Heavy flavour spectroscopy and exotic states at LHCb

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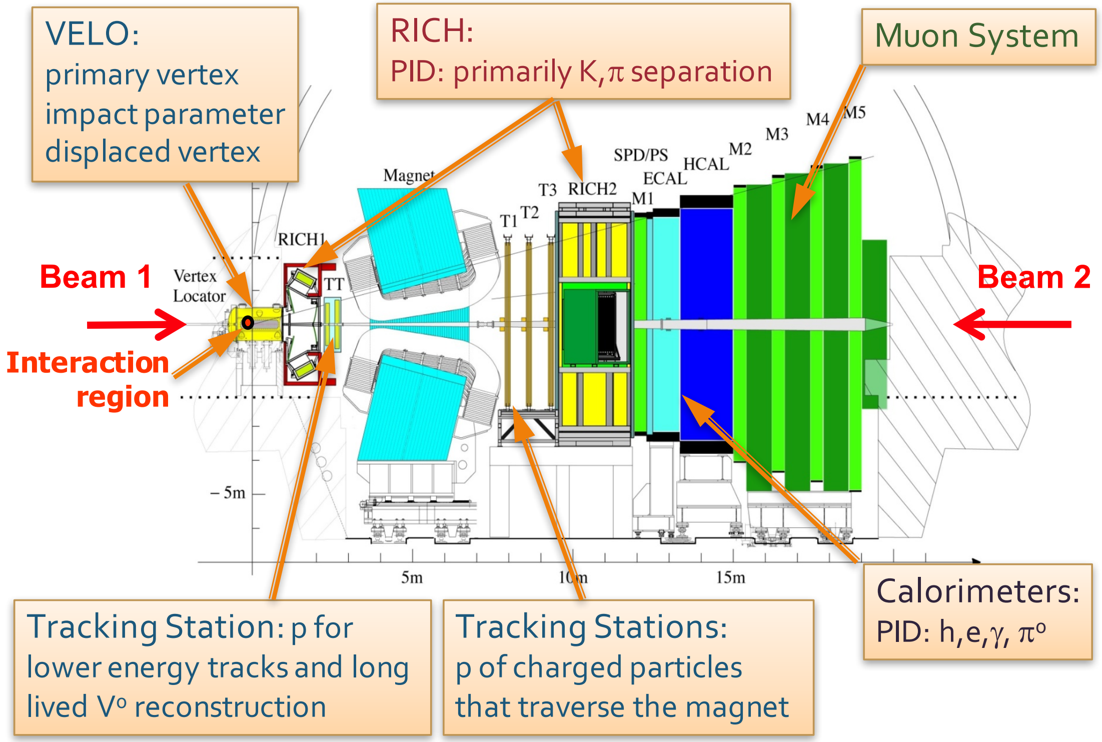
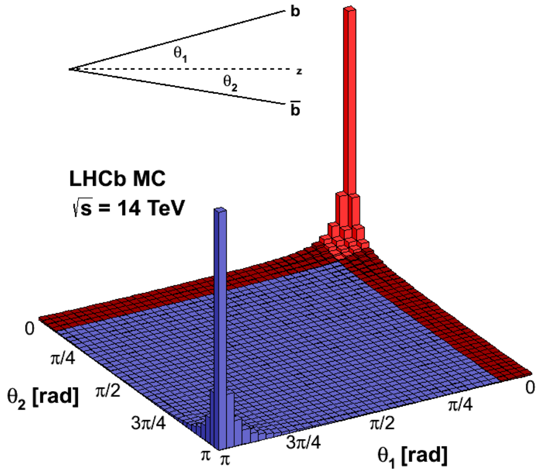
(2018年11月5-9日, 长沙)

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



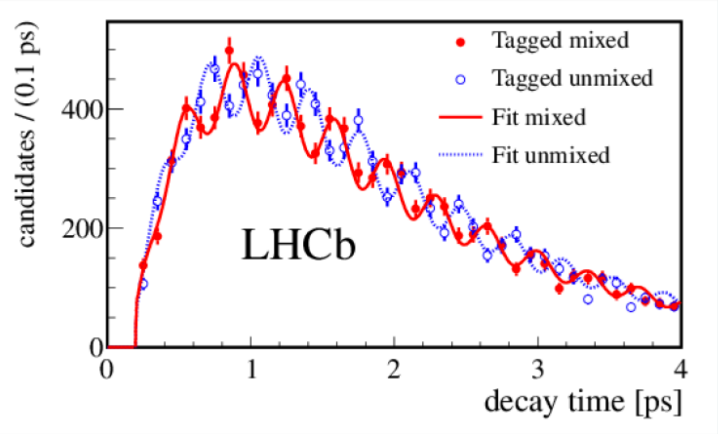
Int. J. Mod. Phys. A 30 (2015) 1530022

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 GeV/c)
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\mathbf{m}_{J/\psi}$**)**
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 detector and performance

Vertexing

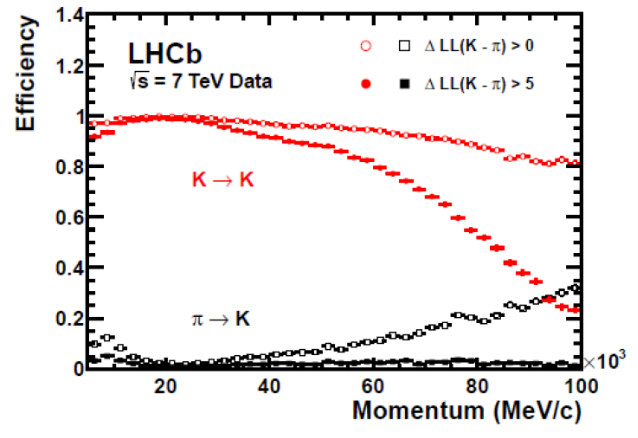
B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

PID

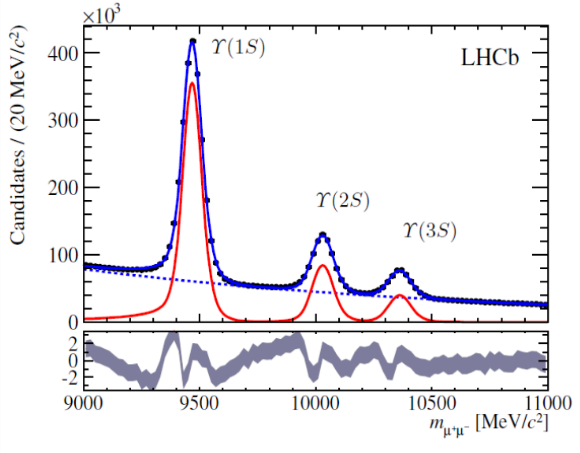
K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

Tracking

$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

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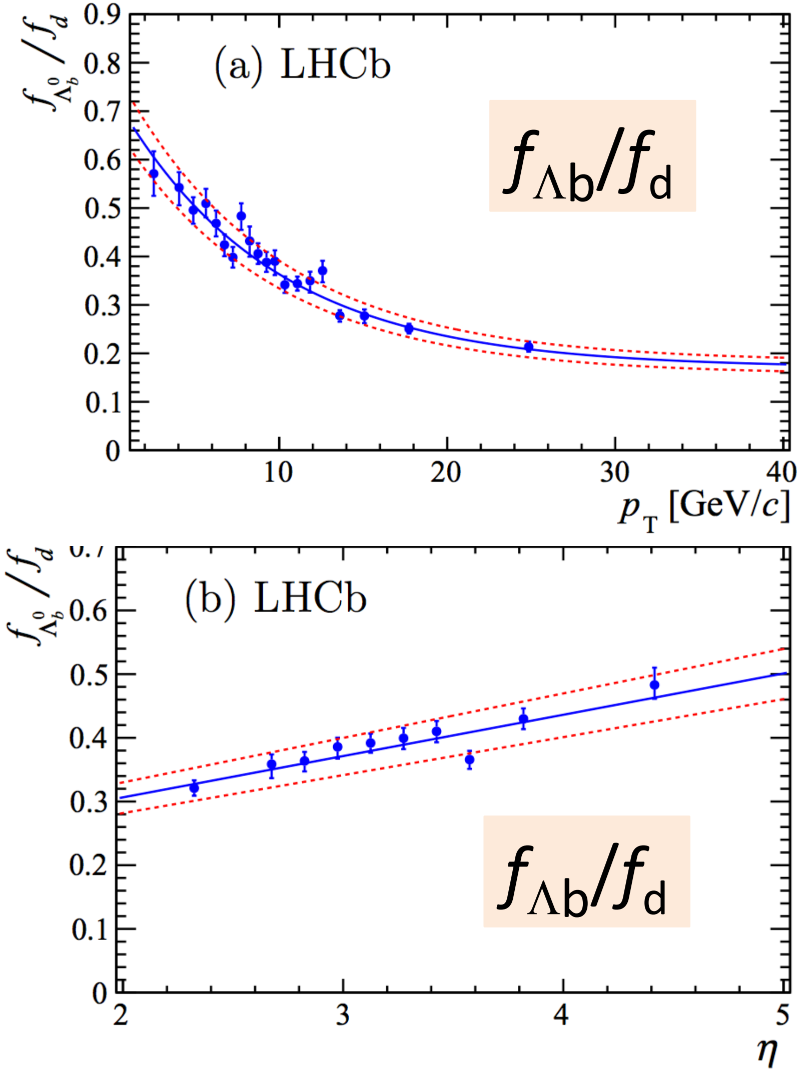
LHCb advantage and disadvantage



