



Открытие дважды- очарованных барионов экспериментом LHCb

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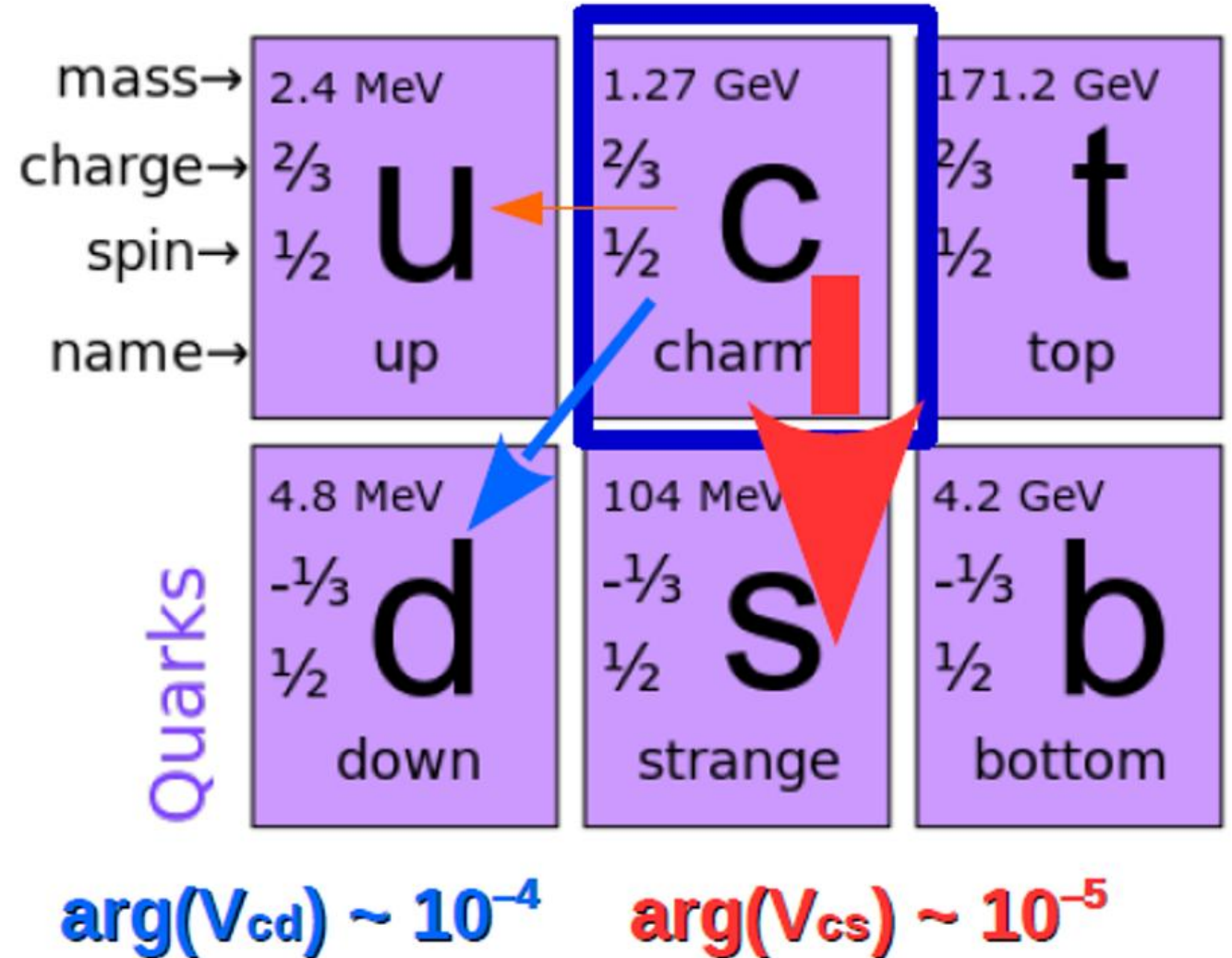
Семинар ОФВЭ

Аннотация

- Систематика адронов на основе группы симметрии SU(4) по кварковым ароматам предполагает наличие 20-плета барионов со спином 1/2. По состоянию на 2015 год были экспериментально обнаружены все состояния 20-плета, кроме дважды очарованных.
- В 2017 году эксперимент LHCb на Большом адронном коллайдере (БАК) объявил о регистрации бариона Ξ_{cc}^{++} . В дальнейшем было открыто несколько каналов распада этого адрона и измерено среднее время его жизни.
- Эти измерения, а также прецизионные измерения времен жизни барионов с одиночным очарованием, позволили оптимизировать критерии отбора событий для поиска частиц Ξ_{cc}^{+} и Ω_{cc}^{+} .
- Ξ_{cc}^{+} и Ω_{cc}^{+} , были обнаружены в 2026 году в результате обработки данных третьего сеанса работы БАК.

Outline

- Baryon states in SU(4) flavor symmetry model
 - SU(2) \rightarrow SU(3) \rightarrow SU(4)
- LHCb (including Upgrade-I)
- Discovery of Ξ_{cc}^{++}
- Lifetime measurements
- Discovery of Ξ_{cc}^+
- Discovery of Ω_{cc}^+



$$SU(2) \rightarrow SU(3) \rightarrow SU(4)$$

Reliable prediction tools

Symmetries and conservation laws

$\psi \rightarrow \psi' = \hat{U} \psi$ Let laws of nature are invariant under some transformation (**symmetrical**)

$$\langle \psi | \psi \rangle = \langle \psi' | \psi' \rangle = \langle \hat{U} \psi | \hat{U} \psi \rangle = \langle \psi | \hat{U}^\dagger \hat{U} | \psi \rangle$$

$$\rightarrow \boxed{\hat{U}^\dagger \hat{U} = 1}$$

To keep normalization of the wave function corresponding operator must have unitarity property

$$\langle \psi | \hat{H} | \psi \rangle = \langle \psi' | \hat{H} | \psi' \rangle = \langle \psi | \hat{U}^\dagger \hat{H} \hat{U} | \psi \rangle \quad \hat{U}^\dagger \hat{H} \hat{U} = \hat{H}$$

Therefore it should commute with the Hamiltonian operator.

$$\hat{U} \hat{U}^\dagger \hat{H} \hat{U} = \hat{U} \hat{H} \quad \rightarrow \quad \hat{H} \hat{U} = \hat{U} \hat{H} \quad \boxed{[\hat{H}, \hat{U}] = 0}$$

Generator of transformation

$$\hat{U} = 1 + i\varepsilon \hat{G} \quad \hat{U} \hat{U}^\dagger = (1 + i\varepsilon \hat{G})(1 - i\varepsilon \hat{G}^\dagger) = 1 + i\varepsilon(\hat{G} - \hat{G}^\dagger) + \cancel{O(\varepsilon^2)}$$

$$[\hat{H}, \hat{U}] = 0 \quad \Rightarrow \quad [\hat{H}, 1 + i\varepsilon \hat{G}] = 0 \quad \Rightarrow \quad [\hat{H}, \hat{G}] = 0$$

$$\frac{d}{dt} \langle \hat{G} \rangle = i \langle [\hat{H}, \hat{G}] \rangle = 0$$

Schoedinger equation requires **conservation of some property**

Symmetry of L_{QCD}

$= m_q$ Small wrt QCD scale parameter

$$m_u \approx m_d \ll m_s \ll m_c \ll m_b \ll m_t.$$



$$L_{\text{QCD}}(x) = -\frac{1}{4}G^{\mu\nu a}(x)G_{\mu\nu}^a(x) + \sum_{q=u,d} \bar{\psi}_{q\alpha}(i\gamma^\mu D_{\mu(\alpha\beta)} - I\delta_{\alpha\beta}m_q)\psi_{q\beta},$$

$$D_{\mu(\alpha\beta)} = \delta_{\alpha\beta}\partial_\mu - ig_s\frac{\lambda_{\alpha\beta}^a}{2}B_\mu^a(x).$$

- One can construct additional bi-spinor:
- Which U remain L_{QCD} unchanged?
- Unitarity!
- Skip phase \rightarrow SU(2)

$$\psi_\alpha(x) = \begin{pmatrix} \psi_{u\alpha}(x) \\ \psi_{d\alpha}(x) \end{pmatrix} = \begin{pmatrix} \psi^1 \\ \psi^2 \end{pmatrix}.$$

$$\phi^i(x) = \hat{U}_j^i \psi^j(x) \quad \longrightarrow \quad \bar{\phi}_i(x) = (U_i^l)^* \bar{\psi}_l(x),$$

$$\bar{\phi}_{j\alpha}(x)(i\gamma^\mu D_{\mu(\alpha\beta)} - I\delta_{\alpha\beta}m_q)\phi_\beta^j(x) = \bar{\psi}_{l\alpha}(x)(i\gamma^\mu D_{\mu(\alpha\beta)} - I\delta_{\alpha\beta}m_q)(U_i^l)^*(U_j^i)\psi_\beta^j(x).$$

$$(U_i^l)^*(U_j^i) = \delta_j^l \quad \Leftrightarrow \quad \hat{U}^\dagger \hat{U} = \hat{1}, \quad \det \hat{U} = e^{i\xi}.$$

$$L_{\text{QCD}}(x) = -\frac{1}{4}G^{\mu\nu a}(x)G_{\mu\nu}^a(x) + \bar{\psi}_{j\alpha}(x)(i\gamma^\mu D_{\mu(\alpha\beta)} - I\delta_{\alpha\beta}m_q)\psi_\beta^j(x).$$

- Conservations of corresponding current and charge

$$j_i^\mu(x) = \bar{\psi}(x)\tau_i\gamma^\mu\psi(x).$$

$$Q_i(t) = \int_V d\vec{x} j_i^0(x)$$

Isospin

$$V_{pp} \approx V_{np} \approx V_{nn}$$

Strong nuclear forces are charge independent

1932 Heisenberg propose that if one could “switch-off” of electromagnetic interaction proton and neutron would be not distinguishable

$$p = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad n = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

Two states (**proton** and **neutron**), but one entity (**nucleon**) → **ISOSPIN concept**
Iso-doublet with isospin=1/2 and its projections = +/- 1/2

Laws of physics of strong nuclear forces are invariant under rotation in the isospin space

This is approximate symmetry which is broken by electromagnetic interactions, so one can distinguish between proton and neutron

At quark level isospin projections corresponds to a doublet of two light quarks

$$u = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad d = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

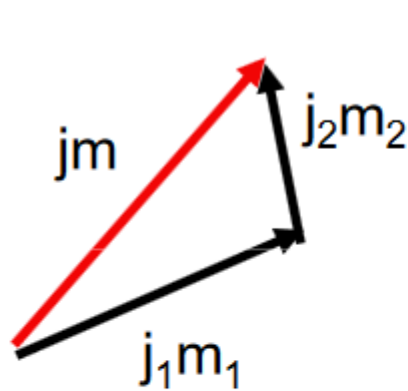
Generator of the group are Pauli matrices and math is almost identical to the math for the spin-1/2 states (**SU(2)** symmetry)

$$\begin{pmatrix} u' \\ d' \end{pmatrix} = \hat{U} \begin{pmatrix} u \\ d \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}$$

$$|S, m\rangle \longrightarrow |I, I_3\rangle \quad T^2 |I, I_3\rangle = I(I+1) |I, I_3\rangle \quad T_3 |I, I_3\rangle = I_3 |I, I_3\rangle$$

Best predictive tool for strong interaction sector of the Standard Model!

Strong force driven decays and CG coefficients



$$|j_1 j_2 j m\rangle = \sum_{m_1 m_2} C_{j_1 m_1 j_2 m_2}^{j m} |j_1 m_1 j_2 m_2\rangle = \sum_{m_1 m_2} (j_1 m_1 j_2 m_2 | j m) |j_1 m_1 j_2 m_2\rangle;$$

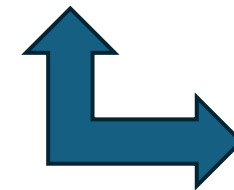
$$|j_1 m_1 j_2 m_2\rangle = \sum_{j m} C_{j_1 m_1 j_2 m_2}^{j m} |j_1 j_2 j m\rangle = \sum_{j m} (j_1 m_1 j_2 m_2 | j m) |j_1 m_1 j_2 m_2\rangle$$

<http://pdg.lbl.gov/2011/reviews/rpp2011-rev-clebsch-gordan-coefs.pdf>

Particle Data Group tables:

$$|j_1 - j_2| \leq j \leq j_1 + j_2;$$

$$m = m_1 + m_2$$



Notation:		J	J	...
		M	M	...
m ₁	m ₂	Coefficients		
m ₁	m ₂			
.	.			
.	.			

Applicable to spin and to isospin

K* decay into pion and kaon

Decay amplitudes →

Charged decay channel

Neutral decay channel

1 × 1/2		3/2		
	+3/2	3/2	1/2	
+1	+1/2	1	+1/2	+1/2
	+1	2/3	1/3	2/3
	0 + 1/2	2/3	-1/3	

Isospin of K*

Isospin projection

Don't forget square root!!

Note: A square-root sign is to be understood over every coefficient, e.g., for $-8/15$ read $-\sqrt{8/15}$.

Isospin operator; ladder operators

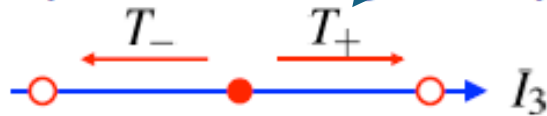
$$\vec{T} = \frac{1}{2} \vec{\sigma} \quad \hat{U} = e^{i\vec{\alpha} \cdot \vec{T}}$$

$$[T_1, T_2] = iT_3 \quad [T_2, T_3] = iT_1 \quad [T_3, T_1] = iT_2$$

$$[T^2, T_3] = 0 \quad T^2 = T_1^2 + T_2^2 + T_3^2$$

$$T_- \equiv T_1 - iT_2$$

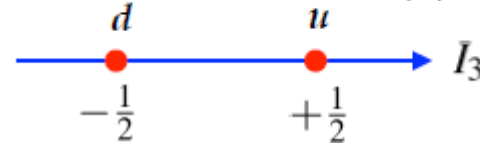
u → d



$$T_+ |I, I_3\rangle = \sqrt{I(I+1) - I_3(I_3+1)} |I, I_3+1\rangle$$

$$T_- |I, I_3\rangle = \sqrt{I(I+1) - I_3(I_3-1)} |I, I_3-1\rangle$$

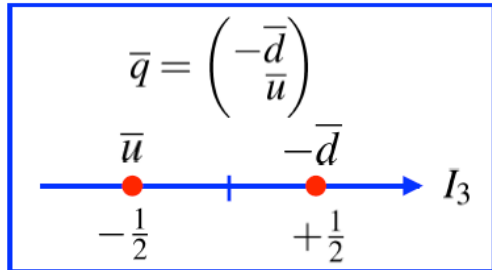
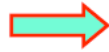
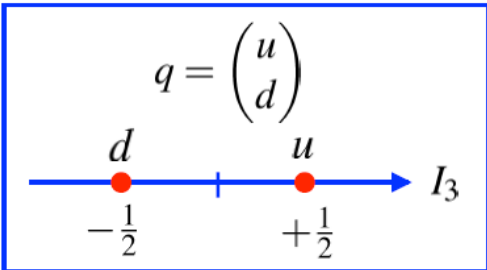
$$u = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = |\frac{1}{2}, +\frac{1}{2}\rangle \quad d = \begin{pmatrix} 0 \\ 1 \end{pmatrix} = |\frac{1}{2}, -\frac{1}{2}\rangle$$



$$I = \frac{1}{2}, \quad I_3 = \pm \frac{1}{2}$$

$$T_+ \equiv T_1 + iT_2$$

d → u



$$\bar{u} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\bar{d} = -\begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

One can take one state (for example meson), apply ladder operator and construct full set of states (meson multiplet)

$$T_+ \bar{u} = T_+ \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = -\bar{d}$$

$$T_+ \bar{u} = -\bar{d} \quad T_+ \bar{d} = 0 \quad T_- \bar{u} = 0 \quad T_- \bar{d} = -\bar{u}$$

$$T_+ u = 0 \quad T_+ d = u \quad T_- u = d \quad T_- d = 0$$

Prediction of neutral pion!

Pions

Isospin representation
for antiquarks

$$|1, +1\rangle = \left| \frac{1}{2}, +\frac{1}{2} \right\rangle \overline{\left| \frac{1}{2}, +\frac{1}{2} \right\rangle} = -u\bar{d}$$

$$|1, -1\rangle = \left| \frac{1}{2}, -\frac{1}{2} \right\rangle \overline{\left| \frac{1}{2}, -\frac{1}{2} \right\rangle} = d\bar{u}$$

Charged pions

$$I_3 = 0 \quad T_- |1, +1\rangle = T_- [-u\bar{d}]$$

$$\sqrt{2}|1, 0\rangle = -T_- [u]\bar{d} - uT_- [\bar{d}]$$

$$= -d\bar{d} + u\bar{u}$$

Also worked for Σ^0
prediction from properties
of charged Σ states

$$\Rightarrow |1, 0\rangle = \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d}) \quad \text{Neutral pion}$$

$$|0, 0\rangle = \frac{1}{\sqrt{2}} (u\bar{u} + d\bar{d}) \quad \leftarrow ??$$

There were too many candidates into a pseudoscalar singlet.
Some of them belongs to a so-called strange particles.
What to do with this “zoo” keeping idea of symmetry?

SU(3) flavor symmetry

$$\begin{pmatrix} u' \\ d' \\ s' \end{pmatrix} = \hat{U} \begin{pmatrix} u \\ d \\ s \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} & U_{13} \\ U_{21} & U_{22} & U_{23} \\ U_{31} & U_{32} & U_{33} \end{pmatrix} \begin{pmatrix} u \\ d \\ s \end{pmatrix}$$

$$\vec{T} = \frac{1}{2} \vec{\lambda} \quad \hat{U} = e^{i\vec{\alpha} \cdot \vec{T}}$$

Let's add third (strange) quark: $m_s > m_u, m_d$

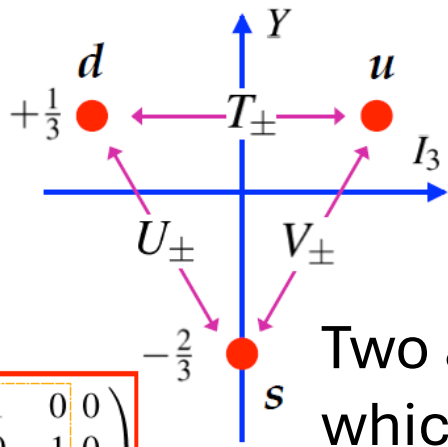
18 parameters, but the requirement of unitarity for U will bring us to 9 matrices of the **U(3) symmetry group**, one of which is trivial, and other **8 Hermitian matrices** forms **SU(3)** group

$$T_{\pm} = \frac{1}{2}(\lambda_1 \pm i\lambda_2)$$

$$V_{\pm} = \frac{1}{2}(\lambda_4 \pm i\lambda_5)$$

$$U_{\pm} = \frac{1}{2}(\lambda_6 \pm i\lambda_7)$$

$$I_3 = \frac{1}{2}\lambda_3 \quad Y = \frac{1}{\sqrt{3}}\lambda_8$$



Gell-Mann matrices are generators of the SU(3) group группы

Two additional ladder operators (U and V), which are analogous of the isospin ladder operator \rightarrow U- and V-spins

$$\boxed{u \leftrightarrow d} \quad \lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

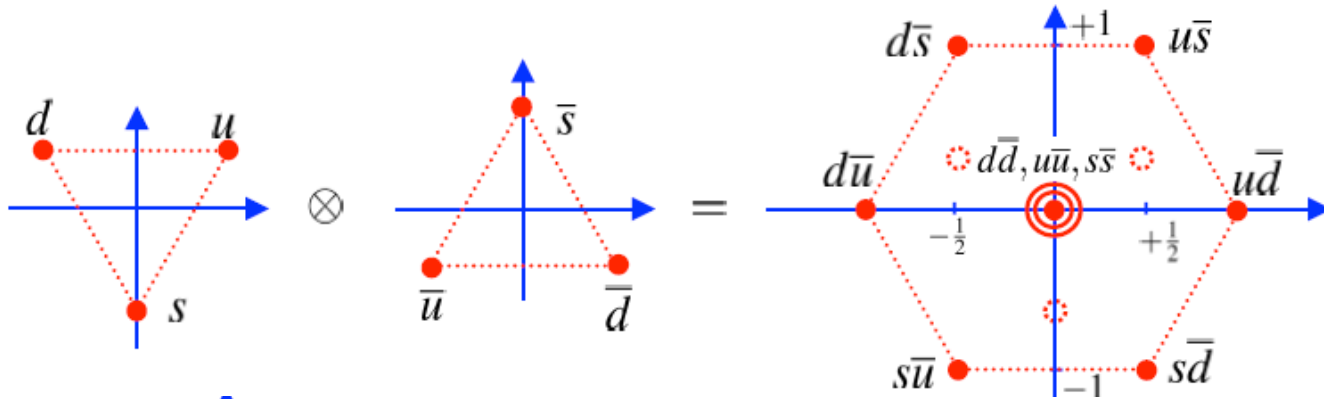
$$\boxed{u \leftrightarrow s} \quad \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

$$\boxed{d \leftrightarrow s} \quad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

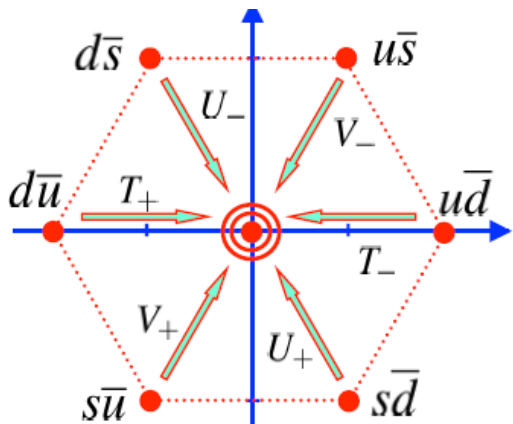
$$\lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

$$\begin{array}{ll} T_+ d = u; & T_- u = d; & T_+ \bar{u} = -\bar{d}; & T_- \bar{d} = -\bar{u} \\ V_+ s = u; & V_- u = s; & V_+ \bar{u} = -\bar{s}; & V_- \bar{s} = -\bar{u} \\ U_+ s = d; & U_- d = s; & U_+ \bar{d} = -\bar{s}; & U_- \bar{s} = -\bar{d} \end{array}$$

Mesons (octet and singlet flavor states)



- Three central have zero hypercharge and I_3 .
- Their wave functions can be found using ladder operators as orthogonal state.
- Applying (T, U and V) one can found six relation and using first as for neutral pion find another as orthogonal to it.



$$\begin{aligned}
 T_+ |d\bar{u}\rangle &= |u\bar{u}\rangle - |d\bar{d}\rangle & T_- |u\bar{d}\rangle &= |d\bar{d}\rangle - |u\bar{u}\rangle \\
 V_+ |s\bar{u}\rangle &= |u\bar{u}\rangle - |s\bar{s}\rangle & V_- |u\bar{s}\rangle &= |s\bar{s}\rangle - |u\bar{u}\rangle \\
 U_+ |s\bar{d}\rangle &= |d\bar{d}\rangle - |s\bar{s}\rangle & U_- |d\bar{s}\rangle &= |s\bar{s}\rangle - |d\bar{d}\rangle
 \end{aligned}$$

$$\psi_1 = \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d})$$

Neutral pion

$$\psi_2 = \alpha (|u\bar{u}\rangle - |s\bar{s}\rangle) + \beta (|d\bar{d}\rangle - |s\bar{s}\rangle)$$

$$\langle \psi_1 | \psi_2 \rangle = 0; \quad \langle \psi_2 | \psi_2 \rangle = 1$$



$$\psi_2 = \frac{1}{\sqrt{6}} (u\bar{u} + d\bar{d} - 2s\bar{s})$$



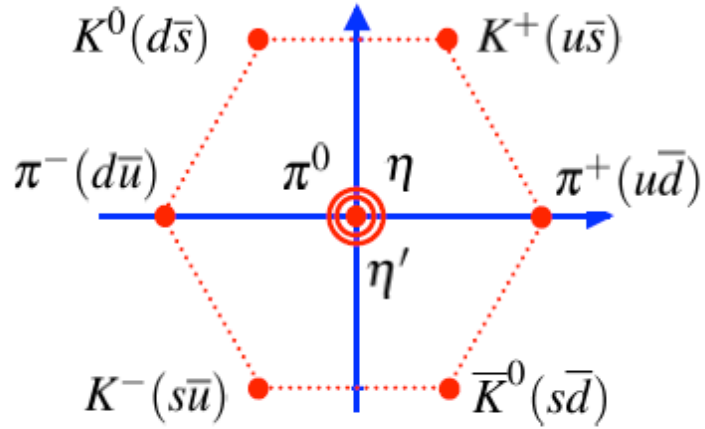
$$\psi_3 = \frac{1}{\sqrt{3}} (u\bar{u} + d\bar{d} + s\bar{s})$$

The last of nine states (**singlet one**) couldn't be found using ladder operators (it is not member of **octet**), but it could be found as orthofgoanl with respect to other wave functions of neutral mesons.

