University of Chinese Academy of Sciences

LHCb上双重味重子研究

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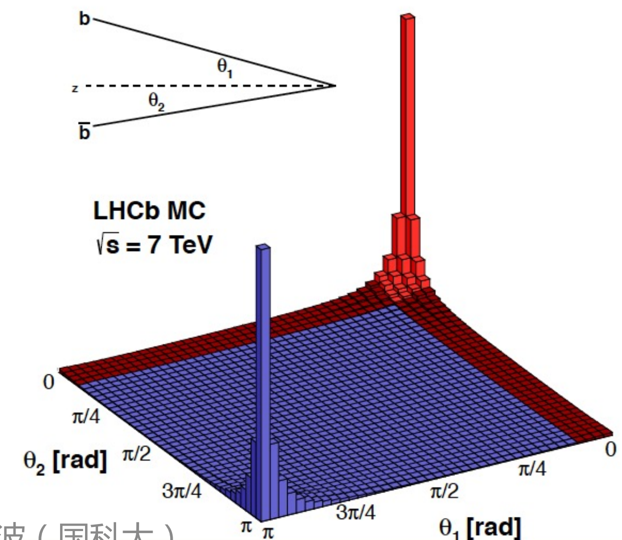
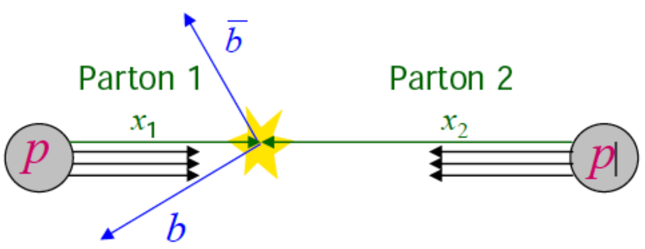
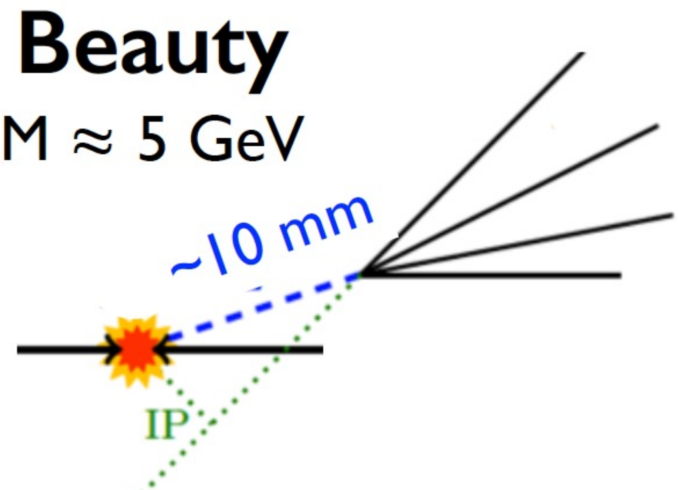
底/粲夸克对的产生

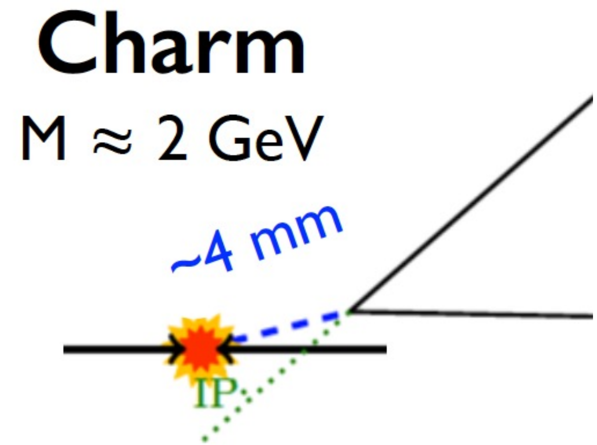
- 质心能量为7 TeV时的产生截面
  - Minimum bias ~60 mb $(1\ \mathrm{barn} = 10^{-28}\ \mathrm{m}^2)$ 
  - 粲夸克对 ~6 mb 
  - 底夸克对 ~0.3 mb
- 主要集中在前向/后向锥体内





底/粲强子“签名”

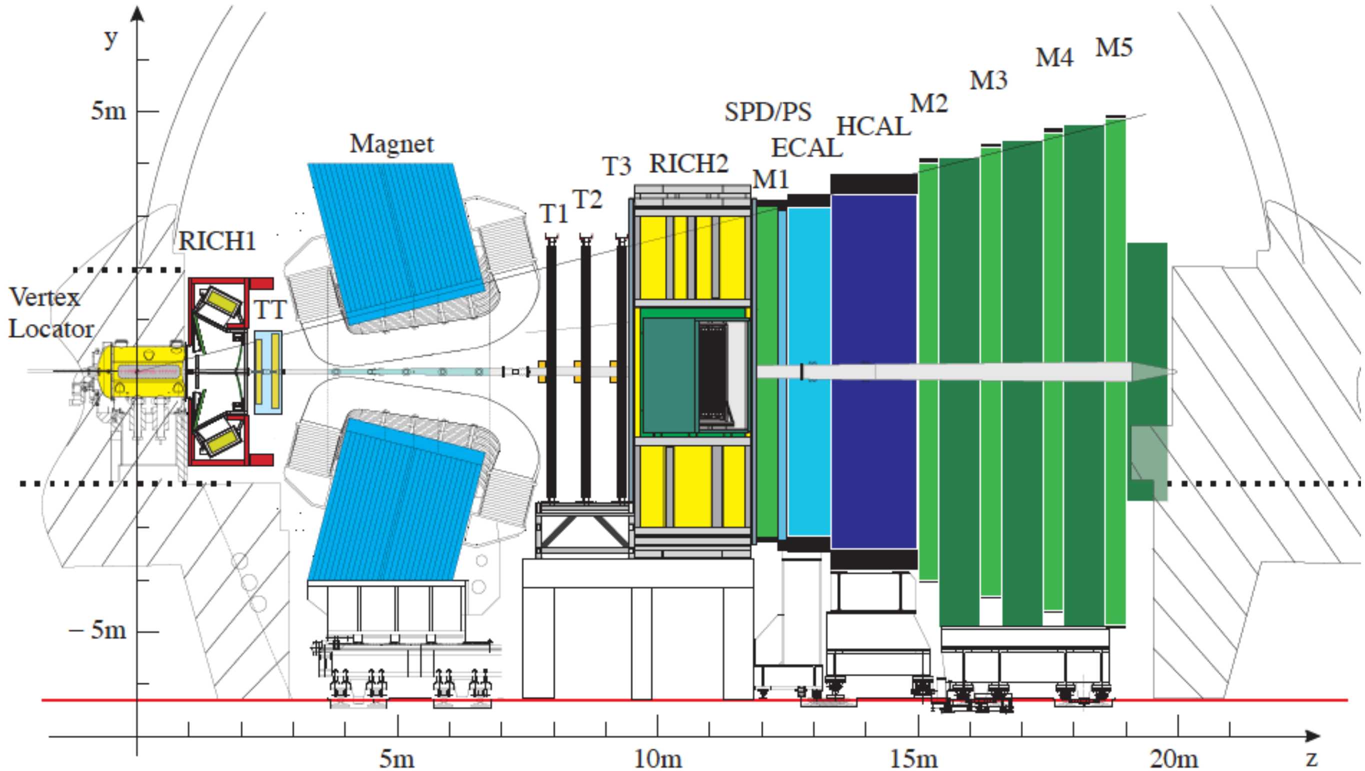




- 和minimum bias (本底)相比
  - 相对大的质量 → 高（横）动量
  - 相对长的寿命 → 大的碰撞参数(IP)
- 利用这些特性来选择信号，需要探测器具有优秀的顶点/径迹重建、粒子鉴别性能

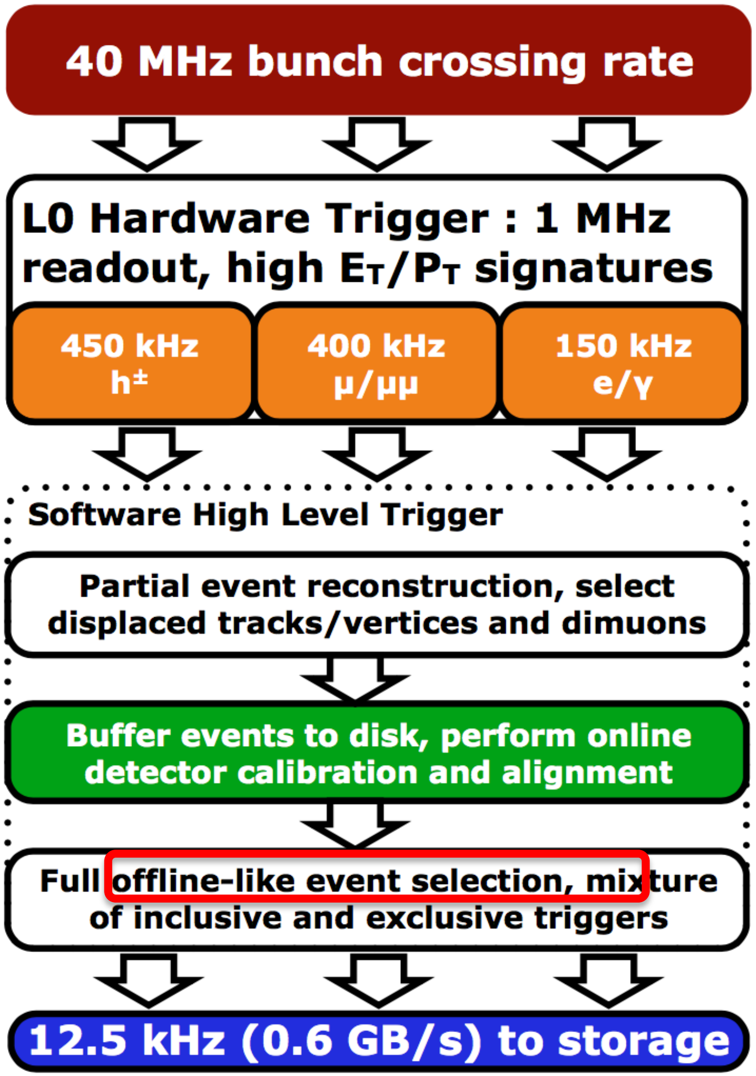
LHCb探测器

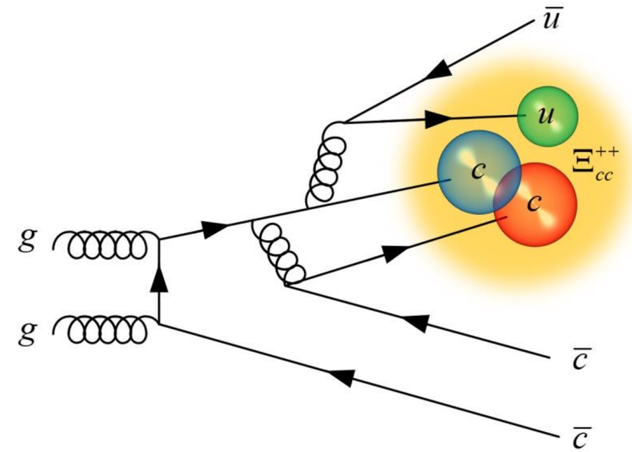
[JINST 3 (2008) S08005]



