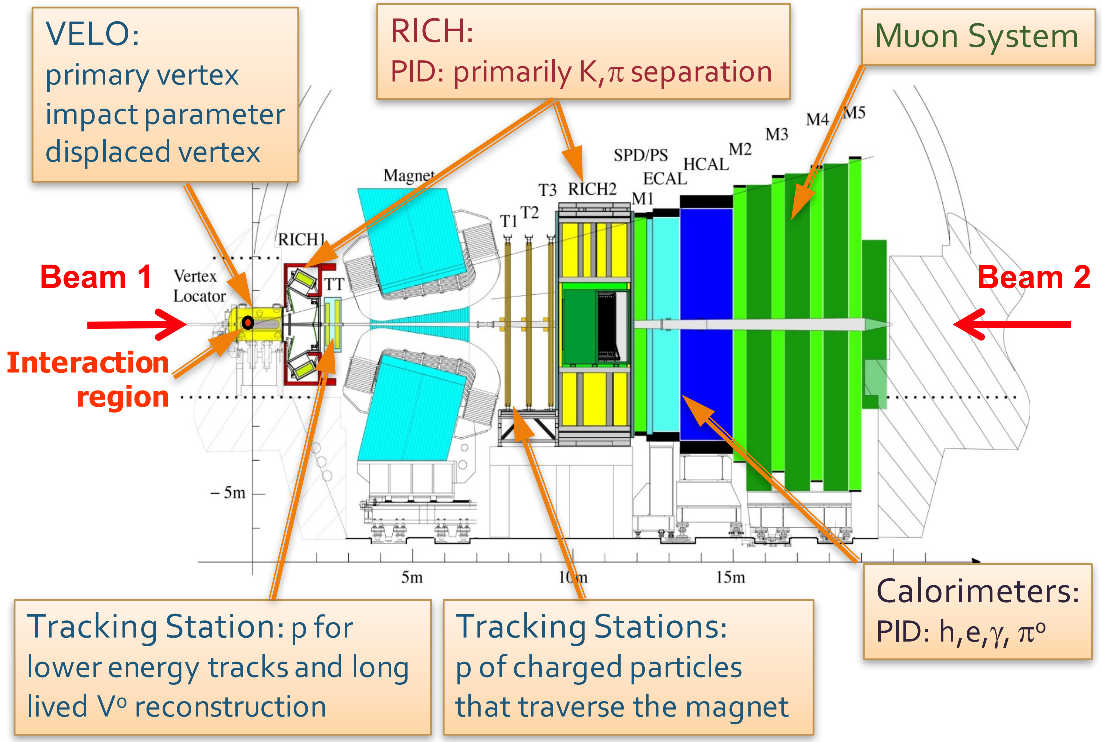
Baryon exotics at LHCb

张黎明
(清华大学)

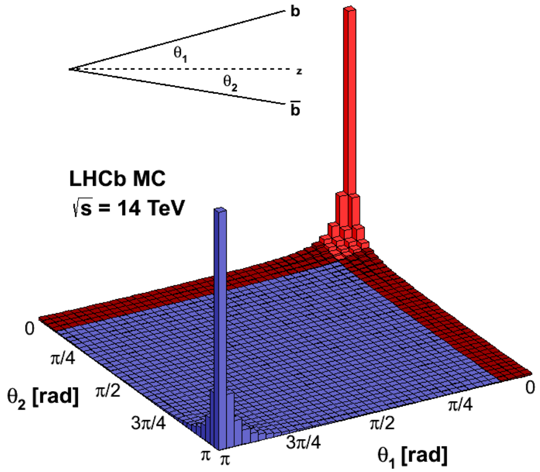
第二届LHCb前沿物理研讨会
(2020年12月12-13日)

LHCb detector and performance

The LHCb detector described in [JINST 3 (2008) S08005]



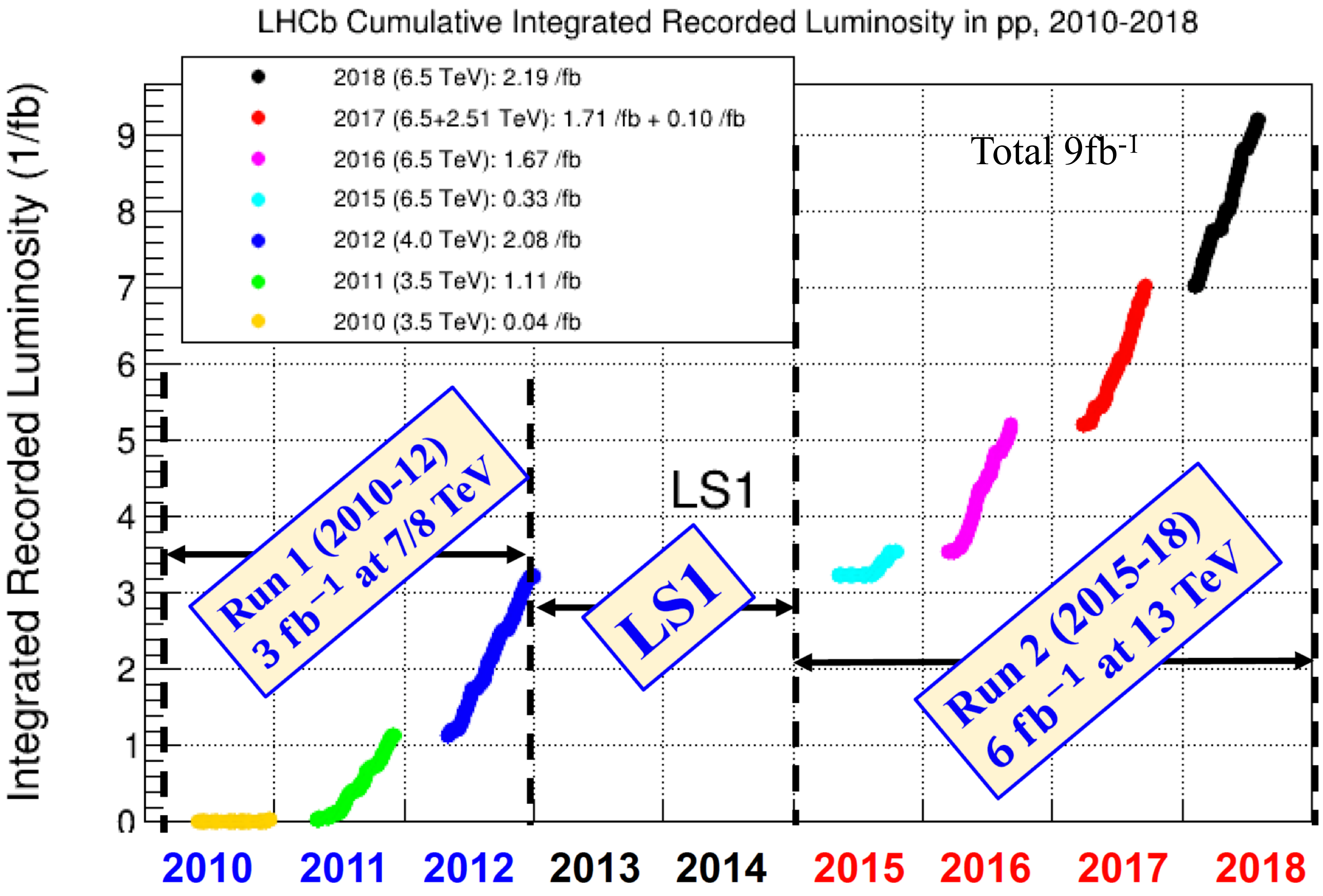
- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



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

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\boldsymbol{m_{J/\psi}}$**)**
RICH $K - \pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1 - 3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb collected luminosity



Signal: Run2 = 4× Run1

Such large samples, we are able to observe exotic states in fine structures, and see/observe exotics with strangeness