As SU(3) is approximate symmetry singlet and octet state can mix!

Pseudoscalar mesons

(L=0, S=0, J=0, P= -1)



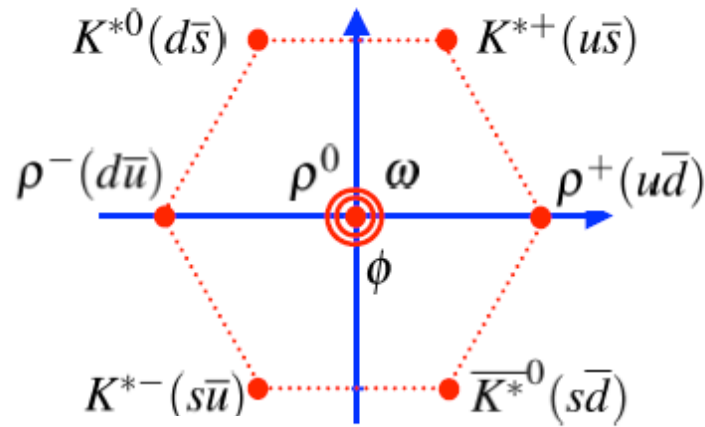
$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

$$\eta \approx \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

$$\eta' \approx \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s}) \leftarrow \text{singlet}$$

Vector mesons

(L=0, S=1, J=1, P= -1)



Symmetry is not precise and mixing between singlet and octet states is possible (introduced via mixing angle).

$$\rho^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$

$$\omega \approx \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

$$\phi \approx s\bar{s}$$

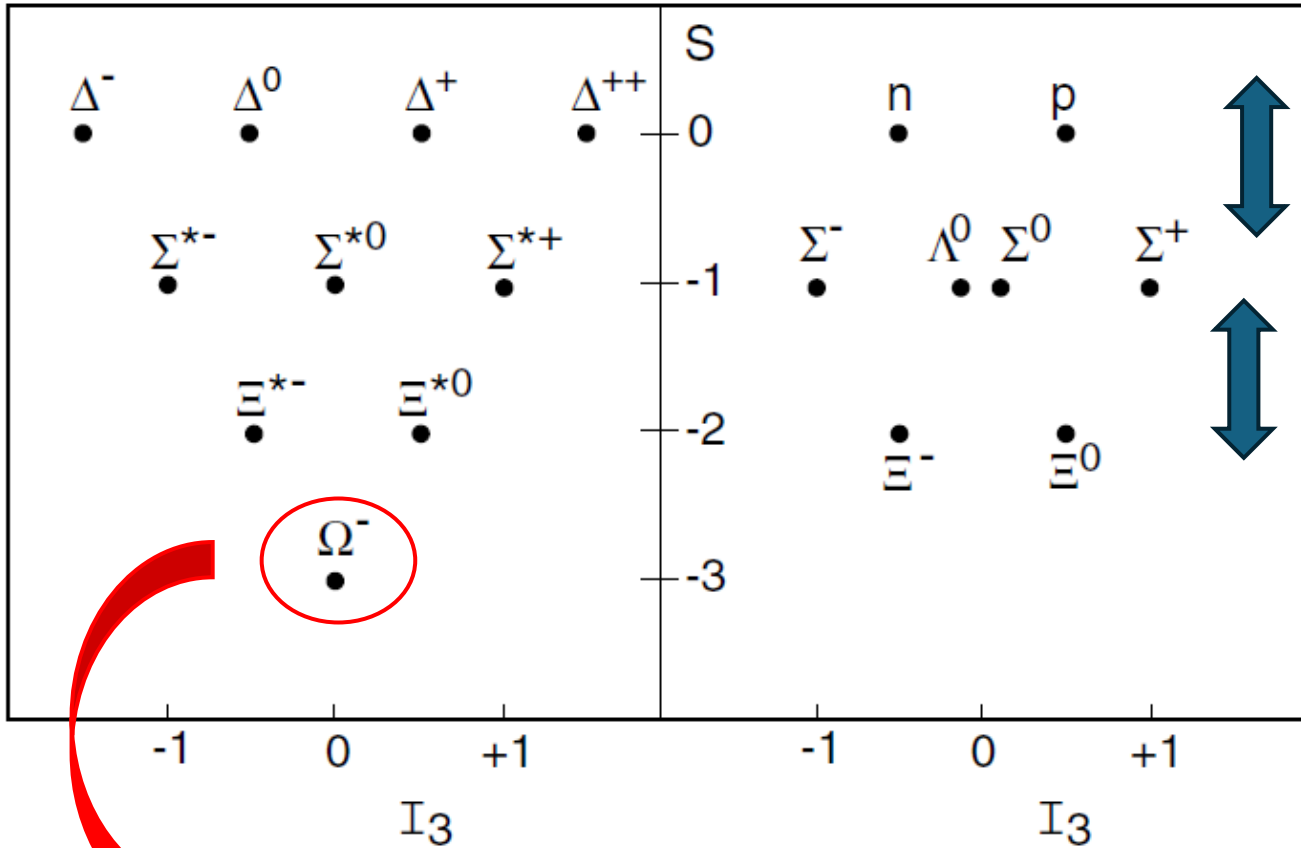
π^\pm : 140 MeV	π^0 : 135 MeV
K^\pm : 494 MeV	K^0/\bar{K}^0 : 498 MeV
η : 549 MeV	η' : 958 MeV

ρ^\pm : 770 MeV	ρ^0 : 770 MeV
$K^{*\pm}$: 892 MeV	K^{*0}/\bar{K}^{*0} : 896 MeV
ω : 782 MeV	ϕ : 1020 MeV

SU(3) flavor multiplets for baryons

$$J^P = \frac{3}{2}^+$$

$$J^P = \frac{1}{2}^+$$



Mass and decay chains were predicted at SU(3) basis

$$|\Delta^{++}\rangle = |u^\uparrow u^\uparrow u^\uparrow\rangle \quad |\Delta^+\rangle = |u^\uparrow u^\uparrow d^\uparrow\rangle \quad |\Delta^0\rangle = |u^\uparrow d^\uparrow d^\uparrow\rangle \quad |\Delta^-\rangle = |d^\uparrow d^\uparrow d^\uparrow\rangle$$

$$|\Sigma^{*+}\rangle = |u^\uparrow u^\uparrow s^\uparrow\rangle \quad |\Sigma^{*0}\rangle = |u^\uparrow d^\uparrow s^\uparrow\rangle \quad |\Sigma^{*-}\rangle = |d^\uparrow d^\uparrow s^\uparrow\rangle$$

$$|\Xi^{*0}\rangle = |u^\uparrow s^\uparrow s^\uparrow\rangle \quad |\Xi^{*-}\rangle = |d^\uparrow s^\uparrow s^\uparrow\rangle$$

$$|\Omega^-\rangle = |s^\uparrow s^\uparrow s^\uparrow\rangle.$$

Mass splitting due to m_s

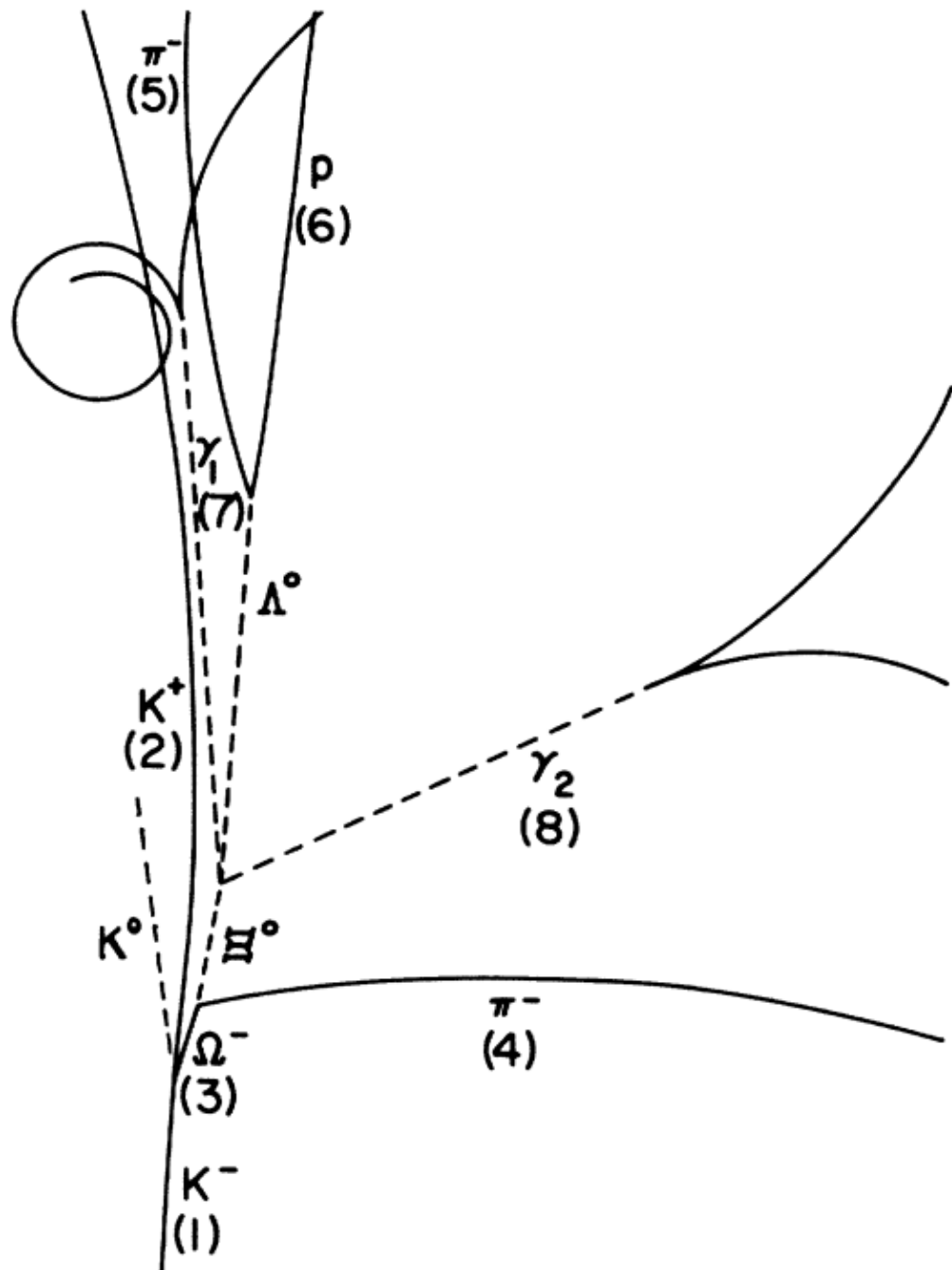
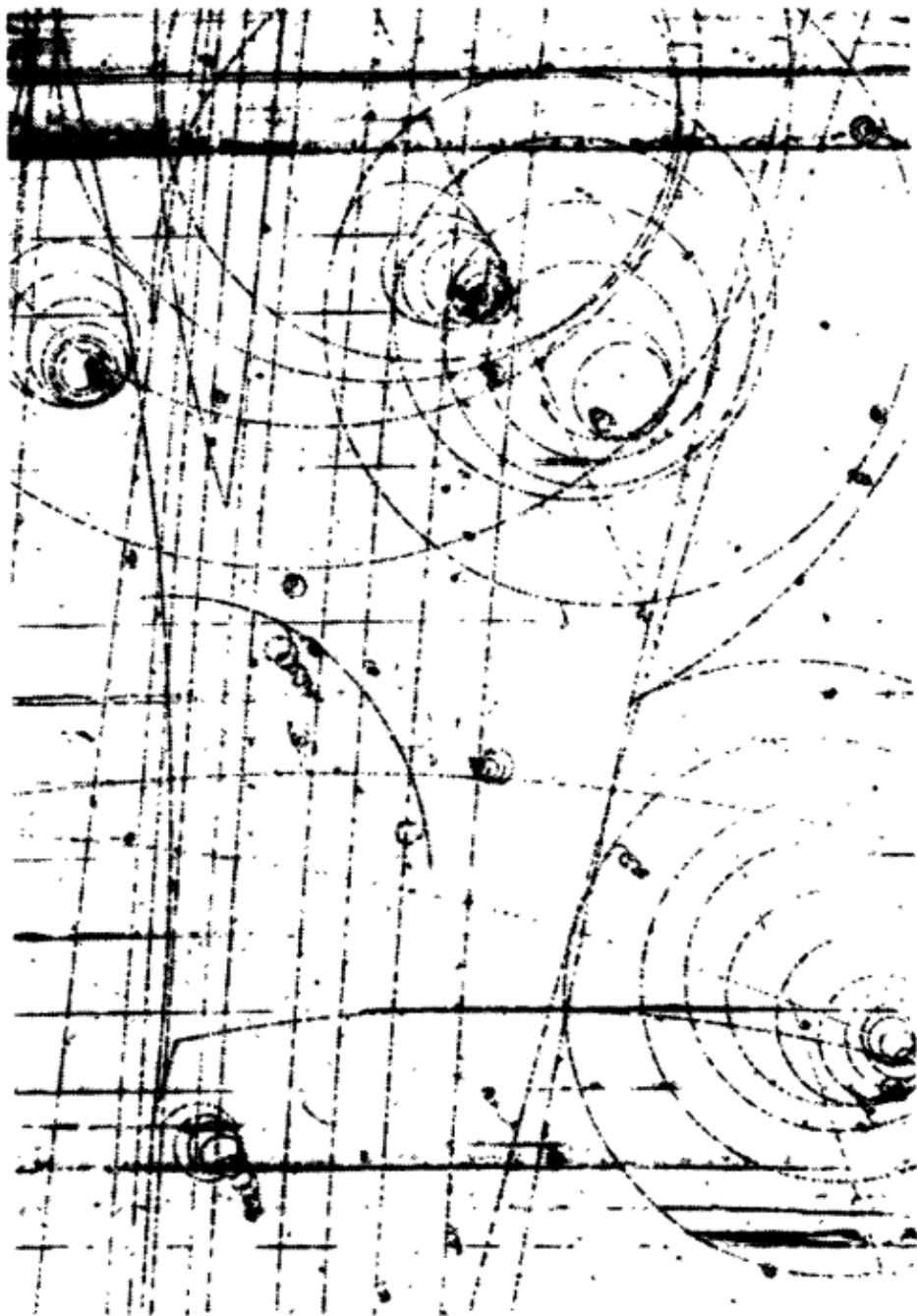
$$\psi_{\text{total}} = \xi_{\text{spatial}} \cdot \zeta_{\text{flavour}} \cdot \chi_{\text{spin}} \cdot \phi_{\text{colour}}$$

$$\phi_{\text{colour}} = \frac{1}{\sqrt{6}} \sum_{\alpha=r,g,b} \sum_{\beta=r,g,b} \sum_{\gamma=r,g,b} \epsilon_{\alpha\beta\gamma} |q_\alpha q_\beta q_\gamma\rangle$$

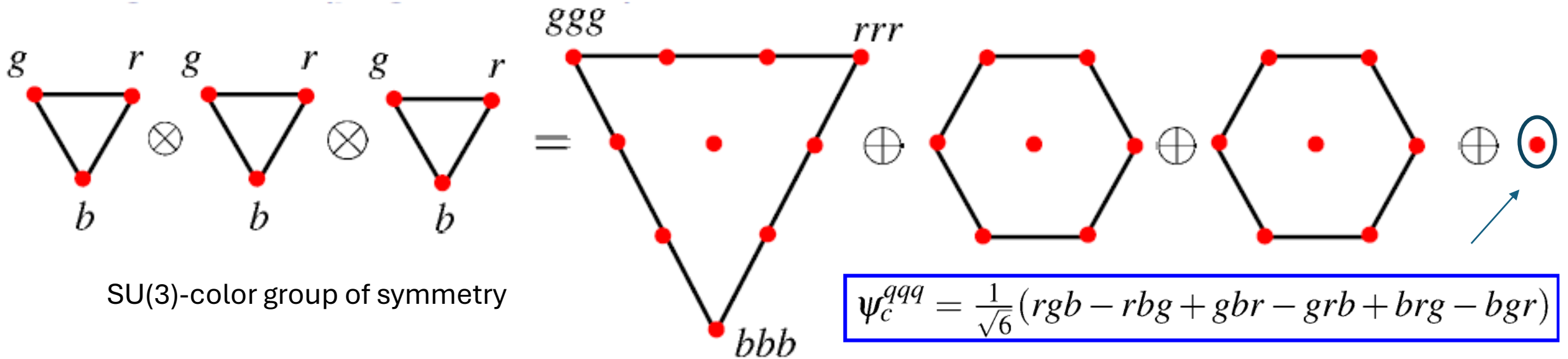
$$|\Sigma^{+\uparrow}\rangle = |u^\uparrow u^\uparrow s^\downarrow\rangle$$

$$|\Sigma^{0\uparrow}\rangle = |u^\uparrow d^\uparrow s^\downarrow\rangle \quad |\Lambda^{0\uparrow}\rangle = |u^\uparrow d^\downarrow s^\uparrow\rangle$$

$$|\Sigma^{-\uparrow}\rangle = |d^\uparrow d^\uparrow s^\downarrow\rangle.$$



Color singlet for baryon wave-function



To prove that this is indeed a singlet combination one can use ladder operators to show:

$$T_+ \psi_c^{qqq} = \frac{1}{\sqrt{6}} (rrb - rbr + rbr - rrb + brr - brr) = 0$$

$$T_- \psi_c^{qqq} = 0; \quad V_{\pm} \psi_c^{qqq} = 0; \quad U_{\pm} \psi_c^{qqq} = 0;$$

For which quark states color singlets are possible to construct?



$q\bar{q}, qqq$

Mesons and baryons



$q\bar{q}q\bar{q}, qqqq\bar{q}$

Tetraquarks and pentaquarks

Discovery of doubly charmed tetraquark

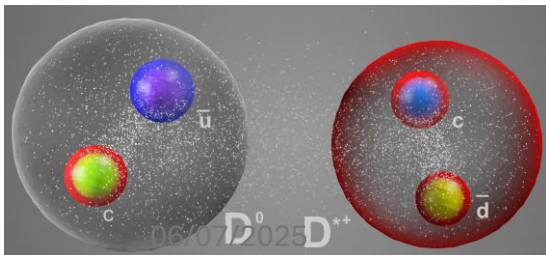
- Narrow resonance has been discovered in the mass spectrum of promptly produced system of $D^0 D^0 \pi^+$ mesons.
- Doubly charmed exotic resonance has a mass below $D^{*+} D^0$ threshold
- Minimal quark content [ccud](#).

Nature Physics **18**, 751–754 (2022)

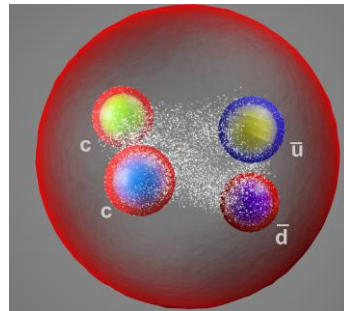
- More informatio:
 - Seminar of I.Belyaev ([video](#))
 - Seminar of V.Baru ([video](#))

Compact hadrocharmonium-like state

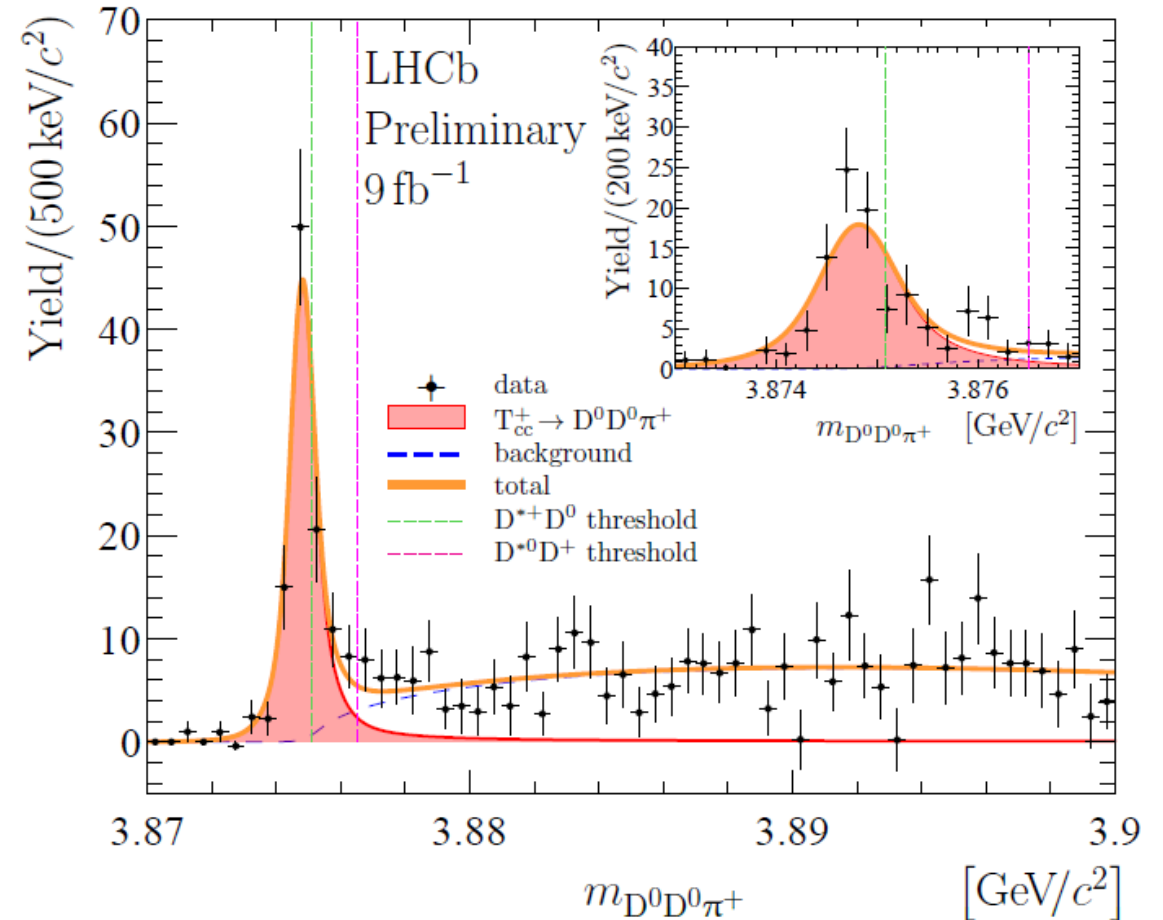
Hadronic molecule



or



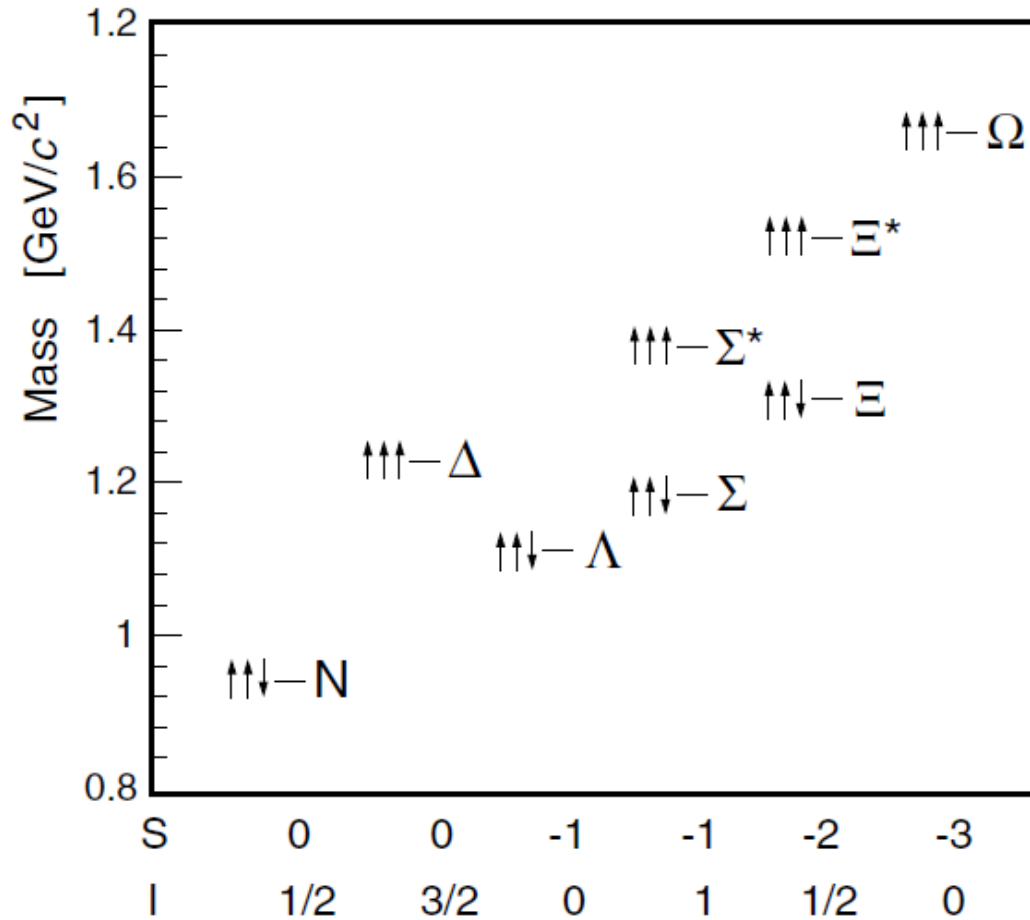
?



