XIII[th] International Conference on

Heavy Quarks and Leptons

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Exotic Spectroscopy at LHCb

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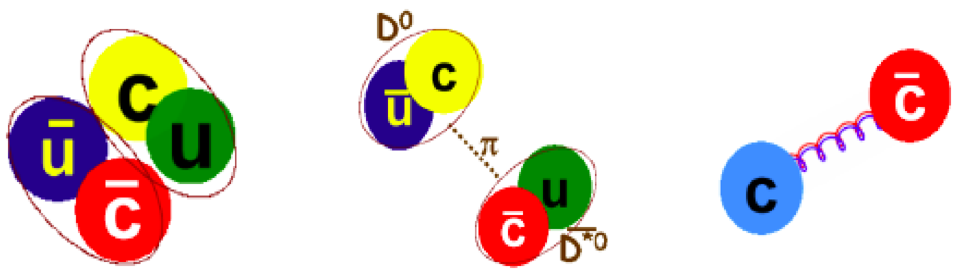
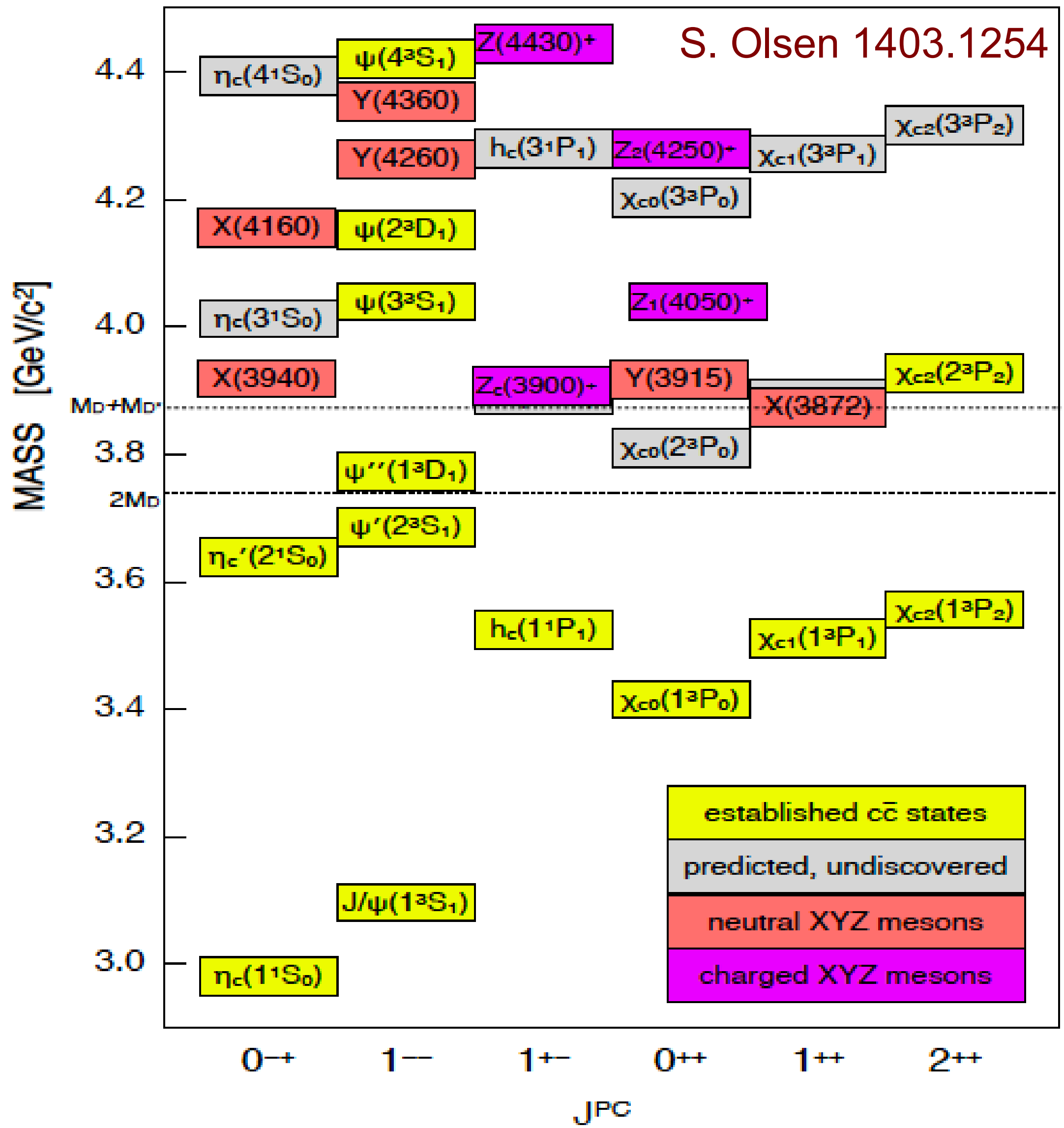
LHCb Collaboration

Exotics: charmonium "like" XYZ and beyond

- Many different exotic charmonium "like" states has been seen so far
  - Various explanations are possibile
  - Excellent tetraquark candidates!





- Tetraquarks (and pentaquarks) have been widely searched in light quark systems
  - Difficult from experimental and theoretical point of view
- Systems with heavy quarks: better signature and more "reliable" theoretical predictions

Pentaquark candidates $P_c(4380)$ and $P_c(4450)$ observed by LHCb

Outline

- Pentaquark candidates in $\Lambda_b \rightarrow J/\psi\ p\ K$
  - Amplitude analysis PRL 115 (2015) 072001
  - Moment analysis arXiv:1604.05708 (submitted to PRL)
- Confirmation of the resonant nature of the $Z(4430)^-$
  - Amplitude analysis PRL 112 (2014) 222002
  - Moment analysis PRD 92 (2015) 112009
- Confirmation of X(3872) quantum numbers
  - $J^{PC} = 1^{++}$ PRD 92 (2015) 011102
- Tetraquark searches in $B_s\pi$
  - LHCb-CONF-2016-004

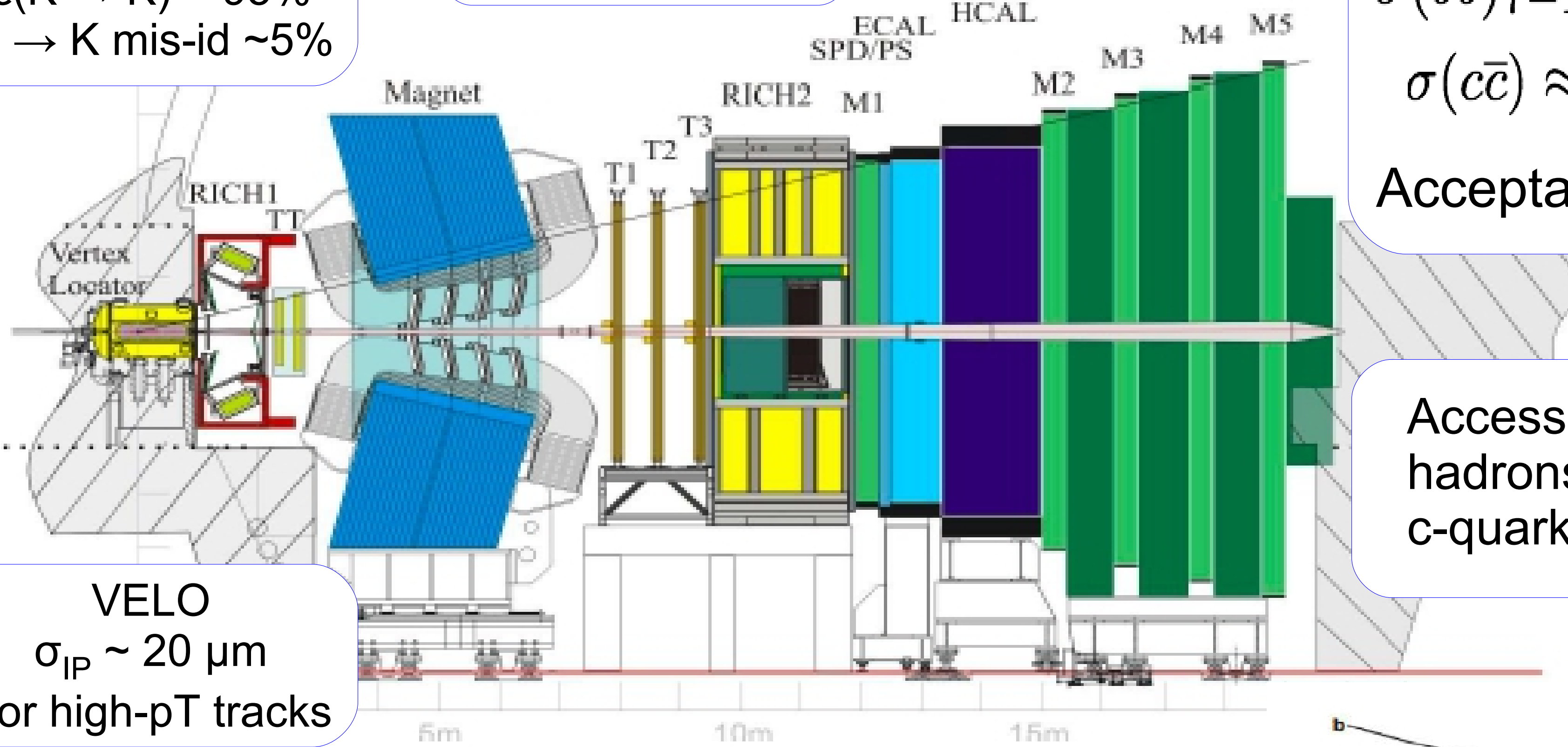
The LHCb experiment

RICH 1 & 2
ε(K → K) ~ 95%
π → K mis-id ~5%

Tracking system
Δp/p = 0.5-1.0%

$$\sigma(b\bar{b})_{7-TeV} \approx 290\mu b$$
$$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$$

Acceptance ~ 25 %

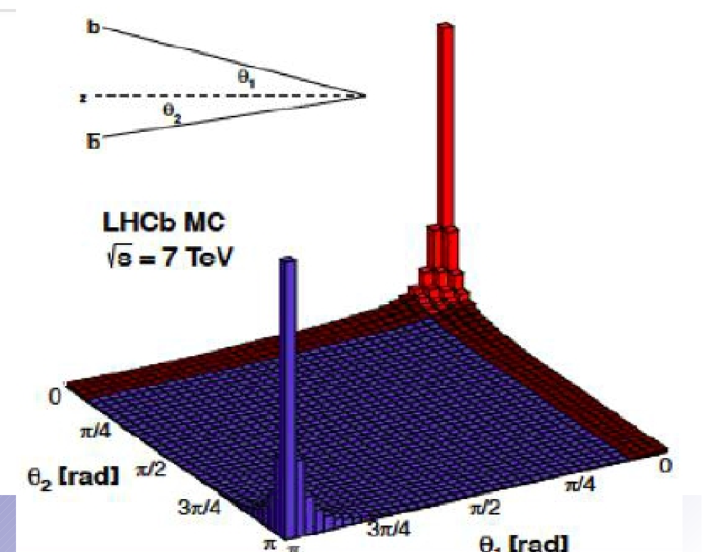


Access to all kind of hadrons with b- and c-quarks

VELO
σ_{IP} ~ 20 μm
For high-pT tracks

LHCb: forward spectrometer for flavor physics
Excellent tracking and vertexing capabilities.
Excellent PID performances

Collected 3.0 fb^{-1} in 2011-2012

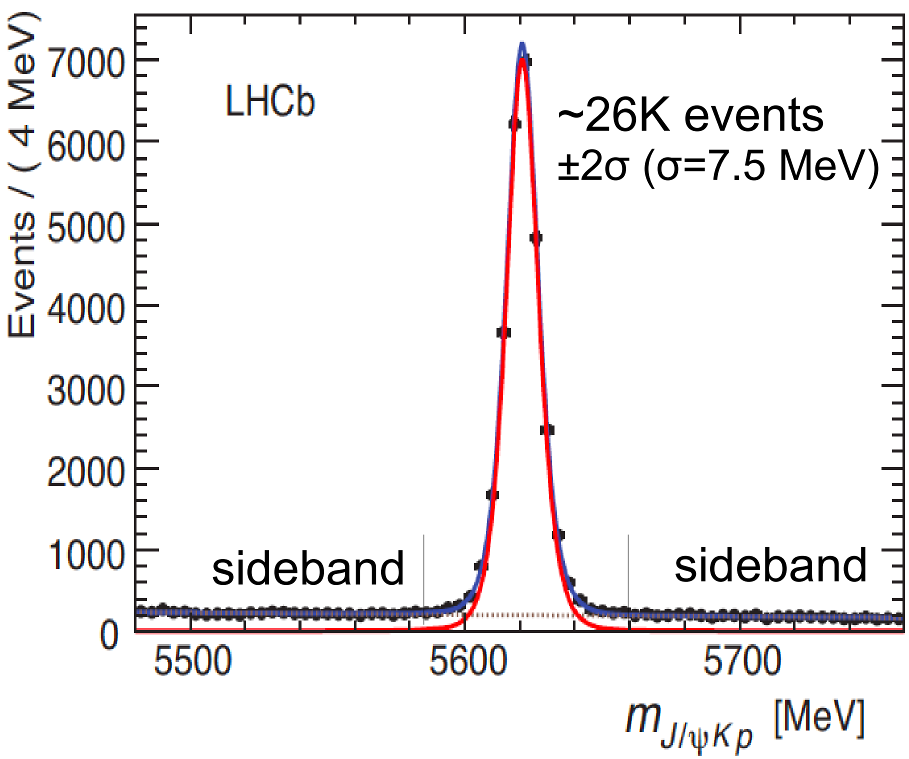


Exotic J/ψp contributions in $\Lambda_b \rightarrow J/\psi\ p\ K$

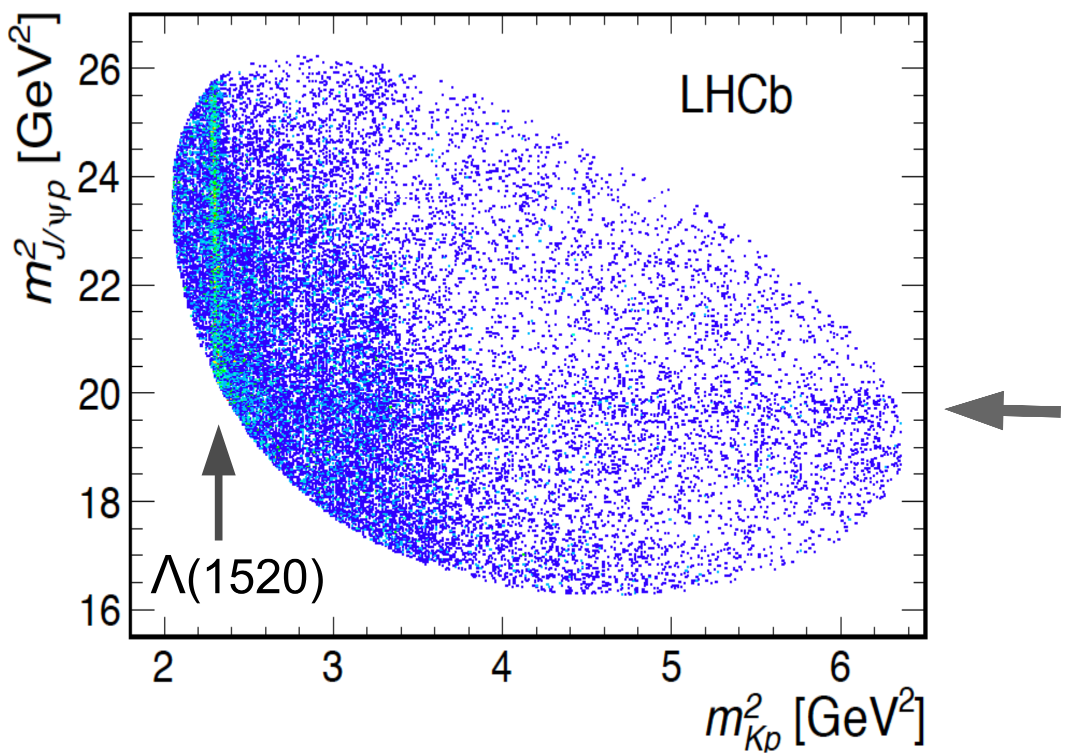
$\Lambda_b \to J/\psi\, p\, K$ at LHCb

PRL 115 (2015) 072001

- Clean sample: more than 26.000 signal candidate
- Background subtracted from sidebands
  - 5.4% of combinatorial background in the signal region