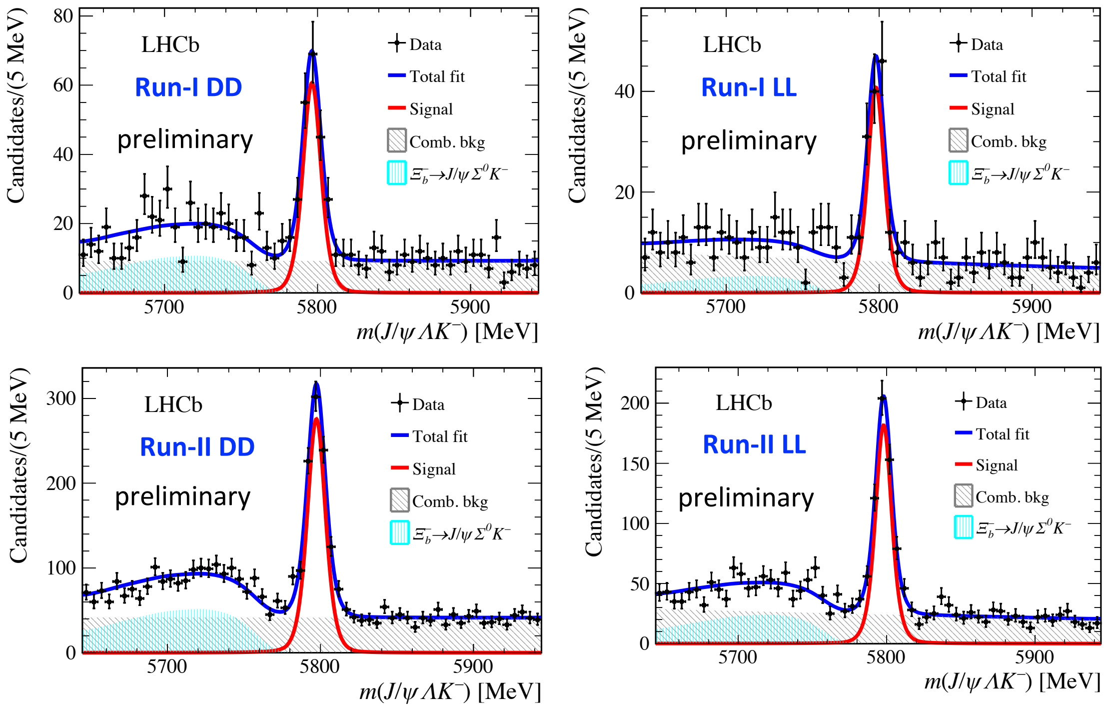
Evidence of $J/\psi\Lambda$ resonance: data sample

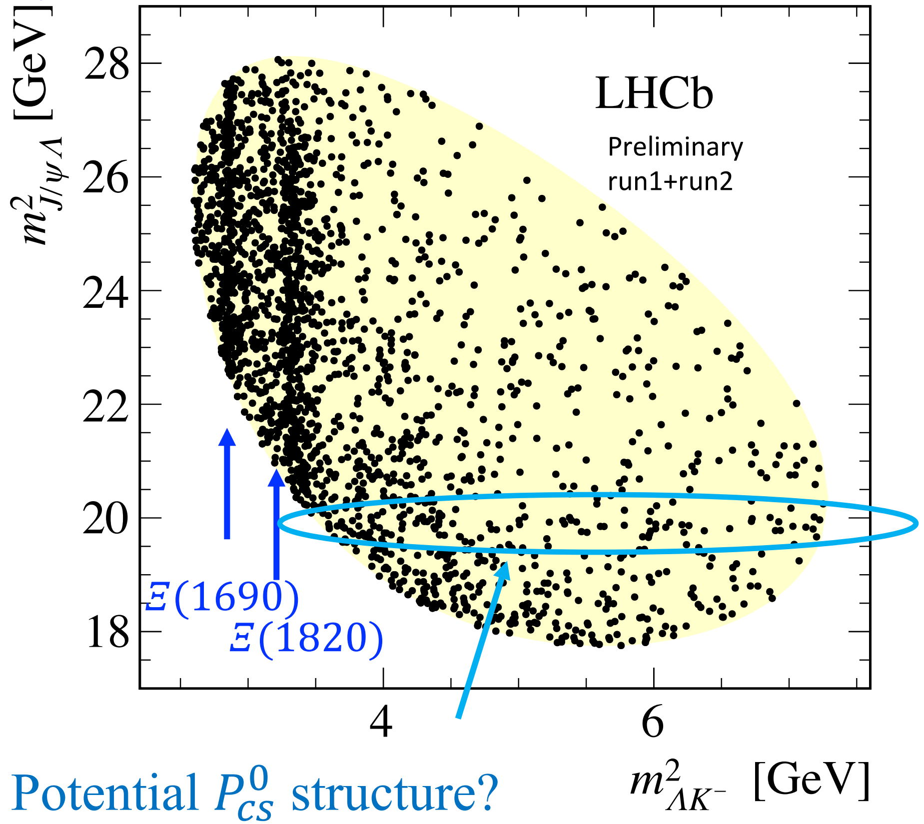
- Hidden-charm pentaquark with strangeness P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]

[LHCb-PAPER-2020-039, to be submitted soon]

$\Lambda \to p\pi^-$ reconstructed by Long-Long, or Downstream-Downstream tracks

~1750 $\Xi_b^- \to J/\psi\Lambda K^-$ signals (purity ~80%)