$D^0 D^0 \pi^+$ mass spectrum with the approximation. In addition T_{cc}^+ mass region is shown. Vertical lines corresponds to thresholds for production of pairs: $D^+ D^{*0}$ and $D^0 D^{*+}$

Baryon masses

In the constituent quark model masses of state are defined by masses of dressed quarks and spin-spin interaction



$$M = \sum_i m_i + \Delta M_{ss}.$$

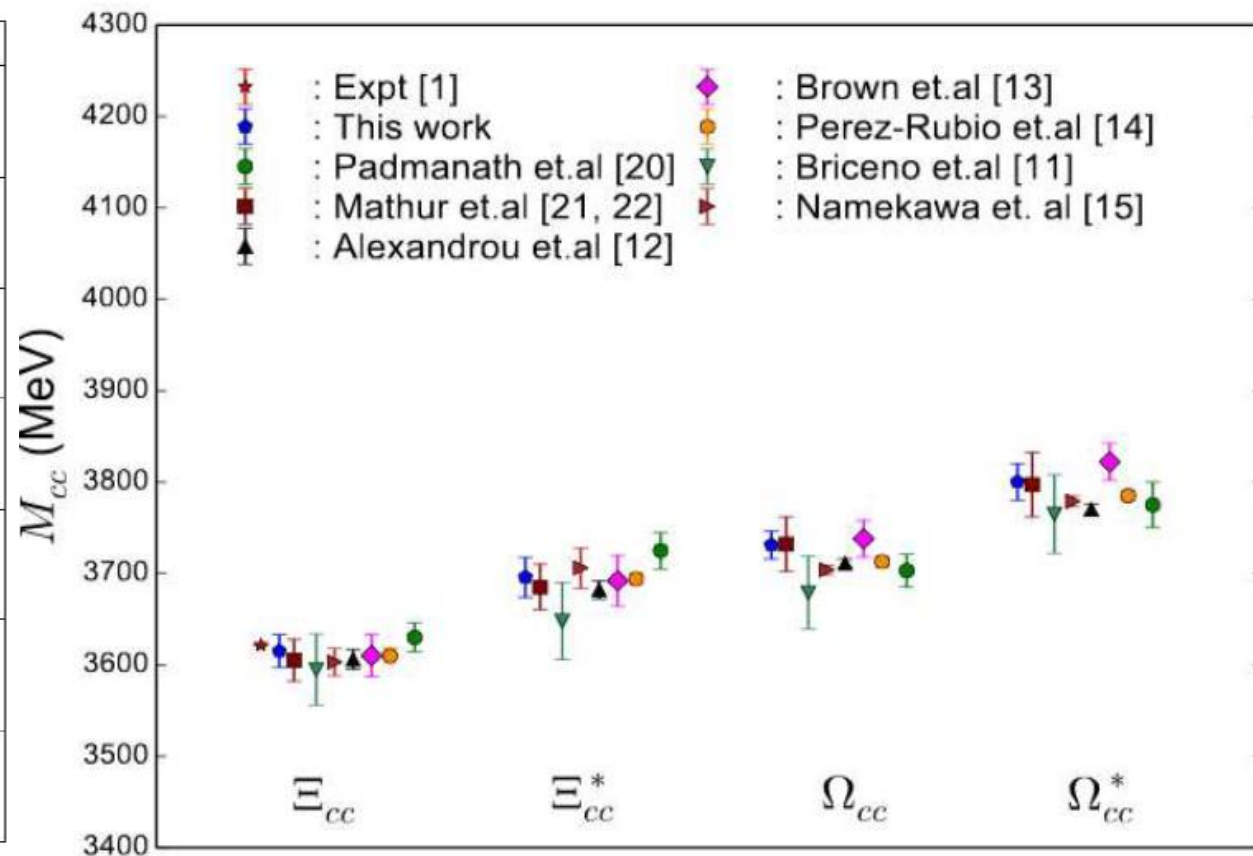
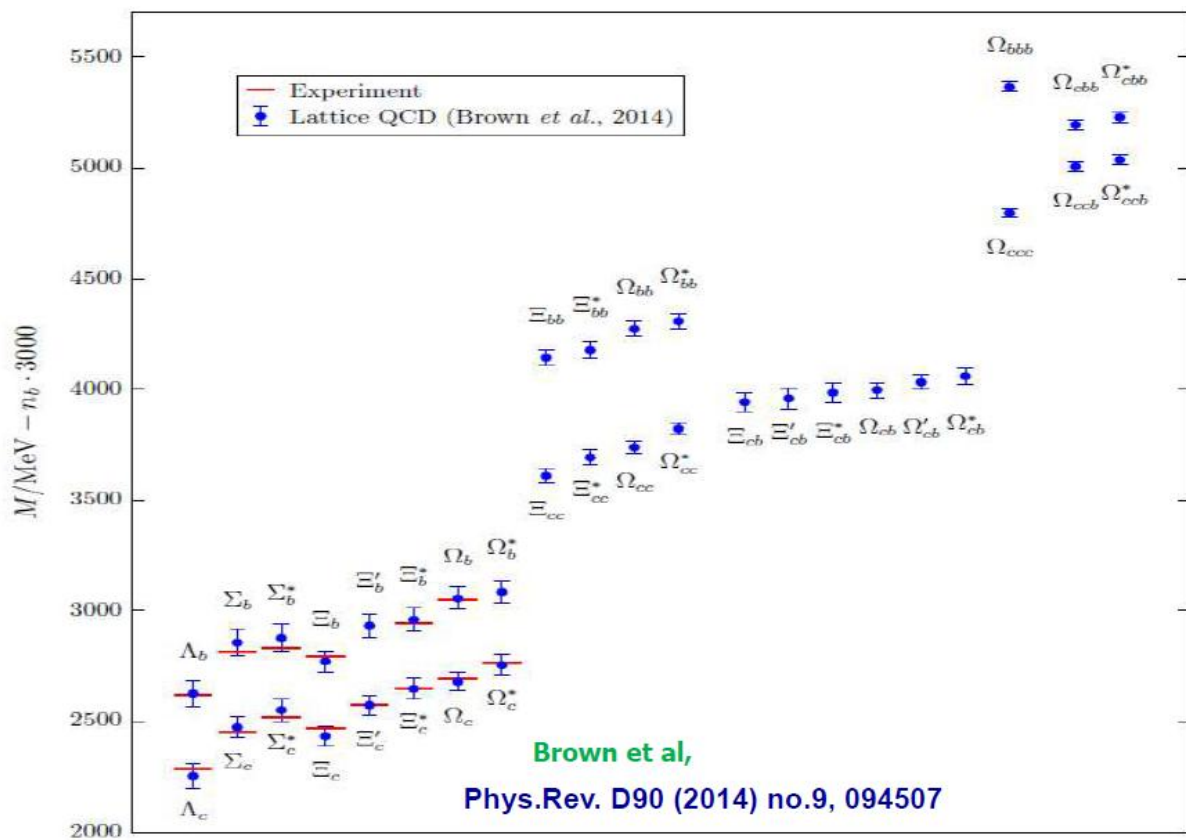
$$V_{ss}(q_i q_j) = \frac{4\pi \hbar^3}{9} \frac{\alpha_s}{c} \frac{\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j}{m_i m_j} \delta(\mathbf{x}),$$

$$\sum_{\substack{i,j=1 \\ i < j}}^3 \boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_j = \frac{4}{\hbar^2} \sum_{\substack{i,j=1 \\ i < j}}^3 \mathbf{s}_i \cdot \mathbf{s}_j = \begin{cases} -3 & \text{for } S = 1/2, \\ +3 & \text{for } S = 3/2. \end{cases}$$

$$\Delta M_{ss} = \begin{cases} -3 \cdot \frac{4 \hbar^3}{9} \frac{\pi \alpha_s}{c^3} \frac{1}{m_{u,d}^2} |\psi(0)|^2 & \text{for the nucleons,} \\ +3 \cdot \frac{4 \hbar^3}{9} \frac{\pi \alpha_s}{c^3} \frac{1}{m_{u,d}^2} |\psi(0)|^2 & \text{for the } \Delta \text{ states,} \\ +3 \cdot \frac{4 \hbar^3}{9} \frac{\pi \alpha_s}{c^3} \frac{1}{m_s^2} |\psi(0)|^2 & \text{for the } \Omega \text{ baryon.} \end{cases}$$

$$m_{u,d} \approx 363 \text{ MeV}/c^2, \quad m_s \approx 538 \text{ MeV}/c^2$$

Predictions from Lattice QCD



As before Charm-2017

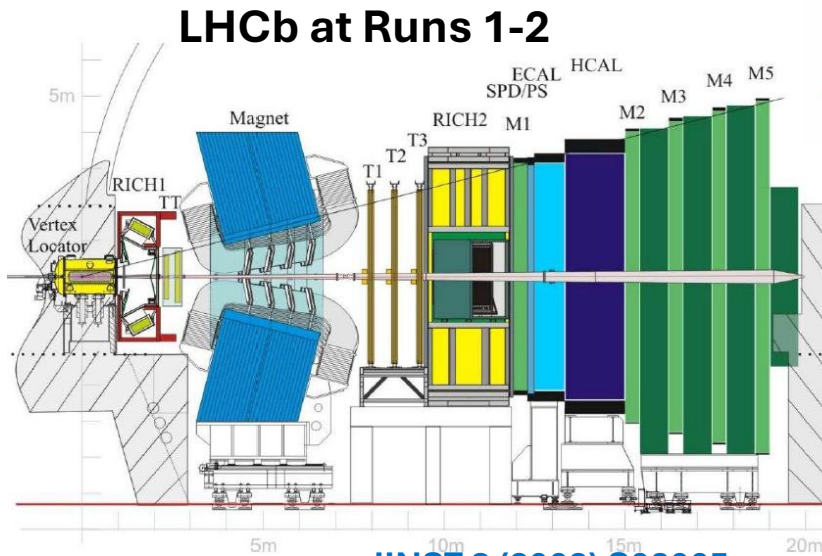
Ξ_{cc}^{++} - Lifetime

Reference	Ξ_{00}^{++} (ps)	Ξ_{00}^{+} (ps)	Ω_{00}^{+} (ps)
Karliner, Rosner, 2014	0.185	0.053	
Kiselev, Likhoded, Onishchenko, 1998	0.430 +/- 0.100	0.110 +/- 0.010	
Kiselev, Likhoded, 2002	0.460 +/- 0.050	0.160 +/- 0.050	0.270 +/- 0.060
Guberina, Melic, Stefancic, 1998	1.050	0.200	0.300
Chang, Li, Li, Wang, 2007	0.670	0.250	0.210

Three editions of LHCb

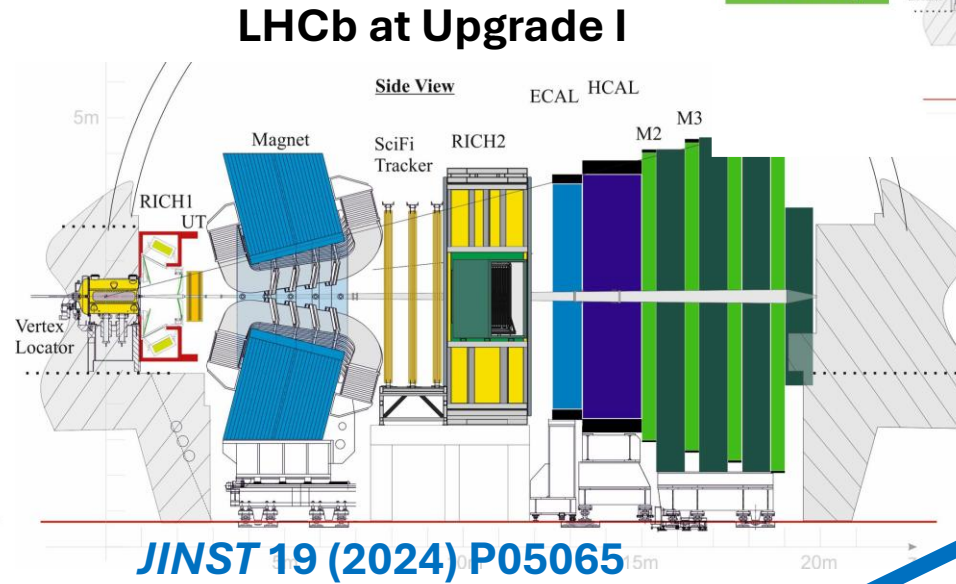
Three editions of LHCb

Consecutive efforts to attack challenges that higher luminosity measurements at forward region are bringing

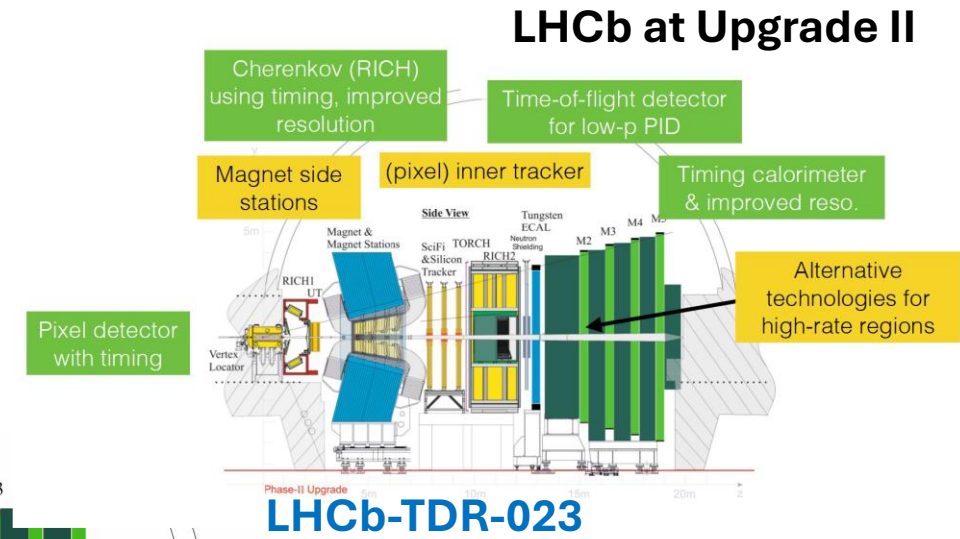


JINST 3 (2008) S08005

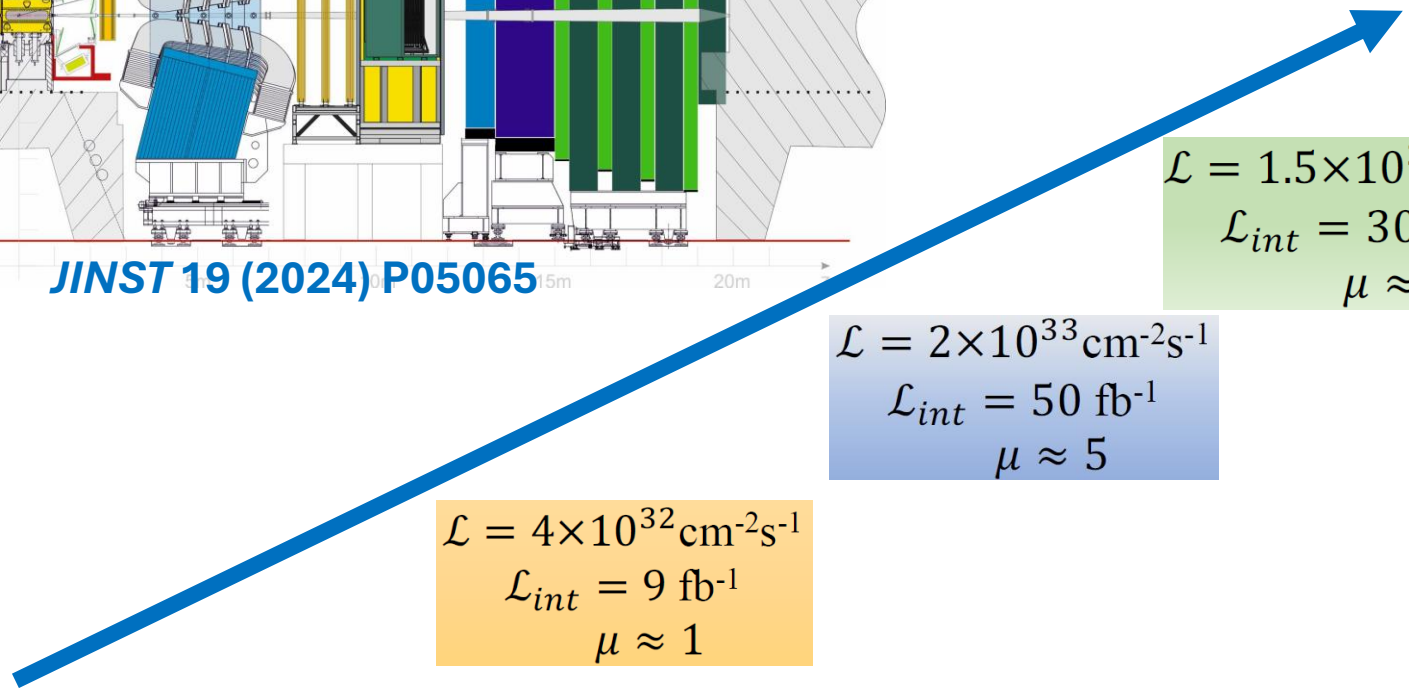
Int. J. Mod. Phys. A 30 (2015) 153022



JINST 19 (2024) P05065



LHCb-TDR-023



Luminosity

$$\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\mathcal{L}_{int} = 300 \text{ fb}^{-1}$$

$$\mu \approx 40$$

$$\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\mathcal{L}_{int} = 50 \text{ fb}^{-1}$$

$$\mu \approx 5$$

$$\mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\mathcal{L}_{int} = 9 \text{ fb}^{-1}$$

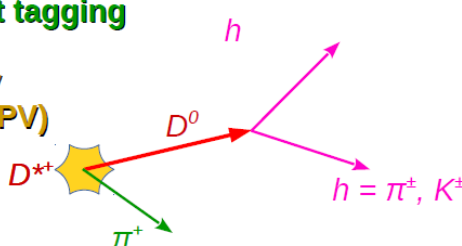
$$\mu \approx 1$$

Charm and beauty production into forward region

- Gluon fusion is main production mechanism for pairs of heavy (**c** & **b**) quark-antiquark pairs
- Produced charmed hadrons go together in forward direction (**LHCb** acceptance $2 < \eta < 5$)
- Lorentz boost provides signature for **c**- & **b**-hadrons selection
- Tagging for prompt-**c** and **c**-from-**b**

Prompt tagging

Primary vertex (PV)

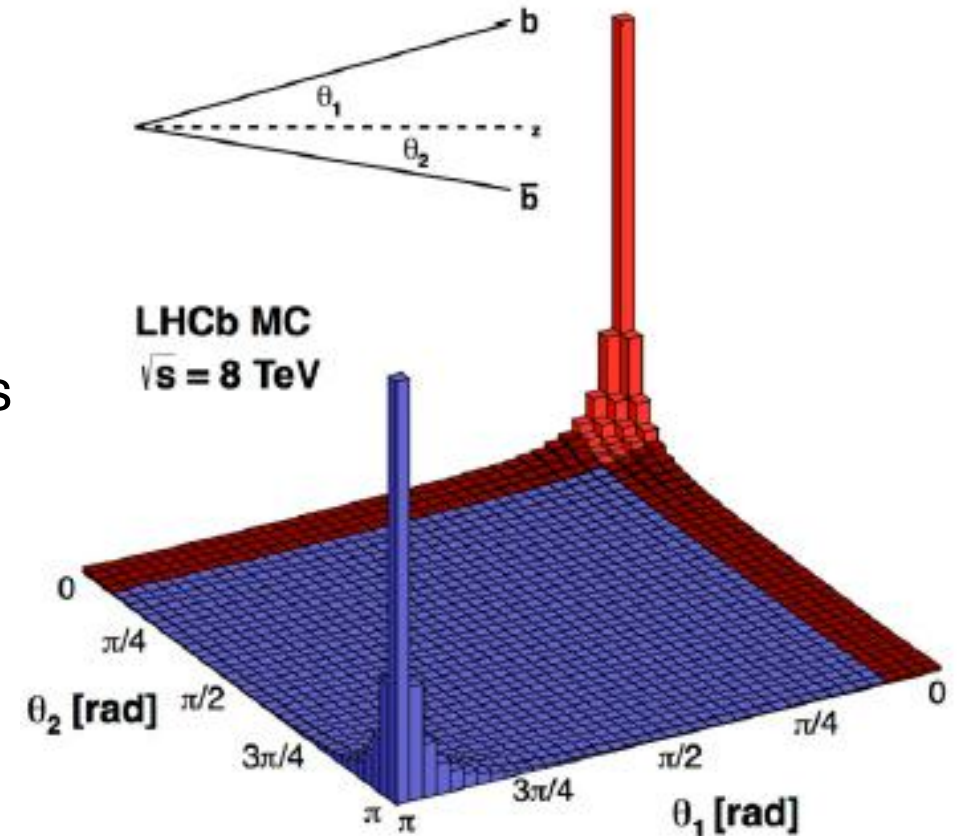


Higher tagging rate

Secondary (semileptonic)



More efficient triggering



LHCb: Find \ Identify \ Measure

Excellent vertexing allows efficient heavy quark hadrons selection / gives access to decay time distribution / prompt-secondary separation for charm

Protons collision point

Excellent PID allows to suppress background dramatically and explore many decay modes

Excellent tracking

Muon system – nice tagging & great potential to search for rare decays with di-muons

$$\epsilon_{PID}(K) > 95\%$$

$$MisID(K \rightarrow \pi) < 5\%$$

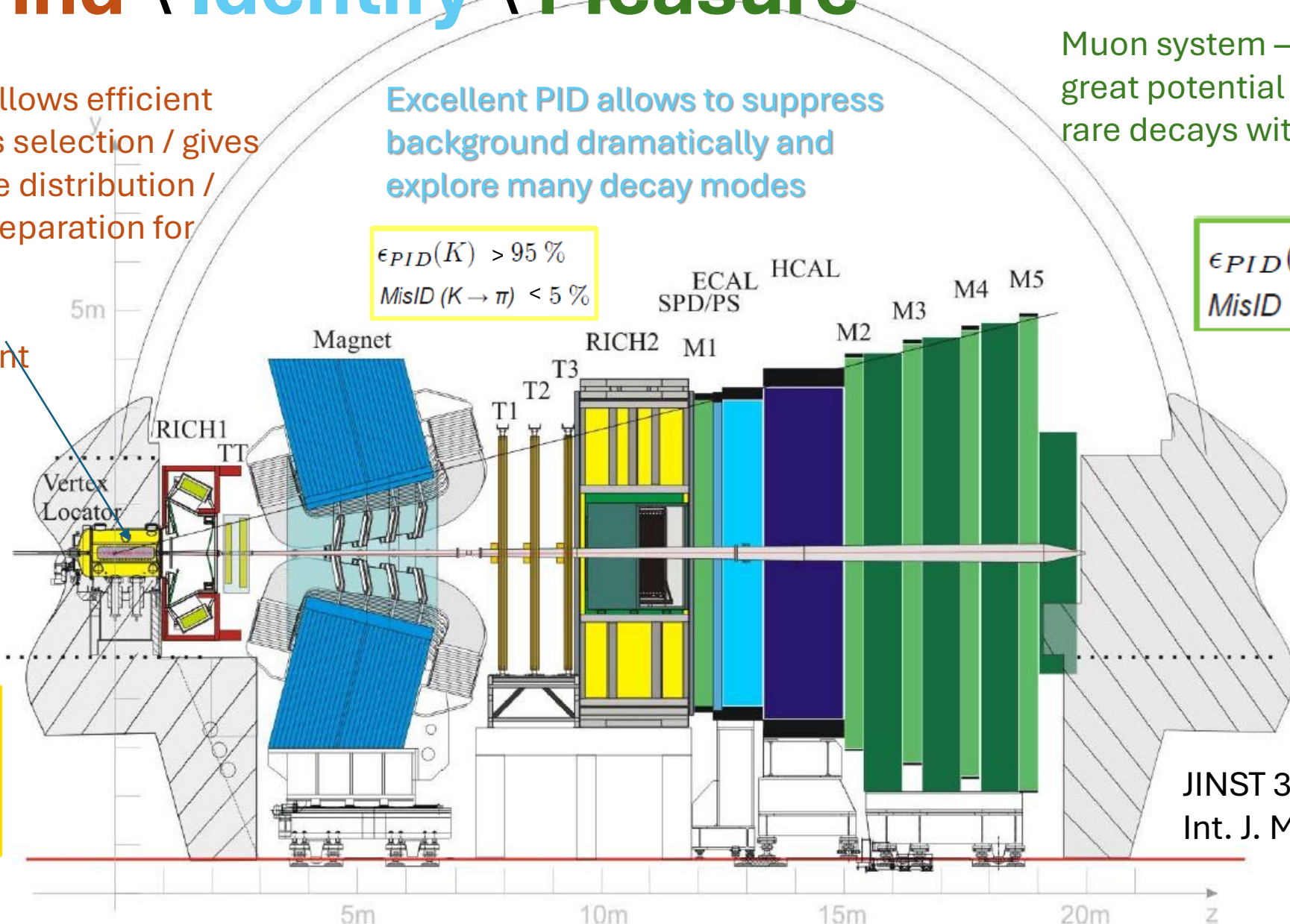
$$\epsilon_{PID}(\mu) > 97\%$$

$$MisID(\pi \rightarrow \mu) < 3\%$$

$$\sigma(IP) \approx 20\mu m$$

$$\delta p/p = 0.4 - 0.6\%$$

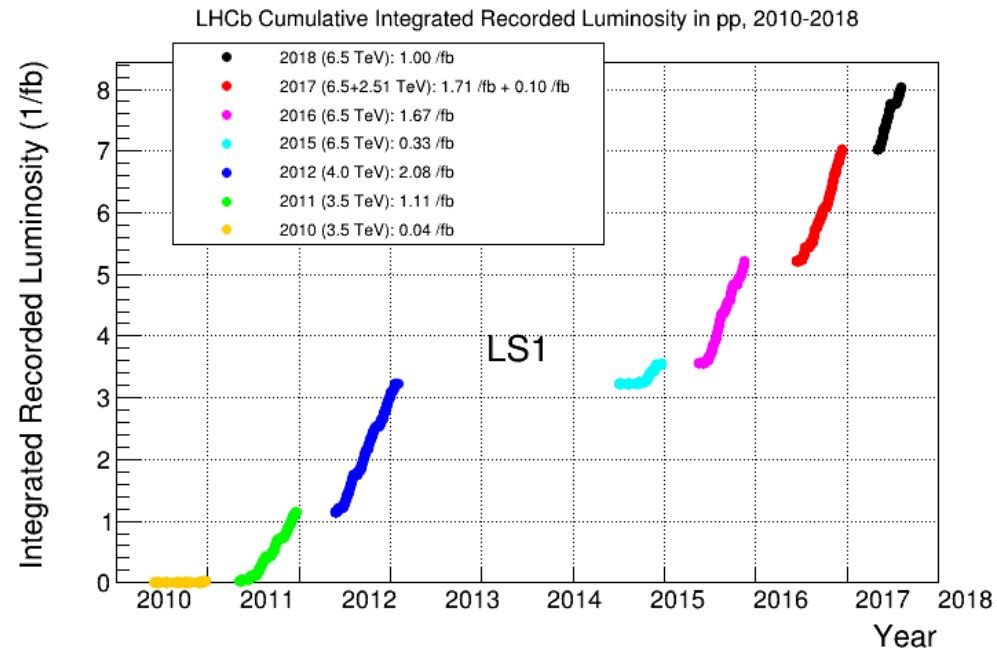
$$\epsilon_{track} > 96\%$$



JINST 3, (2008) S08005;
Int. J. Mod. Phys. A 30,
(2015) 153022

Luminosity and trigger

- LHCb operated in constant instantaneous luminosity mode (1.1 visible interactions per bunch crossing)
- Two stage trigger, which is efficient for hadrons and muons
- **Turbo stream for Run-2** – candidates reconstructed at the trigger level saved directly for offline analysis + (online alignment and calibration):
 - huge accepted rates (more data, as event sizes are smaller)



