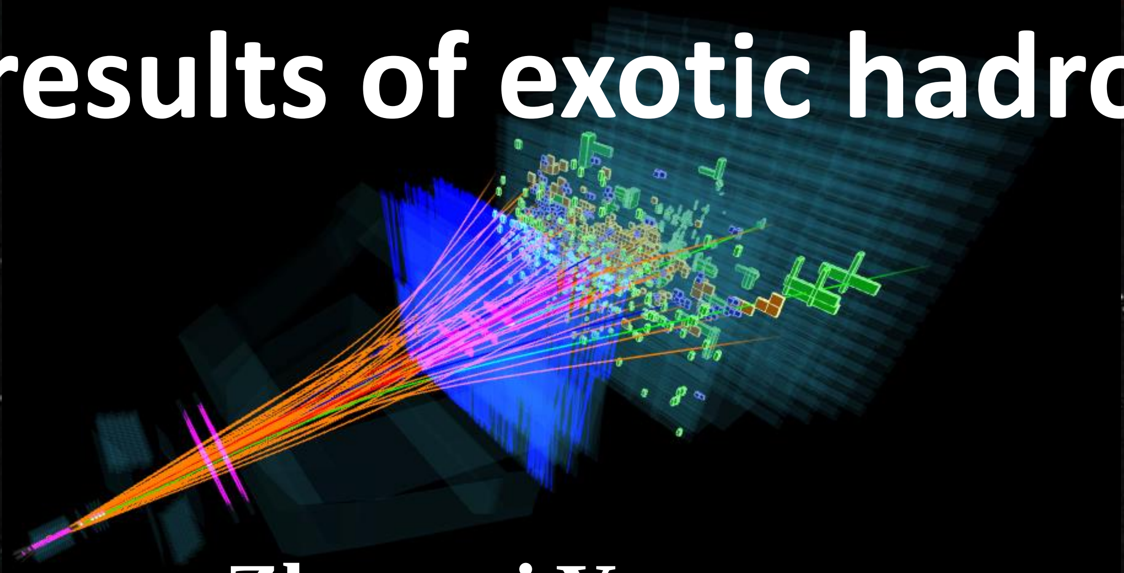
2016 JAEA/ASRC Reimei Workshop
24-26 October, Inha University

LHCb results of exotic hadrons



Zhenwei Yang
Tsinghua University, Beijing
On behalf of the LHCb collaboration

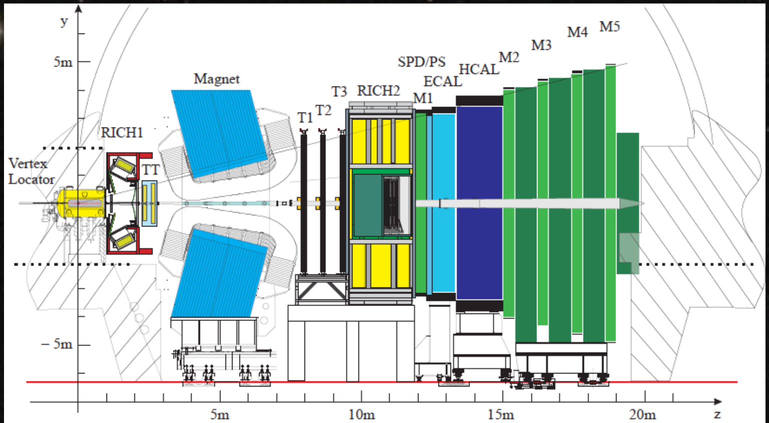
25 October, 2016

Outline

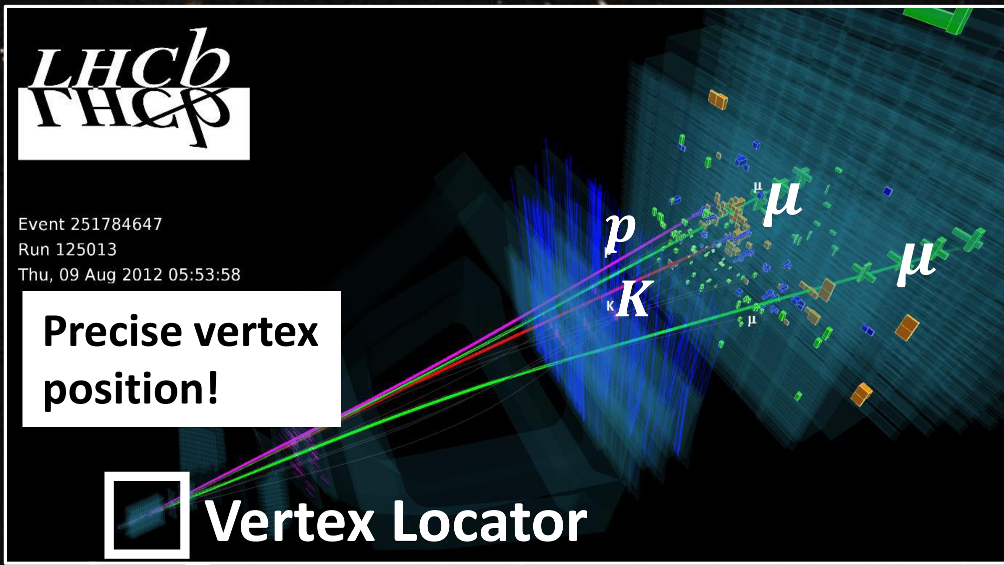
- Introduction
- Exotic spectroscopy at LHCb
  - Pentaquarks
  - Tetraquarks
- Conventional spectroscopy at LHCb
- Summary and outlook

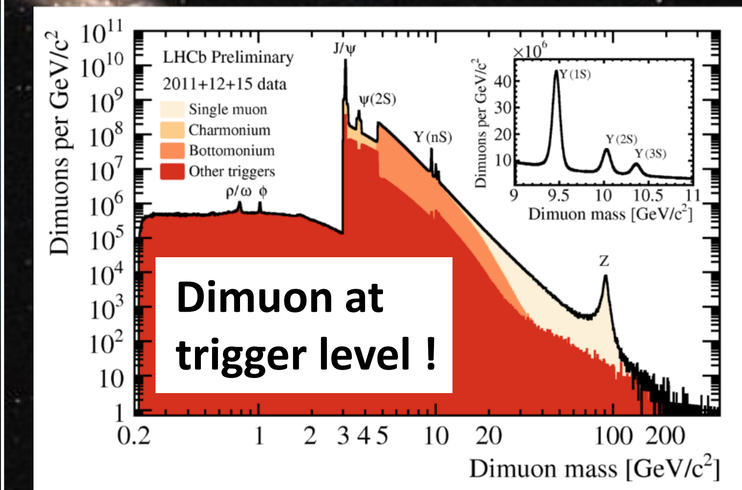
The LHCb experiment

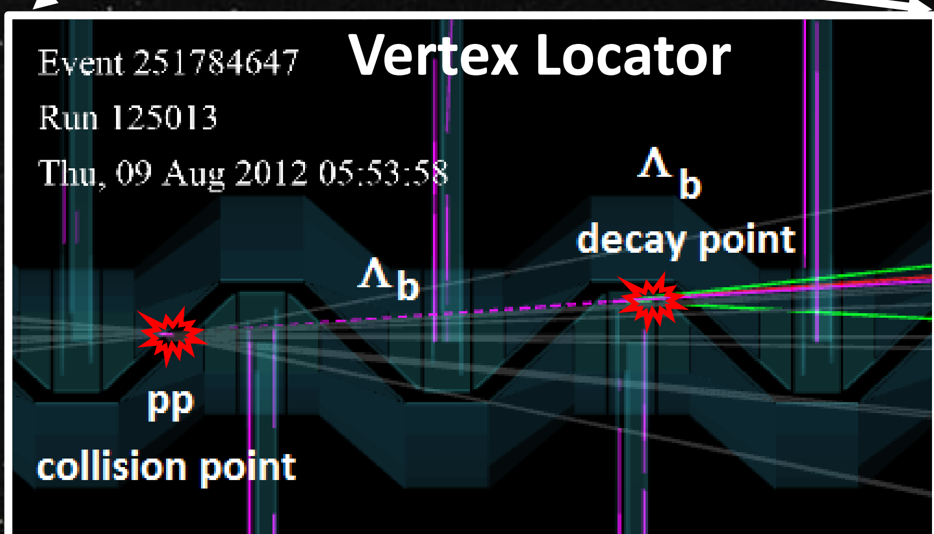
- Designed for heavy flavor physics, covering a broad scope of physics, e.g.
  - Indirect search of New Physics via precision measurements of CPV, CKM and rare decays
  - Hadron spectroscopy
- Pros of hadron spectroscopy study at LHCb
  - Large production cross-section at the LHC
  - Efficient trigger
  - Vertex locator with high precision
  - High precision tracking system
  - Powerful PID of hadrons
  - Efficient muon system