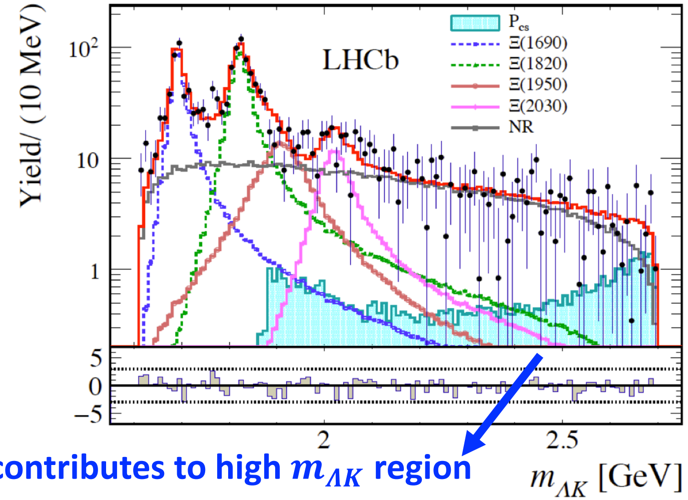


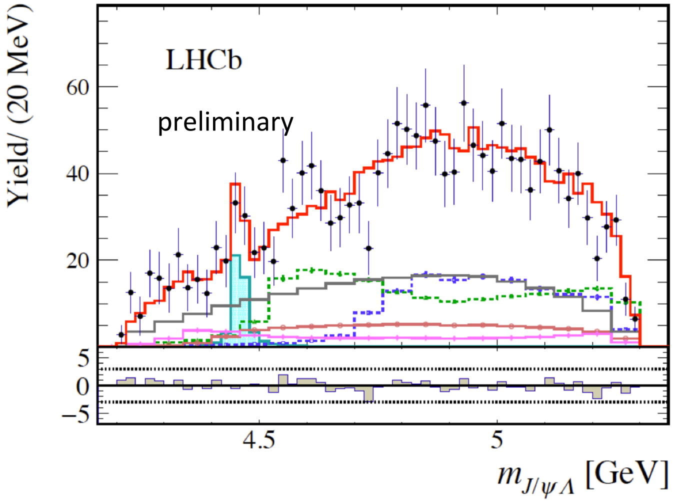


Potential P_{cs}^0 structure?
Full amplitude analysis is required

Evidence of $J/\psi\Lambda$ resonance: amplitude fit

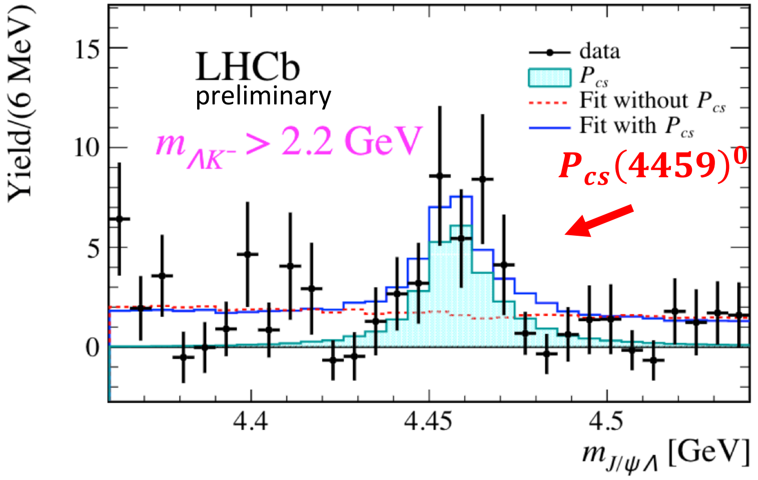
- Modelled by one P_{cs}
  - Adding a P_{cs} improves $2\ln\mathcal{L}$ by 43 units, statistical significance of $\boldsymbol{4.3\sigma}$ evaluated by toy experiments
  - Including various syst. uncertainty, the smallest significance is 3.1σ
  - Look-elsewhere effect is included in both cases
- Statistics not enough for J^P determination

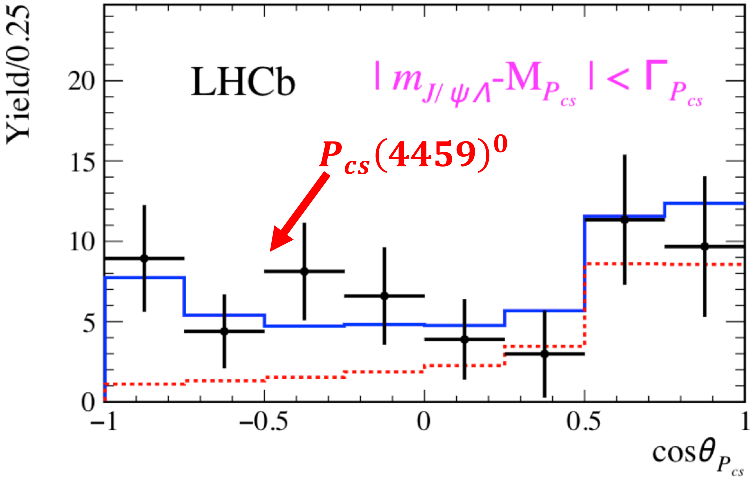




P_{cs} contributes to high $m_{\Lambda K}$ region

Zooms in to P_{cs} signal region. Visible improvement.

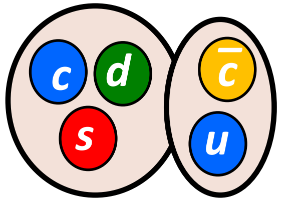




[LHCb-PAPER-2020-039, to be submitted soon]

Evidence of $J/\psi\Lambda$ resonance: discussion

- The peak position is consistent with $\Xi_c^0\bar{D}^{*0}$ molecule model prediction



Predicts **two states** with J^P 1/2(3/2)⁻

System	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

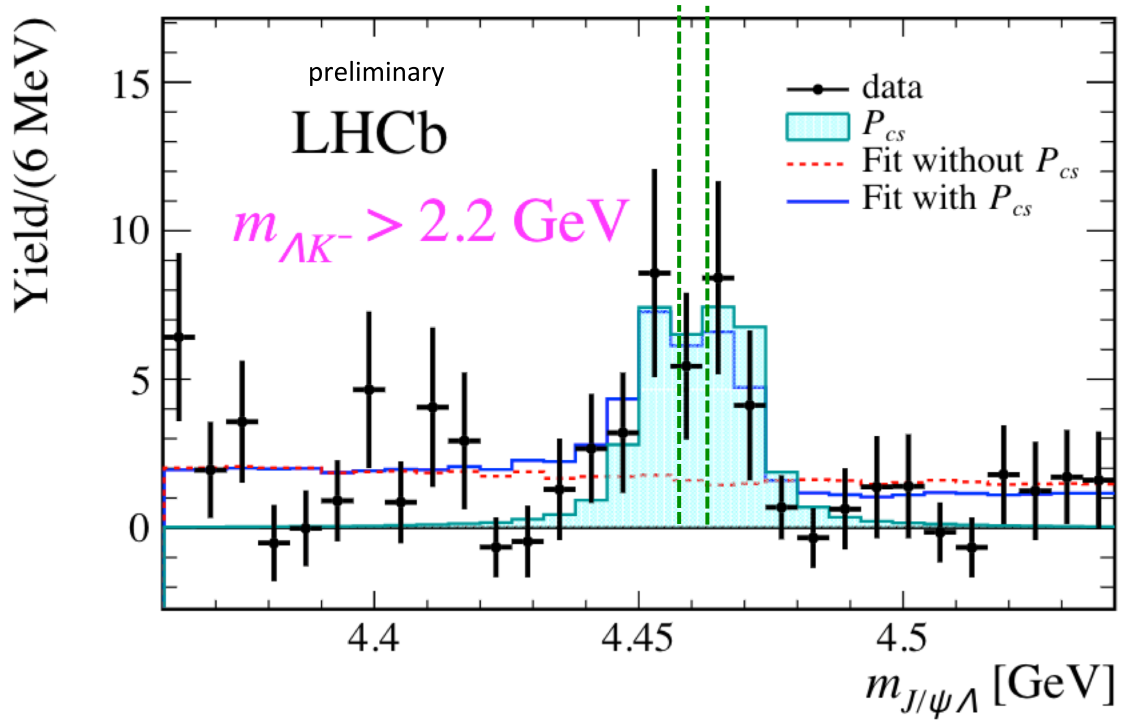
- Two-peak hypothesis is allowed
  - More data is required to distinguish one-peak vs two-peak
- $\Xi_c^0\bar{D}^{*0}$ SU(3) partner is $\Lambda_c^+\bar{D}^{*0}$, not $\Sigma_c\bar{D}^*$ for observed $P_c(4440)^+$ and $P_c(4457)^+$
  - Indict $\Lambda_c^+\bar{D}^{*0}$ molecule exist?
  - The theory paper disfavors it, but should be examined by experiments

Mass is about 19 MeV below $\Xi_c^0\bar{D}^{*0}$ threshold

State	M_0 [MeV]	Γ[MeV]	FF (%)
$P_{cs}(4459)^0$	$4458.8 \pm 2.9\,^{+4.7}_{-1.1}$	$17.3 \pm 6.5\,^{+8.0}_{-5.7}$	$2.7\,^{+1.9}_{-0.6}\,^{+0.7}_{-1.3}$

[Bo Wang, Lu Meng, Shi-Lin Zhu，PRD 101 (2020) 034018, arXiv:1912.12592]

Fit with two BW (Predicted two states)



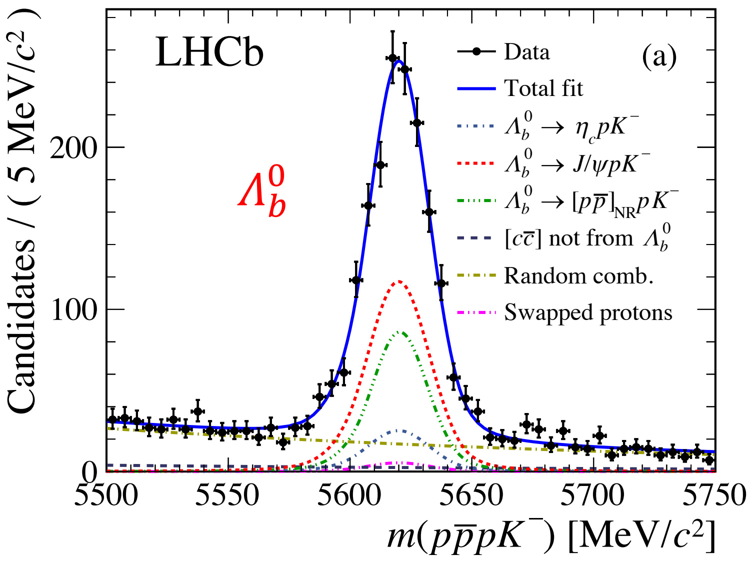
[LHCb-PAPER-2020-039, to be submitted soon]