LHCb 2015 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz
 h^\pm

400 kHz
 $\mu/\mu\mu$

150 kHz
 e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

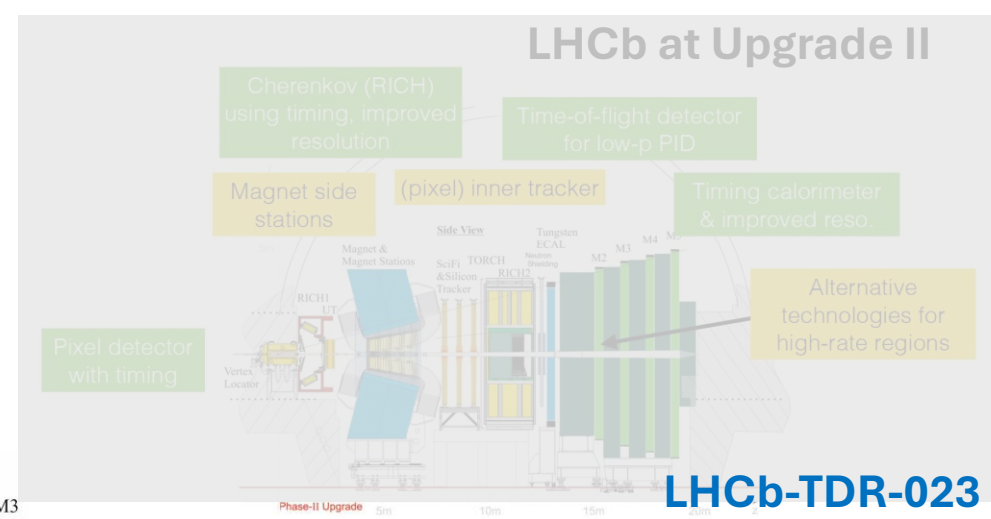
Buffer events to disk, perform online detector calibration and alignment

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

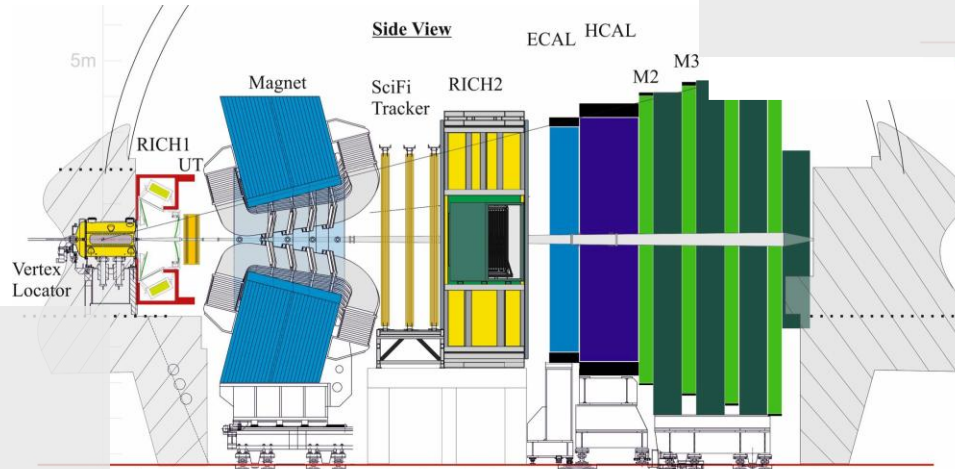
12.5 kHz (0.6 GB/s) to storage

LHCb Upgrade I (Runs 3 & 4)

Higher luminosity (roughly factor 5)
 + higher sensitivity
 40 MHz redout
 Software trigger

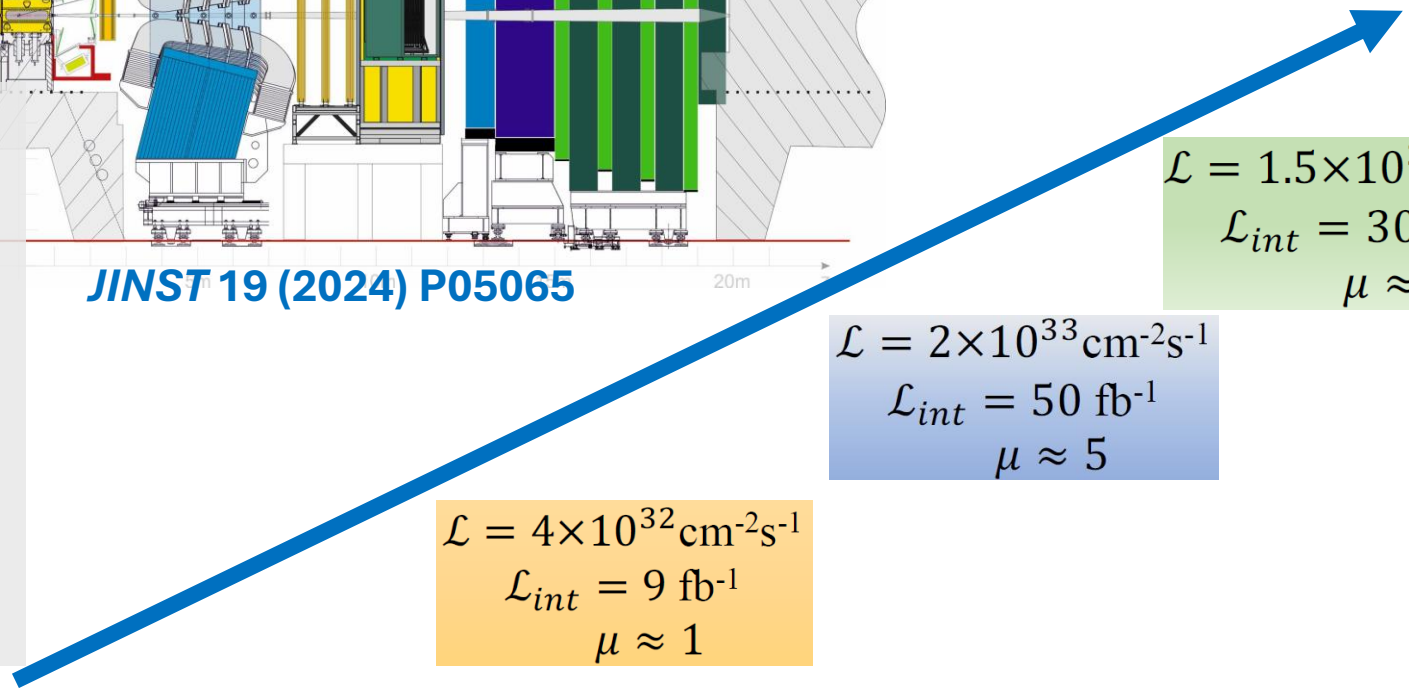


LHCb at Upgrade I



JINST 19 (2024) P05065

Luminosity



$$\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\mathcal{L}_{int} = 300 \text{ fb}^{-1}$$

$$\mu \approx 40$$

$$\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$$

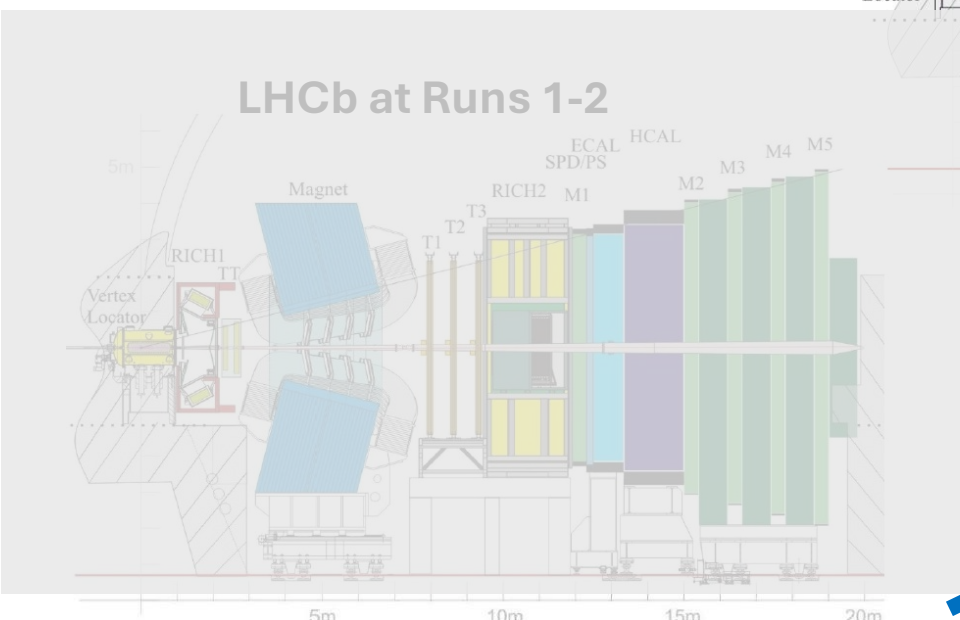
$$\mathcal{L}_{int} = 50 \text{ fb}^{-1}$$

$$\mu \approx 5$$

$$\mathcal{L} = 4 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

$$\mathcal{L}_{int} = 9 \text{ fb}^{-1}$$

$$\mu \approx 1$$



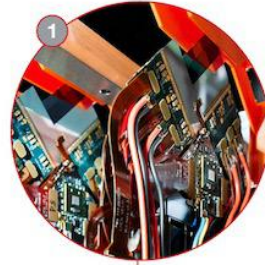
JINST 3 (2008) S08005

Int. J. Mod. Phys. A 30 (2015) 153022

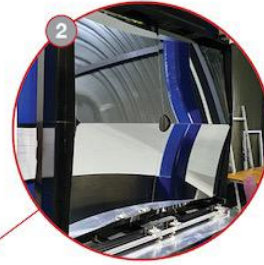
What's new?

- Pixel-based VELO closer to the beam pipe:
 - 8.2mm → 5.1mm
- Upstream tracker with higher granularity
- New SciFi tracker
- RICH with new mechanics, optics and PMT readout
- PLUME new detector to measure luminosity
- New SMOG2 system for fixed target physics

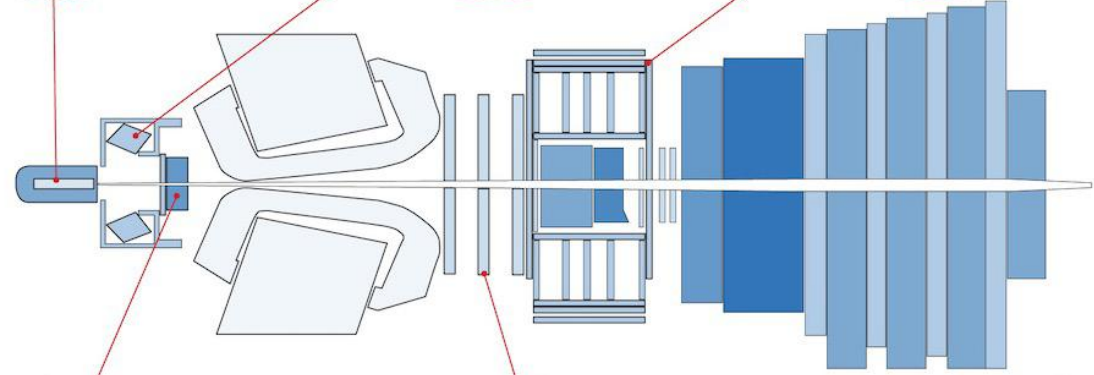
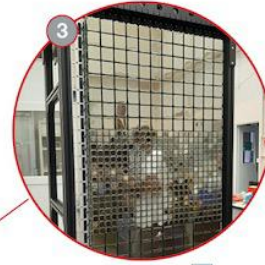
VELO: NEW SILICON PIXEL DETECTOR
Vertex Locator (VELO) replaced by a new silicon pixel detector, installed as close as 5.1 mm to the proton beams.



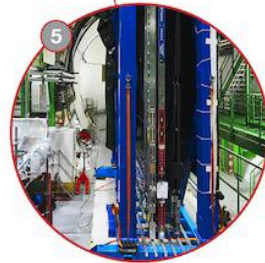
RICH1
New optics of RICH1 mirrors, with larger curvature radius.



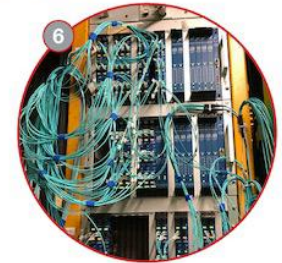
RICH2
New multi-anode photomultipliers replaced the hybrid photon detectors (HPD) in RICH1 and RICH2.



TRACKER: New UT
New high granularity silicon microstrip upstream tracker (UT).



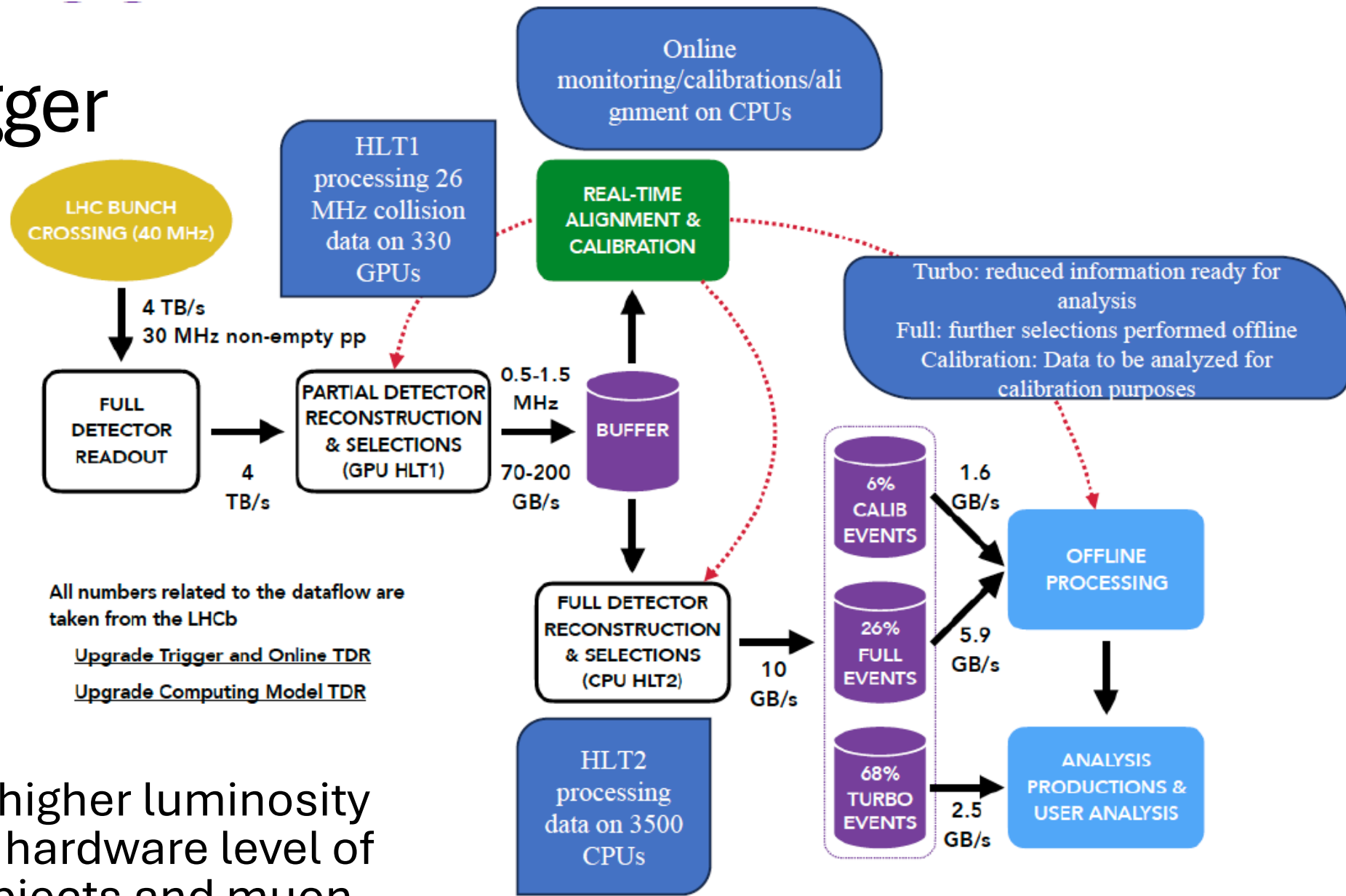
TRACKER: SCI-FI
Three new scintillating fibre tracker (Sci-Fi) stations.



FRONT-END ELECTRONICS
All front-end electronics (i.e. those connected directly to the detectors) have been modified.

Software trigger

JINST 14 (2019) P04006



All numbers related to the dataflow are taken from the LHCb
Upgrade Trigger and Online TDR
Upgrade Computing Model TDR

Write ~10GB/s at 1 MHz

- We can't run into a higher luminosity regime with the old hardware level of the trigger (HCAL objects and muon thresholds) → **Software trigger!**

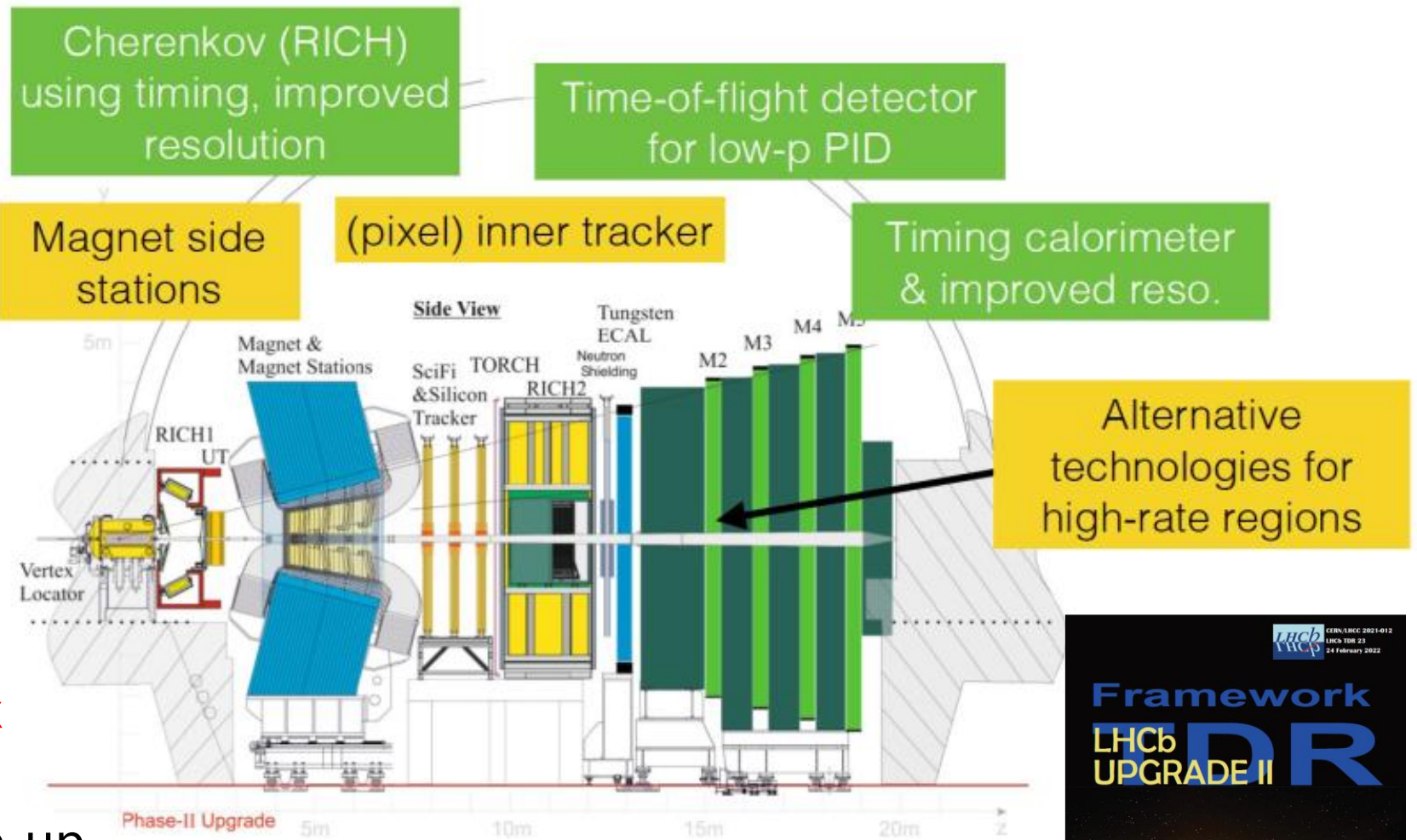
Upgrade II

$$\mathcal{L} = 1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$$

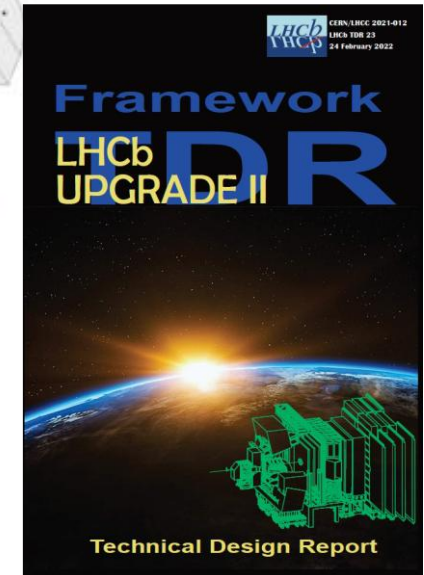
$$\mathcal{L}_{int} = 300 \text{ fb}^{-1}$$

$$\mu \approx 40$$

Pixel detector with timing



- Use **O(10 ps) timing in vertex reconstruction** and **particle identification** to mitigate pile-up
- Increase granularity of trackers (UT and MAPs sectors in SciFi)
- Add tracking stations in the magnet to increase efficiency for low-momentum tracks

