LHCb上双重味重子实验研究

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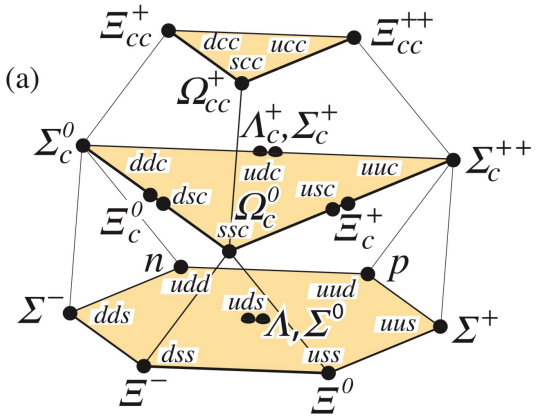
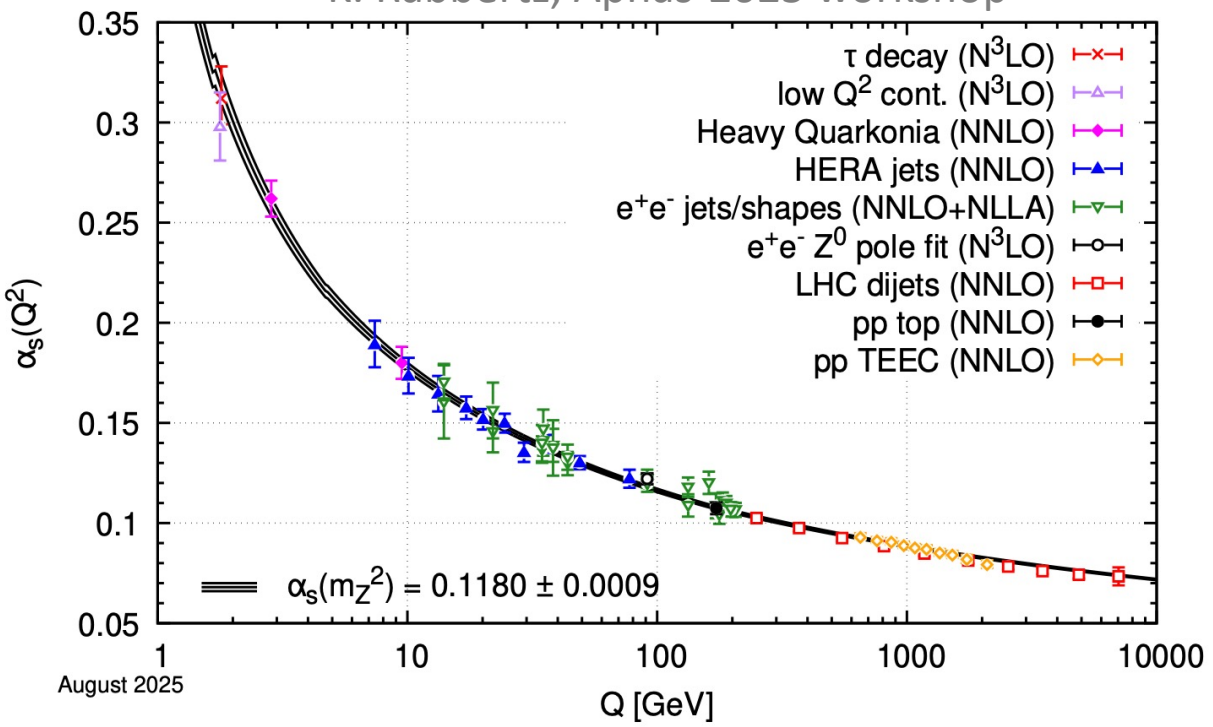
2026年7月16日

Introduction

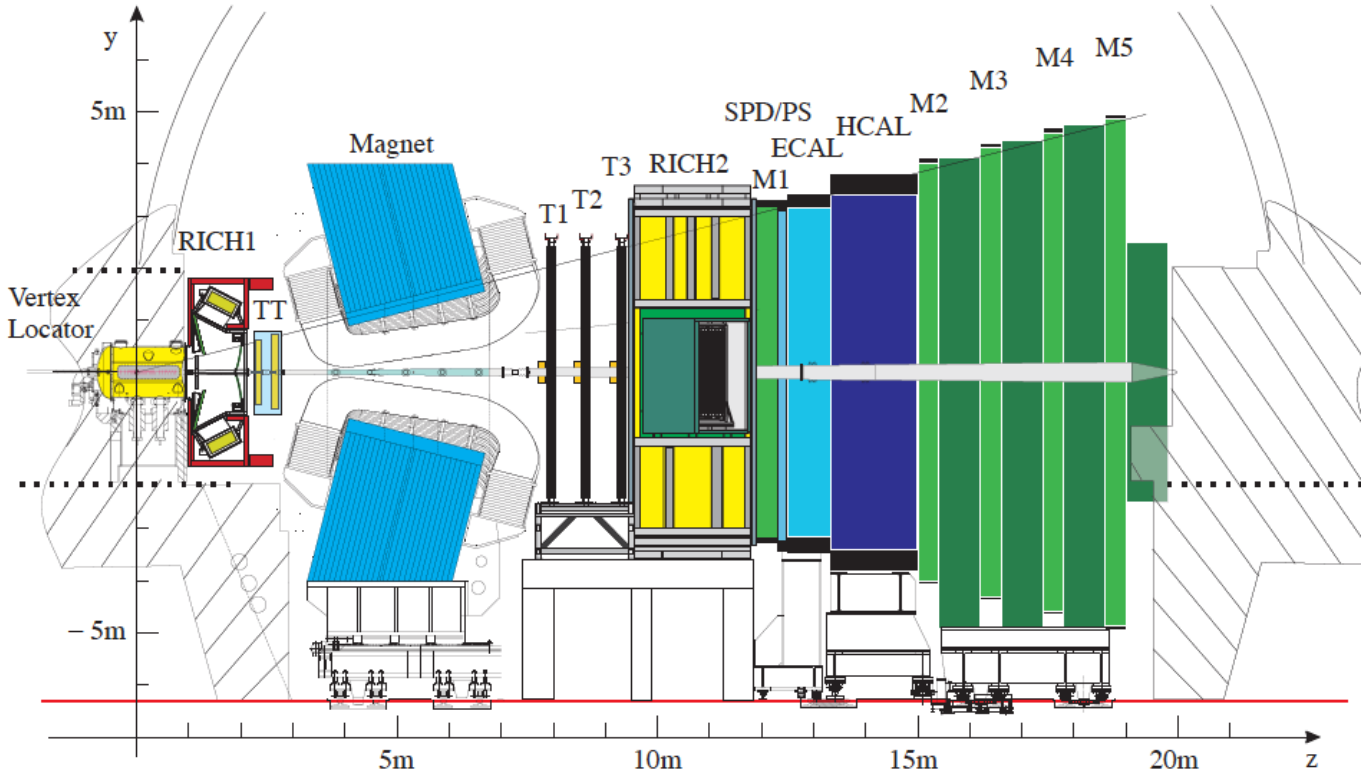
- Quark model: particle zoo v1
- Exprimental measurements required to determine the nature of particles & calibrate LQCD
- Doubly heavy baryons
  - Unique to study quark model & strong interaction



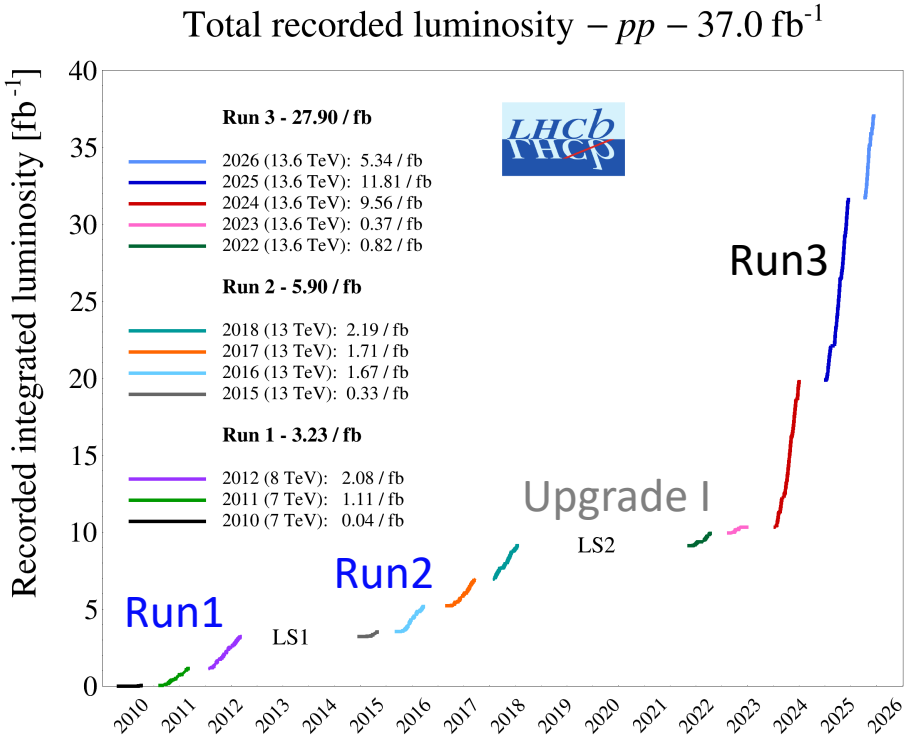
K. Rabbertz, Aphas-2025 workshop



The LHCb experiment



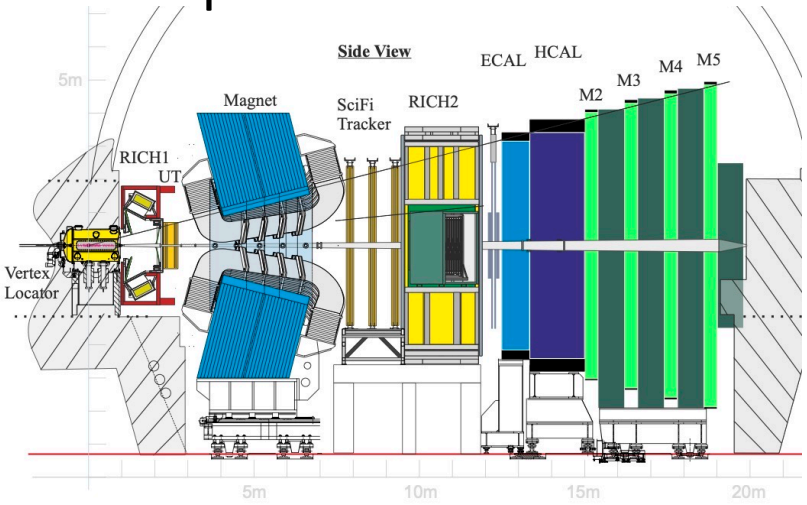
Vertex Locator	$\sigma_{PV,x/y} \sim 10\ \mu m$, $\sigma_{PV,z} \sim 60\ \mu m$
Tracking (TT, T1-T3)	$\Delta p/p$: 0.4% at 5 GeV/c, to 0.6% at 100 GeV/c
RICHs	$\varepsilon(K \to K) \sim 95\%$, mis-ID rate $(\pi \to K) \sim 5\%$
Muon system (M1-M5)	$\varepsilon(\mu \to \mu) \sim 97\%$, mis-ID rate $(\pi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

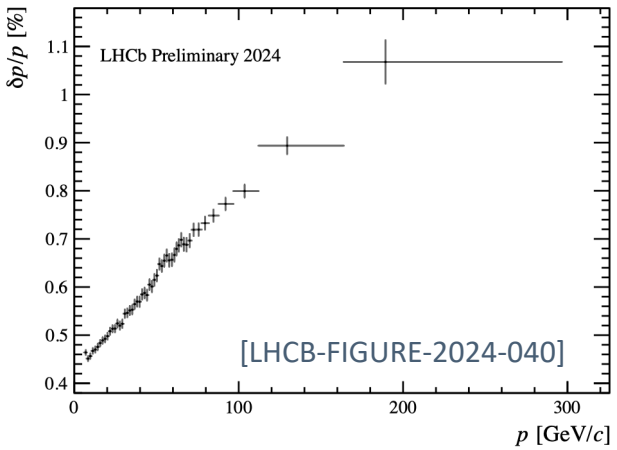


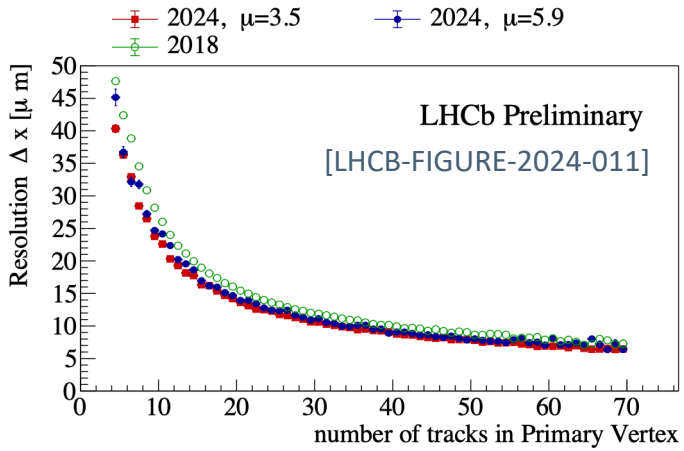
- Run1-2 (2010-2018)
  - Luminosity: ~9 fb^{-1}
  - Yields, complementary to ATLAS/CMS
    - Muon modes: Down to zero p_T
    - Hadronic modes: Unique