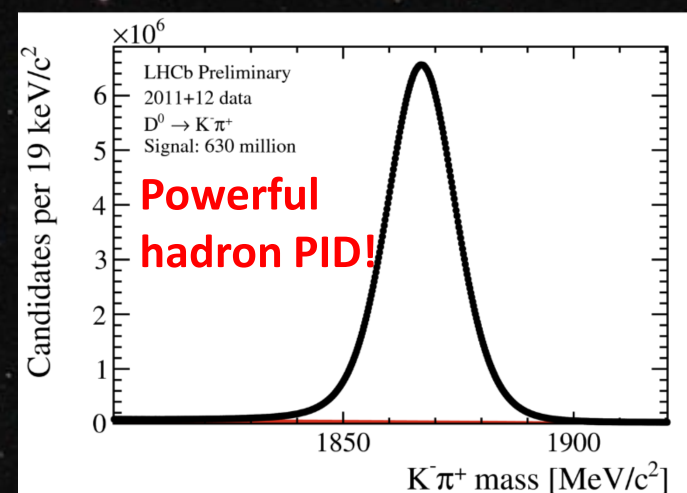


Excellent performance

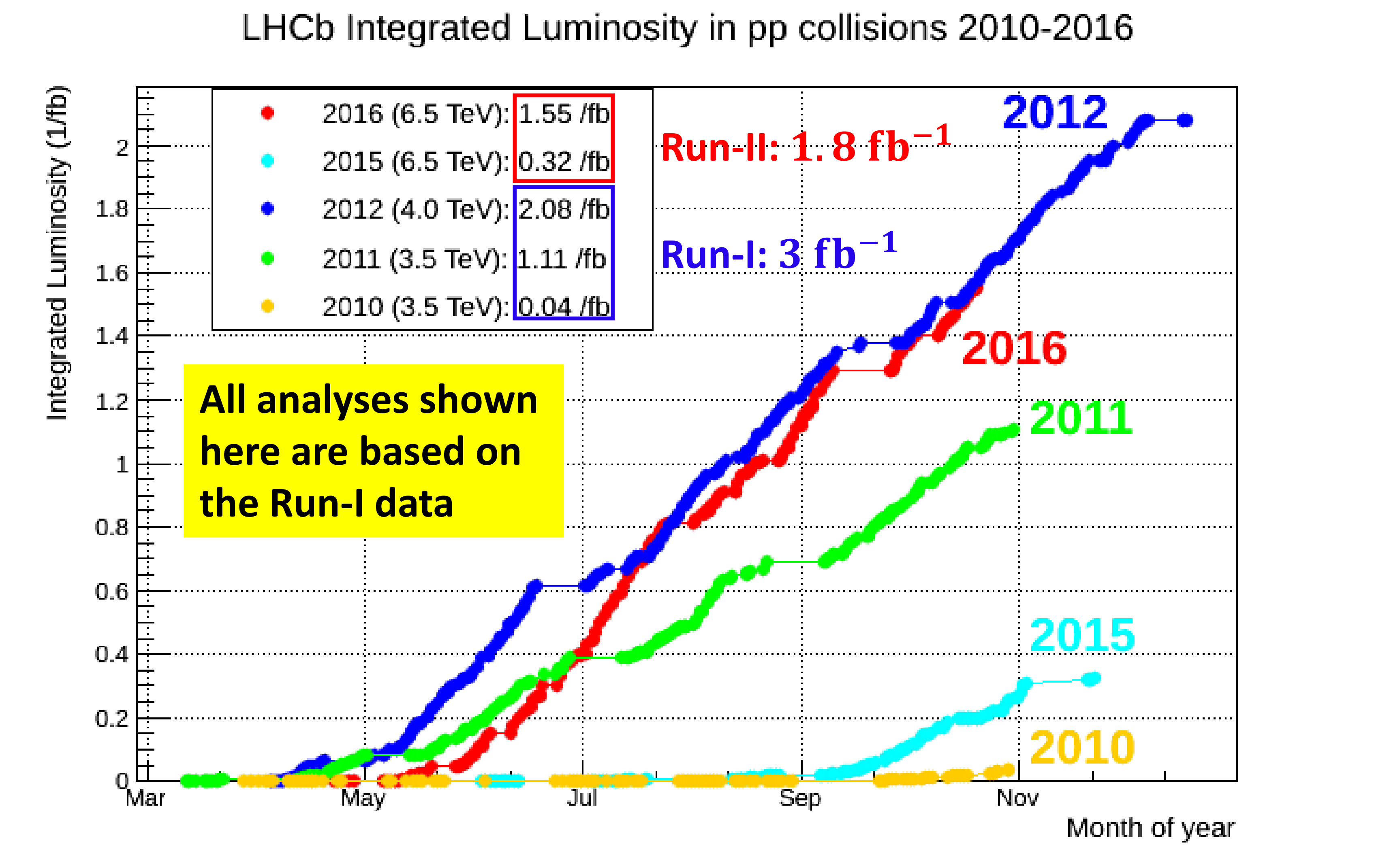








LHCb data taking



Data taking efficiency $> 90\%$

Spectroscopy at LHCb

- Study of spectroscopy can help to understand the nature of QCD
- LHCb has been playing an important role in the study of spectroscopy, standard or exotic, since the LHC started
  - $X(3872), Z(4430)^+, P_c(4380)^+, P_c(4450)^+, \ldots$
  - Excited c and b hadrons
- Topics today focus on the following recent results
  - Model-independent study in $\Lambda_b^0 \to J/\psi p K^-$ decays — PRL 117 (2016) 082002
  - Study in Cabibbo-suppressed $\Lambda_b^0 \to J/\psi p \pi^-$ decays — PRL 117 (2016) 082003
  - Four exotic states in $B^+ \to J/\psi \phi K^+$ — arXiv:1606.07895/8, submitted to PRL, PRD
  - Search for $X(5568)^+ \to B_s^0 \pi^+$ — PRL 117 (2016) 152003
  - Properties of the Ξ_b^{0*} baryon — JHEP 05 (2016) 161
  - Study of $D_{sJ}^{(*)+}$ mesons — JHEP 02 (2016) 133
  - Excited D mesons in $B \to D^+ \pi^- \pi^-$ decays — PRD 94 (2016) 072001

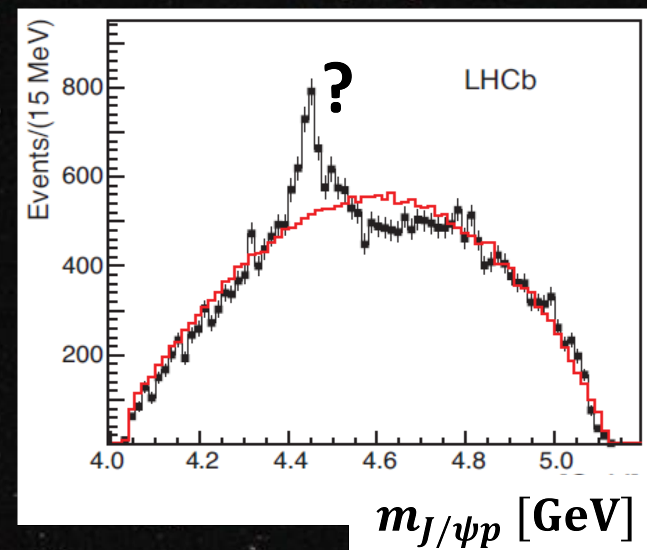
Exotic spectroscopy

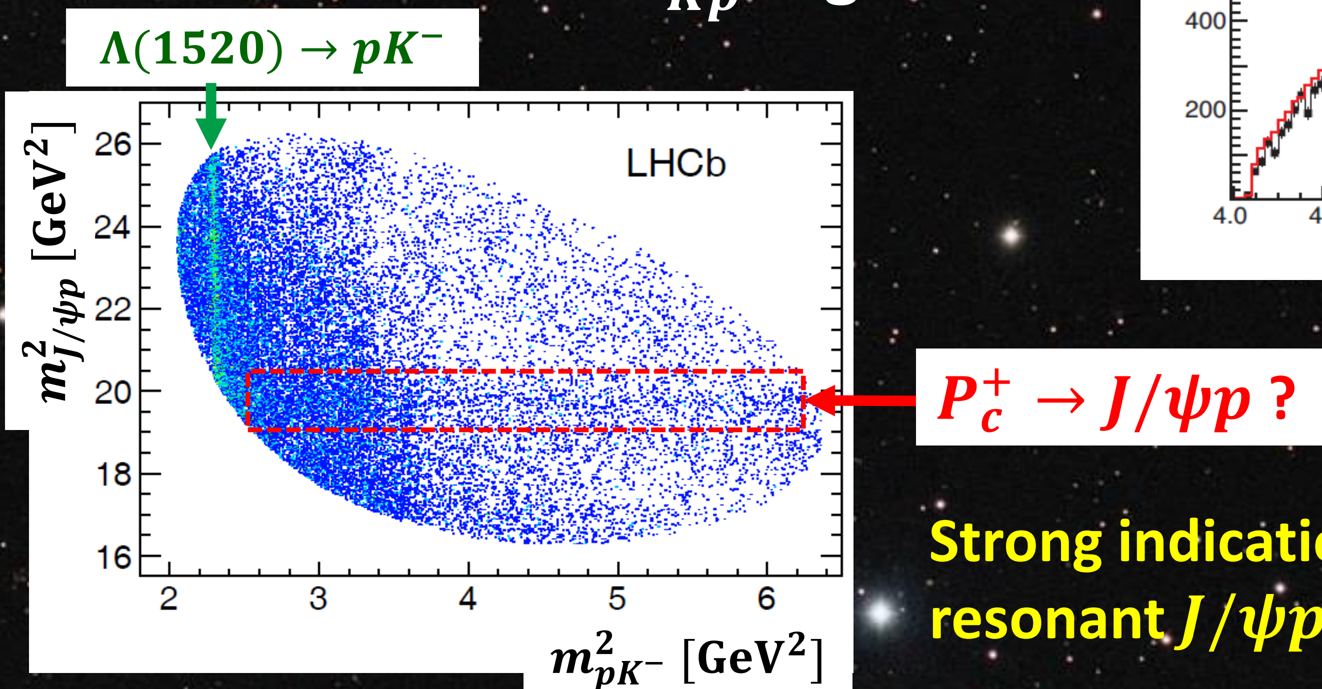
- Model-independent study in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays
- Study in Cabibbo-suppressed $\Lambda_b^0 \rightarrow J/\psi p \pi^-$ decays
- $X \rightarrow J/\psi\phi$ in $B^+ \rightarrow J/\psi\phi K^+$
- Search for $X(5568)^+ \rightarrow B_s^0\pi^+$

Observation of $P_c(4380)^+$ and $P_c(4450)^+$

PRL 115 (2015) 072001

- The peak structure of $J/\psi p$ in the $\Lambda_b^0 \to J/\psi p K^-$ decay attracted the attention of LHCb in late 2014
- The Dalitz plot show a horizontal band around $m^2_{J/\psi p} = 20\ \mathrm{GeV}^2$ across the whole m^2_{Kp} region





Strong indication of a resonant $J/\psi p$ state

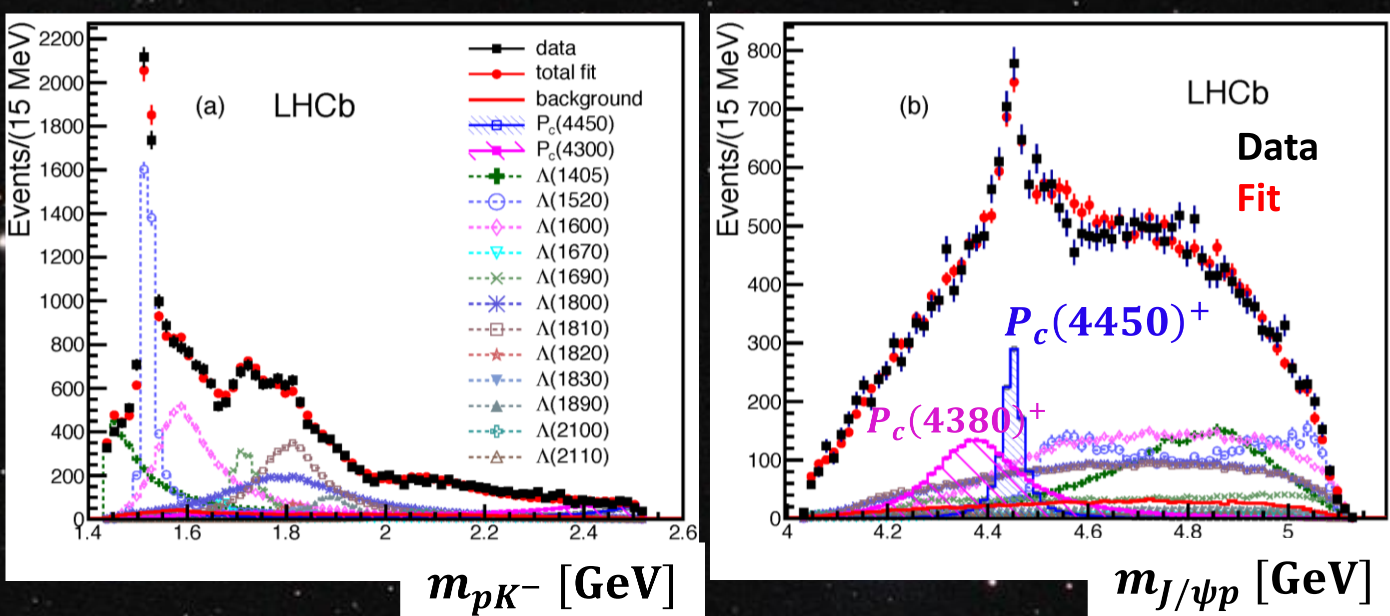
Observation of $P_c(4380)^+$ and $P_c(4450)^+$