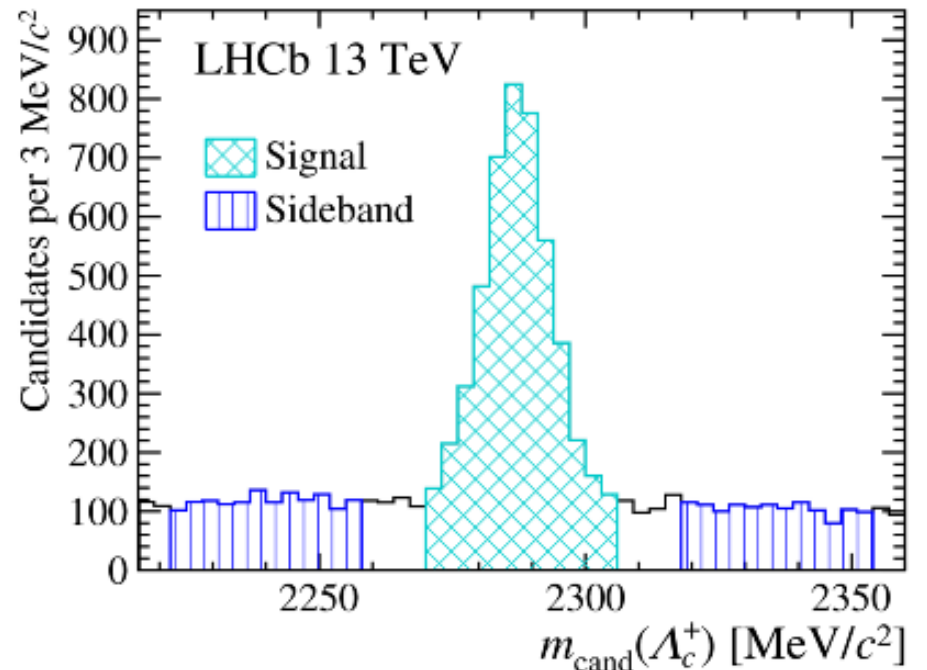
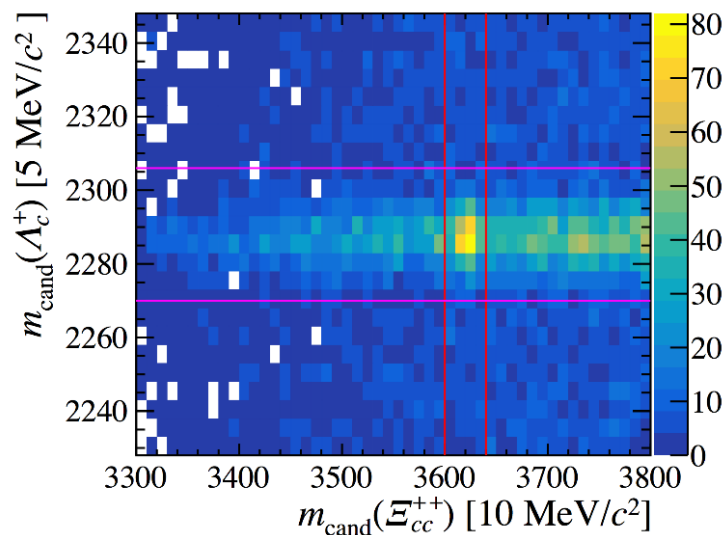
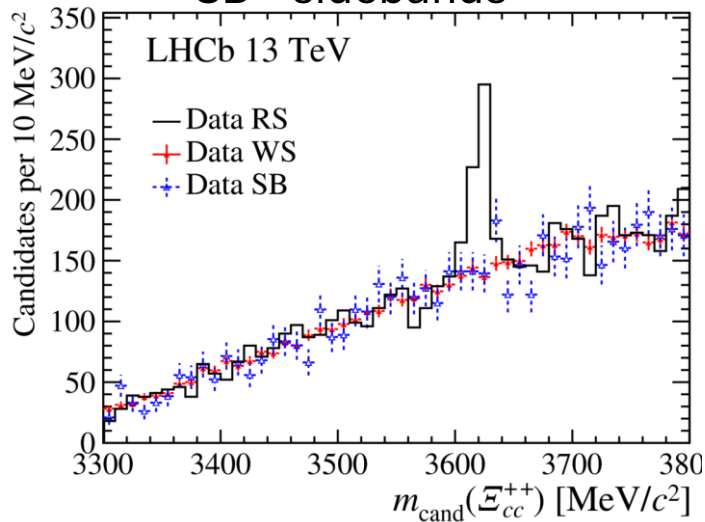
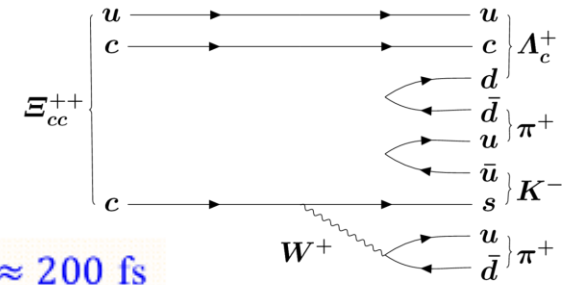
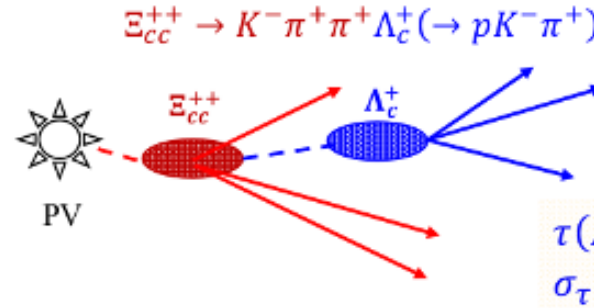


Discovery of Ξ_{cc}^{++}

First DCB discovered

Discovery of Ξ_{cc}^{++}

- Use Run II data 1.7 fb^{-1} , exclusive high efficient trigger (Turbo) / result is confirmed with Run-I data 2 fb^{-1}
- Expected up 10% branching fraction for decay of interest
- Cross check with different category $\Lambda_c^+ K^- \pi^+ \pi^+$ ion:
 - RS – right sign combination
 - WS – wrong sign
 - SB – sidebands



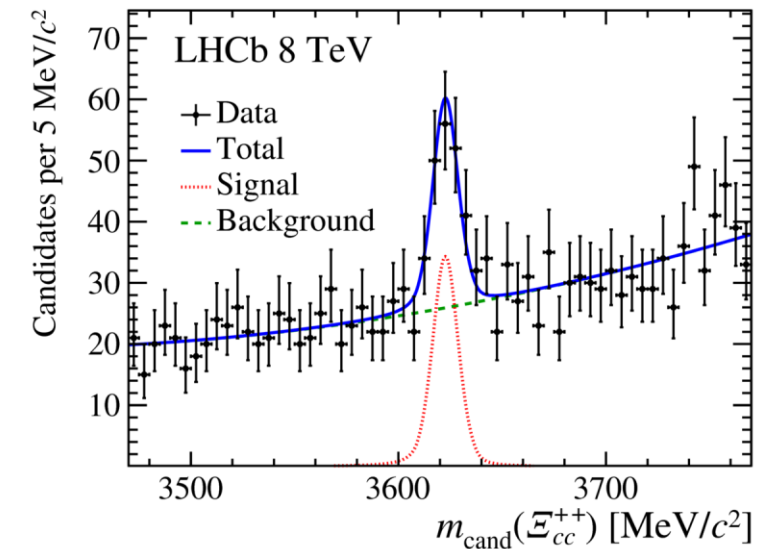
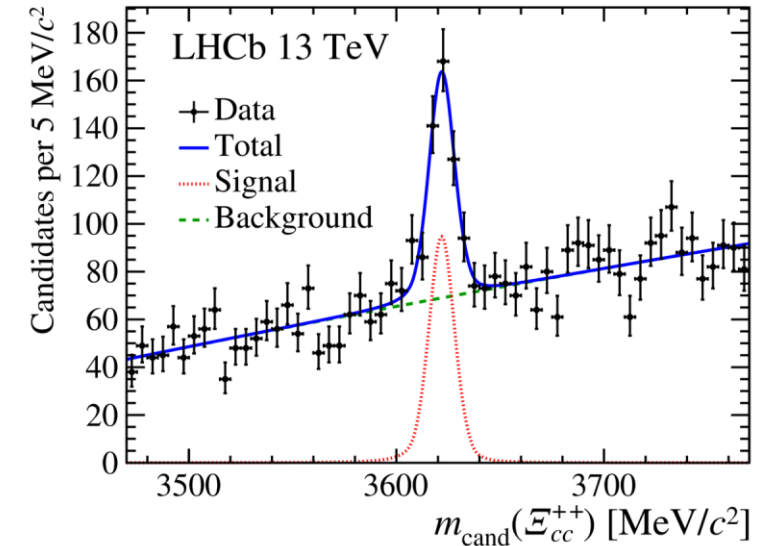
Discovery of Ξ_{cc}^{++}

- Signal yield of 313 ± 33 events
- Local significance greater than 12σ
- Confirmed with Run-I data (113 ± 21 ev. / $>7\sigma$ sign.)

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

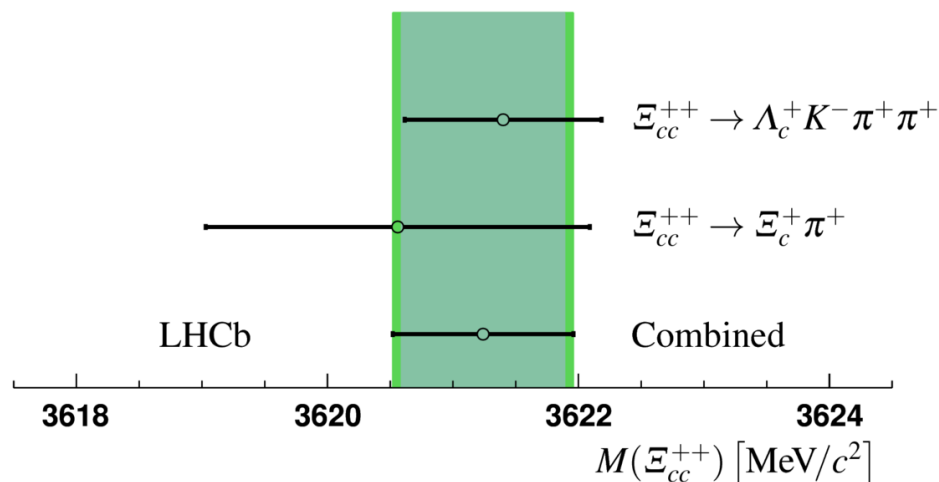
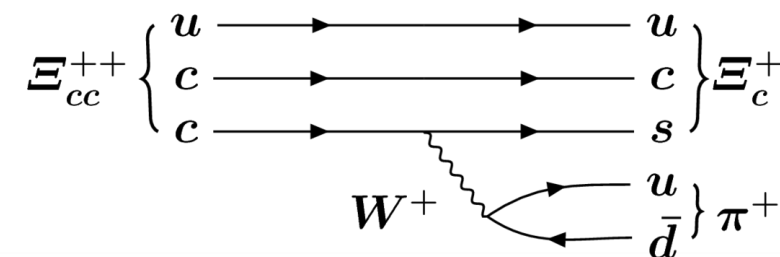
$$m(\Xi_{cc}^{++}) - m(\Lambda_c^+) = 1134.94 \pm 0.72(\text{stat}) \pm 0.27(\text{syst}) \text{ MeV}$$

- Sub-MeV precision for observation
- Obtained values are consistent with many theoretical calculations (including LQCD)
- Weakly decay (as has $\sim 0,25\text{ps}$ lifetime, see lifetime measurement part)

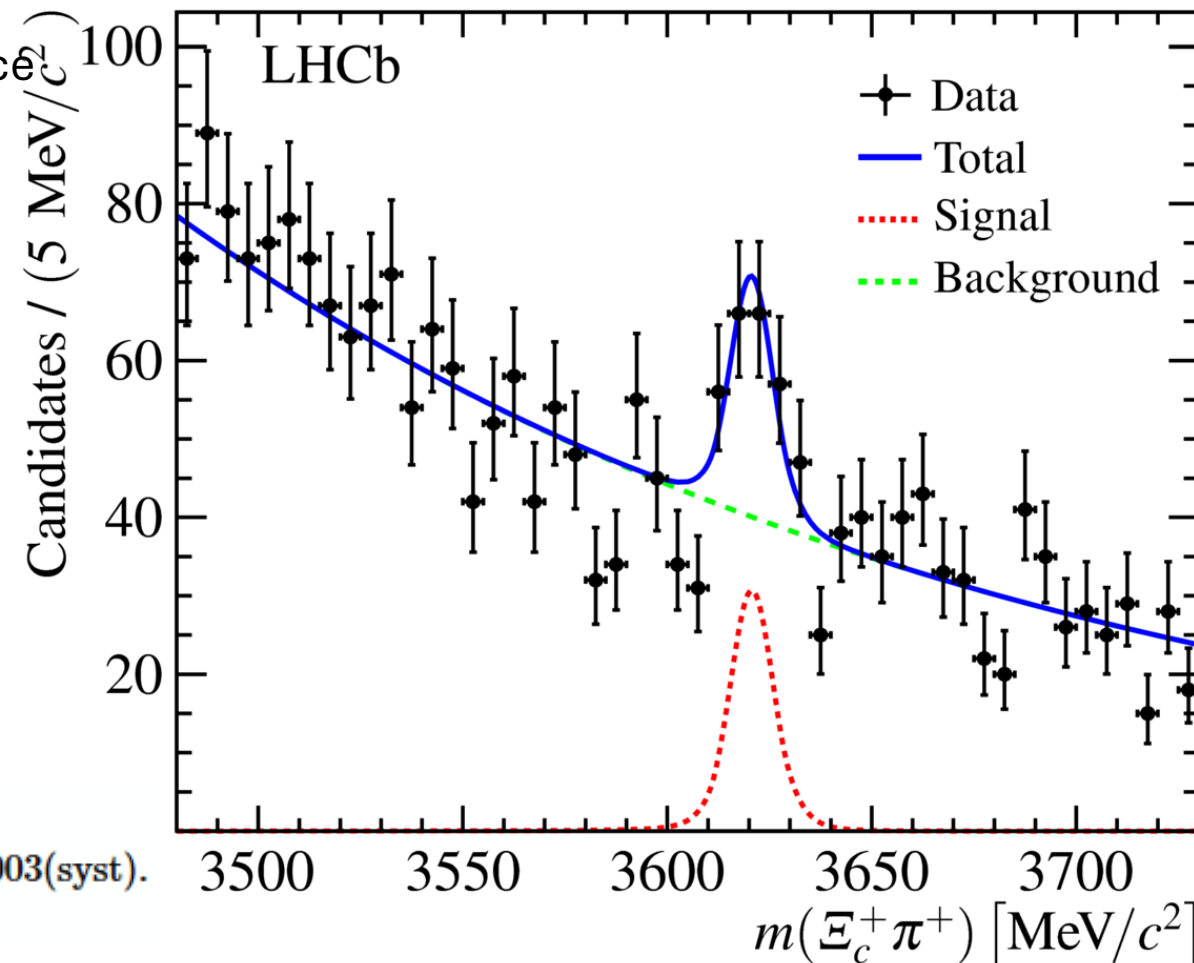


“Re-Discovery” of Ξ_{cc}^{++}

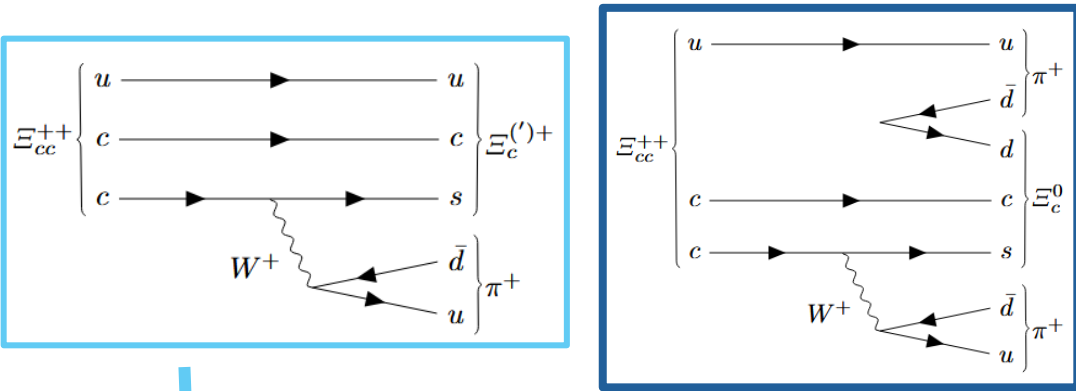
- Another channel with assumed high branching fraction
- Use Run II data 1.7 fb^{-1}
- Yield: 90 ± 20 candidates, corresponds 5.9σ significance
- Mass measurement is in agreement with previously measured value



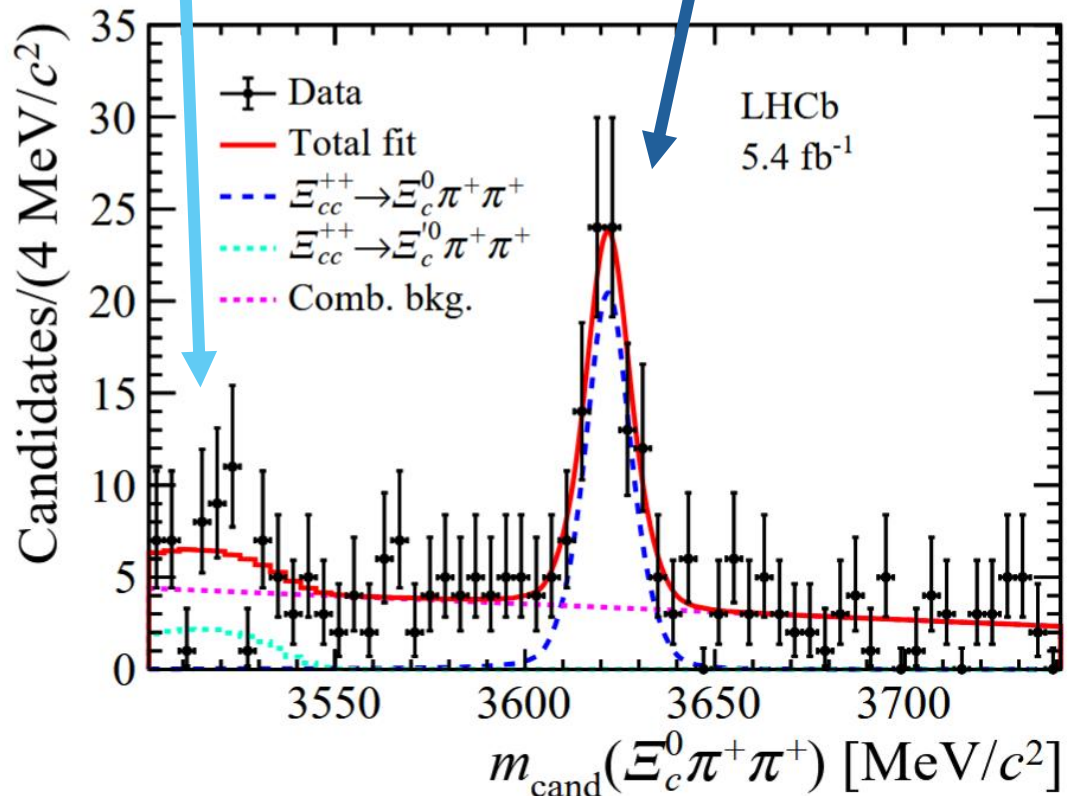
$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \rightarrow p K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \rightarrow p K^- \pi^+)} = 0.035 \pm 0.009(\text{stat}) \pm 0.003(\text{syst}).$$



One more decay channel observed for Ξ_{cc}^{++}



- A search for the doubly-charmed-baryon decay $\Xi_{cc}^{++} \rightarrow \Xi_c^0 (\rightarrow pK^-K^-\pi^+) \pi^+ \pi^+$ is performed using pp collision data collected by the LHCb experiment at a centre-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 5.4 fb^{-1} .



$$\frac{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Xi_c^0 \pi^+ \pi^+) \times \mathcal{B}(\Xi_c^0 \rightarrow pK^-K^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)} = 0.105 \pm 0.014 (\text{stat}) \pm 0.007 (\text{syst})$$

Lifetime measurements

Important ingredient for further searches

Lifetime measurement for Ξ_{cc}^{++}

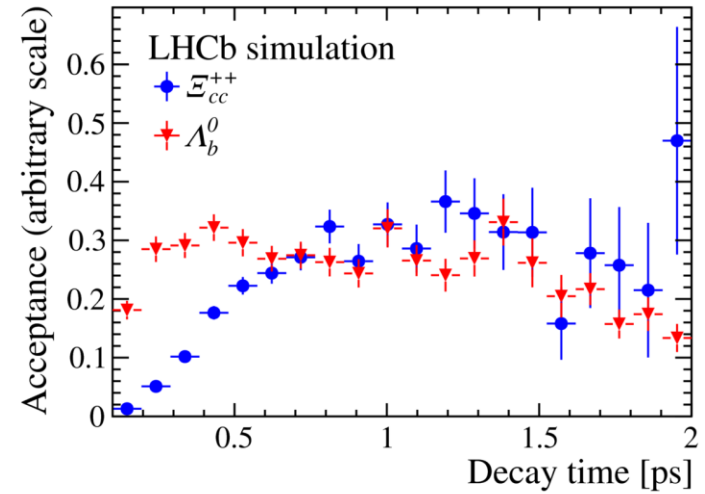
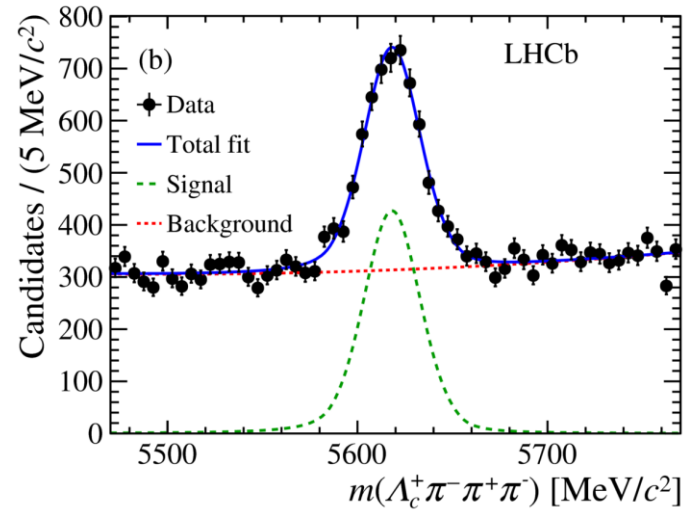
- Significant yields for non-zero lifetime
- Lifetime was measured wrt. Λ_b^0 decay
- Semi-unbinned method used: only lifetime acceptances are defined as histogram pdf's

$$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022} \text{ (stat)} \pm 0.014 \text{ (syst) ps.}$$

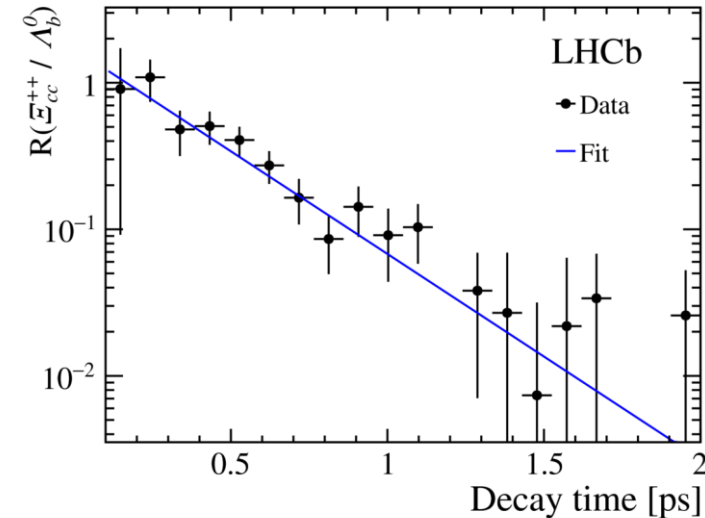
This result favors smaller lifetime values in the range of theoretical predictions

Ref. to theory papers in backup

- **Result suggests small lifetime values for isospin partner Ξ_{cc}^+ .**
- **Hard to search for!!**



