Charm quark physics

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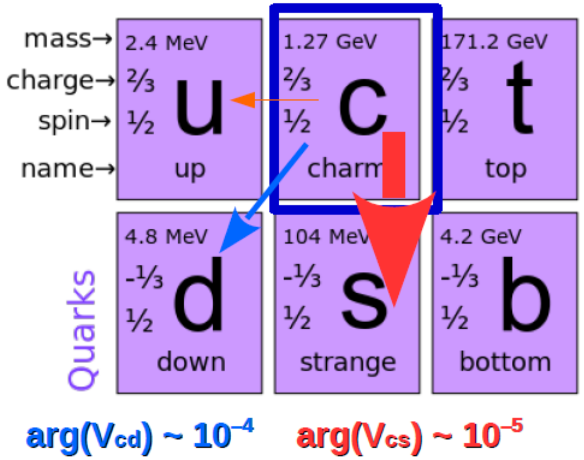
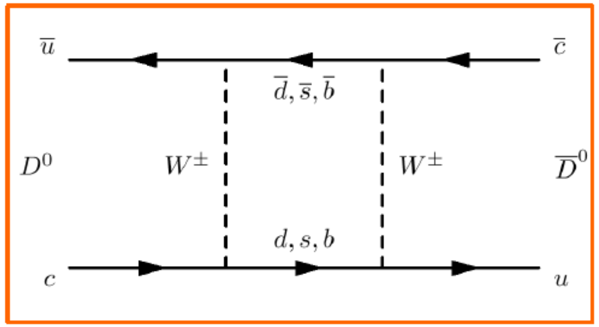
Scope of this talk

What are main goals of charm physics at LHCb?

- CP violation at charm sector
- Indirect searches of New Physics in loops
- Further QCD development with heavy baryons and exotica.



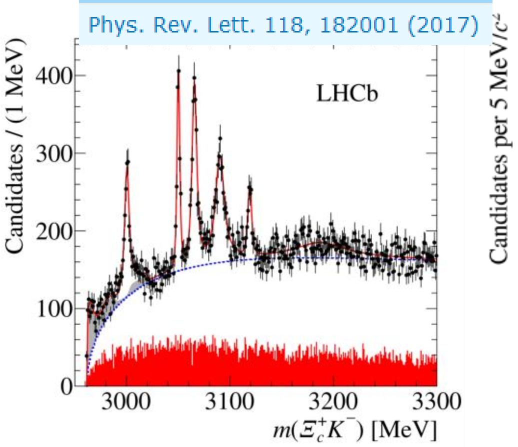


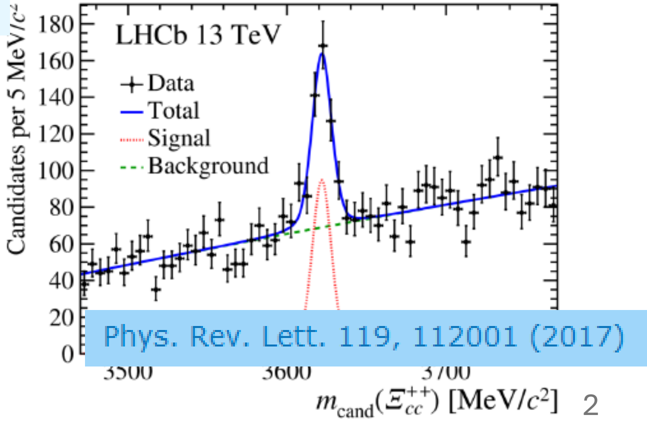
Mixing / FCNC

- **Summary of LHCb results in charm sector** (Charm Physics Analysis Working Group)

Also, I'd like to

- Show advantages of HEP hadronic machines as the tool for charm
- Remind how LHCb works



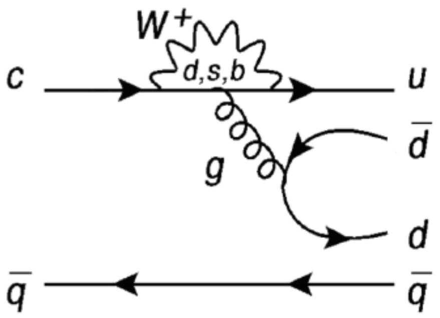


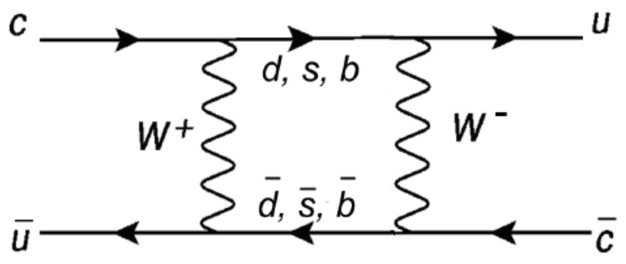
CPV at charm sector & New Physics in loops

$$
\begin{array}{cccc}
 & d & s & b & \\
V^{CKM}_{\text{Wolf}} = & \left(\begin{array}{c} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8} \\ -\frac{\lambda^6}{16}[1+8A^2(\rho^2+\eta^2)]\,, \end{array}\right. & \lambda\,, & \left.A\lambda^3(\rho-i\eta)\right) & u \\
 & -\lambda+\underline{\frac{\lambda^5}{2}A^2(1-2\rho-2i\eta)}\,, & \begin{array}{c} 1-\frac{\lambda^2}{2}-\frac{\lambda^4}{8}(1+4A^2) \\ \underline{-\frac{\lambda^6}{16}[1-4A^2(1-4\rho-4i\eta)]}\,, \end{array} & A\lambda^2 & c \\
 & \begin{array}{c} A\lambda^3(1-\rho-i\eta) \\ +\frac{\lambda^5}{2}A(\rho+i\eta)\,, \end{array} & \begin{array}{c} -A\lambda^2+\frac{\lambda^4}{2}A(1-2\rho-2i\eta) \\ +\frac{\lambda^6}{8}A\,, \end{array} & \begin{array}{c} 1-\frac{\lambda^4}{2}A^2 \\ -\frac{\lambda^6}{2}A^2(\rho^2+\eta^2) \end{array} & t
\end{array}
$$

$$+\,\mathcal{O}(\lambda^7)$$

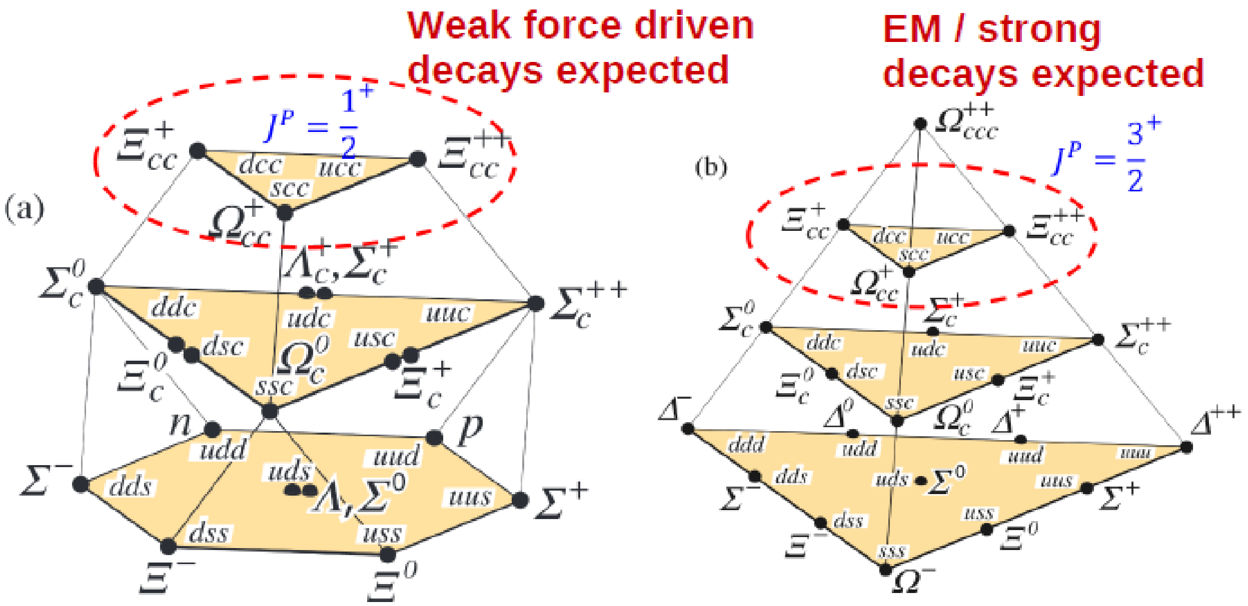
$\lambda = 0.2257^{+0.0009}_{-0.0010}$, $A = 0.814^{+0.021}_{-0.022}$, $\rho = 0.135^{+0.031}_{-0.016}$, and $\eta = 0.349^{+0.015}_{-0.017}$.





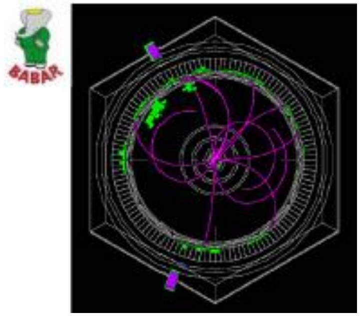
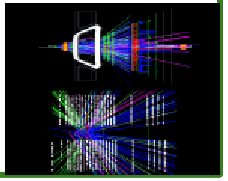
- CKM matrix provides clear prediction of very small CPV in charm sector (***D***-mesons are the only up-type quark system, where mixing and CPV can occur)
- New Physics in loop-diagrams driven processes, which are very suppressed in the SM (Keeping in mind: long-distance contributions, for which precise theoretical predictions are difficult, but can play important role)
- Need a lot of $c\bar{c}$ for discoveries

Better understanding of QCD



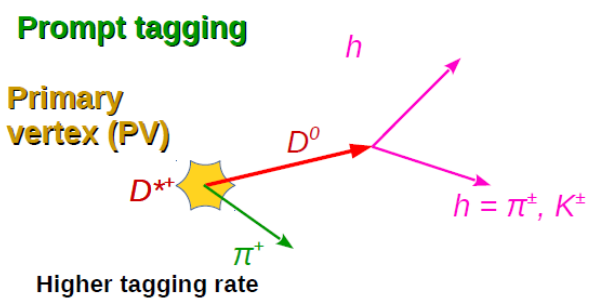
- QCD is a natural part of the SM
- Chiral perturbation theory is valid between 0.1 and 1 GeV
- Perturbative QCD calculations >> 1 GeV
- Although charm hadrons are in between of these two regimes, due to high **c** mass double and triple charm systems, as well as exotica are kind of natural bridges for QCD development
- Need intensive charm source to produce such bound systems

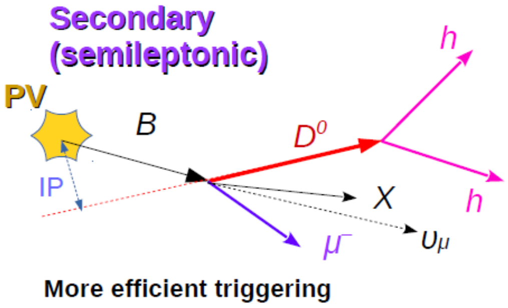
Machines for charm studies (Luminosity / $N_{c\bar{c}}$)

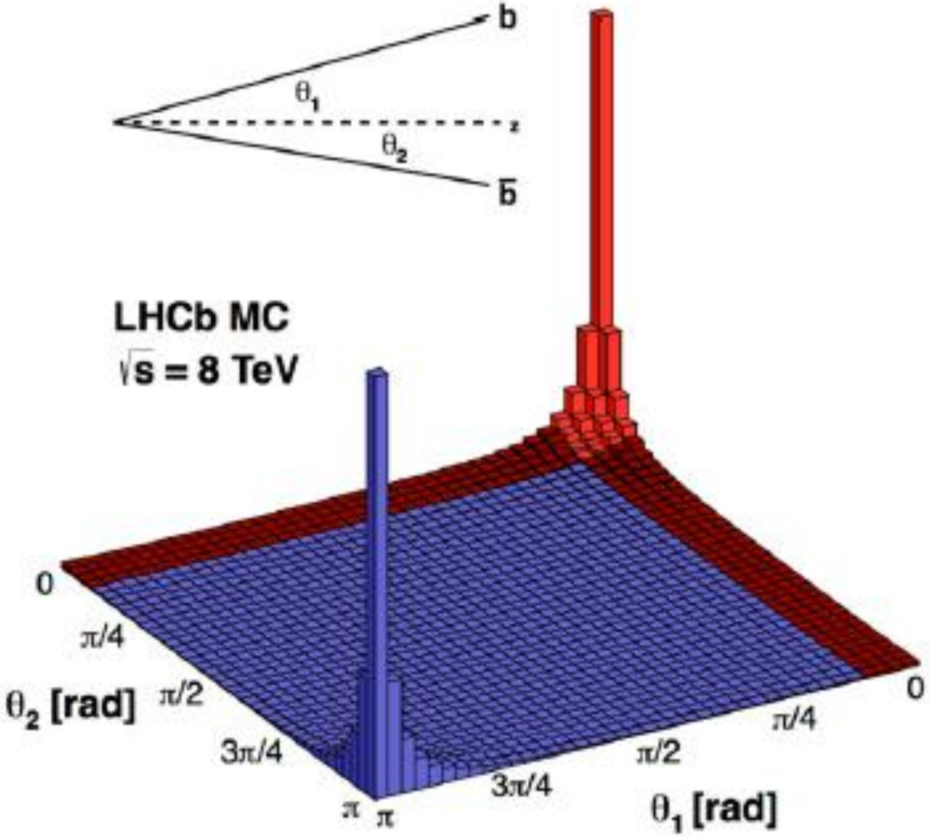
	At threshold	Higher energies
e^+e^- colliders	**CLEO-c** (0.8 fb^{-1} / $5*10^6$) / **BESIII** (3fb^{-1} / $2*10^7$) In future **Super-tau-charm Factories (??)** • at *ψ(3770)* resonance • Quantum coherence, which allows to measure strong phase • Almost no background • No boost – no lifetime measurements • Small sample size	**Belle** (1 ab^{-1} / $13*10^8$) / **BaBar** (550 fb^{-1} / $8*10^8$) In future **Belle2** (50 ab^{-1}) • Neutrals / neutrino studies • Clean environment • Lifetime studies possible 
hadron machines	In future **PANDA (??)** • Selective to hadron production thresholds • Production cross sections measurements • Polarization studies possible • no lifetime measurements / not large sample	**CDF** (10 fb^{-1} / $23*10^{10}$) / **LHCb** (9 fb^{-1} / $1.4*10^{13}$) In future **LHCb Upgraded** (→ 50 fb^{-1} → 300 fb^{-1}) • **Huge rates** • **Excellent lifetime resolution due to the boost** • **Large backgrounds** • **Difficult to work with neutral** 