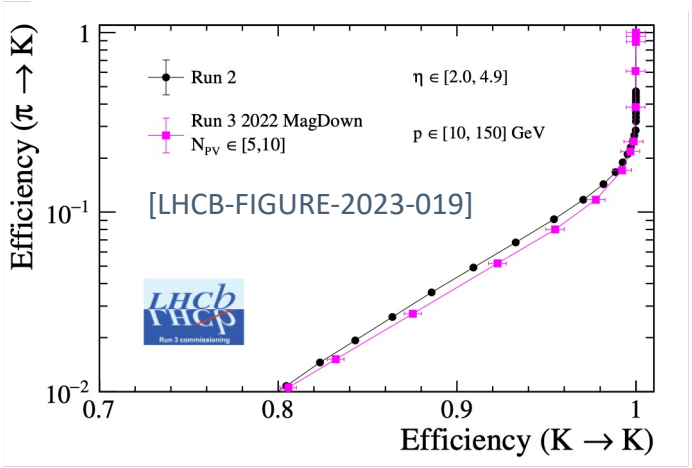
The LHCb Upgrade

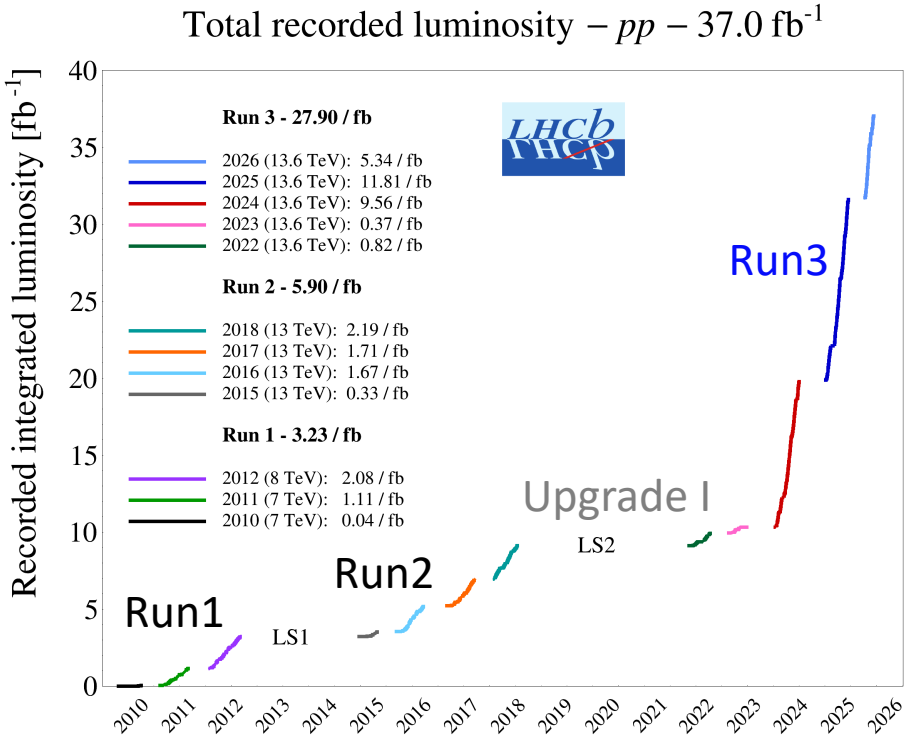
- Detector mostly upgraded to achieve enhanced capabilities at five times higher luminosity





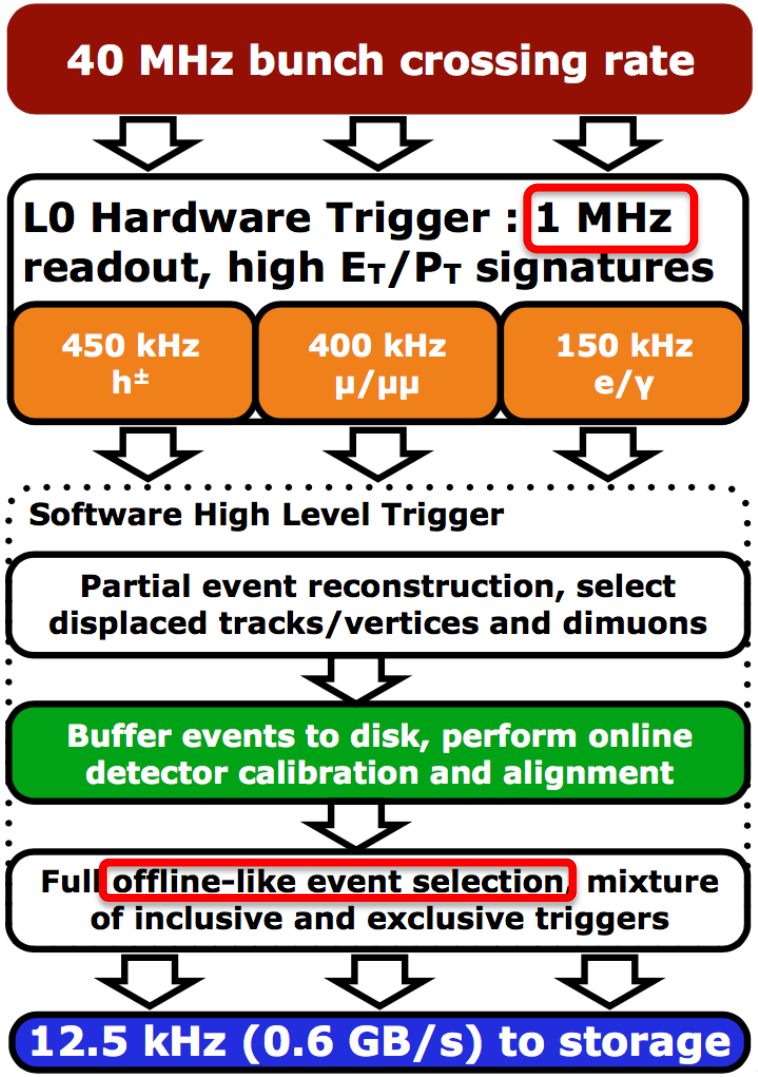






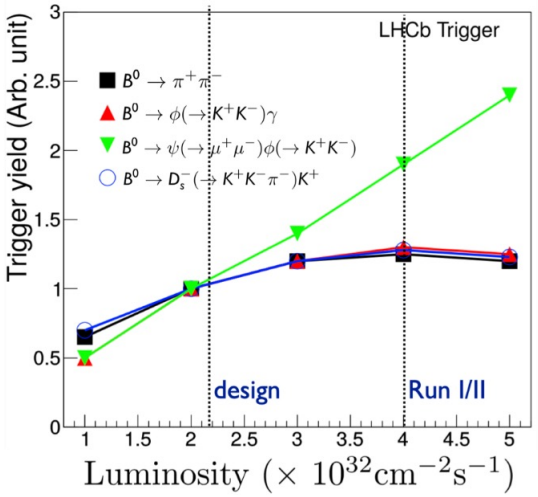
- Run3 (2024-2026)
  - Luminosity: ~28 fb^{-1}
  - Yields, compared to Run 1+2
    - Muon modes ~4
    - Hadronic modes ~8 (higher trigger eff.)

The LHCb trigger (2018)



- L0, Hardware
  - $p_{\mathrm{T}}(\mu_1) \times p_{\mathrm{T}}(\mu_2) > (1.5\ \mathrm{GeV})^2$
  - $p_{\mathrm{T}}(\mu) > 1.8$ GeV
  - $E_{\mathrm{T}}(e) > 2.4$ GeV
  - $E_{\mathrm{T}}(\gamma) > 3.0$ GeV
  - $E_{\mathrm{T}}(h) > 3.7$ GeV
- High Level Trigger
  - Stage1, p_{T}, IP
  - Stage2, full selection

The LHCb trigger (Run3)



Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

L0 removed

30 MHz inelastic event rate (full rate event building)

Software High Level Trigger

Full event reconstruction, inclusive and exclusive kinematic/geometric selections

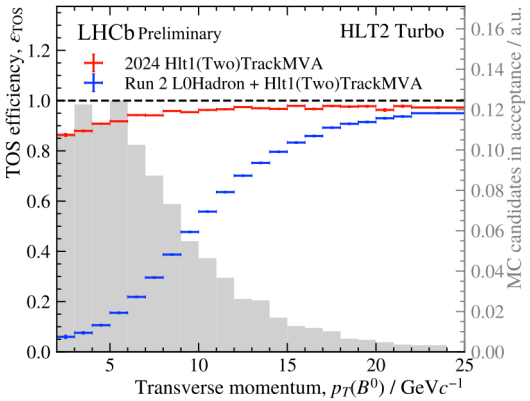
Buffer events to disk, perform online detector calibration and alignment

Add offline precision particle identification and track quality information to selections

Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers

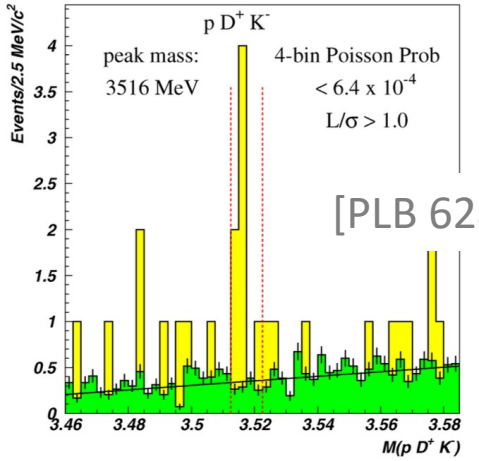
2-5 GB/s to storage

[LHCB-FIGURE-2024-030]



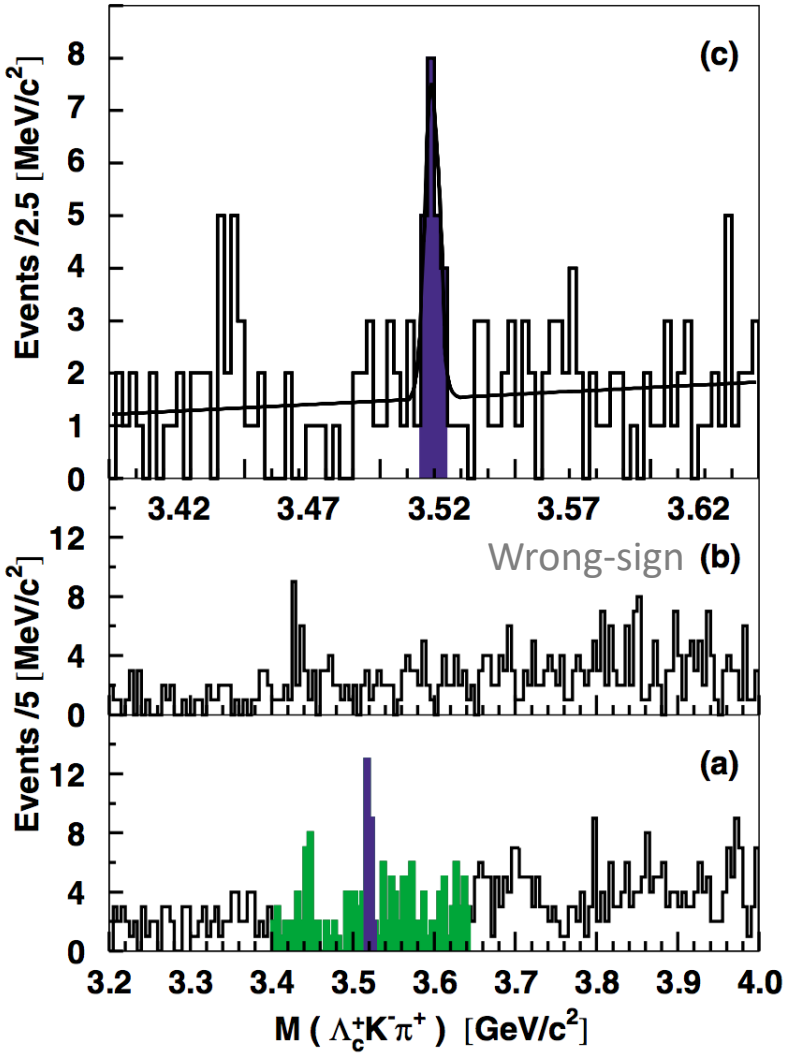
Ξ_{cc}^{+} @ SELEX

- SELEX claimed $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ (6.3σ)
  - M: 3519 ± 1 MeV
  - τ: <33 fs @90%CL
  - σ_{prod}: 20% Λ_c^{+} from Ξ_{cc}^{+}
- Also $\Xi_{cc}^{+} \to p D^{+} K^{-}$



