Charmed mesons and baryons at LHCb

Alexey Dzyuba \ HEPD PNPI NRC KI on behalf of LHCb Collaboration

1st of March 2019, PhiPsi-2019 – Novosibirsk, Russia

Scope of this talk

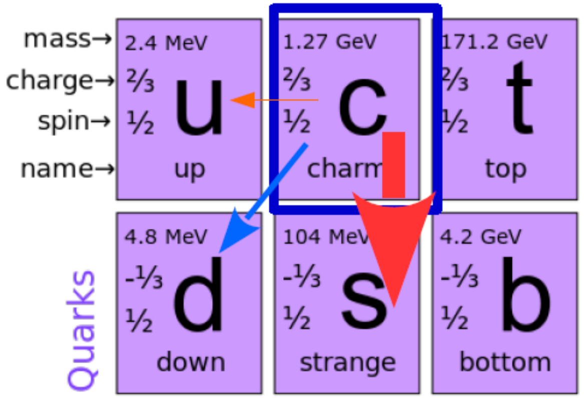
What are main goals of charm physics at LHCb?

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

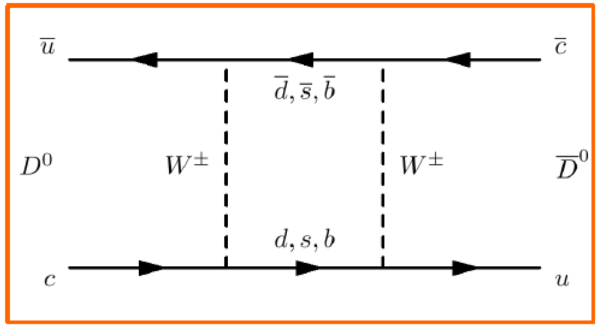
- **Recent LHCb results in charm**

Also I'd like to

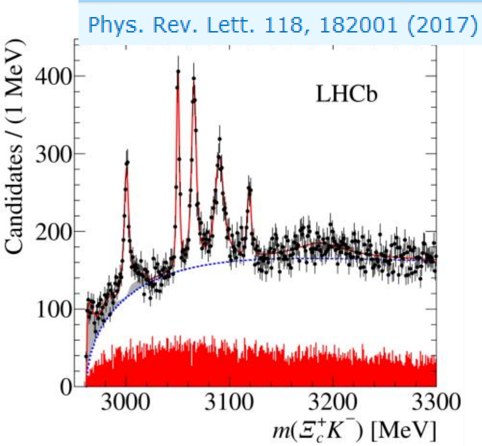
- Advantages of HEP hadronic machines as the tool for charm
- Remind how LHCb works
- Show the impact of LHCb Upgrade

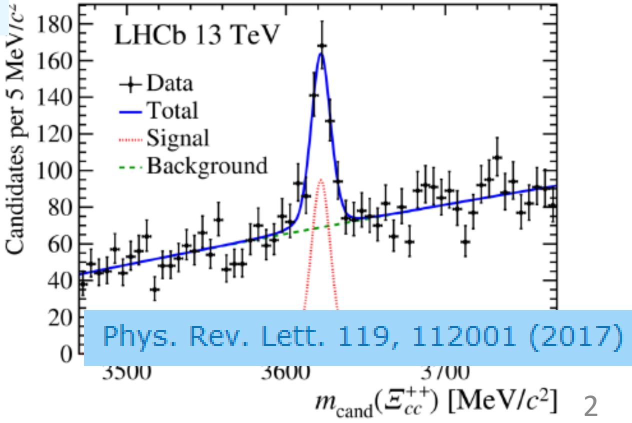


$\arg(V_{cd}) \sim 10^{-4}$ $\arg(V_{cs}) \sim 10^{-5}$



Mixing / FCNC


Phys. Rev. Lett. 118, 182001 (2017)

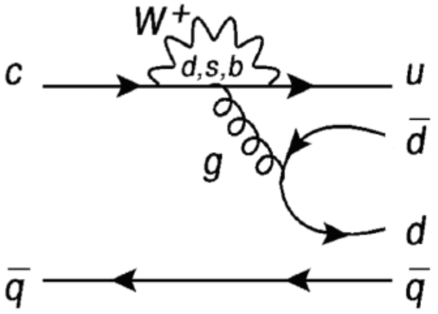


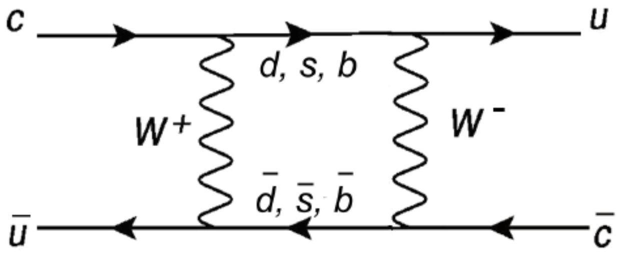
Phys. Rev. Lett. 119, 112001 (2017)

CPV in charm sector & New Physics in loops

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

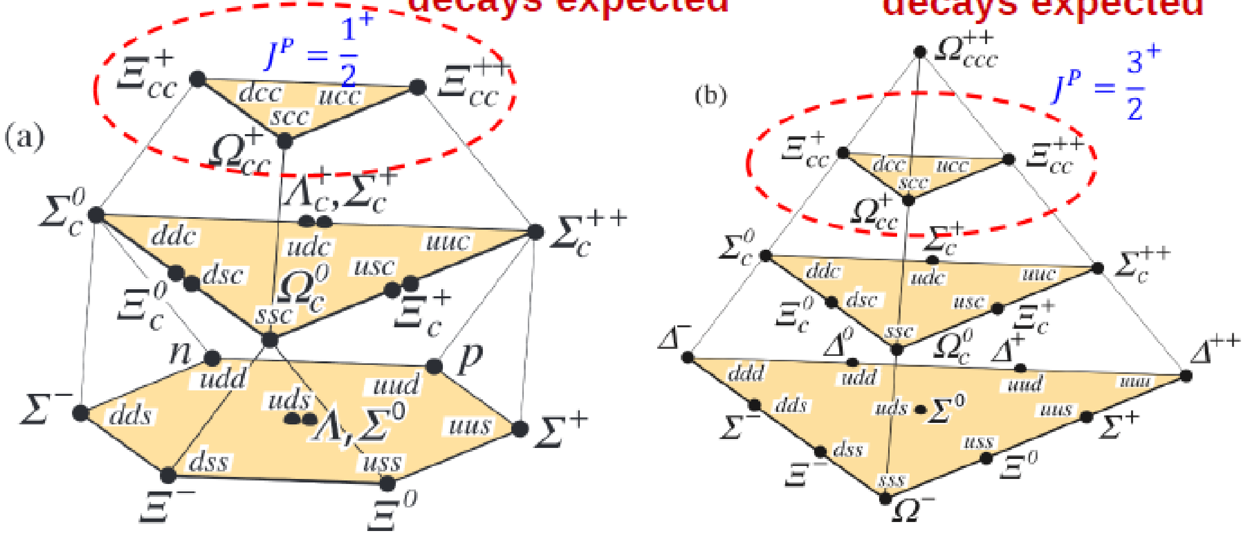
$$+\mathcal{O}(\lambda^7)$$





- 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



Weak force driven decays expected

EM / strong decays expected

- QCD is a natural part of the SM
- Chiral perturbation theory 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**

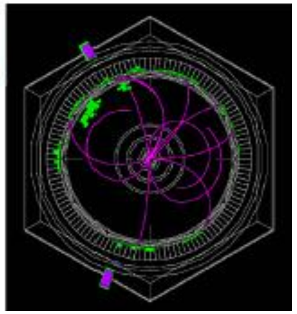
- at $\psi(3770)$ resonance
- Quantum coherence, which allows to measure strong phase
- Almost no background

- 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

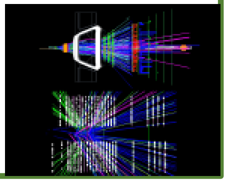
- no lifetime measurements / not large sample

CDF (10 fb^{-1} / $23*10^{10}$) / **LHCb** (5 fb^{-1} / $8*10^{12}$)

In future **LHCb Upgraded** (→ 50 fb^{-1} → 300 fb^{-1})

- **Huge rates**
- **Excellent lifetime resolution due to the boost**

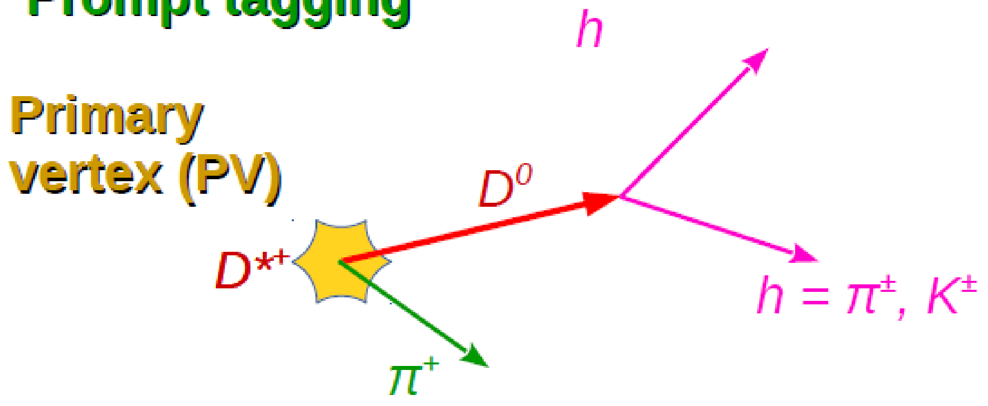
- **Large backgrounds**
- **Difficult to work with neutral**



Charm and beauty production into forward region

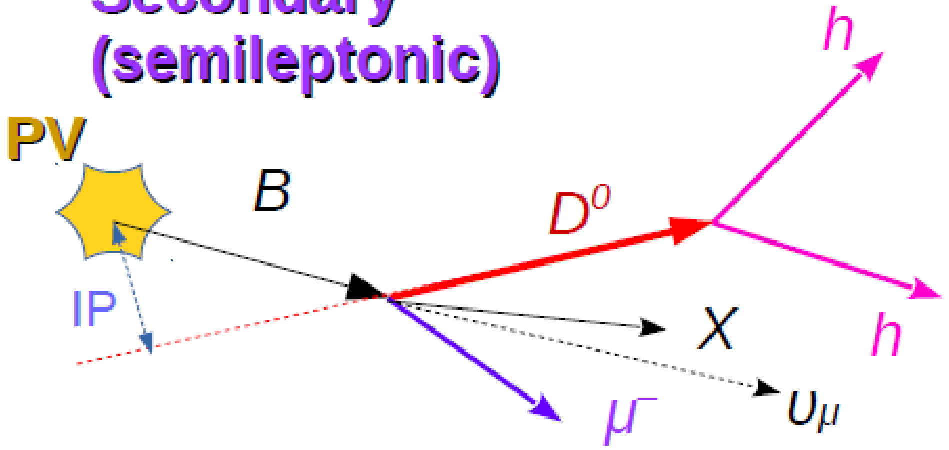
- Gluon fusion is main production mechanism for pairs of heavy (***c*** & ***b***) quark-antiquark pairs
- Produced charmed hadrons go together in forward direction (LHCb acceptance $2<\eta<5$)
- Lorentz boost provides signature for ***c***- & ***b***-hadrons selection
- Tagging for prompt-***c*** and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

Prompt tagging



Higher tagging rate

Secondary (semileptonic)



More efficient triggering

LHCb: Find \ Identify \ Measure

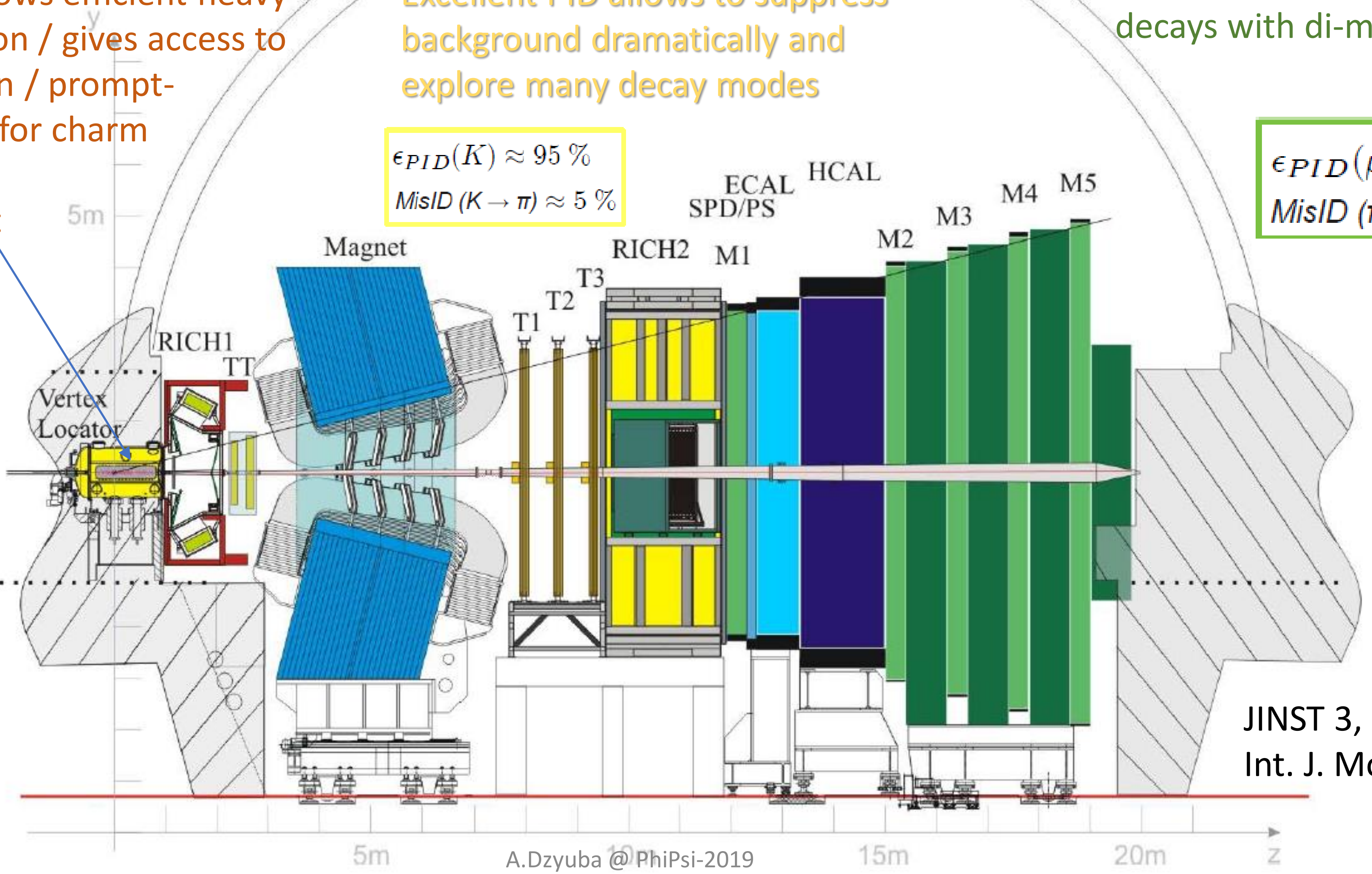
Excellent tracking

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

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

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

Protons collision point



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

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

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

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

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

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

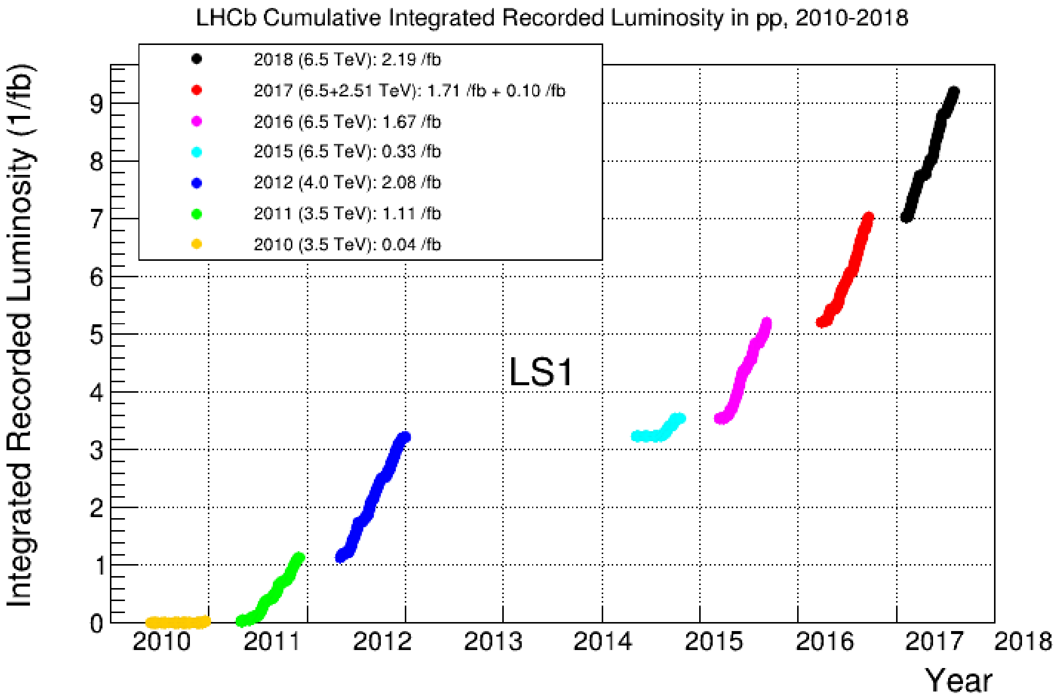
$\epsilon_{track} > 96\ \%$

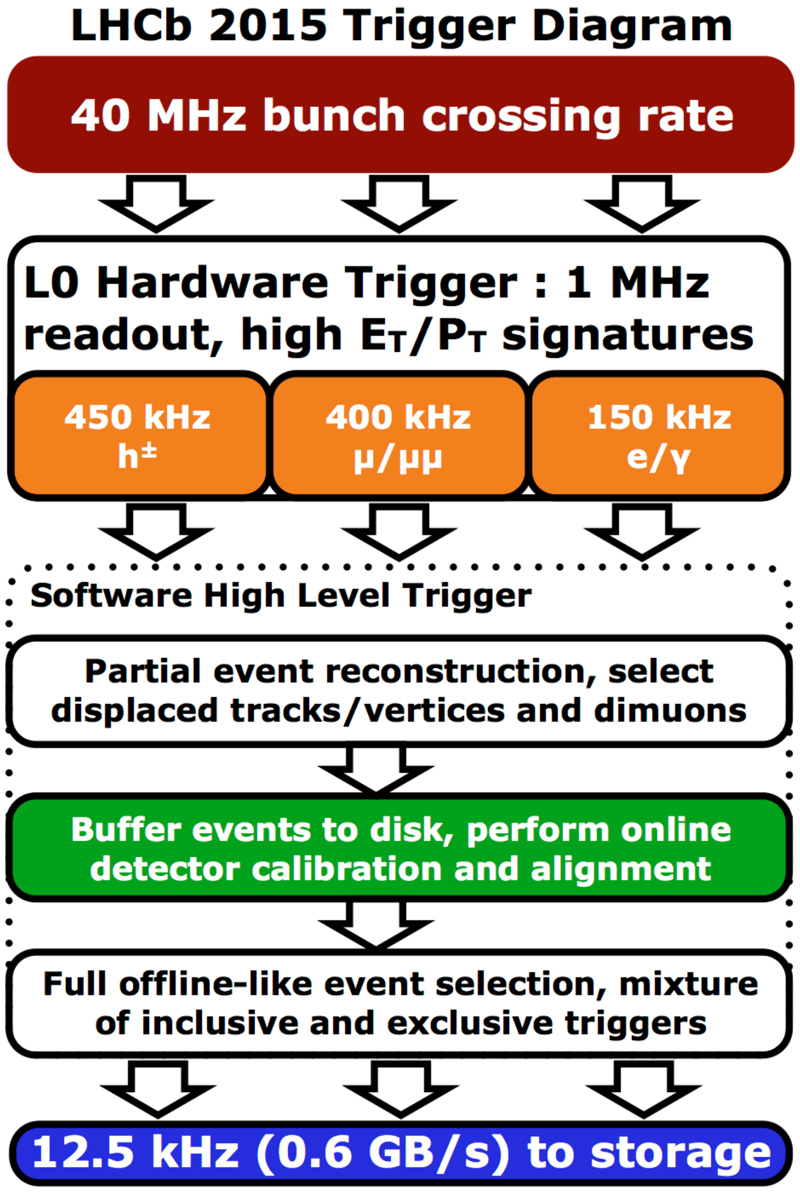
JINST 3, (2008) S08005; Int. J. Mod. Phys. A 30, (2015) 153022

