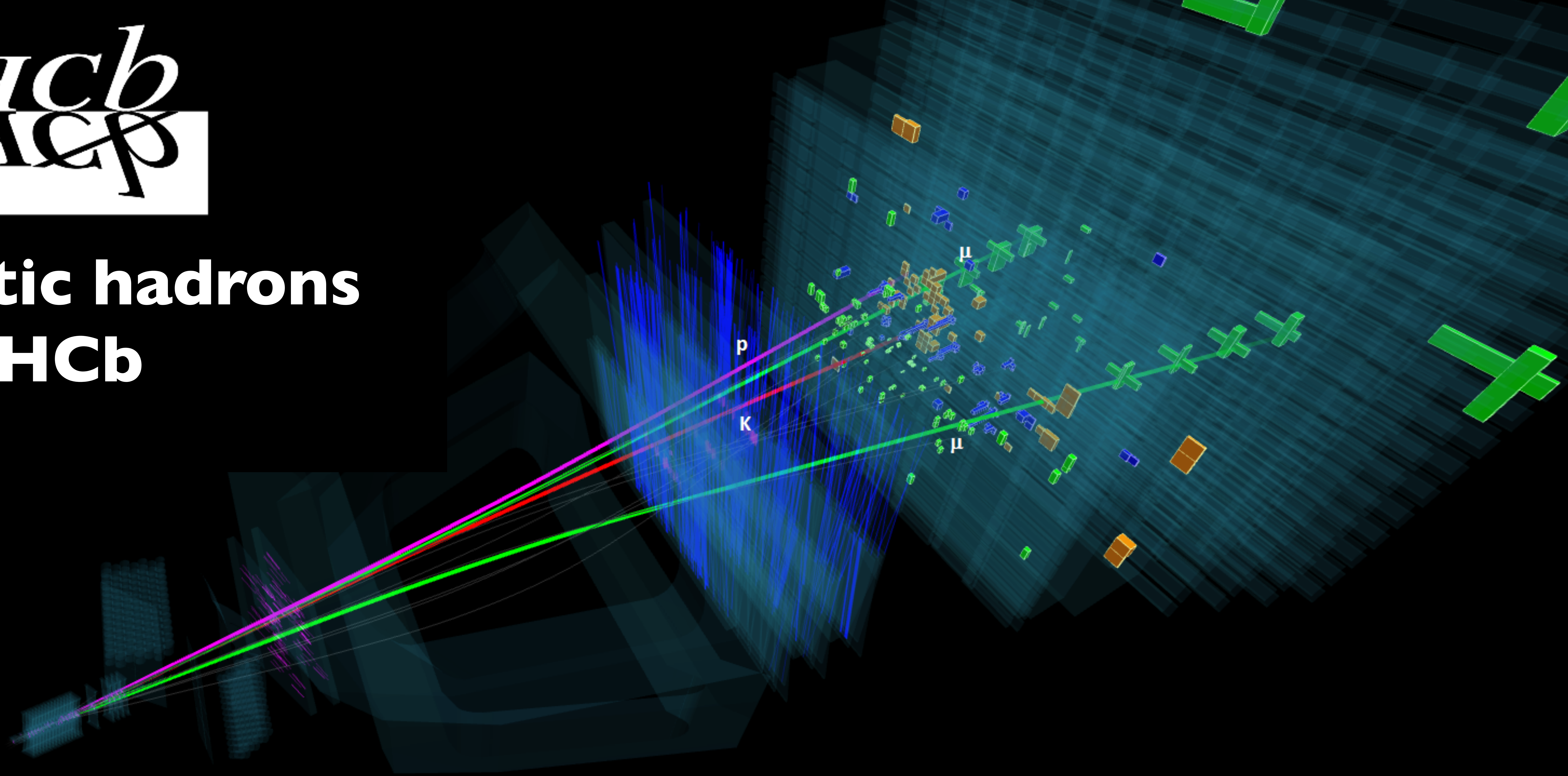
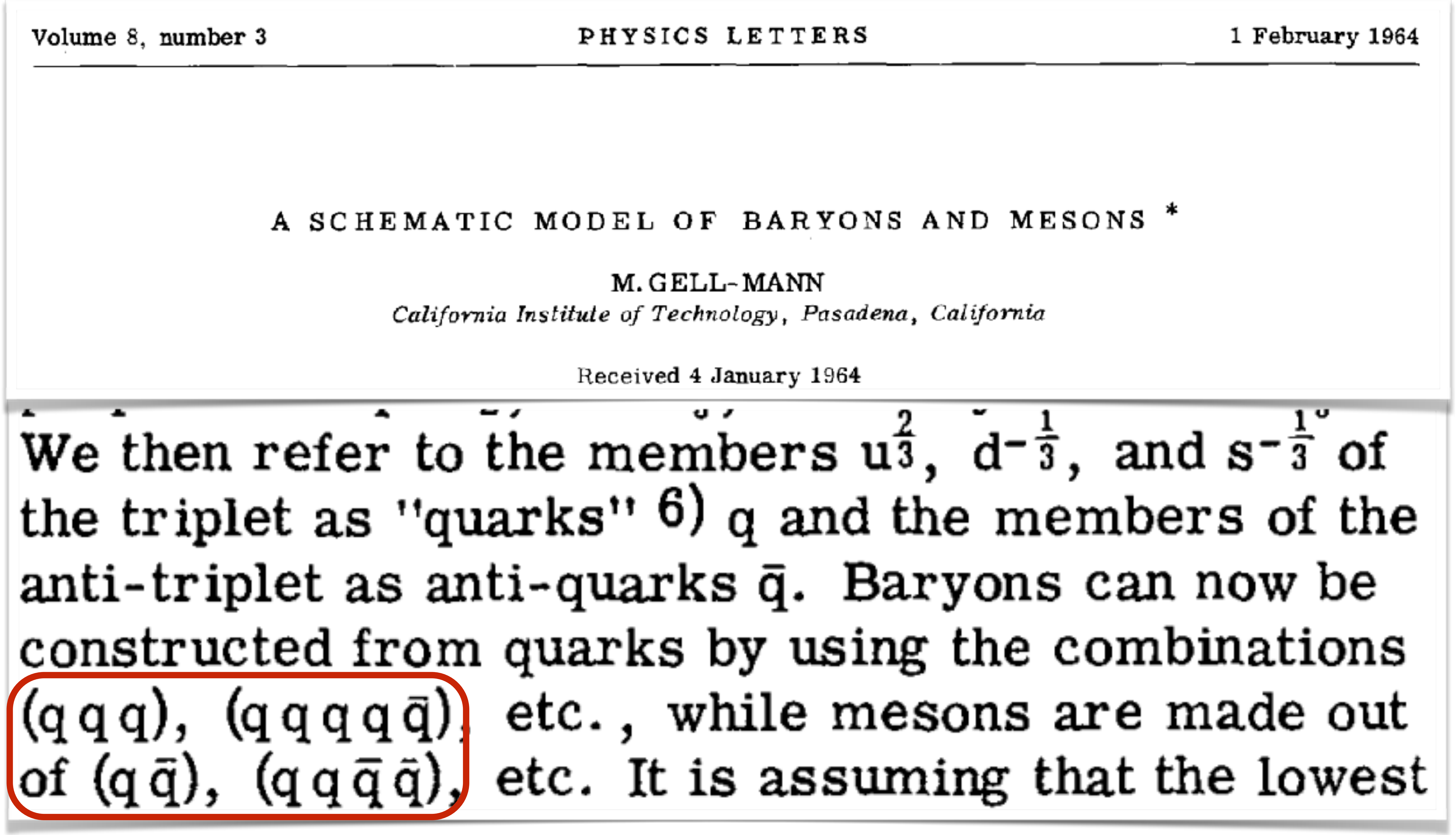
Exotic hadrons at LHCb



@GreigCowan (Edinburgh)
UK Flavour meeting
IPPP, 6th September 2017

The birth of the quark model



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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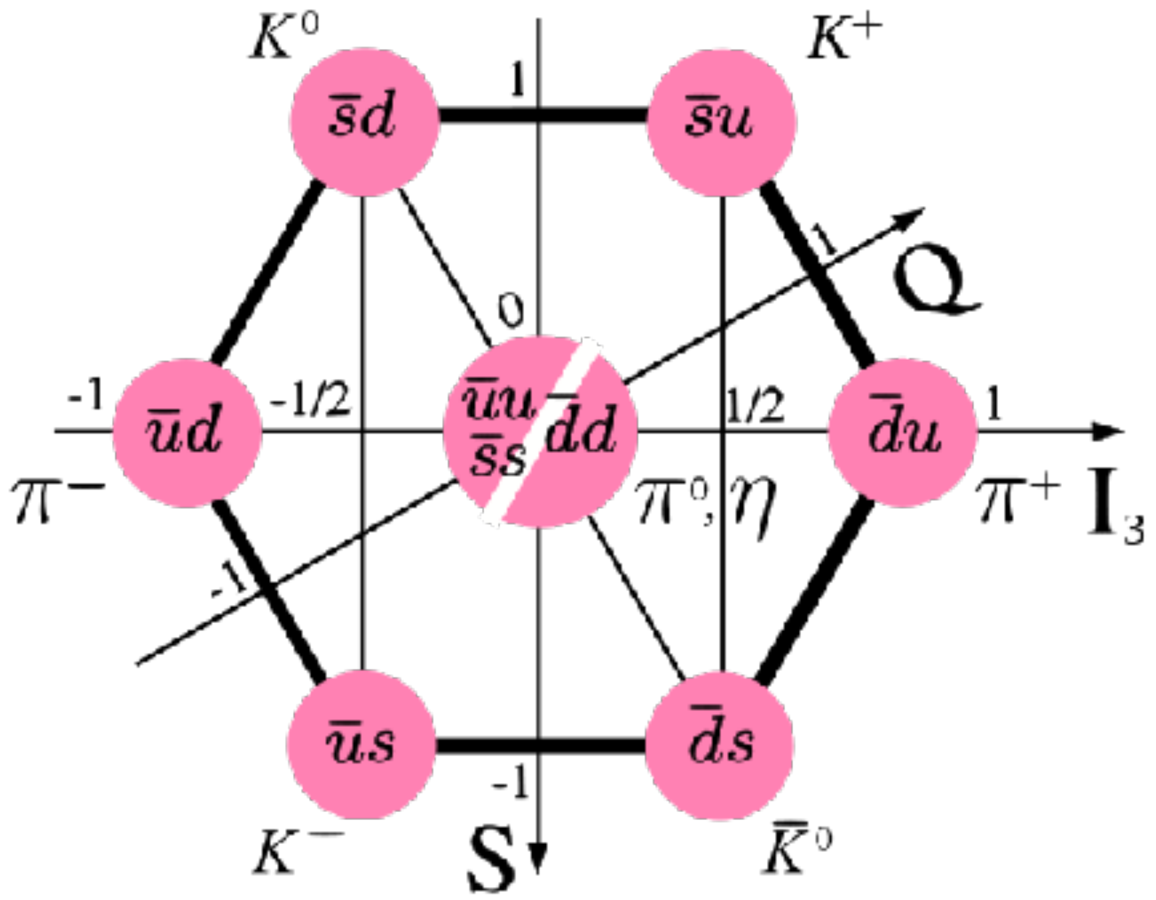
California Institute of Technology, Pasadena, California

Received 4 January 1964

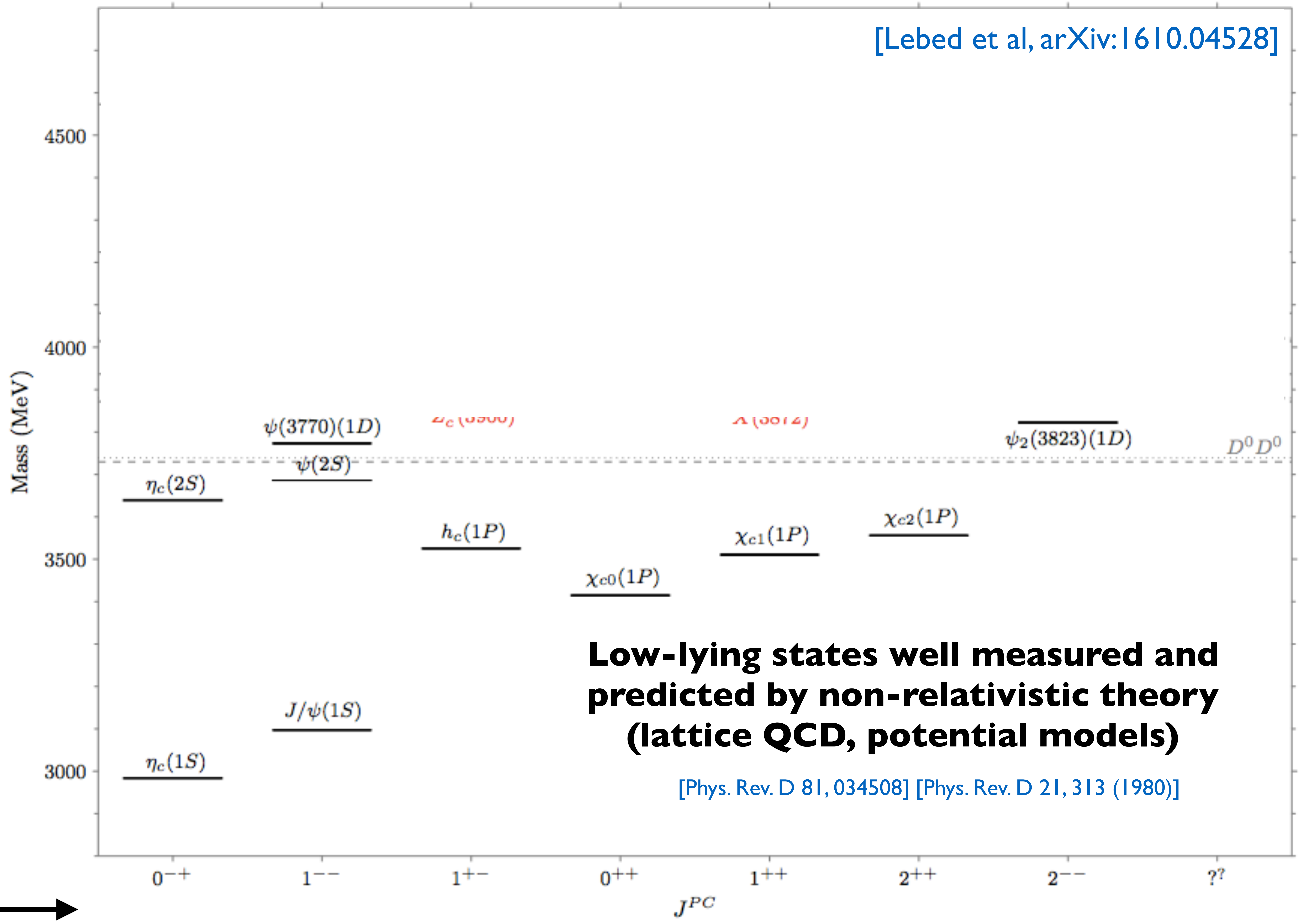
We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while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

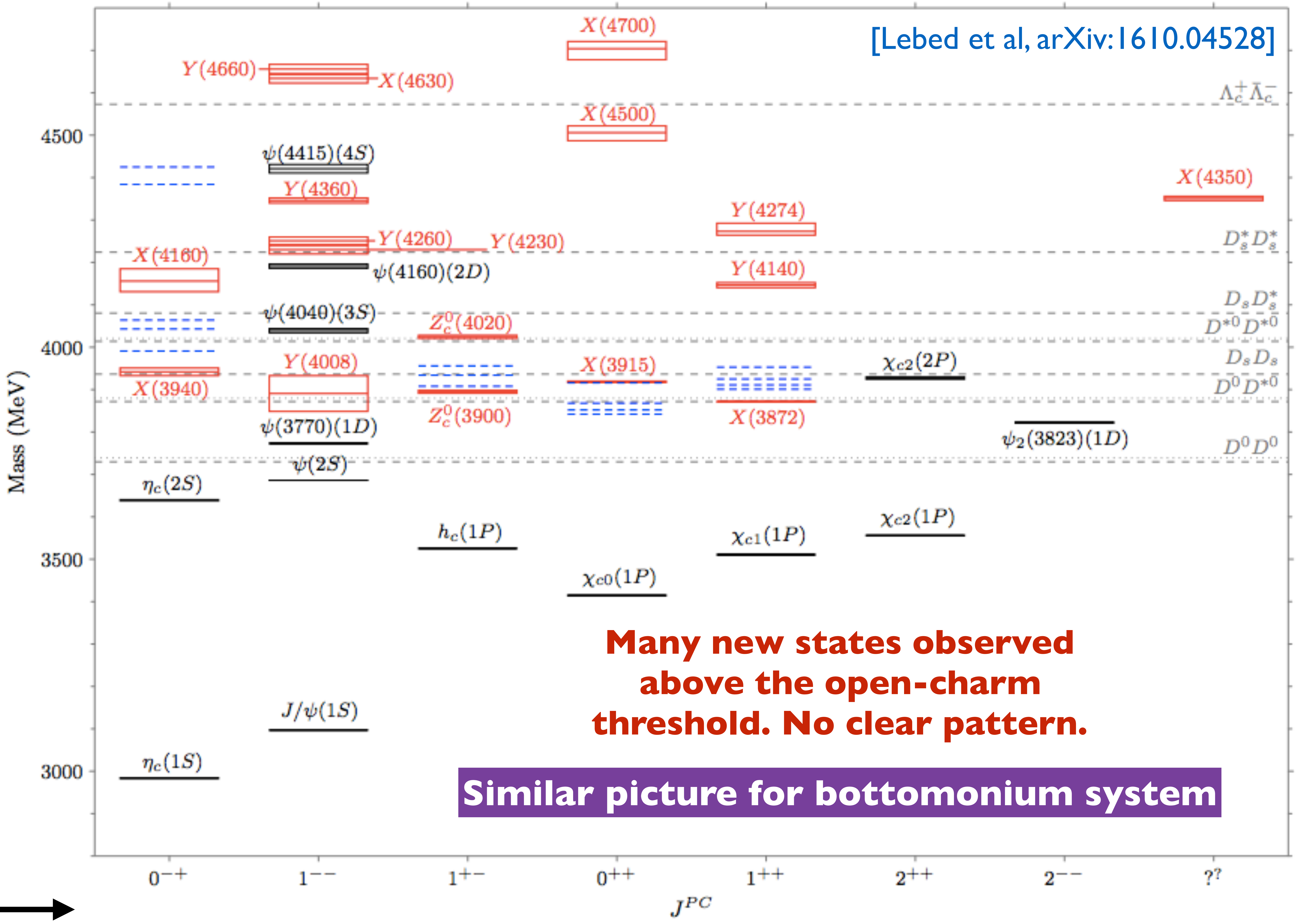
$J = L \oplus S$

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

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

$n^{2S+1}L_J$ →

Charmonium spectroscopy



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

Similar picture for bottomonium system

Classify using J^{PC}

$J = L \oplus S$

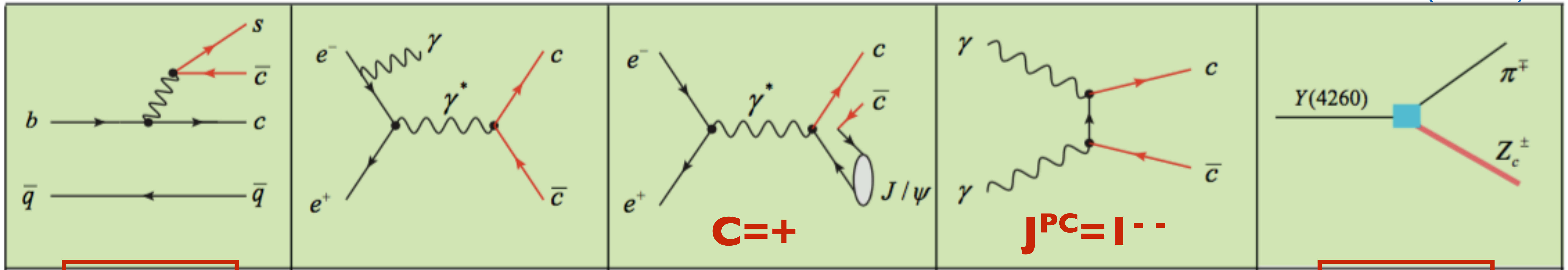
$P = (-1)^{L+1}$

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

$n^{2S+1}L_J$ ⟶

Meet the family

Production mechanism



b hadrons	ISR	double charmonium	$\gamma\gamma$ collisions ($e^+e^- \to e^+e^-X$)	ISR $\to$ 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

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

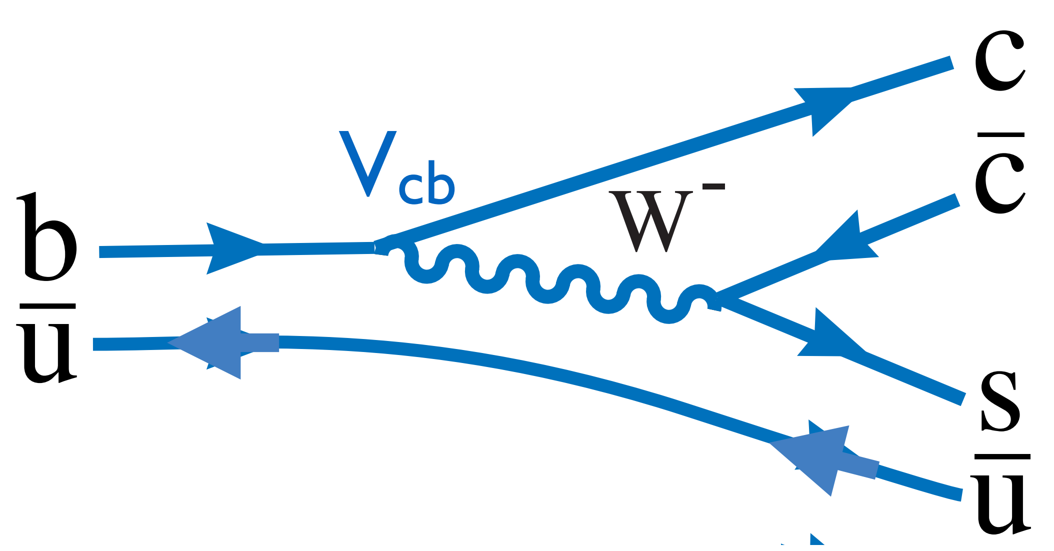
b hadrons for spectroscopy

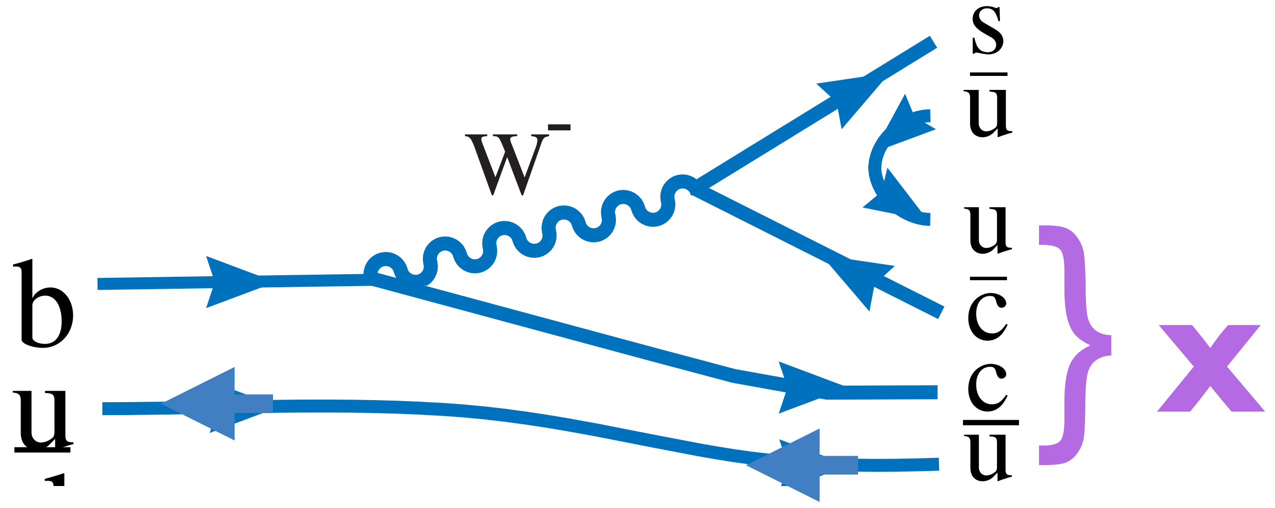
Large production cross-section at the LHC. [PRL 118 (2017) 052002]

Charmonium, particularly with J/ψ or ψ(2S), in the final state is experimentally useful for triggering (muons/electrons).

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

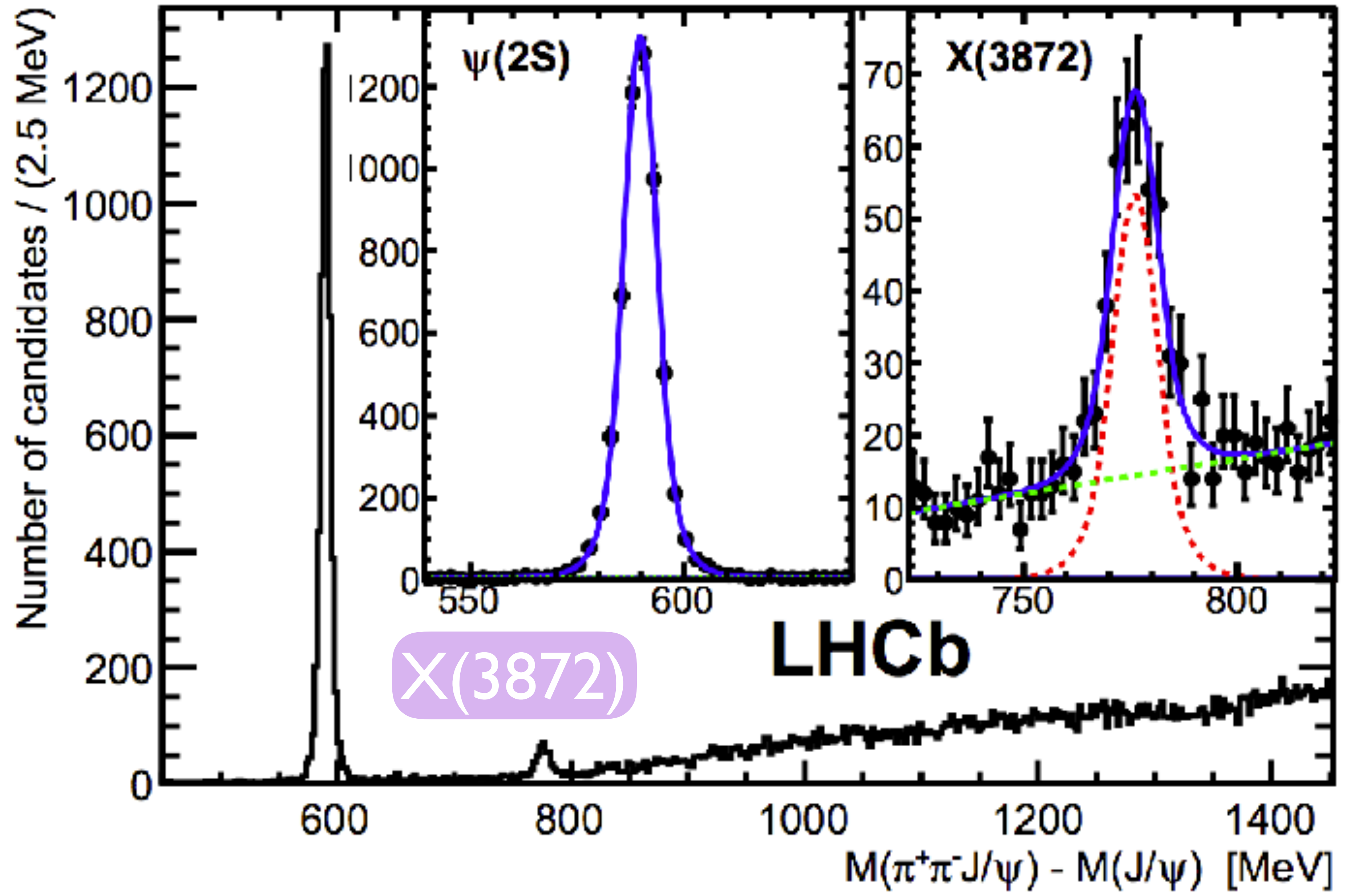
Mass fit is sufficient to separate if state isolated and narrow, otherwise need **amplitude analysis**.

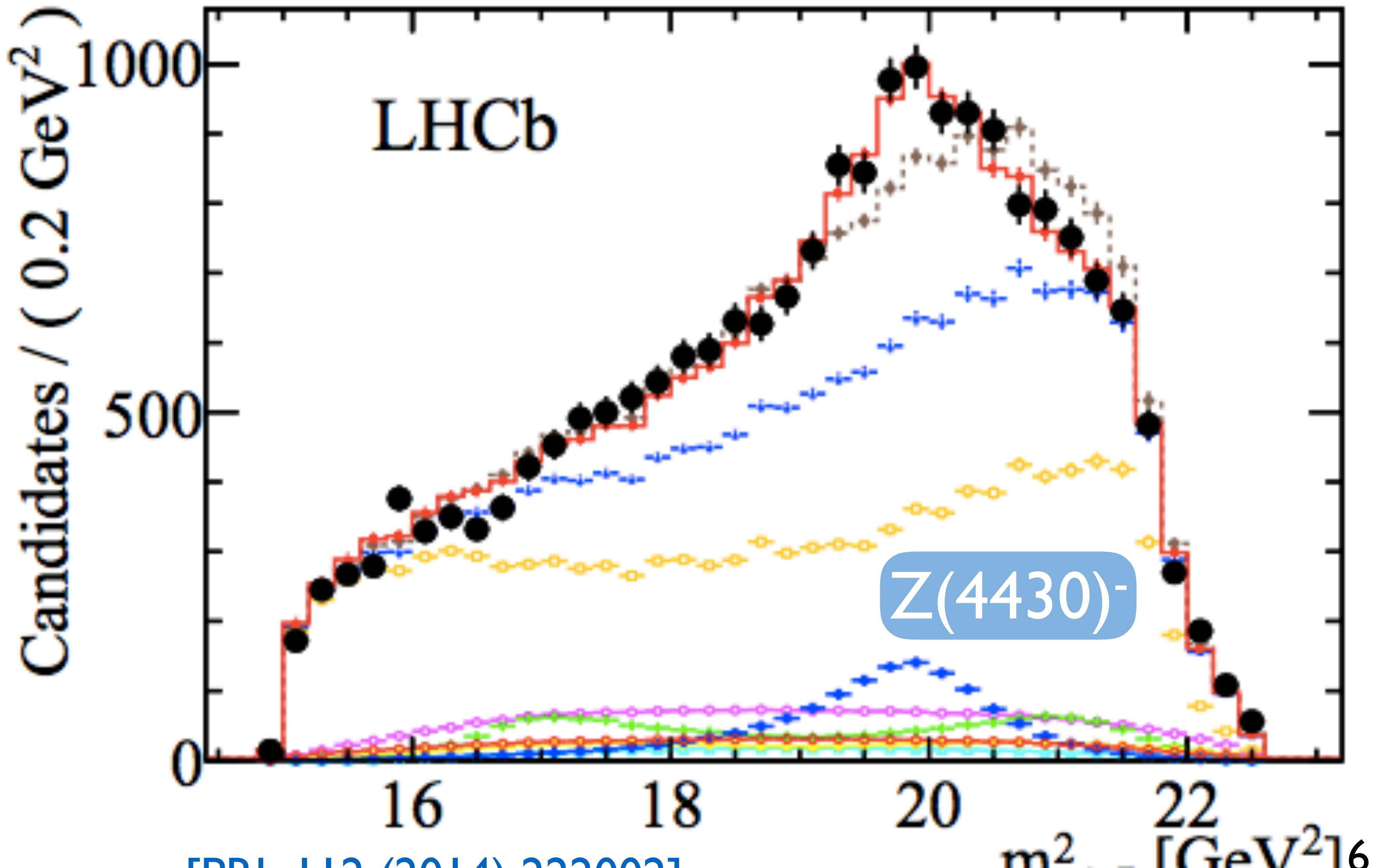




$$B^+ \to X(3872)K^+, X(3872) \to J/\psi\pi^+\pi^-$$
$$B^0 \to Z(4430)^-K^+, Z(4430)^- \to \psi(2S)\pi^-$$

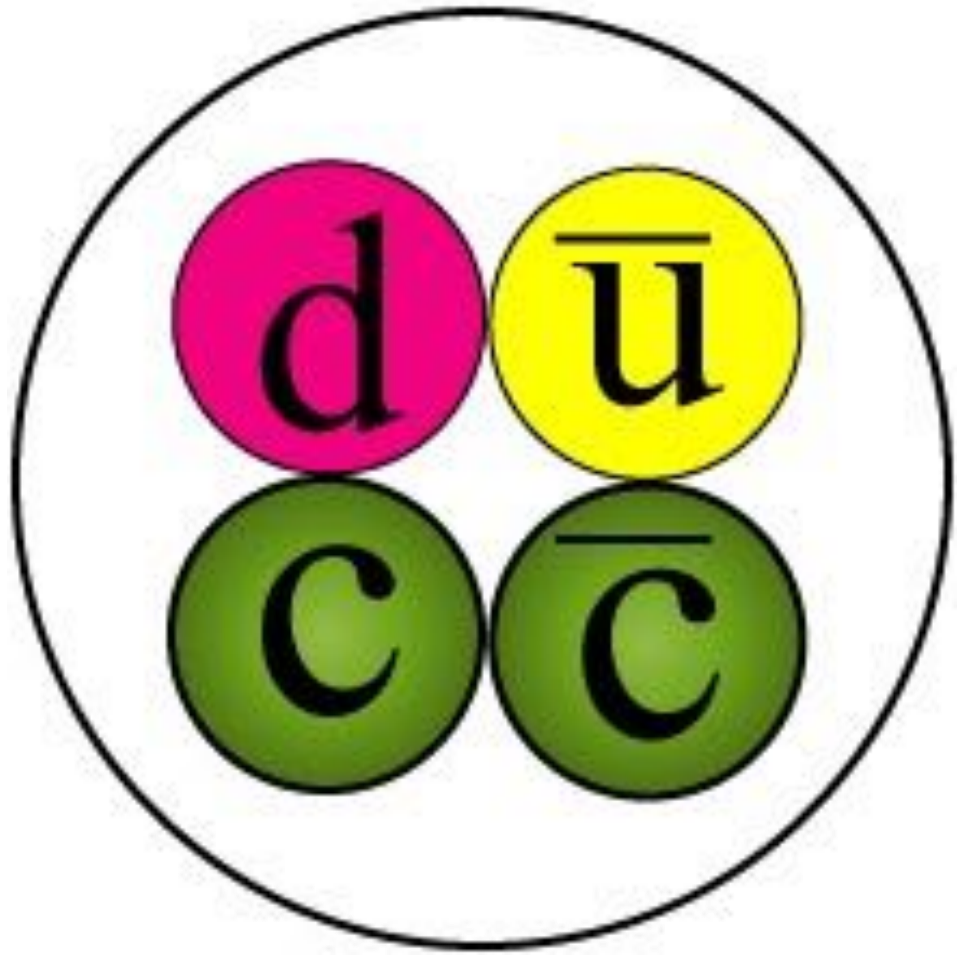
[PRL 110 (2013) 222001]





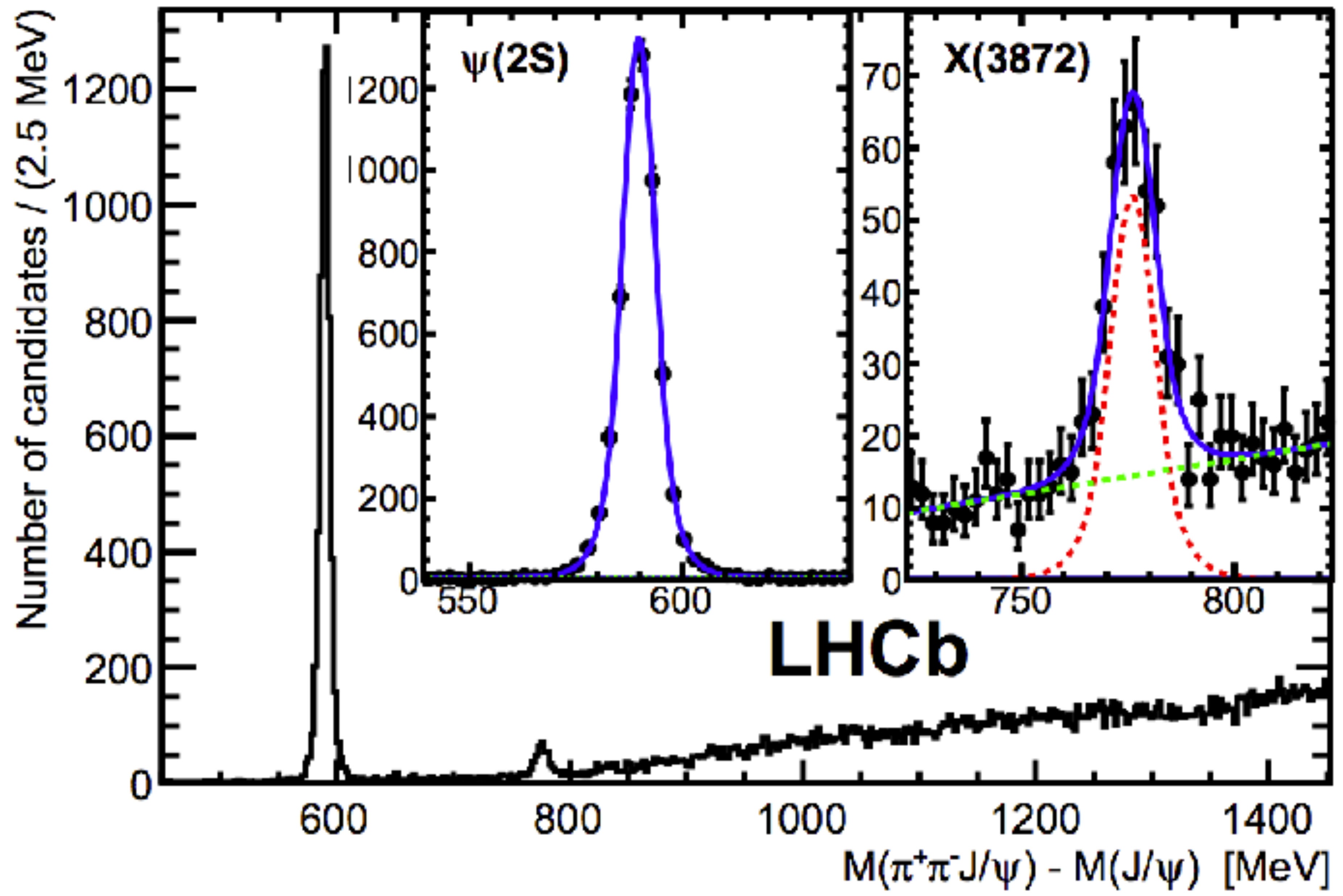
[PRL 112 (2014) 222002]

Exotic mesons



The X(3872) revolution

[PRL 110 (2013) 222001]



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

[See talk from Tim Burns]

$J^{PC} = 1^{++}$ 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]
$B \to KX(3872)$ $\to J/\psi\omega(\to \pi^+\pi^-\pi^0)$	Belle [75], BaBar [90]
$B \to KX(3872)$ $\to D^0\bar{D}^{*0}, D^0\bar{D}^0\pi^0$	Belle [76], BaBar [87]
$B \to KX(3872)$ $\to \gamma J/\psi, \gamma\psi(3686)$	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]
$pp \to \cdots + X(3872)$ $\to \gamma J/\psi, \gamma\psi(3686)$	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