Vertex Locator	$\sigma_{\mathrm{PV},x/y} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV},z} \sim 60\ \mu\mathrm{m}$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi \to \mu) = 1 - 3\%$
ECAL	$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\%$ (E in GeV)
HCAL	$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\%$ (E in GeV)

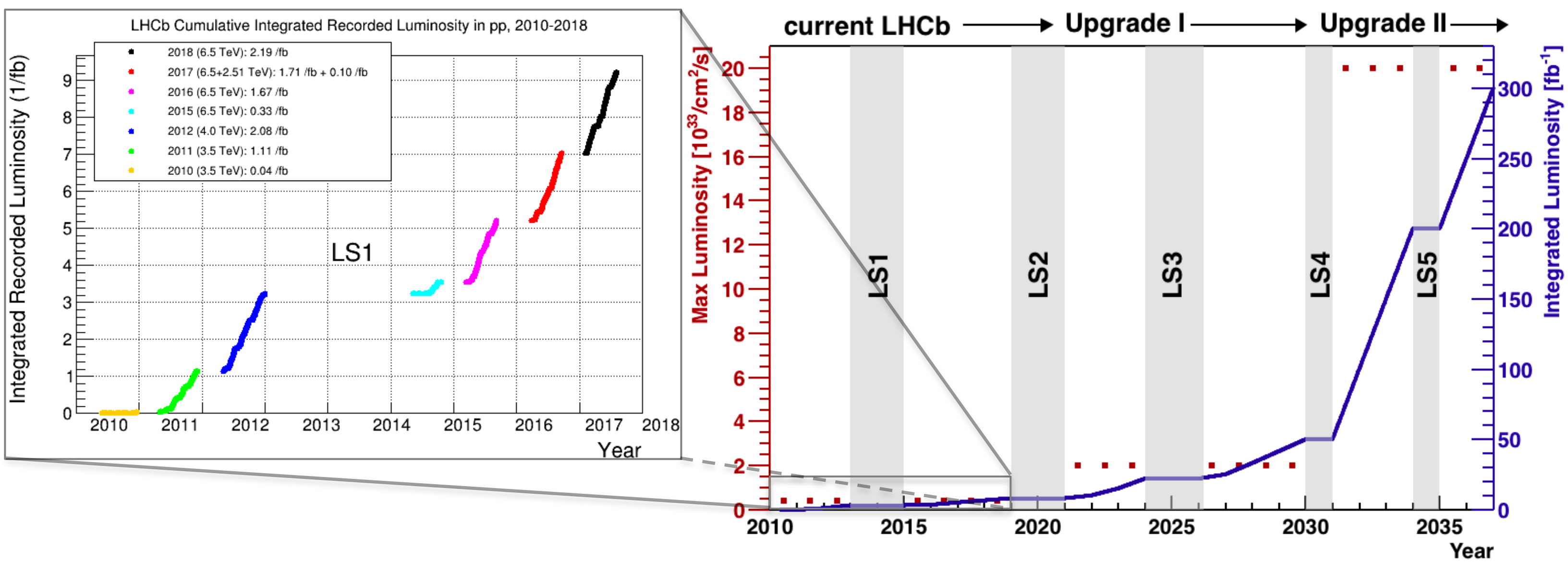
LHCb触发系统 (2018)





- 硬件触发
  - $p_T(\mu_1)\times p_T(\mu_2) >$ (1.5 GeV)^2
  - $p_T(\mu) >$ 1.8 GeV
  - $E_T(e) >$ 2.4 GeV
  - $E_T(\gamma) >$ 3.0 GeV
  - $E_T(h) >$ 3.7 GeV
- 软件触发
  - 第一级, p_T, 碰撞参数
  - 第二级, 完全重建

LHCb数据量



LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
3 fb^{-1}	6 fb^{-1}	23 fb^{-1}	46 fb^{-1}	>300 fb^{-1} ??

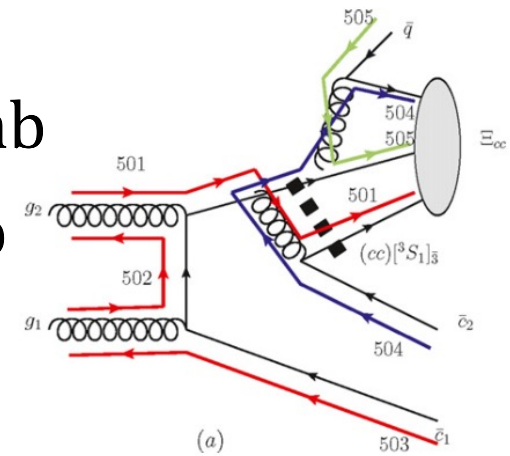
Phase-1 Upgrade!!

Phase-1b Upgrade!?

Phase-2 Upgrade??

双重味重子性质

- 产生截面 @ 13 TeV, LHCb接受度
  - $\sigma(\Xi_{cc}^{++}) = \sigma(\Xi_{cc}^{+})\sim 40$ nb, $\sigma(\Omega_{cc}^{+})\sim 13$ nb
  - $\sigma(\Xi_{bc}^{+}) = \sigma(\Xi_{bc}^{0})\sim 17$ nb, $\sigma(\Omega_{bc}^{0})\sim 5$ nb

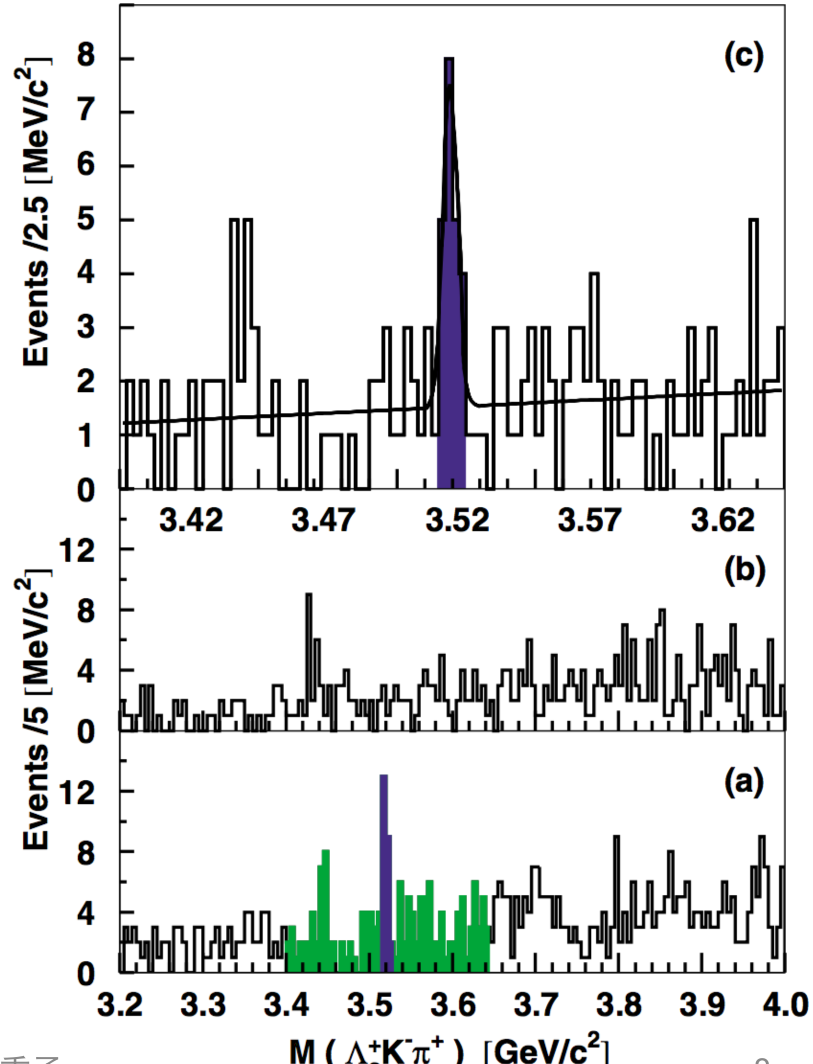


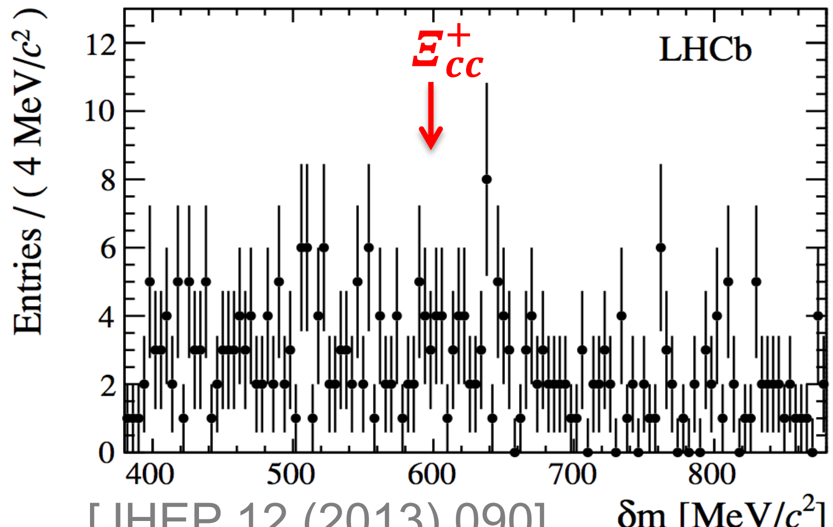
- 质量
  - $M(\Xi_{cc}^{+}) \approx M(\Xi_{cc}^{++})$：3.5-3.7 GeV，$\Omega_{cc}^{+}$重0.1-0.2 GeV
  - $M(\Xi_{bc}^{+}) \approx M(\Xi_{bc}^{0})$：6.8-7.1 GeV，$\Omega_{bc}^{0}$重0.05-0.1 GeV
- 寿命
  - $\tau(\Xi_{cc}^{+}) \approx \tau(\Omega_{cc}^{+}) \approx \frac{1}{3}\tau(\Xi_{cc}^{++})$，$\tau(\Xi_{cc}^{++})$：0.2-1.05 ps
  - Ξ_{bc}^{+}，Ξ_{bc}^{0}，Ω_{bc}^{0}基本一致：0.1-0.5 ps

2015年前实验状态

- 费米实验室SELEX观测到 $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$(显著度6.5σ)
  - 质量：3520 MeV
  - 寿命：<33 fs @90%CL
  - 产生：20%Λ_c^{+}来自Ξ_{cc}^{+}
- 未被其它实验证实，如LHCb

[SELEX, PRL 89 (2002) 112001]