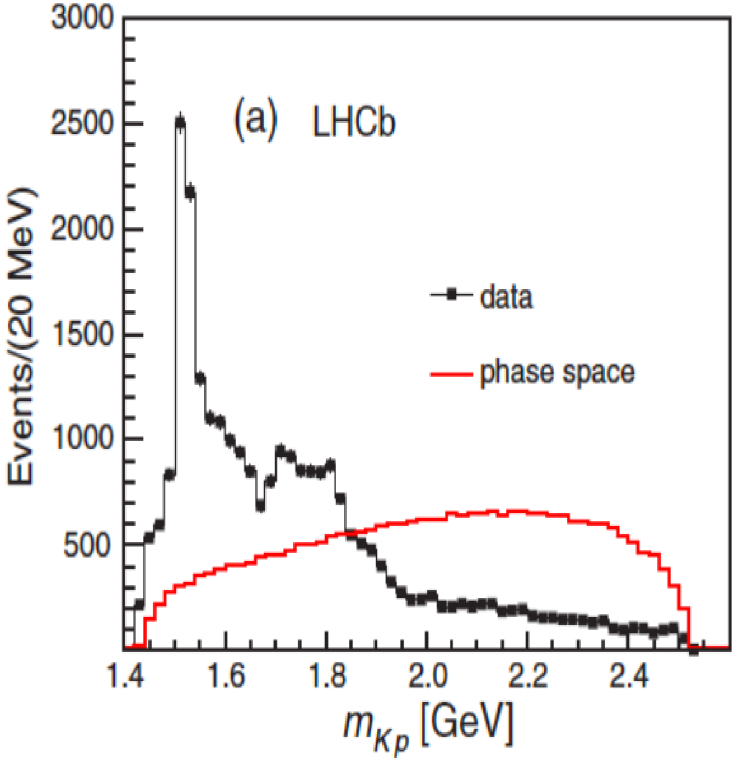
Background subtracted Dalitz plot

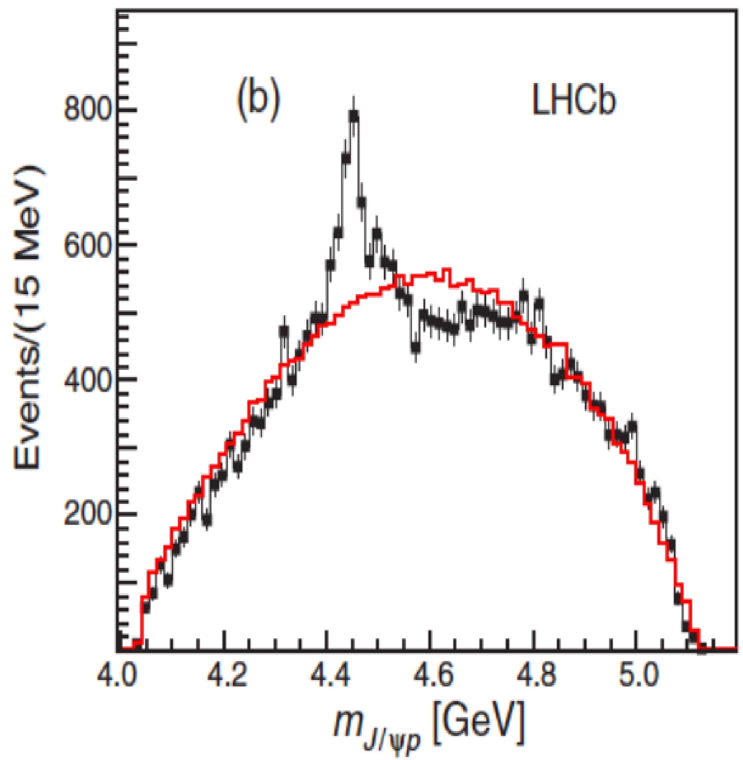


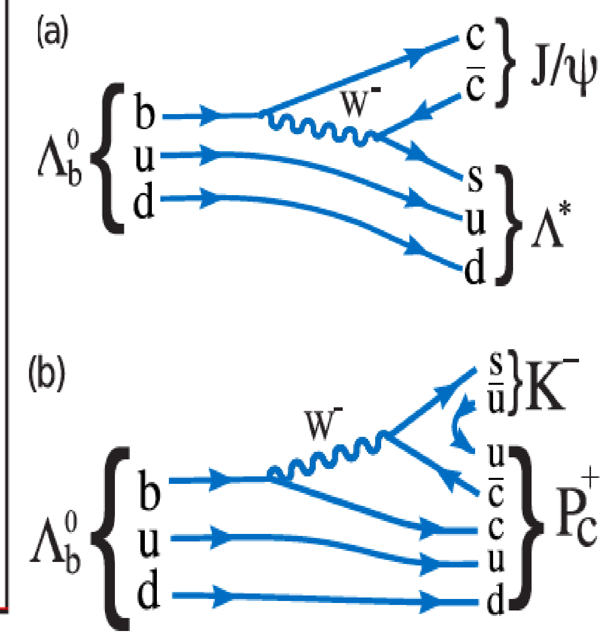
- Unusual feature in $m^2_{J/\psi p}$ at 19.5 GeV^2
- Large activity due to Λ^* excited states in the m^2_{Kp} at projection

$\Lambda_b \to J/\psi\ p\ K$ projections

PRL 115 (2015) 072001



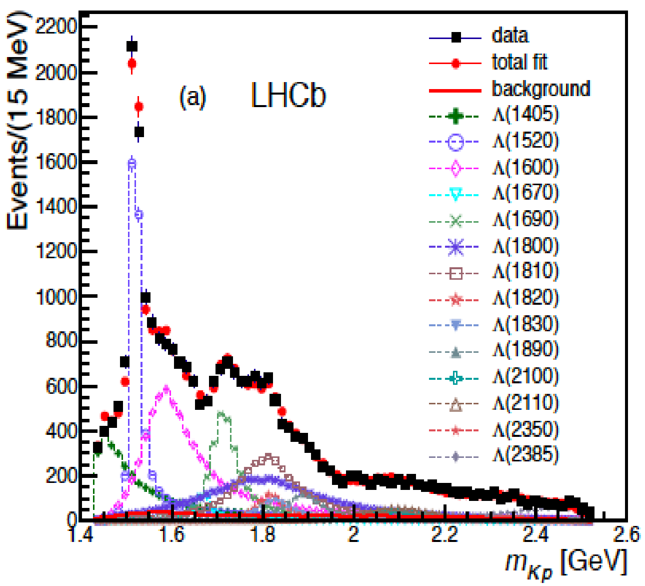


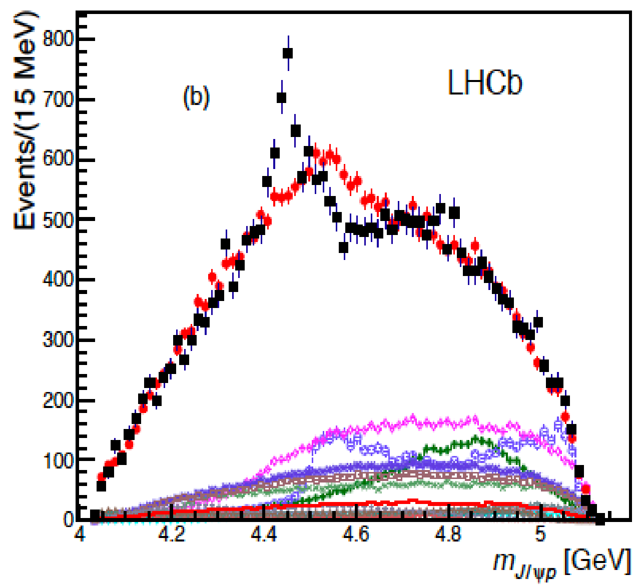


- Can interference between Λ^* resonances generate a peak in the J/ψ p mass spectra?
  - Full amplitude analysis that incorporate both decay sequences
  - 6-D amplitude fit: invariant masses, helicity angles and decay plane angles

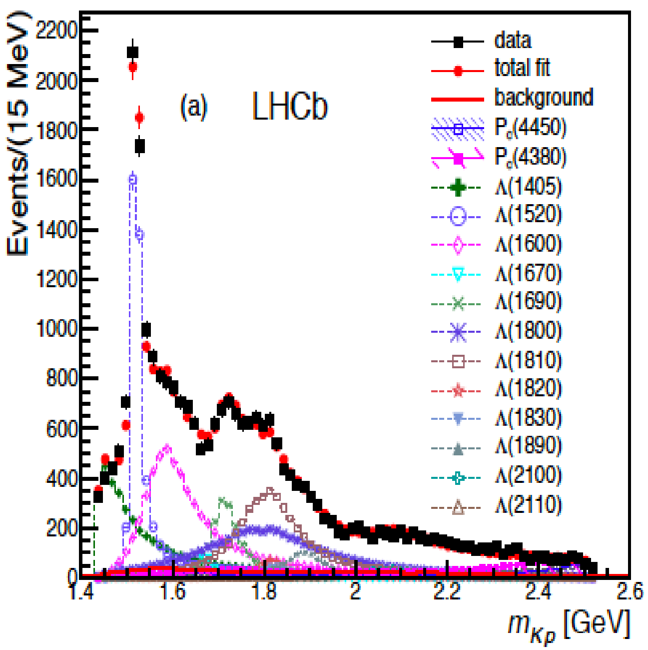
$\Lambda_b \rightarrow J/\psi\ p\ K$ fit results

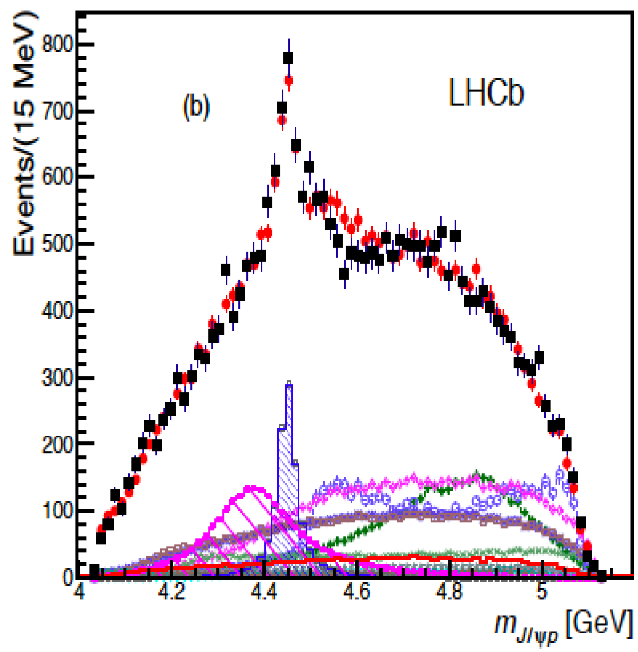
PRL 115 (2015) 072001





- Considering all Λ^* known states
  - Does not improve $m_{J/\psi p}$





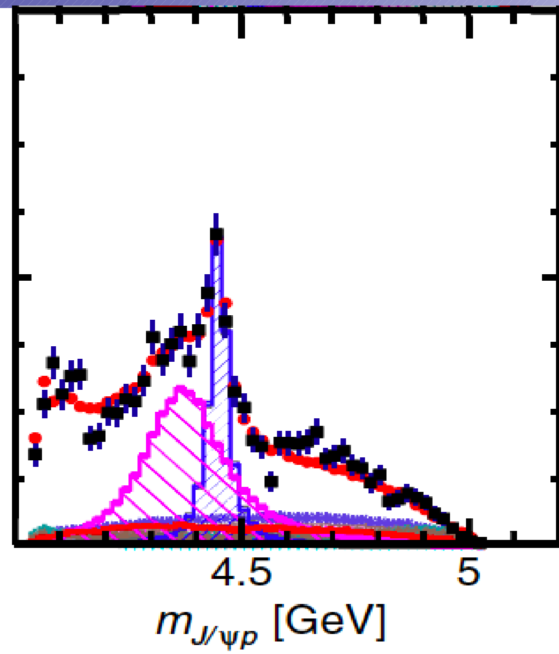
- Adding two P_c states improve the fit quality
- Explored all J^P up to $7/2^{\pm}$
  - Best fit $(3/2^-, 5/2^+)$
  - Good fit also with $(5/2^+, 3/2^-)$

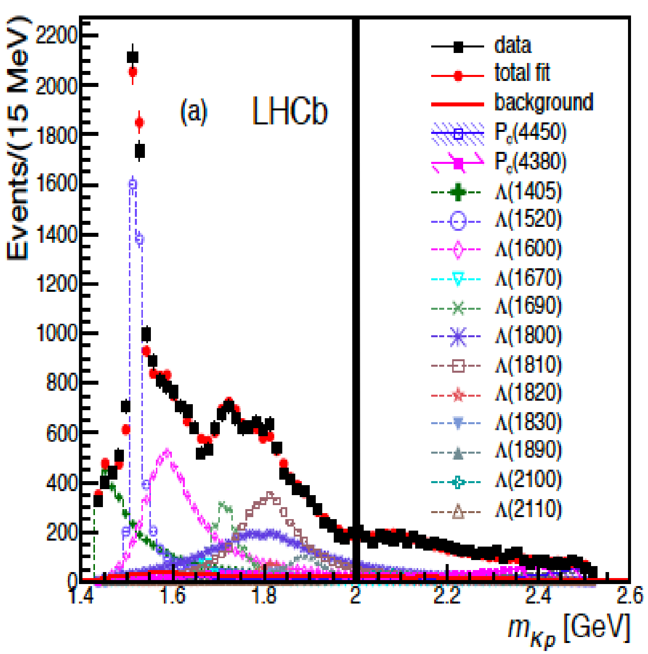
	$P_c(4380)^+$	$P_c(4450)^+$
	$\frac{3}{2}^-$	$\frac{5}{2}^+$
M	$4380 \pm 8 \pm 29$	$4449.8 \pm 1.7 \pm 2.5$
Γ	$205 \pm 18 \pm 86$	$39 \pm 5 \pm 19$
f %	$8.4 \pm 0.7 \pm 4.2$	$4.1 \pm 0.5 \pm 1.1$

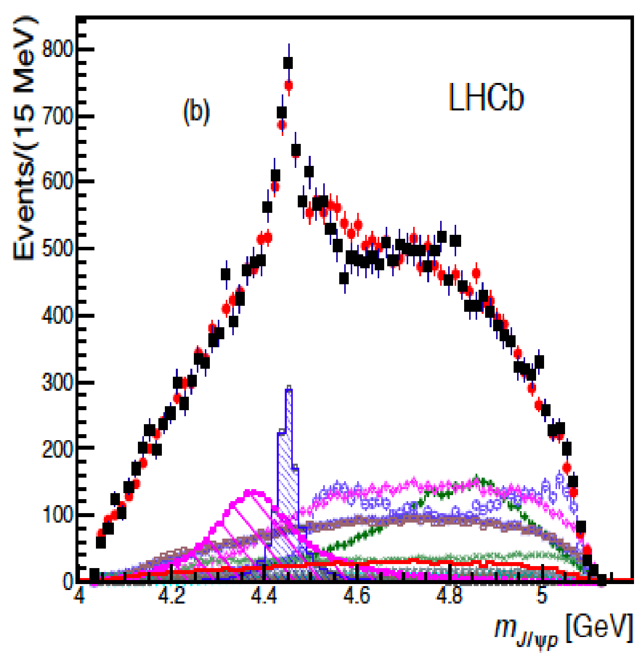
$\Lambda_b \to J/\psi\ pcK$ fit results

PRL 115 (2015) 072001

large interference between $P_c(4380)$ and $P_c(4450)$







- Considering all Λ* known states
  - Does not improve $m_{J/\psi p}$

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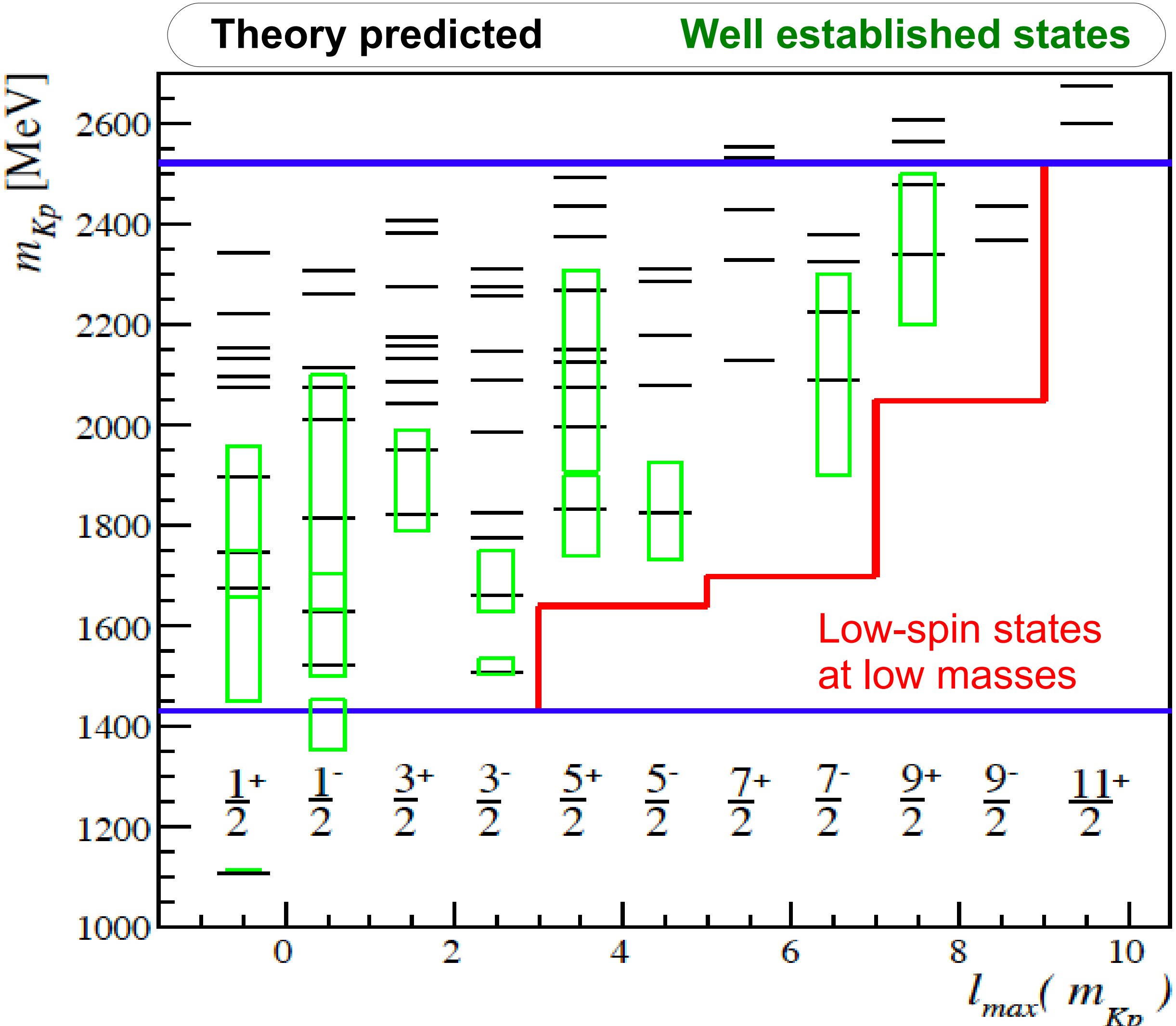
P_c: Model independent analysis