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***







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

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

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

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

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

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

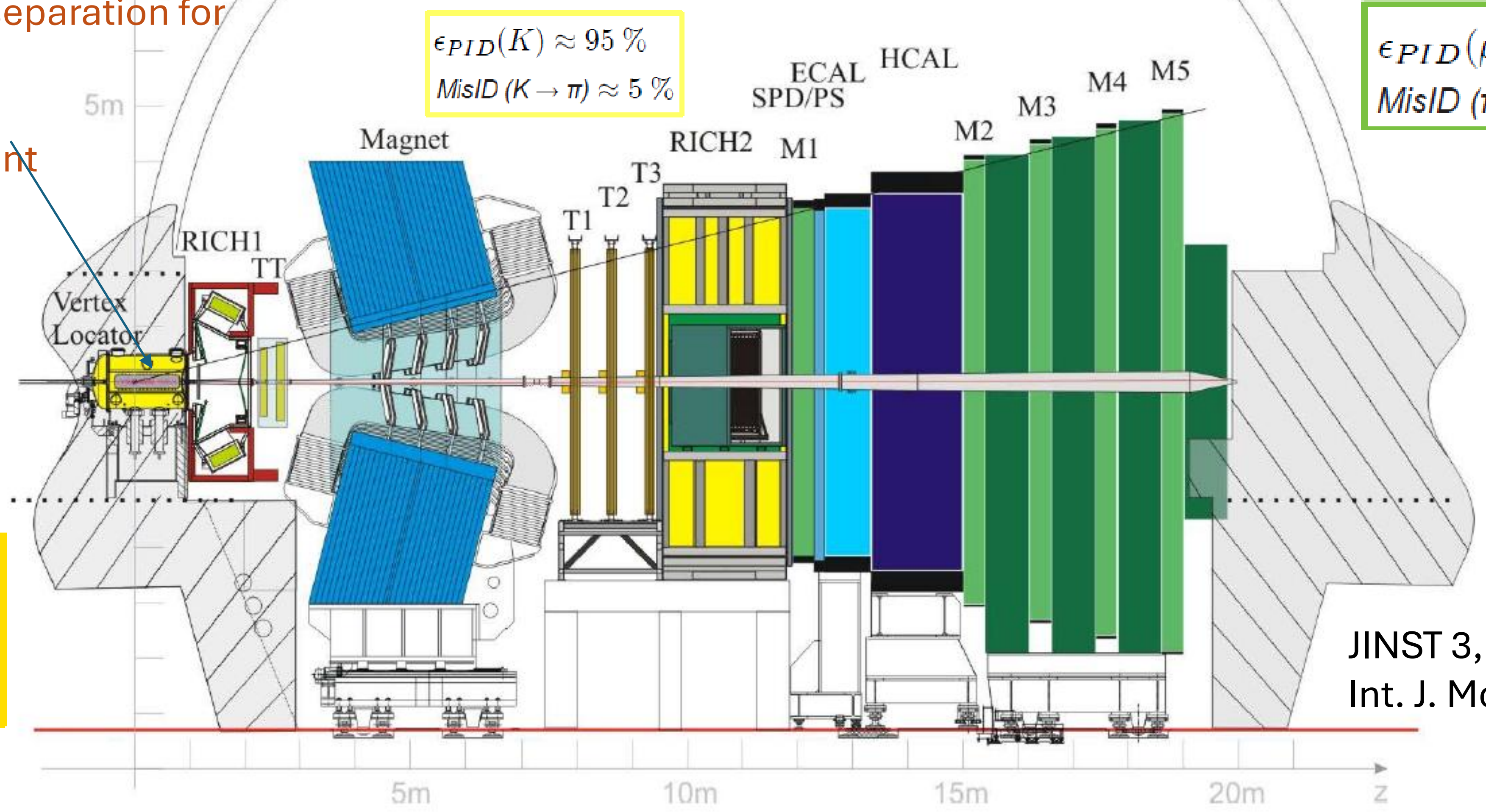
$MisID\ (K \to \pi) \approx 5\ \%$

Excellent tracking

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

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

$MisID\ (\pi \to \mu) \approx 3\ \%$

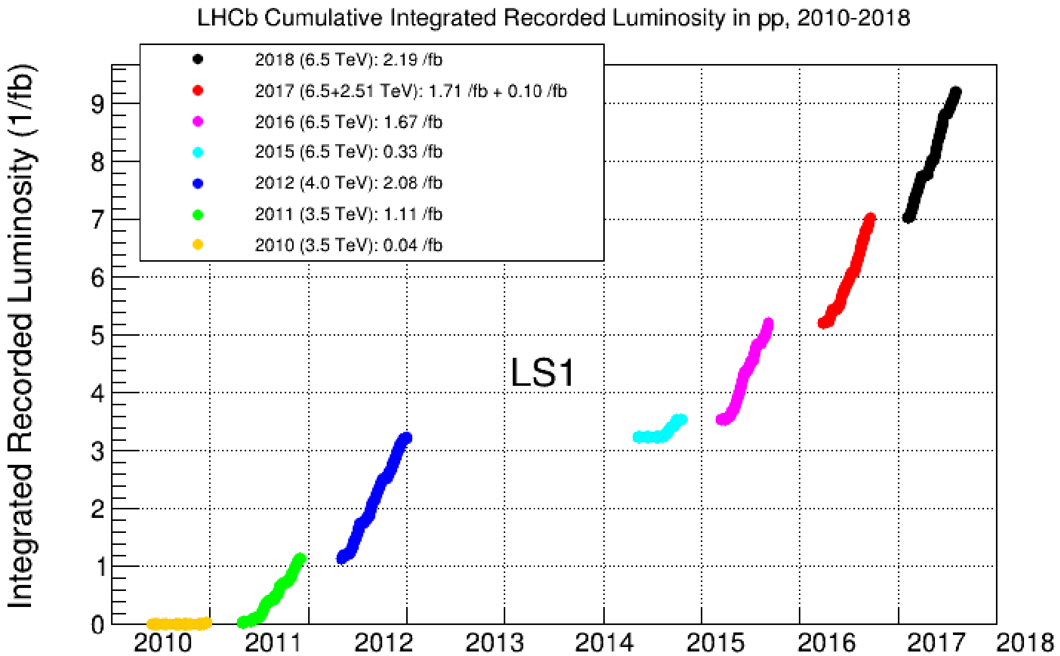


JINST 3, (2008) S08005; Int. J. Mod. Phys. A 30, (2015) 153022

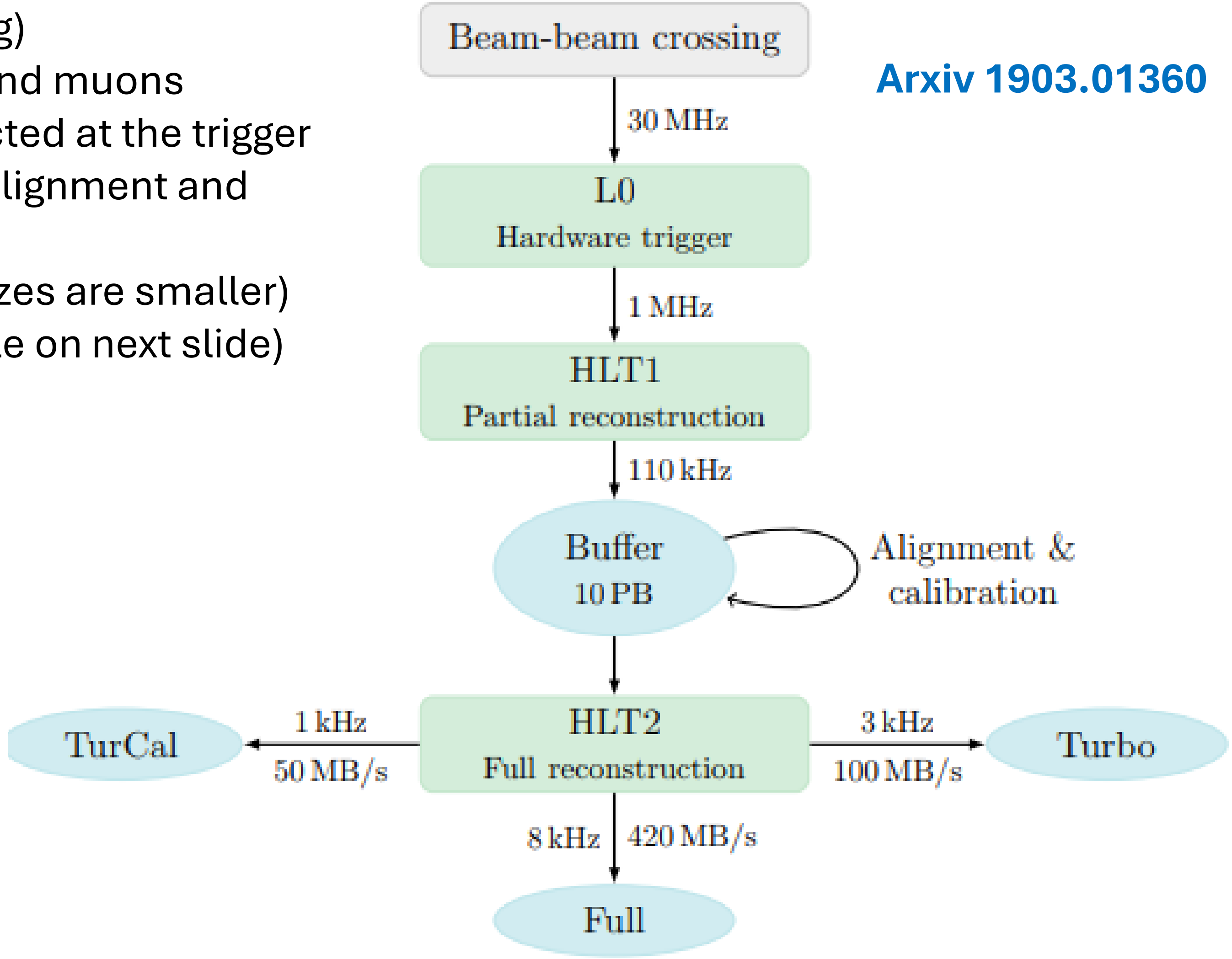
Luminosity and trigger

Comput. Phys. Commun. 208 35-42
Int. J. Mod. Phys. A 30, 1530022 (2015)

- 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)
  - widely used for charm analyses (see example on next slide)



Arxiv 1903.01360



Production and spectroscopy

```
}-> Production
      |-> Cross sections
      |-> Asymmetries
      |-> Polarisation
|-> New hadrons
      |-> D_{sJ}
      |-> Excited baryons
      |-> Doubly charmed systems
            |-> Doubly charmed baryon
            |-> Doubly charmed exotic meson
}-> New decay modes
      |-> Suppressed decays
            |-> Cabibbo-suppressed
            }-> Doubly Cabibbo-suppressed
      }-> Amplitude analysis and branchings
            |-> Three-body decays`
            |-> Four-body decays
}-> Lifetimes
      |-> Charmed baryons
      |-> Doubly charmed baryons
```