[LHCb, JHEP 08(2014) 143]

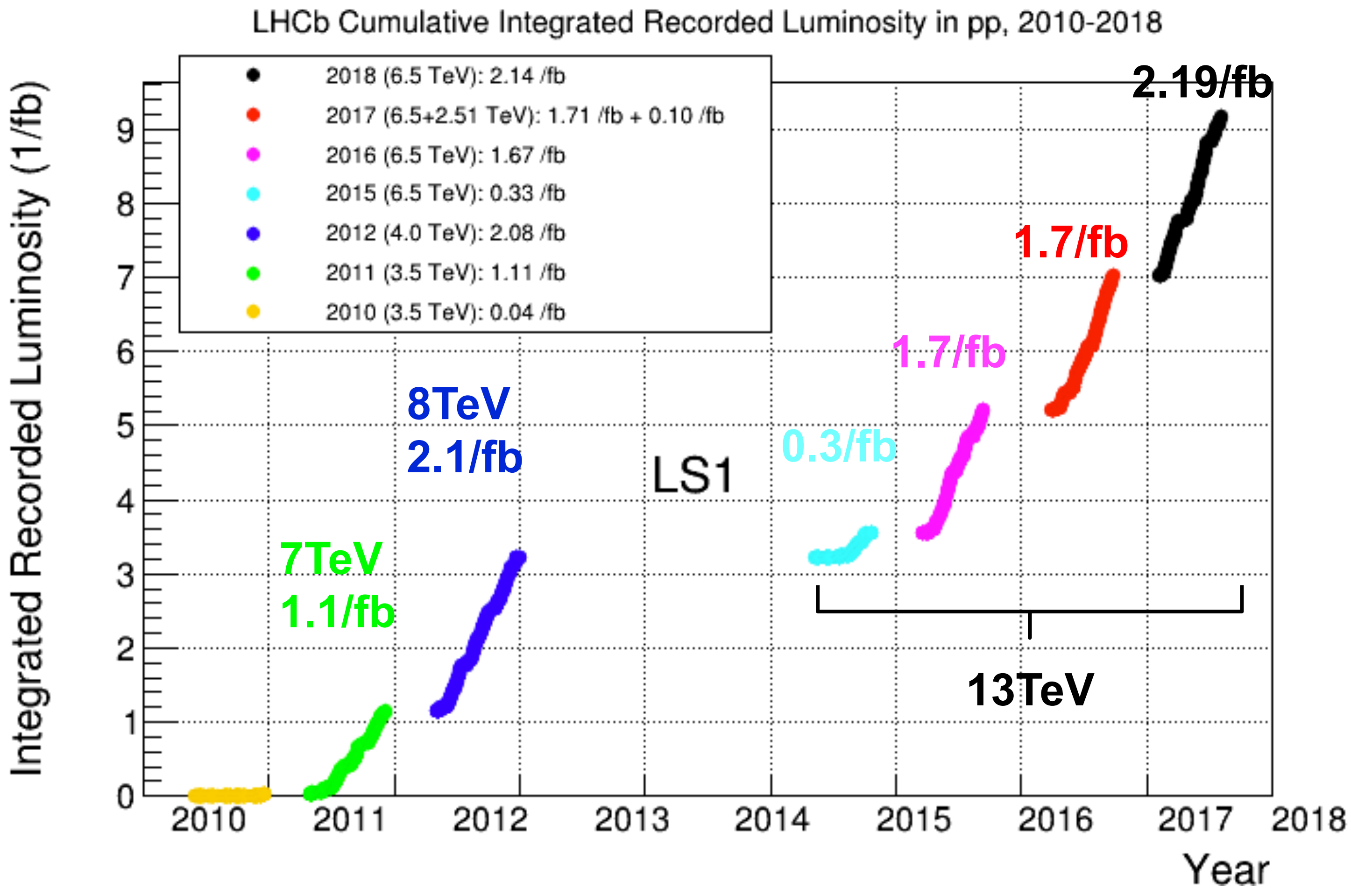
- **Advantage at LHCb:**
  - Huge *b*-production cross-section

    $\sigma(pp \to b\bar{b}X) \approx 72$ μb @7 TeV $\approx$ 144 μb @13 TeV in LHCb acceptance PHYS. REV. LETT. 118, 052002 (2017)
  - Can also access Λ_b^0, B_s^0, B_c^+

    $B^0:\Lambda_b:B_s = 4:2:1$

- **Disadvantage at LHCb:**
  - Efficiency of one track ~50% (not good for large number of finial states)
  - Inefficiency for K_S^0, Λ^0, γ

LHCb collected luminosity

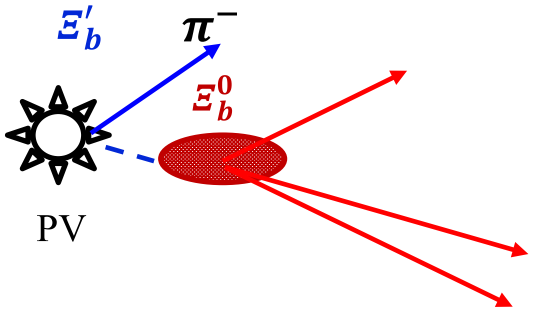


$\sigma(pp \to b\bar{b}X) \approx$ **72 μb @7 TeV vs ≈ 144 μb @13 TeV in LHCb acceptance**

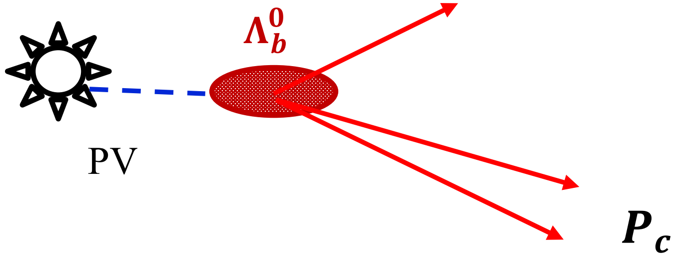
Expect Yield(Run1+2) ≈ 4.5 Yield(Run1)

Two methods for spectroscopy

- Direct production in pp collisions
  - Ξ_{cc}^{++}, $\Omega_c^* \to \Xi_c K$
  - All excited B, $\Xi_b^* \to \Xi_b\pi; \Lambda_b K$



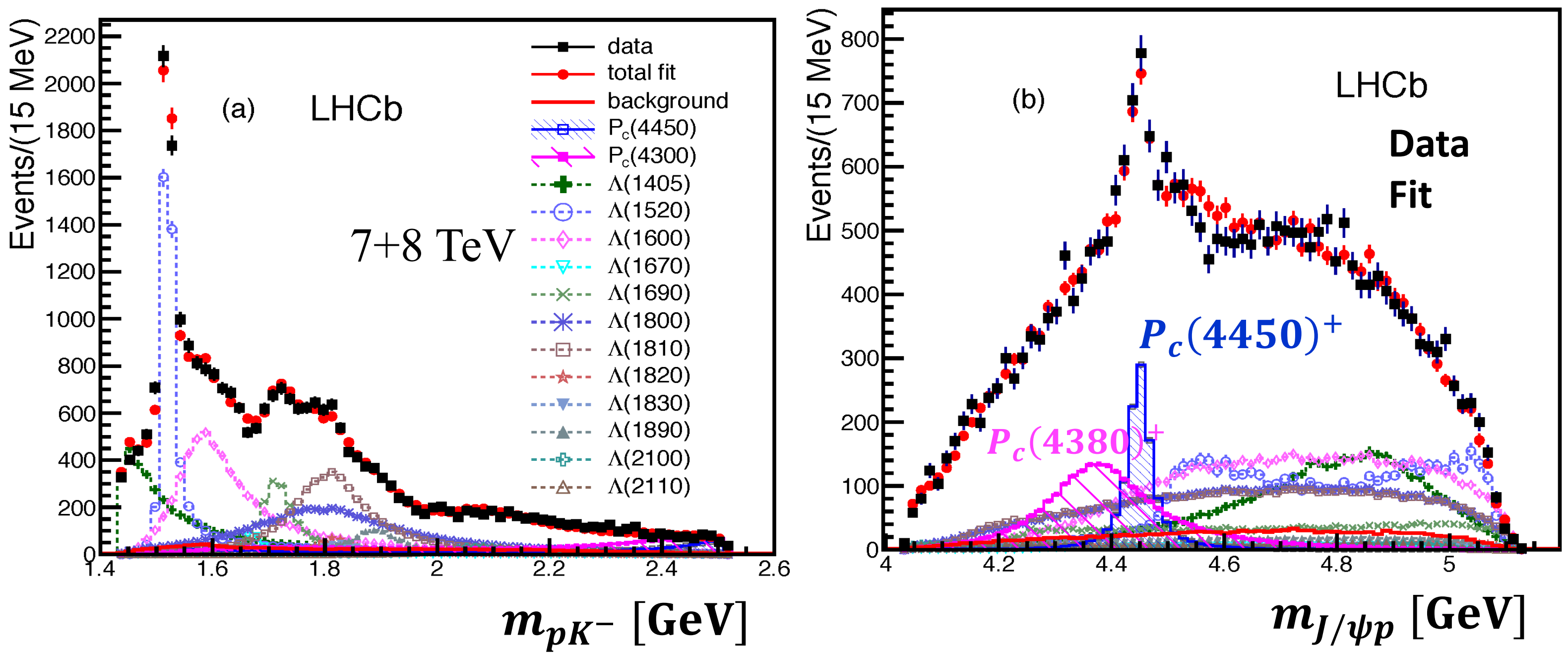
- Production by a B or D decays
  - X(3872) J^P
  - $Z_c(4430)$
  - X(4140) ….
  - $P_c(4450)$, $P_c(4380)$
  - $D_{(s)J}$