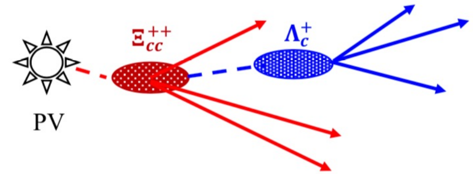


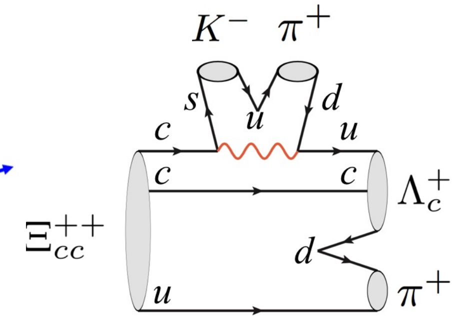
[JHEP 12 (2013) 090]

Ξ_{cc}^{++}的发现

- $\Lambda_c^+ K^- \pi^+ \pi^+$确定为最佳衰变道

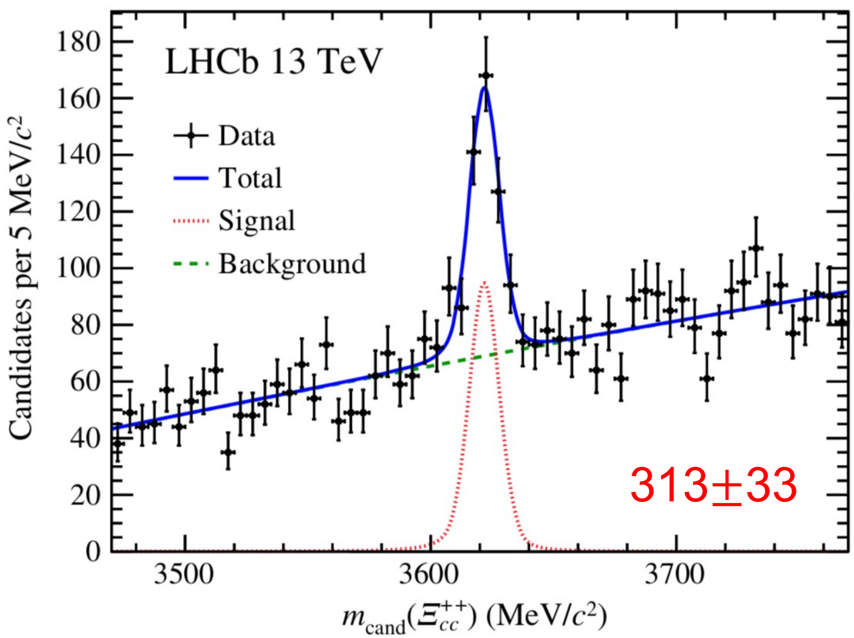
[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

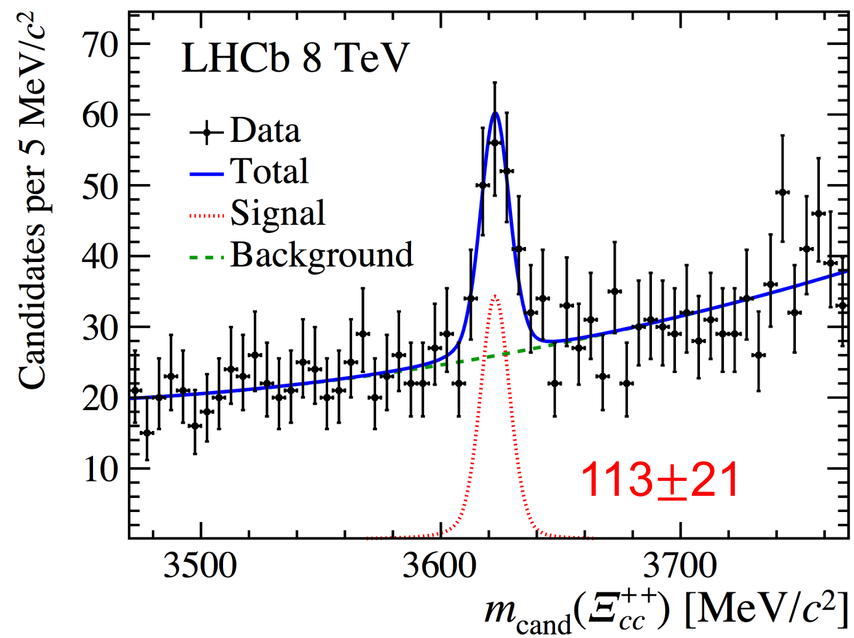




- 首次发现，2016数据 (>12σ) & Run-I (>7σ)

[PRL 119 (2017) 112001]





Ξ_{cc}^{++}性质

[PRL 119 (2017) 112001]

- LHCb测得Ξ_{cc}^{++}质量：

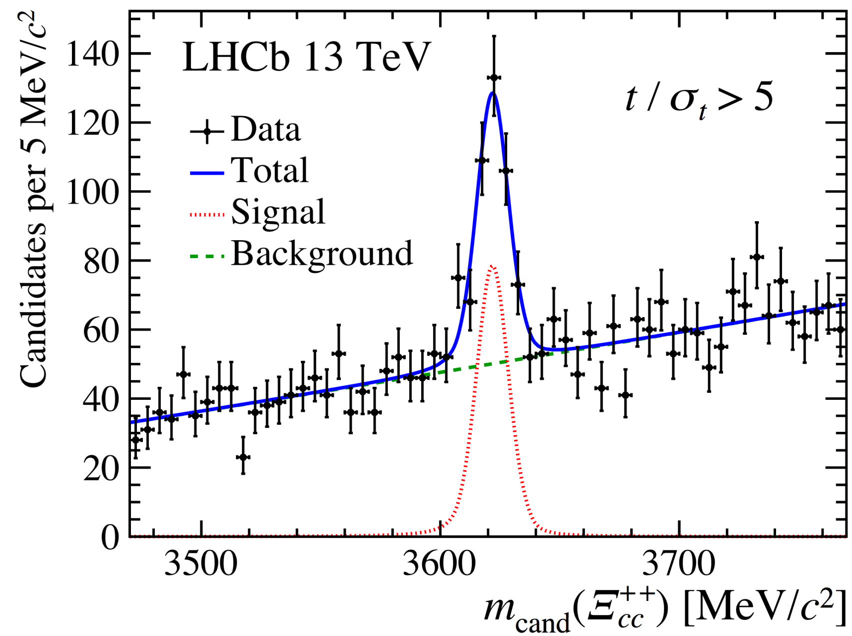
$$3621.40 \pm 0.72(\text{stat.}) \pm 0.27(\text{syst.}) \pm 0.14(\Lambda_c^+)\ \text{MeV}/c^2$$

SELEX: $M(\Xi_{cc}^{+})$=3519±1 MeV

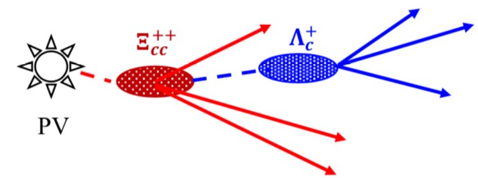
同位旋伙伴？

- 要求较长衰变时间后仍然有明显的质量峰。通过弱相互作用衰变？

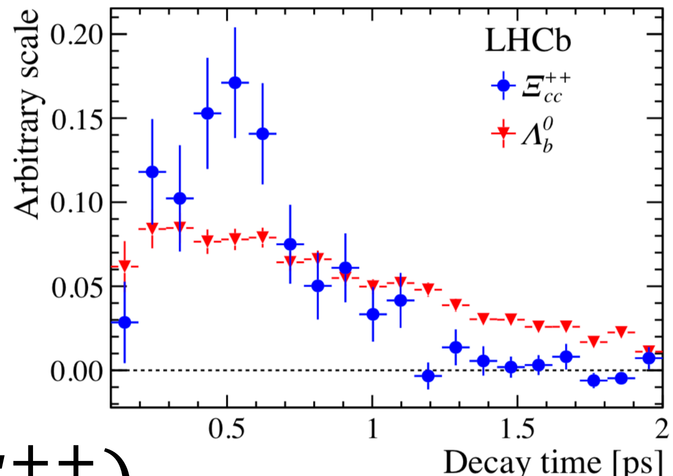
$\Rightarrow$需要测量$\tau(\Xi_{cc}^{++})$

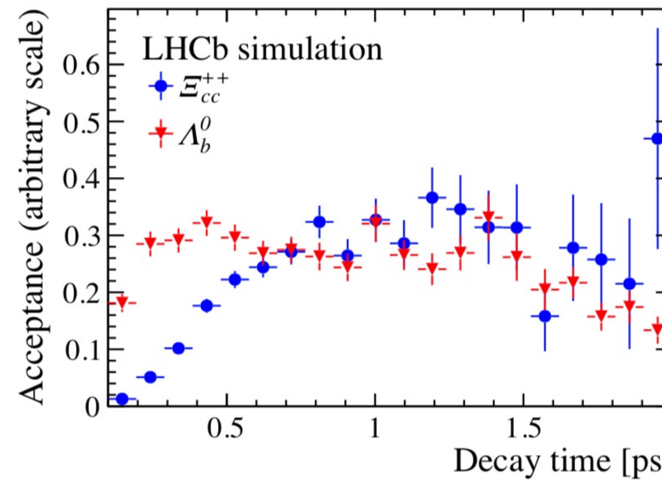


Ξ_{cc}^{++}寿命的测量

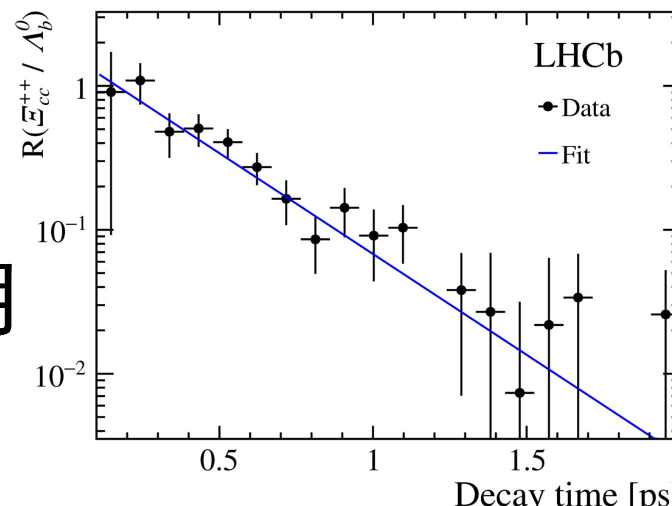


- $\Lambda_b^0 \to \Lambda_c^+ 3\pi$作为控制道





- $\tau(\Xi_{cc}^{++})$
$$= 0.256^{+0.024}_{-0.022} \pm 0.014\ \text{ps}$$
  – 处于理论预言低端0.2-1.05ps
- 确立Ξ_{cc}^{++}通过弱相互作用衰变的性质！