Comput. Phys. Commun. 208 35-42
Int. J. Mod. Phys. A 30, 1530022 (2015)
+ arXiv:1812.10790

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





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

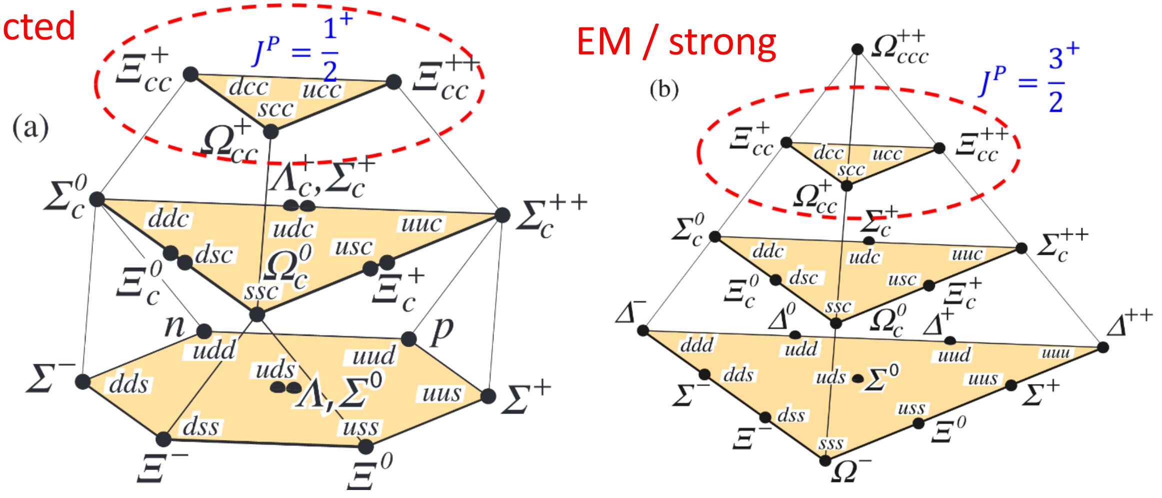
Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz (0.6 GB/s) to storage

Spectroscopy of hadrons with open charm

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

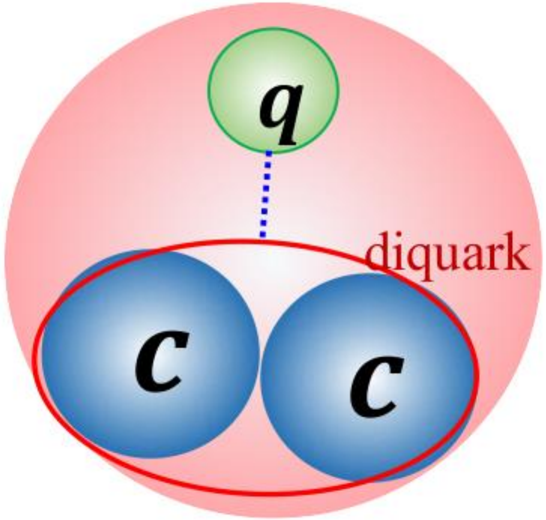
- Few MeV isospin splitting between Ξ_{cc}^{++} and Ξ_{cc}^{+}

- Lattice QCD: M($\Xi_{cc}^{++,+}$) ≈ 3.6 GeV, M(Ω_{cc}) ≈ 3.7 GeV

- HQET: core from heavy diquark

- Lifetimes prediction $\tau(\Xi_{cc}^{++}) \in [\,200 - 700]$ fs

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

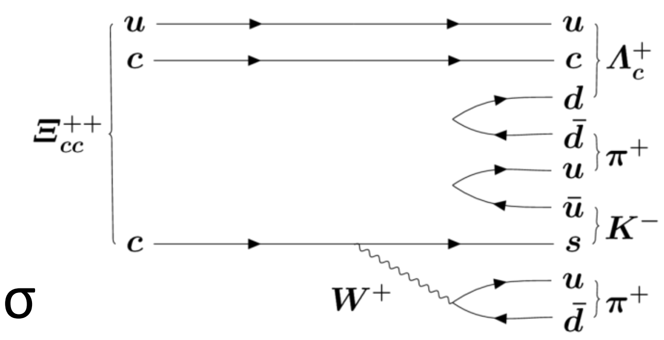


Doubly heavy baryon expected to be similar to a heavy *Qq* meson

Ref. to theory papers in backup

Discovery of Ξ_{cc}^{++}

PHYS. REV. LETT. 119, 112001

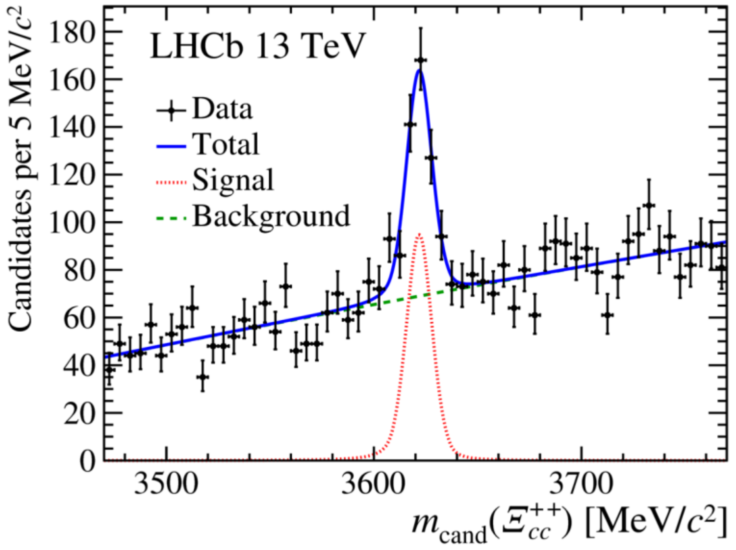


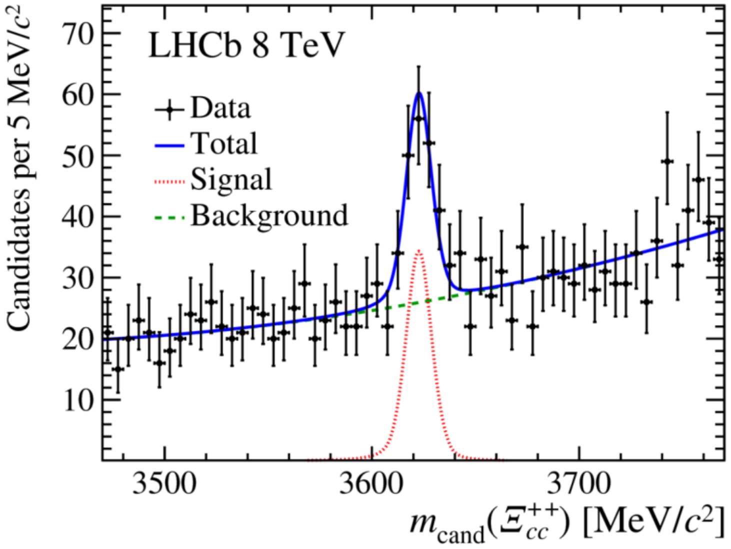
- Signal yield of 313 ± 33 events
- Local significance grater than 12σ
- Confirmed with Run-I data (113 ± 21 ev. / >7σ sign.)

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

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

- 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)

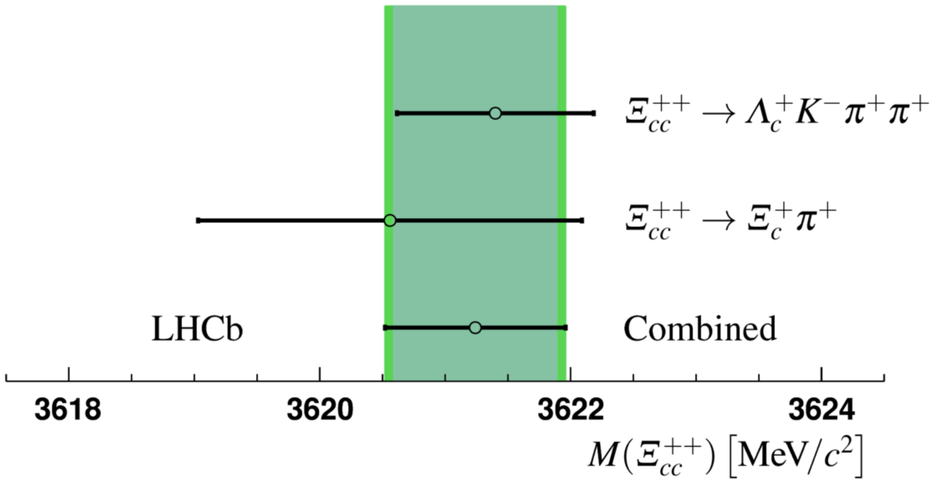




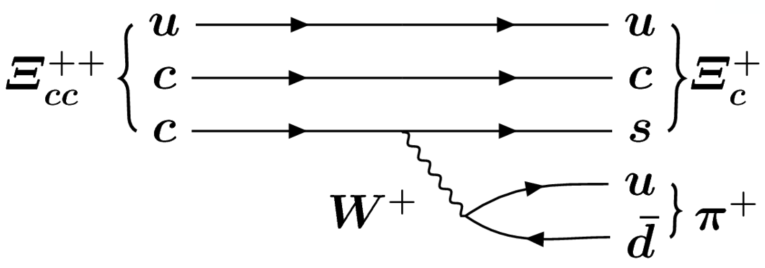
“Re-Discovery” of Ξ_{cc}^{++}

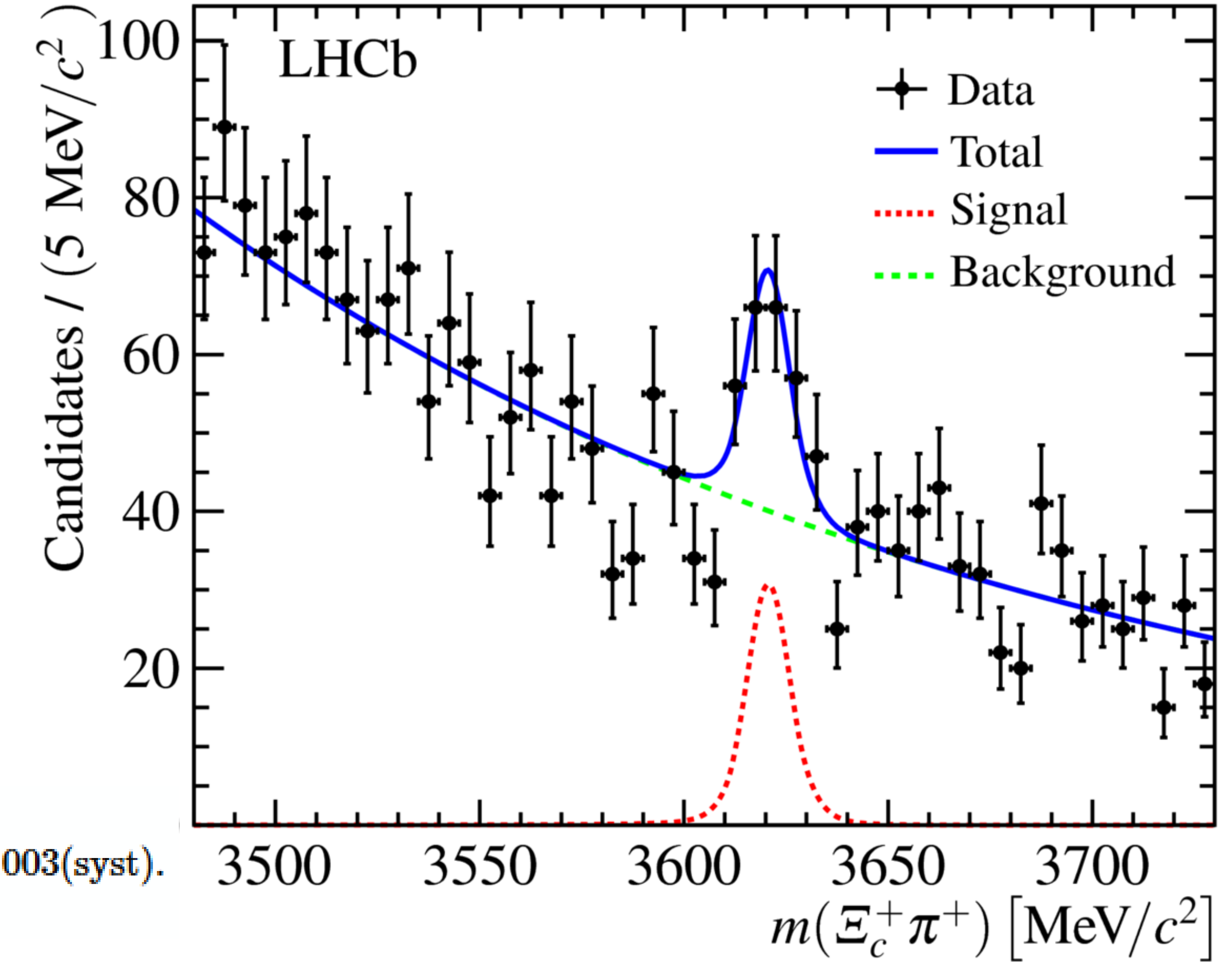
PHYS. REV. LETT. 121 162002 (2018)

- 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



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

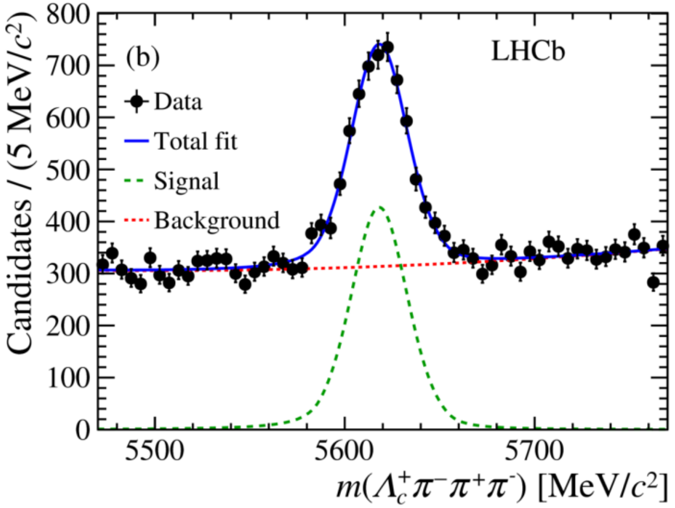


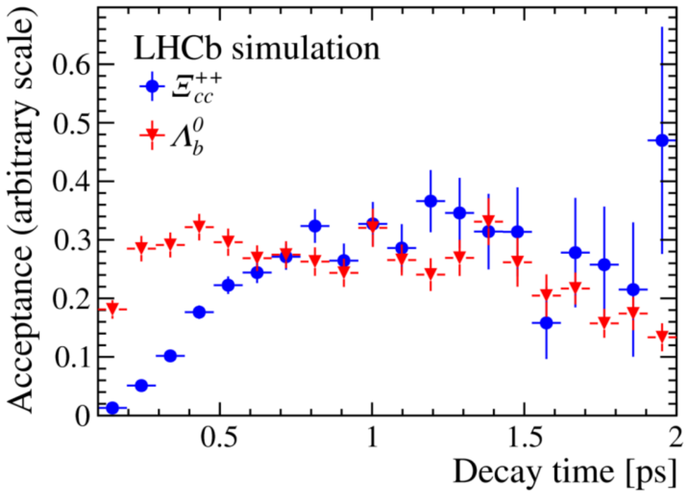


Lifetime measurement for Ξ_{cc}^{++}

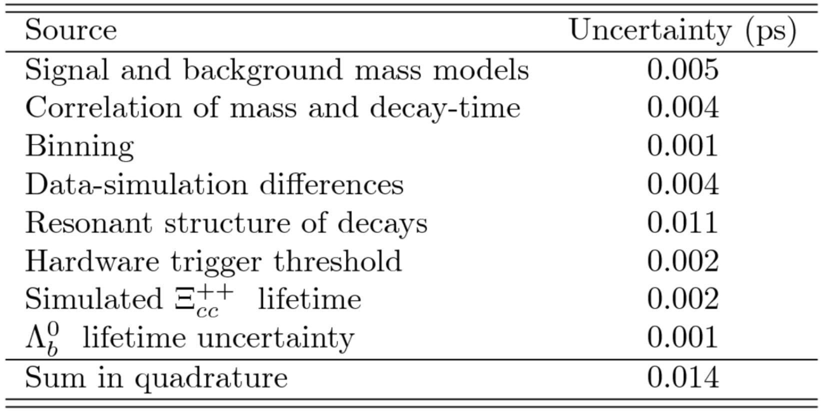
PHYS. REV. LETT. 121, 052002

- 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

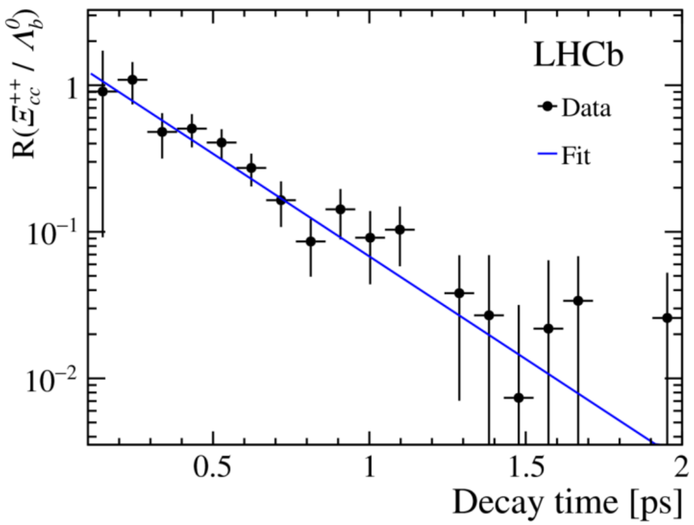




$$\tau\left(\Xi_{cc}^{++}\right) = 0.256\,^{+0.024}_{-0.022}\,(\text{stat}) \pm 0.014\,(\text{syst})\ \text{ps}.$$



