Experimental Status of Charm Physics

Sascha Stahl, CERN

Flavour-Workshop Neckarzimmern

21/03/2019

Biased choice of measurements

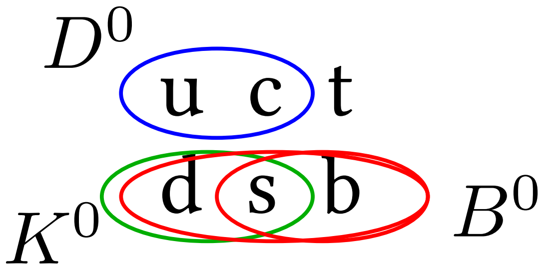
+ one measurement published today!

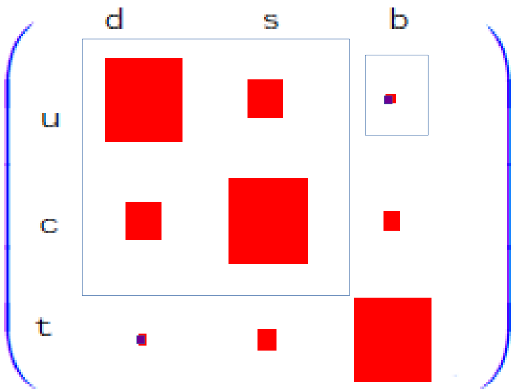
TITLE	DOCUMENT NUMBER	JOURNAL	SUBMITTED ON	CITED
Measurement of the mass difference between neutral charm-meson eigenstates	PAPER-2019-001 arXiv:1903.03074 [PDF]	PRL	07 Mar 2019	
Search for CP violation in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0 K^+$ and $D^+ \to \phi\pi^+$ decays	PAPER-2019-002 arXiv:1903.01150 [PDF]	PRL	04 Mar 2019	
Dalitz Plot analysis of the $D^+ \to K^-K^+K^+$ decay	PAPER-2018-039 arXiv:1902.05884 [PDF]	JHEP	15 Feb 2019	
Observation of the doubly Cabibbo-suppressed decay $\Xi_c^+ \to p\phi$	PAPER-2018-040 arXiv:1901.06222 [PDF]	JHEP	18 Jan 2019	1
Search for CP violation through an amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ decays	PAPER-2018-041 arXiv:1811.08304 [PDF]	JHEP 02 (2019) 126	20 Nov 2018	
Measurement of the charm-mixing parameter y_{CP}	PAPER-2018-038 arXiv:1810.06874 [PDF]	Phys. Rev. Lett. 122 (2019) 011802	16 Oct 2018	2
Measurement of the branching fractions of the decays $D^+ \to K^-K^+K^+$, $D^+ \to \pi^-\pi^+K^+$ and $D_s^+ \to \pi^-K^+K^+$	PAPER-2018-033 arXiv:1810.03138 [PDF]	JHEP	07 Oct 2018	2
Measurement of the Ω_c^0 baryon lifetime	PAPER-2018-028 arXiv:1807.02024 [PDF]	Phys. Rev. Lett. 121 (2018) 092003	05 Jul 2018	8
First observation of the doubly charmed baryon decay $\Xi_{cc}^{++} \to \Xi_c^+\pi^+$	PAPER-2018-026 arXiv:1807.01919 [PDF]	Phys. Rev. Lett. 121 162002 (2018)	05 Jul 2018	20
Measurement of angular and CP asymmetries in $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$ decays	PAPER-2018-020 arXiv:1806.10793 [PDF]	Phys. Rev. Lett. 121 (2018) 091801	28 Jun 2018	6
First measurement of the lifetime of the doubly charmed baryon Ξ_{cc}^{++}	PAPER-2018-019 arXiv:1806.02744 [PDF]	Phys. Rev. Lett. 121 052002	07 Jun 2018	26
Measurement of the time-integrated CP asymmetry in $D^0 \to K_S^0 K_S^0$ decays	PAPER-2018-012 arXiv:1806.01642 [PDF]	JHEP 11 (2018) 048	05 Jun 2018	4
Measurement of $D_s^\pm$ production asymmetry in pp collisions at $\sqrt{s} = 7$ and 8 TeV	PAPER-2018-010 arXiv:1805.09869 [PDF]	JHEP 08 (2018) 008	24 May 2018	5
Studies of the resonance structure in $D^0 \to K^\mp\pi^\pm\pi^\pm\pi^\mp$ decays	PAPER-2017-040 arXiv:1712.08609 [PDF]	Eur. Phys. J. C78 (2018) 443	22 Dec 2017	7
Search for the rare decay $\Lambda_c^+ \to p\mu^+\mu^-$	PAPER-2017-039 arXiv:1712.07938 [PDF]	Phys. Rev. D 97, 091101	21 Dec 2017	9
A measurement of the CP asymmetry difference in $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays	PAPER-2017-044 arXiv:1712.07051 [PDF]	JHEP 03 (2018) 182	19 Dec 2017	9
Updated determination of D^0-$\overline{D}^0$ mixing and CP violation parameters with $D^0 \to K^+\pi^-$ decays	PAPER-2017-046 arXiv:1712.03220 [PDF]	Phys. Rev. D97 (2018) 031101	08 Dec 2017	7
Measurements of the branching fractions of $\Lambda_c^+ \to p\pi^-\pi^+$, $\Lambda_c^+ \to pK^-K^+$, and $\Lambda_c^+ \to p\pi^-K^+$	PAPER-2017-026 arXiv:1711.01157 [PDF]	JHEP 03 (2018) 043	03 Nov 2017	8
Observation of D^0 meson decays to $\pi^+\pi^-\mu^+\mu^-$ and $K^+K^-\mu^+\mu^-$ final states	PAPER-2017-019 arXiv:1707.08377 [PDF]	Phys. Rev. Lett. 119 (2017) 181805	26 Jul 2017	11
Observation of the doubly charmed baryon Ξ_{cc}^{++}	PAPER-2017-018 arXiv:1707.01621 [PDF]	Phys. Rev. Lett. 119 (2017) 112001	06 Jul 2017	173
Observation of five new narrow Ω_c^0 states decaying to $\Xi_c^+K^-$	PAPER-2017-002 arXiv:1703.04639 [PDF]	Phys. Rev. Lett. 118 (2017) 182001	14 Mar 2017	126
Measurement of the CP violation parameter A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays	PAPER-2016-063 arXiv:1702.06490 [PDF]	Phys. Rev. Lett. 118 (2017) 261803	21 Feb 2017	21

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

CP violation in charm decays

- Charm quark of up-type:
  Complementary to kaon and B systems
- No CP violation observed yet

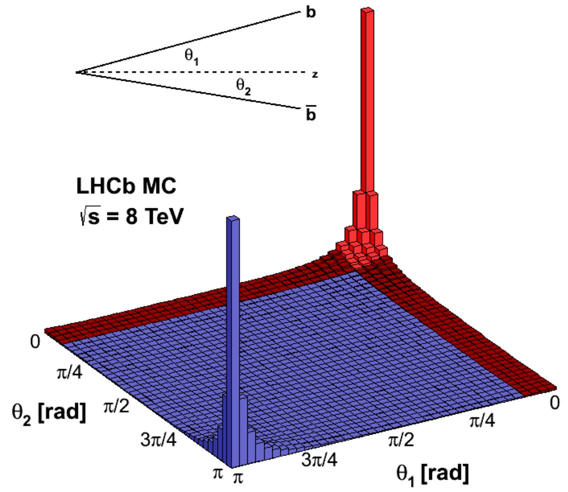


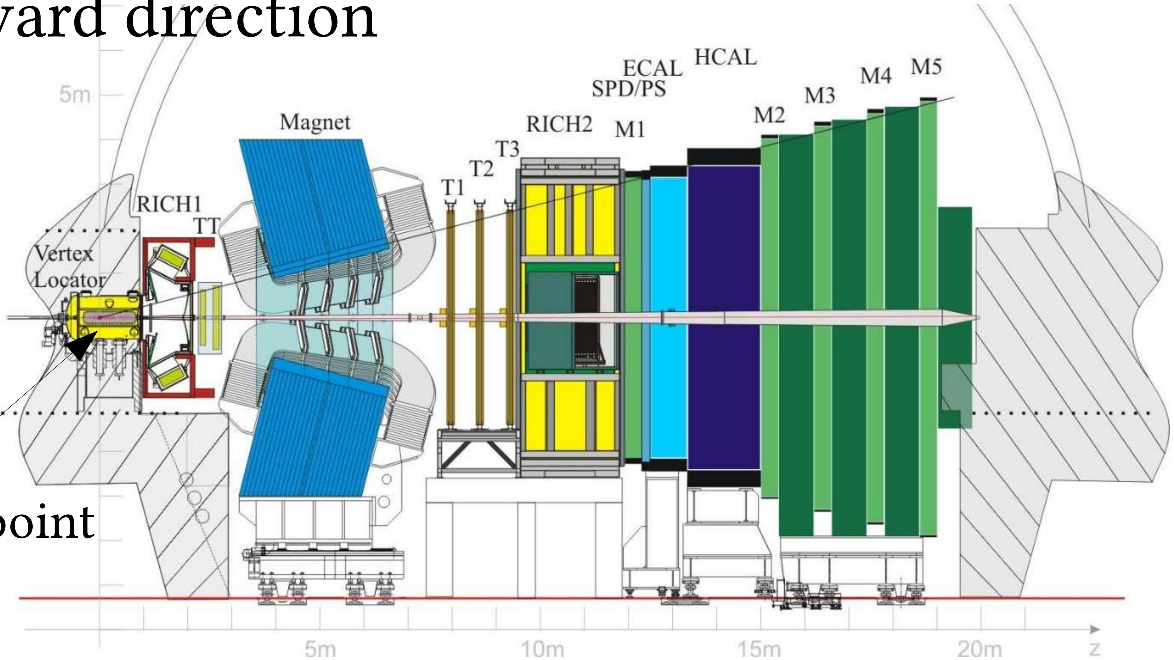


- CP violation in Standard Model suppressed:
  - Powerful probe to effects beyond Standard Model
  - Predictions difficult due to long-range effects
- High charm production rate in proton-proton collisions

The LHCb experiment

- Records LHC proton-proton collisions
  - Run 1 3 fb^{-1} (7 and 8 TeV), Run 2 6 fb^{-1} (13 TeV)
- b and c quarks produced in pairs
  - Predominantly in forward direction
- Coverage 2<η<5:
  - Boosted pairs
  - 45 kHz $b\bar{b}$ pairs and 1 MHz $c\bar{c}$ pairs





The challenge to collect charm*

~1 MHz $c\bar{c}$ pairs!

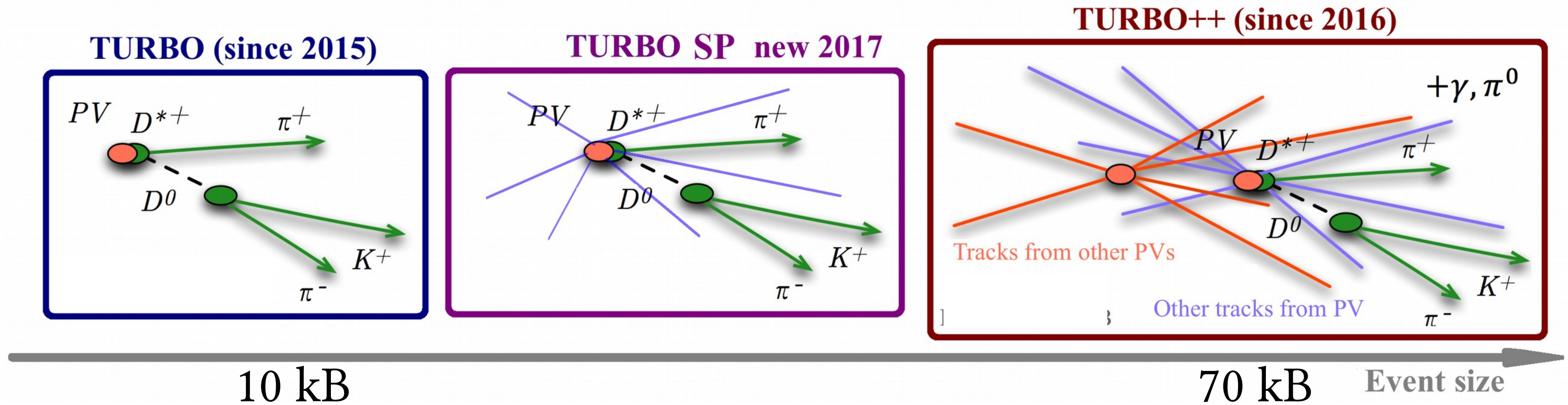
- Assume 10 (5) % efficiency of full trigger selection chain
- Event size 70 kB
- $\longrightarrow$ Beauty bandwidth = 45 kHz * 0.1 * 70 kB = 0.32 GB/s,
  Charm bandwidth = 1 MHz * 0.05 * 70 kB = 3.5 GB/s
- Limit to tape storage 1 GB/s

  $\longrightarrow$ Cannot write out full information of all signal events, even with a very pure trigger

*very rough estimates

CERN-LHCb-DP-2019-002

Turbo stream in Run 2

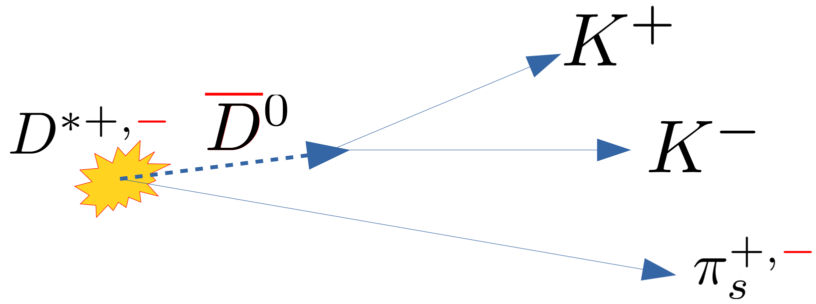


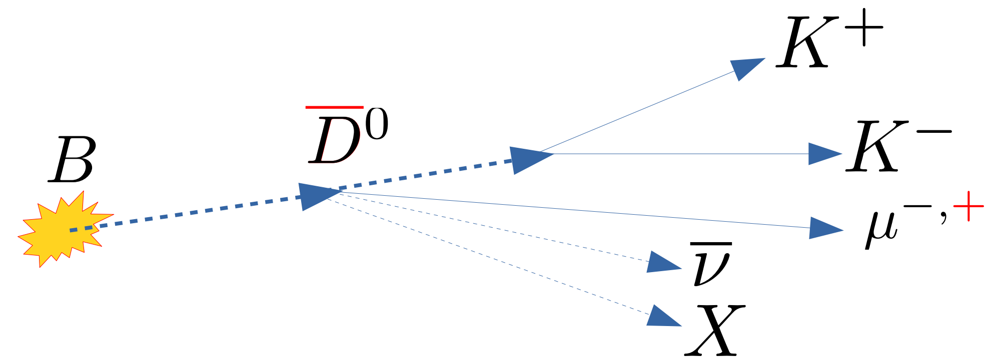
- Persist reconstructed objects, discard raw information
- Analysts choose what to persist
  - Up to factor 10 reduction of event size
- More events at same bandwidth → more physics
- Big success story
  - 2/3 of triggered events persist raw detector information,
    1/3 of triggered events go to Turbo stream (almost all charm)

Some advertisement for LHCb people:
A lot of (exciting) work to prepare
the trigger for Run 3.
Feel free to get in contact with me or Stephie.

https://twiki.cern.ch/twiki/bin/viewauth/LHCb/RealTimeAnalysis

Two charm samples at LHCb





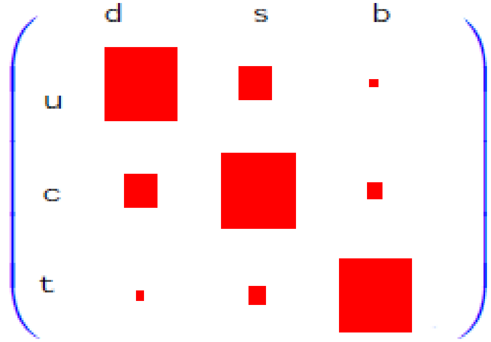
Prompt produced charm:

- (Slow) pion charge tags flavour
- Unambiguous tag due to full D* reconstruction
- Hardware trigger: 40% triggered by D, 60% parasitically
- Higher statistics

Semileptonic B decays:

- Muon charge tags flavour
- B partially reconstructed
- Hardware trigger: High muon trigger efficiency
- Cross-checks and some other advantages

Two-body modes

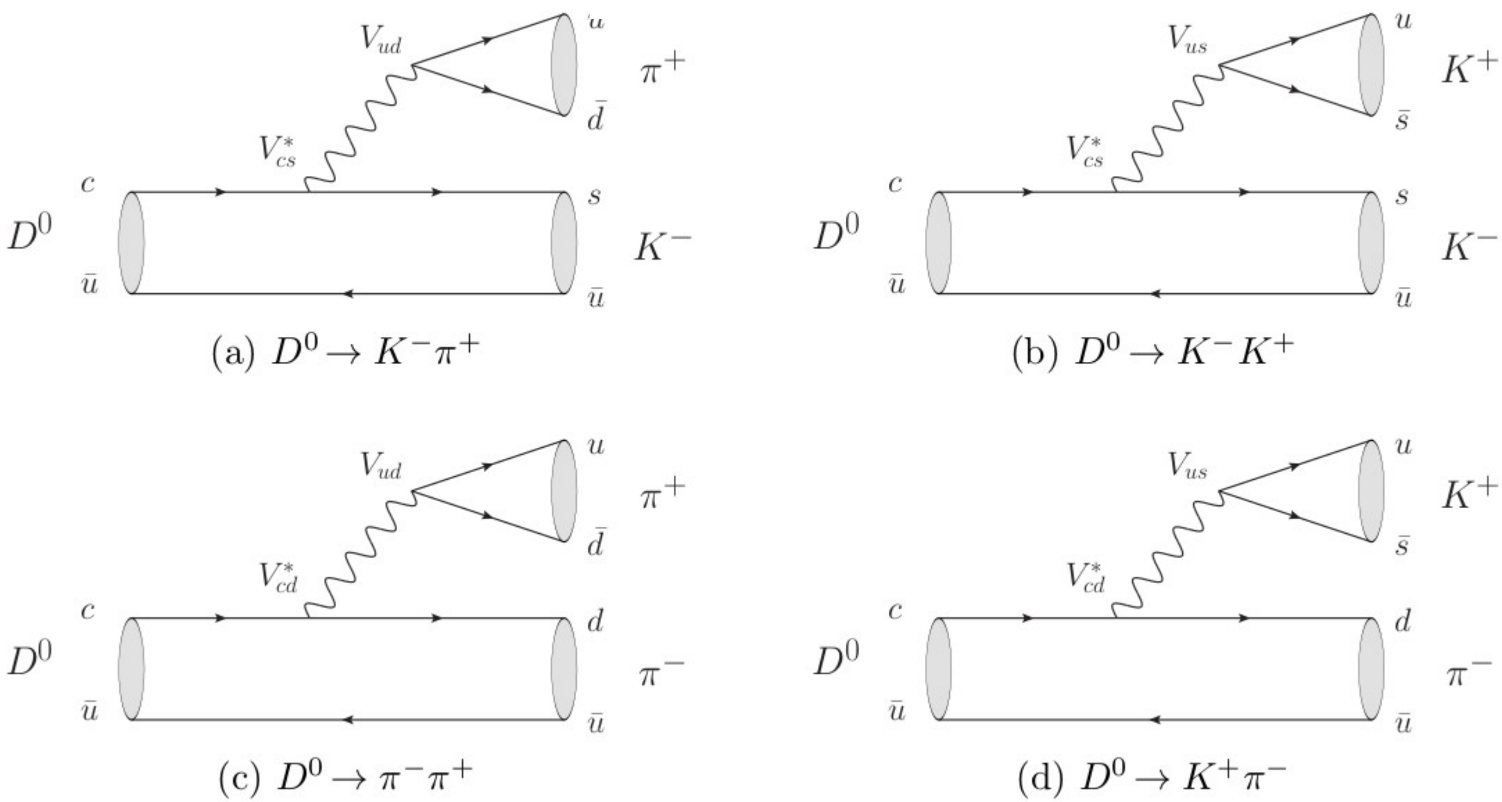


Cabibbo-favoured

Cabibbo-suppressed

Cabibbo-suppressed

Doubly-Cabibbo-suppressed

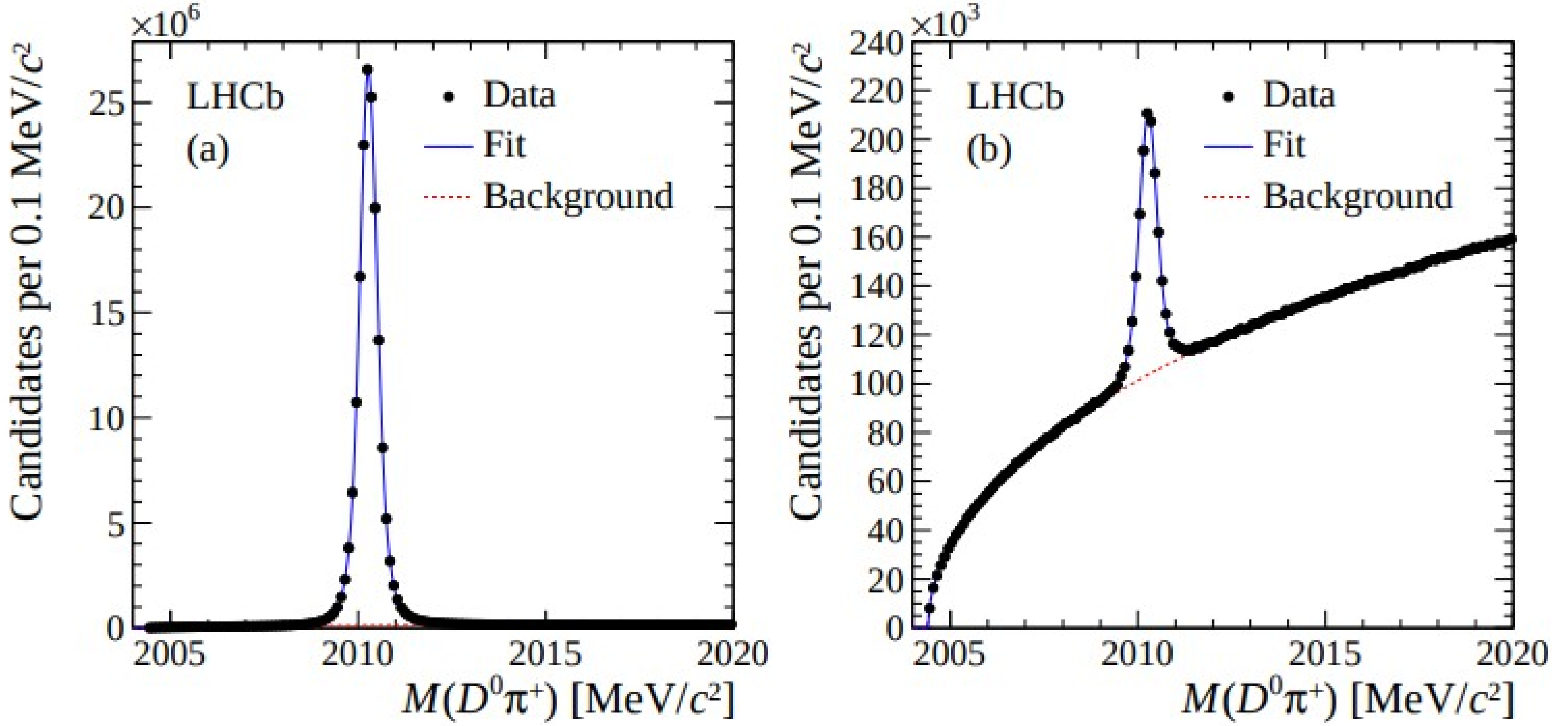


Phys. Rev. D 97 (2018) 031101

Two-body modes

Run 1 + 2015 + 2016 (Run 2 Turbo)

$D^{*+} \to D^0(\to K^-\pi^+)\ \pi^+$ $D^{*+} \to D^0(\to K^+\pi^-)\ \pi^+$



177 Million

0.07 Million

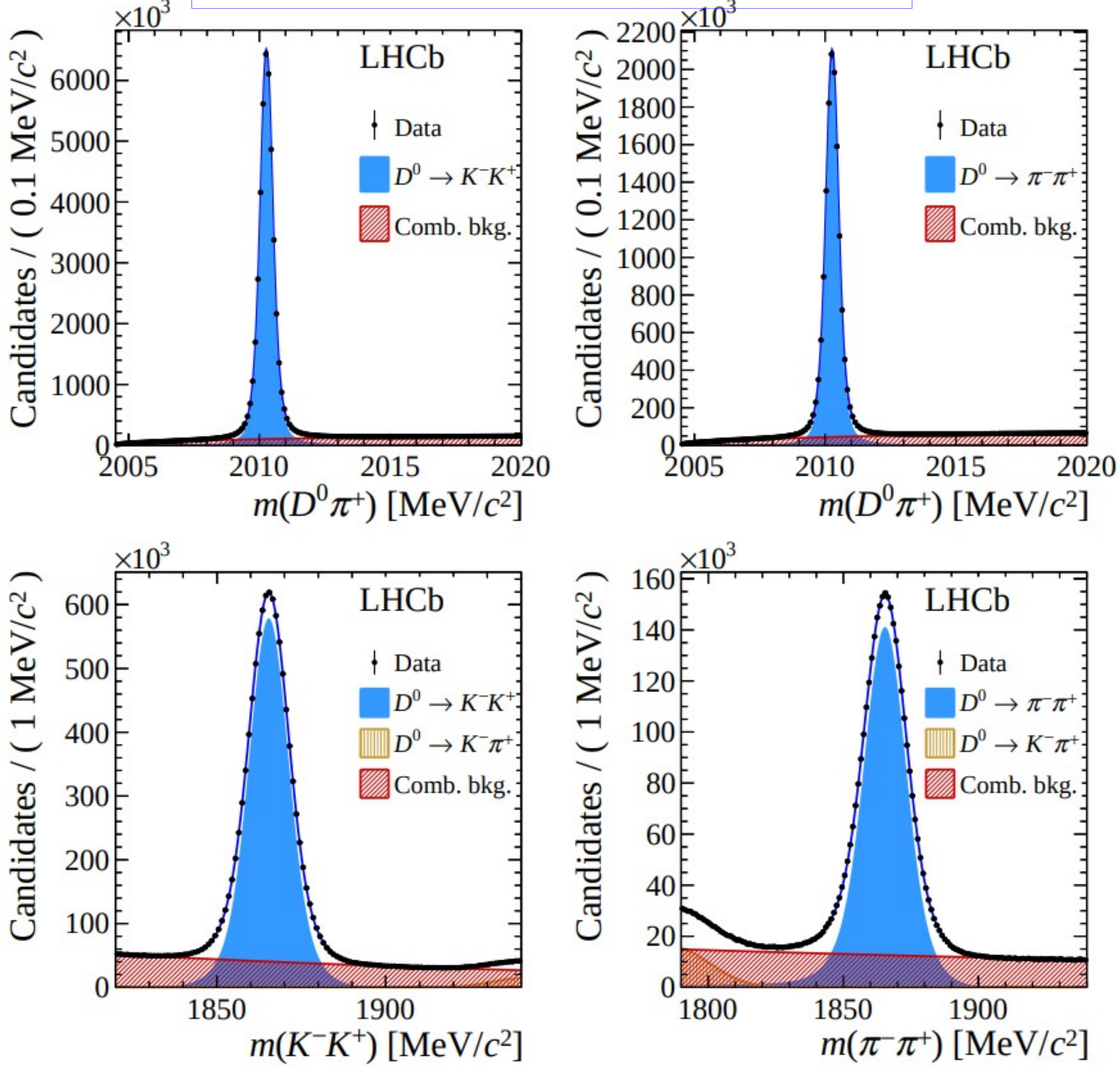
Two-body modes

Full Run 2 data set, only Turbo

Prompt

44 Million
(Run 1 7.7)

14 Million
(2.5)



Semileptonic

9 Million
(2.2)

3 Million
(0.77)

2 – 3 more yield per fb^{-1} in Run 2

A lot of charm!