1604.05708

- The spectroscopy of Λ^* is complex and not completely understood
- High density of states with large widths
- Non resonant contributions could also be present

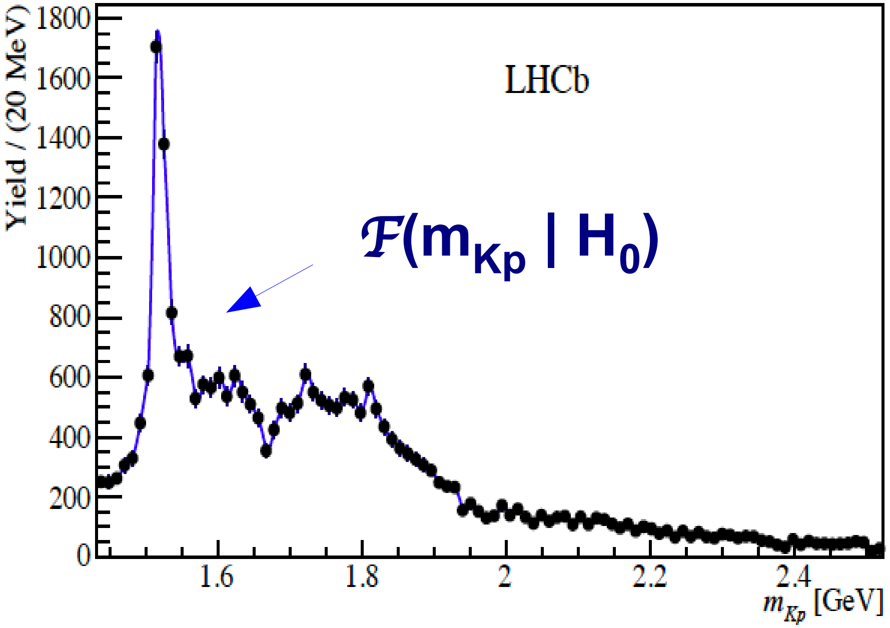
Only restrict the maximal spin of allowed Λ^* components at given m(Kp)

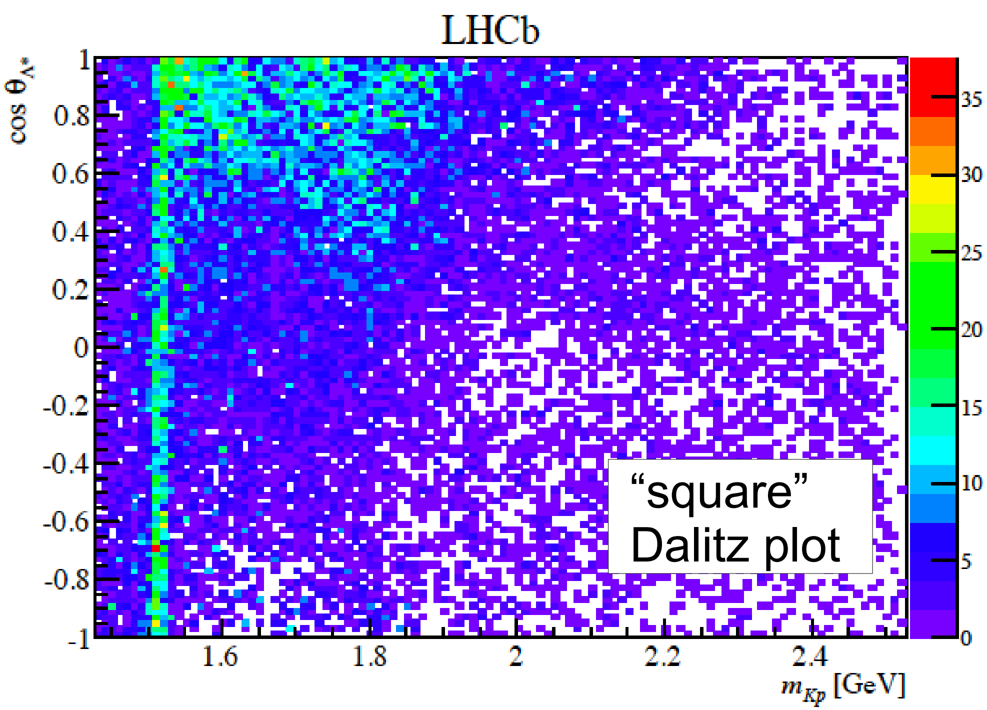


- Study the $\Lambda_b \rightarrow J/\psi pK$ decay with a model independent approach respect to the Kp contributions
  - H_0: hypothesis that the data are described by $\Lambda_b \rightarrow J/\psi \Lambda^*$ ($\Lambda^* \rightarrow pK$)

P_c: Model independent analysis

1604.05708





- Efficiency-corrected and background subtracted mass distribution
  - Interpolation to obtain $\mathcal{F}(m_{Kp} \mid H_0)$

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

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

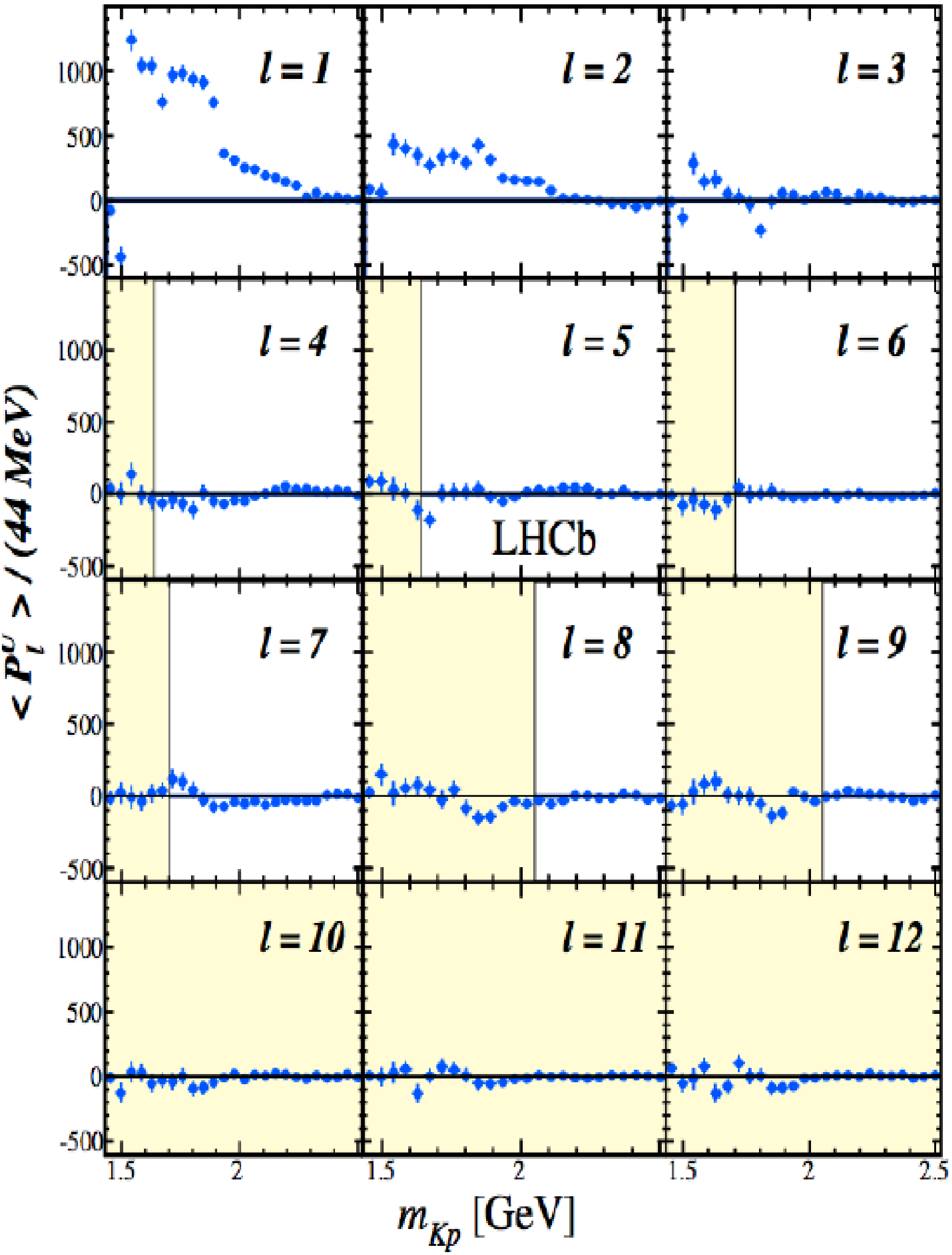
- Moments from data in bins of m_{Kp}

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

- Maximal rank l_{max}, cannot be higher than $2J_{max}$: J_{max} is the highest (Kp) spin which is present in the data at a given m_{Kp} value

P_c: Model independent analysis

1604.05708



Filter out maximum spin for each m_{Kp}

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

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

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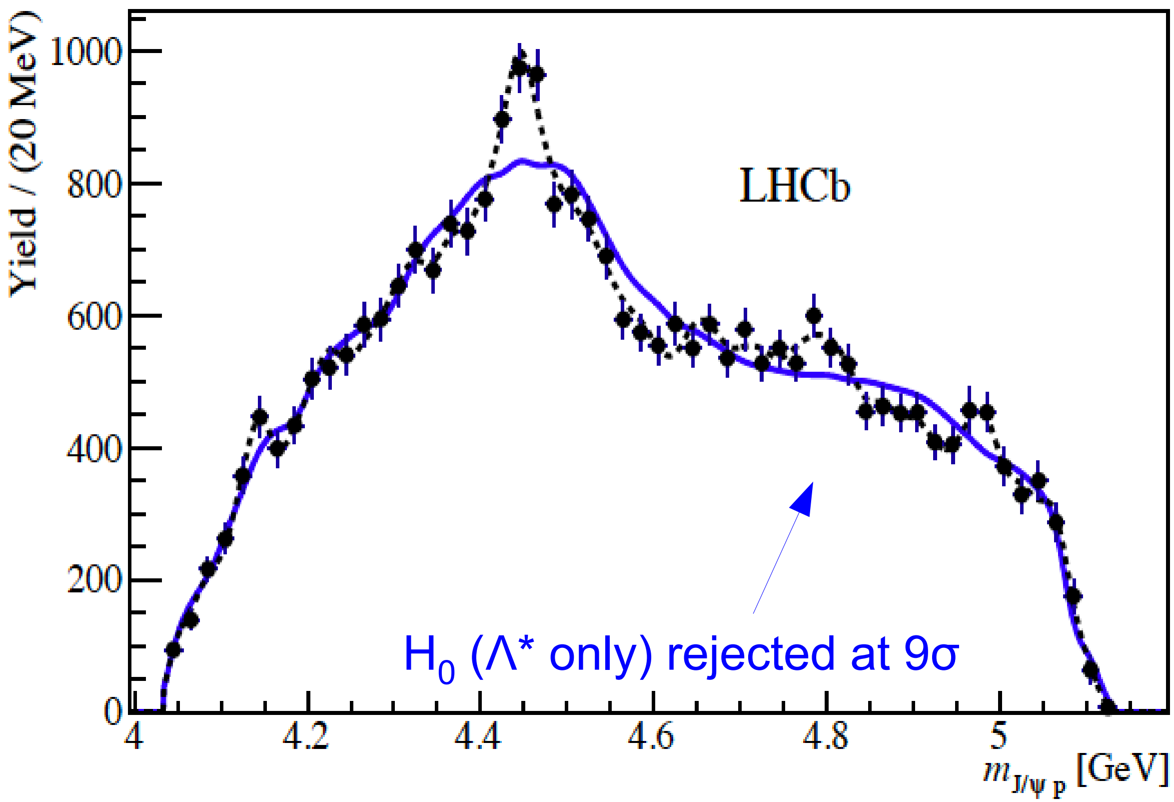
P_c: Model independent analysis

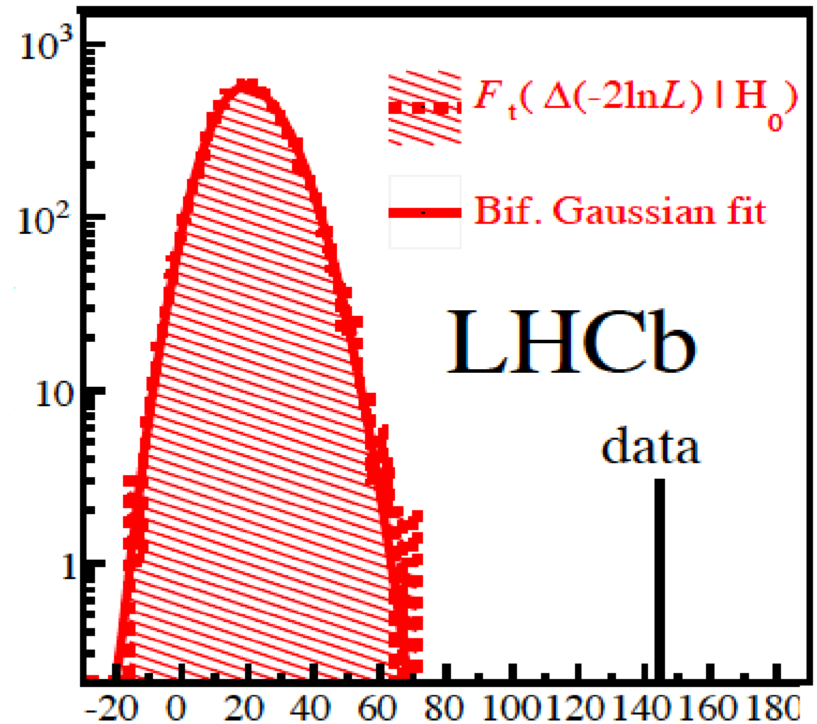
1604.05708

- Generate high statistics toy MC:
  - Phase space $\Lambda_b \rightarrow J/\psi pK$
  - Weight according to m_{Kp} and the moments (filter out ℓ_{max} according to m_{Kp})
  - Search for reflections of the Kp system into the $J/\psi p$ system