Couple of examples

Production and spectroscopy

JHEP 06 (2017) 147

```
}-> Production
    |-> Cross sections
    |-> Asymmetries
    |-> Polarisation
|-> New hadrons
    |-> D_{sJ}
    |-> Excited baryons
    |-> Doubly charmed syste
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        |-> Doubly charmed
}-> New decay modes
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        }-> Doubly Cabibbo-suppressed
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 > Lifetimes
    |-> Charmed baryons
    |-> Doubly charmed baryons
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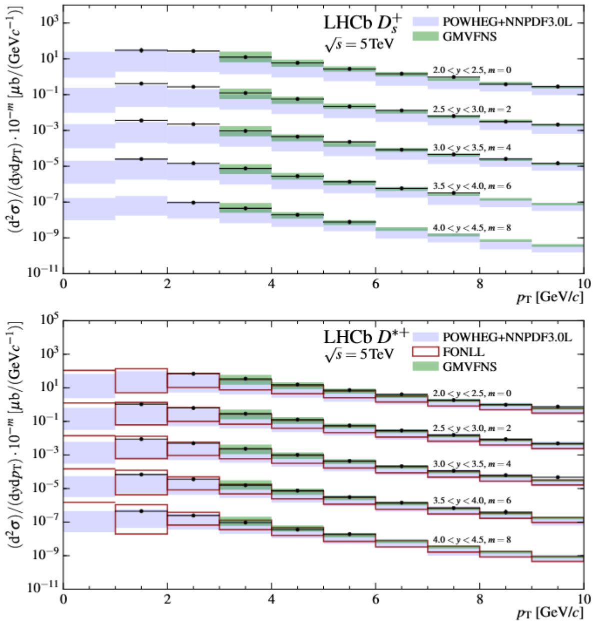
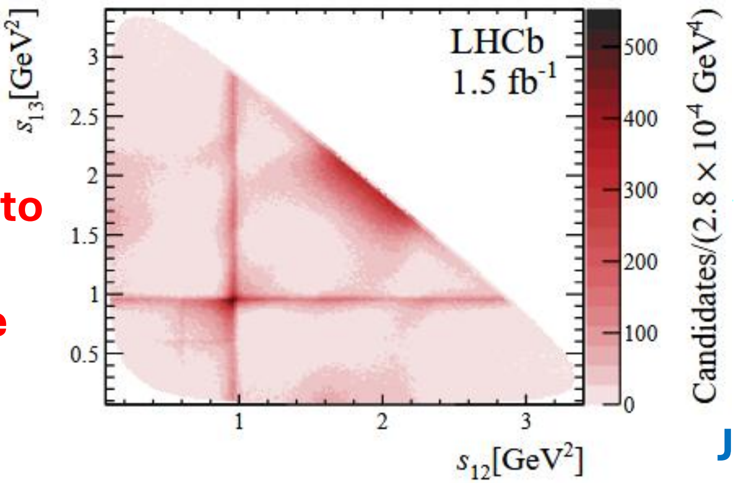


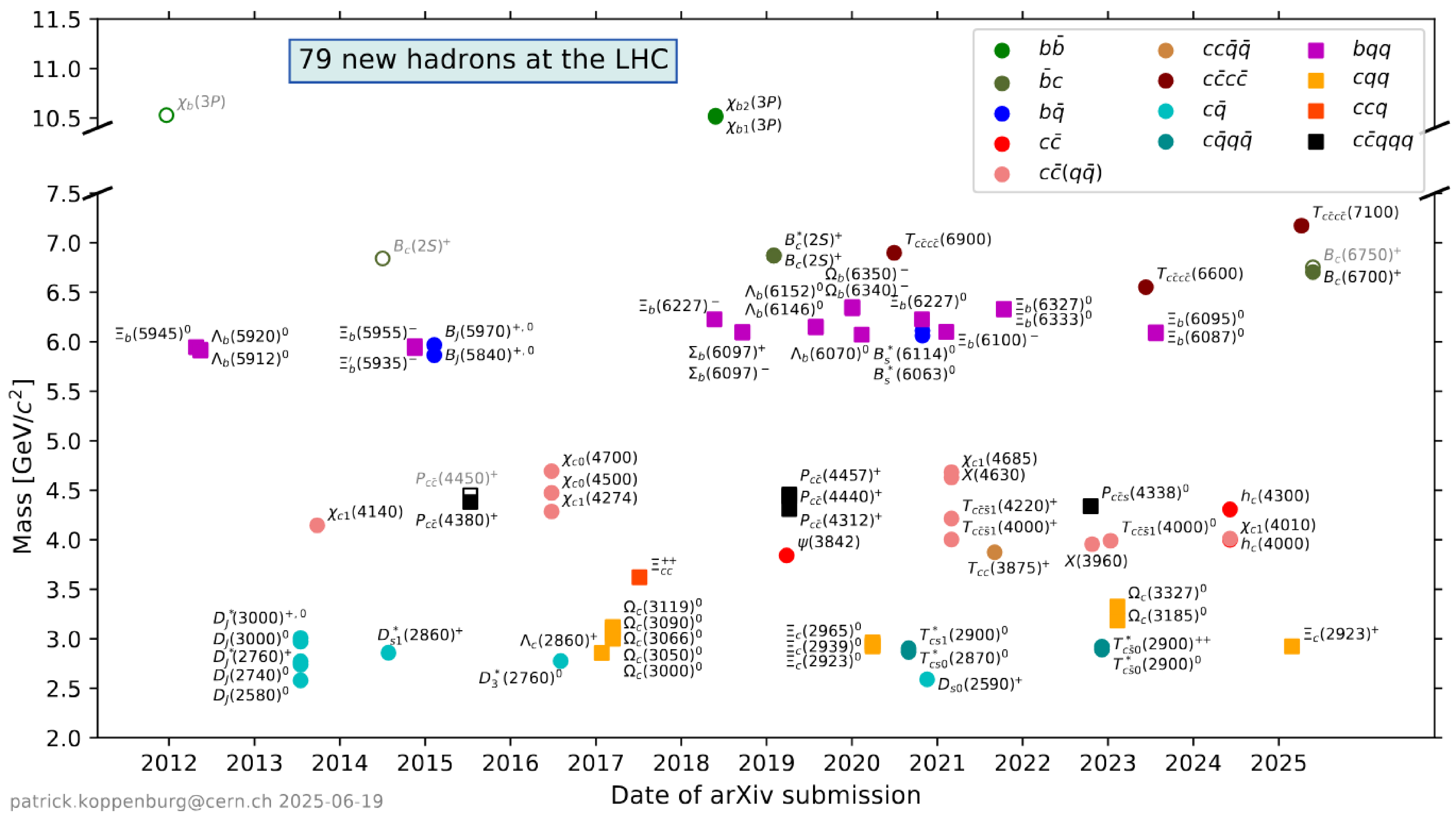
5,7,8 and 13 TeV data

$D_s^+ \to \pi^- \pi^+ \pi^+$



Huge rates leads to a opportunity to investigate phase space in greait details

JHEP 07 (2023) 204


79 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
$c\bar{c}qqq$
$\chi_b(3P)$
$\chi_{b2}(3P)$
$\chi_{b1}(3P)$
$B_c(2S)^+$
$B_c^*(2S)^+$
$B_c(2S)^+$
$T_{c\bar{c}c\bar{c}}(6900)$
$T_{c\bar{c}c\bar{c}}(7100)$
$T_{c\bar{c}c\bar{c}}(6600)$
$B_c(6750)^+$
$B_c(6700)^+$
$\Omega_b(6350)^-$
$\Omega_b(6340)^-$
$\Lambda_b(6152)^0$
$\Lambda_b(6146)^0$
$\Xi_b(6227)^-$
$\Xi_b(6227)^0$
$\Xi_b(6327)^0$
$\Xi_b(6333)^0$
$\Xi_b(6095)^0$
$\Xi_b(6087)^0$
$\Xi_b(6100)^-$
$\Sigma_b(6097)^+$
$\Sigma_b(6097)^-$
$\Lambda_b(6070)^0$
$B_s^*(6114)^0$
$B_s^*(6063)^0$
$\Xi_b(5945)^0$
$\Lambda_b(5920)^0$
$\Lambda_b(5912)^0$
$\Xi_b(5955)^-$
$\Xi_b'(5935)^-$
$B_J(5970)^{+,0}$
$B_J(5840)^{+,0}$
$\chi_{c0}(4700)$
$\chi_{c0}(4500)$
$\chi_{c1}(4274)$
$\chi_{c1}(4140)$
$P_{c\bar{c}}(4450)^+$
$P_{c\bar{c}}(4380)^+$
$P_{c\bar{c}}(4457)^+$
$P_{c\bar{c}}(4440)^+$
$P_{c\bar{c}}(4312)^+$
$\psi(3842)$
$\chi_{c1}(4685)$
$X(4630)$
$T_{c\bar{c}\bar{s}1}(4220)^+$
$T_{c\bar{c}\bar{s}1}(4000)^+$
$T_{cc}(3875)^+$
$P_{c\bar{c}s}(4338)^0$
$T_{c\bar{c}\bar{s}1}(4000)^0$
$X(3960)$
$h_c(4300)$
$\chi_{c1}(4010)$
$h_c(4000)$
Ξ_{cc}^{++}
$\Omega_c(3119)^0$
$\Omega_c(3090)^0$
$\Omega_c(3066)^0$
$\Omega_c(3050)^0$
$\Omega_c(3000)^0$
$\Lambda_c(2860)^+$
$D_3^*(2760)^0$
$D_{s1}^*(2860)^+$
$D_J^*(3000)^{+,0}$
$D_J(3000)^0$
$D_J^*(2760)^+$
$D_J(2740)^0$
$D_J(2580)^0$
$\Xi_c(2965)^0$
$\Xi_c(2939)^0$
$\Xi_c(2923)^0$
$T_{cs1}^*(2900)^0$
$T_{cs0}^*(2870)^0$
$D_{s0}(2590)^+$
$\Omega_c(3327)^0$
$\Omega_c(3185)^0$
$T_{c\bar{s}0}^*(2900)^{++}$
$T_{c\bar{s}0}^*(2900)^0$
$\Xi_c(2923)^+$
Mass [GeV/c^2]
11.5
11.0
10.5
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
2012
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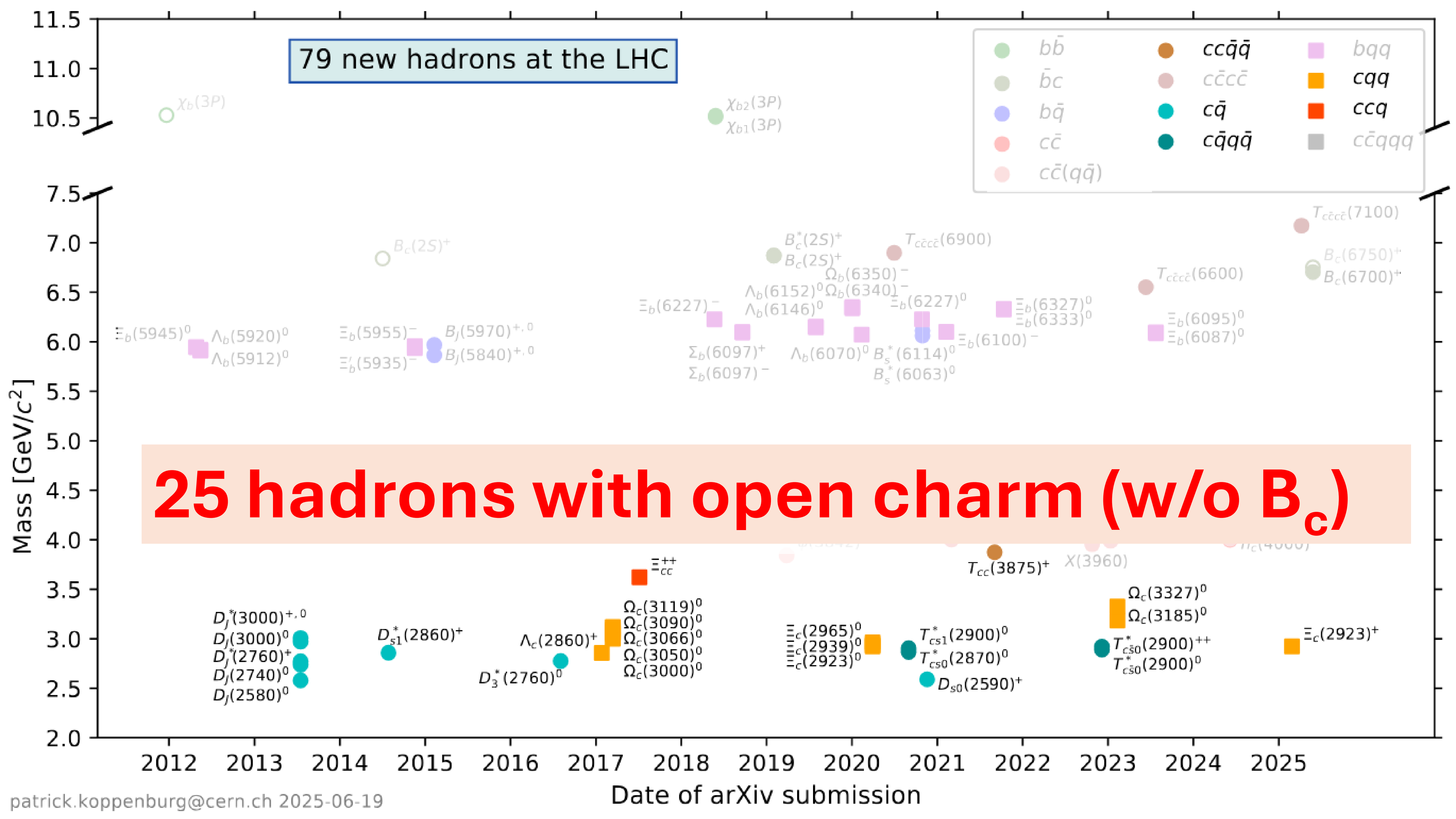
Date of arXiv submission
patrick.koppenburg@cern.ch 2025-06-19



79 new hadrons at the LHC
25 hadrons with open charm (w/o B_c)
Mass [GeV/c^2]
Date of arXiv submission
bb̄
b̄c
bq̄
cc̄
cc̄(qq̄)
ccq̄q̄
cc̄cc̄
cq̄
cq̄qq̄
bqq
cqq
ccq
cc̄qqq
χb(3P)
χb2(3P)
χb1(3P)
Bc(2S)+
Bc*(2S)+
Bc(2S)+
Tcc̄cc̄(6900)
Tcc̄cc̄(6600)
Tcc̄cc̄(7100)
Bc(6750)+
Bc(6700)+
Ξb(5945)0
Λb(5920)0
Λb(5912)0
Ξb(5955)−
Ξb′(5935)−
BJ(5970)+,0
BJ(5840)+,0
Ξb(6227)−
Σb(6097)+
Σb(6097)−
Λb(6152)0
Λb(6146)0
Ωb(6350)−
Ωb(6340)−
Λb(6070)0
Ξb(6227)0
Bs*(6114)0
Bs*(6063)0
Ξb(6100)−
Ξb(6327)0
Ξb(6333)0
Ξb(6095)0
Ξb(6087)0
Ξcc++
Tcc(3875)+
X(3960)
DJ*(3000)+,0
DJ(3000)0
DJ*(2760)+
DJ(2740)0
DJ(2580)0
Ds1*(2860)+
Λc(2860)+
D3*(2760)0
Ωc(3119)0
Ωc(3090)0
Ωc(3066)0
Ωc(3050)0
Ωc(3000)0
Ξc(2965)0
Ξc(2939)0
Ξc(2923)0
Tcs1*(2900)0
Tcs0*(2870)0
Ds0(2590)+
Ωc(3327)0
Ωc(3185)0
Tcs̄0*(2900)++
Tcs̄0*(2900)0
Ξc(2923)+
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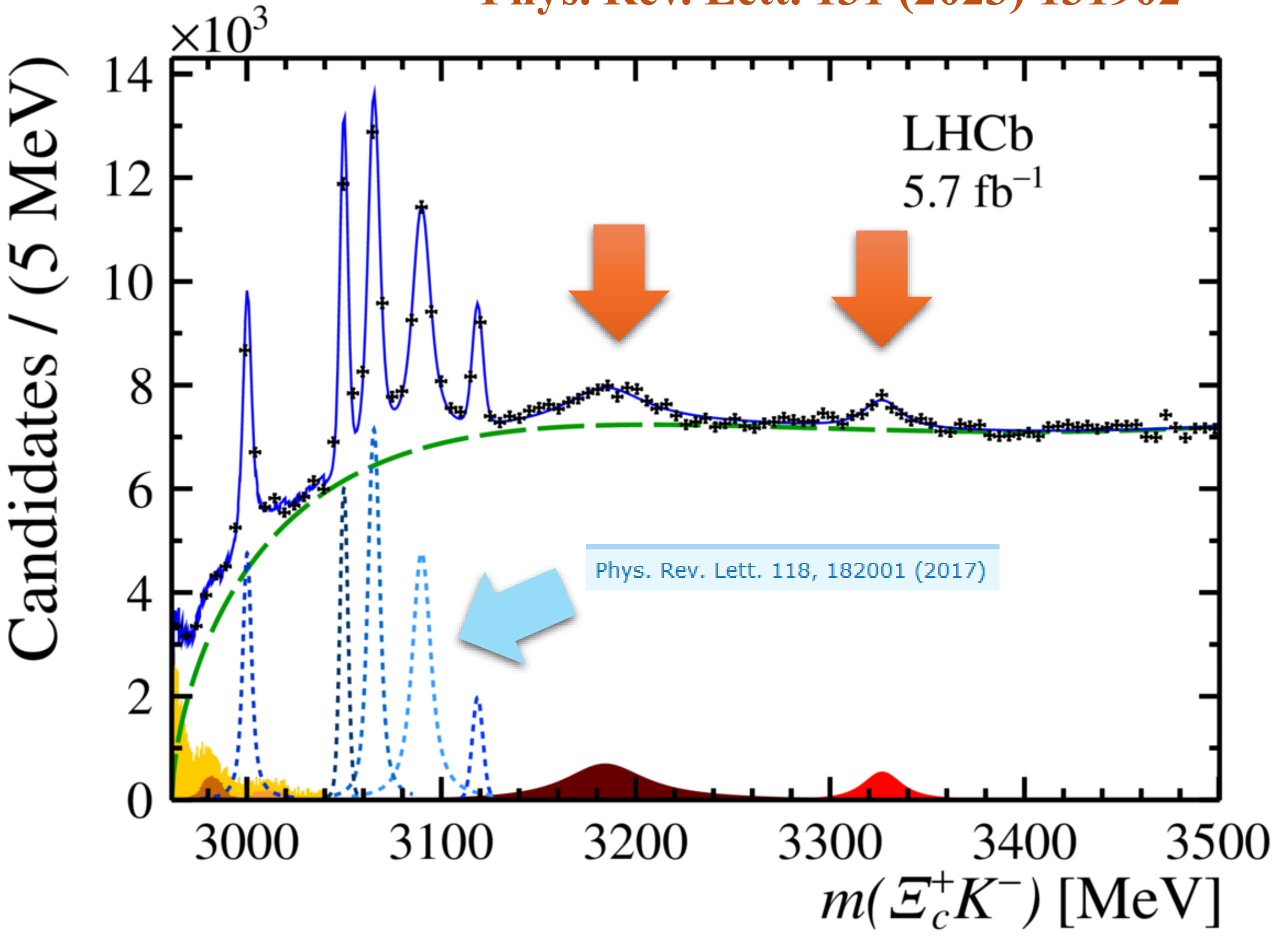
$\Omega_c(3185)^0$ и $\Omega_c(3327)^0$

- In 2015 году LHCb announced simultaneous discovery of **five new excited states** of Ω_c^{*0}, which were observed in the $\Xi_c^+K^-$ decay channel
- These investigations have been continued with LHCb Run-2 data.
- New analysis demonstrated **two more broad (resonant) structures** in $\Xi_c^+K^-$ spectrum.

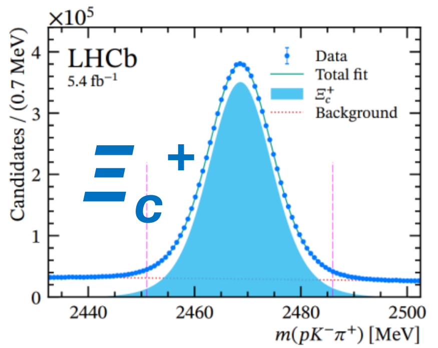
Phys. Rev. Lett. 131 (2023) 131902