What do we measure?

What are the experimental challenges?

Neutral meson mixing

- Mass eigenstates unequal flavour eigenstates:

$$\begin{aligned} |D_1\rangle &= p\left|D^0\right\rangle + q\left|\bar{D}^0\right\rangle \\ |D_2\rangle &= p\left|D^0\right\rangle - q\left|\bar{D}^0\right\rangle \end{aligned}$$

CPT:

$$|q^2| + |p^2| = 1$$

$$|D_{1,2}(t)\rangle = e^{-im_{1,2}\,t}\, e^{-\Gamma_{1,2}\,t/2}\, |D_{1,2}\rangle$$

- Mixing parameters:

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \qquad x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

- CPV parameters:

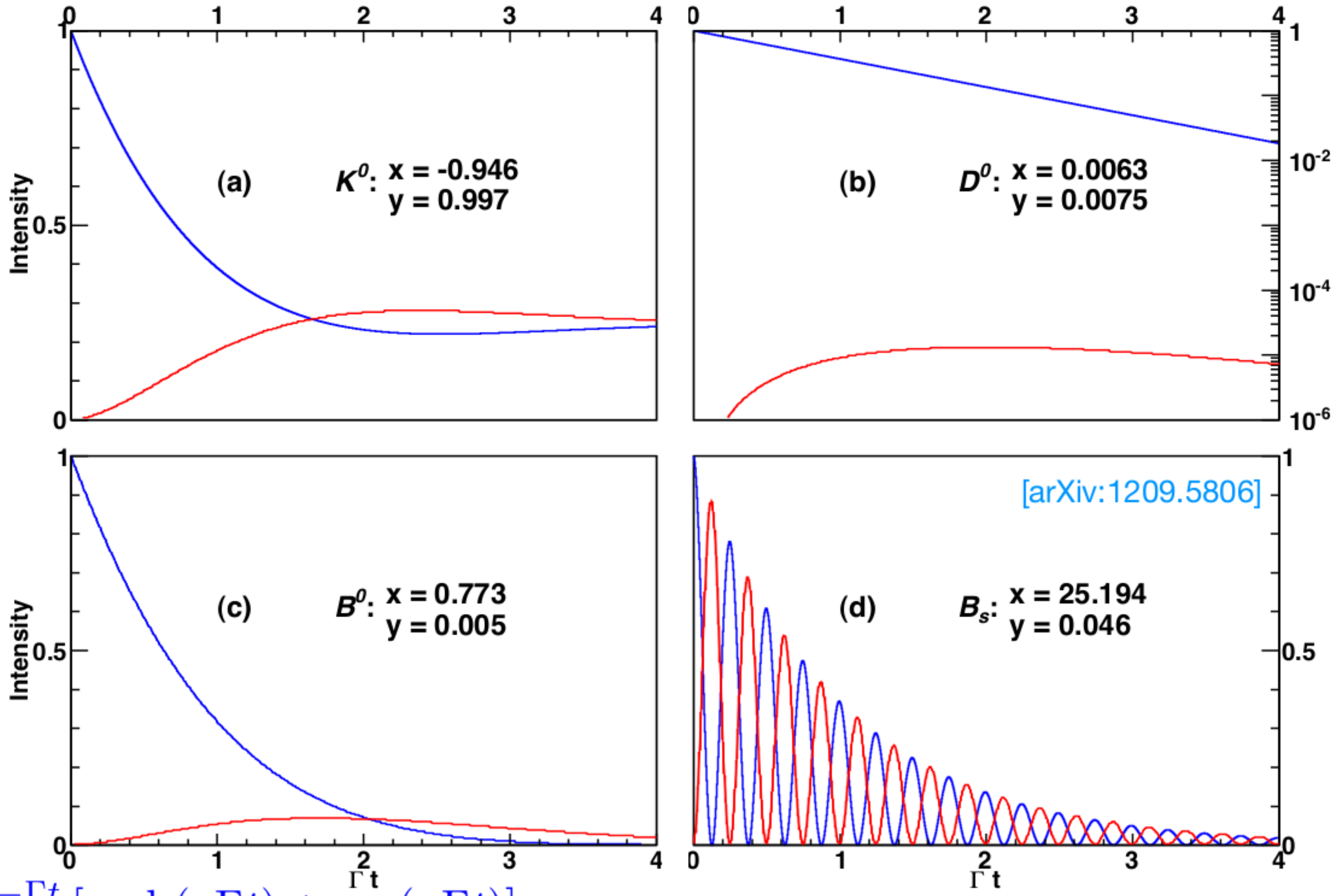
$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} \approx \left|\frac{q}{p}\right| \left|\frac{\bar{A}_f}{A_f}\right| \; e^{i(\phi + \Delta_f)}$$

Weak phase + strong phase

Time evolution of different mesons

Blue line:
given a P^0 at t=0, the probability of finding a P^0 at t

Red Line:
given a P^0 at t=0, the probability of finding a $\overline{P}^0$ at t



$$|\langle P^0(0)|P^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) + \cos(x\Gamma t)\right]$$

$$|\langle P^0(0)|\overline{P}^0(t)\rangle|^2 \propto e^{-\Gamma t}\left[\cosh(y\Gamma t) - \cos(x\Gamma t)\right]$$

Time evolution of flavour states

- Time evolution of initially produced D^0, $\overline{D}^0$ meson

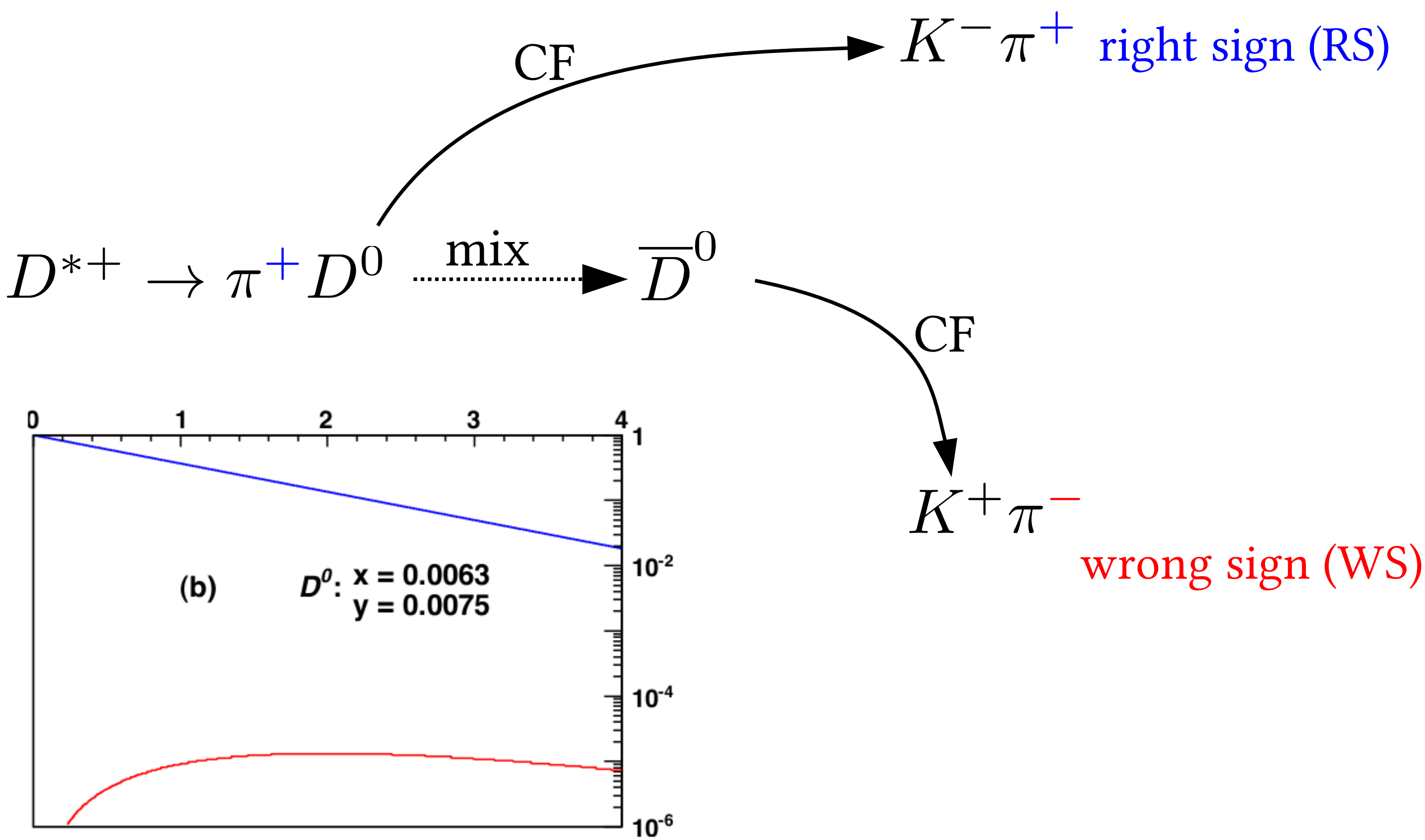
$$\Gamma(D^0(t) \to f) \propto \left| A(D^0 \to f) g_+(t) + \tfrac{q}{p} A(\overline{D}^0 \to f) g_-(t) \right|^2$$
$$\Gamma(\overline{D}^0(t) \to \overline{f}) \propto \left| A(\overline{D}^0 \to \overline{f}) g_+(t) + \tfrac{p}{q} A(D^0 \to \overline{f}) g_-(t) \right|^2$$

- Mixing parameters small for D^0 mesons

$$z \equiv -(y + ix)$$
$$|g_+(t)|^2 \approx e^{-t} + \frac{1}{4} e^{-t} t^2 \,\mathrm{Re}(z^2) + \mathcal{O}(z^4)$$
$$|g_-(t)|^2 \approx \frac{1}{4} e^{-t} t^2 |z|^2 + \mathcal{O}(z^4)$$
$$g_+^\star(t) g_-(t) \approx \frac{1}{2} e^{-t} t z + \mathcal{O}(z^3)$$

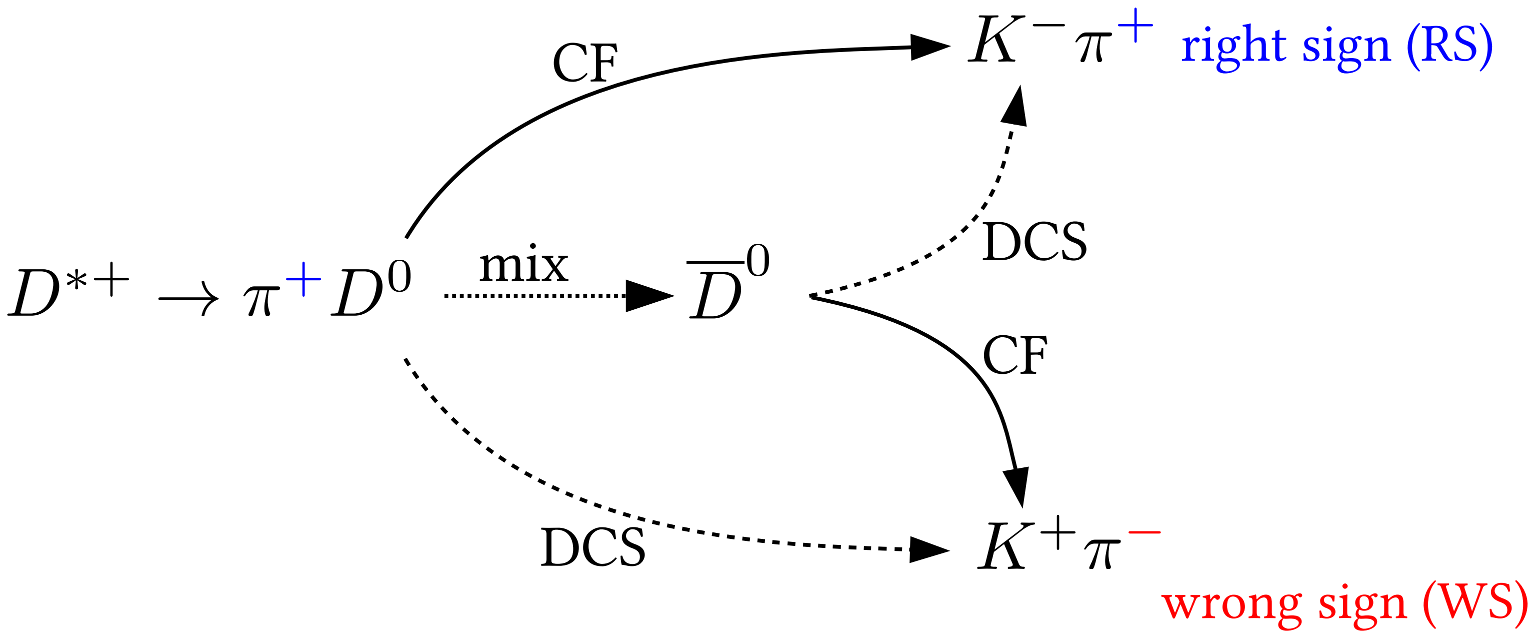
Measurement of D mixing

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



Measurement of D mixing

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



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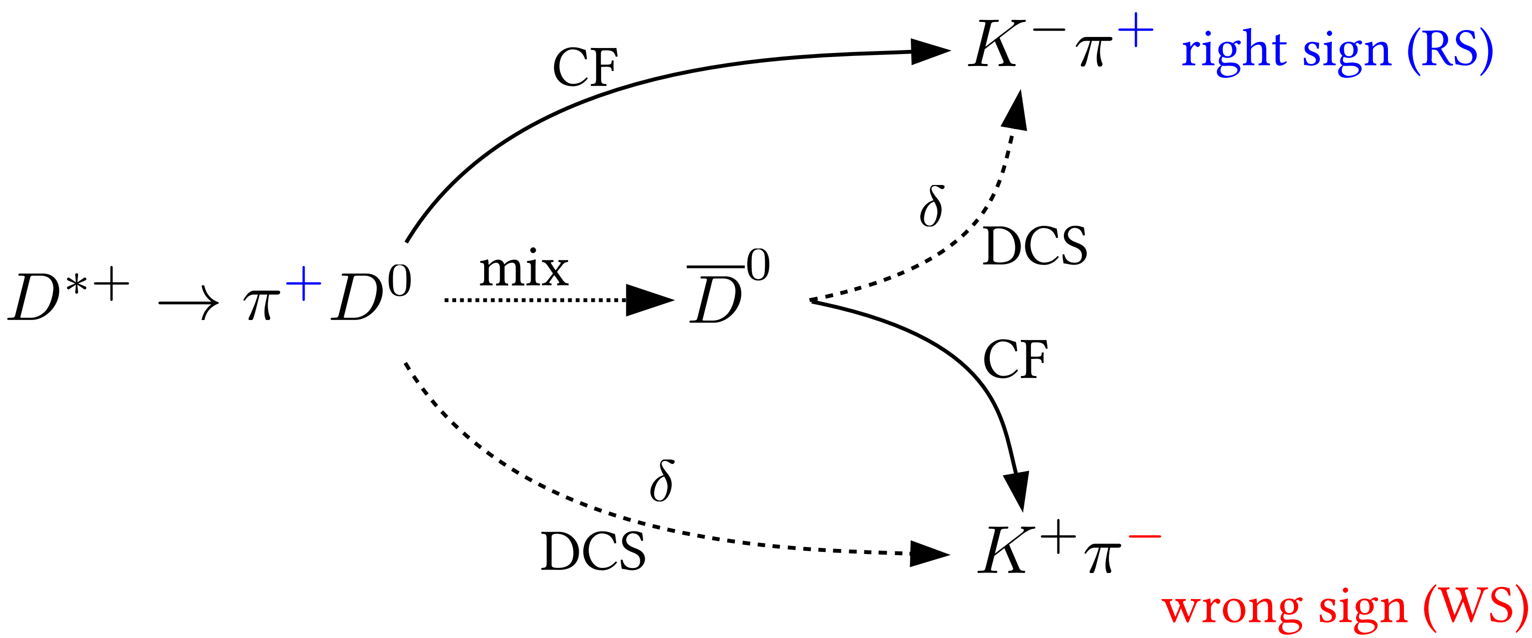


$$\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)} = -\sqrt{R_D} e^{-i\delta}$$

(strong phase)

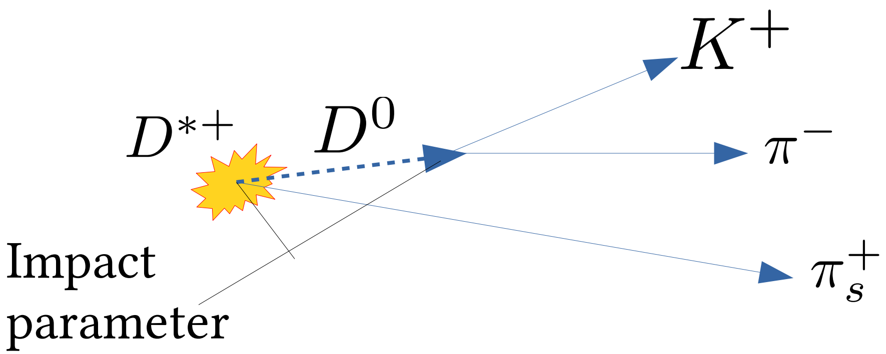
$$y' = y\cos\delta - x\sin\delta$$

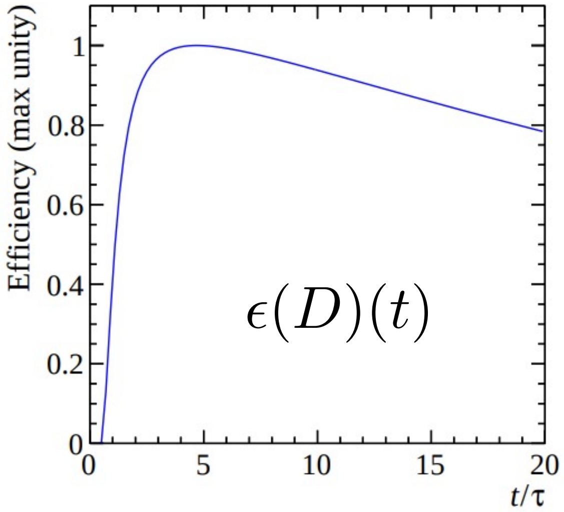
$$x' = x\cos\delta + y\sin\delta$$

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

(interference) (mixing)

Observed ratios





$$R_{\text{obs}}(t) = \frac{N(D^{*+} \to [K^+\pi^-]_D \pi_s^+)}{N(D^{*+} \to [K^-\pi^+]_D \pi_s^+)}(t) = R(t) \; \frac{\epsilon(\pi_s^+)}{\epsilon(\pi_s^+)} \frac{\epsilon(D)(t)}{\epsilon(D)(t)} = R(t)$$

- Tight displacement cuts (in trigger) to reject background
- Detection efficiencies cancel in ratio of wrong sign over right sign

Measurement of mixing and CP violation

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

CP violation in mixing and interference

Direct CP violation

$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

$$y'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1} (y' \cos\phi \mp x' \sin\phi)$$

$$x'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1} (y' \cos\phi \pm x' \sin\phi)$$

$$\frac{q}{p} \frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)} = -\left|\frac{q}{p}\right| \sqrt{R_D} e^{-i(\phi+\delta)}$$

$$R^+_{\text{obs}}(t) = \frac{N(D^{*+} \to [K^+\pi^-]_D \pi_s^+)}{N(D^{*+} \to [K^-\pi^+]_D \pi_s^+)}(t) = R^+(t) \frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)}$$

$$R^-_{\text{obs}}(t) = \frac{N(D^{*-} \to [K^-\pi^+]_D \pi_s^-)}{N(D^{*-} \to [K^+\pi^-]_D \pi_s^-)}(t) = R^-(t) \frac{\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)}$$