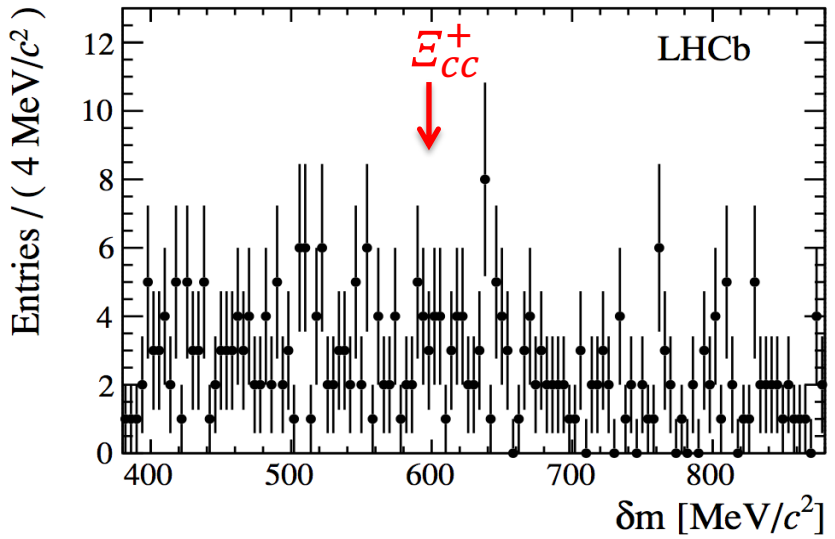
[PLB 628 (2005)18]

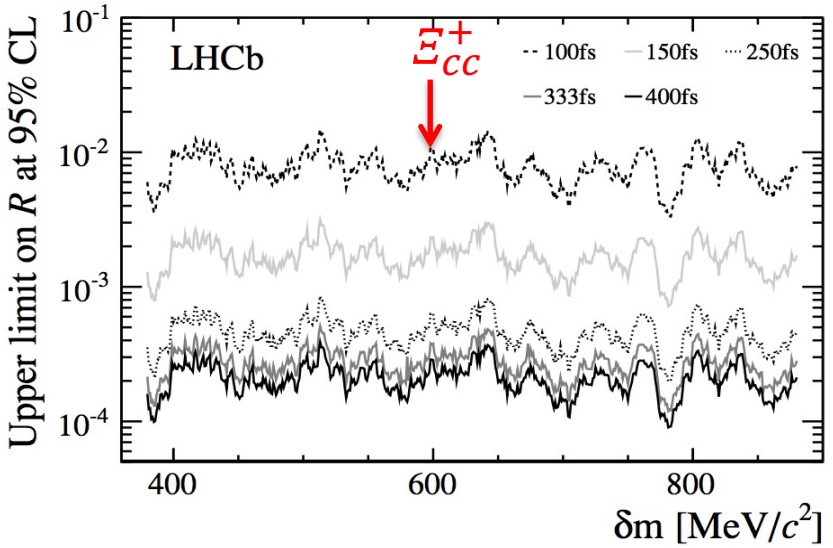
[PRL 89 (2002) 112001]



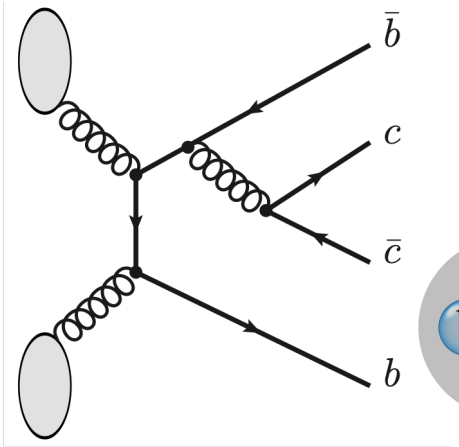
Ξ_{cc} @ LHCb & others

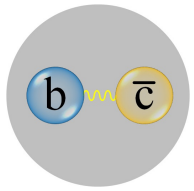
- SELEX results not confirmed by FOCUS, Babar, Belle & LHCb
- $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ searched by LHCb with 2011 data



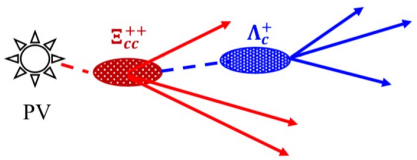


- However, LHCb already had lots of B_c^{+} events, and double-charm events…



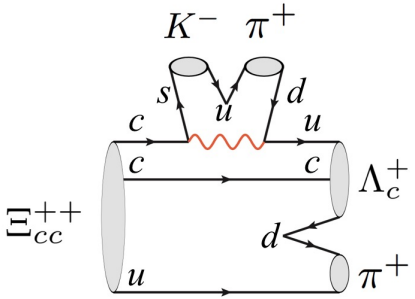


Observation of Ξ_{cc}^{++}

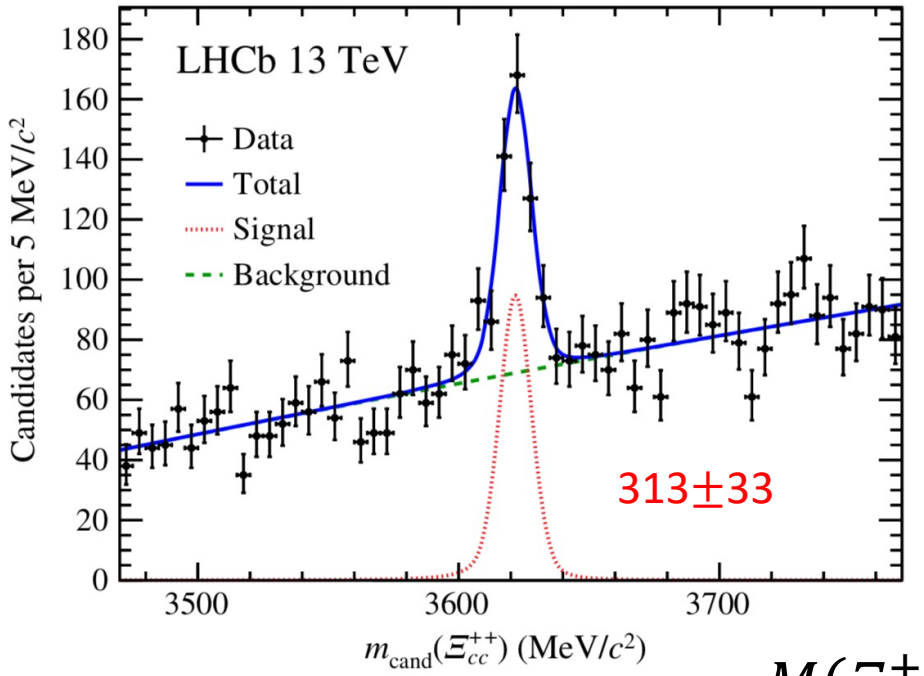


[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

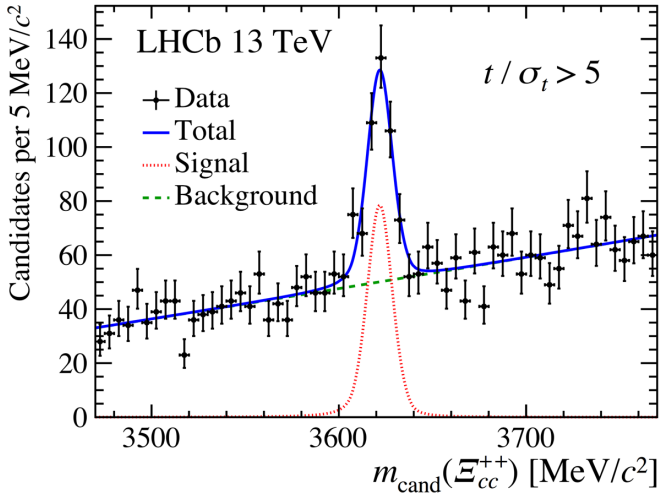
- $\Lambda_c^+ K^- \pi^+ \pi^+$ identified as the most promising channel
- First observation, in 2016 (>12σ) & Run1 (>7σ)

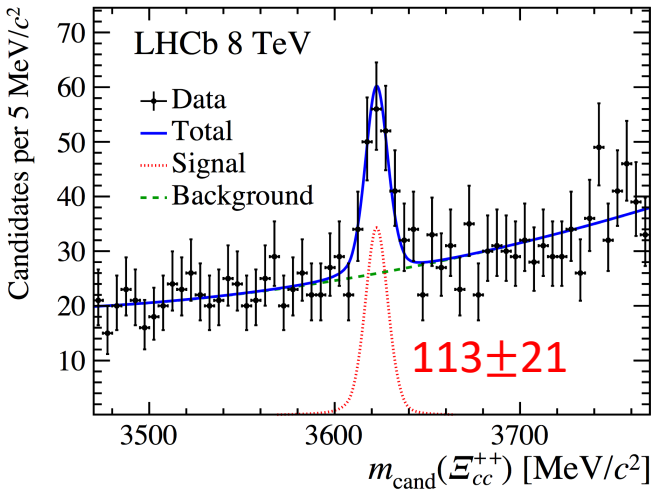


[PRL 119 (2017) 112001]



Weakly decay!





$$M(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \pm 0.27 \pm 0.14\,(\Lambda_c^+)\ \mathrm{MeV}/c^2$$

Observation of Ξ_{cc}^{++}

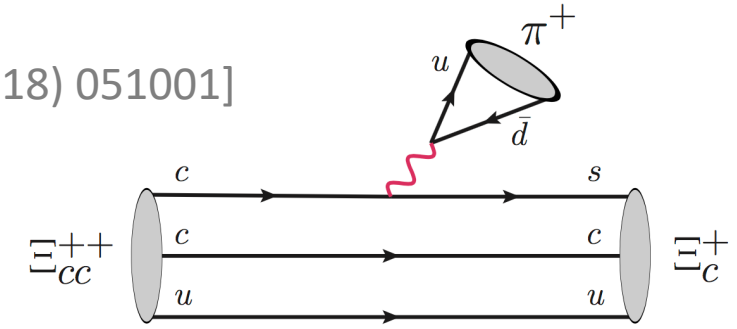
[F.-S. Yu *et al.*, CPC 42 (2018) 051001]

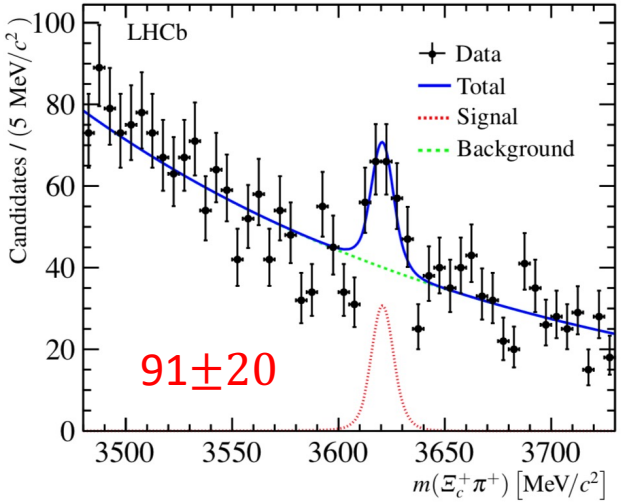
- $\Xi_{cc}^{++} \to \Xi_c^+ \pi^+$ expected to have large BR
  - Rule of thumb: 2 less tracks, 10 times higher eff.
- Re-discovery with 2016 data, 5.9σ
- BR ratio measured

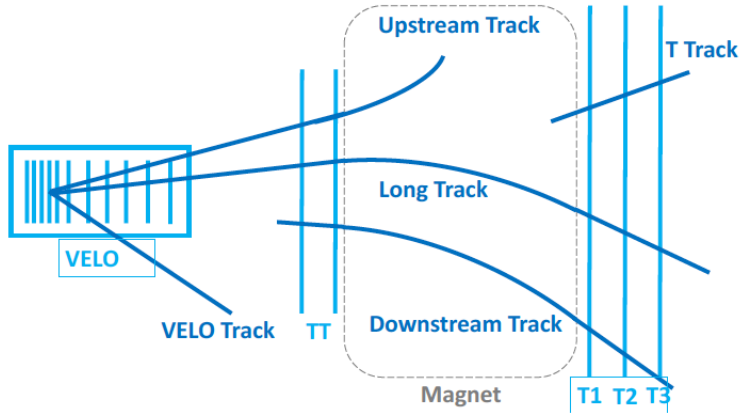
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \cdot \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \cdot \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$

$$= 0.035 \pm 0.009 \pm 0.003$$

[PRL 121 (2018) 162002]







