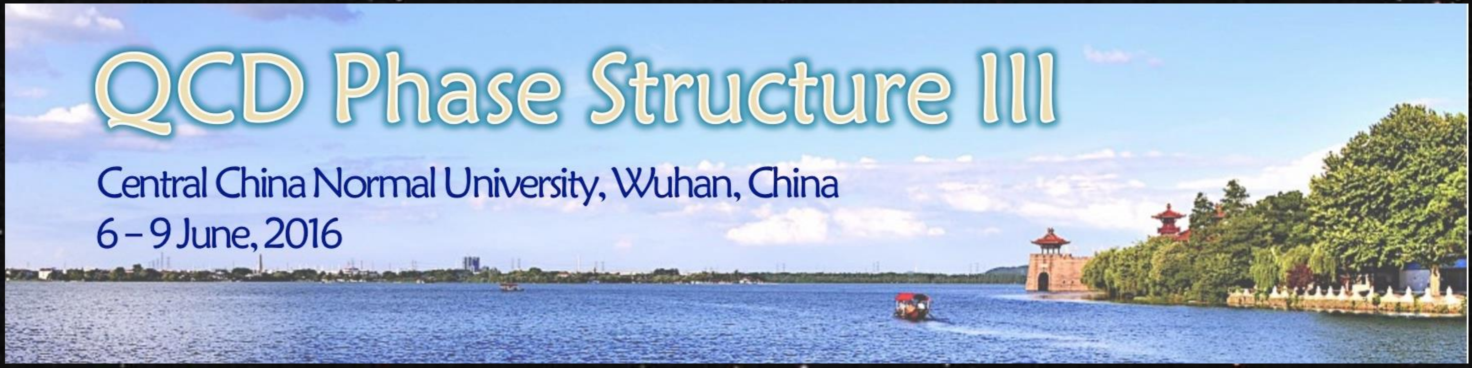
Pentaquark at LHCb

Zhenwei Yang (杨振伟)
on behalf of the LHCb collaboration

Center for High Energy Physics,
Tsinghua University

8 June, 2016



Outline

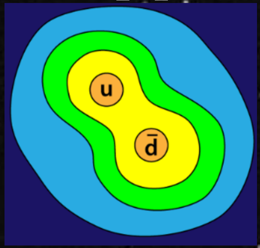
- **Introduction**
- **Pentaquarks observed in $\Lambda_b^0 \to J/\psi p K^-$ decays**
  - **Full amplitude analysis** — PRL 115 (2015) 072001
  - **Model independent analysis** — arXiv:1604.05708
- **Studies in Cabibbo-suppressed $\Lambda_b^0 \to J/\psi p \pi^-$ decays** — LHCb-PAPER-2016-015 (in preparation)
- **Summary and outlook**

Why pentaquarks?

- Possible existence of pentaquarks was proposed by Gell-Mann and Zweig at the birth of quark model
- Study of the nature of pentaquarks could fertilize our understanding of QCD
- Many searches in the past 50 years, but no convincing experimental evidence

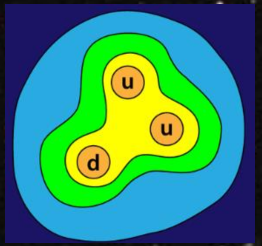
Normal hadrons

$q\bar{q}$



Meson

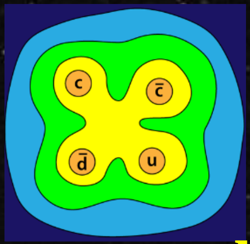
qqq



Baryon

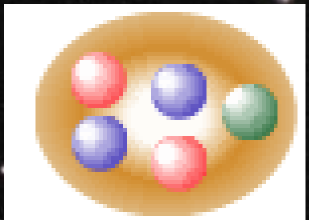
Exotic hadrons

$qq\bar{q}\bar{q}$



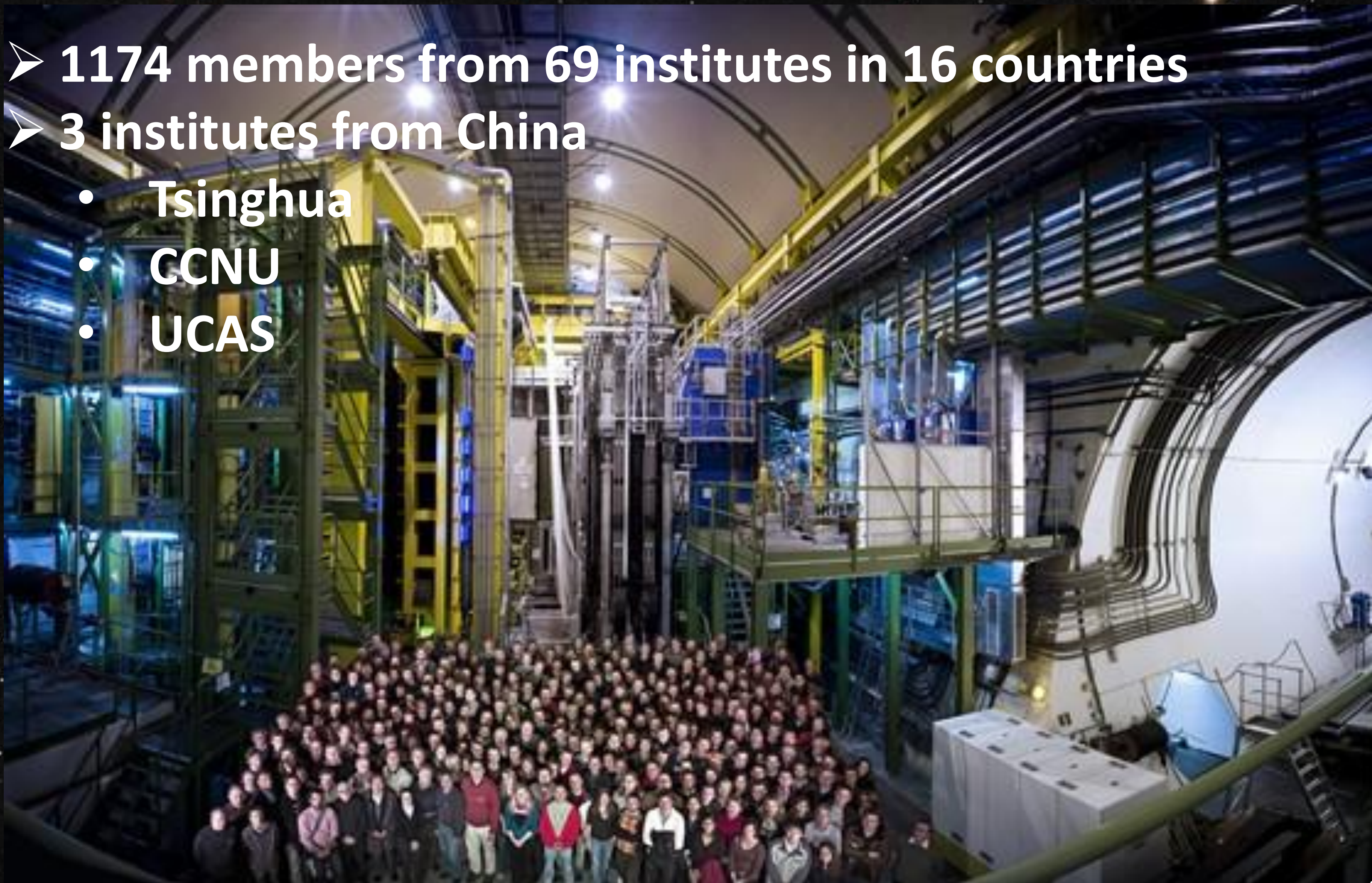
Tetraquark

$qqqq\bar{q}$



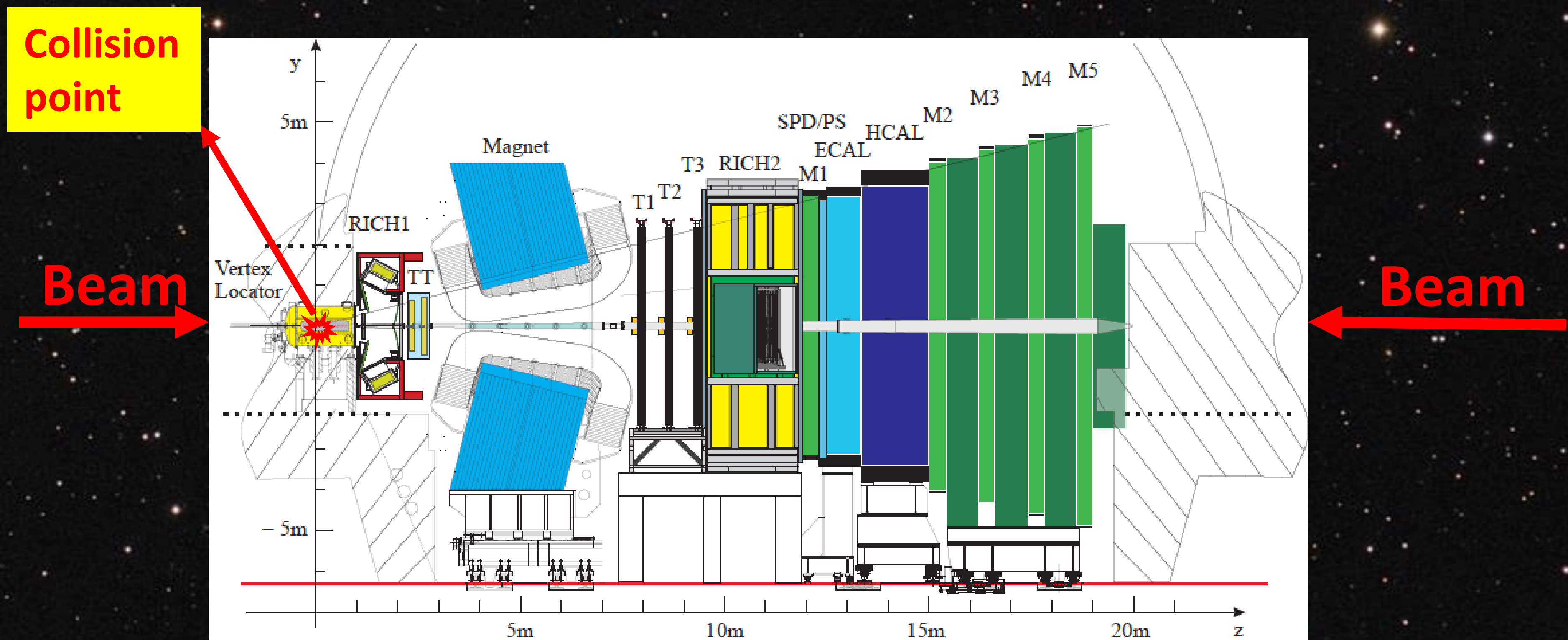
Pentaquark

LHCb collaboration



- 1174 members from 69 institutes in 16 countries
- 3 institutes from China
  - Tsinghua
  - CCNU
  - UCAS