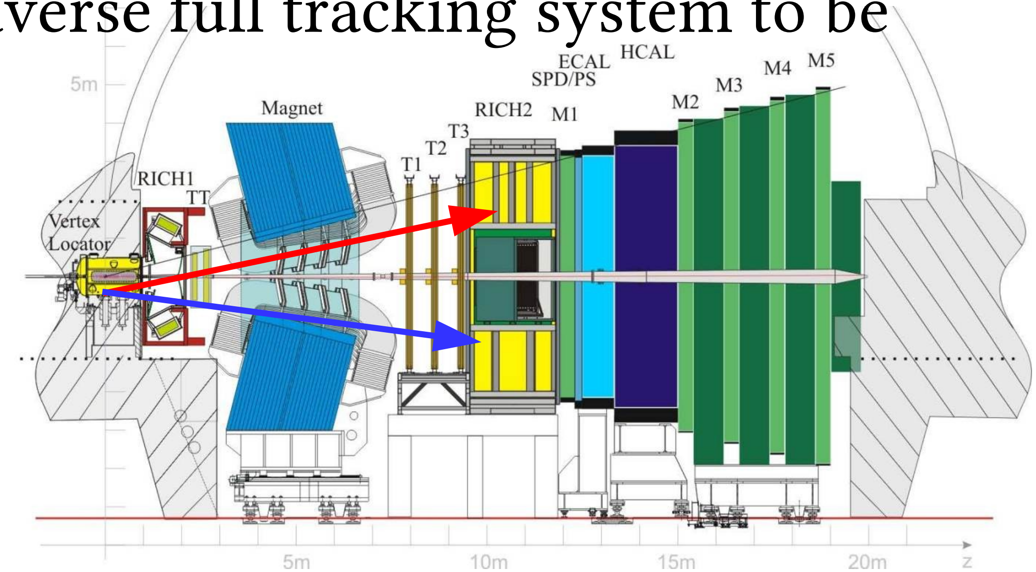
Charged-kaon detection asymmetry

- Charged kaons have to traverse full tracking system to be reconstructed

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

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

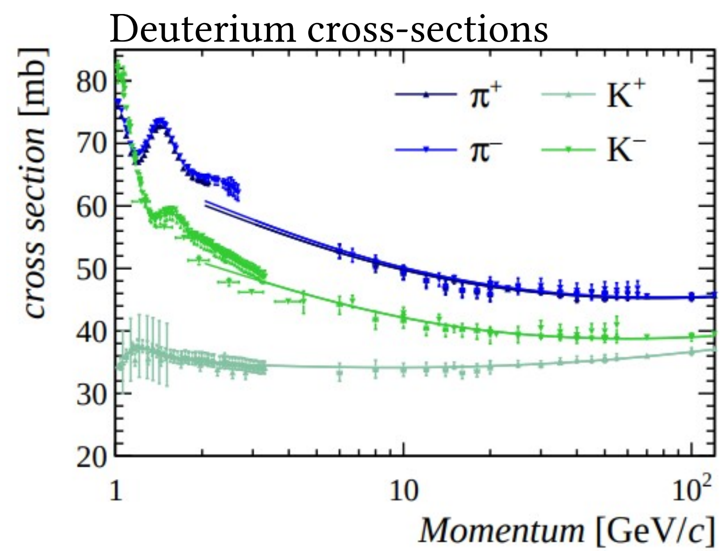
$$\text{"LHCb"} = (udq\overline{q})$$



- Different absorption rate for positive and negative kaons

$$A_D(K^-\pi^+) = \frac{\epsilon(K^-\pi^+) - \epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+) + \epsilon(K^+\pi^-)}$$

→ Expected asymmetry about 1%



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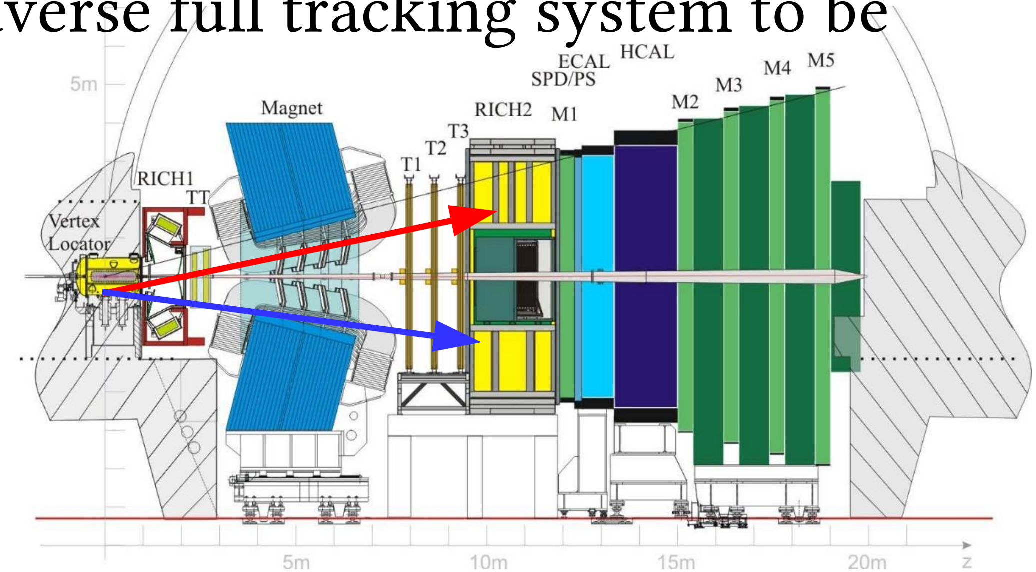

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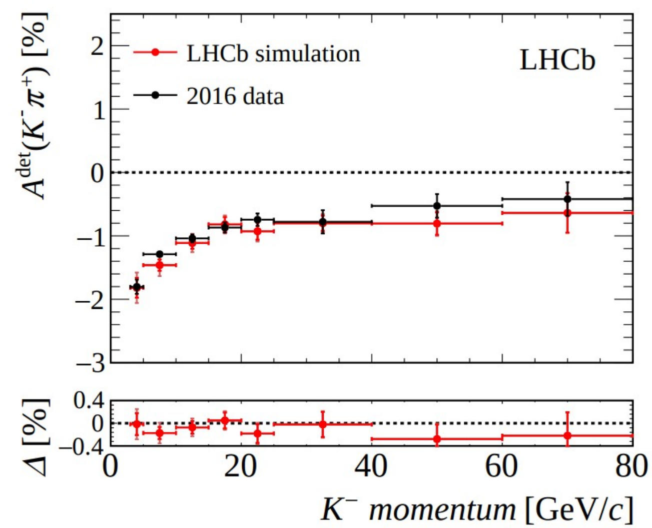

Measurement of mixing and CP violation

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Direct CP violation

CP violation in mixing and interference

$$A_D \equiv \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

$$y'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1} (y' \cos\phi \mp x' \sin\phi)$$

$$x'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1} (y' \cos\phi \pm x' \sin\phi)$$

$$R^+_{\text{obs}}(t) = \frac{N(D^{*+} \to [K^+\pi^-]_D \pi_s^+)}{N(D^{*+} \to [K^-\pi^+]_D \pi_s^+)}(t) = R^+(t) \; \frac{\epsilon(K^+\pi^-)}{\epsilon(K^-\pi^+)}$$

$$R^-_{\text{obs}}(t) = \frac{N(D^{*-} \to [K^-\pi^+]_D \pi_s^-)}{N(D^{*-} \to [K^+\pi^-]_D \pi_s^-)}(t) = R^-(t) \; \frac{\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)}$$

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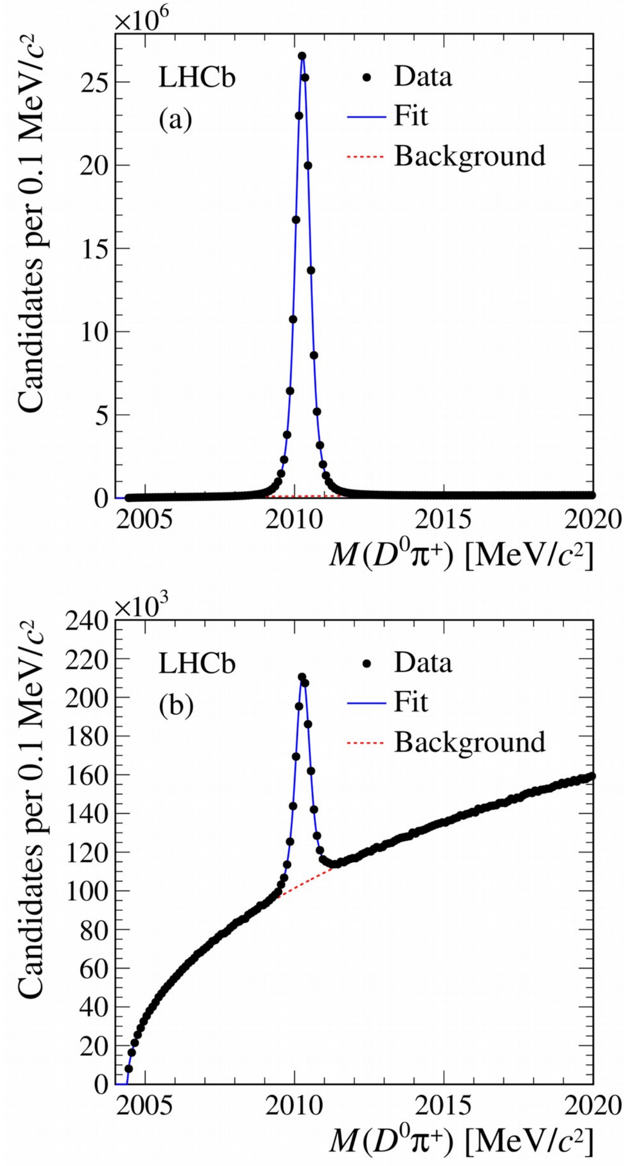
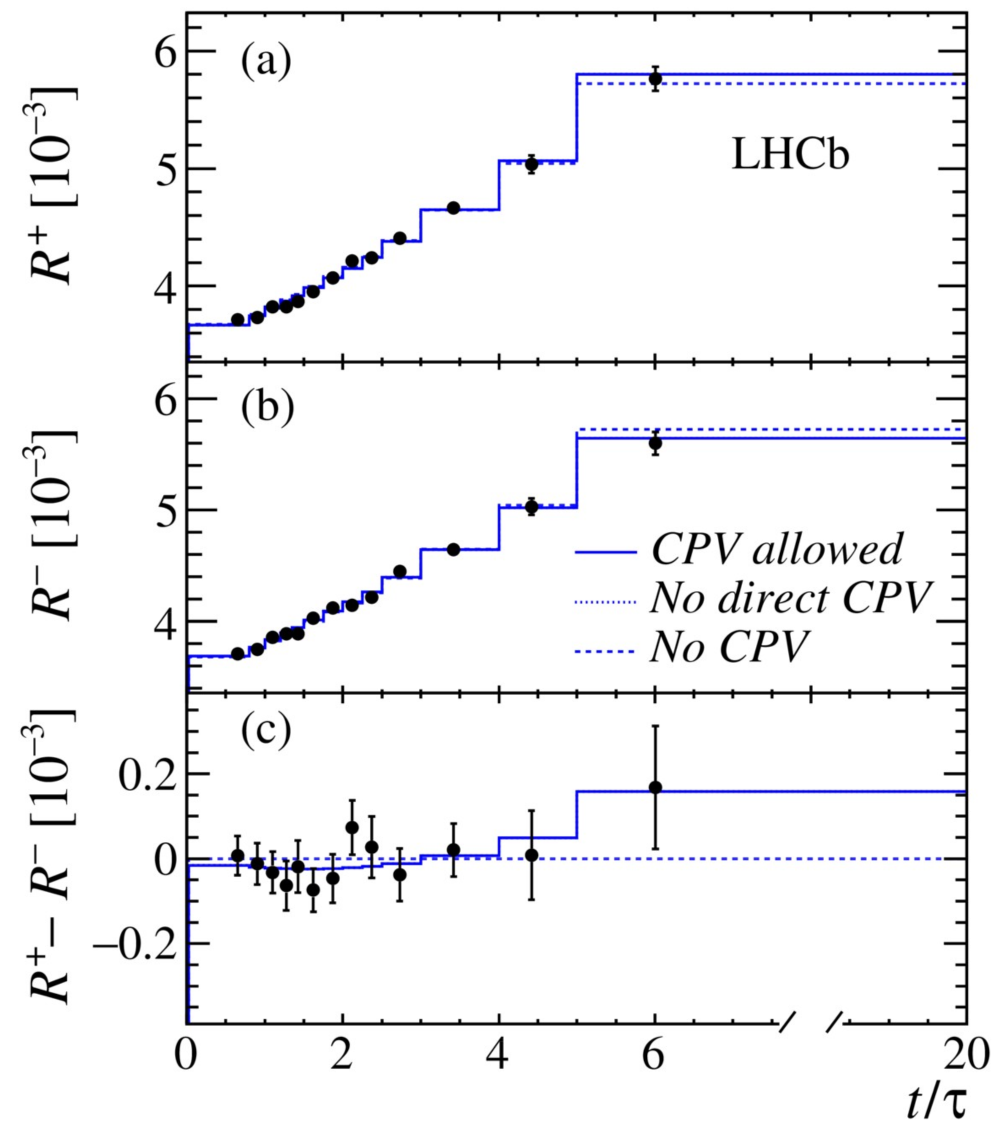
Results

Run 1 + 2015 + 2016





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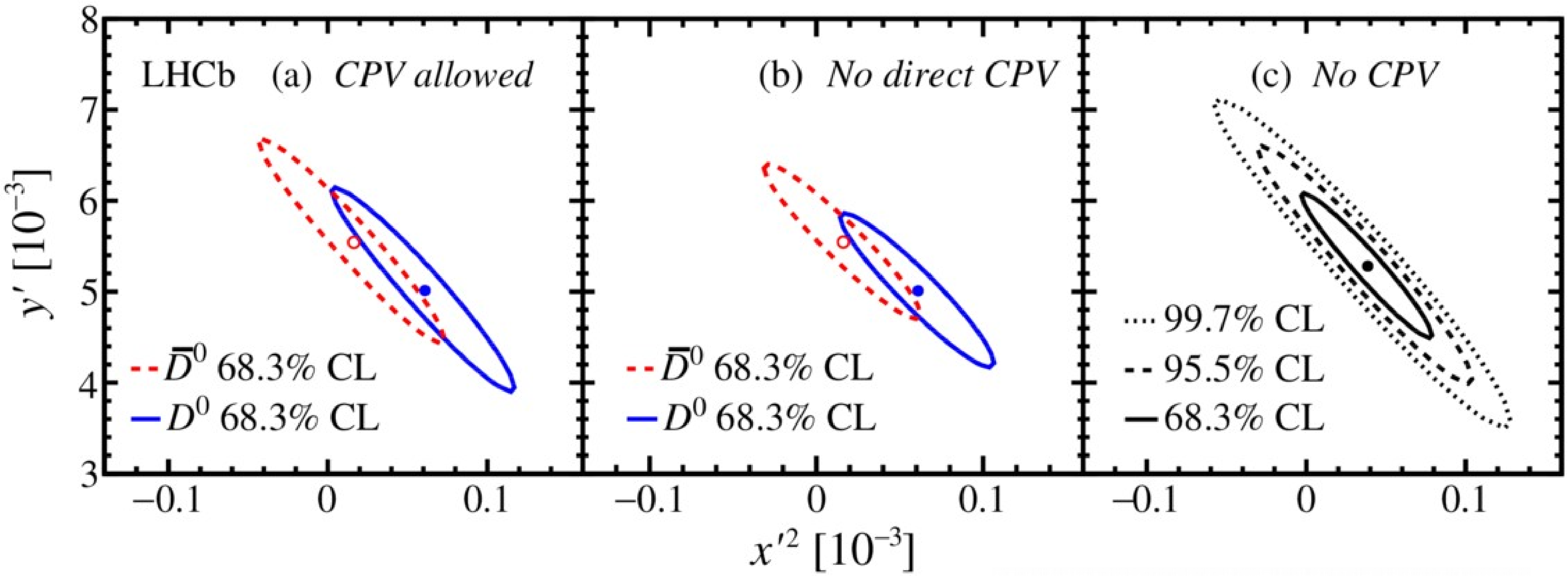
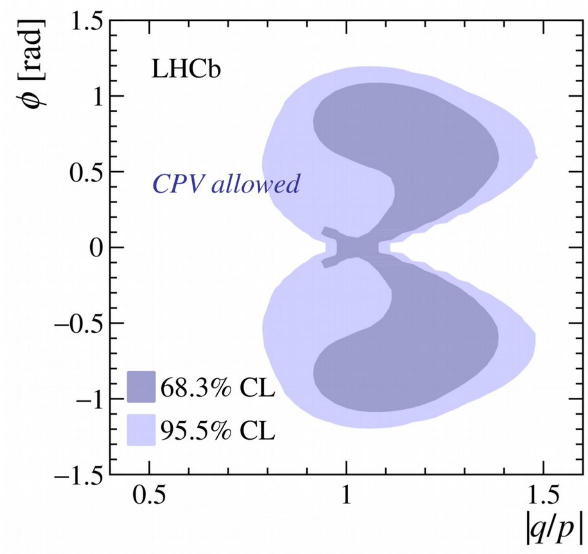
Results



$$y' = (5.28 \pm 0.45 \pm 0.27) \times 10^{-3}$$
$$x'^2 = (0.039 \pm 0.023 \pm 0.014) \times 10^{-3}$$
$$1 < \left|\frac{q}{p}\right| < 1.35 \text{ at } 68.3\%\text{CL}$$

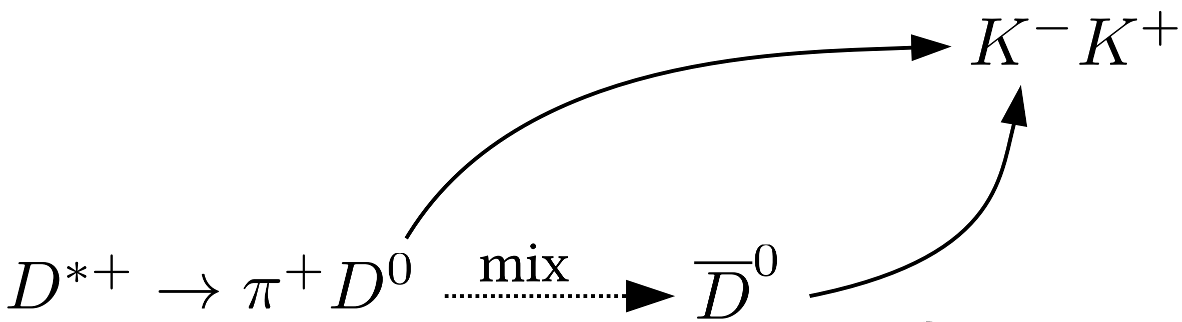


CP asymmetry in mixing with $D^0 \to h^- h^+$

S. Bergmann et al.,
Phys. Lett. B486 (2000) 418,
arXiv:hep-ph/0005181.

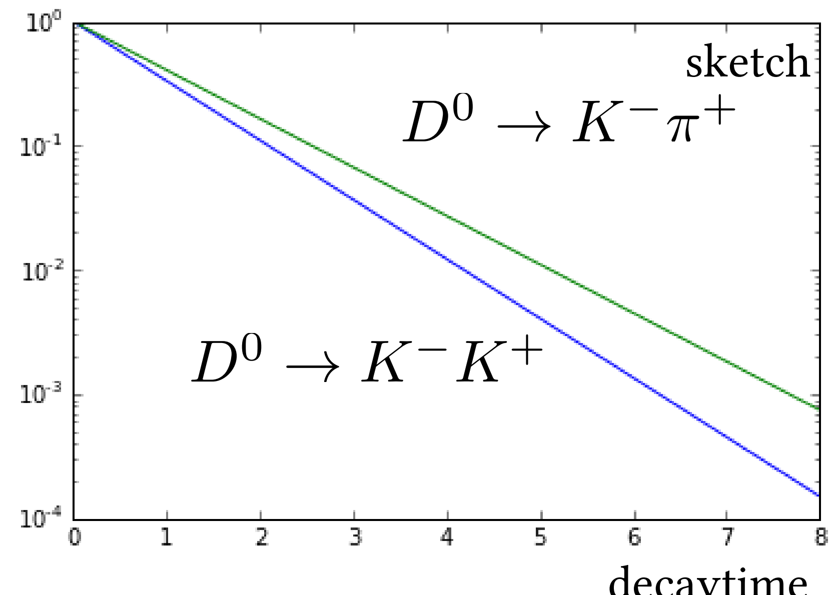
- Two-body decays to CP-even eigenstates

$$D^0 \to K^- K^+ \quad \text{and} \quad D^0 \to \pi^- \pi^+$$



→ Mixing and CPV changes effective decay width

Effective decay width: Decay constant when fitting a pure exponential to the decay time distribution.



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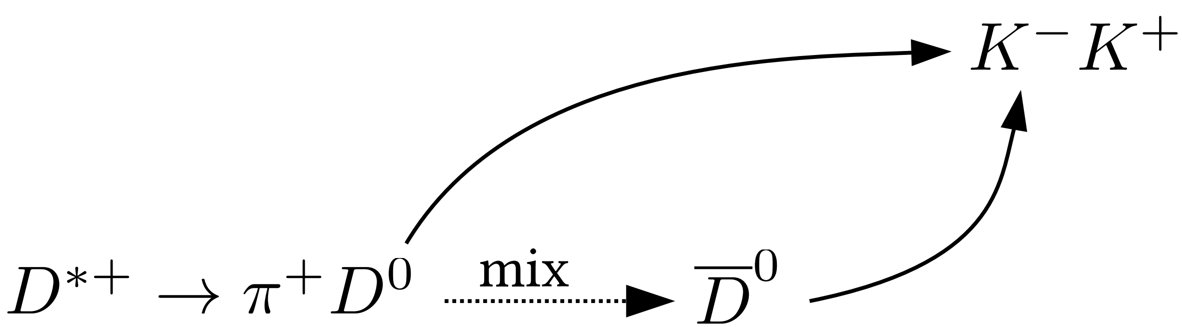
$$D^0 \to K^- K^+ \quad \text{and} \quad D^0 \to \pi^- \pi^+$$



$\longrightarrow$ Mixing and CPV changes effective lifetime

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

$$y_{CP} = +\frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) y \cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x \sin\phi$$

CP conservation implies: $\quad y_{CP} = y$

Measurement of y_{CP}

- Two-body decays to CP-even eigenstates

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

- CP-mixed final state

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

- Measure width difference, calculate y_{CP} from known lifetime

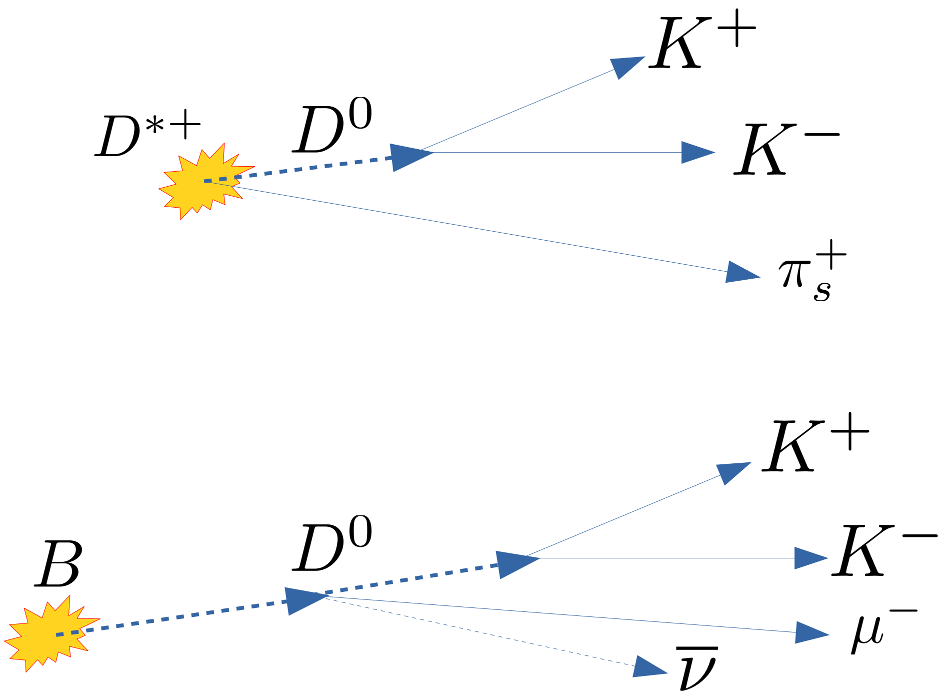
  $\Delta_\Gamma = \Gamma_{CP+} - \Gamma \qquad y_{CP} = \frac{\Delta_\Gamma}{\Gamma}$

- Measure ratios of yields in decay-time bins
  - Need correction of decay-time acceptance effects

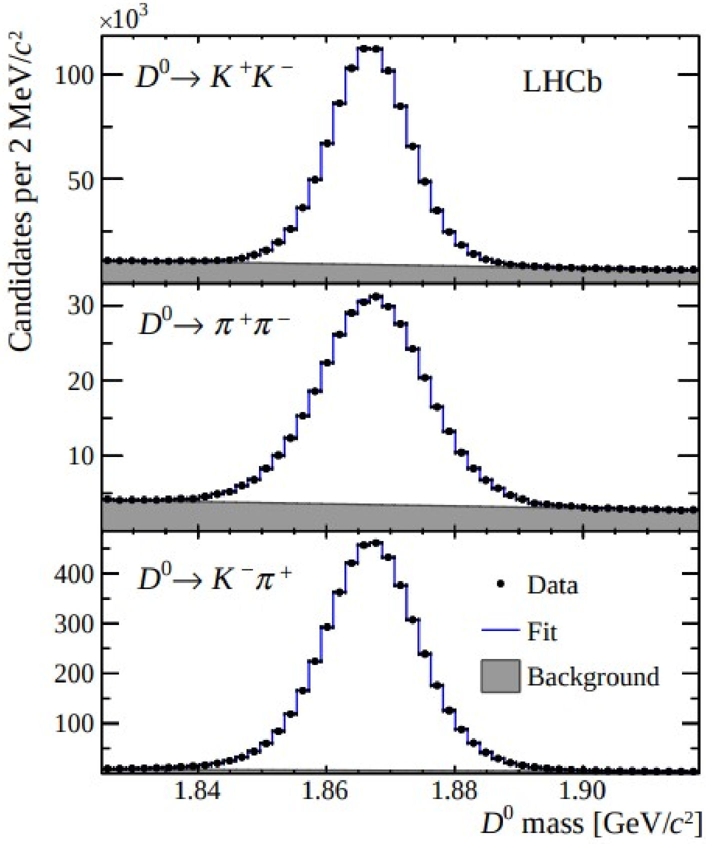
Phys. Rev. Lett. 122 (2019) 011802

Sample

- Analysis uses Run 1 Semileptonic sample
- Trigger on muon
- Looser selection on D decay products