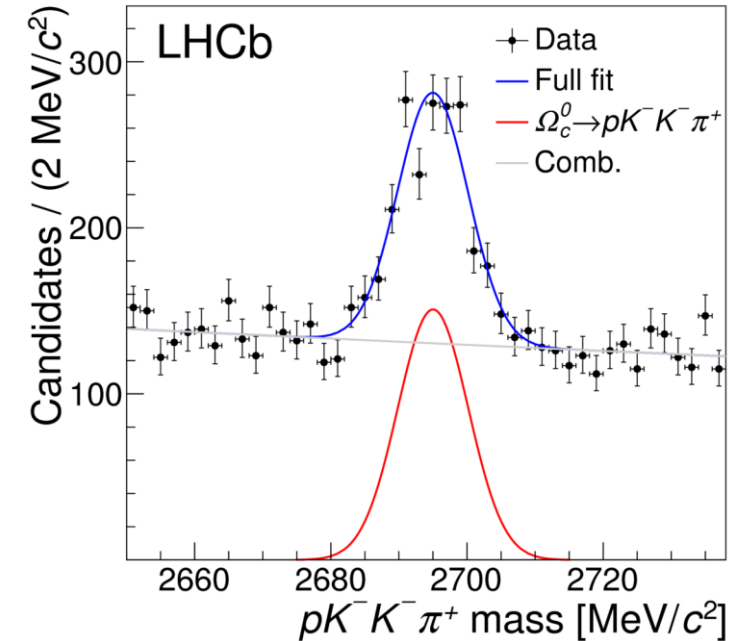
Source	Uncertainty (ps)
Signal and background mass models	0.005
Correlation of mass and decay-time	0.004
Binning	0.001
Data-simulation differences	0.004
Resonant structure of decays	0.011
Hardware trigger threshold	0.002
Simulated Ξ_{cc}^{++} lifetime	0.002
Λ_b^0 lifetime uncertainty	0.001
Sum in quadrature	0.014



Measurement of Ω_c lifetime

- Lifetime hierarchy charmed baryons was considered (see backup Refs.) to be:

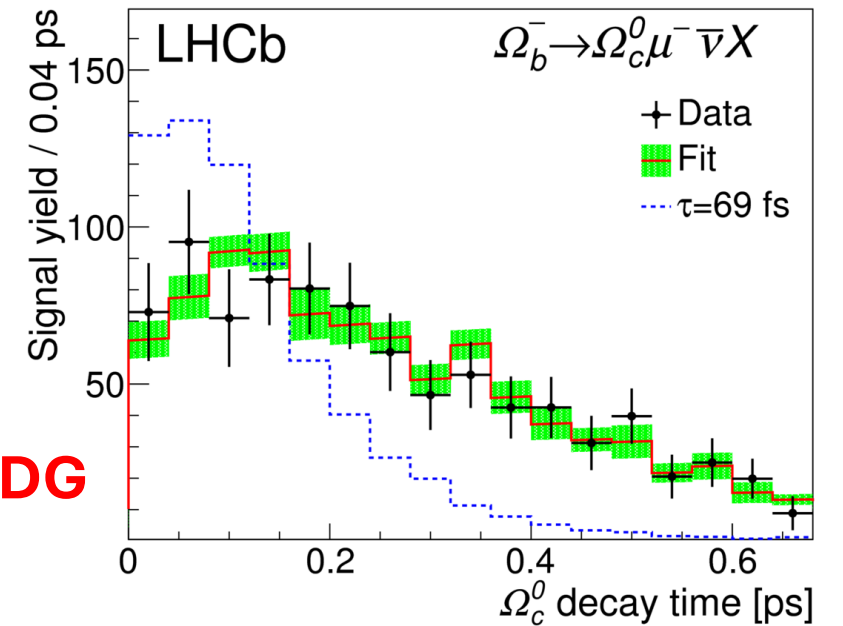
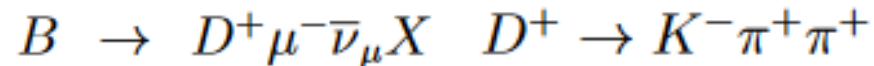
$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}.$$



- Muons from semileptonic decays of Ω_b baryons and decay vertex of Ω_c baryon provide opportunity for lifetime measurement

- To reduce uncertainty the lifetime ratio were measured

$$\tau_{\Omega_c^0} \equiv \frac{\tau_{\Omega_c^0}}{\tau_{D^+}}$$



- Result is incompatible with 69 fs lifetime reported in PDG**

Measurement of Ω_c lifetime

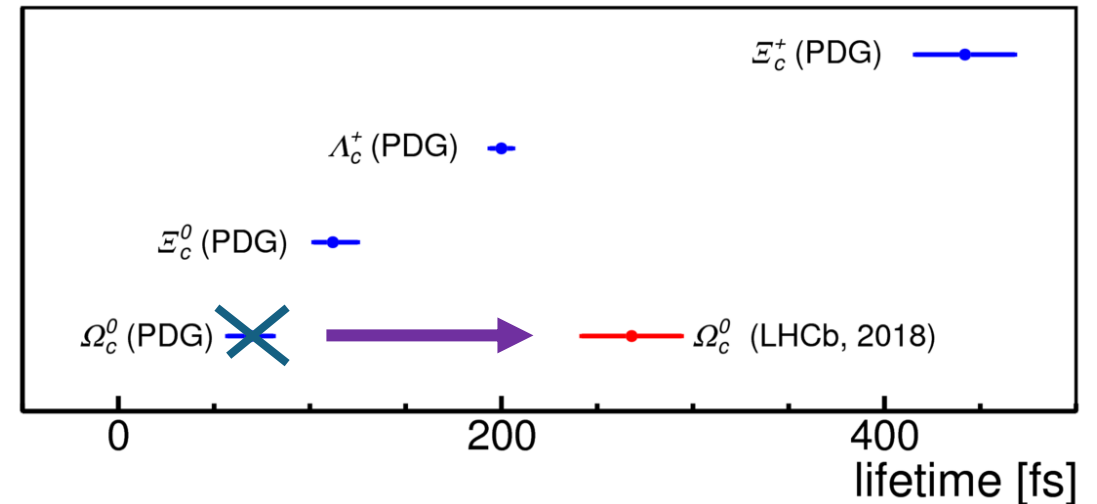
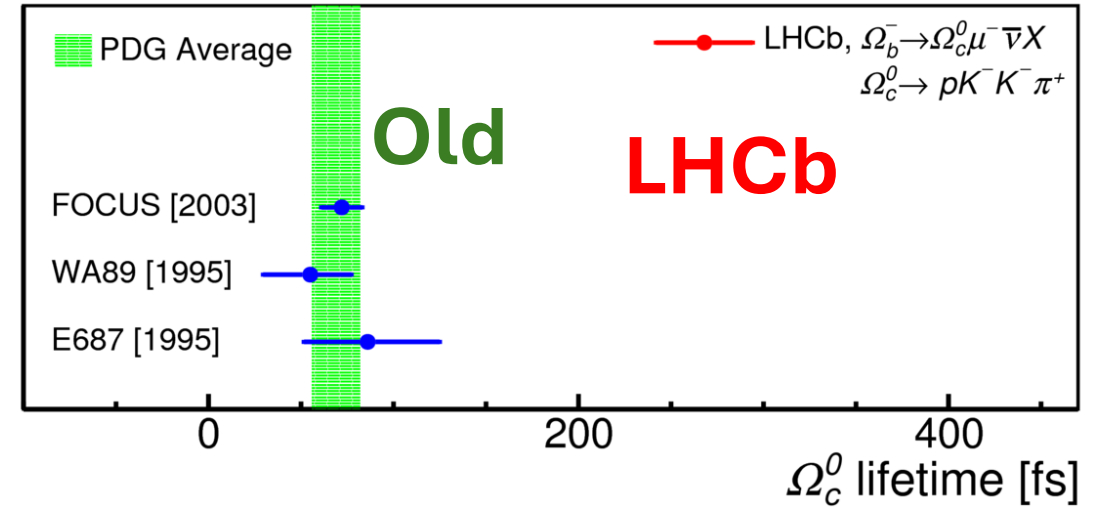
Phys. Rev. Lett. 121 (2018) 092003

$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$

$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs,}$$

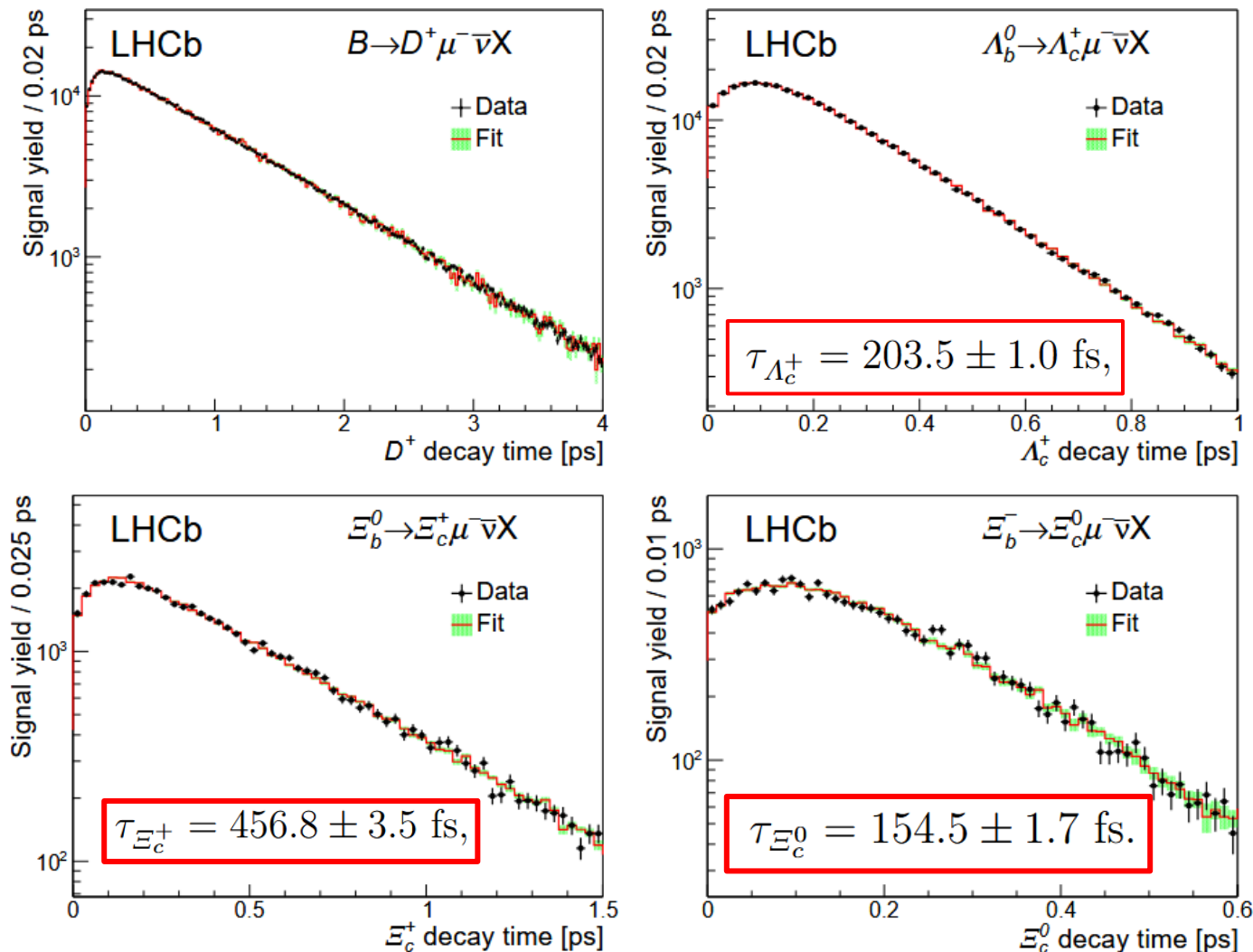
- Previous experiments were done using much smaller sample obtained on nucleus targets
- Very intriguing / Theorist are kindly welcome to explain:

$$\tau_{\Xi_c^+} > \tau_{\Omega_c^0} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0}.$$

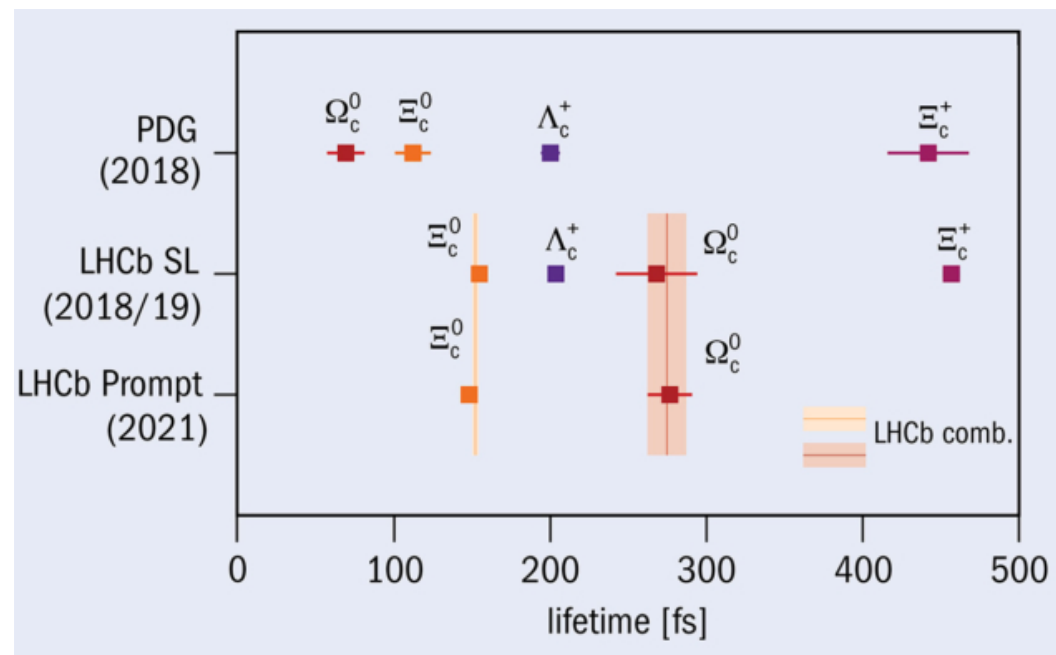


Lifetimes of charmed baryons

Plot from [CERN Courier](#)



Phys. Rev. D 100, 032001 (2019)



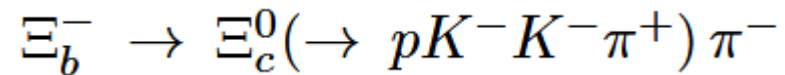
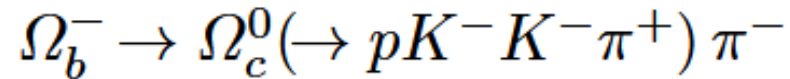
- Measurements done with prompt baryons
Science Bulletin 2022, v.67, p.479
confirmed results of the semi-muonic method
- **New hierarchy of lifetimes is confirmed!**

Fully hadronic decay modes

$$\tau_{\Omega_c^0} = 276.3 \pm 19.4 \text{ (stat)} \pm 1.8 \text{ (syst)} \pm 0.7 \text{ } (\tau_{D^0}) \text{ fs,}$$

$$\tau_{\Xi_c^0} = 149.2 \pm 2.5 \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 0.4 \text{ } (\tau_{D^0}) \text{ fs,}$$

• JHEP 09 (2025) 157



• Combination of all LHCb results

$$\tau_{\Omega_c^0} = 274.8 \pm 10.5 \text{ fs,}$$

$$\tau_{\Xi_c^0} = 150.7 \pm 1.6 \text{ fs,}$$

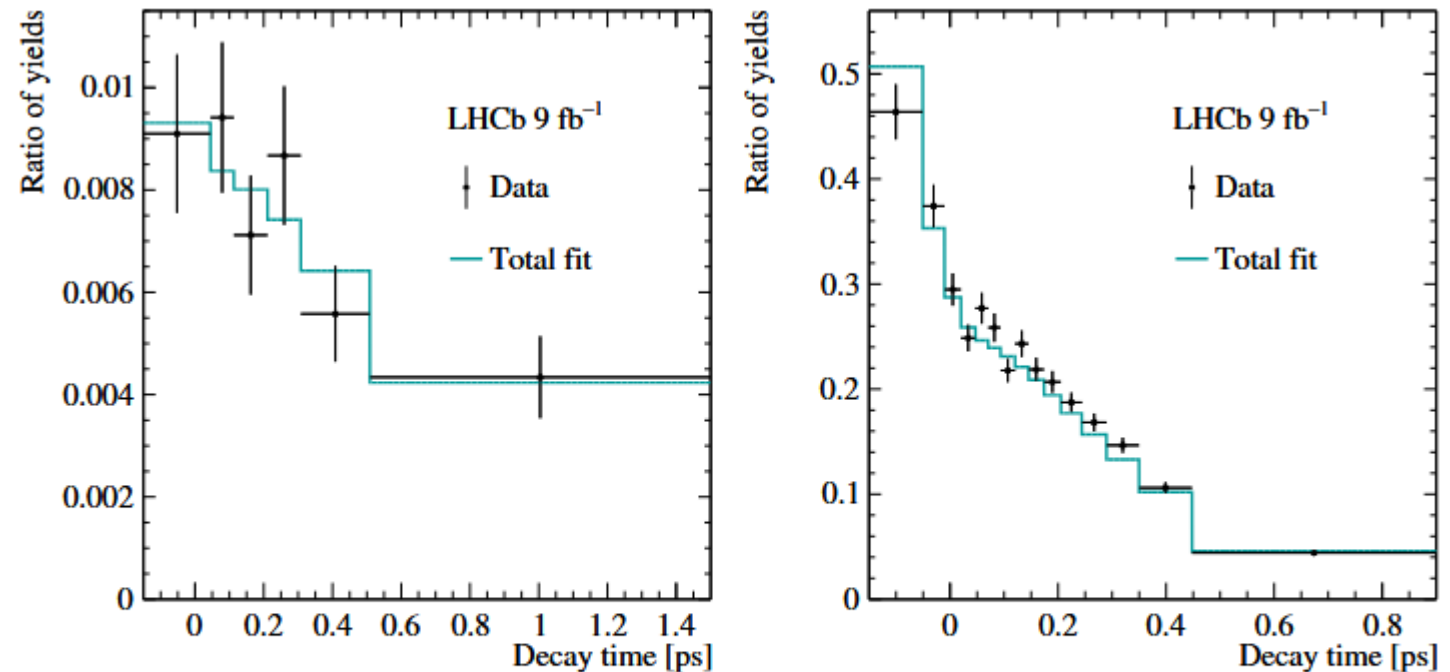


Figure 3. Ratio of yields (r_i) between the (left) $\Omega_b^- \rightarrow \Omega_c^0 \pi^-$ and (right) $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$ decays, and the $B^- \rightarrow D^0 \pi^-$ decays, in bins of decay time. The results from the fit with the model given in eq. 5.1 are shown.

Lifetime measurements created a solid ground to select strategy of searches for doubly-charmed baryons in LHCb Run-3 data

Discovery of Ξ_{cc}^+

Yet another check of the isospin symmetry

Previous searches

SELEX:

Reported evidence

$$3518.7 \pm 1.7 \text{ MeV}/c^2$$

Not confirmed by other experiments.

LHCb:

$$\bar{E}_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$$

full Run 1 + Run 2 data

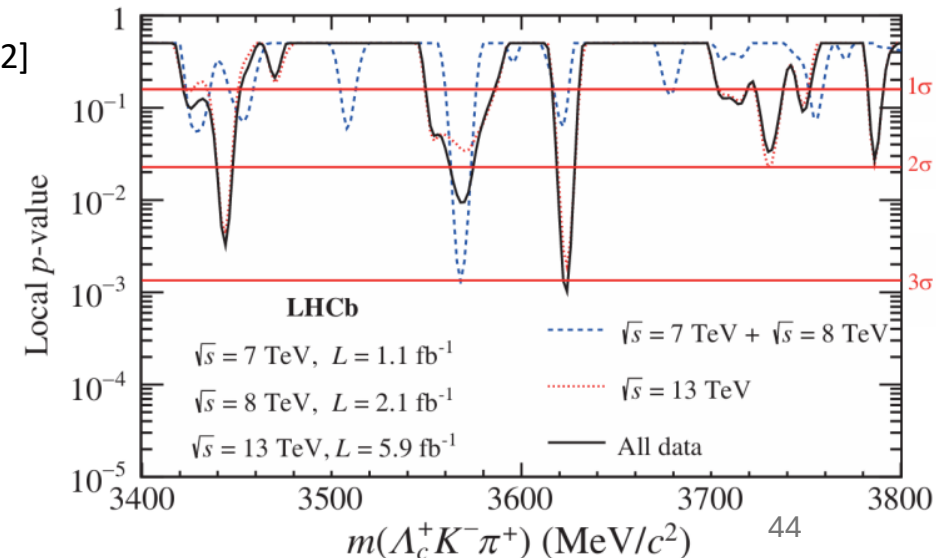
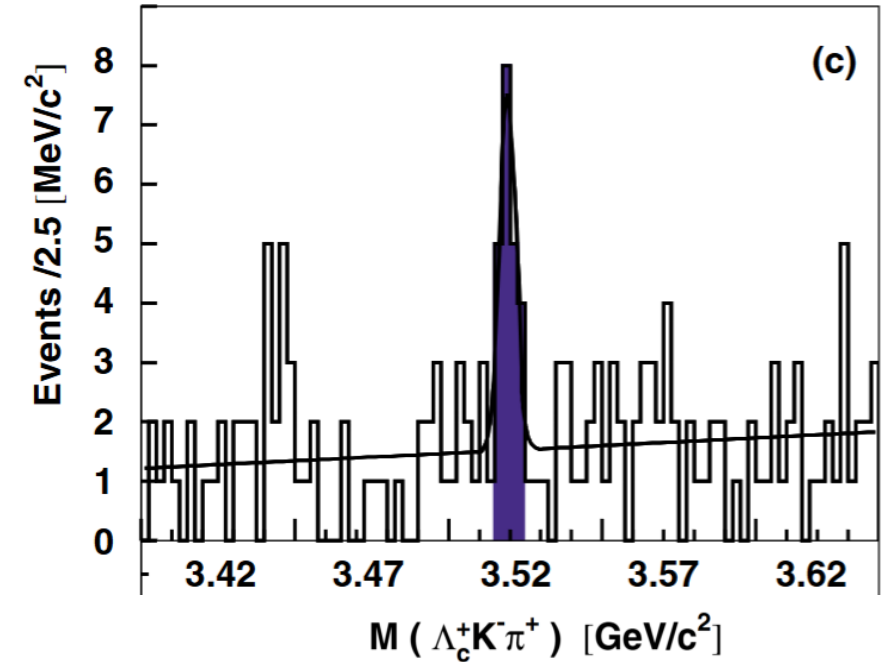
$$\mathcal{L} = 9.0 \text{ fb}^{-1}$$

3.0 σ local significance near observed

\bar{E}_{cc}^{++} mass peak.

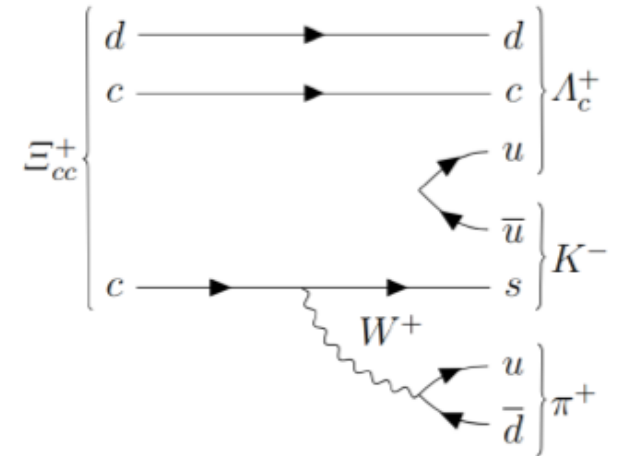
[SCPM 63(2020) 221062]

[PhysRevLett.89.112001]



Analysis strategy

- Search Ξ_{cc}^+ in the decay mode: $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+$ ($\Lambda_c^+ \rightarrow p K^- \pi^+$)
 - MC sample: $\tau(\Xi_{cc}^+) = 45 \text{ fs}$, considering first Dim-7 calculation.
 - $\tau(\Xi_{cc}^+)$ assumed in the range **15-160 fs** based on $\tau(\Xi_{cc}^+)/\tau(\Xi_{cc}^{++})$ predictions and $\tau(\Xi_{cc}^{++})$ measured by LHCb.
- Off-line selection based on **MVA** method (BDT).
 - MVA trained with data and simulation.
- Keep signal window (3.5-3.65 GeV) **blinded**.
 - Measure the mass of Ξ_{cc}^+ , if global significance $> 3\sigma$ or local significance $> 5\sigma$.
- Use $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ as control channel to optimize algorithm:
study about uncertainties and cross-check the performance of the detectors
 - Event-selection of Ξ_{cc}^+ is very similar to Ξ_{cc}^{++} , except one less pion, and shorter lifetime.
- Run 2 data (2016-2018) as cross-check.

