Doubly heavy baryons

双粲重子的发现、研究现状和展望

谢跃红

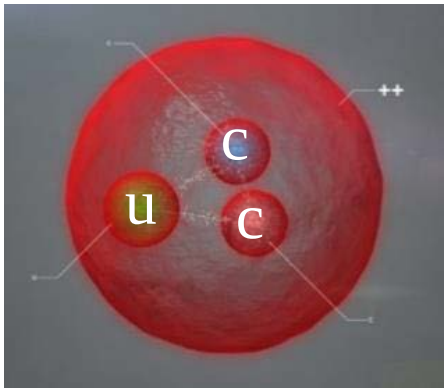
华中师范大学

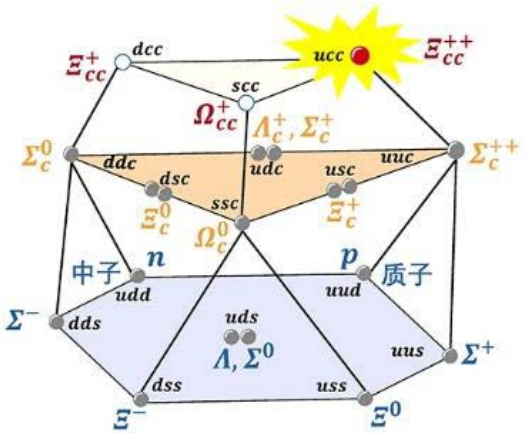
强子与重味物理理论与实验联合研讨会

2018年3月31-4月1日

2017年中国科学十大进展之第三名

2017年7月LHCb实验宣布发现首个双粲重子Ξ_{cc}^{++}





- 中国LHCb团队起到主导作用
- 中国理论家做出重要理论贡献


荣誉证书

“首次探测到双粲重子”荣获2017年度中国科学十大进展

主要完成单位和完成人

LHCb国际合作中国组（清华大学、华中师范大学、中国科学院大学和武汉大学）

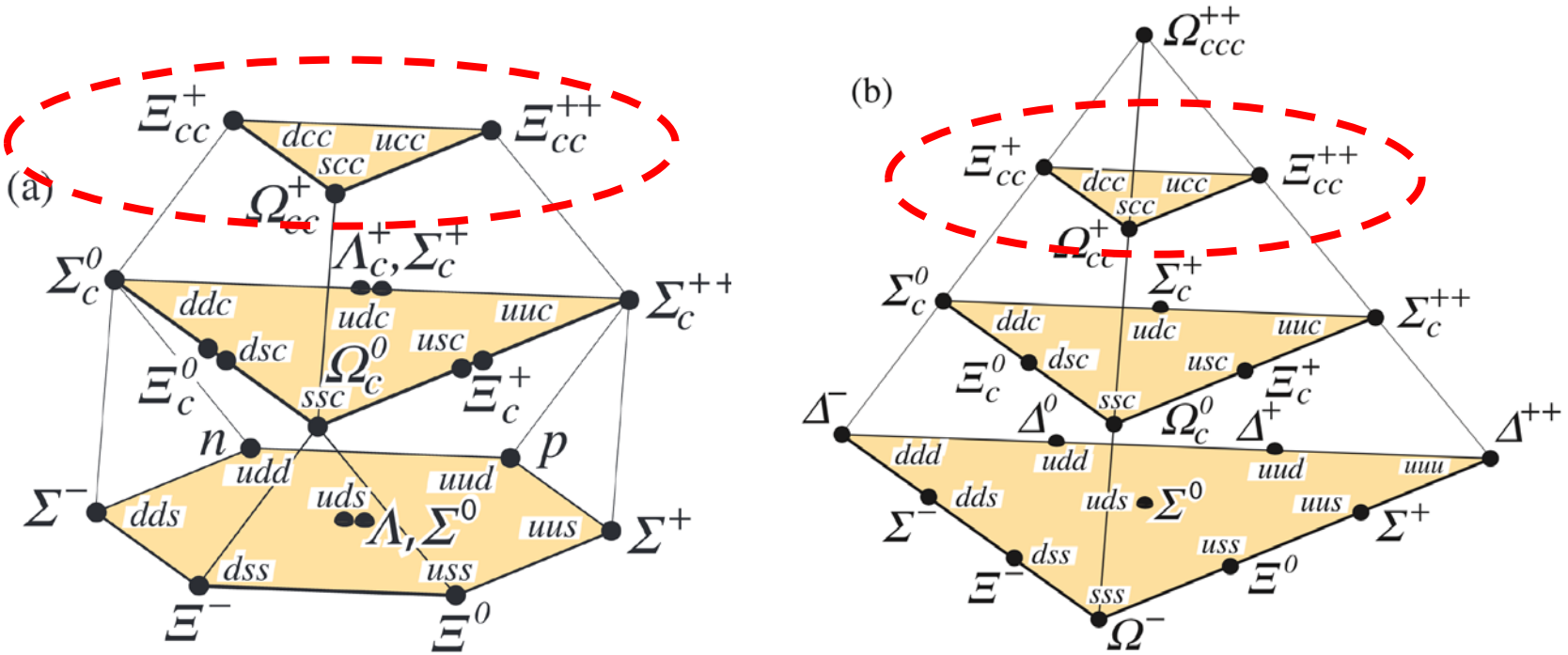
主办单位：科学技术部基础研究管理中心

协办单位：《中国基础科学》编辑部 《科技导报》编辑部 《中国科学院院刊》编辑部 《中国科学基金》编辑部 《科学通报》编辑部

Doubly charm baryons in quark model

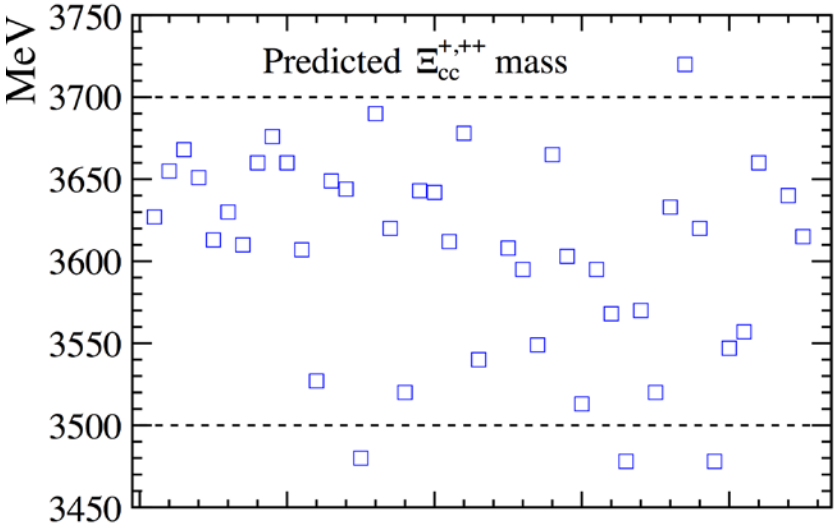
Three c=2 baryons: $\Xi_{cc}^{+}(ccd)$, $\Xi_{cc}^{++}(ccu)$, $\Lambda_{cc}^{+}(ccs)$

- $J^P = \frac{1}{2}^+$: decay weakly with a c quark → lighter quark
- $J^P = \frac{3}{2}^+$: decay to $\frac{1}{2}^+$ states via strong or EM interactions



Predicted properties of $\frac{1}{2}^+$ states

- Many masses predictions : QCD potential models, triple harmonic-oscillator potential model, QCD sum rules, bag model or quark model



$m(\Xi_{cc}^{+}) = m(\Xi_{cc}^{++}) \approx 3.5 - 3.7$ GeV

$m(\Omega_{cc}^{+}) = m(\Xi_{cc}) + 0.1$ GeV

- Pattern of lifetimes due to interference of spectator and W-exchange contributions