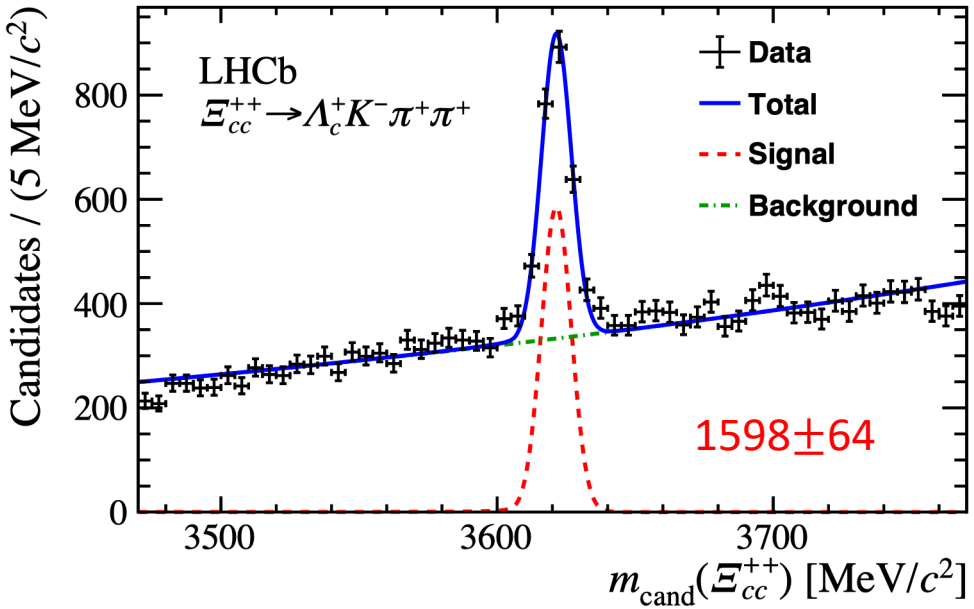
Not very good at hyperon…

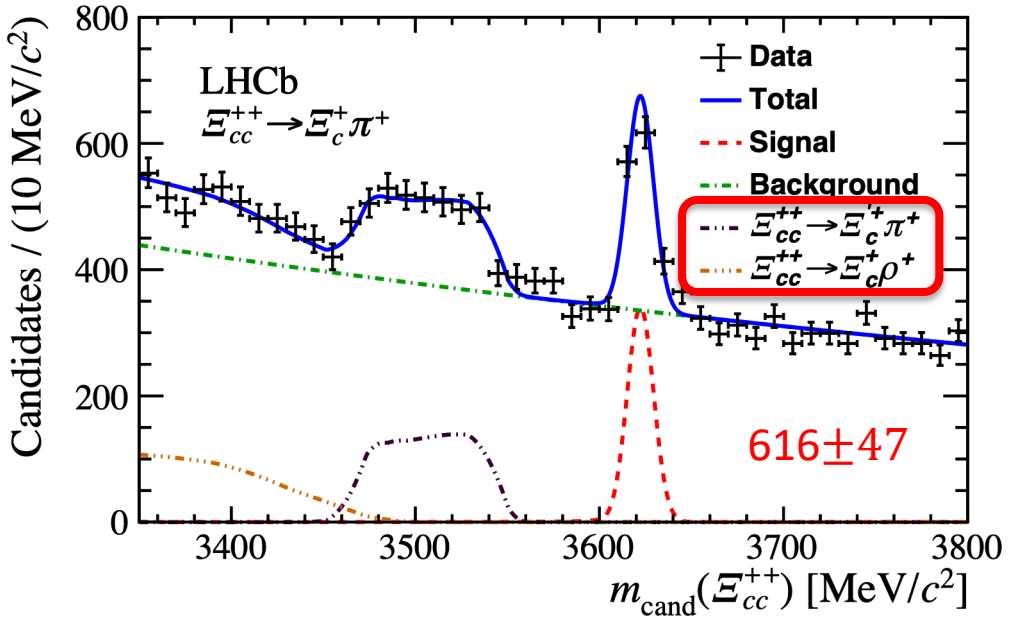
UROP

Precision measurement of $M(\Xi_{cc}^{++})$

- Preparing to search for excited states, selection re-optimised
- 5-6 times signal yields with a factor of 3 data

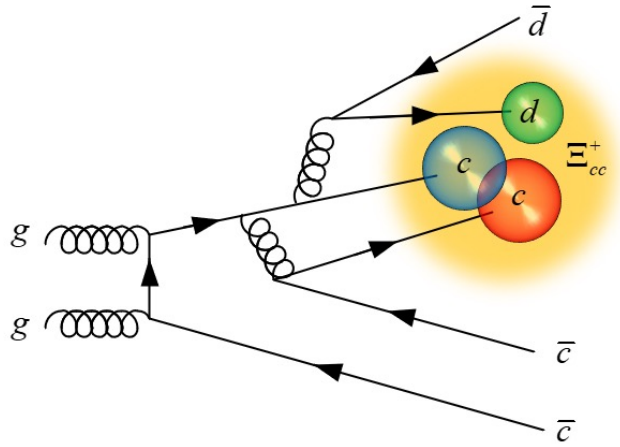
[JHEP 02 (2020) 049]





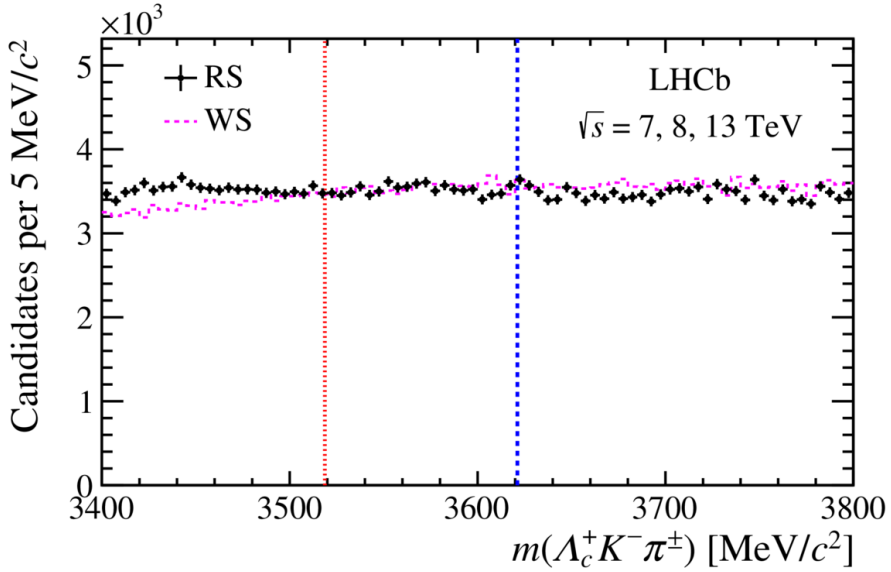
$$M(\Xi_{cc}^{++}) = 3621.55 \pm 0.23 \pm 0.30\ \text{MeV}/c^2$$ taken as WA by PDG

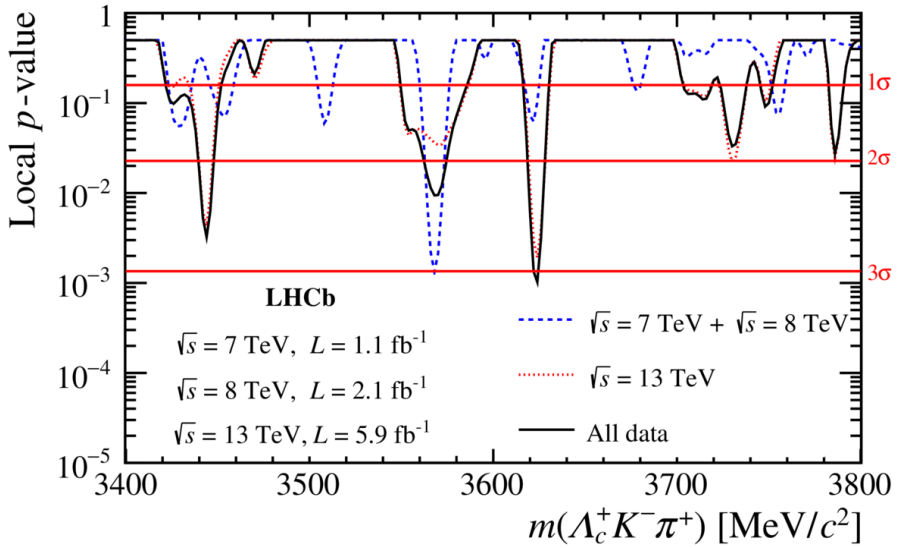
Ξ_{cc}^{+} search

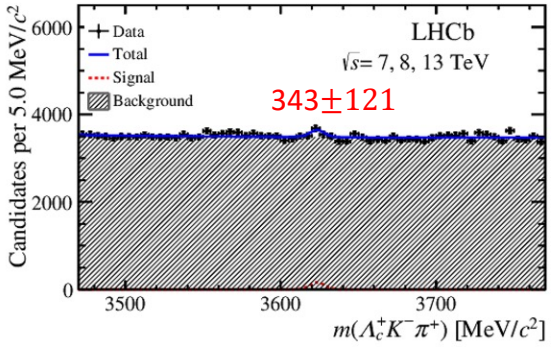


- Updated w/ $\Lambda_c^+ K^- \pi^+$ using all Run1-2 data
- $\tau(\Xi_{cc}^{+})$: (0 fs, 80 fs) × (non)observation
- Evidence at Ξ_{cc}^{++}, w/ local (global) significance 3.1σ (1.7σ)

[SCPMA 63 (2020) 221062]

