LHCb实验上奇特强子态研究

张冬亮

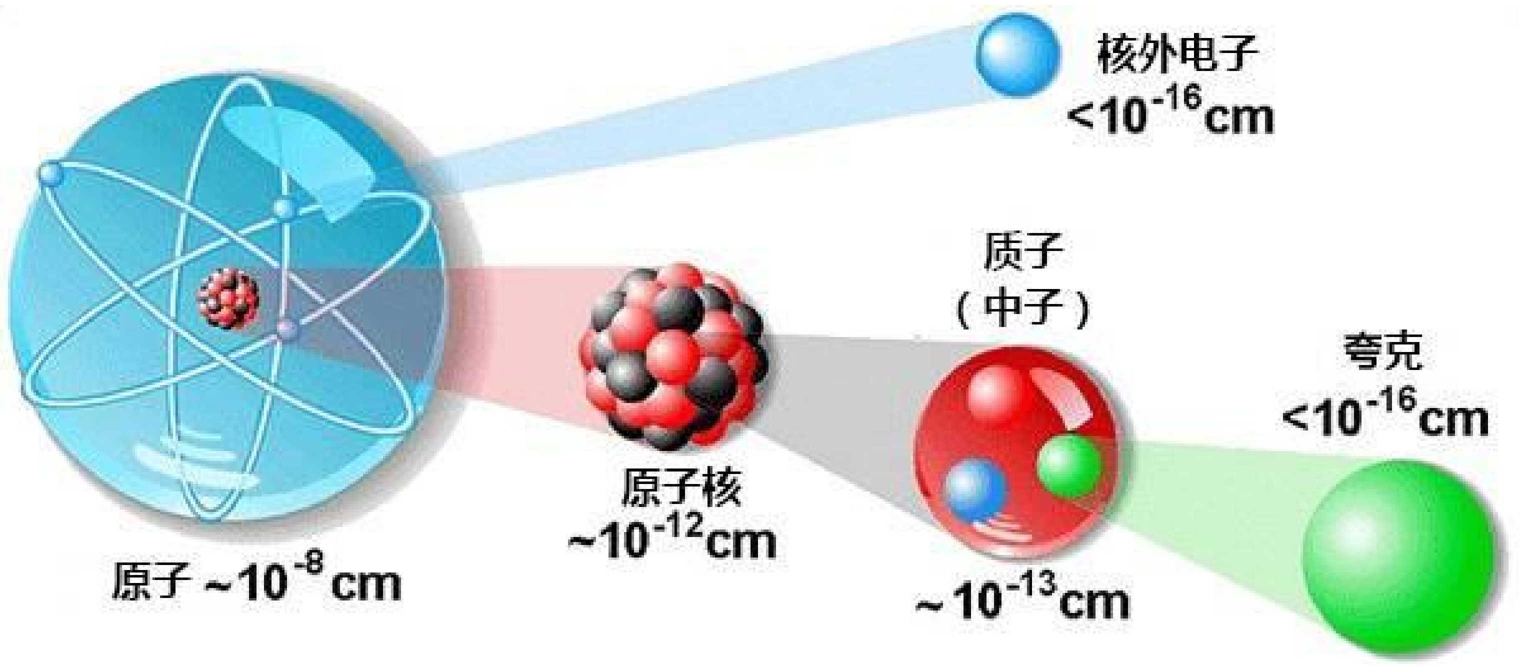
华中师范大学

内容

- 简要回顾强子态相关知识
- LHCb实验
- LHCb实验上奇特态研究的例子
  - 四夸克态
    - X(3872)
    - X(4140)
    - T(2900)
  - 五夸克态

LHCb实验上奇特强子态研究

- 强子
  - 介子（$q\bar{q}$）
  - 重子（qqq，$\bar{q}\bar{q}\bar{q}$）



http://image.sciencenet.cn/home/202005/15/170708pew09s65zunv5i99.jpg

元素周期表

原子序数 — 92 U — 元素符号，红色指放射性元素

元素名称注*的是人造元素 — 铀

$5f^36d^17s^2$ — 外围电子层排布，括号指可能的电子层排布

238.0 — 相对原子质量

非金属　金 属　过渡元素

族/周期	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0	电子层	0族电子数
1	1 H 氢 $1s^1$ 1.008																	2 He 氦 $1s^2$ 4.003	K	2
2	3 Li 锂 $2s^1$ 6.941	4 Be 铍 $2s^2$ 9.012											5 B 硼 $2s^22p^1$ 10.81	6 C 碳 $2s^22p^2$ 12.01	7 N 氮 $2s^22p^3$ 14.01	8 O 氧 $2s^22p^4$ 16.00	9 F 氟 $2s^22p^5$ 19.00	10 Ne 氖 $2s^22p^6$ 20.18	L K	8 2
3	11 Na 钠 $3s^1$ 22.99	12 Mg 镁 $3s^2$ 24.31											13 Al 铝 $3s^23p$ 26.98	14 Si 硅 $3s^23p^2$ 28.09	15 P 磷 $3s^23p^3$ 30.97	16 S 硫 $3s^23p^4$ 32.07	17 Cl 氯 $3s^23p^5$ 35.45	18 Ar 氩 $3s^23p^6$ 39.95	M L K	8 8 2
4	19 K 钾 $4s^1$ 39.10	20 Ca 钙 $4s^2$ 40.08	21 Sc 钪 $3d^14s^2$ 44.96	22 Ti 钛 $3d^24s^2$ 47.87	23 V 钒 $3d^34s^2$ 50.94	24 Cr 铬 $3d^54s^1$ 52.00	25 Mn 锰 $3d^54s^2$ 54.94	26 Fe 铁 $3d^64s^2$ 55.85	27 Co 钴 $3d^74s^2$ 58.93	28 Ni 镍 $3d^84s^2$ 58.69	29 Cu 铜 $3d^{10}4s^1$ 63.55	30 Zn 锌 $3d^{10}4s^2$ 65.39	31 Ga 镓 $4s^24p^1$ 69.72	32 Ge 锗 $4s^24p^2$ 72.61	33 As 砷 $4s^24p^3$ 74.92	34 Se 硒 $4s^24p^4$ 78.96	35 Br 溴 $4s^24p^5$ 79.90	36 Kr 氪 $4s^24p^6$ 83.80	N M L K	8 18 8 2
5	37 Rb 铷 $5s^1$ 85.47	38 Sr 锶 $5s^2$ 87.62	39 Y 钇 $4d^15s^2$ 88.91	40 Zr 锆 $4d^25s^2$ 91.22	41 Nb 铌 $4d\ 5s^1$ 92.91	42 Mo 钼 $4d^55s^1$ 95.94	43 Tc 锝 $4d^55s^2$ [99]	44 Ru 钌 $4d^75s^1$ 101.1	45 Rh 铑 $4d^85s^1$ 102.9	46 Pd 钯 $4d^{10}$ 106.4	47 Ag 银 $4d^{10}5s^1$ 107.9	48 Cd 镉 $4d^{10}5s^2$ 112.4	49 In 铟 $5s^25p^1$ 114.8	50 Sn 锡 $5s^25p^2$ 118.7	51 Sb 锑 $5s^25p^3$ 121.8	52 Te 碲 $5s^25p^4$ 127.6	53 I 碘 $5s^25p^5$ 126.9	54 Xe 氙 $5s^25p^6$ 131.3	O N M L K	8 18 18 8 2
6	55 Cs 铯 $6s^1$ 132.9	56 Ba 钡 $6s^2$ 137.3	57-71 La-Lu 镧系	72 Hf 铪 $5d^26s^2$ 178.5	73 Ta 钽 $5d^36s^2$ 180.9	74 W 钨 $5d^46s^2$ 183.8	75 Re 铼 $5d^56s^2$ 186.2	76 Os 锇 $5d^66s^2$ 190.2	77 Ir 铱 $5d^76s^2$ 192.2	78 Pt 铂 $5d^96s^1$ 195.1	79 Au 金 $5d^{10}6s^1$ 197.0	80 Hg 汞 $5d^{10}6s^2$ 200.6	81 Tl 铊 $6s^26p^1$ 204.4	82 Pb 铅 $6s^26p^2$ 207.2	83 Bi 铋 $6s^26p^3$ 209.0	84 Po 钋 $6s^26p^4$ [209]	85 At 砹 $6s^26p^5$ [210]	86 Rn 氡 $6s^26p^6$ [222]	P O N M L K	8 18 32 18 8 2
7	87 Fr 钫 $7s^1$ [223]	88 Ra 镭 $7s^2$ 226.0	89-103 Ac-Lr 锕系	104 Rf 𬬻* $(6d^27s^2)$ [261]	105 Db 𬭊* $(6d^37s^2)$ [262]	106 Sg 𬭳* $(6d^47s^2)$ [263]	107 Bh 𬭛* $(6d^57s^2)$ [262]	108 Hs 𬭶* $(6d^67s^2)$ [265]	109 Mt 鿏* $(6d^77s^2)$ [266]	110 Ds 𫟼* $(6d^97s^1)$ [269]	111 Rg 𬬭* $(6d^{10}7s^1)$ [272]	112 Cn 鿔* $(6d^{10}7s^2)$ [285]	113 Nh 鿭* $(7s^27p^1)$ [284]	114 Fl 𫓧* $(7s^27p^2)$ [289]	115 Mc 镆* $(7s^27p^3)$ [288]	116 Lv 𫟷* $(7s^27p^4)$ [293]	117 Ts 鿬* $(7s^27p^5)$ [291]	118 Og 鿫* $(7s^27p^6)$ [294]	Q P O N M L K	8 18 32 32 18 8 2

镧系	57 La 镧 $5d^16s^2$ 138.9	58 Ce 铈 $4f^15d^16s^2$ 140.1	59 Pr 镨 $4f^36s^2$ 140.9	60 Nd 钕 $4f^46s^2$ 144.2	61 Pm 钷 $4f^56s^2$ [147]	62 Sm 钐 $4f^66s^2$ 150.4	63 Eu 铕 $4f^76s^2$ 152.0	64 Gd 钆 $4f^75d^16s^2$ 157.3	65 Tb 铽 $4f^96s^2$ 158.9	66 Dy 镝 $4f^{10}6s^2$ 162.5	67 Ho 钬 $4f^{11}6s^2$ 164.9	68 Er 铒 $4f^{12}6s^2$ 167.3	69 Tm 铥 $4f^{13}6s^2$ 168.9	70 Yb 镱 $4f^{14}6s^2$ 173.0	71 Lu 镥 $4f^{14}5d^16s$ 175.0
锕系	89 Ac 锕 $6d^17s^2$ 227.0	90 Th 钍 $6d^27s^2$ 232.0	91 Pa 镤 $5f^26d^17s^2$ 231.0	92 U 铀 $5f^36d^17s^2$ 238.0	93 Np 镎 $5f^46d^17s^2$ 237.0	94 Pu 钚 $5f^67s^2$ [244]	95 Am 镅* $5f^77s^2$ [243]	96 Cm 锔* $5f^76s^17s^2$ [247]	97 Bk 锫* $5f^97s^2$ [247]	98 Cf 锎* $5f^{10}7s^2$ [251]	99 Es 锿* $5f^{11}7s^2$ [252]	100 Fm 镄* $5f^{12}7s^2$ [257]	101 Md 钔* $(5f^{13}7s^2)$ [258]	102 No 锘* $(5f^{14}7s^2)$ [259]	103 Lr 铹* $(5f^{14}6d^17s^2)$ [260]

注:

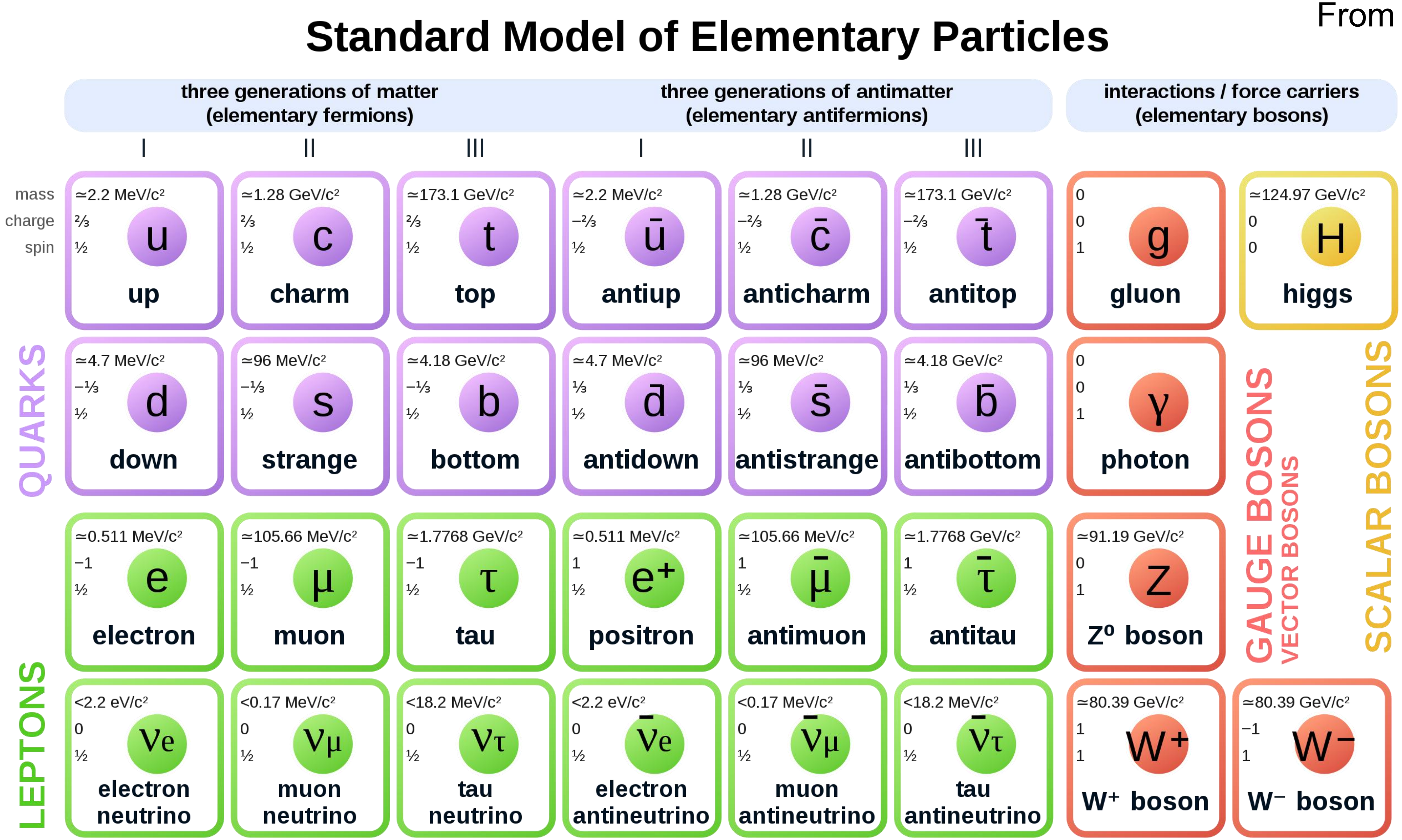
1.相对原子质量录自1995年国际原子量表,并全部取4位有效数字。

2.相对原子质量加括号的为放射性元素的半衰期最长的同位素的质量数。

图片来源

标准模型中的粒子

From wikimedia



夸克之间的强相互作用-色相互作用

- 夸克有3种颜色：红、绿、蓝
- 反夸克有相应的3种反颜色
- 传递强相互作用的胶子有8种颜色
- 夸克-反夸克

$$V_{q\bar{q}}=-\frac{4}{3}\frac{\alpha_s}{r}\quad(\text{色单态})$$

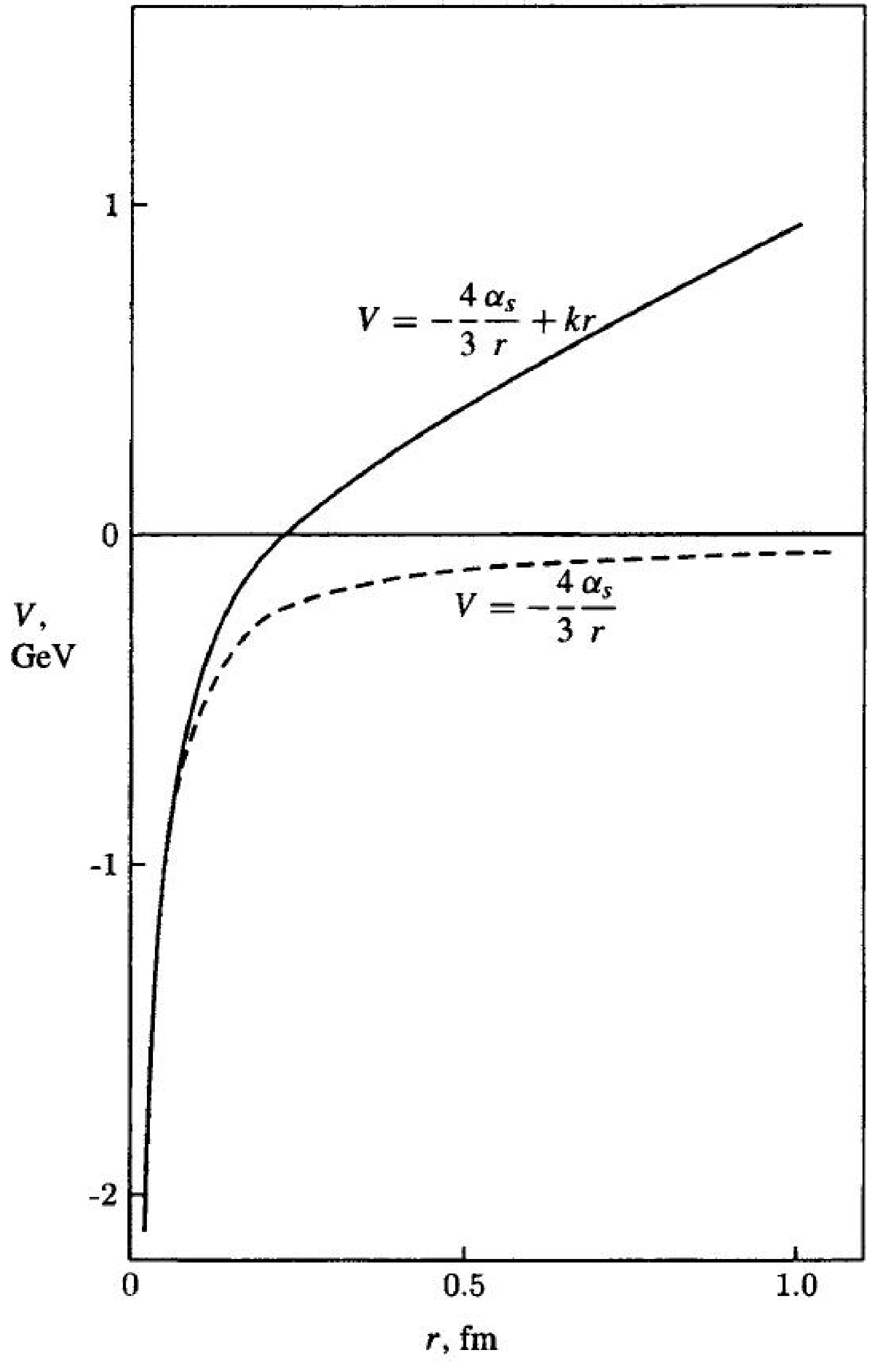
$$V_{q\bar{q}}=\frac{1}{6}\frac{\alpha_s}{r}\quad(\text{色八重态})$$

- 夸克-夸克

$$V_{qq}=-\frac{2}{3}\frac{\alpha_s}{r}\quad（\text{三重态}）$$

$$V_{qq}=\frac{1}{3}\frac{\alpha_s}{r}\quad（\text{六重态}）$$

- 色禁闭：实验中只能观察到色中性的粒子



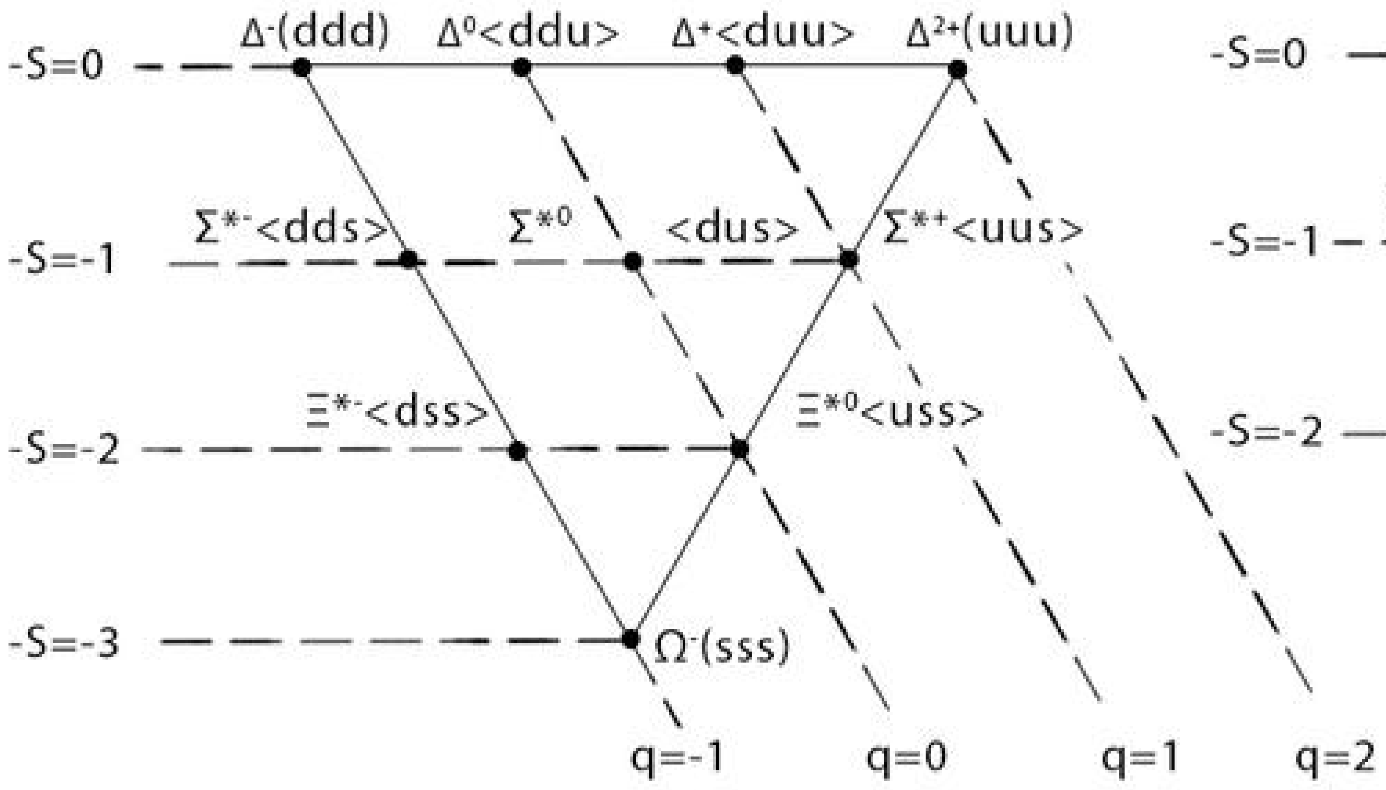
味对称性

- 六种味的夸克
  - 同样可以携带色荷
  - 不同电荷
  - 不同质量
- 同位旋
  - u和d质量接近
  - 原子核中质子和中子非常相似

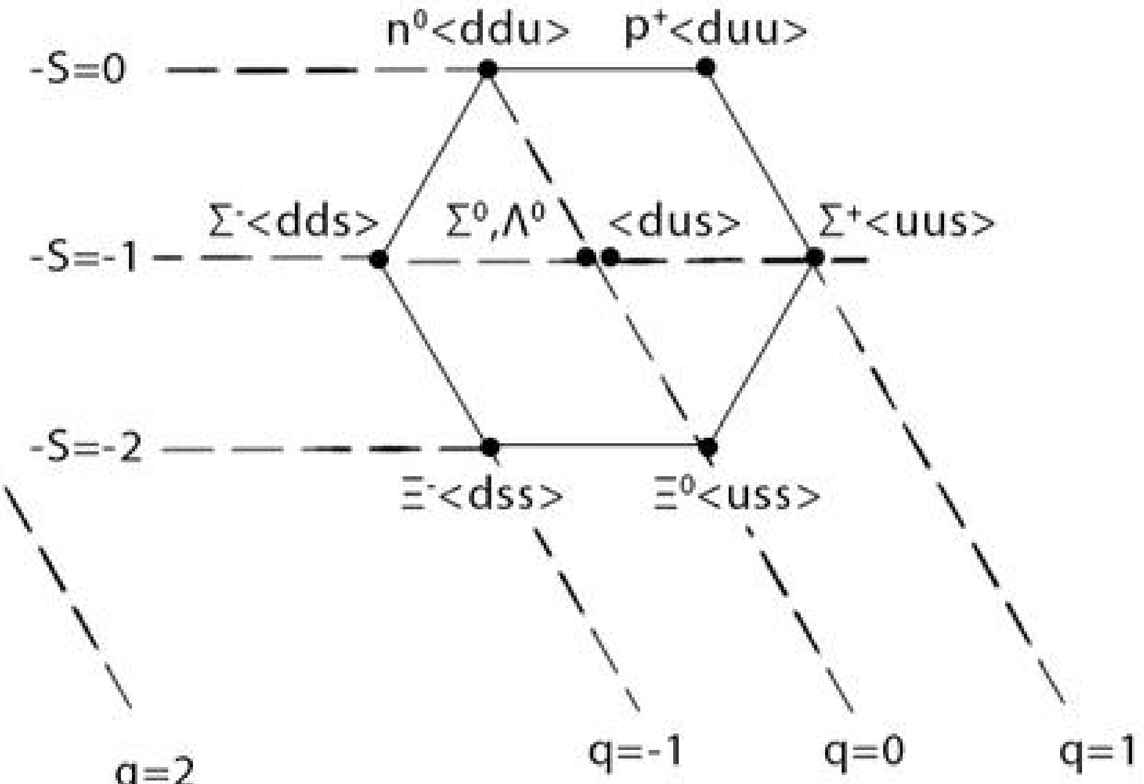
图片来源

重子

- 十重态（自旋3/2, 波函数全对称）

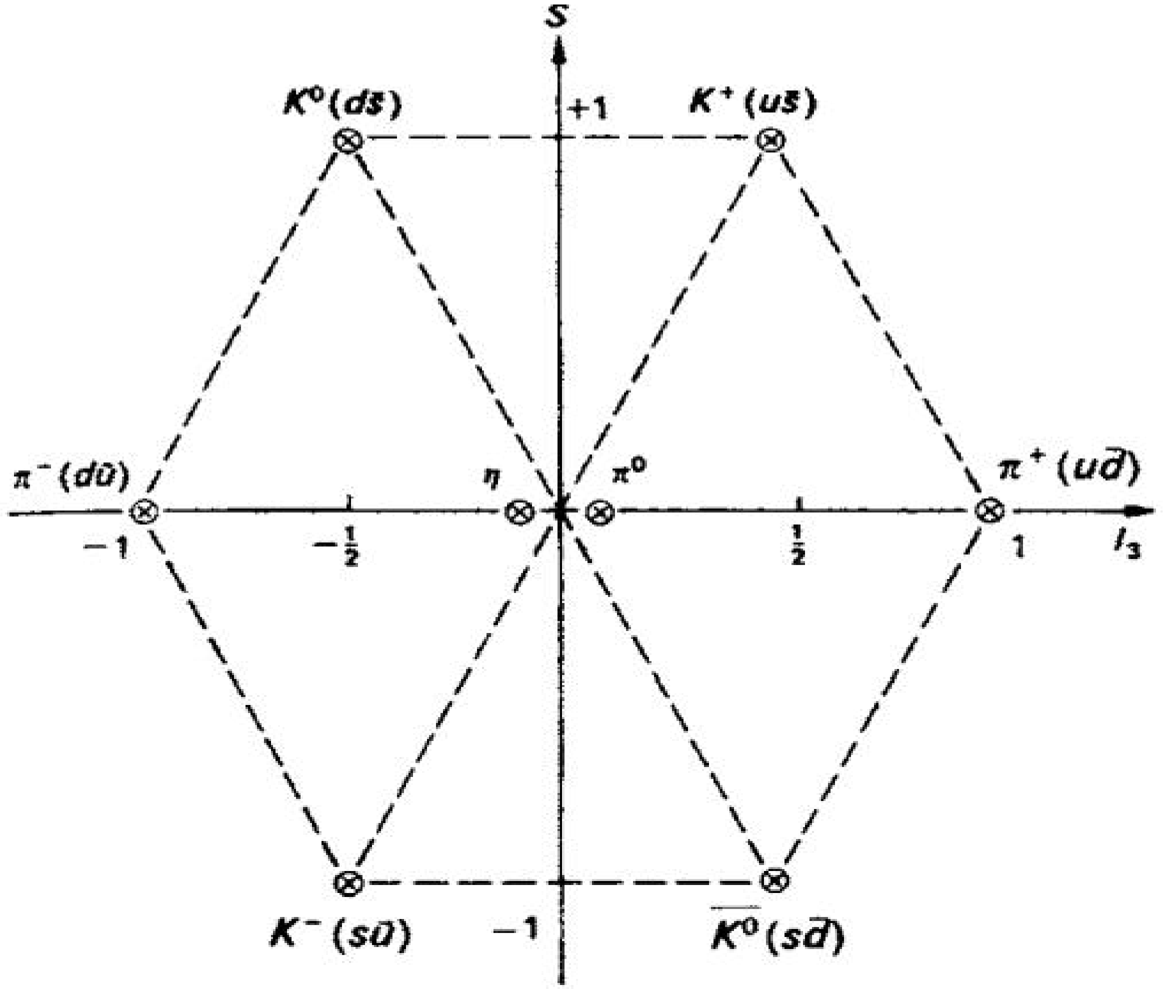


- 八重态 （自旋1/2, 波函数混合对称）



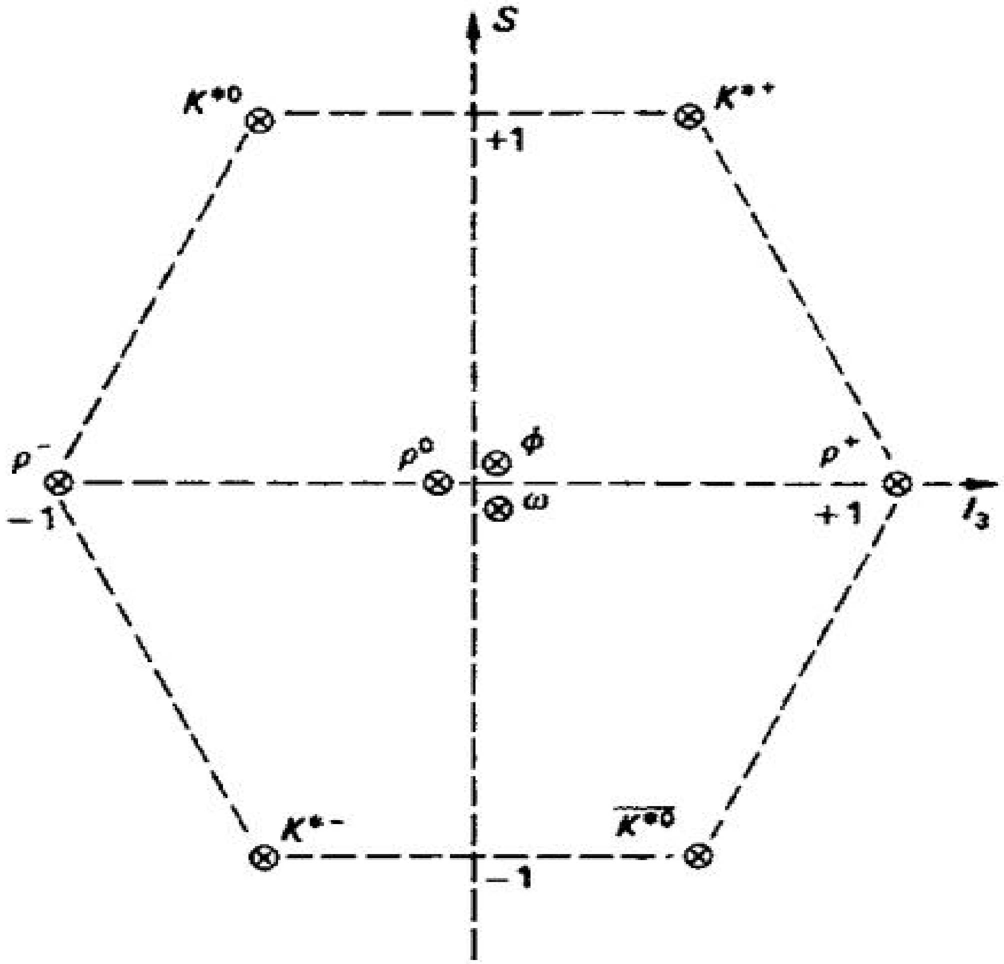
介子八重态

- 标量 （自旋J=0）



(a)

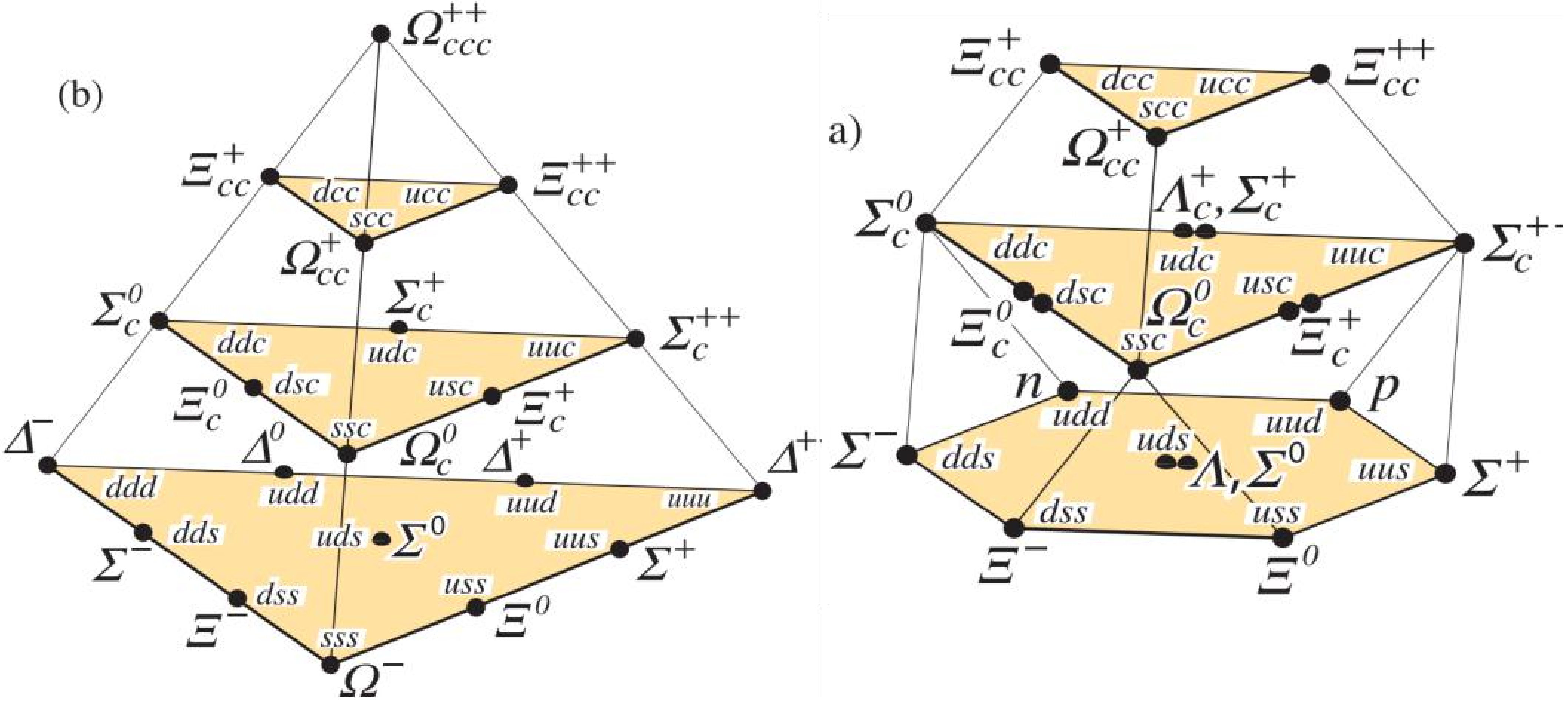
- 矢量（自旋J=1）



(b)

加入重夸克

- 加入c夸克


(b)
Ω_{ccc}^{++}
Ξ_{cc}^{+}
Ξ_{cc}^{++}
dcc
ucc
scc
Ω_{cc}^{+}
Σ_c^{+}
Σ_c^{0}
Σ_c^{++}
ddc
udc
uuc
dsc
usc
Ξ_c^{0}
Ξ_c^{+}
ssc
Ω_c^{0}
Δ^{-}
Δ^{0}
Δ^{+}
Δ^{++}
ddd
udd
uud
uuu
dds
uds
Σ^{0}
uus
Σ^{-}
Σ^{+}
dss
uss
Ξ^{-}
Ξ^{0}
sss
Ω^{-}
a)
Ξ_{cc}^{+}
Ξ_{cc}^{++}
dcc
ucc
scc
Ω_{cc}^{+}
$\Lambda_c^{+}, \Sigma_c^{+}$
Σ_c^{0}
Σ_c^{++}
ddc
udc
uuc
dsc
usc
Ω_c^{0}
Ξ_c^{0}
Ξ_c^{+}
ssc
n
p
udd
uud
Σ^{-}
dds
uds
Λ, Σ^{0}
uus
Σ^{+}
dss
uss
Ξ^{-}
Ξ^{0}

四夸克态和五夸克态？

- 满足色中性的不只有$q\bar{q}$和qqq
- 还可以有
  - $q\bar{q}q\bar{q}$
  - $qqqq\bar{q}$
  - $qqq\bar{q}\bar{q}\bar{q}$
  - $q\bar{q}g$
  - ggg
  - …

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

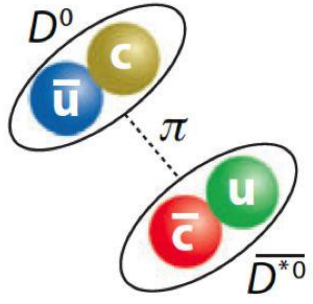
AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

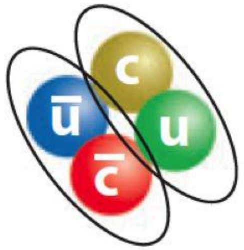
5) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".