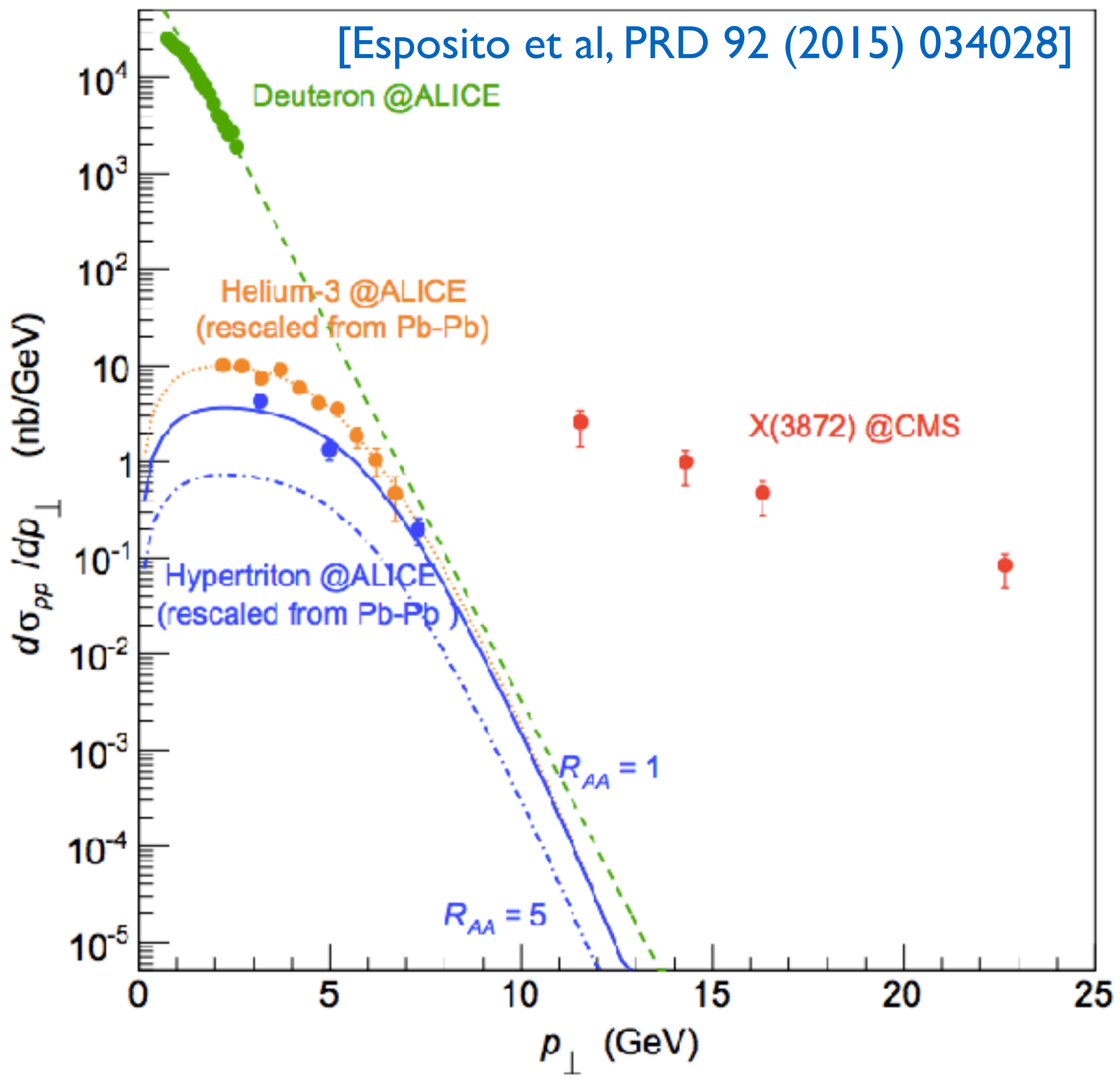
$$\Gamma_{X(3872)} < 1.2 \text{ MeV}/c^2$$

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

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

[PDG]

X(3872) production

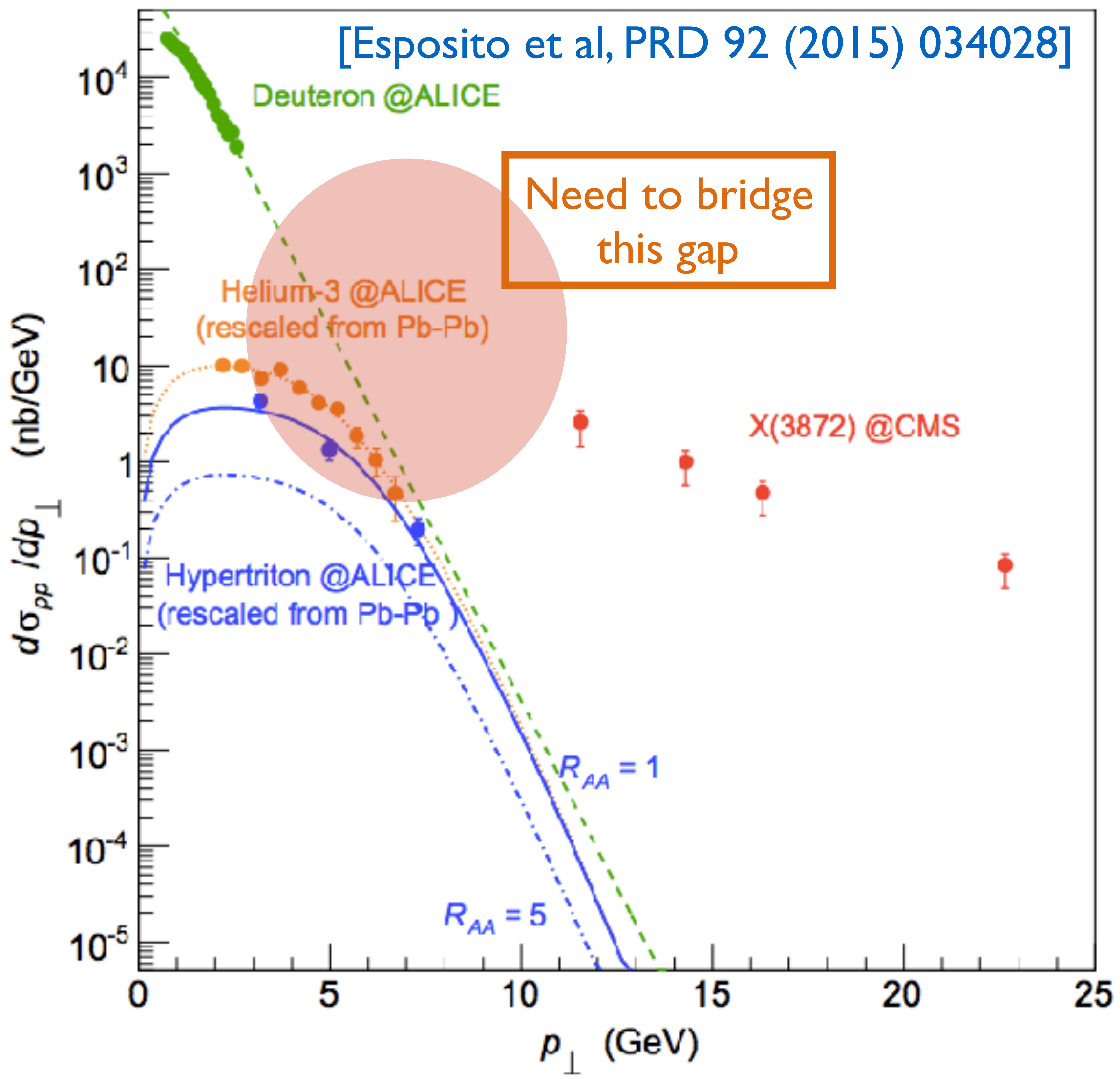


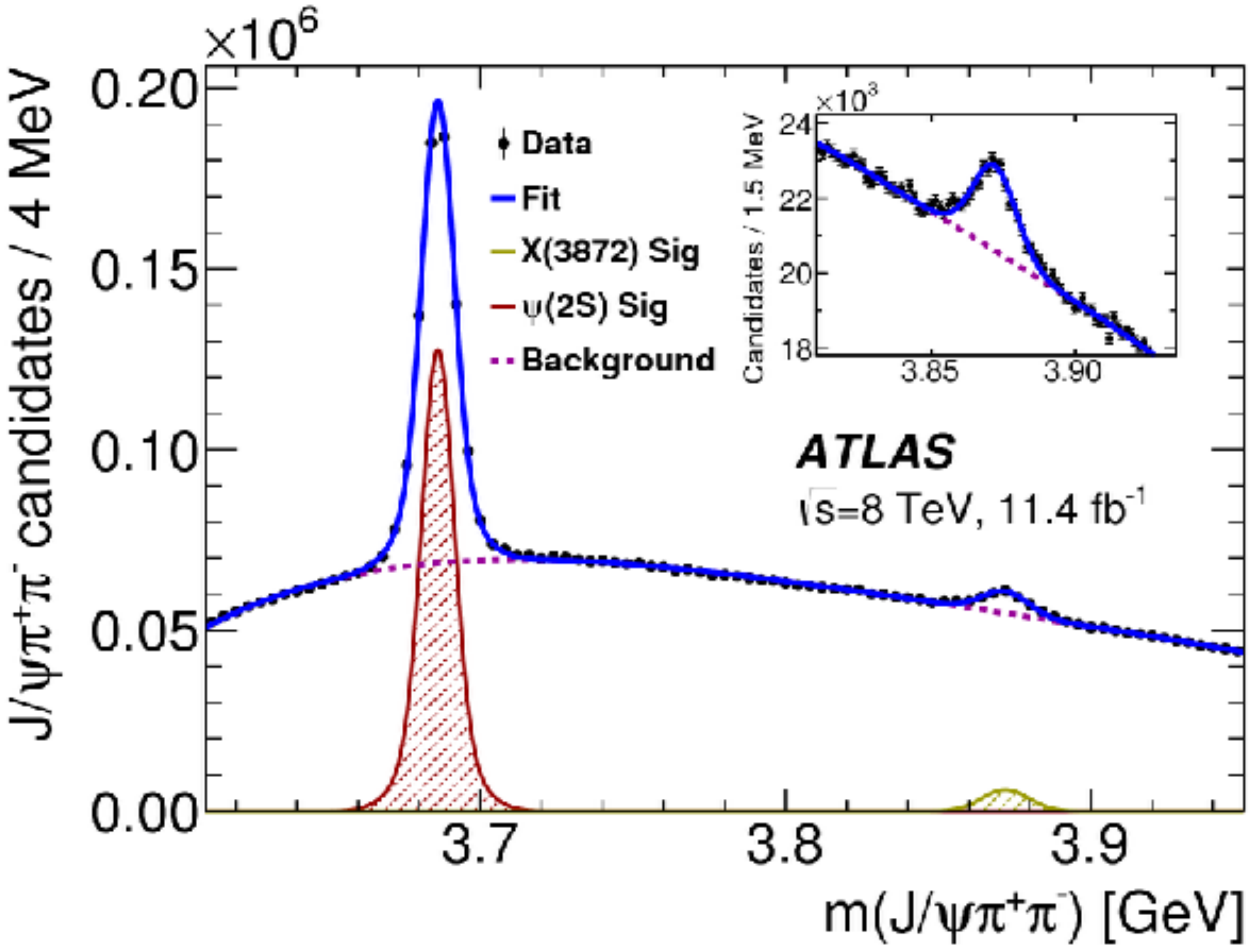
X(3872) seen in pp and and $p\bar{p}$ collisions.

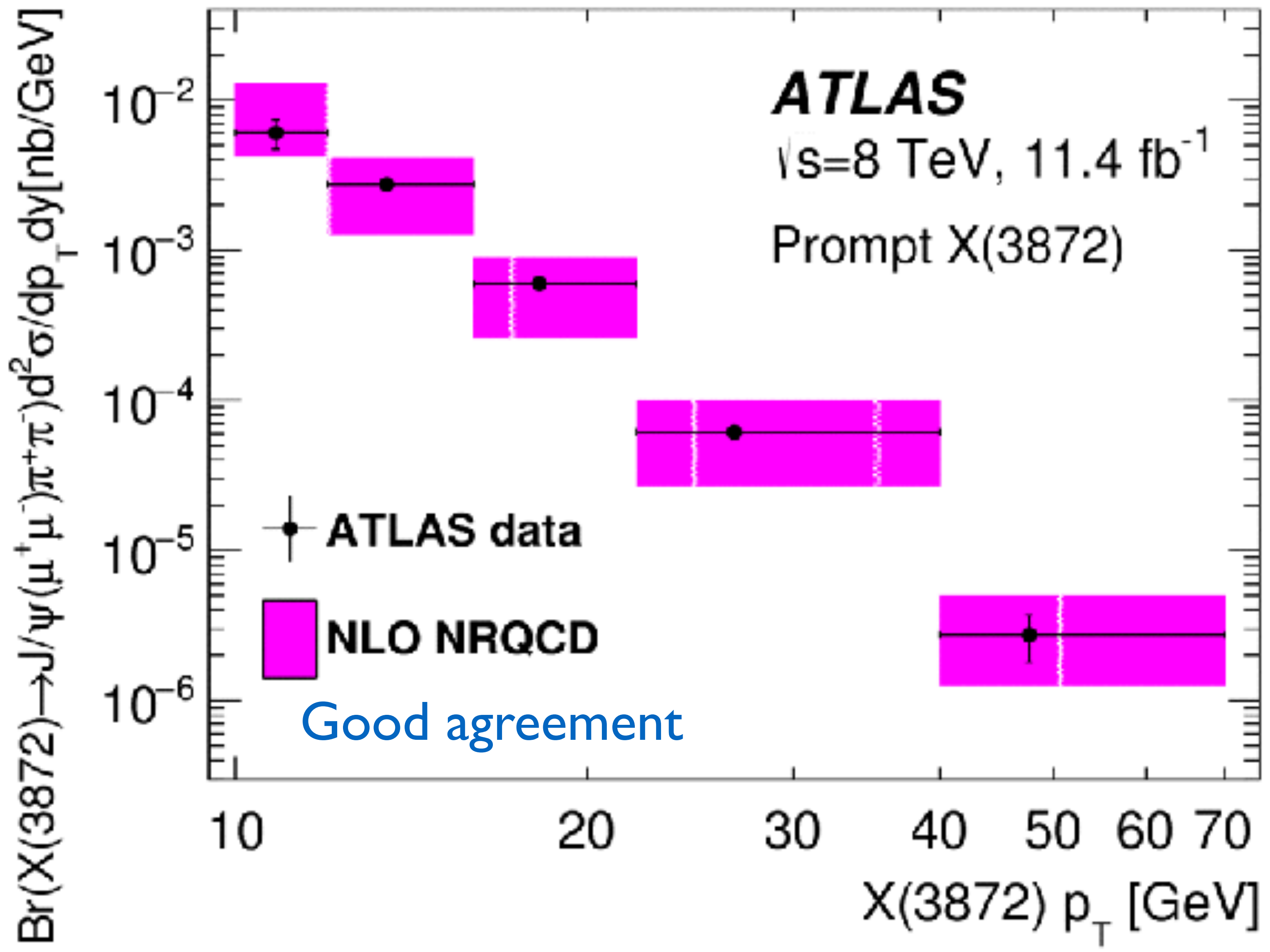
[D0, PRL 103 (2009)152001] [CDF, PRL 103 (2009)152001] [ATLAS, JHEP 01 (2017) 117] [CMS, JHEP 04 (2013) 154] [LHCb, JHEP 04 (2013) 154]

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

X(3872) production







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[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 $D^0 D^{*0}$ 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]

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]

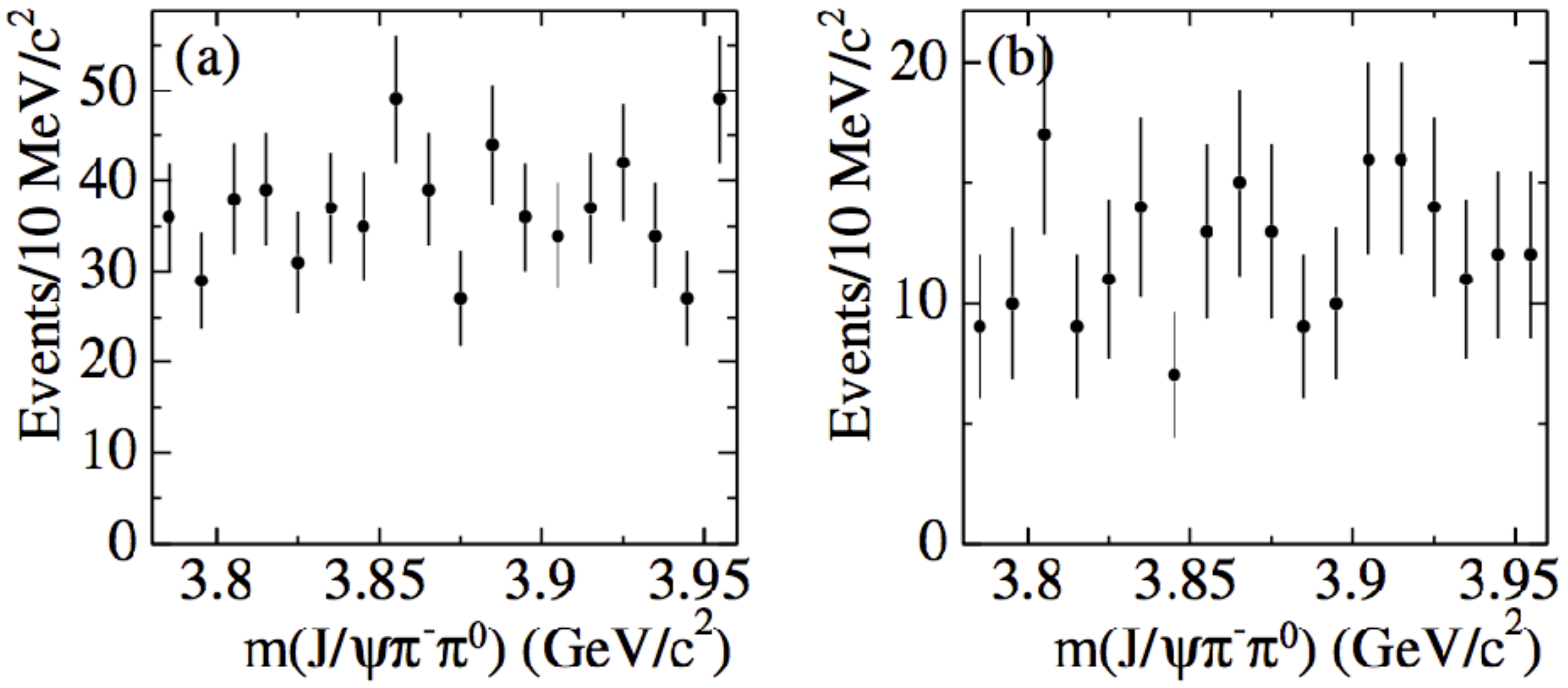
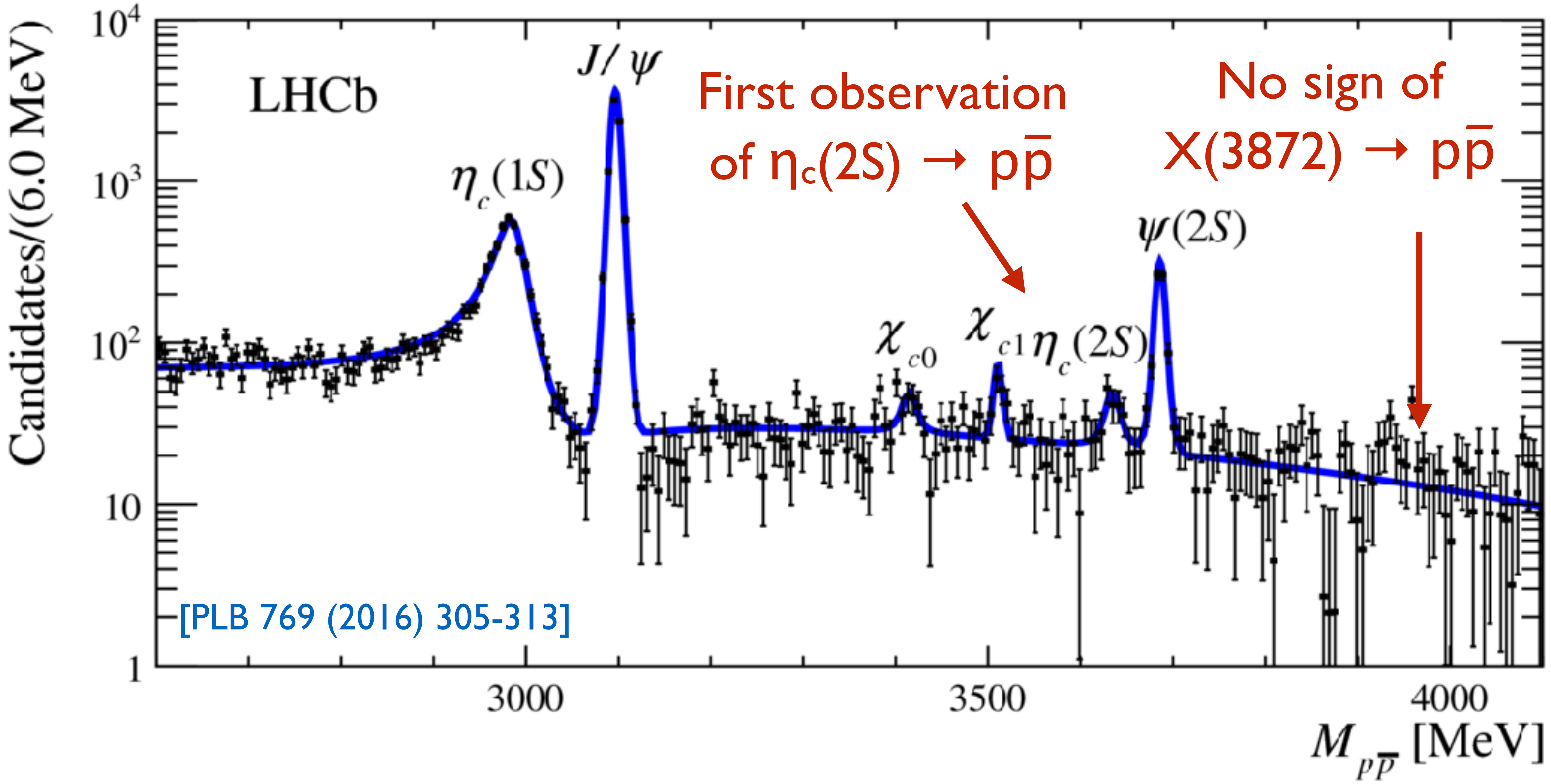
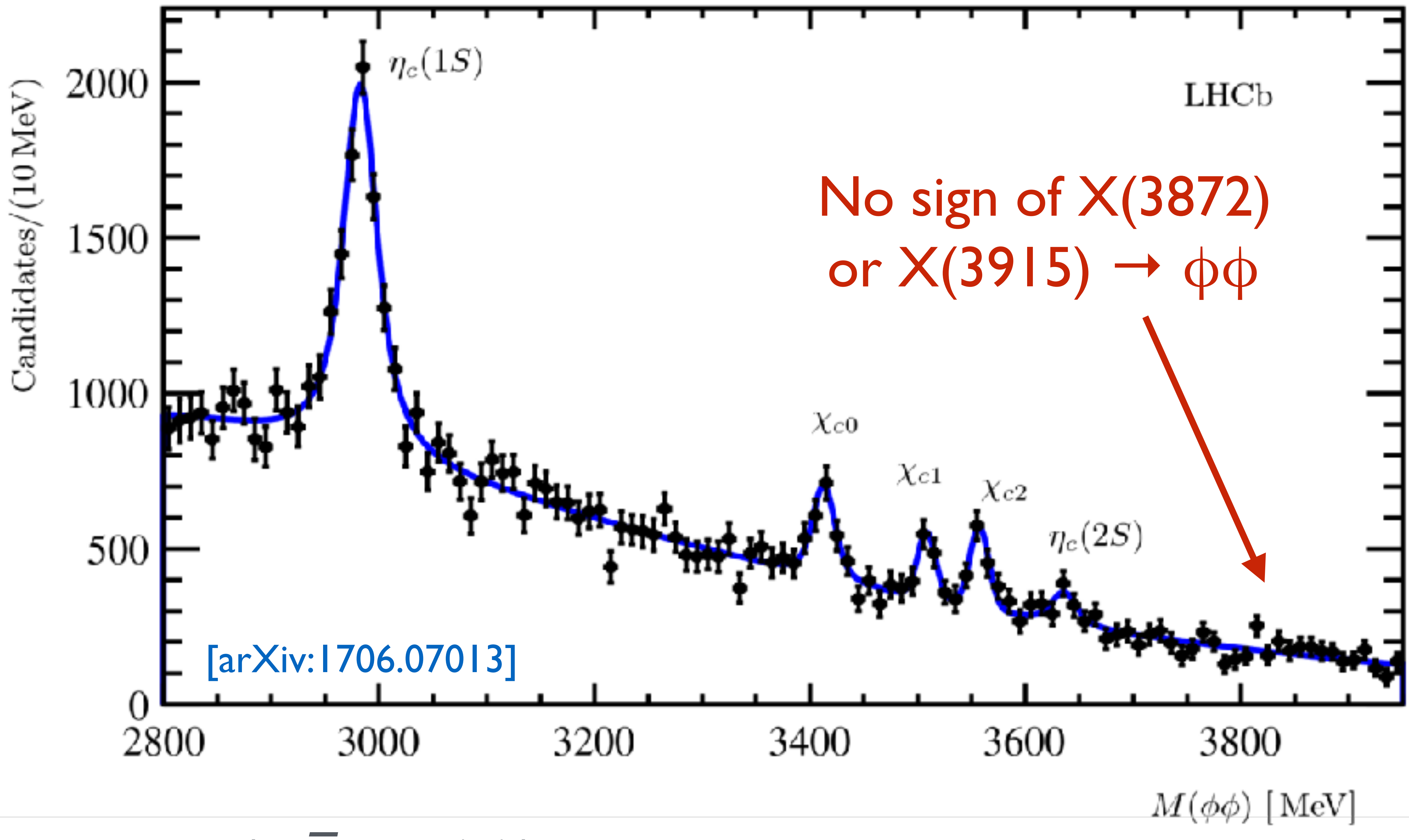


FIG. 3. The $J/\psi\pi^-\pi^0$ invariant mass in 10 MeV/c^2 bins for (a) $B^0 \to J/\psi\pi^-\pi^0 K^+$ and (b) for $B^- \to J/\psi\pi^-\pi^0 K^0_S$. No indication for the decay $X^- \to J/\psi\pi^-\pi^0$ can be found.

$$\mathcal{B}(\bar{B}^0 \to K^- X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 4.2 \times 10^{-6},$$
$$\mathcal{B}(B^+ \to K^0 X^+) \times \mathcal{B}(X^+ \to \rho^+ J/\psi) < 6.1 \times 10^{-6},$$

Charmonium production in b-hadron decays





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

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

(has implications for PANDA)

$b \to ([c\bar{c}] \to \phi\phi)\, X$
require separation between PV and secondary vertices

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

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

X(4140) → J/ψϕ : some history

Seen by CDF, D0 and CMS

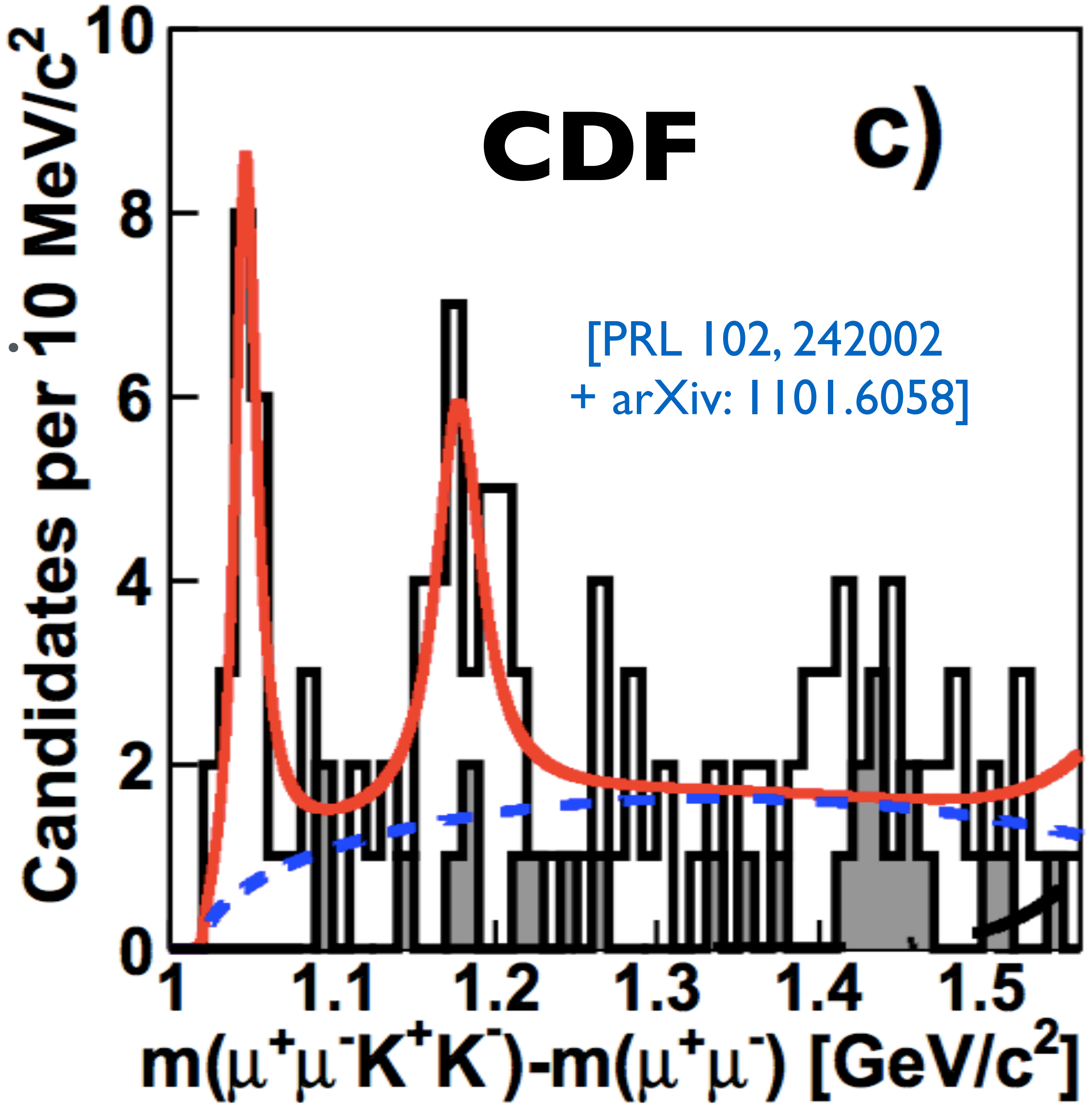
Not seen by LHCb, BaBar, BES-III, Belle (γγ fusion).

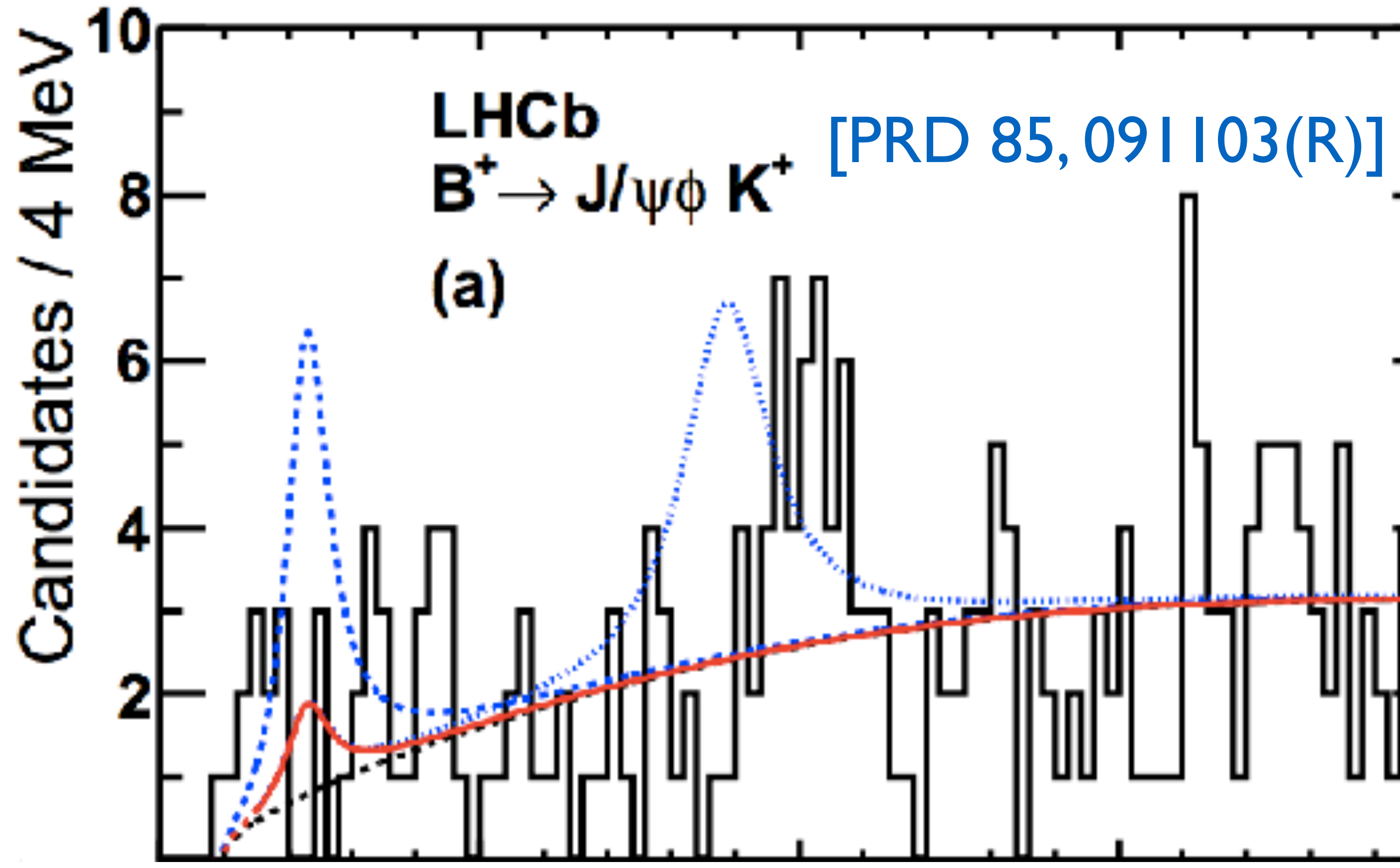
Well above open-charm threshold but has **narrow width** → not conventional $c\bar{c}$.

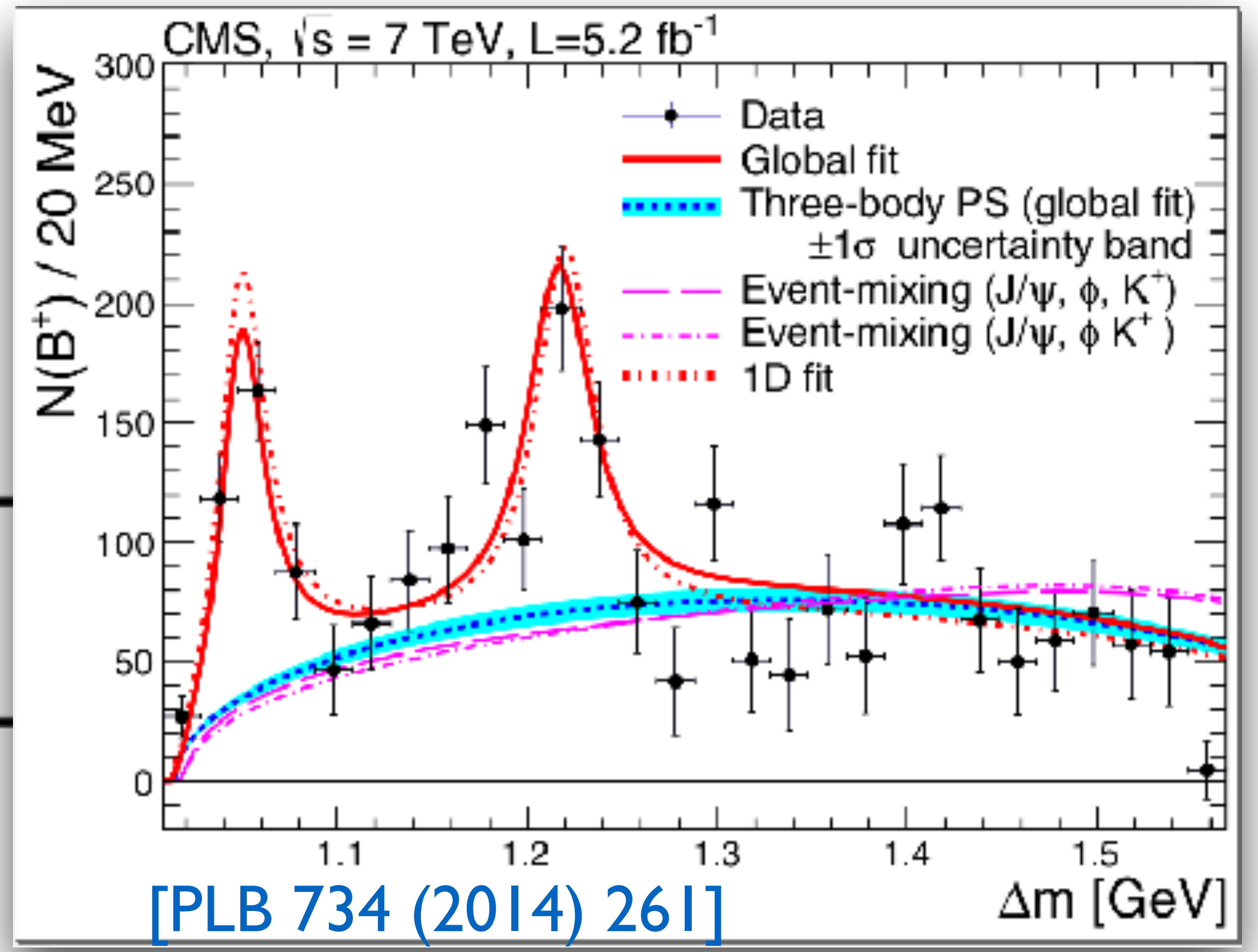
Also second state at higher mass…

Full amplitude analysis of decay is essential!

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







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

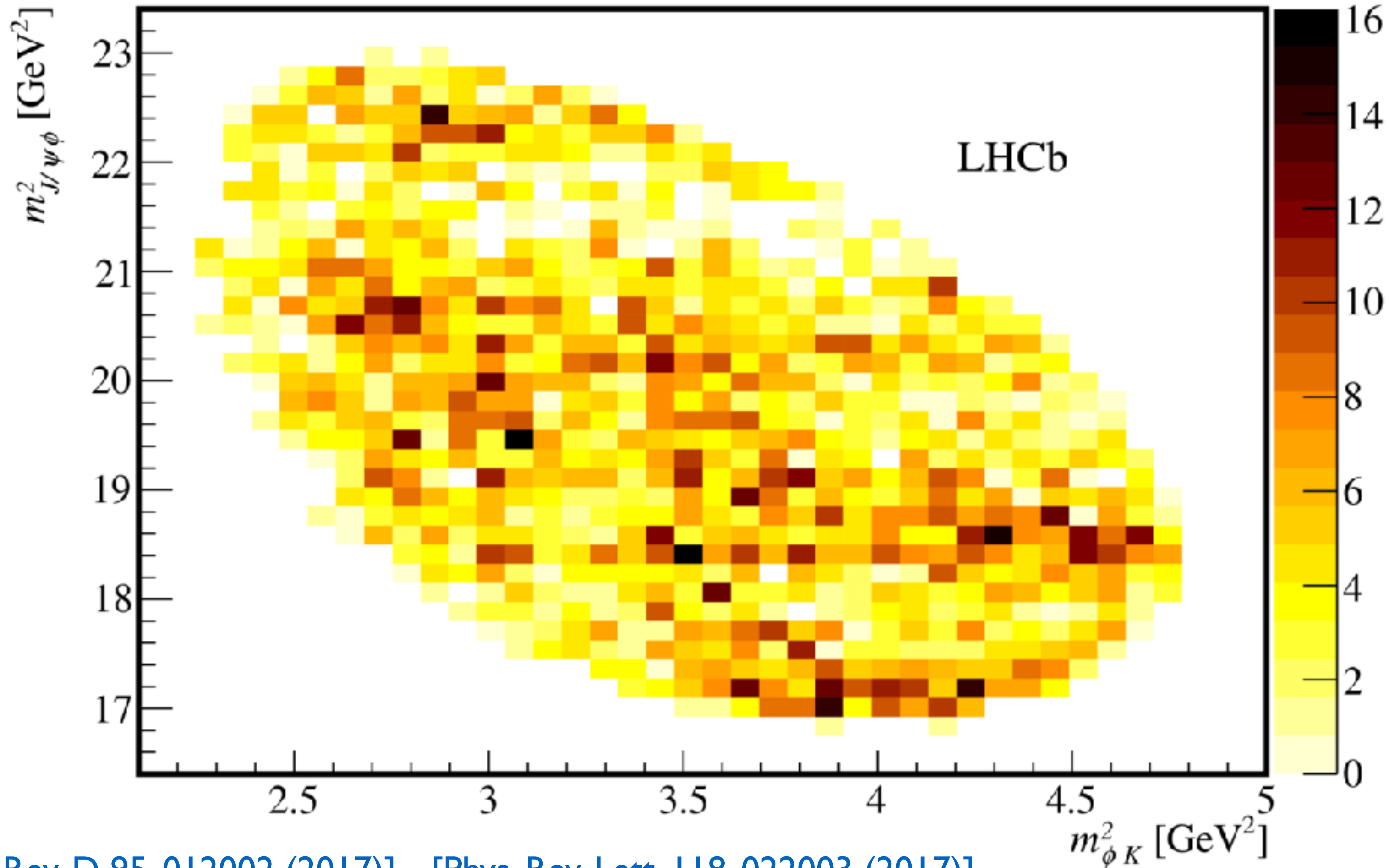
[D0 PRD 89, 012004]
[Belle PRL 104, 112004]
[BES-III PRD 91 (2015) 032002]

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

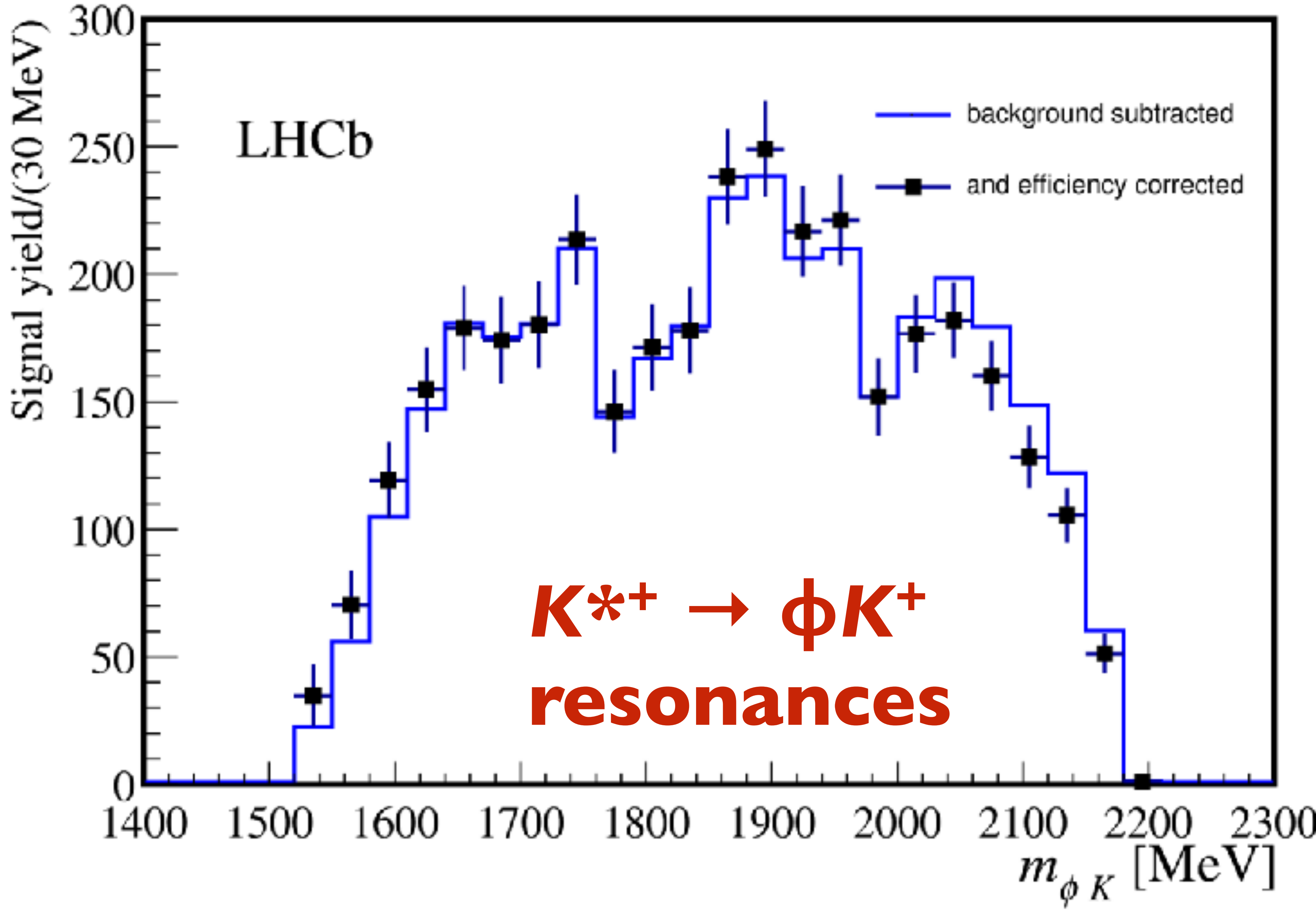
Are reflections from K^* system causing structure in $J/\psi\phi$?

