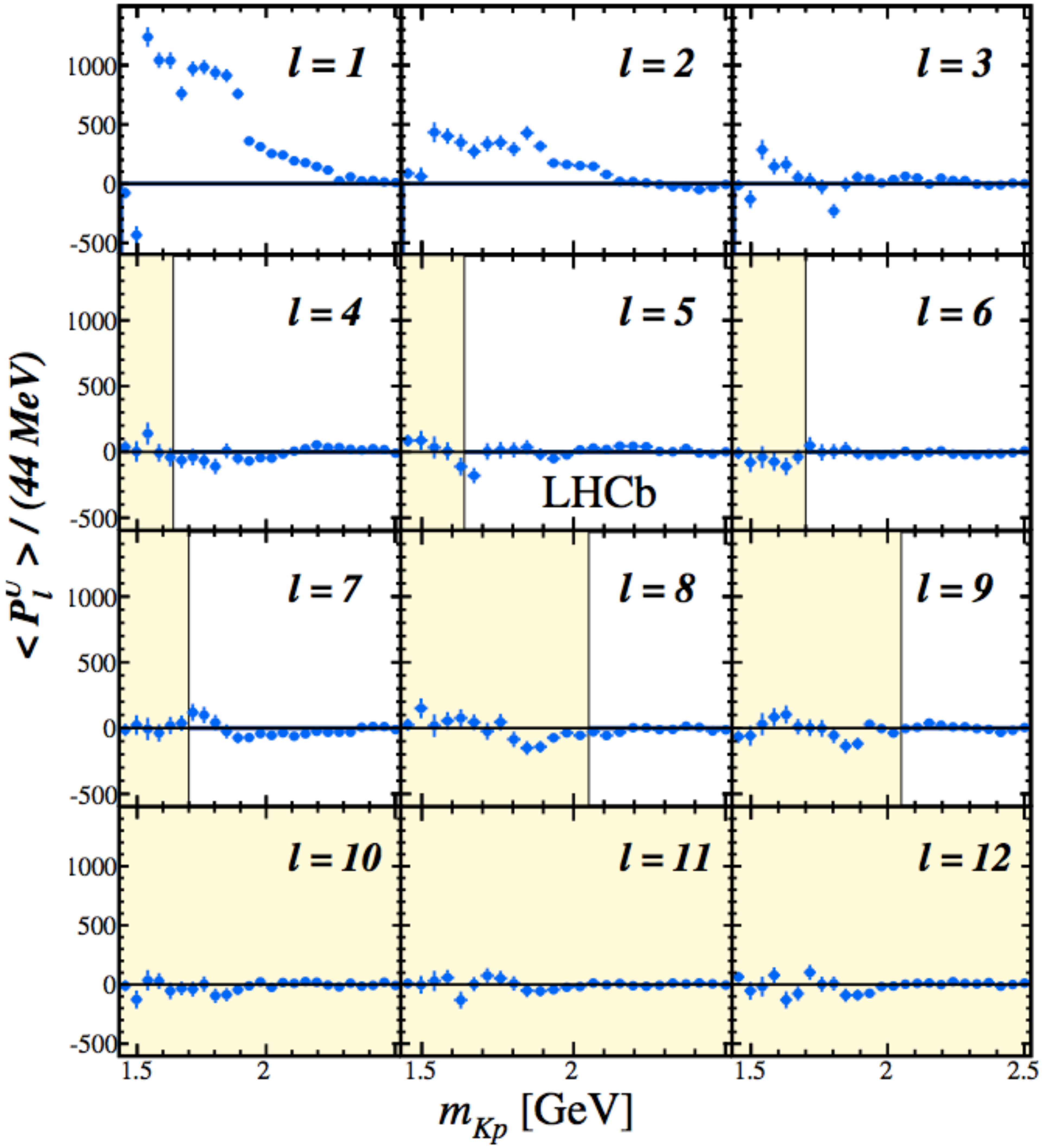




No prominent pentaquark-like peaks

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

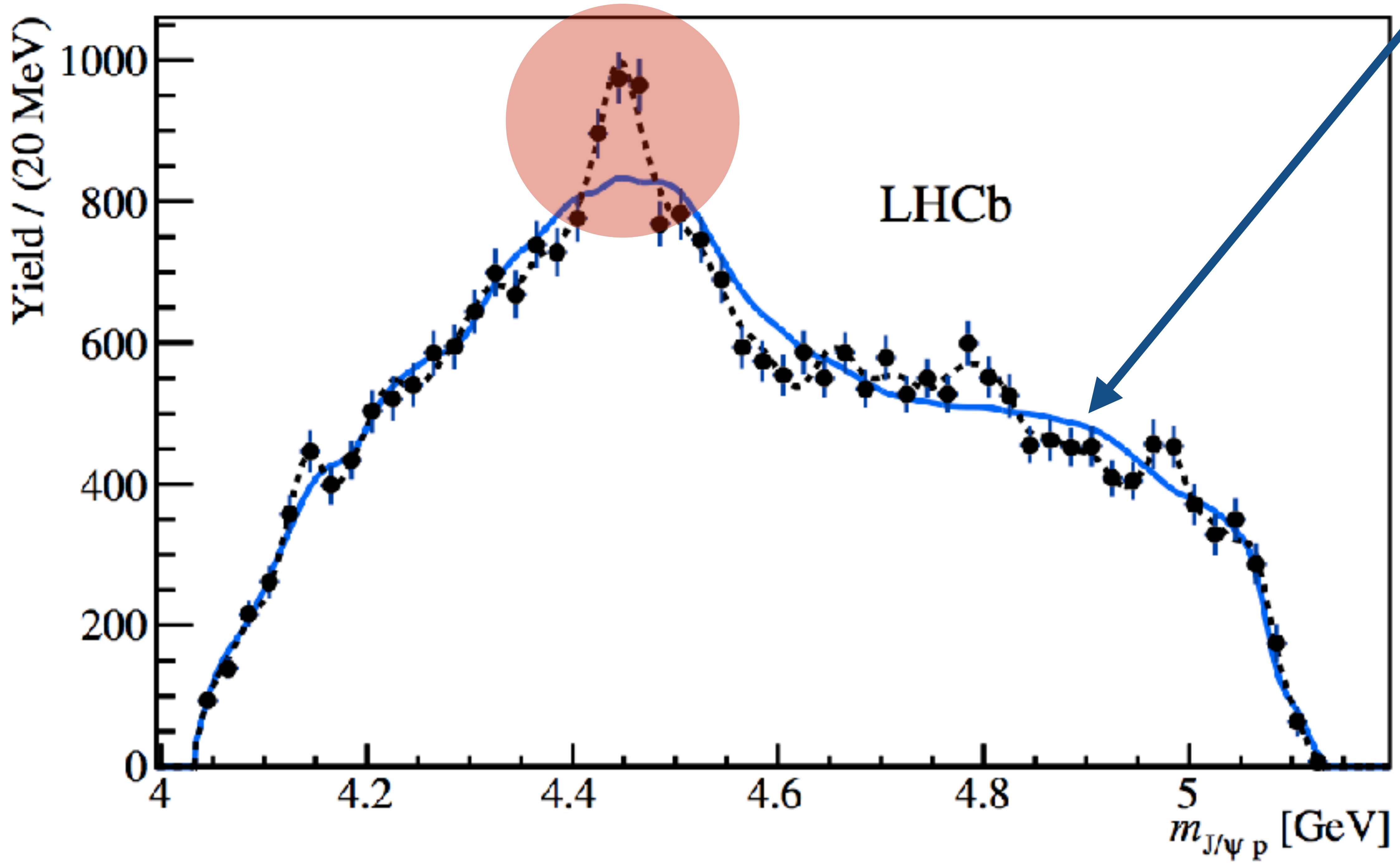
Pentaquark model-independent

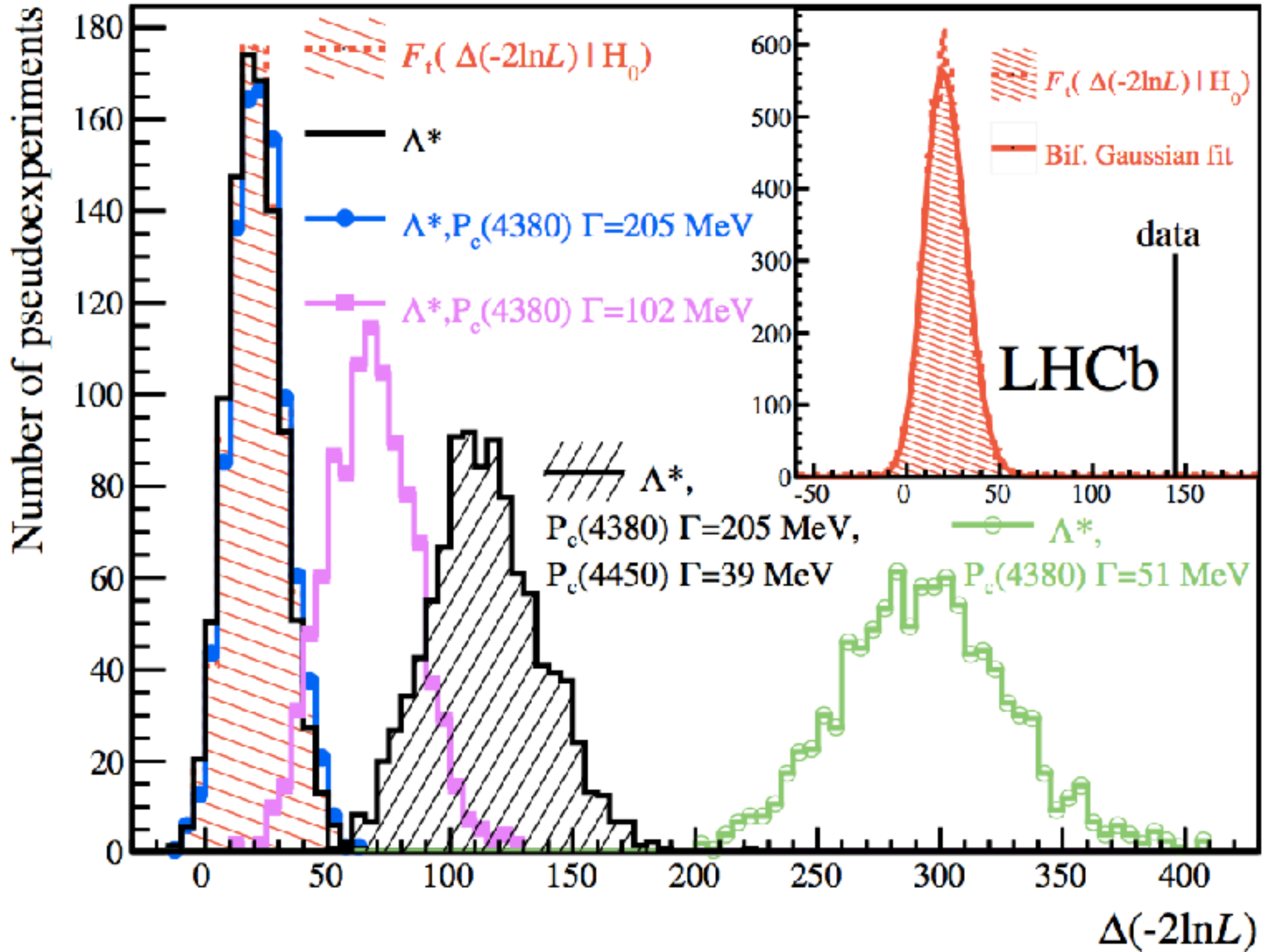
Simulate phase-space decays of $\Lambda_b^0 \to J/\psi p K^-$ [PRL 117 (2016) 082002]