- H_0 hypothesis rejected at > 9σ

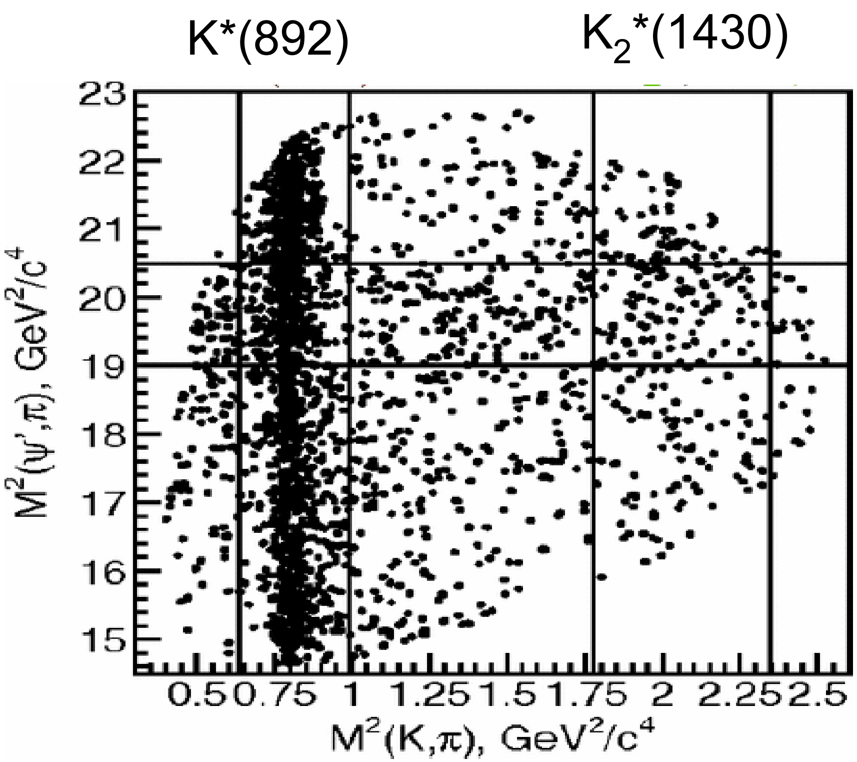
Likelihood ratio to test H_0

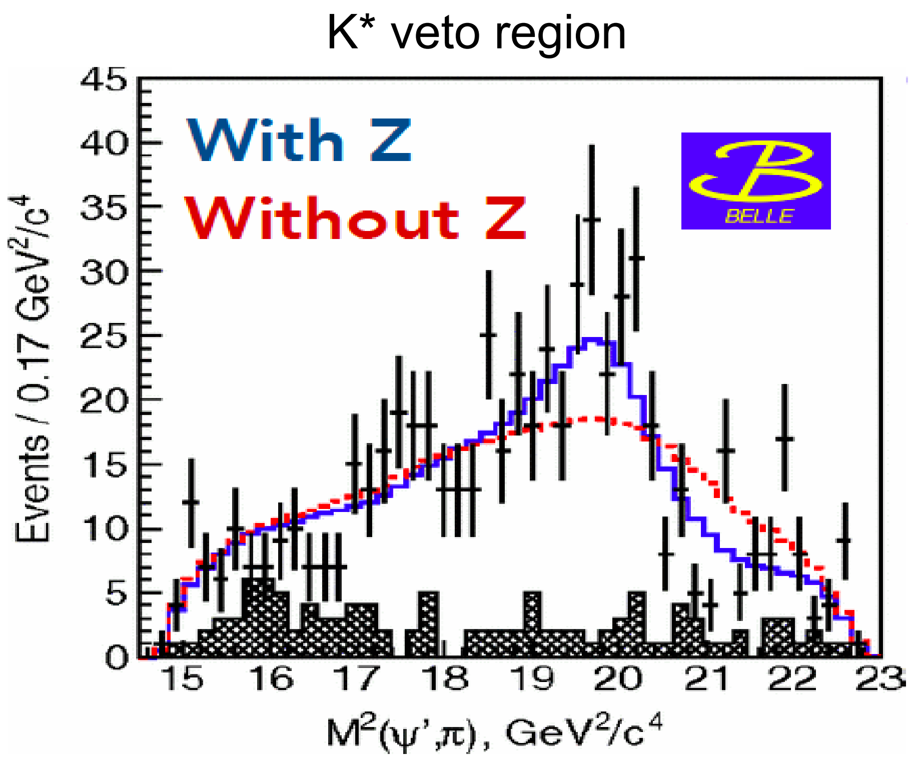


Charged exotic $Z(4430)^{\pm}$

$Z(4430)^+$ charged charmonium exotic

- Charged charmonium like state in $B^0 \rightarrow \psi(2S)\pi K$ decays
  - Belle PRL 100 (2008) 142001, PRD 79 (2009) 112001, PRD 80 (2009) 031104
  - BaBar PRD 79 (2009) 112001 Not observed but not in contradiction with Belle

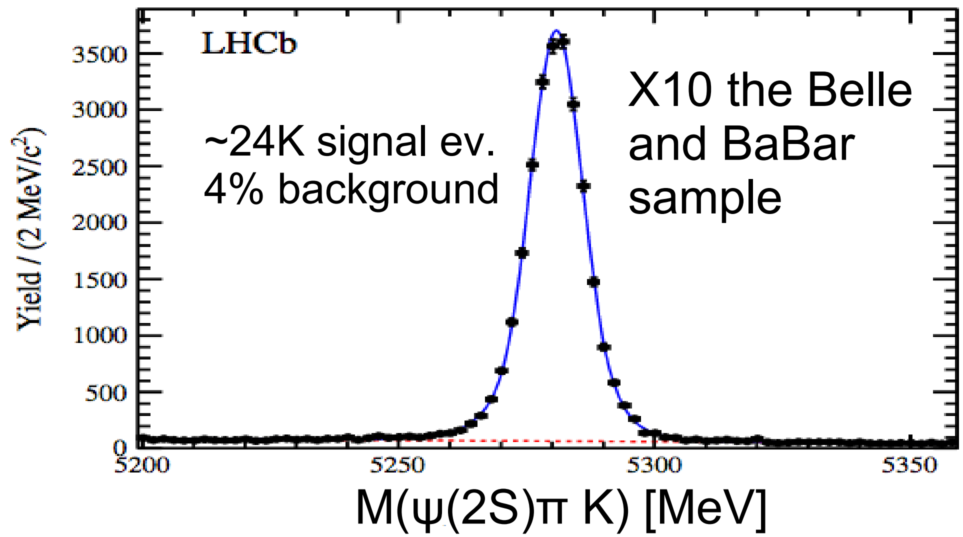




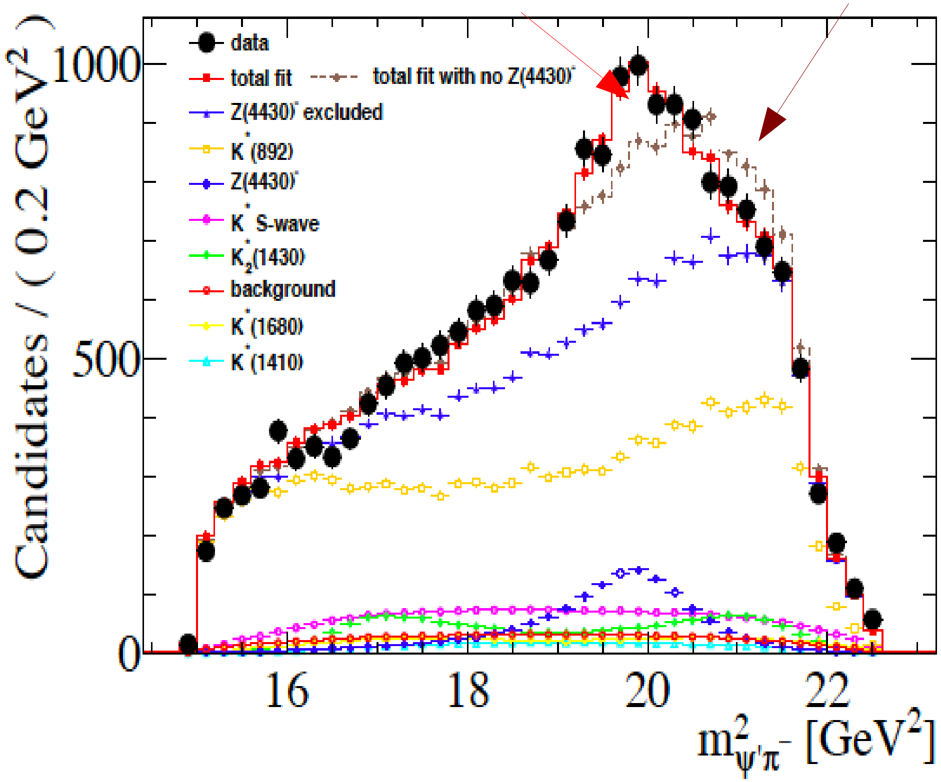
- $B^0 \rightarrow \psi(2S)\pi K$
- $B^0 \rightarrow Z(4430) K$, $Z(4430) \rightarrow \psi(2S)\pi$

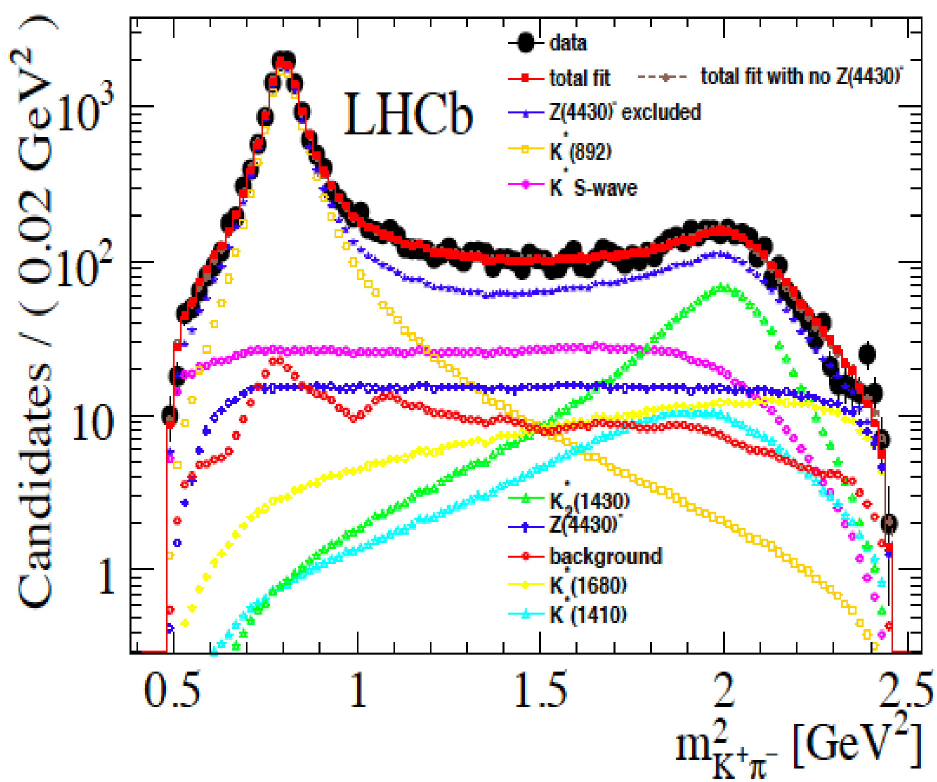
$$M = 4485^{+22+28}_{-22-11}\ \mathrm{MeV/c^2}$$
$$\Gamma = 200^{+41+26}_{-46-35}\ \mathrm{MeV}/c^2$$