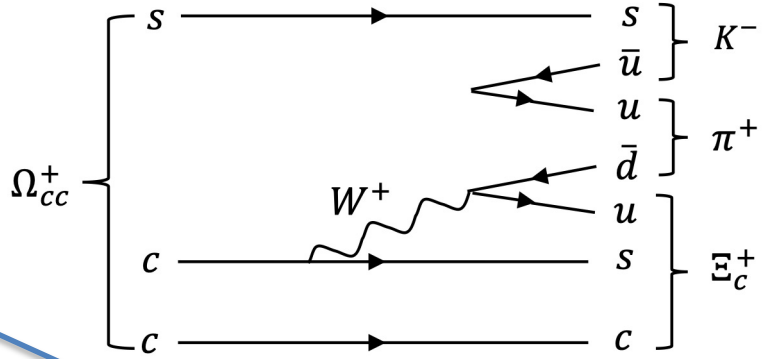


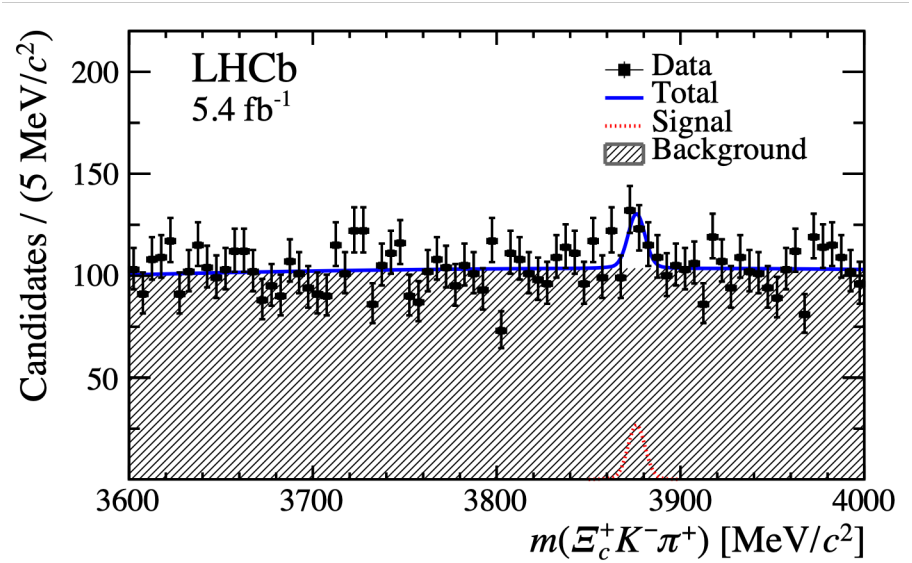


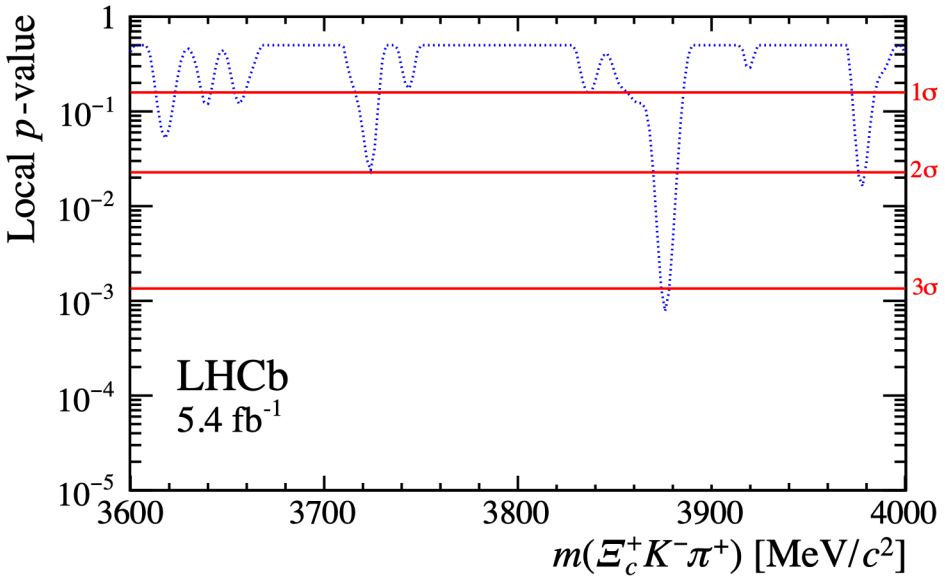


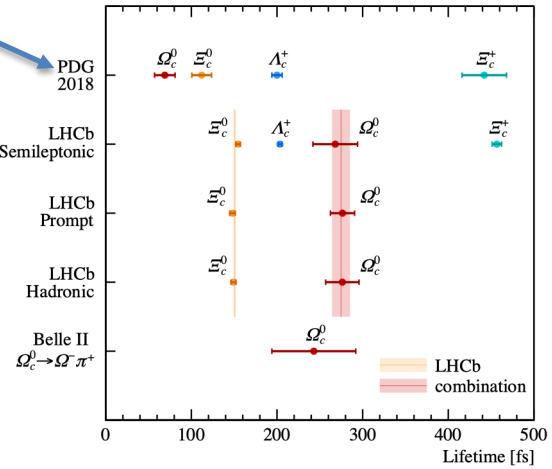
Ω_{cc}^{+} search

- $\Xi_c^+ K^- \pi^+$ chosen for the first search using Run-2 data, as Ω_c^0 lifetime WAS too short
- No significant signal after considering LEE





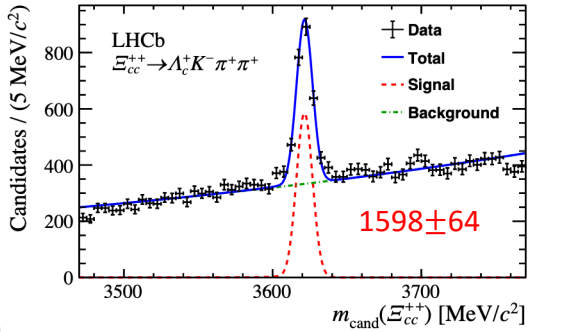


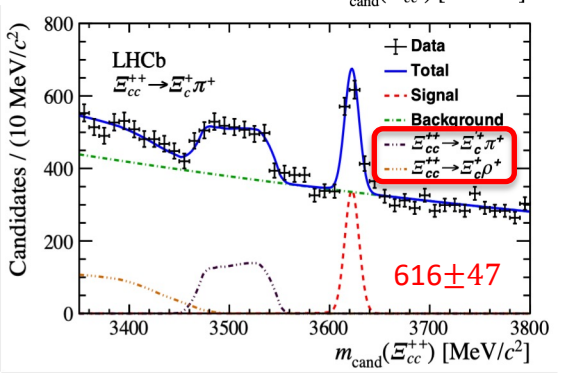


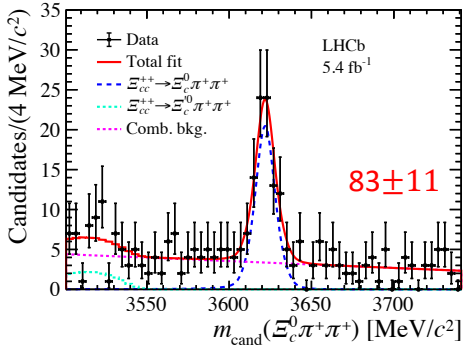
[JHEP 09 (2025) 157]

[SCPMA 64 (2021) 101062]

Doubly heavy baryons w/ Run1-2 data

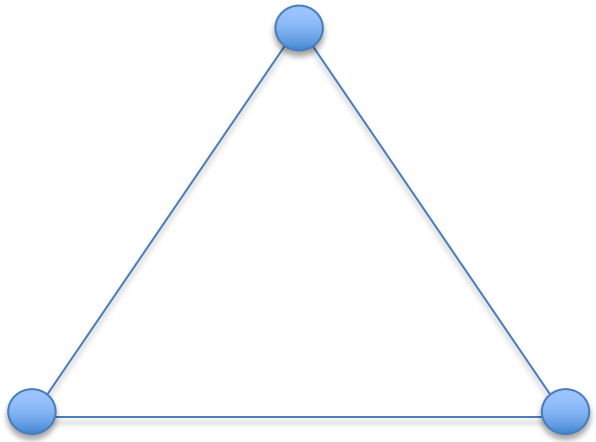






First search, Hint[SCPMA 64 (2021) 101062]

Ω_{cc}^+ (ccs)



Ξ_{cc}^{++} (ccu)

Observation[PRL 119 (2017) 112001]

Mass[JHEP 02 (2020) 049]

Lifetime[PRL 121 (2018) 052002]

Production[CPC 44 (2020) 022001]

Decay $\Xi_c^+\pi^+$[PRL 121 (2018) 162002]

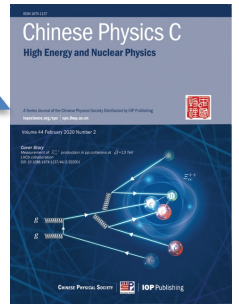
$\Xi_c'^+\pi^+$[JHEP 05 (2022) 038]

$\Xi_c^0\pi^+\pi^+$[JHEP 10 (2025) 136]

Ξ_{cc}^+ (ccd)

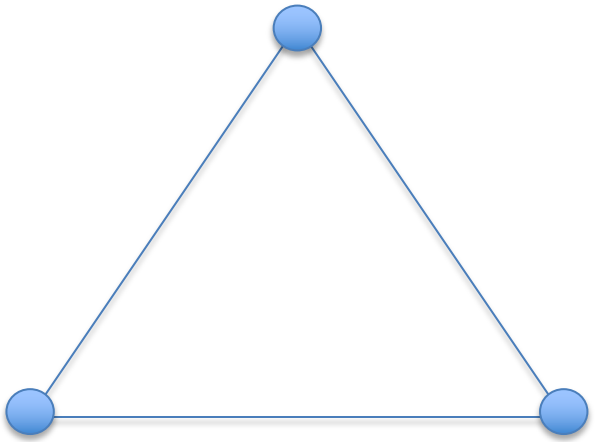
Hint/Evidence

[SCPMA 63 (2020) 221062, JHEP 12 (2021) 107]



First search[CPC 45 (2021) 093002]

Ω_{bc}^0 (bcs)

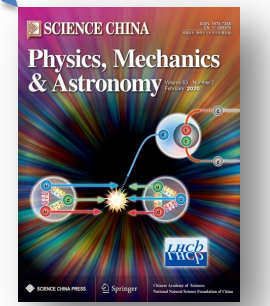


Ξ_{bc}^+ (bcu)

First search

Hint

[CPC 47 (2023) 093001]

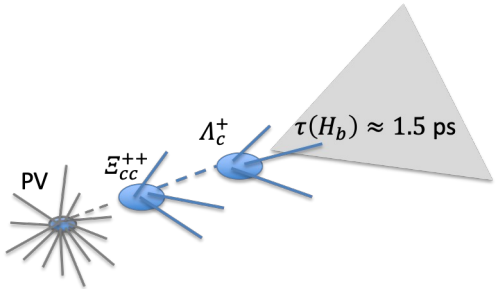


Ξ_{bc}^0 (bcd)

First search

[JHEP 11 (2020) 095]

Ξ_{cc}^{++} in 2024

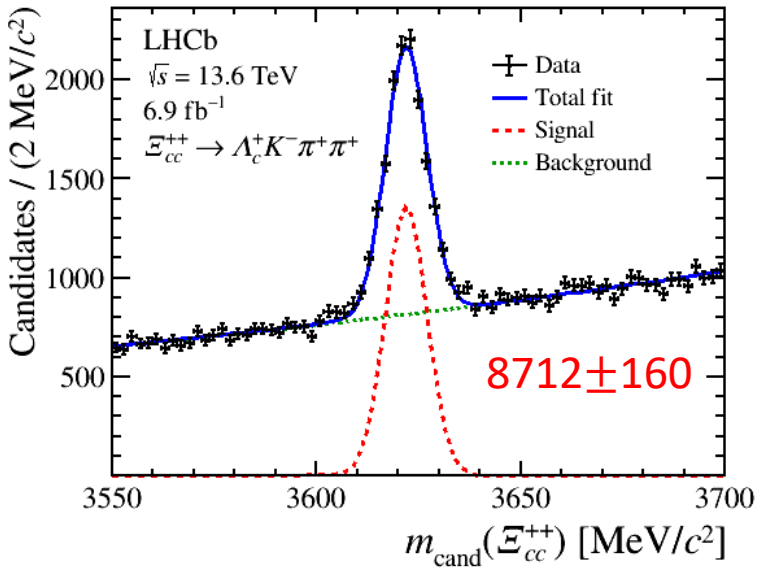


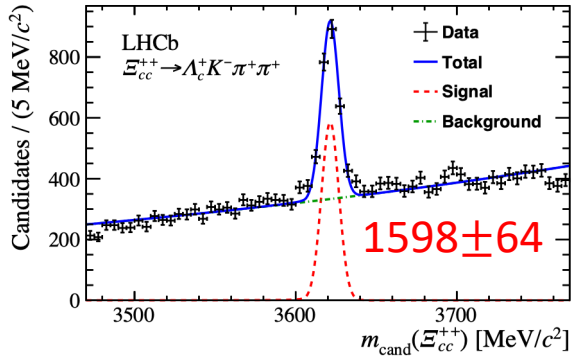
- Event-Selection (early measurement)
  - Several iterations. BDT trained w/ Λ_c^+ in data, included in BDT for Ξ_{cc}^{++} (p_{T}, χ^2_{IP}, PID)
  - BDT without PID as cross-check
- Efficiency increased by a factor of 4, compared with Run2
- Mass consistent with Run2

$$M(\Xi_{cc}^{++}) = 3621.74 \pm 0.10\ \mathrm{MeV}/c^2$$

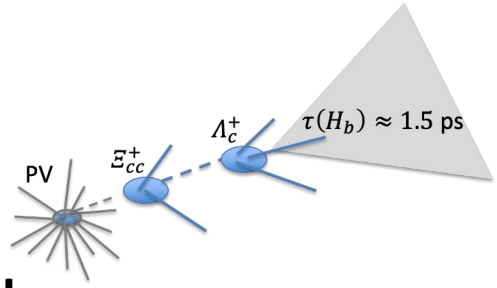
c.f., $3621.55 \pm 0.23 \pm 0.30\ \mathrm{MeV}/c^2$

[PRL 137 (2026) 021902]