LHCb实验上奇特强子态研究

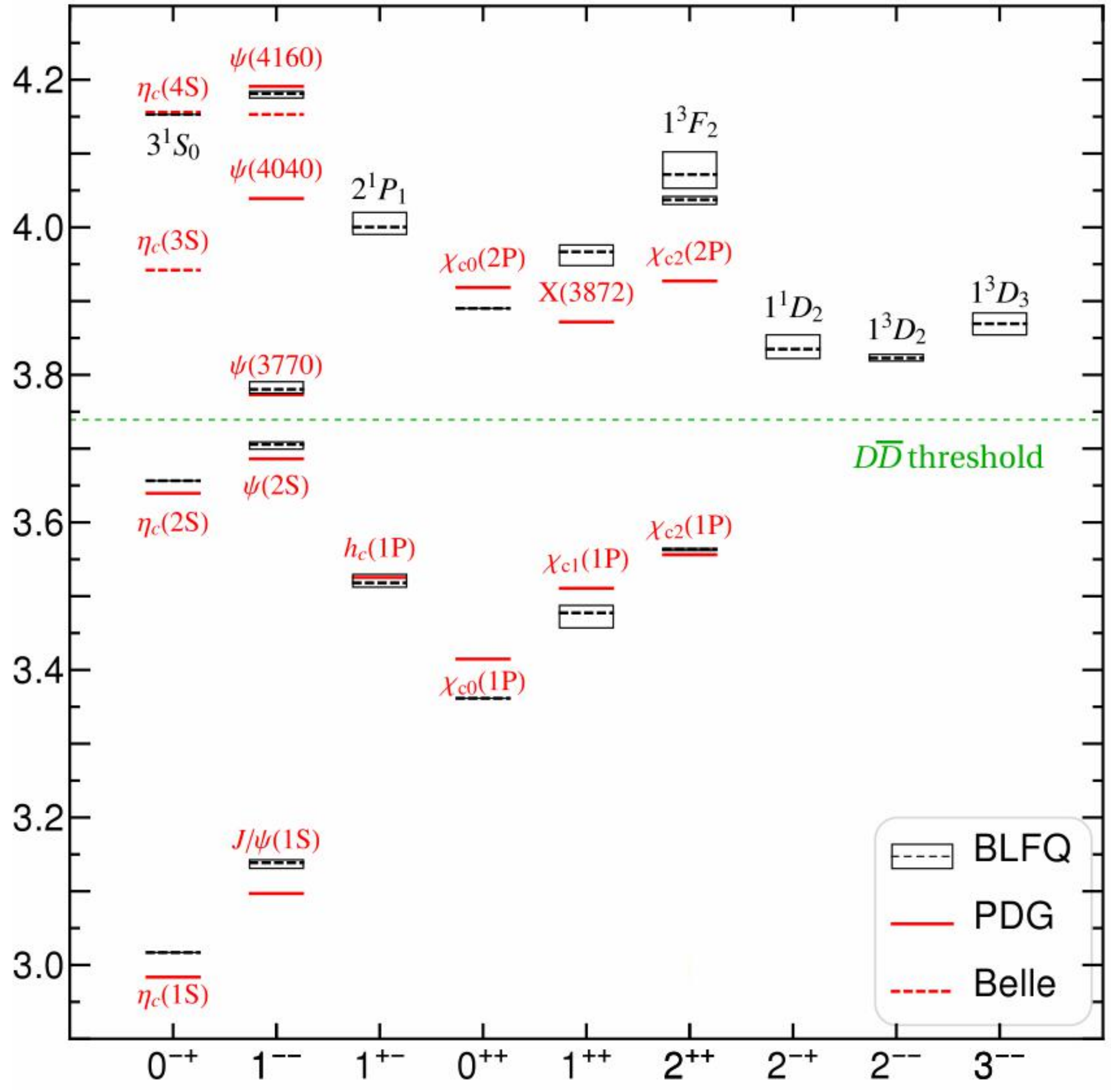
- X(3872)
  - 质量不符合预期
  - 衰变中同位旋破坏
  - 质量接近$D^0\bar{D}^{*0}$阈值
    - 分子态？



D^0–$\overline{D^{*0}}$ **“molecule”**



Diquark–diantiquark

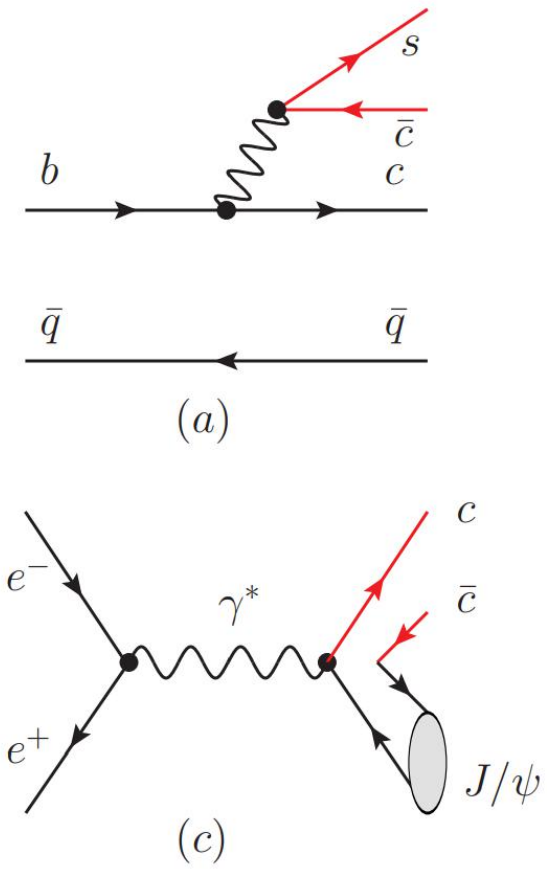


图片来源

更多的奇特态被发现

Chin. Sci. Bull. 59, 3815-3830 (2014)

- 多种产生机制



A [1–5]	B [6–10]	C [11, 12]	D [13–15]	E [16–20]
$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_b(10610)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_b(10650)$
$Z^+(4430)$	$Y(4360)$	–	$Z(3930)$	$Z_c(3900)$
$Z^+(4051)$	$Y(4660)$	–	–	$Z_c(4025)$
$Z^+(4248)$	$Y(4630)$	–	–	$Z_c(4020)$
$Y(4140)$	–	–	–	$Z_c(3885)$
$Y(4274)$	–	–	–	–

LHCb实验上奇特强子态研究

- 新强子态的寻找
  - 拼图游戏

- 更多相关测量
  - 基本性质
    - 质量、自旋、宇称、同位旋
  - 和其他物质相互作用
    - 产生
    - 衰变

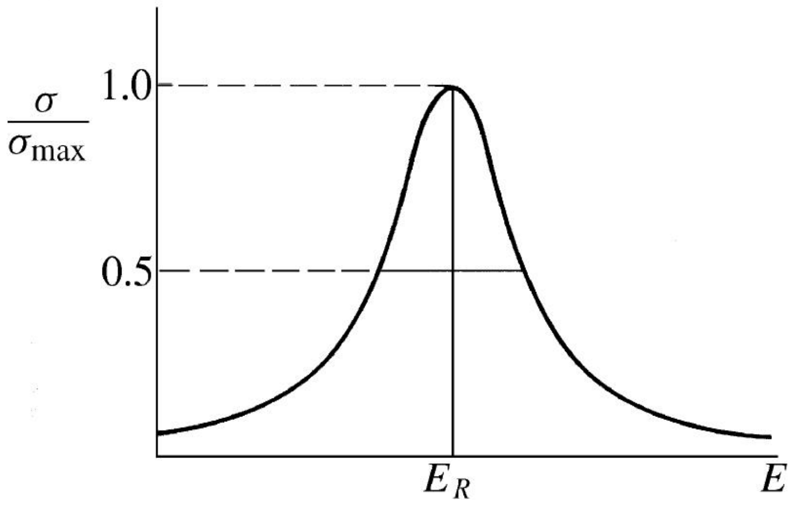
新奇特态的寻找

- 末态的运动学分布

- 共振峰

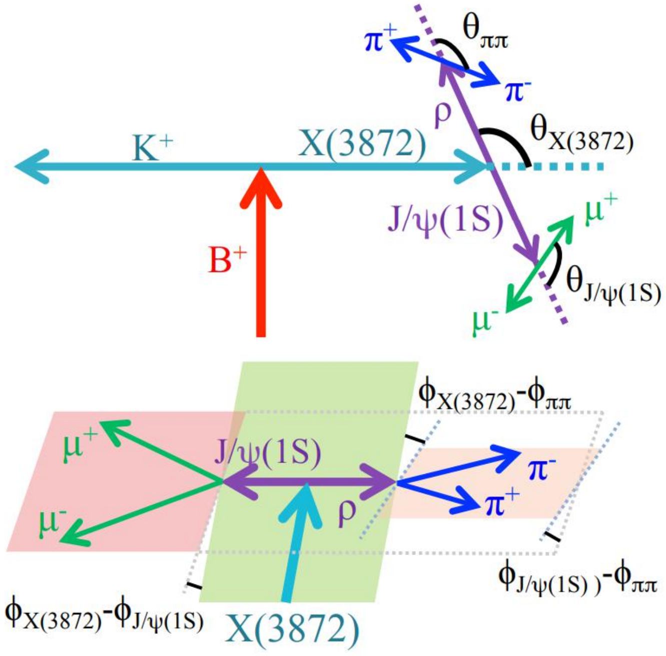
$$\chi(E) = \frac{K}{(E - E_R) - i\Gamma}$$

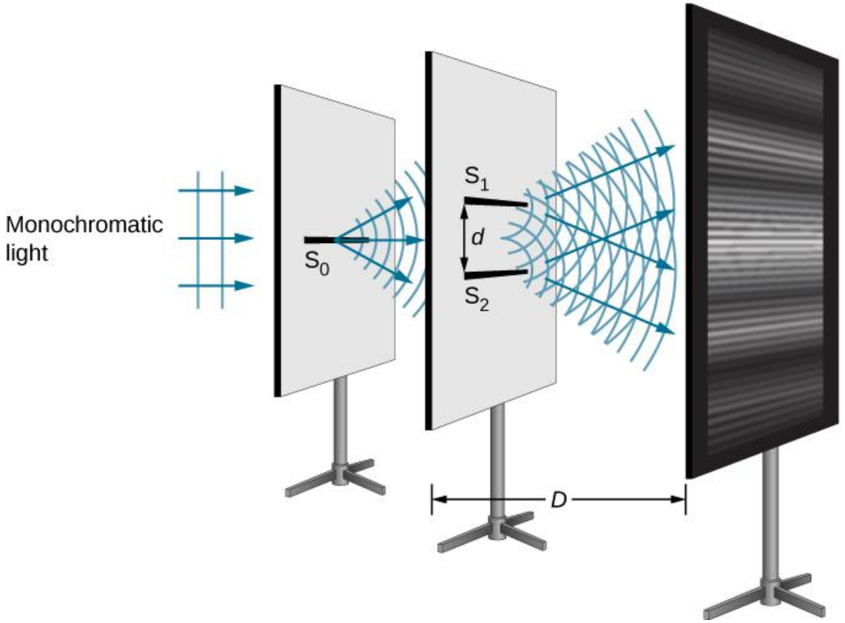
$$\sigma(E) \propto \chi^*(E)\chi(E) = \sigma_{max}\frac{\Gamma^2/4}{(E - E_R)^2 + \Gamma^2/4}$$



- 多个过程的相互干涉
  - 增强或减弱
  - 相位变化

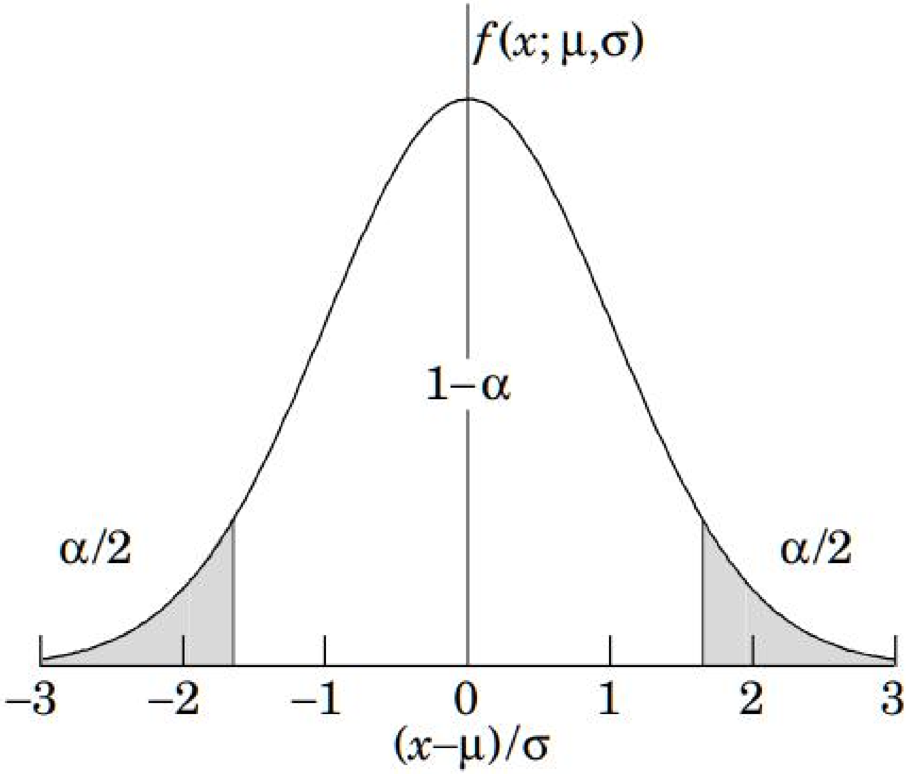
- 已有理论和实验的指导
  - 对称性
    - 味对称性
    - 同位旋
    - 重夸克……





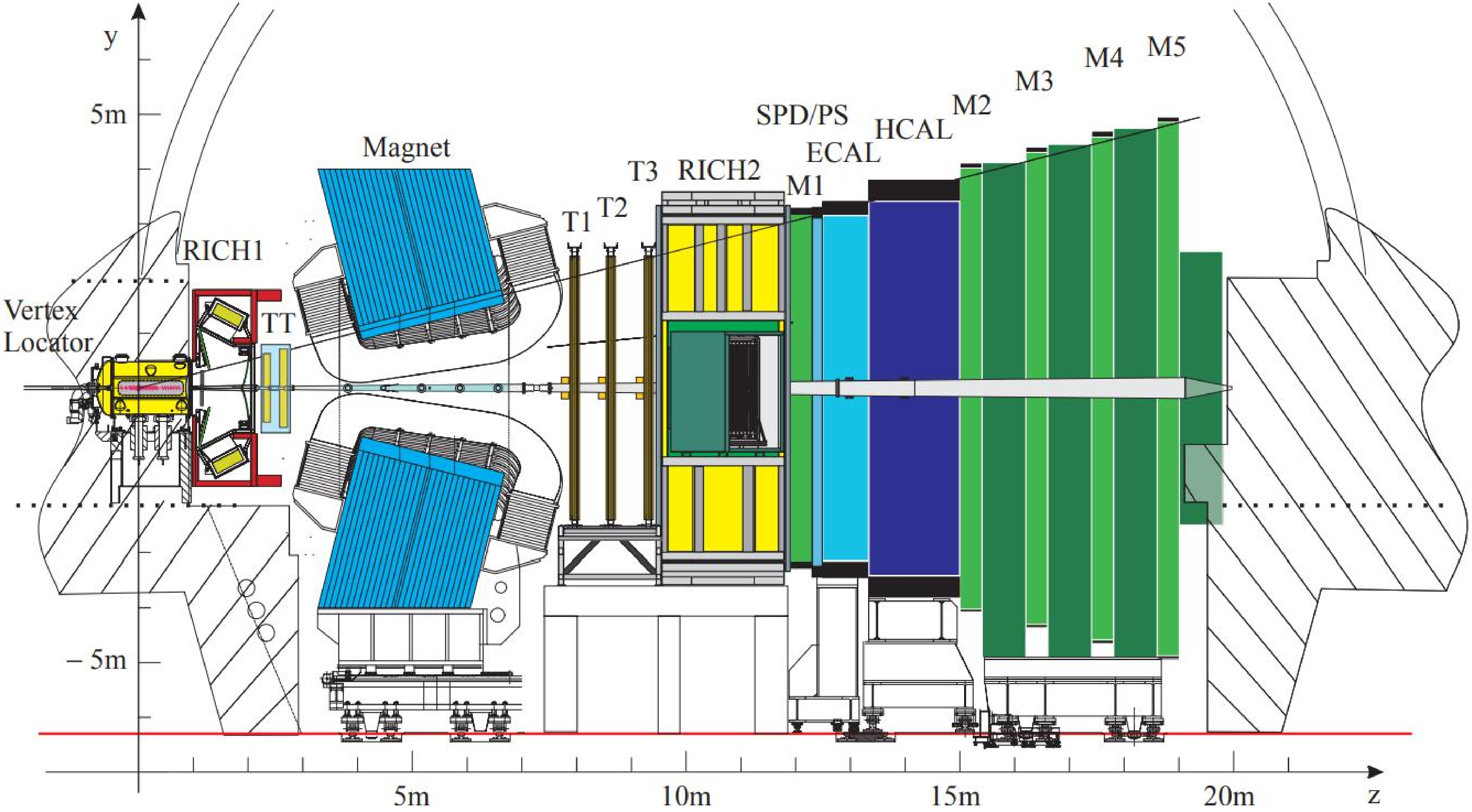
显著度

- 3σ “evidence”
- 5σ “discovery”
- 显著度越高，数据与本底期望值的偏离是由本底涨落造成的可能性越小



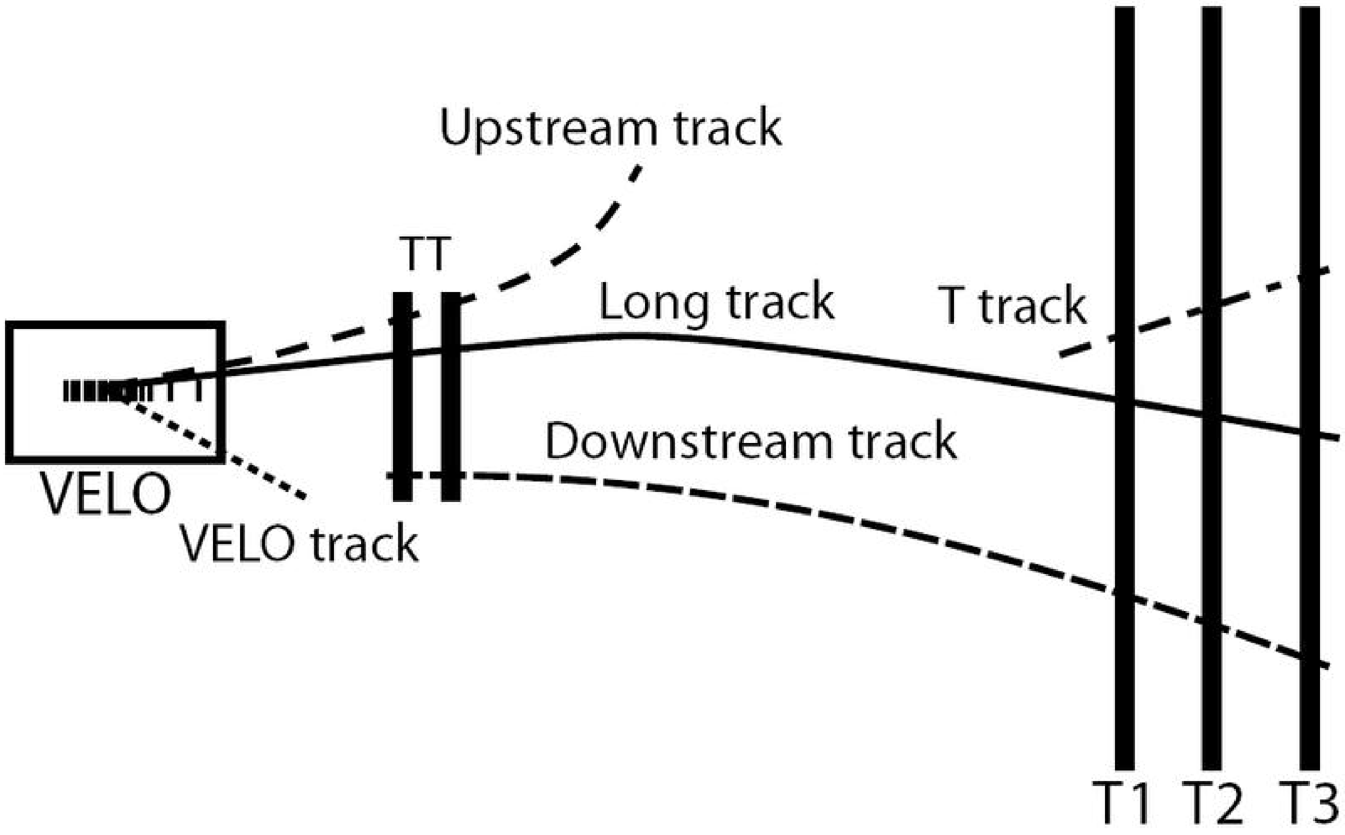
概率 α	偏离 δ	α	δ
0.3173	1σ	0.2	1.28σ
4.55×10^{-2}	2σ	0.1	1.64σ
2.7×10^{-3}	3σ	0.05	1.96σ
6.3×10^{-5}	4σ	0.01	2.58σ
5.7×10^{-7}	5σ	0.001	3.29σ
2.0×10^{-9}	6σ	10^{-4}	3.89σ

LHCb实验上奇特强子态研究



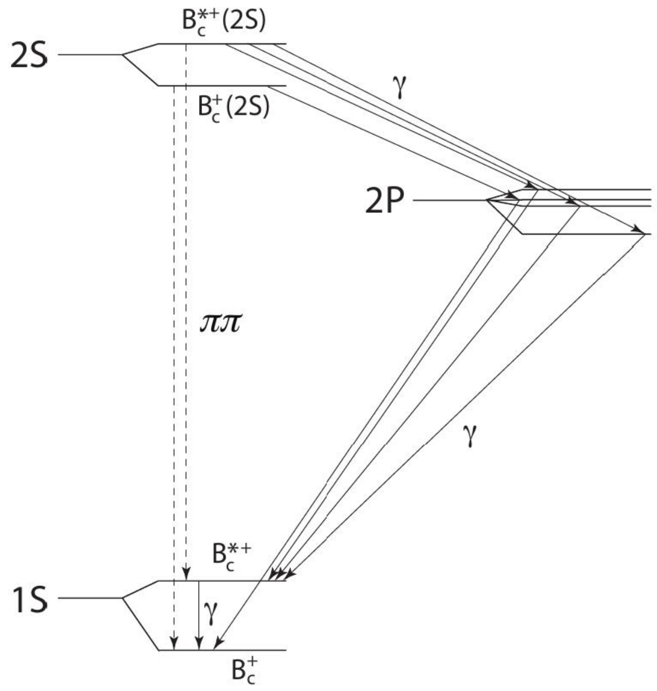
径迹重建

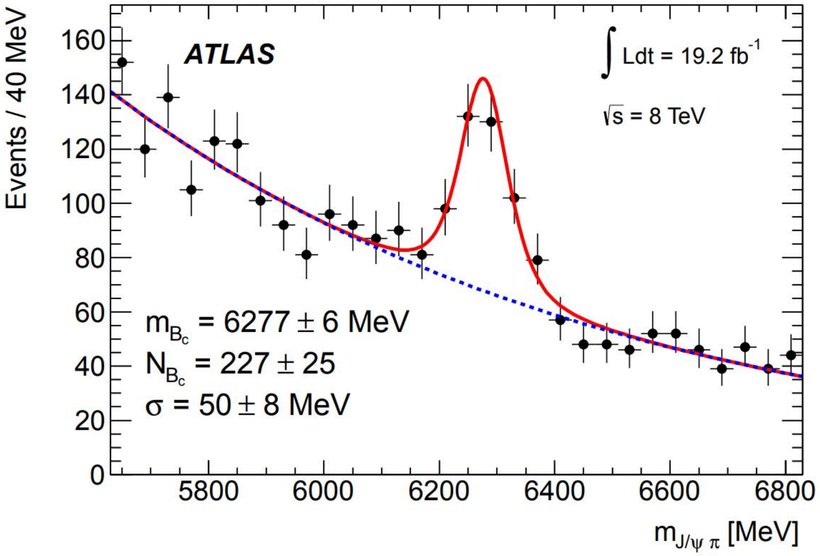
- 带电粒子在磁场下偏转
- 动量的测量
  - $\sigma_p/p \sim 0.5 - 1\%$

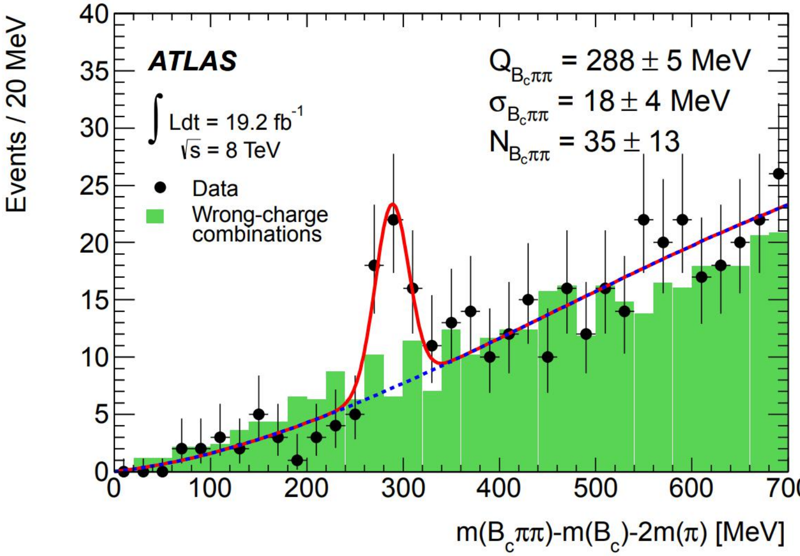


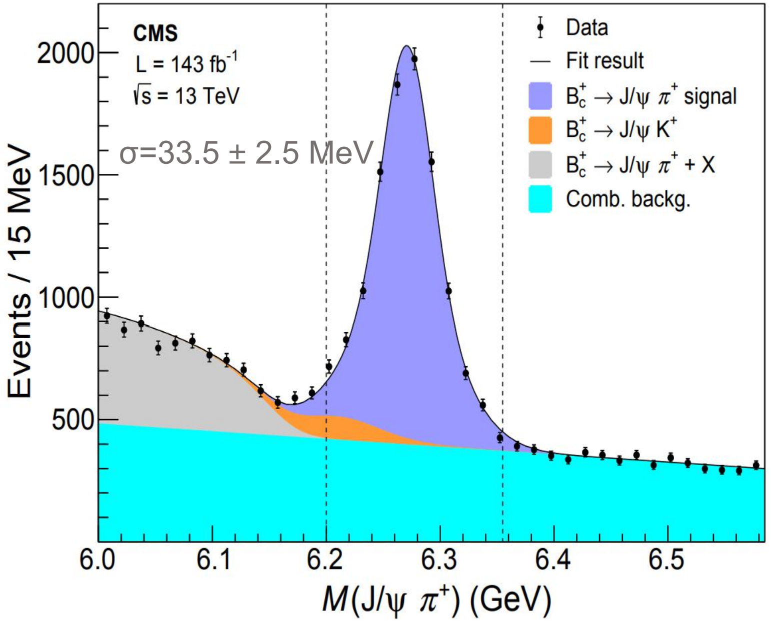
图片来源

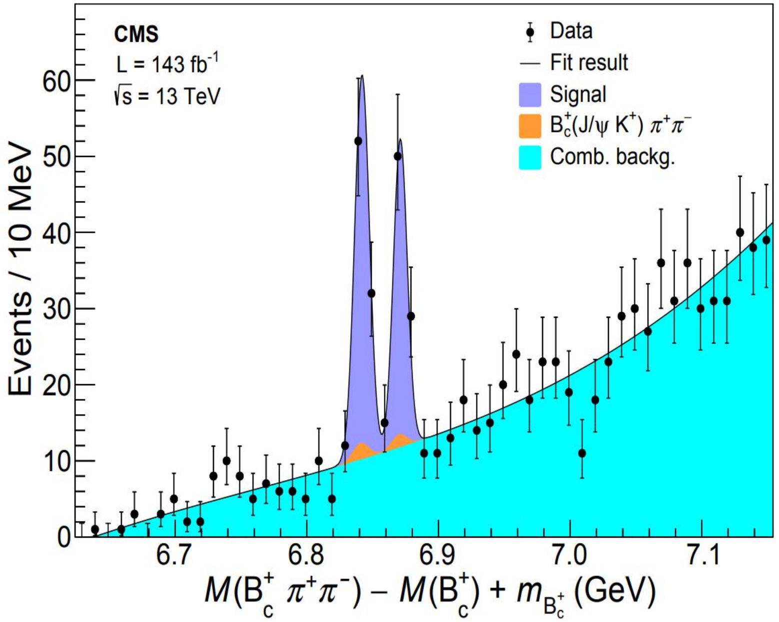
B_c^+ 激发态发现


$B_c^{*+}(2S)$
2S
$B_c^+(2S)$
γ
2P
ππ
γ
B_c^{*+}
1S
γ
B_c^+

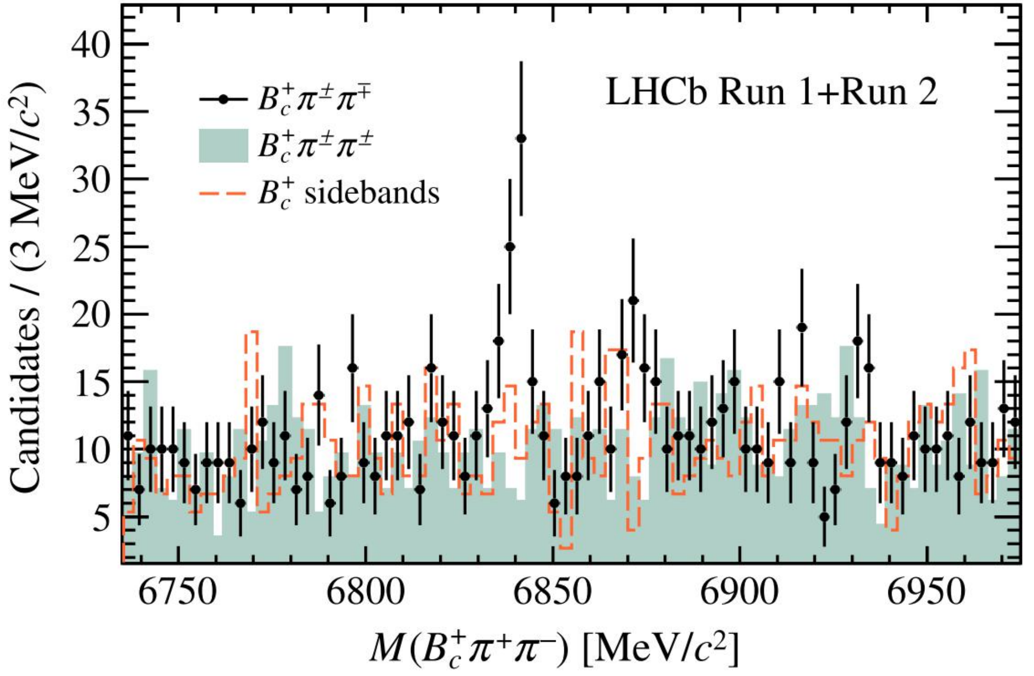

ATLAS
$\int Ldt = 19.2\ fb^{-1}$
$\sqrt{s} = 8$ TeV
$m_{B_c} = 6277 \pm 6$ MeV
$N_{B_c} = 227 \pm 25$
$\sigma = 50 \pm 8$ MeV
Events / 40 MeV
$m_{J/\psi\ \pi}$ [MeV]


ATLAS
$\int Ldt = 19.2\ fb^{-1}$
$\sqrt{s} = 8$ TeV
$Q_{B_c\pi\pi} = 288 \pm 5$ MeV
$\sigma_{B_c\pi\pi} = 18 \pm 4$ MeV
$N_{B_c\pi\pi} = 35 \pm 13$
Data
Wrong-charge combinations
Events / 20 MeV
$m(B_c\pi\pi)-m(B_c)-2m(\pi)$ [MeV]

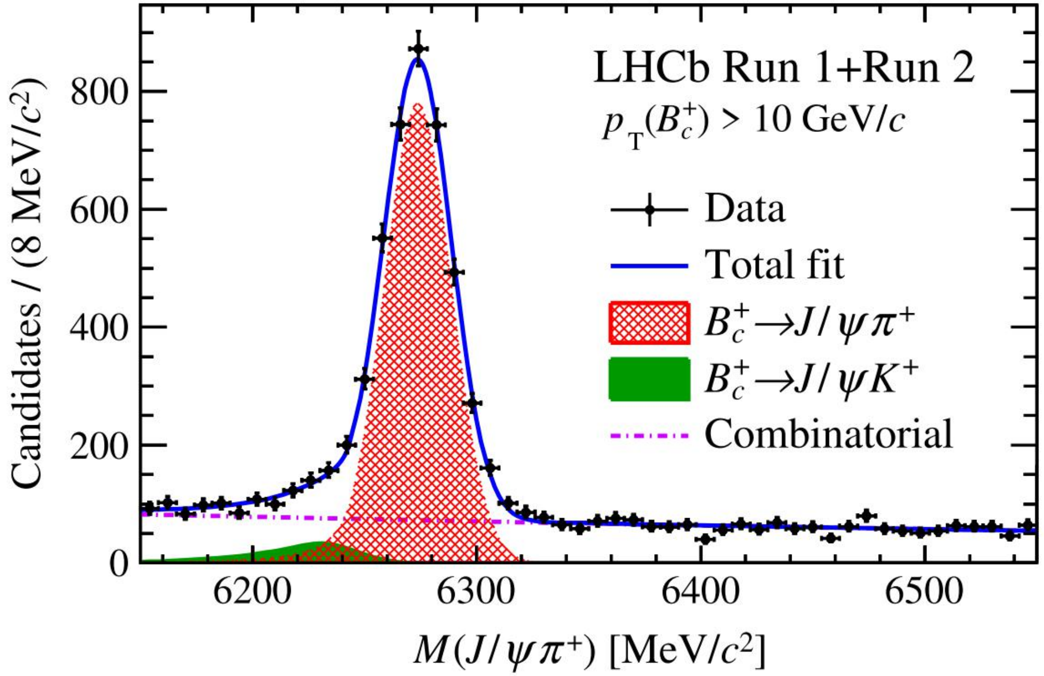

CMS
L = 143 fb^{-1}
$\sqrt{s}$ = 13 TeV
σ=33.5 ± 2.5 MeV
Data
Fit result
$B_c^+ \to J/\psi\ \pi^+$ signal
$B_c^+ \to J/\psi\ K^+$
$B_c^+ \to J/\psi\ \pi^+ + X$
Comb. backg.
Events / 15 MeV
$M(J/\psi\ \pi^+)$ (GeV)

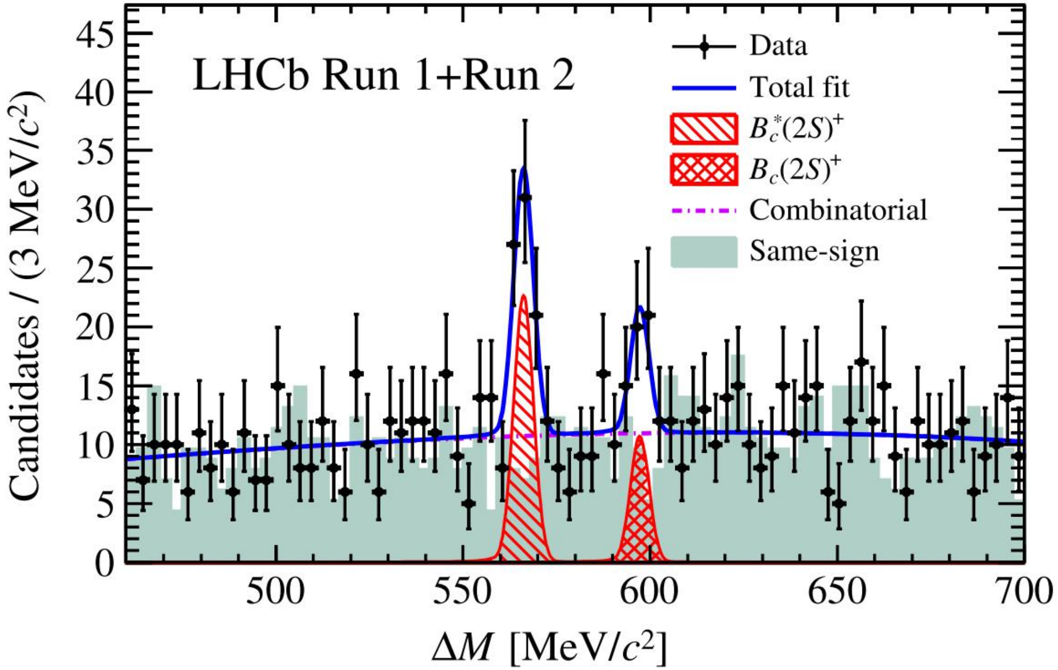

CMS
L = 143 fb^{-1}
$\sqrt{s}$ = 13 TeV
Data
Fit result
Signal
$B_c^+(J/\psi\ K^+)\ \pi^+\pi^-$
Comb. backg.
Events / 10 MeV
$M(B_c^+\ \pi^+\pi^-) - M(B_c^+) + m_{B_c^+}$ (GeV)