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



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

Ref. to theory papers in backup

Measurement of ***Ω**$_c$* lifetime

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

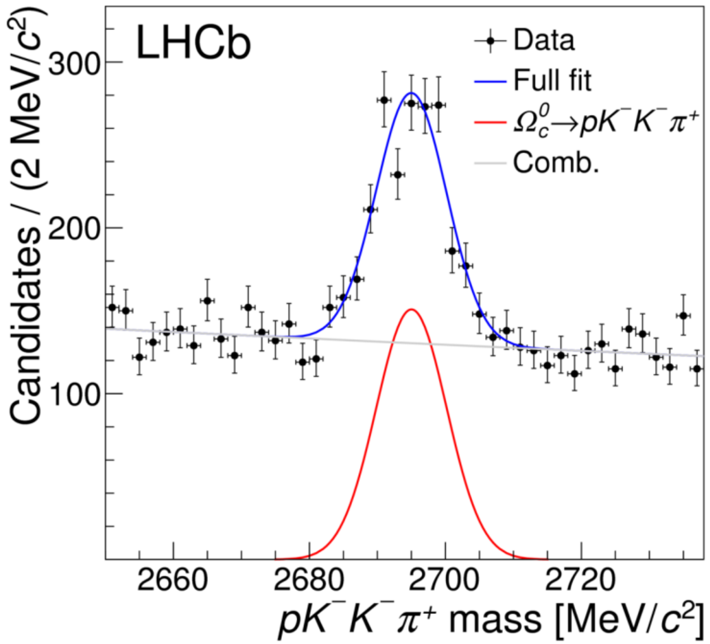
$$\tau_{\Xi_c^+} > \tau_{\Lambda_c^+} > \tau_{\Xi_c^0} > \tau_{\Omega_c^0}.$$

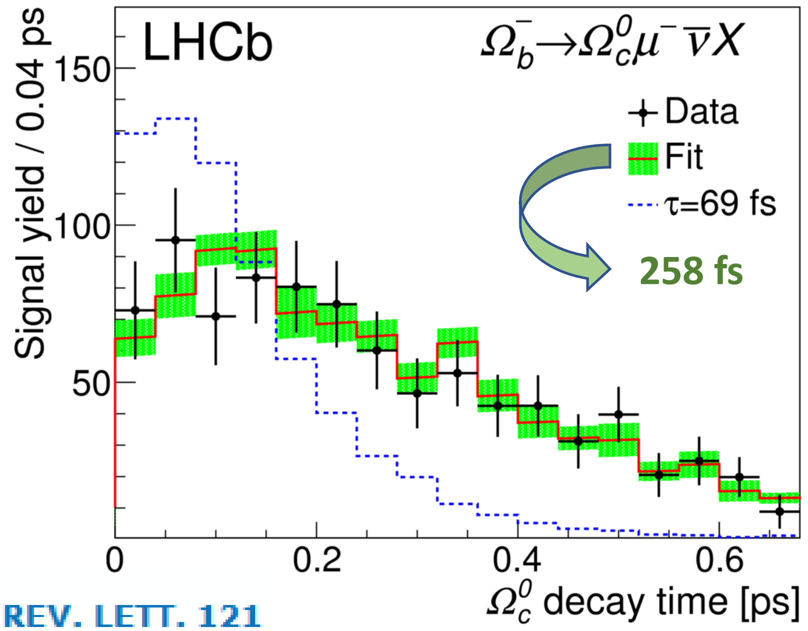
- Muons from semileptonic decays of ***Ω**$_b$* baryons and decay vertex of ***Ω**$_c$* baryon provide opportunity for lifetime measurement

- To reduce uncertainty the lifetime ratio $r_{\Omega_c^0} \equiv \frac{\tau_{\Omega_c^0}}{\tau_{D^+}}$ were measured

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

- **Fit result of 258 ± 23 fs is incompatible with 69 ± 12 fs lifetime reported in PDG!**





PHYS. REV. LETT. 121 (2018) 092003

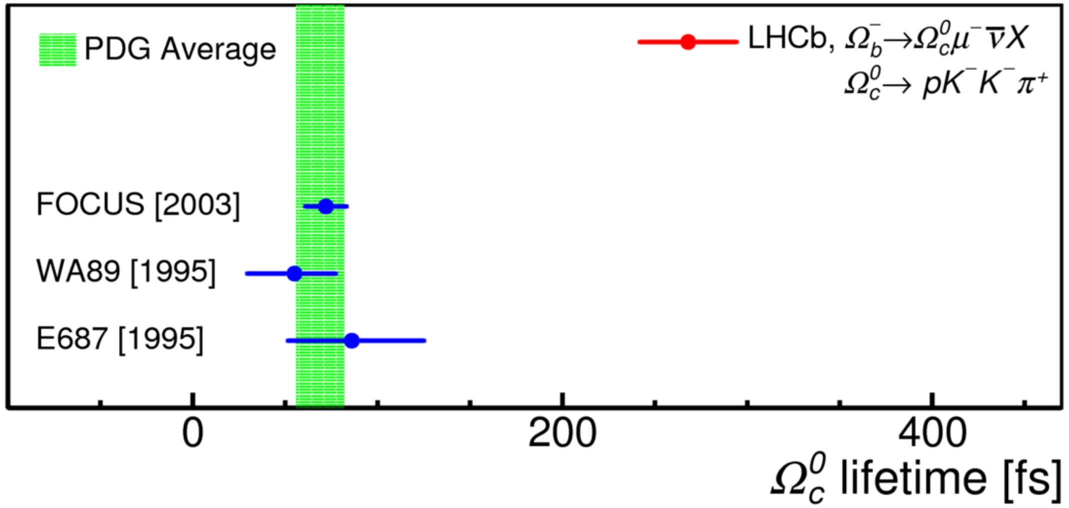
Measurement of Ω_c lifetime

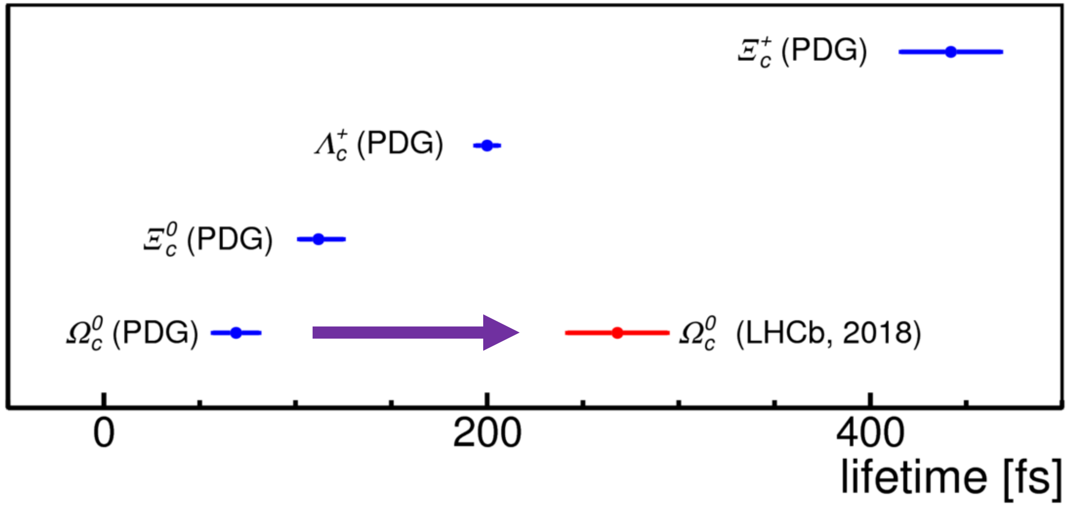
PHYS. REV. LETT. 121 (2018) 092003

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

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

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





Observation of doubly Cabibbo-suppressed decay of Ξ_c^+

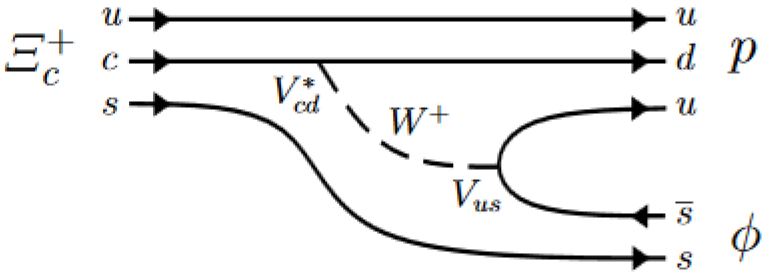
NEW

ARXIV:1901.06222

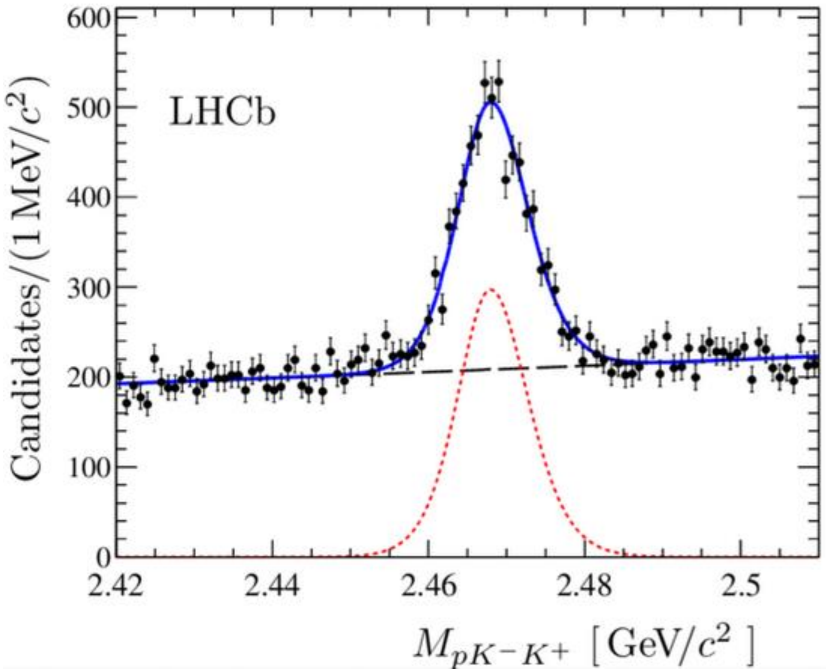
- Decay of systems into the same state from strong interaction point of view, but different from the flavor one

- Help to study the influence of “spectator”-quarks (in particular, Pauli interference effects). Important for understanding of the lifetime hierarchy

- Only one DCS decay ($\Lambda_c^0 \longrightarrow pK^+\pi^-$) for was observed so far:
  - Belle Phys. Rev. Lett.117 (2016) 011801
  - LHCb JHEP 03 (2018) 043



LHCb, Run-I, 2012, 2 fb^{-1} $M_{KK} < 1070\ \text{MeV}/c^2$

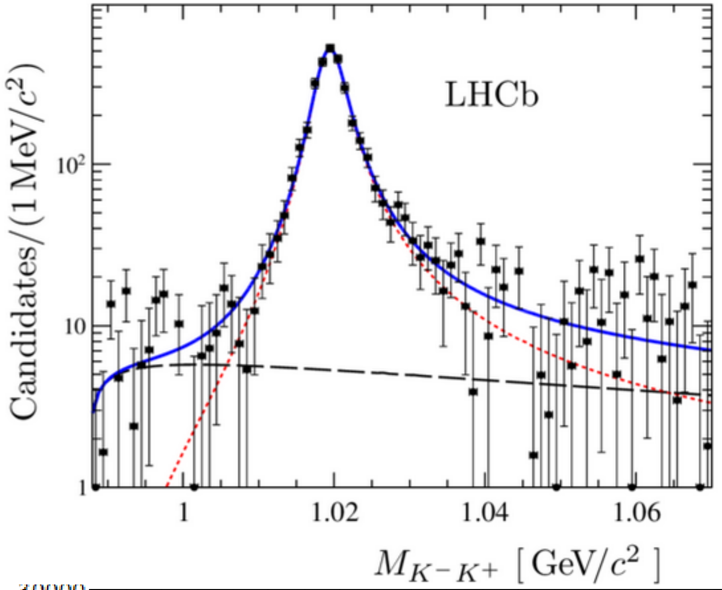


NEW

Observation of doubly Cabibbo-suppressed decay of Ξ_c^+

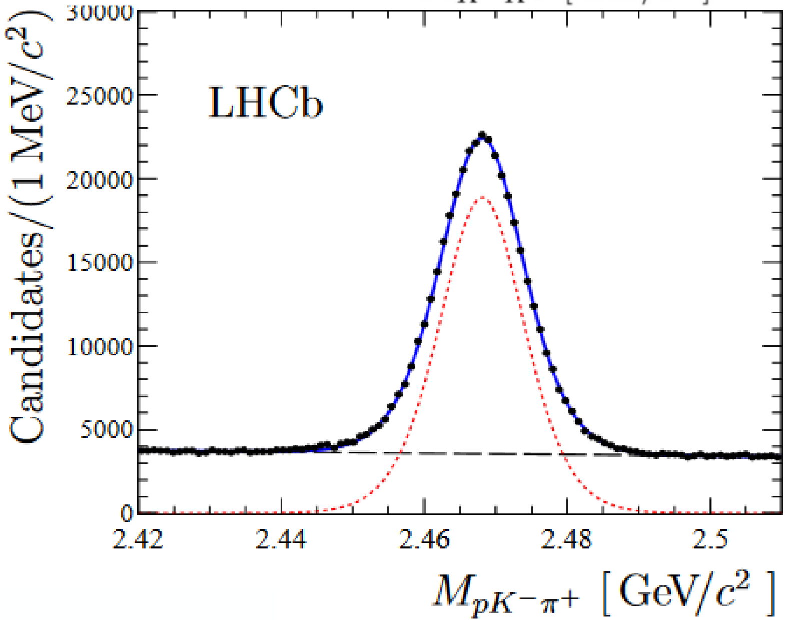
Measurement of the ratio of BF's

$$R_{p\phi} = \frac{N_{pKK} f_\phi}{\mathcal{B}(\phi \to K^+K^-)} \times \frac{1}{N_{pK\pi}} \times \frac{\epsilon^{pK\pi}_{\text{total}}}{\epsilon^{p\phi}_{\text{total}}}.$$



- *sPlot* technique is validated and used to obtain the M_{KK} lineshape for Ξ_c^+ candidates
- Statistical significance more than 15σ
- Evidence of non-φ contribution (at the level 3.5 σ)
- Main systematics – trigger and particle identification

$$R_{p\phi} = (19.8 \pm 0.7 \pm 0.9 \pm 0.2) \times 10^{-3},$$

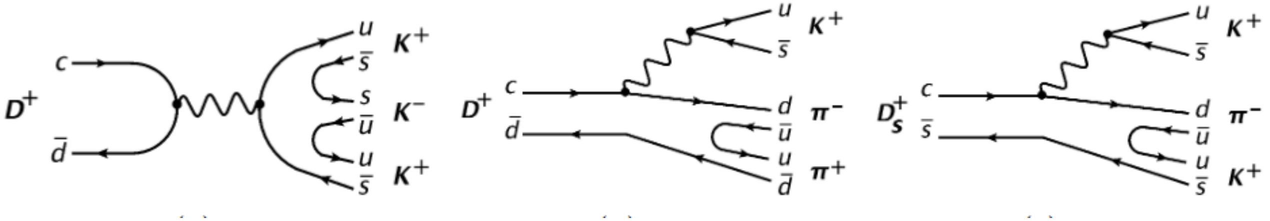


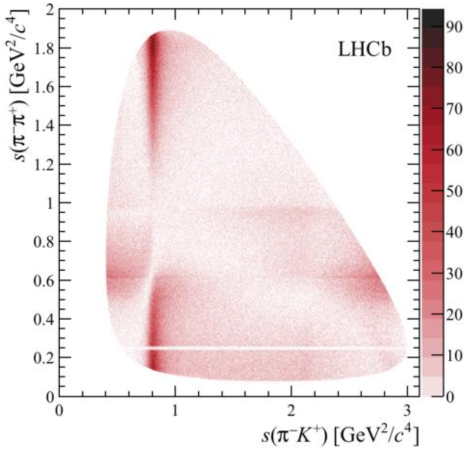
ARXIV:1901.06222

Doubly Cabibbo-suppressed decays of mesons

- Unprecedent statistics collected for *D* mesons (this work LHCb,2012, 2 fb^{-1})
- Push-down uncertainties for the branching fraction measurements
- Face with the lack of Monte-Carlo (main systematic uncertainty)
- Further studies of the DCS decays (see next slide)

ARXIV:1810.03138





Channel	Yields [$\times 10^3$]
$D^+ \to K^-K^+K^+$	134.30 ± 0.47
$D^+ \to \pi^-\pi^+K^+$	794.9 ± 1.4
$D_s^+ \to \pi^-K^+K^+$	67.2 ± 0.5
$D^+ \to K^-K^+\pi^+$	$23\,139 \pm 5$
$D^+ \to K^-\pi^+\pi^+$ (†)	$204\,290 \pm 14$
$D^+ \to K^-\pi^+\pi^+$ (††)	$158\,727 \pm 13$
$D_s^+ \to K^-K^+\pi^+$	$23\,044 \pm 5$

$$\frac{\mathcal{B}(D^+ \to K^-K^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (6.541 \pm 0.025 \pm 0.042) \times 10^{-4},$$

$$\frac{\mathcal{B}(D^+ \to \pi^-\pi^+K^+)}{\mathcal{B}(D^+ \to K^-\pi^+\pi^+)} = (5.231 \pm 0.009 \pm 0.023) \times 10^{-3},$$

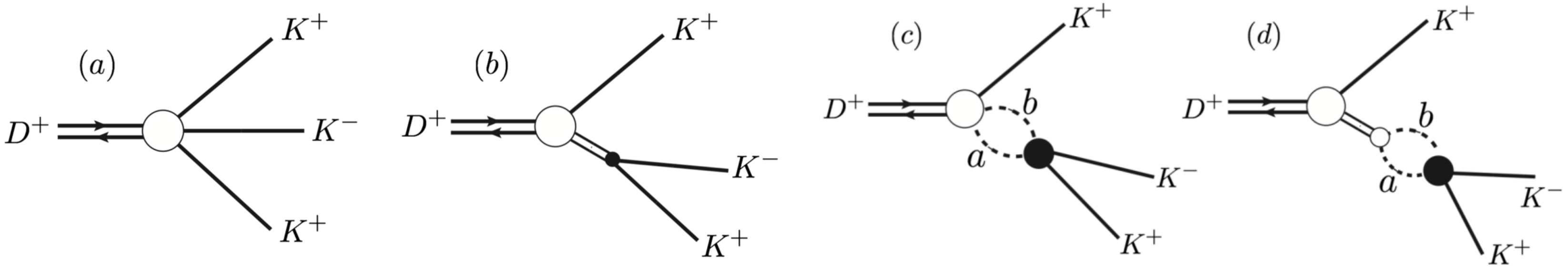
$$\frac{\mathcal{B}(D_s^+ \to \pi^-K^+K^+)}{\mathcal{B}(D_s^+ \to K^-K^+\pi^+)} = (2.372 \pm 0.024 \pm 0.025) \times 10^{-3},$$