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**





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

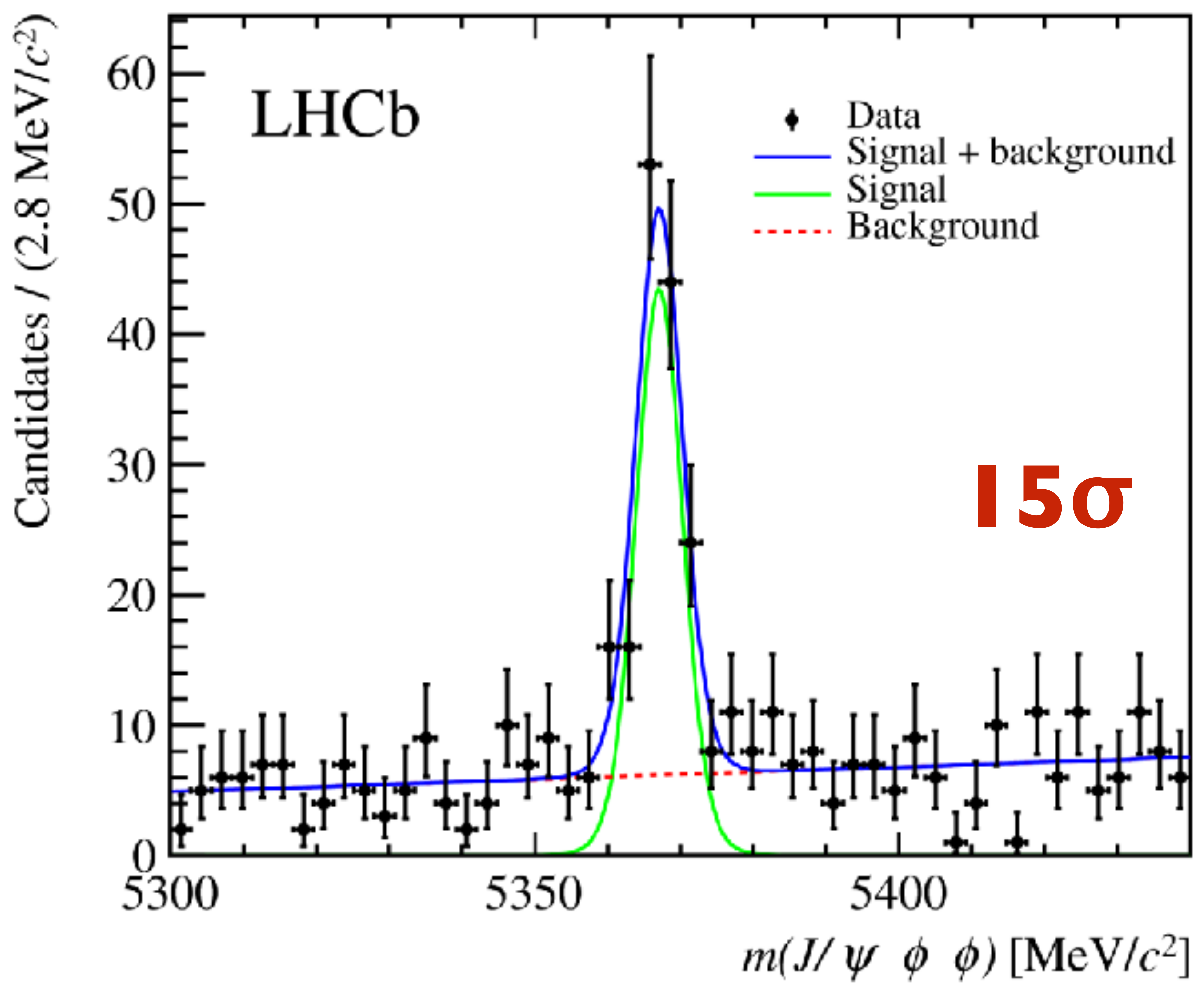
Contamination from non-res decays

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

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

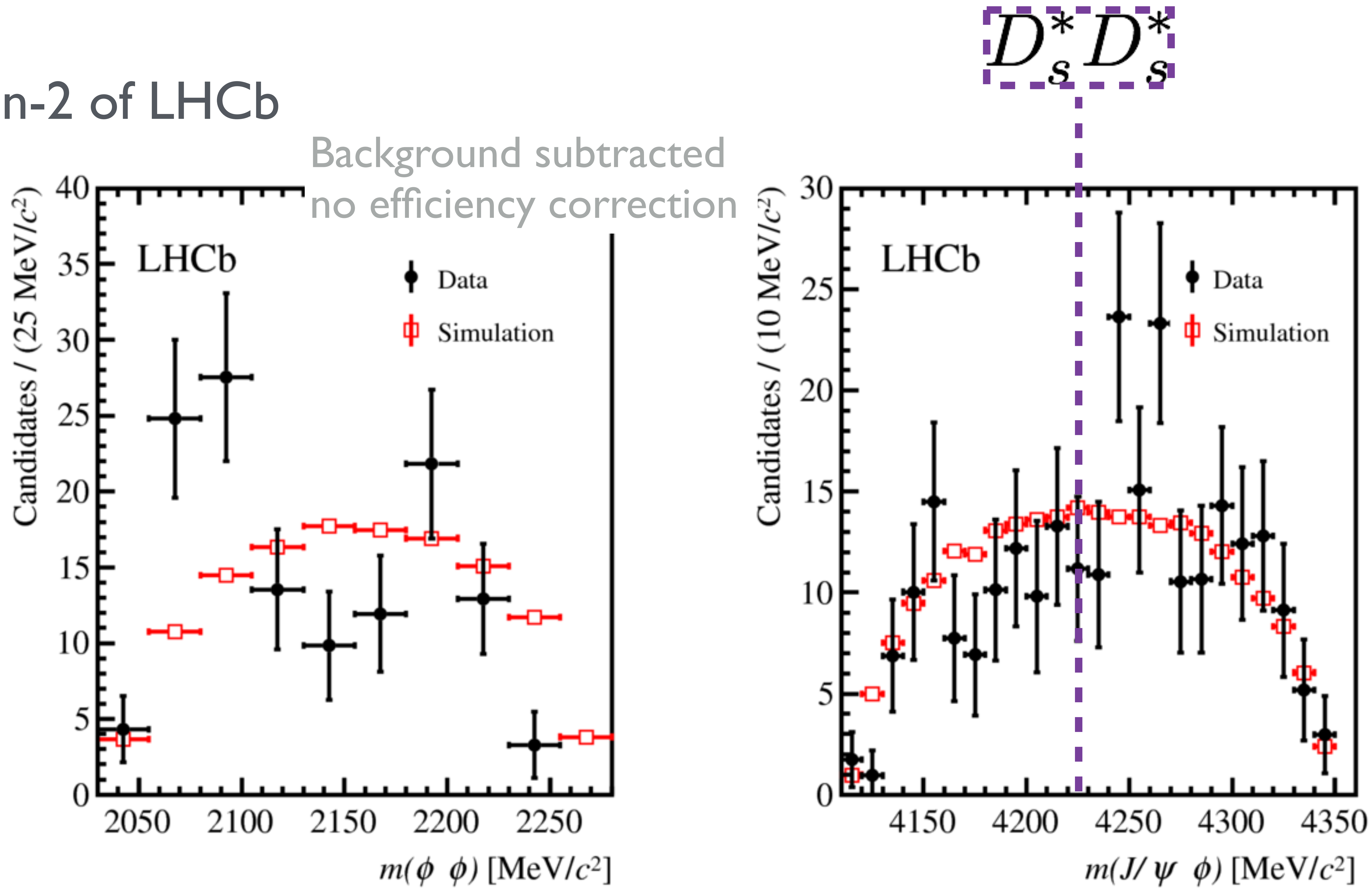
Simplified phase-space simulation inadequate to describe structure

Looking forward to more data in Run-2 of LHCb



[JHEP 1603 (2016) 040]

Background subtracted
no efficiency correction



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

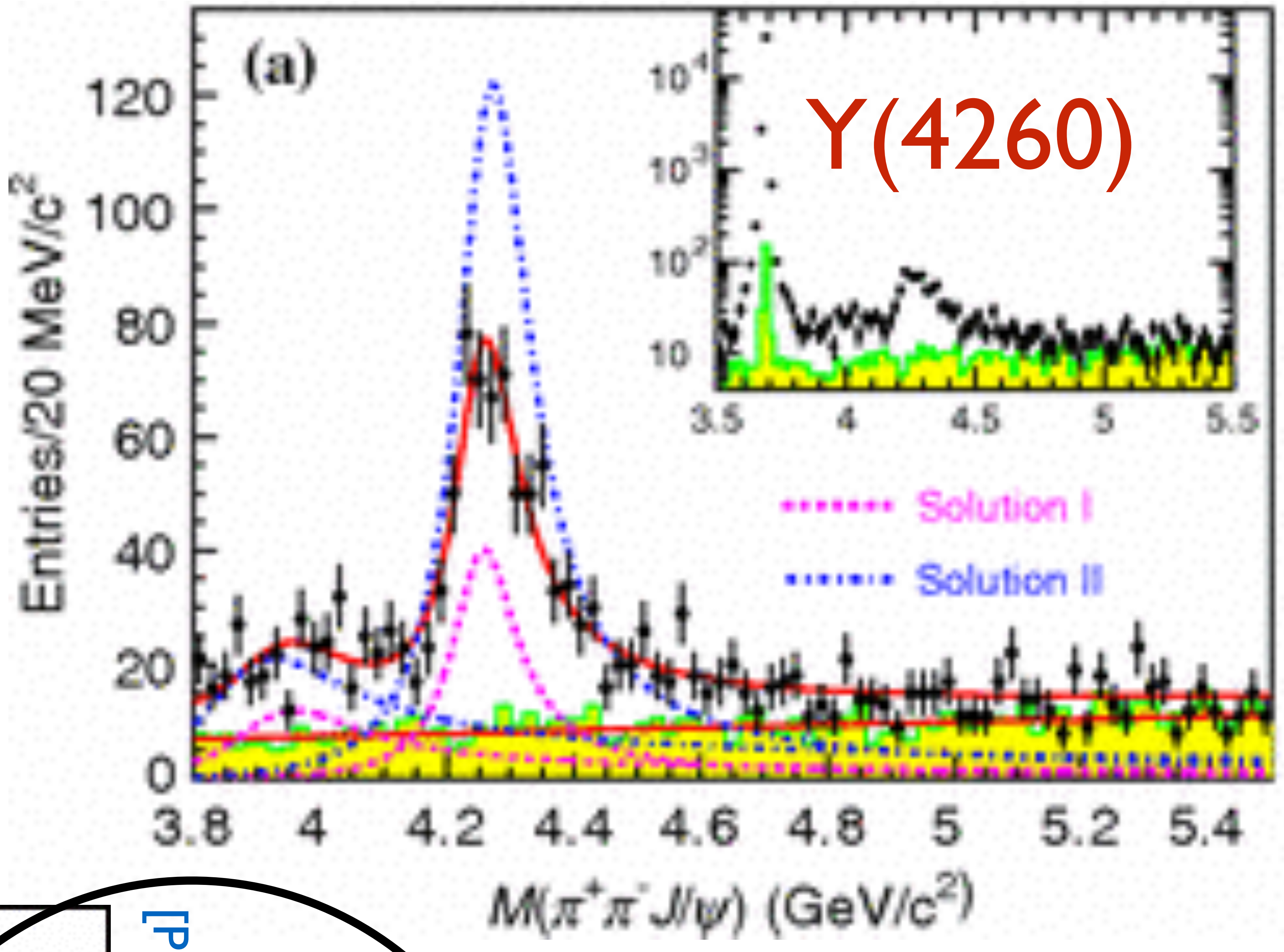
Observation of another possible **exotic charged state.**

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 $\pi^0 J/\psi$.

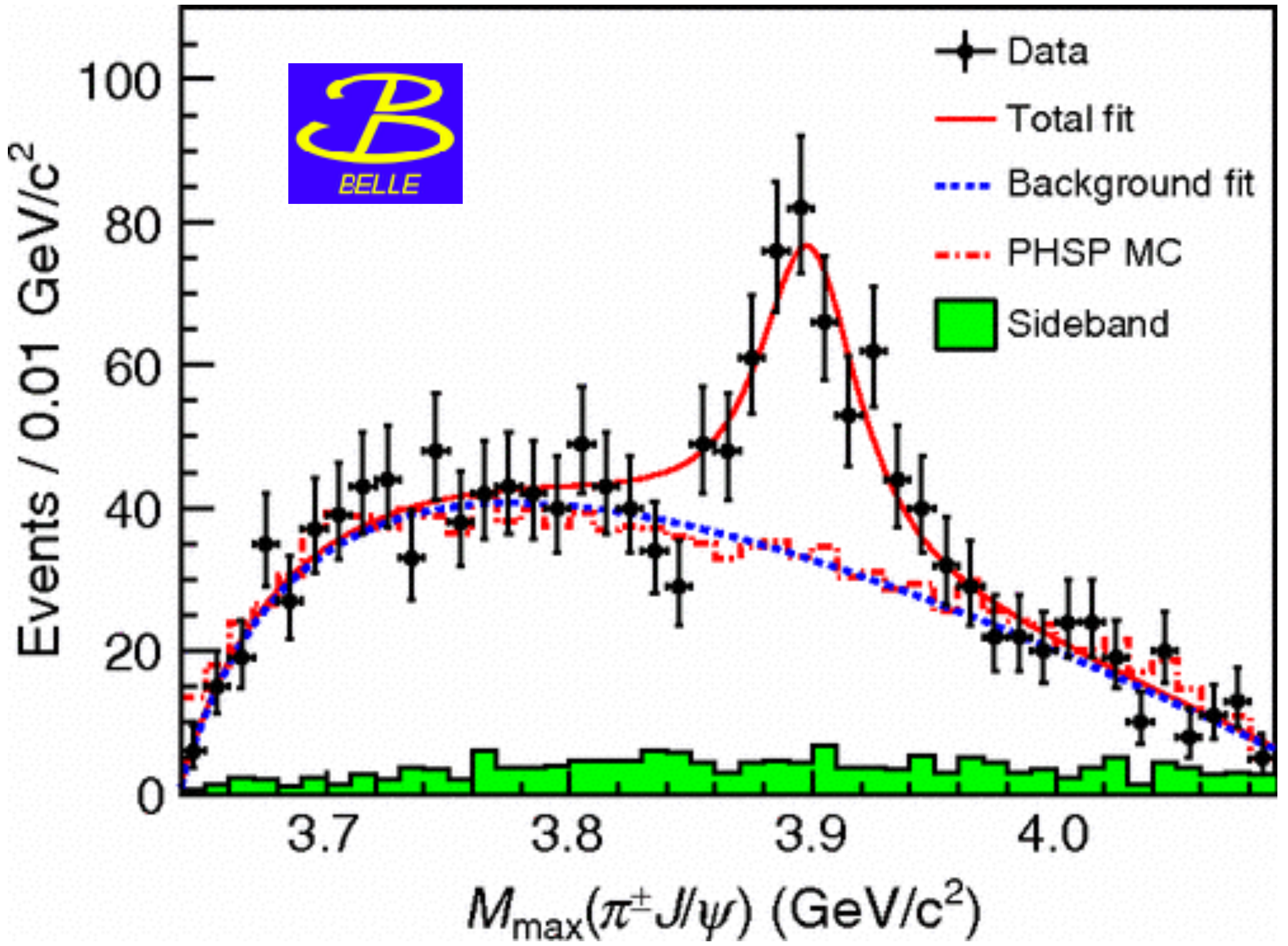
[PLB 727 (2013) 366] [PRL 115 (2015) 112003]

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

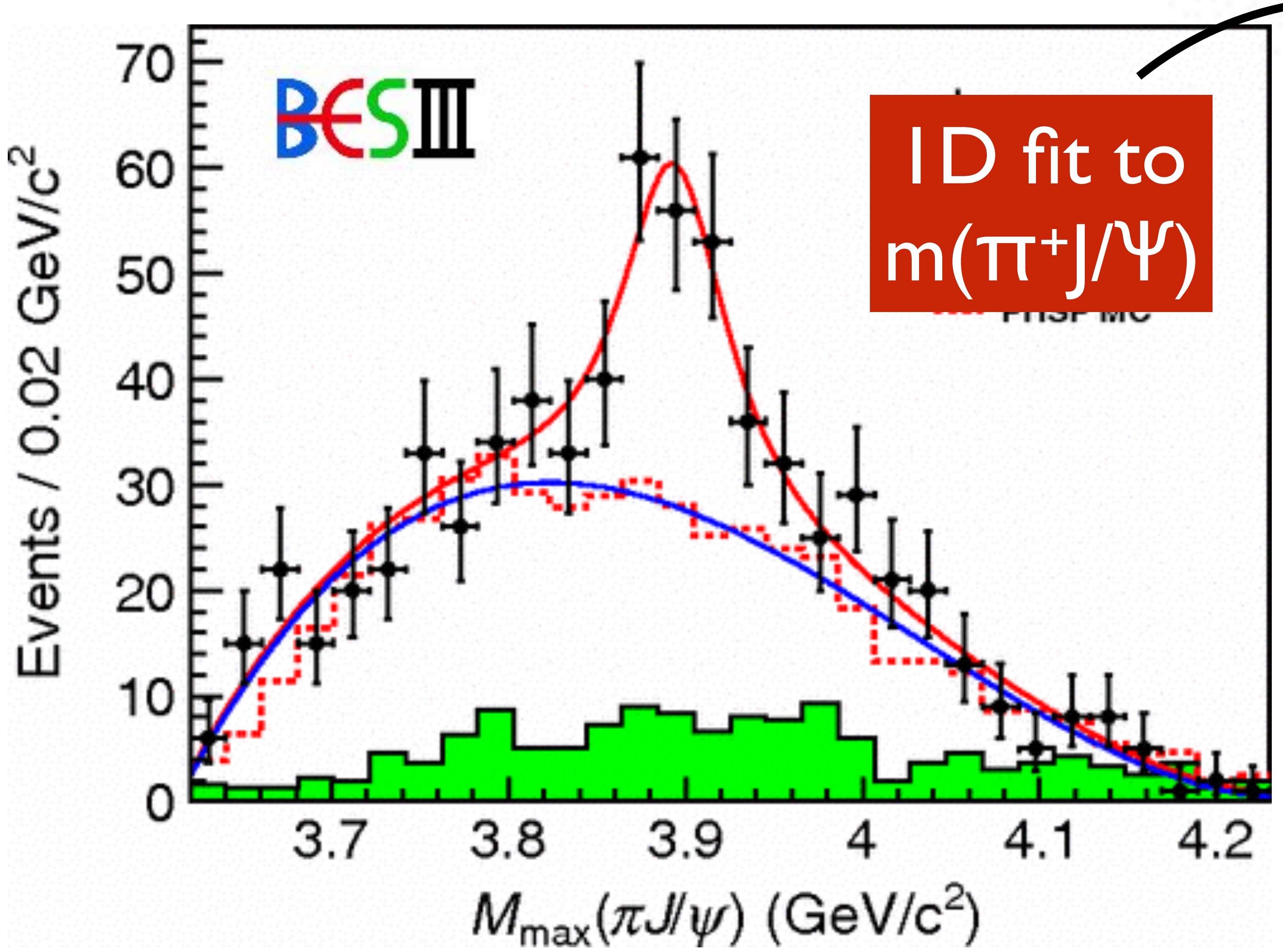


[PRL 110 () 252002]