LHCb detector



Int. J. Mod. Phys. A 30 (2015) 1530022

Impact parameter: $\sigma_{IP} = 20\ \mu\text{m}$

Proper time: $\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$

Momentum: $\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)

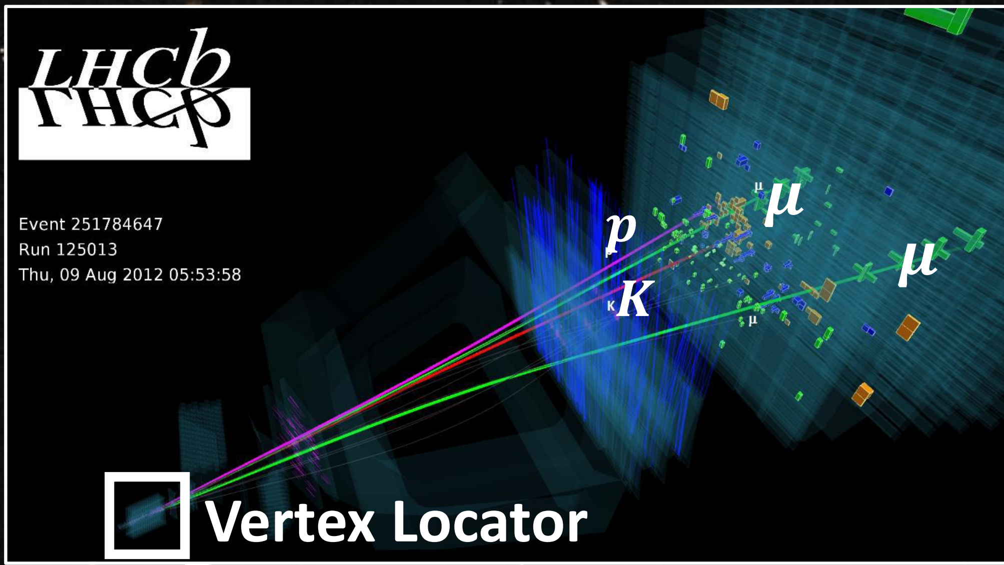
Mass : $\sigma_m = 8\ \text{MeV}/c^2$ for $B \to J/\psi X$ (constrainted $\text{m}_{J/\psi}$)

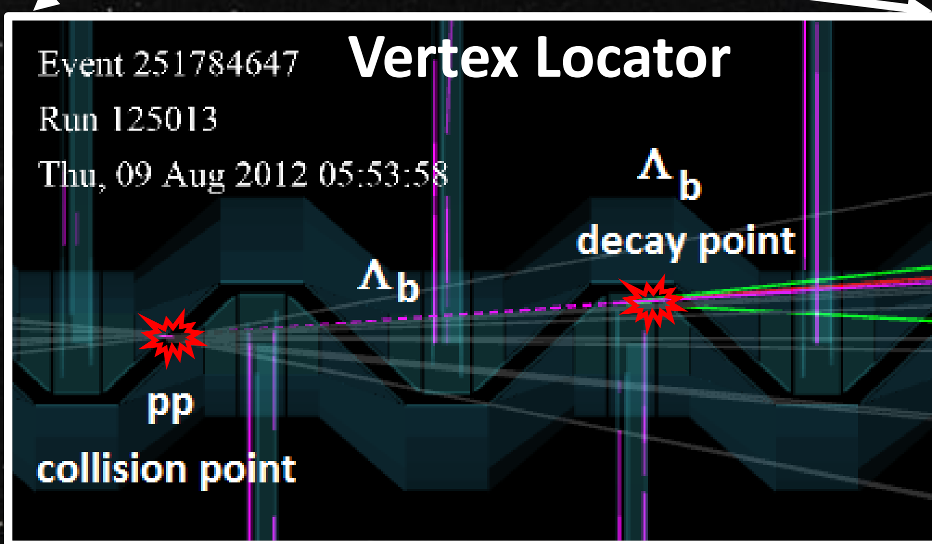
RICH $K - \pi$ separation: $\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$

Muon ID: $\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$

ECAL: $\Delta E/E = 1 \oplus 10\%/\sqrt{E(\text{GeV})}$

Event display of $\Lambda_b^0 \to J/\psi p K^-$ decay

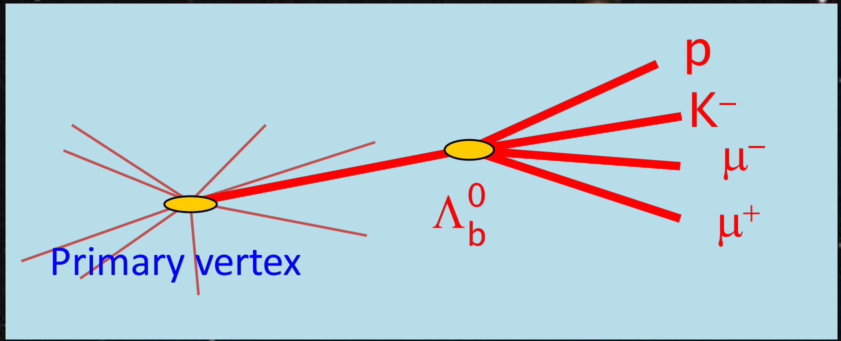




- Two RICH detectors allow for good identification of proton and kaon
- Primary vertex and decay vertex well reconstructed and separated in the Vertex Locator

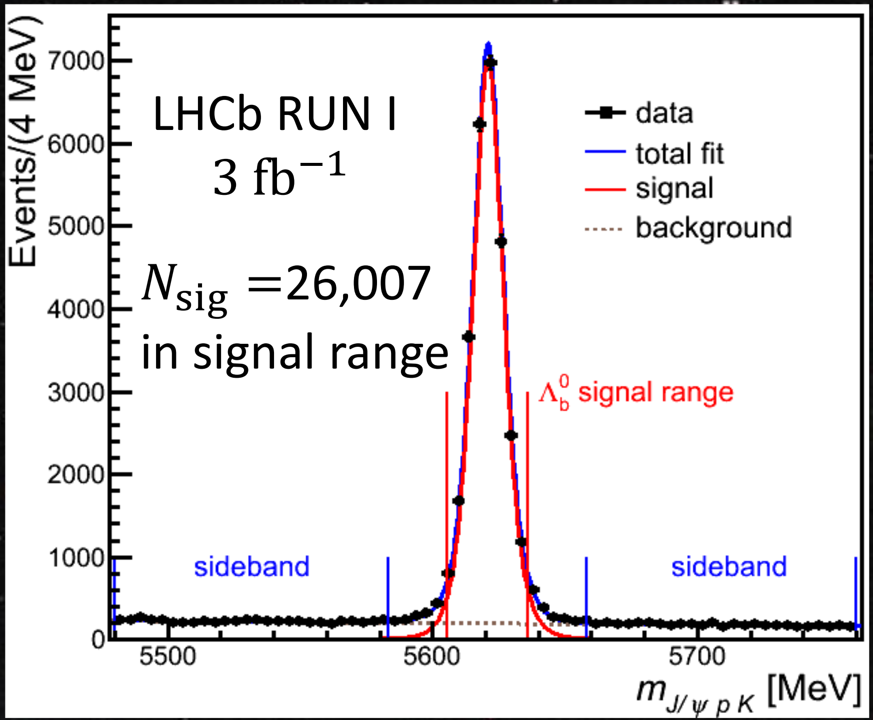
$\Lambda_b^0 \to J/\psi p K^-$ and event selection

- **First observed by LHCb as a potential background for**
  $B_s^0 \to J/\psi K^+ K^-$
  - **Large signal yield found, used for Λ_b^0 lifetime measurement**
    (PRL 111, 102003)



Event selection:

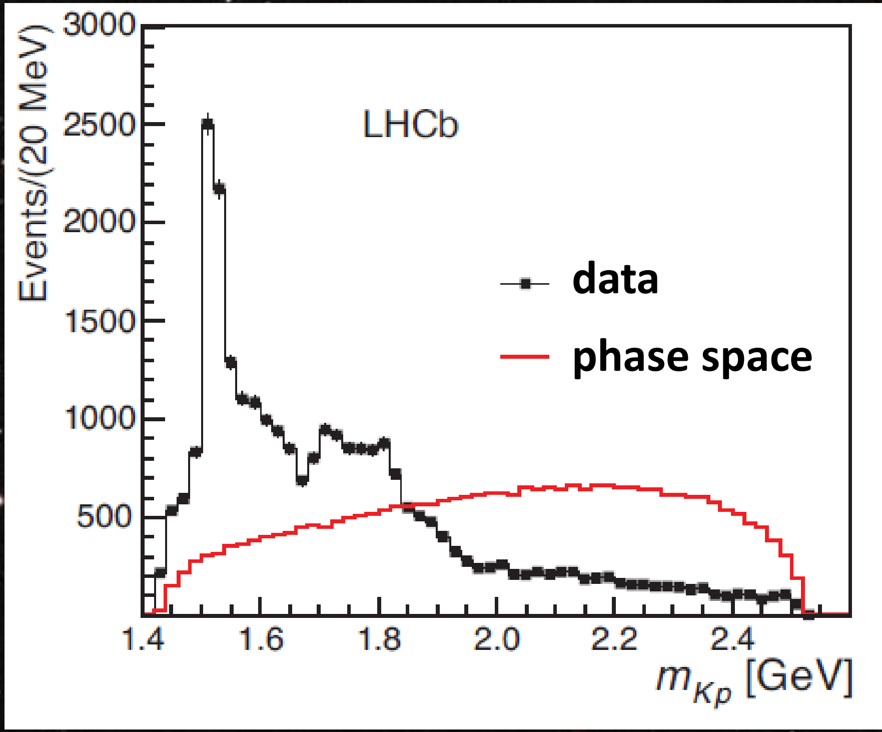
- **Standard preselection**
- **Followed by selection with Gradient Boosted Decision Tree (BDTG)**
- $B_s^0 \to J/\psi K^+ K^-$ **and** $B^0 \to J/\psi K^+ \pi^-$ **reflections vetoed, where** K^- **and** π^- **are misidentified as** $\bar{p}$



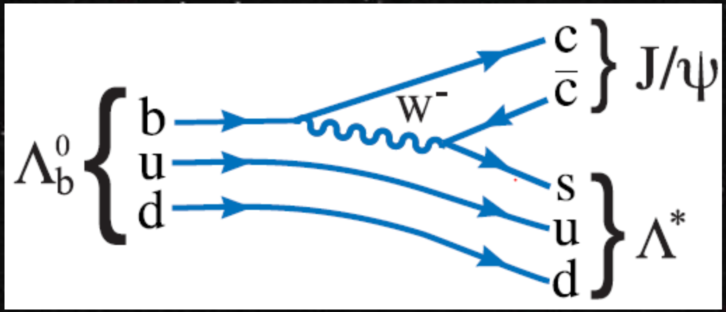
PRL 115 (2015) 072001

5.4% background in $\pm 2\sigma$

Expected rich structures in $m(Kp)$

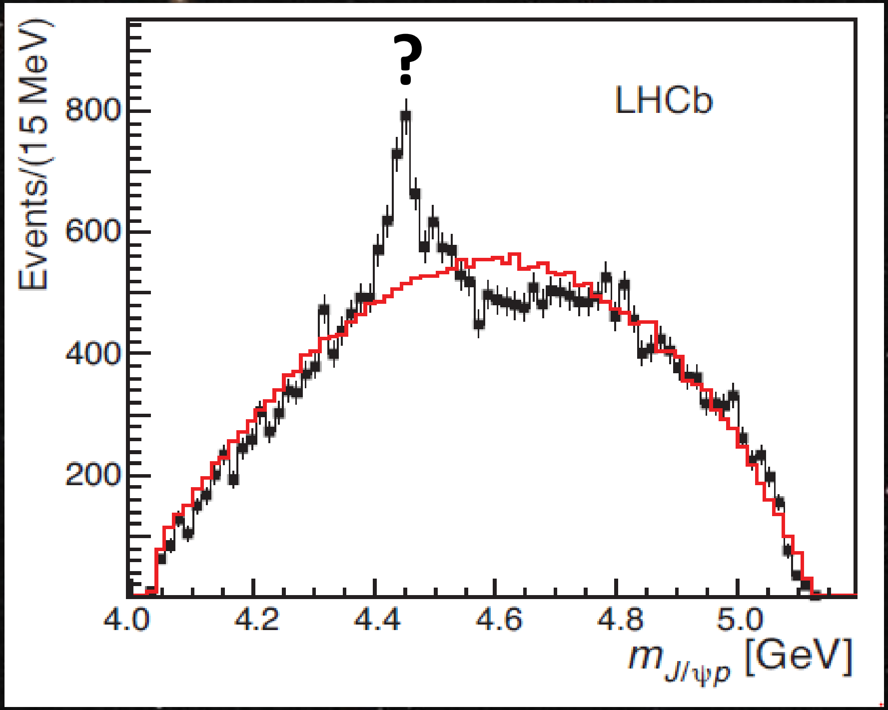


PRL 115 (2015) 072001

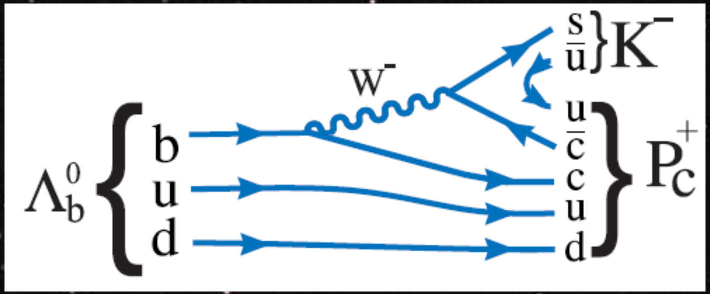


- Many Λ^* resonances as expected

Unexpected structures in $m(J/\psi p)$



PRL 115 (2015) 072001

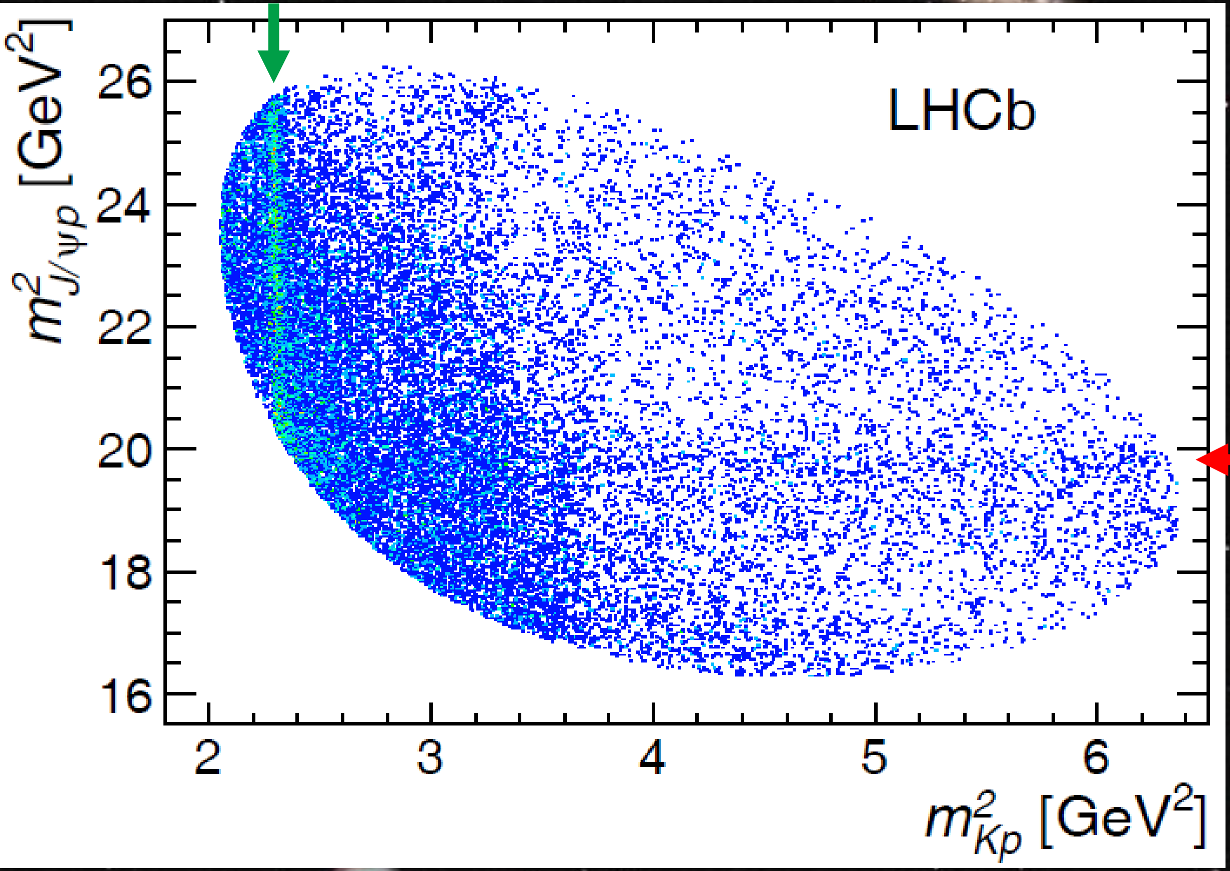


- Reflection from $\Lambda_b^0 \to J/\psi\Lambda^*$?
- Or structure of $J/\psi p$?
- Careful checks needed

"Dalitz plot"

$\Lambda(1520) \to pK^-$

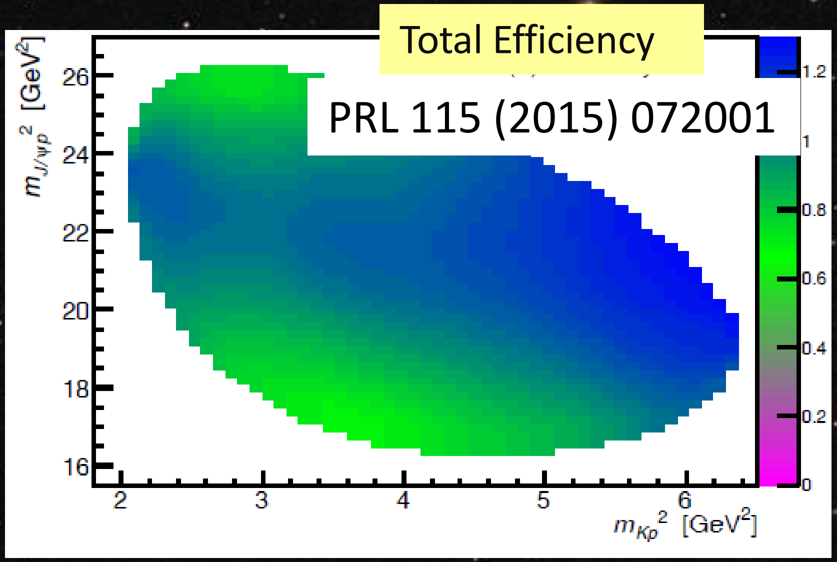
PRL 115 (2015) 072001



$P_c^+ \to J/\psi p$?