PRL 115 (2015) 072001

- A full amplitude analysis shows the necessity of two resonant states $P_c(4380)^+$ and $P_c(4450)^+$

Resonance	Mass (MeV)	Width (MeV)	Significance	Fit fraction(%)
$P_c(4380)^+$	$4380\pm8\pm29$	$205\pm18\pm86$	$9\ \sigma$	$8.4\pm0.7\pm4.2$
$P_c(4450)^+$	$4449.8\pm1.7\pm2.5$	$39\pm5\pm19$	$12\ \sigma$	$4.1\pm0.5\pm1.1$

$$\mathcal{B}(\Lambda_b^0 \to P_c(4380)^+K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38}) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c(4450)^+K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5}$$



CPC40 (2016) 011001

J^P combination:
$(3/2^-, 5/2^+)$
$(3/2^+, 5/2^-)$
$(5/2^+, 3/2^-)$

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

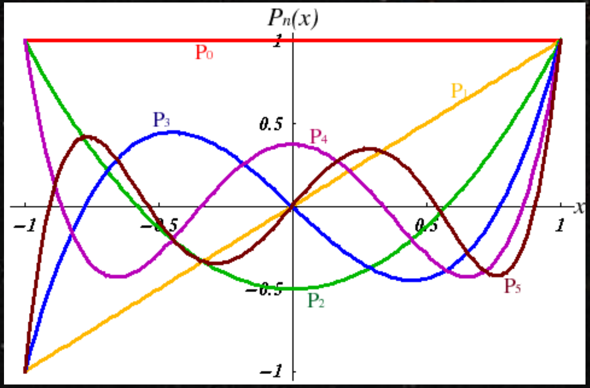
PRL 117 (2016) 082002

- Model independent proof is especially important, due to the difficulties in construction of a complete Λ^* states

Legendre moments:

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta), \quad \theta = \theta_{K^*} \text{ or } \theta_{\Lambda^*}$$

$$\langle P_l^U \rangle = \int_{-1}^{+1} \frac{\mathrm{d}N}{\mathrm{d}\cos\theta} P_l(\cos\theta)\mathrm{d}\cos\theta \propto \sum_{i=1}^{n_{\mathrm{evt}}} \frac{1}{\varepsilon_i} P_l(\cos\theta_i)$$



Λ^* can contribute only to low-order moments

Λ^*-only hypothesis called H_0

$$l_{\max} = 2J_{\max}$$

$J_{\max}$: the highest spin of possible Λ^* resonances

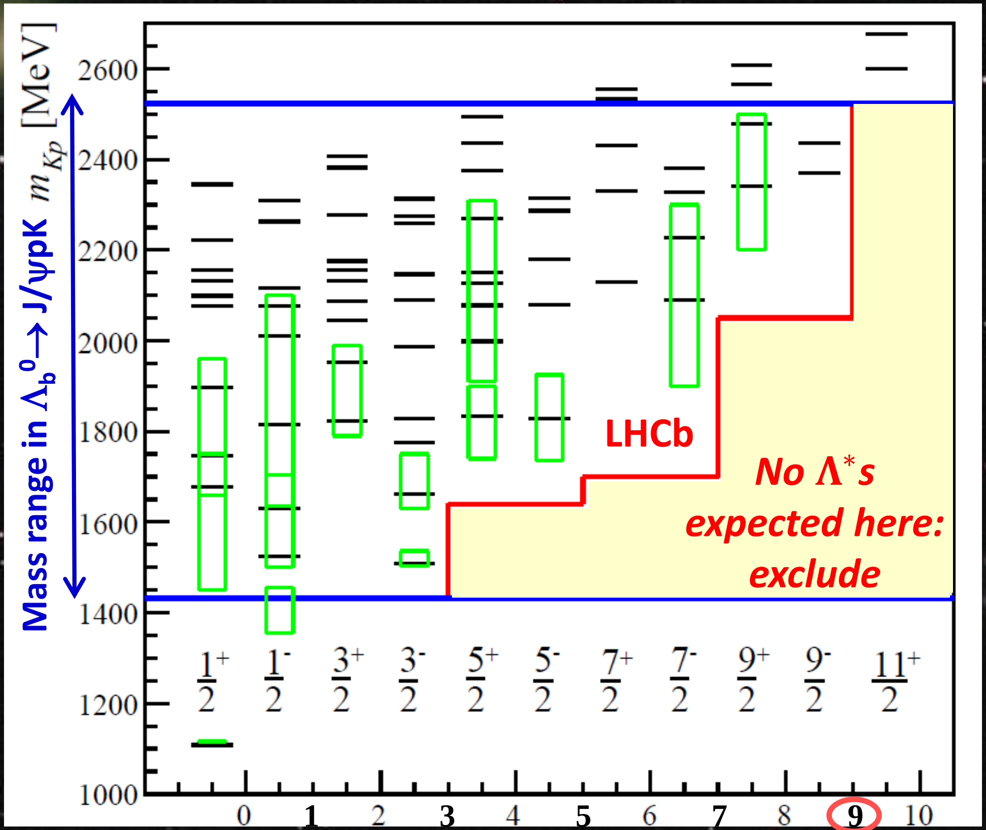
Reflections of exotic hadrons can contribute to low and high order moments:

Detecting non-zero moments above $2J_{\max}$ signals presence of exotic states

Setting $l_{\max}$ as function of m_{pK}

PRL 117 (2016) 082002

- From known Λ^*, and quark model predictions used as a guide
- Much fewer known states than predicted!
- Known Λ^* states: boxes $M_0 \pm \Gamma_0$
- Λ^* mass predictions by Loring-Metsch-Petry EPJA10 (2001) 447

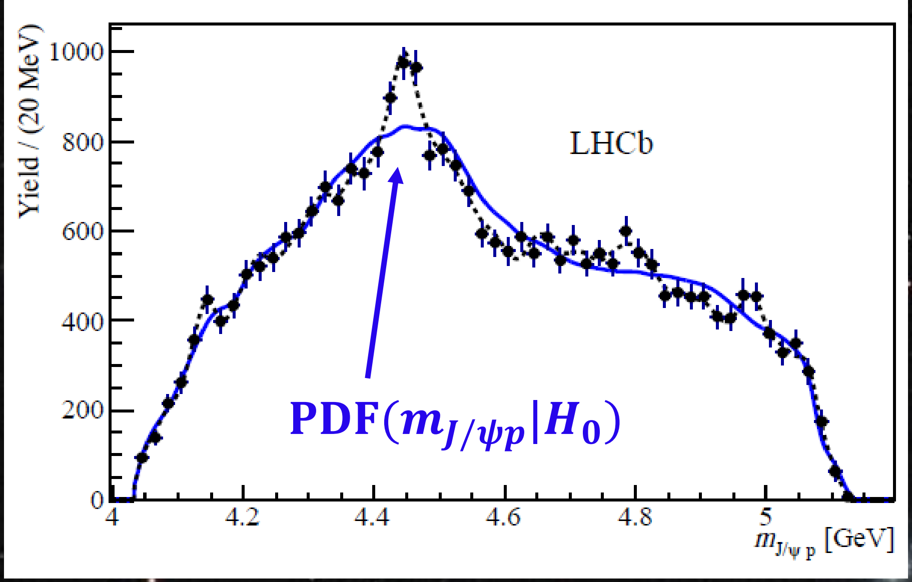


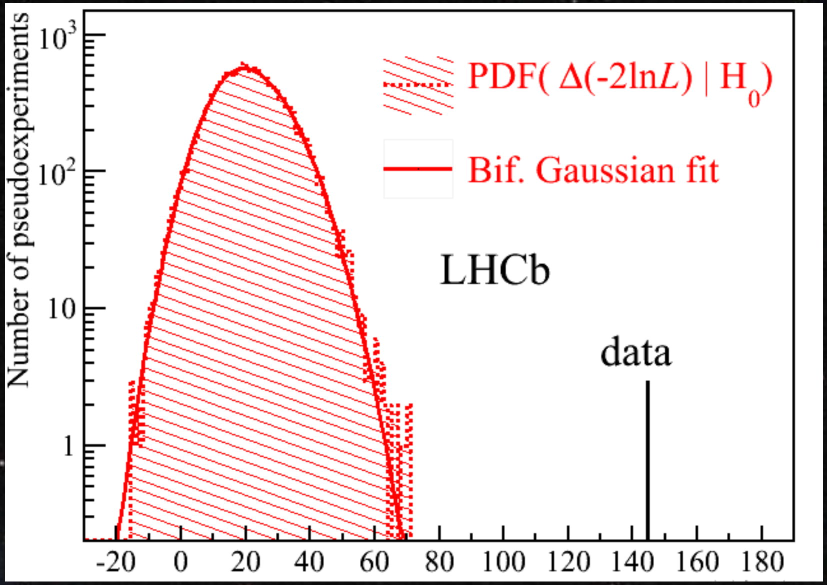
$l_{\max}(\, m_{pK} \,)$

Null hypothesis versus data

PRL 117 (2016) 082002

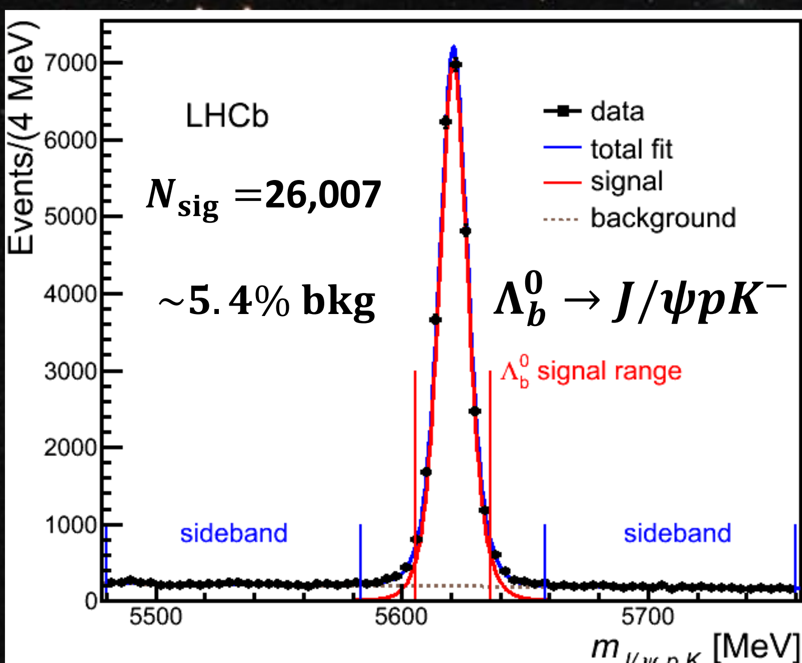
- Toy MC simulates the reflection of mass and angular structure of Kp onto $m_{J/\psi p}$
- Limits of $l_{\max}$ used (i.e. zero moments for orders $> l_{\max}$)
- $m_{J/\psi p}$ cannot be explained by the reflections of conventional (non)resonances alone