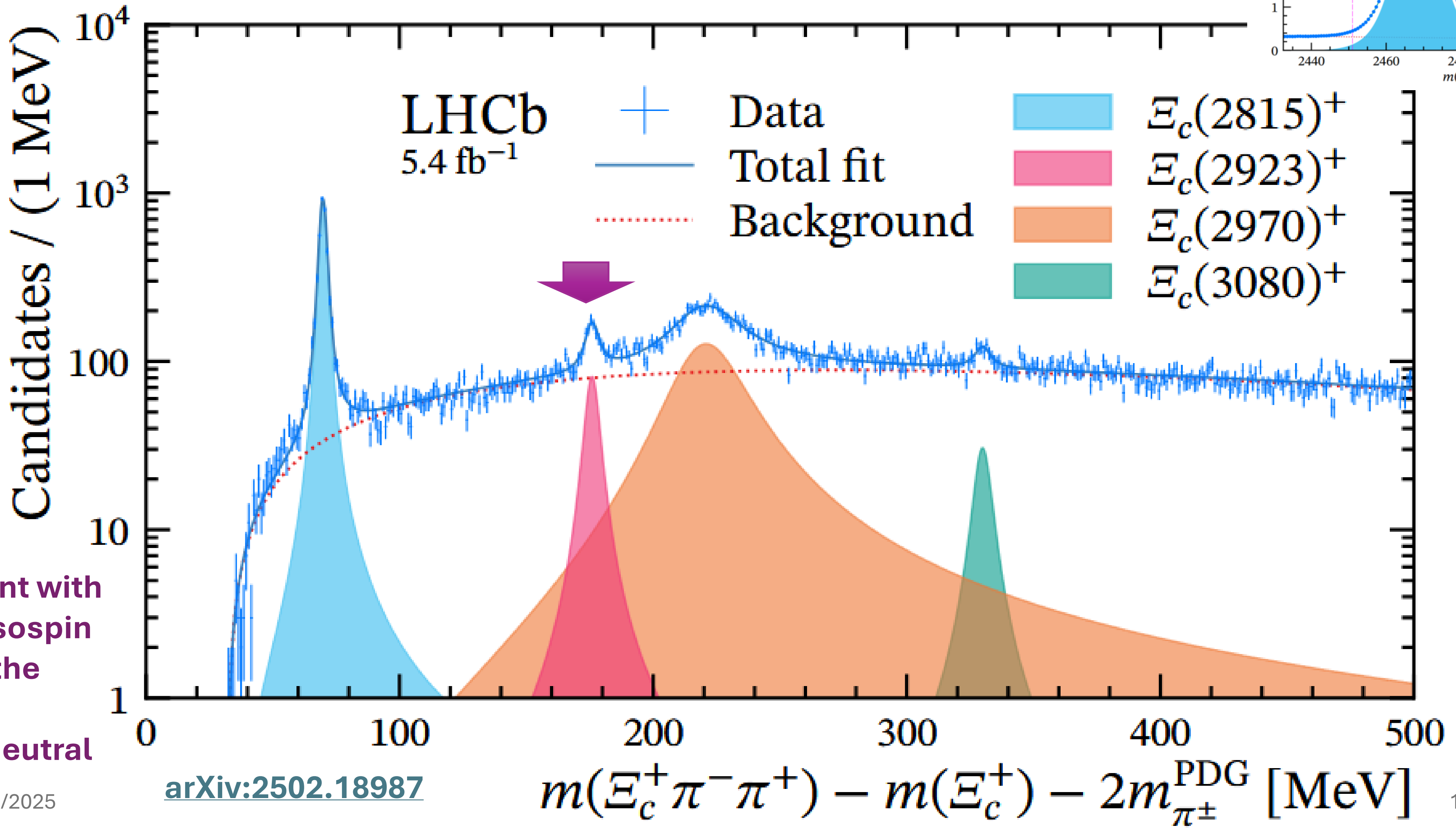


$\Omega_c(3185)^0$: m = $3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2$ MэВ/c^2 $\Gamma = 50 \pm 7^{+10}_{-20}$ MэВ

$\Omega_c(3327)^0$: m = $3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2$ MэВ/c^2 $\Gamma = 20 \pm 5^{+13}_{-1}$ MэВ

Observation of $\Xi_c(2923)^+$





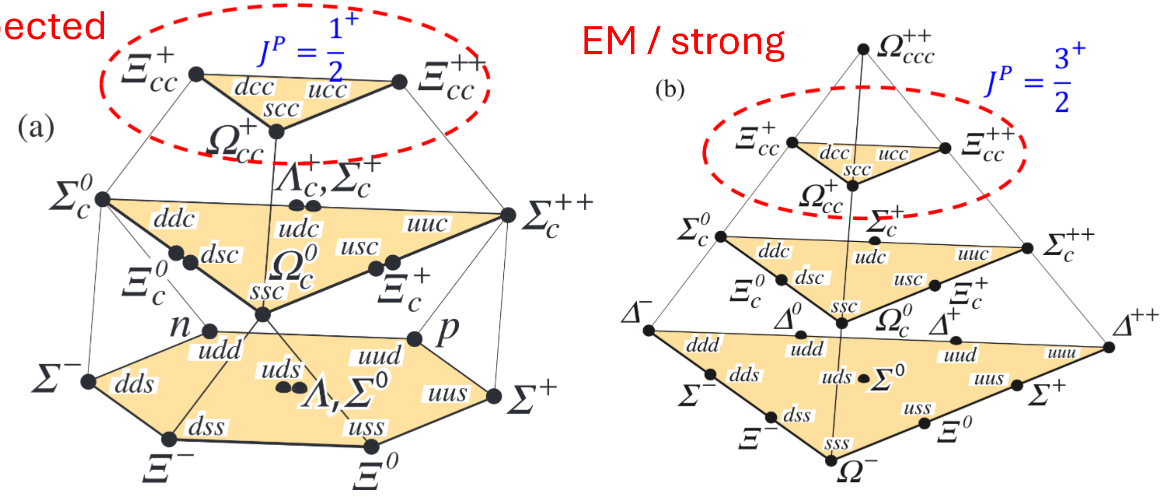
Is consistent with being the isospin partner of the previously observed neutral state

arXiv:2502.18987

Discovery of Ξ_{cc}^{++}

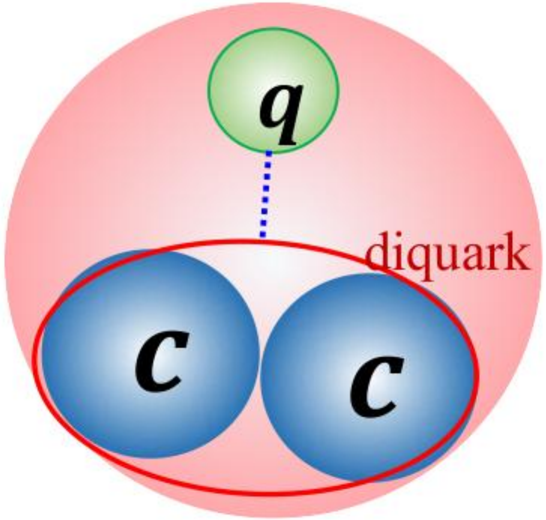
Weak force driven decays expected

EM / strong



- Two SU3 triplets are predicted as parts of two SU4 baryons 20-plets
- Many predictions:
  - M($\Xi_{cc}^{++,+}$) in [3.5-3.7] GeV
  - M(Ω_{cc}) ≈ M(Ξ_{cc}) + 0.1 GeV
- Few MeV isospin splitting between Ξ_{cc}^{++} and Ξ_{cc}^{+}
- Lattice QCD: M($\Xi_{cc}^{++,+}$) ≈ 3.6 GeV, M(Ω_{cc}) ≈ 3.7 GeV
- HQET: core from heavy diquark
- Lifetimes predictio $\tau(\Xi_{cc}^{++}) \in [\,200 - 700]$ fs

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

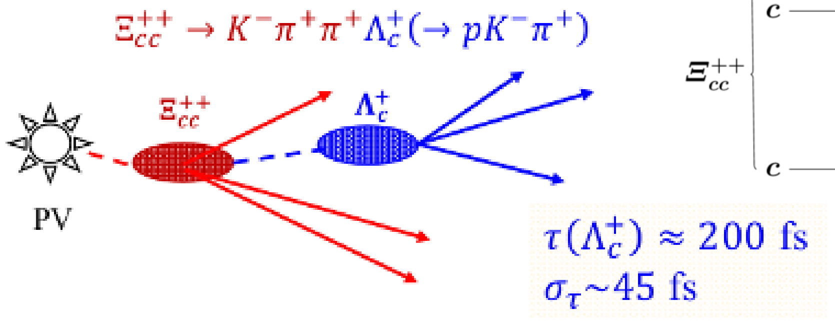


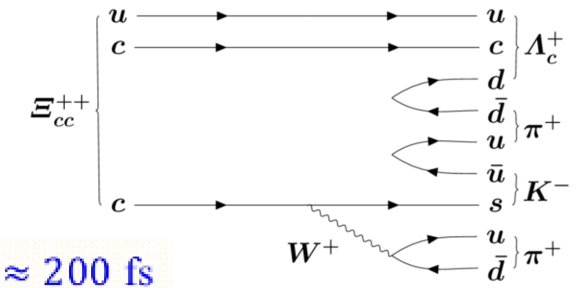
Doubly heavy baryon expected to be similar to a heavy *Qq* meson

Ref. to theory papers in backup

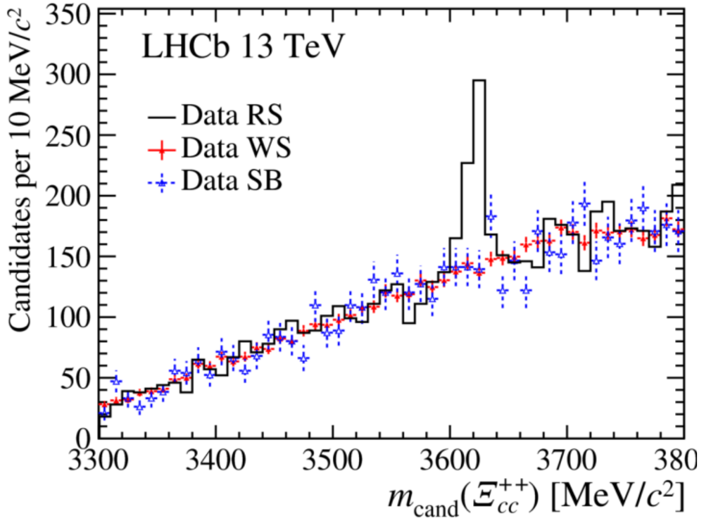
PHYS. REV. LETT. 119, 112001

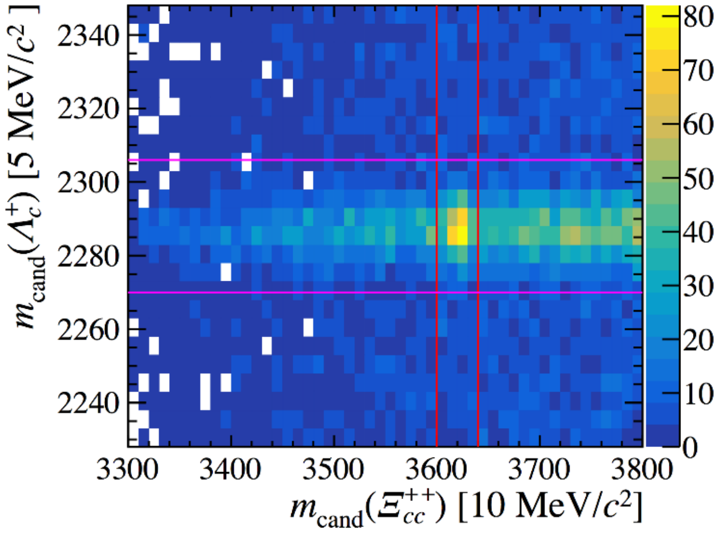
Discovery of Ξ_{cc}^{++}

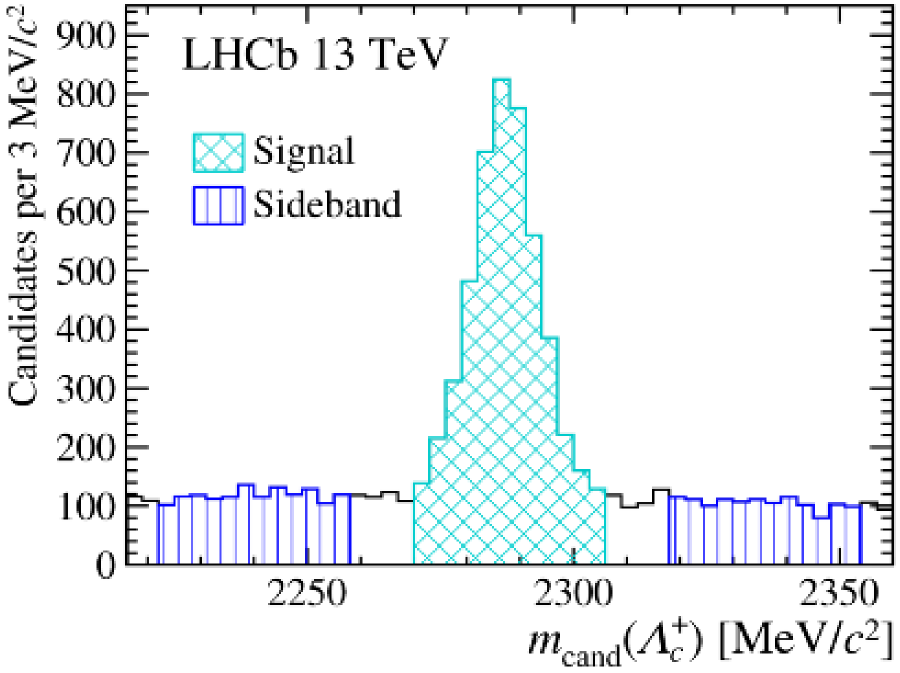




- Use Run II data 1.7 fb^{-1}, exclusive high efficient trigger (Turbo) / result is confirmed with Run-I data 2 fb^{-1}
- Expected up 10% branching fraction for decay of interest
- Cross check with different categor $\Lambda_c^+K^-\pi^+\pi^+$ion:
  - RS – right sign combination
  - WS – wrong sign $\Lambda_c^+K^-\pi^+\pi^-$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







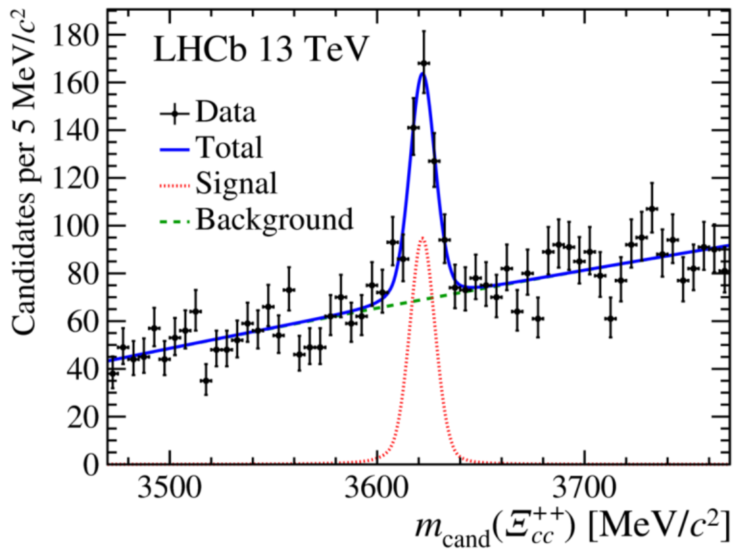
Discovery of Ξ_{cc}^{++}

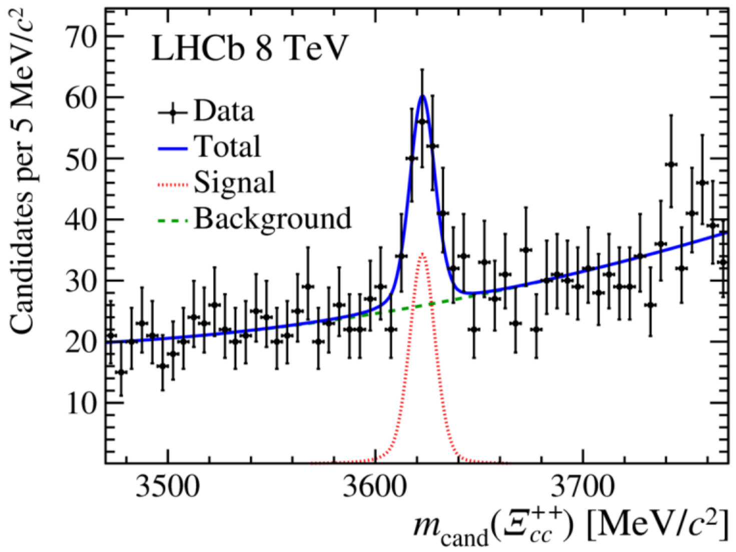
PHYS. REV. LETT. 119, 112001

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

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

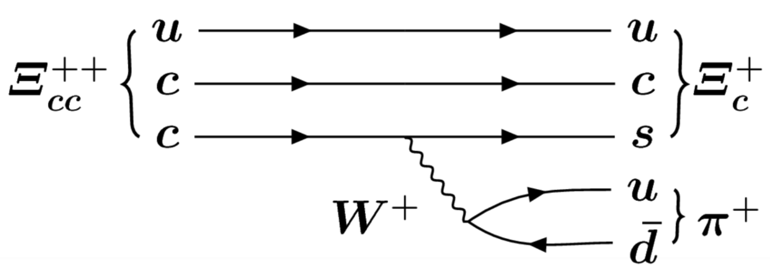
- Sub-MeV precision for observation
- Obtained values are consistent with many theoretical calculations (including LQCD)
- Weakly decay (as has ~0,25ps lifetime, see. next slides)



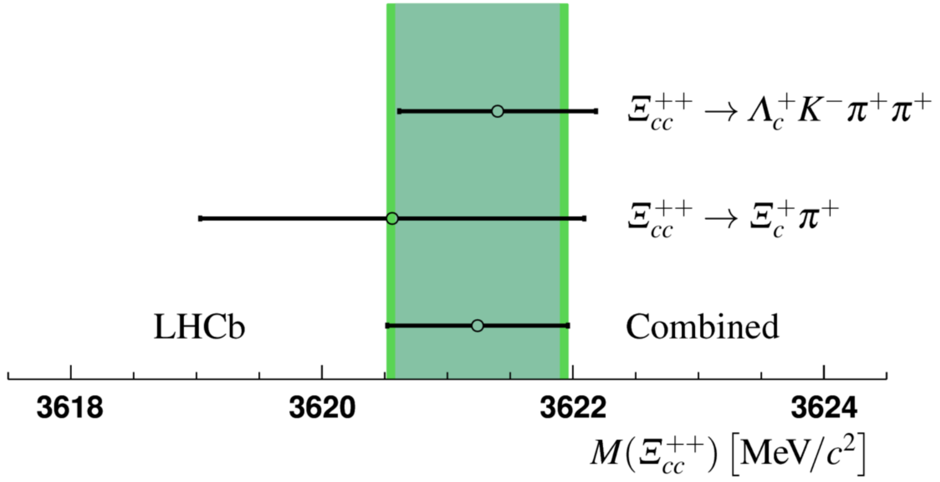


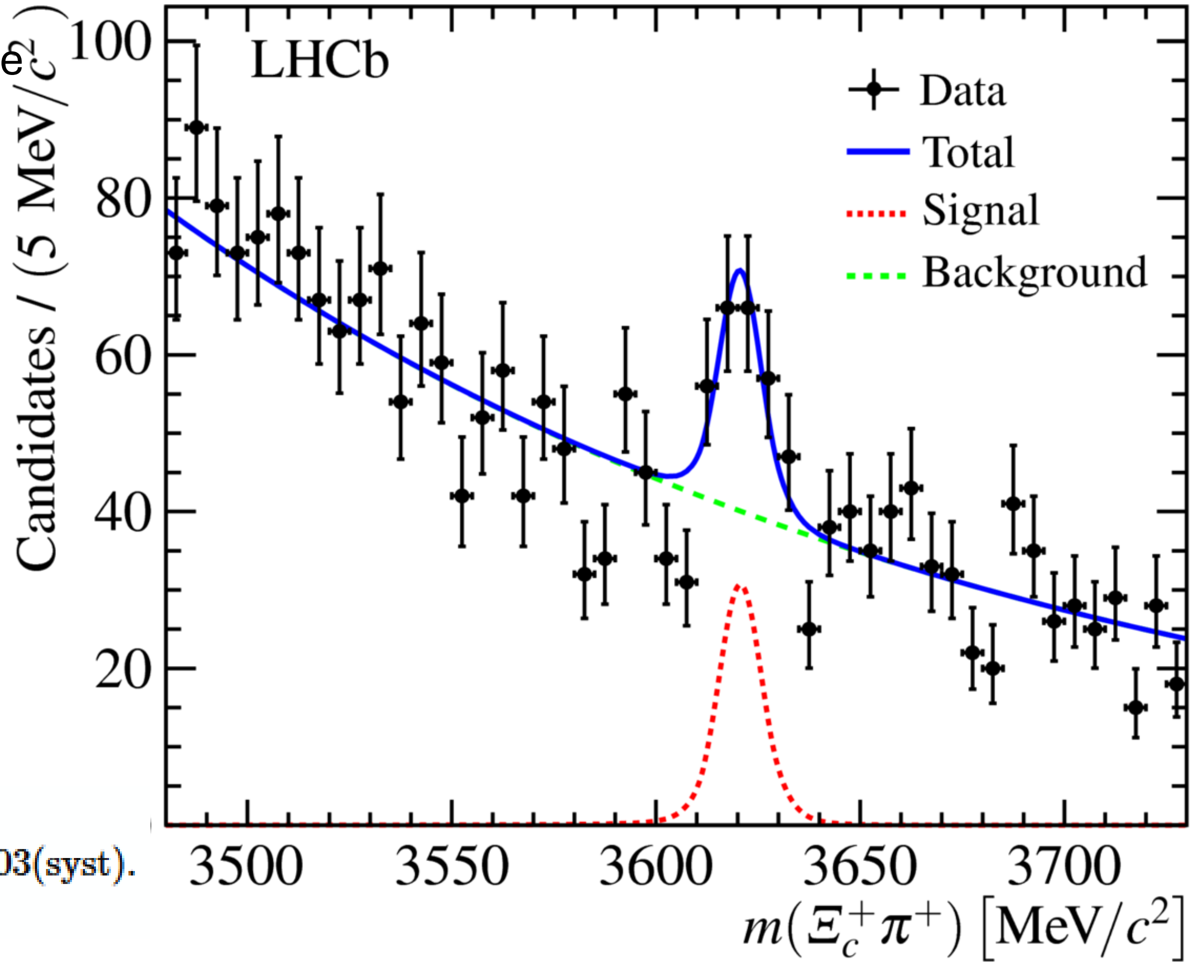
“Re-Discovery” of Ξ_{cc}^{++}

ARXIV:1807.01919



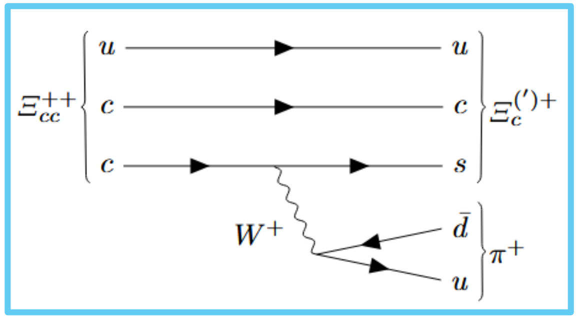
- Another channel with assumed high branching fraction
- Use Run II data 1.7 fb^{-1}
- Yield: 90 ± 20 candidates, corresponds 5.9σ significance
- Mass measurement is in agreement with previously measured value

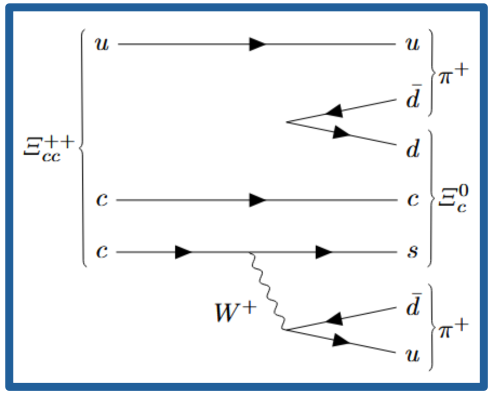


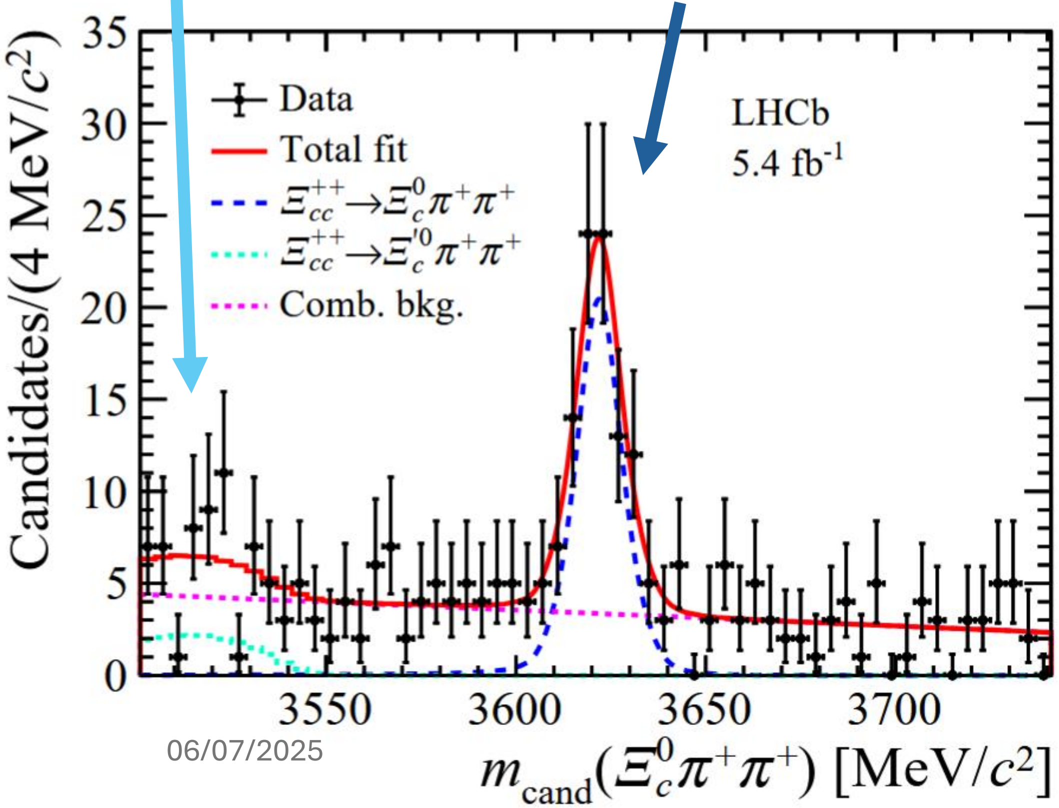


$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^+ \pi^+) \times \mathcal{B}(\Xi_c^+ \to pK^-\pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = 0.035 \pm 0.009(\text{stat}) \pm 0.003(\text{syst}).$$

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







- A search for the doubly-charmed-baryon decay $\Xi_{cc}^{++} \to \Xi_c^0 (\to pK^- K^- \pi^+)\pi^+\pi^+$ 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}.

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^0 \pi^+ \pi^+) \times \mathcal{B}(\Xi_c^0 \to pK^- K^- \pi^+)}{\mathcal{B}(\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+) \times \mathcal{B}(\Lambda_c^+ \to pK^- \pi^+)} = $$

$$= \; 0.105 \pm 0.014\,(\text{stat}) \pm 0.007\,(\text{syst})$$

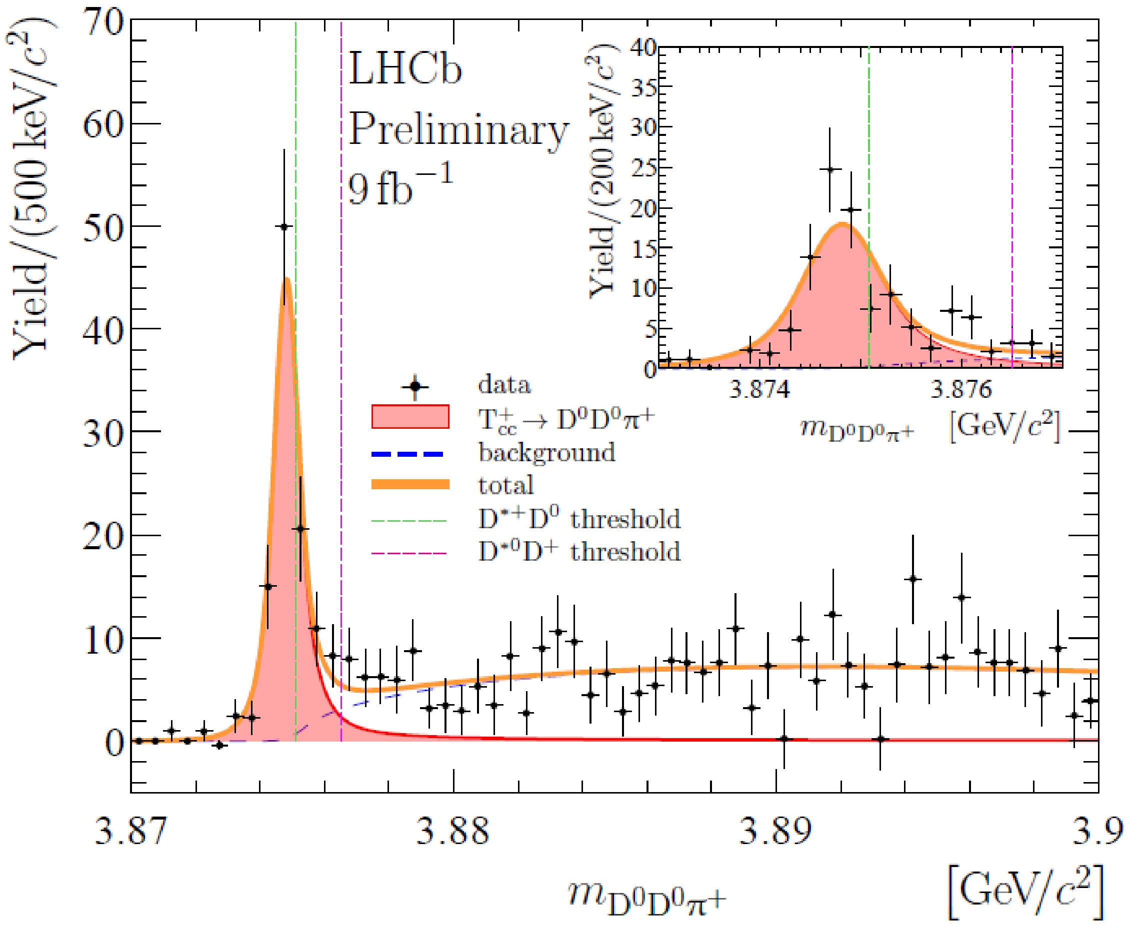
arXiv:2504.05063

Discovery of doubly charmed tetraquark

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

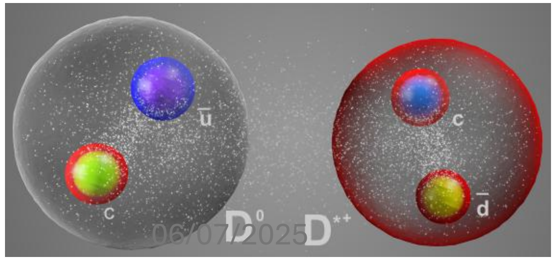
Nature Physics **18**, 751–754 (2022)

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



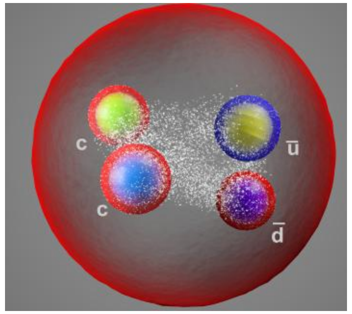
$D^0D^0\pi^+$ **mass spectrum with the approximation. In addition *T_{cc}^+* mass region is shown. Vertical lines corresponds to thresholds for production of pairs: *D^+D^{*0}* and *D^0D^{*+}***