- Clear horizontal band at $m^2_{J/\psi p} \approx 20$ GeV^2
- Λ^* structures dominate low m^2_{Kp} region, interferences unlikely generate the horizontal band at high m^2_{Kp} region

Is the peak due to “artifacts”?



- Many checks done
  - Reflections of $B_s^0 \to J/\psi K^+K^-$ and $B^0 \to J/\psi K^+\pi^-$ are vetoed
  - Efficiency doesn’t make narrow peak
  - Clones & ghost tracks eliminated
  - Ξ_b decays checked as a source

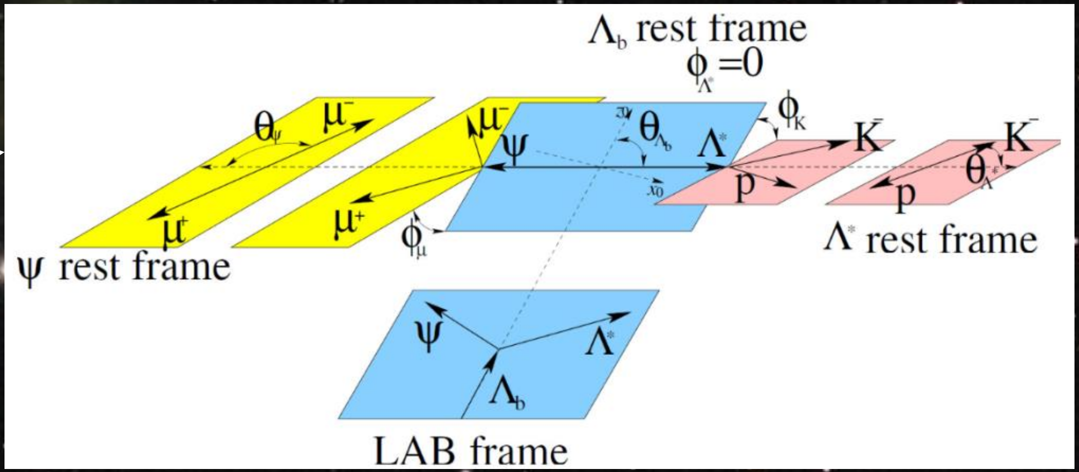
To confirm that the peak is NOT a reflection of interfering Λ^*’s$\to pK^-$, a **full amplitude analysis** is performed using all known Λ^* resonances.

- to maximize sensitivity to the decay dynamics
- to avoid biases due to averaging over some dimensions in presence of the non-uniform detector efficiency

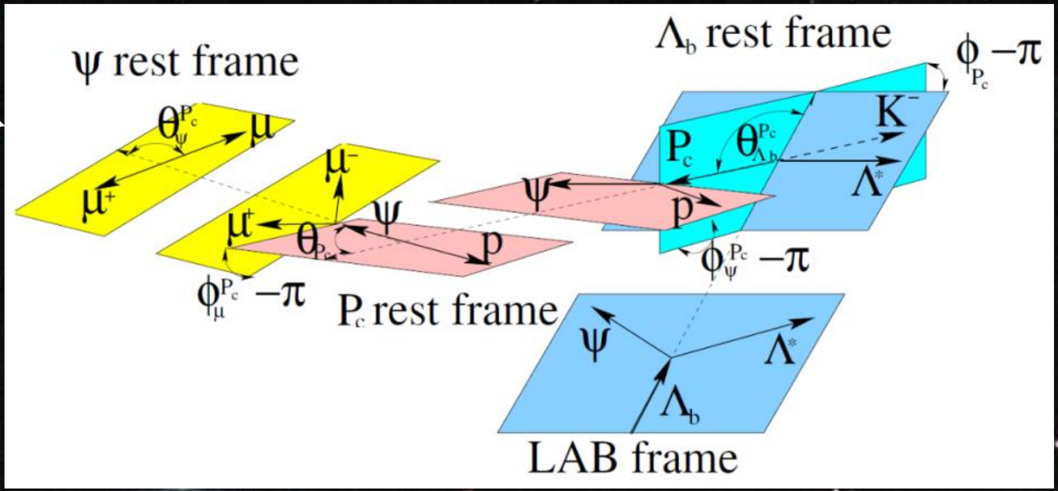
Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$

- Allows for $\Lambda^* \to pK^-$ resonances to interfere with pentaquark states $P_c^+ \to J/\psi\, p$

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



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



- **Independent variables: 1 mass (m_{pK^-}) and 5 angles ➔ 6D fit**

Λ^* resonances

- Each Λ^* resonance: $J = \frac{1}{2}$ ($> \frac{1}{2}$) has 4 (6) complex helicity couplings
- Masses and widths fixed to PDG values
  - Uncertainties are considered as systematics
- Two models: “reduced” and “extended” to test dependence of the Λ^* model

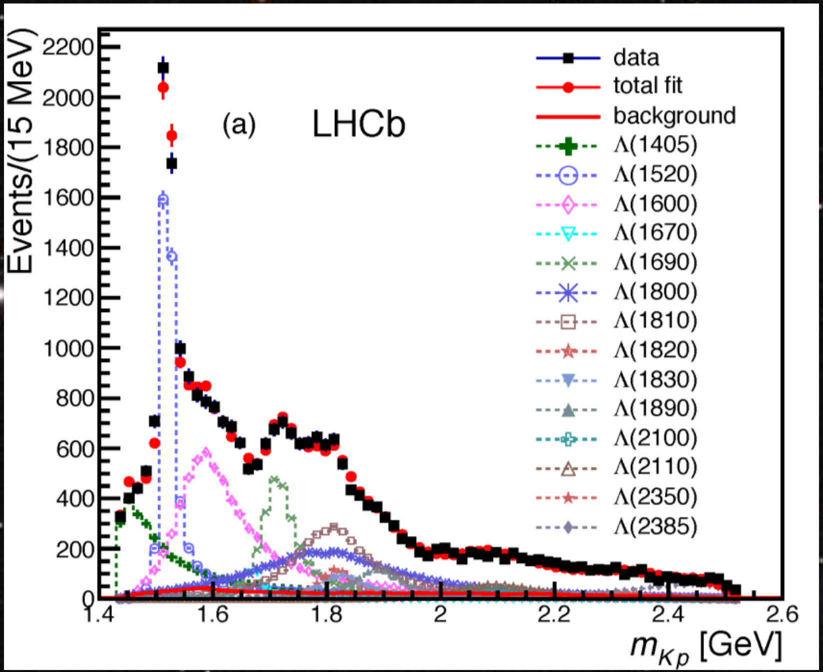
Limited L All states, L

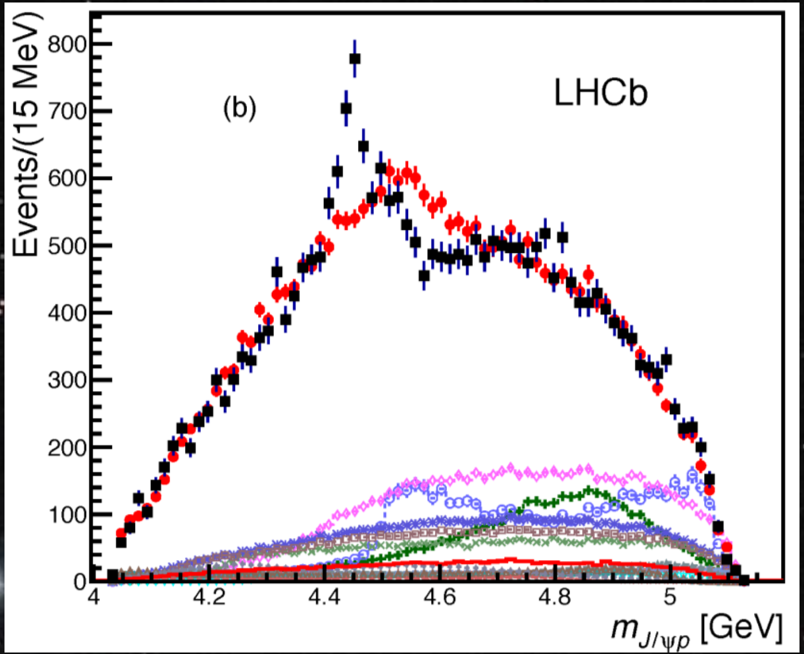
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6