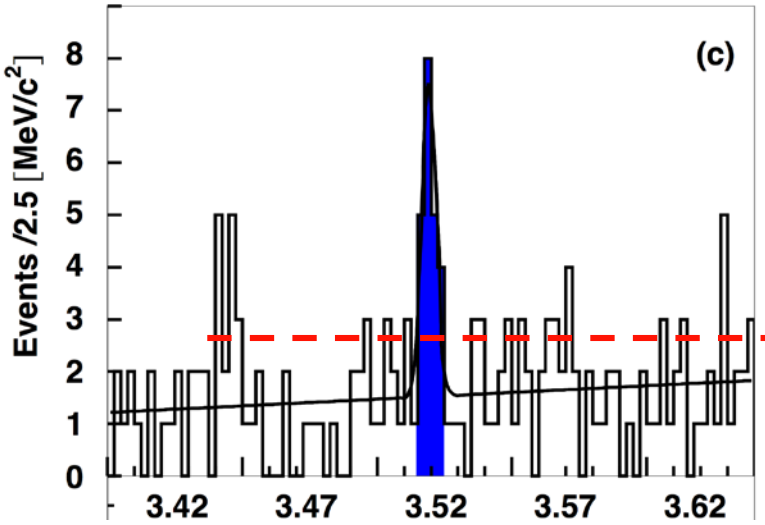
$\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+}) \approx \tau(\Omega_{cc}^{+})$

$\tau(\Xi_{cc}^{++}) \in [200, 700]$ fs, $\tau(\Xi_{cc}^{+}) \in [50, 250]$ fs

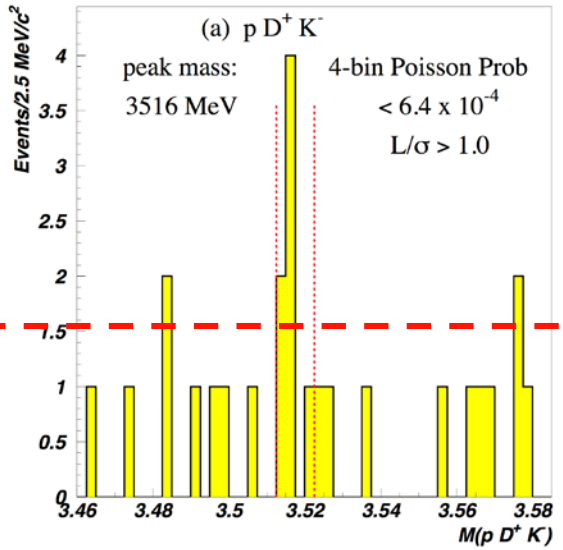
Searches for Ξ_{cc}^{+} by SELEX

- SELEX(FermiLab E781): hyperon (Σ^{-},p) beams with nuclear targets for study of charm baryons
- Reported observation of $\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+}$ and $\Xi_{cc}^{+} \to pD^{+}K^{-}$
  - Mass: 3518.17 $\pm$ 1.7MeV
  - Short lifetime: $\tau(\Xi_{cc}^{+})$ < 33 fs @ 90% CL, but not zero
  - Large production: $\sigma(\Xi_{cc}^{+}) \cdot BF(\Xi_{cc}^{+} \to \Lambda_c^{+}K^{-}\pi^{+})/\sigma(\Lambda_c^{+})$~ 20%

PRL 89 (2002) 112001



PLB 628 (2005) 18



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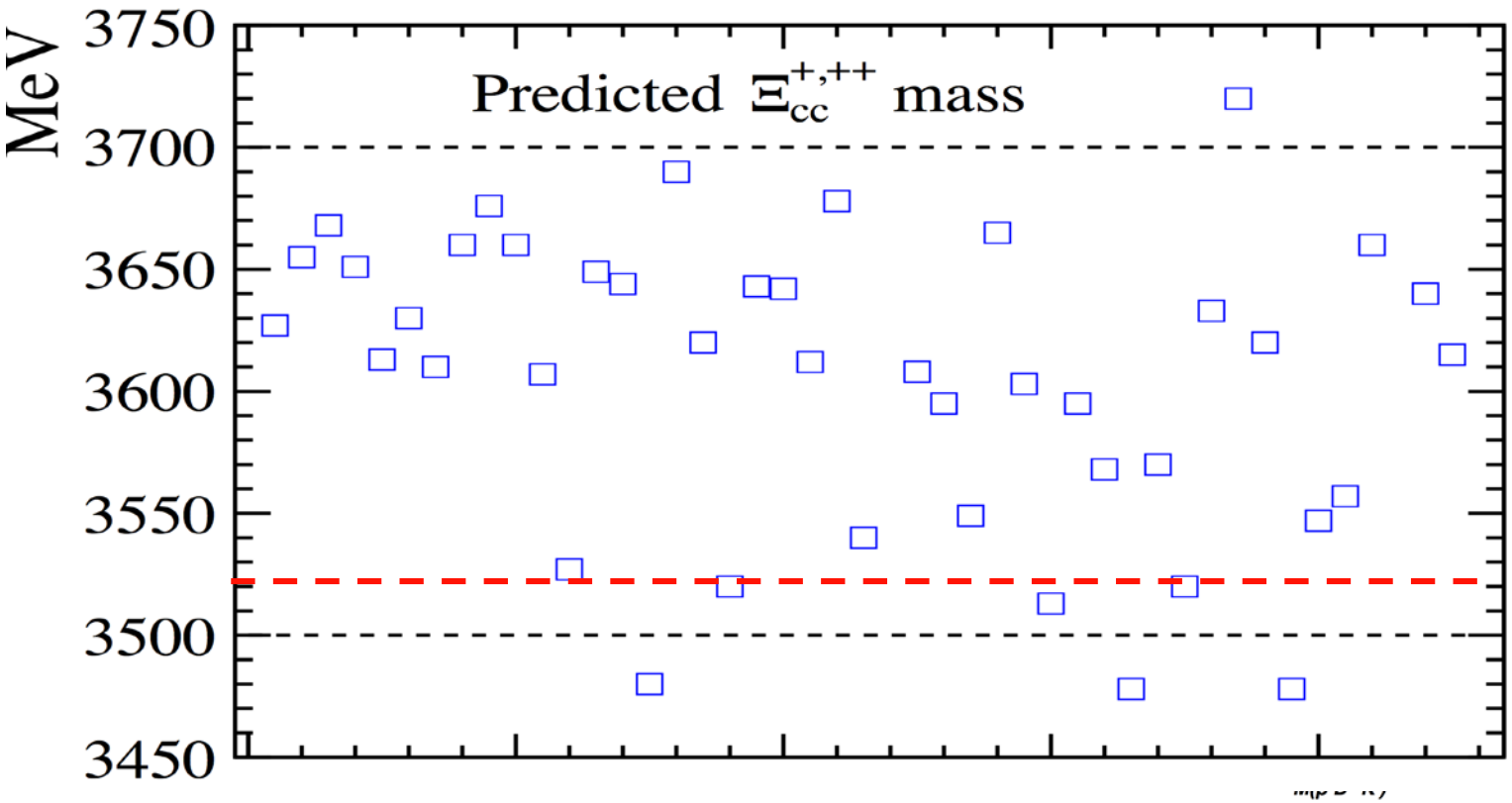
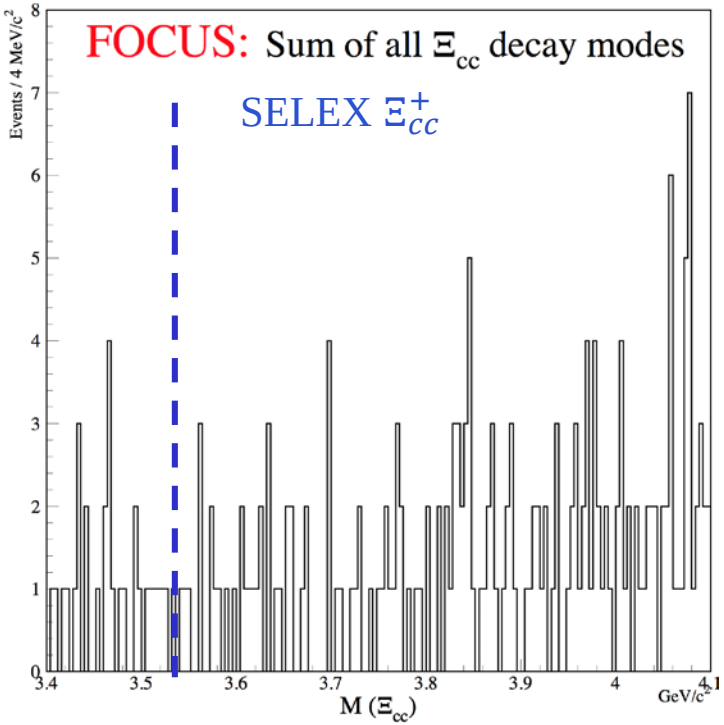
  - Mass: 3518.17 $\pm$ 1.7MeV