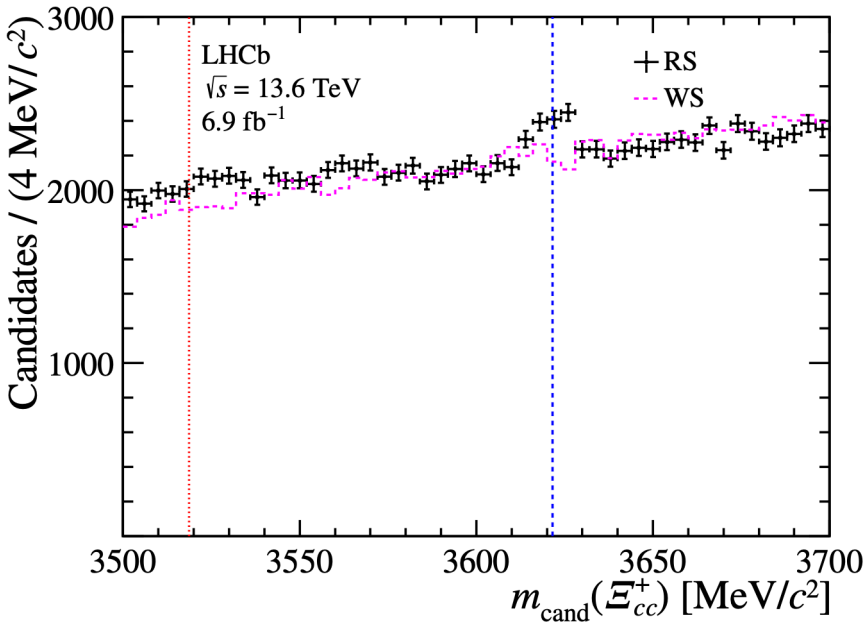


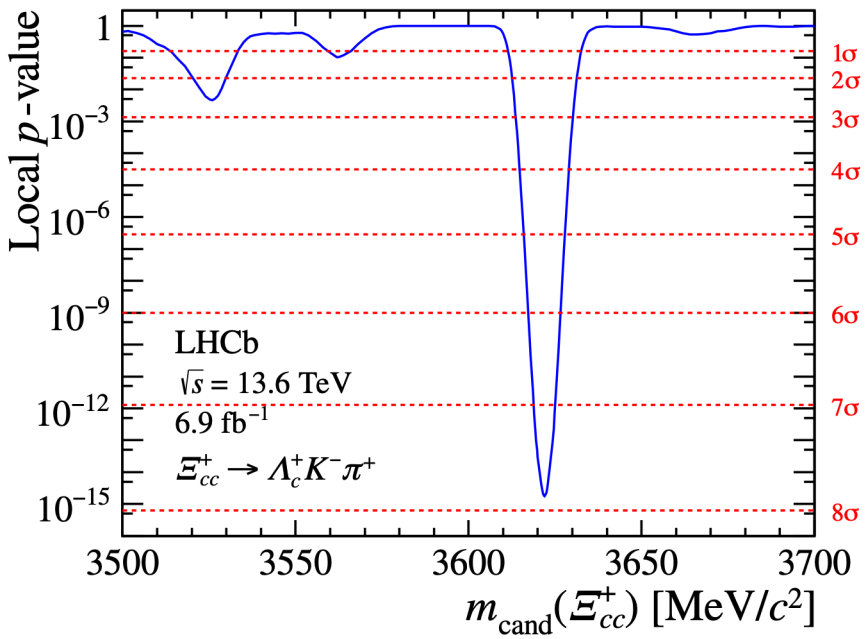
Ξ_{cc}^{+} in 2024



- Event-Selection, similar strategy to Ξ_{cc}^{++}, many checks
  - Effects of $\tau(\Xi_{cc}^{+})$, no fake peaks in wrong-sign, Λ_c^+ sidebands…
- After unblinding, first observation!

[PRL 137 (2026) 021902]





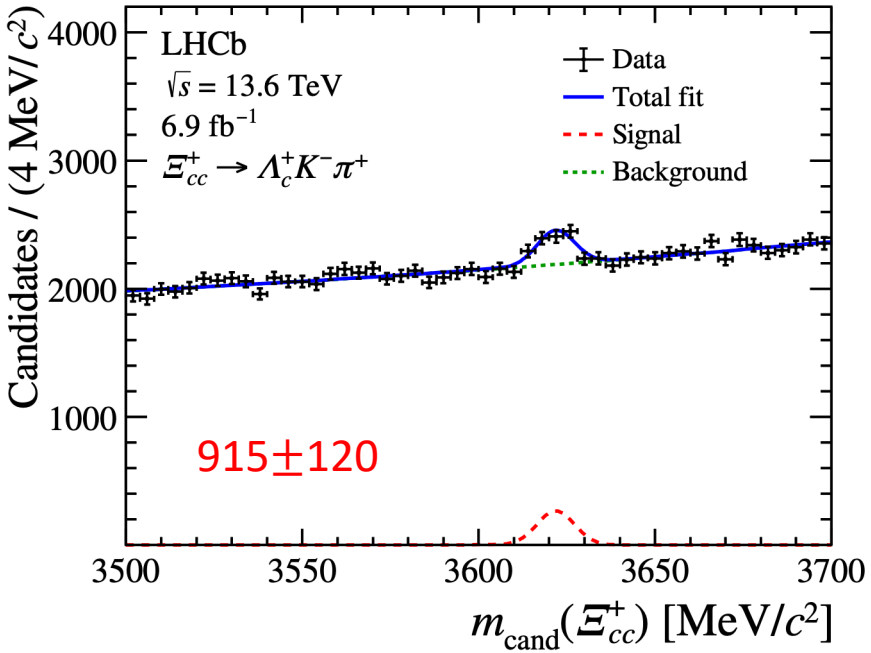
Ξ_{cc}^{+} mass

- Mass, $M(\Xi_{cc}^{+}) = 3619.97 \pm 0.83 \pm 0.26^{+1.90}_{-1.30}$ MeV/c^2

  after correcting for the bias due to FSR and event-selection

- Mass diff., $M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84 \pm 0.25^{+1.90}_{-1.30}$ MeV/c^2

[PRL 137 (2026) 021902]



Source	$M(\Xi_{cc}^{+})$ [MeV/c^2]	ΔM [MeV/c^2]
Momentum-scale calibration	0.14	0.03
Energy loss	0.10	0.05
Selection bias correction	0.10	0.10
Mass fit model	0.10	0.10
Λ_c^{+} mass uncertainty	0.14	–
Sum in quadrature	0.26	0.15
Ξ_{cc}^{+} lifetime	$^{+1.90}_{-1.30}$	$^{+1.90}_{-1.30}$

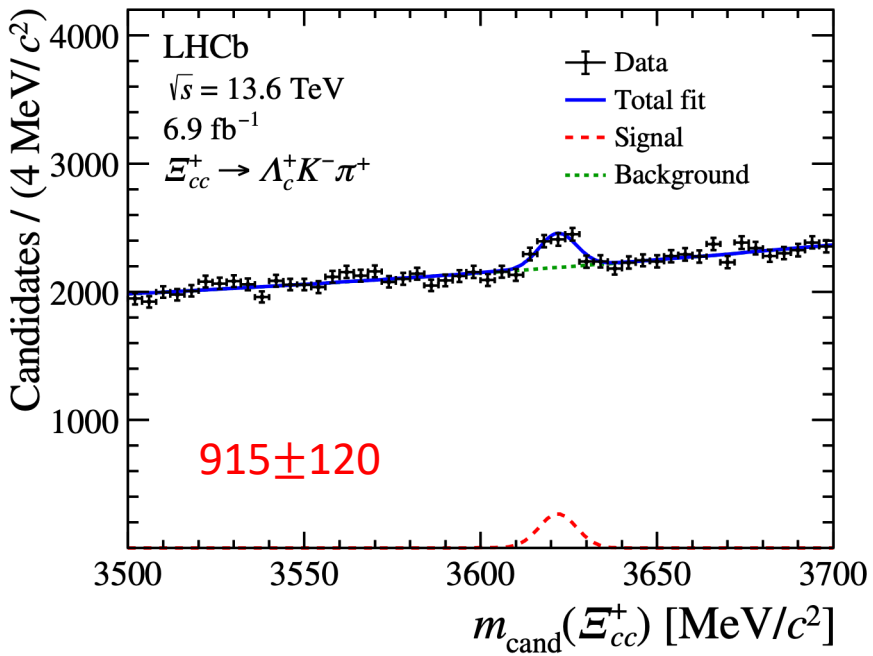
Ξ_{cc}^{+} in Run2

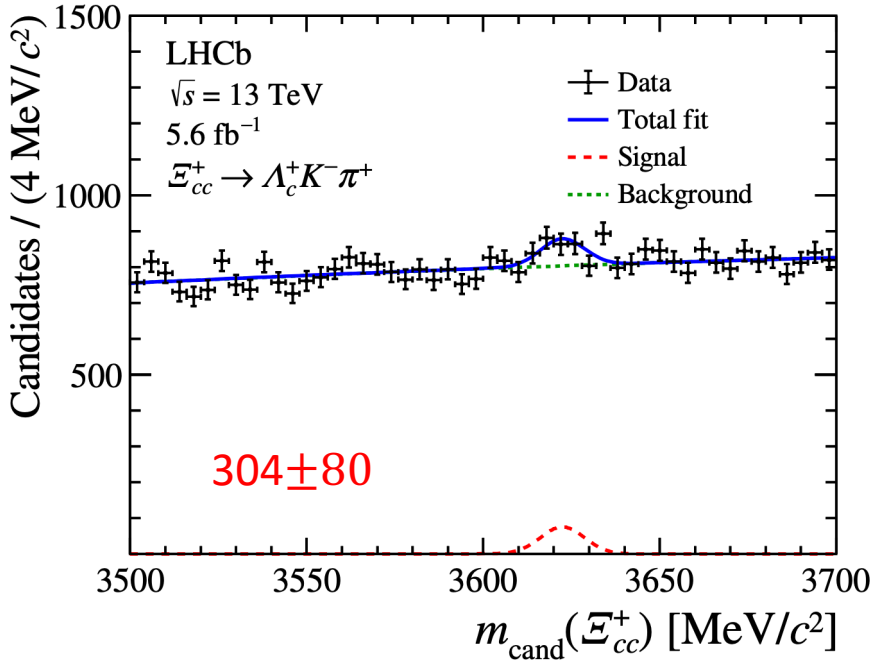
- Signal w/ a local significance of 4σ, $M(\Xi_{cc}^{+}) = 3620.8 \pm 2.2\ \mathrm{MeV}/c^2$, consistent with 2024

$M(\Xi_{cc}^{+}) = 3619.97 \pm 0.83 \pm 0.26^{+1.90}_{-1.30}\ \mathrm{MeV}/c^2$

- Efficiency in 2024 increased by a factor of 2.5, compared w/ Run2

[PRL 137 (2026) 021902]

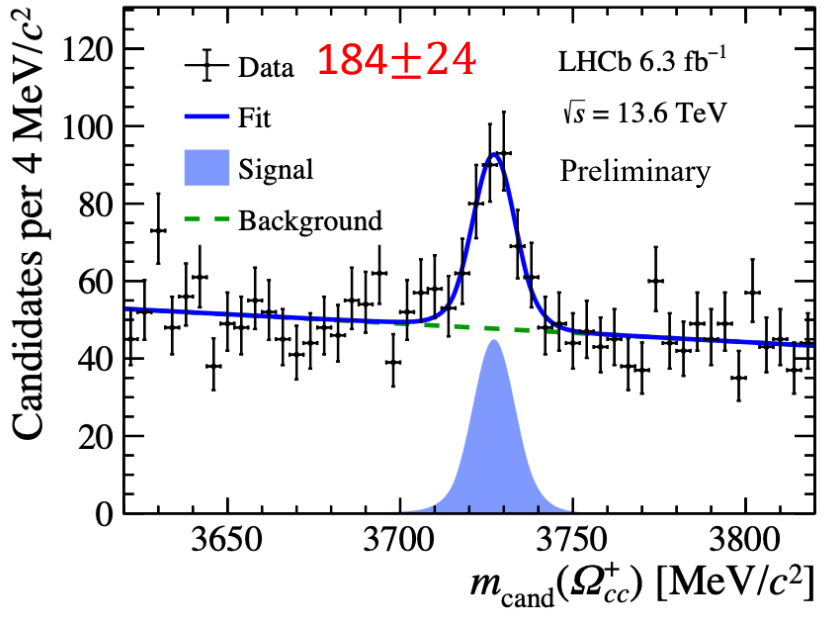


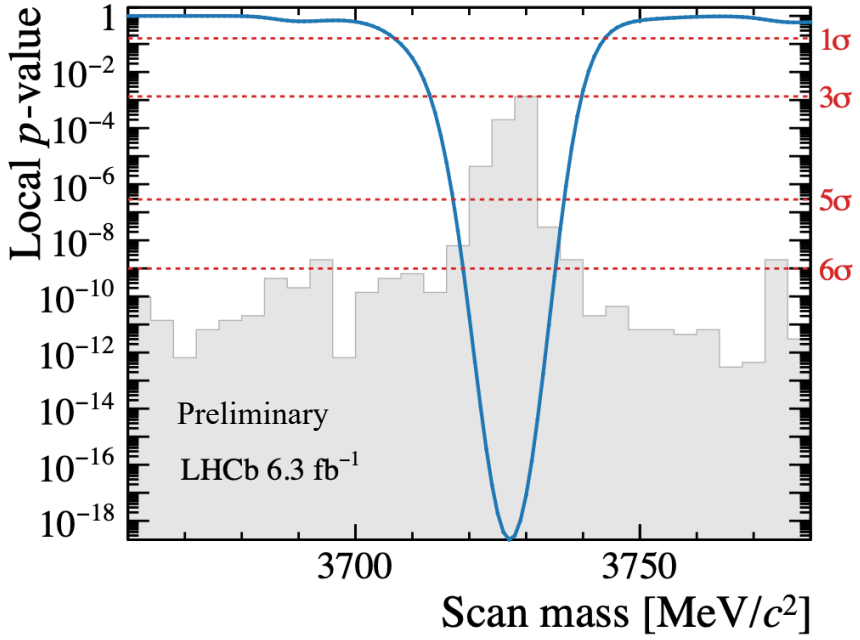


Ω_{cc}^{+} in 2024

- Observation using $\Omega_c^0\pi^+$, global significance 8.7σ
- $M(\Omega_{cc}^{+}) = 3725.9 \pm 1.0 \pm 0.2 \pm 0.4\,(\tau) \pm 0.6\,(\text{ext})\ \text{MeV}/c^2$