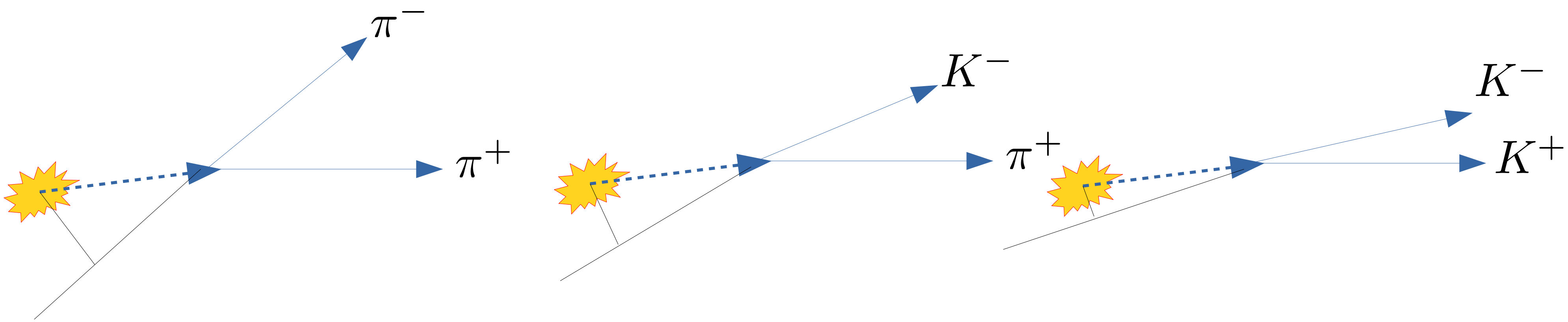
$$\overline{B} \to D^0 \mu^- \nu X$$



Phys. Rev. Lett. 122 (2019) 011802

Lifetime acceptance

- Opening angle depends on masses of decay products



Phys. Rev. Lett. 122 (2019) 011802

Lifetime acceptance

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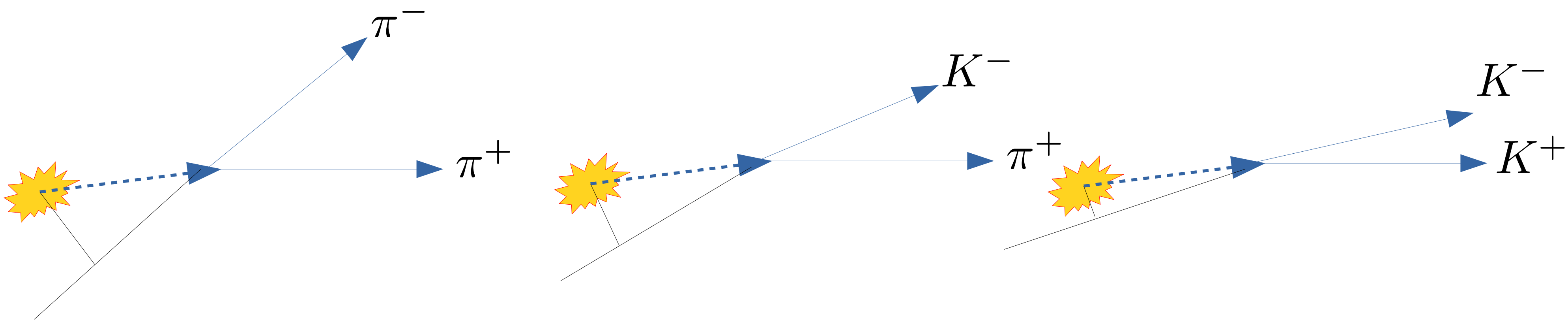
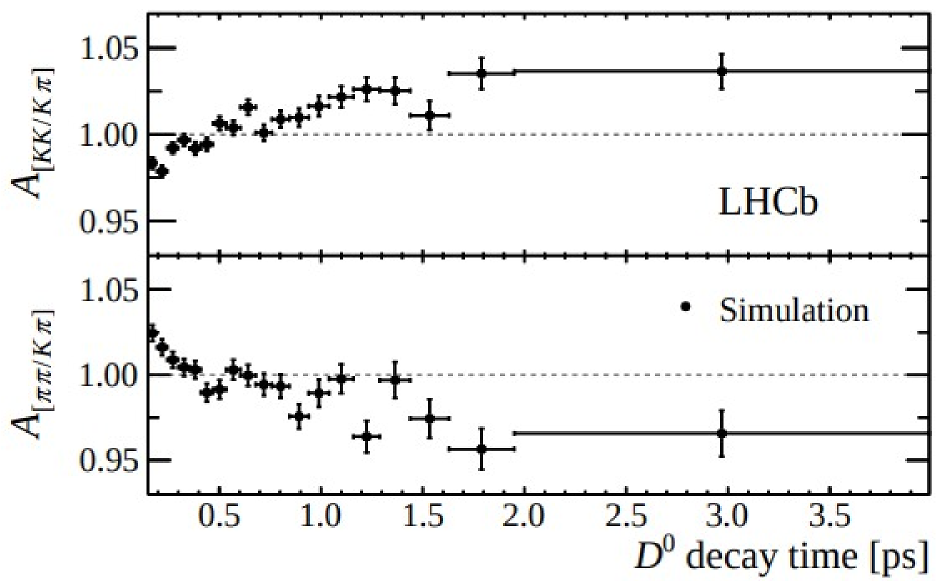


Acceptance ratios:

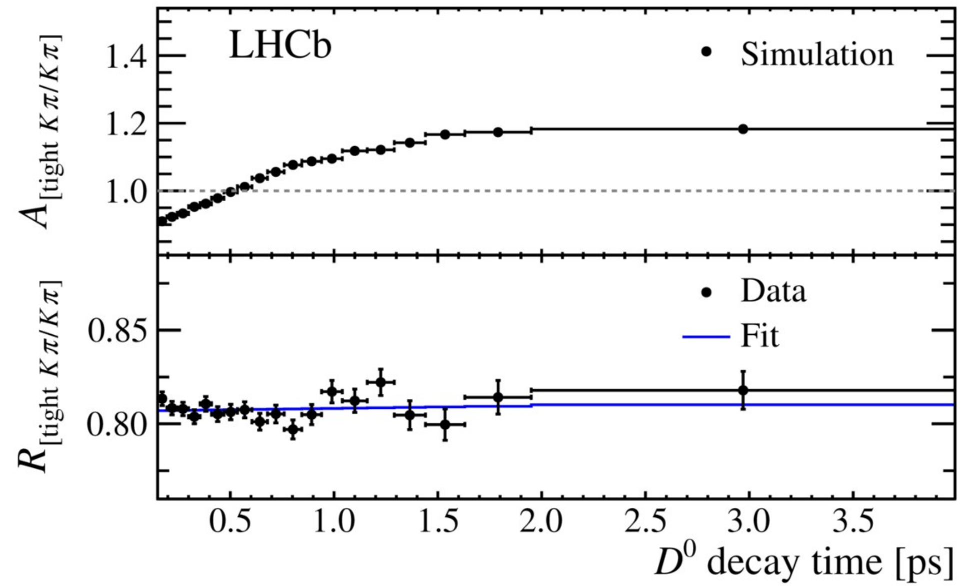


Robustness tests

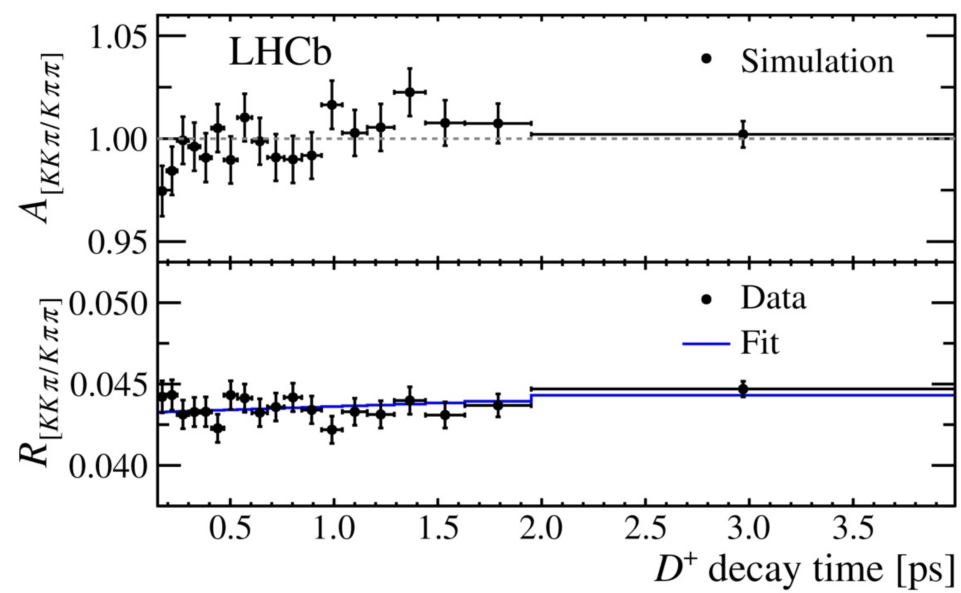
- Tighter impact parameter requirements
- Different decay-modes

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

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

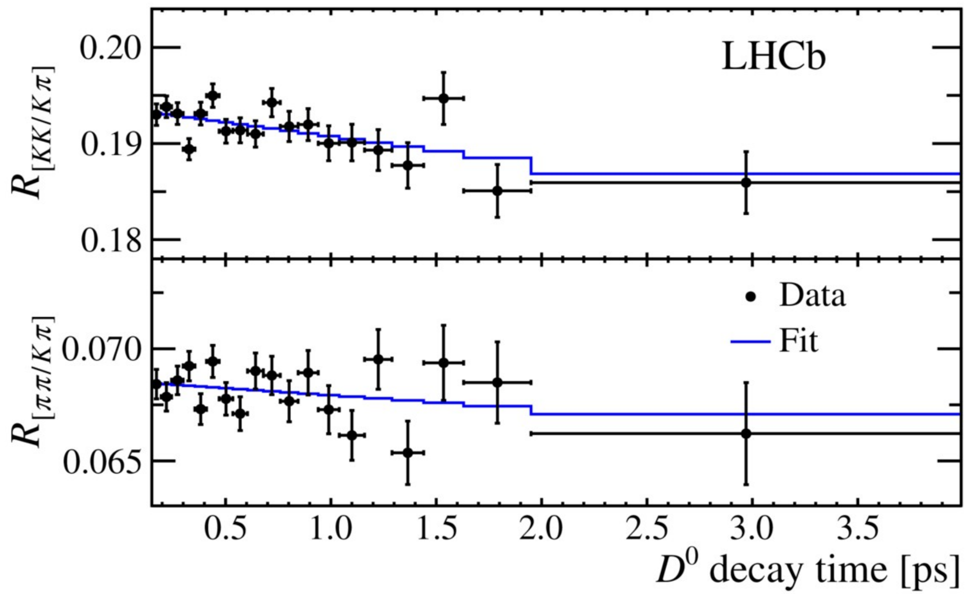


- Decay-width differences consistent with 0
- Biggest systematic from Monte Carlo statistics



Phys. Rev. Lett. 122 (2019) 011802

Result of y_{CP} measurement



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

As precise as previous world average.

No evidence for CP violation.

$$y_{CP} = (0.57 \pm 0.13(\text{stat}) \pm 0.09(\text{syst}))\%$$
$$y_{CP,\text{HFLAV}} = (0.84 \pm 0.16)\%$$

$$y_{\text{HFLAV}} = (0.62 \pm 0.07)\%$$

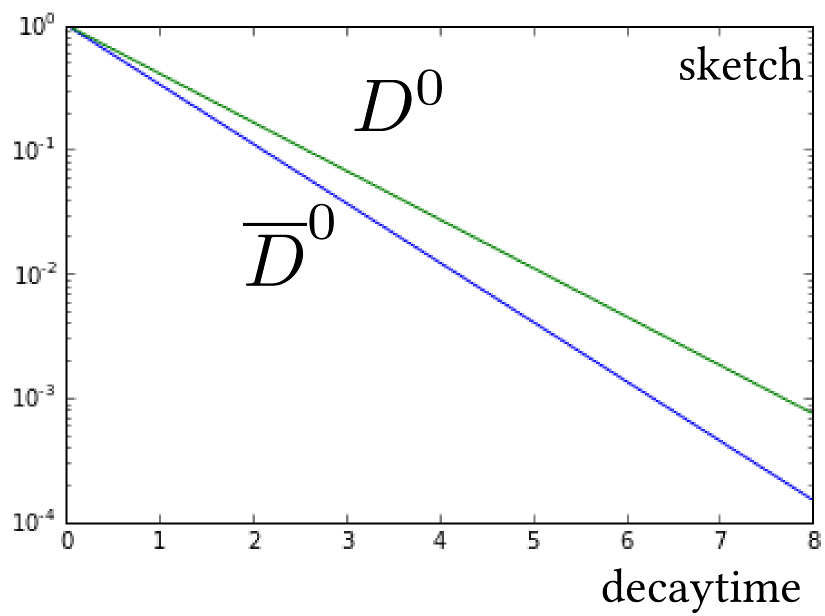
Phys. Rev. Lett. 118, 261803 (2017)

Asymmetry of effective decay widths

- Asymmetry between D^0 and $\overline{D}^0$ effective decay widths

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

$$A_\Gamma = +\frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi - \frac{1}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) x\sin\phi$$



Phys. Rev. Lett. 118, 261803 (2017)

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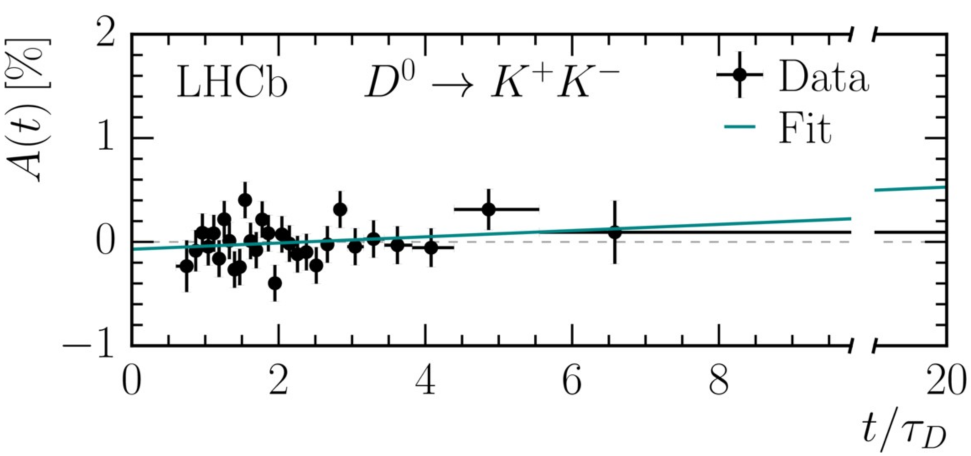
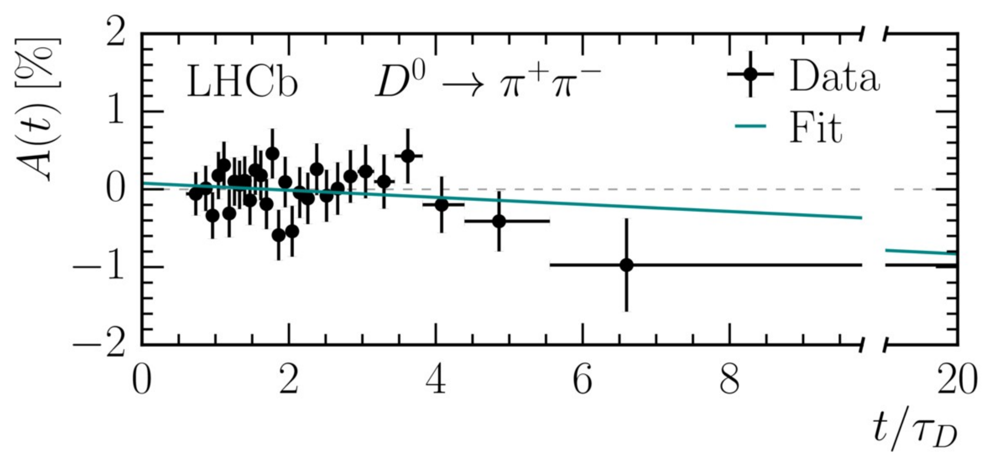


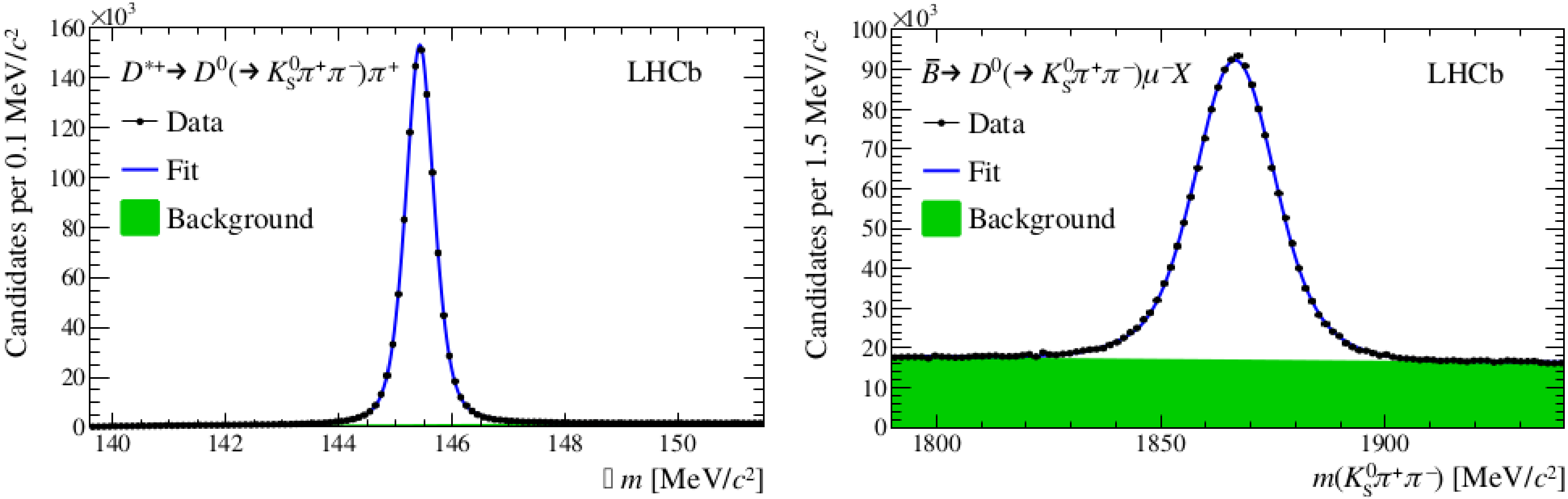


$$A_\Gamma = (0.29 \pm 0.28) \times 10^3$$

(LHCb Run 1 data)

Multi-body decays

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

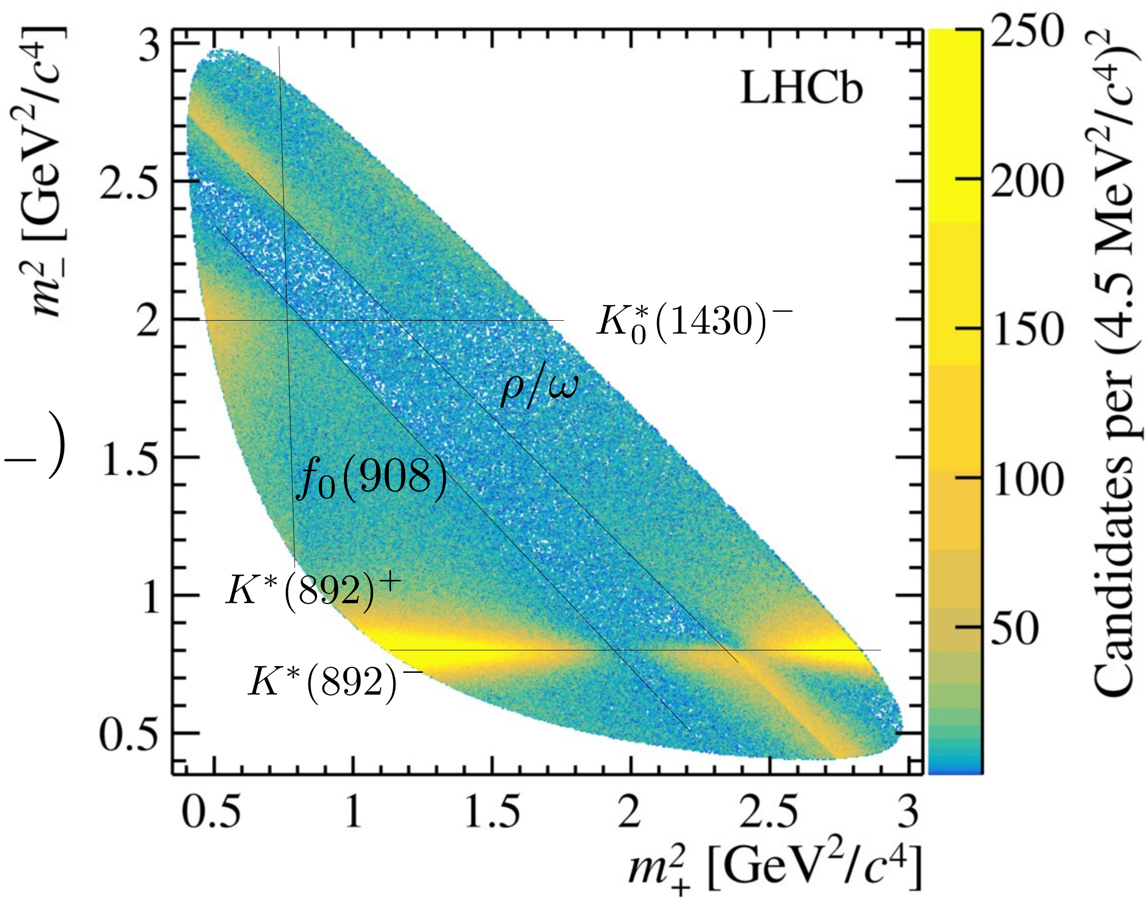


- Analysis with Run 1 data
- 1.3 Million prompt decays
- 1 Million semileptonic decays

Dalitz plot and interference

$$m_\pm^2 \equiv \begin{cases} m^2(K_S^0\pi^\pm) & \text{for } D^0 \\ m^2(K_S^0\pi^\mp) & \text{for } \overline{D}^0 \end{cases}$$

$D^0 \xrightarrow{\text{mix}} \overline{D}^0 \rightarrow f(m_+, m_-)$, $D^0 \rightarrow f(m_+, m_-)$



Multiple interfering amplitudes:

$$\mathcal{P}_D(m_+, m_-) \propto e^{-\Gamma t}\left[|A_D|^2 + \mathrm{Re}(A^*_{\overline{D}}(m_+, m_-)A_D(m_+, m_-)(z)\Gamma t) + \ldots\right]$$

Reminder WS method

- Remember WS method

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

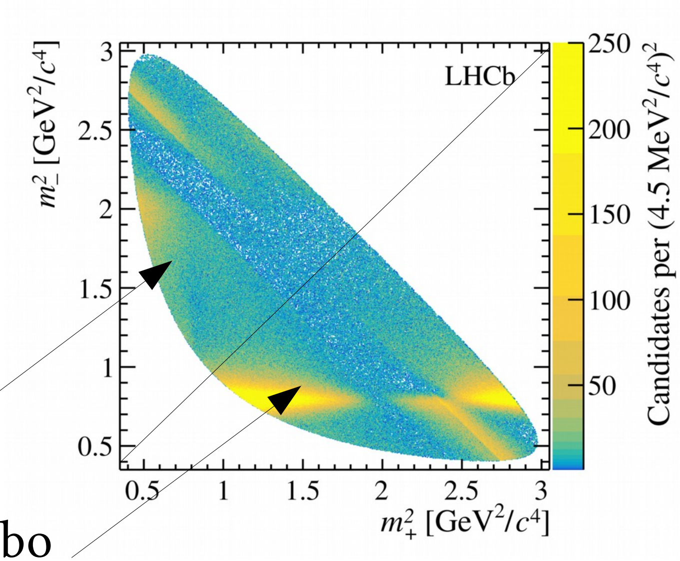
$$\frac{A(D^0 \to K^+\pi^-)}{A(\overline{D}^0 \to K^+\pi^-)} = -\sqrt{R_D} e^{-i\delta}$$