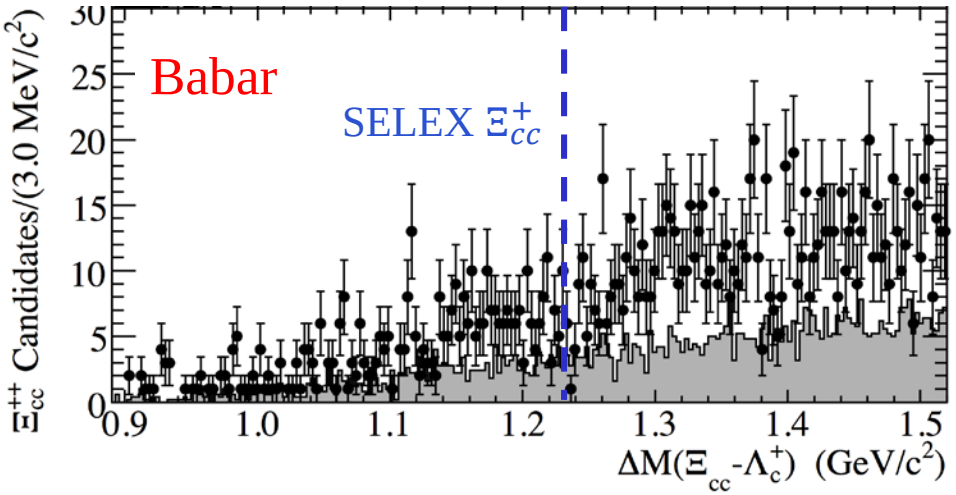
Non-confirmation @ Focus, Babar, Belle

FOCUS used 10 times more Statistics than SELEX

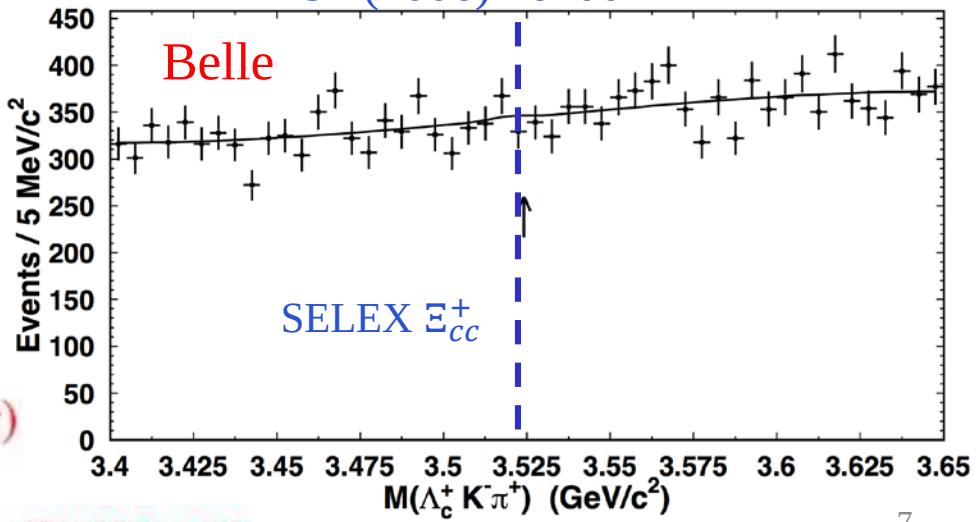
Nucl. Phys. Proc. Suppl. 115 (2003) 33



PRD 74 (2006) 011103



PRL 97 (2006) 162001



$$\frac{\sigma(\Xi_{cc}^{+})\times BF(\Xi_{cc}^{+}\to\Lambda_c^{+}K^{-}\pi^{+})}{\sigma(\Lambda_c^{+})} < 2.7\times10^{-4}\ \text{(BaBar)}$$

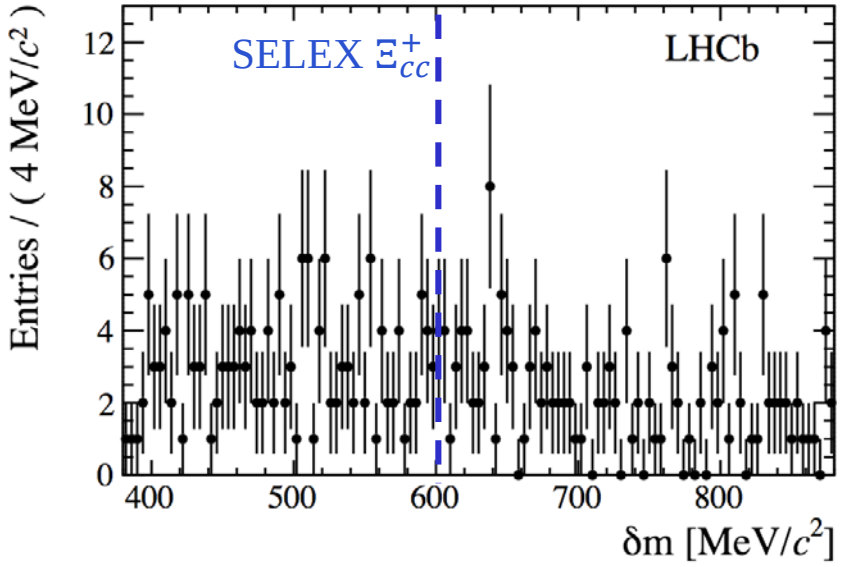
1.5×10^{-4} (Belle) @ 95% CL

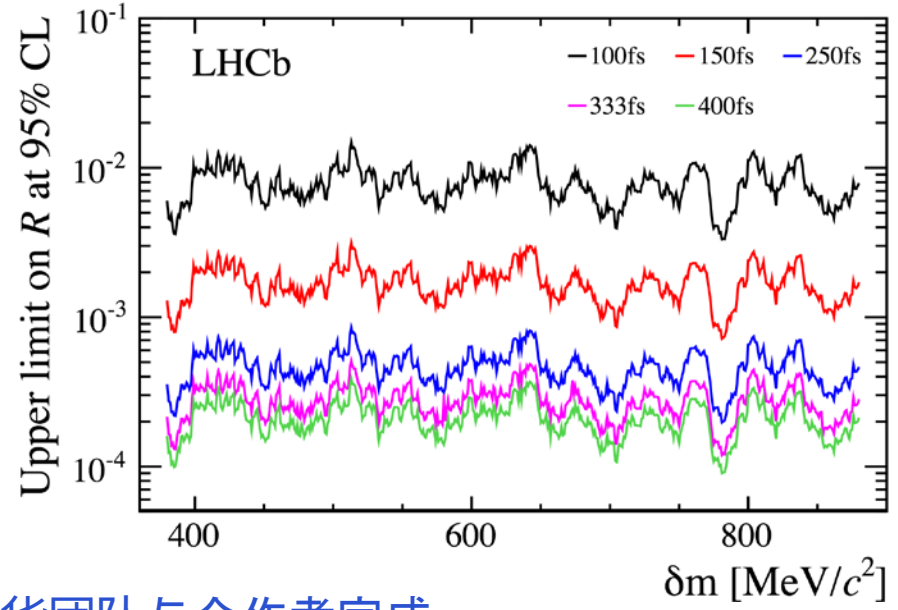
Early search for Ξ_{cc}^{+} at LHCb

- Searched for $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ using 0.65 fb^{-1} of run-1 data
  - No peaking signal found
  - Sensitivity depends on lifetime