Fit without P_c^+

- $m(pK^-)$ looks fine, but not $m(J/\psi p)$
- Other possibilities:
  - All Σ^{*0} $(I = 1)$
  - two new Λ^* with free $m\&\Gamma$
  - 4 non-resonant Λ^* with $J^P = \frac{1}{2}^{\pm}$ and $\frac{3}{2}^{\pm}$
- Still fail to describe the data

PRL 115 (2015) 072001

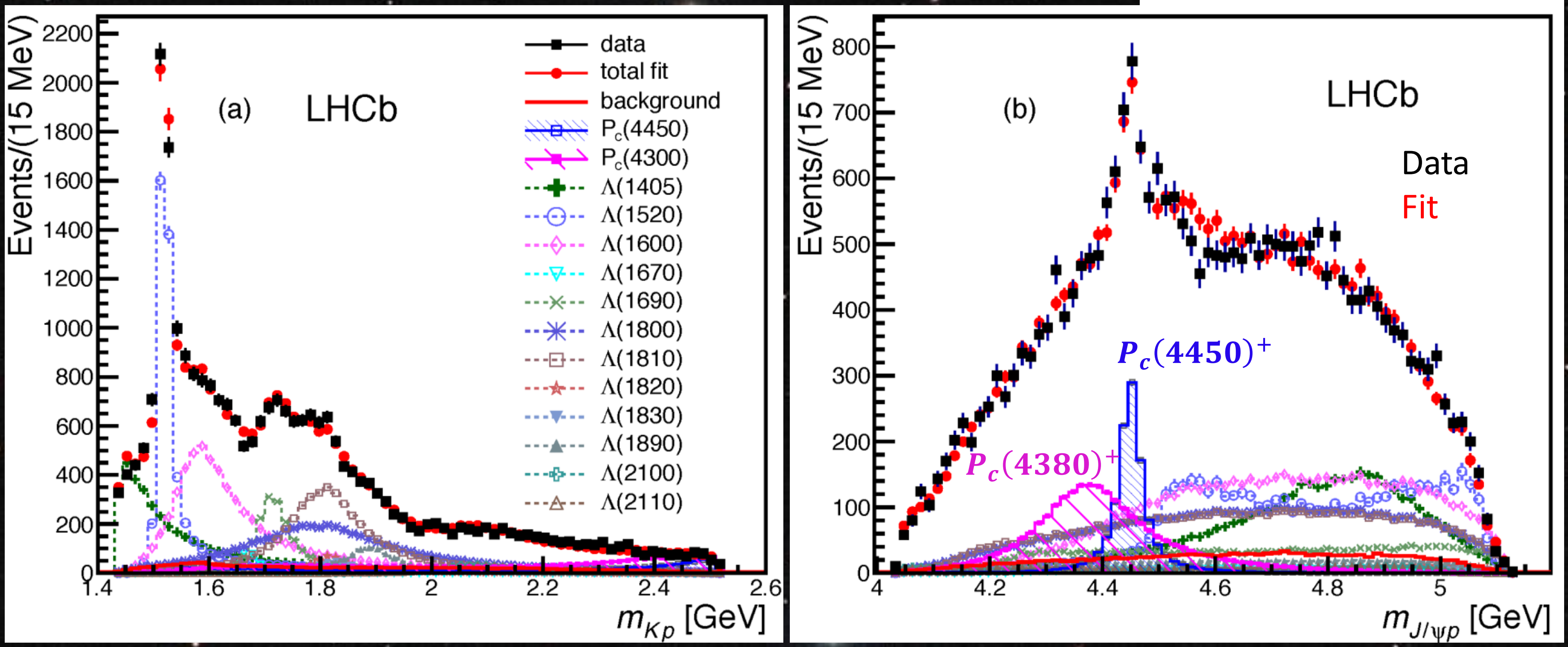




Fit results with P_c states

- Two P_c states: $P_c(4450)^+$ and $P_c(4380)^+$
- Best fit has $J^P = (3/2^-, 5/2^+)$
  - $J^P = (3/2^+, 5/2^-)$ & $(5/2^+, 3/2^-)$ also preferred

PRL 115 (2015) 072001



Fit results with P_c states

PRL 115 (2015) 072001

Resonance	Mass (MeV)	Width (MeV)	Significance	Fit fraction(%)
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$9\,\sigma$	$8.4 \pm 0.7 \pm 4.2$
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$12\,\sigma$	$4.1 \pm 0.5 \pm 1.1$
$\Lambda(1405)$				$15 \pm 1 \pm 6$
$\Lambda(1520)$				$19 \pm 1 \pm 4$

Using $\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)$, the branching fractions are:

For $P_c(4380)^+$,

$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38}) \times 10^{-5}$$

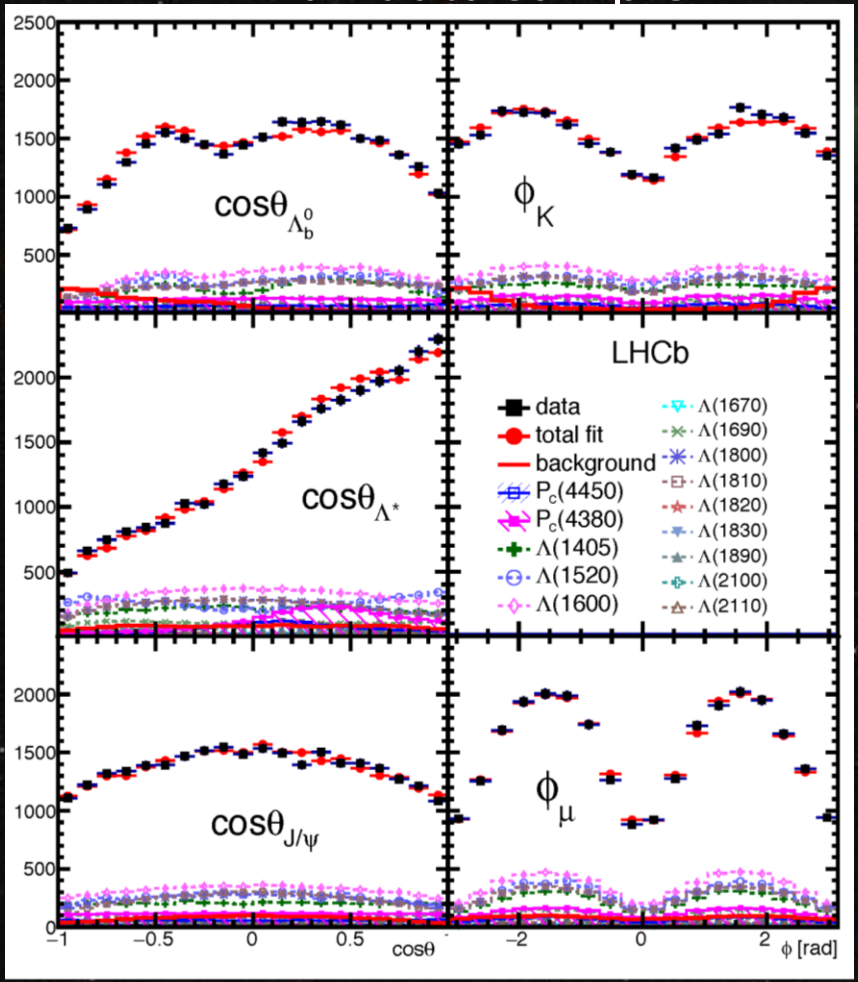
For $P_c(4450)^+$,

$$\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5}$$

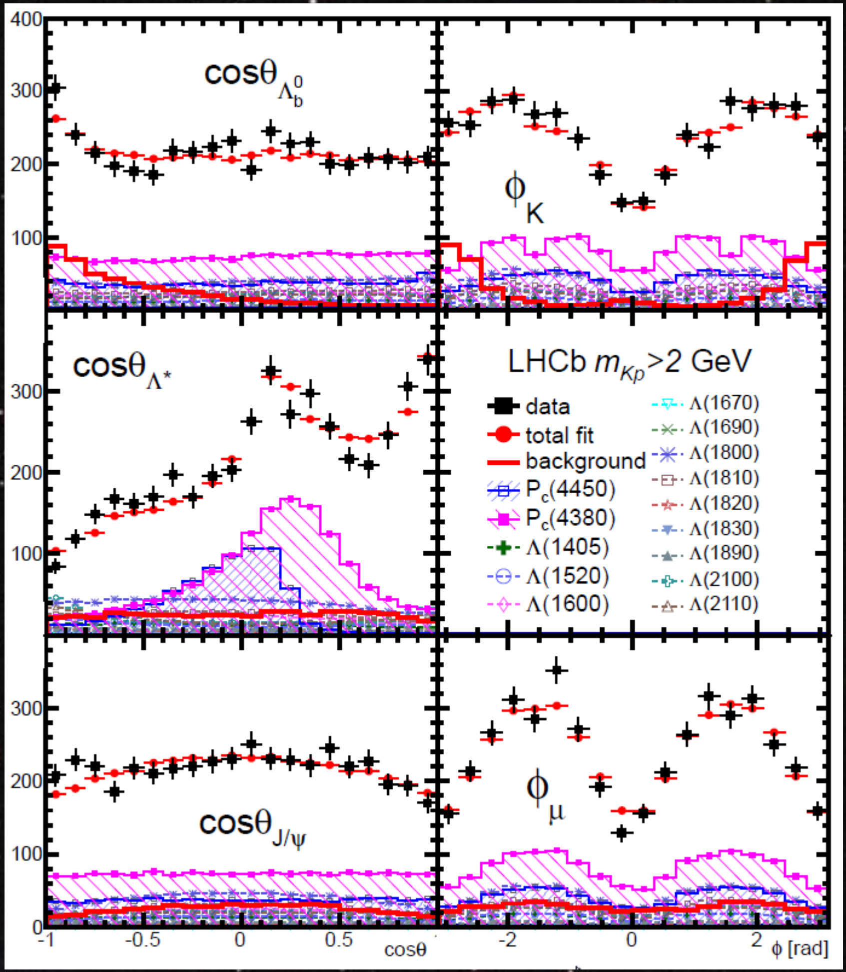
Chin. Phys. C40 (2016) 011001

Angular distributions

Full data sample



P_c^+ enriched region

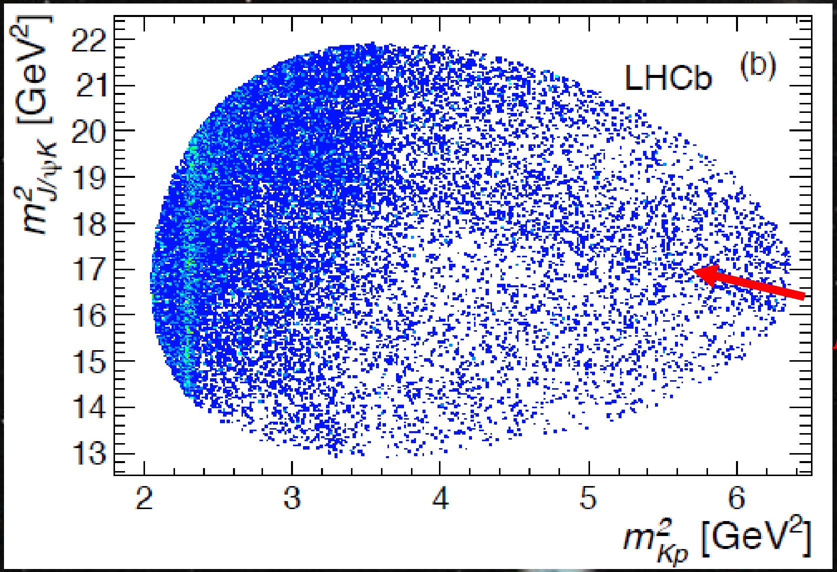


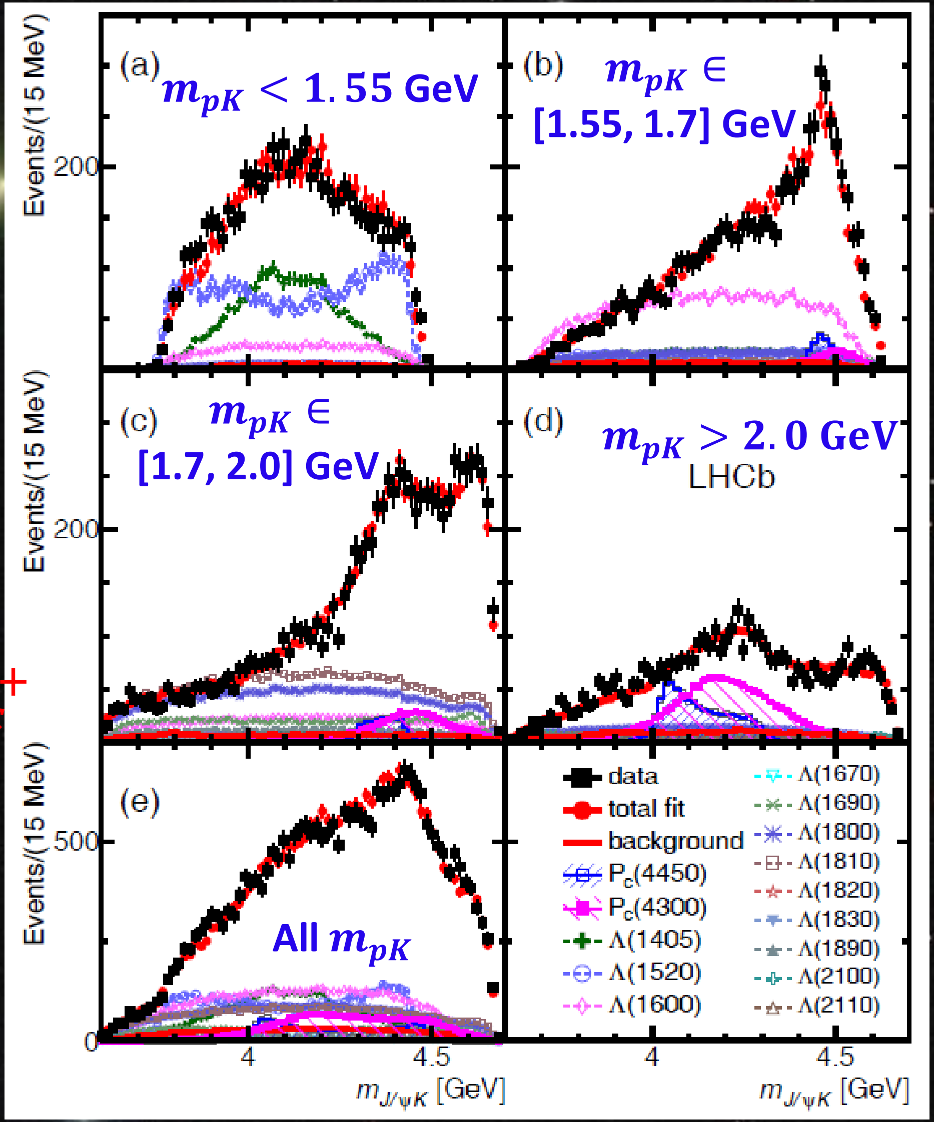
- Good fits to the data in all 6 dimensions

PRL 115 (2015) 072001

No need for exotic $J/\psi K^-$ contributions

- $J/\psi\, K$ system is well described by the Λ^* and P_c reflections





PRL 115 (2015) 072001

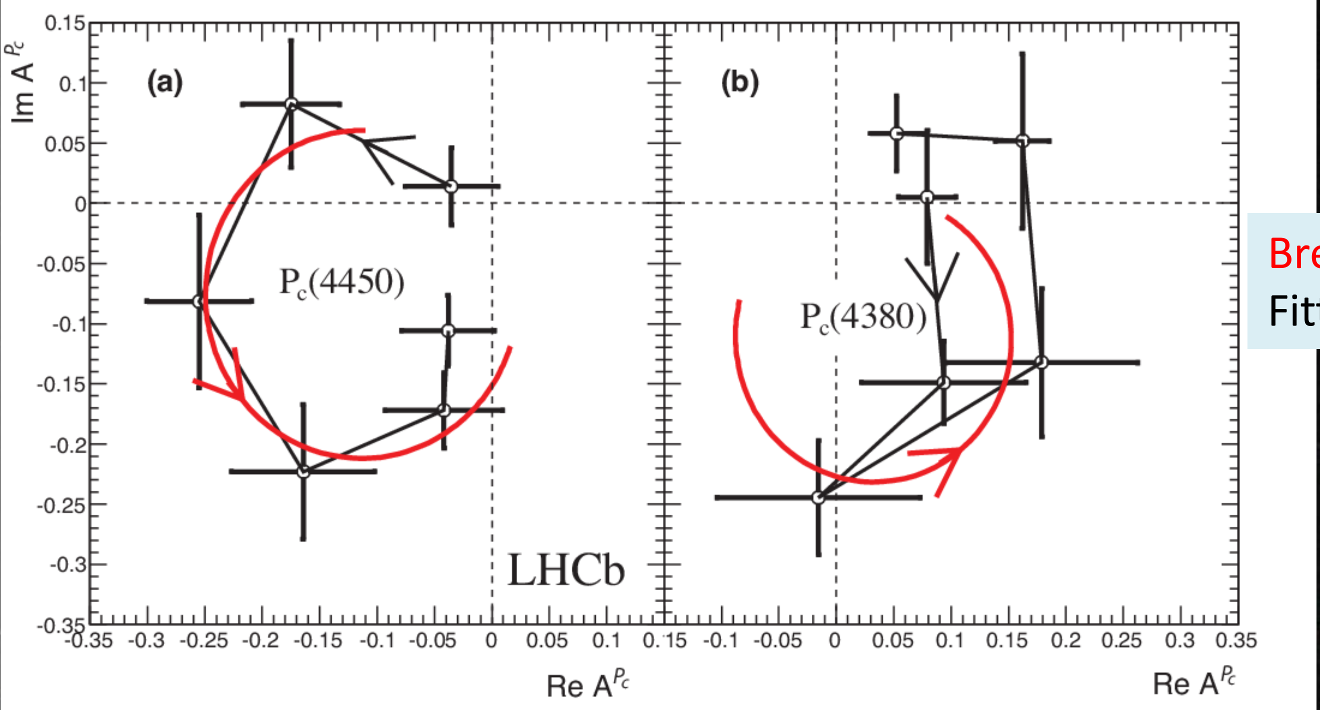
Additional cross-checks

Many additional cross-checks were done, such as

- Two independently coded fitters using different background subtractions (sFit & cFit)
- Split data show consistency:
  - 2011/2012
  - Magnetic polarities (Up/Down)
  - $\Lambda_b^0/\overline{\Lambda}_b^0$
  - $\Lambda_b^0(\text{low } p_{\rm T})/\Lambda_b^0(\text{high } p_{\rm T})$
- Varied selection
- B^0 and B_s^0 reflections modelled in the fit instead of veto

Argand diagrams

- Exotic hadron amplitudes for 6 $m_{J/\psi p}$ bins near the peak mass, while all other model parameters fitted simultaneously
- $P_c(4450)^+$
  - Good evidence for the resonant character
- $P_c(4380)^+$
  - Uncertainties too large to be conclusive