- LHCb
    - 分辨率好
    - 对撞亮度低



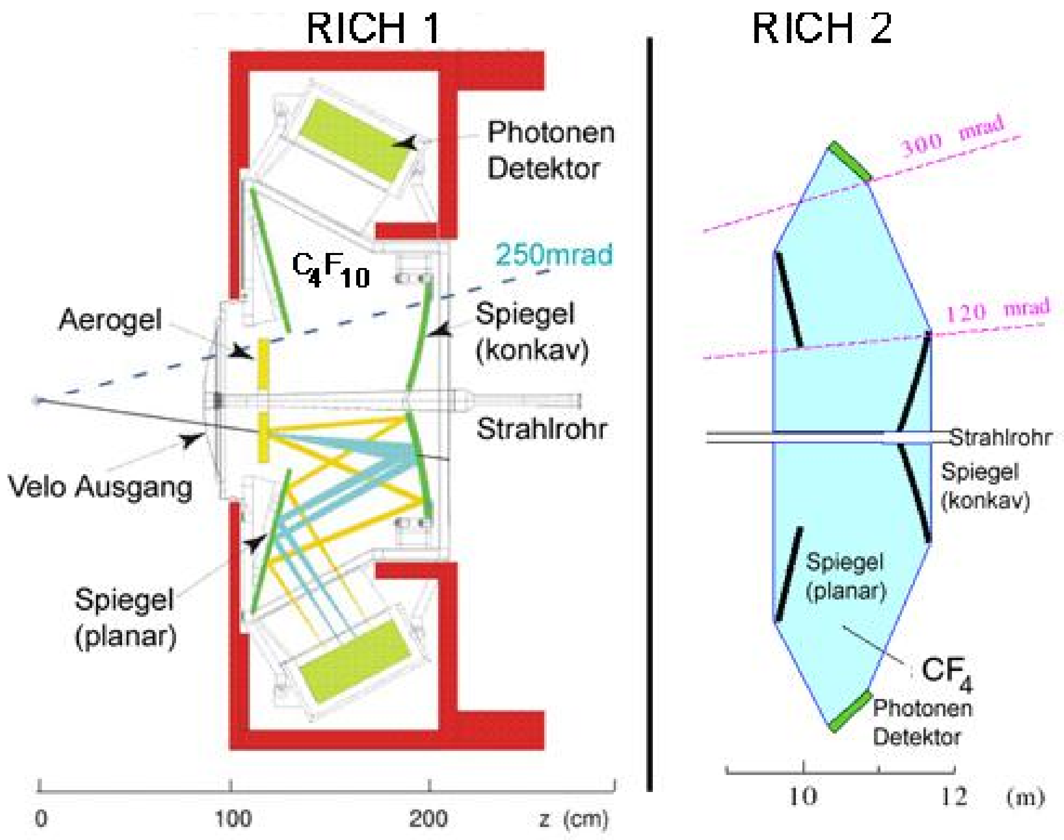
σ=15.1 ± 0.3 MeV

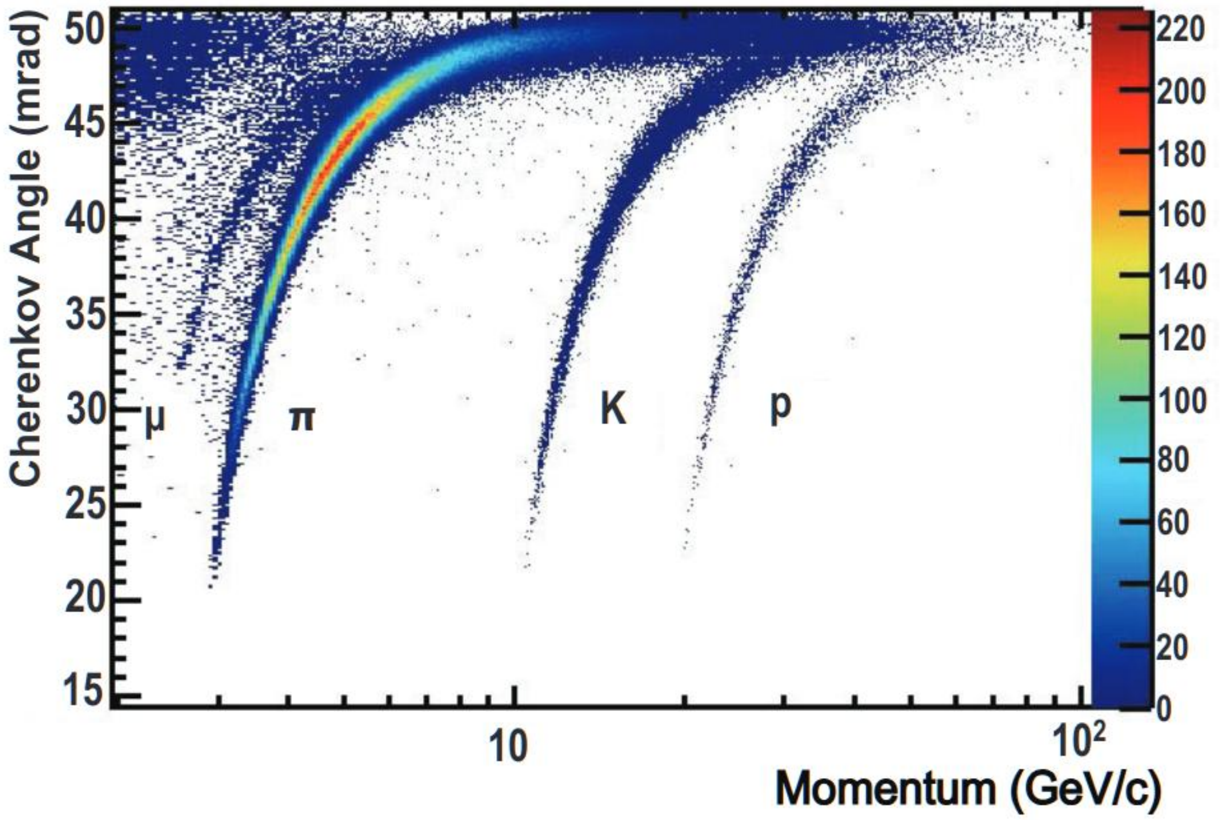




粒子鉴别

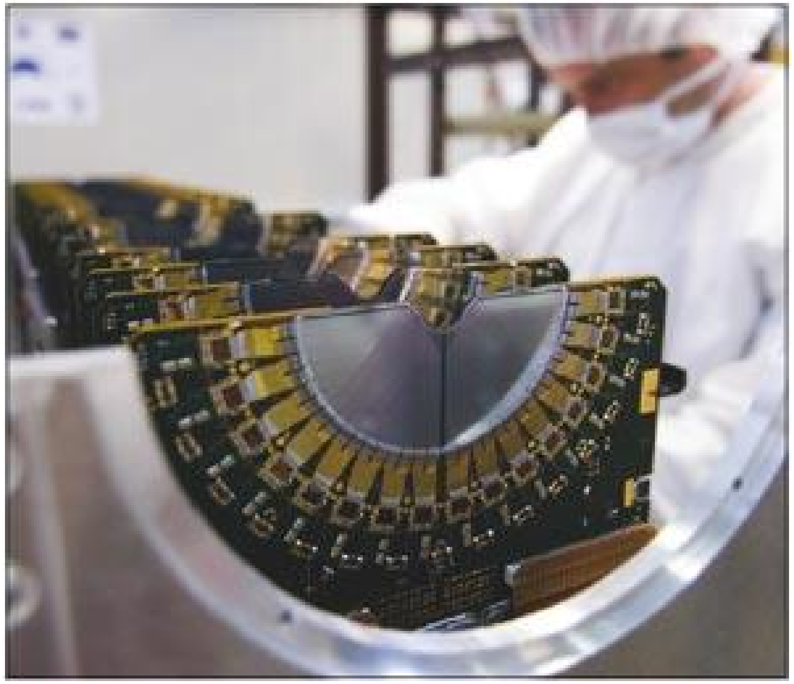
- 切伦科夫辐射探测器

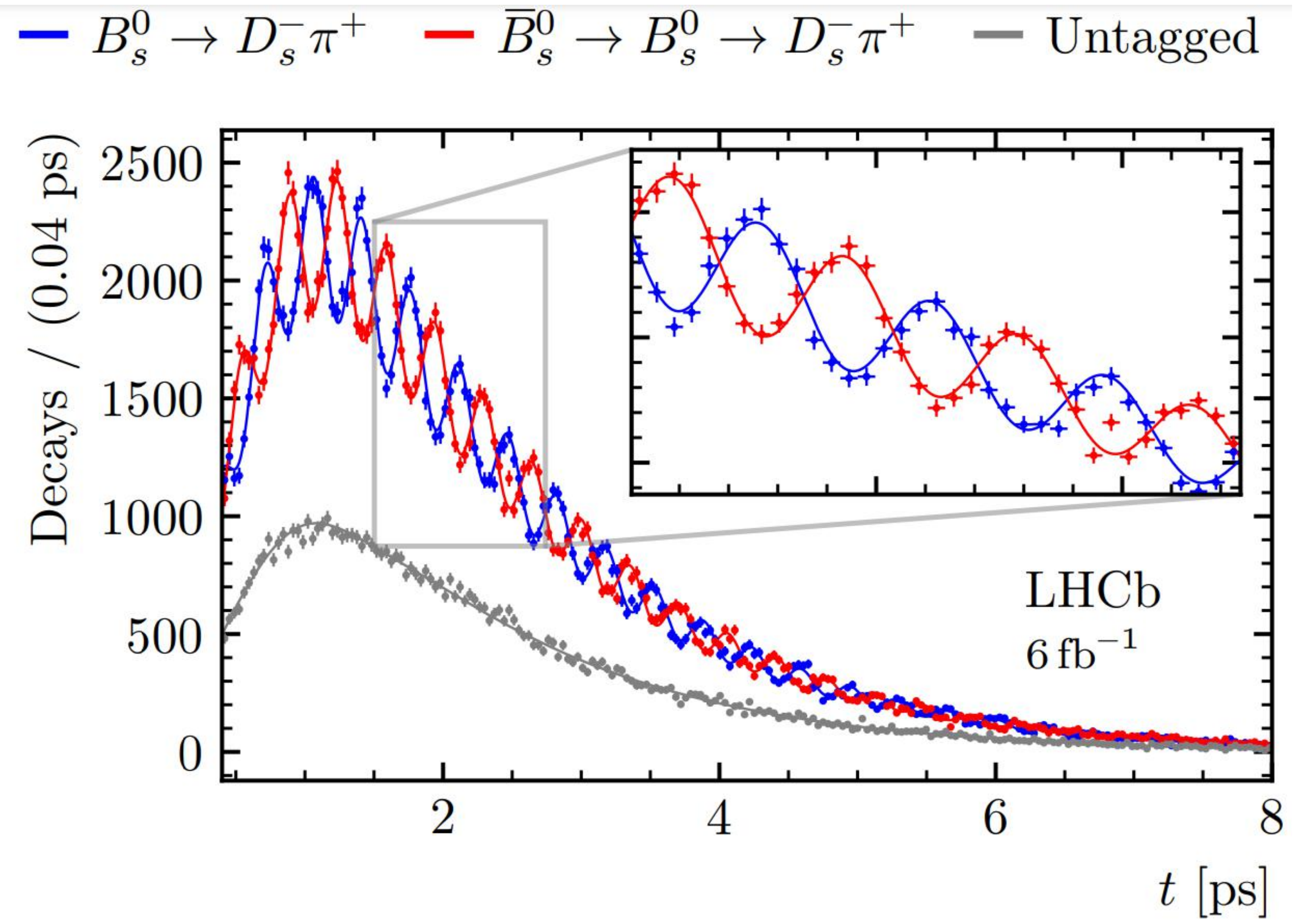




顶点重建

- 顶点探测器

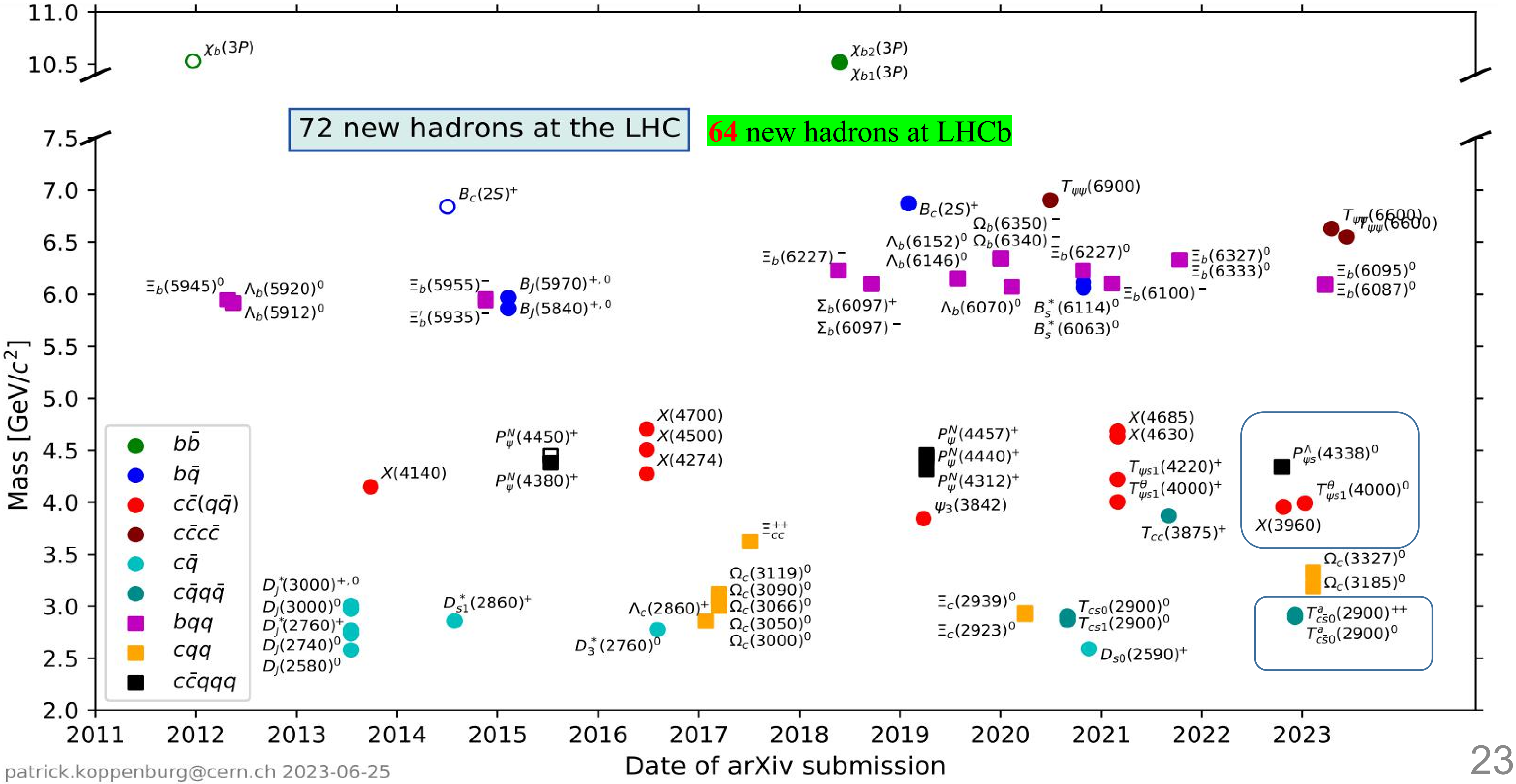




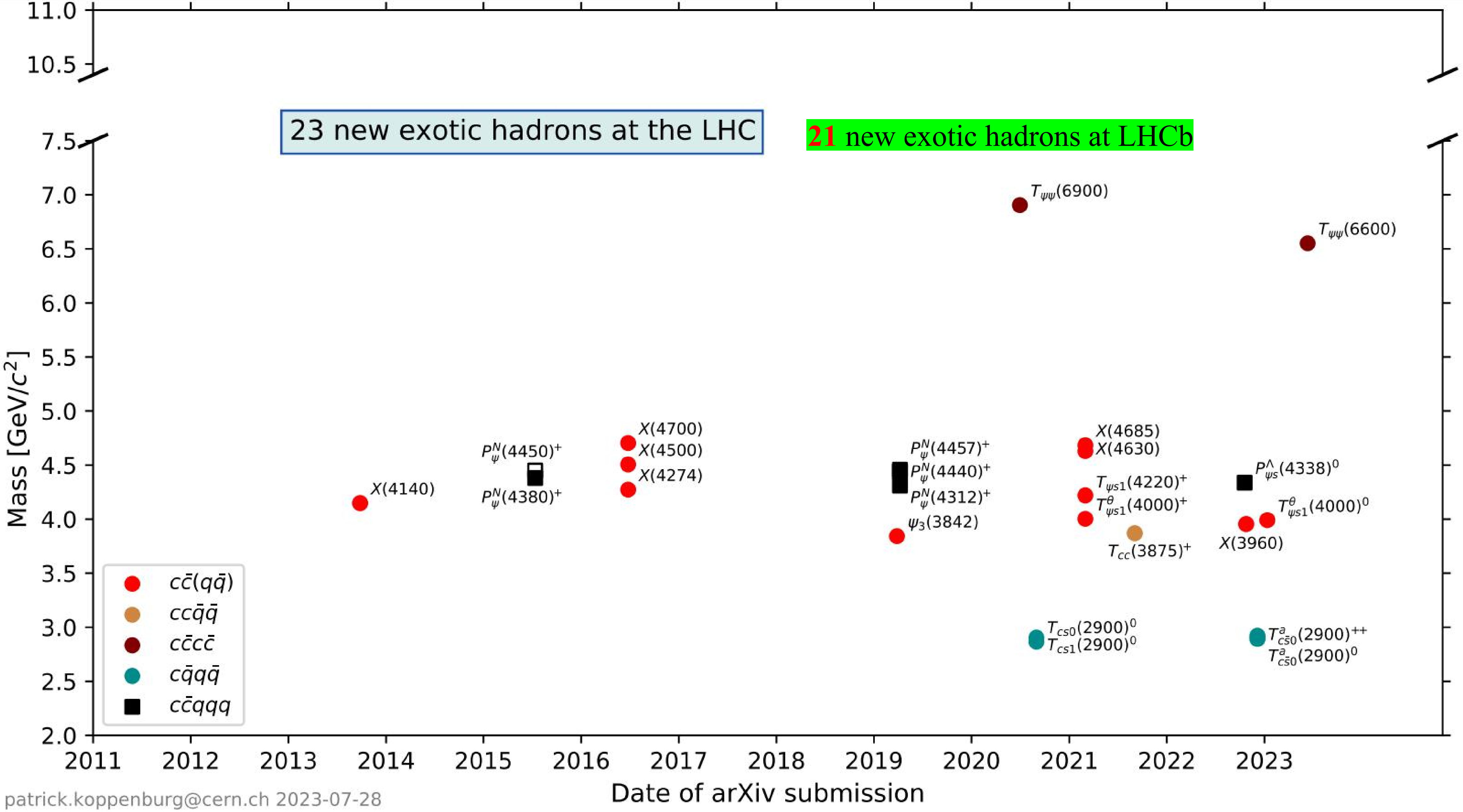
Nature Phys. 18 (2022) 1, 1-5

LHCb的优势

- 专为b强子和c强子物理设计 -- 探测精度高
- 对撞能量高，可以产生b重子



奇特态

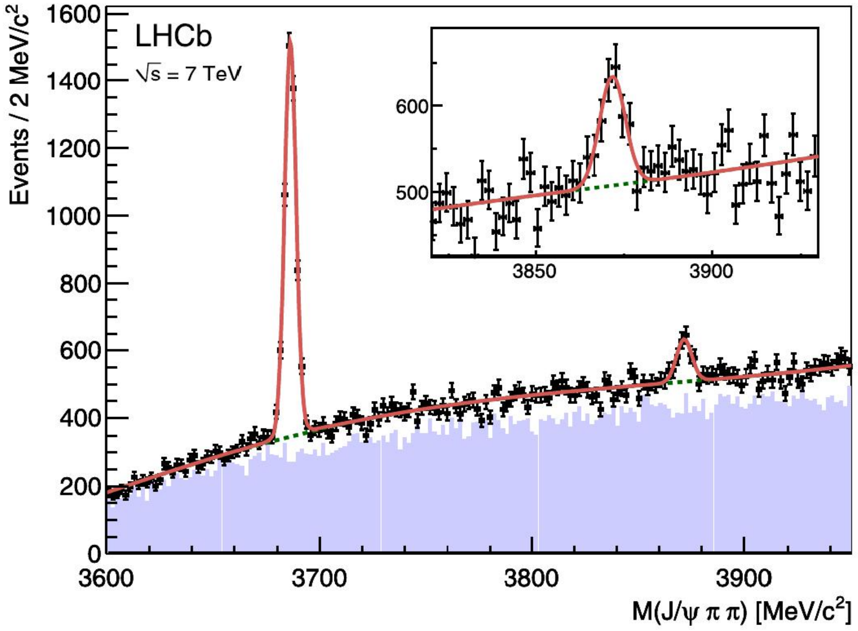


patrick.koppenburg@cern.ch 2023-07-28

X(3872)基本性质

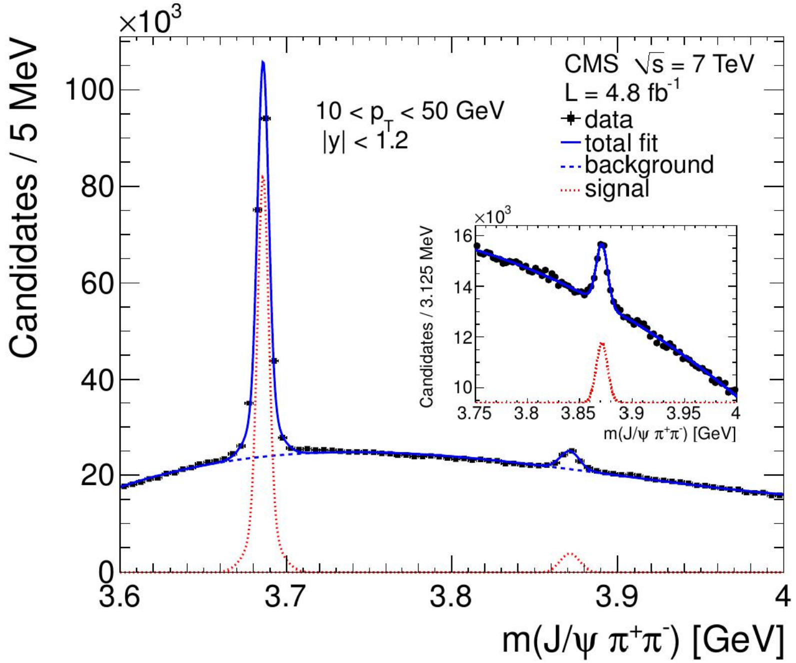
- 独立验证其存在

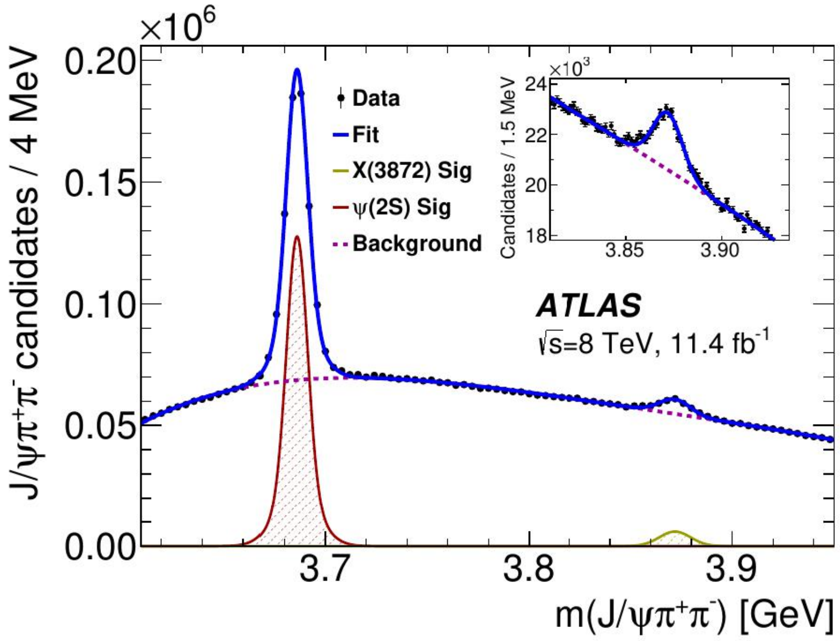
Eur. Phys. J. C 72 (2012) 1972



34.7 pb^{-1}

High Energy Phys. 04 (2013) 154

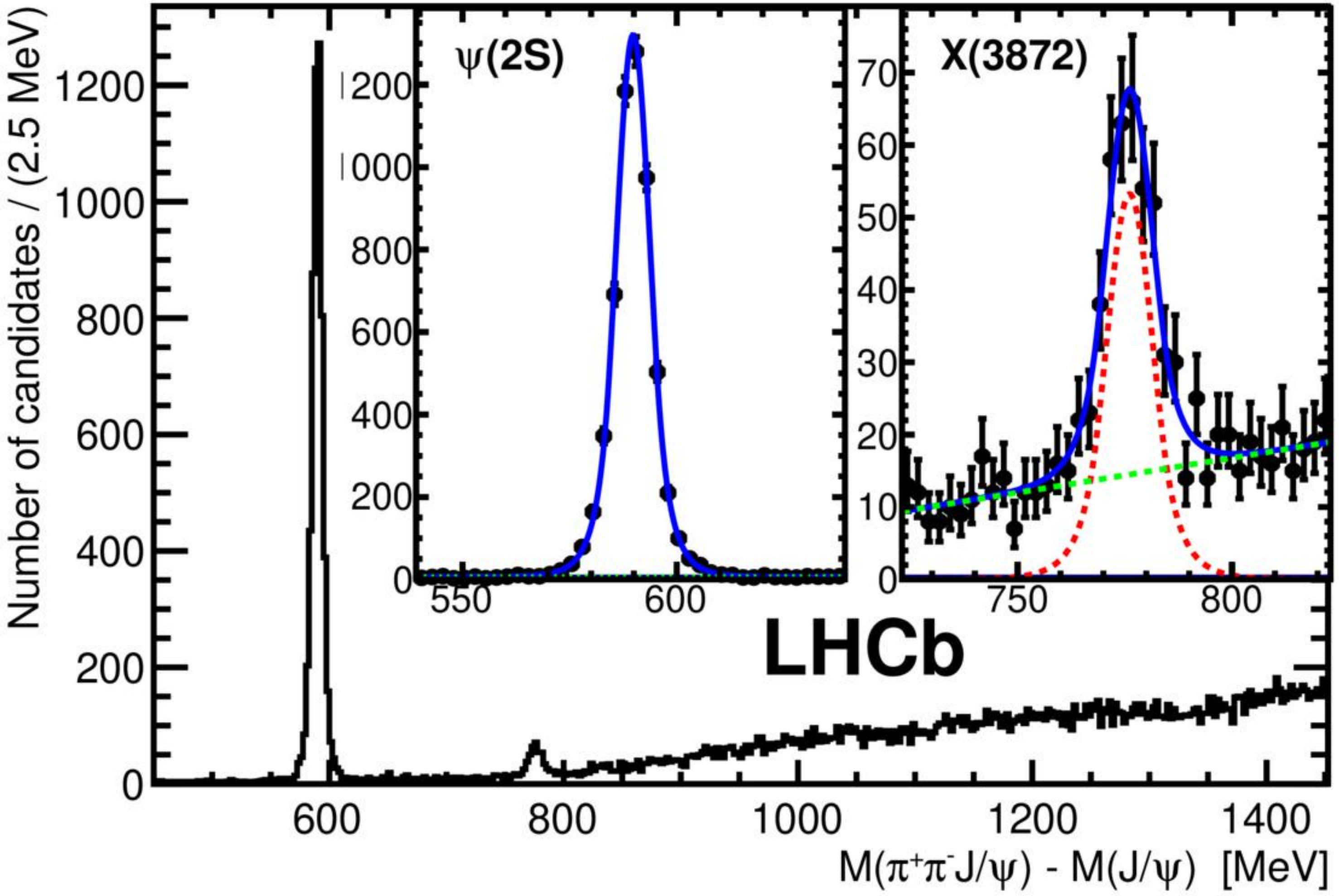


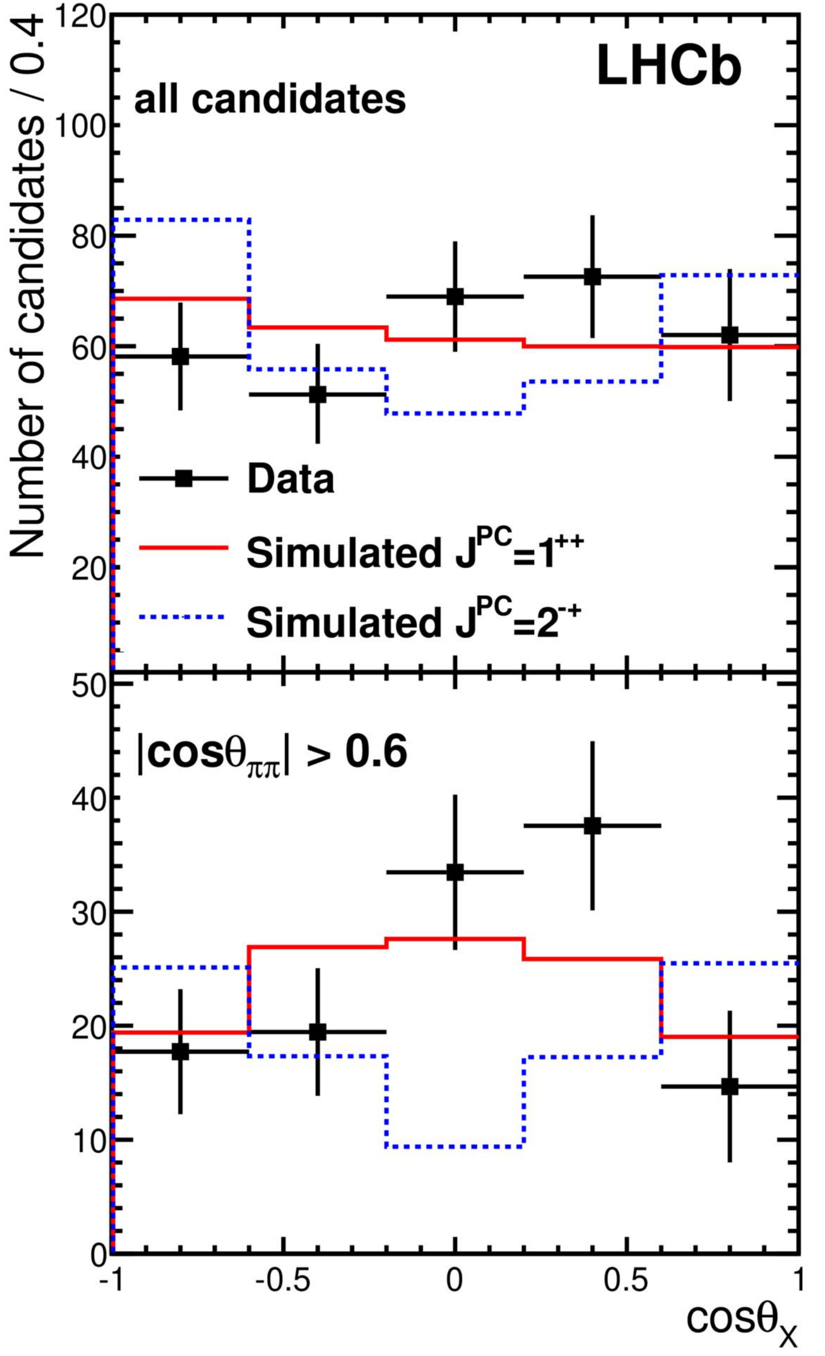


J. High Energy Phys. 01 (2017) 117

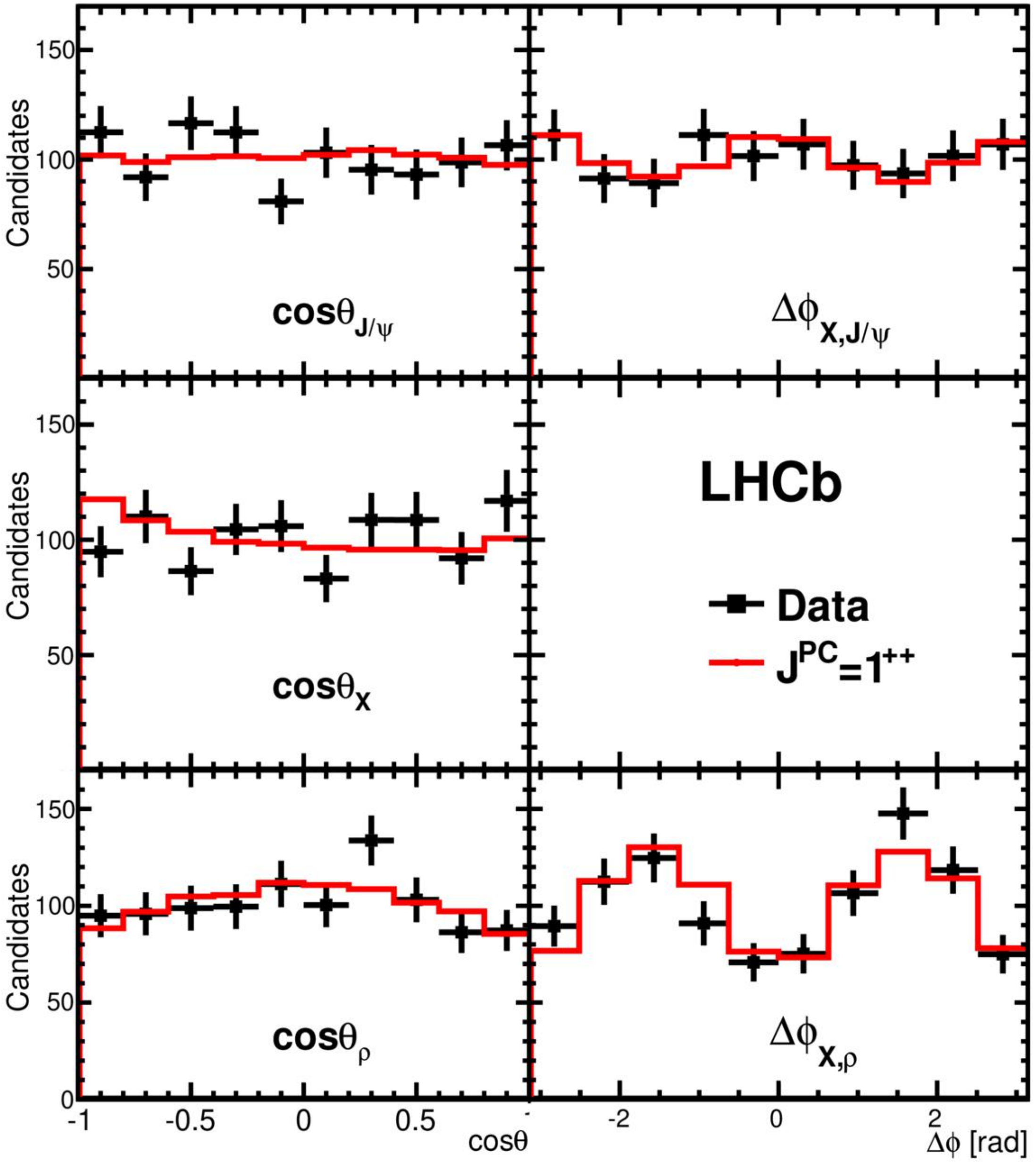
自旋、量子数的测量：$J^{PC}=1^{++}$

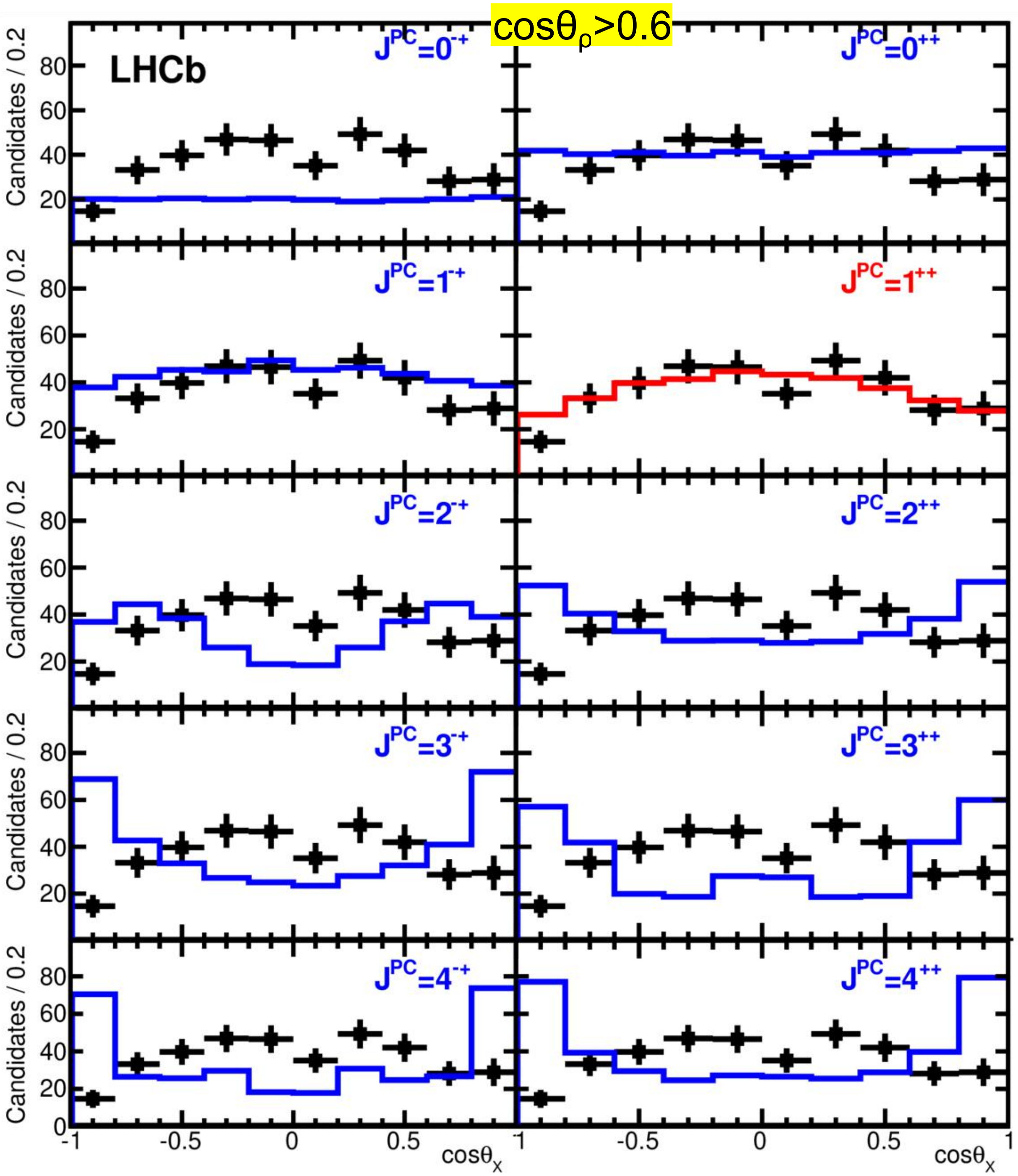
- PRL 110 (2013) 222001





PRD92 (2015) 011102(R)



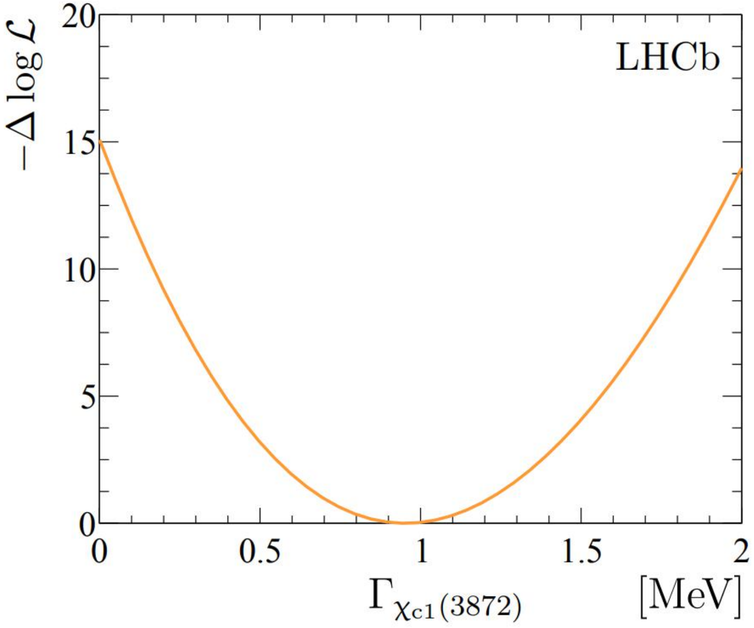


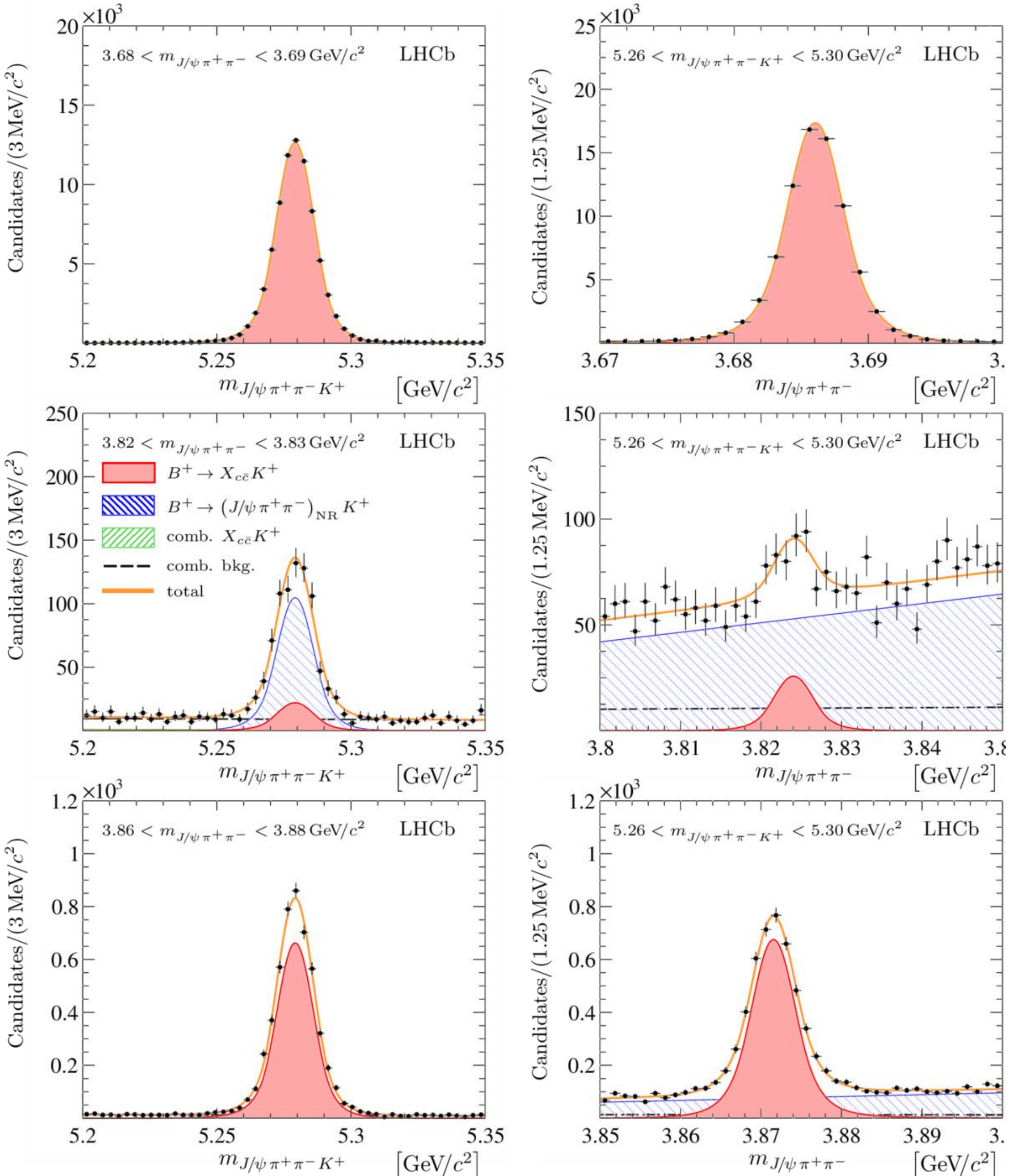
质量的精确测量

- $B^+ \to J/\psi\pi^+\pi^-K^+$事例

$$m_{\chi_{c1}(3872)} - m_{\psi(2S)} = 185.49 \pm 0.06 \pm 0.03\,\mathrm{MeV}/c^2$$

$$\Gamma^{\mathrm{BW}}_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21\,\mathrm{MeV}$$