$$R = \frac{\sigma(\Xi_{cc}^{+}) \times \mathrm{BF}(\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+})}{\sigma(\Lambda_c^{+})} < 0.013 \text{ for } \tau = 100 \text{ fs},$$

$$< 3.3 \times 10^{-4} \text{ for } \tau = 400 \text{ fs} \quad @95\%$$





JHEP 12 (2013) 090，主要由清华团队与合作者完成

大科学装置专项指南的要求

- 2016年底发布的国家重点研发计划大科学装置前沿研究专项指南

1.3 LHCb 实验数据分析

研究内容：利用 LHCb 的实验数据，寻找和研究重味强子的稀有衰变过程间接寻找超出粒子物理标准模型的新物理。

考核指标：寻找含有双重味夸克重子，大幅度提高实验灵敏度；利用 RUNII 数据研究五夸克态性质，确认其量子数；完成 2 项 B 介子稀有衰变过程寻找，对稀有衰变过程分支比的探测灵敏度好于 1.0^{-7}。

- LHCb四个中国单位共同申请，专门设立“双重味重子寻找”课题
- 针对此课题，向国内理论家提出了问题：

哪个双粲重子的什么衰变方式在实验上最容易观测？

LHCb实验方面的限制因素

- 电子以外的稳定带电粒子相对容易探测，光子和电子探测效率很低
- 寿命很短（几十飞秒）粒子的纯强子衰变触发效率很低，不易探测
- 整个级联衰变的总分支比要足够大

理论和实验的互动

- 在双重味重子研究方面，LHCb中国组一直得到国内理论家的支持和帮助（感谢张肇西，吕才典，吴兴刚，于福升，…）
- LHCb中国组此次提出的问题很快有了回应
  - 于福生应邀于2016年12月在国科大与LHCb中国组讨论并作报告
  - 于福生代表合作团队于2017年3月在LHCb实验charm WG 作报告

Weak Decays of Ξ_{cc}

Fu-Sheng Yu (于福升)

Lanzhou University

15.03.2017 @ LHCb Charm WG

Thank Ji-Bo and Andrea for invitation to give a talk!

Based on [arXiv:1703.xxxxx]

In collaboration with Hua-Yu Jiang, Run-Hui Li, Ying Li, Cai-Dian Lü, Wei Wang, Zhen-Xing Zhao

理论计算结果

Baryons	Modes	Br	secondary decay Br's	tracks
Ξ_{cc}^{++}	$\Lambda_c^+ K^- \pi^+ \pi^+$	$\mathcal{O}(10\%)$	×6%	6
	$\Xi_c^+ \pi^+$	$(0.2 \sim 5.2)\%$	×(1.6±0.5)%	4
	$\Lambda_c^+ \pi^+$	$(0.1 \sim 0.6)\%$	×6%	4
	pD^+	$(0.1 \sim 0.6)\%$	×9%	4
Ξ_{cc}^{+}	$\Xi_c^0 \pi^+$	$(5 \sim 8)\%$		5
	$\Xi_c^+ \pi^+ \pi^-$	$\mathcal{O}(10\%)$	×(1.6±0.5)%	5
	$\Lambda_c^+ K^- \pi^+$	$\mathcal{O}(10\%)$	×6%	5
	ΛD^+	$(0.2 \sim 1.4)\%$	×9%	5
	pD^0	$(0.005 \sim 0.04)\%$	×4%	3

$$\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+})$$

理论家的建议

Summary

- Ξ_{cc} could be discovered and established by LHCb, with large data collected
- We develop a theoretical method to calculate the branching fractions of some processes of Ξ_{cc} decays
- We suggest to measure the following processes with the largest possibilities to be observed.

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$$

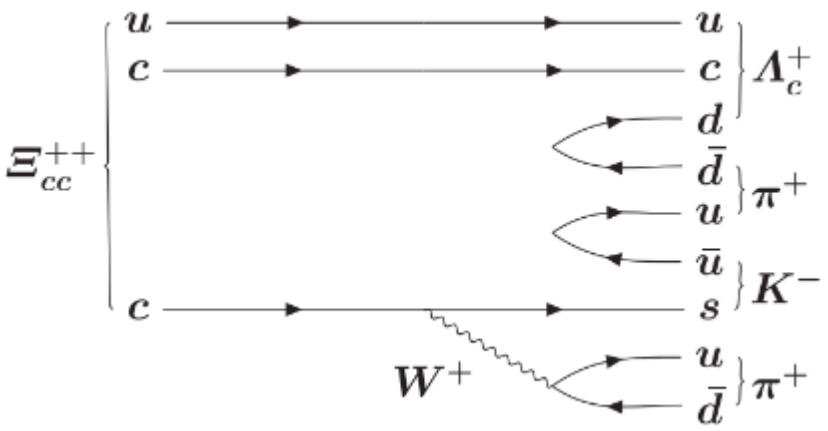
$$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$$

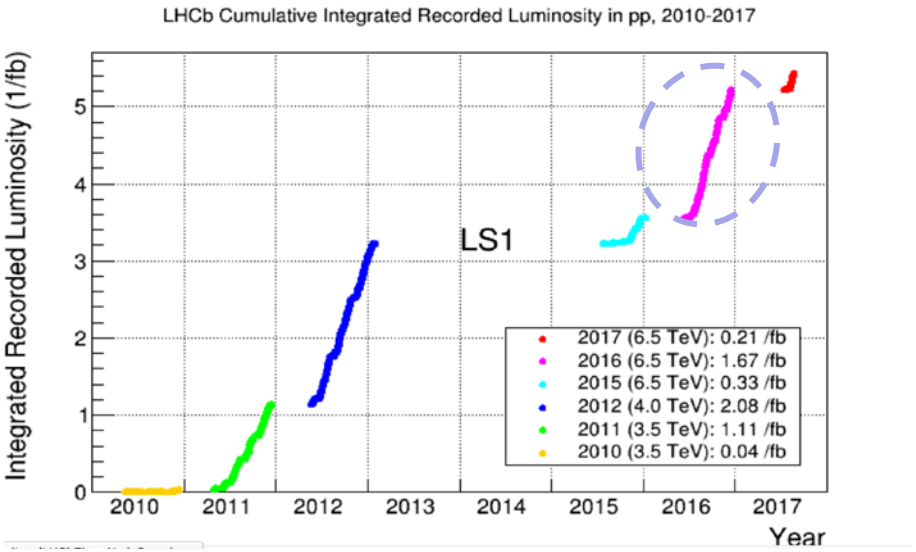
$$\Xi_{cc}^{++} \to p D^+$$

- Predict branching fraction of $\Xi_c^+ \to p K^- \pi^+$

于福升报告的结论，详情见 CPC 42 (2018) 051001

优先寻找$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$





- 集中四个单位几乎所有力量，争分夺秒地分析2016年1.7 fb^{-1}数据
- 分拆成多项子任务，大家分工负责、密切合作，确保在合作组内保持领先

- CCNU : YIN, Hang ; XIE, Yuehong ; YU, Jiesheng ; XU, Menglin
- Glasgow: SOLER JERMYN, Paul ; SPRADLIN, Patrick ; TRAILL, Murdo Thomas
- LAL : ZHANG, Yanxi; Robbe, Patrick
- LPNHE/UPMC: CHARLES, Matthew John
- Tsinghua: GAO, Yuanning ; XU, Ao ; YANG, Zhenwei ; ZHANG, Liming ; AN, Liupan; WANG, Mengzhen
- UCAS: HE, Jibo; HUANG, Wenqian; LYU Xiao-Rui; QIN, Jia-Jia; VIEIRA, Daniel; XU Qingnian; ZHENG, Yangheng
- Wuhan: SUN, Liang; CAI, Hao