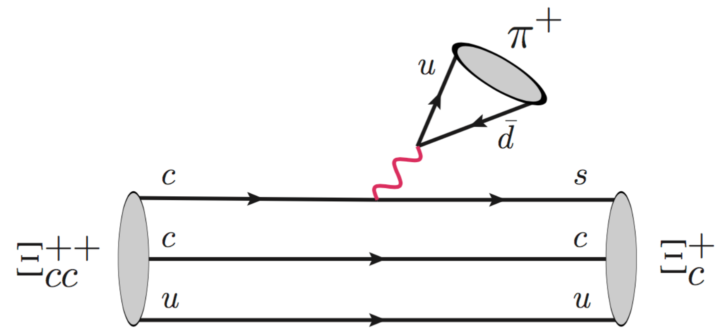
[PRL 121 (2018) 052002]

$\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$的发现

[PRL 121 (2018) 162002]

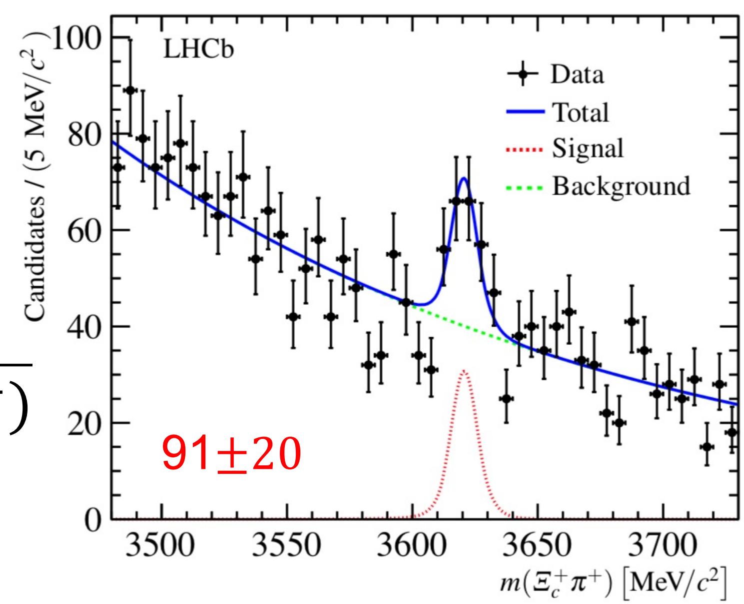
- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$预期有较大的衰变分支比

  [F.-S. Yu *et al.*, CPC 42 (2018) 051001]



- 利用2016数据进行搜寻，5.9σ，证实!
- 衰变分支比的比值

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \cdot \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \cdot \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$
$$= 0.035 \pm 0.009 \pm 0.003$$

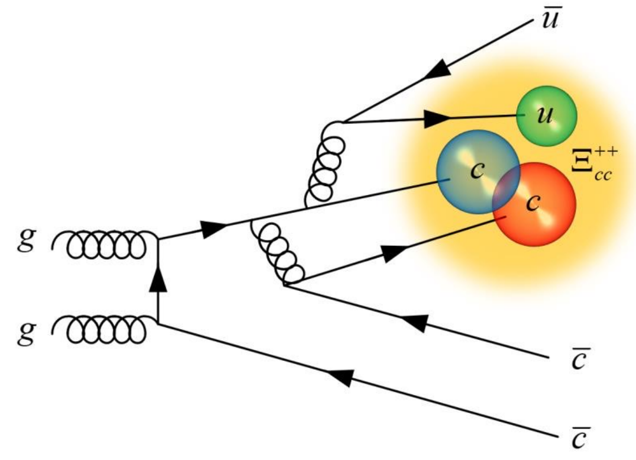


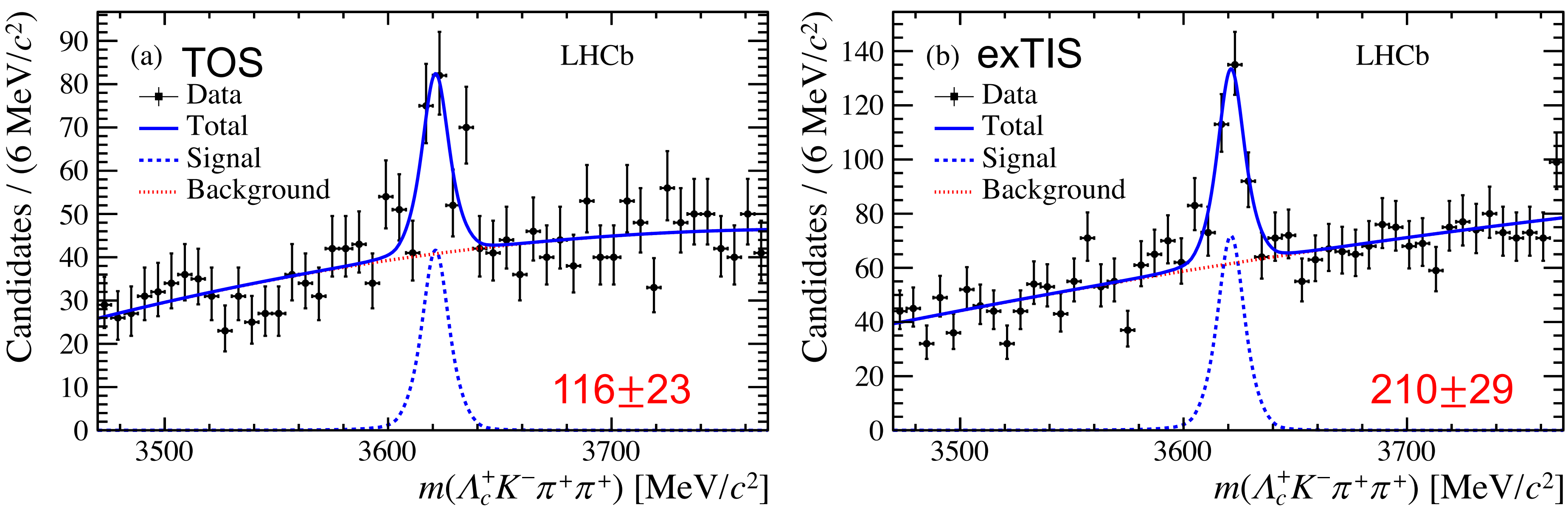
Ξ_{cc}^{++}的产生

- 确定产额和效率

$$N = \sigma_{\text{prod}} \cdot \mathcal{L} \cdot \mathcal{B} \cdot \varepsilon, \quad \sigma_{\text{prod}} \cdot \mathcal{B} = \frac{N}{\varepsilon \mathcal{L}}$$

- 伴随的$\bar{c}\bar{c}$ 对触发贡献很大



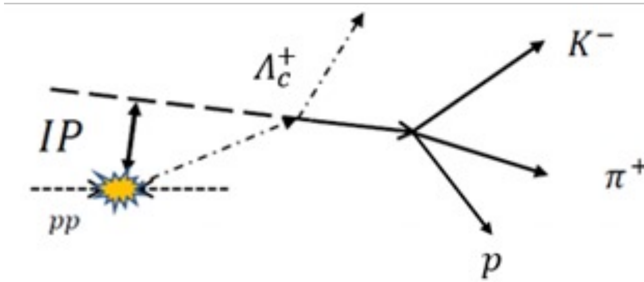


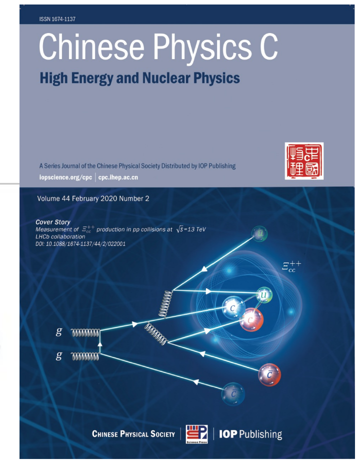
Ξ_{cc}^{++}的产生

- 相对于$\Lambda_c^+(udc)$，运动学范围：

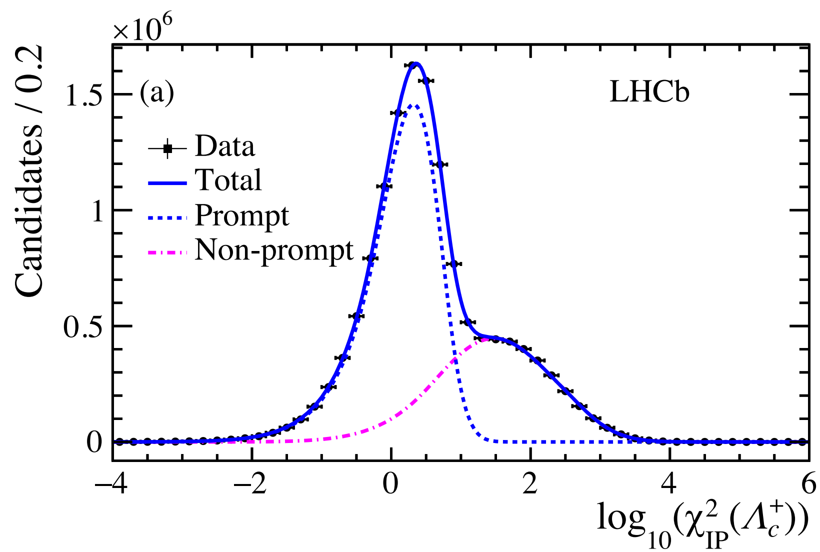
  $4 < p_{\mathrm{T}} < 15$ GeV,

  2<y<4.5





$$\frac{\sigma(\Xi_{cc}^{++})}{\sigma(\Lambda_c^+)}\mathcal{B}(\Xi_{cc}^{++}\to\Lambda_c^+K^-\pi^+\pi^+)$$
$$=(2.22\pm0.27\pm0.29)\times10^{-4}$$



