Charm Physics at LHCb: Legacy of Run 1+2 and prospects for Run 3

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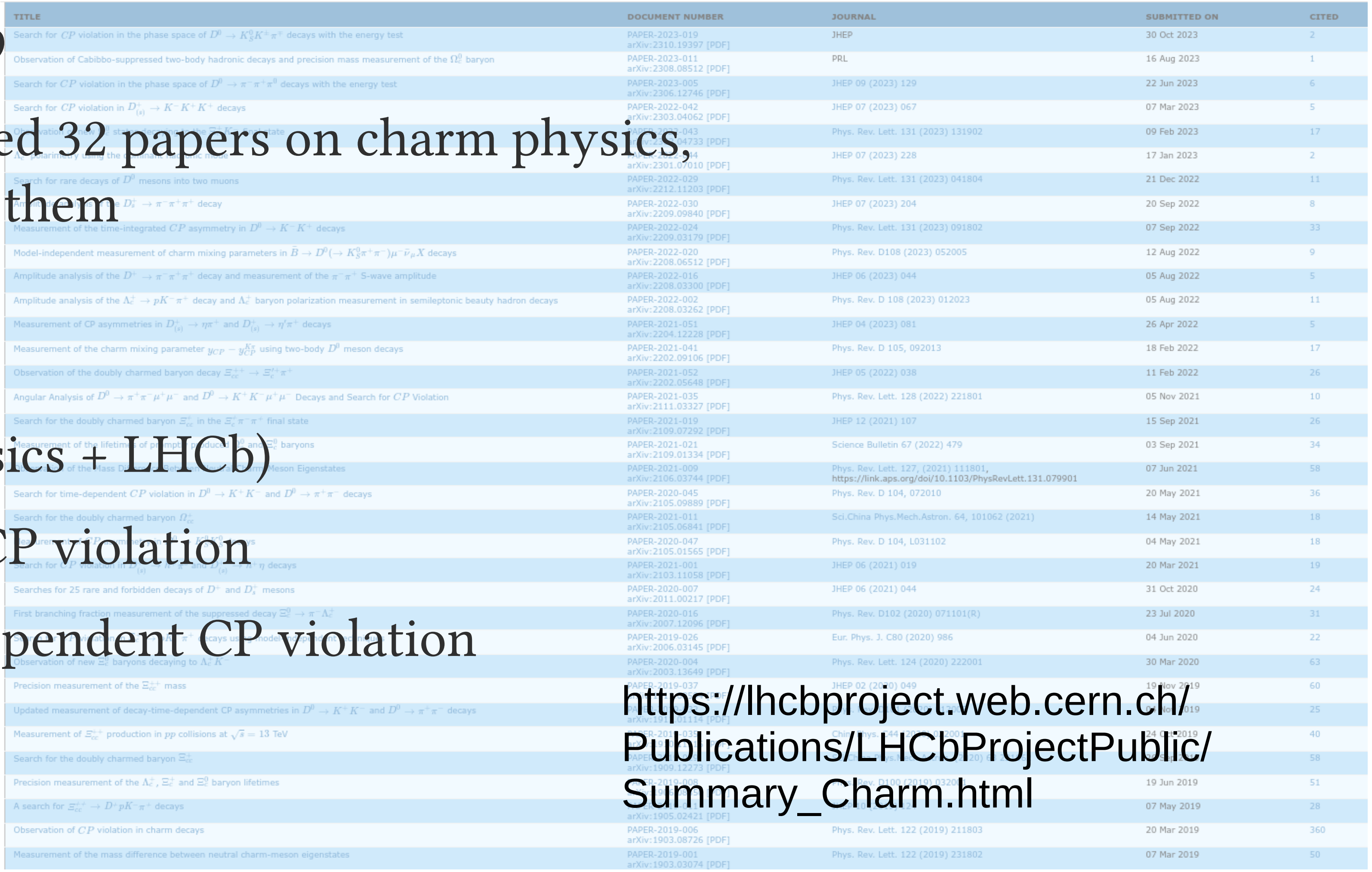
Outline

- My last talk here was in 2019
  - Since then LHCb published 32 papers on charm physics, I will only cover a few of them

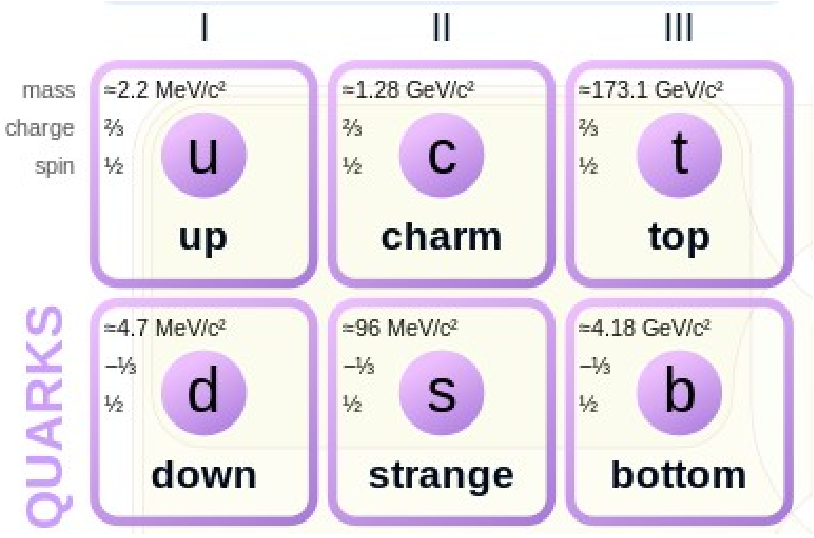
- Today:
  - Introduction (charm physics + LHCb)
  - Measurements of direct CP violation
  - Measurements of time-dependent CP violation
  - Rare charm
  - Outlook to Run 3



https://lhcbproject.web.cern.ch/Publications/LHCbProjectPublic/Summary_Charm.html

What is charm physics?

- Study of particles (mesons, baryons) that contain charm quark
  - Second generation up-type quark
  - Theorized in 1964 and discovered in 1974 via the J/Ψ meson ($c\bar{c}$)
- Top quark too heavy to form bound states
  - Charm hadrons complementary to kaons and b-hadrons in the down-type sector
- Measurements of properties of charm mesons and baryons (and their decays) allow to test the Standard Model of Particle Physics.



wikipedia

Charm is different, part 1

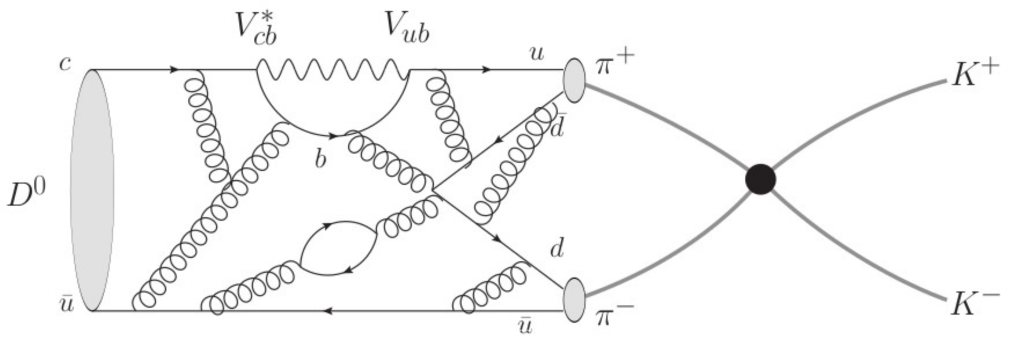
- Charm quark mass similar to hadronic scale

$$\Lambda_{QCD}/m_c = \mathcal{O}(1)$$

- Strong coupling constant at charm mass

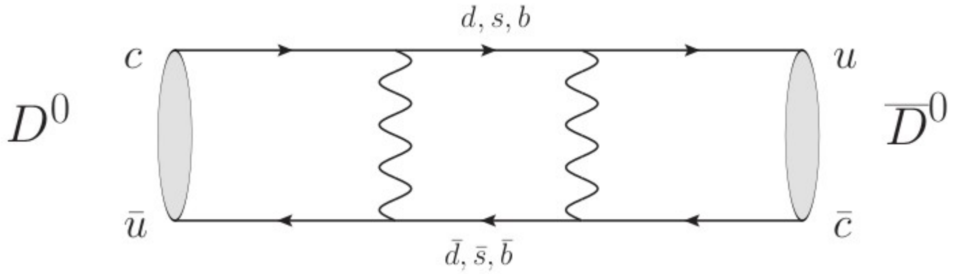
$$\alpha_S = 0.33 \pm 0.01$$

- Higher order corrections likely important and there might be sizable non-perturbative effects



- Effects referred to as Long distance effects or rescattering
- Theoretical predictions at today's experimental precision not easy

Charm is different, part 2



short distant, virtual states

$$\sim |\sum_{q=d,s,b} c_q(m_q/m_W)(V_{uq}^* V_{cq})|^2$$

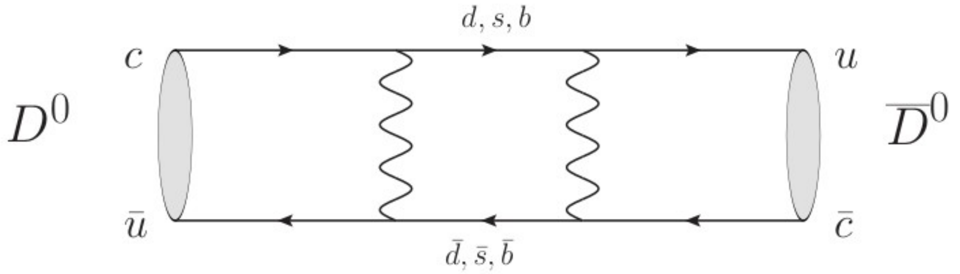
- Small mixing from SM box diagrams
  - Effective GIM cancellation of d and s diagrams ($m_d \approx m_s$).
  - m_b / m_W small unlike m_t / m_W .
  - $|V_{cb}{}^*V_{ub}|^2 = 10^{-8}$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

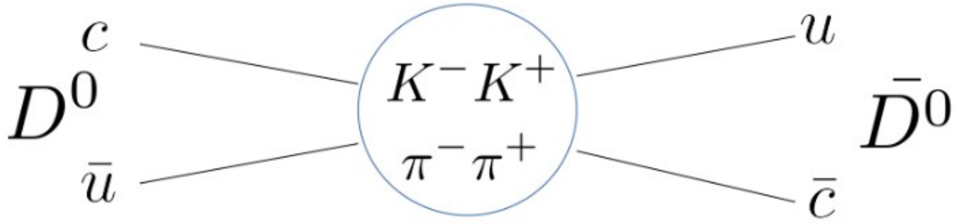
$$\approx \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\lambda \approx 0.22$$

Charm is different, part 2



short distant, virtual states



- Small mixing from SM box diagrams
  - Effective GIM cancellation of d and s diagrams ($m_d \approx m_s$).
  - m_b /m_W small unlike m_t /m_W .
  - $|V_{cb}{}^* V_{ub}|^2 = 10^{-8}$
- Short distant and long distant processes of similar size ($O(10^{-3})$).
- Similar arguments also make CP violation small

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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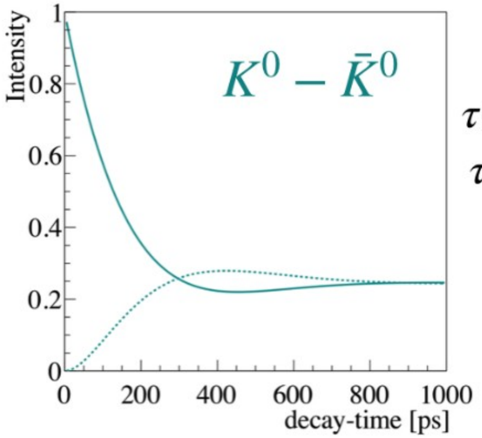
$$\lambda \approx 0.22$$

From A. Dziurda and S. Stahl CERN seminar 8/6/2021,
The beauty and charm of fast and slow neutral meson oscillations at LHCb

Charm is different, part 3

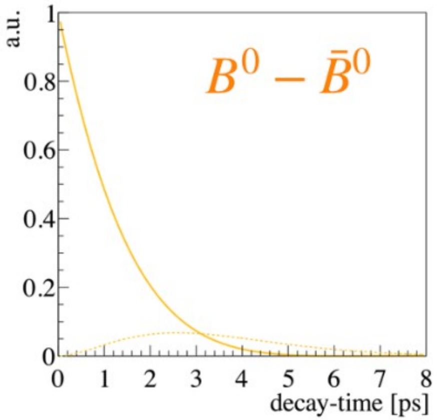


Very different lifetime:

$\tau(K_S^0) \sim 0.9 \times 10^{-10}$

$\tau(K_L^0) \sim 0.5 \times 10^{-7}$

the oscillation period longer than the K_S lifetime, but K_L^0 exceptionally long



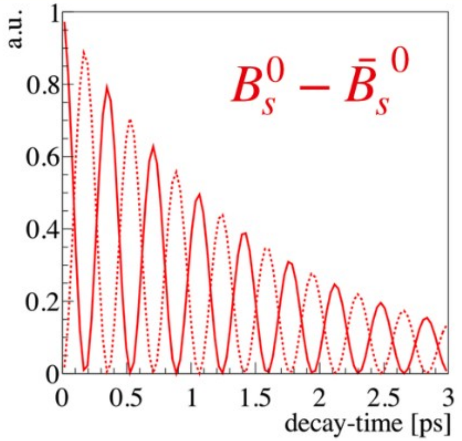
Oscillations

$\Delta m \sim 0.5\ ps^{-1}$

Lifetime

$\tau(B^0) \sim 1.5\ ps$

The same order of magnitudes

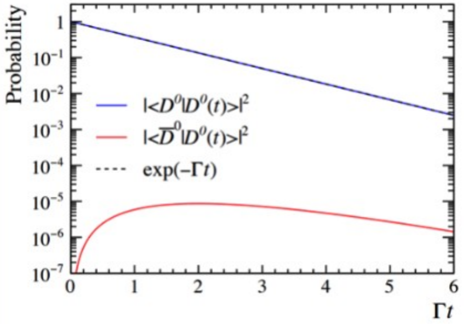


Very fast oscillations

$\Delta m_s > 15\ ps^{-1}$

$\tau(B_s^0) \sim 1.5\ ps$

Non-zero $\Delta\Gamma_s$



$D^0 - \bar{D}^0$

Very slow oscillations

$\Delta m \sim 10^{-3}\ ps^{-1}$

Very short lifetime

$\tau(D^0) \sim 0.4\ ps$

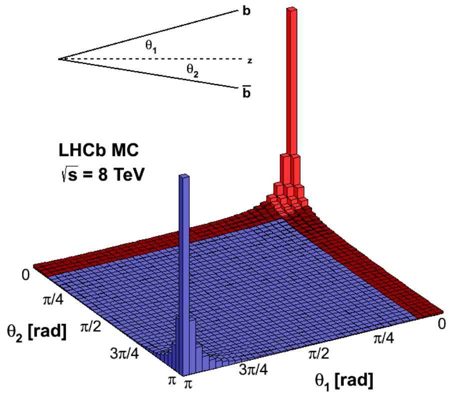
D^0 decays before has a chance to oscillate

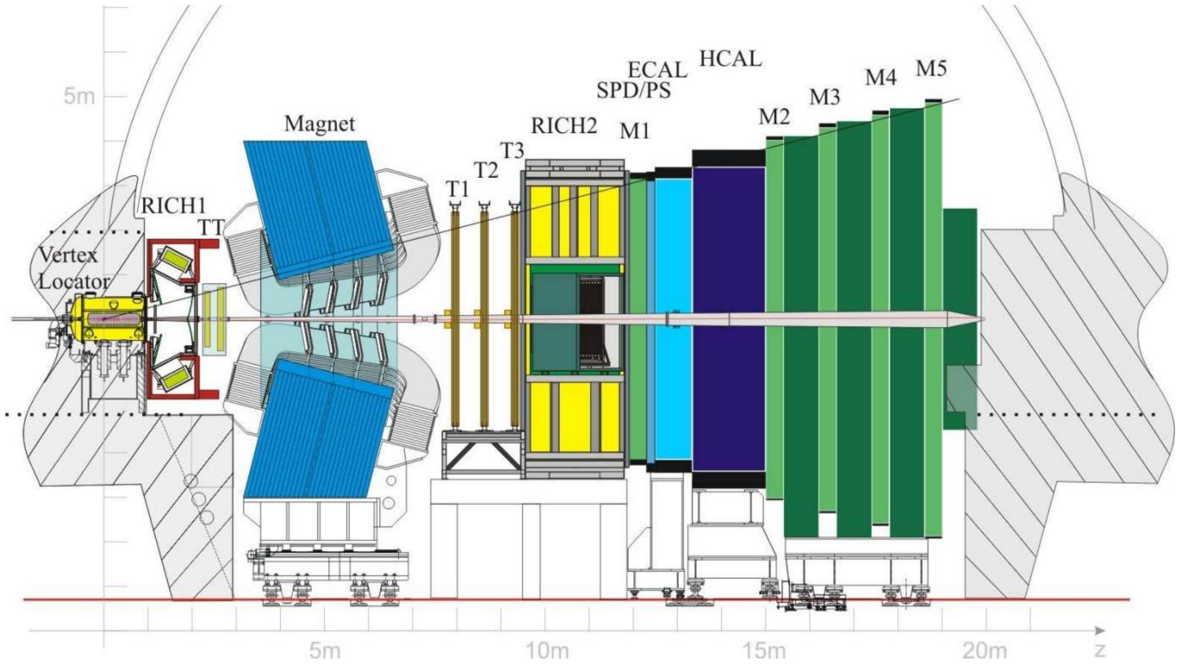
- Mixing and CP violation effects are very small

$\longrightarrow$ need a lot of data

The LHCb experiment

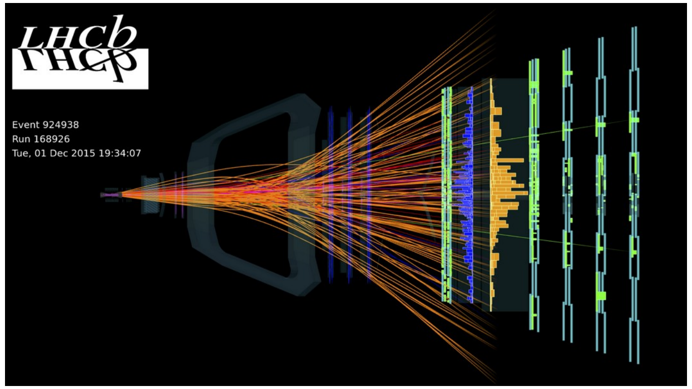
- Records LHC proton-proton collisions
  - Run 1 3 fb^{-1} (7 and 8 TeV),
  - Run 2 6 fb^{-1} (13 TeV)
  - Run 3 after upgrade ongoing
- b and c quarks produced in pairs
  - Predominantly in forward direction
- Coverage $2<\eta<5$:
  - Boosted pairs
  - 45 kHz $b\bar{b}$ pairs and
    1 MHz $c\bar{c}$ pairs or
    bzw.
    $O(10^{11})$ $b\bar{b}$ Paare und
    $O(10^{13})$ $c\bar{c}$ Paare



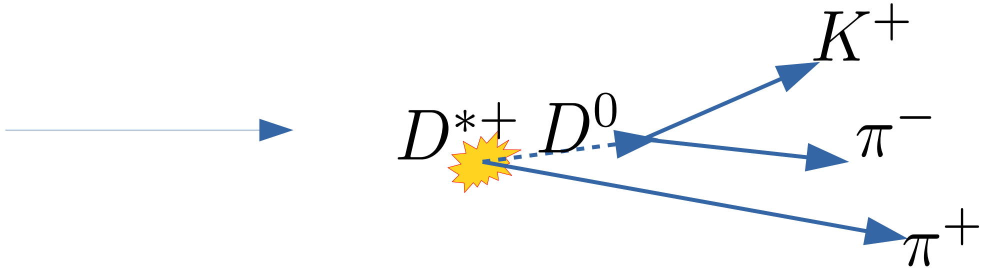


Challenge for the trigger and offline storage

- Limit is offline storage (1GB/s for the whole physics programme (Run 1 + 2))
  - Charm bandwidth = (signal eff.*signal rate+background eff.*LHC rate)*event size
  - Ignoring background and assuming 1.5% efficiency, bandwidth with full raw event would be 1 GB/s for charm alone
- Three handles: reduce background efficiency, reduce signal efficiency, reduce event size
  - Raw event size 70 kB, only charm decay 7 kB



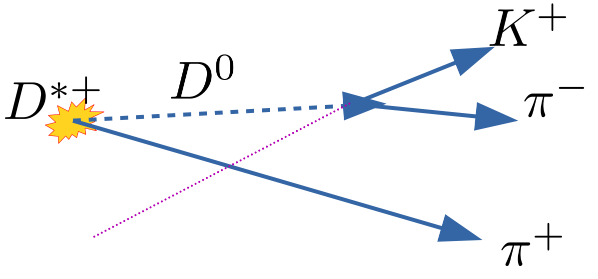
70 kB



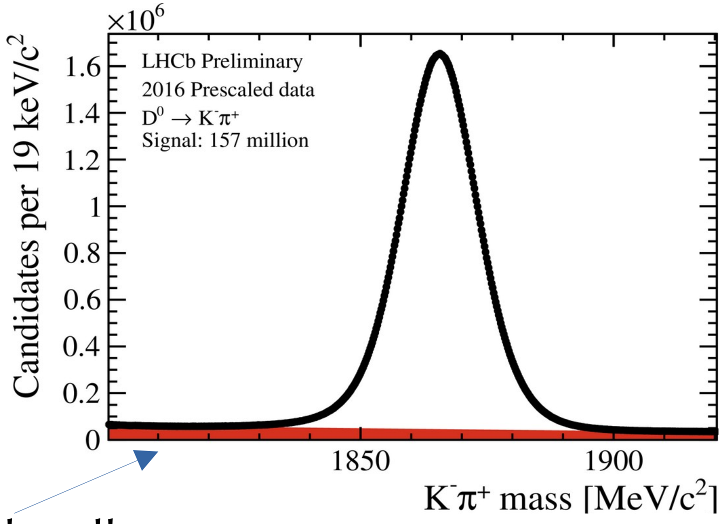
7 kB

Real-time analysis and selection

- Selections mostly based on momentum, particle identification and displacement
- Requirements
  - Good impact and momentum resolution
  - Good particle identification
  - Reconstruct all particles in trigger
- Detector aligned and calibrated in real-time, best possible reconstruction in trigger in Run 2 and going forward in Run 3.
- Impact of new strategy for Run 2 seen later.