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

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

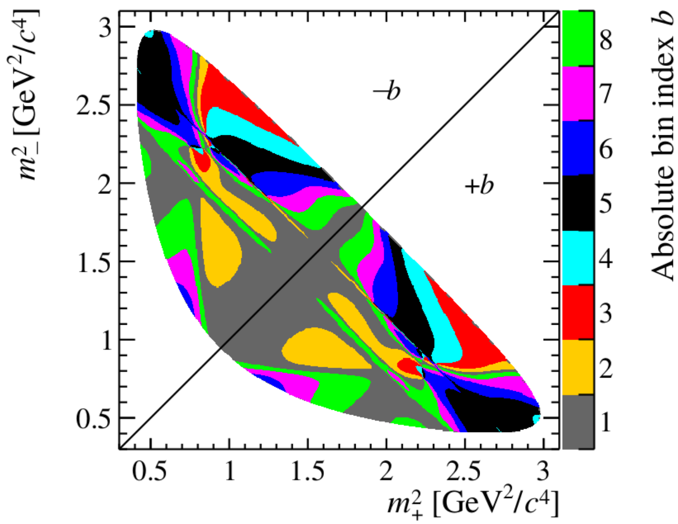
(strong phase)

Cabibbo suppresed



Cabibbo favoured

- Here, strong phase varies in each point
- CLEO measured strong phases with correlated DD pairs in bins of Dalitz plot

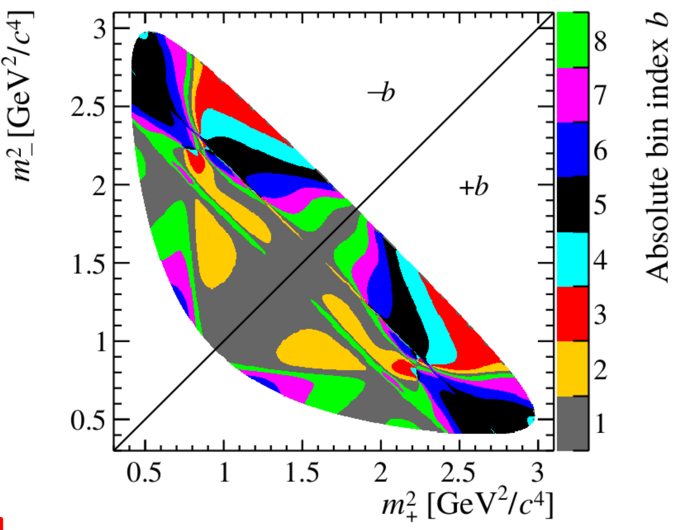


Phys. Rev. D99 (2019) 012007

Binflip method

$$R_{bj} = \frac{N_{-bj}}{N_{bj}}$$

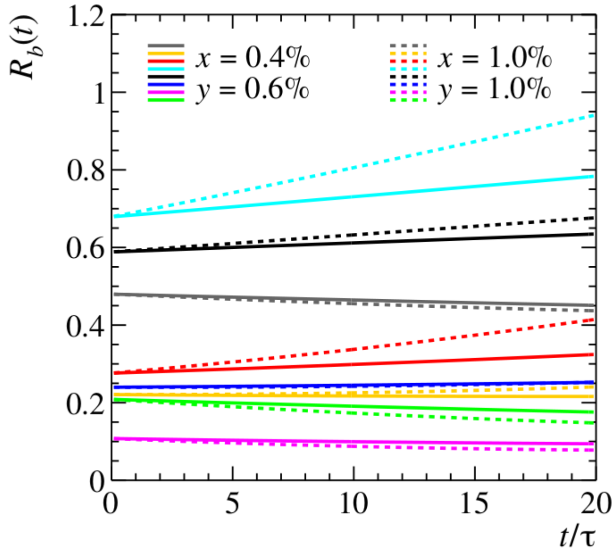
- Measure ratios of yields in Dalitz bins b and -b in decay-time bins j



No CPV:

$$R_{bj} \approx \; r_b - \langle t\rangle_j \sqrt{r_b}\left[(1-r_b)c_b\; y - (1+r_b)s_b\; x\right],$$

- External input from CLEO c_b, s_b
- Nuisance parameter r_b
- Use binning which minimizes strong phase variations



Phys. Rev. D99 (2019) 012007

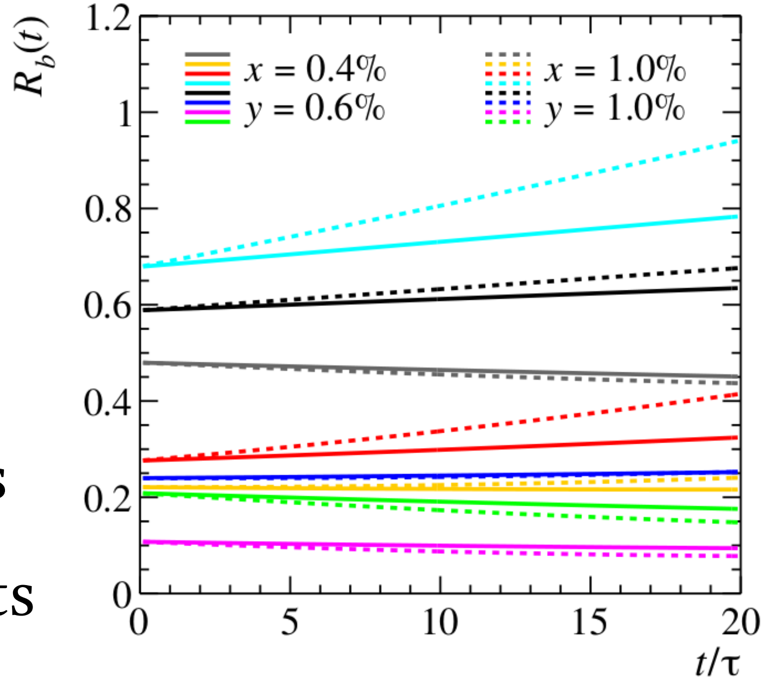
Binflip method

$$R_{bj} = \frac{N_{-bj}}{N_{bj}}$$

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

$$X_b \equiv c_b - i s_b$$

- r_b nuisance parameter
- X_b external input from CLEO
- Avoids modeling of D decay dynamics
- Cancellation of most acceptance effects



Binflip method – Expected Sensitivity

	Signal yield	$\sigma(x_{CP})$ [%]	$\sigma(y_{CP})$ [%]	$\sigma(\Delta x)$ [%]	$\sigma(\Delta y)$ [%]
Run 1 →	1×10^6	0.22 (0.21)	0.43 (0.41)	0.16 (0.15)	0.31 (0.29)
	5×10^6	0.10 (0.093)	0.24 (0.19)	0.068 (0.065)	0.16 (0.13)
	1×10^7	0.085 (0.066)	0.16 (0.13)	0.048 (0.046)	0.095 (0.091)
Run 2 →	5×10^7	0.047 (0.030)	0.120 (0.059)	0.021 (0.021)	0.041 (0.041)
	1×10^8	0.043 (0.021)	0.091 (0.042)	0.015 (0.015)	0.028 (0.028)
	5×10^8	0.034 (0.009)	0.091 (0.018)	0.006 (0.006)	0.013 (0.013)

Hadronic parameters constrained (CLEO uncertainties)

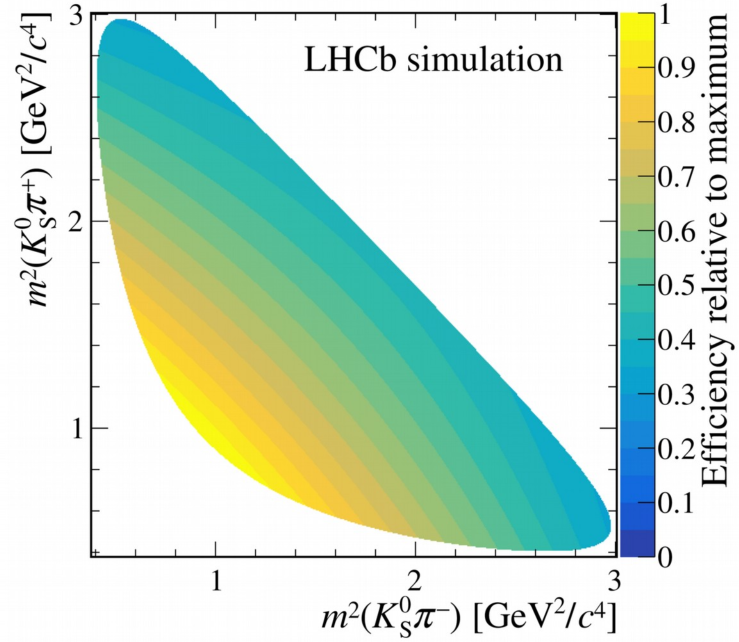
Hadronic parameters fixed

- CLEO uncertainties, marginal impact on precision for Run 1 data set
- For future measurements, improved input from BESIII needed

Phys. Rev. D99 (2019) 012007

Dalitz-plot acceptance

Decay-time integrated:



Measured by CLEO:

$$\boxed{c_b} \propto \int_b dm_+^2 dm_-^2 \; |A_f(m_+^2, m_-^2)| \; |A_f(m_-^2, m_+^2)| \cos[\Delta\delta(m_+^2, m_-^2)]$$

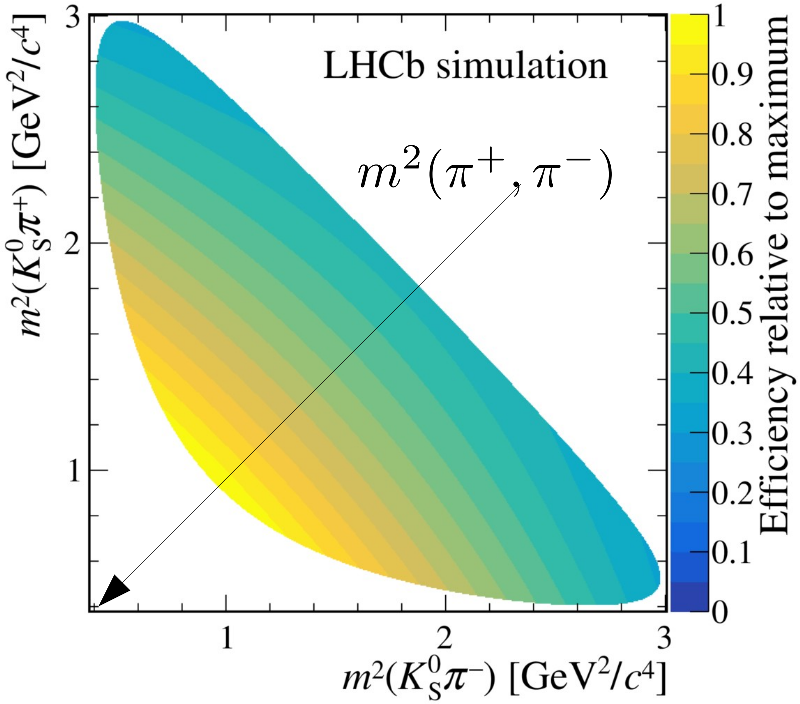
Measured by LHCb:

$$\tilde{c}_b \propto \int_b dm_+^2 dm_-^2 \boxed{\epsilon(m_+^2, m^2)} |A_f(m_+^2, m_-^2)| \; |A_f(m_-^2, m_+^2)| \boxed{\cos[\Delta\delta(m_+^2, m_-^2)]}$$

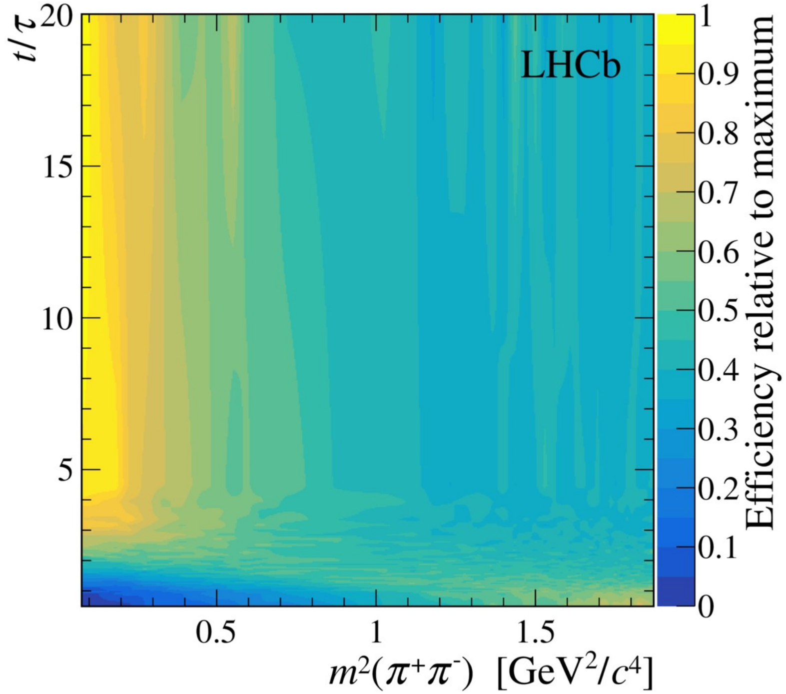
Pseudo experiments: Negligible bias if appropriate selection and binning.

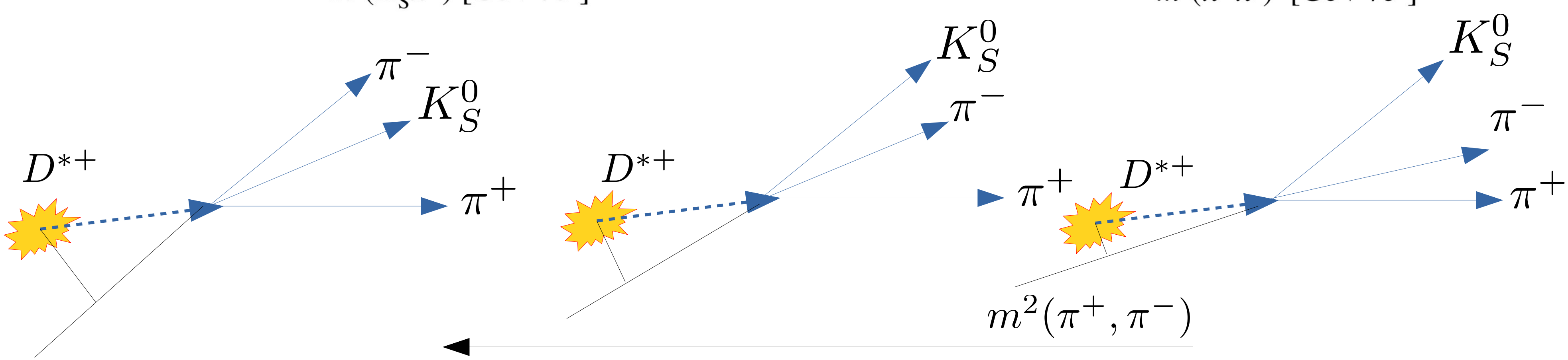
Dalitz-plot and decay-time acceptance

Decay-time integrated:



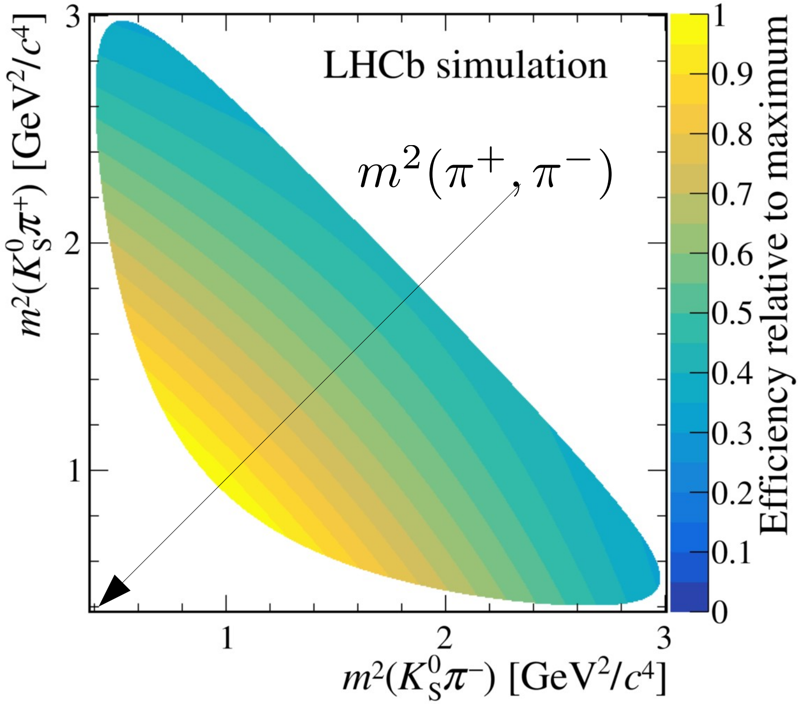
Decay-time dependent:



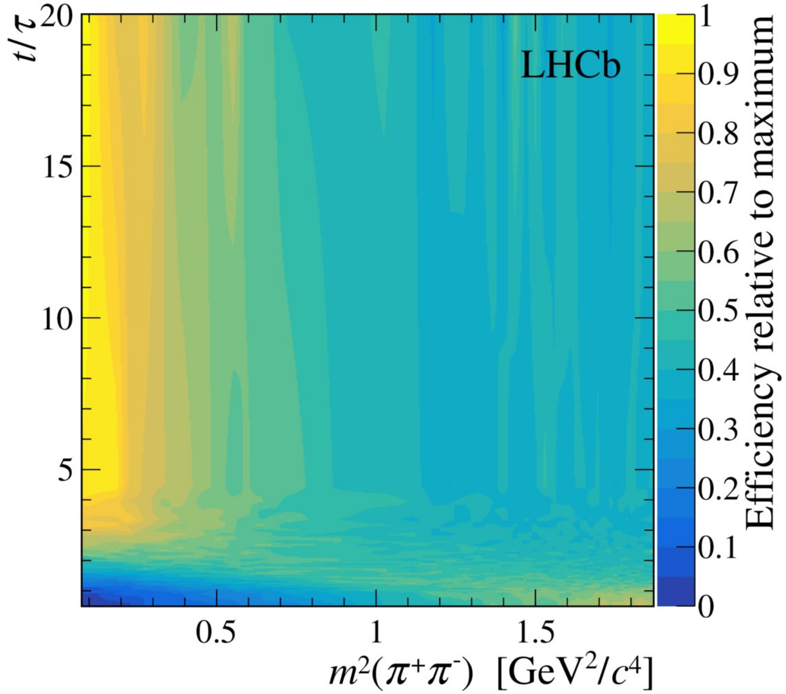


Dalitz-plot and decay-time acceptance

Decay-time integrated:



Decay-time dependent:

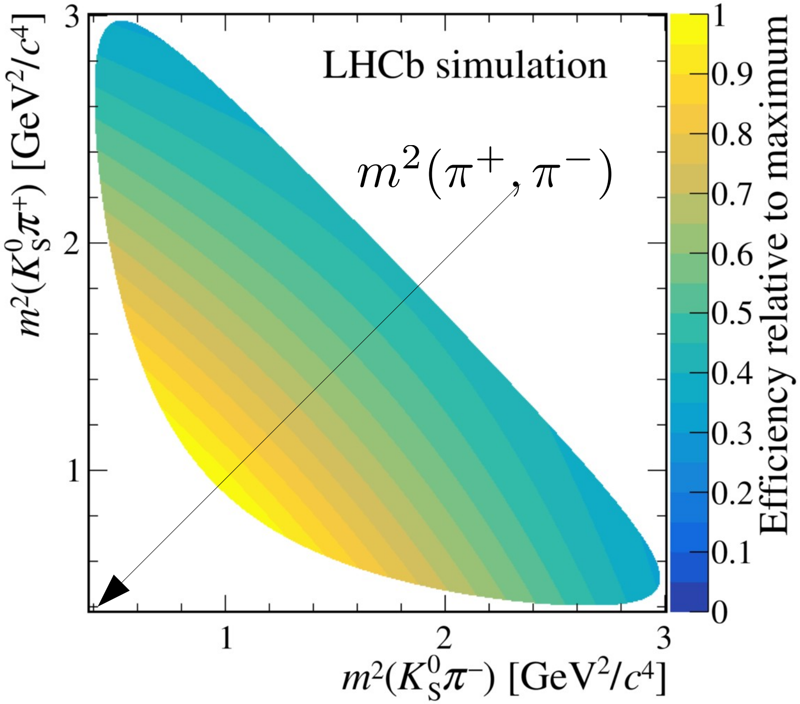


$$\tilde{c}_b(t) \propto \int_b dm_+^2 dm_-^2 \, \epsilon(m_+^2, m_-^2, t) \left|A_f(m_+^2, m_-^2)\right| \left|A_f(m_-^2, m_+^2)\right| \cos[\Delta\delta(m_+^2, m_-^2)]$$

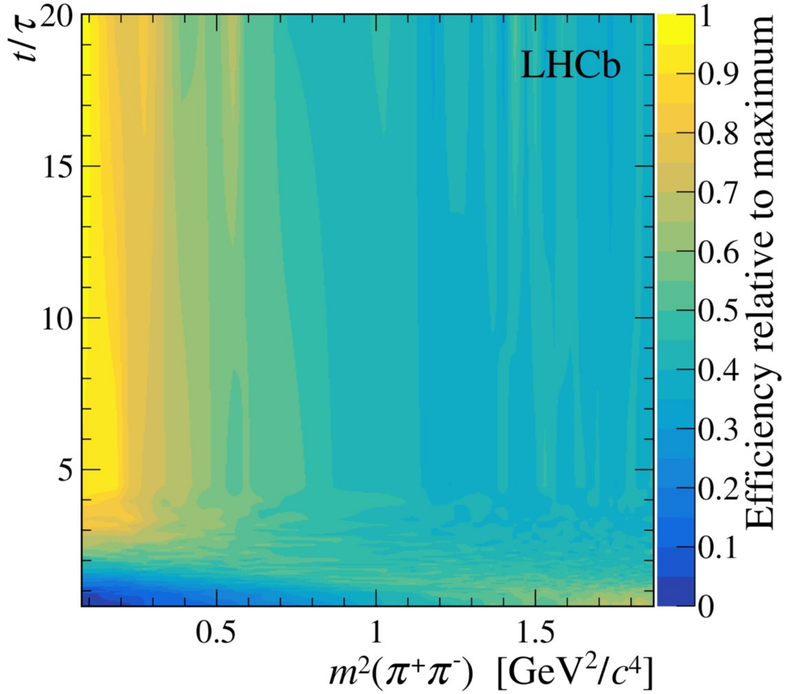
(Uncorrected) correlation ($m^2(\pi^+, \pi^-)$, t) introduces bias in measurement.