1st observation of $\Lambda_b^0 \to \eta_c p K^-$

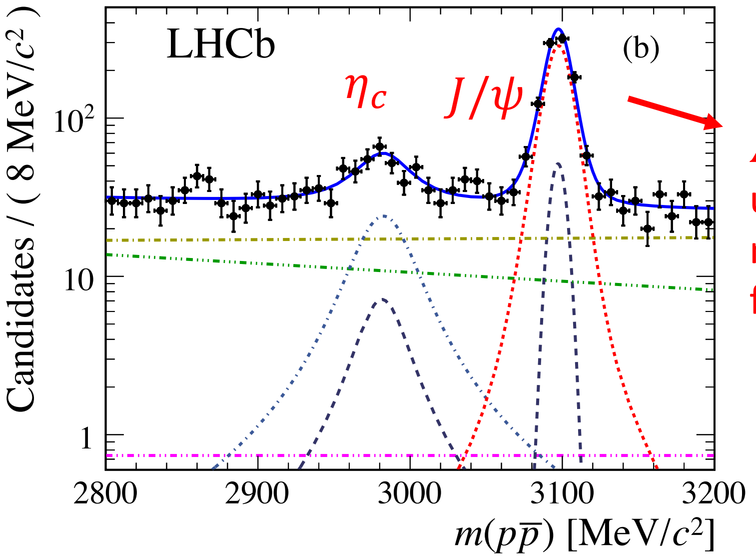
[arXiv:2007.11292]
Accepted by PRD

- Same quark contents as $\Lambda_b^0 \to J/\psi p K^-$. Provide unique environment for P_c studies
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule, predicted $\frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$

  [PRD 100 (2019) 034020, 100 (2019) 074007, 102 (2020) 036012]
- LHCb run2 data (5.5 fb^{-1})
  - η_c reconstructed using $\eta_c \to p\bar{p}$
- Fit 2D mass spectrum to confirm the existence



~170 $\Lambda_b^0 \to \eta_c p K^-$ signals



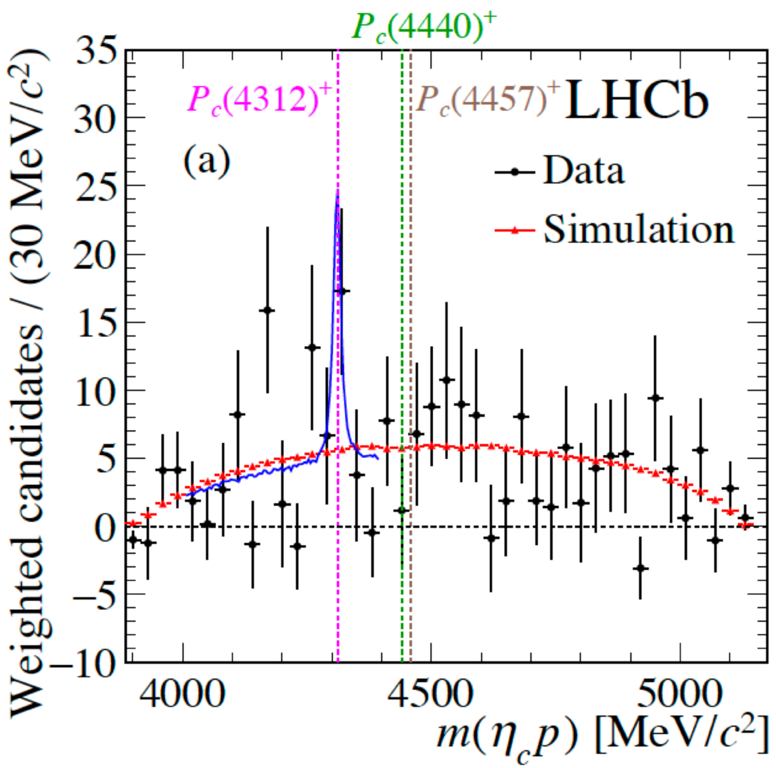
$\Lambda_b^0 \to J/\psi p K^-$ used as reference mode for branching fraction measurement

Search for P_c^+ in $\eta_c p$ system

[arXiv:2007.11292]
Accepted by PRD

- Check background-subtracted $\eta_c p$ mass spectrum
  - sPlot technique. 2D mass as discriminating variable.

No significant $P_c(4312)^+$ contribution (~2σ)



Relative P_c^+ production rates

$$R(P_c(4312)^+) < 0.24\ @\ 95\%\ \text{C. L.}$$

(Uncertainty is too large to give any conclusion yet)

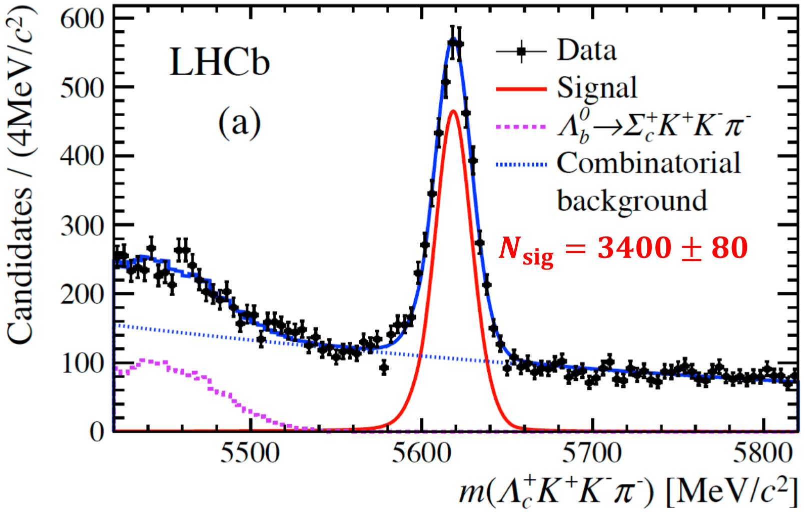
- The $\Lambda_b^0 \to \eta_c p K^-$ branching fraction measured

$$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.333 \pm 0.050\ (\text{stat.}) \pm 0.019\ (\text{syst.}) \pm 0.032\ (\mathcal{B})$$

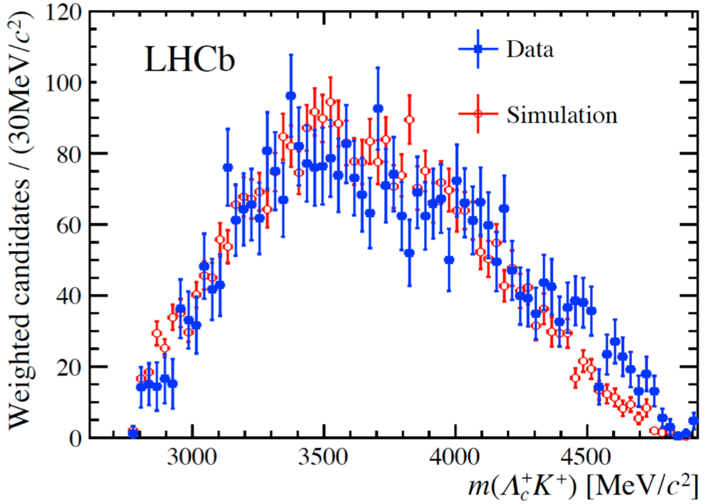
Search for pentaquark in $\Lambda_c^+ K^+$ system