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



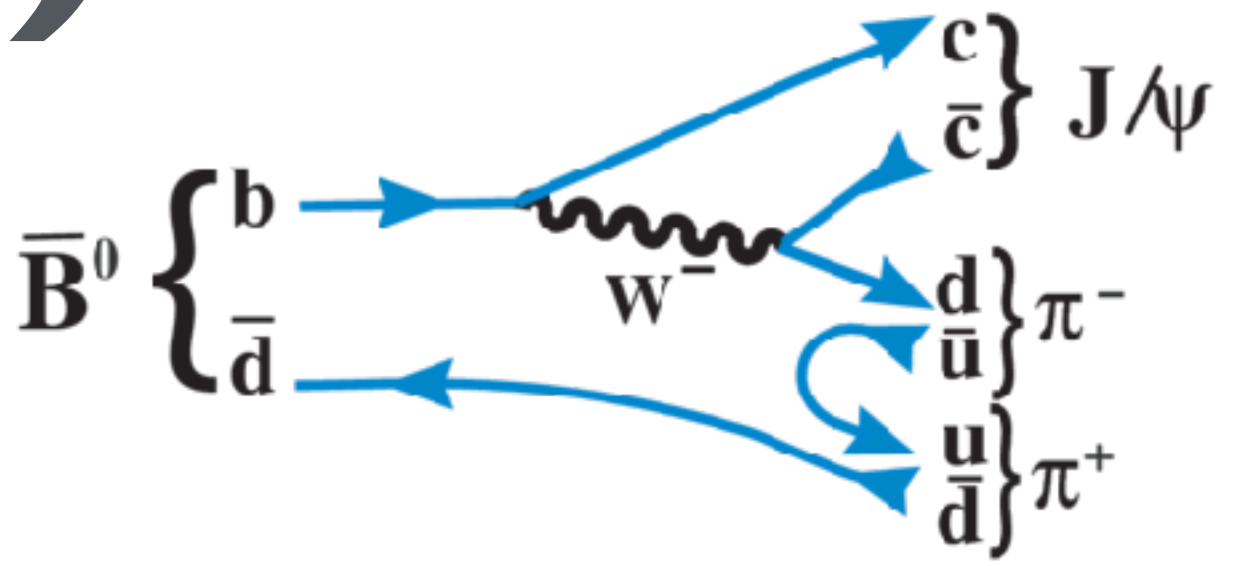
[PRL 110 (2013) 252001]



[PRL 110 (2013) 252002]

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

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

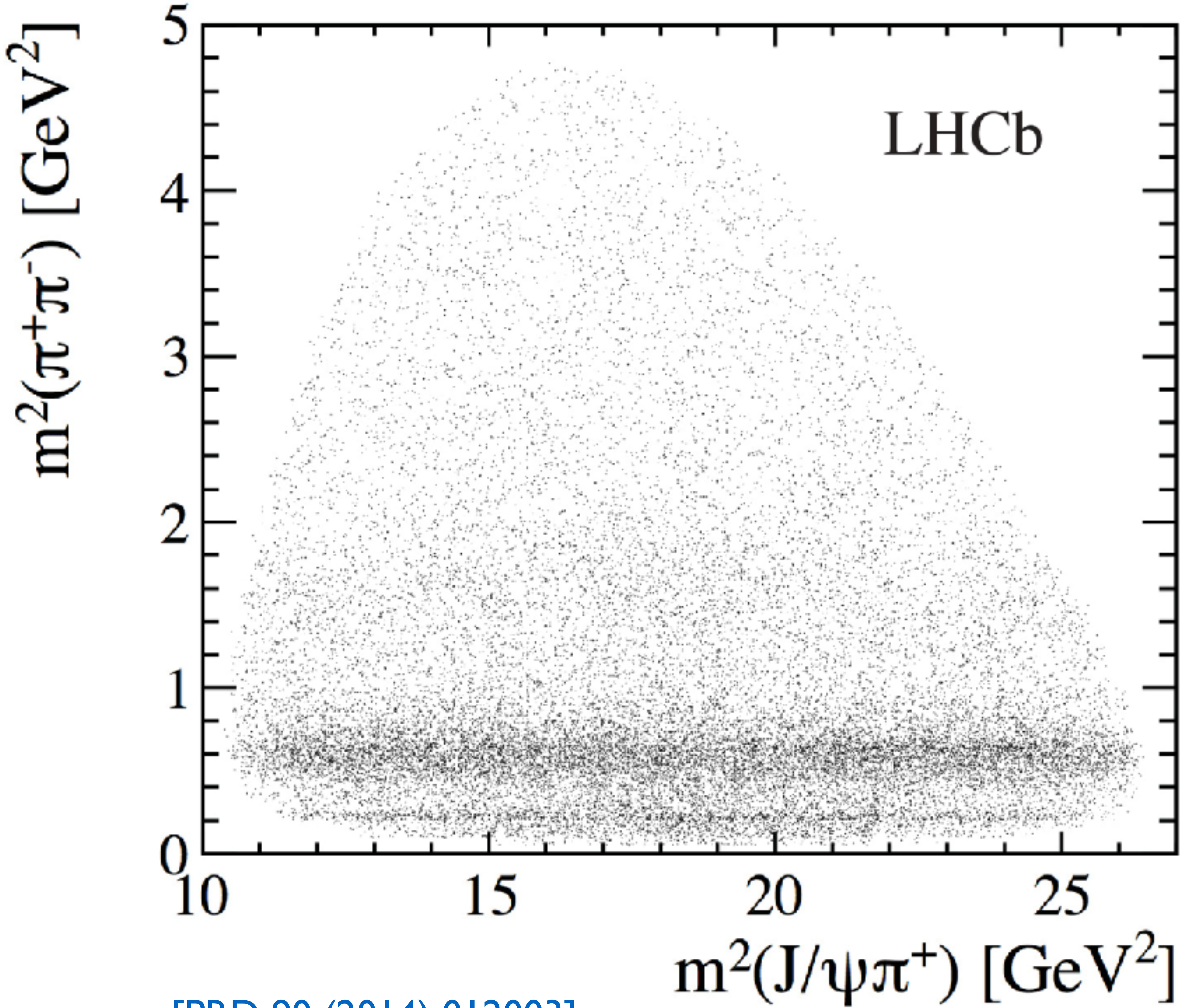


Some lattice QCD calculations do not support existence of $Z_c(3900)^{\pm}$ [Prelovsek et al PRD 91 (2015) 014504]

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]

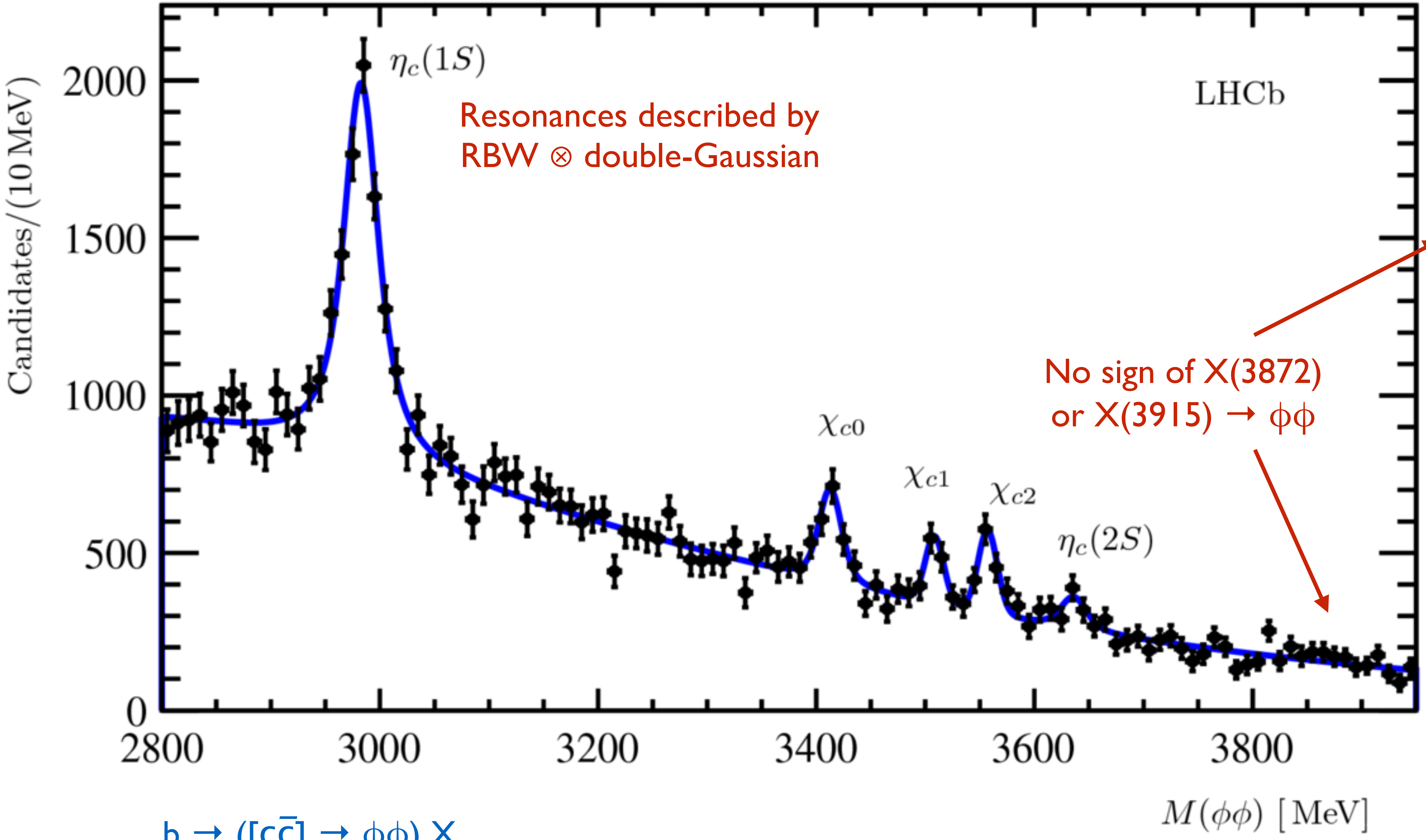
Or maybe not? [Cleven et al arXiv:1510.00854]



[PRD 90 (2014) 012003]

Charmonium production in b-hadron decays

[arXiv:1706.07013]



Resonances described by RBW ⊗ double-Gaussian

No sign of X(3872) or X(3915) → ϕϕ

$R^{X(3872)}_{\chi_{c1}} < 0.39\ (0.34)$

$R^{X(3915)}_{\chi_{c0}} < 0.14\ (0.12)$

$R^{\chi_{c2}(2P)}_{\chi_{c2}} < 0.20\ (0.16)$

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

b → ([$c\bar{c}$] → ϕϕ) X

by requiring separation between primary and secondary vertices

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]

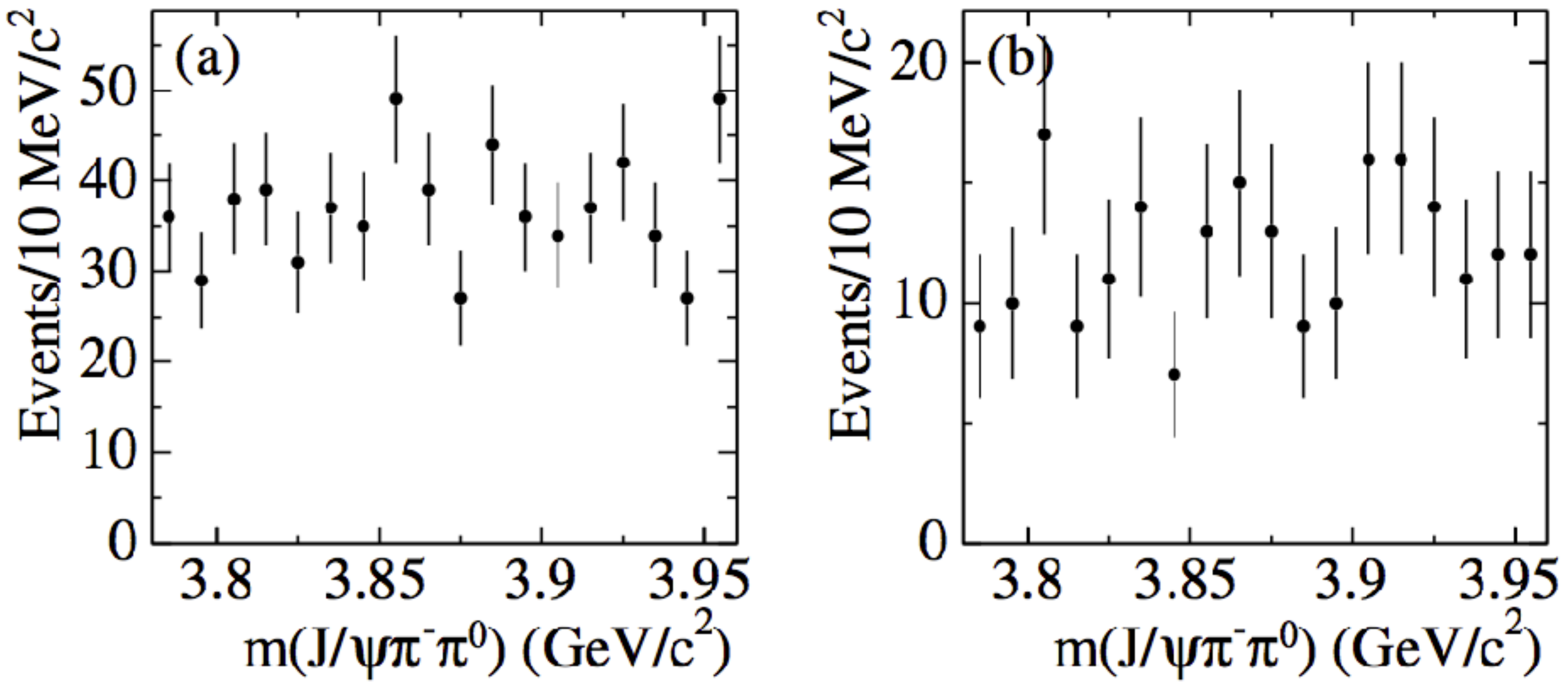


FIG. 3. The $J/\psi\pi^-\pi^0$ invariant mass in 10 MeV/c^2 bins for (a) $B^0 \to J/\psi\pi^-\pi^0K^+$ and (b) for $B^- \to J/\psi\pi^-\pi^0K^0_S$. No indication for the decay $X^- \to J/\psi\pi^-\pi^0$ can be found.