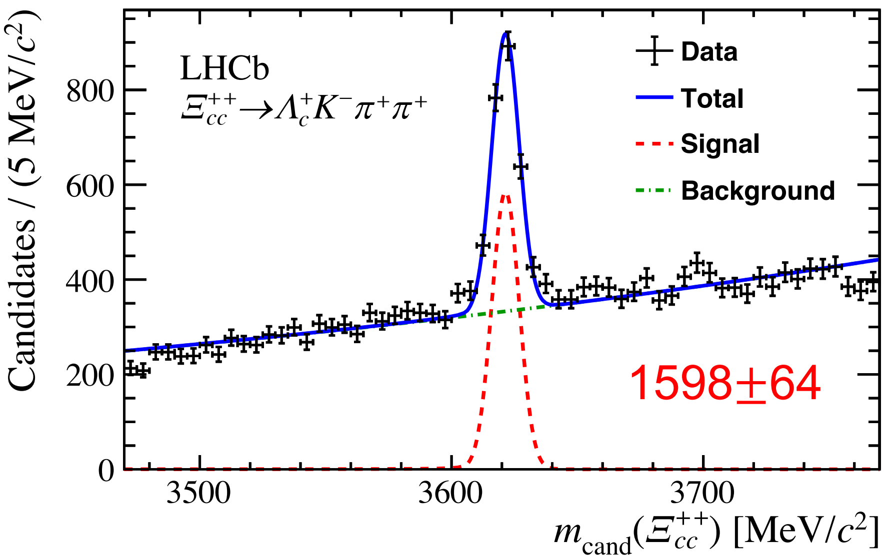
SELEX, 20% Λ_c^+ from Ξ_{cc}^+

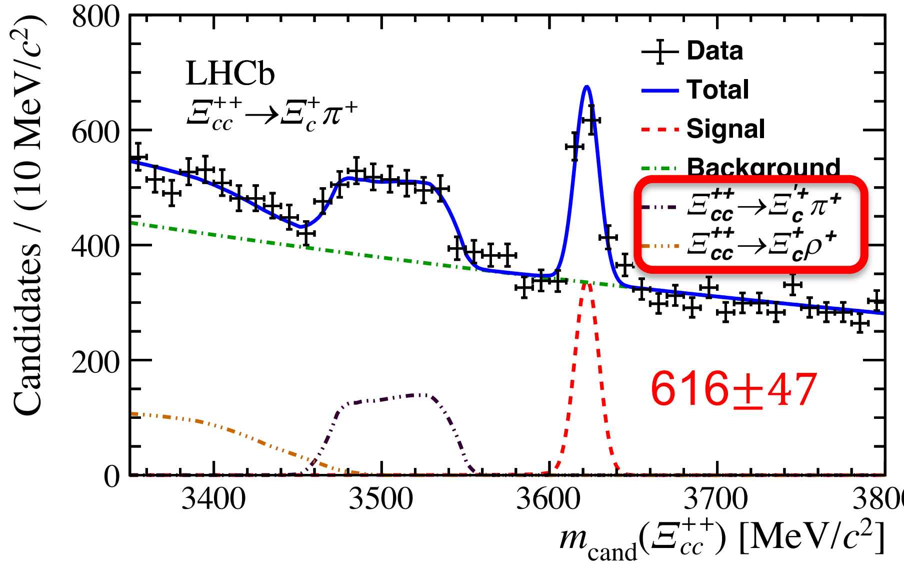
[CPC 44 (2020) 022001]

Ξ_{cc}^{++}质量精确测量

- 科创计划，重新优化，效率同比提高50%！
LHCb中屈指可数的由本科生主导的分析

[JHEP 02 (2020) 049]





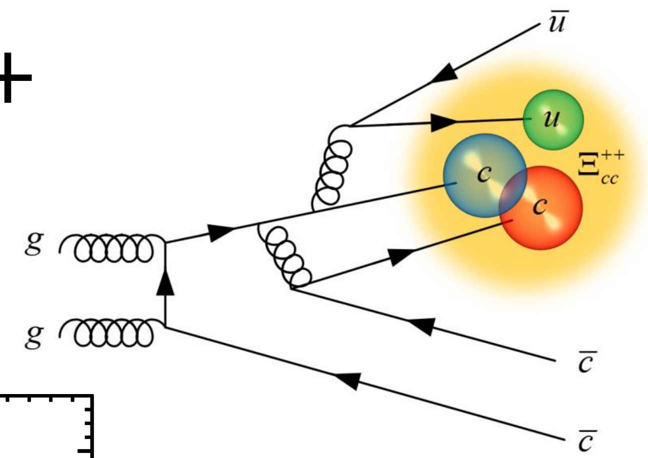
$$m(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30\ \mathrm{MeV}/c^2$$

c.f., $3620.6 \pm 0.65 \pm 0.31\ \mathrm{MeV}/c^2$

- 格点QCD: $3610 \pm 23 \pm 22\ \mathrm{MeV}/c^2$

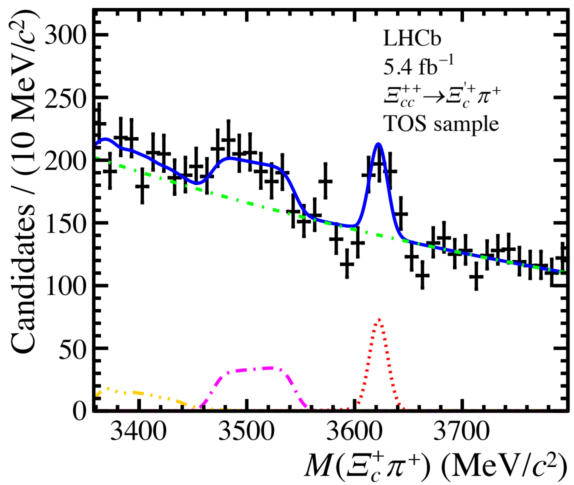
[Z. S. Brown *et al.*, PRD 90 (2014) 094507]

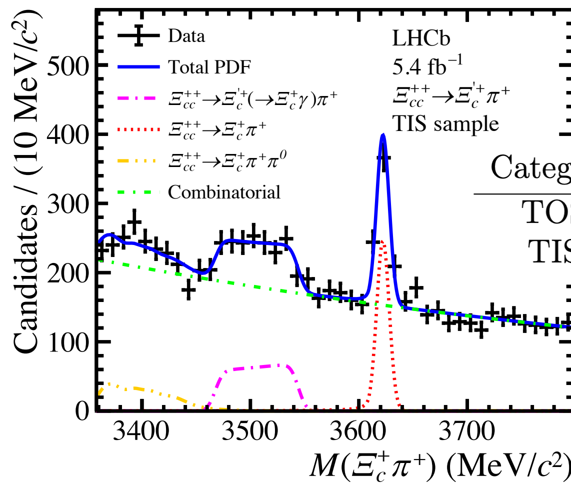
$\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$



- 2016-2018数据

$\Xi_{cc}^{++} \to \Xi_c^{\prime +}(\to \Xi_c^+\gamma)\pi^+$





Category	$\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+$	$\Xi_{cc}^{++} \to \Xi_c^+\pi^+$
TOS	262 ± 53	159 ± 32
TIS	494 ± 63	379 ± 32

[JHEP 05 (2022) 038]

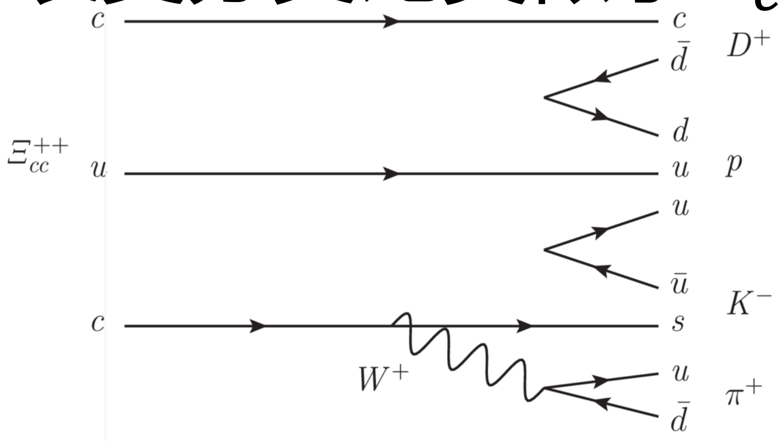
- 衰变分支比的比值

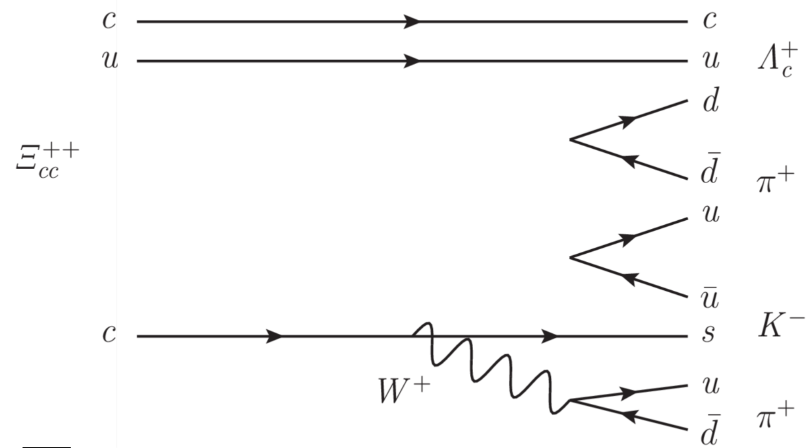
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{\prime +}\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+\pi^+)} = 1.41 \pm 0.17 \pm 0.10$$

– 理论预言有一定偏离

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

- 衰变分支比类似于$\Lambda_c^+ K^- \pi^+ \pi^+$?

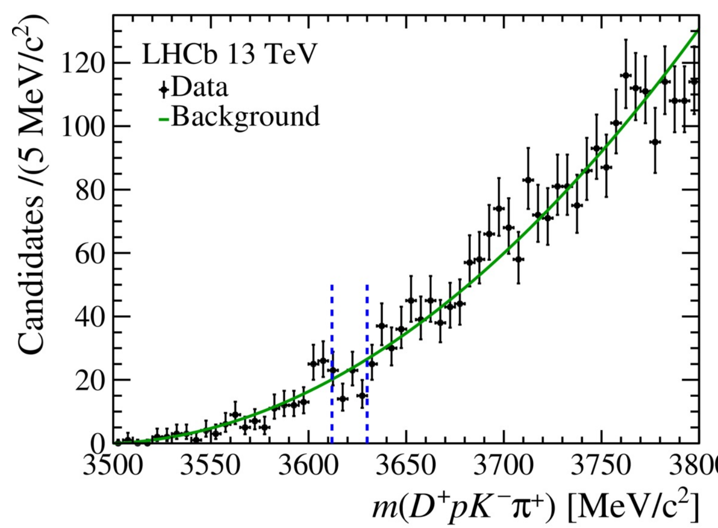




- 2016数据中无明显信号

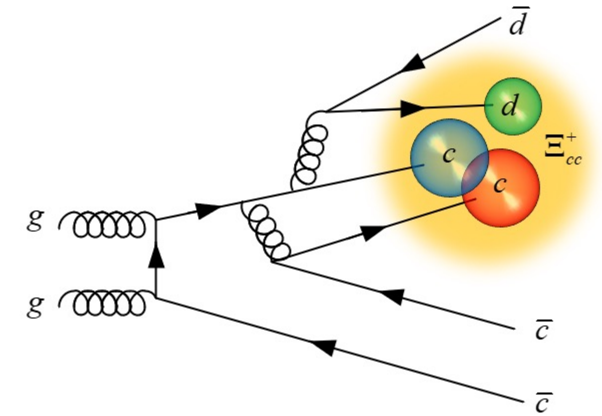
$$\mathcal{R} = \frac{\mathcal{B}(\Xi_{cc}^{++} \to D^+ p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$

$< 1.5\ (1.9) \times 10^{-2}$ @ 90% (95%) CL

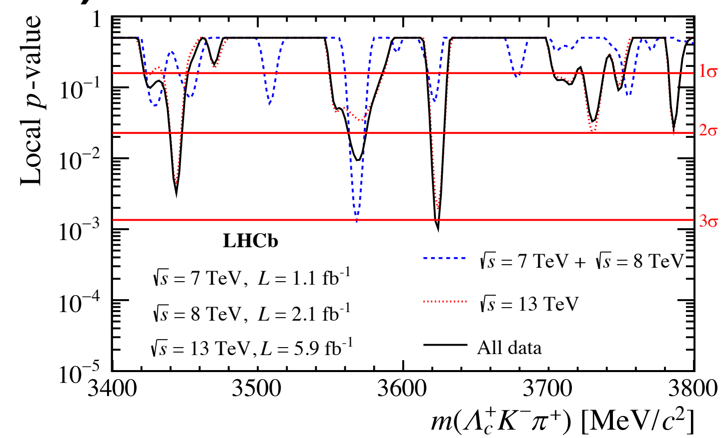


[JHEP 10 (2019) 124]