Trigger output



Not much handle on background

Direct CP violation

$$D^0 \longrightarrow f \quad \overset{CP}{\longleftrightarrow} \quad \overline{D}^0 \longrightarrow \overline{f}$$

f some final state

Observe and count

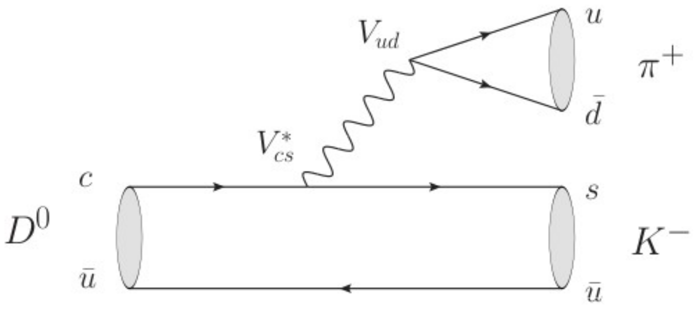
$$\#\ D^0 \longrightarrow f \quad \neq ? \quad \#\ \overline{D}^0 \longrightarrow \overline{f}$$

$$= \rightarrow \text{no } CPV \qquad \neq \rightarrow CPV$$

Two body modes

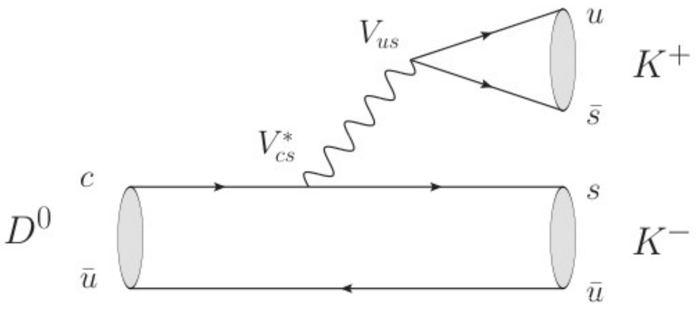
$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix} = \begin{bmatrix} 0.97373 \pm 0.00031 & 0.2243 \pm 0.0008 & 0.00382 \pm 0.00020 \\ 0.221 \pm 0.004 & 0.975 \pm 0.006 & 0.0408 \pm 0.0014 \\ 0.0086 \pm 0.0002 & 0.0415 \pm 0.0009 & 1.014 \pm 0.029 \end{bmatrix}.$$

Cabibbo-favoured



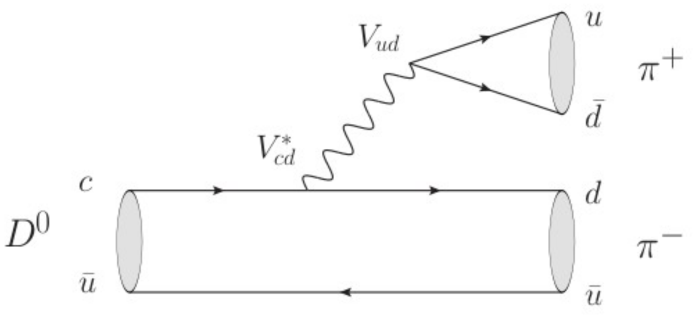
(a) $D^0 \to K^- \pi^+$

Cabibbo-suppressed



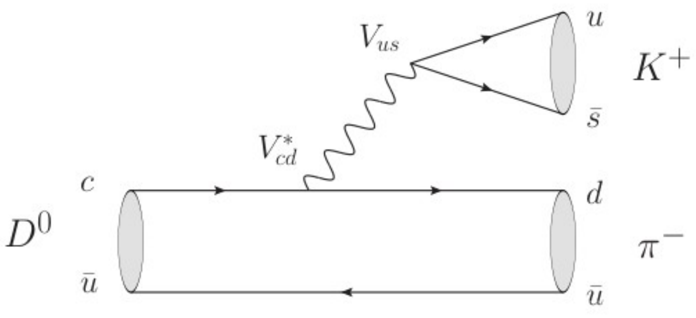
(b) $D^0 \to K^- K^+$

Cabibbo-suppressed



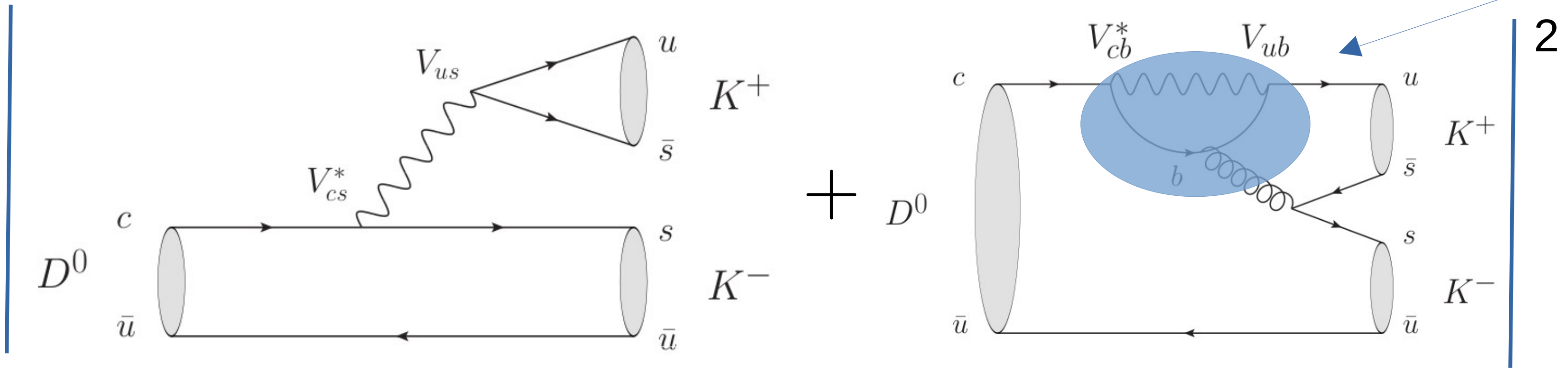
(c) $D^0 \to \pi^- \pi^+$

Doubly-Cabibbo-suppressed



(d) $D^0 \to K^+ \pi^-$

Direct CPV in CP conjugate final states



Don’t really know what’s happening in here yet .

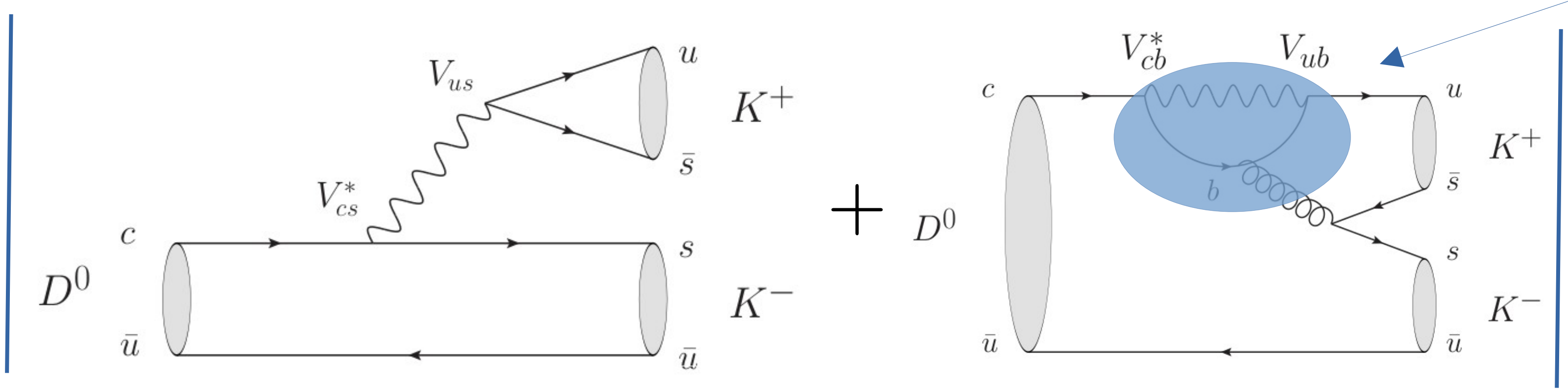
Similar for $D^0 \rightarrow \pi^- \pi^+$

$$D^0 \rightarrow K^- K^+ \text{and } \overline{D}^0 \rightarrow K^- K^+ \text{exist}$$

$$\mathcal{A}(D^0 \rightarrow f) = A(f) + iB(f)$$

$$\mathcal{A}(\overline{D}^0 \rightarrow f) = A(f) - iB(f)$$

Direct CPV in CP conjugate final states



Don't really know what's happening in here yet.

Similar for $D^0 \rightarrow \pi^- \pi^+$

$$D^0 \rightarrow K^- K^+ \text{and } \overline{D}^0 \rightarrow K^- K^+ \text{exist}$$

- Take away from Feynman diagrams CP violation possible in SM and it is not big

$$\mathcal{A}(D^0 \rightarrow f) = A(f) + iB(f)$$

$$\mathcal{A}(\overline{D}^0 \rightarrow f) = A(f) - iB(f)$$

$$a_{CP}^{dir} = \frac{|\mathcal{A}|^2 - |\overline{\mathcal{A}}|^2}{|\mathcal{A}|^2 + |\overline{\mathcal{A}}|^2} \approx 2 \quad r_{CKM} \quad \frac{|B(f)|}{|A(f)|} \quad \sin \arg \frac{B(f)}{A(f)}$$

weak phases — strong phases

$$r_{CKM} = \mathrm{Im} \frac{V_{cb}^* V_{ub}}{V_{cs}^* V_{us}} \approx 6.2 \cdot 10^{-4}$$

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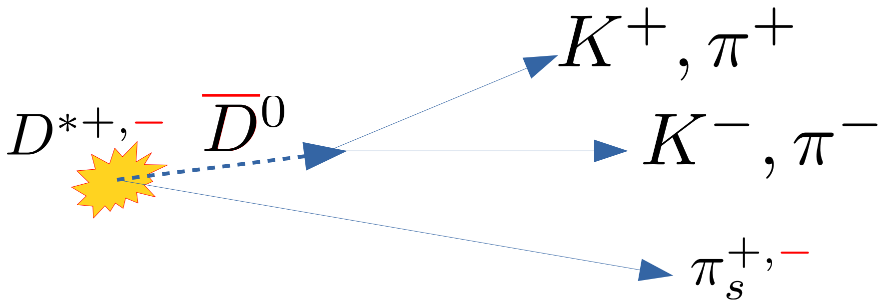
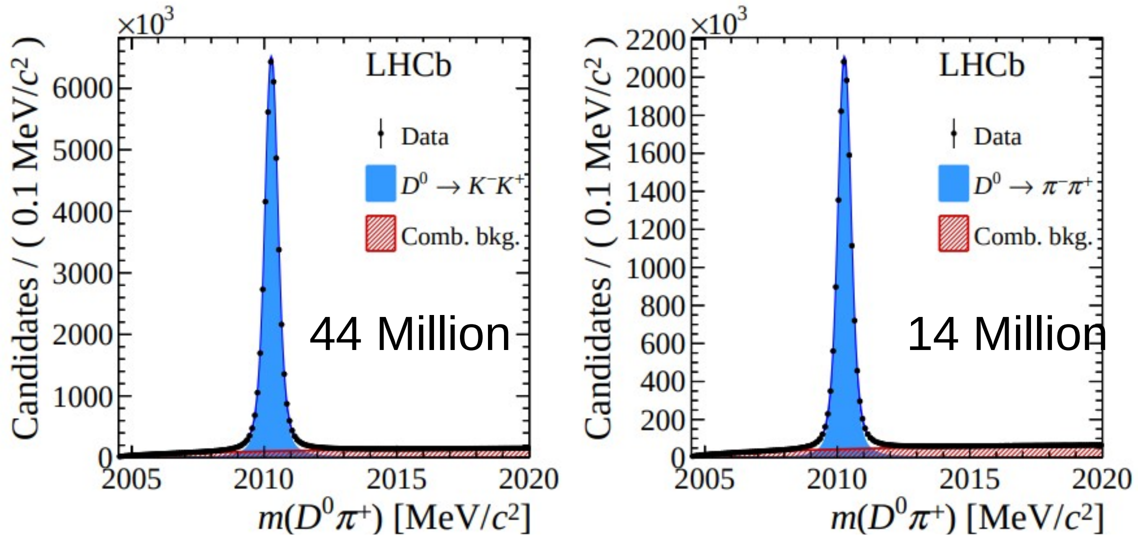
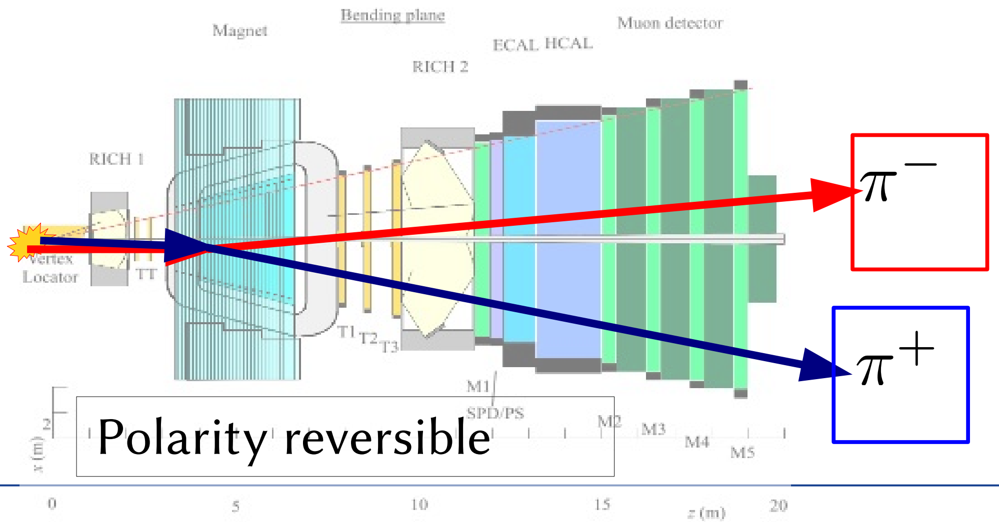
Flavour tagging and detection asymmetries





- Need to know flavour of charm meson (D^0 or $\overline{D}^0$?)
  - Charge of extra pion determines initial state
- Breaks symmetry of the final state

  $\longrightarrow$ Measurement becomes sensitive to efficiency difference to reconstruct positive and negative particles



Measurement of CP asymmetries

Measured asymmetry:

$$A_{\text{raw}}(f) = \frac{N(D^0 \to f, \pi^+) - N(\overline{D}^0 \to f, \pi^-)}{N(D^0 \to f, \pi^+) + N(\overline{D}^0 \to f, \pi^-)}, \quad f = K^+K^-, \pi^+\pi^-$$

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(\pi^+) + A_P(D^{*+})$$

CP asymmetry | Detection asymmetry | Production asymmetry

All of order 1% or below.

- Production asymmetry from asymmetric production of baryons and mesons in pp collisions
  - 2 baryons in initial state
- Need to either determine detection and production asymmetries or cancel them with another mode which has the same asymmetries.

Measurement of CP asymmetries

Measured asymmetry:

$$A_{\text{raw}}(f) = \frac{N(D^0 \to f, \pi^+) - N(\overline{D}^0 \to f, \pi^-)}{N(D^0 \to f, \pi^+) + N(\overline{D}^0 \to f, \pi^-)}, \quad f = K^+K^-, \pi^+\pi^-$$

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(\pi^+) + A_P(D^{*+})$$

CP asymmetry

Detection asymmetry

Production asymmetry

All of order 1% or below.

Experimentally robust quantity:

$$\begin{aligned} \Delta A_{CP} &= A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-) \\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \end{aligned}$$

Assumption: Detection and production asymmetry cancel.

Full LHCb result

- Run 2 result:

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-18.2 \pm 3.2\ (\text{stat.}) \pm 0.9\ (\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [-9 \pm 8\ (\text{stat.}) \pm 5\ (\text{syst.})] \times 10^{-4}$$

- Run1 result:

$$\Delta A_{CP}^{\pi-\text{tagged}} = [-10 \pm 8\ (\text{stat.}) \pm 3\ (\text{syst.})] \times 10^{-4}$$
$$\Delta A_{CP}^{\mu-\text{tagged}} = [+14 \pm 16\ (\text{stat.}) \pm 8\ (\text{syst.})] \times 10^{-4}$$

Increase in statistical precision from more luminosity and higher cross-section but also factor 2-3 more efficient trigger

- Combination

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

First observation of CP violation in charm decays!

What to do with the result?

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

- Can the size be explained within the SM? ⟶ Difficult
  - Doesn't mean it's New Physics, problem is a good estimate of the hadronic effects.

$$\mathcal{A}(D^0 \to f) = A(f) + iB(f)$$

$$\mathcal{A}(\overline{D}^0 \to f) = A(f) - iB(f)$$

$$a_{CP}^{dir} \approx 2 \; r_{CKM} \; \frac{|B(f)|}{|A(f)|} \; \sin\arg\frac{B(f)}{A(f)}$$

- Naive expectation that $A_{CP}(\pi^-\pi^+)$ and $A_{CP}(K^-K^+)$ have opposite sign.
  - SU(3) flavour symmetry (m_d=m_u≈m_s)
  - $|V_{us|} \approx -|V_{cd}|$
- Next steps:

  Measure individual asymmetries to get handle on hadronic effects (and also confirm CP violation in other decay channels).

Measurement of $A_{CP}(K^-K^+)$

- Initial problem:

$$A_{\text{raw}}(K^-K^+) = A_{CP}(K^-K^+) + A_D(\pi^+) + A_P(D^{*+})$$

- Can get detection and production asymmetry **from $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$**

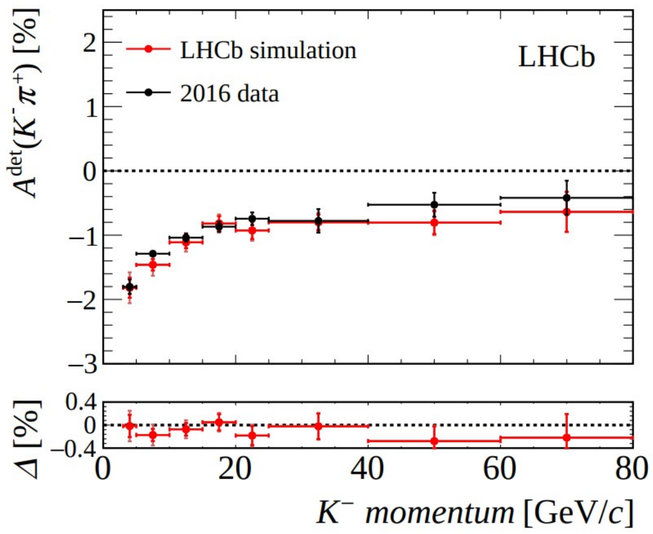
$$A_{\text{raw}}(K^-\pi^+) = A_D(\pi^+) + A_P(D^{*+}) + A_D(K^-\pi^+)$$

- **$K^-\pi^+$** is a charged neutral state but not symmetric
  - Different interaction rate of positive and negative kaons with detector material

$$K^- = (\overline{u}s)$$

$$K^+ = (u\overline{s})$$

“LHCb” = (ud)



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Determination of $K^-\pi^+$ asymmetry

- Can use D^+ and D_s^+ decays to get $K^-\pi^+$ asymmetry:

$$D^+ \to K^-\pi^+\pi^+$$
$$D^+ \to \overline{K}^0\pi^+$$

$$D_s^+ \to \phi\pi^+$$
$$D_s^+ \to \overline{K}^0 K^+$$

with $\overline{K}^0 \to \pi^+\pi^-$

New method developed for Run 2 measurement!