- $X_{0,1}(2900) \to D^+K^-[cs\bar{u}\bar{d}]$ observed in LHCb implies possibility of open-charm pentaquark $[c\bar{s}uud]$ decay to $\Lambda_c^+ K^+$
- Run1 data (3 fb^{-1})
  - Λ_c^+ reconstructed using $\Lambda_c^+ \to pK^-\pi^+$
  - $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ used for normalization channel
- **1st observation of $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$**

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-) = (1.02 \pm 0.03 \pm 0.05 \pm 0.10) \times 10^{-3}$$



- No excess observed in $m(\Lambda_c^+ K^+)$ spectrum
- Will search with more data and can also look for pentaquark $[c\bar{s}udd]$ in $\Lambda_c^+ K^+ \pi^-$ system



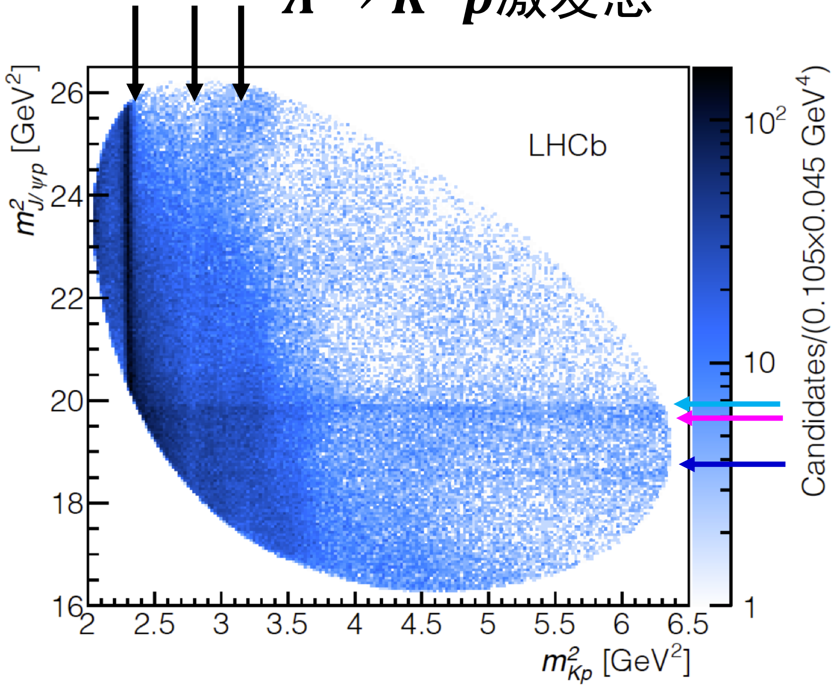
[arXiv:2011.13738，submitted to PLB]

Discussion on P_c

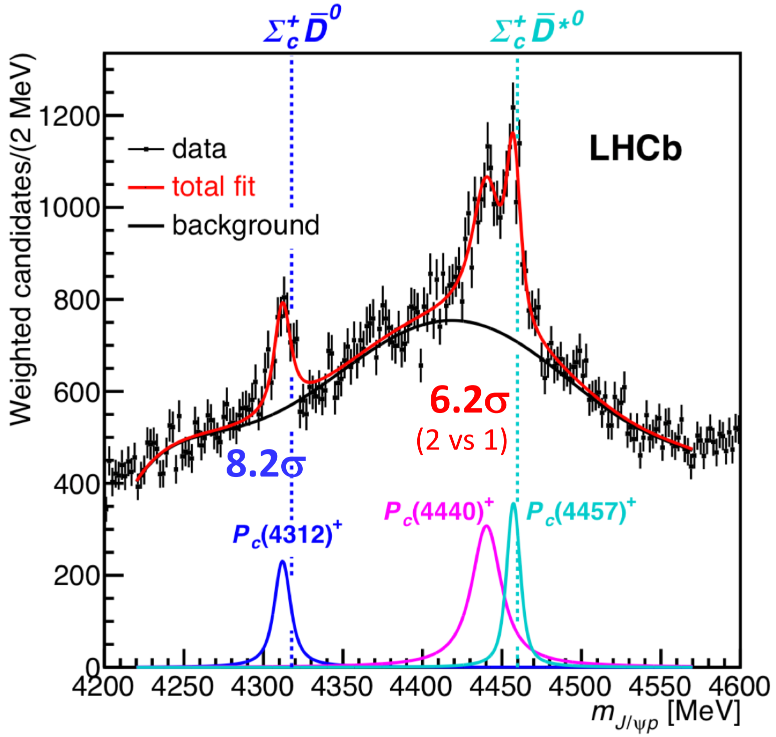
$\Lambda_b^0 \to J/\psi p K^-$ 1维拟合结果

- 信号数×10
  - 优化的选择 ➜ 效率×2
  - 增加Run2数据 ➜ 产额×5
  - 信号数25万

$\Lambda \to K^- p$激发态



- 1维$J/\psi p$质量拟合
  - 发现新的五夸克态$P_c(4312)^+$
  - 4450 MeV 结构是$P_c(4440)^+$和$P_c(4457)^+$的叠加



需要振幅分析来研究J^P和宽的P_c^+

$\Lambda_b^0 \to J/\psi p K^-$ 1维拟合结果

- 测量给出质量$\boldsymbol{M}$、宽度$\boldsymbol{\Gamma}$和比份$\mathcal{R}$
- 对每个事例做效率修正，拟合给出

$$\mathcal{R} \equiv \frac{\mathcal{B}(\Lambda_b^0 \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\psi\, p)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)}$$

State	M [MeV]	Γ [MeV]	(95% CL)	$\mathcal{R}$ [%]
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$	(< 27)	$0.30 \pm 0.07^{+0.34}_{-0.09}$
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$	(< 49)	$1.11 \pm 0.33^{+0.22}_{-0.10}$
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$	(< 20)	$0.53 \pm 0.16^{+0.15}_{-0.13}$

五夸克态的结构和比份已和2015年结果发生很大变化（当时 $\boldsymbol{P_c(4380)^+}$ 8%，$\boldsymbol{P_c(4450)^+}$ 4%）。是不是要有能力确定0.5%贡献的$\boldsymbol{J^P}$，有待评估。
跃红建议用toy MC方法检验，是下一步的亟需完成

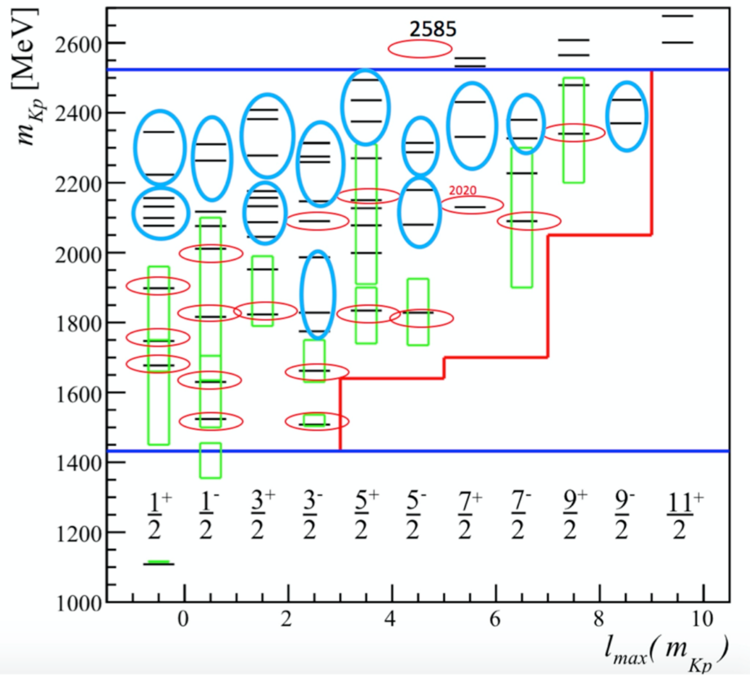
Λ^*共振态描述复杂

- $\Lambda_b^0 \to J/\psi\Lambda^*(\to pK^-)$是五夸克态最主要的干扰过程
- 基准模型中考虑18个Λ^*共振态的贡献（BW sum）
  - 相较于2015年分析，额外考虑4个Λ^*态
  - 利用已有的实验观测结果，限制Λ^*共振参数的浮动范围