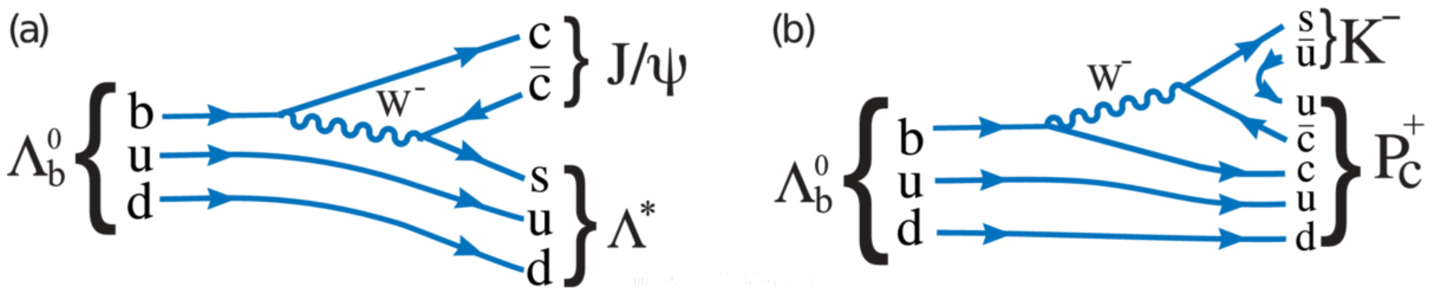


Discovery of pentaquark states

PRL 115, 072001 (2015)

- Two pentaquark states observed in 26,000 $\Lambda_b^0 \to J/\psi p K^-$ decays





New analysis efficiency increased by 90%

- Gain from loosen PID and use them in MVA

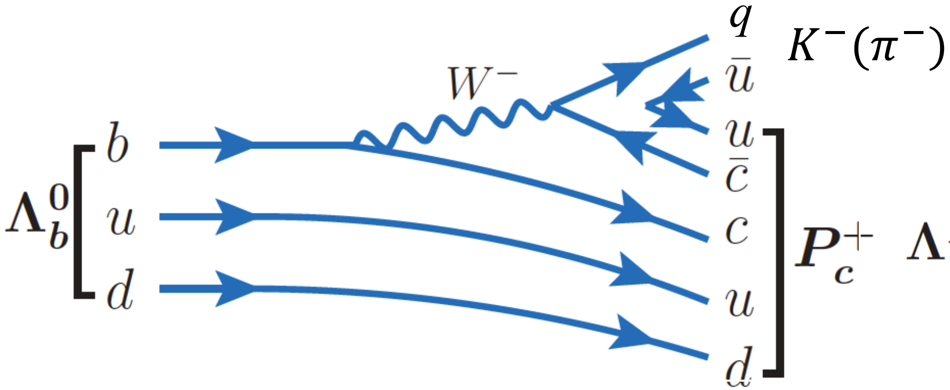
Data period	Total Signal Yield $\Lambda_b^0 \to J/\psi p K^-$	Signal Yield in 5605-5635 MeV	background fraction
Run1 PRL	$(27.3 \pm 0.2) \cdot 10^3$	$25.8 \cdot 10^3$	$(5.6 \pm 0.2)\%$
Run1 new	$(52.7 \pm 0.3) \cdot 10^3$	$50.2 \cdot 10^3$	$(7.1 \pm 0.2)\%$
2015	$(8.8 \pm 0.1) \cdot 10^3$	$8.3 \cdot 10^3$	$(5.5 \pm 0.4)\%$
2016	$(57.2 \pm 0.3) \cdot 10^3$	$54.4 \cdot 10^3$	$(6.1 \pm 0.1)\%$
2017	$(60.1 \pm 0.3) \cdot 10^3$	$57.4 \cdot 10^3$	$(6.0 \pm 0.1)\%$
2018	$(43.4 \pm 0.3) \cdot 10^3$	$41.6 \cdot 10^3$	$(6.1 \pm 0.2)\%$
Run2	$(169.6 \pm 0.5) \cdot 10^3$	$161.7 \cdot 10^3$	$(6.0 \pm 0.1)\%$
Run1+Run2	$(222.2 \pm 0.6) \cdot 10^3$	$211.9 \cdot 10^3$	$(6.3 \pm 0.1)\%$

8 x larger data sample than used in 2015 PRL paper !

Cabibbo-suppressed decays

- **Find the same P_c^+ in other channels is helpful to understand the production mechanism and internal structure**
- $\Lambda_b^0 \to J/\psi p \pi^-$ is Cabibbo-suppressed w.r.t. $J/\psi p K^-$
- Two production mechanisms predicted:

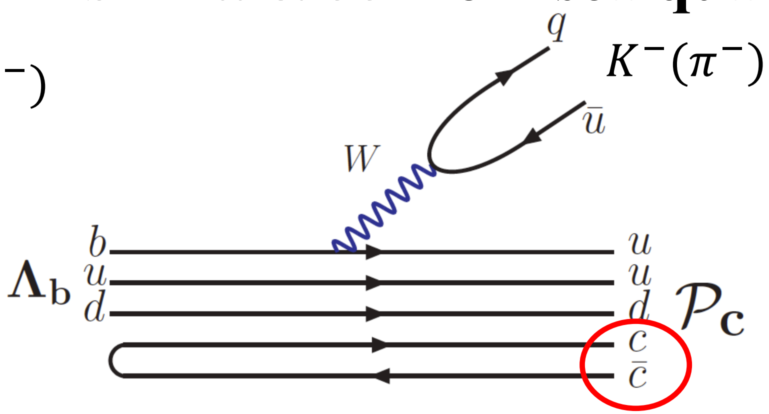
$\boldsymbol{b \to c}$



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

[Cheng, Phys. Rev. D 92, 096009 (2015)]