Confirmation of the $Z(4430)^+$ by LHCb



- 4D amplitude analysis: extract resonance parameters and quantum numbers J^P

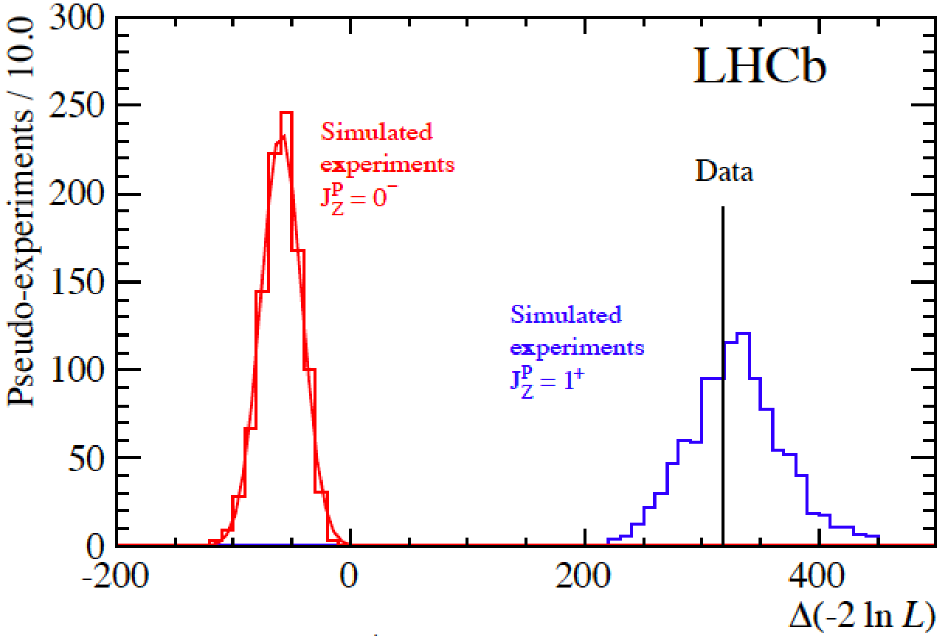




PRL 112 (2014) 222002

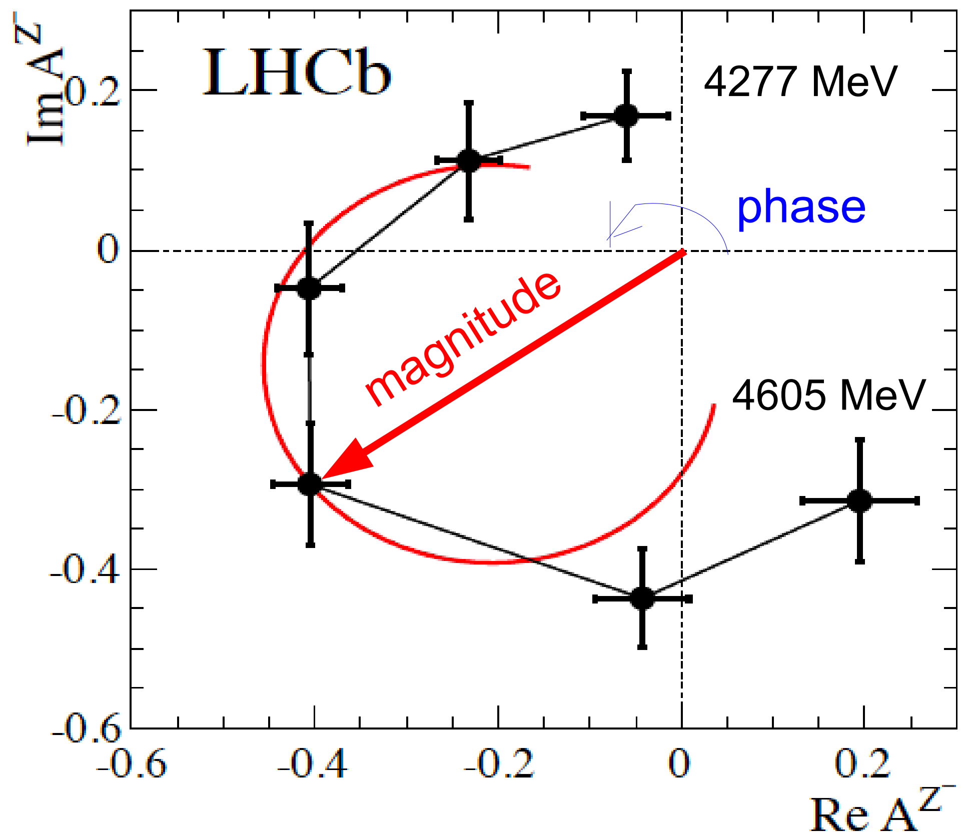
Z(4430): resonant nature

PRL 112 (2014) 222002



- $J^P = 1^+$
- Others assignment are ruled out with large significance

Clear resonant behavior

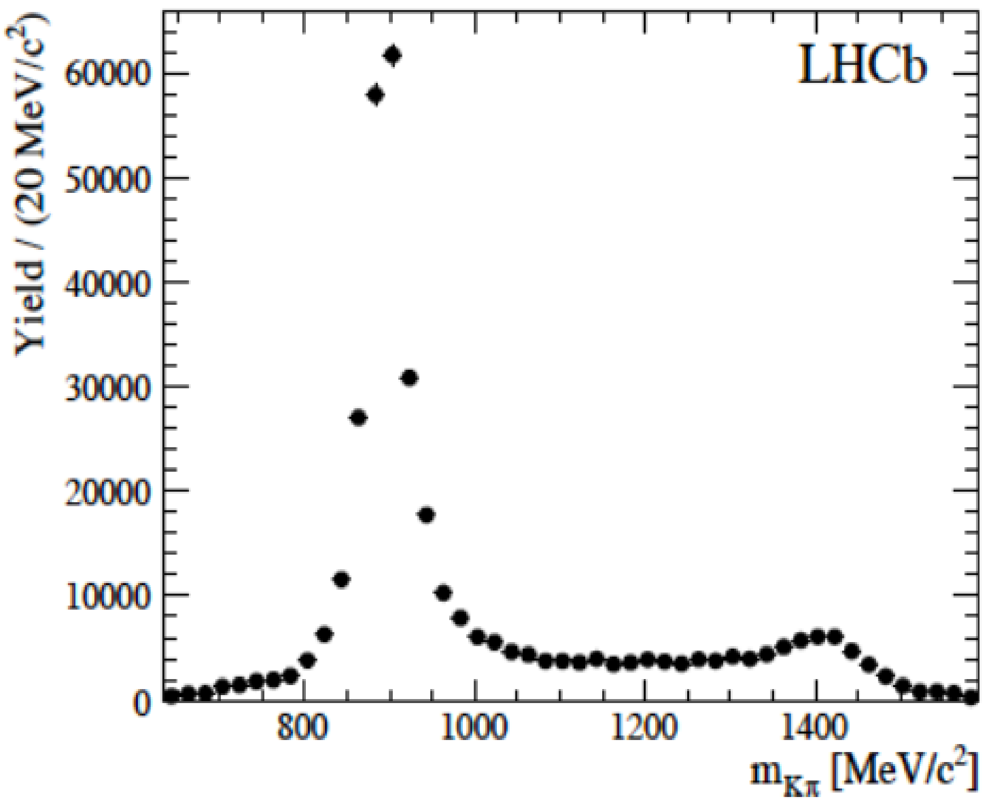


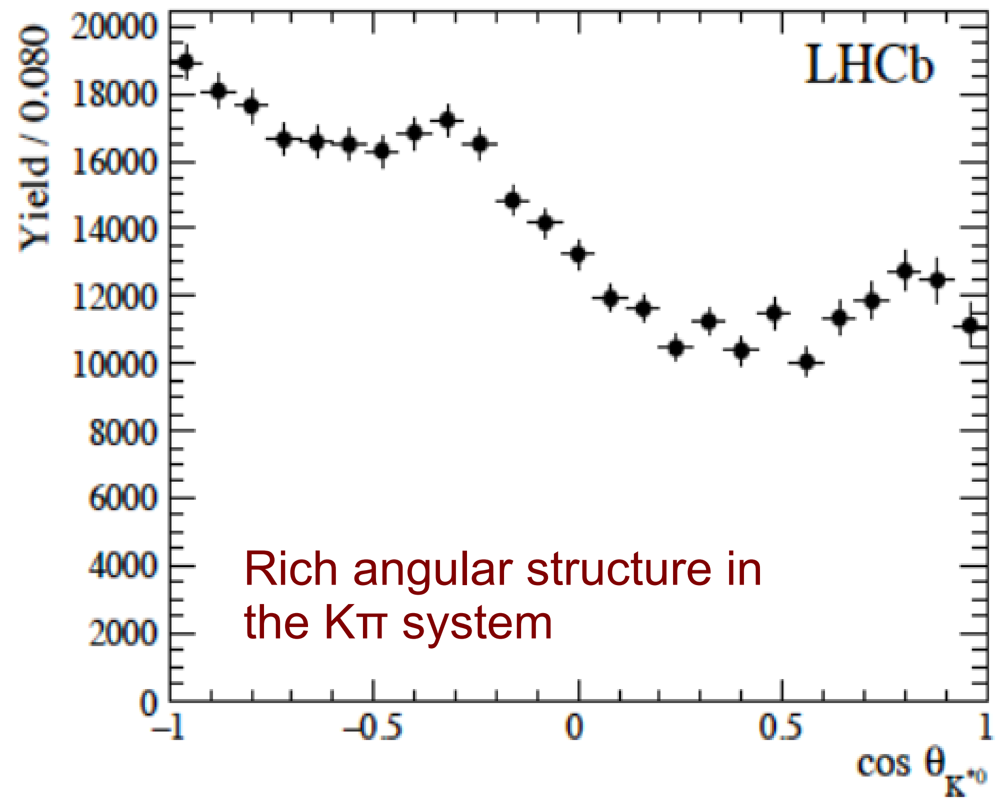
	LHCb	Belle
$M(Z)$ [MeV]	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
$\Gamma(Z)$ [MeV]	$172 \pm 13^{+37}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$
f_Z [%]	$5.9 \pm 0.9^{+1.5}_{-3.3}$	$10.3^{+3.0}_{-3.5}{}^{+4.3}_{-2.3}$
f_Z^I [%]	$16.7 \pm 1.6^{+2.6}_{-5.2}$	–
significance	$> 13.9\sigma$	$> 5.2\sigma$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

Z(4430): model independent analysis

PRD 92 (2015) 112009

- Check if the structures in the $m_{\psi(2S)\pi}$ spectrum can be explained as reflections of the resonance activity in the Kπ system
  - No assumptions on the K* resonances: only its maximum J is restricted
  - Angular structure of the Kπ system is extracted with Legendre polynomial moments

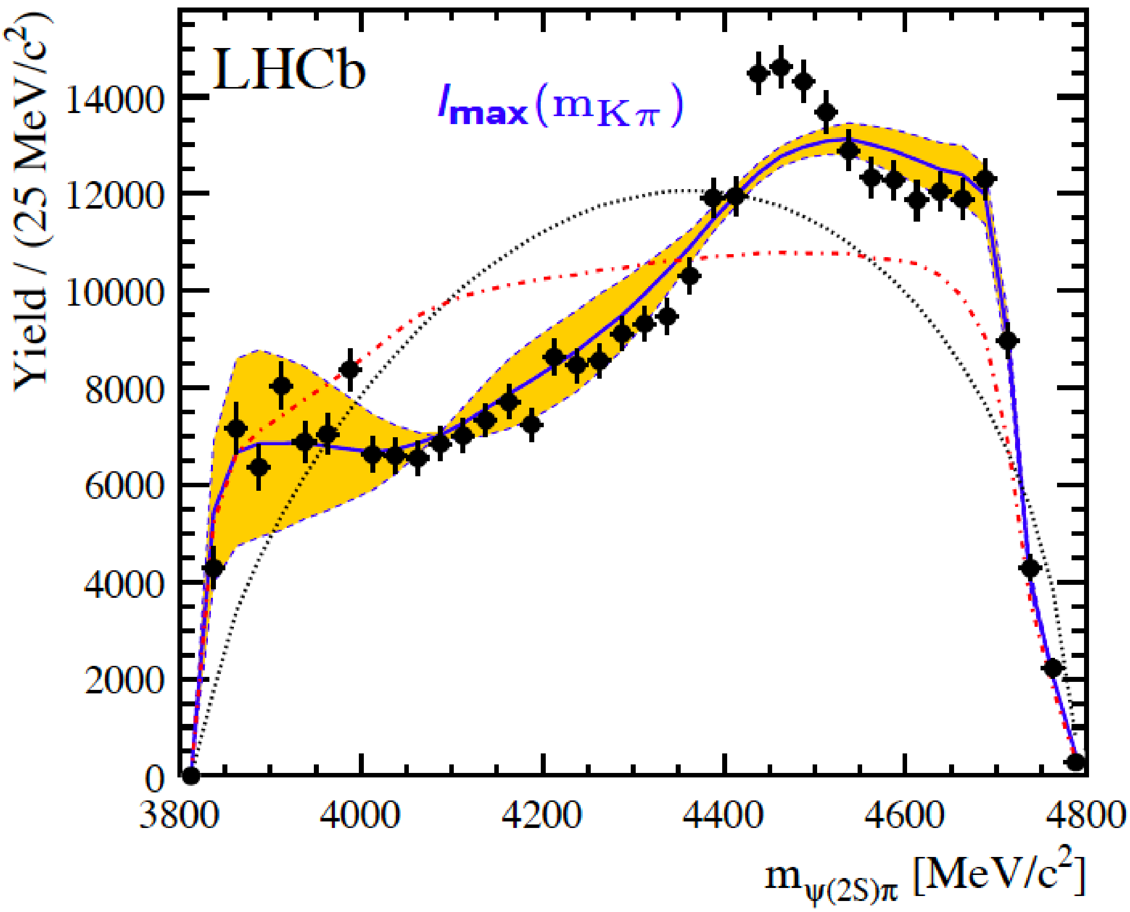




Rich angular structure in the Kπ system

Z(4430): model independent analysis

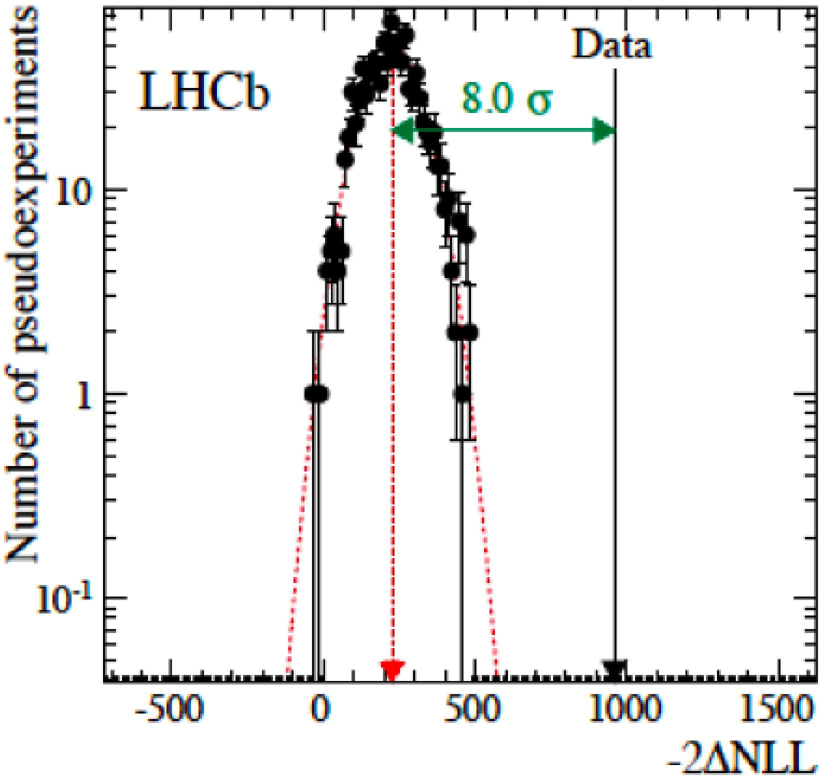
- Large toy MC with events weighted according to the moments to predict the $m_{\psi(2S)\pi}$ spectrum



$$l_{max}(m_{K\pi}) = \begin{cases} 2 & m_{K\pi} < 836\ \mathrm{MeV}/c^2 \\ 3 & 836\ \mathrm{MeV}/c^2 < m_{K\pi} < 1000\ \mathrm{MeV}/c^2 \\ 4 & m_{K\pi} > 1000\ \mathrm{MeV}/c^2. \end{cases}$$

- Hypothesis test based on likelihood ratio

$l_{max} < 6$



Hypothesis that the structure of the $m_{\psi(2S)\pi}$ spectrum can be described as reflection of the activity of the resonances in the Kπ system is ruled out with more than 8σ

Properties of X(3872) state

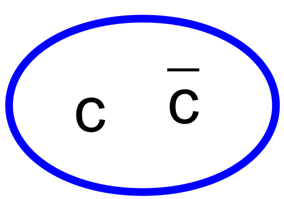
X(3872)

PRD 92 (2015) 011102

M(X) = 3871.68 ± 0.17 MeV
M(D*)+M(D) = 3871.85 ± 0.20 MeV

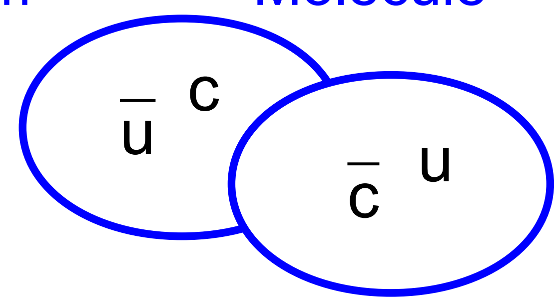
- Mass close to DD* threshold
- Still debates: molecular state? Tetra-quark? Mixture? Ordinary charmonium?
- Crucial unambiguous quantum number J^{PC} determination
  - Decay to J/Ψγ and Ψ(2S)γ → C=+1
  - Using X(3872) → $J/\Psi\pi^+\pi^-$ decay CDF establish 1^{++} or 2^{-+}
  - With $1fb^{-1}$ LHCb rules out 2^{-+} → $J^{PC}=1^{++}$
    - CDF and LHCb assumed minimal L, this assumption is not obvious

Standard charmonium



R (size) is small

Molecule



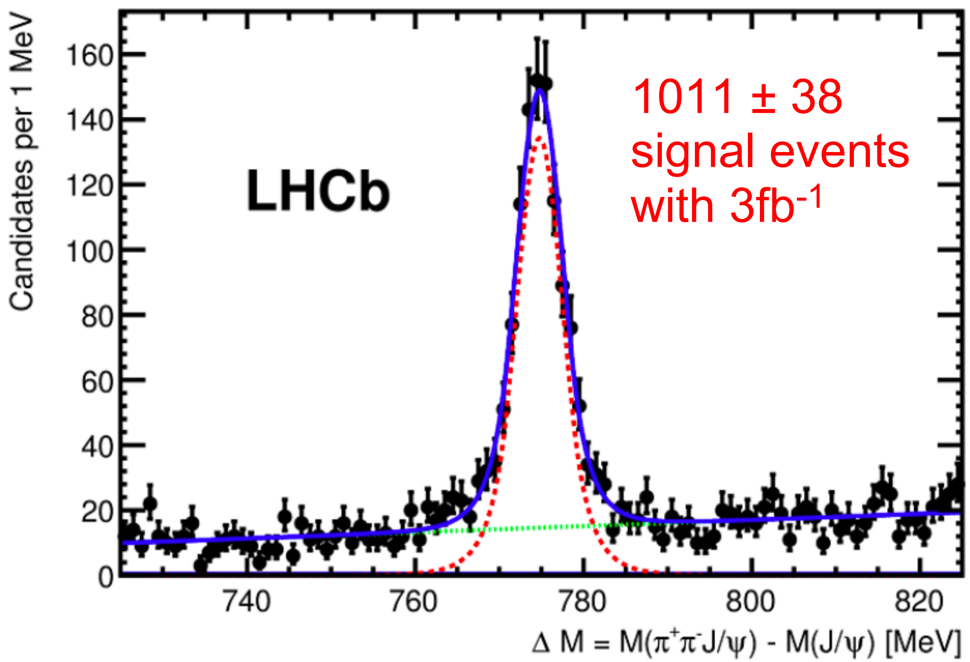
R larger, what about L = R x p ?

Significant L > L_{min} could:
- invalidate the previous $J^{PC}=1^{++}$ assignment
- hint of molecular structure

X(3872): angular analysis

PRD 92 (2015) 011102

$$B^+ \to X(3872)K^+,\ X(3872) \to J/\psi\rho^0\ ,\ J/\psi \to \mu^+\mu^-,\ \rho^0 \to \pi^+\pi^-$$



Helicity formalism: decay described by 5 angles

J^{PC}	B_{LS} Any L value	B_{LS} Minimal L value
0^{-+}	B_{11}	B_{11}
0^{++}	B_{00}, B_{22}	B_{00}
1^{-+}	$B_{10}, B_{11}, B_{12}, B_{32}$	B_{10}, B_{11}, B_{12}
1^{++}	B_{01}, B_{21}, B_{22}	B_{01}
2^{-+}	$B_{11}, B_{12}, B_{31}, B_{32}$	B_{11}, B_{12}
2^{++}	$B_{02}, B_{20}, B_{21}, B_{22}, B_{42}$	B_{02}
3^{-+}	$B_{12}, B_{30}, B_{31}, B_{32}, B_{52}$	B_{12}
3^{++}	$B_{21}, B_{22}, B_{41}, B_{42}$	B_{21}, B_{22}
4^{-+}	$B_{31}, B_{32}, B_{51}, B_{52}$	B_{31}, B_{32}
4^{++}	$B_{22}, B_{40}, B_{41}, B_{42}, B_{62}$	B_{22}

CDF

LHCb 1 fb^{-1}

Full angular analysis
without assumptions on L

Assuming parity conservation

$$P_X = P_{J/\psi} P_\rho (-1)^L = (-1)^L$$

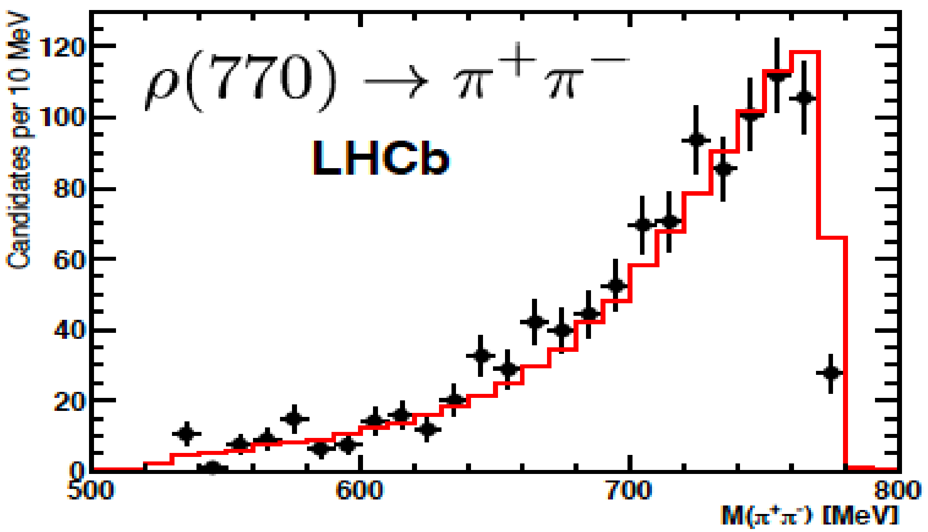
Helicity couplings:

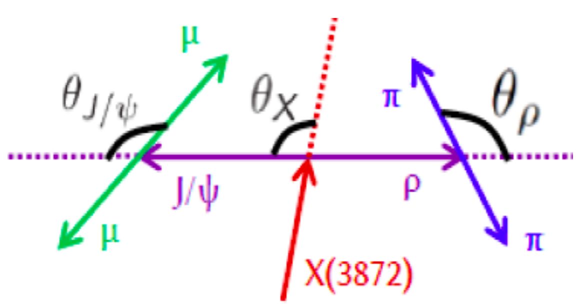
$$A_{\lambda_{J/\psi},\lambda_\rho} = \sum_L \sum_S B_{LS} \left(\begin{array}{cc|c} J_{J/\psi} & J_\rho & S \\ \lambda_{J/\psi} & -\lambda_\rho & \lambda_{J/\psi}-\lambda_\rho \end{array}\right) \left(\begin{array}{cc|c} L & S & J_X \\ 0 & \lambda_{J/\psi}-\lambda_\rho & \lambda_{J/\psi}-\lambda_\rho \end{array}\right)$$

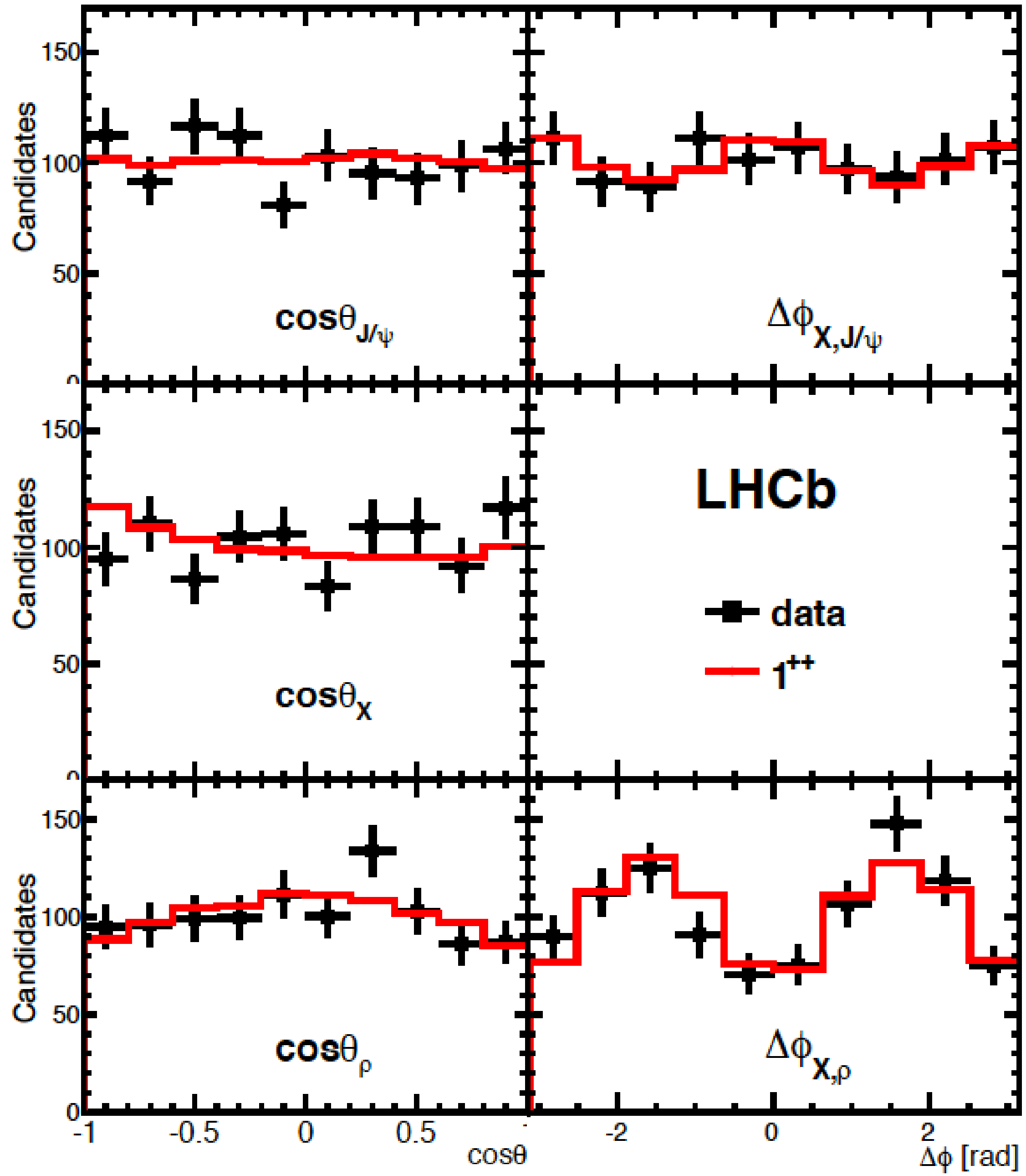
X(3872): $J^{PC} = 1^{++}$ confirmed

PRD 92 (2015) 011102

- Decay mainly through S-wave
- Total D-wave contribution < 4% @95% C.L.
- The $\rho(770) \to \pi\pi$ dominates



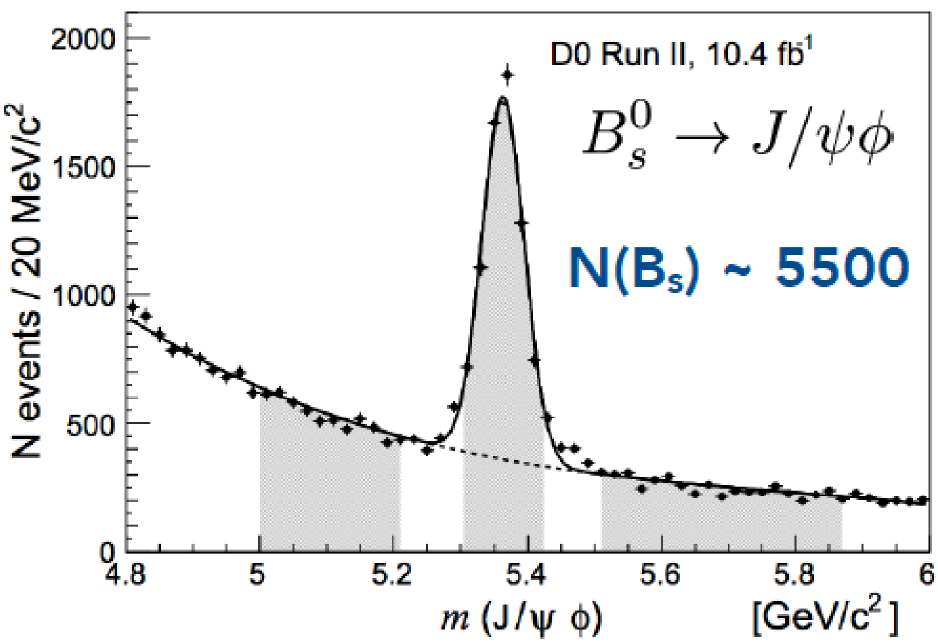




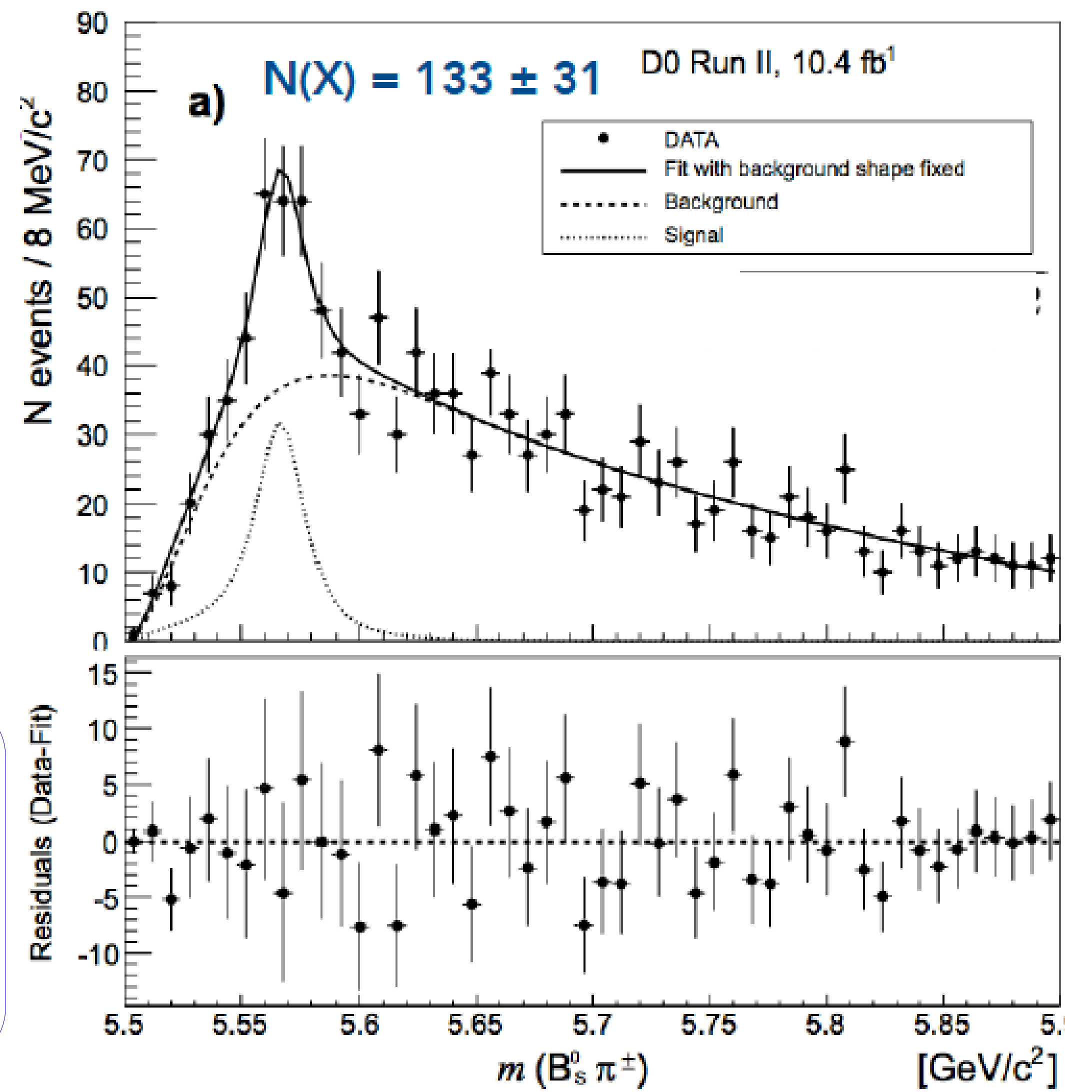
Search for exotics in $B_s\pi$ mass spectrum

The X(5568) ?

- ArXiv: 1602.07588: D0 new state X(5568) → $B_s\pi$
  - 5.1σ significance and high production rate: minimal quark content $\bar{b}s u\bar{d}$



$$m = 5567.8 \pm 2.9\,(\mathrm{stat})\,^{+0.9}_{-1.9}\,(\mathrm{syst})\ \mathrm{MeV}/c^2$$
$$\Gamma = 21.9 \pm 6.4\,(\mathrm{stat})\,^{+5.0}_{-2.5}\,(\mathrm{syst})\ \mathrm{MeV}/c^2$$
$$\rho_X = (8.6 \pm 1.9 \pm 1.4)\%$$

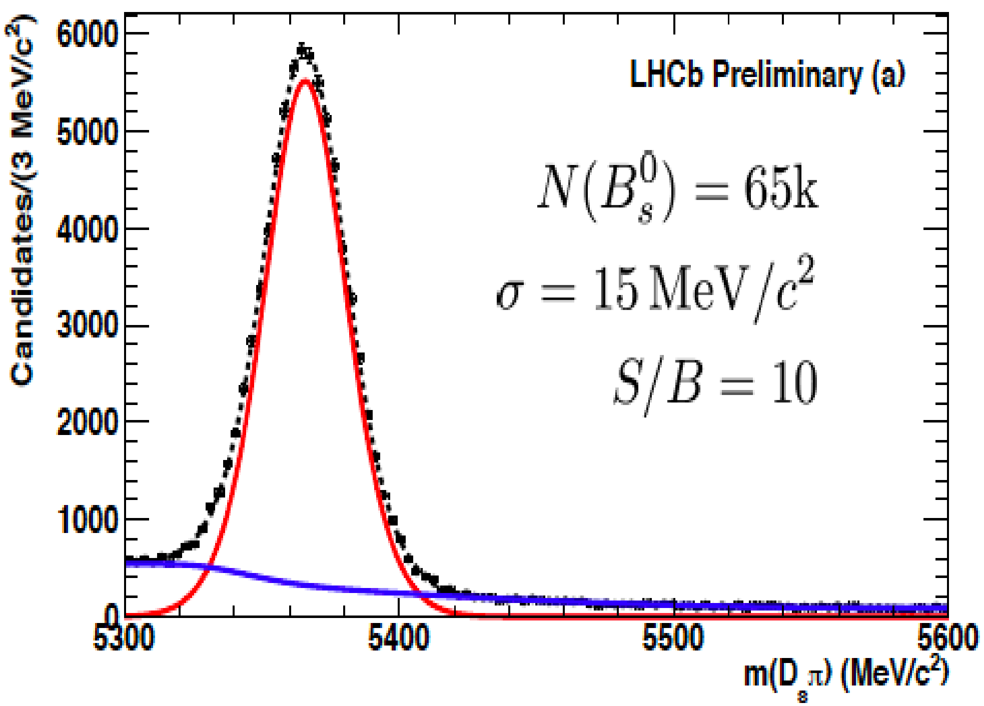


LHCb data sample of B_s

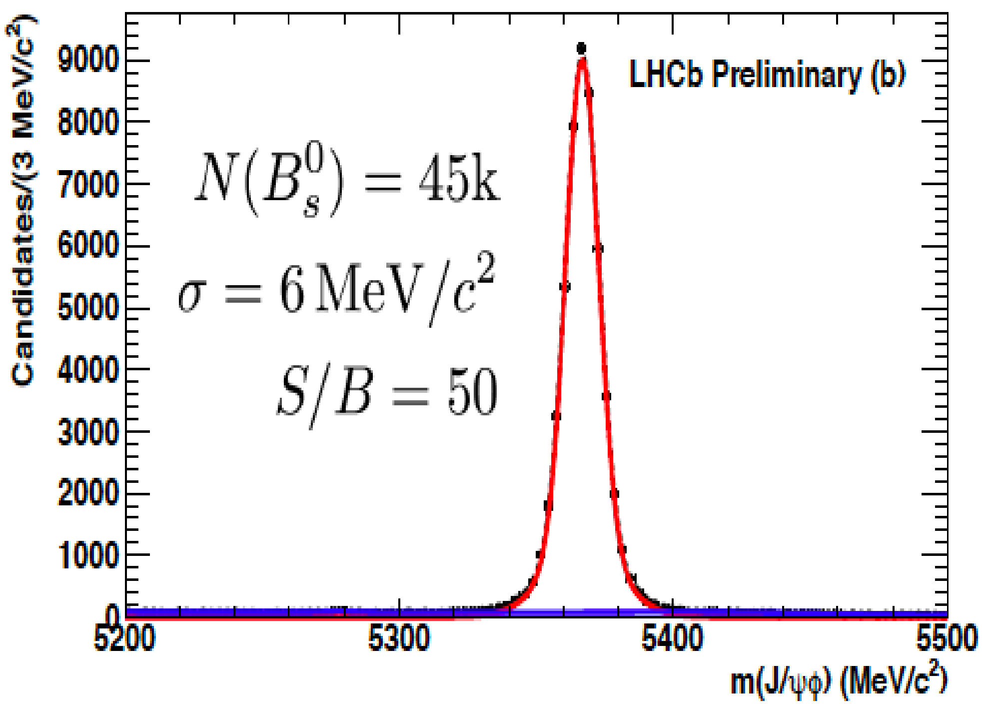
- Cut-based selection for clean B_s sample
- Mass constraints on J/ψ and D_s to improve mass resolution