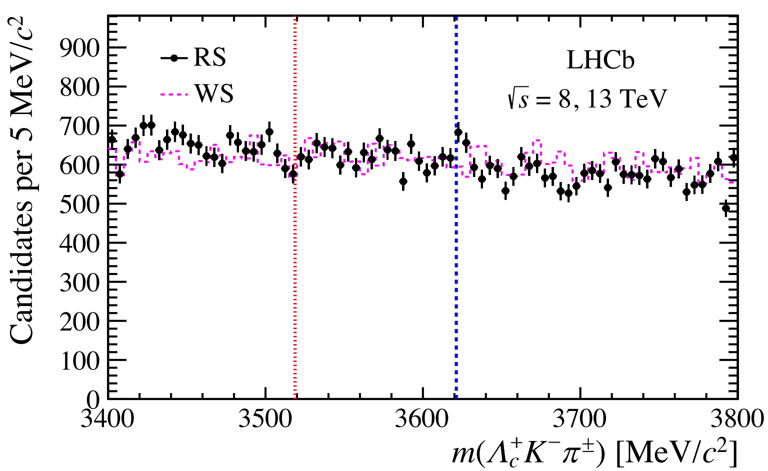
Ξ_{cc}^{+}的搜寻：$\Lambda_c^+ K^- \pi^+$

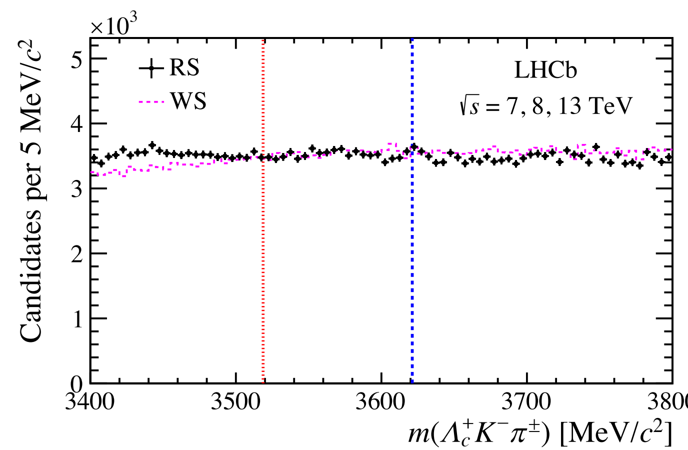


- Ξ_{cc}^{++}质量处出现迹象，局部（全局）显著度：3.1σ (1.7σ)



- 用于产生测量的事例选择，局部显著度达到4σ
  - $\tau(\Xi_{cc}^{+})$比预期的更小

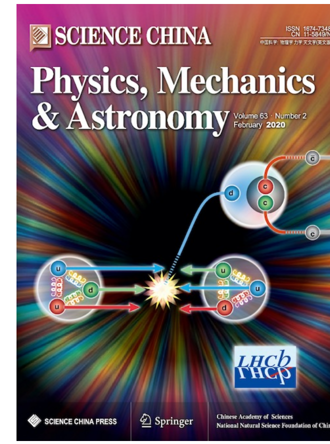




[SCPMA 63 (2020) 221062]

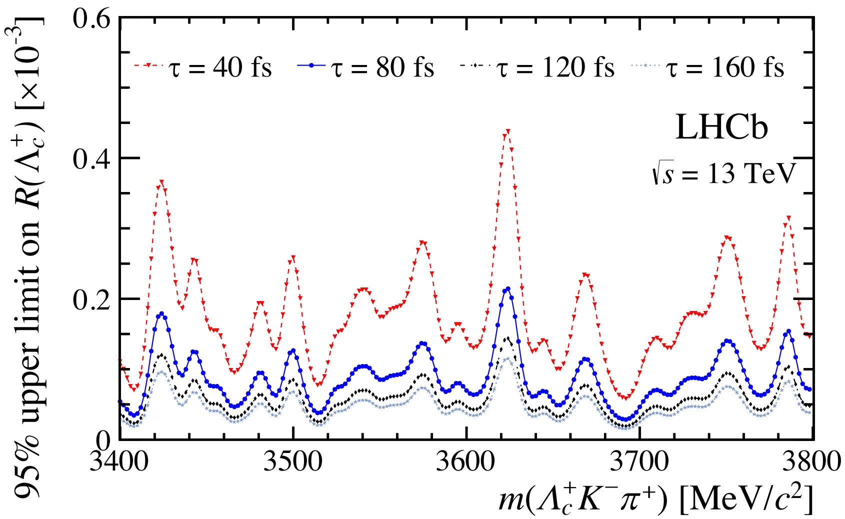
Ξ_{cc}^{+}的搜寻：$\Lambda_c^+ K^- \pi^+$

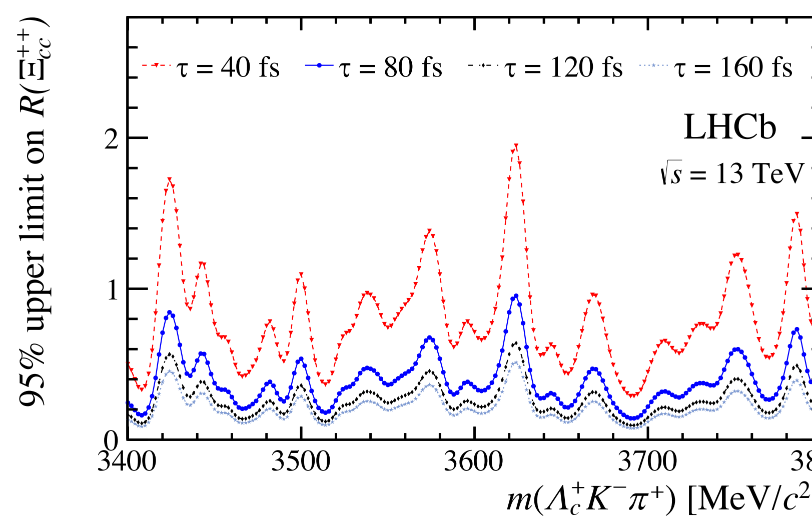
- Ξ_{cc}^{+}相对于Λ_c^+和Ξ_{cc}^{++}的产生截面，在运动学范围：
  $4 < p_{\mathrm{T}} < 15$ GeV, 2<y<4.5
- 灵敏度相比提高一个数量级



$$R(\Lambda_c^+) = \frac{\sigma(\Xi_{cc}^+)}{\sigma(\Lambda_c^+)} \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)$$

$$R(\Xi_{cc}^{++}) = \frac{\sigma(\Xi_{cc}^+) \cdot \mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Xi_{cc}^{++}) \cdot \mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+)}$$



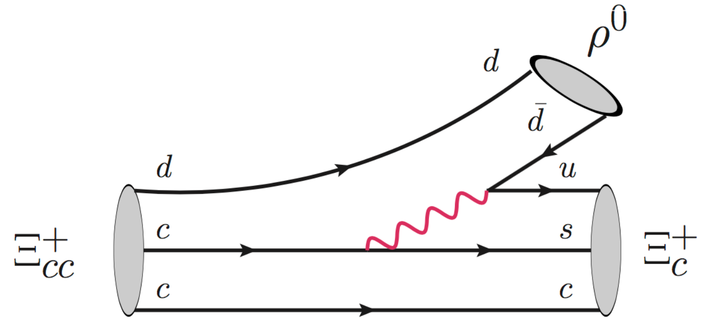


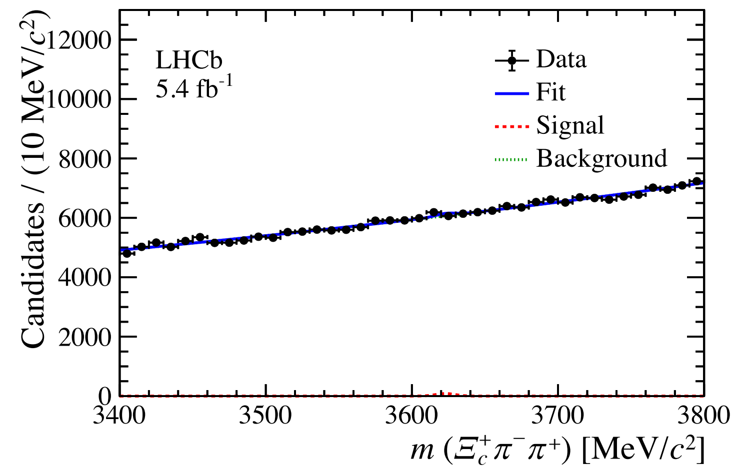
[SCPMA 63 (2020) 221062]

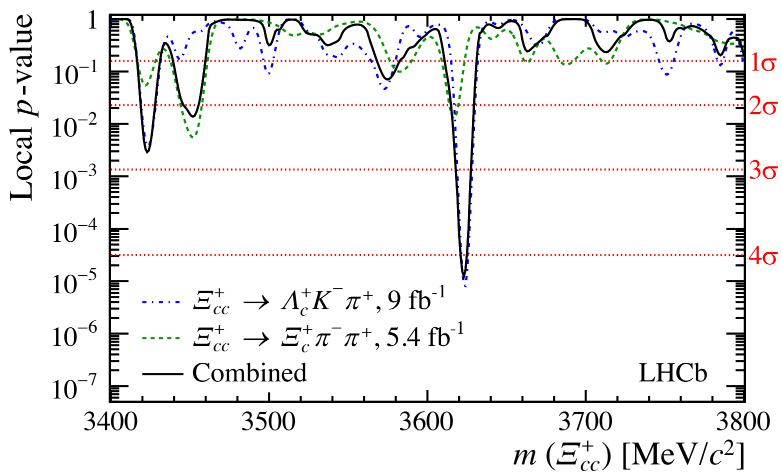
Ξ_{cc}^{+}的搜寻：$\Xi_{c}^{+}\pi^{+}\pi^{-}$

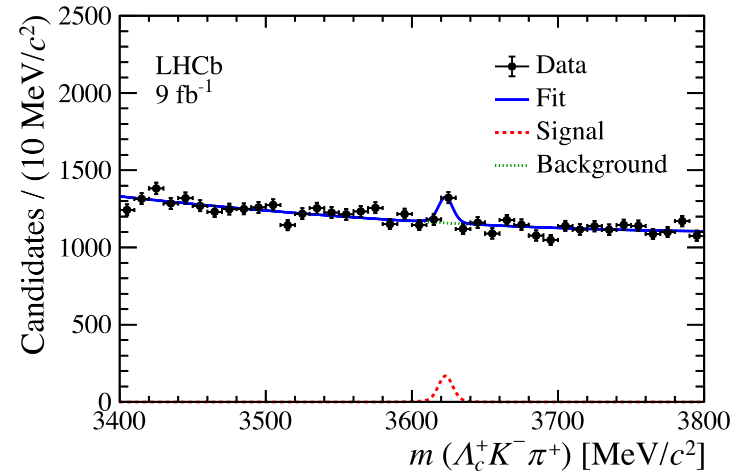
- $\Xi_{cc}^{+} \to \Xi_{c}^{+}\pi^{+}\pi^{-}$，无明显信号
- 与$\Xi_{cc}^{+} \to \Lambda_{c}^{+}K^{-}\pi^{+}$合并，$\Xi_{cc}^{++}$质量处有局部（全局）显著度为4.0$\sigma$ (2.9σ)的暗示