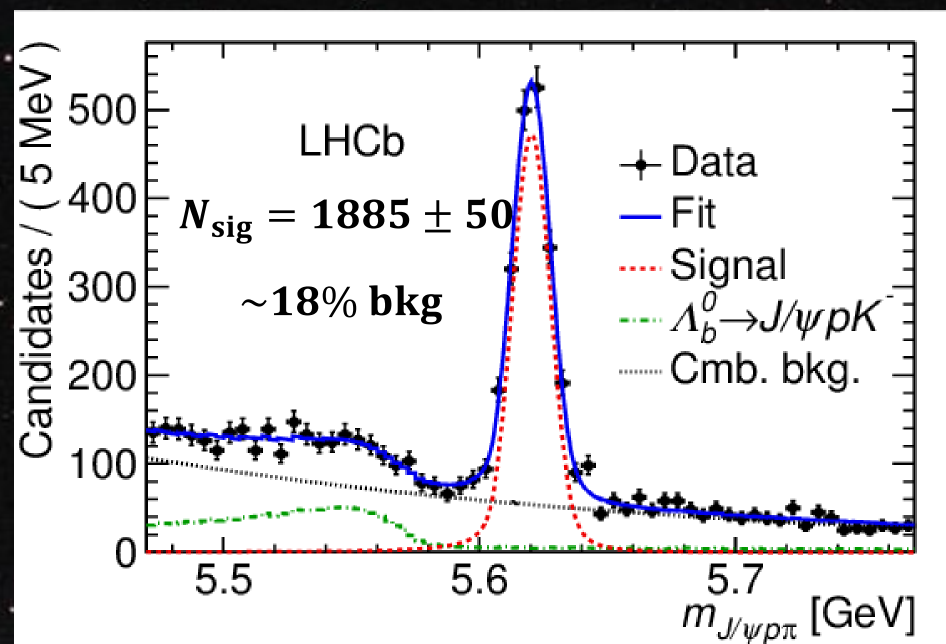


Cabibbo suppressed decays: $\Lambda_b^0 \to J/\psi p \pi^-$

- Signal statistics lower than $\Lambda_b^0 \to J/\psi p K^-$ (Cabibbo-favored): **1885** versus **26007**
- Higher background fraction: **18% versus 5.4%**
- Many N^* and Δ states involved in the decay



PRL 115 (2015) 072001



PRL 117 (2016) 082003

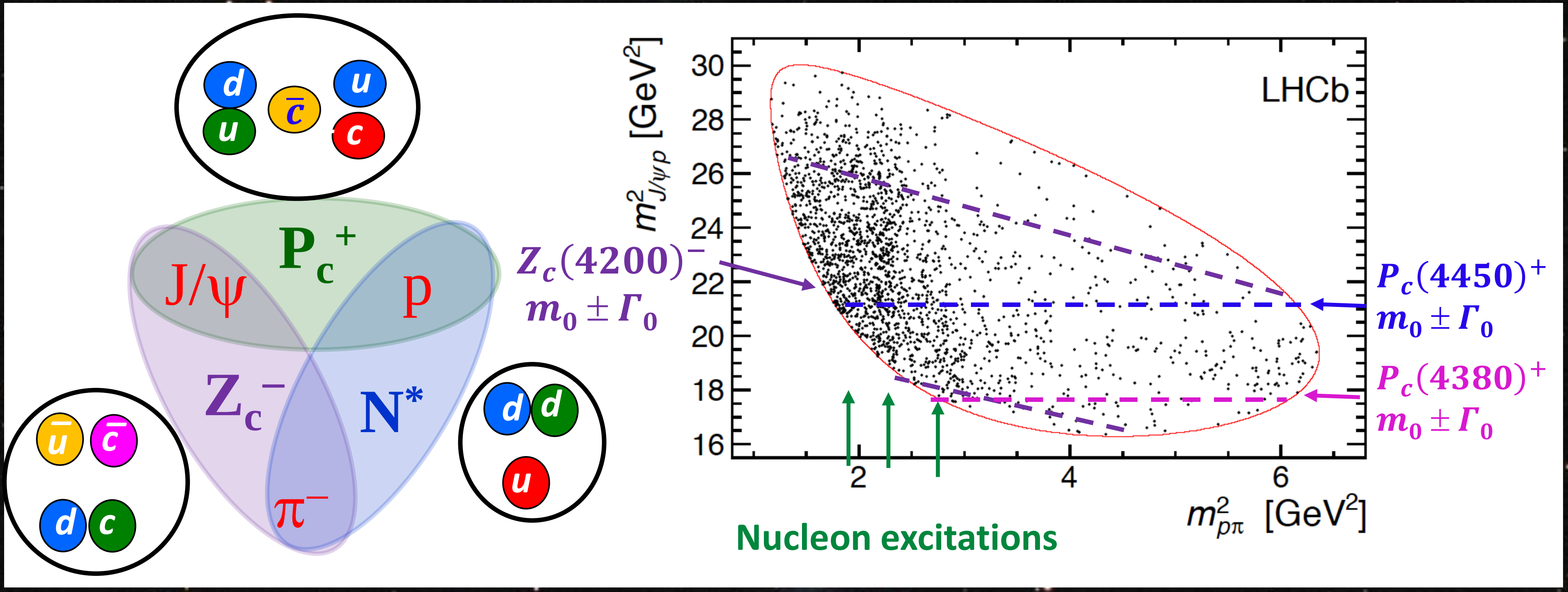
Possible exotic constribution in $\Lambda_b^0 \to J/\psi p \pi^-$

PRL 117 (2016) 082003

- More complicate due to possible Z_c^- states
- Exotic hadron contributions examined are:

$P_c(4380)^+, P_c(4450)^+ \to J/\psi p^+$ and $Z_c(4200)^- \to J/\psi \pi^-$

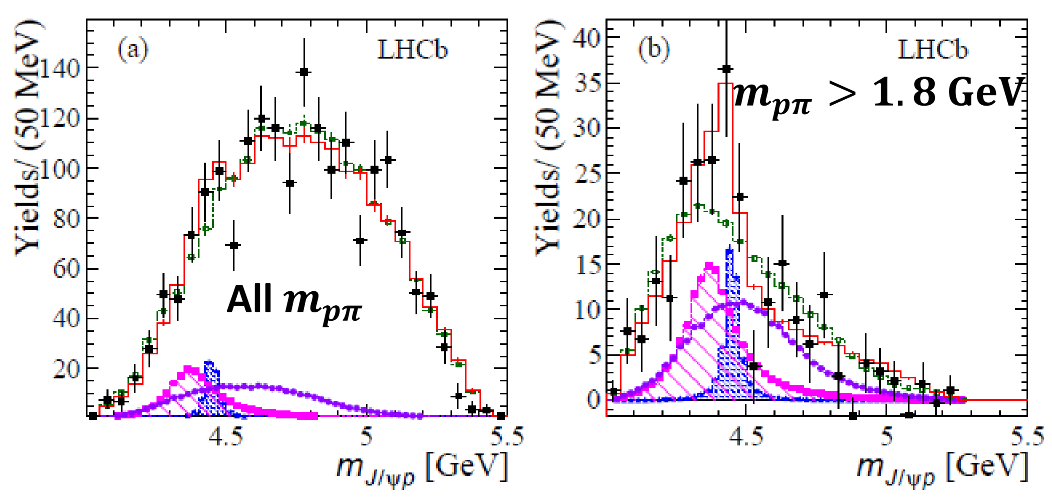
- $Z_c(4200)^-$: $m_0 = 4196^{+35}_{-32}$ MeV, $\Gamma = 370^{+99}_{-149}$ MeV, $J^P = 1^+$ by Belle (6.2σ) in $B^0 \to J/\psi \pi^- K^+$ decays [PRD88(2013) 074026]