$\boldsymbol{b \to u}$ **&** $\boldsymbol{c\bar{c}}$ **from sea quarks**

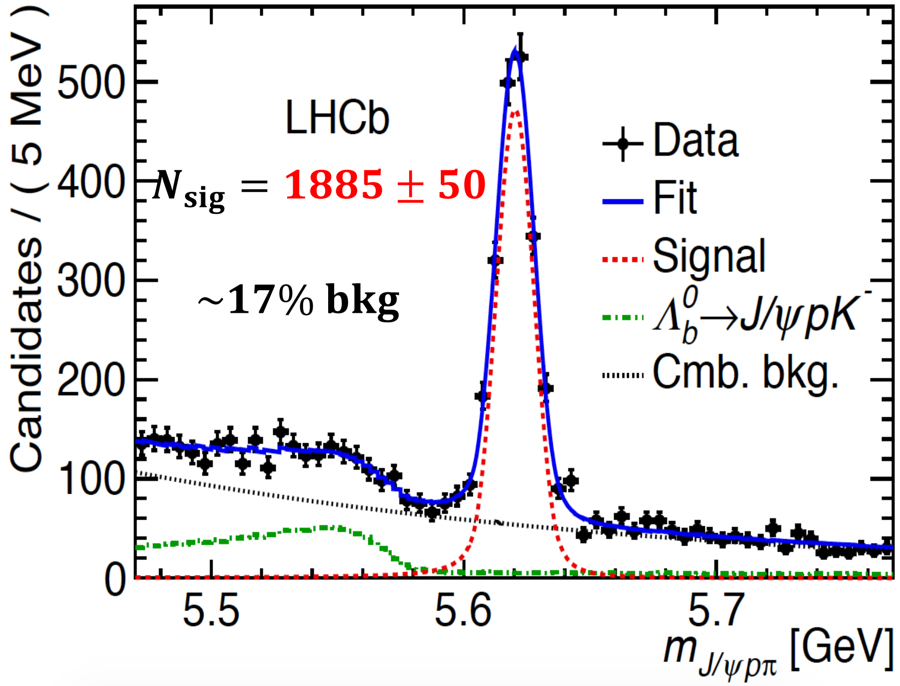


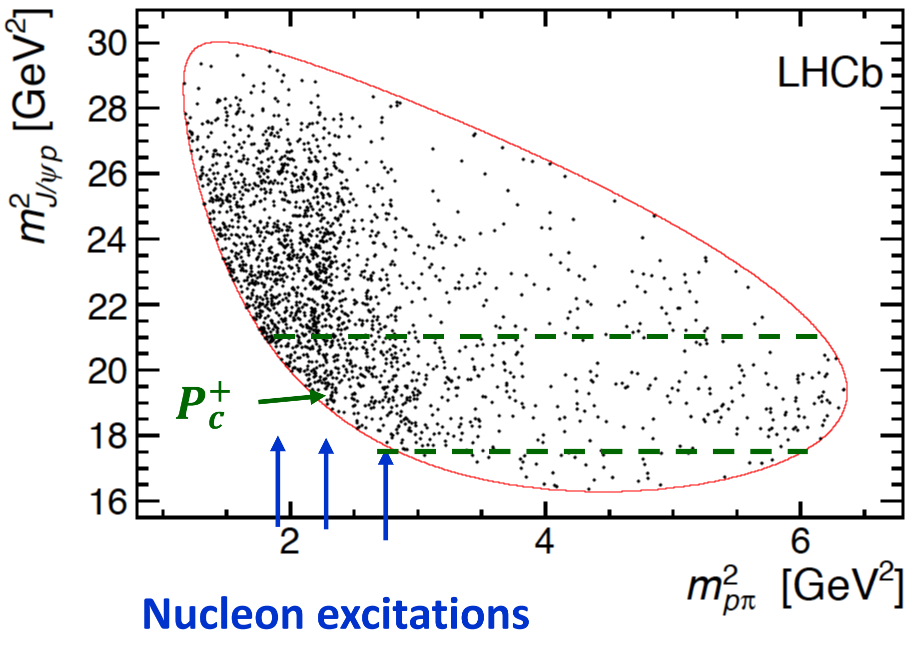
$$R_{\pi/K} = 0.58 \pm 0.05$$

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

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

PRL 117, 082003 (2016)





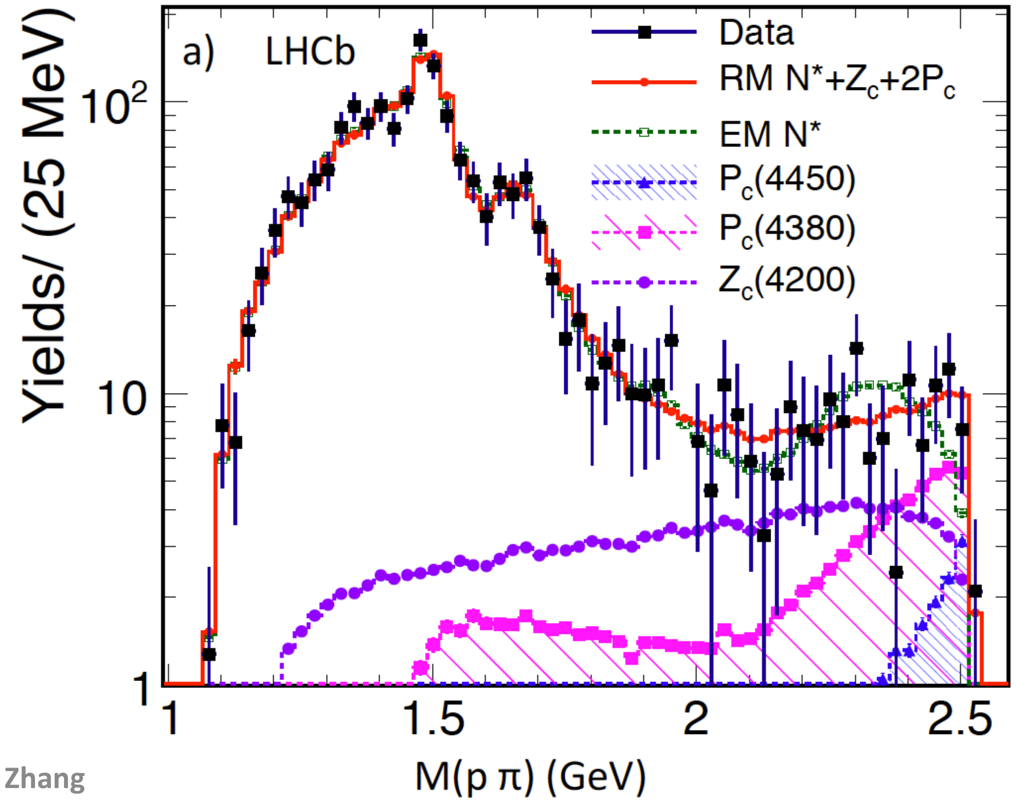
- >10 lower signal in $\Lambda_b^0 \to J/\psi p \pi^-$ than in $\Lambda_b^0 \to J/\psi pK^-$
- But more complex because of possible $Z_c^- \to J/\psi \pi^-$

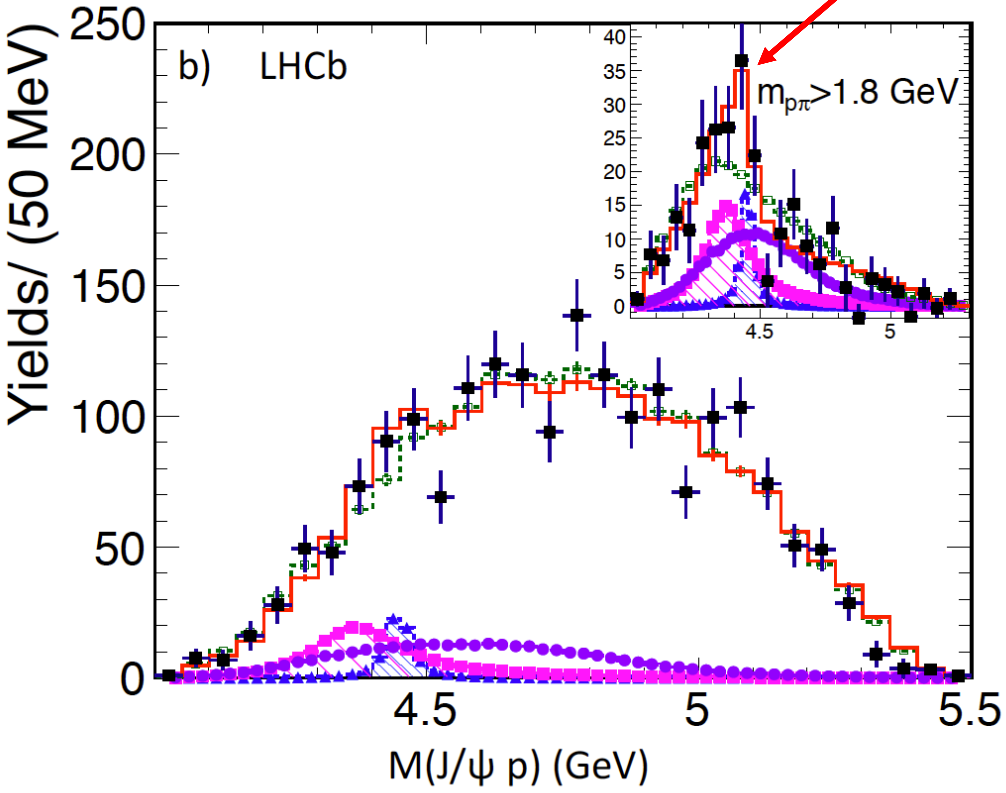
Full amplitude fits to $\Lambda_b^0 \to J/\psi p \pi^-$

- Significance of $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ take together is 3.1 σ including syst.
- First evidence!