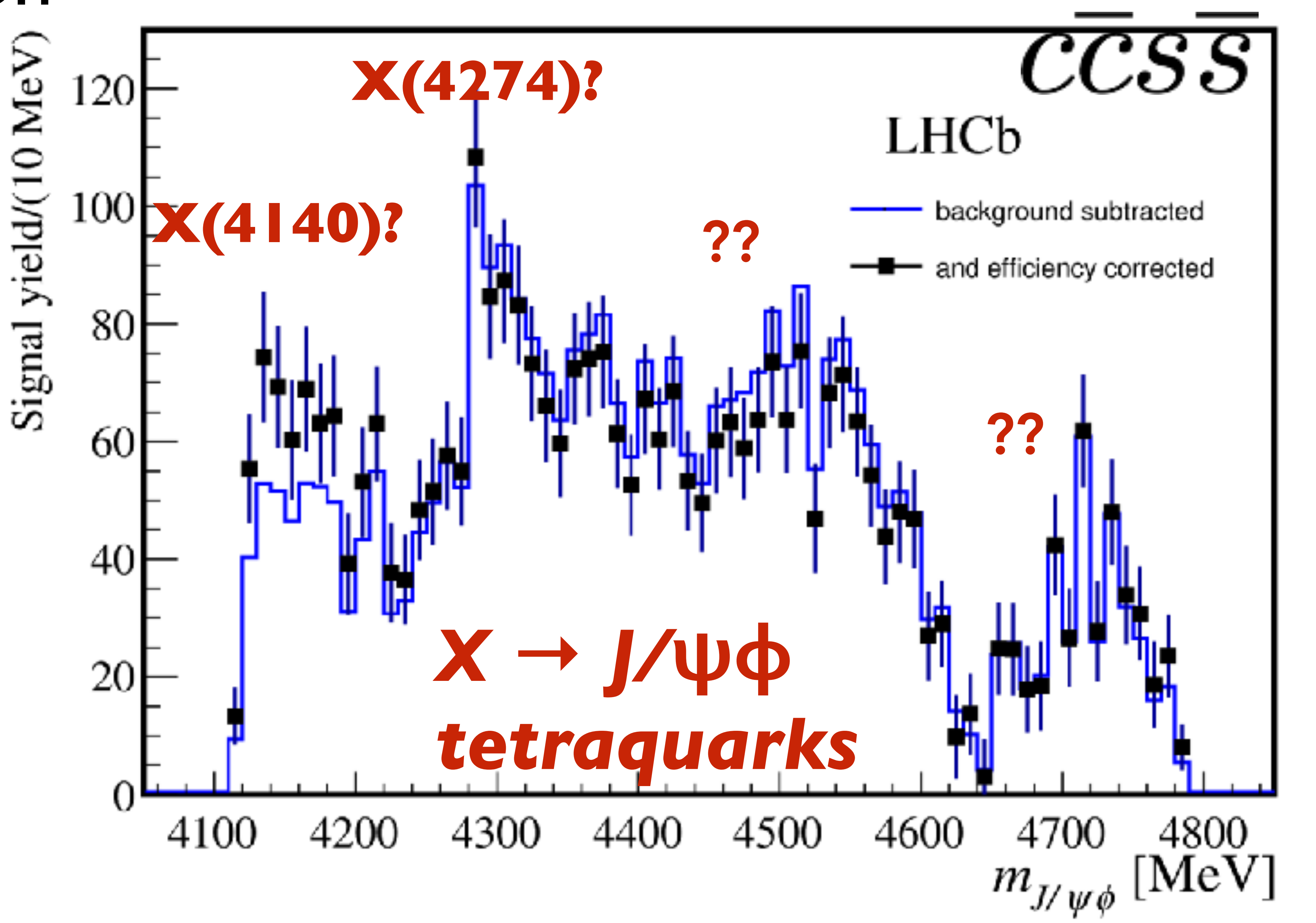
Not sufficient to just fit 1D mass distributions with ad-hoc assumptions about K* contributions

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 $J/\psi\phi$?

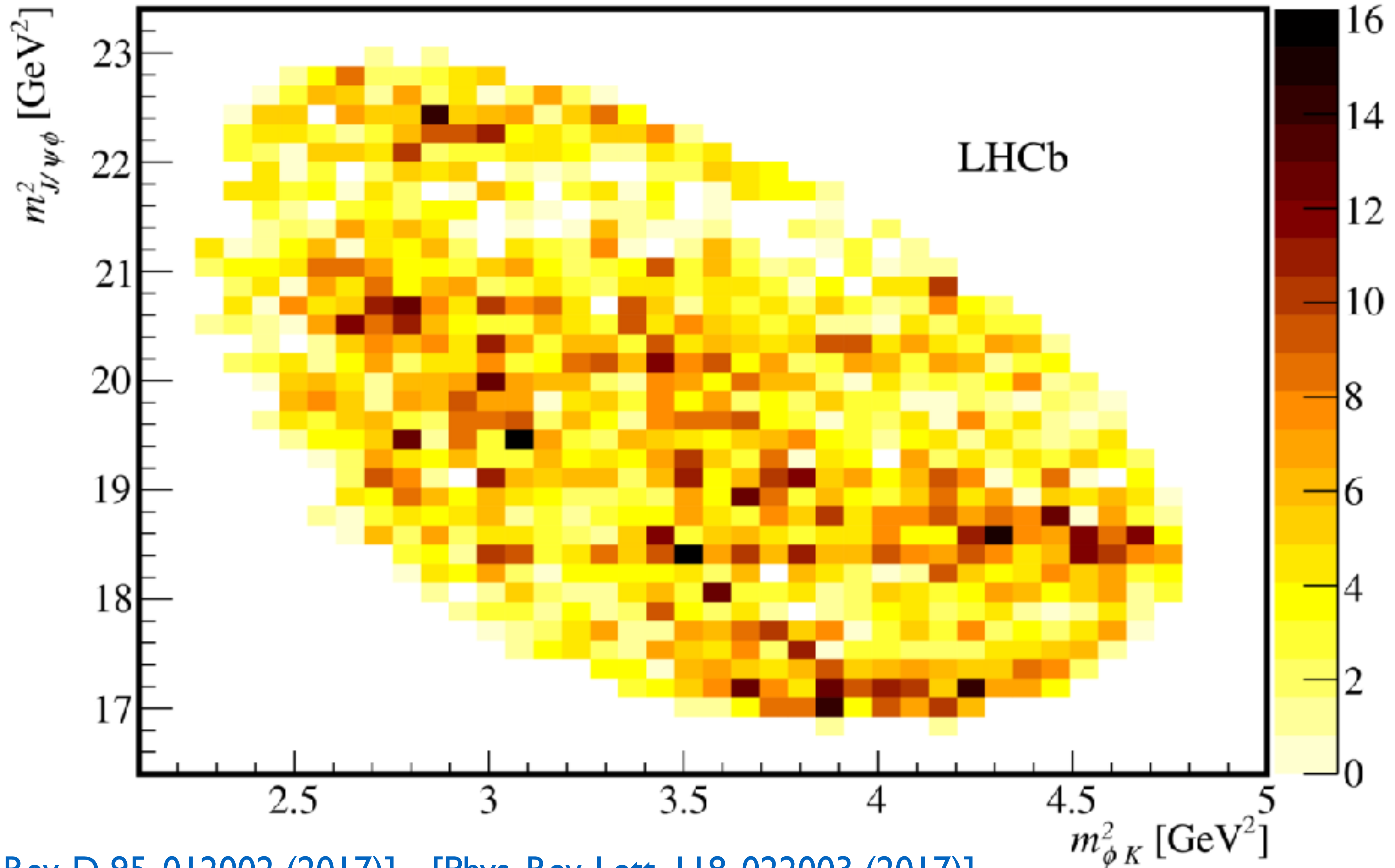
Not sufficient to just fit 1D mass distributions with ad-hoc assumptions about K* contributions

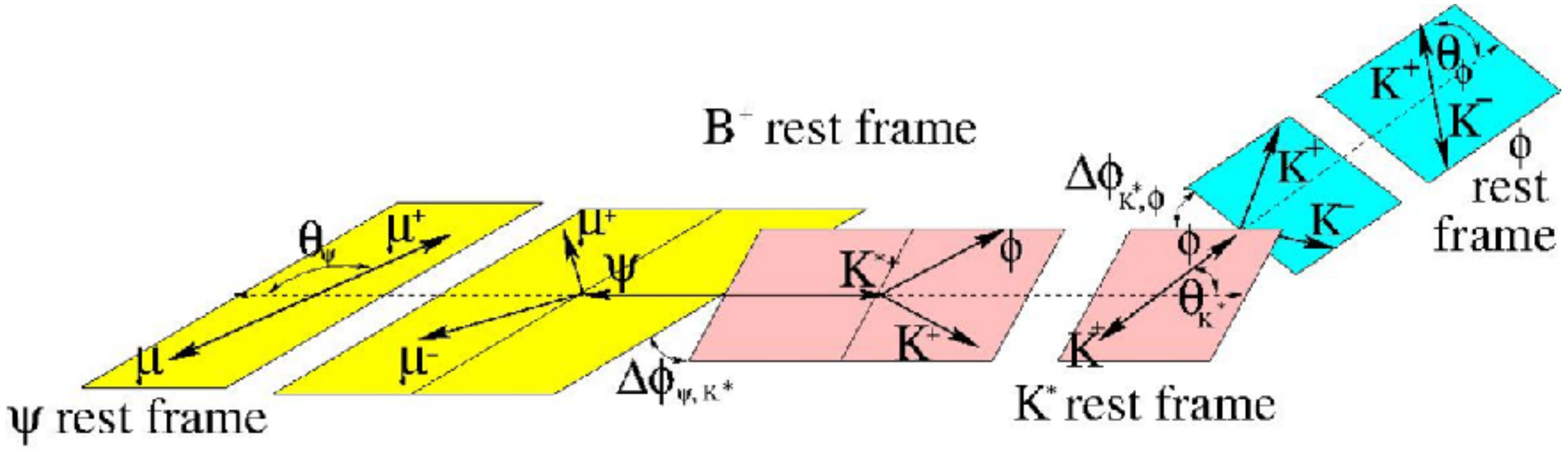
K^{*+} resonances expected to be broad (scattering expts)

6D amplitude analysis to understand structure in final state

Three interfering decay chains:

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

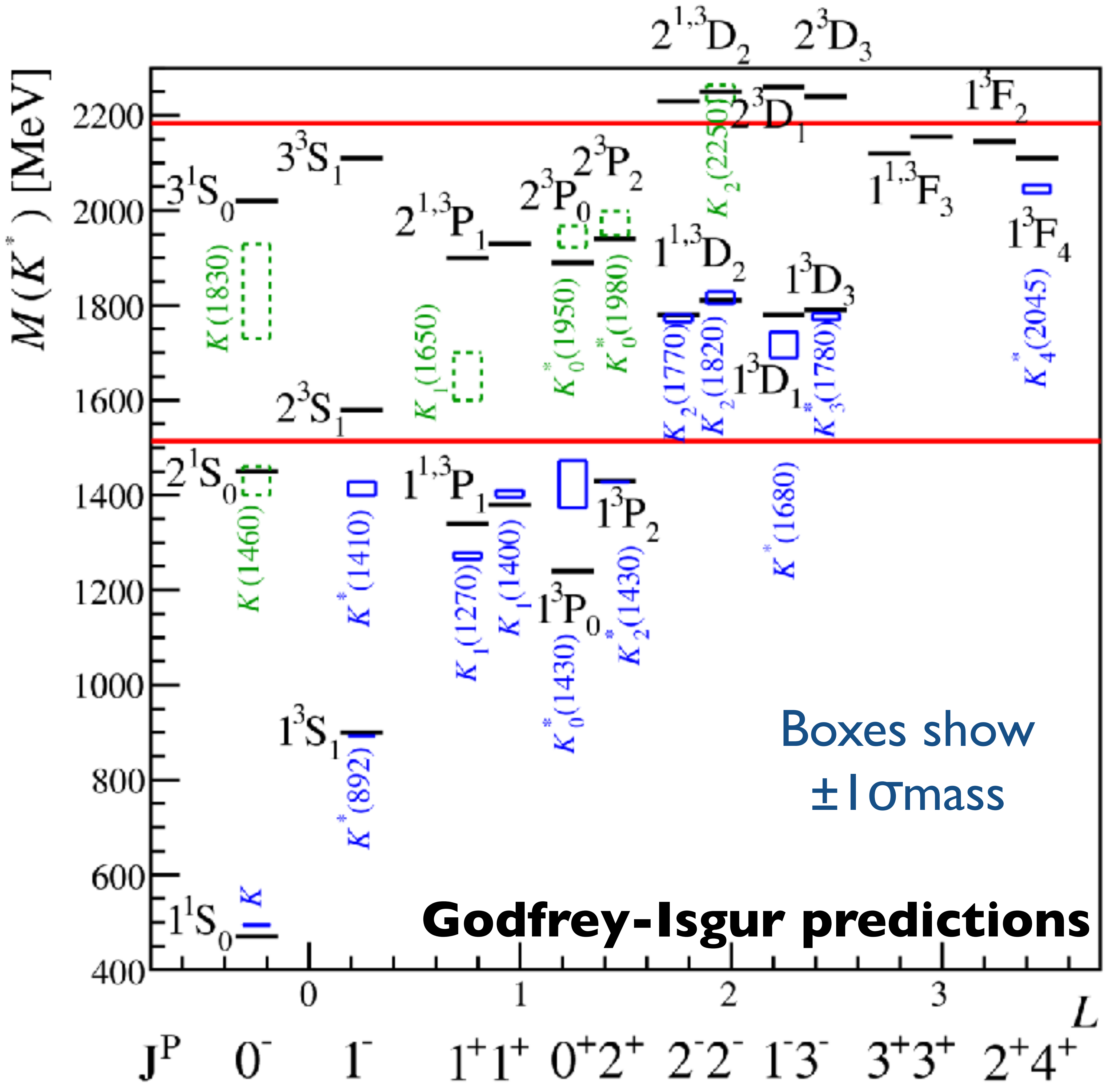




$$\Omega \equiv (\theta_{K^*}, \theta_\psi, \Delta\phi_{\psi,K^*}, \theta_\phi, \Delta\phi_{K^*,\phi})$$

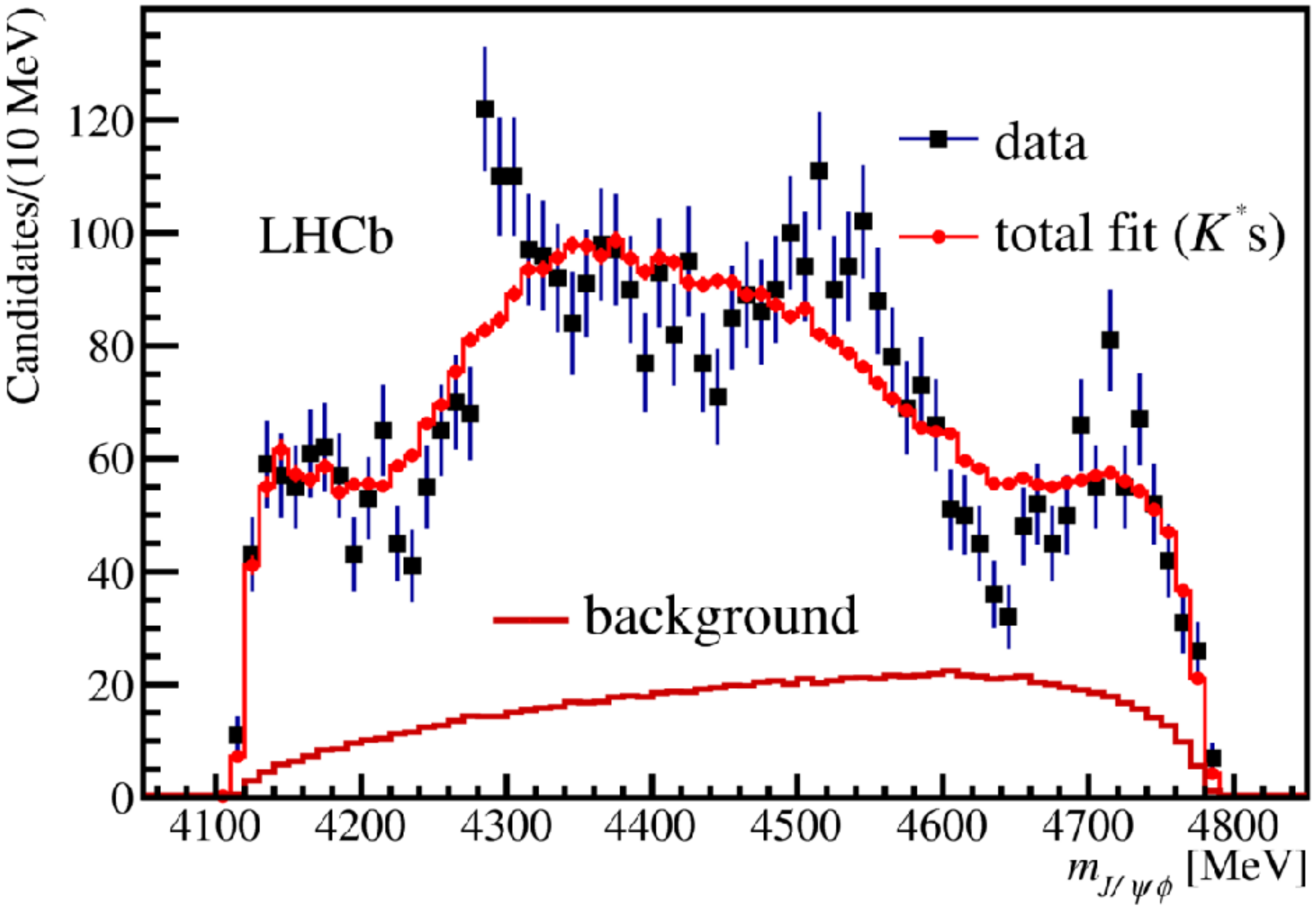
[Phys. Rev. D 95, 012002 (2017)] [Phys. Rev. Lett. 118, 022003 (2017)]

Which *K** resonances to include?



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

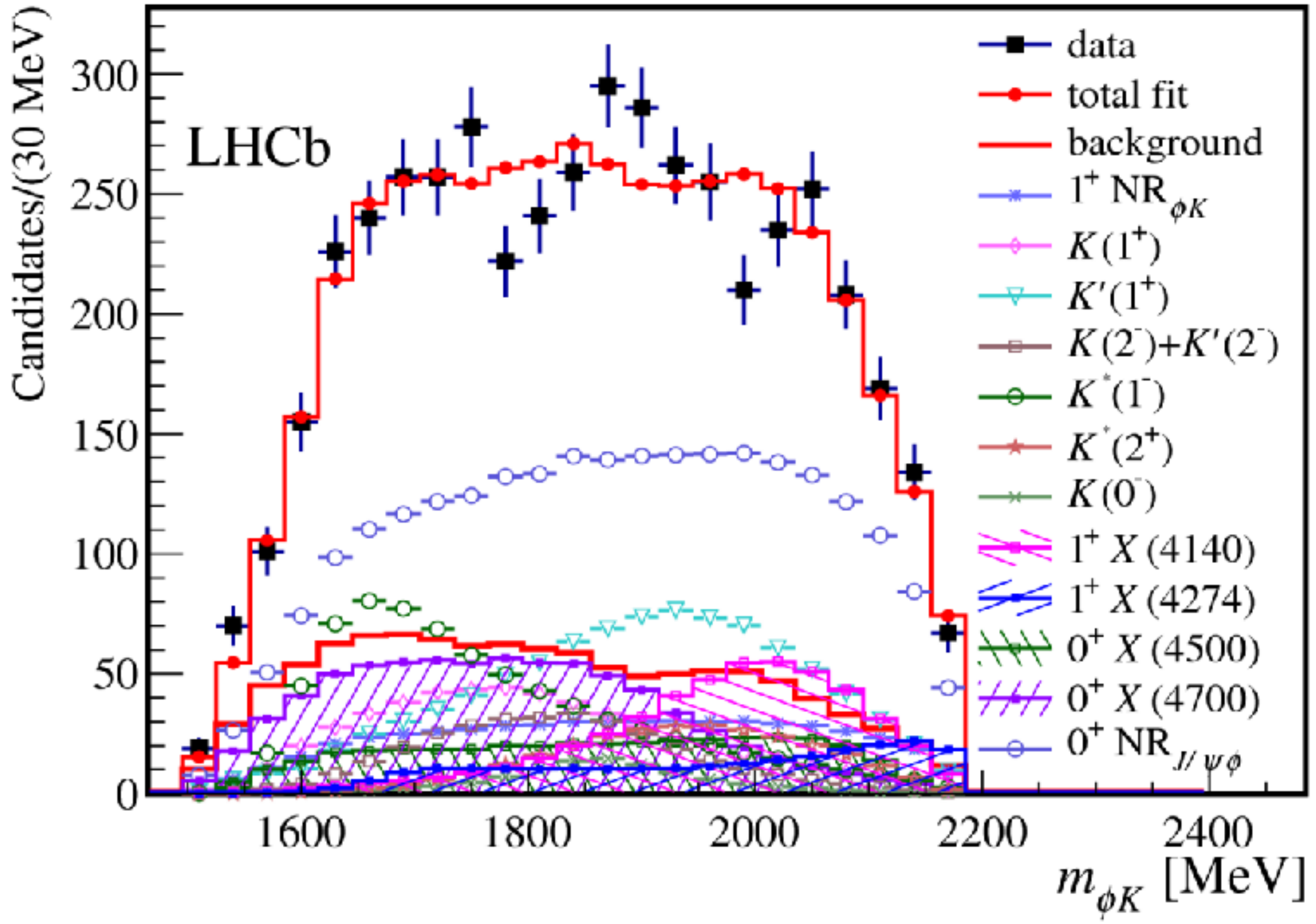
Higher spin states expected to be suppressed in B decays due to orbital angular momentum required to produce them

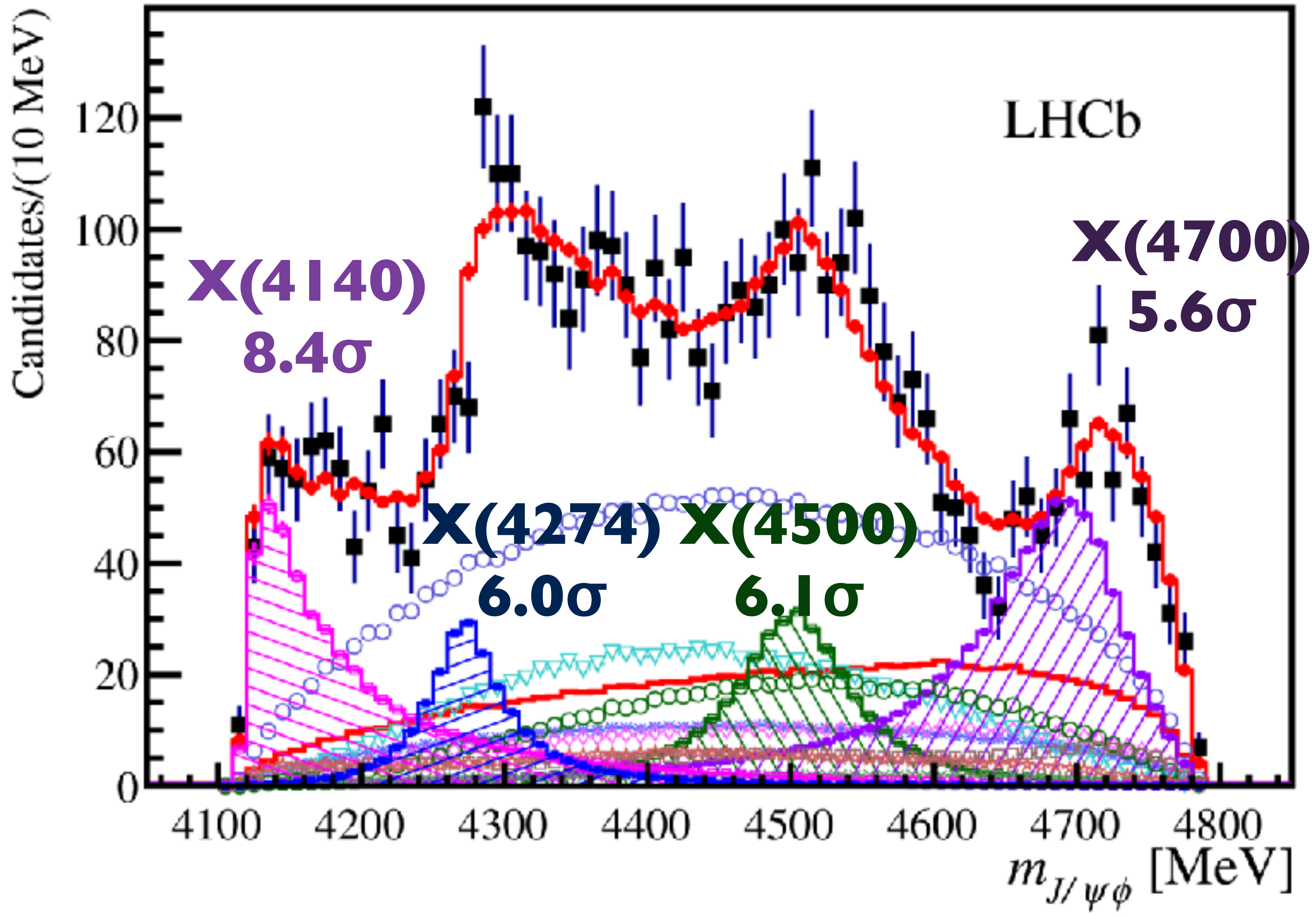


104 free parameters in fit

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

Fit results including X → J/ψφ 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%

Contribution	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)$^{\pm}$ → $B_s\pi^{\pm}$?

4.8σ 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

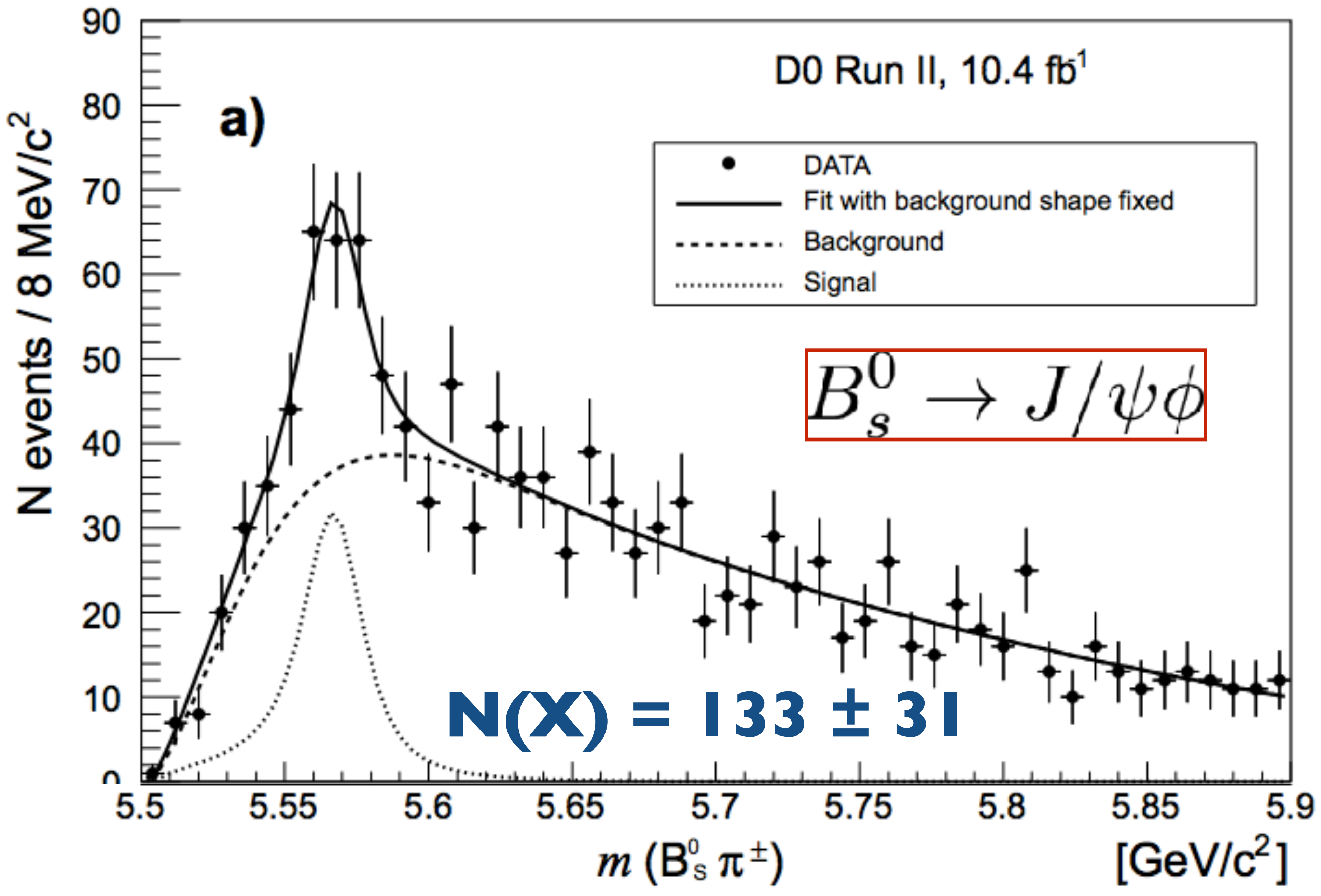
$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\mathrm{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\mathrm{MeV}/c^2$$

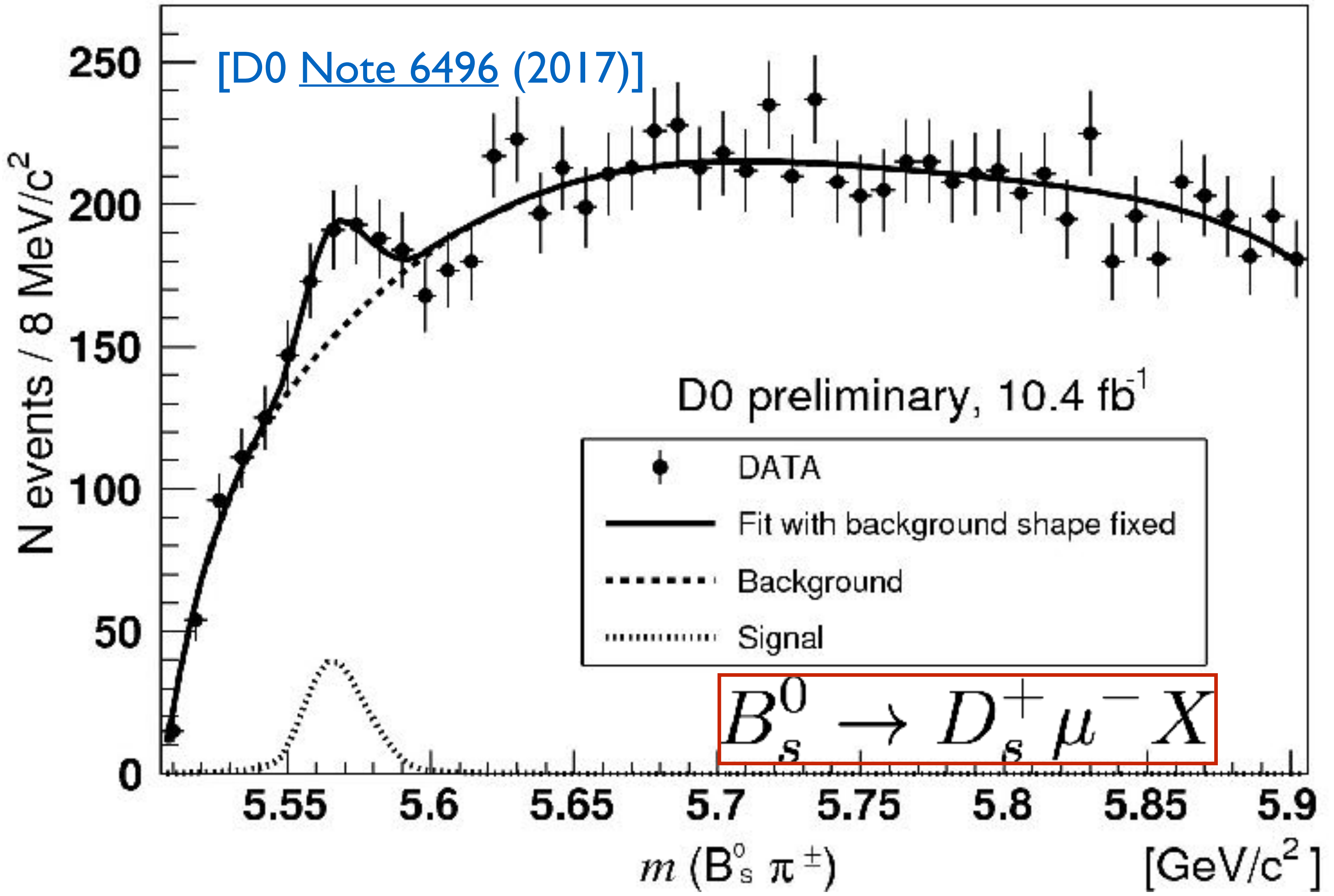
Possible ***bsud*** tetraquark/molecule but difficult to explain when considering QCD chiral symmetry, heavy quark symmetry and threshold effects.

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

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

[D0 PRL 117, 022003 (2016)]





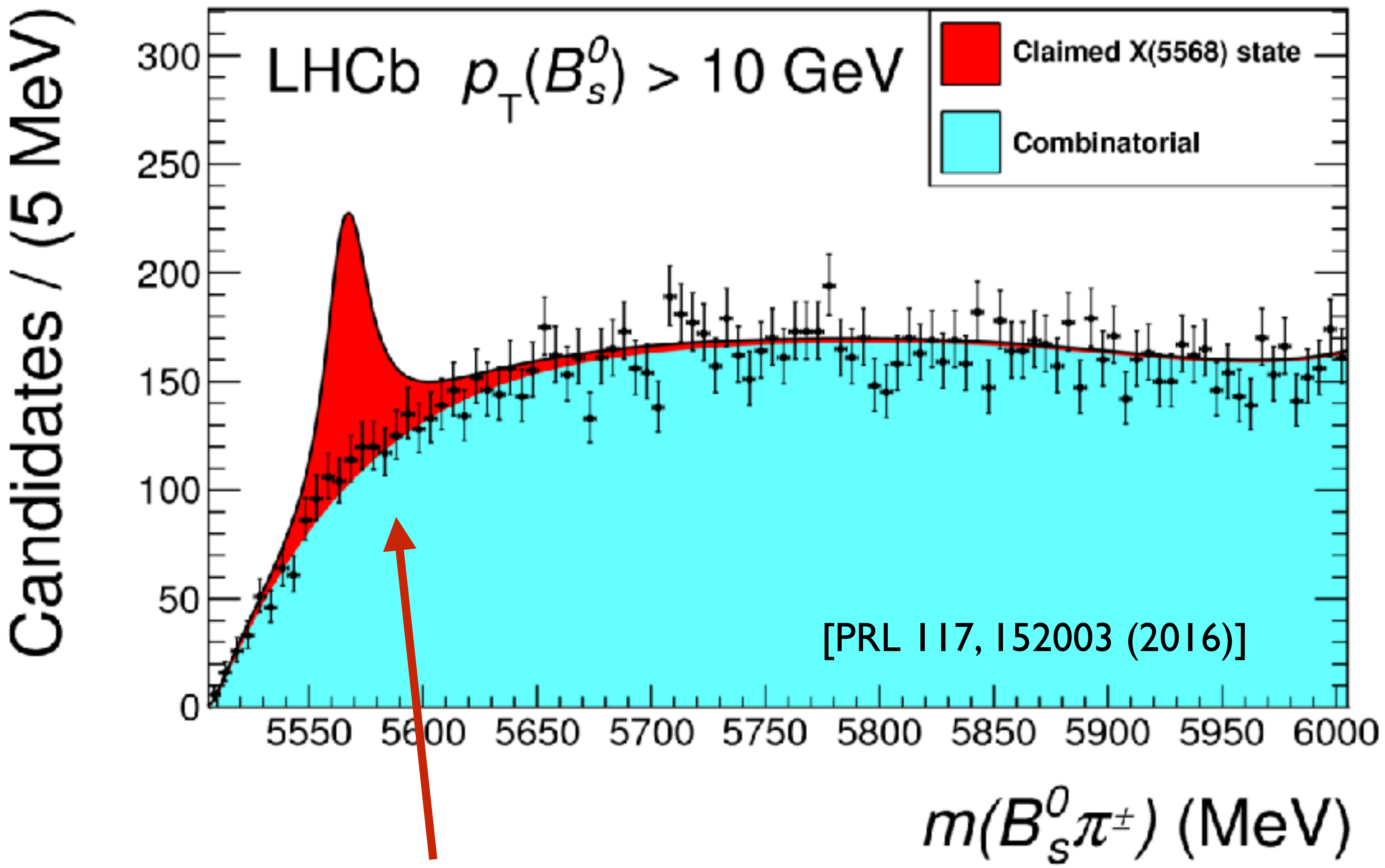
LHC searches for X(5568)$^{\pm}$

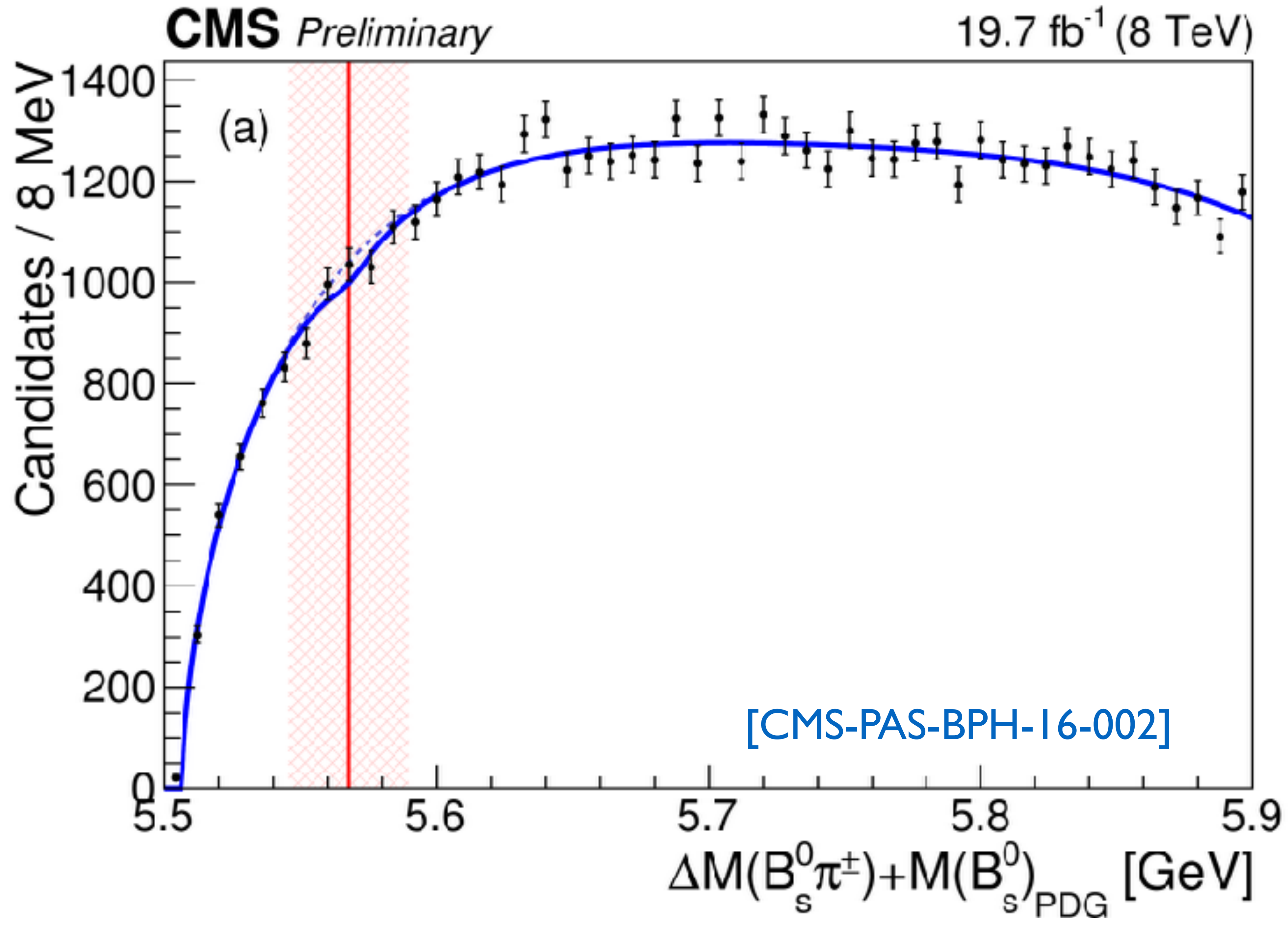
LHCb use >100k B_s mesons and combine with $\pi^{\pm}$.
Sample 20x larger than D0 and much less background.