[JHEP 12 (2021) 107]



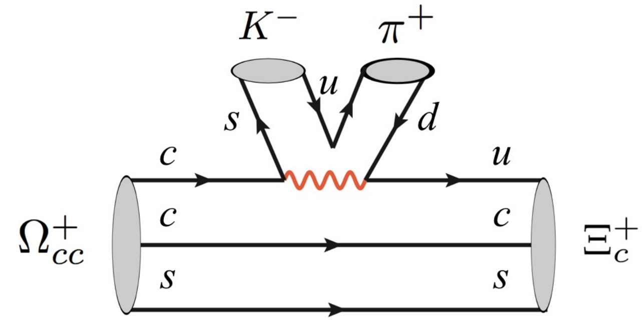


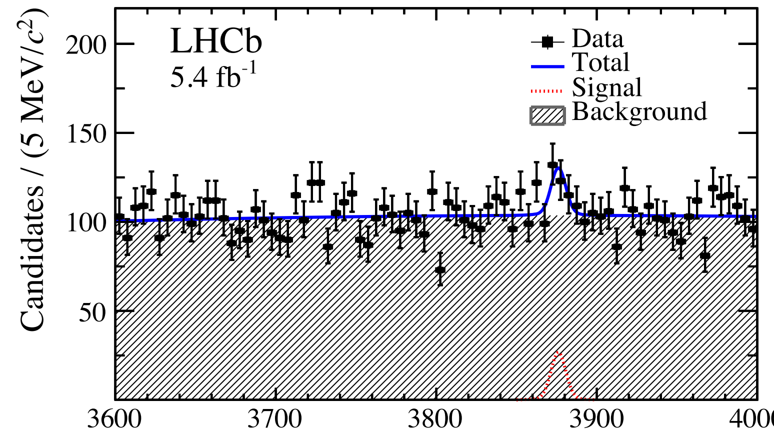


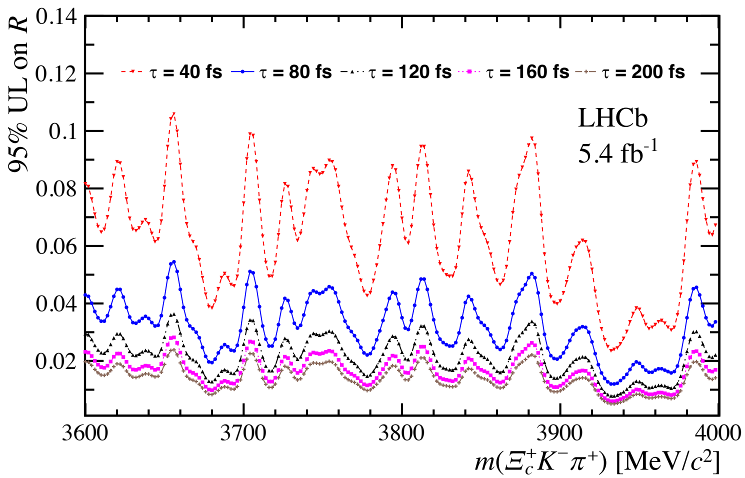


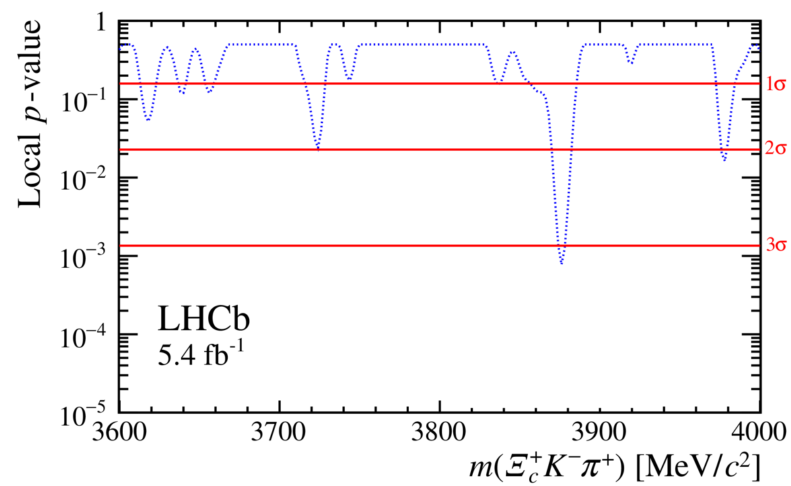
Ω_{cc}^{+}的首次搜寻

- $\Omega_{cc}^{+} \rightarrow \Xi_c^{+} K^{-} \pi^{+}$
  - 3876 MeV有局部（全局）显著度为3.2σ (1.8σ)的暗示，显著高于大部分理论预言值
  - 相对Ξ_{cc}^{++}产率的上限









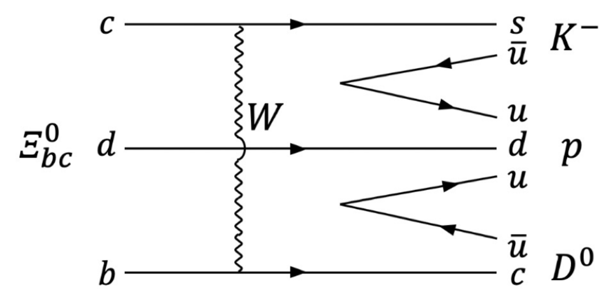
[SCPMA 64 (2021) 101062]

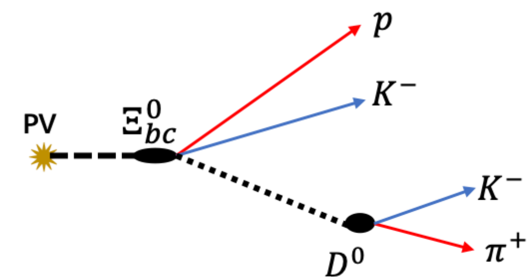
Ξ_{bc}^{0}的首次搜寻

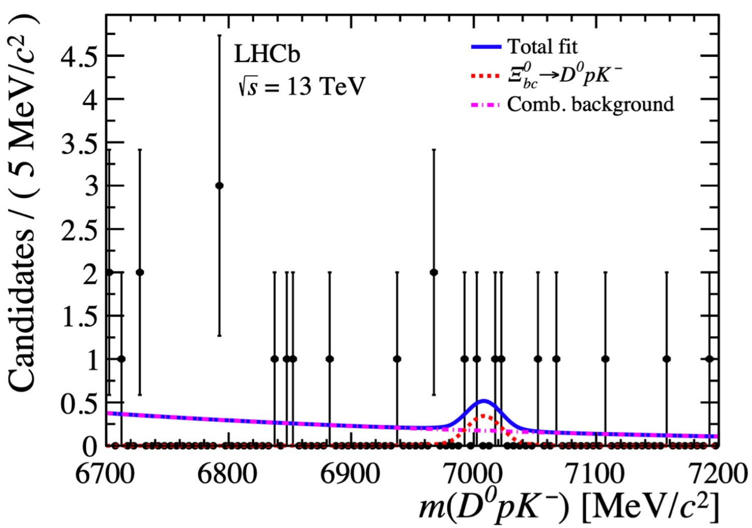
[JHEP 11 (2020) 095]

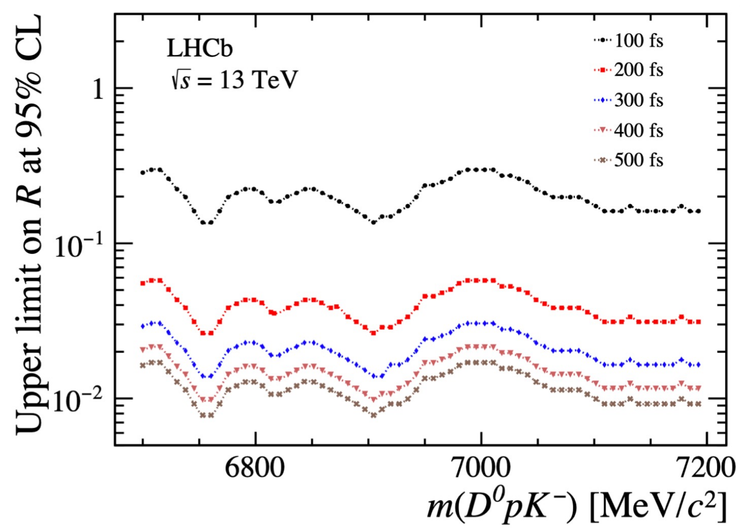
- 主要挑战，总分支比较小，采用实验上有利的衰变道$\Xi_{bc}^{0} \to D^{0}pK^{-}$
- 尚未观测到信号，给出截面上限

$$R = \frac{\sigma(\Xi_{bc}^{0})\cdot\mathcal{B}(\Xi_{bc}^{0}\to D^{0}pK^{-})}{\sigma(\Lambda_{b}^{0})\cdot\mathcal{B}(\Lambda_{b}^{0}\to D^{0}pK^{-})}$$