PRL 117, 082003 (2016)

2 P_c^+?



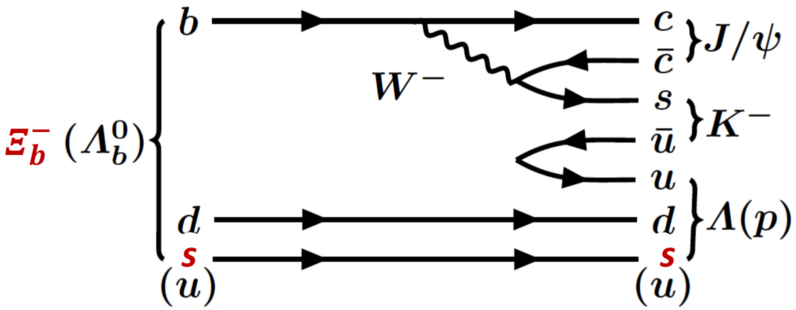


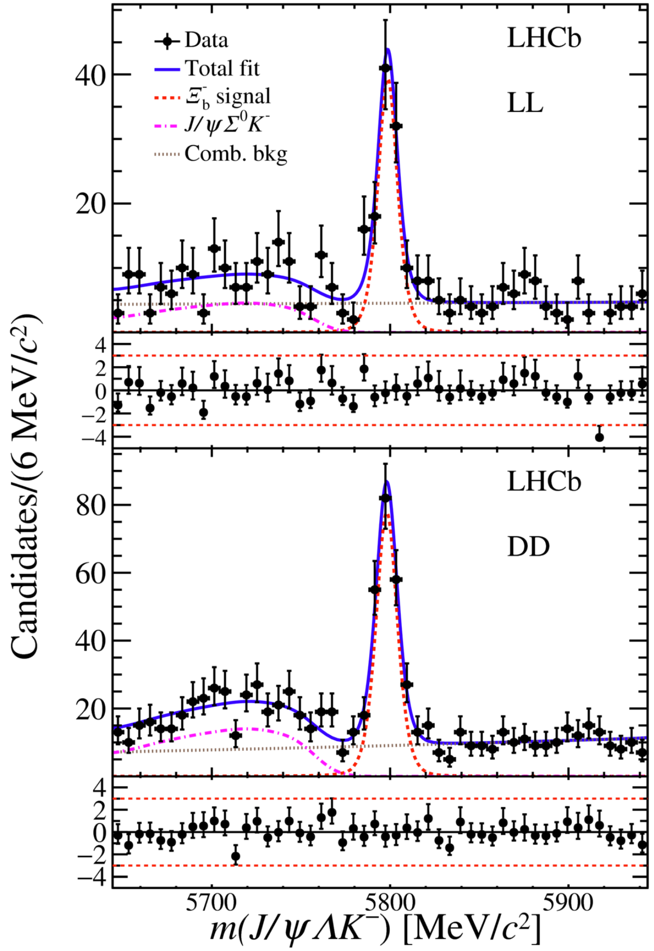
New analysis

- New analysis expect to have ~10,000 signal
- If can do independent Pc fit without inputs from $\Lambda_b^0 \to J/\psi p K^-$?

Observation of $\Xi_b^- \to J/\psi \Lambda K^-$

- Strange pentaquark ($uds c\bar{c}$) predicted in [PRL 105, 232001 (2010)]
- Can be searched for in the Ξ_b^- decay [PRC 93, 065203 (2016)]





$N_{sig} = 308 \pm 21$ (21σ) PLB 772 (2017) 265-273

$$\boxed{\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29 \pm 0.15) \times 10^{-2}}$$

Expect ~1700 signals, amplitude analysis is in good progress

Observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

- Search for $P_c(4450)^+$ in $\Lambda_b^0 \to \boxed{\chi_{c(1,2)} p} K^-$ decays
  $\Rightarrow$Test hypothesis of kinematic rescattering effect

PRD 92 (2015) 071502

- First step: observe the decays, measure $\mathcal{B}$
- Use $\chi_{c(1,2)} \to J/\psi\gamma$, constrain $J/\psi\gamma$ mass to known χ_{c1} mass

PRL 119 (2017) 062001

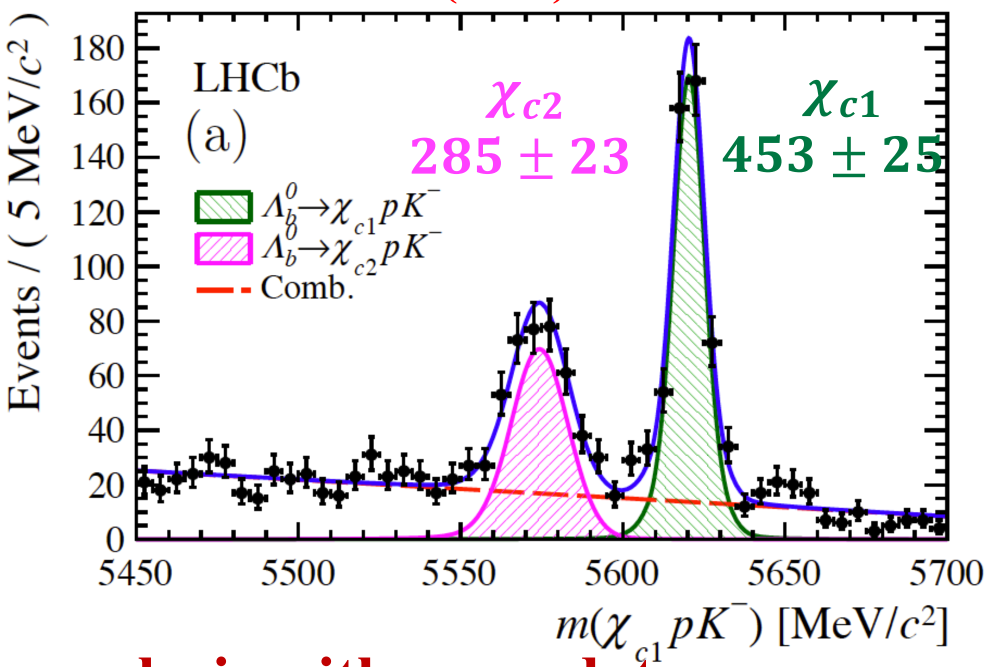
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} =$$

$$0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)} =$$

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

$$0.248 \pm 0.020 \pm 0.014 \pm 0.009$$



Next step: full amplitude analysis with more data

Other P_c channels

- Other LHCb ongoing activities:
  - **Hadronic: $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$**
  - **J=1/2 P_c^+ in $\Lambda_b^0 \to \eta_c p K^-$**
  - Generic pentaquarks: $[\bar{b}qqqq]$ and $[\bar{c}qqqq]$
- From non-hadron collider experiment:
  - $\gamma p \to J/\psi p,\ \pi p \to J/\psi p$
  - $e^+e^-(\Upsilon) \to J/\psi p\bar{p}$

YH Lin, CW Shen, FK Guo, BS Zou, PRD 95, 114017 (2017)

	Widths (MeV)			
	$P_c(4380)$		$P_c(4450)$	
Mode	$\bar{D}\Sigma_c^*(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{3}{2}^-)$	$\bar{D}^*\Sigma_c(\frac{5}{2}^+)$
☞ $\bar{D}^*\Lambda_c$	131.3	35.3	72.3	20.5
✓ $J/\psi p$	3.8	16.6	16.3	4.0
☞ $\bar{D}\Lambda_c$	1.2	17.0	41.4	18.8
πN	0.06	0.07	0.07	0.2
$\chi_{c0}p$	0.9	0.004	0.02	0.002
$\eta_c p$	0.2	0.09	0.1	0.04
ρN	1.4	0.15	0.14	0.3
ωp	5.3	0.6	0.5	0.3
$\bar{D}\Sigma_c$	0.01	0.1	1.2	0.8
$\bar{D}\Sigma_c^*$	...	...	7.7	1.4
$\bar{D}\Lambda_c\pi$	11.6	...	...	...
Total	144.3	69.9	139.8	46.4

Preferred interpretations

Expected yields with full Run1+2 data

- Reference channel with optimized selection:

$N_{\mathrm{Run1+2}} = 200{,}000\ \Lambda_b^0 \to J/\psi p K^-$

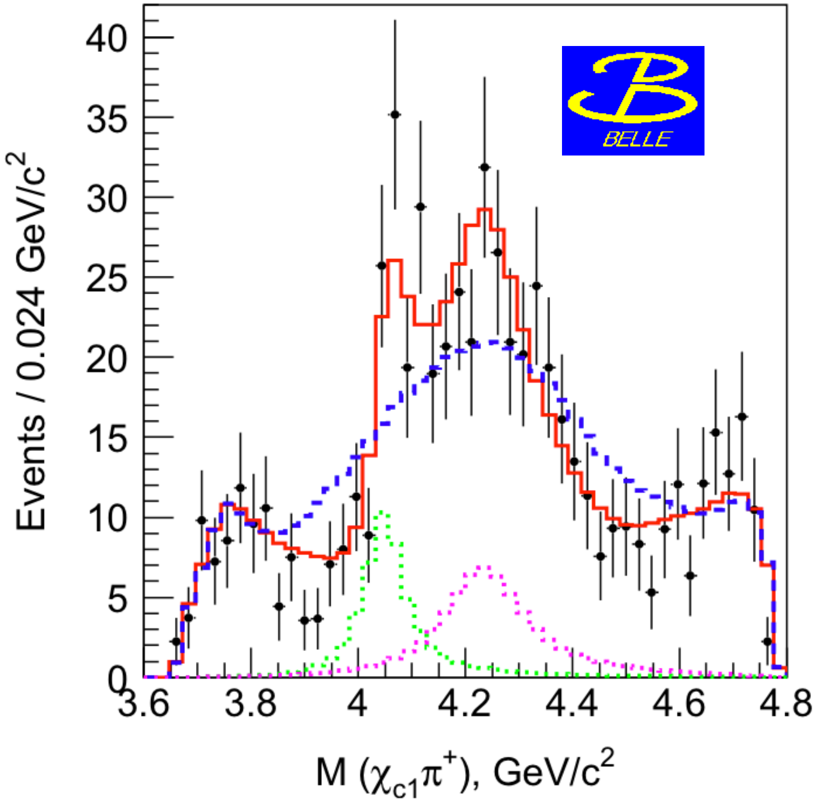
$N_{\mathrm{Run1+2}} = 8{,}000\ P_c(4450)^+ \to J/\psi p$