- Final measurement:

$$\begin{aligned} \mathrm{C}_{D^+}: \mathcal{A}^{CP}(K^-K^+) &= A(K^-K^+) - A(K^-\pi^+) + A(K^-\pi^+\pi^+) - A(\overline{K}^0\pi^+) + A(\overline{K}^0), \\ \mathrm{C}_{D_s^+}: \mathcal{A}^{CP}(K^-K^+) &= A(K^-K^+) - A(K^-\pi^+) + A(\phi\pi^+) - A(\overline{K}^0K^+) + A(\overline{K}^0). \qquad (6) \end{aligned}$$

- Both methods have similar sensitivity

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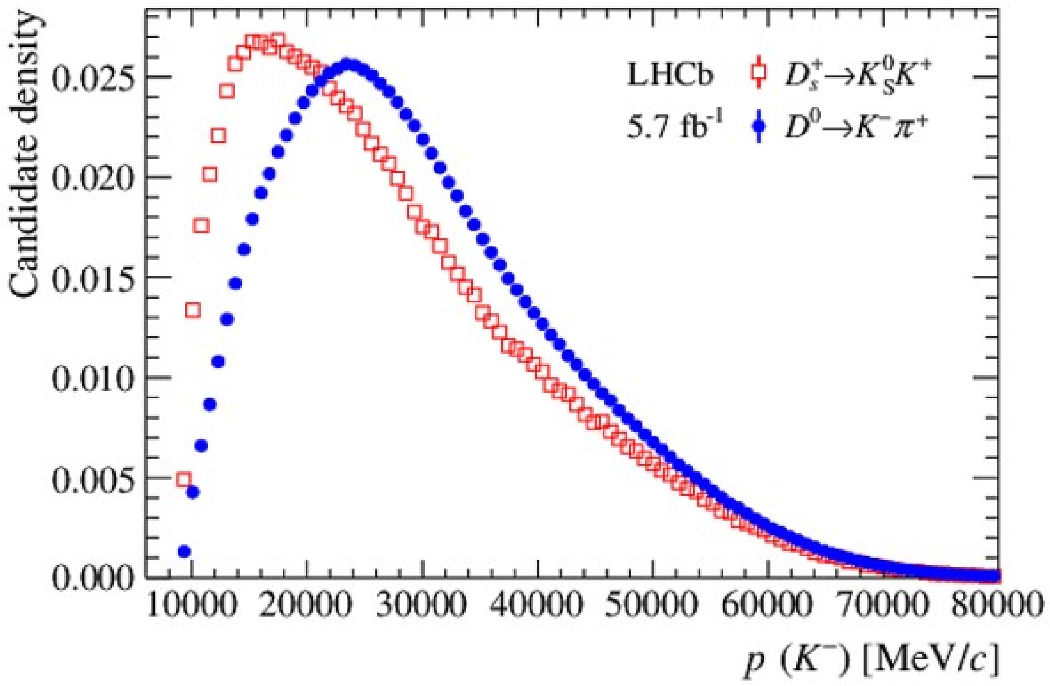
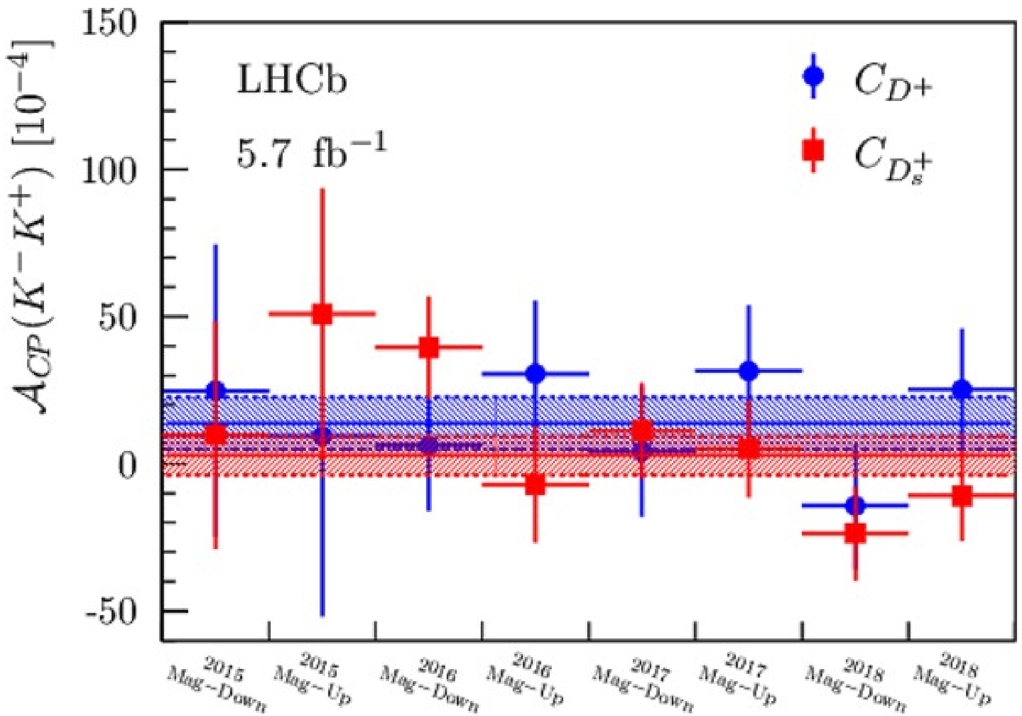
Weighting and consistency checks

- Weighting:



- Consistency checks:



A lot of detailed work needed to check that the method is correct and reliable at 10^{-4} precision.

Results

Run 2 result:

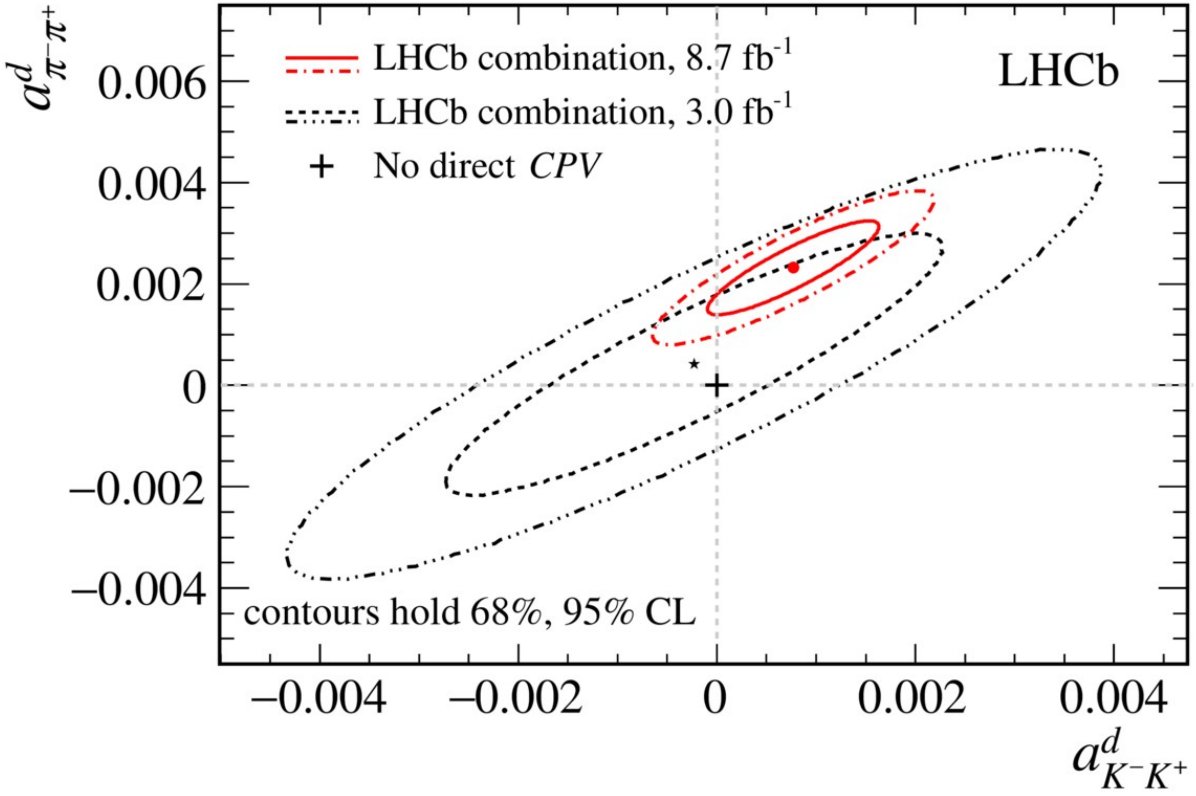
$$\mathcal{A}^{CP}(K^-K^+) = [6.8 \pm 5.4\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-4},$$

- Combination with Run 1, ΔA_{CP} and time dependent CPV to extract direct asymmetries in both modes:

$$a^d_{K^-K^+} = (\ 7.7 \pm 5.7) \times 10^{-4},$$
$$a^d_{\pi^-\pi^+} = (23.2 \pm 6.1) \times 10^{-4},$$

- Significances of 1.4 and 3.8 sigma
  - First evidence of a single non-zero asymmetry

Uncertainty significantly improved due to extra method and better trigger

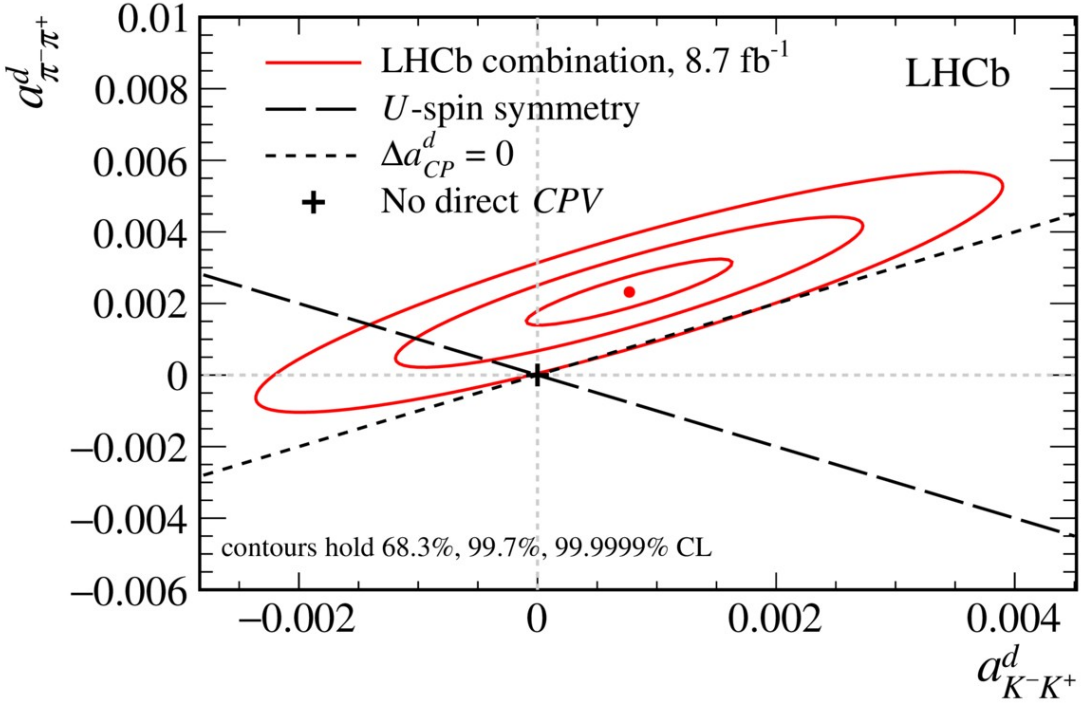


Discussion

- U-spin symmetry $m_d = m_s$

  Broken by 2.7 sigma

$$a_{CP}^{\text{dir}}(D^0 \to K^+K^-) + a_{CP}^{\text{dir}}(D^0 \to \pi^+\pi^-) \overset{U\text{-spin limit}}{=} 0\,,$$



Discussion

- U-spin symmetry $a_{CP}^{\mathrm{dir}}(D^0 \to K^+K^-) + a_{CP}^{\mathrm{dir}}(D^0 \to \pi^+\pi^-) \overset{U\text{-spin limit}}{=} 0\,,$

  $m_d = m_s$

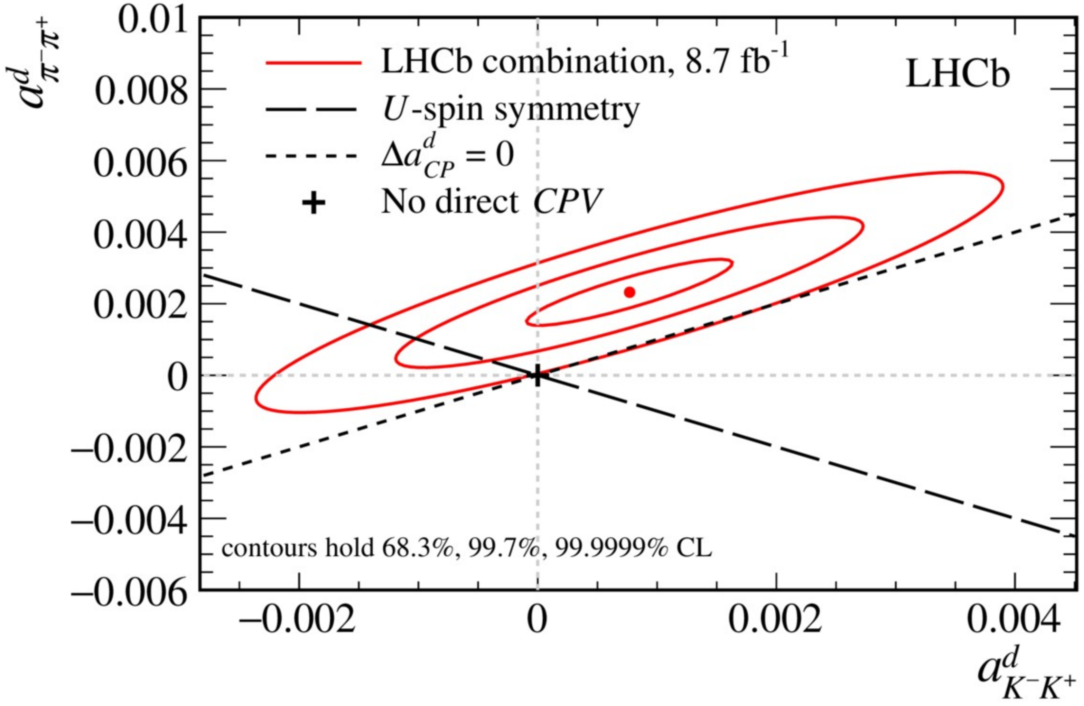
  Broken by 2.7 sigma

- Improved version ($m_d \approx m_s$): See S. Schacht, arXiv:2207.08539, for a review

$$\frac{\Gamma(D^0 \to K^-K^+)}{\Gamma(D^0 \to \pi^-\pi^+)} = -\frac{a_{CP}^{dir}(D^0 \to \pi^-\pi^+))}{-a_{CP}^{dir}(D^0 \to K^-K^+))}$$

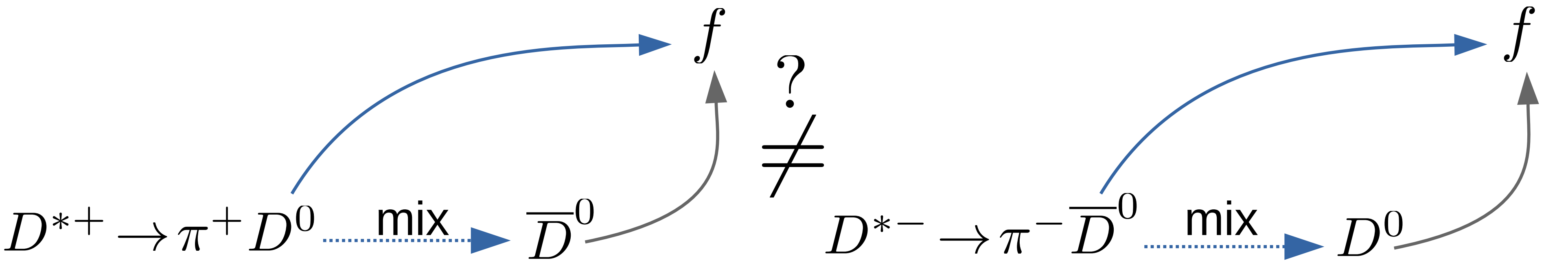
$$2.81 \pm 0.06 \neq -3 \pm 0.95$$

- Biggest "problem" both asymmetries have same sign.
  ⟶ not easy to explain with theory
  ⟶ More precise measurements and measurement in other channels needed

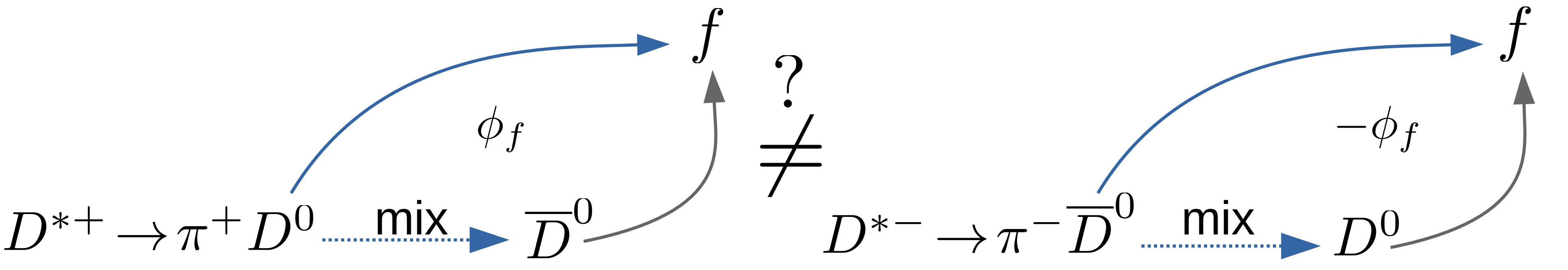


Questions?

Mixing and time-dependent CP violation



Mixing and time-dependent CP violation



- Neutral meson mixing:

$$|D_1\rangle = p\,|D^0\rangle + q\,|\overline{D}^0\rangle\,, |D_2\rangle = p\,|D^0\rangle - q\,|\overline{D}^0\rangle$$

with mixing parameters $x = \frac{m_2 - m_1}{\Gamma}$ and $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$

CP violation in mixing if $|\frac{q}{p}| \neq 1$

- CP violation in mixing and decay if weak phase $\phi_f = \arg\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 1$

Search for time-dependent CP violation in $D^0 \to h^+h^-$

- Time-dependent asymmetry between D^0 and $\overline{D}^0$ measured in decays to CP eigenstates $\pi^-\pi^+$, K^-K^+

Very small mixing

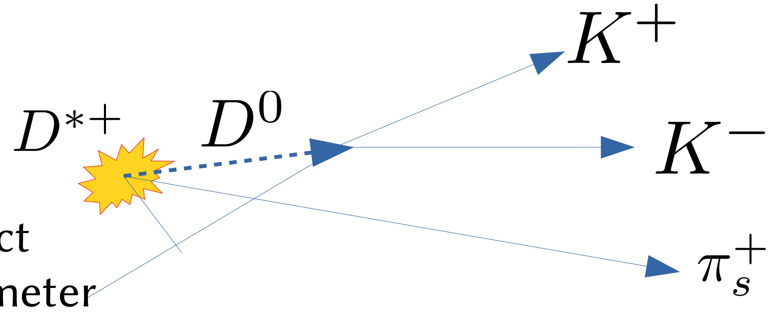
$$A_{CP}(t) = \frac{\Gamma(D^0(t)\to f) - \Gamma(\overline{D}^0(t)\to f)}{\Gamma(D^0(t)\to f) + \Gamma(\overline{D}^0(t)\to f)} \approx a^f_{\rm dir} + \Delta Y_f \frac{t}{\tau_D}$$

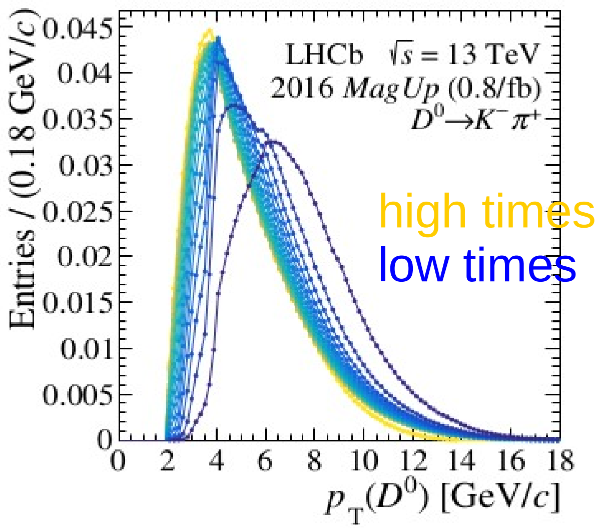
$$\Delta Y_f \approx -A^f_\Gamma$$

(Used in previous measurements)

- Standard model predictions $O(10^{-5}\text{-}10^{-4})$ below experimental sensitivity 2×10^{-4}
- Needed for interpretation of time-integrated asymmetries (not mentioned before).
- Basically like direct CPV measurement but in bins of time

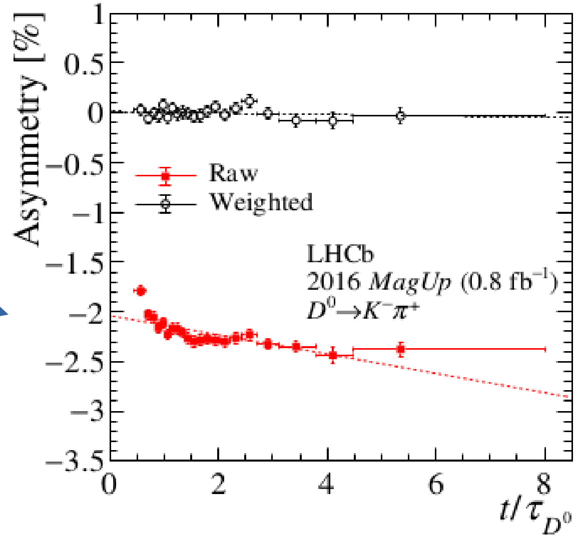
Detection asymmetries



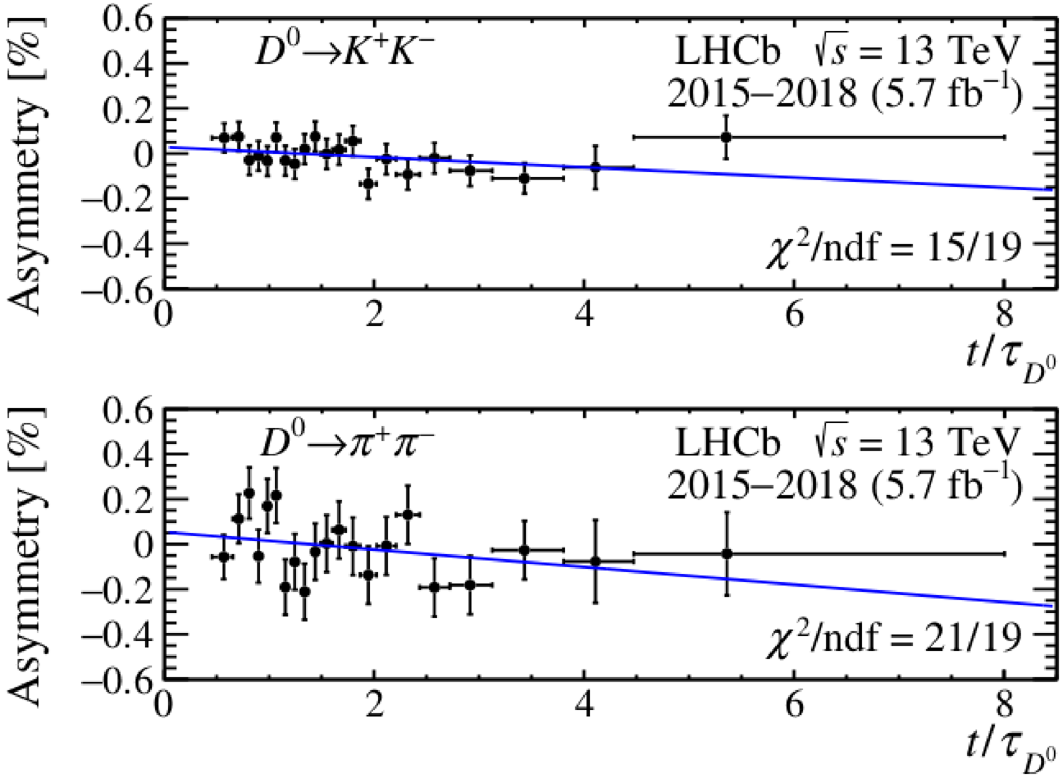


$$A_{\rm raw}(f,t) = A_{CP}(f,t) + A_D(\pi_s^+, p(t)) + A_P(D^{*+}, p(t))$$

- Correlation between decay-time and momentum induced by trigger requirements
  ⟶ fakes time-dependent CPV
- Control mode Cabibbo-favoured $D^0 \longrightarrow K^-\pi^+$,
- Weighting of D^0 and anti-D^0, and π^+ and π^- momentum distributions to equalise kinematics



Results



No significant slopes observed → no CPV.
Slopes consistent between modes.