Dalitz plot analysis for the $D^+ \longrightarrow K^+K^-K^+$

NEW

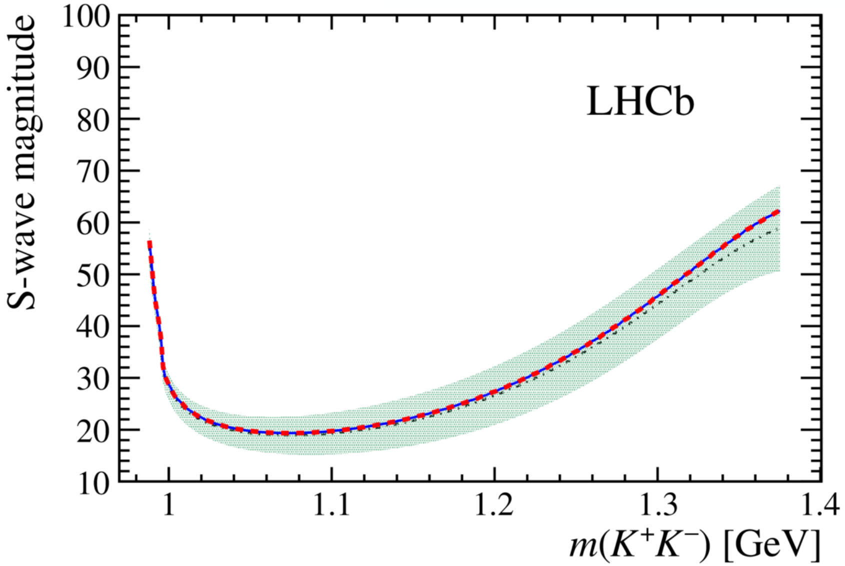
ARXIV:1902.05884

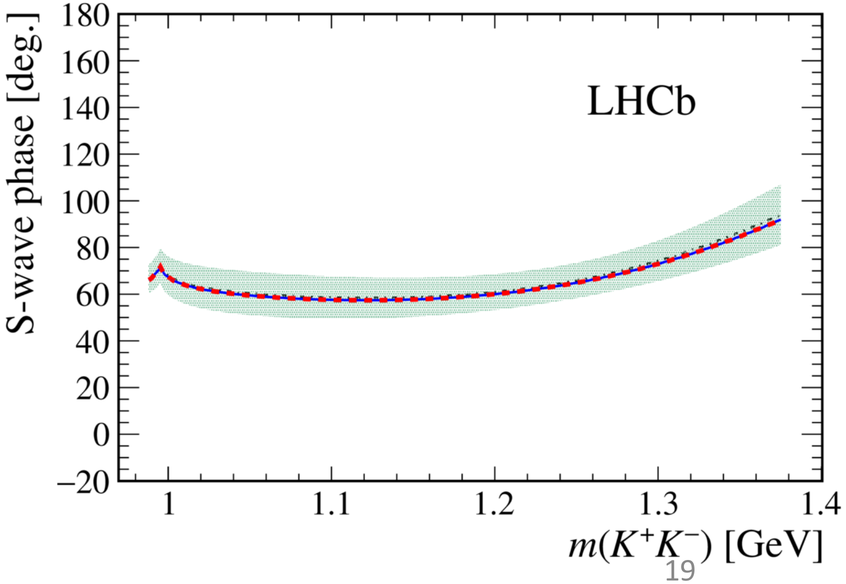
- The amplitude analysis of this decay is performed with the **isobar model** and a **phenomenological model based on an effective chiral Lagrangian**.



- Both found dominance of the S-wave contribution into K^+K^- system, with a small φ-contribution.

- **K^+K^- scattering amplitudes** for the considered combinations of spin (0,1) and isospin (0,1) of the two-body system are obtained from the Dalitz plot fit with the phenomenological decay amplitude.



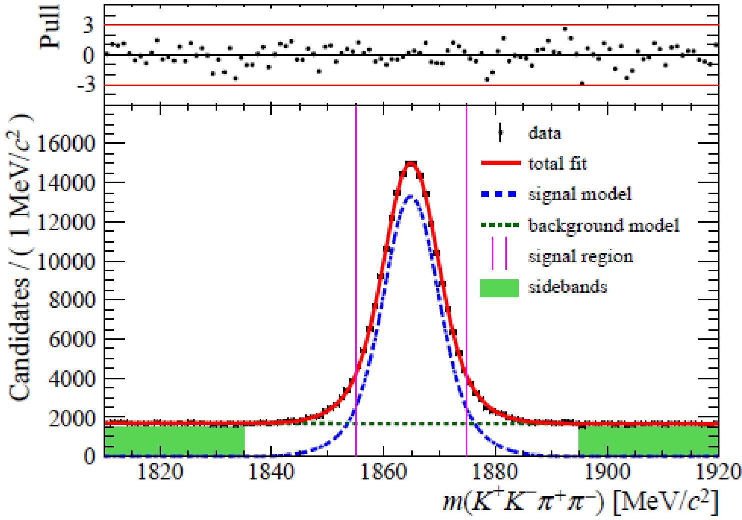


Mixing and CPV searches in charm sector

Amplitude analysis for $D^0 \longrightarrow K^+K^-\pi^+\pi^-$

ARXIV:1811.08304

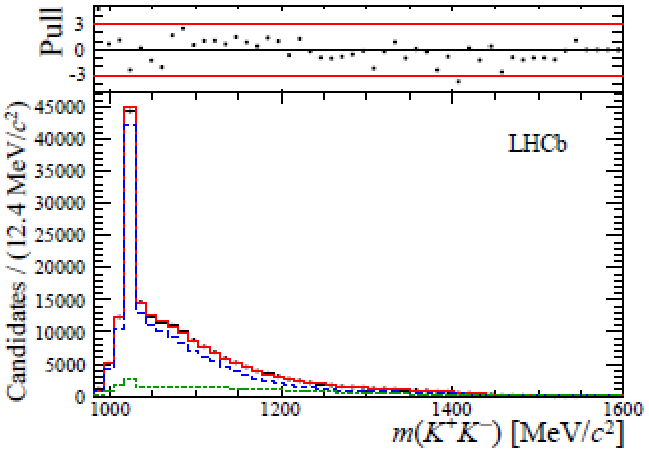
LHCb, Run-I, 3 fb^{-1}
SL tagging

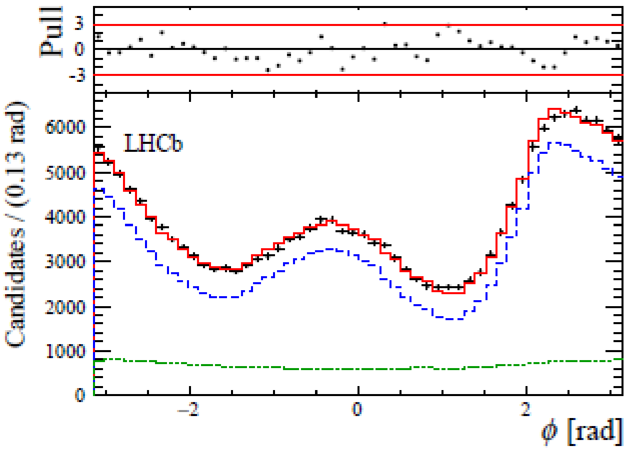


- Singly Cabibbo-suppressed decays are most promising channel, as for them CPV may arise from the interference btw. tree and penguin amplitudes. **Potentially up to 1% CPV effects!**

- Test of the rich resonance structure of many-body decays. The variation of the strong phases over the decay phase space may provide regions with enhanced sensitivity to CP violation.

- Challenge to build amplitude model, which will describe multy-dimancial distribution → the feature of this analysis is the self-consistent approach to select (one-by-one) most important contributions





Amplitude analysis for $D^0 \longrightarrow K^+K^-\pi^+\pi^-$

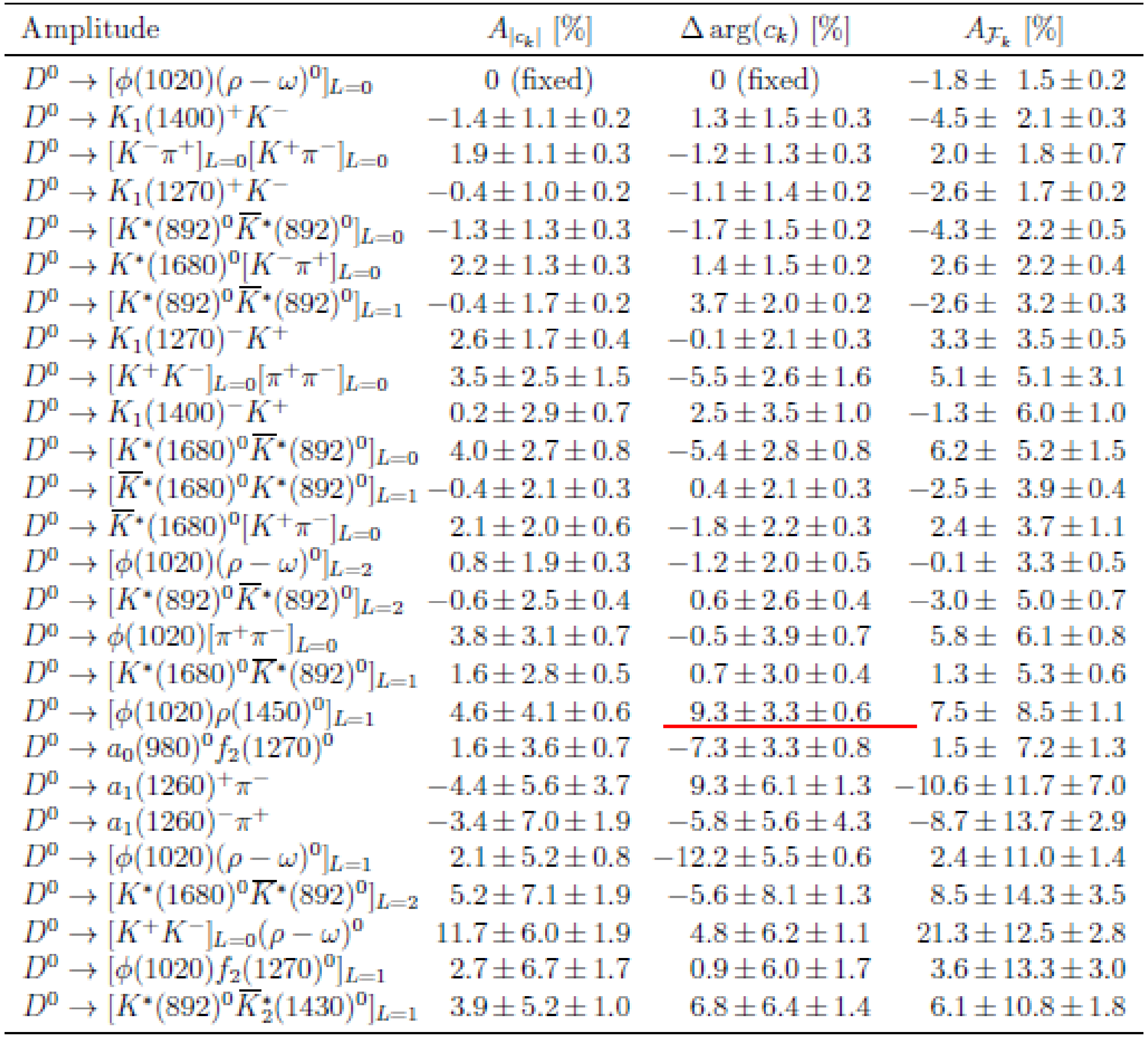
ARXIV:1811.08304

LHCb, Run-I, 3 fb^{-1} SL tagging

- More than 25 decay amplitudes are identified. Model fairly well describes data

$$\chi^2/\text{ndf} \qquad 9242/8121 = 1.14$$

- Search for CPV in the individual resonant contributions
- All of them consistent with the no-CPV hypothesis
- The most deviating one has 2.8 sigma significance (toy MC suggests that such deviations appear in 35% cases as a consequence of statistical fluctuations).

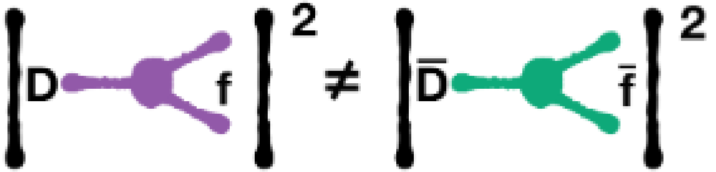


Amplitude	$A_{\lvert c_k\rvert}$ [%]	$\Delta\arg(c_k)$ [%]	$A_{\mathcal{F}_k}$ [%]
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=0}$	0 (fixed)	0 (fixed)	$-1.8 \pm 1.5 \pm 0.2$
$D^0 \to K_1(1400)^+K^-$	$-1.4 \pm 1.1 \pm 0.2$	$1.3 \pm 1.5 \pm 0.3$	$-4.5 \pm 2.1 \pm 0.3$
$D^0 \to [K^-\pi^+]_{L=0}[K^+\pi^-]_{L=0}$	$1.9 \pm 1.1 \pm 0.3$	$-1.2 \pm 1.3 \pm 0.3$	$2.0 \pm 1.8 \pm 0.7$
$D^0 \to K_1(1270)^+K^-$	$-0.4 \pm 1.0 \pm 0.2$	$-1.1 \pm 1.4 \pm 0.2$	$-2.6 \pm 1.7 \pm 0.2$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=0}$	$-1.3 \pm 1.3 \pm 0.3$	$-1.7 \pm 1.5 \pm 0.2$	$-4.3 \pm 2.2 \pm 0.5$
$D^0 \to K^*(1680)^0[K^-\pi^+]_{L=0}$	$2.2 \pm 1.3 \pm 0.3$	$1.4 \pm 1.5 \pm 0.2$	$2.6 \pm 2.2 \pm 0.4$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=1}$	$-0.4 \pm 1.7 \pm 0.2$	$3.7 \pm 2.0 \pm 0.2$	$-2.6 \pm 3.2 \pm 0.3$
$D^0 \to K_1(1270)^-K^+$	$2.6 \pm 1.7 \pm 0.4$	$-0.1 \pm 2.1 \pm 0.3$	$3.3 \pm 3.5 \pm 0.5$
$D^0 \to [K^+K^-]_{L=0}[\pi^+\pi^-]_{L=0}$	$3.5 \pm 2.5 \pm 1.5$	$-5.5 \pm 2.6 \pm 1.6$	$5.1 \pm 5.1 \pm 3.1$
$D^0 \to K_1(1400)^-K^+$	$0.2 \pm 2.9 \pm 0.7$	$2.5 \pm 3.5 \pm 1.0$	$-1.3 \pm 6.0 \pm 1.0$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=0}$	$4.0 \pm 2.7 \pm 0.8$	$-5.4 \pm 2.8 \pm 0.8$	$6.2 \pm 5.2 \pm 1.5$
$D^0 \to [\overline{K}^*(1680)^0K^*(892)^0]_{L=1}$	$-0.4 \pm 2.1 \pm 0.3$	$0.4 \pm 2.1 \pm 0.3$	$-2.5 \pm 3.9 \pm 0.4$
$D^0 \to \overline{K}^*(1680)^0[K^+\pi^-]_{L=0}$	$2.1 \pm 2.0 \pm 0.6$	$-1.8 \pm 2.2 \pm 0.3$	$2.4 \pm 3.7 \pm 1.1$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=2}$	$0.8 \pm 1.9 \pm 0.3$	$-1.2 \pm 2.0 \pm 0.5$	$-0.1 \pm 3.3 \pm 0.5$
$D^0 \to [K^*(892)^0\overline{K}^*(892)^0]_{L=2}$	$-0.6 \pm 2.5 \pm 0.4$	$0.6 \pm 2.6 \pm 0.4$	$-3.0 \pm 5.0 \pm 0.7$
$D^0 \to \phi(1020)[\pi^+\pi^-]_{L=0}$	$3.8 \pm 3.1 \pm 0.7$	$-0.5 \pm 3.9 \pm 0.7$	$5.8 \pm 6.1 \pm 0.8$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=1}$	$1.6 \pm 2.8 \pm 0.5$	$0.7 \pm 3.0 \pm 0.4$	$1.3 \pm 5.3 \pm 0.6$
$D^0 \to [\phi(1020)\rho(1450)^0]_{L=1}$	$4.6 \pm 4.1 \pm 0.6$	$9.3 \pm 3.3 \pm 0.6$	$7.5 \pm 8.5 \pm 1.1$
$D^0 \to a_0(980)^0f_2(1270)^0$	$1.6 \pm 3.6 \pm 0.7$	$-7.3 \pm 3.3 \pm 0.8$	$1.5 \pm 7.2 \pm 1.3$
$D^0 \to a_1(1260)^+\pi^-$	$-4.4 \pm 5.6 \pm 3.7$	$9.3 \pm 6.1 \pm 1.3$	$-10.6 \pm 11.7 \pm 7.0$
$D^0 \to a_1(1260)^-\pi^+$	$-3.4 \pm 7.0 \pm 1.9$	$-5.8 \pm 5.6 \pm 4.3$	$-8.7 \pm 13.7 \pm 2.9$
$D^0 \to [\phi(1020)(\rho-\omega)^0]_{L=1}$	$2.1 \pm 5.2 \pm 0.8$	$-12.2 \pm 5.5 \pm 0.6$	$2.4 \pm 11.0 \pm 1.4$
$D^0 \to [K^*(1680)^0\overline{K}^*(892)^0]_{L=2}$	$5.2 \pm 7.1 \pm 1.9$	$-5.6 \pm 8.1 \pm 1.3$	$8.5 \pm 14.3 \pm 3.5$
$D^0 \to [K^+K^-]_{L=0}(\rho-\omega)^0$	$11.7 \pm 6.0 \pm 1.9$	$4.8 \pm 6.2 \pm 1.1$	$21.3 \pm 12.5 \pm 2.8$
$D^0 \to [\phi(1020)f_2(1270)^0]_{L=1}$	$2.7 \pm 6.7 \pm 1.7$	$0.9 \pm 6.0 \pm 1.7$	$3.6 \pm 13.3 \pm 3.0$
$D^0 \to [K^*(892)^0\overline{K}^*_2(1430)^0]_{L=1}$	$3.9 \pm 5.2 \pm 1.0$	$6.8 \pm 6.4 \pm 1.4$	$6.1 \pm 10.8 \pm 1.8$

Search for direct CPV in decays of D^+ and D_s^+

NEW

- Singly Cabibbo-suppressed decays are most promising channel, as for them CPV may arise from the interference between tree and penguin amplitudes



- Measurement of the CP asymmetry for $D_s^+ \rightarrow K_s^0\pi^+$, $D^+ \rightarrow K_s^0K^+$ and $D^+ \rightarrow \varphi\pi^+$
- Easy-to-reconstruct high statistical channels, Run-II data used (2015-2017)
- Production and detection asymmetry should be taken into account to determine A_{CP}
- Cabibbo-favored decays are used as a control sample (A_{CP} can be neglected) for A_{prod} and A_{det}
- **No evidence of CPV is found (Result is PRELIMINARY)**

$$\mathcal{A}_{CP}(D_s^+ \rightarrow K_s^0\pi^+) = \Big(1.3 \pm 1.9\,(\text{stat}) \pm 0.5\,(\text{syst})\Big) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \rightarrow K_s^0K^+) = \Big(-0.09 \pm 0.65\,(\text{stat}) \pm 0.48\,(\text{syst})\Big) \times 10^{-3}$$
$$\mathcal{A}_{CP}(D^+ \rightarrow \phi\pi^+) = \Big(0.05 \pm 0.42\,(\text{stat}) \pm 0.29\,(\text{syst})\Big) \times 10^{-3}$$

LHCb-PAPER-2019-002 (in preparation)

Measurement of the y_{CP} parameter

PHYS. REV. LETT. 122 (2019) 011802

$$y_{CP} \equiv \frac{\Gamma_{CP+}}{\Gamma} - 1$$

- Because of the mixing the effective decay width of decays into CP-even final states (in this work K^+K^- and $\pi^+\pi^-$) differs from the average width (can be eval. from $K^-\pi^+$ decay).