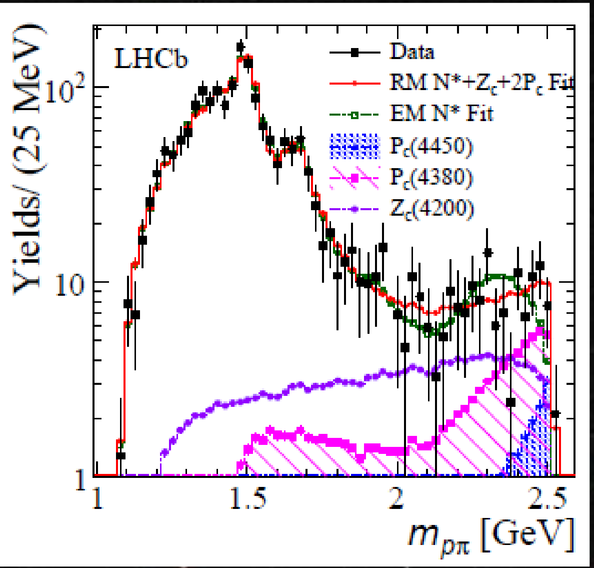


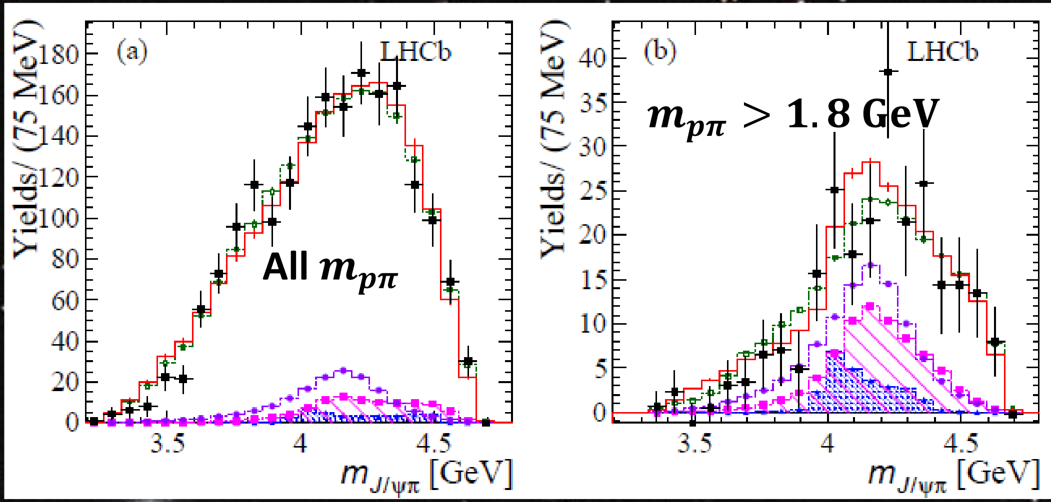
Amplitude fits to $\Lambda_b^0 \to J/\psi p \pi^-$

PRL 117 (2016) 082003

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







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

PRL 117 (2016) 082003

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together is $3.1\ \sigma$ (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 $3.3\ \sigma$

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: $0.07 \sim 0.08$
[H.-Y Cheng and C.-K Chua, PRD92 (2015) 096009]

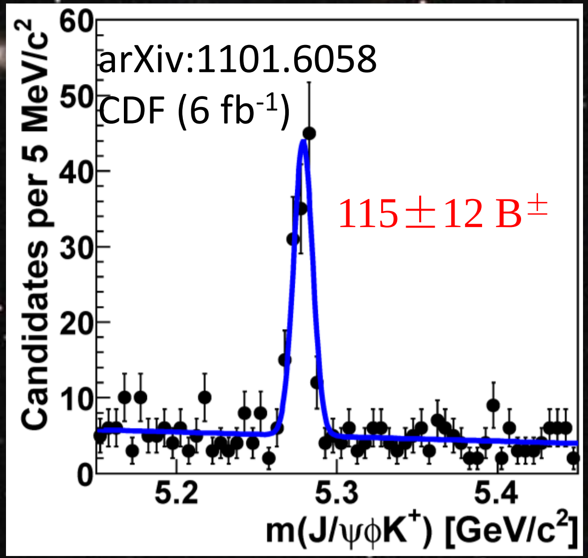
The results are consistent with those obtained from the $\Lambda_b^0 \to J/\psi p K^-$ decay

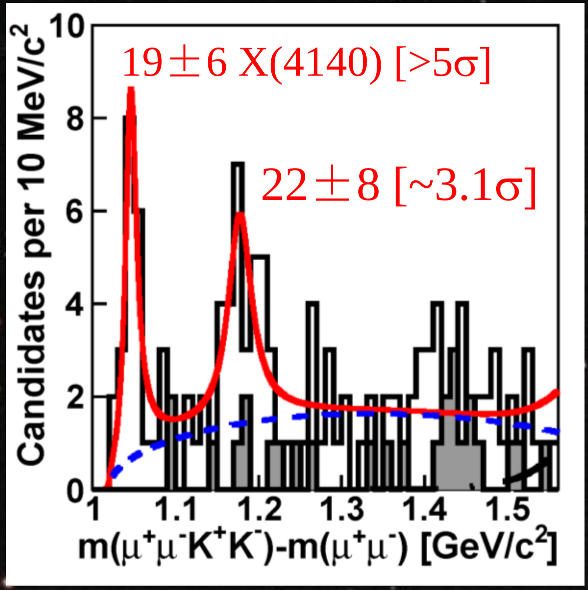
Exotic spectroscopy

- **Model-independent study in $\Lambda_b^0 \to J/\psi p K^-$ decays**
- **Study in Cabibbo-suppressed $\Lambda_b^0 \to J/\psi p \pi^-$ decays**
- **$X \to J/\psi \phi$ in $B^+ \to J/\psi \phi K^+$**
- **Search for $X(5568)^+ \to B_s^0 \pi^+$**

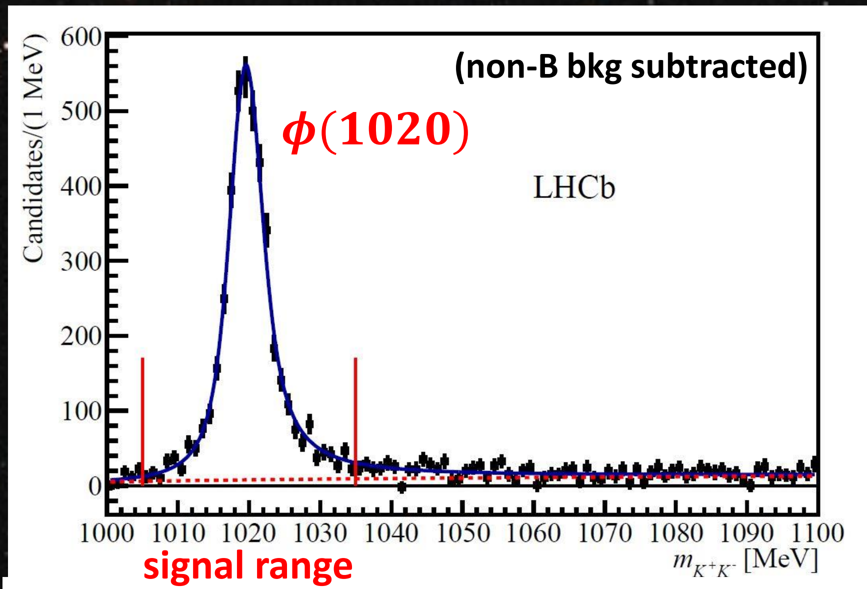
$X(4140)$ and $X(4274)$ at CDF

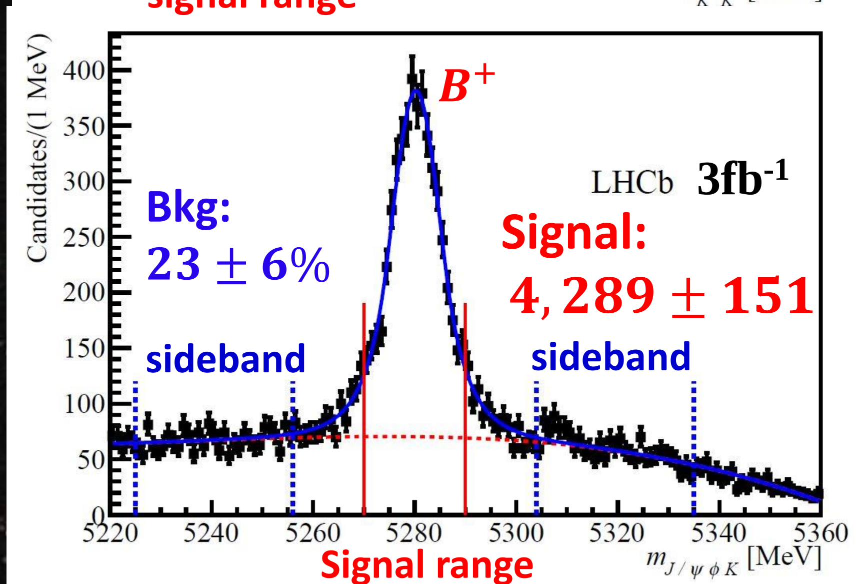
- CDF observed a narrow $J/\psi\phi$ structure in $B^+ \to J/\psi\phi K^+$ decays
  [Initial publication on $2.7\ \mathrm{fb}^{-1}$ PRL102(2009)242002]
  - $M = 4143.4 \pm 3.0 \pm 0.6\ \mathrm{MeV}$
  - $\Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5\ \mathrm{MeV}$
  - Necessarily exotic since it is narrow and above the $D_s\overline{D}_s$ threshold
  - $[cs\overline{c}\overline{s}]$ tetraquark ?
  - Hint of a second structure: $X(4274)$
- Not confirmed by B-factories and LHCb with $0.37\ \mathrm{fb}^{-1}$ data
- Confirmed by D0 and CMS, both with narrow width