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.

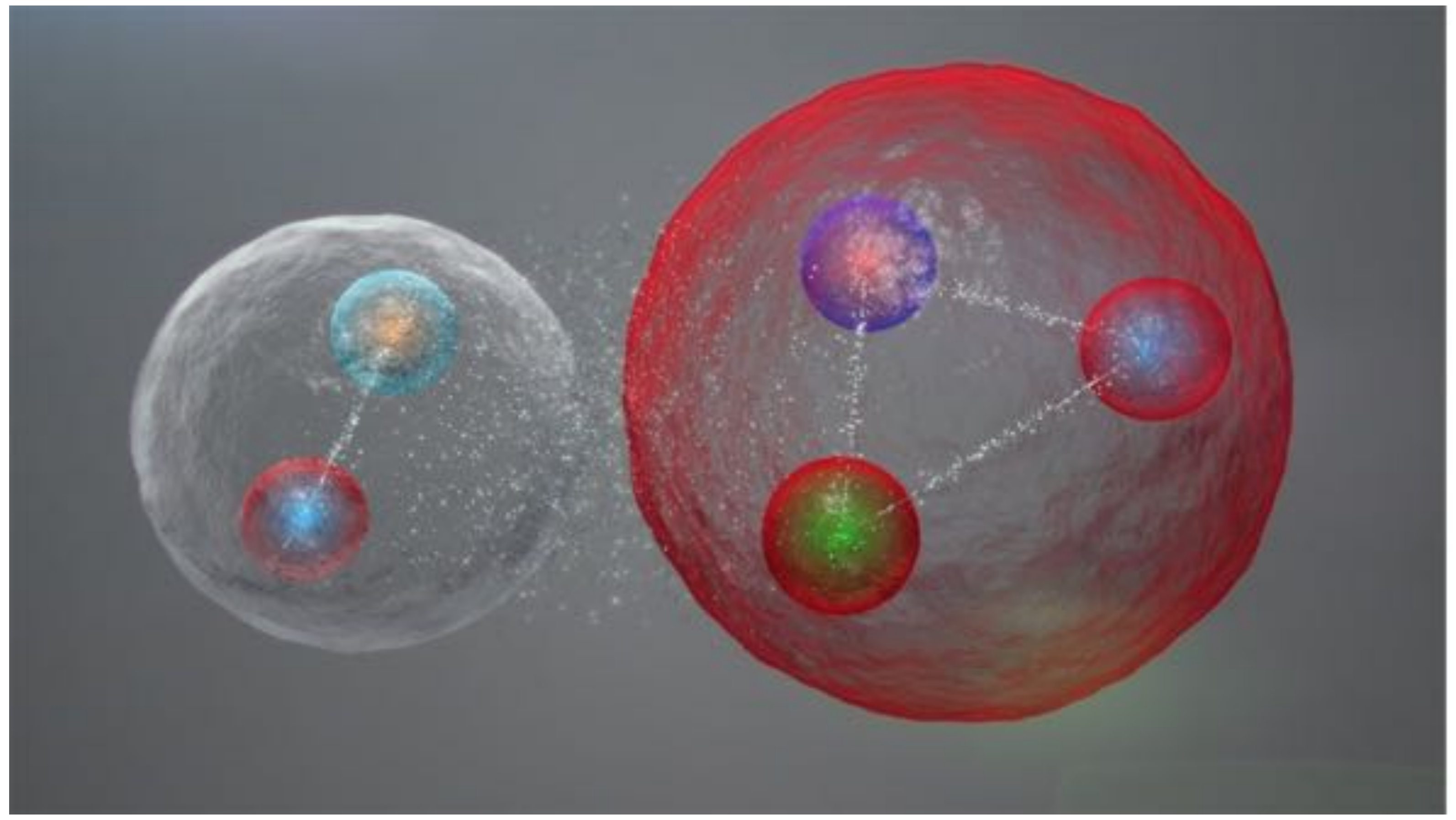
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 5\,\mathrm{GeV}/c) < 0.009\,(0.010)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$
$$\rho_X^{\mathrm{LHCb}}(B_s^0\ p_{\mathrm{T}} > 10\,\mathrm{GeV}/c) < 0.016\,(0.018)\ @\ 90\,(95)\,\%\ \mathrm{CL}$$

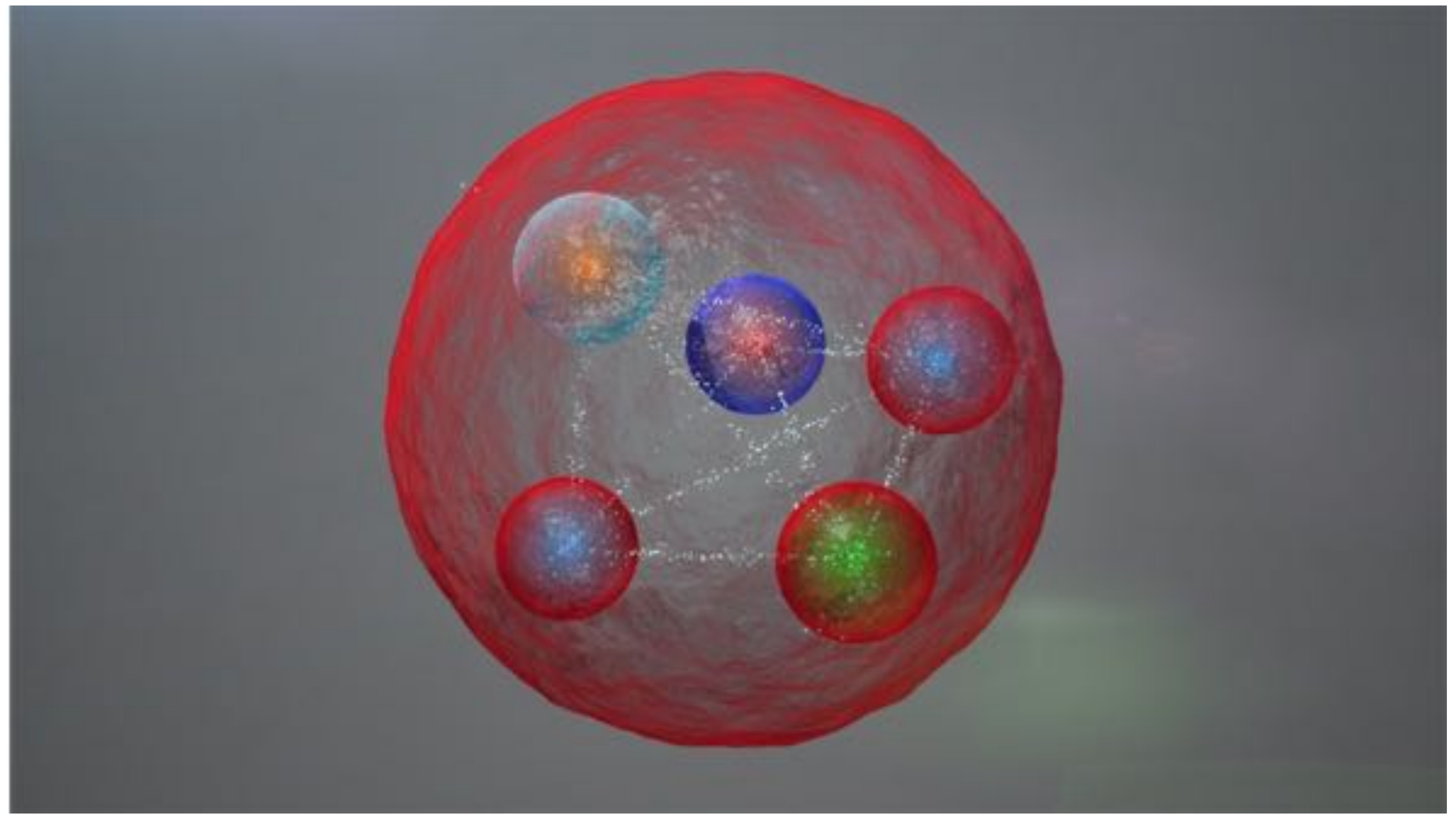




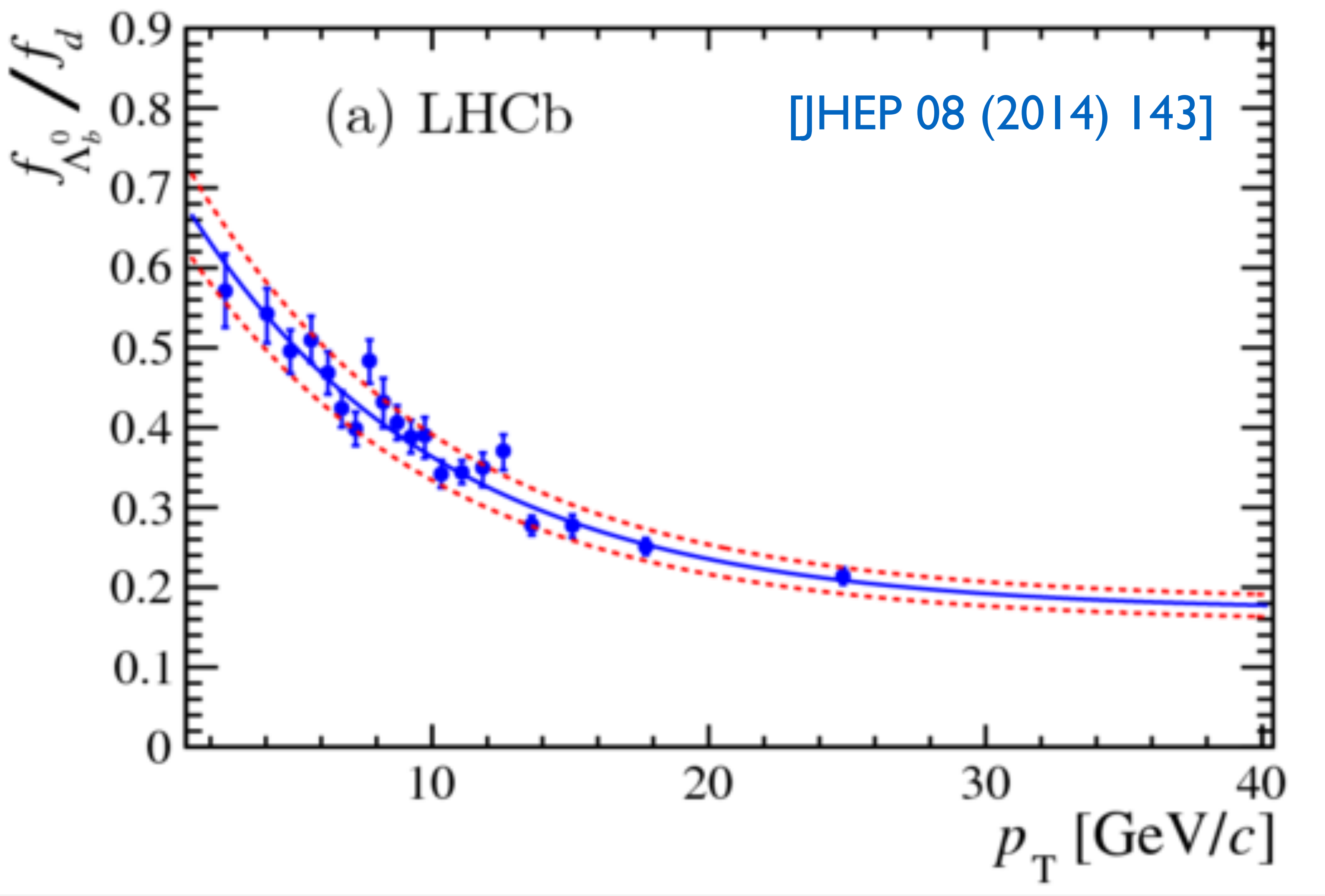
How signal would look according to D0 result

Exotic baryons





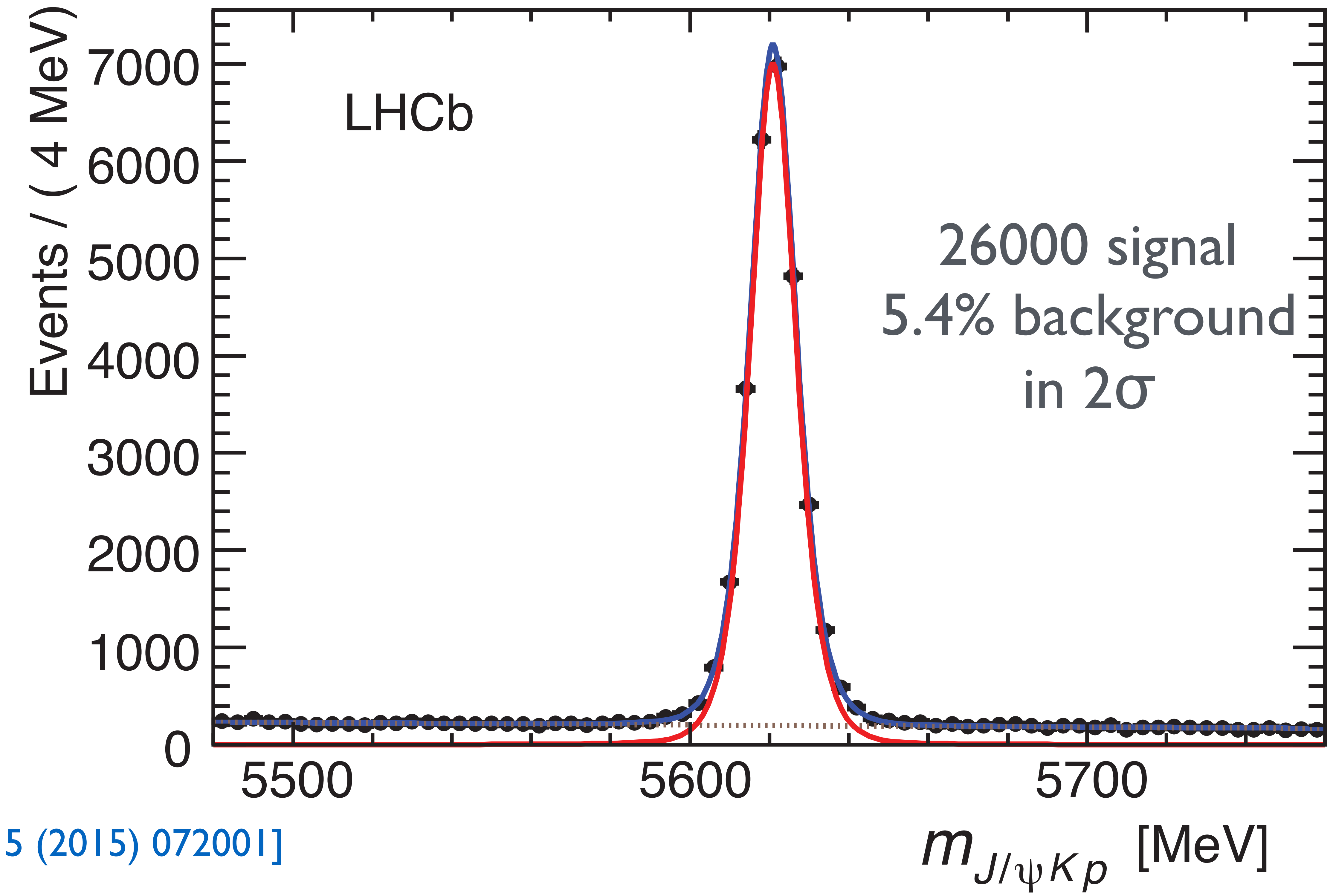
Pentaquark observation

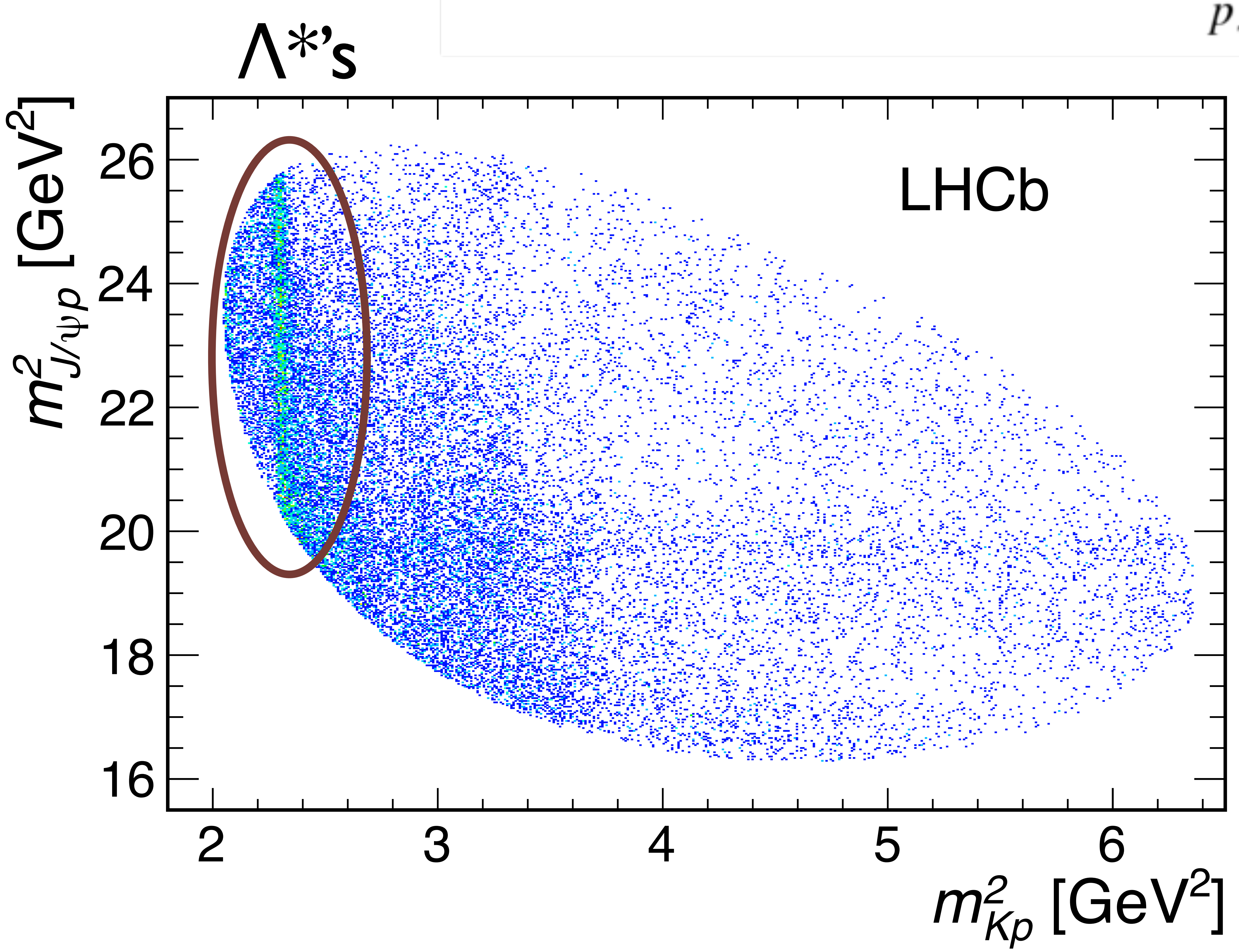


Large production of b-baryons at LHC.

Many more Λb in LHCb than central detectors.

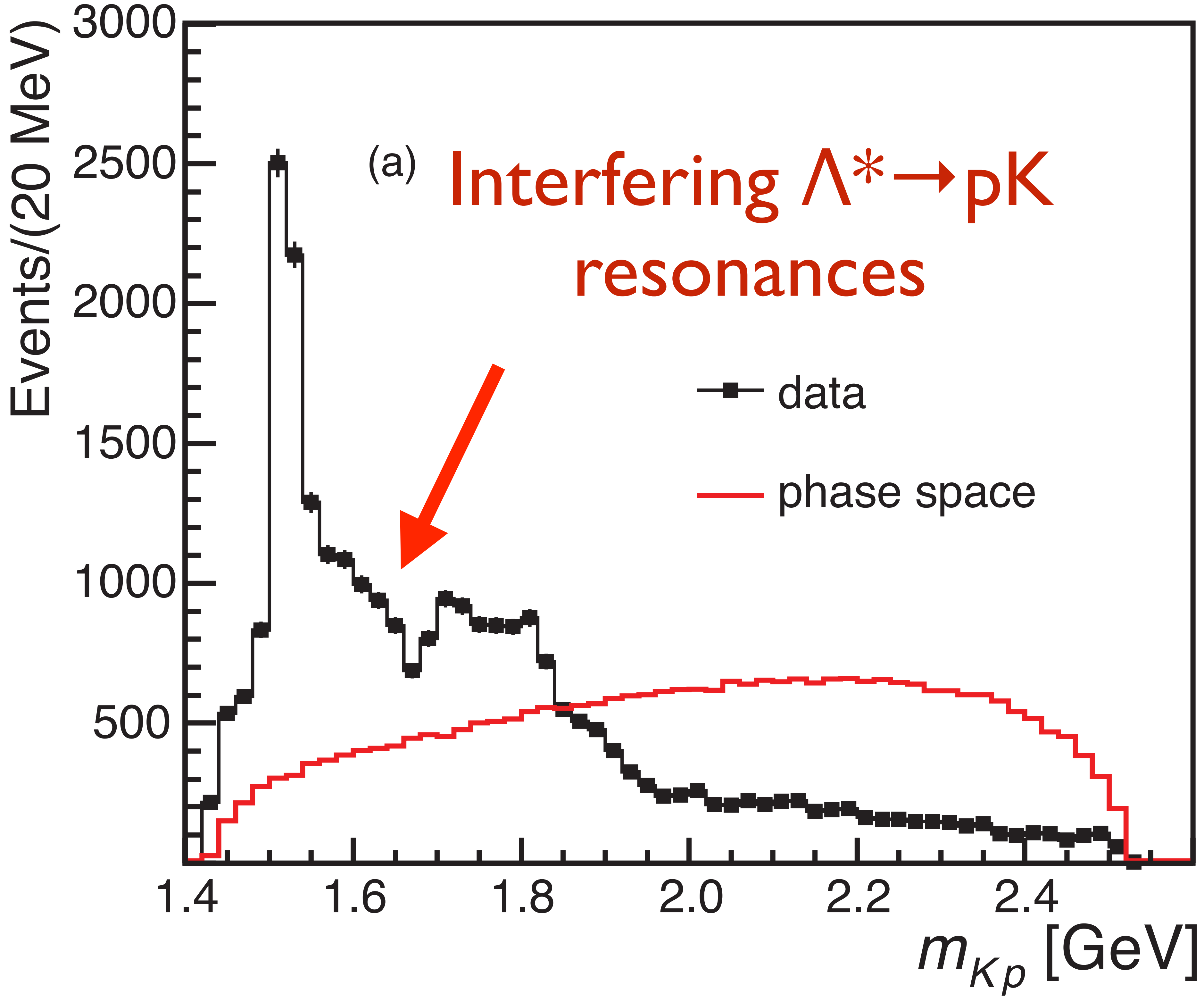
$$\Lambda_b^0 \to J/\psi p K^-$$

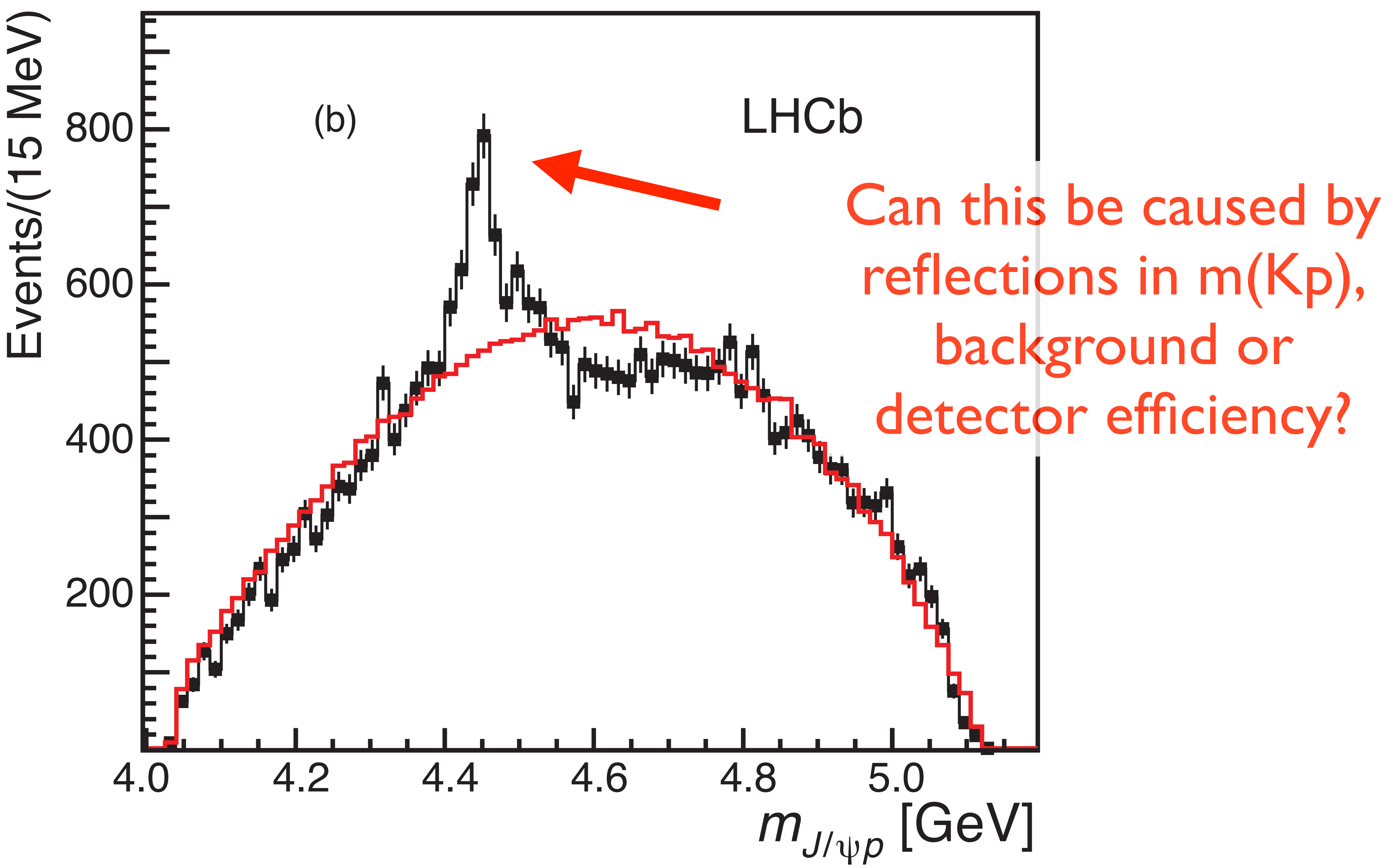


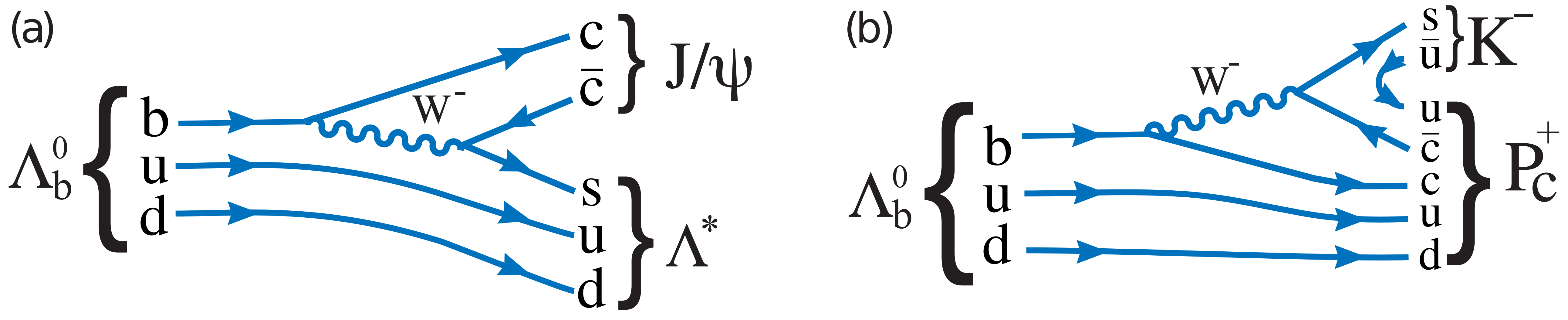


[PRL 115 (2015) 072001]

Pentaquark observation

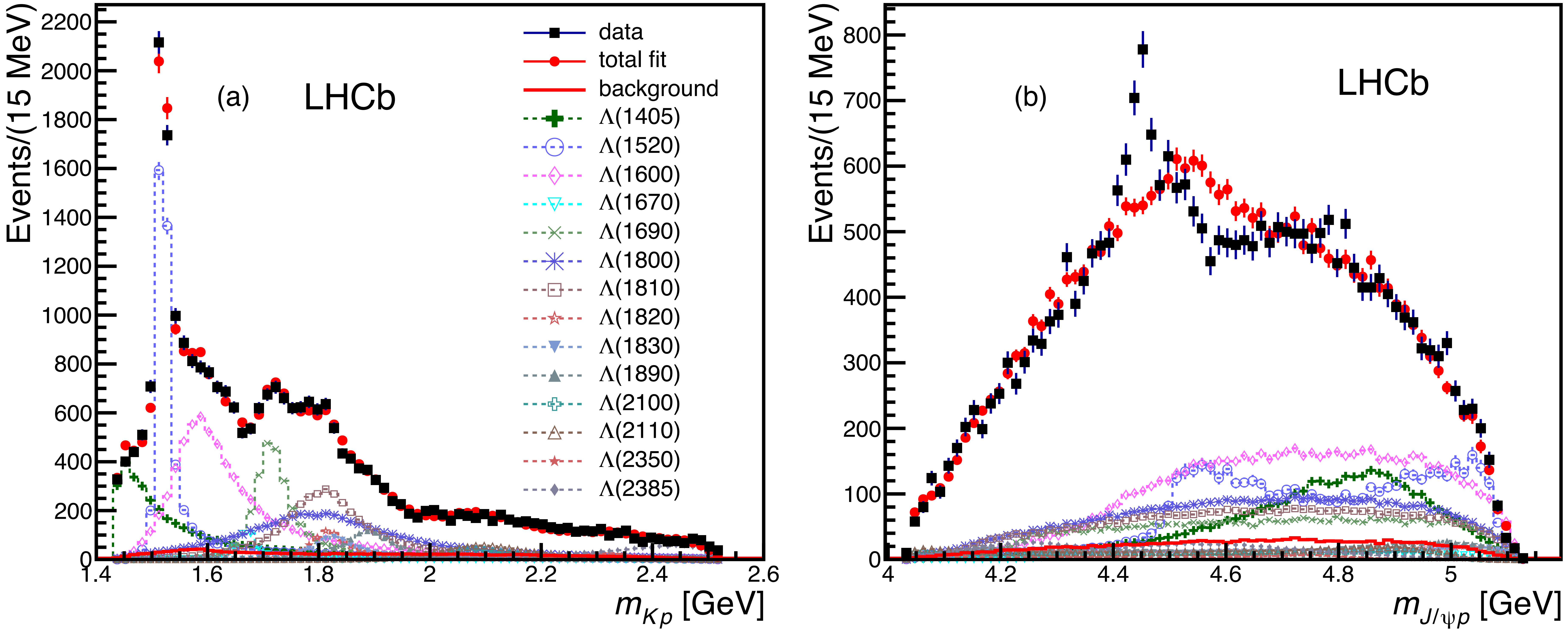






[PRL 115 (2015) 072001]

Results without P_c states

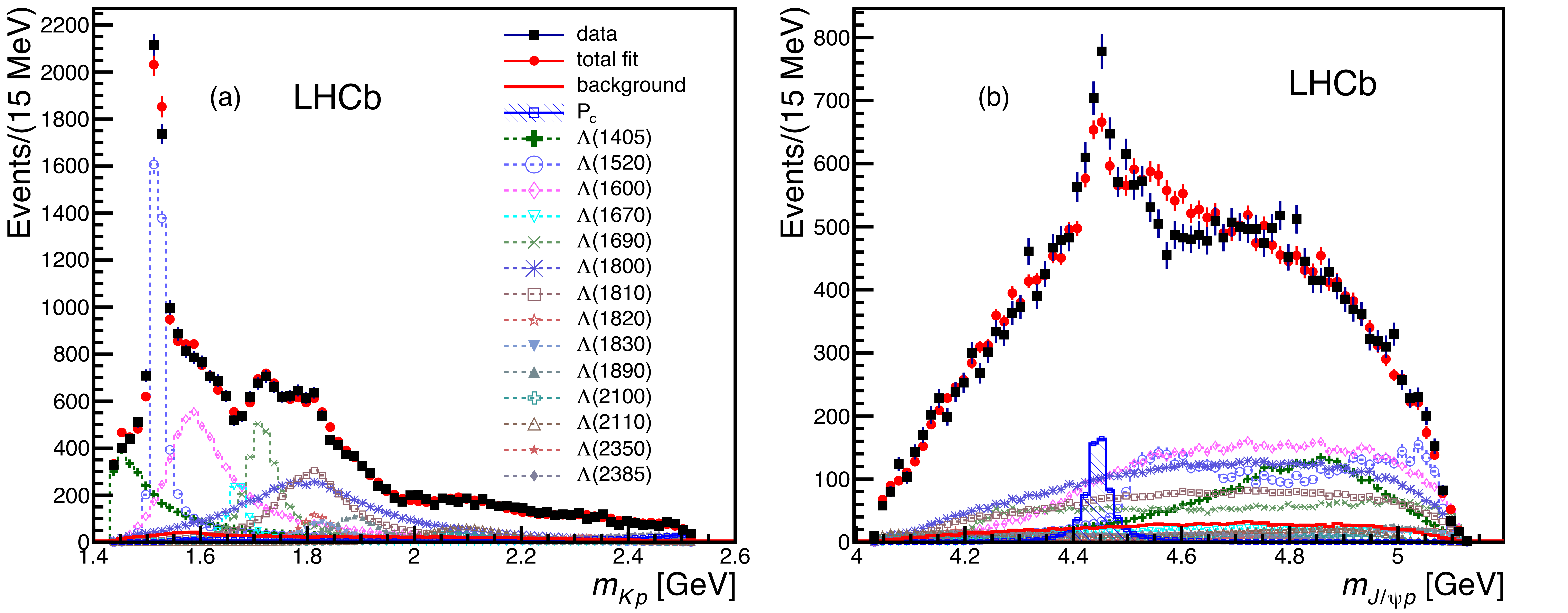


Using full set of Λ*'s the m(Kp) distribution looks good but not m(J/ψp).