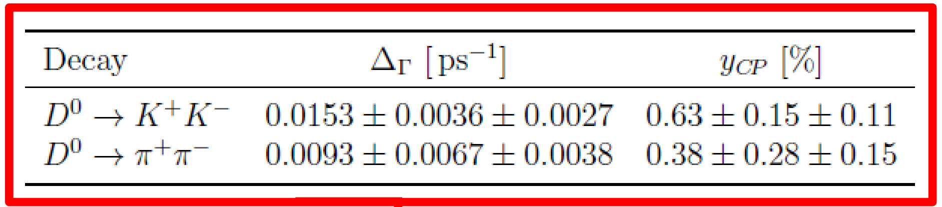
$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, \qquad \phi \equiv \arg(q\overline{\mathcal{A}}/p\mathcal{A})$$

$$\Gamma_{CP+} = \Delta_\Gamma + \Gamma, \qquad x \equiv (m_1 - m_2)/\Gamma \qquad y \equiv (\Gamma_1 - \Gamma_2)/2\Gamma$$

- The quantity y_{CP} is equal to the mixing parameter y in case of CP conservation.

$$2y_{CP} \approx (|q/p| + |p/q|)\, y \cos\phi - (|q/p| - |p/q|)\, x \sin\phi$$

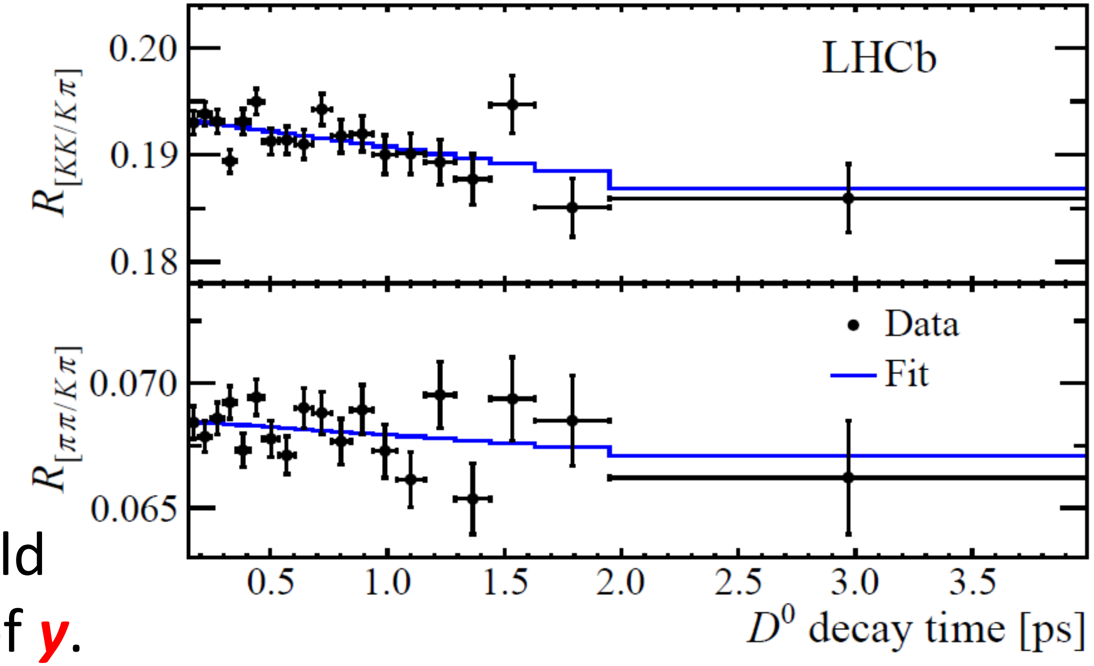
- Correction on LHCb decay time acceptance



Decay	Δ_Γ [ps^{-1}]	y_{CP} [%]
$D^0 \to K^+K^-$	$0.0153 \pm 0.0036 \pm 0.0027$	$0.63 \pm 0.15 \pm 0.11$
$D^0 \to \pi^+\pi^-$	$0.0093 \pm 0.0067 \pm 0.0038$	$0.38 \pm 0.28 \pm 0.15$

$$\rightarrow \quad y_{CP} = (0.57 \pm 0.13\,(\text{stat}) \pm 0.09\,(\text{syst}))\%$$

- Consistent with and as precise as the current world average value. Consistent with the known value of y.

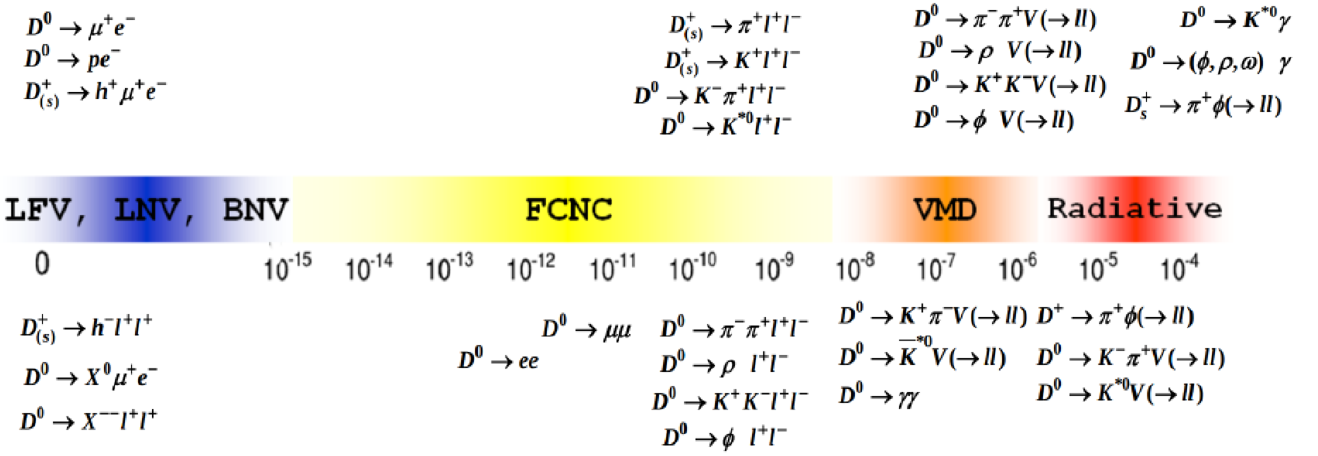


Corrected ratios

LHCb, Run-I, 3 fb^{-1} SL tagging

Rare decays of charmed hadrons

LHCb impact for rare charm decays

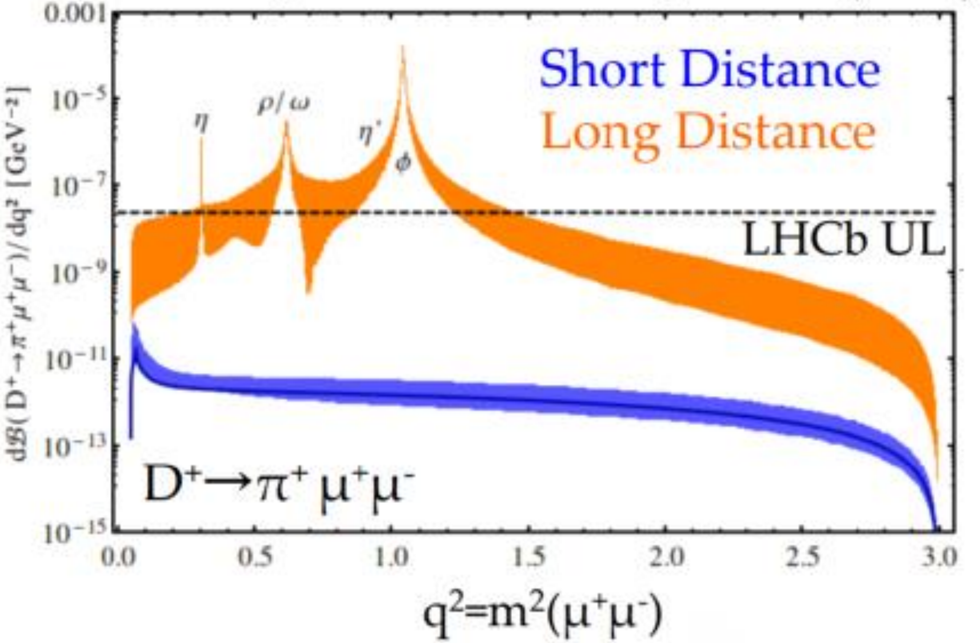


[PRD 66 (2002) 014009]

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

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

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

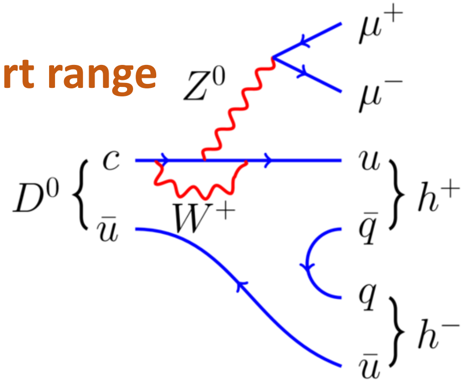


$D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $D^0 \rightarrow K^+K^-\mu^+\mu^-$

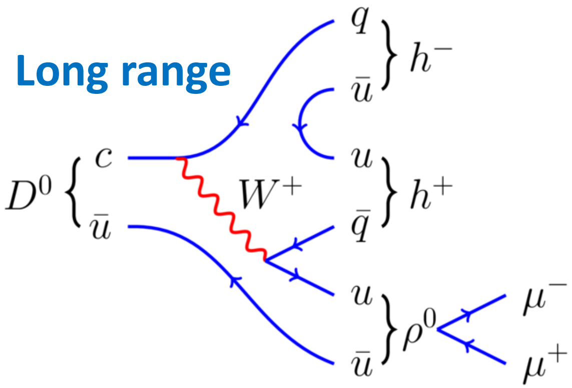
Goal: Probe New Physics in $c \rightarrow u$ transitions, appears at **short distances** and very suppressed in SM ($< 10^{-9}$)

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)

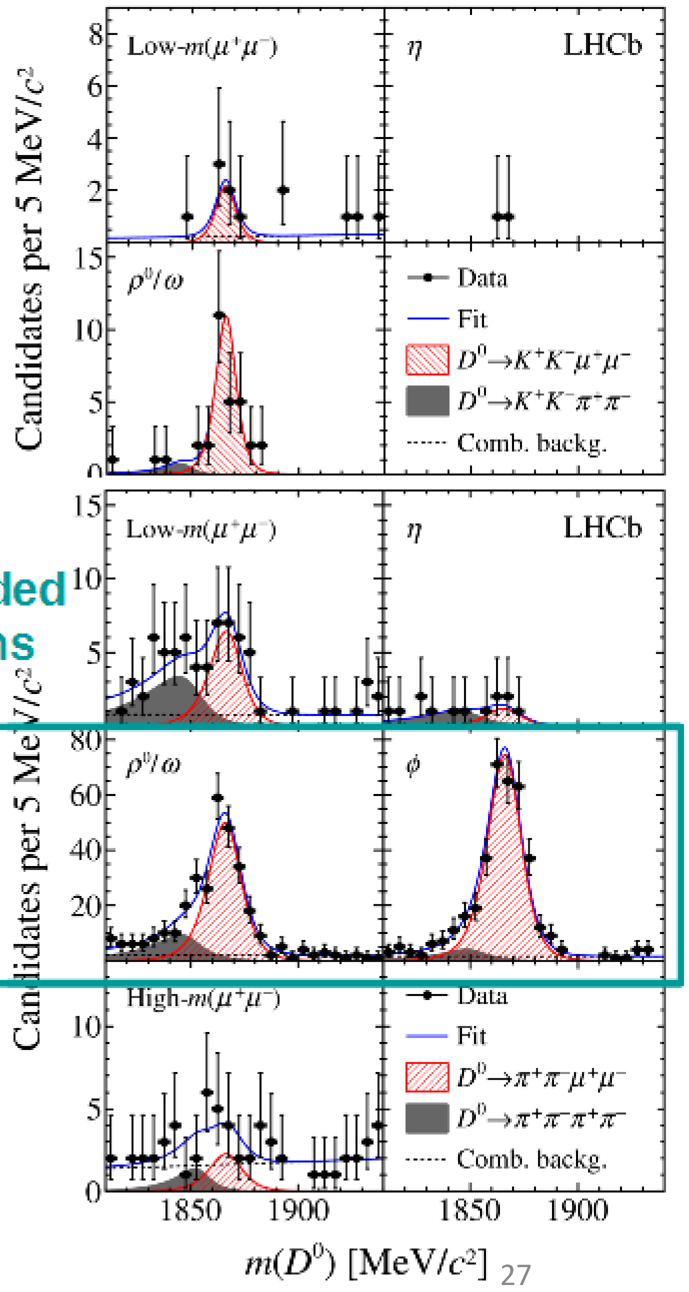
Short range



Long range



PHYS. REV. LETT. 119, 181805



Non-blinded mass bins

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

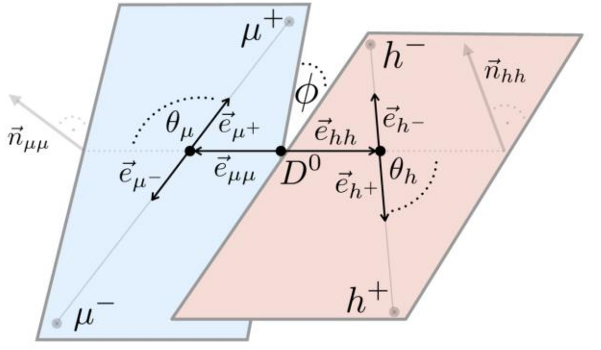
$D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ and $D^0 \rightarrow K^+K^-\mu^+\mu^-$

PHYS. REV. LETT. 121 (2018) 091801

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

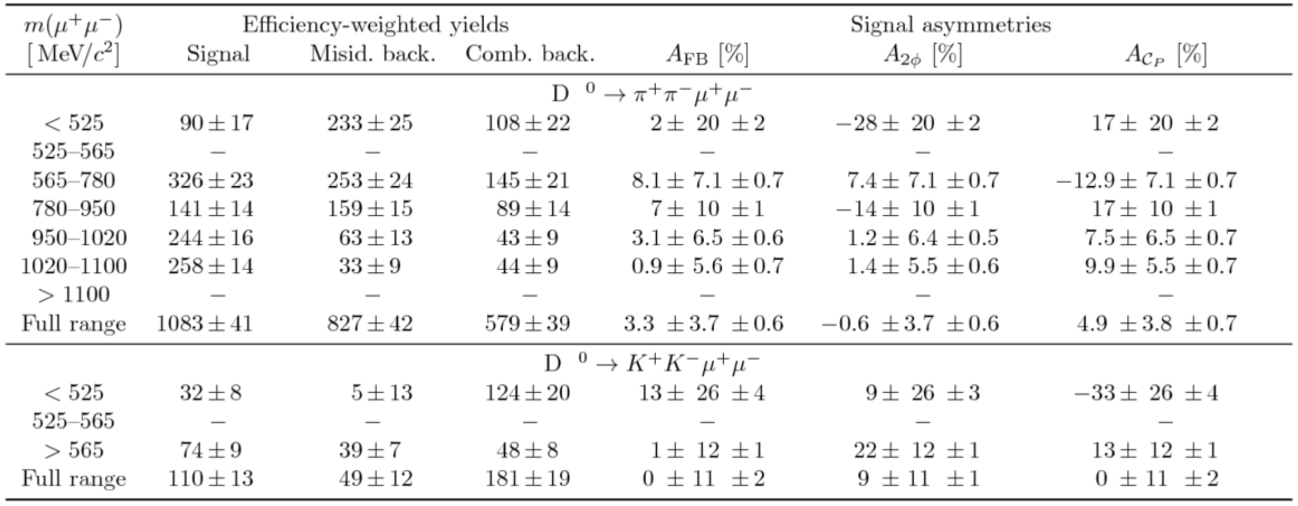
- A_{FB} – forward-backward asymmetry of $\mu^+\mu^-$
- $A_{2\varphi}$ – triple product asymmetry →
- A_{CP} – CP asymmetry (using prompt (D^*) tagging)

Quite promising probe for searches of New Physics

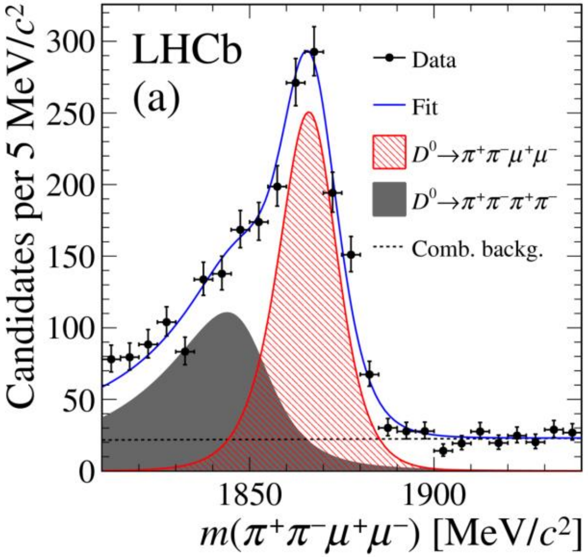


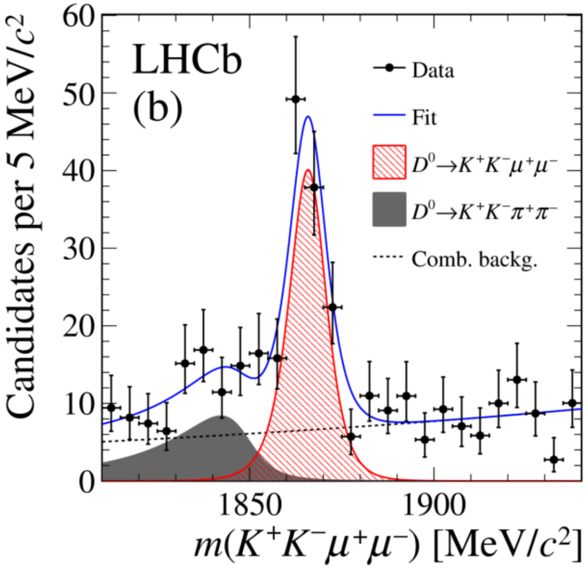
$$\sin 2\phi = 2(\vec{n}_{hh} \cdot \vec{n}_{\mu\mu})(\vec{n}_{hh} \times \vec{n}_{\mu\mu}) \cdot \vec{e}_{hh}.$$