[LHCb-Paper-2026-022]

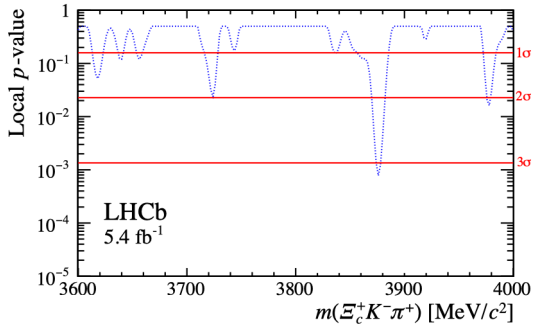




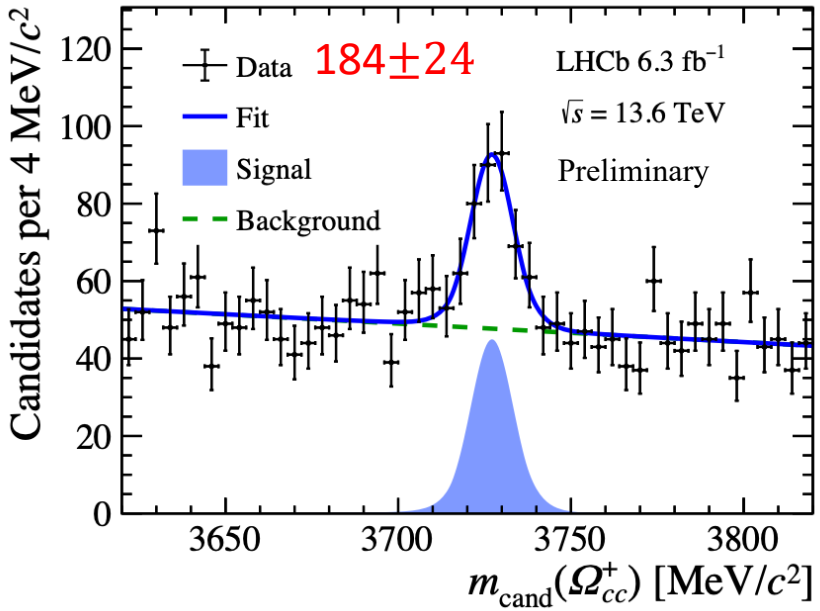
Ω_{cc}^{+} in Run-2

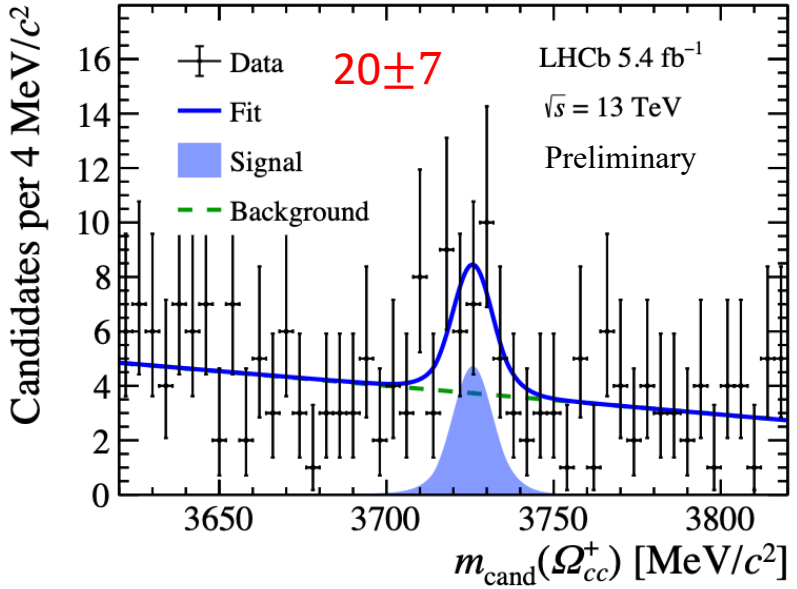
- Local (global) significance of 3.2σ (2.4σ)
- Efficiency increased by a factor of 8!

[SCPMA 64 (2021) 101062]



[LHCb-Paper-2026-022]





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The discovery helps physicists better understand how the strong force binds particles together

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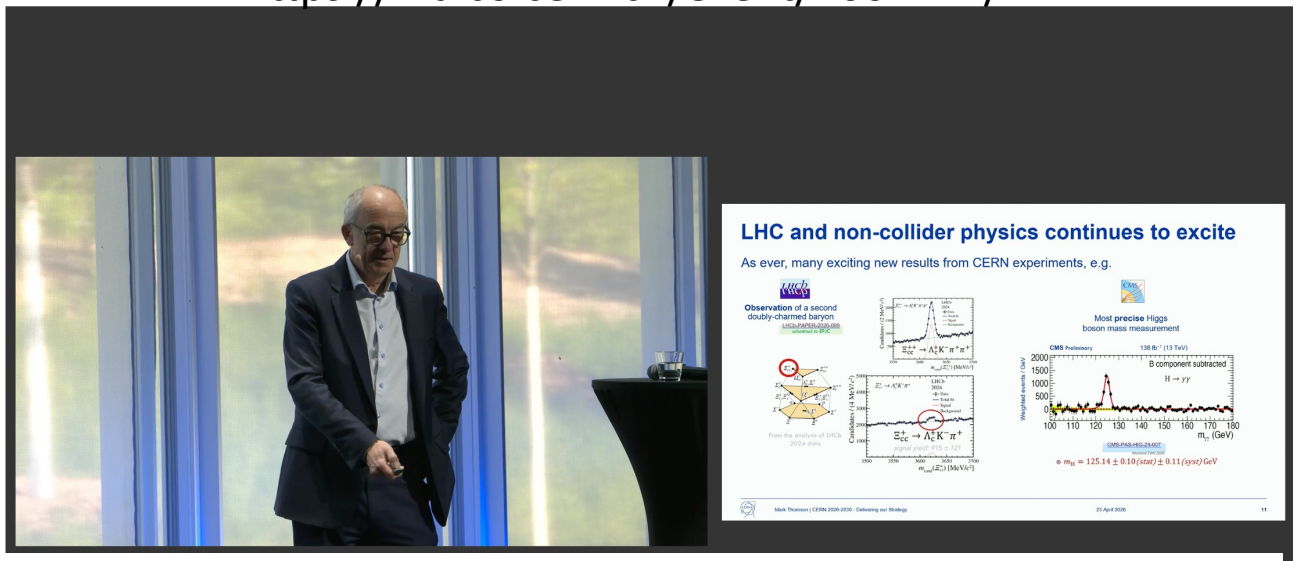

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"This major result is a fantastic example of how LHCb's unique capabilities play a vital role in the success of the LHC," says Mark Thomson, CERN Director-General. "It highlights how experimental upgrades at CERN directly lead to new discoveries, setting the stage for the transformative science we expect from the High-Luminosity LHC. These achievements are only possible thanks to the exceptional performance of CERN's accelerator complex and the teams who make it all work and to the commitment of the scientists on the LHCb experiment."

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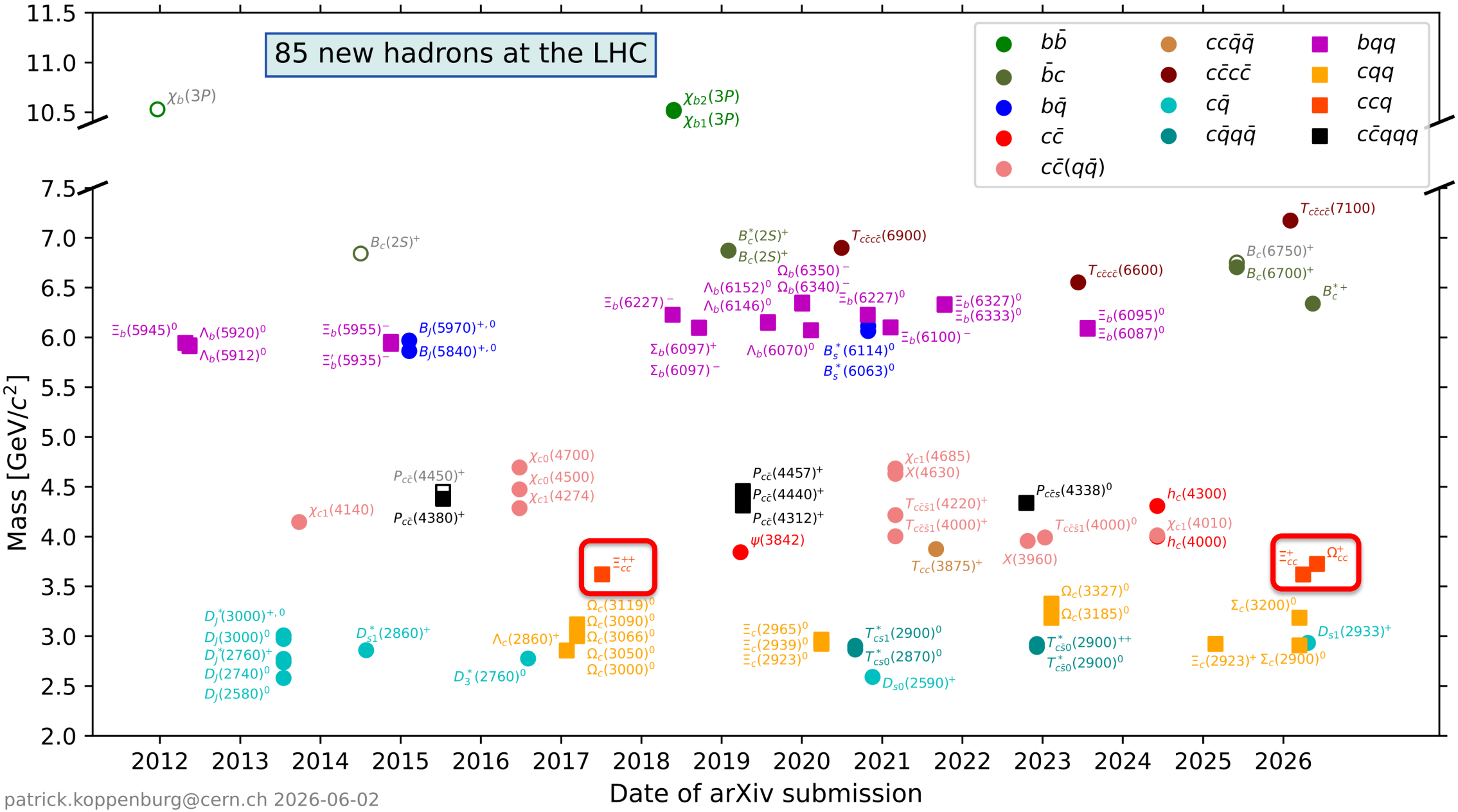
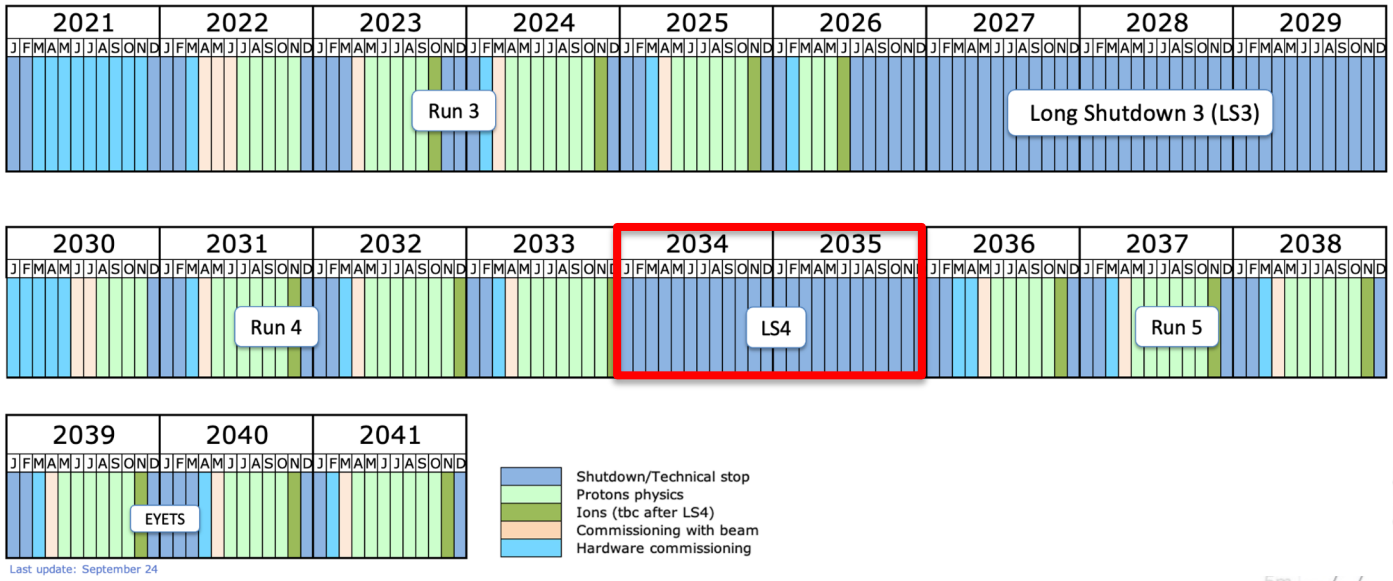
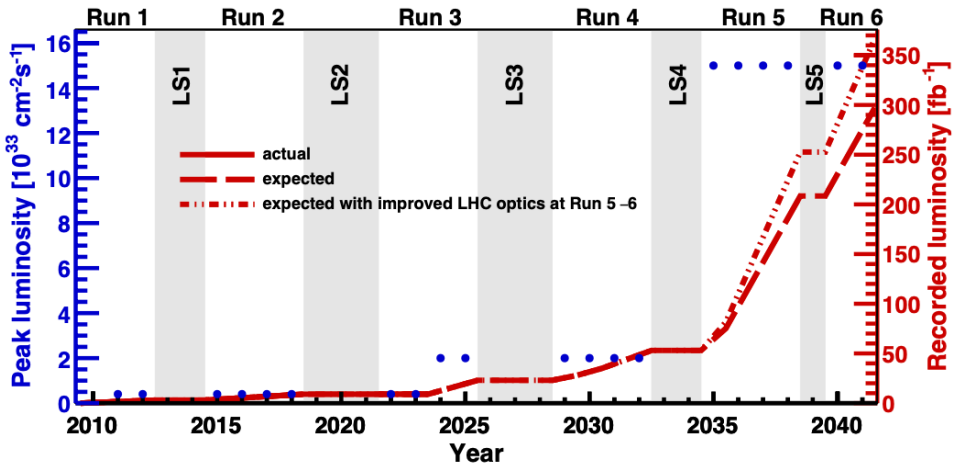
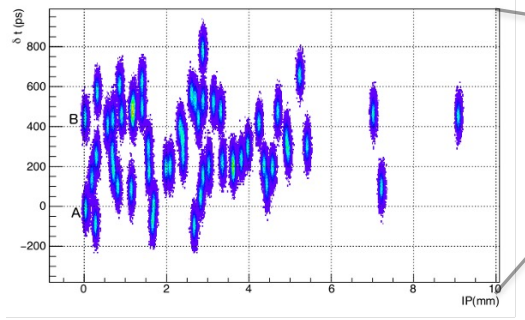