Channel	Efficiency	$\mathcal{B}$	Eff x $\mathcal{B}$	P_c(4450)
$\Lambda_b^0 \to J/\psi p K^-$	1	1	1	8000
$\Lambda_b^0 \to J/\psi p \pi^-$	$\approx 60\%$	8%	5%	400?
$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^0 K^-$	$\approx 10\%$	5(P_c)×4%	2%	200?
$\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$ *partial rec.*	$\approx 10\%$	5(P_c)×4%	2%	200?
$\Lambda_b^0 \to \chi_{c1} p K^-$	$\approx 12\%$	8%	1%	

Ongoing LHCb analyses for exotics

- Tetraquark
  - $B^0 \to \chi_{c1} K^+ \pi^-$ (~10,000 signals in Run1)
  - $B \to D^{(*)} \overline{D}^{(*)} K$
- Pentaquarks (amplitude)
  - $\Lambda_b^0 \to J/\psi p K^-$
  - $\Lambda_b^0 \to J/\psi p \pi^-$
  - $\Lambda_b^0 \to \chi_{c1} p K^-$
  - $\Lambda_b^0 \to \Lambda_c^+ \overline{D}^{(*)0} K^-$
  - $\Xi_b^- \to J/\psi \Lambda^0 K^-$
- Observation of decay
  - $\Lambda_b^0 \to \eta_c p K^-$

2126 signal events



Belle, PRD 78, 072004 (2008)

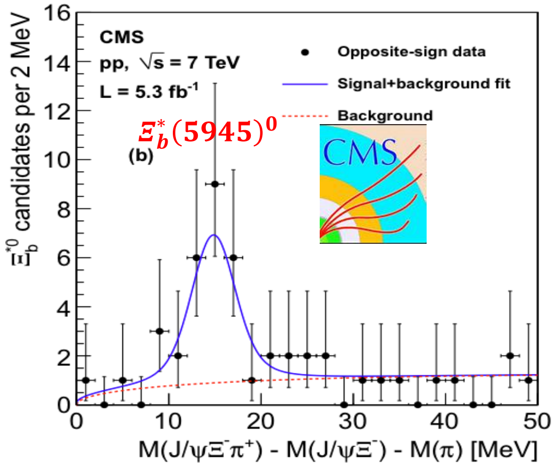
ANY SUGGESTIONS ON EXOTICS?

Ξ_b baryon spectroscopy

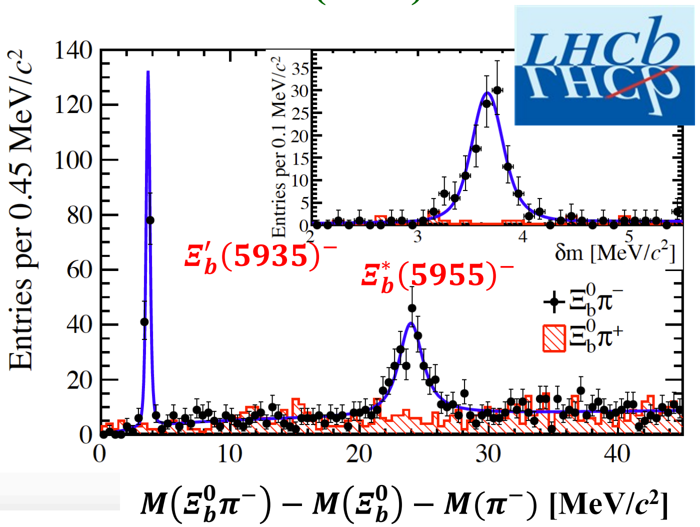
- Numbers of excited *b*-baryons have already been discovered
  - $\Xi_b^*(5945)^0 \to \Xi_b^- \pi^+$ [CMS'12]
  - $\Xi_b'(5935)^-, \Xi_b^*(5955)^- \to \Xi_b^0 \pi^-$ [LHCb'15]
  - $\Xi_b'^{\,0}$ not yet observed

State	J^P	$b(sq)$
Ξ_b	$1/2^+$	$\uparrow(\uparrow\downarrow)$
Ξ_b'	$1/2^+$	$\downarrow(\uparrow\uparrow)$
Ξ_b^*	$3/2^+$	$\uparrow(\uparrow\uparrow)$

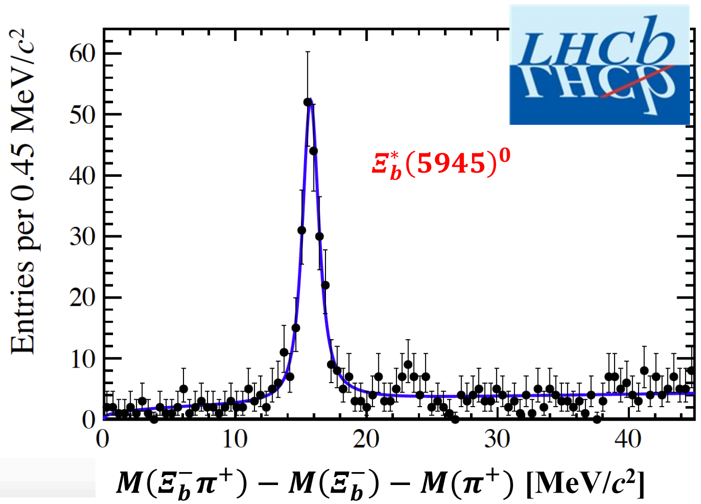
PRL 108, 252002 (2012)