Percent accuracy achieved with existing dataset



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

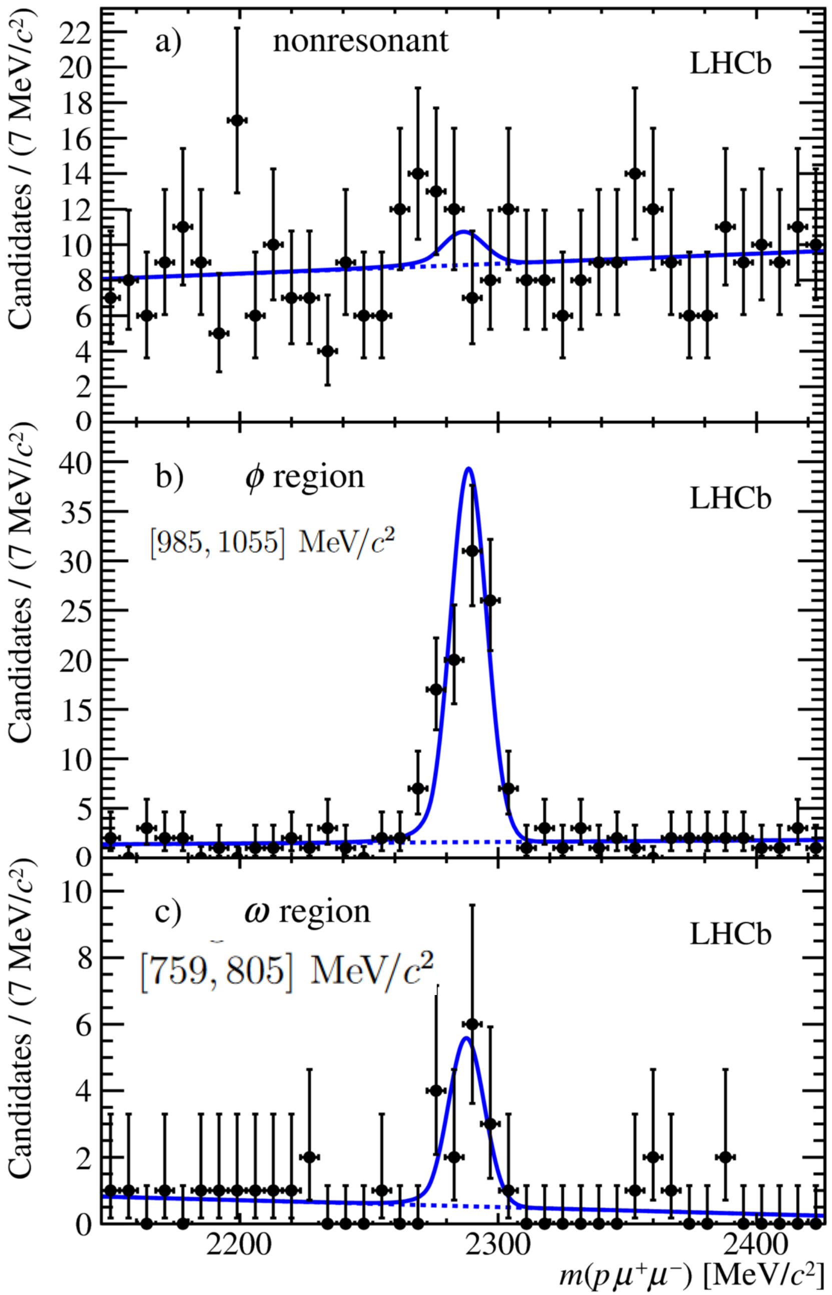




we are at the beginning of the long way

PHYS. REV. D 97, 091101 (2018)

Search for $\Lambda_c^+ \to p\mu^+\mu^-$

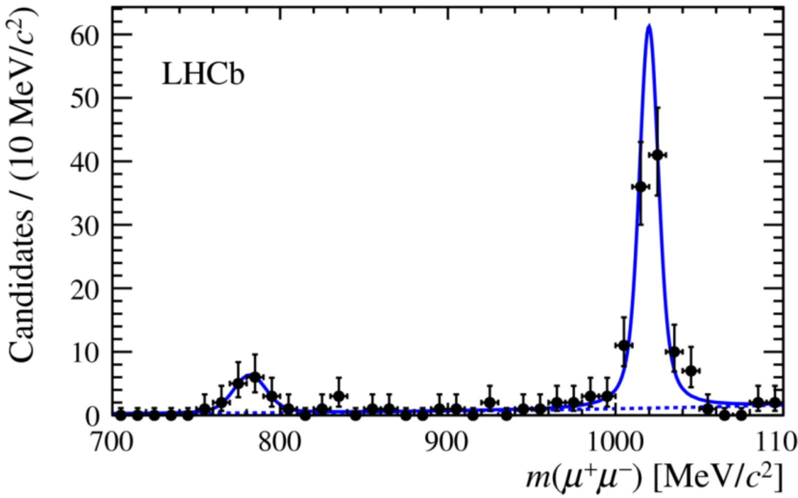


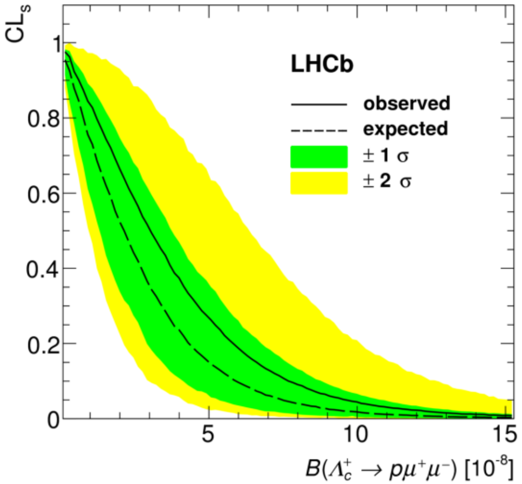
Expected signals from ϕ, $\omega \to \mu^+\mu^-$

In the SM non-resonant contribution ~10^{-9}

Run-I 3 fb^{-1} / BDT / Tight PID requirements

$$\mathcal{B}(\Lambda_c^+ \to p\mu^+\mu^-) < 7.7\ (9.6) \times 10^{-8} \quad \text{at} \ \ 90\%\ (95\%)\ \text{CL.}$$



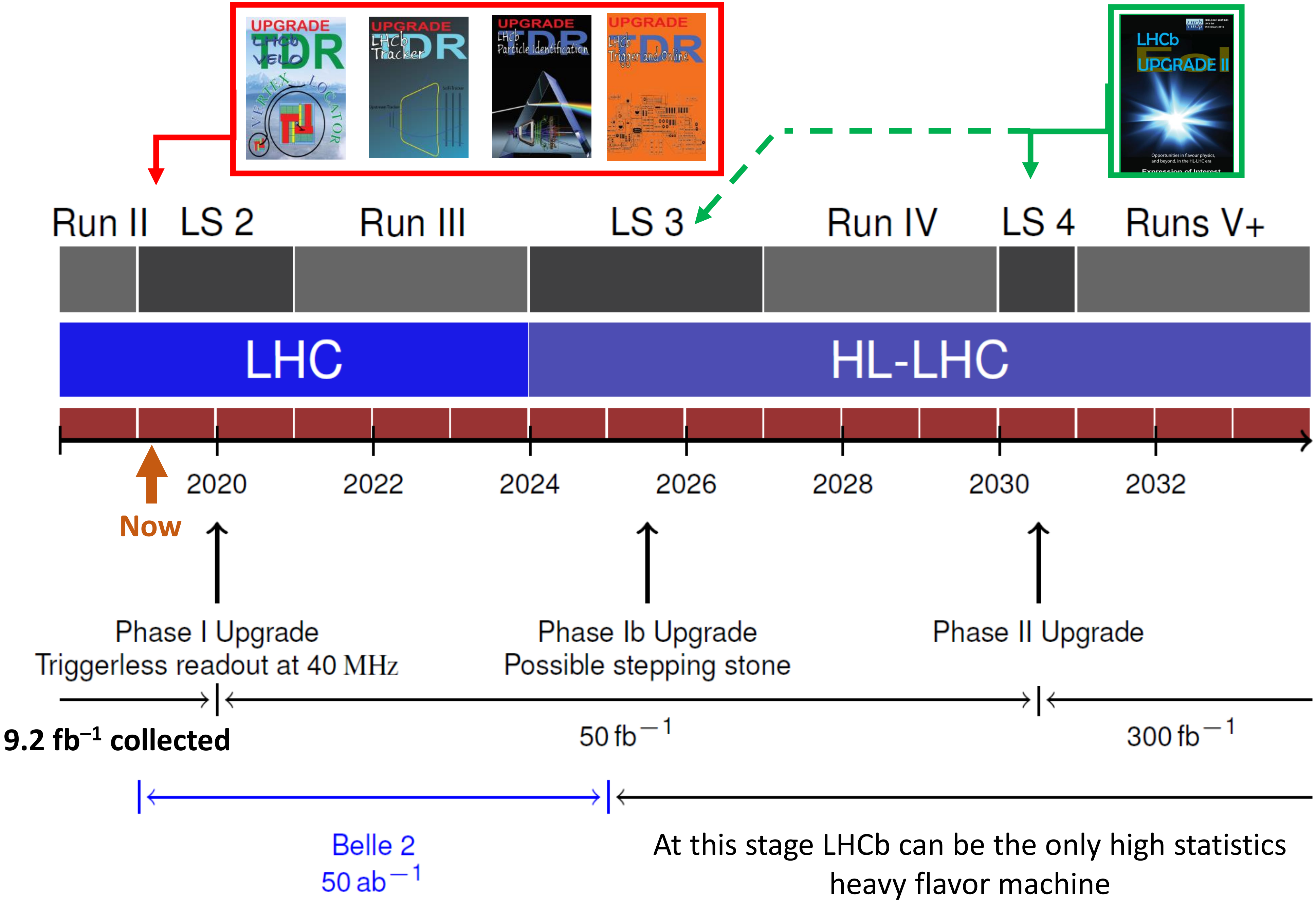


Future prospects / Upgrades

Timeline

Upgrade I is under construction for installation from 2019

Expression of Intent for the second phase



Run II LS 2 Run III LS 3 Run IV LS 4 Runs V+

LHC HL-LHC

2020 2022 2024 2026 2028 2030 2032

Now

Phase I Upgrade
Triggerless readout at 40 MHz

Phase Ib Upgrade
Possible stepping stone

Phase II Upgrade

$9.2\ \text{fb}^{-1}$ collected

$50\ \text{fb}^{-1}$

$300\ \text{fb}^{-1}$

Belle 2
$50\ \text{ab}^{-1}$

At this stage LHCb can be the only high statistics heavy flavor machine


CERN/LHCC 2017-003
LHCb EoI
08 February 2017

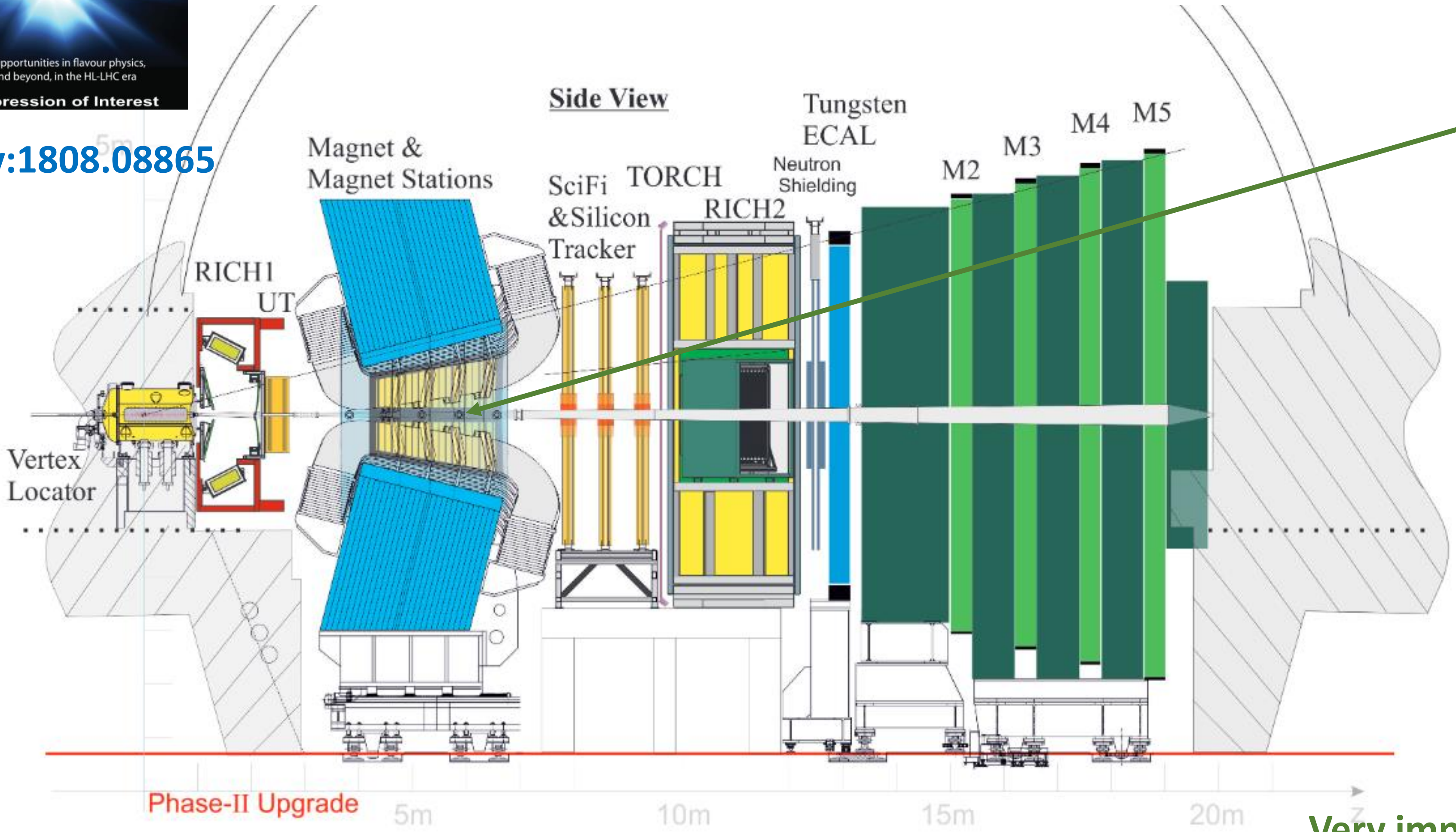
LHCb UPGRADE II

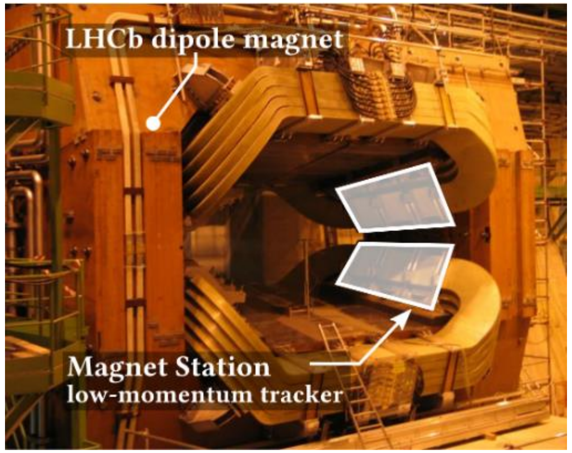
Opportunities in flavour physics, and beyond, in the HL-LHC era

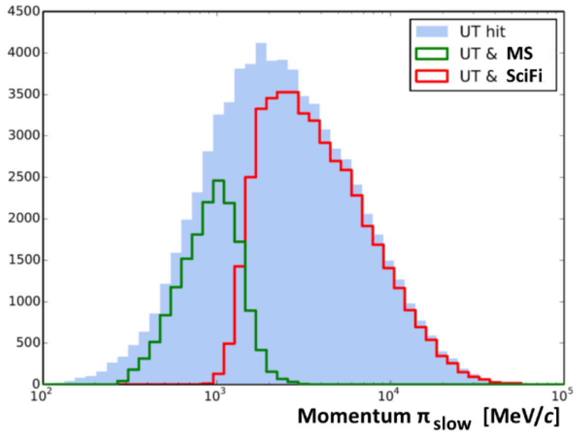
Expression of Interest

Example of modification important for charm (magnet stations)

arXiv:1808.08865







Very important for prompt tagging for charm CPV studies

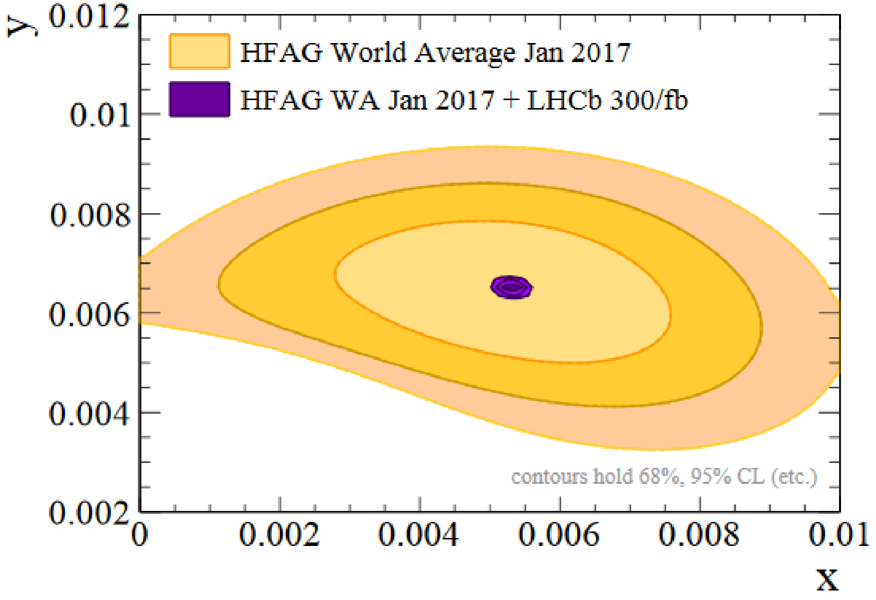
Incredible precision can be achieved with 300 fb^{-1}


LHCb UPGRADE II

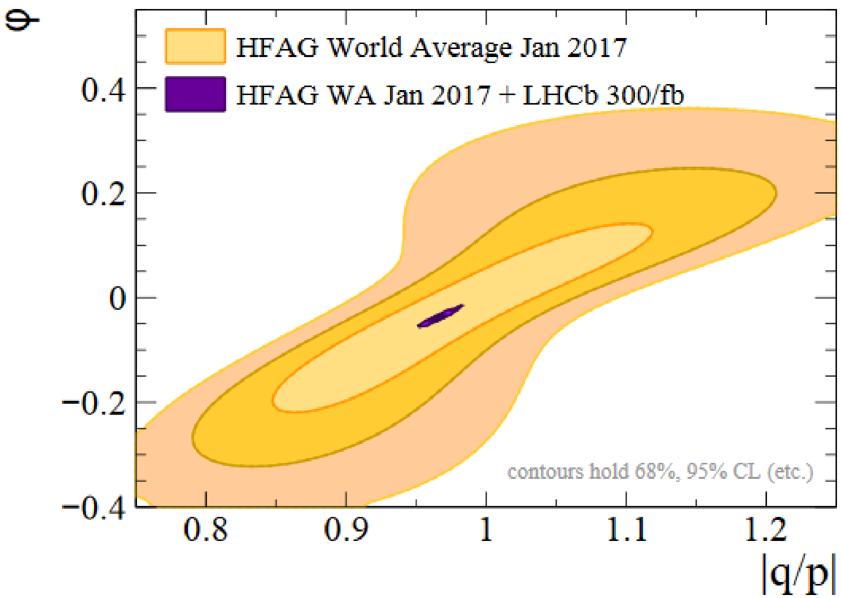
Opportunities in flavour physics, and beyond, in the HL-LHC era

Expression of Interest

Mixing parameters



Indirect CPV parameters in charm



arXiv:1808.08865

- We expect that systematical uncertainty will scale down together with statistical one.
- All chances to find CPV in charm sector