LHCb中国组集体攻关

01 Apr LHCb-China group meeting

March 2017

30 Mar SciFi China Meeting (protected)
26 Mar LHCb-China group meeting
23 Mar SciFi China Meeting (protected)
19 Mar LHCb-China group meeting
17 Mar LHCb masterclass at China
16 Mar SciFi China Meeting (protected)
12 Mar LHCb-China group meeting
11 Mar - 12 Mar LHCb software tutorial
09 Mar SciFi China Meeting (protected)
05 Mar LHCb-China group meeting

February 2017

26 Feb LHCb-China group meeting
19 Feb LHCb-China group meeting
14 Feb LHCb-China group meeting
07 Feb LHCb-China group meeting

January 2017

26 Jan LHCb-China group meeting
05 Jan China MOST meeting

December 2016

26 Dec Discussion on doubly heavy baryons

June 2017

04 Jun LHCb-China group meeting

May 2017

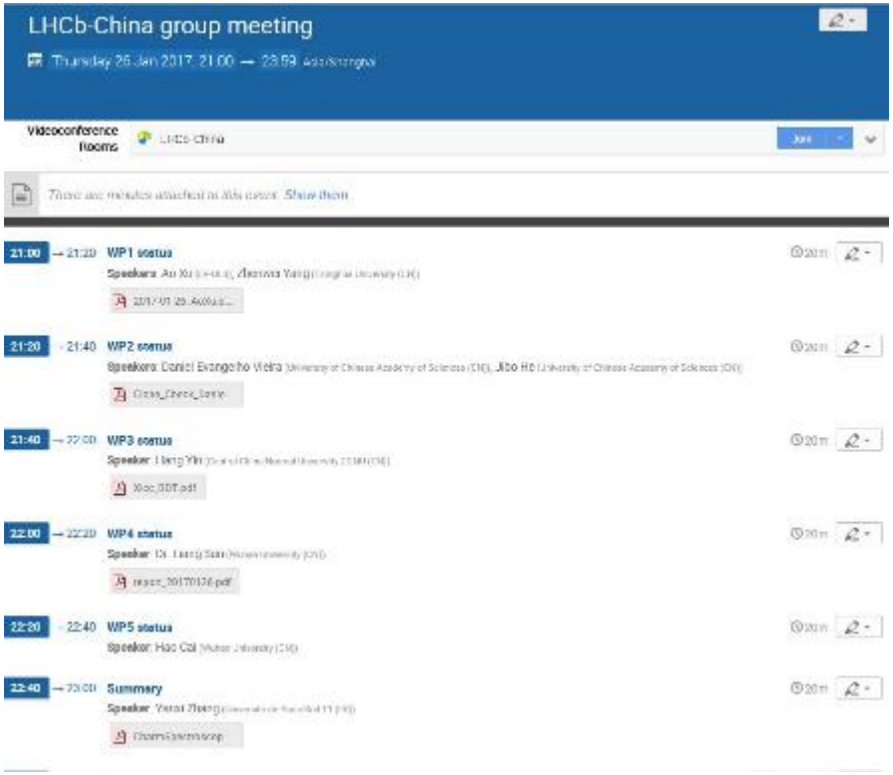
21 May LHCb-China group meeting
11 May SciFi China Meeting (protected)
07 May LHCb-China group meeting
04 May SciFi China Meeting (protected)
01 May LHCb-China group meeting

April 2017

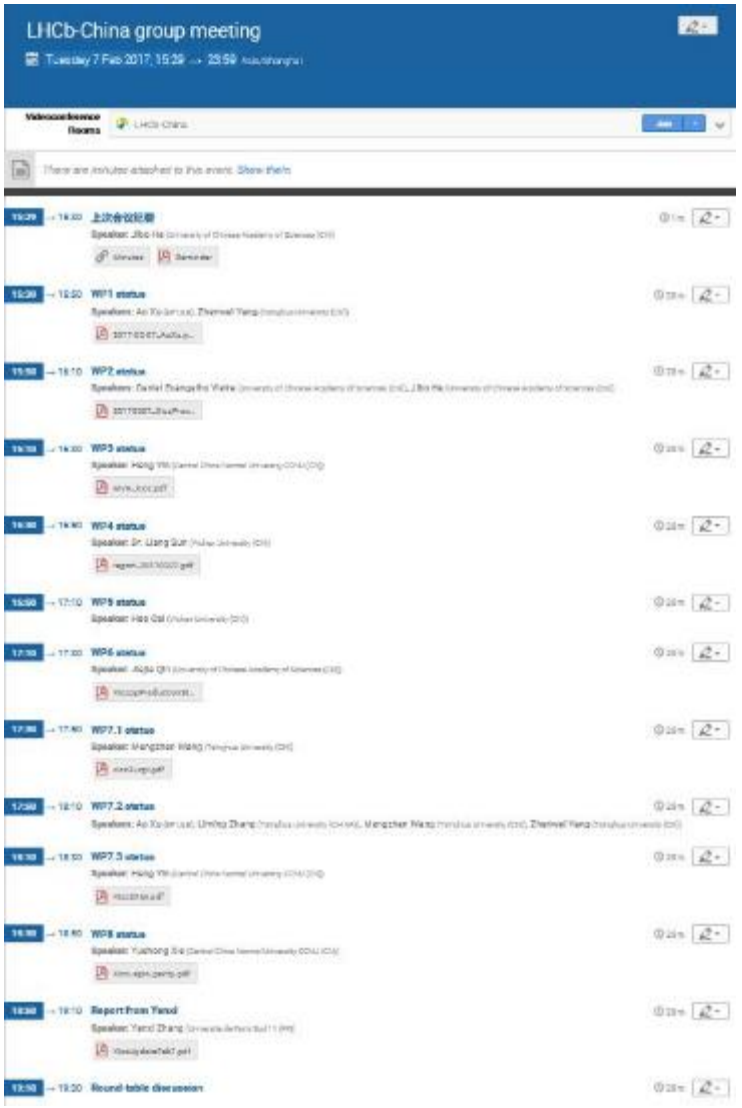
27 Apr SciFi China Meeting (protected)
23 Apr LHCb-China group meeting
20 Apr SciFi China Meeting (protected)
16 Apr LHCb-China group meeting
13 Apr SciFi China Meeting (protected)
11 Apr SciFi China Meeting (protected)
06 Apr SciFi China Meeting (protected)
04 Apr MOST rehearsal
01 Apr LHCb-China group meeting