【PRC 88, 035205 (2013)】

Res.	m_0	$\sigma(m_0)$	Fit	Γ_0	$\sigma(\Gamma_0)$	Fit	J^P	Wave
Λ(1405)	1405.1		fix	40-250		268.6	1/2⁻	S01
Λ(1670)	1672	3	1666.3	29	5	11.7	1/2⁻	S01
Λ(1800)	1783	19	1617.4	256	35	284.2	1/2⁻	S01
Λ(2000)	2020	16	2108.4	255	63	152	1/2⁻	S01
Λ(1600)	1592	10	1566.4	150	28	299.2	1/2⁺	P01
Λ(1710)	1713	13	1750	180	42	134.3	1/2⁺	P01
Λ(1810)	1821	10	1835	174	50	122.1	1/2⁺	P01
Λ(1890)	1900	5	1874.3	161	15	113.6	3/2⁺	P03
Λ(1520)	1519.6	0.5	1518.4	17	1	13.4	3/2⁻	D03
Λ(1690)	1691	3	1697.1	54	5	35.3	3/2⁻	D03
Λ(2050)	2056	22	1938.3	493	61	819.7	3/2⁻	D03
Λ(1830)	1820	4	1811.5	114	10	168	5/2⁻	D05
Λ(2580)	2580		fix	250		300	5/2⁻	D05
Λ(1820)	1823.5	0.8	1822.5	89	2	84	5/2⁺	F05
Λ(2110)	2036	13	2109.8	400	38	285.8	5/2⁺	F05
Λ(2020)	2043	22	1848	200	75	410.1	7/2⁺	F07
Λ(2100)	2086	6	2102.1	305	16	258.9	7/2⁻	G07
Λ(2350)	2350	15	2283.4	150	15	130.9	9/2⁺	H09

带来的系统误差可能也是J^P确定的主要障碍之一

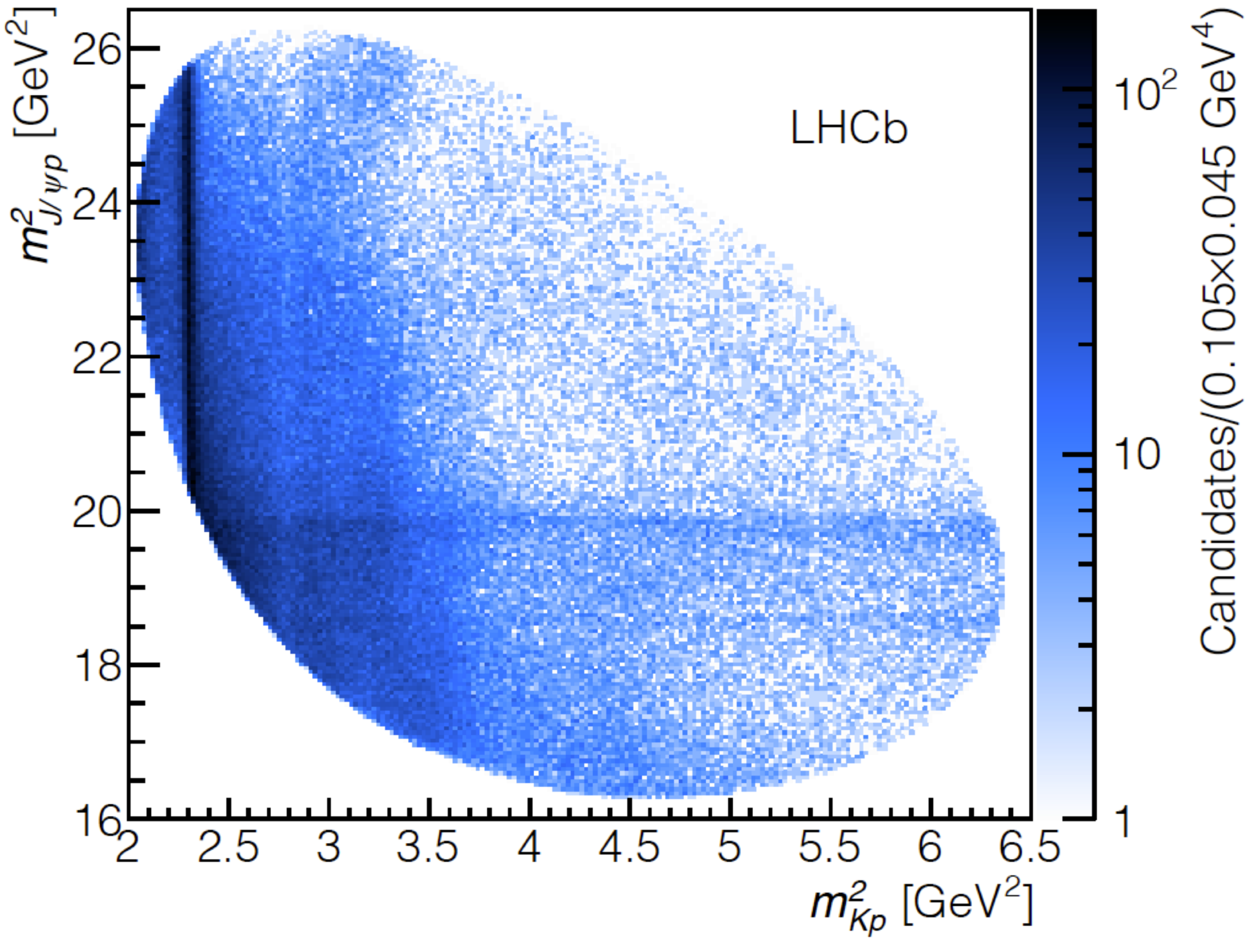


【EPJA 10(2001) 447-486】

理论预言存在，但未被实验发现的Λ^*共振态。引入其贡献，测试对拟合得到的五夸克态性质的影响。

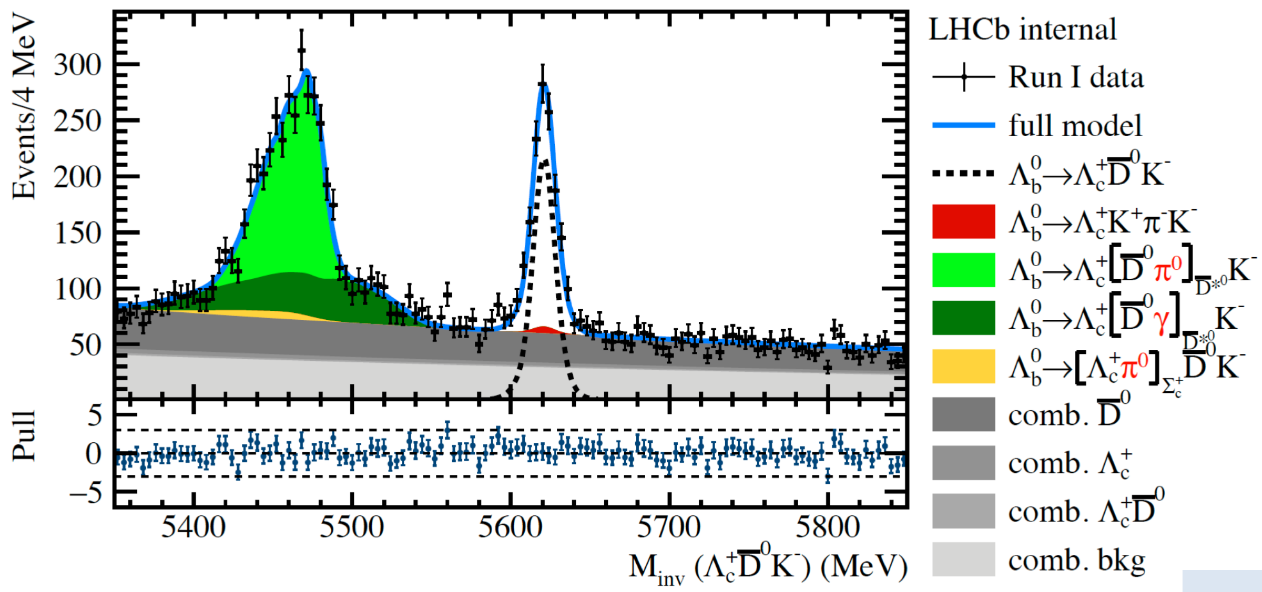
Focus on J^P of $P_c(4312)$?