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

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

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?

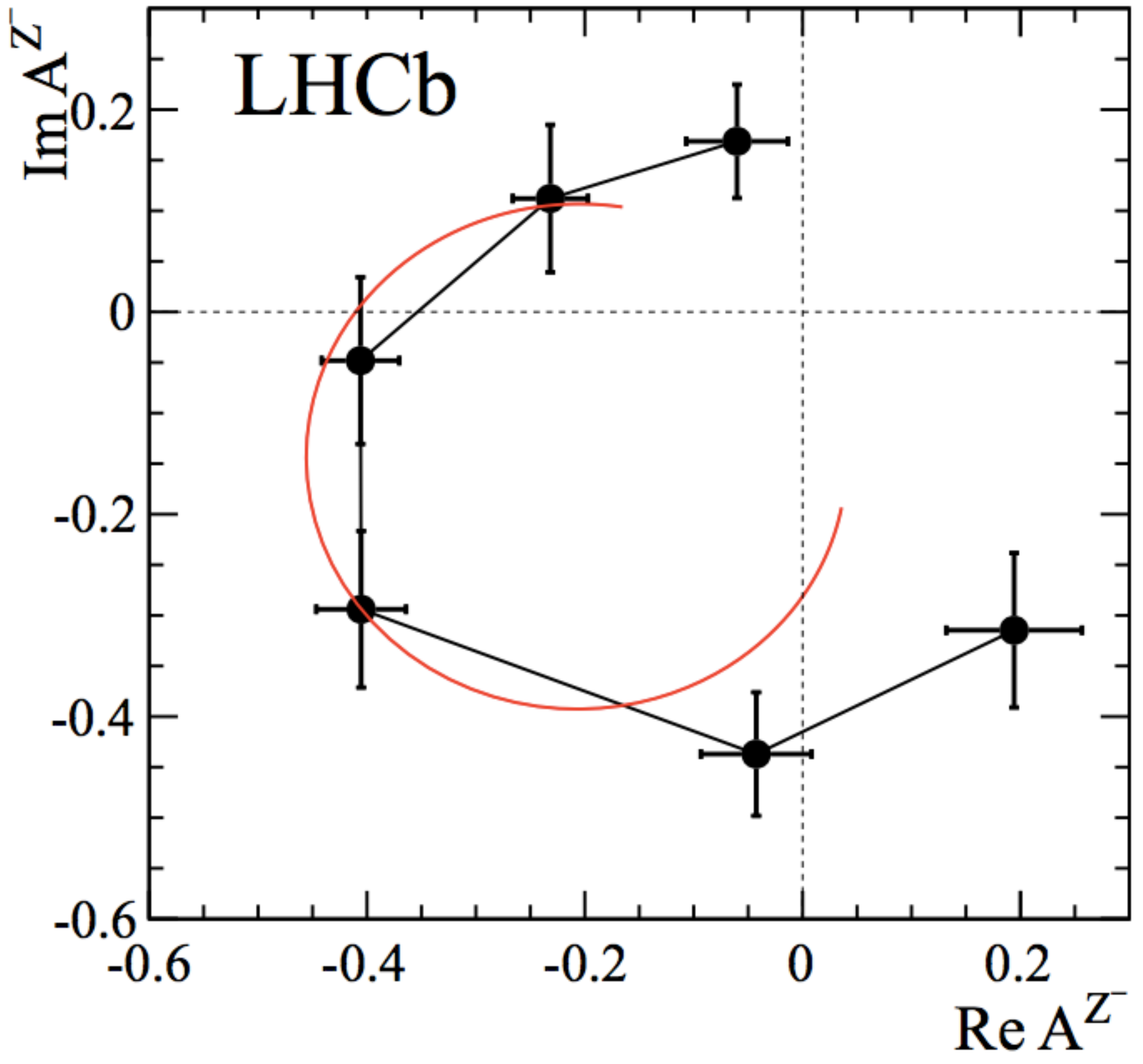
P=+ rules out interpretation in terms of **$\bar{D}$*(2010)D*$_1$(2420)** molecule or threshold effect (cusp).
[Rosner, PRD 76 (2007) 114002] [Bugg, J. Phys. G35 (2008) 075005]

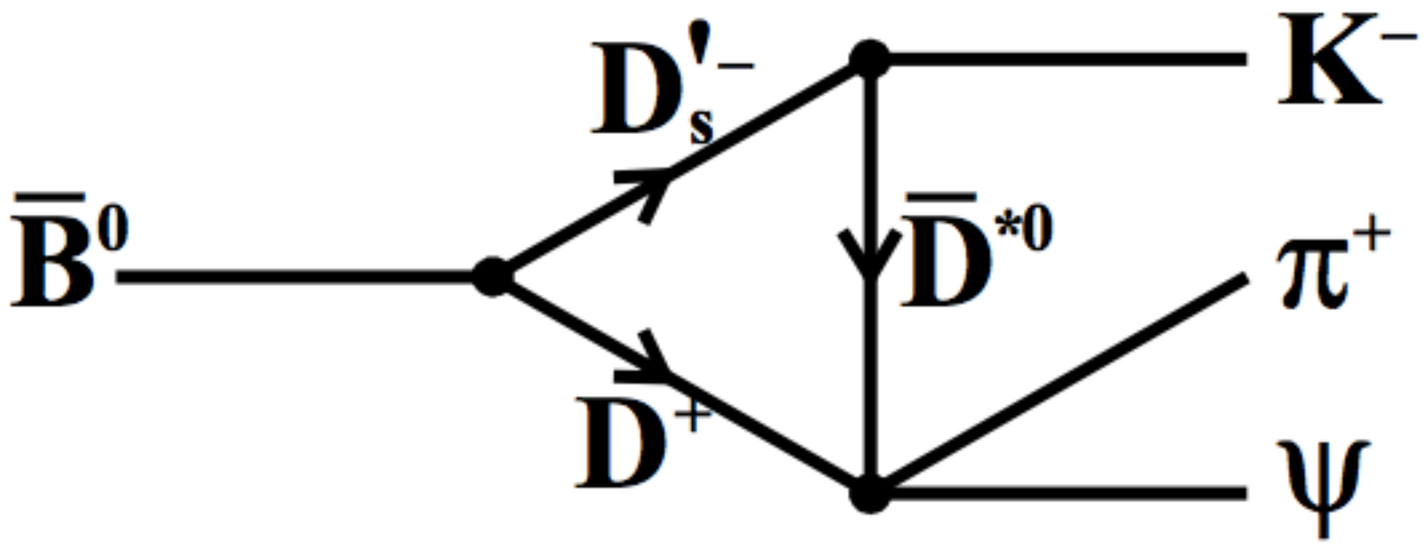
Rescattering effect proposed, but phase motion in wrong direction?
[Pakhov, Uglov PLB748 (2015) 183]

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

Potential neutral **isospin partner?**

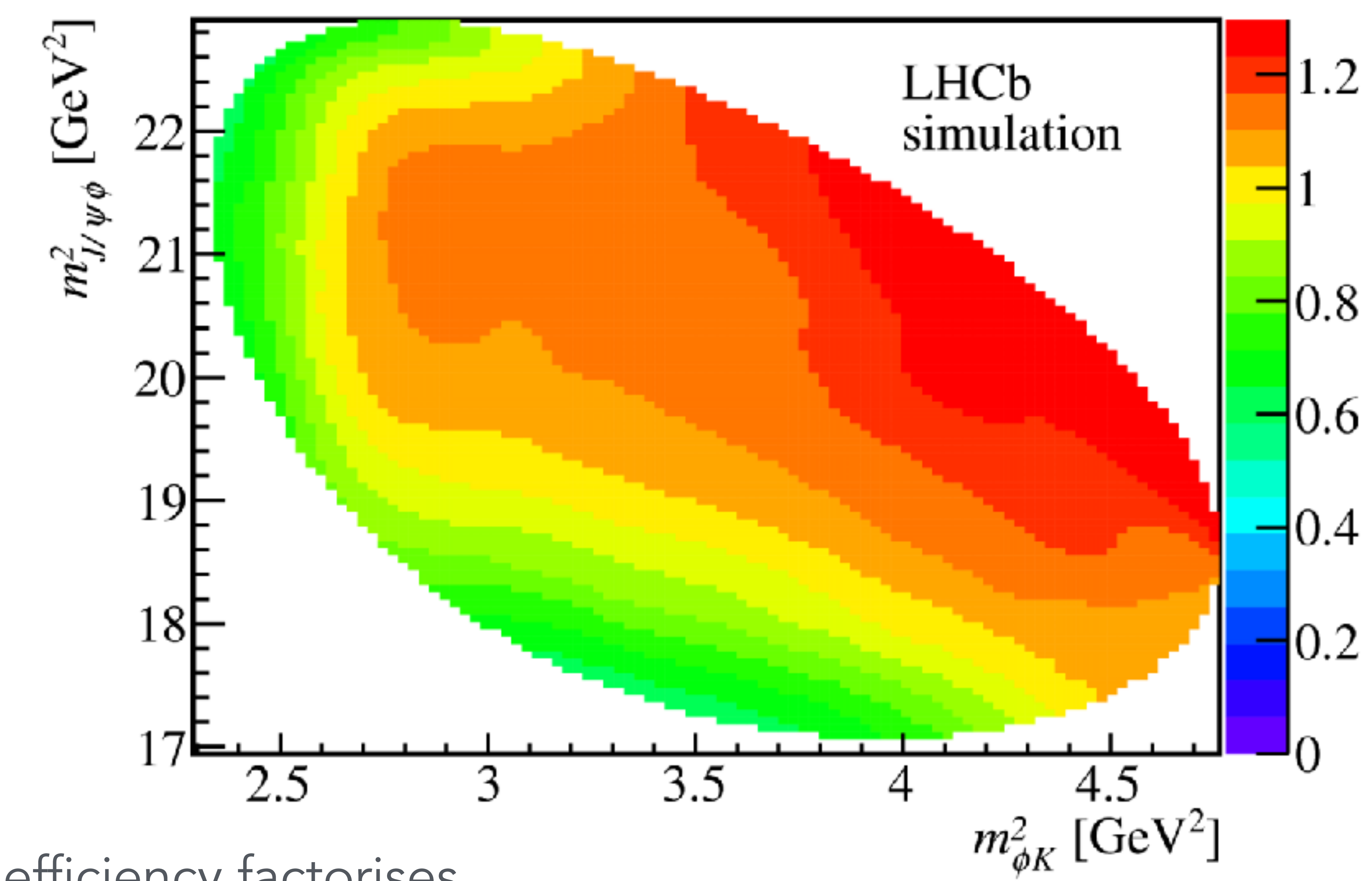
Z(4430)^0 in $B^+ \to \psi(2S)\pi^0K^+$

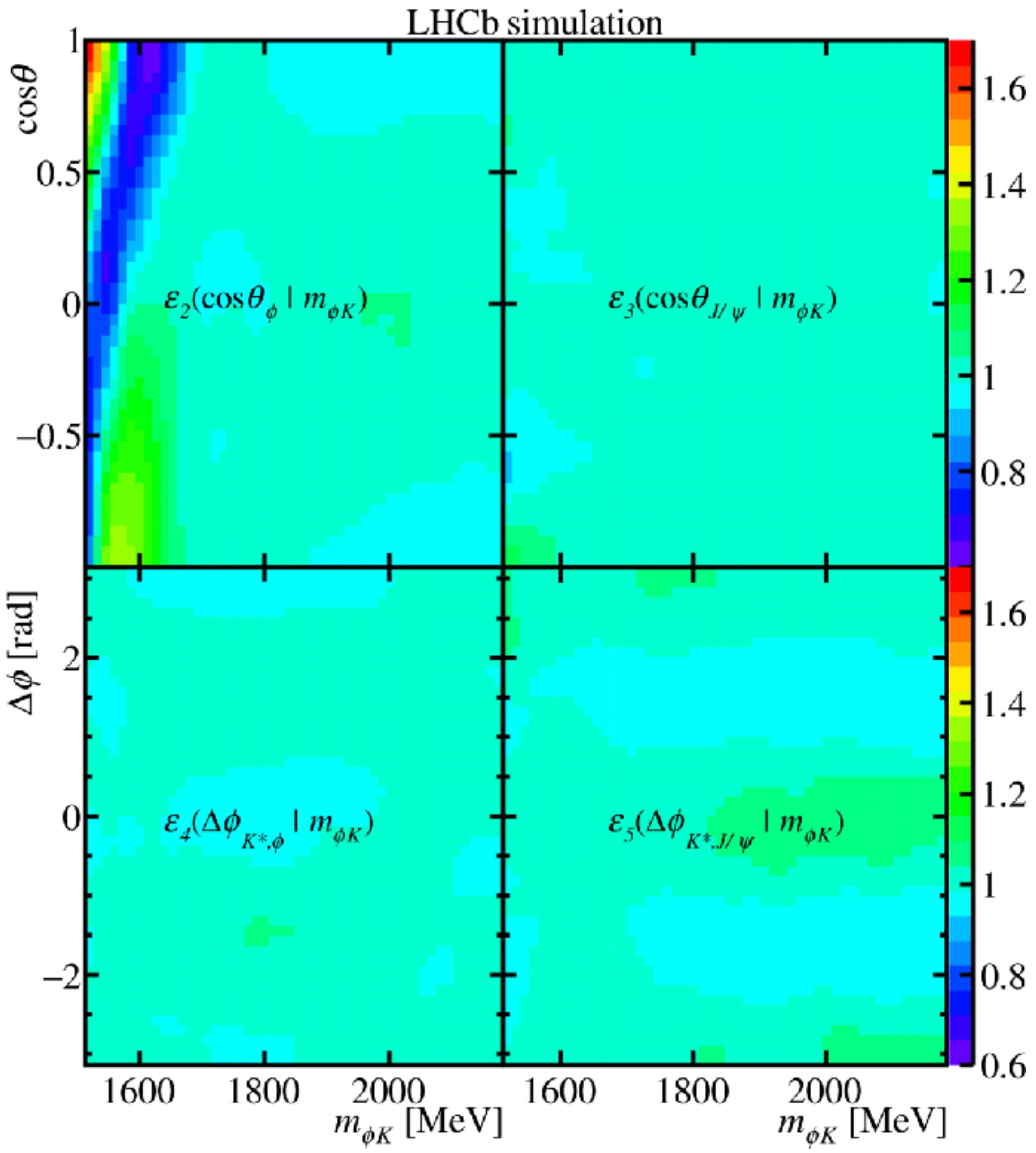




Efficiency

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





Assume efficiency factorises.