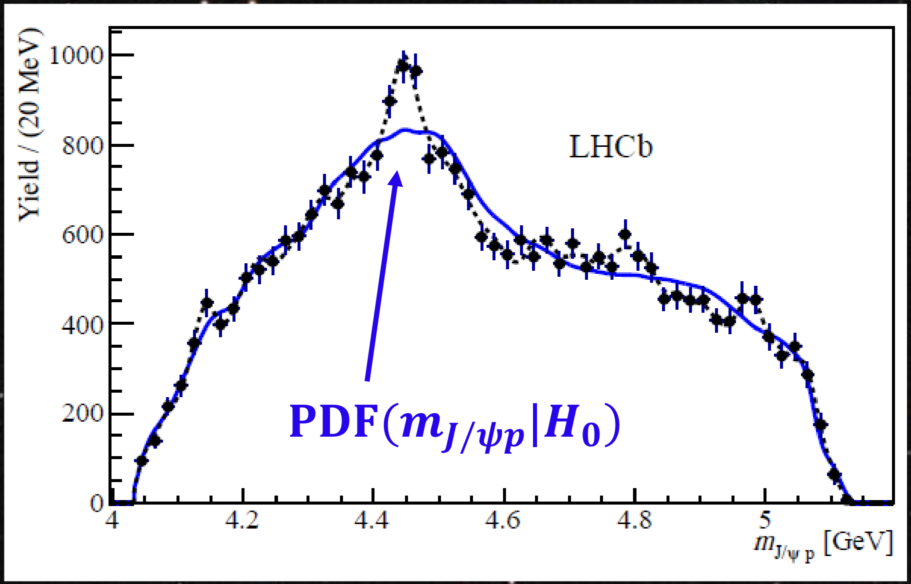
Breit-Wigner expectation
Fitted values

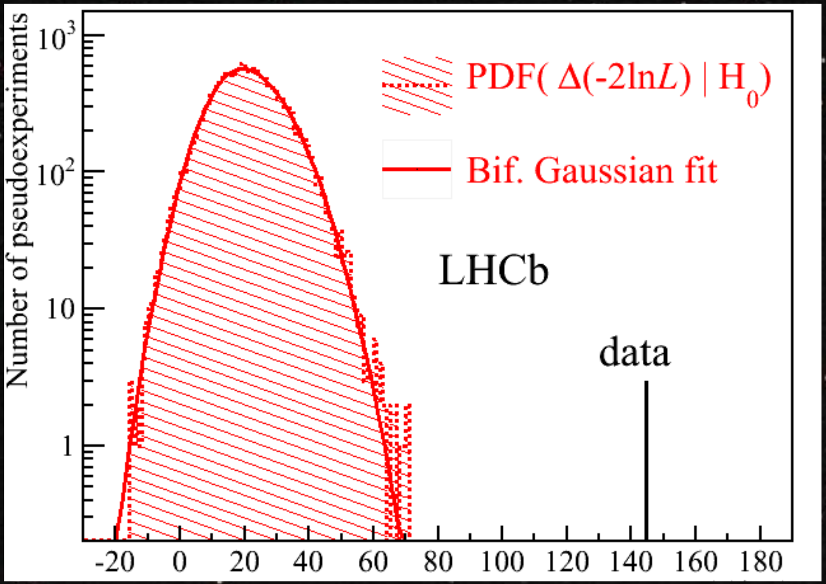
PRL 115 (2015) 072001

Model independent analysis

arXiv:1604.05708

- Model independent proof is especially important for the $\Lambda_b^0 \to J/\psi p K^-$ data, due to the difficulties in construction of a complete of Λ^* states

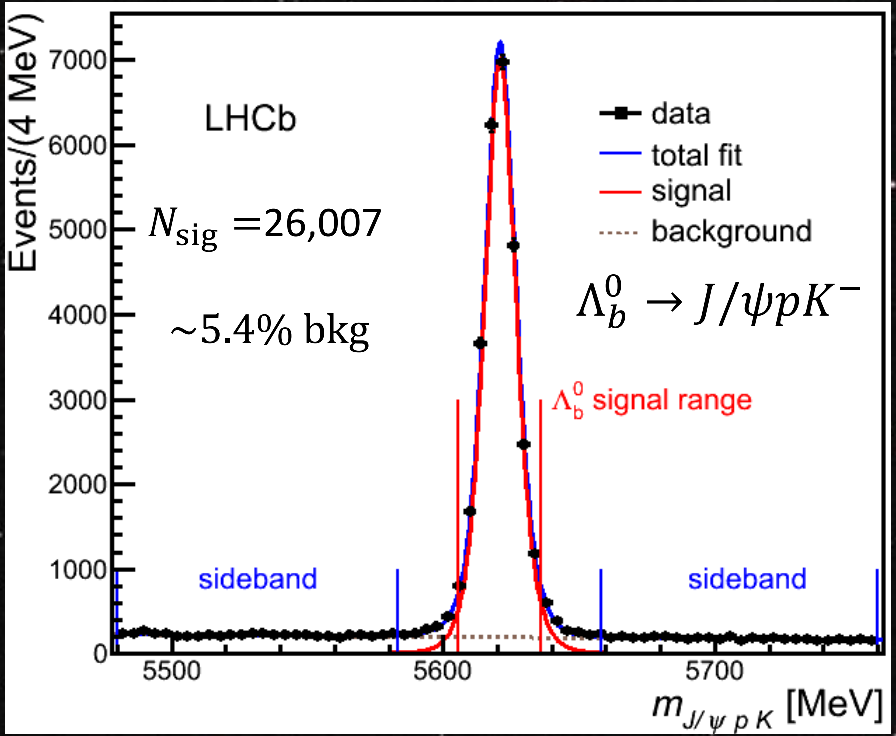


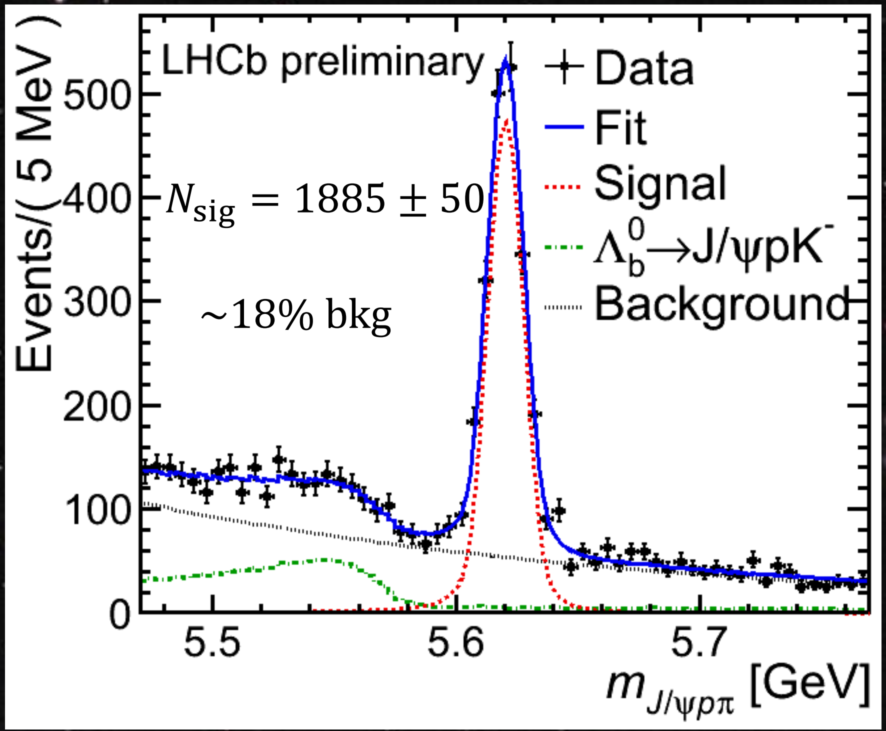


H_0: hypothesis of no pentaquark states

Studies in $\Lambda_b^0 \to J/\psi p \pi^-$ decays

- More than a factor of 10 lower signal statistics in $\Lambda_b^0 \to J/\psi p \pi^-$ than in $\Lambda_b^0 \to J/\psi p K^-$ (Cabibbo-favored)
- Relatively background fraction higher by more than a factor of 3