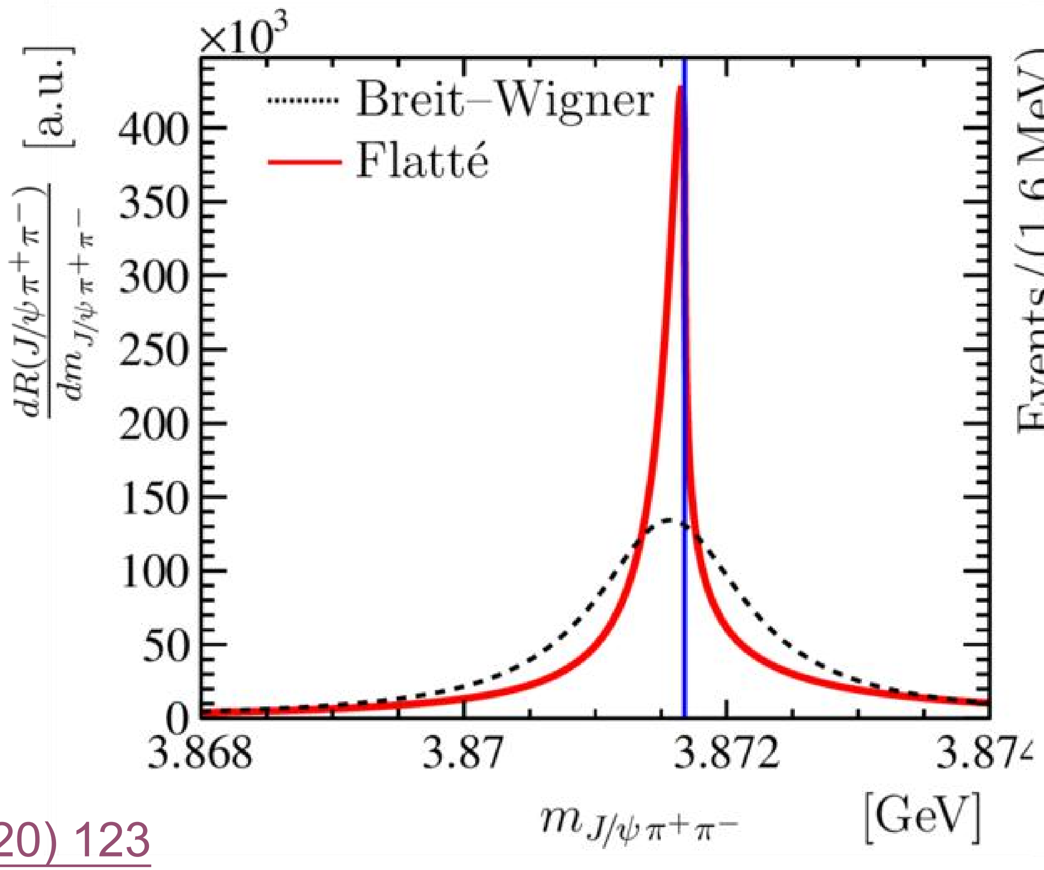
共振态形状测量

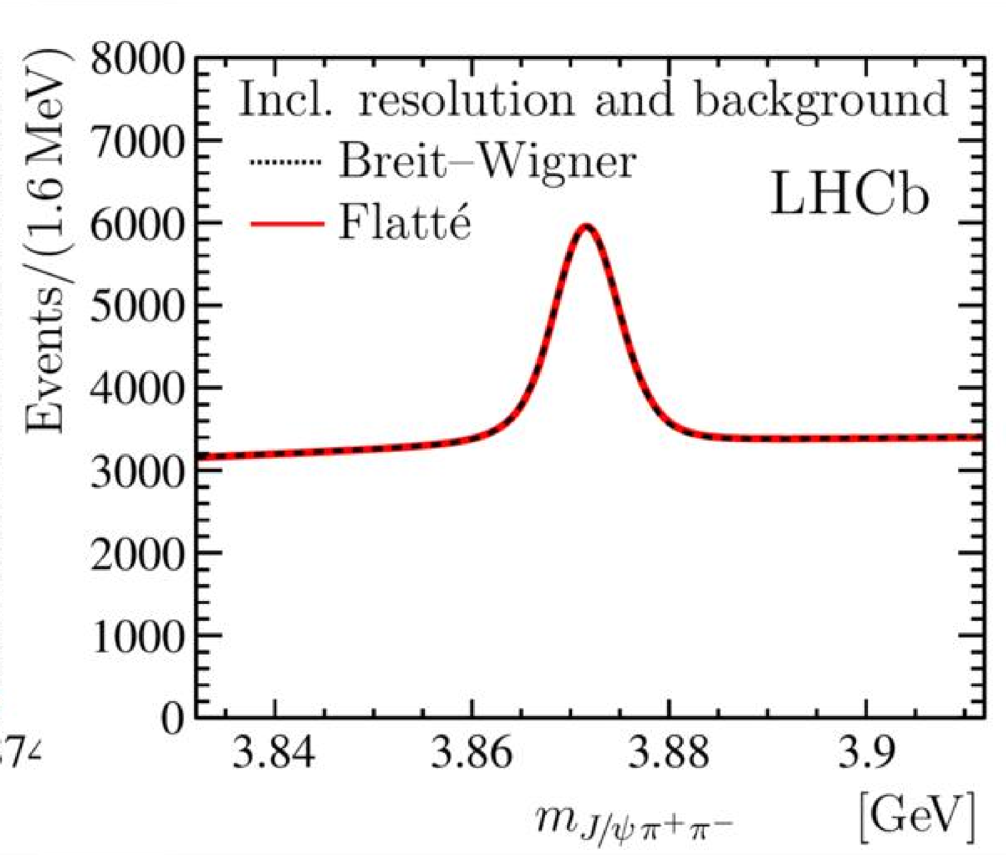
- Breit-Wigner共振态

$$\Delta m = 185.598 \pm 0.067 \pm 0.068\,\text{MeV}$$
$$\Gamma_{\text{BW}} = \quad 1.39 \quad \pm 0.24 \quad \pm 0.10\ \text{MeV}$$

- Flatte 模型

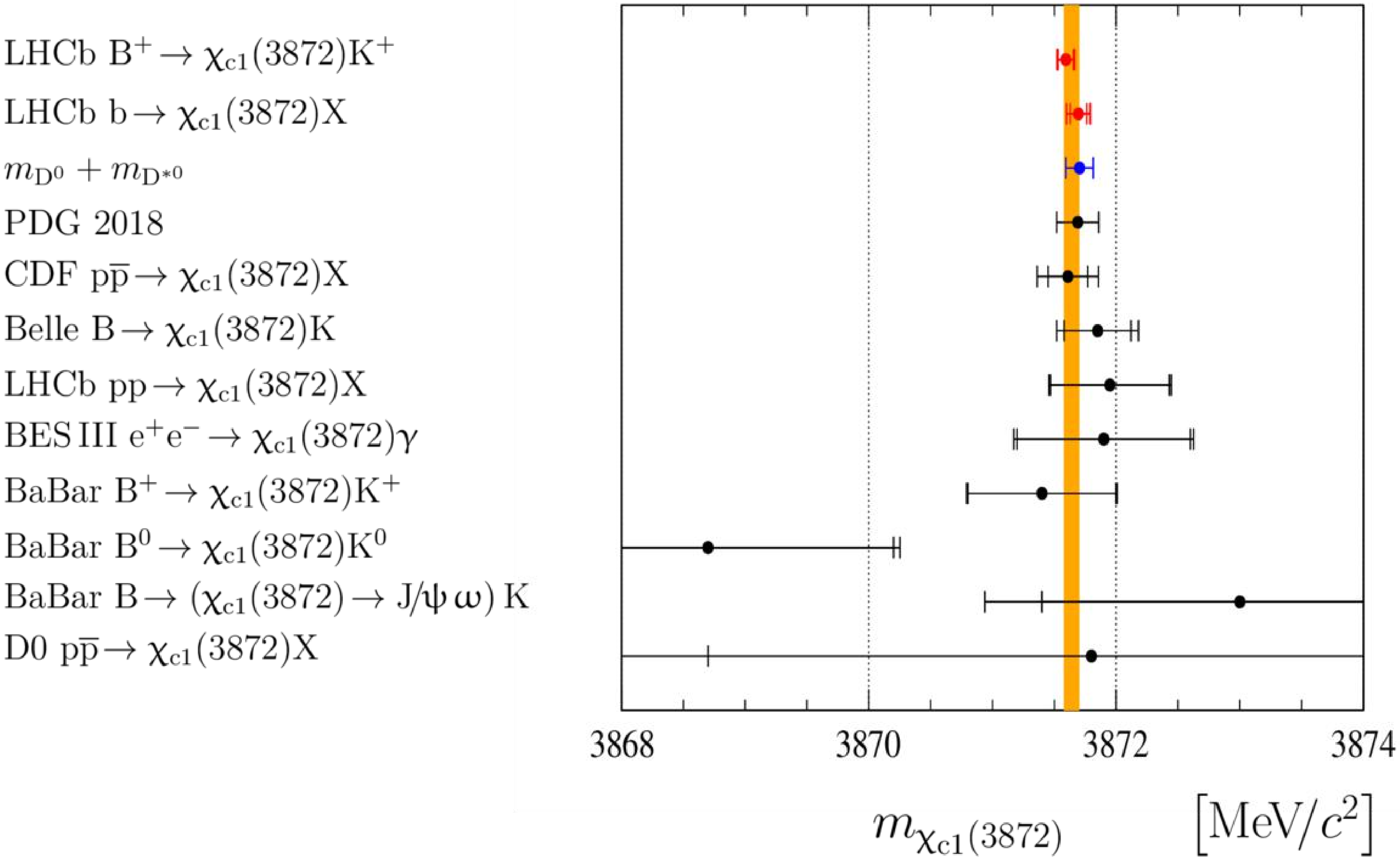
$$\text{mode} = 3871.69^{+0.00+0.05}_{-0.04-0.13}\ \text{MeV}$$
$$\text{FWHM} \quad = 0.22^{+0.07+0.11}_{-0.06-0.13} \quad \text{MeV}$$





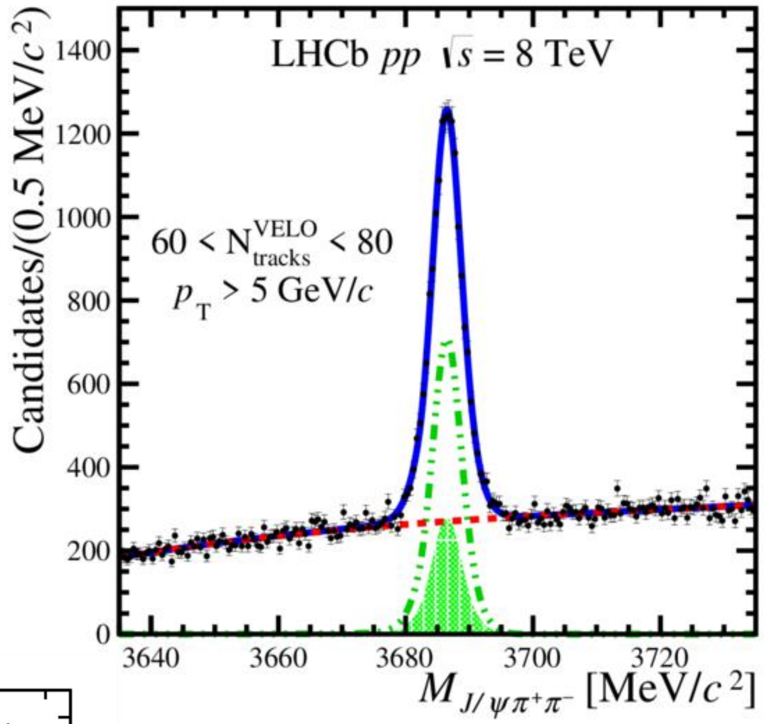
JHEP 08 (2020) 123

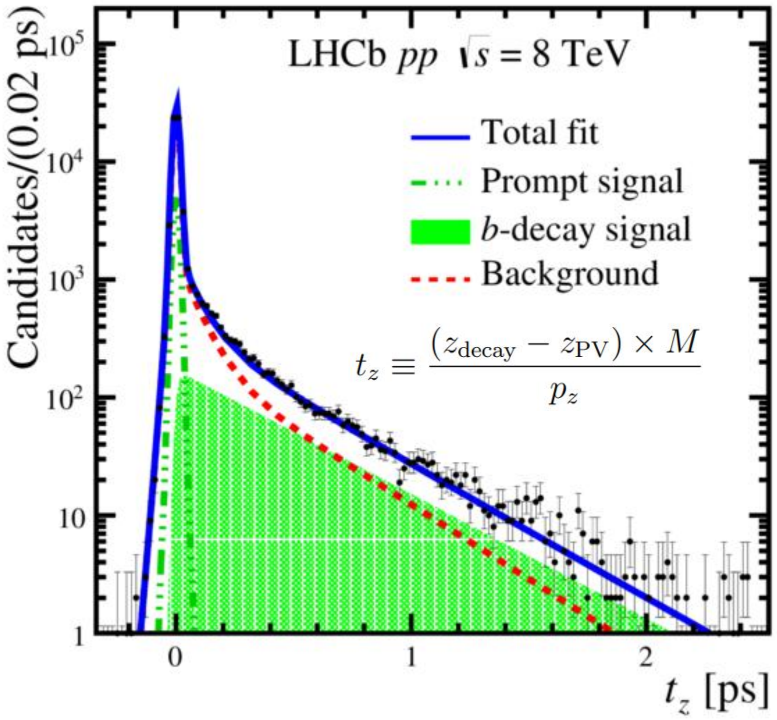
PRD102 (2020) 092005

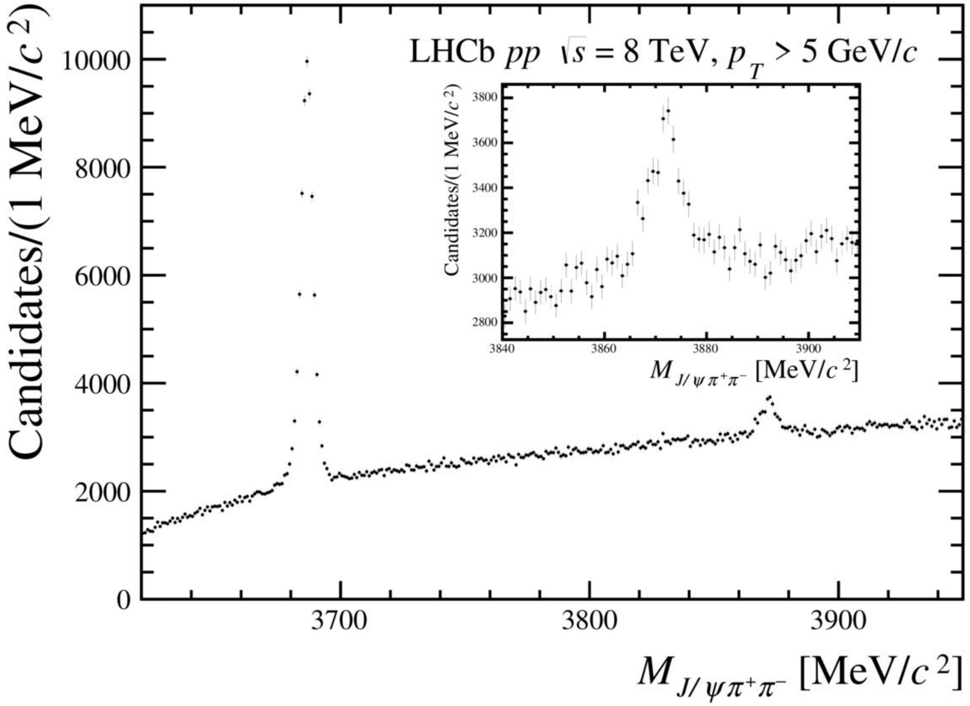


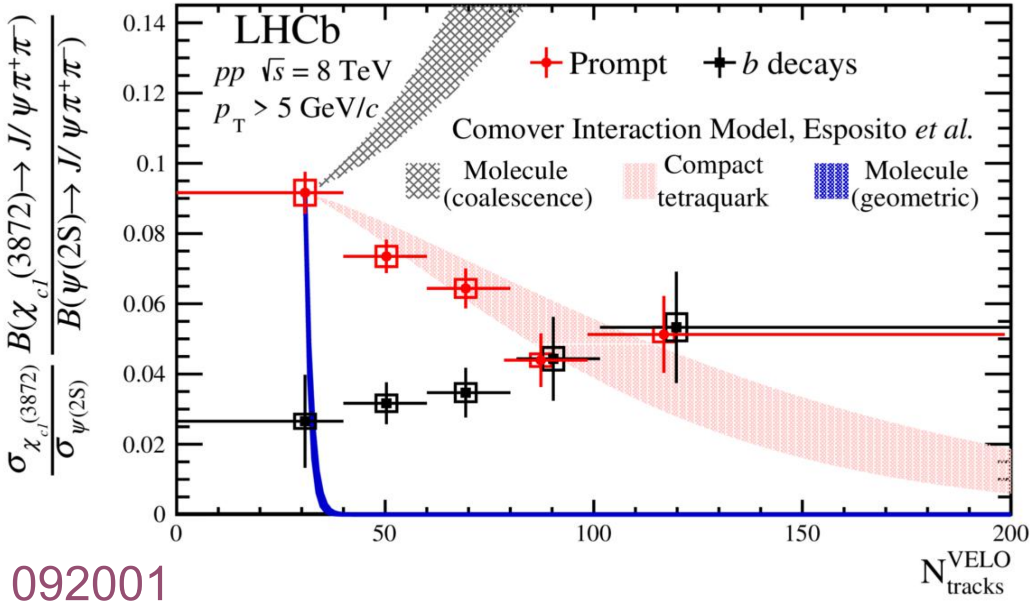
X(3872)产生

- 直接产生-t_z ~0
- b-衰变产生 t_z >0
- 以ψ(2S)为参考
- 检查两个过程产生截面的比值随事径迹个数的变化





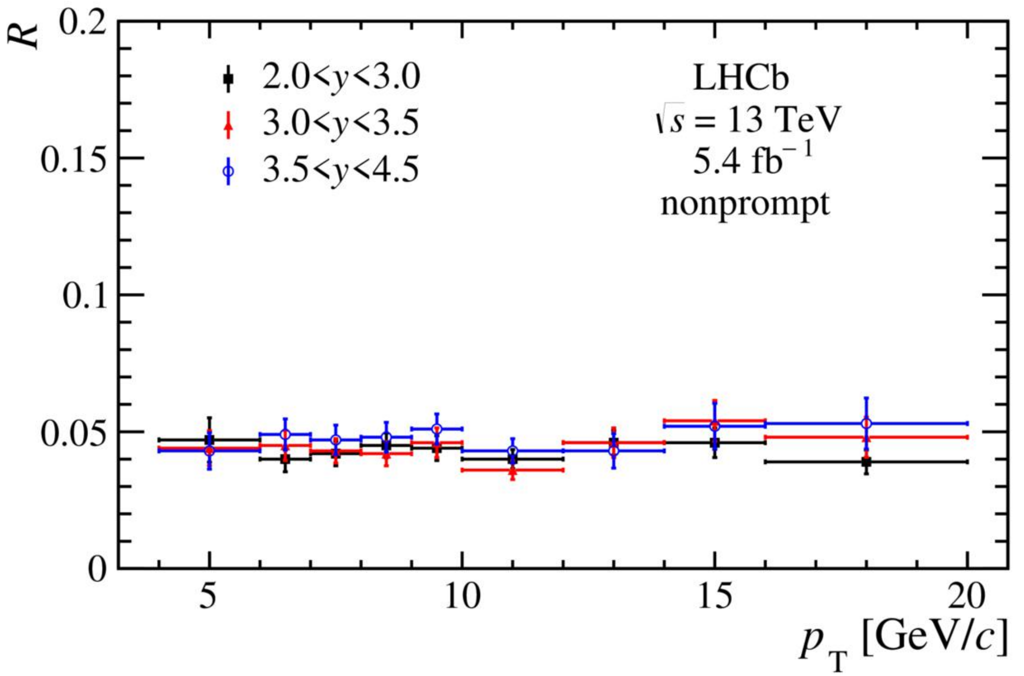


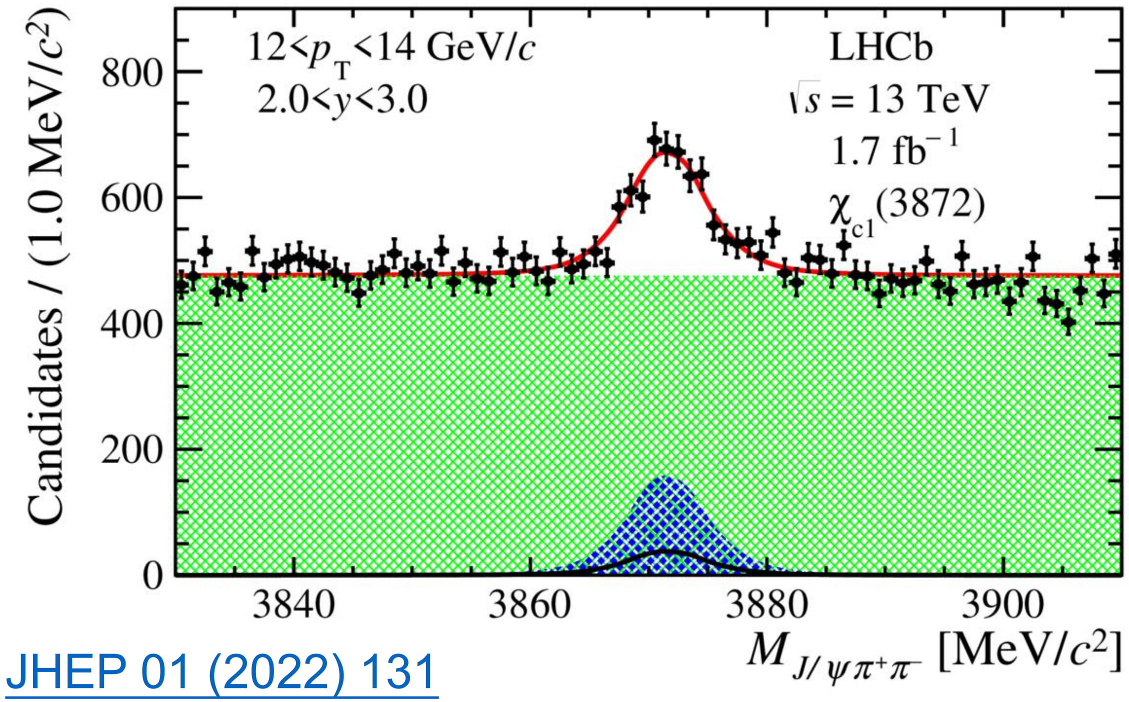


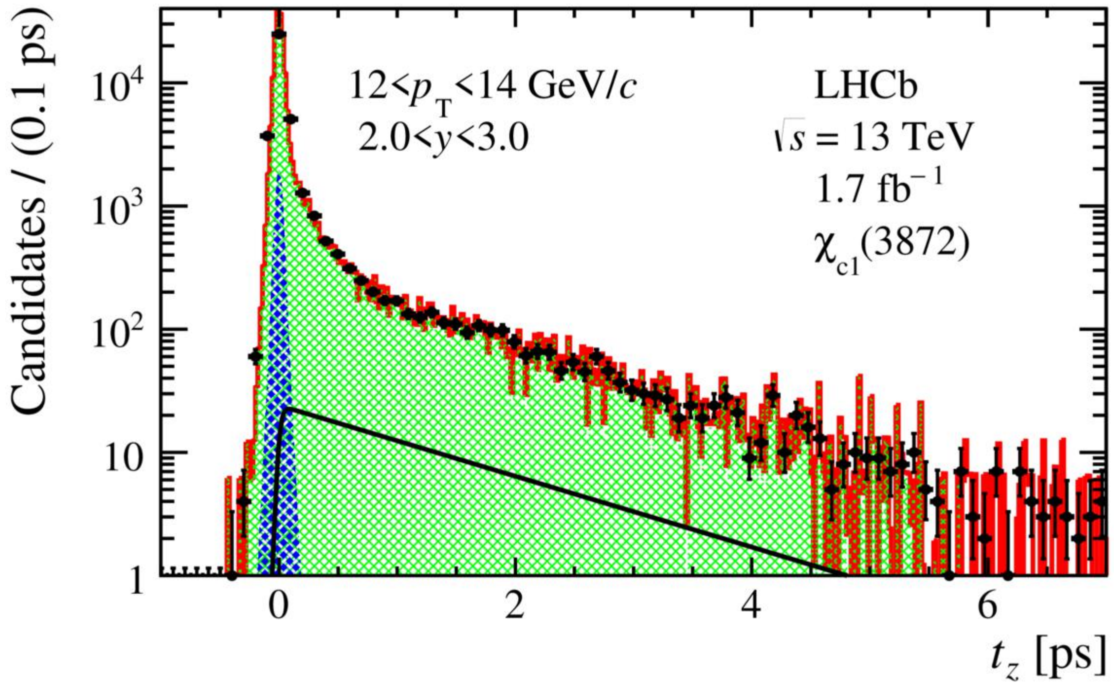
[PRL 126 (2021) 092001](PRL 126 (2021) 092001)

产生截面测量

- 直接产生-t_z ~0
- b-衰变产生 t_z >0
- 以ψ(2S)为参考
- 不同对撞能量下的产生截面的比值



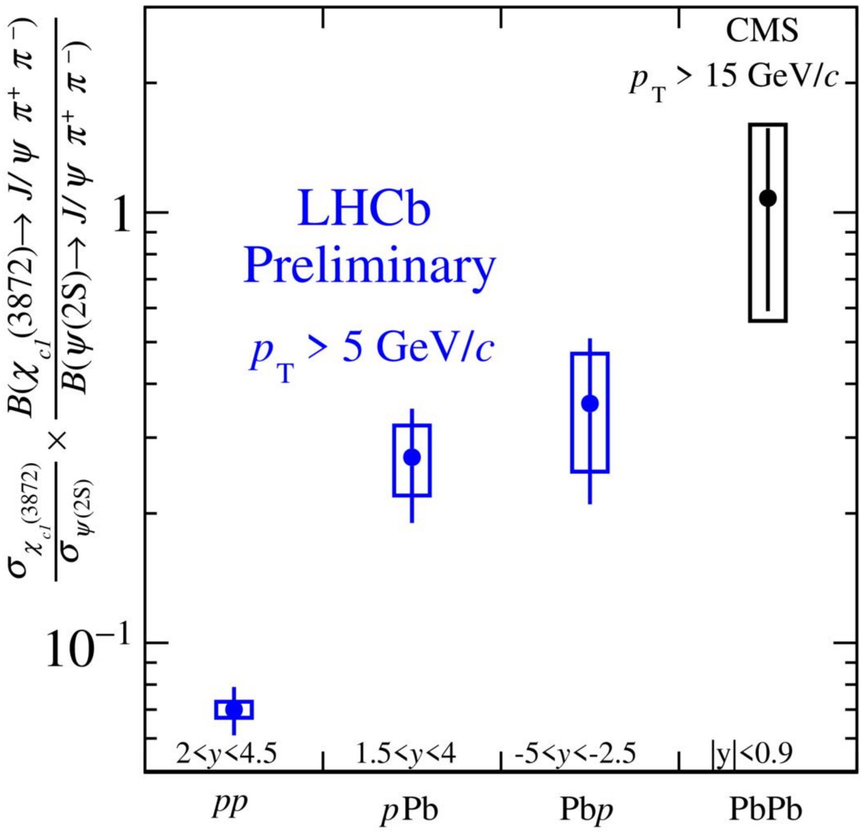




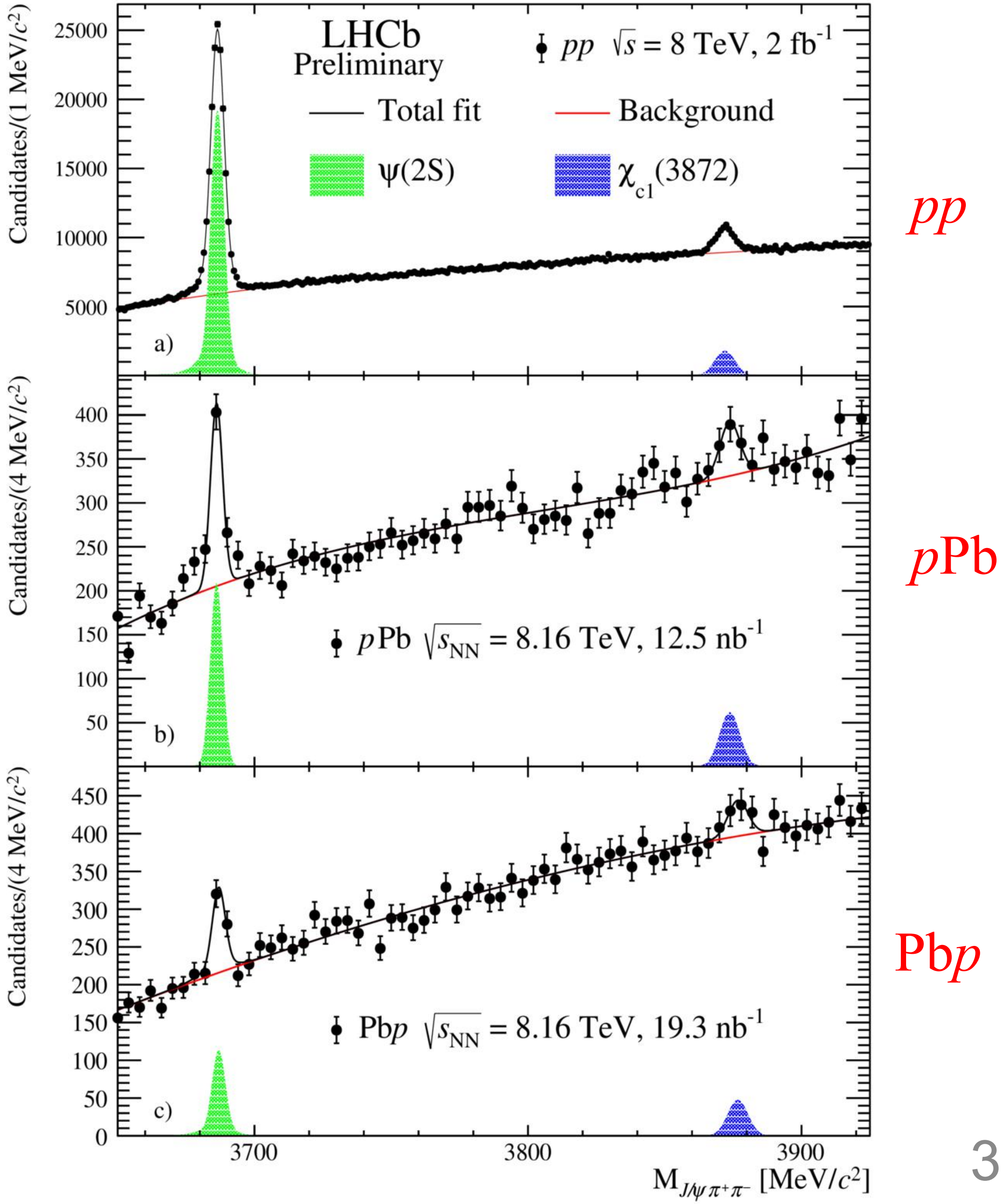
[JHEP 01 (2022) 131](https://doi.org/10.1007/JHEP01(2022)131)