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



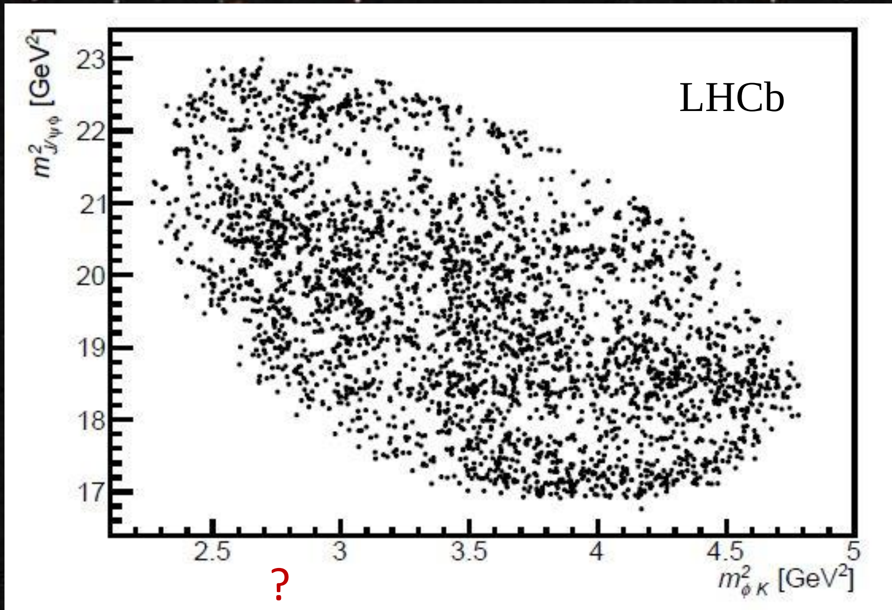


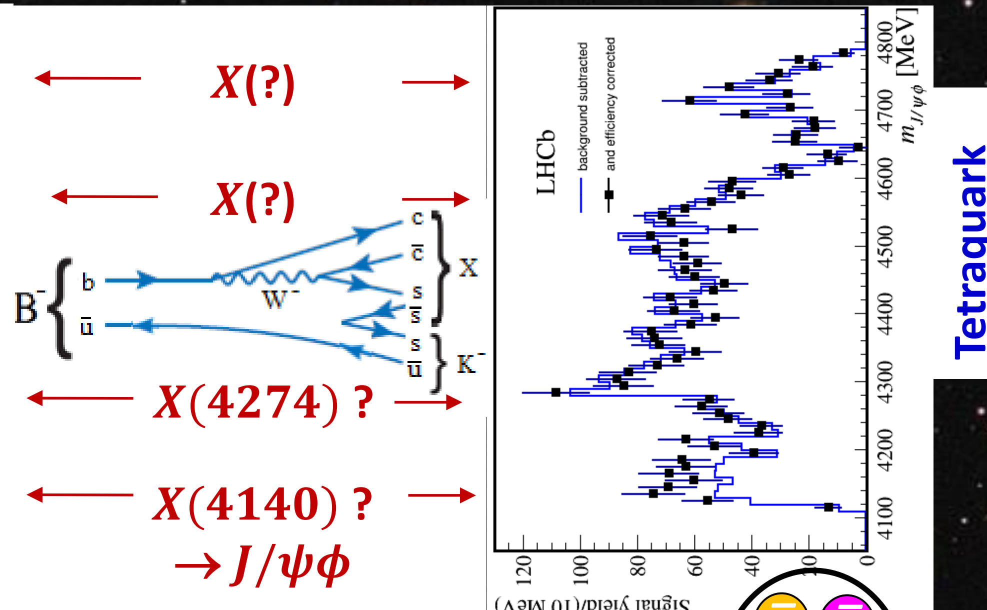
arXiv:1606.07895 , submitted to PRL
arXiv: 1606.07898, submitted to PRD

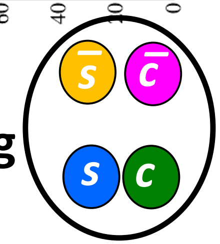
Statistically, the most powerful $B^+ \to J/\psi\phi K^+$ sample analyzed so far

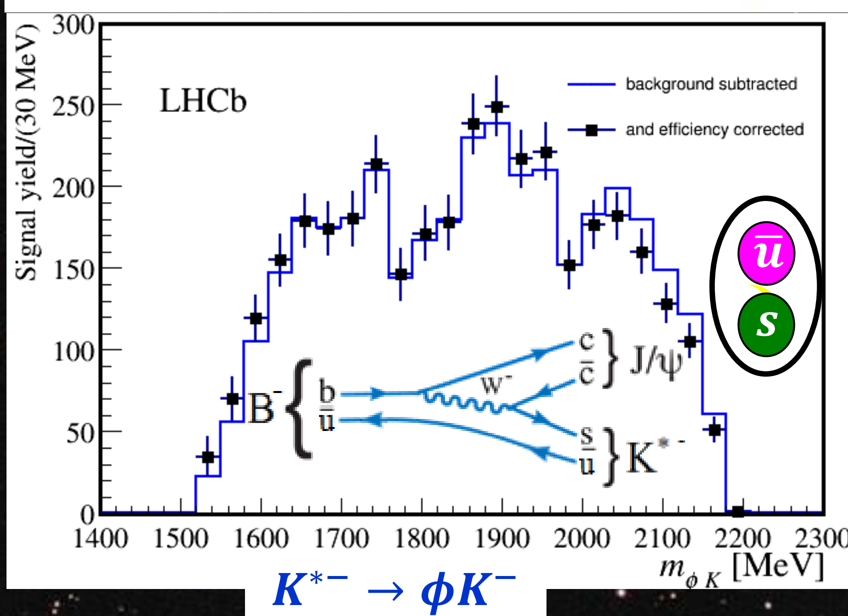
Use sidebands to subtract background

Dalitz plot of $B^+ \to J/\psi\phi K^+$ decays







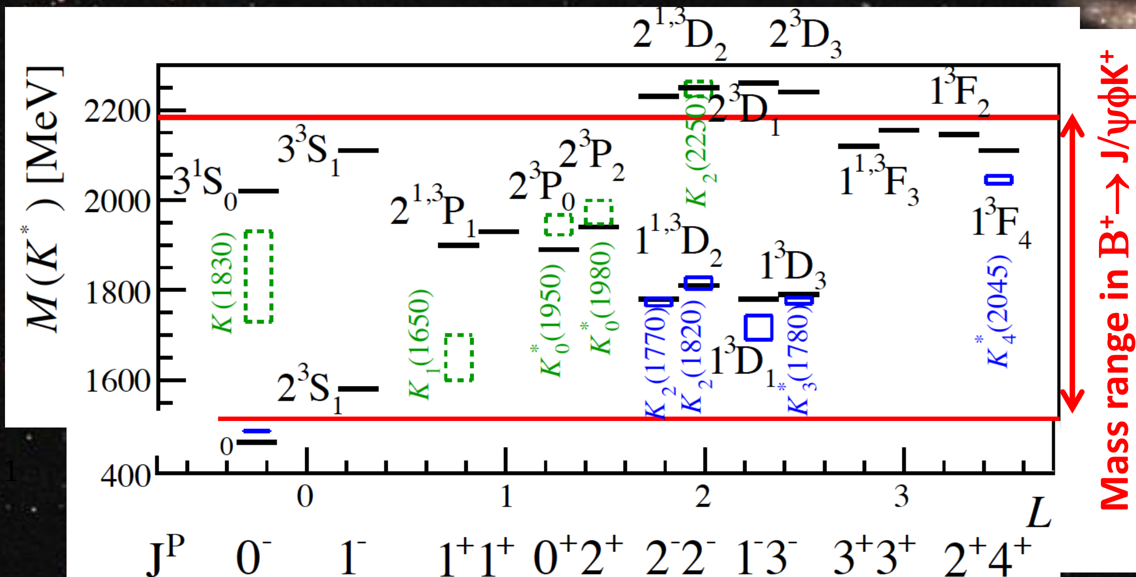


- Is it a reflection of interfering $K^{*\pm} \to \phi K^\pm$
- **Proper amplitude analysis needed!**
- **All previous analyses performed naïve 1D mass fits to $m_{J/\psi\phi}$**
  - Ad hoc assumptions for K^{*-}
  - No sensitivity to J^{PC} of X structure

arXiv:1606.07895 , submitted to PRL
arXiv: 1606.07898, submitted to PRD

Amplitude fits with K^* only

arXiv:1606.07895 , submitted to PRL
arXiv: 1606.07898, submitted to PRD



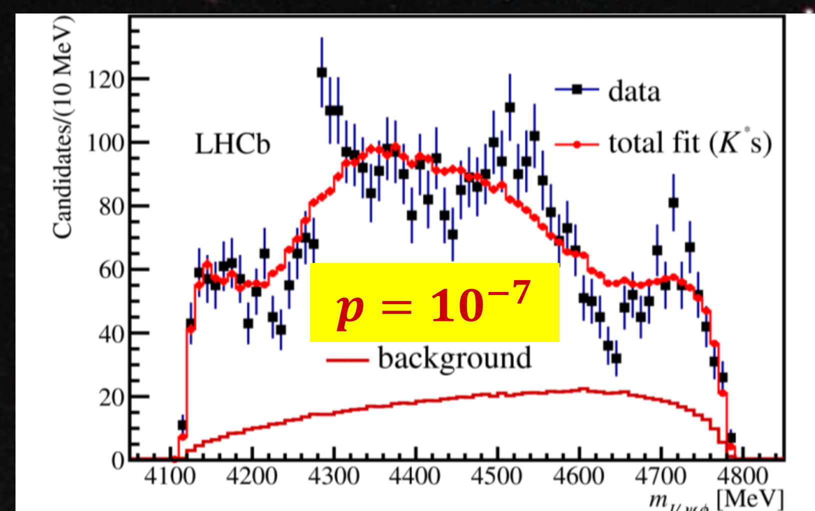
Guidance from quark model prediction

Godfrey-Isgur, PRD 32, 189 (1985)

Established

Unconfirmed

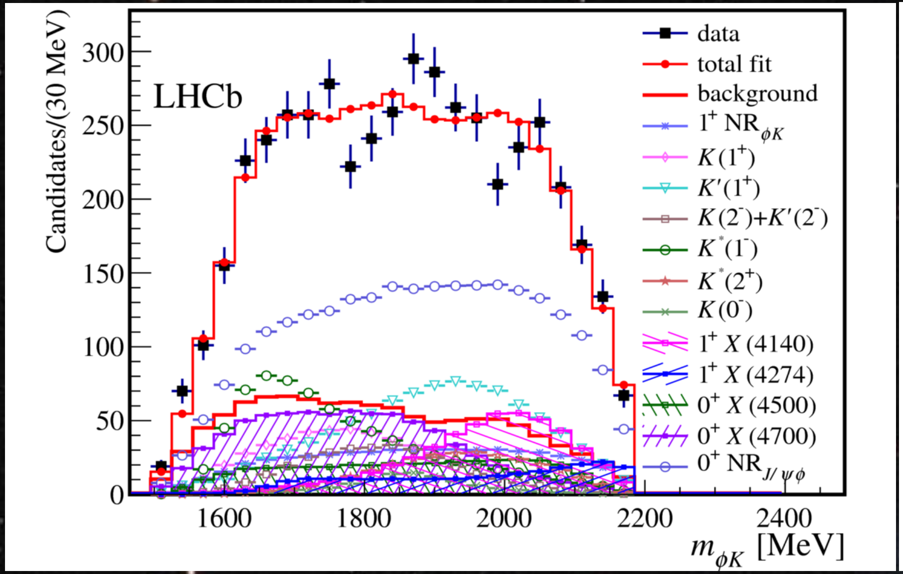
- M_0 and Γ_0 of K^*s are free parameters in the fits
- Data cannot be described by K^* only
  - Example fit: 12 K^* + NR ϕK