- Run 2 only:

$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4},$$
$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4},$$

- All LHCb measurements combined

$$\Delta Y_{K^+K^-} = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4},$$
$$\Delta Y_{\pi^+\pi^-} = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4},$$
$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4},$$

- Last combination is assuming that the final state has negligible impact.

Most precise measurement. No sign of time-dependent CPV yet.

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Interpretation of ΔY_f

- Observable connected to mixing and CPV parameters as

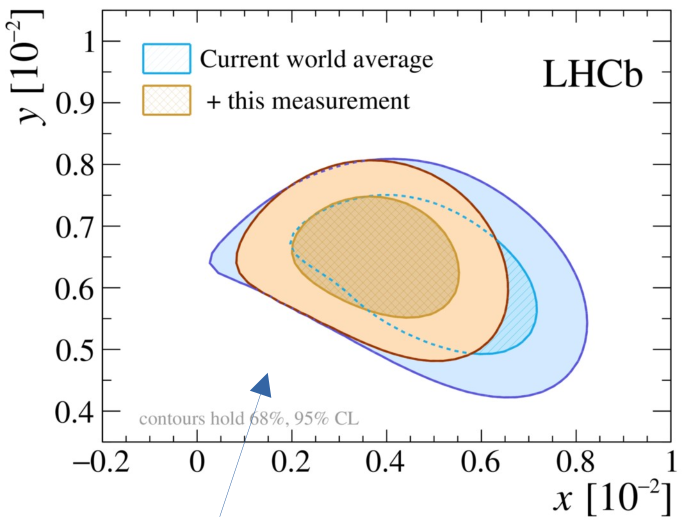
$$\Delta Y_f \approx x \sin\phi - y(|\tfrac{q}{p}| - 1) - y a_{CP}^{dir,f} (1 + \tfrac{x}{y} \cot\delta_f)$$

$$\Delta Y \approx x \sin\phi - y(|\tfrac{q}{p}| - 1)$$

- To extract CP violating phase and |q/p|,
  y and x need to be non zero and need to be known.

  → precise measurement of mixing parameters needed

Status Neckarzimmern 2019

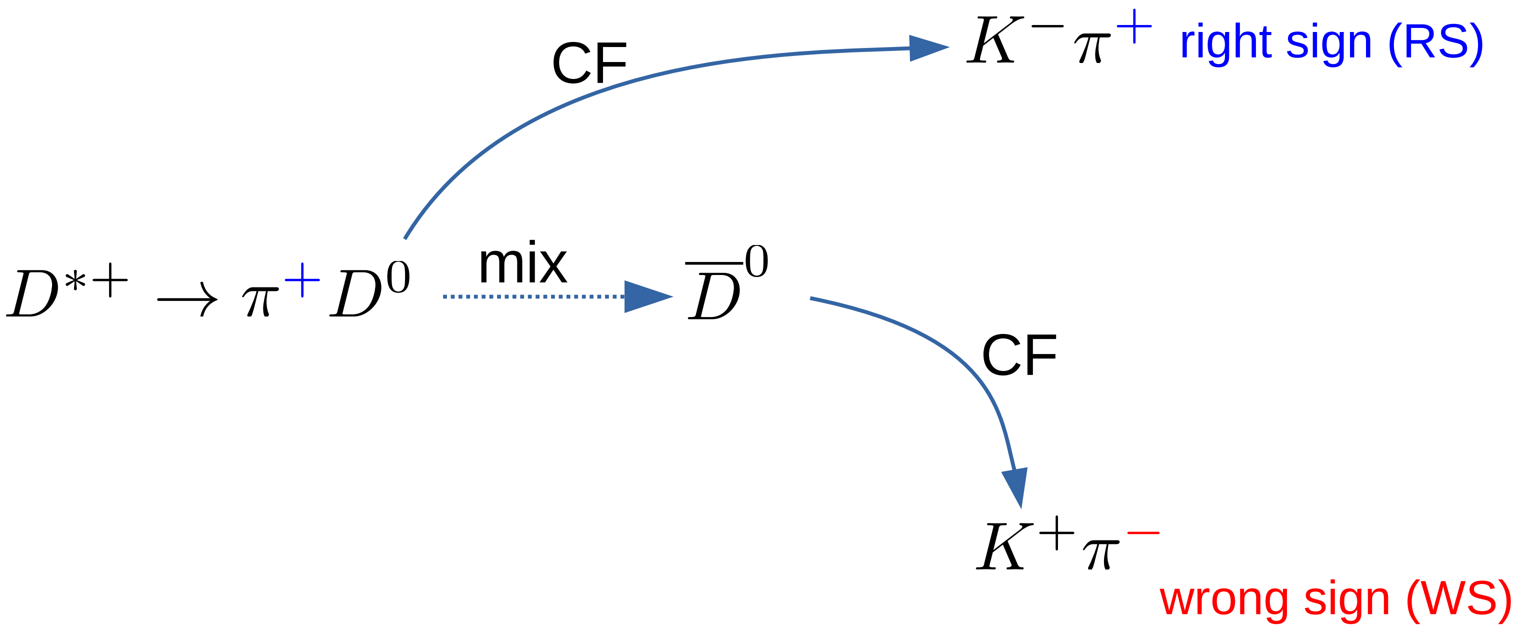


3 sigma

- About the middle in case we need a break

How to measure mixing?

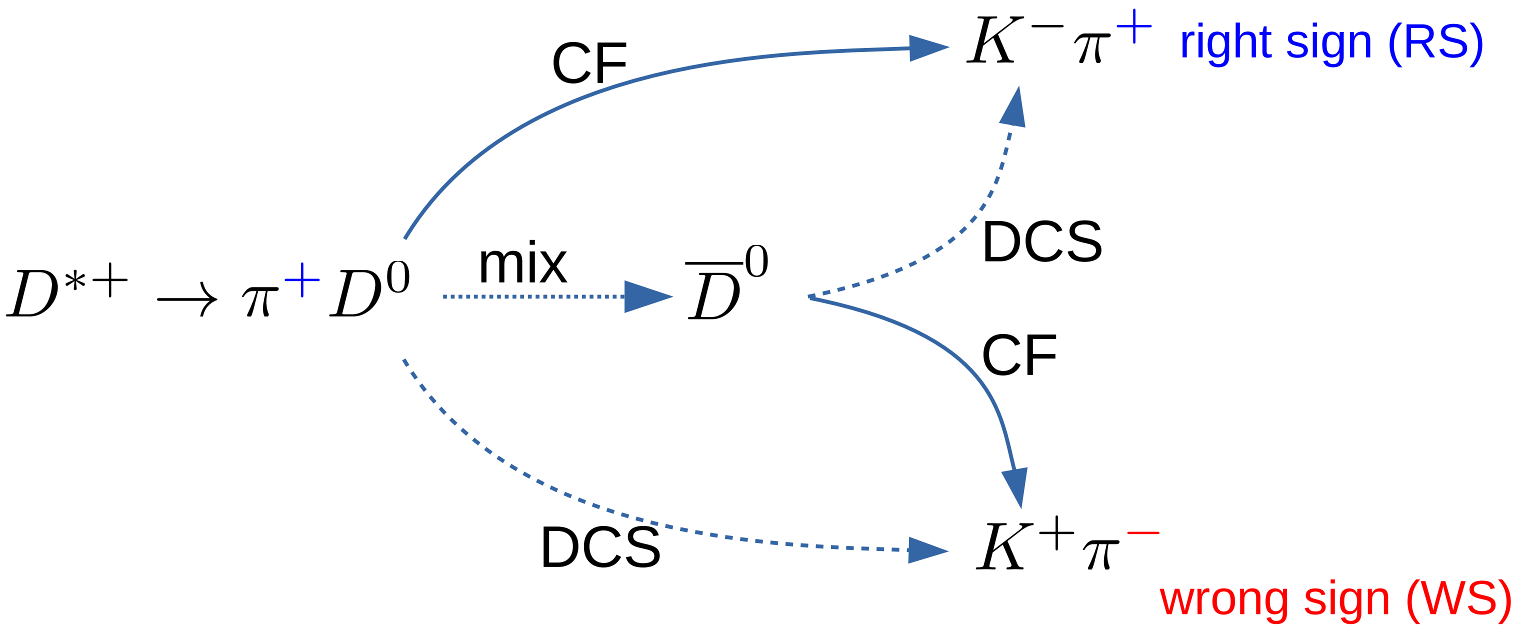
- Cabibbo-favoured $D^0 \to K^- \pi^+$



How to measure mixing?

- Cabibbo-favoured $D^0 \to K^- \pi^+$ and doubly-Cabibbo-suppressed $D^0 \to \pi^- K^+$ decays

Count!
R = RS(t)/WS(t)



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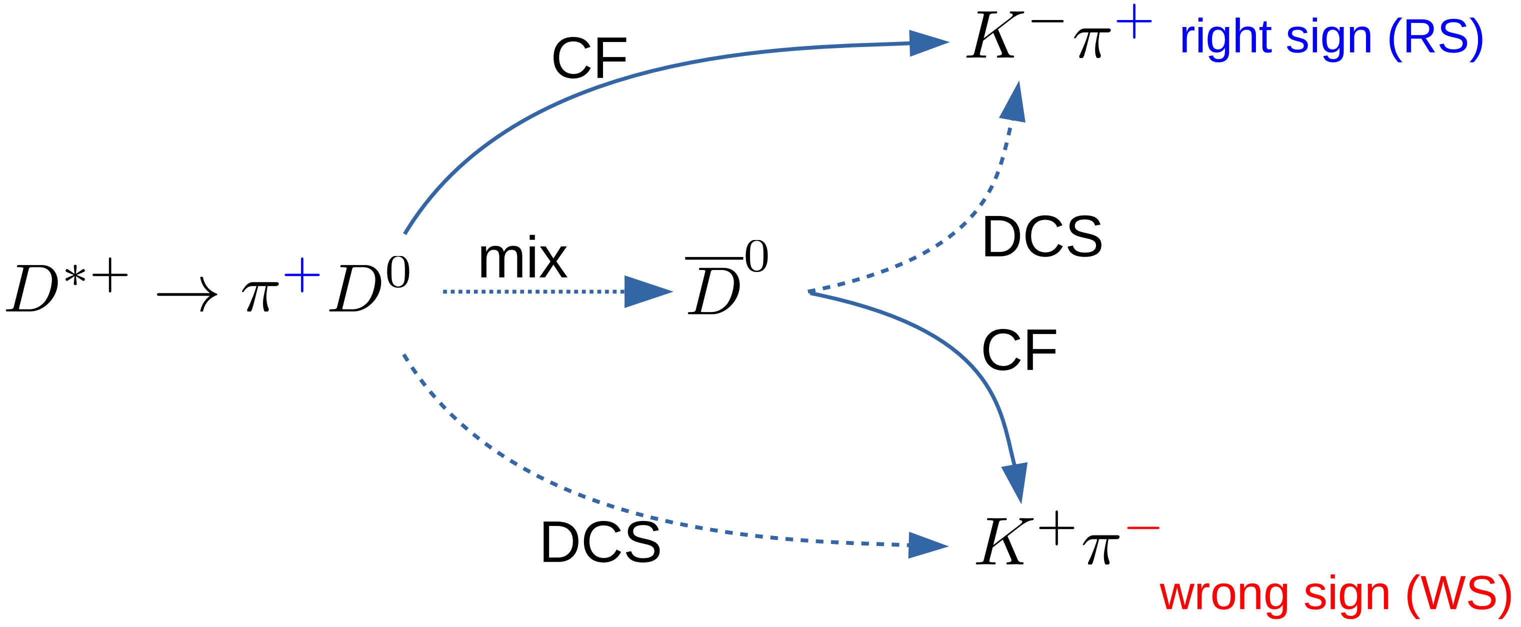
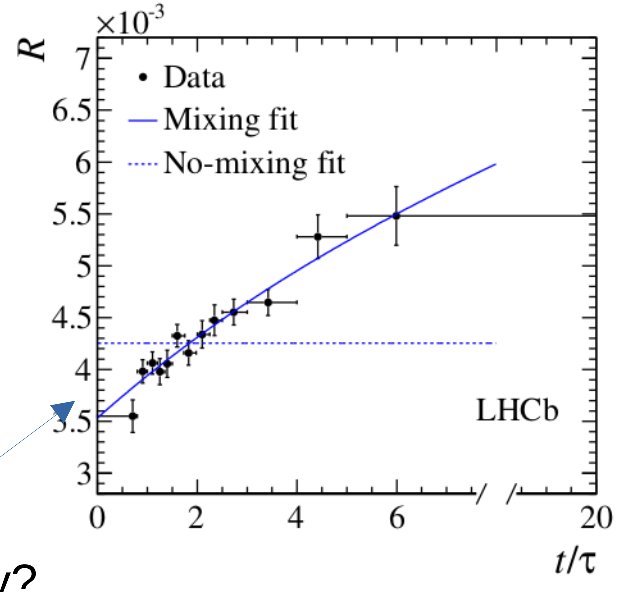


Phys. Rev. Lett. 110, 101802 (2013)



Mixing! x? y?

What is measured?

- Observable:

$$R(t) = \frac{N(\text{wrong})(t)}{N(\text{right})(t)}$$

- Theory:

$$R(t) \approx r_D + \underbrace{\sqrt{r_D}\, y' \frac{t}{\tau}}_{\text{(Interference)}} + \underbrace{\frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2}_{\text{(Pure mixing)}}$$

- Strong phase rotates x and y

$$\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)} = -\sqrt{R_D} e^{-i\delta}$$

$$y' = y\cos\delta - x\sin\delta$$

$$x' = x\cos\delta + y\sin\delta$$

$$\cos\delta \approx 1$$

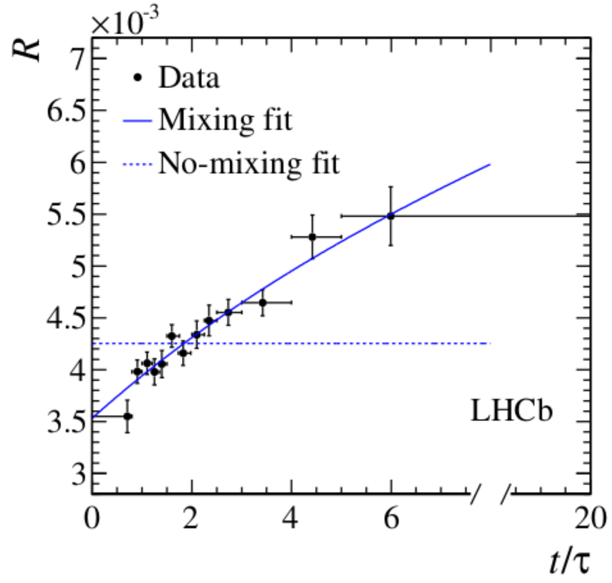
Interference enhances sensitivity!

Mostly measurement of y.

Currently need experiments like BES III for that!

There is an update with some Run 2 data, but the full update is not yet out.

Phys. Rev. Lett. 110, 101802 (2013)



Multi-particle final states

- Look at

$$D^0 \to K_s^0 \pi^+ \pi^-$$

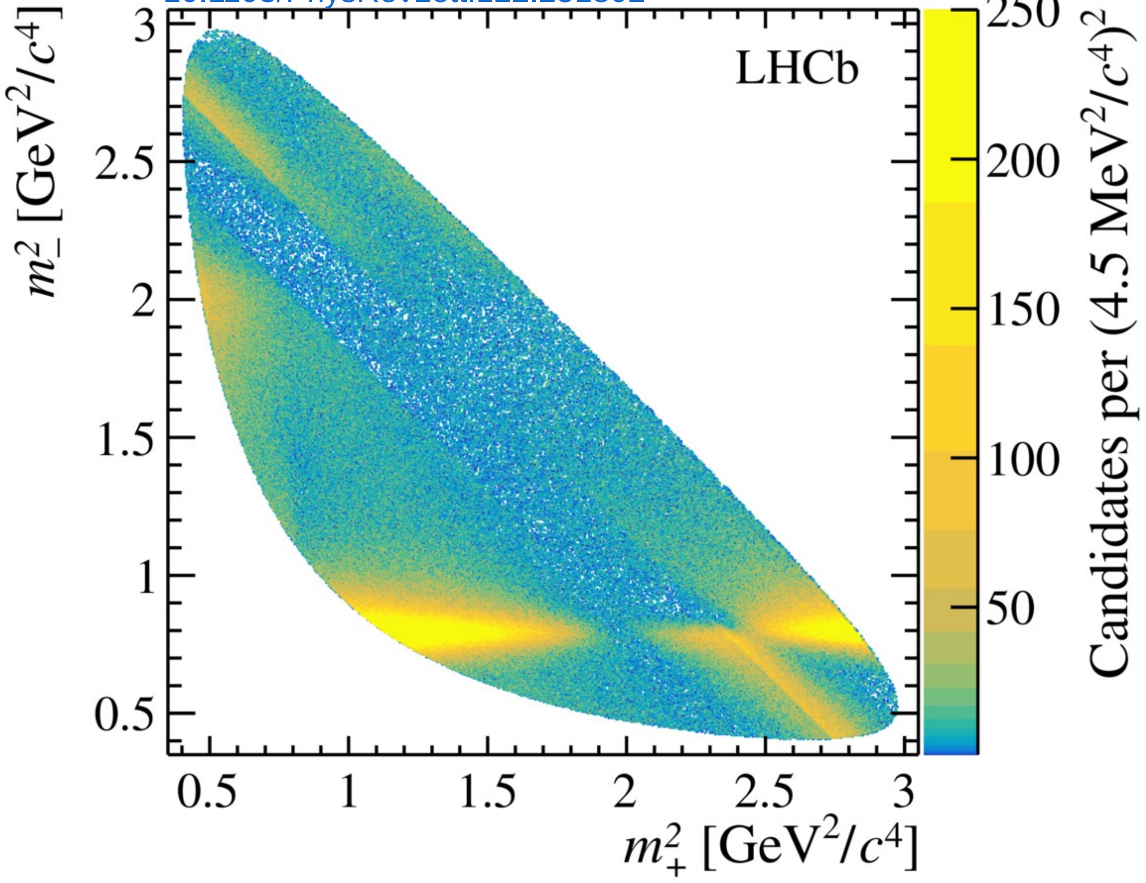
- Phase-space described by two variables

$$\text{For } D^0 \begin{cases} m_+^2 \equiv m^2(K_S^0 \pi^+) \\ m_-^2 \equiv m^2(K_S^0 \pi^-) \end{cases}$$

Swapped for $\overline{D}^0$

Dalitz-Plot

10.1103/PhysRevLett.122.231802



Multi-particle final states

- Look at

$$D^0 \to K_s^0 \pi^+ \pi^-$$

- Phase-space described by two variables

$$\text{For } D^0 \begin{cases} m_+^2 \equiv m^2(K_S^0\pi^+) \\ m_-^2 \equiv m^2(K_S^0\pi^-) \end{cases}$$

Swapped for $\overline{D}^0$

- Structures coming from strongly decaying intermediate resonances, e.g.

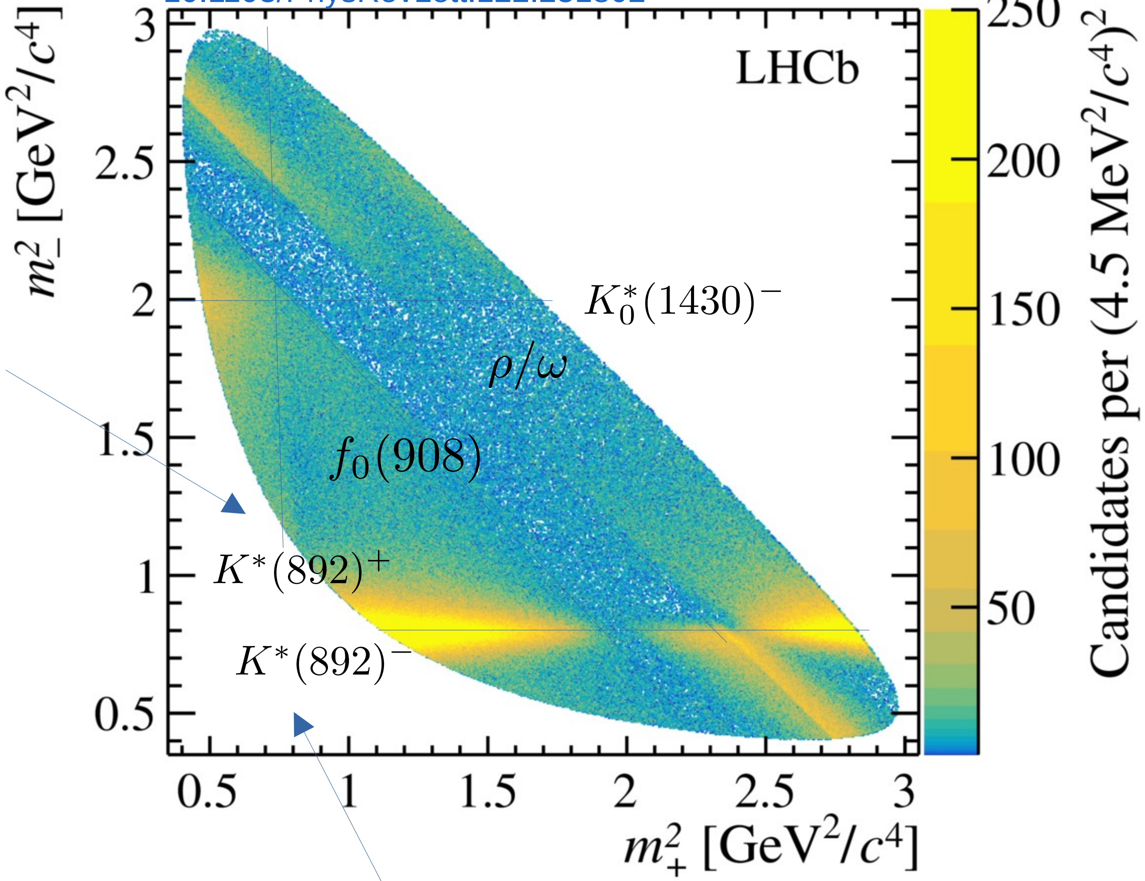
$$K^*(892)^\pm \to K_S^0 \pi^\pm$$
$$f_0(908) \to \pi^+\pi^-$$

Lot's of different strong phases

Dalitz-Plot

10.1103/PhysRevLett.122.231802

Doubly Cabibbo suppressed.