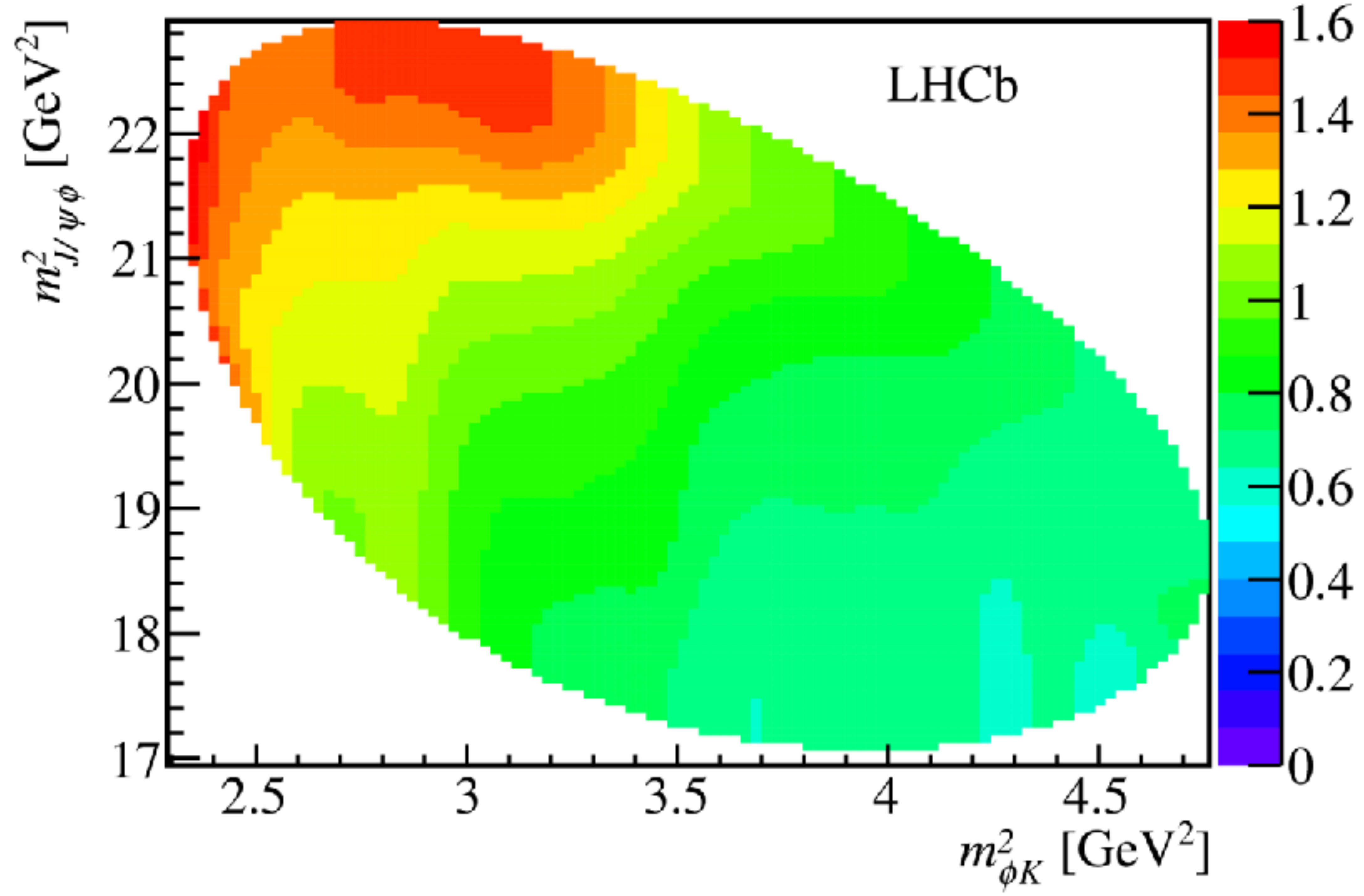
Fully simulated signal decay used to get parameterisation (bi-cubic interpolation between bin centres).

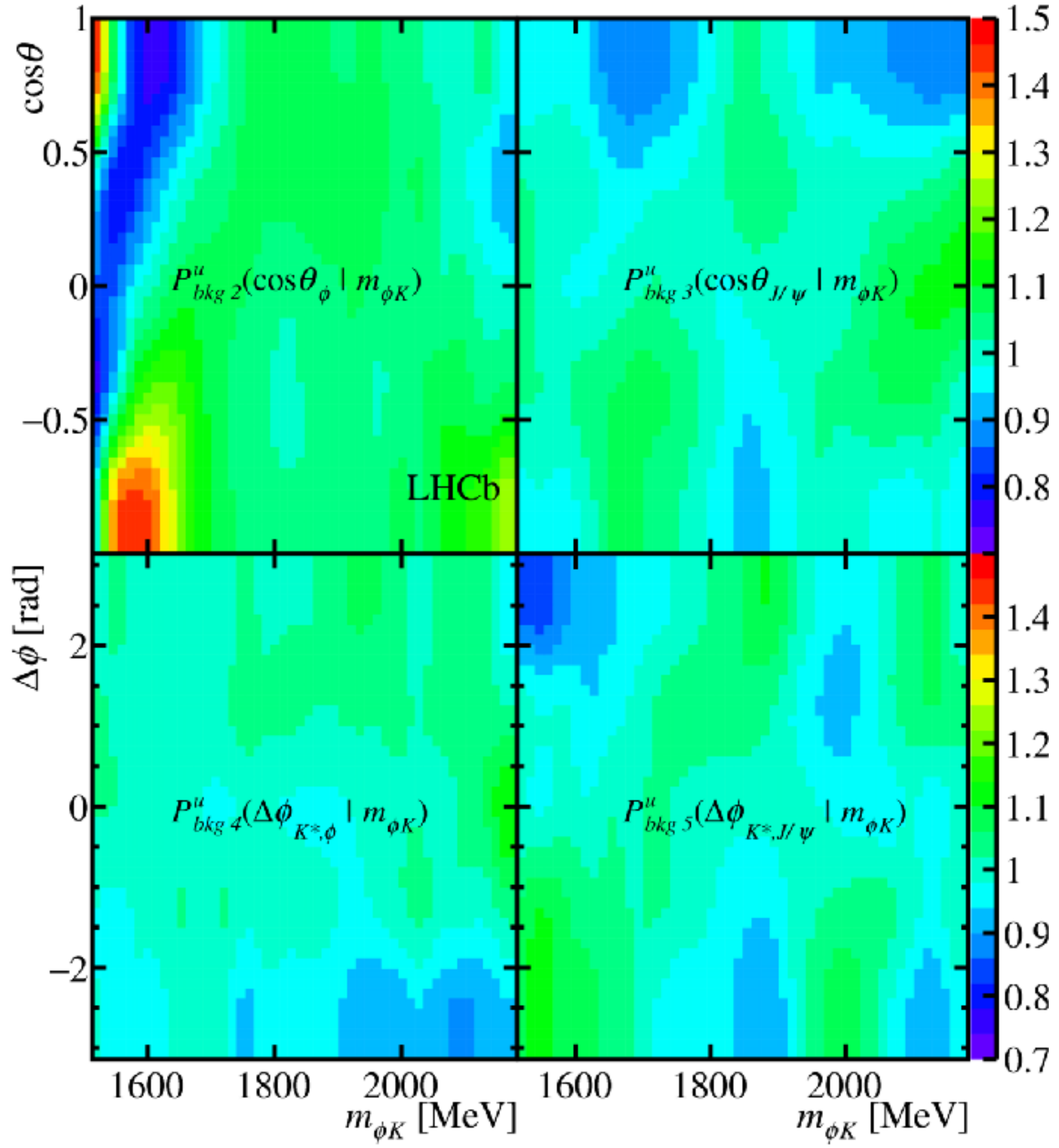
Simulation is weighted to match *p(K)*, *pT(B)* and nTracks distributions in dat

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.

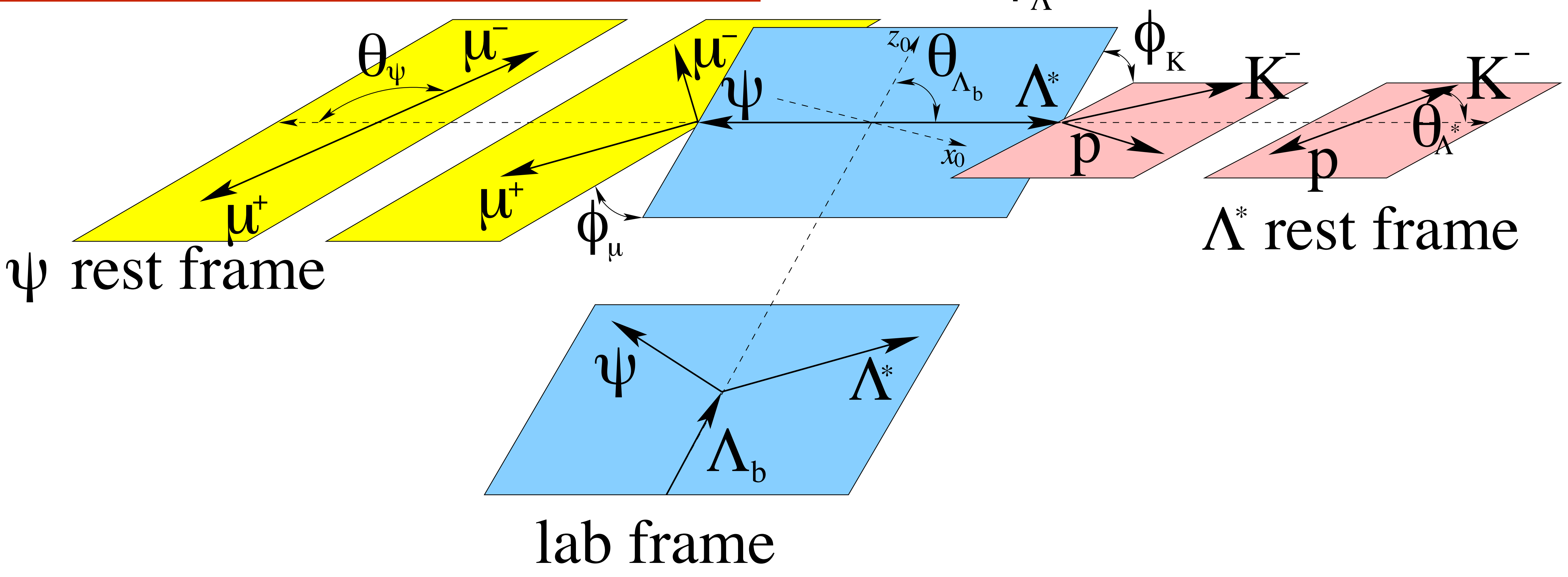
Amplitude model

Two interfering channels.

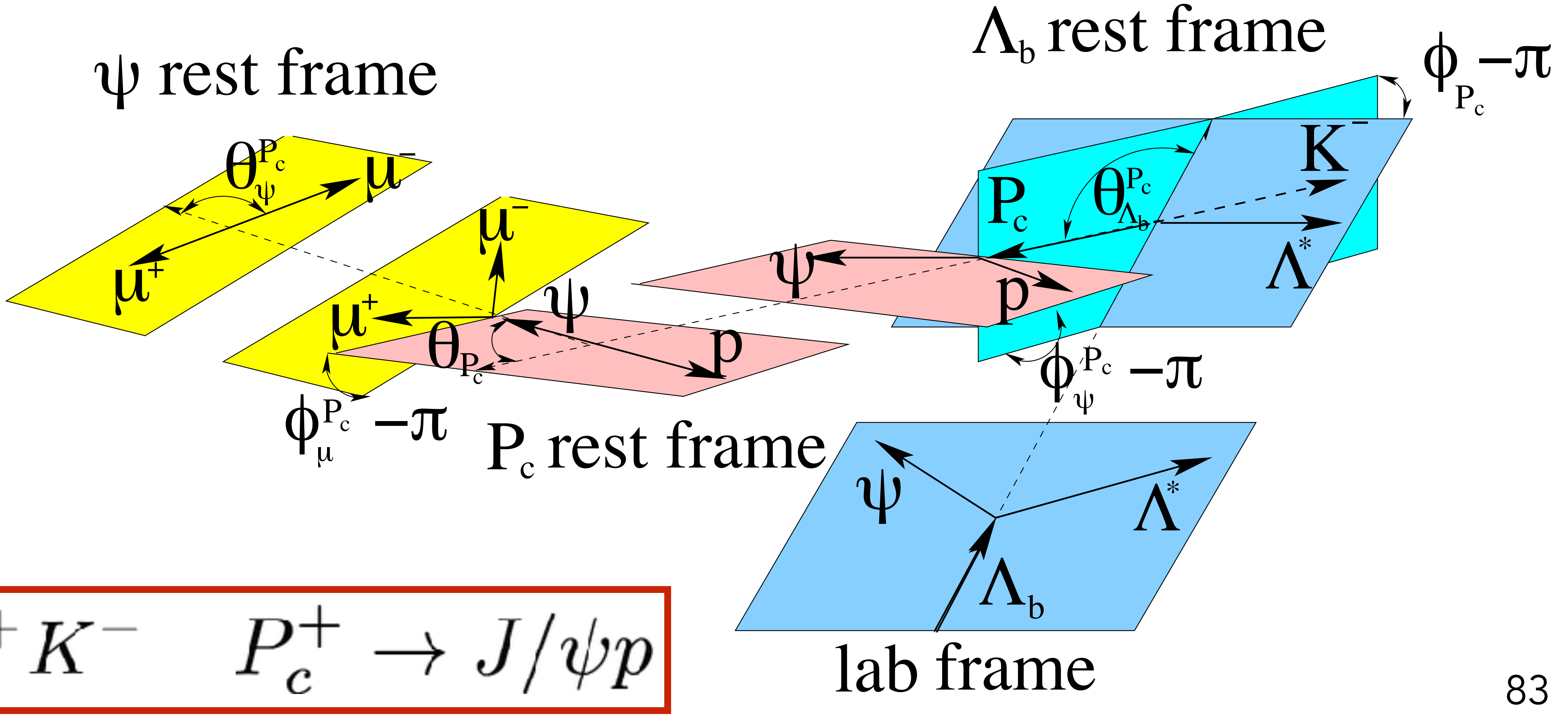
Use 5 angles and m(Kp) as fit observables.