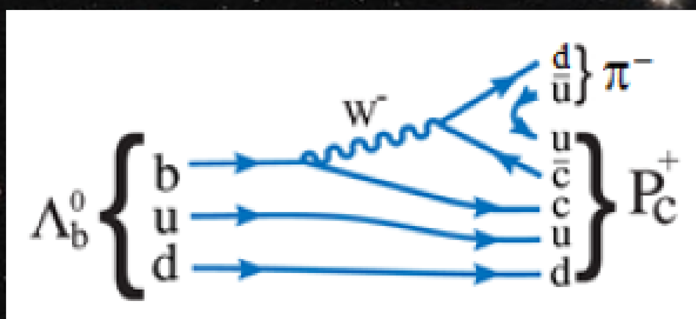


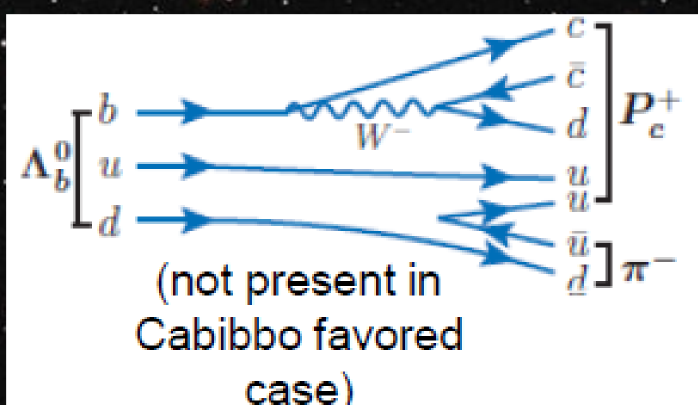
PRL 115 (2015) 072001

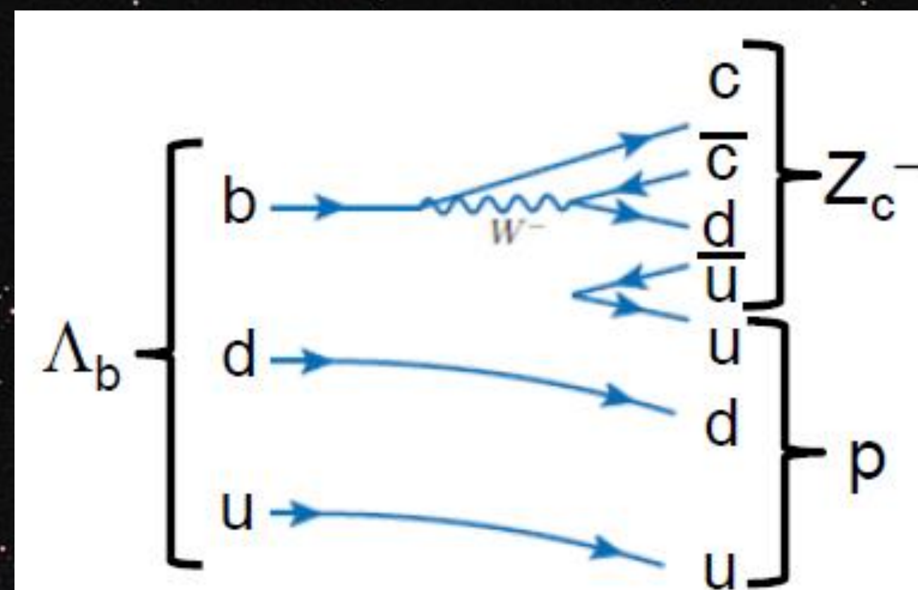
LHCb-PAPER-2016-015 (in preparation)

Exotic hadron contributions to $\Lambda_b^0 \to J/\psi p \pi^-$

- Test $P_c(4380)^+$ and $P_c(4450)^+$ ($\to J/\psi p$) observed by LHCb in $\Lambda_b^0 \to J/\psi p K^-$
- Test $Z_c(4200)^+ \to J/\psi \pi^+$ observed by Belle in $B^0 \to J/\psi \pi^+ K^-$

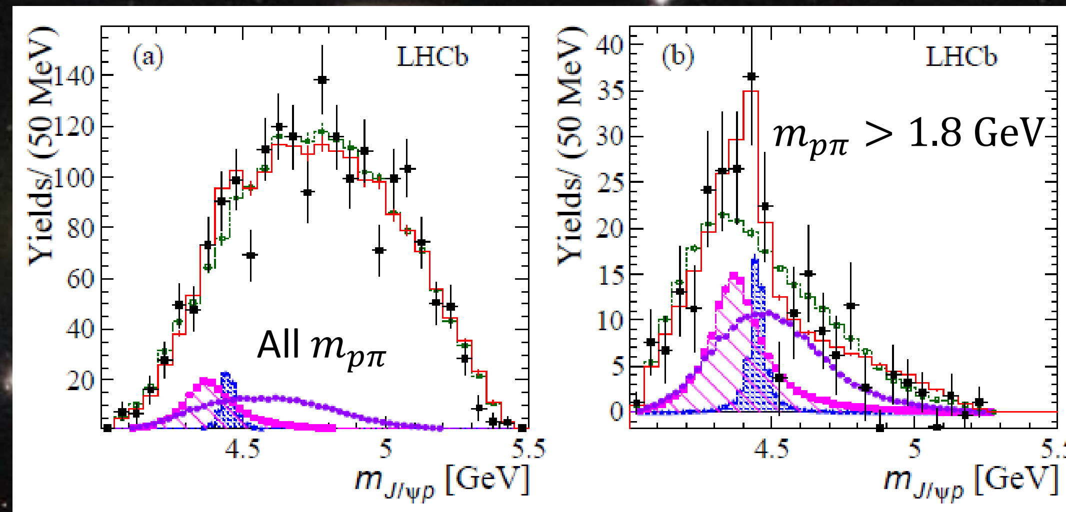


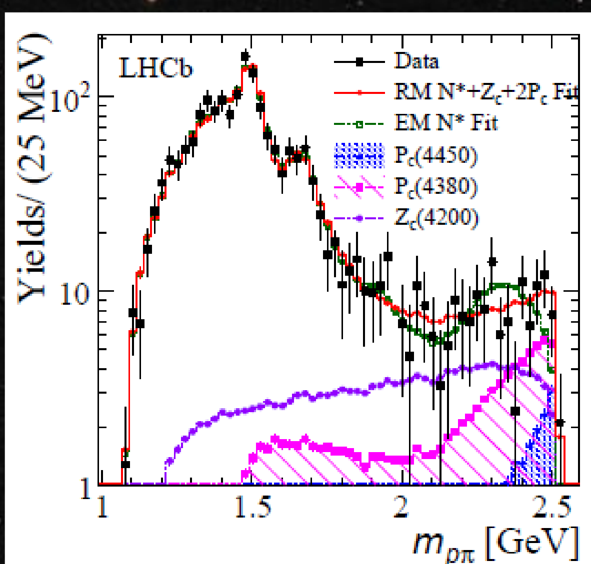


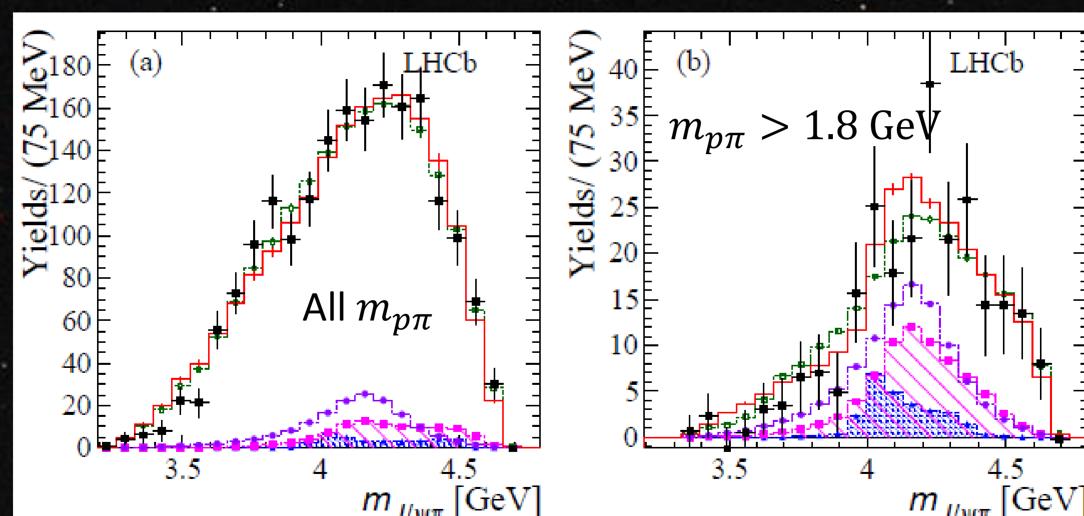


Amplitude fits to $\Lambda_b^0 \to J/\psi p \pi^-$

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1 σ
- Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p \pi^-$







LHCb-PAPER-2016-015
(in preparation)

Fit results for $\Lambda_b^0 \to J/\psi p \pi^-$

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is 3.1 σ (including systematic uncertainty)➔ evidence for exotics
- Individual exotic hadron contributions are not significant
- If assume $Z_c(4200)^-$ contribution negligible, significance of P_c^+ states increases to 3.3 σ

State	Fit fraction (%)	$\mathcal{B}(\Lambda_b^0 \to P_c^+ \pi^-)/\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)$
$Z_c(4200)^-$	$7.7 \pm 2.8^{+3.4}_{-4.0}$	$-$
$P_c(4380)^+$	$5.1 \pm 1.5^{+2.1}_{-1.6}$	$0.050 \pm 0.016^{+0.020}_{-0.016} \pm 0.025$
$P_c(4450)^+$	$1.6^{+0.8}_{-0.6}{}^{+0.6}_{-0.5}$	$0.033^{+0.016}_{-0.014}{}^{+0.011}_{-0.009} \pm 0.025$

Expected if the additional internal W emission diagram negligible: 0.07~0.08
[H.-Y Cheng and C.-K Chua, PRD92 (2015) 096009]

The results are consistent with those obtained from the $\Lambda_b^0 \to J/\psi p K^-$ decay

Summary and outlook

- Two resonance states, $P_c(4380)^+$ and $P_c(4450)^+$, decaying to $J/\psi p$ have been observed by LHCb in a full amplitude analysis of $\Lambda_b^0 \to J/\psi\, pK^-$ decays
- Model independent analysis confirmed the necessity of exotic hadron contributions
- Amplitude in the Cabibbo suppressed $\Lambda_b^0 \to J/\psi p\pi^-$ decay shows evidence of exotic hadron contributions, consistent with the results in $\Lambda_b^0 \to J/\psi\, pK^-$ decays
- Nature of the P_c^+ states not clear: loosely-bound, tightly-bound, hybrid?
- We look forward to establishing the structure of many other states or other decay modes using RUN 2 data

一万年太久，只争朝夕！

谢谢！