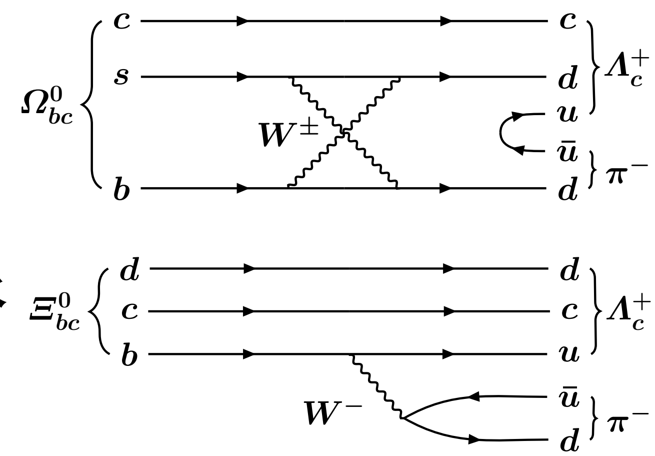




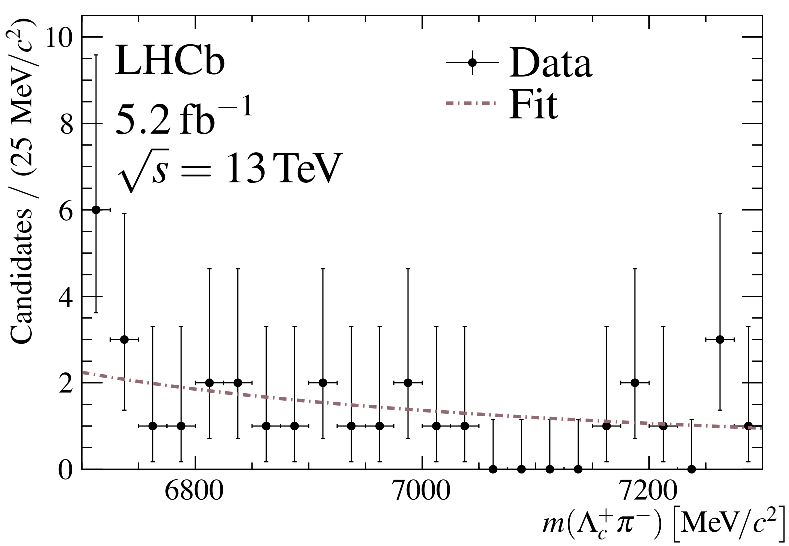
$\Omega_{bc}^0, \Xi_{bc}^0$的首次搜寻

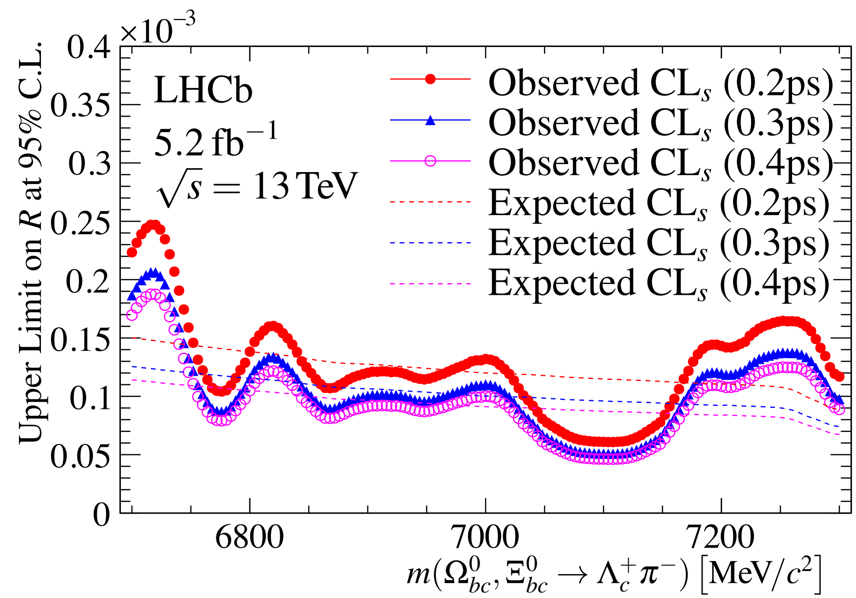
- 主要挑战，总分支比较小，采用实验上有利的衰变道$\Lambda_c^+/\Xi_c^+\pi^-$
- 尚未观测到信号，给出截面上限

$$R = \frac{\sigma(\Omega_{bc}^0)\cdot\mathcal{B}(\Omega_{bc}^0\to\Lambda_c^+\pi^-)}{\sigma(\Lambda_b^0)\cdot\mathcal{B}(\Lambda_b^0\to\Lambda_c^+\pi^-)}$$



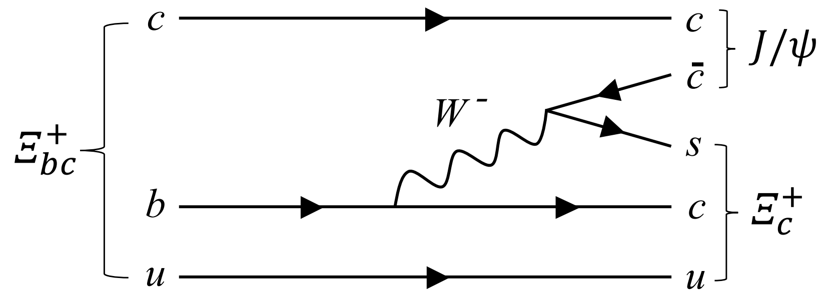
[CPC 45 (2021) 093002]

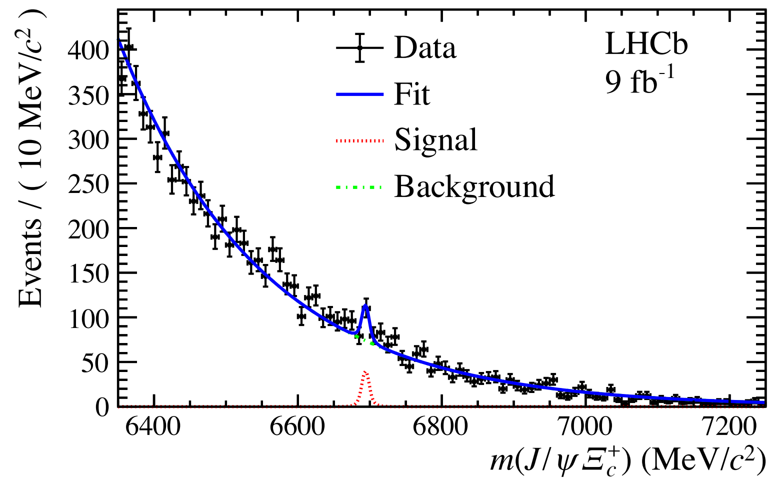


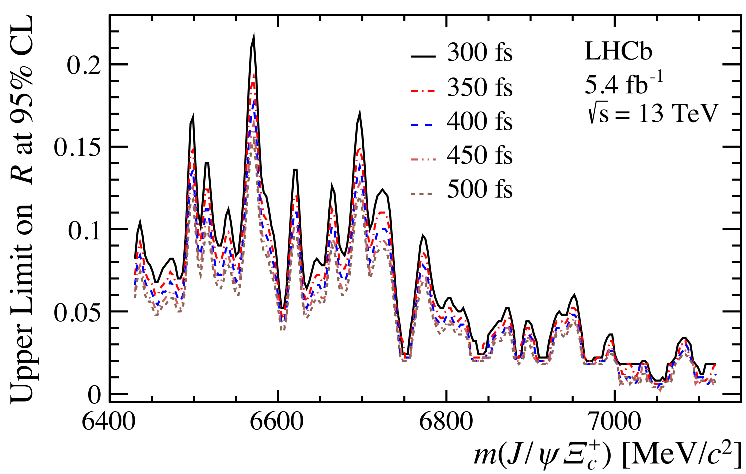


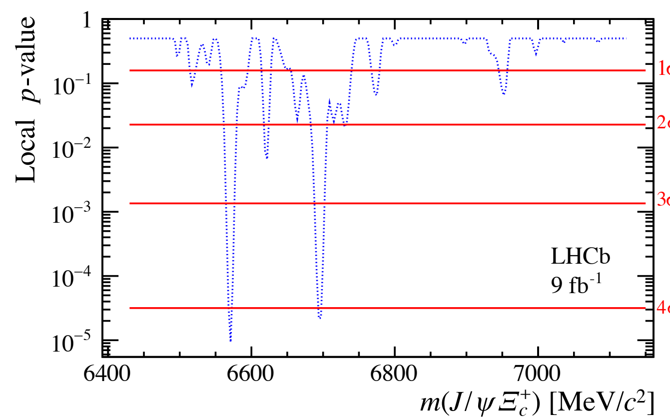
Ξ_{bc}^{+}的首次搜寻

- 全部数据， $\Xi_{bc}^{+} \to J/\psi \Xi_c^{+}$
  - 6571、6694 MeV处分别有局部（全局）显著度为4.3σ (2.8σ)、4.1σ (2.4σ)的暗示
  - 相对$B_c^{+} \to J/\psi D_s^{+}$产率上限





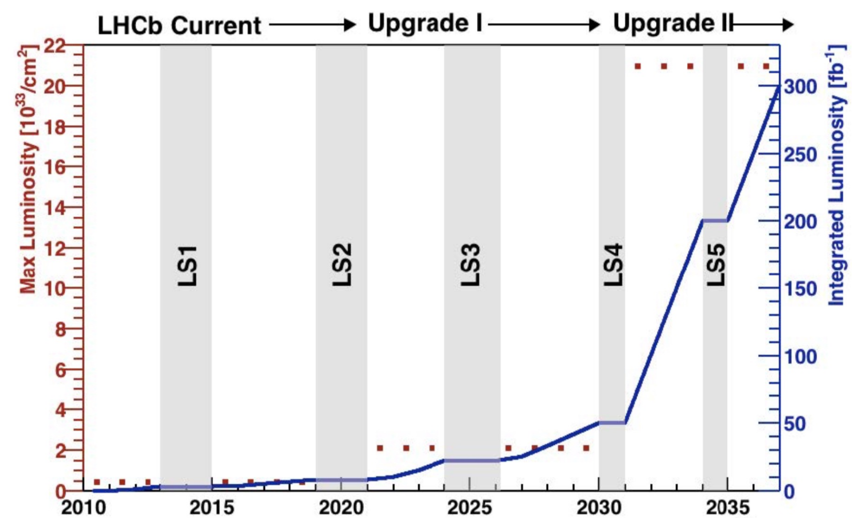




[arXiv:2204.09541, to appear in CPC]

实验研究展望

- LHCb (9 fb^{-1})
  - Ξ_{cc}^{++}，发现+性质
  - $\Xi_{cc}^{+}, \Omega_{cc}^{+}, \Xi_{bc}^{+}$，暗示
  - $\Xi_{bc}^{0}, \Omega_{bc}^{0}$，首次搜寻
- LHCb 升级 (50 fb^{-1})
  - Ξ_{cc}^{++} $\mathcal{O}(10\mathrm{k})$信号，寻找激发态，观测到更多的衰变道，CP破坏研究?
  - Ξ_{cc}^{+} $\mathcal{O}(1\mathrm{k})$ 信号，性质测量更精确
  - $\Omega_{cc}^{+}, \Xi_{bc}^{+}$ 发现?
- LHCb 进一步升级, 数据量扩大6倍



总结

- 在国内理论家们长期强有力的支持下，系统地开展了双重味重子的实验研究
  - 发现 Ξ_{cc}^{++} [PRL 119 (2017) 112001]，测量了其质量[JHEP 02 (2020) 049]、寿命[PRL 121 (2018) 052002]、产生[CPC 44 (2020) 022001]，以及发现新的衰变道$\Xi_c^{(\prime)+}\pi^+$ [PRL 121 (2018) 162002, JHEP 05 (2022) 038]
  - 更新了Ξ_{cc}^{+}的搜寻，灵敏度提高一个数量级，已有迹象[SCPMA 63 (2020) 221062, JHEP 05 (2022) 038]
  - 首次搜寻了Ω_{cc}^{+} [SCPMA 64 (2021) 101062]，Ξ_{bc}^{+} [arXiv:2204.09541]，Ξ_{bc}^{0} [JHEP 11 (2020) 095]，Ω_{bc}^{0} [CPC 45 (2021) 093002]
- LHCb升级，将进一步推进双重味重子研究