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



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

[PRL 115 (2015) 072001]

$Z_c(3900)^{\pm}$ 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

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

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

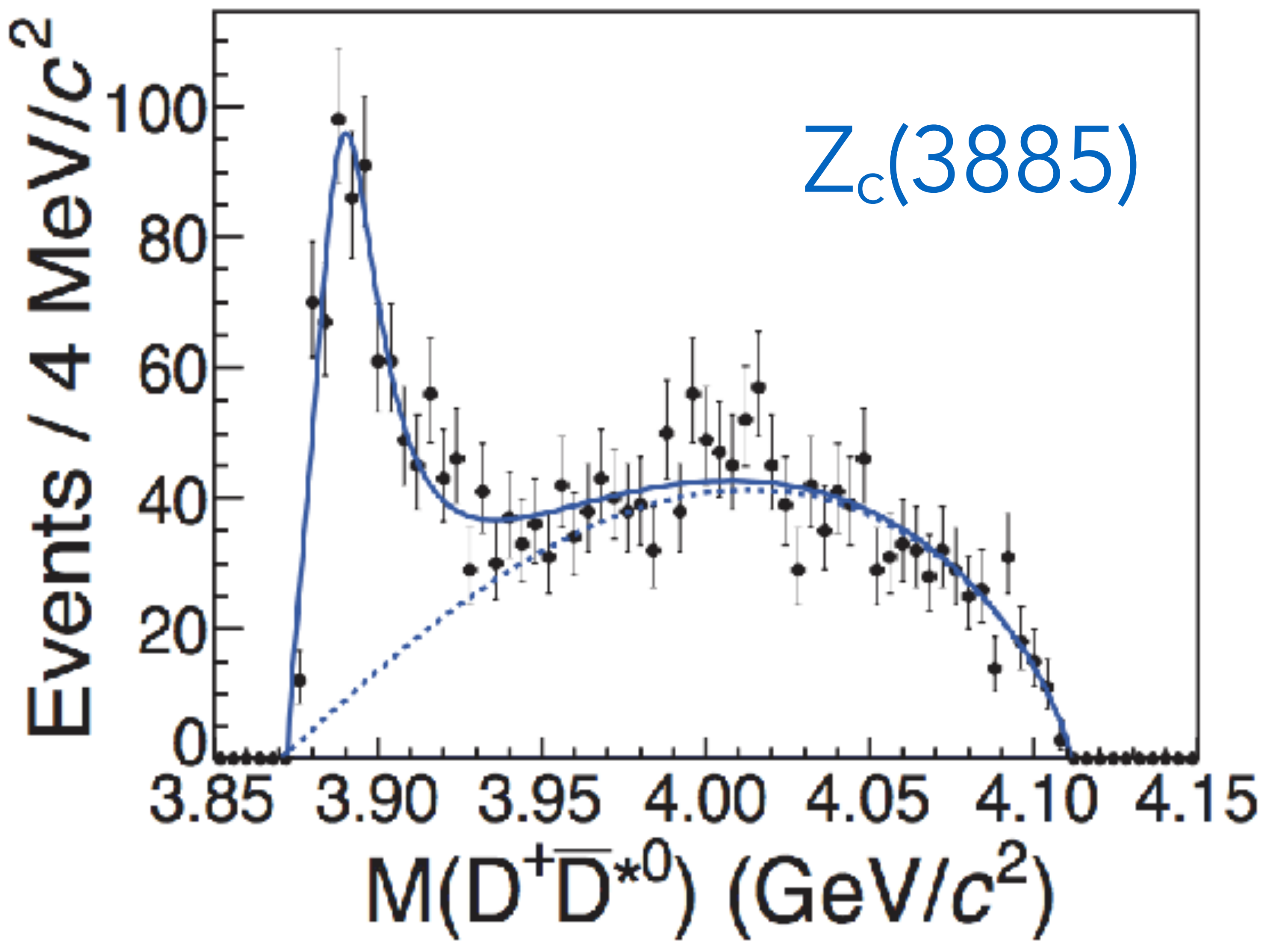
Does $D^{*-}D^0$ analysis use full amplitude fit?

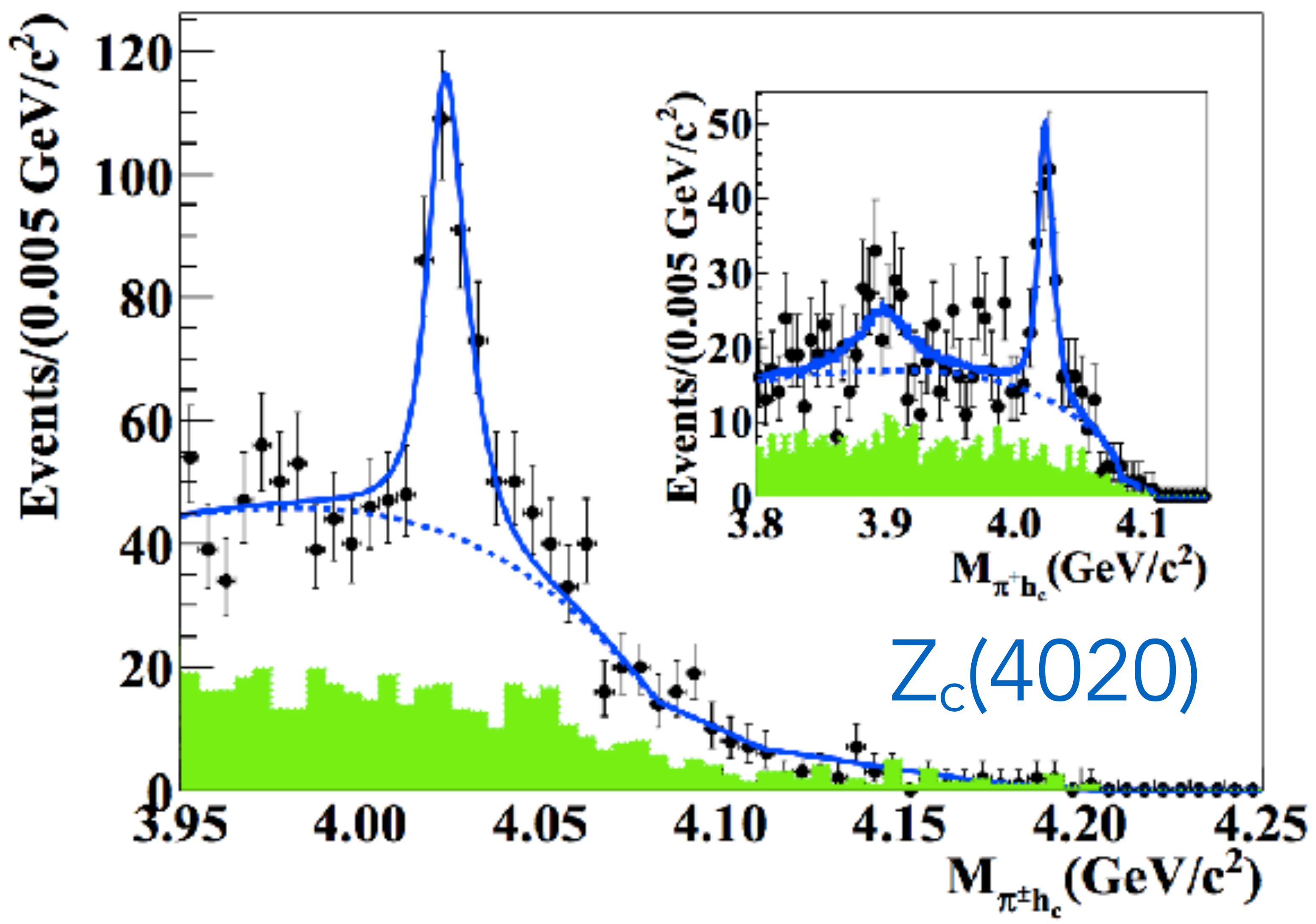
Other exotic states

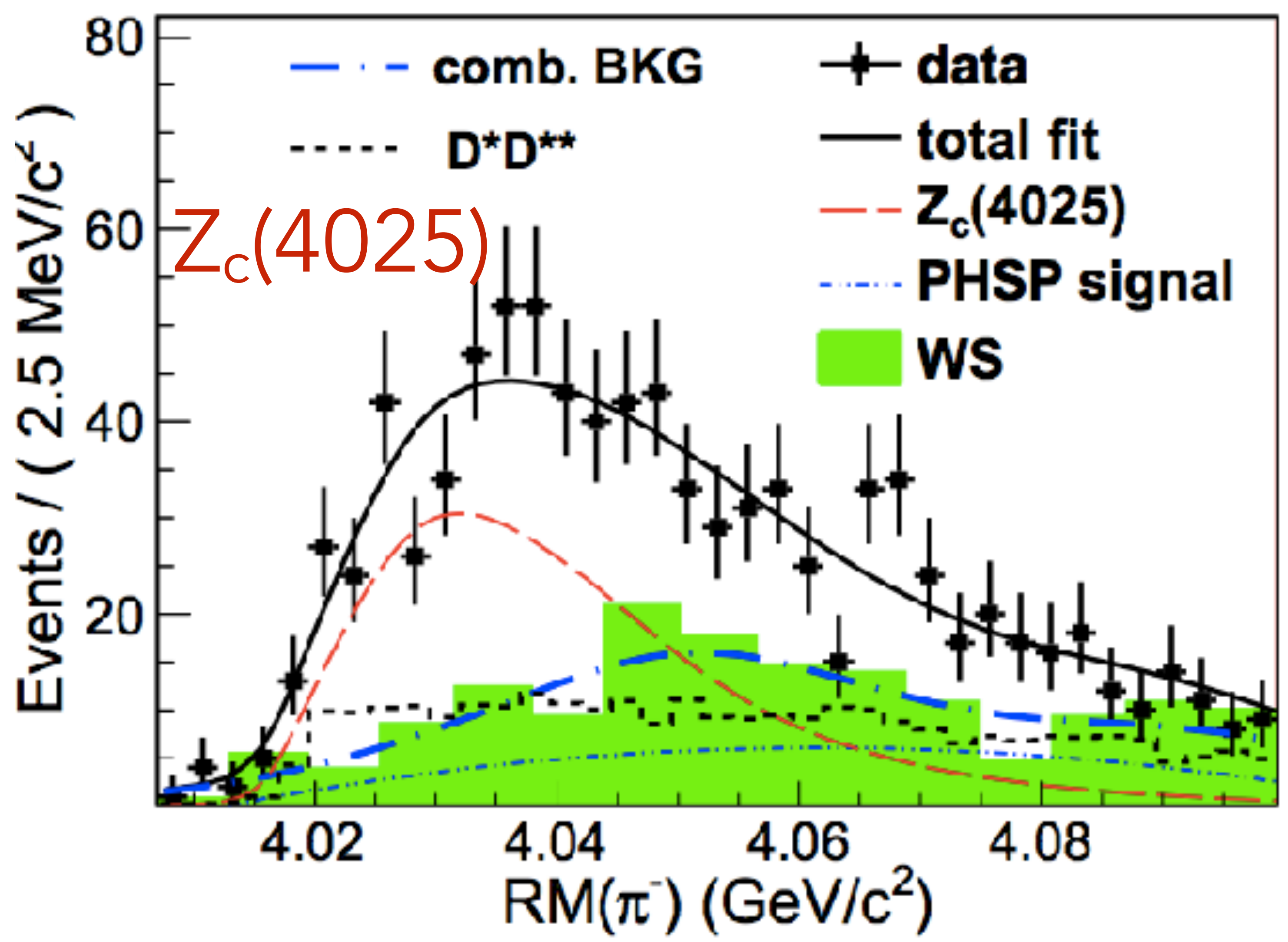
$Z_c(3900)^+$ seen in $J/\psi\pi^+$. Also have $Z_c(3885)^+$ in $(D\bar{D}^*)^+$, showing a dramatic near threshold peak. These could be the same state. Need partial wave analysis of $J/\psi\pi\pi$ final state to determine this.