- Huge and clean sample of B_s mesons
  - 20 times the D0 sample

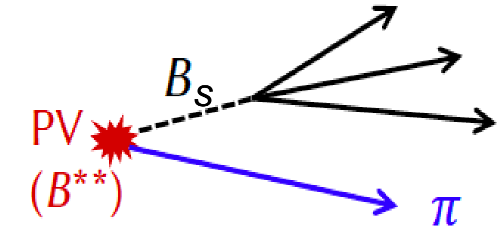
$B_s^0 \to D_s^- \pi^+$



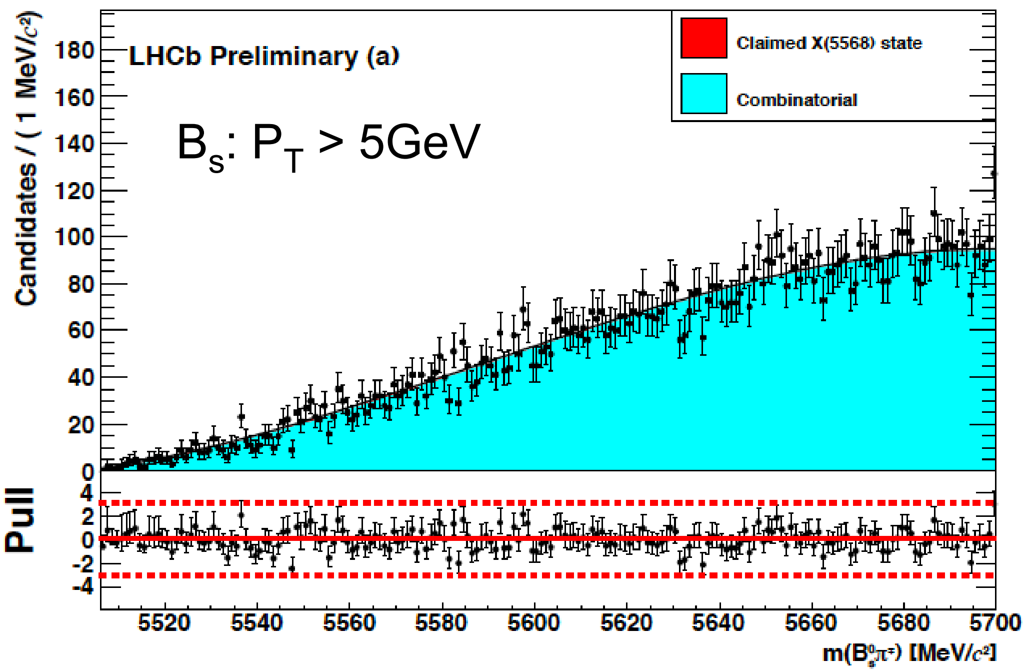
$B_s^0 \to J/\psi\phi$

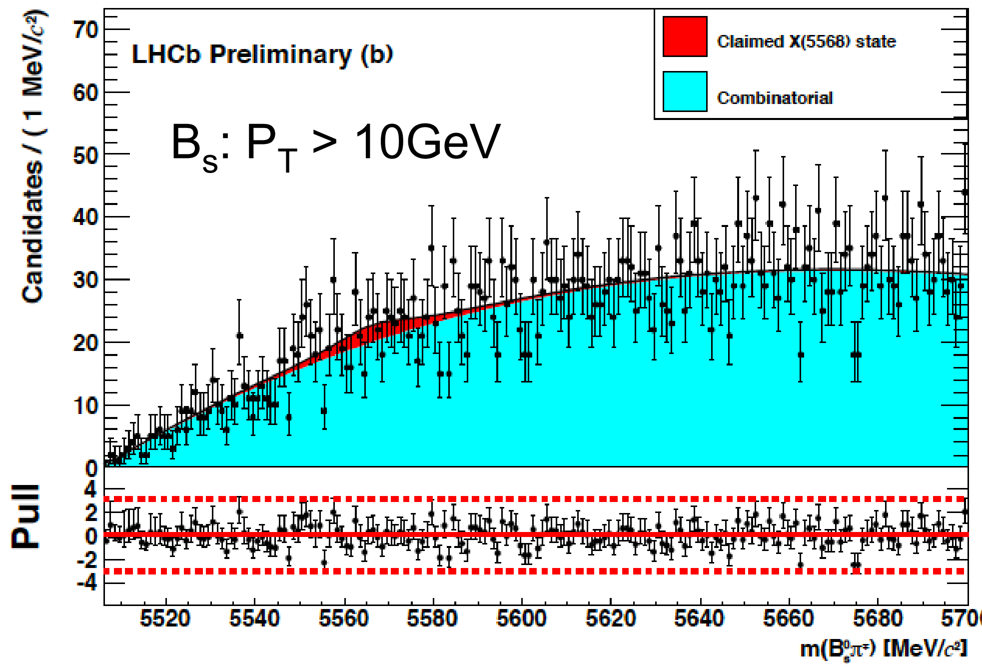


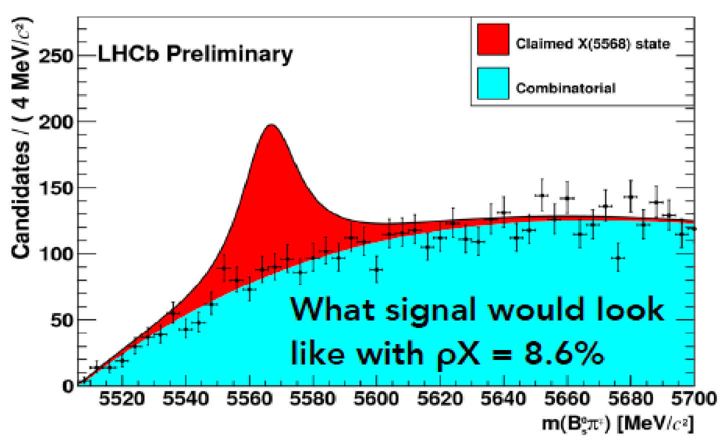
$B_s\pi$ mass spectrum LHCb-CONF-2016-004



- Add a pion, requiring that it comes from the same PV
- Signal shape is a BW with parameters from D0 collaboration







- No signal observed: stringent UL on the production rate (no dependence on rapidity)

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

Conclusions

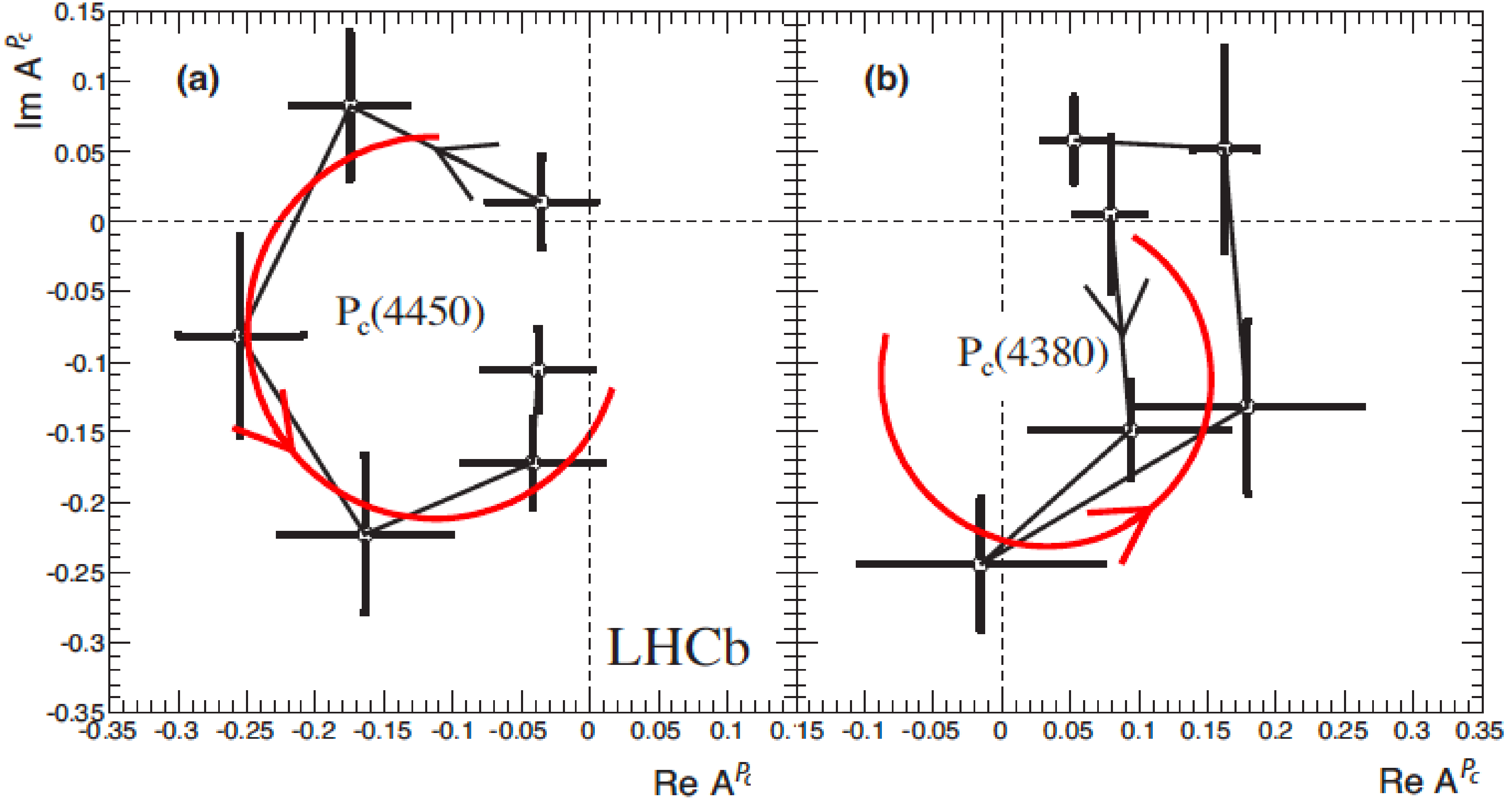
Summary

- Many new states discovered since the first observation of the X(3872)
    - Some of them have been observed by many experiments, other need confirmations
- Crucial to study these states in different production and decay modes
    - Look for isospin/charged partners
    - Measure Branching ratios
    - Full angular analysis to establish the quantum numbers and exclude some dynamical production mechanisms: threshold, rescattering...
- P_c states are good candidate for penta-quarks
    - Loosely bound molecule? Tightly bound penta-quarks? Hybrid?
    - Extensive experimental program ahead

LHCb, CMS, ATLAS, BaBar, Belle, Belle-II, BES-III, COMPASS: all have role to play

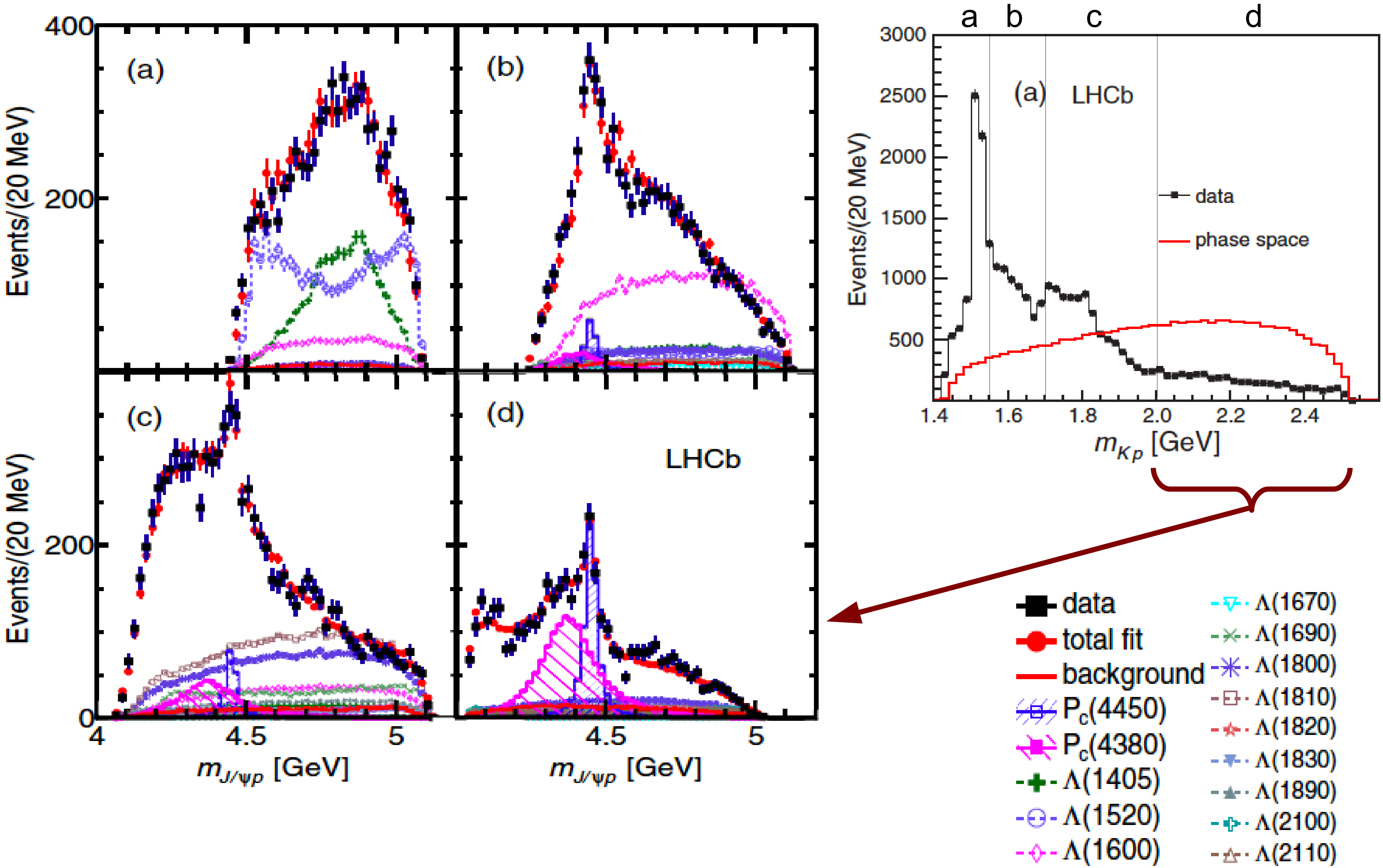

STOP

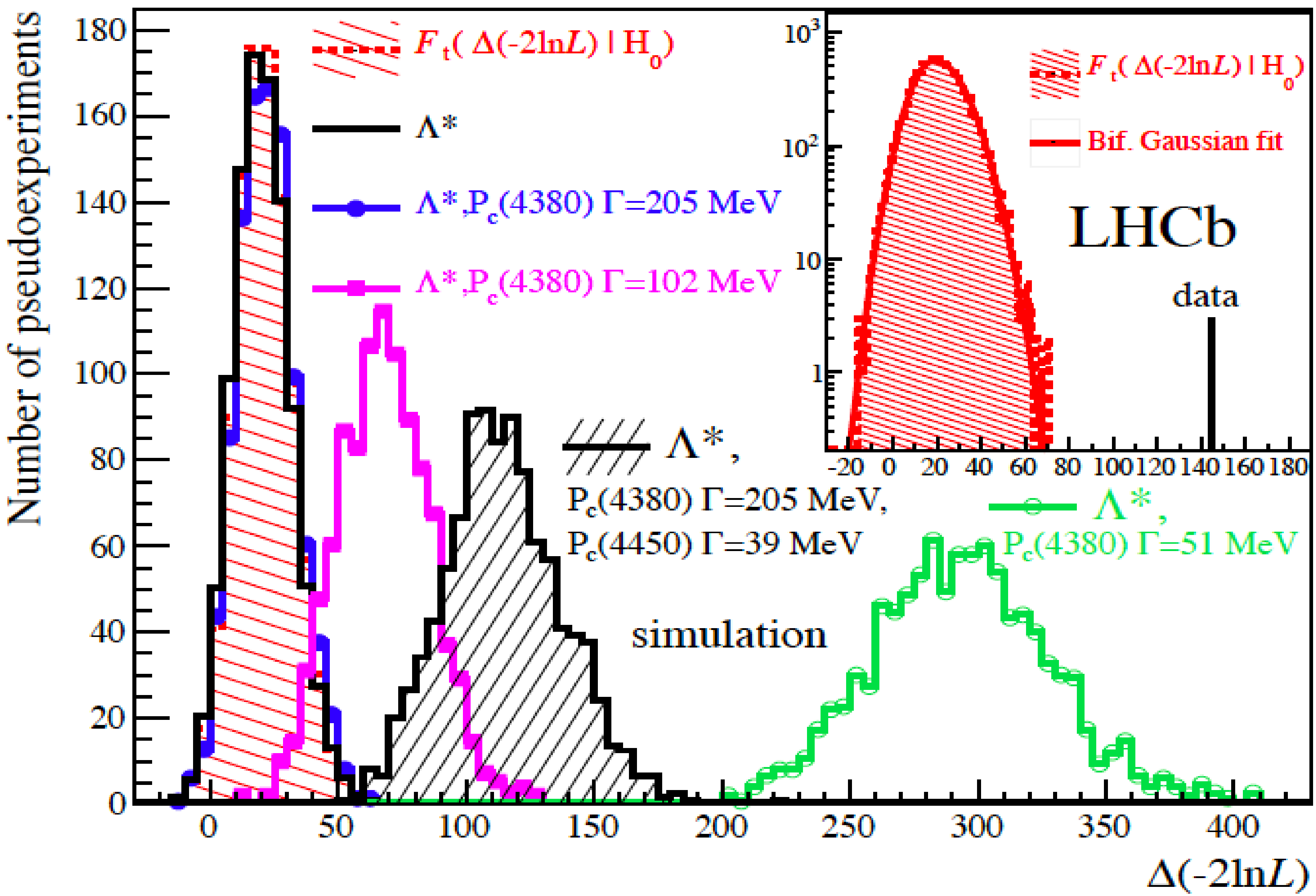
P_c^+: resonant character of the P_c states