85 new hadrons at the LHC
$b\bar{b}$
$\bar{b}c$
$b\bar{q}$
$c\bar{c}$
$c\bar{c}(q\bar{q})$
$cc\bar{q}\bar{q}$
$c\bar{c}c\bar{c}$
$c\bar{q}$
$c\bar{q}q\bar{q}$
bqq
cqq
ccq
$c\bar{c}qqq$
Mass [GeV/c^2]
Date of arXiv submission
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$B_c^*(2S)^+$
$T_{c\bar{c}c\bar{c}}(7100)$
$T_{c\bar{c}c\bar{c}}(6900)$
$T_{c\bar{c}c\bar{c}}(6600)$
$B_c(6750)^+$
$B_c(6700)^+$
B_c^{*+}
$\Xi_b(5945)^0$
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
$\Xi_b(5955)^-$
$\Xi_b'(5935)^-$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$\Xi_b(6227)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Xi_b(6227)^0$
$\Xi_b(6327)^0$
$\Xi_b(6333)^0$
$\Xi_b(6100)^-$
$\Xi_b(6095)^0$
$\Xi_b(6087)^0$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6070)^0$
$B_s^*(6114)^0$
$B_s^*(6063)^0$
$\chi_{c1}(4140)$
$P_{c\bar{c}}(4450)^+$
$P_{c\bar{c}}(4380)^+$
$\chi_{c0}(4700)$
$\chi_{c0}(4500)$
$\chi_{c1}(4274)$
$P_{c\bar{c}}(4457)^+$
$P_{c\bar{c}}(4440)^+$
$P_{c\bar{c}}(4312)^+$
$\psi(3842)$
$\chi_{c1}(4685)$
$X(4630)$
$T_{c\bar{c}s1}(4220)^+$
$T_{c\bar{c}s1}(4000)^+$
$T_{cc}(3875)^+$
$P_{c\bar{c}s}(4338)^0$
$T_{c\bar{c}s1}(4000)^0$
$X(3960)$
$h_c(4300)$
$\chi_{c1}(4010)$
$h_c(4000)$
Ξ_{cc}^{++}
Ξ_{cc}^+
Ω_{cc}^+
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$D_{s1}^*(2860)^+$
$\Lambda_c(2860)^+$
$D_3^*(2760)^0$
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Xi_c(2965)^0$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
$T_{cs1}^*(2900)^0$
$T_{cs0}^*(2870)^0$
$D_{s0}(2590)^+$
$\Omega_c(3327)^0$
$\Omega_c(3185)^0$
$T_{c\bar{s}0}^*(2900)^{++}$
$T_{c\bar{s}0}^*(2900)^0$
$\Sigma_c(3200)^0$
$D_{s1}(2933)^+$
$\Xi_c(2923)^+$ $\Sigma_c(2900)^0$

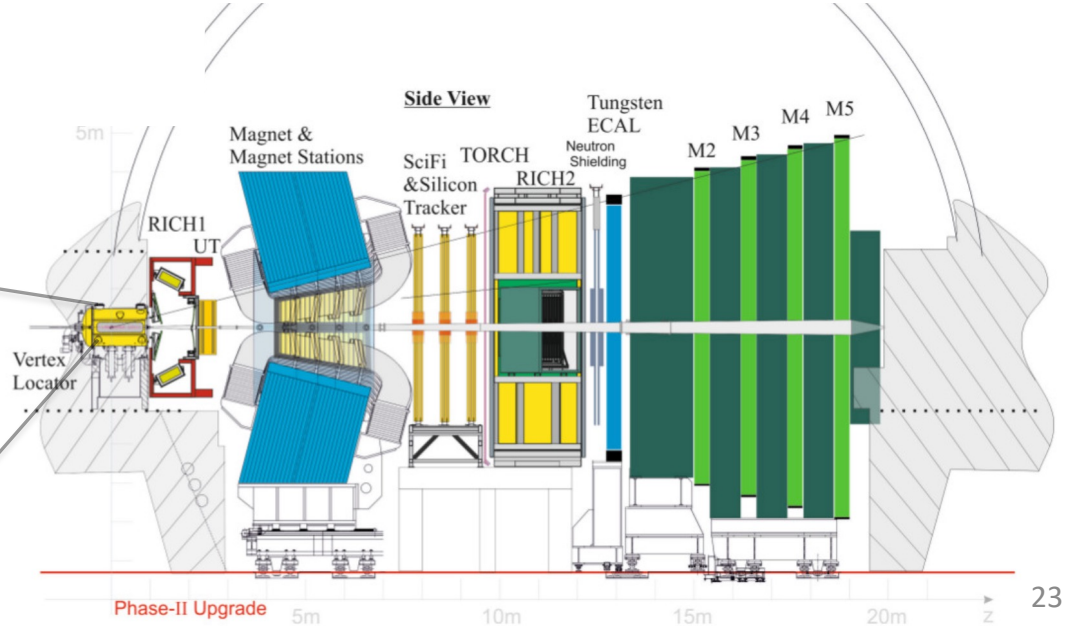
The LHCb upgrades

[CERN-LHCC-2018-027, 2021-012]





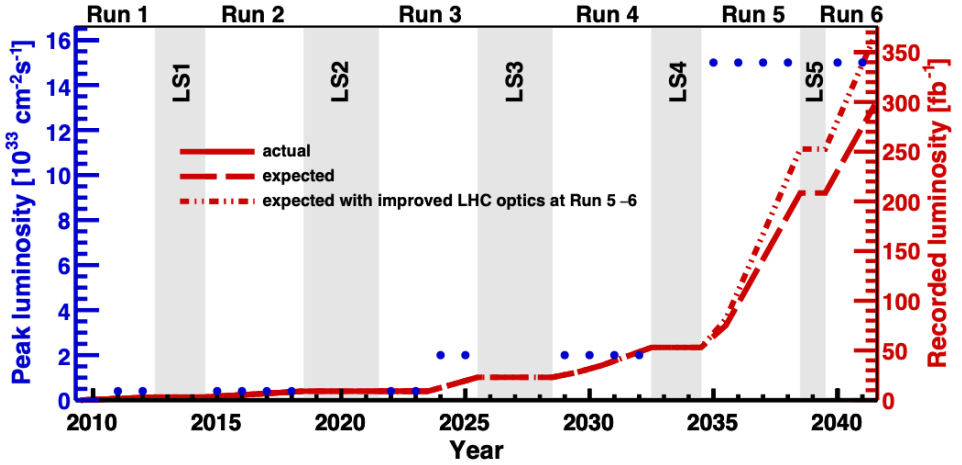


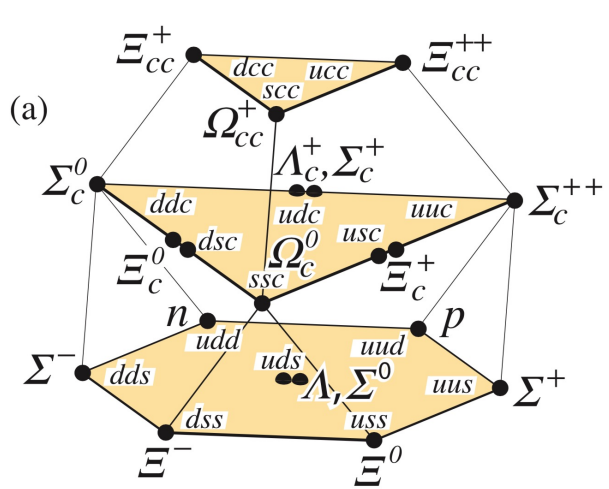


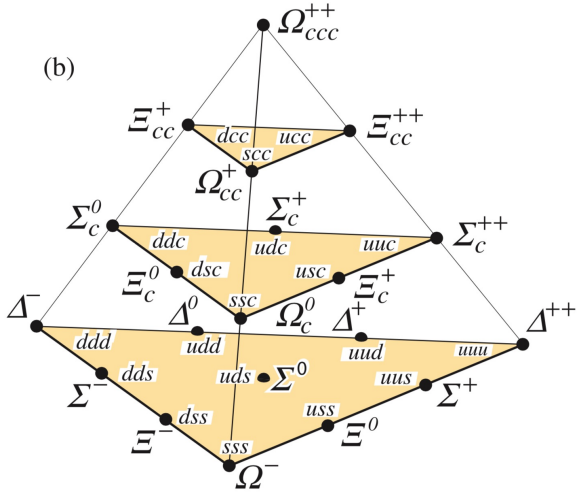
Upgrade II, 4D detector ,
Timing, $\mathcal{O}(10\ \text{ps})$, is essential

Prospects

- LHCb ($9\ \mathrm{fb}^{-1}$)
  - Ξ_{cc}^{++} >1000 signal
  - Ξ_{cc}^{+} Evidence
  - Ω_{cc}^{+} Hint
- LHCb Upgrade ($50\ \mathrm{fb}^{-1}$)
  - Ξ_{cc}^{++} $\mathcal{O}(10\mathrm{k})$ signal, excited states?
  - Ξ_{cc}^{+} $\mathcal{O}(1\mathrm{k})$ signal
  - Ω_{cc}^{+} Observation
- LHCb Upgrade-II ($300\ \mathrm{fb}^{-1}$)
  - Ω_{ccc}^{++}?







Summary

- Upgraded LHCb detector and trigger, efficiency of hadronic modes increased by a factor 2-4!
- Ξ_{cc}^{++}: a factor of 4 sginal yield per fb^{-1}, compared w/ Run2
- Ξ_{cc}^{+}: First new particle observed w/ the upgraded LHCb detector
  - $M(\Xi_{cc}^{+}) = 3619.97 \pm 0.83 \pm 0.26^{+1.90}_{-1.30}\ \mathrm{MeV}/c^2$
  - $M(\Xi_{cc}^{+}) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84 \pm 0.25^{+1.90}_{-1.30}\ \mathrm{MeV}/c^2$
- Ω_{cc}^{+}: observation
  - $M(\Omega_{cc}^{+}) = 3725.9 \pm 1.0 \pm 0.2 \pm 0.4\ (\tau) \pm 0.6\ (\mathrm{ext})\ \mathrm{MeV}/c^2$
- Many thanks to your continued and strong supports