Cabibbo favoured

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Measure mixing with Binflip method

- Perform "WS/RS" measurement in bins of Dalitz plot

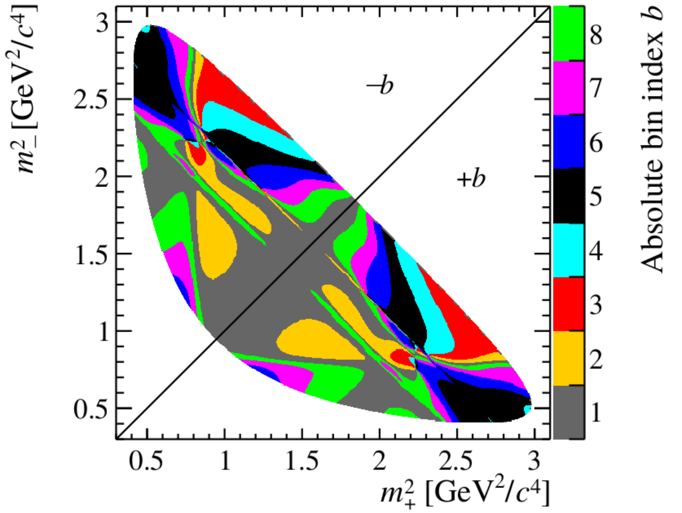
$$R_b(t) = \frac{N_{-b}(t)}{N_b(t)}\,, \qquad R_b(0) = r_b$$

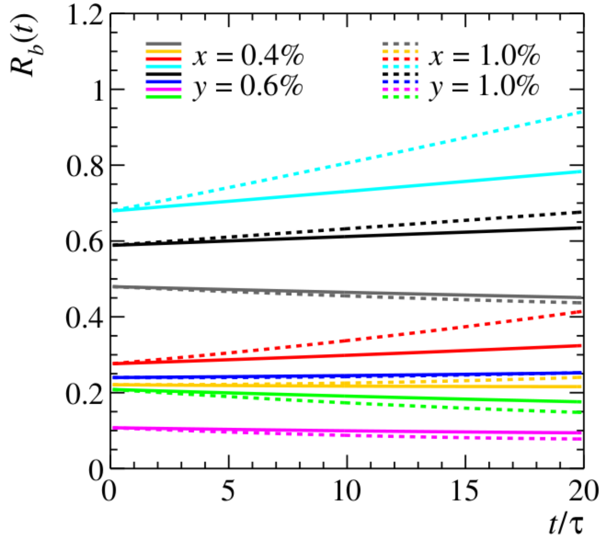
$$R_b(t) \approx r_b - \frac{t}{\tau}\sqrt{r_b}\left[(1-r_b)c_b\, y - (1+r_b)s_b\, x\right] (\text{no CPV}).$$

- Parameters c_b and s_b are the so-called amplitude weighted strong phase differences

  → Measured with quantum correlated DD pairs at CLEO and BESIII → See Alex talk

- Varying strong phase allows to separate x and y
- Enhanced sensitivity to x.
- Acceptance effects (mostly) cancel in ratio





Full fit accounting for CP violation

- Ratios measured separately for D^0 and $\overline{D}^0$

$$R_{bj}^{\pm} \approx \frac{r_b + r_b \frac{\langle t^2 \rangle_j}{4} \mathrm{Re}(z_{CP}^2 - \Delta z^2) + \frac{\langle t^2 \rangle_j}{4} \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} \langle t \rangle_j \mathrm{Re}[X_b^* (z_{CP} \pm \Delta z)]}{1 + \frac{\langle t^2 \rangle_j}{4} \mathrm{Re}(z_{CP}^2 - \Delta z^2) + r_b \frac{\langle t^2 \rangle_j}{4} \left| z_{CP} \pm \Delta z \right|^2 + \sqrt{r_b} \langle t \rangle_j \mathrm{Re}[X_b (z_{CP} \pm \Delta z)]}$$

$$z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1} (y + ix)$$

$$x_{CP} = \mathrm{Im}(z_{CP})$$

$$y_{CP} = \mathrm{Re}(z_{CP})$$

$$\Delta x = \mathrm{Im}(\Delta z)$$

$$\Delta y = \mathrm{Re}(\Delta z)$$

Xb contain cb and sb

- Observables x_{CP} and y_{CP} equal x and y in case of CP symmetry
- Δx, Δy (“slope differences”) unequal 0 sign of CP violation

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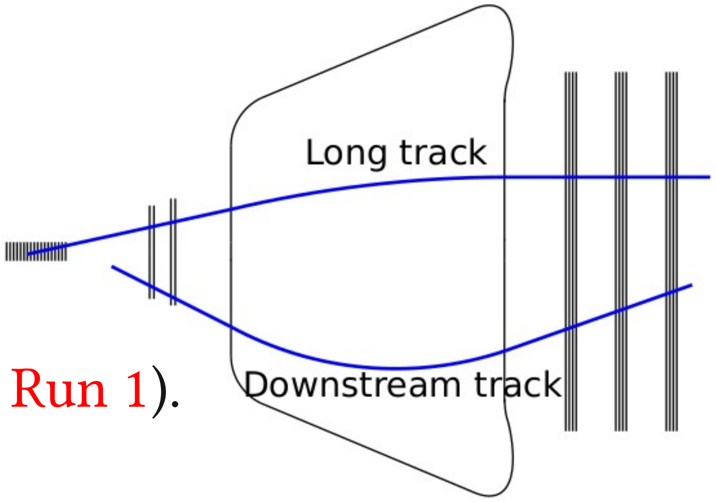
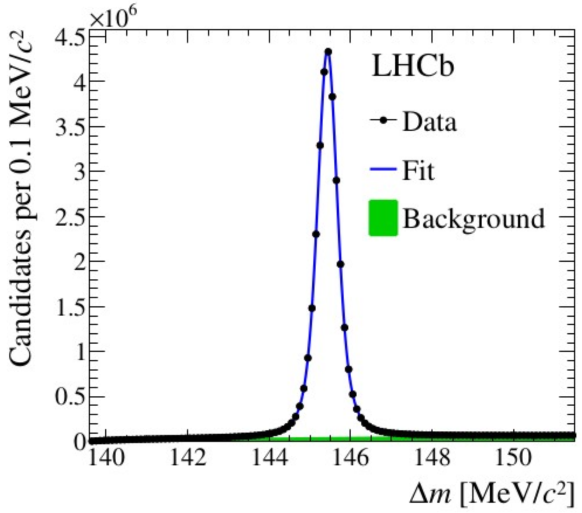
Event selection of $D^0 \longrightarrow K_S^0\, \pi^+\, \pi^-$

- Run 2 data with 5.4 fb^{-1} (2016-2018)
- $K_S^0 \longrightarrow \pi^+\, \pi^-$ reconstructed in two ways
- Large charm production rate (reminder)
  - Real-Time analysis: Offline quality reconstruction in trigger (especially downstream tracking very inefficient in Run 1).
  - Persist only trigger candidate to save bandwidth to storage.
  - Detachment cuts to reduce background from proton-proton collisions.
- After selection very little background left.
- Signal yields determined with fit to $\Delta m = m(D^{*+}) - m(D^0)$.
- 31 Million signal $D^{*+} \longrightarrow D^0 (\longrightarrow K_S^0\pi^+\pi^-)\pi^+$, $\longrightarrow$ 30 times more D^{*+} than in Run 1 (3 fb^{-1})

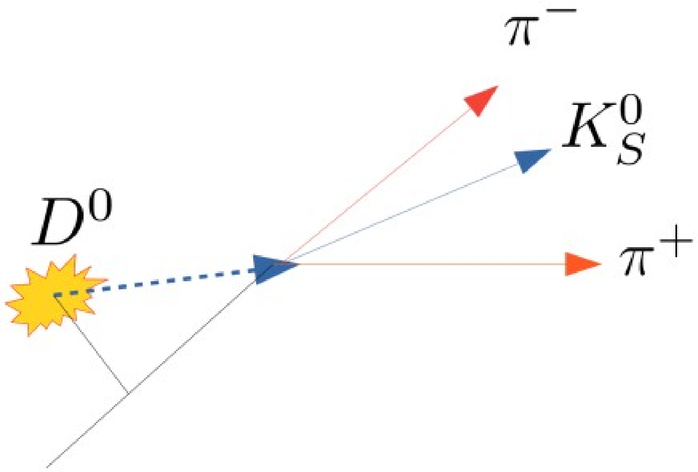


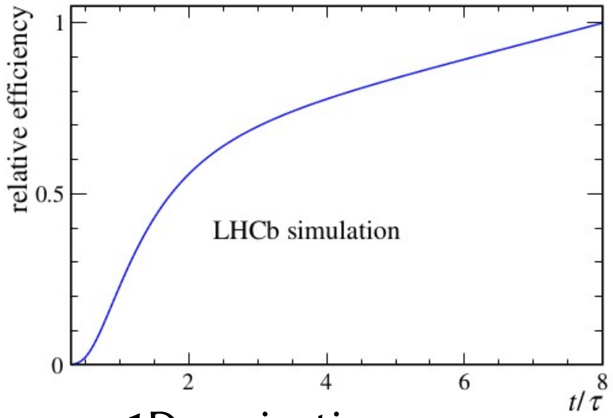


Decay-time acceptance

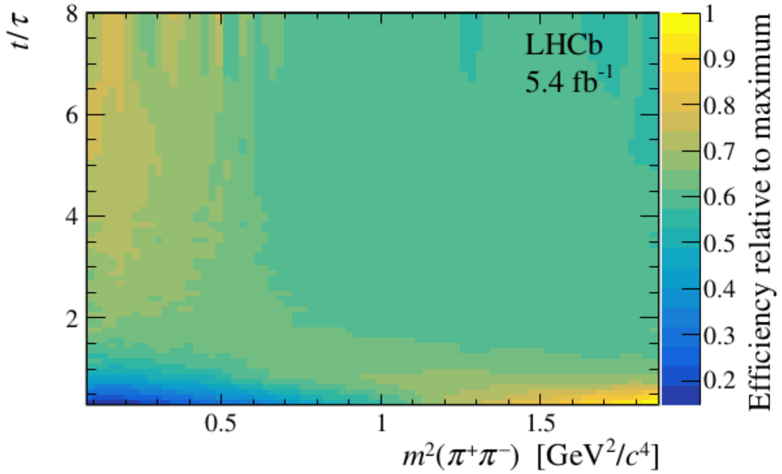
- Requirements in trigger to suppress prompt tracks.
  →correlate Dalitz-plot coordinate with decay time.
- Effect most pronounced in $m(\pi^+\pi^-)$ (diagonal in Dalitz plot)
- Dalitz-plot binning too coarse for full cancellation of variations in ratios.
- Mimics time-dependent variation of strong phases.

  → Large biases on x and y (if not corrected)





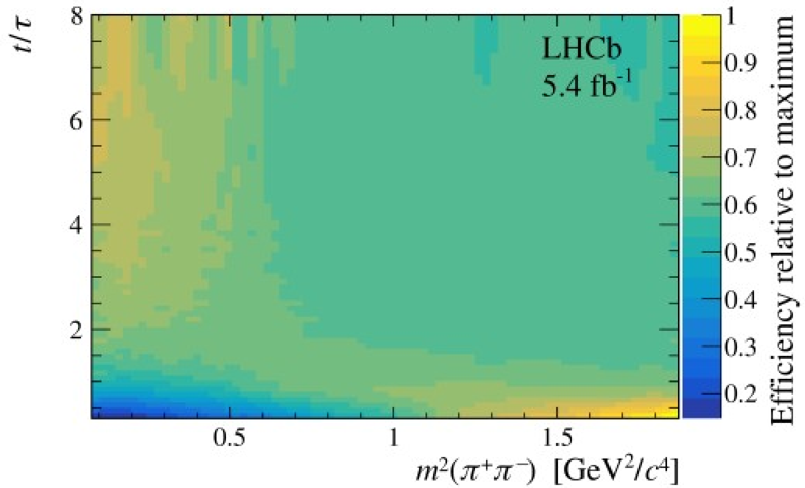
1D projection

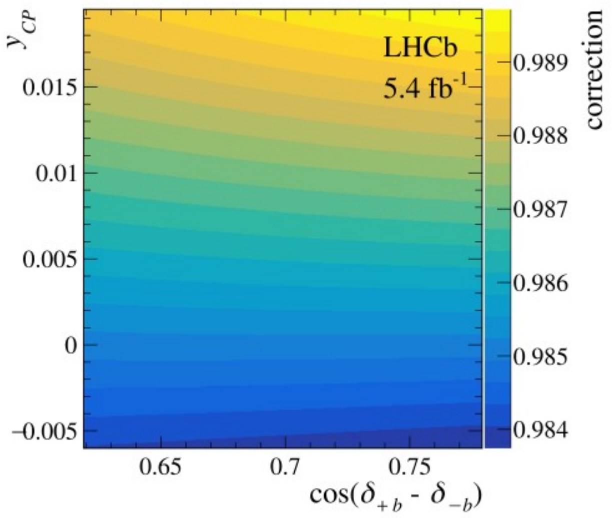


2D projection

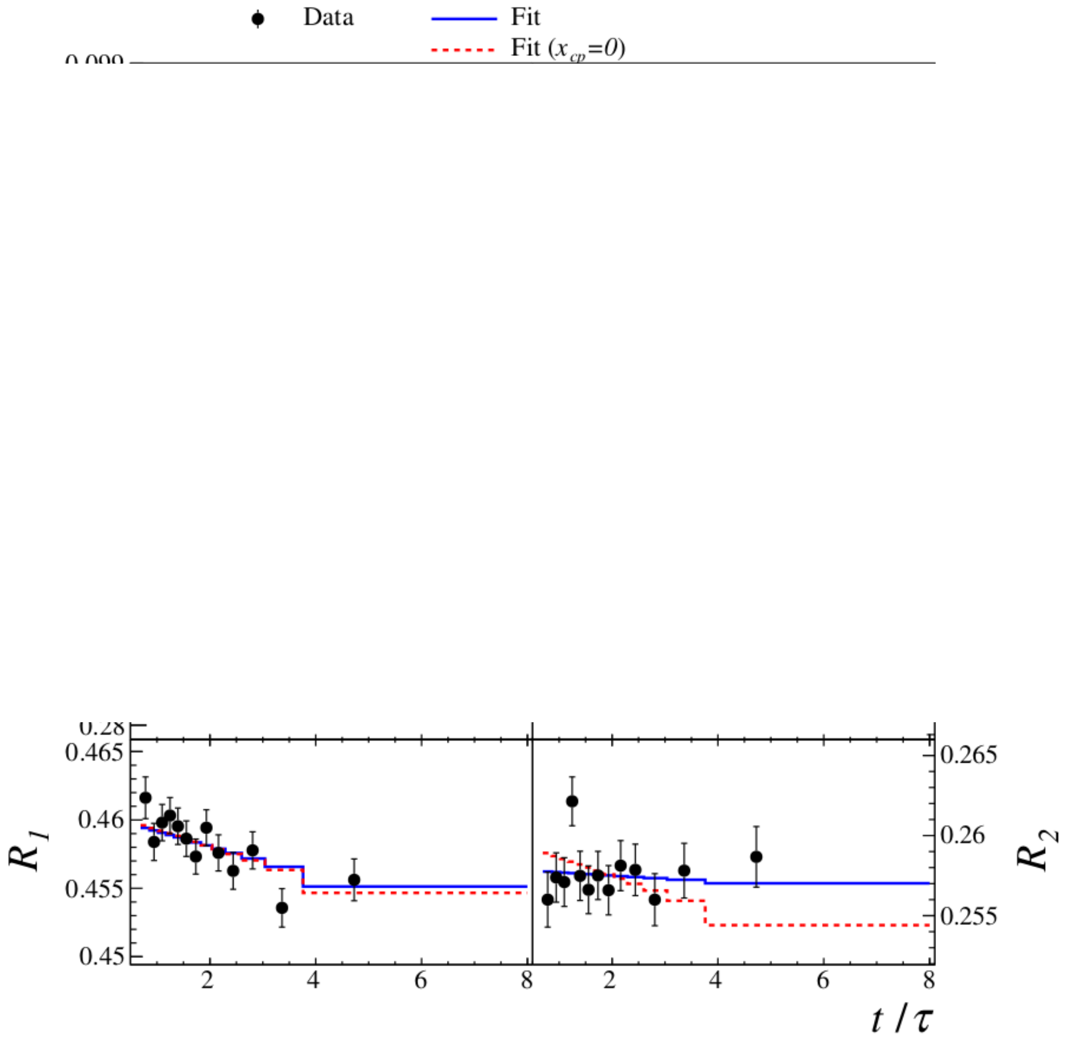
Acceptance correction

- Absolute efficiencies not needed due to ratios.
- Oscillations move events from one side of the diagonal to the other.
- Define small regions symmetrically across the diagonal.
  - Calculate efficiency relative to phase-space integrated distribution on data.
  - Align decay-time distributions across all these regions (≈ 50% correction at low decay times).
- About 1% extra correction due to "physical" correlations from mixing accounted for in fit.
- Mainly y, no effect due to x. (Dalitz bin 1 shown)
- Method validated with pseudo-experiments





Mixing fit



- $\chi 2$ fit to determine mixing and CP violation parameters
- Effect of mixing clearly visible

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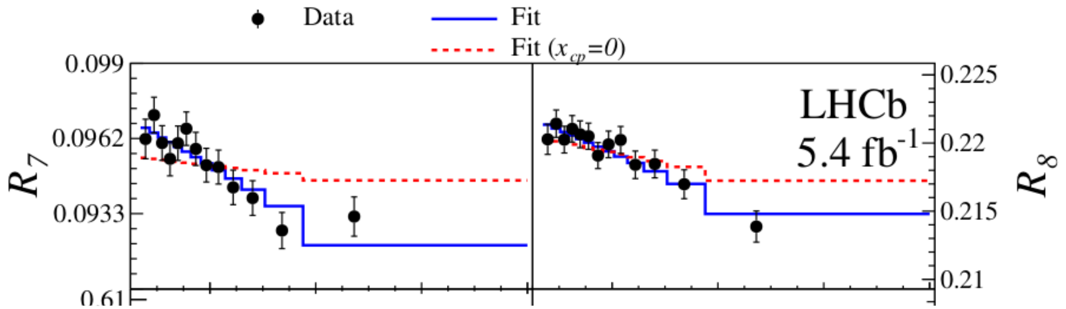
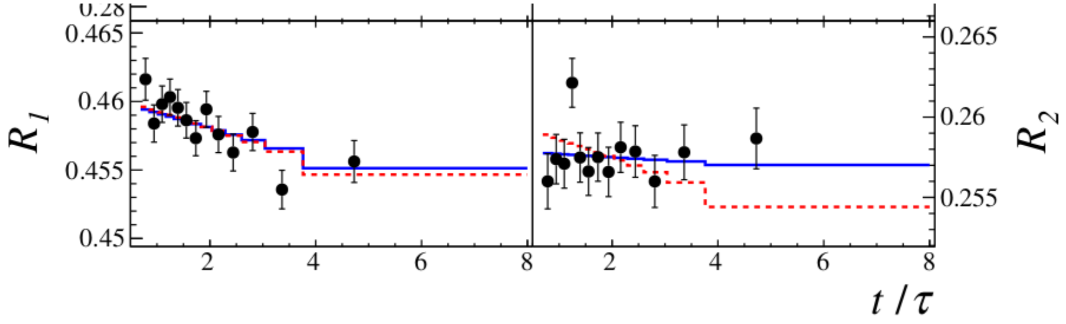
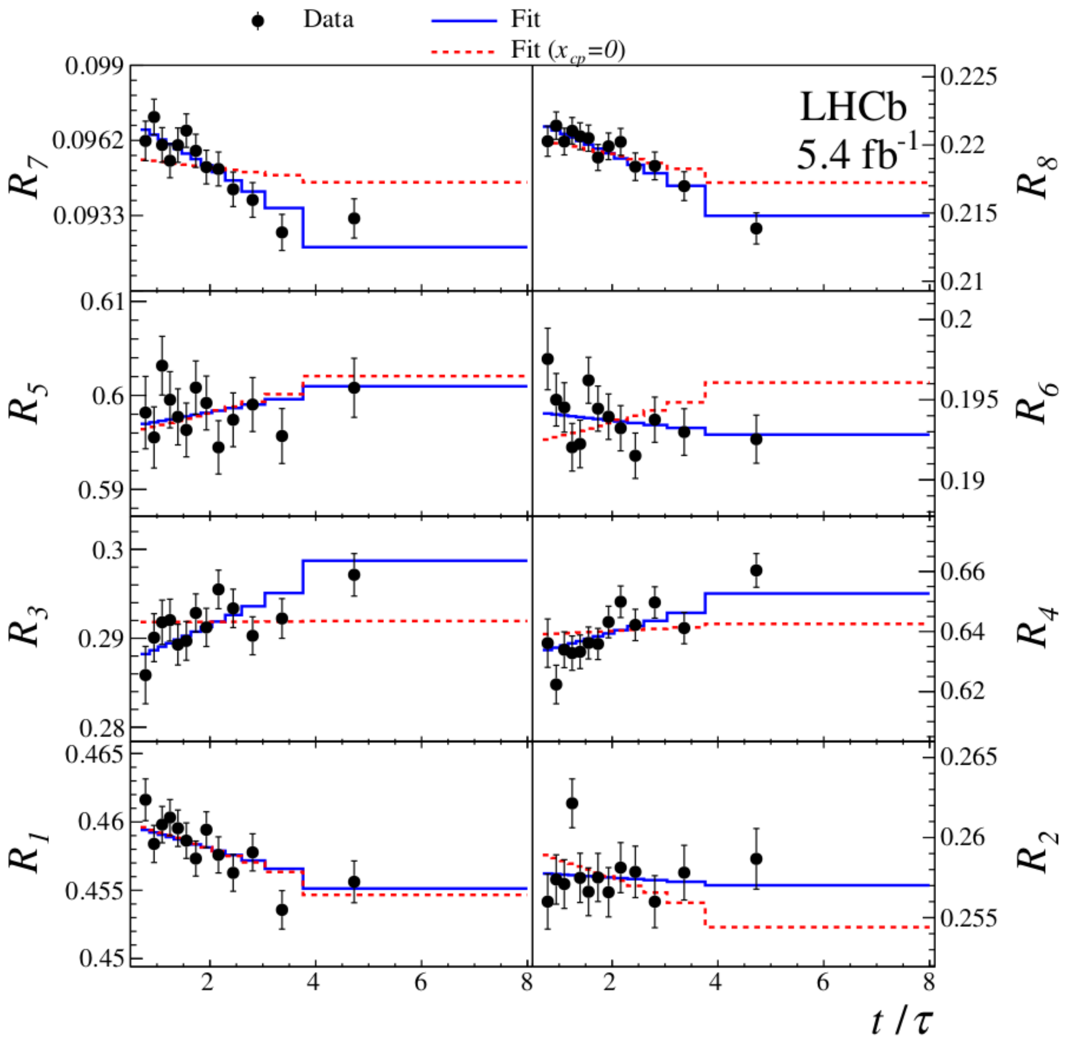
Mixing fit



- $\chi 2$ fit to determine mixing and CP violation parameters
- Effect of mixing clearly visible
- Significant x_{CP} needed to describe data.