- Any suggestion how to do it?



Pentaquark in hadronic decays

- Two LHCb PHD theses in public (**LHCb unofficial results**)
  - https://doi.org/10.11588/heidok.00025126
  - https://doi.org/10.11588/heidok.00027350



- Branching fractions

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (14.04 \pm 0.58 \pm 0.33 \pm 0.45)\ \%$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{0*}(2007)^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = \left(43.5 \pm 1.4\,^{+1.2}_{-0.8} \pm 1.4\right)\ \%\ .$$

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

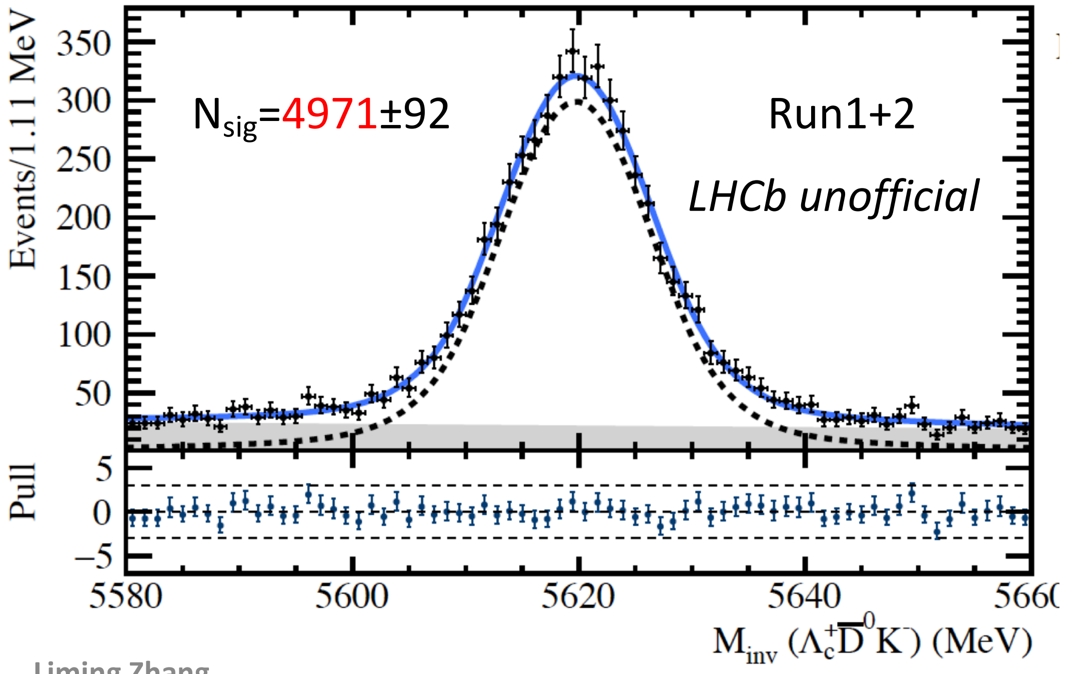
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 4.8 \pm 1.0 (\text{stat.} + \text{syst.})$$

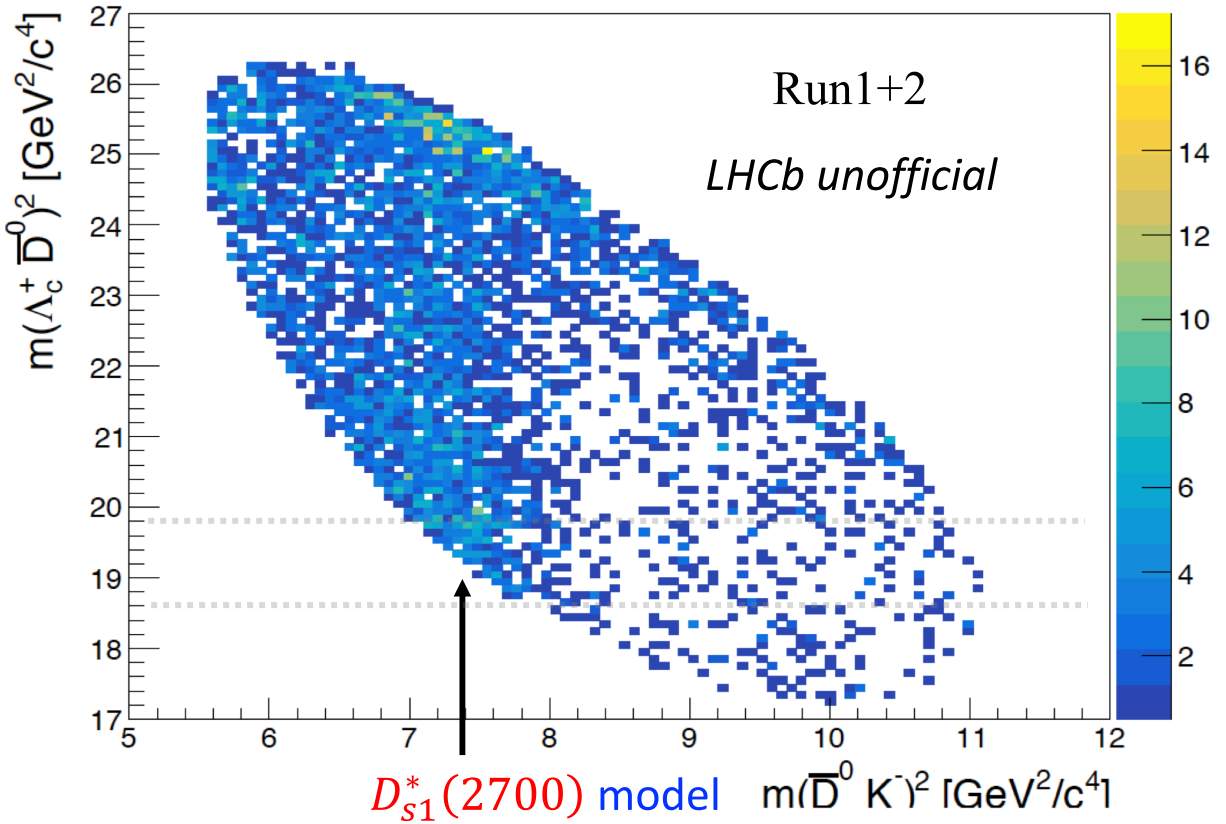
$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} = 15.0 \pm 3.2 (\text{stat.} + \text{syst.})$$

大的比值对P_c研究并不好，意味着$\frac{\Gamma(P_c \to \Lambda^+ \bar{D}^{(*)0})}{\Gamma(P_c \to J/\psi p)}$=这些值时，$P_c$在open charm三体末态的占比才$= J/\psi$道

Amplitude result

- Only 5k signal vs 250k $\Lambda_b^0 \to J/\psi p K^-$) [Signal/Jpsi mode = 2%]
  - $\mathcal{B}(\Lambda_c^+ \to pK\pi)\times\mathcal{B}(D^0 \to K\pi)$ vs $\mathcal{B}(J/\psi \to \mu^+\mu^-)$ [4%], addition ε of 2 more tracks (0.5^2) and hadron trigger (0.5) [10%]
  - $\mathcal{B}(\Lambda_b^0)$ [5]
- More data is required to give clear picture