Dalitz-plot and decay-time acceptance

Decay-time integrated:



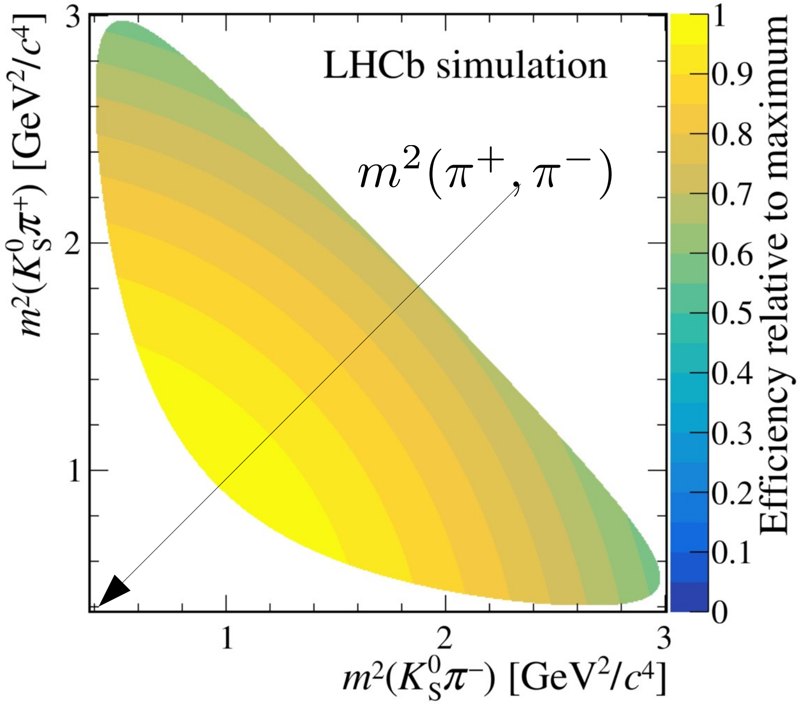
Decay-time dependent:



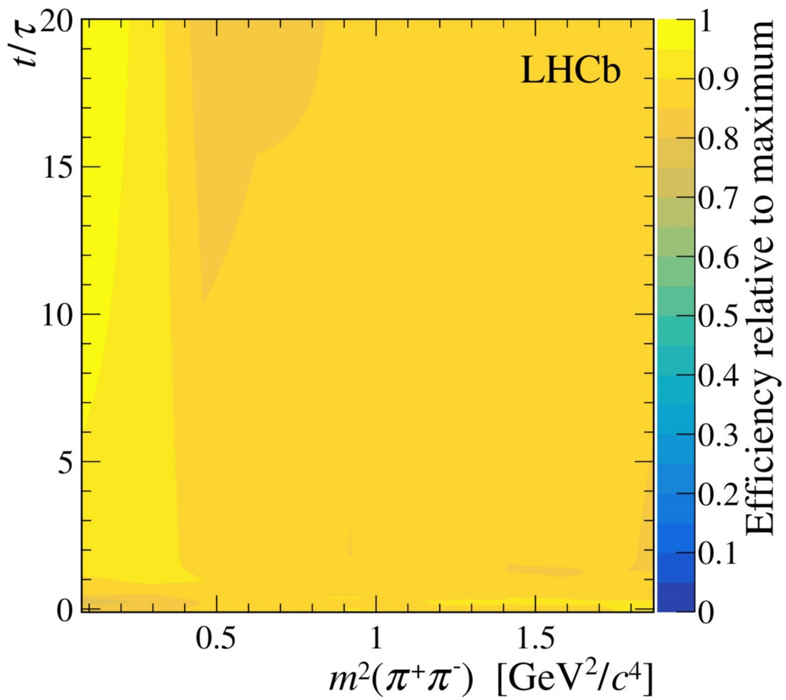
- Correlation ($m^2(\pi^+, \pi^-)$, t) introduces bias in measurement
- Extract efficiency map from data, normalized to average decay-time distribution
- Assign per-candidate weight depending on ($m^2(\pi^+, \pi^-)$, t)
- Extensive pseudo-experiment studies to validate method

Dalitz-plot and decay-time acceptance

Decay-time integrated:

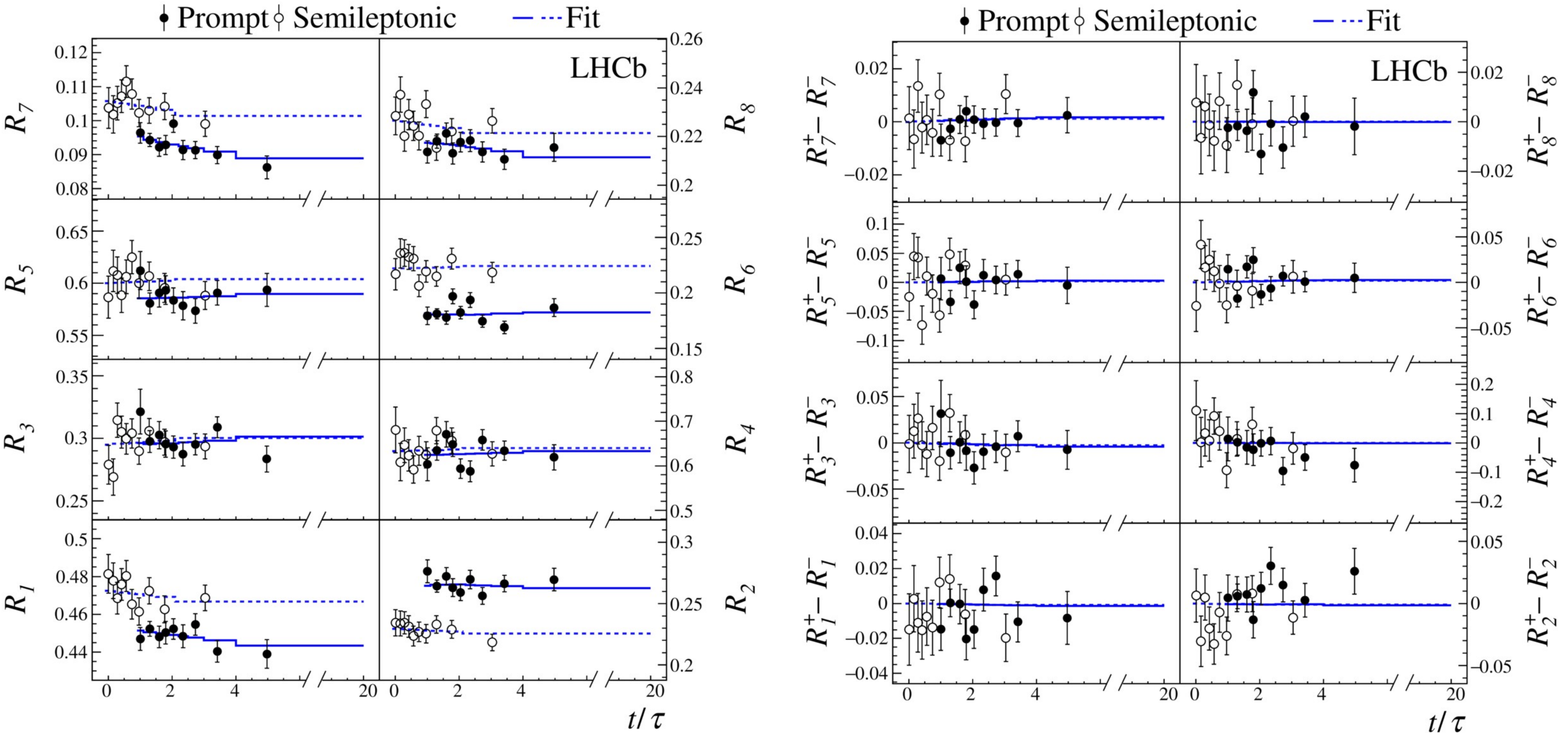


Decay-time dependent:

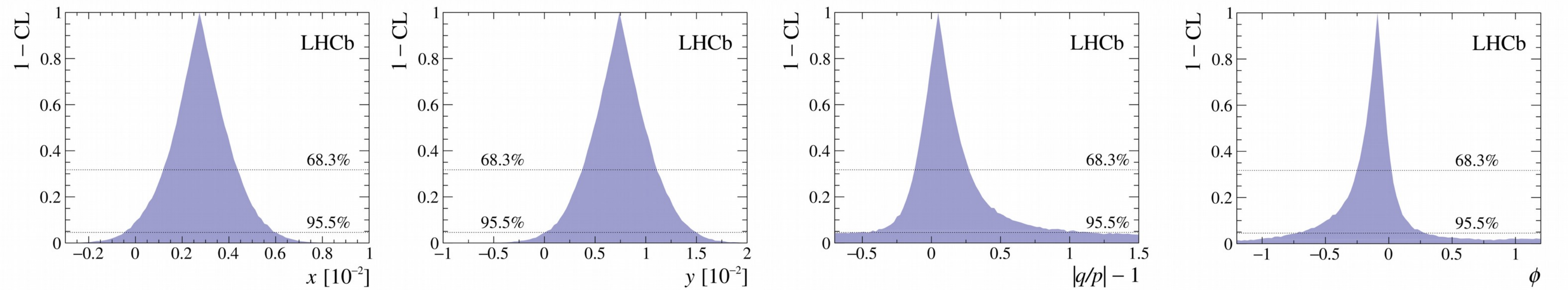


- D's from semileptonic decays show almost no correlation
- No correction applied
- Extensive pseudo-experiment studies to validate method

Mixing and CPV fit



Fit results

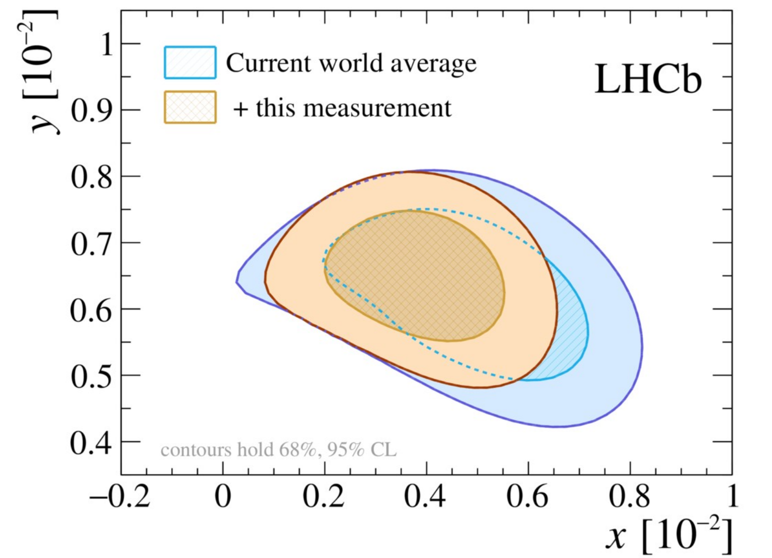


Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\;\;0.00, 1.50]$
$\lvert q/p \rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\;\;0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

- Most precise measurement of x by a single experiment
- No sign of CP violation

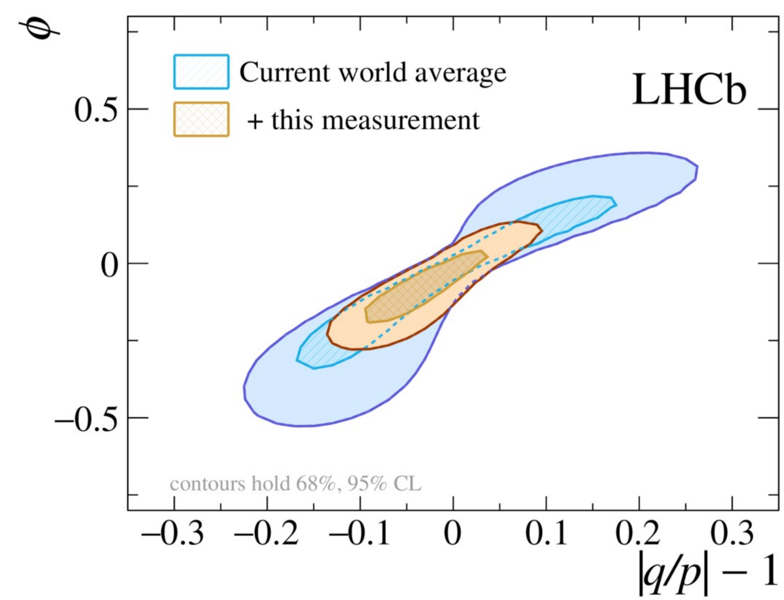
Impact on world average

Parameter	Value	Allowed interval 68.3% CL	95.5% CL	99.7% CL
x $[10^{-2}]$	0.38 ± 0.12	[0.26 , 0.50]	[0.14, 0.61]	[0.02, 0.71]
y $[10^{-2}]$	$0.655\,^{+0.062}_{-0.067}$	[0.588, 0.717]	[0.52, 0.78]	[0.44, 0.84]
$\lvert q/p\rvert$	$0.967\,^{+0.050}_{-0.045}$	[0.922, 1.017]	[0.88, 1.07]	[0.84, 1.13]
ϕ	$-0.070\,^{+0.079}_{-0.081}$	[−0.151, 0.009]	[−0.24, 0.09]	[−0.33, 0.19]



- Includes all measurements shown today
- Significantly improved limits on CPV parameters
- First evidence of non-zero x

… 30 times more data in Run 2



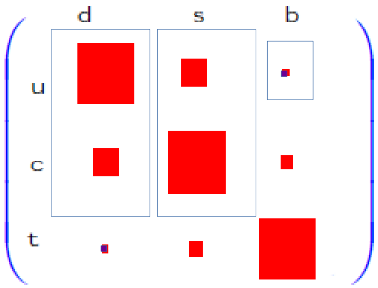
Direct CP violation

Measurement published today!

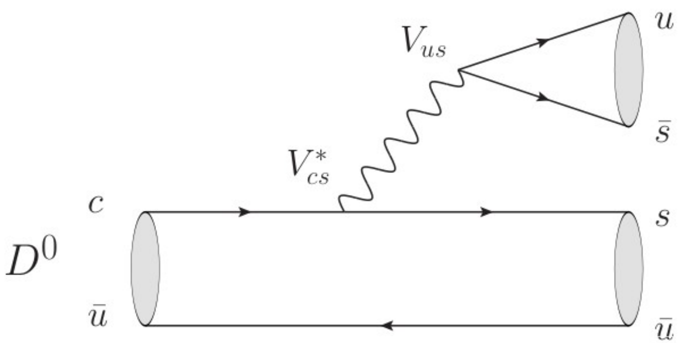
LHCb-PAPER-2019-006

Direct CP violation in two-body charm decays

- Singly Cabibbo-suppressed decays:



$$D^0 \to K^- K^+ \quad \text{and} \quad D^0 \to \pi^- \pi^+$$



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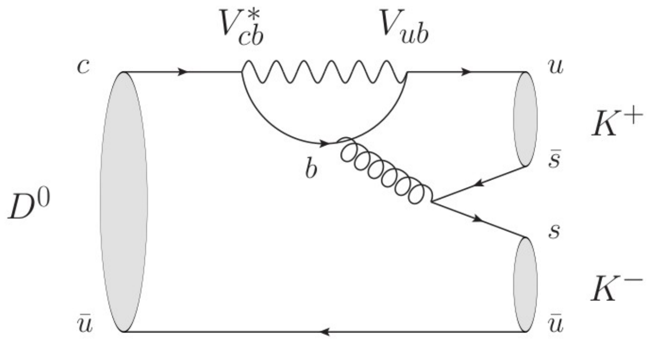


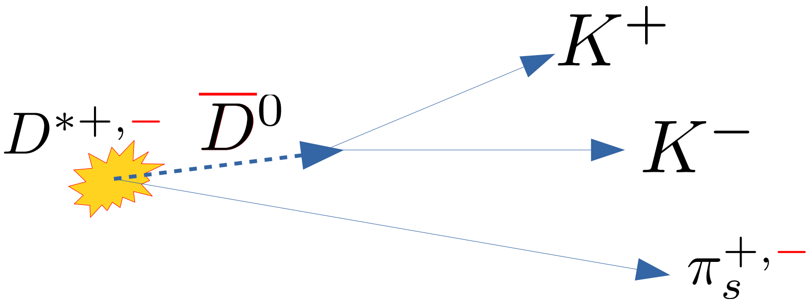
(d and s loop cancel)

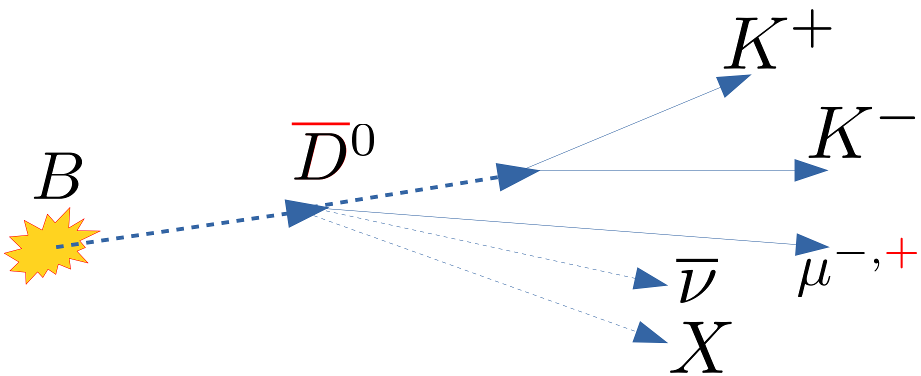
- Observable:

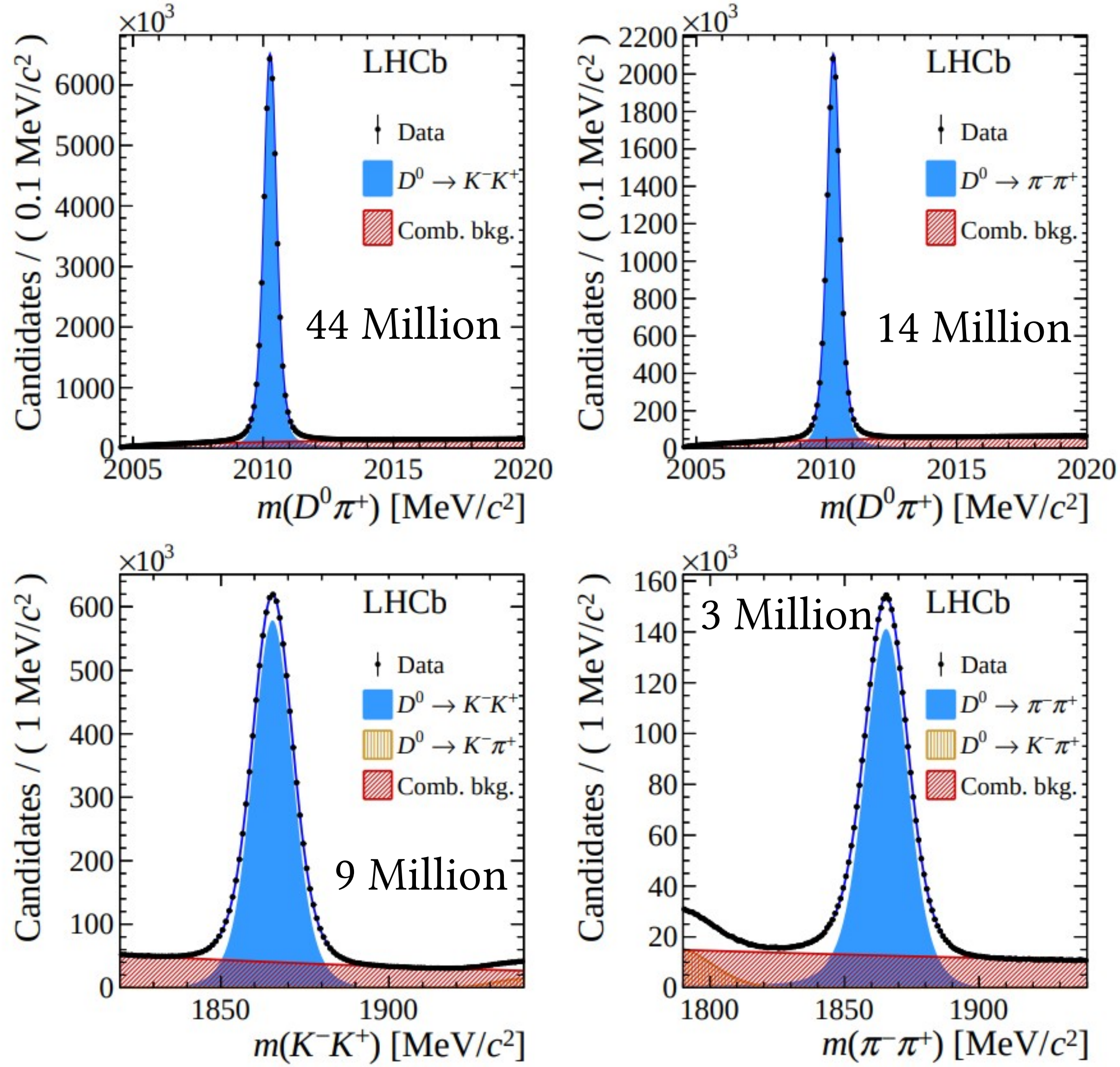
$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} \propto \left| \frac{V^*_{cb} V_{ub}}{V^*_{cs} V_{us}} \right| \lesssim \mathcal{O}(0.1\ \%)$$

Naively: $A_{CP}(K^- K^+) = -A_{CP}(\pi^- \pi^+)$

Two-body modes







Sub-per mille precision!

Measured quantity: ΔA_{CP} (prompt)

Measured asymmetry:

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

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

CP asymmetry

Detection asymmetry

Production asymmetry

All of order 1% or below.

Experimentally more robust:

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

Assumption: Detection and production asymmetry cancel.

Measured quantity: ΔA_{CP} (SL)

Measured asymmetry:

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

$$A_{\text{raw}}(f) = A_{CP}(f) + A_D(\mu^-) + A_P(B)$$

CP asymmetry

Detection asymmetry

Production asymmetry

All of order 1% or below.

Different nuisance asymmetries in both modes.

Experimentally more robust:

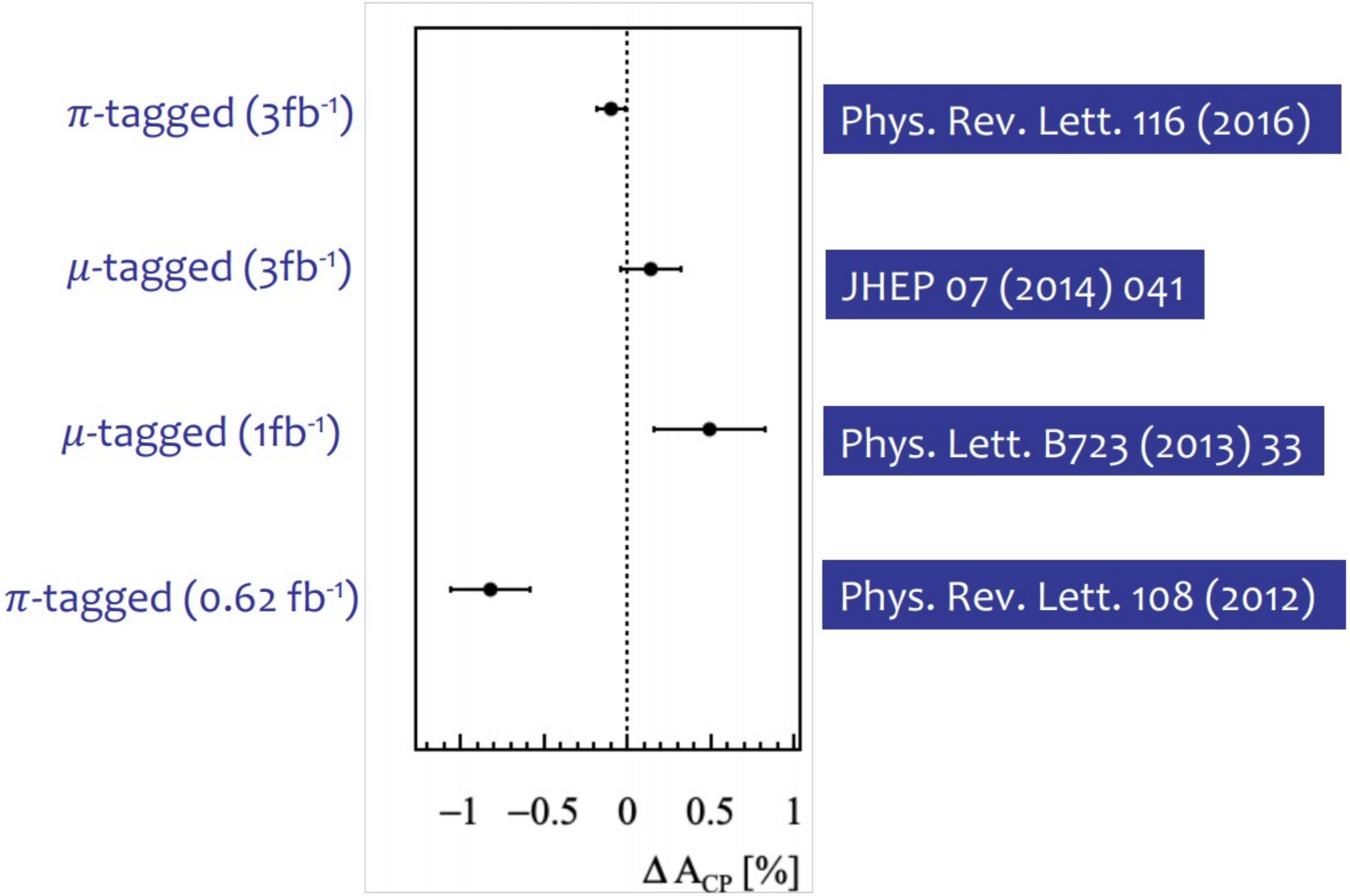
$$\begin{aligned}\Delta A_{CP} &= A_{\text{raw}}(K^+K^-) - A_{\text{raw}}(\pi^+\pi^-)\\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\end{aligned}$$

Assumption: Detection and production asymmetry cancel.