PRL 114 (2015) 062004



JHEP 05 (2016) 161

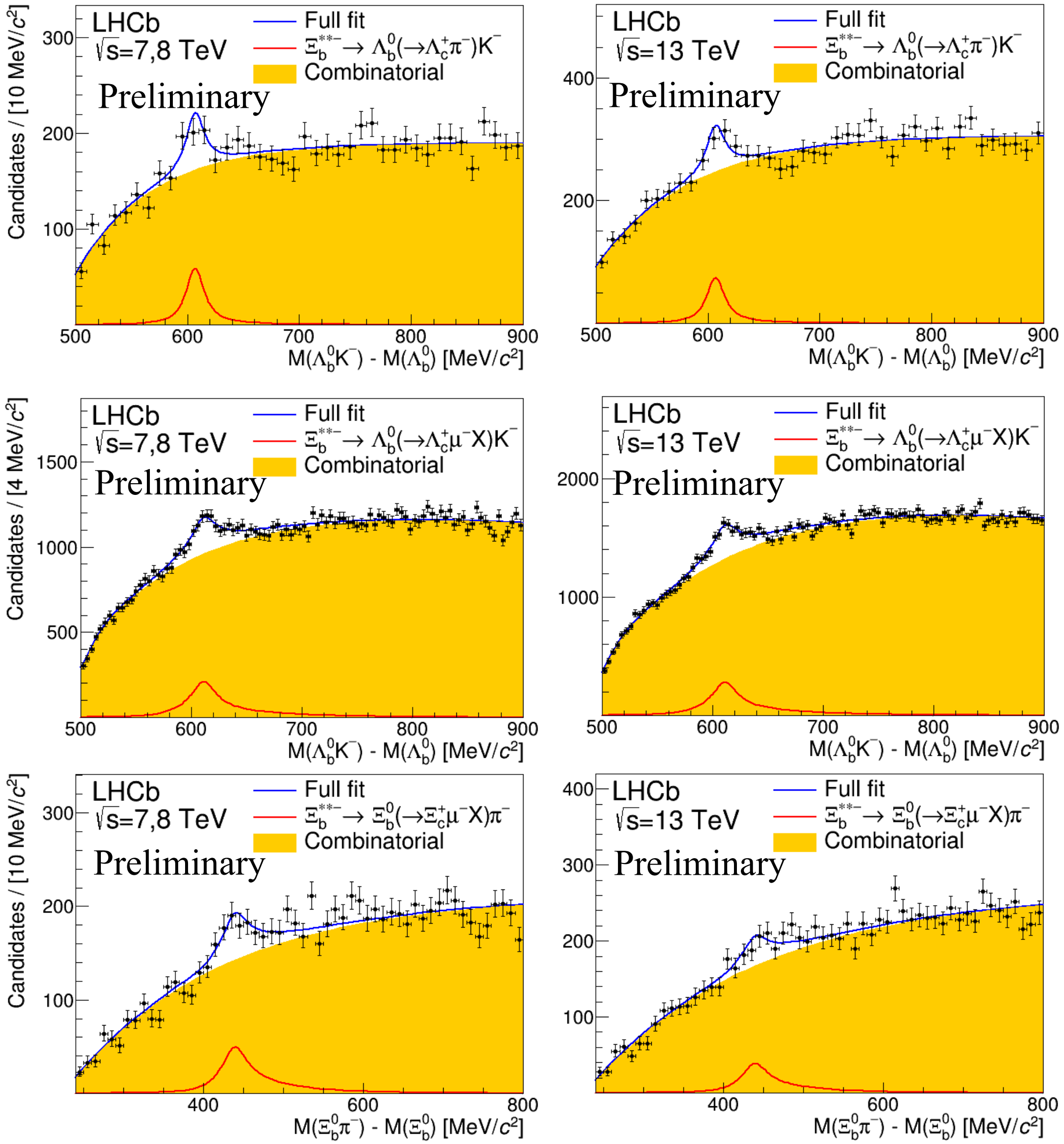


Observation of a new Ξ_b^{**-} state

- Hadronic $\Lambda_b^0 \to \Lambda_c^+\pi^-$:
  - Resolution: 2 MeV
  - 7.9σ
- Semileptonic (SL) **(new method)**
  $\Lambda_b^0 \to \Lambda_c^+\mu^- X\bar{\nu}_\mu$
  - Resolution: ~18 MeV
  - **Yields ~15 larger**
  - 25σ
- Semileptonic (SL)
  $\Xi_b^0 \to \Lambda_c^+\mu^- X\bar{\nu}_\mu$
  - 9.2σ

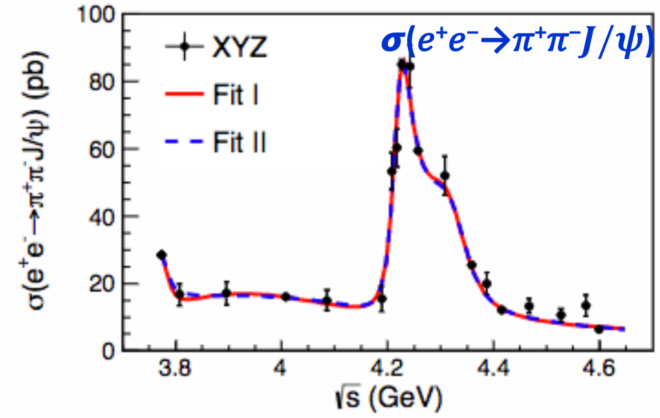
可以寻找Ω_b^{**}

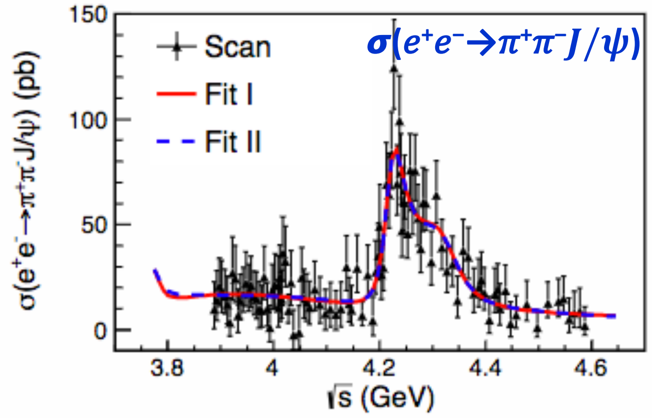
LHCb-PAPER-2018-013, arXiv:1805.09418



LHCb上寻找$pp \to Y$…是不是有意义？

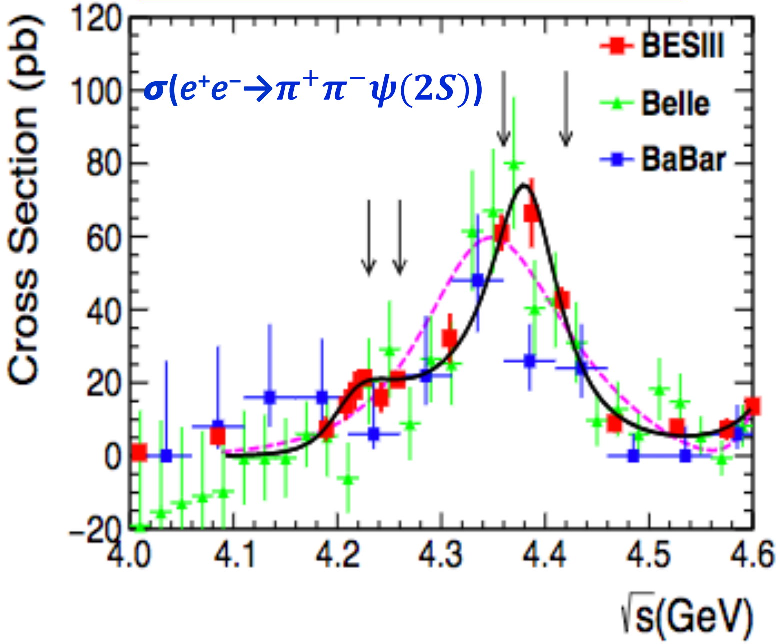
PRL118, 092001 (2017)



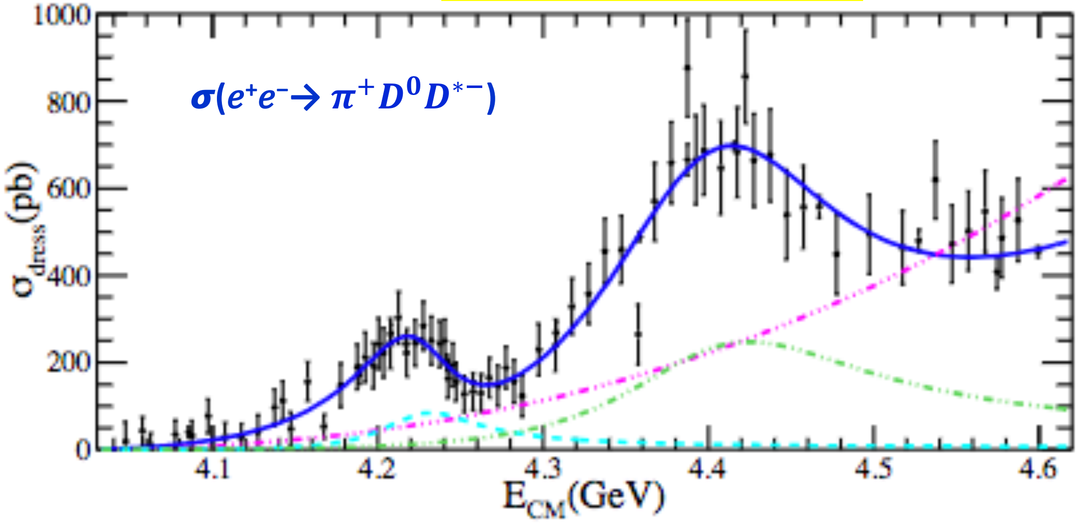


如果只能给出上限，
是不是有意义？

PRD96, 032004 (2017)