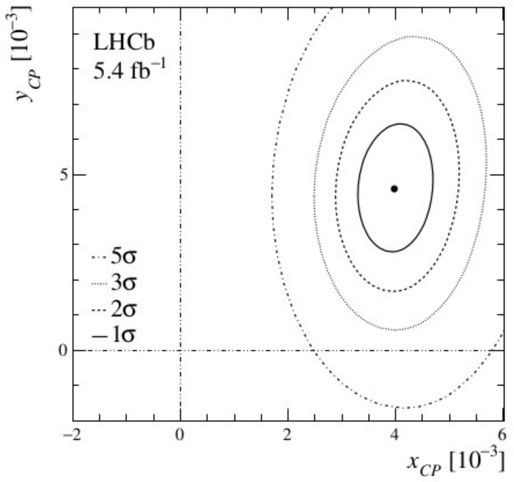
Mixing fit



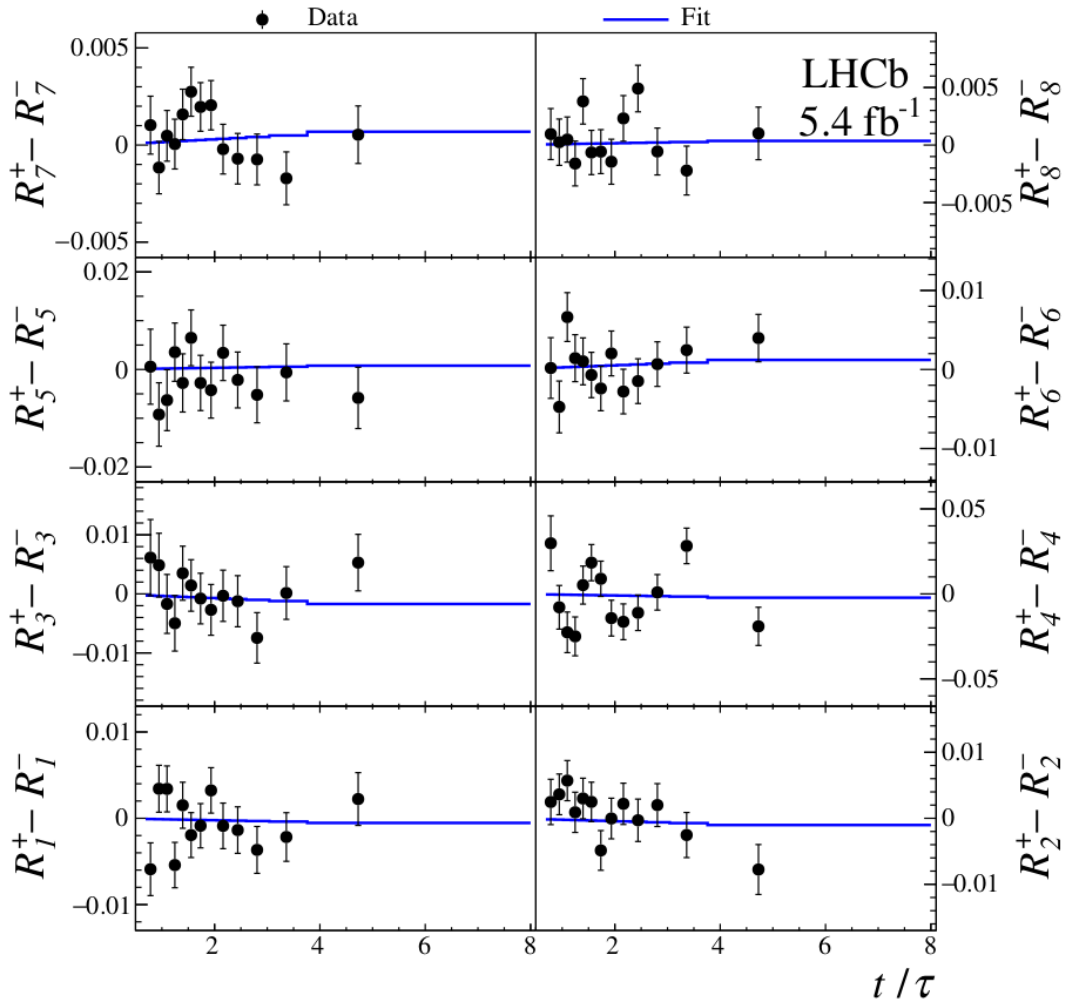
- $\chi 2$ fit to determine mixing and CP violation parameters
- Effect of mixing clearly visible
- Significant x_{CP} needed to describe data.

$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$

Strong phases uncertainty included in statistical uncertainty, contributes about 50% (e.g. 0.4⟶0.46).

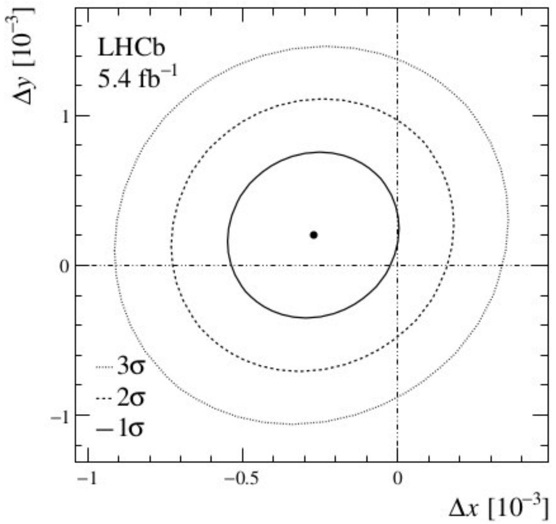


CP violation fit



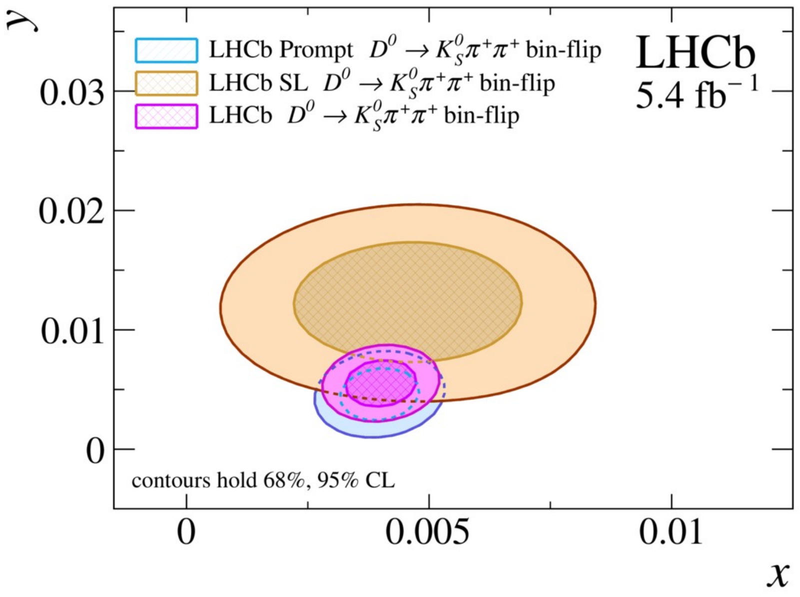
- Look at differences of ratios for D^0 and $\overline{D}^0$
- Measurement consistent with CP symmetry.

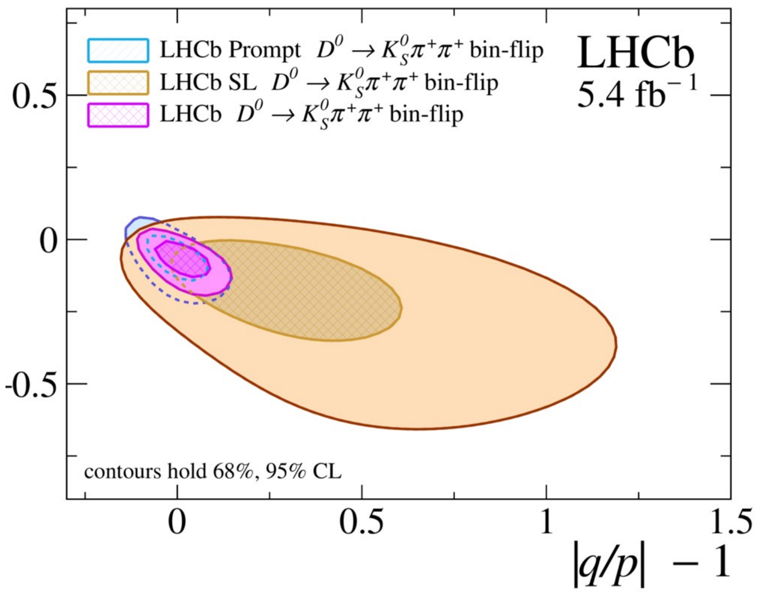
$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (\quad 0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$



LHCb Run 2 legacy x, y, |q/p|, ϕ from $D^0 \to K_S^0 \pi^+ \pi^-$

- Also performed analysis with a differently tagged sample (B-decays).



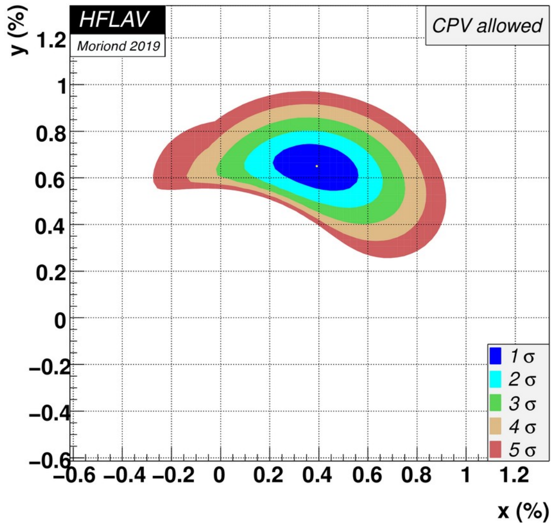


$$x = (4.01 \pm 0.49) \times 10^{-3},$$
$$y = (\;5.5 \pm 1.3\;) \times 10^{-3},$$
$$|q/p| = \quad 1.012\,^{+0.050}_{-0.048},$$
$$\phi = -0.061\,^{+0.037}_{-0.044}\ \text{rad}.$$

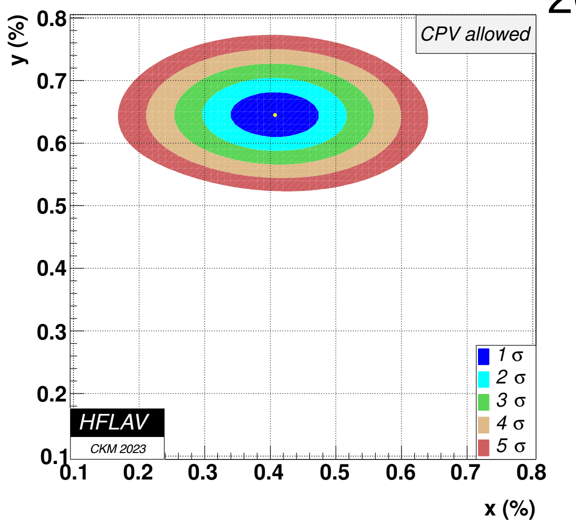
- First observation of the mass difference x of charm meson mass eigenstates with significance of 8 sigma
- D_2 (with CP|D_2> ≈ |D_2>) now D_H , D_1 now D_L?

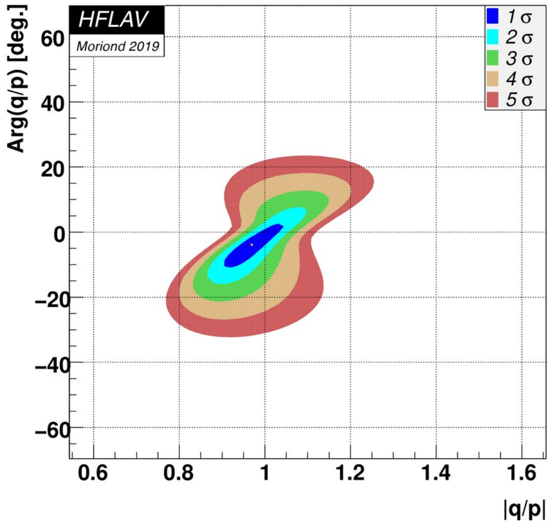
World average x, y, |q/p|, ϕ

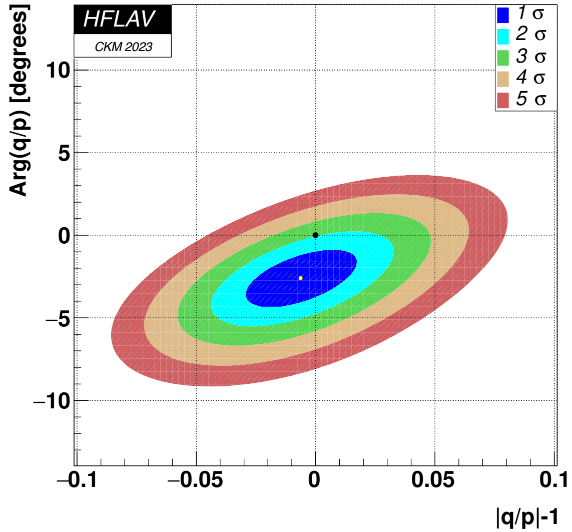
2019



2023







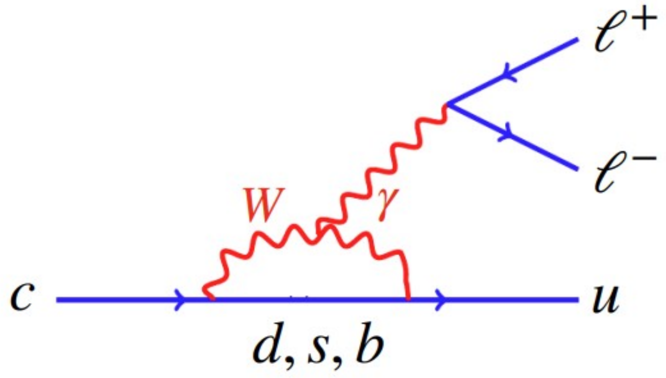
- Improvements driven by LHCb measurements of x, (y), q/p, ϕ with $D^0 \longrightarrow K_S^0\pi^+\pi^-$ and ΔY and y_{CP} with two body decays
- Mass and lifetime differences of D_1 and D_2 well established now.
- No sign of CP violation in mixing or in interference of mixing and decay yet.

Note the different scales!

Questions?

Rare charm

- Huge event rates can be used for ultra precise measurements or study very rare decays
  - Almost exact GIM cancellation of $|\Delta c| = |\Delta u| = 1$ processes (Non resonant contribution < 10^{-10}, resonant contribution 10^{-6})



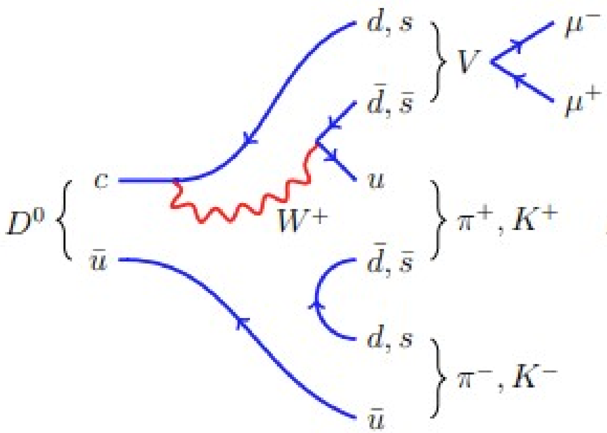
- 1) Searches for extremely rare and forbidden decays, eg.
  - $D^0 \to \mu\mu$ (PHYS. REV. LETT. 131 (2023) 041804)
  - $D^+ \to \pi\mu e$ (JHEP 06 (2021) 044)

- 2) Study of angular observables and CP asymmetries in resonance dominated semileptonic decays (e.g. $D^0 \to \pi\pi\mu\mu$)
  - Null tests based on (approximate) symmetries

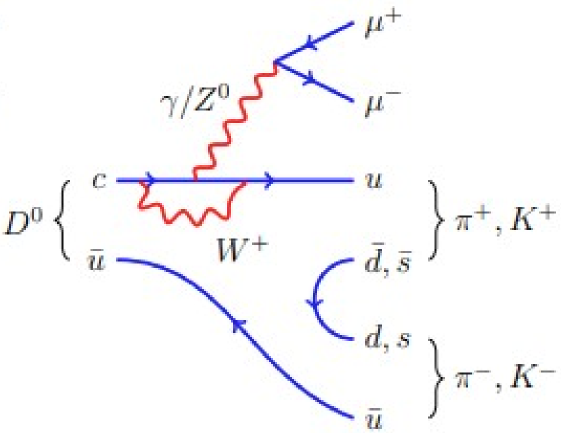
Study of $D^0 \to hh\mu\mu$

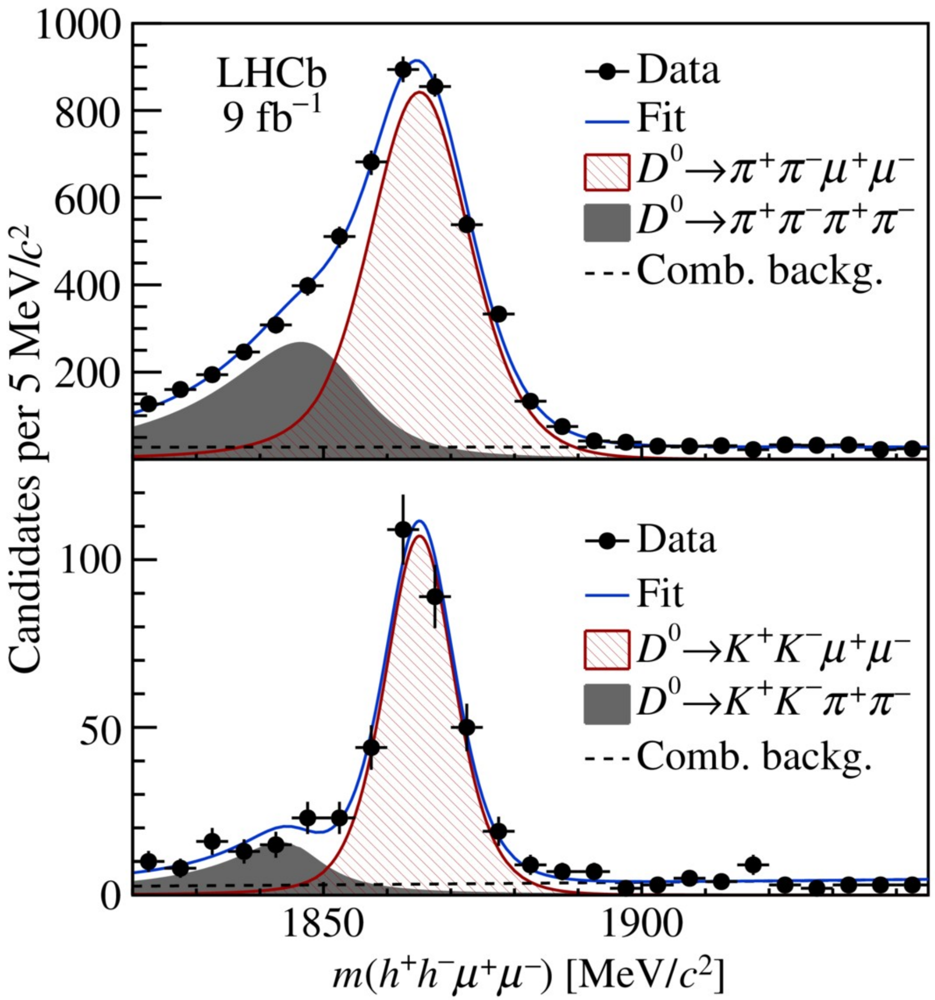
- Rarest charm meson decays observed
  - $B(D^0 \to \pi^+\pi^-\mu^+\mu^-) \sim 9.6 \times 10^{-7}$, 3500 events
  - $B(D^0 \to K^+K^-\mu^+\mu^-) \sim 1.5 \times 10^{-7}$, 300 events