重离子对撞中的产生

- 质子-铅
- 铅-质子



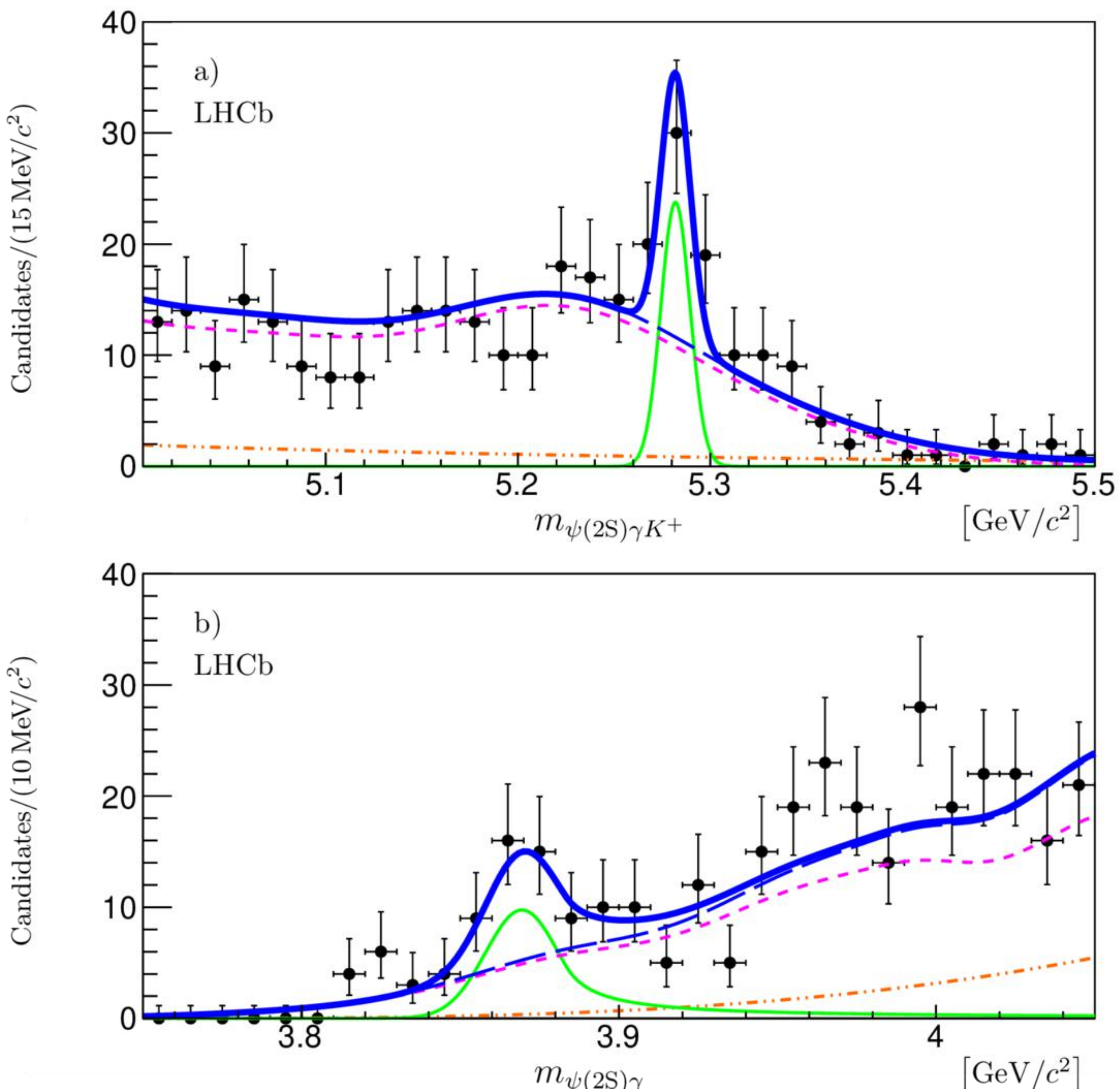
LHCb-CONF-2022-001



X(3872)衰变

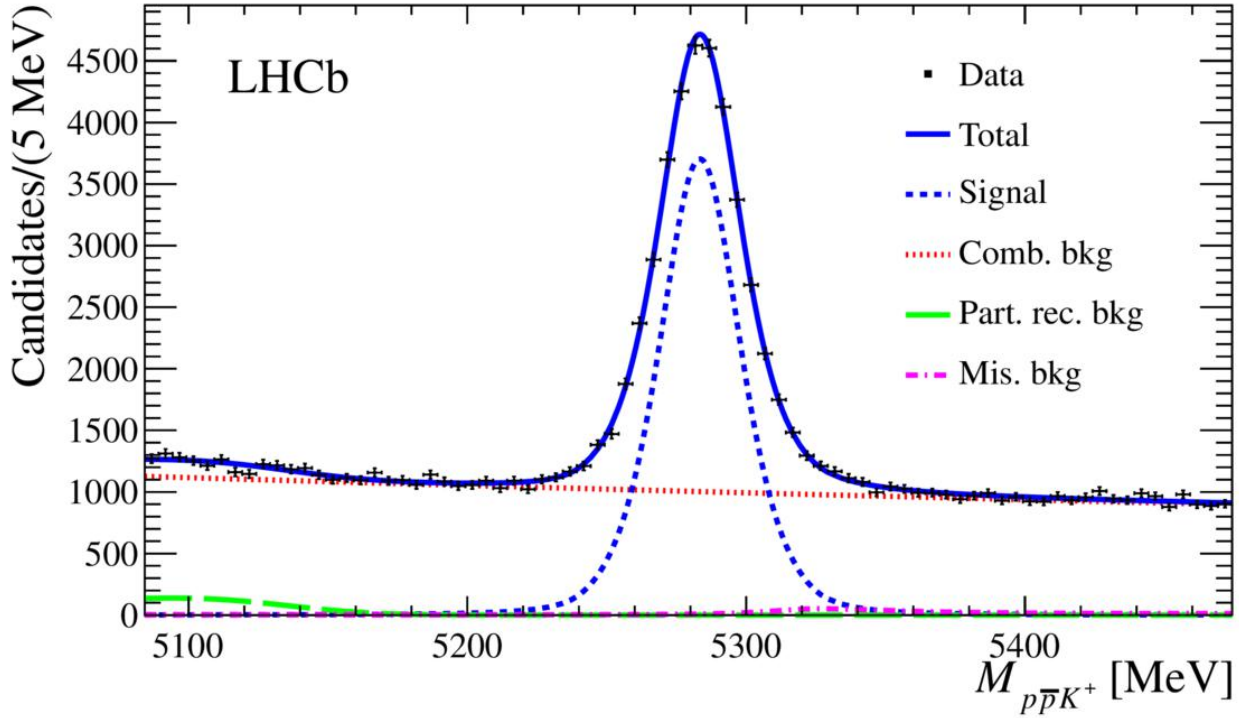
Nucl. Phys. B886 (2014) 665

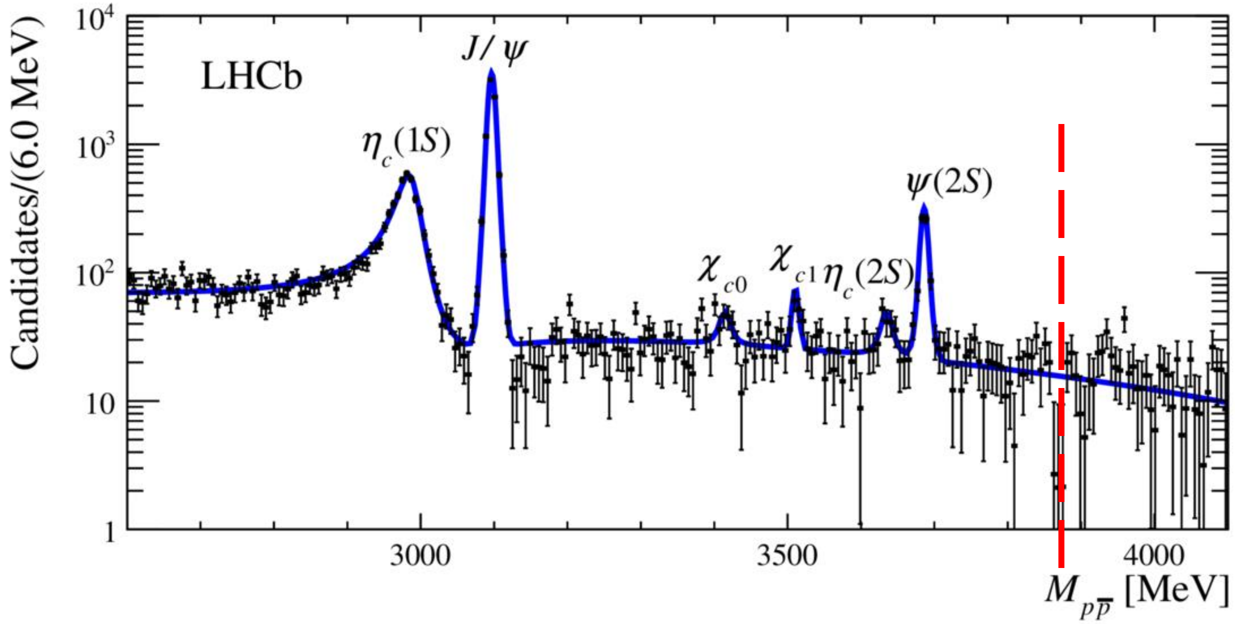
- $\chi_{c1}(3872) \to \psi(2S)\gamma$



$\chi_{c1}(3872) \to p\overline{p}$ 衰变

- $B^+ \to p\overline{p}K^+$事例
- sPlot



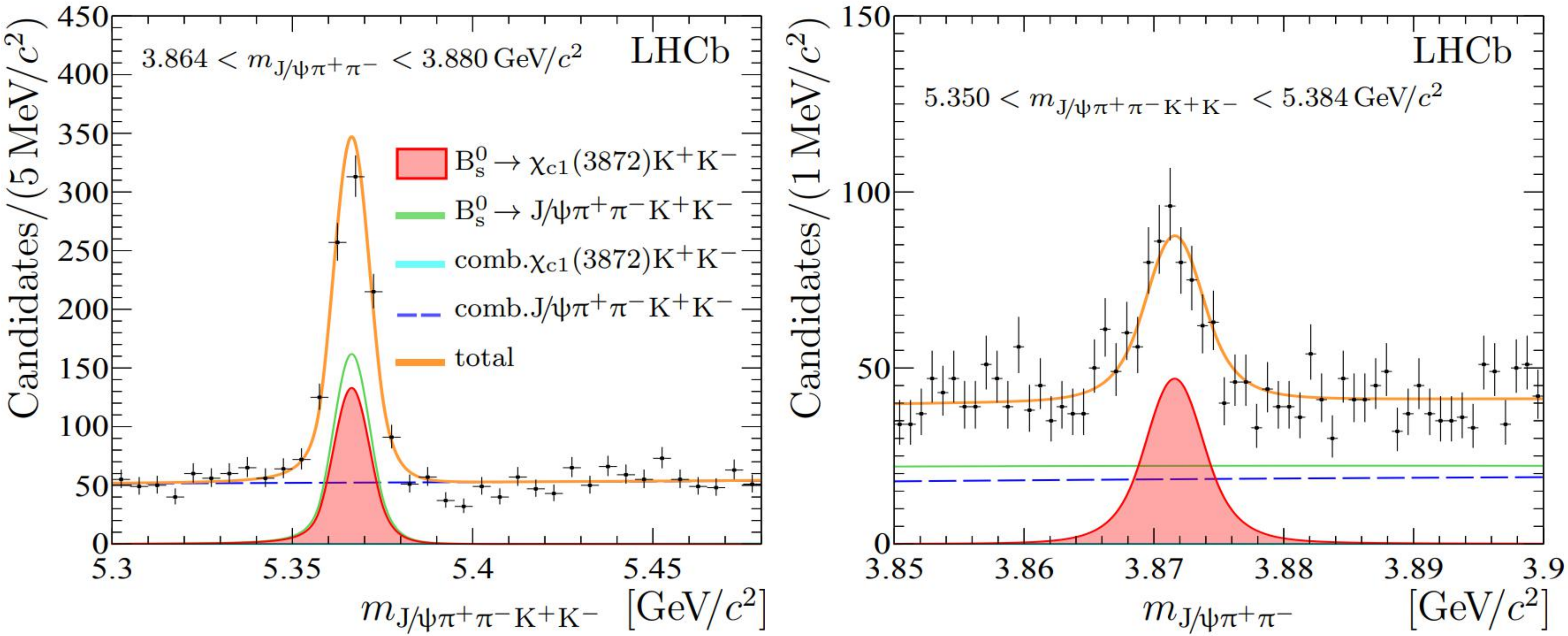


PLB769 (2017) 305

X(3872)衰变

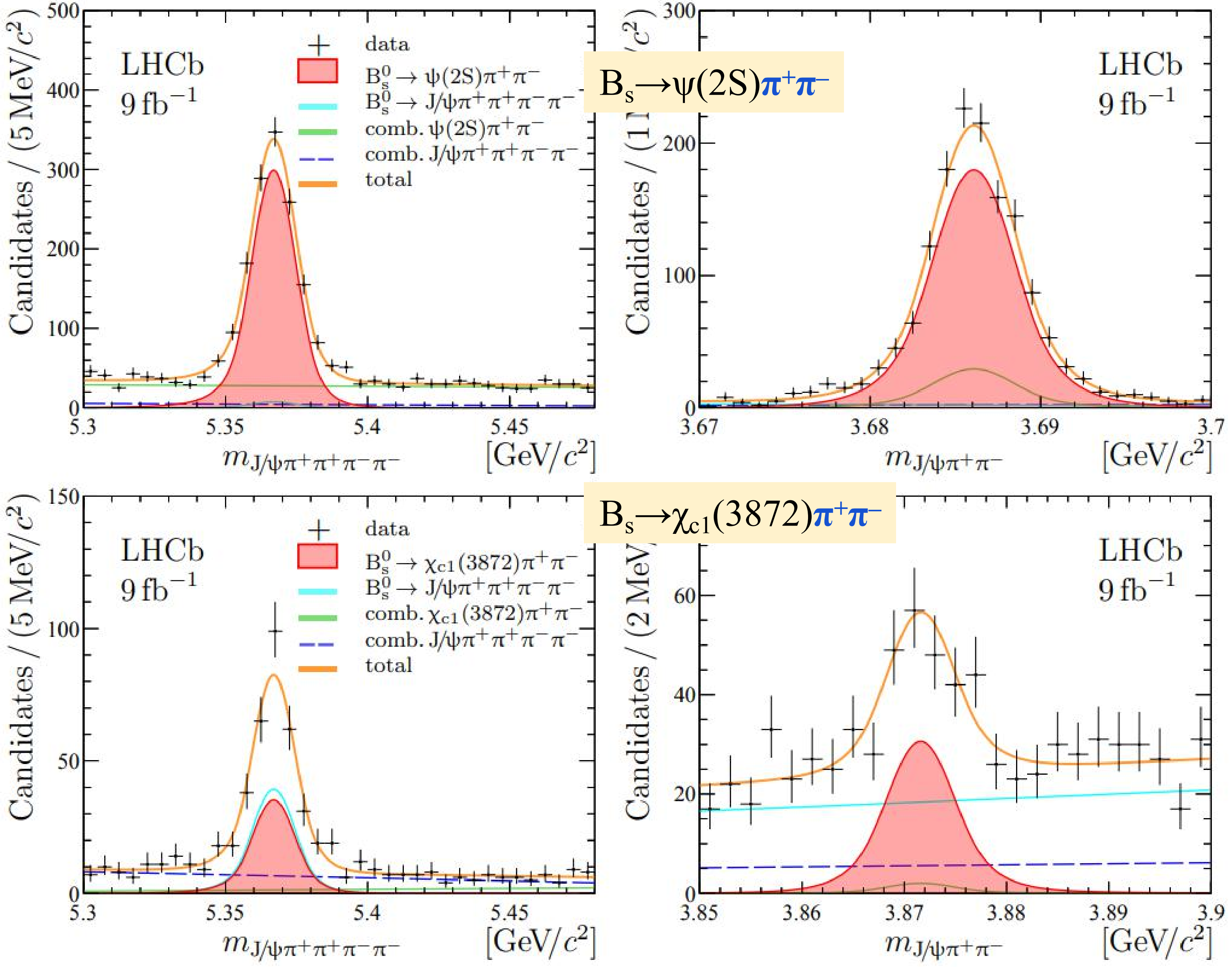
- $B_s^0 \to \chi_{c1}(3872)\phi$

JHEP 02 (2021) 024



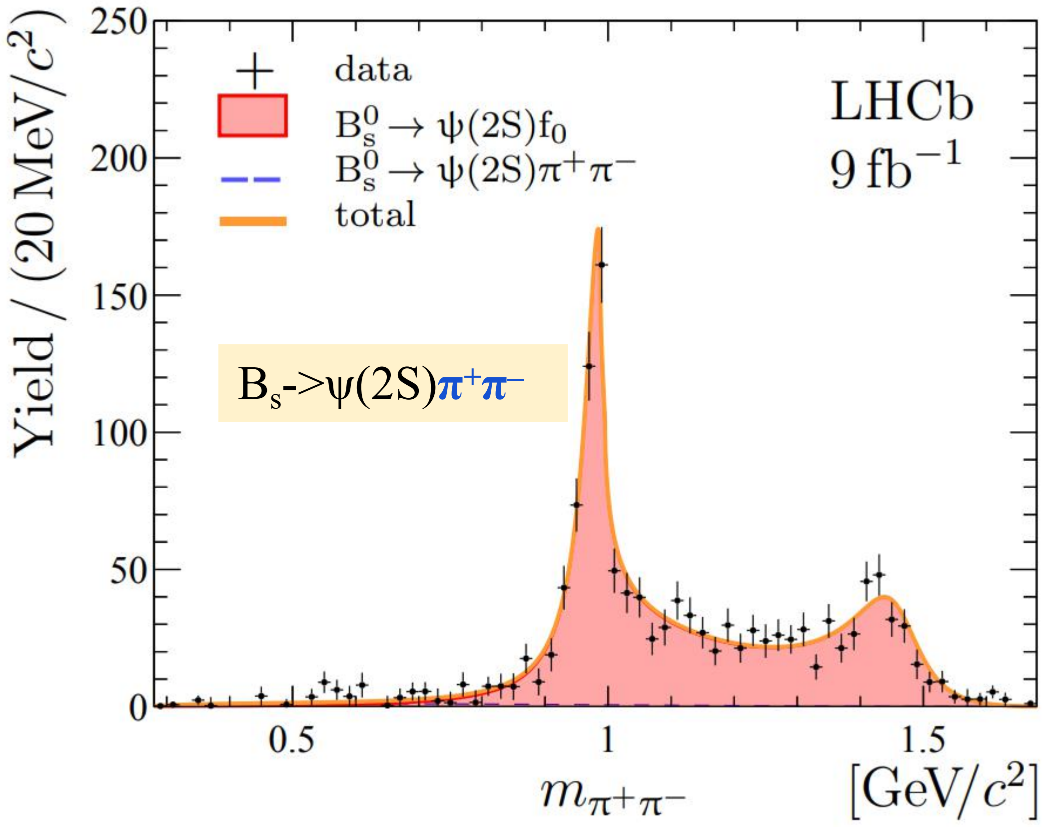
X(3872)衰变

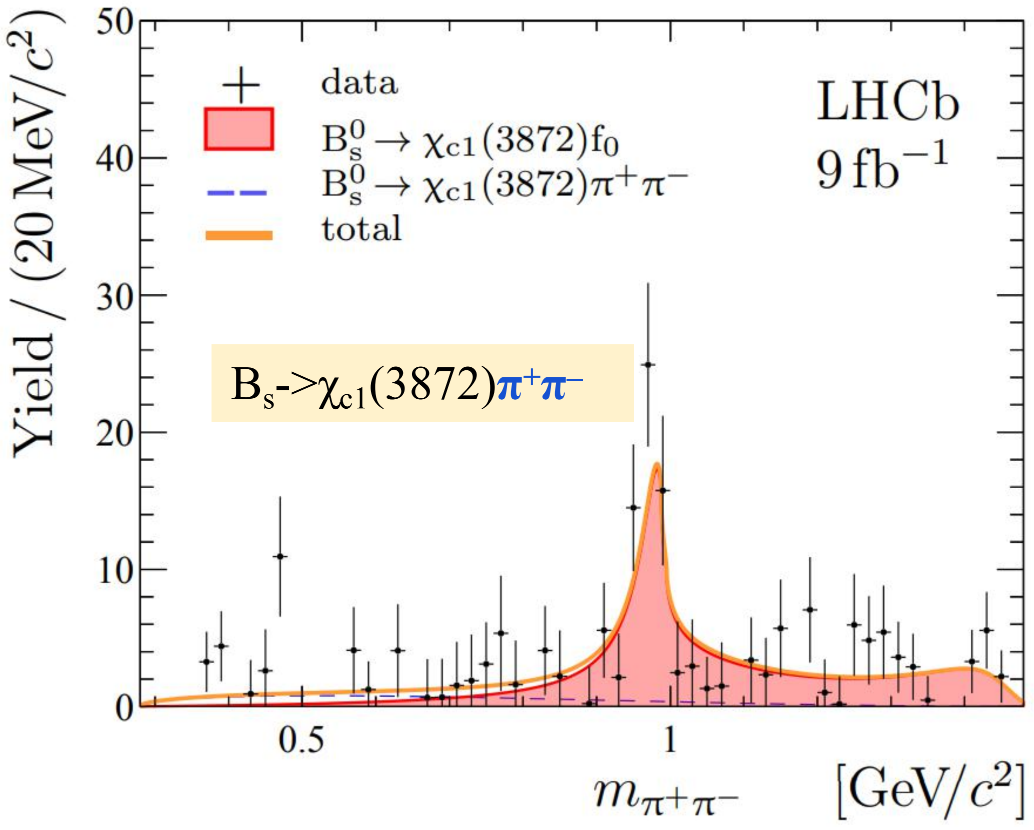
- $B_s^0 \to \chi_{c1}(3872)\phi$



arXiv:2302.10629

- $\pi^+\pi^-$系统中$f_0(980)$的贡献



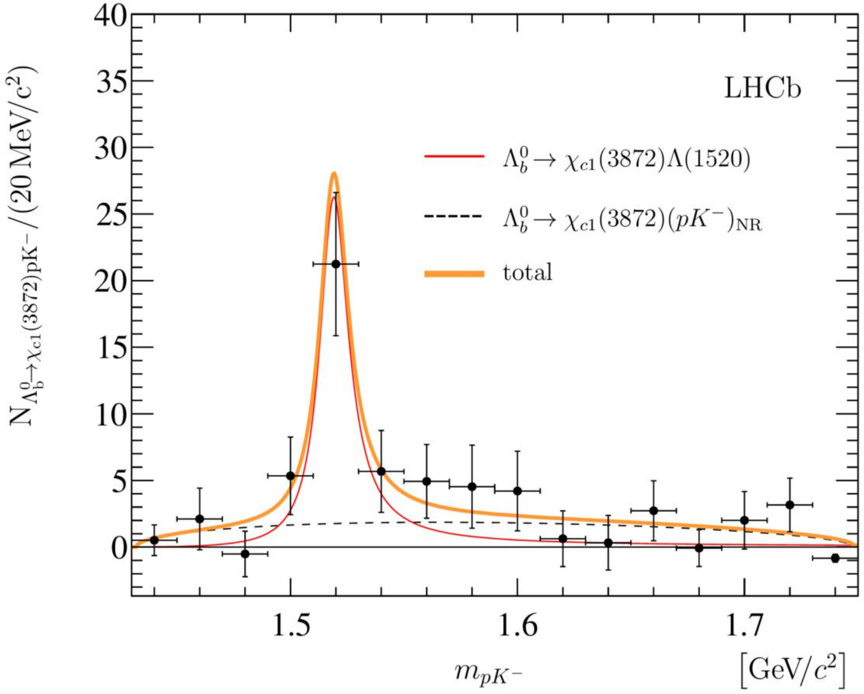


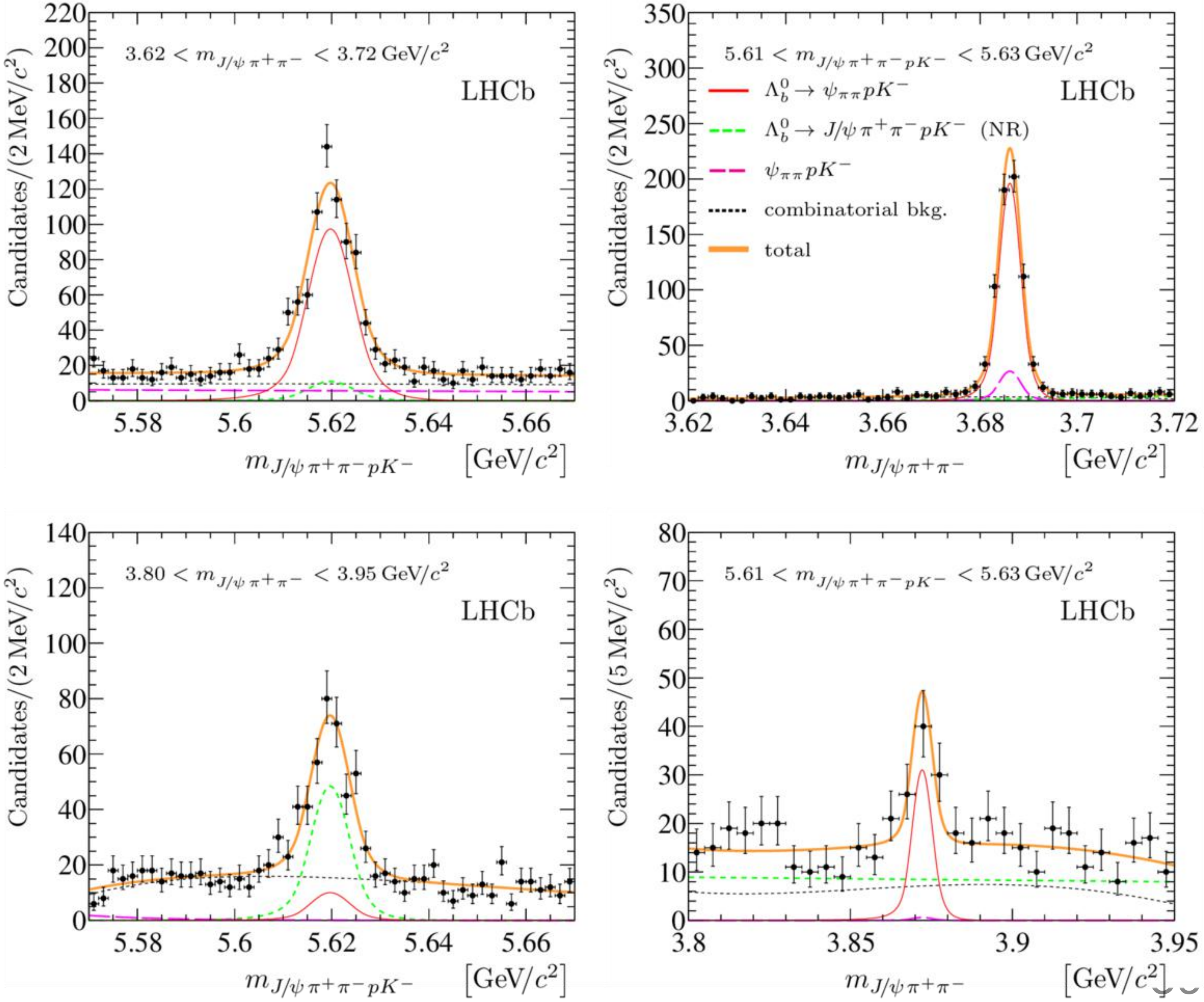
X(3872)衰变

JHEP 09 (2019) 028

- $\Lambda_b \to \chi_{c1}(3872)pK^-$

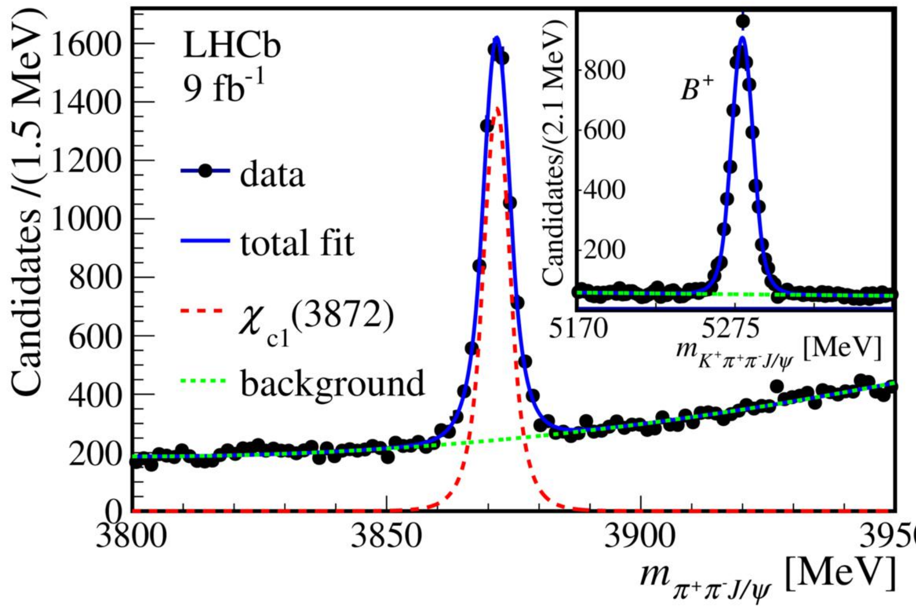
$\Lambda(1520)$->pK^-贡献

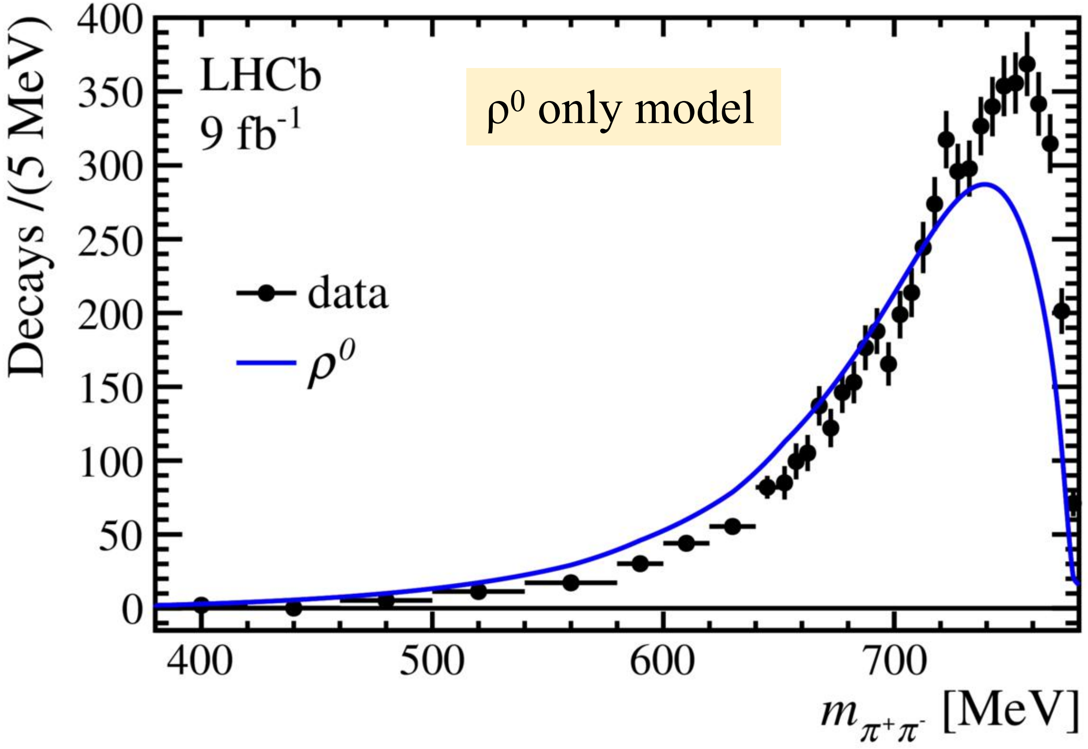


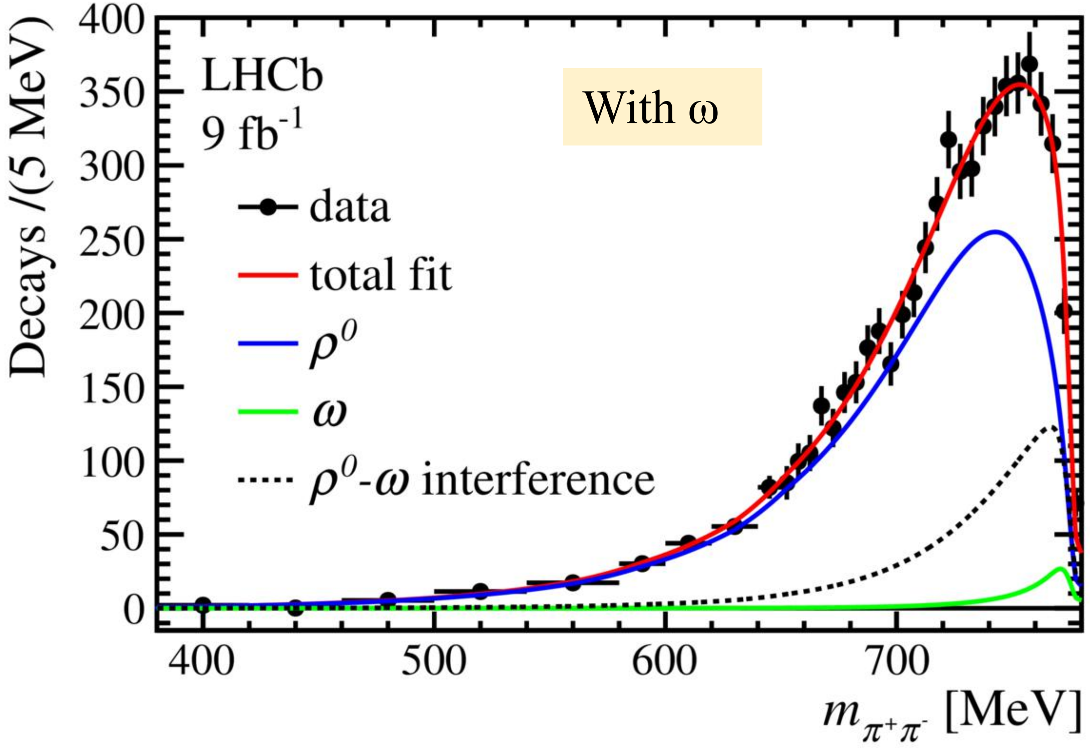


X(3872)衰变中ω成分

- $B^+ \to J/\psi\pi^+\pi^-K^+$
- ω成分
  - 单独贡献～2%
  - 干涉贡献～22%
- 同位旋破坏程度大于传统由$c\bar{c}$构成的粲偶素



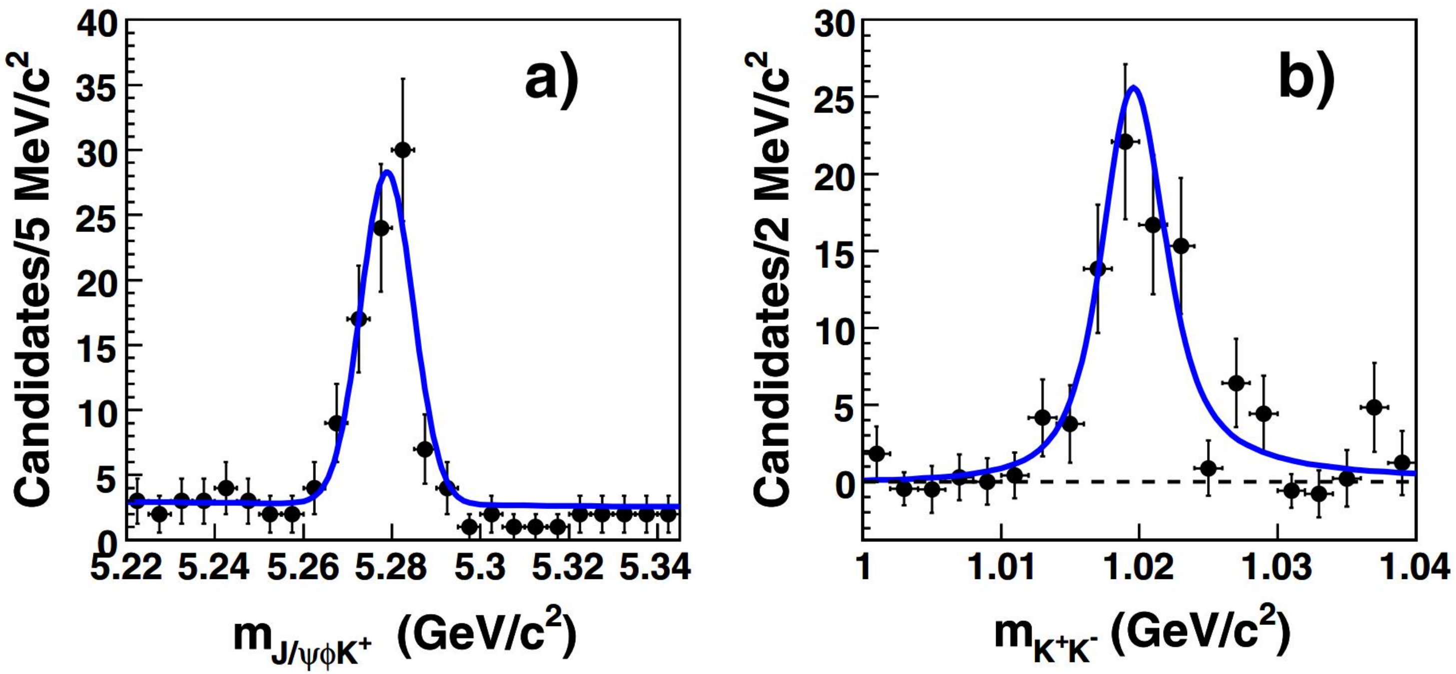


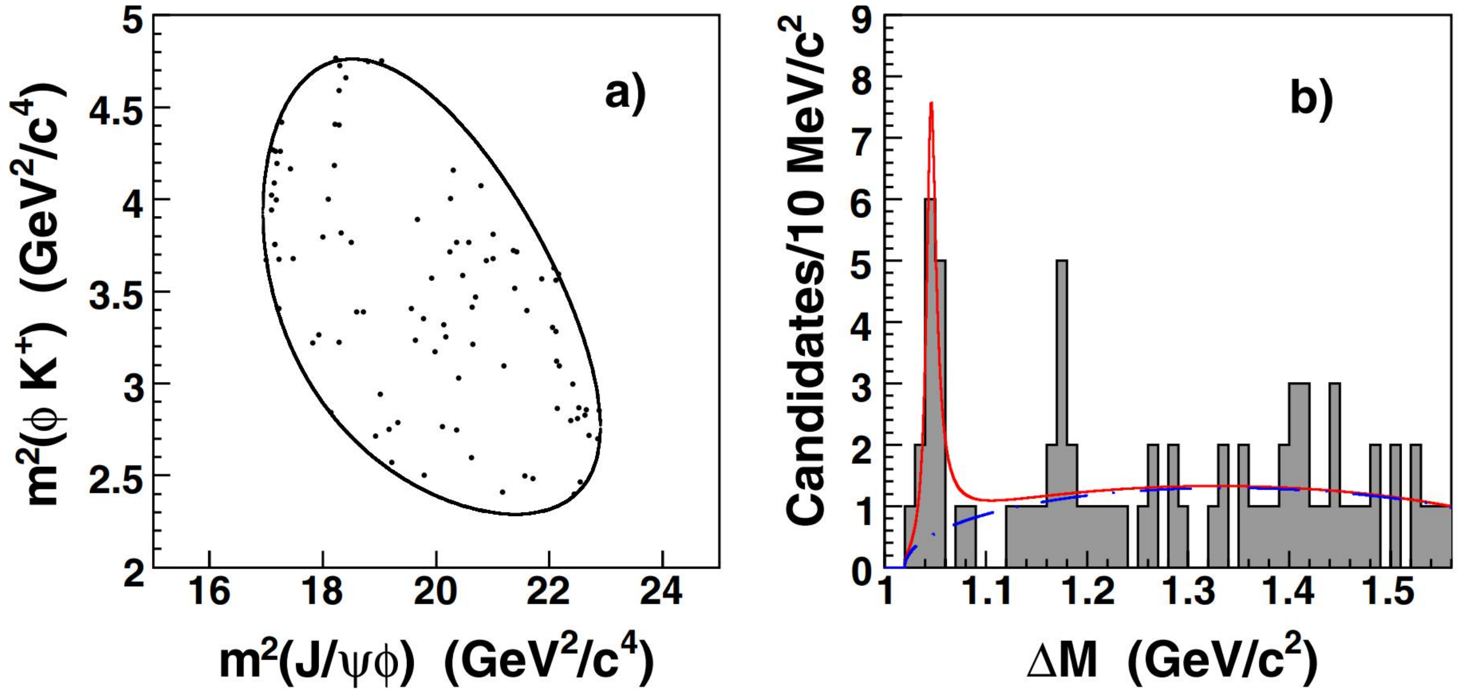


X(4140)

- CDF 2009
- 75 个事例
- 3.8 σ

- 高于D介子对质量阈值
- 传统粲偶素态应该更容易衰变到D介子对
- 4280MeV的峰, < 3σ





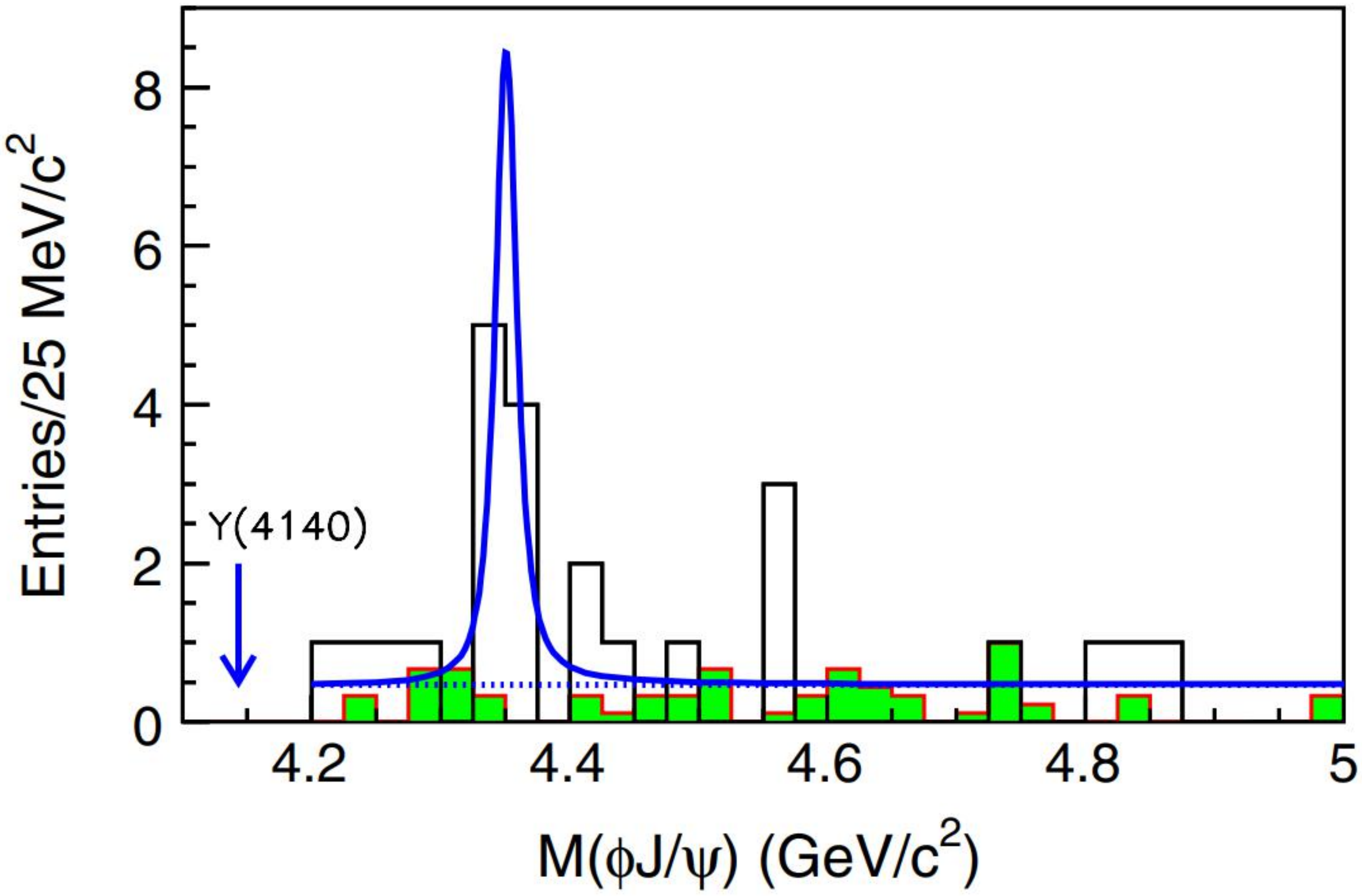
[Phys. Rev. Lett. 102, 242002 (2009)]

X(4140)

- Belle 2010
- No observation in B decay
- $\gamma\gamma \to J/\psi\phi$
- disfavour D_s*+ D_s*- molicule with JPC = 0++ or 2++

- A new state in X(4350)