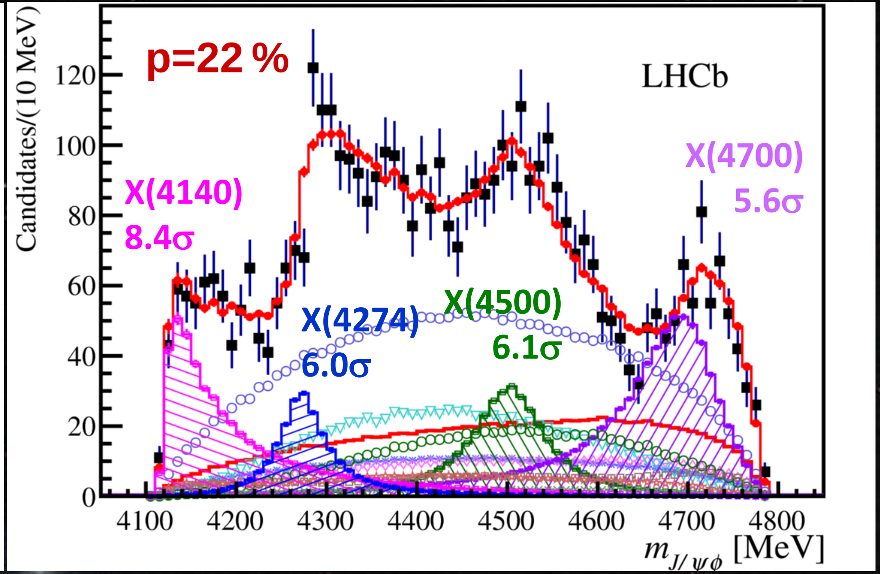


Amplitude fit including 4 exotic X

arXiv:1606.07895 , submitted to PRL
arXiv: 1606.07898, submitted to PRD

- **Four X states + NR $J/\psi\phi$ give very significant improvements over the models with K^*s alone**
- **Default model also includes NR ϕK+ 7 K^* (float M_0 and Γ_0) that are significant**
- **These results improve significantly the knowledge of K spectroscopy (results in the paper and backup slides)**





Results of amplitude fits

arXiv:1606.07895 , submitted to PRL
arXiv: 1606.07898, submitted to PRD

- **Full amplitude analysis** allows us to identify J^{PC}, useful for interpretations of the states
- $X(4140)$ and $X(4274)$: identified as $J^{PC} = 1^{++}$ at > 5σ
- $X(4500)$ and $X(4700)$: $J^{PC} = 0^{++}$ at > 4σ

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	$4146.5\pm4.5\ ^{+4.6}_{-2.8}$	$83\pm21\ ^{+21}_{-14}$	$13\pm3.2\ ^{+4.8}_{-2.0}$
Average other expt.		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	$4704\pm10\ ^{+14}_{-24}$	$120\pm31\ ^{+42}_{-33}$	$12\pm\ 5\ ^{+\ 9}_{-\ 5}$

substantially larger at LHCb

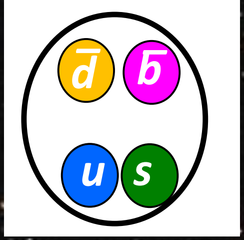
Exotic spectroscopy

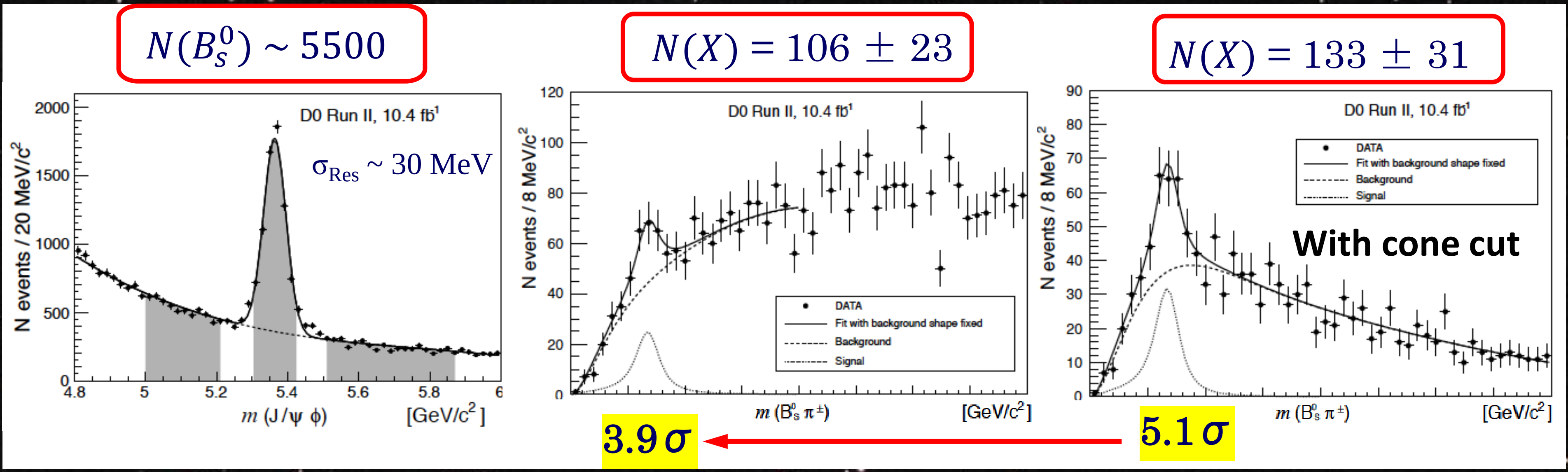
- Model-independent study in $\Lambda_b^0 \to J/\psi p K^-$ decays
- Study in Cabibbo-suppressed $\Lambda_b^0 \to J/\psi p \pi^-$ decays
- $X \to J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$
- Search for $X(5568)^+ \to B_s^0\pi^+$

$X(5568)^+$ by DØ

PRL 117, 022003 (2016)

- D0 claimed a state $X(5568)^{\pm} \to B_s^0 \pi^{\pm}$ with $B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$
  - $M = 5567.8 \pm 2.9^{+0.9}_{-1.9}$ MeV, $\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}$ MeV
  - Fraction of B_s^0 from $X^{\pm}$ decay: $\rho_X^{D\text{Ø}} = (8.6 \pm 1.9 \pm 1.4)$ %
- **If confirmed, would be unique with 4 different flavours**



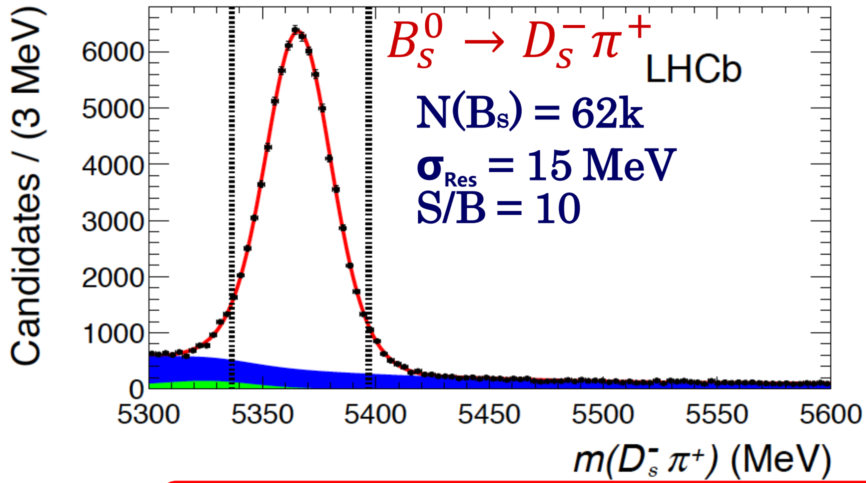


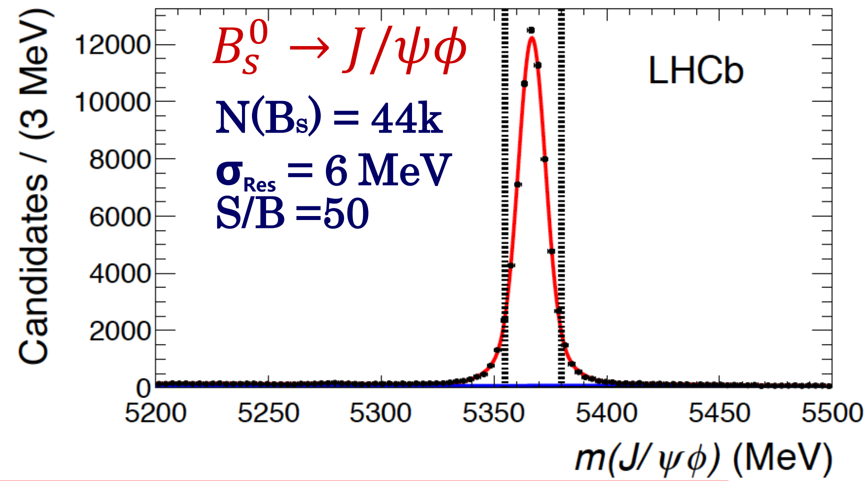
Signal significance changes a lot when applying the cone cut:

$$\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$$

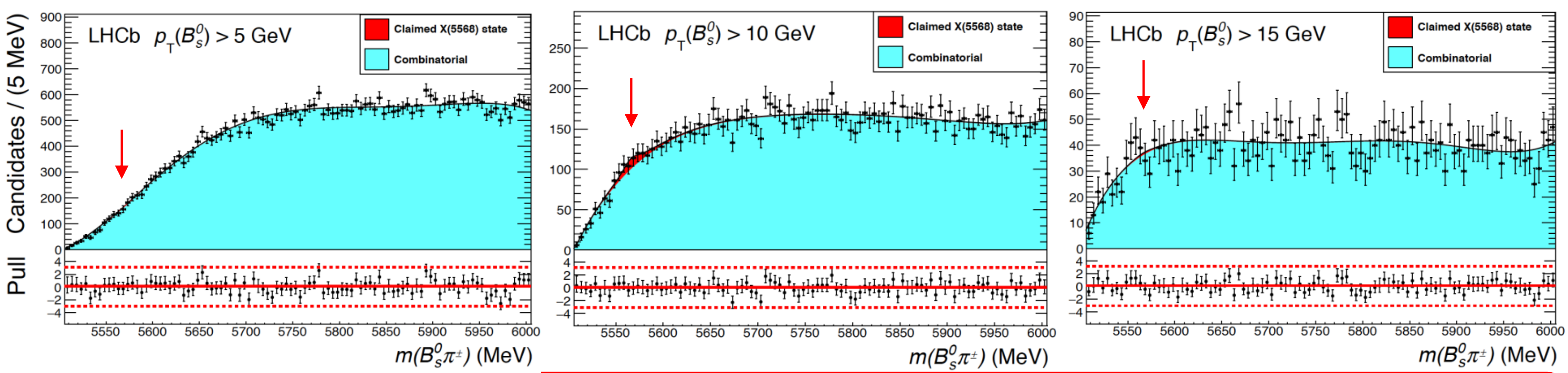
$X(5568)^+$ search at LHCb

PRL 117 (2016) 152003





B_s^0 sample 20x larger and much cleaner than DØ



No evident X(5568) in $B_s^0\pi^\pm$ sample for 3 different $p_T(B_s^0)$ cuts

Upper limits at LHCb

PRL 117 (2016) 152003

- **At 90% (95%) CL**

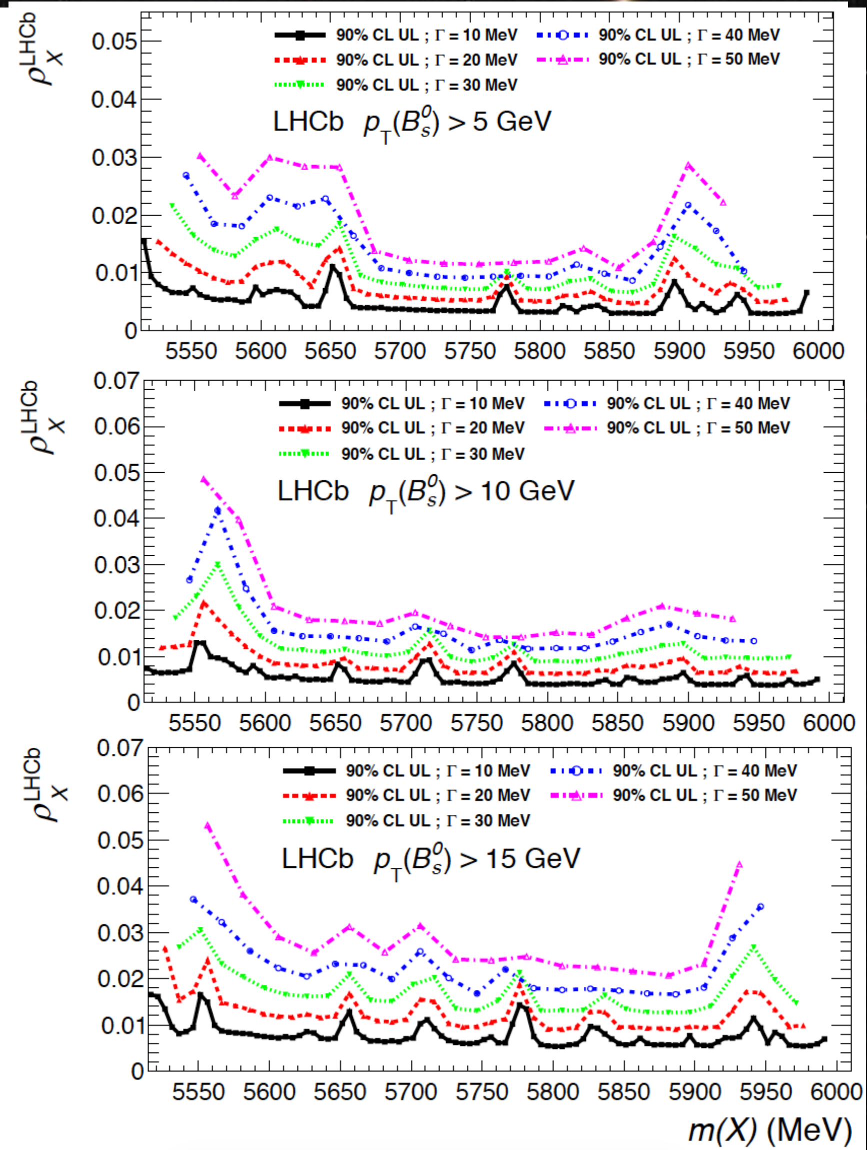
$$\rho_X^{\text{LHCb}} = \frac{\sigma(pp \to X + \text{anything};\, X \to B_s^0 \pi^\pm)}{\sigma(pp \to B_s^0 + \text{anything})}$$

in LHCb acceptance

$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 5\,\text{GeV}) < 0.011\ (0.012)$$
$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 10\,\text{GeV}) < 0.021\ (0.024)$$
$$\rho_X^{\text{LHCb}}(p_T(B_s^0) > 15\,\text{GeV}) < 0.018\ (0.020)$$

- **No significant $B_s^0\pi^\pm$ states for any mass and width below 6 GeV**
- **Upper limit is set as a function of $m(X)$ and $\Gamma(X)$**
- **Search in CMS did not observe any structure either**

[CMS-PAS-BPH-16-002]



Standard hadron spectroscopy at LHCb

- LHCb also contributed a lot to standard hadron spectroscopy, owing to large cross-sections at the LHC and excellent detector performance. Very recent results include,
- **Properties of the Ξ_b^{*0} baryon** JHEP 05 (2016) 161
  - Confirmation of Ξ_b^{*0}
  - Precise mass and first natural width measurements
- **Study of $D_{sJ}^{(*)+}$ mesons (prompt production)** JHEP 02 (2016) 133
  - First observation of $D_{s2}^{*}(2573)^{+}$
  - Properties of $D_{s1}(2536)^{+}$, $D_{s1}^{*}(2700)^{+}$
- **Amplitude analysis of $B^{-} \rightarrow D^{+}\pi^{-}\pi^{-}$ decays** PRD94(2016)072001
  - First observation of $D_3^{*}(2760)^{0}$ (10σ) and $D_2^{*}(3000)^{0}$ (6.6σ)

Summary and outlook

- Using the Run-I data LHCb has made great contributions to exotic and conventional spectroscopy
- During the Run-II, the integrated luminosity will be doubled, and the statistics will be greatly increased considering the larger production cross-section at higher energy and the improved efficiencies
- Stay tuned for more results from LHCb

Thanks!

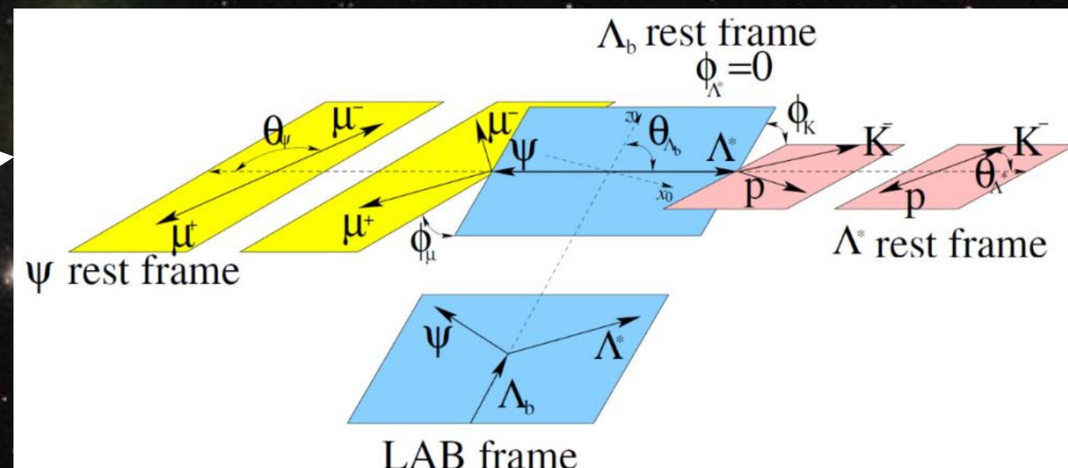
谢谢！

고맙습니다！

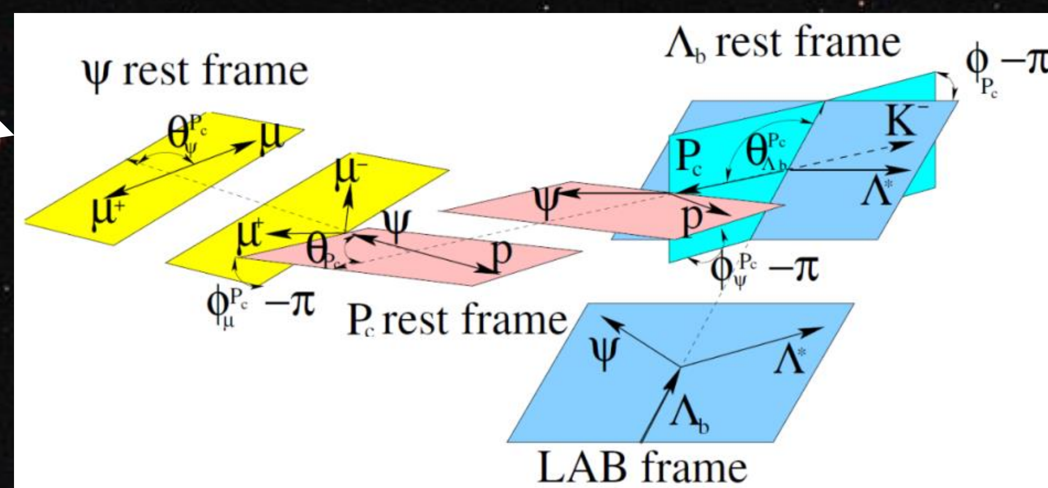
Amplitude analysis of $\Lambda_b^0 \to J/\psi p K^-$

- 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

Fit results of ϕK^+ (non)resonant states

Contribution	Sign. or Ref.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $K(1^+)$	8.0σ			$42 \pm 8^{+5}_{-9}$
$NR_{\phi K}$				$16 \pm 13^{+35}_{-6}$
$K(1^+)\, 2^1P_1$	7.6σ	$1793 \pm 59^{+153}_{-101}$	$365 \pm 157^{+138}_{-215}$	$12 \pm 10^{+17}_{-6}$
$K_1(1650)$	[31]	1650 ± 50	150 ± 50	
$K'(1^+)\, 2^3P_1$	1.9σ	$1968 \pm 65^{+70}_{-172}$	$396 \pm 170^{+174}_{-178}$	$23 \pm 20^{+31}_{-29}$
All $K(2^-)$	5.6σ			$11 \pm 3^{+2}_{-5}$
$K(2^-)\, 1^1D_2$	5.0σ	$1777 \pm 35^{+122}_{-77}$	$217 \pm 116^{+221}_{-154}$	
$K_2(1770)$	[31]	1773 ± 8	188 ± 14	
$K'(2^-)\, 1^3D_2$	3.0σ	$1853 \pm 27^{+18}_{-35}$	$167 \pm 58^{+82}_{-72}$	
$K_2(1820)$	[31]	1816 ± 13	276 ± 35	
$K^*(1^-)\, 1^3D_1$	8.5σ	$1722 \pm 20^{+33}_{-109}$	$354 \pm 75^{+140}_{-181}$	$6.7 \pm 1.9^{+3.2}_{-3.9}$
$K^*(1680)$	[31]	1717 ± 27	322 ± 110	
$K^*(2^+)\, 2^3P_2$	5.4σ	$2073 \pm 94^{+245}_{-240}$	$678 \pm 311^{+1153}_{-559}$	$2.9 \pm 0.8^{+1.7}_{-0.7}$
$K_2^*(1980)$	[31]	1973 ± 26	373 ± 69	
$K(0^-)\, 3^1S_0$	3.5σ	$1874 \pm 43^{+59}_{-115}$	$168 \pm 90^{+280}_{-104}$	$2.6 \pm 1.1^{+2.3}_{-1.8}$
$K(1830)$	[31]	~ 1830	~ 250	