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



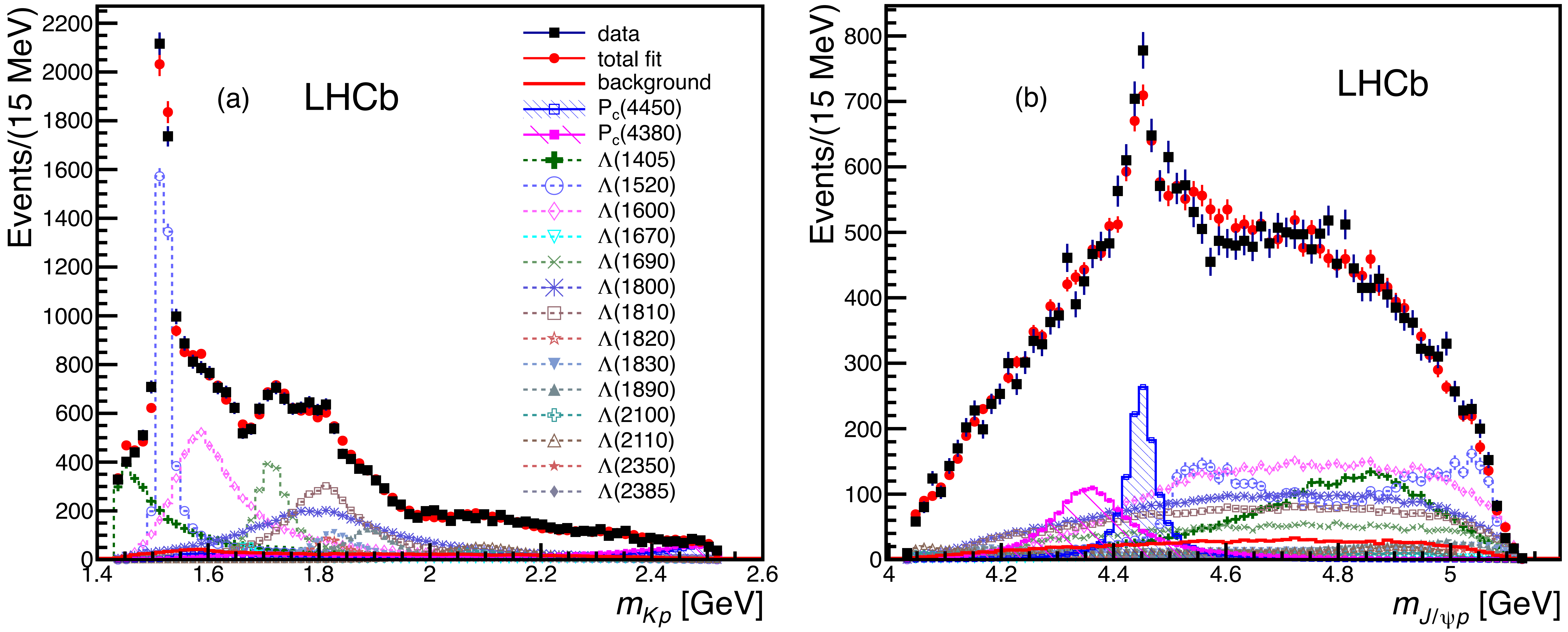
Try all Λ*'s with J^P up to $7/2^{\pm}$

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



$uud c\bar{c}$

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

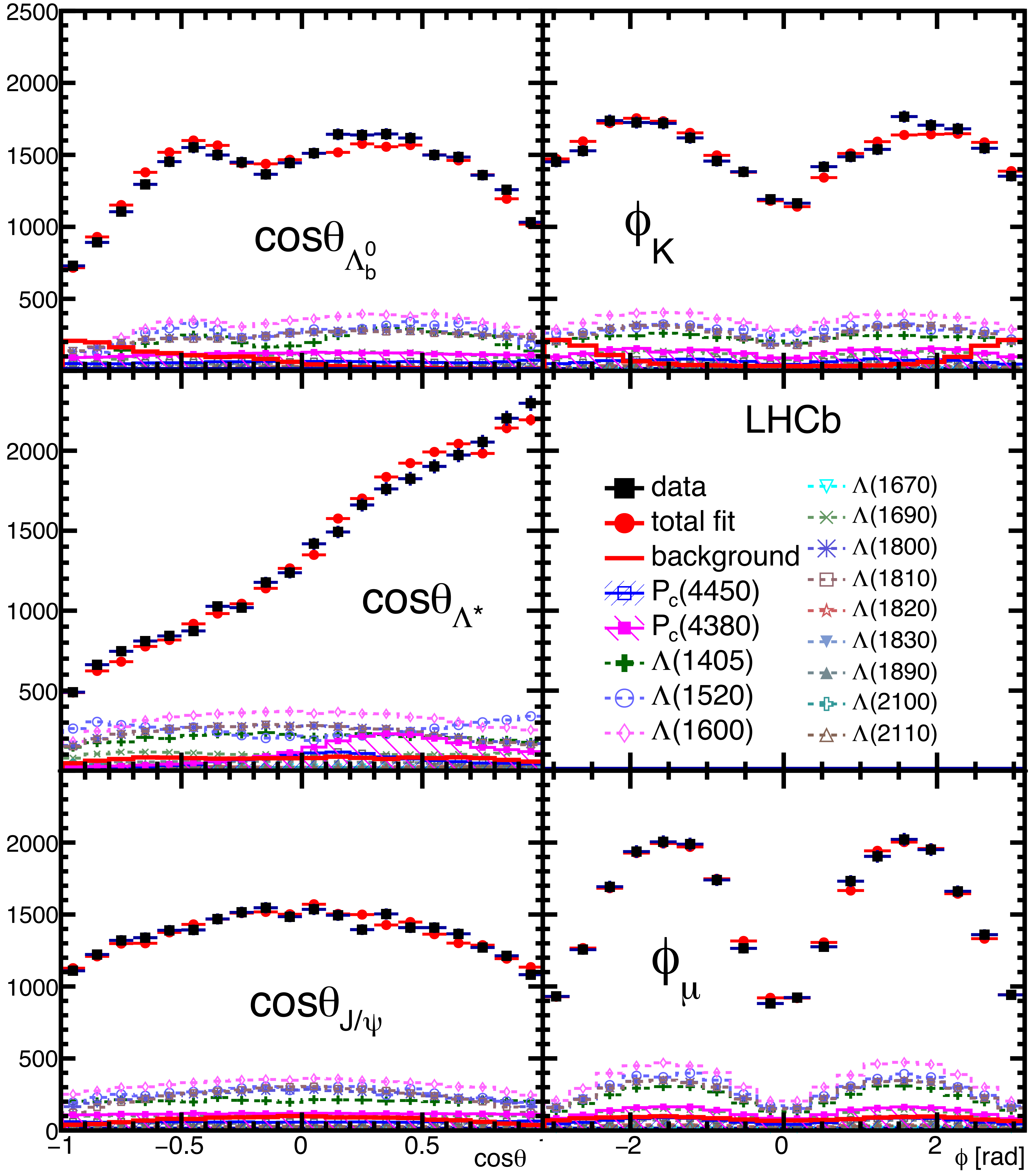
Significance evaluated using toy simulation

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]

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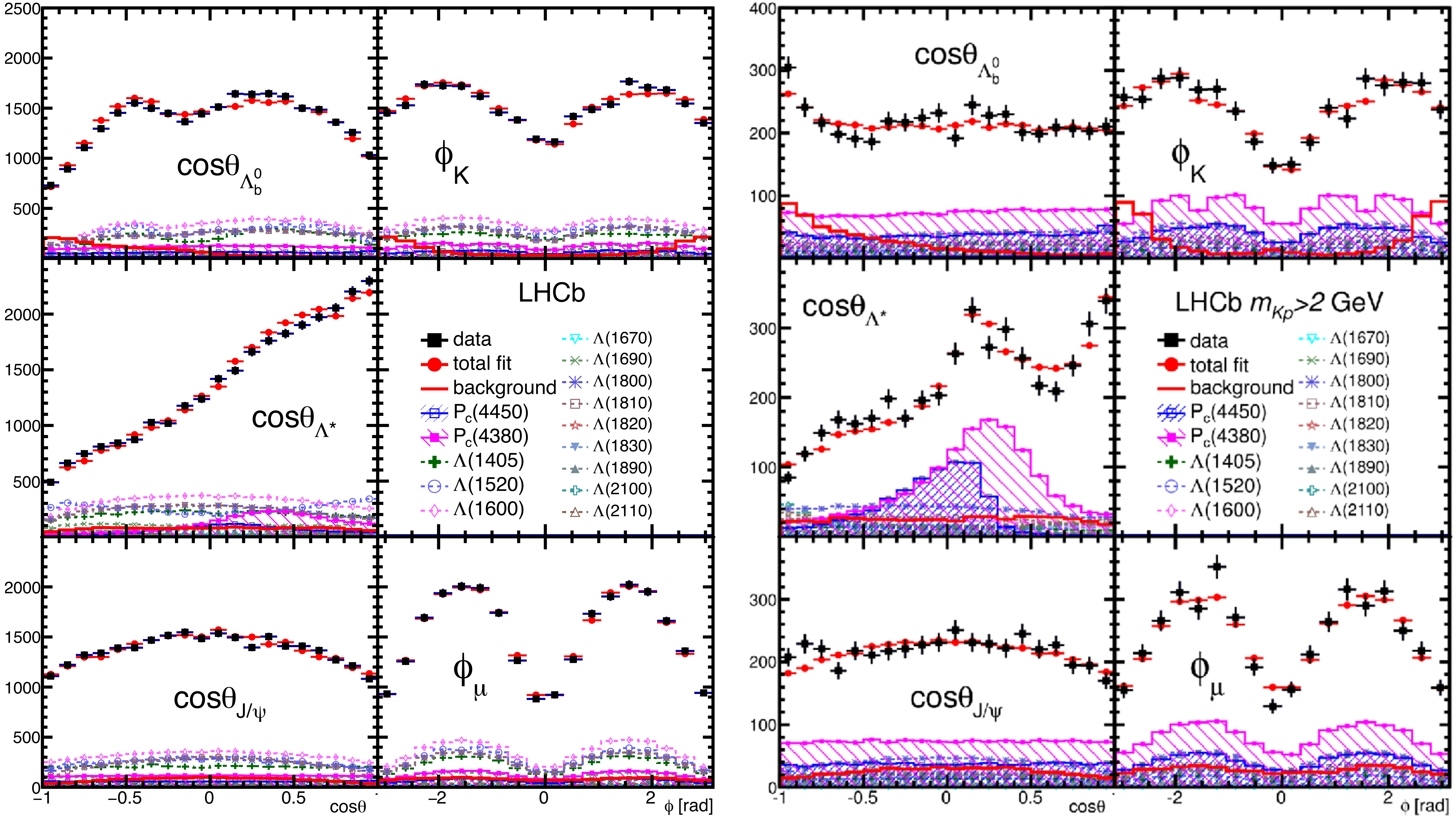
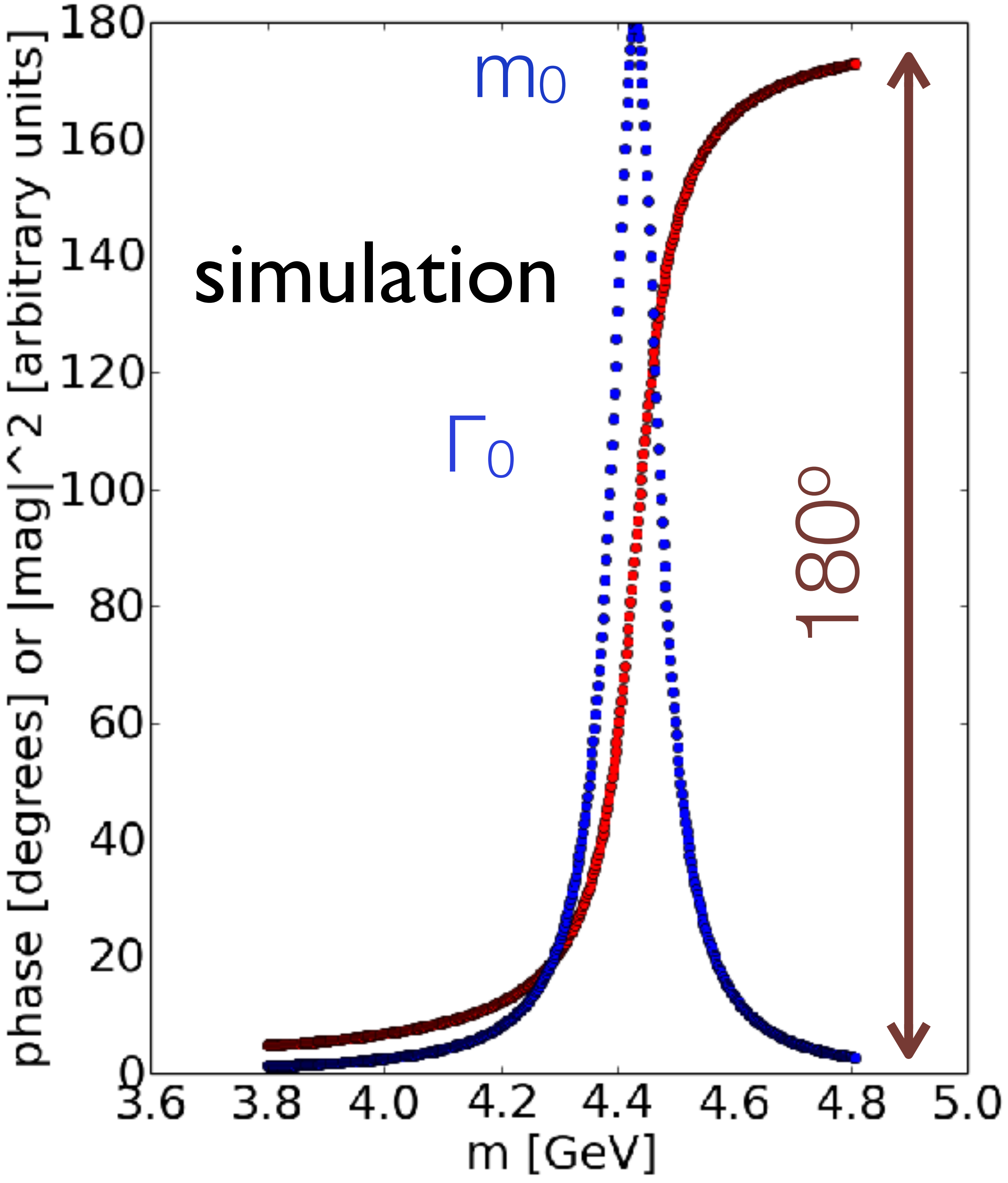
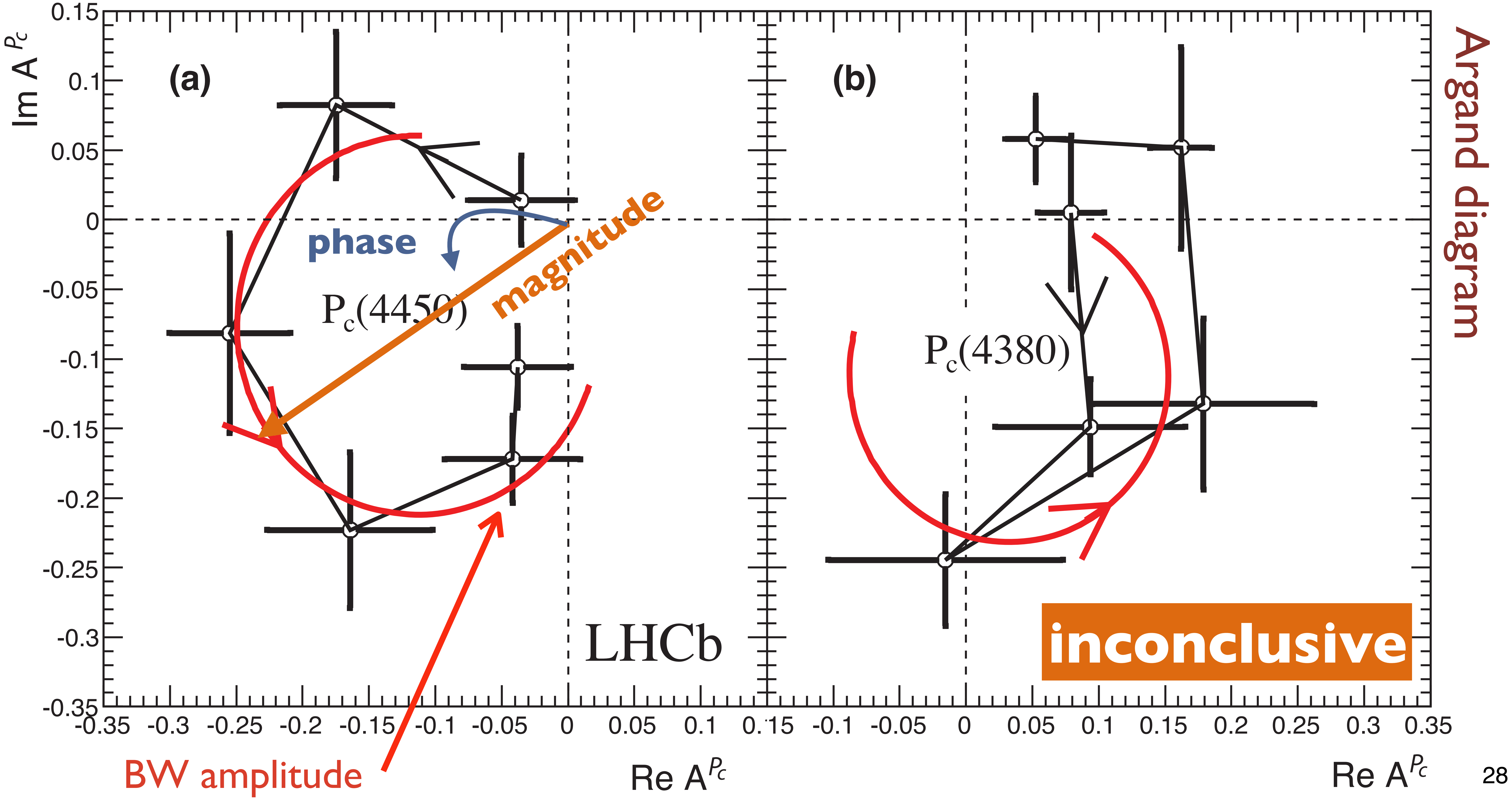


[PRL 115 (2015) 072001]

Resonant behaviour - a bound state?

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





Pentaquark model-independent

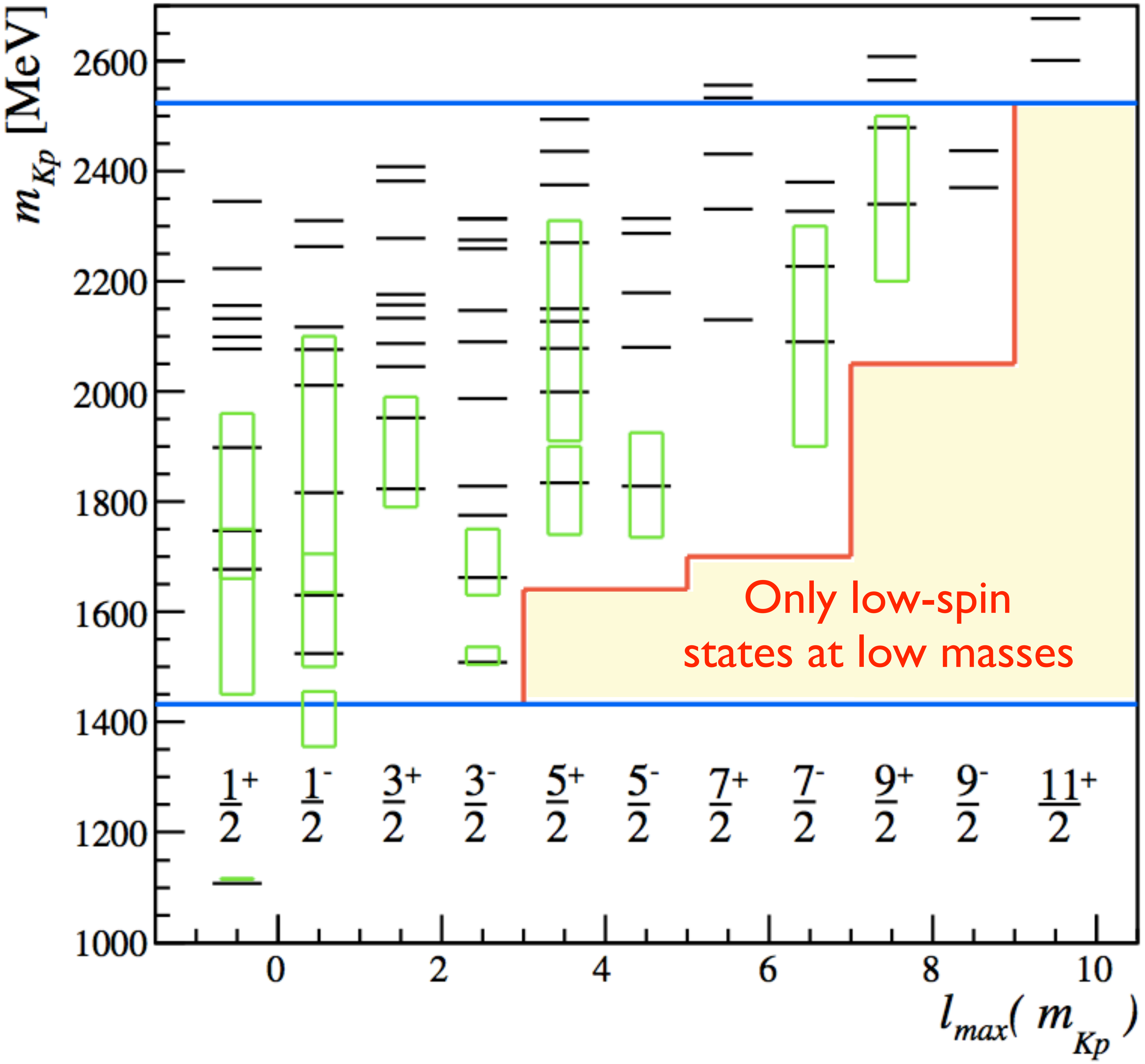
Λ^* spectrum is largest systematic uncertainty in observation of P_c states.

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*

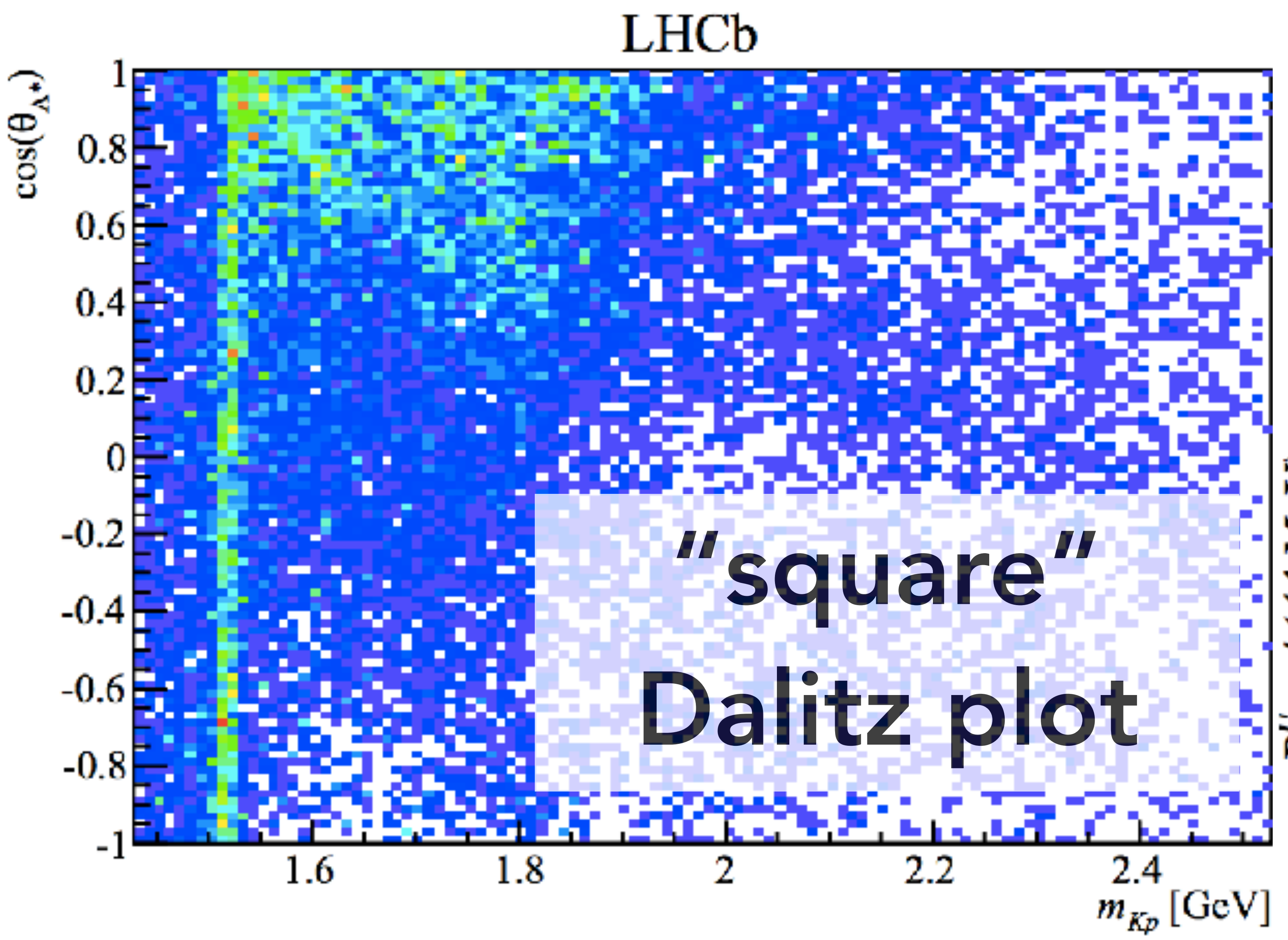
Well established Λ* states

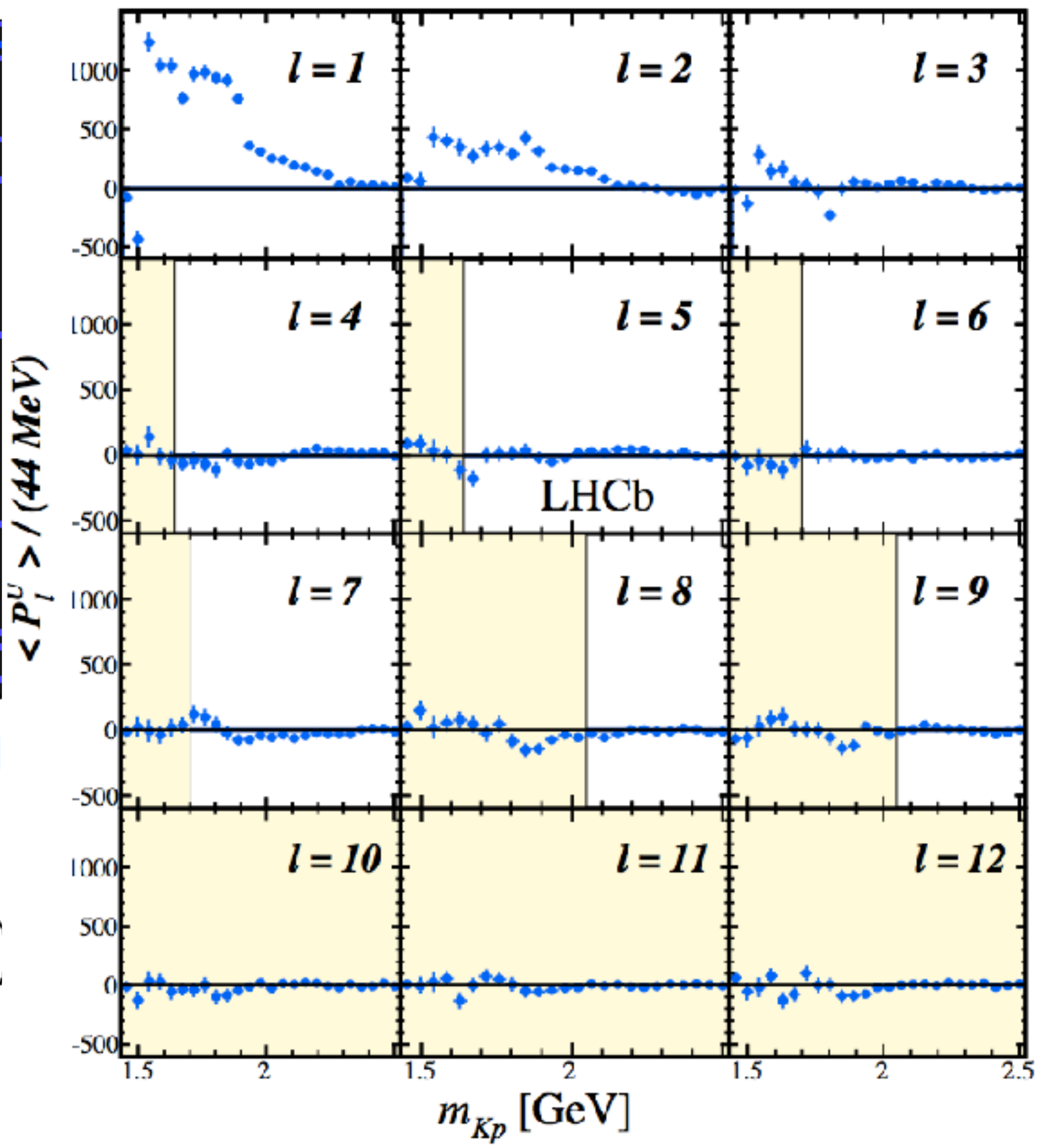


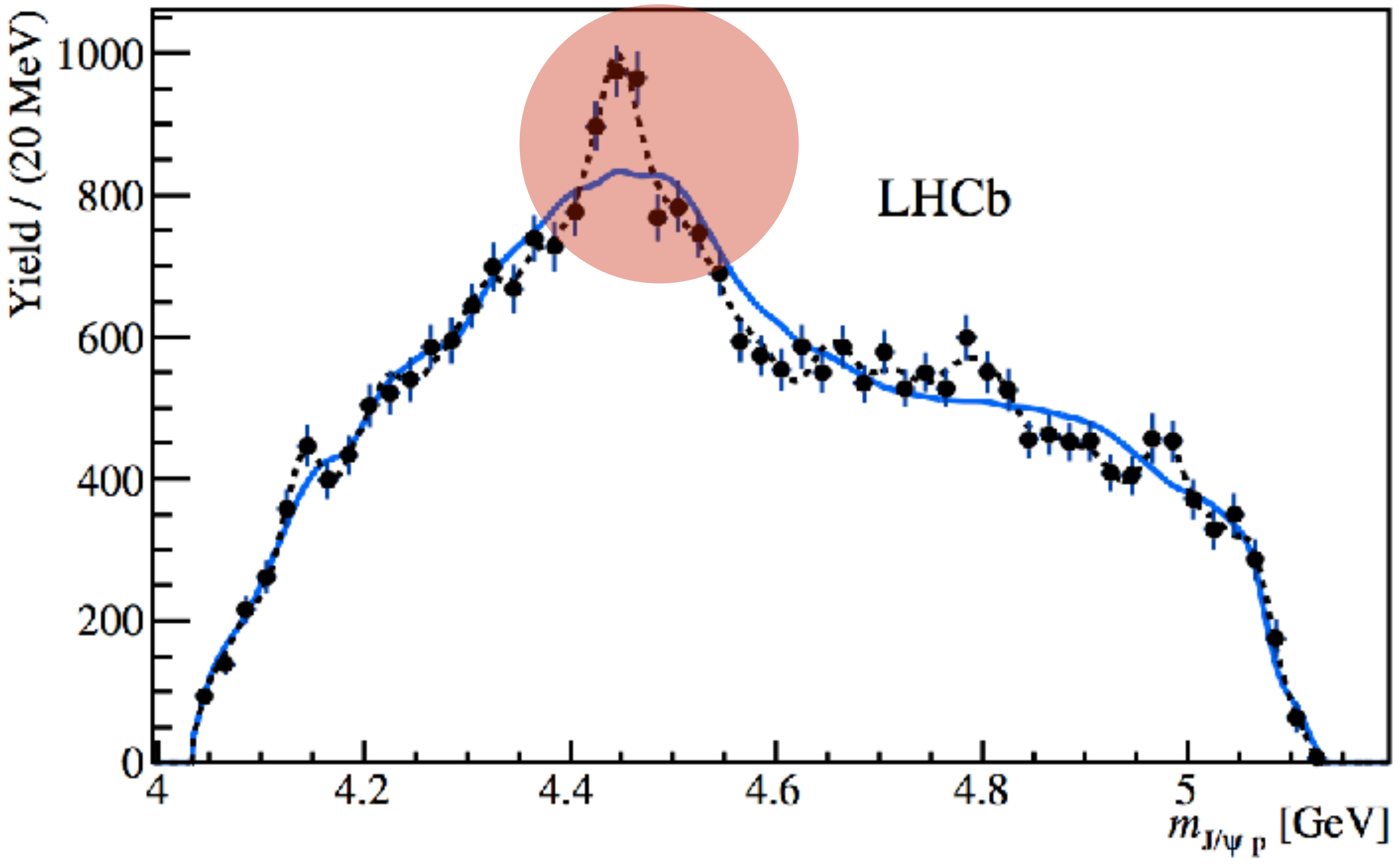
Extension of [BaBar PRD 79 (2009) 112001]

[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 (Kp) spin which is present in the data at a given m(Kp) value

filter out maximum spin for each m(Kp)

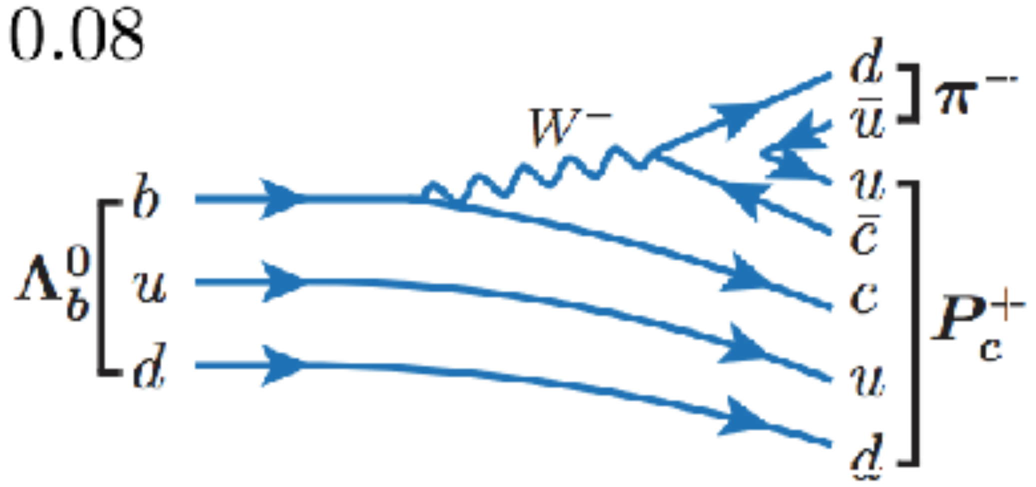
Null hypothesis (Λ* only) rejected at **9σ**

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

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

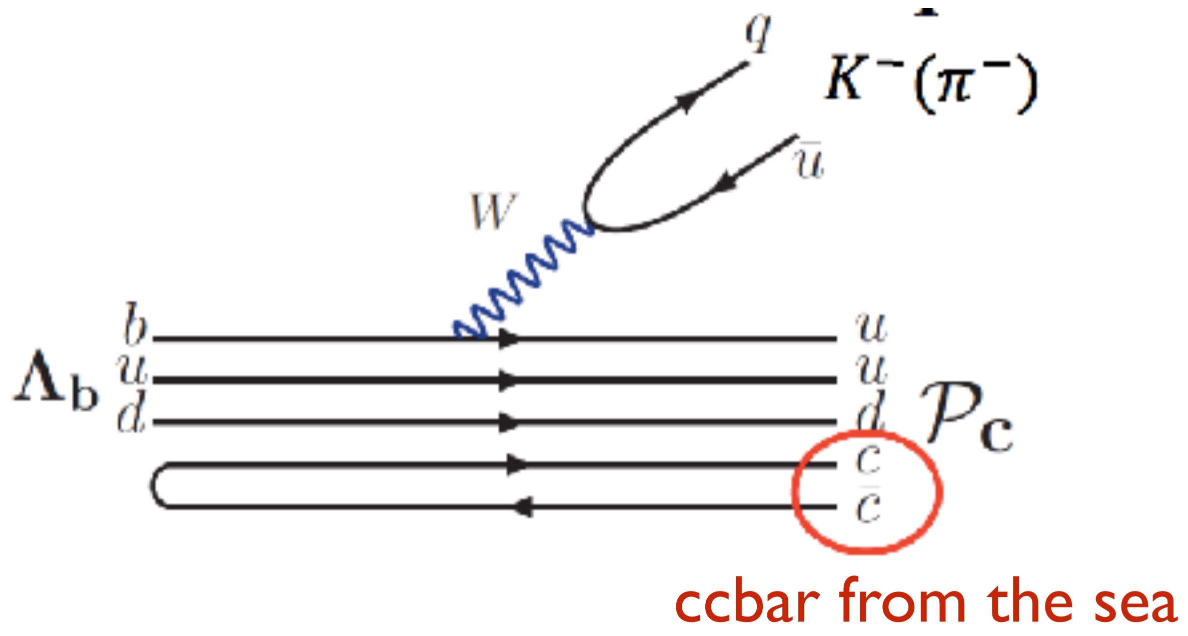
$$R_{\pi^-/K^-} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to \pi^- P_c^+)}{\mathcal{B}(\Lambda_b^0 \to K^- P_c^+)} \approx 0.07 - 0.08$$

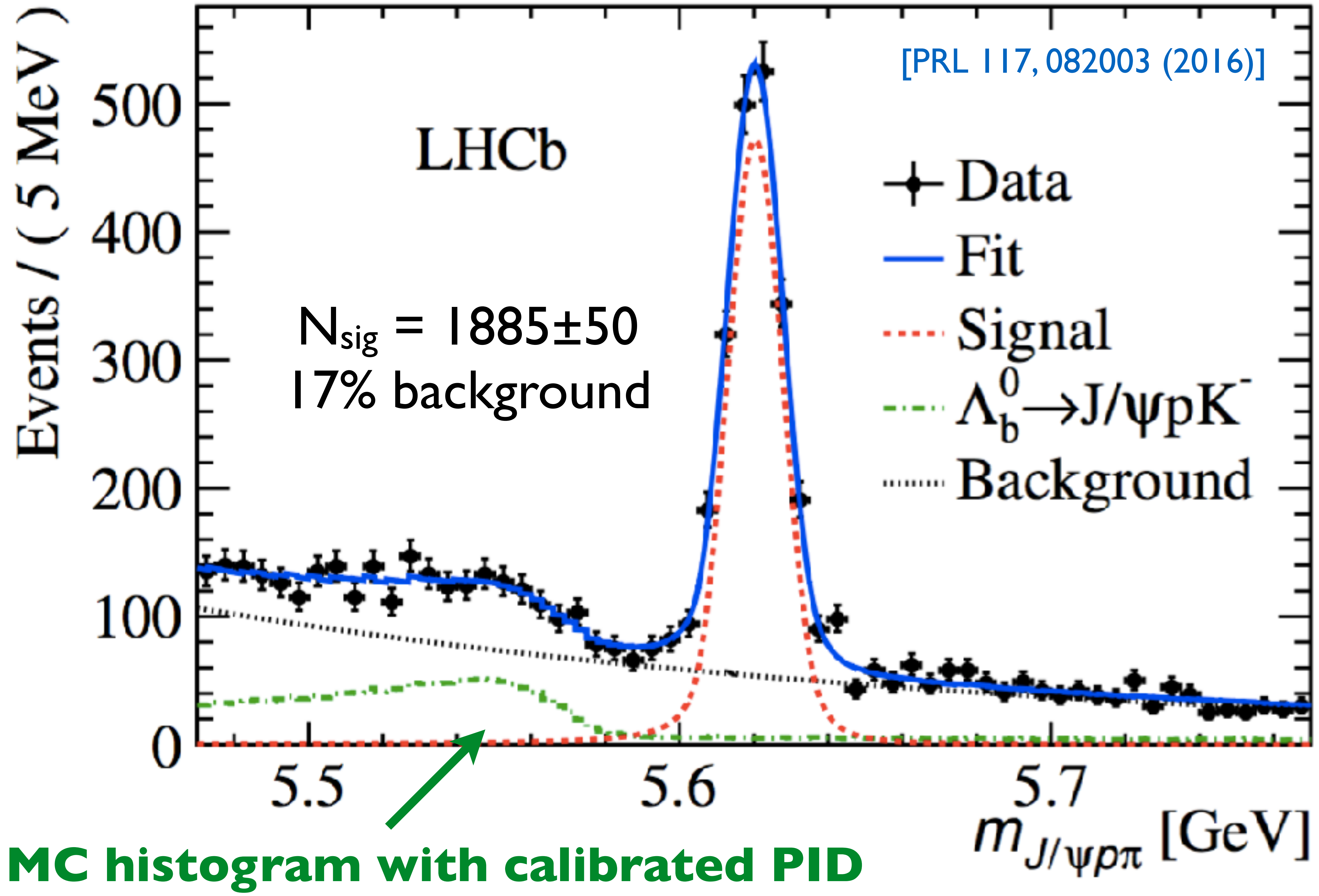
[Cheng et al. PRD 92, 096009 (2015)]

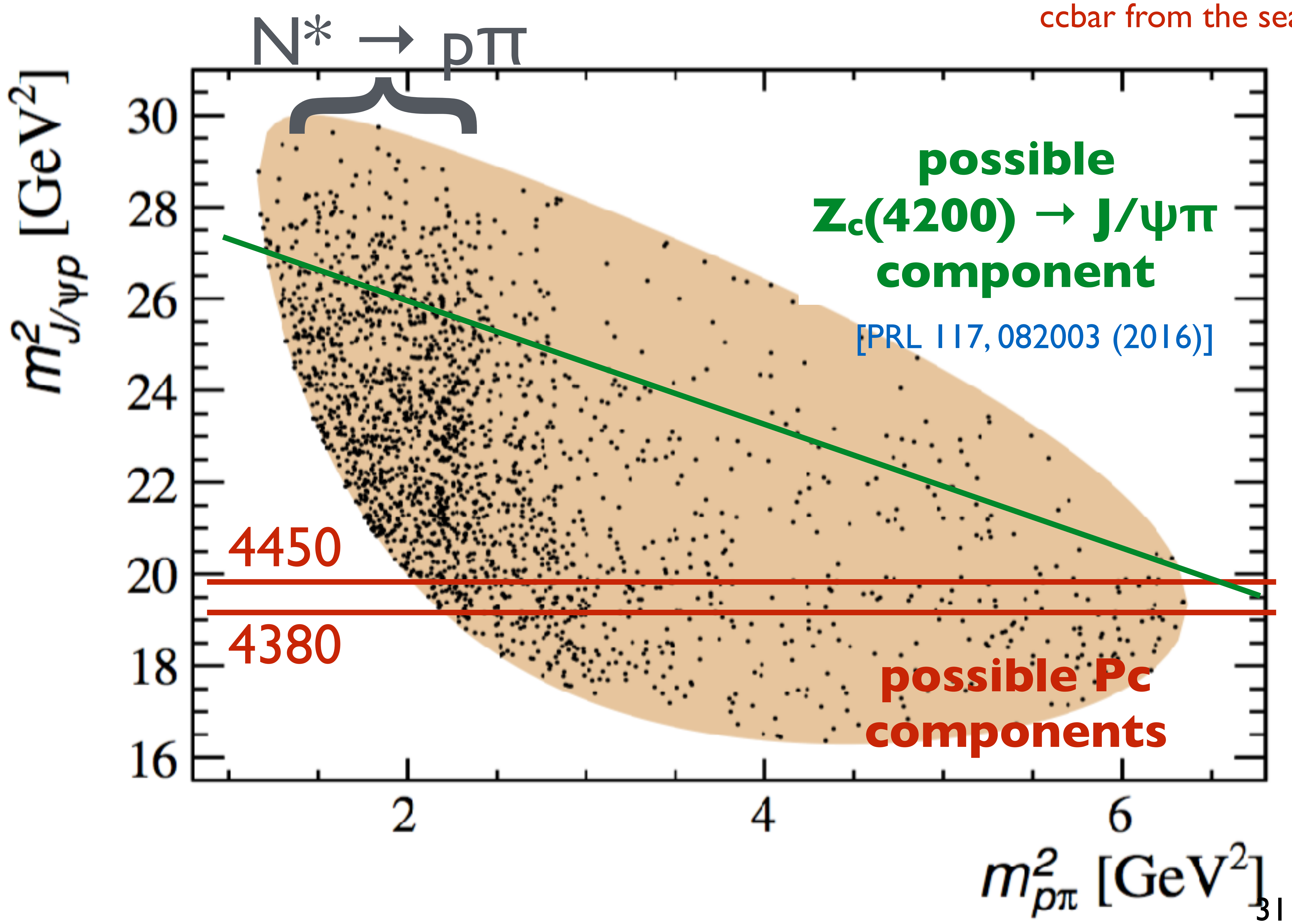


$$R_{\pi^-/K^-} = 0.58 \pm 0.05$$

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







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

[PRL 117, 082003 (2016)]