Resonance contribution, e.g. ω



Short-distance





Study of $D^0 \to hh\mu\mu$

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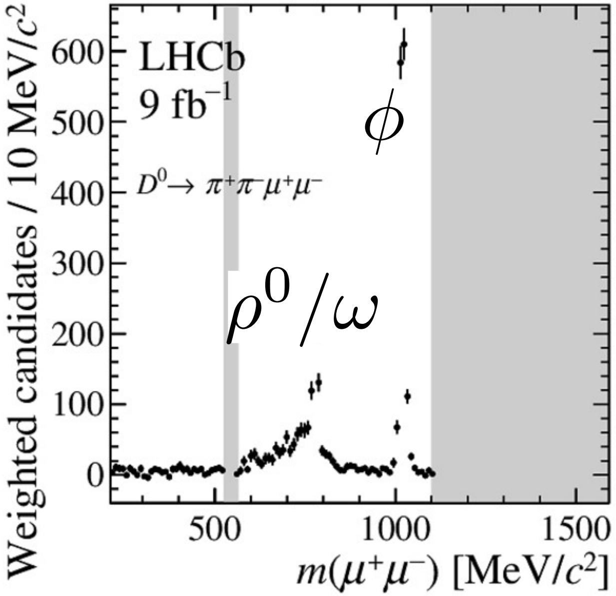
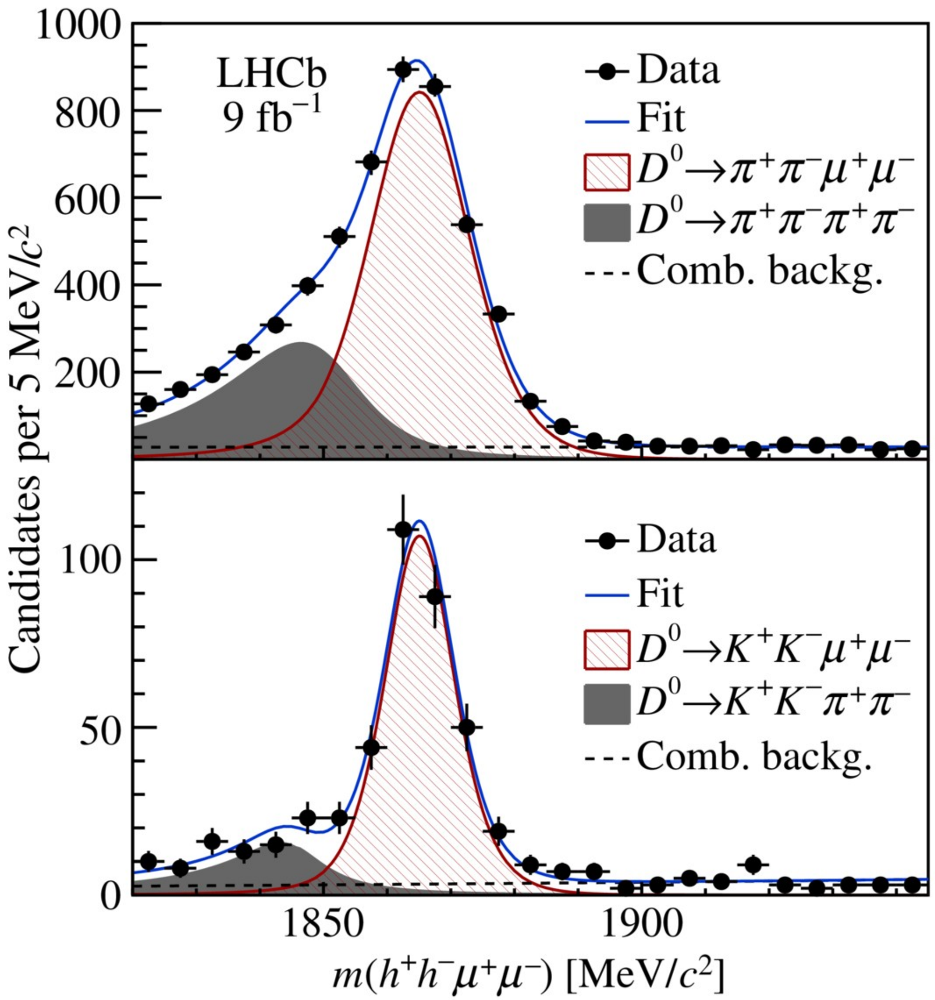
  - $B(D^0 \to K^+K^-\mu^+\mu^-) \sim 1.5 \times 10^{-7}$, 300 events
- Dominated by resonances (η not observed)





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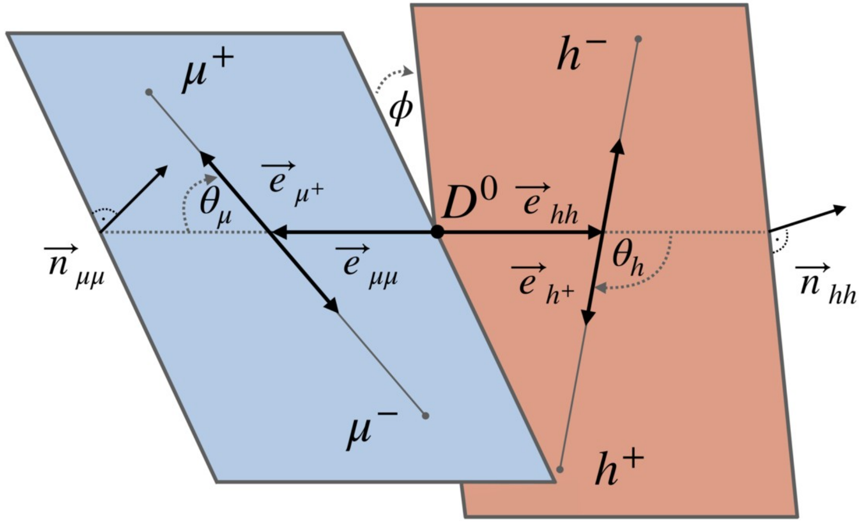
Phase-space and differential decay rate

- Phase space described by 5 variables

$$q^2 = m^2(\mu^+\mu^-), p^2 = m^2(h^+h^-), \theta_\mu, \theta_h, \phi$$



- Differential decay-rate:

$$\frac{d\Gamma}{d\cos\theta_\mu d\cos\theta_h d\phi} = I_1 + I_2 \cdot \cos 2\theta_\mu + I_3 \cdot \sin^2 2\theta_\mu \cos 2\phi + I_4 \cdot \sin 2\theta_\mu \cos\phi + I_5 \cdot \sin\theta_\mu \cos\phi + I_6 \cdot \cos\theta_\mu + I_7 \cdot \sin\theta_\mu \sin\phi + I_8 \cdot \sin 2\theta_\mu \sin\phi + I_9 \cdot \sin^2\theta_\mu \sin 2\phi$$

Angular coefficients I_i encode the physics

- Depending on integration different terms survive, e.g.

$$I_2 = \int_{-\pi}^{\pi} d\phi \left[\int_{-1}^{-0.5} d\cos\theta_\mu + \int_{0.5}^{1} d\cos\theta_\mu - \int_{-0.5}^{0.5} d\cos\theta_\mu \right] \frac{d^5\Gamma}{dq^2\, dp^2\, d\vec{\Omega}} .$$

S. De Boer and G. Hiller, , Phys. Rev. D98 (2018) 035041

Measured observables (sketch)

- Integrate observable I_i over p^2 and $\cos\theta_h$.
- Observables I_i determined separately for D^0 and $\overline{D}^0$ and in bins of q^2
- Integration over θ_μ can be expressed as angular asymmetries, e.g.

$$\langle I_2 \rangle = \frac{1}{\Gamma}\left[\Gamma(|\cos\theta_\mu| > 0.5) - \Gamma(|\cos\theta_\mu| < 0.5)\right].$$

- Then CP averages and CP asymmetries are defined as

$$\langle S_i \rangle = \frac{1}{2}\left[\langle I_i \rangle + (-)\langle \overline{I}_i \rangle\right] \qquad \langle S_{5,6,7} \rangle \overset{\text{SM}}{=} 0$$

$$\langle A_i \rangle = \frac{1}{2}\left[\langle I_i \rangle - (+)\langle \overline{I}_i \rangle\right] \qquad \langle A_i \rangle \overset{\text{SM}}{=} 0$$

i=2,..,9

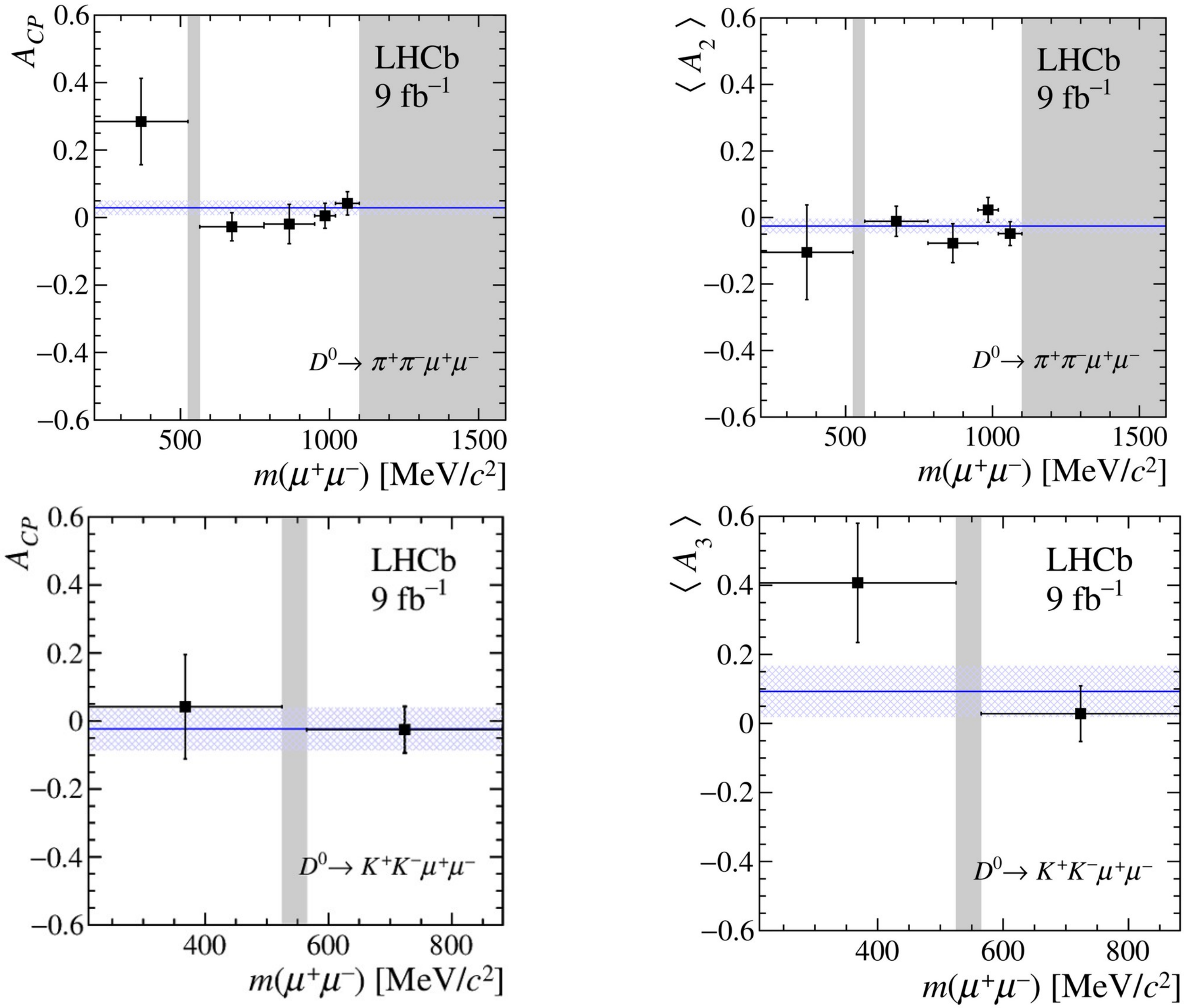
for CP even (CP odd) coefficients

Important point, it is possible to define Flavour averages and CP asymmetries which are null-tests of the SM.

PHYS. REV. LETT. 128 (2022) 221801

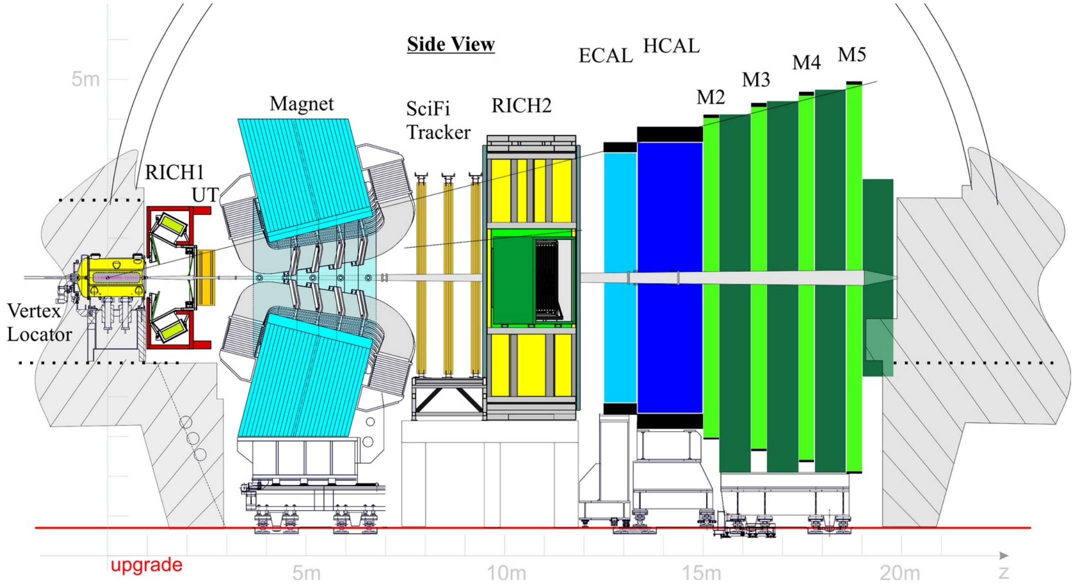
Results

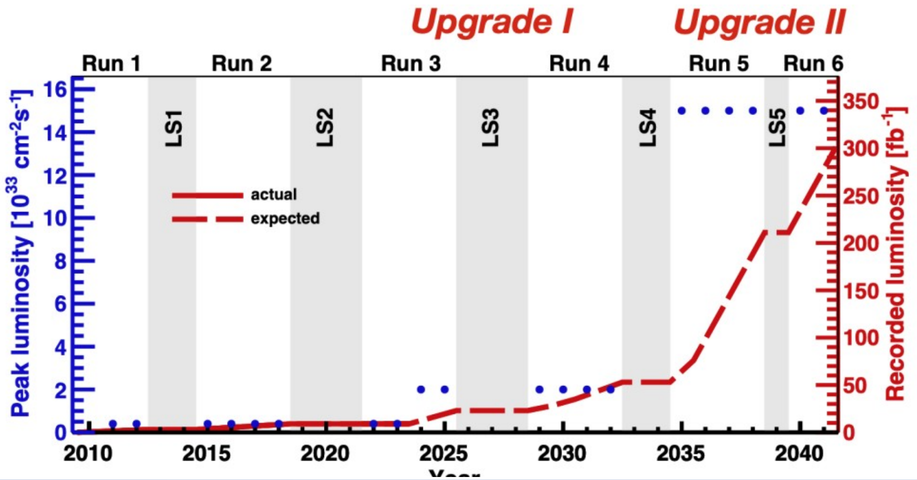
- In total 17 observables per channel, 12 are SM null tests, in 5 (2) bins of m(μμ) for ππμμ (KKμμ)
  - 4 examples shown
  - Phase space corrected for efficiencies and detection asymmetries are corrected when necessary
- SM null hypothesis with overall p values of 79% (0.8%) for the 12 tests, for ππμμ (KKμμ) corresponding to 0.3 (2.7) sigma



LHCb Run 3 (Upgrade 1) and beyond (Upgrade 2)

- Upgrade of detector for LHC Run 3 (2022-2025)
  - All detector upgrades are now installed
  - Velo RF foil repaired
- Nominal instantaneous luminosity increases by factor 5
  - Hard work ongoing to reach it quickly this year
  - Goal is to collect 14 fb^{-1} in 2024 and 2025 (~2 times more than Run1+2)
- Long term goals
  - 50 fb^{-1} by Run 4 (small detector upgrades)
  - 300 fb^{-1} by Run 6 (complete detector upgrade)

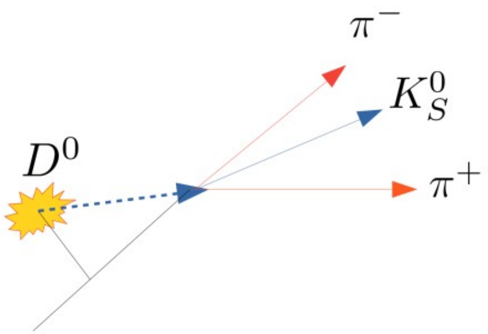


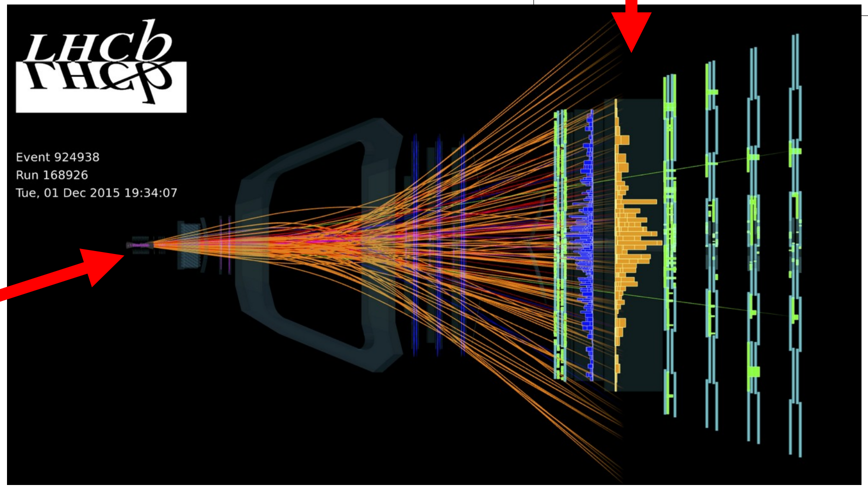


Trigger-less read-out with Upgrade 1

- Of course all detectors upgraded to withstand higher luminosity
- Biggest conceptual change is trigger-less read-out at full LHC frequency without hardware trigger
- First level trigger implemented in software running on GPUs in Event builder farm
- Second level trigger running full event reconstruction, producing output for analysis
  $\longrightarrow$ no offline reconstruction anymore
- Big improvement in efficiencies (factor 2+) possible

L0 was triggering here on high momentum high energy signatures

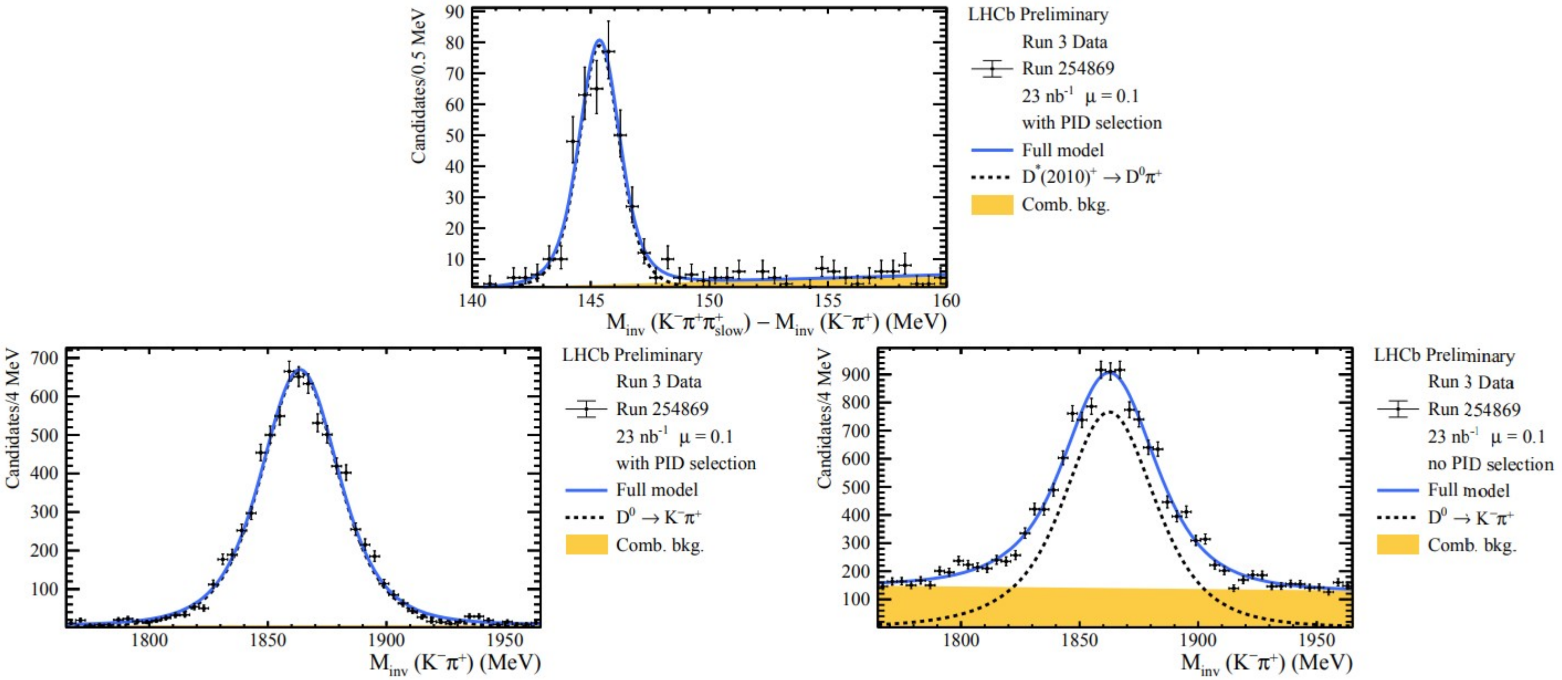




Now triggering here in first stage: Displacement plus momentum, secondary vertices