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

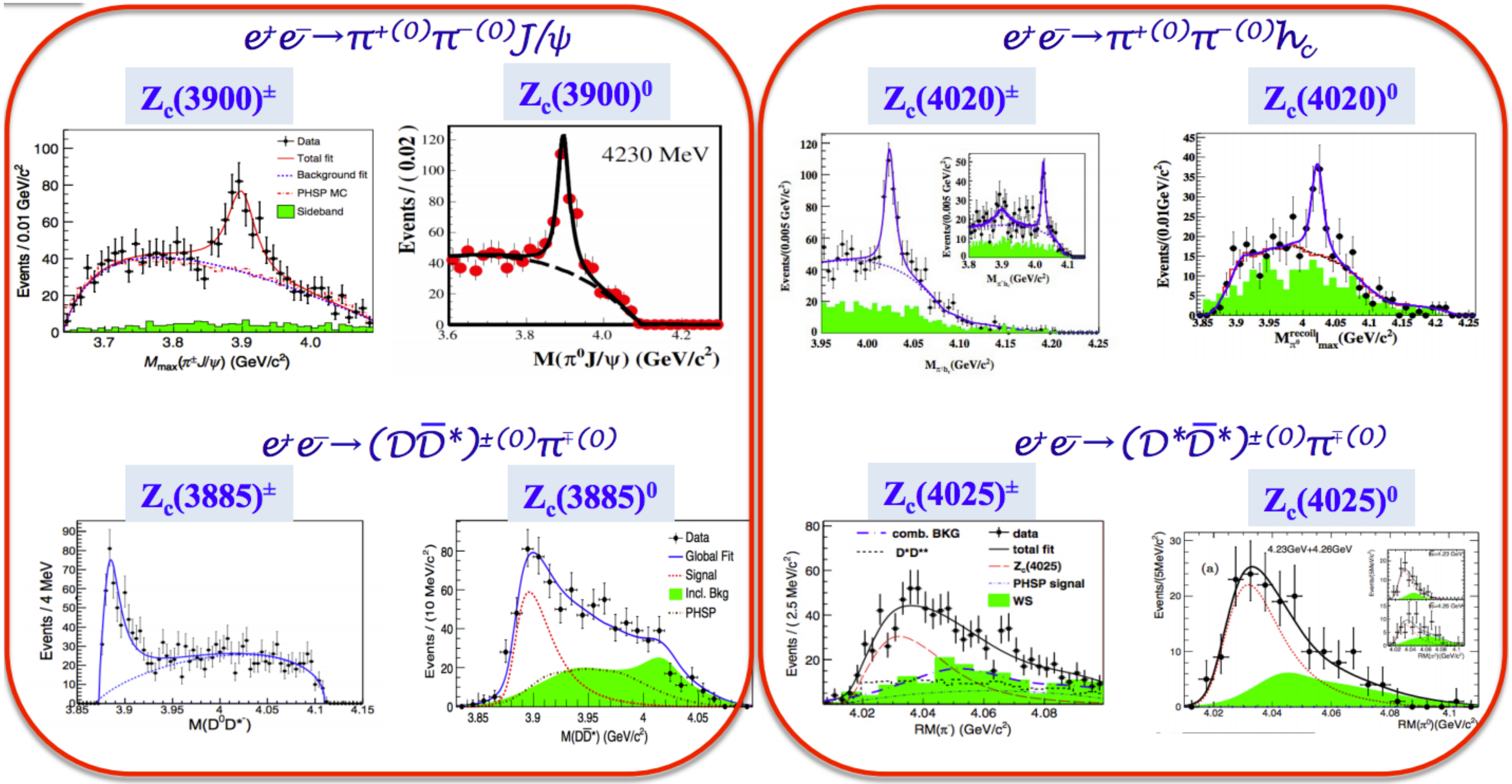
$Z_c(4025)^+$ seen recently by BESIII just above $(D^*\bar{D}^*)^+$ threshold. $m(D^*\bar{D}^*)$ distribution not described by phase space. This could be same state as $Z_c(4020)^+$.







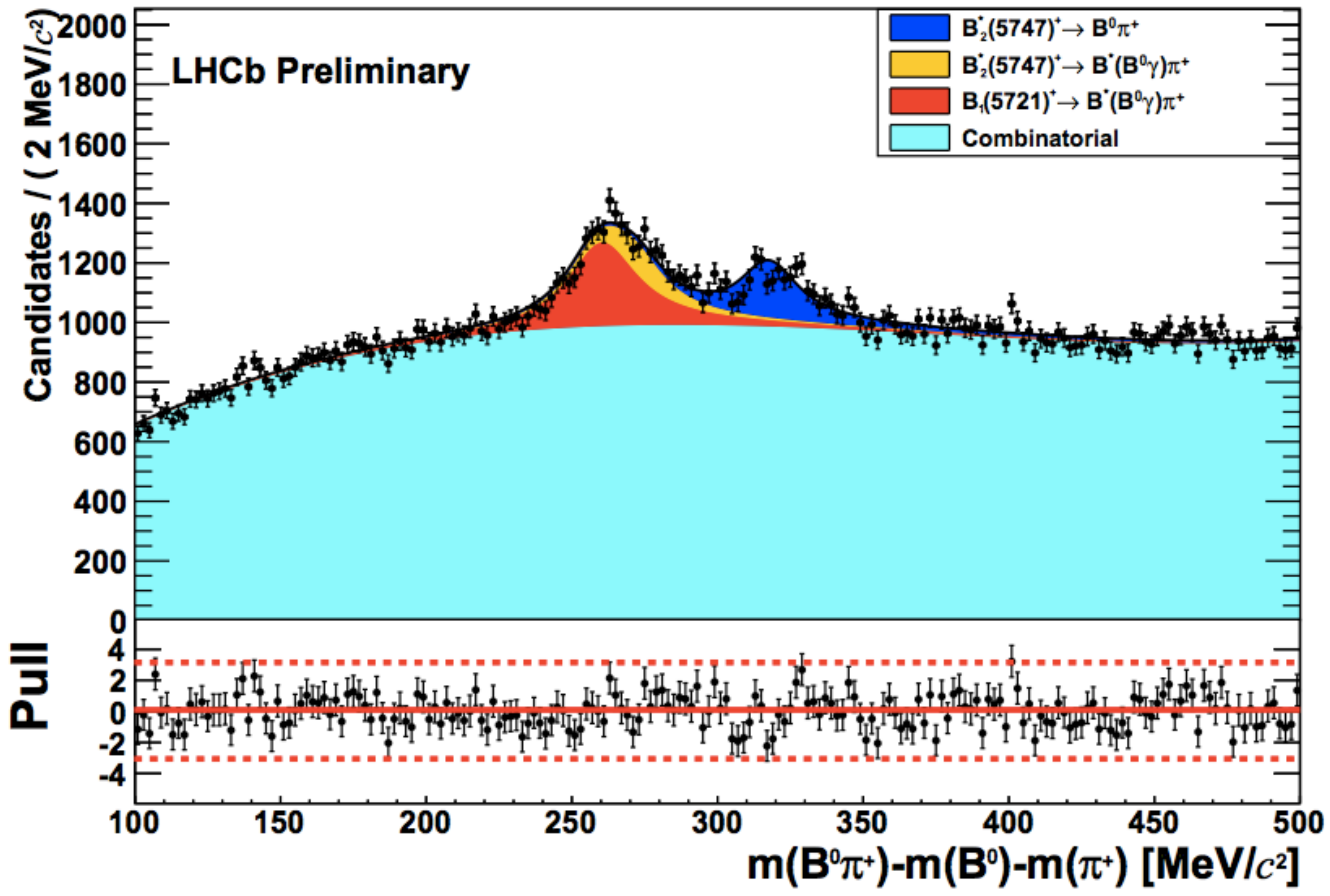
Exotic Z_c states from BES-III



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

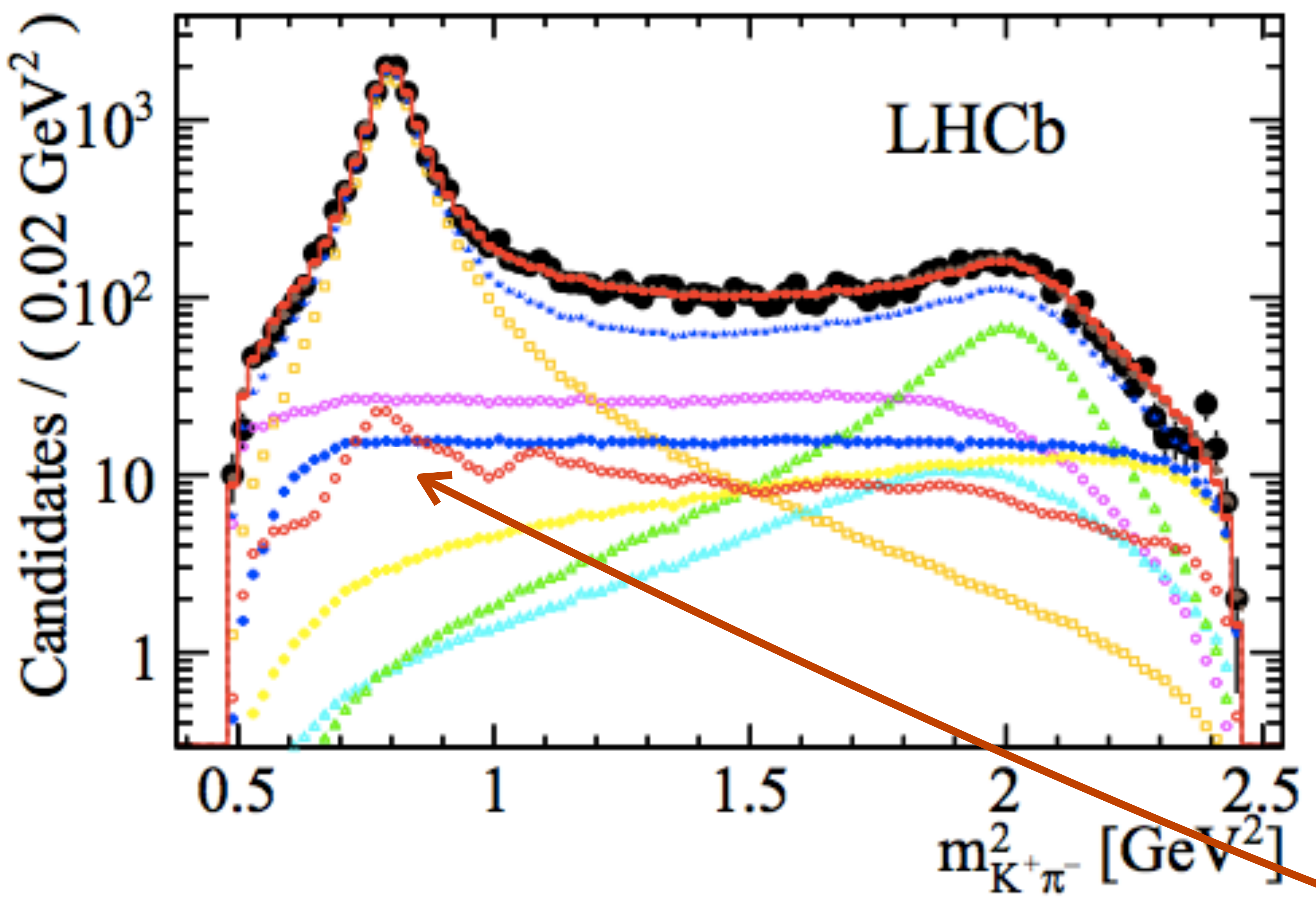
http://moriond.in2p3.fr/QCD/2016/WednesdayAfternoon/Garzia.pdf

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



Well known excited B states found using same analysis techniques

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).

Reconstruction and selection efficiency

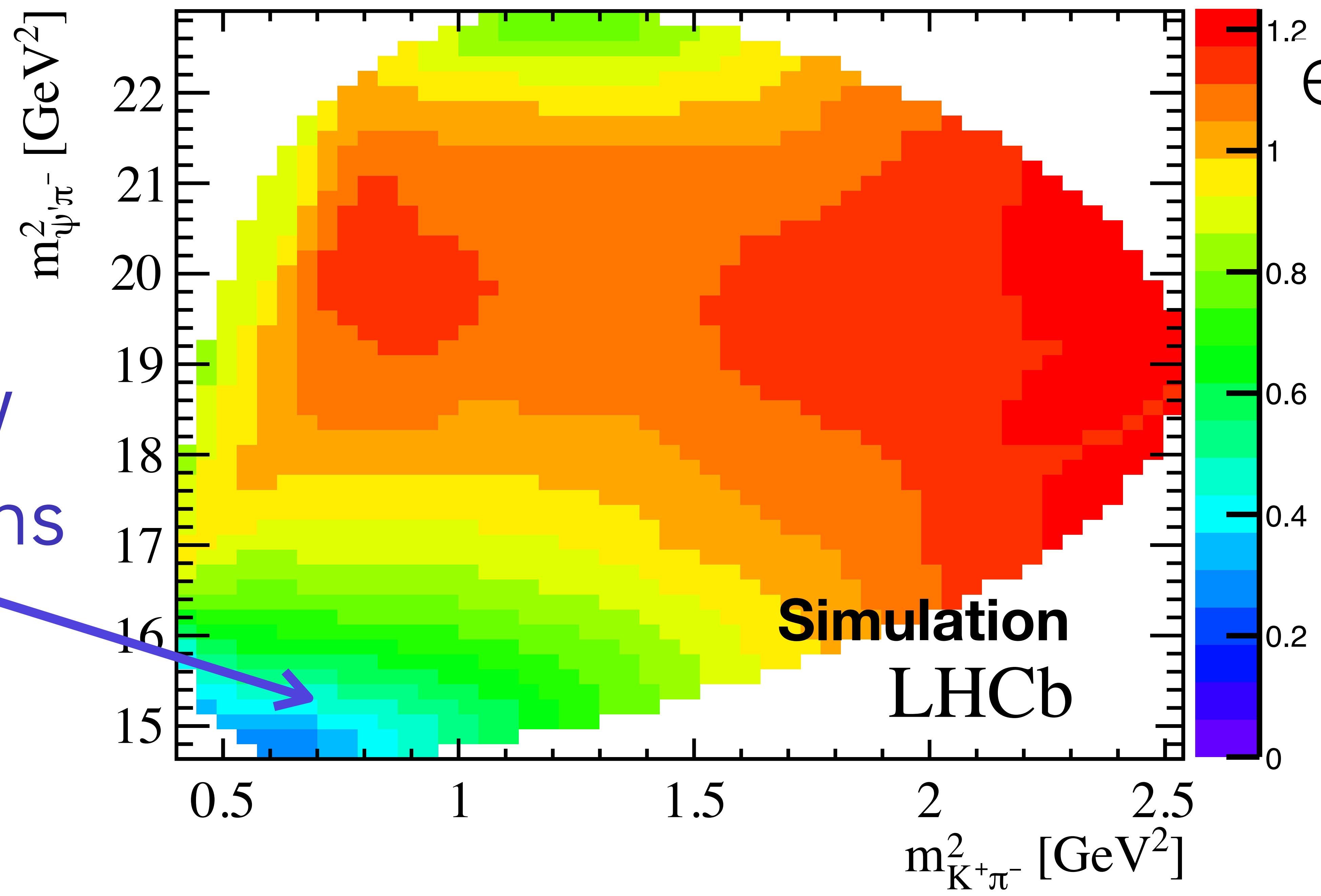
LHCb < 100% efficient at reconstructing the decay particles in 4D space.