Hadronic molecule



or

Compact hadrocharmonium-like state



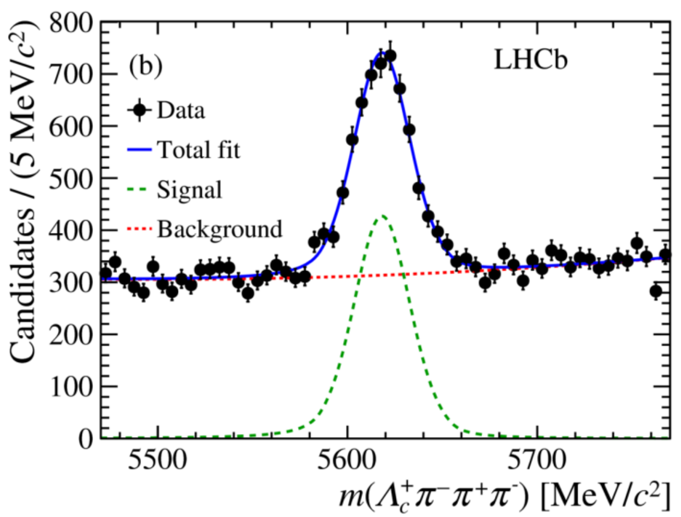
?

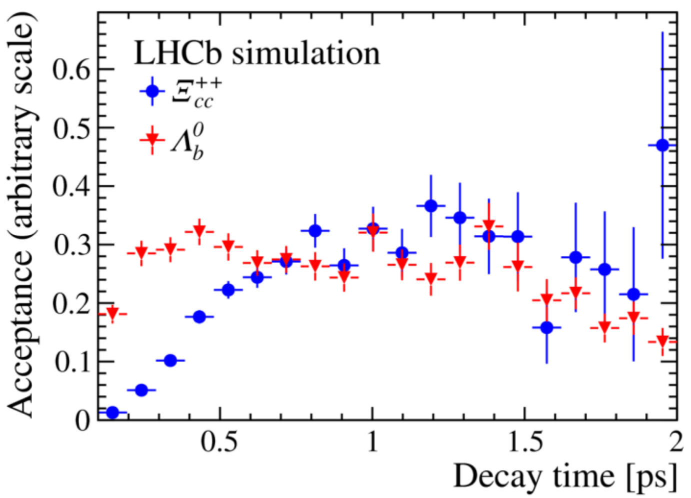
PHYS. REV. LETT. 121, 052002

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

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

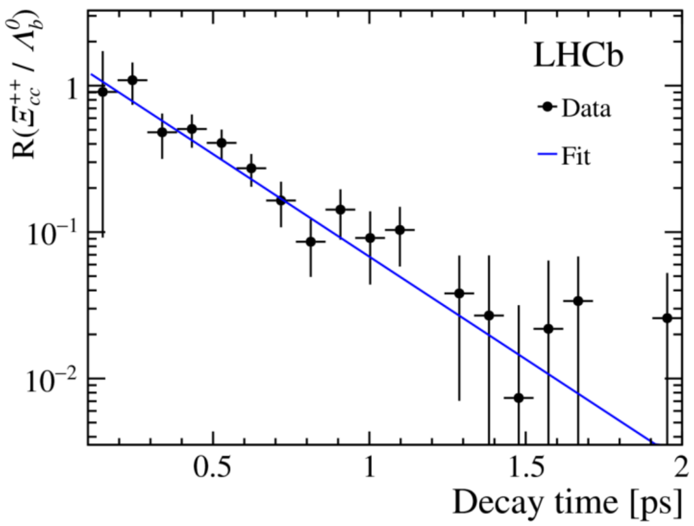




This result favors smaller lifetime values in the range of theoretical predictions

Ref. to theory papers in backup

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



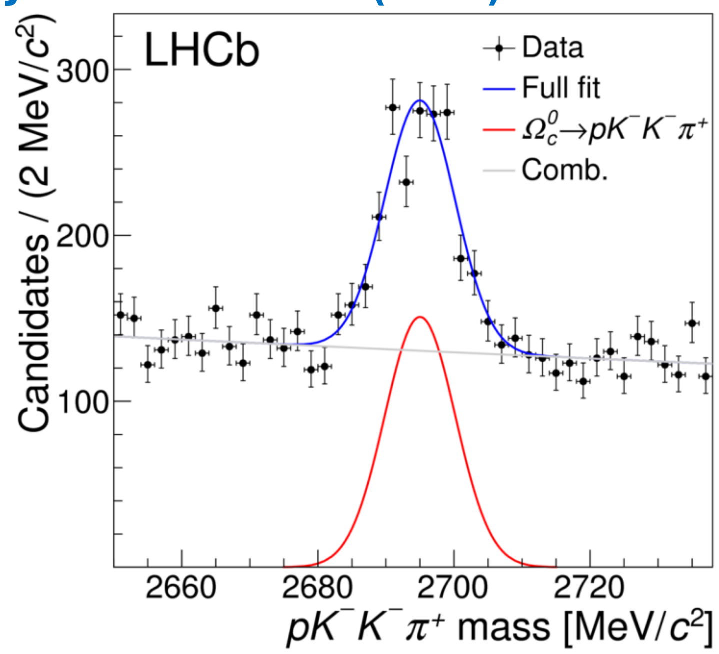
- **Result suggests small lifetime values for isospin partner Ξ_{cc}^{+}.**
- **Hard to search for!!**
- **Searches in progress (see JHEP 12 (2021) 107 and refs. there in)**

Measurement of Ω_c lifetime

Phys. Rev. Lett. 121 (2018) 092003

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

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

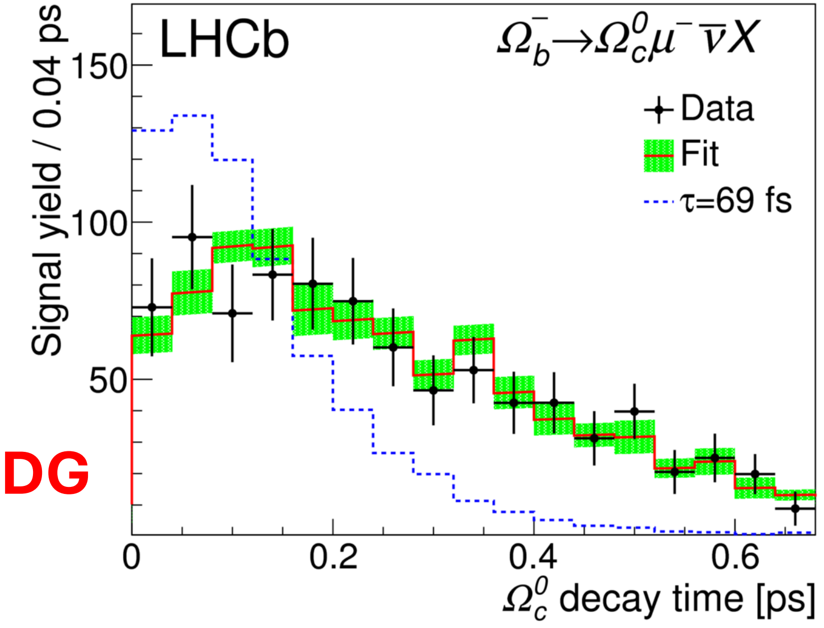


- Muons from semileptonic decays of Ω_b baryons and decay vertex of Ω_c baryon provide opportunity for lifetime measurement

- To reduce uncertainty the lifetime ratio were measured

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

$$B \to D^+\mu^-\overline{\nu}_\mu X \quad D^+ \to K^-\pi^+\pi^+$$

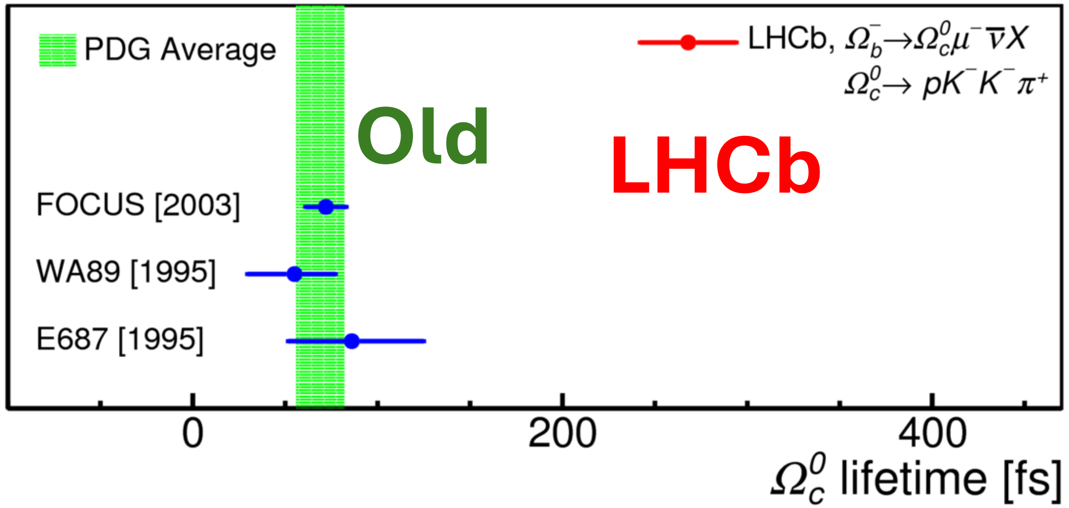


- **Result is incompatible with 69 fs lifetime reported in PDG**

Measurement of Ω_c lifetime

Phys. Rev. Lett. 121 (2018) 092003

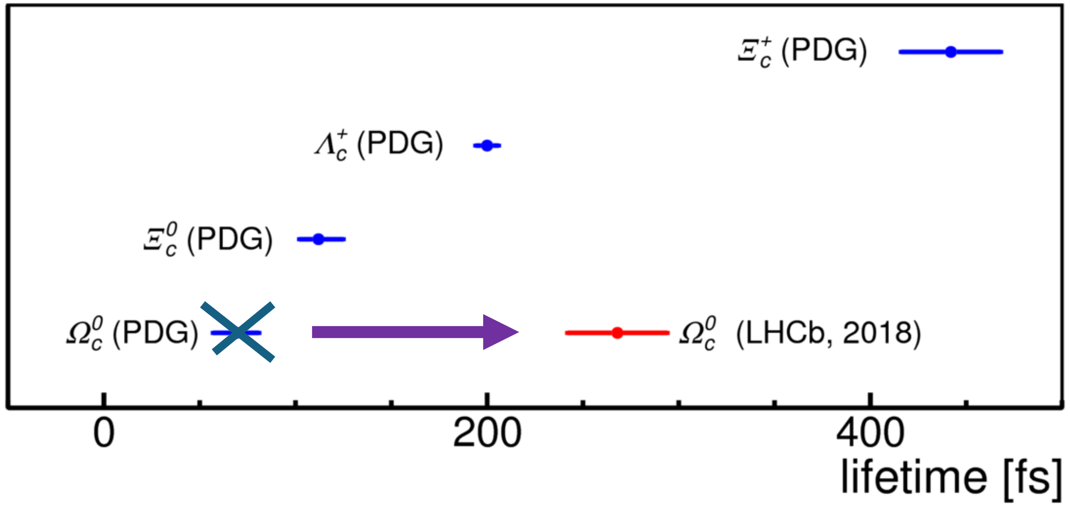
$$\frac{\tau_{\Omega_c^0}}{\tau_{D^+}} = 0.258 \pm 0.023 \pm 0.010$$
$$\tau_{\Omega_c^0} = 268 \pm 24 \pm 10 \pm 2 \text{ fs},$$



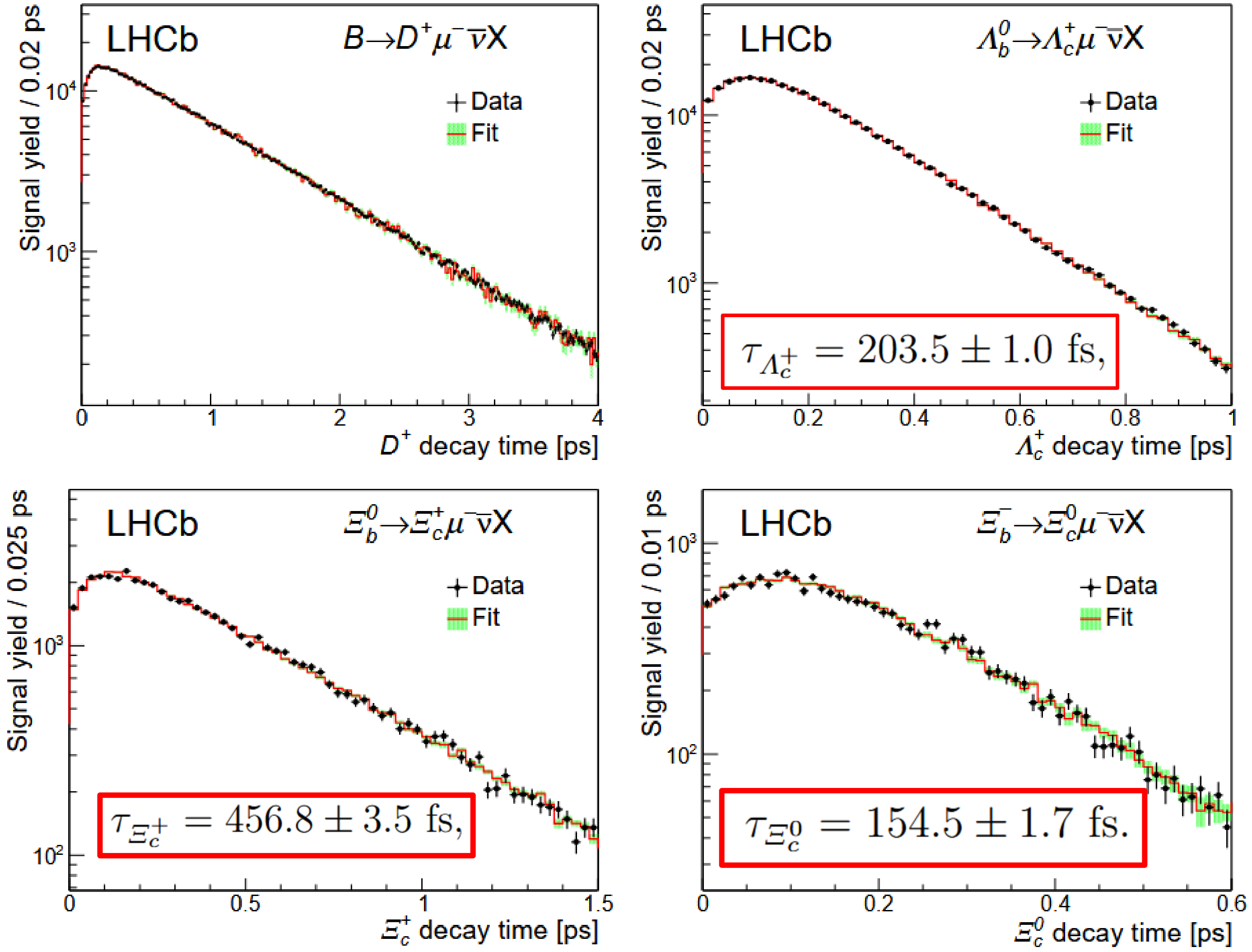
- Previous experiments were done using much smaller sample obtained on nucleus targets

- Very intriguing / Theorist are kindly welcome to explain:

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

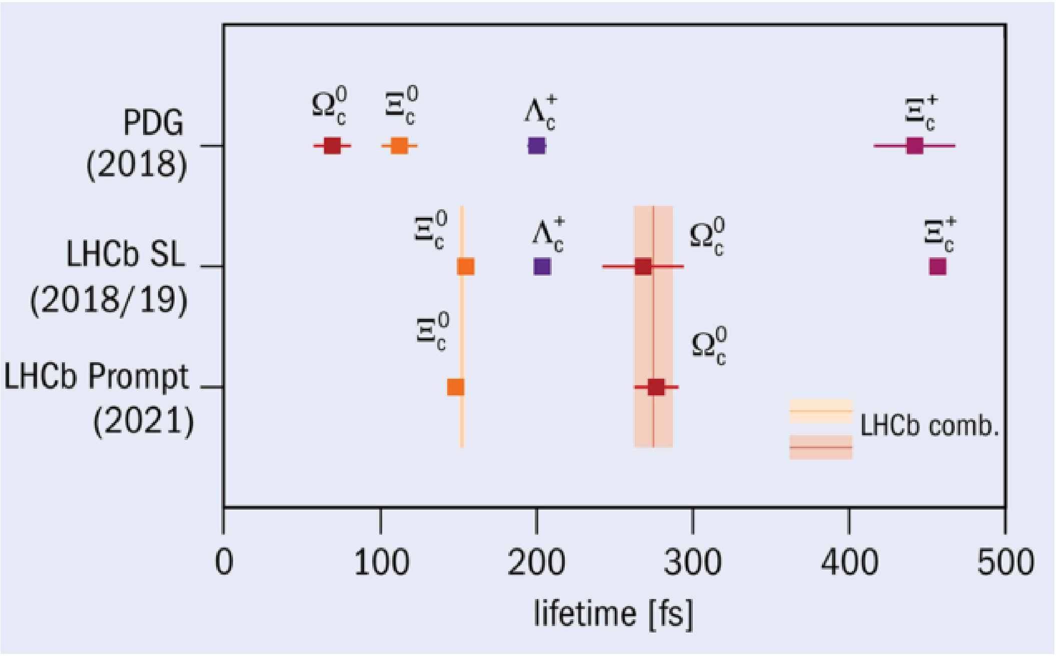


Lifetimes of charmed baryons



Phys. Rev. D 100, 032001 (2019)

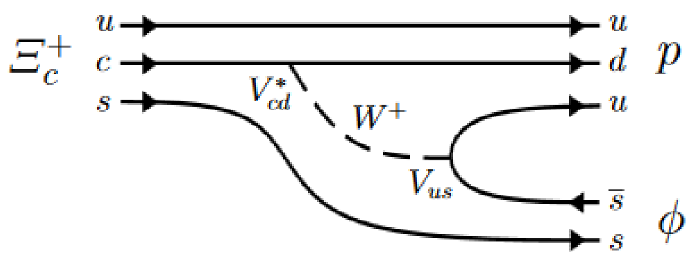
Plot from CERN Courier



- 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!**

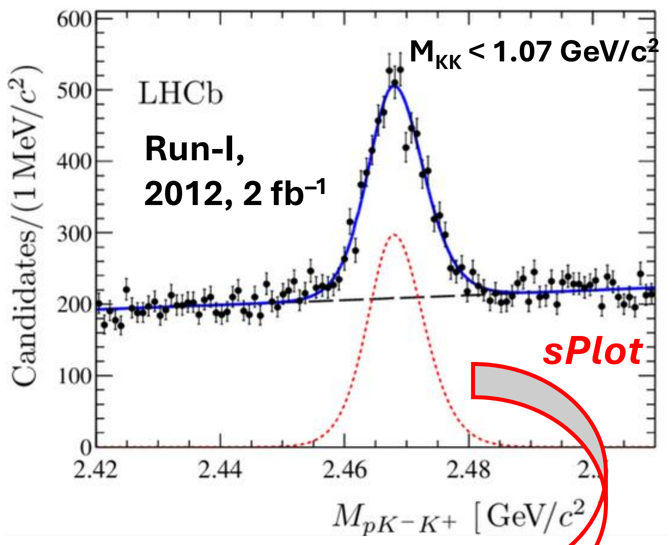
Doubly Cabibbo suppressed decay of Ξ_c^+ baryon

Quark diagram for the decay: $\Xi_c^+ \to p\phi$

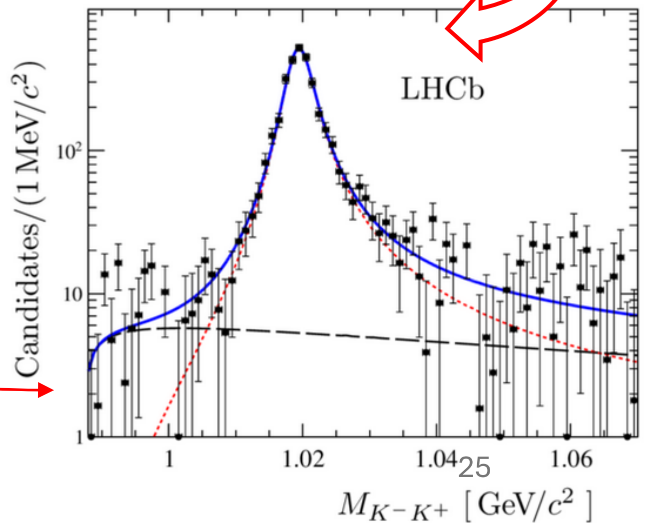


- In the SM decays driven by the $c \to d$ and $u \to s$ transition are suppressed because of hierarchy of the elements of the Cabibbo-Kobayashi-Maskawa quark mixing matrix

- Decays, for which both of these transitions play roles are named ***doubly Cabibbo supressed***.
- Their investigation will allow to understand the role of the spectator quarks (in particular the role of the Pauli principle) on dynamics of the decay.
- **Important for the explanation of the hierarchy of the charmed hadron lifetimes** (see. LHCb: ***Phys. Rev. D 100 (2019) 032001***).



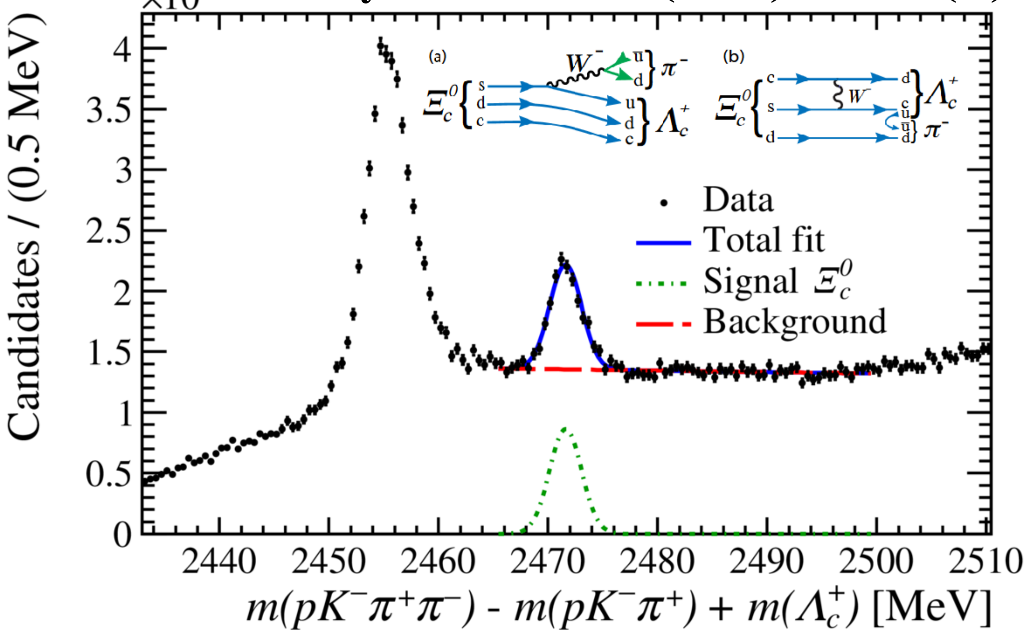
- Signal from the $\Xi_c^+ \to p\phi$ decay has been discovered with high statistical significance (>15σ)
- An evidence (3,5σ) for the non-ϕ мезоном decays $\Xi_c^+ \to pK^+K^-$ also has been found
- A ratio of $\Xi_c^+ \to p\phi$ and $\Xi_c^+ \to pK^+\pi^-$ has been measured
- ***JHEP 04 (2019) 084***).

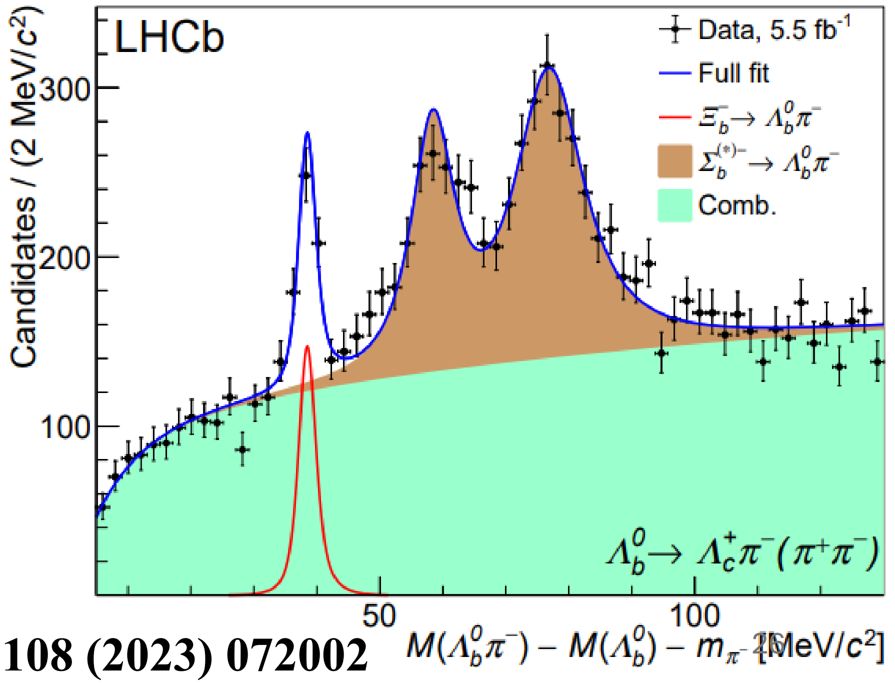


s-quark transitions in heavy (c-/b-) baryons

- LHCb has discovered decays $\Xi_c^0 \to \Lambda_c^+ \pi^-$ and $\Xi_b^- \to \Lambda_b^0 \pi^-$
- These decays are interesting because they are driven by the strange quark (s) weak decay, while charm (c) of beauty (b) quark plays spectator role.
- Some theoretical models predict enhancement of branching fractions of decays of these type .
- With the known fragmentation functions ratio ($f_{\Xi b-}/f_{\Lambda b0}$) the branching ratio has been measured:
- **B($\Xi_b^- \to \Lambda_b^0 \pi^-$) = (0.89 ± 0.10 ± 0.07 ± 0.29) %**
- Measured value rejects some theoretical models, which describe decay

Phys. Rev. D 102 (2020) 071101(R)





Phys. Rev. D 108 (2023) 072002

Mixing and CPV searches in charm sector