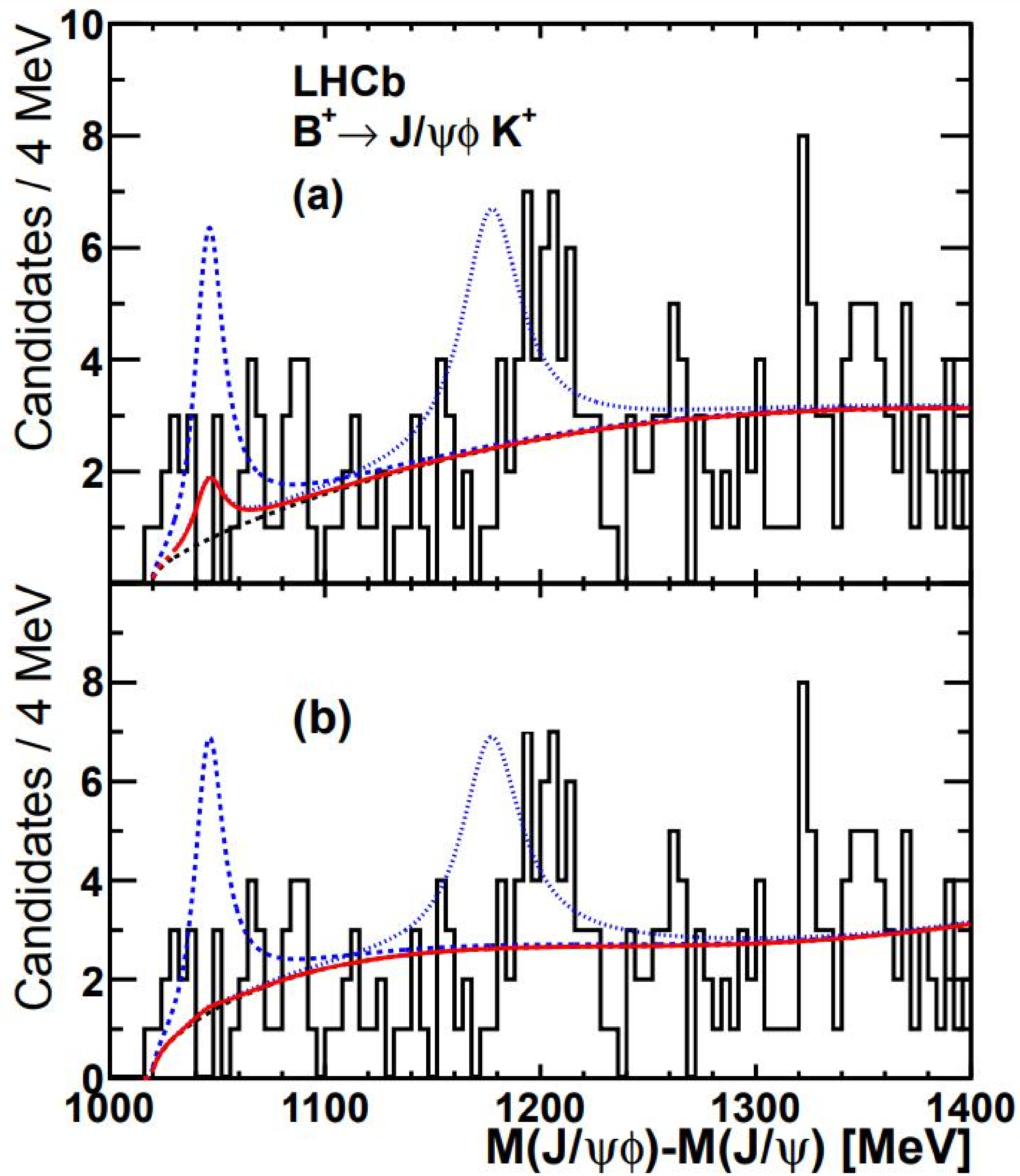
PRL 104, 112004 (2010)



X(4140)

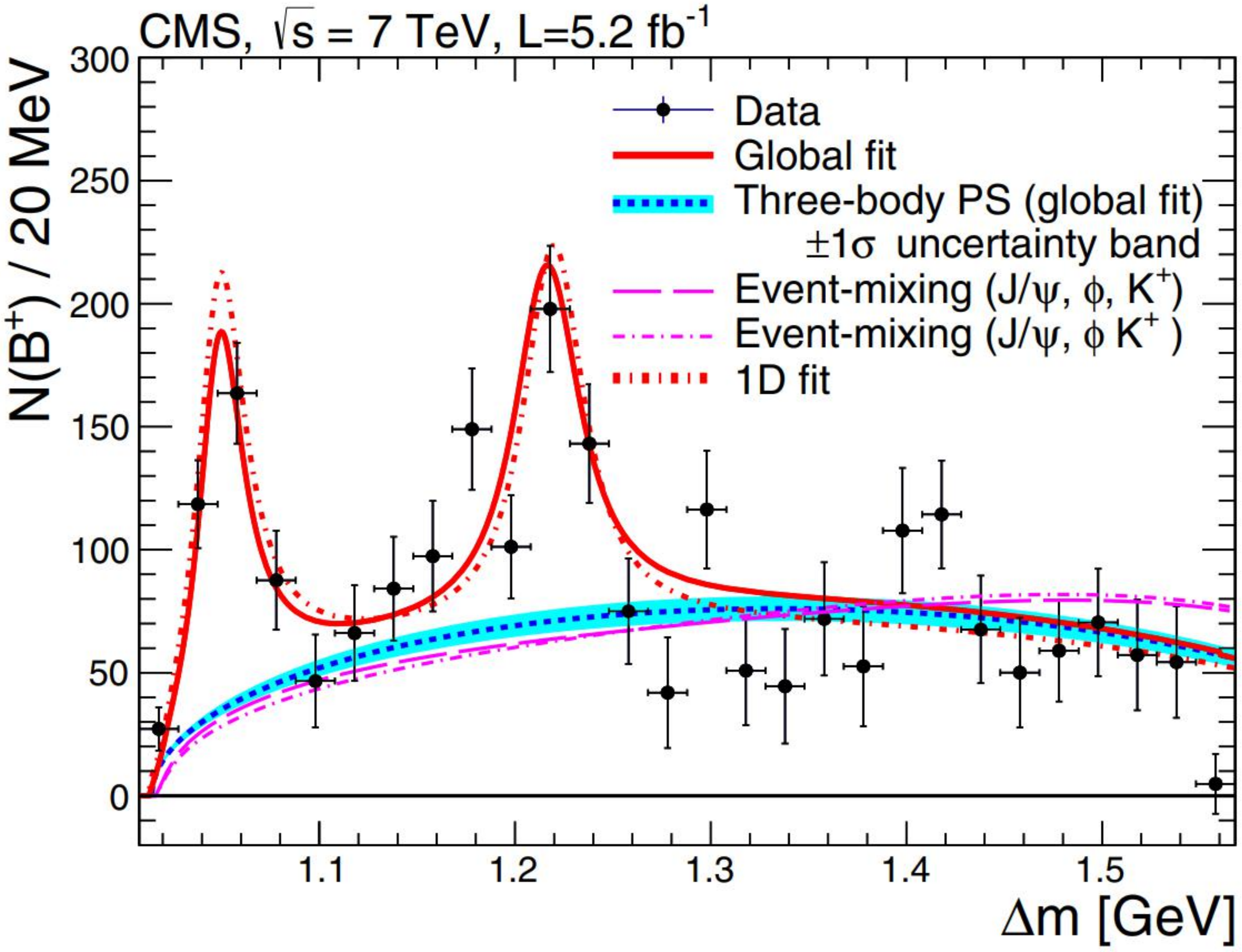
- LHCb, 2012, 0.37 /fb data
- No observation

Phys. Rev. D 85 (2012) 091103



X(4140)

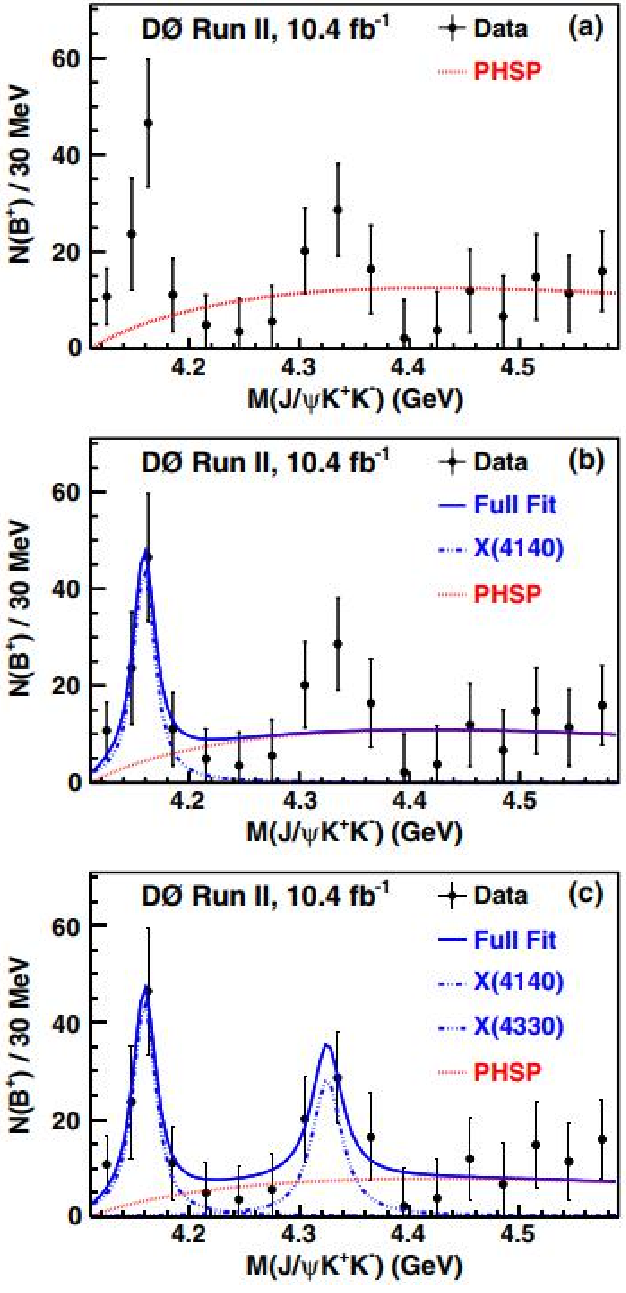
- CMS, 2014



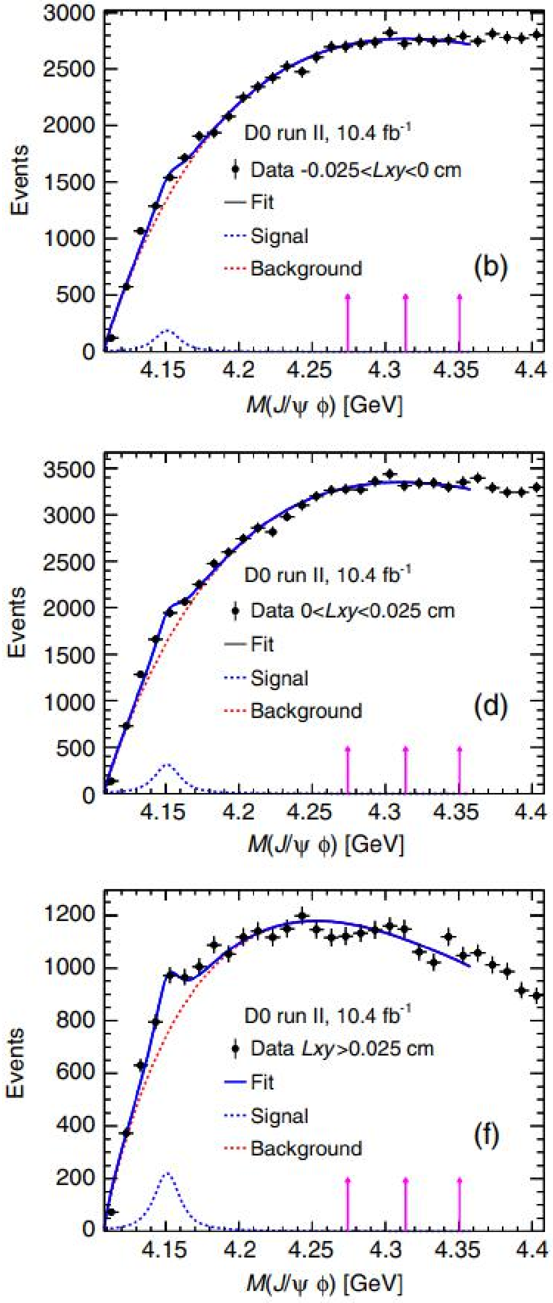
X(4140)

- D0, 2014
- $B^+ \to J/\psi\ \phi\ K^+$
- 3.1σ for X(4140)
- 1.7σ for 4.3 GeV 峰

- D0, 2015
- 首次看到直接产生的“证据” (4.7σ)
- 显著b-衰变的贡献 (5.6σ)



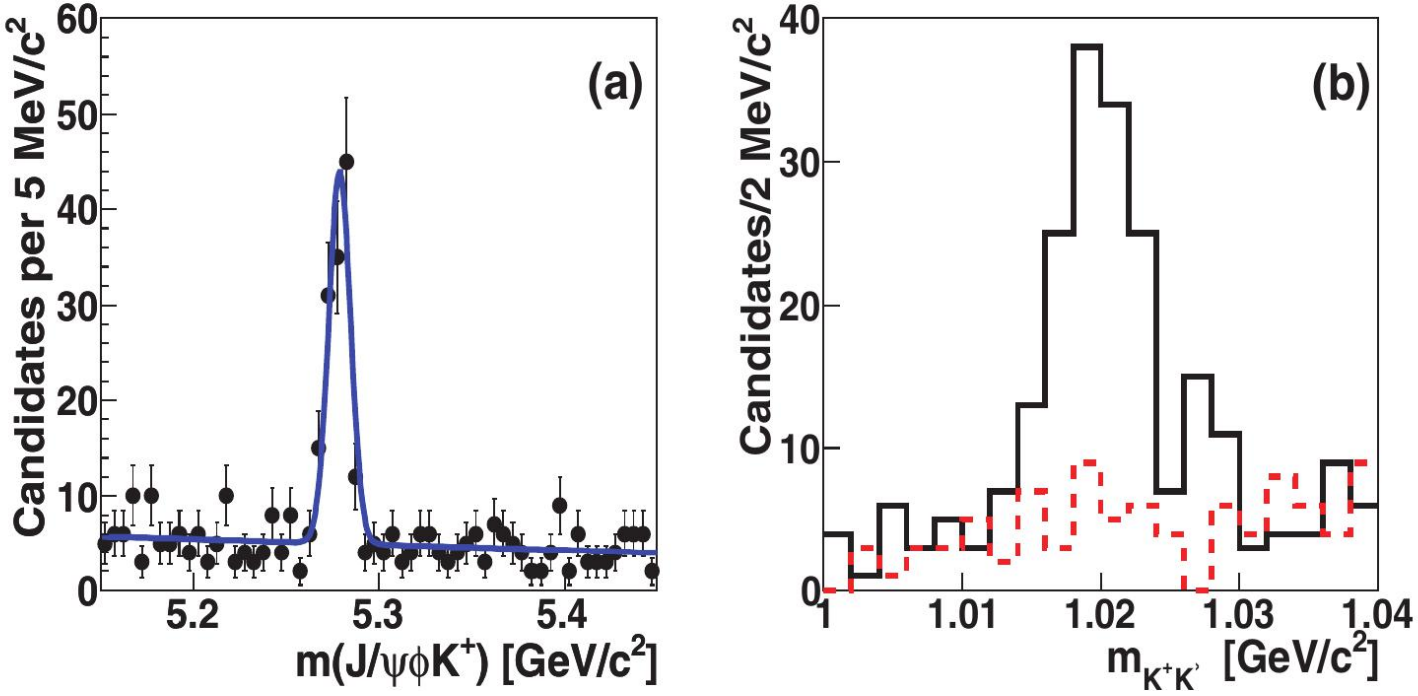
Phys. Rev. D 89, 012004 (2014).

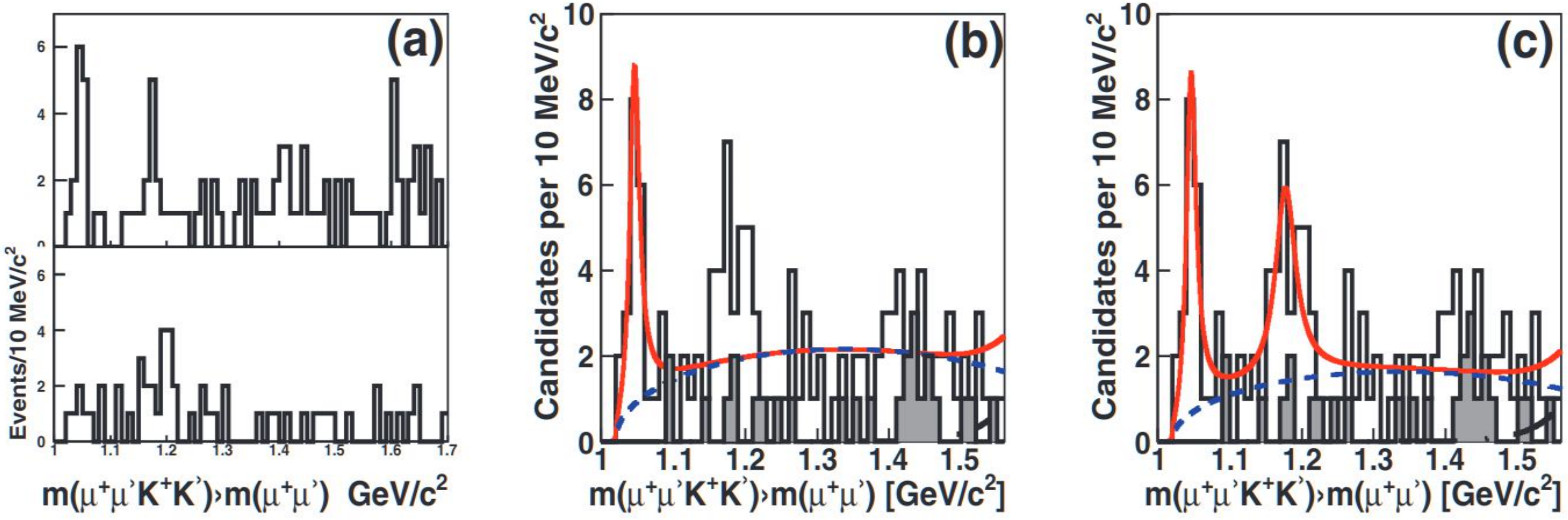


PhysRevLett.115.232001

X(4140)

- CDF, 2017
- 19±6事例
- >5σ





Mod.Phys.Lett.A 32 (2017) 26, 1750139

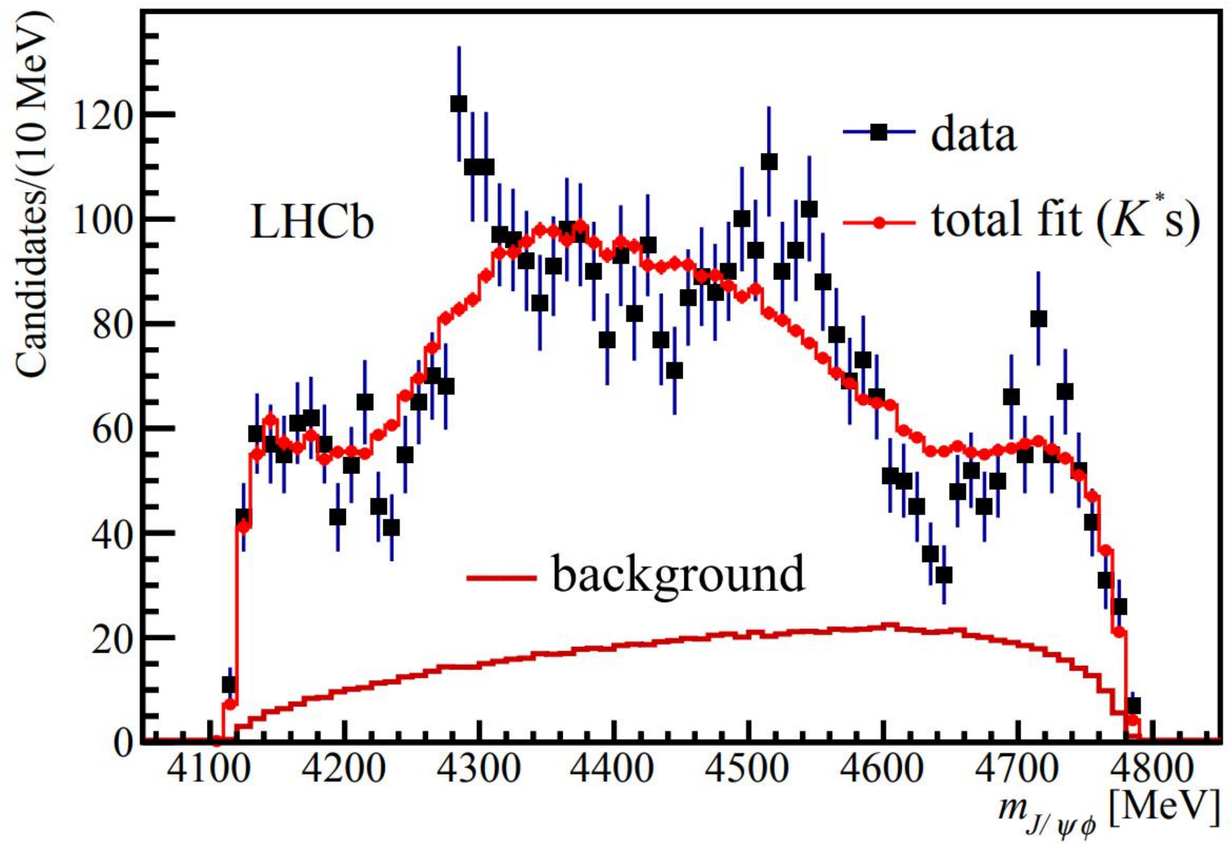
TABLE I. Previous results related to the $X(4140) \to J/\psi\phi$ mass peak. The number of reconstructed $B^+ \to J/\psi\phi K^+$ decays (N_B) is given if applicable. Significances (σ) correspond to numbers of standard deviations. Upper limits on the $X(4140)$ fraction of the total $B^+ \to J/\psi\phi K^+$ rate are at 90% confidence level. The statistical and systematic errors are added in quadrature and then used in the weights to calculate the averages, excluding unpublished results (shown in italics).

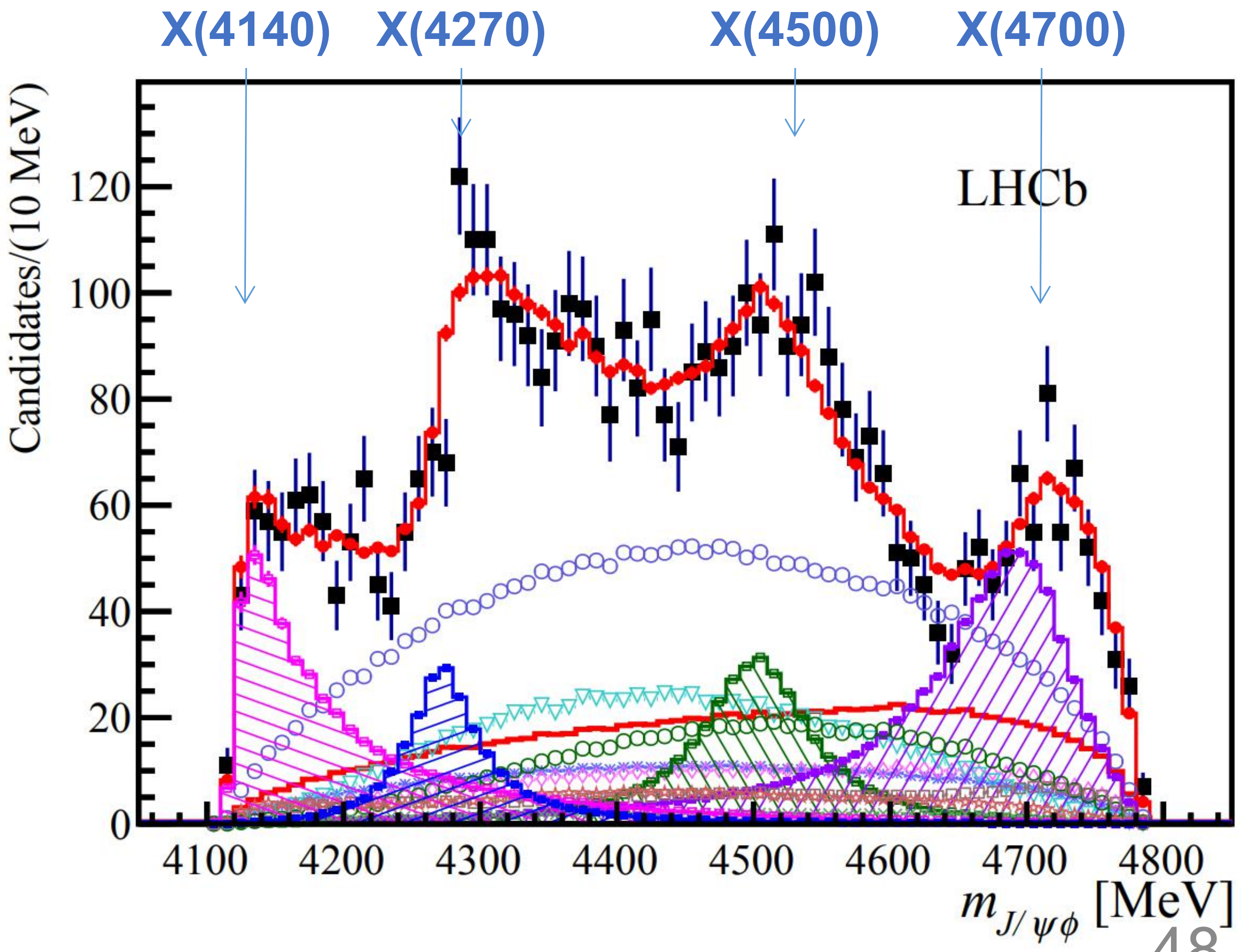
Experiment	N_B	Mass (MeV)	Width (MeV)	σ	Fraction (%)
CDF [1]	58	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8	
Belle [19]	*325*	*4143.0 fixed*	*11.7 fixed*	*1.9*	
CDF [26]	*115*	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	*5.0*	$15 \pm 4 \pm 2$
LHCb [21]	346	4143.4 fixed	15.3 fixed	1.4	<7
CMS [23]	2480	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0	10 ± 3
D0 [24]	215	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.1	$21 \pm 8 \pm 4$
BABAR [22]	189	4143.4 fixed	15.3 fixed	1.6	<13
D0 [25]		$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7–5.7	
Average		4147.1 ± 2.4	15.7 ± 6.3		

Phys. Rev. Lett. 118 (2017) 022003

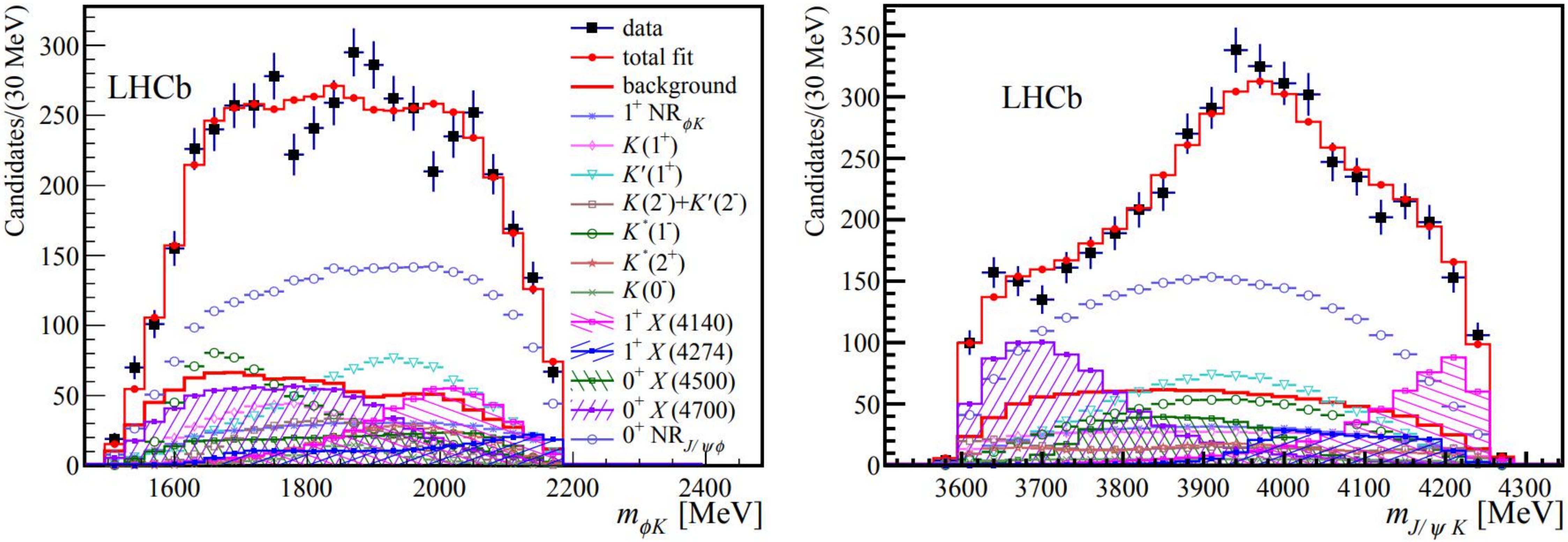
X(4270), X(4500), X(4700)

- LHCb， 2017， 一期数据（3/fb）
- 确定X(4140)的$J^{CP}=1^{++}$
- 宽度显著大于以前实验的测量值





- 其他不变质量组合


LHCb
Candidates/(30 MeV)
data
total fit
background
1^+ NR$_{\phi K}$
$K(1^+)$
$K'(1^+)$
$K(2^-)+K'(2^-)$
$K^*(1^-)$
$K^*(2^+)$
$K(0^-)$
1^+ $X(4140)$
1^+ $X(4274)$
0^+ $X(4500)$
0^+ $X(4700)$
0^+ NR$_{J/\psi\phi}$
$m_{\phi K}$ [MeV]
LHCb
Candidates/(30 MeV)
$m_{J/\psi K}$ [MeV]

X(4685), X(4630), Z_{cs}(4000), Z_{cs}(4220)

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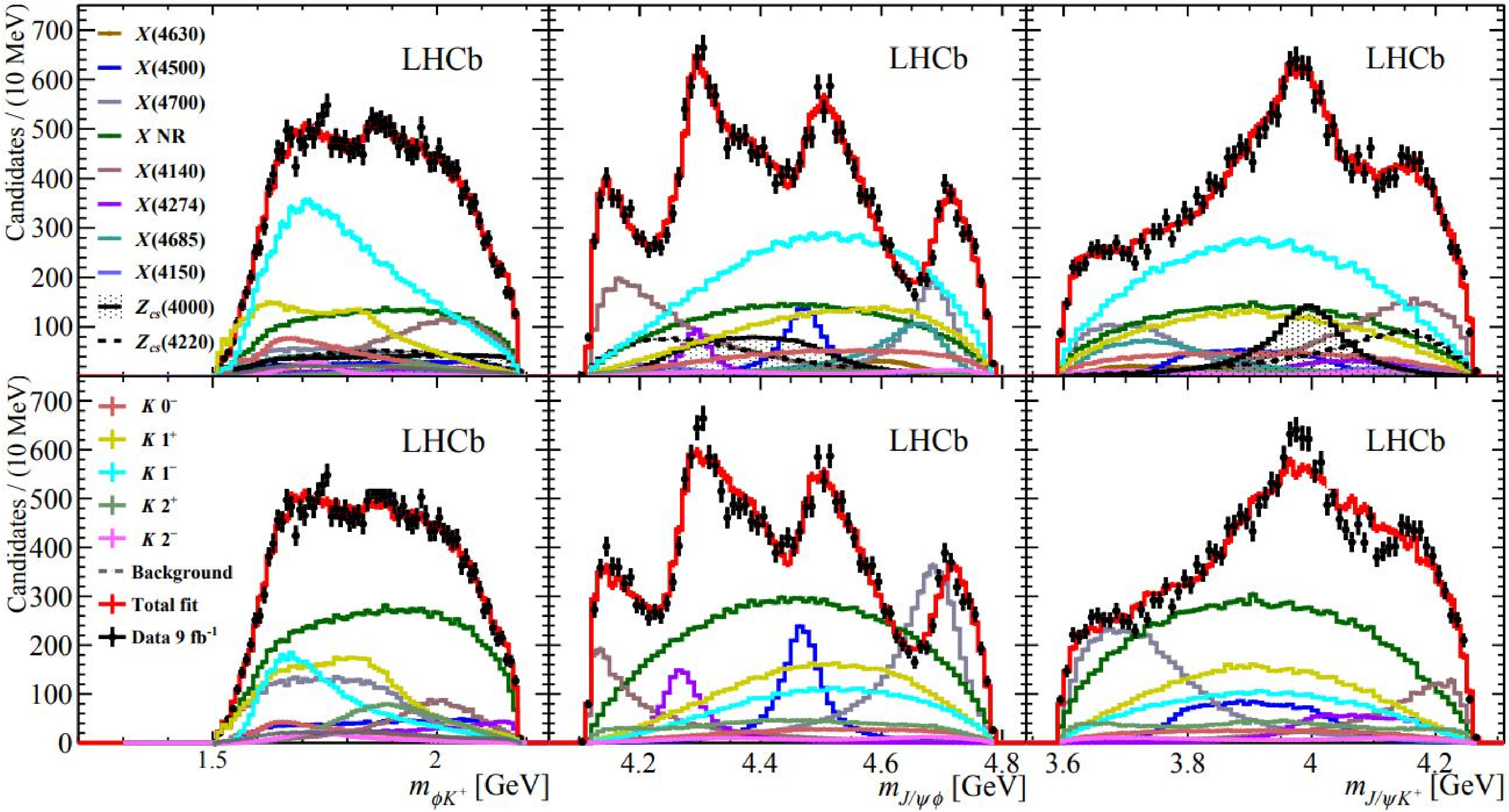
- LHCb， 一期和二期数据（9/fb）

加入新的态

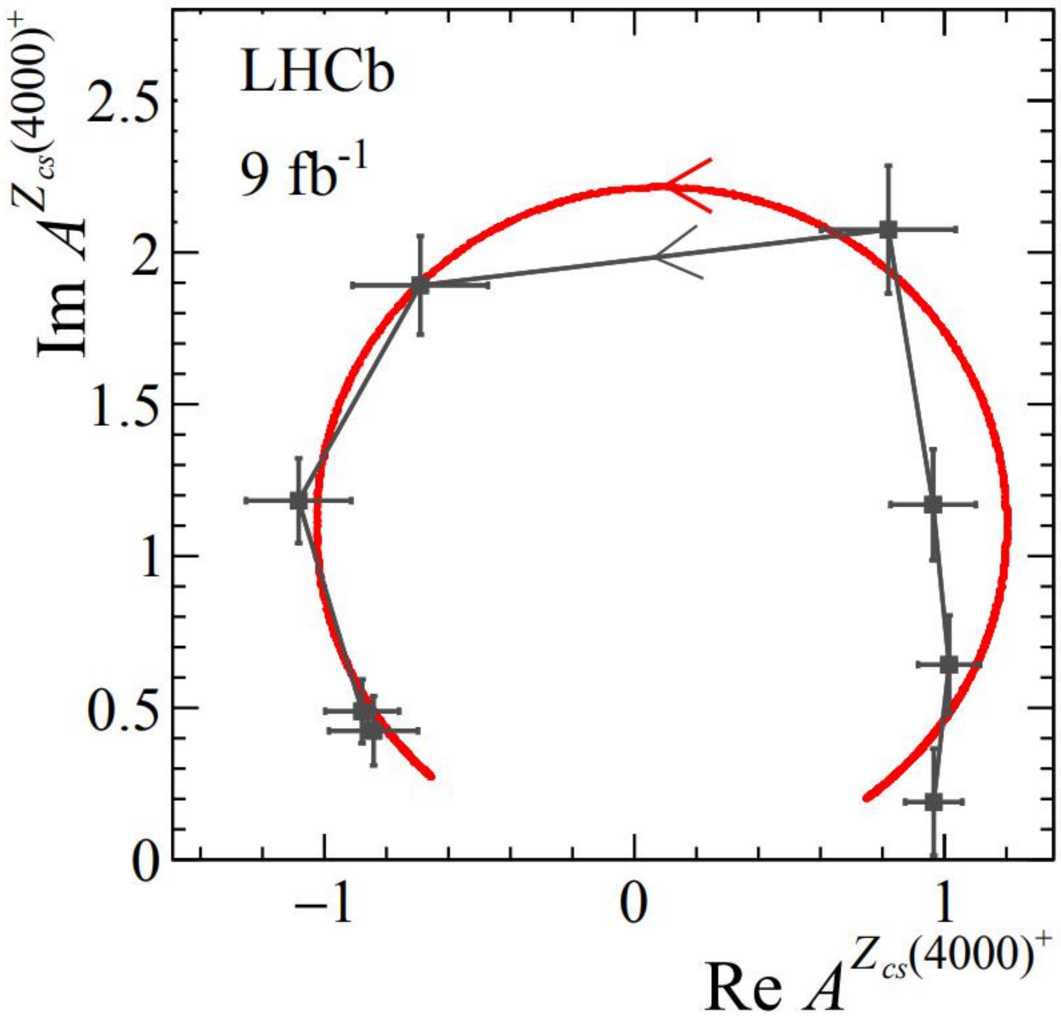
旧模型



Zcs(4000)的共振态特性

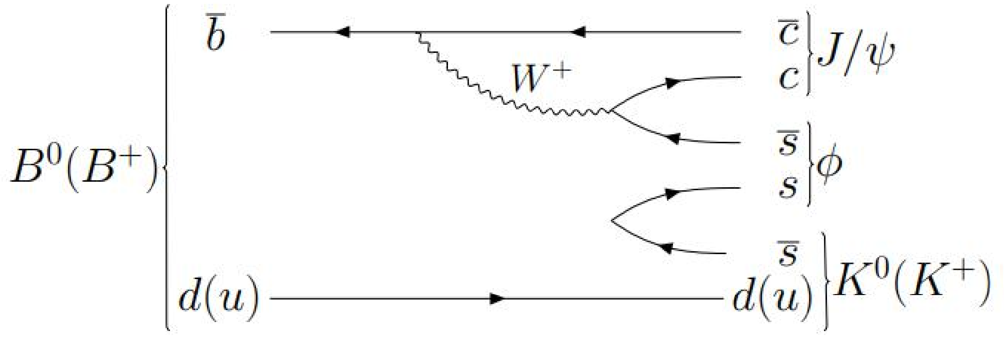
- Argand图

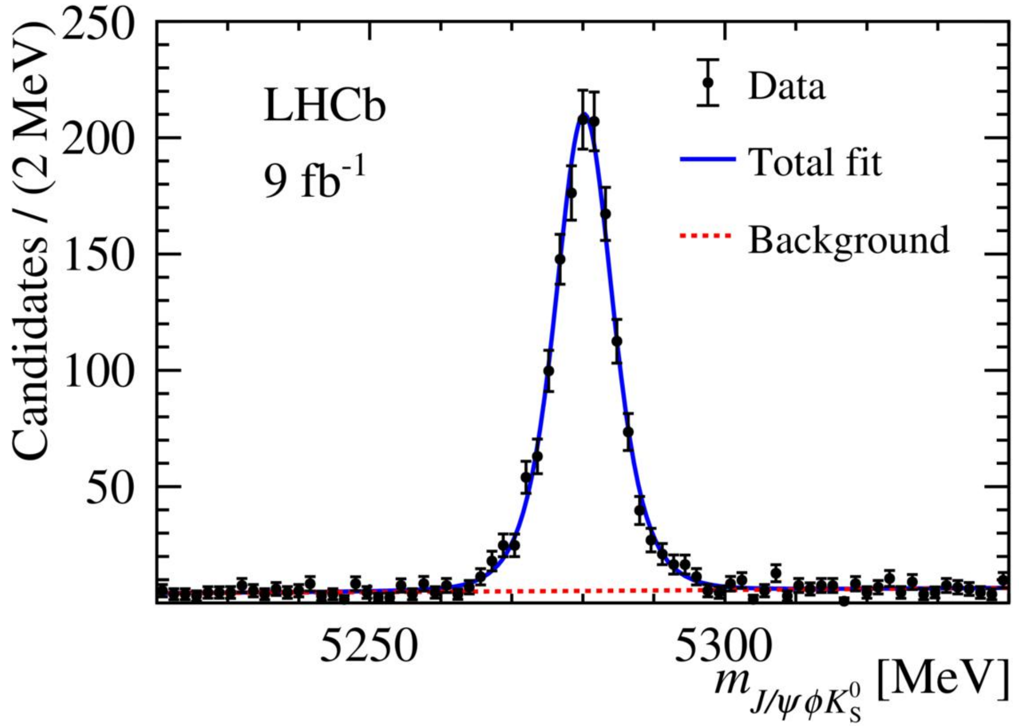
$$\chi(E) = \frac{K}{(E - E_R) - i\Gamma}$$