- Amplitudes for 6 bins of $m_{J/\psi p}$ between $-\Gamma$ and $+\Gamma$

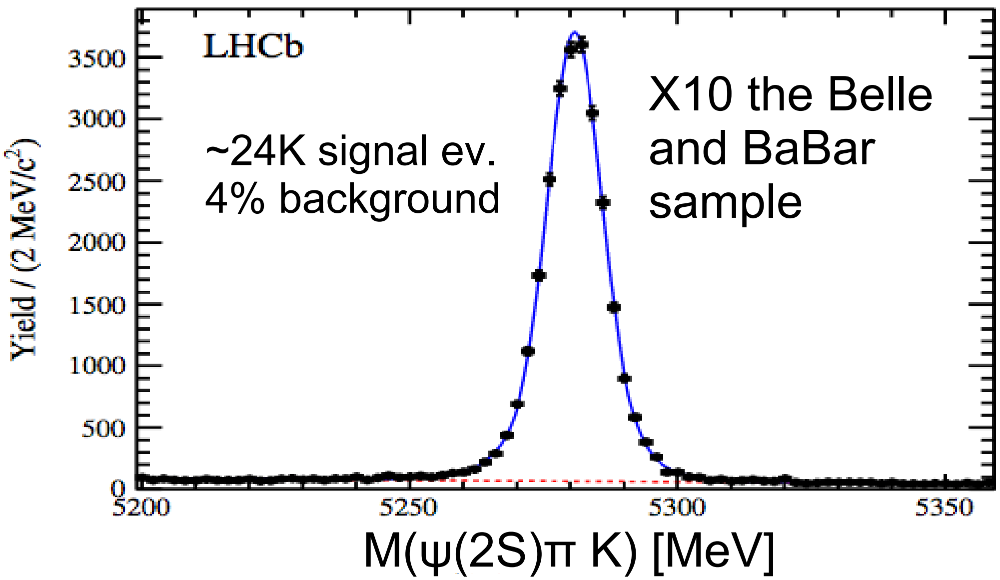
PRL 115 (2015) 072001





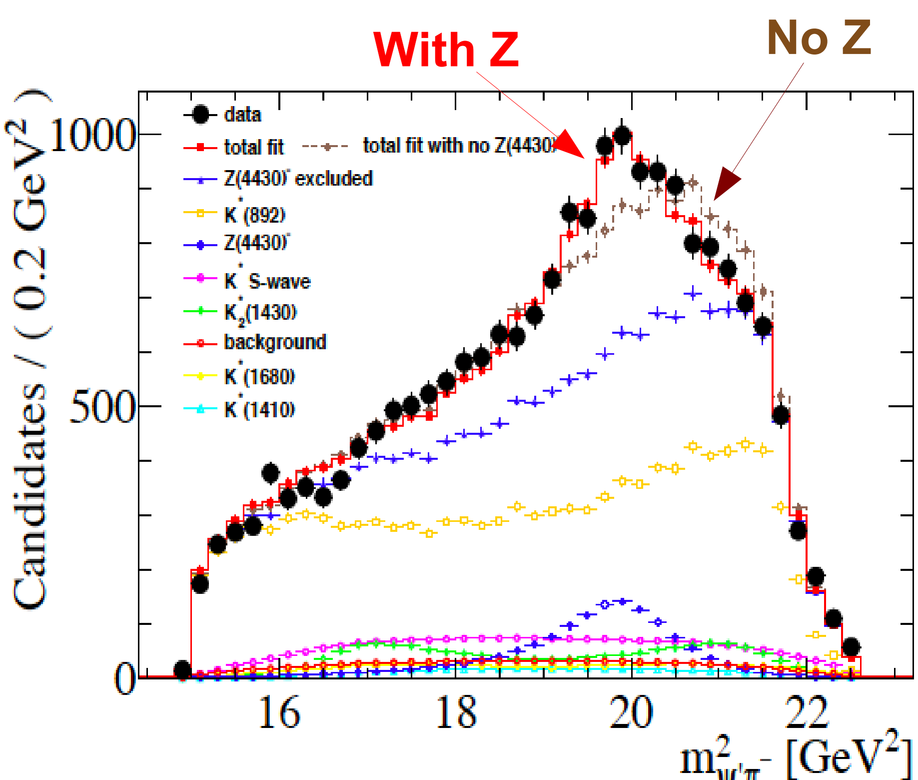
Number of pseudoexperiments
$F_t(\Delta(-2\ln L) \mid H_0)$
Λ*
Λ*,Pc(4380) Γ=205 MeV
Λ*,Pc(4380) Γ=102 MeV
Λ*,
Pc(4380) Γ=205 MeV,
Pc(4450) Γ=39 MeV
Λ*,
Pc(4380) Γ=51 MeV
simulation
Bif. Gaussian fit
LHCb
data
Δ(-2lnL)

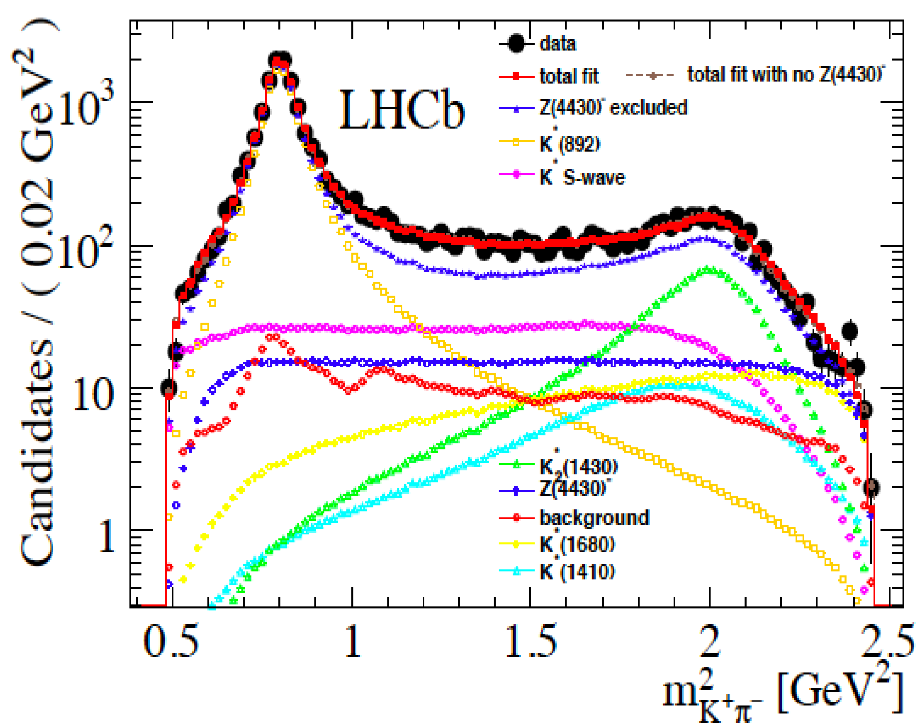
Confirmation of the Z(4430)



Two analysis methods

- 4D amplitude analysis: extract resonance parameters and J^P
  - PRL 112 (2014) 222002
- Model independent based on Legendre polynomial moments from the Kπ system (similar to the P_c analysis)
  - PRD 92 (2015) 112009



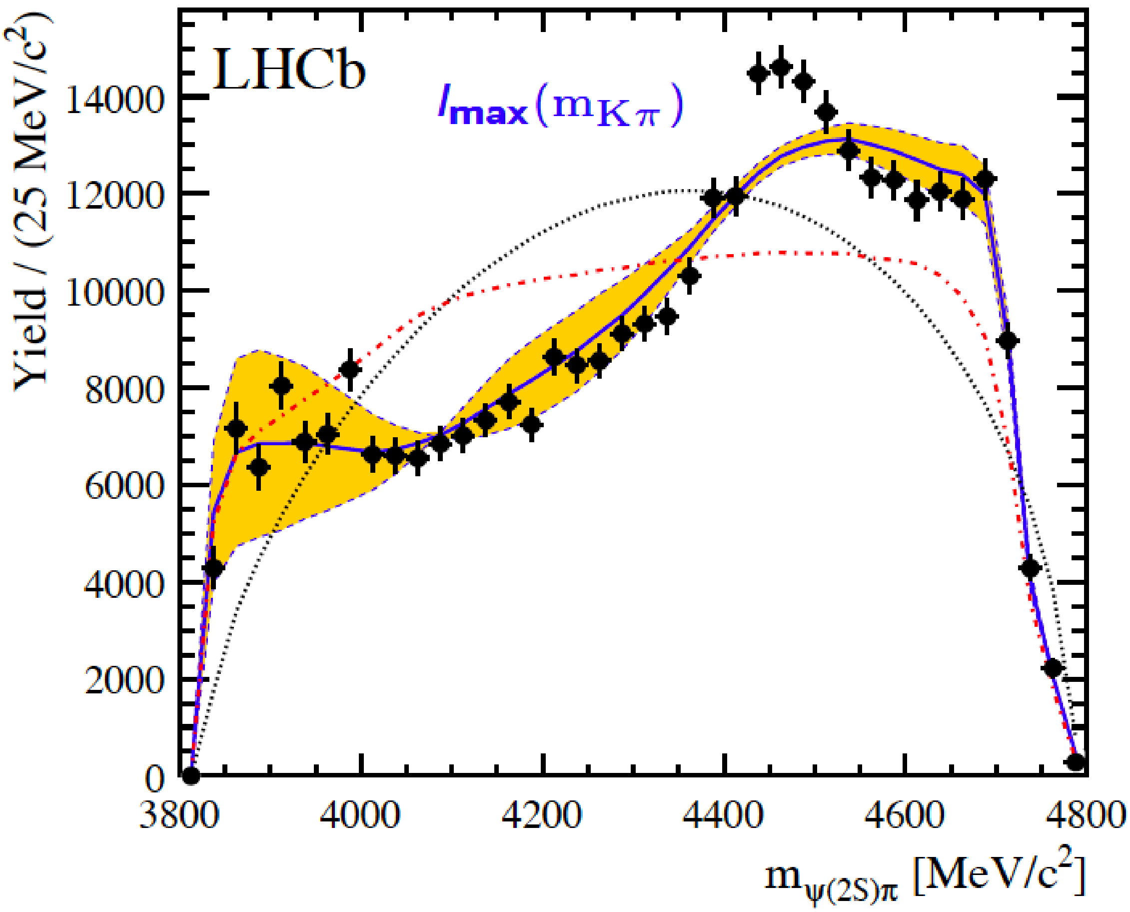


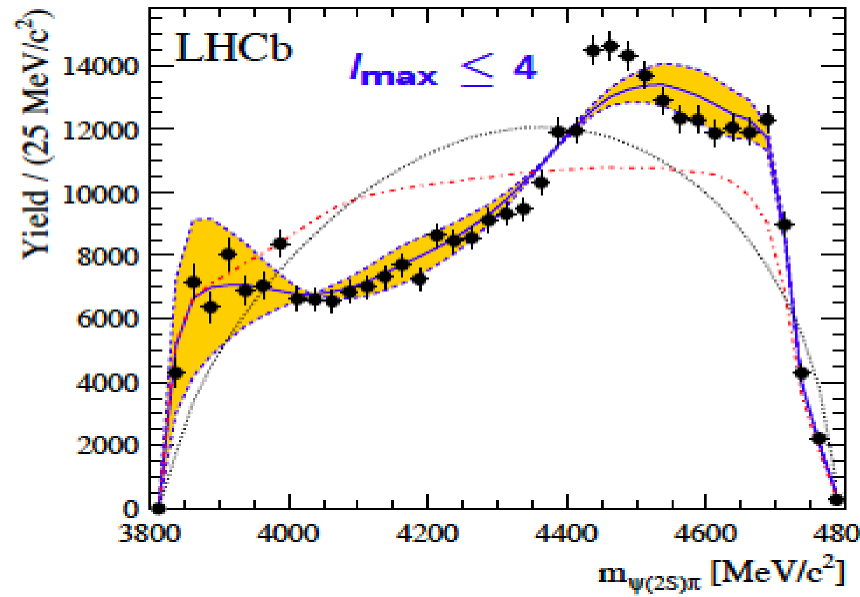
PRL 112 (2014) 222002

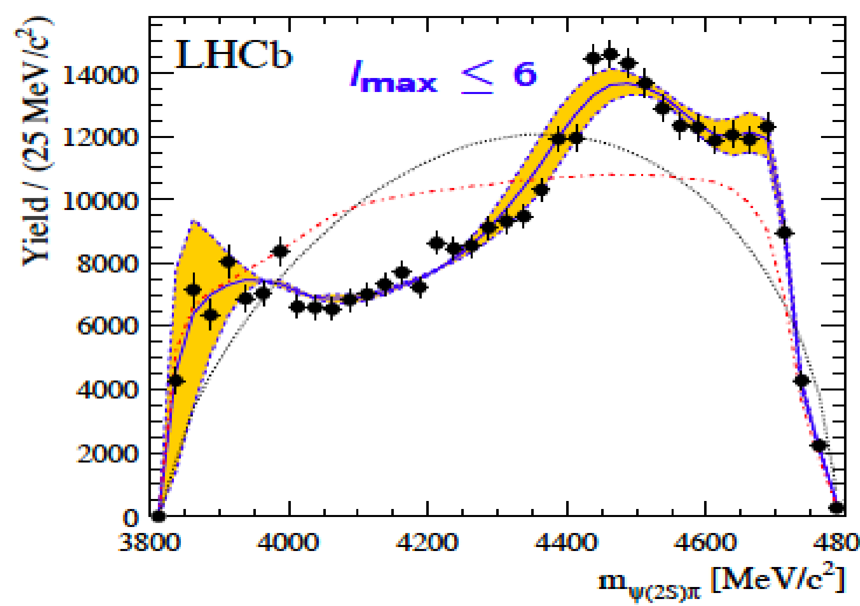
Z(4430): model independent analysis

PRD 92 (2015) 112009

- Large toy MC simulation with events weighted according to the moments to predice the $m_{\psi(2S)\pi}$ spectrum





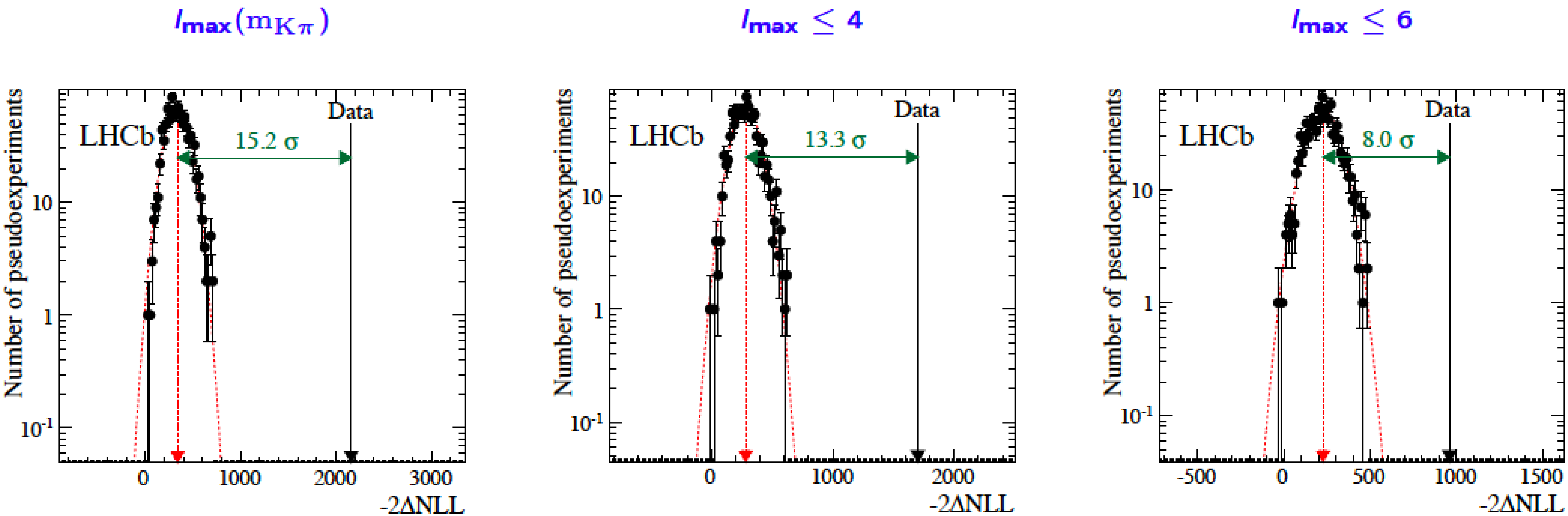


$$l_{max}(m_{K\pi}) = \begin{cases} 2 & m_{K\pi} < 836\ \mathrm{MeV}/c^2 \\ 3 & 836\ \mathrm{MeV}/c^2 < m_{K\pi} < 1000\ \mathrm{MeV}/c^2 \\ 4 & m_{K\pi} > 1000\ \mathrm{MeV}/c^2. \end{cases}$$

Z(4430): model independent analysis

PRD 92 (2015) 112009

- Hypothesis test based on likelihood ratio
  - Physical configurations compared with prediction with l_{max} = 30



Hypothesis that the structure of the $m_{\psi(2S)\pi}$ spectrum can be described as reflection of the activity of the resonances in the Kπ system is ruled out with more than 8σ