春节前后

除夕前一晚的中国组会议日程

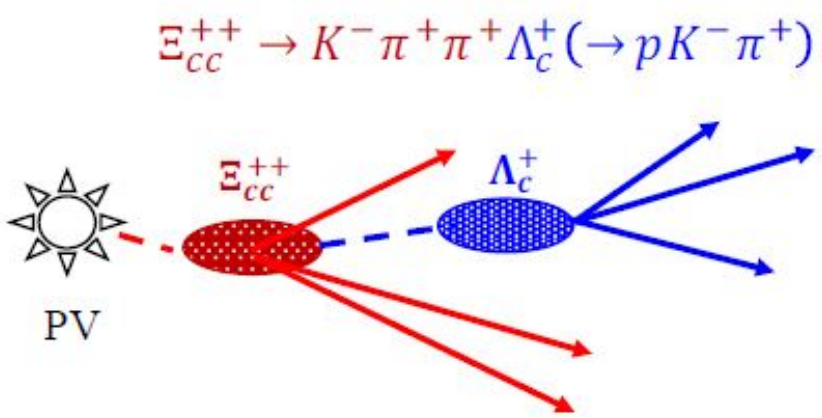


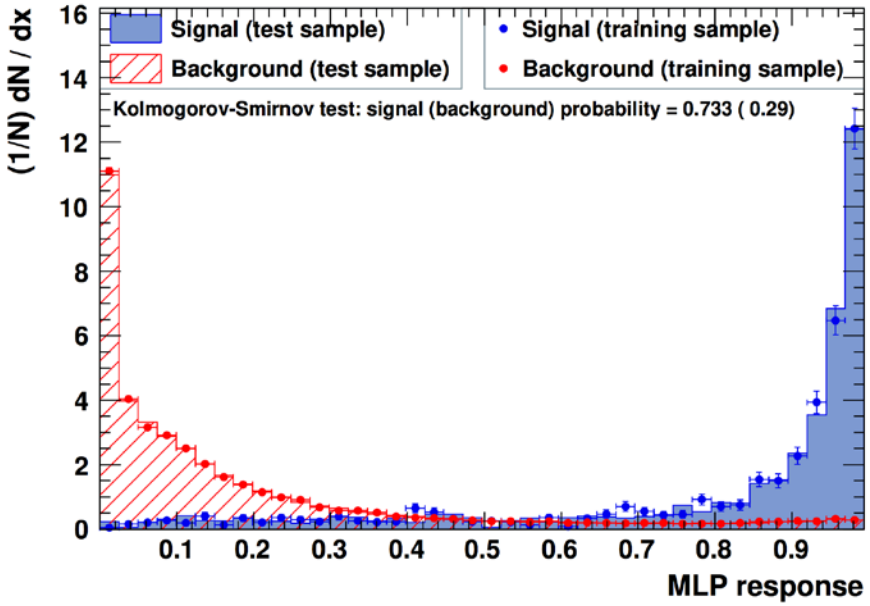
春节一周后的中国组会议日程



Candidate selection

- Trigger requires
  - displacement of tracks from PV due to long Ξ_{cc}^{++} and Λ_c^+ lifetimes
  - Large pT of tracks

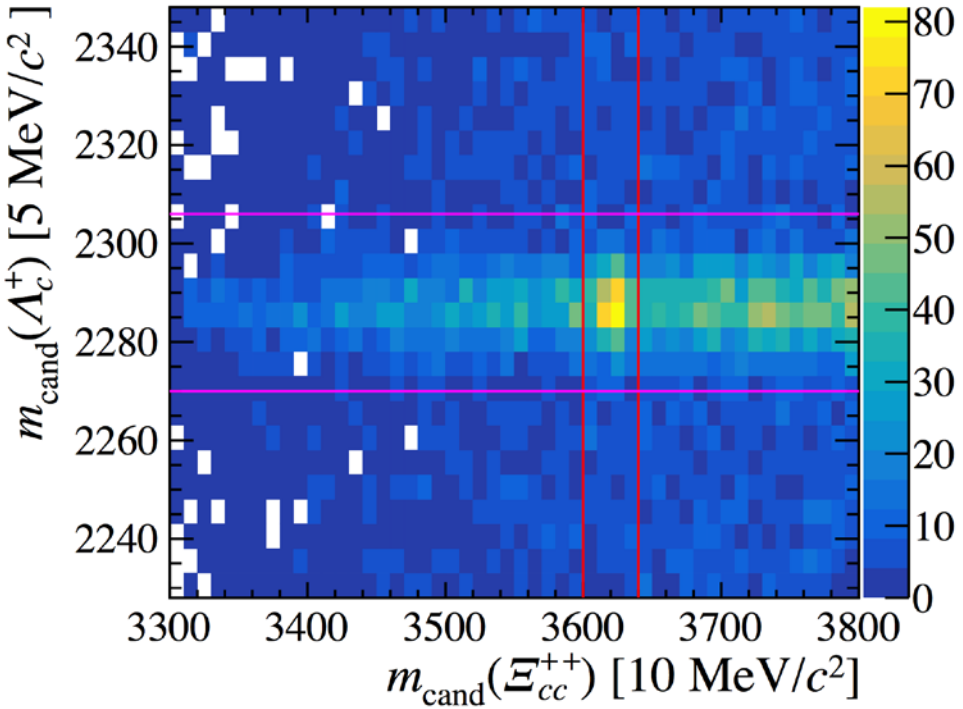


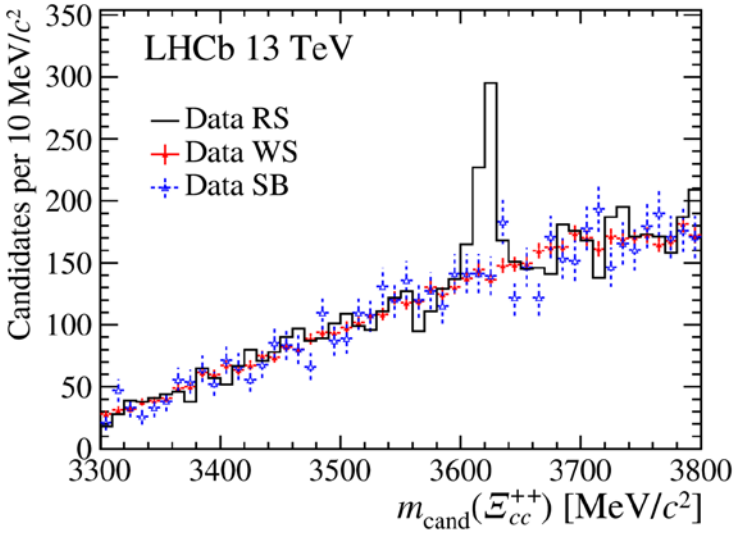


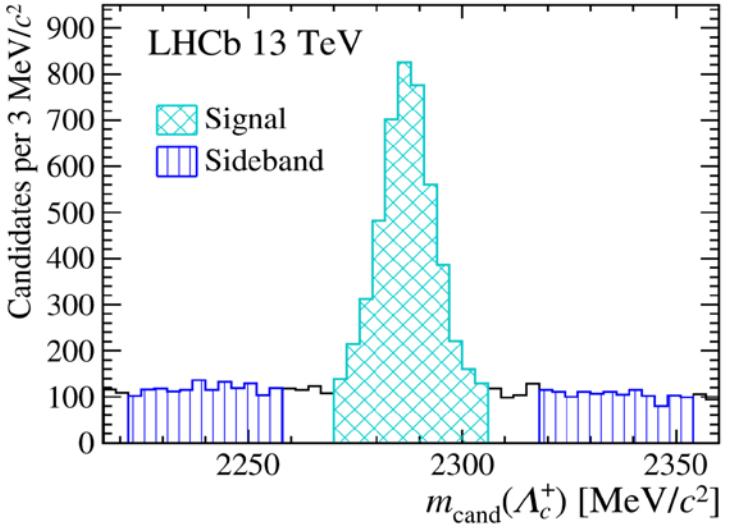
- Offline selection uses multivariate technique and machines learning
  - Kinematics
  - Fit quality
  - Vertex separation