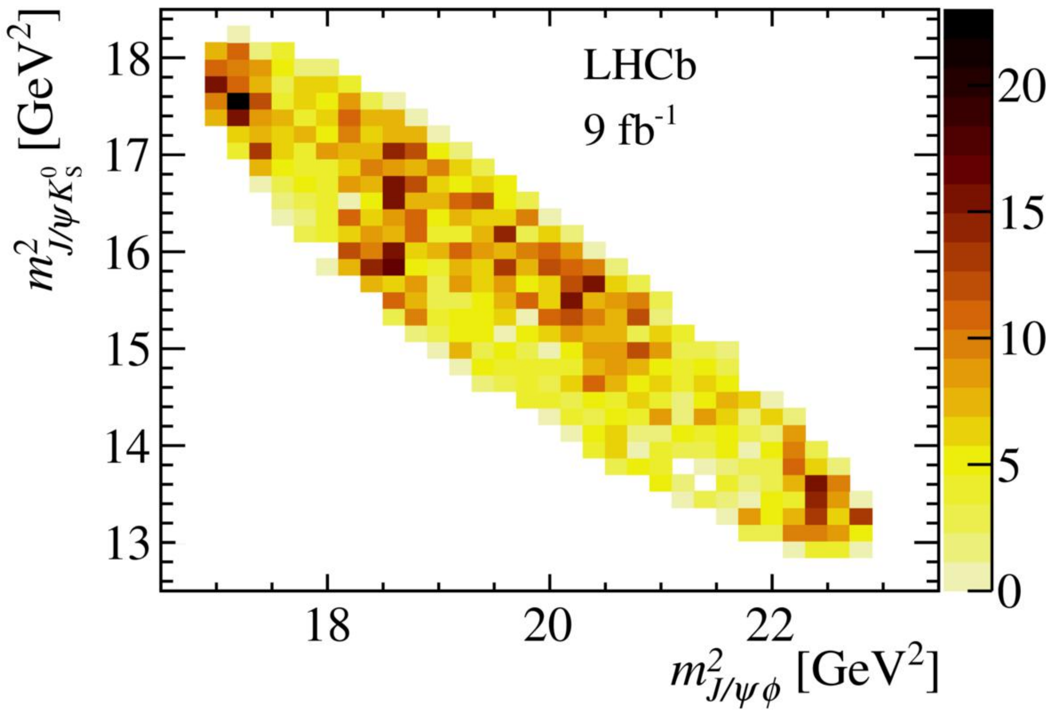


Discovery of $T^{\theta}_{\psi s1}(4000)^0 \to J/\psi K_s^0$

- $B^0 \to J/\psi\phi K_s^0$ 衰变
  - 1866 ± 47 信号事例
- 与$B^+ \to J/\psi\phi K^+$过程有同位旋对称性
  - $T^{\theta}_{\psi s1}(4000)^+$, $T^{\theta}_{\psi s1}(4220)^+$

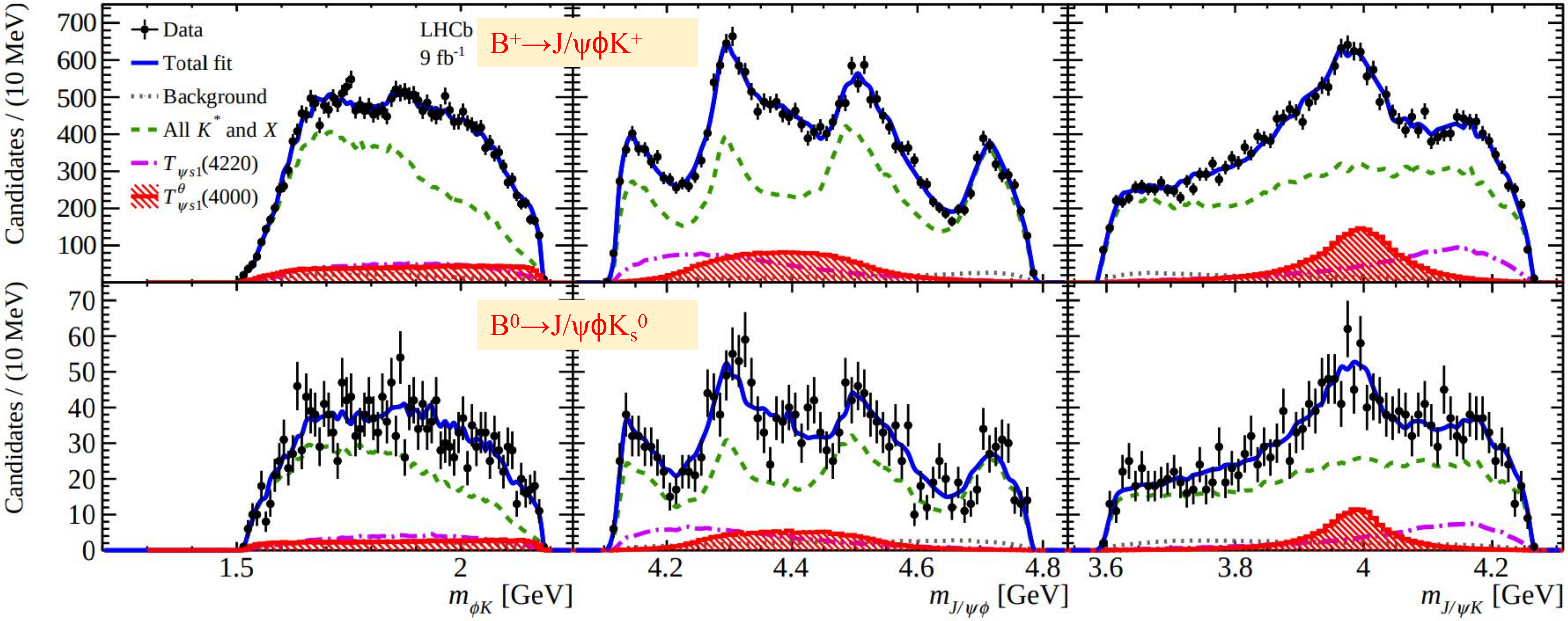






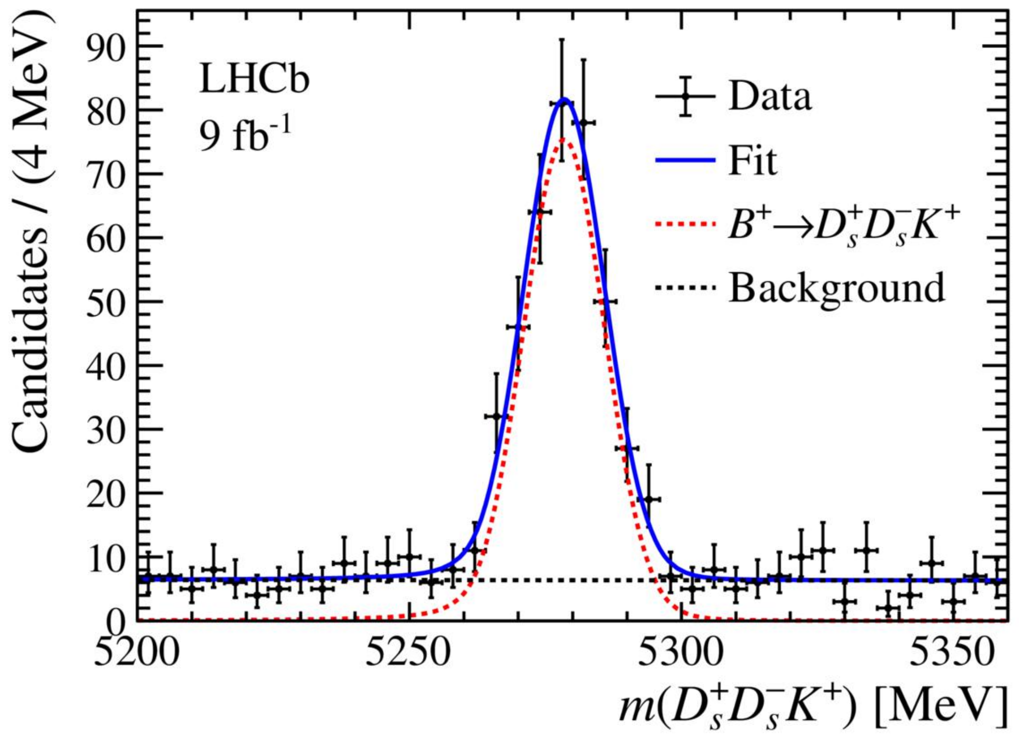
$T^{\theta}_{\psi s1}(4000)^0 \to J/\psi K_s^0$

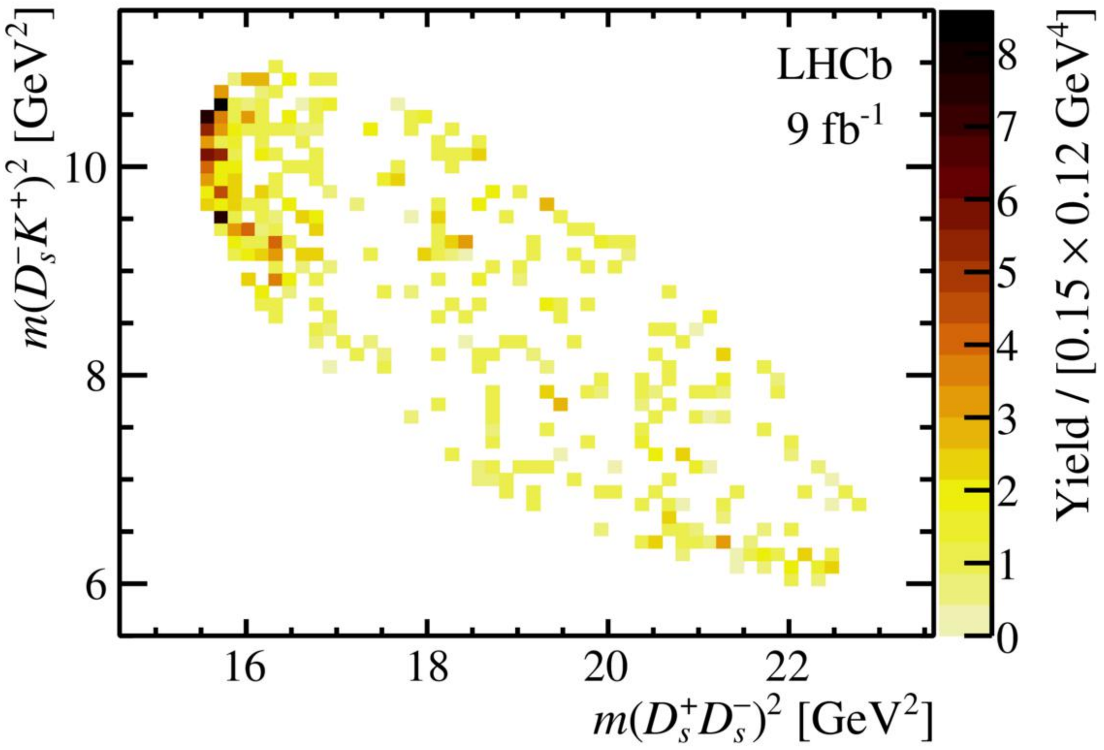
- 以$B^+ \to J/\psi\phi K^+$为参考道



$X(3960) \to D_s^+ D_s^-$

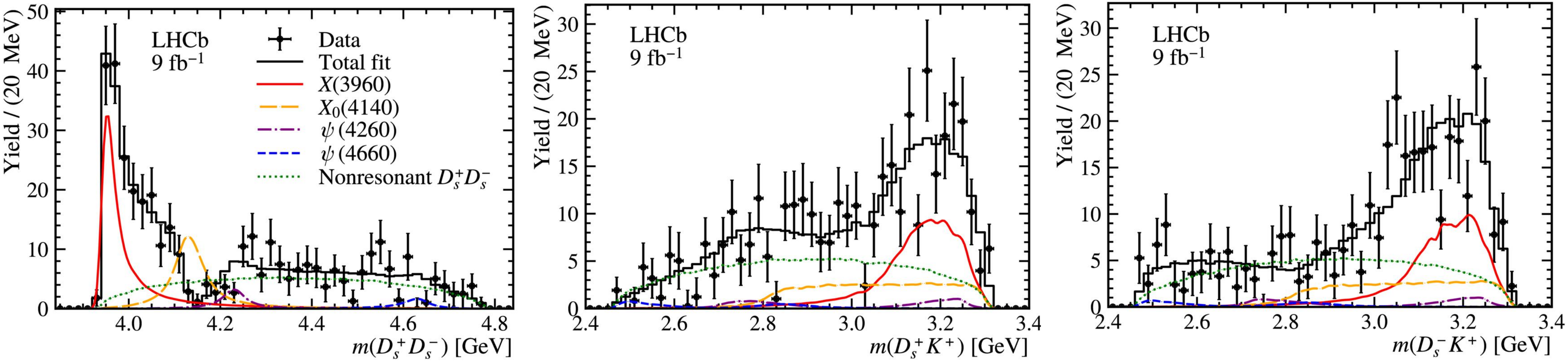
- $B^+ \to D_s^+ D_s^- K^+$ 衰变，末态夸克构成与$J/\psi\phi$相同
  - 360 ± 22 信号事例





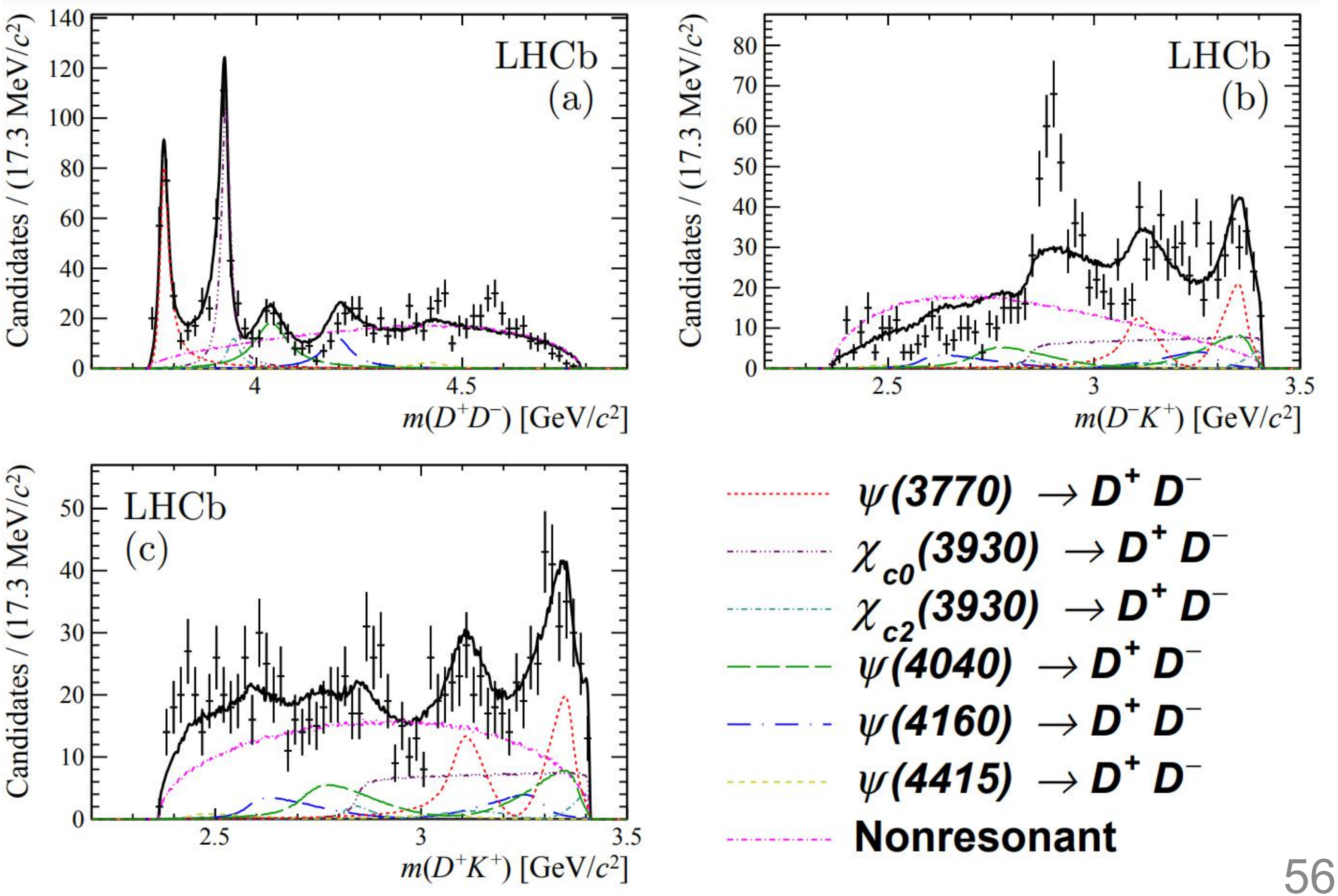
arXiv:2210.15153

- 显著的X(3960)态
- 也需要一个X_0(4140)态
  - $J^{PC} = 0^{++}$
  - 显著度3.7σ
  - 可能是新的态，或者由J/ψϕ↔$D_s^+D_s^-$导致



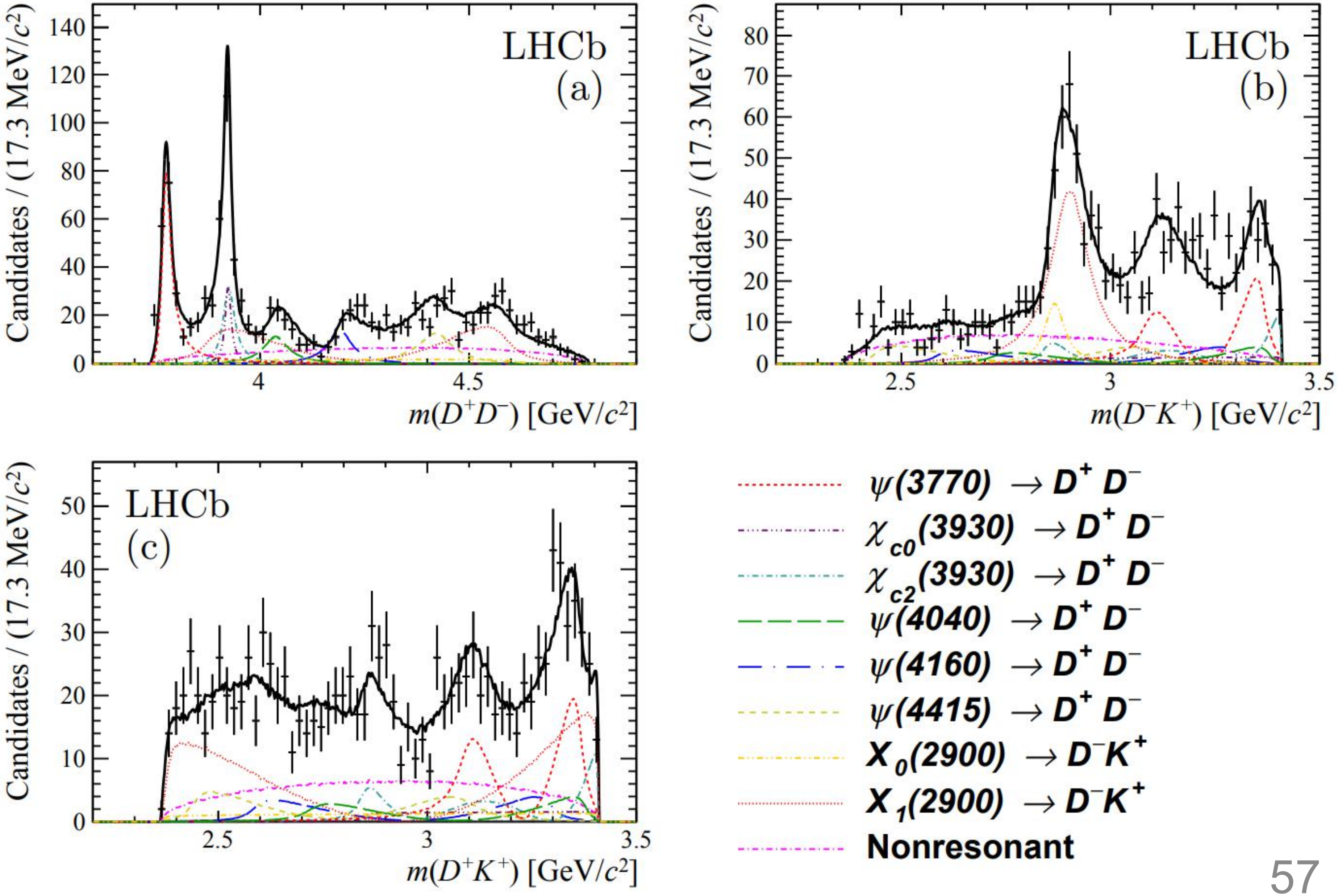
$T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$

- $B^+ \to D^+D^-K^+$
- 只使用已知的共振态



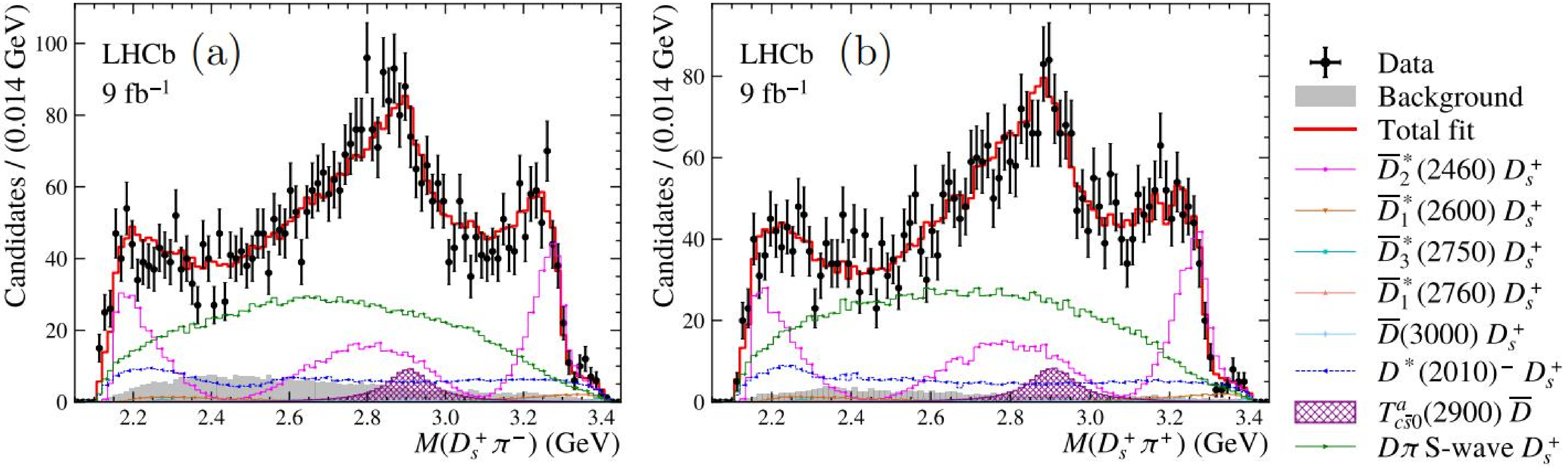
$T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$

- $B^+ \to D^+ D^- K^+$
- 加入两个新的共振态



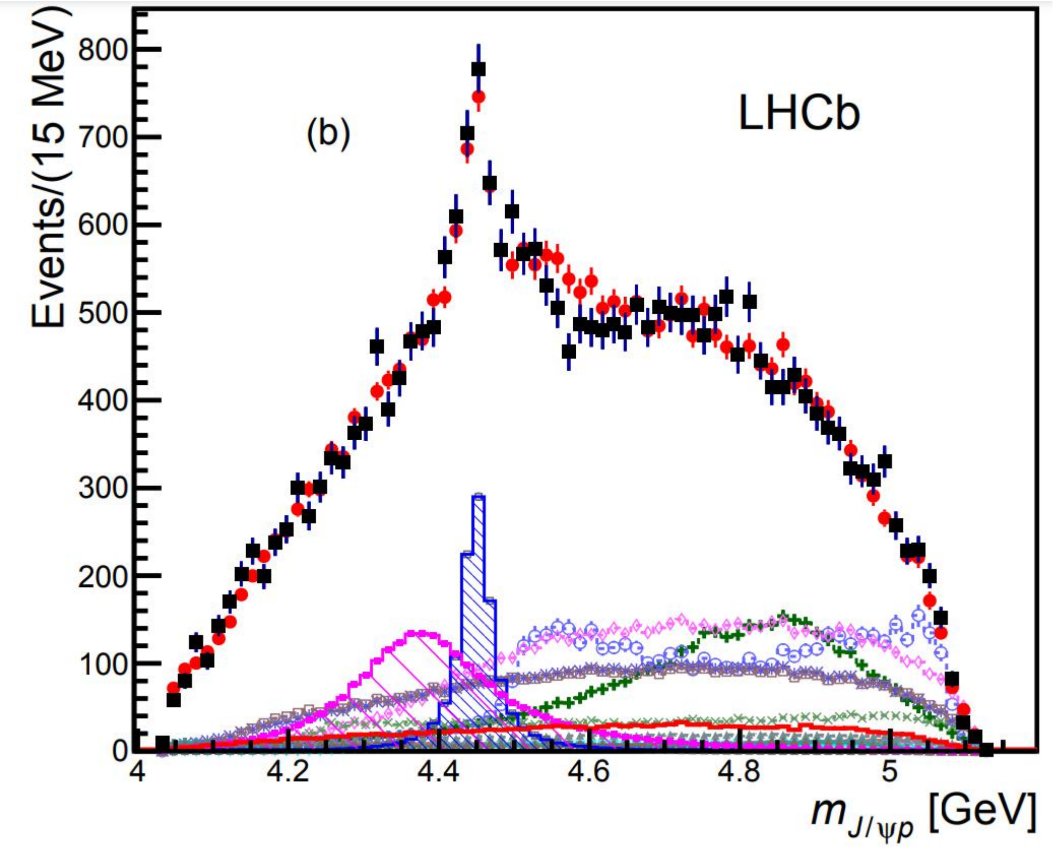
$T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$

- $B^0 \to \overline{D}^0 D_s^+ \pi^-$ 和 $B^+ \to D^- D_s^+ \pi^+$事例
  - 同位旋对称
- 首次观察到带2个单位电荷的奇特态

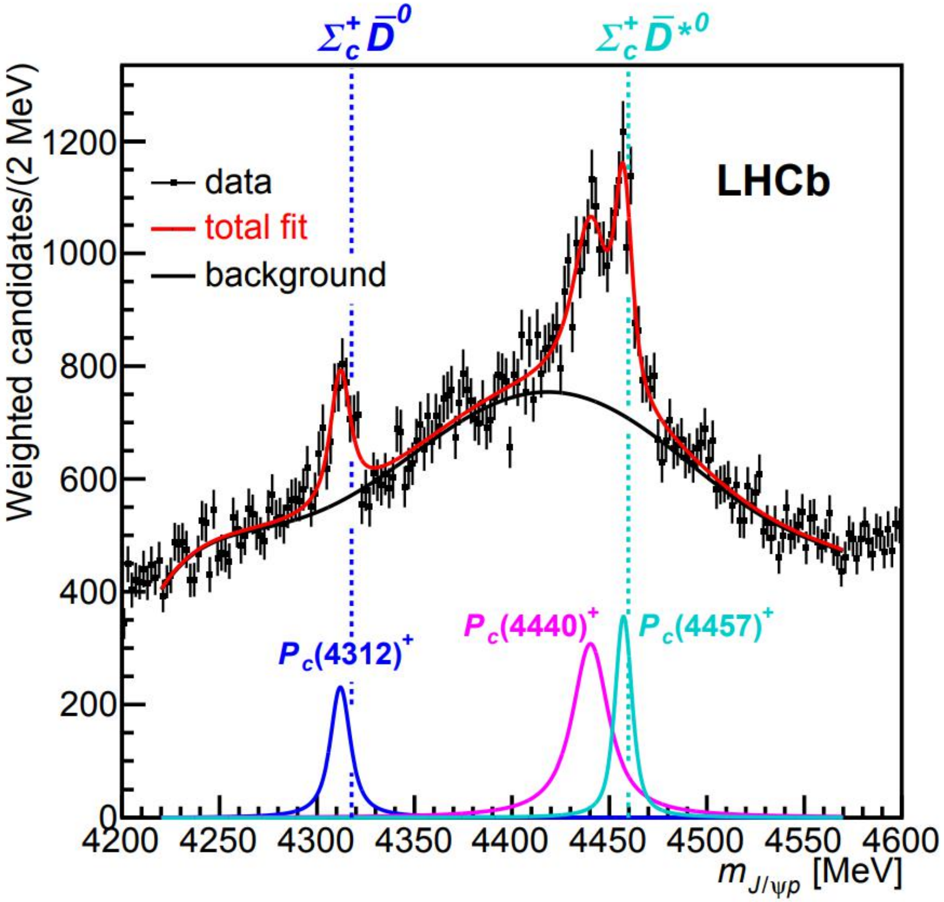


五夸克态

- $\Lambda_b \to J/\psi p K$事例
  - 2015年：Pc(4312), Pc(4450)
  - 2019年：Pc(4380), Pc(4450)→Pc(4440), Pc(4457)



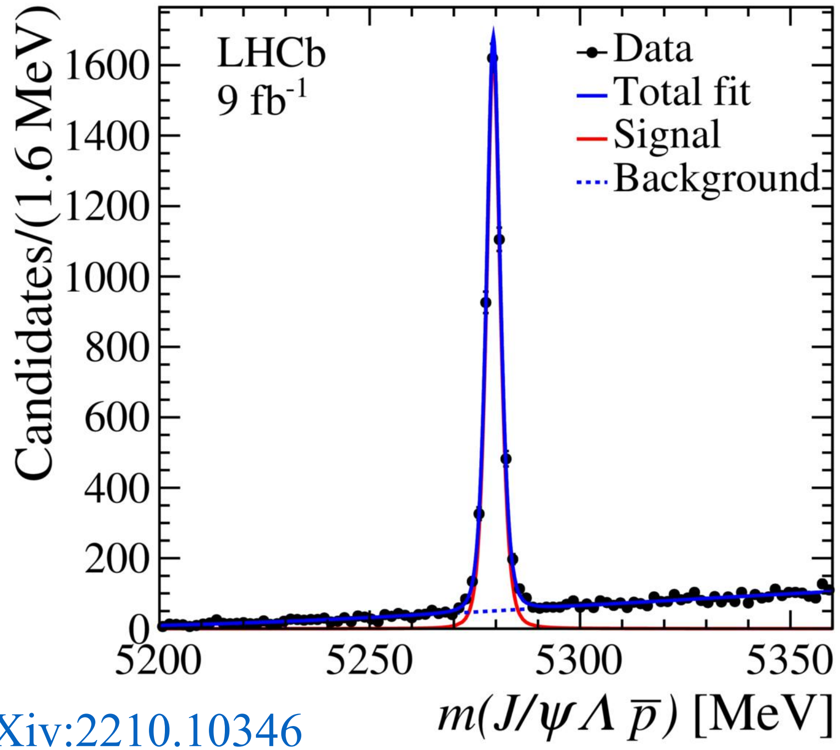
PhysRevLett.115.072001



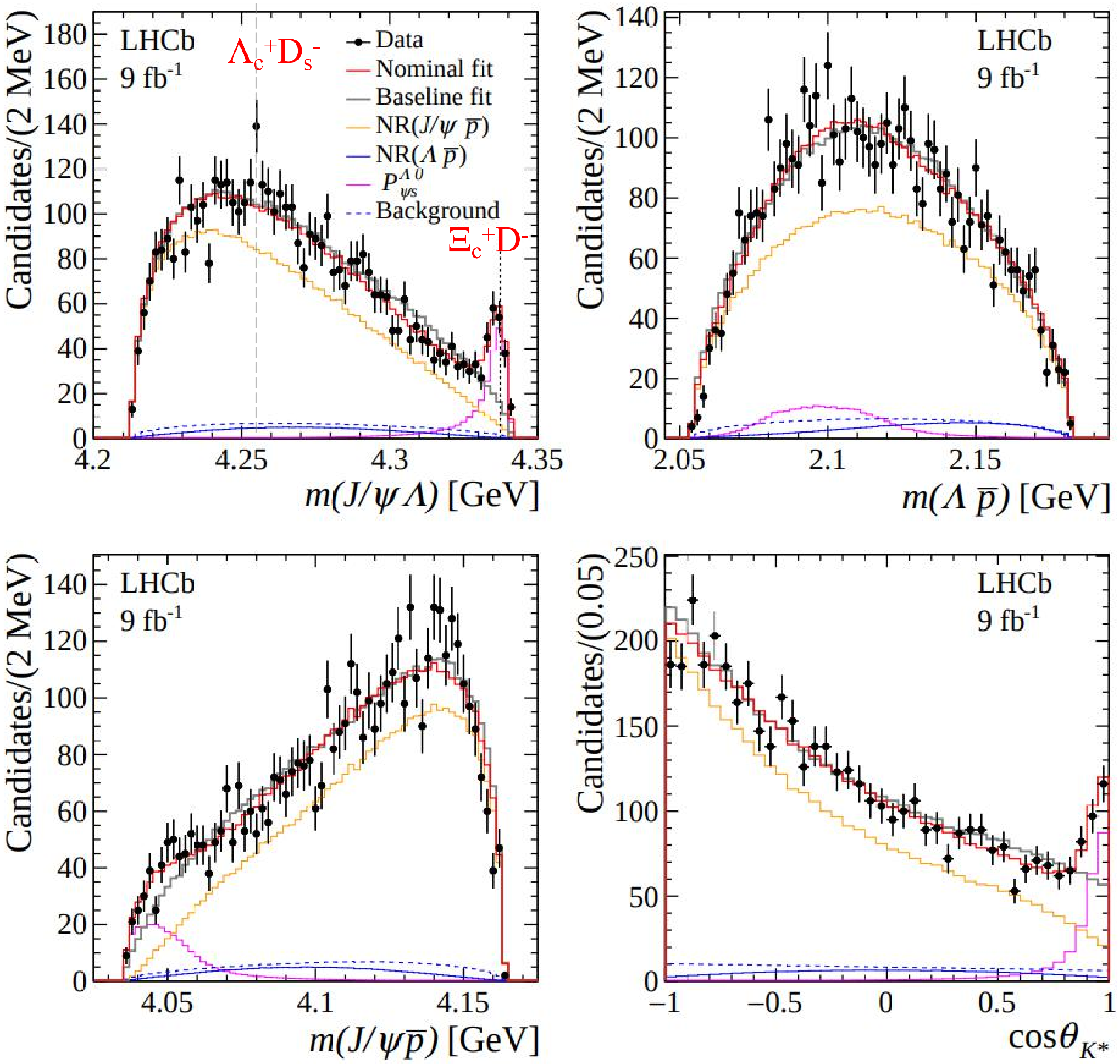
PhysRevLett.122.222001

$P^{\Lambda}_{\psi s0}(4338)^0 \to J/\psi\Lambda$

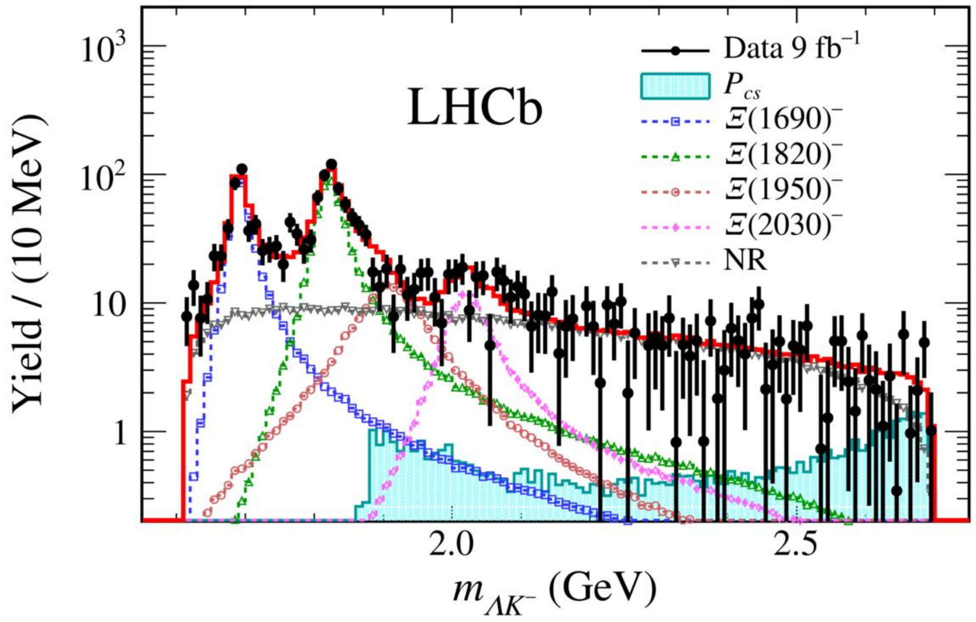
- $B^- \to J/\psi\Lambda\bar{p}$衰变
- 6维相空间振幅分析
- 无明显$P^{\Lambda}_{\psi s0}(4255)^0$信号
- 显著信号$P^{\Lambda}_{\psi s0}(4338)^0$，$1/2^-$