ΔA_{CP} history in LHCb

Picture by A. Carbone

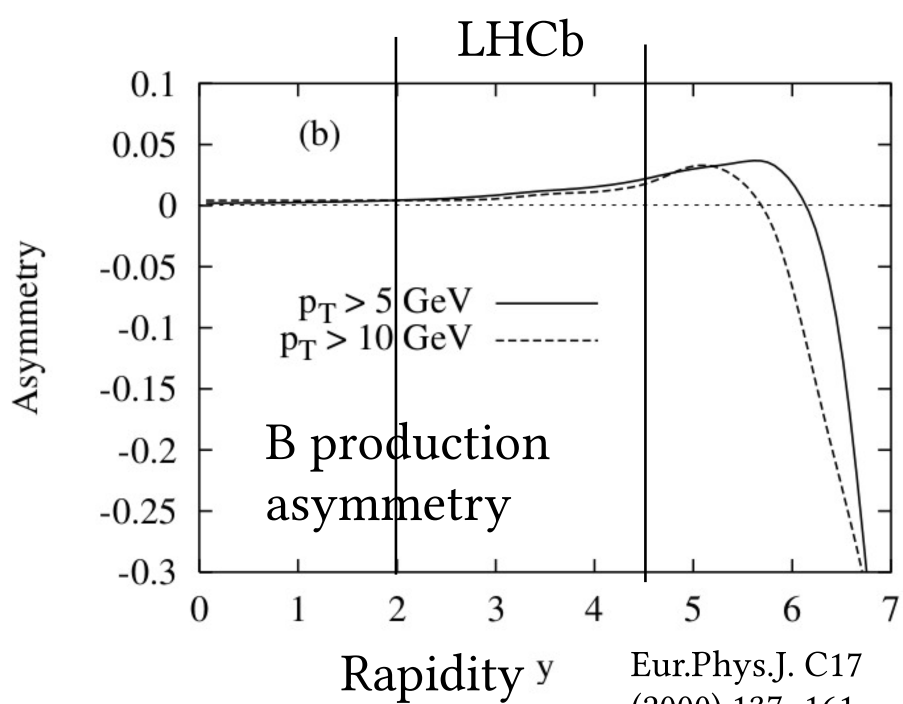
$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$



Validity of the method

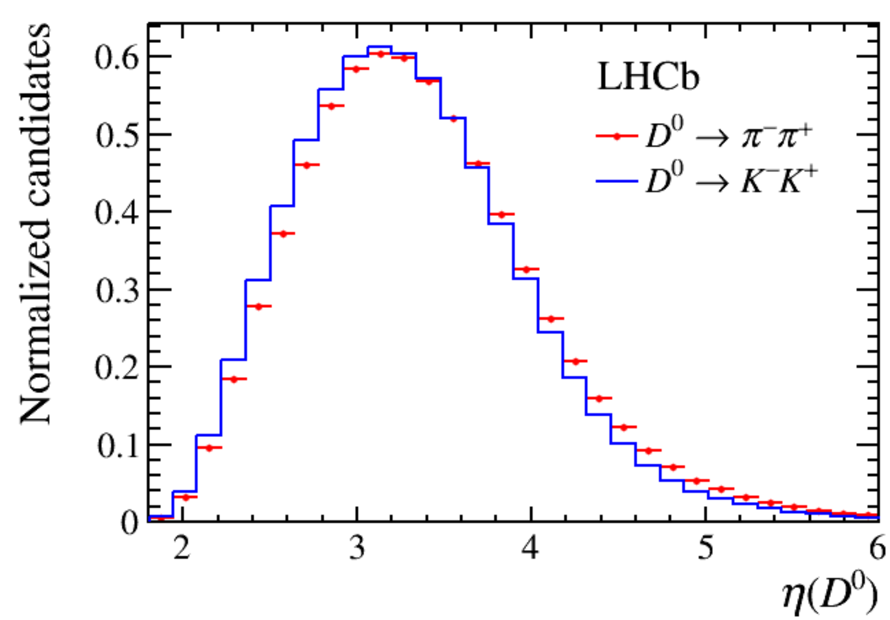
- Assumption: Cancellation of production and detection asymmetry in difference
  - Asymmetries depend on kinematics

  ⟶ Residual asymmetries in difference
- Remember sub-per mille precision

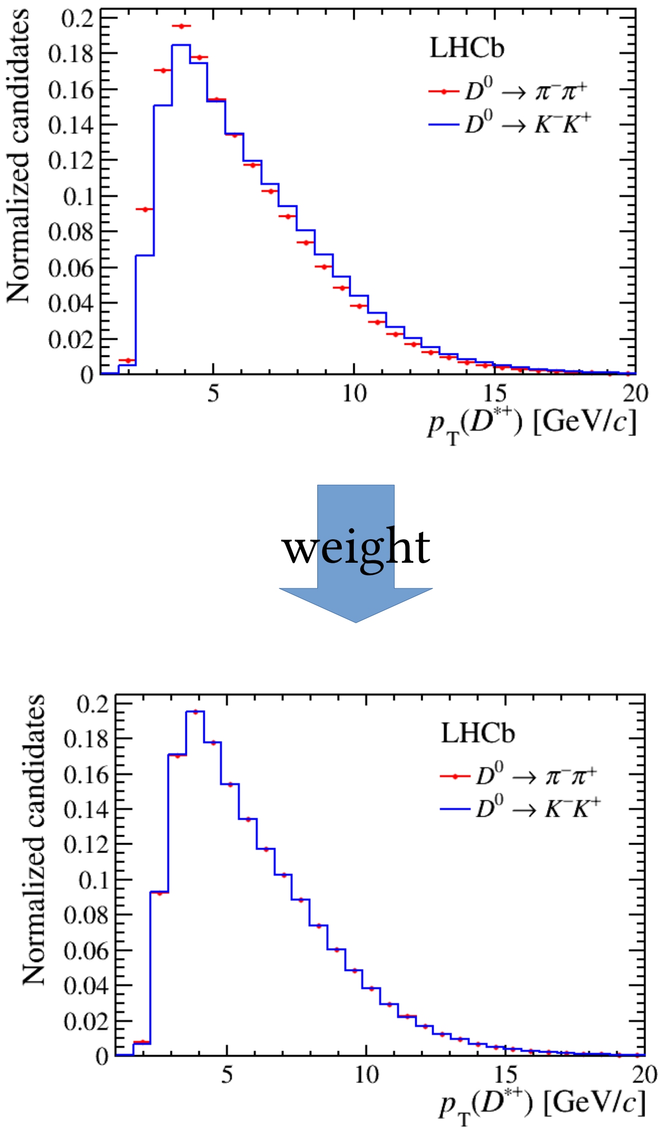


Eur.Phys.J. C17 (2000) 137–161

Observed distributions:



Kinematic weighting



- Small differences in kinematics
- Weights assigned to each KK event:

$$w(p_T^{D^*}, \eta^{D^*}, \phi^{D^*}) \propto \frac{n_{\pi^-\pi^+}(p_T^{D^*}, \eta^{D^*}, \phi^{D^*})}{n_{K^-K^+}(p_T^{D^*}, \eta^{D^*}, \phi^{D^*})}$$

- Production and detection asymmetries cancel in difference

- Effect on ΔA_{CP} smaller than 10^{-4}

Systematic uncertainties

in 10^{-4}

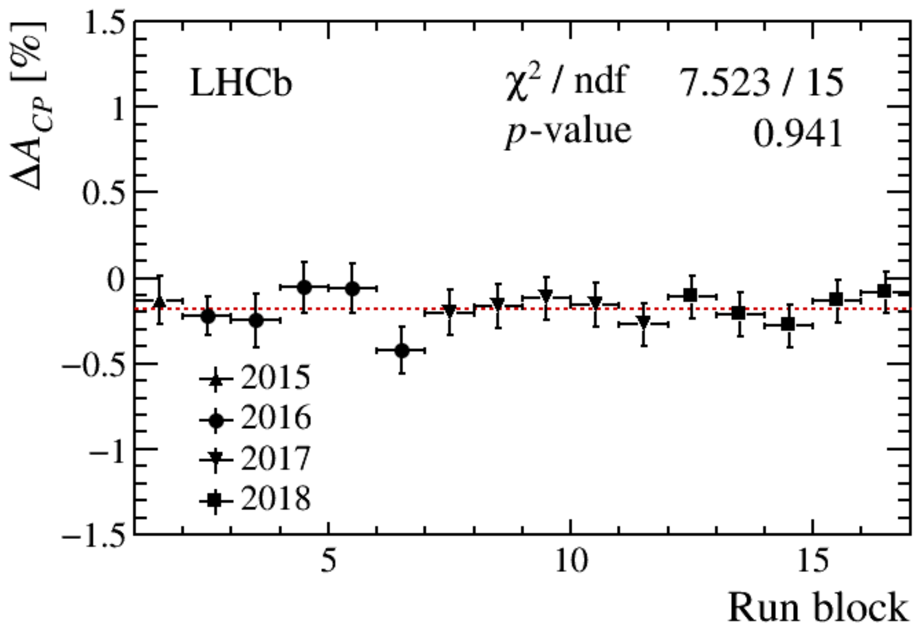
Source	π-tagged	μ-tagged
Fit model	0.6	2
Mistag	–	4
Weighting	0.2	1
Secondary decays	0.3	–
B fractions	–	1
B reco. efficiency	–	2
Peaking background	0.5	–
Total	0.9	5
σ_{stat}	3.2	8

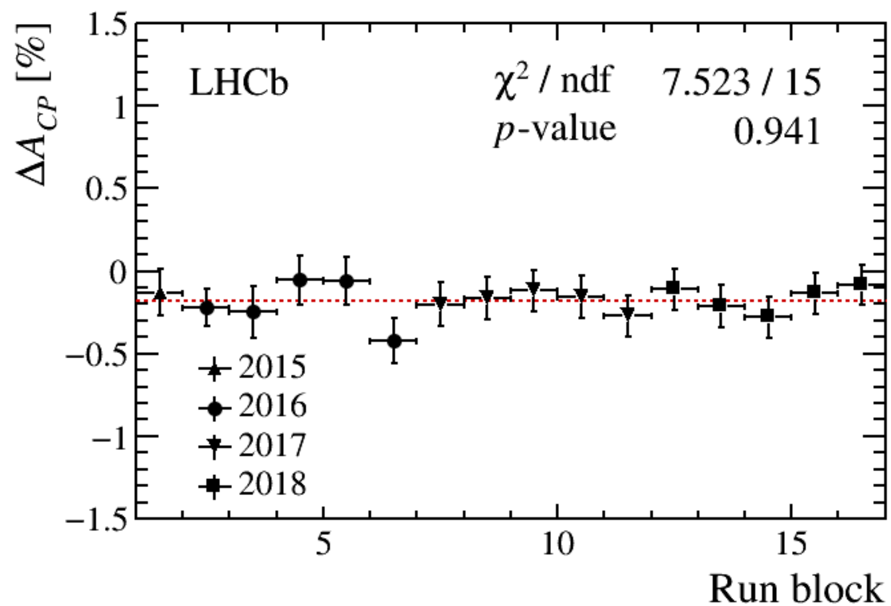
Wrong tag due to random combination with muon.

Description of signal and background shape.

Robustness checks

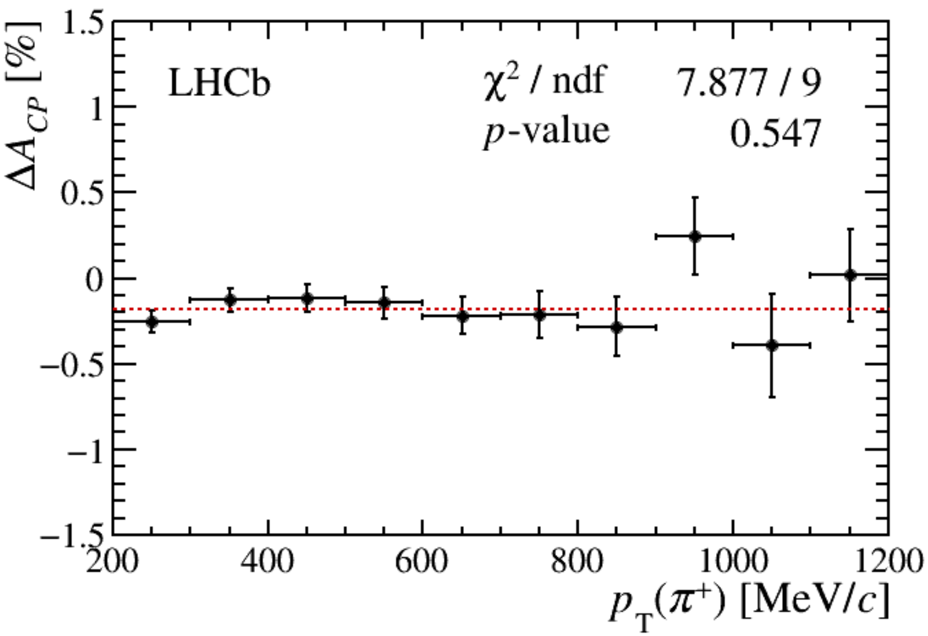
- Remember sub-per mille precision.
- Detection asymmetries can change over time,
  CP asymmetries should not.
- Results compatible for different run periods and magnet polarities.

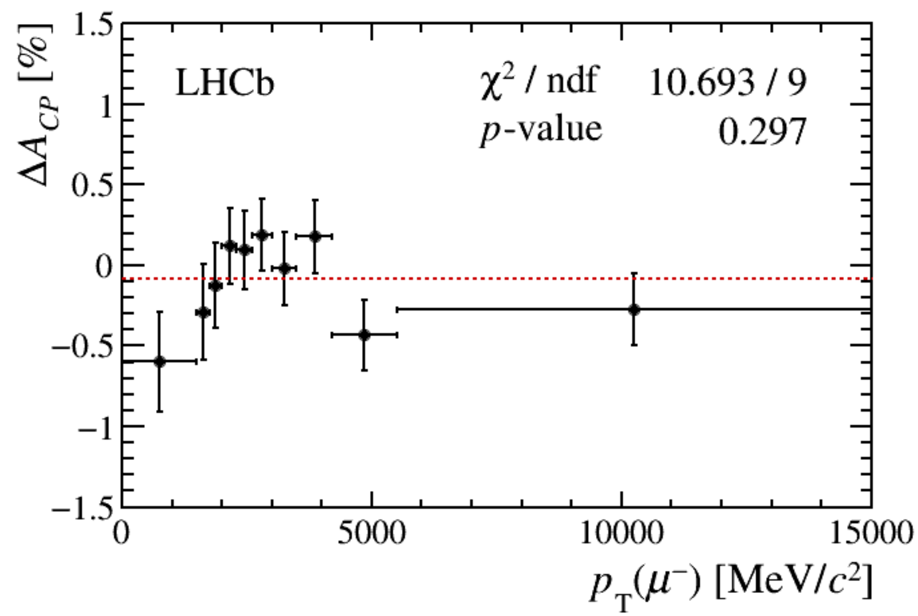




Robustness checks

- Remember sub-per mille precision.
- Detection asymmetries depend on kinematics, CP asymmetries should not.
- Huge number of tests





Results

- Full Run 2 result:

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

- Full Run 1 result:

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

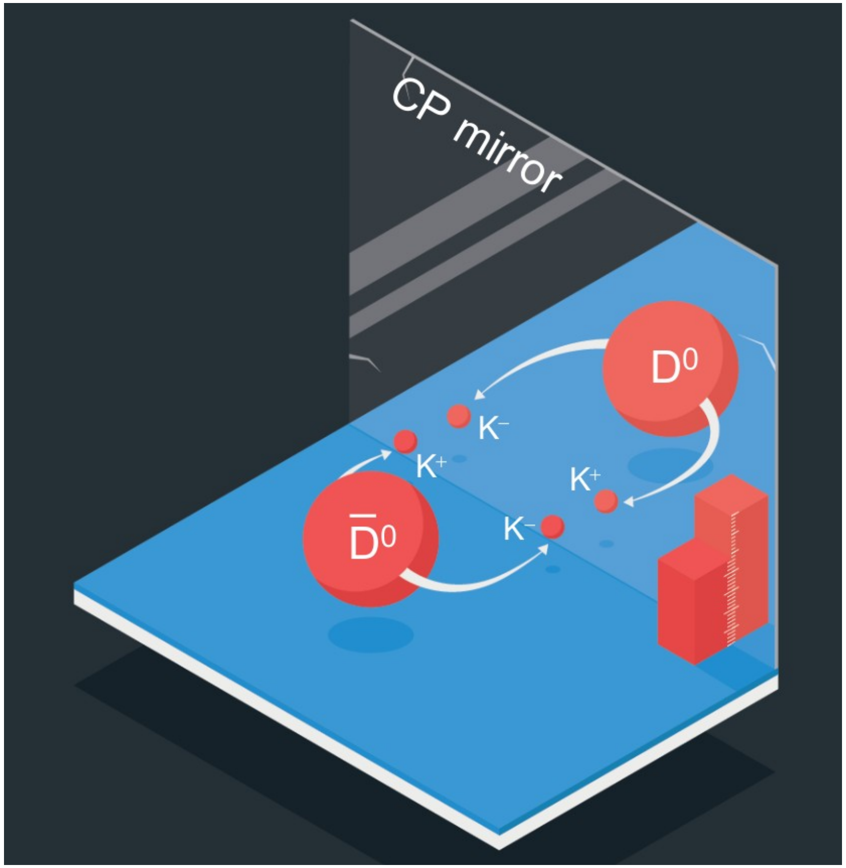
- All results compatible → combined result:

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

Combined LHCb result

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

- The significance of the deviation from zero corresponds to 5.3 standard deviations.
- This is the first observation of CP violation in the decay of charm hadrons.



Interpretation of the results

- ΔA_{CP} mostly sensitive to direct CP violation.
- Small contribution from indirect CP violation.

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &\approx \Delta a_{CP}^{\text{dir}}\left(1 + \frac{\overline{\langle t \rangle}}{\tau(D^0)}\, y_{CP}\right) + \frac{\Delta\langle t\rangle}{\tau(D^0)}\, a_{CP}^{\text{ind}},\end{aligned}$$

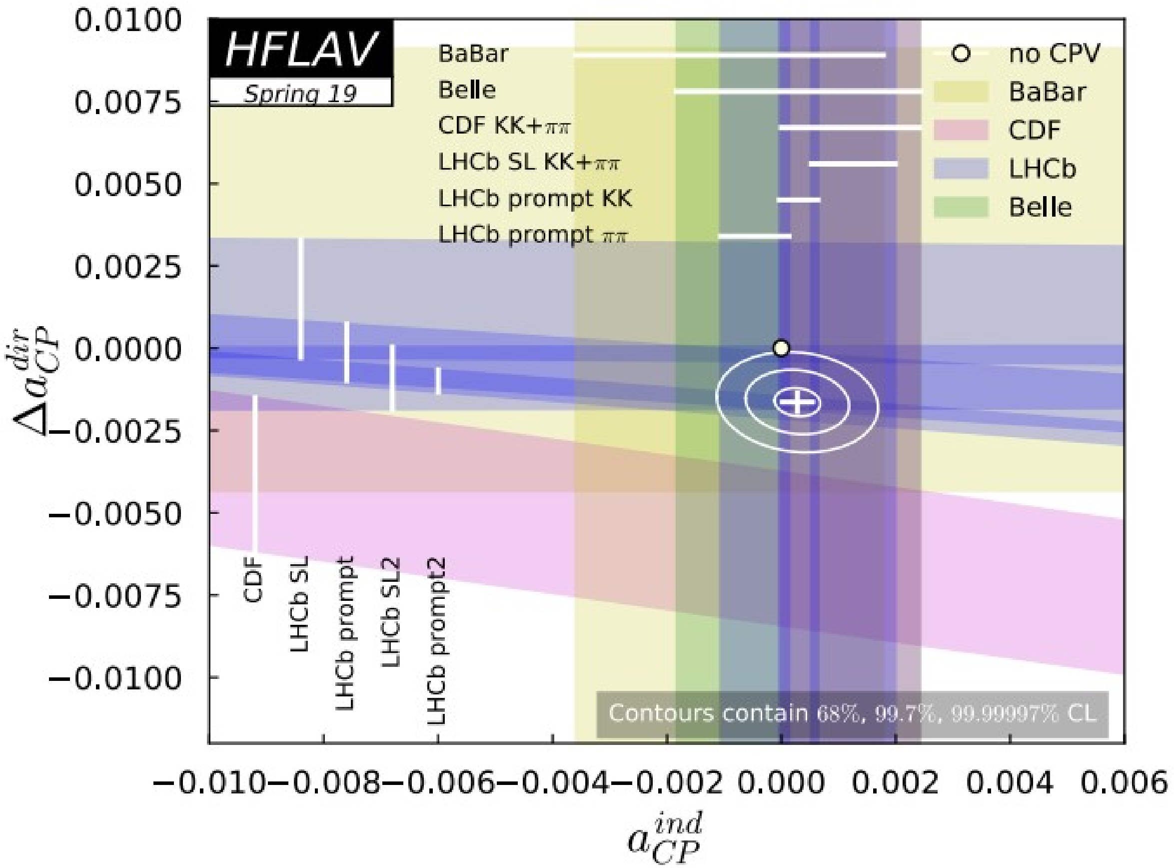
- Use average decay-times, their difference and the other results shown today:

$$\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9) \times 10^{-4}$$

$$a_{CP}^{\text{ind}} = -\frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) y\cos\phi + \frac{1}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) x\sin\phi$$

HFLAV combination

[https://hflav.web.cern.ch]



HFLAV combination (dominated by LHCb):

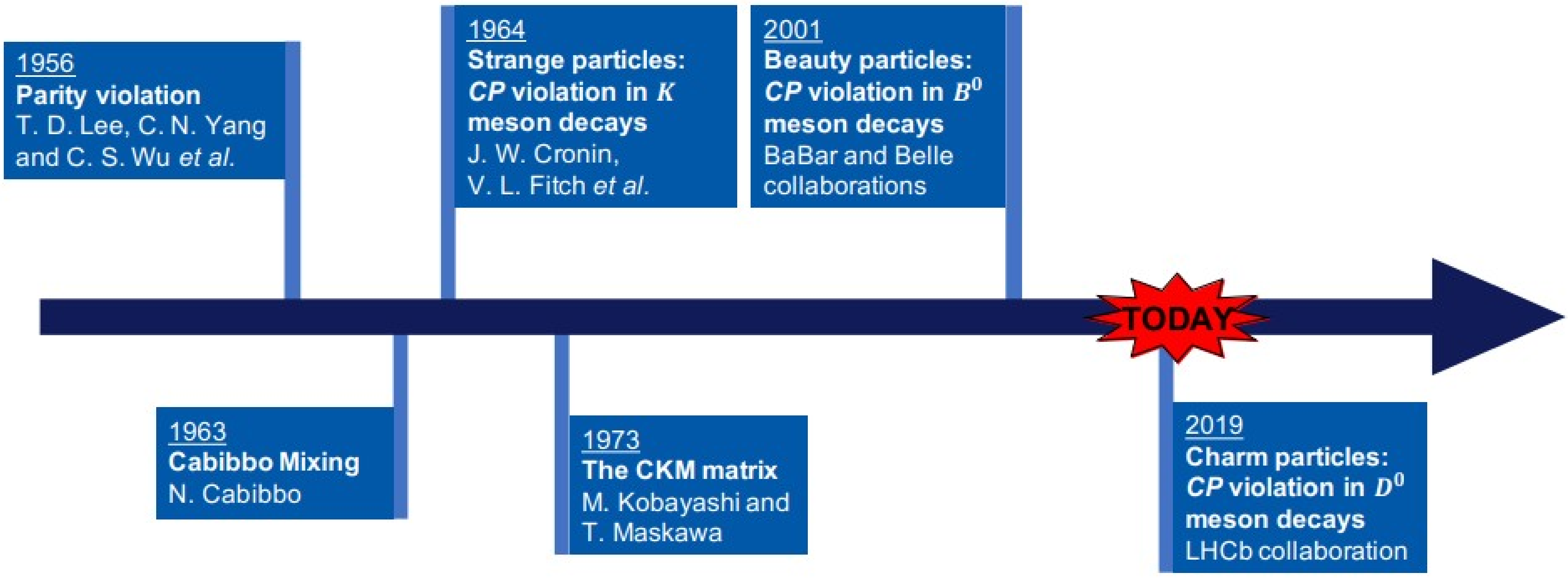
$$a_{CP}^{\text{ind}} = (-0.028 \pm 0.026)\%$$

$$\Delta a_{CP}^{\text{dir}} = (-0.164 \pm 0.028)\%$$

Consistency with NO CPV Hypothesis:

$$5\times 10^{-8}$$

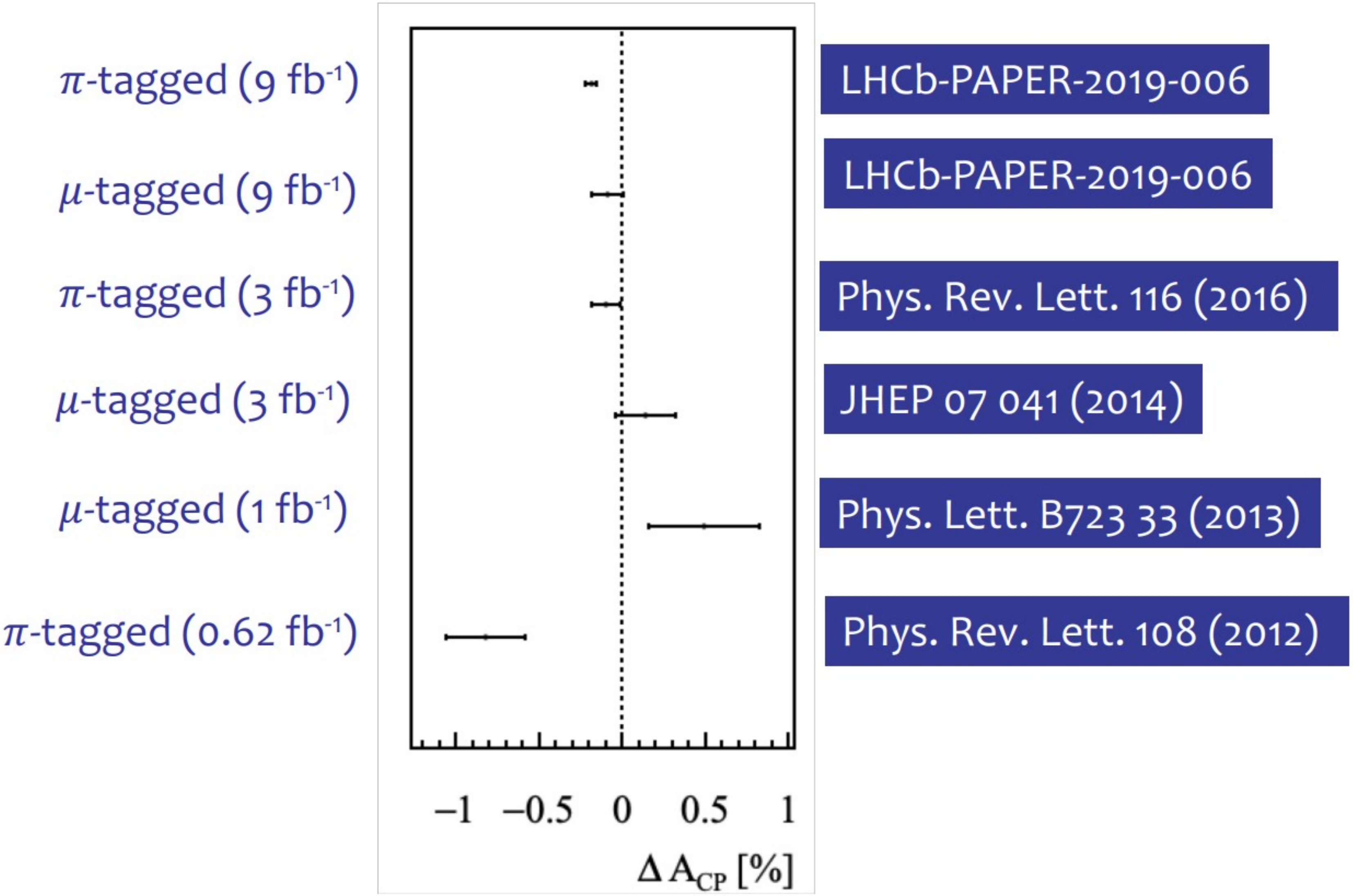
Picture by A. Carbone



Credits:
Slides inspired by:
”Charm physics at LHCb”,
Angelo Di Canto,
LHCb UK Student Meeting,
December 14th, 2015