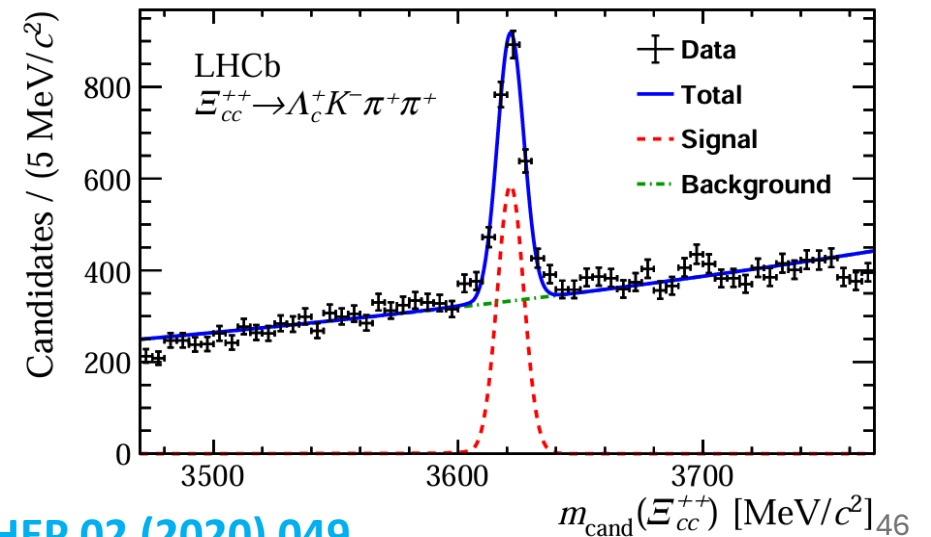
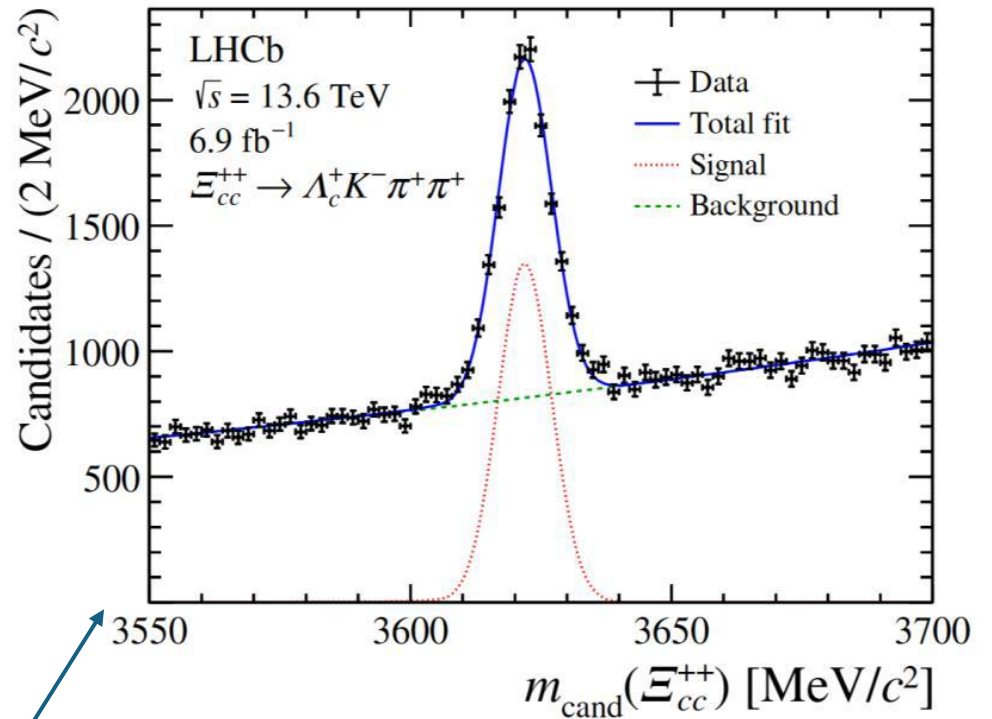


Control channel

- Output of a MVA trained with Λ_c^+ data is included in the MVA for Ξ_{cc}^{++}
 - $(p_T, \text{PID}, \chi_{\text{IP}}^2)$.
 - To mitigate the difference of particle-identification variables in data and simulation.
- Efficiency increased by a factor 4, compared with Run 2.
 - Signal yield per fb⁻¹ is 1262 in 2024 data, 285 in Run 2 data.
 - Thanks to removal of hardware trigger and improved event-selection.
- Corrected mass:
 - $M(\Xi_{cc}^{++}) = 3621.74 \pm 0.10 \text{ MeV}/c^2$ (stat. only)
- Consistent with Run 2 result.

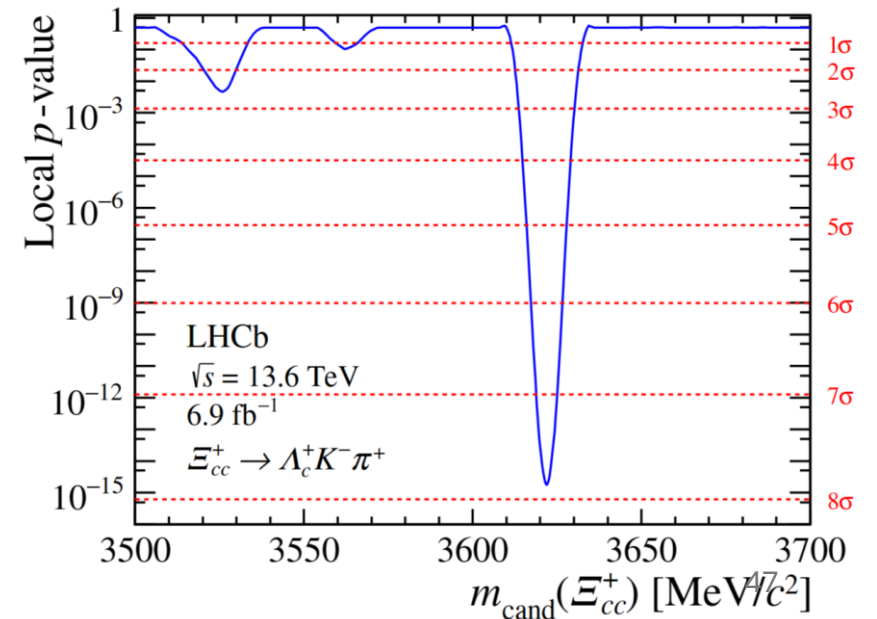
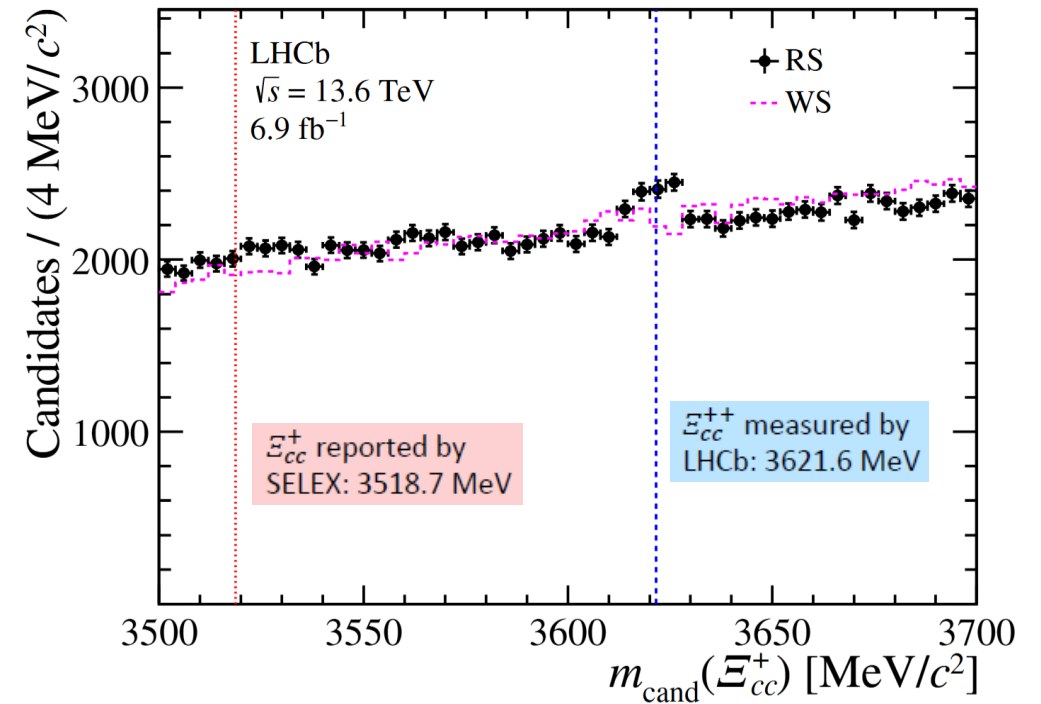
$$N_{\text{sig}} = 8712 \pm 160$$

$$N_{\text{sig}} = 1598 \pm 64$$



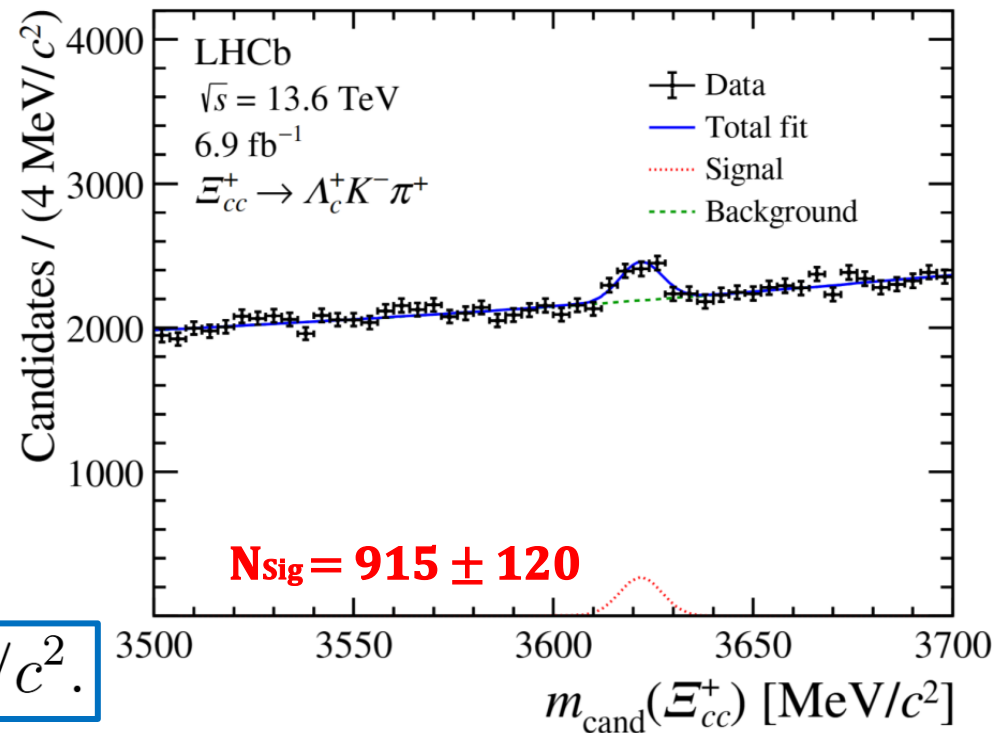
Ξ_{cc}^+ in 2024 data

- No fake peak in the Wrong-Sign sample, or at the $m(\Xi_{cc}^+)$ reported by SELEX.
- The local significance around 3622 MeV/c^2 **exceeds 7σ** , evaluated with a likelihood ratio test.
- Efficiency increased by a factor 2.5, c
- Signal yields per fb^{-1} are:
 - 133 in 2024 data
 - 54 in Run 2 data



Mass of Ξ_{cc}^+

- Sub-MeV statistical uncertainty for the mass measurement



$$3619.97 \pm 0.83 \text{ (stat)} \pm 0.26 \text{ (syst)}_{-1.30}^{+1.90} \text{ (lifetime)} \text{ MeV}/c^2.$$

- Leading systematics due to unknown lifetime of the Ξ_{cc}^+

Source	$M(\Xi_{cc}^+)$	ΔM
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
Unknown Ξ_{cc}^+ lifetime	$+1.90$ -1.30	$+1.90$ -1.30

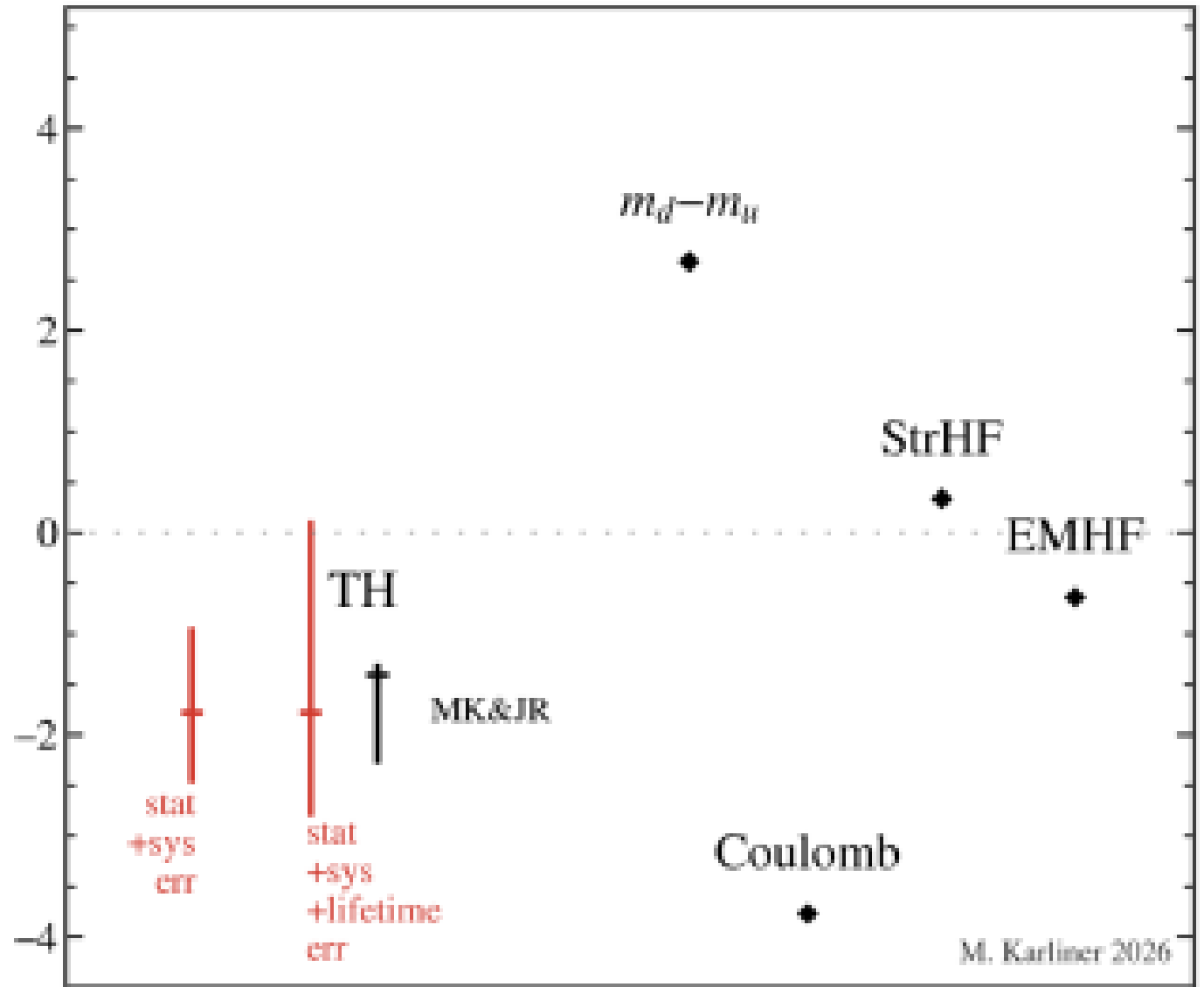
Mass difference (isospin splitting): Prediction: -0.4 to $-2.3 \text{ MeV}/c^2$.

$$\Delta M \equiv M(\Xi_{cc}^+) - M(\Xi_{cc}^{++}) = -1.77 \pm 0.84 \text{ (stat)} \pm 0.15 \text{ (syst)}_{-1.30}^{+1.90} \text{ (lifetime)} \text{ MeV}/c^2.$$

Isospin splitting

$$M(\Xi_{cc}^+) - M(\Xi_{cc}^{++})$$

MeV

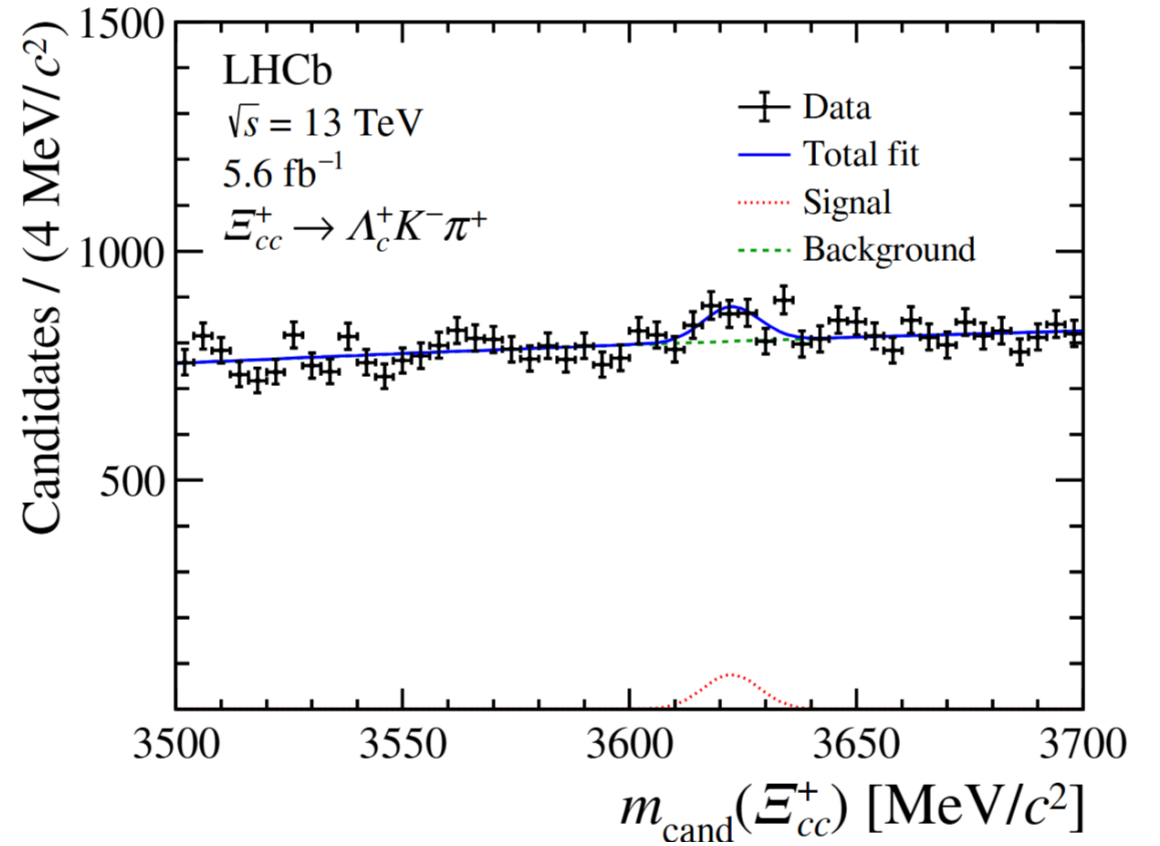
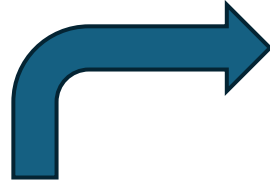


arXiv: 2603.28456

[PRD 96 (2017) 3, 033004]

arXiv: 2603.28456

Run-2 data



- New selection allows to perform a cross-check with the Run-2 data
- The local significance around $3622 \text{ MeV}/c^2$ is over 4σ .
 - Thanks to improved event-selection enabled by using inclusive Λ_c^+ line.
- Ξ_{cc}^+ mass with correction: $3620.8 \pm 2.2 \text{ (stat)}_{-1.2}^{+1.5} \text{ (lifetime) MeV}/c^2$
- Consistent with 2024 result. $3619.97 \pm 0.83 \text{ (stat)} \pm 0.26 \text{ (syst)}_{-1.30}^{+1.90} \text{ (lifetime) MeV}/c^2$.

Discovery of Ω_{cc}^+

Analogue of the proton but made of 2nd generation of quarks

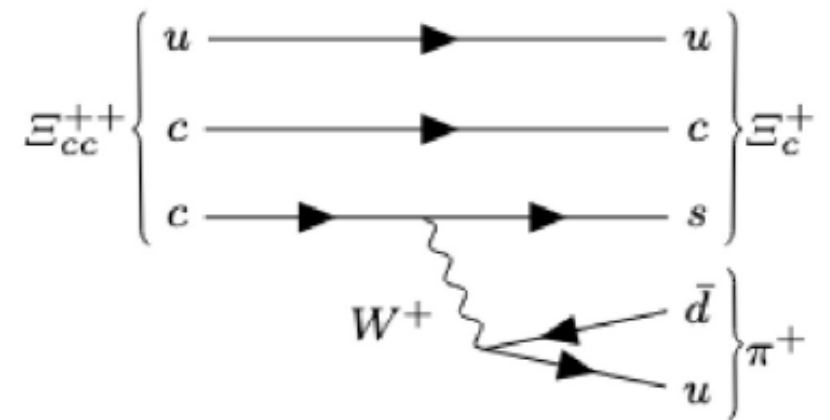
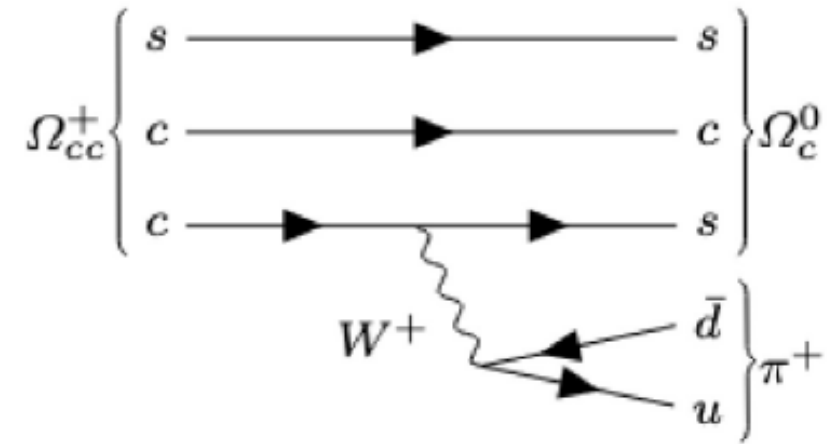
Signal and control channel

Reasons for using $\Omega_c^0\pi^+$ final states:

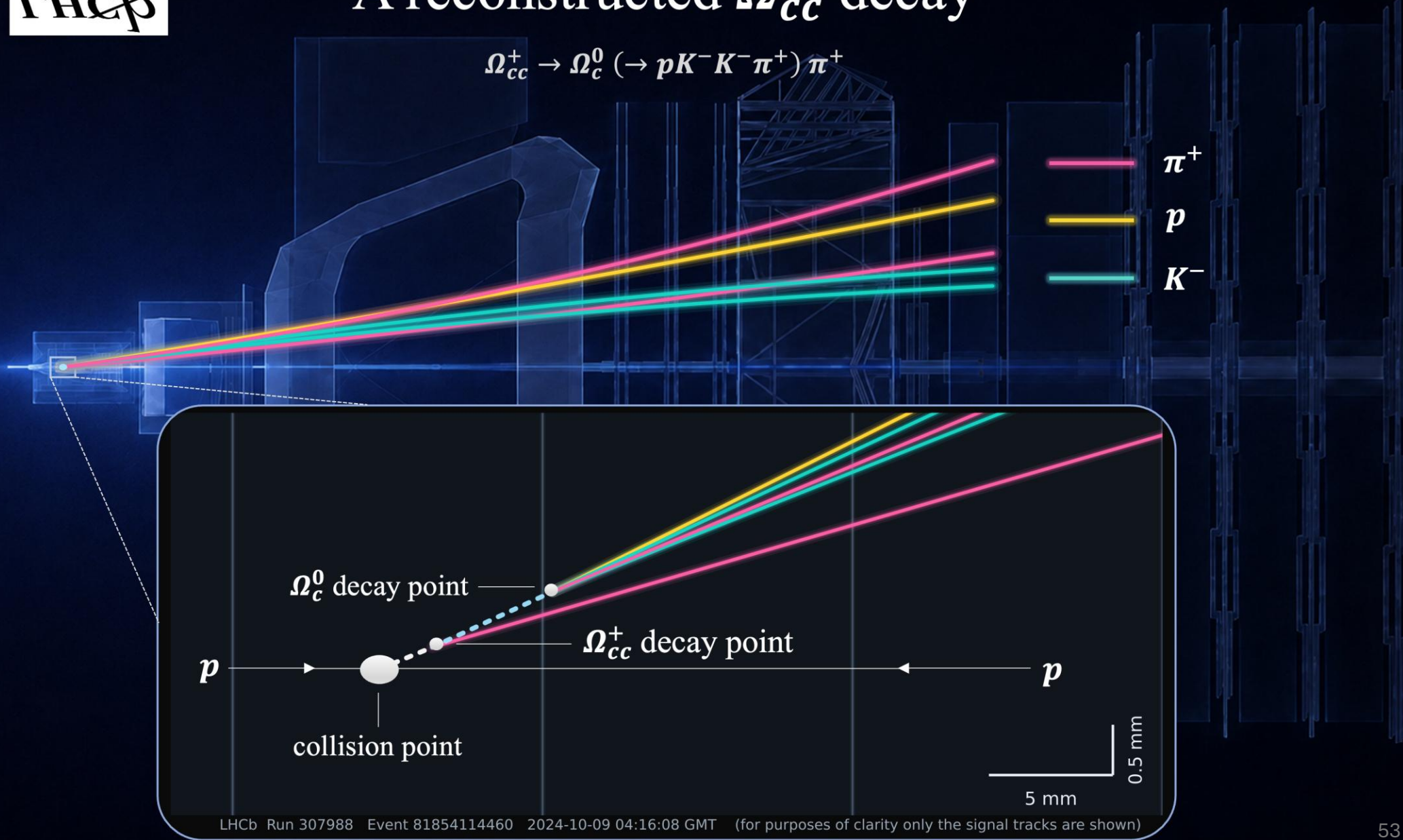
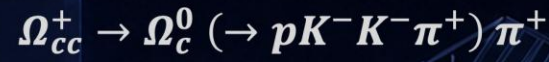
- ▶ Not previously searched for
- ▶ The $\Omega_{cc}^+ \rightarrow \Omega_c^0\rho^+/\pi^+$ are predicted to have **leading hadronic branching fractions**
- ▶ The $\tau(\Omega_c^0)$ turned out to be longer (280 fs) than previously known (70 fs)
⇒ more efficiently to be triggered on