```
}-> Direct CPV
        }-> Search ans Observation
        }-> Many CP asymmetries
}-> Mixing
        }-> Observation
        }-> Mixing parameters
        |-> Search CPV in mixing
```

Mixing and CPV searches in charm sector

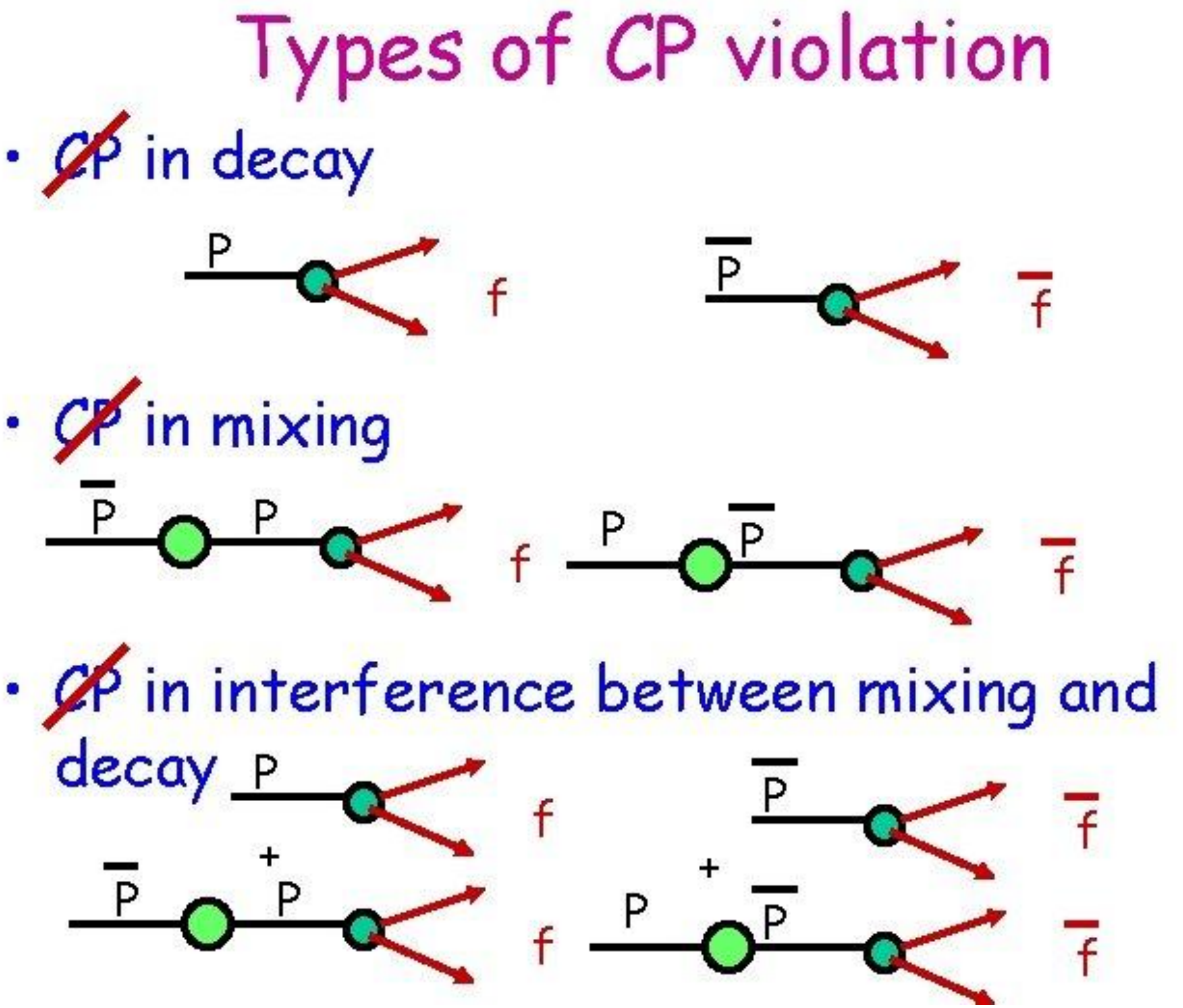
Observation of *CP* violation in charm decays
Phys. Rev. Lett. 122 (2019) 211803 , 20 Mar 2019