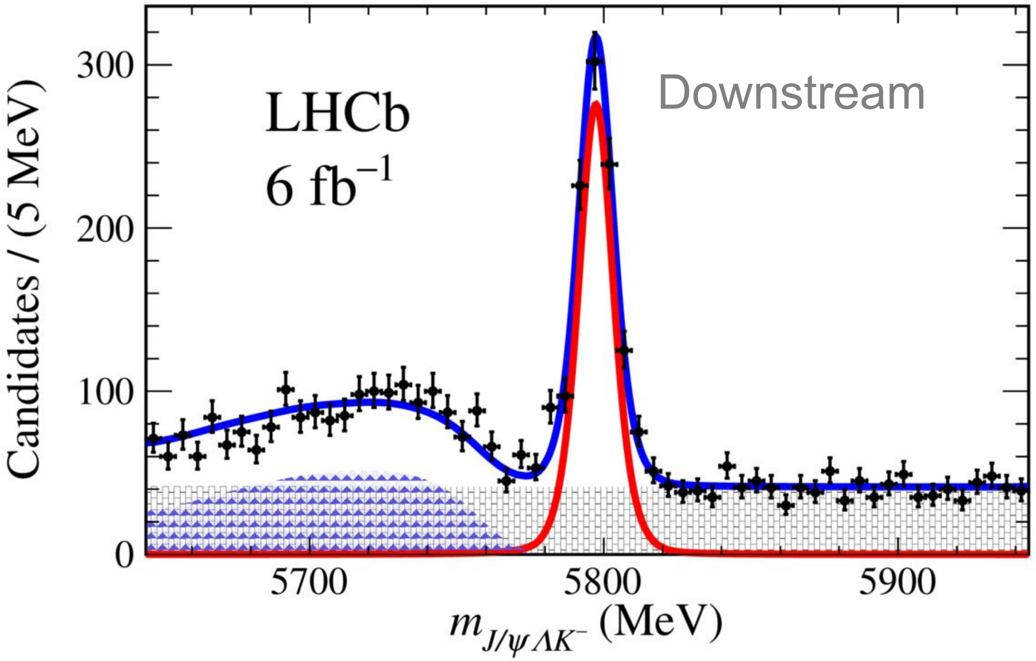


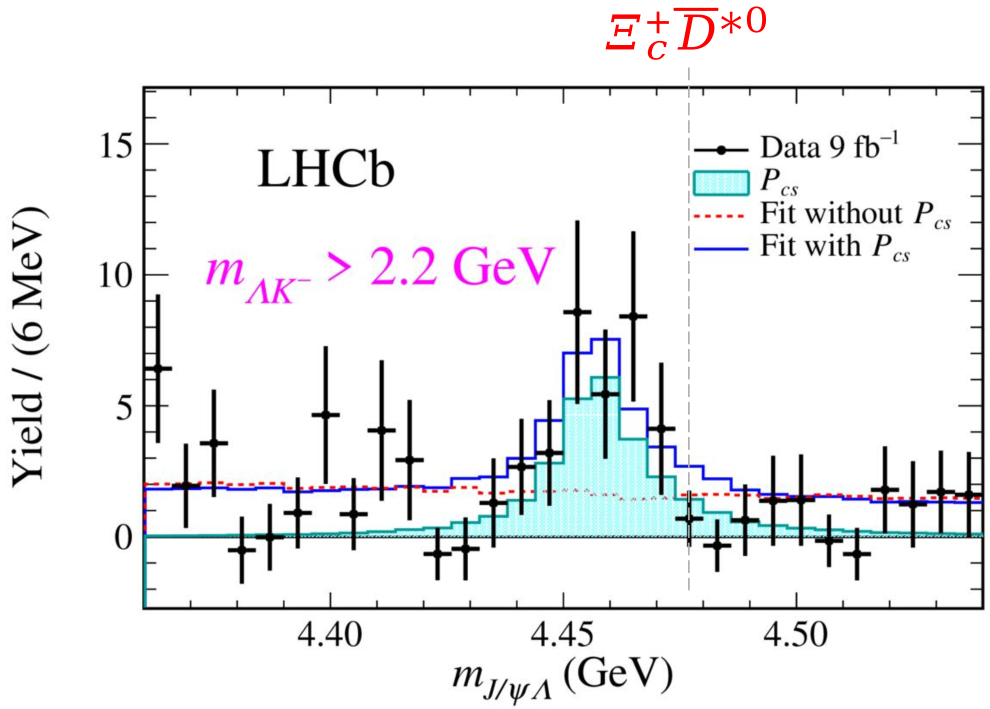
arXiv:2210.10346



- $\Xi_b^- \to J/\psi\,\Lambda K^-$衰变
- 6维振幅分析
- 显著P^$_{\psi s0}$(4459)^0-> J/ψΛ信号3.1σ
- 接近$\Xi_c^+\overline{D}^{*0}$阈值
    - 两个峰？

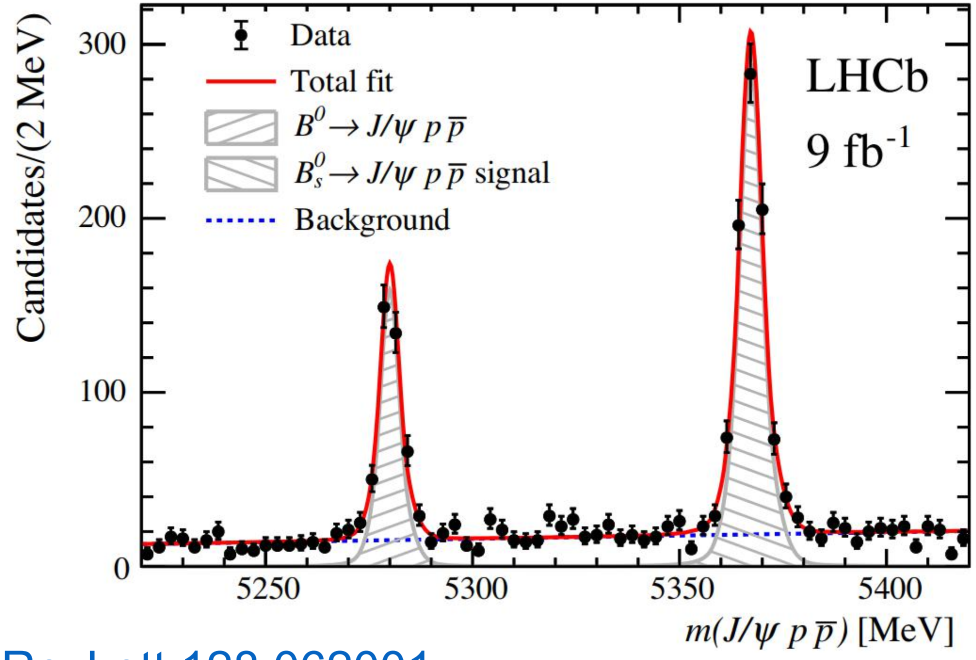




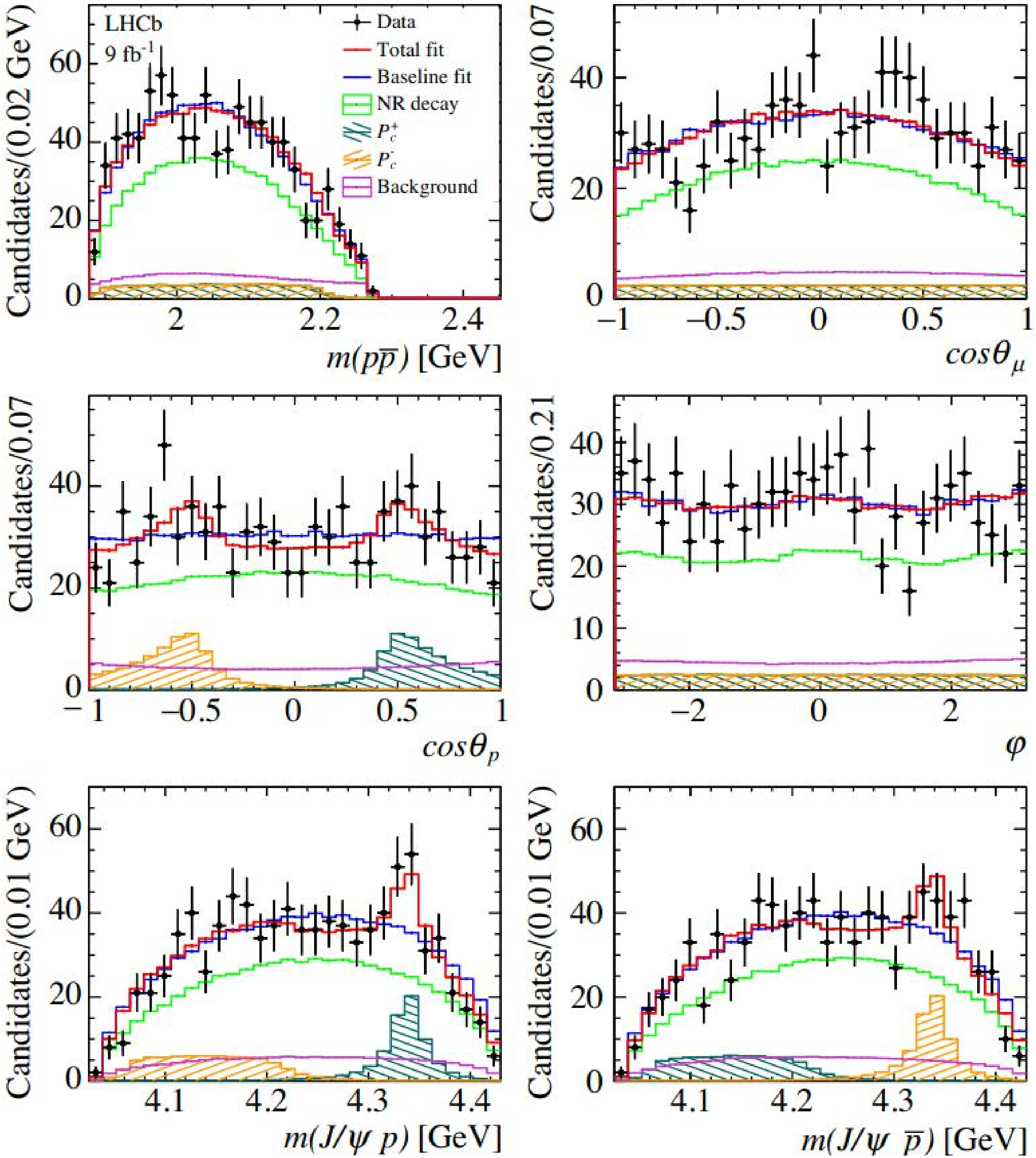


J/ψ p共振态

- $B_s^0 \to \mathrm{J}/\psi p\bar{p}$事例
- 4维相空间拟合
- 没有明显$\mathrm{P_c}(4312)$信号
- $\mathrm{P_c}(4337)$:
  - 3.1σ (J^P=1/2$^+$)
  - 3.7σ (J^P=3/2$^+$)



PhysRevLett.128.062001



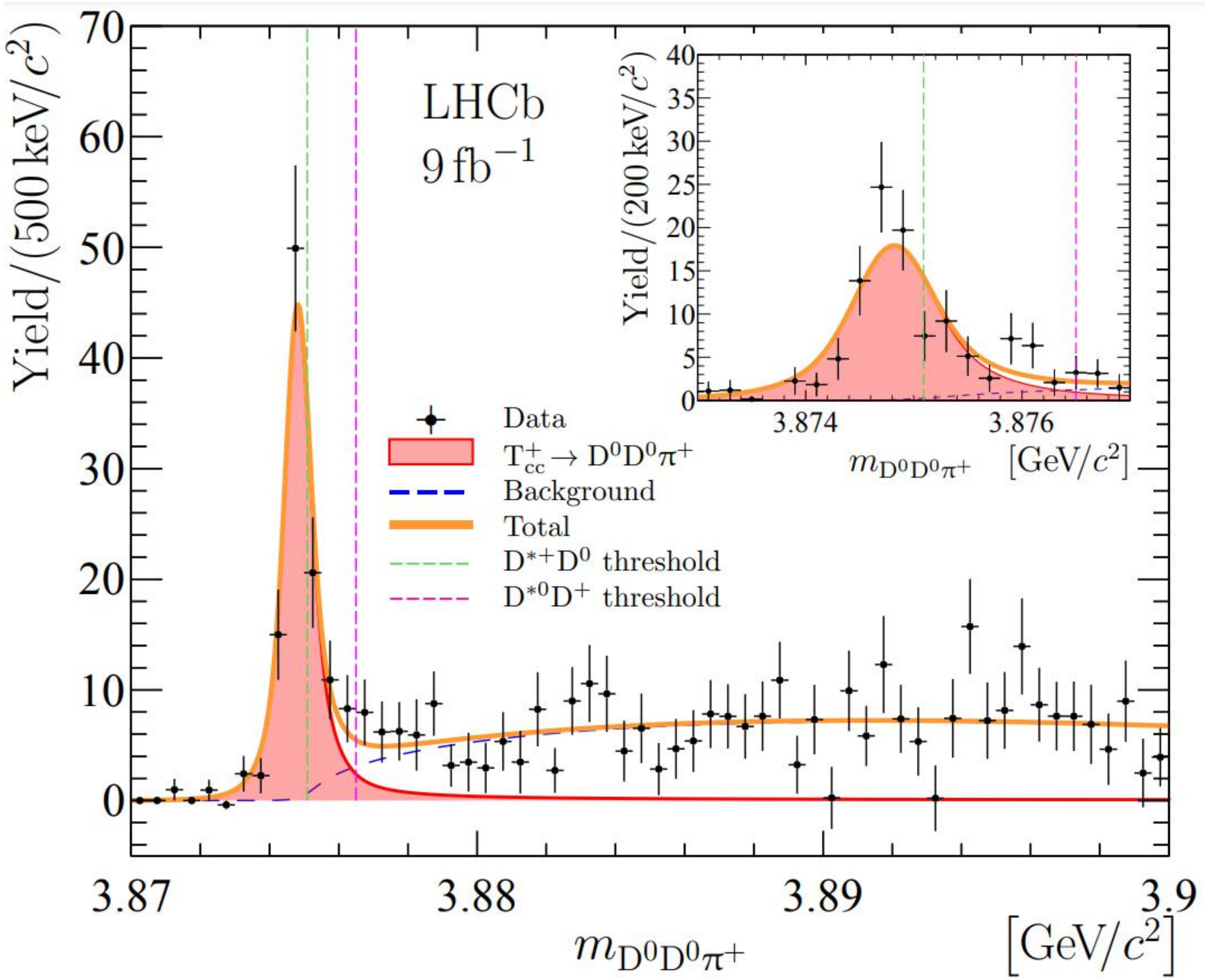
总结

- 粒子物理研究内容丰富，是基础物理研究的前沿
- LHC为奇特态的寻找提供了条件
- LHCb在奇特态的研究和寻找方面有独特的优势
  - LHCb“发现”了21个新的奇特态
- 奇特态的研究需要足够的统计量和复杂而细致的分析
  - 已经有很好的工具

Backup

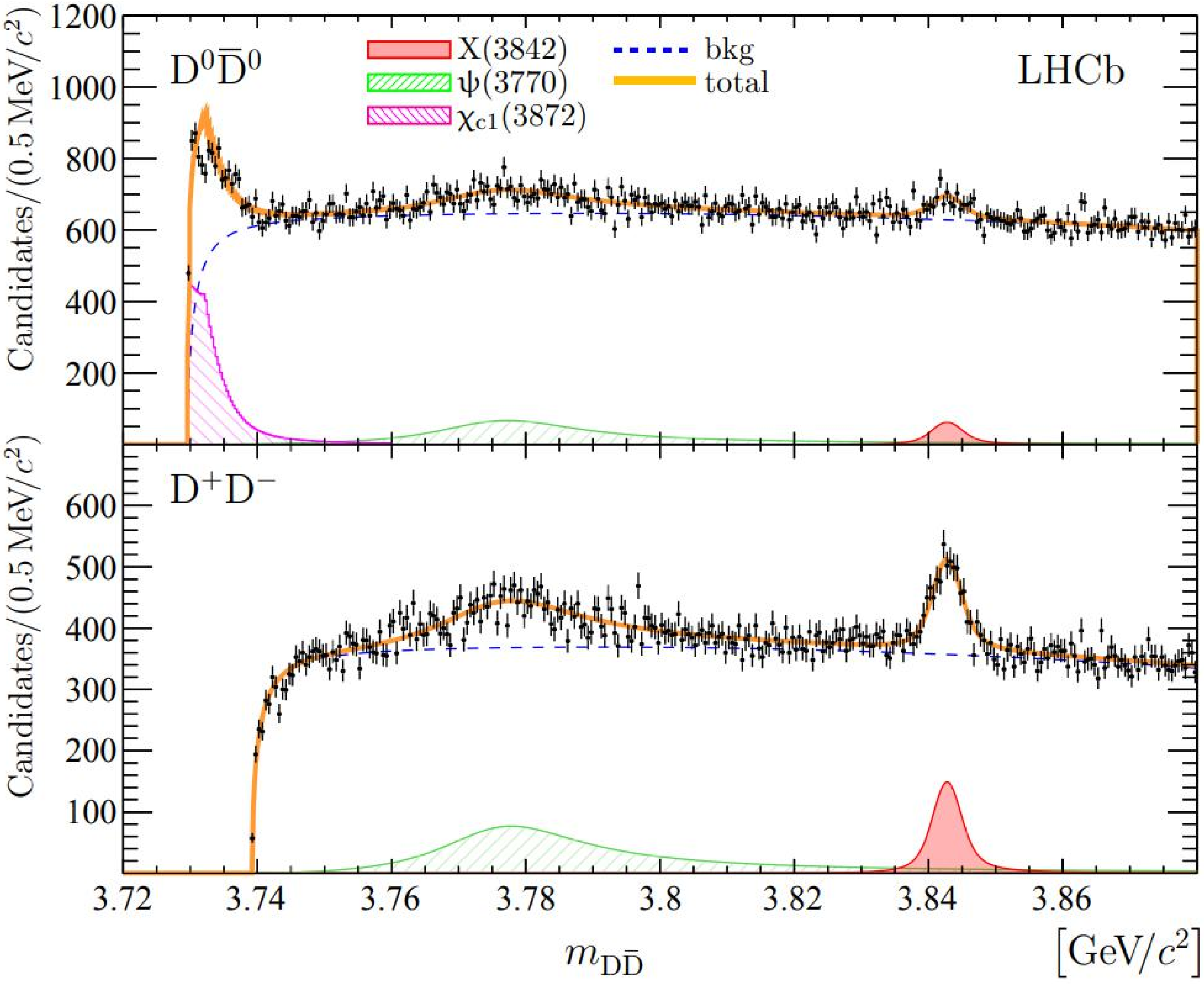
$T_{cc}(3875)^{+}$

- mass



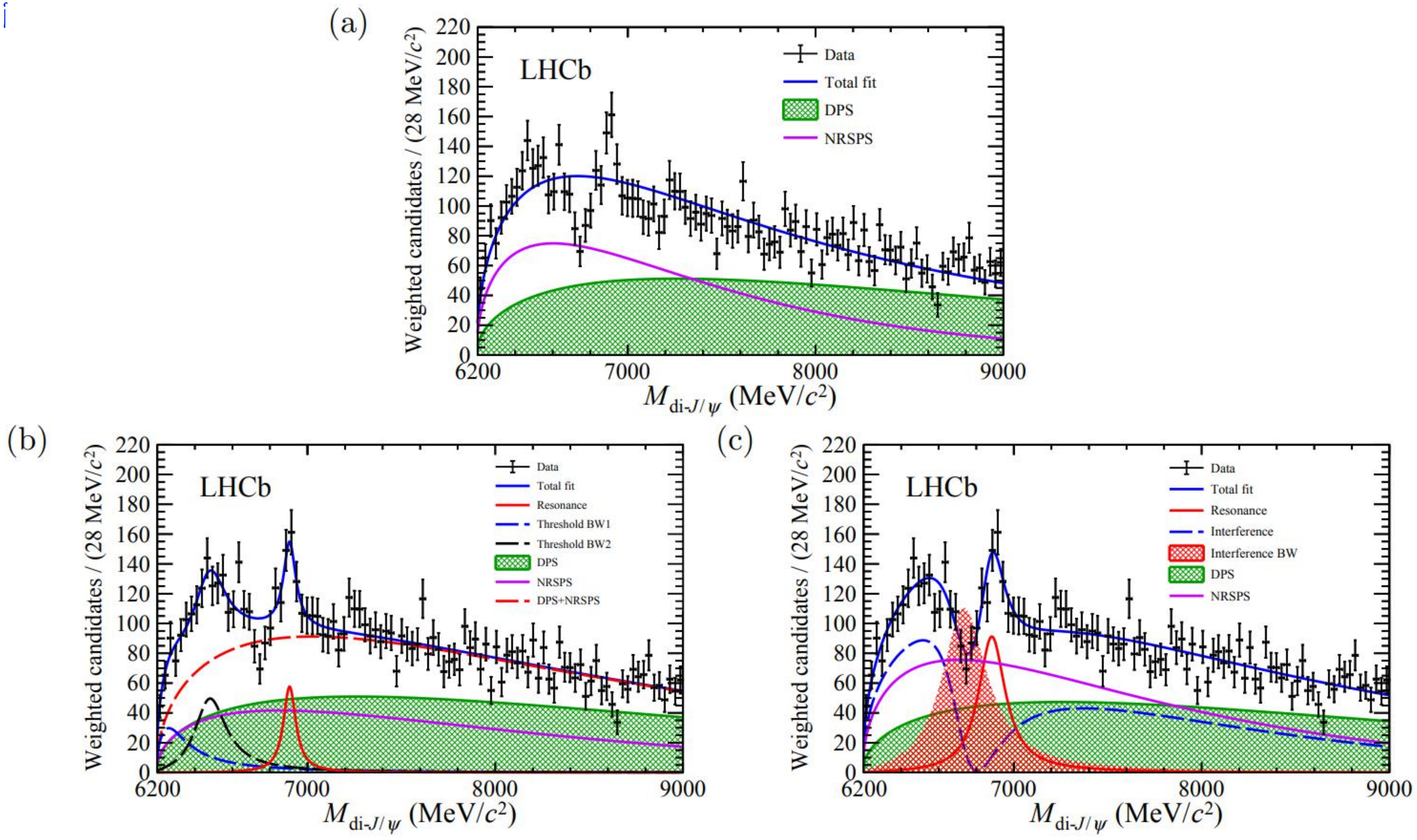
$\psi_3(3842)$

- near threshold



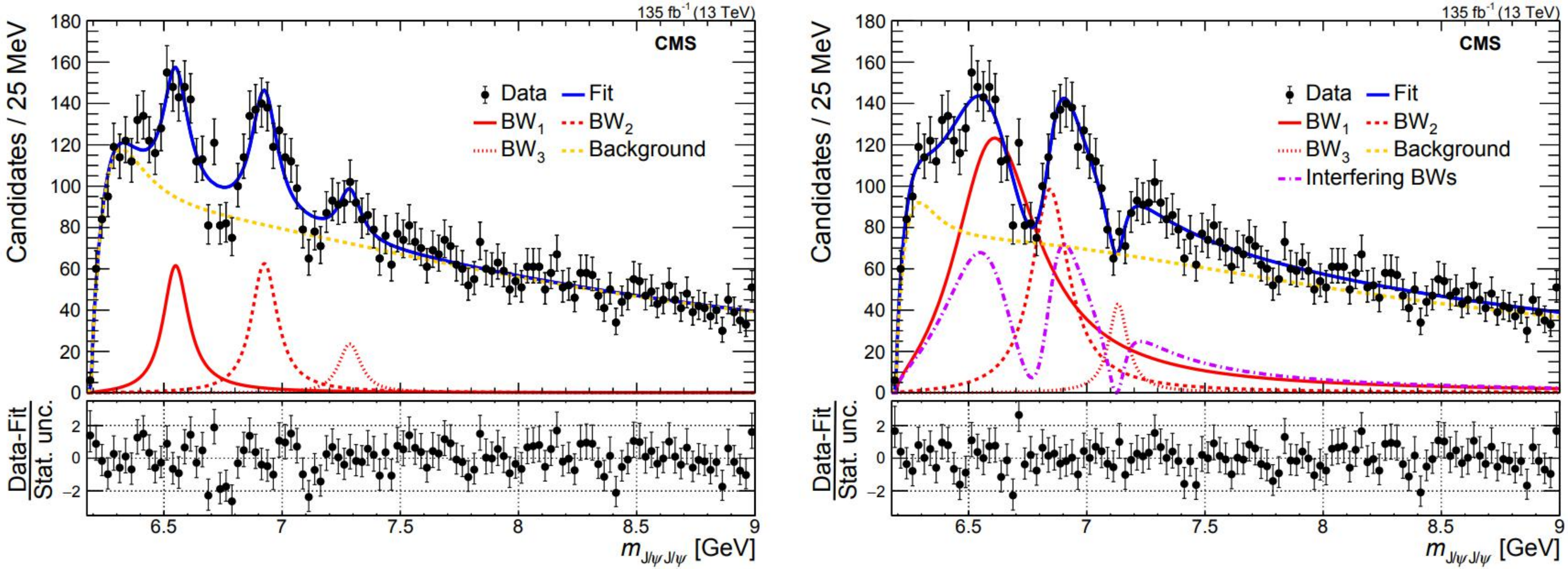
$T_{\psi\psi}(6900)$

- Jpsi



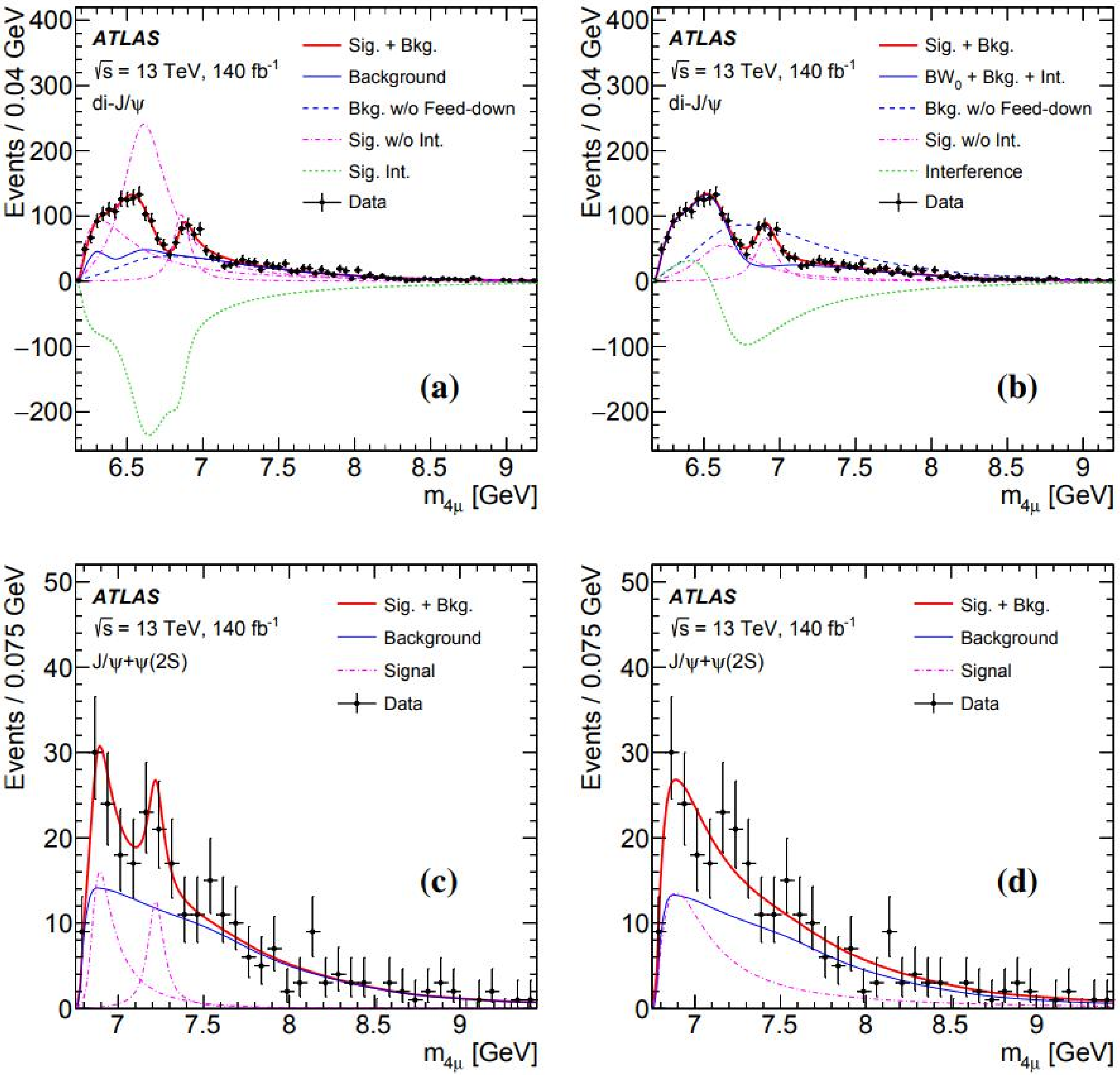
T(6600)

- here

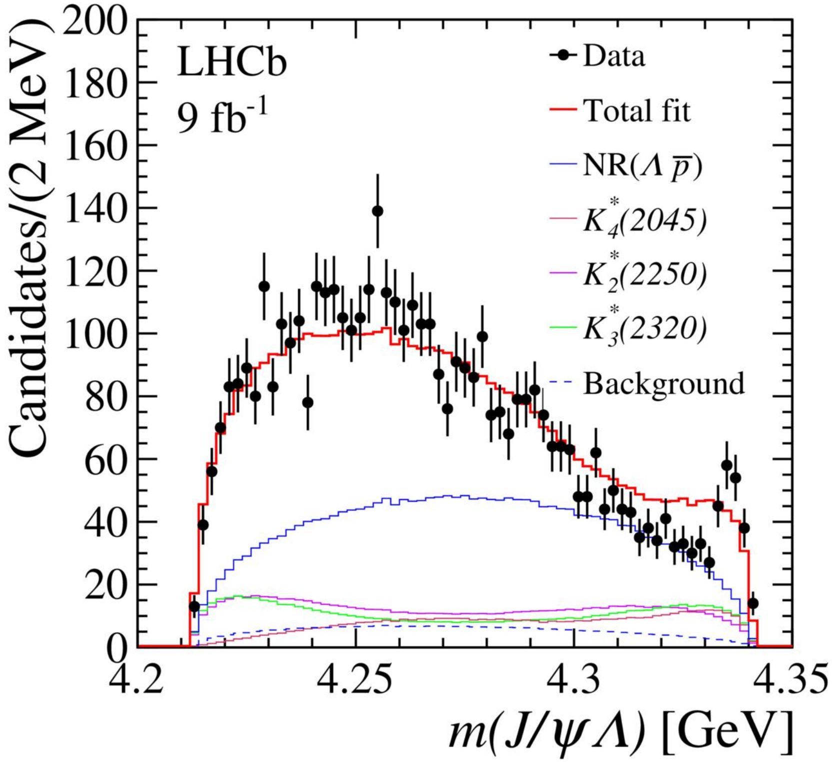


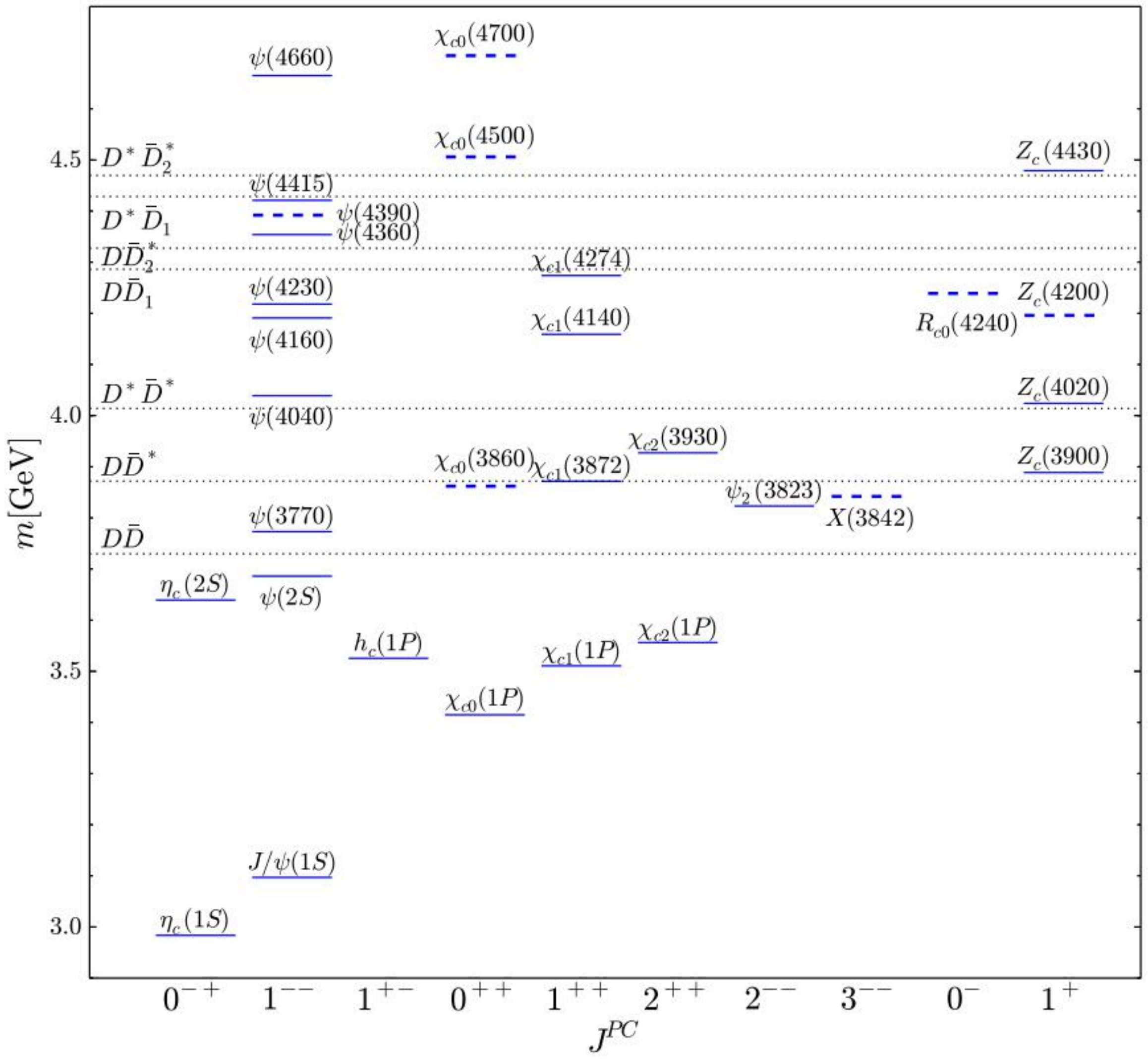
135 fb^{-1} (13 TeV)
CMS
Data
Fit
BW$_1$
BW$_2$
BW$_3$
Background
Interfering BWs
Candidates / 25 MeV
Data-Fit / Stat. unc.
$m_{J/\psi J/\psi}$ [GeV]

- ATLAS results

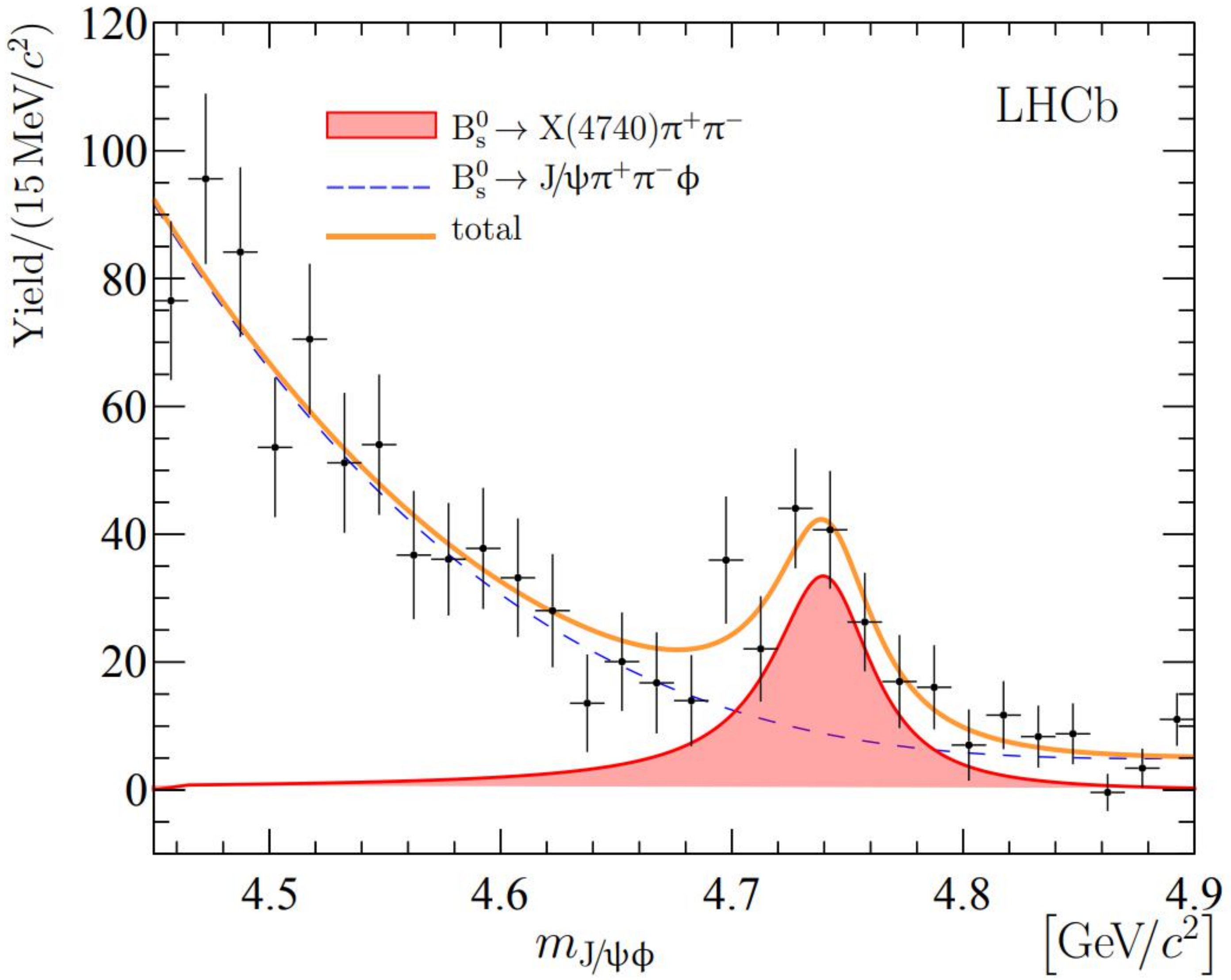


$P^{\Lambda}_{\psi s0}(4338)^0 \rightarrow J/\psi\Lambda$





$\chi_{c0}(4700)$
$\psi(4660)$
$\chi_{c0}(4500)$
$D^*\bar{D}_2^*$
$Z_c(4430)$
4.5
$\psi(4415)$
$D^*\bar{D}_1$
$\psi(4390)$
$\psi(4360)$
$D\bar{D}_2^*$
$\chi_{c1}(4274)$
$D\bar{D}_1$
$\psi(4230)$
$Z_c(4200)$
$\chi_{c1}(4140)$
$R_{c0}(4240)$
$\psi(4160)$
$D^*\bar{D}^*$
$Z_c(4020)$
4.0
$\psi(4040)$
$\chi_{c2}(3930)$
$D\bar{D}^*$
$\chi_{c0}(3860)$
$\chi_{c1}(3872)$
$Z_c(3900)$
$\psi_2(3823)$
$X(3842)$
$\psi(3770)$
$D\bar{D}$
$\eta_c(2S)$
$\psi(2S)$
$h_c(1P)$
$\chi_{c2}(1P)$
$\chi_{c1}(1P)$
3.5
$\chi_{c0}(1P)$
$J/\psi(1S)$
$\eta_c(1S)$
3.0
m[GeV]
0^{-+} 1^{--} 1^{+-} 0^{++} 1^{++} 2^{++} 2^{--} 3^{--} 0^{-} 1^{+}
J^{PC}



LHCb
$B_s^0 \to X(4740)\pi^+\pi^-$
$B_s^0 \to J/\psi\pi^+\pi^-\phi$
total
Yield/(15 MeV/c^2)
120
100
80
60
40
20
0
4.5
4.6
4.7
4.8
4.9
$m_{J/\psi\phi}$ [GeV/c^2]

Discovery of $T^{a}_{c\bar{s}0}(2900)^0$ and $T^{a}_{c\bar{s}0}(2900)^{++}$

- sadf