Significant signal peak

313±33 signals,
12σ local significance

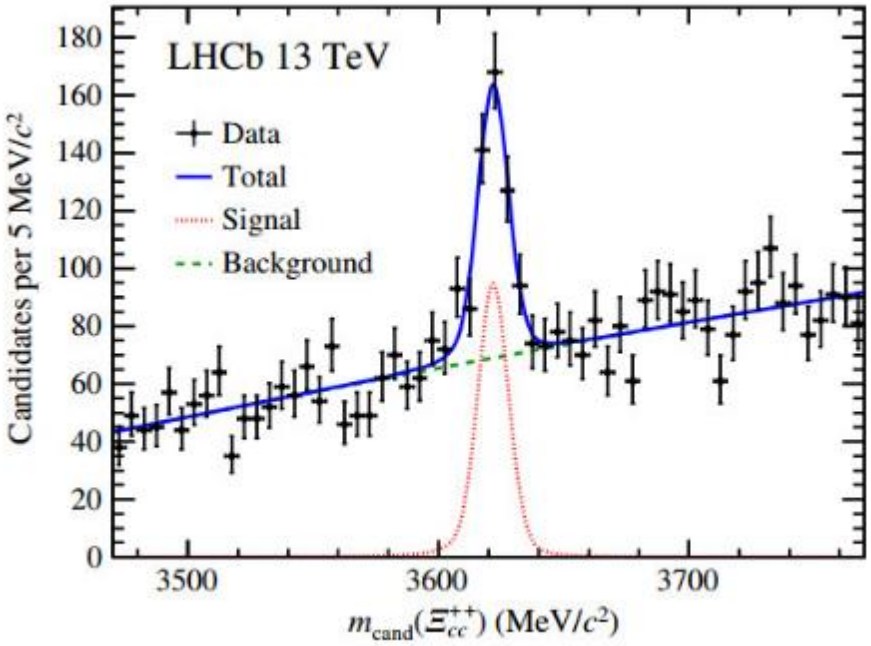


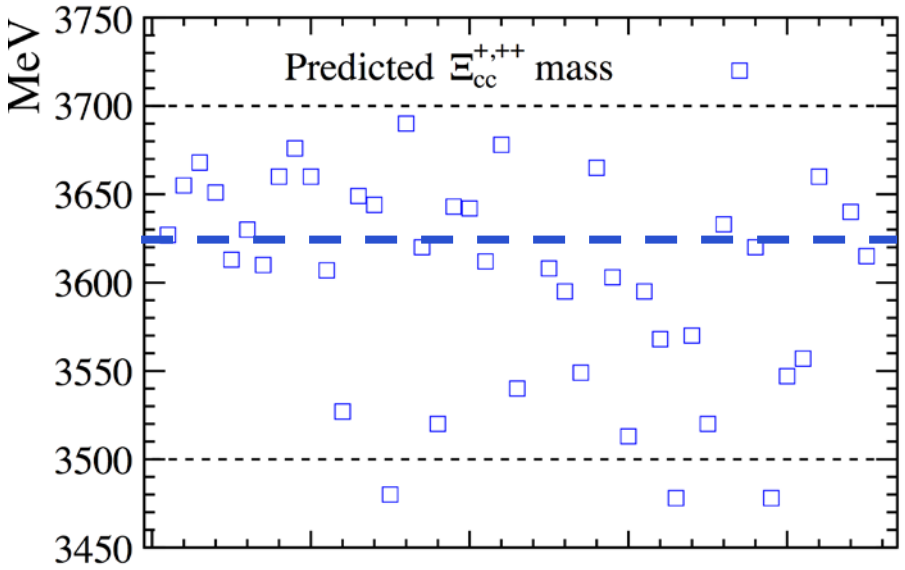




PRL 119 (2017) 112001

Mass measurement





$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72\,(\text{stat}) \pm 0.27\,(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$

PRL 119 (2017) 112001

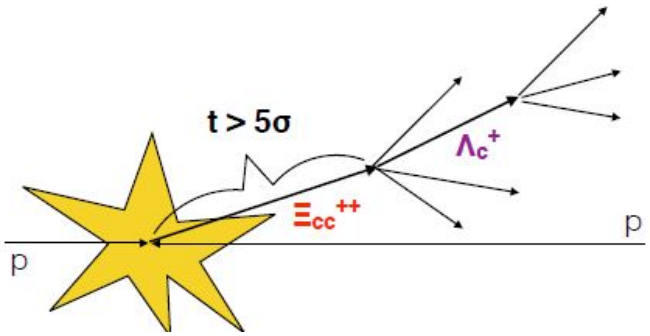
Mass systematics

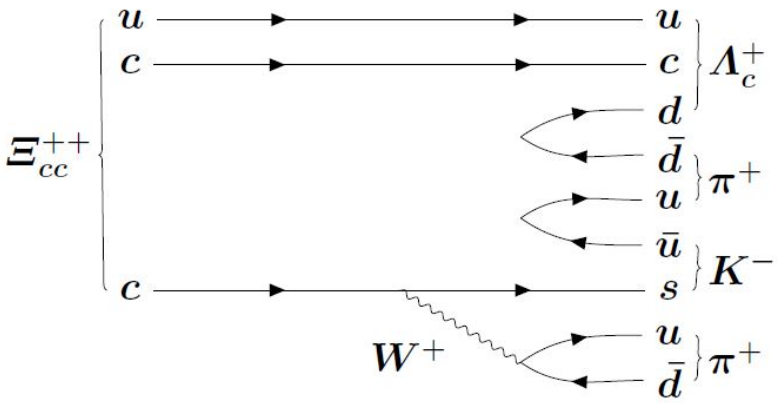
$$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \pm 0.14(\Lambda_c^+)\ \text{MeV}$$
$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst})\ \text{MeV}$$

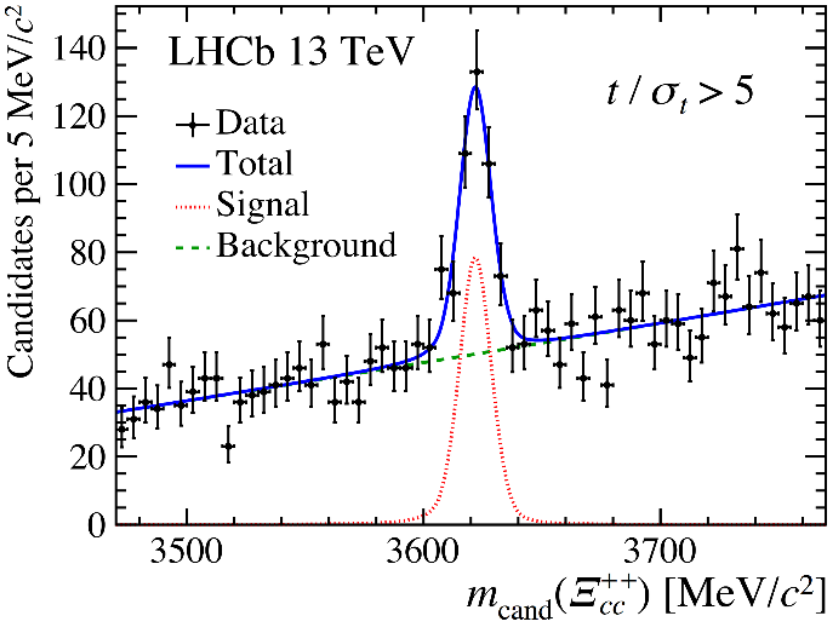
Systematic uncertainties

Source	Value [MeV/c^2]
Momentum-scale calibration	0.22
Selection bias correction	0.14
Unknown Ξ_{cc}^{++} lifetime	0.06
Mass fit model	0.07
Sum of above in quadrature	0.27
Λ_c^+ mass uncertainty	0.14