First charm signals with new detector

- Several people in this room actively working on analyses of charm decays with Run 3 data.



https://cds.cern.ch/record/2848498

Charm in the upgrade(s)

- Need to confirm direct CP violation
  - Same channels but different detector
  - Need to measure more channels

$$D^0 \to K_S^0 K_S^0$$ *

Suppressed decay with potentially enhanced CPV

$$D^0 \to \pi^+\pi^-\pi^0$$

Similar as h+h- but multi-body final state gives more information on hadronic parameters

$$D^+_{(s)} \to h^+\pi^0$$ *

$$D^+_{(s)} \to h^+\eta$$

SU3f symmetry can be used to relate to h^+h^- modes

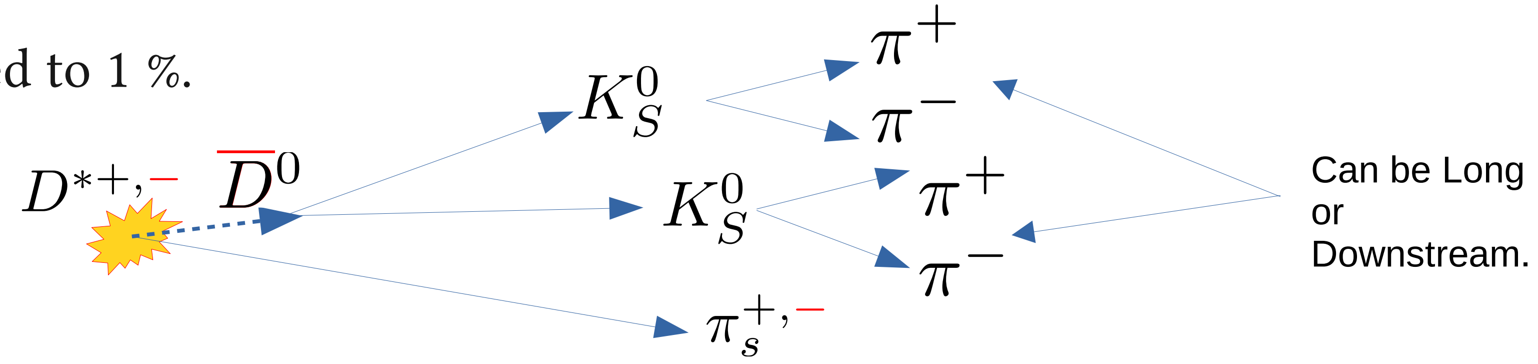
- More precise measurements of time-dependent CP violation
  - Systematics will be a challenge
  - Likely need some help from BESIII or find a way to determine hadronic parameters at LHCb

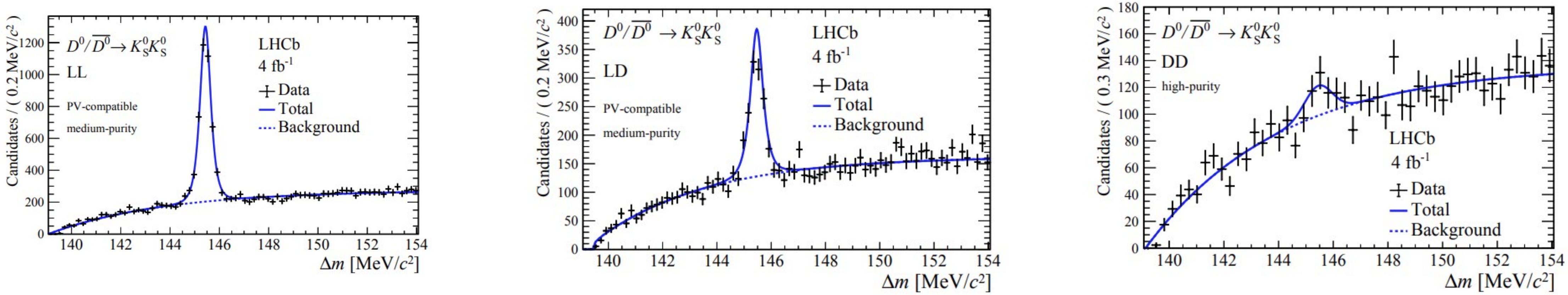
- Expand rare-charm programme
  - Increased efficiencies will help to accumulate more data

PHYS. REV. D 104, L031102

Measurement of *CP* asymmetry in $D^0 \to K_s K_s$ decays

- CP asymmetry potentially enhanced to 1 %.





- From Ks lifetime one would expect DD>LD>LL
- Trigger efficiency should be much improved in Run 3 and beyond
  - Dedicated lines trigger KS from charm in HLT1 already working.
  - Downstream reconstruction in HLT1 would help even further.

Measurement of *CP* asymmetry in $D^0 \rightarrow K_s K_s$ decays

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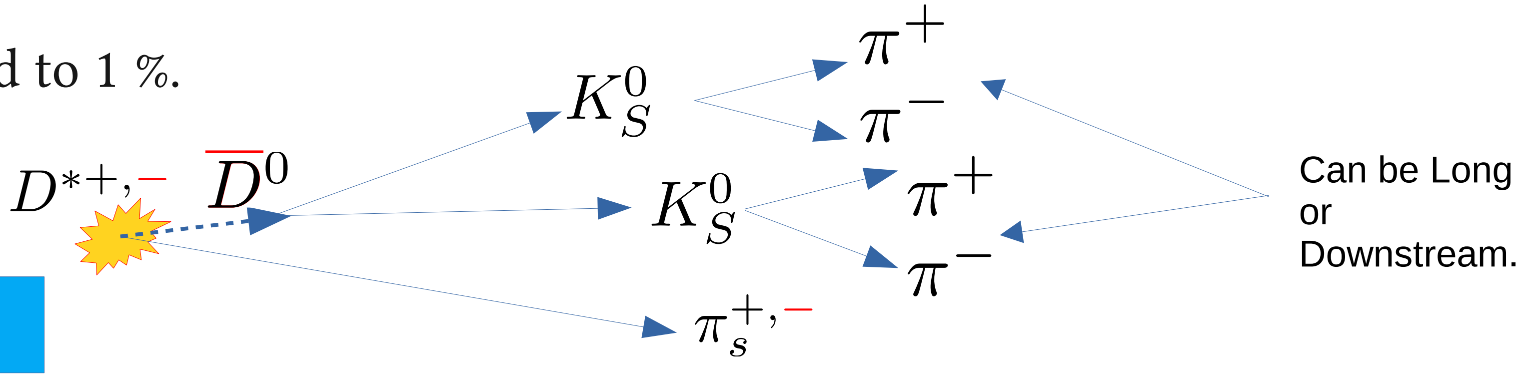
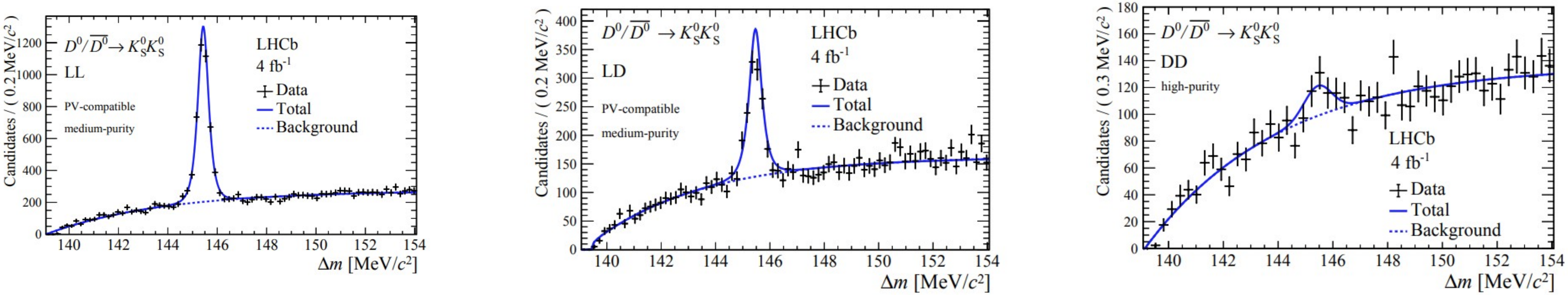


Run 2 result:

$$\mathcal{A}^{CP}(K_S^0 K_S^0) = (-3.2 \pm 1.2 \pm 0.4 \pm 0.2)\%$$



- From Ks lifetime one would expect DD>LD>LL
- Trigger efficiency should be much improved in Run 3 and beyond
  - Dedicated lines trigger KS from charm in HLT1 already working.
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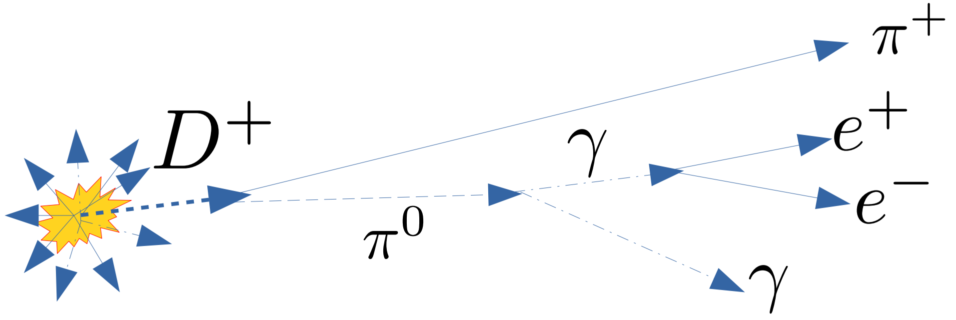
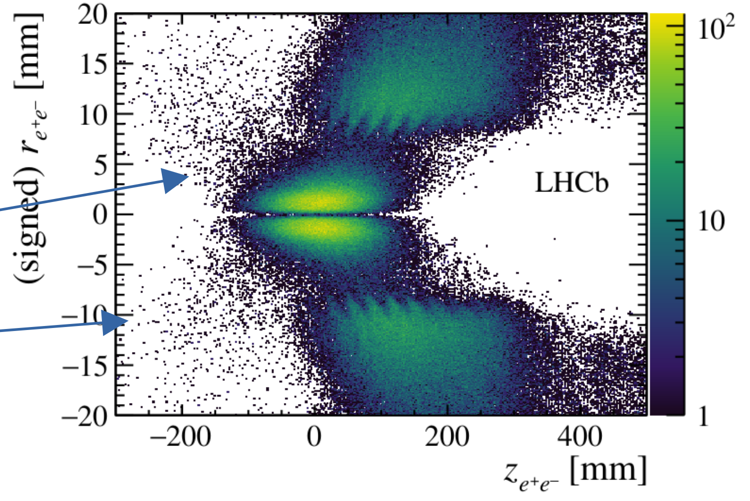
Two body modes with neutral particle in final state

$$D^+_{(s)} \to h^+\pi^0$$
$$D^+_{(s)} \to h^+\eta$$

JHEP 06 (2021) 019
JHEP 04 (2023) 081



- Motivation: SU3f symmetry can be used to relate to h^+h^- modes
- π^0 and η predominantly decay to two photons (98% and 40%)
  - One charged particle plus calorimeter signals not enough to reject background.
- Reconstruct neutral particles as
  $\pi^0 \to e^+e^-\gamma$ (suppressed decay, 14%) or
  $\pi^0 \to \gamma(\to e^+e^-)\gamma$ (conversion in material, 86%)
  $\eta \to \pi^+\pi^-\gamma$ has 5% branching fraction



JHEP 06 (2021) 019
JHEP 04 (2023) 081

Results

$$\mathcal{A}^{CP}(D^+ \to \eta\pi^+) = (0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta\pi^+) = (0.32 \pm 0.51 \pm 0.12)\%,$$
$$\mathcal{A}^{CP}(D^+ \to \eta'\pi^+) = (0.49 \pm 0.18 \pm 0.06 \pm 0.05)\%,$$
$$\mathcal{A}^{CP}(D_s^+ \to \eta'\pi^+) = (0.01 \pm 0.12 \pm 0.08)\%,$$

$$\mathcal{A}_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%,$$
$$\mathcal{A}_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%,$$
$$\mathcal{A}_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\%,$$
$$\mathcal{A}_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\%,$$
$$\mathcal{A}_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\%.$$

- No CP violation observed in these modes.
- In these modes LHCb is competing with Belle/Belle 2.
  - Some are better, some are worse.
- Likely significantly more precision needed to observe CP violation in these modes
- Calorimeter Upgrade planned already for Run 4

Measurement of y_{CP}

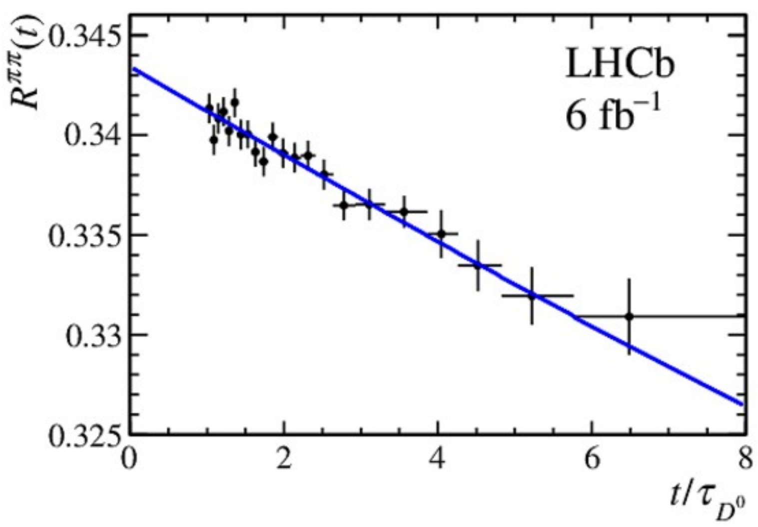
- Ratio of lifetimes of flavour specific and CP conjugate decays

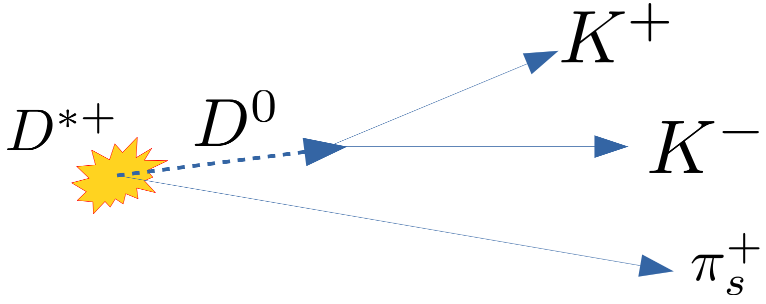
$$\frac{\tau(D^0 \to K^- \pi^+)}{\tau(D^0 \to f)} = y_{CP}^{f} - y_{CP}^{K\pi} \approx y(1 + \sqrt{r_D})$$

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

- Measured by

$$R^f(t) = \frac{N(D^0 \to f, t)}{N(D^0 \to K^-\pi^+, t)} \propto e^{-(y_{CP}^{f} - y_{CP}^{K\pi})\, t/\tau_{D^0}} \frac{\varepsilon(f, t)}{\varepsilon(K^-\pi^+, t)}$$





- Analysis uses selection which cuts on decay-time already in first trigger stage to control systematics from efficiency correction.
  - 44 versus 18 Million KK events
- Might need more selections like that (at high efficiency though)

PHYS. REV. D 105, 092013

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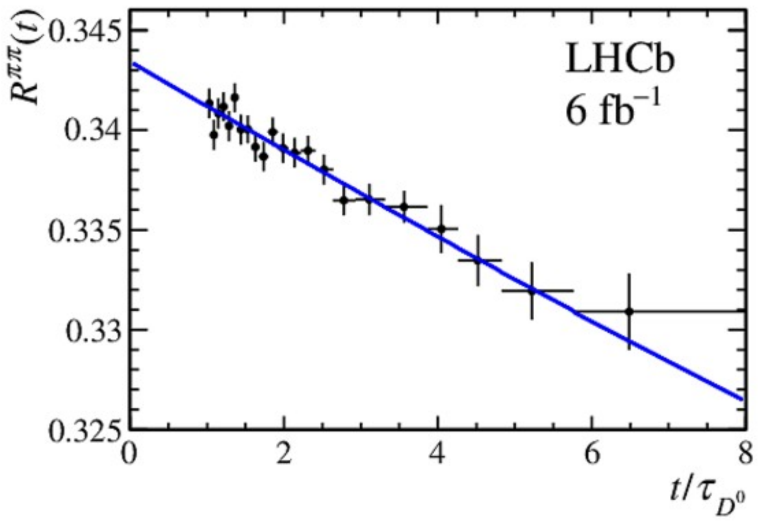

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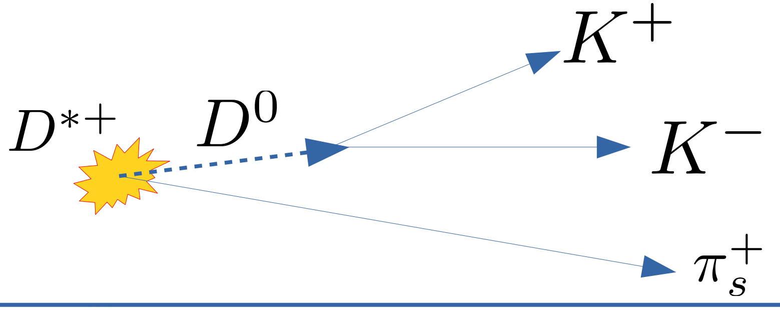


- Analysis uses selection which cuts on decay-time already in first trigger stage to control systematics from efficiency correction.
  - 44 versus 18 Million KK events

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}\,.$$

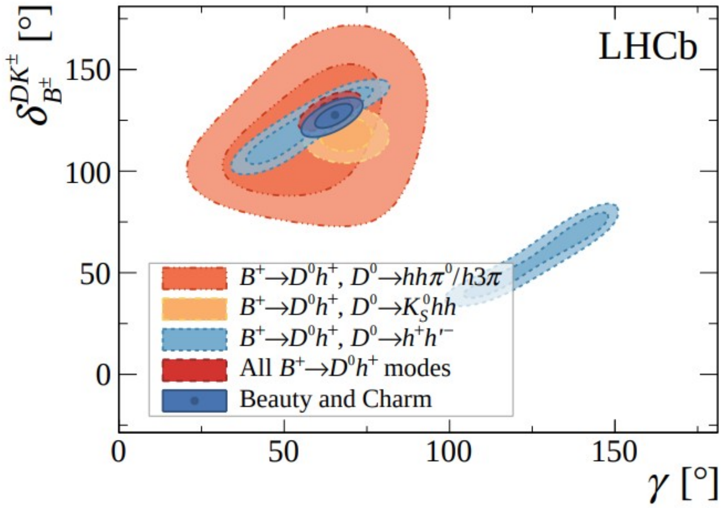
- Might need more selections like that (at high efficiency though)

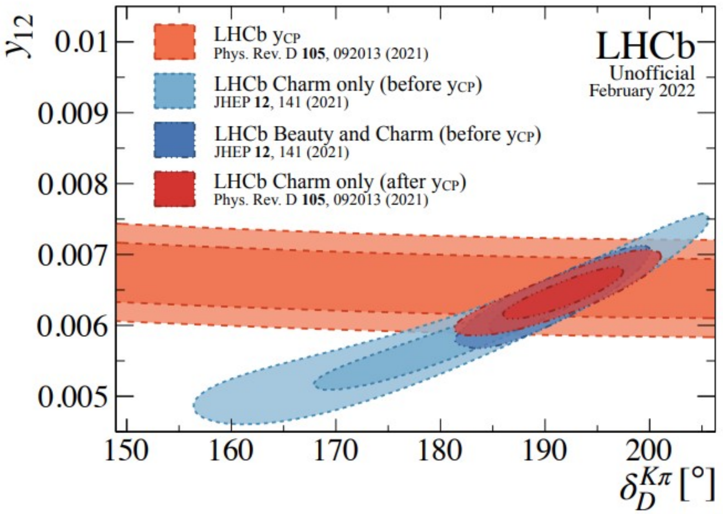
Combination beauty and charm

- Hadronic parameters are also important for extraction of CP violating angle gamma in B → Dh decays

$$\Gamma(B^\pm \to (K^\mp\pi^\pm)_D h^\pm) \propto |r_D^{K\pi} e^{-i\delta_D^{K\pi}} + r_B^{Dh} e^{i(\delta_B^{Dh} \pm \gamma)}|^2$$
$$= (r_D^{K\pi})^2 + (r_B^{Dh})^2 + r_D^{K\pi} r_B^{Dh} \cos(\delta_D^{K\pi} + \delta_B^{Dh} \pm \gamma),$$

- Combined fit of charm mixing and CP violation in B decays can improve precision on charm parameters





Admittedly in this case y_{CP} alone would have been enough.

But might be useful in other decay channels, $K\pi\pi\pi$, $K_S{}^0\pi\pi$ etc.

Summary

- LHCb has performed the world's best measurements of standard charm observables.
  - ΔA_{CP}, x, y q/p, ϕ
  - Non-zero mass difference of neutral charm meson eigenstates now established
  - CP violation observed in difference of CP asymmetries in $D^0 \rightarrow KK$ and $D^0 \rightarrow \pi\pi$
  - Interpretation currently limited by understanding of theory.

- Expanding programme with many more decay channels to provide more input to theory.

- More data to come in Run 3 and beyond

Thank you!

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