```
}-> Direct CPV
    }-> Search ans Observation
    }-> Many CP asymmetries
}-> Mixing
    }-> Observation
    }-> Mixing parameters
    |-> Search CPV in mixing
```

Observation of the mass difference between neutral charm-meson eigenstates
Phys. Rev. Lett. 127, (2021) 111801, 07 Jun 2021

Observation of $\boldsymbol{D^0 - \overline{D}^0}$ oscillations
Phys. Rev. Lett. 110 (2013) 101802, 06 Nov 2012

CP-violation and mixing



- *CP* Violation in the Quark Sector, T. Gershon, Y. Nir (PDG)
  - CKM Quark-Mixing Matrix, A. Ceccucci, Z. Ligeti, Y. Saka (PDG)
  - *CPT* Invariance Tests in Neutral Kaon Decay, M. Antonelli, G. D'Ambrosio, M.S.Sozzi (PDG)
  - *CP* Violation in K_L Decays, L. Wolfenstein,, C.-J. Lin (LBNL), T.G. Trippe (PDG)
  - **D^0-$\bar{D}^0$** Mixing, D.M. Asner, A.J. Schwartz (PDG)
  - **B^0-$\bar{B}^0$** Mixing, O. Schneider (PDG)

Discovery of the direct *CP* in decays of charmed mesons

- Standard Model predict quite small CPV for the ***c***-quarks decays.
- LHCb reaches sensitivity which allows to search for CPV at the SM level
- A difference of CP asymmetries for two different CP-even decay modes of the ***D^0*** meson has been measured. This allowed to decrease significantly systematic uncertainties related to production and detection asymmetries.
- Flavor of the initial state is determined using so-called *tagging algorithm*: soft pion charge /muon charge allow to tag ***D*** meson flavor.
- Statistical significance 5,3σ → **First observation of direct CPV in decays of charmed hadrons**
- ***Phys. Rev. Lett. 122 (2019) 211803***

$$\Delta A_{CP} \equiv A_{raw}(KK) - A_{raw}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

CP asymmetry:

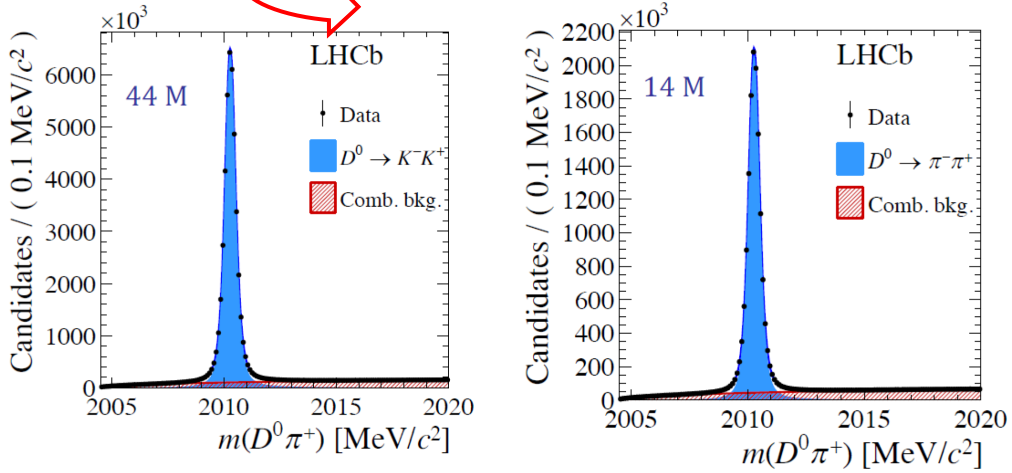
$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

$$f = \pi^-\pi^+, K^-K^+$$

Tagging:

$D^{*\pm} \to D^0\pi^+$

$B \to D^0(\to f)\mu^- X$



Results for Run 1 + Run 2 :

$$\Delta A_{CP} = (-15.4 \pm 2.9)\times 10^{-4}$$

$\Delta A_{CP} \neq 0$ → Violation of *CP*

$D^0 \to K^-K^+$ or $D^0 \to \pi^-\pi^+$?

Phys. Rev. Lett. 131 (2023) 091802

- **2019:** $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$
- $\Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) \neq 0$
- CPV exists but what is the source?!

Two methods to measure $A_{CP}(D^0 \to K^-K^+)$

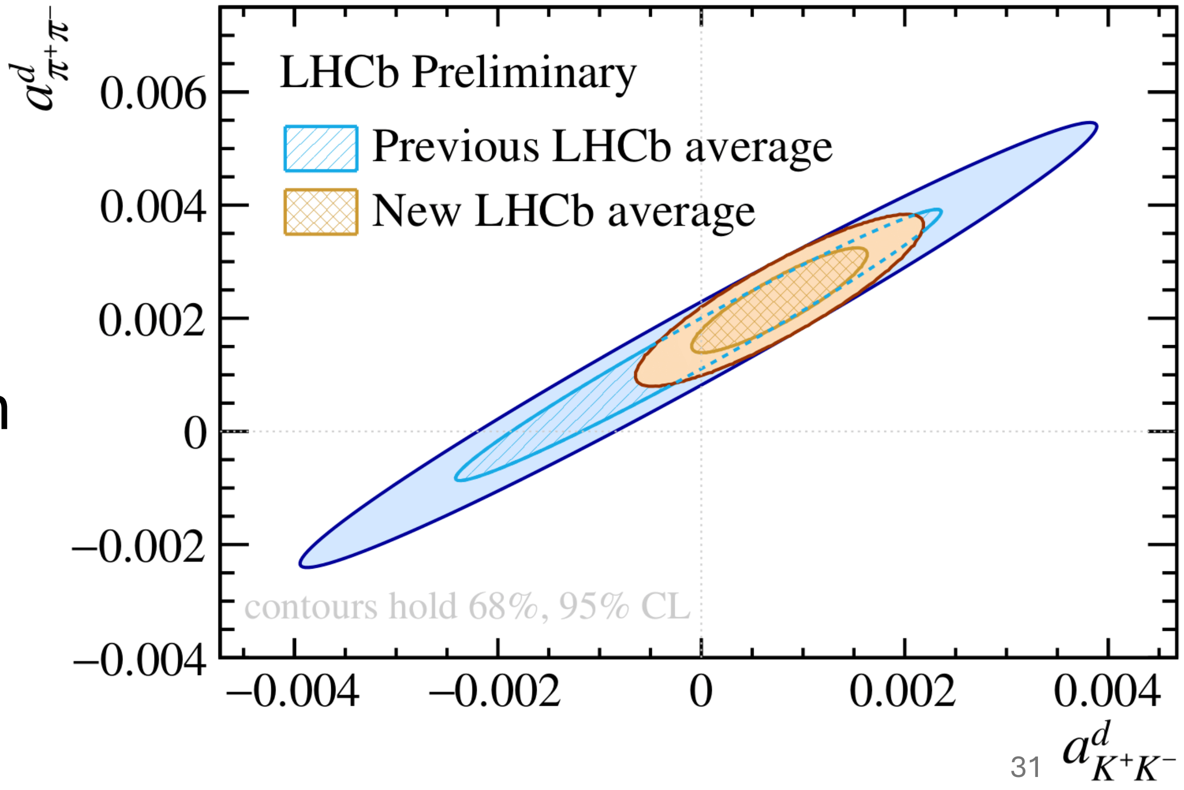
$$A_{CP}(D^0 \to K^-K^+) = A(D^{*+} \to (D^0 \to K^-K^+)\pi^+) - A(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+) + A(D^+ \to K^-\pi^+\pi^+) - [A(D^+ \to \bar{K}^0\pi^+) - A(K^0)],$$

$$A_{CP}(D^0 \to K^-K^+) = A(D^{*+} \to (D^0 \to K^-K^+)\pi^+) - A(D^{*+} \to (D^0 \to K^-\pi^+)\pi^+) + A(D_s^+ \to \varphi\pi^+) - [A(D_s^+ \to \bar{K}^0K^+) - A(K^0)].$$

- **2022:** $D^0 \to K^-K^+$ – measurement $A_{CP}(KK)$
- Two methods of the corrections

$A_{CP}(KK) = (6.8 \pm 5.4_{стат.} \pm 2.0_{сист.}) \times 10^{-4}$

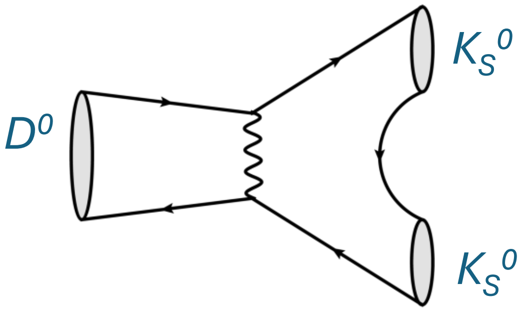
- Using ΔA_{CP}, one can distinguish between $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ channels
- $a^d_{\pi\pi}$ is non-zero at 3.8σ level
- **Evidence for direct *CPV* in decays of $D^0 \to \pi^-\pi^+$**



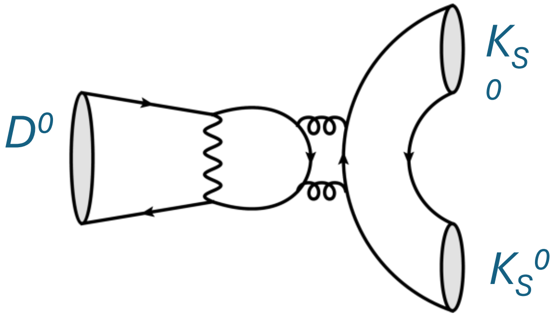
JHEP 11 (2018) 048

Time integrated $D^0 \rightarrow K_S^0 K_S^0$

Exchange diagram



Penguin diagram



Promising channel to observe CPV, as only exchange and loop-suppressed annihilation amplitudes (with different strong and weak phases; similar sizes) can contribute.

Effect could reach ~1% levels in time-integrated CP asymmetry.

$$\mathcal{A}^{\text{raw}} \approx \mathcal{A}^{CP} + \mathcal{A}^{\text{prod}} + \mathcal{A}^{\text{det}},$$

$$\begin{aligned}\Delta\mathcal{A}^{CP} &\equiv \mathcal{A}^{\text{raw}}(K_S^0 K_S^0) - \mathcal{A}^{\text{raw}}(K^+K^-) \\ &= \mathcal{A}^{CP}(K_S^0 K_S^0) - \mathcal{A}^{CP}(K^+K^-).\end{aligned}$$

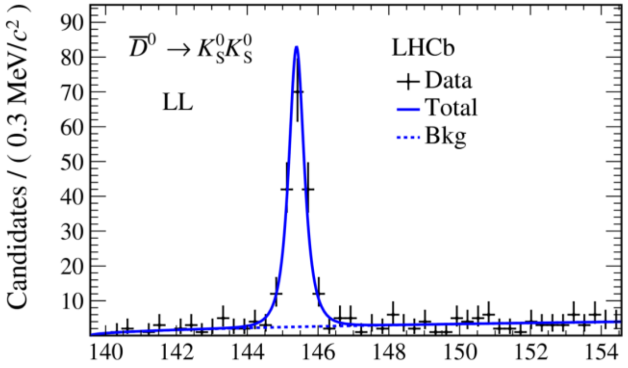
Huge rate, measured with per-mile precision

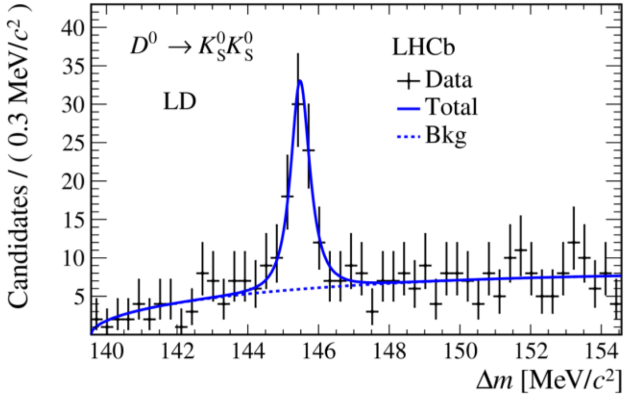
Prompt tagging using D^*.

Two track categories: Long (decays inside VELO) and Down (TT & OT hits)

Two event categories: LL and LD

$$\begin{aligned}\mathcal{A}^{CP}(\text{LL}) &= 0.067 \pm 0.038 \pm 0.009, \\ \mathcal{A}^{CP}(\text{LD}) &= -0.053 \pm 0.074 \pm 0.013,\end{aligned}$$





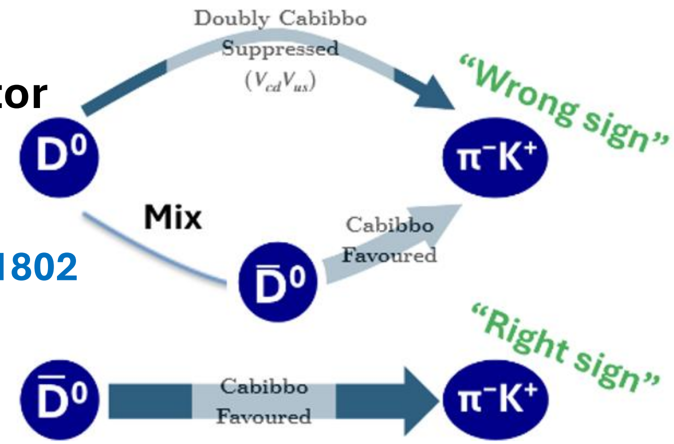
Compatible with SM predictions and with previous measurements

$$\mathcal{A}^{CP}(K_S^0 K_S^0) = 0.020 \pm 0.029 \pm 0.010.$$

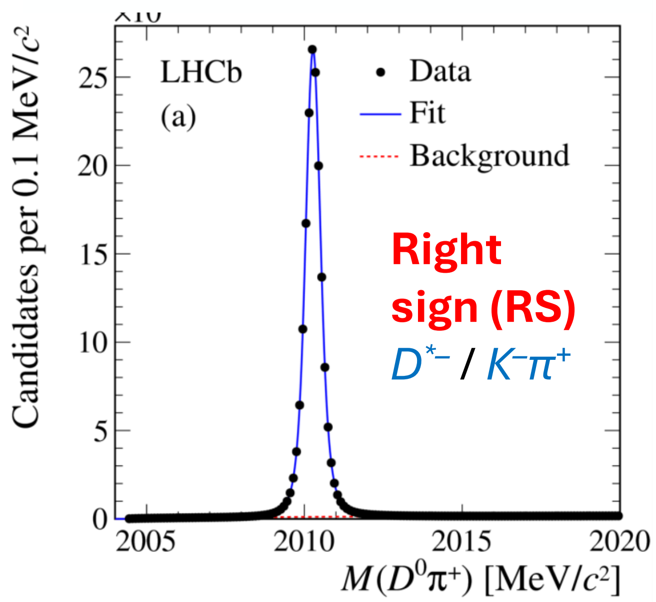
A lot of papers of asymmetries of such types from LHCb

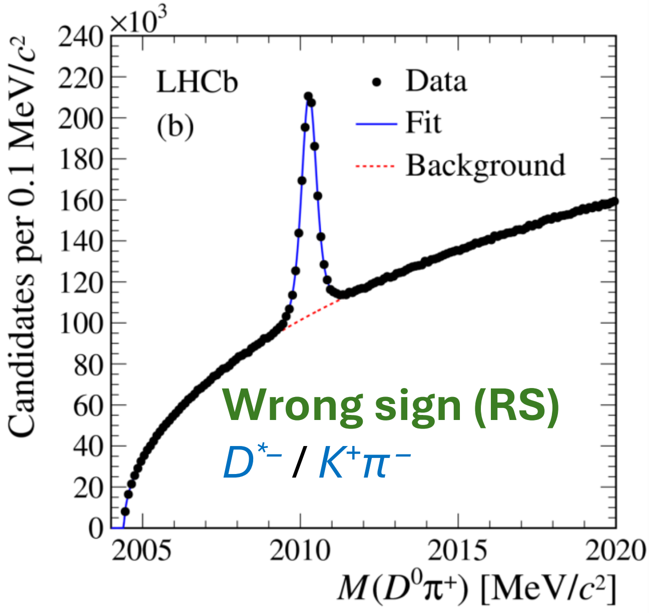
Mixing and CPV for D^0

- **Direct CP-violation in charm sector has been discovered at LHCb**
  - **$\Delta A_{CP} \neq 0$, PRL 122 (2019) 211803**
  - **Likely $D \rightarrow \pi\pi$, PRL 131 (2023) 091802**
- **What about CPV in nixing?**



PHYS. REV. D 97, 031101 (2018)





Using both Run I and II data 5 fb^{-1}

Observation of $D^0 - \overline{D}^0$ oscillations

Phys. Rev. Lett. 110 (2013) 101802, 06 Nov 2012

– RS appears, when no-mixing AND Cabibbo-favored (CF) decay
– WS either [mixing AND CF] or [no-mixing and Doubly-Cabibbo suppresed decay]
– Probe for all possible CPV scenarious (direct, in mixing, interference of direct and mixing)
– As mixing parameters (x' and y') are small the WS / RS ratio can be approximated as:

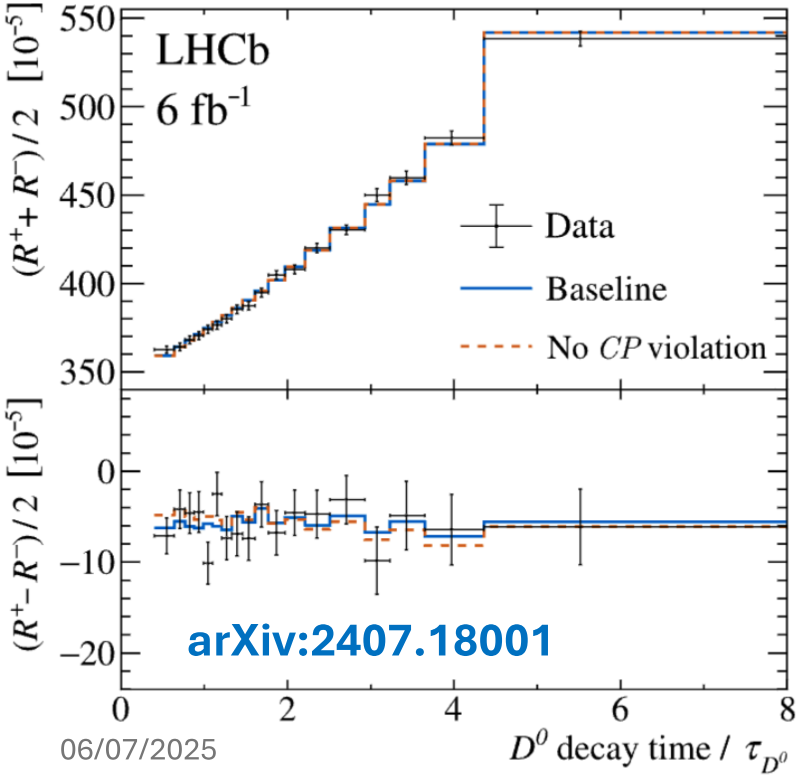
$$R(t)^{\pm} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm}\left(\frac{t}{\tau}\right) + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4}\left(\frac{t}{\tau}\right)^2,$$

$R_D^+ = |\mathcal{A}_{\overline{f}}/\mathcal{A}_f|^2$ $\quad R_D^- = |\overline{\mathcal{A}}_f/\overline{\mathcal{A}}_{\overline{f}}|^2$ $\quad R_D^+ \neq R_D^- \Rightarrow$ direct CPV

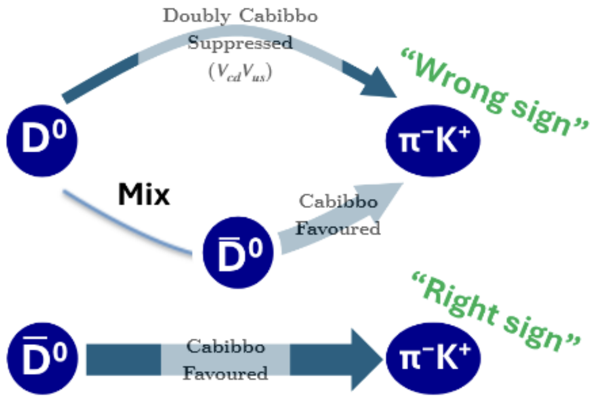
$x'^+ \neq x'^-$, $y'^+ \neq y'^- \Rightarrow$ CPV in mixing and interference

Поиск CP-нарушения при смешивании очарованных мезонов

- **Direct CP-violation in charm sectoe has been discovered at LHCb**
  - **$\Delta A_{CP} \neq 0$, PRL 122 (2019) 211803**
  - **Likely D→ππ , PRL 131 (2023) 091802**
- **What about CPV in nixing?**
- Run-2 / Prompt-tagging (**$D^{*\pm} \to D^0 \pi^\pm$**)



arXiv:2407.18001



Fit the time-dependent ratio R(t)

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\bar{D}^0(t) \to K^+\pi^-)}$$

$$R^-_{K\pi}(t) \equiv \frac{\Gamma(\bar{D}^0(t) \to K^-\pi^+)}{\Gamma(D^0(t) \to K^-\pi^+)}$$

Ratios depends on D^0 mixing parameters and CP violating parameters

CPV in decay — CPV in mixing

$$R^\pm_{K\pi}(t) \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\frac{t}{\tau_{D^0}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

DCS — Interference — Mixing

$R_{K\pi}$	$(343.1 \pm 2.0) \times 10^{-5}$
$c_{K\pi}$	$(51.4 \pm 3.5) \times 10^{-4}$
$c'_{K\pi}$	$(13.1 \pm 3.7) \times 10^{-6}$
$A_{K\pi}$	$(-7.1 \pm 6.0) \times 10^{-3}$
$\Delta c_{K\pi}$	$(3.0 \pm 3.6) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-1.9 \pm 3.8) \times 10^{-6}$

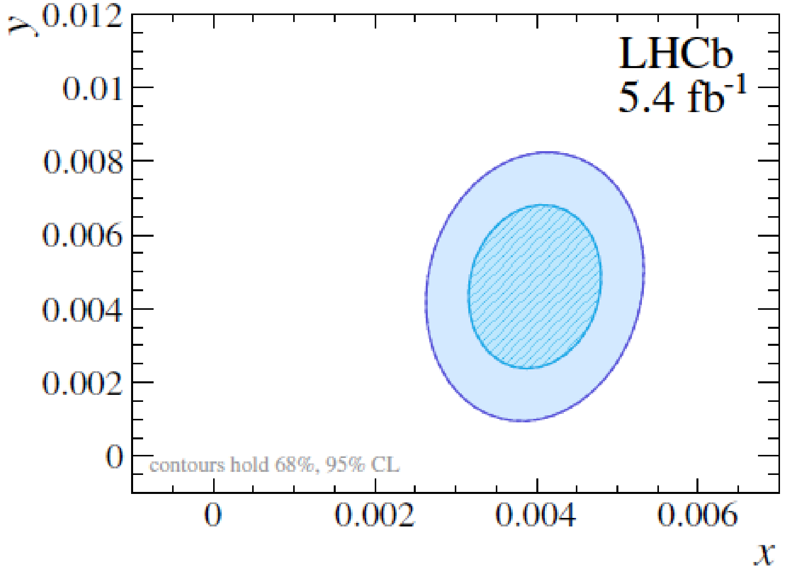
First measuremet of quadratic terms

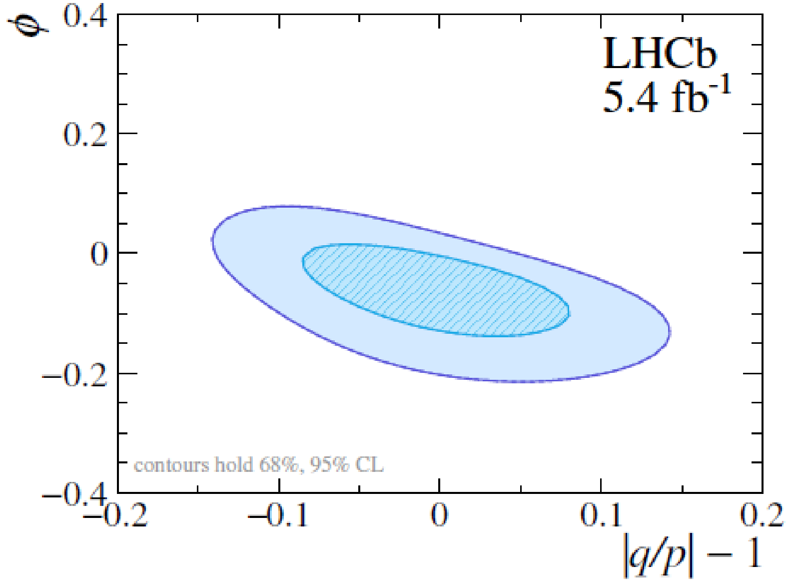
No evidence for the CPV in mixing

$\Delta m \neq 0$ for mass states of D^0

Phys. Rev. Lett. 127, 111801 (2021)
Phys. Rev. Lett. 131, 079901 (2023)

Done with decay: $D^0 \rightarrow K_S^0 \pi^+ \pi^-$





These result dominates World average

Parameter	Value
$x\ [10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$
$y\ [10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$
$\lvert q/p \rvert$	0.996 ± 0.052
ϕ	$-0.056\,^{+0.047}_{-0.051}$

- First observation of mass difference between D_1 and D_2
- Statistical signinficance of $\Delta m \neq 0$ *is* 7 standard deviations!

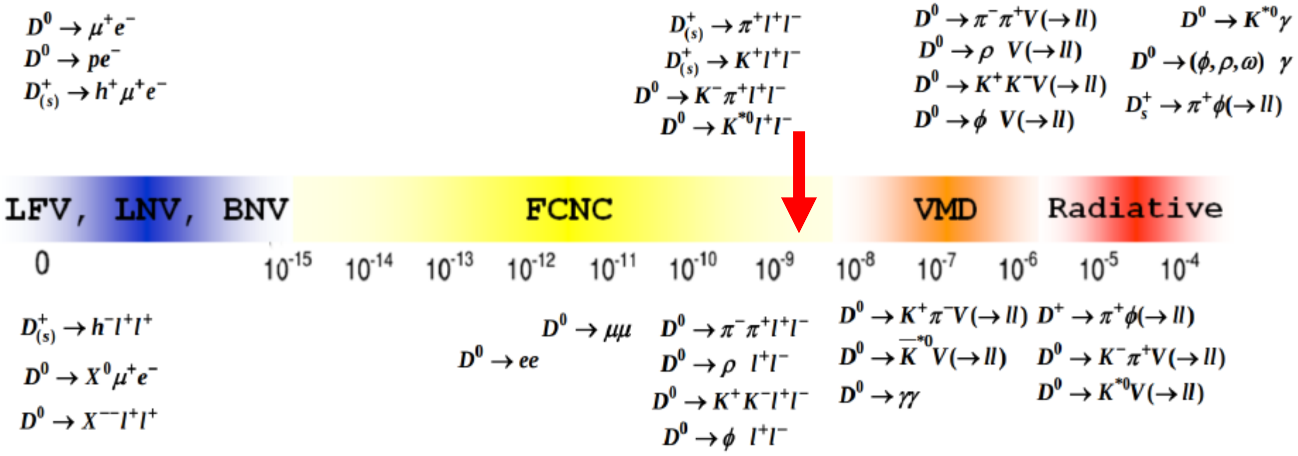
Ratio of DNA molecule's mass and mass of Earth is of the order of 10^{-38} !

Measured mass difference $6{,}4\times10^{-6}$ eV,
0,00000000000000000000000000000000000001 gram (10^{-38} gram).

Rare decays of charmed hadrons