Being a doubly charmed baryon





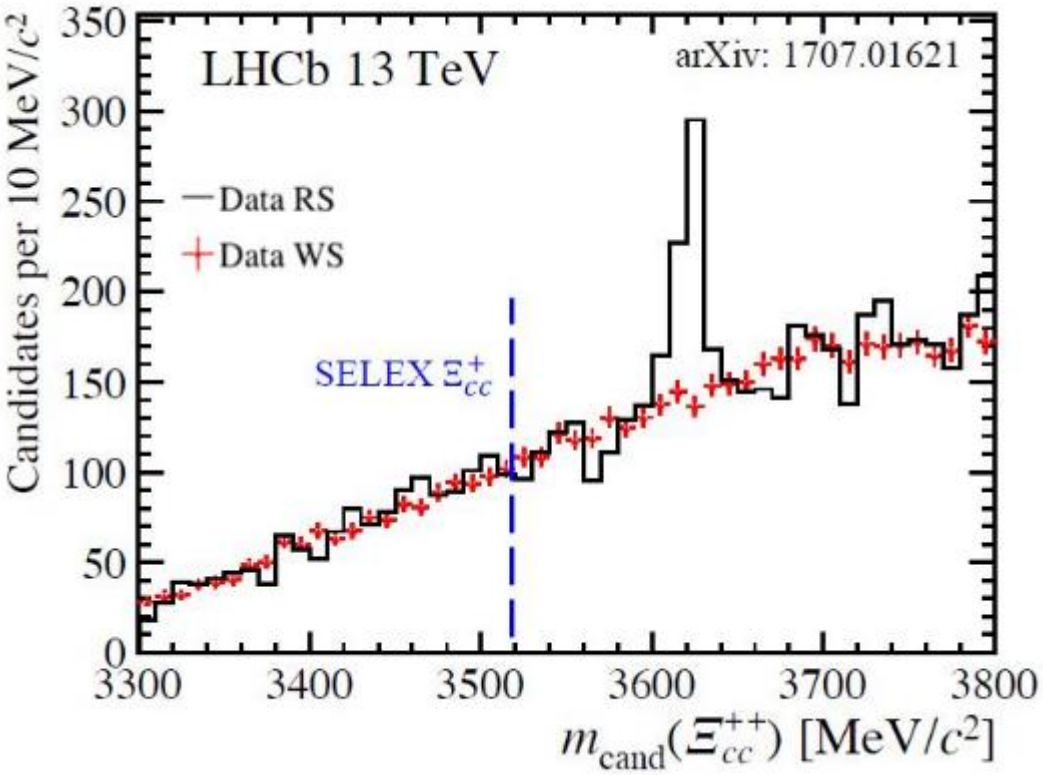


Long lifetime implies its weakly decay nature.

新粒子为含有双粲夸克、自旋1/2的Ξ_{cc}^{++}重子！

PRL 119 (2017) 112001

Comparison with SELEX



Large mass difference (103±2 MeV) inconsistent with being isospin partners

Prospects

- Studies of Ξ_{cc}^{++} properties
  - Ξ_{cc}^{++} lifetime measurement: collaboration review
  - Search for $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$: collaboration review

  } Coming soon
  - Ξ_{cc}^{++} production measurement: in progress
  - Direct determination of spin-parity: how?
  - Search for spin 3/2 Ξ_{cc}^{++} state: which mode? Production X-section?
- Searches for Ξ_{cc}^{+} ongoing
  - Focusing on $\Xi_{cc}^{+} \to \Lambda_c^+ K^- \pi^+$ and $\Xi_{cc}^{+} \to \Xi_c^+ \pi^+ \pi^-$
- Searches for $\Xi_{bc}^{+}(bcu)$, $\Xi_{bc}^{0}(bcd)$, $\Omega_{bc}^{0}(bcs)$ ongoing
  - Focusing on $\Xi_{bc}^{0} \to pK^-$, $\Xi_{bc}^{0} \to \Xi_c^+ \pi^-$ and $\Xi_{bc}^{0} \to D^0 pK^-$

欢迎理论家们提出新的建议和想法！

科技部重点专项“双重味重子”课题

主要研究内容：

1) 寻找含双粲夸克的重子

a) Ξ_{cc}^{+}重子：提高 $\Xi_{cc}^{+} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}$分析的灵敏度，并利用理论预言总分支比大的其它衰变道，如 $\Xi_{cc}^{++} \rightarrow D^{+}pK^{-}$，来进行搜索；

b) Ξ_{cc}^{++}重子：利用理论预言总分支比大的衰变道，如 $\Xi_{cc}^{++} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}\pi^{+}$，来进行首次搜索；

c) Ω_{cc}^{+}重子：利用理论预言总分支比大的衰变道，如 $\Omega_{cc}^{+} \rightarrow \Lambda_c^{+}K^{-}\pi^{+}$，进行首次搜索。

2) 寻找含粲夸克和底夸克的重子

a) Ξ_{bc}^{+}重子：利用理论预言总分支比大的衰变道，如 $\Xi_{bc}^{+} \rightarrow pK^{-}\pi^{+}$，来进行首次搜索；

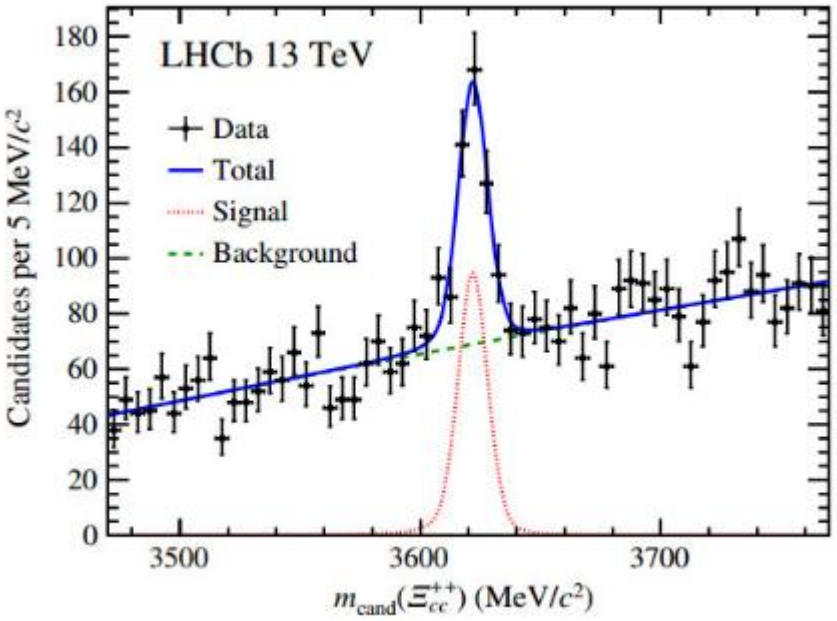
b) Ξ_{bc}^{0} 重子：利用理论预言总分支比大的衰变道，如 $\Xi_{bc}^{0} \rightarrow pK^{-}$，来进行首次搜索；

c) Ω_{bc}^{0} 重子：利用理论预言总分支比大的衰变道，如 $\Omega_{bc}^{0} \rightarrow \Xi_c^{+}\pi^{-}$，来进行首次搜索。

对于发现的双重味重子测量其质量、寿命和产生截面等性质，否则测定其产生截面上限。

Summary

- LHCb 实验发现双粲重子 $\Xi_{cc}^{++}(ccu)$
- 其质量为3621.40±0.78 MeV，并非SELEX观察到的Ξ_{cc}^{+}的同位旋伴侣
- 开启了重味强子研究的新窗口，一系列相关研究在进行之中



理论与实验成功合作的典范

- LHCb国际合作组发言人、意大利国家核物理研究院乔瓦尼·帕萨洛瓦教授评价说："LHCb实验的中国科学家对Ξ_{cc}^{++}粒子的发现做出了关键性贡献，这是他们长期不懈努力的成果。"

- 多年来，LHCb中国组坚持理论和实验相结合，始终与国内的粒子物理理论家保持着密切的合作关系，国内理论家对双粲重子Ξ_{cc}^{++}的发现同样功不可没，获得了LHCb国际合作组的尊重。乔瓦尼·帕萨洛瓦教授说："中国的理论家也提供了重要帮助，他们的关键建议引导该分析在正确的方向上取得了突破。"

- 期待未来能够继续合作，取得更多成果