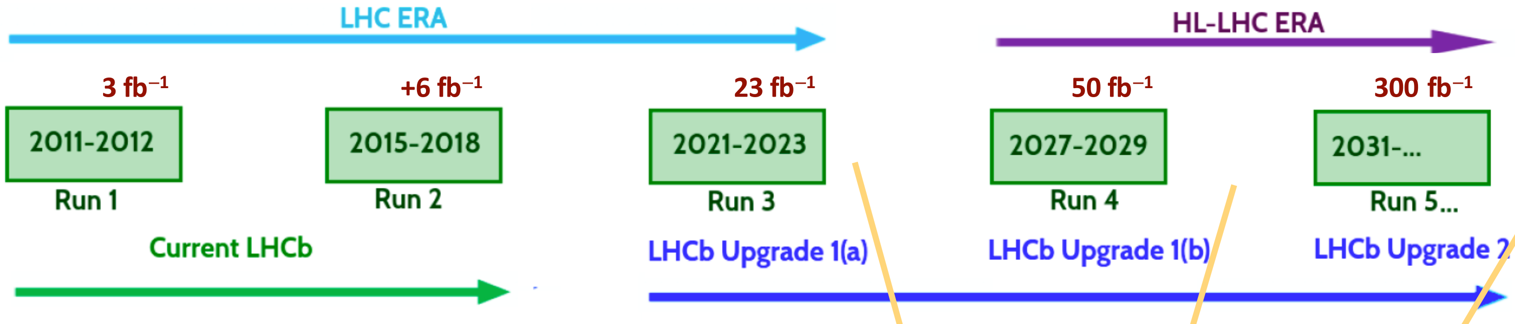


$D_{s1}^*(2700)$ model

$D_{s1}^*(2860)$ by K-matrix

Prospects

[arXiv:1808.08865]



- **LHCb is now boosting the data to a new level**
  - Expect to 7x more data (14x hadronic events) by 2029 than current, half of these by 2023
  - Could have another 6x increase from Upgrade II

Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi p K^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600
$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^+$	23k	58k	390k

$\chi_{c1}(3872)$ **lineshape from multi-channels**

$Z_c(4430)$**, also explore** $B \to D_{(s)}^{(*)}\overline{D}_{(s)}K^-$?

Doubly-charmed tetraquark $\mathcal{T}_{cc}^+ \to D_s^+ D^0$

More information for pentaquarks

[*] updated according to the latest result

Summary

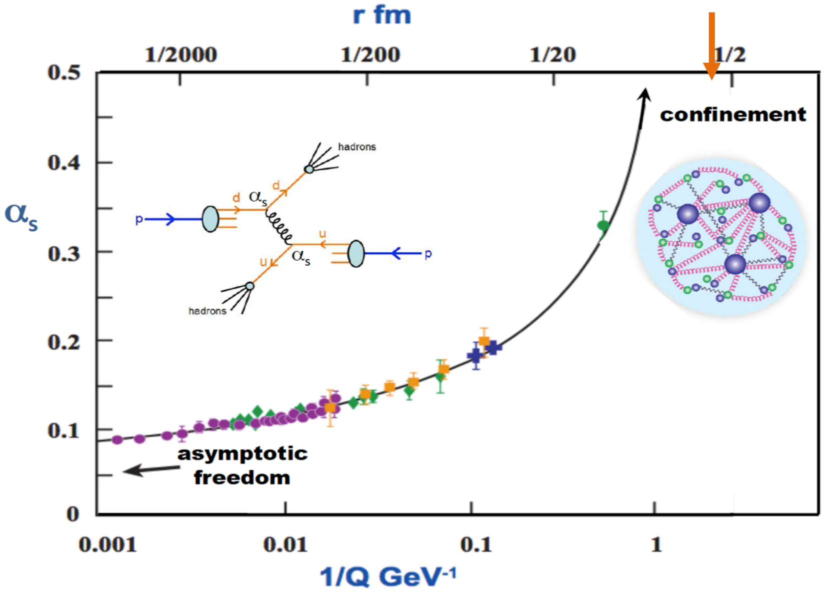
- Pentaquark studies are shown
  - Evidence of first candidate for hidden-charm pentaquark with strangeness $P_{cs}(4459)^0$
  - $\eta_c p$ final state is studied, more data is needed.
  - Open charm pentaquark search just started
  - Progress on $\Lambda_b^0 \to J/\psi p K^-$ shows things may be even more complicated
  - Pentaquark to open charm final states needs more data

Backup

Introduction

- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge
- Complex exotic hadrons can reveal new or hidden aspects of the dynamics of strong interactions
  - Predicted in quark model
  - Recent results show strong evidence for their existence

Hardon size



【1】H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Phys. Rept. 639 (2016) 1-121.
【2】A. Ali, J. Lange, S. Stone, Prog. Part. Nucl. Phys. 97 (2017) 123-198.
【3】F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, Rev. Mod. Phys. 90 (2018) 015004.
【4】S. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 15003.
【5】Y.-R. Liu, H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Prog. Part. Nucl. Phys. 107 (2019) 237-320.
【6】F.-K. Guo, X.-H. Liu and S. Sakai, Prog. Part. Nucl. Phys. 112 (2020) 103757

tetraquark ?   pentaquark ?   hybrid ?

… EXOTIC

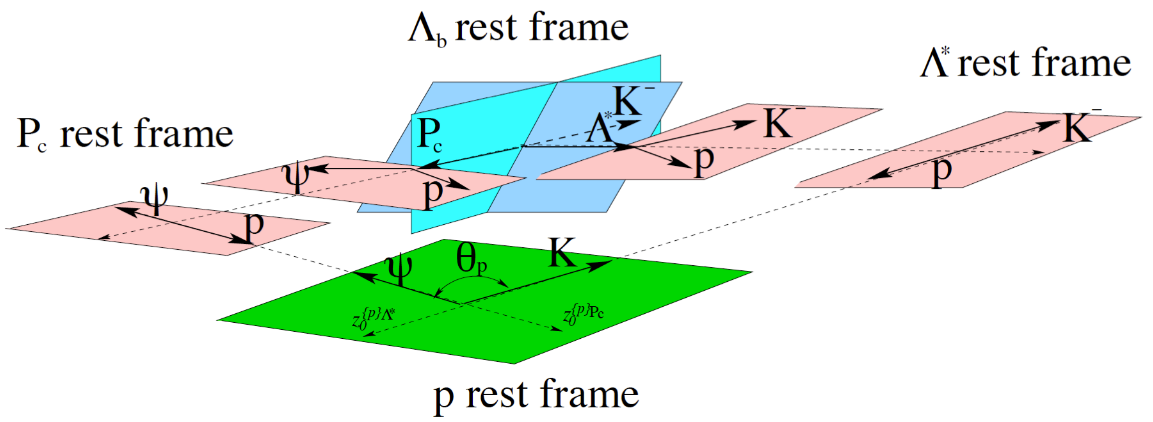
Improvements in amplitude analysis

- GPU fitter
  - 10×faster compensate yield increase
- Mass resolution of $J/\psi p$ included
- A bug in 2015 fit is fixed that affected interference between P_c and Λ^* and parity determination
  - Related to alignment of proton frames for the two decays
  - Traps in $J = 1/2$ particle alignment (helicity $\lambda = \pm 1/2$), a term for P_c

$$e^{i\lambda\alpha} = \begin{cases} 1 \text{ for } \alpha = 0 \text{ (we took)} \\ -1 \text{ for } \alpha = 2\pi \text{ (but half is)} \end{cases}$$

  - Fix is supported by data distribution, data shows two halves are consistent

We proposed a method to validate this.
Also useful for other amplitude fits using helicity formalism with baryon final states [arXiv:2012.03699, submitted to CPC]



α between alignment planes, half events are 0 and half are 2π

Interference term