Topics and observables	Experimental reach	Remarks
Charm		
CP-violation studies with $D^0 \to h^+h^-$, $D^0 \to K^0_S\pi^+\pi^-$ and $D^0 \to K^\mp\pi^\pm\pi^+\pi^-$	*e.g.* 4×10^9 $D^0 \to K^+K^-$; $\boxed{\text{Uncertainty on } A_\Gamma \sim 10^{-5}}$	Access *CP* violation at SM values.

current one is 30 times higher

Summary & Conclusions

- Excellent LHCb performance during Run-I and II.
- A lot of important results in charm sector exploiting huge charm rate:
    - Spectroscopy – discovery of Ξ_{cc}^{++} / intriguing Ω_c lifetime measurement
    - Systematic studies for DCS decays of charm hadrons
    - Mixing & CPV – LHCb is dominating here
    - Rare decays – push down limits for di-muon decays / asymmetries studies

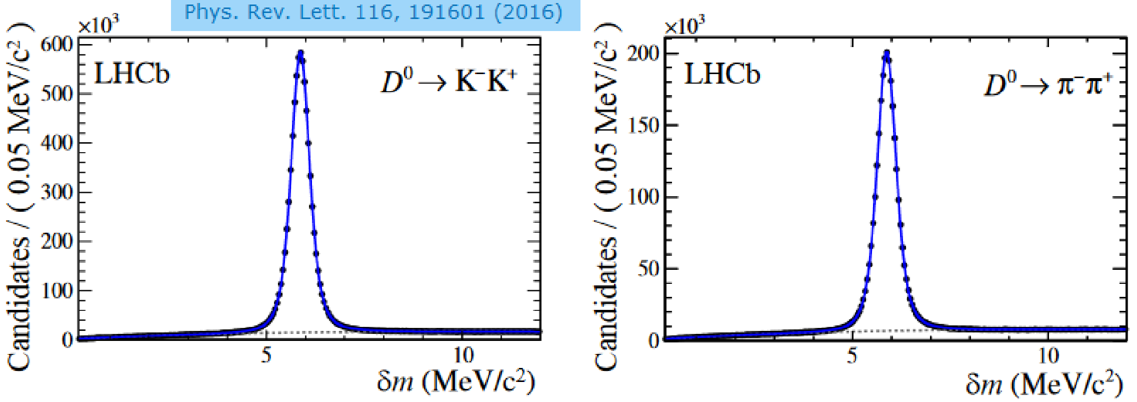
Many more in the stream of LHCb charm results: http://lhcbproject.web.cern.ch/lhcbproject/Publications/LHCbProjectPublic/Summary_Charm.html

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

Future prospects / Upgrades

Direct and indirect CPV in charm projections

Phys. Rev. Lett. 116, 191601 (2016)

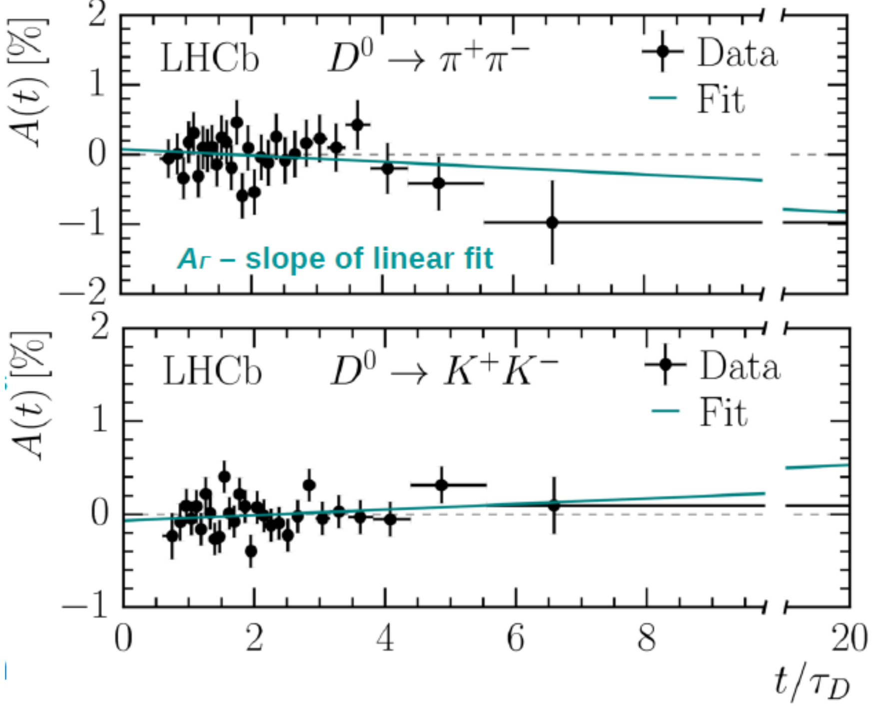


Run-I dataset: $\Delta A_{CP} = (-0.10 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst}))\,\%,$

Type	Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**
CP violation	ΔA_{CP} (10^{-3})	0.8	0.5	**0.1**

PRL 118 (2017) 261803

$A_\Gamma = (-0.29 \pm 0.28) \times 10^{-3}$



A_Γ – slope of linear fit

More improvement after Upgrade (we expect that systematics will improve with increasing L as data driven method are used):

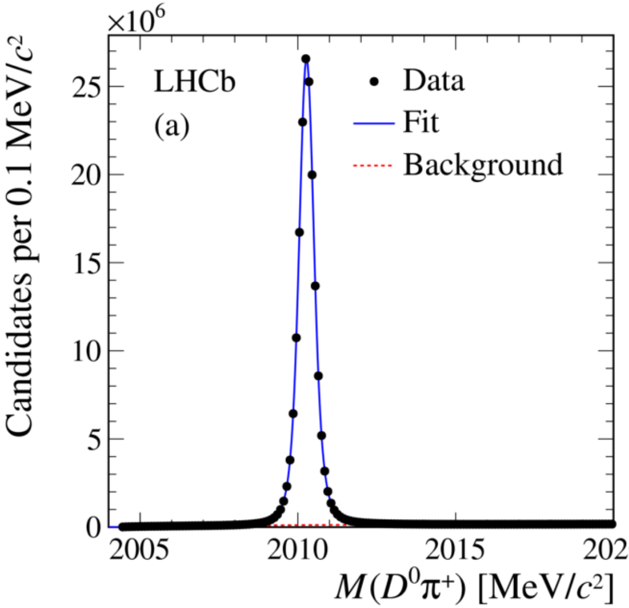
Observable	LHC Run 1	LHCb 2018	**LHCb upgrade**
$A_\Gamma(D^0 \to K^+K^-)$ (10^{-4})	3.4	2.2	**0.4**

LHCb-PUB-2014-040

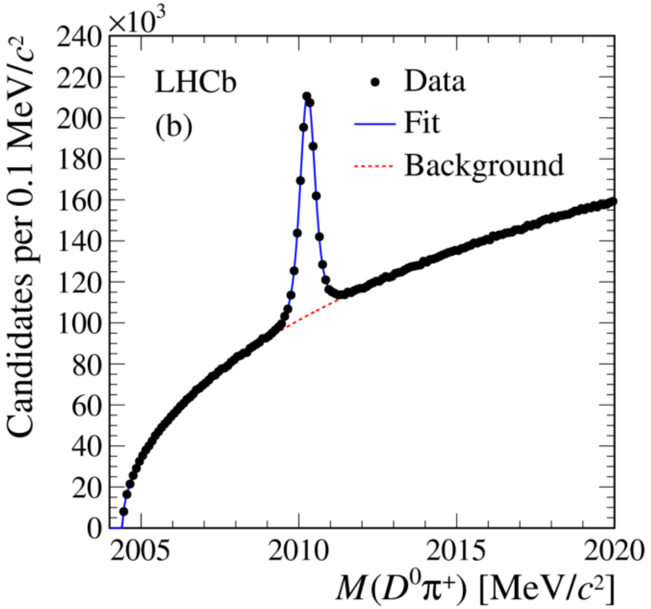
Mixing and CPV for *D^0*

PHYS. REV. D 97, 031101 (2018)

Right sign (RS) D^{*-} / $K^-\pi^+$



Wrong sign (RS) D^{*-} / $K^+\pi^-$



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

– 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:

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

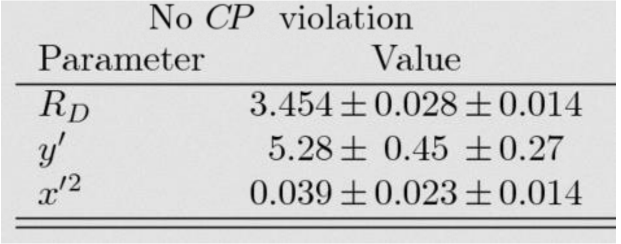
$R_D^+ = |\mathcal{A}_{\bar{f}}/\mathcal{A}_f|^2$ $R_D^- = |\overline{\mathcal{A}}_f/\overline{\mathcal{A}}_{\bar{f}}|^2$ $R_D^+ \neq R_D^-$ ⇒ direct CPV

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

PHYS. REV. D 97, 031101 (2018)

Mixing and CPV for D^0

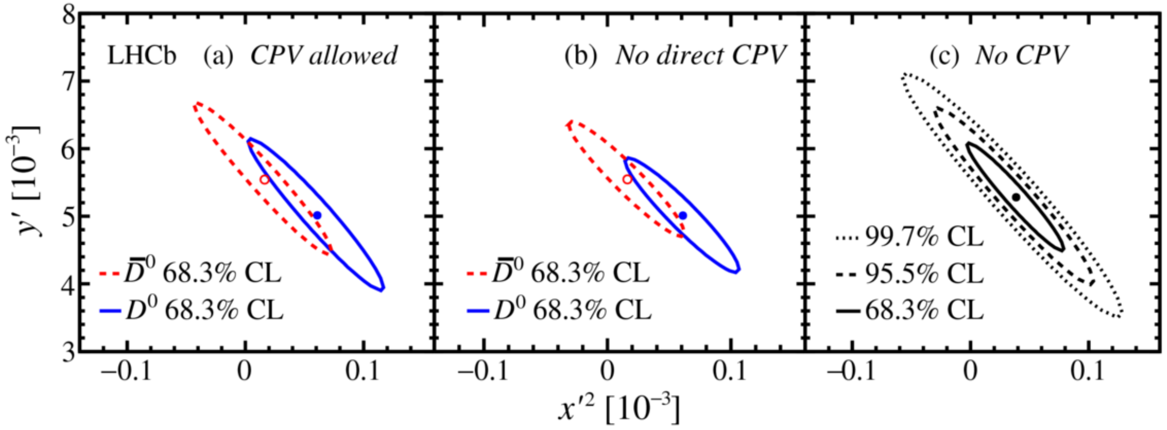
- Systematics with data driven methods includes: instrumental asymmetry / peaking background / *D*-from-*b* / background from ghost pions

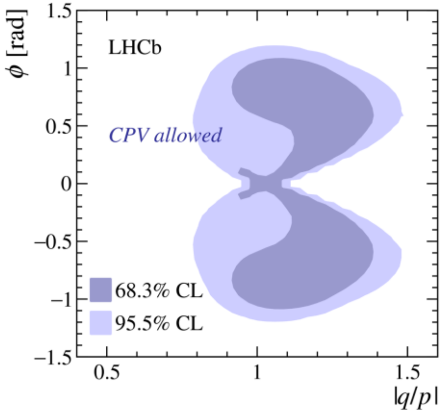


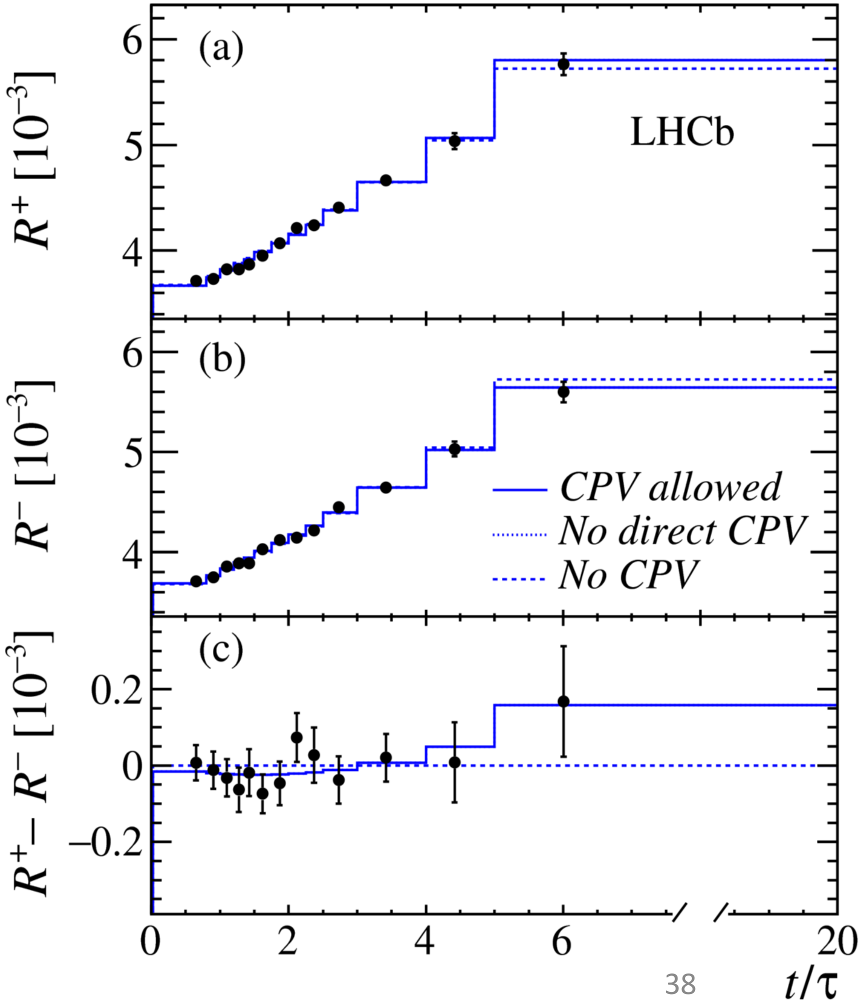
No CP violation	
Parameter	Value
R_D	$3.454 \pm 0.028 \pm 0.014$
y'	$5.28 \pm 0.45 \pm 0.27$
x'^2	$0.039 \pm 0.023 \pm 0.014$

- Fit efficiency corrected data to extract mixing parameters under 3 hypotheses

- Mixing parameters extracted with the precision order of magnitude better than in other experiments





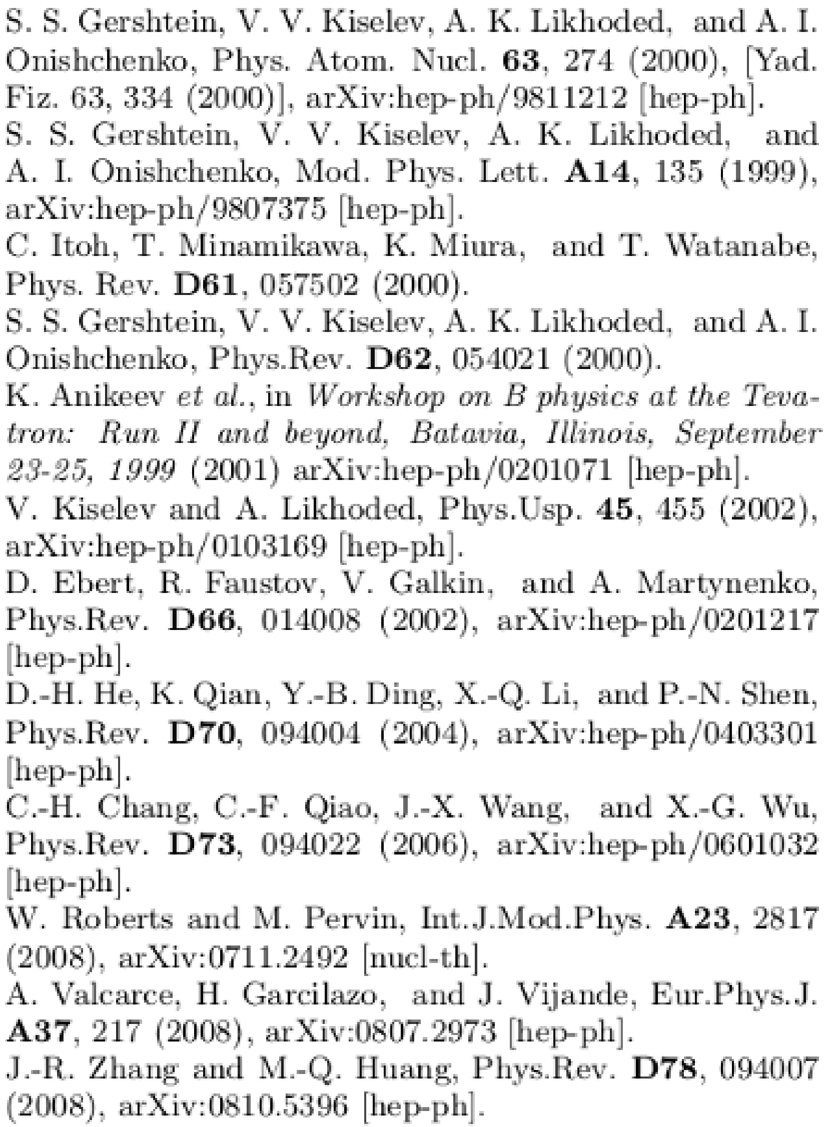


- Limits on parameters of indirect CPV

$1.00 < |q/p| < 1.35$ @ 68.3% C.L.

$0.82 < |q/p| < 1.45$ @ 95.5% C.L.

Theoretical references for mass of Ξ_{cc}^{++}



S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Phys. Atom. Nucl. **63**, 274 (2000), [Yad. Fiz. 63, 334 (2000)], arXiv:hep-ph/9811212 [hep-ph].

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Mod. Phys. Lett. **A14**, 135 (1999), arXiv:hep-ph/9807375 [hep-ph].