General strategy

- ▶ Run data and a subset of the 2024 LHCb data are used (6.3 fb^{-1})
- ▶ Signal mode : $\Omega_{cc}^+ \rightarrow \Omega_c^0\pi^+, \Omega_c^0 \rightarrow pK^-K^-\pi^+$
- ▶ Control mode: $\Xi_{cc}^{++} \rightarrow \Xi_c^+\pi^+, \Xi_c^+ \rightarrow pK^-\pi^+$ (similar Q-value and bachelor pion)
- ▶ Blind analysis with mass window $m \in [3660, 3780] \text{ MeV}$
⇒ covering most recent predictions with a margin of $\pm 50 \text{ MeV}$

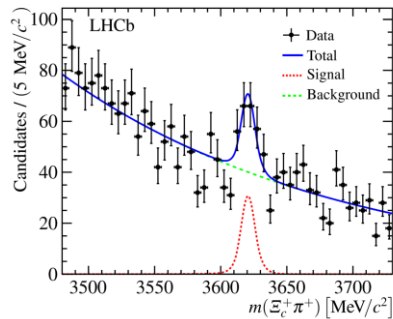


A reconstructed Ω_{cc}^+ decay

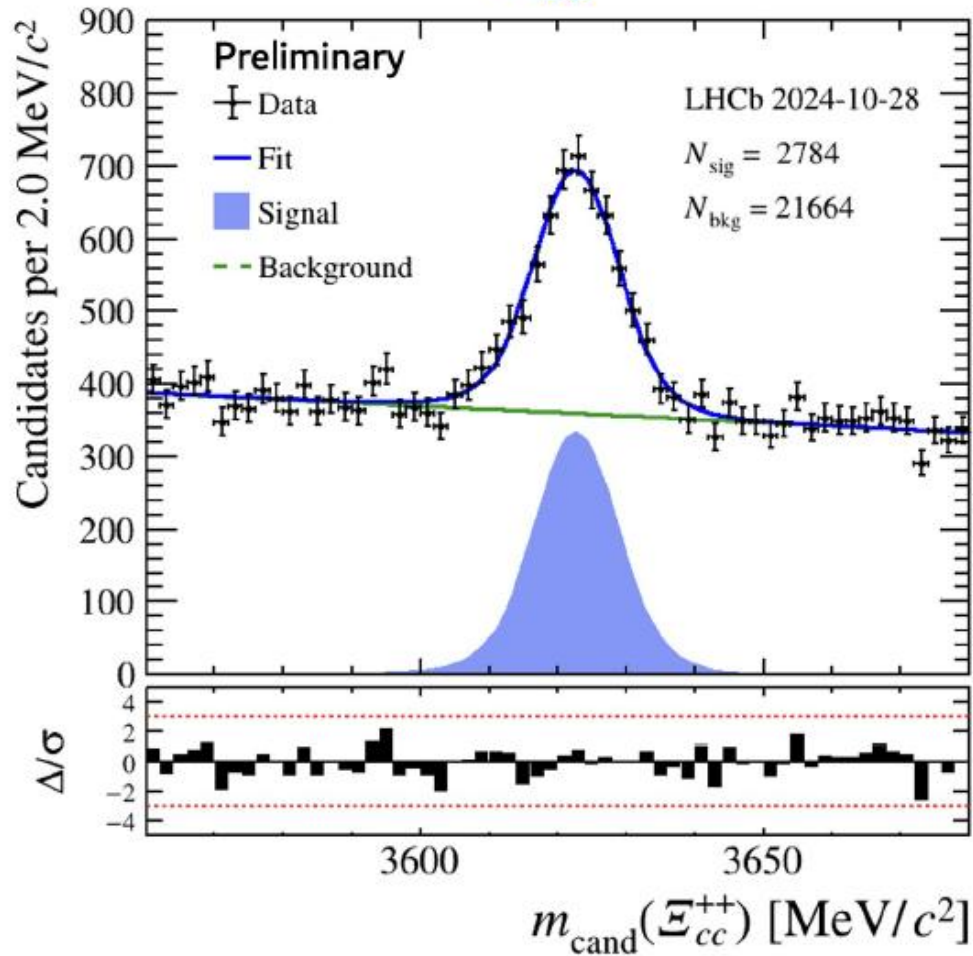


Mass spectra

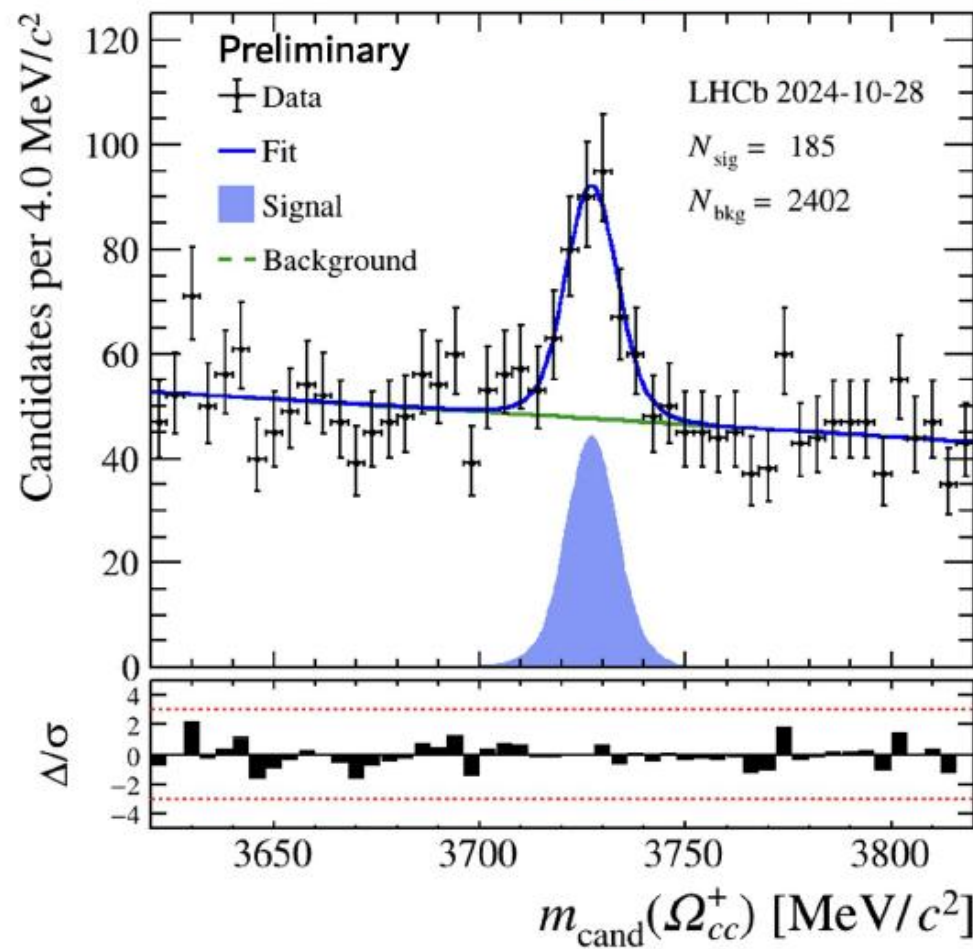
Statistics at the discovery of channel



Ξ_{cc}^{++}

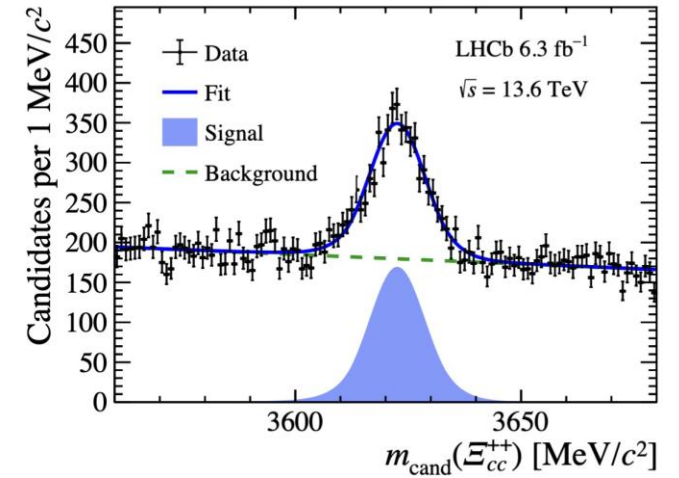
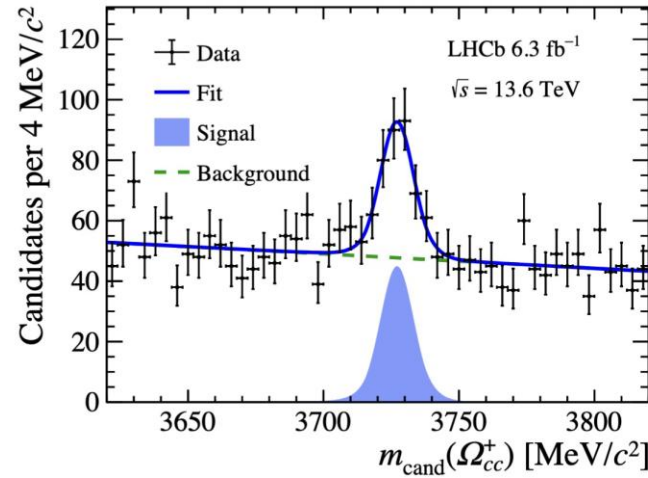


Ω_{cc}^+



Mass measurement

$$N_{\text{sig}} = 184 \pm 24$$



$$N_{\text{sig}} = 2771 \pm 114$$

- A clear peak observed with local significance $> 8\sigma$
- Ξ_{cc}^{++} yield per $\text{fb}^{-1} = 440$ at 2024 wrt 110 at Run2 data
 - \Rightarrow also improved by a factor of 4
- The peak remains significant after a tight requirement on the decay time $t > 170$ fs, indicating weakly-decaying nature
- Precise measurements of the lifetime and production are underway with the full LHCb Run 3 data

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$$m(\Omega_{cc}^+) = 3725.9 \pm 1.0 (\text{stat}) \pm 0.2 (\text{syst}) \pm 0.4(\tau) \pm 0.6(\text{ext}) \text{ MeV}/c^2$$
$$m(\Omega_{cc}^+) - m(\Xi_{cc}^{++}) = 104.3 \pm 1.0 (\text{stat}) \pm 0.2 (\text{syst}) \pm 0.4(\tau) \pm 0.5(\text{ext}) \text{ MeV}/c^2$$

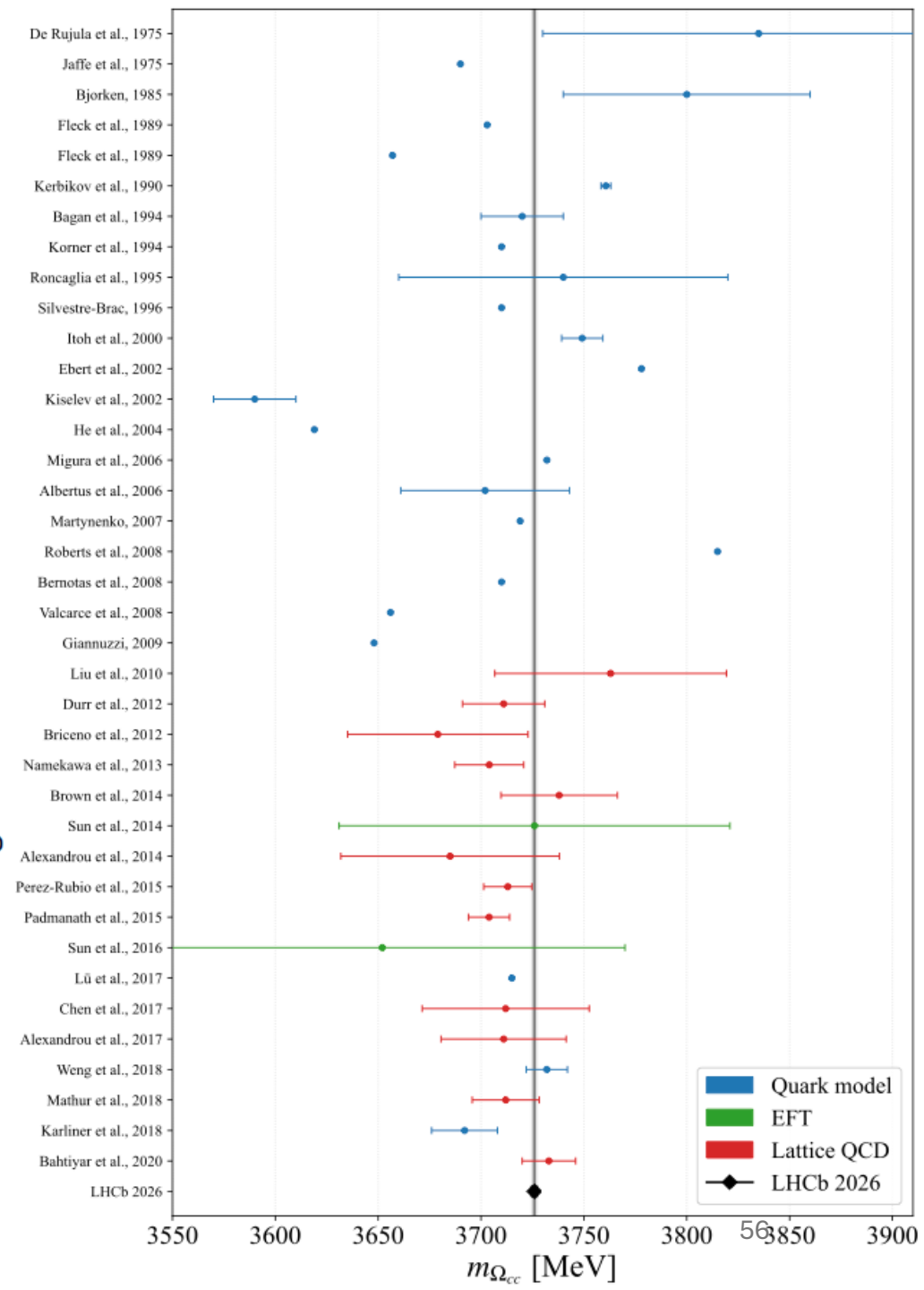
Theory predictions

Picture of cc -diquark + quark

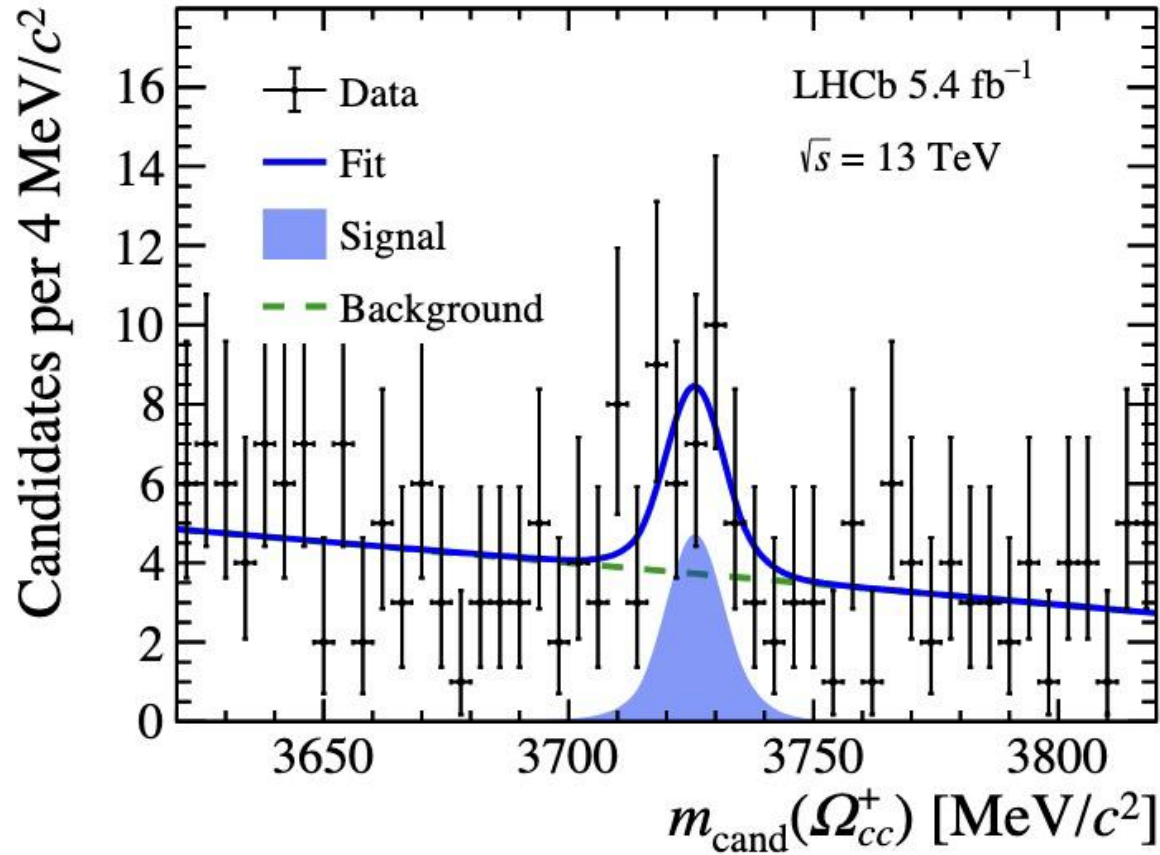
- ▶ $m(\Omega_{cc}) - m(\Xi_{cc}) \approx 105 \text{ MeV}$
- ▶ Similar as $m(D_s) - m(D) \approx 100 \text{ MeV}$ and $m(B_s^0) - m(B) \approx 90 \text{ MeV}$

Comparison with theoretical predictions on mass

- ▶ **Quark Model:** Gave estimations with $\sim 100 \text{ MeV}$ precision right after the discovery of the charm quark (J/ψ)
 - ▶ **Lattice QCD:** Calculations emerged in the last decade, providing reasonable predictions with uncertainties
 - ▶ **EFT/Sum Rules:** Calculations also exist, but the theoretical uncertainty is difficult to control
- ⇒ in general, measured mass is compatible with theoretical predictions



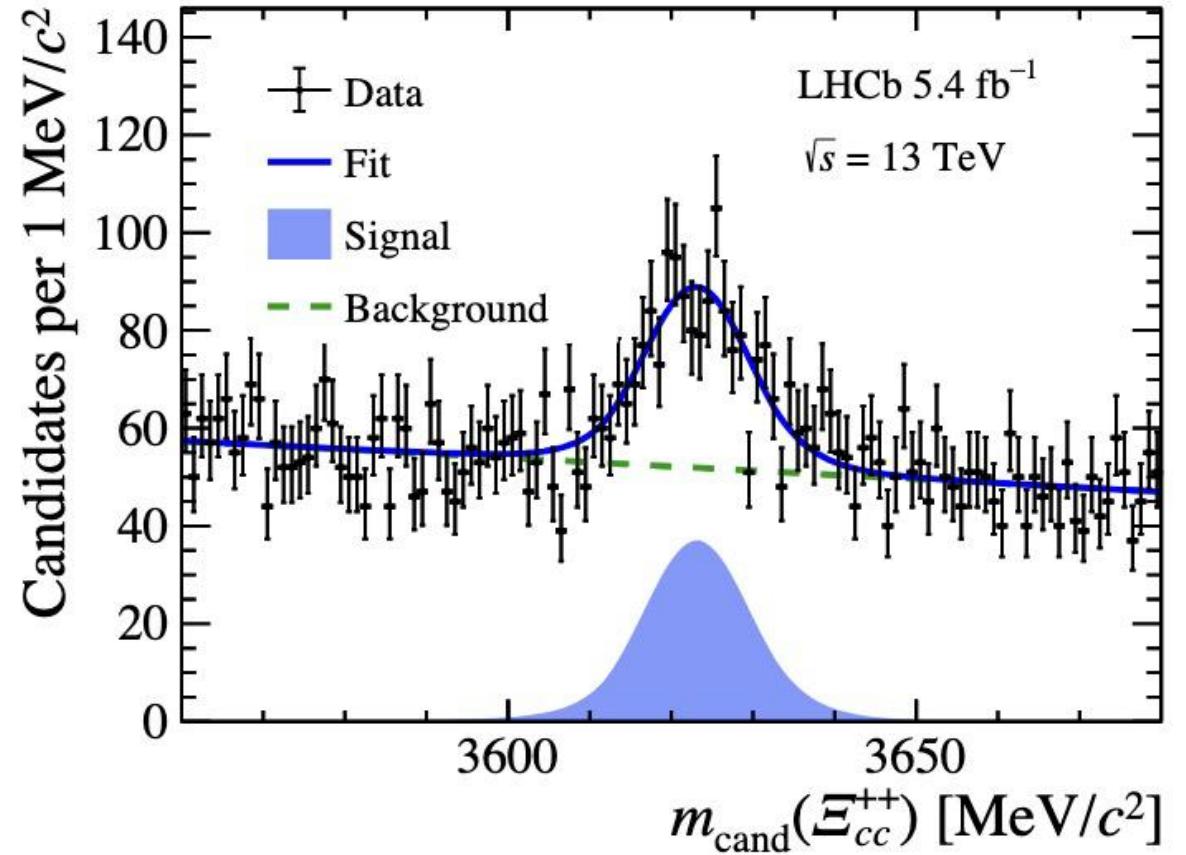
Run-2 vs. Run-3 data



Signal yields in Run2

$\triangleright N(\Omega_{cc}^+) = 20 \pm 7$

$\triangleright N(\Xi_{cc}^{++}) = 644 \pm 65$

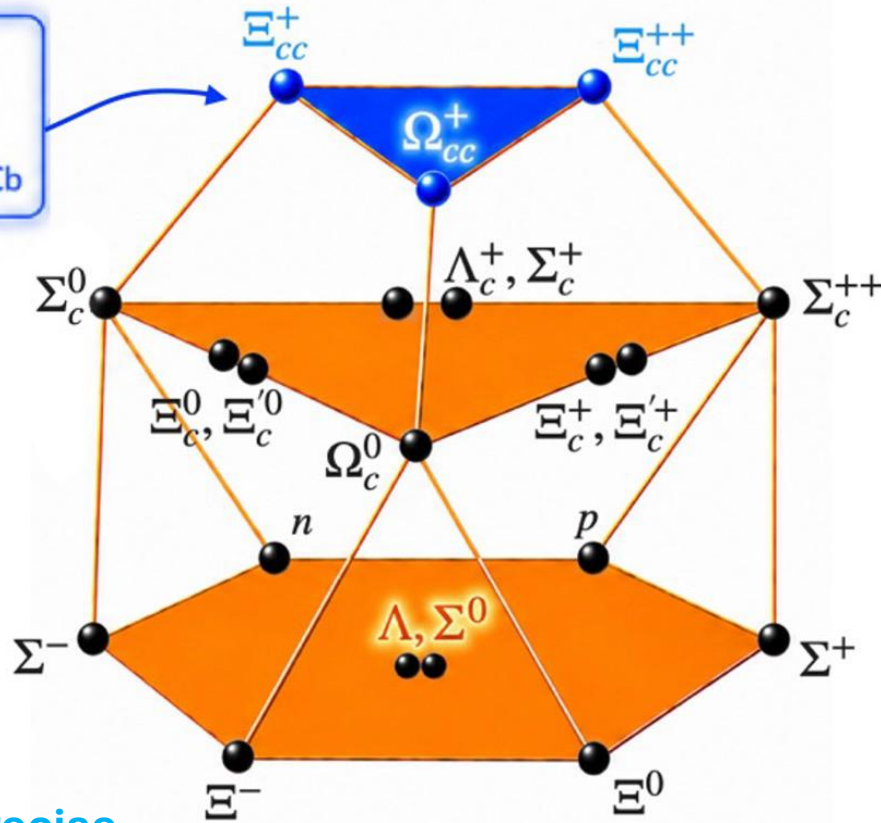


LHCb-PAPER-2026-022

Summary

LHCb
discoveries

All three new doubly charmed baryon states discovered by LHCb



Run-3 goals: precise measurements of lifetimes and search for other decay channels

Run-5 (LHCb Upgrade-II)