```
}-> Flavor changing neutral currents SM
     }-> Two-body
     }-> Three-body
          }-> Meson decays
          }-> Baryon decays
     }-> Four-body
          }-> Branchings
          }-> CP asymmetries
          |-> Seach di-electrons decays
}-> Lepton Fflavor violating decays
```

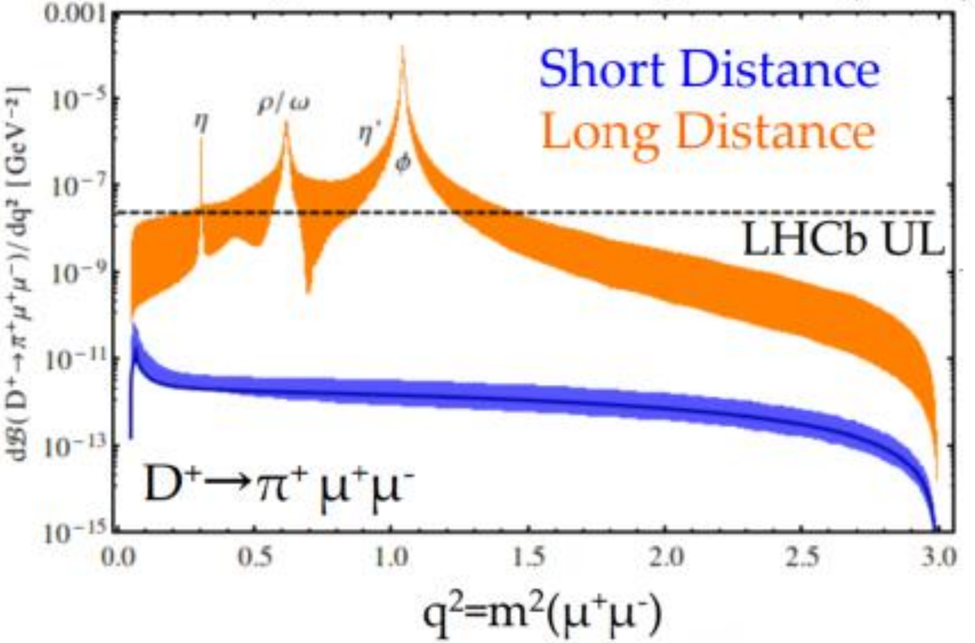
LHCb impact for rare charm decays



[PRD 66 (2002) 014009]

Intermediate vector resonances in the dimuon spectrum can hide short distance (SM) contribution

S.de Boer, G.Hiller PRD 93, 074001(2016)



- Pushing down the limits
- *CP*- and *T*-asymmetries
- Lepton Flavor Violation (LFV) will be examined
- Lepton Universality (LU) in charm sector
- Angular and amplitude analyses

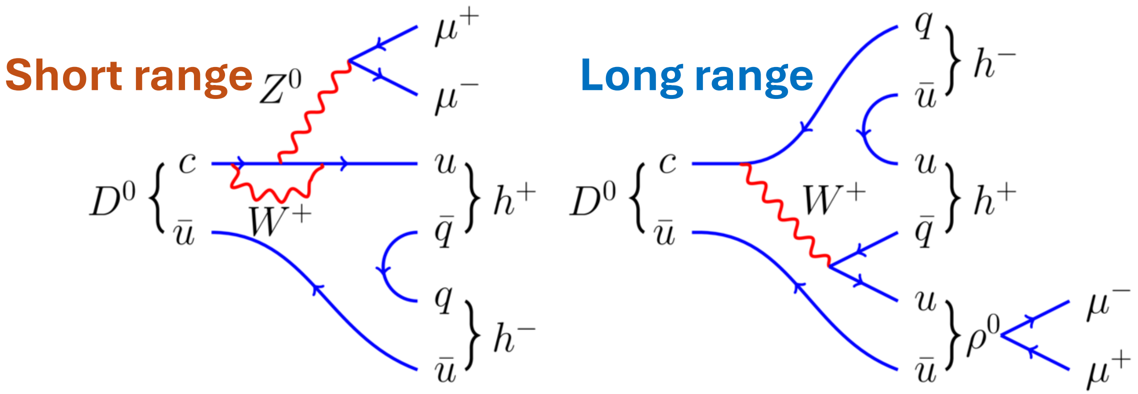
Recent LHCb upper limit with 9 fb^{-1} dataset
Phys. Rev. Lett. 131 (2023) 041804

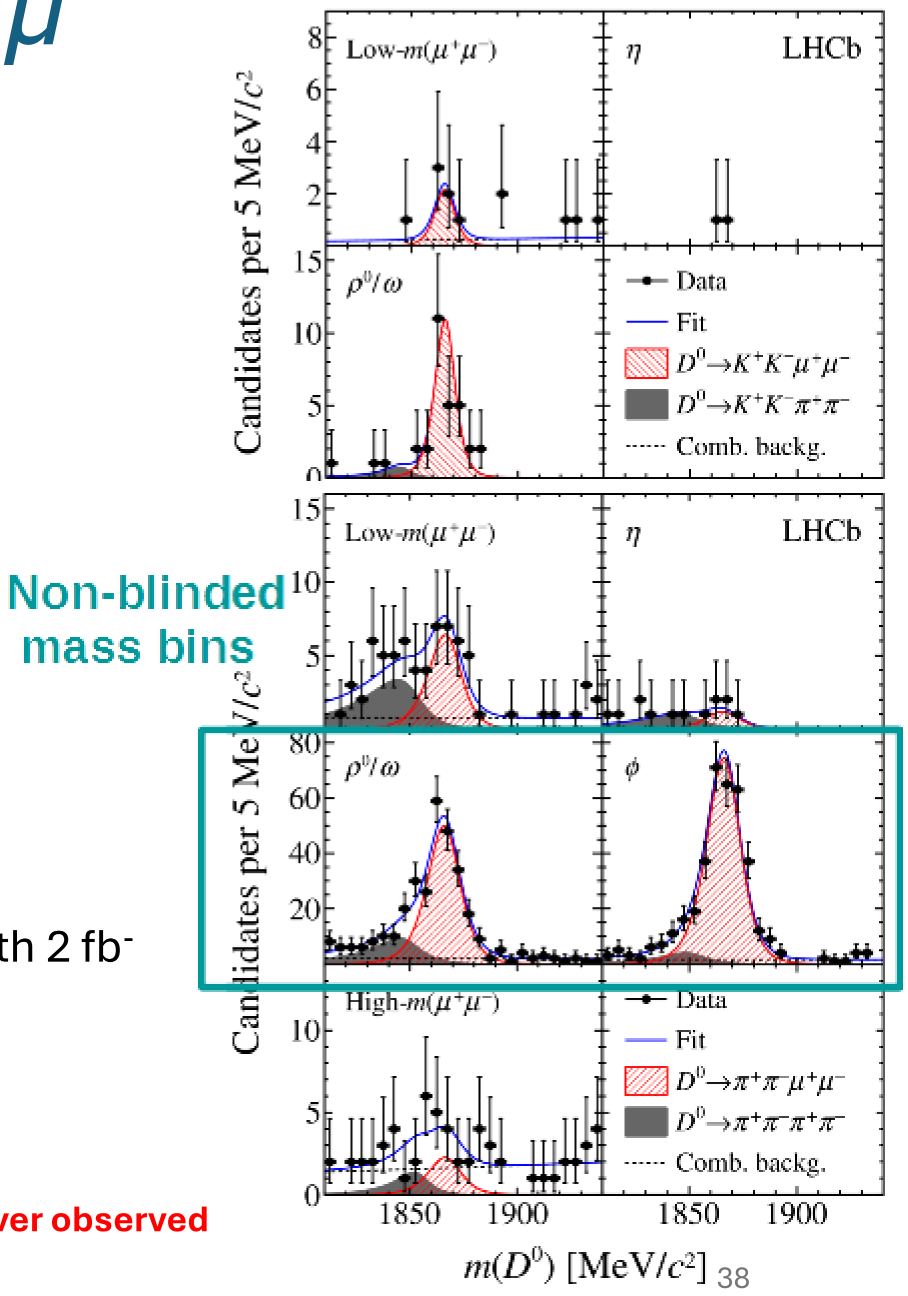
$$\mathcal{B}(D^0 \to \mu^+ \mu^-) < 3.1 \times 10^{-9}$$

$D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

PHYS. REV. LETT. 119, 181805

Goal: Probe New Physics in $c \to u$ transitions, appears at **short distances** and very suppressed in SM ($< 10^{-9}$)
Long range contribution from ρ, ω, ϕ due to decays into $\mu^+\mu^-$ pair (difficult to predict leakage of events from resonance tails into search region)





Event "leakage" into Low-m bins, as expected
Observed branching fractions are consistent with SM expectations (done with 2 fb^{-1})

$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \times 10^{-7},$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \times 10^{-7}.$$

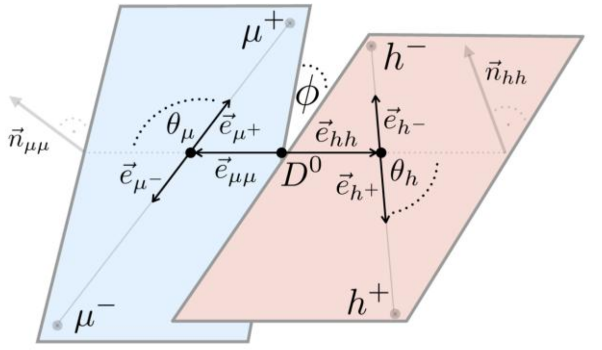
rarest charm decays ever observed

$D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

Phys. Rev. Lett. 121 (2018) 091801

Observation was done with 2 fb^{-1} / **Start to learn properties (asymmetries) with 5 fb^{-1}**

- A_{FB} – forward-backward asymmetry of $\mu^+\mu^-$
- $A_{2\phi}$ – triple product asymmetry →
- A_{CP} – CP asymmetry (using prompt (D^*) tagging)

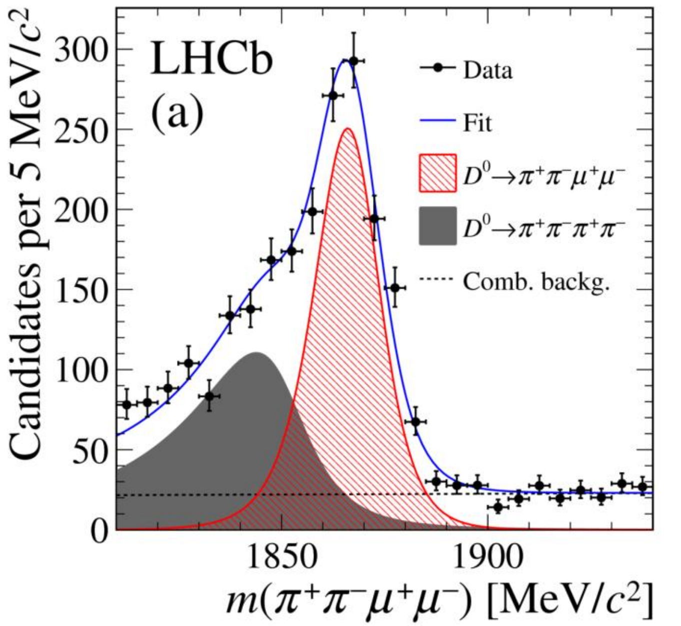


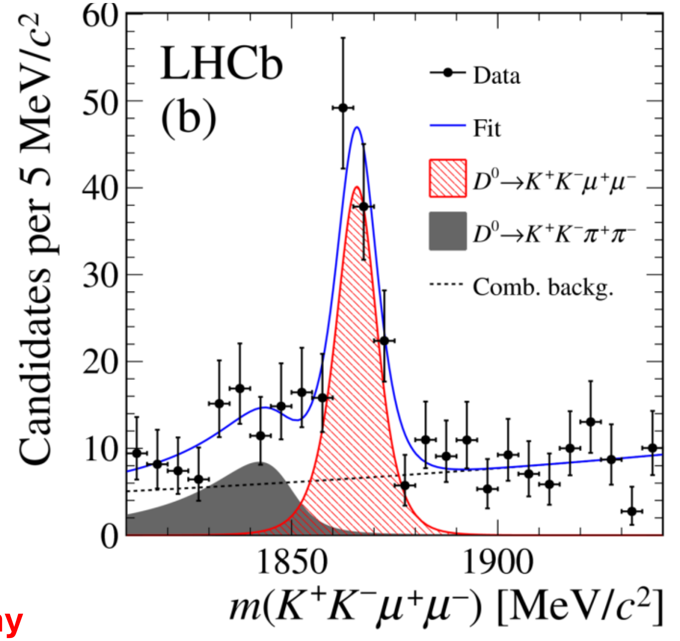
$$\sin 2\phi = 2(\vec{n}_{hh} \cdot \vec{n}_{\mu\mu})(\vec{n}_{hh} \times \vec{n}_{\mu\mu}) \cdot \vec{e}_{hh}.$$

Quite promising probe for searches of New Physics

~~Percent accuracy achieved with existing dataset~~

$m(\mu^+\mu^-)$ [MeV/c^2]	Efficiency-weighted yields Signal	Misid. back.	Comb. back.	Signal asymmetries A_{FB} [%]	$A_{2\phi}$ [%]	A_{CP} [%]
			$D^0 \to \pi^+\pi^-\mu^+\mu^-$			
< 525	90 ± 17	233 ± 25	108 ± 22	2 ± 20 ± 2	−28 ± 20 ± 2	17 ± 20 ± 2
525–565	–	–	–	–	–	–
565–780	326 ± 23	253 ± 24	145 ± 21	8.1 ± 7.1 ± 0.7	7.4 ± 7.1 ± 0.7	−12.9 ± 7.1 ± 0.7
780–950	141 ± 14	159 ± 15	89 ± 14	7 ± 10 ± 1	−14 ± 10 ± 1	17 ± 10 ± 1
950–1020	244 ± 16	63 ± 13	43 ± 9	3.1 ± 6.5 ± 0.6	1.2 ± 6.4 ± 0.5	7.5 ± 6.5 ± 0.7
1020–1100	258 ± 14	33 ± 9	44 ± 9	0.9 ± 5.6 ± 0.7	1.4 ± 5.5 ± 0.6	9.9 ± 5.5 ± 0.7
> 1100	–	–	–	–	–	–
Full range	1083 ± 41	827 ± 42	579 ± 39	3.3 ± 3.7 ± 0.6	−0.6 ± 3.7 ± 0.6	4.9 ± 3.8 ± 0.7
			$D^0 \to K^+K^-\mu^+\mu^-$			
< 525	32 ± 8	5 ± 13	124 ± 20	13 ± 26 ± 4	9 ± 26 ± 3	−33 ± 26 ± 4
525–565	–	–	–	–	–	–
> 565	74 ± 9	39 ± 7	48 ± 8	1 ± 12 ± 1	22 ± 12 ± 1	13 ± 12 ± 1
Full range	110 ± 13	49 ± 12	181 ± 19	0 ± 11 ± 2	9 ± 11 ± 1	0 ± 11 ± 2

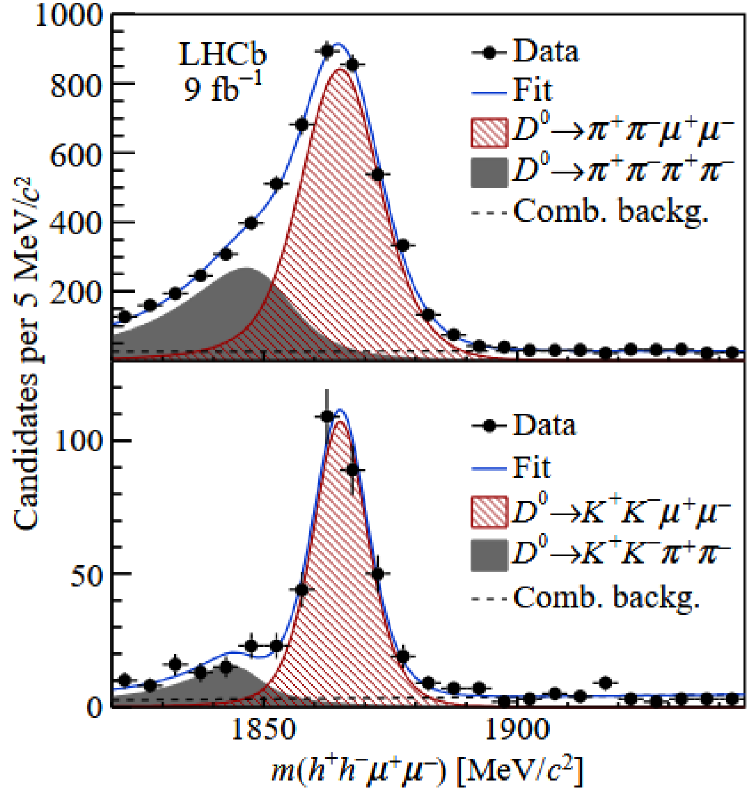


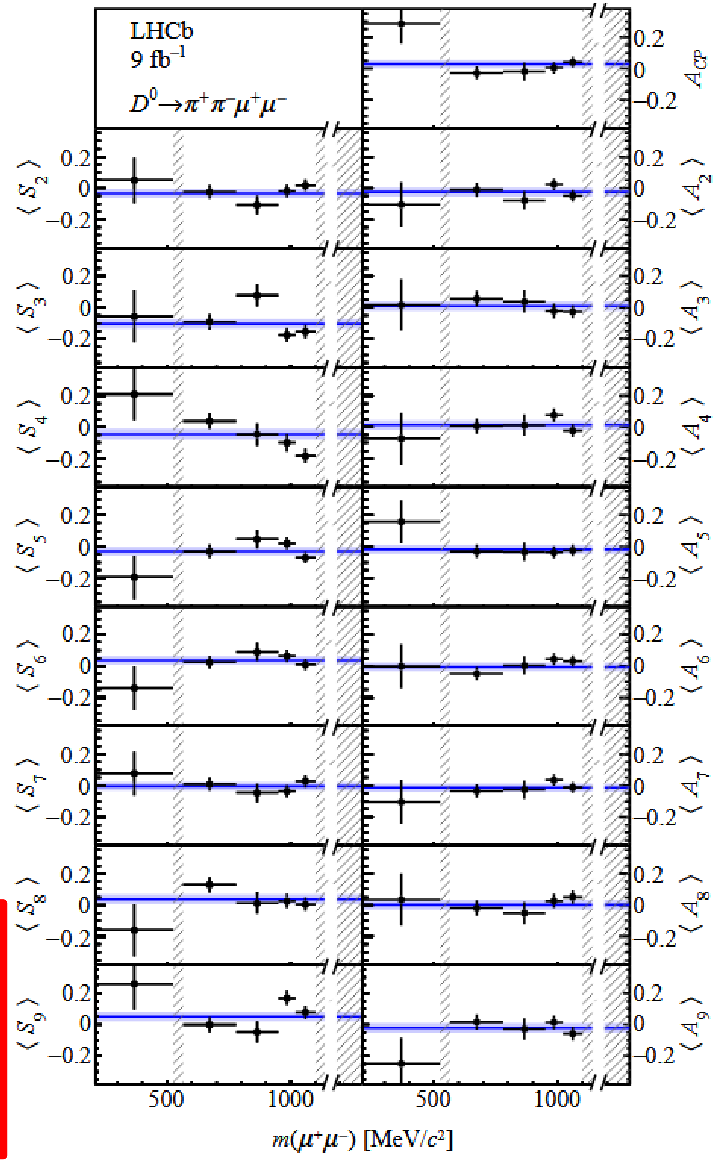


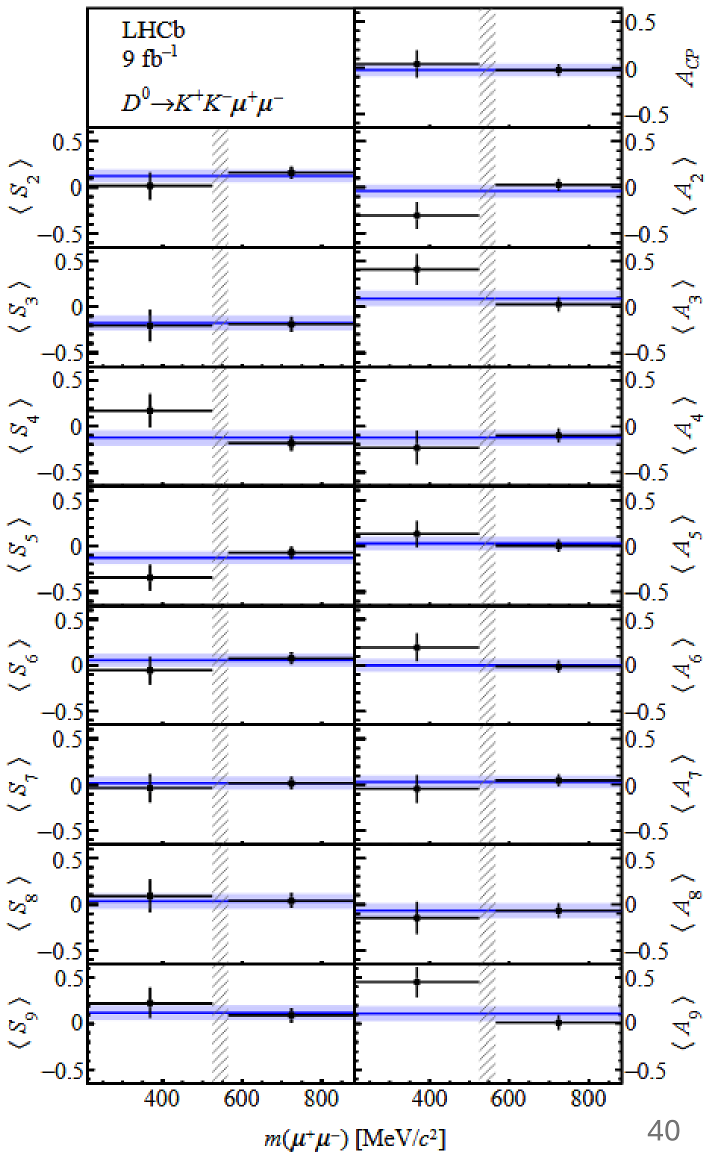
we are at the beginning of the long way

$D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$

The results are consistent with expectations from the standard model and with CP symmetry





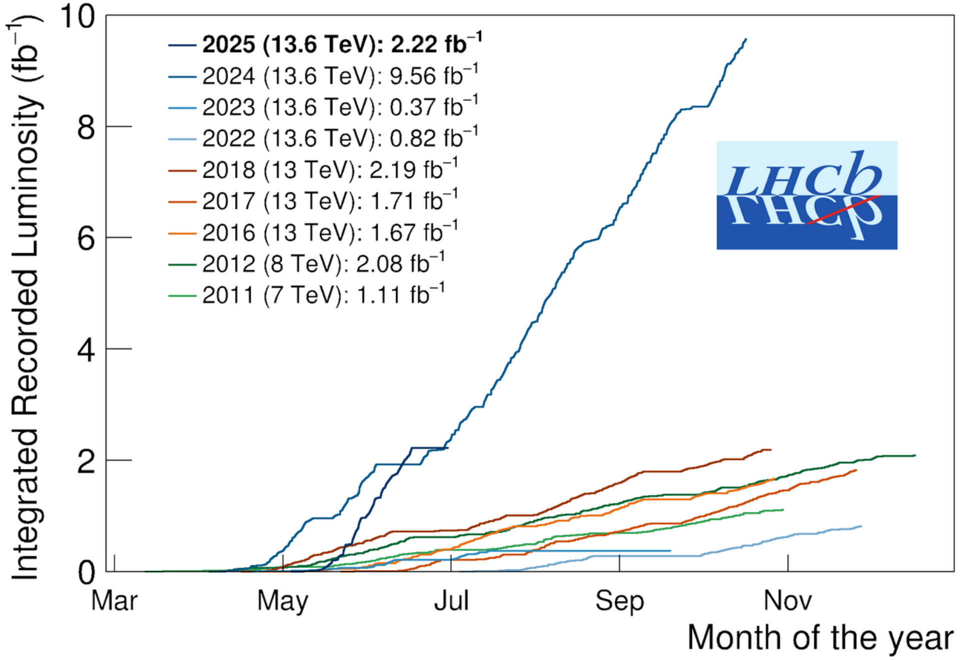


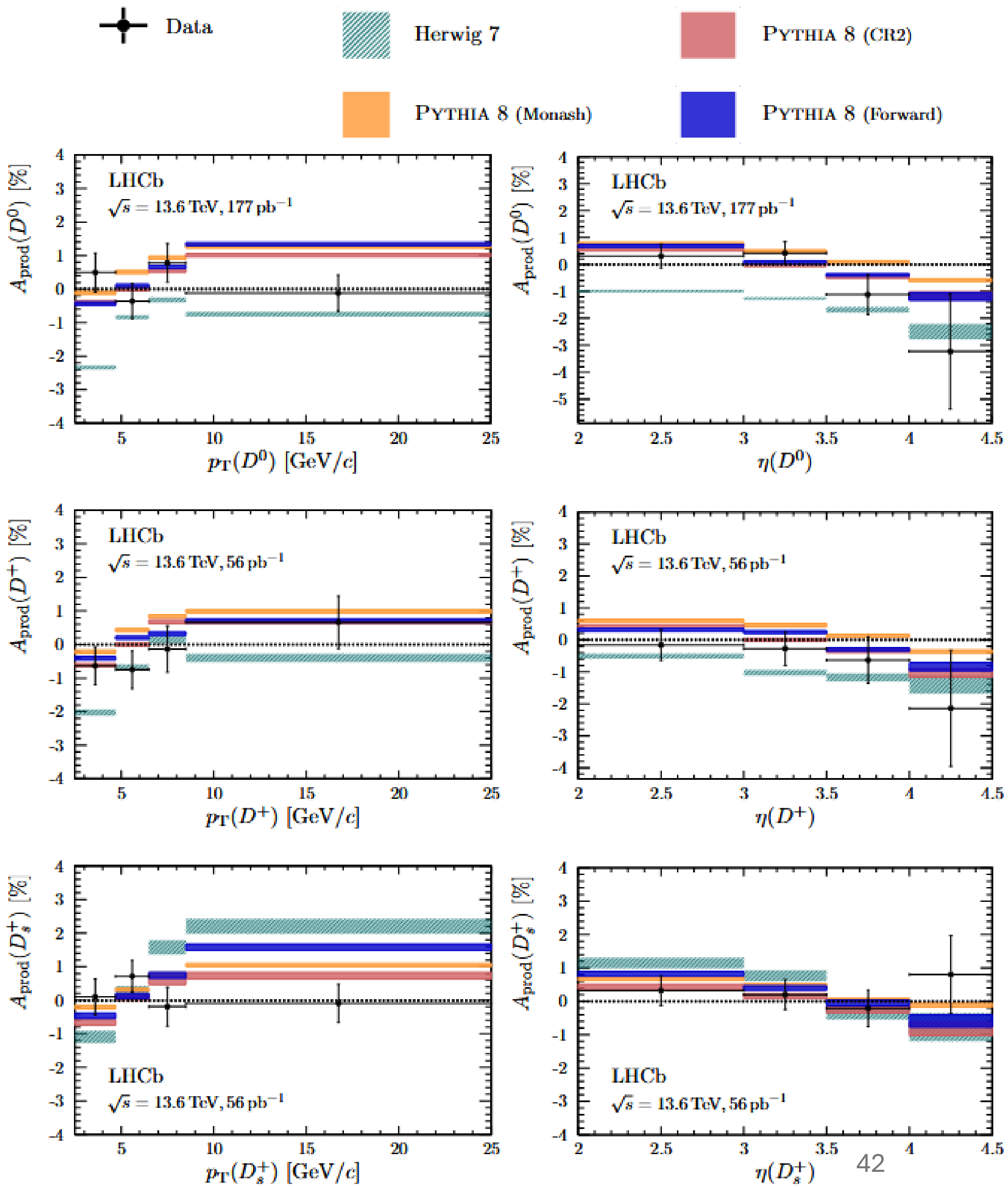
Phys. Rev. Lett. 128 (2022) 221801

Rare decays studies reflects an impact of the stable work of LHCb MUON (responsibility of PNPI: concept, design, construction, commissioning, operation)

Run-3

First paper after Upgrade I





- The asymmetries of ***D*$^+$**, ***D*^{0}** and ***D*$_s^+$** mesons are measured for two-dimensional intervals in transverse momentum and pseudorapidity.
- **No significant production asymmetries are observed.**

arXiv:2505.14494

Summary & Conclusions + Future

- Excellent LHCb performance during Run-I and II.
- A lot of important results in charm sector exploiting huge charm rate:
  - Production and Spectroscopy – LHCb is mega-factory of charm
  - Mixing & CPV – LHCb is dominating here
  - Rare decays – push down limits for di-muon decays / asymmetries studies

Many more in the stream of LHCb charm results

- Upgrades I/II approaching L_{int} = 50 / 300 fb^{-1}
- Expect to have a lot of new and important results for Charm Physics in future