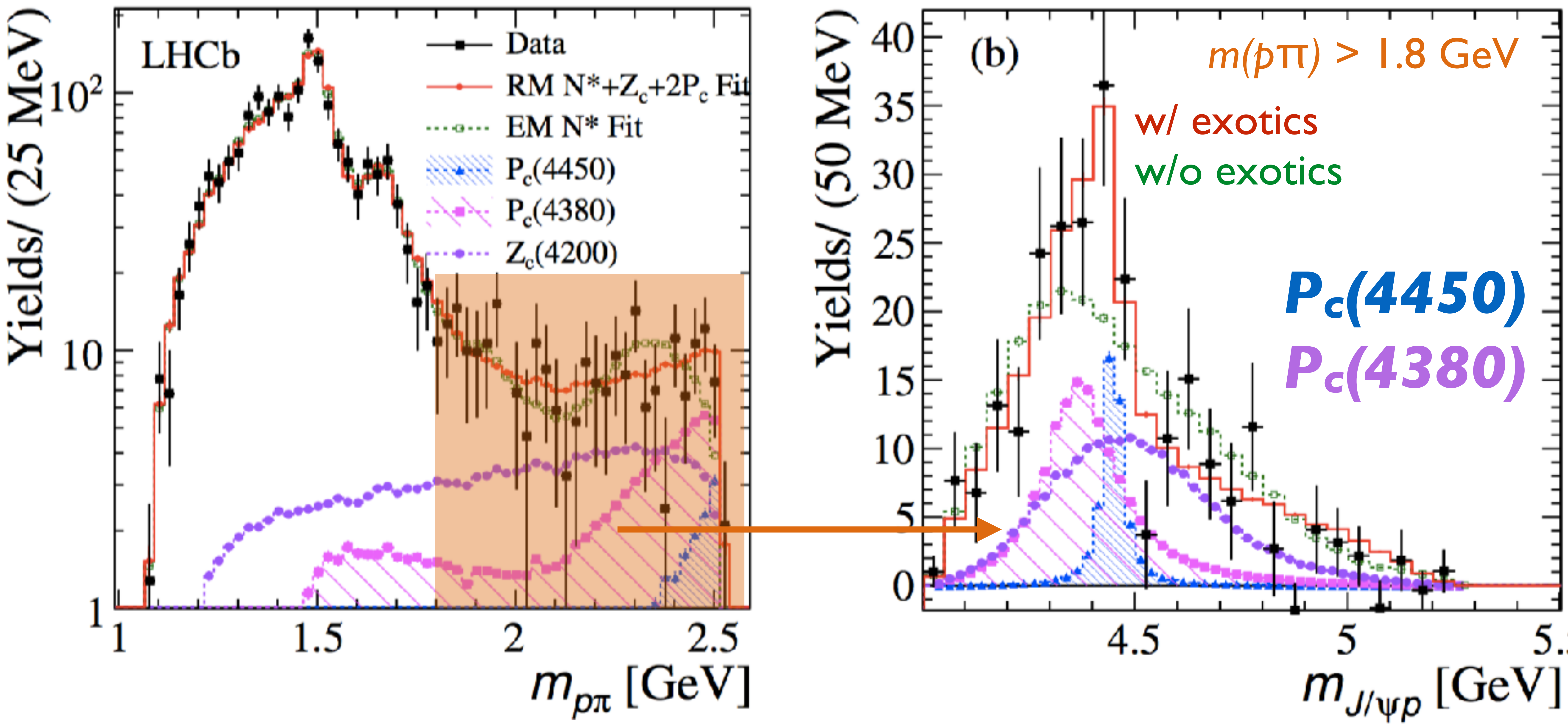
N*-only model not a good fit

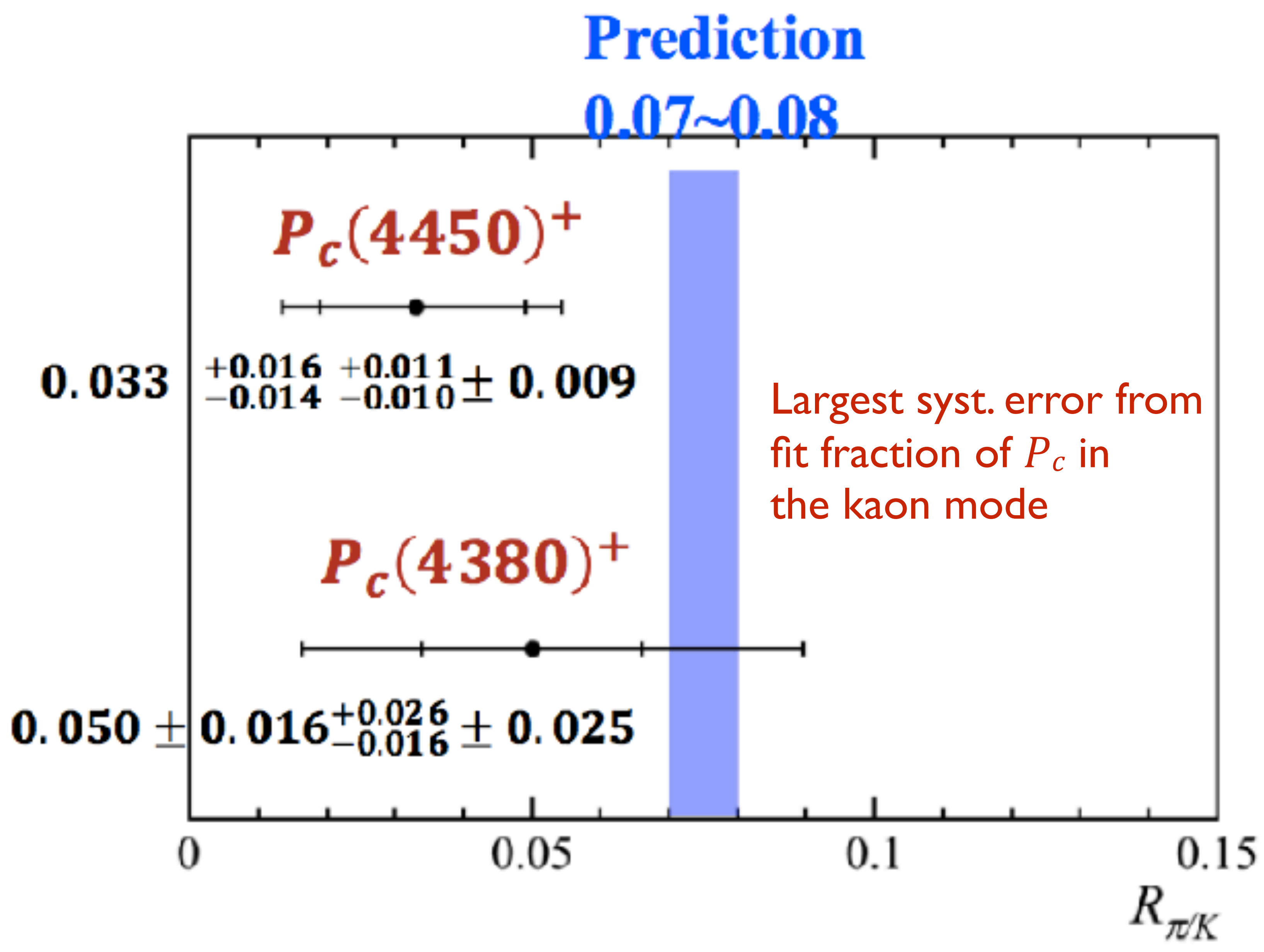
Good fit using 15 N* components + exotic components

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



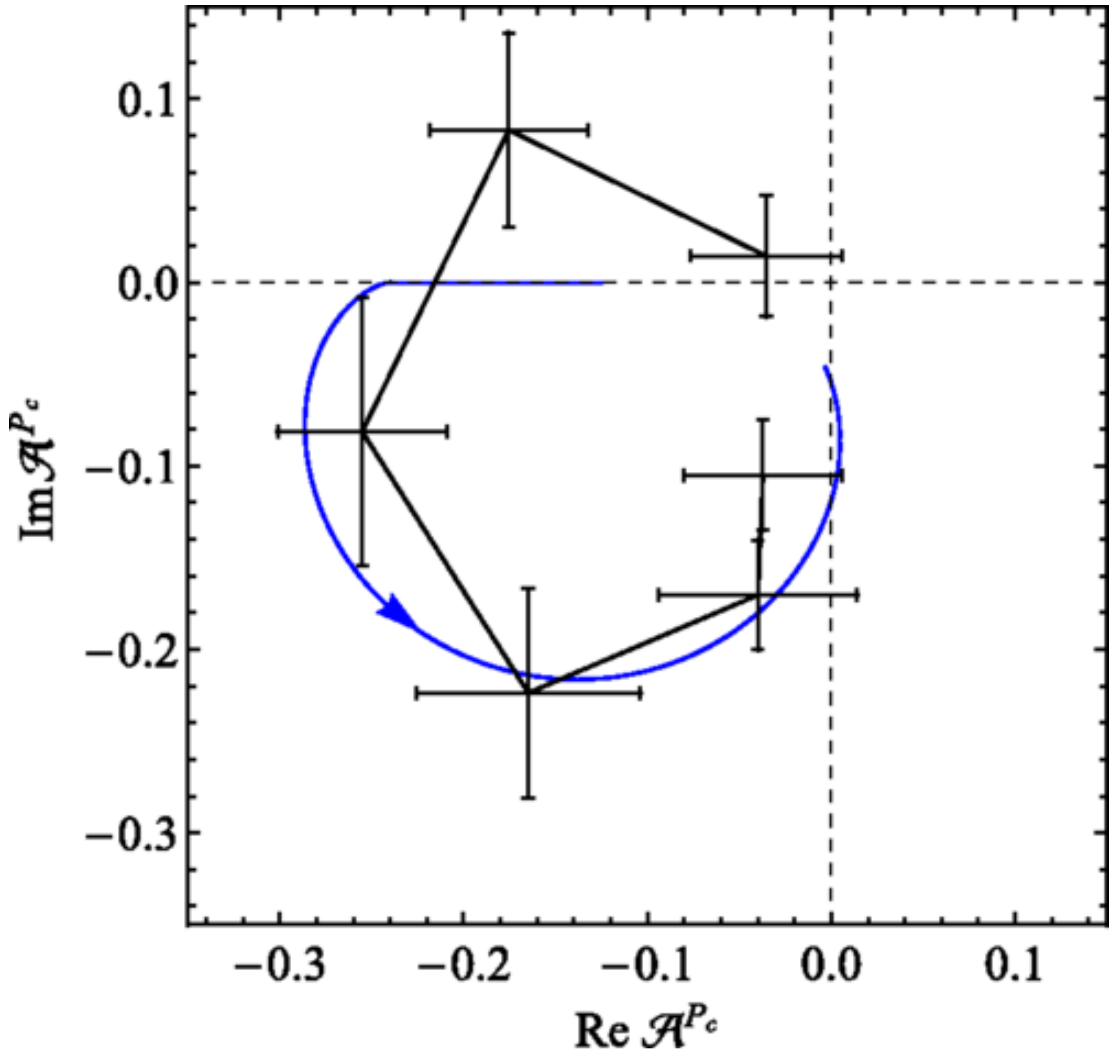


rules out [Hsiao, Phys. Lett. B 751, 572 (2015)]

Pentaquark interpretations

$D^{*}\Sigma_c - D^{*}\Sigma^{*}_c$ molecular state, tightly bound pentaquark or a hybrid?

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

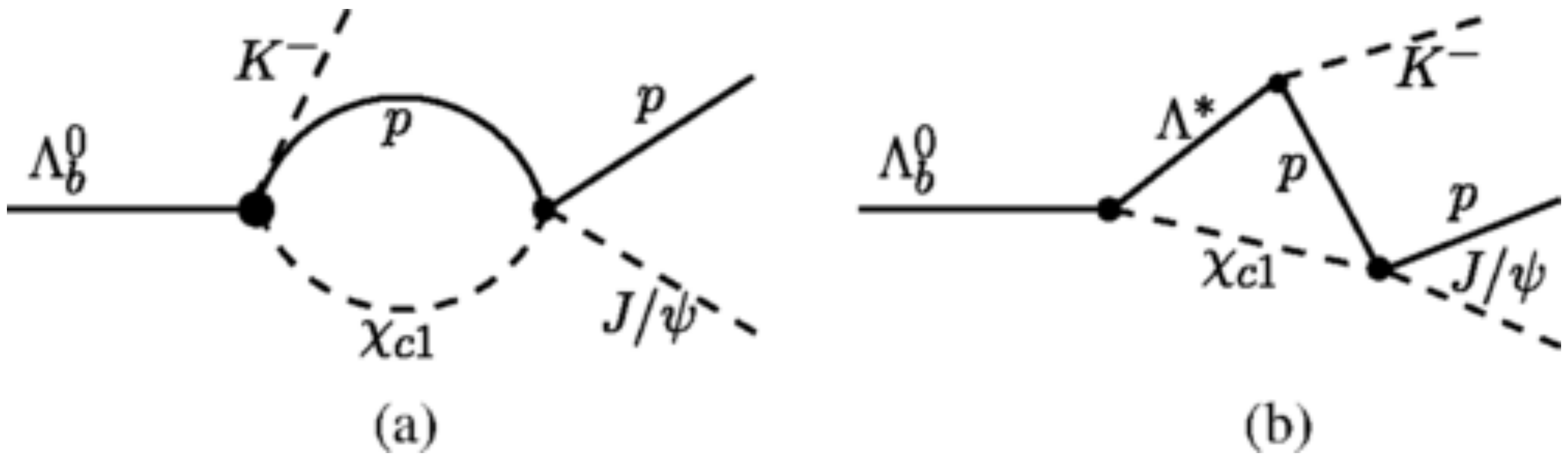


$P_c(4450)$ has mass just above threshold of $\chi_{c1}p$ so could be due to $J/\psi p \to \chi_{c1}p$ kinematic rescattering effect.

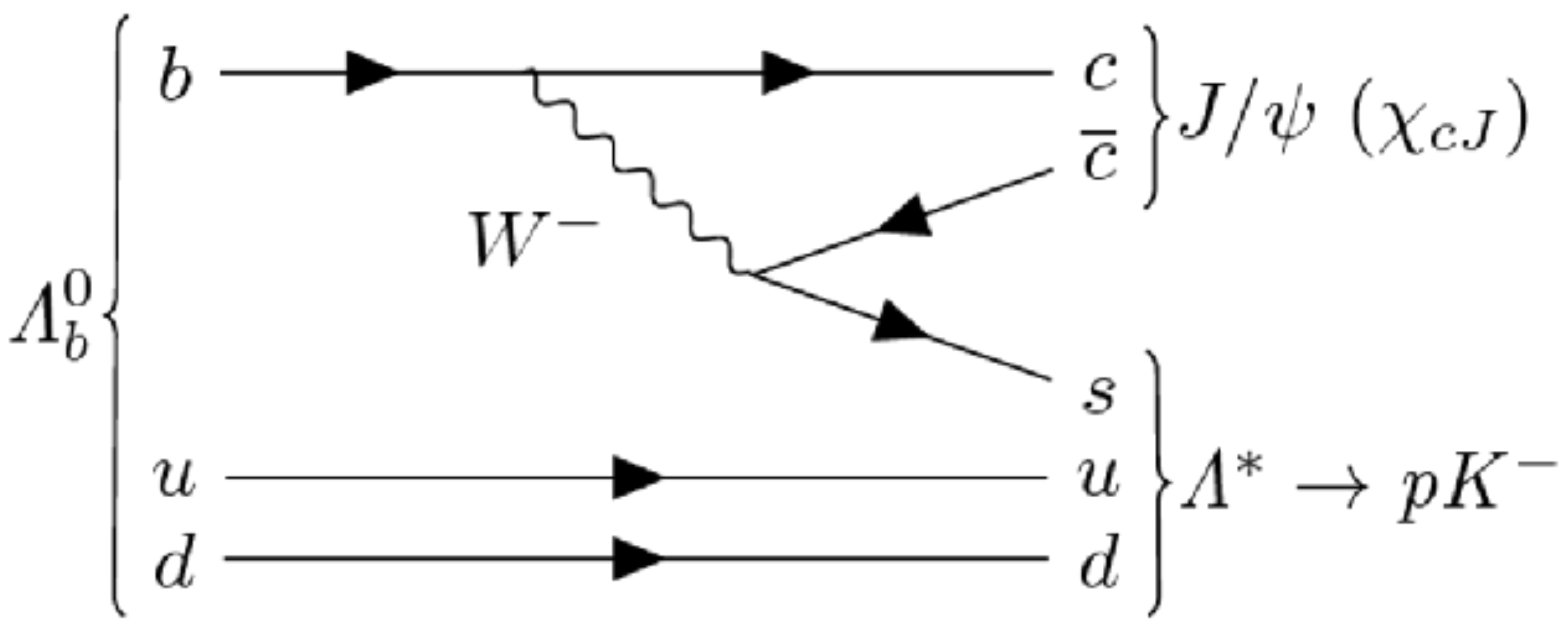
[Guo et al, PRD 92 (2015) 071502(R)]
[PRD 94 (2016) 074039]

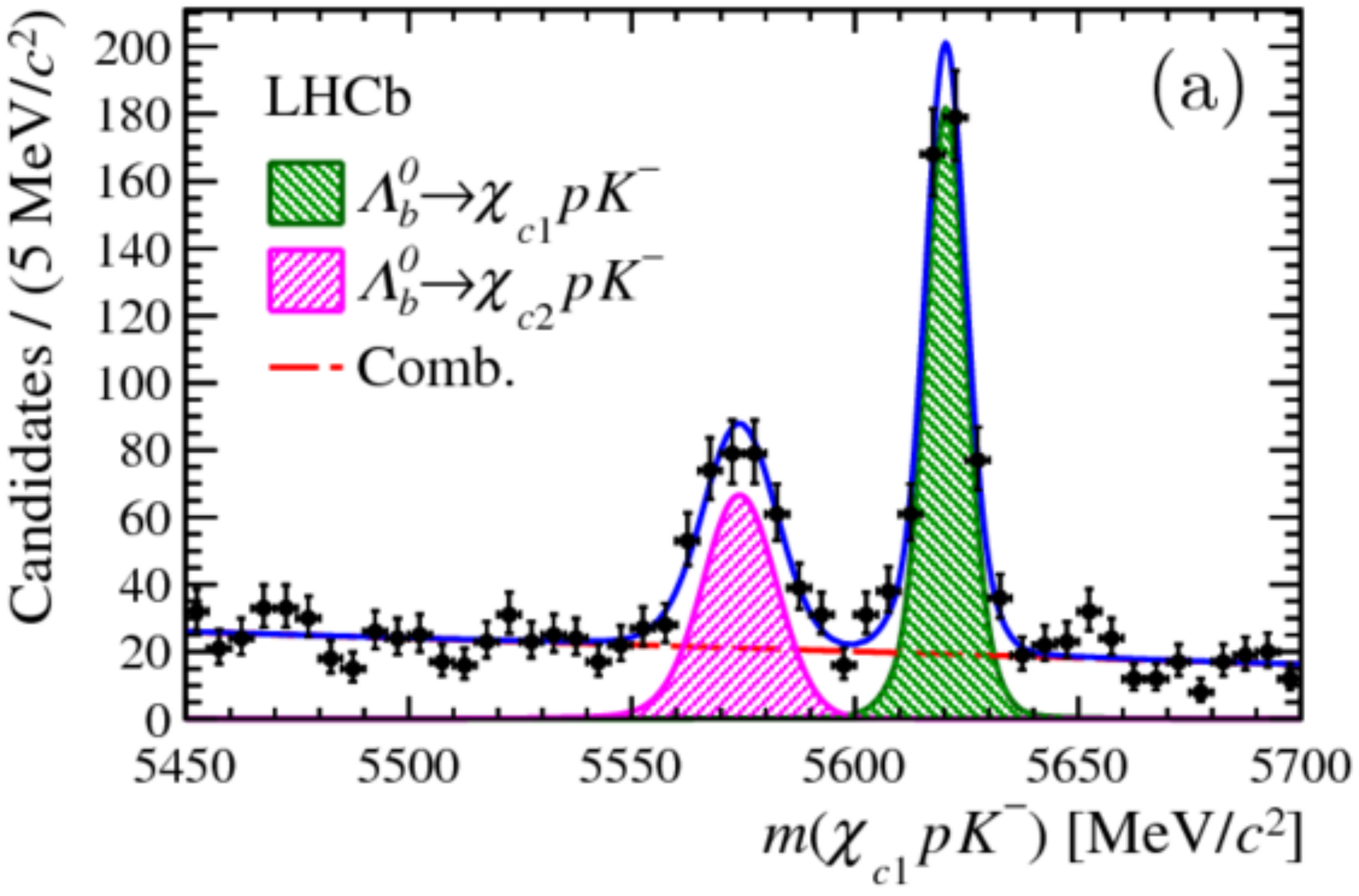
Reproduces phase motion of $P_c(4450)$, but what about $P_c(4380)$?

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



Observation of the decays $\Lambda^0_b \to \chi_{cJ} p K^-$





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

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

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

[Phys. Rev. Lett. 119, 062001 (2017)]

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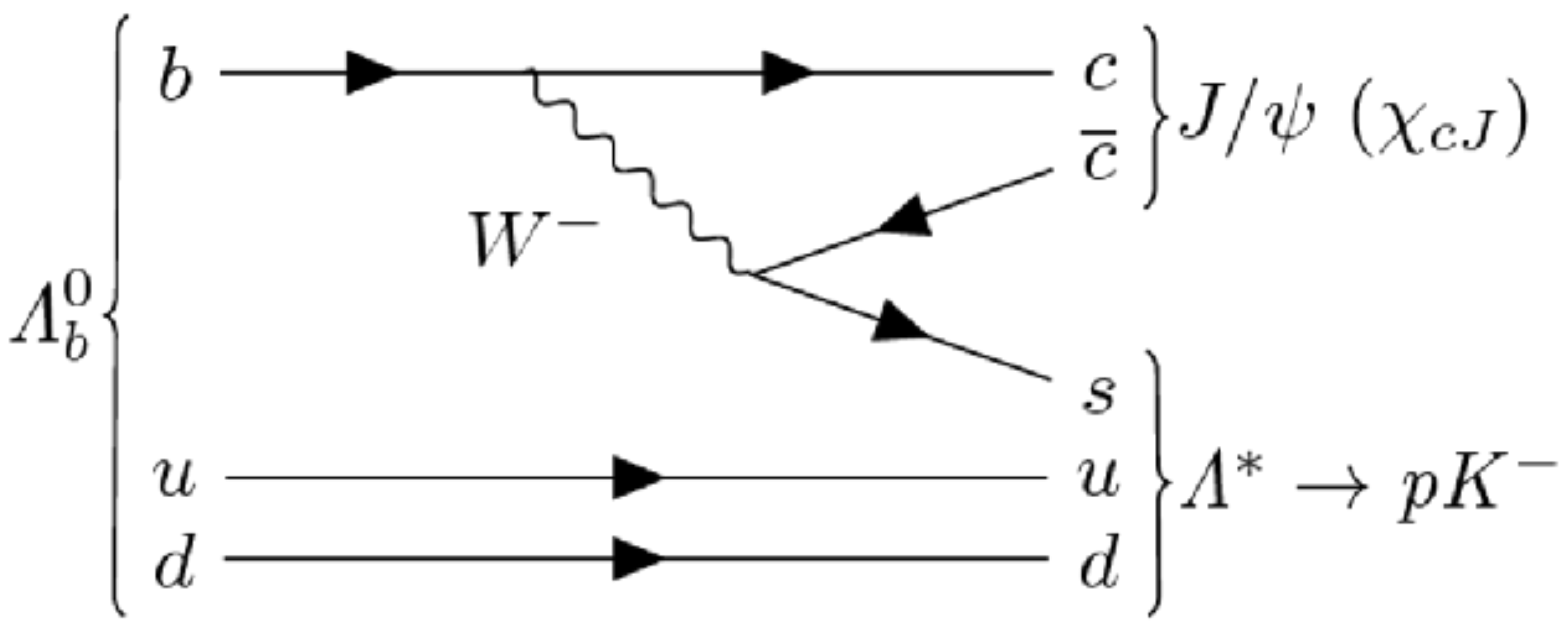

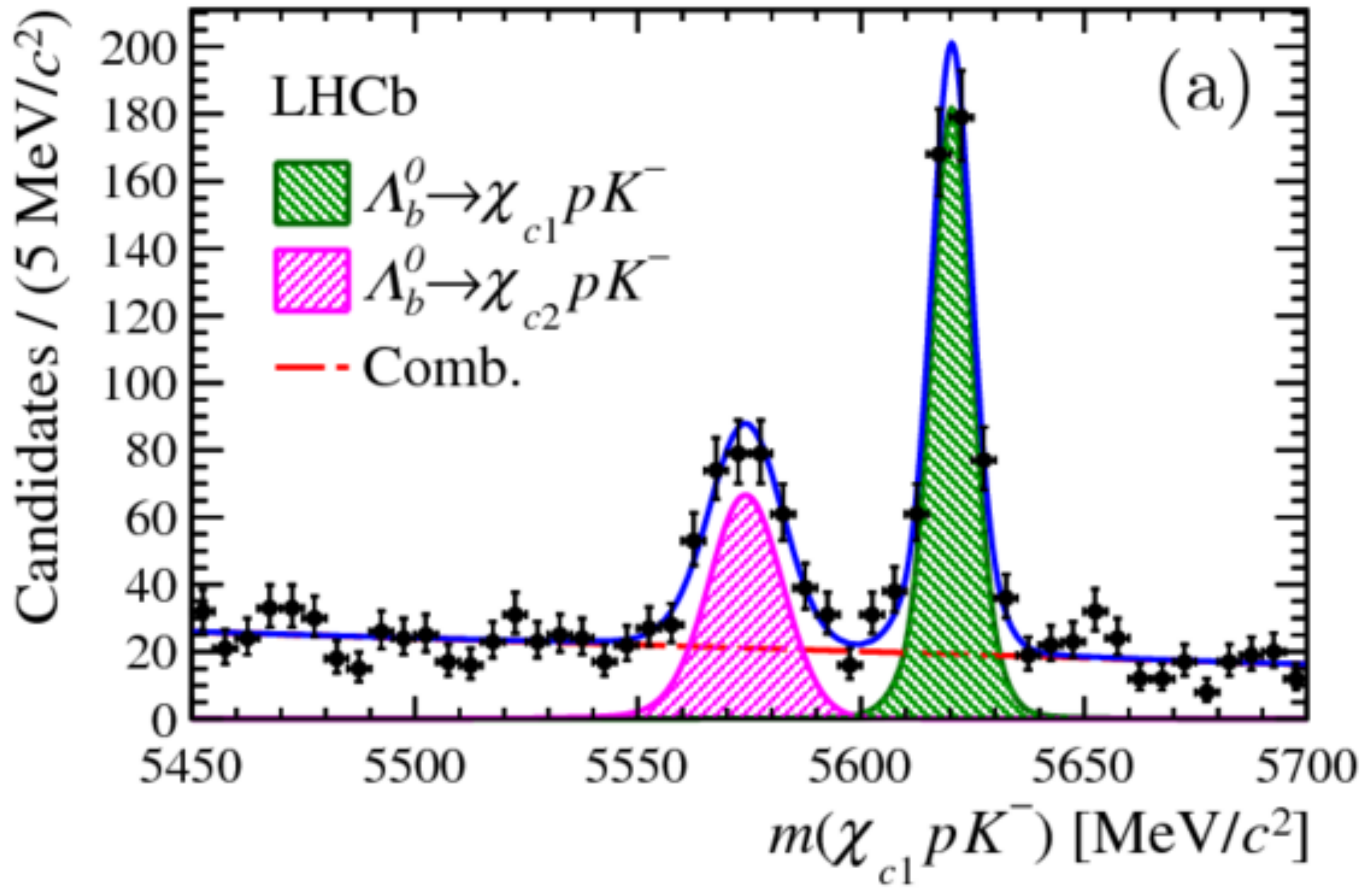

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$\mathcal{B}(\chi_{cJ})$

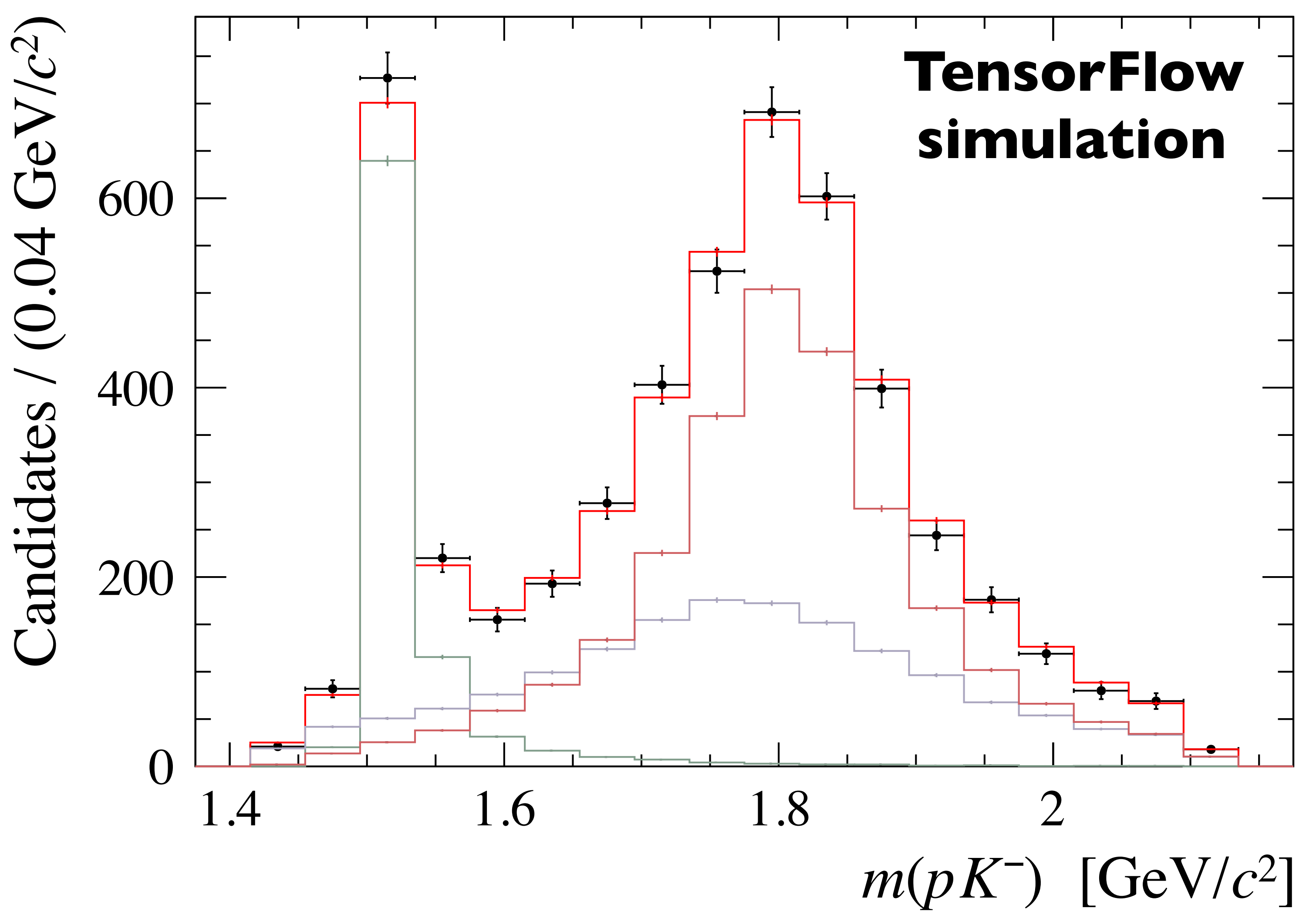
[Phys. Rev. Lett. 119, 062001 (2017)]

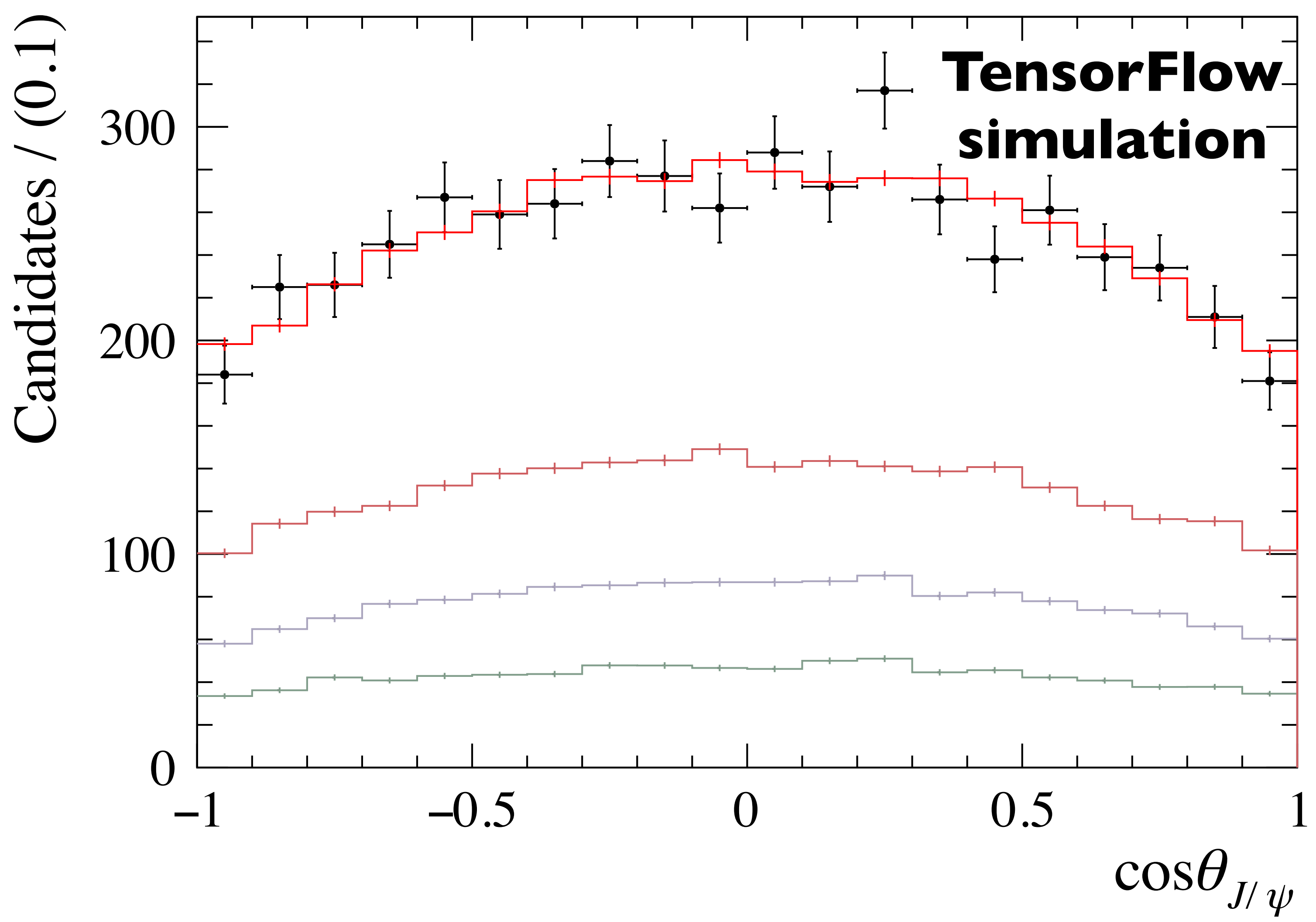
Test rescattering hypothesis by searching for P_c contributions.

Need **8D** amplitude analysis of the final state to search for pentaquarks.