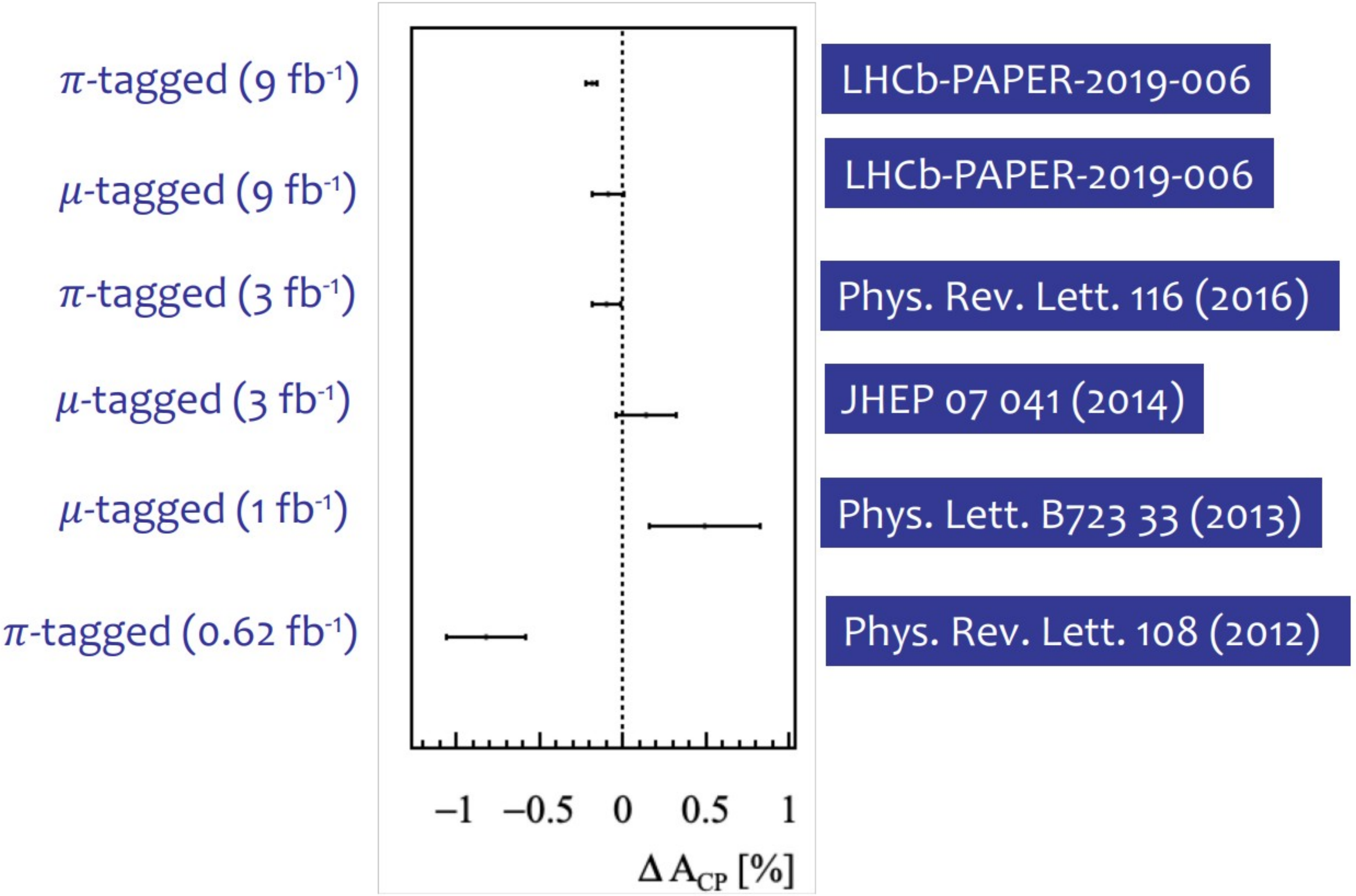
ΔA_{CP} history in LHCb since today

Picture by A. Carbone



ΔA_{CP} history in LHCb since today

Picture by A. Carbone



Systematic uncertainties

Source	x_{CP}	y_{CP}	Δx	Δy
Secondary charm decays	0.24 (0.44) (0.00)	0.36 (0.65) (0.00)	< 0.01	< 0.01
Unrelated $D^0\mu^-$ combinations	0.34 (0.00) (0.94)	0.31 (0.00) (0.60)	< 0.01	< 0.01
Reconstruction and selection biases	0.08 (0.24) (0.08)	0.94 (1.37) (0.21)	0.22 (0.24) (0.28)	0.25 (0.29) (0.22)
Mass-fit model	0.04 (0.02) (0.10)	0.03 (0.08) (0.15)	< 0.01	0.03 (0.04) (< 0.01)
VELO length scale	< 0.01	< 0.01	< 0.01	< 0.01
Input D^0 lifetime	< 0.01	< 0.01	< 0.01	< 0.01
Total systematic	0.43 (0.50) (0.95)	1.05 (1.52) (0.65)	0.22 (0.24) (0.28)	0.25 (0.29) (0.22)
CLEO inputs	0.70 (0.65) (0.87)	1.22 (1.54) (1.35)	0.19 (0.25) (0.28)	0.26 (0.36) (0.65)
Statistical (w/o CLEO inputs)	1.46 (1.76) (2.64)	3.35 (4.02) (6.12)	0.68 (0.74) (1.67)	1.58 (1.76) (3.93)
Statistical	1.62 (1.87) (2.78)	3.57 (4.30) (6.27)	0.70 (0.78) (1.69)	1.60 (1.80) (3.98)

Effect of direct CPV on CPV parameters

M Gersabeck et al.
http://arxiv.org/abs/1111.6515v2

$$|\lambda_f^{\pm 1}|^2 \approx (1 \pm A_m)(1 \pm A_d),$$

$$y_{CP} \approx \eta_{CP}\left[\left(1-\frac{1}{8}A_m^2\right) y\cos\phi - \frac{1}{2}(A_m)x\sin\phi\right], \qquad (7)$$

and

$$A_\Gamma \approx \left[\frac{1}{2}(A_m+A_d)y\cos\phi - x\sin\phi\right]\frac{\eta_{CP}}{1+y_{CP}} \approx \eta_{CP}\left[\frac{1}{2}(A_m+A_d)y\cos\phi - x\sin\phi\right]. (8)$$

One step further: $A_{CP}(K^-K^+)$

- Similar strategy as ΔA_{CP}, just more complicated

$$A_{\rm raw}(K^-K^+, {\rm SL}) = A_{CP}(K^-K^+) + \boxed{A_D(\mu^-) + A_P(B)}$$

- Cabibbo-favoured decays $B \to (D^0 \to K^-\pi^+)\mu^- X$

$$A_{\rm raw}(K^-\pi^+, {\rm SL}) = \boxed{A_D(\mu^-) + A_P(B)} + \boxed{A_D(K^-\pi^+)}$$

- Charged kaon asymmetry from Cabibbo-favoured D^+ decays

$$A_{\rm raw}(K^-\pi^+\pi^+, {\rm Pr}) = \boxed{A_D(K^-\pi^+)} + \boxed{A_D(\pi^+) + A_P(D^+)}$$

$$A_{\rm raw}(\overline{K}^0\pi^+, Pr) = \boxed{A_D(\pi^+) + A_P(D^+)} + \boxed{A_D(K^0)}$$

(small)

$$\boxed{A_D(K^-\pi^+) = A_{\rm raw}(K^-\pi^+\pi^+) - A_{\rm raw}(\overline{K}^0\pi^+) - A_D(K^0)}$$

$$\boxed{A_{CP}(K^-K^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(K^-\pi^+) + A_D(K^-\pi^+)}$$

One step further: $A_{CP}(K^-K^+)$

- Similar strategy as ΔA_{CP}, <u>just more complicated</u>

$$A_{\text{raw}}(K^-K^+,\text{SL}) = A_{CP}(K^-K^+) + A_D(\mu^-) + A_P(B)$$

- Cabibbo-favoured decays $B \to (D^0 \to K^-\pi^+)\mu^- X$

$$\ldots) + A_D(K^-\pi^+)$$

More challenging to control systematics due to detection efficiencies.

- Charged ka … red D^+ decays

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

$$A_{\text{raw}}(\overline{K}^0\pi^+,Pr) = A_D(\pi^+) + A_P(D^+) + A_D(K^0)$$

(small)

$$A_D(K^-\pi^+) = A_{\text{raw}}(K^-\pi^+\pi^+) - A_{\text{raw}}(\overline{K}^0\pi^+) - A_D(K^0)$$

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

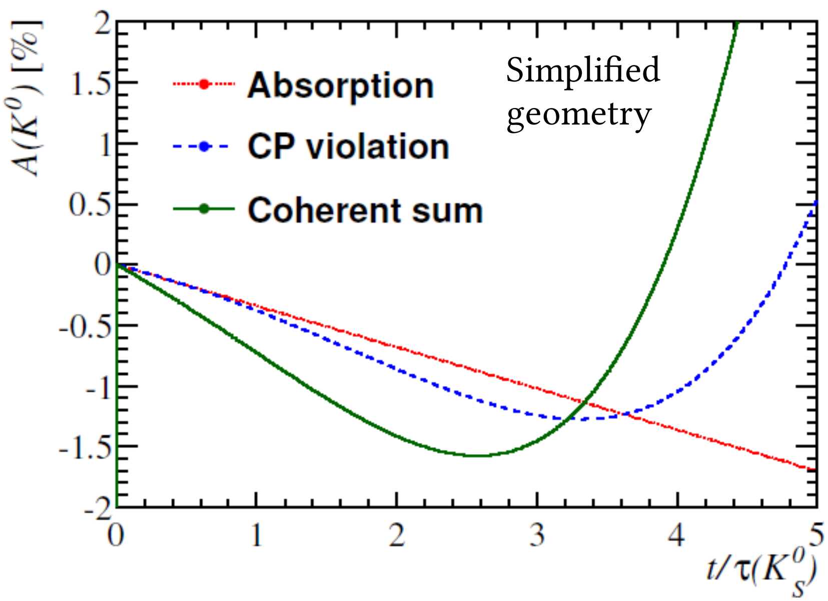
Neutral kaon asymmetry

- Flavour of kaon at production defined

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

- At decay we measure ππ final state (almost pure K^0_S)
- Feature 1: Neutral Kaons mix and decay is CP violating
- Feature 2: Different matter interaction rates for $K^0/\overline{K}^0$
- Feature 3: Both effects interfere

Thesis, S. Stahl



Neutral kaon asymmetry

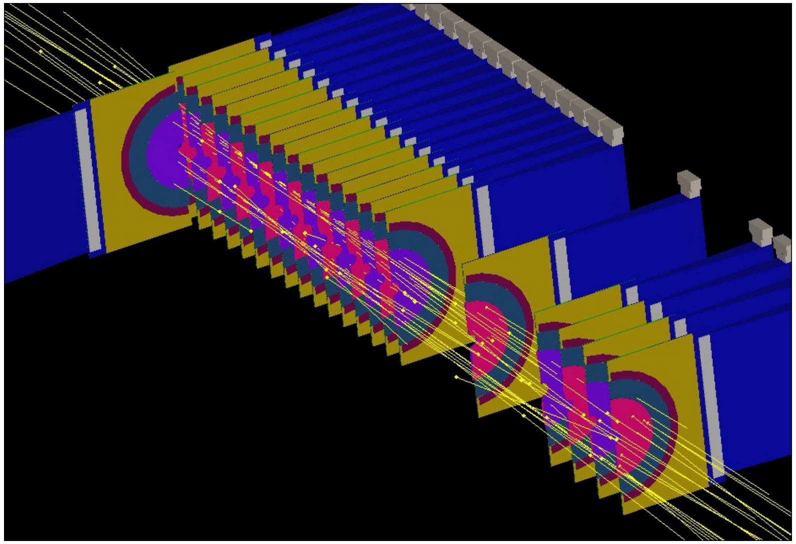
- Formalism well known:

$$\alpha_{\mathrm{L,S}}(t) = \mathrm{e}^{-i\Sigma\cdot t}\left[\alpha^0_{\mathrm{L,S}}\cos(\Omega t) \mp i\,\frac{\Delta\lambda\alpha^0_{\mathrm{L,S}} \pm \Delta\chi\alpha^0_{\mathrm{S,L}}}{2\Omega}\sin(\Omega t)\right]$$

Mixing and CP violation

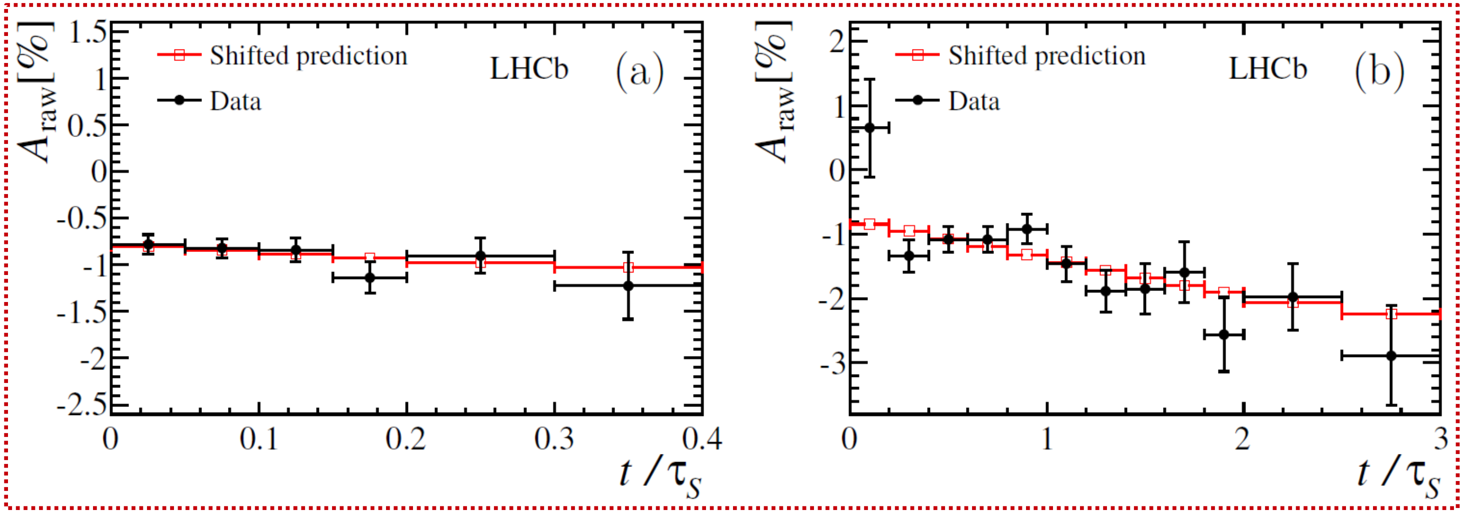
Coherent scattering in material (regeneration)

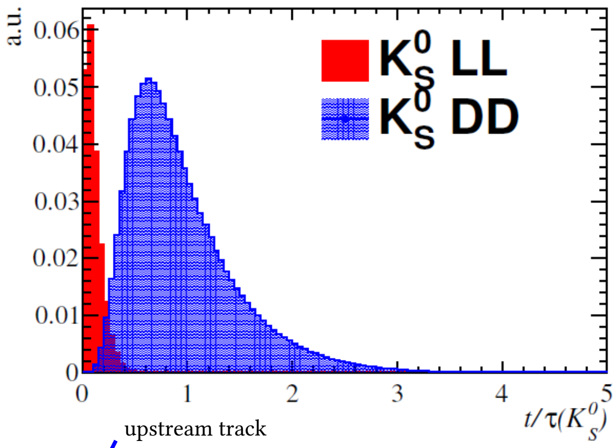
$$|K^0\rangle, |\overline{K}^0\rangle = \frac{\sqrt{1+|\epsilon|^2}}{2}\frac{1}{1\pm\epsilon}\left[|K^0_{\mathrm{L}}\rangle \pm |K^0_{\mathrm{S}}\rangle\right]$$

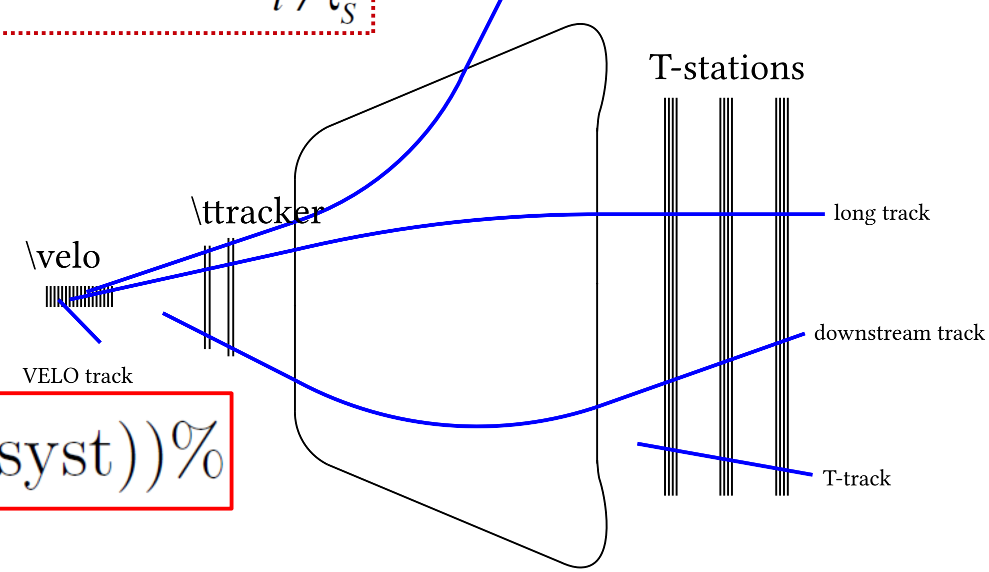


Propagate particles step wise through material map.
$\longrightarrow$ Extract expected asymmetry

Neutral kaon asymmetry







- Model describes data well
- Assigned correction to LL sample

$$A_D(K^0) = (0.054 \pm 0.014\,(\text{syst}))\%$$

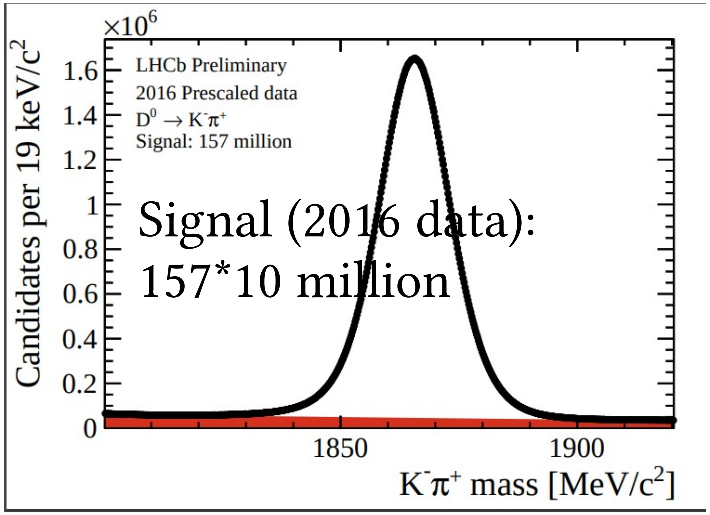
- DD only used to derived systematic
  - effect much bigger

JHEP07(2014)041, S. Stahl PhD thesis

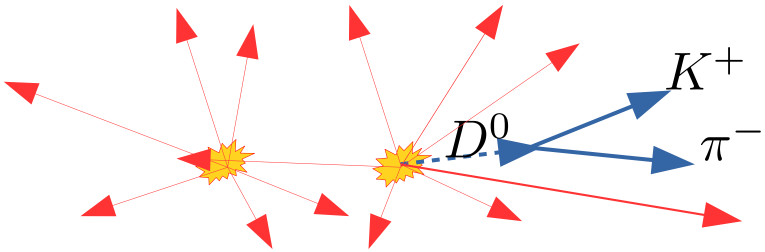
Charm at LHCb (Run 2)

~1 MHz $c\bar{c}$ pairs!

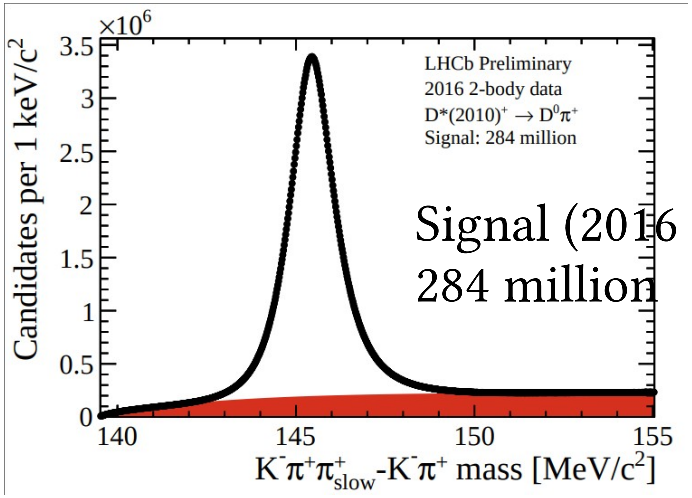
Trigger output:



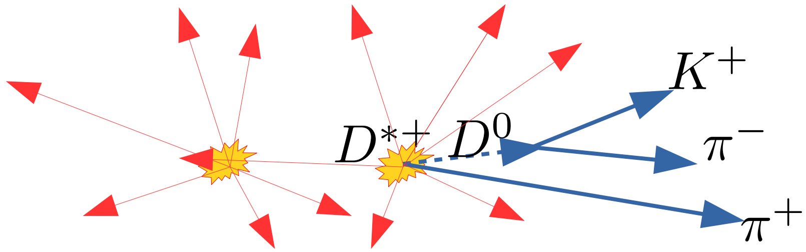
Signal (2016 data):
157*10 million



Trigger output:



Signal (2016 data):
284 million



Huge event rates $\longrightarrow$ limited off-line storage.

ΔA_{CP} history in LHCb since today

Picture by A. Carbone