C. Itoh, T. Minamikawa, K. Miura, and T. Watanabe, Phys. Rev. **D61**, 057502 (2000).

S. S. Gershtein, V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, Phys.Rev. **D62**, 054021 (2000).

K. Anikeev *et al.*, in *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999* (2001) arXiv:hep-ph/0201071 [hep-ph].

V. Kiselev and A. Likhoded, Phys.Usp. **45**, 455 (2002), arXiv:hep-ph/0103169 [hep-ph].

D. Ebert, R. Faustov, V. Galkin, and A. Martynenko, Phys.Rev. **D66**, 014008 (2002), arXiv:hep-ph/0201217 [hep-ph].

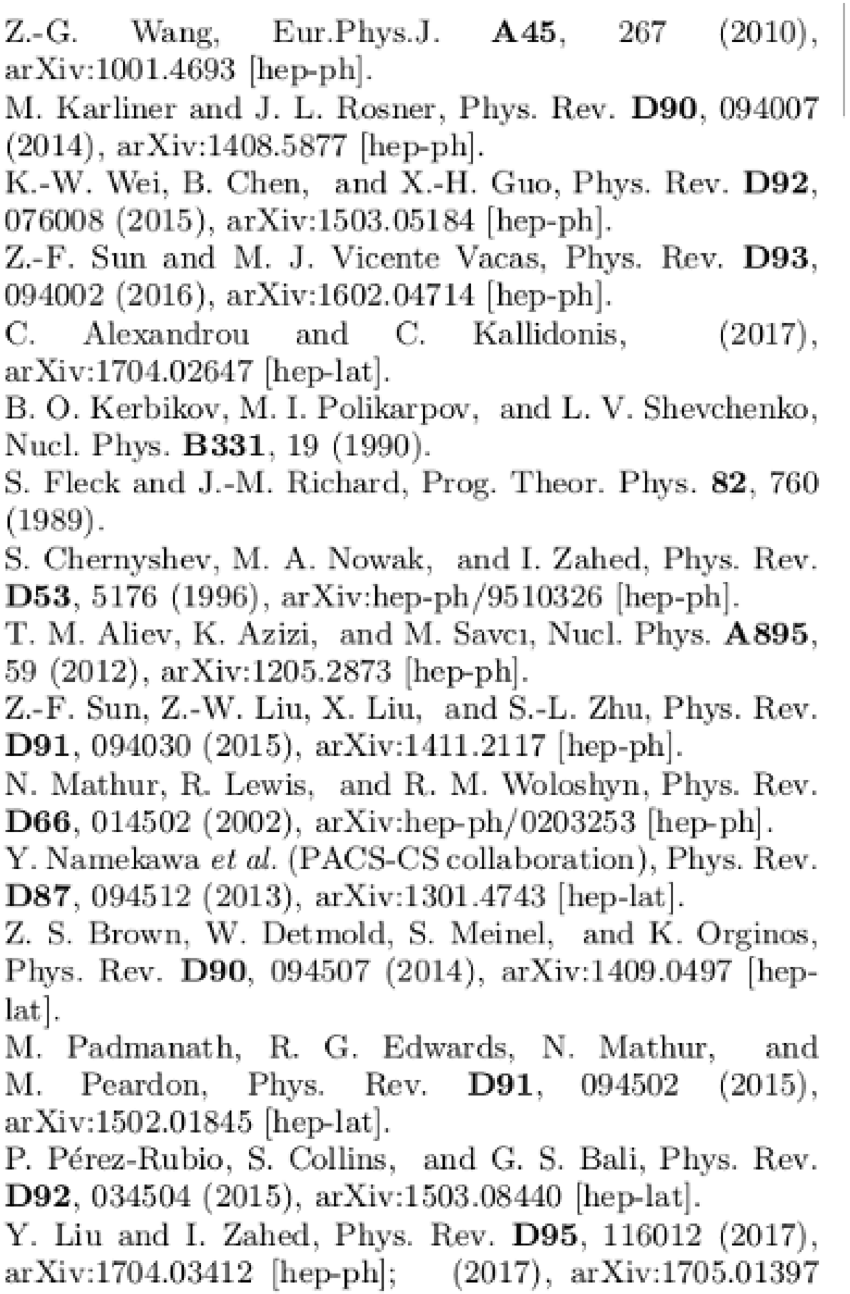
D.-H. He, K. Qian, Y.-B. Ding, X.-Q. Li, and P.-N. Shen, Phys.Rev. **D70**, 094004 (2004), arXiv:hep-ph/0403301 [hep-ph].

C.-H. Chang, C.-F. Qiao, J.-X. Wang, and X.-G. Wu, Phys.Rev. **D73**, 094022 (2006), arXiv:hep-ph/0601032 [hep-ph].

W. Roberts and M. Pervin, Int.J.Mod.Phys. **A23**, 2817 (2008), arXiv:0711.2492 [nucl-th].

A. Valcarce, H. Garcilazo, and J. Vijande, Eur.Phys.J. **A37**, 217 (2008), arXiv:0807.2973 [hep-ph].

J.-R. Zhang and M.-Q. Huang, Phys.Rev. **D78**, 094007 (2008), arXiv:0810.5396 [hep-ph].



Z.-G. Wang, Eur.Phys.J. **A45**, 267 (2010), arXiv:1001.4693 [hep-ph].

M. Karliner and J. L. Rosner, Phys. Rev. **D90**, 094007 (2014), arXiv:1408.5877 [hep-ph].

K.-W. Wei, B. Chen, and X.-H. Guo, Phys. Rev. **D92**, 076008 (2015), arXiv:1503.05184 [hep-ph].

Z.-F. Sun and M. J. Vicente Vacas, Phys. Rev. **D93**, 094002 (2016), arXiv:1602.04714 [hep-ph].

C. Alexandrou and C. Kallidonis, (2017), arXiv:1704.02647 [hep-lat].

B. O. Kerbikov, M. I. Polikarpov, and L. V. Shevchenko, Nucl. Phys. **B331**, 19 (1990).

S. Fleck and J.-M. Richard, Prog. Theor. Phys. **82**, 760 (1989).

S. Chernyshev, M. A. Nowak, and I. Zahed, Phys. Rev. **D53**, 5176 (1996), arXiv:hep-ph/9510326 [hep-ph].

T. M. Aliev, K. Azizi, and M. Savcı, Nucl. Phys. **A895**, 59 (2012), arXiv:1205.2873 [hep-ph].

Z.-F. Sun, Z.-W. Liu, X. Liu, and S.-L. Zhu, Phys. Rev. **D91**, 094030 (2015), arXiv:1411.2117 [hep-ph].

N. Mathur, R. Lewis, and R. M. Woloshyn, Phys. Rev. **D66**, 014502 (2002), arXiv:hep-ph/0203253 [hep-ph].

Y. Namekawa *et al.* (PACS-CS collaboration), Phys. Rev. **D87**, 094512 (2013), arXiv:1301.4743 [hep-lat].

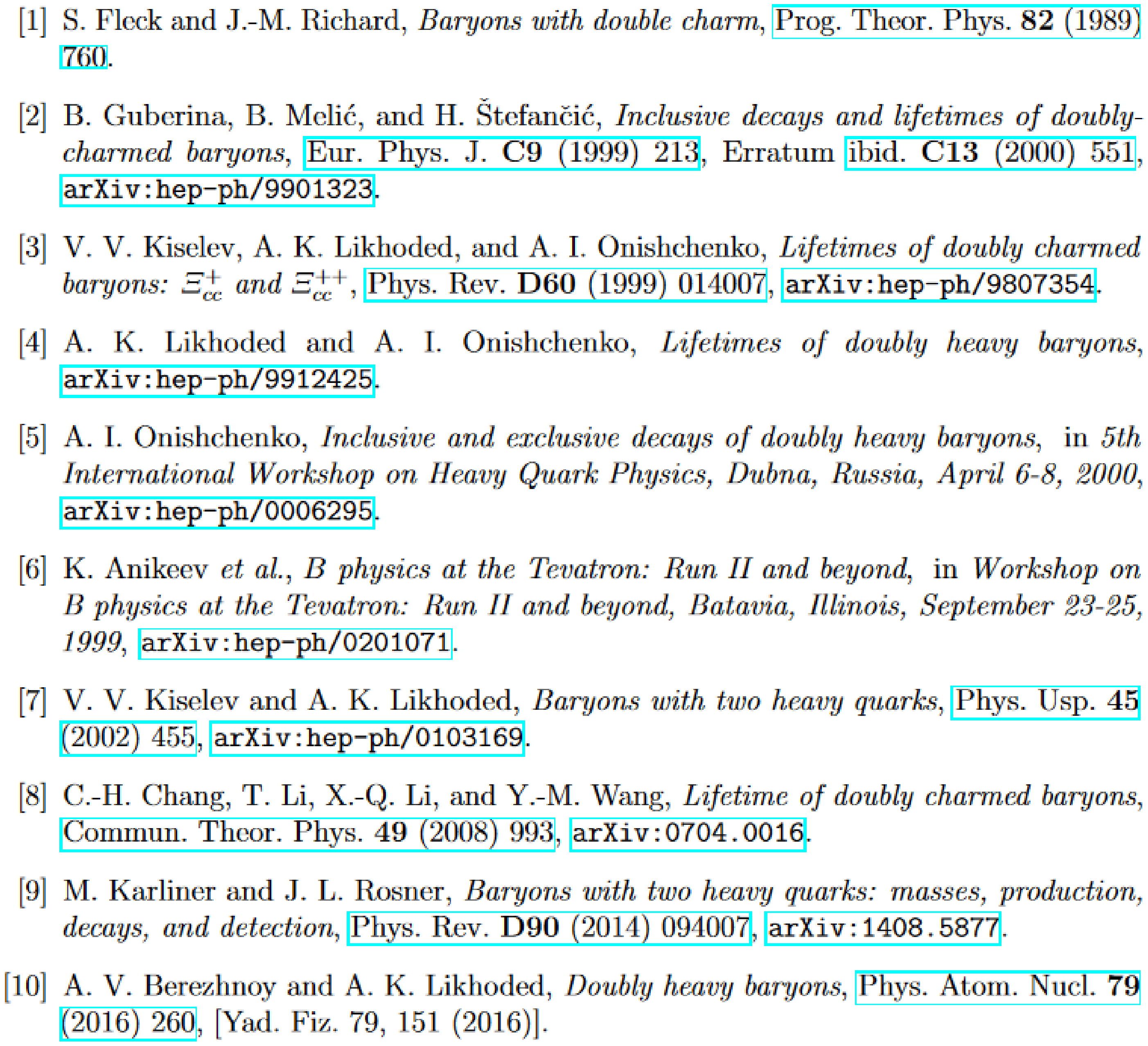
Z. S. Brown, W. Detmold, S. Meinel, and K. Orginos, Phys. Rev. **D90**, 094507 (2014), arXiv:1409.0497 [hep-lat].

M. Padmanath, R. G. Edwards, N. Mathur, and M. Peardon, Phys. Rev. **D91**, 094502 (2015), arXiv:1502.01845 [hep-lat].

P. Pérez-Rubio, S. Collins, and G. S. Bali, Phys. Rev. **D92**, 034504 (2015), arXiv:1503.08440 [hep-lat].

Y. Liu and I. Zahed, Phys. Rev. **D95**, 116012 (2017), arXiv:1704.03412 [hep-ph]; (2017), arXiv:1705.01397

Theoretical references for lifetime of Ξ_{cc}^{++}



[1] S. Fleck and J.-M. Richard, *Baryons with double charm*, Prog. Theor. Phys. **82** (1989) 760.

[2] B. Guberina, B. Melić, and H. Štefančić, *Inclusive decays and lifetimes of doubly-charmed baryons*, Eur. Phys. J. **C9** (1999) 213, Erratum ibid. **C13** (2000) 551, `arXiv:hep-ph/9901323`.

[3] V. V. Kiselev, A. K. Likhoded, and A. I. Onishchenko, *Lifetimes of doubly charmed baryons: Ξ_{cc}^{+} and Ξ_{cc}^{++}*, Phys. Rev. **D60** (1999) 014007, `arXiv:hep-ph/9807354`.

[4] A. K. Likhoded and A. I. Onishchenko, *Lifetimes of doubly heavy baryons*, `arXiv:hep-ph/9912425`.

[5] A. I. Onishchenko, *Inclusive and exclusive decays of doubly heavy baryons*, in *5th International Workshop on Heavy Quark Physics, Dubna, Russia, April 6-8, 2000*, `arXiv:hep-ph/0006295`.

[6] K. Anikeev *et al.*, *B physics at the Tevatron: Run II and beyond*, in *Workshop on B physics at the Tevatron: Run II and beyond, Batavia, Illinois, September 23-25, 1999*, `arXiv:hep-ph/0201071`.

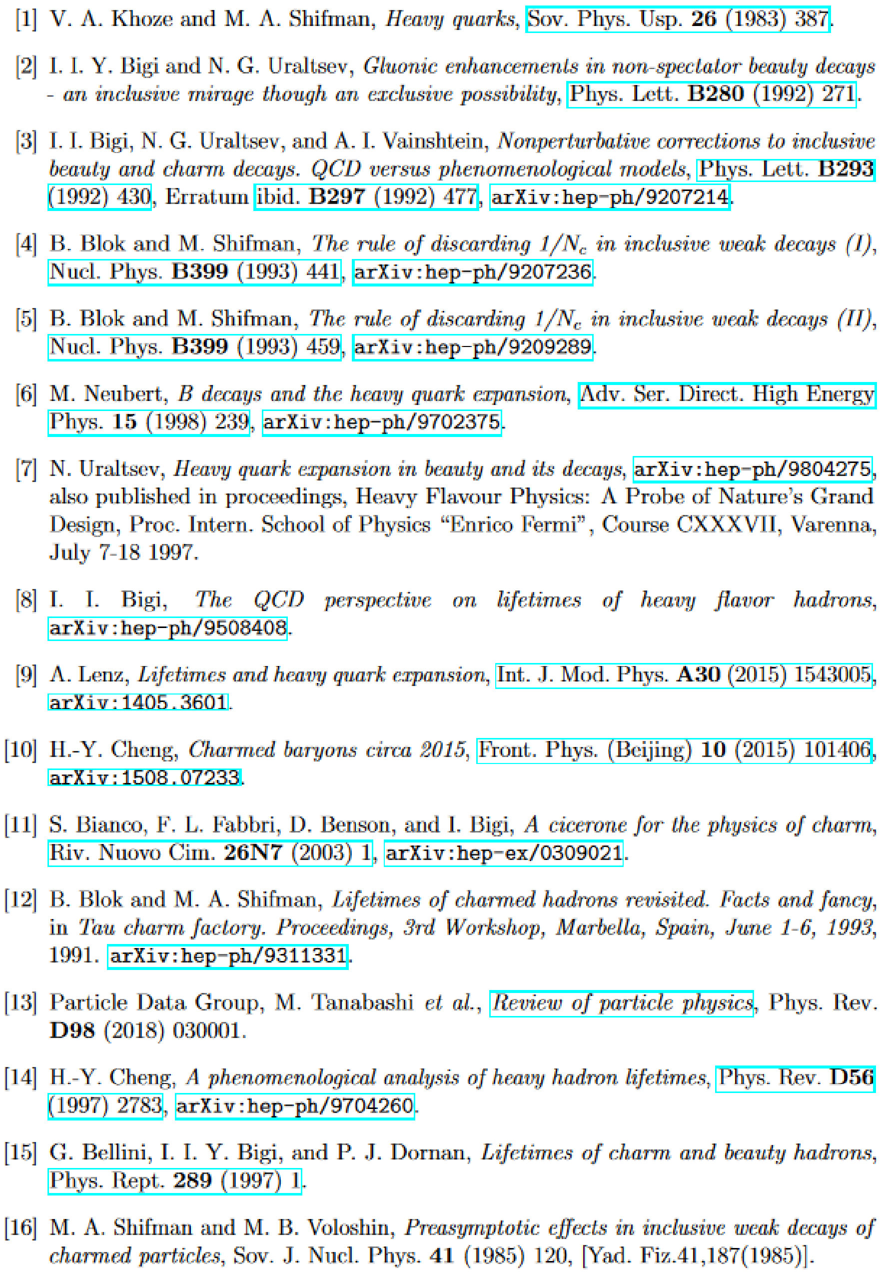
[7] V. V. Kiselev and A. K. Likhoded, *Baryons with two heavy quarks*, Phys. Usp. **45** (2002) 455, `arXiv:hep-ph/0103169`.

[8] C.-H. Chang, T. Li, X.-Q. Li, and Y.-M. Wang, *Lifetime of doubly charmed baryons*, Commun. Theor. Phys. **49** (2008) 993, `arXiv:0704.0016`.

[9] M. Karliner and J. L. Rosner, *Baryons with two heavy quarks: masses, production, decays, and detection*, Phys. Rev. **D90** (2014) 094007, `arXiv:1408.5877`.

[10] A. V. Berezhnoy and A. K. Likhoded, *Doubly heavy baryons*, Phys. Atom. Nucl. **79** (2016) 260, [Yad. Fiz. 79, 151 (2016)].

Theoretical references for lifetime of Ω_c^0



[1] V. A. Khoze and M. A. Shifman, *Heavy quarks*, Sov. Phys. Usp. **26** (1983) 387.

[2] I. I. Y. Bigi and N. G. Uraltsev, *Gluonic enhancements in non-spectator beauty decays - an inclusive mirage though an exclusive possibility*, Phys. Lett. **B280** (1992) 271.

[3] I. I. Bigi, N. G. Uraltsev, and A. I. Vainshtein, *Nonperturbative corrections to inclusive beauty and charm decays. QCD versus phenomenological models*, Phys. Lett. **B293** (1992) 430, Erratum ibid. **B297** (1992) 477, `arXiv:hep-ph/9207214`.

[4] B. Blok and M. Shifman, *The rule of discarding $1/N_c$ in inclusive weak decays (I)*, Nucl. Phys. **B399** (1993) 441, `arXiv:hep-ph/9207236`.

[5] B. Blok and M. Shifman, *The rule of discarding $1/N_c$ in inclusive weak decays (II)*, Nucl. Phys. **B399** (1993) 459, `arXiv:hep-ph/9209289`.

[6] M. Neubert, *B decays and the heavy quark expansion*, Adv. Ser. Direct. High Energy Phys. **15** (1998) 239, `arXiv:hep-ph/9702375`.

[7] N. Uraltsev, *Heavy quark expansion in beauty and its decays*, `arXiv:hep-ph/9804275`, also published in proceedings, Heavy Flavour Physics: A Probe of Nature's Grand Design, Proc. Intern. School of Physics "Enrico Fermi", Course CXXXVII, Varenna, July 7-18 1997.

[8] I. I. Bigi, *The QCD perspective on lifetimes of heavy flavor hadrons*, `arXiv:hep-ph/9508408`.

[9] A. Lenz, *Lifetimes and heavy quark expansion*, Int. J. Mod. Phys. **A30** (2015) 1543005, `arXiv:1405.3601`.

[10] H.-Y. Cheng, *Charmed baryons circa 2015*, Front. Phys. (Beijing) **10** (2015) 101406, `arXiv:1508.07233`.

[11] S. Bianco, F. L. Fabbri, D. Benson, and I. Bigi, *A cicerone for the physics of charm*, Riv. Nuovo Cim. **26N7** (2003) 1, `arXiv:hep-ex/0309021`.

[12] B. Blok and M. A. Shifman, *Lifetimes of charmed hadrons revisited. Facts and fancy*, in *Tau charm factory. Proceedings, 3rd Workshop, Marbella, Spain, June 1-6, 1993*, 1991. `arXiv:hep-ph/9311331`.

[13] Particle Data Group, M. Tanabashi *et al.*, *Review of particle physics*, Phys. Rev. **D98** (2018) 030001.

[14] H.-Y. Cheng, *A phenomenological analysis of heavy hadron lifetimes*, Phys. Rev. **D56** (1997) 2783, `arXiv:hep-ph/9704260`.

[15] G. Bellini, I. I. Y. Bigi, and P. J. Dornan, *Lifetimes of charm and beauty hadrons*, Phys. Rept. **289** (1997) 1.

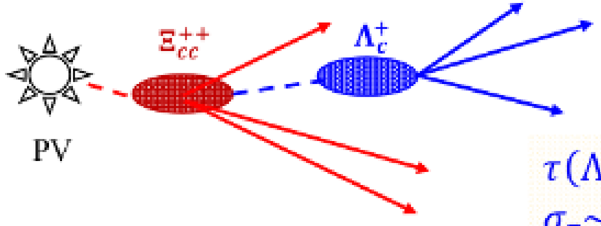
[16] M. A. Shifman and M. B. Voloshin, *Preasymptotic effects in inclusive weak decays of charmed particles*, Sov. J. Nucl. Phys. **41** (1985) 120, [Yad. Fiz.41,187(1985)].

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 categories of selection:
  - RS – right sign combination $\Lambda_c^+ K^- \pi^+ \pi^+$
  - WS – wrong sign $\Lambda_c^+ K^- \pi^+ \pi^-$
  - SB – sidebands

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



$\tau(\Lambda_c^+) \approx 200$ fs
$\sigma_\tau \sim 45$ fs