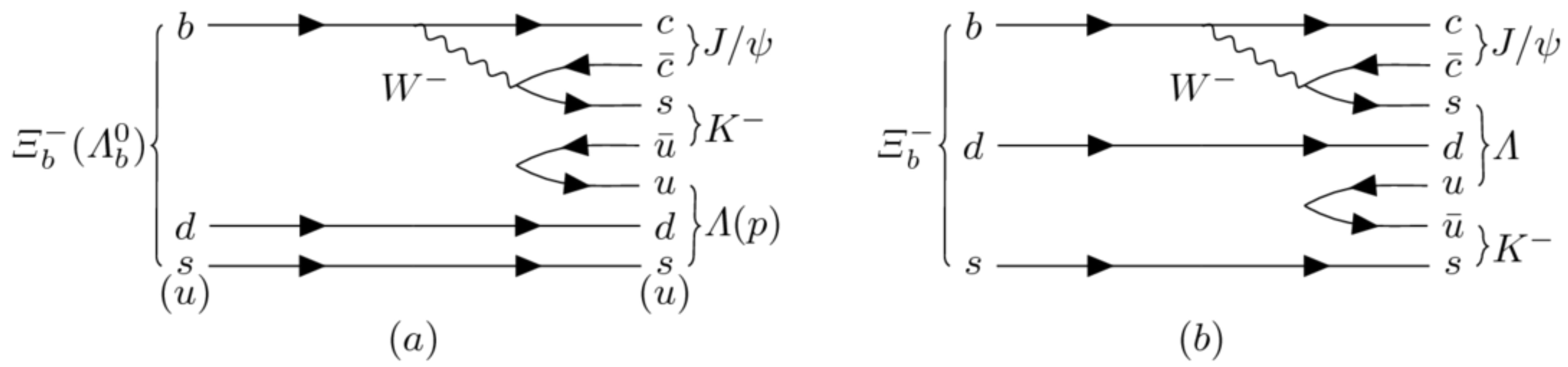
New technique: build full amplitude using dataflow graph

[tensorflow.org]





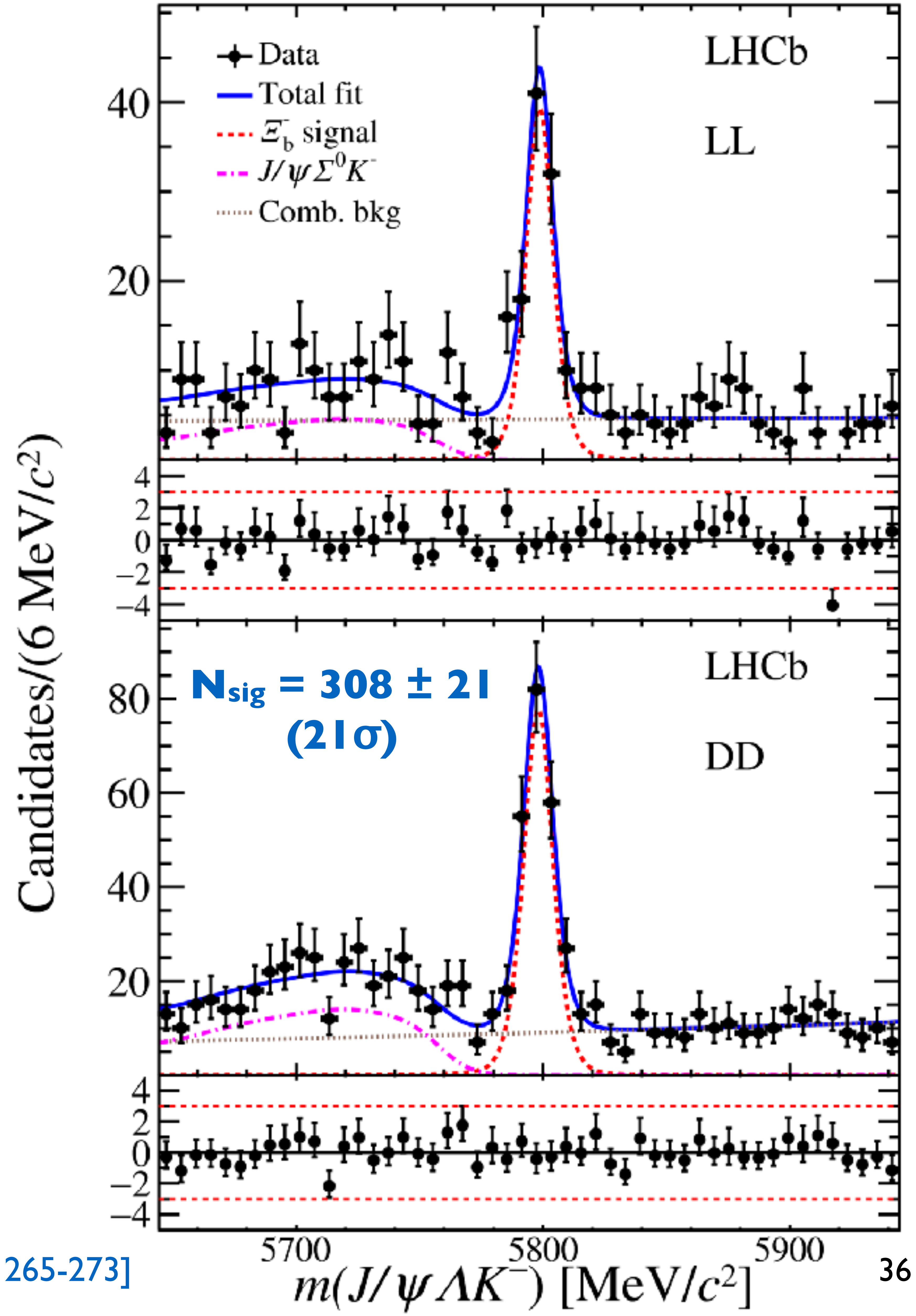
Observation of the $\Xi^-_b \to J/\psi \Lambda K^-$ decay



Strange pentaquark (*udsccbar*) predicted [PRL 105, 232001 (2010)]

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

Expect ~1500 signal events after 2018
→ amplitude analysis



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

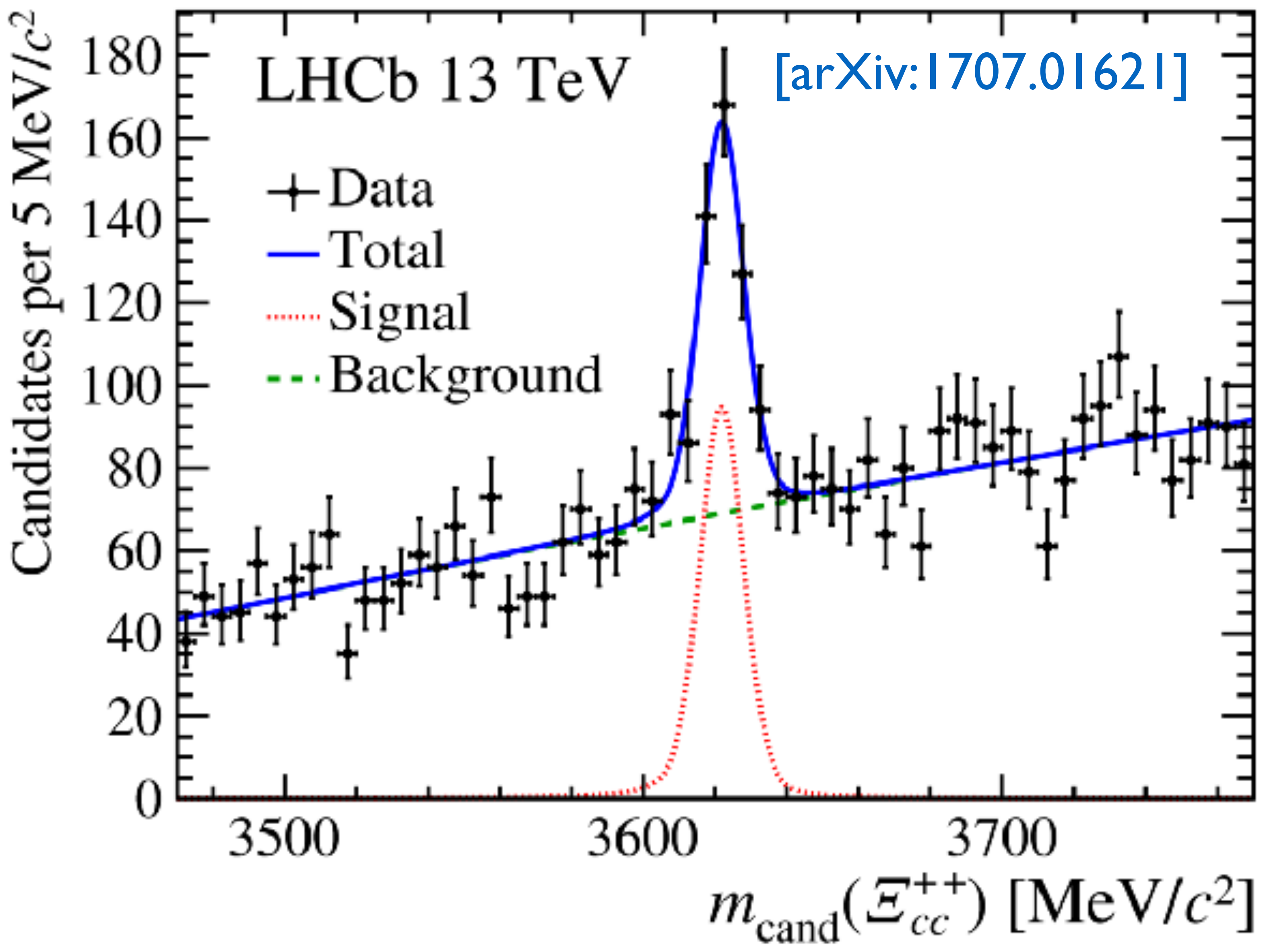
Connections with “conventional” spectroscopy

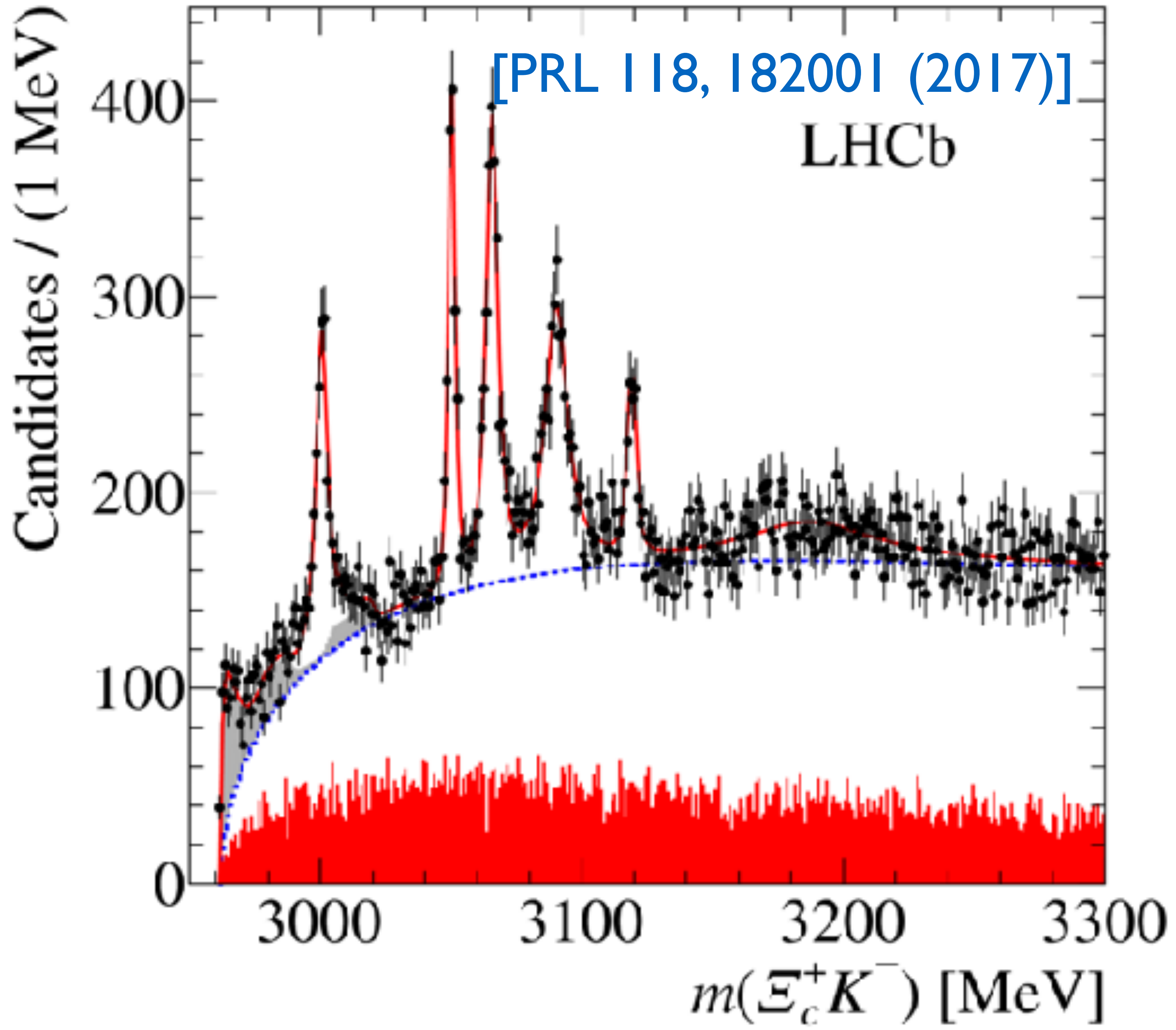
Discovery of Ω_c^{**} and Xi_{cc}^{++} have spurred theoretical investigations, motivated by the calibration of the binding energy of their constituent **diquarks**.

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 …)





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]

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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., $Y(4260) \to X(3872)\gamma$)

   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

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

   [PRL 105, 232001 (2010)]

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

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4. Measure **branching ratios**

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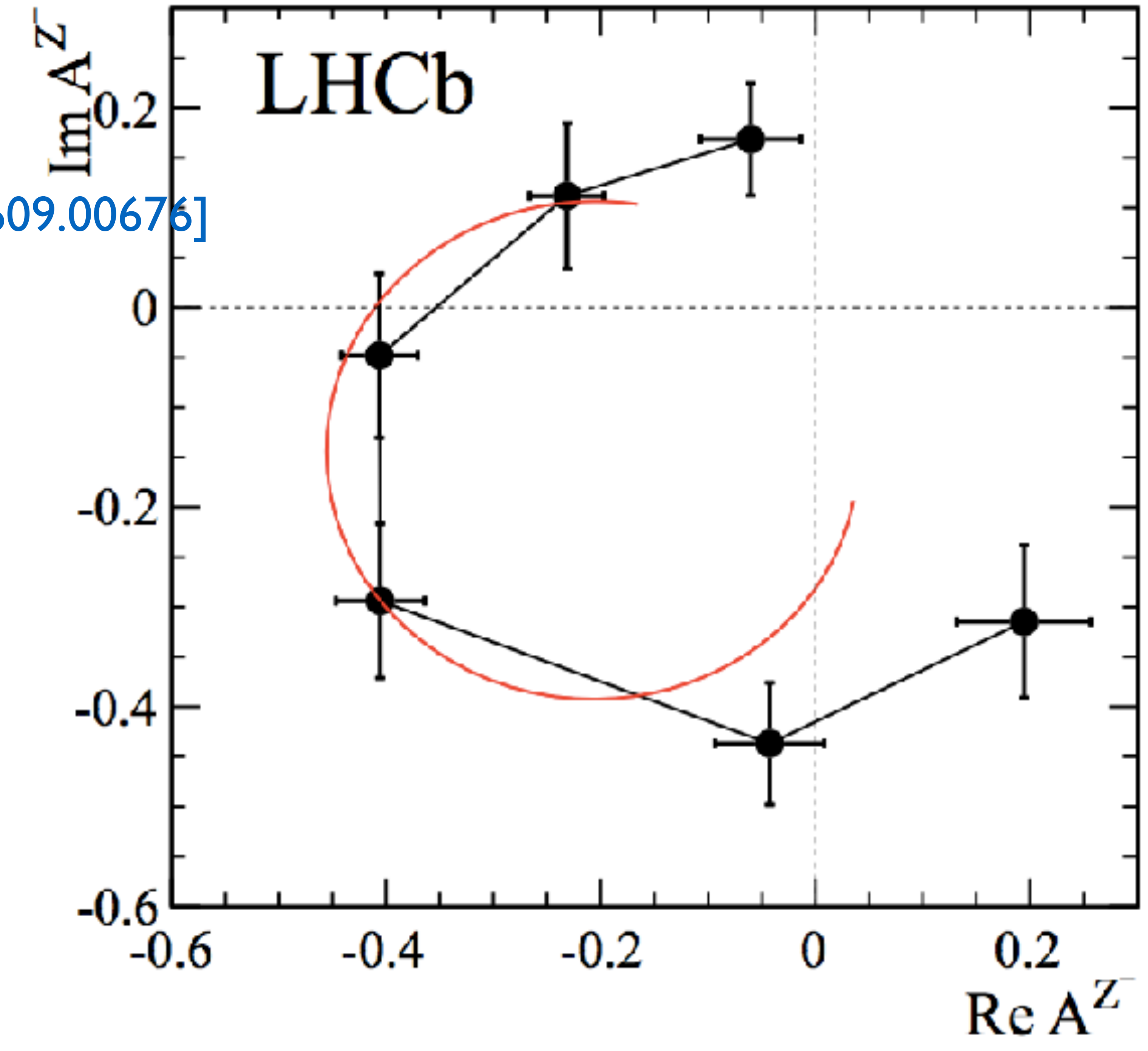
   [PRL 105, 232001 (2010)]

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!

Ad break

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

IPPP associateship

Please register if you would like to attend.

Get in contact if you would like to propose a topic.

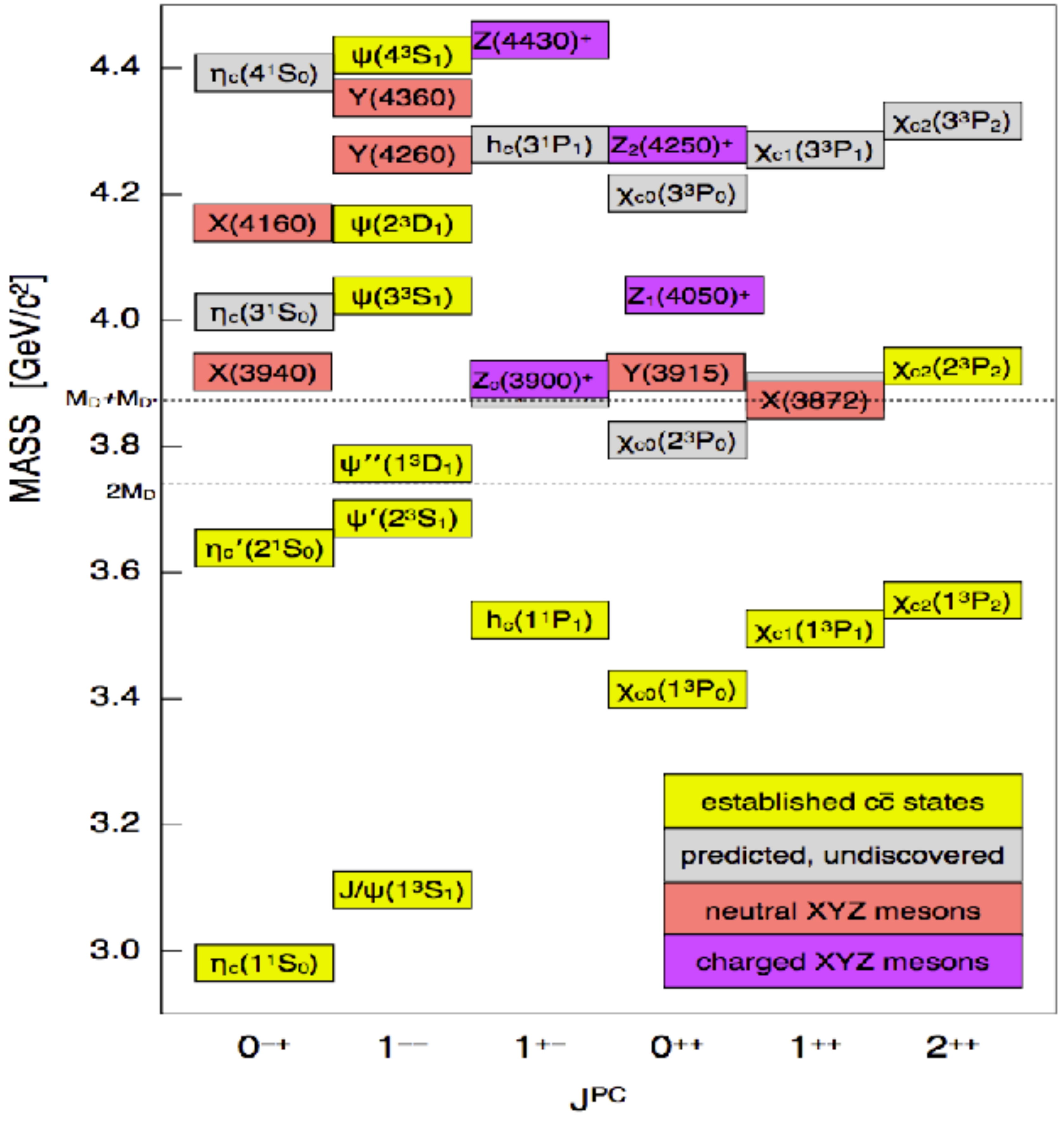
Summary

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.



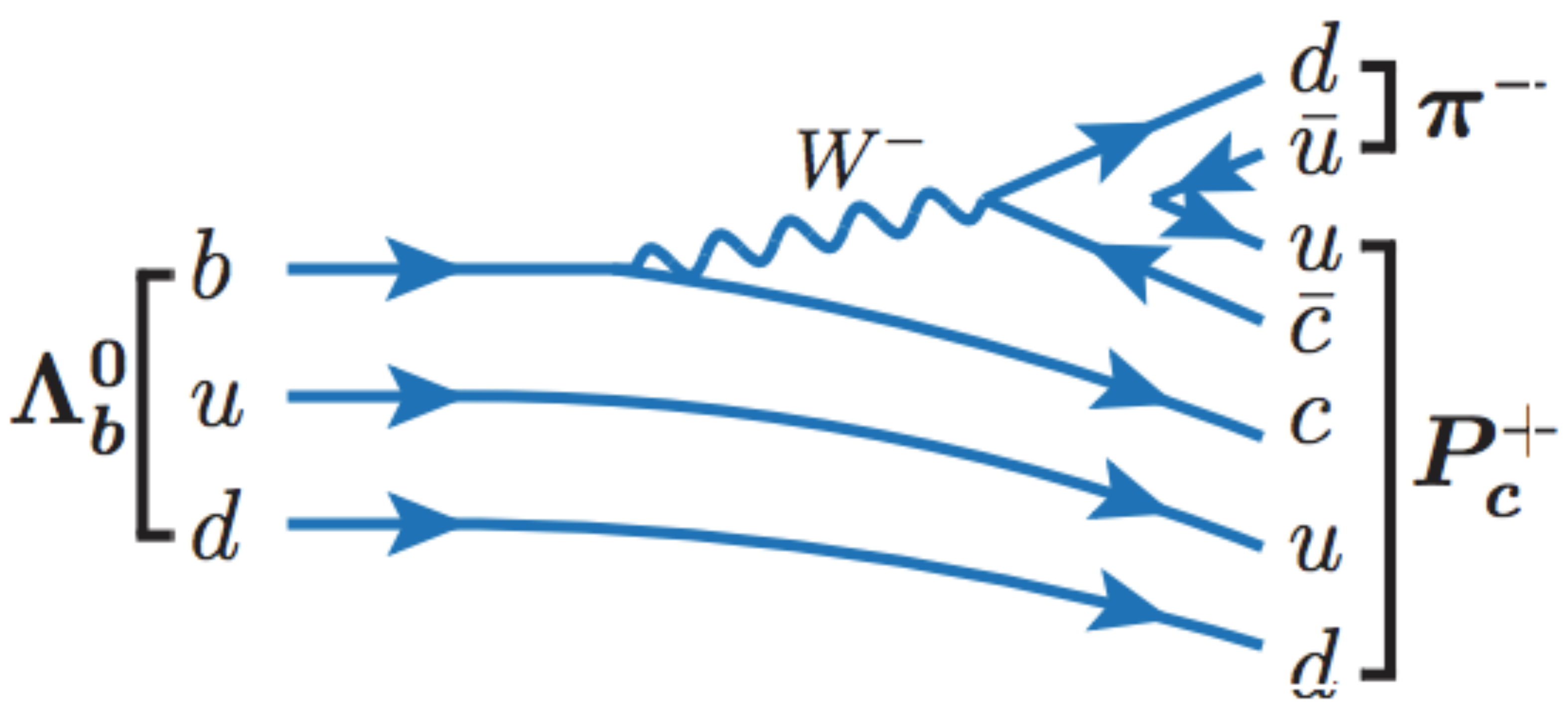
Backup

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

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

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



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

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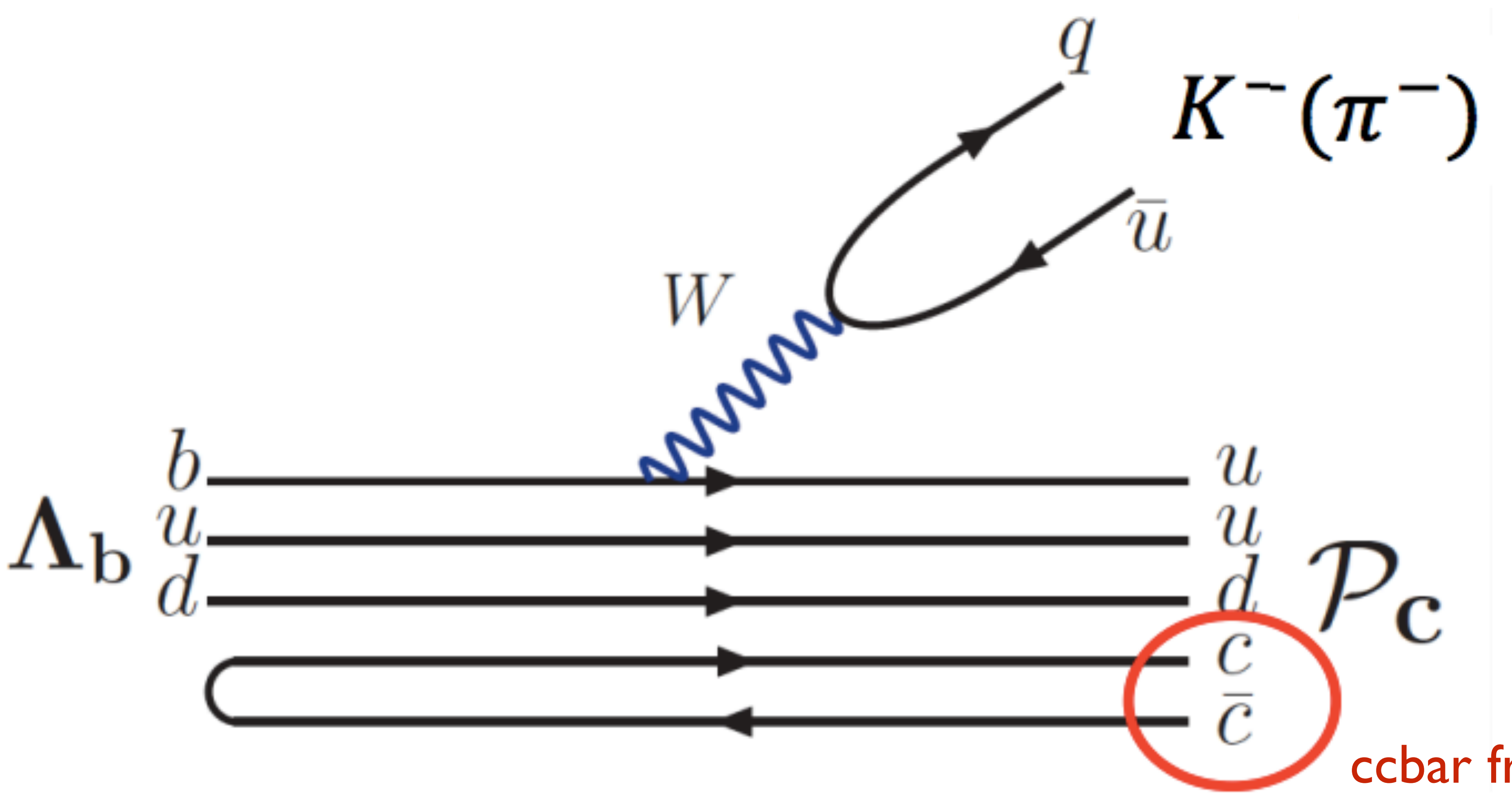
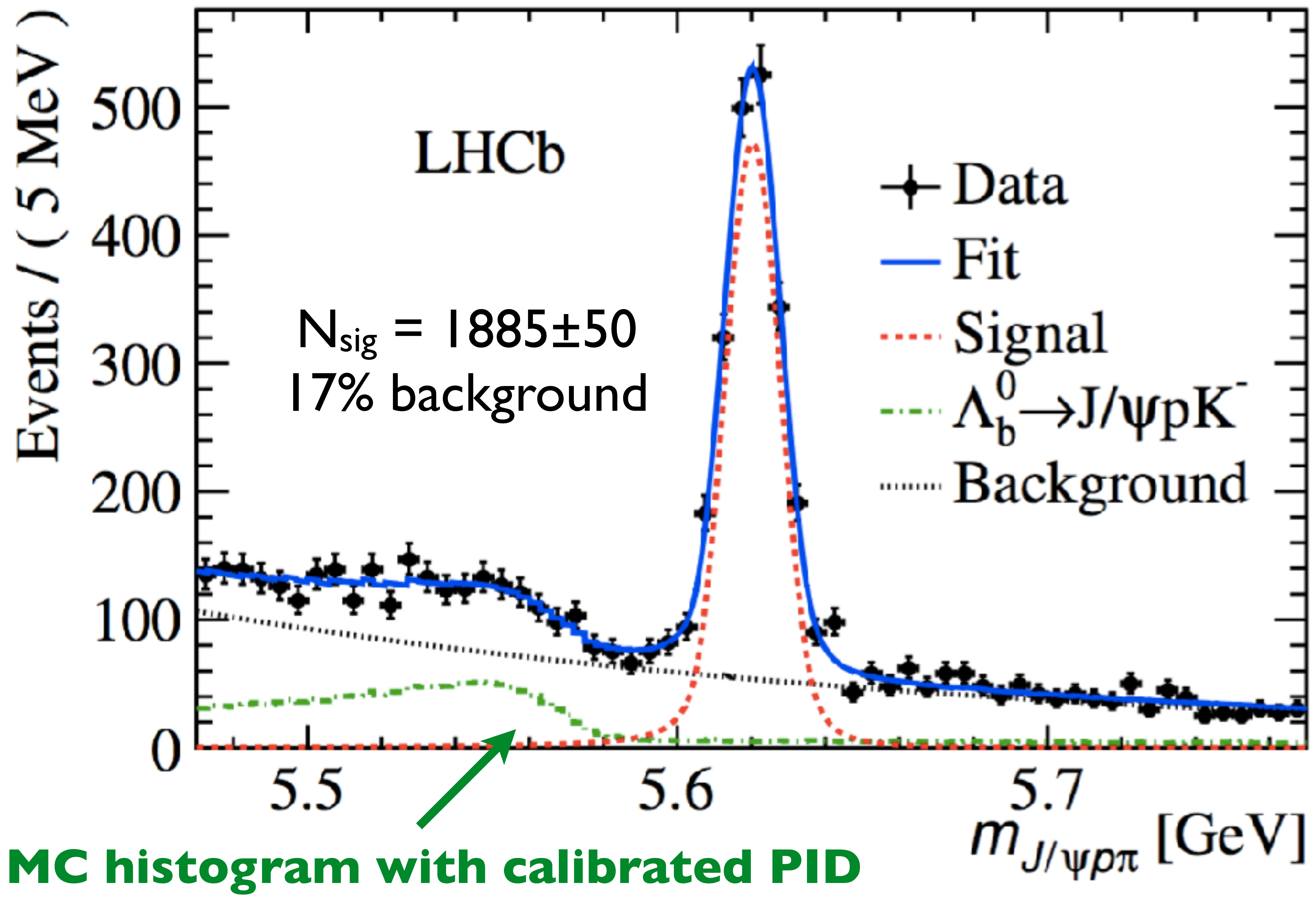
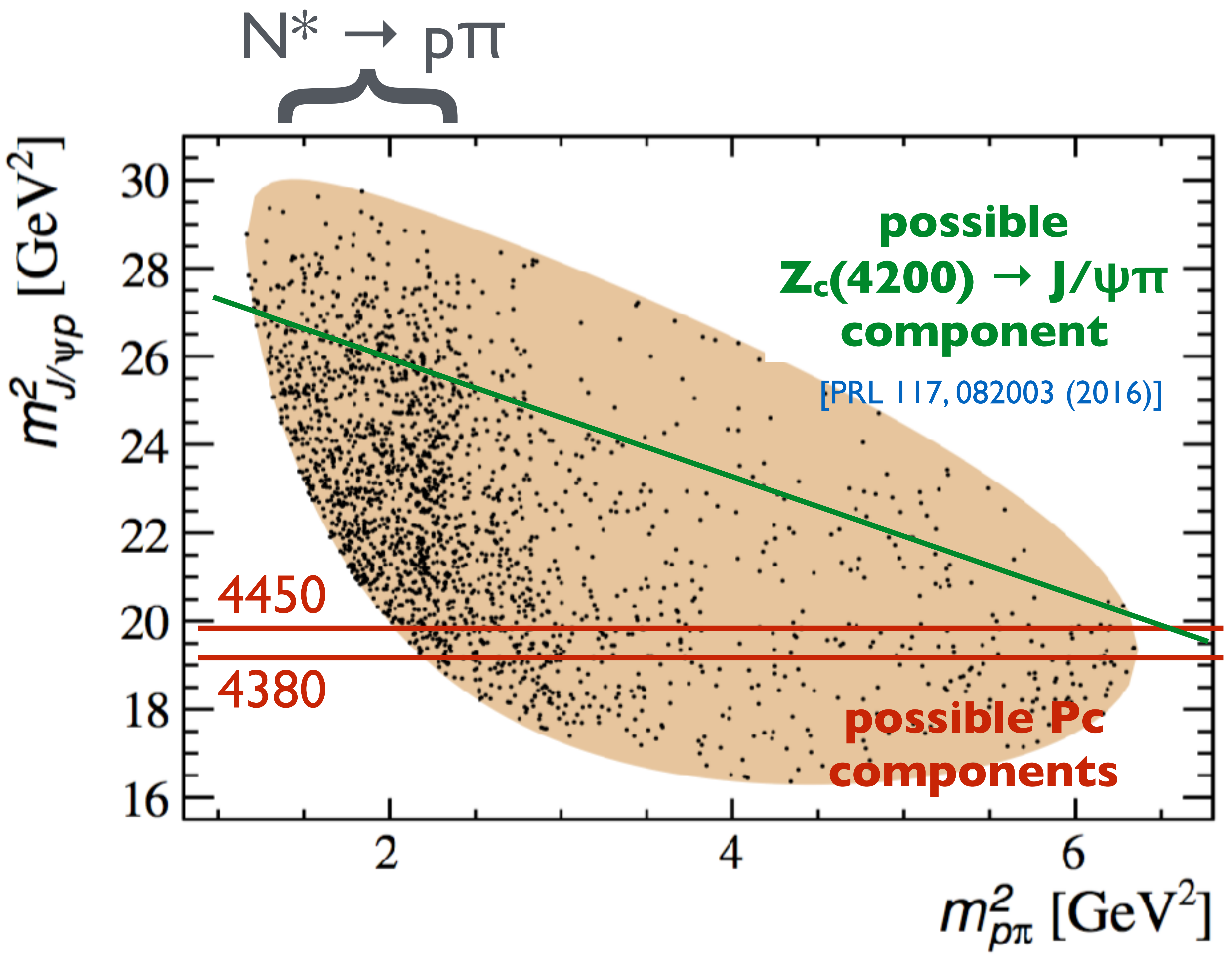


[Hsiao, Phys. Lett. B 751, 572 (2015)]

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

[PRL 117, 082003 (2016)]

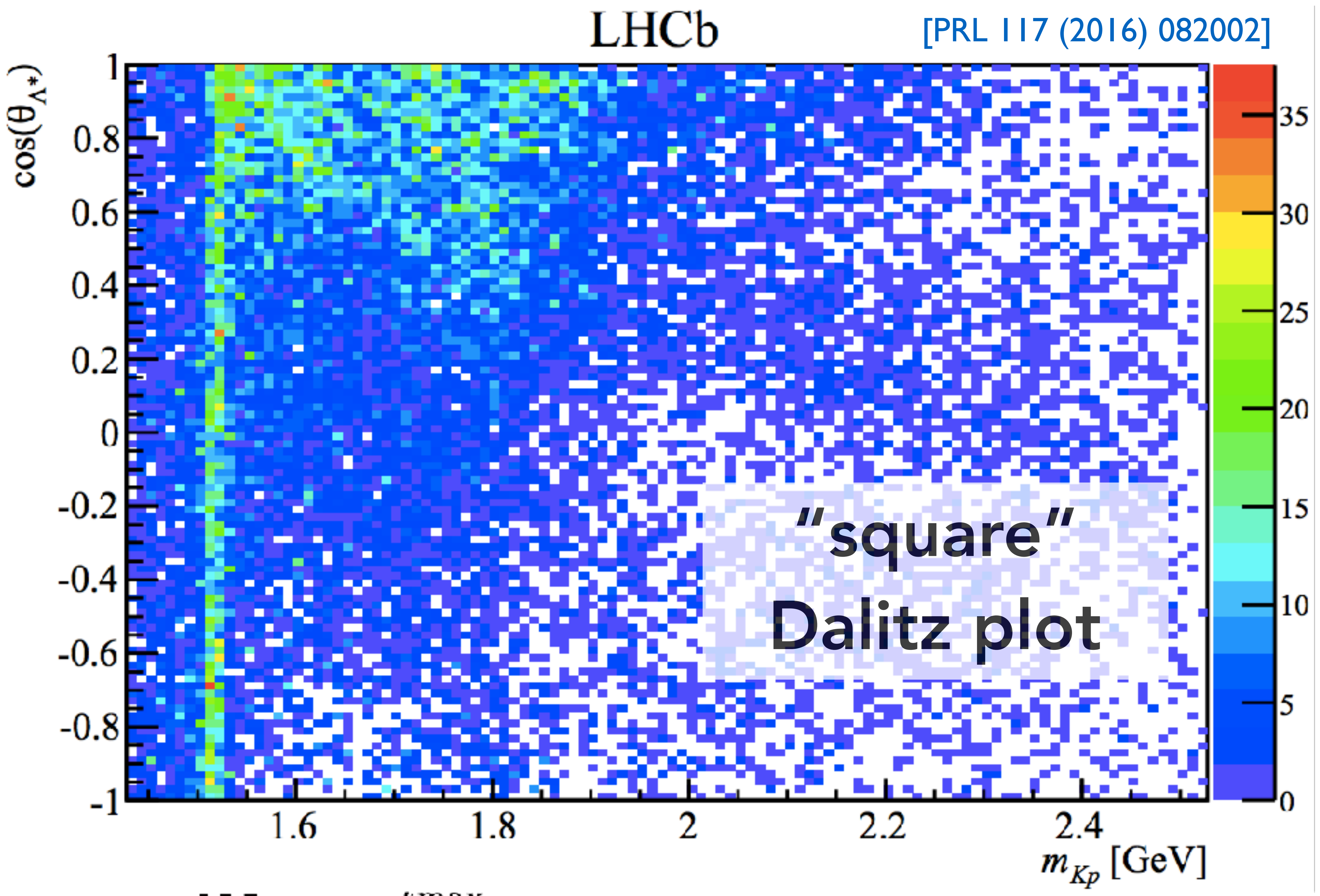


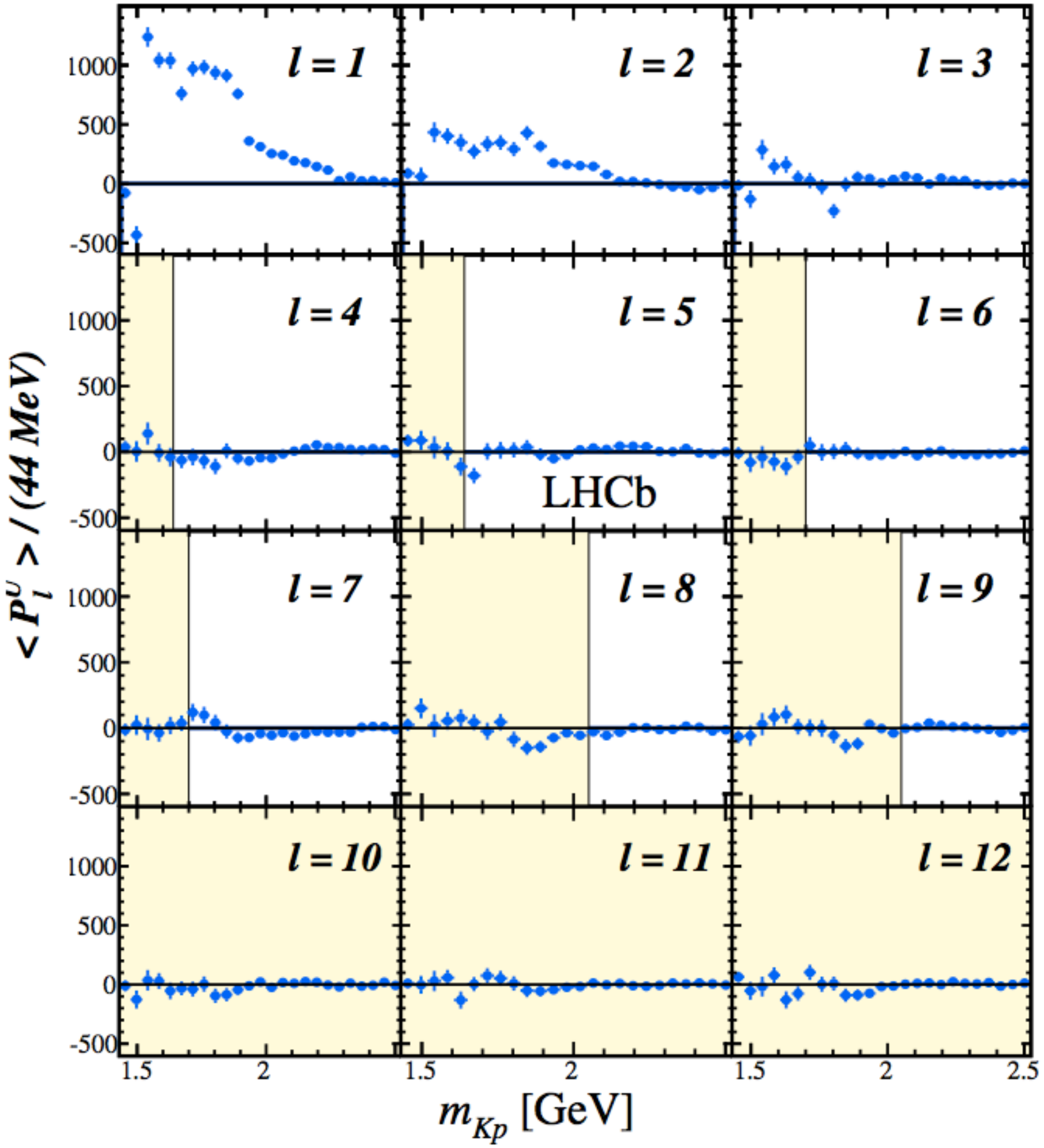


No prominent pentaquark-like peaks

Pentaquark model-independent

[PRL 117 (2016) 082002]





filter out maximum spin for each m(Kp)