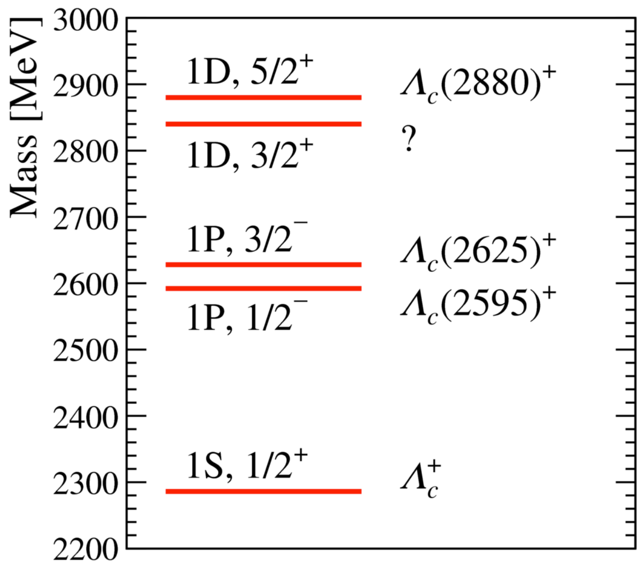


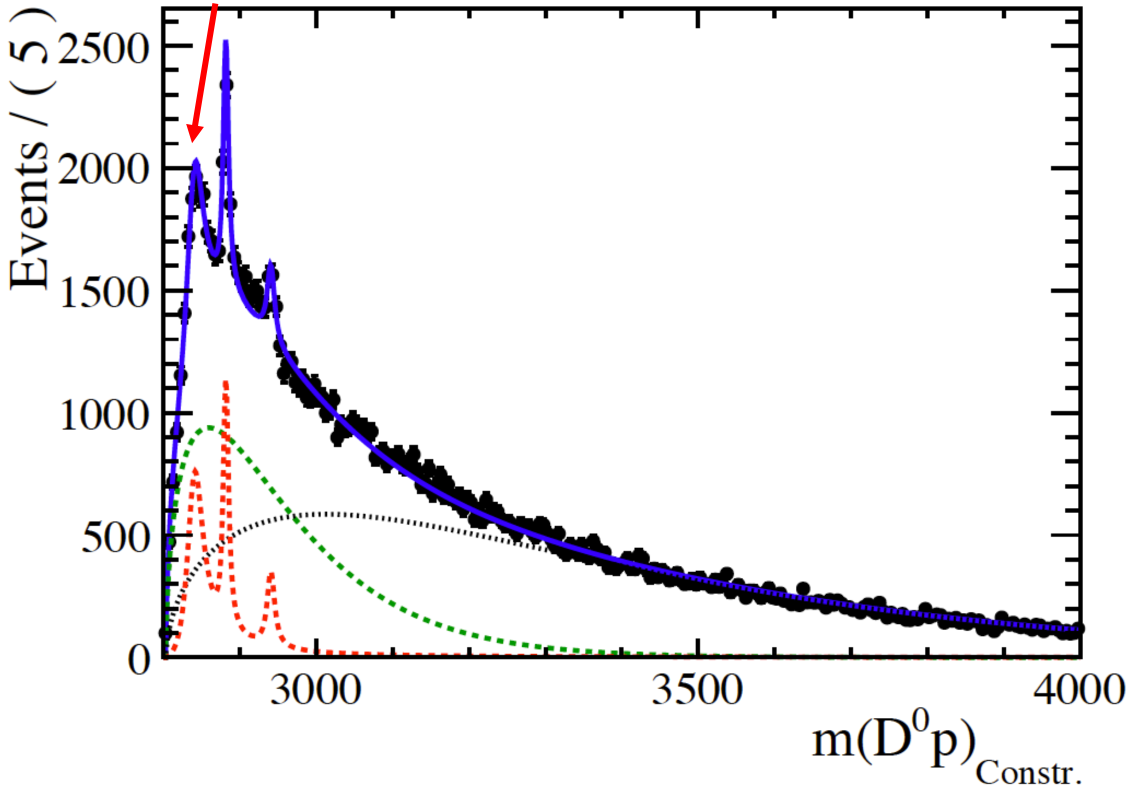
arXiv:1808.02847



Excited charm from B semileptonic decay

- We have $B \to D^0\mu X; D_s^+\mu X; D^+\mu X; \Lambda_c^+\mu X; \Xi_c^+\mu X$
- We can add any tracks to them, to form excited charm
  - for example, $\Lambda_c^{*+} \to D^0 p$
  - $\Lambda_c(2860)^+$ was just observed in LHCb from $\Lambda_b^0 \to D^0 p\pi^-$ [[JHEP (2017) 2017, 30]]



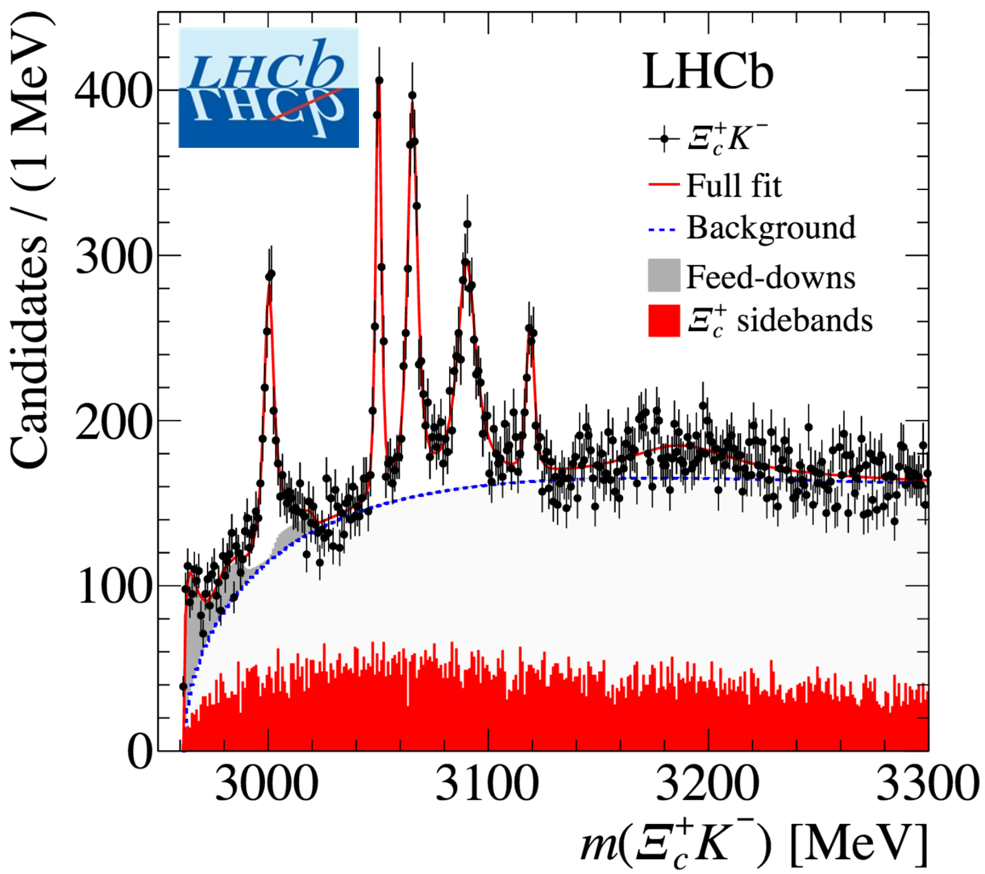


还有哪些质量比较轻，还没找到的charm态？

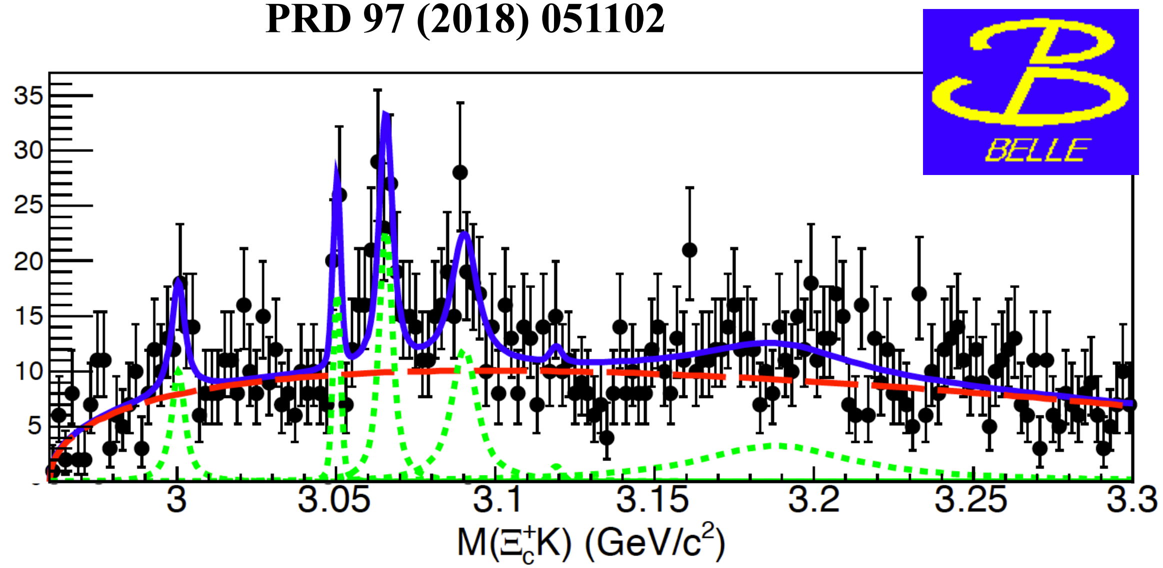
Excited Ω_c states from pp production

- LHCb observed 5 narrow states (+ possible one wide one) in 2017
- Belle confirmed the first four states this year

PRL 118 (2017) 182001



PRD 97 (2018) 051102



The measured masses are consistent with LHCb values

$B^0 \to X(3872)K^-\pi^+$ to search for $X(3872)\pi^+$?

- $\mathcal{B}(B^0 \to X(3872)K^-\pi^+, X(3872) \to J/\psi\pi^+\pi^-) = (7.9 \pm 1.4)\times10^{-6}$
- $\mathcal{B}(B^0 \to J/\psi\pi^-\pi^+) \approx 4.0\times10^{-5}$
- $R_{\mathcal{B}} = \frac{1}{5}$
- $R_{\mathrm{eff}} = \frac{1}{5}$ (two more tracks)
- Run-1, N $(B^0 \to J/\psi\pi^-\pi^+)$=18,000
- Expect ~3000 $B^0 \to X(3872)K^-\pi^+$

Charmonium under DD* threshold

- Only two unobserved
  - $^1D_2\ 2^{-+}$
  - $^3D_3\ 3^{--}$
- Narrow