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…

Caused by low momentum pions



∈ High efficiency

Low efficiency

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	

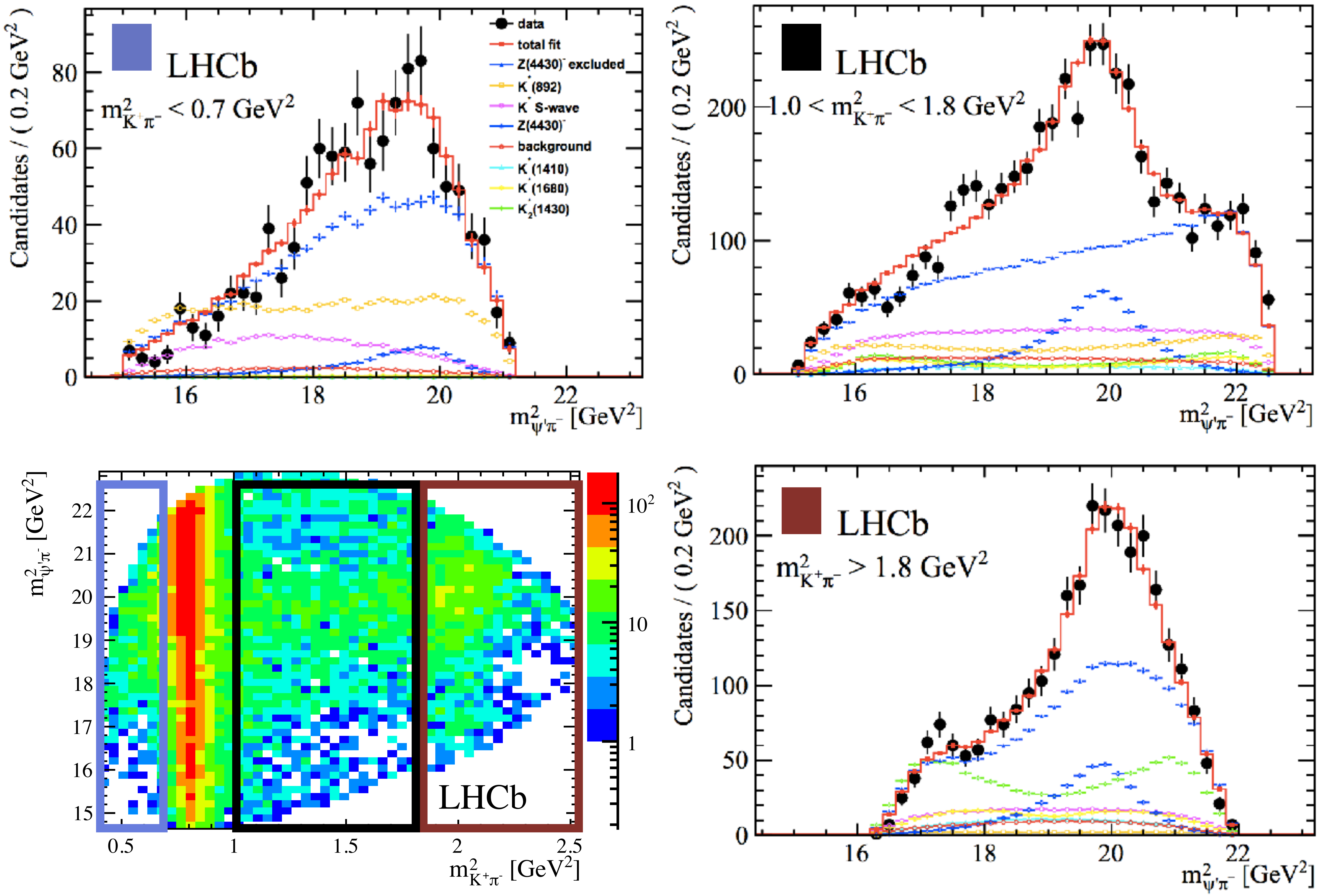
Amplitude fractions [%]

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?

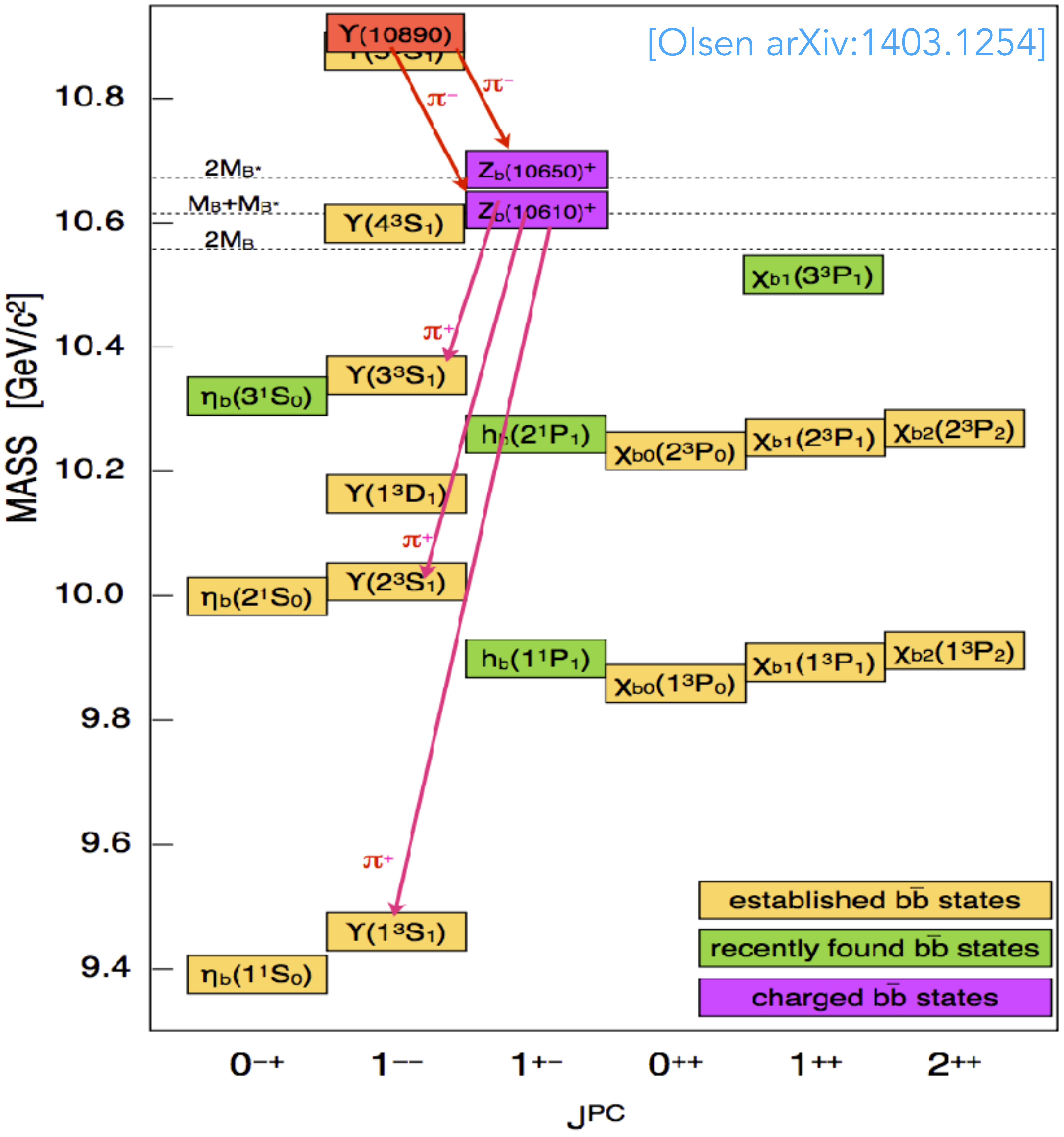
$$f_i = \frac{\int |A_i(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega}{\int |\sum_k A_k(m_{K\pi}, \Omega)|^2 dm_{K\pi} d\Omega}$$

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



[PRL 112 (2014) 222002]

Bottomonium spectrum

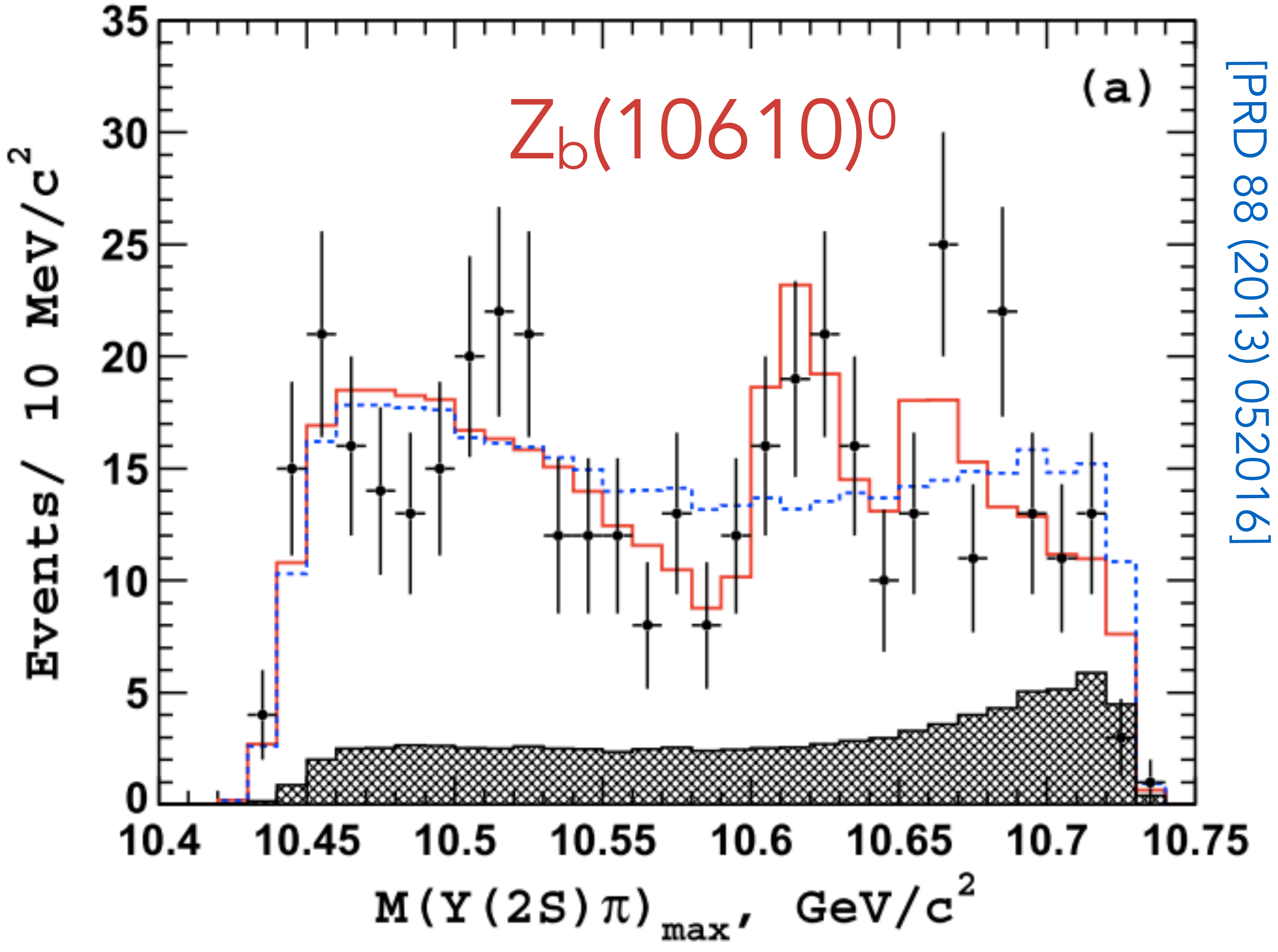


Bottomonium-like states

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?

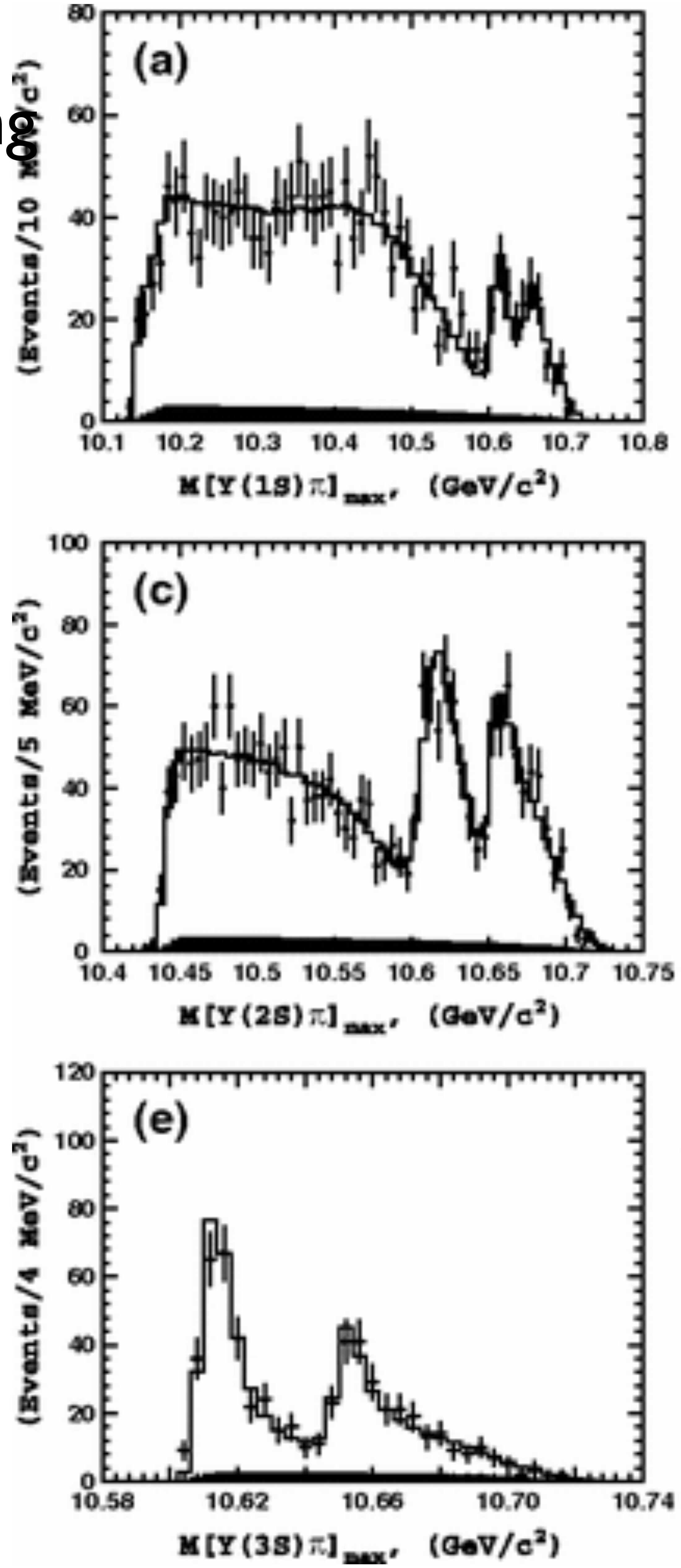
Also first evidence for neutral isospin partners in $\pi^0\pi^0\Upsilon(2S)$ amplitude fit.



[PRD 88 (2013) 052016]

Projections of Dalitz plots

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



[PRL 108 (2012) 122001]