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

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

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

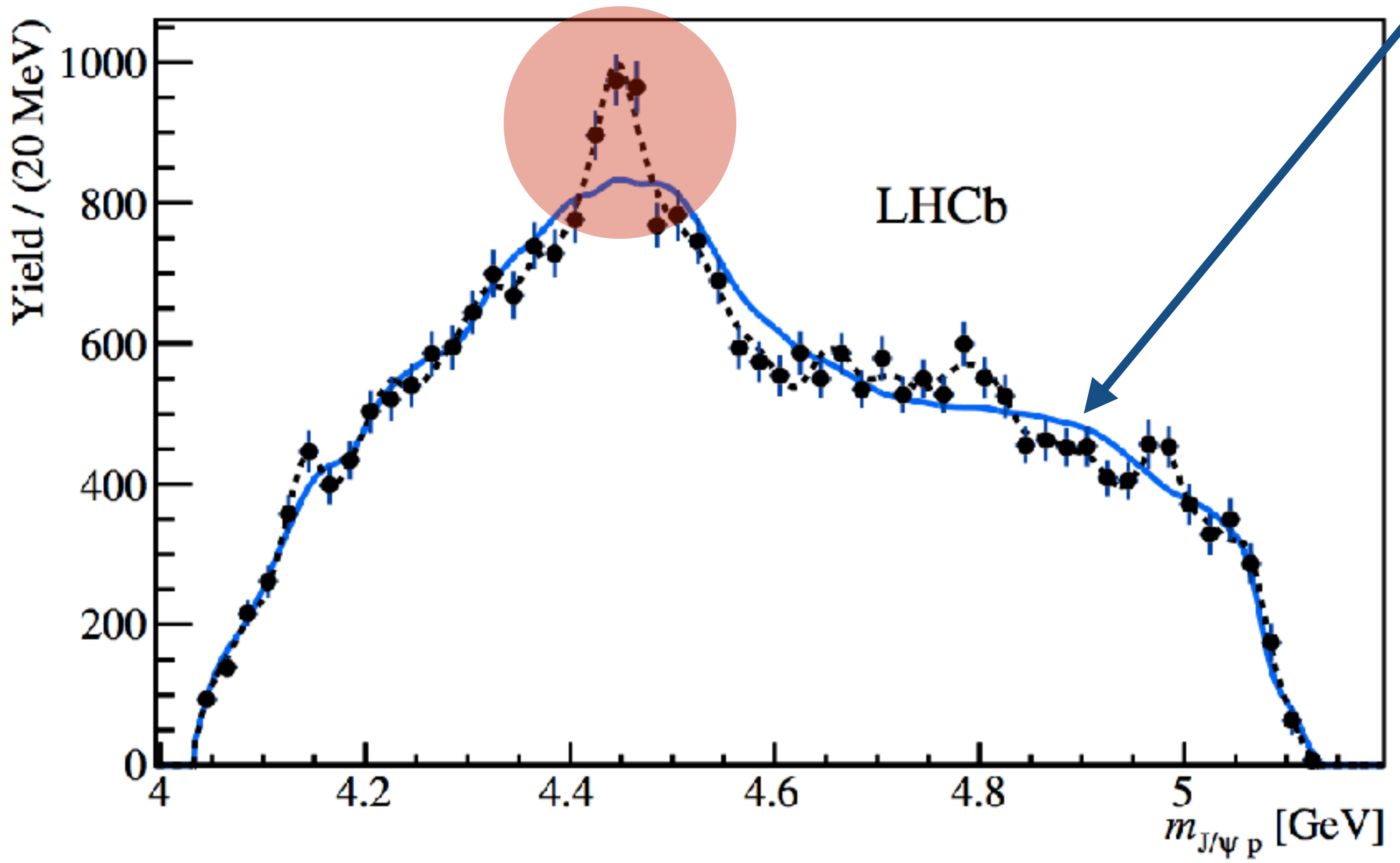
Pentaquark model-independent

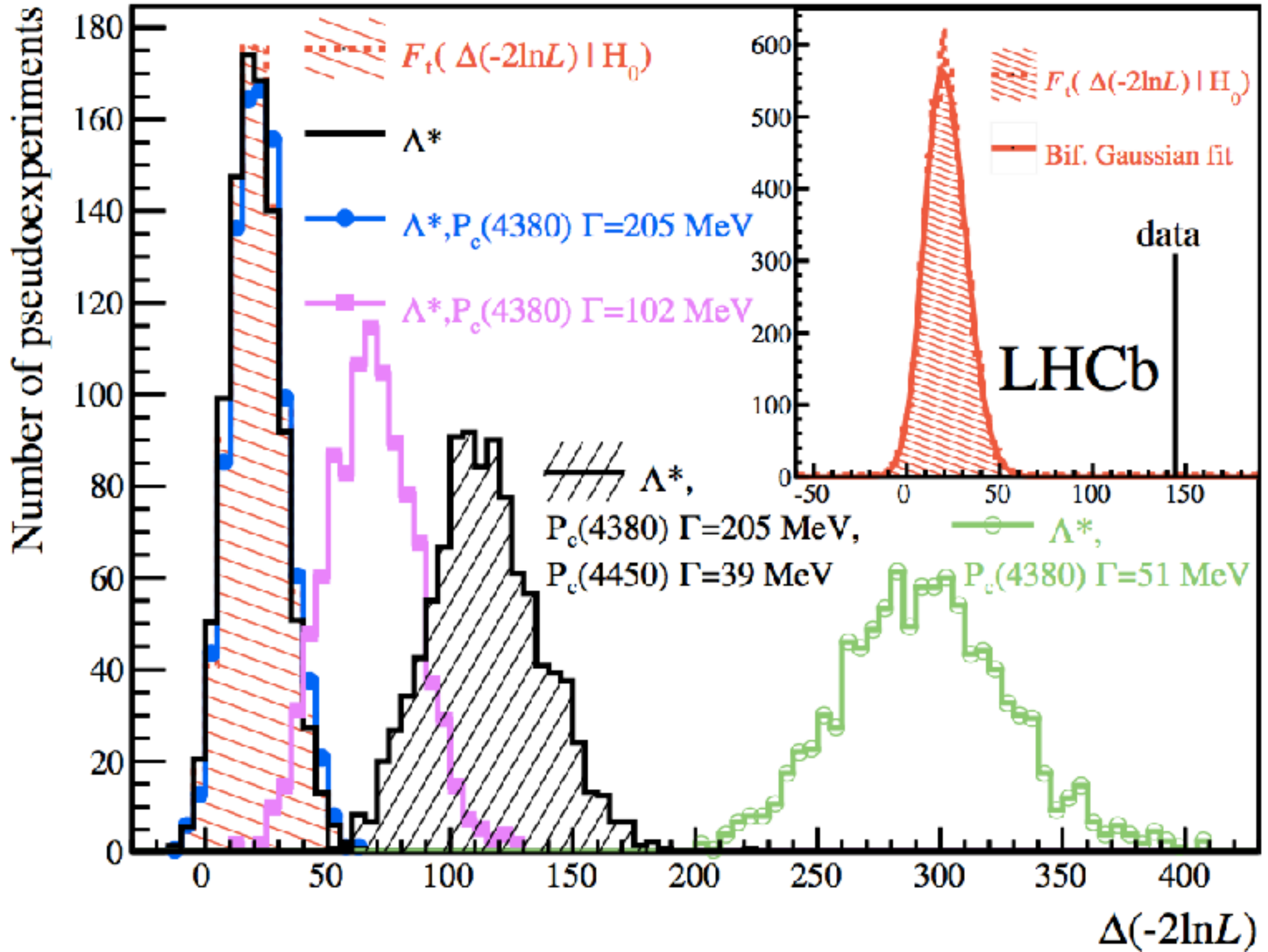
Simulate phase-space decays of $\Lambda_b^0 \to J/\psi p K^-$ [PRL 117 (2016) 082002]

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

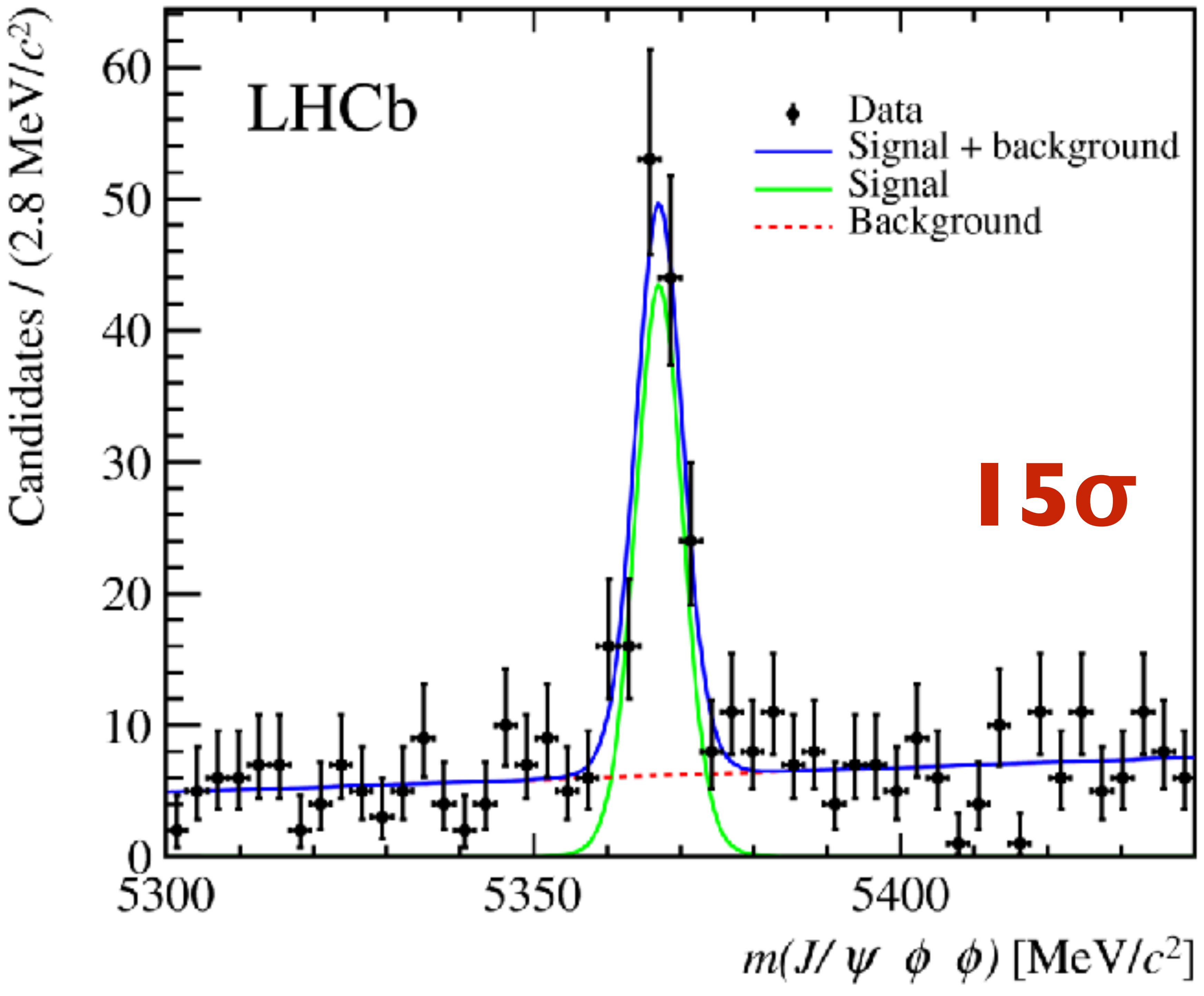
Possible threshold effects in $B_s^0 \to J/\psi\phi\phi$ and other modes [Swanson PRD 91 (2015) 034009]

Simplified phase-space simulation inadequate to describe structure

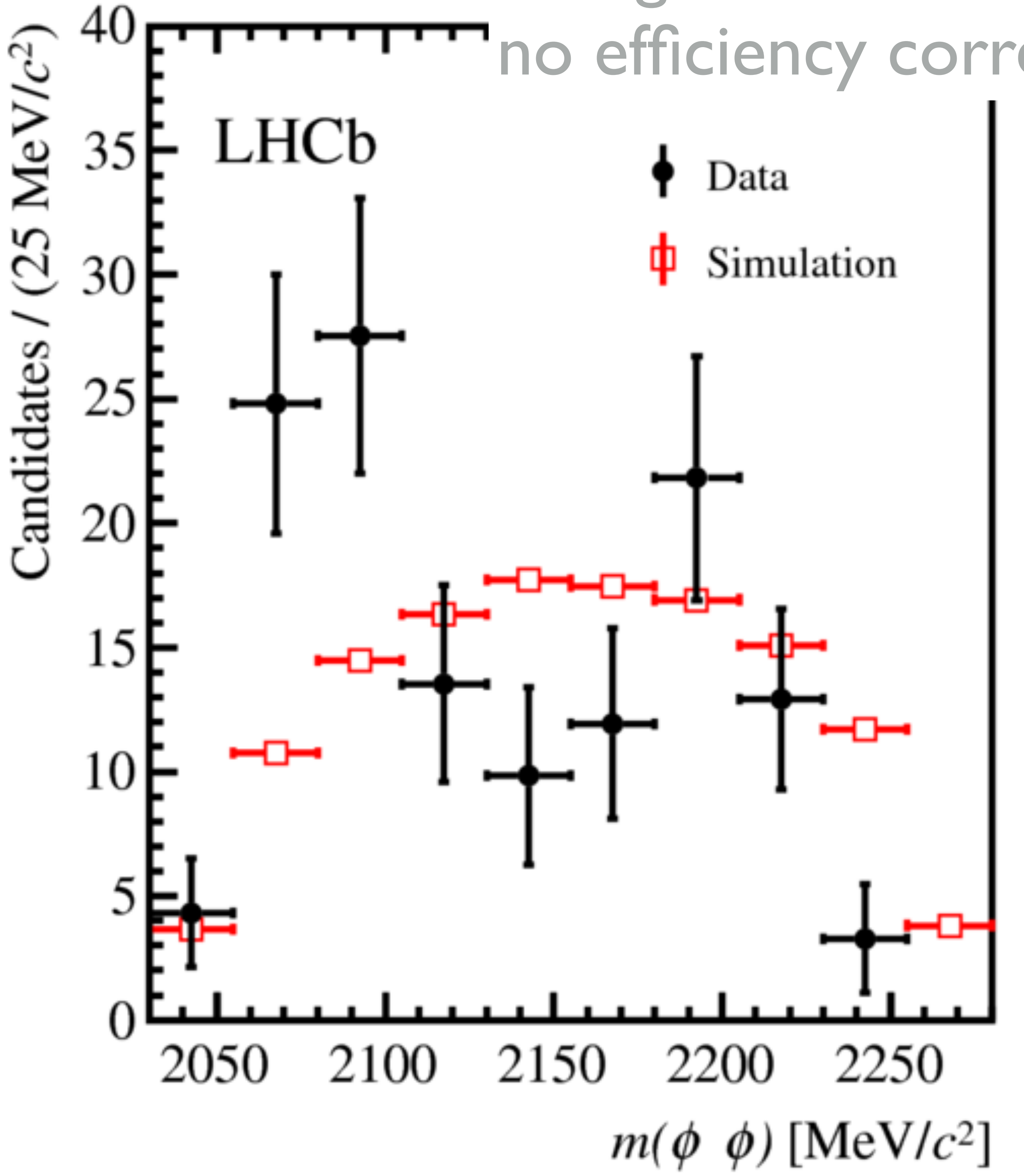
Looking forward to more data in Run-2 of LHCb

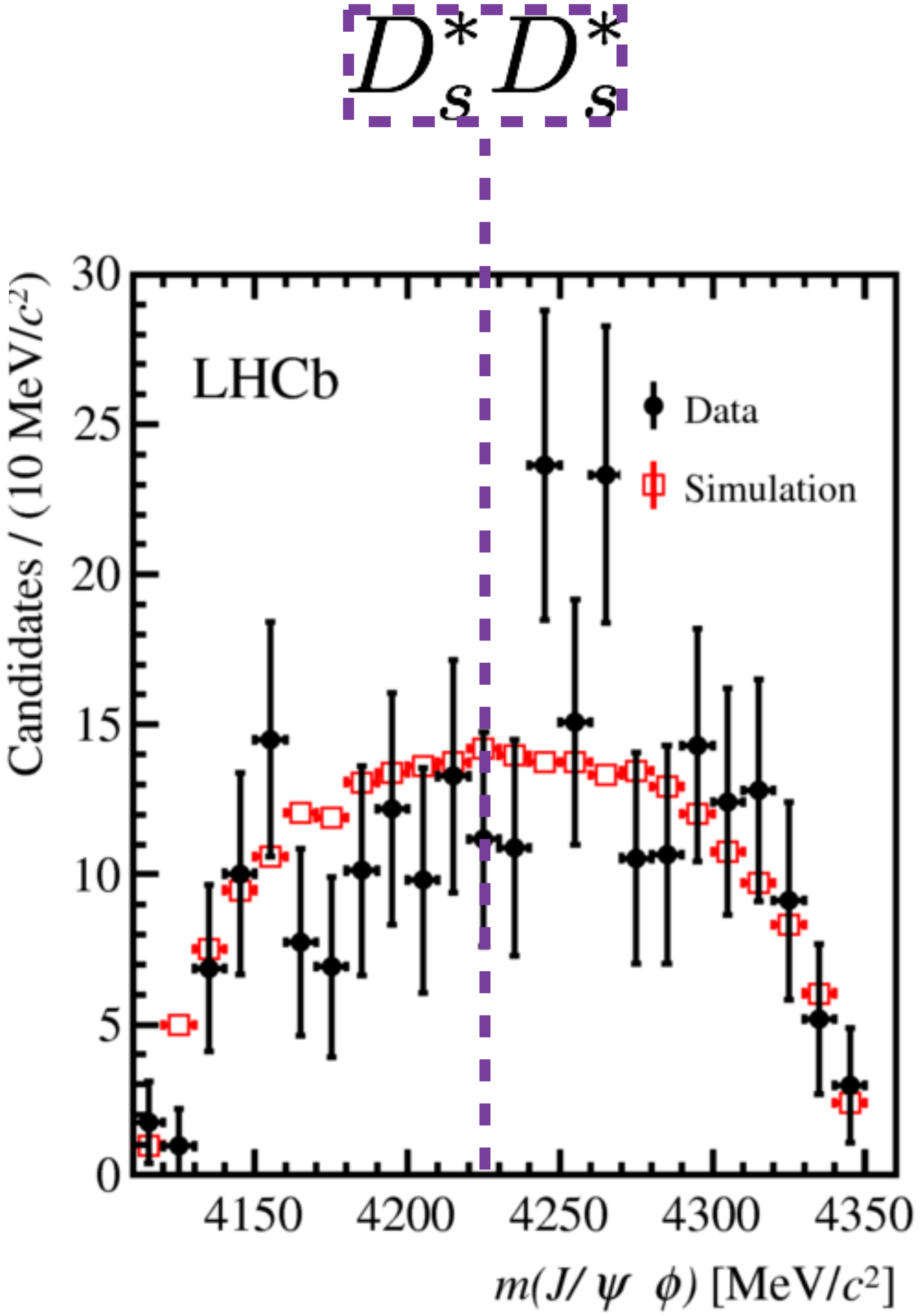
Contamination from non-res decays

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



Background subtracted
no efficiency correction





[JHEP 1603 (2016) 040]

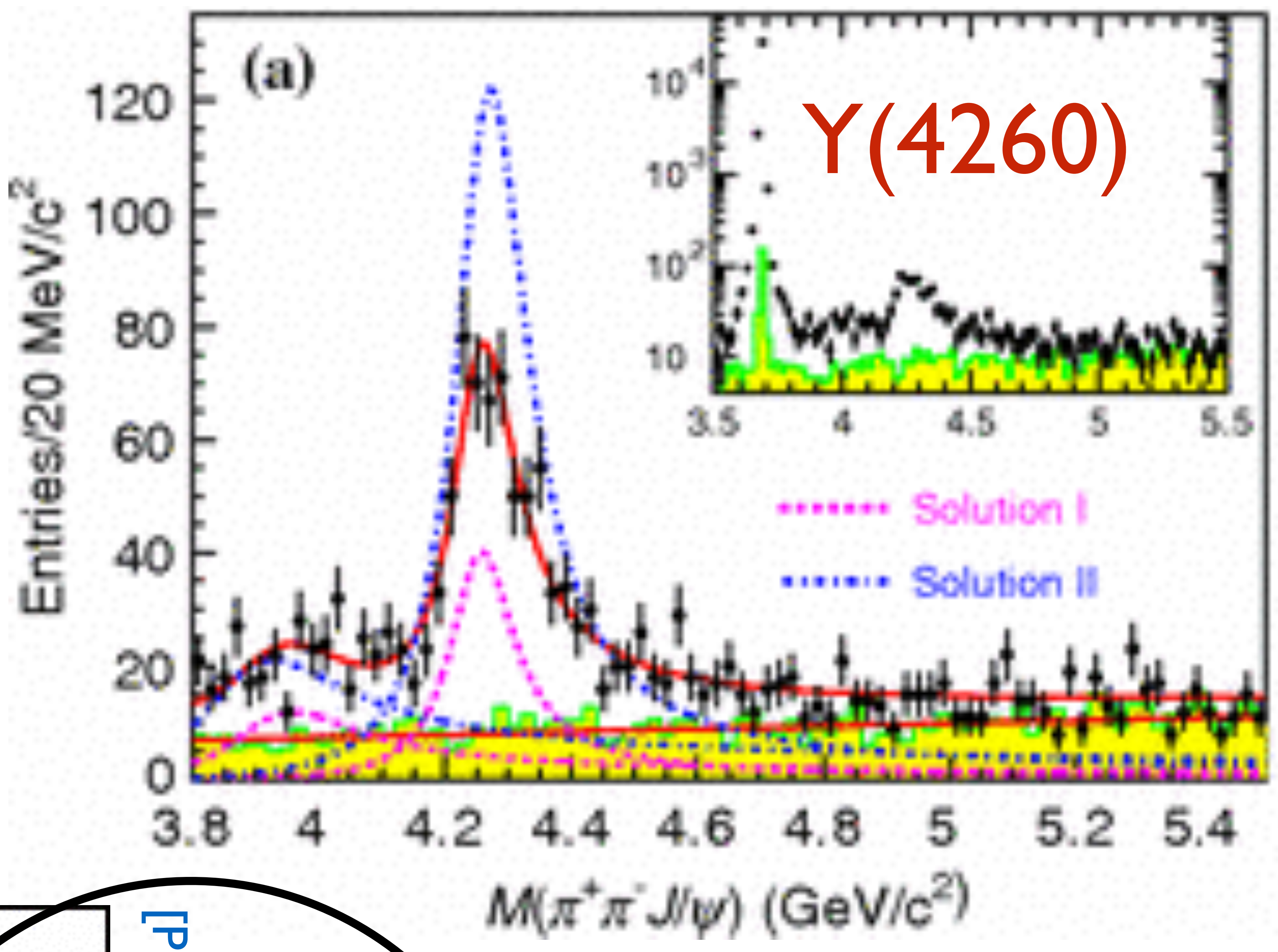
$Z_c(3900)^{\pm}$ in $e^+e^- \to Y(4260) \to \pi^+\pi^- J/\psi$

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

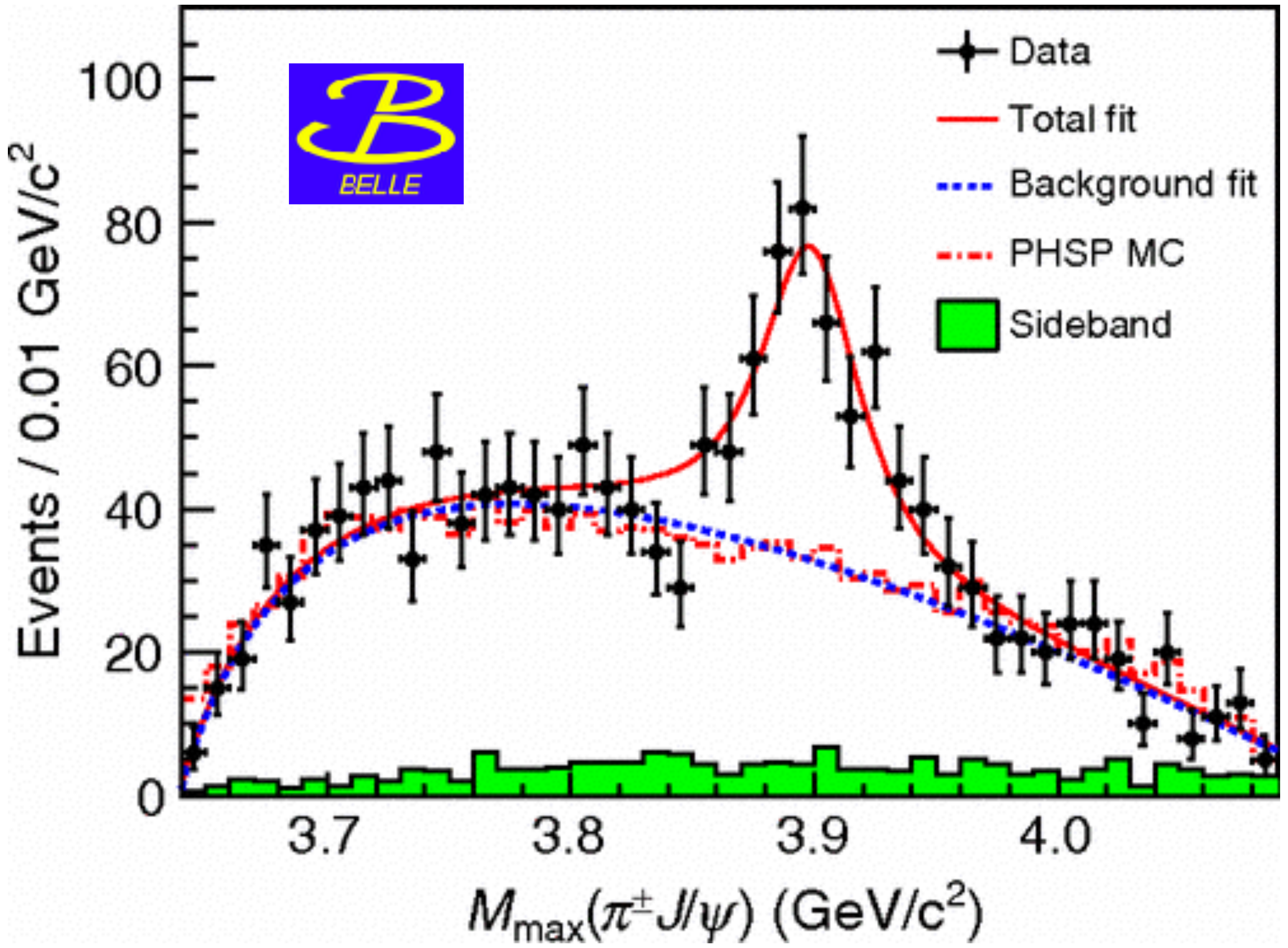
Is $Z(4430)^{\pm}$ a radial excitation of $Z_c(3900)^{\pm}$? [Maiani et al, NJP 10 (2008) 073004] [Wang, arXiv:1405.3581] [Agaev et al, arXiv:1706.01216]

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]

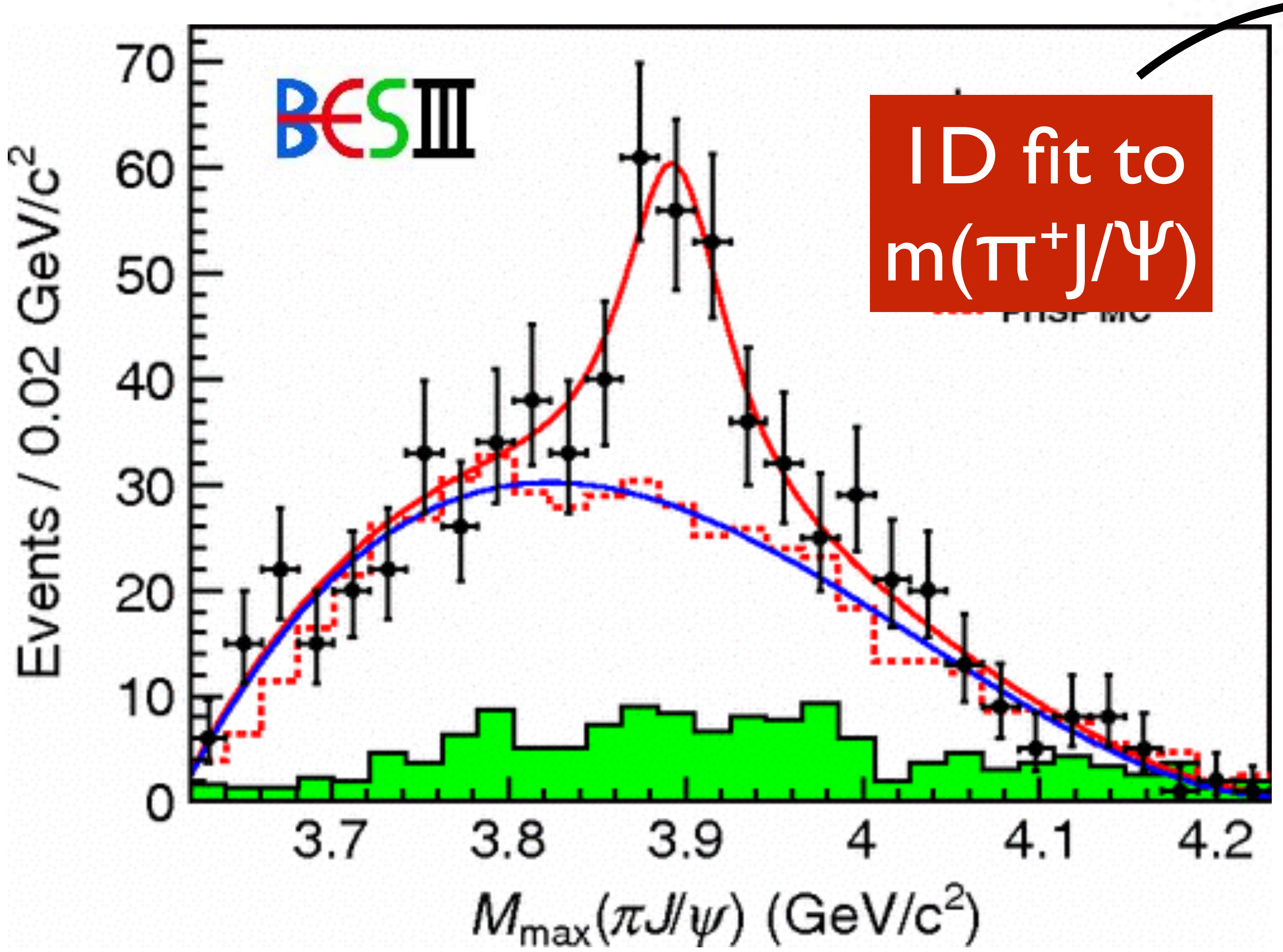
Also appears in $D^{\pm}D^*$ decay mode ($Z_c(3885)^{\pm}$)



[PRL 110 () 252002]



[PRL 110 (2013) 252001]



[PRL 110 (2013) 252002]

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

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

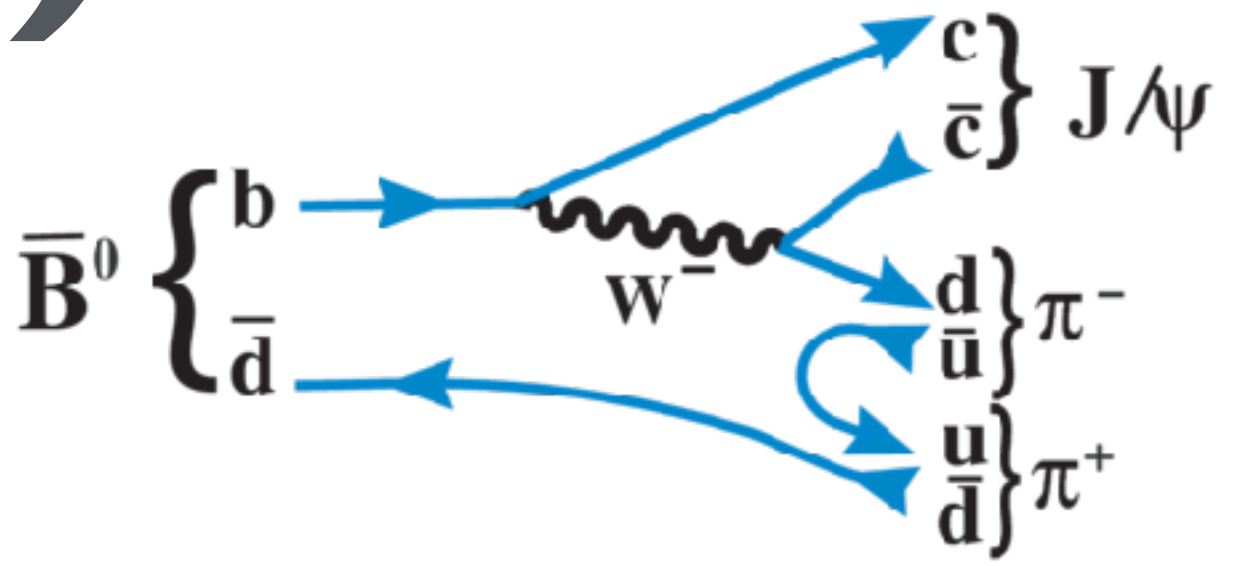
Understanding the $Z_c(3900)^{\pm}$

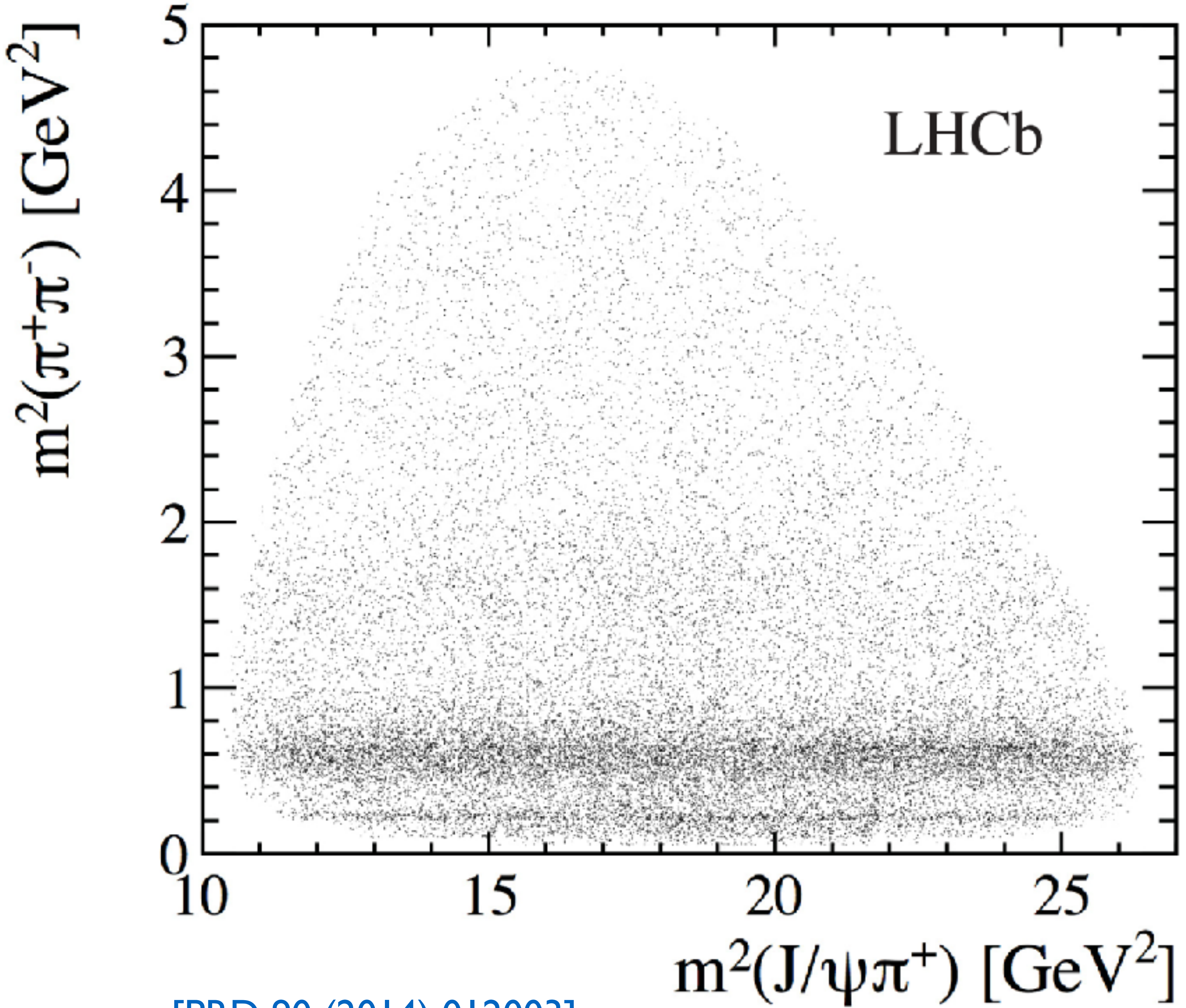
Some lattice QCD calculations do not support existence of $Z_c(3900)^{\pm}$ [Prelovsek et al PRD 91 (2015) 014504]

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]

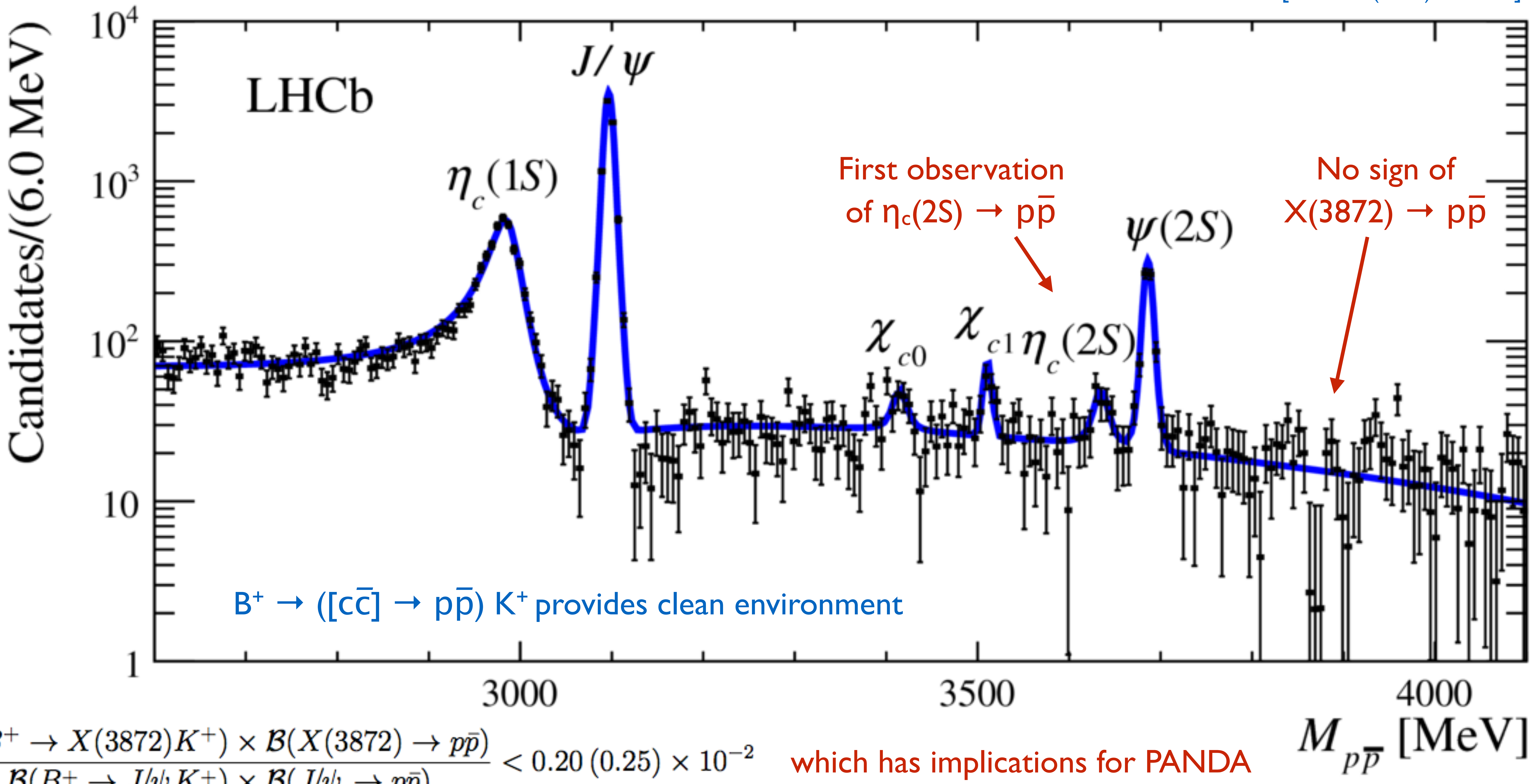




[PRD 90 (2014) 012003]

Charmonium production in b-hadron decays

[PLB 769 (2016) 305-313]

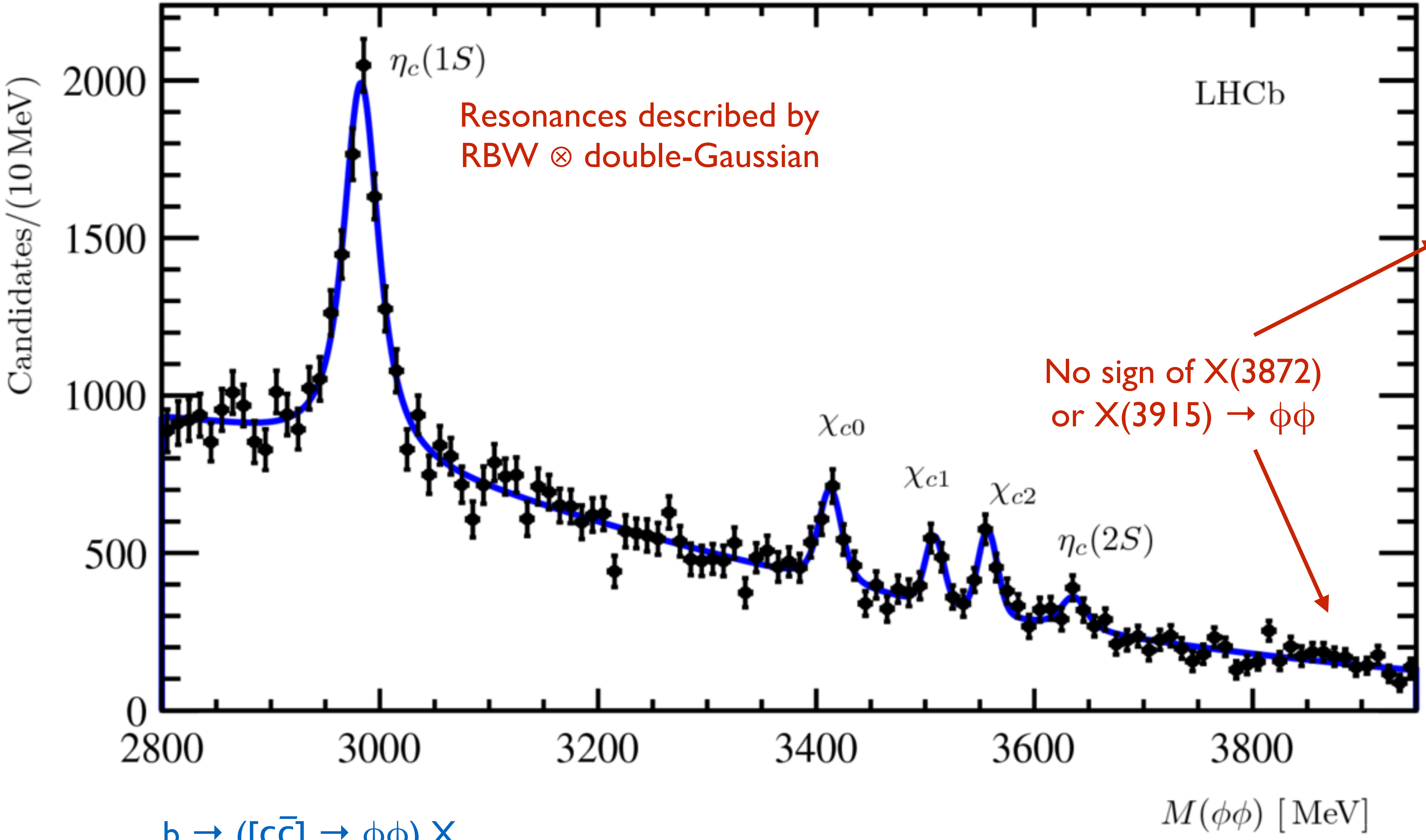


$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.20\,(0.25) \times 10^{-2}$$

which has implications for PANDA

Charmonium production in b-hadron decays

[arXiv:1706.07013]



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

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

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

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

$b \to ([c\bar{c}] \to \phi\phi)\ X$
by requiring separation between primary and secondary vertices